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MEASUREMENT AND SIMULATION OF WHOLE BEAM BRIGHTNESS ON THE ETA-II LINEAR INDUCTION ACCELERATOR *

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Abstract

Measurement of beam radius as a function of focusing strength of an upstream solenoidal field allows simultaneous determination of the beam energy, brightness and tilt of the phase space ellipse. On ETA-II beam radius has been measured by analyzing foil emitted Cherenkov light with a gated (5 ns) image intensified CCD camera. The beam energy measurement is corroborated with a spectrometer magnet and core brightness with a two hole emittance diagnostic. For a 6 MeV, 1.6 kA beam, the whole beam brightness was measured to be 4.0×10^8 A/(m-rad)^2 with an inner core (few percent) brightness of 1.2×10^9 A/(m-rad)^2. The data was simulated with a particle transport code that includes the effects of energy sweep and magnetic misalignment. The code predicts a halo produced by an orbital resonance that is also observed experimentally.

Introduction

The Experimental Test Accelerator-II (ETA-II)[1] is the first induction linac designed specially to be used as a driver for a 140 GHz microwave FEL. The nominal beam parameters for these experiments are 6 MeV energy, 2 kA current, 1×10^8 A/(m-rad)^2 brightness, 20 ns pulse flat top at the wiggler with a pulse repition frequency of 0.5 Hz. In this paper we present the results of measurements and simulation of beam brightness on ETA-II. The 2-hole brightness measurement, the Cherenkov measurement and the energy measurement were all made in a single run for each injector configuration in order to get a reasonable comparison of the data. The Cherenkov data are simulated with two particle simulation codes. Good agreement is found between the computer simulation results and the experiment.

Experiments

ETA-II consists of an injector and six 10-cell blocks. Two injector configurations, the D-1 diode and the T-3 triode, with a 12.7 cm diameter cathode were used. The D-1 diode was designed to achieve 3 kA at 1 MV from the injector for the microwave FEL experiments. It was expected that the diode would have an inherent brightness less than the T-3 triode that was designed for high brightness for up to 2 kA of beam current. The brightness measurements at 2.5 MeV with the T-3 triode was reported in Ref. 2. No previous brightness measurements had been made with the D-1 diode.

The beamline configuration of ETA-II is shown in Fig. 1. The energy analyzer and the 2-hole brightness diagnostic rely on quadrupole focusing for imaging the beam. The solenoid lens F1 is also used for the 2-hole brightness measurements in order to obtain the needed focus at the first aperature. The energy analyzer measures the beam energy by measuring the deflection of the beam in a known dipole magnetic field.

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The magnetic field in the bending magnet is calibrated using a rotating coil gaussmeter that is accurate to better than 0.1%. The entrance angle to the bending magnet is determined from the offsets of the current monitors T2 and T3 which are in a field free drift space. Likewise, the exit angle is determined from the offsets of EA1 and EA2. The offset and the bending magnet data is combined to get the energy as a function of time.

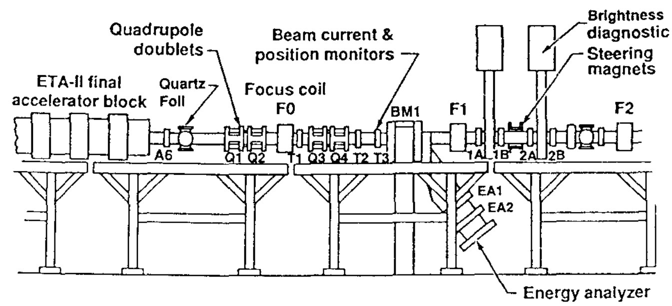

Fig. 1 ETA-II beamline configuration

The field-free, 2-hole emittance selector consists of two aperatures with 3 mm holes separated by 67.5 cm. The impinging current is I_1. The current tasnsmitted through the first aperture is I_2, and that through current through the second aperature is I_3. The configuration is the same as that used in energy measurements except that the apertures have been modified to be installed and removed remotely so that the beam can be characterized and then transported into the FEL wiggler. The normalized brightness is

$$J = \frac{I_3}{(\beta\gamma)^2 V_4 \delta} \quad , \tag{1}$$

where $\beta\gamma$ is the usual relativistic factor, V_4 is the acceptance of the collimator and δ is a space charge correction factor. The brightness measurements are made by focusing the beam current I_1 to obtain a waist at the center of the two apertures. About 125-150 A of current I_2 is transmitted through the first aperture. Steering and focusing of the beam onto the first aperture is aided by a fast-gated TV camera that views the beam image at the first graphite aperture. The sine/cosine steering coil set located between the two apertures is used to steer the beam onto the second aperture, and current I_3 is maximized with this steering.

The radial distribution of beam brightness was made at the same time by measuring the beam generated light intensity profile at the end of the accelerator as a function of the upstream solenoid magnetic field in the last 10-cell block. This allowed the beam energy, brightness and tilt of the phase space ellipse to be extracted from a self consistent fit to the focusing data. The excitation of the solenoid focusing field of the sixth ten cell block was varied from 30 to 280A. The beam profile was measured using a fast-gated image intensified CCD camera viewing the Cherenkov light generated in a thin quartz foil which is located 32.3 cm away from the end of the accelerator.

Energy Analyzer results

The energy measured 5.9 to 6.4 MeV over the main part of the pulse for the D1 diode configuration. The energy used for the brightness calculation is 6.2 MeV. This is the best match for the energy during the 5 ns gate-width of the TV camera and corresponds to a time near the peak of the I_3 current, though it is not possible to precisely measure the relative timing because of unknown propagation delays through different instruments such as the oscilloscopes and the TV cameras. The relative timing in the pulse is probably known to within 5 ns.

The T-3 configuration requires a higher injector volatge to obtain a 1.6 kA beam current. The individual accelerator gap voltages were reduced to compensate for the increase in injector voltage, however, the total beam energy is slightly higher. In this case the energy measured 6.4 to 6.7 MeV. The energy used in the 2-hole brightness calculation was 6.5 MeV. The energy from the Cherenkov data is 6.4 MeV for both the D-1 and T-3 configurations.

2-hole brightness measurement results

The results of the brightness meaurements for the D-1 diode and the T-3 triode are summarized in Table I. The beam energy used in the calculation of brightness is taken from the energy analyzer measurements. In both the D-1 and the T-3 sets of data the I_3 current is considerably narrower in time than the I_2 current. This is a result of the beam sweep induced by the corkscrew instability[3,4].

Table I. 2-Hole Brightness

Date	I_2(A)	I_3(A)	J(A/(m-rad)^2)	$1/\delta$	E(MeV)
D-1 injector					
12/06/89	148.7	14.9	9.0×10^8	1.15	6.2
12/06/89	129.2	14.3	8.4×10^8	1.14	6.2
12/06/89	140.7	14.0	8.4×10^8	1.14	6.2
T-3 injector					
12/18/89	144.4	24.5	1.40×10^9	1.18	6.5
12/18/89	138.0	21.3	1.20×10^9	1.16	6.5
12/18/89	135.0	21.0	1.17×10^9	1.16	6.5
12/21/89	129.8	15.3	8.30×10^8	1.13	6.5
12/21/89	129.2	14.7	8.00×10^8	1.13	6.5

Cherenkov measurement results

Analysis of the Cherenkov data (beam size versus upstream focusing solenoid field) at different light intensity contours unfolds the beam emittance, phase space tilt and energy as functions of radius. In the data analysis the beam is reconstructed at the beginning of the sixth cell block. The whole beam energy used in the analysis is 6.24 MeV for both configurations.

The whole beam brightness is

$$J = \frac{2I_1}{\pi^2\beta^2\gamma^2\epsilon^2} \quad , \tag{2}$$

where ϵ is the whole beam emittance. The Cherenkov light intensity is at its maximum on the beam axis. The light intensity within the 90% light contour represents the very inner core of the beam. If we assume that the beam has a parabolic four-volume distributrion function. then 97% of the beam is enclosed by the 10% light intensity contour. The 10% light intensity contour defines the beam edge. The beam current $I_4(r)$ is the current enclosed by a radius r. The core current I_c within the sub-ellipsoidal phase space associated with a betatron amplitude r is roughly the same as the current passing through the two slit emittance selector of aperture radius r. The core brightness J_c, core current I_c, and I_4 as functions of radius obtained from the analysis for the D-1 and T-3 configurations are given in Fig. 2. The brightness of the D-1 beam varies from 3.83×10^8 A/(m-rad)^2 at the beam edge to 1.14×10^9 A/(m-rad)^2 at the core to be compared with a value of 8.6×10^8 A/(m-rad)^2 measured by 2-hole emittance selector (Table 1). The brightness of the T-3 beam varies from 5.68×10^8 A/(m-rad)^2 at the beam edge to 1.71×10^9 A/(m-rad)^2 at the core. The core brightness measured by the 2-hole brightness diagnostic on the same day is 8.2×10^8 A/(m-rad)^2.

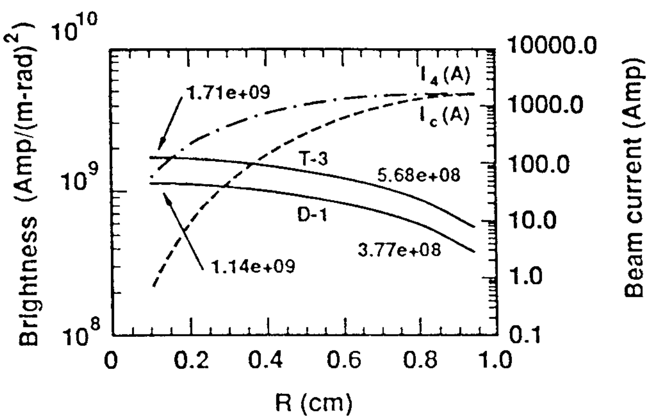

Fig. 2 Core brightness, core current I_c and I_4 as functions of radius obtained from Cherenkov analysis for the D-1 and the T-3 configurations

Simulations

The experimental conditions of the T-3 configuration on 12/21/89 were simulated with the DPC[5] and WIRE[6] codes. DPC was used to simulate the beam from the cathode to 20cm into the anode pipe. The WIRE code was then used to follow the beam through the six ten-cell blocks to the Cherenkov foil. In the simulations, we used the measured tilts of the cell block solenoids. The tilts of the intercell magnets were chosen such that the corkscrew amplitudes of a 1200 A, 4.6MeV beam calculated by the BREAKUP[7] code matched the experimental corkscrew amplitude[1] at all beam bug locations. The Cherenkov light was gathered over a 5 ns time slice. Typically, the beam energy changes 3% within a 5 nsec period[1]. In order to simulate the effects of corkscrew oscillations on the Cherenkov measurements, the WIRE code was run three times with 2000 particles with slightly different accelerating gap voltages for each given solenoid focusing current. The accelerating gap voltages were chosen such that the beam energy of each run differents by 1.5% with an average energy of 6.2 MeV. The particle data generated by these three runs are analyzed together in order to obtain the beam radius and brightness.

Simulation results

The WIRE code calculations indicate that some particle orbits are in resonance with the periodic magnetic structure in the first two 10-cell blocks. This resonance leads 20-25% of particles to walk away from the bulk of the beam and form a halo. The normalized beam emittance tripled within the first two 10-cell blocks. There is a large corkscrew motion for the 5 nsec beam segment. The large corkscrew motion and beam halo cause some current loss when the beam is defocused. The beam current at the Cherekov foil varies from 1350A to 1650A over the 50-280A focusing current range of the last 10-cell block. The images of the T-3 beam and the simulated beam agree very well.

Comparison between the beam sizes obtained from the simulations (dashed curves) and Cherenkov analysis (solid curves) is shown in Fig. 3. The locations of the minimum and maximum beam radius at the various intenisty levels agree between simulations and experiment. The simulated beam sizes are somewhat larger than that fitted from the Cherenkov light data. Only the light intensity data measured within ± 3 cm from the center of the beam in both the x and y directions were recorded in the experiments. When the beam is large and fills the image frame, the backgroud subtraction during the data processing will lead to an underestimated beam size. By applying this procedure to the simulation data, we found that the beam sizes at the 10% intensity contour were reduced by roughly 10%.

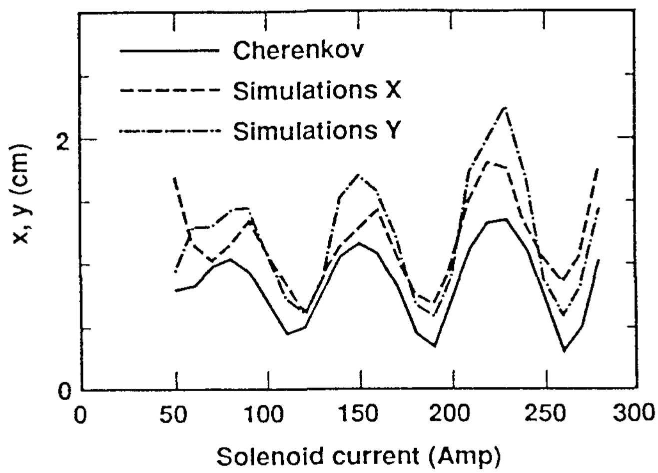

Fig. 3 Comparison between the simulated (dashed) and Cherenkov analysis (solid) beam sizes for the 10% beam intensity contours.

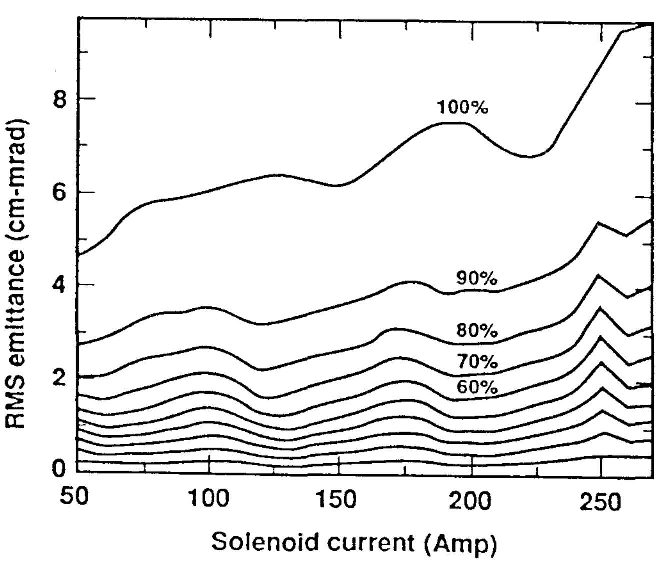

Fig. 4 Effective emittance versus focusing current for 10, 20, ... 90% of the beam current. The effective emittance increases as the focusing current in the last cell block moves away from 80 A.

The effective emittance[4] of the beam within a 5 ns slice is larger than the "instantaneous" beam emittance due to the presence of the corkscrew oscillations. The effective emittance increases when the corkscrew amplitude increases. If the solenoid focusing current in the last 10-cell block is very different from that in the fifth 10-cell block, the corkscrew amplitude increases due to the large transverse magnetic field at the intercell region. In the experiment the focusing current in the fifth 10-cell block is 81.93A. The simulations show that the effective emittance increases (see Fig. 4) and the effective brightness decreases as the focusing current in the last 10-cell block moves away from 80A. Ten curves of effective RMS emittance versus focusing current are plotted for 10, 20, ... 100% of the beam current. For the 80 A focusing solenoid current case, the calculated effective RMS emittance is 2.5 cm-mrad for 80% of the beam (enclosed by the 10% light intensity contour) and 5.7 cm-mrad for the whole beam. The edge emittance is four times of the RMS emittance for a parabolic beam. The Cherenkov analysis gives a value of 1.53 cm-mrad for the RMS emittance within the 10% light intensity contour. The brightness averaged over the 50-280A range of focusing solenoid current for 80% of the beam current (1280 A) is 1.37×10^8 A/(m-rad)^2 which is to be compared with a value of 5.75×10^8 A/(m-rad)^2 obtained from the Cherenkov analysis. The inner core brightness is 1.81×10^9 A/(m-rad)^2 from the simulations, 1.71×10^9 A/(m-rad)^2 from the Cherenkov technique, and 8.15×10^8 A/(m-rad)^2 from the 2-hole brightness diagnostic. By subtracting the beam halo of 20% current, the adjusted Cherenkov value becomes 4.60×10^8 A/(m-rad)^2 for 80% of the beam and 1.37×10^9 A/(m-rad)^2 for the inner core.

Conclusions

The whole beam brightness measured by the Cherenkov technique on ETA-II ranges from 3.8×10^8 to 6.8×10^8 A/(m-rad)^2 for both injector configurations operating at about a beam current of 1600 A. The beam core brightness from the Cherenkov analysis ranges from 1.1×10^9 to 2.0×10^9 A/(m-rad)^2 to be compared with the 2-hole brightness diagnostic values of 8.15×10^8 and 1.4×10^9 A/(m-rad)^2. The WIRE code predicts a halo caused by a parametric instability of particle orbits that is also observed experimentally. Simulations show the ETA-II beam experienced large corkscrew oscillations within the 5 ns time slice of the experiment. In general, parametric instabilities are relatively easy to avoid simply by adjusting the parameters of the machine such as the magnetic tune and beam energy. Studing the ETA-II tune theorectically before running the experiments will allow us to avoid parametric instabilities[8].

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