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TESI DI LAUREA
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DESIGN OF A BEAM STOPPER FOR THE NEW CERN LINEAR ACCELERATOR LINAC4

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Sezione II

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I express my gratitude to Prof Pier Gabriele Molari, Dr Cesare Maglioni and all the CERN EN-STI TCD section for the great opportunity they gave me in this work placement.

> I now walk into the wild.
>
> (A. Supertramp)

Contents

Introduction

In this paper ***I will present the work I have completed during a five months work placement at CERN***, European Organisation for Nuclear Research, from March to July 2011. This stage was done in the EN Department (ENgineering Department), STI Group (Sources, Targets and Interactions), TCD Section (Targets, Collimators and Dumps) under the supervision of Dr Cesare Maglioni.

The task I was given concerned all the beam stoppers in the PS Complex: *a beam stopper is a mechanical safety device used in particle accelerators to intercept the particle beam and guarantee the personnel safety in those zones of the particle accelerator itself that may require access for any reason* (for a clear definition of a beam stopper, see Chapter 1).
In the PS Complex there are 33 of these devices; they all differ from one to the other in mechanism, material, lifting principle, etc. since they were built in more than 50 years following the construction of each of the different accelerators.

Specifically the work involved these devices from start to finish: from the creation of an updated catalogue containing all the current beam stoppers to the design of a new stopper for the CERN's new linear accelerator, the Linac4. The work has been divided into four steps, which correspond to each chapter within this thesis; in detail:

1. **General definition and requirements**. Due to the unclear definition of a beam stopper, some of these devices were used improperly. Hence, the first part consisted of proposing a document with a functional specification of beam stopper, to clarify its use, and with an engineering specification, to list all the requirements a beam stopper

should possess

2. **Creation of a digital archive**. Since the beam stoppers have been designed, manufactured and modified over many years, from the 1960‘s right up to present day, a lot of informations have been not archived and lost. The second part of my work was to find any and all information I could and collete them into a digital archive

3. **Verification of the stoppers of the PS Complex**. Due to their age it was necessary to study and understand if the beam stoppers are able to resist the increased energy levels which are now in place after upgrades over previous years of the accelerator complex. Some preliminary checks have been accomplished to make this clearer.
   Particular attention has been paid to two stoppers, the BI.STP FA and the BI.STP SW. In the coming years an important upgrade will take place at CERN: the substitution of the actual 50 MeV Linac2 injection into the PS Booster with the new 160 MeV Linac4. Due to this change in energy and beam parameters, all beam intercepting devices in the transfer line between the Linac4 to the PS Booster must be investigated and verified for use or accidental use with the new Linac4 beam parameters.
   These two stoppers are not foreseen to be used as safety devices for the Linac4 beam, but the accident scenario HAD to be taken into account

4. **Design of the L4T.STP.1**. As every accelerator, the new Linac4 will need a lot of devices to be working properly; in this part of the paper the design of a new beam stopper for it is proposed

In Appendix A a scheme which summarizes the CERN accelerator Complex and its experimental areas is presented.

Introduzione

In questa tesi ***presenterò il lavoro svolto durante un tirocinio di cinque mesi***, da marzo a luglio 2011, ***presso il CERN***, European Organisation for Nuclear Research. Questo stage è stato compiuto nella sezione EN Department (ENgineering Department), STI Group (Sources, Targets and Interactions), TCD Section (Targets, Collimators and Dumps) sotto la supervisione del Dr. Cesare Maglioni.

Il lavoro svolto riguardava i beam stopper del Complesso PS: *un beam stopper è un dispositivo di sicurezza meccanico utilizzato negli acceleratori di particelle per intercettare il fascio di particelle e garantire la sicurezza del personale in quelle zone dell'acceleratore che possono richiedere accesso per qualsiasi motivo* (per una chiara definizione di beam stopper cfr. Chapter 1).
Nel Complesso PS sono presenti 33 di questi dispositivi; si differenziano tutti uno dall'altro per meccanismo, materiale, principio di attuazione, ecc. poiché sono stati realizzati in più di 50 anni e hanno seguito la costruzione dei diversi acceleratori del complesso.

In dettaglio durante il tirocinio ho trattato questi dispositivi dall'inizio alla fine: dalla creazione di un archivio digitale aggiornato fino alla progettazione di uno stopper per il nuovo acceleratore lineare Linac4 in costruzione al CERN. Il lavoro è stato diviso in quattro passi, corrispondenti ognuno ad un capitolo di questa tesi:

1. **General definition and requirements**. A causa di una definizione poco chiara di beam stopper, alcuni di questi dispositivi erano usati in modo improprio. La prima parte del lavoro è stata quindi la proposta di un documento con la specifica funzionale di beam stopper, a chiarirne

l'utilizzo, e con la specifica ingegneristica, per elencare tutti i requisiti che uno di questi dispositivi deve possedere;

2. **Creation of a digital archive**. Poiché i beam stopper sono stati progettati, realizzati e modificati a partire dagli anni 60 fino ai giorni nostri, molte informazioni non sono state archiviate e sono, quindi, andate perse. La seconda parte del lavoro ha riguardato la ricerca di tutte queste informazioni e la loro collezione in un archivio digitale aggiornato;

3. **Verification of the stoppers of the PS Complex**. A causa dei cambiamenti dei livelli energetici nel complesso di acceleratori, è stato necessario capire se i beam stopper siano ancora in grado di resistere ai fasci di particelle poiché, al contrario, questi dispositivi non hanno visto nessun aggiornamento. A tale scopo sono state compiute alcune simulazioni numeriche che verranno qui presentate.
   Un′attenzione particolare è stata posta a due beam stopper, il BI.STP FA e il BI.STP SW, poiché nei prossimi anni avverrà un importante potenziamento al CERN: la sostituzione dell'attuale acceleratore lineare Linac2 a 50 MeV con il nuovo Linac4 a 160 MeV. Per questo cambio tutti i dispositivi di intercettazione nella linea di trasferimento tra il Linac4 e il PS Booster devono essere verificati in caso di utilizzo accidentale.
   Non è previsto per questi due stopper un impiego con il nuovo fascio proveniente dal Linac4, ma la possibilità DEVE essere considerata.

4. **Design of the L4T.STP.1**. Come tutti gli acceleratori anche nel nuovo Linac4 è previsto l′inserimento di alcuni beam stopper come dispositivi di sicurezza; questa parte della tesi tratta la proposta di design per uno di questi.

Nell'Appendice A viene presentato uno schema riassuntivo che descrive il complesso di acceleratori del CERN e delle sue aree dedicate ai diversi esperimenti.

Chapter 1

General definition of beam stopper and requirements

The first part of the work about beam stoppers was to give a clear definition of that device. With this aim in mind my supervisor and me have proposed a ***document collecting clear statements*** about what a beam stopper is and which is ***its purpose*** to the Organisation. All these statements have been inserted in the CERN internal document EDMS (Engineering and Equipment Data Management Service) $n°1148427$ (see [1]).

The ***first section*** of the chapter presents the ***definition*** of a beam stopper and the ***requirements*** it must possess as they are reported in the original CERN paper.

The ***second section*** contains the ***considerations*** which brought to the statements present in the document and the ***explainations*** of the most important of them in refers to the characteristics of a particle accelerator.

The ***third*** section tells the ***history*** of the document and its ***possible developments***.

1.1 General definition and requirements

1.1.1 Functional definition

A beam stopper is a ***mechanical safety device*** used to intercept a particle beam, to ***guarantee the personnel safety***.

Beam stoppers are situated in a particle accelerator complex in a zone (Zone 1, see Figure 1.1) before any other zone (Zone 2) that may require access for any reason, e.g. maintenance, survey, etc. The stopper guarantees the personnel safety in Zone 2 only.

1.1.2 Engineering definition

The stopper intercepts the particle beam ***by moving its core***, which is specific to the beam characteristics in each zone, on the beam axis.

The beam stopper core is specifically designed to absorb a certain amount of the particle energy (see 1.1.3).

The stopper control is driven by the access system.

The stopper status is an input to the interlock security system, where it exists.

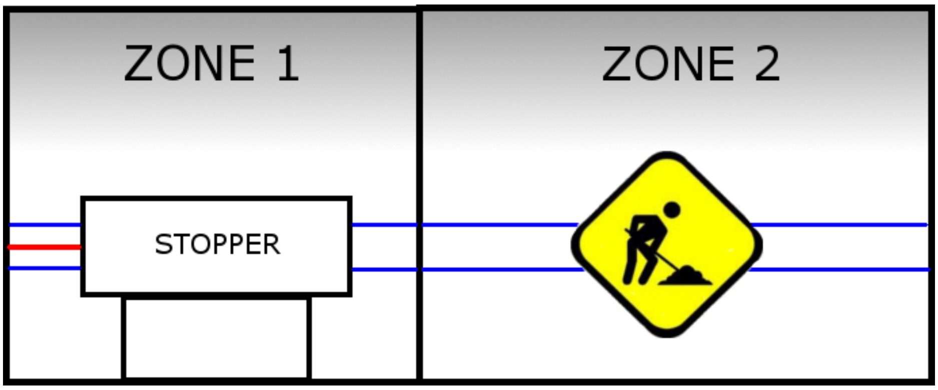


Figure 1.1: Position of the beam stopper referred to the zone which may require access by the personnel

1.1.3 Requirements

General requirements

- The beam stopper ***does not receive any beam during normal operating conditions*** of the accelerator complex; for the same reason it does not have a cooling system
- The beam stopper has only ***two positions***: ***IN*** when the stopper intercepts the particle beam, and ***OUT*** when the stopper does not intercept it
- The stopper ***must not interfere*** with the beam during the operation of the accelerator complex
- The beam stopper is used to stop the beam in an ***emergency case only***, i.e. the rest of the safety system fails to dump the beam; for the same reason the beam stopper is never used as a beam dump
- Depending on the configuration of the beam line the stopper ***has to absorb at least the minimum amount of energy*** which is necessary ***to define 'safe'*** the zone protected by it: the proportion between the amount of stopped energy and the beam energy has to be specified case by case during the design phase of the stopper itself, in collaboration with the RP group (Radio Protection group). This value must get the approval from the RP group to validate the stopper functionality
- The expected life time of the beam stopper assembly, apart that of the core, has to be 20 years under a normal maintenance program, which is defined case by case due to the specific fatigue, thermal and radiation resistance of its components
- In the event of a beam emergency stop, the robustness of the beam stopper core has to be guaranteed for at least one beam pulse, i.e. the interlock system has to trigger the emergency and dump the beam before the following pulse hits the stopper
- The stopper must possess proper values of reliability and availability for its driving mechanism

- The stopper core has to be produced with a sufficient number of spare parts, and the owner of the stopper have to be informed at any time the stopper is supposed to have received a beam pulse

Control requirements

- Switch indicating the position of the block must be present
- The controls of the stopper must allow the operator to place the core block into the beam at any time, but it ***must inhibit its removal*** unless the zone has been cleared
- At least an alarm that warns if the beam stopper has fallen in its in-line position must be present
- An out-of-range alarm has to warn that the driving system has an error (i.e. a pressure fail in the pneumatic or hydraulic system, an electrical problem in the electrical system etc.) and/or if there is a vacuum failure for those stoppers which are under vacuum
- If someone has accessed the zone during ‘no access‘ conditions (e.g. a door is forced), ***the control system must put the stopper in-line immediately***

Safety requirements

The stopper is ***fail-safe***, which means that if there is a failure or a power interruption to the stopper driving system, the block must fall into the beam path (fail safe condition).

1.1.4 Assumptions

- The stopper is designed based on the worst case scenario, i.e. the most severe beam characteristics in the zone of the tunnel where the stopper has to be installed have to be taken into account (considering also an opportune safety factor)

- The stopper is designed to stop and resist to at least one pulse and at maximum few of them. The interlock system is assumed to be able to intervene before the second pulse hits the stopper

- The stopper must follow a proper maintenance program as for any safety device

1.2 Explanation of the beam stopper definition

In this section there are explained definitions and requirements previously reported; reasons of the statements are detailed referred to the aspects of a particle accelerator which must taken into account for the design of a beam stopper.

To make easier for the reader to relate to the first part of the chapter the numeration of the section, except for the number of the section, mirrors exactly the previous one.

1.2.1 Functional definition

As it is stated in 1.1.1 a beam stopper is placed in a zone that is not the zone it has to protect; this assertion calls for a clarification.

The reason lies in the fact that it is not possible to fully stop a particle beam of high primary energy with a block of material of reasonable length. The example in Figure 1.2 clears this concept: it refers to the FLUKA simulation (the fully integrated particle physics MonteCarlo simulation package used at CERN, see [3]) of a 25 GeV proton beam hitting a stainless steel AISI 304 beam stopper core. The graphic shows the proton fluence escaping from the back of the beam stopper core every 500 mm of material.

As can be noticed ***there still are particles escaping from the back of the stopper*** although its core is stainless steel and three meters long. This example refers to the PS 25 GeV beam, but energies at CERN can reach 450 GeV in the SPS and 7 TeV in the LHC.

Because of the impossibility for high energes of the beam to stop all the particles going to Zone 2 the design scope for a beam stopper is ***to deviate***

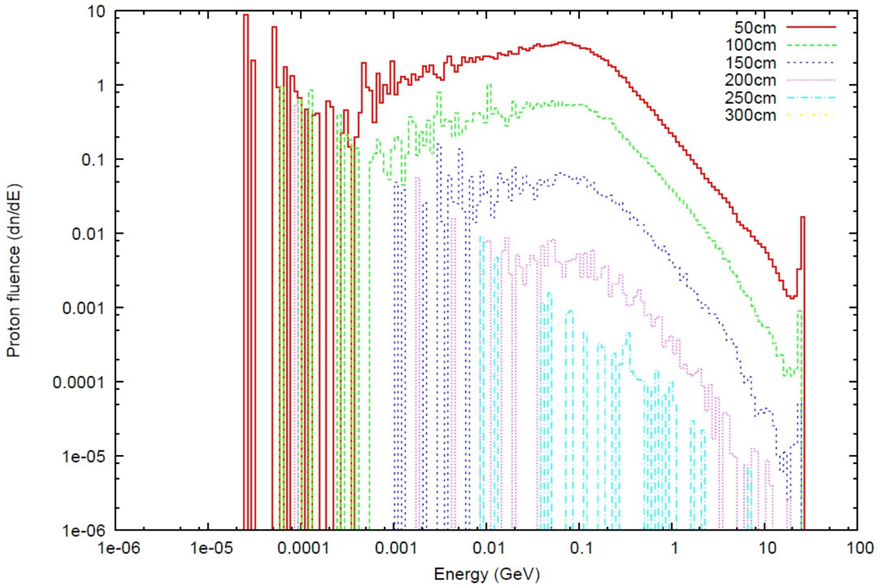


Figure 1.2: FLUKA simulation of the proton fluence caused by a 25 GeV proton beam on an AISI 304 stainless steel beam stopper core

them from their linear path such a way to keep them in a zone of the tunnel where the personnel have not access (Zone 1).

1.2.2 Engineering definition

There are different kind of stoppers present in CERN accelerator Complex (see Chapter 2) but all them have the same functional principle: a block of material is moved into the beam path to deviate the particles and absorb a specific amount of their primary energy (Figure 1.3 and 1.4 are examples taken from the CERN digital archive).

Moderately relativistic charged particles other than electrons lose energy in matter primarily by ionization and atomic excitation. The mean rate of energy loss, or the ‘stopping power‘ of the absorber, can be calculated by the

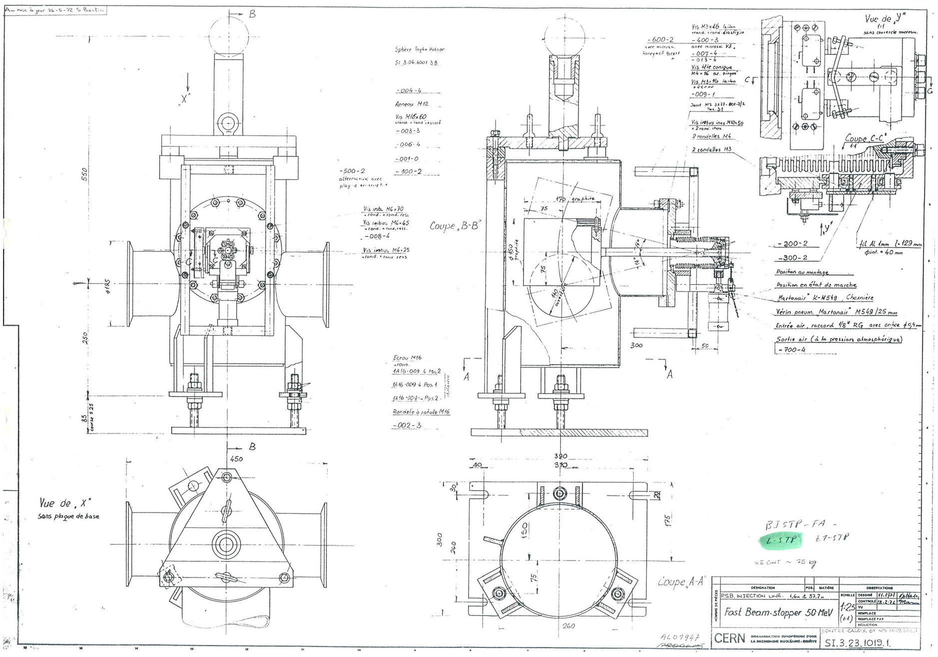


Figure 1.3: Assembly drawing of the beam stopper BI.STP FA with its graphite core

Bethe-Bloch equation (see [4]):

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2\, m_e c^2 \beta^2 \gamma^2 \, T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \qquad [MeV\, g^{-1}\, cm^2] \tag{1.1}$$

Here T_{max} is the maximum kinetic energy which can be imparted to a free electron in a single collision; it is given by:

$$T_{max} = \frac{2\, m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma\, m_e/M + (m_e/M)^2} \tag{1.2}$$

The definition of the other variables are reported in Table 1.1. In this form the equation describes the energy loss in a given material for energies between about 6 MeV and 6 GeV (range comprehending Linac2, Linac3, future Linac4 and PS Booster); at lower energies various corrections must be made (see [4]), while at higher energies radiative effects begin to be important. The equation of course may be integrated to find the total (or partial) projected range R (see Chapter 4) in the ‘continuous slowing-down approximation‘.

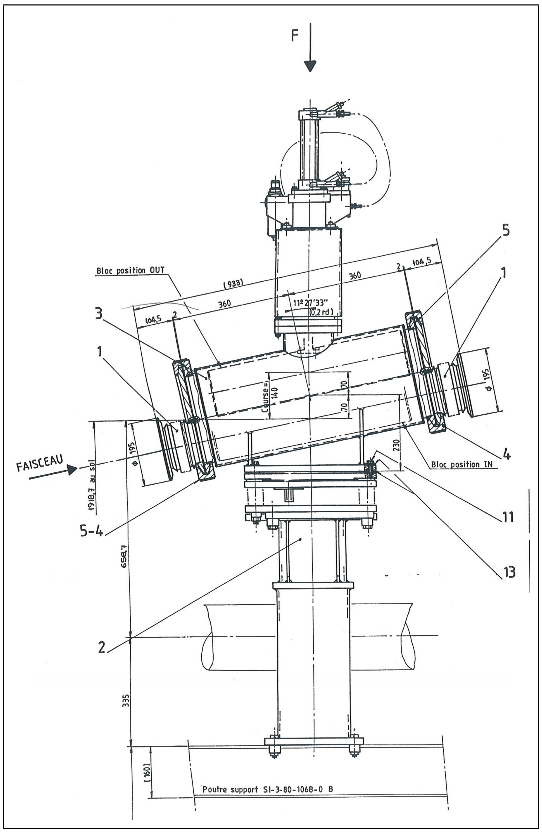


Figure 1.4: Assembly drawing of the beam stopper BY.STP 103 with its stainless steel core

As can be seen from the formula the stopping power primary depends on incident particles velocity (β) and on the absorber (it is sufficent to multiply the Bethe-Bloch equation to the density of the hit material to find the energy loss per distance travelled by the particle).

In accord with the Bethe-Bloch equation previously reported, the word ‘specific‘ used in 1.1.2 refers to the caracteristics (material and length) of the beam stopper core specifically designed for the peculiarities of the beam (primary its kinetic energy) in the zone the beam stopper is placed.

Symbol	Definition	Unit or value
M	Incident particle mass	MeV/c^2
E	Incident particle energy $\gamma\, M\, c^2$	MeV
$m_e c^2$	Electron mass $\times c^2$	$0.510998918(44)\, MeV$
r_e	Classical electron radius $\frac{e^2}{4\pi\epsilon_0}$	$2.817\,940\,325(28) fm$
N_A	Avogadro‘s number	$6.022\,1415(10) \times 10^{-23}\, mol^{-1}$
ze	Charge of incident particle	
Z	Atomic number of absorber	
A	Atomic mass of absorber	$g\, mol^{-1}$
K/A	$4\pi N_A r_e^2 m_e c^2/A$	$0.307\,075\, MeV\, g^{-1}\, cm^2$ for $A = 1\, g\, mol^{-1}$
I	Mean excitation energy	eV
$\delta(\beta\gamma)$	Density effect correction to ionization energy loss	
$\beta = \nu/c$	Velocity of the particle / c	
$\gamma \frac{1}{\sqrt{1-\beta^2}}$	Lorentz factor	

Table 1.1: Summary of the variables used in the equations

1.2.3 Requirements

General requirements

In *General requirements* of section 1.1.3 is stated that a beam stopper is used in emergency situations only if the rest of the safety system fails to dump the beam. During a maintenace operation the personnel ***is always protected by the safety system composed at least by two EIS-beam devices plus the interlock*** (see [5] and [6]); the most common case is interlock, bending magnet, beam stopper. A beam stopper is always placed as the last safety device of the chain and it is used only when each apparatus before it does not work properly.

A ***beam dump*** is a device placed at the end of an accelerator line and it is used to ***dump the beam during normal operating condition*** of the accelerator. For its continuous functioning it has a cooling system. A

beam stopper is designed to dump a beam in an ***emergency case only*** so to dump a single beam pulse; for its noncontinuous functioning it does not require a cooling system.

1.2.4 Assumptions

Through the same part of the accelerator complex more kinds of beam pass, depending in which zone they have to go to or the purpouse of the experiment which is into study in that period.

1.3 Motivations for the document EDMS n° 1148427

The necessity to give a clear definition to the device beam stopper came out during an intersection meeting with Mr Luca Bruno, engineer in the RP - RW section (Radio Protection - Radioactive Waste and Services) HSE (occupational Health and Safety and Environmental protection unit). Mr Bruno is one of the designer of the LHC beam dump and accomplied studies about beam obstacles and their interactions with the beam (see [7], [8] and [9]). The similarities between beam dumps and beam stoppers make confusion to the personnel and they could induce the operators to use beam stoppers in continuous way like beam dumps. This dangerous possibility ***must be avoided*** in any way. The document EDMS n° 1148427 has the important scope to teach the personnel the functions of a beam stopper and to reasume most important requirements it must possess.

The document has been released on 10 June in the EDMS CERN internal database and it finished the first engineering check on 12 July. The comments the document received were discussed in the following STI group meeting on 13 July; the most important consequence was the writing of a child document specific for the Linac4 (see [2]), the new CERN linear accelerator which will take service on 2016. This document will be discussed in Chapter 4 when the design of a stopper for Linac4 will be proposed.

Chapter 2

Creation of a digital archive

This chapter presents the ***logistic work*** about the beam stoppers: collecting all the existing information, checking corrispondances between real devices and the ones on the documents, upgrading missing drawings, converting everything in digital support, etc.

The chapter is divided in ***three sections***: the ***first*** section presents the ***necessity of this work***, the ***starting situation*** and the ***choises*** for the new archive.

The ***second*** section describes the ***new archive*** in its division and ***each part in deep***.

The ***third*** section opens to possible ***extensions and integration*** to the work done.

2.1 The old archive

The ***primary purpose*** of this logistic work was ***to give a new and upgraded form to the old archive of beam stoppers***. Figure 2.1 shows a picture of that archive. In the PS Complex there are 33 beam stoppers at the moment, displaced as they are in the map reported in Figure 2.2.

Three folders composed the old archive. The ***blue covered*** one (see

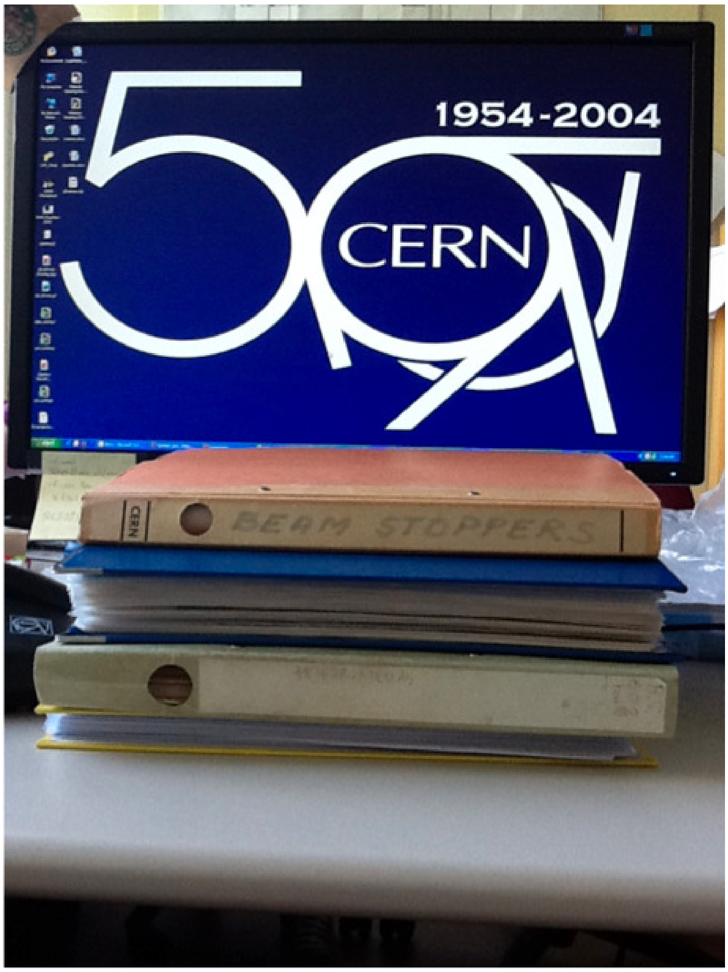


Figure 2.1: The old EN-STI-TCD archive of beam stoppers

Figure 2.1) contained ***all beam stoppers' available informations*** divided into zones of the PS Complex (Linac2, Linac3, LEIR, PS Booster and its ejection, PS Ring, East Hall Area, AD Hall, TT2 to nTOF and SPS; see Appendix A). In particular for each beam stopper it had:

- Assembly drawing
- Part drawings
- Picture(s) of the device
- Scheme of the connection to the power supply

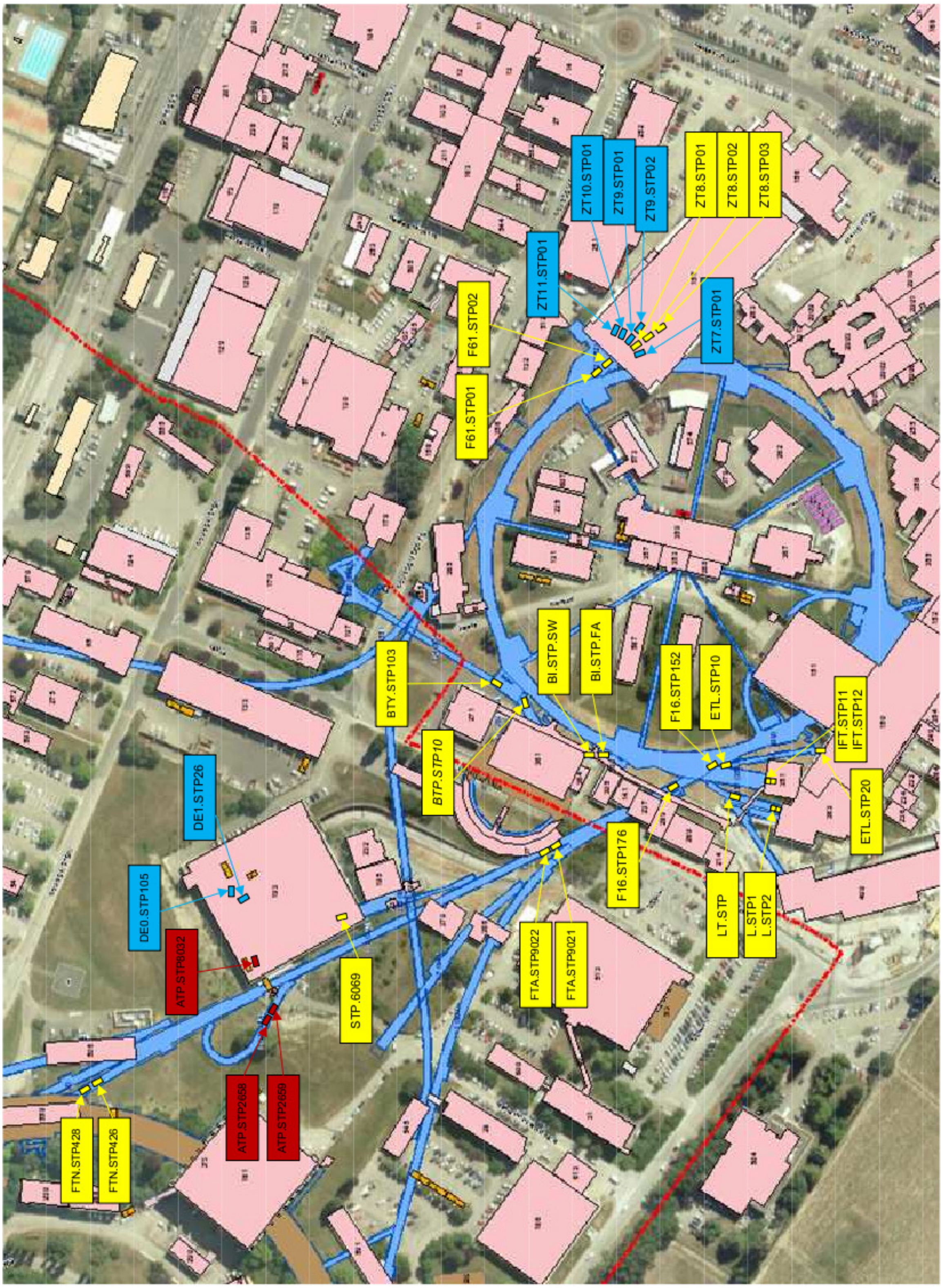


Figure 2.2: Map showing the position of the beam stoppers in the PS Complex

It also contained maintenance operation reports in table sheet format.
The folder with the ***green cover*** collected the ***assembly drawing*** and the ***part drawings of two particular beam stoppers***, the ZT9.STP 01 and the ZT9.STP 02 placed in the East Hall Area.
The folder with the ***red cover*** contained ***maintenance operation reports*** before the 1980's.
The yellow covered folder was a collection of articles about passage of particles through matter and SPS' and LHC's beam stoppers and beam dumps design reports. It was not a real part of the archive.

After a ***comparison*** between the ***archive*** and the ***devices*** really placed along the PS Complex came out that:

- 17 beam stoppers had not an assembly drawing
- Only 2 beam stopper had all part drawings and 2 more had some part drawings
- There were spare photos without any reference
- 3 beam stoppers had changed their name without upgrading the archive
- 2 beam stoppers had been substituted without any trace
- The most recent table of maintenace operations was dated 1996
- There were no design reports for each beam stopper of the PS Complex

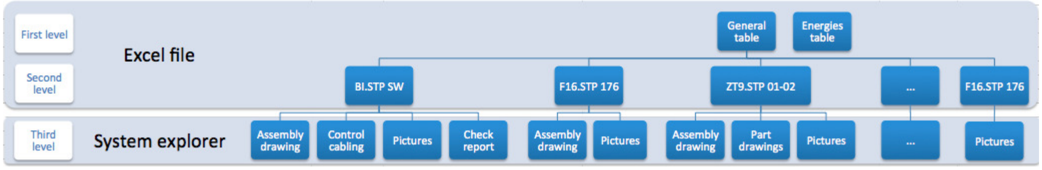


Figure 2.3: Structure of the new beam stoppers' archive

2.2 The new digital archive

The new archive has a ***tree scheme*** in ***three levels*** (see Figure 2.3). Its main part is composed by a Microsoft Excel file (PS Beam stoppers' archive.xslx) whose principal sheets, ***'General table'*** and ***'Energies table'***, form the ***first level***; these two last sections will be illustrated in 2.2.1. The ***second level*** is composed by sheets dedicated to ***single beam stoppers***; identical beam stoppers following each other on the line are grouped together, e.g. F61.STP 01 and F61.STP 02 at East Hall Area entrance (see Figure 2.2). This level will be detailed in 2.2.2.
The ***third level*** is formed by all those files that gives useful information about the beam stoppers of the Complex, typically ***pictures***, ***drawings*** and ***check reports***. Those files and their connection to 'single beam stopper' sheets will be explained in 2.2.3.

2.2.1 First level

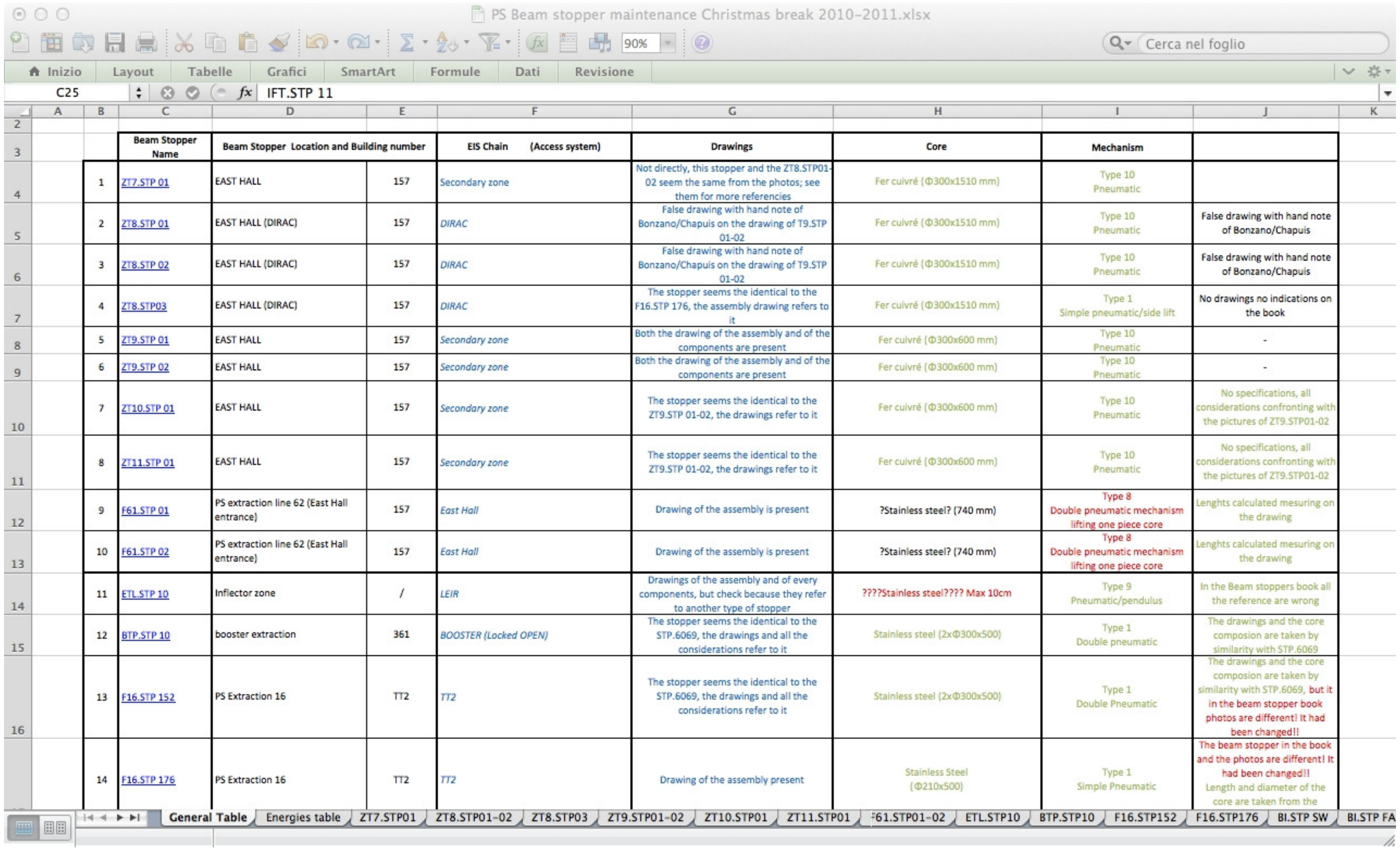
General table

The General 'table' sheet is the top of the tree from which every part of the archive is easely accessible. The ***purpose*** of this table is ***to give an overall look*** about the beam stoppers in the PS Complex (see Figure 2.4); to facilitate this intent a multiple color approach has been used:

- Blue is used to write the EIS chain which the beam stopper belongs to and to describe the drawings inserted in the archive
- Green is employed for data which have a reference to CERN documents or verified in loco by the operator responsible for the beam stoppers (F. Loprete, EN-STI-TCD)
- Black is used for details which could not be verified
- Red is used for uncertain informations

This table is composed by seven columns; in detail from left to right:

1. ***'Beam Stopper Name'*** is filled with the names of the beam stopper; each name is an hyperlink to the dedicated sheet



	Beam Stopper Name	Beam Stopper Location and Building number		EIS Chain (Access system)	Drawings	Core	Mechanism	
1	ZT7.STP 01	EAST HALL	157	Secondary zone	Not directly, this stopper and the ZT8.STP01-02 seem the same from the photos; see them for more referencies	Fer cuivré (Φ300x1510 mm)	Type 10 Pneumatic	
2	ZT8.STP 01	EAST HALL (DIRAC)	157	DIRAC	False drawing with hand note of Bonzano/Chapuis on the drawing of T9.STP 01-02	Fer cuivré (Φ300x1510 mm)	Type 10 Pneumatic	False drawing with hand note of Bonzano/Chapuis
3	ZT8.STP 02	EAST HALL (DIRAC)	157	DIRAC	False drawing with hand note of Bonzano/Chapuis on the drawing of T9.STP 01-02	Fer cuivré (Φ300x1510 mm)	Type 10 Pneumatic	False drawing with hand note of Bonzano/Chapuis
4	ZT8.STP03	EAST HALL (DIRAC)	157	DIRAC	The stopper seems the identical to the F16.STP 176, the assembly drawing refers to it	Fer cuivré (Φ300x1510 mm)	Type 1 Simple pneumatic/side lift	No drawings no indications on the book
5	ZT9.STP 01	EAST HALL	157	Secondary zone	Both the drawing of the assembly and of the components are present	Fer cuivré (Φ300x600 mm)	Type 10 Pneumatic	-
6	ZT9.STP 02	EAST HALL	157	Secondary zone	Both the drawing of the assembly and of the components are present	Fer cuivré (Φ300x600 mm)	Type 10 Pneumatic	-
7	ZT10.STP 01	EAST HALL	157	Secondary zone	The stopper seems the identical to the ZT9.STP 01-02, the drawings refer to it	Fer cuivré (Φ300x600 mm)	Type 10 Pneumatic	No specifications, all considerations confronting with the pictures of ZT9.STP01-02
8	ZT11.STP 01	EAST HALL	157	Secondary zone	The stopper seems the identical to the ZT9.STP 01-02, the drawings refer to it	Fer cuivré (Φ300x600 mm)	Type 10 Pneumatic	No specifications, all considerations confronting with the pictures of ZT9.STP01-02
9	F61.STP 01	PS extraction line 62 (East Hall entrance)	157	East Hall	Drawing of the assembly is present	?Stainless steel? (740 mm)	Type 8 Double pneumatic mechanism lifting one piece core	Lenghts calculated mesuring on the drawing
10	F61.STP 02	PS extraction line 62 (East Hall entrance)	157	East Hall	Drawing of the assembly is present	?Stainless steel? (740 mm)	Type 8 Double pneumatic mechanism lifting one piece core	Lenghts calculated mesuring on the drawing
11	ETL.STP 10	Inflector zone	/	LEIR	Drawings of the assembly and of every components, but check because they refer to another type of stopper	????Stainless steel???? Max 10cm	Type 9 Pneumatic/pendulus	In the Beam stoppers book all the reference are wrong
12	BTP.STP 10	booster extraction	361	BOOSTER (Locked OPEN)	The stopper seems the identical to the STP.6069, the drawings and all the considerations refer to it	Stainless steel (2xΦ300x500)	Type 1 Double pneumatic	The drawings and the core composion are taken by similarity with STP.6069
13	F16.STP 152	PS Extraction 16	TT2	TT2	The stopper seems the identical to the STP.6069, the drawings and all the considerations refer to it	Stainless steel (2xΦ300x500)	Type 1 Double Pneumatic	The drawings and the core composion are taken by similarity with STP.6069, but it in the beam stopper book photos are different! It had been changed!!
14	F16.STP 176	PS Extraction 16	TT2	TT2	Drawing of the assembly present	Stainless Steel (Φ210x500)	Type 1 Simple Pneumatic	The beam stopper in the book and the photos are different! It had been changed!! Length and diameter of the core are taken from the

Figure 2.4: 'General table' of the new beam stoppers' archive

2. In ***'Beam Stopper Location and Building number'*** there are reported the place where the beam stoppers is and the building from which is faster to reach it
3. ***EIS Chain (Access system)*** tells in which sequence of Élement Important de Securité (see 1.2.3) the beam stopper takes part
4. In ***'Drawings'*** column notes and comments about the drawings are detailed referred to the ones present in the old archive
5. The column ***'Core'*** focuses on this part of the beam stoppers detailing its material, diameter and length
6. The part ***'Mechanism'*** specifies which mechanism is mounted on the beam stopper
7. The last column is filled with important notes and comments about each stopper and/or links to documents about stopper's functioning as check reports

'General table' is the first sheet in the Excel file 'PS Beam stoppers' archive.xslx'; it is sufficient to ***click on its label*** on the bottom left of the Excel window ***to activate it***.

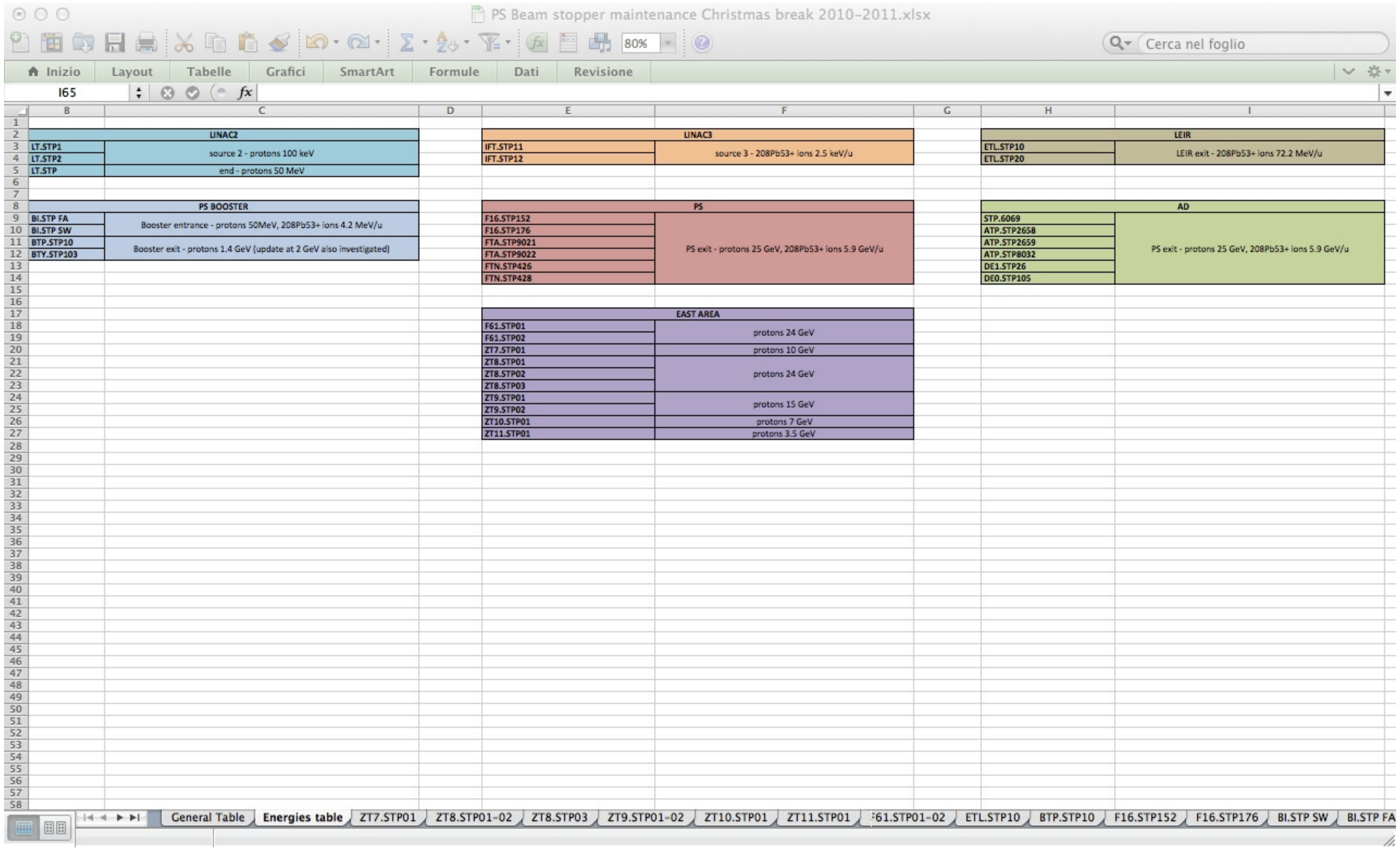
Energies Table

In 'Energies table' there are listed the beam stoppers divided into area of installation and into energy of the beam. Because of some stoppers are exposed to both proton and heavy lead ion ($208Pb53^{+}$) rays, for each its kind of particle is detailed. This way to present the beam stoppers of the CERN Accelerator Complex is usefull for check and tests.

As 'General table', this sheet can be activated by ***clicking its label*** on the bottom left of the Excel window.

2.2.2 Second level

The ***sheets dedicated to each beam stopper*** form the second level of the archive; as can be seen in Figure 2.6 this part ***consists of two tables***.



	B	C	D	E	F	G	H	I
1								
2	LINAC2			LINAC3			LEIR	
3	LT.STP1	source 2 - protons 100 keV		IFT.STP11	source 3 - 208Pb53+ ions 2.5 keV/u		ETL.STP10	LEIR exit - 208Pb53+ ions 72.2 MeV/u
4	LT.STP2			IFT.STP12			ETL.STP20	
5	LT.STP	end - protons 50 MeV						
6								
7								
8	PS BOOSTER			PS			AD	
9	BI.STP FA	Booster entrance - protons 50MeV, 208Pb53+ ions 4.2 MeV/u		F16.STP152	PS exit - protons 25 GeV, 208Pb53+ ions 5.9 GeV/u		STP.6069	PS exit - protons 25 GeV, 208Pb53+ ions 5.9 GeV/u
10	BI.STP SW			F16.STP176			ATP.STP2658	
11	BTP.STP10	Booster exit - protons 1.4 GeV (update at 2 GeV also investigated)		FTA.STP9021			ATP.STP2659	
12	BTY.STP103			FTA.STP9022			ATP.STP8032	
13				FTN.STP426			DE1.STP26	
14				FTN.STP428			DE0.STP105	
15								
16								
17				EAST AREA				
18				F61.STP01	protons 24 GeV			
19				F61.STP02				
20				ZT7.STP01	protons 10 GeV			
21				ZT8.STP01	protons 24 GeV			
22				ZT8.STP02				
23				ZT8.STP03				
24				ZT9.STP01	protons 15 GeV			
25				ZT9.STP02				
26				ZT10.STP01	protons 7 GeV			
27				ZT11.STP01	protons 3.5 GeV			

Figure 2.5: ‘Energies table’ of the new beam stoppers’ archive

The ***upper one*** is a two-rows table, which mirrors exactly each line of the 'General table' except for two columns. In fact here 'Beam Stopper Name' is a ***hyperlink to the third level of the folder*** where all the important files of the stoppers are orderly collected (see 2.2.3), while 'Drawings' opens the ***photo book*** where are stored assembly drawing and part drawings. A photograph of the stopper always supports this table.

The ***lower table*** (see Figure 2.6) resumes a ***preliminary check of each beam stopper core*** faced to the beam(s) it must resist. This check was a study to understand if the beam stopper could make safe the zone it protects. These checks use two free software programs, PSTAR and ATIMA.

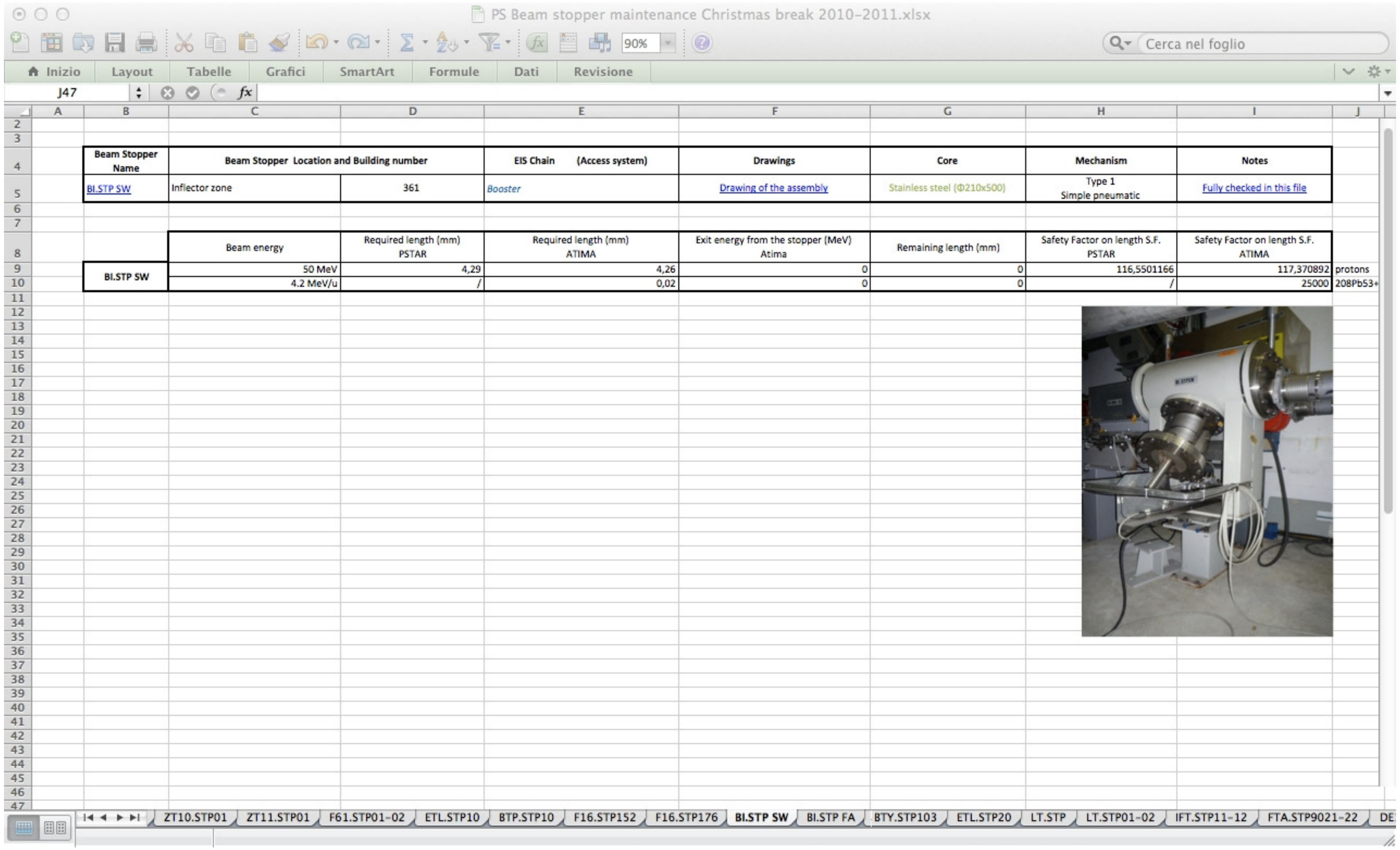
- The ***PSTAR*** program has been developed by the NIST (National Institute for Standards and Technology, see [10]) and calculates stopping power and range tables for protons in various materials for specific kinetic energies from 1 keV up to 10 GeV
- The ***ATIMA*** (ATomic Interaction with MAtter) program is a product developed at GSI Helmholtzzentrum für Schwerionenforschung (see [11]) which calculates various physical quantities characterizing the slowing-down of protons and heavy ions in matter for specific kinetic energies ranging from 1 keV/u to 450 GeV/u

These studies were conducted following the procedure:

- First it has been calculated the required length needed to stop all the primary energy of the particles with the programs previously mentioned
- Second it has been compared the real length of the core to the required length using a factor of safety

$$S.F. = \frac{length\, of\, the\, core\, of\, the\, beam\, stopper}{projected\, range} \tag{2.1}$$

These analysis will be discussed in detail in Chapter 3. What is important to say here is that, because the two programs take into account only atomic interactions, the results reported in the beam stopper sheets are informations usable just for a first study level. In fact at high primary energies of the beam nuclear interactions between the particles and the matter become more and



Beam Stopper Name	Beam Stopper Location and Building number		EIS Chain (Access system)	Drawings	Core	Mechanism	Notes
BI.STP SW	Inflector zone	361	Booster	Drawing of the assembly	Stainless steel (Φ210x500)	Type 1 Simple pneumatic	Fully checked in this file

	Beam energy	Required length (mm) PSTAR	Required length (mm) ATIMA	Exit energy from the stopper (MeV) Atima	Remaining length (mm)	Safety Factor on length S.F. PSTAR	Safety Factor on length S.F. ATIMA	
BI.STP SW	50 MeV	4,29	4,26	0	0	116,5501166	117,370892	protons
	4.2 MeV/u	/	0,02	0	0	/	25000	208Pb53+

Figure 2.6: Example of a beam stopper dedicated sheet of the new archive

more important, so a deep analysis on a beam stopper core must take them into account and it must use software that consider this kind of relationship too. Experieces facing FLUKA simulations (the fully integrated particle physics Monte Carlo simulation package used at CERN to study interaction between beam and matter, see [3]) to PSTAR and ATIMA solutions find out similar values up to 400 MeV of primary energy of the beam.

The beam stopper dedicated sheets are on the bottom of the Excel window; they can be reached by ***clicking on their labels*** or ***activating the hyperlinks*** in ‘General table’.

2.2.3 Third level

The ***third level*** of the archive is the base of the Excel file and it is formed by all the ***files of useful information*** about the beam stoppers, which can from here be recalled, and someone else more. Because of this stage is a collection of folders and files of any kind, ***it can be reached by the file manager of the operating system*** (e.g. Finder on Mac OS X or Windows Explorer on Windows Vista), but the easiest way to reach it is ***using the hyperlinks in the main Excel file*** of the archive.
Each folder has inside at first glance the most important files like assembly drawing and check reports. If more files of one kind were available they have been grouped in dedicated subfolders (see Figure 2.7).

2.3 Conclusion

The creation of the new digital archive has been a work of collecting informations and finding drawings; this work has been possible thanks to Frederic Loprete (technician at the EN-STI-TCD and responsible of the beam stoppers in the PS Complex) while the pictures of the devices and their controls are courtesy of Jerome Lendaro, Alessandro Masi and all the EN-STI-ECE section.

In 2.3.1 there will be presented the features of the new archive faced to the old one.

Further works induced by this document will be described in 2.3.2.

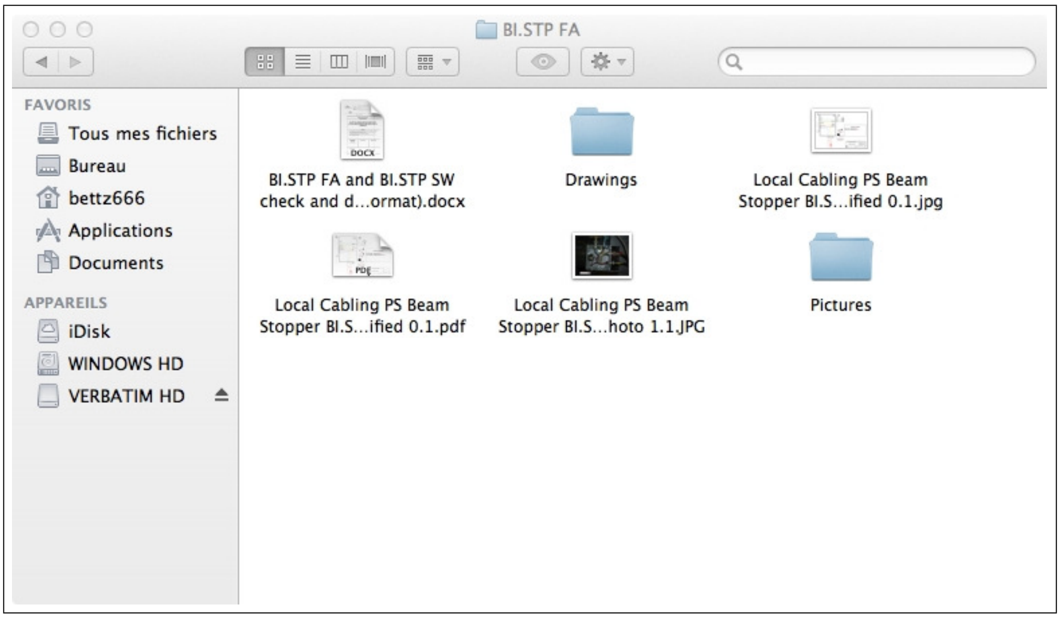


Figure 2.7: Example of a beam stopper dedicated folder (in Finder on Mac Os X operating system)

2.3.1 Old vs. new

Faced to the old paper one, the new archive has all the ***advantages*** proper to the digital format; the most important ones are:

- Ease of upgrade and modification
- Ease of add-on and connection of documents
- Ease of share

These features are the answer to some problems of the old archive listed in 2.2.1; in particular to the substitution of two beam stoppers and to the change of name of three ones more.
Some aspects of the old archive have been improved, in particular:

- 31 of 33 beam stoppers have now at least the assembly drawing (instead of 17 of the old version)
- Every device has pictures of its mechanism and of its controls

- Engineering details like dimension and material of the core added
- Characteristics of the beam linked to the devices

2.3.2 Further work

The lack of knowledge about the design of the beam stoppers, which came out from this logistic work, persauded the TCD section to further investigate the matter. First the problem to understand the real behaviour of the beam stoppers hitten by a beam pulse emerged: can they guarantee the personnel safety in the areas they are called to protect?
Second the question of future upgrade of the accelerator complex turned up: can they withstand to the beam of the new Linac4 or of future projects like the raise of the PS Booster?

This further work called for numerical simulations and specific checks about some devices that will be involved in the nearer upgrades; they will be discussed in Chapter 3.

Chapter 3

Verification of the beam stoppers of the PS Complex

The creation of the digital archive has just been a first step to possess a complete knowledge about the beam stoppers in the PS Complex, their behaviour when faced to the beam must be known as well.
With this aim in mind the most important situations along the accelerators have been simulated; particular regard has been used to the BI.STP FA and BI.STP SW, these two stoppers being involved in the change of the current proton source Linac2 with the new Linac4.

The ***first section*** of the chapter reports ***how the simulations previously mentioned have been carried out***: first the software which has been used will be briefly described; then the simulations which have been done will be explained with their connection to the most important real case.

The ***second section of the chapter focuses on the BI.STP FA and BI.STP SW***: in the coming years an important upgrade will take place at CERN, the substitution of the actual 50 MeV Linac2 injection into the PS Booster with the new 160 MeV Linac4. Due to this change in energy and beam parameters, all beam intercepting devices in the transfer line between the Linac4 to the PS Booster must be investigated and verified for use or accidental use with the new Linac4 beam parameters. These two stoppers

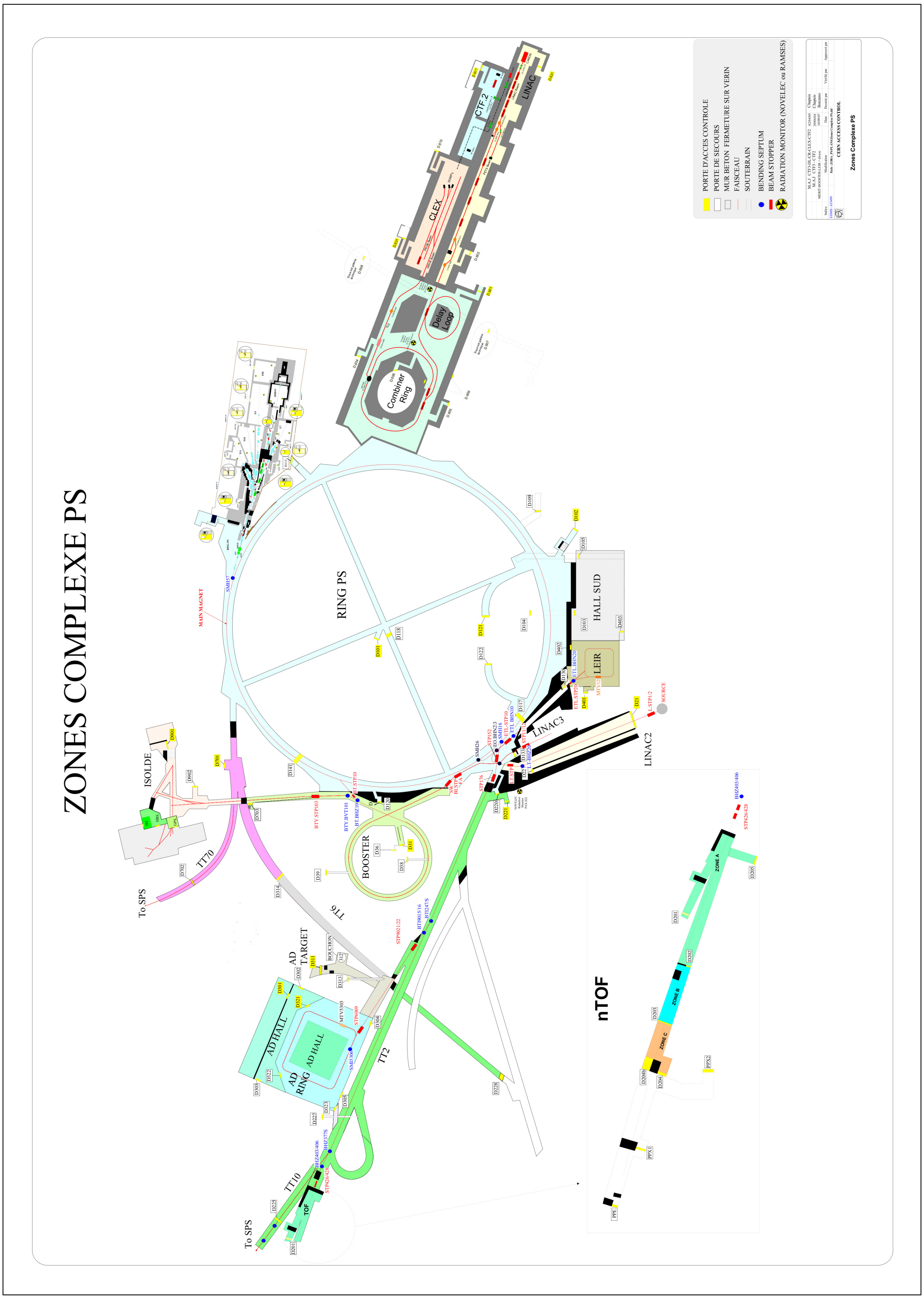


Figure 3.1: Map of the PS Complex

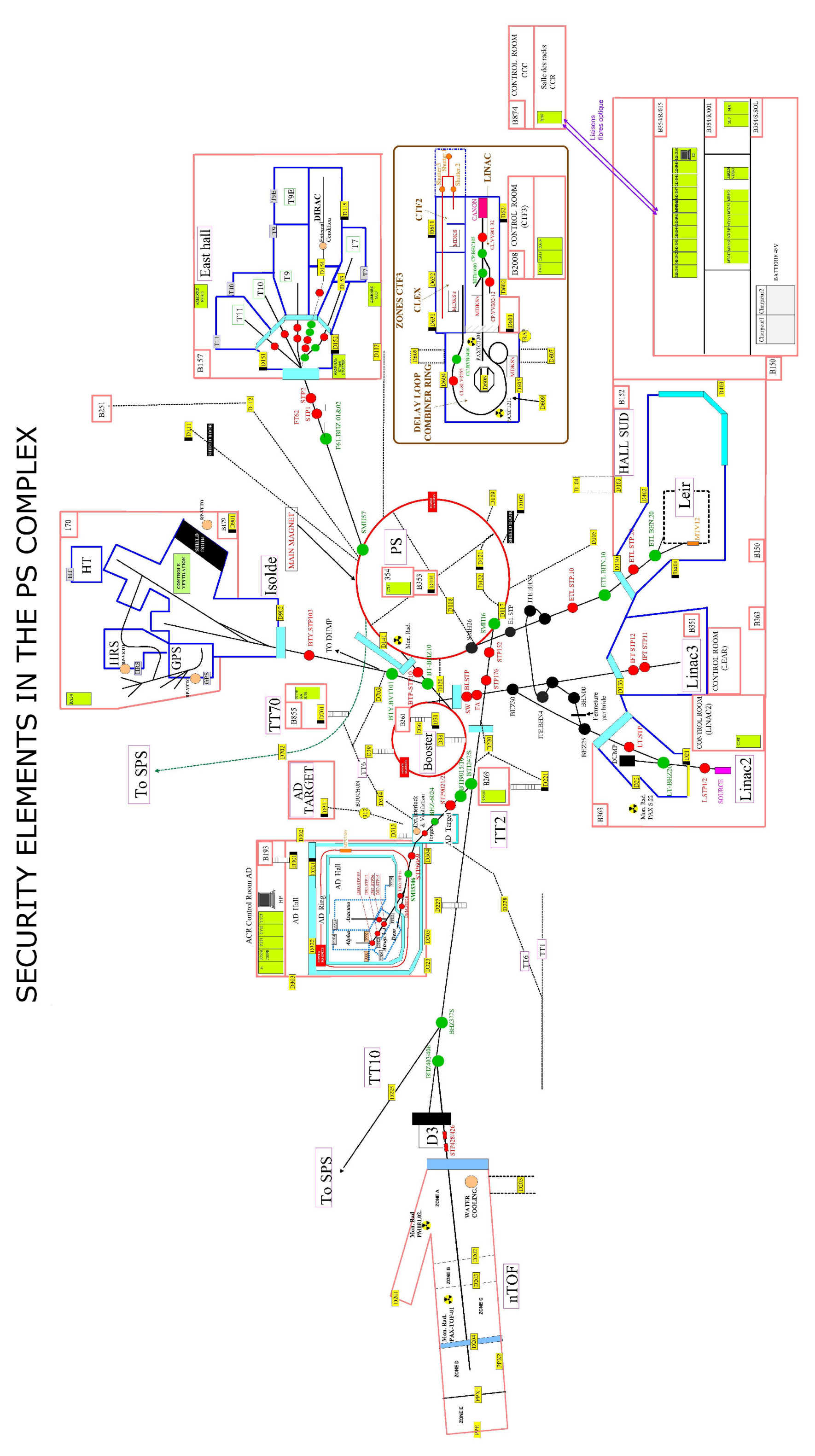


Figure 3.2: Schematic view of the security elements placed in the PS Complex

are not foreseen to be used as safety devices for the Linac4 beam, but the accident scenario HAD to be taken into account.

3.1 Status of the beam stoppers of the PS Complex

The creation of the beam stoppers‘ digital archive has been a huge logistic effort, but the work was incomplete without a study about the capability of these devices to stand the beam specific to their position in the accelerator complex. This lack has been filled with ***numerical simulations*** mirroring ***the most critical real situations*** within the complex.

These simulations have been carried out with the use of the software FLUKA, a fully integrated particle physics MonteCarlo simulation package developed by CERN and the Italian INFN (Instituto Nazionale di Fisica Nucleare) in collaboration with several universities and international organizations [3].

3.1.1 Simulation procedure

The goal of the simulations was to find out the status of the beam stopper after being hit by the beam; with this aim in mind three entity have been determined:

- **Proton fluence escaping from the back of the core**. The purpose of a beam stopper is to guarantee the personnel safety intercepting the particle beam; determing the proton fluence means to define how many particles escape from the last end of the core and which are their energy

- **Energy deposition map**. While the particles are traveling they slowly release their energy to the core; to map the energy deposition implies the possibility to find out thermo-mechanical stresses along the adsorber

- **Maximum energy deposition profile**. The maximum energy deposition profle permits to calculate the maximum temperature reached by the core

Specimen cores

The specimen core has been modeled as a cylinder of $\Phi = 300\,mm$, which is the most common diameter in the PS Complex, while its length has been assumed as infinite. This choice is important considering the proton fluence: this value has been graphed every $50\,cm$ both to consider the real cores and to determine the ideal lengths to define safe Zone 2 (see 1.1.1).
Three material have been take into account as they include almost the totality of the cores: stainless steel AISI 304, coppered iron and pure iron.

Specimen beams

The specimen beams has been modeled as a pulse of a single bunch of 4.88×10^5 protons, while energies and beam sizes reflect the most critical cases of the accelerator complex:

- 1.4 GeV related to the PS Booster extraction
- 15 GeV of the T9 line in the East Hall Area
- 25 GeV owned by the PS extraction

3.1.2 Results

The results of the numerical analyses will be presented in the following pages. All the values are normalised to one incident proton.

1.4 GeV proton beam - Stainless steel - PS Booster extraction

Beam energy	1.4 GeV
Beam size ($\sigma_x \times \sigma_y$)	$9.30 \times 6.95\ mm$
Core material	Stailess steel AISI 304

Table 3.1: Beam characteristics and core material

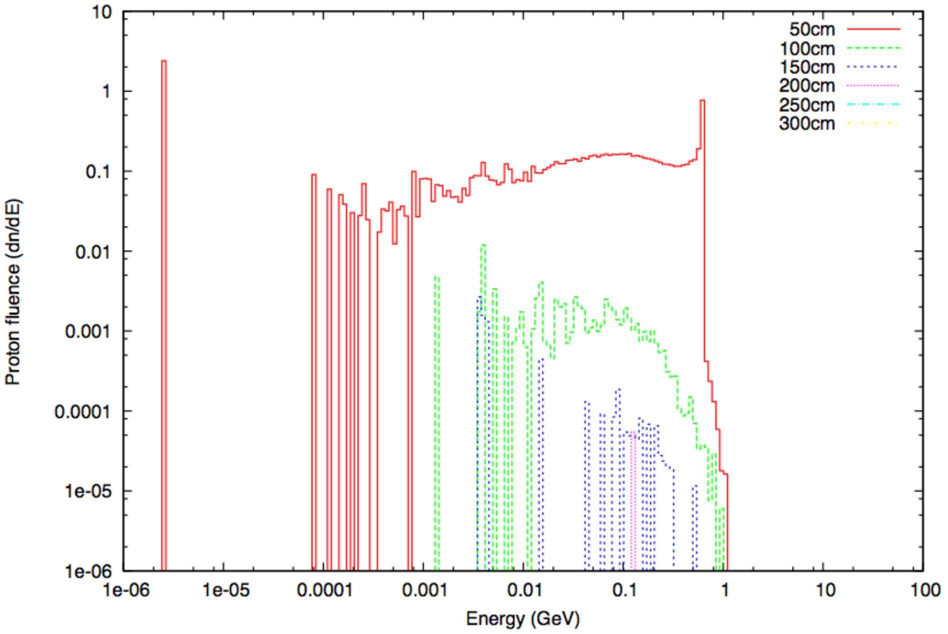


Figure 3.3: Proton fluence caused by a 1.4 GeV beam on an AISI 304 stainless steel core

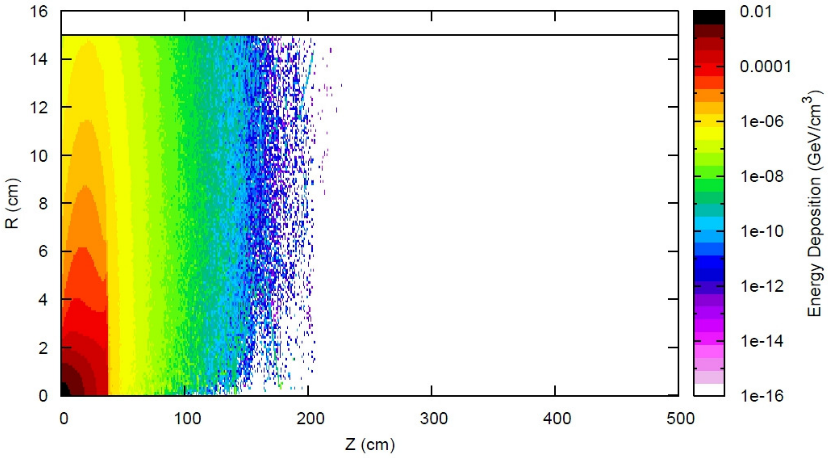


Figure 3.4: Energy deposition map of a 1.4 GeV beam along an AISI 304 stainless steel core

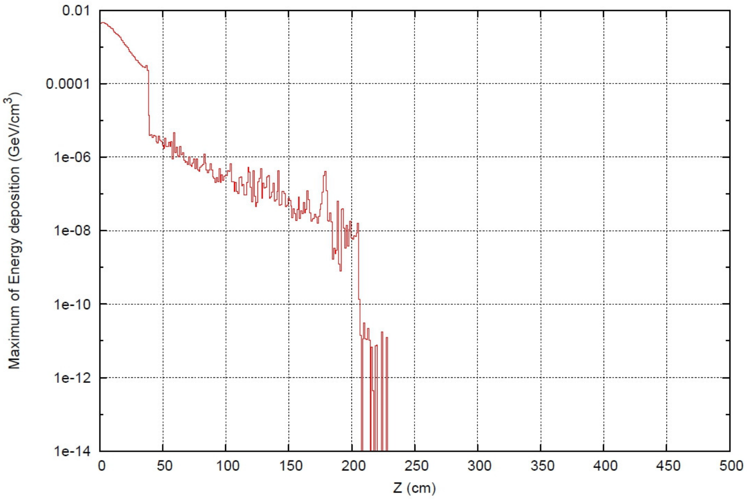


Figure 3.5: Maximum energy deposition profile of a 1.4 GeV beam along an AISI 304 stainless steel core

15 GeV proton beam - Pure iron - East Hall Area

Beam energy	15 GeV
Beam size ($\sigma_x \times \sigma_y$)	$5.26 \times 5.38\ mm$
Core material	Iron

Table 3.2: Beam characteristics and core material

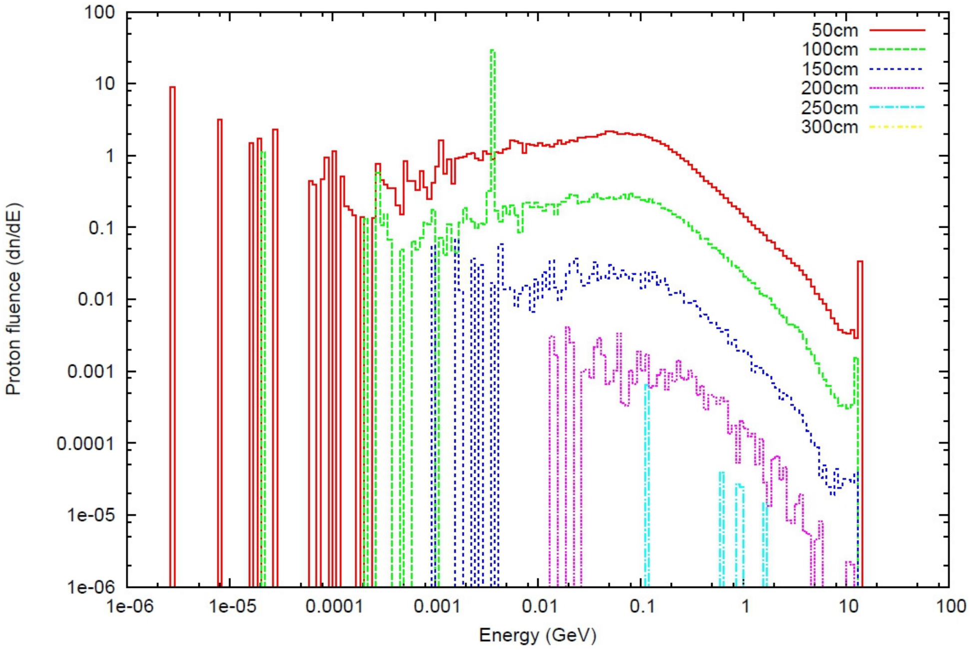


Figure 3.6: Proton fluence caused by a 15 GeV beam on a pure iron core

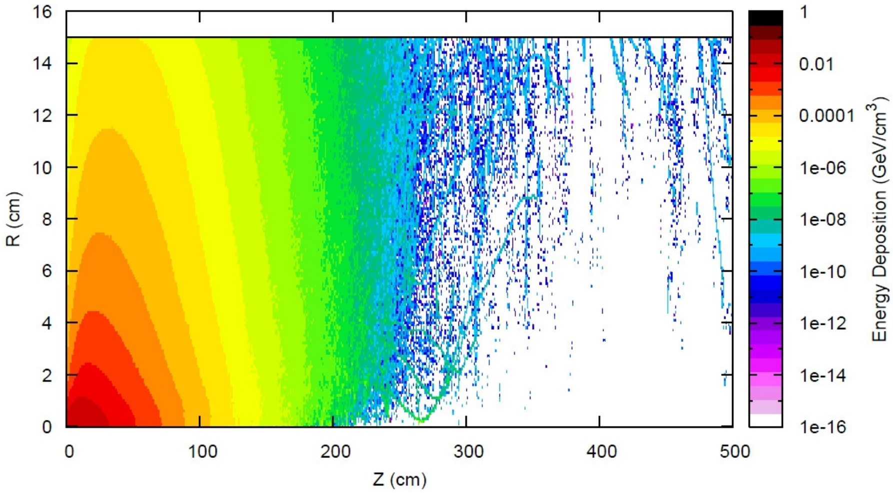


Figure 3.7: Energy deposition map of a 15 GeV beam along a pure iron core

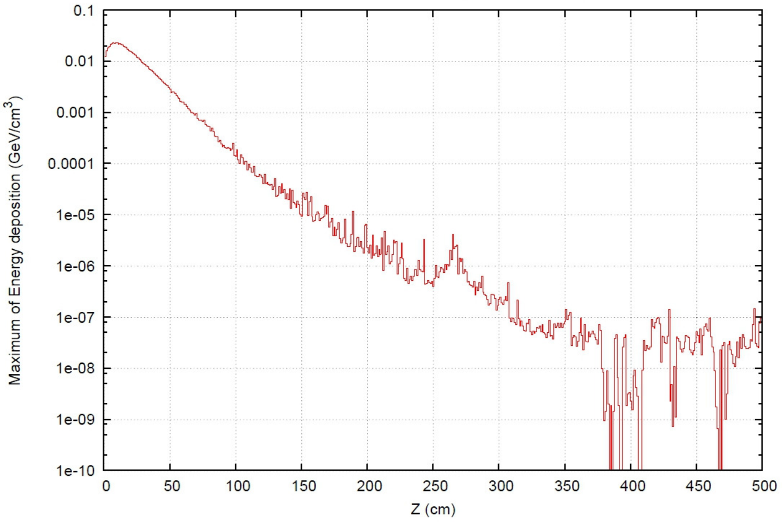


Figure 3.8: Maximum energy deposition profile of a 15 GeV beam along a pure iron core

15 GeV proton beam - Coppered iron- East Hall Area

Beam energy	15 GeV
Beam size ($\sigma_x \times \sigma_y$)	$5.26 \times 5.38\ mm$
Core material	Coppered iron

Table 3.3: Beam characteristics and core material

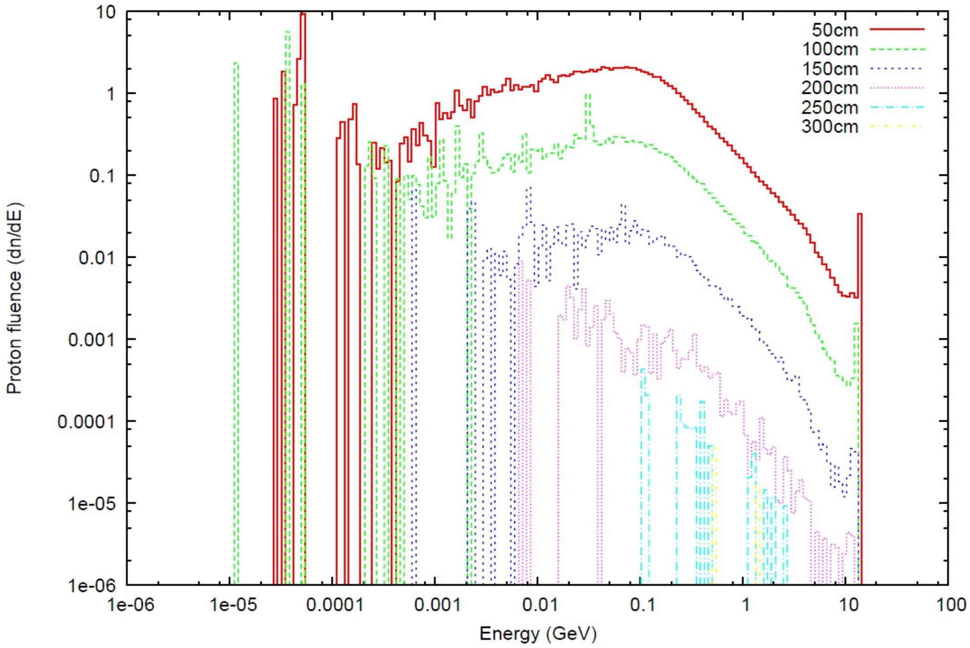


Figure 3.9: Proton fluence caused by a 15 GeV beam on a coppered iron core

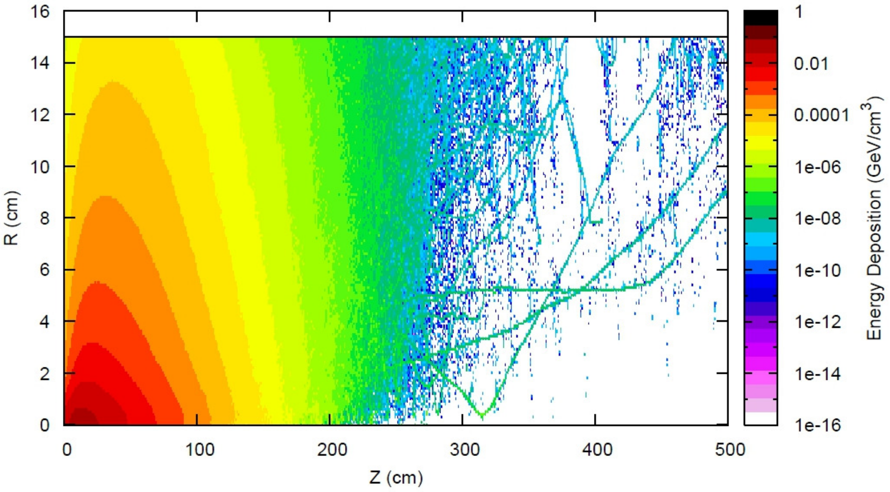


Figure 3.10: Energy deposition map of a 15 GeV beam along a coppered iron core

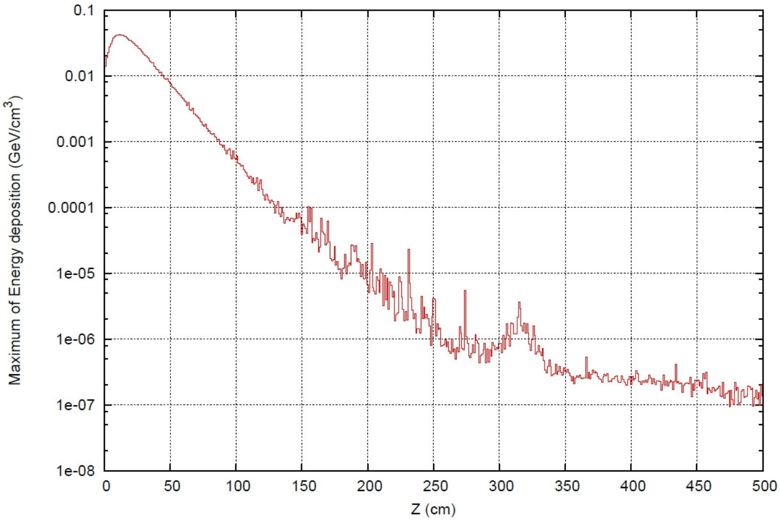


Figure 3.11: Maximum energy deposition profile of a 15 GeV beam along a coppered iron core

25 GeV proton beam - Pure iron - PS extraction

Beam energy	25 GeV
Beam size ($\sigma_x \times \sigma_y$)	$5.26 \times 5.38\ mm$
Core material	Iron

Table 3.4: Beam characteristics and core material

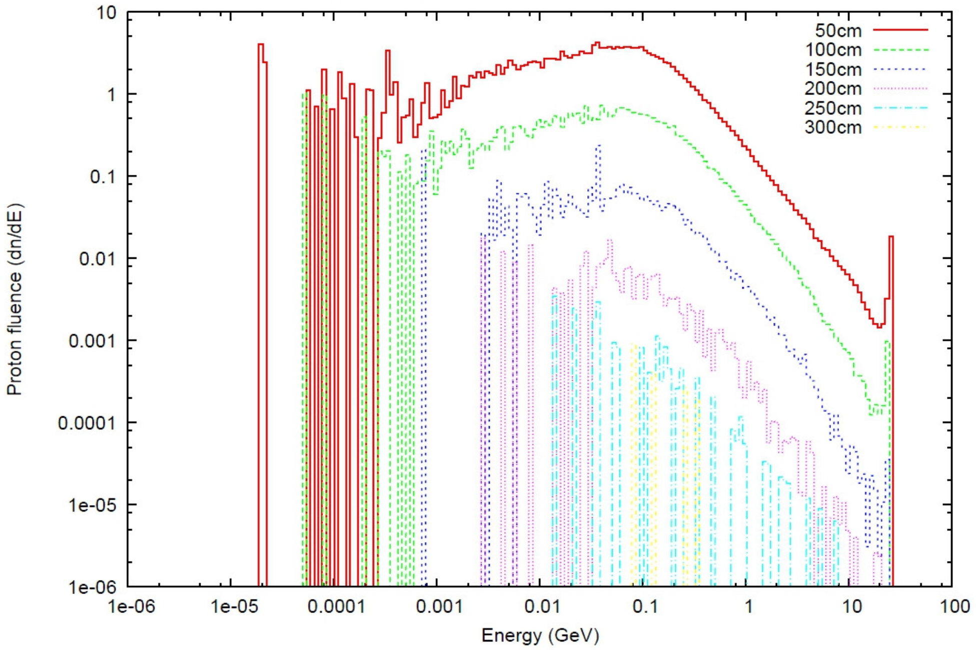


Figure 3.12: Proton fluence caused by a 25 GeV beam on a pure iron core

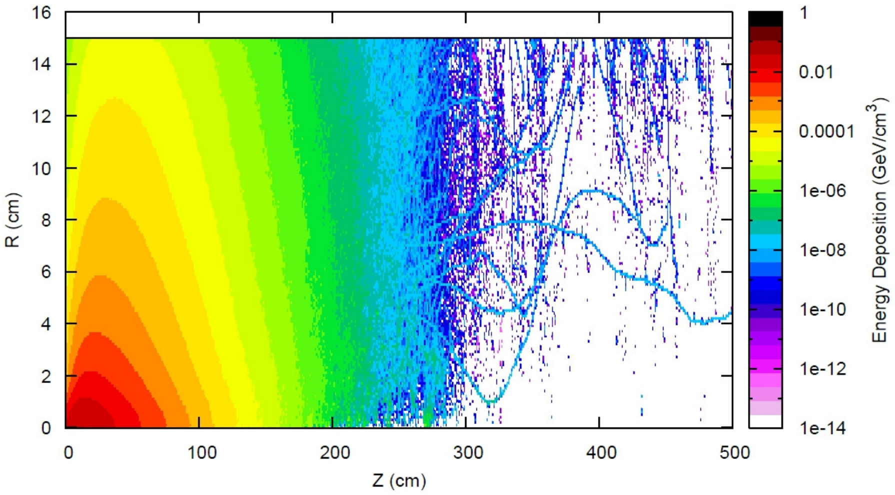


Figure 3.13: Energy deposition map of a 25 GeV beam along a pure iron core

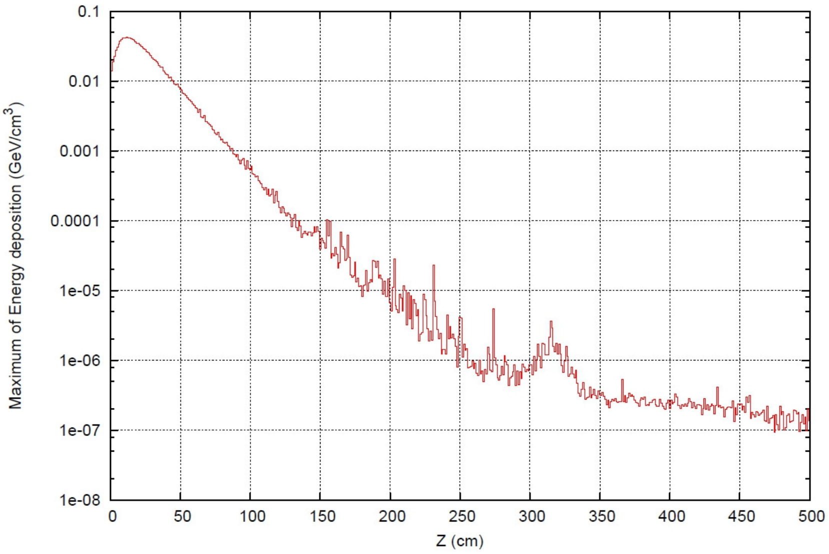


Figure 3.14: Maximum energy deposition profile of a 25 GeV beam along a pure iron core

25 GeV proton beam - Coppered iron- PS extraction

Beam energy	25 GeV
Beam size ($\sigma_x \times \sigma_y$)	$5.26 \times 5.38\ mm$
Core material	Coppered iron

Table 3.5: Beam characteristics and core material

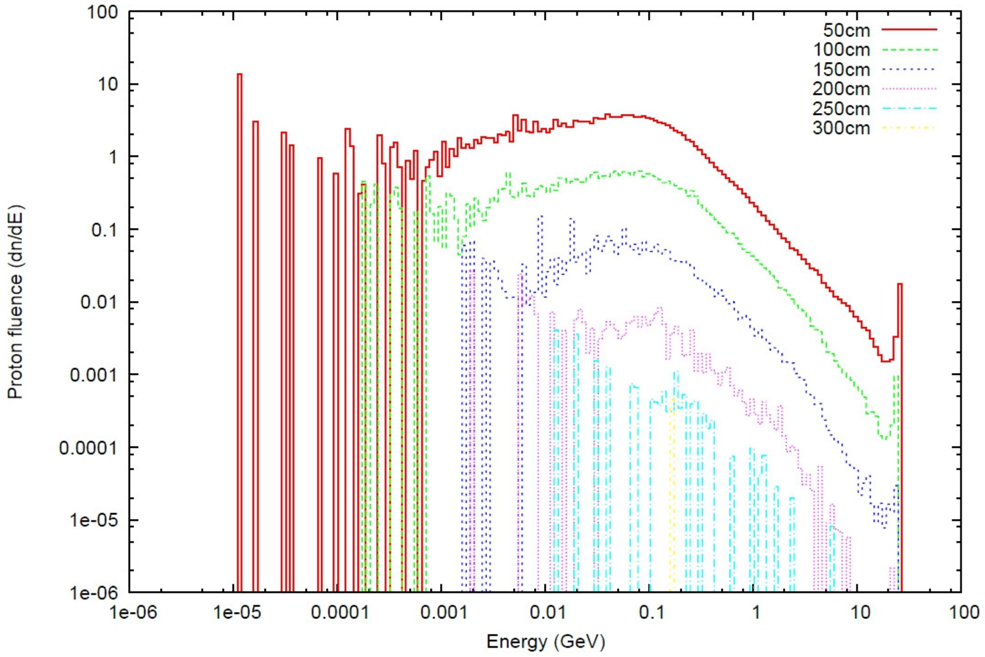


Figure 3.15: Proton fluence caused by a 25 GeV beam on a coppered iron core

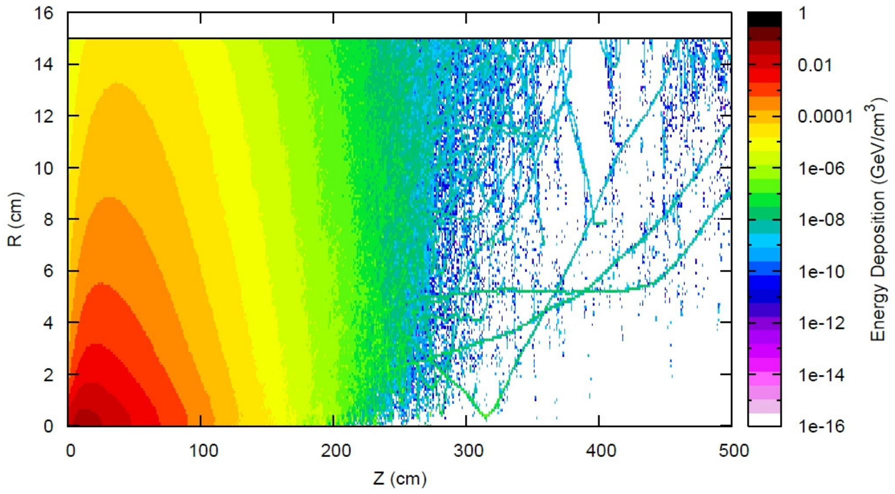


Figure 3.16: Energy deposition map of a 25 GeV beam along a coppered iron core

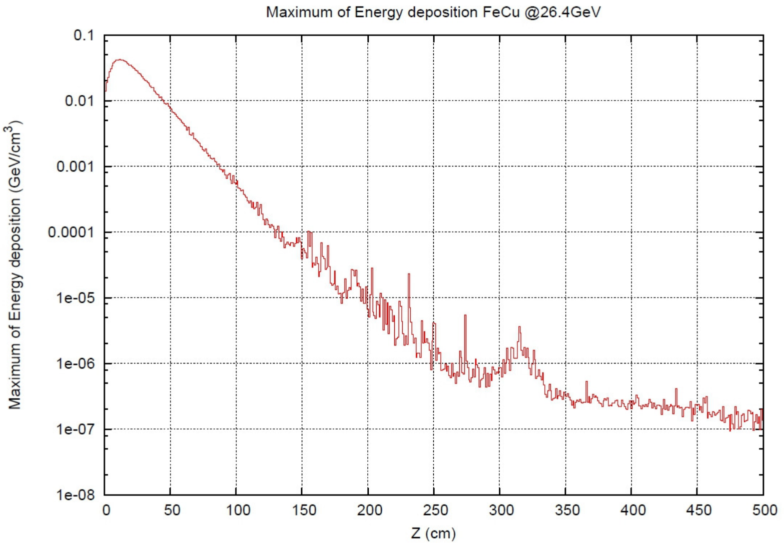


Figure 3.17: Maximum energy deposition profile of a 25 GeV beam along a coppered iron core

25 GeV proton beam - Stainless steel AISI 304 - PS extraction

Beam energy	25 GeV
Beam size ($\sigma_x \times \sigma_y$)	$5.26 \times 5.38\ mm$
Core material	Stainless steel AISI 304

Table 3.6: Beam characteristics and core material

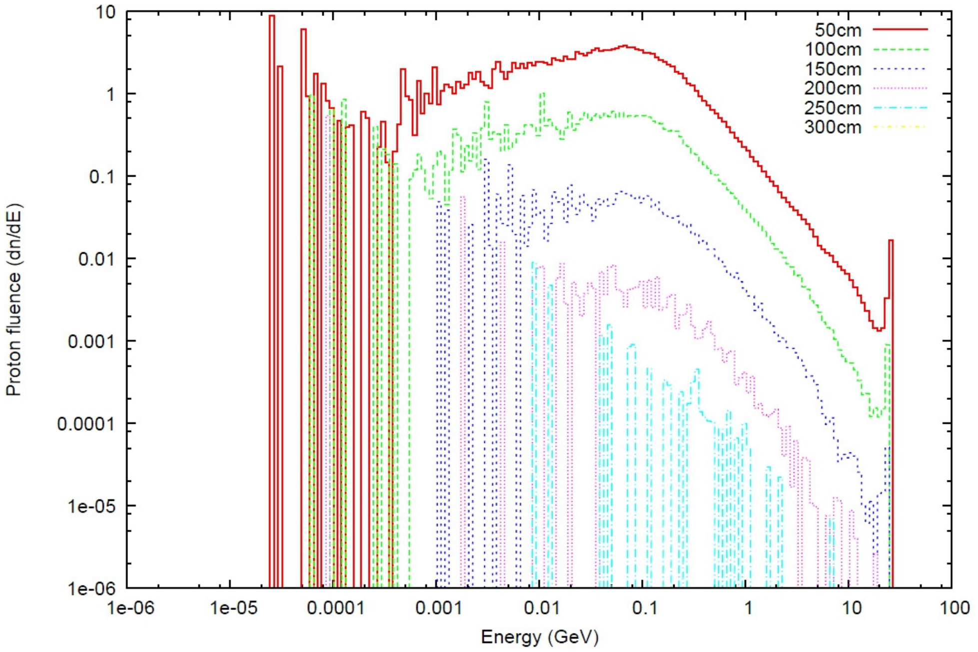


Figure 3.18: Proton fluence caused by a 25 GeV beam on a Stainless steel AISI 304 core

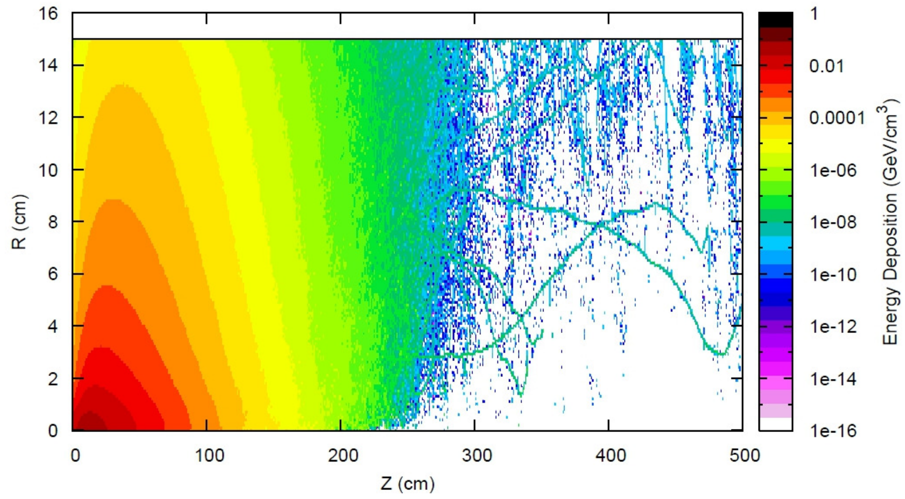


Figure 3.19: Energy deposition map of a 25 GeV beam along a Stainless steel AISI 304 core

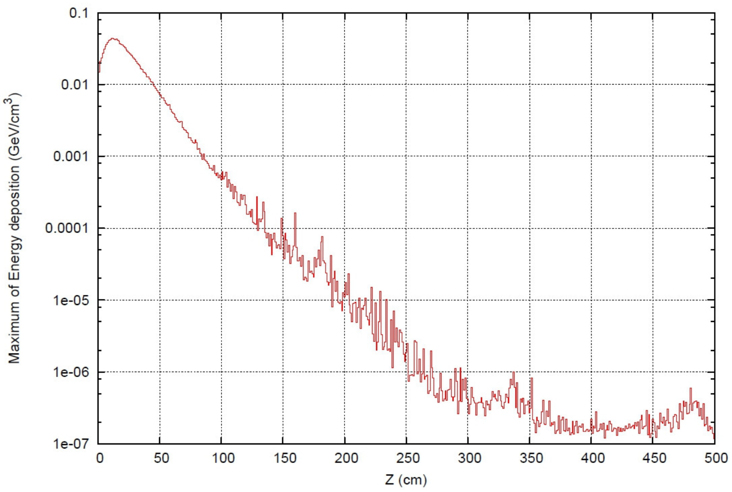


Figure 3.20: Maximum energy deposition profile of a 25 GeV beam along a Stainless steel AISI 304 core

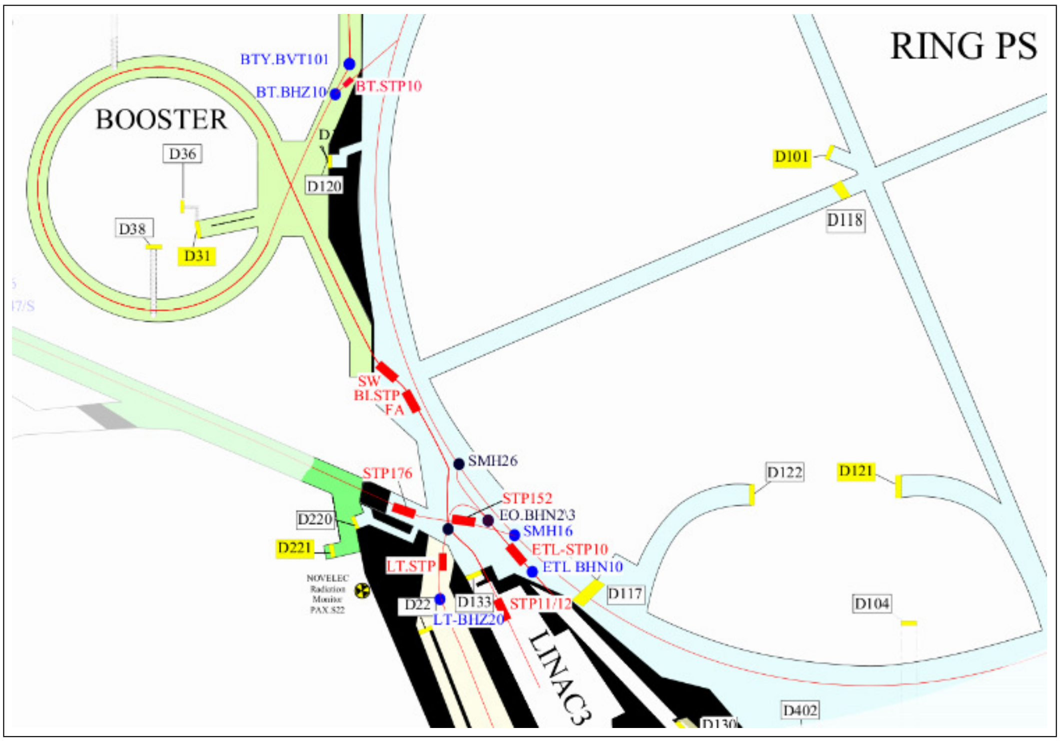


Figure 3.21: Position of the BI.STP FA and BI.STP SW in the PS Complex

3.1.3 Conclusions

The **Proton fluence** graphs show that in the PS extraction and East Hall Area a large amount of particles exit from the beam stopper cores at potential dangerous energies; these values have to be analysed by the RP Group (Radio Protection Group) which is in charge to estimate the risk of injuries for the personnel.

The **Energy deposition** and **max energy deposition profile** graphs need further thermo-mechanical analysis to evaluate if the beam stoppers core can stand the beam without failure.

3.2 Focus on the BI.STP FA and BI.STP SW

The BI.STP FA and BI.STP SW are placed in the Inflector Zone between the Linacs and the PS Booster (see Figure 3.21). Due to the low beam energies involved the verification of these stoppers have been conducted by the use of two computer free programs, PSTAR and ATIMA (see Section 2.2.2 for more informations). Those programs calculate the ***projected range***, which is the average path length traveled by a charged particle in a given material as it slows down to rest. This value, computed with the assumption of the continuous-slowing-down approximation of the particle, has been taken as the requested length to the BI.STA FA and BI.STP SW cores to complete their task.

The validation consists of the confront of the real lengths to the projected ranges by the use of a Factor of Safety:

$$S.F. = \frac{length\, of\, the\, core\, of\, the\, beam\, stopper}{projected\, range} \tag{3.1}$$

The two stoppers presently see both the protons beam of Linac2 and the $208Pb53^{+}$ ions beam from Linac3. The projected ranges have been calculated considering all the materials pure, uniform and isotropic.

3.2.1 Verification to the Linac2 50 MeV proton beam

The beam parameters corresponding to the worst condition for the verification of the beam stopper for Linac2 are reported in Table 3.7.

Beam energy	50 MeV
Pulse length	150 μs
Pulse current	180 mA
Repetition rate	1 Hz

Table 3.7: Linac2 beam characteristics

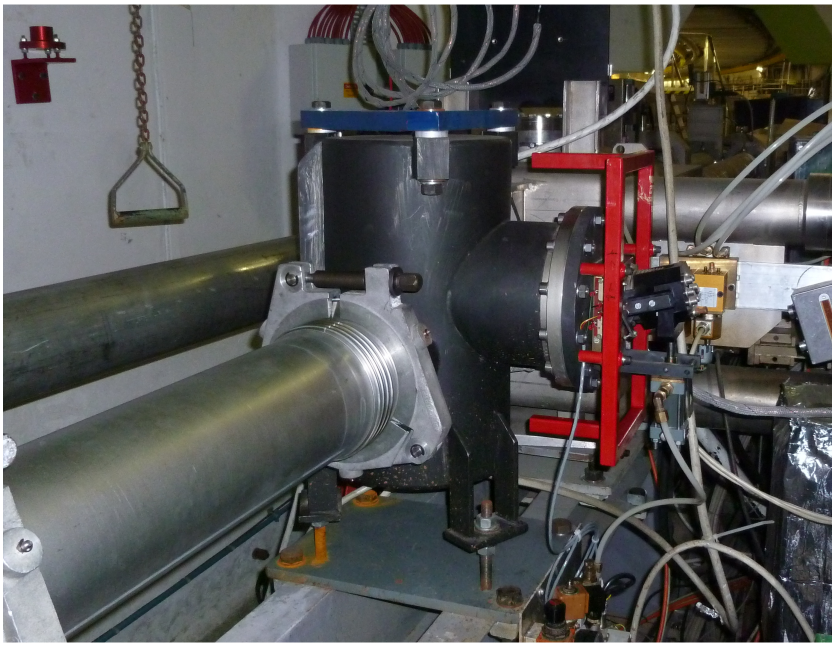


Figure 3.22: The BI.STP FA beam stopper

BI.STP FA

The BI.STP FA is a fast stopper with a graphite core: four hollow concentric cylinders of pyrolytic graphite ($\rho = 2.16\, g/cm^3$)) are mounted on a pendulum which falls into the beam line if there is the need to intercepts the particle flux (see Figure 3.22, Figure 3.23 and Figure 3.24).
The dimensions of the four cylinders are ($external\, diameter \times thickness \times lenght$ in mm):

- 150 × 1.60 × 170, external
- 140 × 1.75 × 170, medium external
- 130 × 1.85 × 170, medium internal
- 120 × 2.10 × 170, internal

The beam has to pass through a total thickness of:

$$t_{tot} = (1.60 + 1.75 + 1.85 + 2.10) \cdot 2 = 14.6\, mm \tag{3.2}$$

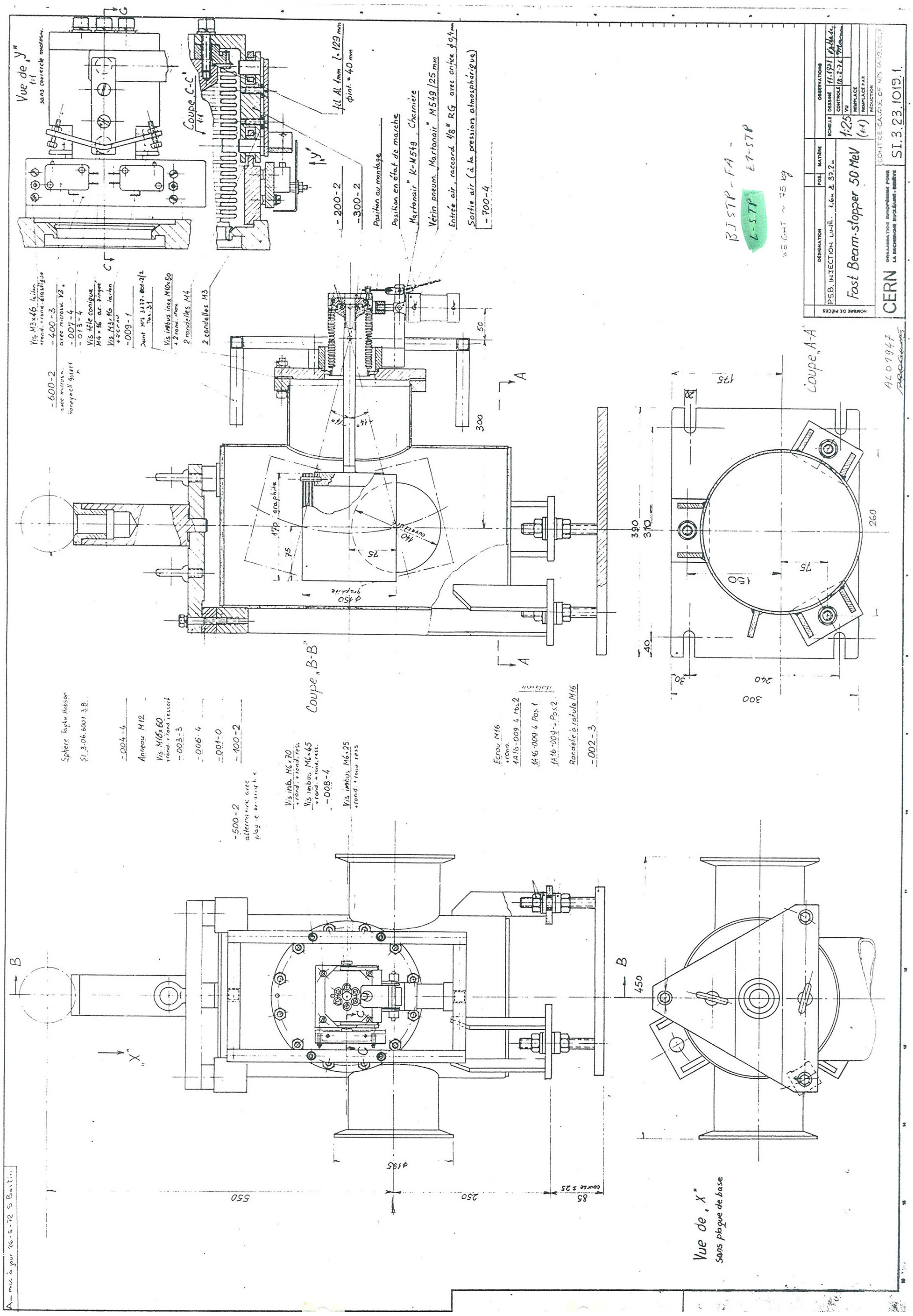


Figure 3.23: BI.STP FA assembly drawing

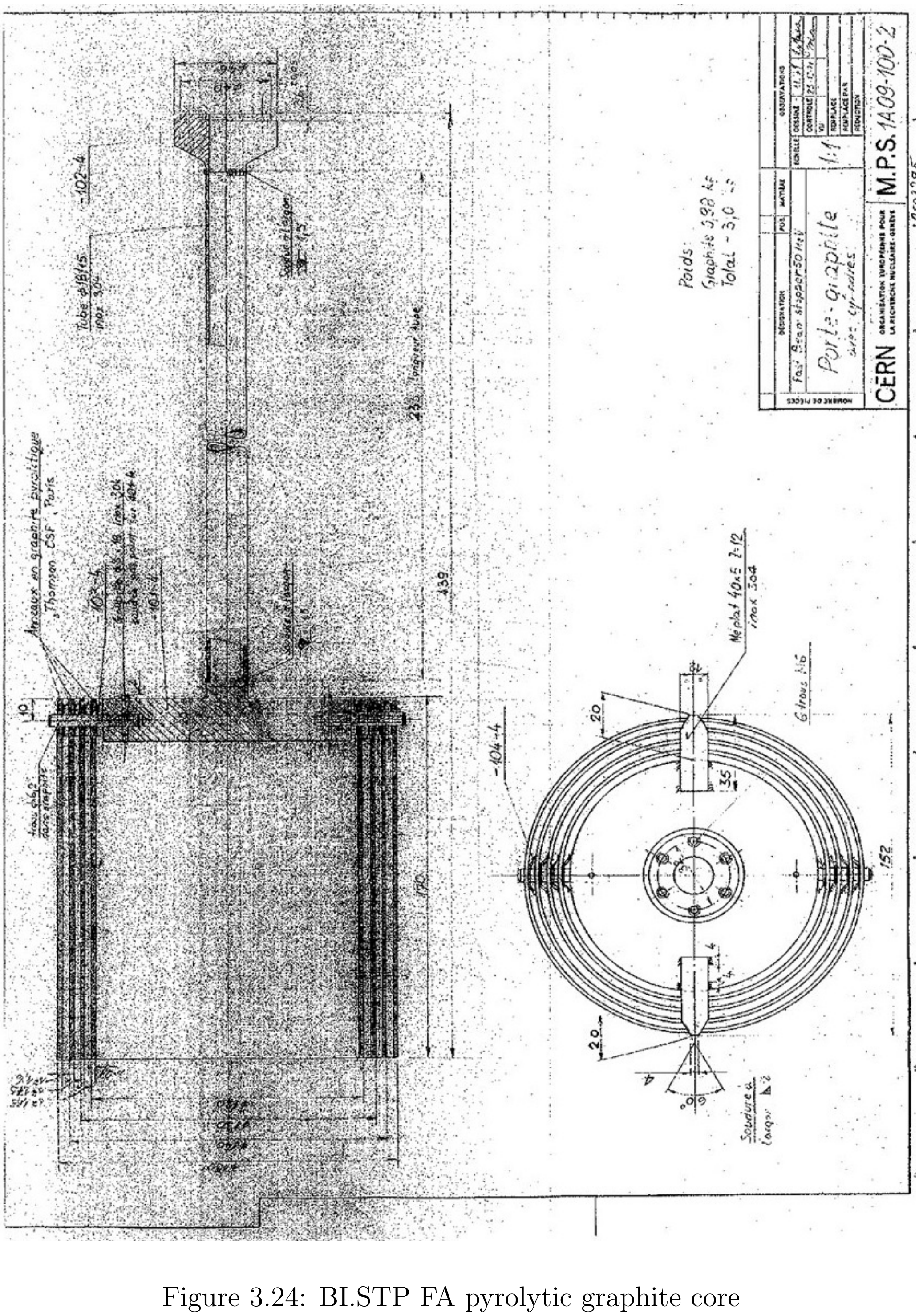


Figure 3.24: BI.STP FA pyrolytic graphite core

The results are summerized in Table 3.8.

Program	**Projected range** $[mm]$	**Factor of safety S.F.**	**Remaining energy** $[MeV]$
PSTAR	12.50	1.17	0.00
ATIMA	11.30	1.29	0.00

Table 3.8: BI.STP FA response to actual parameters beam

BI.STP SW

The BI.STP SW (see Figure 3.25 and Figure 3.26) is a stopper with a stainless steel core: a cylinder with dimensions ($external\,diameter \times length$, in mm) 280×500 is mounted on a pneumatic mechanism and moves into the beam line if there is the need to stop the particle flux.
Calculations are made for a pure iron target because the real composition of the steel which forms the core is unknown and because the software do not permit to consider steels non-pure iron; the final result is not strongly affected by this assumption.
The results are summerized in Table 3.9.

Program	**Projected range** $[mm]$	**Factor of safety S.F.**	**Remaining energy** $[MeV]$
PSTAR	4.29	116.55	0.00
ATIMA	4.27	117.10	0.00

Table 3.9: BI.STP SW response to actual parameters beam

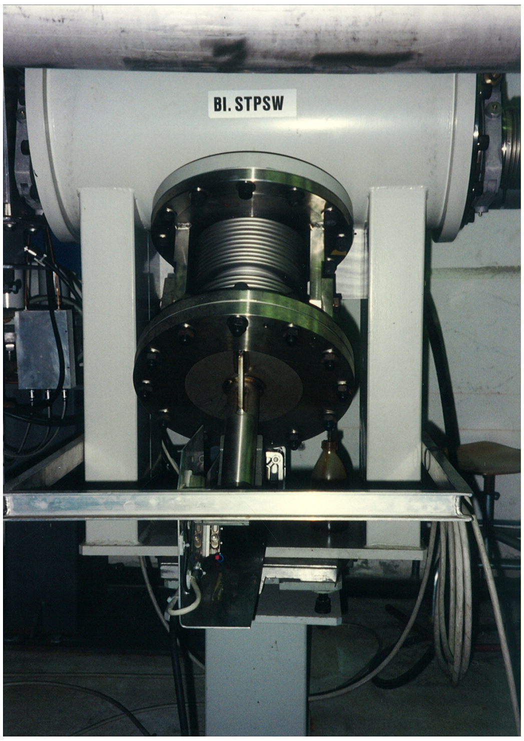


Figure 3.25: The BI.STP SW beam stopper

3.2.2 Verification to the Linac3 4.2 MeV/u $208Pb53^{+}$ ion beam

The beam parameters corresponding to the worst condition for the verification of the beam stopper for Linac3 are reported in Table 3.10.

Beam energy per unit mass	4.2 MeV/u
Pulse length	200 μs
Pulse current	50 mA
Repetition rate	5 Hz

Table 3.10: Linac3 beam characteristics

Due to the fact that PSTAR does not mean the use of any particle but

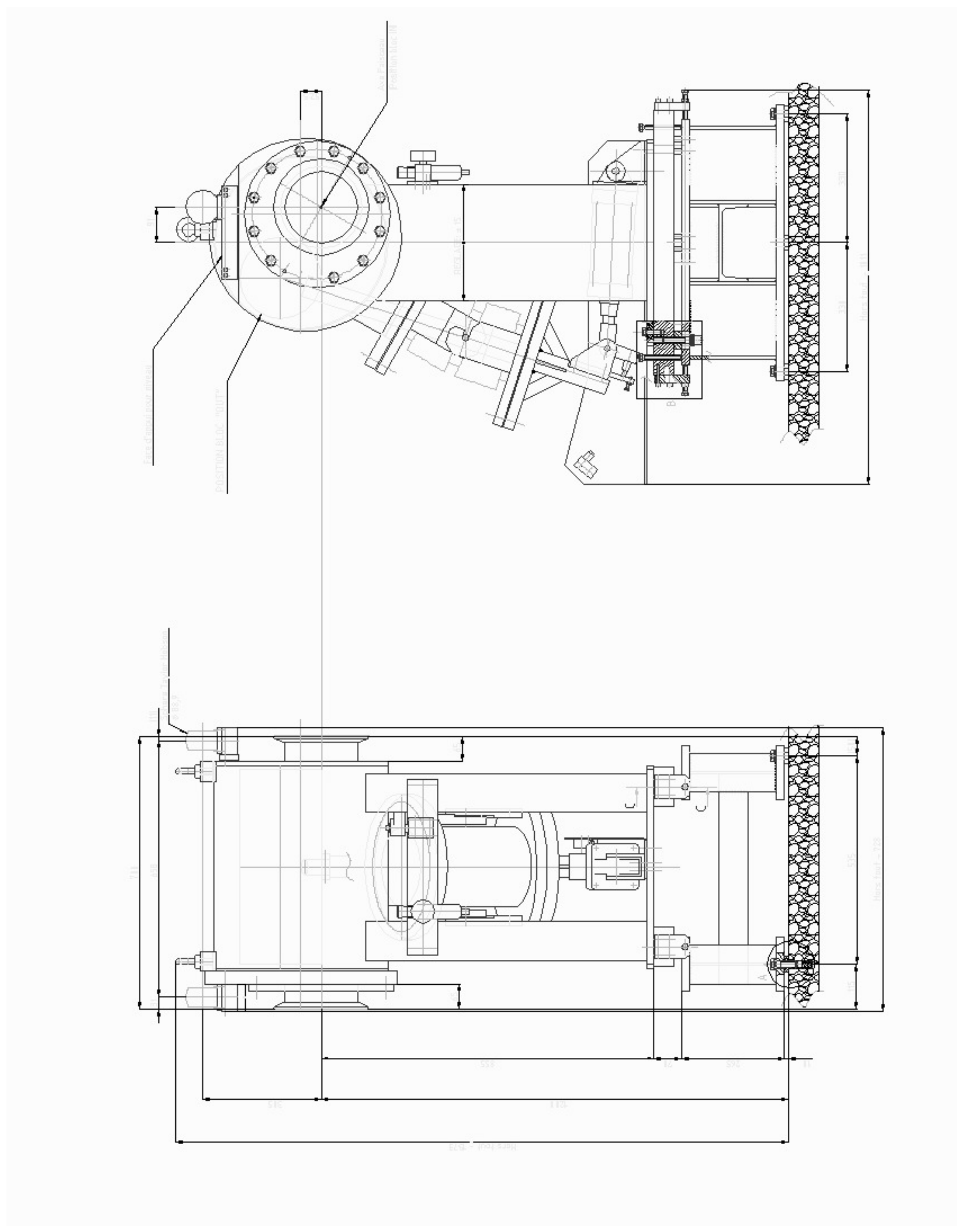


Figure 3.26: BI.STP SW assembly drawing

protons, the results for both beam stoppers have been calculated only with the program ATIMA. They are summerized in Table 3.11.

Beam stopper	**Projected range** $[mm]$	**Factor of safety S.F.**	**Remaining energy** $[MeV/u]$
BI.STP FA	0.042	347.62	0.00
BI.STP SW	0.020	$25,000$	0.00

Table 3.11: BI.STP FA and BI.STP SW response to actual parameters beam

3.2.3 Verification of an accidental use of the BI.STP FA and BI.STP SW with Linac4 beam

The Linac4 is now under construction and it will replace the Linac2 in the next future to inject in the CERN accelerator chain.
Following some preliminary discussion, a decision has been taken to design and manufacture a new stopper for the Linac4 beam, also considering the uncertainty about the capability of the two stoppers to withstand and safely stop the beam coming from Linac4. This paragraph focuses on the verification of this uncertainty by simulating the accidental use of the two stoppers with Linac4 beam.
The beam parameters corresponding to the worst condition for the verification of the beam stopper for Linac4 are reported in Table 3.12.

Beam energy	160 MeV
Pulse length	400 μs
Pulse current	40 mA
Repetition rate	1.11 Hz

Table 3.12: Linac4 beam characteristics

Program	**Projected range** $[mm]$	**Factor of safety S.F.**	**Remaining energy** $[MeV]$
PSTAR	99.20	0.15	≈ 145
ATIMA	89.67	0.16	144.52

Table 3.13: BI.STP FA response to future Linac4 parameters beam

BI.STP FA

BI.STP SW

Program	**Projected range** $[mm]$	**Factor of safety S.F.**	**Remaining energy** $[MeV]$
PSTAR	32.59	15.34	0.00
ATIMA	32.49	15.39	0.00

Table 3.14: BI.STP SW response to future Linac4 parameters beam

3.2.4 Conclusions

While the BI.STP FA can stand to the actual beams, although with a low Factor of Safety in refers to the Linac2 proton beam response, it seem s from the simulations that it will not resist the upgrade of the Linac4.

The BI.STP SW will stand the change between Linac2 and Linac4 still keeping an high Factor of Safety.

Chapter 4

Design of a beam stopper for the Linac4

The Linac4 is an H^- linear accelerator, intended to replace the Linac2 as injector to the PS Booster (PSB). By delivering to the PSB a beam at 160 MeV energy, Linac4 will provide the conditions to double the brightness and intensity of the beam from the PSB, thus removing the first bottleneck towards higher brightness for the LHC. Moreover, this new linac constitutes an essential component of any of the envisaged LHC upgrade scenarios and could open the way to future extensions of the CERN accelerator complex towards higher performance. The last part of this work placement report focus on the new linear accelerator, which will start its functioning in 2014.

The ***first section*** of the chapter ***introduces the Linac4***, it will describe its importance and how it will change the characteristics of the beam spreading possibilities of new research at CERN.

The ***second section*** of the chapter ***focuses on the beam stoppers of the Linac4***; each of these safety devices will be detailed and its role, which is specific to the position in the accelerator, will be clarified.

The ***third section*** introduces ***the proposal of design for one of the beam stoppers*** of the Linac4: the ***L4T.STP.1***.

4.1 The new linear accelerator Linac4

A linear accelerator is the first vital stage of any hadron accelerator complex. The history of CERN accelerators illustrates the importance of having a modern linear accelerator, capable to fulfil the ever increasing needs of a versatile accelerator complex.

4.1.1 The CERN proton Linacs, brief history to Linac4

The pioneering 50 MeV ***Linac1*** (Figure 4.1) started operation in 1959, injecting into the PS a beam of a few mA. Soon after commissioning, the PS required continuous increases in the linac current, which was eventually raised to 50 mA by the mid-70's, after several hardware upgrades. The commissioning of the PS Booster in 1972 further increased the strain on Linac1, now at the limit of its capabilities. The increasing demands on the linac together with the need to modernise the injectors in preparation for the SPS construction led to the decision to build Linac2, designed for a proton current as high as 150 mA, but bound to the PSB injection energy of 50 MeV.
Between the set in motion and its final retirement placed in the summer of 1992, the Linac1 not only continued to supply protons for machine experiments but it was also used to accelerate alphas, deuterons, oxygen and sulphur ions. The latter two ions required a 33% increase in the design accelerating and focusing fields. Additionally it acted as a test bed for the first Radio Frequency Quadrupole experiments. Eventually it was provided with two injectors (protons from a duoplasmatron and via the RFQ for LEAR tests and light ions, Oxygen and sulphur, for SPS fixed target physics). In spite of this it continued its faithful service until retirement after 33 years of service.

On 6 September 1978 what was then called the New Linac, and now called ***Linac2*** (see Figure 4.2), produced its first beam of 50 MeV Protons. By 3 October the intensity out of the linac had been pushed up to its design intensity and on 6 October was used in a study session to inject into the original 800 MeV PS Booster (PSB). Soon afterwards it was used for a short time as the operational injector, a role it was to take over from the start of

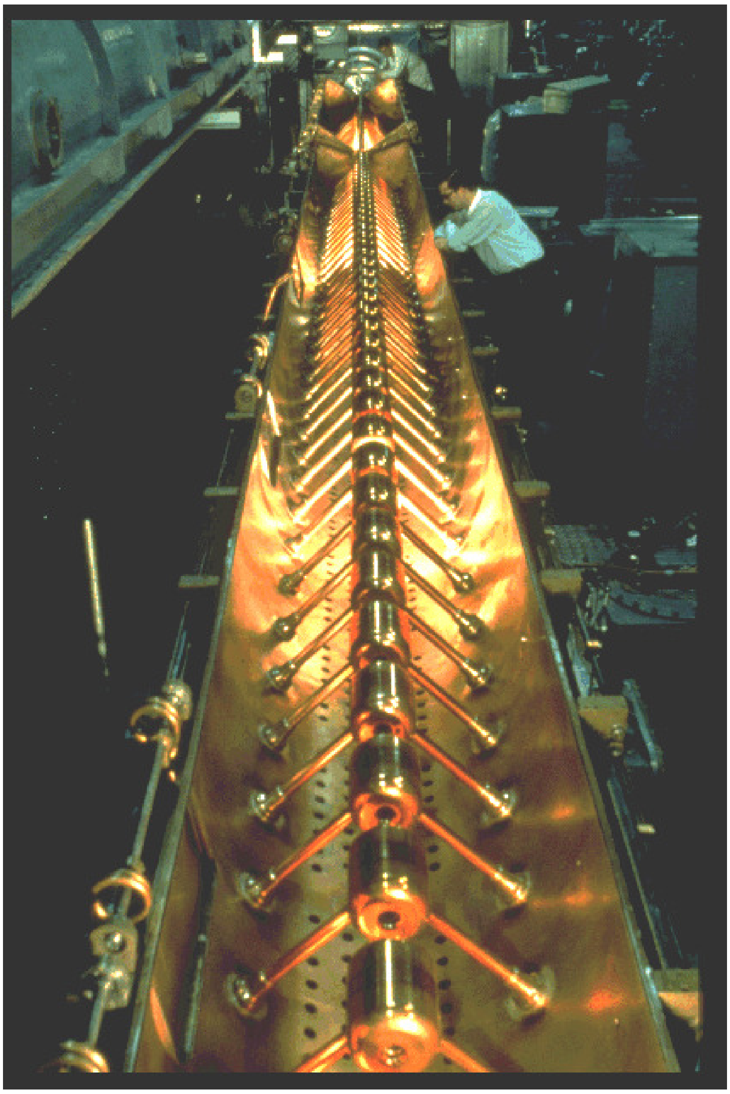


Figure 4.1: The 50 MeV proton linear accelerator Linac1

operations in 1979. Now the Linac2 is still going strong with even higher intensities.

This apparatus provides pulsed (1 Hz) beams of up to 175 mA at 50 MeV, now at the PSB entrance, with pulse lengths varying between 20 and 150 μs depending on the number of protons required by the eventual user. The ion source is a Duoplasmaton giving up to 300 mA of beam current. Originally the pre-injector was a 750 kV Cockcroft-Walton but this has now

Figure 4.2: The 50 MeV proton linear accelerator Linac2

been replaced by a 4-vane Radio Frequency Quadrupole with an injection energy of 92 kV and an output energy of 750 keV. A three tank, post coupled stabilised, drift tube linac with quadrupole focusing in the drift tubes follows. An 80 meter beam transport, partially in common with the ion Linac3, carries the linac beam to the 1.4 GeV PSB .

Beams from this linear accelerator are used, after additional acceleration:

- At ***ISOLDE*** for nuclear physics
- For the ***East Experimental Hall*** and the neutron ***Time of Flight faciliy***
- For the 450 GeV ***SPS fixed target*** physics
- For antiproton production in the ***Antiproton Decelerator*** (AD)

- For the ***LHC beams***

The annual operation time is about 6000 hours.
The original design for this linac was for a 150 mA beam out of the machine. When the requirements for LHC became evident, effort was expended to increase the output to 180 mA at the transfer point to the PS Booster. On 10 November 1999 this figure was attained in a controlled manner. However, to reduce the strain on the RF systems, it only runs at these very high intensities when requested.

The preparation of the CERN injectors for the LHC, which took place in the years 1995-2000, allowed reaching the LHC goals but at the same time showed clearly that the present injectors are at the limit of their capabilities in terms of both brightness (for LHC) and intensity (for other users). In fact even if the Linac2 went through some upgrades and its reliability has been steadily improving during the 80's and 90's (reaching the remarkable availability of 98.5% averaged over the last 10 years), the basic hardware is the same as at the time of commissioning and it always requires important repair interventions during the shutdown periods. Moreover the technology of linear accelerators has significantly progressed during the over 30 years of Linac2 operations.
In 2007, a replacement of this accelerator was approved.

4.1.2 Linac4 history and motivations

The preparation of the CERN injectors for the LHC, which took place in the years 1995-2000, allowed reaching the LHC goals but at the same time showed clearly that the present injectors are at the limit of their capabilities in terms of both brightness (for LHC) and intensity (for other users).

During the same years, the foreseen decommissioning of the Large Electron-Positron Collider (LEP, the particle accelerator predecessor of the LHC) with its powerful 352 MHz RF system triggered the proposal to build a modern high-energy high-intensity linear accelerator at 352 MHz based on the LEP RF technology. The first designs were addressed at energy production applications, but soon came a proposal to build a 2 GeV linac at CERN to inject directly into the PS ring. After some studies, this idea materialised into the conceptual design of a 2.2 GeV H^- linac called the Superconducting Proton Linac (SPL) published in 2000. This machine was meant to produce a low-intensity and high-brightness beam in the PS for LHC, but at the same time to generate high-intensity beams for other potential users, like a neutrino factory or a radioactive ion beam facility. In its original design as well as in the recent design update, the SPL is a modern H^- linear accelerator, equipped with a chopping section and with a sophisticated beam dynamics design. The starting RF frequency of 352 MHz is almost ideal for a linear accelerator of protons (or H^-), providing a good compromise between size, maximum gradient and focalisation in the first stages of acceleration.

The low-energy front-end of the SPL uses normal-conducting accelerating structures up to an energy of 180 MeV. ***The initial part up to 160 MeV energy is now proposed as the successor of Linac2, with the name***

Ion species	H^-
Output energy	$160\,MeV$
Bunch frequency	$352.2\,MHz$
Maximum repetition rate	$2\,Hz$
Beam pulse length	$400\,\mu s$
Maximum beam duty cycle	$0.08\,\%$
Chopper beam-on factor	$62\,\%$
Chopping scheme	$222/133\ full/empty\,buckets$
Source current	$80\,mA$
RFQ output current	$70\,mA$
Linac current	$40\,mA$
Avarage current	$0.032\,mA$
Beam power	$5.1\,kW$
No. particles per pulse	1.00×10^{14}
No. particles per bunch	1.14×10^{9}
Source transverse emittance	$0.2\,\pi\,mm\,mrad$
Linac transverse emittance	$0.4\,\pi\,mm\,mrad$

Table 4.1: Linac4 beam parameters

of Linac4. The length of Linac4 is compatible with the space available in the PS South Hall, making possible an effective reuse of existing building, water and electricity infrastructure. In case of SPL approval, the entire Linac4 could be reused, although in a different location defined by future needs.

4.1.3 Linac4 layout and parameters

The goal of the Linac4 project is to build a 160 MeV H^- linear accelerator replacing Linac2 as injector to the PS Booster (PSB). The new linac is expected to increase the beam brightness out of the PSB by a factor of 2, making possible an upgrade of the LHC injectors for higher intensity and eventually an increase of the LHC luminosity. Furthermore, Linac4 is designed for possible operation at high-duty cycle (5%), if required by future high-intensity programs (SPL).
Linac4 will be located in an underground tunnel connected to the Linac4-PSB

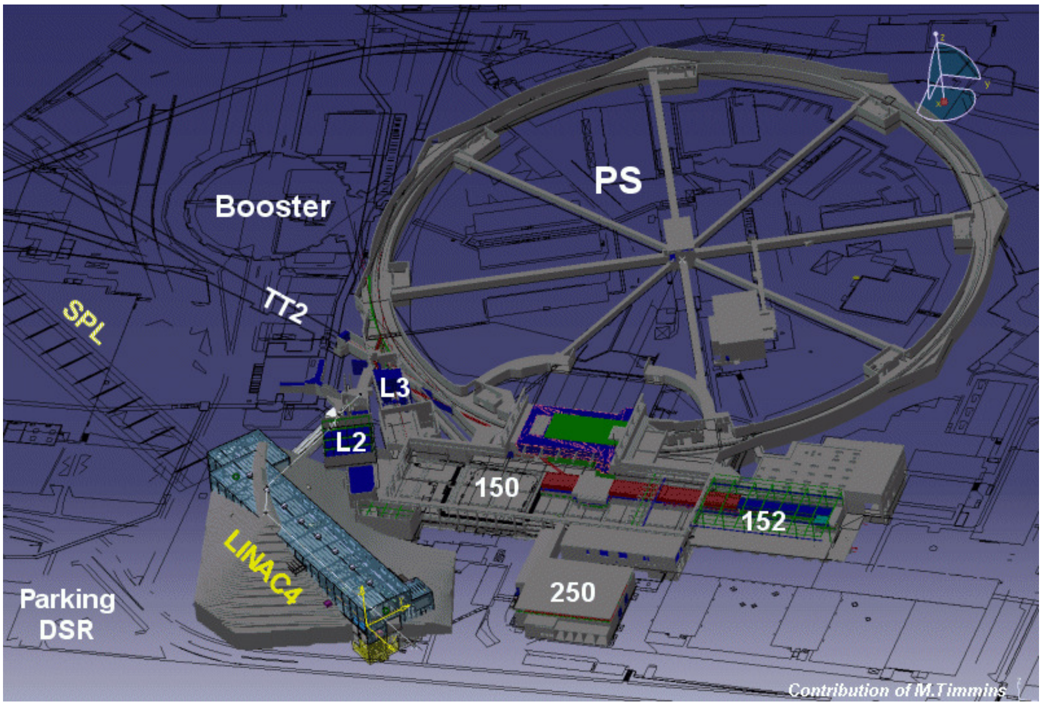


Figure 4.3: Linac4 location in the PS Complex

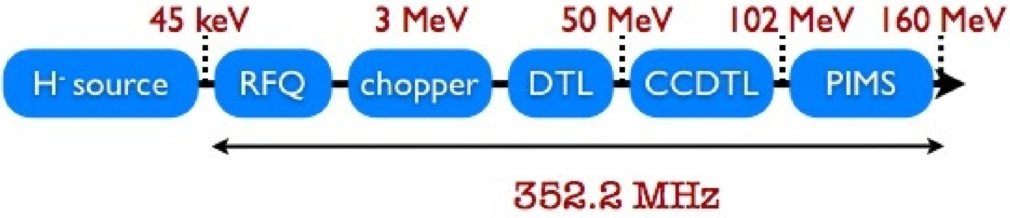


Figure 4.4: Linac4 basic structure

transfer line (see Figure 4.3). A surface building will house RF equipment, power supplies, electronics and other infrastructure. The main Linac4 beam parameters are reported in Table 4.1.

The Linac4 is composed of an ion source, a Front-end (Radio Frequency Quadrupole and a chopper line), an Alvarez Drift Tube Linac (DTL), a Cell-Coupled Drift Tube Linac (CCDTL) and a Pi-mode structure (PIMS), for an overall length of 86 metres. A 70 m long transfer line joins the present Linac2 to the PSB line. The RF accelerating structures will operate at a frequency of 352.2 MHz, re-using some RF equipment from LEP and taking advantage of existing RFQ technology. Charge exchange injection will be implemented in the PSB, together with the modifications required in the PSB injection line to cope with the higher injection energy. Although the duty cycle for the PSB does not exceed 0.1%, all the accelerating structures are designed for a maximum duty cycle of 5%, to allow for future operation of Linac4 as the first part of a high-power SPL (Superconducting Proton Linac).

The Linac4 basic architecture is shown in Figure 4.4. The new linear accelerator has to start its activity in 2014, as the actual project schedule shows in Figure 4.5.

4.1.4 Performance of the CERN accelerator Complex with the Linac4

While it has been demonstrated that the nominal LHC luminosity ($1.0 \times 10^{34}\, cm^{-2}\, s^{-1}$) can be reached and slightly exceeded with the present LHC injector chain (Linac2, PSB, PS and SPS), it is now clear that attaining

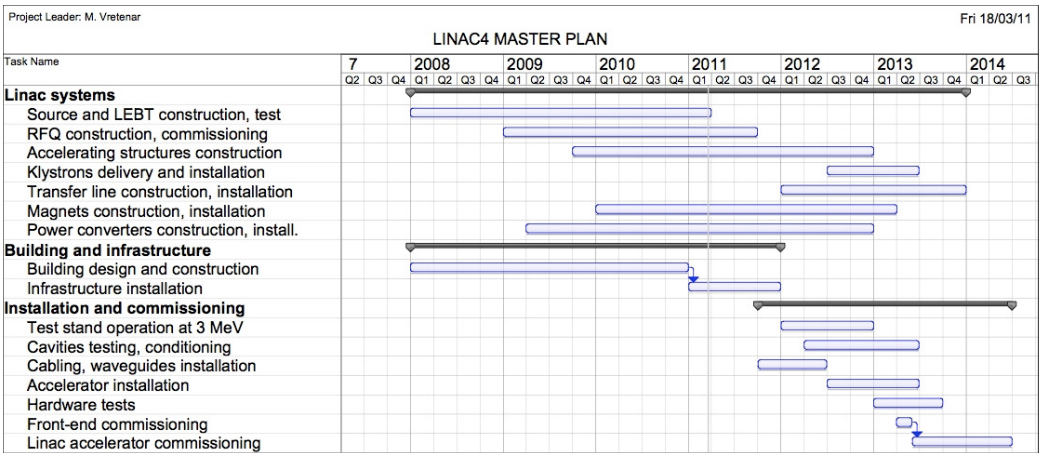


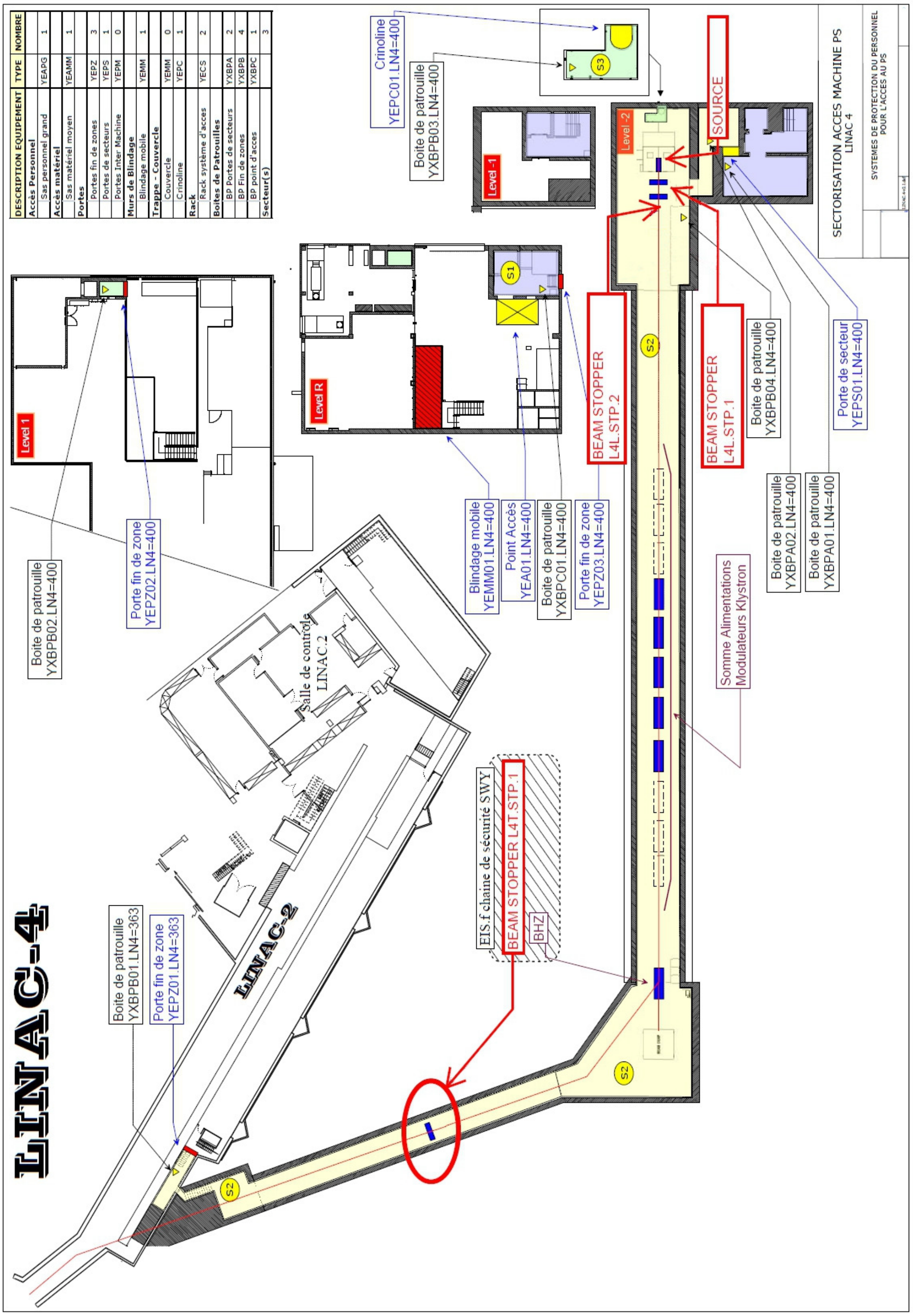
Figure 4.5: Linac4 project schedule

and possibly exceeding the ultimate luminosity of $2.3 \times 10^{34}\, cm^{-2}\, s^{-1}$ will require higher beam brightness (intensity/emittance) from the injector chain, which can be obtained only after a major upgrade of the LHC injectors. Using double-batch injection from the PSB, the PS can currently deliver the LHC beam with a maximum population of about $1.4 \times 10^{11}\, ppb$ (protons per bunch), sufficient to obtain the nominal beam characteristics at 450 GeV in the SPS ($1.15 \times 10^{11}\, ppb$ within a normalised emittance $\epsilon_n = 3.5\, \mu m$). Although the systematic on-going investigations are expected to improve transmission in the cascade of accelerators, the PSB with Linac2 will never allow to reliably operate at the ultimate performance level of $1.7 \times 10^{11}\, ppb$ in the LHC.

Different schemes for increasing the brightness out of the PS have been considered and several limitations to higher beam brightness have been identified. The first bottleneck is the space-charge dominated injection into the PS Booster. Removing this restriction with the construction of a new higher energy linac replacing the 50 MeV Linac2 appears as the scenario offering most advantages in terms of reliability and flexibility. A basic requirement for the new linac injector is the ability to make the LHC beam in a single PSB batch instead of the present double batch, which requires doubling the bunch population in the PSB within constant normalised transverse emittances. Delivering to the PS 4.1×10^{12} protons/ring, the brightness out of the PSB will be doubled and the single-batch operation for LHC will considerably simplify operation and reduce the filling time, with a beneficial effect on integrated luminosity. If the transfer efficiency is finally brought up to $\approx 100\,\%$, the ultimate bunch population of $1.7 \times 10^{11}\,ppb$ in the LHC could be obtained with single-batch filling of the PS by the PSB. Alternatively, double-batch operation of the PSB could still be used to ‘comfortably’ provide and probably significantly exceed the ultimate beam characteristics. Another possibility would be to use all 4 rings of the PSB instead of 3 as presently foreseen. This would, however, involve new splitting schemes and hardware modifications in the PSB which have not been studied in detail so far.

The ISOLDE experiment, the only direct user of the PSB, will also benefit from Linac4. The present intensity for ISOLDE is limited by space-charge tune shift to some 3.2×10^{12} protons/pulse. In principle, twice the intensity could be achieved for the same tune shift. However, with the present injection at 50 MeV the vertical space-charge tune spread exceeds 0.5 and, thus, the vertical tune has to be shifted above the vertical half-integer resonance to $QV \approx 4.55$. In preliminary simulations of H^- injection at 160 MeV beam into the PSB, no feasible scheme with such a high working point has been found up to now and if further studies do not succeed in finding such a scheme, the assumption that the intensity can be doubled should be considered slightly optimistic. However, even with a working point just below the vertical half-integer resonance, a substantial increase in the average current, compensating at the same time for the reduced number of pulses that will be available for ISOLDE once LHC is in operation, can be expected.

In terms of expected performance, the typical impact of Linac4 (accompanied by proper modifications to the LHC injectors, like the reduction of the PSB-PS repetition period to 0.9 s and some upgrades to PS and SPS for higher intensity) is summarised in Table 4.2. Thanks to smaller transverse emittances, high intensity beams should be more efficiently transmitted between accelerators. The improvement for neutrino experiments could ultimately reach a factor 1.7 (flux increase to CNGS from 4.5×10^{19} to 7.5×10^{12} pr./year), provided that the CNGS experiment is given priority over the other fixed-target experiments like COMPASS. For radioactive ions, a maximum



DESCRIPTION EQUIPEMENT	TYPE	NOMBRE
Accès Personnel		
Sas personnel grand	YEAPG	1
Accès matériel		
Sas matériel moyen	YEAMM	1
Portes		
Portes fin de zones	YEPZ	3
Portes de secteurs	YEPS	1
Portes Inter Machine	YEPM	0
Murs de Blindage		
Blindage mobile	YEMM	1
Trappe - Couvercle		
Couvercle	YEMM	0
Crinoline	YEPC	1
Rack		
Rack système d'acces	YECS	2
Boites de Patrouilles		
BP Portes de secteurs	YXBPA	2
BP Fin de zones	YXBPB	4
BP point d'acces	YXBPC	1
Secteur(s)		3

Figure 4.6: Linac4 simple layout

factor 3.5 can be achieved (from 1.9 to 6.4 μA) assuming a doubled intensity per pulse and more pulses available for ISOLDE. The bunch population out of the PS could reach the LHC ultimate figure of 1.7×10^{12} protons in a 72 bunch train with single-batch injection from the PSB, if beam transmission from PSB to PS ejection is brought up to $\approx 100\,\%$.

The replacement of the ageing Linac2 with the new Linac4 is an important contribution to the general consolidation of the CERN accelerators which will reduce the 'turn-around time' for LHC (time between physics coasts) and hence increase its integrated luminosity. It is also a fundamental component of all scenarios for upgrading the luminosity in the LHC and for increasing the flux of protons available to all experiments. Finally, Linac4 can also become the front end of a superconducting proton linac (the SPL), which can replace the PSB and open the way for a future extension of the CERN accelerator complex towards higher performance and for addressing the needs of new physics experiments on neutrinos and/or radio-active ions.

4.2 Beam stoppers in the Linac4

As each accelerator line in the Complex, the Linac4 too requires beam stoppers to assure personnel safety during maintence operations. Figure 4.6 shows a simple layout of the Linac4 and the positions where the stoppers are placed.

As stated in Chapter 1, *a beam stopper is a mechanical safety device used to intercept a particle beam, to guarantee the personnel safety. Beam stoppers are situated in a particle accelerator complex in a zone (Zone 1, see Figure 4.7 repeated from Chapter 1) before any other zone (Zone 2) that may require access for any reason, e.g. maintenance, survey, etc. The stopper guarantees the personnel safety in Zone 2 only.*

In the Linac4 two kinds of stoppers will be present (see Figure 4.6): L4T.STP and L4L.STP types; both kinds accomplish the task stated few lines above, but since they differ from one to the other for some peculiarities, they will be separetely described.

Beam	**PSB intensity per ring for loss-free/lossy trasmission to LHC** [10^{12} **particles]**	**PSB transversal emittances r.m.s.- -normalised normalised** [μm]	**PS intensity after injection loss-free/lossy** [10^{12} **particles]**
LHC nominal			
Linac2[1] (double batch)	1.38/1.62 (1 bunch per ring)	$2.5(H)$ $2.5(V)$	8.3/9.7 (6 bunches)
Linac4[3] (double batch)	2.76/3.25 (2 bunches per ring)	$2.5(H)$ $2.5(V)$	8.3/9.7 (6 bunches)
LHC ultimate			
Linac2 (double batch)	2.04/2.55 (1 bunch per ring)	$2.5(H)$ $2.5(V)$	12.2/15.3 (6 bunches)
Linac4 (double batch)	4.08/5.1 (2 bunches per ring)	$2.5(H)$ $2.5(V)$	12.2/15.3 (6 bunches)
Linac4 (double batch)	4.08/5.1 (1 bunch per ring)	$2.5(H)$ $2.5(V)$	12.2/15.3 (6 bunches)
CNGS			
Linac2 (double batch)	6.25 (1 bunch per ring)	$11.5(H)$ $4.6(V)$	50 (8 bunches)
Linac4 (single batch)	12.5 (2 bunches per ring)	$11.5(H)$ $4.6(V)$	50 (8 bunches)
ISOLDE			
Linac2 (SINGLE batch)	6.25 (1 bunch per ring)	$11.5(H)$ $7(V)$	– –
Linac4 (single batch)	12.5 (1 bunch per ring)	$12(H)$ $7(V)$	– –

Table 4.2: Beam intensities to be delivered by the PSB assuming 100% transmission to the LHC and, where applicable, beam intensities in the PS after injection. Also quoted are the intensities required if the transmission efficiency from PSB to LHC at 7 TeV is 85% for the nominal beam and 80 % for the ultimate

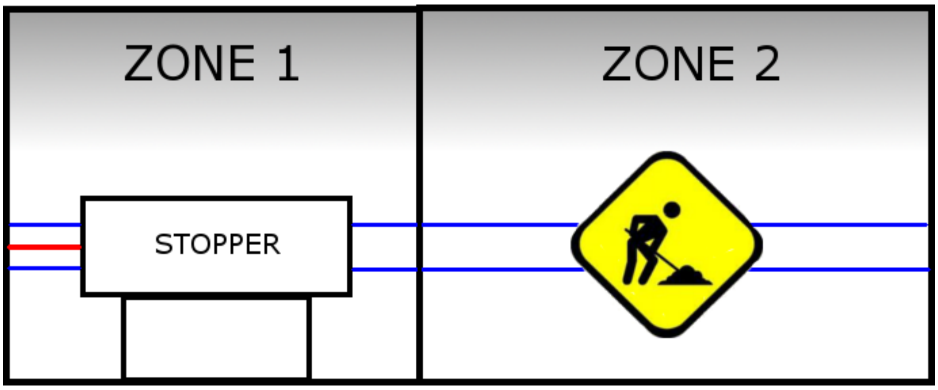


Figure 4.7: Position of the beam stopper referred to the zone which may require access by the personnel

4.2.1 The L4T.STP beam stopper

There is one stopper of this type, the L4T.STP.1, situated in the Linac4 Transfer line (L4T, as Zone 1). The stopper is used to guarantee the personnel safety in LT (Linac Transfer) and LTB (Linac Transfer Booster) lines and in the LTP tunnel (and followings, Zone 2; see Figure 4.8 for names in the area) from any beam coming from Linac4 (L4Z, Zone 1).

The functional requirements for this kind of stopper are as follow:

1. During normal operating conditions of the Linac4, the L4T.STP beam stopper core does not receive any beam and it does not interfere with the beam itself

2. The L4T.STP beam stopper is used to stop the beam in an emergency case only. A typical case of use is during the short time which lasts between the input to it from the access system (or an operator manual input) and the time at which the interlock system intervenes to dump the beam to the L4 Main Dump

3. For what stated in II, ***the L4T.STP beam stopper is never used as a beam dump***

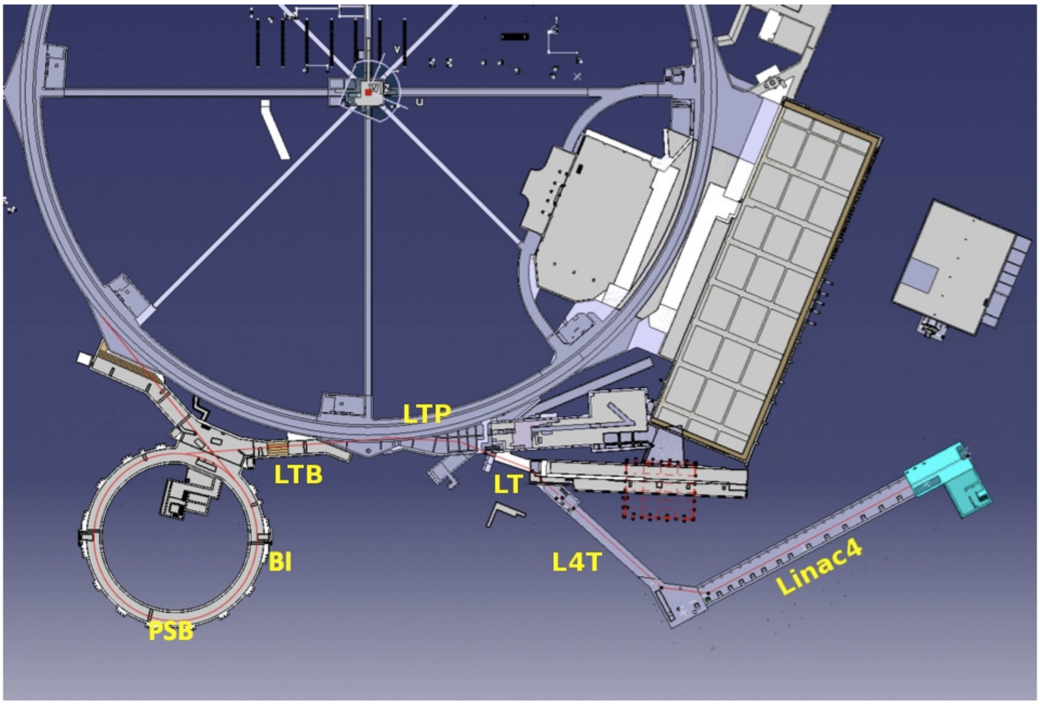


Figure 4.8: Names of transfer lines and tunnels concting the Linac4 to PS Booster and PS

4. In the event of a beam emergency stop, the robustness of the L4T.STP beam stopper core has to be guaranteed for at least one beam pulse, i.e. the interlock system has to trigger the emergency and dump the beam before the following pulse hits the stopper

From (2), it follows that the L4T.STP beam stopper is designed to withstand only a limited amount of beam (see Chapter 1 for more details). If the other components of the safety chain (interlock, bending magnet, etc.) fail for any reason and the stopper should accidentally receive more beam than that for which it has been dimensioned for, an automatic signal should be sent to the control system and to the control room to take into account this unwanted condition. The person responsible for the beam stopper has then to be contacted. This accidental condition could only be obtained if the stopper position is 'IN' or 'MOVING' [13] and the condition BEAM_PERMIT is equal to 'TRUE' at the same time and for longer than one pulse.

Beam particle	H^-
Beam energy energy	$45\,keV$
Beam intensity	$80\,mA$
Beam pulse length	$400\,\mu s$
Repetition rate	$2\,Hz$
Pipe aperture	$100\,mm$
Beam width	$70\,mm$
Beam width	$>\ 100\,mm$

[1] Full width with upstream solenoid on

Approximate value for operational condition

[2] Full width with upstream solenoid off

Approximate value

Table 4.3: Design parameters for the L4L.STP beam stoppers

The proposal of design for this stopper will be treat in 4.3.

4.2.2 The L4L.STP beam stopper

There will be two stoppers of this type, the L4L.STP.1 and L4L.STP.2, which will be situated just after the L4 source (see Figure 4.9) in the Low Energy Beam Transfer unit (as Zone 1) to guarantee personnel safety in the Linac4 Line (L4L) and in the Linac4 Dump line (L4Z), both considered as Zone 2, from any beam coming from the L4 H^- source (see Figure 4.8 for the names in the area). These two devices will be, anyhow, particular to their application since they will also be used as beam dumps [14], so these stopper-dumps must be capable of withstanding permanent operation of the ion source beam onto the beam stoppers.

The reasons for this specificity are due to the particular requirements of the source. The functional requirements for this kind of stopper are as follow:

1. The L4L.STP beam stopper core does not receive any beam during normal operating conditions of the machine Linac4 and the stopper does not interfere with the beam itself

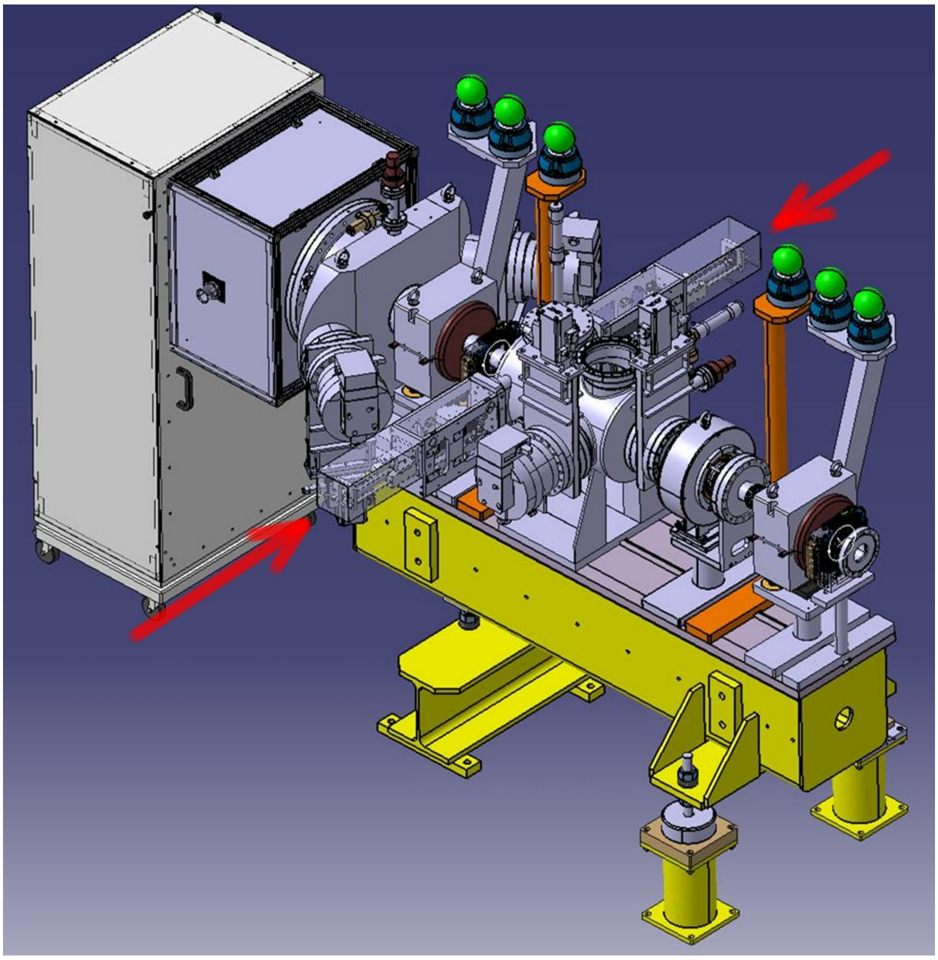


Figure 4.9: The L4L.STP.1 and L4L.STP.2 in the Low Energy Beam Transport (LEBT) in its final configuration. Red arrows indicate the stoppers

2. When the L4L.STP beam stopper is used as beam dump, it must be capable of withstanding permanent operation of the beam (at 2Hz) and so avoid switching off the source itself. For specific requirements see [14]

3. The L4L.STP beam stopper is used as beam stopper in an emergency case only, but this condition is less stringent than (2)

The design parameters for these stoppers are reported in Table 4.3.
The design of these two stoppers can enterely be found in [14], while here

there will be summarized only their most important features:

- The core of the stoppers will be a thin plate of Tantalium, as the projected range of 45 keV protons in such material is below 1 μm
- For the energy deposition profile along the thickness of the plate and the characteristics of the material chosen, no active water cooling is foreseen for the source beam stopper
- The beam interception device will be activated by its controls system and the position of the stopper will be interlocked; for redundancy, two identical stoppers will be installed and activated simultaneously
- The chosen mechanism for each stopper will be pneumatic; the stopper will move 'IN' position and stay there in case of a power cut or a drop of compressed air pressure
- The devices are designed for an operational year of 300 day of beam stopper operation time, which comprises 200 days of beam operation, the source running time after each physics run and the source conditioning periods before the start up of the Linac after a shut-down; in such a way during one year a total cycling of the activation system and the vacuum bellows of 1000 cycles is assumed, guaranteeing the full Linac 4 life time (at present the Linac2 stopper is actived IN and OUT once per day, considering 1000 cycles for the Linac4 we assume the cautelative valor of five actions per day)

A CAD drawing of the device is reported in Figure 4.10.

4.3 Design of the L4T.STP.1 beam stopper

In this section it will be presented a proposal of design for the beam stopper which will take place in the Linac4 Transfer Line: the L4T.STP.1, briefly presented in 4.2.1.

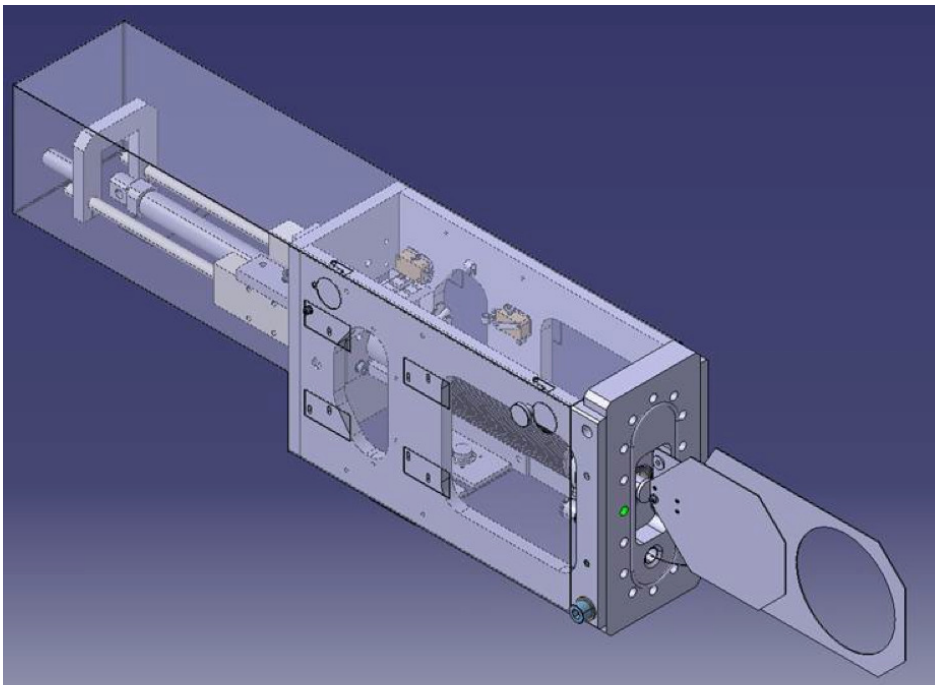


Figure 4.10: Assembly drawing of the L4L.STP beam stopper

4.3.1 Design specifications

The design parameters for the Linac4 Transfer Line are summarized in Table 4.4.

During the section meeting which had place on the 3 March 2011 it has been decided on a beam stopper with these characteristics:

Beam particle	H^-
Beam energy energy	$160\,MeV$
Beam intensity	$40\,mA$
Beam pulse length	$400\,\mu s$
Repetition rate	$2\,Hz$
Pipe aperture	$160\,mm$

Table 4.4: Design parameters for the L4T.STP beam stopper

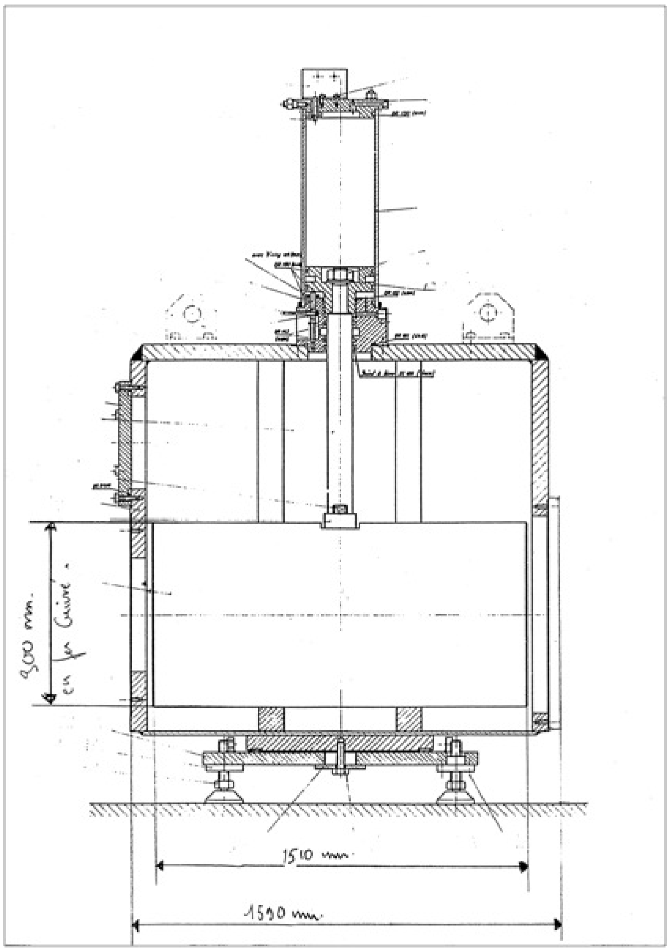


Figure 4.11: The ZT8.STP 01 beam stopper placed in the East Hall Area

- The core will be cylindrical and composed of one material only due to low primary energy of the beam involved
- The lifting mechanism will lift the core from the top of the beam stopper (e.g. Figure 4.11); this type possess the fail safe condition and it showed the best values of reliability and availability in the past

The last specification will not deal only with the L4T.STP.1 but with all the future beam stoppers which will be placed in the PS Complex; this choice reflects the effort of the EN-STI TCD section to standardize these safety devices.

4.3.2 Design of the core

The core will have a diameter $\Phi = 250\,mm$; in the PS complex all the beam pipes have an internal diameter of 160 mm, then a 250 mm core should safely cover the pipe hole and fully intecept the particle flux.

Five materials have been taken into account for the core: ***graphite***, ***aluminium***, ***titanium***, ***steel*** and ***copper***. The reasons of this choice lie in the fact that they are common materials used for beam stoppers core and they are currently employed at CERN in several machines.

The stopper core has been designed to effort a H^- ***beam at 300 MeV primary energy*** (stand still the other characteristics of the beam); this choice is due to two intents:

- The necessity to consider an high safety factor for this safety device
- The beam stopper can effort a possible future upgrade to the SPL beam of 180 MeV

Length of the core

The average path length traveled by a charged particle in a given material as it slows down to rest is called ***the projected range***; this value, computed with the assumption of the continuous-slowing-down approximation of the particle, ***has been taken as the requested length to the beam stopper core*** to complete its task. The evaluation of this average path for each material has been accomplished by the use of two indipent and free programs, PSTAR and ATIMA (see 2.2.2 for more information), with the hypothesis that all the materials are pure, uniform and isotropic.

The projected range for a proton beam of 300 MeV energy are reported in Table 4.5.

To understand the safety about the choice to design the beam stopper for a 300 MeV beam the previous results will be compared to the projected ranges of the nominal Linac4 proton beam; the ranges for the beam at 160 MeV are shown in Table 4.6, while the comparison between the two value is given by the use of a Factor of Safety, calculated as follows:

Target	**Projected range** $[mm]$	**Volume of the core** $[cm^3]$	**Weight of the core** $[kg]$
PSTAR			
C	289.30	$14,200.98$	31.24
Al	243.51	$11,953.27$	32.26
Ti	159.43	$7,826.00$	35.53
Fe	93.62	$4,595.56$	36.19
Cu	85.34	$4,189.12$	37.53
ATIMA			
C	261.67	$12,844.32$	28.26
Al	243.28	$11,941.63$	32.23
Ti	159.16	$7,812.52$	35.47
Fe	93.40	$4,584.63$	36.10
Cu	85.17	$4,180.65$	37.46

Table 4.5: Projected range for a proton beam of 300 MeV energy

$$S.F. = \frac{length\, of\, the\, core\, of\, the\, beam\, stopper}{projected\, range} \tag{4.1}$$

and it is reported in Table 4.7.

Both programs have given the same results; in fact the values differ between each other for a 0.25 % maximum. Exeption has to be made for the graphite core at 300 MeV: the results given by PSTAR and ATIMA are different for 10% of their value, but this fact is primay due to the two programs tha use different density values for the graphite: 1.7 g/cm^3 for PSTAR and 2.0 g/cm^3 for ATIMA.

Nonetheless the length of the beam stopper core will follow PSTAR value due to its more conservative estimations.

Energy deposition and temperature rise into the core

The slowing-down of the particles while passing through a target entails an energy release into the medium, hence a temperature rise within it; this

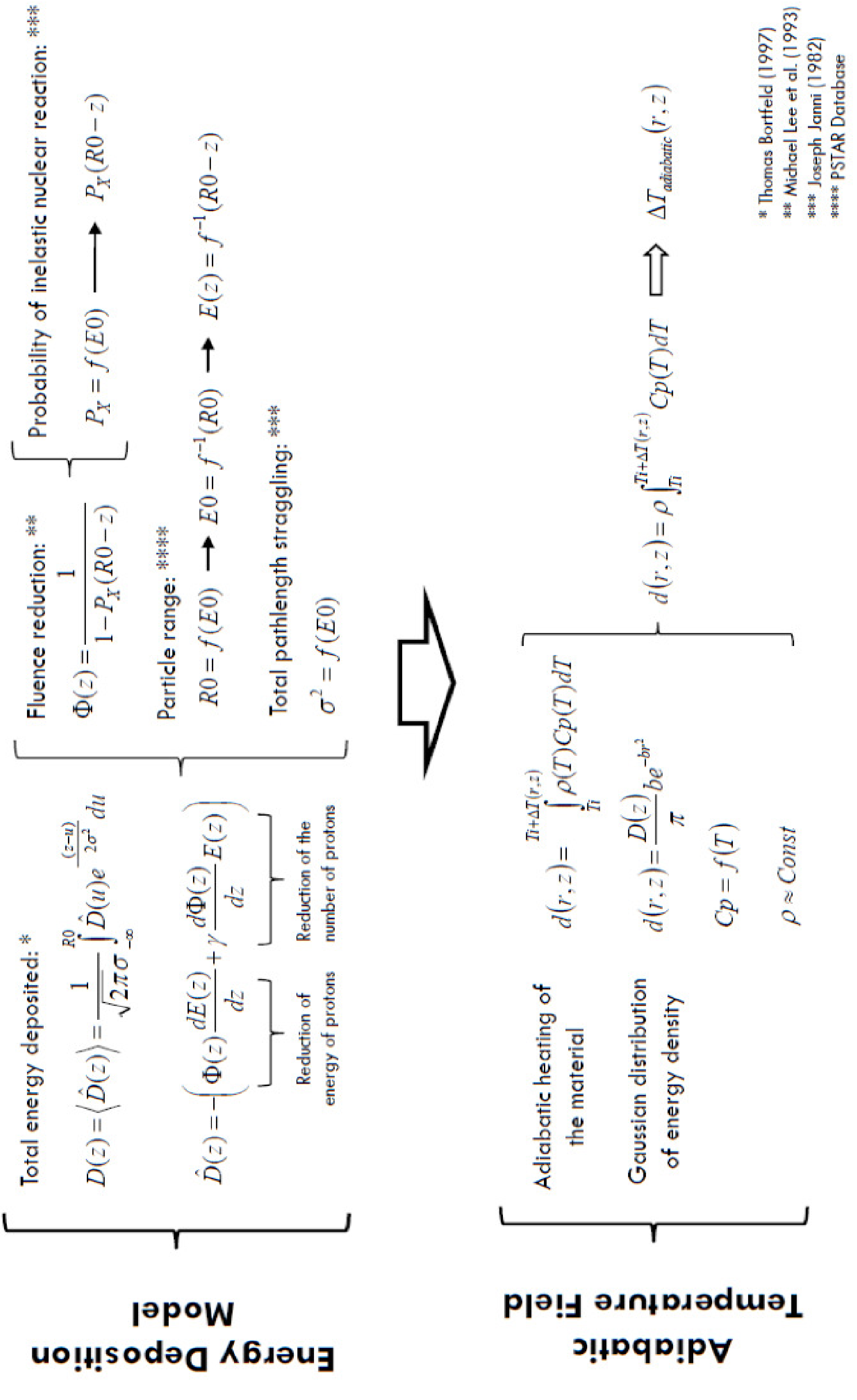


Figure 4.12: Summary of the model used to determine the temperature inside the beam stopper core

increase primary depends on the kind of beam particles, on the energy of the beam and on the density of the adsorber.
The nominal Linac4 beam can cause a temperature rise of hundreds of degrees and bring to partially melting of the beam stopper core; this risk must be avoided thus a deep analysis has been carried out in the design of the

Target	**Projected range** $[mm]$	**Volume of the core** $[cm^3]$	**Weight of the core** $[kg]$
PSTAR			
C	99.20	4,869.48	9.74
Al	84.18	4,132.31	11.15
Ti	55.35	2,716.99	12.23
Fe	32.58	1,599.27	12.79
Cu	29.77	1,461.33	13.05
ATIMA			
C	89.67	4,401.68	9.68
Al	84.12	4,129.24	11.14
Ti	55.26	2,712.59	12.21
Fe	32.49	1,594.85	12.76
Cu	29.71	1,458.39	13.03

Table 4.6: Projected range for a proton beam of 160 MeV energy

Target	**PSTAR**	**ATIMA**
C	2.92	2.92
Al	2.89	2.89
Ti	2.88	2.88
Fe	2.87	2.87
Cu	2.87	2.87

Table 4.7: Factor of Safety for the projected range for a 300 MeV and a 160 MeV energy beam

L4T.STP.1.

The study has been based on the energy deposition model presented by T. Bortfeld [16] and fluence reduction by M. Lee [17], while the needed data about the proton range have been taken from J. Janni's work [18] and PSTAR database [10]; it has been realized thanks to Mr. Ivo Leitão [15], engineer at the EN-STI TCD section, who developed those models into a Wolfram Mathematica program also capable to calculate the temperature reached by the beam stopper core after the beam pulse. The path of the study is summerized in Figure 4.12.

The energy deposition has been calculated for the nominal Linac4 beam hitting a target of pure, uniform and isotropic material and infinite length; the results reported in Figure 4.13 refer to the centre of the target after a beam pulse. The temperature rise has been determined with the hypotheses of adiabatic heating of the material and density as a constant; the solution is shown in Figure 4.14 while the maximum values are reported in Table 4.8.

From the results it is clear that ***not all the materials previously considered could really be used for the core*** of the beam stopper; in fact Table 8 shows that a beam stopper with ***an aluminium core will not stand the beam*** proper to the new accelerator Linac4. That reason extends to ***a copper core*** too; in fact the reached temperature after a beam pulse ***will be too close to the melting point*** of the material.

Material	**$T_{critical}$ [°C] (cause)**	**T_{max} [°C]**	**S.F.** **$T_{critical}/T_{max}$**
Graphite	(degassing) 2,000	684.1	2.92
Aluminium	*(melting) 660*	*693.5*	*0.95*
Titanium	(melting) 1,650	926.9	1.78
Iron	(melting) 1,535	793.9	1.93
Copper	*(melting) 1,083*	*1075.2*	*1.01*

Table 4.8: Maximum temperature inside the target

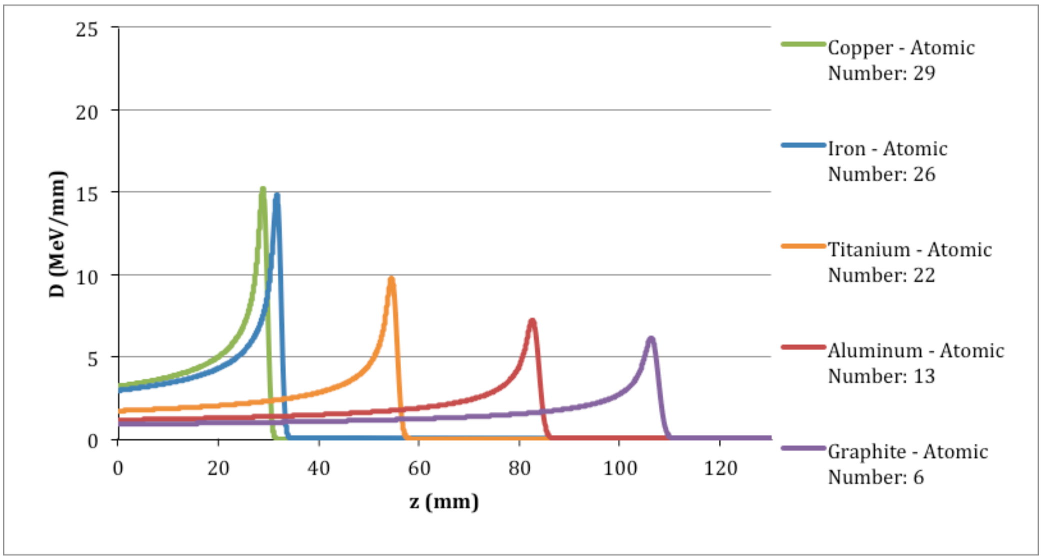


Figure 4.13: Energy deposition of a 160 MeV proton beam along the centre the target after a beam pulse

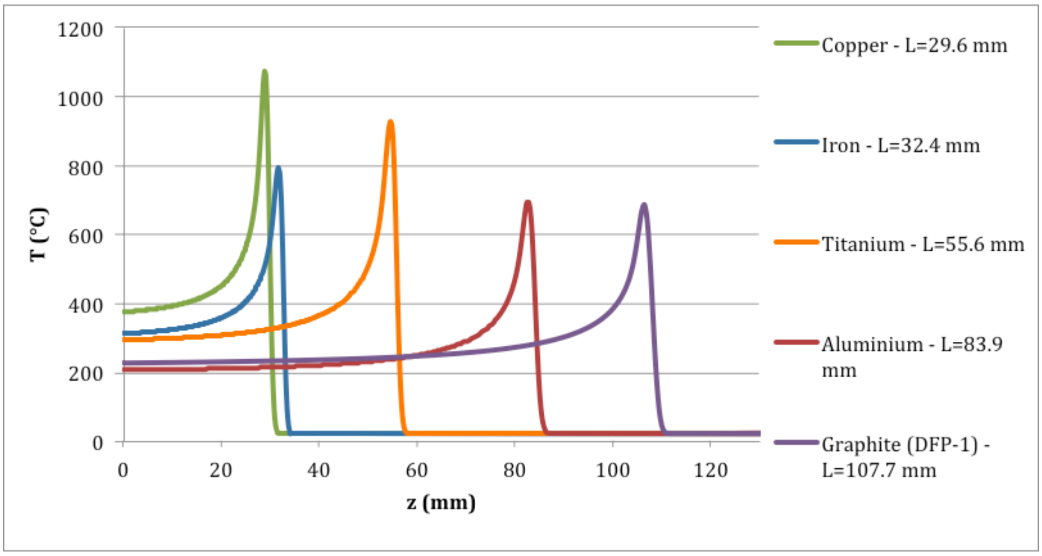


Figure 4.14: Temperature of the centre of the target after a 160 MeV proton beam pulse. L is the distance where the target reaches the maximum temperature

Material of the core	**Dimensions** *external diameter* × *length* $[mm]$	**Volume of the core** $[cm^3]$	**Weight of the core** $[kg]$
Stainless steel AISI 304	250×93.62	$4,595.56$	36.76

Table 4.9: Characteristics of the core for the L4T.STP

Density $[g/cm^3]$	8.00
Tensile strength, ultimate $[MPa]$	505
Tensile strength, yield $[MPa]$	215
Modulus of elasticity $[GPa]$	193
Melting point [°C]	$1,400$

Table 4.10: Properties of the stainless steel AISI 304

Definite core

In spite of the fact that the graphite owns the higher Factor of Safety on temperature, the core will be in iron to limit the beam stopper dimensions. Instead of pure iron, ***stainless steel AISI 304 will be employed for the L4T.STP.1 core*** due to its better thermo-mechanical properties and because of the similar response to the a proton beam they showed in precedent Fluka simulations (see Chapter 3); data and characteristics of the final core are summerized in Table 4.9 while the core is shown in Figure 4.15.

4.3.3 Mechanism

Design specifications for the mechanism

The core will be lifted from the beam path by a linear transfer unit that will lift the core from the top of the beam stopper, as it has been said in 4.3.1. A peumatic cylinder supported by guide rods will compose that unit. The pressure of the compressed air system at CERN is set at $p_{true} = 7\,bar$, but to guarantee the functioning of the device also in non perfect condition

Figure 4.15: The L4T.STP.1 core

Core weight $[kg]$	36.76
Factor of safety	5
Nominal pressure p_n $[bar]$	5
Load F_{load} $[N]$	$1,803.08$
Stroke $[mm]$	$>$ 250

Table 4.11: Design specifications for the linear transfer unit

of the system, the nominal pressure will be considered as $p_n = 5\,bar$.

The beam stopper will operate in a high radioactive environment, hence malfunctions due to radiation ageing of the mechanism are probable. A high factor of safety S.F. $=$ 5 has been considered in the load capacity of the cylinder to avoid this failure. The nominal load is then:

$$F_{load} = (mg) \cdot S.F. = (36.76 \cdot 9.81) \cdot 5 = 1,803.08 \tag{4.2}$$

The design specifications for the choise of the mechanism are summarized in Table 4.11.

Model $[kg]$	SMC MGGF80-400
Bore size $[mm]$	80
Action	Double acting
Fluid	*Air*
Theoretical output at $5\,bar$	
OUT - IN	$2,520\;-\;2,270$
Maximum operating pressure $[MPa]$	1.0
Minimum operating pressure $[MPa]$	0.15
Ambient and fluid temperature [°C]	$-10\,to\,60$
Piston speed $[mm/s]$	$50\,to\,700$
Stroke $[mm]$	400
Weight $[kg]$	62.42

Table 4.12: Characteristics of the linear transfer unit SMC MGGF80-400

Definite Mechanism

The linear transfer unit that has been chosen is the ***MGGF80-400 by SMC Pneumatics*** (see Figure 4.16); its characteristics are reported in Table 4.12.

4.3.4 Case

The L4T.STP.1 will be housed in a case and placed into the accelerator; as the rest of the line, the case will be put under-vacuum.
Charged particle beams interact electromagnetically with their vacuum chamber surroundings. The electromagnetic fields generated by an oscillating beam itself, through induced currents in the vacuum chamber walls, can drive the beam unstable by initiating transverse oscillations that grow in amplitude [19].
With the aim to reduce those 'wake' fields and all the interactions between the beam stopper and the particle beam, ***the beam stopper case will be constituted by six plates of the aluminium alloy AA5052-O welded together***. Material properties are presented in Table 4.14.

The case is represented in Figure 4.17, its carachteristics are recapitulated

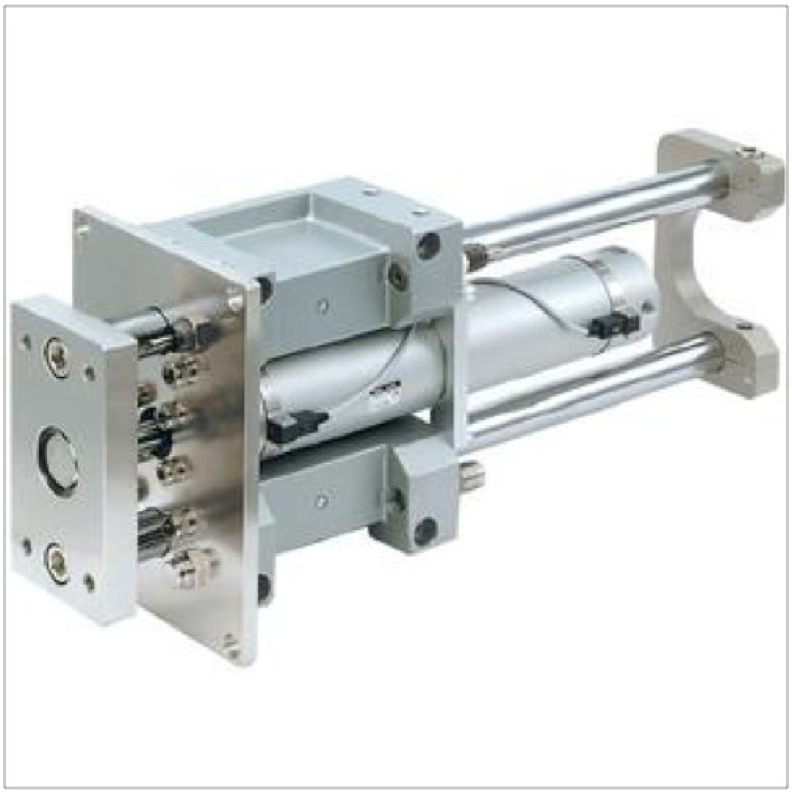


Figure 4.16: The linear transfer unit SMC MGGF80-400

in Table 4.13. The connection of the stopper to the line will be assured by two flanges UHV 325/273 SCEM (in accord to ISO 2768, see Figure 4.18) fixed on the front and end walls of the case.

Dimensions $height \times width \times length[mm]$	$682 \times 303 \times 143$
Material	$Aluminium\, alloy\, AA5052 - O$
Weight $[kg]$	25.30
Internal pressure	$Vacuum$
Load on the top $core + mechanism + others\, [N]$	$1,072.62$

Table 4.13: L4T.STP.1 case characteristics

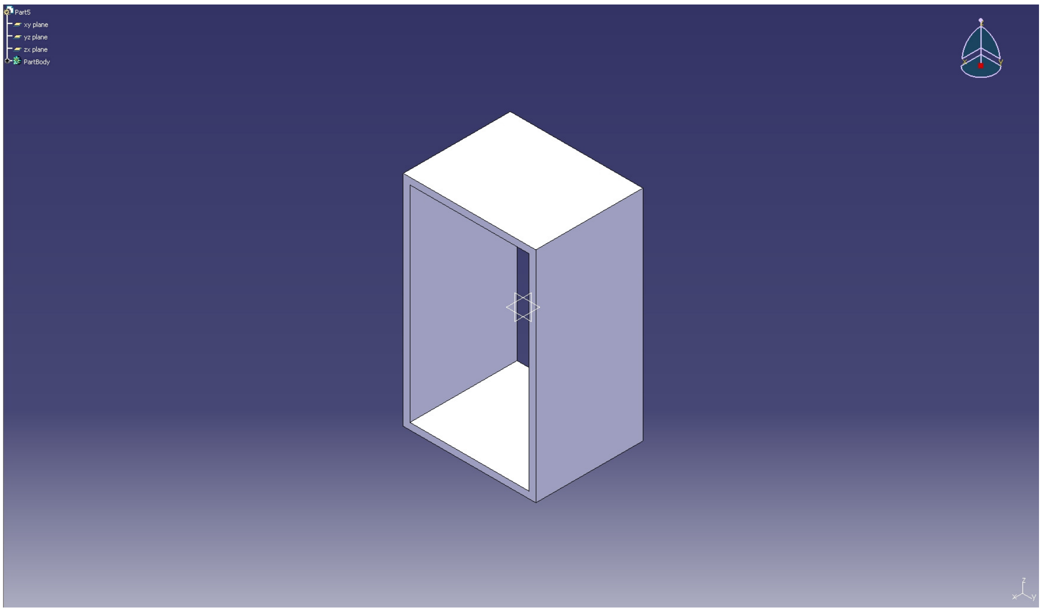


Figure 4.17: The L4T.STP.1 beam stopper case

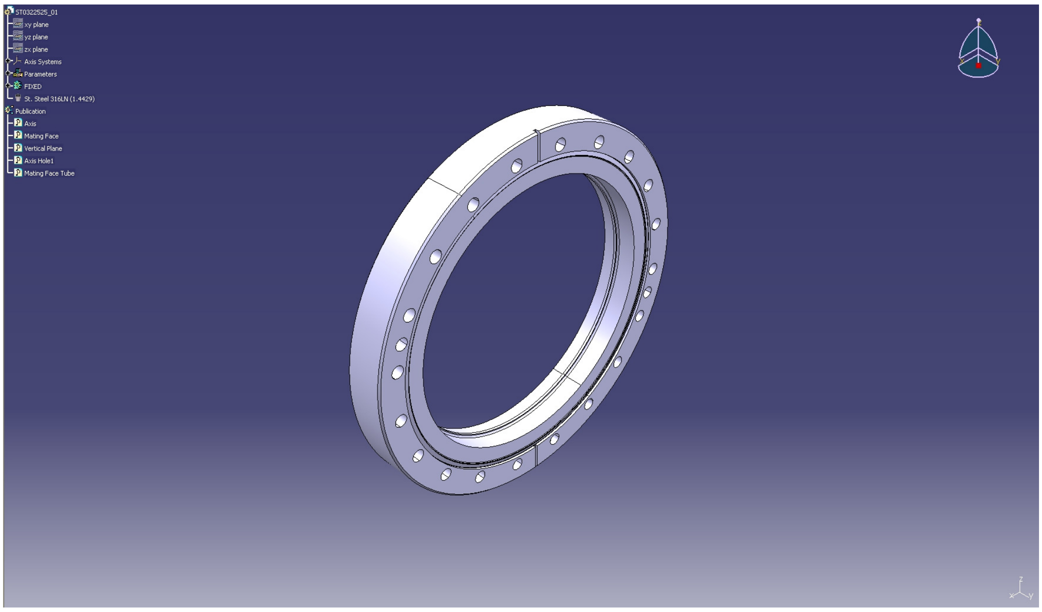


Figure 4.18: UHV 325/273 SCEM flange according to ISO 2768 for connection of the beam stopper to the Linac4 transfer line

Density $[g/cm^3]$	2.68
Tensile strength, ultimate $[MPa]$	193
Tensile strength, yield $[MPa]$	89.6
Modulus of elasticity $[GPa]$	70.3
Melting point [°C]	607.2

Table 4.14: Properties of the aluminium alloy AA5052-O

ANSYS simulation of the case

The stailess steel core and the lifting mechanism are mounted on the case, hence their weight loads its walls; moreover the container is under vacuum. A FEM simulation using ANSYS software has been carried out to understand the behaviour of the case under these loads; the path has been:

- Transfer of the domain from CATIA to ANSYS environment; due to its simmetry, the simulation has been performed on a reduced domaine to shorten the time required for calculation
- Insertion of the exact AA5052-O properties of in ANSYS
- Discretization of the domain and load of the forces on the numerical structure
- Calculation of the equivalent stress, deformations and of the safety factor of the case:

  $$S.F. = \frac{S_y}{\sigma_{eq,max}} \tag{4.3}$$

  where S_y is the ultimate yield stress of the material and $\sigma_{eq,max}$ is the maximum equivalent stress within the case

The deformed structure is shown in Figure 4.19 and 4.20, while the numerical results are reported in Table 4.15.

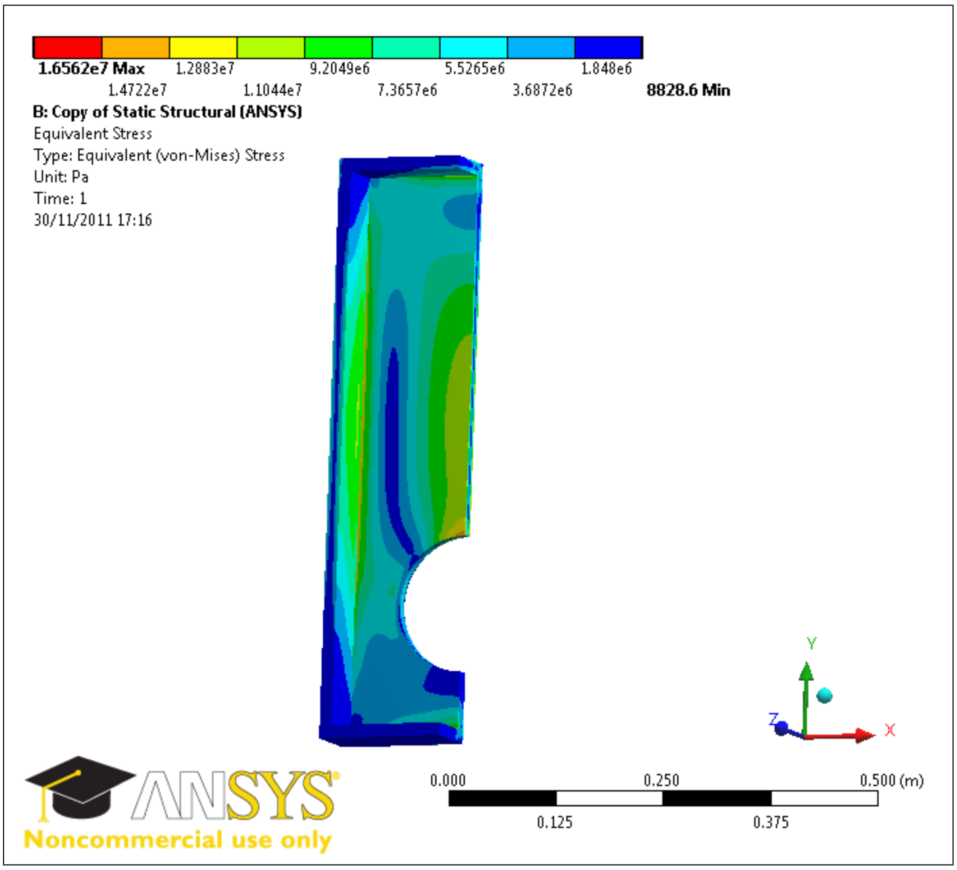


Figure 4.19: Equivalent stresses carried out by the ANSYS simulation on the beam stopper case

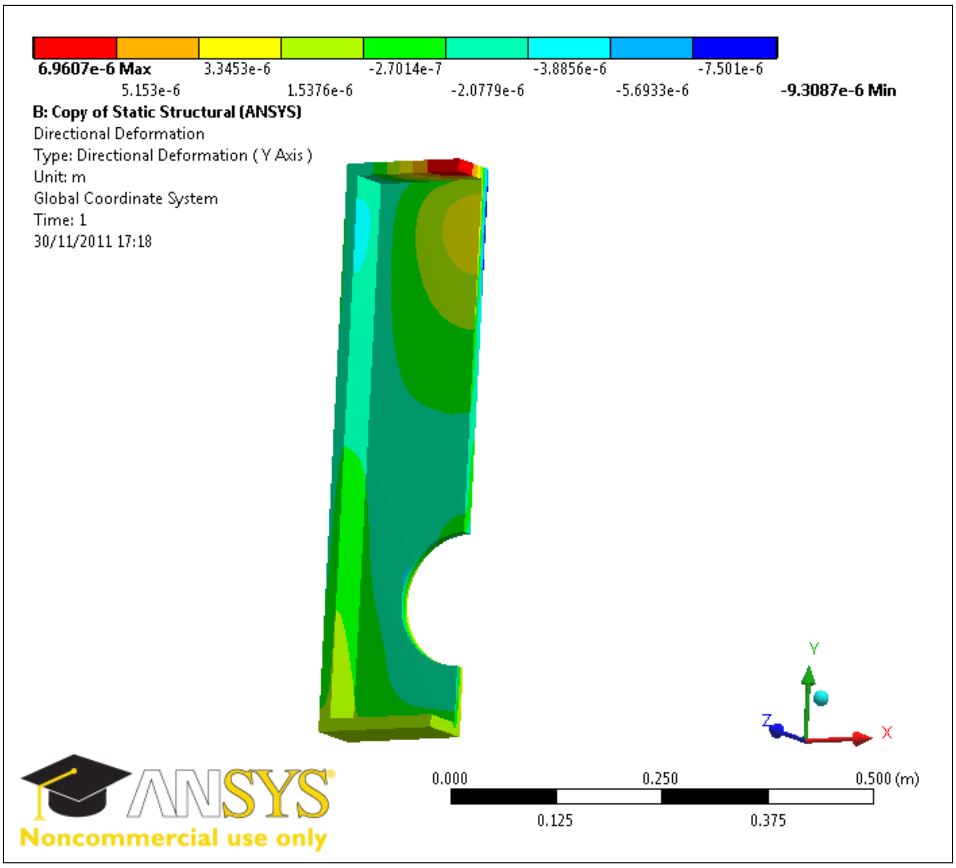


Figure 4.20: Directional deformation carried out by the ANSYS simulation on the beam stopper case

Pressure [Pa]	**Force on top** [N]	**Equivalent stress** [MPa]	**Deformation maximum** [μm]	**Factor of safety minimum**
1×10^5	-536.31	16.56	6.96	5.41

Table 4.15: Numerical values relative to ANSYS simulation

4.3.5 Remarks

The proposed design of the L4T.STP.1 beam stopper ***completely fulfils the requirements*** listed in Chapter 1; among other:

- The core has been thought to face a proton beam with a primary energy of 300 MeV, then ***it will be able to keep safe the LP and LTB lines and LTP tunnel beyond itself*** if an emergency case happens
- Due to what stated in 4.3.3, ***the L4T.STP.1 can safely be employed in radiational environment***
- Thanks to the aluminium alloy case, ***the L4T.STP.1 will interfere as less as possible with the pulsed proton beam***
- ***The L4T.STP.1 is fail-safe***

Material and dimensions of the core have been chosen facing the maximum temperature reached by the core itself to the melting temperature of the material and considering the projected range needed to stop the particles passing through the stopper; no analysis has been done on the stresses within the core during the transitory time to the peak temperature, further step needed to obtain the approval from the CERN commission to the design project. This next stage will be execute by a following student at the EN-STI TCD section.

Appendix A

CERN accelerator complex

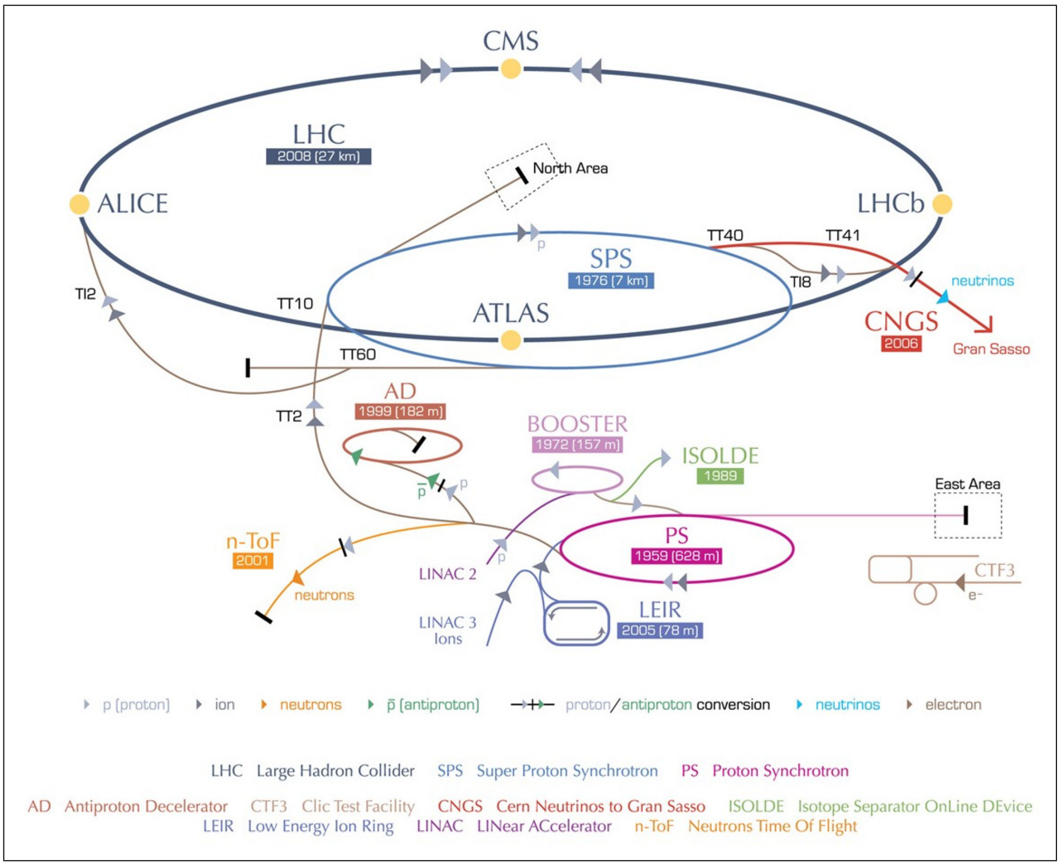


Figure A.1: Scheme of accelerator complex at CERN - see Table A.1 page 90

Accelerator	Experiments	Overview
LINAC2		accelerates protons from the source and sends them to the booster (PSB)
LINAC3		accelerates ions from the source and sends them to LEIR
PSB		accelerates proton and sends them to the PS and ISOLDE
PS	EA	East Area - various experiments
	nTOF	neutron time-of-flight
	DIRAC	to observe and then measurelifetimes of Muons and Kaons
	CLOUD	to study possible links between cosmic rays and cloud formation
	SPS	send beam to SPS (CNGS, fixed target, LHC)
ISOLDE		to produce a range of isotopes for research
AD	ALPHA	to make, capture and study atoms of antihydrogen and compare these with hydrogen atoms
	ASACUSA	to compare anti-protons and protons using antiprotonic helium
	ATRAP	to compare hydrogen atoms with their antimatter equivalents
LEIR		accelerates ions and sends them to the PS
SPS	NA	North Area - various experiments
	CNGS	to send muon neutrinos to the Gran Sasso National Laboratory in Italy
	COMPASS	to study how elementary quarks and gluons work together to give particles we observe
	LHC	injects beam to the LHC at 450 GeV
LHC	CMS	to search for the Higgs boson, extra dimensions, and particles that could make up dark matter
	ATLAS	to search for the Higgs boson, extra dimensions, and particles that could make up dark matter
	LHCb	to understand why we live in a Universe composed almost entirely of matter, but no antimatter
	ALICE	to study a state of matter known as quark-gluon plasma
	TOTEM	to measure the size of the proton and also monitoring the LHC's luminosity
	LHCf	to simulate cosmic rays to interpret and calibrate large-scale cosmic-ray experiments

Table A.1: Accelerators and Experiments at CERN

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