

3D Electromagnetic Design and Beam Dynamics Simulations of a Radio-Frequency Quadrupole

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- Summary

Argonne's ATLAS Upgrade Project

- ATLAS is a low-energy heavy-ion accelerator at Argonne
 - It will be upgraded to:
 - Improve the efficiency of accelerating radioactive beams: double or more
 - Accelerate more intense stable beams: 10 times or more
 - The upgrade consists of:
 - A new 60.625 MHz CW RFQ to accelerate beams from 30 keV/u to ~ 300 keV/u
 - A new Cryomodule with 7 QWR- 72.75 MHz cavities & 4 solenoids (9T)
- ✓ For more details, See “ATLAS Upgrade” Talk by Peter Ostroumov on Thursday Afternoon (THOCN5)

ATLAS RFQ: Design Goals & Parameters

- Satisfy beam requirements: energy, emittance, transmission, ...
- Low RF power consumption
- Target frequency tunable to operational frequency
- High order modes, far away from operational frequency
- Tuners capable of correcting both the frequency and field flatness
- Beam dynamics verification with more than one code
- Vane modulation for manufacturing

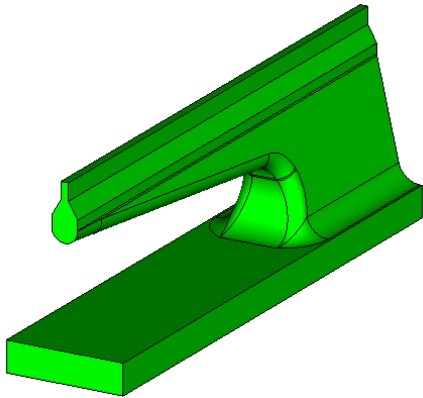
Parameter	Value
Input Energy	30 keV/u
Output Energy	> 250 keV/u
Frequency	60.625 MHz
Vane Voltage	70 kV
Power	60 kW
Average Radius	7.2 mm
Length	3.81 m
Transverse Acceptance	2π mm.mrad
Longitudinal RMS Emittance	20π deg.keV/u
Bunching	External 4-h
Duty Cycle	CW

- ✓ Very few CW RFQs are actually working as designed
- Need a very careful design and fabrication procedure

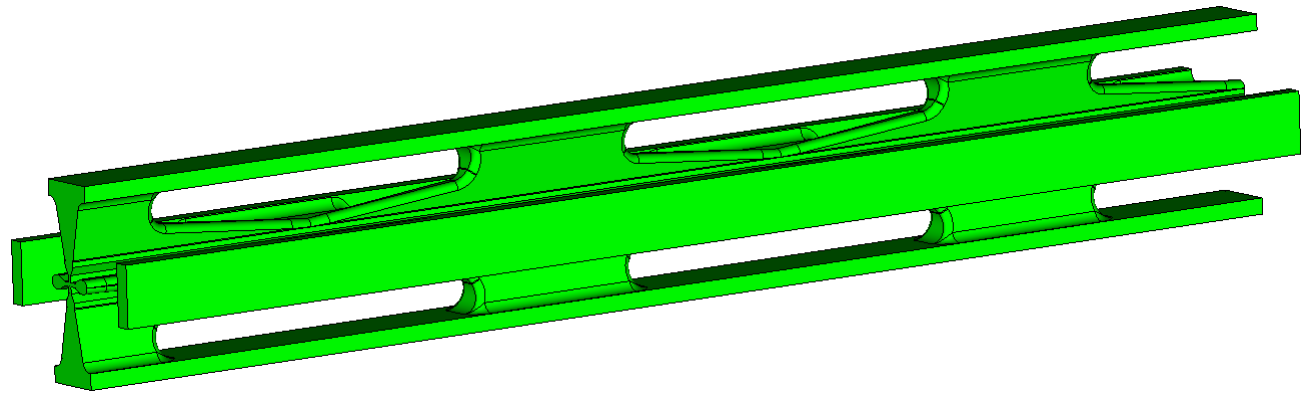
The New Full 3D Design Approach

- Most Common Design Approach
 - Beam dynamics and electromagnetic design of a RFQ are done separately
 - A code such as Parmteq or DesRFQ is used for the beam dynamics design
 - A code such as Superfish, Mafia or CST Microwave Studio is used for the EM design
 - Only a short segment of the RFQ is modeled due to computing power limitations
 - A prototype is built to verify the EM design
- The New Full 3D Design Approach
 - The whole structure is modeled in the EM design code (CST Microwave Studio)
 - The actual vane modulation is appropriately included in the model
 - The effects of matchers, modulation and tuners are carefully studied
 - Full 3D fields maps are extracted and used for beam dynamics simulations
 - Comparisons of the fields from the 8-term potential, cell by cell and whole cavity 3D fields.
- ✓ Integrating the electromagnetic and beam dynamics simulations into the same software offers a more consistent way for RFQ design evaluation

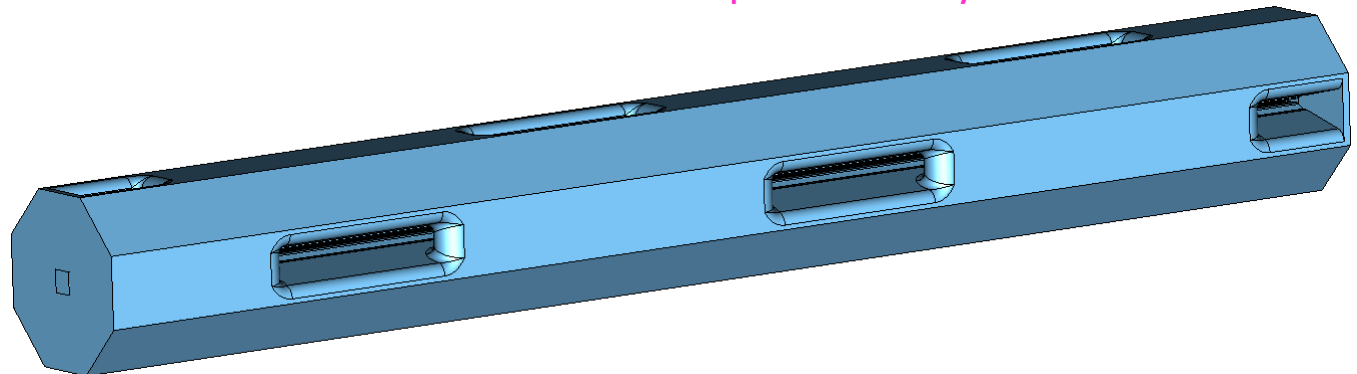
Full 3D Modeling: Building the Geometry



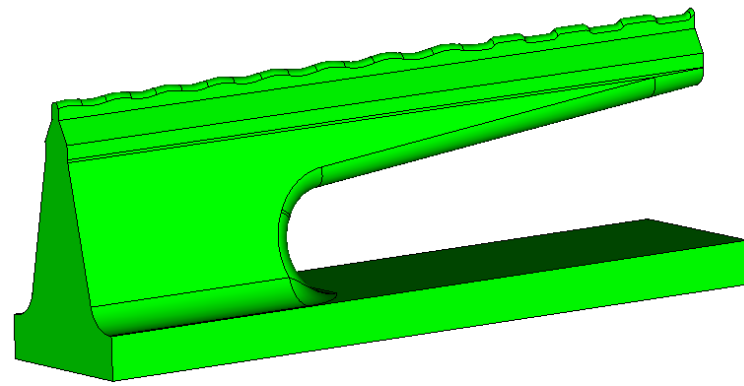
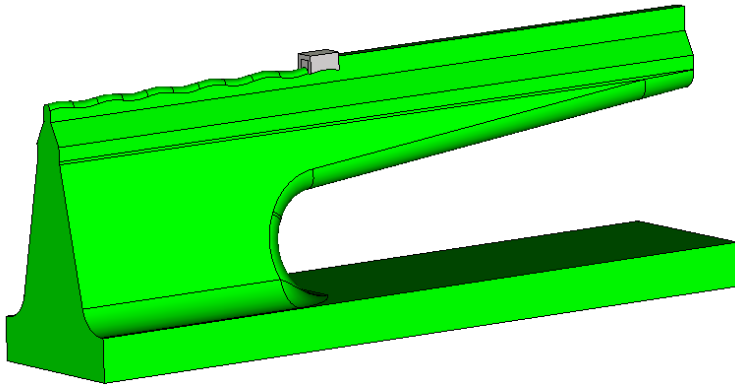
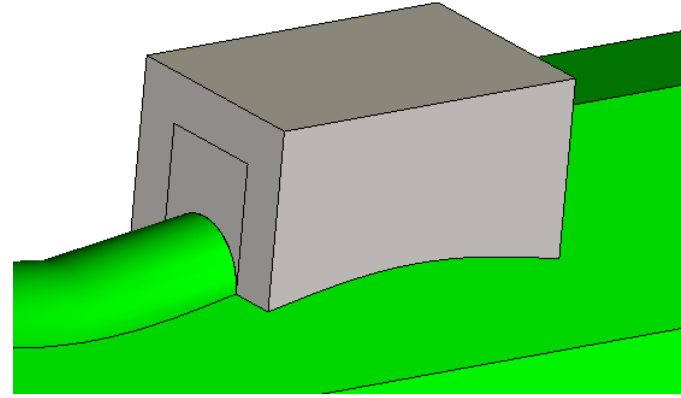
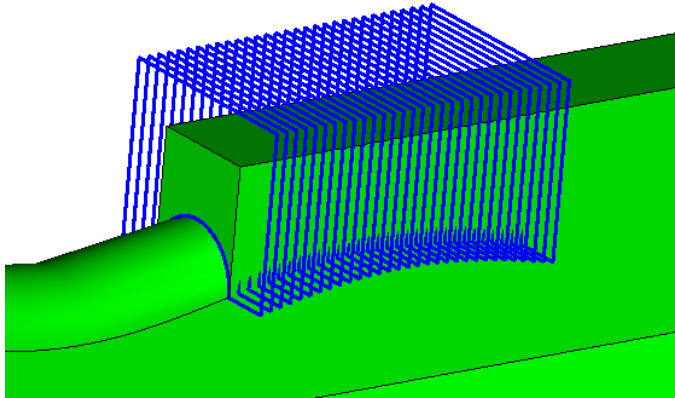
- 1) Engineering 3D model for a single vane (Pro/E step file)
- 2) Imported into Micro-Wave Studio
- 3) Copied and mirrored to build the whole structure
- 4) An octagonal RF volume is defined for the enclosure



A Window coupled structure → Reduces transverse size & pushes away HOMs

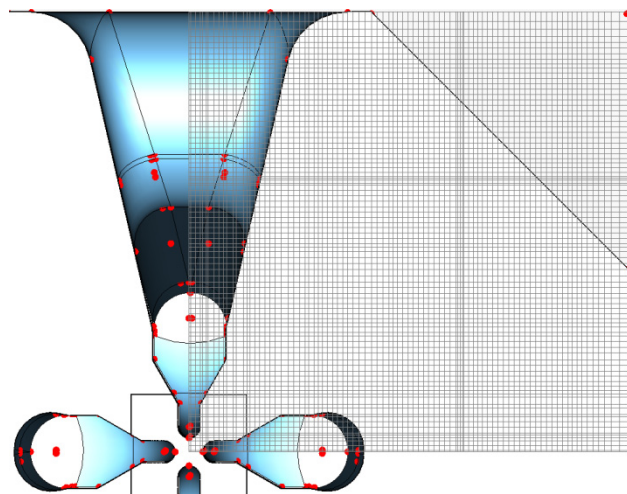


Full 3D Modeling: Applying Vane Modulation

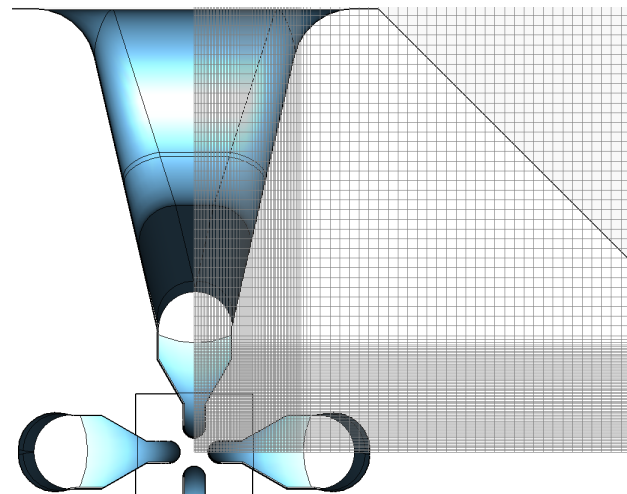


- With this level of geometry detail, the results are very sensitive to the meshing choice
- Benchmarking using measurements on a real RFQ is very important
- We are fortunate to have a prototype 57.5 MHz RFQ along with the original drawings

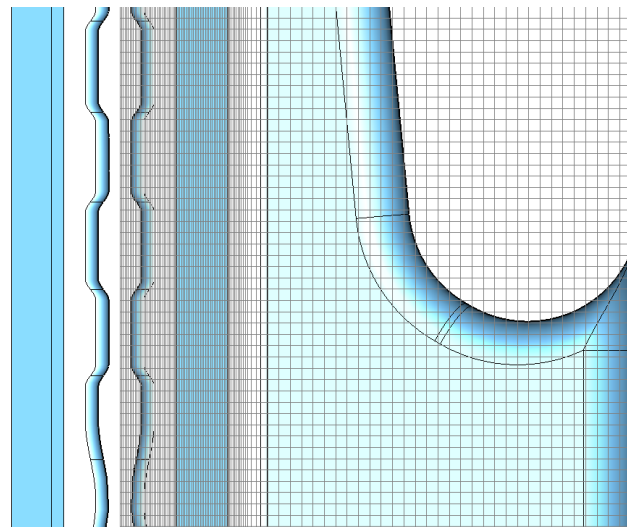
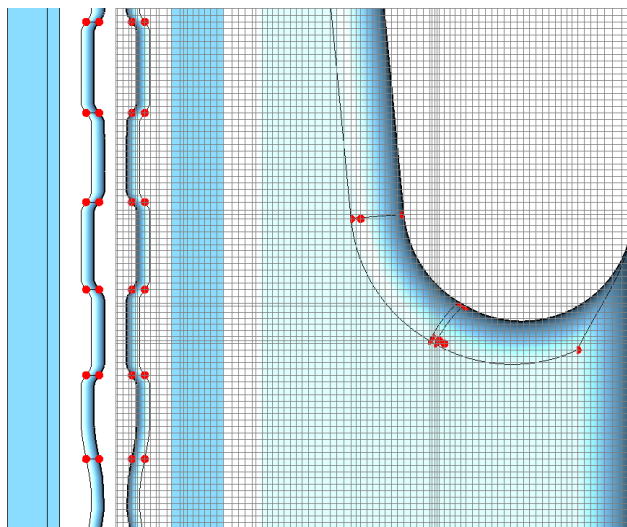
Full 3D Modeling: Mesh Choice & Setup



Auto-mesh



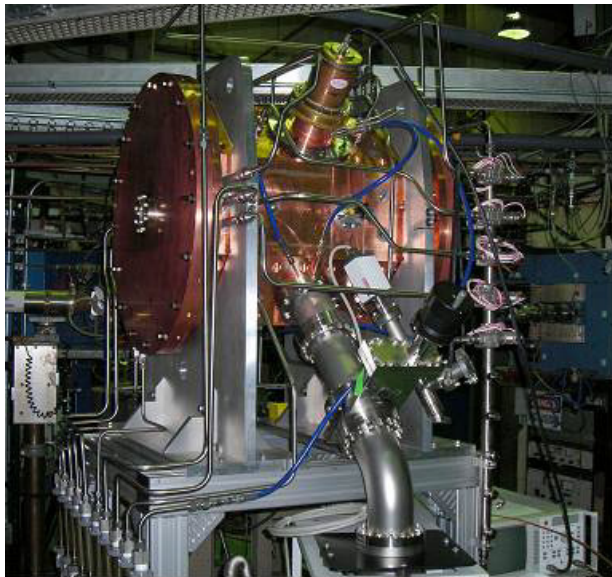
Finer local mesh



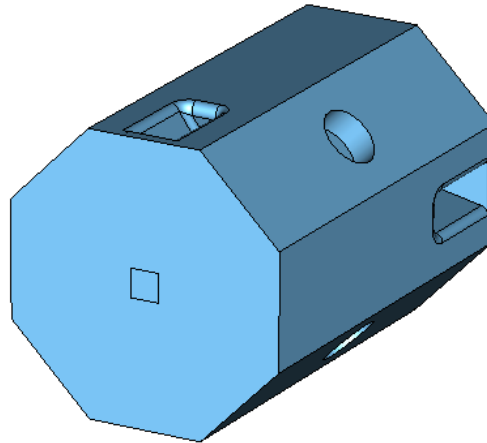
Benchmarking Using Measurements on a Prototype 57.5 MHz RFQ

- Measured frequency on the prototype RFQ, with three 4" diameter plug tuners inserted 2" deep, is **55.852 MHz**
- Simulated effect of 4 tuners using symmetry is: **600 kHz $\rightarrow$ 450 kHz per 3 tuners**

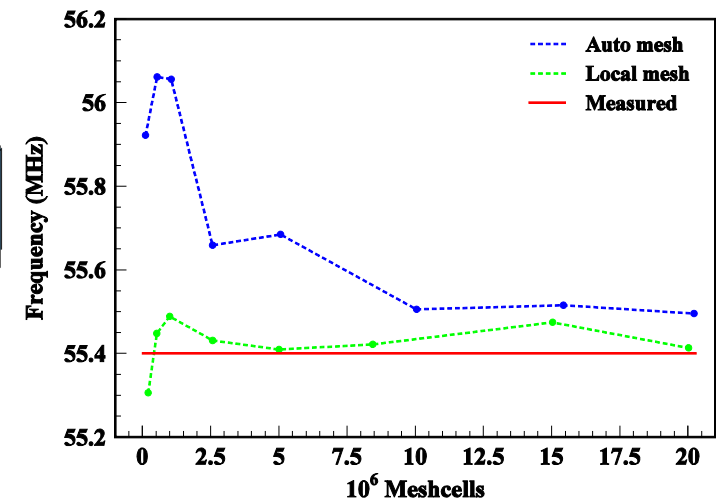
Real RFQ



Simulated Model



Comparison

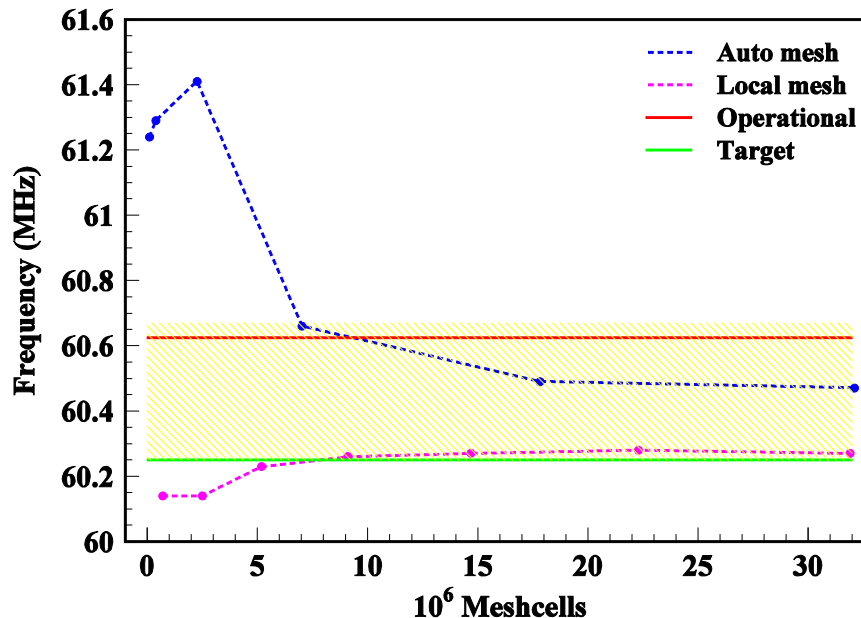


$$55.852 - 0.45 = 55.402 \text{ MHz}$$

- Local mesh option seems to converge faster to the measured value

Full Model of ATLAS RFQ: Frequency Simulations

- Simulated with auto mesh @ 32 M mesh-cells : $f = 60.47$ MHz
- local mesh : $f = 60.27$ MHz
- 200 kHz Error with upper value below the operational frequency : $f = 60.625$ MHz
- The local mesh value is very close to the target frequency value : $f = 60.25$ MHz



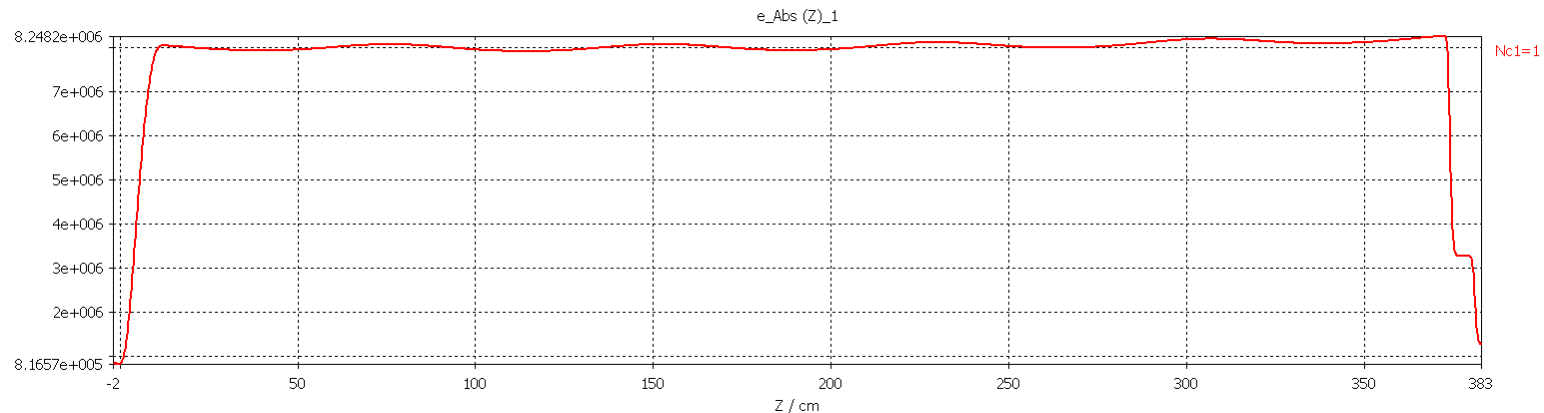
- 15 Tuners (5" Φ , 1" deep) $\rightarrow$ 420 kHz Tuning range (Tuners could go 2" deep if needed)
- Closest higher order mode is at 71 MHz, more that 10 MHz above operational frequency

Full Model of ATLAS RFQ: Different Effects

- Radial matchers, modulation and tuners effect on the frequency

Effect	Frequency (MHz)	Frequency shift (kHz)
No Matchers	59.77	0
Input Matcher Only	59.97	200
Output Matcher Only	59.90	130
Input and Output Matchers	60.10	330
Modulation	60.27	170
15 Tuners (5" Φ , 1" deep)	60.69	420

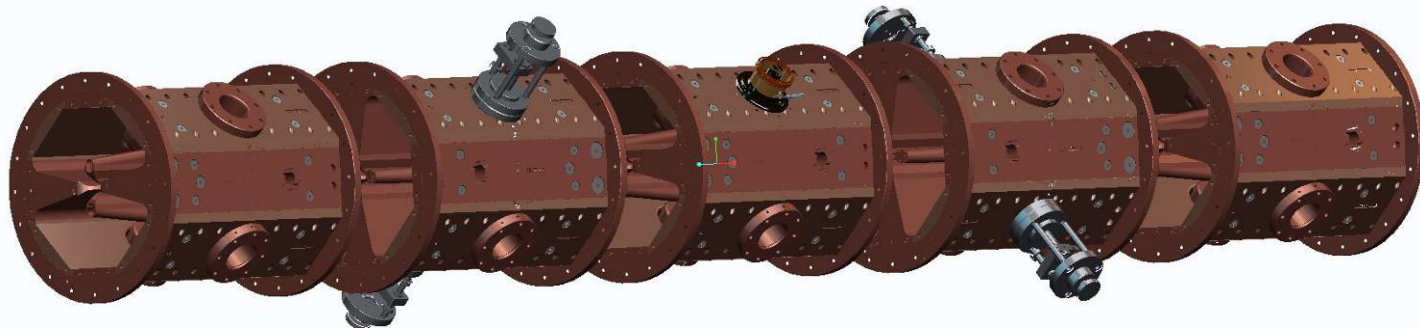
- Field flatness: $\sim 2\text{-}3\%$ tilt over the whole RFQ



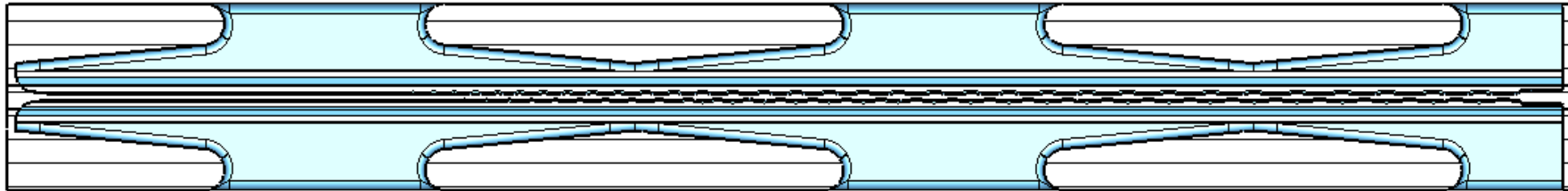
- Both frequency and field flatness could be effectively adjusted using the appropriate tuners

Full Model of ATLAS RFQ: 3D Model & Fields

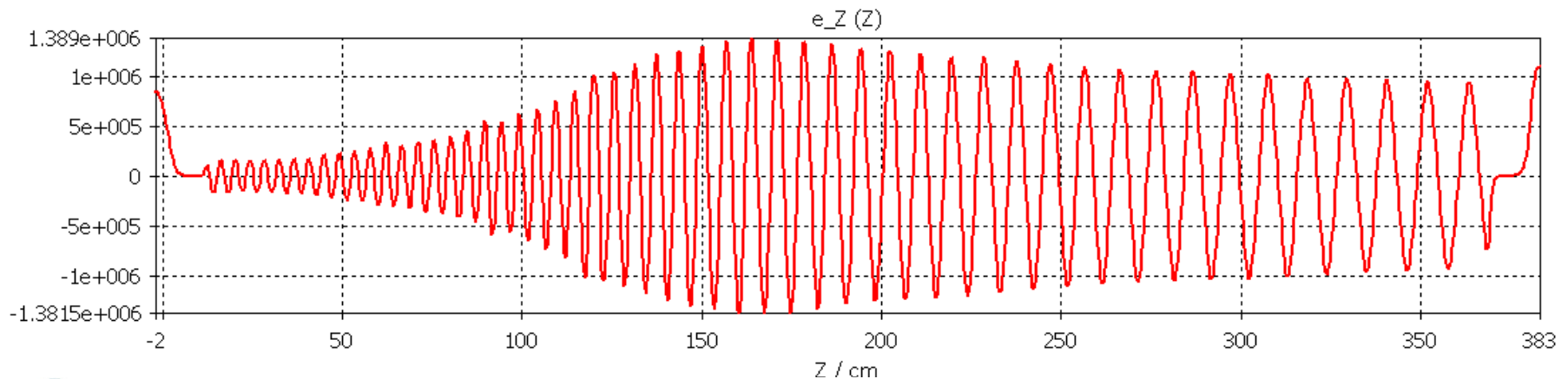
- 3D Engineering model



- 3D EM model with vane modulation



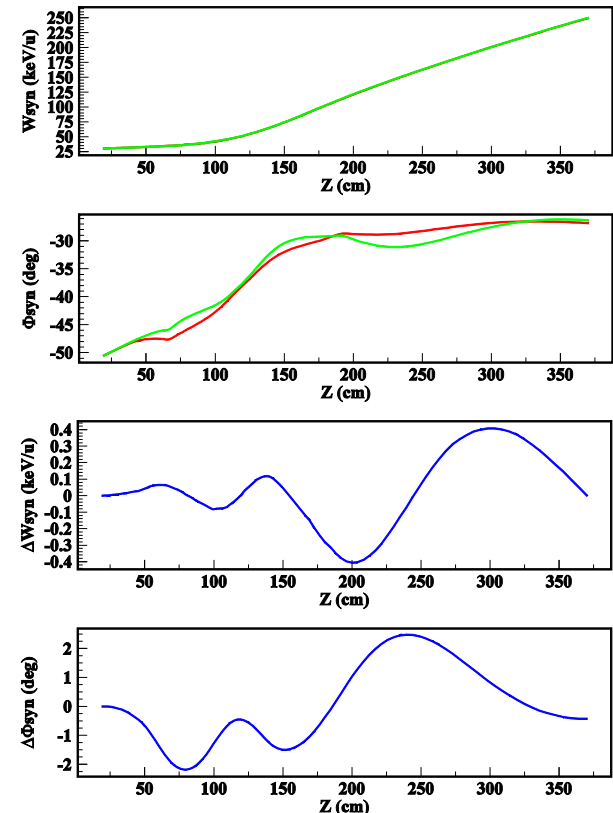
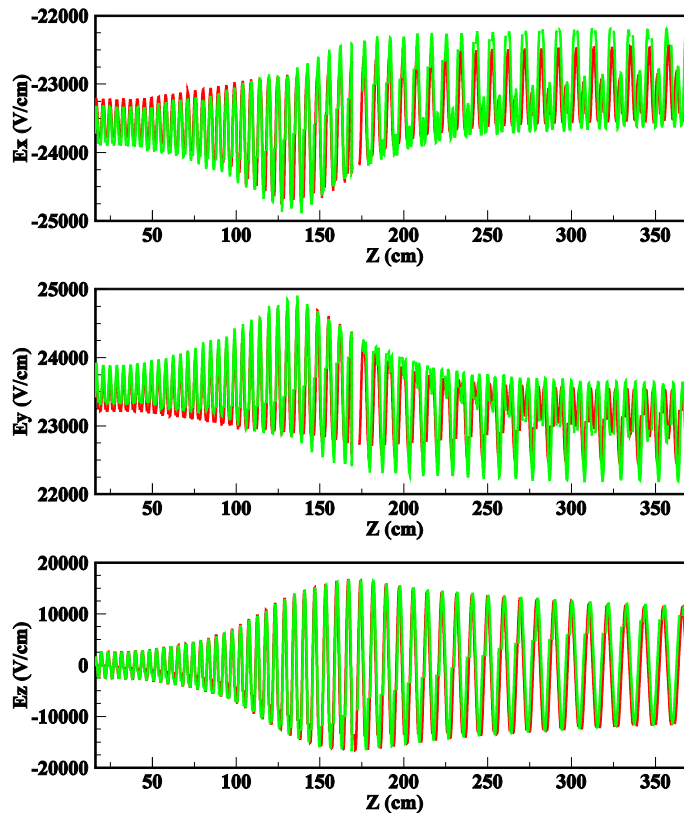
- Field on axis along the RFQ



RFQ Beam Dynamics: 8-term Potential vs. 3D Fields

- Comparison of the E-field components (E_x , E_y , E_z) along the RFQ at R0/4
- Longitudinal component agree to $\sim 1\%$, the transverse components agree to 1-2 %

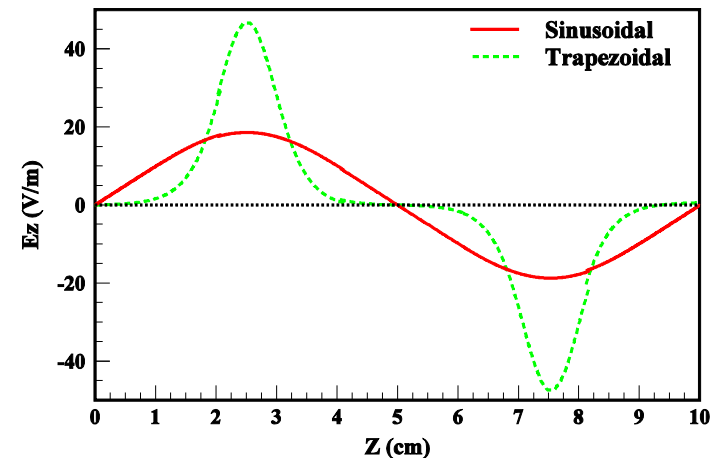
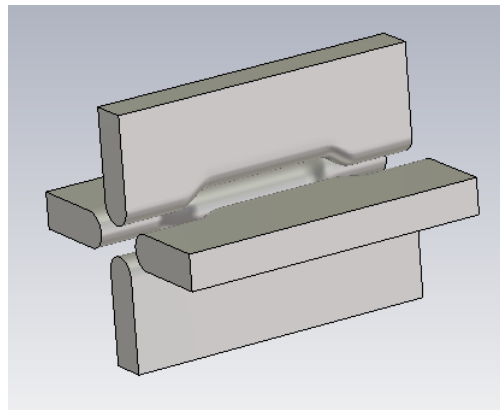
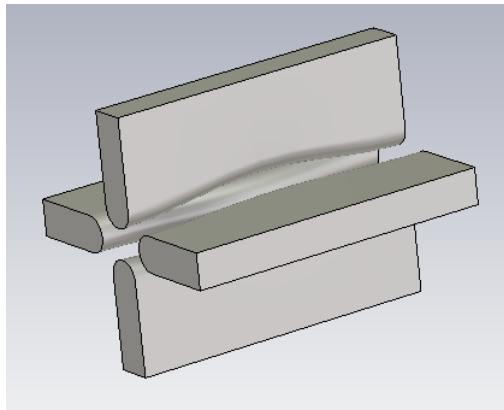
- 8-term pot.
- 3D fields
(Cell by Cell)



- Synchronous particle energy agree to ~ 0.4 keV/u and the phase to 1-2 deg
- This is a good agreement between two different approaches

RFQ Vane Modulation: From Sinusoidal to Trapezoidal

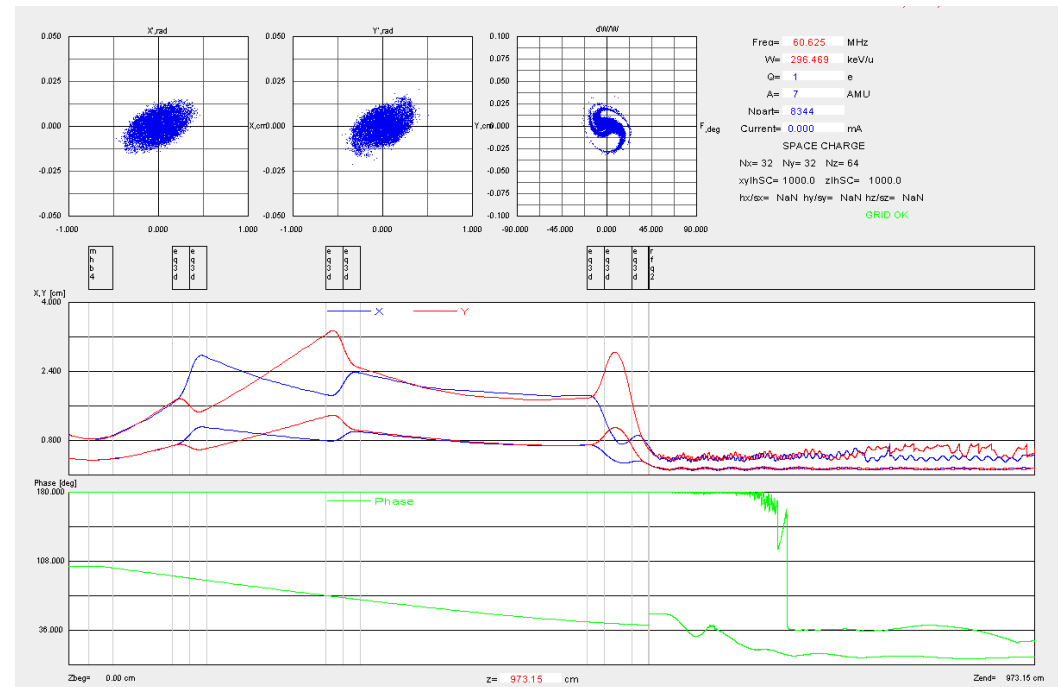
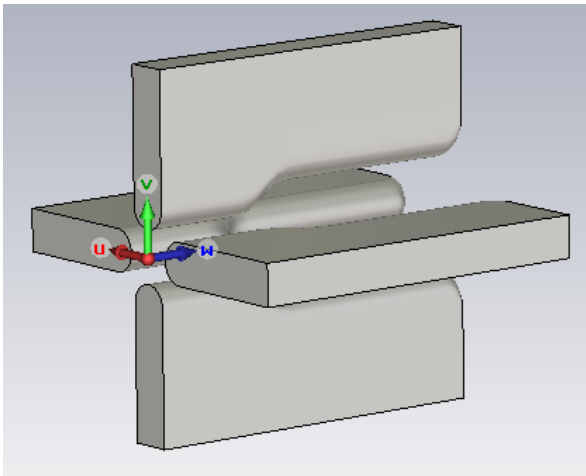
- ✓ Trapezoidal modulation was originally proposed and adopted at IHEP-Protvino (Russia) O.K. Belayev et al, Proceedings of Linac-1998, Monterey California.
- EM-Studio models: Geometry for one modulation period for both trapezoidal and sinusoidal modulations: same length, same average radius and modulation



- The field is more peaked in the trapezoidal case → more efficient acceleration
- Converting the last 40 cells from sinusoidal to trapezoidal vane modulation increased the output energy from 260 keV/u to 295 keV/u
- The final design combines both sinusoidal and trapezoidal vane modulation
- The peak surface field is 10-15% higher but it is still around 1.5 Kilpatrick
- No major change in the beam dynamics except for the higher output energy

RFQ Beam Dynamics: New Type of Output Matcher

- Geometry parameters: 1st straight section (L0, R0) followed by a curved section (LC) and ending with a 2nd straight section (L1, R1)
- R0 and the total length are defined, other parameters (L0, L1 and R1) are determined by fit to produce an axis symmetric beam at the RFQ exit
- This type of output matcher relaxes the constraint on the total RFQ length ...

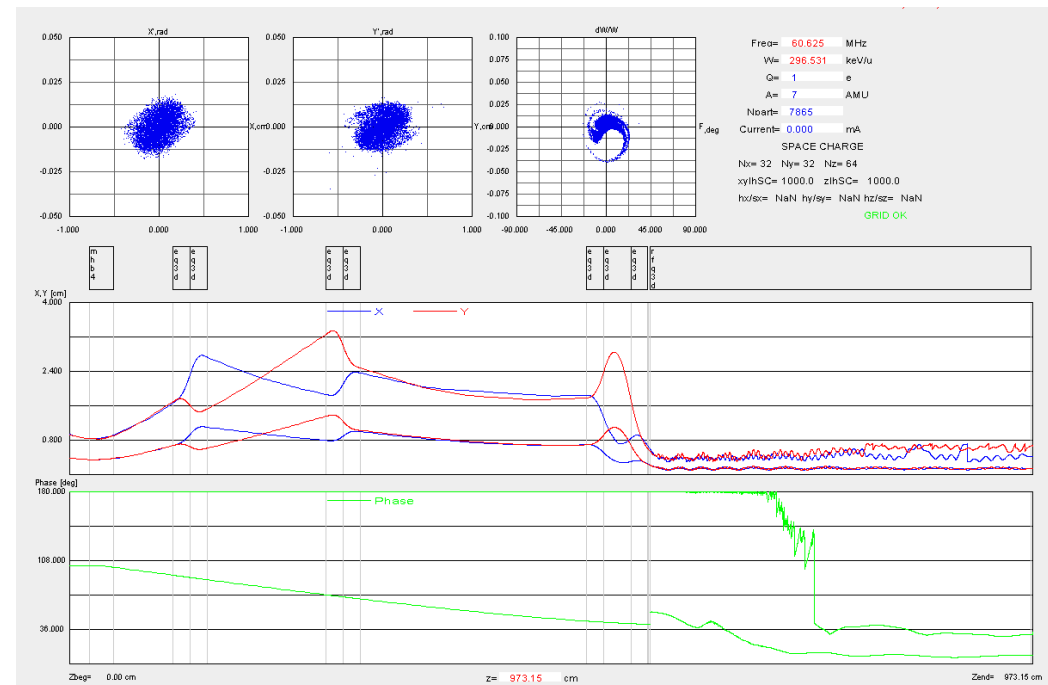


- Note the axis symmetric beam at the RFQ exit on the right

RFQ Beam Dynamics: Tracking using Full 3D Fields

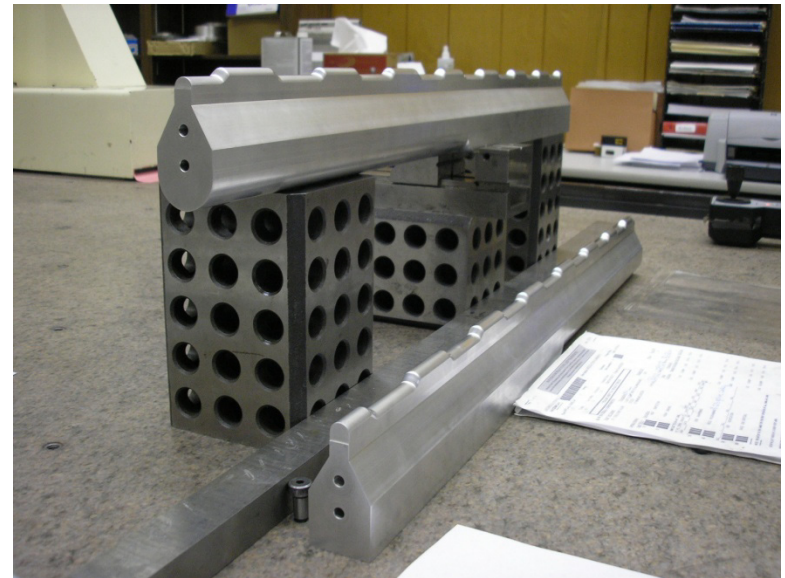
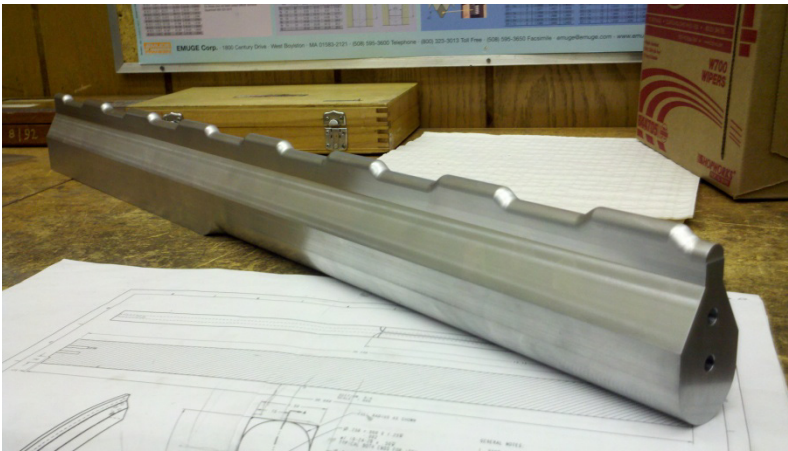
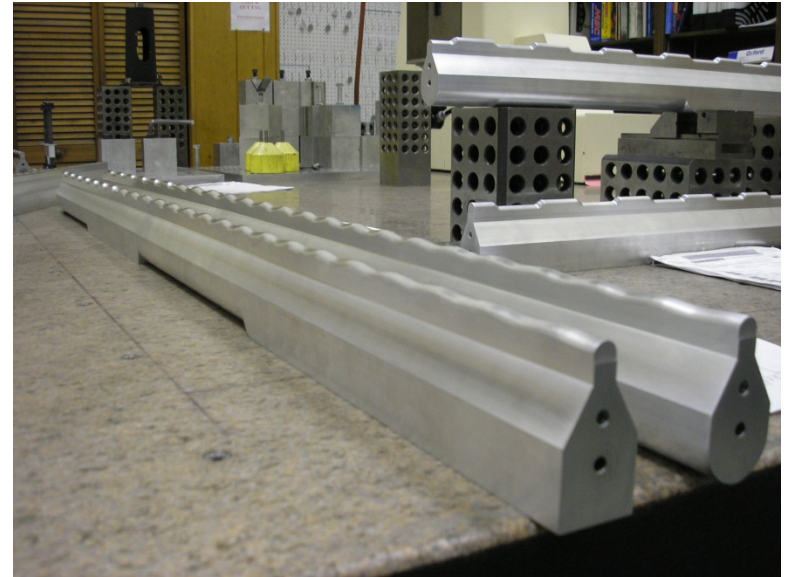
- The Full 3D field distribution was exported from MW-Studio into TRACK as a single cavity
- Despite the low precision of the single cavity 3D fields we were able to get very similar beam dynamics as the cell by cell 3D fields simulation.

Quantity	EM-Studio Cell by Cell	MW-Studio Full RFQ
W-output (keV/u)	296.5	296.5
Transmission (%)	83 %	79%
Long. RMS π deg.keV/u	18.6	22.4
Trans. RMS π mm.mrad	0.215	0.22
Output Beam	Symmetric	Almost symmetric



- The lower transmission and the larger longitudinal emittance may be due to the lower precision of the 3D fields extracted for the Full model (mesh limitation).

Aluminum Models of Vane Modulation in all RFQ Segments



Summary

- Established a new approach to simulate a RFQ: Full 3D model with modulation and beam dynamics using 3D fields
- The EM design approach was successfully benchmarked using a prototype 57 MHz RFQ
- The EM simulation of the full 3D model of the ATLAS RFQ produced the target frequency
- The designed tuners are capable to tune the operational frequency and correct for field flatness
- The beam dynamics were verified using 3 methods:
 - TRACK using the 8-term potential from the design code DesRFQ
 - TRACK using the cell by cell 3D fields from EM-Studio
 - TRACK and CST Particle Studio using full 3D fields from MW-Studio
- Trapezoidal vane modulation was adopted to increase the output energy without perturbing the rest of the beam dynamics