LINAC4, A NEW H^- LINEAR INJECTOR AT CERN

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Abstract

Linac2, the present injector of the CERN PS Booster, limits the performance of the proton accelerator complex because of its low output energy (50 MeV). To remove this bottleneck, a higher energy linac is proposed (called “Linac4”) which will double the brightness and the intensity of the beam delivered by the PSB and ensure the “ultimate” beam is available for LHC. Linac4 will deliver H^- ions at a kinetic energy of 160 MeV. It is designed to be usable as the front-end of a future multi-GeV multi-MW linear accelerator, the “Superconducting Proton Linac” (SPL). R&D for Linac4 is now actively taking place with the support of the European Union through the Joint Research Activity HIPPI (“High Intensity Pulsed Proton Injectors”), and of three ISTC projects involving three major Russian laboratories (BINP, IHEP and ITEP) and two nuclear centres (VNIIEF and VNIITF). The design of this new accelerator and the on-going developments are described.

INTRODUCTION

The beginning of LHC operation, expected in 2007, will mark the start of a crucial phase for its chain of injectors. They will have to provide reliably the nominal beam to the collider and, at the same time, to satisfy demanding users, like the neutrino experiment CNGS and the radioactive ion community of ISOLDE. For this reason a study group has worked during 2003 and part of 2004 to identify possible scenarios for improving the performance of the “low” energy injector chain [1]. The replacement of the present PS Booster (PSB) proton injector, the Linac2, has been clearly identified as a very effective way to increase the performance of the PSB and of the whole accelerator complex. The switch to an H^- linac associated with charge-exchange injection into the PSB, and the upgrade of the injection energy from 50 MeV to 160 MeV will double the brightness of the proton beam for the LHC and the intensity available from the PSB for other users. This new injector, called Linac4 [2], is being designed at the same time as the front end of a more ambitious accelerator, the SPL, a 4 MW 2.2 GeV linac that would upgrade the CERN hadron injector system to the requirements of the next class of experiments in the field of neutrino and radioactive ion physics and could contribute to push the LHC beam beyond its ultimate intensity.

LINAC4 DESIGN PARAMETERS

The goal of Linac4 is the doubling of the bunch population in the PSB, so that a single PSB batch will be sufficient for the PS to deliver the required beams for LHC and CNGS. The fundamental parameter to be considered is the incoherent space charge tune shift at PSB injection as a function of beam energy, which scales like $1/\beta\gamma^2$. In order to gain a factor two on the beam intensity, the injection energy has to be increased from 50 to 160 MeV.

While the average beam intensity in Linac4 is modest when feeding the PSB, with 30 mA peak current and 0.1% duty cycle, the SPL operation is much more demanding and requires 13 mA with 14% duty cycle. The RF structures and the beam dynamics have been designed to comply with both requirements. In order to obtain the longitudinal time structure required by the CERN scheme for a Neutrino Factory, a high performance chopper line is needed at 3 MeV.

Beam parameters are summarized in Table 1 for the two foreseen uses of Linac4.

Table 1: Linac4 parameters.

	PSB	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)	0.47	0.47	π deg MeV

ACCELERATOR LAYOUT AND BEAM DYNAMICS

The beam dynamics of Linac4 has been designed according to the challenging SPL operating mode [3]. With such a high beam power and the need to provide hands-on-maintenance, a severe control of the beam quality all along the accelerator is required; halo formation has to be avoided and losses must be kept at a minimum level in order to avoid material activation. For this reason, the evolution of the longitudinal and transverse phase advance has been kept as smooth as possible. The possibility of resonant emittance exchange has been prevented by keeping the phase advance ratio $0.5 < k_l/kt < 0.8$ all along the accelerator. The bore aperture is made larger than 7 to 8 times the r.m.s. beam size all along the machine.

Chopper line

The most serious exception to the above mentioned rules is represented by the chopper section, at 3 MeV. Fig. 1 shows the beam envelopes along the chopper line.

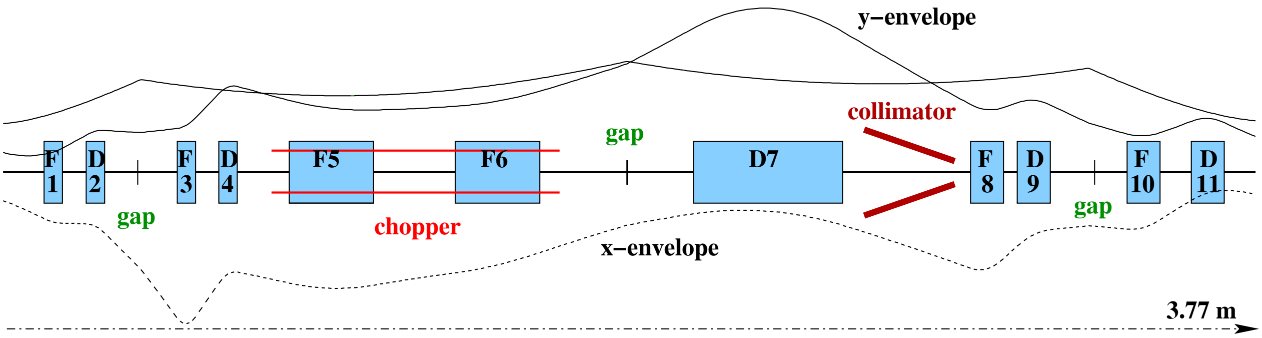

Fig. 1: Chopper line and beam envelopes from TRACE3D

The change in the transverse phase advance period is clearly visible. In fact the periodicity of the FODO lattice could not be kept because of the mechanical constraint of installing a 1 m long chopping structure.

The beam halo originating from this part of the accelerator will be removed by movable scrapers and by the collimation aperture of the dump for the chopped beam.

This chopping line is specified for the needs of the SPL as a proton driver for a Neutrino Factory, where the beam is accumulated in an accumulator ring with an RF frequency of 44 MHz. A 2 cm transverse separation is required between the transmitted and the chopped beam at the cone-shaped beam dump that is located 1 m downstream from the last chopping cavity. This is achieved by means of a 1 m long chopper structure where the beam experiences a 800 V effective voltage transverse kick. Beam deviation is amplified by the two quadrupoles F5 and F6 and reaches 7 mrad at the chopper exit; a 90° phase advance between the chopper and the beam dump then provides the required separation. Two FODO cells by each side of the chopper section perform the transverse matching between the RFQ and the DTL, mastering the transition through the slow phase advance chopper section (20 $\beta\lambda$). Simulations show that effective matching to the DTL can be obtained on a very wide range of beam currents, from 20 mA to 60 mA. Three nose-cone equipped pillbox cavities perform the longitudinal matching along the chopper line. 98% of the main beam is transmitted through the line and the chopped beam is eliminated to better than 0.02%.

Acceleration from 3 MeV to 160 MeV

A schematic layout of Linac4 is shown in Fig. 2, and the transition energies between the different RF structures are indicated.

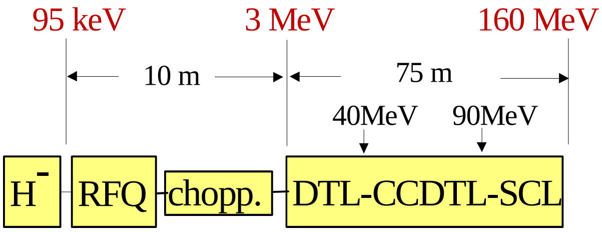

Fig. 2: The Linac4 schematic layout

The DTL Alvarez is the standard choice for accelerating particles with a β range lying between 0.05 and 0.4. The transition energy from the RFQ to the DTL Alvarez has been decided on the basis of a compromise between the need to avoid any irradiation of the chopper line and the adoption of a reasonable DTL drift tube size , which can house the quadrupole of required strength. In this respect the choice of a FOFODODO lattice in the DTL permits to obtain the same phase advance per unit length of the FODO lattice using a quadrupole with a factor $\sqrt{2}$ less gradient. In the Linac4 this choice for the DTL structure becomes favourable with respect to the RFQ already at 3 MeV, giving an effective shunt impedance per unit length which is almost twice as much that of the RFQ, allowing for a lower longitudinal phase advance and a much larger bore aperture. While the DTL could work with acceptable efficiency up to about 100 MeV, a mechanically simpler and more efficient RF structure has been introduced in this design from 40 MeV, the CCDTL.

Fig. 3 shows a comparison between DTL and CCDTL in terms of effective shunt impedance as a function of the beam energy.

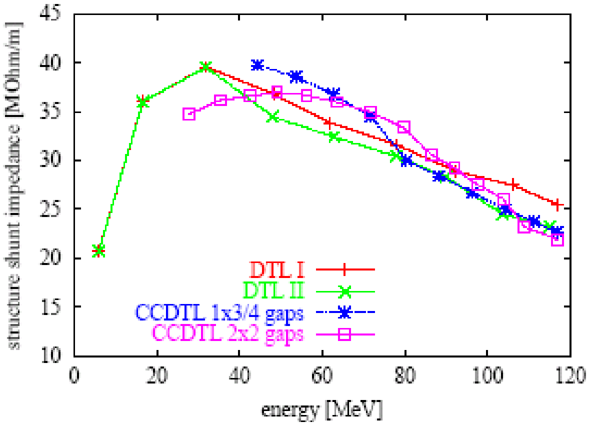

Fig. 3: Effective shunt impedance for DTL and CCDTL structures.

The idea of using compact DTL resonators, resonantly coupled to each other, was first tested at Los Alamos, where the potentiality of taking the quadrupoles out of the vacuum was fully understood. The shunt impedances per unit length of DTL and

CCDTL are comparable, the simpler mechanical construction and the easier accessibility to the quadrupoles have led us to give preference to the CCDTL in the segment between 40 MeV and 90 MeV.

Each CCDTL tank consists of three gaps. The intra-tank distance is kept constant in order to standardize the coupling cells and the $3\beta\lambda/2$ spacing between gaps of adjacent tanks, to allow sufficient place for quadrupoles, is obtained by changing the drift tube length on the end walls. The focusing period along the CCDTL is $7\beta\lambda$.

In the CCDTL the FODO lattice can be re-established, thanks to the increased length of the focussing period. The beam quality is preserved at the transition between the DTL and the CCDTL by slightly changing the synchronous phase and by allowing the beam to expand with the adoption of larger bore aperture quadrupoles (14 mm).

The final section of Linac4 (90 MeV to 160 MeV) is is built as a Side Coupled Linac (SCL), operating at 704.4 MHz. This choice maximizes the effective shunt impedance, as shown in Fig. 4.

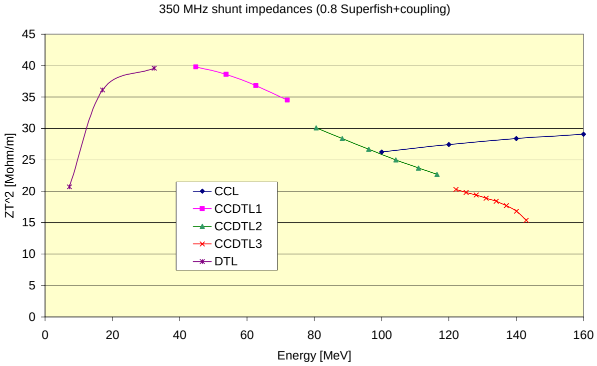

Fig. 4: Shunt impedances for different kinds of accelerating structure.

The accelerating and coupling cells are constant inside each tank, because of the limited variation of the particle velocity. The tank length results from the periodicity of $16\beta\lambda$ of the FODO lattice, which corresponds to a good compromise between RF efficiency and effective beam focusing.

The synchronous phase is ramped at the frequency transition in order to compress the bunch in the longitudinal phase space and to optimize the matching.

A ratio of about 0.7 is kept between longitudinal and transverse phase advance, thus requiring a gradient of 17 T/m from the permanent magnet quadrupoles.

Tanks are grouped by 4 and fed by a single 4 MW klystron. The coupling between tanks is done by means of $3\beta\lambda/2$ bridge couplers.

End to end simulations have been performed, assuming a 6-D waterbag beam distribution from the ion source, with 4% energy spread. The PATH code has been used and it has been cross-checked with IMPACT. Some discrepancies remain between the two simulations and the analysis is going on. The responsibility for the 73% of transverse emittance growth is mainly shared among the LEBT (33%) and the RFQ (14.4%) and a fundamental role will be played by the beam distribution at the output of the ion source output. The reduction to 2% of the effective energy spread at the source output (mainly due to beam divergence) could drastically reduce the transverse emittance growth at the end of Linac4. Therefore, testing the low energy part of Linac4 is very important for the whole project. An additional unexpected increase of longitudinal emittance within the DTL is presently under study. Table 2 summarizes the results of beam dynamics calculations over a population of 50000 particles.

RF ACCELERATING STRUCTURES

As shown in Fig. 2, different kinds of accelerating structure are used in the Linac4. The main characteristics of the different accelerating sections are listed in Table 3.

Table 3: Linac4 main parameters.

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

Table 2: Emittance growth, transmission and energy per section from PATH (50000 particles)

section	**freq.** **[MHz]**	**length** **[m]**	$\mathbf{W_{out}}$ **[MeV]**	$\varepsilon_{rms,t}$ 1) **[π mm mrad]**	$\varepsilon_{rms,l}$ **[π mm mrad]**	$\Delta\varepsilon_{rms,t}$ 1) **[%]**	$\Delta\varepsilon_{rms,l}$ **[%]**	**transm.** **[%]**
LEBT		1.27	0.095	0.188	-	33	-	100
RFQ	352.2	5.96	3	0.25	-	14.4	-	98.9
CHOPPER	352.2	3.77	3	0.286	0.5	4.9	0.6	91
DTL	352.2	16.71	40	0.3	0.5	5.0	0.0	99.9
CCDTL	352.2	30.54	90	0.315	0.58	3.8	1.2	100
SCL	704.4	27.78	160	0.327	0.59	-0.6	0.2	100
TOTAL		86.03	160	0.325	0.59	73	18	89.9

1) average value of emittance.

The IPHI RFQ

The 95 keV beam extracted from the ECR ion source is matched by the LEBT to an RFQ that has been designed by CEA Saclay and IN2P3 and is presently under construction. This IPHI ("Injecteur de Protons de Haute Intensite") RFQ is 6 m long. It is able to operate in CW mode with 100 mA beam current and accelerates the beam from 95 keV to 3 MeV. An agreement between CERN and the IPHI collaboration has led to a change of the original RFQ parameters [4] in order to adapt them to the requirements of the Linac4 and SPL and in particular to optimize the operation of the beam chopper line. A very detailed description of the IPHI RFQ has been presented at EPAC04 [5].

The DTL

The DTL section of Linac4 is made up of 3 tanks of the Alvarez type. The first tank is fed by one 1 MW klystron of the LEP kind, while two klystrons feed each of the following two tanks.

Transverse focusing is provided by Permanent Magnet Quadrupoles in the first tank, while Electromagnetic Quadrupoles are used in the second and third tanks.

A detailed list of parameters is shown in Table 4.

Table 4: Summary of Linac4 DTL parameters

DTL		**units**
Input Energy	3	MeV
Output Energy	40	MeV
RF Frequency	352.2	MHz
Number of tanks	3	
Aperture radius	10	mm
Gradient	3	MV/m
Lattice	FFDD	
Max. surface field	1.1	Kilpatrick
Length	16.7	m
Real estate gradient	2.21	MeV/m
Number of quads	111	

The first tank is being presently designed in the frame of an ISTC (International Science and Technology Centre - Moscow) supported project involving two Russian scientific centres, ITEP (Moscow) and VNIIEF (Sarov). It will be submitted to high power RF at CERN at the end of 2006.

CEA and IN2P3 give additional contribution to this section of the Linac4 by developing the high power coupler for the DTL tanks within the EU funded Joint Research Activity (JRA) HIPPI.

The CCDTL

The CCDTL section of Linac4 (40 MeV to 90 MeV) is composed of 27 small DTL tanks, with 3 accelerating gaps each, that are grouped into 6 modules. Each module, about 5 m long, is fed by one 352.2 MHz klystron and the tanks within the module are resonantly coupled to each other by means of coupling cells.

The RF operating mode is π/2 between tanks and coupling cells, which assures a satisfactory mode separation and stability for the whole resonant module.

Also in the case of the CCDTL, ISTC is supporting the activity of BINP (Novosibirsk) and VNIIEF (Sarov) in order to develop a high-power prototype of two complete tanks that will be tested at CERN in 2006. The main parameters concerning the CCDTL section are listed in Tab. 5.

Table 5: Summary of Linac4 CCDTL parameters.

CCDTL		**units**
Input Energy	40	MeV
Output Energy	90	MeV
RF Frequency	352.2	MHz
Number of tanks	27	
Gradient	3	MV/m
Lattice	FD	
Max. surface field	1.3	Kilp.
Aperture radius	14 - 16	mm
Synchronous phase	-25	deg
Length	30.1	m
Real estate gradient	1.7	MeV/m
Number of quads	28	

A first prototype of two half-tanks is under construction at CERN and will be tested at high power in 2005. The purpose is to check the accuracy of the computations and to measure the thermal load at the coupling irises [6]. Fig 6 shows the CAD model of the CERN prototype.

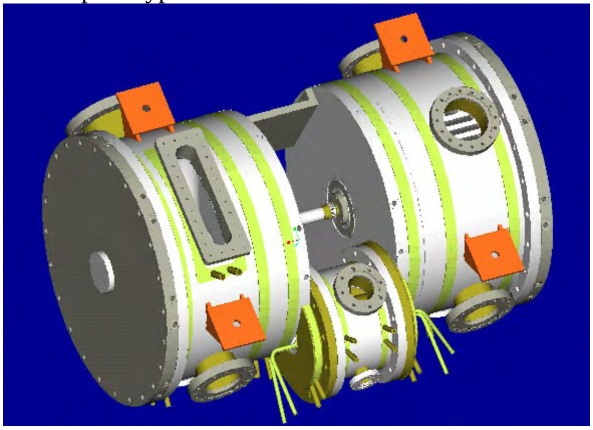

Fig 6: Assembled CCDTL prototype.

The SCL

The loss of efficiency of the CCDTL above ~90 MeV, as shown in Fig. 4, has lead to the choice of a π/2-mode Coupled Cavity Linac (CCL). The doubling of the RF frequency to 704.4 MHz in this section further contributes to the increase of efficiency. Among the possible choices, the Side Coupled Linac (SCL) has been adopted because of easy machining, tunability, intrinsic stability and because of the large experience with this type of structures. In Table 6 the SCL main parameters are listed.

Table 6: Summary of Linac4 SCL parameters.

SCL		**units**
Input Energy	90	MeV
Output Energy	161.3	MeV
Length	27.8	m
RF Frequency	704.4	MHz
No. cells/tank	11	
No. tanks	20	
No. tanks/klystron	4	
Structure RF power	11.7	MW
Beam RF power	2.1	MW
Total RF power	13.8	MW
Total RF power (SPL)	12.6	MW
Max. power/klystron	2.8	MW
No. of klystrons	5	
Shunt Impedance	24.5-30.4	MΩ/m
Q-value	14-17	x 10^3
Gradient	4	MV/m
Synchr. phase	-25	deg
Peak electric field	0.76-0.81	Kilpatrick
Aperture radius	16	mm
Focusing	FD	
Quad. gradient	17.5	T/m
Transv. phase advance	23-20	deg/m
Long. phase advance	17-13	deg/m

IN2P3 and CEA (France) also contribute to the SCL within their participation to the HIPPI JRA. The ISTC funds the realization at BINP-Novosibirsk of a 2-cell full-copper technological model.

Further Options under Study

As a possible alternative to the Alvarez DTL, IHEP (Protvino) and VNIIEF (Sarov) are developing an RFQ-DTL structure at 352 MHz, with the support of the ISTC. This structure should benefit from a high shunt impedance, but also represents a technological challenge at that frequency. A full scale prototype is being designed and constructed. It will be tested at high power without beam.

Within the JRA HIPPI, superconducting alternatives to the SCL are being investigated. Two alternative schemes are under consideration, one adopting 704.4 MHz elliptical cavities and the other based on 4-gap spoke cavities operated at 352.2 MHz.

INTEGRATED SCHEDULE

The Linac4 project is now considered as a very useful step for the upgrade of the LHC injector chain. With the purpose of testing the technological issues and checking the beam dynamics at low energy, a test place is being realized at CERN in order to characterize the beam at 3 MeV, at the chopper line exit. This first section of Linac4 has been called SPL Front End. It will give valuable information about the halo formation mechanism and the validity of the chopping technique adopted. A tentative schedule for the realization of Linac4 and of the SPL is shown in Fig. 7, integrated with the planning for the construction of the 3 MeV Test Place.

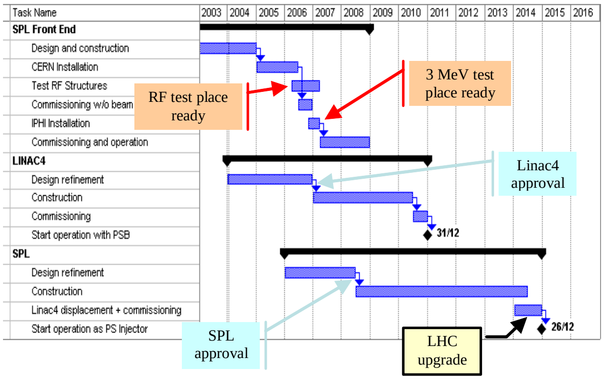

Fig.7: Integrated planning of the project.

ACKNOWLEDGMENTS

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) and the valuable collaboration of the CERN Groups involved. As mentioned in the main text, the ISTC supported projects # 2875, 2888 and 2889 are important contributions which accelerate the developments for Linac4 and the SPL.

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