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DESIGN STUDY OF HIGH GRADIENT COMPACT S-BAND TW ACCELERATING STRUCTURE FOR THE THOMX LINAC UPGRADE

M. El Khaldi, M. Alkadi, C. Bruni, L. Garolfi, A. Gonnin, H. Monard,
LAL, Univ. Paris-Sud and Paris-Saclay, CNRS/IN2P3, France

Abstract

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-rays average flux of 10^{12}-10^{13} ph/s. A demonstrator was funded and is being built on the Orsay university campus. The S-band injector Linac consists of *2.5 cell* photocathode RF gun and a TW accelerating section. During the commissioning phase, a standard LIL 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 development of a new S-band accelerating section, intended to replace the LIL structure on loan from Soleil Synchrotron**,** will provide an electron beam energy of 70 MeV. This requires essentially the development of more reliable high gradient compact S band accelerating section. Such design is tailored for high gradient operation, low breakdown rates. We present here the RF design of the LINAC upgrade and the performances obtained in terms of beam dynamics.

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-rays average flux of $10^{12}/10^{13}$ ph/s. The emitted flux will be characterized by a dedicated X-ray line. Different users are partners in the ThomX project [1], especially in the area of medical science and cultural heritage. Their main goal will be the transfer of all the experimental techniques developed on big synchrotron rings to these more compact and flexible machines. A demonstrator was funded and is being built on the Orsay university campus.

Basically, the ThomX linear accelerator is composed of two main warm RF components: the RF gun and the accelerating section that boosts the electron beam to the final energy for the ring injection.

The THOMX RF gun designed and developed at LAL is a 2.5 cell standing wave copper cavity with resonance frequency of 2998.55 MHz at 30 °C under vacuum. The electrons are emitted on the cathode (Cu/Mg) through a laser that hit the surface and are then accelerated by an axial longitudinal electric field component (80 MV/m). The beam energy at the exit of the RF Gun is about 5 MeV for an input peak RF power of 6 MW.

To increase the current per bunch with less vacuum constraints, a metallic 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 [2].

During the commissioning phase, a 4.8 m S-band TW LIL section on loan from Soleil synchrotron will be used to achieve around 50 MeV corresponding to around 45 keV X-rays energy. The LEP Injector Linac (LIL) structure is an S-band travelling wave quasi-constant gradient section composed of 135 cells, with $2\pi/3$ phase advance per cell at 2998.55 MHz (30 °C in vacuum) [3]. The project goal is to produce a high flux of 45 keV X-rays energy [4] leading to specifications for the Linac that are summarized in Table 1.

Table 1: Nominal Linac Parameters

Parameter	**Value**
Nominal e-beam energy	50 MeV
Bunch per RF pulse length	1
Normalized rms emittance	< 5 π mm mrad
Energy spread rms	< 0.3%
Bunch length rms	< 5 ps
Average current	50 nA
Repetition rate	50 Hz

The Thomx injector linac energy will be upgraded from 50 MeV to more than 70 MeV by replacing a 4.8 m long S-band TW LIL section with a compact high gradient (HG) S-band one. The proposed ThomX compact HG structure is a travelling wave constant-gradient type with 96 regular cells and 2 coupling cells, resonating at a frequency of 2998.55 MHz at 30 °C at the TM_{010}-$2\pi/3$mode.

The electromagnetic design of the HG structure has been performed with the codes CST MWS. The choice of a regular cell shape derives from an optimization aiming to maximize RF efficiency and minimize surface fields and modified Poynting vector at very high accelerating gradients. Such gradients can be achieved utilizing shape optimized elliptical irises, surface finish, appropriate materials and specialized fabrication procedures developed for high gradient structures. We present here the RF design of the LINAC upgrade and the performances obtained in terms of beam dynamics.

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RF DESIGN OF THE HG SECTION

Traditionally, the surface electric field was long considered to be the main quantity which limits the accelerating electric field because of its direct role in field emission [5]. There is clear evidence however, in data from both CLIC and NLC [6, 7] which covers structures with a wide range of RF parameters, that a simple constant surface field limit is insufficient to predict the performances of the different structures. Recently, new quantities such as the averaged power flow through the cell by the iris aperture circumference P/C [8] and the peak modified Poynting vector $S_c = Re\{S\} + Im\{S\}/6$ [9] have been considered to be responsible for high gradient limits.

During the design phase, the optimization of the main RF properties for the accelerating cavities (shunt impedance, accelerating gradient, group velocity, modified Poynting vector, surface fields, etc.) was carried out, by using the 3D simulation code CST MWS. A scan over several parameters has been performed in order to find the best combination of geometrical parameters in term of high gradient operations performance and reduced power consumption. In order to have a quantitative approach, it has been decided to find the cell geometry which minimizes the quantity μ:

$$\mu = \frac{P}{{E_a}^2} \cdot \frac{S_c}{{E_a}^2} = \frac{v_g}{\omega} \cdot \frac{S_c/{E_a}^2}{r/Q}. \quad (1)$$

This corresponds to having simultaneously the minimum power consumption and the minimum risk of breakdown (based on the S_c model) for a given accelerating field E_a. Where ω is the angular frequency, r is the effective shunt impedance per unit length, v_g is the group velocity and Q is the quality factor.

The plots as shown in Fig. 1 summarize the results obtained for regular cells as a function of the iris aperture radius (a) and cell to cell iris thickness (t).

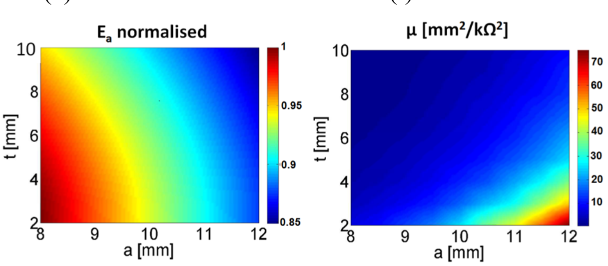

Figure 1: Normalized axial electric field and μ parameter as function of the iris radius and the iris thickness.

From these plots, the main trend is that the accelerating gradient decreases when the iris aperture is increased. However, a structure consisting of purely small-aperture cells would not be practical, as the group velocity in these cells is very small. The thickness of the iris has been carefully studied as well. The modified Poynting vector S_c and the surface electric field increase when the iris thickness is decreased for a given iris aperture. The cell-to cell iris thickness t has been optimized in order to get an acceptable compromise between the desired effective shunt impedance, the acceptable filling time and the mechanically rigidity, and is fixed at 5 mm along the structure.

These irises have an elliptical cross-section with an aspect ratio 1.7:1. An elliptical rounding profile at the iris reduces the peak surface field by 10-15%, which is desirable in high gradient applications. The rounding of the cell edge (ρ=10 mm) noticeably improves the quality factor by more than 10% and reduces the wall power consumption. The optimized cell shape is the result of a trade-off between RF efficiency, optimal accelerating gradient, optimal filling time, Wakefield considerations, and breakdown limitations. Figure 2 shows the distribution of electric field and modified Poynting vector S_c in the cell volume for 2a = 19 mm, t = 5 mm, r_2/r_1=1.7 at the input power P_{in} = 20 MW. Both peak surface electric field and peak Poynting vector are located on the iris insert.

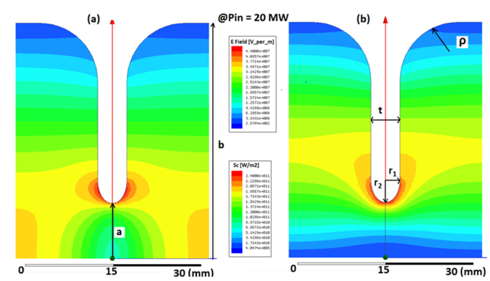

Figure 2: Distribution of (a) the electric field and (b) the modified Poynting vector in the regular cell.

The proposed high gradient (HG) structure is a travelling wave constant-gradient type with 96 regular cells and equipped with two quasi –symmetric single feed couplers which have a guide of λ/4 length at the coupling slot opposite site in order to compensate the asymmetry of the electromagnetic field in the coupling cells, resonating at a frequency of 2998.5 MHz at 30 °C at the TM_{010}-2π/3mode. The coupler type is simpler and more compact than J-type couplers and dual feed couplers; consequently, it can bring the manufacturing cost down.

To achieve the constant-gradient design, the iris radius (a) was tapered from 11.5 mm to 8.65 mm. This range of iris radius was chosen as a compromise between maximizing the energy gain and minimizing the filling time.

The resulting longitudinal electric field amplitude along the structure has been determined as shown in the Fig. 3. As you can see the longitudinal electric field amplitude is almost constant along the total length of the section.

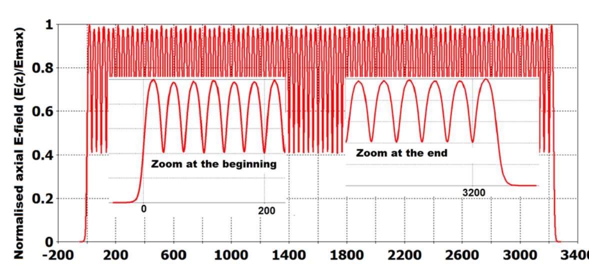

Figure 3: Normalized axial E-field along the structure.

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The simulated phase shift of the longitudinal electric field between two adjacent cells is reported in Fig. 4. The phase advance per cell is equal to 120 ±0.7 °.

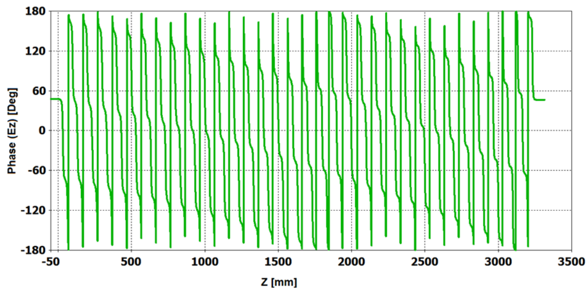

Figure 4: Phase of the axial electric field TM $_{010}$-2π/3 mode along the whole accelerating structure.

All the main RF characteristics based on the design are summarized in Table 2. A detailed description is found in [10].

Table 2: HG Structure RF Parameters

Parameter	Value
Operating freq. (f_{oper})	2998.55 MHz in vacuum
S_{12}/S_{11}@ f_{oper}	-5.4 dB /-38 dB
Phase advance per cell	2π/3
Number of cells	96 regular +2 coup. cells
Structure length	3267 mm
Iris diameter	23 → 17.3 mm
Group velocity (v_g/c)	1.71% →0.67%
Output power	0.29 P_{in}
Filling time	< 1 µs
Series impedance	17.3 →55.5 MΩ.m^{-2}
Shunt impedance	71→85 MΩ.m^{-1}
unloaded quality factor Q	15200→15100
Effective Acc. gradient E_a	21 MV/m @ P_{in} =26 MW
Unloaded energy gain	65 MeV @ P_{in} =26 MW
$E_{surf\ max}/ E_a$	1.6
$S_{c\ max}/ E_a^2$	3.8 10^{-4}→1.8 10^{-4} A/V
RF pulse / repetition rate	3 µs/50 Hz
Pulsed surface heating	< 8°C @ P_{in}= 26 MW
BDR @ P_{in}= 26 MW	≤ 10^{-18} bpp/m

The effective accelerating gradient seen by an electron beam and the unloaded energy gain are related to the input power by the following expressions:

$$E_a\left[\frac{MV}{m}\right] = 4.12\sqrt{P_{in}[MW]} \quad (2)$$

$$\Delta U[MeV] = 12.75\sqrt{P_{in}[MW]} \quad (3)$$

LINAC BEAM DYNAMICS STUDY

ThomX linac scheme was designed to be near a waist of the electron beam at the accelerating section entrance to optimise the emittance and to keep a reasonable beta function bellow 30m at the Linac exit [10]. We compare in the table 3 the performances for the High gradient (HG) shortest section with the LIL one, first keeping the same output energy, and then increasing the final energy to 70 MeV. As expected the longitudinal properties are kept the same as the energy spread depends on the product of the gradient with the length of the accelerating section. As this product is constant for the both cases, the energy spread remains the same. The improvement comes from the emittance keeping a similar beta function for the 50 MeV and 70 MeV case. As a conclusion, the HG structure allows higher performances for the emittance mainly due to the compactness of the structure. Table 3 summarizes the Beam performances at the exit of linac for the HG section at z=4.8m and for the LIL section at z=6m.

Table 3: Thomx Linac Beam Performances

Section	LIL	HG	HG
E [MeV]	50	50	70
Energy spread ΔE [keV]	125	125	200
$\sigma_{x,y}$ [mm]	1	1	1
Bench length [ps]	4	4	4
$\varepsilon_{x,y}$ [π mm mrad]	5	4	4
β_{xy} [m]	20	30	30

CONCLUSION

The RF design of a new accelerating section, aimed to replace the existing LIL structure, has been presented. Great care has been devoted to guarantee an efficient acceleration while minimizing the surface fields in both the regular cells and the RF couplers. So, a higher accelerating gradient with a low breakdown rates could be theoretically achieved, bringing the linac energy at 70 MeV level. Beam dynamics simulations show that the proposed HG structure allows higher performances for the emittance mainly due to its compactness.

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