SUPERCONDUCTING PROTON LINAC DEVELOPMENT AT CERN

K. Hanke, R. Garoby, F. Gerigk, A.M. Lombardi, C. Rossi, M. Vretenar, CERN, Geneva, Switzerland
S. Chel, R. Duperrier, D. Uriot, CEA Saclay, Gif-sur-Yvette, France
P. Pierini, INFN Milano, Italy

Abstract

A superconducting proton linac (SPL) is considered since a few years as a very interesting accelerator for the future of CERN. This device is planned to serve at the same time as a proton driver for EURISOL, for future neutrino experiments (beta beams, super beams, neutrino factory) and as injector for the CERN accelerator complex. Its parameters have recently been revised, taking into account the evolution of the physics requests and the latest developments in superconducting rf. This work will be summarized in a revised conceptual design report (CDR2) to be published by the end of 2005. This paper highlights the most important changes and the foreseen staged approach towards the SPL.

INTRODUCTION

The design of the Superconducting Proton Linac (SPL) at CERN was originally based on the re-use of the rf equipment, which became available with the end of LEP operation. In this design (CDR1) [1], the frequency was dictated by the LEP klystrons and cavities operating at 352 MHz. The final energy of the machine was designed to be 2.2 GeV, which was suitable for a proton driver in the CERN design of a Neutrino Factory.

The reason for re-visiting the design is twofold. Concerning the rf technology, significant progress in the field of superconducting rf has been made since the development of the LEP cavities. Recent results for 704 MHz bulk niobium cavities at $\beta < 1$ are very promising [3, 4]. Concerning the overall design, a final energy of 2.2 GeV appears not competitive for a super beam, as it would not mean a significant progress w.r.t. the T2K (Tokai to Kamioka) long-baseline neutrino oscillation experiment [5, 6].

Driven by these arguments, the overall design has been revisited. The most important changes w.r.t. CDR1 are the use of 704 MHz superconducting rf for the superconducting part of the linac and an increase of the final energy from 2.2 GeV to 3.5 GeV. In the following sections, the superconducting rf at 704 MHz is briefly reviewed, followed by a presentation of the revised SPL design and a description of a staged approach for its construction.

SUPERCONDUCTING RF AT 704 MHZ

Figure 1: Superconducting cavity as proposed for the CERN SPL.

The normal-conducting front-end of the SPL, consisting of RFQ (radio-frequency quadrupole), DTL (drift tube linac), and CCDTL (cell-coupled drift tube linac) uses 352 MHz rf. On the technical side, this allows to re-use de-commissioned LEP klystrons. From a beam dynamics point of view, 352 MHz appears an appropriate frequency for the low-energy part. At 704 MHz, the RFQ focusing would be too weak, the acceptance too low and the dimensions of the DTL very small. The optimum energy for a frequency jump to 704 MHz appears 90 MeV, which is the transition from the CCDTL to the SCL (side-coupled linac) [2]. The normal-conducting SCL as well as the subsequent superconducting linac are hence designed for 704 MHz. A second frequency jump to 1408 MHz is not foreseen, as this would require longitudinal re-matching and would make the control of energy and phase jitter more difficult.

Recent progress in superconducting rf suggests that gradients of up to 25 MV/m appear feasible for $\beta = 1$ bulk niobium cavities at 704 MHz. For lower relativistic β, gradients of up to 18 MV/m have been experimentally demonstrated for a 5-cell, $\beta = 0.65$, 704 MHz bulk niobium cavity [3]. It has been shown, that the surface electric field, which is presently limiting the achievable gradient, depends only very weakly on the frequency and more on the quality of the surface itself. High surface electric fields of 50 MV/m have been demonstrated by the TESLA collaboration for $\beta = 1$ cavities at 1300 MHz, while SNS cavities operating at 800 MHz and $\beta = 0.6$ and 0.8 achieve values between 40 and 50 MV/m. Also at 704 MHz, values of above 40 MV/m have been demonstrated for low relativistic β. These figures are no longer based on single cavities but on large-scale production as e.g. for SNS and TTF. The accelerating field is related to the surface electric field by an empirically found curve, which represents an optimization process. The factors relating the two quantities vary between 2.0 for $\beta = 1$ (TTF) and about 3.5 for $\beta = 0.47$

Table 1: Main linac parameters

	Linac4	SPL	
ion species	H^-	H^-	
length	80	446	m (including source)
beam energy	160	3500	MeV
beam power	5.1	4000	kW
bunch frequency	352.2	352.2	MHz
repetition rate	2	50	Hz
source current	80	80	mA
peak current	64*	64*	mA
chopper beam-on factor	62	62	%
chopping scheme	133/355	3/8	
average pulse current	40	40	mA
average current	0.032	1.14	mA
beam pulse length	0.4	0.57	ms
beam duty cycle	0.08	2.85	%
particles per pulse	1.0	1.42	$\cdot 10^{14}$
particles per bunch	1.14	1.14	$\cdot 10^{9}$
maximum uncontrolled beam loss	1	1	W/m
tr. rms emittance (DTL-in)	0.28	0.28	π mm mrad†
long. rms emittance* (DTL-in)	0.17	0.17	π deg MeV
	0.43	0.43	π mm mrad†
tr. rms emittance (output)	0.29	0.35	π mm mrad†
long. rms emittance* (output)	0.18	0.2	π deg MeV
	0.45	0.50	π mm mrad†

* at 352.2 MHz,

† normalized, at 704.4 MHz only every 2nd bucket is filled and the peak bunch current doubles

(TRASCO, RIA).
Based on these figures, and assuming further progress of R&D in superconducting rf, we base the SPL design on two families of cavities ($\beta = 0.65$ and $\beta = 1.0$) with 5 cells per cavity and the following gradients:

$\beta = 0.65$: 19 MV/m
$\beta = 1.0$: 25 MV/m.

REVISED PARAMETERS

Table 1 shows the main linac parameters for two phases of the SPL. Linac 4 corresponds to the normal conducting part of the SPL consisting of RFQ, DTL, CCDTL and SCL. SPL, corresponds to the full 3.5 GeV linac, i.e. the normal conducting (Linac 4) part plus the superconducting linac up to the final energy of 3.5 GeV.

STAGED APPROACH

The construction of the SPL will be staged. In a first step, a 3 MeV test place is being built which consists of ion source, LEBT, RFQ, MEBT with beam chopper and a dedicated beam diagnostic line. This set-up is presently under construction at CERN. In a second step, a normal conducting linac will be added to the 3 MeV set-up. This linac, referred to as Linac 4, will serve as a new injector for the existing CERN PS Booster. In a third step, the superconducting part will be added, leading to the full SPL. In the following subsections, we describe the three different stages.

3 MeV Test Place

The test stand, presently in construction, consists of an ion source, an RFQ from the French IPHI project [7], a chopper line and a diagnostic line. This part is, except for the diagnostic line, considered the front-end of the Linac 4 and SPL. A 352 MHz RFQ accelerates a beam current of 64 mA H^- ions from 0.095 MeV to 3 MeV. The beam then passes through a chopper line of 3.7 m total length, where a chopper with rise and fall time of less than 2 ns removes 3 out of 8 subsequent bunches. This generates the time structure required to fill an accumulator and compressor ring operating at 44 MHz. Apart from the chopper structure, the chopper line comprises a total of 11 quadrupoles and three bunchers. Downstream of the chopper line, the beam will be characterized using a dedicated diagnostic line which, as the RFQ, is provided in the frame of the IPHI-CERN collaboration with the French CEA and IN2P3. In this line, beam emittance, energy and energy spread can be measured. A dedicated halo monitor has been developed at CERN to monitor the correct functioning of the chopper structure and, at the same time, provide a transverse image of the beam [8]. As this device has an extremely high dynamic range of 10^6, it can measure an intensity of down to 1×10^3 ions in the vicinity of a bunch populated with 10^8 ions and can hence verify if a bunch has been fully chopped. In the transverse plane, the high dynamic range allows to measure the beam halo, populated with 10^3 ions, and at the same time the beam core populated with 10^8 ions.

Linac 4

In a second phase, a normal conducting linac will be installed downstream of the chopper line. This linac, referred to as Linac 4, consists of several parts: a drift tube linac (DTL) up to an energy of 40 MeV, a cell-coupled drift tube linac (CCDTL) from 40 to 90 MeV and a side coupled linac (SCL) from 90 to 160 MeV (CERN PS Booster injection) respectively 180 MeV (SPL front-end). While the frequency of DTL and CCDTL is 352.2 MHz, the SCL operates at 704.4 MHz. The DTL uses permanent magnets for focusing. Prototype hardware is being developed and manufactured by Russian laboratories and nuclear cities in the frame of ISTC projects. In the DTL and CCDTL, the peak beam current is 64 mA and the average current 40 mA. In the SCL, the peak current is 128 mA, while the average current is still 40 mA.
The Linac 4 is planned to be installed in an existing hall and to serve as a new injector for the CERN PS Booster. The H^- injection will, together with the higher injection energy (160 MeV instead of 50 MeV with the existing Linac 2) significantly increase the intensity in the Booster for fixed-target and LHC beams [9].

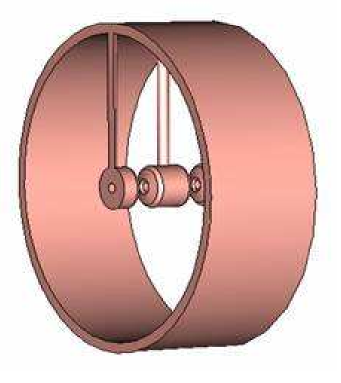

Figure 2: One DTL cell used in the first part of the normal conducting linac. Focusing is performed by permanent magnet quadrupoles inside the drift tubes.

SPL

In its final stage, the linac will consist of the 3 MeV front-end, a normal conducting part (DTL, CCDTL and SCL) up to an energy of 180 MeV and a superconducting part up to the final energy of 3.5 GeV. The superconducting part uses bulk niobium cavities at 704.4 MHz for β=0.65 and β=1.0. The design gradients are 19 and 25 MV/m respectively. As every other bucket is filled, the peak beam current is 128 mA, while the average current remains 40 mA. The overall length of the superconducting linac is 357 m. Figure 5 shows a block diagram of the final stage, including the normal conducting part with its three sections and the superconducting part.

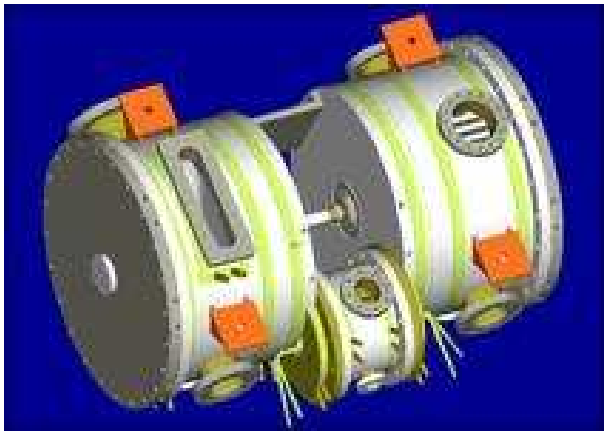

Figure 3: CCDTL hot model as used for tests at CERN.

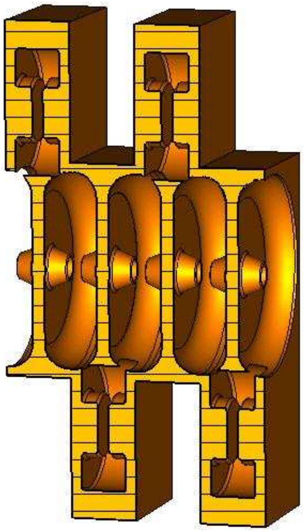

Figure 4: Side coupled linac used in the last part of the normal conducting linac.

LINAC 4 AND SPL USERS

The staged Linac 4/SPL satisfies the needs of CERN's physics users at each stage of its construction. The normal conducting Linac 4 with its 160 MeV final energy will become the new injector for the CERN PS Booster. It will significantly increase the flux to ISOLDE and improve the beam delivered to the LHC, allowing to reach the ultimate luminosity.
In its final stage, the SPL can satisfy various users at dif-

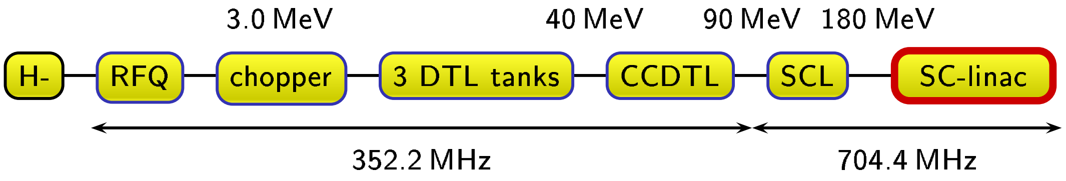

Figure 5: Block diagram of the SPL, consisting of the normal conducting front-end (Linac 4) and the superconducting linac.

ferent beam energies. The EURISOL facility requires an energy of about 1-2 GeV. The same energy is appropriate for generating beta beams. The SPL beam at 3.5 GeV will be directly injected into the PS, replacing the present Booster and reducing space charge by a factor of 4. For applications aimed at neutrino production like super beams or neutrino factories, the full 4 MW beam power at 3.5 GeV is required. The SPL is hence a multi-purpose facility, opening the door to a wide physics program.

CONCLUSION

A superconducting H^- linac, presently under study at CERN, offers an interesting physics program for the future of CERN at each stage of its completion. The normal conducting part, or Linac 4, re-uses rf equipment from the de-commissioned LEP machine. The superconducting part takes advantage of recent achievements in superconducting rf.

ACKNOWLEDGEMENTS

We acknowledge the contributions of CEA/DSM and CNRS/IN2P3 (France), RAL (U.K.), CAT (India), IHEP (China) as well as the Russian institutes ITEP, VNIIEF, BINP, VNIITF and IHEP to the project.

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” programme (CARE, contract number RII3-CT-2003-506395).

REFERENCES

[1] M. Vretenar (ed.), *Conceptual Design of the SPL - A High-Power Superconducting H^- Linac at CERN*, CERN 2000-012 (2000).

[2] F. Gerigk, E. Benedico Mora, A. M. Lombardi, E. Sargsyan, M. Vretenar, *Beam Dynamics for a New 160 MeV H^- Linac at CERN (Linac 4)*, conf. proc. LINAC 2004, Lübeck/Germany and CERN-AB-2004-101 (2004).

[3] S. Chel, *Status of the Elliptical Cavity Developments at Saclay*, talk given at the HIPPI04 Meeting, Frankfurt, not published.

[4] P. Pierini, these proceedings.

[5] CERN PS and SPS Committee, *Fixed-Target Physics at CERN beyond 2005 - Summary and Conclusions of an Evaluation by the SPSC (Villars Meeting 22-28 September 2004)*, CERN-SPSC-2005-010 and SPSC-M-730 (2004).

[6] J.E. Campagne, A. Cazes, *The Theta 13 and Delta CP Sensitivities of the SPL-Frejus Project Revisited*, LAL-04-102; hep-ex/0411062 (2004).

[7] P.-Y. Beauvais, *Recent Evolutions in the Design of the French High-Intensity Proton Injector (IPHI)*, conf. proc. EPAC 2004, Luzern/Switzerland (2004).

[8] K. Hanke, M. Hori, *Design and Construction of a Beam Shape and Halo Monitor for the CERN SPL*, CARE/HIPPI Document 2005-005 and CERN AB-Note-2005-033 OP (2005).

[9] R. Garoby, F. Gerigk, K. Hanke, A. Lombardi, C. Rossi, M. Vretenar, *Linac 4, a New H^- Linear Injector at CERN*, conf. proc. RUPAC 2004, Dubna/Russia (2004) and CERN-AB-2005-012 (2005).