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Abstract

There is growing demand from the industrial and research communities for high gradient, compact RF accelerating structures. The Thomx high gradient structure (HGS) is travelling wave (TW), quasi constant gradient section and will operate at 2998.55 MHz (30°C in vacuum) in the 2π/3 mode. The optimization of the cell shape (Electromagnetic design) has been carried out with the codes HFSS and CST MWS, in order to improve the main RF characteristics of the cavity such as shunt impedance, accelerating gradient, group velocity, modified Poynting vector, surface fields, etc. Prototypes with a reduced number of cells have been designed. For an input power of about 20 MW, EM simulation results show that an average accelerating gradient of 28MV/m is achieved which corresponds to a peak accelerating gradient of 35 MV/m, a peak surface gradient of 44 MV/m and peak modified Poynting vector S_{cmax} of 0.24 MW/mm^2.

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 $10^{11}/10^{13}$ 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. The ThomX project has recently been funded and will be located on the Orsay University campus.

The beam will be generated by a 2.5 cells standing wave RF gun and accelerated with a conventional LIL-type structure with an operating peak accelerating gradient around 20 MV/m during the first commissioning phase. The Thomx injector linac energy will be upgraded from 50 MeV to more than 70 MeV by replacing a low gradient S-band TW section with a short high gradient S-band one.

A LAL-PMB collaboration on high gradient S-band structure research has been established in order to push the performance envelope of RF structures towards higher accelerating gradients. The program foresees the design, prototyping and high power testing of a high gradient compact S-band accelerating structure. The Thomx high gradient structure (HGS) is travelling wave, quasi constant gradient section and will operate at 2998.55 MHz (30°C in vacuum) in the 2π/3 mode. The section consists of five constant impedance (CI) landings with 16 identical cells

plus four transition cells between the landings, in which the iris diameter decreases by 0.175 mm from one cell to another.

Before the construction of the final high gradient structure, prototypes with a reduced number of cells will be realized. The goals of these prototypes are to improve the machining of the cells and the brazing process.

The electromagnetic design of the prototypes has been performed with the codes CST MWS and HFSS. The choice of a single 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.

DESIGN OPTIMIZATION AND ELECTROMAGNETIC SIMULATIONS

Traditionally, the surface electric field was long considered to be the main quantity which limits accelerating gradient because of its direct role in field emission [2]. There is clear evidence however, in data from both CLIC and NLC [3, 4] 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 [5] and the peak modified Poynting vector $S_c = Re\{S\} + Im\{S\}/6$ [6] 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 codes HFSS and 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 η:

$$\eta \equiv \frac{P}{<E_a>^2} \cdot \frac{S_c}{<E_a>^2} = \frac{v_g}{\omega} \cdot \frac{S_c/<E_a>^2}{r/Q} \qquad (1)$$

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.

Where ω is the angular frequency, r is the effective shunt impedance per unit length and Q is the quality factor of the cell. The plots of figures 1 and 2 summarize the results obtained for the 2π/3 phase advance cell as a function of the iris aperture radius (a) and cell to cell iris thickness (t).
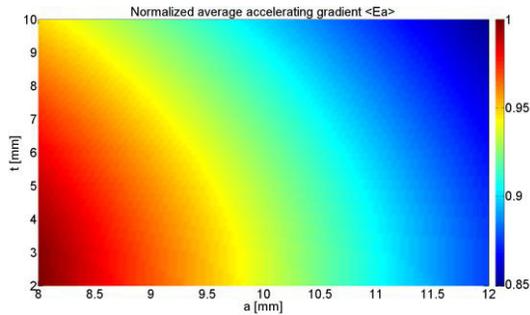

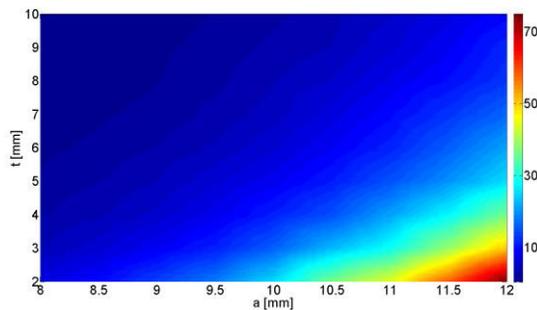Figure 1: Normalized average accelerating gradient as function of the iris radius and thickness.

Figure 2: The optimization quantity η in the iris region.

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 3 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. An average iris radius of 9.5 mm is chosen for RF efficiency and short-range Wakefield considerations. The optimized cell shape is the result of a trade-off between RF efficiency, accelerating gradient, optimal filling time, Wakefield considerations, and breakdown limitations. Figure 3 shows the distribution of electric field and modified Poynting vector S_c in the cell

volume. Both peak surface electric field and peak Poynting vector are located on the iris insert.
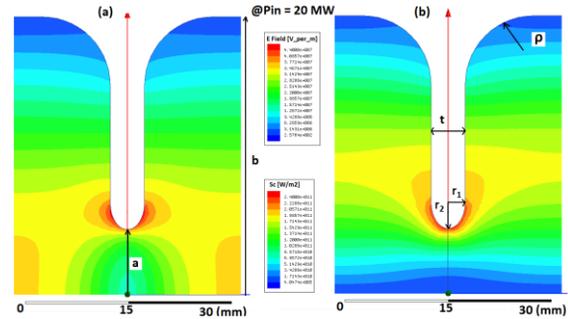

Figure 3: Distribution of (a) electric field and (b) modified Poynting vector in the regular cell.

The S-band prototypes are TW constant impedance (CI) sections with reduced number of cells. Single coupling slots introduce a distortion in the field distribution and multi-pole components can appear and affect the beam dynamics. The simple way to compensate the dipole field is to introduce a symmetric compensating slot opposite to the RF input one. The opposite slot is not feed by RF power and can be used, for example, by pumping the structure. The goals of these prototypes are to test all design, manufacturing procedures and to verify the validity of all technical choices. Table 1 reports the main parameters for the 7-cell HGS prototype.

Table 1: Prototype RF Parameters

Parameter	HFSS	CST MWS
Freq.	3 [GHz]	3 [GHz]
Phase advance per cell	2π/3	
Number of cells	7	
Iris radius	9.5 [mm]	
Group velocity (v$_g$/c)	0.9%	
Field attenuation (α)	0.236 [m^{-1}]	0.232 [m^{-1}]
Series impedance	38.6 [MΩ.m^{-2}]	38 [MΩ.m^{-2}]
Shunt impedance	80 [MΩ.m^{-1}]	81[MΩ.m^{-1}]
Unloaded quality factor Q	15000	15100
P$_{in}$ @ <E$_a$> = 28 MV/m	20 [MW]	20 [MW]
E$_{s\ peak}$/<E$_a$>	1.61	1.62
E$_{s\ peak}$/ E$_{a\ peak}$	1.28	1.29
S$_{cmax}$/< E$_a$ >^{2}	3.10^{-4}[A/V]	3.1.10^{-4}[A/V]
H$_{s\ peak}$ @ 20MW (cells)	65 [kA/m]	65 [kA/m]
Pulsed heating @ 20 MW	< 2°C	< 2°C
BDR @ < E$_a$ >=28 MV/m and RF pulse tp=3 μs	≤ 10^{-18} [bpp/m]	≤ 10^{-18} [bpp/m]

Figure 4 shows the amplitude and phase distribution of the longitudinal electric field along the structure's axis with a reflection coefficient less than -40 dB at the input port. The

simulated phase shift between two adjacent accelerating cells is equal to 120 °.
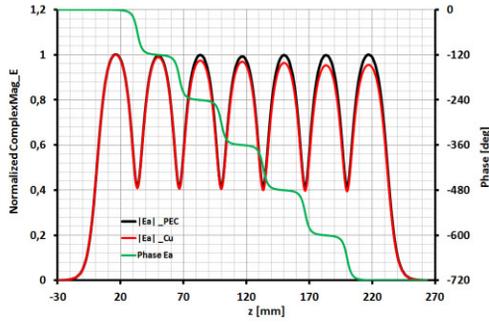

Figure 4: Amplitude and phase of the accelerating gradient along the prototype's axis.

The average and peak accelerating gradients are related to input power (peak value) by the following expressions:

$$< E_a > [MV/m] = 6.26 \sqrt{P_{in}[MW]} \qquad (2)$$

$$E_{a\,peak} [MV/m] = 7.83 \sqrt{P_{in}[MW]} \qquad (3)$$

HIGH GRADIENT LIMITATIONS

The major obstacle to higher gradient is RF breakdown. RF Breakdown (BD) is a phenomenon that abruptly and significantly changes transmission and reflection RF power directed toward the structure under test. BD is accompanied by a burst of x-rays and by a bright flash of visible light. A local field quantity which predicts the high gradient performance of an accelerating structure is the modified Poynting vector S_c. The dependence of the modified Poynting vector on RF pulse length t_p at a fixed breakdown rate (BDR) [7] has well established scaling law observed in many experiments.

$$\frac{S_c^{15} \, t_p^5}{BDR} = const \qquad (4)$$

The BDR is defined as the probability of having a breakdown and it is typically measured in "breakdown per pulse" (bpp) for 1 m long structure. As design guideline for a new RF structures, S_c should not exceed 4 MW/mm² if the structure is supposed to operate at a breakdown rate smaller than 10^{-6} bpp/m and a pulse length of 200 ns [6, 7]. By re-scaling these data to the pulse length of Thomx linac, i.e. 3 µs flat top, the maximum threshold of S_c, $<E_a>$, and peak surface electric field $E_{s\,peak}$ are presented in figure 5.

In our case, S_c should not exceed 1.6 MW/mm² which corresponds to a maximum surface electric field of 117MV/m, and maximum average accelerating gradient of 72 MV/m if the structure is supposed to operate at BDR smaller than 10^{-6} bpp/m (the acceptable breakdown rate for a medical accelerator), and a RF flat top pulse length of 3 µs. For an input power of 20 MW the simulated peak modified Poynting vector S_{cmax} is 0.24 MW/mm². The expected BDR is less than 10^{-18} bpp/m at given S_{cmax}=0.24 MW/mm², $<E_a>_{max}$=28 MV/m and for a RF pulse length t_p=3µs.

These limits are derived for structures which were constructed based on the high gradient assembly procedure which includes keeping everything rather clean and having high temperature bonding or brazing cycle in Hydrogen or in vacuum
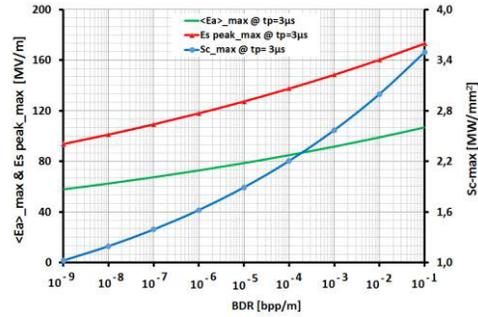

Figure 5: Dependence of the expected BDR versus average accelerating gradient, surface electric field and the modified Poynting vector for the prototype.

Cyclic thermal stresses produced by RF pulsed heating due to intense magnetic fields that is usually at the coupling slot area can be the limiting factor on the attainable reliable gradients for linear accelerators. Electromagnetic Simulations show that a surface magnetic field reaches a peak value of $1.7 *10^5$ [A/m] for an input power of 20 MW as illustrated in figure 6. This field value causes a temperature rise of about 11 °C for a RF flat top pulse length of 3 µs, which is far below the safe limit of 100 °C in the case of copper. As general experimental rule, if this pulsed heating exceeds ~ 110 °C serious damage to the coupler region has a high probability of occurrence.
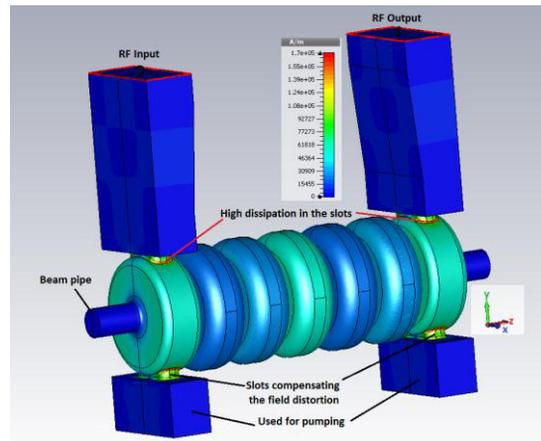

Figure 6: Surface magnetic field distribution for an input power of 20 MW (peak value).

CONCLUSION

Prototypes with a reduced number of cells have been designed and will be fabricated and high power tested in order to verify the validity of all technical choices. With the mode parameters of these sample prototypes and with fitting procedures, a final quasi-constant high gradient TW accelerating structure can be synthetized and assembled.

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