DESIGN OF LINAC4, A NEW INJECTOR FOR THE CERN BOOSTER

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Abstract

A new H^- linac (Linac4) is presently under study at CERN. This accelerator, based on normal conducting structures at 352 and 704 MHz, will provide a 30 mA 160 MeV H^- beam to the CERN PS Booster (PSB), thus overcoming the present space-charge bottleneck at injection with a 50 MeV proton beam. Linac4 is conceived as the first stage of a future 2.2 GeV superconducting linac (SPL) and it is therefore designed for a higher duty cycle than necessary for the PSB.

This paper discusses the design choices, presents the layout of the facility and illustrates the advantages for the LHC and other CERN users. The R&D and construction strategy, which mainly relies upon international collaborations, is also presented.

INTRODUCTION

A 2.2 GeV, 4 MW Superconducting Proton Linac (SPL) [1] represents a very interesting option for the long-term future of CERN (beyond 2010). This linac would serve as high power driver for neutrino production and/or radioactive ion physics. At the same time, as a high-brightness injector, it would modernise and improve the LHC injection chain, paving the way for an LHC upgrade. The low energy part of the SPL, up to 160 MeV, is normal conducting. It could be built first and used to inject H^- in the PSB, advantageously replacing the present 50 MeV proton Linac2. This new linac injector being the 4th hadron linac to be built at CERN would be named Linac4. Re-using part of the 352.2 MHz RF equipment from the decommissioned LEP accelerator and profiting from the available space and infrastructure in the Proton Synchrotron (PS) South Hall, the construction of Linac4 can be particularly cost-effective.

The main expected benefit of Linac4 is the doubling of the intensity and brightness of the beam from the PSB because of the charge-exchange H^- injection and because of the reduction in the space charge induced tune shift at low energy. That will result in an increased proton flux to the CERN users and an increased bunch population for the LHC. The energy of the new linac is set by the requirement for the PSB to deliver to the PS the LHC beam intensity in a single batch as compared to the present double batch, which corresponds to doubling the intensity per bunch in the PSB. Assuming that the maximum intensity at injection is inversely proportional to the tune shift, which in turn scales like $1/\beta\gamma^2$ (at constant normalized emittances), one can estimate that an energy increase from 50 to 160 MeV, corresponding to a factor 2 in $\beta\gamma^2$, will approximately double the maximum injection intensity. Recent simulations have confirmed this expectation. [2].

A recent study has compared different intensity upgrade scenarios for the CERN accelerators, recommending the construction of Linac4 in the medium term [3]. The estimated performance of the CERN complex with Linac4 together with the decrease of the PSB repetition period from 1.2 to 0.9 s and with upgrades to PS and SPS for higher intensity is shown in Table 1 and compared to present performance. The improvement for neutrino experiments is a factor 1.7, while for radioactive ions a factor of 3.5 is expected. The higher beam brightness would allow the bunch population at PS exit to reach 2×10^{11} protons in a 72 bunch train, corresponding to the LHC ultimate luminosity.

Table 1: Possible improvement to the CERN p beams.

	Normal	Improved	
Flux to CNGS (ν beam)	4.5	7.5	$\times10^{19}$ pot/yr
Avg. current to ISOLDE	1.9	6.4	μA
LHC bunch population at PS exit	1.5	2.0	$\times10^{11}$ ppb

PARAMETERS AND LAYOUT

Linac4 will operate in two modes, initially as PSB injector at a maximum repetition frequency of 2 Hz and, at a later stage, at 50 Hz as front-end of the SPL. For injection in the PSB, the beam current is 30 mA, allowing the required number of protons per pulse to be reached in 500 μs, for a duty cycle of 0.1%. For the nominal SPL mode, the available RF power in the SC section limits the beam current to 13 mA, while the pulse length is 2.8 ms, for a duty cycle of 14%. Taking into account the chopping at low energy and the collimation in the front-end, the current required from the source is 50 mA and 30 mA respectively for the two operating modes. The linac structures are designed for the high duty cycle, but they will be operated in a first stage only at low duty cycle. Table 2 summarises the main design parameters.

Table 2: Linac4 parameters.

	Phase 1 (PSB)	Phase 2 (SPL)	
Beam Energy	160		MeV
Maximum repetition rate	2	50	Hz
Source current	50	30	mA
RFQ current	40	21	mA
Chopper beam-on factor	75	62	%
Current after chopper	30	13	mA
Pulse length (max.)	0.5	2.8	ms
Average current	15	1820	μA
Max. beam duty cycle	0.1	14	%
Transv. norm. emitt. (rms)	0.33	0.33	π mm mrad
Long. emittance (rms)	0.24	0.24	π deg MeV

The basic Linac4 building blocks are sketched in Fig. 1 and the main layout parameters reported in Table 3 [4]. A chopper line section generates the beam time structure required for longitudinal injection into the PSB. The transition energy of 3 MeV between RFQ and DTL is considered as the highest value still giving negligible irradiation in case of beam loss, the cross-section for nuclear reactions in Cu still being very small at 3 MeV.

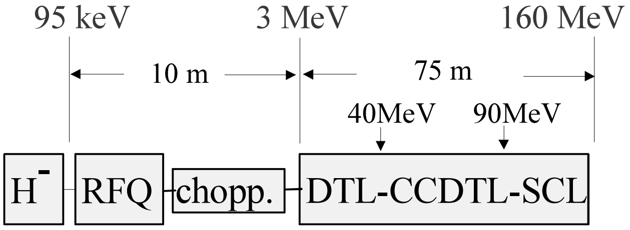

Figure 1: Schematic Linac4 layout.

Table 3: Linac4 layout.

Section	Output energy (MeV)	No. of cavities (tanks)	RF Freq. (MHz)	Peak RF power (MW)	No. of klystr.	Length (m)
LEBT	0.095	-	-	-	-	2
RFQ	3	1	352.2	0.9	1	6
Chopper	3	3	352.2	0.1	-	3.7
DTL	40	3	352.2	4.8	5	16.7
CCDTL	90	27	352.2	5.6	6	30.1
SCL	160	20	704.4	13.8	5	27.8
Totals		54	-	25.2	17	86.3

THE FRONT-END

The Linac4 front-end, up to the energy of 3 MeV, is already in construction, and will be extensively tested in a dedicated test area at CERN [5]. It will use the RFQ of the IPHI project, designed and built by CEA and IN2P3 in France, which at the end of a series of tests at Saclay in 2007 will be transferred to CERN to be used in the new injector. This RFQ is designed to operate in CW mode, while at CERN it will be used at a reduced duty cycle.

An H^- source of the ECR type, preferred for its high reliability, is being developed at CERN in connection with the European network on Negative Ion Sources.

The chopper line is being designed and built at CERN, partly using existing quadrupoles and power supplies, to be extensively tested with the RFQ beam in 2007-08. The 3.6 m long line is based on a FODO focusing structure and contains two 500 mm long chopper structures placed inside quadrupoles, a chopper dump, three bunching cavities as well as diagnostics and focusing elements.

ACCELERATING STRUCTURES

An Alvarez DTL structure follows the RFQ, up to an energy of 40 MeV. The DTL is made of 3 tanks, the first one fed by one klystron, and the others by two klystrons each. Tank 1 is equipped with Permanent Magnet Quadrupoles (PMQ), while the other tanks have conventional electromagnetic quadrupoles (EMQ). Simulations indicate that the quadrupoles in the chopper line allow matching to the fixed gradient focusing channel of Tank 1 for a wide range of beam currents. FFDD focusing has been preferred for all the DTL [4].

With the support of the International Science and Technology Centre (ISTC), the ITEP (Moscow) and VNIIEF (Sarov) laboratories in Russia are presently building a prototype of DTL Tank 1 in collaboration with CERN. Additional contributions to the Alvarez DTL development come from CEA and IN2P3 (France), under the EU-funded HIPPI (High Intensity Pulsed Proton Injector) Joint Research Activity (JRA). High-power RF tests of the prototype are scheduled to take place at CERN in 2006.

Above 40 MeV the focusing periods can be longer than $\beta\lambda$, and alternative structures can be adopted, with quadrupoles outside of the drift tubes,. For Linac4, a particular Cell-Coupled Drift Tube Linac (CCDTL) design at 352 MHz has been selected [4, 6]. This structure is made of short 3-gap tanks connected by bridge couplers. The quadrupoles placed between tanks are mechanically independent of the RF structures, and can be easily aligned. Each klystron feeds a module made of 5 or 4 tanks via a single input coupler. A high-power prototype of 2 half CCDTL tanks is being made at CERN, while another ISTC project with BINP (Novosibirsk) and VNIITF (Snezinsk) will build a high-power prototype made of two complete tanks, again to be tested at CERN in 2006. The CCDTL development is also integrated in the HIPPI JRA.

Above approximately 90 MeV, the shunt impedance of 0-mode DTL-like structures starts to decrease drastically, and a Side-Coupled Linac (SCL) design at 704 MHz has been adopted to cover the energy range to 160 MeV. The SCL is made of 20 tanks with 11 accelerating cells each, connected into 5 modules of 4 tanks, each fed by a 4 MW klystron. Cell-to-cell coupling is 3%, and tanks are connected by 3-cell bridge couplers. The development of the SCL is also part of the HIPPI JRA, IN2P3 and CEA being the main contributors, while ISTC funds the construction of a 2-cell full-copper technological model at BINP Novosibirsk.

Alternative solutions for the low and high-energy part of the linac are under investigation. As a possible alternative to the Alvarez DTL, an ISTC project involving IHEP (Protvino) and VNIIEF (Sarov) will build a prototype of RFQ-DTL tank, from 3 MeV energy. This TE-mode structure offers a high shunt impedance, but is technologically challenging at this relatively high frequency and is based on non-conventional RFQ-type focusing. At high energy, another option is represented by superconducting cavities, a reasonable choice for the high duty cycle of the SPL, but already attractive at the low duty PSB operation. Two superconducting alternatives to the SCL (90-160 MeV) are presently under study in the HIPPI JRA, to be adopted in case they could outperform the SCL. The first is based on 704 MHz elliptical cavities at β=0.5, while the other consists of 4-gap spoke cavities at 352 MHz.

RADIO-FREQUENCY SYSTEMS

The 352 MHz RF system uses 12 klystrons plus circulators and waveguides from the LEP RF inventory presently stored at CERN. Tests have shown that the 1 MW LEP klystrons can be effectively operated in pulsed mode, by pulsing the modulating anode which was originally foreseen for conditioning and testing. When equipped with a storage capacitor bank, the LEP klystron power supplies have been shown to be usable in pulsed mode and potentially able to drive 6 klystrons simultaneously. However, their needs in terms of infrastructure are rather costly and not really justified for the low duty cycle of PSB operation. For this reason, a simpler pulsed power supply design will be used, presently under development at GSI. It will already be employed for the klystrons of the 3 MeV test stand.

The five 704 MHz klystrons will operate at 4 MW, considered as the limit for safe operation of the windows. The necessary power supplies will be developed at CERN when the construction of Linac4 will be authorised.

BEAM DYNAMICS

Linac4, as a first stage of the SPL, is designed to operate at high beam power, and particular care has been given to the beam dynamics, to avoid activation due to losses at high duty cycle operation. To this end, the transverse and longitudinal phase advances at each stage of acceleration have been carefully chosen to avoid resonances and emittance exchange for the nominal beam [4]. In general, abrupt changes in phase advance both transversely and longitudinally have been avoided wherever possible. The only region where, due to hardware constraints, this precaution could not be taken is in the 3 MeV line between the RFQ and the DTL. The chopper itself is about 1 m long and imposes a break in the continuity of a FODO structure which, at this energy and frequency, amounts to about 10 cm in length. Therefore, movable scrapers and a rudimentary collimation system are implemented to remove halo particles coming from the source and/or the RFQ and/or the line itself before acceleration to higher energies where neutron production cross sections are non-negligible.

The ratio between aperture and rms beam size is maintained all along the linac to a value between 7 and 8. This conservative value is chosen with the aim of absorbing a variety of distributions from the source. End-to-end simulations under ideal and slightly-perturbed conditions have validated the overall design [7].

LAYOUT ON SITE AND SCHEDULE

Linac4 will be installed in the South Hall of the PS, in the direct continuation of the test stand beam line. A 100 m long concrete bunker will be built, with a wall thickness between 80 and 200 cm. The klystrons, accessible during operation, are placed on the floor next to the machine bunker, the shielded waveguide access ducts being on the other side, close to the PS ring shielding wall. A switched magnet at the linac end sends the beam into a 200 m long transfer line, parallel to an existing ion transfer line, towards the PSB. After an upgrade for the higher energy, the existing beam measurement lines at the PSB entrance will be used for the Linac4 beam.

The decision on the construction of Linac4 is foreseen at the end of 2006, when the 3 MeV test stand will be ready to operate, the ISTC projects will be concluded and the HIPPI JRA will be more than half way to conclusion. If construction effectively starts at the beginning of 2007, a first beam could be available by the end of 2010. A possible schedule, including the test stand and a tentative schedule for the SPL, is shown in Figure 2.

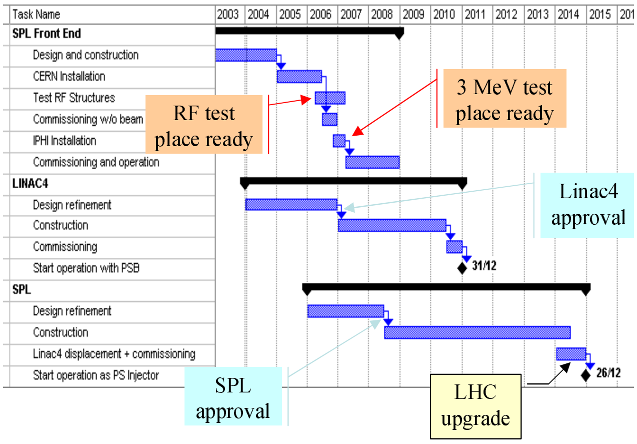

Figure 2: Possible schedule (Front-End, Linac4 and SPL).

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