The beam absorbers of the 3 MeV H^- Test Facility at CERN

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Abstract

A 3 MeV H^- facility in the PS South Hall at CERN has been proposed to test the conceptual design of a front end for a high-power linac. The facility consists of a 95 keV H^- source, a 352 MHz Radio Frequency Quadrupole followed by a transport line containing an electrostatic chopper. The chopper deflects 3 out of 8 micro-bunches at 352 MHz out of the beam line. An off-line dump absorbs the chopped bunches, while an in-line dump stops the beam at the end of the test line.
Based on the assumptions and within the constraints stated in this document, this note identifies available technologies which fulfil the requirements of this dumping system. A design is here proposed, which has paved the way to the detailed design and optimization study.

Introduction

General

A 3 MeV H^- facility in the PS South Hall at CERN has been proposed to test the conceptual design of a front end for a high-power linac [1]. The facility consists of a 95 keV H- source, a 352 MHz Radio Frequency Quadrupole (RFQ) followed by a transport line containing an electrostatic chopper. The chopper deflects 3 out of 8 micro-bunches at 352 MHz out of the beam line. An off-line dump absorbs the chopped bunches, while an in-line dump stops the beam at the end of the test line [2].
Based on the assumptions and within the constraints stated in this document, this note identifies available technologies which fulfil the requirements of this dumping system. A design is proposed which has paved the way to the detailed design and optimization study.

Chopper line layout and interfaces

The facility contains a H^- source producing a 95 keV beam, which is accelerated by an RFQ boosting the H^- energy up to 3 MeV. The beam then enters an electrostatic chopper line, followed by a transport line, which provides space for extracting the chopped bunches to a first dump (the “off-line” or “chopper” absorber). A second dump (the “in-line” or “end” absorber) is foreseen at the end of the test stand. A diagnostic section can be placed in different locations along the facility, in order to characterise the beam after the source, the RFQ and at different locations inside the chopping line.
An artistic view of the chopper section after the RFQ is shown in Figure 1, while the detailed layout is given in Figure 2: it contains two 255 mm-long quadrupoles housing the chopper structure and one 150 mm-long quadrupole to obtain a suitable beam separation at the dump.
The chopper deflects the bunches in the vertical plane, achieving a distance of 15 mm centre-to-centre between the chopped and unchopped beam at the dump location. The beam radius is roughly constant in the chopper section and of the order of 6 mm. The beam position and size are fairly stable.

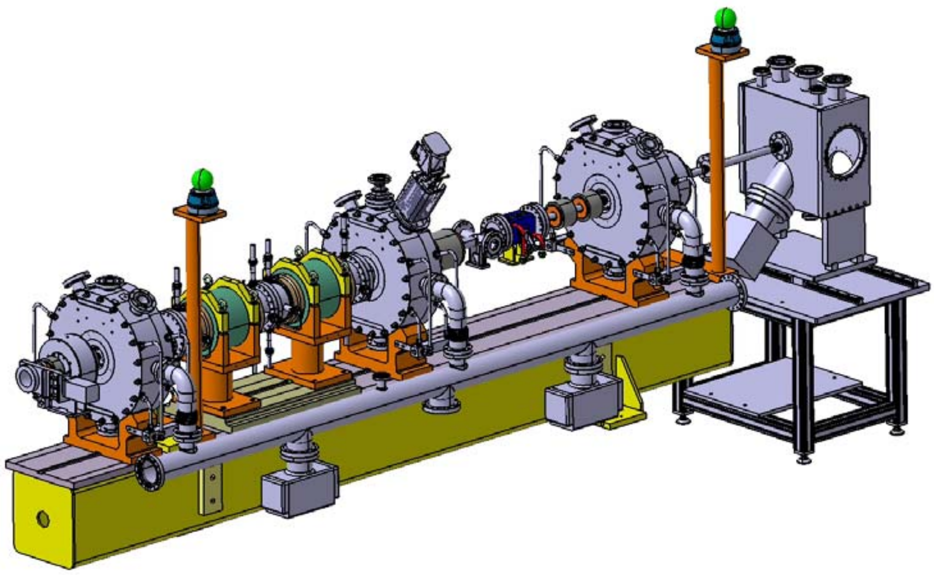

Figure 1 – Artistic view of the chopper line.

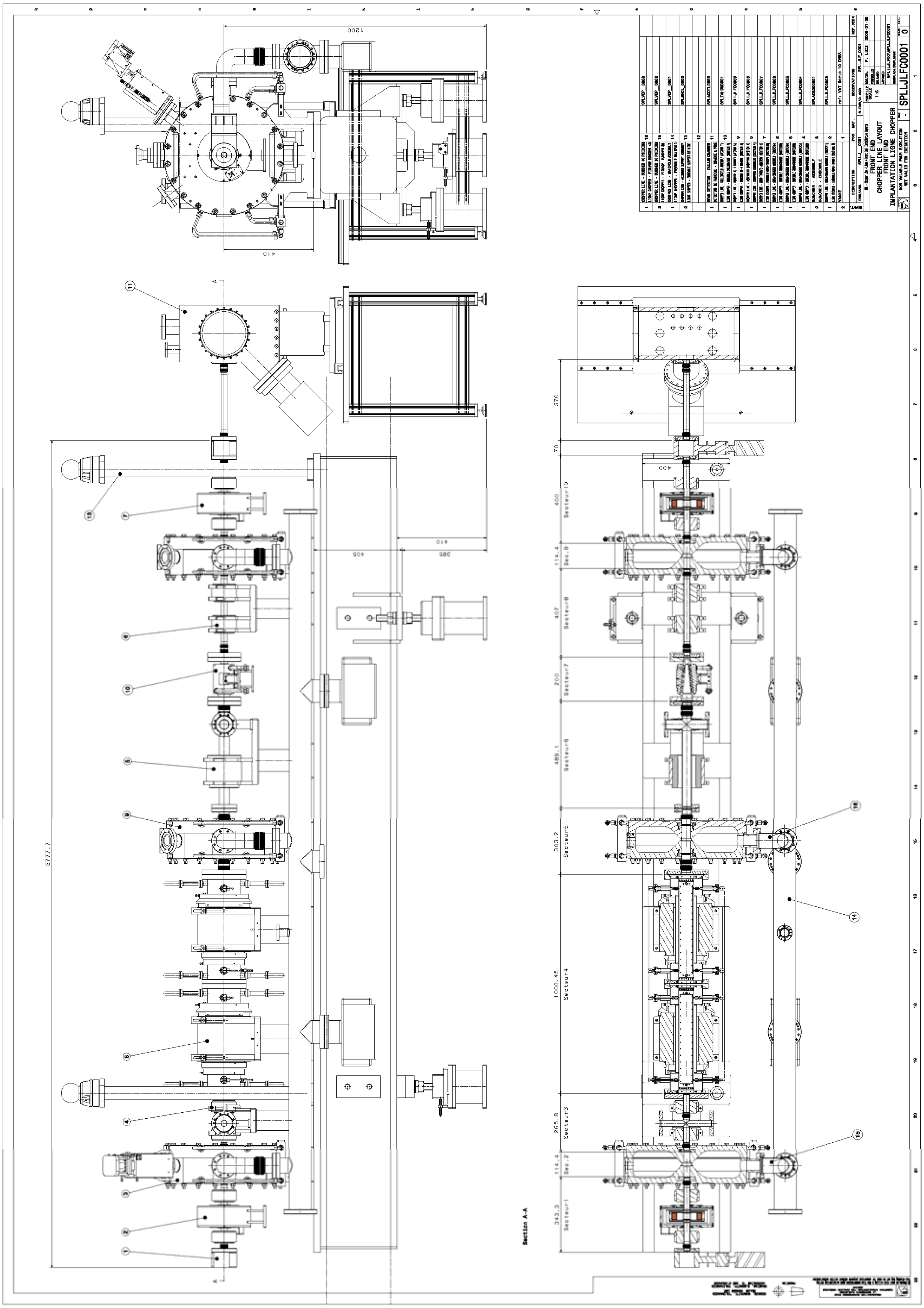

Figure 2 – Layout of the chopper line.

CONSTRAINTS

GENERAL

Basic, operational and safety-related constraints limit the design choices of the beam dumping system. Basic constraints group miscellaneous conditions which any design philosophy of the beam dumping system has to strictly respect; operational constraints limit the machine downtime due to preventive or exceptional maintenance; in addition, it is by respecting safety constraints at the design stage that future expensive interventions in case of accident can be avoided and human health can be protected.

BASIC CONSTRAINTS

Space

In order to limit the space-charge effects while chopping and matching to a downstream accelerator, the beam line has to be kept as short as possible. Therefore, the chopper absorber should aim at the maximum of compactness: the space for the dump has not to exceed 200 mm flange-to-flange (no bellows included), while the vertical dimension is in principle limited only by the beam height (1200 mm).
The in-line absorber has no space limitation in the beam direction, although an identical copy of the off-line one is preferred to limit costs and design effort.

Vacuum

Both the off-line and in-line dumps are internal absorbers, i.e. they are integrated in the vacuum system of the facility. At the dumps location the nominal pressure is 10^{-7} torr. The in-line dump has to close the vacuum line and to guarantee vacuum leak-tightness.
Consistently with the basic space constraint described in the previous section, no dedicated pumping system is to be integrated in both absorbers, and no fast-closure valve is to be provided within the 200 mm section of the beam line dedicated to the off-line dump.

Beam interference

The chopper deflects the bunches in the vertical plane, achieving a distance of 15 mm centre-to-centre between the chopped and unchopped beam at the dump position. The beam size is roughly constant in the chopper section, while it varies considerably along the line. The design beam radius being 6 mm in the chopper line, the off-line absorber core is to be placed at ~6 mm from the unchopped beam.
No interference of such a close off-line absorber on the unchopped beam is expected, and no particular precaution is to be taken. Similarly, there exists no constraint related to the orientation of the absorber’s surface.

OPERATIONAL CONSTRAINTS

Design margin

The beam parameters for the 3 MeV H^- facility line are based on the assumption that it would be the front-end of a new injector for the PSB, and that in a second time it could become the first part of the SPL. The performance of the facility will therefore evolve during its lifetime to achieve these goals, and the design margins have to allow the facility upgrade.

Mantainability & handling

Each absorber must be provided with adjustable, independent supports. Hands-on maintenance is to be guaranteed.

SAFETY CONSTRAINTS

Material choice

The Coulomb barrier of elements with atomic number higher than 6 would classically prevent any nuclear reaction with 3 MeV protons. Nevertheless, because of the quantum phenomenon of tunneling, such reactions are in principle always possible and can activate the core material. This has to be kept to a minimum. With this respect, Ni has been preferred to Cu because the induced radioactivity in Cu will be mainly due to Zn-65 (243 day half-life), whilst in Ni the most radioactive nuclides (Cu-61 and Cu-64) decay relatively fast (3.4 and 12.7 hour half-life, respectively).

REQUIREMENTS

Beam Parameters

The goals of the 3 MeV H^- facility line are: 1) to serve an injector for the Proton Synchrotron Booster (PSB), and 2) to demonstrate the technical feasibility of a pre-injector for a high-power Linac (as the Superconducting Proton Linac, or SPL) by validating the chopper functioning and the optical design of the beam line.
The general time-structure of the 3 MeV H^- beam is shown in Figure 3: a macropulse of duration T_1 = 0.5-0.7 ms is repeated with a frequency $F=1/T_2$ ranging from 2 to 50 Hz. Each macropulse presents a 352 MHz micropulse (bunch) structure imprinted by the RFQ. The chopper removes 3 out of 8 bunches thus creating the time-structure shown on the bottom of the figure. Figure 4 shows the chopped and un-chopped beam in the phase space at the off-line (chopper) dump location (left diagram) and the un-chopped beam at the end of the line.
For PSB injection, the facility would operate at a low frequency and macropulse duration. The average pulse current at the exit of the RFQ is conservatively set to 70 mA. The chopping factor is assumed to be modulated around a mean value of 40%, fixing the goal for the facility to 40 mA average pulse current at the end of the beam line.
For the SPL instead, longer pulses at lower beam current are envisaged. In this case, the source has to provide a stable beam of about 70 mA during 0.7 ms.

Design approach

The beam dumping system may be subjected to a variety of operational scenarios at reduced or full peak current and/or repetition rate. In addition, accidents may occur, which could generate different load conditions for each of the two absorbers. The choice of a design load case driving the conceptual engineering study is therefore mandatory, which must be complemented by considerations and precautions for the other loads.
Table 1 summarises the beam parameters which have driven the design of the off-line and in-line beam absorbers: the dumping system has been designed for the most severe scenario where the highest possible power is delivered to the dumps. This implies continuously intercepting a 3 MeV H^- beam pulsed at 50 Hz with 0.7 ms long pulses. The maximum average beam current to be absorbed is 1.1 mA, with a mean power of 3.3 kW. The beam is circular and has a uniform profile of 6 mm radius, which results in a surface heat flux of

~30 MW m^{-2}. Such a scenario will never be tested in the 3 MeV facility, but it will occur should the facility become the pre-injector of a high power linac.

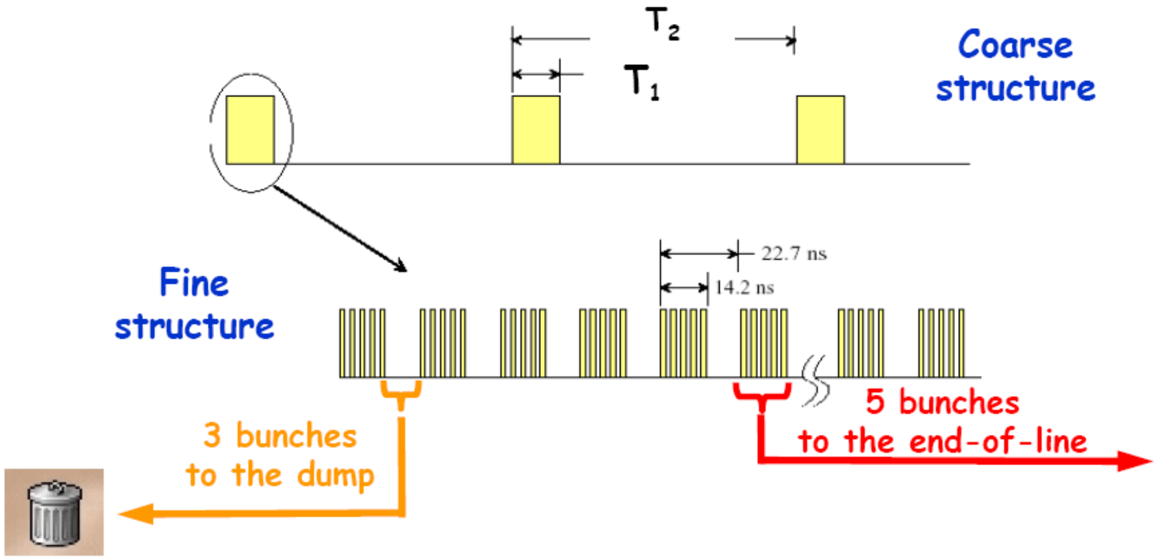

Figure 3 – Time structure of the 3 MeV H$^-$ beam.

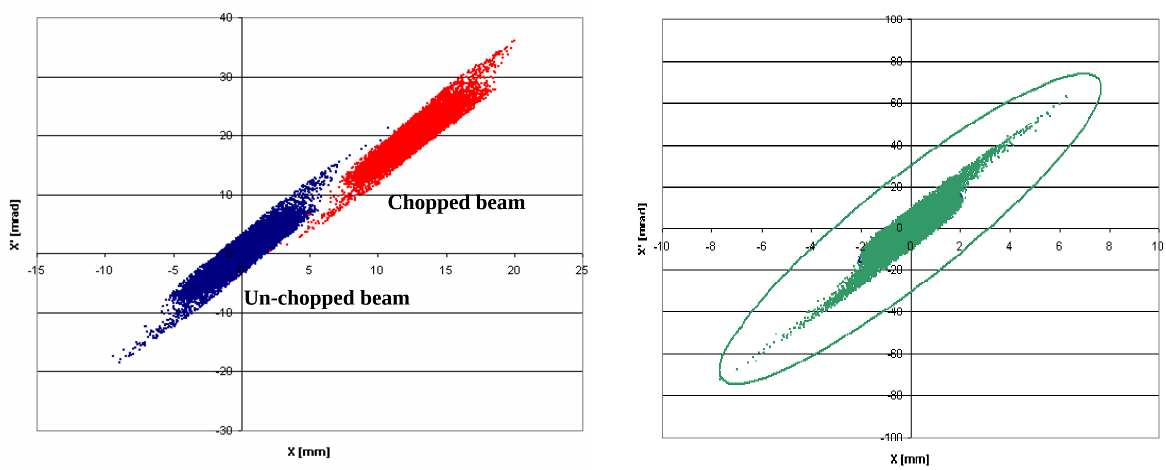

Figure 4 – Beam parameters in the phase space for the off-line (left diagram) and end-of-line (right diagram) absorbers.

Table 1 – Driving parameters for the off-line and in-line beam absorbers.

Parameters				Remarks	Load cases		
					Design	*SPL*	*PSB*
Beam	Particle energy	E	MeV		3	3	3
	avg. curr. before chopper	I_{avg}	mA		2.94	2.94	0.04
	Particles	N_b	$10^{16}\ s^{-1}$		1.83	1.83	0.025
	Mean power	P	kW	E [eV] * I_{avg}	8.82	8.82	0.12
	Reference beam radius	r	mm		6	6	6
	Orthogonal thermal flux	$q''_\perp$	MW/m^2	$P/\pi r^2$	78	78	1
	Chopping factor	c	-		3/8	3/8	2/8
	avg. curr. after chopper	I'_{avg}	mA		1.84	1.84	0.03

Technical Study

General

According to the basic constraints, a unique design has been pursued for both the chopper and the end-of-line absorbers. The heat flux (~10 MW m^{-2}) to be removed by the dumps is in the same range of that observed in the klystron of electronic tubes. Fin enhancement cooling concepts with boiling/condensation effect, named vapotron® and then hypervapotron®, were developed by Thomson CSF Company [3]. As far as the 3 MeV test facility is concerned, this concept is deemed an interesting alternative to microchannel cooling [4] because of no clogging issues and more robust mechanical design.

The ensuing conceptual study has been outlined in [5], where the induced radioactivity and the structural performance of the absorber have been investigated. The main findings of this analysis are hereinafter summarised for the final design choice.

Dump geometry

Each dump is schematically made of a Ø42/12x133 mm^3 conical element (the "dump core" shown in Figure 5) embedded into a thick brick-shaped jacket with 5 hypervapotron circular cooling loops (see Figure 6**Error! Reference source not found.**). Protons impinge on the inner conical surface of the core at an angle of 11 degrees. It is noted that this geometry makes the chopper dump act as an aperture limiter for the un-chopped beam, thus reducing significantly the number of scattered protons downstream of the dump location.

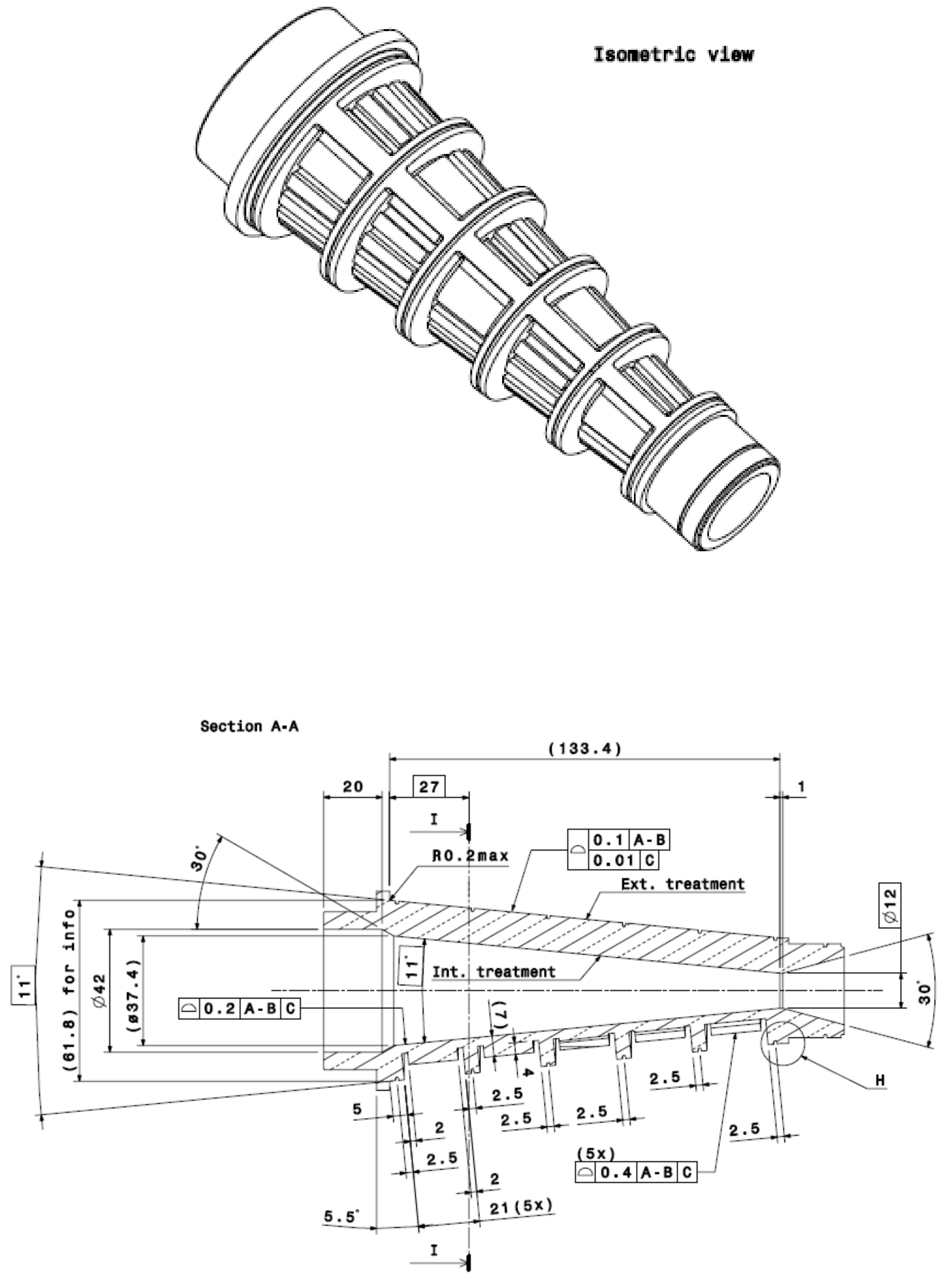

Figure 5 – Technical details of the absorber's core

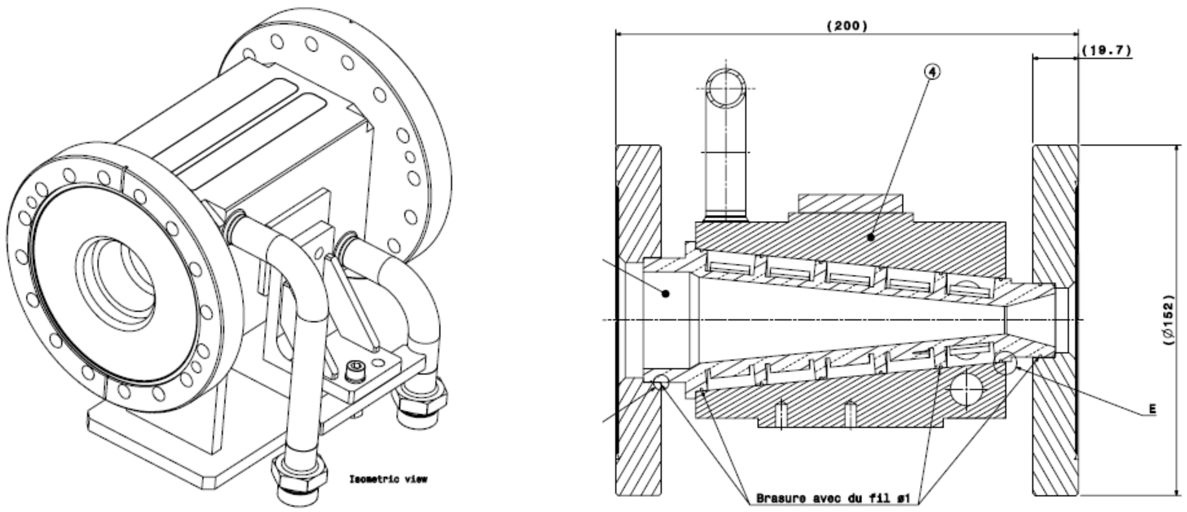

Figure 6 – Isometric view and cross-section of the absorber [6].

Materials

The choice of high-thermal-performance materials for the active core elements of a beam intercepting device is the key to the successful fulfilment of its requirements. In doing this, the constraint of avoiding materials with hazardous physical or chemical properties has been respected to limit the induced activity and ease handling.

Austenitic stainless steel 316LN and alumina dispersion-strengthened copper Glidcop Al60 have been selected for the jacket and the dump core respectively. A 150-µm-thick electrolytic nickel layer is deposited on the inner copper surface, while a 2-µm-thick nickel coating is applied on the outer copper surface. All auxiliary parts (flanges and cooling connections) are made of 316LN. These parts are joined by a single-step brazing.

Cooling

The schematic cross-section of a cooling channel is shown in Figure 7. This geometry has been tested [6**Error! Reference source not found.**] to ascertain the Critical Heat Flux (CHF), and the measured values have shown its good performances up to 25/30 MW/m^2 for water temperature ranges of 65÷103 °C, with a flow rate of 0.3÷1.1 kg s^{-1} at 32÷34 bar **Error! Reference source not found.**]. The test-stand parameters of 0.5 kg s^{-1}/6 bar are deemed acceptable under the test conditions at the Proton Synchrotron Booster. It is noted that because of thermal inertia, the fine bunch time-structure does not affect the behaviour of the dump.

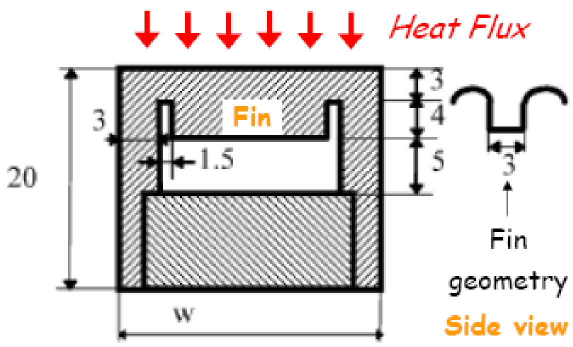

Figure 7 – Schematic cross-section of a cooling channel (dimensions are in [mm]).

Induced radioactivity

The incoming particles interact with the dump core mainly by electronic excitation, ionization, elastic scattering and inelastic interactions. By these processes, a small fraction of particles undergo a partial energy loss before being scattered, while the majority (99.5%) is absorbed in the first ~100 µm of the material.
Slowing down of protons produces X-rays by bremsstrahlung and fluorescence, while inelastic interactions generate radioactive nuclides. Among the possible nuclear reactions produced by protons on Ni, those with cross-sections higher than 10^{-29} [8] (value arbitrarily chosen) generate Co-55, Co-57, Cu-60 and Cu-61. On this basis, the maximum remnant equivalent dose rate after one month operation at 40 µA (40 mA X 500 µs X 2 Hz) is estimated at 80 µSv/h at 1 cm distance, 11 µSv/h at 10 cm and 0.3 µSv/h at one metre, the main contribution coming from Co-55. The expected contact value becomes 25 µSv/h after one day and 0.1 µSv/h after one week.
Samples of Ni have been irradiated with a 3 MeV proton beam at the Tandem machine of Orsay (Paris, May 2004) to measure the dose rate with a scintillator and the specific activity with gamma-ray spectroscopy. At the end of the irradiation, the only radionuclides whose gamma-emissions could be detected were Cu-61 (half-life of 3.4 hours) and Cu-64 (half-life of 12.7 hours). Due to the relatively short half-life, their activity will reach saturation after a few days of operation. The measured dose rate at 50 cm distance from the Ni sample after 8 hour irradiation at 1 µA was 0.05 µSv/h (i.e., 16 nSv/h from induced radioactivity and 34 nSv/h due to the background). For SPL (40 µA average current) this corresponds to 0.16 µSv/h at 1 m distance, in reasonable agreement with the above prediction [9].
During operation, the X-rays produced in nickel are absorbed in the dump and do not significantly contribute to these values. Secondary neutrons are equally deemed negligible. Gamma rays from (p,p') and (p,γ) reactions would generate 1 µSv/h at one metre distance, which could be shielded by a few centimetre thick lead layer.

Structural performance

A simplified dump structure was modelled by the finite element code ANSYS to study the 2D steady-state thermal and stress fields. Based on this numerical analysis, the cooling scheme is effective in limiting the maximum temperature of the dump core below T_{max}=90°C. The maximum expected heat flux at the inner surface of the cooling channels is few MW m^{-2}, which is far below the critical heat flux (30 MW m^{-2}) for the given cooling conditions. The maximum Von Mises stresses are estimated below 2/3 of the yield stress at the working temperature in the dump core (177 MPa) and jacket (200 MPa).

Conclusions

A compact design of a beam dump for the 3 MeV H^- test facility has been put forward where a conical $CuAl_2O_3$ dump core is embedded into a thick 316LN jacket with hypervapotron cooling. High mechanical performances against pressure loads are thereby obtained, while the effective cooling copes with the heat loads even in the ultimate case of SPL operating conditions.

The induced radioactivity is strongly limited by covering the active dump surface with a 150 μm layer of electrolytic Ni. In this case, the remnant equivalent contact dose rate after the end of the irradiation is estimated at 80 μSv/h at 1 cm distance, becoming 25 μSv/h after one day and 0.1 μSv/h after one week. During operation, an additional radiation field of ≈1 μSv/h is found due to γ-rays, to be shielded by few centimetres of lead.

References

[1] "*Proposal dor a 3 MeV H- test facility in the PS south hall*", K. Bongardt, F. Caspers, R. Garoby, D. Küchler, A.M. Lombardi, A. Mostacci, M. Paoluzzi, U. Raich, M. Vretenar (ed.); PS/RF Note 2001-017.
[2] "*Conceptual design of the SPL, a high-power superconducting H⁻ linac at CERN*", B. Autin, A. Blondel, K. Bongardt, R. Cappi, F. Caspers, E. Cennini, E. Chiaveri, S. Claudet, R. Garoby, F. Gerigk H. Haseroth, C. Hill, N. Hilleret, J. Inigo-Golfin, M. Jimenez, A. Krusche, D. Kuchler, M. Lindroos, A. Lombardi, R. Losito, R. Nunes, M. Paoluzzi, J. Pedersen, M. Poehler, H. Ravn, M. Sanmartí, H. Schönauer, M. Silari, J. Tückmantel, A. Vital, M. Vretenar (ed.), CERN 2000–012, 15 December 2000.
[3] "*Transfert de flux supérieur à 1 kW/cm2 par double changement de phase entre une paroi non isotherme et un liquide en convection forcée*", A.Beurthereut, presented at the 4th IHT conference, Versailles, September 1970.
[4] "*Design of the SNS MEBT*", J.Staples, D.Oshatz, T.Saleh, LBNL, Berkeley, CA94720, USA.
[5] "*Conceptual design and radiological* issues *of a dump for a 3 MeV test facility*", L.Bruno, M.Magistris, M. Silari, Technical Note CERN-SC-2004-008-RP-TN.
[6] "*Experimental optimisation of a hypervapotron® concept for ITER plasma facing components*", Frédéric Escourbiac, J. Schlosser, M. Merola, I. Bobin Vastra, Fusion Engineering and Design 66-68 (2003) 301-304.
[7] CERN detailed design drawings SPLTAH3M0001 to SPLTAH3M0012, L.Bruno, F.Luiz.
[8] "*Production of radionuclides at intermediate energies*", A.S. Iljnov, N.M. Sobolevsky and L.V.Udovenko, Landolt-Börnstein Editorial Office (1999).
[9] "*Irradiations de l'arrêt faisceau en Nickel par des protons de 3 MeV*", D. Bondoux, R. Brissot, M. Fruneau, D. Marchand, J.A. Pinston, E. Vernay, A. Olivier, D. Gardes, M. Magistris, S. Million and T. Sauvage, LPSC 05/87, May 2005.

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