# Quadrupole Effects in On-Axis Coupled Linacs

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*Abstract*

Elliptical beam shapes have been seen at the exit of a number of on-axis coupled electron linacs. These non-circular shapes have been attributed to the quadrupole effects produced by the coupling slots in the cell walls. Qualitative and detailed cavity calculations predict that the quadrupole effects cancel if the coupling slots are aligned across the accelerating cavities, as opposed to rotated through 90° as has normally been the case. Two short S-band linacs, identical except for the orientation of the coupling slots, have been built to test the predictions. The results of detailed measurements of the beam profiles at the exit of the two linacs are discussed.

## I. INTRODUCTION

The coupling slots of on-axis slot-coupled $\pi/2$-mode electron linear accelerator structures appear to introduce weak quadrupole fields [1,2], which perturb the accelerated beam. These fields are small relative to the accelerating field, and are therefore difficult to detect in the accelerating structure.

The rf forces affecting the beam may be expanded as

$$\vec{F}(x,y,z) = F_a(z)\hat{k} + f_r(z)\times(x\hat{i}+y\hat{j}) + f_q(z)\times(x\hat{i}-y\hat{j}) \qquad (1)$$

where $F_a(z)$ is the accelerating force, $f_r(z)$ is a radially symmetric focusing force parameter and $f_q(z)$ is a parameter for a force of quadrupole symmetry. The symbols $\hat{i}$, $\hat{j}$ and $\hat{k}$ represent x, y, and z unit vectors, respectively.

For electrons moving at the speed of light, on or off axis and at any rf phase, the radially symmetric focusing forces cancel over each accelerating cavity [3]. Define on-phase and off-phase quadrupole focusing strengths

$$\Gamma' = \frac{\left\langle r_0 f_q(z)\cos\left(\frac{\pi z}{L}\right)\right\rangle_{cell}}{r_0 \times \left\langle F_a(z)\cos\left(\frac{\pi z}{L}\right)\right\rangle_{cell}} \qquad (2)$$

and

$$\Gamma'' = \frac{\left\langle r_0 f_q(z)\sin\left(\frac{\pi z}{L}\right)\right\rangle_{cell}}{r_0 \times \left\langle F_a(z)\cos\left(\frac{\pi z}{L}\right)\right\rangle_{cell}} , \qquad (3)$$

respectively, where $r_0$ is the radius at which the quadrupole force is calculated. If $\Gamma' \neq 0$, electrons at the peak accelerating phase will be focused in one plane, and de-focused in the perpendicular plane. Assuming electron trajectories in the direction of the effective accelerating force, the beam will converge in the focusing plane after a distance equal to $1/\Gamma'$.

For a particle off peak accelerating phase, the net quadrupole focusing strength is

$$\Gamma(\phi) = \Gamma' + \Gamma'' \times \tan(\phi) \qquad (4)$$

where $\phi$ is the rf phase as the electron crosses the centre of the accelerating cavity. Unless $\Gamma'' = 0$, a beam that is not well-bunched at the peak accelerating phase will be distorted by the rf phase-dependence of $\Gamma$. The beam profile will be a superposition of ellipses of varying eccentricity. The emittance of the beam will be conserved in six-dimensional phase-space, but the transverse emittance will increase.

## II. NUMERICAL MODELING

The three-dimensional rf code MAFIA [4] has been used to analyze typical linac accelerating structures. The code calculates the rf fields, allowing one to determine the electric and magnetic quadrupole perturbing fields.

The initial modeling work was done at 1300 MHz. In the simplest case of a single accelerating cavity without coupling slots, no rf fields of quadrupole symmetry are predicted by the code.

The calculation was then expanded to a 2-cell linac structure (Figure 1), with coupling cavities on either side of the accelerating cavity. The coupling cavities were on-axis $TM_{010}$ resonators, coupled by two slots in each of the cavity walls. Coupling slots were rotated 90° across both the accelerating cavity and the coupling cavities.

Significant transverse fields of quadrupole symmetry were predicted in both the accelerating cavity and in the two coupling cavities. Changes in mesh size used in the code had a negligible effect on the magnitude of these quadrupole fields.

Quadrupole forces ($\Gamma' = 5.3\times10^{-4}$ mm$^{-1}$) were predicted for trajectories on peak accelerating phase ($\phi = 0°$). No quadrupole forces ($\Gamma'' = 0$) were predicted for $\phi = \pm 90°$. In a multi-cell linac the transverse impulses will accumulate in successive cells and off-axis deflections of the electrons will result. Beam dynamics calculations predict that the beam profile will become elliptical, with the major axis on a line

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joining the slots in the output end walls of the accelerating cavities.

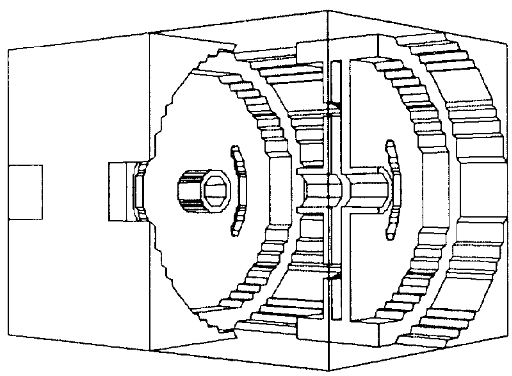

Figure 1. *Rotated slots* MAFIA model of two cells of a typical on-axis slot-coupled linac structure terminated in half-cavities. Note that coupling slots are rotated across each cavity.

An alternate accelerating structure configuration has the coupling slots in each wall of the accelerating cavities aligned. The slots are rotated across the coupling cavities to reduce second-nearest-neighbour coupling (Figure 2). A 2-cell MAFIA model of this type was developed for evaluation.

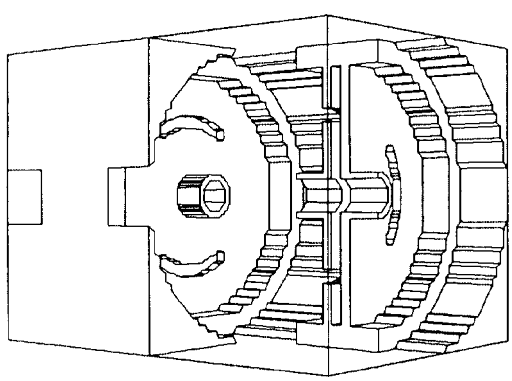

Figure 2. *Aligned slots* MAFIA model of a modified linac structure. Beam quality is improved with the coupling slots on opposite sides of the accelerating cavities aligned.

The coupling cavities contain strong quadrupole magnetic fields in this configuration, but the 90° rotation between cells results in a net cancellation. If the quadrupole components of the calculated fields for two adjacent cells are integrated, the resultant values for $\Gamma'$ and $\Gamma''$ are zero. Electrons should, therefore, not be deflected, regardless of rf phase.

The MAFIA model was then reduced to a single cavity with slots in only the output end wall, to represent the first accelerating cavity of a linac. The asymmetry of the first cavity might be expected to generate large quadrupole fields. The code predicted $\Gamma' = 2.6\times10^{-4}$ mm$^{-1}$ and $\Gamma'' = 2.0\times10^{-4}$ mm$^{-1}$. This value for $\Gamma'$ is lower than for the regular accelerating cavities.

Several 3000 MHz linacs have been built and tested at Chalk River Laboratories and the modeling calculations with MAFIA were repeated at this frequency to predict the effects of the slots on beam shape. Numerical integration of the quadrupole perturbing forces yielded $\Gamma' = 5.0\times10^{-4}$ mm$^{-1}$ for a rotated-slot structure.

## III. EXPERIMENTS

### *A. Coupling-Cavity Fields*

Two 1300 MHz linac segments were assembled between metal plates to form a three-cavity structure with a coupling cavity in the middle and half-cell terminations. The structure was excited in the $\pi/2$ mode and perturbation techniques were used to detect rf fields in the coupling cavity (Figure 3).

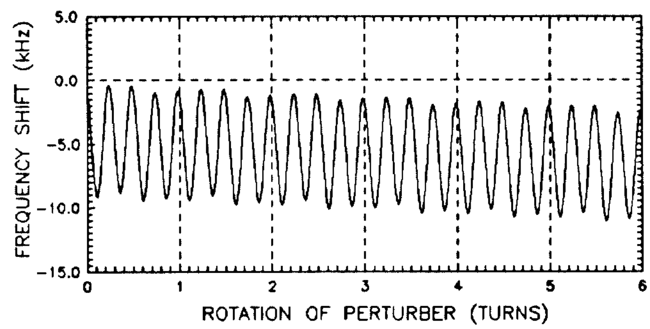


Figure 3. Frequency perturbation due to rotating a transverse dielectric rod about the axis of an on-axis coupling cavity. Four dips per revolution indicates fields with quadrupole symmetry.

The cavity was perturbed using two alumina rods 15 mm long, radially oriented and attached 180° apart to a PTFE shaft, which rotated on the axis of the coupling cavity. The outer ends of the alumina rods were 26 mm from the cavity axis. A single alumina rod in the accelerating cavity caused a frequency shift of -3.8 MHz. The -9 kHz shift in Figure 3 thus indicates a quadrupole electric field 3.4% as strong as the accelerating field.

### *B. Rotated-Slot Structure*

A nine-cell 3000 MHz on-axis slot-coupled electron linac with rotated slots was installed and operated in a facility at Chalk River [5]:

The linac installation incorporated a triode, 24 kV, dispenser-cathode electron gun, controlled with a Wehnelt electrode biased to -3 kV. The gun pulse length was 20 - 30 µs, and the gun output was generally 350-450 mA with no on-bias applied to the Wehnelt. The gun was directly mounted on the accelerator structure without a buncher. Beam was therefore injected at all phases of the rf cycle. No focusing elements were used between the electron gun and the linac.

The 0.5 m long structure was excited by a high-power klystron and 6 μs beam pulses in the 4-6 MeV range were obtained. Beam exited the linac through a 125 μm thick titanium vacuum-air foil, which was located either 0.3 m or 2.3 m from the end of the linac. Radiation-sensitive plastic films were placed against the window to capture an image of the beam profile. Clear images were obtained using bursts of 50 to 100 beam pulses.

Typically, the rotated-slot structure accelerated 13% of the unbunched beam through the structure. The beam profile at the end of the 0.3 m drift space showed a sharp line roughly 9 mm long, parallel to a line joining the coupling slots in the output end wall of the accelerating cavity. The darkest area was at the line's midpoint. This line was crossed at its midpoint by a fainter line roughly half as long, making the central beam profile distinctly cruciform. The image was surrounded by a fainter elliptical halo, which was roughly 10 mm by 14 mm, and which was aligned with the longer arms of the central cross.

Images of the beam profile made using the 2.3 m drift pipe showed the same cruciform shape expanded to 18 mm by 29 mm. This expansion of the beam profile indicated a divergence of ±5 mrad for the ends of the longer arms.

The dependence of the quadrupole fields on rf phase can be used to explain the accelerated beam profile. Given finite $\Gamma''$, electrons far off phase will form perpendicular ellipses. Superimposing these ellipses would produce a cruciform beam profile. Numerical modeling yielded $\Gamma'' = 0$ for the rotated-slot structure, so that $\Gamma$ is not phase-dependent. Equations (2) and (3) assume electrons travelling at the speed of light, so that equation (4) will not be exact in the low-energy end of the structure and $\Gamma$ may be phase-dependent.

Blind slots were cut in the entrance end wall of the first accelerating cavity of the rotated-slot linac. These were aligned with the slots in the exit wall to minimize the quadrupole fields in the first cell. At the end of the 2.3 m drift space, the beam profile was unchanged.

*C. Aligned-Slot Structure*

A second structure with aligned slots was then assembled to test the code predictions. Except for slot orientation, this structure was identical to the first. The two interchangeable rf structures were operated with the same gun, rf supply and drift spaces for a direct comparison. The transmission through this second structure was typically 16% and was clearly and consistently greater than that of the structure with rotated slots.

The profile of the output beam was smaller and more symmetrical than that obtained with the other structure. At the end of the 0.3 m drift space, the darkest part of the image was a 1.5 mm square at the centre. This feature was surrounded by a distinct, circular halo 14 mm across.

At the end of the 2.3 m drift space the beam profile showed a central feature roughly 5 mm across. Its shape was similar to the beam from the rotated-slot structure, but smaller. Expansion of the beam profile indicated a maximum divergence of ±1 mrad for the central feature of the beam. The beam produced by the aligned-slot structure was clearly smaller, less divergent and more symmetrical than the beam produced by the rotated-slot structure. The lower beam transmission of the rotated-slot structure might result from the larger beam scraping the structure bore.

## IV. CONCLUSIONS

Computer simulations indicate that on-axis slot-coupled electron linac structures should have the coupling slots in opposite accelerating cavity walls aligned. This shifts the quadrupole perturbing fields into an orientation that minimizes the perturbation of particles on or near synchronous phase. Experimental comparison of an aligned-slot linac and a rotated-slot linac confirmed the benefit of aligning the slots. The beam produced by the linac with aligned slots had a smaller size, greater symmetry and less divergence.

## V. REFERENCES


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