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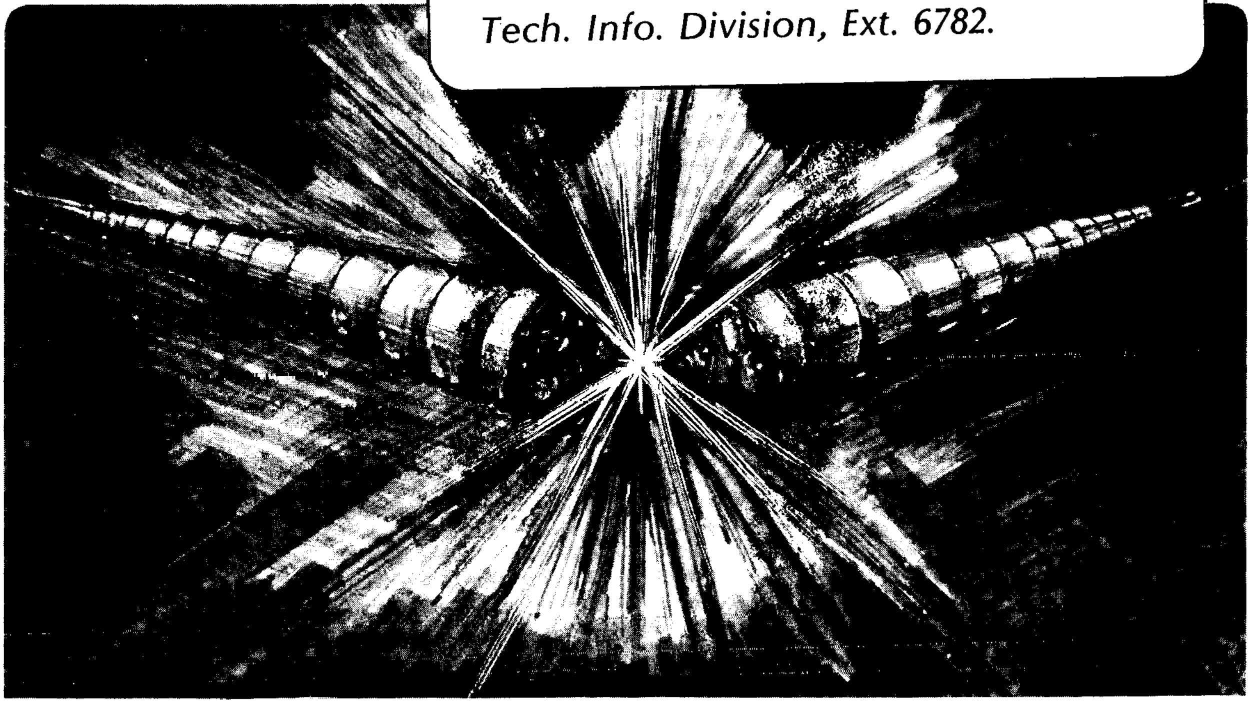

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BEAM DYNAMICS AND VANE GEOMETRY IN THE LBL HEAVY ION RFQ*

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Summary

The LBL Heavy Ion RFQ accelerator, presently undergoing acceptance tests, extends the application of the RFQ principle to charge-to-mass ratios considerably less than one. In this design the aperture is very small compared to the operating wavelength, causing a large capacitive loading of the structure and also in a high sensitivity of the field configuration of the structure to vane alignment. A structure has been derived that eases the vane alignment procedure and reduces the sensitivity to vane misalignment. The selection of the vane cross section facilitates machining and eventual frequency trimming.

Structure

The 199.3 MHz RFQ structure accelerates $_{28}Si^{4+}$ from 8.4 to 200 KeV/n over a distance of 2.25 meters. It is part of an upgrade for the Bevatron injector to provide beams up through silicon and possibly argon for the biomedical program at LBL 1). The basic design technique, developed at LBL, is described by Yamada 2) in which the structure is divided into six sections instead of the usual four. A seventh section has been added, an exit radial matcher, at the end of the structure to improve the match into a following Alvarez linac. Parameters at the end of each section of the linac are as follows:

Section	KE(keV/n)	Lth(cm)	phis	a(cm)	m	A
Input radial match	8.4	6.4	-90.0	.254	1.000	.000
Shaper	8.4	3.2	-88.0	.253	1.007	.012
Prebuncher	8.9	14.1	-60.0	.248	1.055	.016
Buncher	36.9	68.4	-30.0	.233	1.187	.126
Booster	118.4	49.1	-30.0	.205	1.456	.318
Accelerator	125.0	19.6	-30.0	.204	1.463	.331
Exit radial match	200.0	64.1	-30.0	.251	1.463	.333

The total linac length of 224.86 cm is shorter than one designed using the LASL design technique 3), but with a lower space charge limit, about 5 emA in our case. The voltage between the vanes is 50.9 kV and the nominal surface field is 1.85 Kilpatrick (27.2 MV/m). With B = 2.7, the normalized transverse acceptance area is 0.05 pi cm-mrad.

The cavity is driven with one r.f. feed loop and the azimuthal field distribution is controlled with coupling rings that connect opposite vane tips together, stabilizing the quadrant field distribution to a variation of no more than a few percent 4), 5). The longitudinal field distribution will be controlled by a combination of local tuning by means of tuning bars of variable cross section and by end tuners.

Vane Fabrication

The vane blank is flame cut from a hot rolled mild steel blank and cut to a truncated triangular cross section by a planer, Fig. 1. After an annealing operation to 870 degrees centigrade, the finish dimension is obtained with an additional 0.10" cut. The sides have a 15 degree angle to the vertical axis and the vane tip area, machined on a tape controlled mill, is set just inside the tangent of the surface of the sides.

The milling operation on the vane tip was performed on a Giddings and Lewis tape-controlled mill that has a bed travel of 96 inches (244 cm). It was thus possible to machine the entire 225 cm vane tip without remounting or moving the vane. The two pairs of fiducial flats were machined during the same setup so their positions relative to the vane tips were well controlled. 3/4" diameter carbide tip ball end mills were used in both rough and finish maching operation running at a spindle speed of 1400 rpm. The 3/4" diameter is 65% of the maximum tool size that would have fit into the smallest inside diameter of the tightest cell. The geometric error associated with this tool size which occurs at the point of quadrupole symmetry 45 degrees from the tip of the vane has a local maximum of 0.2 mils at the end of the prebuncher section and another local maximum of 0.6 mils at the end of the booster section.

The rough cut of the vane modulations removed nominally 28 mils from the vane blank at cuts spaced longitudinally by .0394". The final machining operation, removing an additional 10 mils every .0197" longitudinally, was done by passing the tool over the work always in one direction to prevent machine hysteresis and to remove position error in the feedback system due to finite velocity of the machine bed. The finish cut on each 225 cm vane tip required a total of 30 hours of machining time, including initial setup and tool changes. Once started, the machining continued nonstop until the vane was completed. The data for each pair of vanes is contained on 25 - 500 foot reels of punched mylar tape, or about 1.5 million characters of information. There were no errors detected in the large amount of data transferred.

The tool was changed once during the finish cut due to a dulling of the cutter edges at the 15 degree position on the flank of the tool where most of the cutting occurs. No significant wear was observed on the part of the tool which cuts the top of the vane tip. The cut with the new tool was blended into the

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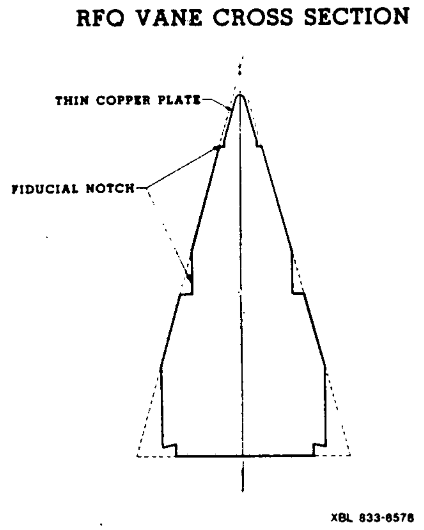

Fig. 1

old cut by modifying the cutting program to recut the last inch cut with the old tool, incrementing the radial offset with each cut, so the flank of the vane has a slight error but the vane tip follows the required contour. An experiment with cobalt tip cutters, which were expected to be better at low surface speed than carbide, revealed that high quality carbide cutters were superior in terms of tool lifetime and surface appearance of the workpiece. The resulting surface roughness before plating is approximately 63 microinches at the vane tip. No electropolishing operation was used.

At the sides of the vane near the base, a recess is machined out for the insertion of tuning bars that run the entire length of the vane. The bars use finger stock on their sides for good r.f. contact. At the high energy end of the machine the exit radial matcher requires a variation in r_0 which produces a local frequency variation of up to 5 MHz which is compensated for by varying the cross section of the tuning bar.

The cavity and vanes are copper plated to a thickness of 2 mils using an acid process except in the area of the vane tips. There, the 0.2 mil cyanide process copper strike, which underlies the 2 mil plate, is the only finish given to the surface. Tests on voltage breakdown and conditioning 6) indicate that a thin copper or nickel plating will quickly sputter off. The plating will protect the mild steel surface until it is under vacuum. The presence of a steel surface near the vane tip will have little effect on the r.f. characteristics: if the entire vane tip area down to the fiducial flat were of mild steel, the Q would be reduced by a factor of two, which is acceptable, and perhaps even desirable from the point of view of stabilizing phase variation with temperature.

Alignment of the vanes relative to each other and to the cavity is facilitated by two sets of fiducial flats machined onto each side of the vane during machining of the vane tip modulation 7). These fiducials reference each vane to its nearest neighbors at two places, and are also used in the radial and transverse positioning of each vane to the cavity, Fig. 2.

A vane is mounted on six plugs penetrating holes in the cavity wall and inserted into sockets in the base of the vane 7). These plugs may be moved transversely by jacking screws and shims and radially by machining one of two surfaces to effect independent and reproducible motion of the vane tip in the vicinity of each plug. A vane can be removed and replaced within 0.5 mils of its original position. The plugs are made vacuum-tight with Viton O-rings.

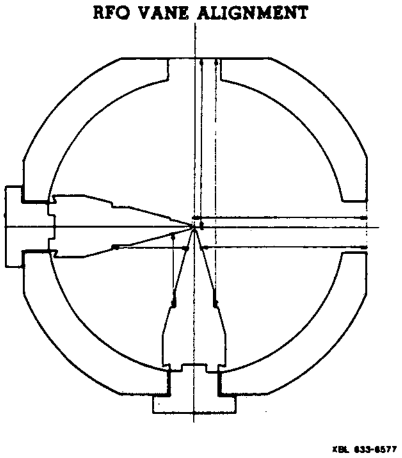

Fig. 2

Entrance End Geometry

The input radial matcher design uses the technique of Tokuda, developed at LBL 8). (The apparent reduction in acceptance for an odd number of radial matcher cells in their paper was due to an error in calculation - no such difference exists). An expansion of the quadrupole field at the end of the machine, including the endwall, indicates that the leading focussing term has a sinusoidal dependance with distance from the front endwall. This fixes the aperture of the radial matcher to have a

$$r_0 = \sin\left(\frac{\pi}{2}\,\frac{z}{L_{RM}+d_{wall}}\right)^{-1/2}$$

dependance. The end of the vane is approximately 1.5 cm from the endwall and 20 cells are provided in the radial matcher, although a somewhat smaller number would have been satisfactory. Over this distance of 6.3 cm the local frequency is higher than the 199.3 MHz nominal frequency and will be compensated for a by a combination of end tuners and variation in tuning bar area.

The beam is focussed into the RFQ by a quadrupole focussing quadruplet with the nearest element 15 cm upstream of the start of the vanes. The beam aperture at the entrance end of the radial matcher is 1.169 cm in radius.

Exit End Geometry

The beam emerging from the exit end of the RFQ is rapidly diverging and cannot be picked up without losses in the following Alvarez linac. In order to minimize these losses, the divergence can be reduced by gradually lowering the value of the focussing parameter B at the exit end of the machine to cause a quasi-adiabatic increase of the betatron functions over the last betatron wavelength. The modulation parameter m is held constant resulting in an almost constant acceleration parameter A. The length of the machine is not changed by the taper in B. Here, the taper of B is linear in energy, but the exact functional dependance is not critical. The betatron functions at the end of the RFQ are listed as a function of the final value of B with the taper starting at 125 keV/n. The value of B in the rest of the machine is 2.7 and the final energy is 200 keV/n.

B_{end}	beta$_x$ (m)	alpha$_x$	beta$_y$ (m)	alpha$_y$	
2.7	.127	-1.60	.144	1.68	(no taper)
2.2	.136	-1.53	.154	1.23	
1.8	.160	-1.40	.160	1.08	(value used)
1.6	.186	-1.44	.186	1.17	

The taper has no effect on the output beam emittance or aperture losses. The focussing parameter B is reduced from 2.7 to our chosen final value of 1.8 at the end of the machine over a distance of 0.65 meters, approximately one betatron wavelength.

We find that tapering B to 1.8 at the end of the machine is sufficient to allow transverse capture in the first focussing quadrupole with a 0.5 cm radius bore 15 cm downstream of the RFQ exit.

As B is varied, r_0, and therefore the local resonant frequency varies. The local frequency at the high energy end of the structure is 5 MHz higher than the rest with the variation roughly linear over the last 65 cm of the structure. The range of the tuning bars attached to the base of the vane is just sufficient to compensate for this frequency variation when the cross sectional area of the bar goes to zero. Any fine tuning at the exit end can be adjusted for with the exit end tuners.

Curvature of Beam Axis

The cavity axis was observed to have a sagitta of 0.050 cm over the 2.4 meter length of the machine. A curvature of the beam axis will result in an average offset of the central beam orbit, with a smaller flutter superimposed on it. We can estimate the magnitude of this offset by equating the centripetal force caused by an instantaneous curvature C to the average restoring force spring constant k due to the quadrupole focussing.

$$F = \frac{mv^2}{r} = Cmc^2 \beta^2 = kx_{offset}$$

The force constant k can be derived from the betatron frequency ω_ϕ

$$k = m\omega_\phi^2$$

The closed orbit offset is

$$x_{offset} = \frac{Cc^2\beta^2}{\omega_\phi^2} = 8C \left(\frac{\pi\beta\gamma}{B}\right)^2$$

For the LBL machine, the offset is .4 mm, which is about 15% of the aperture radius, a substantial amount. Therefore, it was decided to mount the vanes to produce a straight beam axis, and deal with the slight asymmetry in the RFQ cross section due to the curvature in the cavity by adjusting the tune of each quadrant individually. The coupling straps that connect opposing vanes together will help maintain electrical symmetry.

Conclusion

LBL has developed new techniques in cavity construction and vane alignment. The mode structure will be controlled by electrically coupling opposite vanes together. Both entrance and exit radial matching sections have been included in the cell design.

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