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Beam Dynamics Studies in a High-Brightness Photo-Injector

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1. Introduction

A high-brightness photo-injector has been developed at Fermilab in collaboration with the TTF project at DESY. Two systems have been commissioned, one at DESY and one at Fermilab. The injector [1] consists of a 1.625-cell cavity RF gun, a superconducting niobium cavity (both 1.3 GHz), and a magnetic chicane. The gun is designed for an electric field of up to 50 MV/m on the cathode. Emittance compensation solenoids surround the gun to correct the linear space charge emittance growth. A high quantum efficiency Cs_2Te photocathode located in the first half-cell produces electrons when illuminated by 263 nm wavelength light (fourth harmonic of the Nd:YLF laser). The laser [2] was designed to produce a train of up to 800 equal amplitude, 10 μJ UV pulses spaced by 1 μs at 1 Hz repetition rate. The laser pulse length is adjustable between 1 and 20 ps FWHM. The superconducting cavity is a 9-cell Nb structure fabricated by industry for TTF. It was tested with RF at DESY before being sent to Fermilab. At present, the cavity is operated at $\sim$11 MeV/m.

Beam measurements with the injector at Fermilab are in progress. Preliminary results for emittance and bunch length will be discussed in this paper. Future plans for the machine will also be described.

2. Emittance Studies

The normalized vertical RMS emittance $\epsilon_{n,y}$ was measured at 135 cm from the exit of the 9-cell. We sampled the beam at this location with a movable mask consisting of 6 mm thick tungsten slats with 50 μm wide slits between them. The slits were 0.5 mm apart. While passing through the slits, the incident beam was cut into beamlets that were imaged on an aluminum mirror located 384 cm from the mask. The OTR light produced by the screen was viewed by a CCD camera. A program was written with MATLAB using [3] for emittance analysis. This program computes the normalized transverse RMS emittance, defined in the $y-y'$ plane by

$$\epsilon_{n,y} = \beta\gamma\sqrt{\langle y^2\rangle\langle(y')^2\rangle - \langle yy'\rangle^2} \tag{1}$$

where β and γ are the usual relativistic parameters. The emittance was measured for a train of 10 bunches at 1 Hz repetition rate. The charge per bunch was $\sim$1 nC. The radial dimension of the laser was σ_r = 0.8 mm and the longitudinal dimension was σ_t = 4.1 ps. The peak electric field on the cathode was 35 MV/m and the launch phase of the gun was 45°. The peak longitudinal magnetostatic field (produced by the combination of primary, bucking, and secondary solenoids) was 0.12 T. The phase of the

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9-cell was set to maximize the beam total energy (17.2 MeV). The measured normalized vertical RMS emittance was

$$\epsilon_{n,y} = 5.5 \pm 0.8 \text{ mm mrad}$$

PARMELA [4] calculations are in progress to simulate the beam line and for comparison to experimental results.

3. Bunch Length Measurement

The bunch length was measured with a 2 ps resolution streak camera. The beam was viewed via an OTR screen (100 nm of aluminum sputtered on a 50 μm polymide foil) located 3.5 m after the 9-cell. The streak camera was installed inside the bunker (surrounded by 15 cm of lead to avoid radiation damage), 1 m from the OTR screen. The light was brought from the screen to the streak slit with mirrors. We measured the length of a 5 nC bunch. The radial dimension of the laser was σ_r = 1.0 mm and the longitudinal dimension was σ_t = 4.1 ps (measured with the same streak camera). The gun and 9-cell amplitude and phase were the same as for the emittance measurement, as was the solenoidal field (0.12 T). For these parameters, we measured a bunch length of

$$\sigma_t = 7.1 \pm 0.2 \text{ ps}$$

Thus, the electron bunch length was measured to be larger than the laser pulse length. This experiment will be repeated.

4. Future Experiments

4.1. Photo-Injector Experiments

Transverse emittance measurements will be done as a function of charge, solenoid settings, launch phase, and laser diameter; measured emittance values at different z locations along the beam line will be compared. Additional bunch length measurements will also be done in conjunction with magnetic compression studies.

4.2. Bunch Length by Electro-Optic Sampling

The electric field of the passing 10 nC electron bunch is detected by the electro-optic effect. The polarization of a picosecond IR probe laser pulse is modulated as the laser pulse and the bunch's electric field ($\sim$1 MV/m) propagate colinearly in a $LiTaO_3$ or ZnTe crystal. By scanning the relative delay, the bunch length and temporal profile can be obtained. A single shot extension of this technique using a chirped probe laser pulse and a spectrometer is planned.

4.3. Channeling-Plasma Acceleration

An experiment is being prepared to investigate the upper intensity limit for the production of channeling radiation [5] by electrons interacting with a 18 μm Si crystal. It is the aim to explore channeling under extreme conditions and thus to use channeling as a test bench to study the basics of channeling-plasma acceleration [6].

4.4. Plasma Wake Field Acceleration

We plan to investigate plasma wake field acceleration in the underdense regime [7]. A plasma source capable of 1×10^{14} cm^{-3} density is now under development. The short, intense bunches (8 nC, σ_t = 1 mm, design) of the photo-injector can, in principle, yield very high acceleration gradients in the plasma, in excess of 500 MeV/m.

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