PIP I: RFQ Injector

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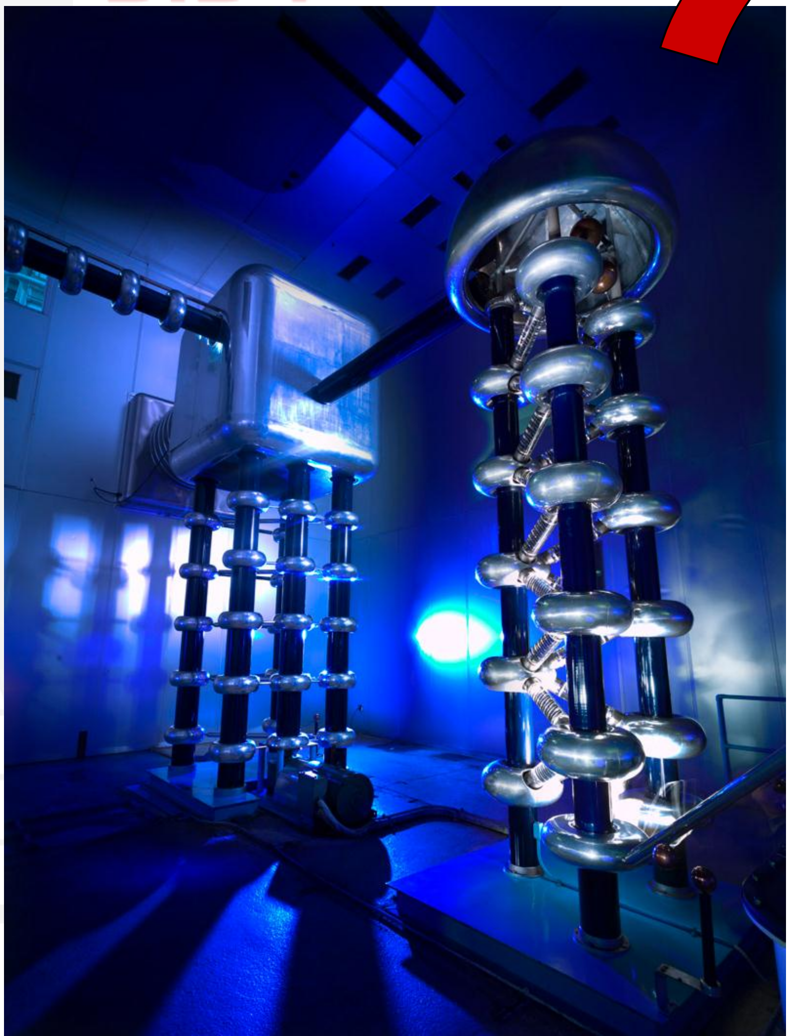
for Proton Source group
25 Mar 2014

U.S. DEPARTMENT OF ENERGY

Fermilab

PIP-I



PIP-I

Acknowledgements

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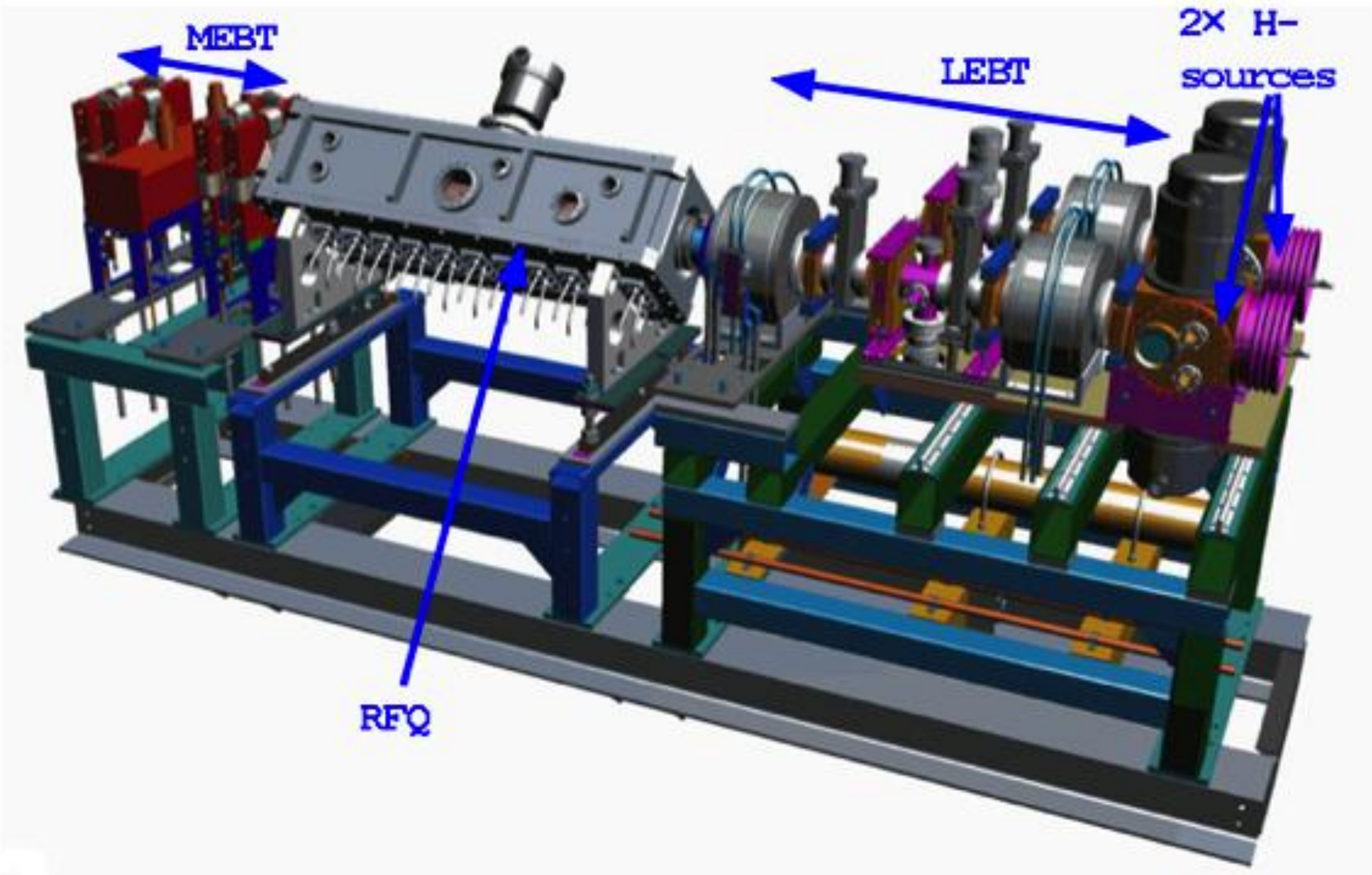
- S. Kurennoy (LANL), G. Romanov (APC)
- W. Pellico
- Summer students and any others whom I have inadvertently left out.

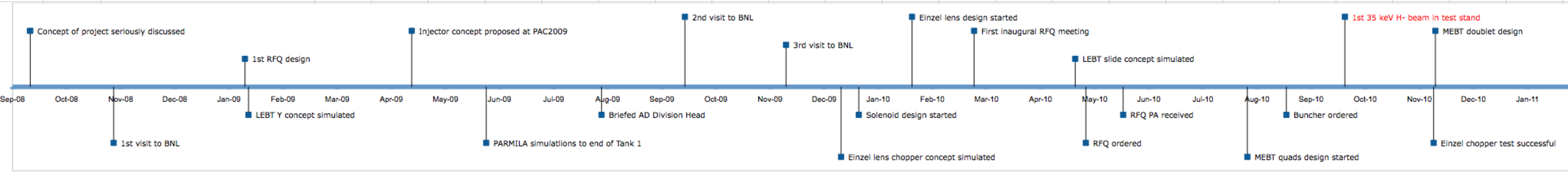
PIP-I The RFQ Injector

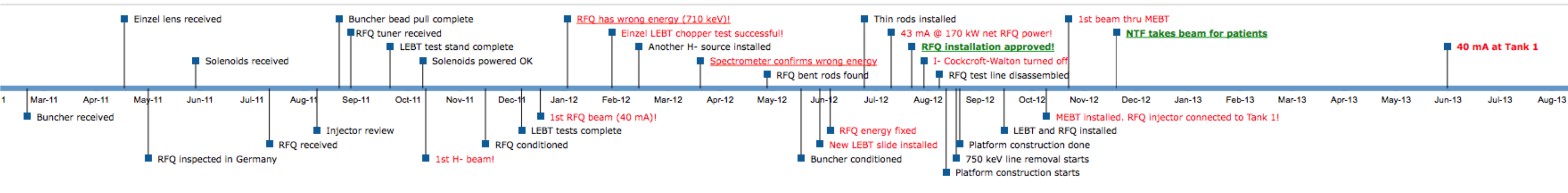


Overview

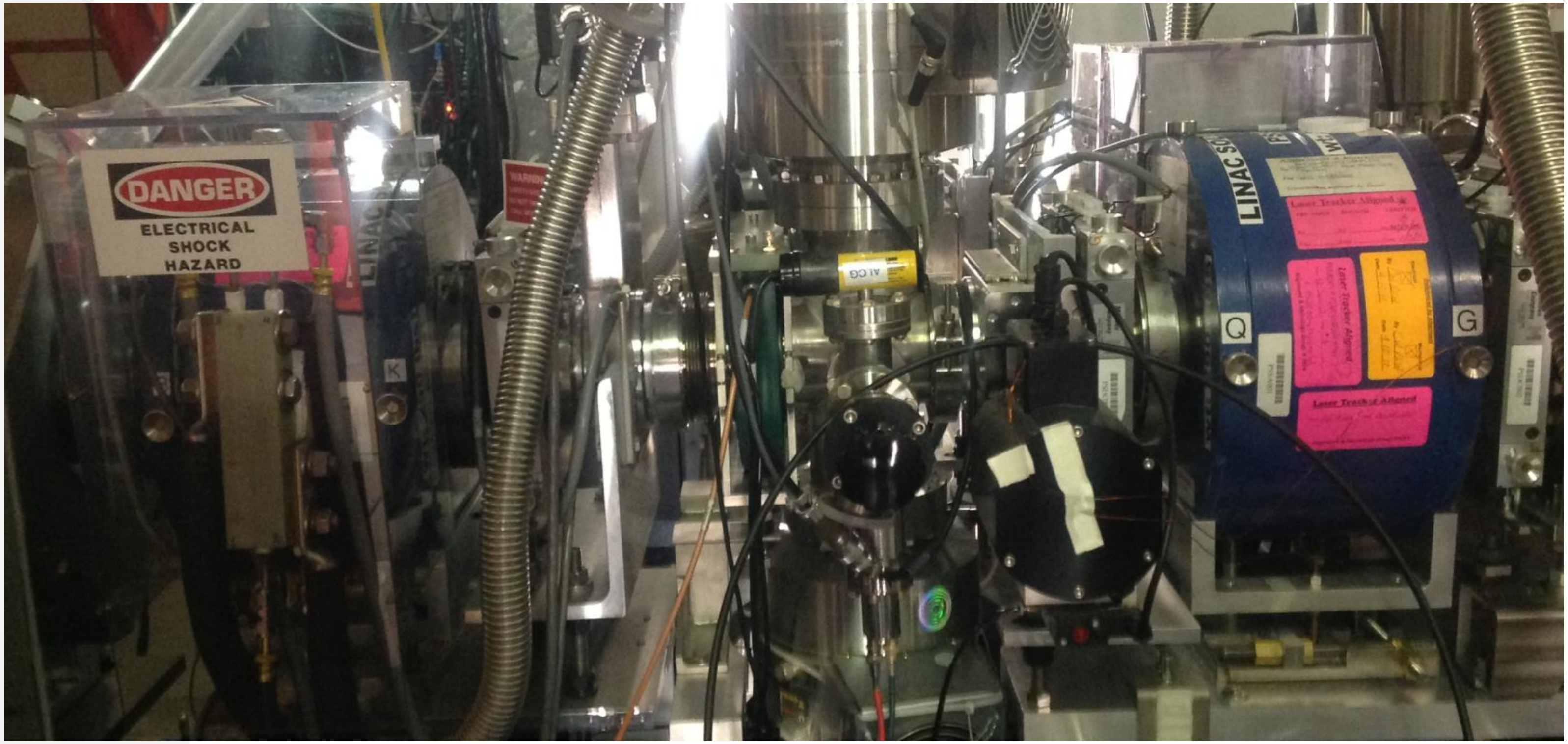
- LEBT
- Einzel lens chopper
- RFQ
  - The commissioning of the FNAL RFQ
    - Output energy problem
    - Transmission efficiency problem
    - Power requirement problem
    - Fixes, fixes and more fixes
    - Details can be found in PRSTab paper:
    - Investigations of the output energy deviation and other parameters during commissioning of the four-rod radio frequency quadrupole at the Fermi National Accelerator Laboratory
- MEBT

PIP-I Timeline





LEBT



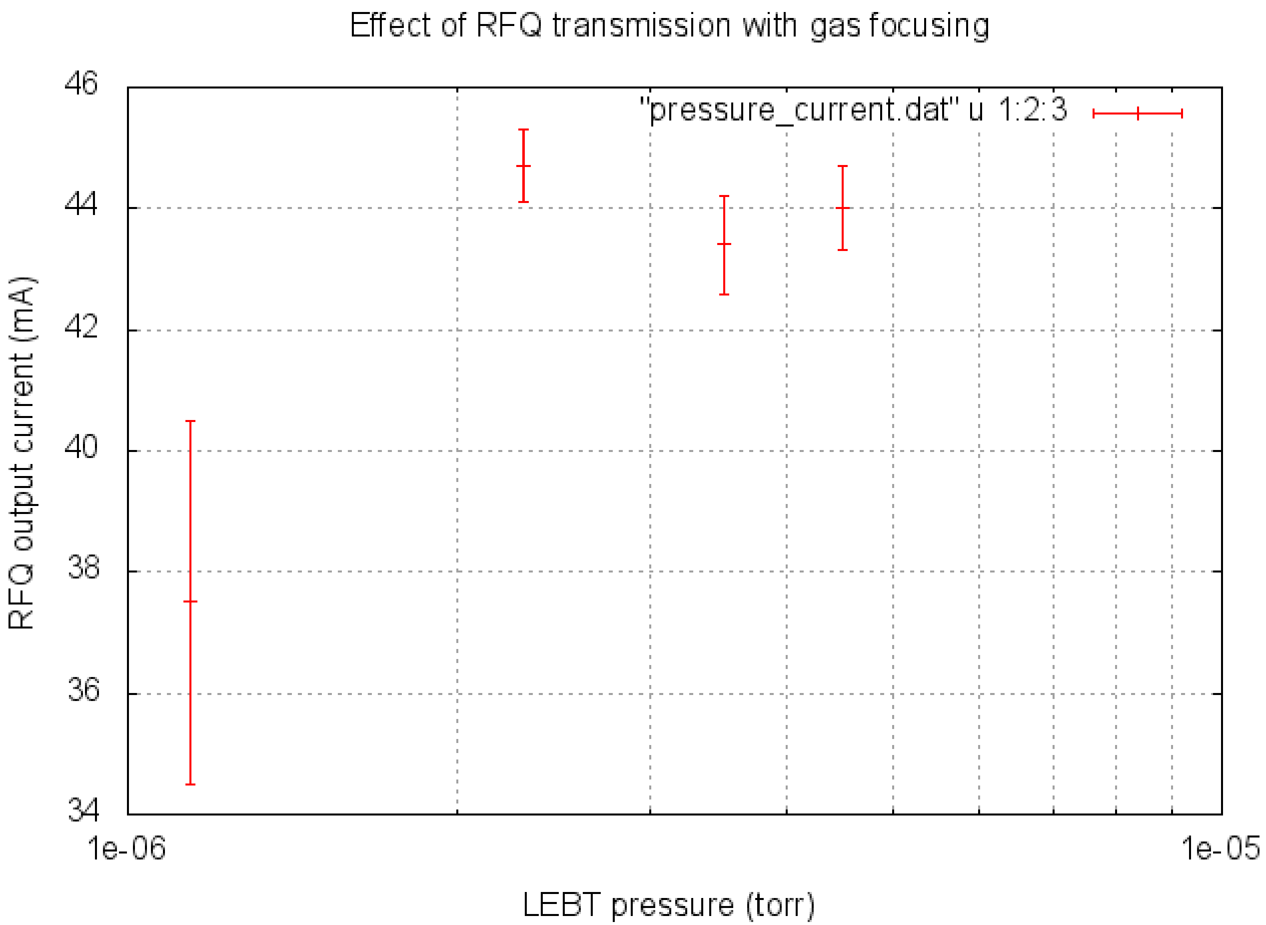
Beam

Classic 2 solenoid design to transport beam from the source to the entrance of the RFQ

Space charge neutralization

- High current beam > 70 mA exits the source
  - Space charge dominant
  - Hard to focus with solenoids
- Employ space charge neutralization to both neutralize and focus the beam
  - Idea is to use residual gas in the beam pipe (probably H2 gas from the source)
  - H- ions strip electron from H2 gas to form H2+
  - H2+ cancels out H- charge
  - If there is enough H2+, H- can be focused in the LEBT.
  - Neutralization takes time ~30 – 60 us.
    - First part of beam must be chopped away.

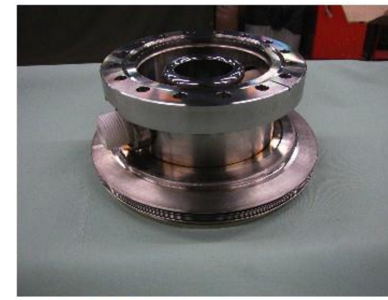
Effect of transmission from LEBT pressure

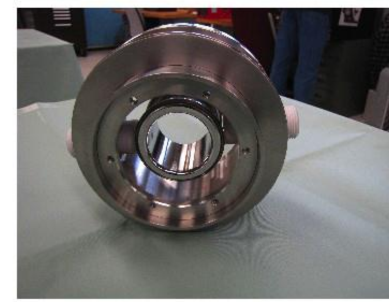


In operations, LEBT pressure 4-7e-6 torr

Einzel lens chopper

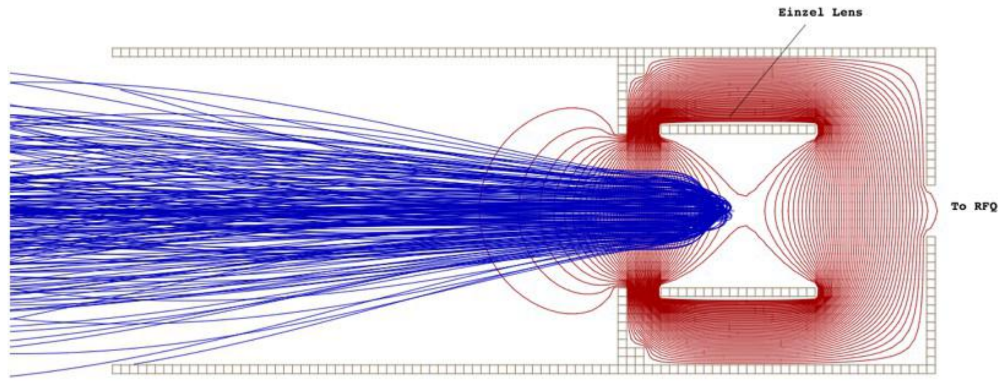
- How it works
- Recent problems
- New design



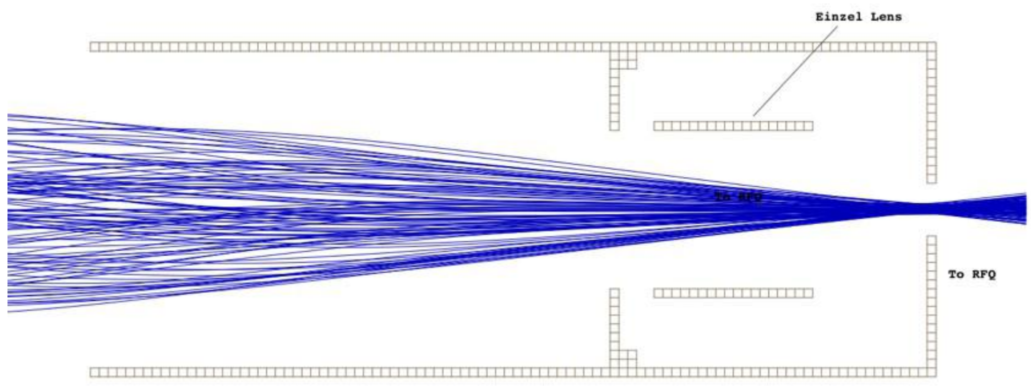


The Einzel lens is just upstream of the RFQ, because E-fields spoil neutralization and so we want it here to minimize deneutralization region.

PIP-I How it works

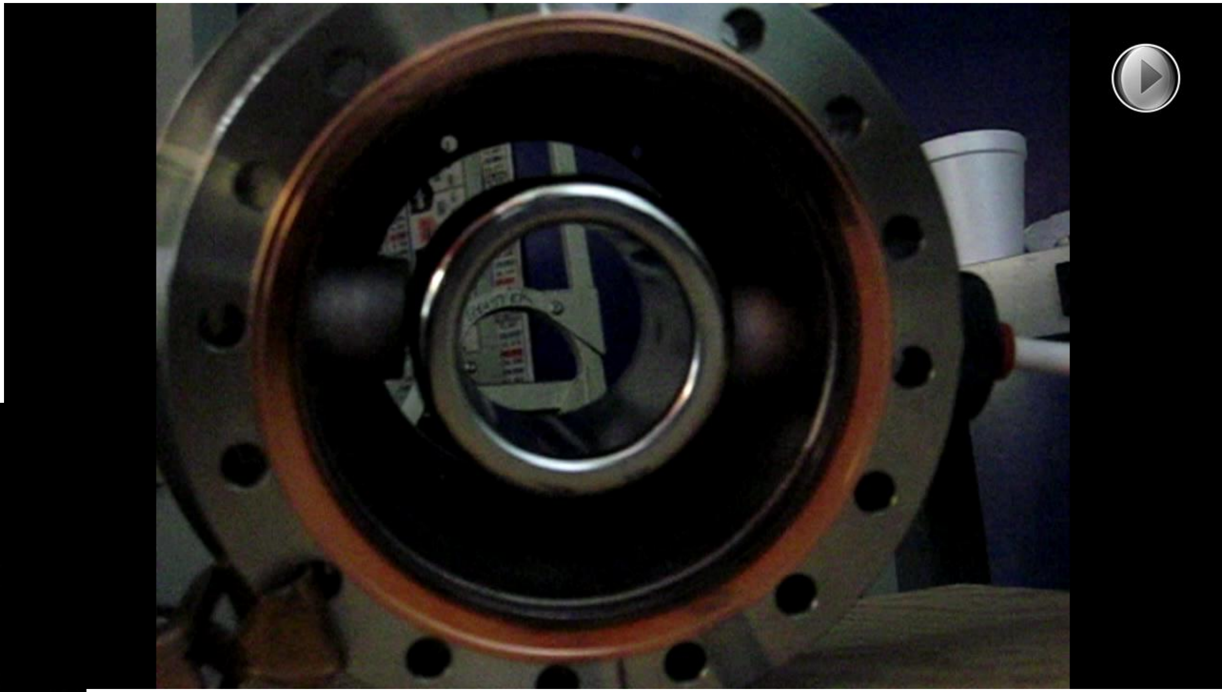


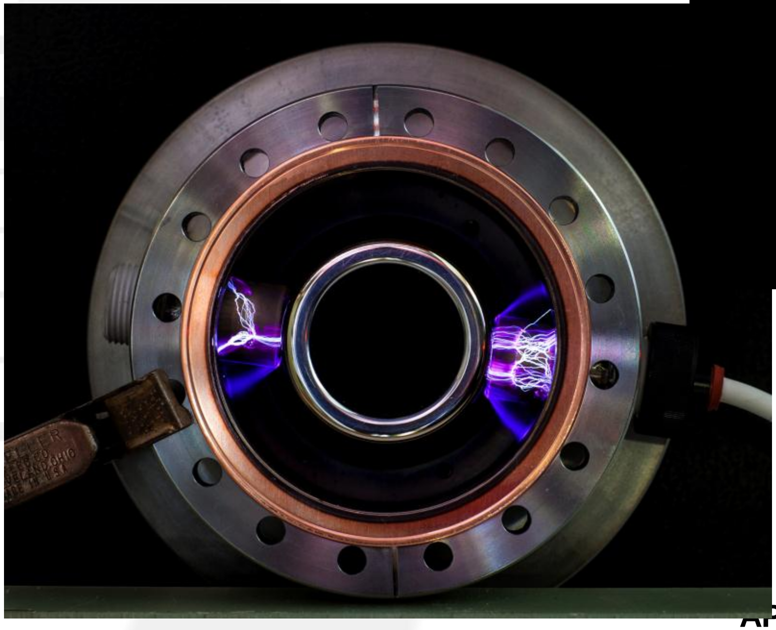
Einzel Lens On at -38kV



Einzel Lens Off

Recent problems

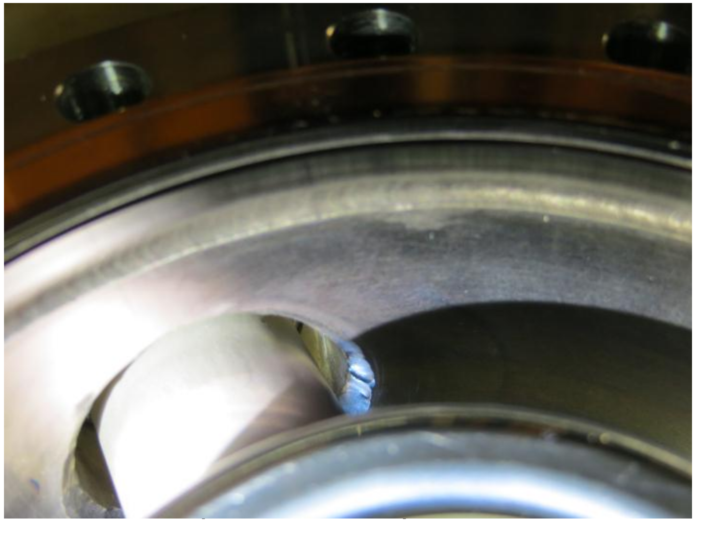




Taken by M. Murphy

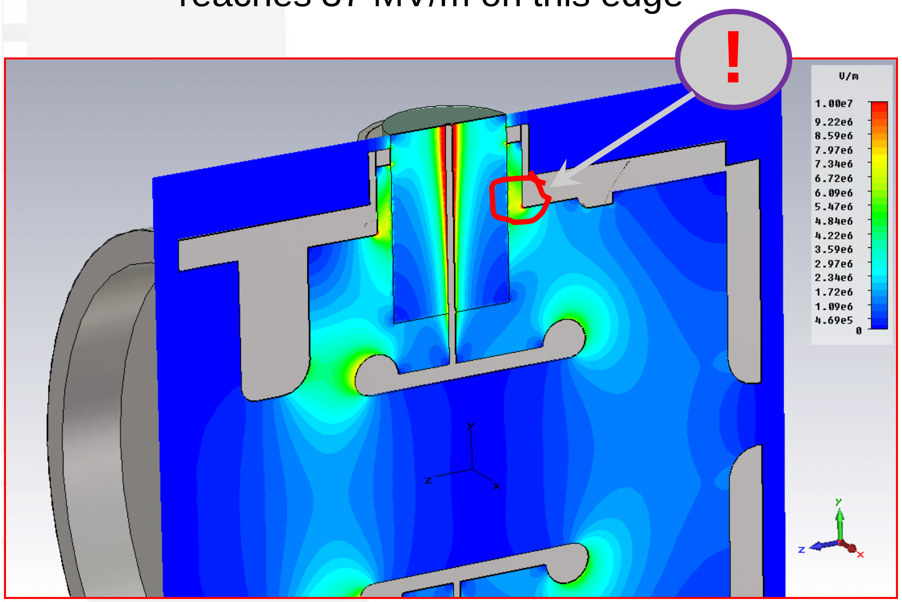
Reasons of Einzel lens sparking

- 2 mechanisms:
  - Initially, high field at edge of weld causes sparking.
  - As time passes, sputtering of copper from the RFQ coats the ceramics giving shortened path for the discharge. This limits the maximum voltage to about 20 kV.

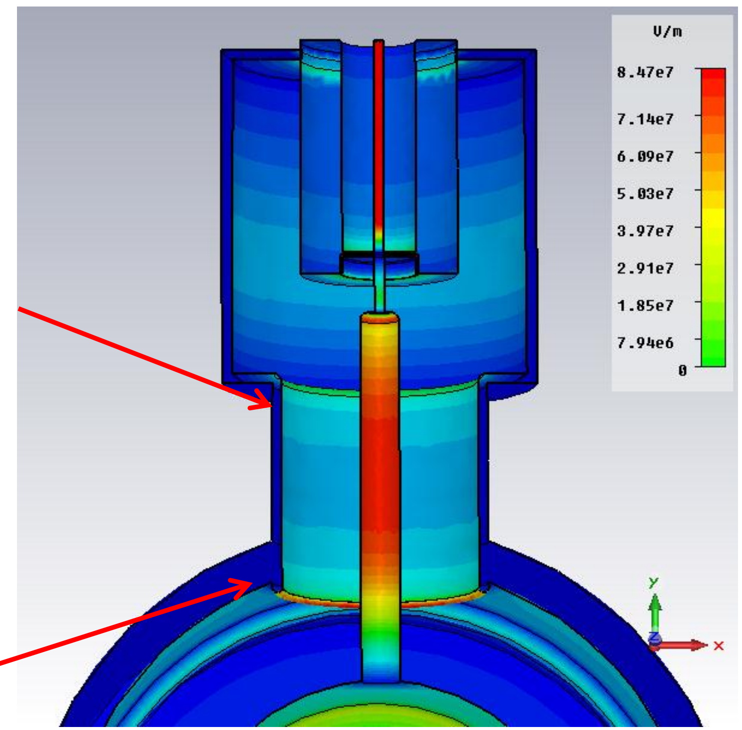


PIP-II Old versus new design

In the original design surface field reaches 37 MV/m on this edge



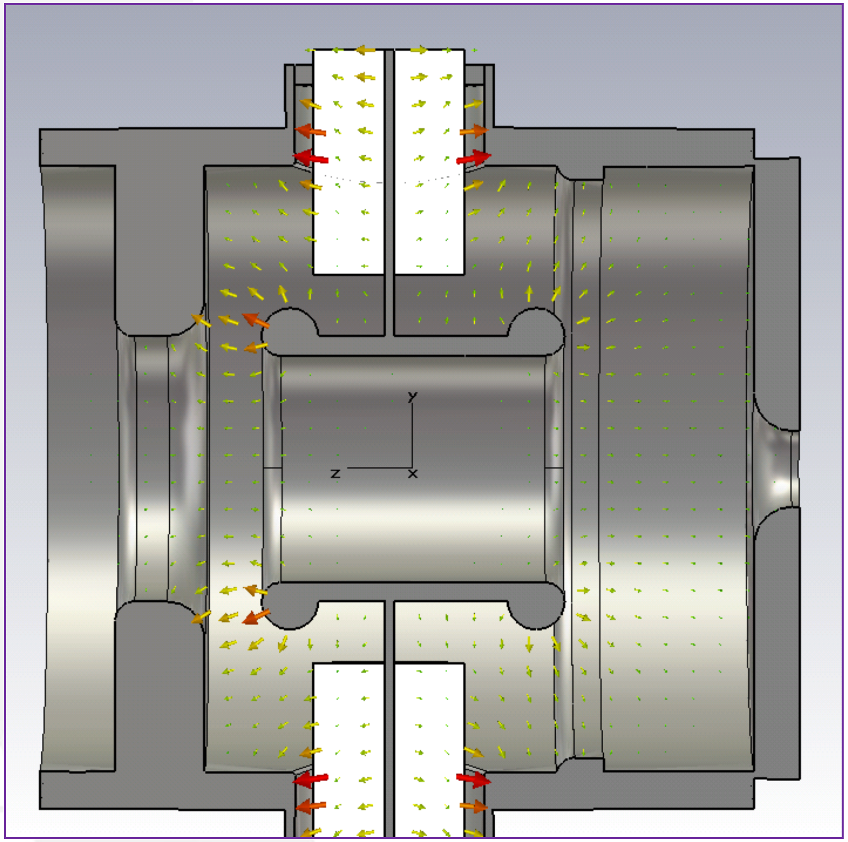
9.5 MV/m

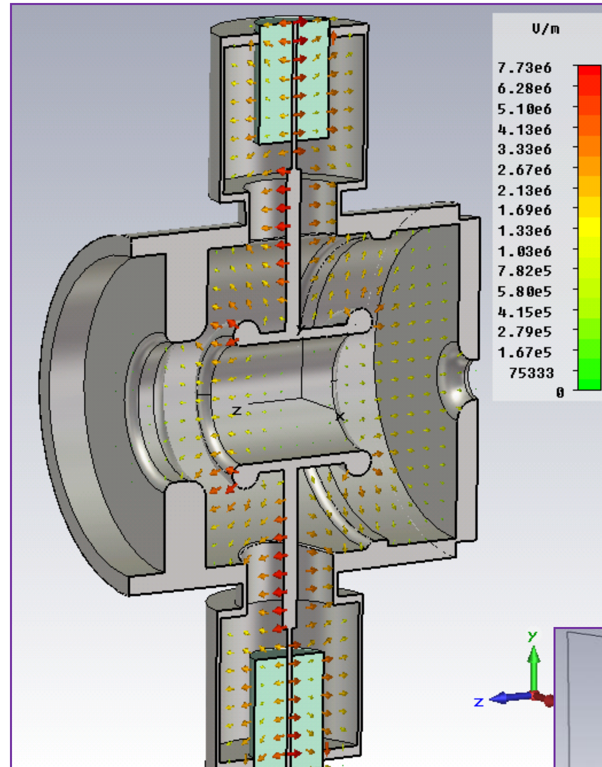


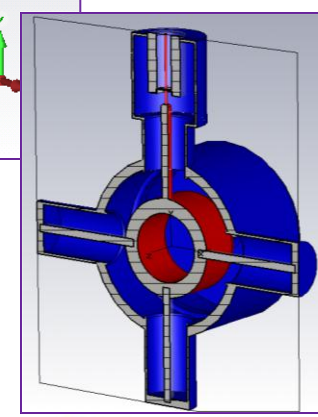
10.2 MV/m

designed by A. Makarov and
simulated by G. Romanov

E-fields

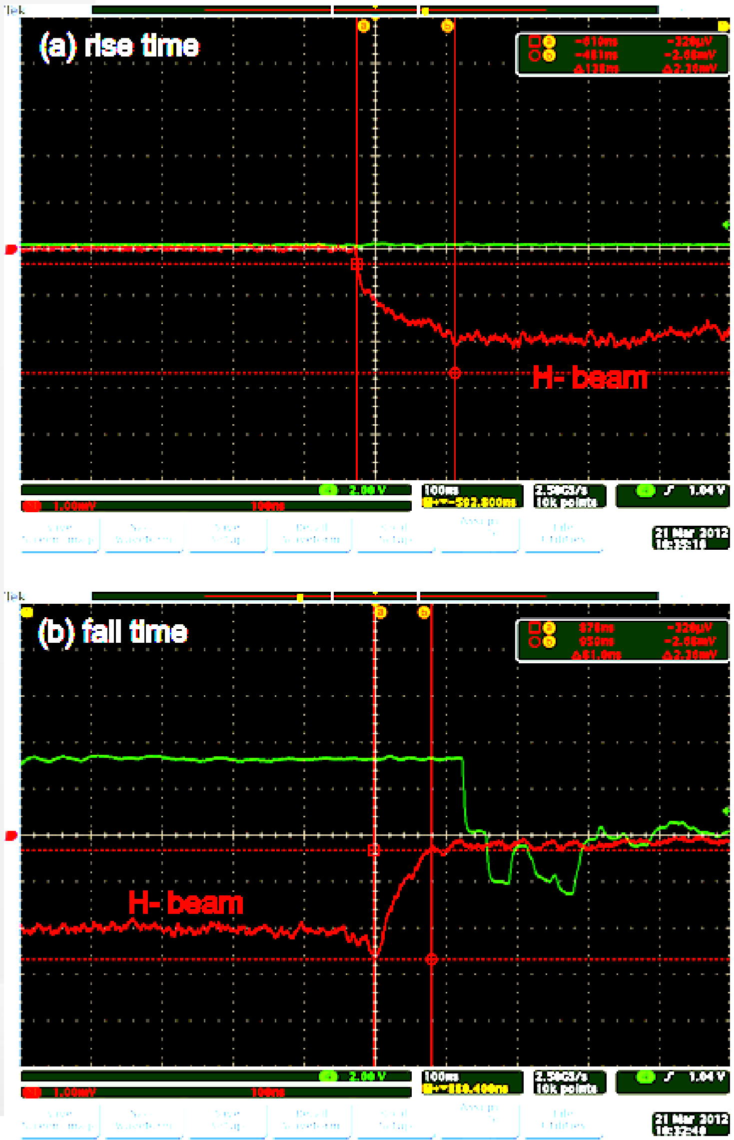




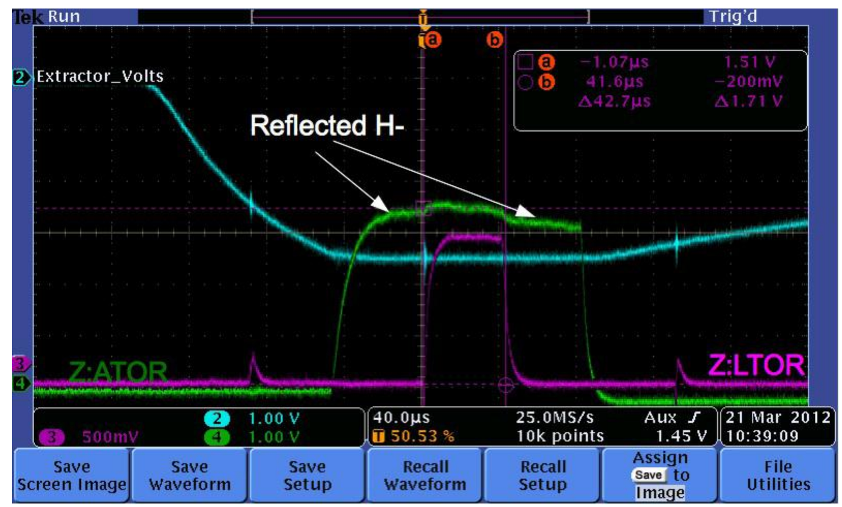


designed by A. Makarov and
calculated by G. Romanov

Rise and fall times



138 ns rise



81 ns fall

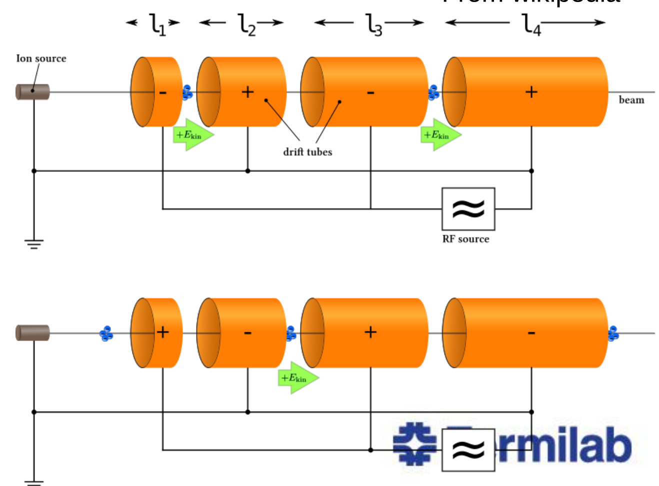
What is an RFQ

- RFQ: radio frequency quadrupole
- It is a very interesting device invented by I.M. Kapchinsky and V.A. Tepliakov in 1970.
  - Linear ion accelerator with spatially homogenous focusing.Prib. Tekh. Eksp., (2):119, 1970.
- This device was invented to both bunch and accelerate ions from “DC” beam at low energy ~ 20-30 keV to MeV range.
  - Utilizes electric fields to do transverse focusing because magnetic fields don’t work well at low energy.

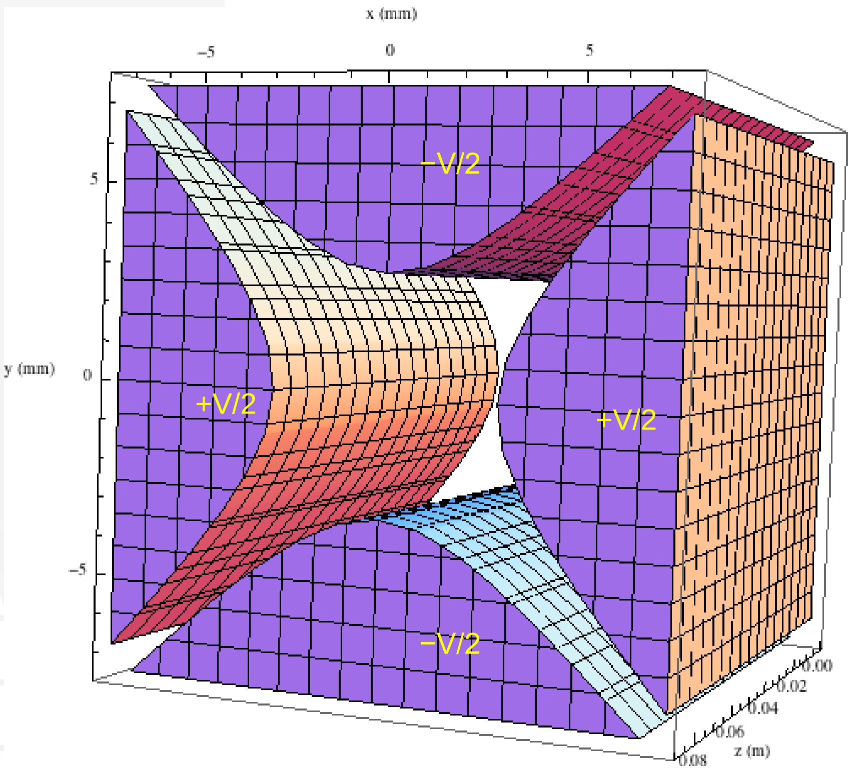
Coolness of RFQ compared to DTL

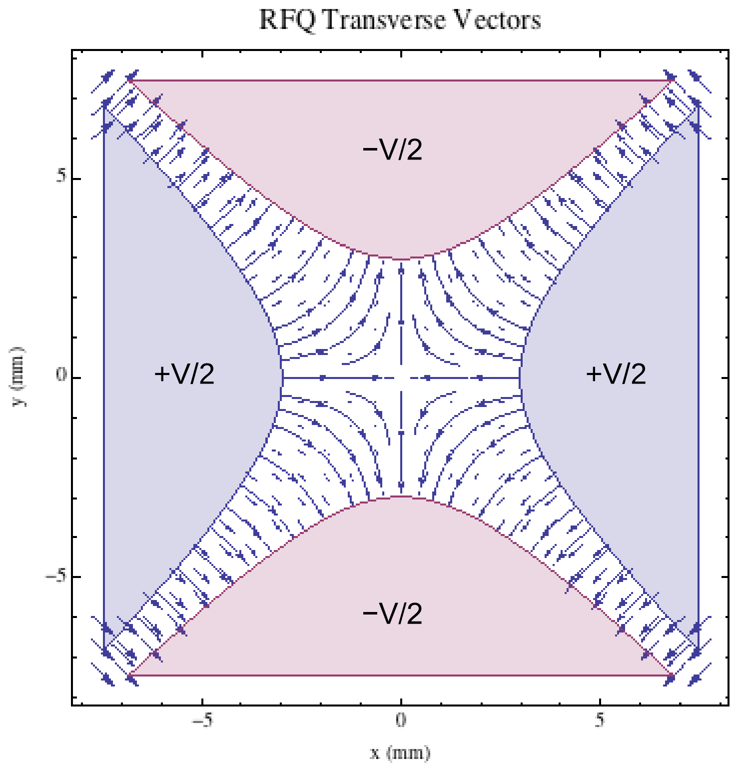
- Unlike a DTL, it doesn’t use “isolation” cylinders to shield the beam from the RF that has the wrong sign for acceleration.
- Unlike a DTL, it doesn’t have embedded quadrupoles to maintain transverse focusing.
- So how does the RFQ do it?

From wikipedia



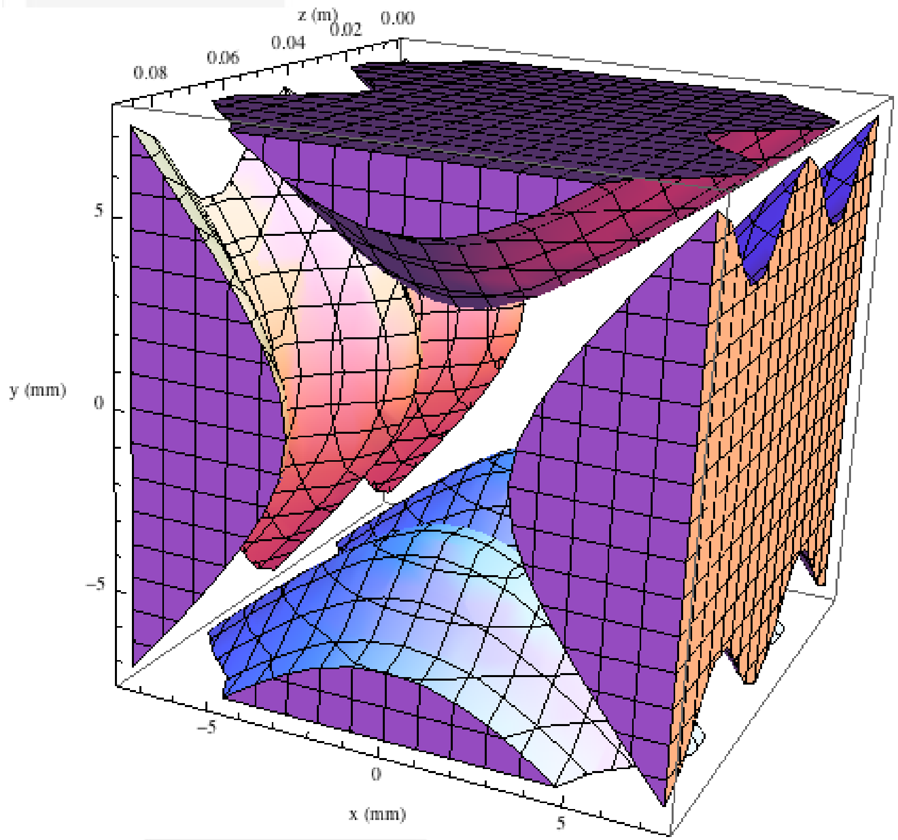
RFQ uses three tricks. First trick: transverse focusing

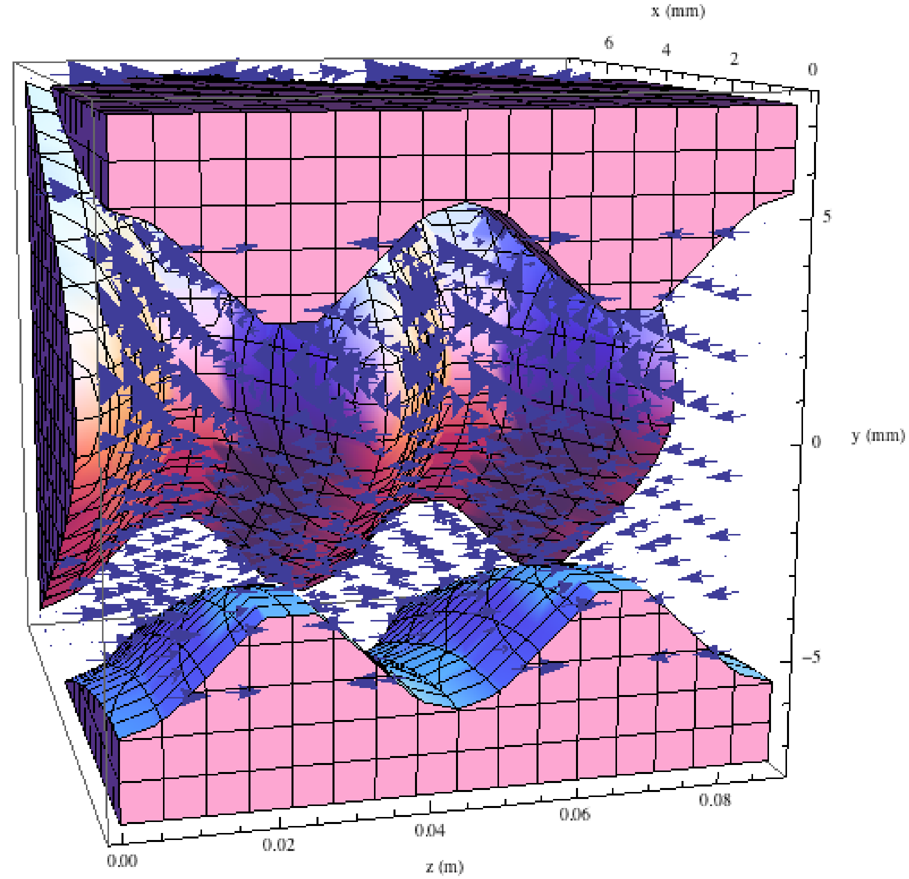




We defocusing on the horizontal plane and focusing in the vector plane for H-. For focus/defocus need RF!

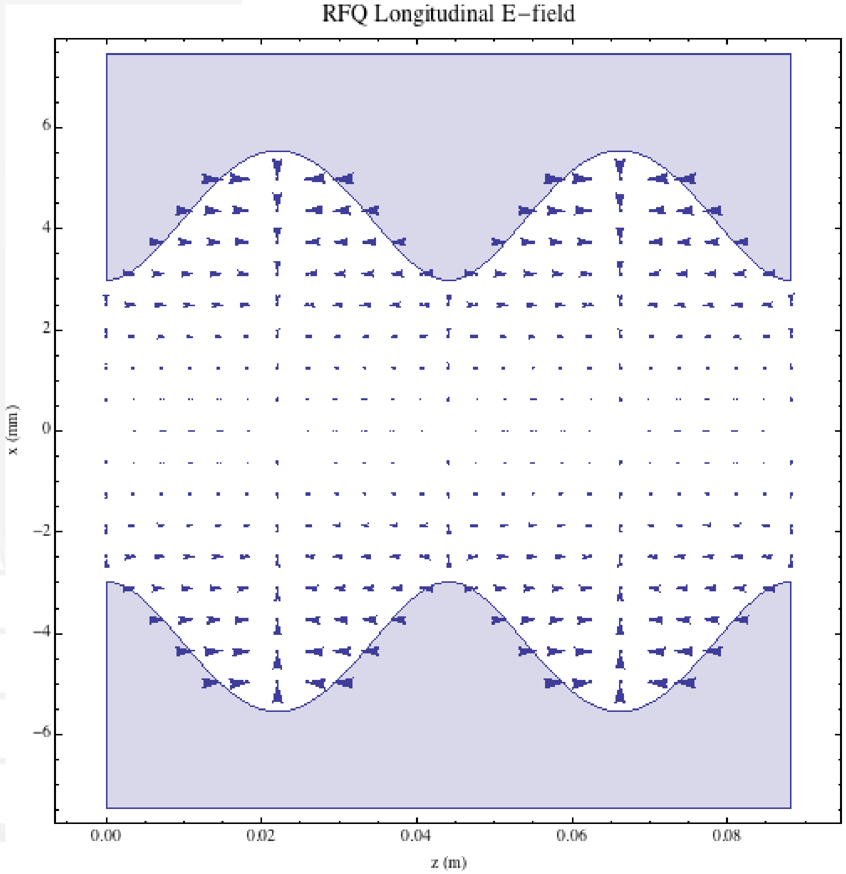
RFQ uses three tricks. Second trick: Create Ez field (part 1)

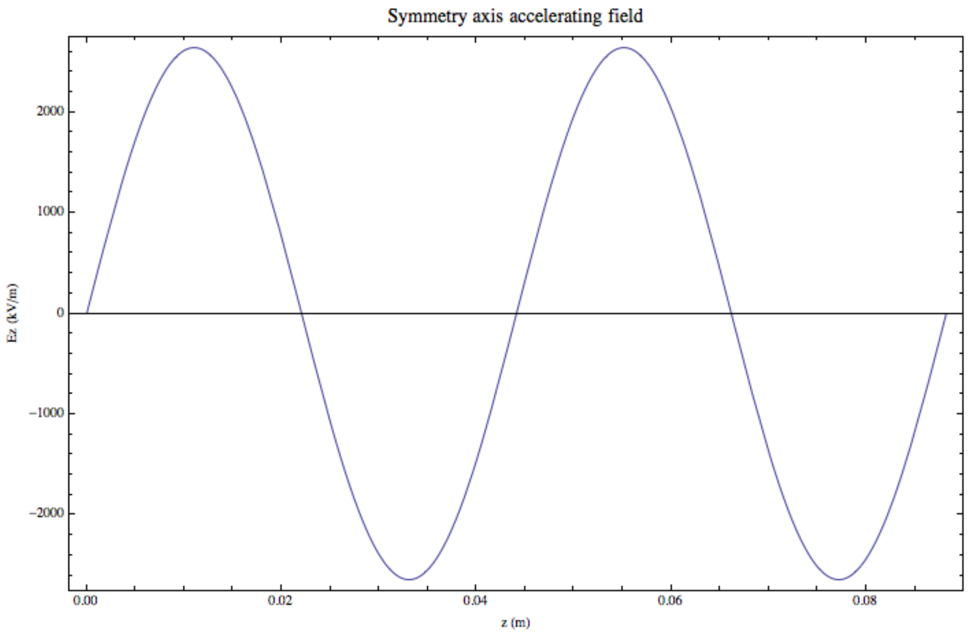




Create modulation in z to make Ez field

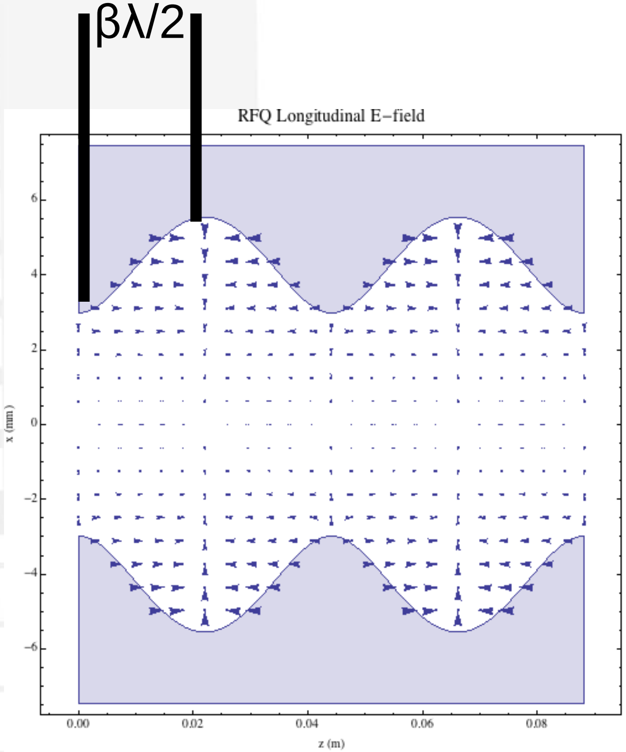
RFQ uses three tricks. Second trick: Create Ez field (Part 2)



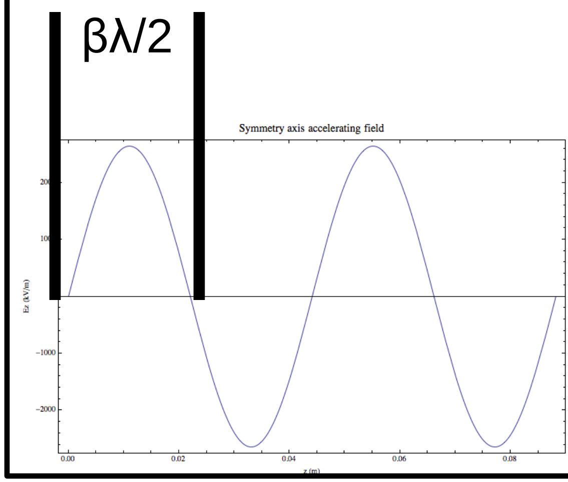


With z modulation, we get a **spatial** Ez field *but* there's a sign change in Ez and so not always accelerating!

RFQ uses three tricks. Third trick: Use RF part of the equation to flip sign

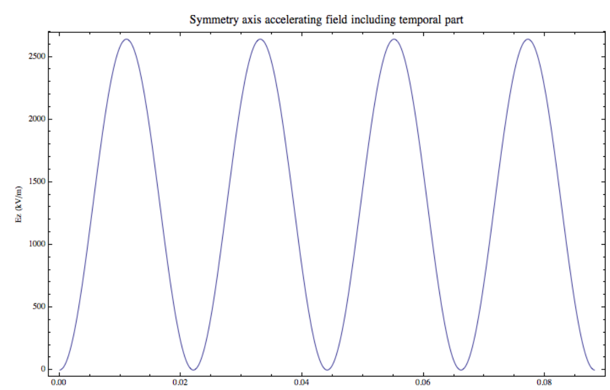


$U(r,\theta,z;\ t) = V(r,\theta,z)\ \sin(\omega\ t + \phi)$



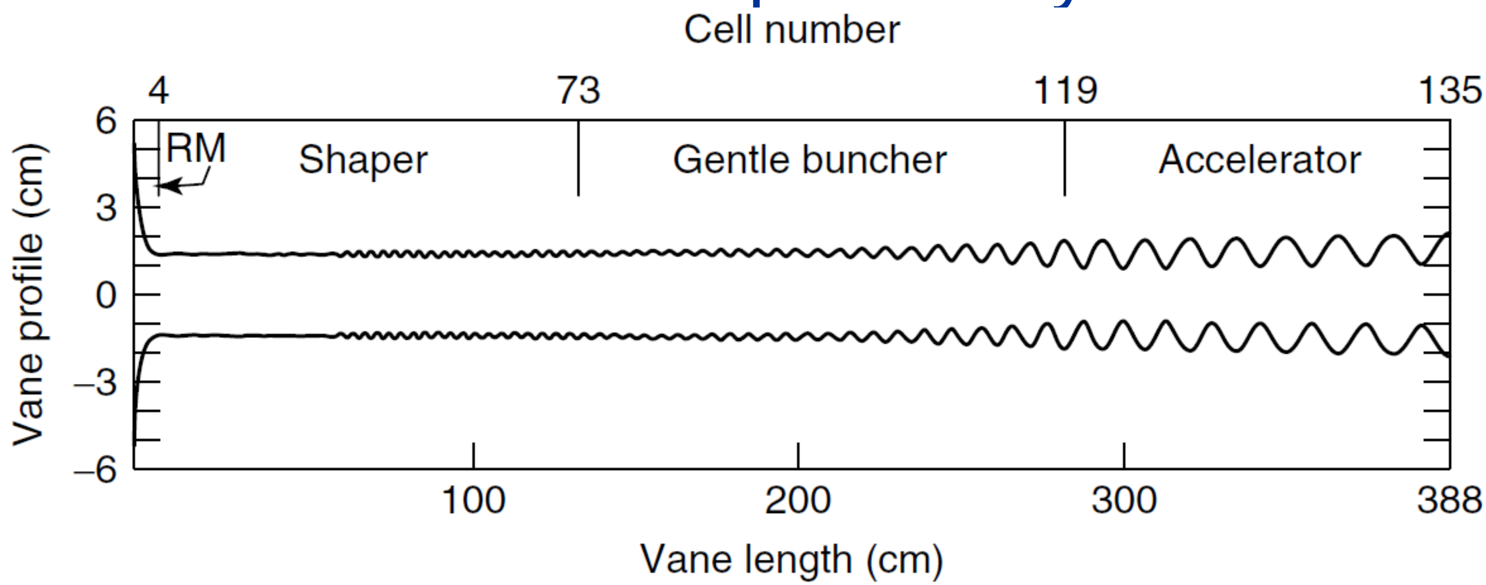
$\times\ \sin(\omega z/\beta c)$

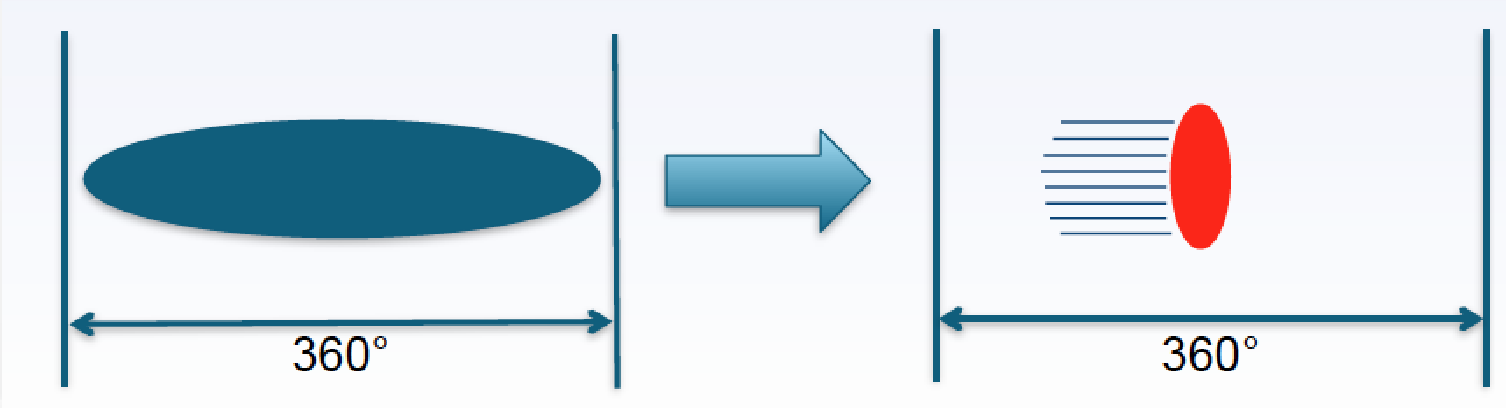
(Spatial Ez) × (RF part)



Always accelerating for particle traveling at βc !

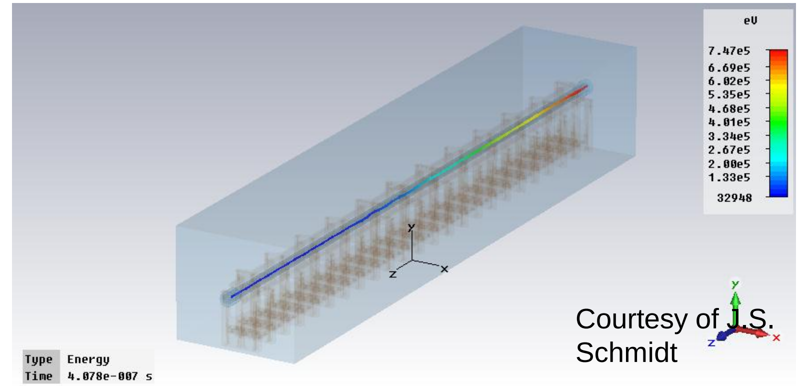
Four sections for particle dynamics





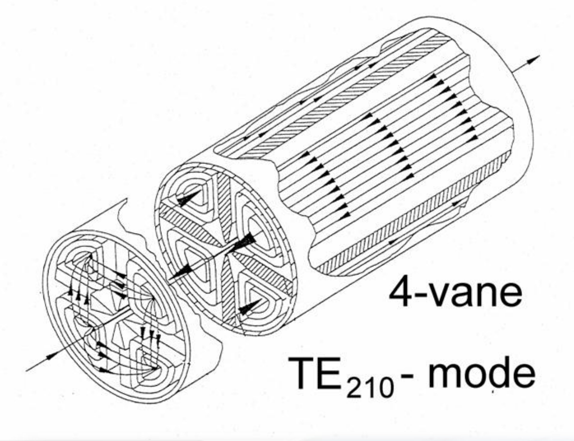
Courtesy of J. Schmidt

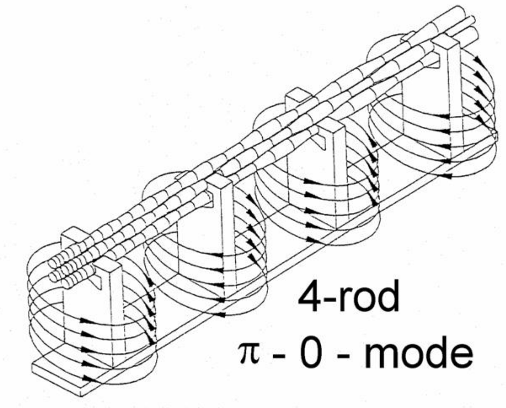
The RFQ movie

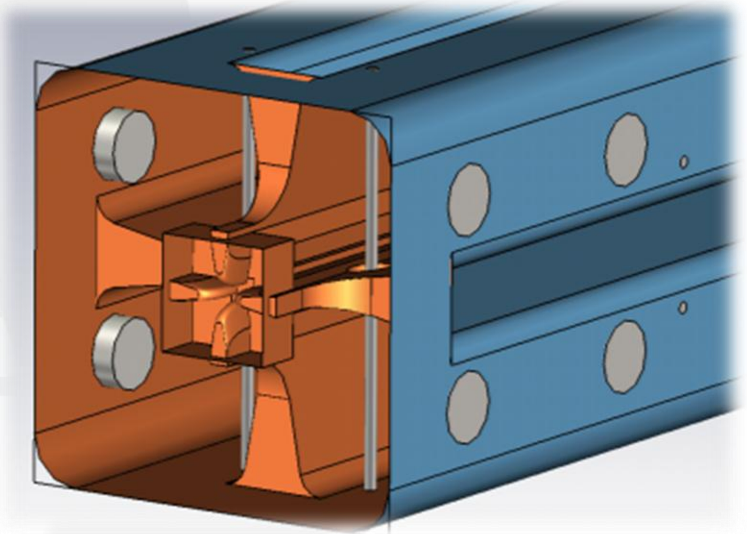


Courtesy of J.S. Schmidt

Types of RFQs

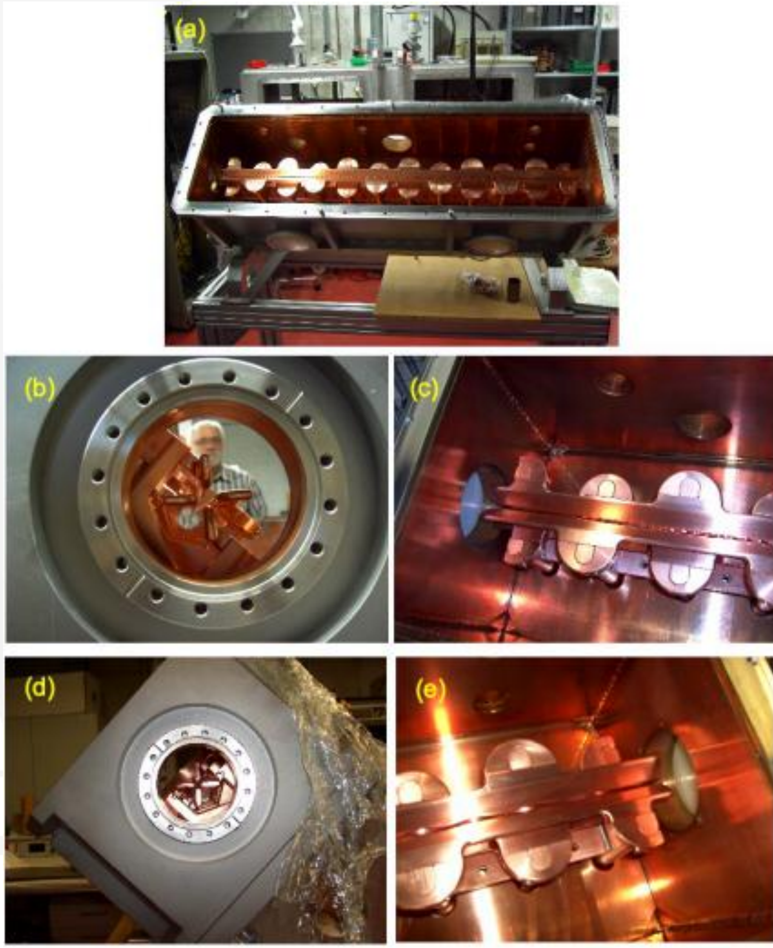


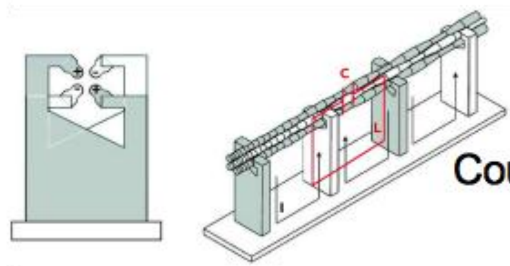




PXIE RFQ

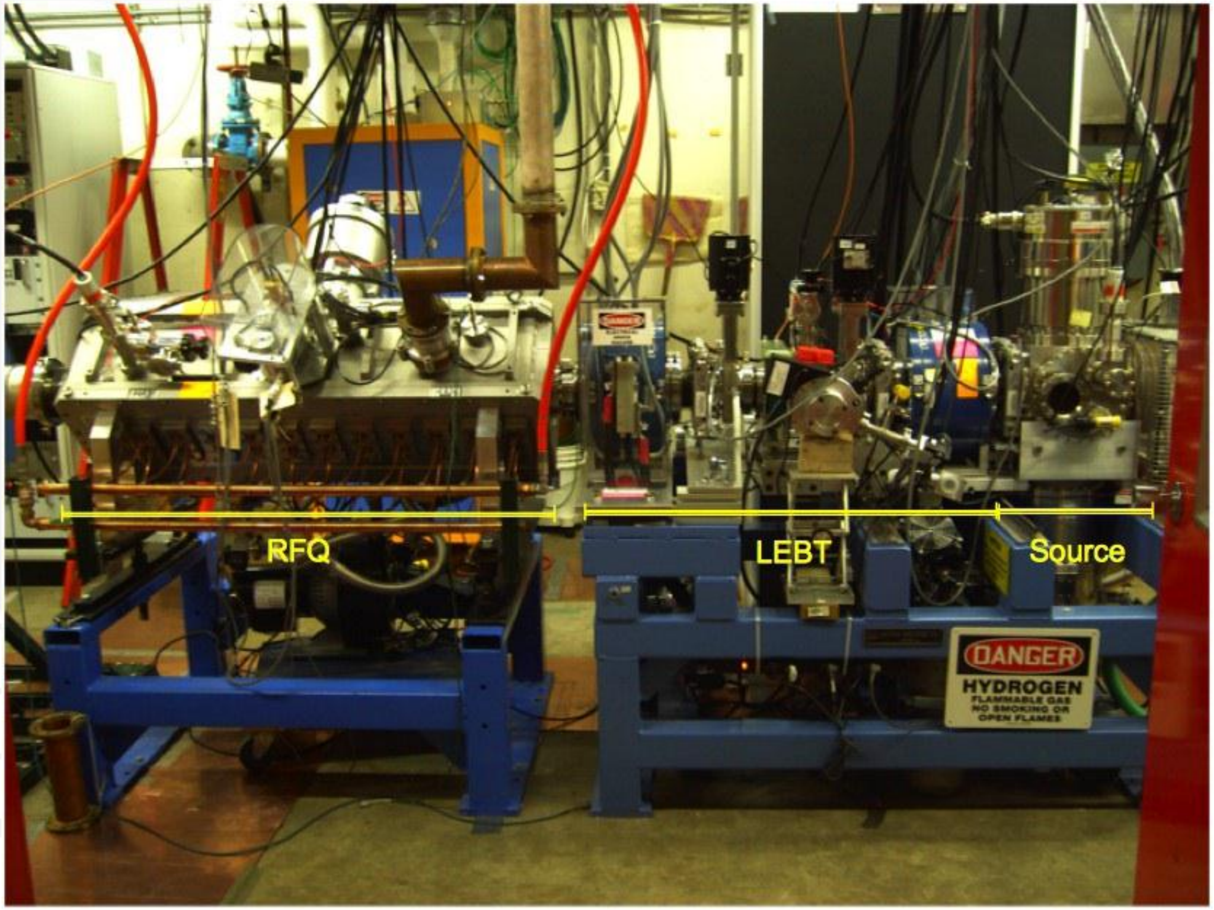
The FNAL RFQ





Parameter	Value	Units
Input energy	35	keV
Output energy	750	keV
Frequency	201.25	MHz
Number of cells	102	
Length	120	cm
Minimum radial aperture	0.3	cm
Maximum peak surface field	25.18	MV/m
Peak cavity power+beam power	~140	kW
Duty factor (80 μs, 15 Hz)	0.12	%
Design current	60	mA
Modulation m	$1 \le m \le 1.95$	
Intervane voltage	72	kV
Transmission efficiency	98	%

PIP-I Testing



1 H- dimpled magnetron source

LEBT with 2 solenoids

Einzel lens chopper

RFQ

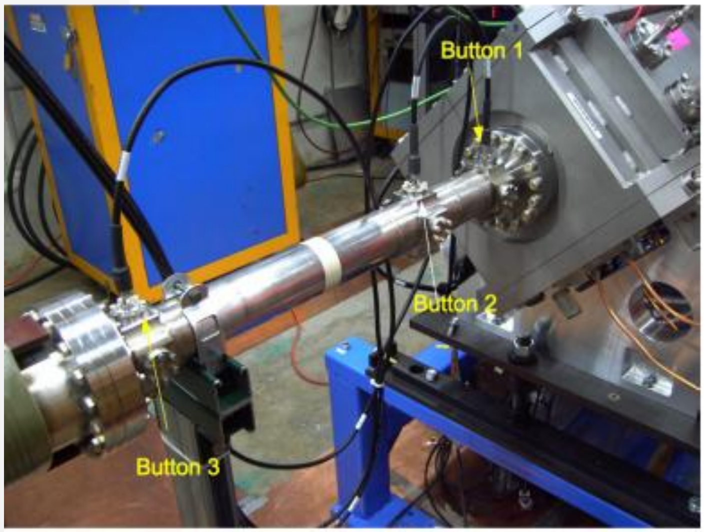
Instruments added to the end of the RFQ

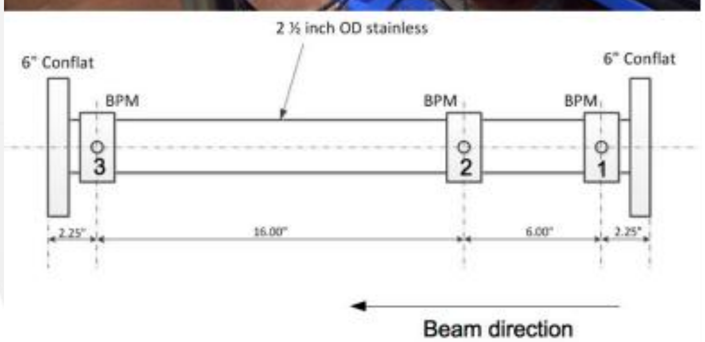
- beam buttons for TOF
- spectrometer
- toroid
- emittance probes.

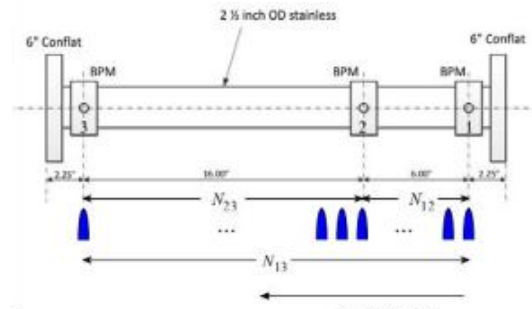
Measuring the output energy

- Time of flight method
  - Very easy to do
    - Measures energy to some integer multiple of RF wavelength. 3 non-equidistant buttons removes this ambiguity.
- Energy spectrometer
  - Time consuming to setup, very accurate if systematics like position of elements are measured accurately and dipole magnet well calibrated.

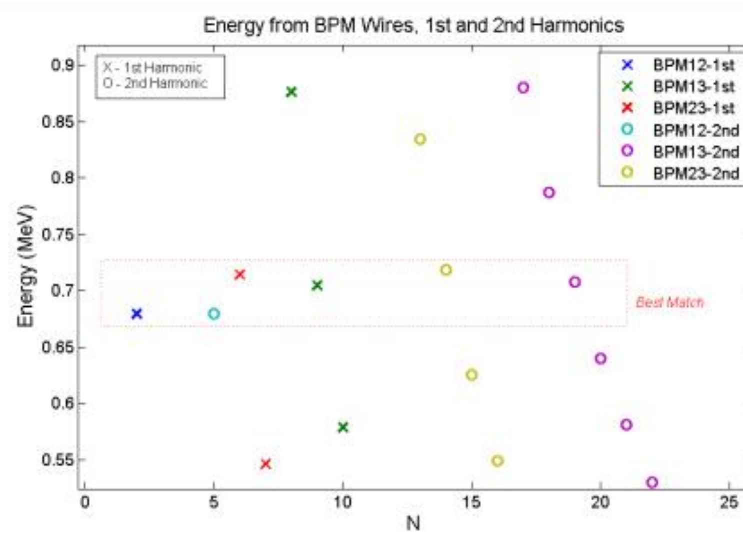
Time of flight method and the first signs of trouble







$$\Delta t_{mn} = \frac{(N_b \times 2\pi) + \Delta\varphi_{mn}}{2\pi f_{RF}} \quad \text{where } \Delta\varphi_{mn} = \varphi_n - \varphi_m \text{ for } n > m$$

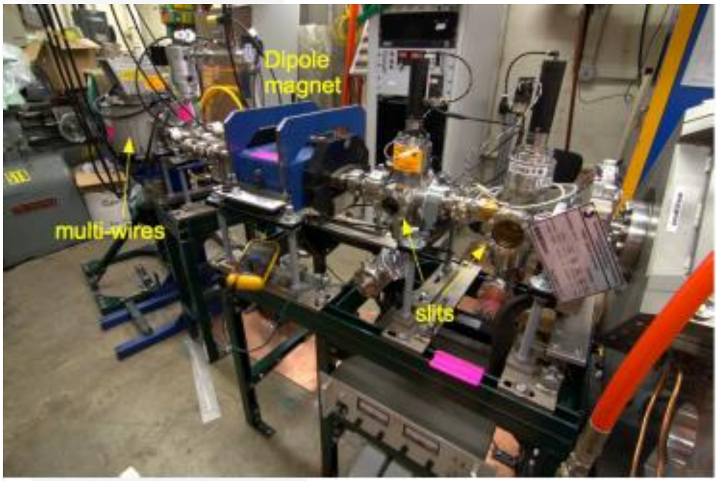


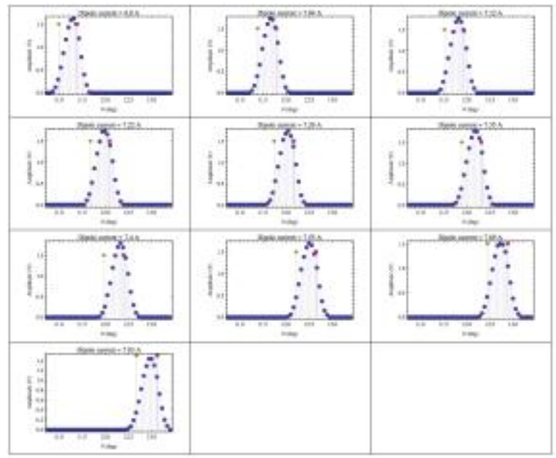
700 keV!!!

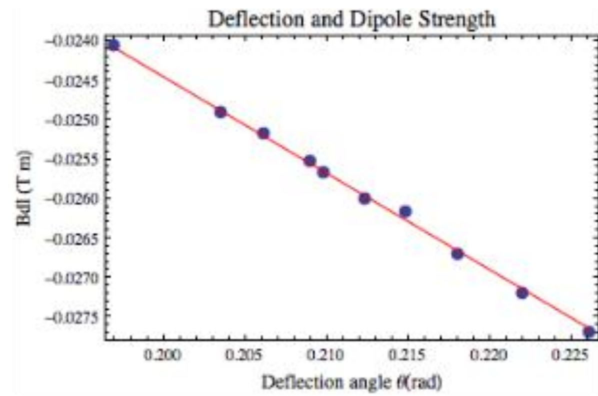
Possible sources for the energy error

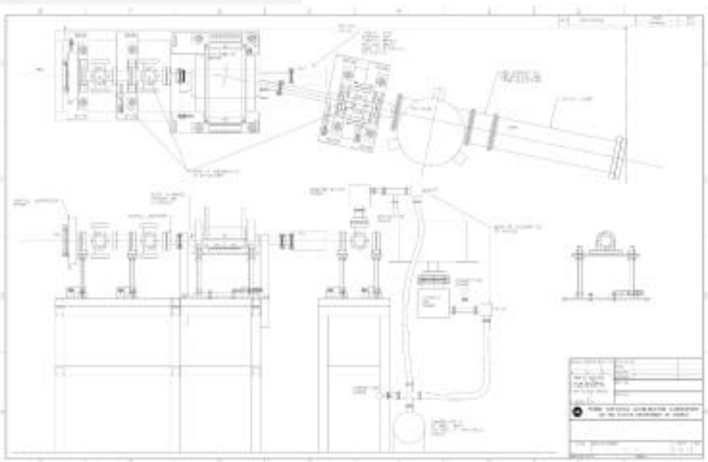
- TOF doesn't work? Why?
- Modulations incorrect?
- Warped rods?
- What could possibly be wrong?

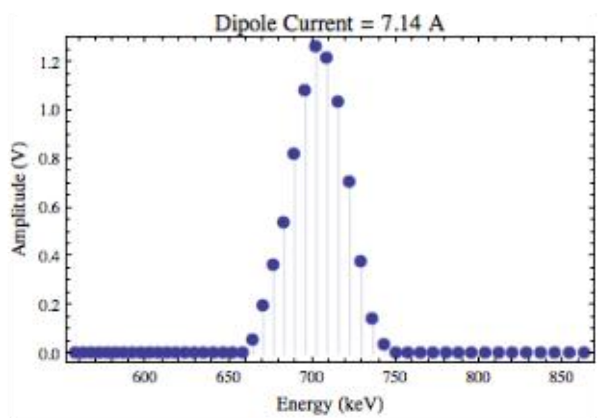
Energy spectrometer confirms energy error





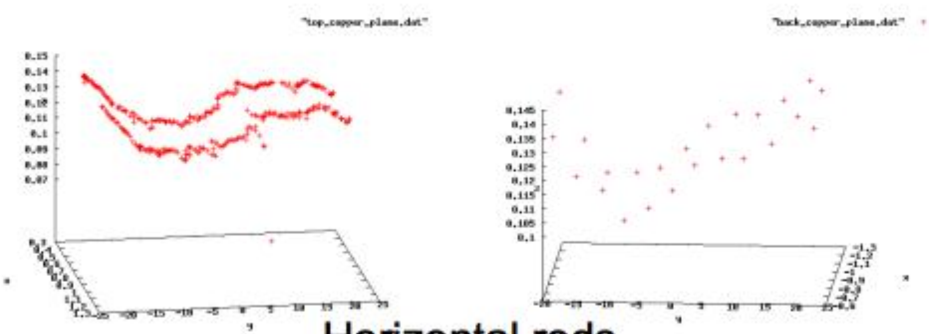




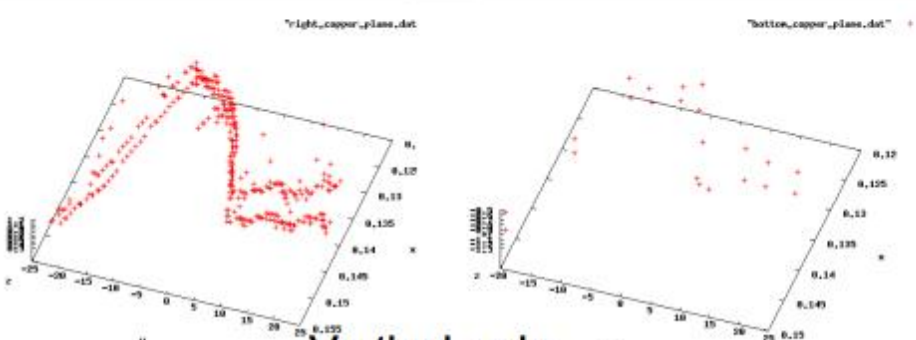


Energy is (703 ± 1) keV @ 168 kW forward 12 reflected

What's wrong? Warped rods?

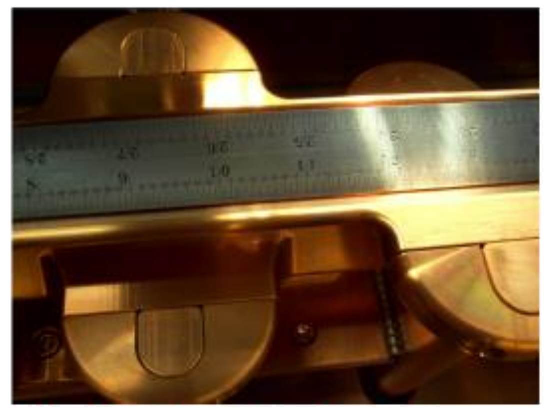


Horizontal rods



Vertical rods

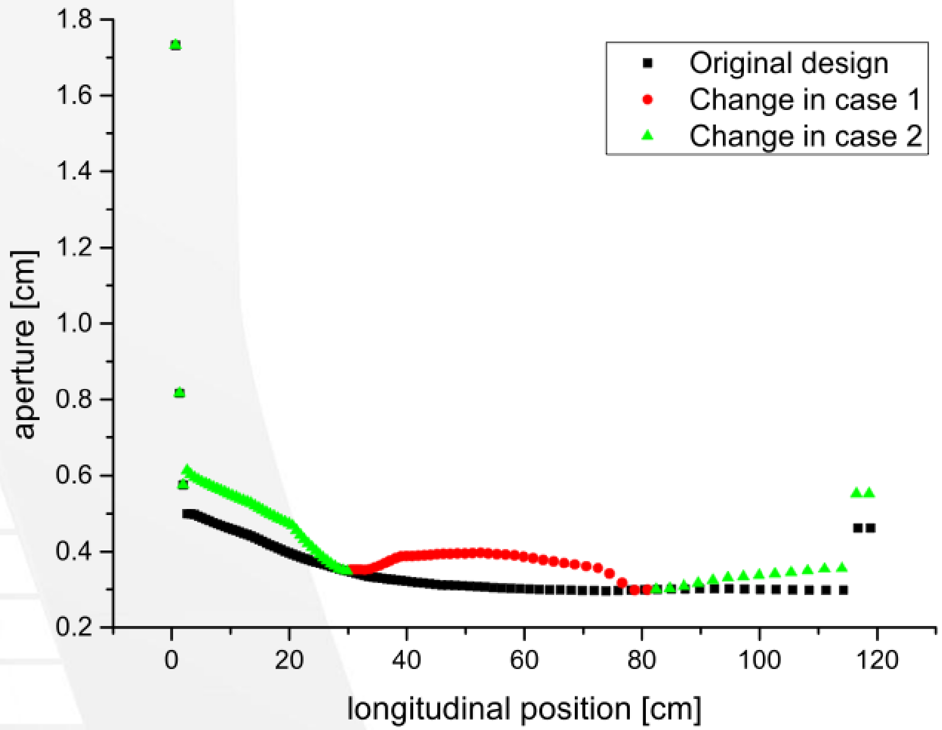
Hypothesis:
Es **is** fixed: determined by βs = 2 cell length/λ
BUT <E> != Es.
Example: rods infinitely far apart. Ez is zero and so <E> = input E, but Es stays the same!

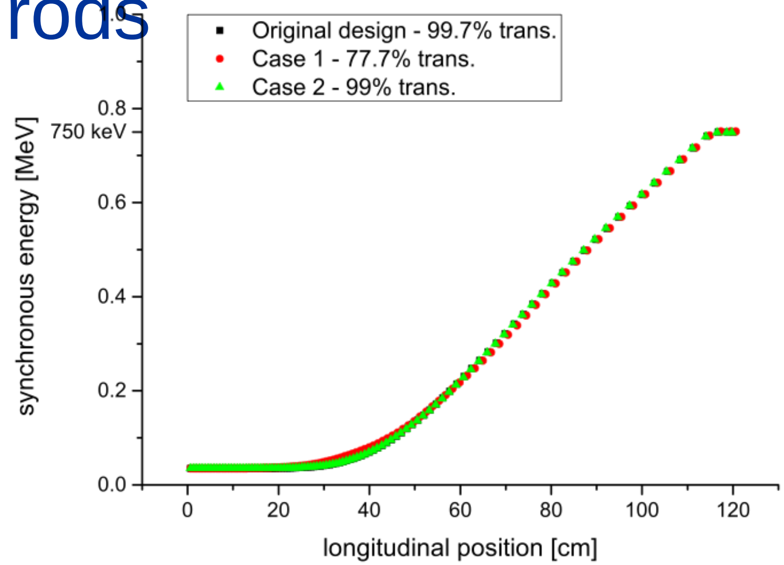


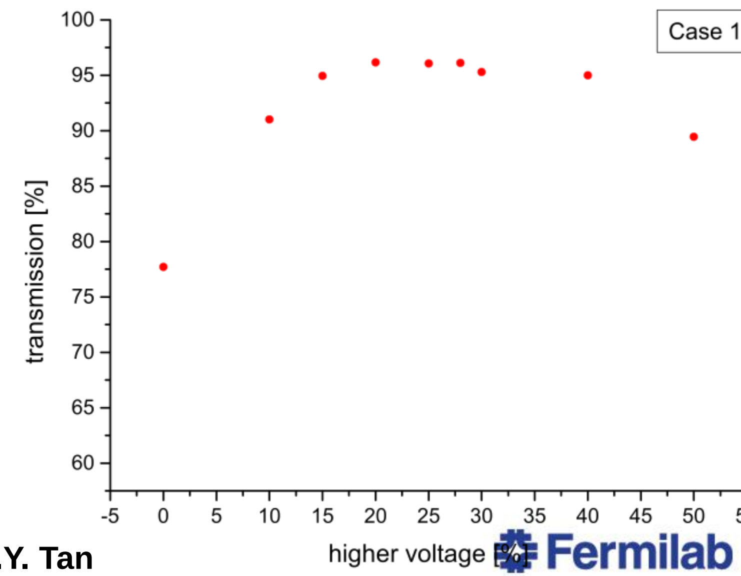
Unfortunately, this was a red herring. Did not fix energy problem when rods were straightened!

Warp not small: 0.5mm/5mm=10%
Fixed warp by straightening out the stands that hold the rods

The effect of warped rods

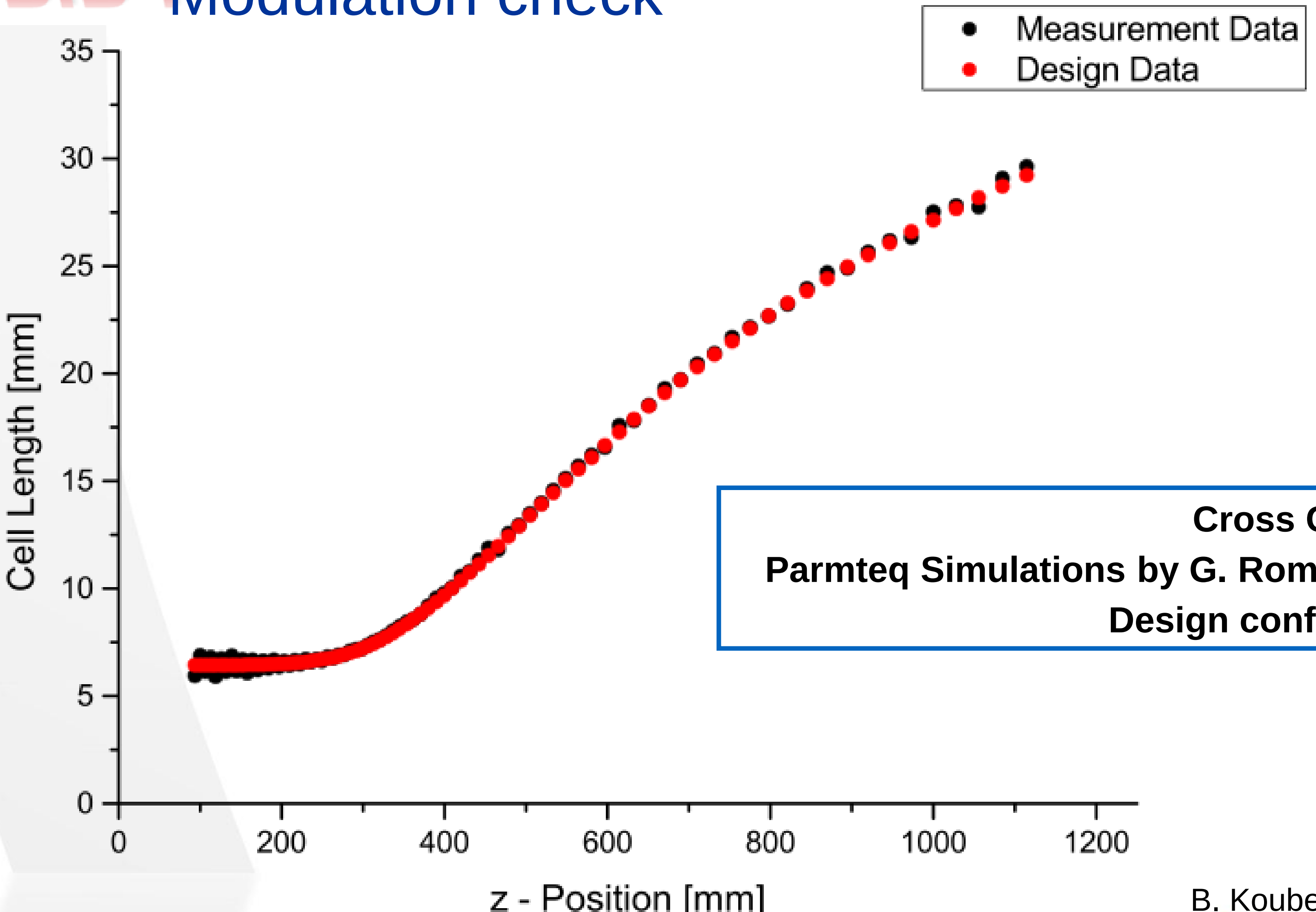






Courtesy of J.S. Schmidt

Modulation check

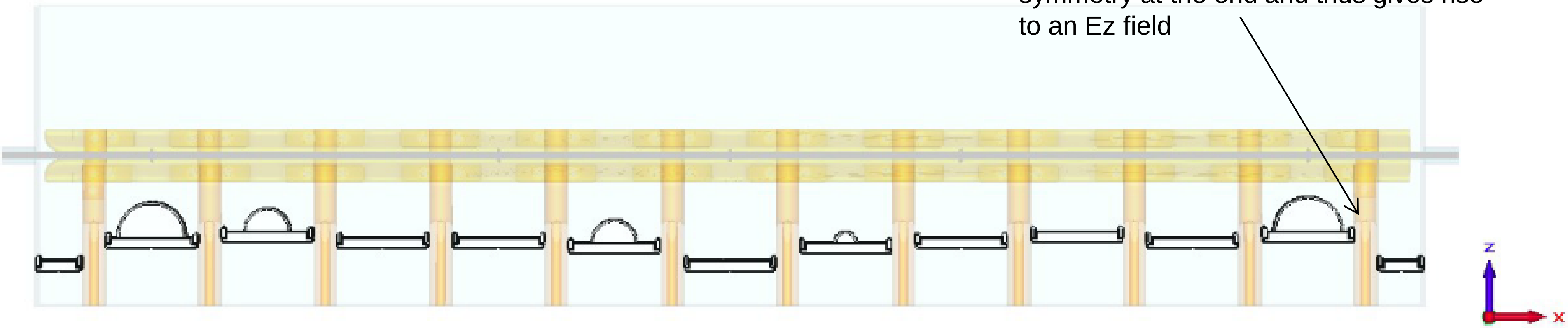


Cross Check
Parmteq Simulations by G. Romanov:
Design confirmed

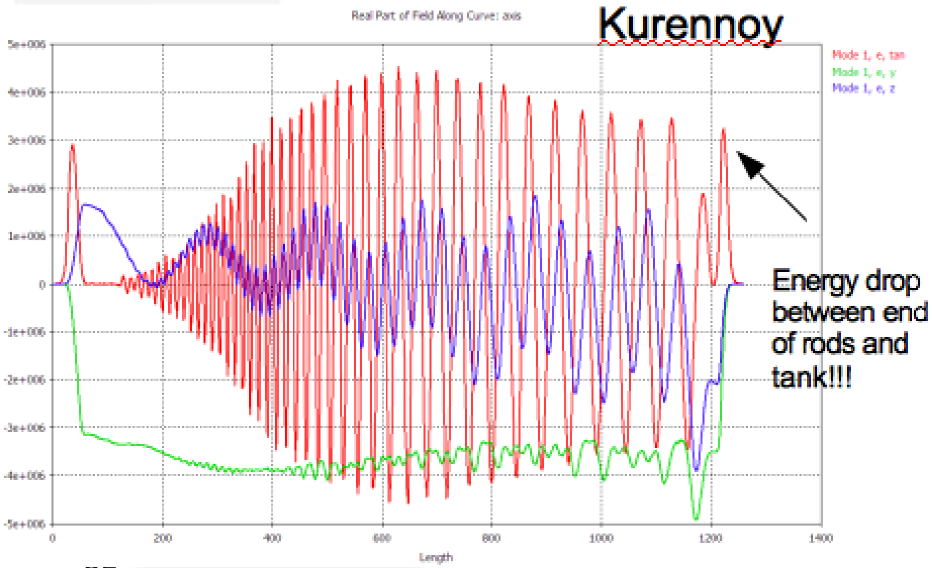
B. Koubek

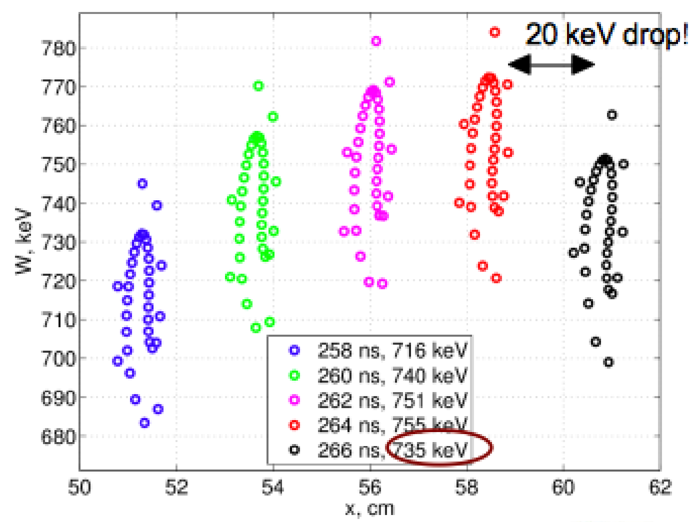
PIP-I CST Simulations

The stands break the quadrupole symmetry at the end and thus gives rise to an Ez field

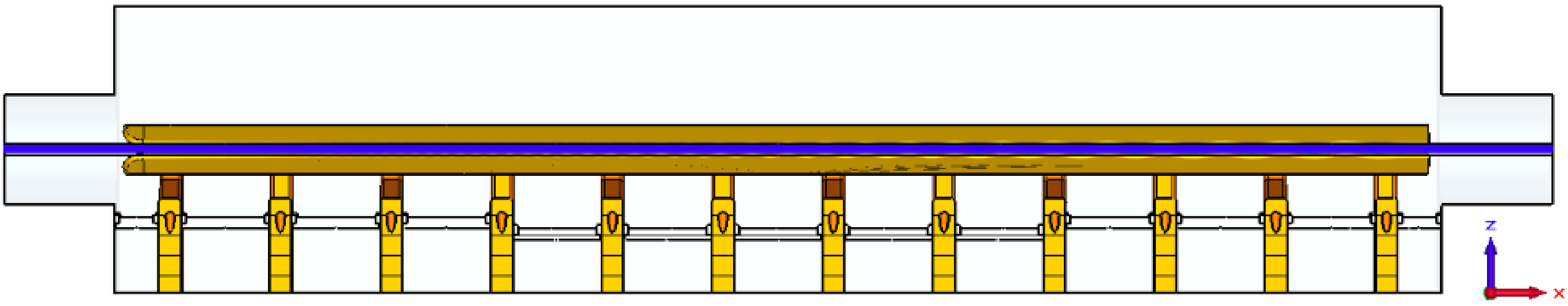


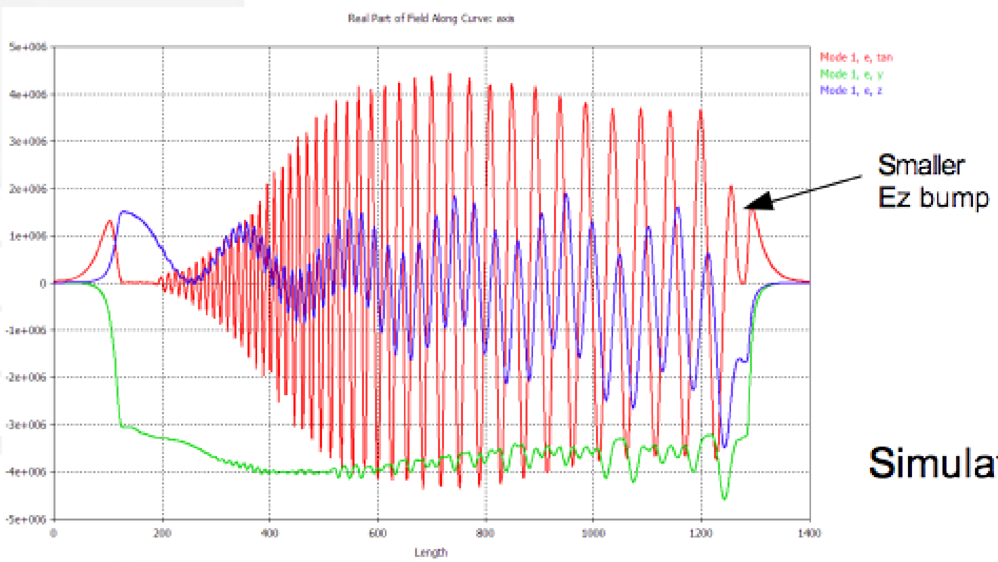
Simulation results by S. Kurennoy





PIP-II The source of the error





Opening up the ends, gives 753 keV!

Simulation results by S. Kurennoy

PIP-I

End plates

End plates are in the tank. Their purpose is to:

•Keep the RF in the tank

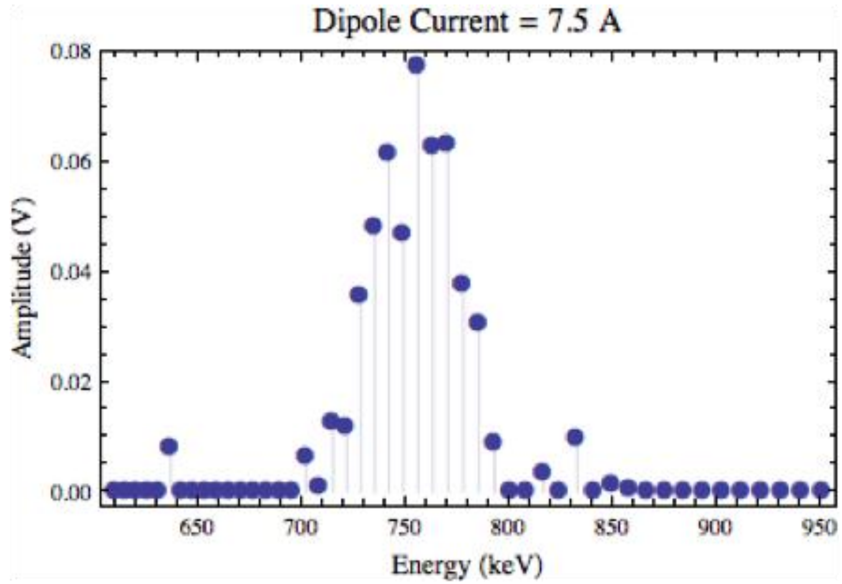
•Add capacitance to the ends of the rods

- This extra capacitance helps to flatten the Ez fields in the transition area.

The hole size is 20 mm in diameter.

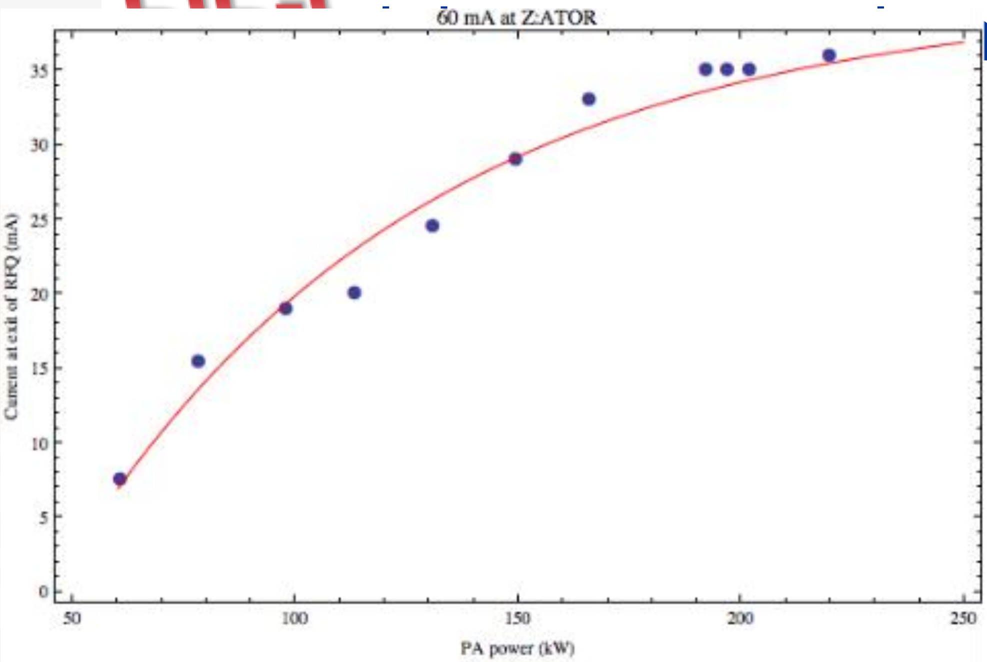
We have to be careful because E&M is Maxwell's equations with appropriate boundary conditions.

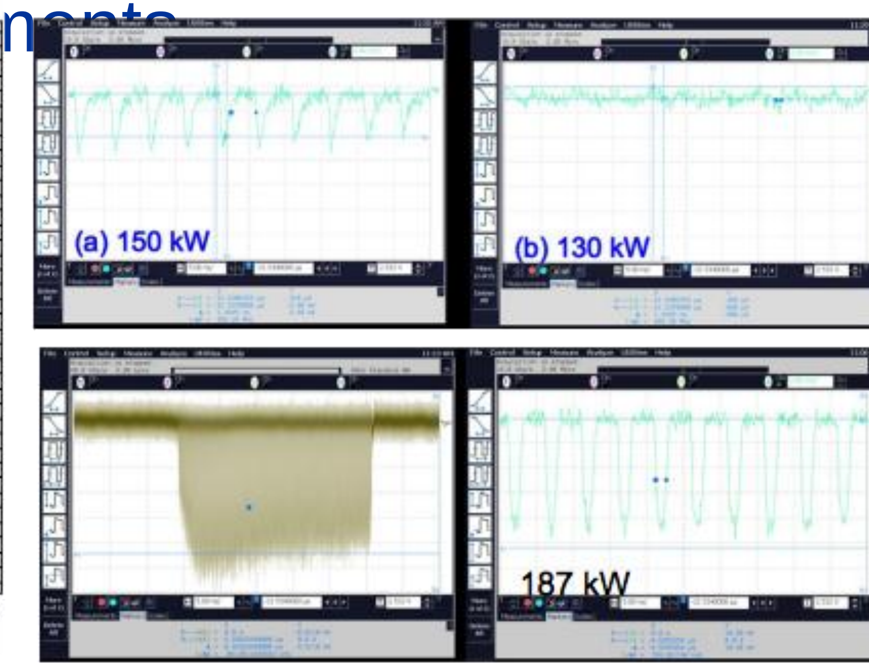
Energy problem fixed after end plate removal!



Energy is 756.5 ± 0.5 keV @ 170 forward, 3 kW reflected.

Energy error is fixed!!!!

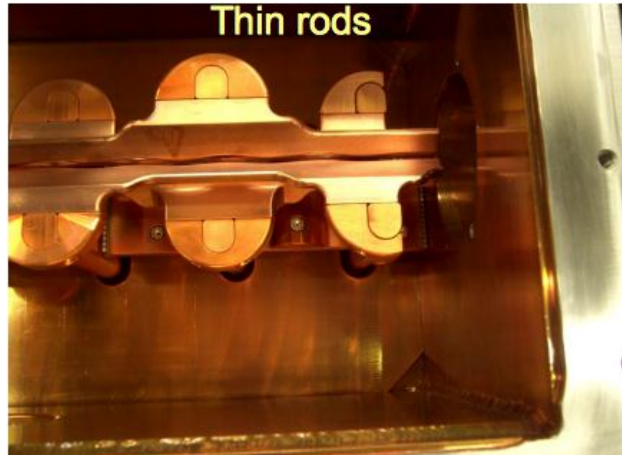




Original specs for RFQ is 100 kW
Capture below 130 kW is poor
> 150 kW for bunching
> 150 kW for transmission efficiency

But just barely can get 40 mA at the exit of the RFQ at limit of PA power

Thick rods versus thin rods



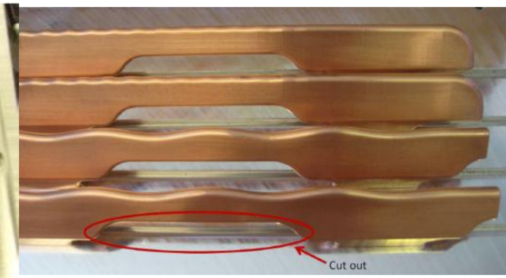


TABLE III. Design Parameters of the FNAL RFQ.

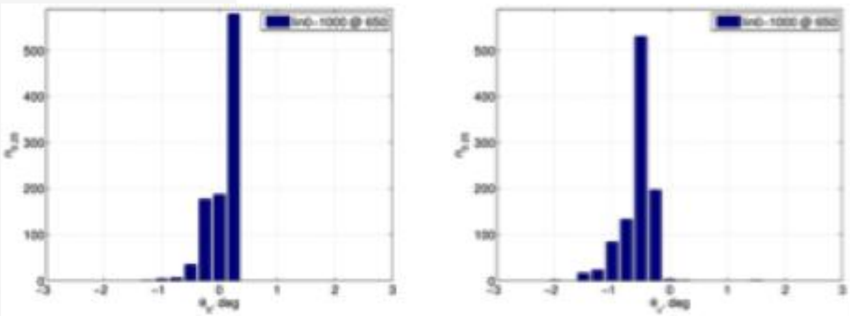
	Thick Electrodes	Thin Electrodes
Shunt Impedance R_{P0}	31.7 kΩ	44.6 kΩ
Power $\bar{N}$ @ U_0=72 kV	163.6 kW	116.3 kW

power reduction ~ 23%

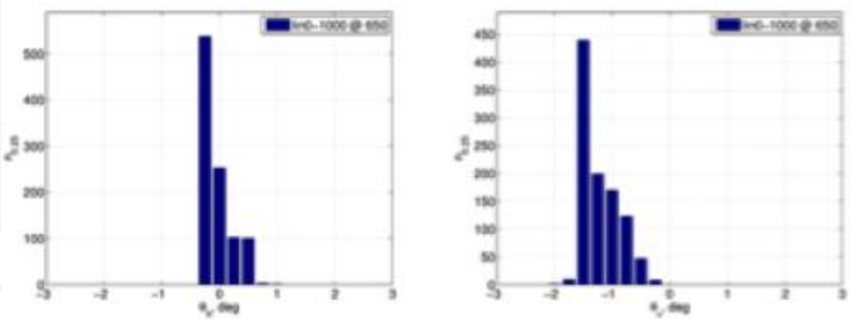
Observed start of bunching ~100 kW with thin rods compared to 130 kW for thick rods.

Operations ~170 kW power.

Exit angle



Vane voltage = 72 kV



Vane voltage = 90 kV

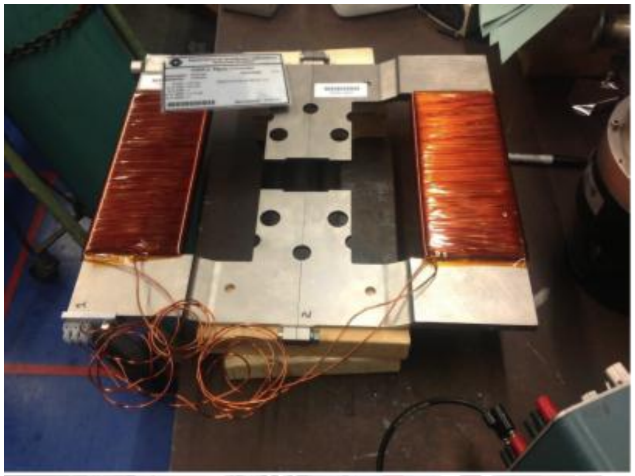
Tuning showed large dipole currents (especially vertically) required to get maximum beam transmission into beginning of Tank 1. The dipole current setting (~3.5 A) is consistent with 1 deg angle.

Simulations by S. Kurennoy (LANL) showed that this is indeed the case.

Vane voltage (kV)	Horizontal exit angle (deg)	Vertical exit angle (deg)
72	0.16	–0.44
90	0.09	–1.10

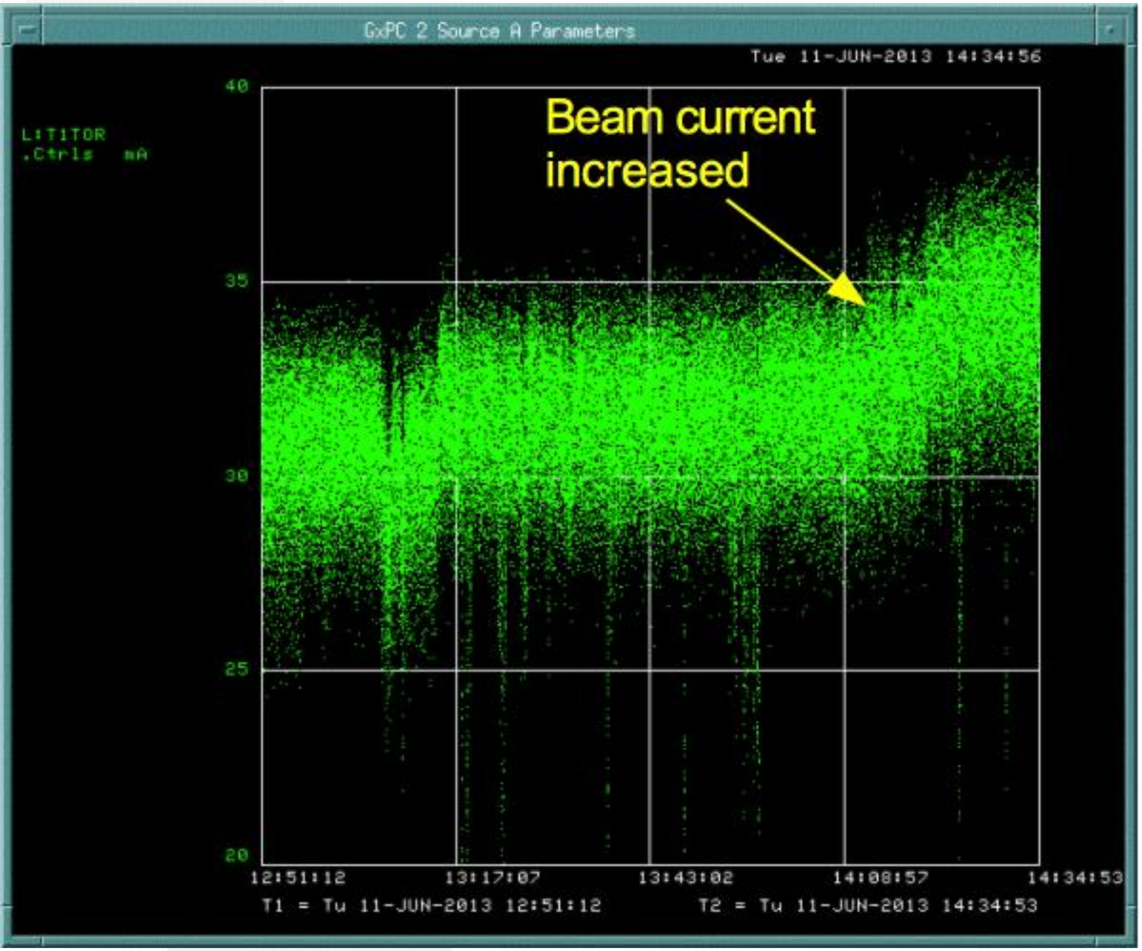
PIP-I

Installing vertical correctors



Only the vertical corrector is installed.

There is an effect!

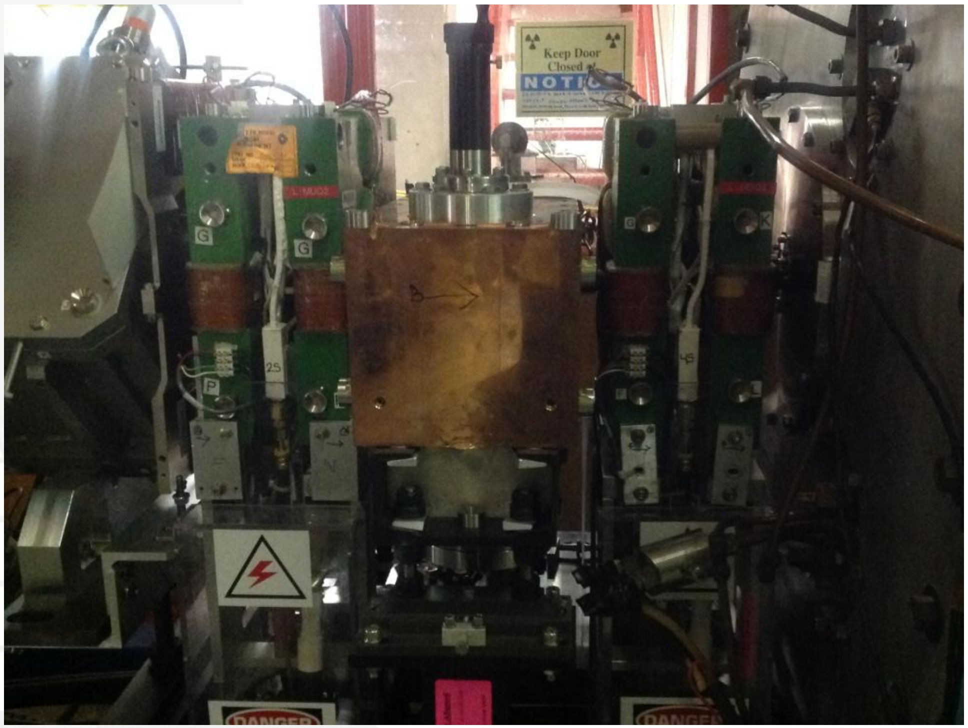


There is an effect to the beam current at the exit of the RFQ:

With the new trim at 7.5 A, the 1st downstream vertical trim is reduced from ~3.5 A to 2.2 A. (In later tuning, reduced even further to 1.0A)

Unfortunately, we only gained about 1 mA from this exercise :-(

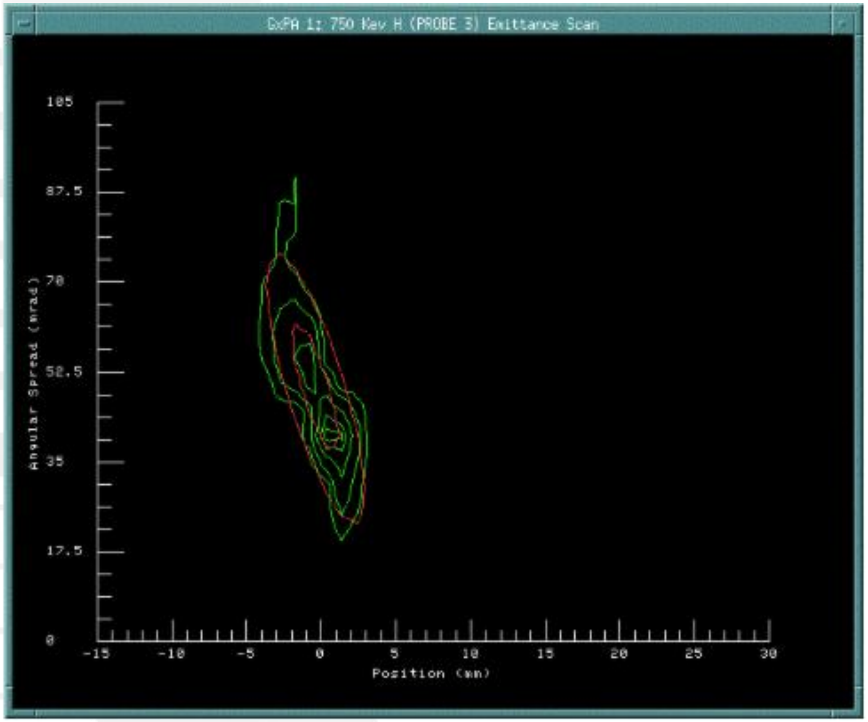
PIP-I MEBT



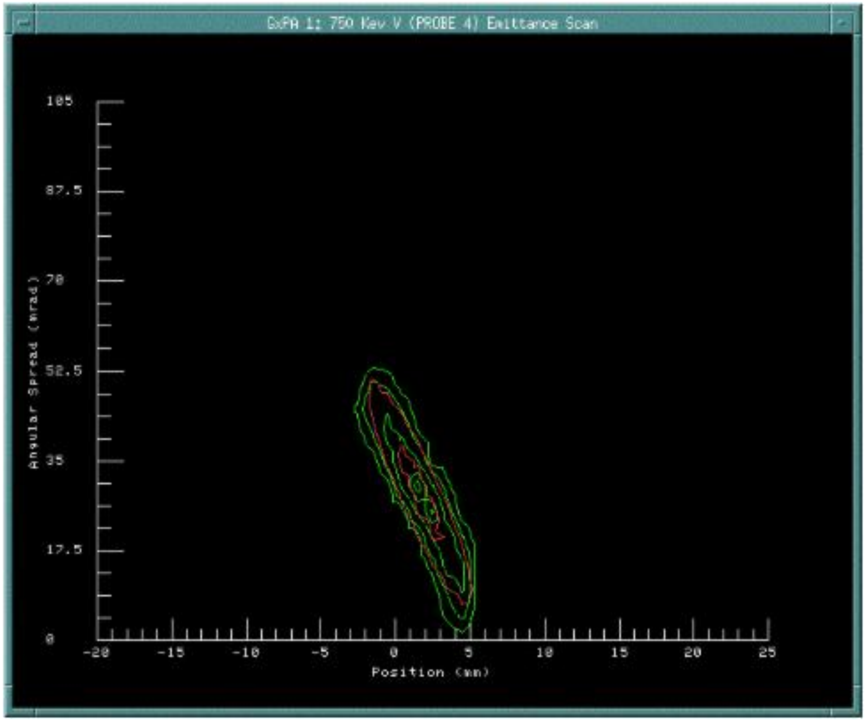
MEBT consists of 2 sets of doublets and a buncher.

Update to add gate valve between MEBT and Tank 1.

Transverse emittance @35 mA at entrance of Tank 1



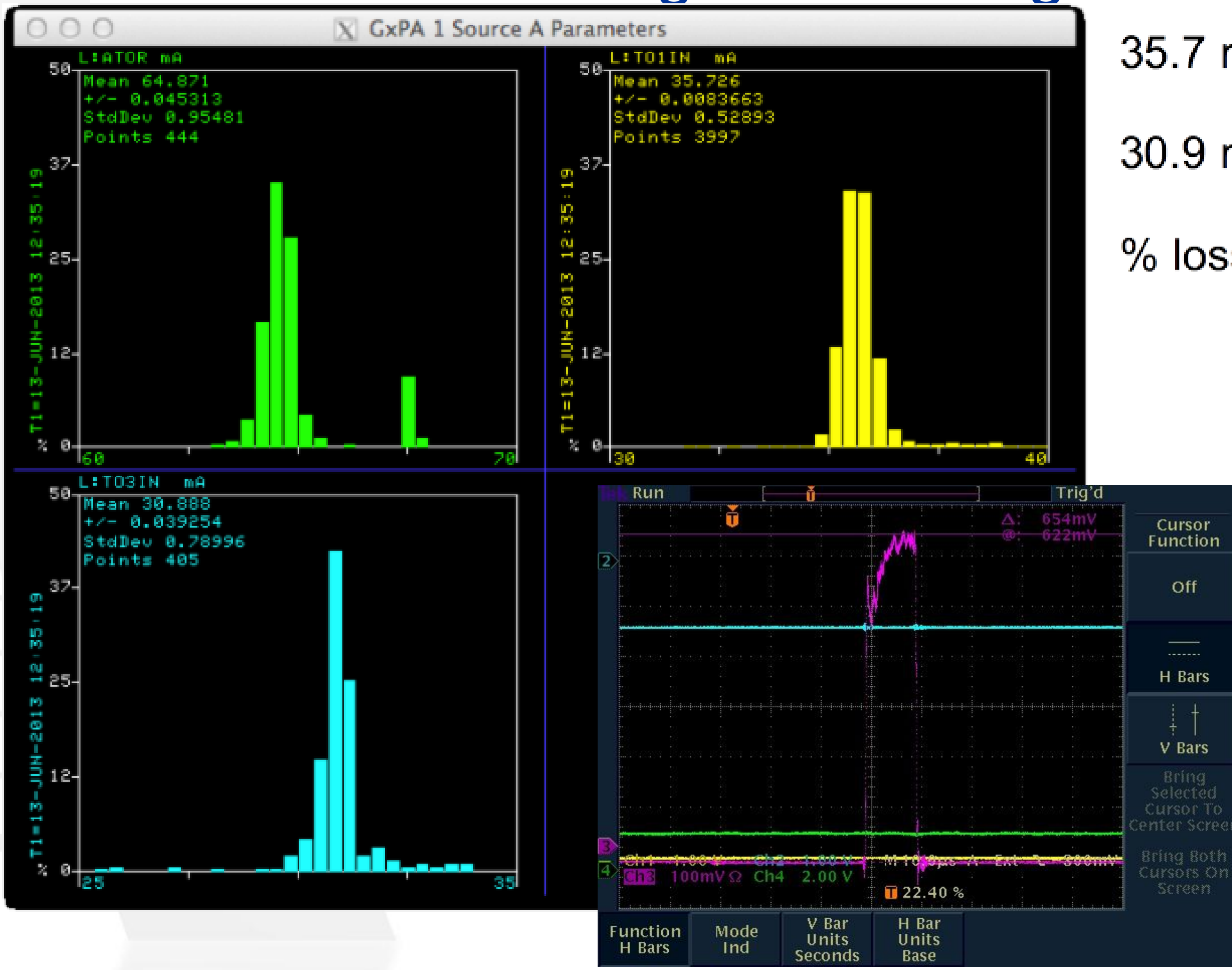
Horizontal emittance: 0.57 pi mm mrad



Vertical emittance: 0.37 pi mm mrad

PIP-I

Best running after tuning



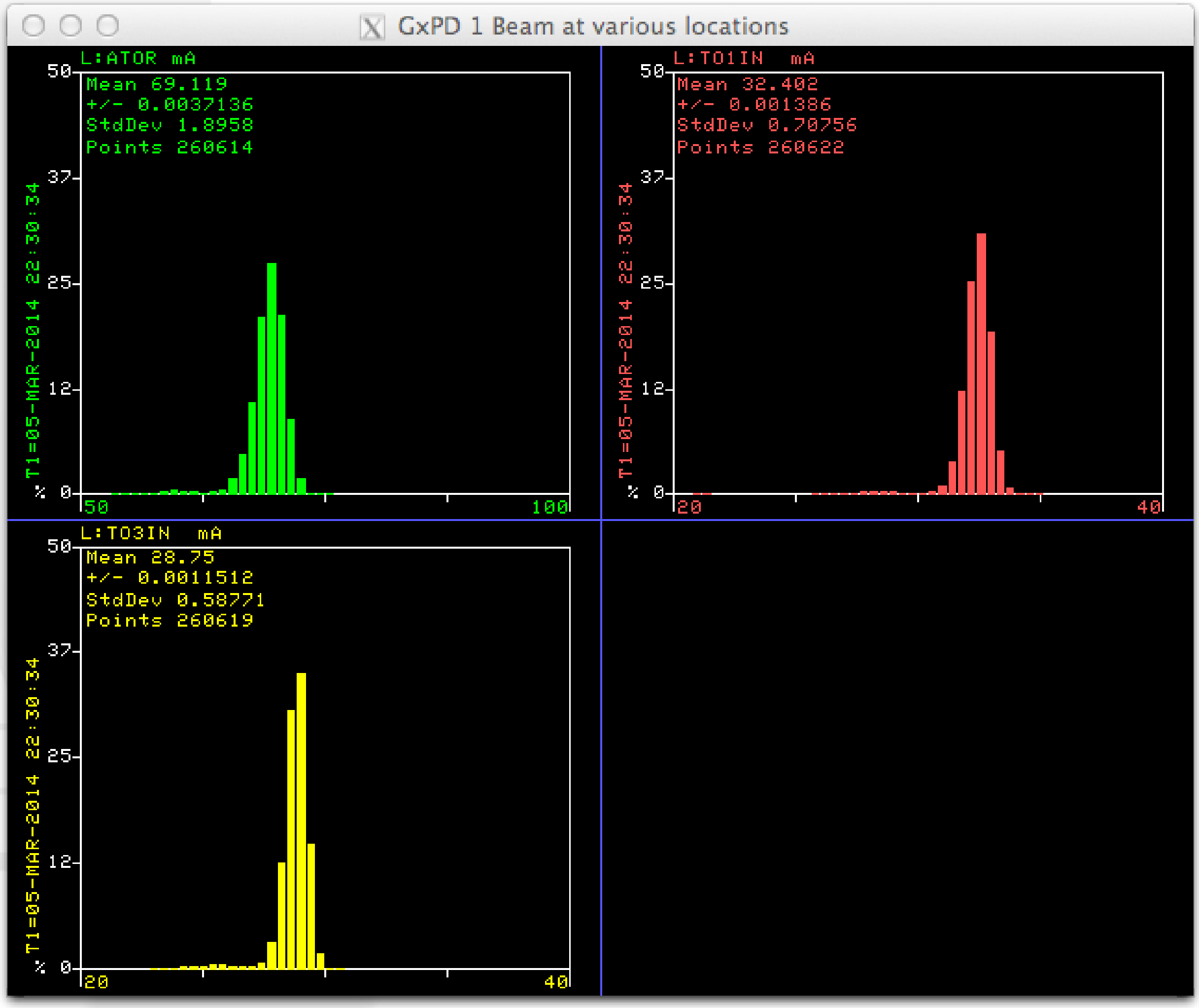
35.7 mA at the start of Tank 1.

30.9 mA at the start of Tank 3.

% loss is (4./35.) = 13%

After a lot of tuning, we can get 40 mA in front of Tank 1

Recent performance



Tank 1 in: 32 mA

Tank 3 in 29 mA

PIP-I

Summary

We do it because we can
We can because we want to
We want to because skeptics said we can't.
Never, never, never, give up!

- A lot of work has gone into the upgrade
  - Installation completed on time.
- Although the RFQ injector is installed and operational, there is still work that needs to be done.
  - We would always like to be able to have more beam from the present ~35 mA at the start of Tank 1.
  - Will removal of the MEBT improve transmission?
    - On test stand best current is ~43 mA at the end of the RFQ.