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SUMMARY FROM WORKING GROUP ON MULTIPLE BEAMS AND FUNNELING*

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INTRODUCTION

The working group on Multiple Beams and Funneling discussed various topics related to multiple beams and funneling, including (1) design considerations for multiple-beam accelerators; (2) scaling of current, emittance, and brightness for multiple-beam systems; (3) funneling lines using either discrete components or a radio-frequency quadrupole (RFQ) funneling structure; and (4) alternatives to funneling. The regular participants included C. Kim, G. Gillespie, R. Thomae, R. Stokes, G. McHarg, F. Guy, R. Burke, K. Bongardt, P. Krejcik, M. Shubaly, P. Grand, and T. Wangler.

MULTIPLE-BEAM ARRAYS

In a practical beam transport or linac channel, the maximum beam current is limited by nonlinear contributions of the focusing elements, by the electric and magnetic focusing fields that are attainable, or by beam resonances or instabilities. To obtain higher currents than are possible in a single channel, multiple beams are required.

Maschke proposed the MEQALAC,[1] in which the beamlets are accelerated in common rf gaps and transported within individual channels using electrostatic quadrupoles. The concept was applied to low-velocity transport and acceleration. Maschke argued from linac current-limit formulas that the brightest linac beams could be obtained by filling the available aperture at the lowest practical velocity and highest possible rf frequency, implying the use of small apertures. The effective emittance, including all beams, is enlarged as a result of the geometrical dilution caused by the finite separation of the beams. Theoretically, it still might be possible to obtain a very bright beam in spite of this geometrical dilution effect by sufficient reduction of the bore size. Maschke and colleagues argued that it is feasible to construct electrostatic quadrupole arrays that contain <u>thousands</u> of separate channels,[1] resulting in a single high-current, low-emittance beam composed of thousands of individual beams. The first MEQALAC, the M1 MEQALAC,[1] was designed, built, and tested at Brookhaven in 1979. It accelerated nine beams of Xe^{+1} from 17 to 73 keV and operated at a 4-MHz rf frequency. The bore diameters were 5/16 in. (0.79 cm). The measured average output current for nine beams was 2.8 mA, compared to a calculated 3.3-mA current limit.

The technical feasibility has not yet been demonstrated for producing a beam composed of thousands of small beams, within bore diameters that are orders of magnitude smaller than in the M1

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MEQALAC. The MEQALAC is being investigated by the FOM-Institute,[a] but this application seems primarily to satisfy a need for high current rather than high brightness. The concept proposed at FOM is a 16-channel, 100-mA, 6-MeV Li^- MEQALAC for plasma diagnostics. In an initial study, they designed and constructed a MEQALAC to accelerate four He^+ beams from 40 to 120 keV within an interdigital cavity resonator that operates at 40 MHz. The bore diameters are 0.6 cm. In the initial measurements, a beam current of 2.2 mA per beam was obtained at full energy, compared to a calculated current limit of about 3 mA. Although it is generally acknowledged that multichannel systems such as the MEQALAC potentially can produce high total beam current, there was no general agreement among the workshop participants that it is practical at the present time to drastically scale down the channel dimensions.

For some applications such as heavy ion fusion, a high current density must be delivered to a target of radius r_T using a lens system whose effective usable radius r_L is limited because of aberrations and whose distance L from the target may be fixed. For this kind of application, the use of multiple-beam arrays may be especially well suited. If the lens is assumed to form a sufficiently small waist at the target, so that the waist size is determined primarily by the emittance term rather than the space-charge term in the envelope equation, then $r_T = L\epsilon/r_L$ in the approximation that $(L\epsilon/r_T^2)2 >> 1$. Thus, the current density j at the target from a single beam can be written

$$j = \frac{r_L^2}{\pi L^2}\left(\frac{i}{\epsilon^2}\right) ,$$

where i is the beam current. This result shows that a large current density at the target is obtained if the transverse brightness (i/ϵ^2) is large. However, space-charge-induced emittance growth, which occurs in a beam that is space-charge-dominated in the beam-transport channel,[3] increases as a function of the quantity i/ϵ, so that although a large value of i/ϵ^2 is desirable for this application, a large value of i/ϵ is undesirable.

However, if the total current I at the target is composed of N overlapping beams of current i and emittance ϵ per beam, these apparently contradictory requirements may both be satisfied. We make the simple assumption[4] that $i \propto a^2$ and $\epsilon \propto a$ for the beam extracted from an ion source, where a is the radius of the ion source extraction aperture, so that $\epsilon \propto \sqrt{i}$. Then $i = I/N$, $\epsilon \propto \sqrt{I/N}$, and $i/\epsilon \propto \sqrt{I/N}$. The current density at the waist for the N overlapping beams is proportional to $I/\epsilon^2 \propto N$. This argument suggests that if the total current at the target is provided by N independent channels, the current density at the target increases, and the quantity i/ϵ decreases as N increases. The geometrical dilution caused by the finite separation of the beams does not reduce the current density at the target.

The use of a multiple-beam array to deliver a high current density to a target is attractive for the induction-linac approach for heavy ion fusion, which is being developed at the Lawrence Berkeley Laboratory (LBL). The MBE-4 induction linac at LBL[5] will model many of the features of such a multiple-beam system and will accelerate four space-charge-dominated beams from 0.2 to 0.8 MeV using individual bore diameters of 5.4 cm. The MBE-4 experiment will provide valuable information on acceleration, current amplification, beam handling and control, and emittance growth, which will be valuable for design of future multiple-beam systems.

As discussed previously, the use of a multiple-beam accelerator is also necessary for applications that require higher currents than are possible in a single channel. An example is a concept for high-power, multiple-beam accelerator for a 1-A cw beam, as discussed at the workshop by Burke from the Hanford Engineering Development Laboratory. The proposed uses of such an accelerator include condensed-matter research, fusion-irradiation simulations, accelerator-breeder development, and strategic-defense R&D. The accelerator system includes a multichannel RFQ and a multibore drift-tube linac using permanent magnets.

FUNNELING

The initial suggestion for funneling was made during the heavy ion fusion workshops.[6] Because the space-charge limits relax with increasing energy, accelerator beams may reach an energy where the funneling of two high-current beams into one becomes attractive. In an rf linac, if the rf frequency is doubled, twice as many stable buckets per unit time are created, and the beam bunches from two linacs at frequency f can be funneled (radially combined and longitudinally interlaced), producing a beam suitable for injection into a new linac at frequency 2f.

Funneling has several desirable consequences. It permits use of more efficient high-frequency linac structures with all available buckets filled with particles, and it reduces the number of beams in a multiple-beam accelerator, resulting in reduced size, weight, complexity, and rf power. However, funneling may result in an unacceptable emittance growth, and the funneling line itself may contribute additional complexity to the overall accelerator system. For some applications, there may be alternatives to funneling, as was discussed at this workshop by Krejcik.[7]

The first simulation studies of beams in funneling lines were made by Bongardt,[8] whose results suggested that controlling emittance growth might be a difficult problem for some applications. Bongardt concluded that most of the emittance growth in his studies was caused by space-charge effects, together with some contribution from nonlinearities in the funneling-line elements. He explained the space-charge contribution as a result of an adaptation of the beam distribution to the funneling line, an explanation that has been supported by more recent studies.[9] Workshop discussions indicated that the requirements in the systems, studied by Bongardt for special elements (such as beam kickers that use up physical space), resulted in a reduced, effective, transverse-focusing strength in the funneling line. The reduced strength would be expected to cause an increased space-charge-induced emittance growth.

One of the challenges of a low-emittance-growth funneling line is to provide strong transverse focusing, especially while the two beams are being deflected by rf fields onto a common axis. Two solutions to this problem were presented during this workshop. One solution, presented by Guy,[10] made use of permanent-magnet quadrupoles, dipoles, and some combined-function elements to funnel two 2-MeV, 100-mA proton beams originating from a two-channel, 212.5-MHz RFQ. The overall funneling-line design was remarkably compact; it was contained within a total length of only 21.5 cm. A numerical simulation of the beam performance has yielded an emittance growth of only 15%. Further studies will be required to evaluate the potential technical difficulties that might be encountered with the combined-function elements that were assumed in this design.

A second funneling approach was presented by Stokes[11] and uses a modified form of the RFQ to provide uninterrupted longitudinal and transverse focusing while funneling two beams. The RFQ funneling structure contains poles or vanes with a special periodic modulation pattern that results in sinusoidal time-varying quadrupole focusing, as in a conventional RFQ, but whose successive lenses are displaced alternately about the central axis in one transverse plane. This results in a time-dependent displacement of the neutral (zero restoring force) axis of the beam. Consequently, for two beams composed of bunches that are injected 180° out of phase, two neutral beam axes are created within the structure on opposite sides of the central axis. By a suitable programming of the modulation pattern, the two beams can be radially combined and interlaced into a single beam with twice the bunch frequency. Evaluations of the current limits and numerical simulation studies for beam performance have not yet been completed.

CONCLUSIONS

The early ideas on multiple beams and funneling that were stimulated by requirements for heavy ion fusion accelerator systems have developed significantly. New experiments will provide important information necessary for a better understanding of multiple-beam systems. Important ideas have been suggested for funneling of high-current, low-emittance beams; however, experimental studies will be required for their evaluation.

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