STUDY OF MISALIGNMENT EFFECTS IN ELECTRON BEAM TRANSPORT THROUGH A PERIODIC SOLENOID CHANNEL*

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Abstract

Recent studies on the Maryland 36-lens electron beam transport experiment had indicated that the fraction of beam transported and the emittance depended strongly on the alignment state of the channel. As a result, the channel lenses were realigned and an adjustment system was built for the electron gun. We report the first experimental results on beam transport through the realigned system. A major improvement in beam centering has been achieved resulting in 100% beam transmission for a wide range of lens magnetic field strengths. The emittance growth observed in this region will be compared with simulation results.

Introduction

The major goal of the electron beam transport experiment at the University of Maryland is to study the physics of space-charge dominated beams propagating through long, periodic transport channels. In our case, the transport channel consists of 38 solenoid lenses two of which are being used to match the beam from the gun into the periodic lattice, and the electron beam parameters are typically 5 kV and 160-240 mA.

Past experiments with only 12 lenses had shown[1] that there was a relatively large window of 100% beam transmission of $45^0 < \sigma_o < 110^0$, where σ_o is the phase advance of the transverse oscillations per period without space charge. Furthermore, the emittance growth was only about 30%, independent of σ_o within this range. (Note that σ_o increases with the magnetic field strength of the lenses.)

First experimental results in the full 36-lens channel, reported at the 1985 Particle Accelerator Conference[2] indicated that considerable beam loss occured in the longer system. Full beam transmission was observed only near $\sigma_o = 70^0$. A major clue for this beam loss was found in the fact that the beam emerged from the 36-lens system off-centered by as much as 1-7 mm depending on σ_o. We concluded that this effect was due to misalignments and injection errors and decided to improve the alignment state of our transport experiment.

The first phase involved the construction of an alignment system for the electron gun and the two matching lenses to permit changing of the beam injection angle and position. This resulted in considerable improvements with 100% beam transmission occurring in the interval $65^0 < \sigma_o < 80^0$, as reported at the 1986 Heavy Ion Fusion Symposium.[3] However, the window of full beam transmission was still smaller than in the 12-lens system.

The second phase which was just completed, consisted of realigning all lenses in the system. The technique used involves the accurate determination of the magnetic field axis of each lens, as will be described below.

The conclusion that beam transmission depends very sensitively on alignment errors and the length of the channel is consistent with the "random-walk" theorem. Applied to a periodic focusing channel with N lenses randomly displaced by an rms value $\bar{x}_\ell$ from the ideal center line, the theorem implies that the beam off-centering $\bar{x}_c$ increases with the number of lenses and $\bar{x}_\ell$ as $\bar{x}_c = \bar{x}_\ell(N)^{1/2}$. Thus, if the rms alignment error of the lenses is $\bar{x}_\ell = 0.5$ mm, then the beam off-centering is 1.5 mm after 9 lenses and 3.0 mm after traversal of 36 lenses. The application of this random-walk theorem to our beam transport channel is under investigation.

Emittance Measurements before Realignment of Lenses

Prior to disassembling of the system for realignment of the lenses, the emittance of the electron beam was measured for two values of σ_o. Emittance values were determined using an improved computerized data-gathering system and a data-reduction program which assumes Maxwellian velocity spread and a non-uniform current density which closely simulates experimental conditions.

An electron beam is produced by a converging Pierce-type gun with a cathode radius of 12.7 mm. The gun is typically operated at 5 kV, 160 to 240 mA, 2 μs pulse length with a 60 Hz repetition rate. The diagnostic chamber at the end of the 36-lens channel contains the slit-pinhole system which is schematically depicted in Fig. 1. The slit is constructed from 0.05 mm thick tantalum foil with a slit width 2d = 0.25 mm. In the collector plane, which is at a distance L = 108 mm from the slit, a Faraday-cup assembly with a pinhole of diameter $2r_p = 0.1$ mm scans across the beam in the x-direction. The cup is mounted on an XYZ manipulator which, in turn, is driven by a computer-controlled stepper motor. Figure 1 shows in schematic form a beam profile measured with the Faraday-cup pinhole when the slit is located a distance x_o from the beam axis and the distribution is Gaussian in transverse angles $x' = \xi/L$. The mean angle $\bar{x}' = \eta$ is defined by the peak of the curve while the rms width of the distribution is measured by the parameter α, as illustrated in the figure.

An Apple IIe controls the stepper motor which employs a separate closed-loop feedback system to accurately drive the pinhole-cup assembly to within ± 0.02 mm. The signal from the charge collector is displayed on a Tektronix 2430 digital scope. The Apple then extracts the pertinent information from the scope trace and stores the current density for the present pinhole position in memory before proceeding to the next pinhole position.

Following the method described by Rhee and Schneider,[4] we assume that the beam distribution function $f_4(x,x',y,y')$ can be written as

$$f_4 = \frac{n(r)}{\sqrt{2\pi}\,\alpha(r)} \exp\left\{-\frac{[x' - \eta(r)x/r]^2 + [y' - \eta(r)y/r]^2}{2\alpha^2(r)}\right\}$$

From this relation, one can obtain the two-dimensional distribution $f_2(x,x')$ by numerically integrating over y and y'. Then one calculates the second moments $\langle x^2\rangle$,

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$\langle x'^2 \rangle$, and $\langle xx'^2 \rangle$ and the effective emittance of the beam defined as

$$\bar{\varepsilon} = 4\, \varepsilon_{rms} = 4\, (\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2)^{1/2} \, .$$

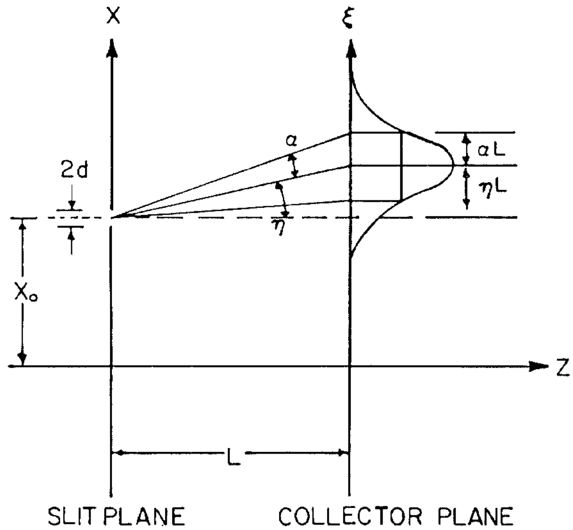

FIG. 1. Geometry of the slit-pinhole method.

The functions $\alpha(r)$, $n(r)$, and $\eta(r)$ can be determined by assuming that all measurements are taken at $y = 0$ so that $n(x,0) = n(r)$ and similiarly for the other functions.

The emittance of the beam at the electron gun has not been measured, but we know from past studies[1] that it is within about 10% of the theoretical inherent emittance of $\bar{\varepsilon}_i = r_c (2kT_c/eV_o)^{1/2}$, where r_c is the cathode radius, T_c is the temperature of the cathode and V_o is the accelerating voltage. In our studies kT_c was 0.11 eV yielding $\bar{\varepsilon}_i$ = 0.085 mm-rad.

Table I. Results of Emittance Measurements before Realignment of Lenses.

σ_o	Injected Current (mA)	Transmitted Current (mA)	Measured Emittance $\bar{\varepsilon}_f$ (mm-mrad)	Ratio $\bar{\varepsilon}_f/\bar{\varepsilon}_i$
56^0	160	154	134	1.58
70^0	160	154	143	1.68

Table I summarizes the emittance measurements done before the system was realigned at two values of σ_o (56^0 and 70^0). Note that transmission was less than 100% because the beam matching conditions were not fully optimized due to restrictions imposed by the data-gathering system. The measured emittance values at the end of the channel are between 60% and 70% larger than the intrinsic emittance of the injected beam.

C. R. Prior of the Rutherford-Appleton Laboratory just completed a computer simulation run for the $\sigma_o = 70^0$ case using a perfectly aligned system. He found[5] an emittance increase of $\bar{\varepsilon}_f/\bar{\varepsilon}_i$ = 1.8 which is slightly higher than the measured value obtained with our misaligned system. On the other hand, first results obtained by Rudd, Haber, and Reiser with a newly developed code[6] show an emittance growth of only 1.25 in a perfectly aligned system. These differences are not understood at this time.

Lens Realignment Procedure

The symmetry properties of the solenoid lens magnetic fields were exploited to align the lenses to a common axis defined by a surveyor's transit. In Fig. 2, the principle is illustrated schematically. A transverse Hall probe is rotated about the transit-defined axis at several principal points within the lens bore. The radial field peaks near the pole-piece edges. If the probe's axis is displaced from the symmetry axis, then the detected field varies as the probe is rotated. If the probe is stationed at the lens center where the field lines are parallel to the symmetry axis, the signal from the probe is sensitive to lens pitch and yaw relative to the probe rotation axis.

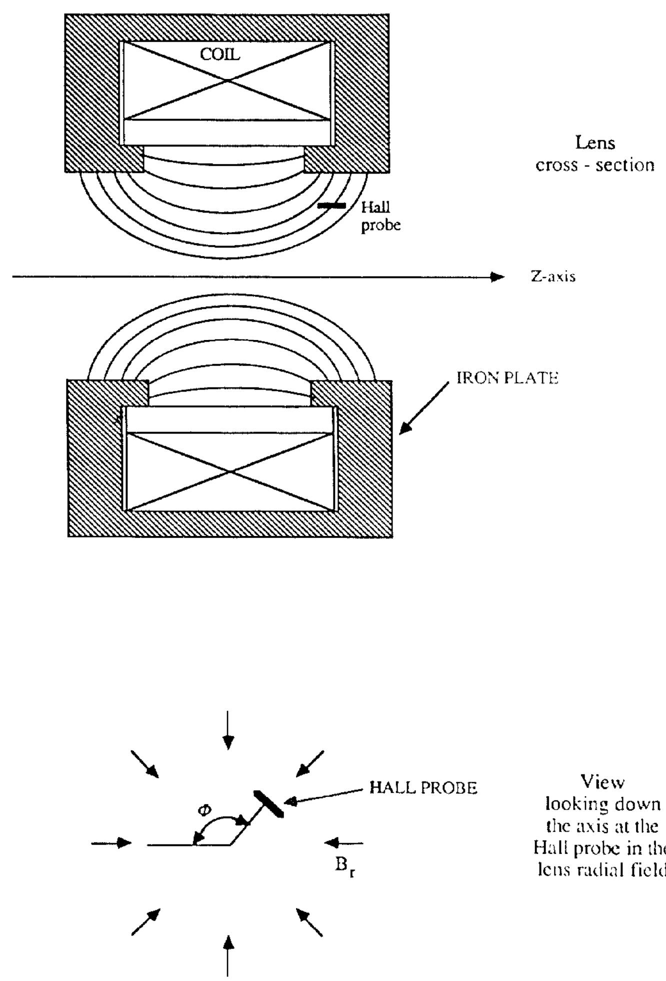

FIG. 2. Principle of the Hall Probe Field Line Finder (HAPROLIF) technique. The probe is placed near maximum of B_r (top) and rotated with azimuth (bottom); field variation is zero when lens magnetic axis and axis of probe rotation coincide.

The alignment procedure starts with the probe placed at the lens center to adjust pitch and yaw. In this step the alignment accuracy of ± 1 m-rad was limited by the lens mounting mechanics. Next the probe is stationed at a radial field maximum, and the lens is translated until there is no variation in signal with probe rotation. Here the lens mounting mechanics limit the accuracy of translational alignment to ± 200 μ. A typical plot of field strength versus angular position of the probe before and after lens alignment is given in Fig. 3.

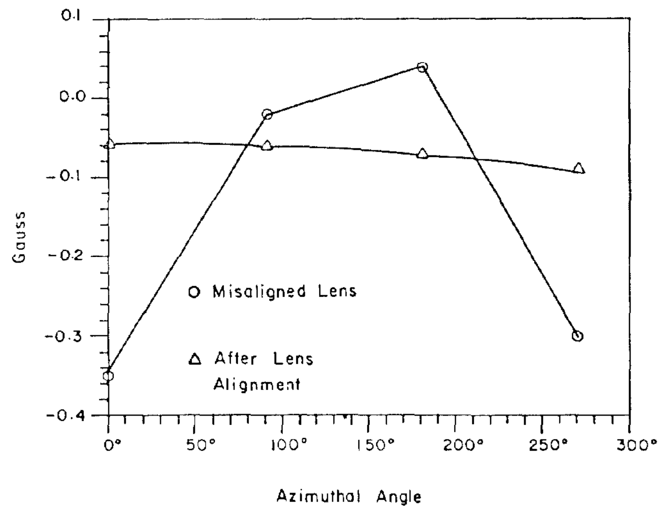

FIG. 3. Typical radial magnetic field versus azimuthal angle measured by Hall probe before and after lens alignment.

The probe rotates about a pair of hollow axles, each mounted in gimbals temporarily anchored in a lens bore. Fine cross hairs placed over the axle ends mark the center of rotation. The axle ends can be translated to the transit sight by operating screws which adjust the gimbals' position. Axial motion of the probe is achieved by pushing the probe on a trolley along a precision track supported by a tube which extends through six lenses.

This instrument, called Hall Probe Field Line Finder (HAPROLIF), was also used to measure the residual fields between lenses and the straightness of the symmetry axes of the lenses. The alignment precision was limited by the mounts rather than the wiggle of the symmetry axis, to about 50 μ.

Since weights of a few pounds could significantly bend the lens table, the alignment of the system was performed with the table loaded the way it would be during operation.

First Beam Transport Results with Realigned Lens System

The realignment of the lens system was completed by the end of February 1987. We also replaced the cathode assembly of our electron gun and discovered that the old cathode assembly was tilted with respect to the symmetry axis due to the weakening of alignment washers. This tilt undoubtedly contributed to the difficulties we had encountered in centering the beam.

First results with the realigned system and the new cathode assembly show a dramatic improvement of beam transmission efficiency. This is evident in Fig. 4, where we plotted the fraction of beam transported through the channel versus σ_o. For comparison, we also show the previous curves of 1985 and 1986. Note that the window of 100% transmission has increased to $55^0 < \sigma_o < 90^0$, with significantly higher currents transported through the channel above 90^0. At $\sigma_o < 50^0$ the beam transmission is less than in the 1986 experiments. We attribute this mostly to the higher current, hence larger beam radius with our new cathode: 220 mA versus 160 mA before. At values of σ_o near 40^0, the beam size becomes comparable to the tube diameter, and the loss in this region is thus mostly a geometrical effect.

We also started to measure the beam off-centering. The first results indicate that the amplitudes of the coherent radial oscillations have decreased by a factor two to three. This explains the improvement in the transmission curve and indicates that the realignment project has achieved its goals. More detailed studies are planned in the near future to find the best injection conditions for optimum beam transport. Emittance measurements are also being planned with the new system, and we hope that the differences between the two computer codes and between codes and experiment mentioned above can be resolved.

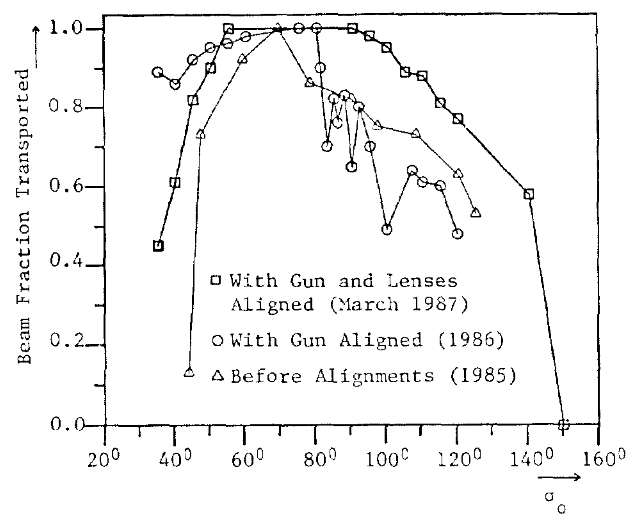

FIG. 4. Fraction of transported beam measured with realigned lens system, compared with previous results (1985 and 1986).

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