PXIE RFQ Beam Dynamics and Error Tolerances

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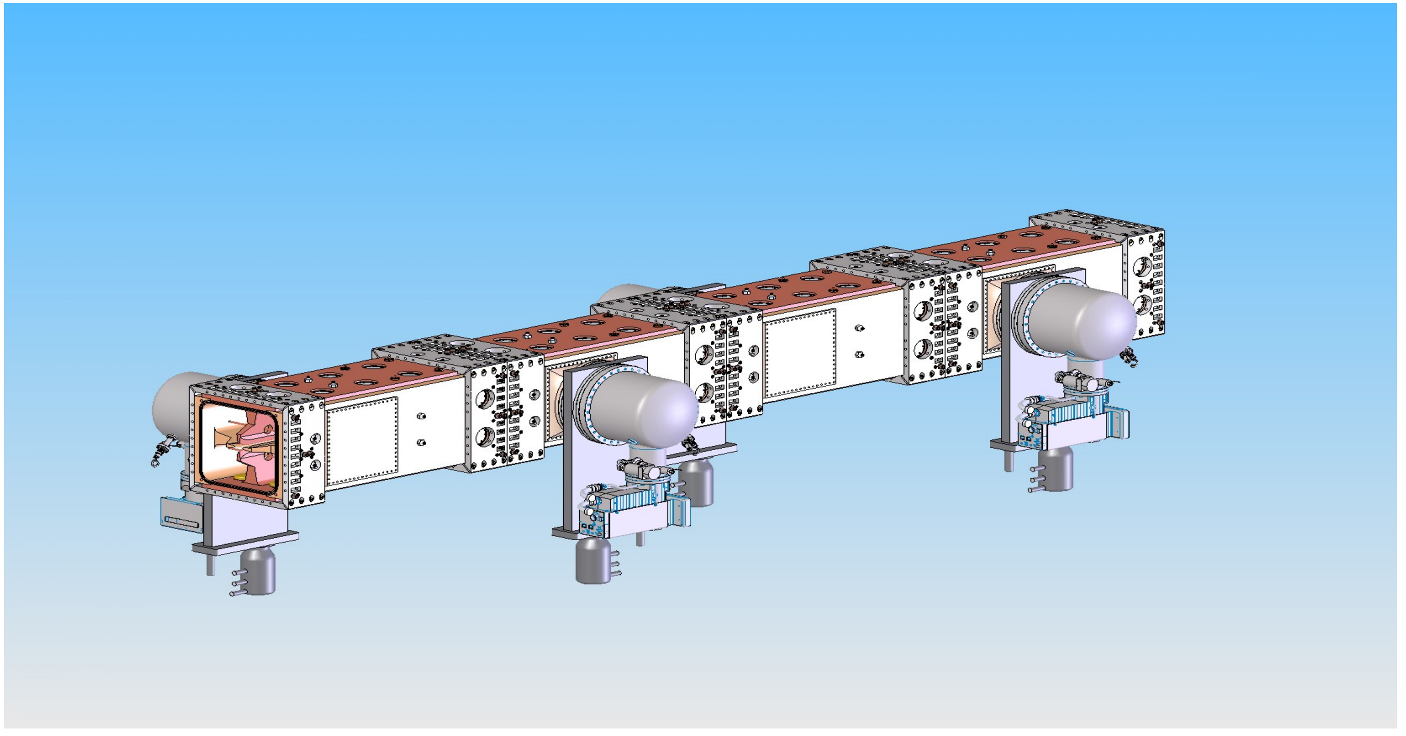


RFQ Parameter List

	PXIE	IMP	
Input energy	30	35	keV
Output energy	2.1	2.1	MeV
Frequency	162.5	162.5	MHz
DC Current	5-15	5-20	mA
Vane-vane voltage	60	65	kV
Vane Length	444.6	416.2	cm
RF Power	100	110	kW
Beam Power	10.5	21	kW
Duty Factor	100	100	percent
Transverse emittance	<0.15		mm-mrad, rms, normalized
Longitudinal emittance	<1.0		keV-nsec

What's New?

The beam dynamics design is frozen for both machines

At FNAL's request, an exit radial matcher has been added to reduce the divergence of the output beam

Transmission >99% to 10 mA

Output transverse emittance <0.15 pi mm-mrad to 10 mA

Longitudinal emittance <0.25 pi mm-mrad (<.78 keV-deg) to 10 mA

Vane length is 443.0 cm, cavity length 444.66 cm

Error analysis of the structure and of the beam dynamics implications carried out

LEBT chopper design integrated with the transverse acceptance of the RFQ

Detailed MWS simulations of the structure (G. Romanov, FNAL) carried out

Design Highlights

Constant cross-section of structure along entire length
constant transverse vane radius: only one form cutter profile needed

The minimum longitudinal vanetip radius = 1.03 cm: easy design of cutter

Four modules, joined with butt joints

Each module assembled with brazes: no electron-beam welding, except to close the ends of the gun-bored water channels.

No complex brazing operations: (No Glidcop in structure)

Wall power density less than 0.7 Watts/cm^2 CW (SNS was 1.7 at 6% duty factor)

Pi-mode stabilizers offer very large mode separation and field stability against machining errors.   32 stabilizers used: 4 pairs/module.

Mode separation, quadrupole to dipole frequency is 17.5 MHz.

Length only 2.4 free-space wavelengths long (SNS was over 5 wavelengths)

80 tuners, 48 sensing loops, two drive ports

Beam Dynamics Simulations

Beam load derived from ion source emittance measurements: halo present.
Capture is 99.81% of 5 mA input beam

Transverse output emittance 0.15 pi mm-mr
Longitudinal emittance 0.68 keV-nsec

Ellipse parameters at cell 208:

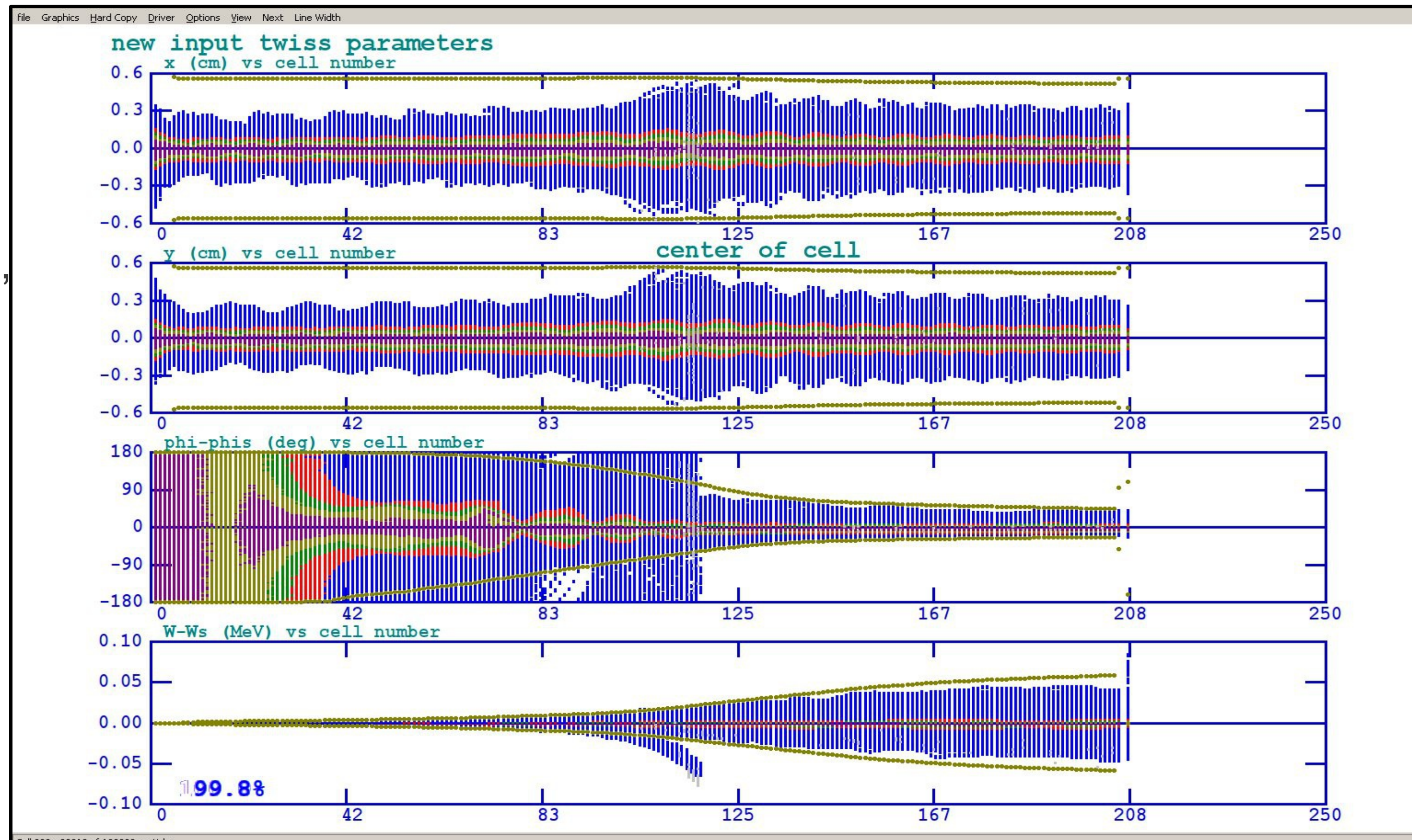
	alpha	beta	Emit,u,rms	Emit,n,rms
		cm/rad	cm-mrad	cm-mrad
x:	0.1833	23.1221	0.2176	0.01463
y:	-0.0853	11.8872	0.2174	0.01462
		deg/MeV	MeV-deg	MeV-deg
z:	0.0428	1010.4380	0.0396	0.03957

Percent of beam within rms multiples for each phase plane:

	1rms	2rms	3rms	4rms	5rms	6rms	7rms	8rms	9rms	10rms
x:	42.2	66.5	80.0	87.3	91.4	94.1	95.9	97.0	97.8	98.4
y:	42.2	66.5	80.1	87.2	91.3	93.9	95.6	96.9	97.8	98.4
z:	47.5	70.5	83.3	88.6	91.2	93.1	94.5	95.7	96.7	97.4

Simulation using 100,000 particles, 5 mA

Very little beam spilled in the RFQ.



Error Analyses

Beam parameters at the end of the RFQ are modeled as a function of:

- Input matching conditions as a function of input Twiss parameters
- Input current
- Input centroid offset created during transition of LEBT chopper
- Flat gradient errors
- Gradient tilts
- Halo content for 100,000 particles
- Periodic field oscillation due to the 20 tuners in each quadrant
- 20 linacs with random errors along the structure

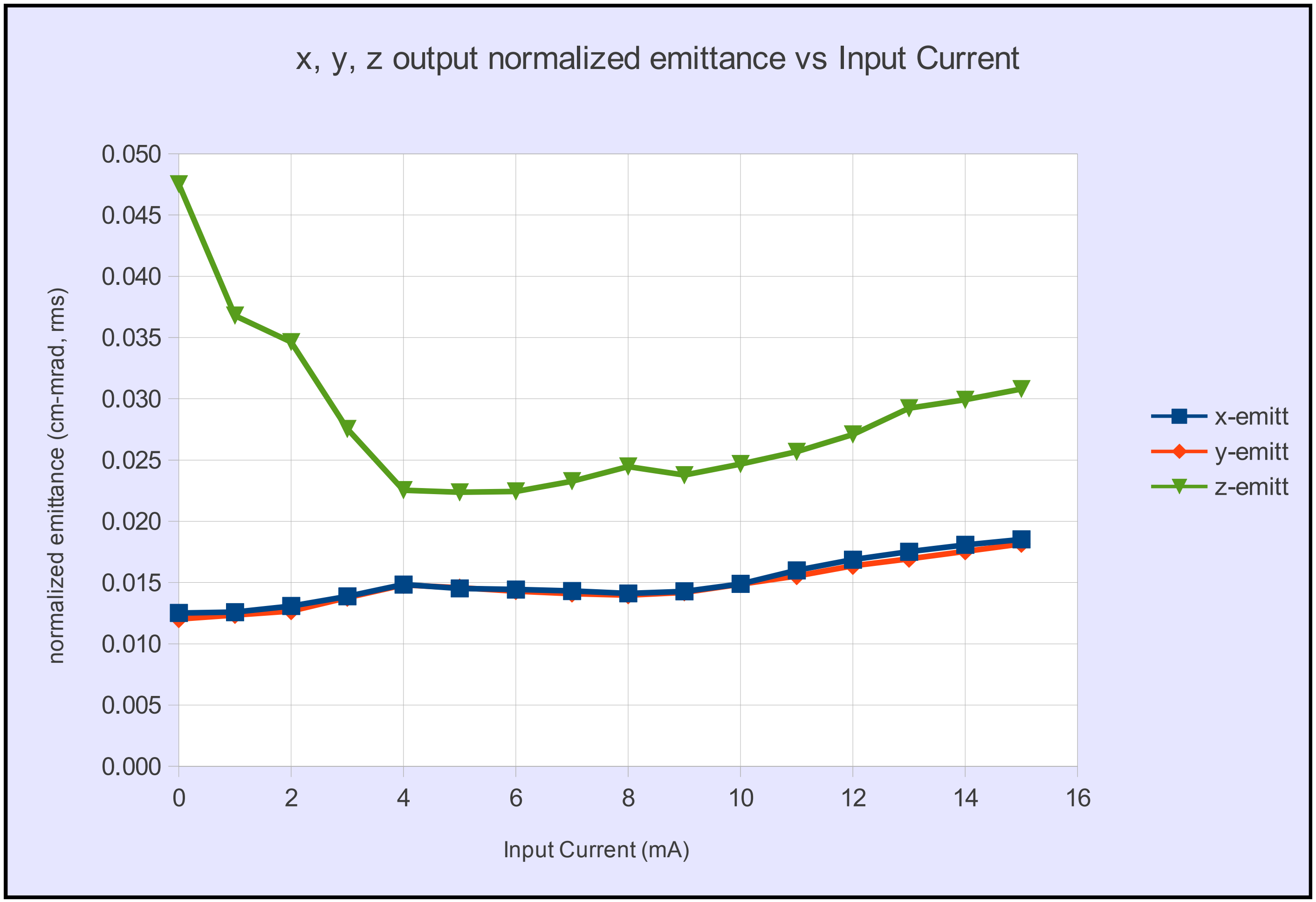
All simulations use a particle distribution based on the measured emittance distribution

All but the 20 tuner errors simulated with PARMTEQM; the tuner error with a modified version of PARMTEQ that allows arbitrary field variations.

Output Emittance vs. Input Current

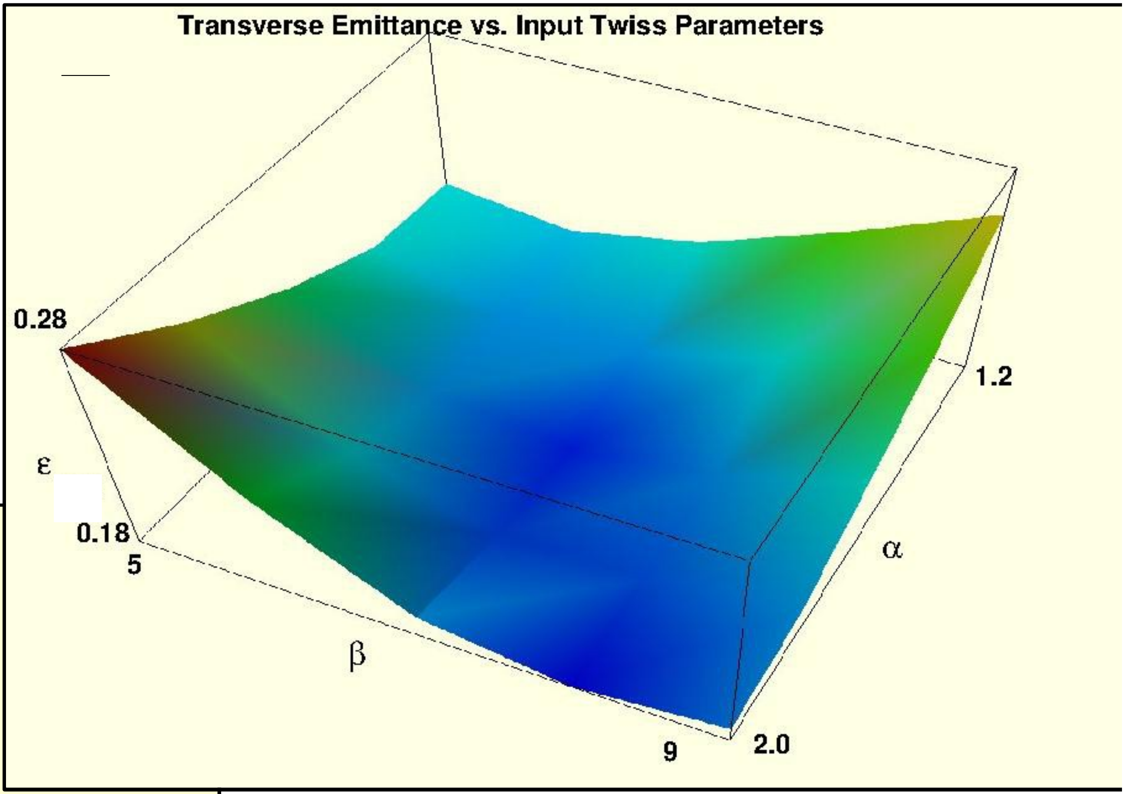
Optimized input current is 5 mA.   Other current values use same input match. Re-matching at other currents may result in lower output emittance, so this represents the worst case away from nominal. The transverse input emittance is 0.011 pi cm-mrad, normalized, rms, derived from emittance scans of the ion source.

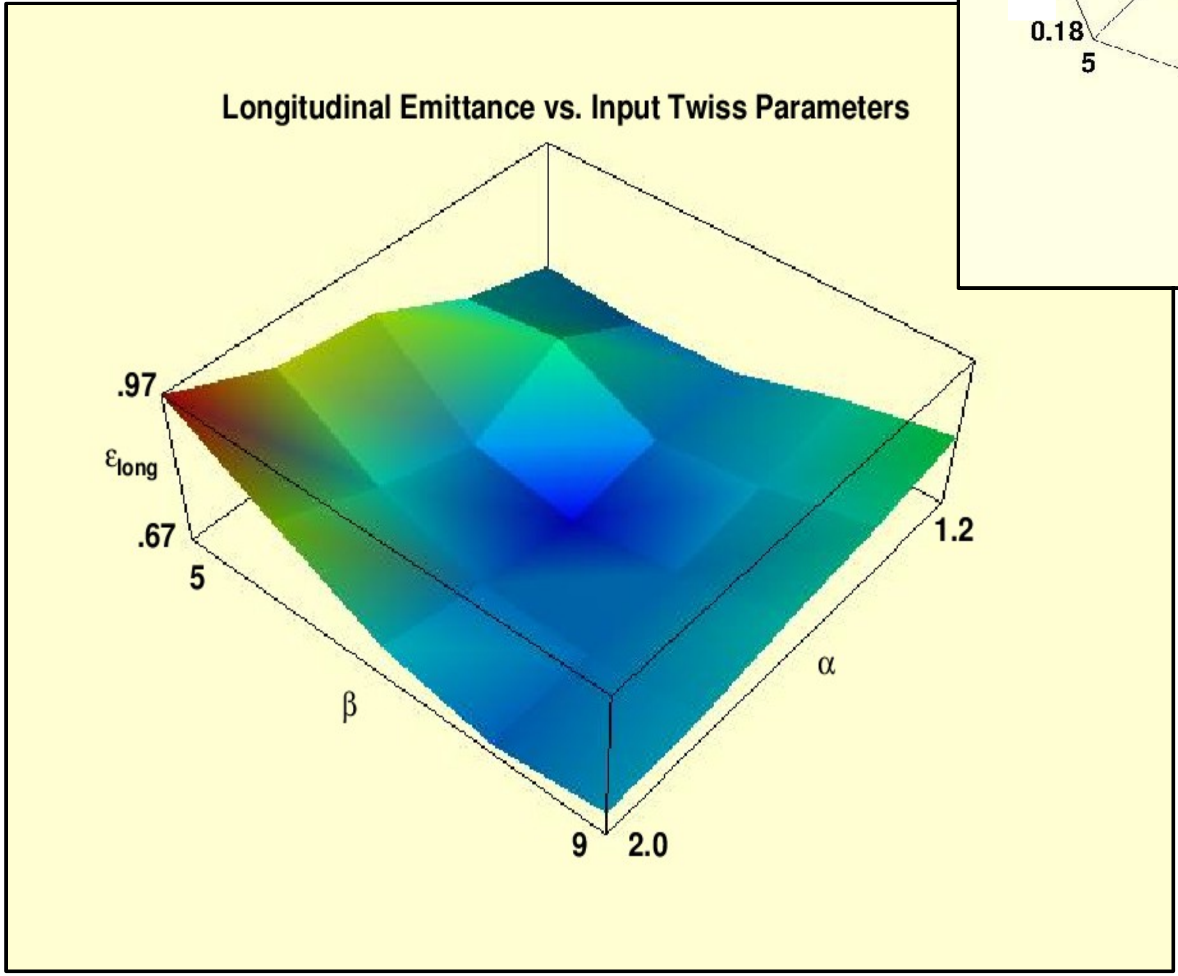
Output longitudinal emittance at 5 mA is 0.68 keV-nsec.



Scan of Output Emittance vs. Input Twiss Parameters

The output emittances are minimized for the nominal value of the input Twiss parameters. Transmission is greater than 99% for all cases.





5 x 5 scan of input Twiss parameters

Nominal input match:

Alpha = 1.6
Beta = 0.07 m (7 cm)

Scan beta from 0.05 to 0.09 meters
Scan alpha from 1.2 to 2.0

Output Beam Parameters vs. RFQ Field Errors

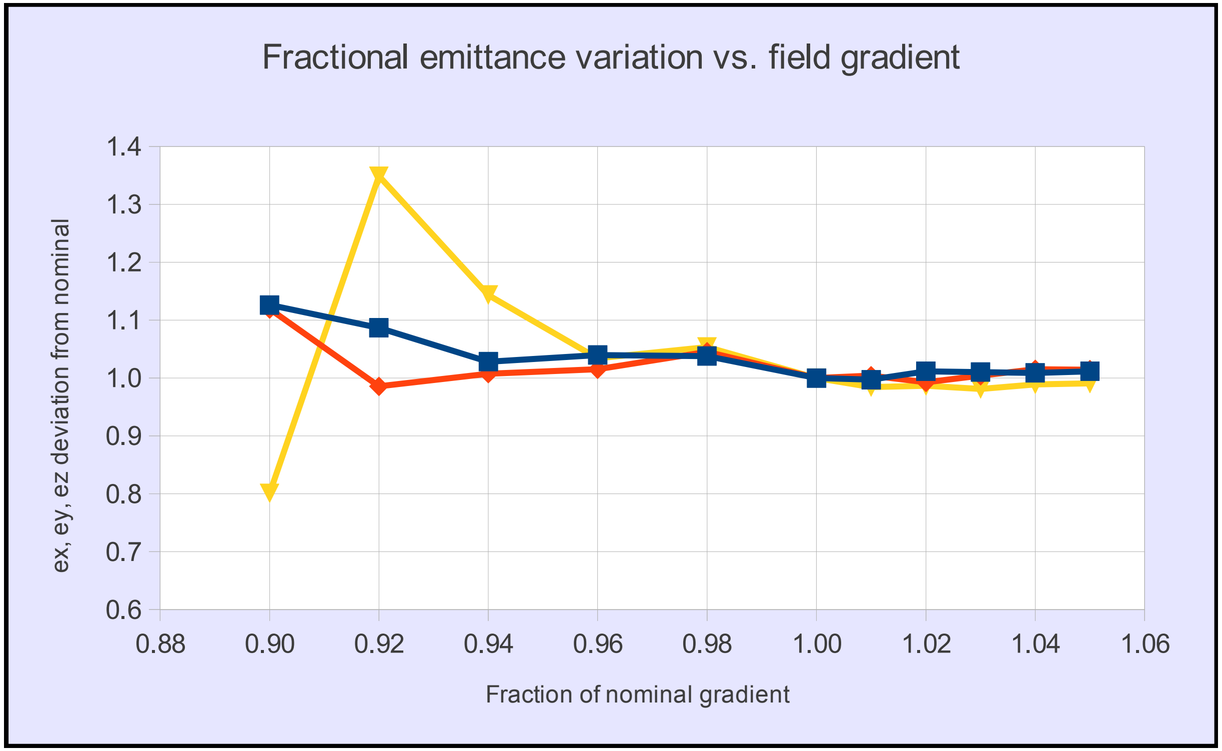
Errors Considered

- Flat-field gradient error
- Field tilt error, field held constant at entrance
- Field tilt error, field held constant at exit
- Field ripple error from the tuners

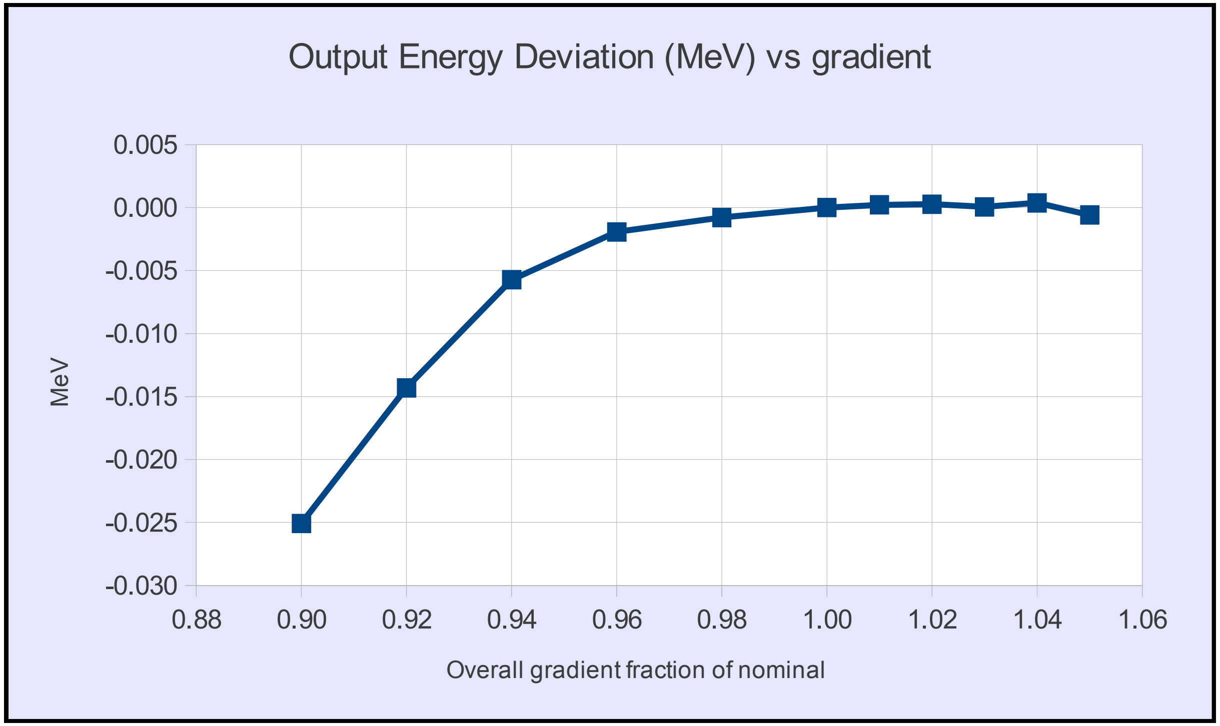
PARMTEQM can only simulate the first three: the field ripple is simulated with another version of parmteq with arbitrary field error.

Independent Parameter:

Flat field gradient



Output emittance and deviation from nominal 2.13 MeV output energy as a function of flat gradient error.



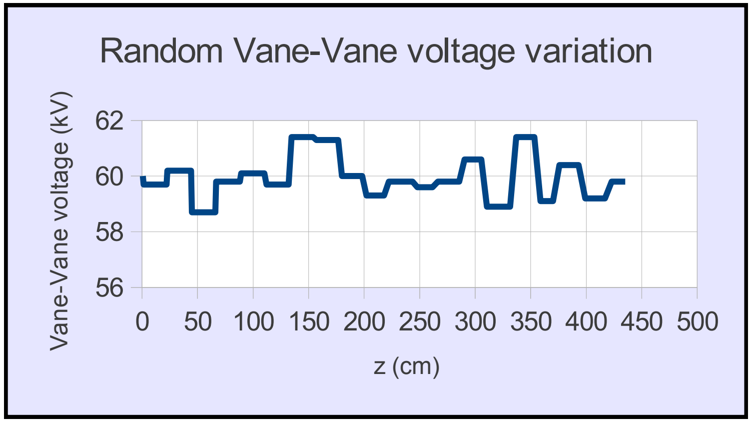
Independent Parameter:

Random Field Errors along Z

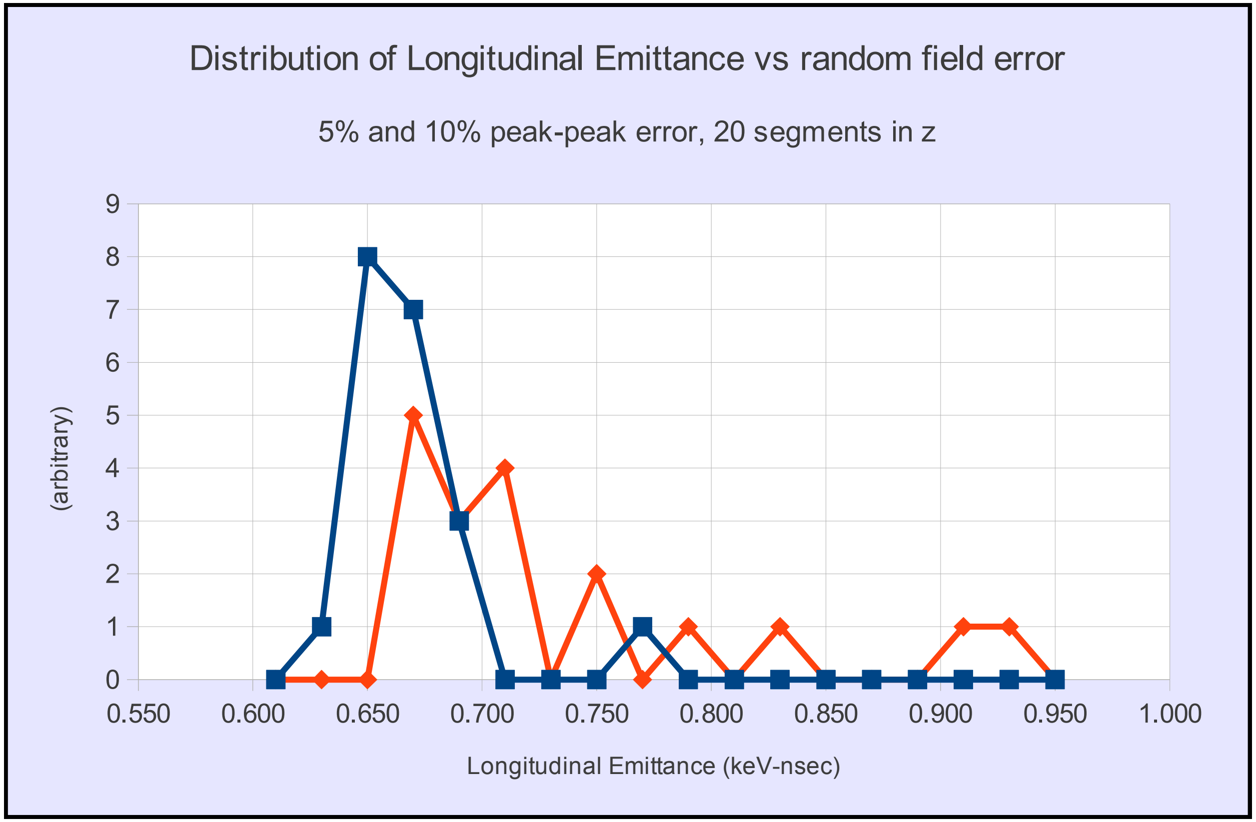
20 linacs each with 5% and 10% peak-to-peak random field error in each of 20 equal length segments along z, same distribution as number of tuners.

Almost no effect on transverse emittance or capture. Plot histogram of output longitudinal emittance in MeV-deg.

Zero error longitudinal emittance is 0.038 MeV-deg = 0.65 keV-nsec



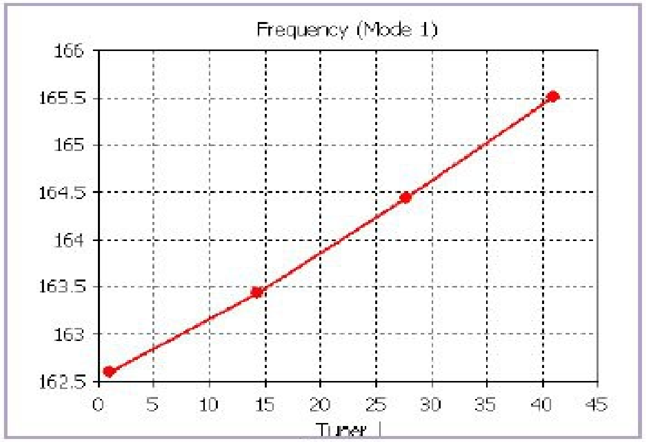
Sample random voltage variation along RFQ.



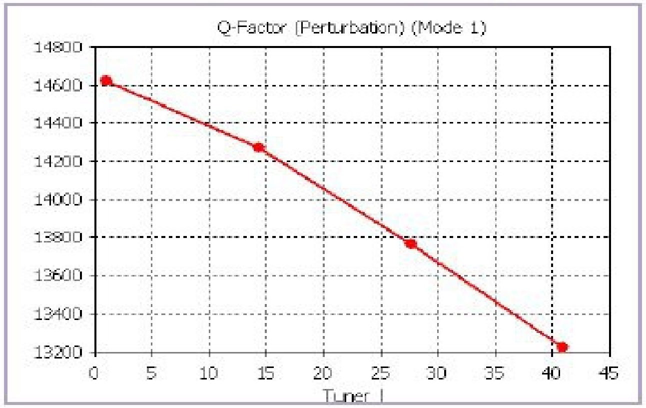
Field Ripple due to the Tuners (G. Romanov)

Effect of the plug tuners.

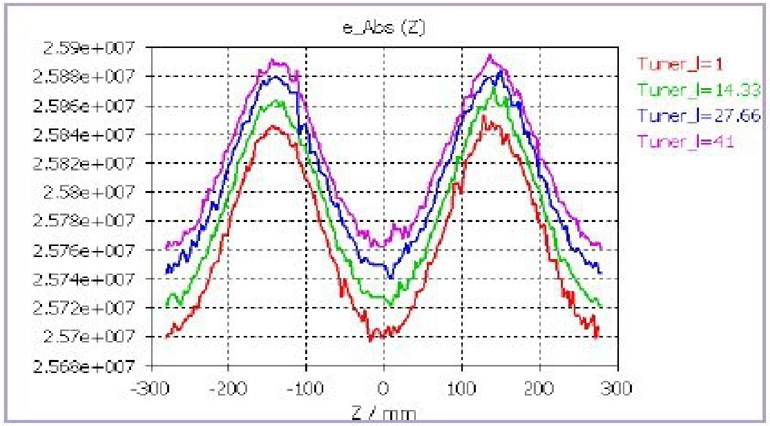
Tuner diameter – 60 mm,
Penetration 0-40 mm



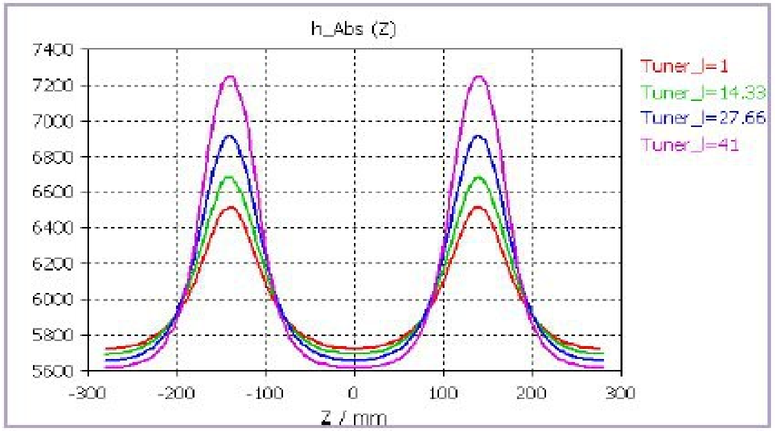
Operating mode frequency



Q-factor



E_abs in the gap (X=Y=5 mm) vs Z. No visible changes.



H_abs in the center of quadrant (X=Y=100 mm) vs Z.

Tuner sensitivity = 0.75 MHz/cm. Peak field ripple on axis less than 0.5% p-p.

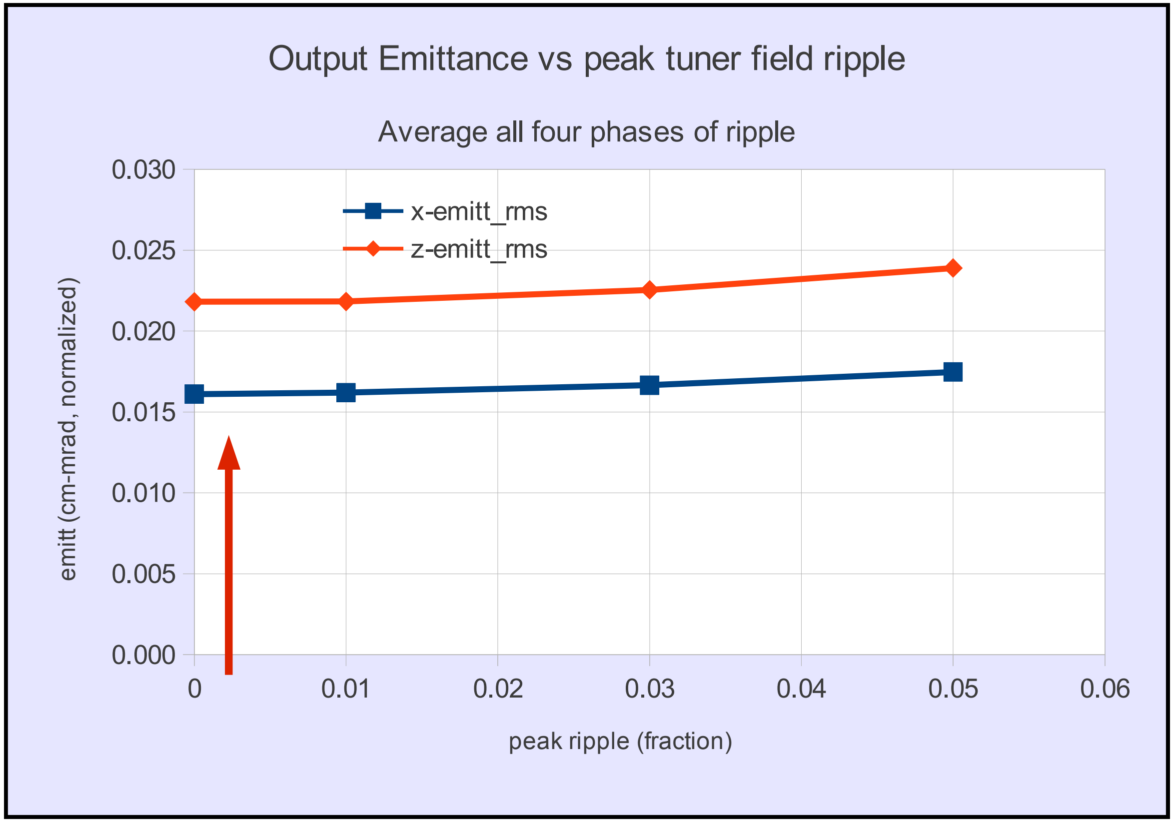
Output Emittance vs. Tuner Ripple on the Field Distribution

The 20 equi-spaced tuners in each quadrant produce a variation in the field distribution. The peak-to-peak variation of the accelerating fiend is less than 1%, but is larger in the outer region near the tuners.

An alternate version of Parmteq was modified to include the tuner ripple on the beam axis. The output emittance for four phases (+sin, +cos, -sin, -cos) of the ripple were averaged, as the absolute phase, relative to the position along the axis, will not be known until the RFQ is tuned.

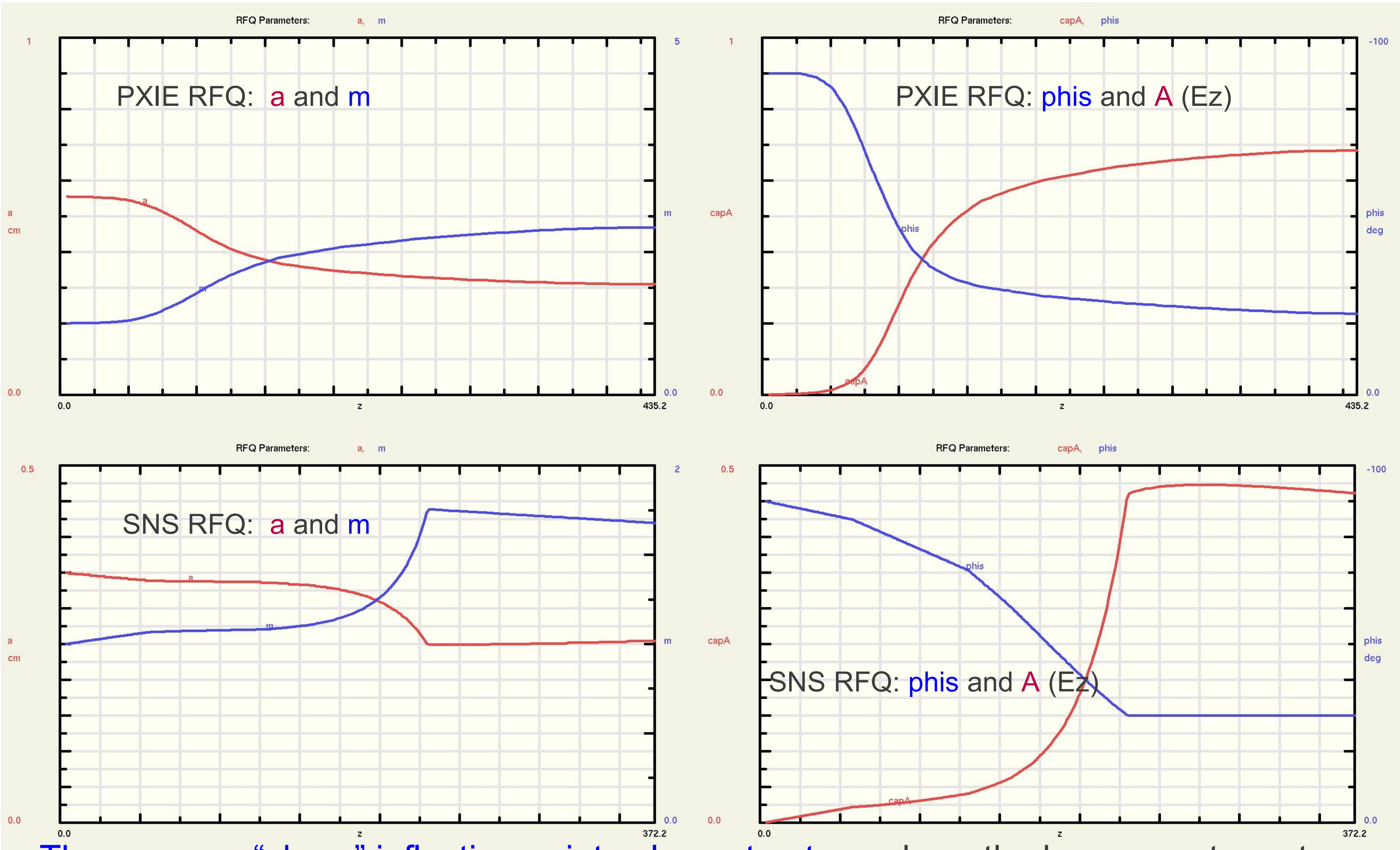
MWS simulation shows a p-p ripple of 0.5% at 5 mm from the axis, corresponding to a peak fraction of 0.0025 on the plot (near zero).

The ripple in the field due to the tuners will not result in a measurable emittance increase.



Why is this design so error tolerant?

Compare parameters to SNS RFQ, which is designed for much higher current.



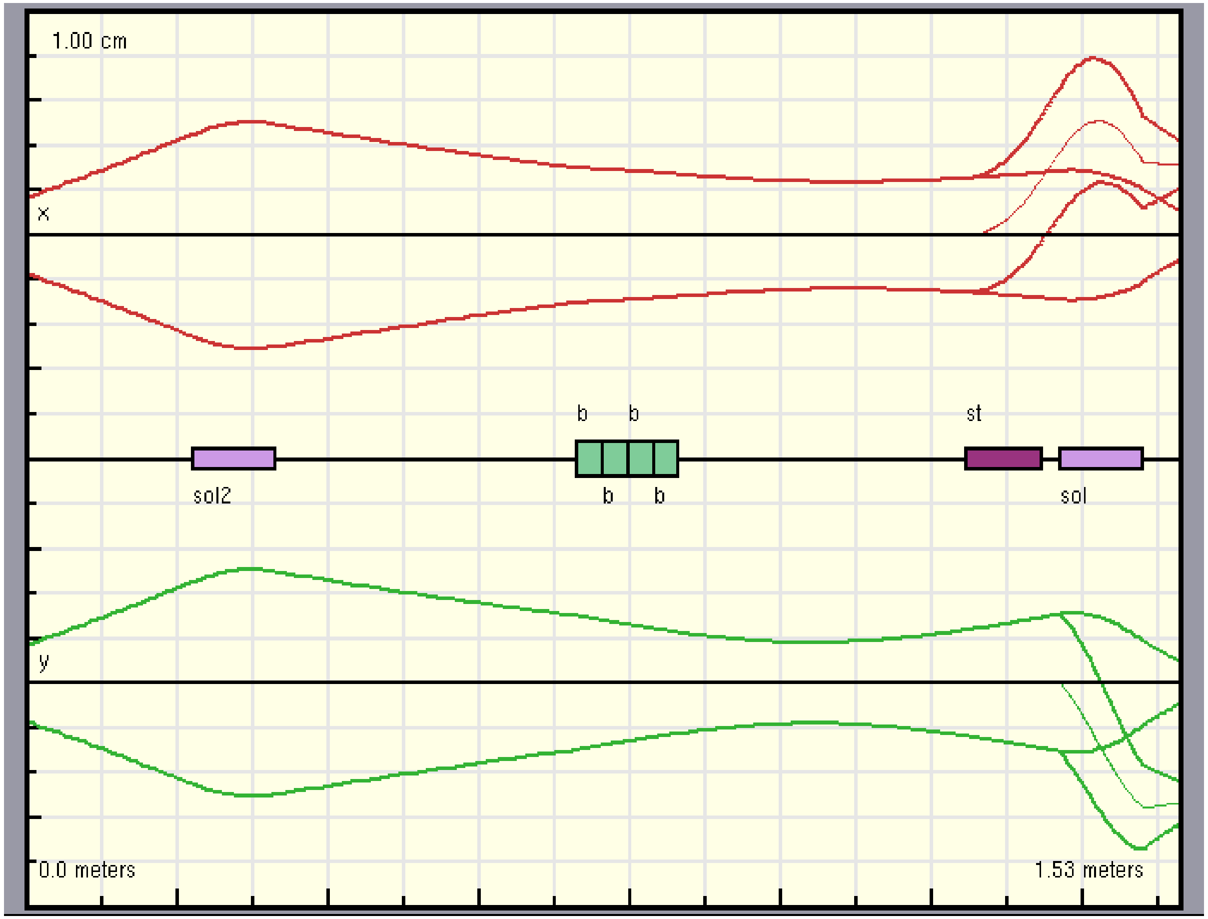
There are no “sharp” inflection points along structure where the beam must meet criteria of proper bunch shape, space charge density, etc. The PXIE aperture is large. Most of the length of the PXIE RFQ is devoted to acceleration (plotted vs. z). Also, the PXIE RFQ has a larger aperture, thus larger transverse acceptance.

RFQ Transmission with LEBT Chopper

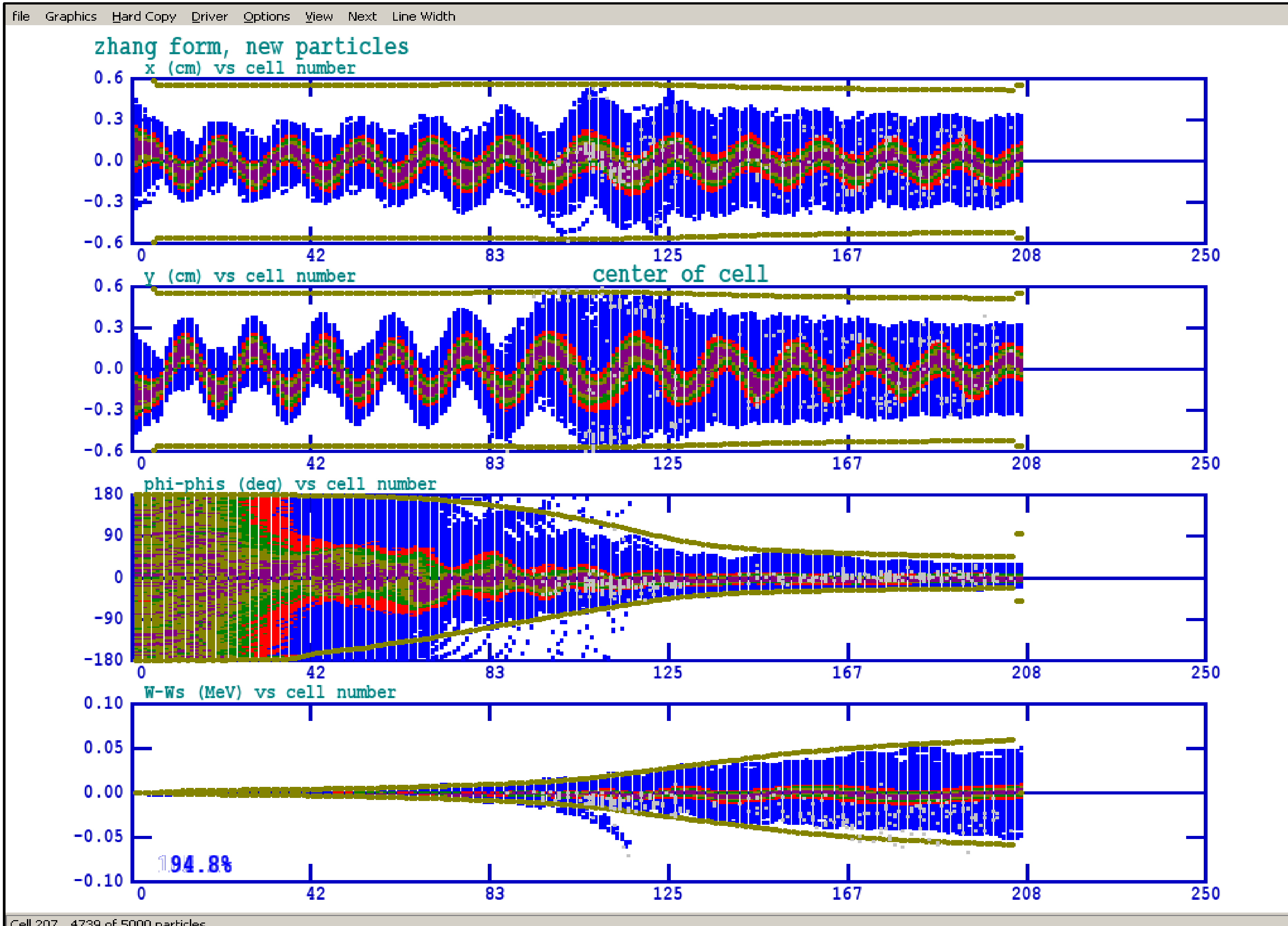
The 2-solenoid LEBT chopper places a parallel-plate deflector in front of the final focusing solenoid. A 0.5 cm radius aperture is placed in the entrance flange of the RFQ.

The maximum chopping frequency is 1 MHz to reduce the average beam current to 1 mA.

The rise/falltime of the beam due to the risetime of the electronics and the transit time of the beam through the 10-long chopper is less than 50 nsec. During this time, the beam will still be captured by the RFQ and sent to the MEBT.



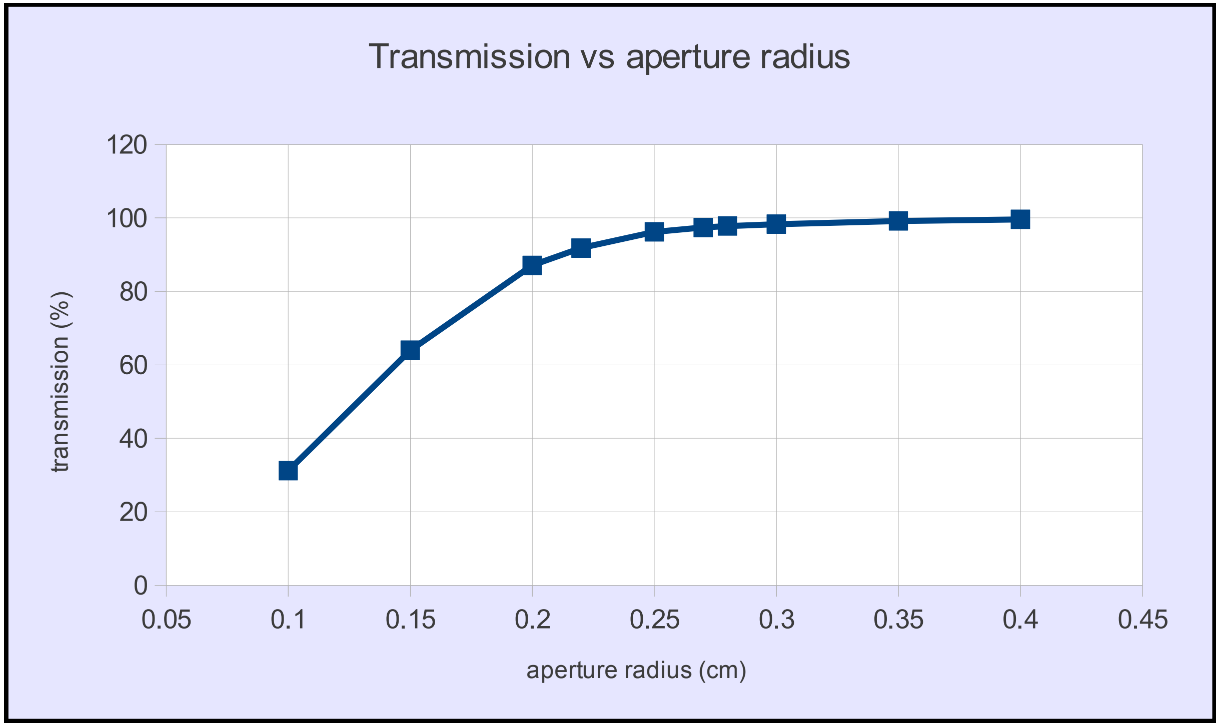
Beam Trajectory of partially chopped beam. About 12 betatron oscillations.



What goes in of axis comes out off axis.

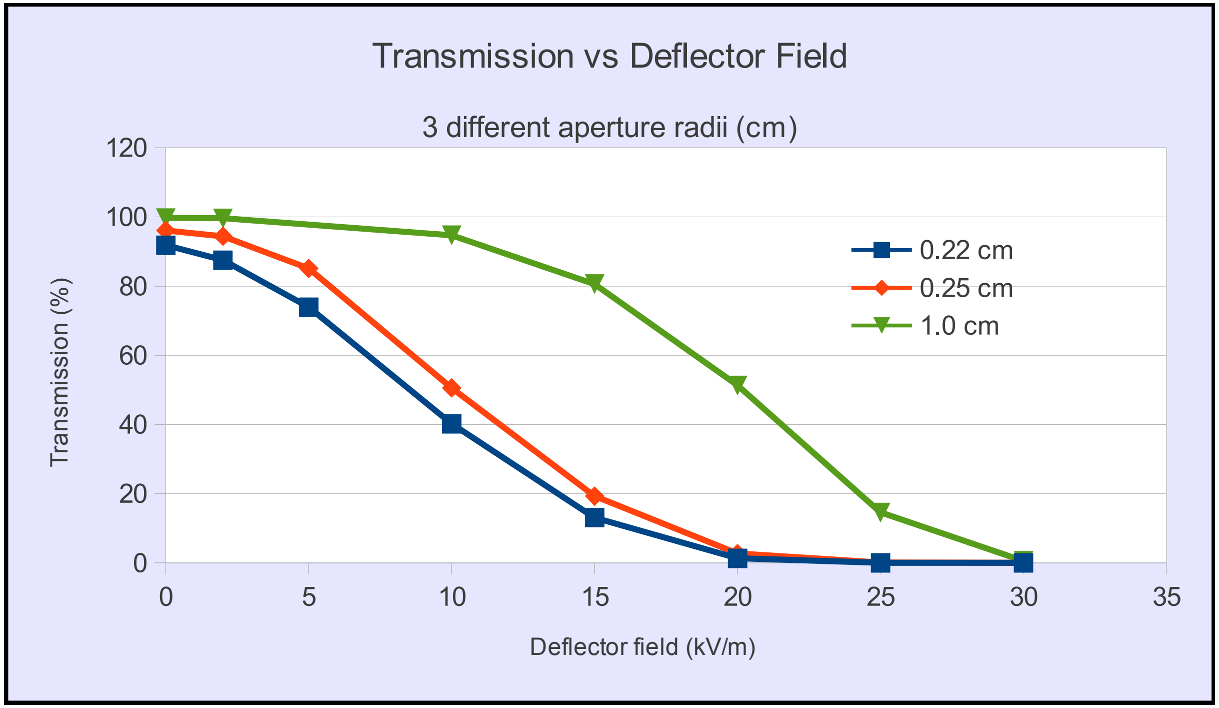
RFQ Entrance Aperture

Transmission through the RFQ of unchopped beam as a function of an aperture at the entrance with given aperture radius



The beam distribution is derived from the emittance measurement and includes halo particles.

The LEBT chopper field requires at least 30 kV/m (±465 volts across a 3.1 cm gap) to extinguish the beam. A larger field will be available.



Transmission through the RFQ of the chopped beam for three different aperture radii as a function of the field on the 11 cm long chopper.

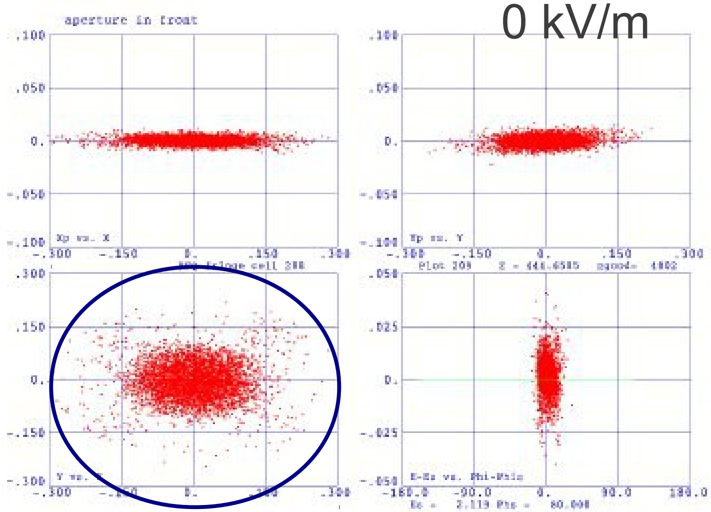
The baseline entrance aperture radius is 0.25 cm.

Particle and phase space distributions at the RFQ exit for various chopper fields.

Almost all of the partially chopped beam stays within the unchopped beam profile

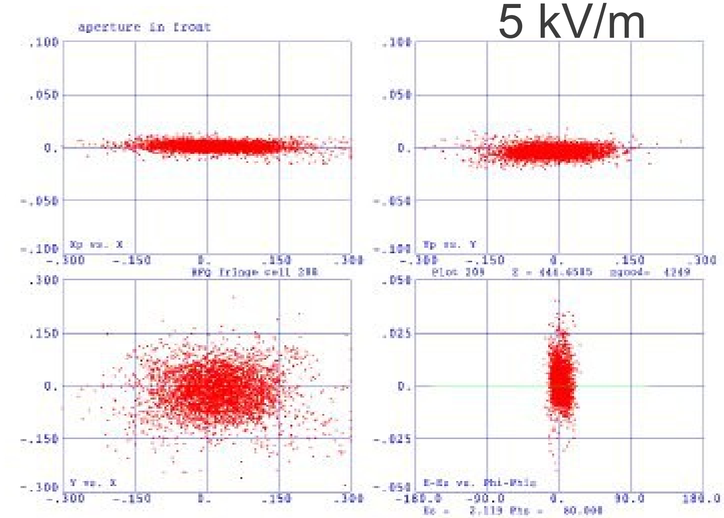
Output Phase Space vs. LEBT Chopper Field, 0.25 cm radius entrance aperture

0 kV/m



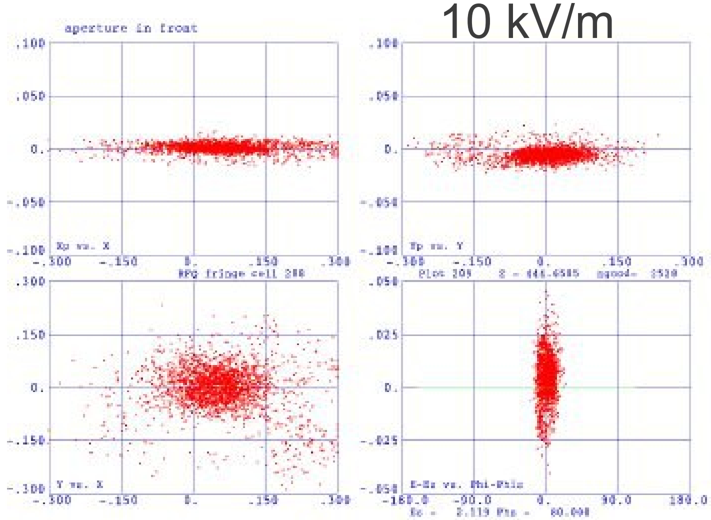
0 kV/m chop, 96.1% transmssion

5 kV/m



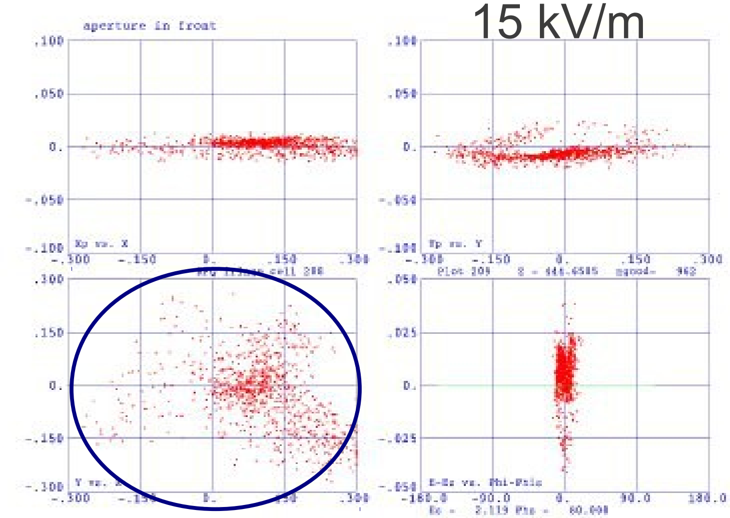
5 kV/m chop, 85.1% transmssion

10 kV/m



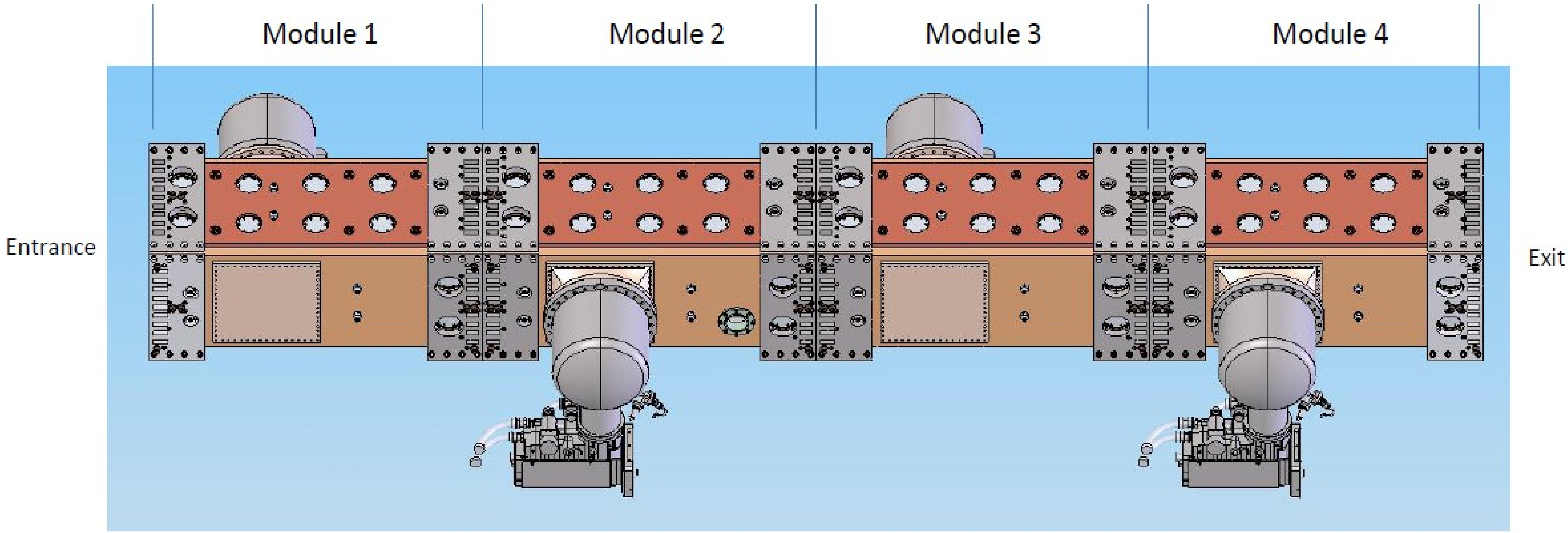
10 kV/m chop, 50.6% transmssion

15 kV/m



15 kV/m chop, 19.3% transmssion

RF Structure

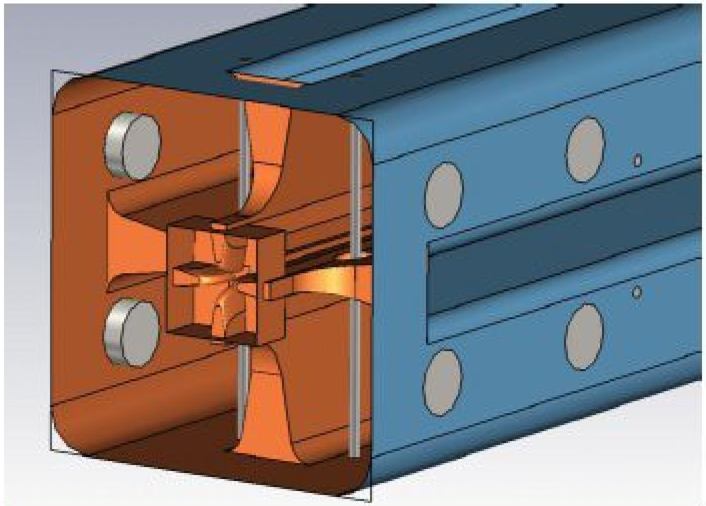


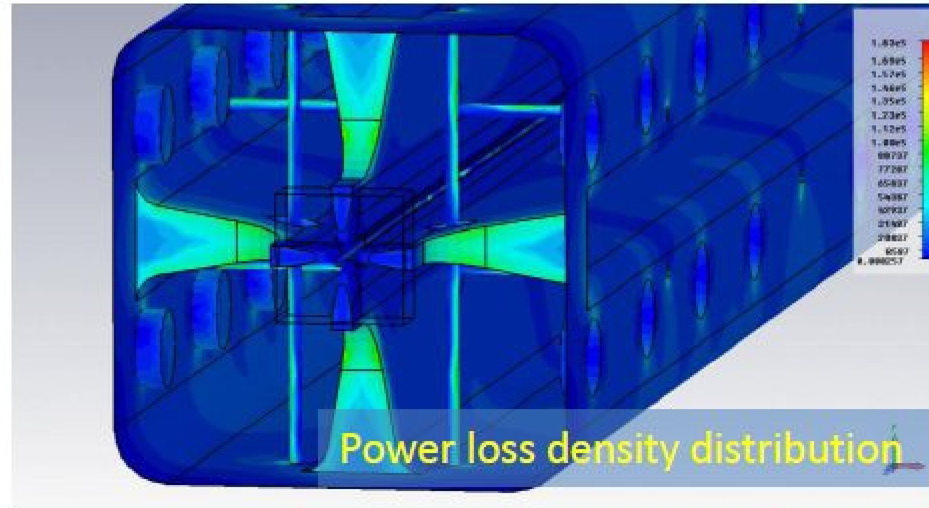
Structure is 444.6 cm long in four modules.

32 pi-mode stabilizers, 4 pairs in each module separate the dipole frequency to 17 MHz above the 162.5 MHz quadrupole frequency

80 tuners, 20 in each quadrant have a diameter of 6 cm, a nominal insertion of 2 cm, and a tuner sensitivity of 170 kHz/cm, all tuners moving together.

MWS Calculation of Cavity Frequency, Power Loss (G. Romanov)





Parameters	IMP	PXIE-T	
Frequency, MHz		162.493	
Frequency of dipole mode, MHz		181.99	
Q factor		14660	
Q factor drop due to everything, %		-14.7	
Power loss per cut-back, W (In/Out)		336/389	
Max power loss density at cut-back, W/cm^2		7.9	To be verified
Total power loss, kW		73.8	
H, mm		172.73	

Distribution of Power Loss on RFQ Components (G. Romanov)

Part	Total, kW	Per unit, W	Percent
Walls	29.5	-	40
Vanes, 4 units	31	7764	42
Input cut-backs, 4 units	1.34	336	1.8
Output cut-backs, 4 units	1.56	389	2.1
Pi-mode rods, 32 units	5.53	173	7.5
Tuners, 80 units	4.79	59.9	6.5

Total power loss for ideal copper, no joint loss is 73.7 kW. With a 30% margin for anomalous losses, the cavity power requirement is 96 kW. Additional losses will occur in the drive loops, coaxial waveguide and circulators.

Multipactoring in the RFQ Cavity

Multipactoring can occur in the cavity and in the RF drive lines.

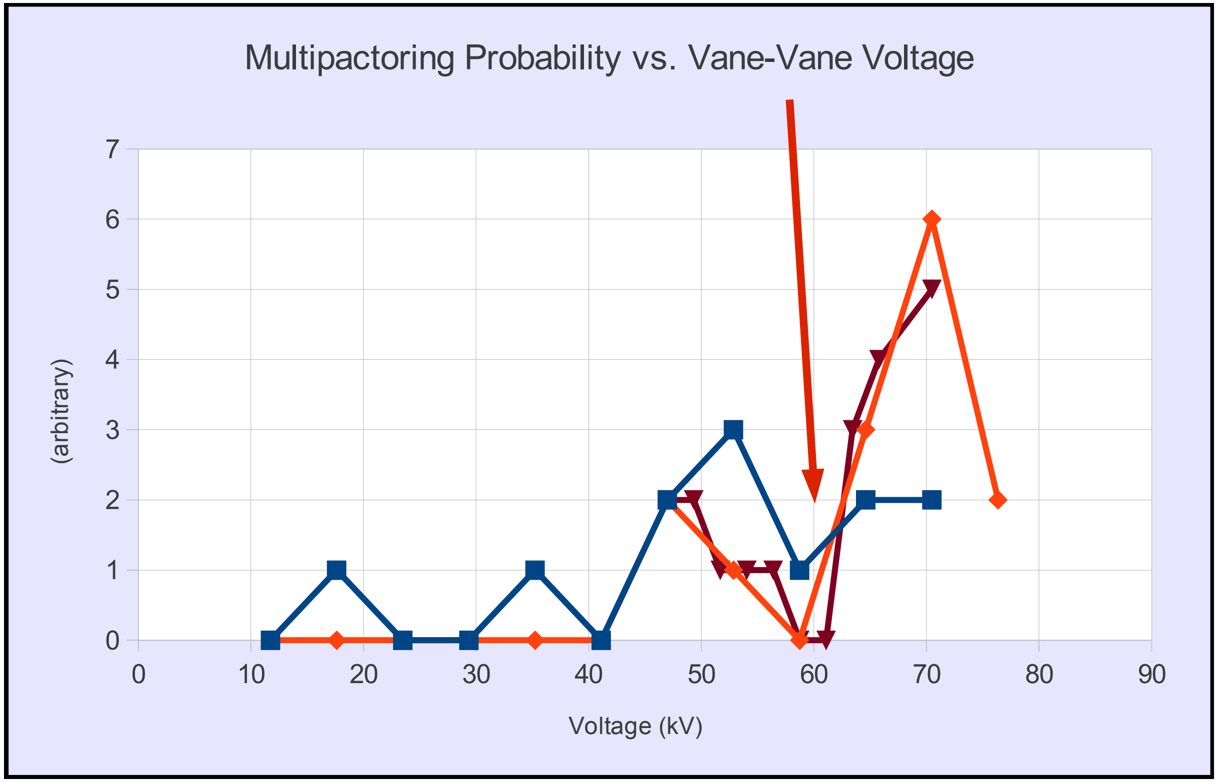
Cavity multipactoring was investigated with FISHPACT, on a 2-D slice of cavity.
Fishpact was used for the APEX photoinjector cavity, which shows no MP activity at gradient.

Fields were stepped over the range of operation, with emitting spots at locations around the periphery, and 6 RF start phases from 0 in steps of 60 degrees.

Three FISHPACT runs with different search parameters show a minimum of activity at 60 kV vane-vane voltage.

All activity is on the outer boundary of the cavity, where the electric field is low and is less likely to pull an electron off the surface.

No activity is noted near the vanetips in the high E-field zone. The electron energy is high so the SEY < 1.0.



It is expected that no significant multipactoring will occur in the cavity.

RF Driveline Multipactoring

The APEX photoinjector runs 100 kW CW at 187 MHz (1.3 GHz / 7) and has two loop couplers, each delivering 50 kW.

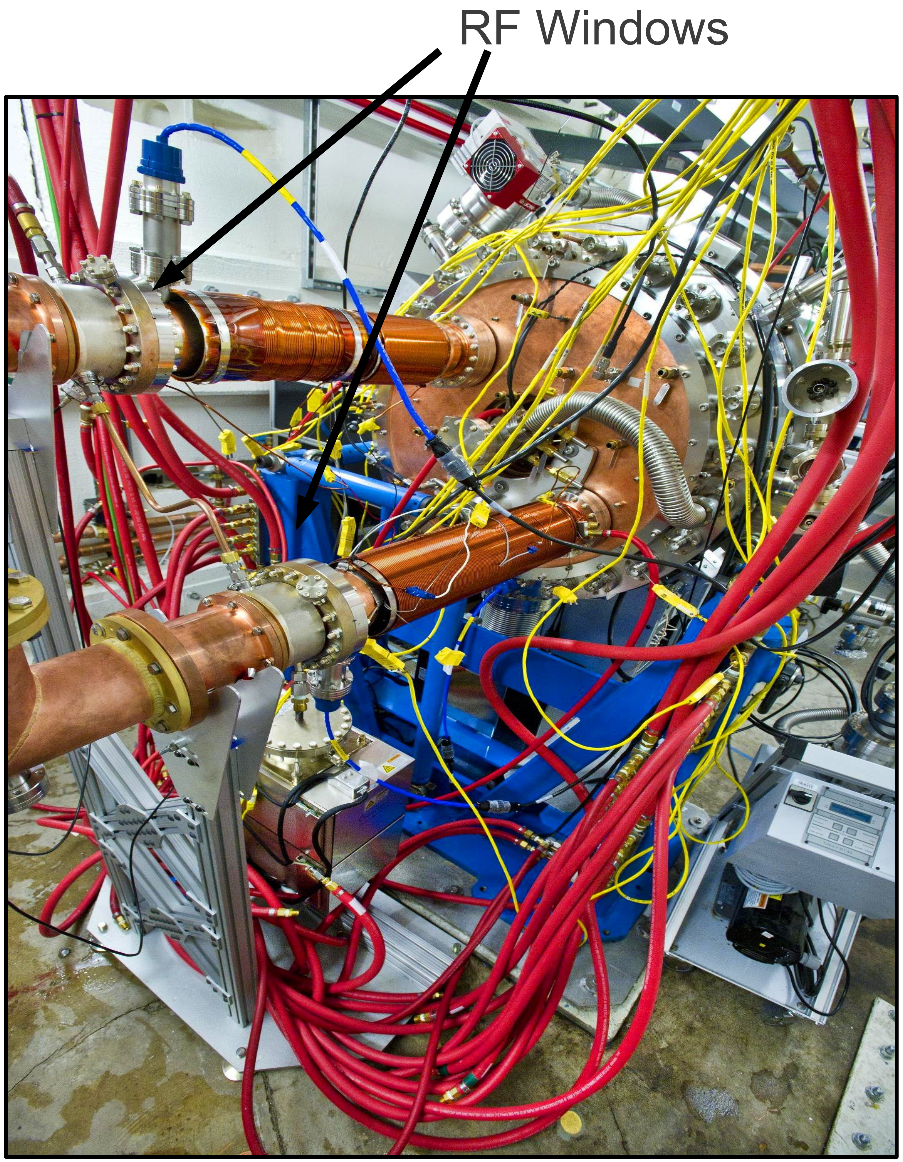
The RF windows are located 80 cm away from the drive loops (half wave).

Severe multipactoring in the vacuum sections of the drive lines was observed.

The multipactoring was suppressed by surrounding them with 100 gauss solenoid coils.

We may shorten the drive lines and move the windows much closer to the coupling loops to eliminate possible magnetic fields at the photocathode.

A similar situation may affect the PXIE RFQ drive lines and should be taken into account.



Lessons Learned from other RFQs

Most run just fine, but there have been problems with some.

SNS: Two instances of frequency jumps with field redistribution. Required retuning. Pi-mode stabilizers probably kept the fields close to nominal even though a quadrant asymmetry may still exist. Investigated thoroughly, cause not found. RFQ continues to operate satisfactorily.

Other RFQs:

- Sloppy assembly
- Inability to gain access to structure through surrounding jacket
- Insufficient thermal capability at required gradients
- Poor mechanical design
- Four-rod warping problem
- Poisoning from severe vacuum accident
- Discharges due to poor vacuum at entrance

PXIE RFQ: None of the above problems are expected for the PXIE RFQ.

The thermal wall loading is 1/3 of SNS, the peak gradient is 1.2 kilpatrick.
Possible multipactoring problems with the drive loops has been recognized.
The water passages are gun-bored into the structure itself: no exoskeleton.
Vacuum at the RFQ entrance will be in the low 7's due to a small entrance aperture and a 1.5 meter distance from the ion source. Beam loss in the RFQ, including chopping, is expected to be very small.

Recap: Issues Addressed

Design frozen: final engineering proceeds

Easily meets requirements
- High acceptance, 0-10 mA characteristics, low output divergence

Error Analysis
- Current dependence
- Beam quality dependence on field errors
- Large field errors results in small emittance growth

RF Design
- Stabilizers, mode separation, tuning
- Large separation of quadrupole and dipole modes
- Large immunity to asymmetry and machining errors

RF Power issues
- Power distribution within structure
- No expected multipactoring in cavity, but watch drive lines.

Lessons learned from other RFQs
- Design avoids issues that have arisen in other RFQs