FIRST RESULTS OF THE FERMILAB HIGH-BRIGHTNESS RF PHOTOINJECTOR

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1 INTRODUCTION

A collaboration has been formed between FNAL, UCLA, INFN Milano, the University of Rochester, and DESY to develop the technology of an RF photoinjector, followed by a superconducting cavity, to produce high bunch charge (8 nC) with low normalized emittance (< 20 mm $\cdot$ mrad) in trains of 800 bunches separated by 1μs. The activities of the collaboration fall into two categories:

1. the development of Injector II for the TeSLA/TTF accelerator [1]. This photoinjector (*TTF RF Gun*) was tested at Fermilab in September and October 1998 and installed at DESY in November 1998.

2. the installation at the A0 Hall of Fermilab of a modified version of the TTF photoinjector, for photoinjector R&D and to study novel applications of high-brightness, pulsed electrons beams. This photoinjector (*A0 RF Gun*) produced its first beam in March 1999.

This paper presents a summary of the tests done at Fermilab on the TTF Injector II and the first results obtained on the new Fermilab photoinjector.

Table 1. Injector II Parameters.

Before compression	
Bunches per macropulse	800
Macropulse spacing	100 ms
Bunch spacing	1μs
Bunch charge	8.0 nC
Laser pulse length FWHM	28 ps
Beam radius at cathode	3.0 mm
Peak field on cathode (nominal)	35 MV/m
Beam total energy	18 MeV
Transverse emittance (normalized)	11 mm $\cdot$ mrad
Longitudinal emittance (100 % RMS)	820 deg-keV
Momentum spread	4.2%
Bunch Length	4.3 mm
Peak Current	276 A
After compression, from theory	
Transverse emittance (normalized)	15 mm $\cdot$ mrad
Bunch Length	1.0 mm
Peak Current	958 A

2 EXPERIMENTAL LAYOUT

The photoinjector consists of an RF gun with a high efficiency photocathode, driven by a Nd:YLF laser, followed by a 9-cell superconducting cavity and a magnetic chicane, composed of four dipoles, to compress the bunches. At the end of the beam line, a spectrometer magnet is used to measure the energy. The electrons are accelerated to 4-5 MeV in the gun and further accelerated to 14-18 MeV in the 9-cell superconducting cavity. The parameters of the photoinjector are summarized in Table 1. The upstream portion of the beam line is shown in Fig. 1.

2.1 RF Gun

The high duty cycle (1%) RF gun [2] consists of a standing wave structure with a one-and-a-half-cell cavity resonating in the π mode at a frequency of 1.3 GHz. The gun was designed to be operated at a nominal RF power of 4.5 MW for 800 μs at 10 Hz, which corresponds to an average power dissipation of 36 kW. The gun is cooled via channels machined into the walls, with 4L/s of water flow. In order to obtain a high brightness and low emittance beam, the emittance growth due to mainly linear space charge must be reduced. To reduce the linear space charge, a high gradient is used (E_c=50MV/m at 4.5MW and 35MV/m at 2.2MW) and, as required by the Carlsten emittance compensation scheme [3], a focussing solenoid (divided into a primary and a secondary solenoid) surrounds the gun, as shown in Fig. 1.

2.2 Laser

A Cs_2Te photocathode [4] located in the first half-cell of the gun produces photoelectrons when illuminated by a 263 nm wavelength light (fourth harmonic of the Nd:YLF laser). The laser [5] 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 to 1-20ps FWHM at Fermilab and to a longer length at DESY.

*Operated by the Universities Research Association under contract with the U. S. Department of Energy.

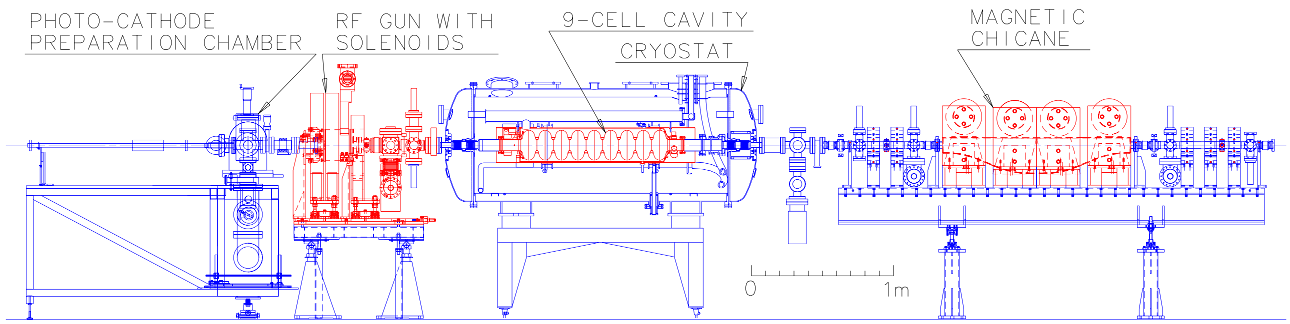

Figure 1. A0 beam line layout.

2.3 Nine-cell Cavity

The superconducting accelerating cavity is a 9-cell Nb structure [1]. Sub-systems include a high-power coaxial input coupler (Q_{ext} = 10^6 to $9 \cdot 10^6$), a cold tuner (range $\approx \pm$ 400 kHz), and 2 coaxial higher-order mode couplers. The cavity is a prototype fabricated by industry for TTF. It was etched, rinsed, heat treated, and tested with RF at DESY. The cavity is one of a batch with low quench field (13 MeV/m in CW for this cavity), attributed to contamination in the electron beam welds at the equator. The horizontal cryostat was designed at Orsay [6] for the TTF capture cavity and built by industry. The cavity and cryostat were assembled at Fermilab, cooled to 1.8 K, and tested with RF, as well as beam [7].

3 TTF RF GUN

Using a molybdenum cathode, the TTF RF gun was conditioned with an RF pulse of 3.4 MW (the maximum power available from the klystron) for 100 μs at 1 Hz repetition rate, providing an RF field of 44 MV/m on the cathode. At 800 μs, the peak power was limited to 2.8 MW at 1 Hz due to trips. Dark current associated with field emission was observed with a Faraday cup on an actuator located about 40 cm from the exit of the gun. The integrated Faraday cup signal indicated 0.4 mA of dark current with an electric field of 40 MV/m on the cathode. With a Cs_2Te photocathode, the gun was operated at 3 MW with 100 μs at 1Hz. RF trips limited the power to 2.2 MW at 800 μs and 1Hz. However, measurements with the Faraday cup showed a decrease of the dark currrent: 0.08 mA at 40 MV/m on the Cs_2Te photo-cathode.

The dark current was significantly smaller for the TTF gun than the first prototype gun [8]. The decrease may be explained by careful cleaning of the TTF gun and the installation in the beam line under a HEPA filtered laminar flow and by the use of a different type of spring around the photocathode.

Electron beam measurements were made at Fermilab on the TTF RF gun. Pulse trains of 800 bunches at 1 Hz with 0.3-0.4 nC per bunch were accelerated, as shown in Fig. 2. Other experiments with 1-10 bunches per train at 1-10 nC per bunch were carried out to characterize the gun. Phase scans of the gun showed a phase acceptance of 100°. The energy measurements were done with 35 MV/m on the cathode, producing electrons with a total energy of 4.3 MeV (according to the PARMELA code [9]); the 9-cell had an accelerating gradient of 14.5 MV/m. Electrons of total energy of 19.3 MeV were expected and measured at 18.5 MeV. The uncertainties in the measurement of the electric field and in the calibration of the spectrometer are sufficient to account for this difference.

4 AO RF GUN: FIRST RESULTS

After the modulator and the TTF gun were sent to DESY, the A0 RF gun was installed in its place, following the same procedures as for the TTF RF gun. A new modulator was installed at A0, with a maximum RF pulse length of 600 μs and 1 Hz repetition rate. It was operated with pulse lengths of up to 400 μs.

Thus far, we have been able to power the A0 RF gun with the maximum output of the klystron, i.e 3 MW, at 400 μs and 1 Hz. Dark current measurements were done with a Faraday cup at the same location as for the TTF RF gun. At 37 MV/m on the cathode (2.44 MW of forward power), a current of 0.05 mA and 0.06 mA was measured with the molybdenum and the Cs_2Te cathodes, respectively. The values of the dark current for the A0 RF gun are thus comparable to those of the TTF RF gun.

Preliminary measurements with beam in the A0 RF gun have been done. Phase scans were made, measuring the charge in the Faraday cup versus the phase of the RF relative to the laser. Results showed a phase acceptance of 100°. The phase that gave the maximum amount of charge was chosen for operation. Once the gun phase was fixed, we measured the energy of the beam versus the phase of the 9-cell (Fig. 3), with 35 MV/m on the gun and 7.8 MV/m of accelerating gradient in the superconducting cavity. The total energy of the beam was expected to be 12.4 MeV and we measured 13.7 MeV. As for the TTF RF gun, uncertainties in the calibration of the spectrometer and in the measurement of the field level are enough to explain this difference.

5 FUTURE EXPERIMENTS

5.1 Tests on the A0 RF Gun

Beam dynamics studies will be done on the A0 RF gun. The transverse emittance will be measured via emittance slits located after the quadrupole triplet. A quadrupole scan emittance measurement will also be carried out. A 2 ps streak camera will be used to measure the longitudinal emittance of the beam and the longitudinal compression of

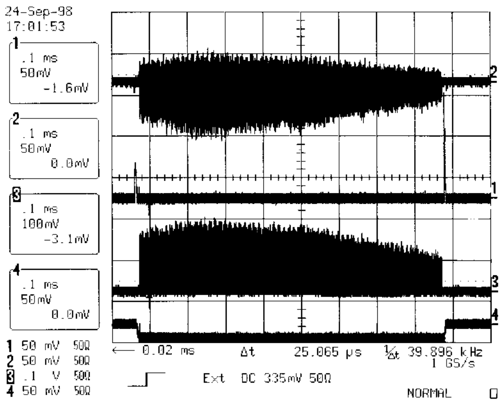

Figure 2. Scope traces for 800-bunch operation of the TTF RF gun, showing the laser photo-diode signal (channel 3) and the Faraday cup signal (channel 2).

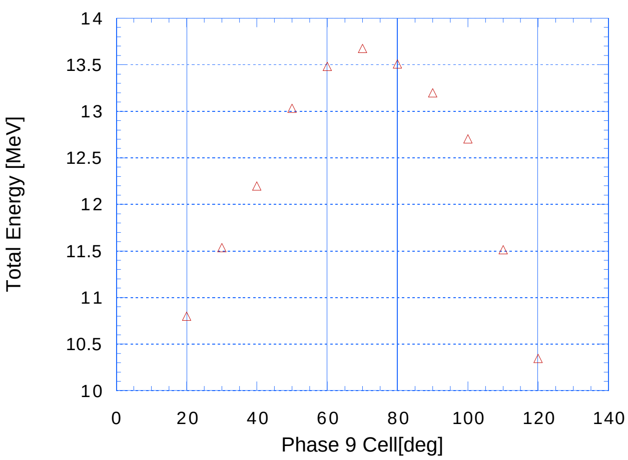

Figure 3. Energy of the beam versus phase of the superconducting cavity.

the chicane. These quantities will be measured as a function of beam parameters, charge, and solenoid strength, among others.

5.2 Bunch Length Measurement by Electro-Optic Sampling

The electro-magnetic field of a 10 nC electron bunch will be detected using the electro-optic effect [10]: the polarization of a picosecond IR probe laser pulse is modulated as the laser pulse and the beam field propagate collinearly in a $LiTaO_3$ crystal. By scanning the relative delay, the bunch length and temporal profile can be obtained.

5.3 Plasma Wake Field Acceleration

The photoinjector will be used to carry out a test of plasma wake-field acceleration. In this acceleration scheme, a high brightness relativistic electron beam is injected into a underdense plasma (having density less than the density of the beam). The plasma electrons are ejected from the beam's path to form an ion channel. A second bunch is injected at the correct time to be accelerated by the plasma wave, typically 1 ps after the drive beam pulse. In an underdense plasma, the plasma focuses and accelerates the second bunch. Gradients up to 1 GeV/m are expected.

5.4 Crystal Channeling Experiment

While gaseous plasma acceleration gradients can be very large, gradients from solid state plasmas could be even larger, in the range of 10 GeV/m. Solid state plasma acceleration conditions can be reached with the A0 beam. However, at the plasma densities required for acceleration, there are severe limitations. Crystal channeling has been discussed as a method to mitigate the problems associated with the solid state plasmas and also introduce focussing [11]. There have been no studies of the channeling process under these conditions. A Darmstadt-Fermilab group is preparing an experiment to observe channeling at A0 under conditions required for solid state acceleration. This experiment will look for quenching of channeling radiation as the bunch intensity is increased. If the initial experiment is successful, solid state acceleration may be attempted in a later stage.

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