The RFQ Injector Upgrade

C.Y. Tan

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Acknowledgements

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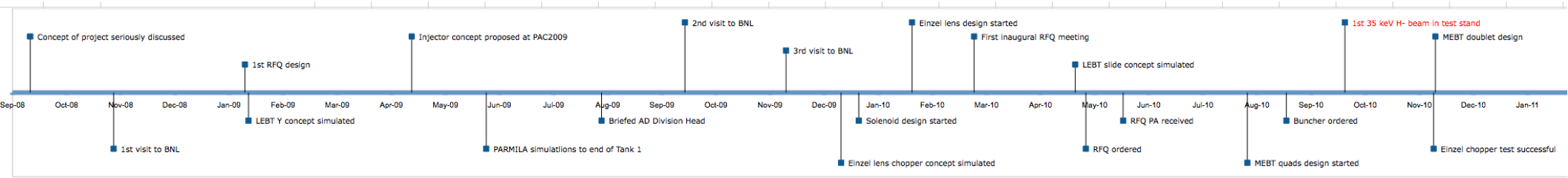
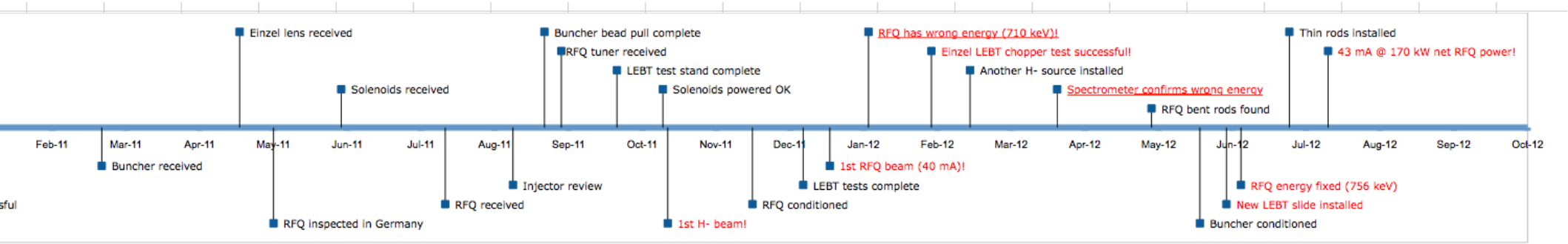
- And anyone whom I have inadvertently left out. Thanks!

Overview

- This talk will mainly concentrate on the problems that we encountered with the RFQ
  - Output energy problem
  - Transmission efficiency problem
  - Power requirement problem
  - Fixes, fixes and more fixes
  - Tuning, tuning and more tuning!
- Nothing is ever simple and this RFQ has tested us to the extreme.

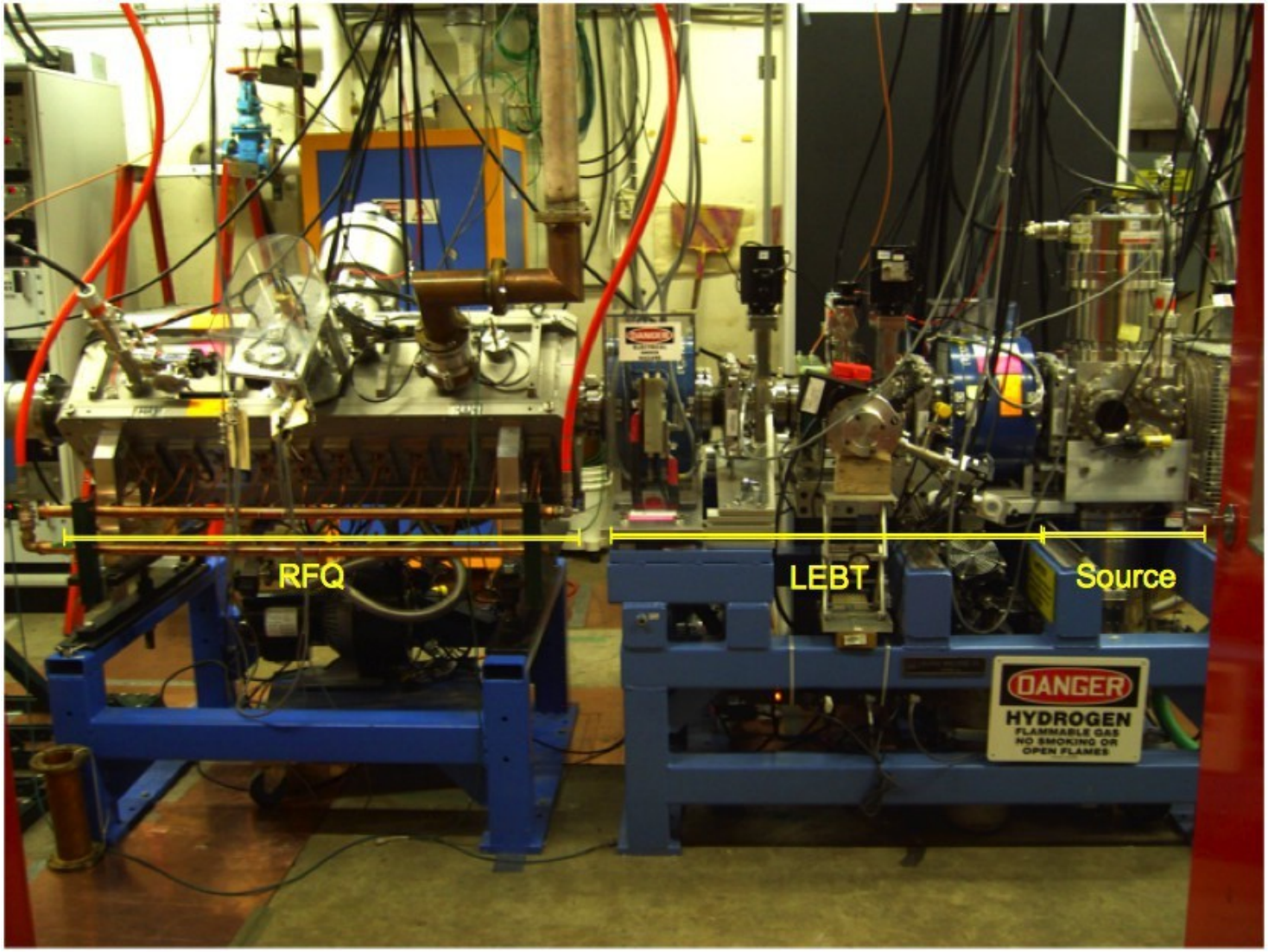
Time Line of project





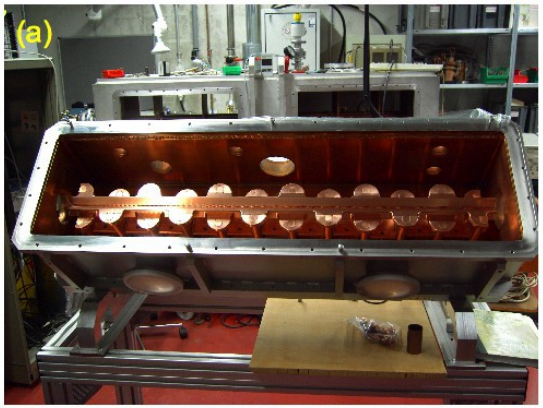
4 years and counting!

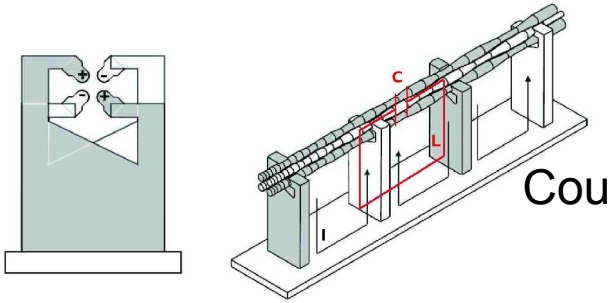
The test line



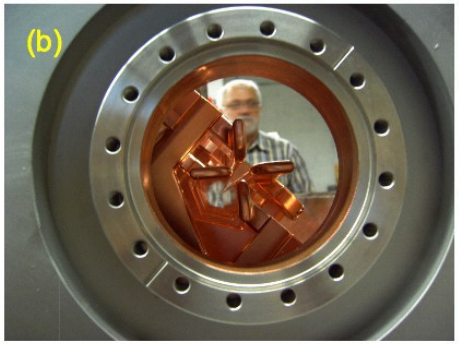
- 1 H- dimpled H- magnetron source.
- LEBT
  - 2 solenoids
- Einzel lens chopper
- RFQ
- Instruments added to the end of the RFQ
  - Spectrometer
  - Beam buttons for time of flight
  - Toroid
  - Emittance probes

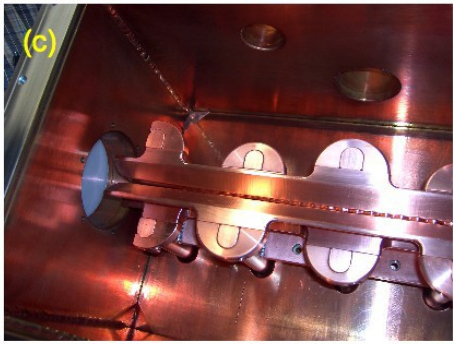
The RFQ

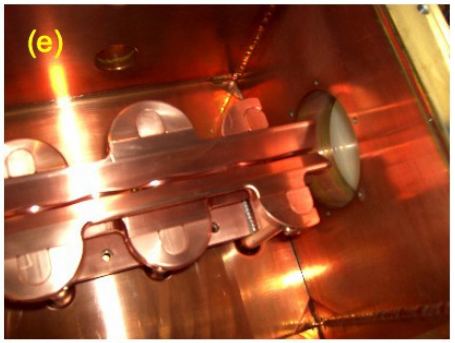




Courtesy of J. Schmidt





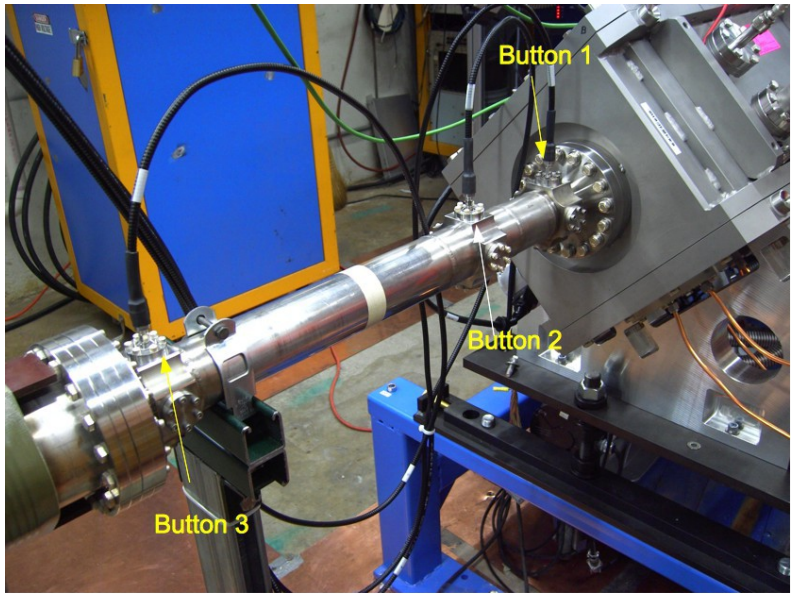


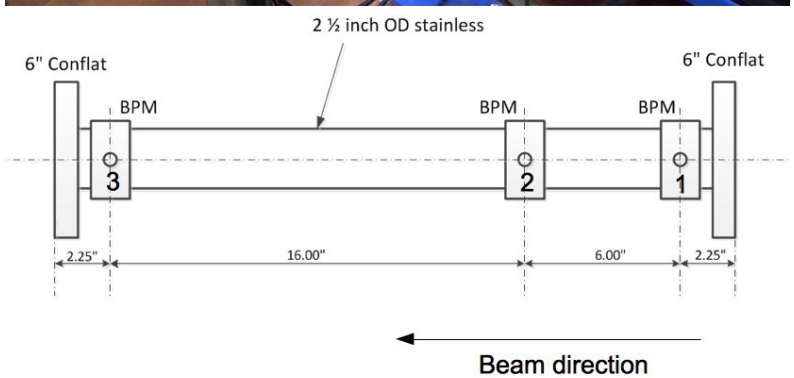
Parameter	Value	Units
Input energy	35	keV
Output energy	750	keV
Frequency	201.25	MHz
Number of cells	102	
Length	120	cm
Minimum radial aperture	0.3	cm
Maximum peak surface field	25.18	MV/m
Peak cavity power+beam power	~140	kW
Duty factor (80 μs, 15 Hz)	0.12	%
Design current	60	mA
Modulation m	$1 \leq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

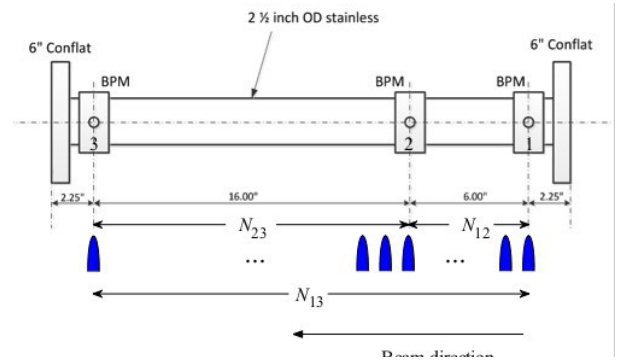
Measuring output energy

- 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.

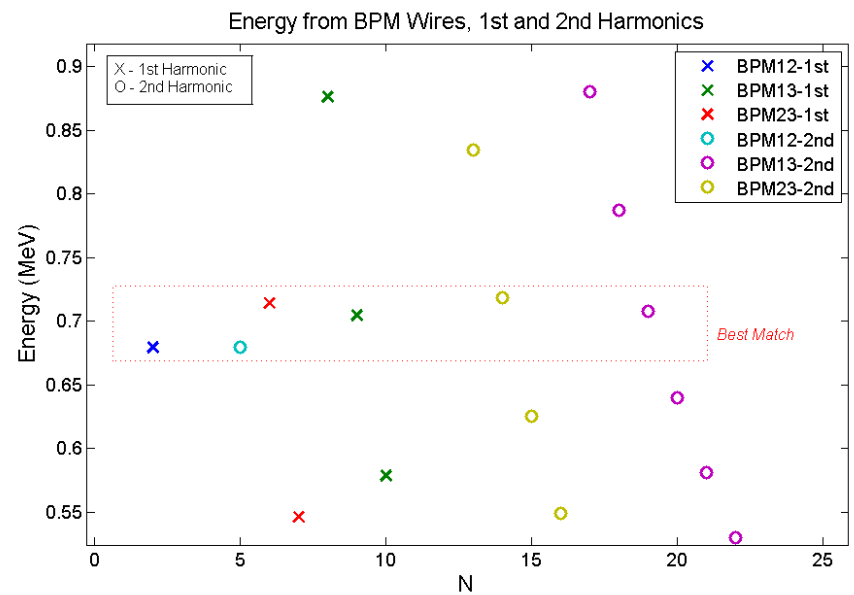
Time of Flight and first signs of trouble





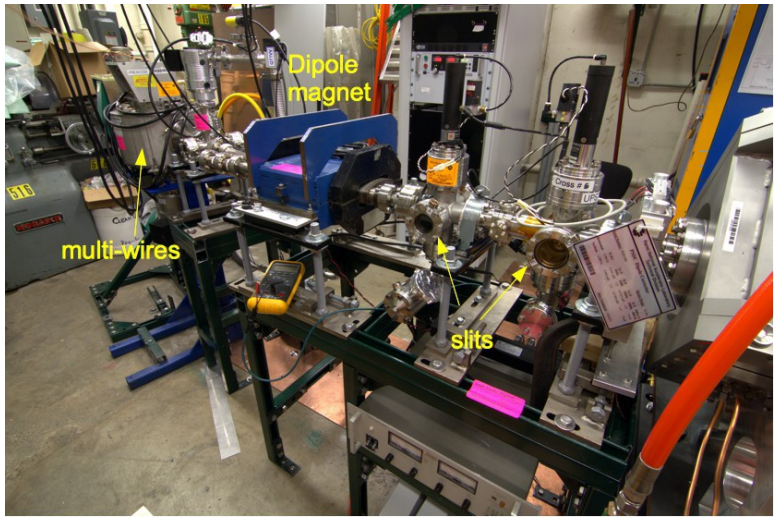


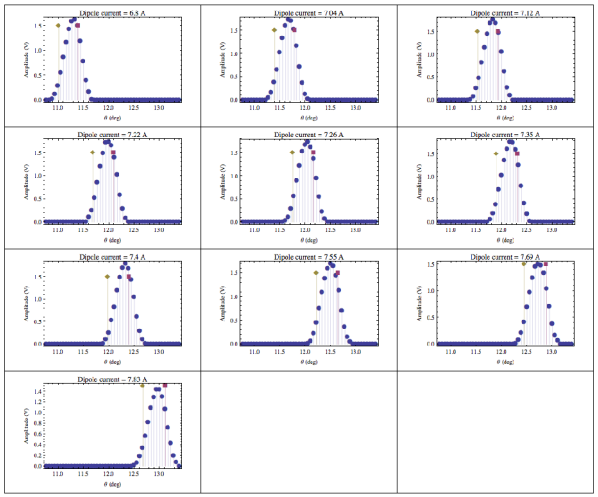
$$\Delta t_{mn} = \frac{(N_b \times 2\pi) + \Delta\varphi_{mn}}{2\pi f_{RF}} \quad \text{where } \Delta\varphi_{mn} = \varphi_n - \varphi_m \quad \text{for } n > m$$

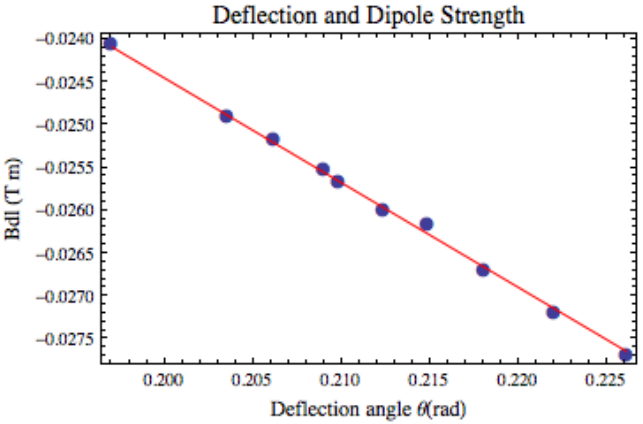


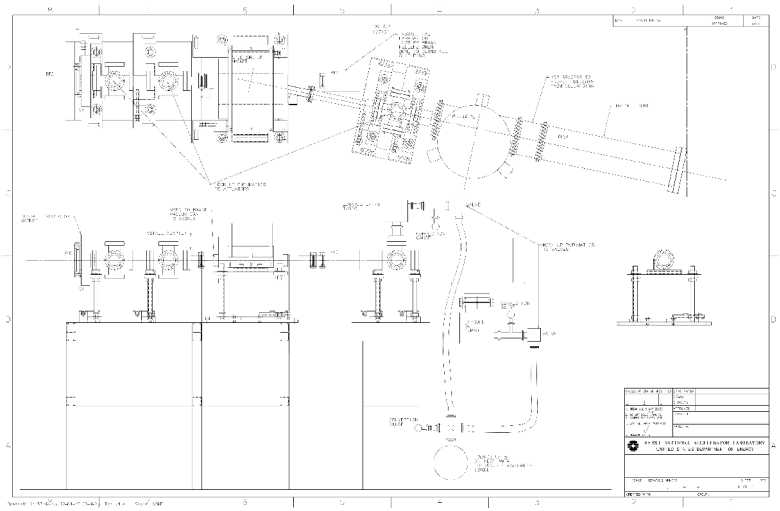
700 keV!

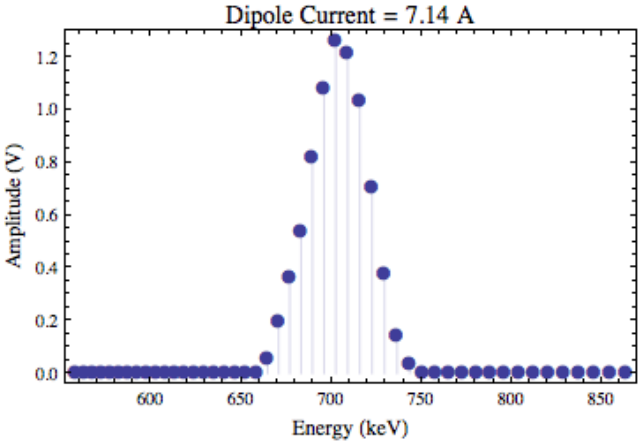
Energy Spectrometer confirms energy error





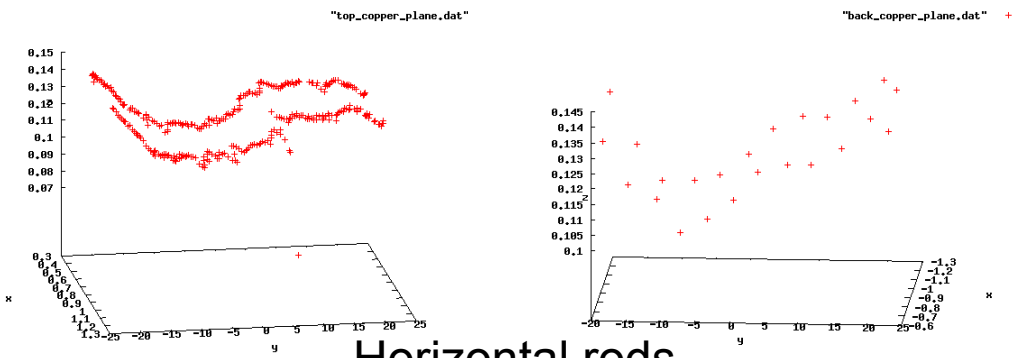




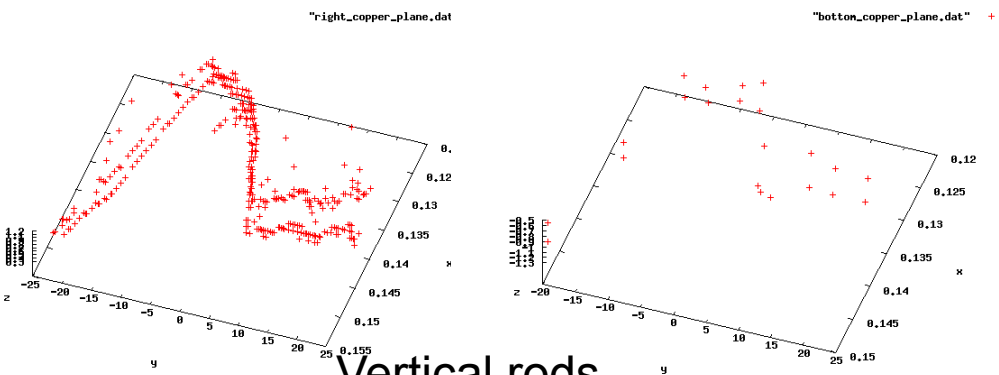


Energy is (703 ± 1) keV @ 168 kW forward 12 reflected

What's wrong? Warped rods?



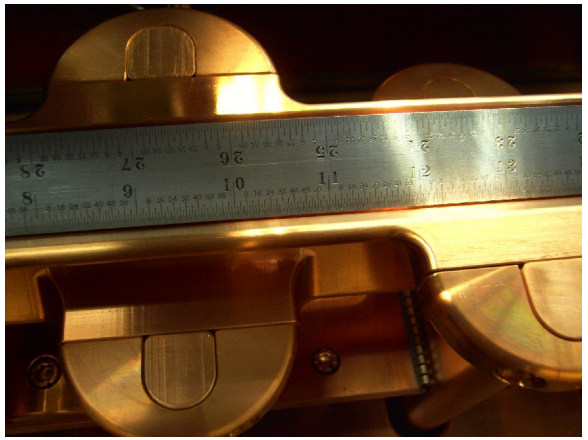
Horizontal rods



Vertical rods

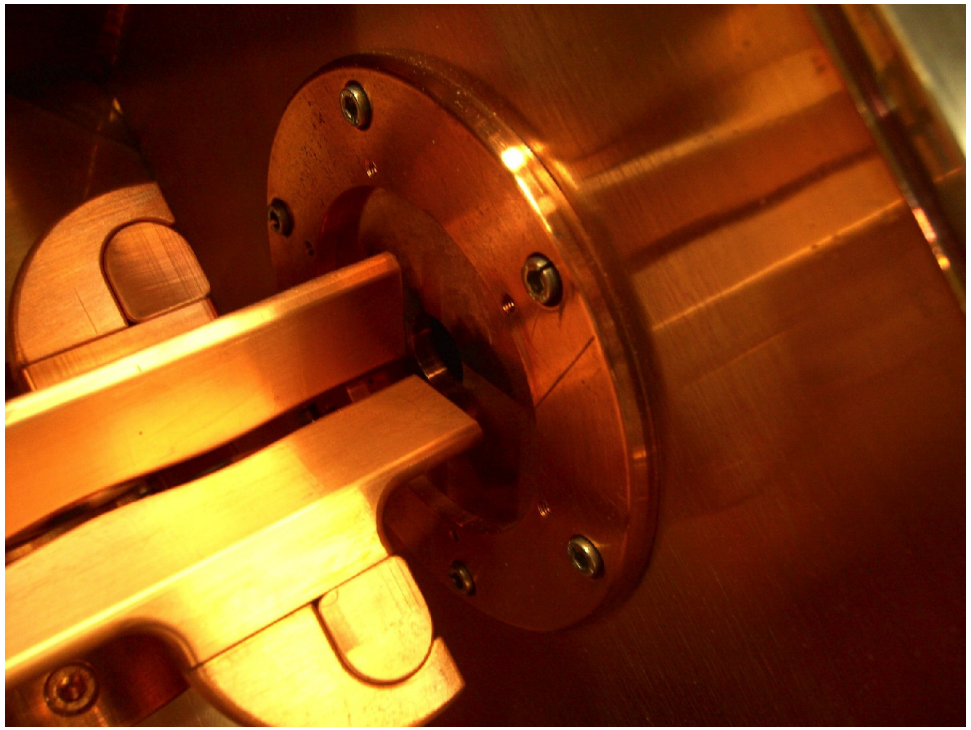
Warp not small: 0.5mm/5mm=10%
Fixed warp by straightening out the stands that hold the rods

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!

End plates



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

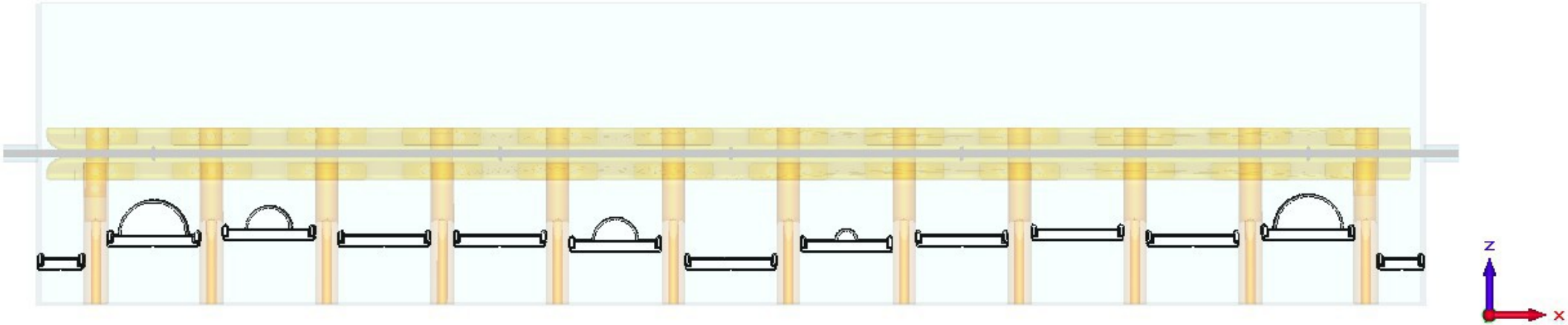
•Keep the RF in the tank

•Add capacitance to the ends of the rods

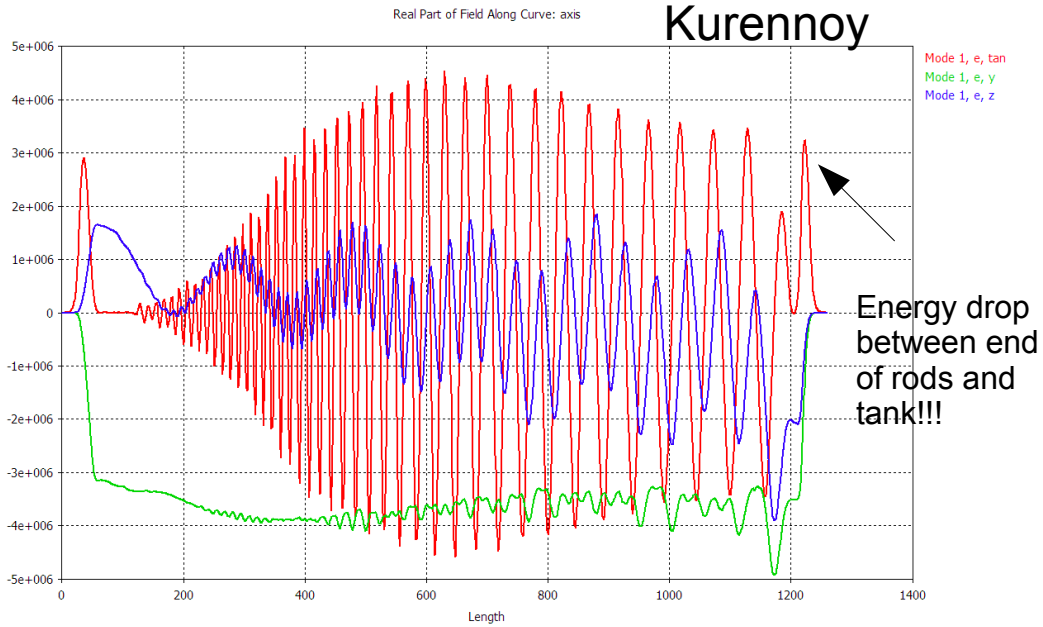
- <u>This extra capacitance helps to flatten the Ez fields in the transition area.</u>

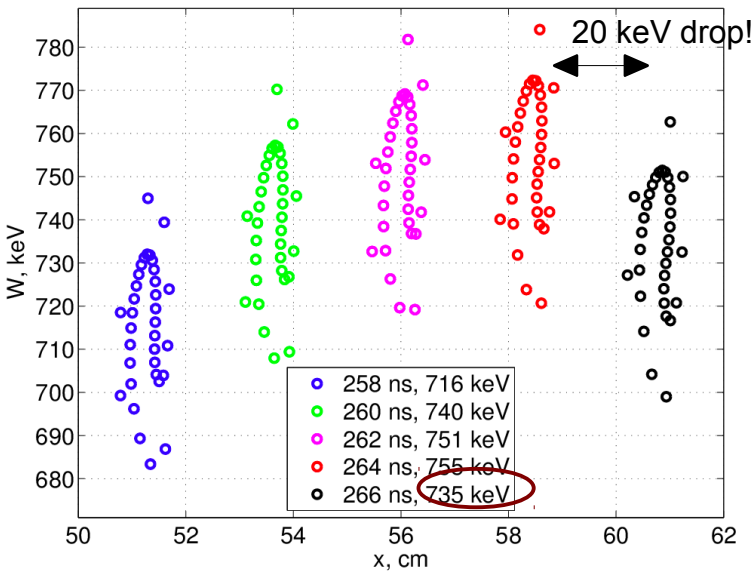
The hole size is 20 mm in diameter.

CST Simulations

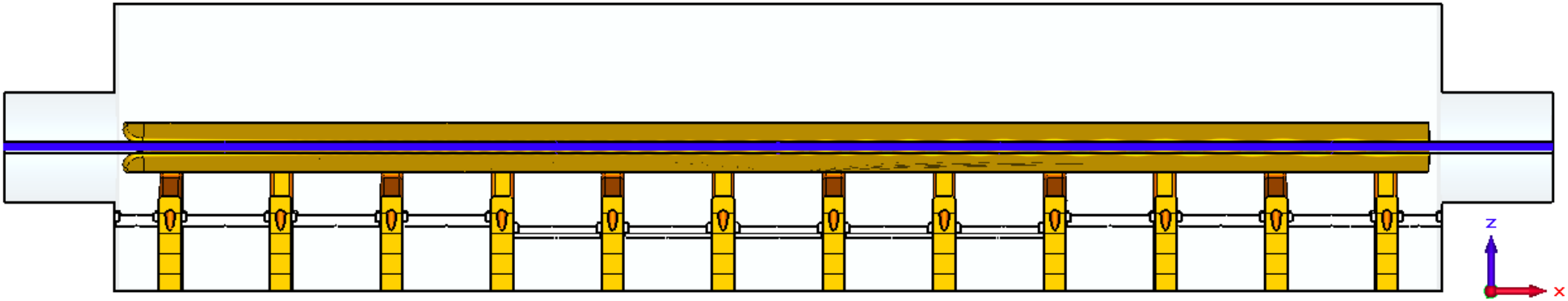


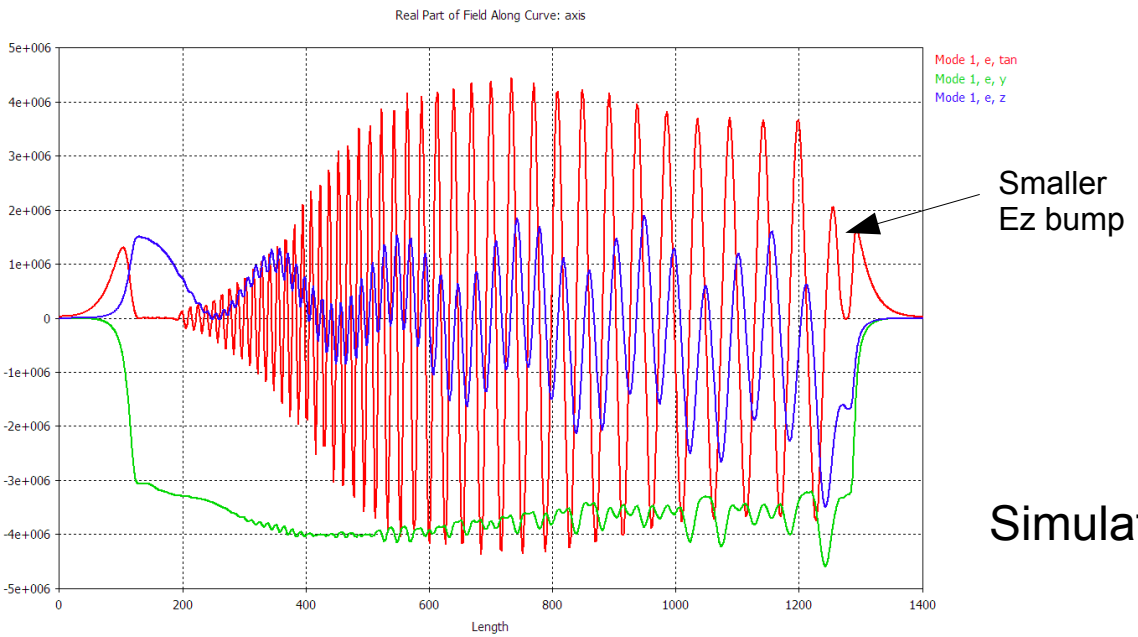
Simulation results by S. Kurennoy





The source of the error

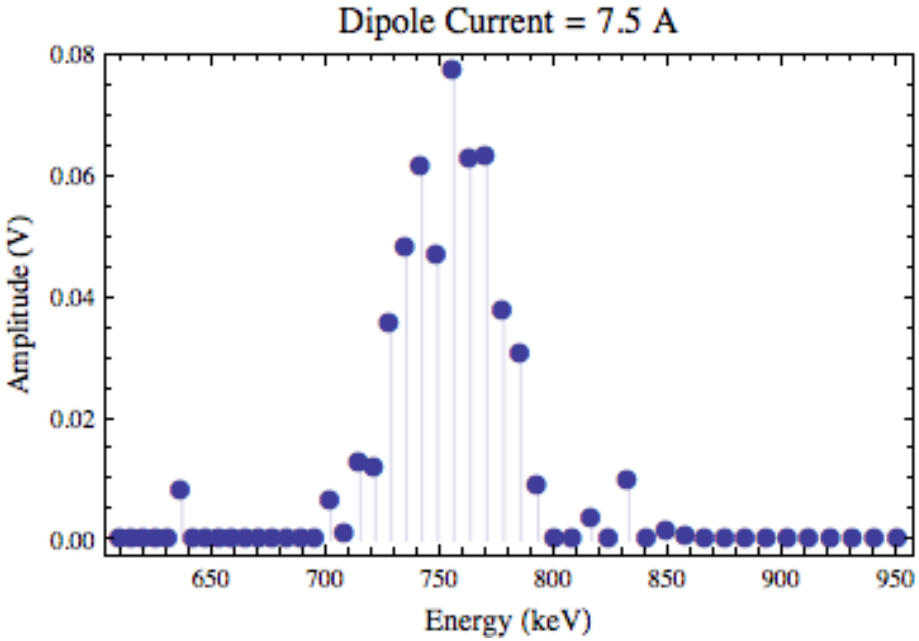




Opening up the ends, gives 753 keV!

Simulation results by S. Kurennoy

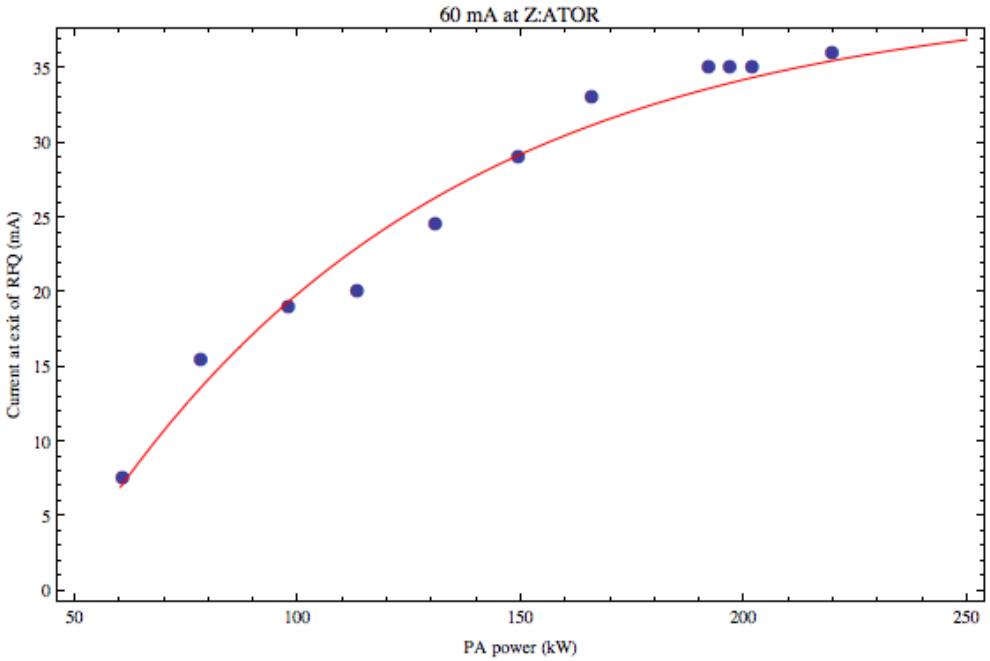
Energy after end plate removal

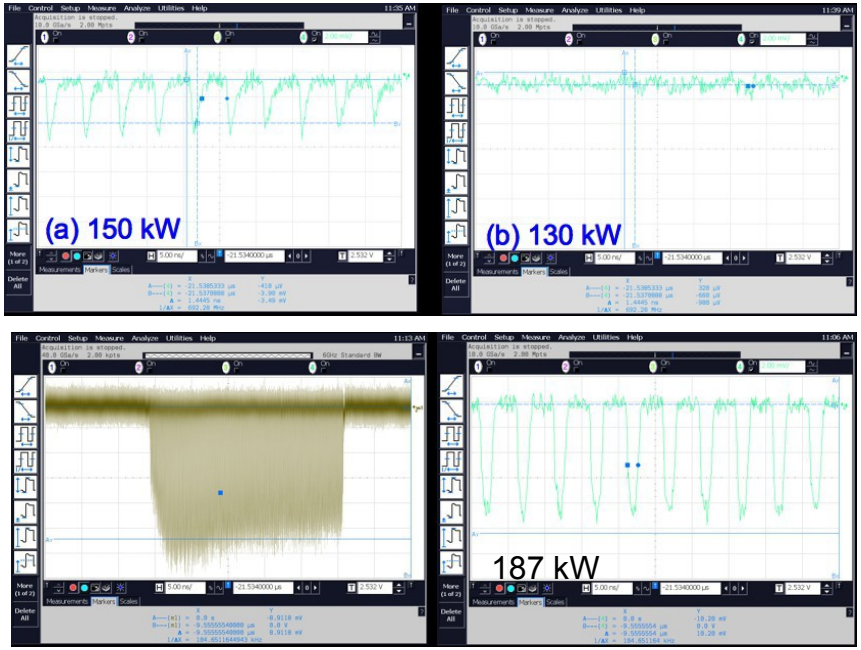


Energy is 756.5 ± 0.5 keV @ 170 forward, 3 kW reflected.

Energy error is fixed!!!!

High Power Requirements

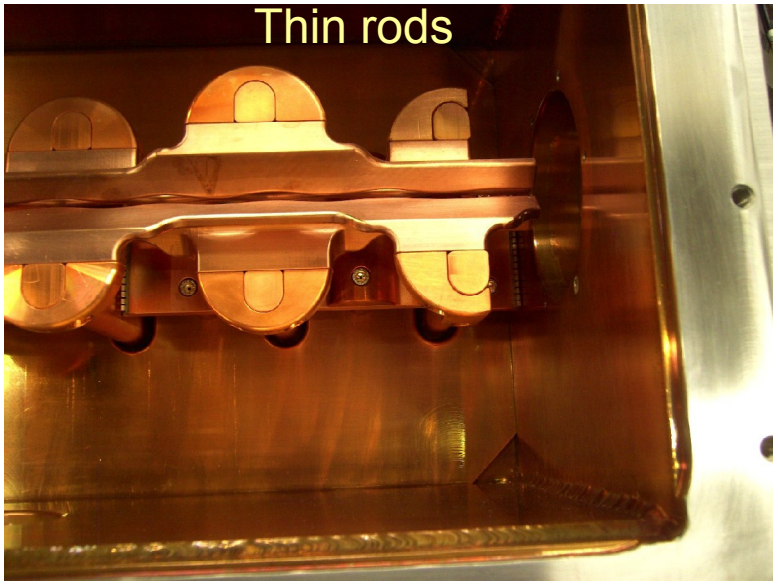




Original specs for RFQ is 100 kW
Capture below 130 kW is poor
> 150 kW for bunching
> 150 kW for transmission efficiency

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

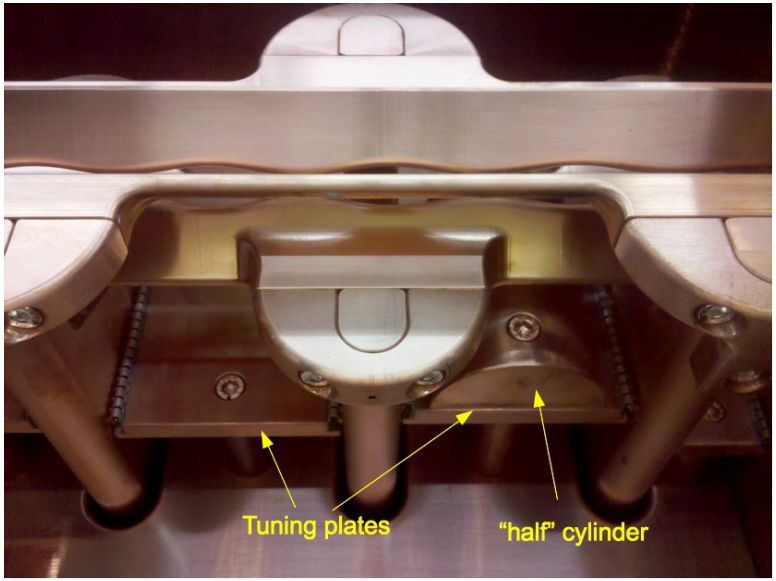
Thick rods vs thin rods

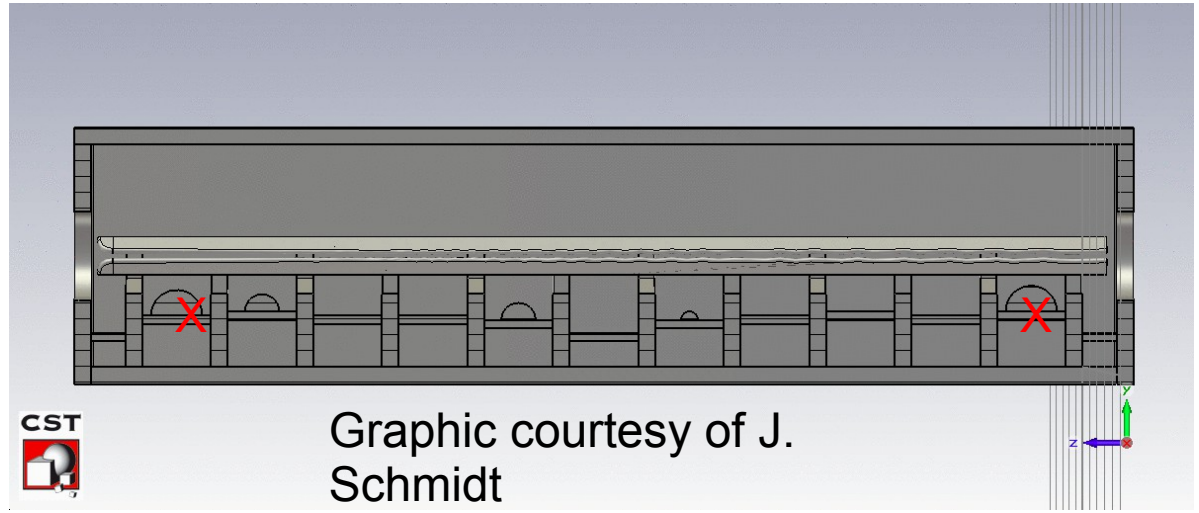


Derived from Q and capacitive perturbations of the fields.
Thick rods power requirements: 144 kW (+beam power = 174 kW)
Thin rods power requirements: 121 kW (+ beam power = 151 kW)
Beam power = 750 kV * 40 mA = 30 kW

$$R_p = \frac{2Q\Delta f}{\pi f_0^2 C_s}.$$

Thin rods reduce use of “half” moons



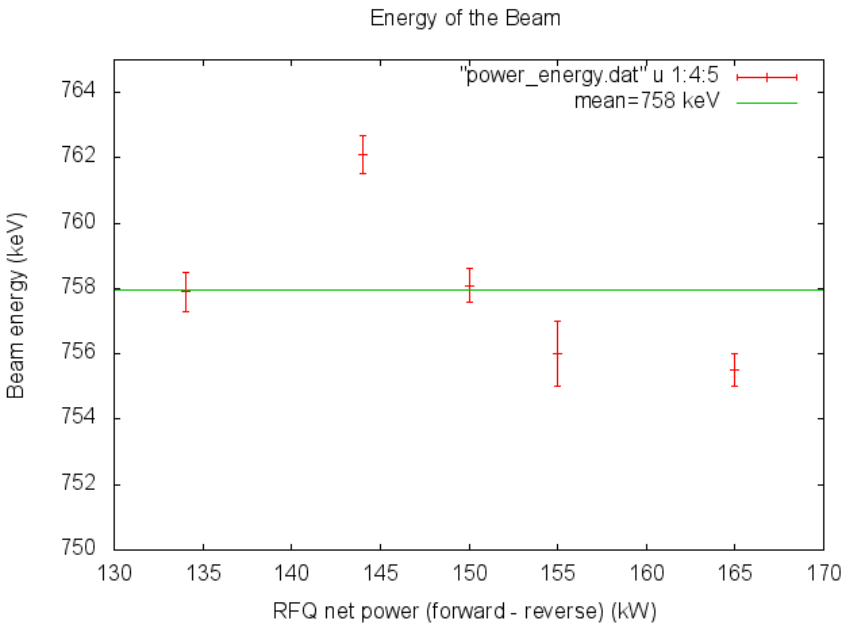


Thin rods reduce capacitance, therefore the resonant frequency is increased. This means that L can be increased, i.e. plates moved further away and half moons removed.

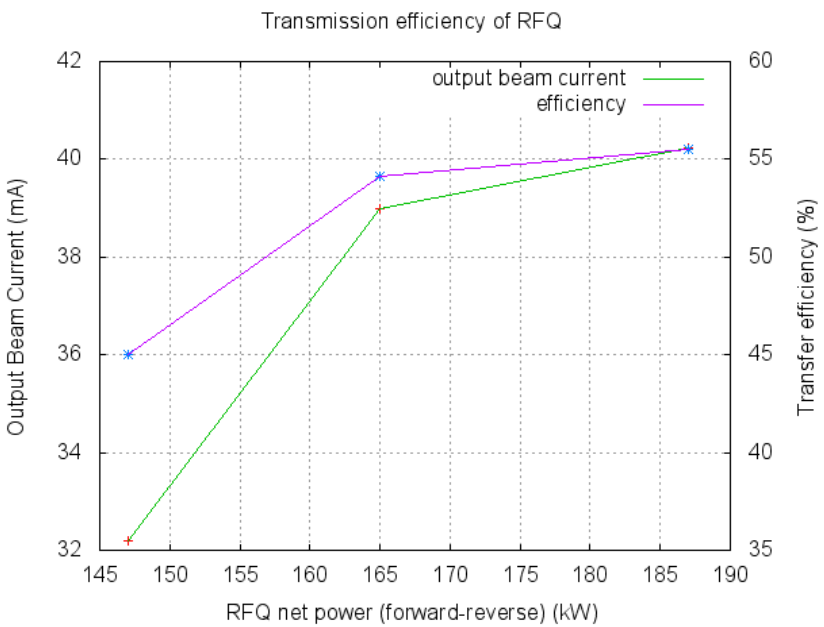
In practice only the largest half moons were removed after retuning.

The fields **may** be better centred in the rods from S. Kurennoy's simulations. This could increase capture efficiency.

But it didn't completely work ...

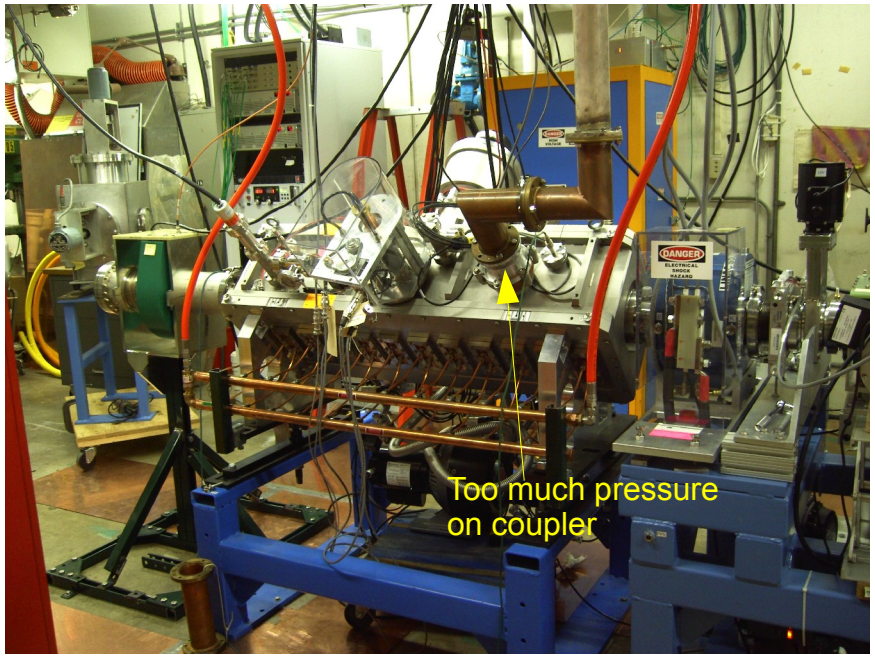


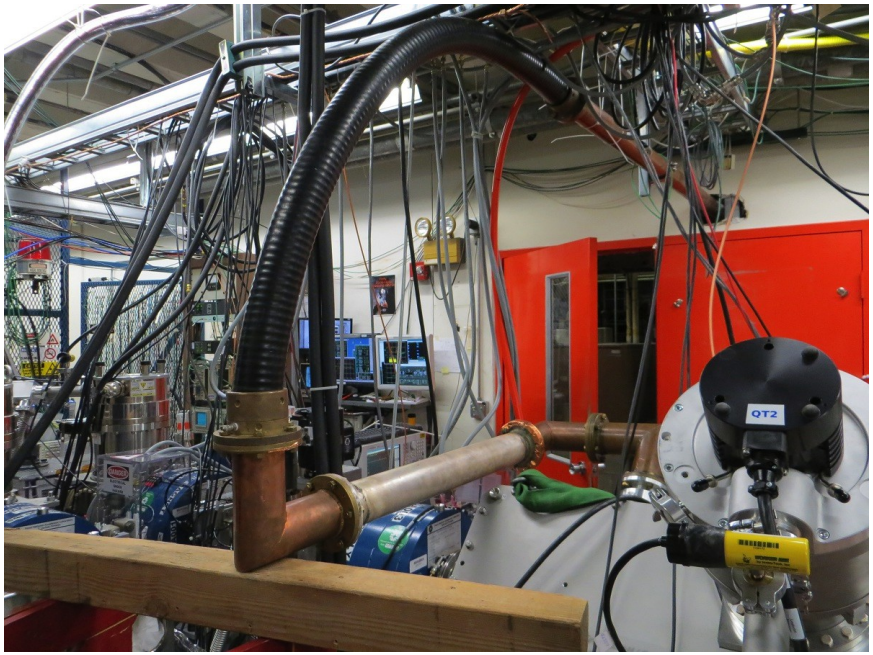
Mean energy is 758 keV (1% from 750 keV). OK.



Output 40 mA for RFQ power > 180 kW (net). Not possible to operationally work here

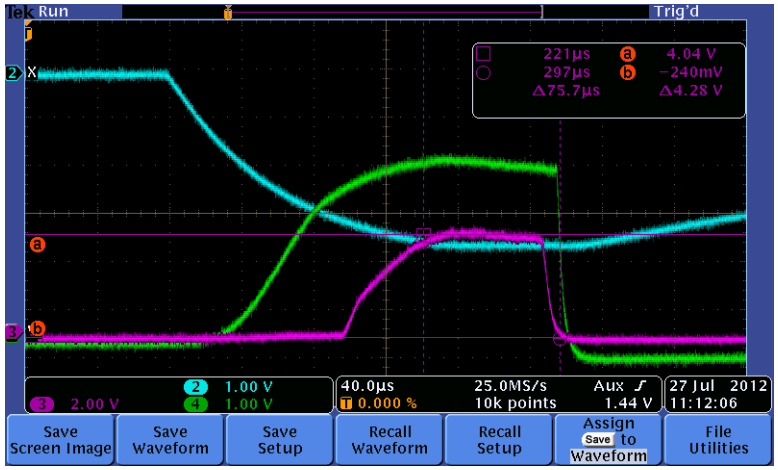
S11 of power coupler is poor

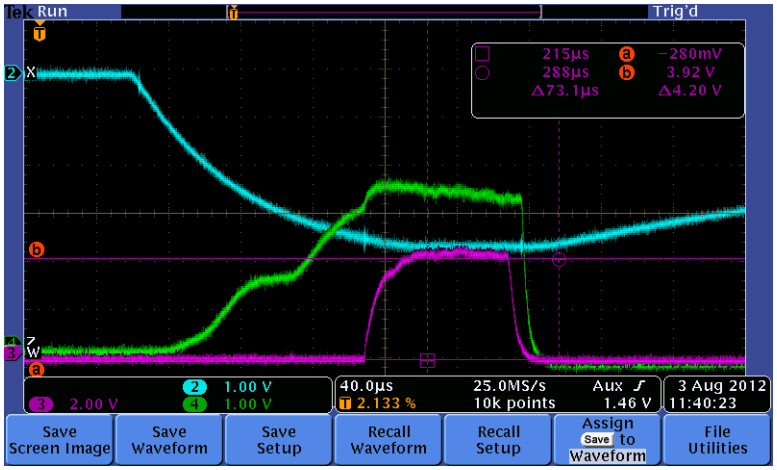


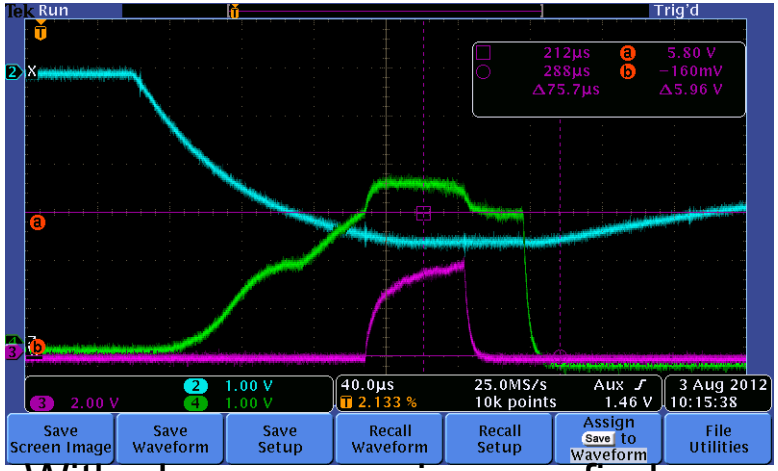


The new configuration with the piece of “magic” wood relieves pressure on the power port. The reflection without beam is now 1-3% compared to 10-15 % previously!

Addition of Chopper





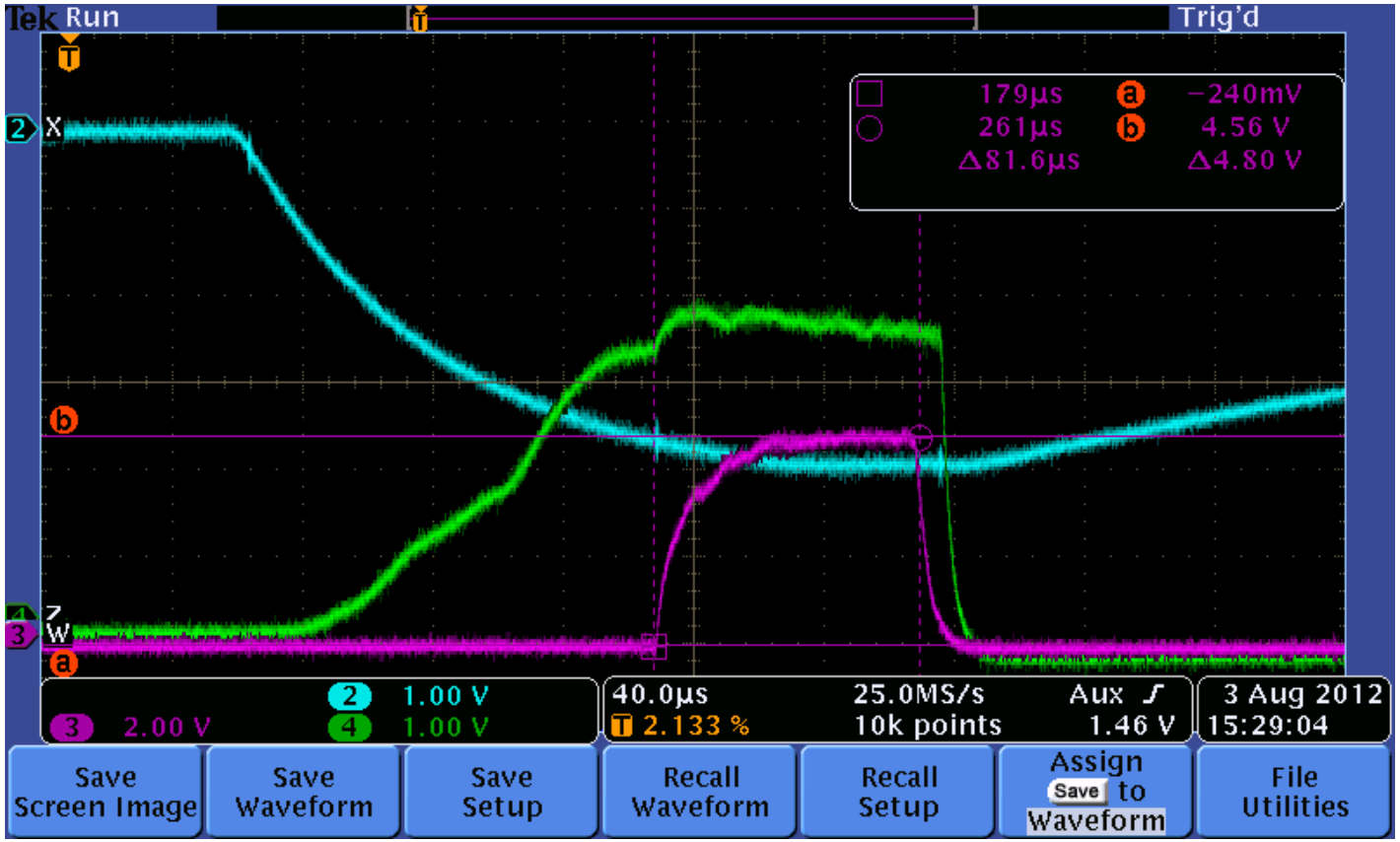


With chopper running, we find that the beam at the output of the RFQ is not flat. Why???

Spoil vacuum in LEBT from 1e-6 torr to 2e-6 torr, and beam becomes flat!

An important consequence, gas focusing increases transmission through RFQ to 42.5 mA @ 170 kW net!!!!

More good things come from tuning with gas focusing!

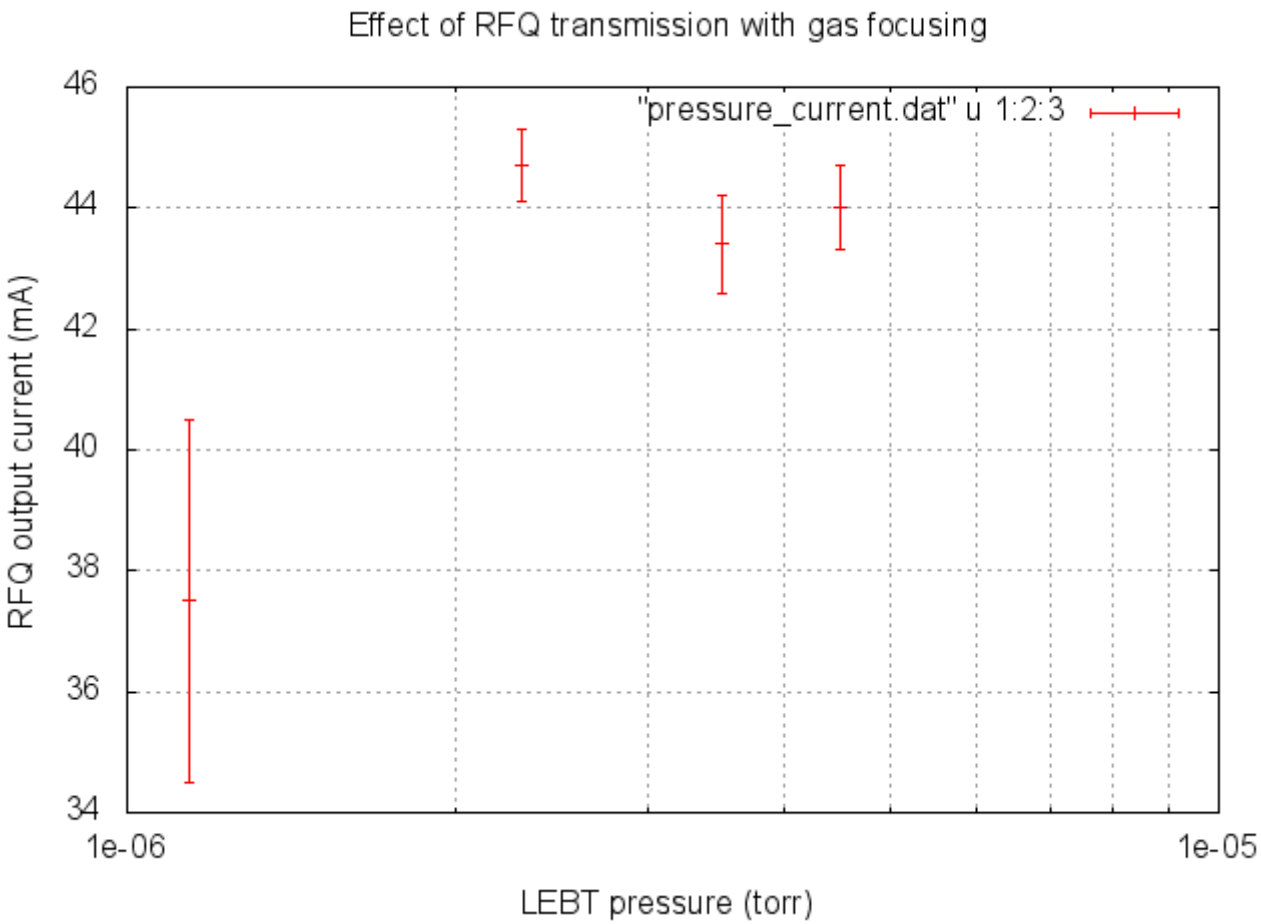


LTOR = 45 mA @166 kW from 67 mA in LEBT (67% efficient)

Scope says 48 mA!

Compare with BNL in 1990s which has approximately the same LEBT as we do. Output is 45 - 50 mA with 55 mA in LEBT (80-90% efficient)

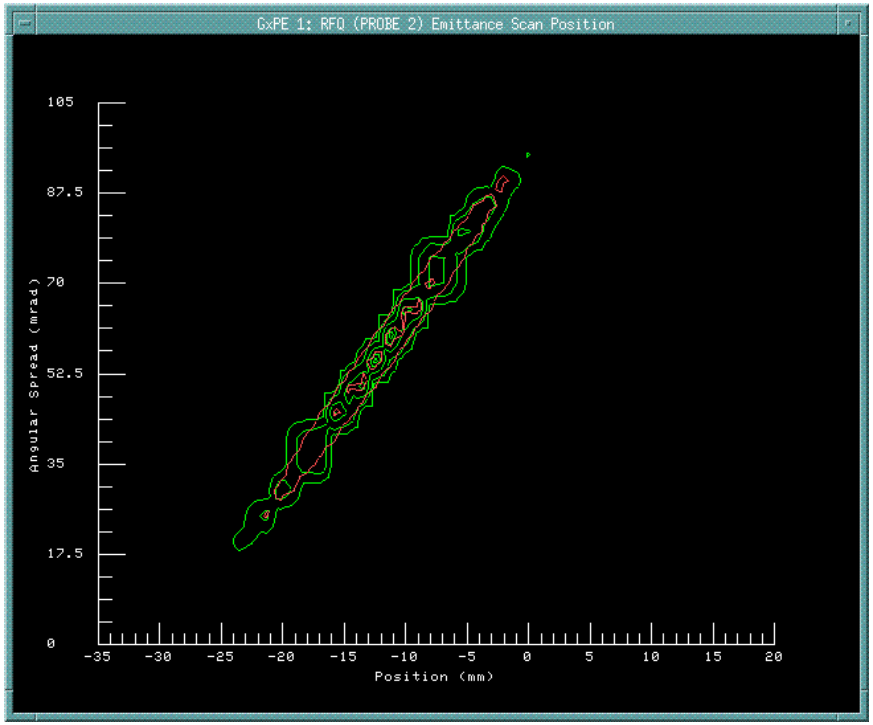
Gas focusing threshold

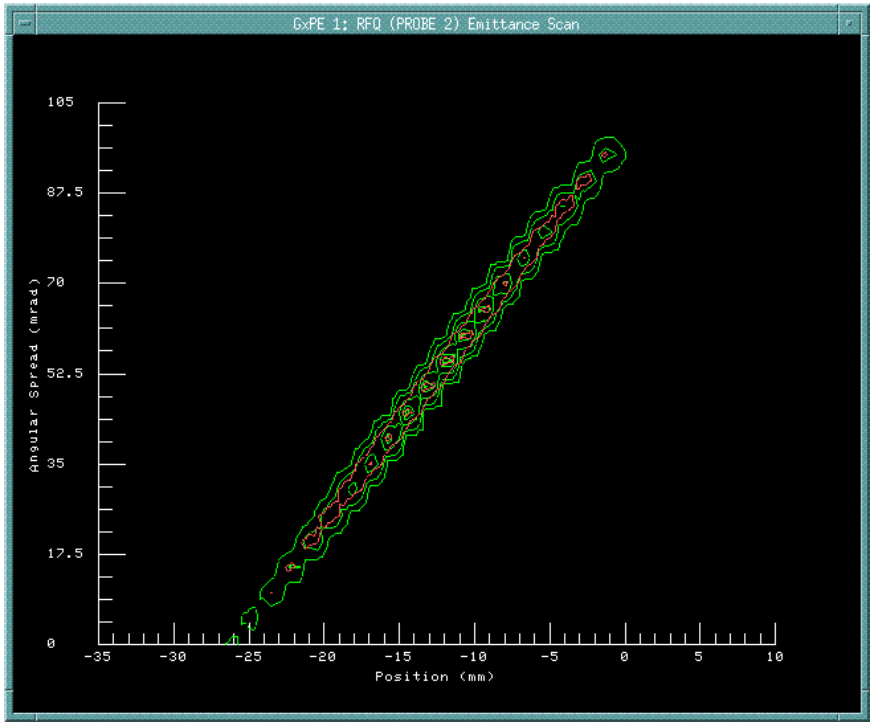


Clear threshold. Required gas pressure in LEBT > 2e-6 torr

Output Transverse Emittance

PA power = 178 kW forward, 7 kW reflected



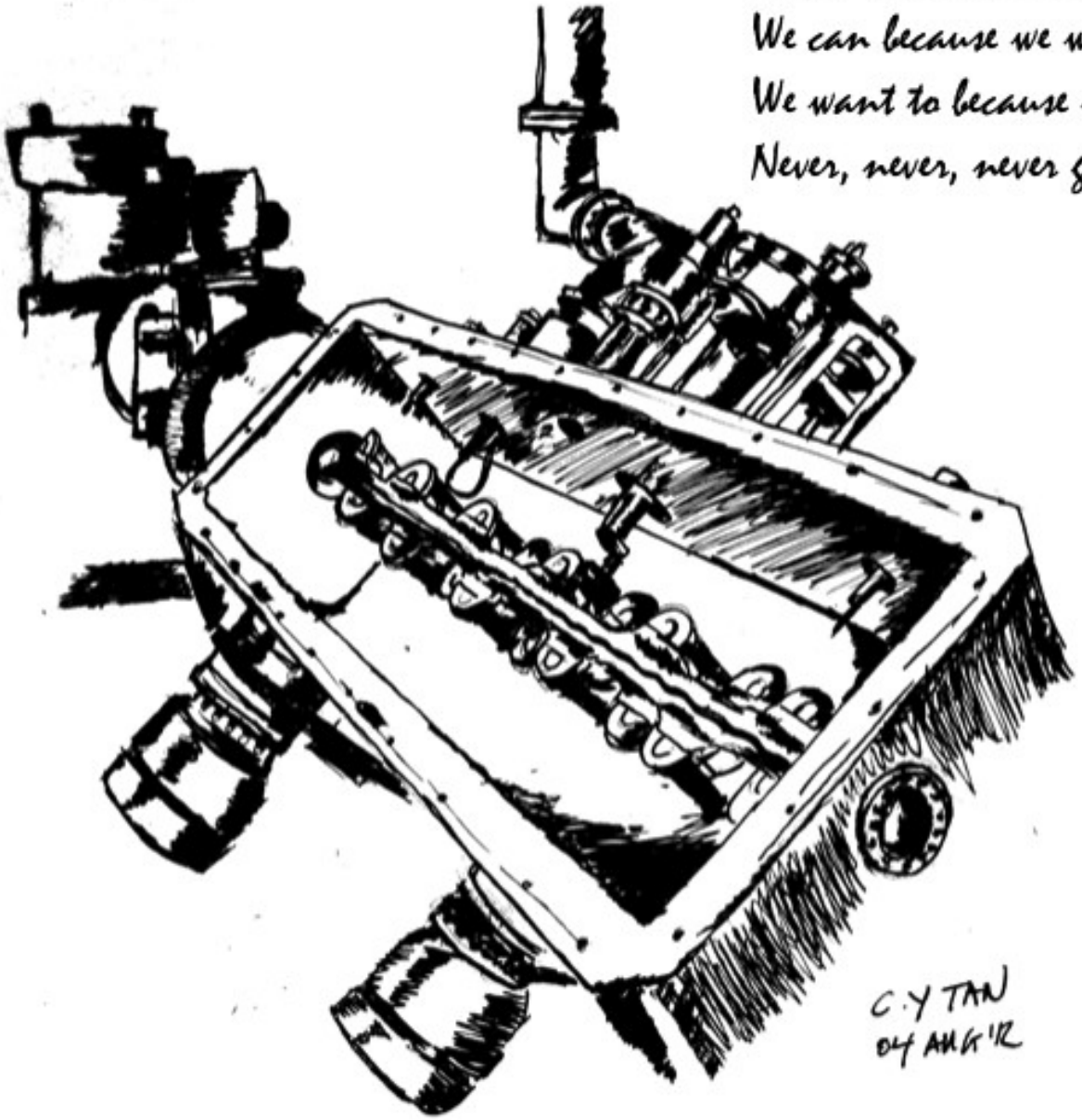


Horizontal emittance
0.60 π mm mrad
(normalized 1 sigma)

Vertical emittance
0.45 π mm mrad (normalized 1 sigma)

Asymmetry comes from the source.
This was the same as before the rod change.

Conclusion

- We had to fix many problems with the RFQ
- The output current is enough for installation
  - Emittance measurements (done)
  - Bunching measurements (being done)
  - Reliability tests

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!