New Design for the SARAF Phase II Linac

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Content

- SARAF Linac
  - Phase I: Current Status
  - Phase II: Future Upgrade
- Argonne's Contribution: New Linac Design
- New RFQ Design
  - Beam Dynamics Design
  - EM & Engineering Design
- Room-Temperature Re-bunchers
- Highly Optimized HWRs Design
  - EM Design Optimization Procedure
  - The New Ring-Shaped HWR Design
- New Cryomodule Design & Its Components
  - Solenoids & Steerers
  - Cold BPMs & Alignment
  - Couplers & Tuners
- The New Linac Layout
- End-to-End Beam Dynamics Simulations

SARAF: Soreq Applied Research Accelerator Facility

Driver: 40 MeV – 5mA proton/deuteron CW linac @ Soreq NRC, Israel

- Phase I of the linac was completed in 2009, it includes:
  - Ion Source: ECR capable of 8 mA – 20 keV/u beam
  - LEBT: Solenoid based with analyzing magnet
  - RFQ: 4-Rod CW 176 MHz - 1.5 MeV
  - MEBT: Simply a triplet for transverse matching
  - PSM: Prototype Superconducting Module with 6 HWRs & 3 Solenoids
- Current Status:
  - 1 mA – 3.5 MeV CW proton beam
  - 50 µA – 4.7 MeV deuteron beam (Not CW due RFQ power limitation)
  - Preliminary experimental program & linac beam studies
- References:
  - L. Weissman et al "The Status of the SARAF Linac Project", LINAC-2010
  - L. Weissman et al "First Experience at SARAF with Proton Beams", DIPAC-09

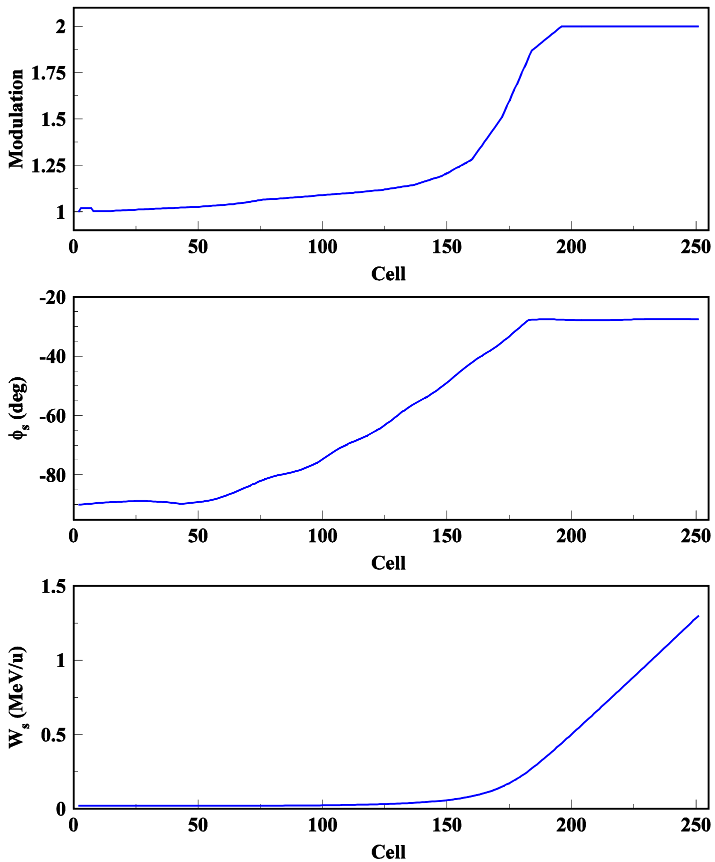
SARAF Phase II: Proposed Upgrades / Modifications

- Scope of Phase II
  - Additional Superconducting Accelerating Modules (SAMs).
  - Beam diagnostics instrumentation between and inside the SAMs.
  - RF control system for the SAMs.
  - Construction of an SRF facility at the SARAF site.
  - Upgrade or fix the existing SARAF RFQ.
- ANL's contribution so far
  - Design of an RFQ Upgrade
  - Optimized designs for RT rebunchers and new SC HWRs
  - New cryomodule design including all the components: Solenoids, Steerers, Cold BPMs, Alignment, Couplers, Tuners, …
  - New linac layout based on the new cavity performance
  - End-to-end beam dynamics studies

176 MHz CW RFQ: General Design Parameters

Parameter	Value
Charge to mass ratio	1/2
Input energy, keV/u	20
Output energy, keV/u	1300
Frequency, MHz	176
Voltage, kV	75
Beam current design value, mA	5.0
RFQ length, m	3.8
Average radius, mm	4.4
Modulation factor, max	2.0
Min. aperture, mm	2.93
Min. transverse phase advance, degree	33.0
Transverse acceptance, norm, mm mrad	2.2
Maximum field at vane surface, Kilpatric units	1.6
Number of cells	250

176 MHz CW RFQ: Beam Dynamics Design

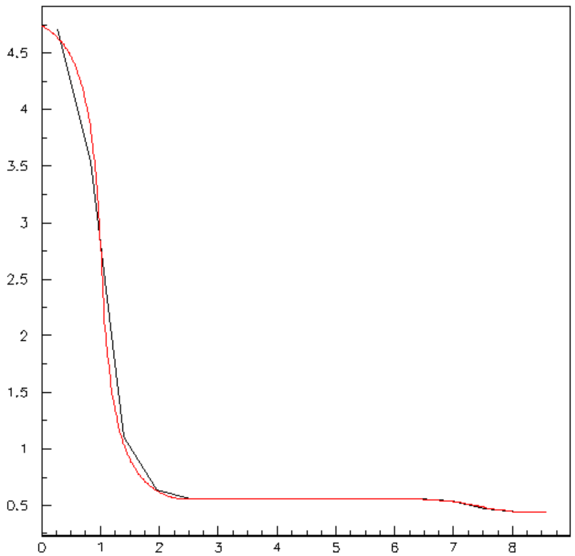


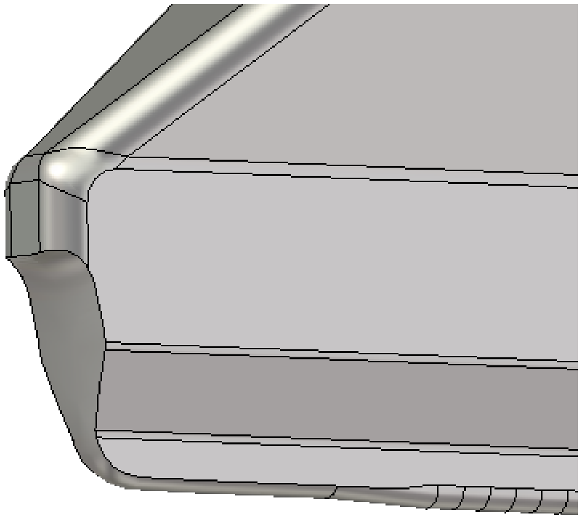
Beam	Proton	Deuteron
Input transverse emittance, rms, norm, mm·mrad	0.25	0.25
Input Twiss α	0.21	0.22
Input Twiss β, cm/rad	3.4	3.1
Transmission, %	99.7	99.9
Output longitudinal emittance, rms, keV/u·deg	36.6	36.3
Transverse rms emittance growth, %	0	0
Transverse 99% emittance growth, %	10	13
Particle loss inside the RFQ	$3\cdot10^{-3}$	$1\cdot10^{-3}$

Two Important Design Features

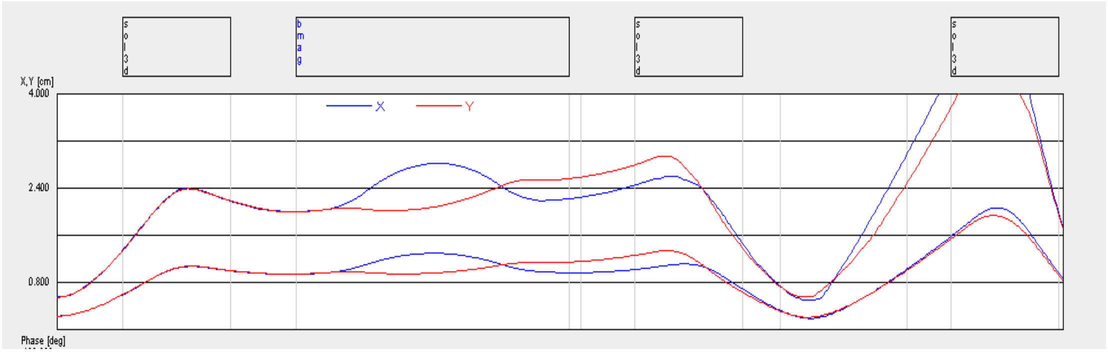
- ✓ Almost 100% transmission to avoid contamination by deuteron breakup reactions
- ✓ A special input matcher to ease the matching and reduce emittance growth in the LEBT

176 MHz CW RFQ: A Special Input Matcher

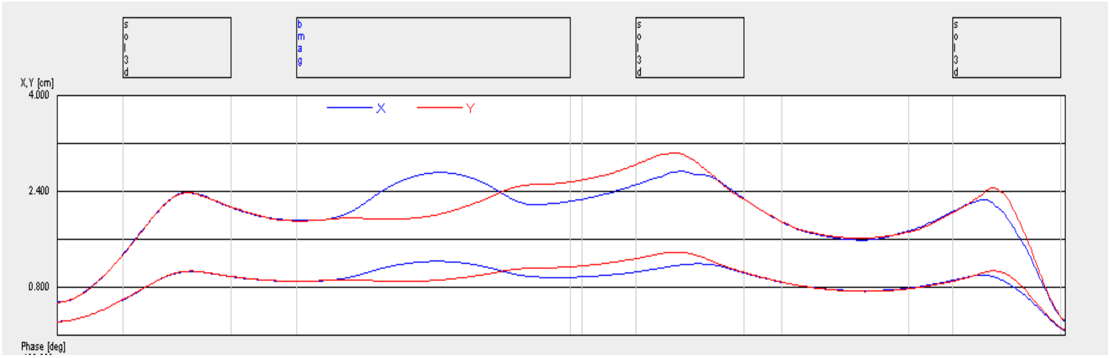




LEBT with original 6 cell input matcher: α ~ 1.5

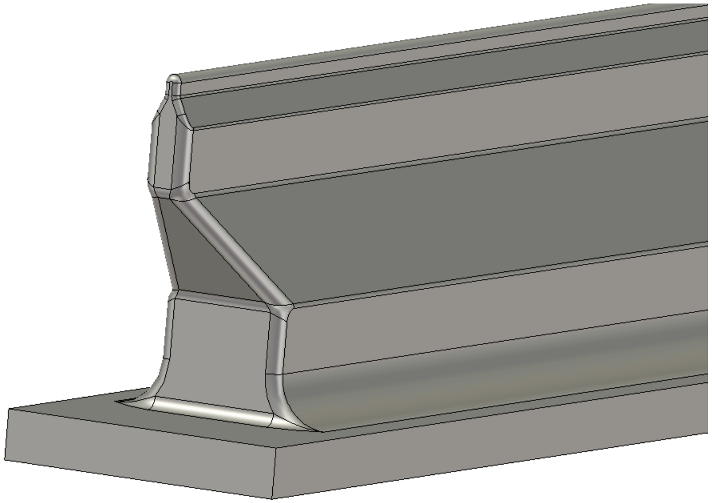


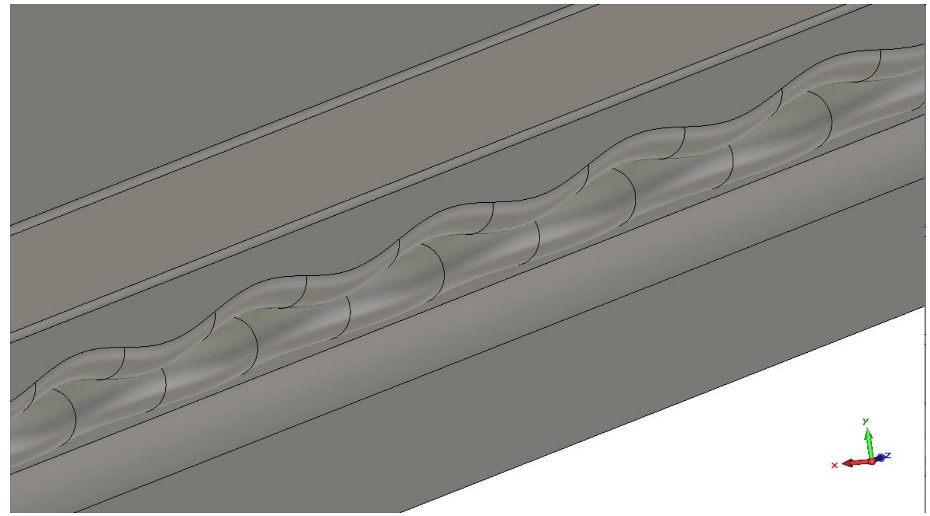
LEBT with special 15 cell input matcher: α ~ 0.25



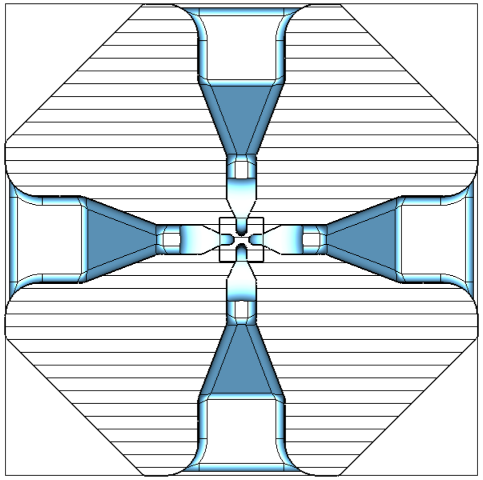
Emittance growth in LEBT reduced from 50% to 10%

176 MHz CW RFQ: EM Design - Full CST Model with Modulation





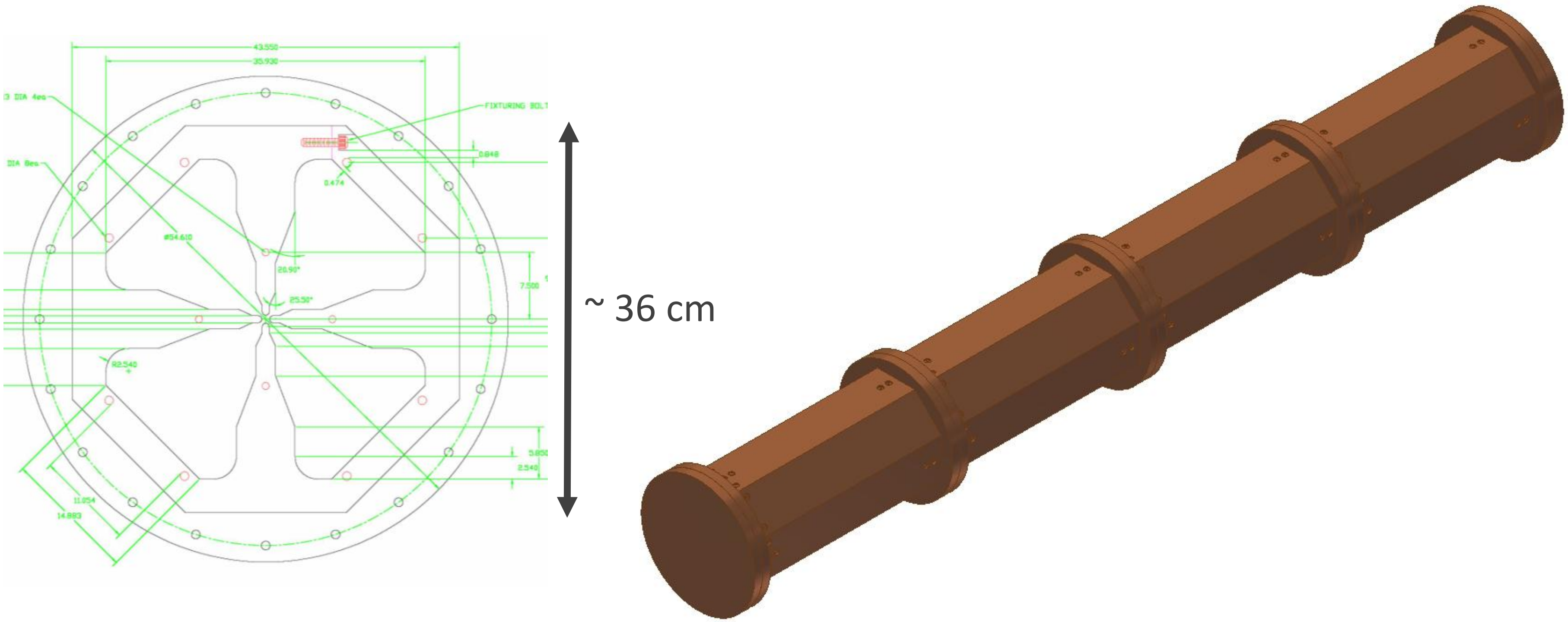
Parameter	Value
Frequency, MHz	176.0
Voltage, kV	75
Power Loss, kW	115
Q-Factor	13900



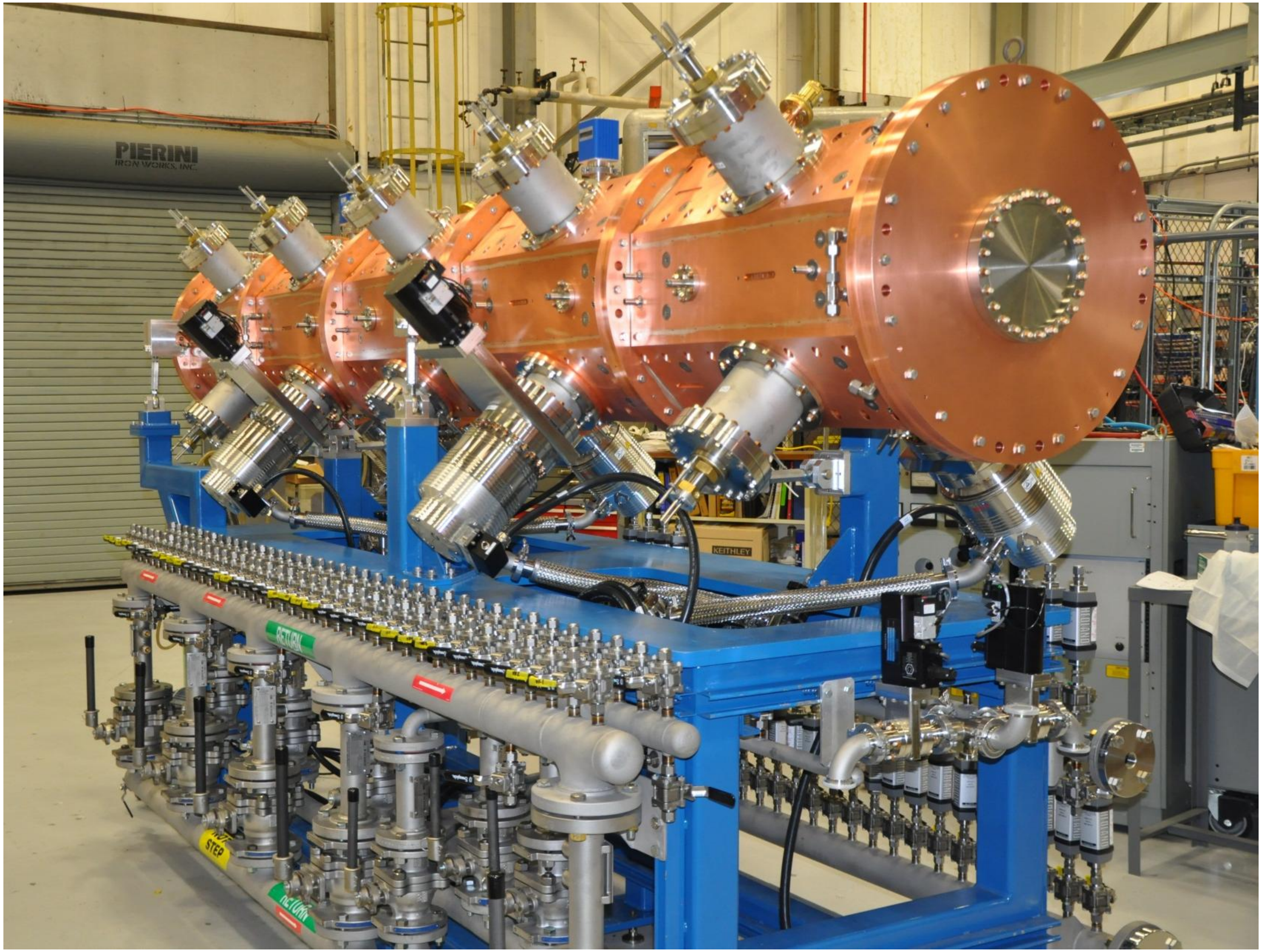
Mode	Frequency, MHz
Dipole Mode	172.9
Main Mode	176.0
Next Mode	178.7

176 MHz RFQ: Engineering Design & Fabrication

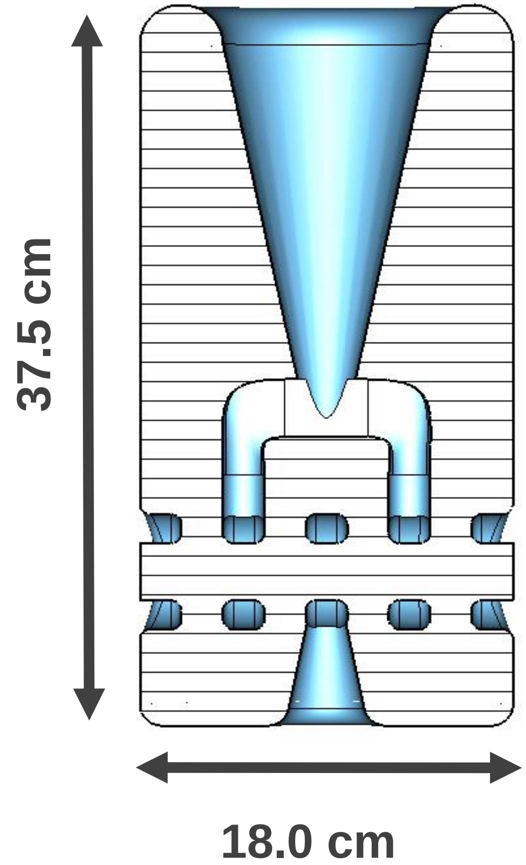
- 4-vane, 4-segments, 3.8-meter long
- OFE copper, furnace brazed in hydrogen atmosphere
- RF Power consumption – 115 kW (MWS), Voltage =75 kV
- The same technology as for the ATLAS Upgrade RFQ
- Transverse dimensions are smaller than the ATLAS RFQ by ~ 15%



Proven & Always Improving Technology

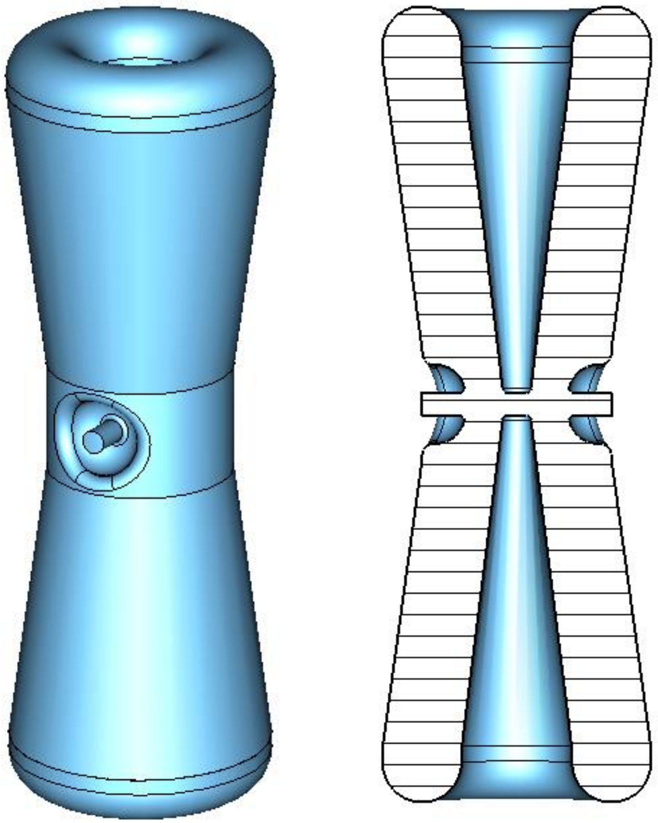


176 MHz Room Temperature Rebuncher: 4-Gap QWR



Aperture diameter – 30 mm
Voltage – up to 160 kV
RF power – 3 kW

EM Design Optimization: Fully Parameterized Geometry



Name	Value	Description
CVAPR	1.5	Cavity Aperture Radius
CVFL	2.0	Cavity Flat Length
CVMH	7.0	Cavity Middle Height
CVMR	12.0	Cavity Middle Radius
CVTBR	(CVTR-ICTR)/2.0	Cavity Top Blending Radius
CVTH	50.46	Cavity Top Height
CVTR	17.0	Cavity Top Radius
DTEBR	1.5	Drift Tube Edge Blending Radius
DTIBR	0.5	Drift Tube Inner Blending Radius
DTIR	5.0	Drift Tube Inner Radius
DTOBR	3.6	Drift Tube Blending Radius
DTOR	5.0	Drift Tube Outer Radius
DTPN	CVMR-(MGD+GapW)/	Drift Tube Penetration
GapW	4.8	Gap Width
ICFL	2.0	Inner Conductor Flat Length
ICRTX	3.8	Inner Conductor Race Track Depth (X)
ICRTY	2.0	Inner Conductor Race Track Height (Y)
ICRTZ	(MGD-GapW)/2.	Inner Conductor Race Track Width (Z)
ICTH	CVTH	Inner Conductor Top height
ICTR	7.0	Inner Conductor Top Radius
MGD	8.4	Mid-Gap Distance

Parameter List — Global

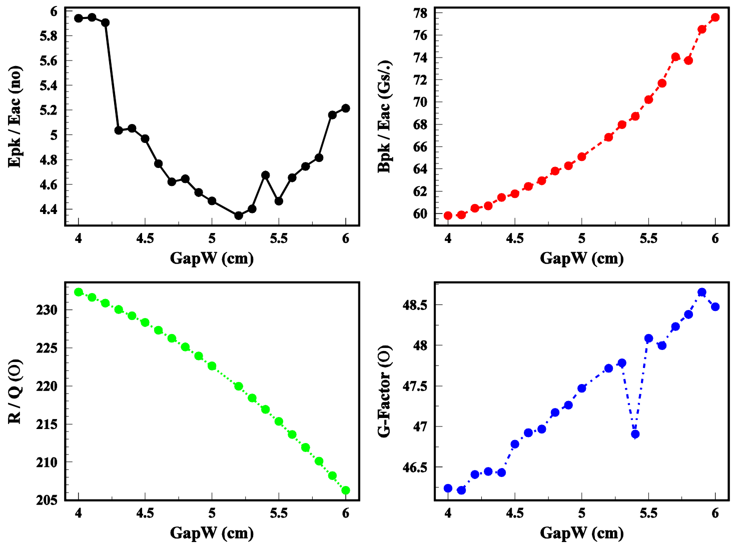
- The table shows the list of geometry parameters as seen in MW-Studio
- The geometry parameters are NOT independent

EM Design Optimization: RF Parameters to Optimize

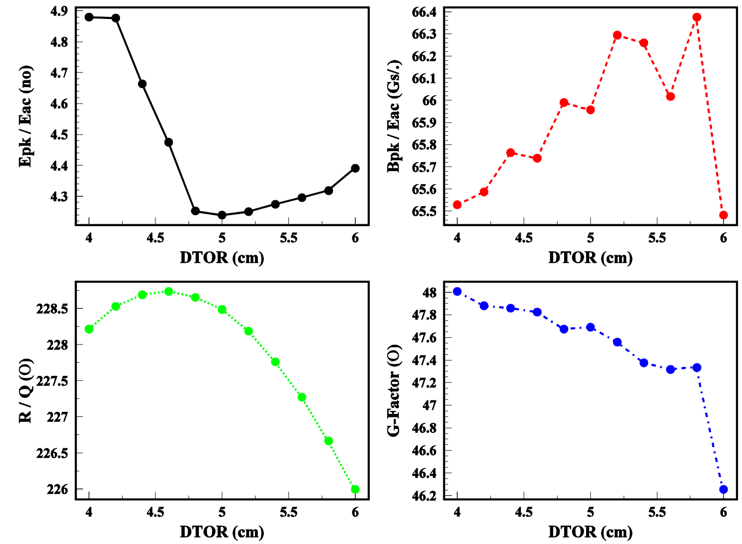
- E-peak: Minimize peak surface electric field to limit field emission
- B-peak: Minimize peak magnetic field to maintain superconductivity
- $R/Q = V^2/\omega U$: Maximize R/Q to produce more accelerating voltage (V) with less stored energy in the cavity (U)
- $G = R_s{*}Q$: Maximize the geometry factor to increase the cavity effectiveness of providing accelerating voltage due to its shape alone

EM Design Optimization: Parameter Sweeps in MWS

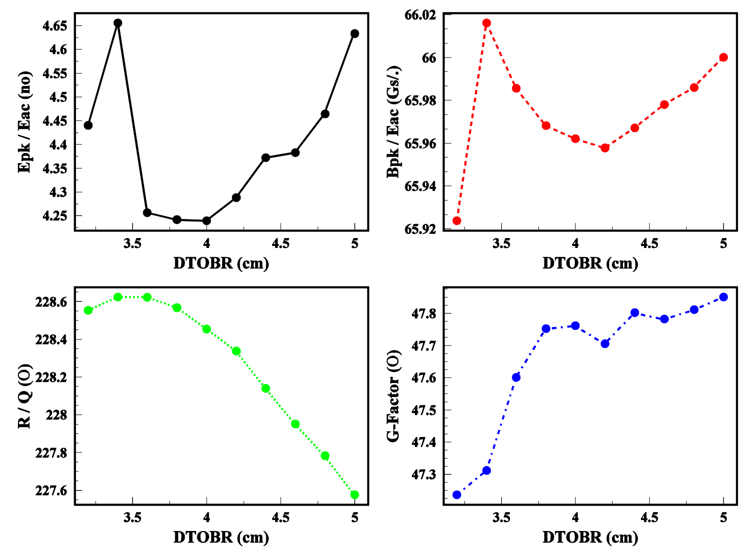
Gap Width



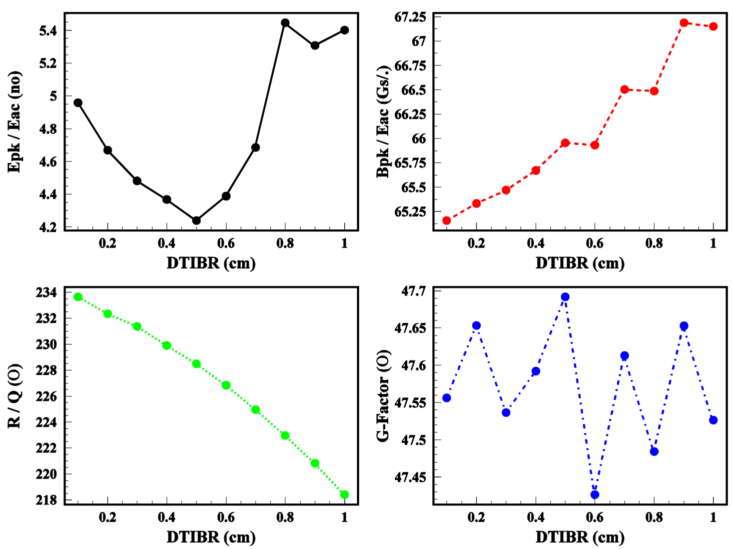
Drift Tube Outer Radius



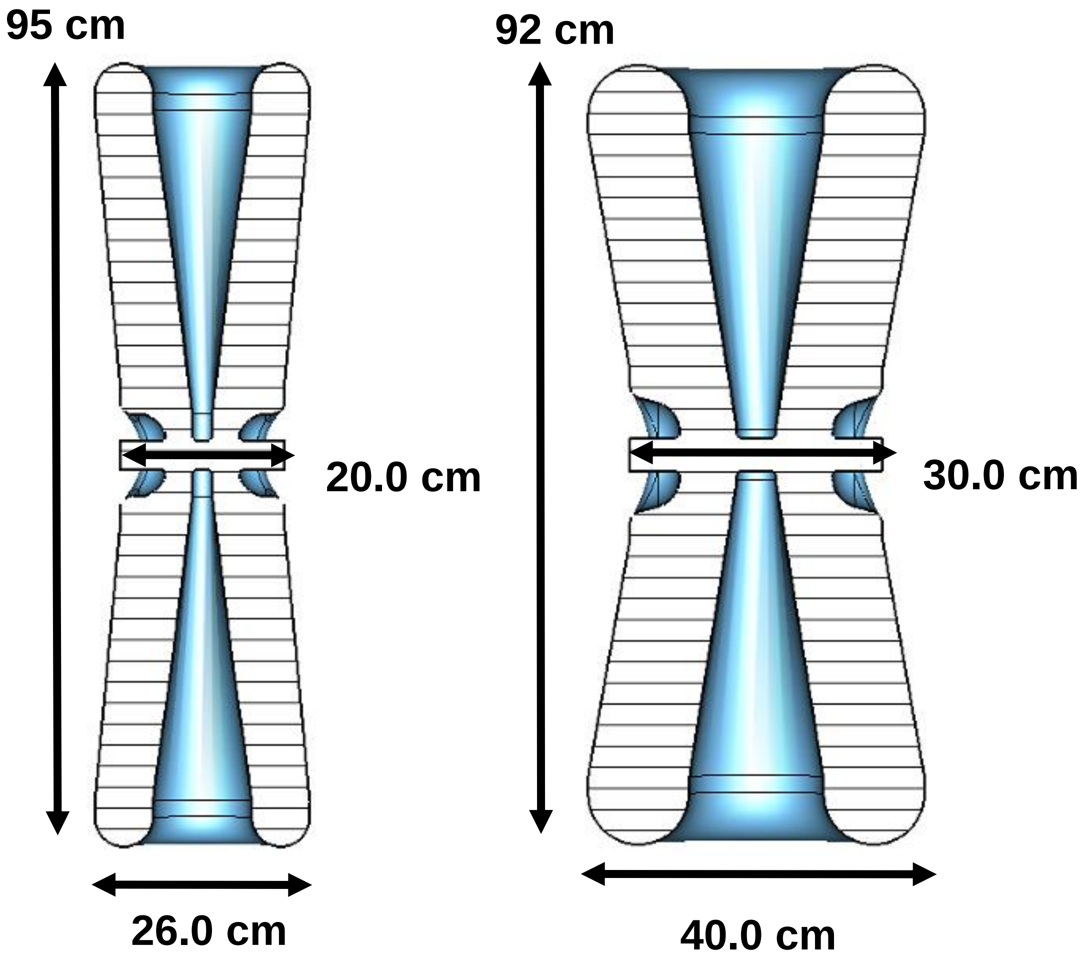
DT Outer Blend Radius



DT Inner Blend Radius



Optimized Coaxial Race-Track HWRs: Some issues

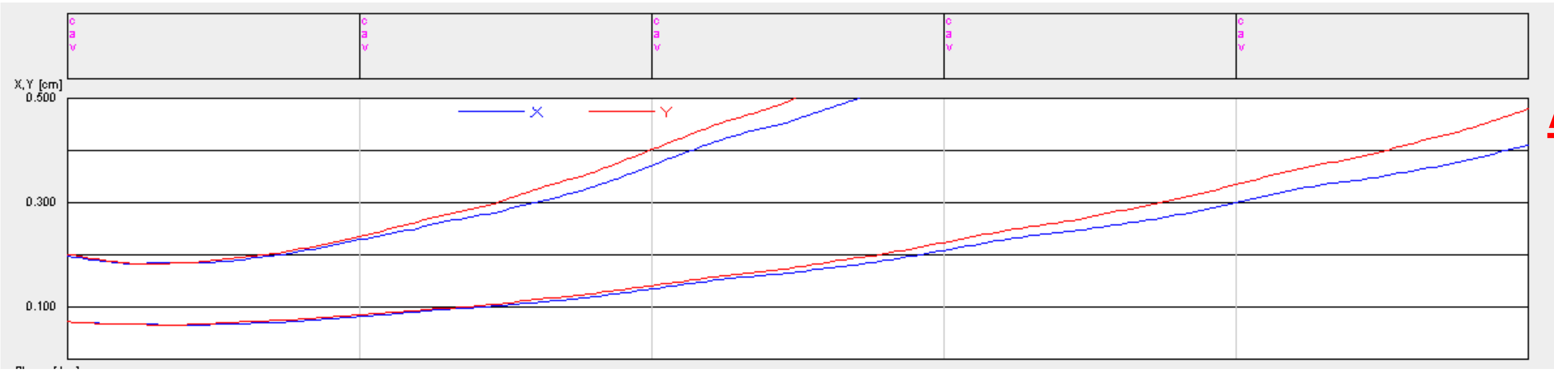


Cavity	Low-β	High-β
β_opt	0.087	0.16
L_eff	14.8	27.3
Epeak/Eacc -	5.1	4.1
Bpeak/Eacc mT/(MV/m)	7.0	7.0
R/Q (Ω)	182	224
G-Factor (Ω)	40	60

- ✓ A Quadrupole field component causing beam asymmetry
- ✓ Peak surface magnetic field in the welding areas

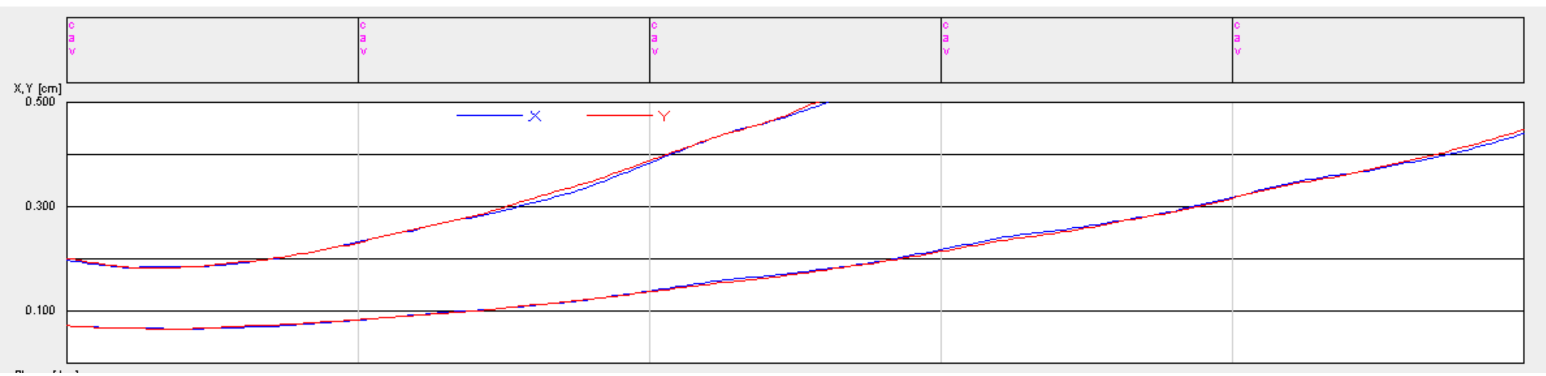
HWR Quadrupole Asymmetry Correction: Elliptical Aperture

Round Aperture



Asymmetry

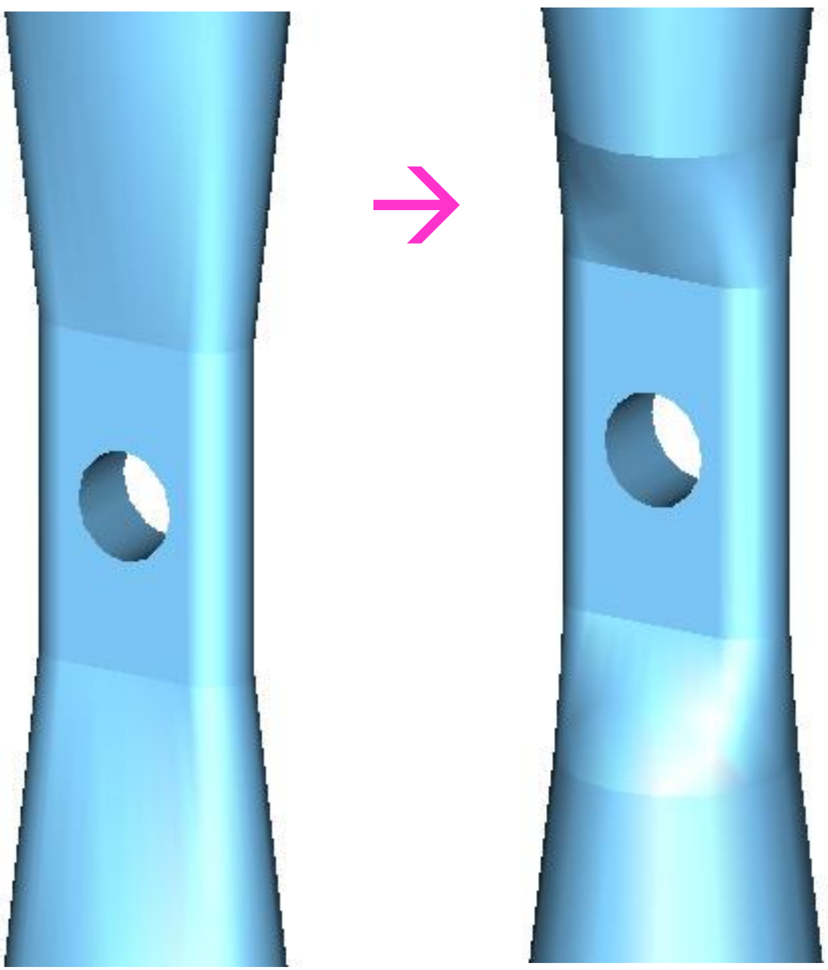
Elliptical Aperture



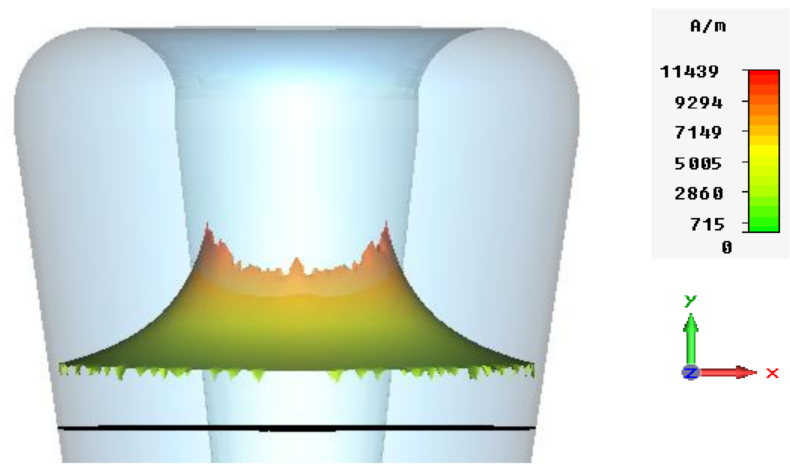
Asymmetry Gone

→ **The required elliptical aperture is 33-36 mm for the low-β and 36-40 mm for the high-β**

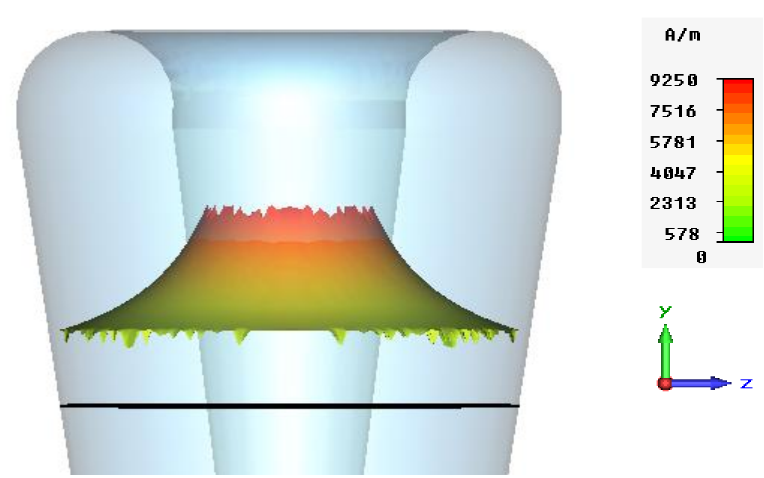
For Uniform Magnetic Field: Round Loft in the CC



Race-Track Loft

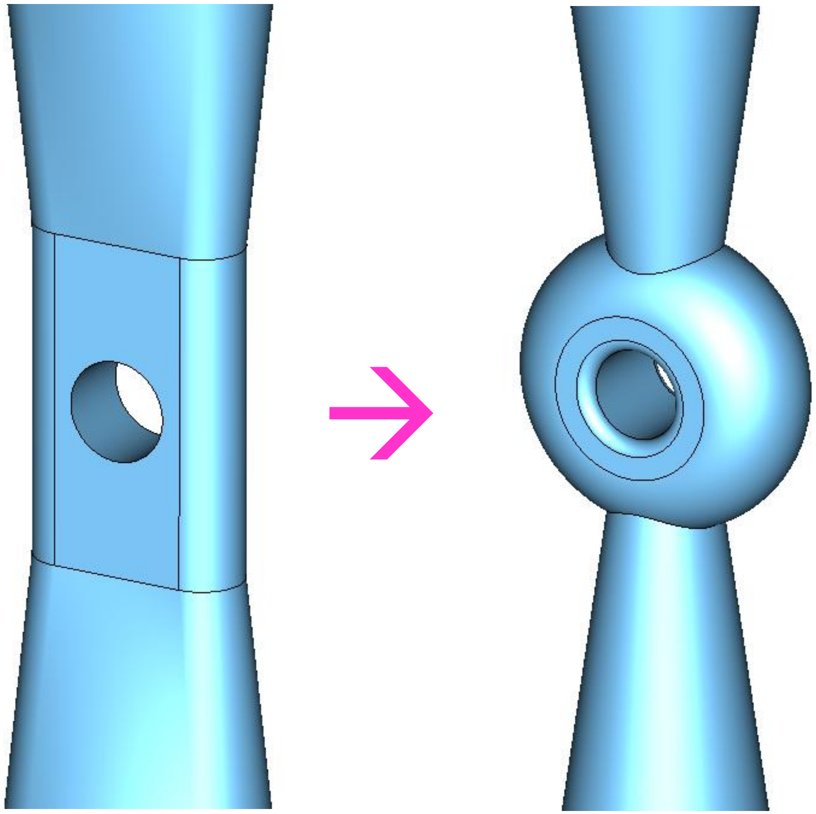


Intermediate Round Loft



The round loft re-distributes the magnetic field uniformly which also reduces the peak value

From Race-Track To Ring-Shaped "Donut" Center Conductor



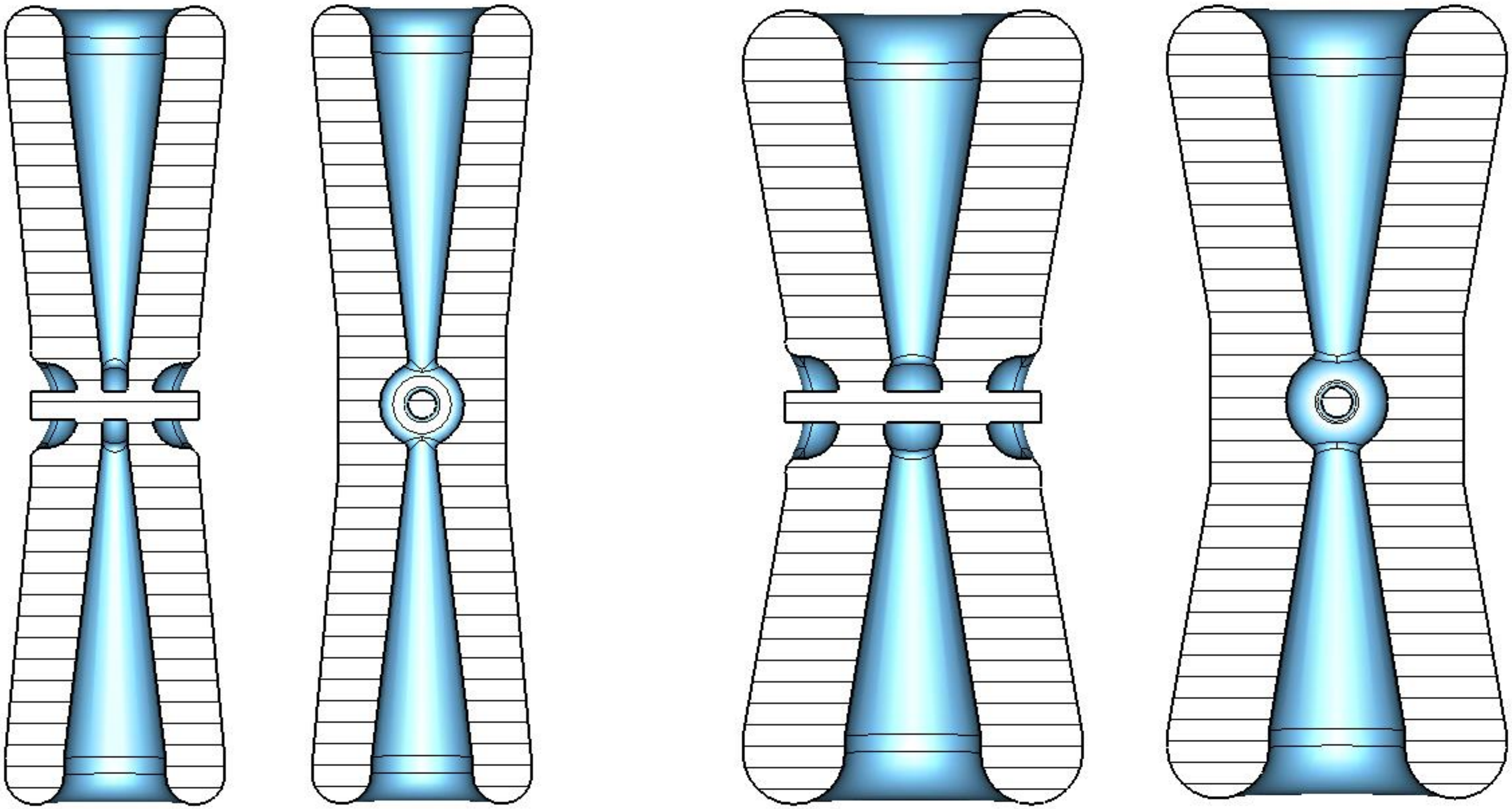
Comparison for the SARAF High-β HWR
176 MHz – β ~ 0.16

Cavity	Race-Track	Ring-Shaped	Diff. (%)
Epeak/Eacc -	4.1	4.7	+14
Bpeak/Eacc mT/(MV/m)	7.0	5.6	-20
R/Q (Ω)	224	296	+32
G-Factor (Ω)	60	60	0

- ✓20% lower peak magnetic field → Farther from quench limit
- ✓30% higher shunt impedance → Same voltage with less power
- ✓No quadrupole field component → No elliptical aperture needed

Optimized Ring-Shaped HWRs: Geometry

Low-β High-β

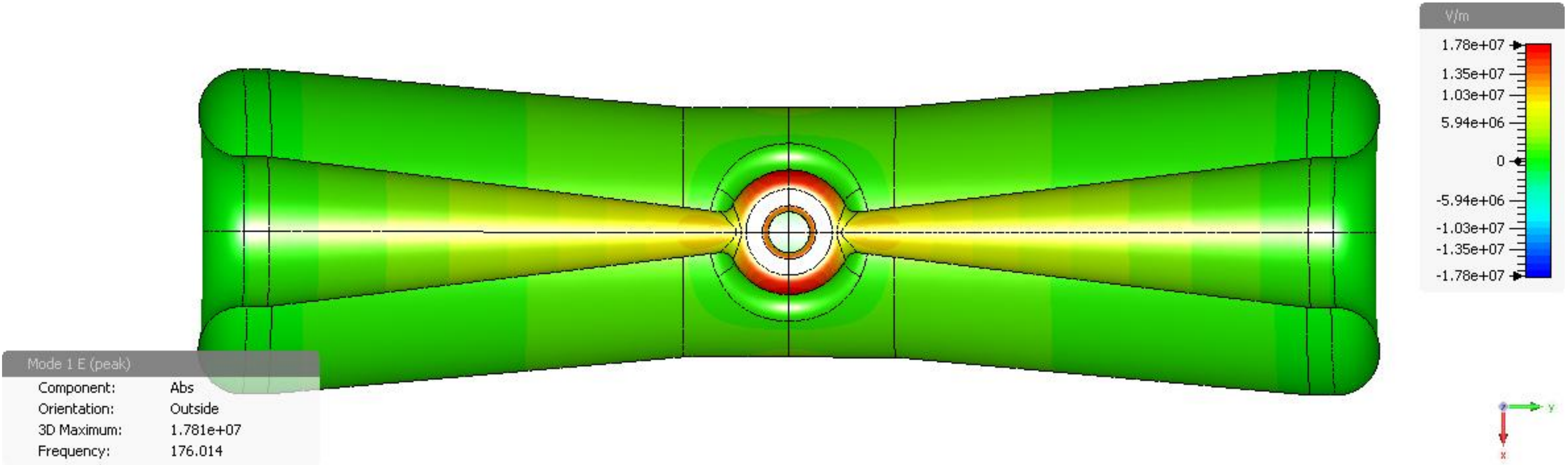


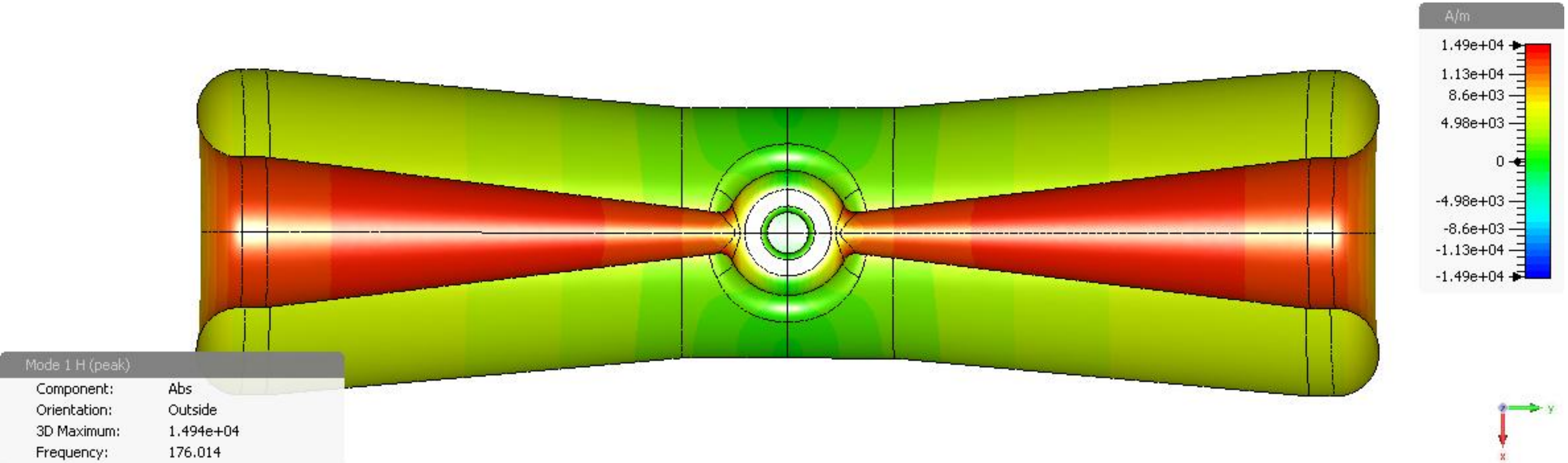
Optimized Ring-Shaped HWRs: RF Parameters

Cavity	β_opt	L_eff (cm)	Epeak/Eacc -	Bpeak/Eacc mT/(MV/m)	R/Q Ω	G Ω
Low-β	0.089	15.2	5.3	5.6	231	40
High-β	0.16	27.3	4.7	5.6	296	60

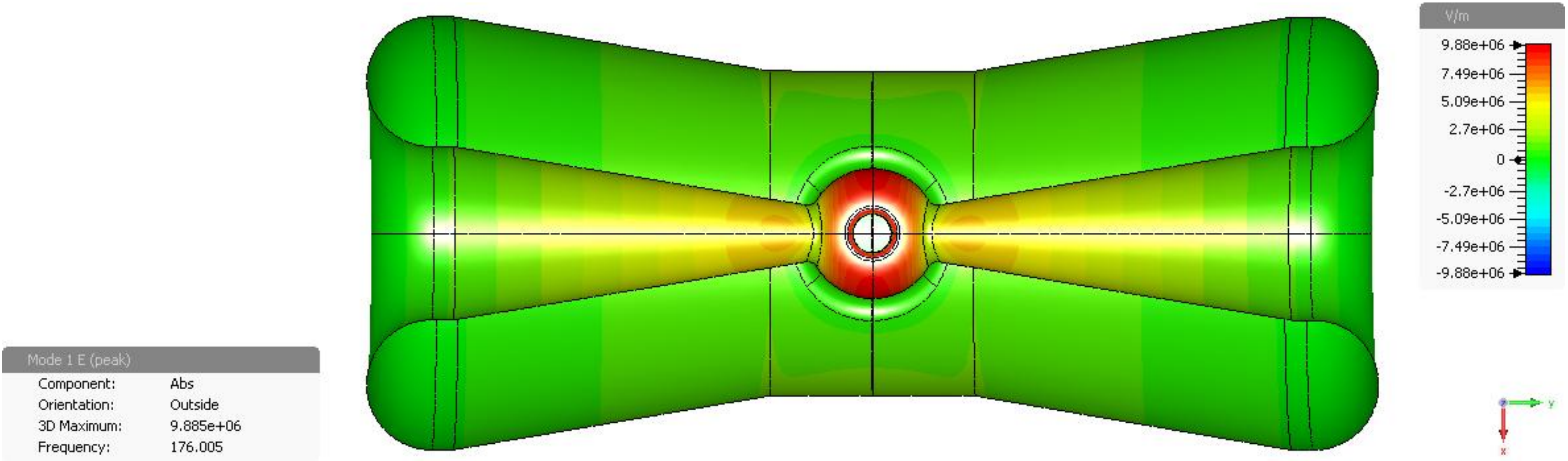
- The low-β HWR is capable of delivering 1.0 MV at 36 MV/m and 49 mT or 1.5 MV at 51 MV/m and 70 mT
- The high-β HWR is capable of delivering 2.4 MV at 36 MV/m and 61 mT or 2.7 MV at 41 MV/m and 70 mT

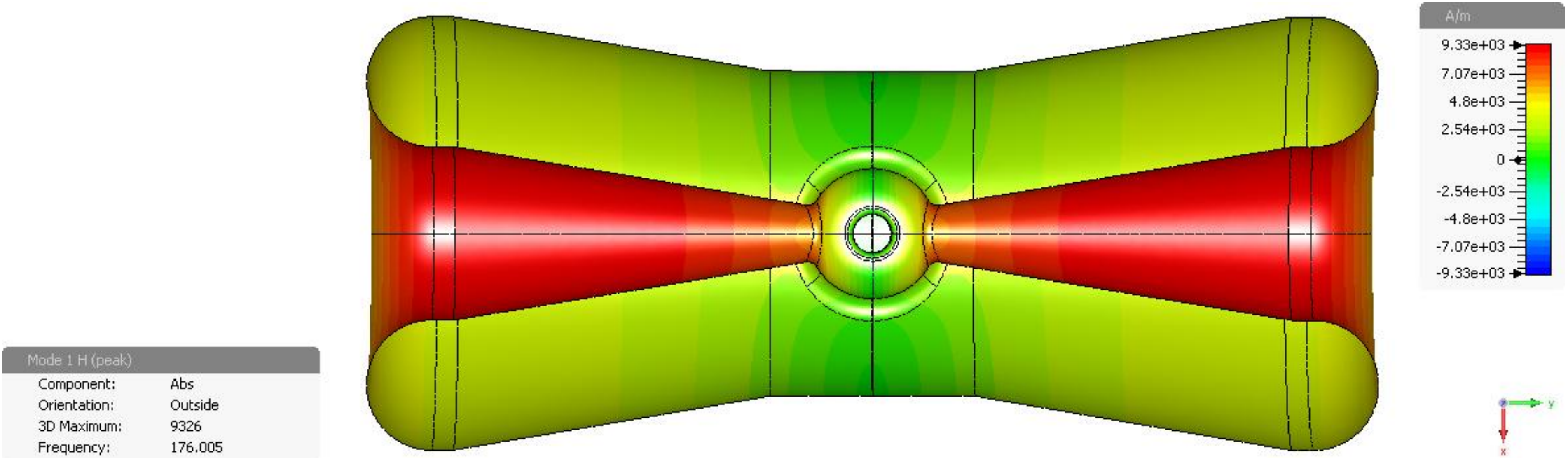
Low-β: Field Distributions



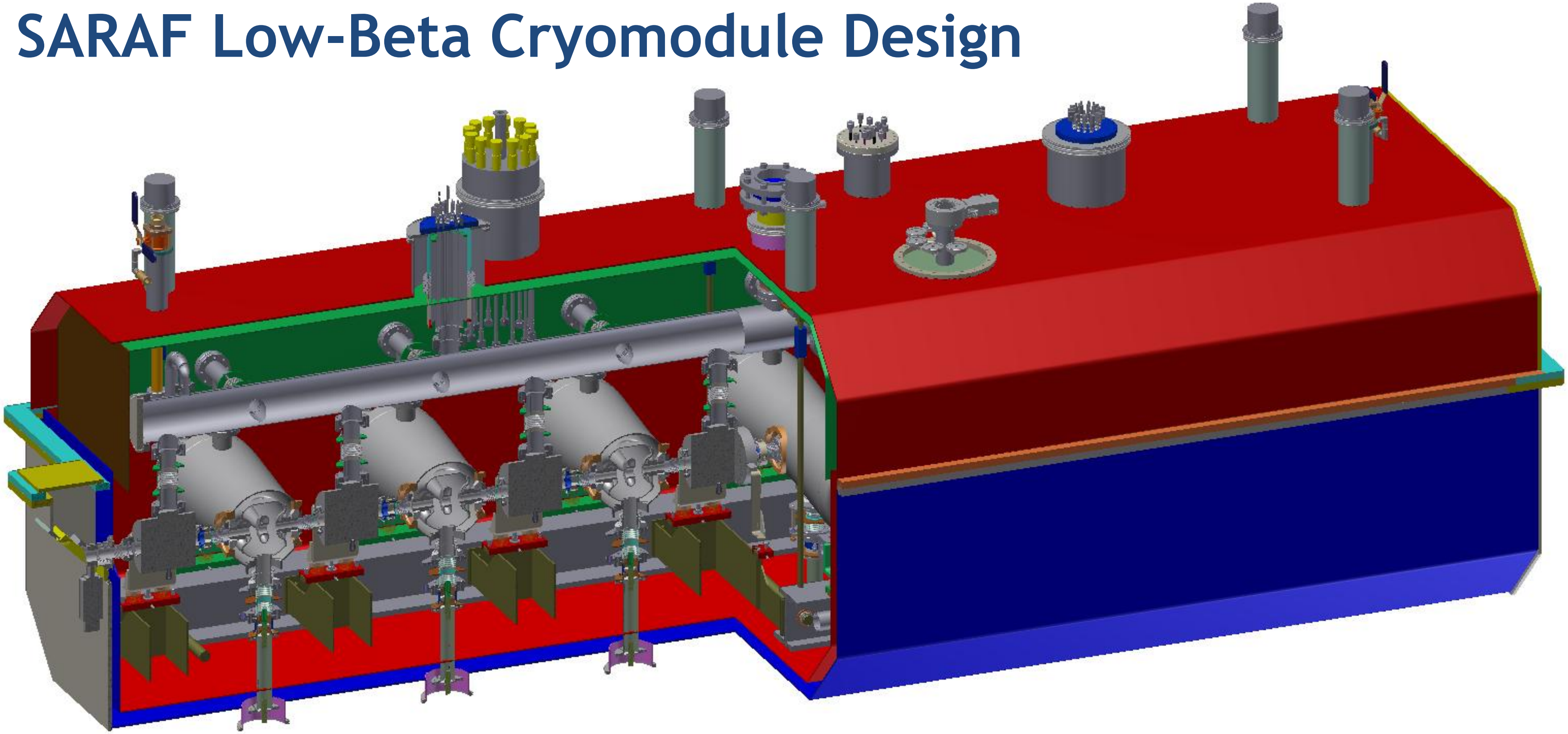


High-β Field Distributions





SARAF Low-Beta Cryomodule Design



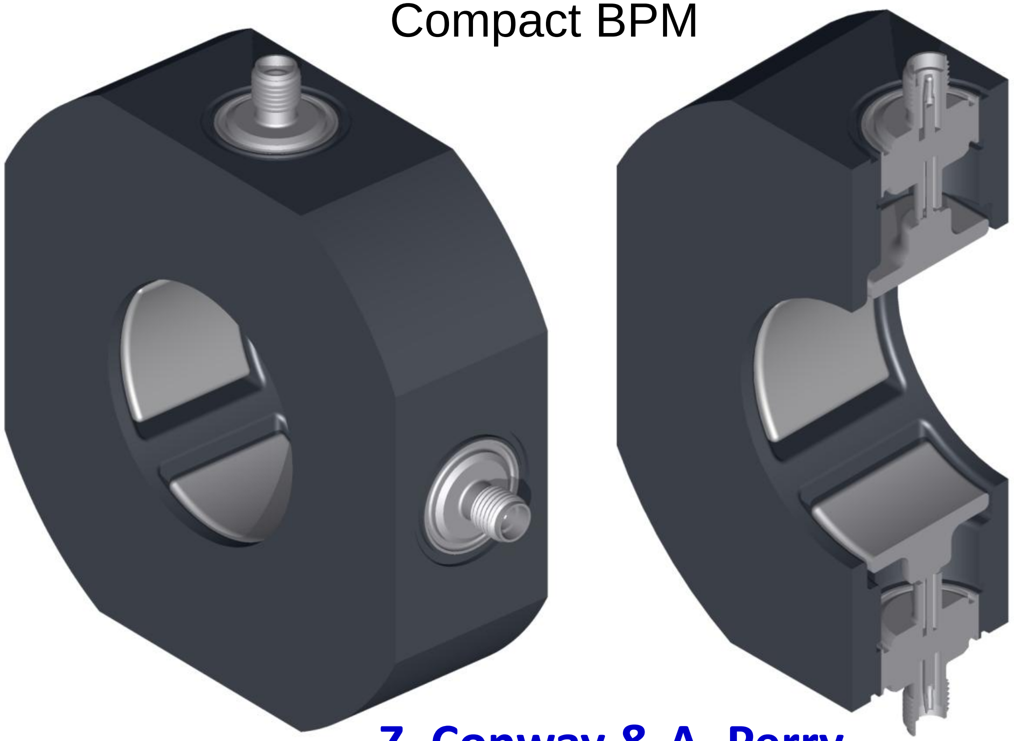
Parameter	Dimension
Cryomodule Width (m)	1.7 m
Cryomodule Height (m)	1.9 m
Cryomodule Length (m)	5.2 m

Z. Conway & G. Sherry

Compact Solenoid & BPM

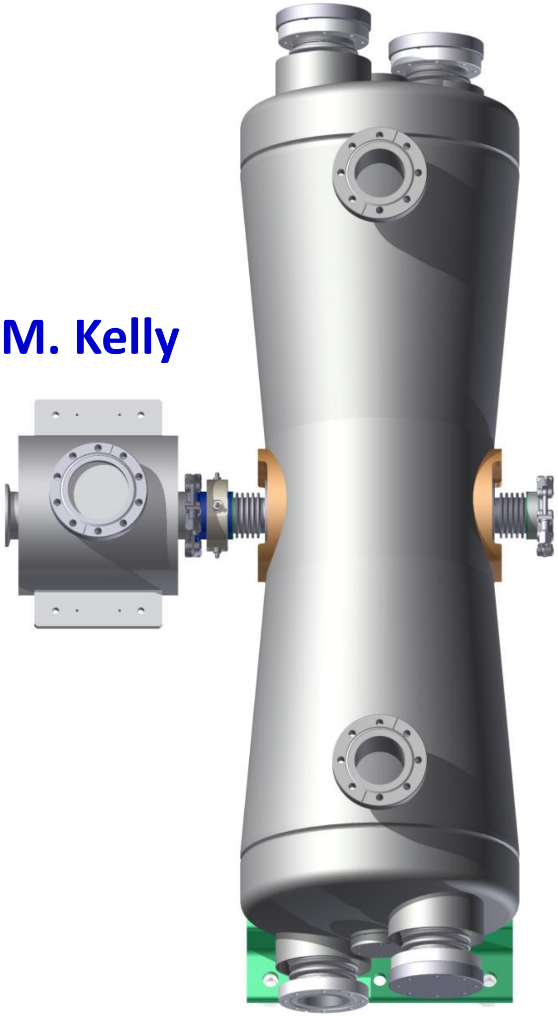
- A combined 6 T solenoid and steering coil design is being developed in collaboration with Meyer Tool and Manufacturing and Cryomagnetics.
- Compact & cleanable BPM with 2.5 cm length. It is being built and will be tested later this year.

Compact BPM



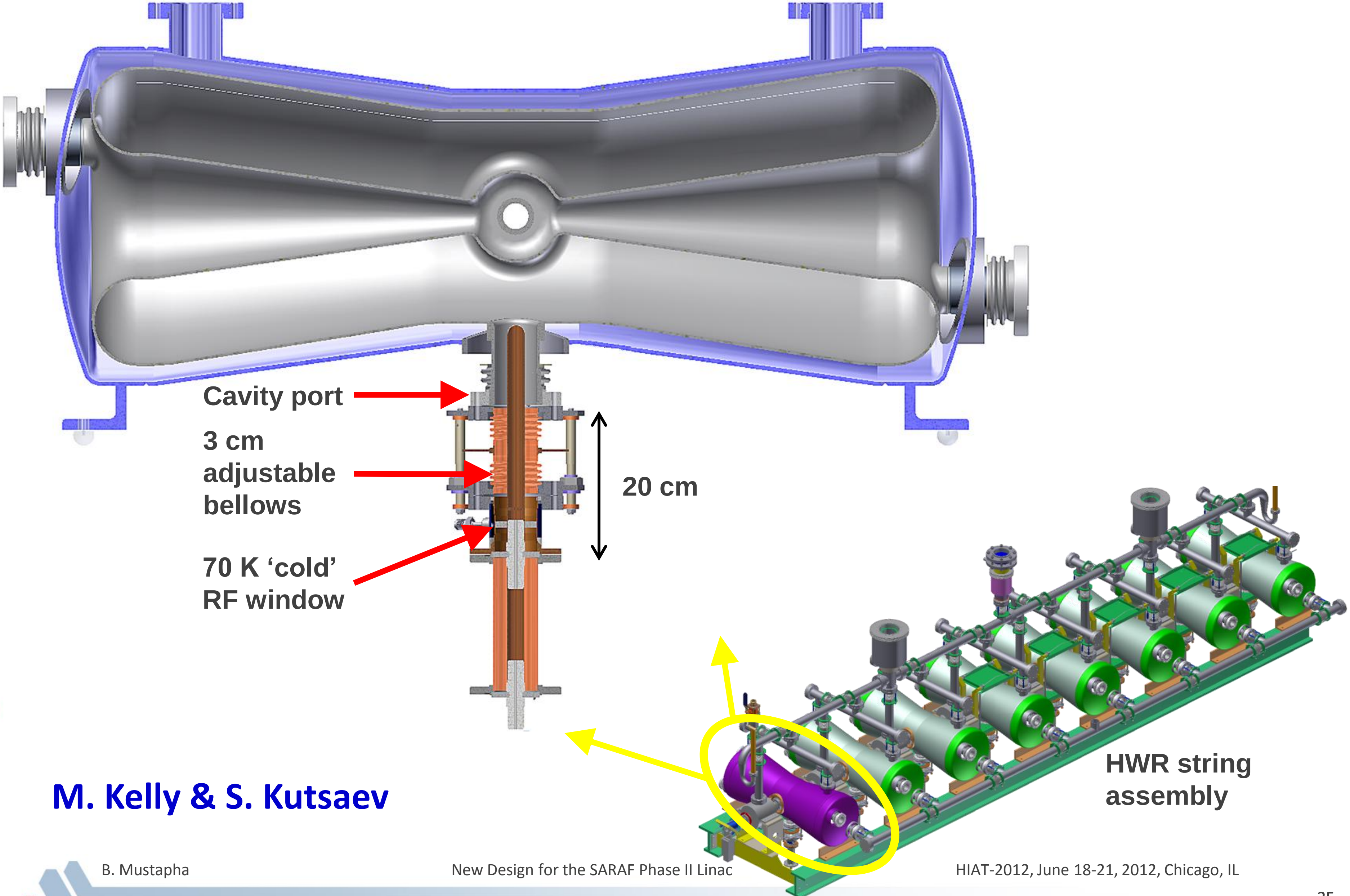
Z. Conway & A. Perry

M. Kelly



Assembly of beam spools, solenoid, BPM and cavity. Each unit = 0.64 m

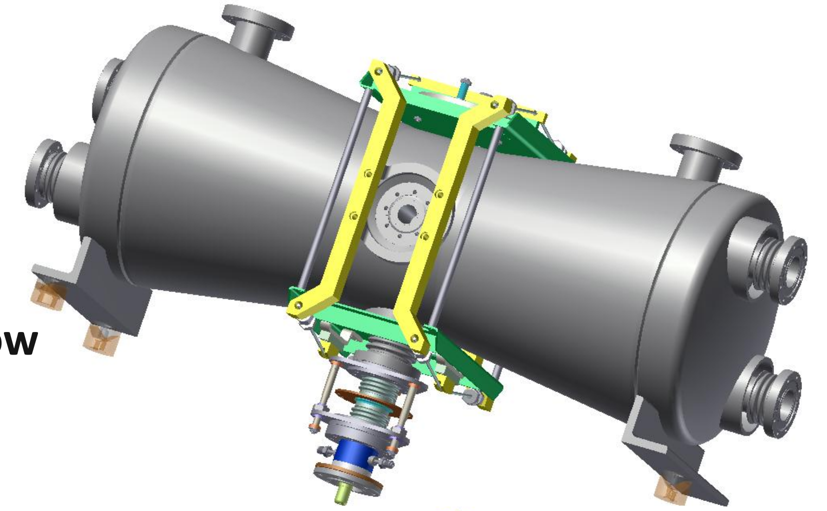
A 15 kW CW Power Coupler for SARAF

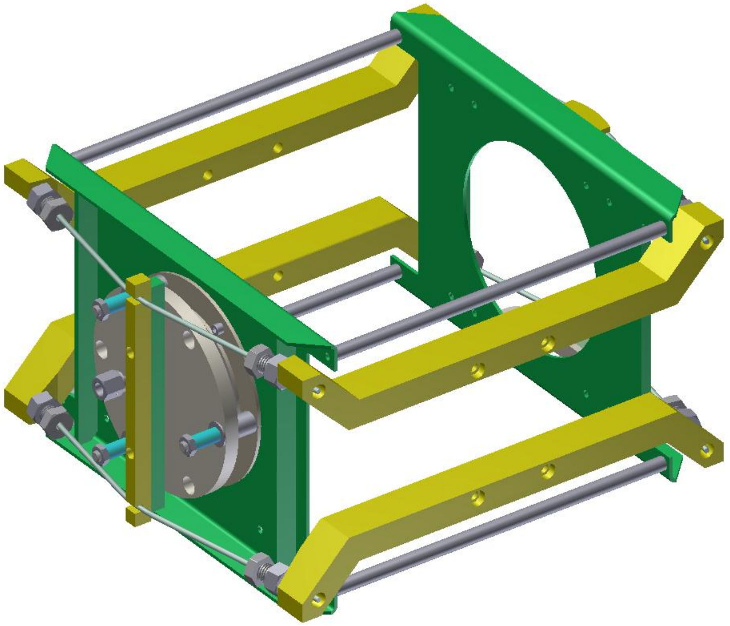


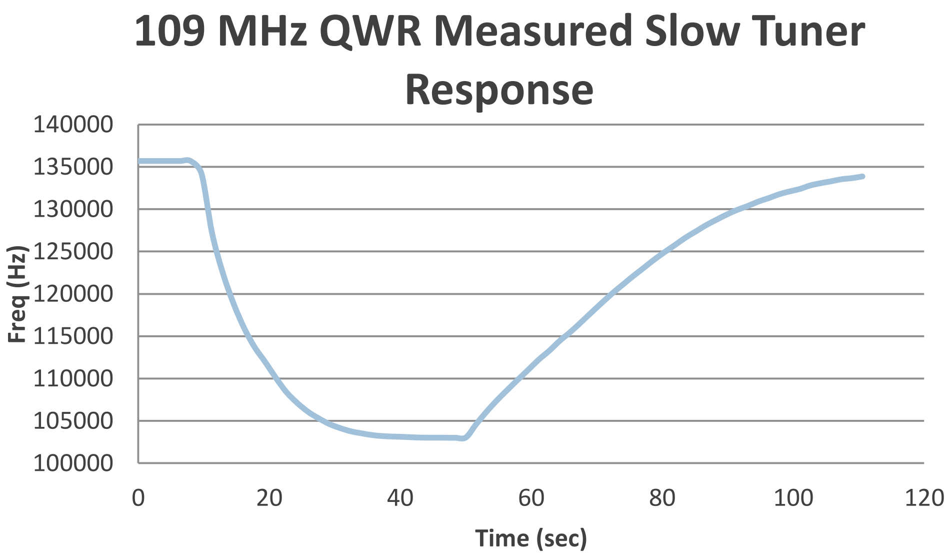
M. Kelly & S. Kutsaev

ANL Pneumatic Tuner Design

- No hysteresis.
- No backlash.
- No vibration; does not excite microphonics.
- Operates in a continuous feedback mode.
- Bellows is the only *moving part.*
- 109 MHz quarter wave cavity 32kHz tuning window ~1kHz / sec slew rate.
- Over $5X10^6$ integrated operating hours with only 77.82 hours of downtime (downtime records are from 1994 to 2011).
- Can be easily applied for HWRs.







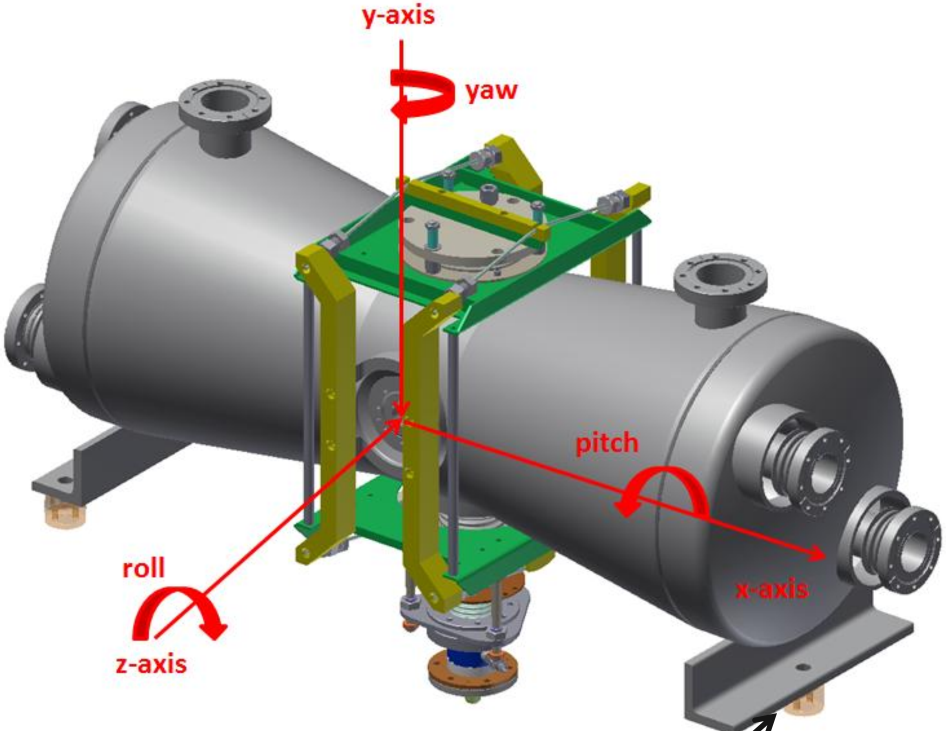
Z. Conway & G. Zinkann

Beam-Line Alignment Tolerances

Dimension	Energy Upgrade	Intensity Upgrade	SARAF HWR
x (mm)	±0.25	±0.25	±0.25
y (mm)	±0.25	±0.25	±0.25
z (mm)	±1	±1	±0.50
Pitch	$\pm0.15^0$	$\pm0.1^0$	$\pm0.1^0$
Yaw	$\pm0.15^0$	$\pm0.1^0$	$\pm0.1^0$
Roll	$\pm0.5^0$	$\pm0.1^0$	$\pm0.1^0$

Results of Measurements with Beam

Alignment Coordinate System



Alignment Puck (QNT 3)

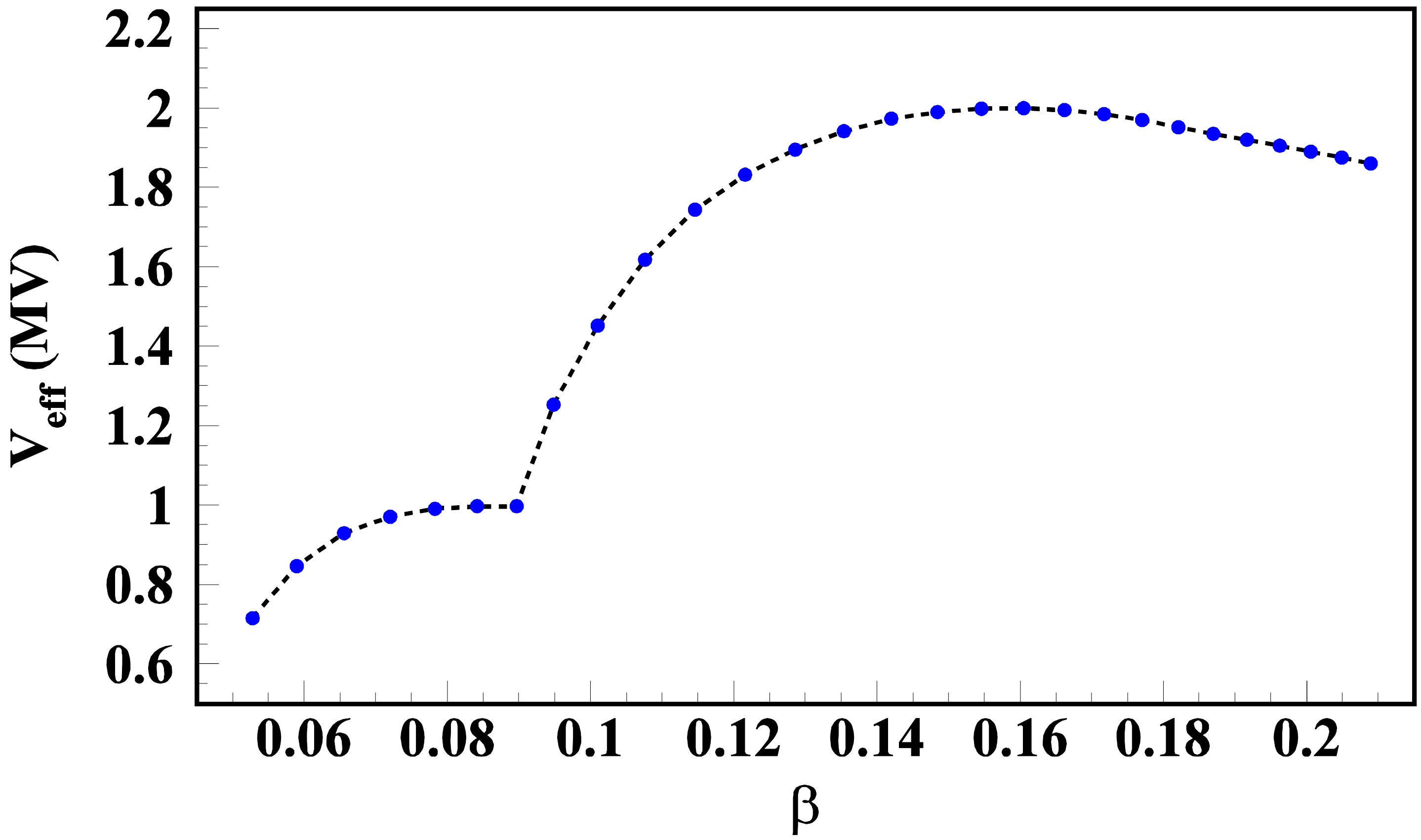
Alignment Hardware Examples

Z. Conway

New Linac Layout: Cavity Count

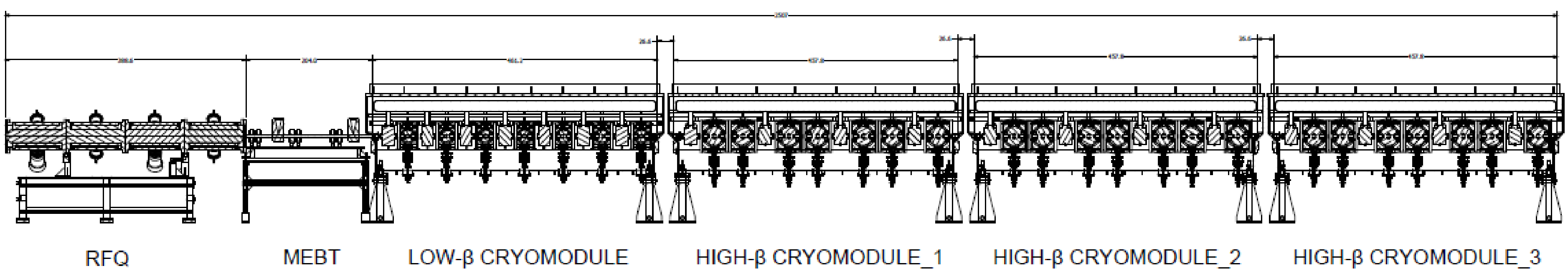
- To reach the desired beam energy of 40 MeV with nominal cavity voltage, we will need 7 low-β HWR at 1 MV and 21 high-β HWR at 2 MV
- The cavities could easily outperform these nominal voltages
- For an adiabatic transition from the RFQ to the low-β section, the focusing period will consist of 1 cavity and 1 solenoid in the first cryomodule
- In the high-β section, the focusing period consists of 2 cavity and 1 solenoid except the last period in every cryomodule where we skip a cavity for better matching between cryomodules

Voltage Curve

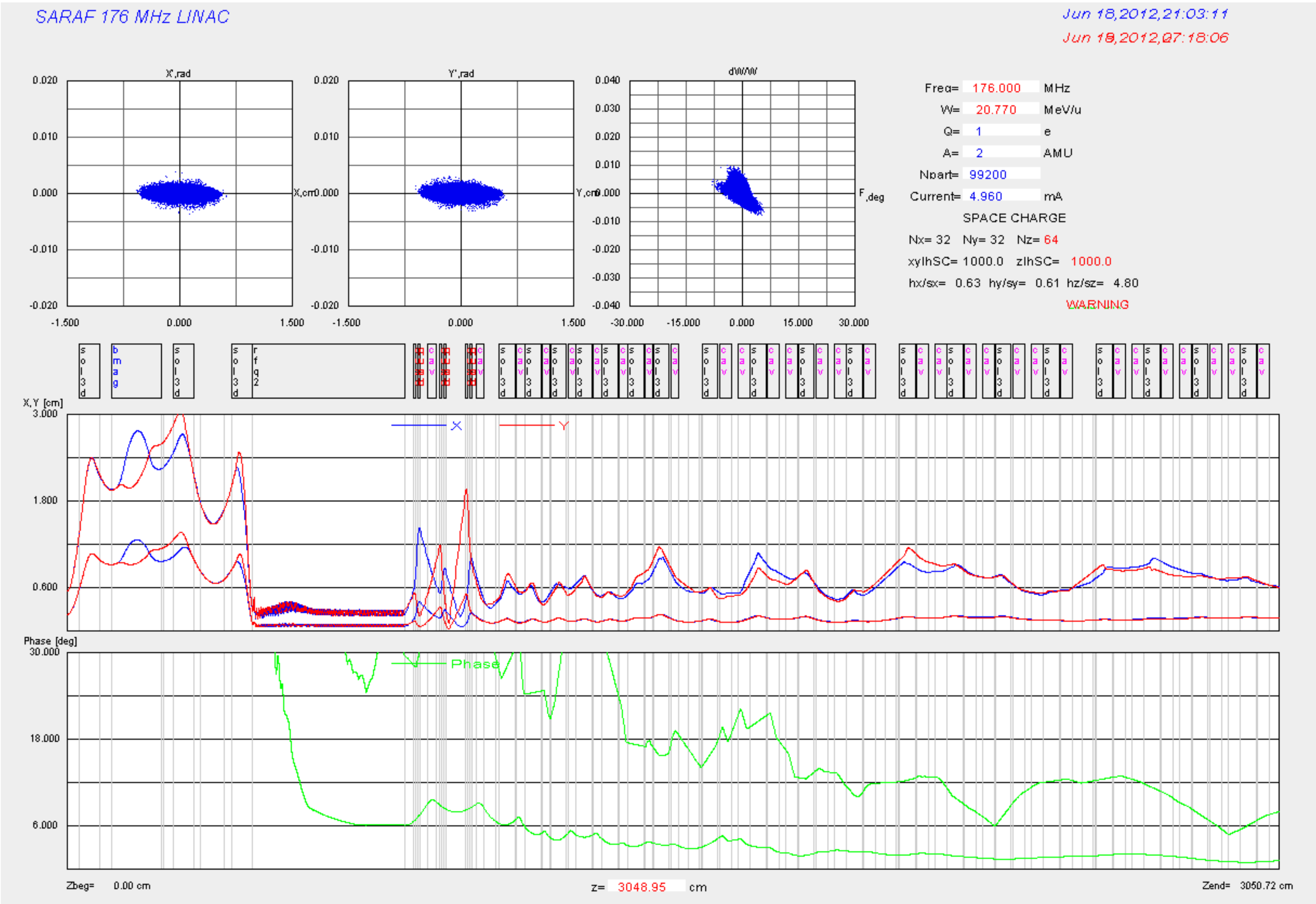


New Linac Layout

- RFQ – 3.9 m
- MEBT - ~2 m
- Low-β cryomodule - 5.2m
- High-β cryomodule - ~5 m
- Total – 26 m



End-to-end Beam Dynamics: From the ECR …



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- Dale Schrage (TechSource)
- Kenneth Shepard (TechSource)
- …