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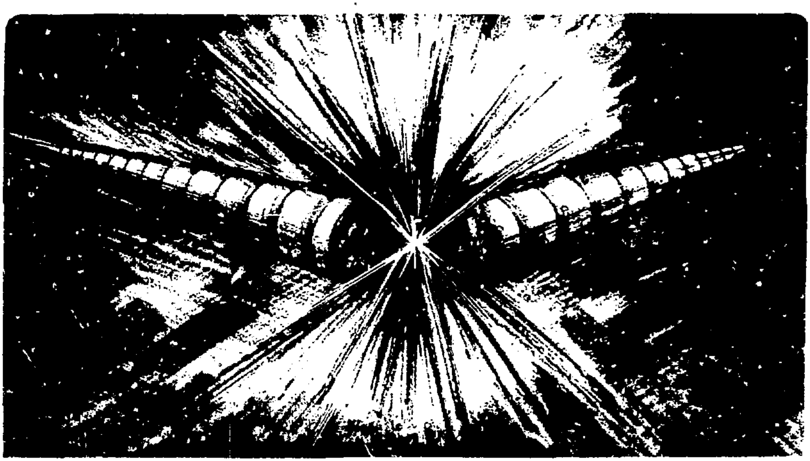

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Summary

A Cs ion-beam-transport experiment is in progress to study beam behavior under extreme space-charge conditions. A five-lens section matches the beam into a periodic electrostatic quadrupole FODO channel and its behavior is found to agree with predictions. With the available parameters (≤200 keV, ≤20 mA, $\pi\epsilon_n > 10^{-7}$ π rad-m, up to 41 periods) the transverse (betatron) oscillation frequency (ν) can be depressed down to one-tenth of its zero current value (ν_0), where $\nu^2 = \nu_0^2 - \omega_p^2/2$, and ω_p is the beam plasma frequency. The current can be controlled by adjustment of the gun and the emittance can be controlled independently by means of a set of charged grids.

Background

Since Maschke[1] first pointed out that an upper limit on beam current may exist in a quadrupole transport channel, extensive computational studies based on the Kapchinskij-Vladimirskij (K-V) distribution and numerical simulation studies using particle-in-cell (PIC) codes[2] have taken place.

An understanding of how intense beams with high optical quality can be safely transported is of vital importance for the design of an inertial confinement fusion system based on a heavy-ion accelerator driver.[3] Depending on whether the understanding of the transported current limit turns out to be either pessimistic or optimistic, so too will the complexity of the final beam-transport to the fusion target become relieved or further aggravated. In addition, a driver based on linear induction acceleration is best suited to operating near the space-charge limit throughout the length of the device; the design (and cost) of such a driver depends significantly on a knowledge of the transport-limited current.[3]

Some years ago, we proposed a test of the relevant physics using a quasi-dc cesium ion beam with an energy close to 2 MeV — and a current of 1 ampere[4] passing through a sequence of electromagnetic quadrupoles; for reasons of cost the experiment was abandoned. Instead, the present experiment, which uses a 200 keV Cs^{+1} beam, was instituted and the quadrupoles were chosen to be electrostatic rather than electromagnetic simply because of their lower cost, albeit greater inconvenience. Interest in the same physics has prompted related experiments.[5-7] The classic experiment on Brillouin flow by Brewer is also relevant.[8]

Statement of the Problem

In a quadrupole focussing channel with a single-particle betatron angular frequency ν_0 — corresponding to a phase advance of σ_0 per period — the presence of space charge results in a reduction of the restoring force so that particles have a decreased frequency and phase-advance denoted by ν and σ respectively. (Magnetic and relativistic effects are ignored since the main interest here is for very slow heavy-ion beams.) In the "smooth approximation" the relation between ν and ν_0 is given by

$$\nu^2 = \nu_0^2 - \frac{1}{2}\omega_p^2 , \tag{1}$$

with $\omega_p^2 = \frac{4\pi ne^2}{M}$, the square of the beam plasma frequency, where n is the number of ions per unit volume. (More realistic considerations show that the coefficient 1/2 is not exact, but depends on lattice parameters.) For constant gun voltage, ω_p^2 is directly proportional to the current density, j = nev.

Clearly, Eq. 1 predicts that an absolute limit on current density exists when $\nu \to 0$, i.e. $\omega_p \to \sqrt{2}\,\nu_0$, and the net restoring force vanishes. As one nears that limit, the current density remains constant, and as the current is increased the area of the matched beam increases proportionately. Generally, the beam size depends on both the emittance (normalized), $\pi\epsilon_N$, and the beam current. Absent from the discussion so far, is the prediction of classes of instabilities that cause emittance growth, with consequent beam loss, well before $\omega_p = \sqrt{2}\,\nu_0$. For the case of $\sigma_0 \lesssim 60^\circ$ the KV treatment predicts fourth and higher order instabilities below $\sigma = 24^\circ$, but the PIC work indicates no change in rms emittance as σ decreases, at least to $\sigma = 6^\circ$.

The object of the experiment is to explore beam properties after transport, such as size, current, current density (and hence σ/σ_0), over a range of values of σ_0, ϵ_N, and injected current. The accessible range of parameters should also make the predicted regions of instability amenable to study.

Apparatus

Source

We have operated so far with a thermionic cesium alumino-silicate source (zeolite) 25 mm in diameter. Erratic results over a period of time with commercially available sources were traced to non-uniform coating, non-uniform emission, and departures from flatness in the coating sufficient to interfere with the gun optics. Satisfactory space-charge-limited flow is almost impossible to achieve under these conditions and we have been forced to develop in-house source preparation and testing facilities that have now produced acceptable zeolite sources for both cesium and sodium ions.

Ion Gun

The gun is designed to have a constant output voltage, nominally 200 kV, and variable current density (j = 3 to 6 mA/cm^2), and to operate under space-charge limited conditions. Designed with the help of the EGUN code[9], a four-electrode structure with Pierce geometry proved adequate to provide satisfactory optics over this dynamic range.[10]

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Attenuators can provide current densities j < 3 mA/cm^2. (See Figs. 1 and 2.)

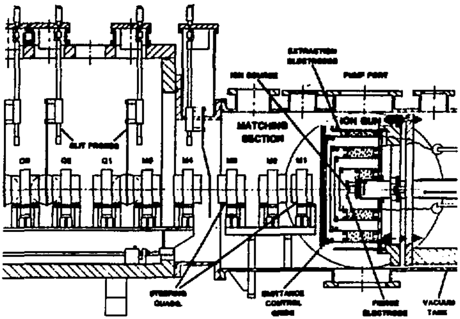

Fig. 1: A drawing of the gun showing emitter with Pierce electrode, separately controlled electrodes, and emittance control grid.

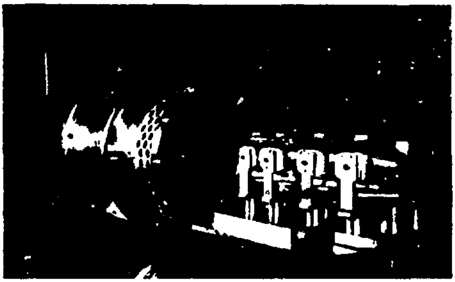

Fig. 2: The gun with four matching quadrupoles in place.

Beam Transport Quadrupoles

When completed, the transport channel will consist of 82 electrostatic quadrupoles — 41 periods of a FODO lattice — housed in a sequence of seven vacuum chambers. At present, just one chamber containing the initial 10 quadrupoles (Q1 - Q10) is in place; the others will be added sequentially as dictated by the progress of experimental understanding. Five quadrupoles (M1 - M5), placed between the gun and the transport system and independently controlled, form the matching section to transform the axially-symmetric transverse phase areas at the gun output into the astigmatic phase ellipses needed at the entry into the transport section.

The design of an experiment to test long-term stability in any quadrupole channel, for conditions where the net restoring force can become very small, is especially demanding. Since one is seeking to detect the threshold at which deterioration in beam quality occurs due to collective instabilities, it is important that damaging effects, such as could arise from non-linearities that affect single-particle motion, be avoided. In designing the system of electrostatic quadrupoles, one of us (L.J.L.)[11] developed 3-D relaxation codes to compute the electric fields for a large variety of electrode shapes, and particle dynamics codes based on the K-V distribution to predict the beam behavior, taking into account non-conservation of particle kinetic energy, asymmetric images, and non-paraxial effects. An additional feature of his work was the development of acceptable electrode shapes that could be very simply machined.

The final configuration chosen had a FODO period of 12", a physical aperture radius of 1", and an inter-lens gap of 2.0", Figure 3 shows the first of the seven transport vacuum tanks in place; as can be seen, a liberal allotment of penetrations has been provided for possible introduction of frequent diagnostic devices.

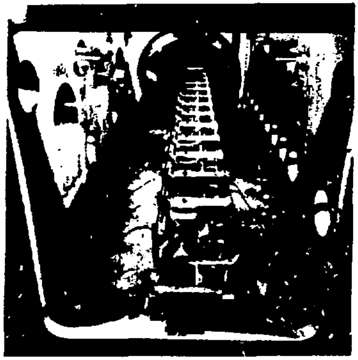

Fig. 3: View (towards gun) of transport and matching quadrupoles.

Beam-conditioning and Diagnostic Devices

Apart from complicating the study of beam-dynamics, electrostatic lenses also impose constraints and difficulties on the incorporation of diagnostics. Measurement devices can be inserted only at the mid-point of the free-space between adjacent lenses, i.e. where there is a ground equipotential, and are constrained to be thin to avoid sparking. Electron production by ions striking material surfaces may also cause some problems.

Beam-conditioning devices include: (a) a grid-structure after the gun to which voltages can be applied to alter the emittance over the range $\epsilon_N = 1\times10^{-7}$ rad-m to 1×10^{-6} rad-m; (b) attenuator grids after the gun; (c) a collimator after the gun to select a 3 mm diameter attenuated pencil beam. On axis, this provides a beam in which the behavior is dominated by emittance, not space-charge. Off-axis, it provides a tool for checking the single-particle tune, σ_0, of the transport system.

Diagnostics include: (i) slim Faraday cups with bias grids to measure beam current; (ii) metal plates with slits which can be moved across the beam upstream of a Faraday cup. Scanning with a single slit determines the projected beam profile. Setting one slit at a sequence of locations and scanning with a second slit downstream allows the beam emittance to be mapped in either plane; (iii) transparent scintillators that can be moved into the beam and the light recorded by a gated photo-diode camera.

Experimental Procedure

In principle, the computer-assisted procedure for arriving at a matched beam throughout the transport section is straightforward. The gun electrodes are set to voltages calculated from EGUN to provide the chosen beam current and gun optics. The emittances in the x and y-planes — described by a set $\rho = (r_x, \theta_x, r_y, \theta_y)$ — are measured at the gun exit. The EQENV code provides the x and y emittance ellipse shapes and orientations that are needed at the entrance of the FODO transport structure to establish the matched beam condition for the chosen values of current and σ_0. A related code, PARAX, is then used to derive the voltages, V_i, needed on the matching quadrupoles to transform the ellipses fitted from observations at the gun exit, ρ_G, into the matched ellipses, ρ_M, after the matching section where they can be checked experimentally. If the measurements do not conform to expectation with an error $\delta\rho$, a computer-constructed linear response matrix, A_{ij}, provides the set of voltage corrections, $\delta V_i = A_{ij}\,\delta\rho_j$, to move towards the correct solution. A further similar iteration can be applied if needed. A necessary check, of course, lies in the measurement of the emittance, ρ_T, at the end of the transport section (at present 5 periods long) to establish that $\rho_T = \rho_M$, and in checking that no beam has been lost along the way.

In practice, the success of this method proved highly sensitive to source imperfections such as spotty emission, misalignment, time variation, etc., which can spoil the adequacy of first order corrections and cause the procedure to fail to converge. With the recent inhouse development of more stable and uniform sources, the procedure has been found to work well, converging to an acceptable value with a single linear correction.

Experimental Results

Figure 4 displays some sample results for a single choice of beam current, $I_b = 11$ mA, and a single choice of emittance, $\epsilon_N \approx 1\times10^{-7}$ rad-meters, for the present set-up with the five matching quadrupoles, followed by five periods of the FODO transport section. The matching procedure described above worked well for $\sigma_0 < 100°$, in the sense that the appropriate beam sizes and emittance ellipse tilts

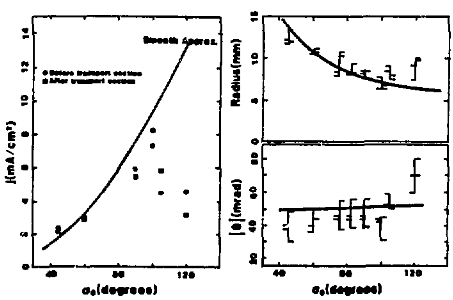

Fig. 4: Measured current density, beam radius, and envelope divergence (curves are calculated matched values).

could be attained within 10 percent at both the entrance and the end of the transport section (Q1 - Q10). At large values of σ_0 some of the calculations indicate beam-envelope sizes that become either large or small in the matching section and the procedure is less reliable. Also, the KV calculations indicate that for 11 mA a strong envelope instability should be present near 120°.

If there is a mismatch the beam area measured at the exit of Q10 may be larger or smaller than the matched value, depending on the phase of the envelope oscillations at that point. This, apart from some uncertainties in the Faraday cup calibrations, leads to errors in the estimates of j. Thus the scatter in the data points for beam size and j in Fig. 4 are seen to be anti-correlated.

If we denote a limiting current density, corresponding to $\omega_p = \sqrt{2}\, v_0$, by j_L, the data indicate transport (over 5 periods) of $j \approx j_L$ for $\sigma_0 \le 100°$. The corresponding value of $\sigma/\sigma_c = (1-j/j_L)^{1/2}$ is poorly determined but is probably in the range of 0.1 to 0.3.

The large dimensionality of the experiment is illustrated by the fact that only a small part of the transport section is being studied and that a range of values of both I_b and ϵ_N remains to be explored.

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