BEAM DYNAMICS SIMULATIONS OF THE THOMX LINAC

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Abstract

ThomX Compton light source is designed to maximise the average X-ray flux providing a compact and tunable machine which can operate in hospitals or in museums. These constraints impose the choice of a high collision rate which is based on S-band Linac whose energy is 50-70 MeV combined to an electron storage ring. As most of the performances of the electron beam at the interaction point depend on the beam quality at the ring entrance, the linear accelerator must be carefully designed and especially the photo-injector. Simulations have been carried out in order to optimise the emittance for the ring entrance. Indeed, for a bunch charge of 1nC, space charge effects usually dominate the total beam emittance. The latter can be minimized at the end of the Linac by means of emittance compensation. The best configuration across all the parameters will be presented.

INTRODUCTION

ThomX is a Compton backscattering compact light source project, aiming to produce an intense flux of monochromatic X rays (40 – 90 keV) resulting from collisions between laser pulses and relativistic electron bunches [1]. The machine is based on a 50 Hz, warm S band (2998.55 MHz) linac whose energy is tunable up to 70 MeV, an injection line and a compact electron storage ring. A demonstrator was recently funded and is under construction in the Orsay University campus. The most important components of the linac injector are the RF gun and the accelerating section which brings the beam to the desired energy. An electron bunch is produced inside the RF gun and then accelerated up to the ring injection energy by an S-band section. A transport line ensures the bunch transfer from the linac exit to the injection in the storage ring. Other components are the laser used for generating electrons bunches, the solenoids for the compensation of emittance growth, the magnetic elements used to transport the beam and the diagnostics. After injection, the electron bunch is stored for 20 ms in the ring. The ring optics and the RF peak value are such that the beam sizes are very small at the interaction point (IP). At the beginning, the project goal is to produce a high flux of 50 keV X-rays energy leading to strict specifications for the linac, such as 50 MeV energy, 1 nC total electron charge, rms normalised transverse emittance lower than 4 pi mm mrad, rms energy spread lower than 0.5% and rms bunch length less than 5 ps [2]. As the beam properties are mostly affected by the RF gun, a classical emittance growth compensation of the photoinjector by means of solenoids will be presented.

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THE PHOTO-INJECTOR

A photo-injector as electron source, rather than the more classical thermoionic gun has been chosen for two main reasons. First, the photo-injector routinely demonstrated its capacity to produce a very low emittance electron beam. Second, the use of a thermionic gun would lead to a more complex and longer accelerator because it needs a prebunching cavity and a buncher. Furthermore, any reduction of transverse emittance allows to enhance the photon beam brightness. Since a low emittance beam together with the possibility of variety operation modes, such as bunch charge and initial bunch length are required, the photo-injector has been considered the best technical choice. The ThomX photo-injector consists in a normal conducting RF gun, a drive-laser and focusing solenoids. Thanks to the long experience accumulated from LAL in the field, the RF gun has the same design to those has been constructed for the CLIC "Test Facility 3" at CERN. To get a good quantum efficiency with less vacuum constraints, a metallic magnesium photo-cathode has been foreseen. Also, this photo-chatode has already been successfully tested at photoinjector facility (PHIL) at LAL [3]. The S-band RF gun is a 2.5 copper cells. To get 1 nC with an emittance lower than 5 pi mm mrad, specific RF characteristics have been defined and listed in Table 1. In Fig. 1, it is easy to see that the gun have two coupling apertures symmetrically opposed with respect to the longitudinal axis.

Table 1: RF Gun Specifications

Laser wavelength and pulse energy	266 nm, 100 μJ
Q-factor	15000
Shunt Impedance	50 MΩ/m
RF input power	5 MW, 3 μs
Laser pulse duration	5 ps
Peak accelerating field	80 MV/m
Energy gain	~5 MeV

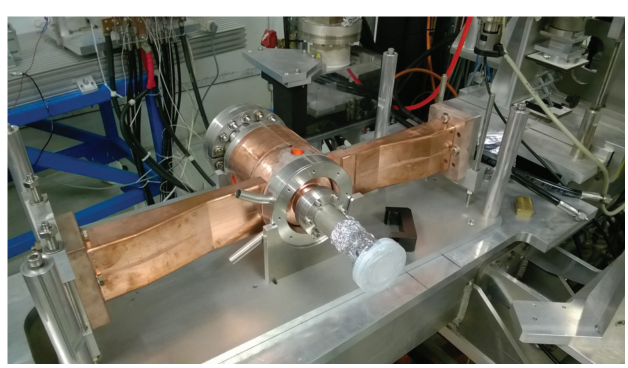

Figure 1: Picture of the brazed ThomX RF gun.

SOLENOIDS

The RF gun is equipped with two solenoids, one is the focusing coil while the other is the bucking coil. The focusing coil produces the focusing force to minimise the beam transverse emittance. The bucking coil sitting behind the gun compensates the residual magnetic field at the cathode, which is generated by the focusing solenoid. If the magnetic field at the cathode is not zero, the residual angular momentum at the end of the focusing field increases the beam transverse emittance. That is why the right current values of the coils is set in order to cancel the magnetic field (B = 0 T) at the photo-cathode location (z = 0 m). In order to reconstruct the strength of the magnetic field along the beam axis, simulations with 3D OPERA solver have been performed and the sketch of the solenoids is displayed in the upper-left corner in Fig. 2. Simulations have confirmed that the maximum value of the magnetic field profiles along the beam axis increases linearly with the current, without saturation of the iron yoke for that range of couples of currents.

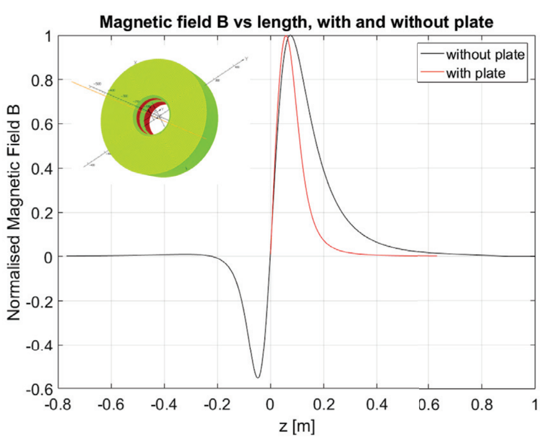

Figure 2: Simulations of the longitudinal magnetic field stength along the beam axis produced by solenoids without shielding (black line) and with shielding (red line) by means of OPERA 3D.

Also, to strongly decrease the fringe field of the focusing coil and improving the efficiency of the RF gun, a shielding plate of 5mm thickness has been set (see Fig. 2). The gun solenoids transversely focus the beam and align the longitudinal slices of the bunch in transverse phase space so that projected emittance growth is minimised.

TRANSVERSE EMITTANCE COMPENSATION

The transverse total emittance of the electron beam in an RF gun arises from the combination of several effects. Traditionally, the dependence of the RF accelerating period, space charge forces in the cathode area and thermal effects are considered as the typical sources of emittance growth in the photoinjector. The dependence of the RF field gives rise to a radial electric field component E_r due to the longitudinal position dependence (z) of the longitudinal field component $E_z(z,t)$. An estimation of the emittance growth due to the RF field is given by the following formula [4]:

$$\epsilon_{RF} = 2.73 \times 10^{-11} E_0 f^2 \sigma_x^2 \sigma_z^2 = 0.25 \; mm \; mrad \quad (1)$$

where E_0 is the peak RF gradient in MV/m, f is the resonance frequency in MHz, σ_x is the transverse rms beam size in mm and σ_z is the bunch length in ps. In this case, the nominal peak accelerating field was set to 80 MV/m, the frequency is 2998.5 MHz, the rms beam size is around 1 mm and the bunch length 3.6 ps.

Also, thermal emittance of the electrons has to be considered. This effect originates during the photoemission process and arisis from the temperature of the cathode surface. As this contribution depends on the area of the emission surface, thermal emittance has been estimated as a function of laser spot size according to the model of the photoemission and the analitic equation is shown below:

$$\epsilon_{n,th} = \gamma \frac{r_c}{2} \sqrt{\frac{k_B T_e}{m_e c^2}} \quad (2)$$

where r_c is the laser spot size impinging the cathode surface. Considering the analitic estimation for 1 mm laser spot size, we can predict that the contribution to the emittance growth is around 0.4 mm mrad [6].

The space charge has significant effects on the emittance growth. As the electrons are extracted from the cathode, they experience the Coulomb force between each others and the electric field produced by the surface charge distribution. According to the Kim's model, the expression for the space charge contribution to the transverse normalised emittance can be calculated by the formula [5]:

$$\epsilon_{sc} = 3.76 \times 10^3 \frac{Q}{E_0(2\sigma_x + \sigma_z)} = 8.4 \; mm \; mrad \quad (3)$$

where the Q is the extracted charge that in this case is equal to 1 nC. The individual contributions from the above mentioned effects are quadratically added to the total normalised beam dynamics emittance. The general formula is:

$$\epsilon_{n,x,y,tot} = \sqrt{\epsilon_{RF}^2 + \epsilon_{sc}^2 + \epsilon_{th}^2} = 8.4 \; mm \; mrad \quad (4)$$

According to the model, the space charge effect near the cathode is the dominant contribution to the emittance growth while the RF field and thermal effects are almost negligible in the RF gun.

Beam dynamics simulations have been performed using A Space Charge Tracking Algorithm (ASTRA). Simulations are based on the 2D profile of the electric field inside the RF gun that has been calculated by SUPERFISH. Performances of the gun have been studied in three different cases, without solenoids, with solenoids without shielding plate and with shielding plate, respectively.

The electron distribution with a total bunch charge of 1 nC, 1 mm transverse laser spot size and 4 ps pulse duration have been set. Results with and without plate are resumed

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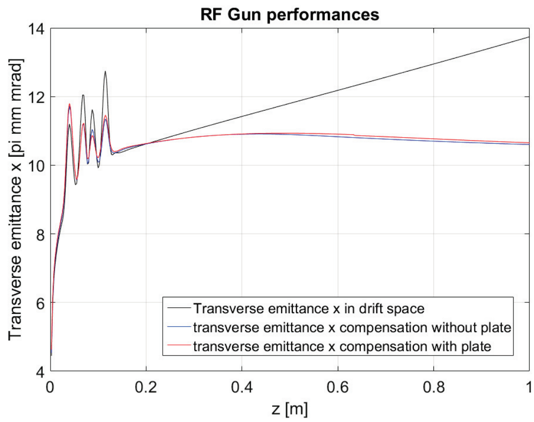

Figure 3: rms normalised transverse emittance x as a function of distance. Total bunch charge 1nC. Laser parameters: rms σ_r = 1mm, rms σ_t = 4ps. Drift space (black line), solenoids without plate (blue line) and solenoids with plate (red line).

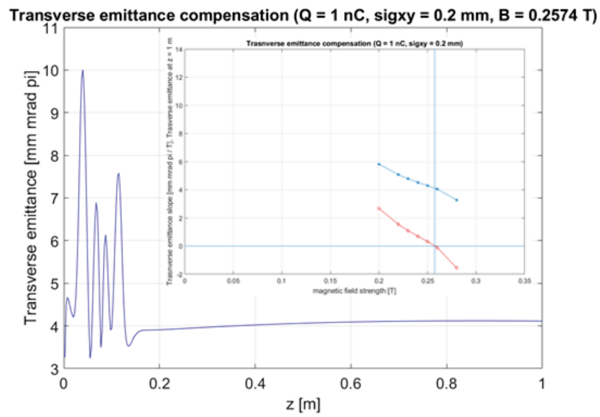

Figure 4: Transverse emittance slope (red line) and trasverse emittance value at z = 1 m (blue line) as a function of magnetic field strength (left). Trasverse emittance as a function of the distance for B = 0.2574 T (right).

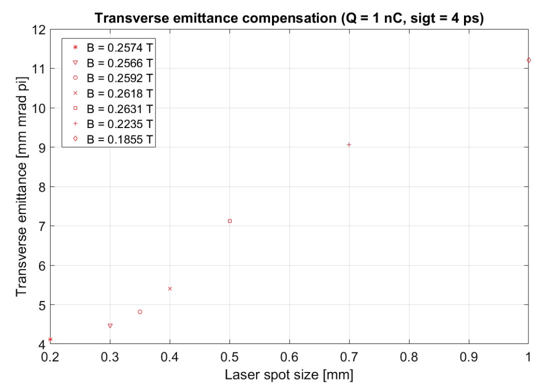

Figure 5: Transverse emittance as a function of the laser spot size. For each value of the spot size, the corresponding value of the magnetic field strength with compensate the emittance growth has been shown.

Table 2: Beam Parameters. Total bunch charge: 1 nC. Laser parameters: rms σ_r = 1mm, rms σ_t = 4ps.

without solenoids, z = 1 m	
E [MeV]	5.4
$\epsilon_{x,y}$ [pi mm mrad]	13.7
$\sigma_{x,y}$ [mm]	9.7
σ_z [ps]	3.8
ΔE / E [%]	0.7
with solenoids without shielding, z = 1 m	
E [MeV]	5.4
$\epsilon_{x,y}$ [pi mm mrad]	10.6
$\sigma_{x,y}$ [mm]	~ 2
σ_z [ps]	3.8
ΔE / E [%]	0.87
with solenoids with shielding, z = 1 m	
E [MeV]	5.4
$\epsilon_{x,y}$ [pi mm mrad]	10.6
$\sigma_{x,y}$ [mm]	~ 3
σ_z [ps]	3.8
ΔE / E [%]	0.84

in Table 2. In Fig. 3 the emittance growth induced by space charge is linear with the distance. The transverse emittance after 1 m is around 14 pi mm mrad (black line) while it is around 11 pi mm mrad (red and blue lines) in the case of the solenoids focusing effect. In general, the effect of the shielding plate is not very much important over several beam parameters, such as emittance, bunch length, energy spread, but it has more much impact on the transverse beam size because of smaller integral magnetic length contribution due to the rapidly decreasing of the fringe field profile. A method to determine the best magnetic field strength which compensates the transverse emittance has been considered (see Fig. 4). In particular, for fixed bunch charge the slope emittance function is calculated for the last 30 cm as a function of different maximum solenoids strength. The intersection between the slope and the zero cross line defines the right magnetic strength value while the blue line gives the corresponding normalised emittance. Fig. 5 shows a scan over different laser spot size and the corresponding normalised emittance values for the suitable magnetic field strength that compensates the emittance growth. It is easy to see that the transverse emittance value of around 4 pi mm mrad is achieved for a laser spot size of 0.2 mm.

CONCLUSION

Main beam dynamics parameters of the ThomX RF gun have been estimated and calculated by means of ASTRA code. A method to determine the right magnetic field strength which compensates the emittance growth has been proposed. Requirements in terms of transverse emittance and energy spread are fulfilled unless improvement to the bunch length. The contribution of the travelling wave section to the beam dynamics is under study.

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