FAST RISETIME MAGNETIC FIELD COIL FOR ELECTRON BEAM PROPAGATION STUDIES

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Abstract

A new method for detuning the betatron frequency of an intense relativistic electron beam is investigated. The method employs a fast rising magnetic field to decrease the beam radius from the head to the tail of the beam. The magnetic field rise time is on the order of 30 ns with a peak value of about 2 kiloGauss. This method may be useful for detuning intense beam instabilities associated with betatron oscillations.

I. INTRODUCTION

Radius tailoring provides betatron detuning for reduction of the growth rate of hose instability. The betatron wavenumber is a function of beam radius R:

$$k_\beta = \left(\frac{I_b}{I_A}\right)^{\frac{1}{2}} \frac{1}{R},$$

where I_b is the beam current and I_A is the Alfven current. The equilibrium (self-pinched) beam radius R_{eq} is a function of normalized emittance $\epsilon_n^2(\zeta)$:

$$R_{eq}^2(\zeta) = \frac{\epsilon_n^2(\zeta) + P_\theta^2(\zeta)}{\gamma^2 I_b \, / \, I_A}, \qquad (2)$$

where ζ is the distance from the beam front and P_θ is the mean canonical angular momentum. Emittance tailoring, therefore, provides radius tailoring, by changing the equilibrium radius, R_{eq}, for the propagating beam.

In this experiment, a magnetic focusing field is used to confine the beam radius preferentially in the beam body and tail, while allowing the beam head to expand due to the beam space charge. This could potentially produce a controllable radius tailor in the beam, however this tailor may not survive further propagation. In order to produce a true emittance tailor the beam may then be passed through a foil to increase the transverse energy by scattering and "freeze" this emittance variation in the beam. This variation of ϵ_n in ζ guarantees the production of a tailor of $R_{eq}(\zeta)$.

The magnetic field is produced by a single turn which is energized by a high voltage pulse-forming-line. The fast variation in magnetic field occurs during the rising portion of the pulse. The risetime is in general determined by the inductance of the coil and the impedance of the pulse-forming line.

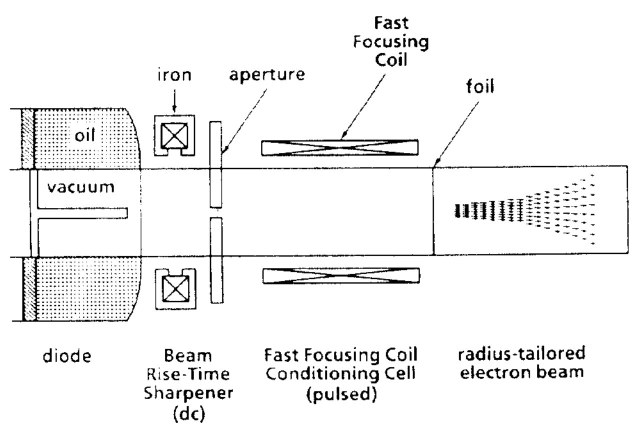

Fig. (1). Magnetic beam conditioning experiment concept.

II. EXPERIMENTAL ARRANGEMENT

Figure (1) provides an overview of the experiment: the Febetron diode, the Beam Rise-Time Sharpener[1] (BRTS), the fast focusing coil (FFC), and the foil. The Febetron

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705X produces a 2 MeV, 7 kA, 20 ns FWHM beam with voltage and current pulse shapes that are approximately triangular.

The BRTS consists of a dc focusing magnet and a graphite aperture: it sharpens the beam rise time to 6 ns with a 12 ns flattop at 3 kA. The operates on the principle of a magnetic lens. The magnetic field is adjusted so that only the highest energy electrons will be focussed to traverse the aperture. Since there is an instantaneously small energy spread in the beam, the lower energy, and lower current rise time portion of the electron beam will be lost.

The FFC conditioning cell consists of a nonmetallic vacuum drift chamber with axial current return bars and the external, single-turn FFC. The portion of the vacuum system surrounded by the FFC is made of glass with copper strips running axially along the inside. These strips provide a current-return path for the electron beam current and allow penetration of the FFC magnetic field to the axis of the system. The FFC is a 38 cm long, 20 cm diameter single turn to minimize inductance, thereby minimizing the rise time of the magnetic field.

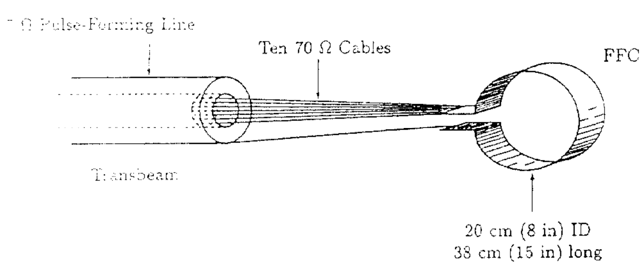

Fig. (2). Transbeam driven fast-focusing coil.

The FFC power source is Transbeam,[2] a 7-Ω machine that has been used to produce a 700 keV, 100-ns electron beam. The electron beam diode has been removed and the machine is used to drive current through the FFC. A transition section connects the end of Transbeam's 7-Ω coaxial transmission line to ten 70-Ω high-voltage (rated at 300 kV dc) coaxial cables, as shown schematically in Fig. 2. These ten cables allow flexibility in positioning the FFC relative to Transbeam. This makes it easier to use the FFC with an electron beam that is produced by another machine, such as the Febetron 705X. The ten cables are connected to the FFC, with the center conductors (#4 AWG) connected to one side of the coil and the outer conductors (braid) connected to the other side.

III. INITIAL DESIGN CALCULATIONS

The maximum magnetic field required is given by the magnetic focusing condition

$$B(kG) \geq 3.4\frac{1}{r_b}\left(\frac{\nu}{\gamma}+\frac{2\gamma T}{m_o c^2}\right)^{\frac{1}{2}} \tag{3}$$

where r_b is the beam radius, ν is Budker's parameter, and T is the beam transverse temperature. Using the Febetron 705X parameters, the magnetic field requirement is 1.2 kG or higher.

It is straightforward to calculate the current needed for the required magnetic field. For a single-turn, long cylindrical coil, a magnetic field B is produced by a surface-current density J_s (A/m), approximately given by $B = \mu_o J_s$. The total current required is $I = J_s l = Bl/\mu_o$, where l is the length of the cylindrical coil. For $B = 1.2$kG, $I = 40$ kA.

The inductance of the FFC determines a lower limit on the rise time of the magnetic field. The inductance is approximately $L = BA/I = \mu_o A/l = 110$nH, where A is the cross-sectional area of the coil; the lower limit on the rise time is $\tau = L/R = 16$ ns. This is sufficiently fast to change the magnetic field during the electron beam pulse.

To predict the field-free radial expansion of the beam head, the beam envelope equation,[4]

$$\frac{d^2R}{dz^2}=\frac{I_b}{\beta^2\gamma^2 I_A R}+\frac{\epsilon_n^2}{\beta^2\gamma^2 R^3}, \tag{4}$$

where r is the beam radius and z is the axial distance, is solved numerically. This provides a value for the radius of the beam head R_h. The radius of the beam tail R_t is confined by the FFC to the initial value of the beam radius at the diode.

The emittance tailoring ratio (the ratio of the emittance of the beam head to the emittance of the beam tail) ϵ_h/ϵ_t, after the conditioning cell, is given by

$$\frac{\epsilon_h}{\epsilon_t}=\left(\frac{\epsilon_o^2+\gamma^2\langle\theta_s^2\rangle R_h}{\epsilon_o^2+\gamma^2\langle\theta_s^2\rangle R_t}\right)^{1/2}, \tag{5}$$

where ϵ_o is the initial beam emittance and $\langle\theta_s^2\rangle$ is the mean-square scattering angle from a foil. For our experimental parameters, including a 1 mil (25 μm) titanium scattering foil and an initially cold beam, Eq. (4) can be approximated by $\epsilon_h / \epsilon_t \approx R_h / R_t$. The predicted emittance tailoring ratio for the Febetron beam with the BRTS is 4:1.

Preliminary circuit simulations have been done to model Transbeam and the fast focusing coil. The voltage and current waveforms of Transbeam in the model resemble experimental waveforms from electron beam experiments in the past. The ten 70-Ω cables were represented by a lumped circuit-element model and the single-turn FFC was modeled as a very low resistance. The results indicate that a 10 ns Transbeam rise time produces a FFC rise time of 15 to 20 ns and that 200 kA could be put through the coil. This agrees well with the analytic calculations above.

The magnetic field was measured with B-dot probes at reduced initial charging voltage. The results shown in Fig. (3), agree with the analytic calculations and circuit simulations.

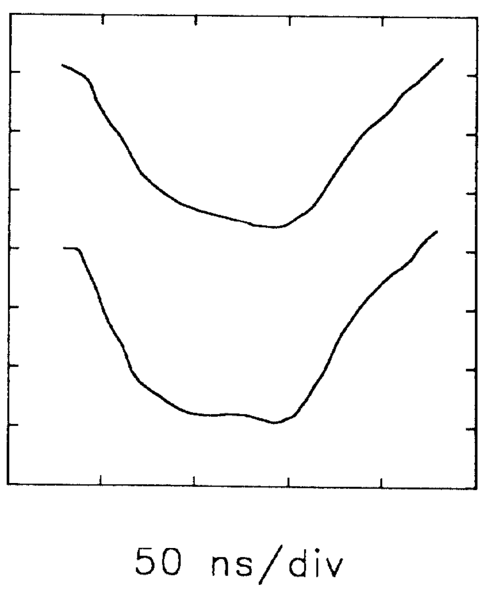

Fig. (3). Current through and magnetic field inside the fast coil. Top trace is current through the coil (10 kA/div) and bottom trace is magnetic field on axis (0.4 kG/div).

IV. STATUS

The FFC has been tested without an electron beam. Testing consists of firing Transbeam into the coil and mapping the magnetic field. The program plan is to test the FFC with an electron beam from the Febetron 705X electron beam accelerator and observe the radii of the beam head and tail. Time-resolved diagnostics will determine parameters such as the beam radius and emittance,[5] by using a slit or an array of slits, a fast detector (scintillator or Cherenkov) and a streak camera, and a segmented Faraday cup.

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VI. REFERENCES

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[1] J. D. Miller, K. T. Nguyen, R. F. Schneider, K. W. Struve, H. S. Uhm, and D. J. Weidman, "Pulse-Shaping a High-Current Relativistic Electron Beam in Vacuum," Naval Surface Warfare Center Technical Report 90--268, (1990).

[2] J. R. Smith, R. F. Schneider, M. J. Rhee, H. S. Uhm, and W. Namkung, J. Appl. Phys. 60, 4119 (1986).

[3] B. Goplen, L. Ludeking, J. McDonald, G. Warren, and R. Worl, MAGIC User's Manual, (MRC, Va. 1989) Unpublished.

[4] E. P. Lee and R. K. Cooper, Part. Accel. 7, 83 (1976).

[5] R. F. Schneider, E. H. Choi, H. I. Cordova, J. R. Smith, D. J. Weidman, M. E. Moffatt, K. T. Nguyen, and H. S. Uhm, "Time-Resolved Measurement of Intense Relativistic Electron Beams," Bull. Am. Phys. Soc. 33, 1951 (1988).