LAYOUT AND MACHINE OPTIMISATION FOR THE SPL AT CERN

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Abstract

During the past 2 years the Superconducting Proton Linac (SPL) study has grown into an international collaboration with the goal of optimising the architecture of a pulsed superconducting (SC) high-power proton linac. This effort includes the study and prototyping of major technical components, such as SC high-gradient cavities, power couplers, the RF distribution system, HOM couplers, cryo-modules, focusing elements, etc. Even though the effort is driven by CERN's specific needs, the established design principles are valid for a range of SC linac projects. In this paper we report on the latest decisions concerning the machine architecture and on the ongoing R&D effort for technical components.

INTRODUCTION

Since the start of the SPL collaboration in the end of 2008 four general SPL collaboration meetings have taken place (e.g. [1, 2]) to elaborate important technical choices for a high-power proton linac, which is based on a frequency choice of 352/704 MHz (or similar) and the use of high-gradient SC cavities operating at 2 K [3]. At CERN such a linac is presently studied as a possible proton driver for neutrino physics with a parameter set as listed in Table 1. The collaboration partners include members of high-power proton linac projects, (such as Project X, ESS, SNS, MYRRHA, and JPARC) and profits from the participation of various Universities (TU Darmstadt, Stockholm, Lancaster, Rostock, Royal Holloway, Aarhus, Manchester, Uppsala), companies (Scandinova, JEMA, TEKNIKER) and Institutes (CEA, CNRS, IPN Orsay, JLAB, BNL, TRIUMF, ESS-Bilbao, Soltan Institute), all generally involved in electron and proton linac studies or which are engaged in the technology of SC cavities.

In collaboration with ESS, CERN foresees high-power tests of a short horizontal cryo-module containing four $\beta = 1$ SC cavities in the first half of 2013. In order to fulfill this ambitious goal the cavities will be constructed in industry and then chemically treated at CERN using the DESY recipe of surface treatments for the XFEL cavities. In parallel CERN starts an in-house design and construction of SC cavities, with the purpose of developing a better understanding of the construction process and then to equip a 2nd generation long cryo-module, representing the nominal SPL layout with 8 cavities per module. High-power tests of this full size module are planned for the first half of 2015.

Table 1: Parameter Table for Low Current (20 mA) and High-current (40 mA) Operation

Parameter	Unit	low-cur. 20 mA	high-cur. 40 mA
Energy	[GeV]	5	5
Beam power	[MW]	4	4
Repetition rate	[Hz]	50	50
Average pulse current	[mA]	20	40
Peak pulse current	[mA]	32	64
Source current	[mA]	40	80
Chopping ratio	[%]	62	62
Beam pulse length	[ms]	0.8	0.4
Protons per pulse	[10^{14}]	1.0	1.0
Beam duty cycle	[%]	4	2
Linac length	[m]	525	525

In the coming years CERN will continue R&D on technical items for the SPL. Further work on civil engineering and site specific integration, however, is put on hold until the direction of the post-LHC physics program at CERN can be defined more clearly.

RF SYSTEM

A model for driving 1-4 cavities with a single klystron was implemented in SIMULINK [4], taking into account Lorentz force detuning, feed-forward and feedback controls as well as jitter on the beam current. First results for the needed power overhead on a "one cavity per klystron system" indicate values of ≈ 40 kW and ≈ 60 kW for the feedback loops compensating Lorentz force detuning and current jitter (5%). A first measurement campaign was done with CERN participation at the CEA 704 MHz test stand in order to verify the modelling of the RF equipment (klystrons, circulators, cavity response, etc.), and this work will continue once the CERN test stand is operational. Another outcome of the LLRF studies [5] is the maximum wave-guide length between klystrons and cavities, which can be accepted by feedback loops. An 80 m distance makes it possible to locate klystrons and modulators over ground and yields a wave-guide related group delay of ≈ 650 ns, which roughly doubles the total group delay when compared to a system where the klystrons are located close to the cavities.

The baseline for the RF power distribution is to have one RF source per cavity in the low-energy section. Due to the lower power needs of $< 700\,\mathrm{kW}$ per $\beta = 0.65$ cavity (incl. all overheads for 40 mA operation) high-power IOTs or phase-locked magnetrons are considered as RF sources. Both options, however, need a dedicated R&D program, which is presently not covered within the SPL study. In the $\beta = 1$ section the baseline is to have 1 klystron per cavity for high-current (40 mA) operation. The possibility of using 2 cavities per klystron for low-current (20 mA) operation remains intriguing but further R&D is needed to come to a viable solution. A splitting to more than 2 cavities per RF source has been ruled out, because of the considerable RF power overhead and the difficulties of controlling amplitude and phase in each cavity to the required precision ($\pm 0.5°$, $\pm 0.5\%$).

In preparation of the high-power test of the short cryo-module, one of the two existing bunkers (SM18) is prepared for the cavity tests at 704 MHz and 2 K. This involves the consolidation of the existing cryo-infrastructure and the installation of a 704 MHz klystron including a pulsed modulator. A high duty cycle device is foreseen to be supplied by ESS (Lund), while a low duty cycle modulator will be available after the testing of the Linac4 accelerating structures, in the beginning of 2013. In parallel CERN is working on its own klystron modulator design, which is expected to be operational for a full-length cryo-module test in 2015. Vertical cryostats for cavity testing are available from the end of 2010. The existing clean room needs refurbishment in order to have a class 100 dressing zone and a dedicated water rinsing zone.

SC CAVITIES

The cavity design (CEA Saclay) for the short cryo-module has been frozen (Fig. 1), and Niobium (RRR 300) sheets for four cavities of 520×520 mm have been ordered from industry. The starting thickness is 3.6 mm and the maximum loss in thickness caused by spinning, chemical etching and EP is estimated to be 1.1 mm. The 1st longitudinal mechanical resonance is at 130 Hz, and the 1st transverse resonance –considered to be less important– was found at 50 Hz. In 2011 one Nb cavities will be built by CEA within the FP7 framework program, and four cavities will be built by industry for tests at CERN. By the end of 2013 four additional cavities will be constructed in the CERN workshops. First trials on field flatness tuning and HOM measurements will be made on two copper cavities, which are expected toward the end of 2010. The main components of a suitable Electropolishing (EP) station have already been assembled, while simulation work is still ongoing for the shape of the electrode [6]. A working model is expected for the beginning of 2011.

For the high-power coupler there are 2 designs under consideration at CERN: i) derived from power couplers of the CERN SPS RF system, using an air cooled coaxial disk [7], ii) derived from LHC couplers featuring an air cooled cylindrical window as shown in Fig. 1 [7]. All versions use a double walled outer tube, which is cooled by Helium gas

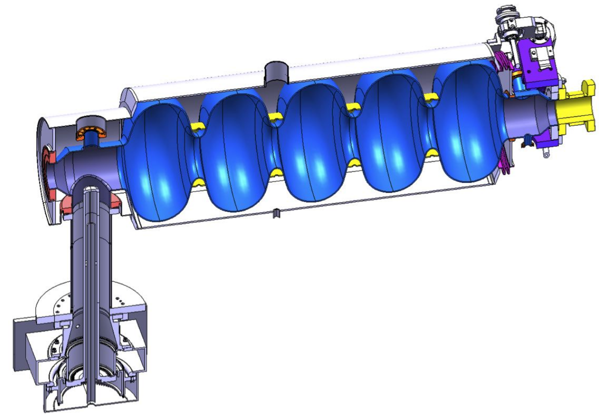

Figure 1: Geometry of 704 MHz $\beta = 1$ cavity with high-power coupler.

at 4.5 K. With a mass flow of 35 mg/sec, the coupler related losses at 2 K are reduced to 0.2 W per unit [8]. In addition the CEA coupler has already been qualified for operation at 1.1 MW with a pulse length of 2 ms and 50 Hz repetition rate. The coupling of fundamental pass band modes and HOMs between cavities is studied at RHUL, where ACE3P is used to simulate a complete string of 4 cavities [9].

BEAM DYNAMICS & HOM DAMPING

The beam dynamics layout includes extraction areas at 1.4 GeV and 2.5 GeV for ISOLDE and a potential future RIB facility, respectively. End to end simulations starting with the expected source beam at 45 keV show an r.m.s. emittance growth of $\approx 10\%$ per plane. Magnetic stripping of H^- has been studied [10] in order to shorten the length of the warm quadrupoles. For the nominal doublet lattice a minimum magnetic length of ≈ 400 mm is needed, which can be reduced for lower energies or for a different lattice type (FODO). Using a FODO lattice after the transition at 2.5 GeV is studied as a promising option [11], which can reduce the number of magnets and the magnet length while keeping the same number of cavities between magnets as for the doublet focusing below 2.5 GeV.

An analysis of Higher Order Modes (HOMs) [12, 13] indicates that for non-resonant HOM excitation a moderate damping (external Q: $Q_{ex} \approx 10^7$) is sufficient to avoid excessive heat loads ($\gtrapprox 1$ W) at the 2 K level and to avoid beam break-up. This assumes that it is always possible to avoid HOM frequencies to coincide with machine lines. In case of the SPL the operation with chopped beams requires beam stability even if an HOM falls on a machine line created by chopping. This reduces the maximum allowable Q_{ex} of the HOMs to 10^5 or even 10^4 when limiting the power (< 100 W) into RF cables, located inside of the insulation vacuum. For the short cryo-module it was decided to have ports available for dismountable HOM couplers with notch filters, currently being designed at Rostock University. The option of HOM damping in the inter-cavity area (e.g. by means of stainless steel bellows or ferrites at temperatures above 2 K) has been discarded for frequencies below 1800 MHz because of the weak HOM coupling to this area. For higher frequencies this option seems viable provided that the heat load into the 2 K system can be limited.

A 5 GeV dump has been studied, which can be used for low duty cycle commissioning (0.1 Hz, $1.5 \cdot 10^{14}$ protons/pulse, $1 \cdot 10^{20}$ protons/year), and for beam set-up ($2.5 \cdot 10^{19}$ protons/year) during regular operation. The design follows the Project X approach of having a layered graphite-tungsten core in a water cooled aluminum shell. The shielding around the core consists of a Tungsten shell surrounded by iron and an external concrete layer bringing its total size to $3 \times 2 \times 2$ m. Fluka simulations [14] indicate a dose rate $\approx 1.7\,\mu\mathrm{Sv\,h}^{-1}$ on the surface above the dump for 7 m of earth in between, which is below the limit for public access ($2.5\,\mu\mathrm{Sv\,h}^{-1}$). The dump itself must be several metres away from sensitive equipment.

CRYOGENICS

The decision was taken [1, 2] to have cold-warm transitions between cryo-modules containing warm magnets, fast vacuum valves and diagnostics. Long continuous cryo-strings rule out the use of fast (warm) valves, meaning that accidental vacuum leaks can spoil the RF performance of a large number of cavities, which would have to be chemically reprocessed for nominal (high-gradient) operation. The drawbacks of a segmented design (separate cryo-line, higher static load, slightly longer linac) are largely compensated by a reduced risk of vacuum incidents, entailing long repair times. An independent analysis recommended the same approach for ESS [2].

In order to define the cryogenic infrastructure, a nominal and ultimate load case was defined for cryogenics. The latter assuming low-current operation of the SPL, twice the nominal pulse length (Table 1), and a 50% reduced cavity Q_0 (Table 2).

CONCLUSIONS AND OUTLOOK

The design and layout of the SPL has been consolidated by the following measures: i) Cryomodules are now segmented to allow for warm fast vacuum valves and for easy replacement of modules. ii) Klystrons and modulators of the high-energy part will be located on the surface, which avoids space restrictions underground and which allows for easier equipment access. In the low-energy part, where the power needs per length are lower, a klystron/modulator gallery will be underground in parallel to the accelerator tunnel. iii) A short 4 cavity cryo-module is under construction to validate design choices for the module and to test cavities and power coupler for nominal performance. Cavity and coupler design has been frozen for the short module but will evolve for the next generation of cavities. iv) Beam dynamics proposes a mixed lattice (doublet and FODO), which reduces the number of magnets, the linac length and which also reduce H^- stripping. v) The feasibility of a beam dump has been demonstrated.

Table 2: Cavity and Cryo-parameters for Nominal (40 mA, 0.4 ms, high Q_0) and Ultimate (20 mA, 0.8 ms, low Q_0, max. Load Case for Cryogenics)

Parameter	Unit	$\beta = 0.65$ nominal/ultimate	$\beta = 1.0$ nominal/ultimate
Energy range	[MeV]	160-790	790-5000
Av. pulse current	[mA]	40/20	
Fill. time τ_l	[ms]	0.27/0.54	0.27/0.55
Tot. fill. time	[ms]	0.37/0.75	0.38/0.76
RF pulse length	[ms]	0.77/1.55	0.78/1.56
RF duty cycle	[%]	3.9/7.8	
Accel. gradient	[MV/m]	19.3	25
Q_0	[10^9]	6/3	10/5
R/Q	[Ω]	290	570
Number of cav.		60	200
Cav. per cryostat		3	8
Cryo duty cycle	[%]	4.1/8.2	
Cavity bath temp.	[K]	2	
Dyn. heat load p.c.	[W]	4.2/16.8	5.1/20.4

REFERENCES

[1] 3d SPL collaboration meeting, 11-13 Nov. 2009, Geneva, `http://indico.cern.ch/63935`.

[2] 4th SPL collaboration meeting jointly with ESS, 30 Jun. - 2 Jul. 2010, Lund, `http://indico.cern.ch/82809`.

[3] O. Brunner *et al*, Phys.Rev.ST Accel.Beams 12, 070402 (2009).

[4] M. Hernandez, Progress report on SIMULINK modelling of RF cavity control for SPL extension to Linac4, to be published, 2010.

[5] W. Höfle, SPL LLRF simulations, (talk at [1]).

[6] S. Calatroni, L.M.A. Ferreira, M. Leitao Macatrao, Y.L. Withofs, Status of the EP simulations and facilities for the SPL design, LINAC'10.

[7] E. Montesinos, SPL power coupler possible designs, 16 March 2010, `http://indico.cern.ch/event/86123`.

[8] O. Capatina, T. Renaglia, SPL power coupler double walled tube thermo-mechanical studies, Review of SPL RF power couplers, 16 March 2010, `http://indico.cern.ch/event/86123`.

[9] S. Molloy, Activities at RHUL, (talk at [2]).

[10] P. Posocco, M. Eshraqi, Magnet stripping studies for SPL, CERN-BE-Note-2010-015.

[11] M. Eshraqi, The mixed SPL architecture, (talk at [2]).

[12] M. Schuh, F. Gerigk, J. Tuckmantel, C.P. Welsch, Higher order mode analysis of the SPL cavities, IPAC'10.

[13] M. Schuh, W. Weingarten, Power dissipation by higher order modes, technical note, to be published.

[14] T. Otto, Considerations for an SPL beam dump, (talk at [2]).