BEAM DYNAMICS FOR THE ThomX LINAC

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Abstract

We report the results of a recent beam dynamics study that has led to promising working points for the split ThomX photoinjector. ThomX is a back-scattering Thomson light source that will use S-band electron linac with tunable energy (from 50 to 70 MeV) to produce high X-rays flux ($10^{11} - 10^{13}$ ph/s) by means of collision between electron bunches and laser pulses, in the energy range from 45 keV to 90 keV. Since ThomX has been conceived to maximise the average X-rays flux in a fixed bandwidth, the high rate electron-photon collision impose a linear accelerator combined with a storage ring. The high performances of the accelerator are largely affected by the high quality of the electron beam at the interaction point in the ring. Beam specifications should be achieved at the interaction point to the extent that 1 nC, 50 nA average current per bunch with normalised rms transverse emittance less than 5 mm and around 0.3% energy spread, at the end of the linac. The beam dynamics along the linac has been studied to demonstrate the capability of the accelerator to meet the requirements for the high spectral flux electron beam using an RF photoinjector configuration.

INFLUENCE OF THE BEAM DYNAMICS

Among the storage ring scheme projects, ThomX is the most advanced [1]. It should provide around 10^{13} ph/s, at a maximum energy between 45 to 90 keV, with a brightness of around 10^{11} ph/s/mm^2/$mrad^2$/0.1%bw and a transverse size of the source to the order of 40 –100 µm [2]. Spectral flux is one of the most relevant parameter for a light source and quantifies the intensity by taking into account its spectral purity and its angular aperture. At present, the performances of current laser systems and electron accelerators are such that the main impact comes out from the electron beam angular divergence σ_e' that, in this case is approximately equal to the divergence of the produced X-rays, σ_X'. The average spectral flux is written [3]

$$< Br >= \frac{N_X \text{‱} F_{tot}}{(2\pi)^2(\sigma_X^2 \sigma_X'^2)} = \frac{N_X \text{‱} F_{tot}}{(2\pi)^2}\left(\frac{\sigma_e^2 + \sigma_L^2}{\sigma_L^2}\right)\left(\frac{\gamma}{\epsilon_n}\right)^2 \tag{1}$$

Assuming that electrons and photons collide head-on, N_X‱ is the fraction of X-rays emitted within a 0.1% bandwidth of a given energy E_X. The transverse source size, σ_X is written in the form $\sigma_X^2 \sim (\sigma_e \sigma_L)^2)/(\sigma_e^2 + \sigma_L^2)$ and the normalised transverse emittance of the beam, $\epsilon_n = \gamma \sigma_e \sigma_e'$. Therefore, for a given flux, Eq. (1) shows that small electron beam emittance is an essential condition for having high spectral flux. However, mainly due to the stochastic effect of the Compton interaction and collective effects inside the ring, the electron beam characteristics such as the transverse emittance and the energy spread are deteriorating with respect to time [4]. This electron bunch degradation drastically reduces the X-ray flux and the spectral purity of the photon source. Taking into account all the aspects above, different working points that minimise transverse emittance and energy spread, at the end of the linac, have been analysed and presented below.

LINAC EMITTANCE COMPENSATION

ThomX photoinjector scheme consists in a 2.5-cells S-band RF gun provided with a copper or magnesium photocathode illuminated by a few picoseconds laser pulses. In the nominal ThomX configuration, the RF gun is embedded in two solenoids, as illustrated in Fig. 1, according to mechanical constraints. 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. After a drift space, the accelerating section boosts the electron bunch emitted by the cathode to relativistic energies. The beam dynamics has been simulated with ASTRA code. We suppose that the laser which impingies on the cathode has Gaussian distribution in the transverse and longitudinal plane with a fixed rms sigma, $\sigma_x = \sigma_y = 0.6$ mm and rms time duration, $\sigma_t = 2$ ps. The total charge extracted from the cathode is about 1 nC. Simulations are based on the 2D profile of the electric field inside the RF gun and the accelerating section that has been calculated by SUPERFISH. The magnetic field profile along the beam line has been obtained by OPERA code, as well.

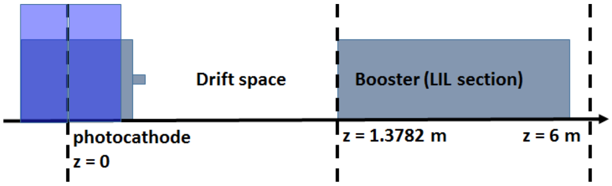

Figure 1: Nominal ThomX configuration.

A cross scan over the maximum magnetic field B_z^{max} as well as TW section dephasing with respect to laser pulses, ϕ_{LIL} has been performed. Figure 2 shows the transverse emittance as a function of maximum magnetic field strength and accelerating cavity dephasing. The plot has a minimum for $B_z^{max} = 0.28$ T and $\phi_{LIL} = 0°$. The increasing of the maximum magnetic field strength allows to decrease the transverse emittance to around 5.7 mm. The dephasing of the RF gun allows to reduce the bunch length and therefore reducing the energy spread value of the order of $\Delta E/E \sim 0.38\%$ while maintaining unchanged the transverse beam size and bunch length values.

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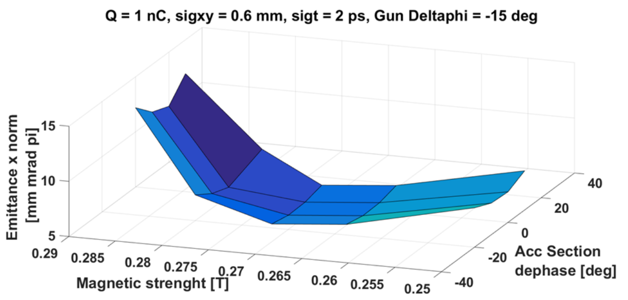

Figure 2: Transverse emittance & Energy spread vs maximum magnetic field strength and RF LIL dephasing.

Beam Matching to the TW Section

The emittance compensation to the emittance growth induced by space charge is usually performed by locating different solenoids around or at the exit of the gun. Then, in the drift space the accelerating section has to be properly matched to the beam, according to the so called "invariant envelope" condition [5]. The principle [6] has been simulated. Figures 3 and 4 shows the emittance evolution and trasverse size in the region downstream the gun as far as 6 meters in the drift space. Clearly visible is the strongly space charge dominated behaviour of the envelope in the RF gun, going through a gentle laminar waist in the drift. The "invariant envelope" condition has been determined by considering the evolution of ϵ_{xy} and $\sigma_{x,y}$ with respect to different magnetic field strength from the solenoids. The condition is fulfilled at z = 0.57 m. The TW accelerating section should be placed in that position corresponding to the local maximum between the so called "double minimum" emittance oscillation (Ferrario working point [7]) and the minimum transverse size ($\sigma'_{x,y} = 0$, waist envelope) in order to shift the second emittance minimum to the exit of the TW section.

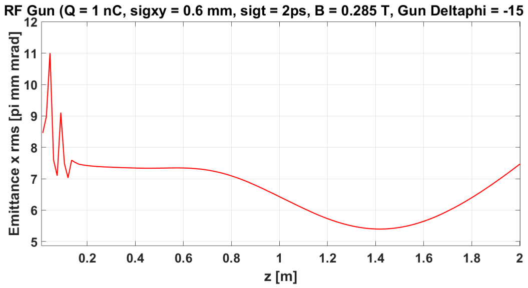

Figure 3: ϵ_{xy} evolution along the RF gun and the drift space.

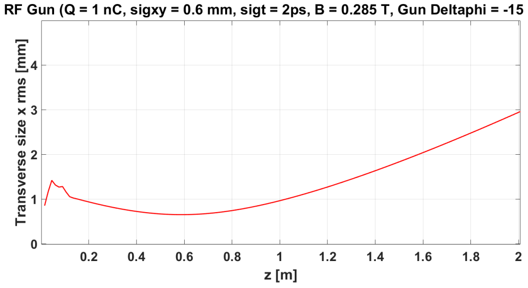

Figure 4: σ_{xy} evolution along the RF gun and the drift space.

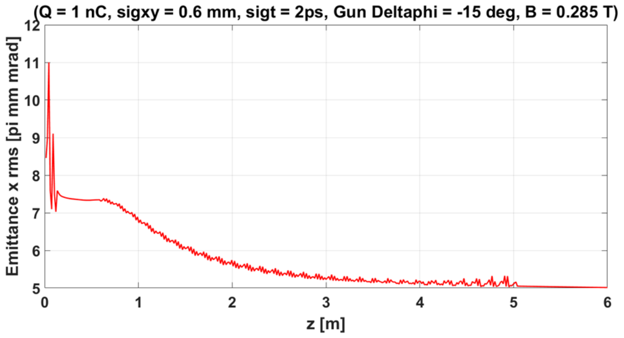

Figure 5: Transverse emittance evolution for the TW section at z = 0,57 m.

The resulting transverse emittance versus beam propagation are plotted in Fig. 5. As expected the second emittance minimum, around 5 mm mrad occurs now downstream the TW structure at z = 6 m.

Impact of the Solenoid Position

The position of the focusing solenoid will strongly impact the optical functions at the TW section exit. In order to maintain beta function around 30 m to avoid transverse emittance dilution in the transfer line, the focusing solenoid can be moved 23cm far away to the bucking coil. The corresponding magnetic field profile along the beam axis has been obtained by means of 3D OPERA software. Figure 6 shows the comparison between the magnetic field strength along the beam axis corresponding to the two different solenoid configurations. This new magnetic field distribution has an impact on the beam dynamics of the bunch throughout the photoinjector. Once again, a cross scan over several maximum magnetic field values has been performed and the evolution of the beam transverse size as well as emittance in the region downstream the gun and the drift space have been analyzed. We have explored two different couples of B_z^{max} and matching position. The results of the matching are represented in the Figs. 7 and 8.

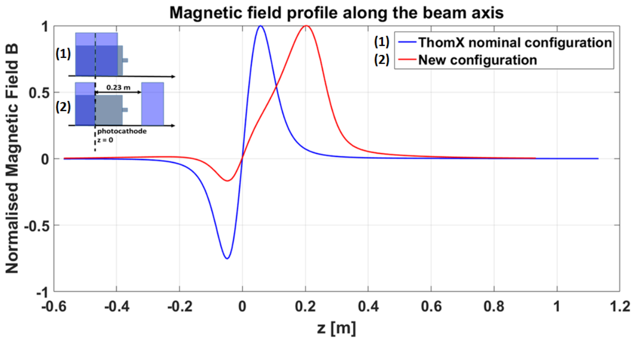

Figure 6: Magnetic field profile along the beam axis. ThomX nominal configuration, focusing solenoid 23 cm away.

ISBN 978-3-95450-182-3

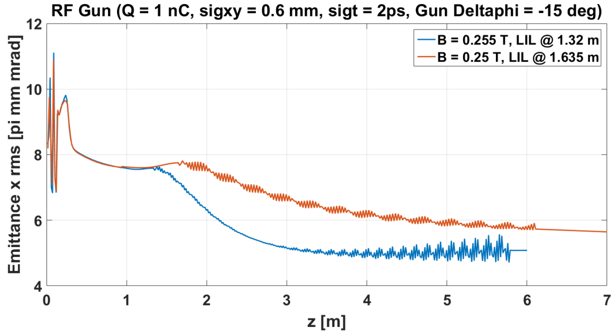

Figure 7: ϵ_{xy} along the beam line.

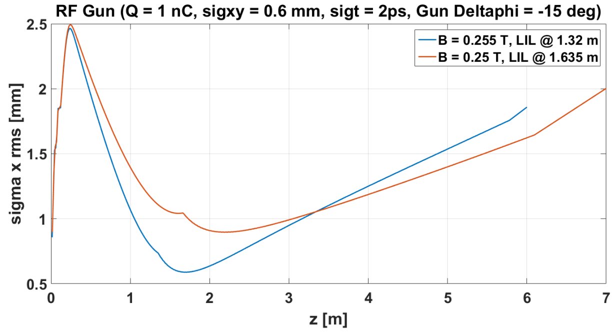

Figure 8: σ_{xy} along the beam line..

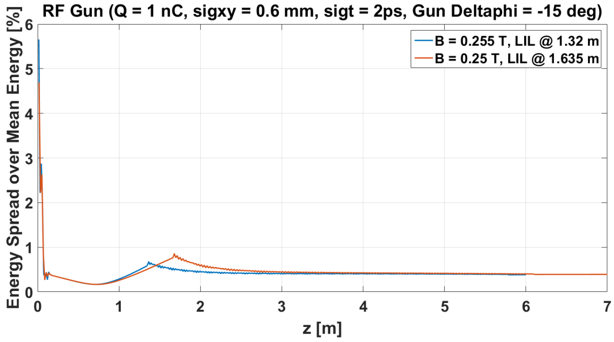

Figure 9: Energy spread along the beam line.

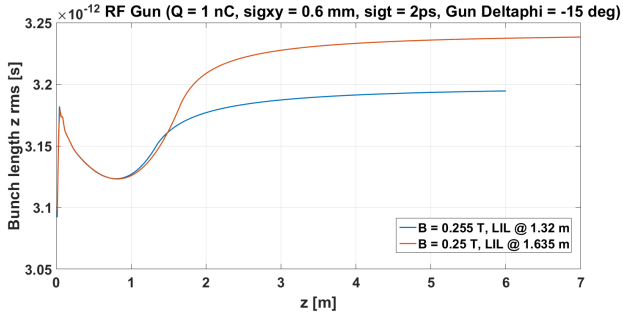

Figure 10: σ_t along the beam line.

Also, the bunch length and the energy spread are showed in Figs. 9 and 10. When the TW section is at 1.32 m from the cathode, the beam size envelope has a minimum corresponding to the maximum value of the transverse emittance in the drift space.

CONCLUSIONS

By investigating a new design for the ThomX injector, several sets of parameters have been considered in order to minimise the transverse emittance and the energy spread in the same time. Comparison between nominal solenoids configuration and new one has been performed. The nominal ThomX configuration with a maximum magnetic field of 0.28 T is still the best compromise to achieve the accelerator specifications in terms of emittance and energy spread but we obtained a significant reduction in the alpha and beta parameters when the focusing coil is placed at 23 cm far away from the nominal position.

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