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ELECTROMAGNETIC AND BEAM DYNAMICS STUDIES OF THE ThomX LINAC

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Abstract

ThomX is a new generation compact Compton source. The machine is composed of a 50/70 MeV injector LINAC and a storage ring where an electron bunch collides with a laser pulse accumulated in a Fabry-Perot resonator. The compact source, built at Irene Joliot-Curie Laboratory (IJCLAB) in the Orsay campus of Paris-Saclay University, is designed to produce a total flux of 10^{13}ph/s and a brightness of 10^{11} ph/(s.mm^2.mrad^2) in 0.1% of bandwidth with a tunable energy ranging from 45 keV to 90 keV on the X-ray beam axis. The photo-injector is composed of a homemade 2.5 cell photocathode RF-gun, placed between two solenoids. An energy of 5 MeV is reached with a 80 MV/m electric field gradient. During the commissioning phase, a 4.8 m S-band LIL section will be used to achieve a 50 MeV corresponding to a 45 keV X-ray energy. The LIL accelerating section is a quasi-constant gradient traveling wave structure. The energy gain in the section is 45 MeV, corresponding to an average effective accelerating gradient of 10 MV/m for an input RF power of 9 MW. Here, we present the electromagnetic and beam dynamics studies of the ThomX LINAC.

INTRODUCTION

ThomX is a Compton source project in the range of the hard X rays (45/90 keV). The machine is composed of a 50/70 MeV injector LINAC and a storage ring where an electron bunch collides with a laser pulse accumulated in a Fabry-Perot resonator. The final goal is to provide an X-ray average flux of 10^{12} – 10^{13} ph/s. The emitted flux will be characterised and used for experiments by a dedicated X-ray line [1]. Different users are partners in the ThomX project [2], especially in the area of medical science [3] and cultural heritage [4]. Their main goal is the transfer of experimental techniques currently developed on large synchrotron rings to more compact and flexible machines. ThomX is a demonstrator built on the Orsay university campus.

The ThomX linear accelerator injector, shown in Fig. 1, is the most important system that accelerates the beam to the desired energy. It is composed of a homemade photocathode RF gun for the electron generation, two solenoids for emittance compensation, the beam diagnostic line, the vacuum equipment and a LIL-type 4.8 m long S-band Travelling Wave (TW) accelerating section that boosts the electron beam to the final energy for the ring injection. The electron beam is produced by a copper photo-cathode with a laser pulse energy of a few tens of a µJ at a wavelength of 266 nm. Here, we present the electromagnetic studies of the ThomX LINAC and the performances obtained in terms of beam dynamics. Table 1 summarizes the nominal LINAC parameters.

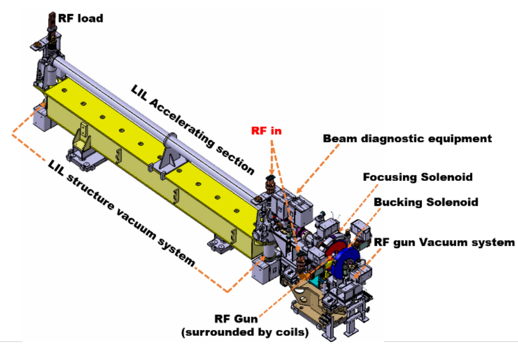

Figure 1: 3D scheme of the ThomX linear accelerator injector.

Table 1: Nominal Linac Parameters

Parameter	Value
Beam Energy	50 MeV (70 MeV upgrade phase)
Cathode laser wavelength and pulse energy	266 nm & 100 J
Charge	1 nC
Number of bunches per RF pulse	1
RF pulse width (Flat top)	3 s
RF repetition rate	50 Hz
Average current	50 nA
Emittance (rms, normalized)	<5 π mm mrad
Bunch length, rms	<5 ps
Energy spread, rms	<1 %

ELECTROMAGNETIC STUDIES OF THE ThomX LINAC

Electromagnetic simulations of the whole LINAC have been performed using CST Studio Suite® [5] to study its RF characteristics, including the electromagnetic field distribution.

The ThomX RF Gun

The ThomX RF gun is a homemade consisting of a 2.5-cell SW copper cavity with a resonating frequency of 2998.55 MHz at 30 °C in vacuum in the π-mode ($TM_{010-\pi}$ mode). The RF gun, placed between two solenoids as illustrated in Fig. 2 (top), guarantees an energy gain of 5 MeV with a peak accelerating gradient of 80 MV/m for an input peak power of 6 MW. Figure 2 (bottom) shows the field profile in the RF gun with a phase advance per cell of 180 ° (π) and a good field balance, "field flatness". A complete simulation of this RF gun has been performed [6] with the

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multi-physics package of the finite element analysis code ANSYS [7]. The ThomX gun main RF characteristics are summarized in Table 2.

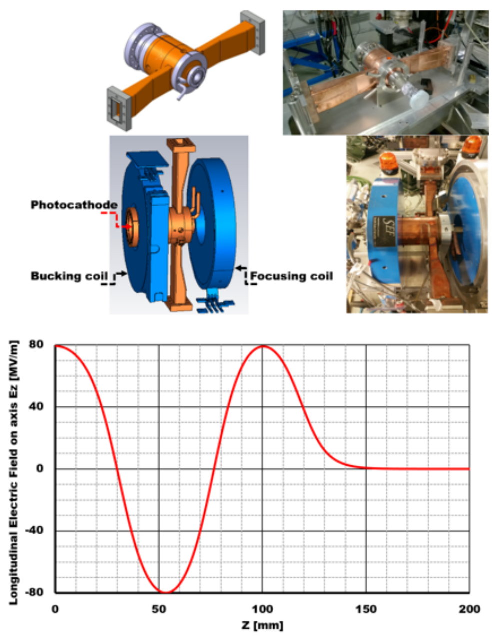

Figure 2: The ThomX RF gun (top) and on-axis electric field along the structure for the π-mode ($TM_{010-\pi}$) of the ThomX RF gun for 6 MW input power (bottom).

Table 2: Main RF Characteristics of the Thomx RF Gun

Parameter	Value
Frequency	2 998.55 MHz under vacuum
Operational temperature	30 ° C (stability±0.1 ° C)
Phase advance per cell	
Unloaded quality factor	15000
Shunt impedance	49 M /m
Filling time	0.7 s
RF pulse width (Flat top) t_p	3 s
RF repetition rate	50 Hz
Peak acc. gradient $E_{max-on\,axis}$	80 MV/m @ 6 MW
Effective acc. gradient $E_{eff-on\,axis}$	46 MV/m @ 6 MW
Energy gain ΔU	5 MeV @ 6 MW
$E_{surf-on\,axis}/E_{max-on\,axis}$	1.07
$\Delta U/\sqrt{P_{in}}$	2.04 MeV/$\sqrt{MW}$
$E_{max-on\,axis}/\sqrt{P_{in}}$	32.65 MV/m/$\sqrt{MW}$
$E_{eff-on\,axis}/\sqrt{P_{in}}$	18.2 MV/m/$\sqrt{MW}$

Solenoids Configuration for Beam Focusing

During the electron beam acceleration in the gun cavity, the beam undergoes strong defocusing due to the space charge effect. In order to compensate this effect, a solenoid pair is installed, see Fig. 3 (top). A magnetic field produced by the main solenoid is used to focus the electron beam at the exit of the gun, and the bucking coil compensates the magnetic field at the cathode. The positions of the coils were calculated and optimized to limit the emittance growth due to space charge forces and in order to move beam waist closer to the accelerating structure entrance. This solenoid configuration not only enables better matching with the accelerating section, but also favours the emittance preservation at the ring entrance. The magnetic field calculated to keep this low emittance value is 0.26 T for a bunch of 1 nC and $E_{max-on\,axis}$ = 80 MV/m as shown in Fig. 3 (top). Figure 3 (bottom) shows the simulated on-axis magnetic field profile for different values of the circulating current in the coils using CST Studio Suite®. The maximum magnetic field for different couples of currents in two coils, as shown in Fig. 3 (bottom), is at the position z = 23 cm from the cathode position (z = 0). One notices zero magnetic field at the cathode position (z = 0) for different couples of currents in the two coils.

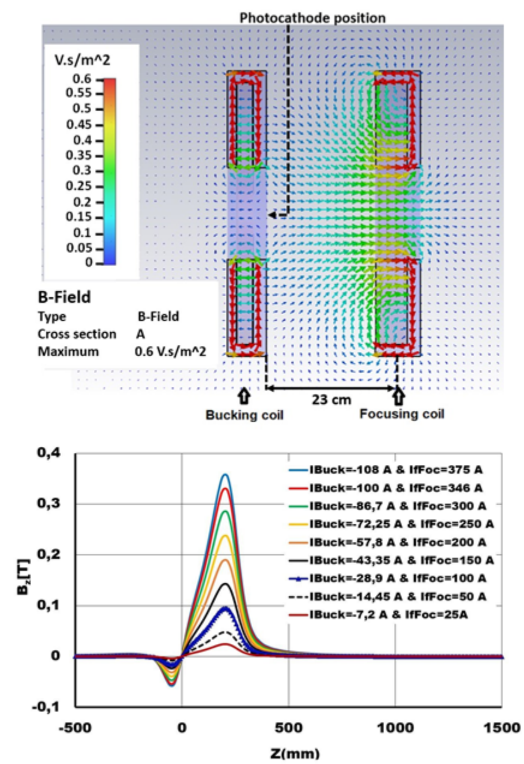

Figure 3: Model of the solenoids surrounding the ThomX gun cavity (cutting plane) with magnetic field distribution (top). Magnetic field strength on the axis for different pairs of currents in the two solenoids (bottom) using CST Studio Suite®.

The LIL-type S-band TW Accelerating Structure

During the commissioning phase, a 4.8 m long S-band TW LIL section will be used to achieve around 45 MeV for an input power of P_{in} = 9 MW corresponding to around 45 keV X-ray energy. The LIL structure is an S-band travelling wave quasi-constant gradient section operating at f_{RF} = 2998.55 MHz (30 °C in vacuum) in the $2\pi/3$ mode ($TM_{010-2\pi/3}$ mode) [8].

The electromagnetic parameters of the LIL structure are calculated using the CST Studio Suite® such as: shunt impedance, quality factor, group velocity, filling time, accelerating field, energy gain, etc. The filling time is the time required for the RF energy to flow from the input to the output end of the structure at a group velocity (v_g). A high group velocity (i.e. large iris radius) gives a small filling time.

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The simulated filling time of the LIL structure is less than 1.35 µs with a reduction in the group velocity from 2.5% to 0.5%. The shunt impedance of an RF accelerator determines how effectively the accelerator can convert the supplied RF power into accelerating gradient, the larger the accelerating field per unit supplied RF power, the more efficient the accelerator. The longitudinal electric field amplitude on the axis (accelerating mode $TM_{010-2\pi/3}$) along the LIL structure is presented in Fig. 4. $E_{max-on\,axis}$ represents the maximum amplitude (peak value) of the longitudinal electric field on the axis at which each data point is monitored at the middle point of a cell. $E_{eff-on\,axis}$ is the effective accelerating gradient (mean value) seen by the electrons crossing the cells. The circulating power decays along the structure, shown in Fig. 4, and the remaining power at the end of the structure (P_{out} = 0.2 P_{in}) is dissipated in a load. Moreover, the unloaded energy gain along the LIL structure is simulated to reach around 46 MeV for an input power of 9 MW. Considering an energy of around 5 MeV provided by the RF gun for an input power of 6 MW, this should be enough to accomplish the final goal of 50 MeV for the commissioning phase of the ThomX LINAC. Table 3 summarizes the important characteristics of the LIL section.

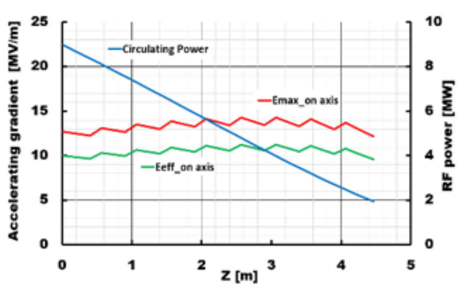

Figure 4: Accelerating gradient and circulating power along the structure with an input power of 9 MW.

Table 3: Main RF Characteristics of the ThomX LIL Section

Parameter	Value
Frequency	2 998.55 MHz under vacuum
Operational temperature	30 ° C (stability± 0.1 ° C)
Number of cells	135 regular cells + 2 coupling cells
Structure length (flange to flange)	4.8 m
Iris diameter (2a)	25 to 18 mm
Phase advance per cell	2 /3
Unloaded quality factor	15080
Shunt impedance	61 to 80 MΩ/m
Group velocity	2.5 to 0.5 %
Filling time	1.35 s
RF pulse width (Flat top) t_p	3 s
RF repetition rate	50 Hz
Peak acc. gradient $E_{max-on\,axis}$	13.2 MV/m@ 9 MW
Effective acc. gradient $E_{eff-on\,axis}$	10.5 MV/m @ 9 MW
Energy gain ΔU	46 MeV @ 9 MW
$E_{surf-on\,axis}/E_{max-on\,axis}$	1.9
$S_{c\,max}/E^2_{eff-on\,axis}$	0.0005 A/V
$\Delta U/\sqrt{P_{in}}$	15.45 MeV/$\sqrt{MW}$
$E_{max-on\,axis}/\sqrt{P_{in}}$	4.4 MV/m/$\sqrt{MW}$
$E_{eff-on\,axis}/\sqrt{P_{in}}$	3.5 MV/m/$\sqrt{MW}$

BEAM DYNAMICS STUDY OF THE ThomX LINAC

ThomX LINAC scheme was designed to be near a waist of the electron beam at the accelerating section entrance to optimize the emittance and to keep a reasonable beta function bellow 30 m at the LINAC exit [9]. This study was performed via ASTRA for the whole LINAC from a starting cathode position until the LINAC exit at z = 6.2 m for an electron charge of 1 nC, peak accelerating gradient of 80 MV/m for RF gun and peak accelerating gradient of 14 MV/m for the LIL section. The whole LINAC was tracked in consideration of the space charge effects. An optimized beam parameters were found with a small dephasing of the gun and the section at $\Delta\phi_{laser-RF\,gun} = -5°$ and $\Delta\phi_{RF\,gun-LIL\,section} = -5°$, with finest tuning of the solenoid magnetic field to 0.26 T and with smaller laser spot size ($\sigma_{x,y}$ = 0.52 mm and σ_t = 2 ps). The characteristics of the beam at the end of the LINAC are summarized in Table 4, the achieved emittance is 4 π mm mrad, the energy spread is 0.25% and beta function is around 20 m.

Table 4: The Beam Parameters of the ThomX Linac at z = 6.2 m. Total Bunch Charge: 1 nC. Laser Parameters: Rms $\sigma_{X,Y}$ = 0.5 mm, Rms σ_T = 2 ps

Parameter	Value
Energy E	50 MeV
Energy spread (ΔE)	122 keV
Beam size ($\sigma_{x,y}$)	1.9 mm
Bunch length (σ_t)	4 ps
Beam emittance ($\epsilon_{x,y}$)	4 π mm mrad
Beta function ($\beta_{x,y}$)	20 m
Particles lost on aperture	3.5 %

CONCLUSION

The electromagnetic and beam dynamics studies of the ThomX LINAC has been presented. It provides an efficient acceleration to achieve an energy gain of 50 MeV corresponding to 45 keV X-ray energy. The first commissioning phase of the ThomX LINAC (0.1 nC, 50 MeV at 10 Hz) will start in June 2021 after obtaining the authorization from the French Nuclear Safety Authority (ASN). Since the maximum targeted X-ray energy is 90 keV, a new S-band TW constant gradient accelerating section is under development, intended to replace the LIL structure, and will provide an electron beam energy of 70 MeV.

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