Bead-pull measurements of module #2 of the PXIE RFQ in April 2014

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On behalf of P. Berrutti, V. Poloubotko, G Romanov, J. Steimel
J. Staples and many others

Task

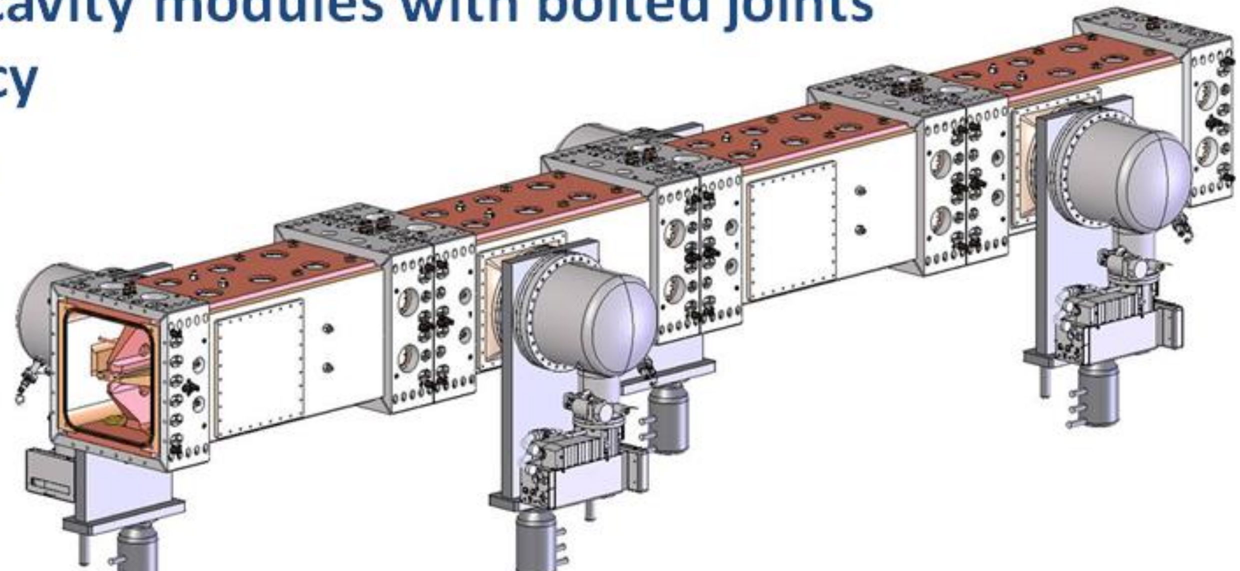
- Good field flatness needed for normal operation of the RFQ in the accelerator
- After manufacturing field flatness usually is not good and should be tuned
- LBNL needed bead pull system for RFQ field flatness tuning for:
  - Field flatness measurements in modules and complete RFQ
  - Field flatness measurements in all four quadrants
- We proposed and build bead pull system with one line allowing measurements near RFQ center and in any four quadrants consist of:
  - Measurements technique
  - Precise positioner drive mechanism
  - Electronics
  - Programming
- Module #2 measurements was for:
  - Verify RFQ simulation
  - Verify RFQ manufacturing process
  - Test new bead pull system and prepare for complete RFQ measurements

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, norm.	
Longitudinal emittance	<1.0		keV-nsec	

PXIE RFQ Design Features

- All OFHC copper body machined from solid billets
- 4-vane cavity structure with fly cut modulated vane tips
- Four ~ 1.12 m long cavity modules with bolted joints
- 162.5 MHz frequency
- Total length: 4.46 m
- Pi-mode rods for mode stabilization
- Distributed fixed slug tuners



CAD model of assembled 4-module PXIE RFQ design concept

Ernest Orlando Lawrence Berkeley National Laboratory

Derun Li: PXIE RFQ Design Overview
PXIE RFQ Design Review, Berkeley, CA
April 12, 2012

Fermilab

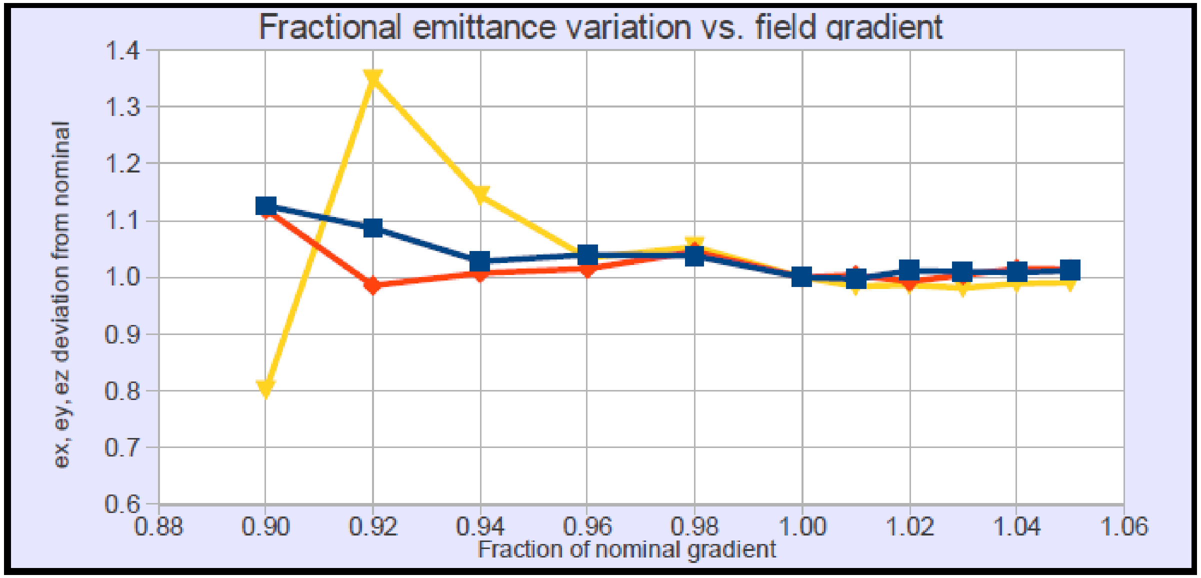
Field flatness requirements

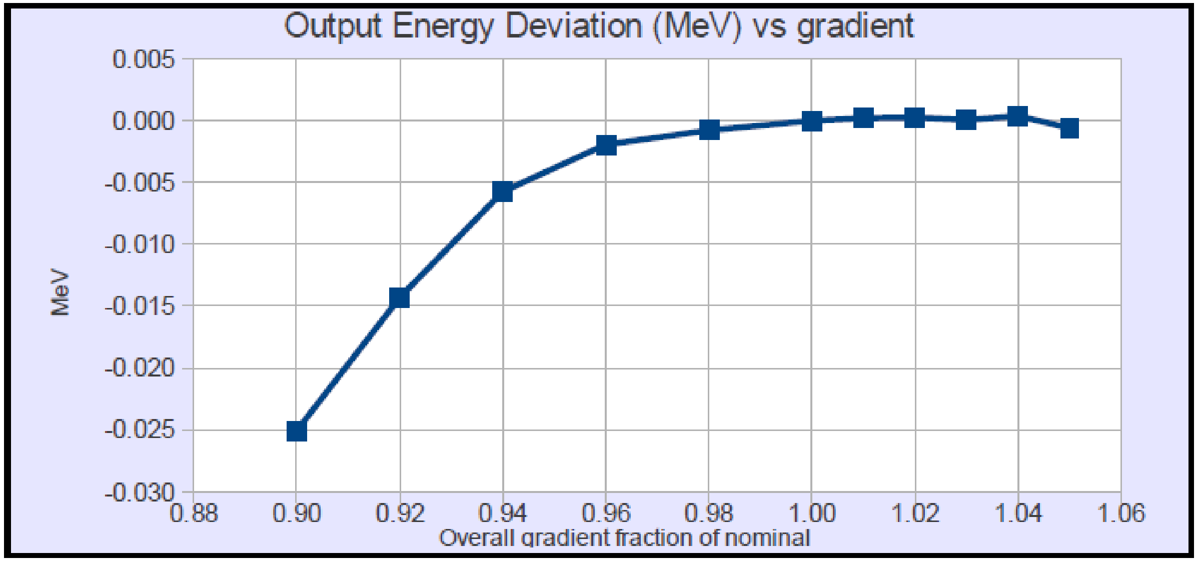
PXIE RFQ Progress
John Staples, LBNL
10-12 April 2012 Collaboration Meeting, LBNL

Independent Parameter:

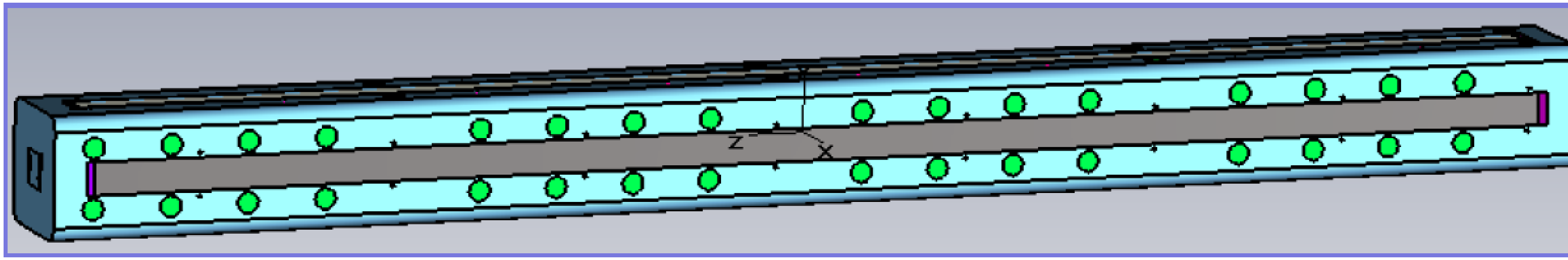
Flat field gradient

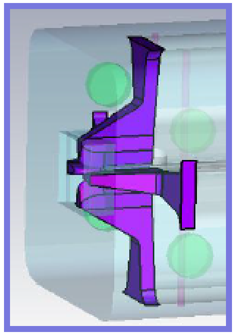
Output emittance and deviation from nominal 2.13 MeV output energy as a function of flat gradient error.

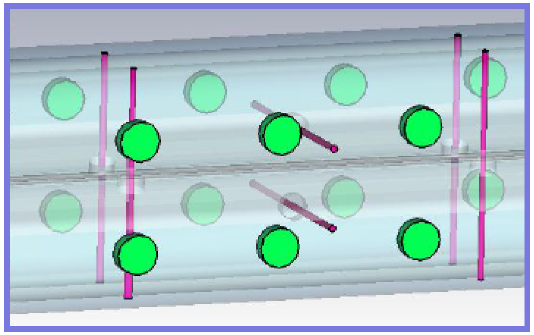


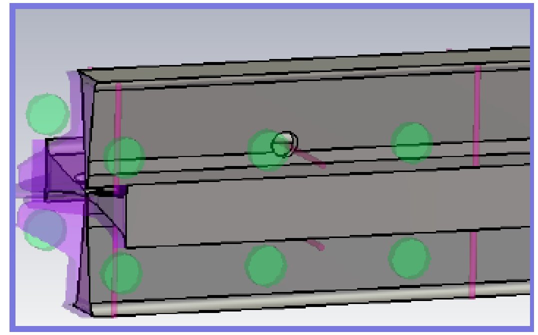


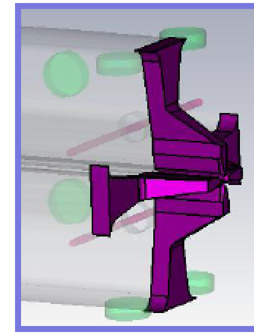
The complete solid model





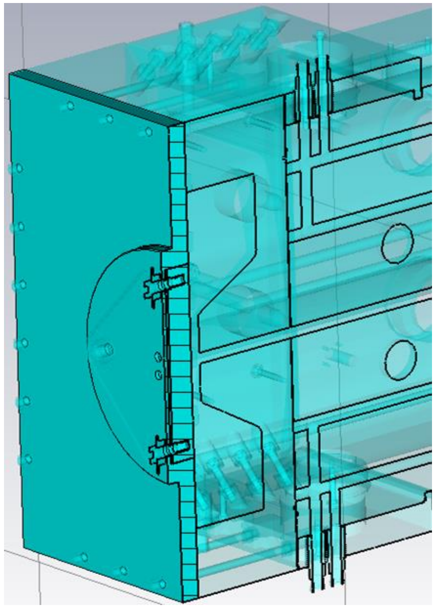




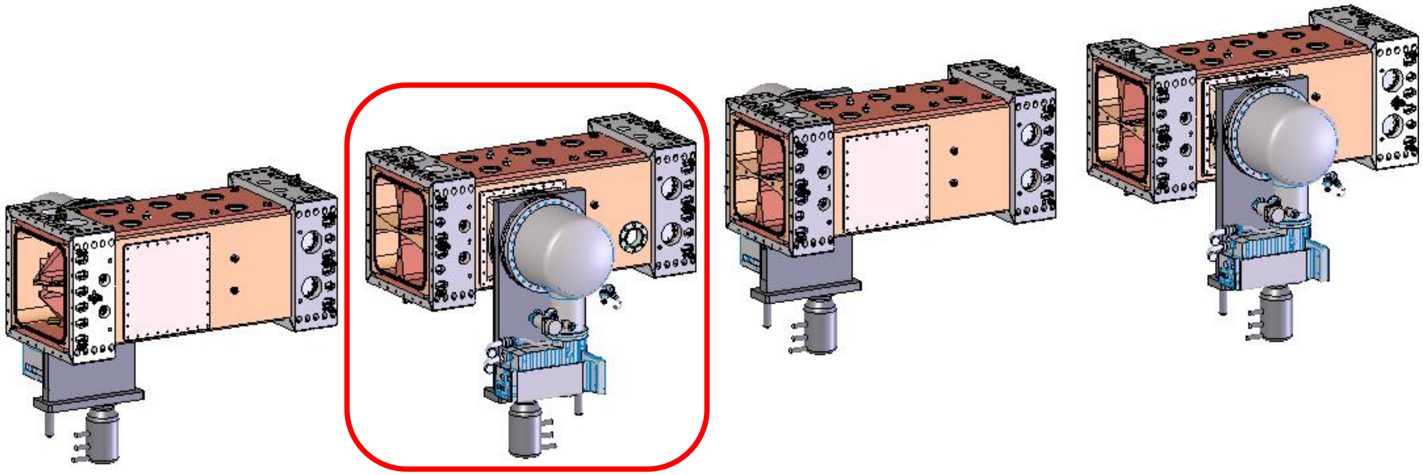


Parameters	PXIE
Frequency, MHz	162.499
Frequency of dipole mode, MHz	181.99
Q factor	14985
Q factor drop due to everything, %	-14.7
Power loss per cut-back, W (In/Out)	336/389
Total power loss, kW	73.8
L_max, mm	172.73

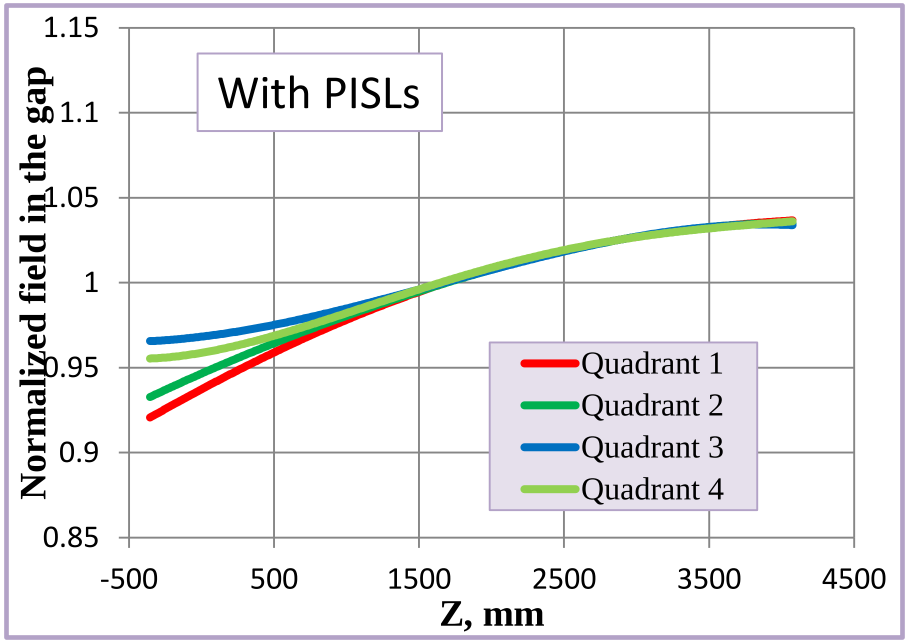
Part	Total, kW	Per unit, W	%
Walls	29.5	-	40
Vanes	31	7764	42
Input cut-backs	1.34	336	1.8
Output cut-backs	1.56	389	2.1
Pi-mode rods	5.53	173	7.5
Tuners	4.79	59.9	6.5

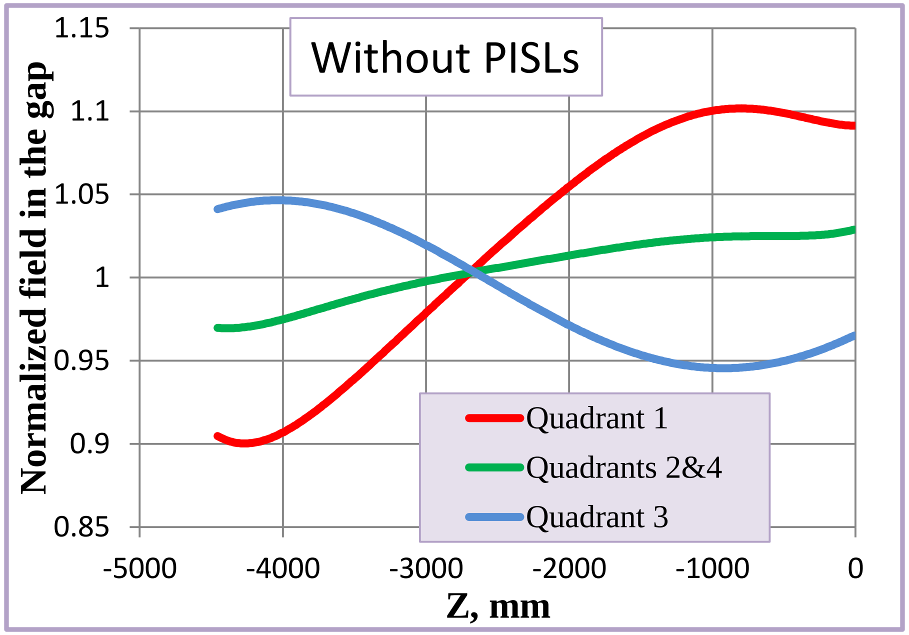


Module #2 was manufactured before other modules

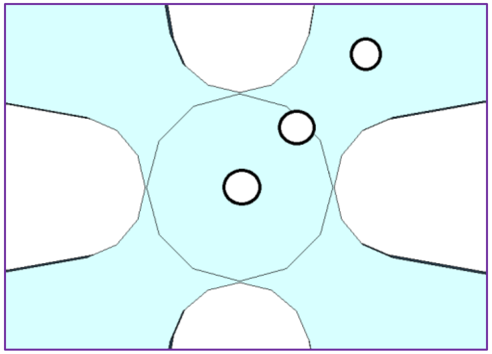


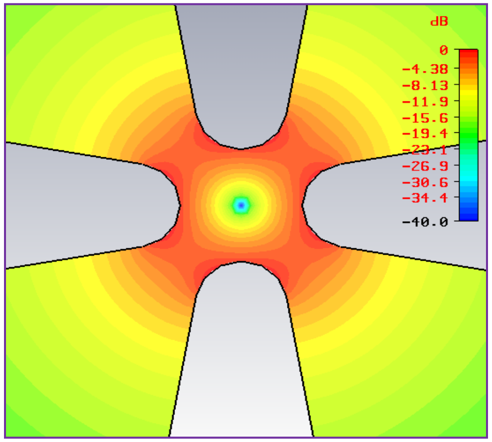
Local perturbation – tuner at one end of the RFQ. 50 mm protrusion, frequency shift is 45 kHz.

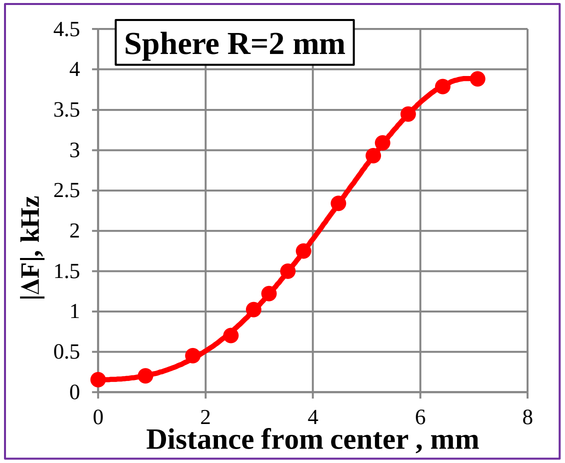


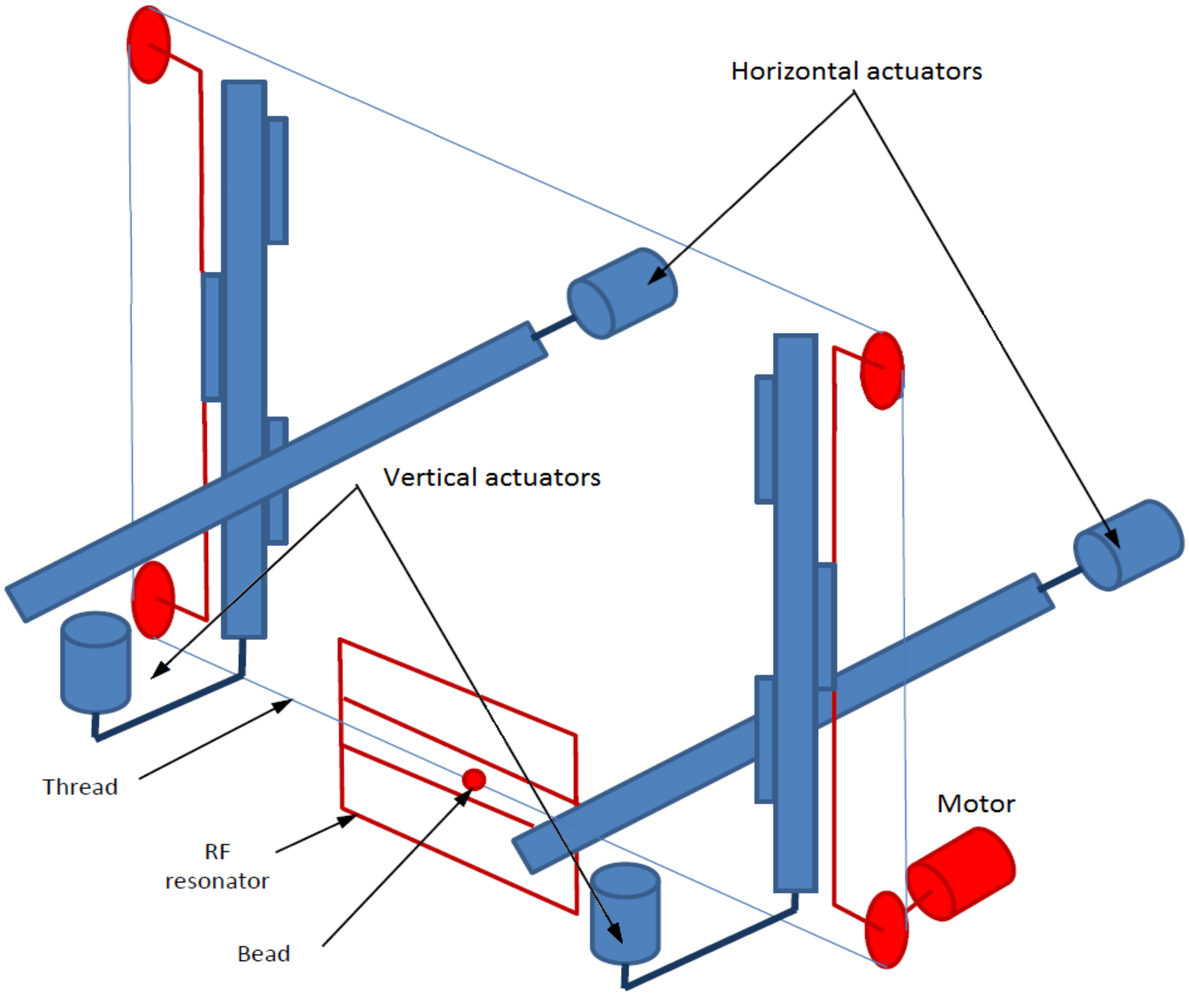


Bead pull diagram



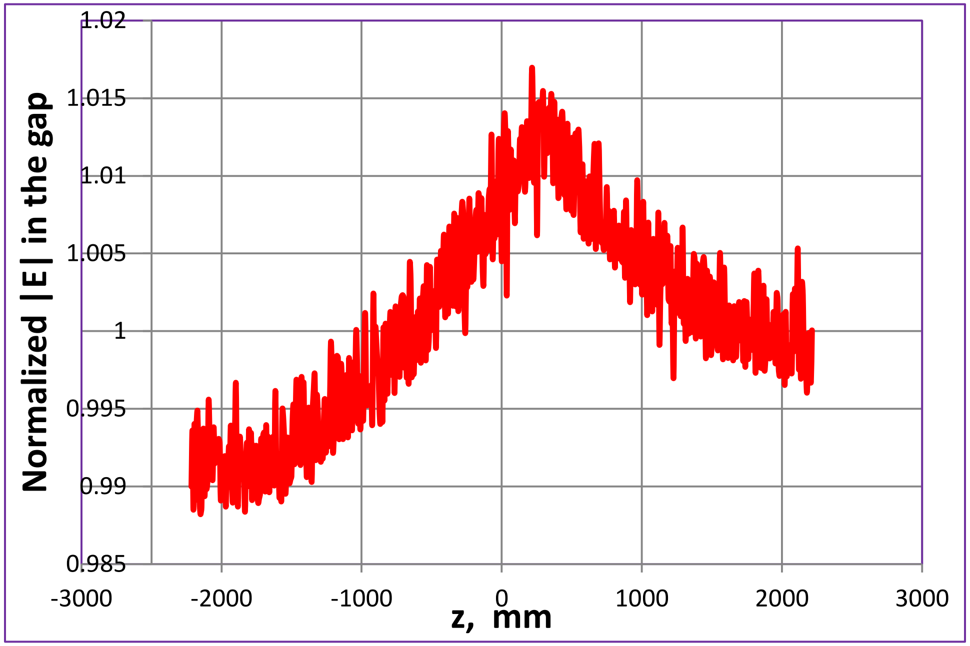




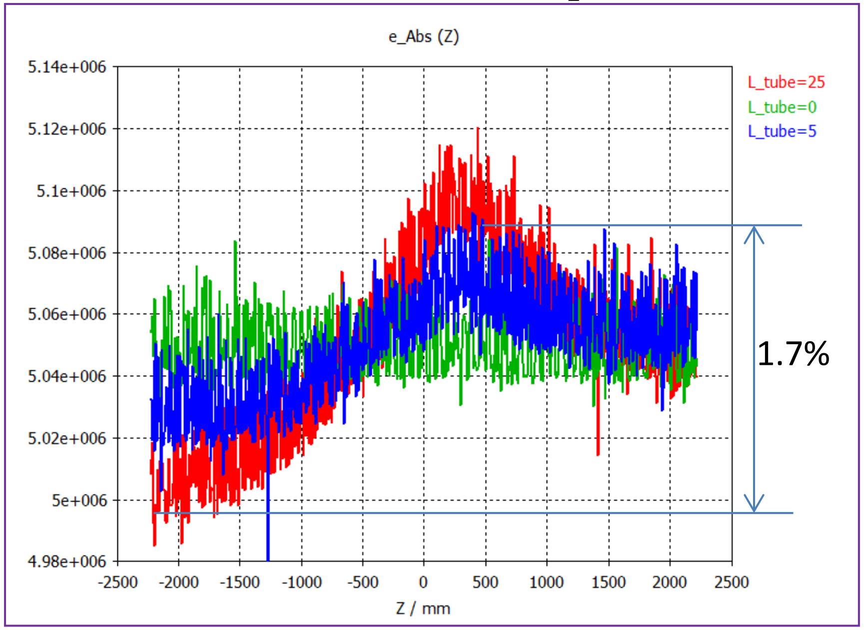


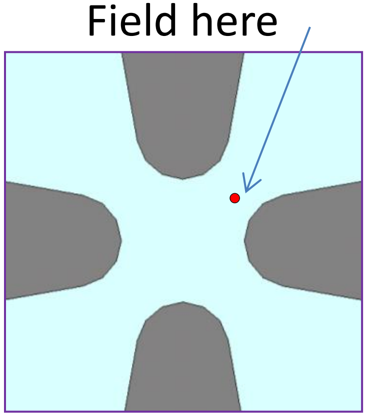
Field distribution in RFQ with and without power couplers

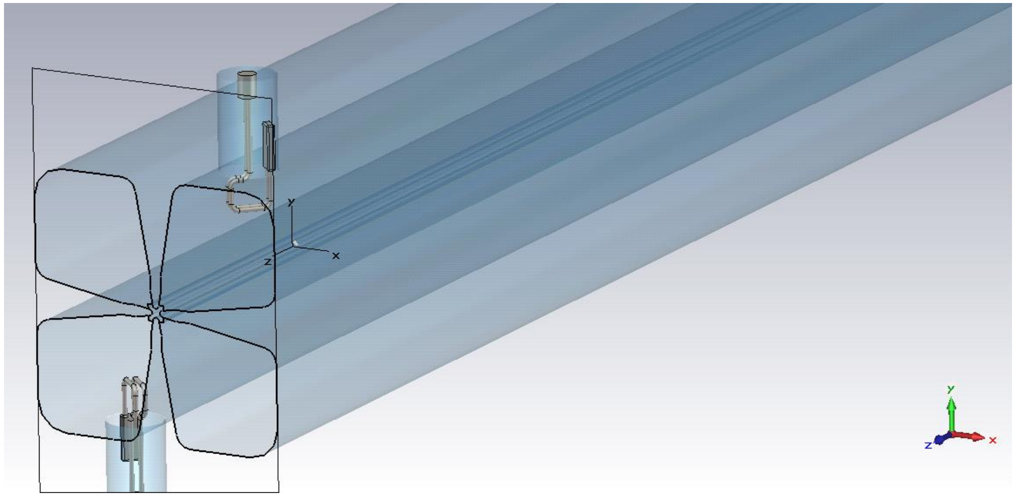
77 mm diameter port tube + 2 power couplers. Field flatness changed 2.5-3 %



77 mm diameter port tube only. Field flatness ~ 1.5 %. Difference due to couplers ~ 1%.



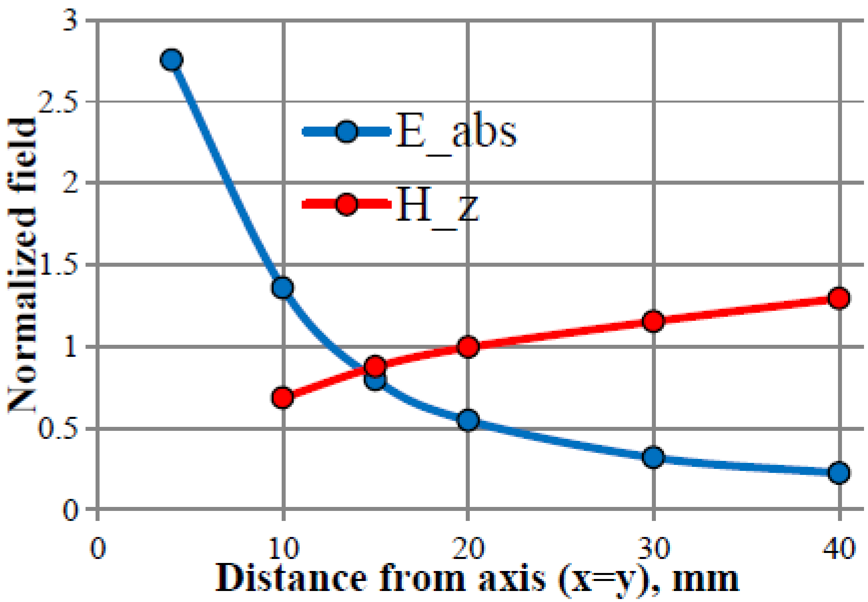


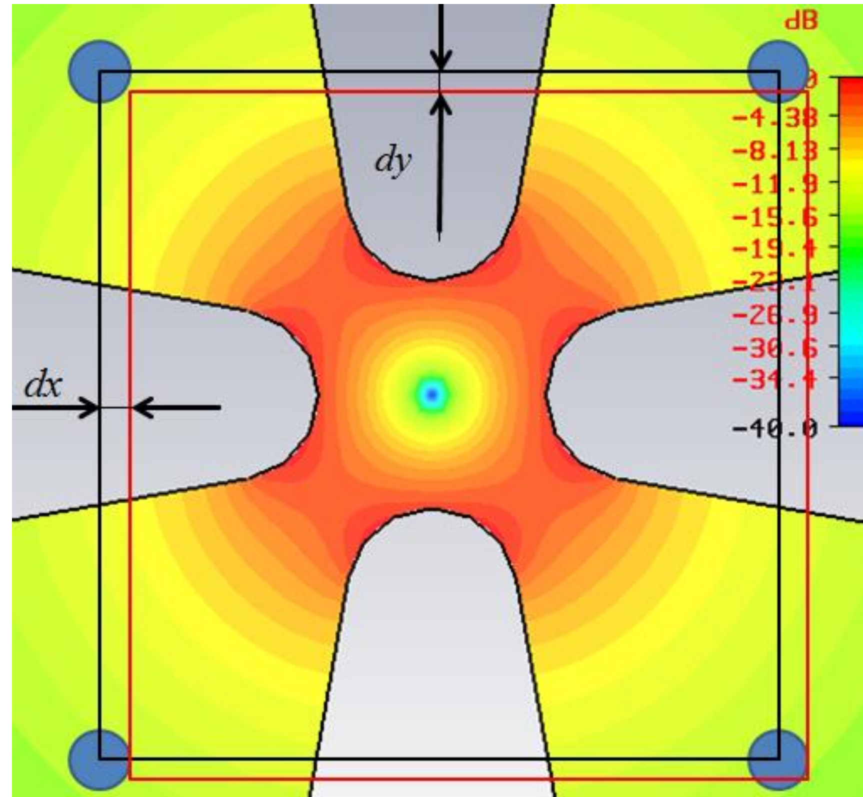


Positioning error can be compensated by averaging of measurements in all four quadrants

$$df\,(x+dx,\,y+dy) \approx c\cdot f\left(x,y\right)+\alpha\left(x,y\right)\cdot dx+\beta\left(x,y\right)\cdot dy$$

$$x=y \Rightarrow \alpha\left(x,y\right)=\beta\left(x,y\right)$$





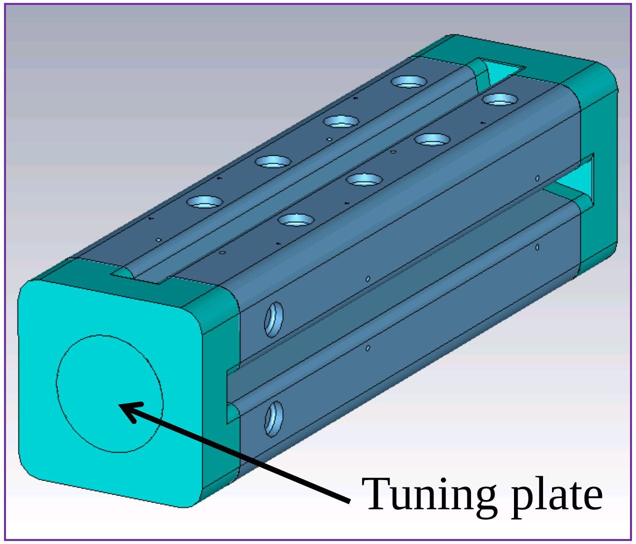
$$\alpha\left(-x,y\right)=-\alpha\left(x,y\right);\ \alpha\left(x,-y\right)=-\alpha\left(x,y\right)$$

$$\beta\left(-x,y\right)=-\beta\left(x,y\right);\ \beta\left(x,-y\right)=-\beta\left(x,y\right)$$

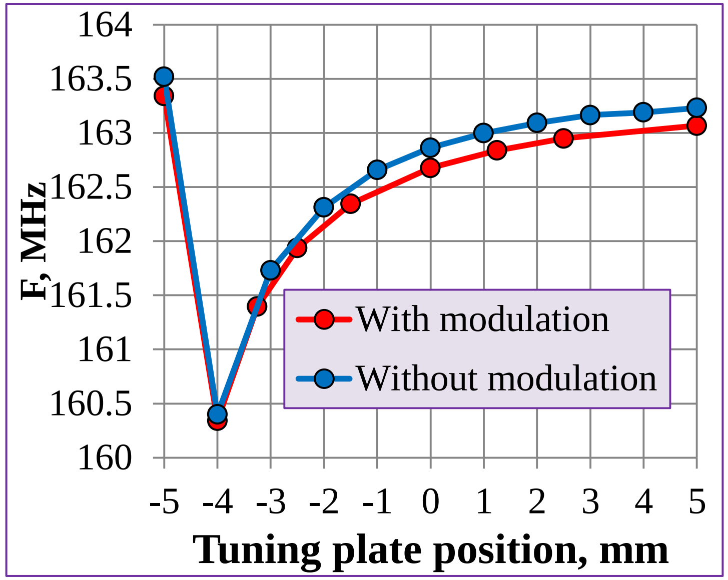
$$df\,(x+dx,\,y+dy)+df\,(-x+dx,\,y+dy)+$$

$$df\,(x+dx,-y+dy)+df\,(-x+dx,-y+dy)\approx 4c\cdot f\left(x,y\right)$$

Module #3 with the temporary end plates



Frequency vs the tuning plates position

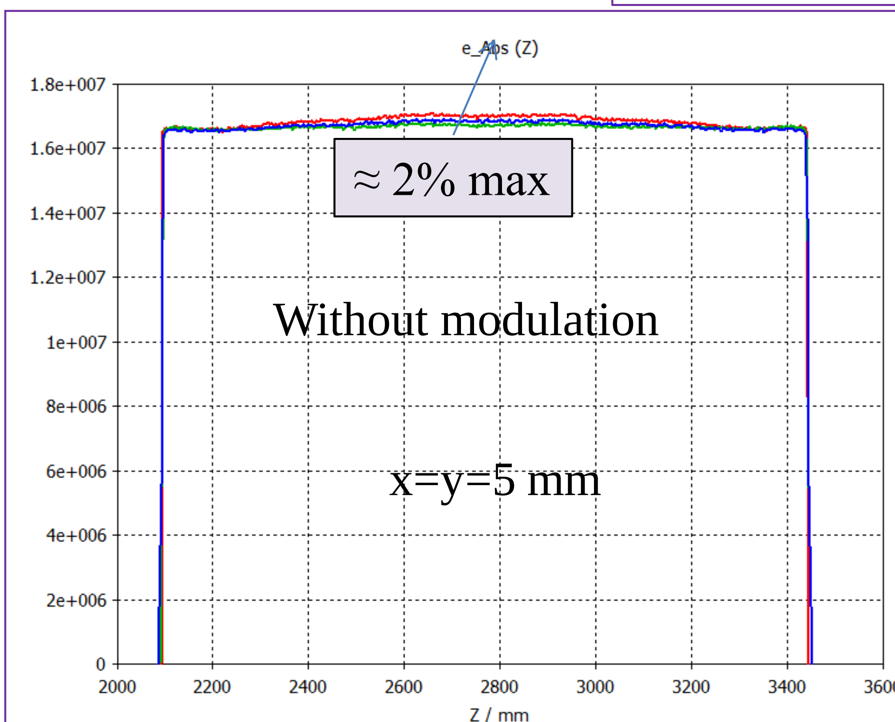


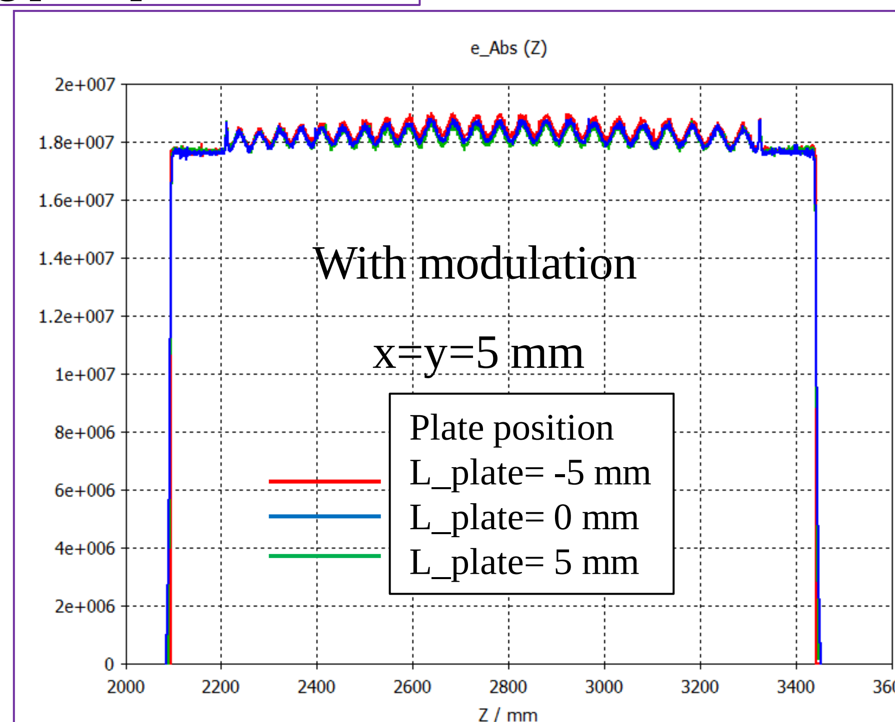
With modulation

mm	MHz
-5	163.3408
-4	160.3409
-3.25	161.3965
-2.5	161.9361
-1.5	162.3444
0	162.676
1.25	162.8373
2.5	162.9487
5	163.0674

No modulation

mm	MHz
-5	163.5178
-4	160.3988
-3	161.7308
-2	162.3115
-1	162.657
0	162.8625
1	162.9979
2	163.0927
3	163.1637
4	163.1893
5	163.2316

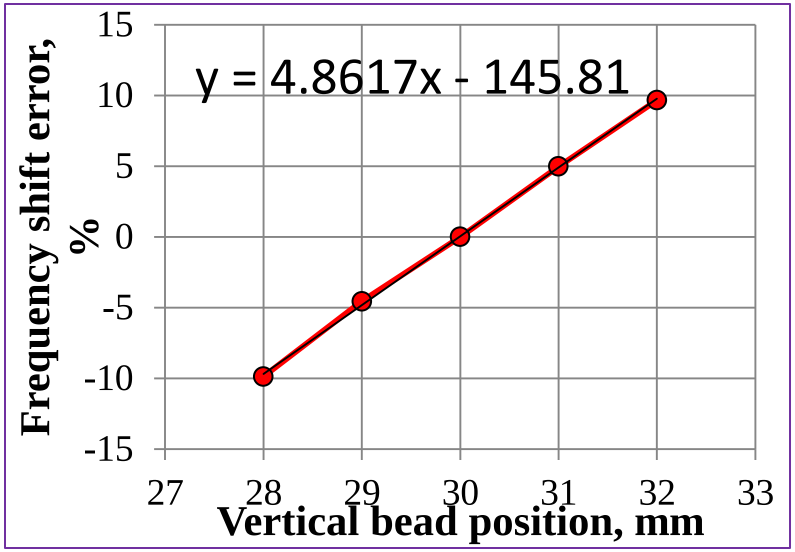




Compensation of vertical sag caused by gravity

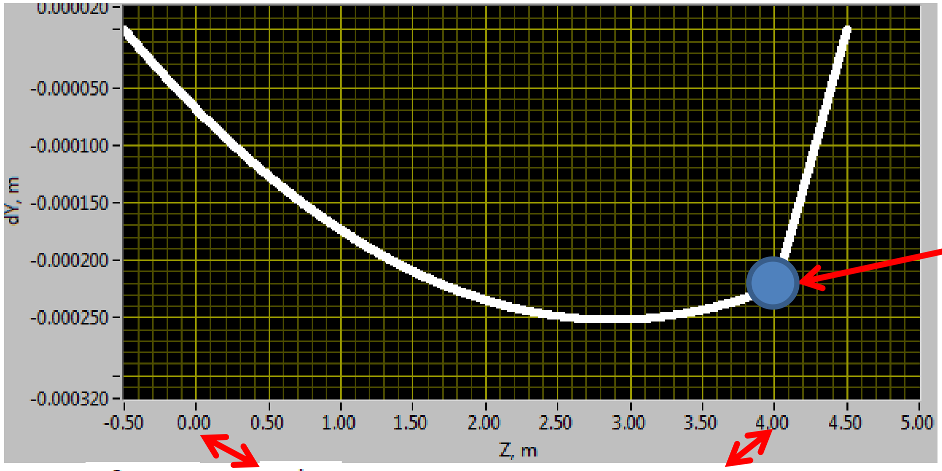
y, mm	δ(Δf), %
28	-9.87937
29	-4.55683
30	0
31	4.97398
32	9.663805

F, N: 10 p_line: 4.5E-5 m_bead: 4E-4

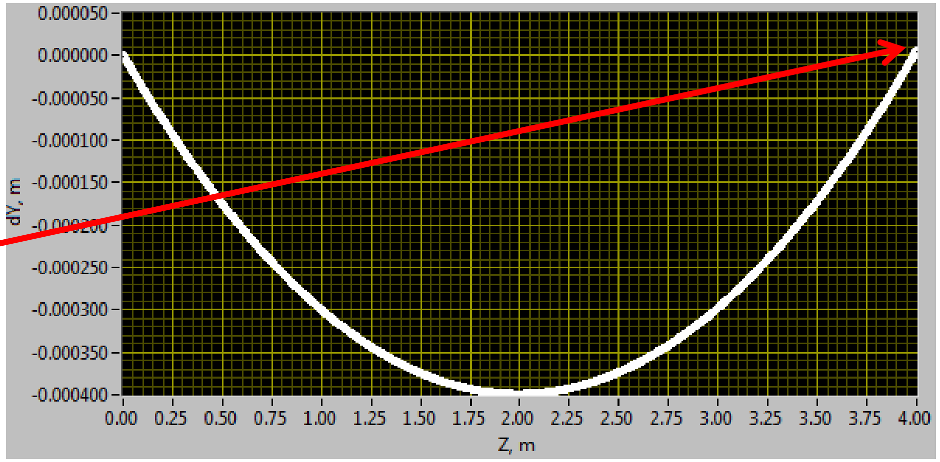


$$\Delta\varphi_{cor}(x,y) = \Delta\varphi_{meas}(x,y)(1-0.048*k*dy*sign(y))$$

Vertical sag of line with bead

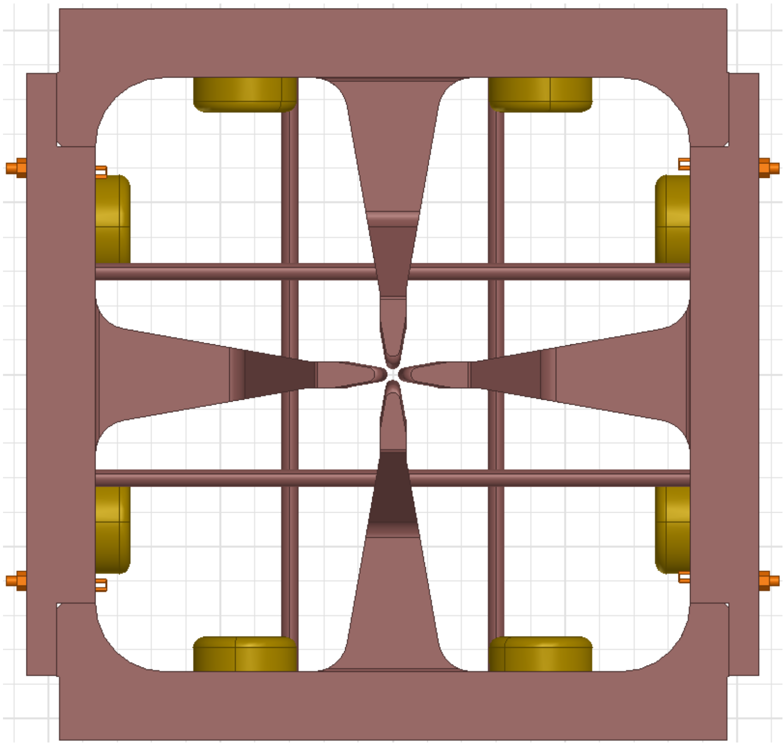


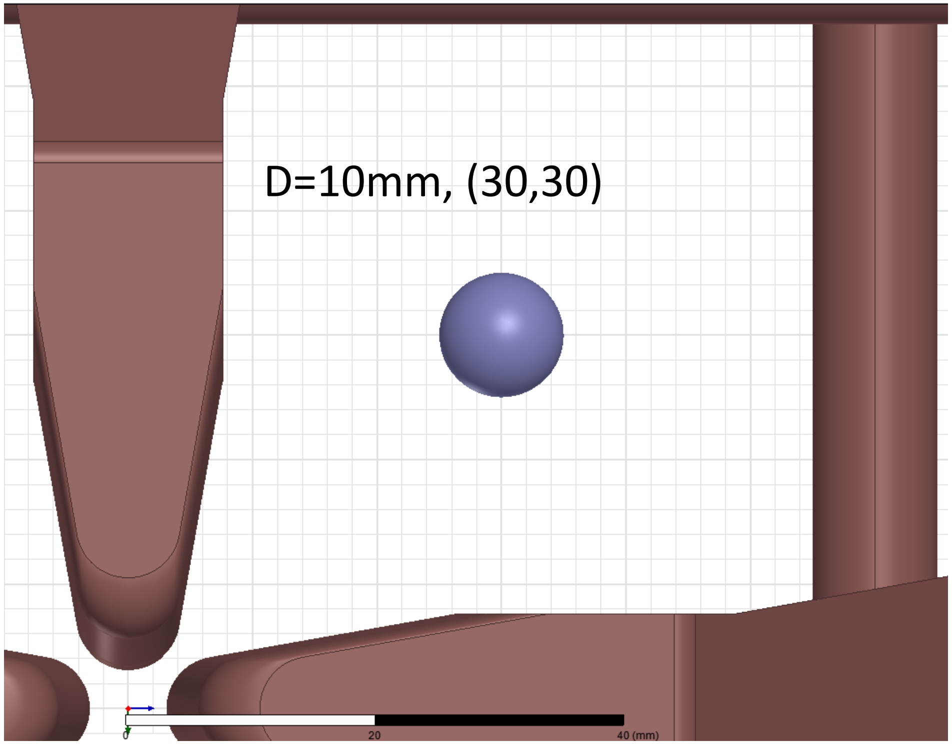
Normalized sag of the bead vs z position

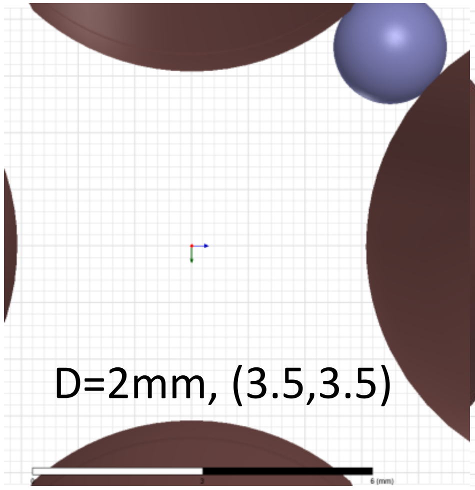


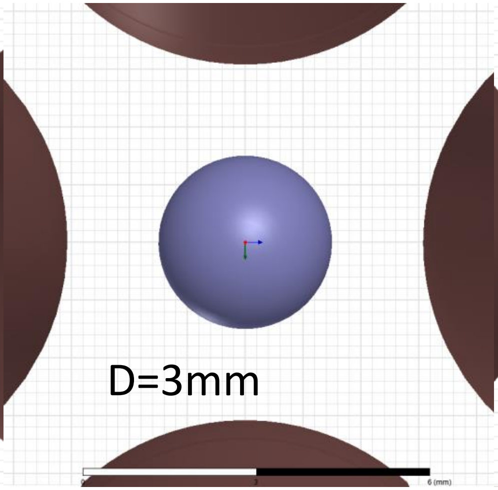
z0: -0.5 z_beg: 0 z_end: 4 z1: 4.5

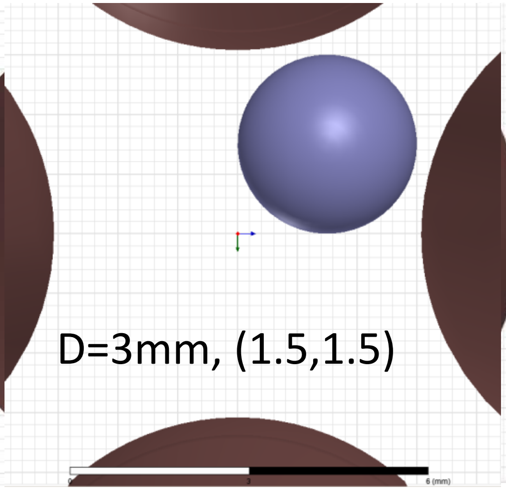
Bead size and positioning

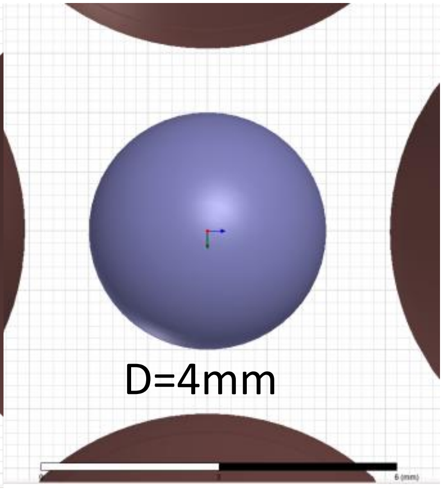






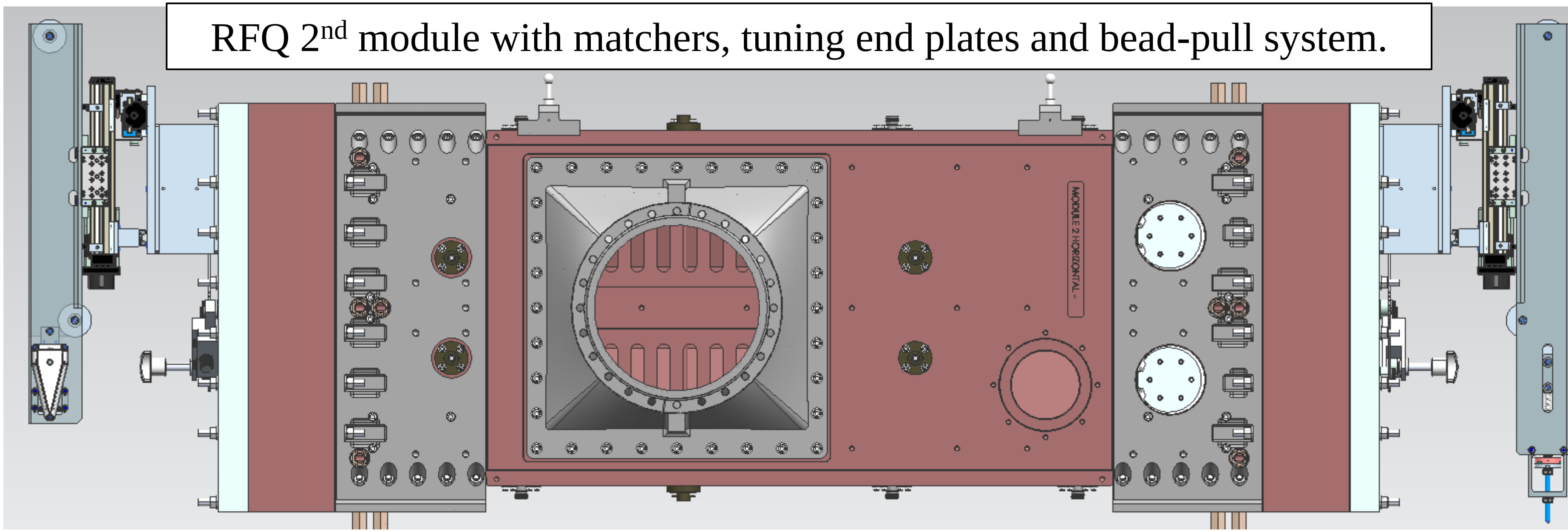


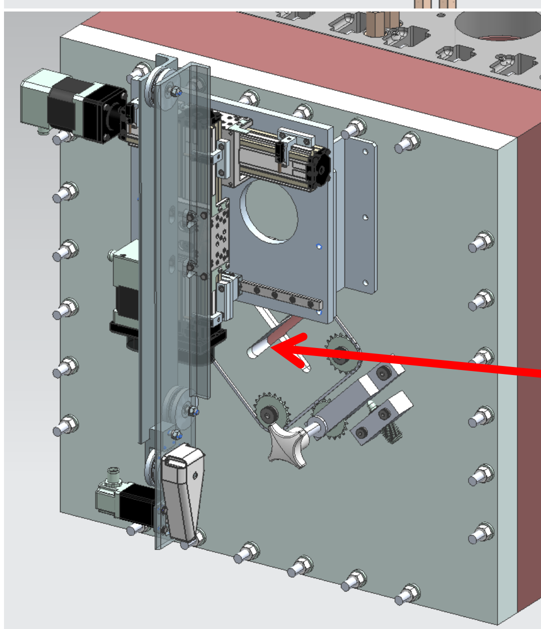




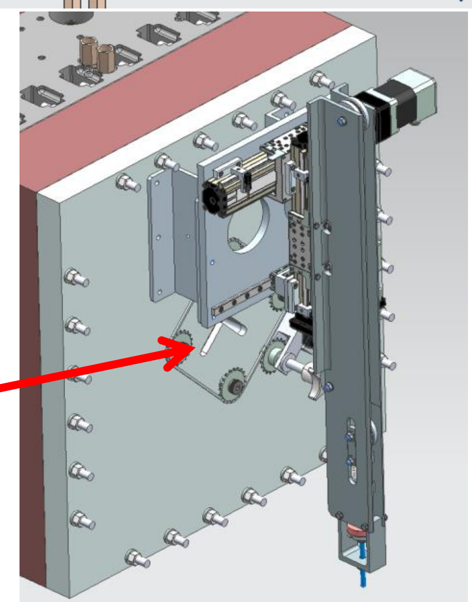
Bead-pull mechanism developed by V. Poloubotko.

RFQ 2nd module with matchers, tuning end plates and bead-pull system.

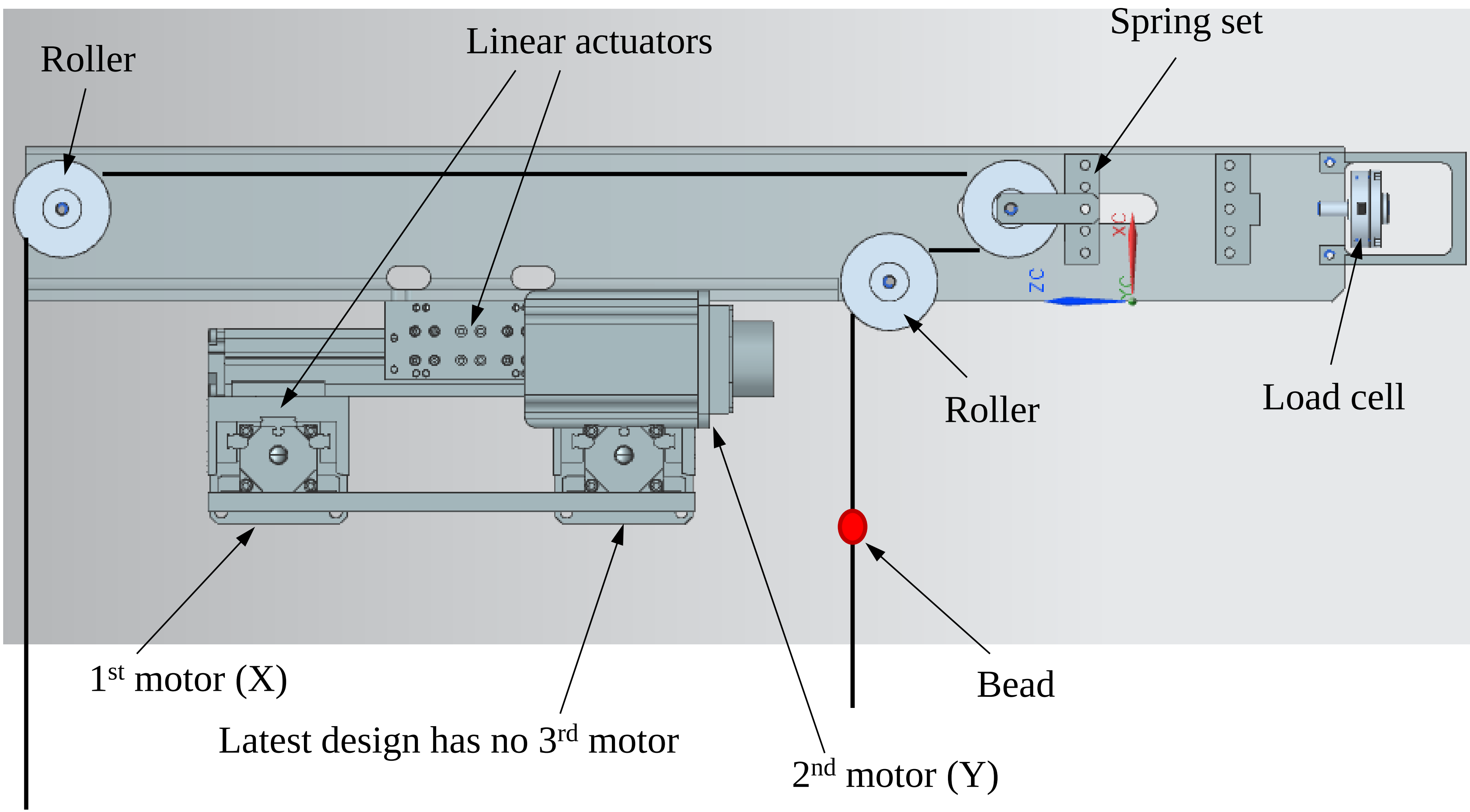




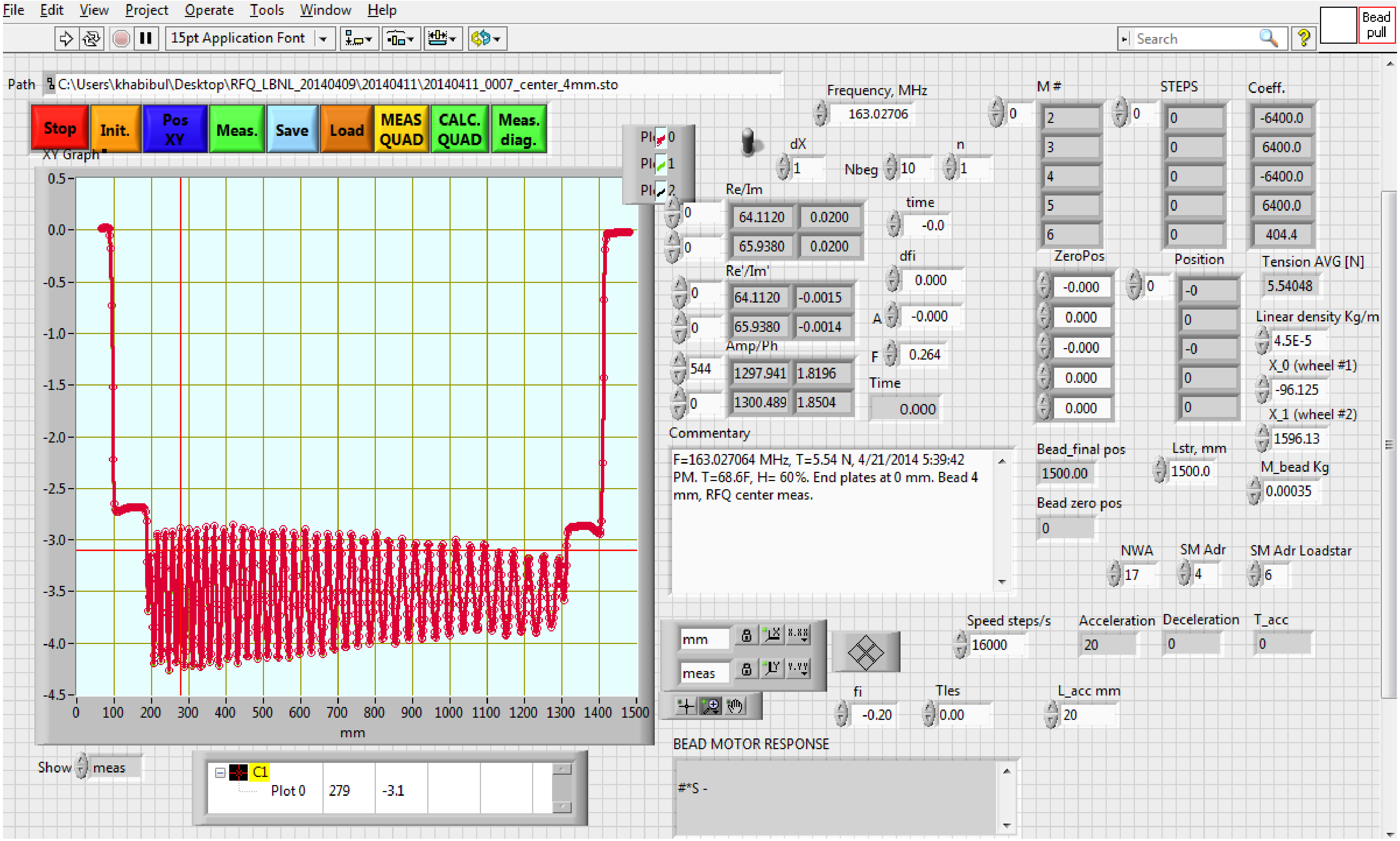
Slots in end plates need to be added



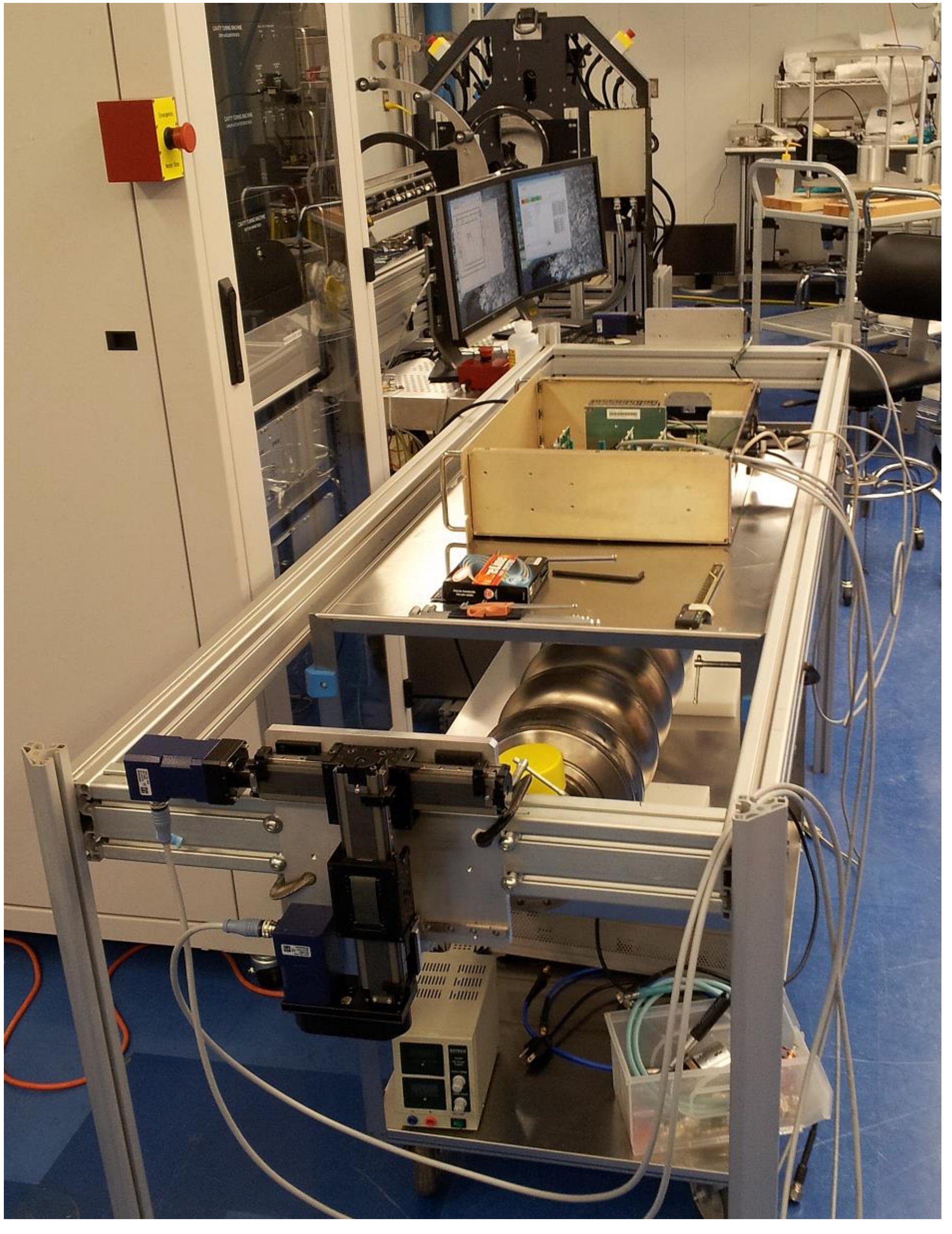
Load cell end XY positioner assembly



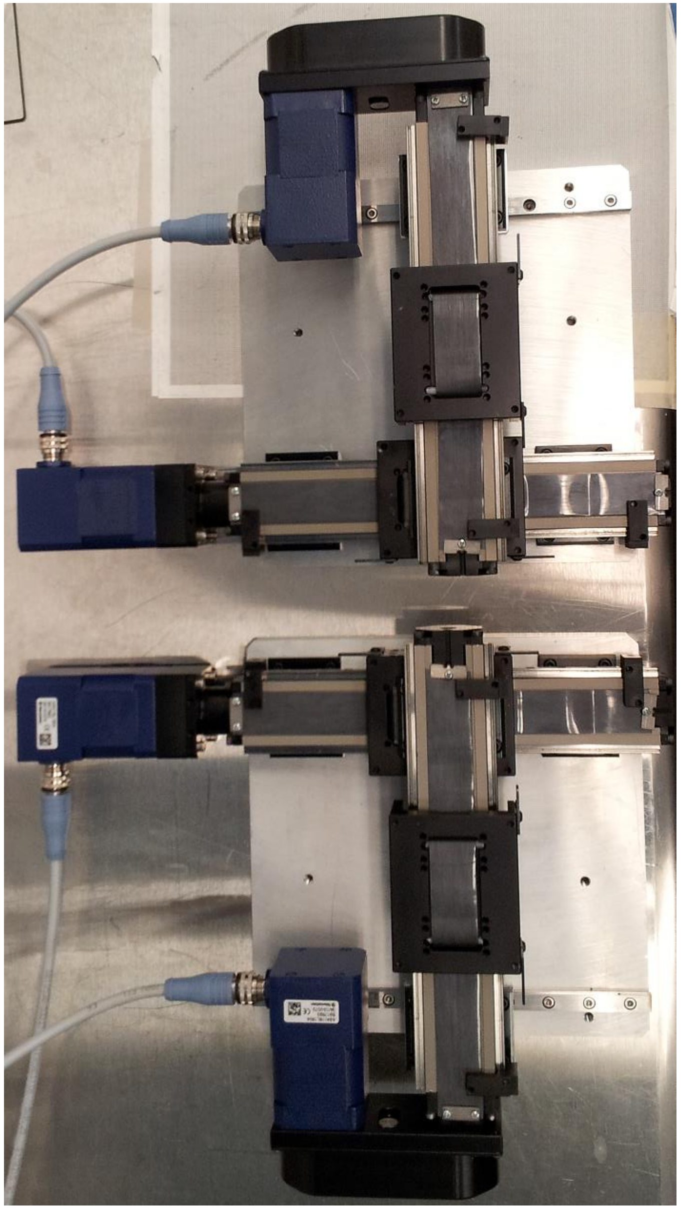
Bead pull program on Labview. By Paolo Berrutti.



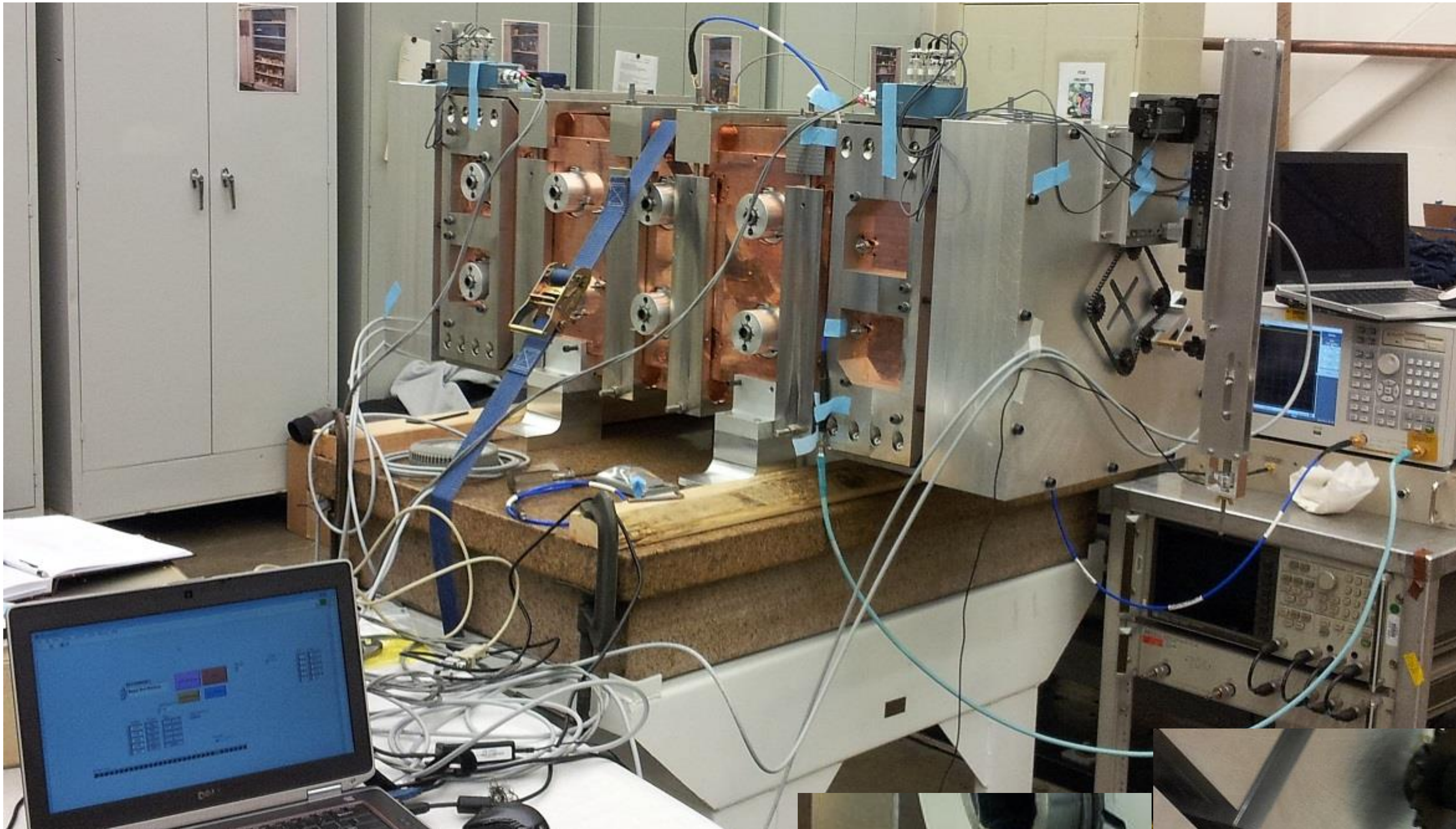
Program allow to position bead in any location near cavity center and measure field flatness. Multiple passes and post processing is included.



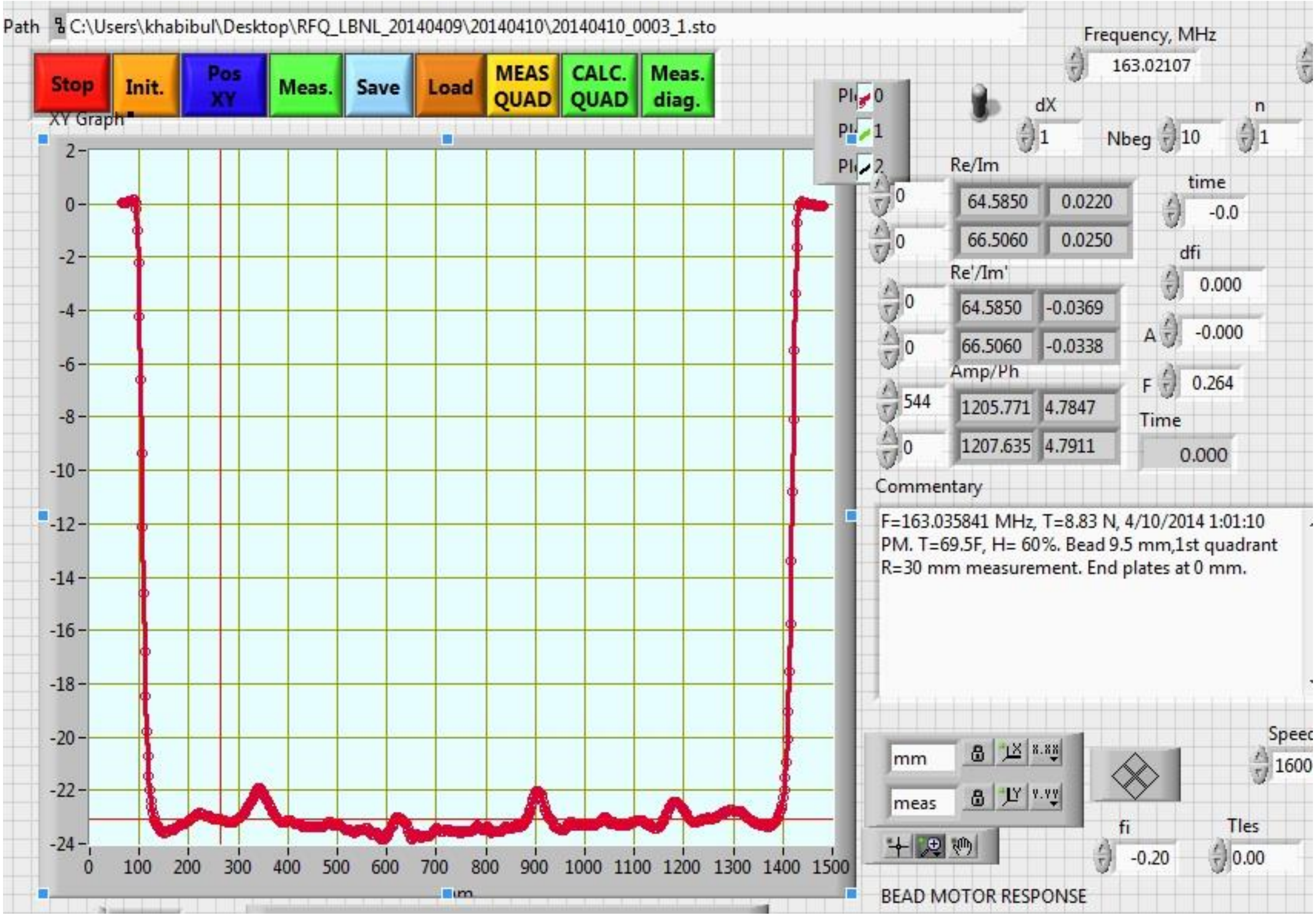
Bead pull test bench in IB4 RF lab



Bead-pull setup on RFQ Module #2

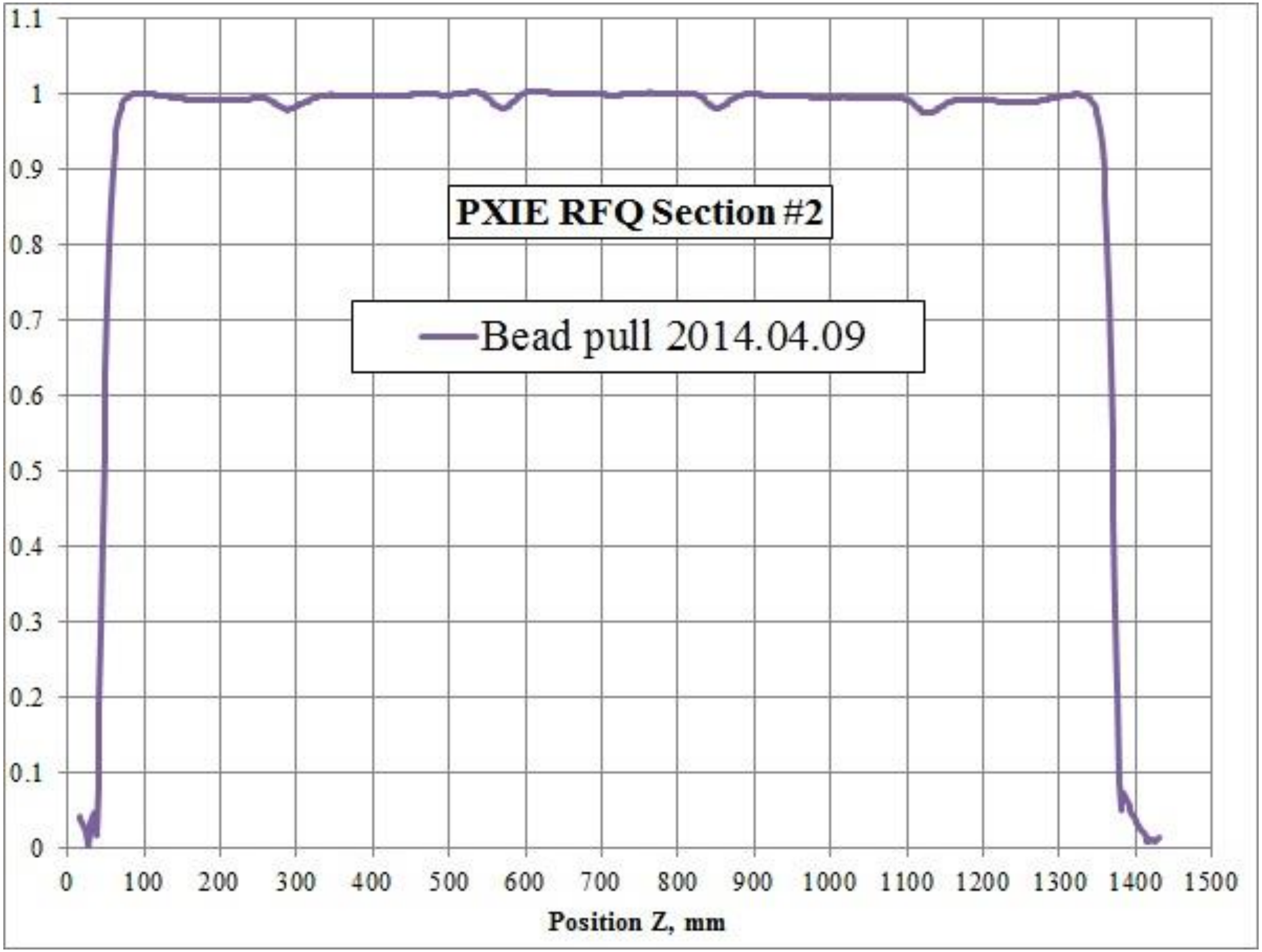


Module #2 assembled with matchers
F=163.02 MHz, Q~7000
Tuners in 20mm, end tuner out (gap10mm)



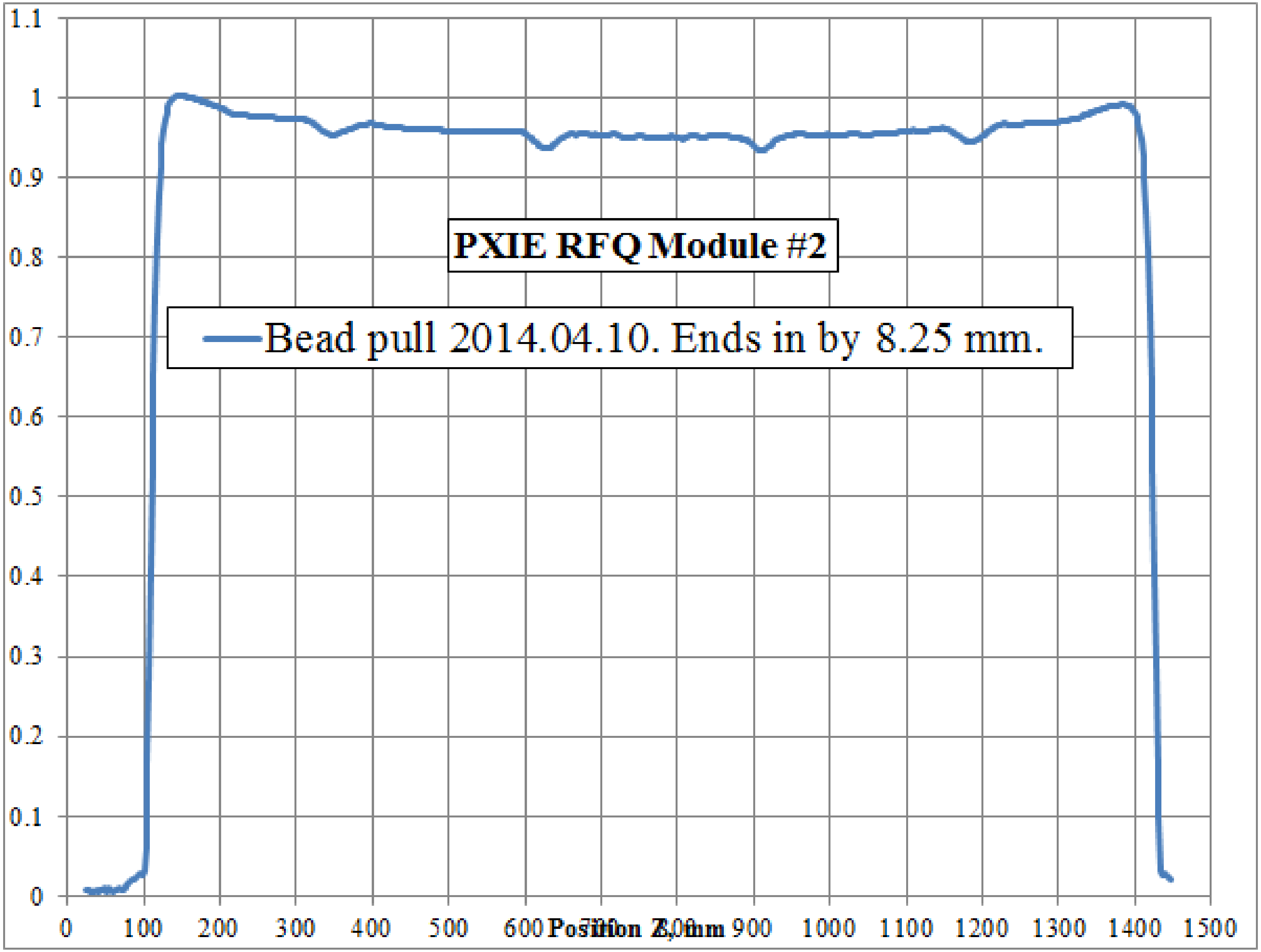
Example of bead pull off axes in 30 mm from the cavity center.
Phase shift vs bead position.

Field flatness of module #2 measured by bead pull in the 1st day.

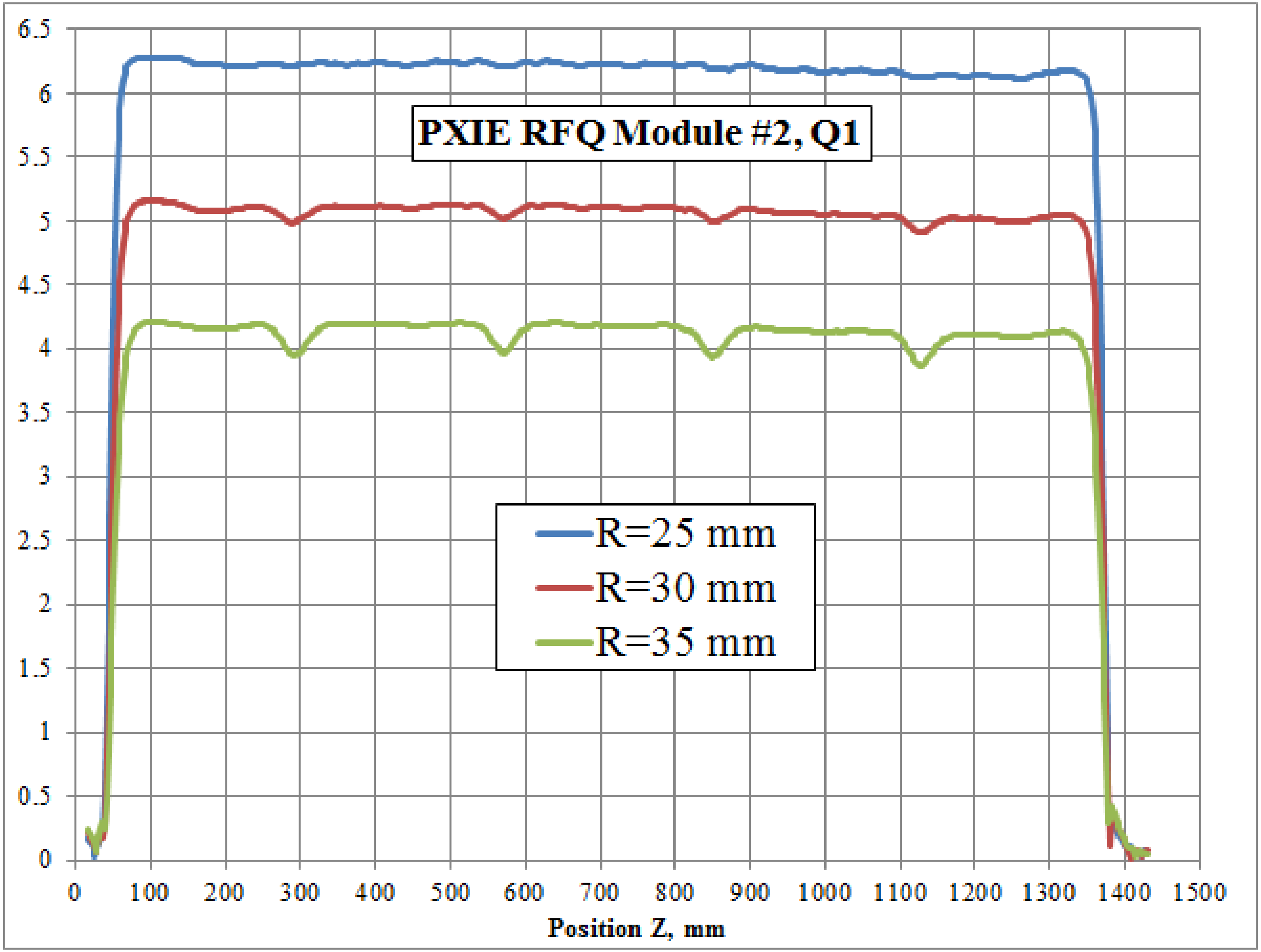


Average of 4 quadrant measurements, normalized field flatness.

Both end plates moved in by 8.25 mm. F=161.242 MHz. dF=-1.78 MHz

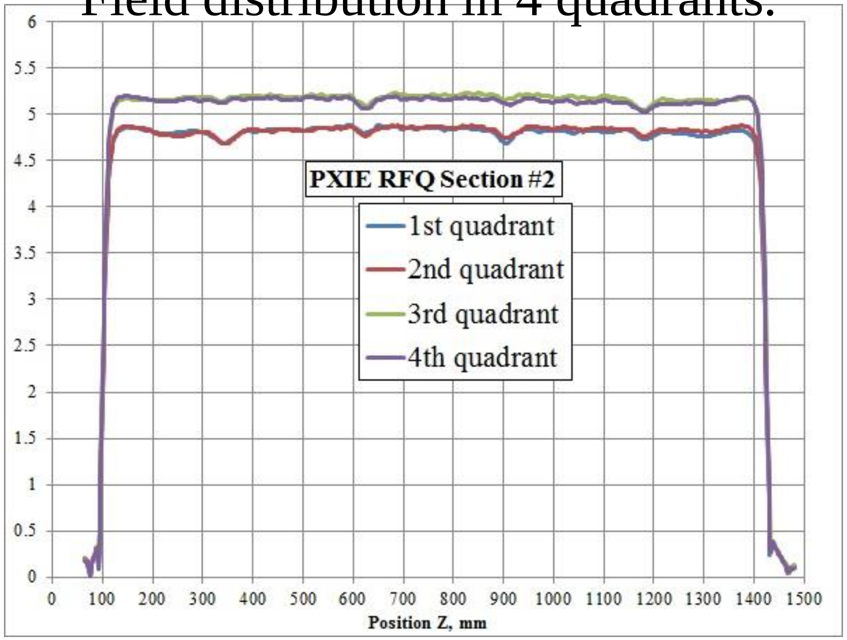


Field flatness measurement sensitivity to line positioning.

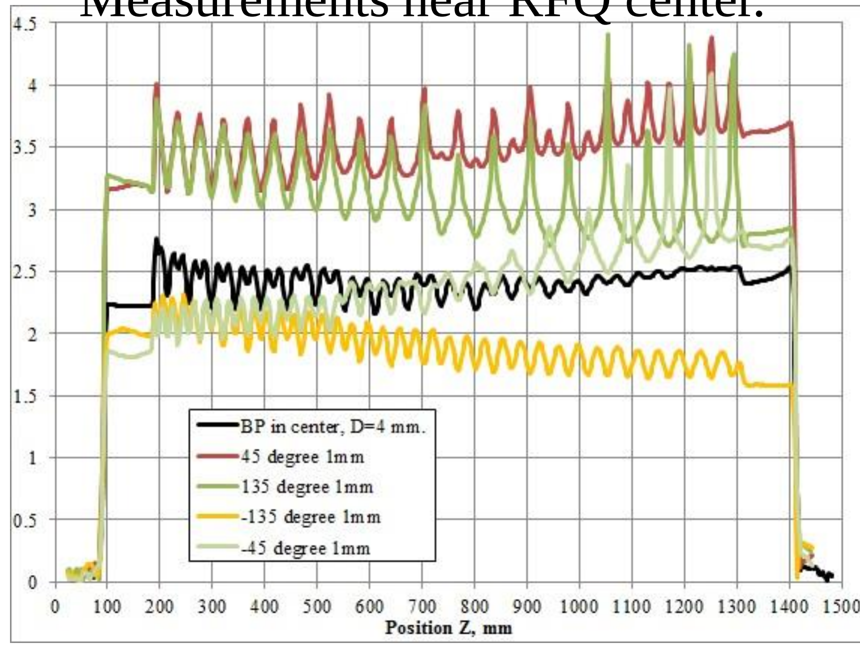


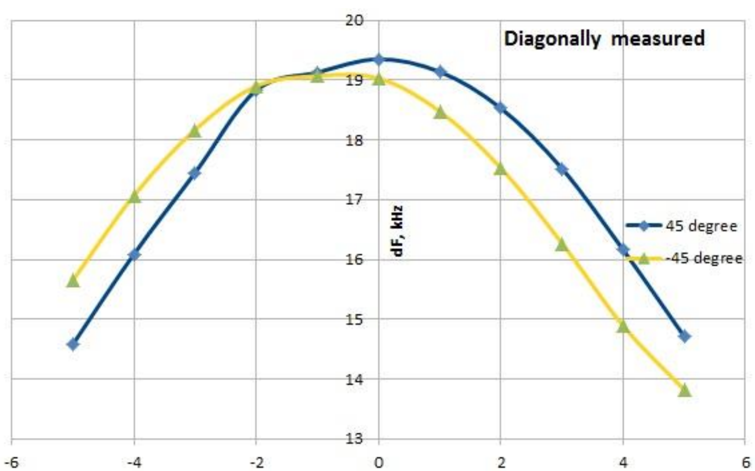
Measurements of module #2 near center and off center

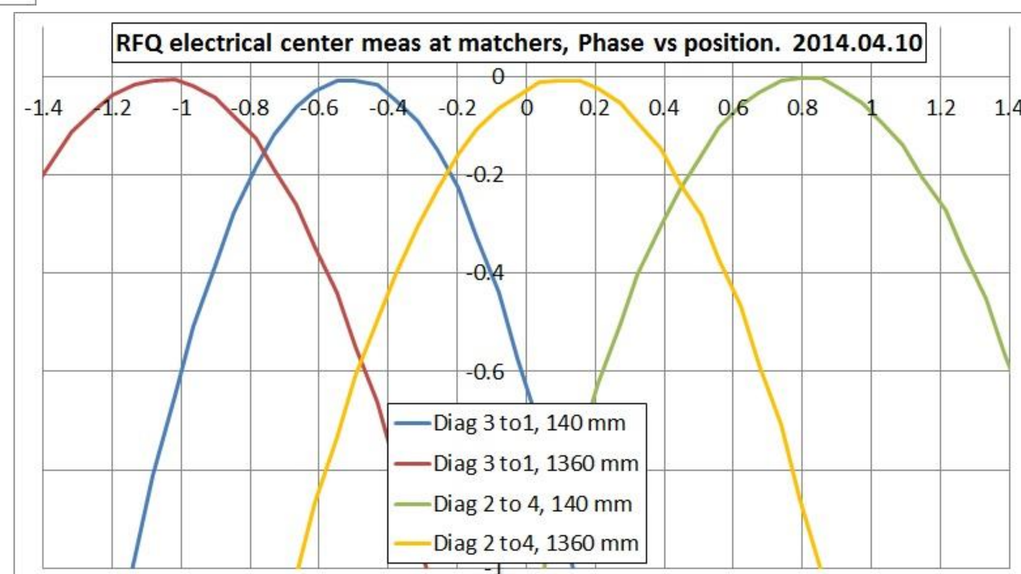
Field distribution in 4 quadrants.



Measurements near RFQ center.







Electrical center measurements.

Correction of line position based on bead pull measurements results

Position before

Z=140 mm, Q1 dR=-0.5
Z=140 mm, Q2 dR=0.8

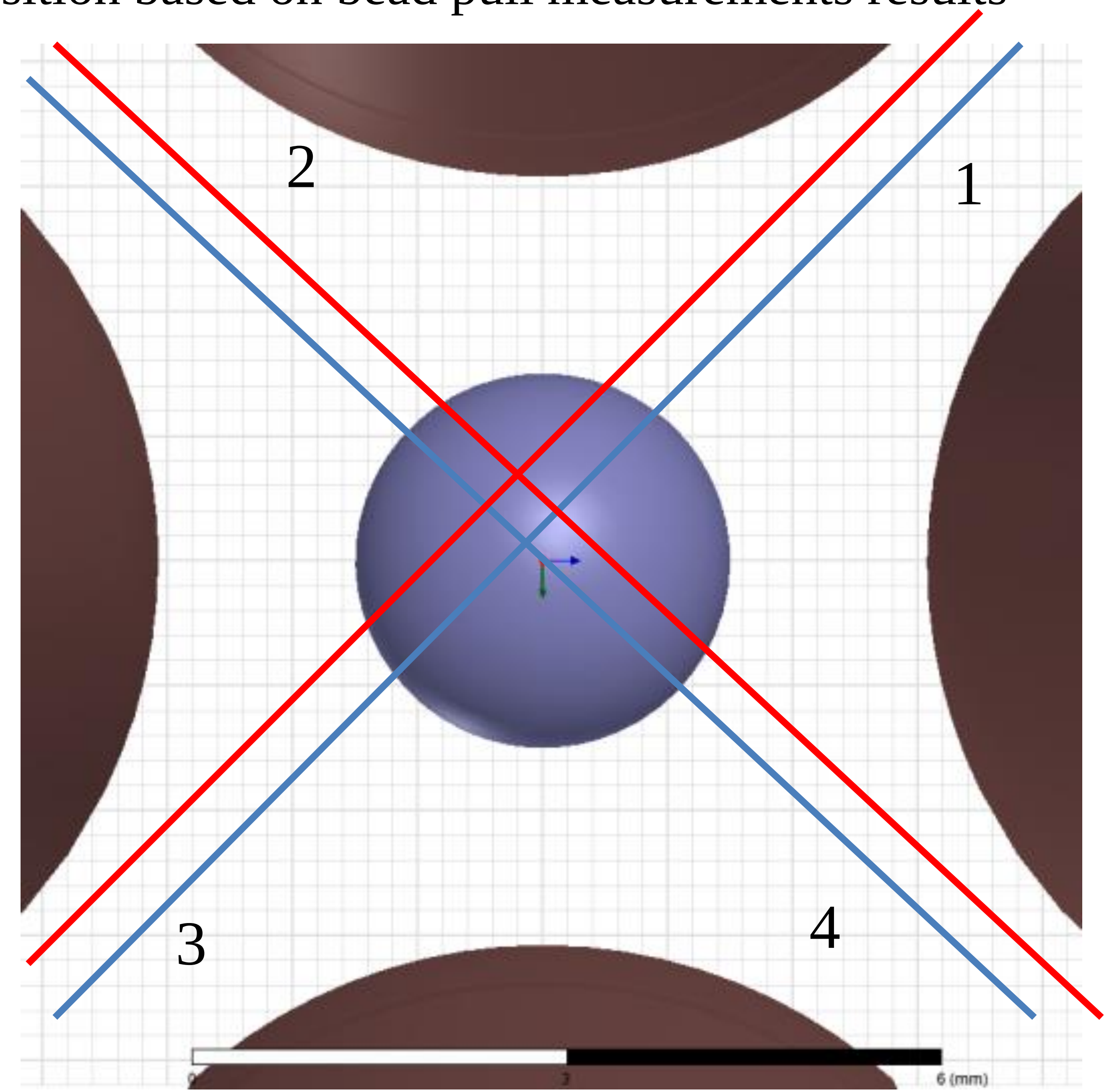
Correction needed

$$X = -R1/\sqrt{2} - R2/\sqrt{2}$$

$$Y = -R1/\sqrt{2} + R2/\sqrt{2}$$

R1	R2
-0.5	0.8
X	Y
-0.212	0.919
0.231	-0.962

At entrance, 1st end plate:
X= X_1+X_2= 0.327 mm
Y=X_1-X_2= -1.361 mm



Position before

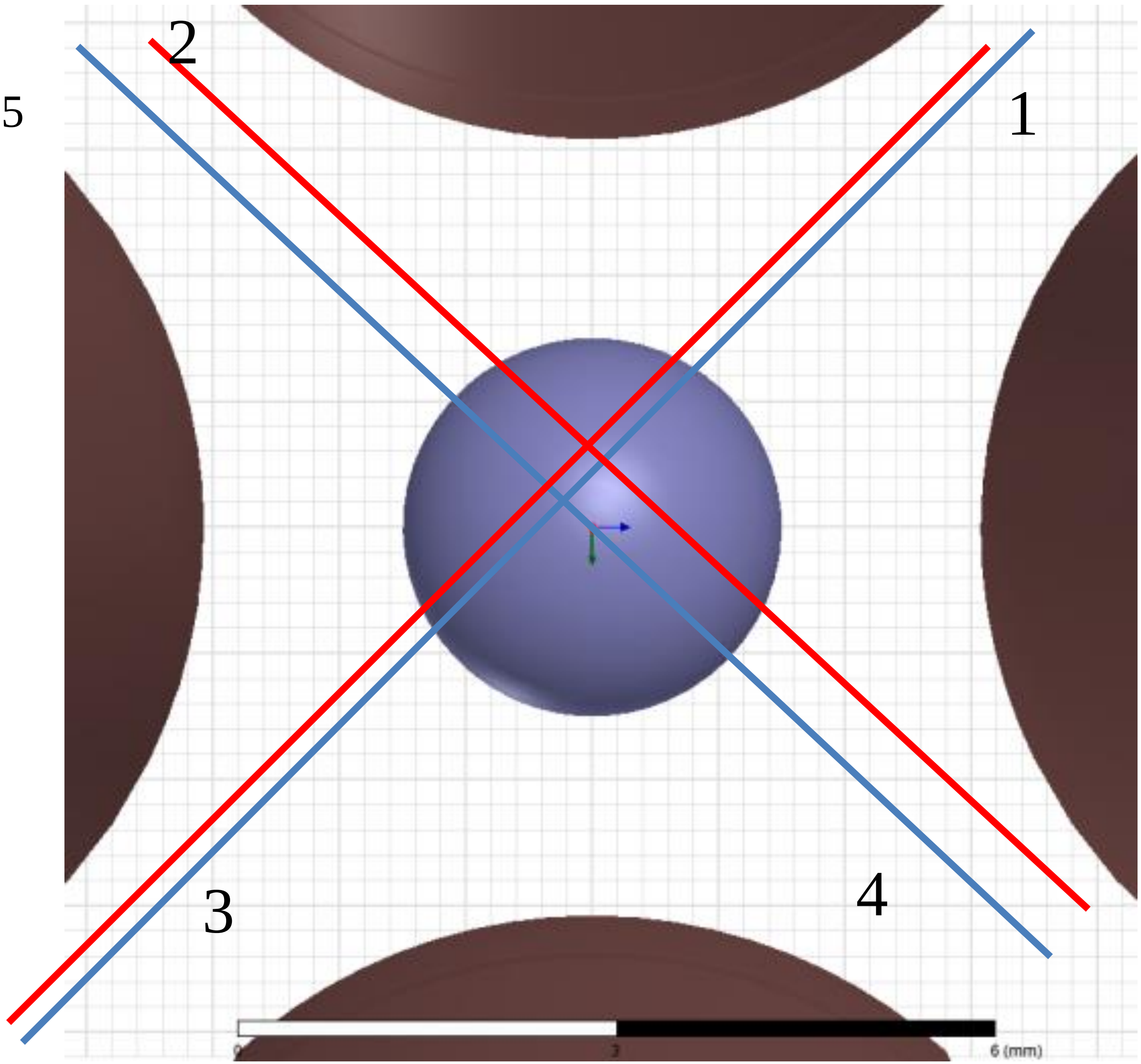
Z=1360 mm, Q1 dR=-1.05
Z=1360 mm, Q2 dR=0.1

Correction needed

$$X = -R1/\sqrt{2} - R2/\sqrt{2}$$
$$Y = -R1/\sqrt{2} + R2/\sqrt{2}$$

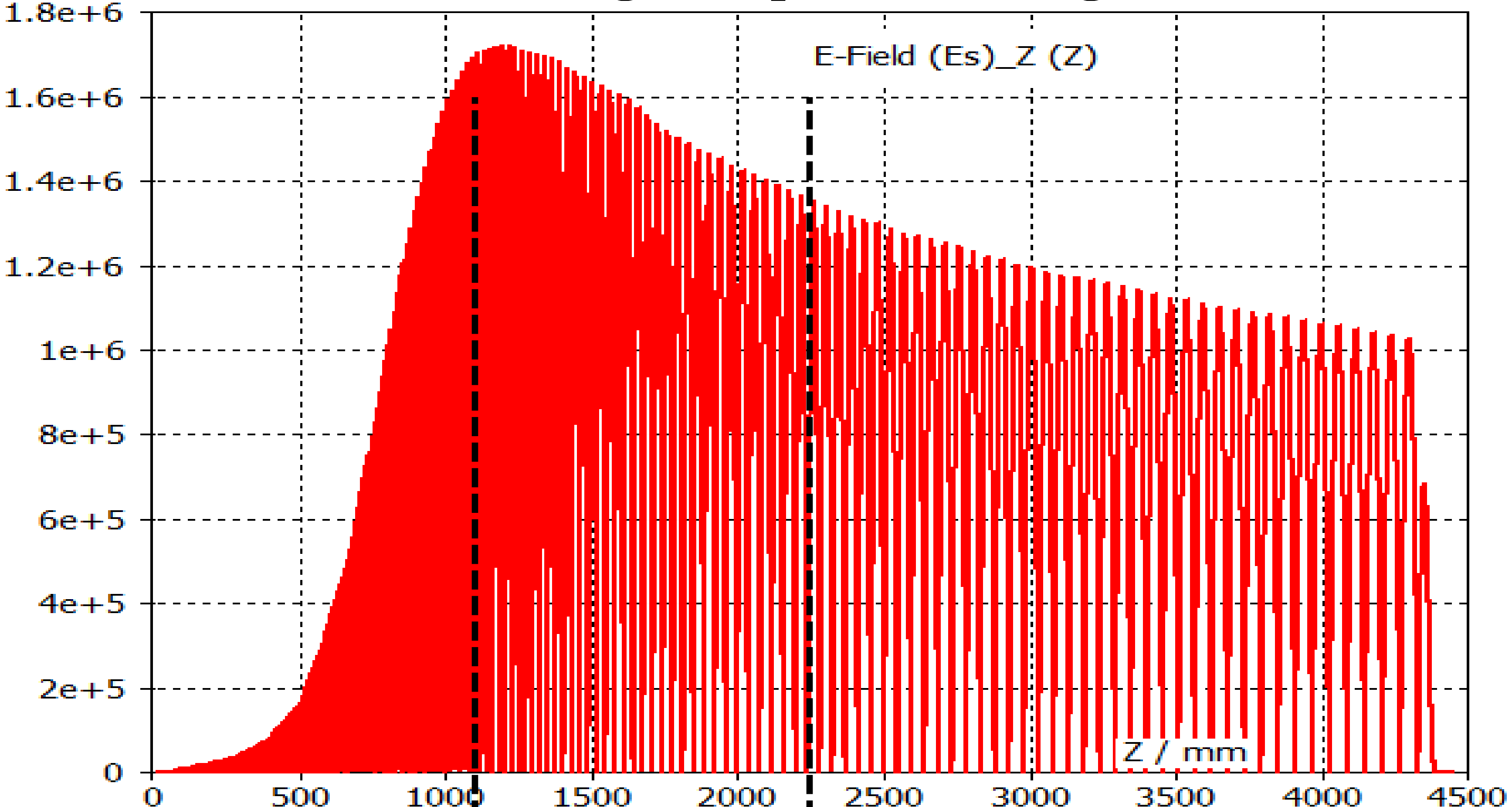
R1	R2
-1.05	0.1
X	Y
0.6718	0.8132
-0.677	-0.822

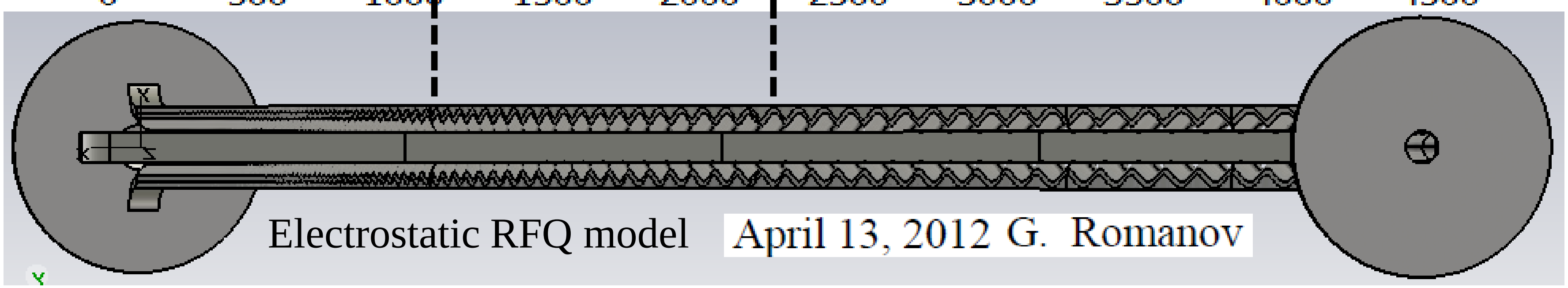
At exit 2nd end plate:
X= X_1+X_2= -0.957 mm
Y=X_1-X_2= -1.163 mm



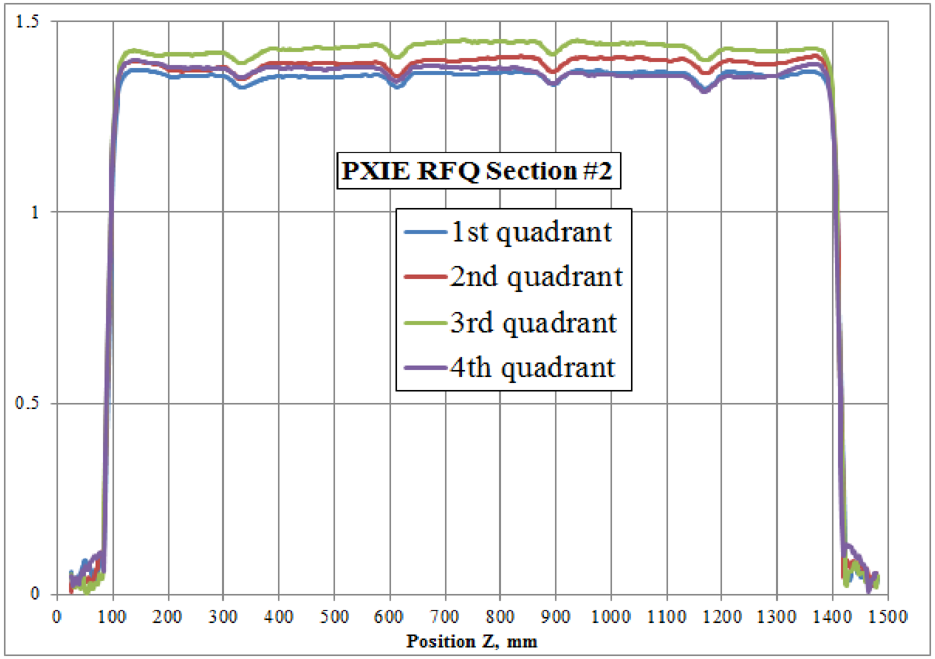
Measurements at center after new alignment base on bead pull.

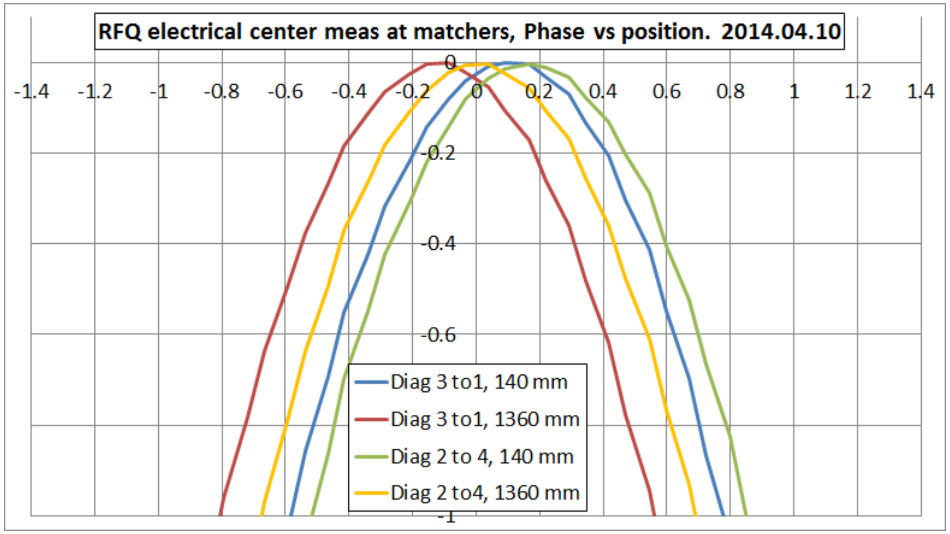
Accelerating component along RFQ.

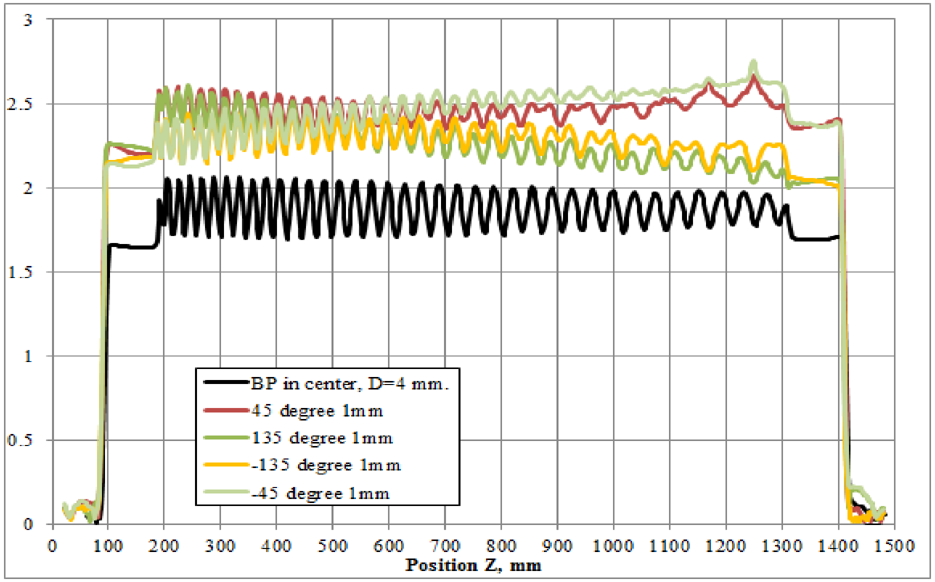




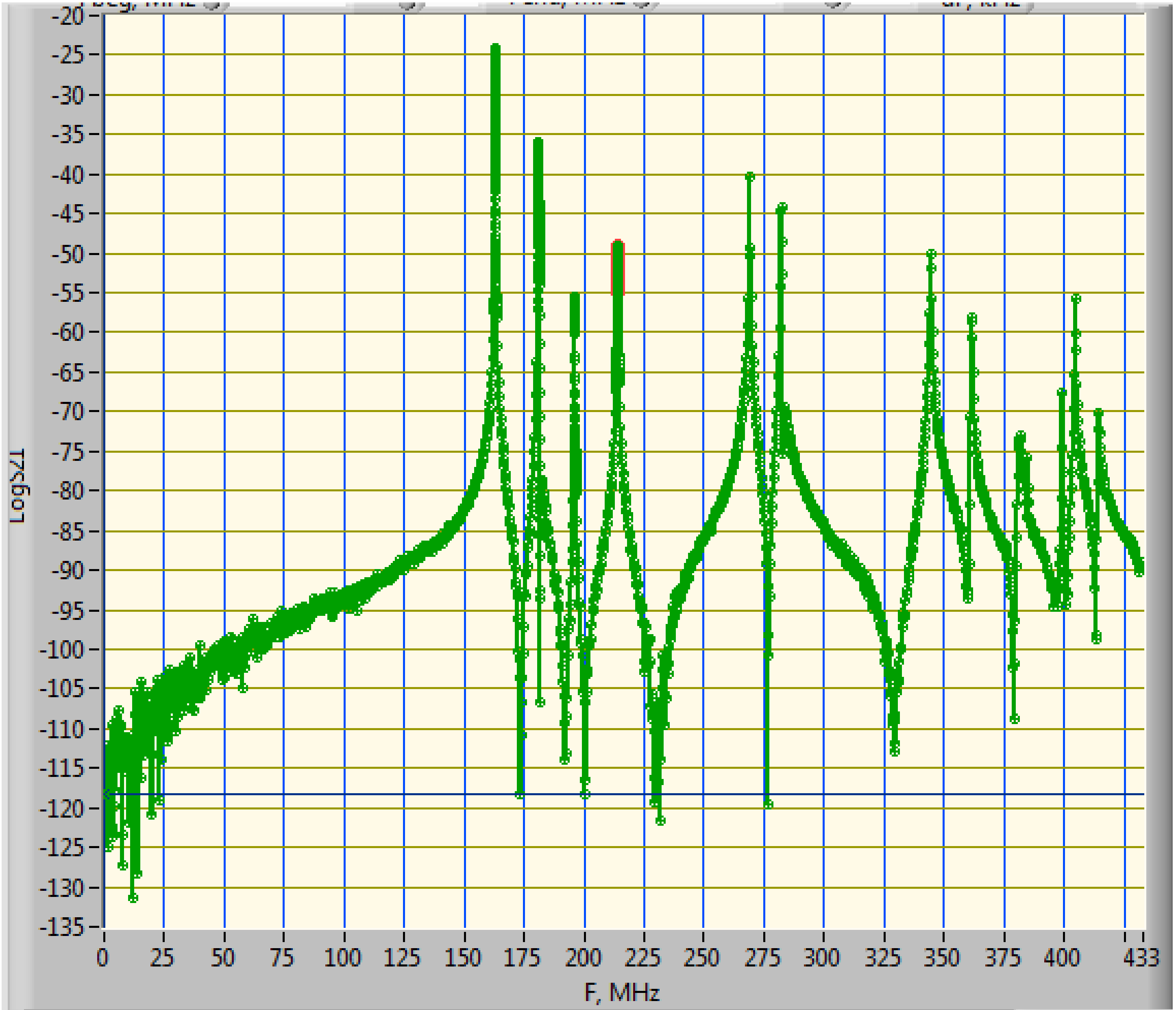
Final bead pull measurements.







S21 measurements.



Frequency tuning range.

Frequency sensitivity to end plates positions:

F=163.022 MHz. Tuners in nominal position 20mm.

F=162.991 MHz. End plate 1 moved in 1 turn 1.25 mm. dF=0.031 MHz.

F=162.963 MHz. End plate 1 moved in 2 turn 2.50 mm. dF=0.059 MHz.

F=162.862 MHz. End plate 1 moved in 4 turns 5.00 mm. dF= 0.16 MHz.

F=162.692 MHz. Both end plates moved in 4 turns 5.00 mm. dF=0.33 MHz.

F=161.242 MHz. End tuners in by 8.25 mm. dF=-1.78 MHz.

Sensitivity to tuners positions:

F=161.896 MHz. All tuners out (~40 mm). **dF=-1.126** MHz

Results

- Module #2 was assembled before brazing
    - Cavity operating frequency close to expected and in the tuning range
    - Quality factor is good for clamped cavity
- Bead pull system was installed in module #2 and tested
    - Bead pull mechanism works fine
    - Electronics works fine
    - Program works fine after small debugging
    - Field flatness measurements done in all four quadrants
    - Field flatness measurement done near RFQ center
    - Field flatness sensitivity to perturbations is very low

- Module #2 RF measurements was successful and equipment was sipped to FNAL

- Next steps:
    - Improve automation of measurements
    - Improve data processing
    - Prepare antennae for complete RFQ measurements
    - Install guide line to complete RFQ measurements during assembly

Summary

- Frequency of the Module #2 is acceptable and in tuning range
  - Operating frequency Module #3 simulated with our temporary cutbacks and endplates 10 mm from vanes and all tuners in 20 mm same as measured for Module #2 assembly
  - Accuracy of the simulation is about ± 100 kHz, given the different modules
  - LBNL simulations/calculations predict a resonant frequency 200 kHz lower than measured, which we may or may not need to reconcile at some point
  - Regardless, all of the simulation errors are well within the ± 1 MHz tuning range of the stub tuners, and the machining process seems to be adequate to continue construction and brazing
- Field flatness was very good min/max*100% > 99% as assembled without any additional tuning
- All measurements were done with spherical shape metallic bead. Same technique will be used for measurements of complete RFQ