RF Simulation Studies of PXIE RFQ.

G. Romanov

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Collaboration Meeting at LBNL

Intro

The simulations of IMP and PXIE RFQs are performed per the LBNL's requests.
The list of tasks:

2D simulations (RFQ cross-section):

- Frequency, Q-value, power dissipation per length unit.

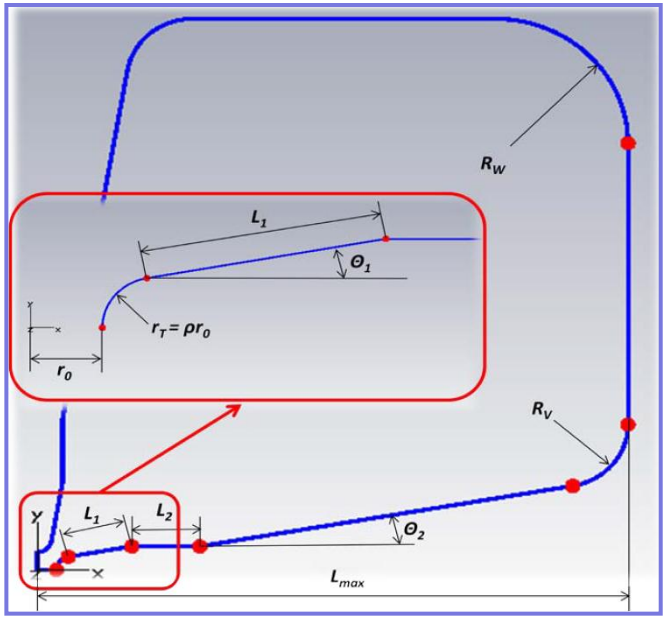
3D simulations:

- Frequency shift/perturbation from pi-rods and Q value (or power dissipation by rods);
- Frequency sensitivity from tuners, and frequency shift/perturbation from tuners at their nominal intrusion and power dissipation by the tuners;
- Perturbations to field distributions due to pi-rods and tuners;
- Frequencies of dipole modes with and without pi-rods;
- Cut-back designs to provide flat field flatness and frequency of 162.5 MHz;
- Power dissipation (and density) at cut-backs and Q value of the whole RFQ structure with everything.

The results are updated on the permanent basis, so today the focus will be on the simulation procedures mostly.

RFQ cross section profile

Project X

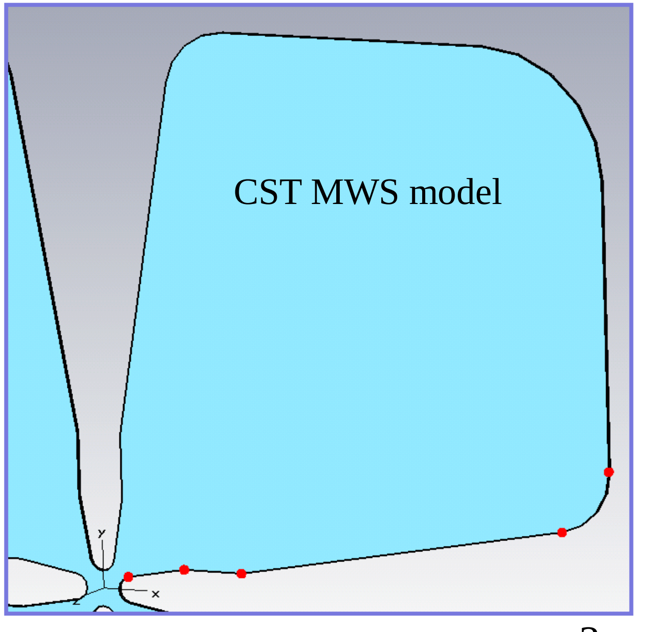


Key points	x	y
0	0	0
1	5.576	0
2	6.554402	2.688138
3	9.031803	4.118466
4	28.72796	7.59143
5	48.72796	7.59143
6	158.273	26.90717
7	170.1209	33.74757
8	174.8	46.60332

Control points from J.Staple's spreadsheet

Control points from CST MWS model

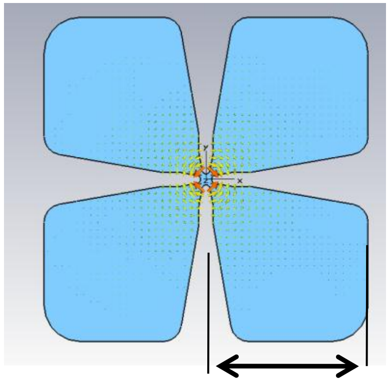
X	Y
9.032e+000	4.118e+000
2.873e+001	7.591e+000
4.873e+001	7.591e+000
1.583e+002	2.691e+001
1.748e+002	4.660e+001



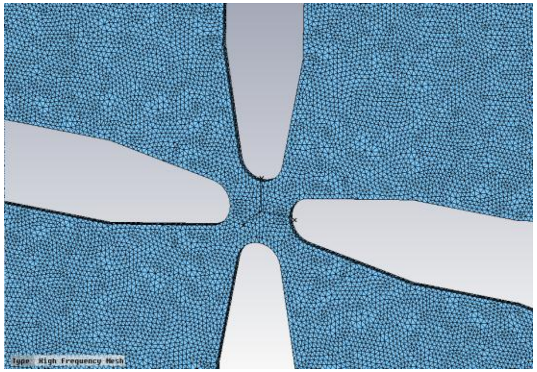
No	Variables	PXIE	Unit	Comments
1	r_0	0.5576	cm	
2	ρ	0.75		Ratio of vane tip radius to r_0
3	L_1	2	cm	Horizontal/vertical length of the sloped lines
4	L_2	2	cm	Horizontal/vertical length of the straight lines
5	θ_1	10	Deg.	First angle of the vane
6	θ_2	10	Deg.	Second angle of the vane
7	R_V	2	cm	Curvature of the vane corner
8	R_W	4	cm	Curvature of the RFQ cavity wall
9	L_{max}	17.48	cm	Maximum inner cavity length
	$r_T = \rho r_0$	0.418	cm	Transverse tip radius (derived parameter)

RFQ cross section simulation

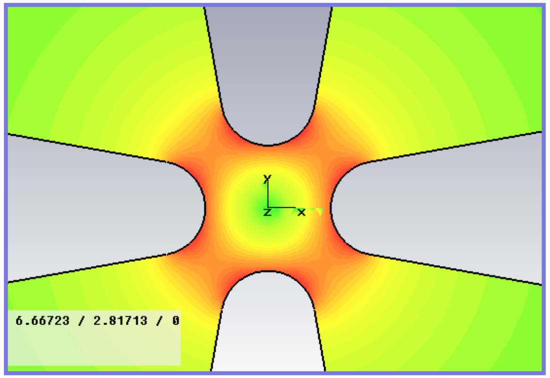
Project X



L_{max}



Mesh, 495,000 tetrahedrons

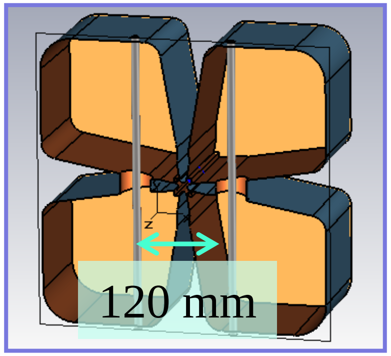


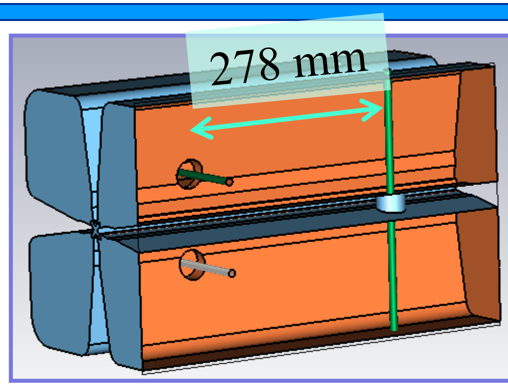
E_abs distribution

Parameters	Original	Tuned
Frequency, MHz	164.39	162.492
Q factor	16747	16813
Power loss per length, W/cm	138.89	133.0
Peak electric field, MV/m	13.4	13.4
Dipole mode freq., MHz	159.33	157.5
Tuning coef. $\Delta F/\Delta L$, MHz/mm	1.04	1.04
L_{max}, mm	174.8	176.59

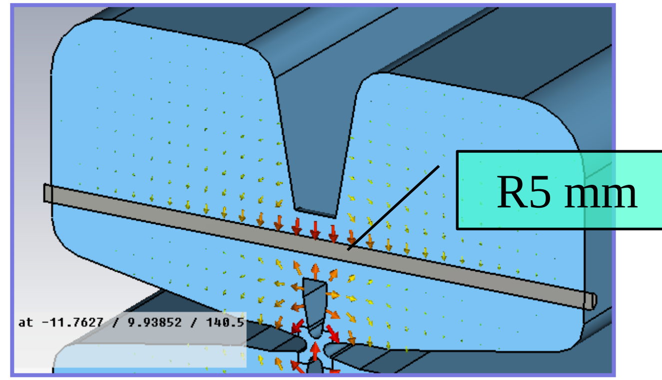
Pi-mode rods period

Project X

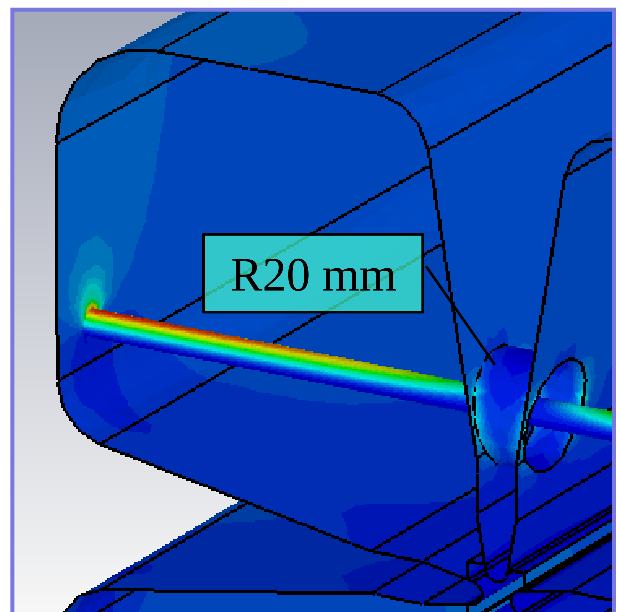




Parameters	Value
Frequency, MHz	162.486
Frequency shift due PISLs, MHz	-5.56
Q factor	15333
Q factor drop due PISLs, %	-9.65
Power loss per PISL, W	188
Dipole mode freq., MHz	179.6
Dipole mode shift., MHz	22.1
Field perturbation at x=y=5 mm, %	0.3
L_{max}, mm	171.44

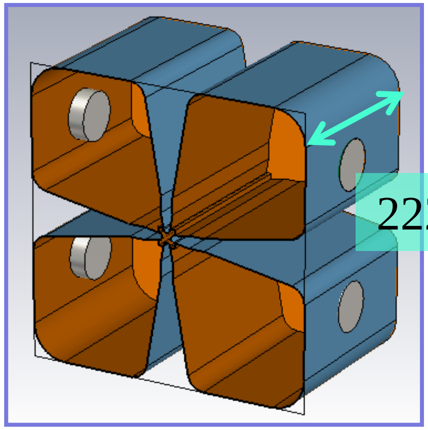


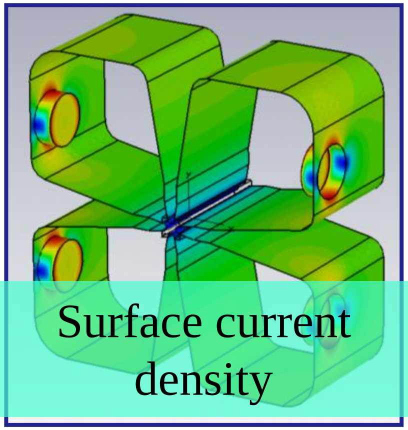
E field

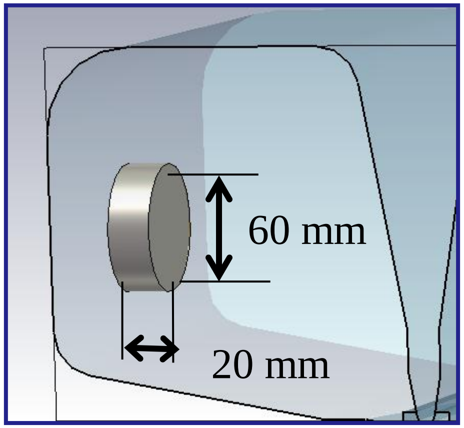


Loss density distribution

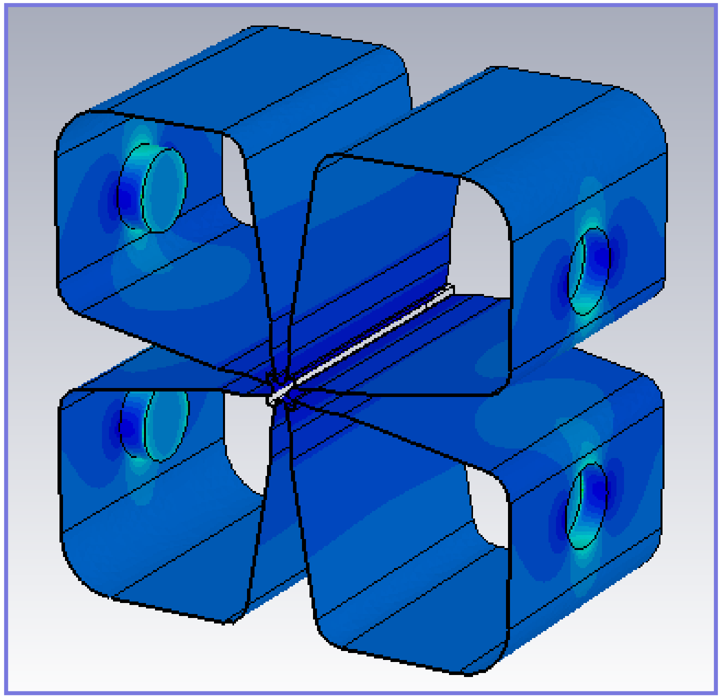
Tuner period





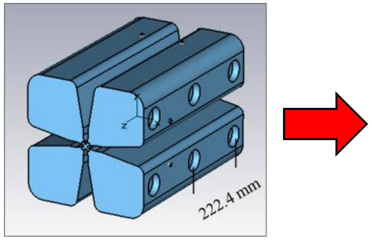


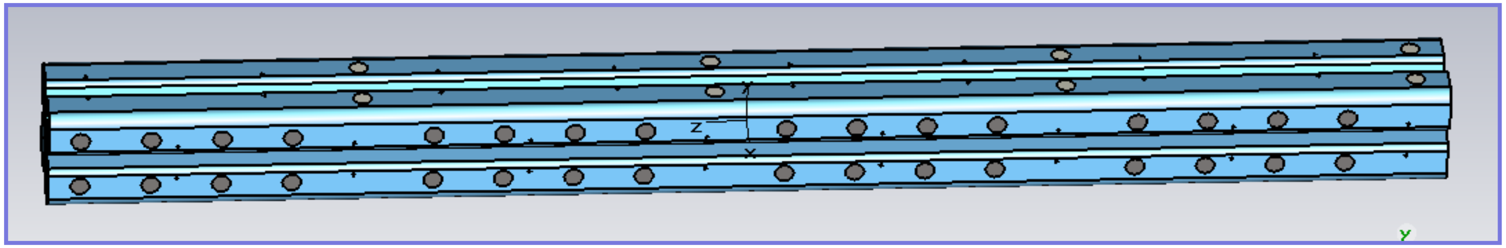
Parameters	PXIE-T
Frequency, MHz	162.495
Frequency shift due tuners, MHz	1.334
Q factor	16115
Q factor drop due tuners, %	-4.1
Power loss per tuner, W	57.7
Tuning sensitivity, kHz/mm	16.7
Nominal tuner intrusion, mm	20
L_{max}, mm	177.84



PISLs and tuners together

In previous simulations a final L_{max} value was defined using PISL period model with the tuners added. But the periods of PISLs and the tuners are not equal. In fact there is no periodicity and symmetry in the RFQ. So, this time the final value L_{max} has been found using full length model with actual positions of the elements, but without cut-backs ("the vane length model").



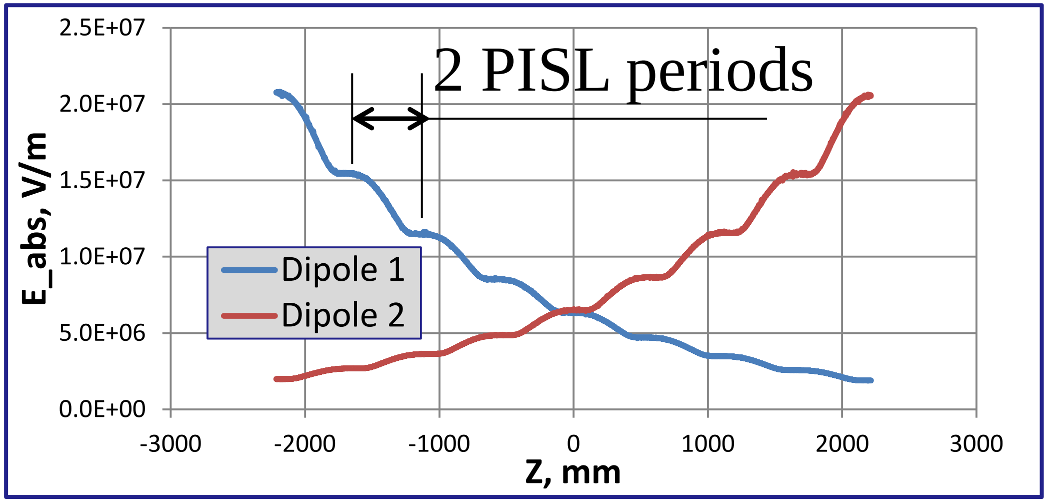


The final L_{max} value is 172.23 mm (which is less than 2 mm different from "periodical" value). This size is kept constant in all following simulations.

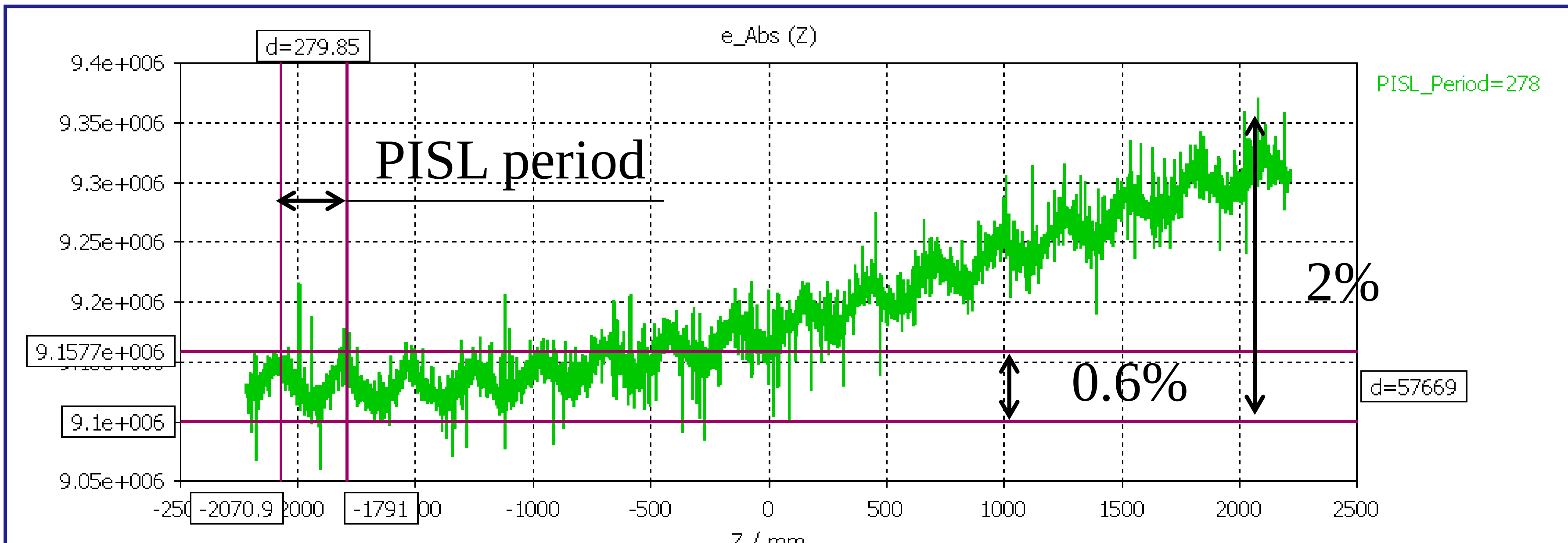
The interesting observation from this model is field distribution distortion due to combined effect of the PISLs and the tuners.

Field distributions in the vane length model

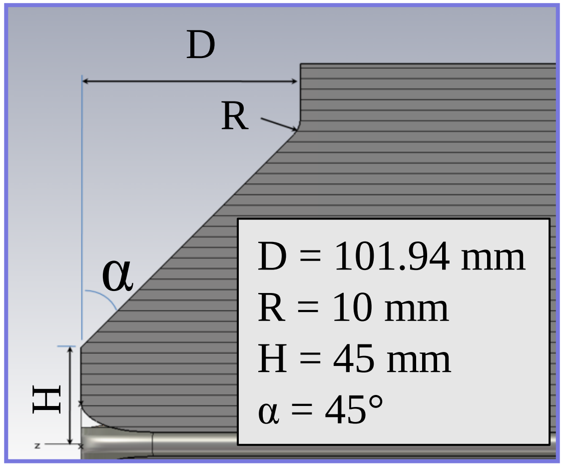
Project X

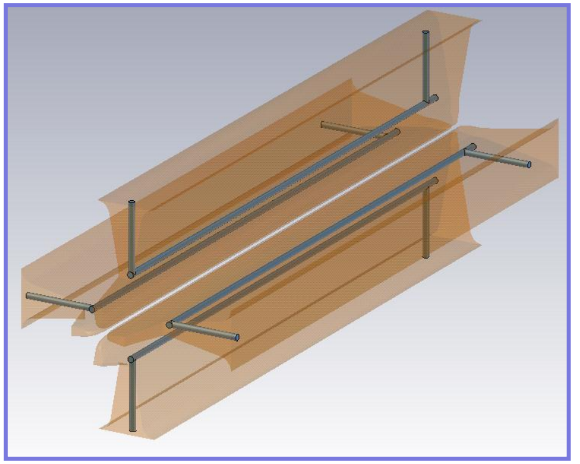


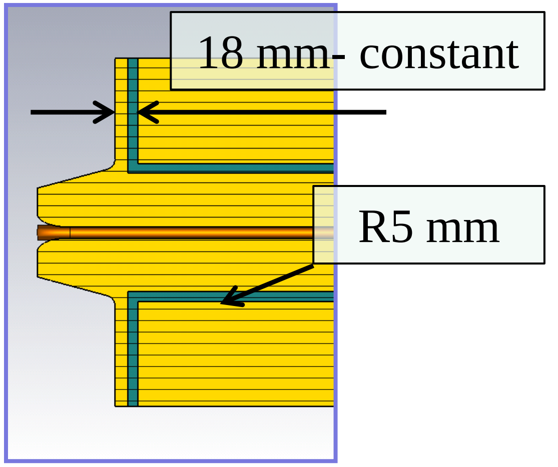
The plots are E_abs along x=y=5 mm line. Modulation of the field distributions is due mostly to the pi-mode rods. The field tilts are due to the asymmetric end terminations. The character of the distortions remains generally the same in the complete RFQ.

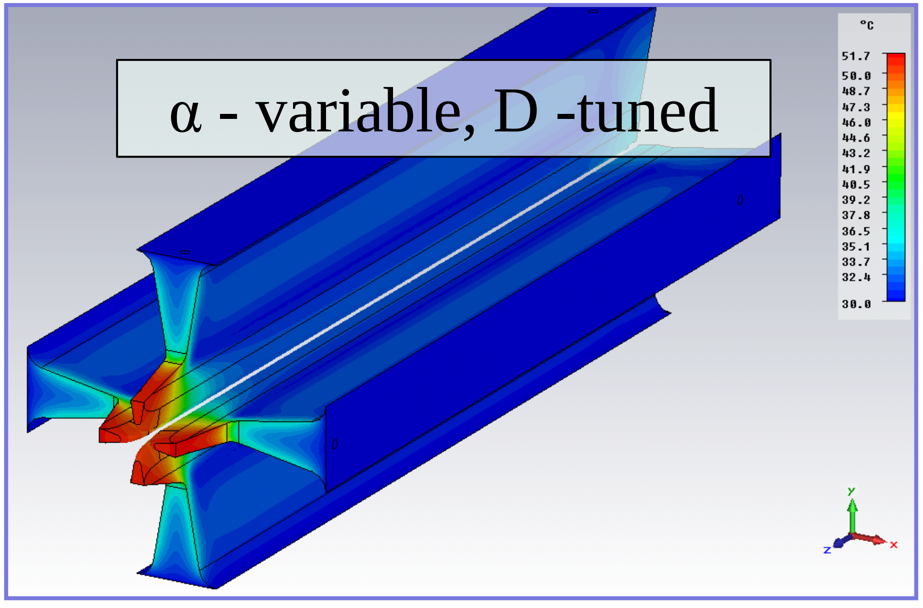


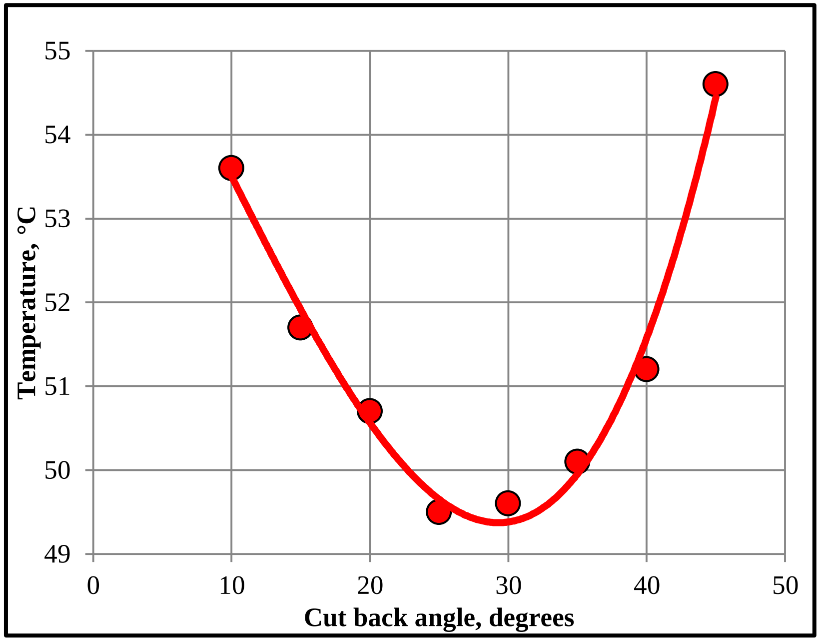
The cut-back shape





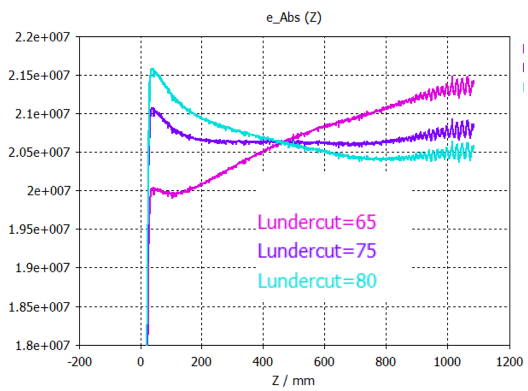


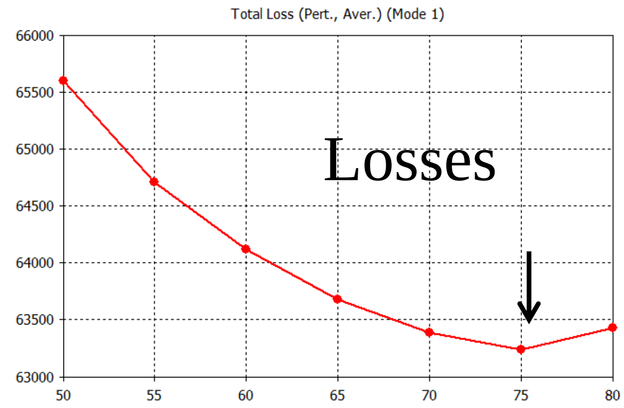


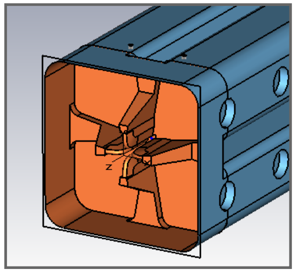


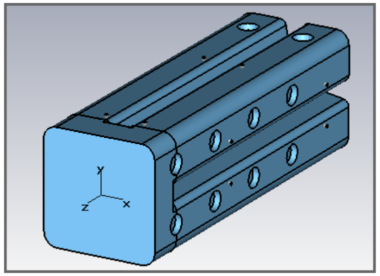
The standard cut-back tuning

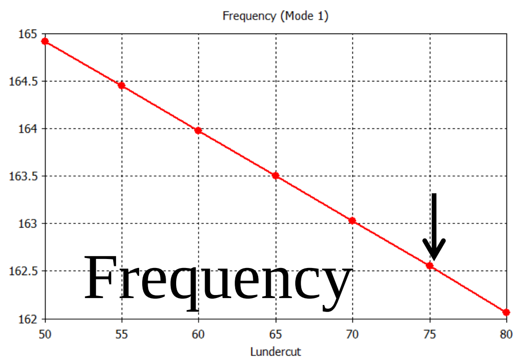
Project X

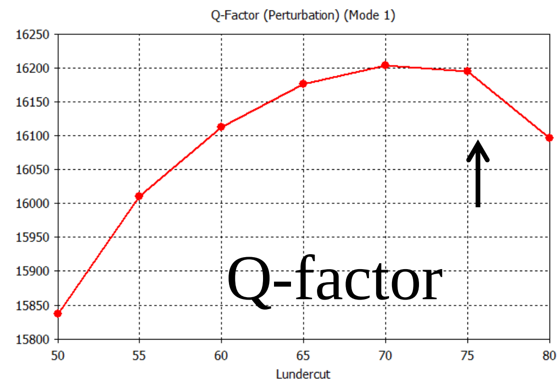








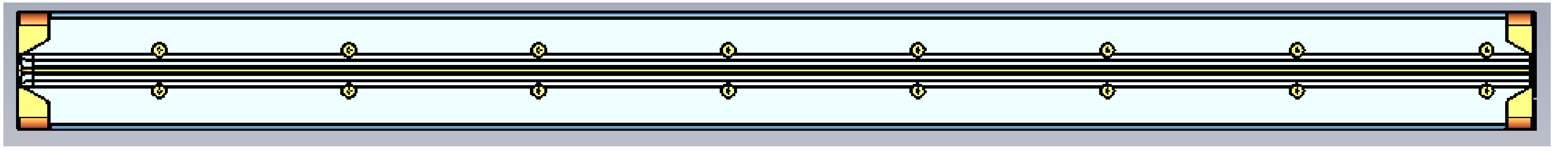


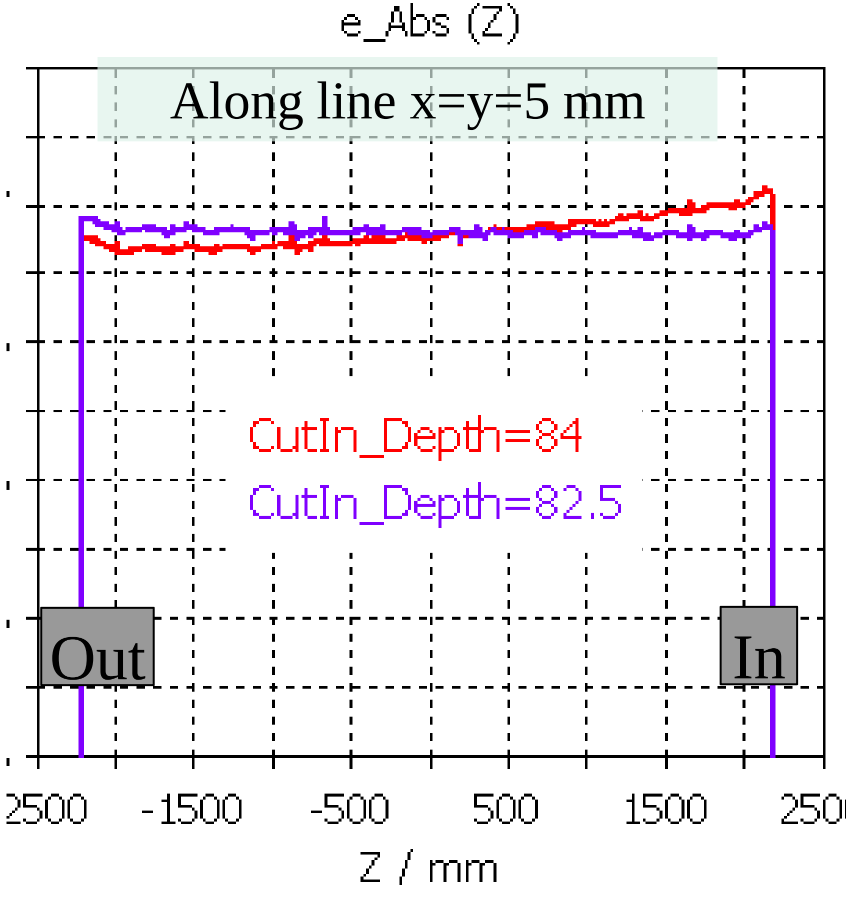


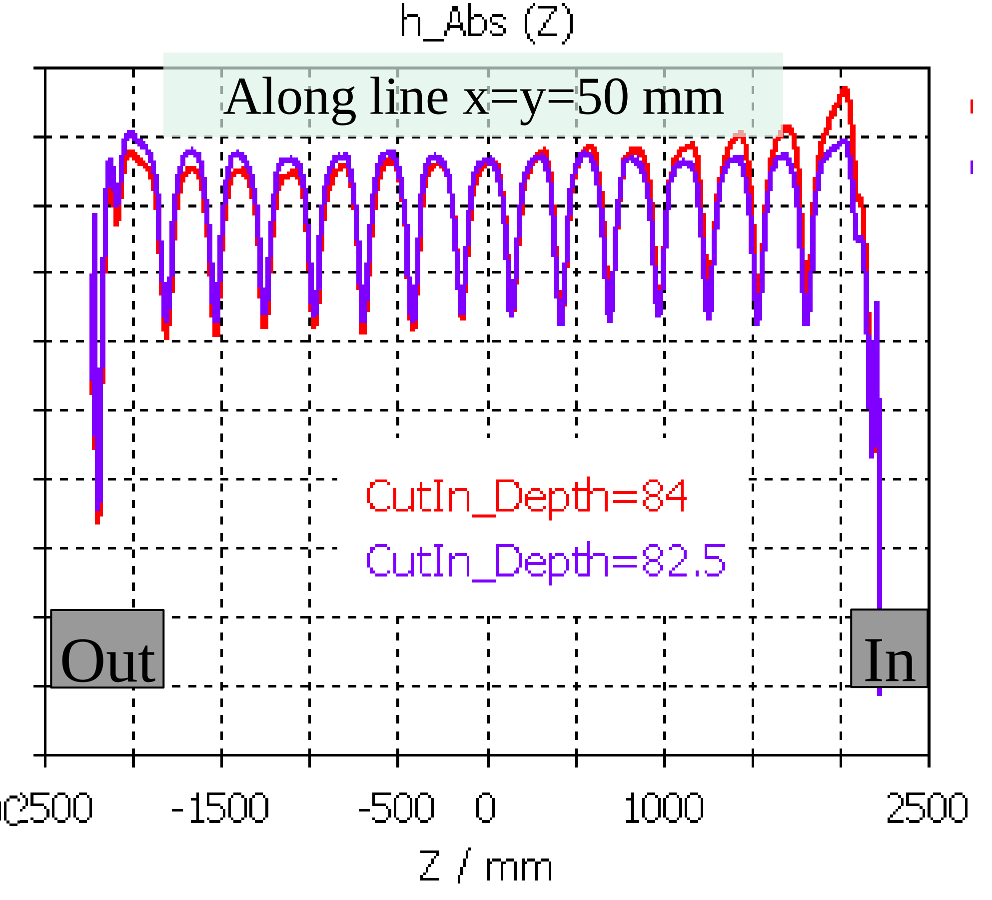
We can tune a frequency of termination using short model. Or flatten a field distribution in a sufficiently long model. Tuning with field tilt control is more accurate, though it requires more resources.

Remarkably that for properly tuned cut-back all parameters are almost optimal. It is not so obvious for full scale model – the changes are too small

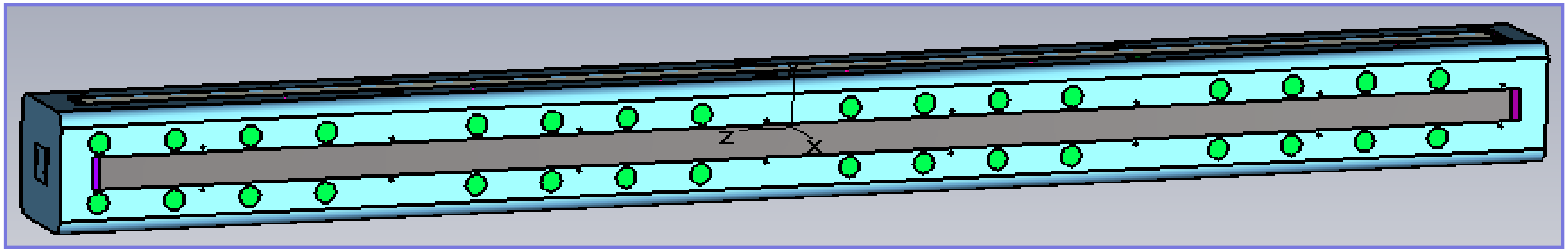
The full scale cut-back tuning

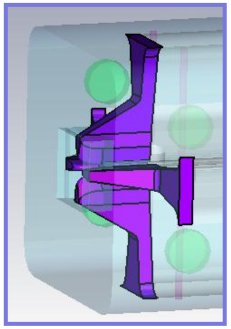


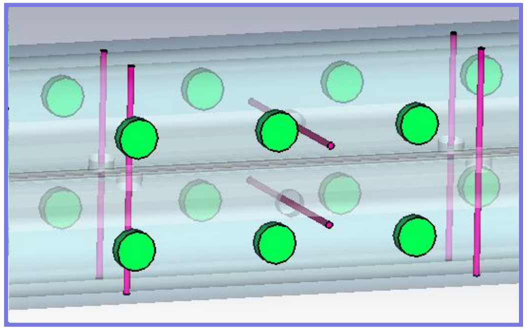


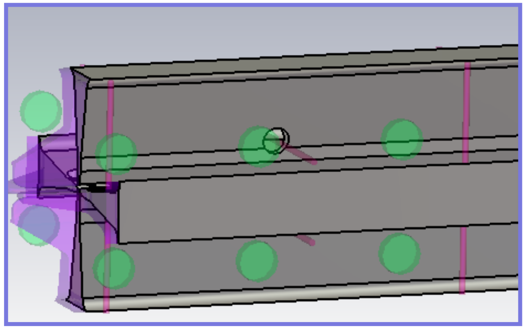


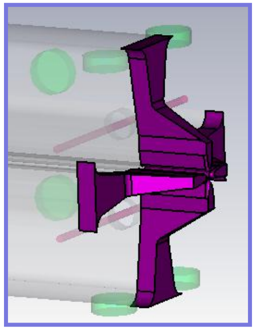
The complete solid model











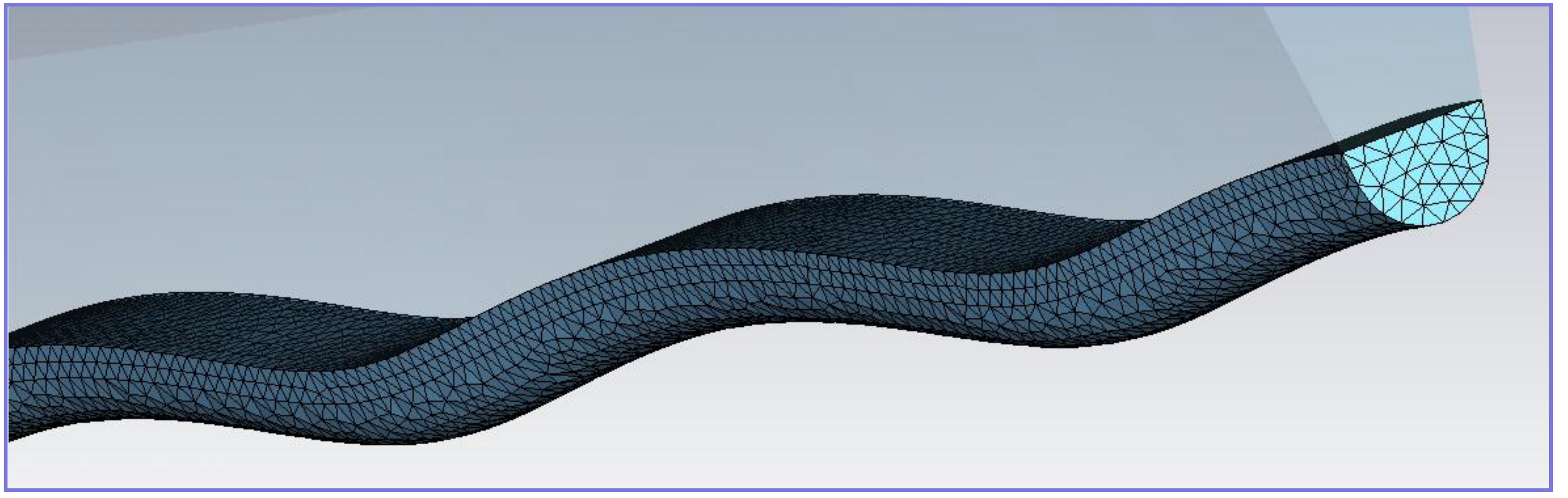
Parameters	PXIE
Frequency, MHz	162.499
Frequency of dipole mode, MHz	181.99
Q factor	14985
Q factor drop due to everything, %	-14.7
Power loss per cut-back, W (In/Out)	336/389
Total power loss, kW	73.8
L_max, mm	172.73

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

Vane modulation

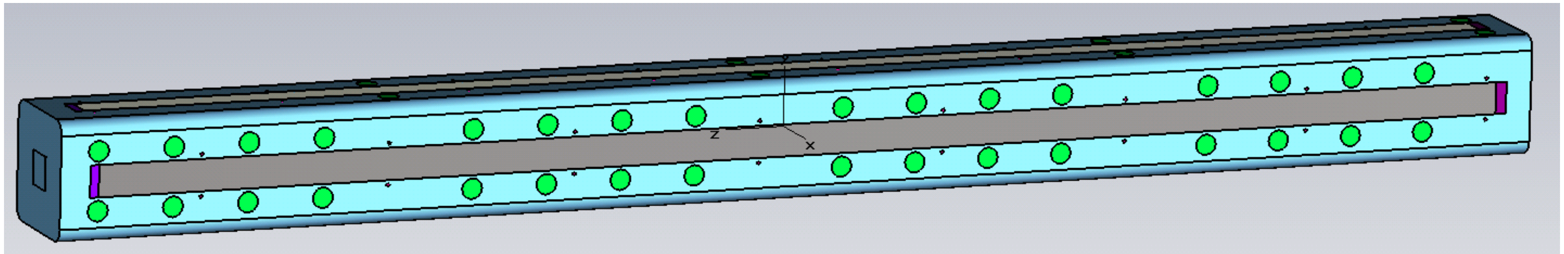
Project X

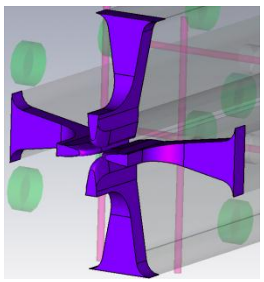
Our computing capability has been increased significantly. We can now create a full scale RFQ model with modulated vanes and solve EM or ES problem.



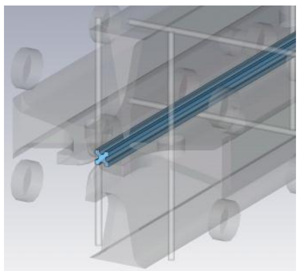
First of all we can now take a modulation into account during RF design. Also we can now use the "real" fields for beam dynamic simulations.

Electrodynamic RFQ model

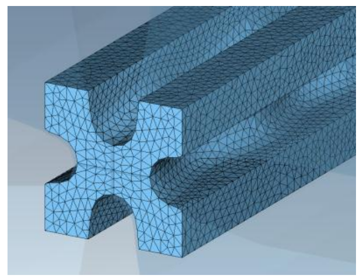




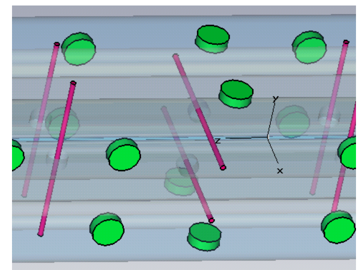
Input matcher.



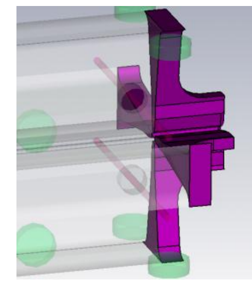
Modulated vane tip.



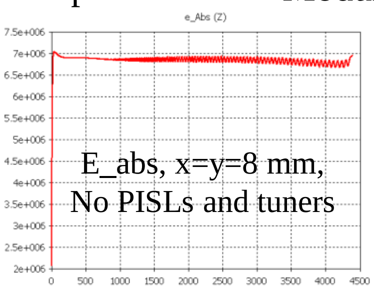
Mesh. 600,000 tets

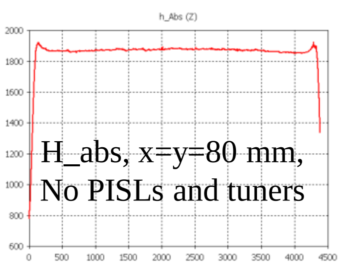


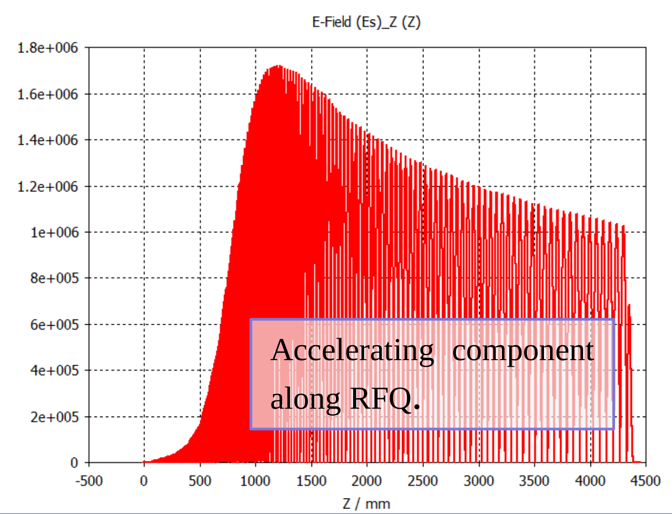
PISLs and tuners



Output termination

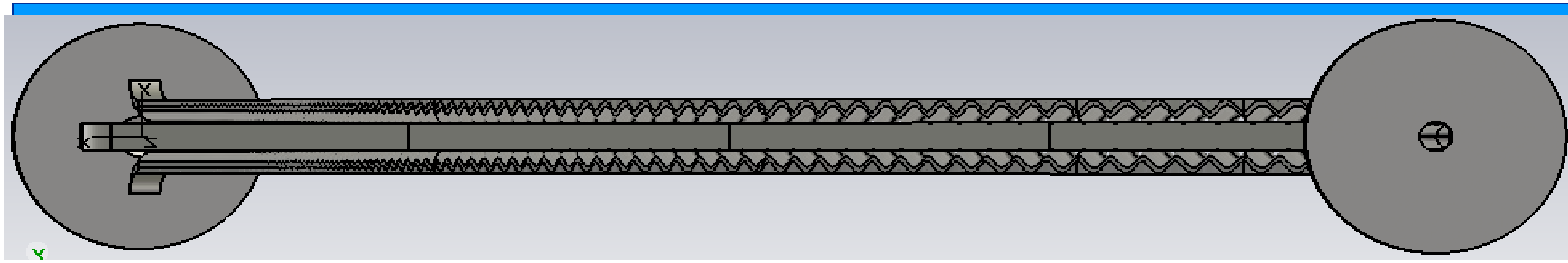


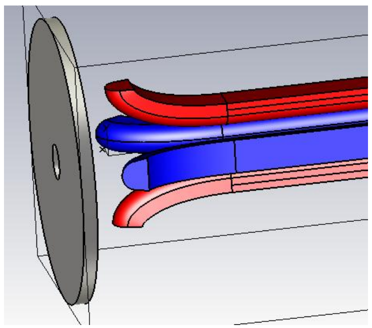




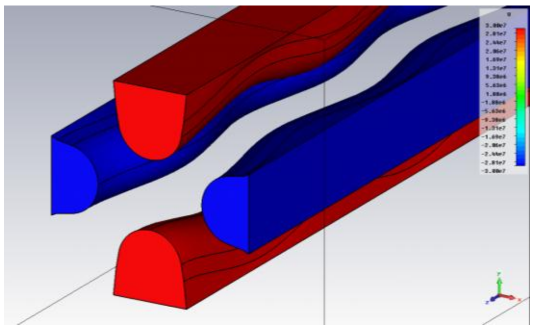
Field distribution in this model reflects influence of many factors – neighboring modes, tuning, stabilizers etc., so the result is never theoretical and may be confusing. On the other hand this is the only approach to analyze real mechanical and tuning errors.

Electrostatic RFQ model

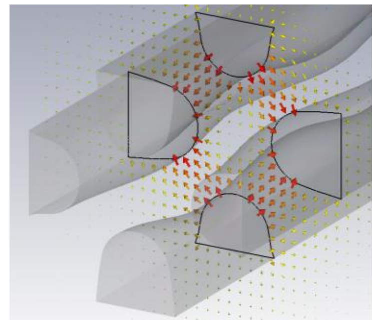




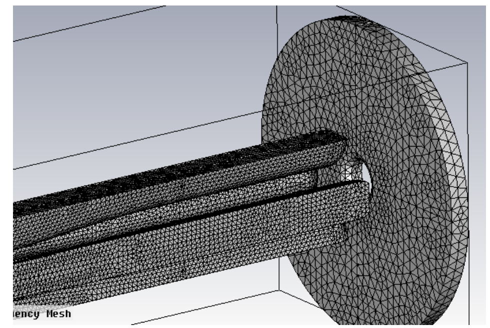
Input matcher with end-wall.



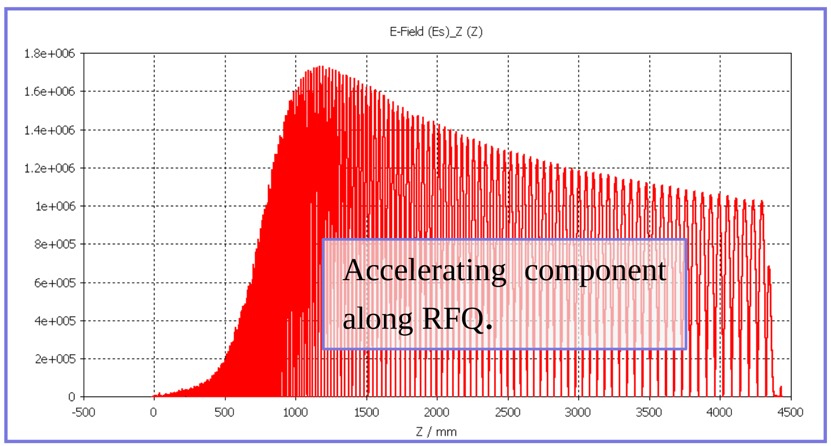
Potentials of ± 30 kV assigned to the electrodes.



Electrostatic field



Meshed output termination with end-wall.

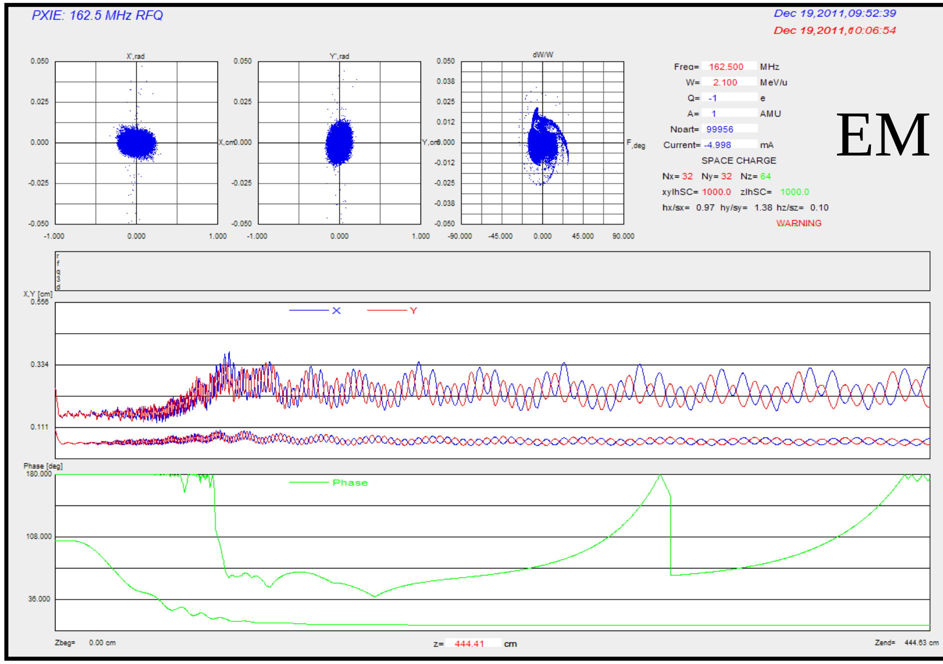


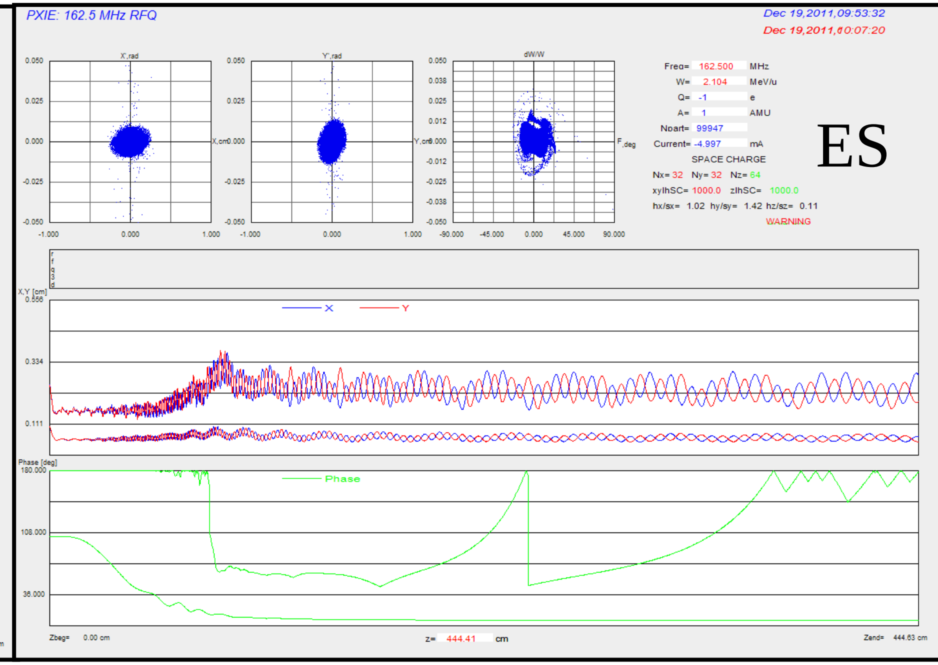
Accelerating component along RFQ.

The main advantage of the electrostatic model is a designed field distribution – only electrode geometry in paraxial area and electrode potentials matter. And an exact operating frequency can be assigned. But the ES solver uses low frequency mesh which is not very advanced. So, a huge mesh up to 10 M tetrahedrons is needed, and mesh building is very time consuming. The solver itself is very fast though.

TRACK simulations

Project X





	α	β	4 ε n_rms	Coord.
EM	0.02	0.025	0.054	x
	-0.55	0.012	0.054	y
	0.2	18.35	3.25	z
ES	0.028	0.023	0.054	x
	-0.1	0.012	0.054	y
	0.209	18.99	3.25	z

TRACK units in xy plane: β[cm/mrad], ε[cm·mrad]
TRACK units in z coordinate: β[°·(% of ΔW/W)], ε[keV·ns]

The Twiss parameters at the RFQ exit are close for electrodynamic and electrostatic fields. But detailed particle distribution seems to be different.

Many thanks to Brahim Mustafa for the help with TRACK.

Conclusion

Project X

- RF simulations of RFQ are now well developed and very capable
- A plan is to perform complete RF simulations with full scale model and modulated vane tips.
- Usage of EM and ES fields simulated with complete RFQ model seems to be interesting and promising.