

ENSOLVE : A SIMULATION CODE FOR FXR LIA DOWNSTREAM SECTION

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Abstract

In this paper, we describe an envelope code, ENSOLVE. It solves the rms beam envelope equation by including space charge depression of the potential, spherical aberration of the solenoidal lens, emittance growth and focusing effects of backstreaming ions in the final focus region. In this paper, we focus on the physics included for beam transport simulations in the downstream section of flash x-ray radiography linear induction accelerators, such as FXR LIA [1]. We have used ENSOLVE to design final focus tunes for FXR LIA downstream section (see Fig.1).

INTRODUCTION

Being able to generate small x-ray spot sizes is essential to achieve good image resolution for radiography experiment [2]. For FXR, we optimize the beam transport by choosing magnet tunes capable of producing small spot sizes at the target. As shown in Fig. 3, the FXR LIA consists of injector section, accelerator section and final focus section. We used ENSOLVE to calculate the beam envelope and optimize the magnet tune at the downstream section (see Fig. 1).

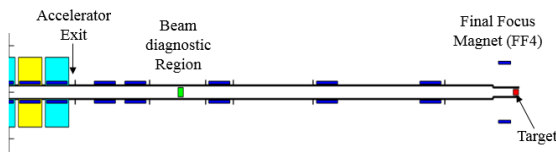


Figure 1: Schematic of FXR final focus section.

ENSOLVE AND ITS IMPLEMENTATION

ENSOLVE is written using MATLAB. It solves the rms beam envelope equation. To obtain the beam envelope on FXR downstream, we use the beam parameters at the accelerator exit, which were unfolded from magnet scan data measured at a diagnostic cross in the downstream section [3], as initial condition.

Energy Depression Due to Space Charge Field

In the final focus region, as the electron beam being rapidly focused onto the target surface, the final magnification

of the beam size changes from 1 cm to just 0.01 cm, which leads to rapid change of the potential suppress caused by the beam space charges. This beam energy change in the final focus region is modelled by ENSOLVE. For simplicity, ENSOLVE calculates the potential suppression at any given longitudinal location, z , by assuming that the beam is an infinite long cylindrical beam (radius r_0) with a uniform distribution inside a beam pipe radius of r_p . Then, the total space charge potential V can be calculated through

$$V = \int_0^{beam\ pipe} V(r) dr \quad (1)$$

where $V(r)$, the space charge potential, is calculated as

$$V(r) = \frac{I}{4\pi\epsilon_0 v} \left[1 + 2 \ln \left(\frac{r_p}{r_0} \right) - \left(\frac{r^2}{r_0^2} \right) \right], r \leq r_0 \quad (2)$$

$$V(r) = \frac{I}{2\pi\epsilon_0 v} \ln \left(\frac{r_p}{r_0} \right), r_0 \leq r \leq r_p \quad (3)$$

where I is the beam current, and v is the beam velocity. For a 2-kA beam with the rms envelope shown in Fig. 2, the total space charge potential can be as high as 0.78 MeV as the electron beam reaching the target, which results to energy loss of the beam. Noted that beam pipe is design to be smaller near the target region to mitigate space charge depression potential.

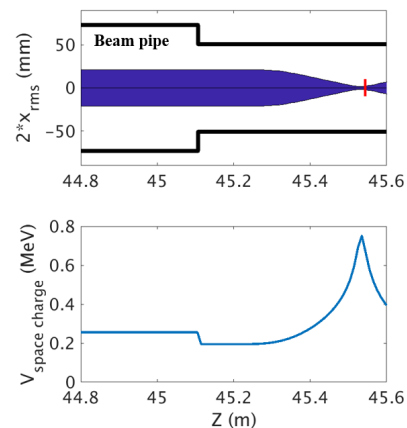


Figure 2: Typical beam envelope of electron in the final focus section (top), and the calculated space charge potential. (bottom).

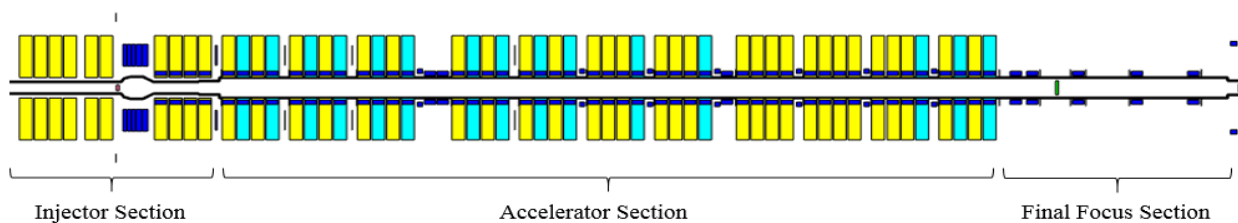


Figure 3: Schematic of FXR Induction Linac. It primarily consists of three sections to produce 2.8 kA, 18 MeV electron beam bombard target to generate X-ray through Bremsstrahlung radiation.

The focal length (L) of the final focusing solenoid is given as

$$\frac{1}{L} = \int \left(\frac{eB_z}{2mc\beta\gamma} \right)^2 dz \quad (4)$$

Where e is the electron charge, $\beta\gamma$ is the Lorentz factor proportional to the beam energy, and B_z is the longitudinal solenoid magnetic field. The magnetic field profile of the final focusing solenoid on FXR is shown in Fig. 4. Using Eqn. 4, a 0.78-MV potential suppression on an 18-MeV beam leads to 4.5 mm reduction in the focal length for $B_z = 8000$ Gauss and beam envelope as show in Fig. 2.

Solenoid Spherical Aberration and Induced Emittance Growth

Focusing an electron beam to a tight spot requires a strong final magnetic field. Due to the high magnetic field, solenoid spherical aberration and emittance growth due to high order nonlinear magnetic fields become important when modelling the final focusing section.

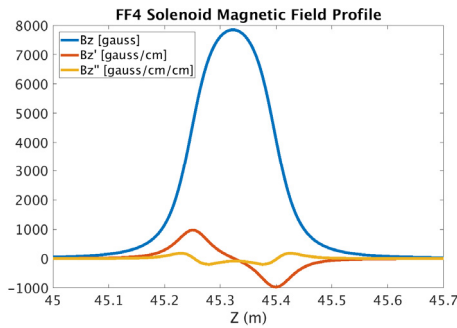


Figure 4: FF4 solenoid field profile for FF4=330 A.

The envelope equation solved in ENSOLVE includes spherical aberration and its induced emittance growth (see Eqn. 5). Note that we have assumed that the beam is born with zero magnetic field. The change of longitudinal kinetic energy $(\gamma\beta)'$ caused by space charge energy depression in the downstream transport section, including the final focus area, is modelled. However, repartitioning of the longitudinal kinetic energy and the transverse kinetic energy due to the rotation of the beam in a strong final focus lens is not included.

$$r'' = -kr - \frac{(\gamma\beta)'}{\gamma\beta} r' + \frac{l}{\gamma\beta^3 l_0 r} \left(\frac{1}{\gamma^2} - f \right) + \frac{(\epsilon_0 + \Delta\epsilon)^2}{\gamma^2 \beta^2 r^3} + Cr^3 \quad (5)$$

where $k = \left[\frac{eB_z}{2mc\beta\gamma} \right]^2$, r is the rms radius,

$C = k \frac{B_z''}{2B_z} - k^2 + \frac{kr'}{r} \frac{B_z'}{B_z} - \frac{kr'^2}{r^2}$, ϵ_0 is the normalized rms emittance, and $\Delta\epsilon$ is normalized rms emittance growth due to solenoid's nonlinear fields [4].

$$\Delta\epsilon = \gamma\beta r_{rms}^4 \int \left(\frac{e^2 B_z B_z''}{8(mc\beta\gamma)^2} - \left[\frac{eB_z}{2mc\beta\gamma} \right]^4 \right) dz \quad (6)$$

Note that the emittance growth in Eq. (6) is important only if the beam size inside the solenoid is comparable to the magnet's inner radius. For the beam associated with the envelope shown in Fig. 5, its emittance growth given in Eq. (6) is small. The third term is the space charge terms

with backstreaming ion focusing, where I_0 is Alfvén current, I is the beam current, and f is the backstreaming ions' neutralization factor. The envelope solved by ENSOLVE is presented in Fig. 5. As shown in Fig. 5, AMBER [5] and ENSOLVE has similar beam envelopes in the final focus region.

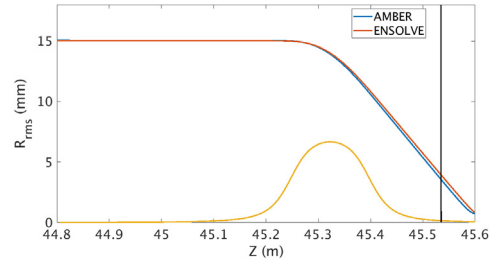


Figure 5: Comparison of beam envelope calculated by ENSOLVE and AMBER, where the vertical solid line is the location of target and the yellow curve is the solenoid field with strength in gauss/1000 for visibility.

Time Integrated Spots Size

At FXR, we have spent many efforts to benchmark the measured spot sizes at target with simulations. Using ENSOLVE, we calculate the rms spot sizes at the target for various time slices with their corresponding ion channels. Then, the simulated time-integrated spot sizes are calculated by using Eqn. 7

$$r_{rms} = \sqrt{\frac{1}{n} (r_{rms,1})^2 + (r_{rms,1})^2 + \dots (r_{rms,n})^2} \quad (7)$$

where $r_{rms,n}$ represents the rms spot size of the n -th beam slice. After obtaining the time integrated rms spot sizes, we can use it to obtain the time-integrated 50% MTF (Modulation Transfer Function) spot sizes.

For the FXR beam at the target, typically the time-integrated distribution is assumed to be Bennett distribution $g(r)$

$$g(r) = \frac{a^2}{2[a^2 + (r)^2]^{3/2}} \quad (8)$$

The rms spot size is given as

$$r_{rms}^2 = \int_0^{beam\ edge} g(r) * r^2 dr \quad (9)$$

The definition for the Modulation Transfer Function is by

$$MTF(k) = \frac{|F(k)|}{F(0)}$$

$$\text{where } F(k) = \int_0^r f(r) J_0(kr) r dr \quad (10)$$

Using these definitions, the correlations between the rms spot size and 50% MTF spot size defined as

$$50\% \text{ MTF spot size} = 4.4301/k_{50\%} \quad (11)$$

where $k_{50\%}$ is the spatial frequency at $MTF=0.5$. For Bennett distribution and Gaussian distribution, the 50% MTF spot sizes versus rms radii are plotted in Fig. 6. Using Fig. 6, we can easily convert the time-integrated rms spot size to the 50% MTF spot size for either a Gaussian or Bennett radial beam distribution.

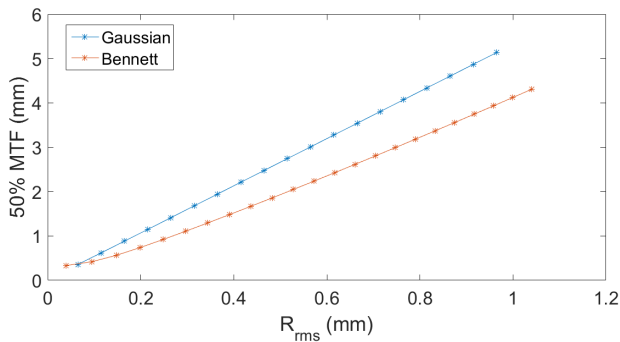


Figure 6: Calculated RMS spot size vs. 50% MTF spot size.

SUMMARY

ENSOLVE is a rms envelope code written to calculate the beam envelope in the entire accelerator. This paper specifically discusses the physics models included for the beam transport in the downstream section for flash x-ray radiography linear induction accelerator (FXR LIA), by including space charge depression potential, spherical aberration, emittance growth and focusing effects of back-streaming ions in the FXR final focus region.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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