LINAC4, A NEW INJECTOR FOR THE CERN PS BOOSTER

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Abstract

The first bottle-neck towards higher beam brightness in the LHC injector chain is due to space charge induced tune spread at injection into the CERN PS Booster (PSB). A new injector called Linac4 is proposed to remove this limitation. Using RF cavities at 352 and 704 MHz, it will replace the present 50 MeV proton Linac2, and deliver a 160 MeV, 40 mA H- beam. The higher injection energy will reduce space charge effects by a factor of 2, and charge exchange will drastically reduce the beam losses at injection. Operation will be simplified and the beam brightness required for the LHC ultimate luminosity should be obtained at PS ejection. Moreover, for the needs of non-LHC physics experiments like ISOLDE, the number of protons per pulse from the PSB will increase by a significant factor. This new linac constitutes an essential component of any of the envisaged LHC upgrade scenarios. It is also designed to become the low energy part of a future 3.5 GeV, multi-megawatt superconducting linac (SPL). The present design has benefited from the support of the French CEA and IN2P3, of the European Union and of the ISTC (Moscow). The proposed machine and its layout on the CERN site are described.

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INTRODUCTION

After a recent revision of the SPL design [1], a technical design report for Linac4 (TDR) is currently being prepared as the basis for a decision by the CERN management on the construction of Linac4, expected towards the end of 2006. The linac consists of an H^- source, an RFQ (0.095 to 3 MeV), a medium energy beam transport line (MEBT) including a beam chopper, a conventional Drift Tube Linac (DTL) with permanent magnet quadrupoles (PMQ) up to 40 MeV, a Cell-Coupled DTL (CCDTL) up to 90 MeV, and finally a Side-Coupled Linac (SCL) reaching the final energy of 160 MeV. Whereas DTL and CCDTL operate at 352 MHz frequency, in the SCL the frequency is doubled to 704 MHz to profit from the higher accelerating gradient and efficiency of the compact SCL structure. Table 1 lists the main Linac4 parameters.

Table 1: main parameters of Linac4

		Linac4	SPL inject.
		phase I	phase II
length	[m]	80	88
beam energy	[MeV]	160	180
beam power	[kW]	5.1	205
bunch frequency	[MHz]	352.2	352.2
repetition rate	[Hz]	2	50
source current	[mA]	80	80
av. bunch current	[mA]	40	40
chopper beam on	[%]	62	62
beam pulse length	[ms]	0.4	0.57
particles per pulse	$[10^{14}]$	1.0	1.42
particles per bunch	$[10^{9}]$	1.14	1.14
tr. rms emittance	[mm mrad]	0.36	0.36
long. rms emittance	[deg MeV]	0.19	0.19

INJECTOR

The H^- beam will be produced by an RF-driven volume source, presently under construction, based on the DESY design. Low-Energy Beam Transport (LEBT) is of the two solenoid type and includes diagnostics and a pre-chopper for the control of the beam rise front.

A 3 MeV Radio Frequency Quadrupole (RFQ) is presently under construction within the IPHI (Injecteur de Protons de Haute Intensité) project [2]. This RFQ, with participation of CEA, IN2P3 and CERN, aims at realizing a 100 mA CW test bench to explore the injector issues of high-intensity proton linacs. After high-intensity CW testing at Saclay, the RFQ will be installed at CERN. While this RFQ is "over designed" for the use in Linac4, it is well adapted to the requirements of high-intensity operation in the SPL.

The RFQ is divided into three resonantly coupled segments consisting of 2 one metre modules each, with a total length of 6 m. The machining of the RFQ modules is subcontracted to an external company. The assembly of each module is done at CERN and requires 2 brazing steps. A 1st brazing in horizontal position assembles the four vanes to form the cavity resonator, and a 2nd brazing in vertical position connects the front and end flanges together with all the flanges of vacuum ports and tuners. The RFQ has a total of 96 tuners for precise field adjustment. Four RF input ports are placed in the fourth module, but only two will be used at CERN because of the lower beam current with respect to the design value.

The first RFQ module was completed in 2004, and after a change of the manufacturing company, the 2nd module (Fig. 1) was built and brazed in 2005/06. The vacuum tests and the validation process for this module are now in progress. The brazing of the 3d module is planned for the end of July. The mechanical fabrication of the RFQ is expected to be completed by the end of 2006.

The RFQ is followed by a "chopper line" at 3 MeV, intended to transport the beam through two chopping structures, to match the beam from the RFQ to the DTL and to scrape halo particles from the beam before injection into the linac. The overall length of the line, presently under construction, is 3.6 m.

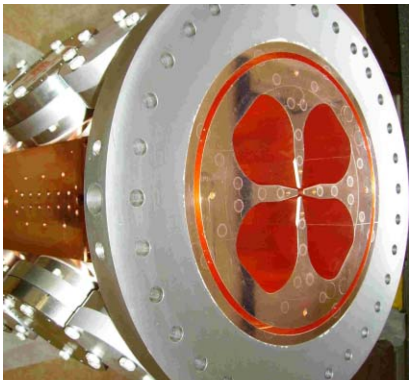

Figure 1: The 2nd RFQ module after final brazing.

ACCELERATING STRUCTURES

Three different structures all with high shunt impedance (DTL, CCDTL and SCL) accelerate the beam from 3 to 160 MeV, making the maximum use of the large inventory of the 352 MHz 1 MW klystrons and other RF equipment recovered from LEP. All structures have been designed for a maximum duty cycle of 14%, to be used without modification in the SPL.

The DTL is made of 3 tanks, powered by 5 LEP klystrons. It is designed with a constant field in the first tank, in order to maximise acceptance. Focusing is provided by PMQ's kept in air inside laser-welded drift tubes. The drift tubes are supported on a girder and aligned with respect to the girder, which is mechanically decoupled from the tank. The detailed mechanical design of DTL tank 1 has been developed by the Russian Institute VNIIEF in the frame of a collaboration with ITEP (Moscow) and CERN aiming at the construction of a tank 1 prototype expected to be delivered in spring 2007 [3]. In a 1st stage, the prototype will be equipped with dummy drift tubes for low-level RF tuning and only one complete drift tube assembly will be built. In a 2nd stage, it is foreseen to equip the tank with the final drift tubes for high-power RF testing. Figure 2 shows a longitudinal cut of the prototype.

The CCDTL section consists of 8 modules of three 3-gap tanks connected by bridge couplers. Each module is fed by a 1 MW klystron. Electromagnetic quadrupoles are placed between tanks. CCDTL construction and alignment are simpler and less expensive than for a DTL, and the easy access to the quadrupoles greatly reduces the intervention time in case of problems during operation. A CCDTL pre-prototype has been built at CERN and is going to be tested at nominal RF power. Another prototype is being built in collaboration between CERN and the Russian Institutes BINP and VNIITF and should be ready for high power RF testing in autumn 2006.

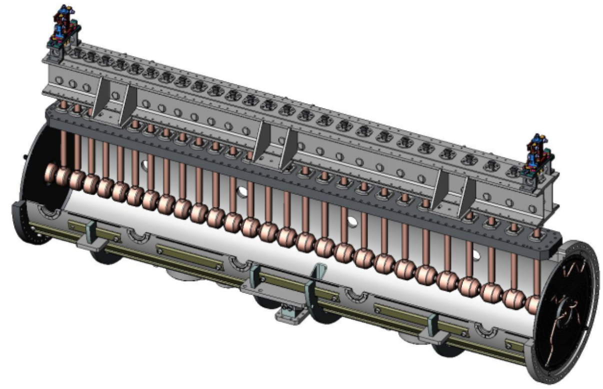

Figure 2: Cut of DTL tank 1 prototype.

The SCL is a conventional structure made of brazed copper parts. It is divided into 4 modules, each fed by a 704 MHz klystron at 4 MW peak power. Modules are made of five 11-cell tanks connected by 3-cell bridge couplers. The SCL design is being developed inside the HIPPI Joint Research Activity supported by the EU, while cold models and prototypes of the SCL are built at LPSC Grenoble and at BINP Novosibirsk.

The complete RF layout of Linac4 is shown in Fig. 3. Table 2 summarises the main design parameters for the accelerating section.

Table 2: main parameters of DTL, CCDTL, and SCL.

		DTL	CCDTL	SCL
output Energy	[MeV]	40	90	160
frequency	[MHz]	352.2	352.2	704.4
gradient E_0	[MV/m]	3.3/3.5	2.8/3.9	4
synchr. phase	[deg]	-30/-20	-20	-20
lattice		F0D0	F0D0	F0D0
aperture radius	[mm]	10	14	16
diameter	[m]	0.52	0.52	0.30/0.31
n. of tanks		3	24	20
length	[m]	13.4	25.2	28.0
max. el. field	[Kilp.]	1.4/1.7	1.4/1.7	1.2/1.2
peak RF Power	[MW]	3.8	6.4	12.5
n. of klystrons		5	8	4

TRANSFER LINE

A new transfer line will transport the beam from Linac4 to the PS Booster. Severe constraints on the layout have been imposed by the integration into the existing

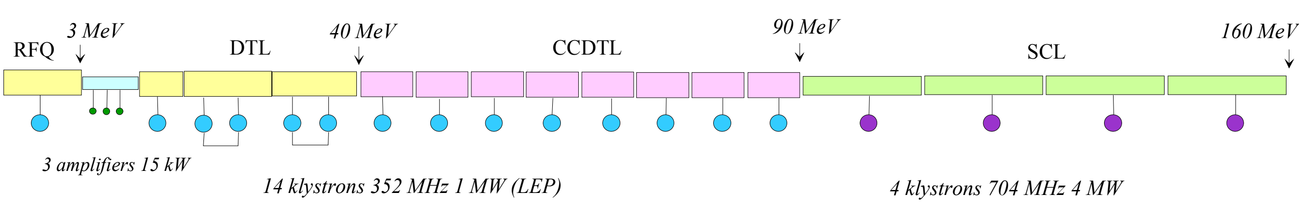

Figure 3: Linac4 RF-power distribution.

accelerator complex and by the need to keep Linac2 operating for the whole duration of Linac4 commissioning.

The layout consists of a matching line and two FODO sections, with periods of 7.2 m and 10.9 m, and a total of 27 quadrupoles. The 3 sections are joined by bendings (47°, -23°, 62°) which are each split into two dipoles to achieve local matching of the dispersion and its derivative to zero to limit emittance growth induced by the energy spread of the beam. After the space charge induced de-bunching the energy spread is reduced with two debuncher cavities.

Beam transport simulations over the 200 m length of this layout up to injection in the PSB show no losses and ≈20% transverse emittance growth for a uniform distribution and ≈40% in case of an end-to-end simulation. Most of the growth is confined to the first part of the line and probably due to a mismatch in phase advance with the last period of the linac. Studies involving a more precise matching of the two sections are ongoing with the aim of reducing this effect.

A more general assessment concerning the feasibility of the involved civil engineering, the construction cost, and the impact on existing structures is ongoing as well as the beam dynamics for injecting into the PSB at higher energy.

BEAM DYNAMICS

A two-solenoid LEBT matches the H^- beam from the source into the RFQ. For 90% space-charge neutralization of the nominal 80 mA beam in the LEBT the emittance growth is ≈7%. The energy spread of the beam from the source is assumed to be ±500 eV due to the extraction voltage jitter. The RFQ which is designed for 100 mA CW operation achieves a simulated beam transmission of 99.9% with 9.4% rms emittance growth, which occurs mainly in the coupling gaps.

The chopper line, placed between RFQ and DTL at 3 MeV, consists of five FODO periods with the chopper plates being housed in the focusing quadrupole (in the chopping plane) of the central FODO. The first two periods match the beam from the fast phase advance in the RFQ to a slow phase advance in the chopper and the last two periods assure the matching to the downstream DTL. The required fast rise time of 2 ns at high voltage is a challenging task, therefore the chopper effective voltage has been limited to ±400 V. This provides a 5.3 mrad kick to the beam that is further amplified by a defocusing quadrupole (in the chopping plane) and transformed into a physical separation at the cone shaped dump. Three buncher cavities in the line provide the longitudinal matching. The beam dynamics is optimized for maximum transmission and minimum emittance growth.

The beam dynamics in DTL, CCDTL, and SCL is determined by the following guidelines: a) continuity of the phase advance per metre between all sections, b) zero current phase advance per period <90° to avoid instabilities, c) phase advance ratio of $0.5<k_z/k_t<0.8$ to avoid emittance exchange and d) provide sufficient phase advance (focusing) to limit the rms emittance growth. In the first DTL tank the synchronous phase is ramped from -30° to -20° and remains at -20° for the remaining linac. A FOFODODO focusing scheme is used in the first tank and then switches to FODO from tank 2 onwards. The nominal settings for 65 mA are suited for accepting currents as low as 20 mA. The beam matching and the smooth transitions between structures are obtained by appropriate setting of the synchronous phase and quadrupoles in the transition regions. Table 3 summarises emittance growth and transmission in Linac4 obtained from an end-to-end simulation starting at RFQ entrance.

Table 3: rms emittance growth in Linac4.

	RFQ	MEBT	DTL	CCDTL	SCL	total
$\Delta\varepsilon_x$ [%]	9.4	21	2.5	-1.1	-0.1	36.8
$\Delta\varepsilon_y$ [%]	9.4	3.5	12.8	1.7	4.3	33.6
$\Delta\varepsilon_z$ [%]	-	17.5	12.6	0.8	2.7	39.6
transm.	99.9	88.9	100	100	100	88.8

DIAGNOSTICS

Depending on the installation schedule, there will be a staged commissioning of source, LEBT, RFQ, MEBT and chopper line followed by DTL tanks 1-3, CCDTL and SCL. In the low-energy part, halo formation is a potential worry for which a dedicated beam shape and halo monitor has been developed [4]. The main tool for the commissioning of the linac is a movable diagnostic bench, equipped with all instruments necessary for a full characterisation of the beam properties. For operation a certain amount of instrumentation will be installed in order to allow for survey and fine tuning of the machine. Altogether we foresee the following equipment: 30 pick-ups for combined current, beam position, and phase measurements, one spectrometer, 14 beam profile monitors, 13 current transformers, 2 emittance scanners, 28 beam loss monitors and 1 Feschenko monitor [5].

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