ELECTRON LINAC UPGRADE FOR THOMX PROJECT

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Abstract

The injector Linac for Thomx consists of an electron gun and S-band accelerating section. The RF gun is a 2.5 cells photo-injector able to provide electron bunches with 5 MeV energy. During the commissioning phase, a standard S-band accelerating section is able to achieve around 50 MeV corresponding to around 45 keV X-rays energy. Since the maximum targeted X-ray energy is 90 keV, the Linac design will provide a beam energy of 70 MeV. The Linac upgrade of the machine covers many different aspects. The purpose is to increase the compactness of the accelerator complex whereas the beam properties for ring injection are kept. A LAL Orsay-PMB ALCEN collaboration has been established. The program foresees the RF design, prototyping and power tests of a high-gradient compact S-band accelerating structure. To fulfill the technical specifications at the interaction point, the Linac must be carefully designed. Beam dynamics simulations have been performed for optimizing the emittance and the energy spread for the ring entrance. The best set of parameters together with the effect of the accelerating section to the beam dynamics at the end of the Linac are presented.

INTRODUCTION

The Thomx project is taking advantage of the preeminent French technology in accelerator and laser fields. The goal is to design and build a demonstrator with cutting edge performances compared to similar projects either in operation or planned. A flux between $10^{11} - 10^{13}$ ph/s in the hard X-ray range is expected and the photon energy tunability will provide a Compton edge that can be set between 45 and 90 keV [1]. Another goal is to provide a compact, reliable, and tunable source which can operate in a non-laboratory environments such as hospitals or museums. These constraints impose the choice of a high collision rate scheme. The layout of the machine is based on a 50 Hz, normal conducting S-band Linac whose energy is tunable up to 70 MeV, an injection line and a compact electron storage ring. A demonstrator was funded and the components are foreseen to be assembled in the Orsay university campus at the beginning of 2017. The Linac injector is composed of the RF gun, the accelerating section and the beam diagnostic elements. Concerning the accelerating section, the French National Synchrotron Facility (SOLEIL), as a partner of the project is willing to lend a standard S-band accelerating structure that the Linear Accelerator Laboratory (LAL) built for the LEP Injector Linac (LIL) at CERN many years ago.

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THOMX LINAC SCHEME

A picosecond electron bunch is produced at the photocathode. Then, the accelerating and magnetic fields in the RF gun and solenoids drive the electron beam. After a drift space at the exit of the gun, the electron bunches are boosted up to the ring injection energy by means of the accelerating section. The transfer line ensures the bunch transport from the linac exit to the storage ring. After injection, the electron bunch is recirculated for 20 ms in the ring. The ring optics is designed as such as the beam size is very small in transverse direction, at the interaction point (IP). The project goal is to produce a high flux of 45 keV X-rays energy [2] leading to specifications for the Linac that are summarised in Table 1.

Table 1: Nominal Linac Parameters

Energy	50 MeV
Total Charge per bunch	1 nC
Number of bunches per RF pulse	1 bunch
Normalised rms emittance	< 5 π mm mrad
Energy Spread rms	< 0.3 %
Bunch Length rms	< 5 ps
Average current	50 nA
Repetition rate	50 Hz

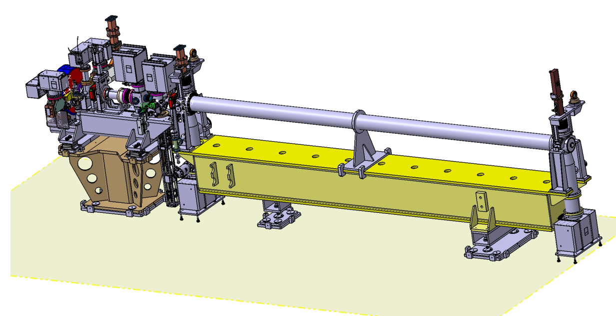

Figure 1: 3D drawing of the Thomx Linac.

RF GUN & SOLENOIDS

The RF gun is 2.5 copper cells with a resonating frequency of 2998.55 MHz. Since low emittance beam together with the possibility of operation with different total charge per bunch are required, the best technical choice is the photo-injector. To minimize risks and taking advantage on the long experience achieved from LAL in the RF gun fabrication, the latter has the same design to that has been constructed for the CLIC Test Facility 3 at CERN (CTF3). This gun has successfully been in operation for four years. To increase the current per bunch with less vacuum constraints, a metallic

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magnesium photo-cathode which can deliver more than 1 nC with a laser pulse energy of a few tens of µJ at the wavelength of 260 nm, has been chosen [3]. To get 1 nC with an emittance lower than 5 π mm mrad, a peak accelerating gradient of 80 MV/m entails a 3 µs RF pulse length and 5 MW power. In this case, the electron beam energy at the gun output is around 5 MeV. For the electron beam steering and focusing, two solenoids and two magnetic correctors are required. The solenoids are placed around the gun. Opposite sign currents circulate in these coils so that the magnetic field vanishes at the cathode position. As the beam properties are mostly affected by the RF gun, a classical emittance growth compensation of the photoinjector by means of solenoids has been performed [4]. The strength of the 2D magnetic field profile along the beam axis has been reconstructed by means of the 3D OPERA solver. To decrease the fringe field of the focusing coil, a shielding plate of 5 mm thickness has been considered for the simulations and future experiments.

ACCELERATING SECTION

The LIL structure is a traveling wave quasi-constant gradient section composed of 135 cells, with 2 π/3 phase advance per cell at 2998.55 MHz (30 °C in vacuum). The section length is about 4.5 m. To reach a final energy of 50 MeV, the energy gain in the section must be 45 MeV. The latter value implies an electrical field of 14 MV/m and an RF power of about 10 MW. However, the accelerator should reach higher energies in order to produce X-rays beyond 45 keV. Since the maximum targeted X-ray energy is 90 keV, the Linac design should allow a beam energy of 70 MeV that for PMB accelerating section corresponds to an RF power of 22 MW. Thus, taking into account the RF system efficiency, the klystron should provide a total RF power of 35 MW with a pulse length of 4.5 µs. The total power is splitted between the RF gun (10 MW) and the accelerating section (25 MW). The main parameters of the standard section are listed in the Table 2.

Table 2: LIL Parameters

Number of cells	135
Phase advance per cell	120 deg
Frequency (T = 30 deg in vacuum)	2998.55 MHz
Shunt impedance	63 - 74 MΩ
Q	15000
$<E_{acc}>$ (input power 9 MW)	12.5 MV/m
Filling time	1.35 µs
Energy gain (9 MW input power)	45 MeV

LINAC BEAM DYNAMICS

The beam dynamics has been simulated with A Space Charge Tracking Algorithm (ASTRA). The performances of the RF gun mainly rely on the choice of the laser parameters and accelerating field. Indeed, the shape of the laser transverse profile can have a strong impact on the emittance of the beam. In these simulations we suppose that the laser which produces the electrons from the cathode has a Gaussian distribution in the transverse and longitudinal plane with a fixed sigma ($\sigma_x = \sigma_y$) and time duration (σ_t).

Simulations inside the RF gun are based on the 2D profile of the electric field that has been obtained by SUPERFISH. A method to determine the best magnetic field strength which compensates the transverse emittance has been applied and explained in the previous work [5]. Also, a scan across different laser spot sizes has been performed in order to minimize the rms transverse emittance value at the exit of the gun. A laser spot size of 0.2 mm allows to fulfil the rms transverse emittance specification, the value that has been obtained is around 4 π mm mrad.

According to the Thomx nominal parameters, 50 MeV energy gain in the simulation can be obtained with a peak electric field of 80 MV/m in the RF gun and 14 MV/m in the accelerating section. It is important to highlight that especially this high transverse density electron emission is strongly affected by self-fields produced by the electron bunch itself [6]. Even at the first stage of the photo-emission at the cathode surface, the electrons undergo their own image charge which produces an electric field that opposes the external RF one. When the image charge field becomes as much strong as the external RF field, electron emission saturates (space charge limit) [7]. This phenomenon has practically been observed in the simulations where more than 40% (see Fig. 2) of the particles were lost even at the photo-cathode position. This phenomenon is more sensitive to the laser spot size (σ_x, σ_y) instead of the pulse duration (σ_t). Indeed, for a laser spot $\sigma_x = \sigma_y = 0.6$ mm and pulse duration of 2 ps, the number of lost particles at the photo-cathode position decreases to 1%.

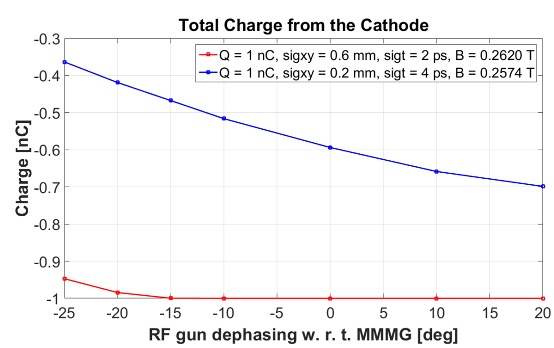

Figure 2: Total charge per bunch vs RF gun dephasing.

Simulations of the bunch charge extracted from the cathode as a function of the relative phase between the RF field and the laser at the cathode has been carried out. In the following, the zero phase corresponds to the Maximum Mean Momentum Gain (MMMG) [8]. In the Fig. 2 one can observe that in the range from 20° to -10°, the total charge of 1 nC per bunch is extracted from the cathode. While, we observe losses of electrons due to the mirror charge effect, when the dephasing is equal to -15°. However, at the dephasing value of -25° the number of particles which are lost is roughly 5 %. In Table 3, the main beam properties at the exit of the RF gun (z = 1 m) are summarised respect with dephasing value. As we can see from the data, the transverse emittance varies from 8.5 to 7.6 π mm mrad , the bunch length remains approximately constant to 3 ps, while the energy spread varies significantly across the dephasing values.

Table 3: Beam Parameters at the Exit of RF Gun

	dephasing [deg]			
	-15	-10	0	10
ϵ_{xy} [mm mrad pi]	7.6	8	8.4	8.5
ΔE/E [%]	0.37	0.6	1.3	2.2
σ_z [ps]	3.1	3	3.1	3.4

In order to minimise the energy spread at the end of the linac while maintaining reasonable values of transverse emittance and longitudinal bunch length, we have considered an RF gun dephasing value of -15°. Figure 3 shows a comparison between the case which RF gun and the accelerating section present MMMG ($\phi_{RFgun} = 0°, \phi_{LIL} = 0°$) and the case with RF gun dephasing ($\phi_{RFgun} = -15°, \phi_{LIL} = 0°$), considering rms transverse emittance and energy spread along the linac.

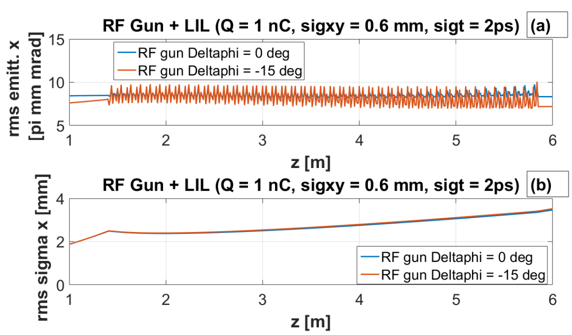

Figure 3: Transverse emittance (a), transverse bunch size (b) along the linac (length = 6 m), for two different RF gun dephasing values (ϕ_{RFgun} = 0°, -15°).

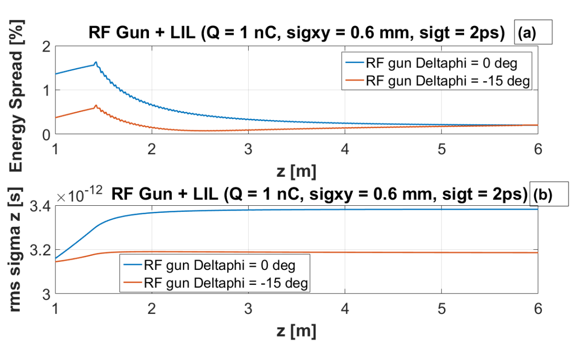

Figure 4: Energy Spread (a), bunch length (b) along the linac (length = 6 m), for two different RF gun dephasing values (ϕ_{RFgun} = 0°, -15°).

In the drift space, just after the gun exit, one can see that in the case of -15° dephasing, the emittance is still linearly increasing while in the case of 0° dephasing the emittance is well compensated by the magnetic field strength. Furthermore, the energy spread is rapidly decreasing along the section. In both cases this value is around 0.2 % at the end of the linac.

CONCLUSIONS AND PROSPECTS

This preliminary beam dynamics investigation on the Thomx Linac has shown that main constraint has been the fixed lattice of the accelerator components such as solenoids that surround the RF gun and position of the accelerating section. In order to improve the energy spread minimisation together with smaller transverse emittance at the end of the linac, several options can be considered. First, a better position of the focusing solenoid may allow to arrange the accelerating section in a place where the contribution of the acceleration damps the emittance oscillations. Second, several magnetic field strength values can be considered for the energy spread minimisation at the expenses of the other beam parameters. Concerning the Linac energy upgrade up to 70 MeV, the electric field profile of the new accelerating section can be used for particle tracking simulations. The stronger accelerating gradient might provide usefull insigths of electric field contribution to the beam dynamics at the end of the linac.

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