DESIGN STUDY FOR THE RF PHOTOINJECTOR FOR THE MIT-BATES X-RAY LASER*

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Abstract

A multiple cell 1.3 GHz room-temperature photoinjector is under design for the MIT Bates x-ray laser project. The design features include tunable intercavity phase shifts allowing separate phasing of the cells for velocity bunching of the beam in the following drift, and optimization of cell shape for high shunt impedance and low wall power density. Beam dynamics are studied for charges ranging from 0.1 to 1 nC using a model, non-ideal laser profile shape. It is shown that collective effects at the high end of the range cause loss of beam brightness.

INTRODUCTION

MIT is studying the possibility of building an x-ray laser user facility [1] based on a seeded free electron laser. The facility would have up to 30 beamlines and be driven by a superconducting linac based on TESLA structures [2] producing a ~4 GeV electron beam. The range of wavelengths produced will be from 100 to 0.3 nm.

The current design foresees using a room-temperature copper RF photoinjector operating at repetition rates up to 10 kHz, and a cesium telluride cathode. Initial design of the RF structure using SUPERFISH is presented in the section below. Following that section, simulations of beam dynamics with the PARMELA code are presented.

These simulations differ from many others in that we do not assume the nearly ideal drive laser distribution having sub-ps rise and fall times and a flat top. The flattop distribution is ideal because it produces linear space charge forces that do not cause emittance growth or fast timescale modulation of the transverse and longitudinal electron beam properties. When the flattop distribution is used, the injector performance can be optimized by matching the beam onto the invariant envelope [3], which relies on linear space charge forces to perform emittance correction. The drawback to this approach is that the flattop distribution has been difficult to produce in practice, leading to photoinjector performance that falls short of simulation predictions. This is due to local in time modulations of the electron beam properties due to modulation of the initial charge distribution. Fig. 1 shows our model laser profile consisting of a distribution with both fast and slow modulation. The details of the modulation are less important than finding an operating mode for the injector that does not depend on the detailed distribution to meet its performance goals.

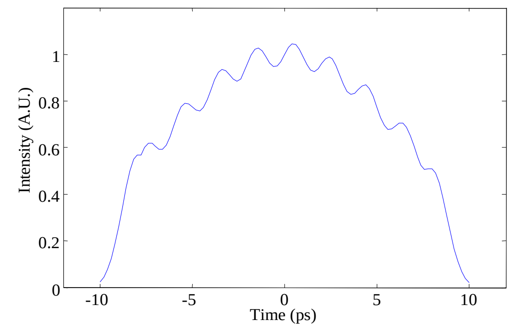

Figure 1: Model laser profile showing 2 ps rise time, and both slow and fast modulations. The fast modulation is +/- 5% amplitude with 2 ps period.

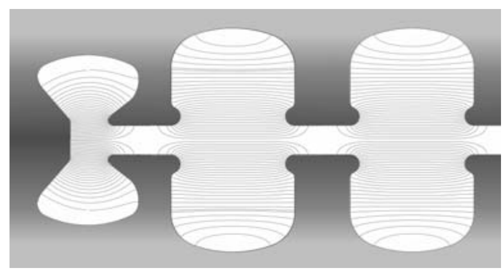

Figure 2: SUPERFISH model of 2 1/2 cell injector with short gap in 1/2 cell

RF STRUCTURE DESIGN

The shape of the 1.3 GHz RF structure is shown in Fig. 2. The cells are uncoupled, and each is independently powered to optimize its separate phasing and peak field. Cell shapes are designed to provide high shunt impedance and low peak wall power density. This is a high repetition rate injector, operating at up to 10 kHz. The important RF design parameters are summarized in Table 1.

Table 1: RF parameters.

Quantity	**½ cell**	**Full cell**
Peak gradient	80 MV/m	60 MV/m
Peak power	1.4 MW	2.7 MW
Max wall power density	41 W/cm^2	34 W/cm^2
Q	16140	27870
Rs*Q	151 Ohm	262 Ohm
r/Q	242 Ohm	224 Ohm

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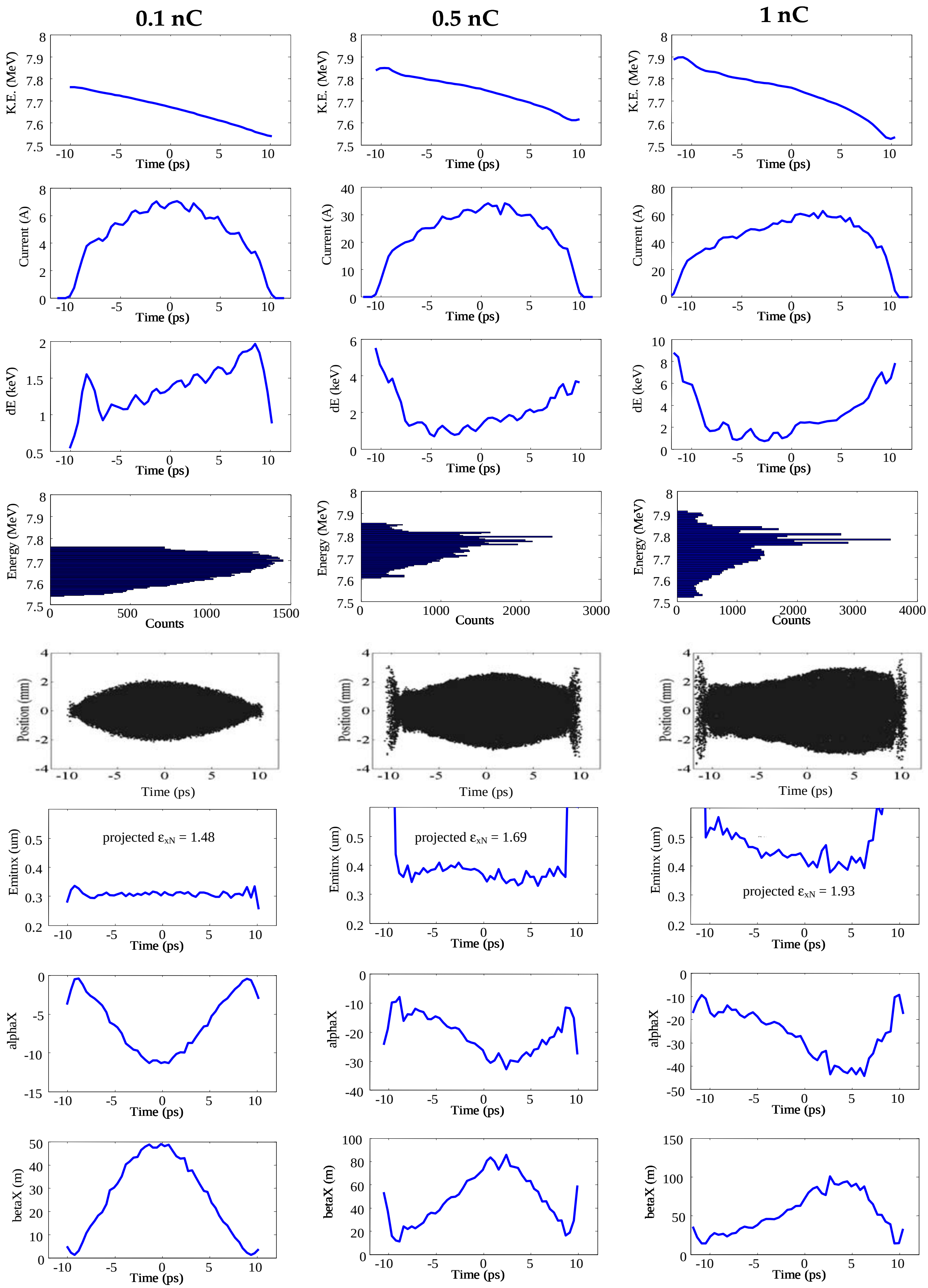

Figure 3: Left, middle, and right columns show electron beam properties vs timeslice for 0.1, 0.5, and 1.0 nC respectively. The slice beam properties evidently deteriorate due to space charge interaction as the charge is increased. Rows 1-4 show longitudinal beam properties, and rows 5-8 show transverse properties.

The power values in Table 1 assume 1% duty factor. The average current is low, approximately 1 μA, so that the structure is not significantly loaded by the beam. The re-entrant cavity design has better RF properties compared with the pillbox design in common use for RF photoinjectors. There has been some concern that the shapes create nonlinear radial fields that could cause emittance growth. In our studies, for beam sizes of ~2 mm, the fields are quite linear and no emittance growth is detected.

BEAM DYNAMICS

The initial beam distribution for each column of fig. 3 is shown in fig. 2. The charge was varied, but the initial pulse length and time profile held constant. The solenoid setting for each charge was adjusted to produce nearly optimum beam properties at the end of a 3 m drift following the injector exit. Each of the figures is of the beam properties at the end of this drift. The PARMELA input file was carefully constructed to vary the space charge mesh and time step to track the (nonrelativistic) birth of the beam from the cathode. Each run used 50k simulation particles with 100 longitudinal mesh points. The transverse distribution was uniform with a hard edge at 0.75 mm radius. Peak cathode gradient was 80 MV/m. The cells were phased for near on-crest acceleration. MATLAB code is used to generate the initial 6D distribution [4], including initial RMS normalized thermal emittance of 0.3 μm.

The linear correlation in energy and time (row 1 of fig. 3) was created by delaying the launch phase to give the bunch head a higher energy. This creates a distribution at the gun exit with symmetry in the Twiss parameters at the head and tail of the bunch (rows 7 and 8). Examining the plots in each column of fig. 3, the evolution of the slice bunch properties from non-space charge dominated case of 0.1 nC (left column) through the space charge influenced case of 1 nC (right column) is apparent. The energy/time plots in row 1 evolve from the highly linear correlation for 0.1 nC to a distorted, stair-stepped distribution for 1 nC. The steps are caused by the 5% fast modulation on the laser profile. Row 2 shows the current profiles. The original laser profile is reproduced accurately in the low charge case, but space charge has smoothed the 1 nC profile, resulting also in higher slice energy spread (row 3). The transverse beam properties are also strongly affected by the time modulations. The symmetric distributions shown in the low charge case of rows 5, 7, and 8 are due to time-varying RF forces. This distortion is repeatable and correctable [5] at high energy. The non-symmetric distortion for the high charge case is only partially correctable. In addition, while the 0.1 nC bunch preserves the 0.3 μm initial thermal emittance in each slice (row 6), the high charge case does not. This instantaneous emittance growth cannot be reversed through solenoid emittance correction. The projected normalized emittance printed on these plots also illustrates the large twist in phase space that occurs at high charge. This is the twist that emittance corrections schemes are designed to remove, however the asymmetries in the head and tail of the bunch complicate its application for this beam distribution.

The 6D beam brightness can be defined as

$$B = \frac{Q}{\varepsilon_{6D}}$$

where Q is the charge and ε_{6D} is the 6D normalized emittance defined as

$$\varepsilon_{6D} = \gamma^2 \sqrt{\det(\mathrm{cov}([x\ x'\ y\ y'\ t\ E]))}$$

in units of μm^2·ps·MeV. The 6D emittances for 0.1, 0.5, and 1 nC are 0.0054, 0.13, and 0.41 μm^2 ps MeV respectively, showing the much more compact phase space volume of the low charge case. The corresponding brightness figures are 18.5, 3.9, and 2.4 nC/(μm^2·ps·MeV) showing that the low charge case has a higher phase space density by nearly an order of magnitude despite an order of magnitude less charge. The key point is that by running the injector at low charge, the phase space is preserved even in the presence of an imperfect initial distribution. The parameters that are important for the FEL are emittance, energy spread, and peak current. The injector should be designed to produce best emittance and energy spread, while the peak current is generated by compression at high energy.

CONCLUSIONS

The RF design for an efficient 2 ½ cell photoinjector operating at kHz repetition rates has been presented. Beam dynamics studies that include a less than ideal laser distribution point toward operation of the photoinjector in a non-space charge dominated regime to preserve the initial low thermal electron beam emittance in the presence of time modulations.

ACKNOWLEDGEMENTS

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