Chapter 9 Structures IV - Tuning and Stabilization

Tuning RFQ

RFQ Mode Stabilization

Tuning RFQ Cavities

The RFQ operates in the TE_{210} mode, which is a transverse electric mode with no E_z component. (Alvarez linacs operate in the TM_{010} mode, which supports the E_z component.)

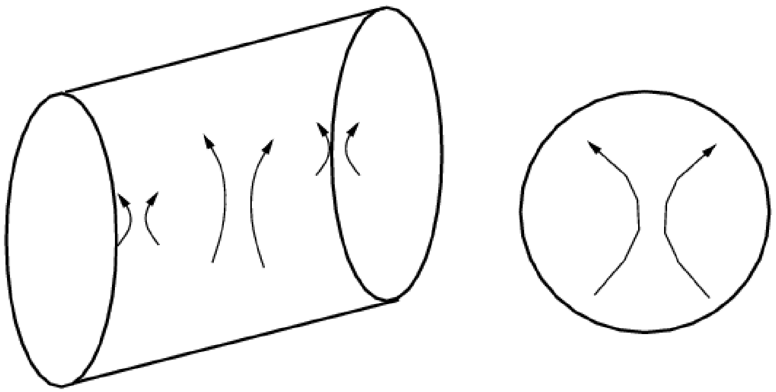
How is the E_z accelerating component generated? The modulations on the vane tip generate the E_z accelerating component.

The depth of the modulations determines the strength of the longitudinal accelerating field.

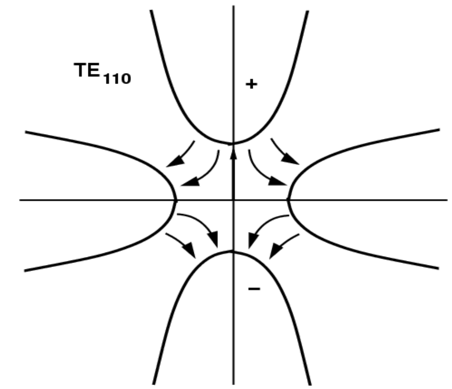
The RFQ is an accelerator which is first a beam transport device with acceleration added as a perturbation.

This makes the RFQ a unique accelerator in which a wide variety of beam dynamics solutions may be applied.

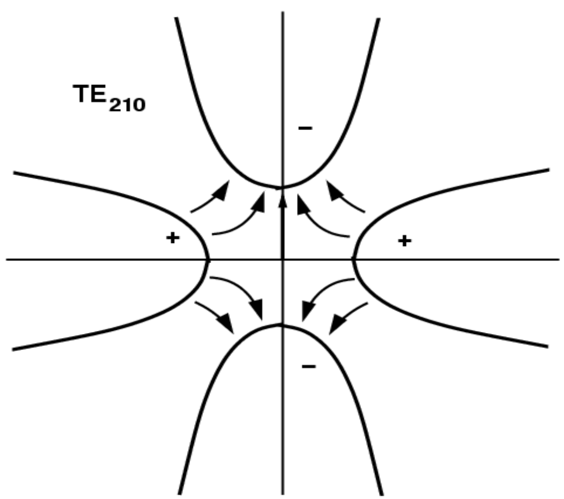
The TE_{210} and TE_{110} modes



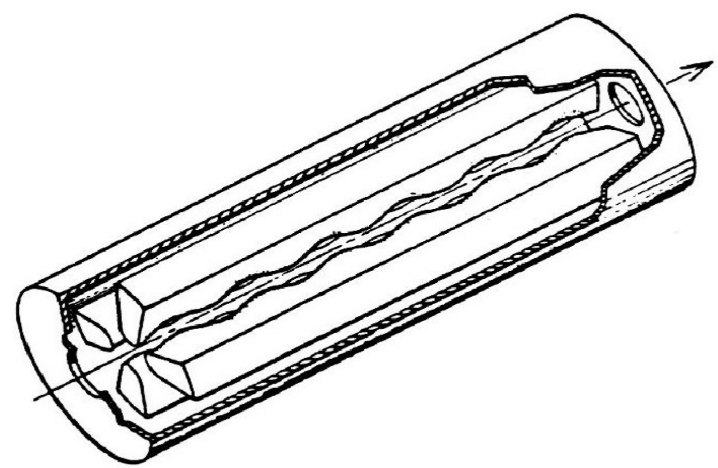
The TE110 mode without vanes in a pillbox



The vanes concentrate the electric field on axis. The TE_{110} mode is a deflecting mode

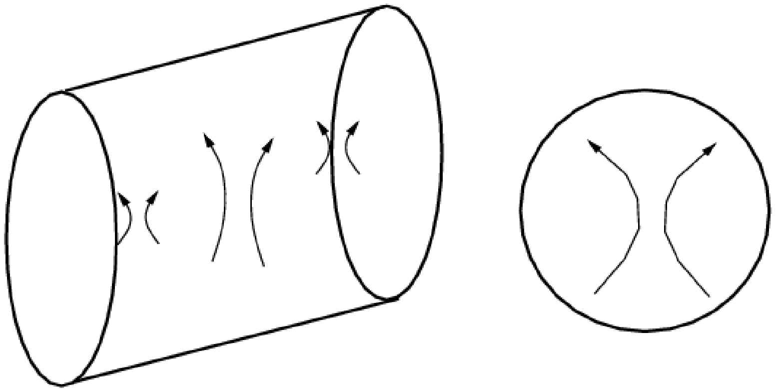


The TE210 mode focuses the beam.



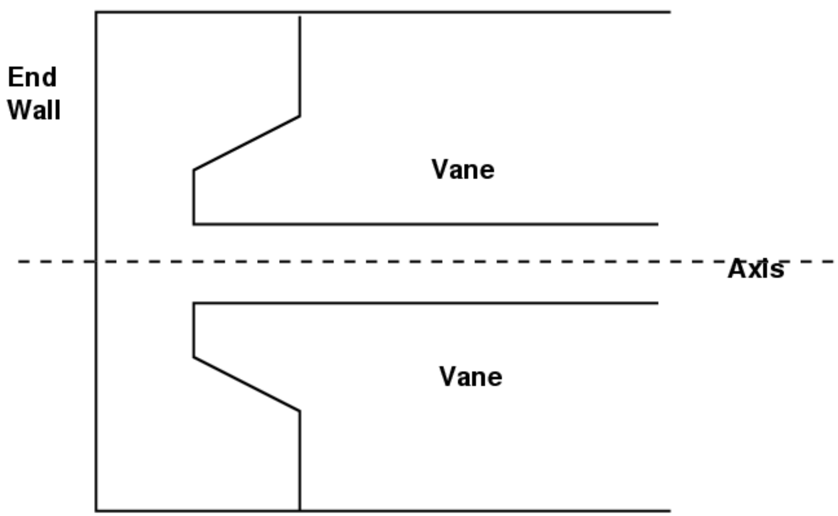
The modulations produce the E_z accelerating field.

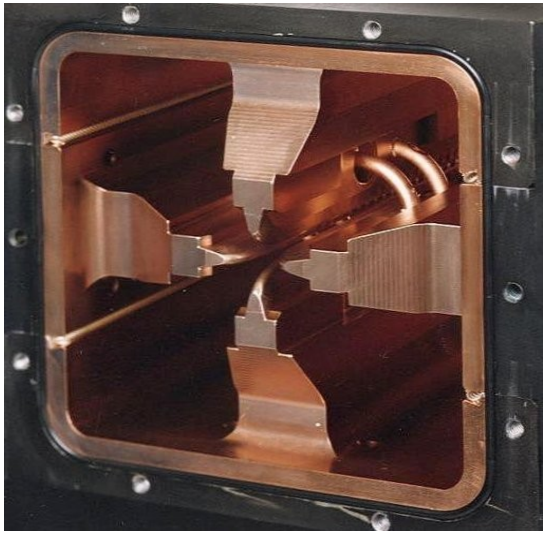
The Field Distribution Along the z-axis



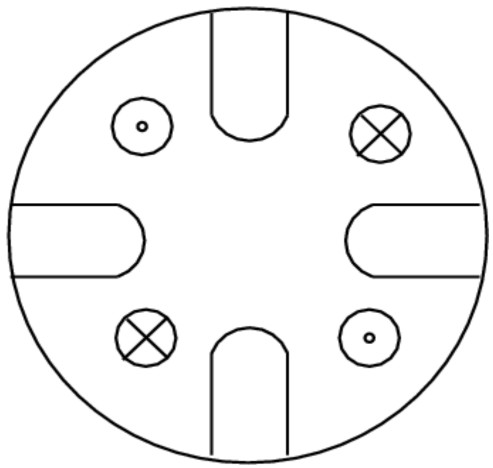
The TE field in a pillbox cavity must go to zero at the ends, due to the boundary condition that the E-field has no component parallel to a conducting surface.

The electric field distribution in an RFQ is flat (or tapered), and does not go to zero at the ends. The ends of the vanes in an RFQ are modified to support a field at their ends.

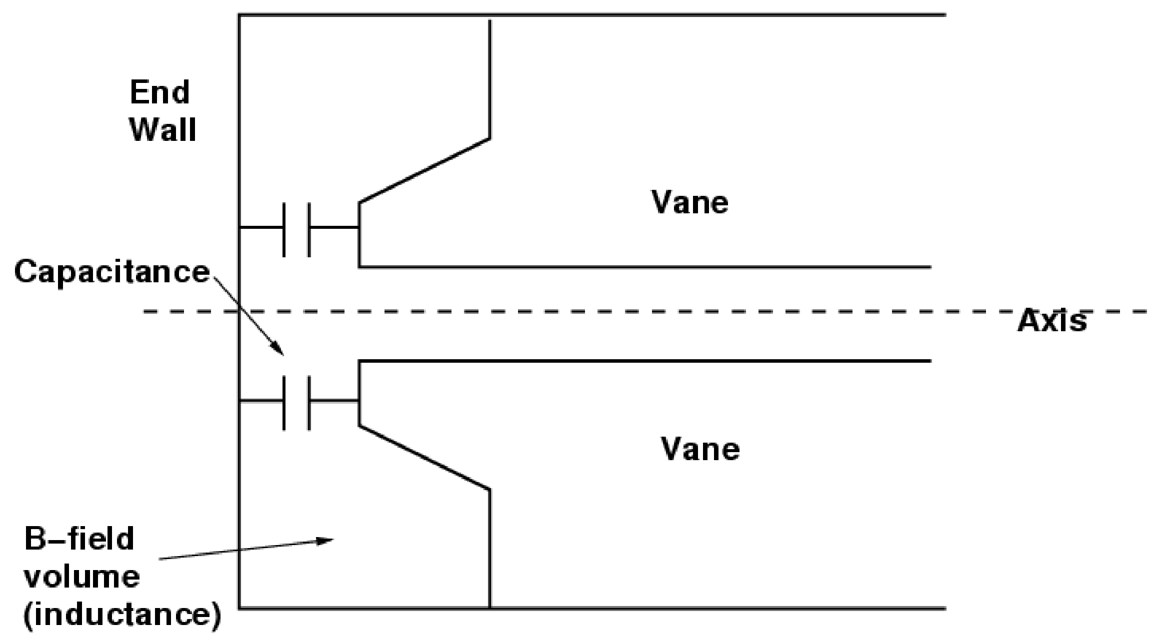




H-Field Distribution in an RFQ



The magnetic field in the TE_{210} mode alternates in adjacent quadrants. At the ends, the magnetic field passes around the vane cutbacks.



The ends of vanes form a capacitance to the endwall, and the area of the cutback forms an inductance. This L-C circuit is resonated at the RFQ resonant frequency and establishes the proper boundary condition for a flat field profile along the structure.

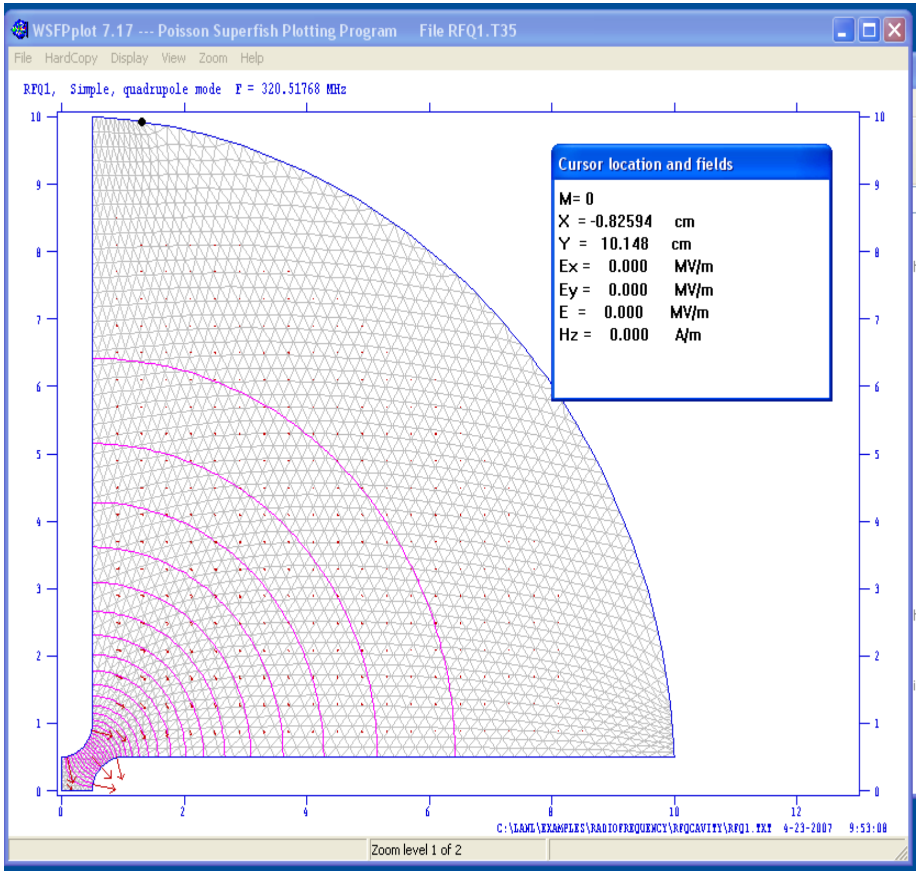
End of RFQ Vane with Cutback

The cutback region was then fitted with a screwed-on attachment to fine-tune the resonance of the end region.

2-D Computation of the RFQ Cavity Geometry

The RFQ calculation is a three-dimensional problem, including the end cutbacks.

Until recently, an accurate 3-D simulation of the cavity was not possible. The 2-D models included only the cross-section of the cavity away from the ends.

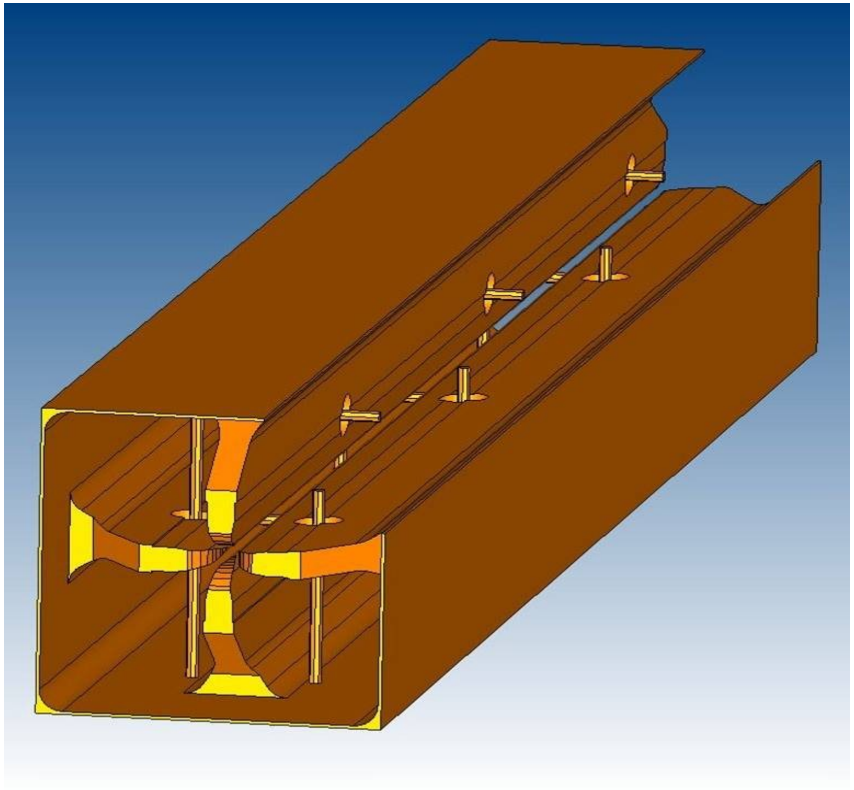


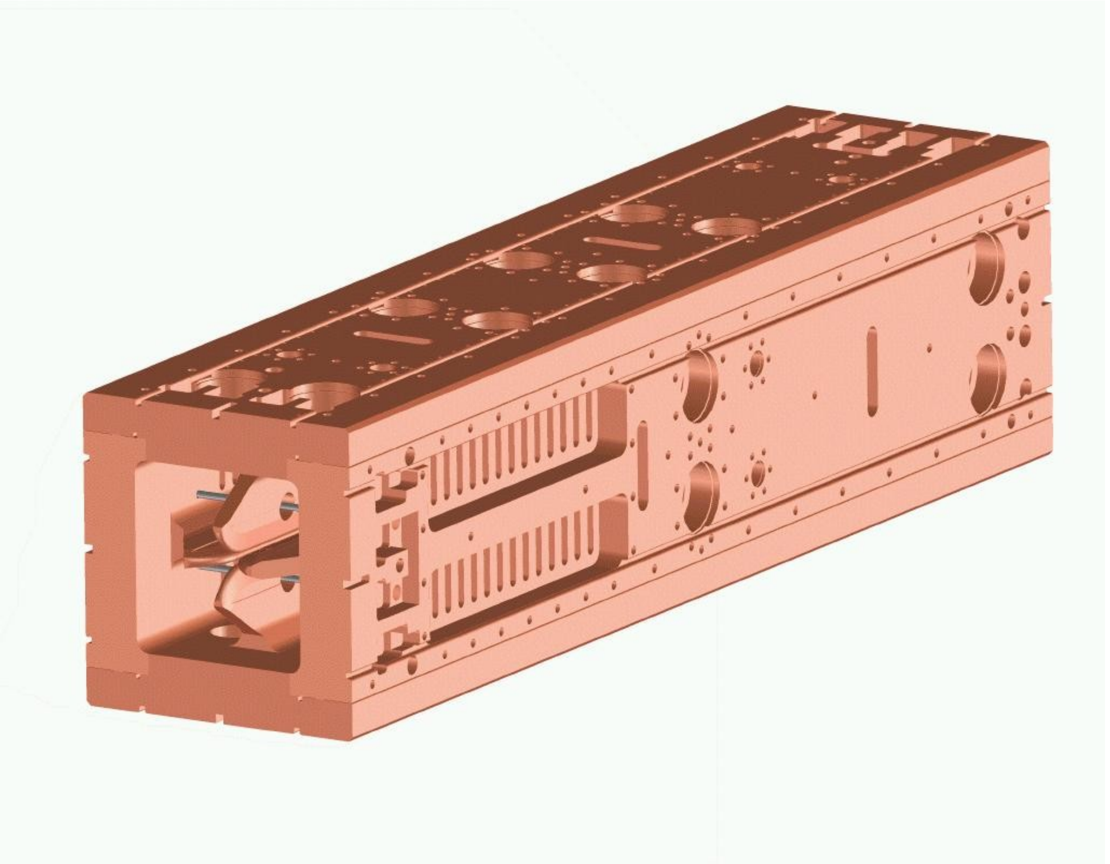
The end region of the RFQ had to be modeled with a scaled hardware version (cold model) to determine the geometry of the end regions.

Three-Dimensional Simulation Codes

The SNS RFQ was modeled (long after it was delivered to SNS) by Derun Li using CST Microwave Studio, including all the fine detail of the end cutbacks and other elements. The agreement of the code of the frequency and field distributions is excellent.

The other picture shows an ANSYS model of one module of the SNS cavity.





Tuning the Longitudinal Field Profile

The z-dependence of the field distribution in both TM and TE cavities is affected by local variations in the cutoff frequency of the waveguide (cavity).

The fundamental frequency of a vibrating string is

$$f = \frac{\sqrt{T/\rho}}{2L}$$

where *T* is the string tension, r is the mass per unit length, and *L* is the length of the string.

What happens if r is non-uniform? The amplitude of the vibration will become non-uniform, compared to the uniform string.

The RFQ (or DTL) comprises a loaded waveguide with a locally varying cutoff frequency. The dependence on the local field amplitude on variation of local cutoff frequency is

$$\frac{d^2}{dz^2}\left(\frac{\delta E_0(z)}{E_0}\right) = \frac{8\pi^2}{\lambda^2}\frac{\delta f_0(z)}{f_0}$$

$\frac{\delta E_0(z)}{E_0}$ is the field variation, l the free-space wavelength

and $\frac{\delta f_0(z)}{f_0}$ is the local frequency variation

The Field Profile Equation

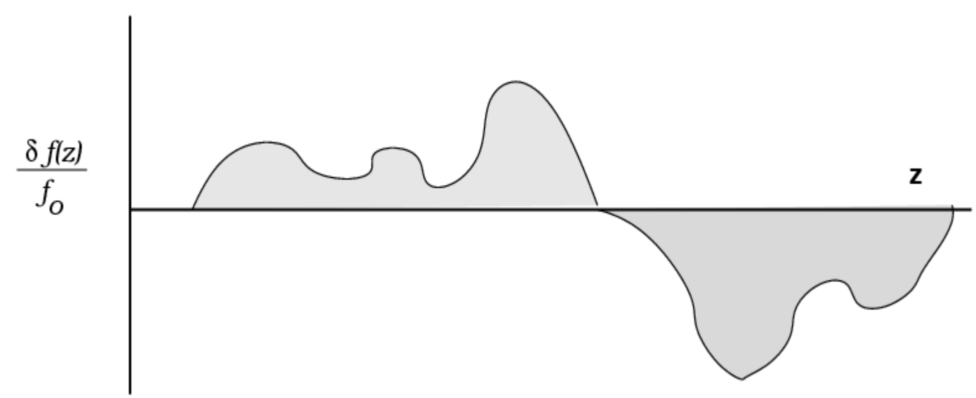
This is a second-order ordinary differential equation that can be integrated by inspection.

$$\frac{d^2}{dz^2}\left(\frac{\delta E_0(z)}{E_0}\right) = \frac{8\pi^2}{\lambda^2}\frac{\delta f(z)}{f_0}$$

The boundary condition $\frac{d}{dz}\left(\frac{\delta E_0(z=ends)}{E_0}\right) = 0$ is satisfied by requiring $\frac{\int \delta f(z)}{f_0} df = 0$

The $\frac{\int \delta f(z)}{f_0} dz = 0$

condition requires that the frequency deviation integrate to zero along the cavity. This renormalizes the frequency offset so its average is zero.



The frequency shift of the cavity due to perturbations is $\Delta f = \frac{1}{L_{cav}}\int \delta f(z)\, dz$

This *Δf* is subtracted from *df(z)* for use in the differential equation above.

Field Profile for a single frequency perturbation in the center

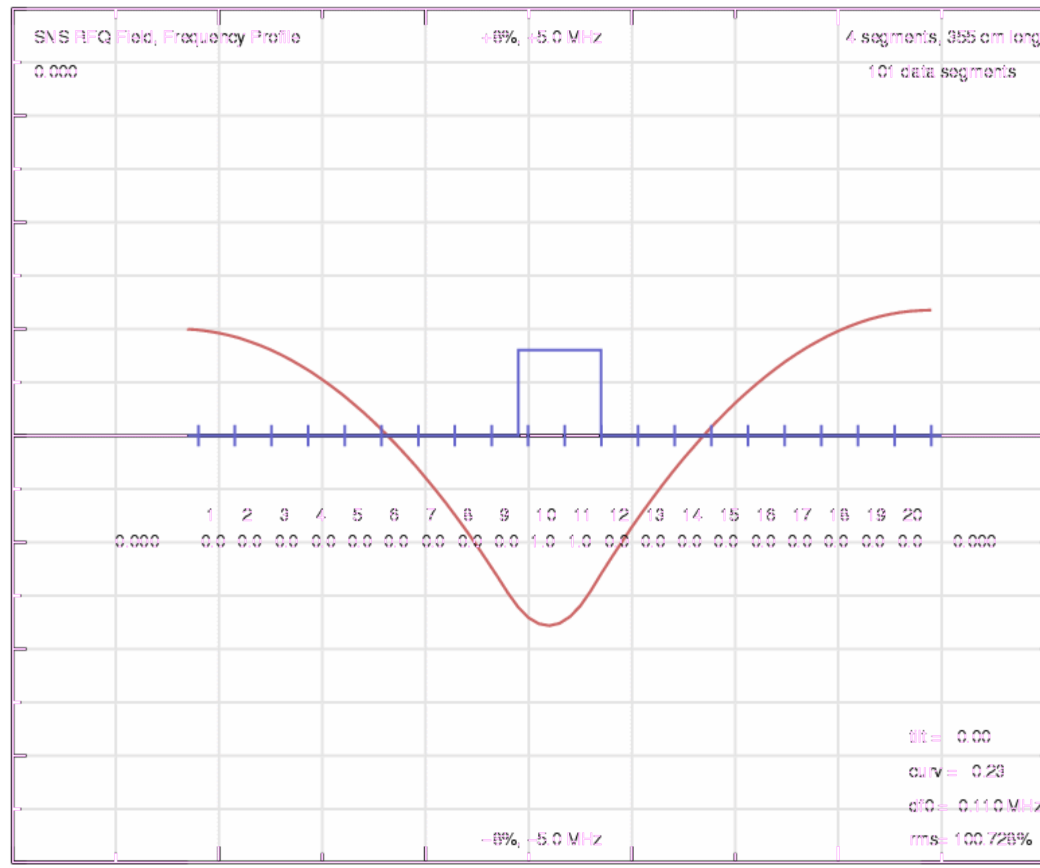
This could be the case for a single tuner in the middle of the RFQ, or a drive loop.

$$\frac{d^2}{dz^2}\left(\frac{\delta E_0(z)}{E_0}\right) = \frac{8\pi^2}{\lambda^2}\frac{\delta f_0(z)}{f_0}$$

Since the frequency deviation determines the curvature of the field distribution, a local positive frequency error causes a curvature upwards of the field distribution.

The boundary condition results in the first derivative of the field at the ends to be zero.

$$\frac{d}{dz}\left(\frac{\delta E_0(z=ends)}{E_0}\right) = 0$$



If the effect of the local frequency variation is to change the overall frequency by Δf, the peak-to-peak field variation is

$$\frac{\Delta E}{E_0} = \pi^2\left(\frac{L}{\lambda}\right)^2\frac{\Delta f_{cavity}}{f_0}$$

RFQ Tuner Assembly

RFQ tuners usually operate in regions of high H-fields by removing a small volume of H-field energy.

One type is the **piston tuner**, which moves in from the sidewall, removing a volume region.   Removing H-field volume **raises** the resonant frequency of the structure.

This tuner avoids moving electrical contacts by rotating a ring. When the ring is perpendicular to the direction of the H-field, a circulating current induced in the ring opposes and nulls out a volume of H-field, raising the cavity resonance.   When the ring is rotated 90 degrees, it is decoupled and has negligible effect.

The vacuum seal for this tuner uses a ferrofluidic fluid in a permanent magnet.

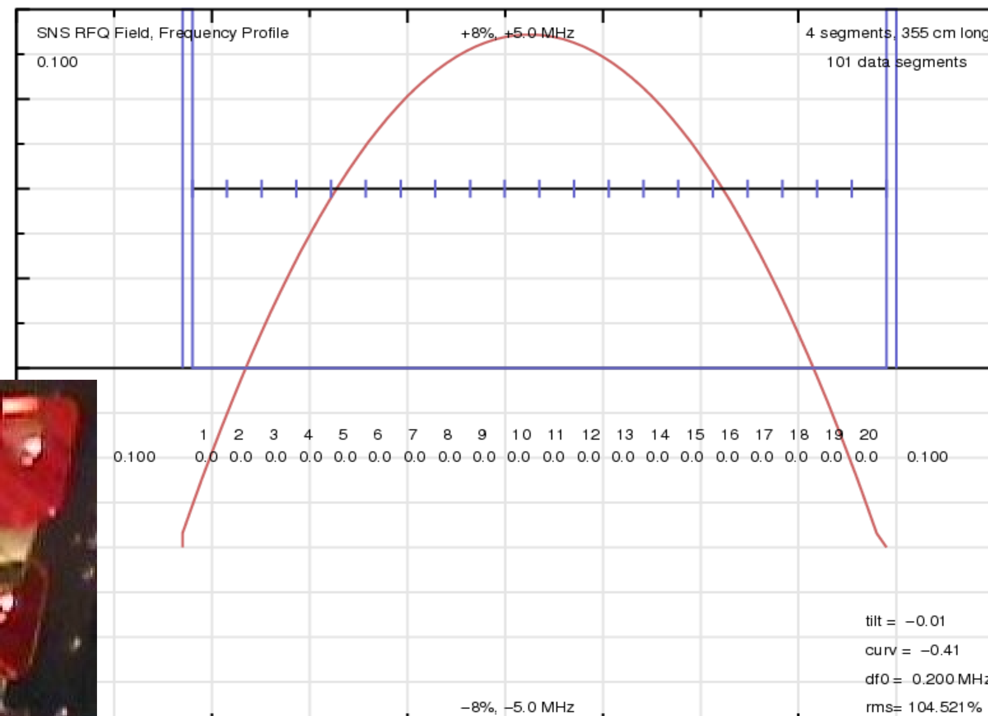
Perturbation at the Ends: End Tuners

RFQs are frequently fitted with tuners at the endwalls to adjust the field profile.

For the case where the end tuners are adjusted together to compensate a curvature in the field profile, the combined shift of the overall frequency of Df produces a peak-to-peak variation of the field along the cavity of

$$\frac{\Delta E}{E_0} = \pi^2 \left(\frac{L}{\lambda}\right)^2 \frac{\Delta f_{cavity}}{f_0}$$

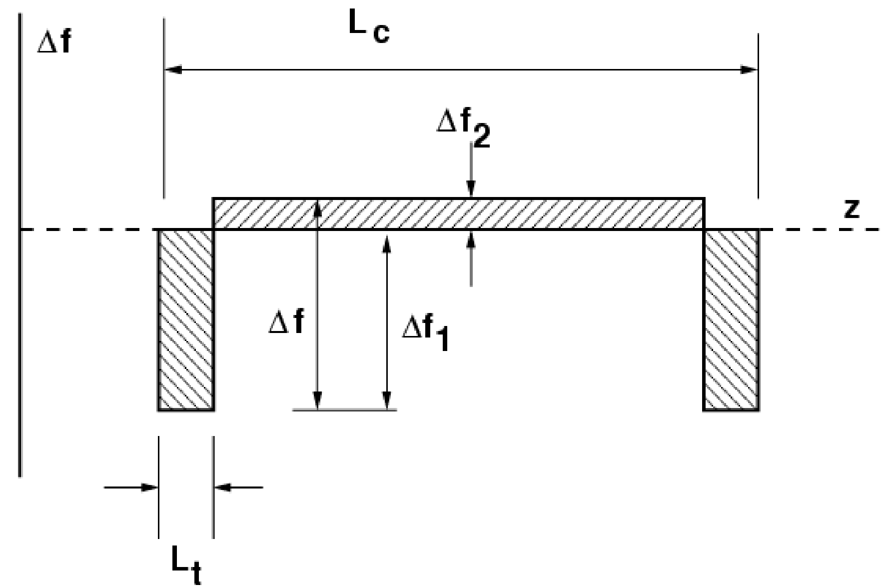
Measurement of the curvature of the field indicates the difference in the cutoff frequency of the RFQ tank and the resonance of the end cut-back regions.



More Detailed Calculation, RFQ End Tuners of non-zero Length

Two tuners, each with an effective length of L_t along the cavity of length L_c, are set with a frequency offset of Δf.

The frequency offset of the cavity, due to the tuner offset of Δf is

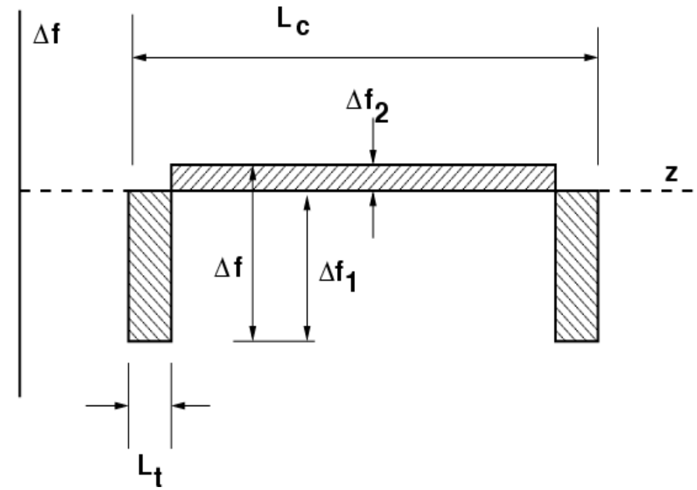


$$\delta f = \frac{1}{L}\int \delta f(z)\,dz = \frac{2L_t}{L_c}\Delta f$$

This is the change of overall frequency of the cavity due to the tuner offset. To satisfy the condition $\frac{\int \delta f(z)}{f_0}dz = 0$ this average value is subtracted off. To simplify the equations, the following substitutions are made:

$$\frac{d^2}{dz^2}\left(\frac{\delta E_0(z)}{E_0}\right) = \frac{8\pi^2}{\lambda^2}\frac{\delta f_0(z)}{f_0} \qquad \Delta = \frac{\delta E(z)}{E_0}, \quad k = \frac{8\pi^2}{\lambda^2}, \quad \delta(z) = \frac{\delta f}{f_0}$$

$$\frac{d^2}{dz^2}\left(\frac{\delta E_0(z)}{E_0}\right) = \frac{8\pi^2}{\lambda^2}\frac{\delta f(z)}{f_0}$$



becomes

$$\Delta'' = k\,\delta(z)$$

and

$$2L_t\,\Delta f_1 + (L_c - 2L_t)\Delta f_2 = 0, \qquad \Delta f_2 - \Delta f_1 = \Delta f, \qquad \Delta f_1 < 0, \quad \Delta f_2 > 0$$

In the center part of the cavity, the field is symmetric around the center, so we choose the origin at the center of the cavity and a parabolic solution: $-L_c/2 < z < L_c/2$

$$\Delta_c = c_2 z^2 + c_1 z + c_0, \qquad c_1 = c_0 = 0 \qquad (why?)$$

The deviation of the field in the central region of the cavity, between the end tuners is

$$\Delta_c'' = 2c_2 = k\,\Delta f_2, \qquad \Delta_c(z) = \frac{\delta E(z)}{E_0} = k\,\Delta f\,\frac{L_t}{L_c}z^2$$

To solve for the fields at the ends, D and its first derivative must be continuous at the interface boundary between the tuner and the rest of the cavity. The form of the field variation in the end tuners is

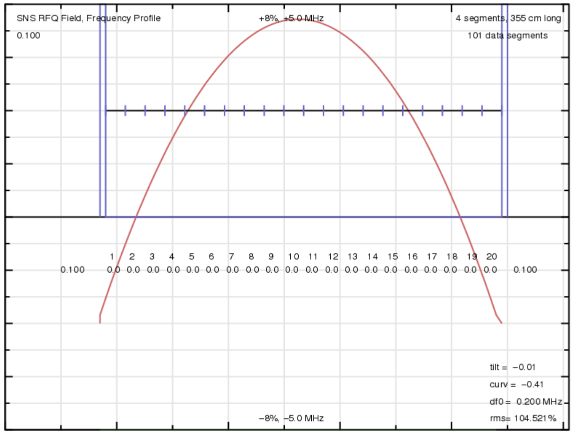
$$\Delta_e(z) = d_2 z^2 + d_1 z + d_0$$

The three conditions that are met, to solve for the three coefficients are

$$\Delta_e(L_c/2) = 0 \qquad \textit{zero slope at ends}$$

$$\Delta_e(L_c/2 - L_t) = \Delta_c(L_c/2 - L_t)$$

$$\Delta_e{}'(L_c/2 - L_t) = \Delta_c{}'(L_c/2 - L_t)$$



Evaluating the coefficients, the field variation in the tuner sections are

$$\Delta_e(z) = \frac{8\pi^2}{\lambda^2}\Delta f\left(\frac{L_c}{2} - L_e\right)\left(-\frac{1}{L}z^2 + z - \frac{1}{2}\left(\frac{L_c}{2} - L_e\right)\right)$$

At the center, $\Delta_c(z=0) = 0$

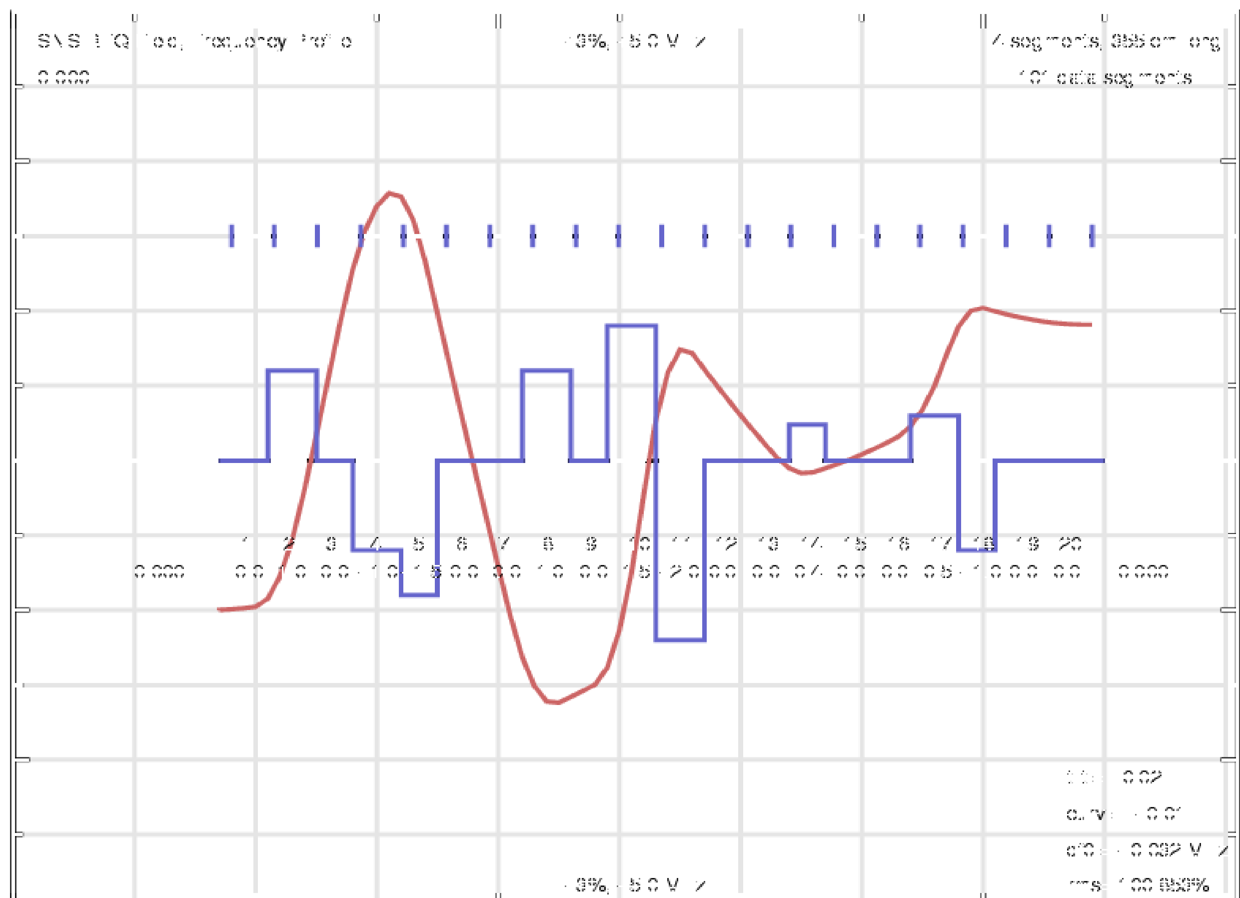
and at the ends $\Delta_c(z = L_c/2) = \dfrac{4\pi^2}{\lambda^2}\Delta f\ L_t(L_c/2 - L_t)$

A More General Tuning Case

In general, a field profile determined by a bead pull will indicate a more complex variation of the field along the axis.   If the RFQ is supplied with tuners along the structure, the variations may be minimize by varying the local cutoff frequency with the tuners to produce the required field profile.

The program shown here, **rfqtune**, was used to tune the SNS RFQ, based on bead pull measurements, iterating the setting of temporary adjustable tuners.

The adjustable tuners were replaced by fixed tuners manufactured to the sizes determined during the tuning process.



Bead Pulling

The electric and magnetic field can be separately measured in the same location by using both a metallic bead, which removes E and H-field volume, and then retracing the path with a dielectric bead, which alters the E-field only.

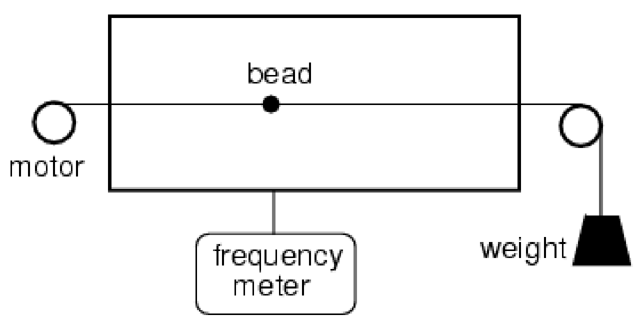
Subtracting one measurement from the other will separate the E and H fields in the path of the bead.

The constant *k* depends on the geometry of the perturber. For a sphere, *k* = 3.

$$\omega^2 = \omega_0^2 \left(1 + k \frac{\int_{bead} (\mu_0 H^2 - \epsilon_0 E^2)\, dV}{\int_{cavity} (\mu_0 H^2 + \epsilon_0 E^2)\, dV} \right)$$

For small perturbation in frequency, where t is the volume of the bead. The frequency shift is proportional to the square of the field intensity.

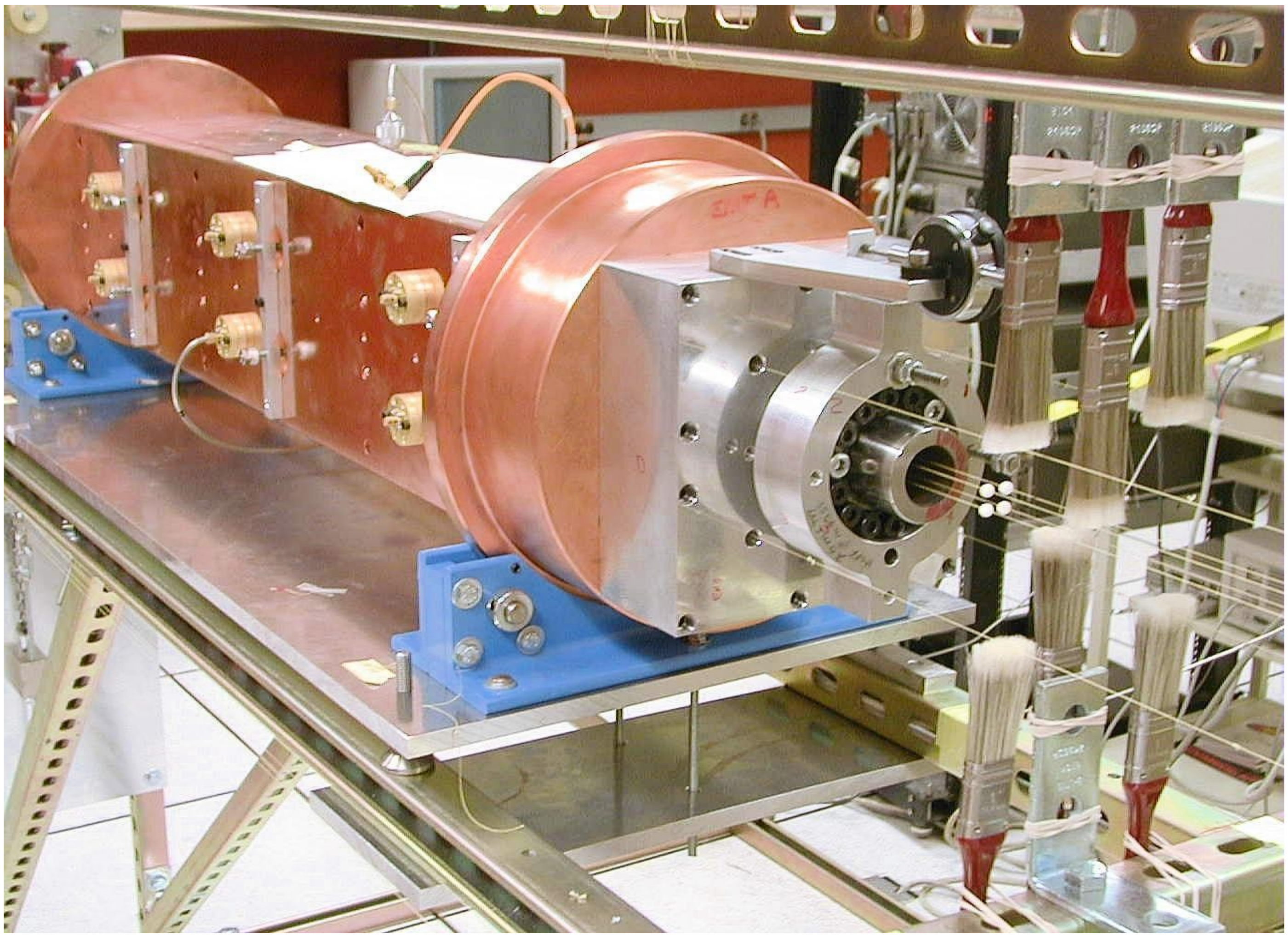
$$\frac{\Delta\omega}{\omega_0} = \frac{3\tau}{4U_{cavity}} \left(\epsilon_0 E^2 - \frac{1}{2} \mu_0 H^2 \right)$$



The beam is usually drawn through by a motor drive, and the measured frequency shift recorded on a computer.

Bead Pull Apparatus

During the development of the SNS RFQ, a cold model was constructed and the end geometry determined by the bead pulling procedure.



Here, four beads are pulled independently through the four quadrants of the RFQ near the vane tips near maximum E-field.

Also, four metallic beads are pulled near the outer wall near the location of maximum H-field.

Later, only one bead needed to be pulled, as the fields were well correlated with each other.

Transverse Field Stabilization Methods

The 4-vane RFQ comprises four weakly-coupled resonators, coupled primarily in the end region. If the four quadrants are not precisely in tune, their amplitudes will differ from each other, and unwanted transverse fields result, as the quadrupole symmetry is broken.

This is a serious drawback of the 4-vane RFQ design. (The 4-rod RFQ does not suffer from this.) An analysis of the field profile dependence on local frequency perturbation

$$\frac{d^2}{dz^2}\left(\frac{\delta E_0(z)}{E_0}\right) = \frac{8\pi^2}{\lambda^2}\frac{\delta f_0(z)}{f_0}$$

shows that the sensitivity of field perturbations to errors scales as the square of the length of the RFQ.

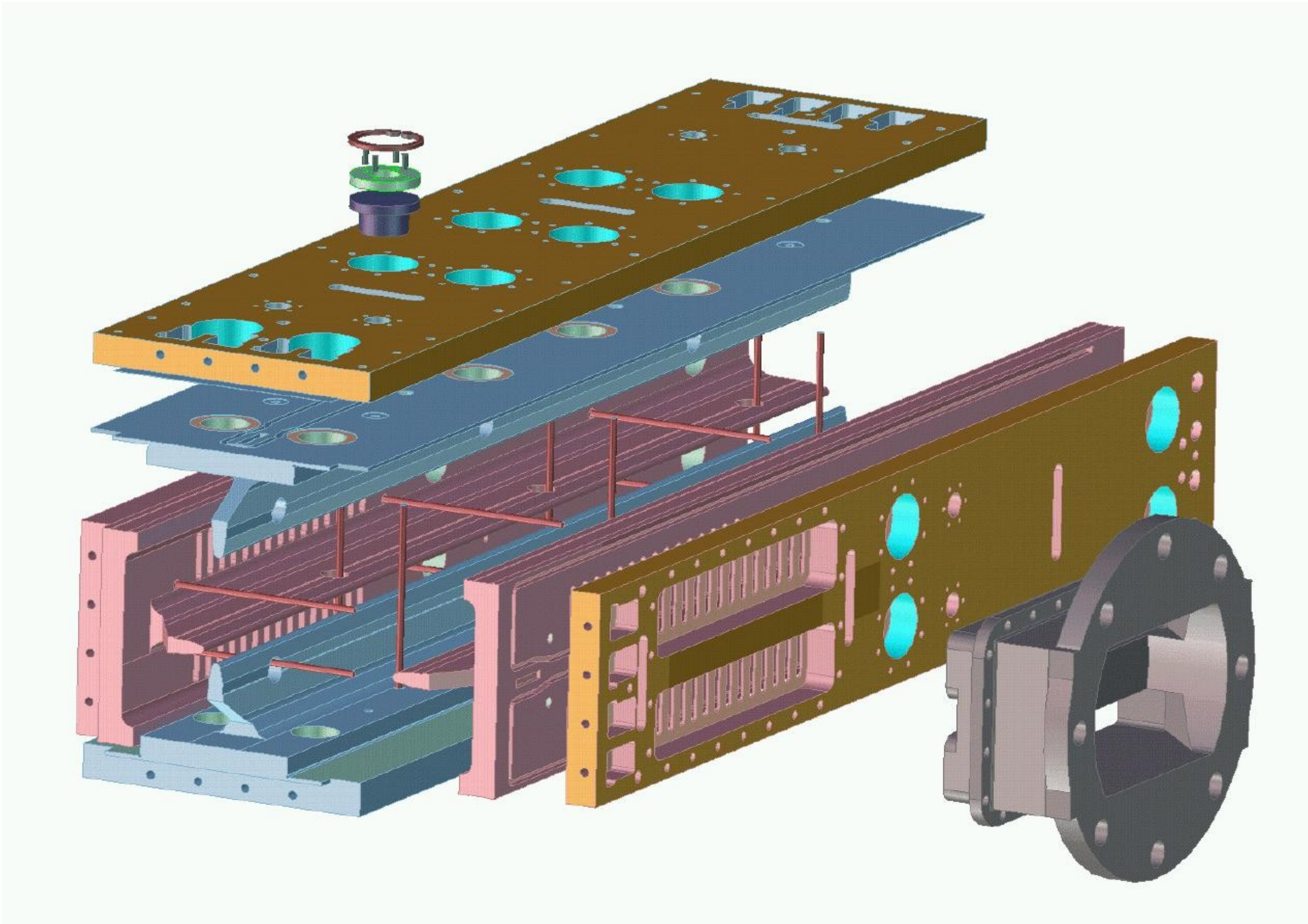
$$\frac{\Delta E}{E_0} = \pi^2\left(\frac{L}{\lambda}\right)^2\frac{\Delta f_{cavity}}{f_0}$$

The TE_{210} and TE_{110} frequencies are usually very close together, and the dipole mode can easily mix with the quadrupole mode. The dipole field will deviate the orbit trajectory off the geometric axis, reducing the acceptance of the RFQ.

In practice, RFQs that are more than about 5 rf-wavelengths long require very precise machining and assembly tolerances.

Various schemes have been used to reduce this sensitivity to errors.

SNS RFQ, showing pi-mode couplers and cooling passages



Vane Coupling Rings

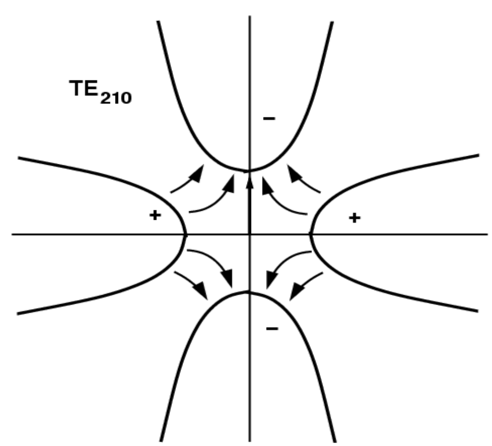
The opposite vanes in an RFQ are at the same potential, so VCRs are installed to lock the potentials together.

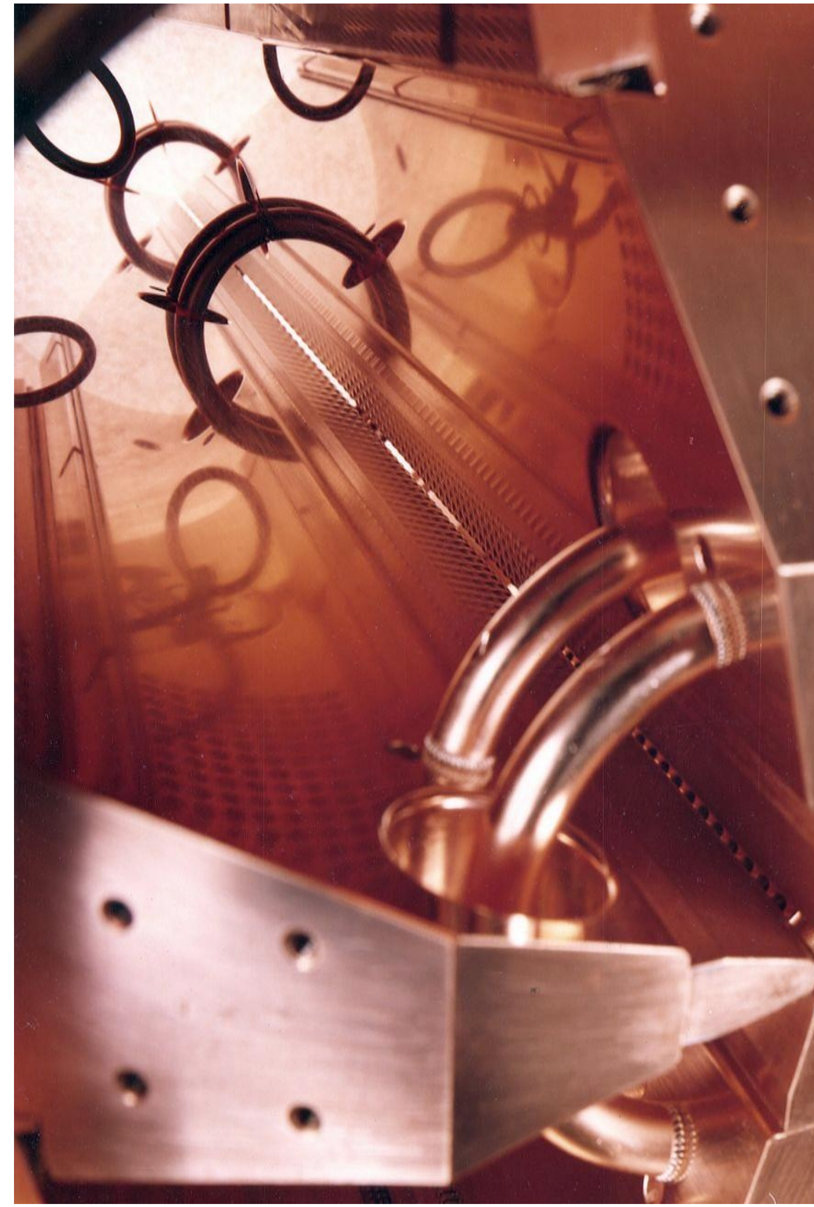
The dipole fields are "shorted out". The dipole modes do not disappear, but are moved far away from the quadrupole frequency and the construction tolerances of the RFQ are significantly eased.

The VCRs alter the resonant frequency of the RFQ in a way that is hard to calculate, and also cause a periodic variation in the field profile which must be taken into account.

VCRs have been used on many RFQs.

They are not applicable to high duty-factor RFQs.





Pi-Mode Stabilizers

The pi-mode stabilizers work by coupling to the quadrupole and dipole modes in the RFQ. Rods extend across pairs of quadrants, threading through holes in the vanes.

Dipole modes induce strong currents in the rods, moving the dipole mode up in frequency.

Quadrupole modes do not couple to the rods, so the quadrupole frequency is relatively unchanged.

This technique is used on the JPARC and SNS RFQs, and is suitable for high duty-factor operation, as the rods can be water-cooled by connection to an external water supply.

Both the VCRs and Pi-mode stabilizers provide very strong transverse stabilization, but no longitudinal stabilization. However, as the fields in the four quadrants are strongly locked together, tuning the RFQ is a simpler problem of just achieving the proper longitudinal field profile.

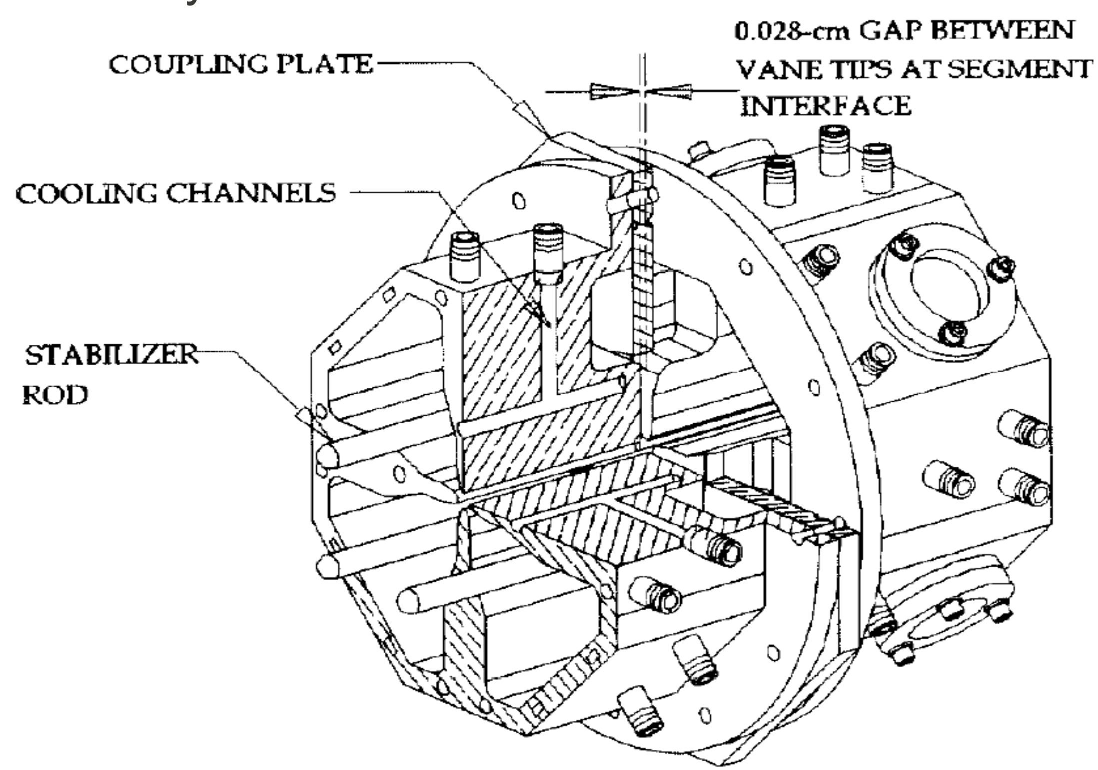
Resonant Coupling RFQ Stabilization

Since the sensitivity of the field distribution is proportional to the square of the length of the RFQ, the resonant coupling approach, used by LANL and others, is to use short modules, coupled to adjacent modules.

This technique is used on LEDA, a very high-power proton RFQ produced at Los Alamos, which provides more robust longitudinal field stability, but less enhancement of transverse field stability.

The RFQ is broken up into short electrical segments, each with vane cutbacks, that exhibit a stability of a series of short RFQs.

The stabilizer rods at each end of the structure provide an additional separation of the quadrupole and dipole modes. *(Why?)*



RFQ Mechanical Engineering

RFQs are precision mechanical devices that require machining and alignment tolerances of the order of 10-20 microns.

Varaible tuners may be provided, or fixed tuners, determined at the initial tuning of the RFQ, and variable water temperature used during operation.

Vacuums in the range of 10^{-7} Torr are usually provided, by turbo, cryo, or ion pumps.

RF is introduced through single or multiple loop or iris couplers.

Additional RF sense probes are provided to monitor cavity field level and to provide signals for RF stabilization systems.