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LA-UR-88-3277

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TITLE:

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LA-UR--88-3277

DE89 000328

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SUBMITTED TO:

Heavy Ion Inertial Fusion Workshop, Darmstadt, W. Germany, June 28-30, 1988

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MASTER

BEAM FUNNELING STUDIES AT LOS ALAMOS*

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Abstract

Funneling two ion beams by interlacing their bunches can reduce the cost and complexity of systems producing intense beams. Applications of funneling could include accelerators for heavy ion inertial fusion, electronuclear breeding, and fusion materials irradiation. Funneling in an RFQ-like structure is an elegant solution at low energy where electric fields are needed to provide strong focusing. Discrete-element funnels, with separate focusing elements, bending magnets, rebunchers and rf deflectors, are more flexible. At sufficiently high energies, magnetic-quadrupole lenses can provide strong focusing in a discrete-element funnel. Such a funnel has been designed as a preliminary example of a second funnel in the HIBALL-II accelerator system. In a simulation, two Bi^{+1} (mass 209 amu) beams at 0.5 MeV/A, 20 MHz, 40 mA, separated by 55 cm and angled at ±6° were combined into a single 80-mA beam at 40 MHz. Emittance growth was calculated, by a modified version of the PIC (particle-in-cell) code PARMILA, to be about 1%. Funnel design experience at Los Alamos has evolved rules-of-thumb that reduce emittance growth. Some of these are to maintain focusing periodicity and strength in both transverse and longitudinal directions; use strong focusing so that the bunch will be small; minimize angles of bend and rf deflection; adjust longitudinal focusing to produce a short bunch at the rf deflector; and design rf deflectors for a uniform electrical field.

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* Work supported by Los Alamos National Laboratory Program Development under the auspices of the US Department of Energy.

1. Introduction

Today's accelerators can be designed to accept the beam current produced by almost any ion source assuming the beam has a reasonable emittance. Some applications, however, require more beam current within a given emittance than is available from a single ion source. In some cases, the higher currents could be achieved by using multiple ion sources followed by multiple accelerators and output optics systems. Such an approach might be applicable to systems designed for neutral-beam heating and current drive in tokamaks. If high-energy beams are required, however, the required multiple-beam accelerator system would be very complicated and expensive both to build and to operate.

Funneling combines two beams that have been bunched and accelerated in identical rf accelerators into a single beam by interlacing the bunches. The funneled beam is then suitable for injection into a single rf accelerator operating at twice the frequency of the initial two accelerators. Funneling can greatly reduce the cost and complexity of accelerators designed to deliver very bright intense beams by restricting the multiple-beam solution to only the lowest energies. Heavy ion inertial fusion is a good application for a funneled accelerator system because it requires bright, high-energy beams having currents significantly greater than those available from a single ion source. Other applications that might benefit from funneled accelerators include electronuclear breeding and fusion materials irradiation.

A perfect two-channel funnel doubles both the beam current and the transverse brightness, but in practice is limited by emittance growth and beam loss. For some applications, emittance growth is of great concern. It results from nonlinear fields, which can be of two types: external fields such as those required for acceleration, focusing, or deflection and internal fields such as space charge.

2. RFQ funneling

Stokes and Minerbo [1] have shown that a single RFQ-like channel can be used to funnel two beams of ions. The RFQ funnel can be designed so that both beams experience strong transverse and longitudinal focusing forces in addition to the deflections required for funneling. Detailed numerical simulation studies have been performed for an RFQ funnel designed to operate at 425 MHz [2]. These studies showed that to avoid emittance growth caused by redistribution of beam charge, strong focusing should be maintained in all three planes throughout the funnel, although this is not always possible [3]. Strong focusing is best achieved by using high intervane voltages because the voltage is proportional to the square of the aperture for constant focusing strength, and the aperture of the funnel must be larger than that of the preceding accelerators to contain both beams. These constraints could be the limiting factors on a funnel design and, therefore, the initial beam separation should be kept small.

Nonlinear forces in the RFQ funnel that affect emittance growth increase as a function of transverse beam displacement divided by the space period $\beta\lambda$, another reason to keep the beam separation small. The potential function that describes the field in the RFQ funnel results in a longitudinal focusing force that is dependent on the transverse beam position. Particles with a large displacement from the central axis are strongly focused longitudinally, whereas the longitudinal forces on axial particles are zero. The lack of focusing on-axis may result in appreciable emittance growth and argues for keeping the funnel very short. Fig. 1 shows two beams having an initial separation of ±2 mm being interlaced in an RFQ funnel [2]. The wavy lines above and below the axis represent the vane-tip profile; the beam bunches are represented by their particle projections on the plane of symmetry. In this example, each 1-MeV input proton beam had a 26-mA current that was simulated by 500 pseudoparticles. The RFQ funnel frequency was 425 MHz, the peak surface electric field was 45 MV/m, and the funnel length was 20 cm. There was no beam loss, and the transverse and longitudinal emittances increased by 2.2% and 2.7%, respectively. The RFQ funnel requires further development to allow the input beams to be closely spaced and to allow the output beam to be matched.

3. Discrete-element funneling

Ion-beam funnels that use conventional discrete elements, including quadrupoles, dipoles, rf rebunchers, and rf deflection cavities, have been described previously by Bongardt [4,5,6] and Guy [7,8]. We have designed a funnel of this type for the HIBALL-II heavy ion linear accelerator. We have assumed an accelerator configuration comprising eight Bi^{+1} ion sources injecting beams of 20 mA into eight linacs operating at 10 MHz. Each linac could consist of an RFQ section followed by an electrostatic, quadrupole-focused Wideröe structure. At the first funnel stage, the eight beams could be funneled into four electrostatic, quadrupole-focused Wideröe linacs operating at 20 MHz. This first funnel could be an RFQ-type funnel or a discrete-element type with electrostatic-quadrupole lenses. The second funnel would combine these four beams into two permanent-magnet quadrupole (PMQ) focused Wideröe linacs. Finally, the third funnel would form one 160-mA beam for injection into a drift-tube linac operating at 80 MHz. Magnetic-quadrupole focusing in a discrete-element funnel could be used in the second and third funnels if the funnel energies are high enough.

Initial efforts to design a second funnel at 0.12 MeV/A and 0.24 MeV/A were unsuccessful because not enough overall focusing could be provided to control the emittance if we used realistic magnetic-focusing elements. A successful attempt was made to design this funnel at an energy of 0.50 MeV/A. A funneling scenario that would be consistent with this example is shown in table 1. A factor of about 6 energy gain was assumed between funnel stages to obtain approximately a factor of 2 phase-damping before doubling the frequency.

At the second funnel, we assume that two beams with an initial separation of ±55 cm are converging with an angle of ±6°. The funnel is designed in four sections. The transport sections use conventional PMQs and rf cavities for focusing and permanent-magnet dipoles for bending. The merging section uses large-aperture PMQs for focusing and deflection of two beams in the same element. The actual funneling or interlacing of the beam is accomplished in a series of three rf-deflector cavities. Not included would be matching sections using PMQs and rf cavities to provide beam matching at the entrances and exit of the funnel. The design characteristics of this bismuth funnel, excluding the matching sections, are listed in table 2. The merging section and part of the funneling section are shown to scale in fig. 2.

The computer code PARMILA was used to perform detailed numerical simulation studies of the funnel's performance. PARMILA is a standard particle-in-cell (PIC) code that includes nonlinear cavity fields and space-charge effects. The space-charge routine used for this simulation calculates 3-D point-to-point forces in which individual particles are represented by spherical clouds of charge. A typical simulation uses 2000 particles, which result in a statistical accuracy of a few percent based on the reproducibility of rms emittances. The two-beam interaction in the merging section has not been included, nor have image-charge effects. The quadrupole transformation assumes a hard-edged field, but does not assume a paraxial approximation in the particle trajectories The dipole transformation is first order. The rf-deflector cavities are represented by a table containing the calculated field resulting from a specific electrode geometry through which the particles are stepwise integrated.

The deflector cavities have been designed so that the field is reasonably uniform in the high field region and does not exceed 12 MV/m. Fig. 3 shows a map of the accelerating component of the electric field in the median plane of the rf deflector cavities. The nonlinearities as a function of transverse displacement are evident in this field map. The beam-dynamics performance of this funnel design, as predicted by PARMILA, is excellent. The calculated emittance grows by only 1% in the longitudinal plane; by 1% in the horizontal plane, the plane of deflection; and none at all in the vertical plane.

4. Design philosophy

The primary sources of emittance growth are usually (1) time dependence of the rf-deflector fields, (2) achromatism in bending fields and deflector, and (3) space charge. An upper limit on the space-charge contribution can be estimated by assuming that the focusing vanishes in a section of the funnel approximately one-fourth plasma-wavelength long. Then the emittance growth is governed by the following relationship:

$$\Delta\varepsilon_T^2 = \left(\frac{q\, I\, \lambda\, a\, |\Delta U_n|}{60\sqrt{5}\, \pi\, \varepsilon_0\, m\, c^3} \right), \tag{1}$$

where ε_0 is the permittivity of free space, c is the speed of light, q and m are the charge and mass, I is the beam current, λ is the rf wavelength, a is the rms beam size, and ΔU_n is the nonlinear field-energy change [3]. The value $\Delta U_n = 0.308$, which corresponds to an initial Gaussian profile that relaxes to a uniform beam, gives an upper limit. It is clear that high frequency and small beam diameter are important to minimize the emittance increase. More important, if the average beam size can be kept constant by maintaining constant focusing periodicity and strength, the charge-redistribution emittance growth can be reduced to an amount well below that caused by the deflector fields and by achromatism.

A conservative estimate of emittance growth from momentum spread in the dipole magnets is given by the following relationship:

$$\Delta\varepsilon_T = \theta\, a\, \frac{\Delta p}{p} , \tag{2}$$

where θ is the total angle of bend in one direction, and p is the momentum. This effect argues for keeping the beam small and minimizing the angle of bend. S-type bends, which in the absence of space charge would be achromatic, can reduce this effect. Such systems, however, are longer and require an intermediate buncher to keep the beam from defocusing longitudinally, which defeats achromaticity.

The emittance can also grow as a result of phase spread in the rf deflectors. This growth is governed by the following relationship:

$$\Delta\varepsilon_T = \frac{q\, E\, \lambda\, a\, (\Delta\phi)^2}{8\, \pi\, m\, c^2\, \beta} , \tag{3}$$

where E is the electric field on-axis, β the velocity relative to the speed of light, and $\Delta\phi$ is the rms phase length of the beam. This is another argument for keeping the beam small and short and for keeping the deflection angle small. Although not included in this equation, it is also very important to tailor the geometry of the deflector cavity to produce fields that are as linear as possible.

Acceleration provides phase damping, which is proportional to $\beta^{3/4}$ for constant accelerating field and when space charge can be neglected. To easily accommodate the frequency doubling inherent in funneling, the phase spread must be halved in each linac. This concept implies that in each linac the beam velocity must increase by a factor of about 2.5, corresponding to an energy increase of 6.25. In the case of the bismuth design, the phase length of the beam was held constant throughout the funnel. The subsequent matching would provide an additional 20° phase compression just before injection into the next linac. The accelerating field amplitude and stable phase would be programmed to provide the optimal longitudinal beam dynamics.

The energies of the funnels should be chosen to be as low as possible, consistent with the attainable phase compression, to benefit from reducing beam multiplicity. The energy must be high enough, however, to support the current limit in the new linac. When transverse focusing is the limiting constraint, the current limit is governed by the following approximate relationship [9]:

$$I_{lim} \propto \frac{q}{A} \beta^n \lambda^2 , \tag{4}$$

where n = 1 for electric quadrupoles and n = 3 for magnetic quadrupoles. For magnetic focusing, the phase-damping criterion is often more important than current limits for determining funneling energies, whereas for electric focusing, the linac-current limit may dominate.

5. Summary

Funneling will probably be required in an rf-accelerator-based, heavy-ion-fusion reactor scenario to provide the required amount of beam current. Two funneling approaches show promise. The RFQ funnel has been analyzed at high frequencies and found to be appropriate for funneling low-velocity beams. A discrete-element funnel example using magnetic focusing has been designed for Bi^{+1} at 0.5 MeV/A, which effectively doubles the beam current while keeping the emittance growth to 1%.

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TABLE 1

HIBALL-II funneling scenario, assumed parameters

Funnel		I	II	III
Energy				
• Total	MeV	16.7	104	627
• Per nucleon	MeV/A	0.08	0.50	3.0
Current	mA	20-40	40-80	80-160
Frequency	MHz	10-20	20-40	40-80
$\varepsilon_{n,rms}$ (x, y, z)	cm-mrad	0.04 π	0.04 π	0.04 π
$\Delta\phi$	deg	±20	±20	±20

TABLE 2

Characteristics of the 104-MeV HIF funnel design

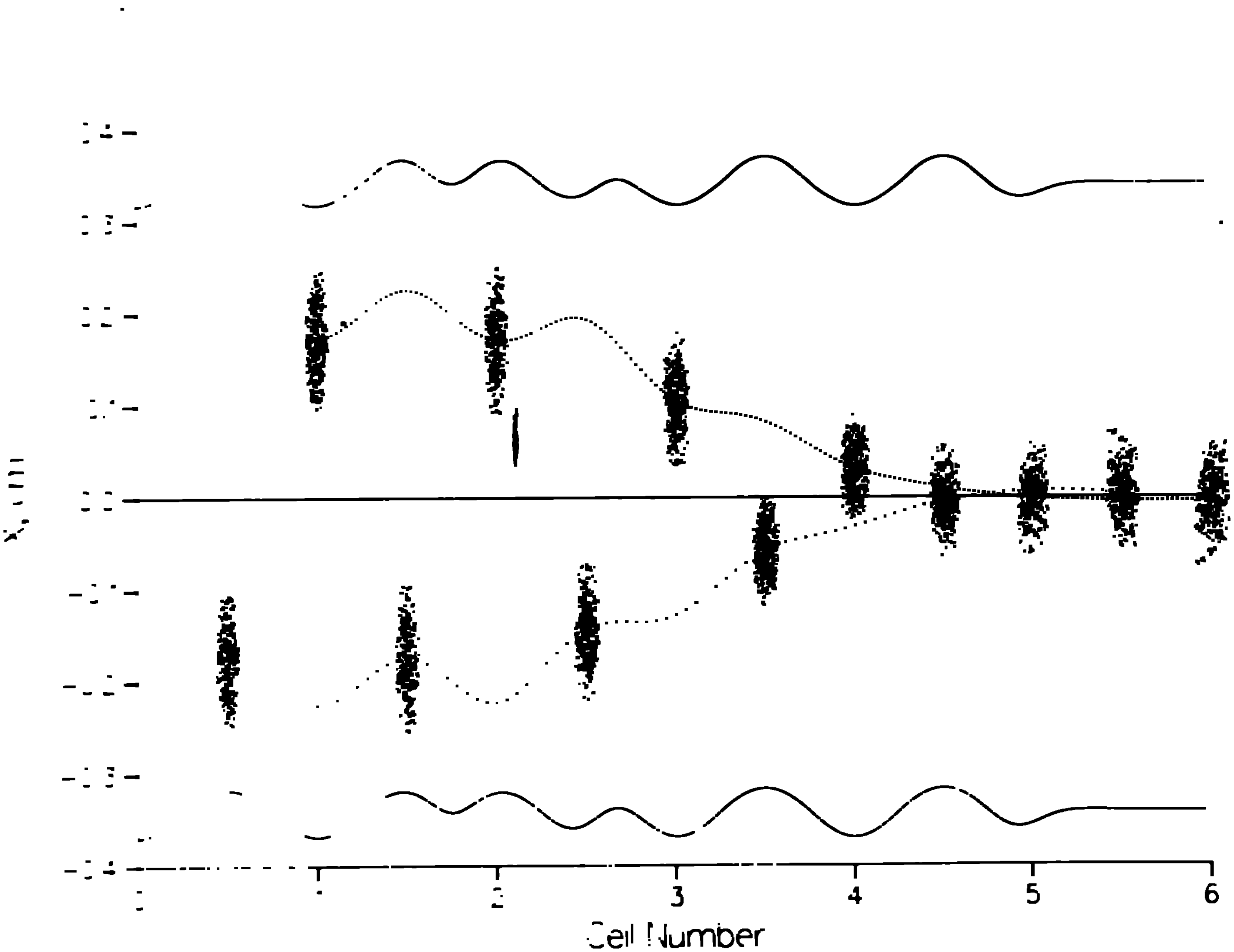
Ion	Bi^{+1}
Energy	0.5 MeV/A
Current per input channel	40 mA
Initial beam spacing	110 cm
Length	8.5 m
Bend angle	±6°
Quadrupoles	2×6 + 3
Quad pole-tip field	≤12 kG
Dipole magnets	2×3
Dipole field	10 kG
Rebuncher cavities	2×1
Deflectors	3
Deflector bend, each	0.4°
Deflector peak-surface field	12 MV/m

FIGURE CAPTIONS

Fig. 1 RFQ funnel cross section showing the bunch structure of two converging beams.

Fig. 2 Merging section of a discrete-element funnel.

Fig. 3 Deflecting component of the electric field on-axis in the rf deflector.



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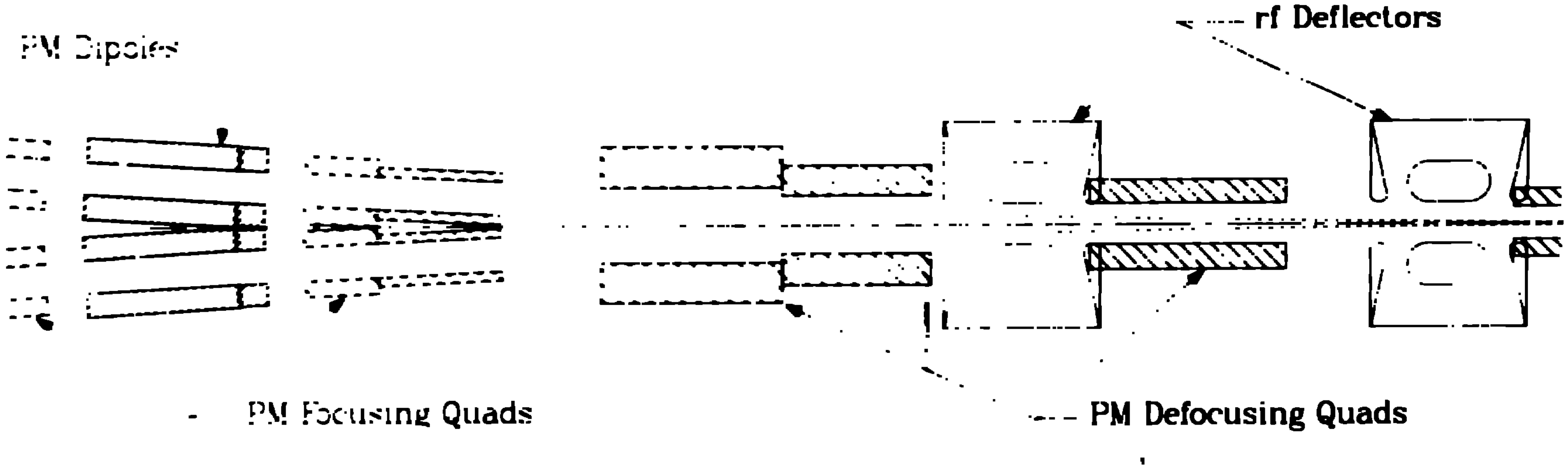
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PM Defocusing Quads