SARAF PHASE II P/D 40 MEV LINAC DESIGN STUDIES

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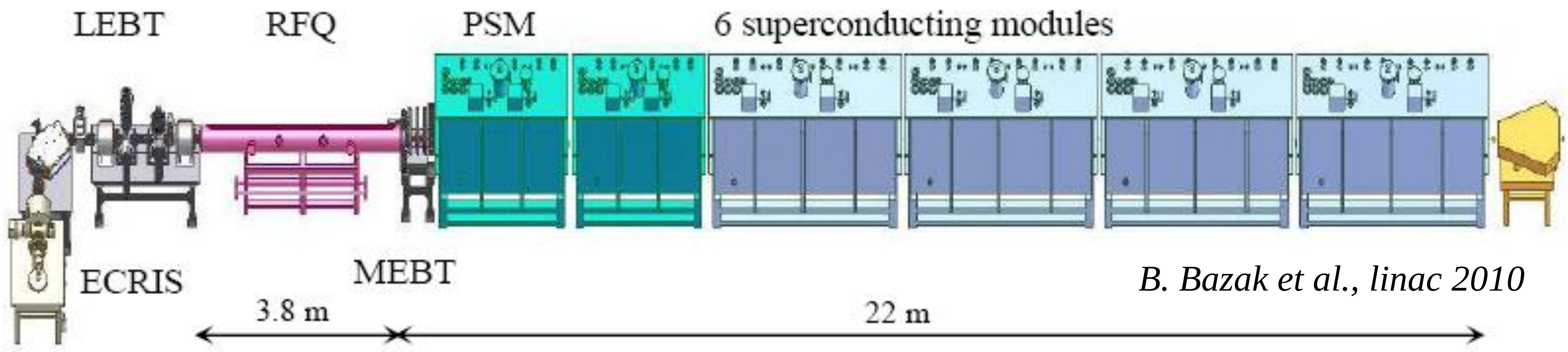
SARAF Accelerator (2003 design view)

PSM – Prototype Superconducting Module



B. Bazak et al., linac 2010

Phase I of SARAF includes (Ion source, RFQ and one cryomodule housing 6 HWRs 176 MHz) delivering:

- 3.6 MeV 1mA p beam
- 4.7 MeV low duty cycle 0.3 mA d beam

SARAF Phase II CW linac is planned to produce:

- variable energy (5-40) MeV p&d
- beam currents (0.04-5) mA

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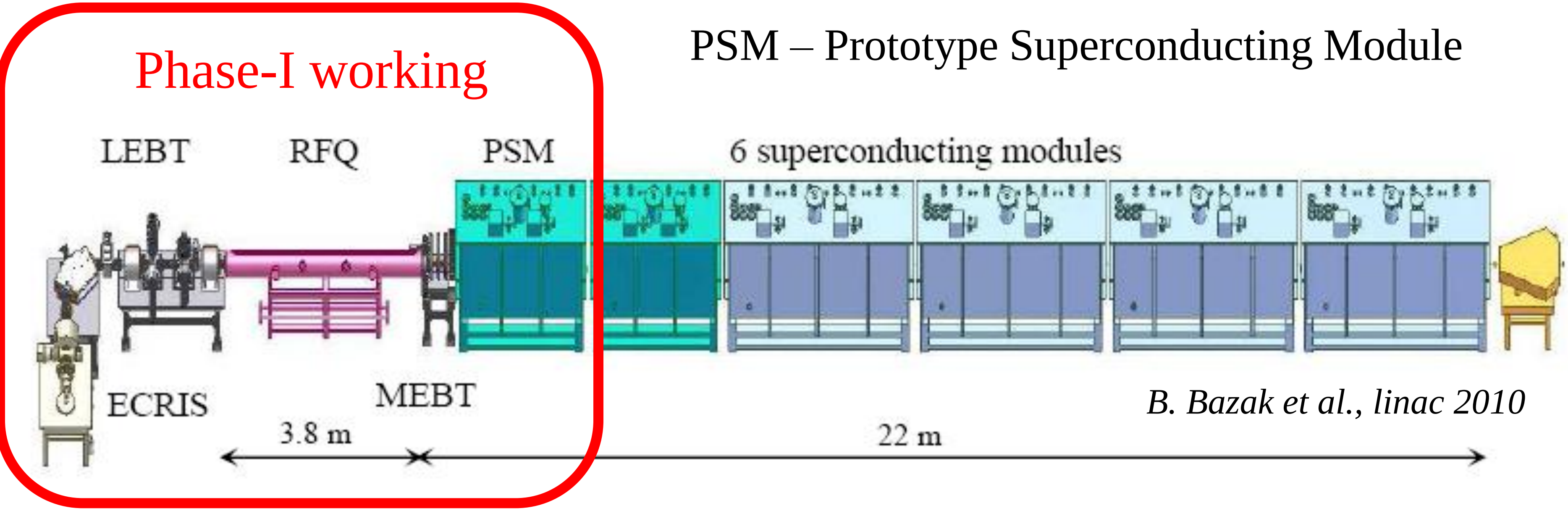

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- beam currents (0.04-5) mA

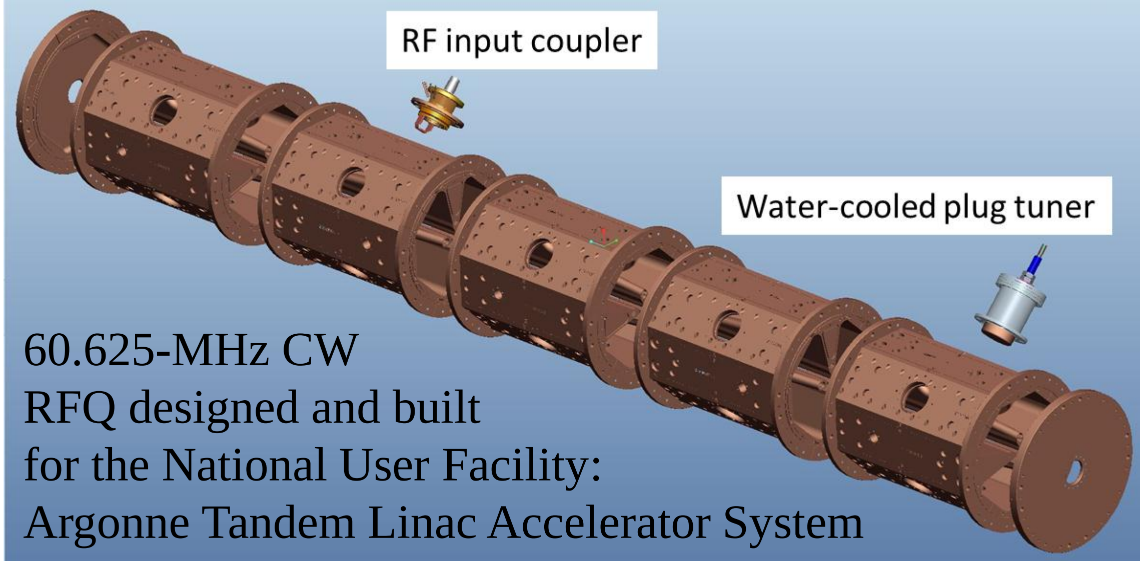
Outline: SARAF Phase II conceptual study

Two linac options: 176 MHz HWR & 109 MHz QWR lattices downstream a 20 keV/u - 1.3 MeV/u RFQ. Both options were studied for Phase II:

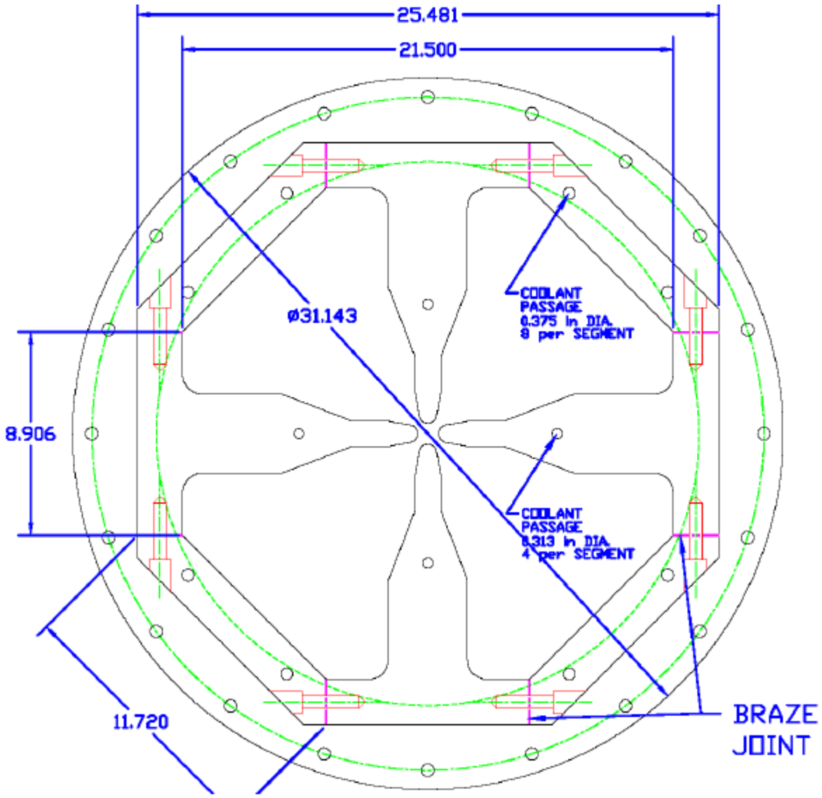
- Design of CW RFQs according to engineering and beam dynamics guidelines
- Matching the LEBT beam to the RFQ
- MEBT design
- SC cavity main EM parameters
- EM optimization of both QWRs and HWRs
- Engineering and beam physics design of the linac and its cryomodules
- Detailed beam dynamics simulations with realistic fields and machine errors.

Design of CW RFQs guidelines

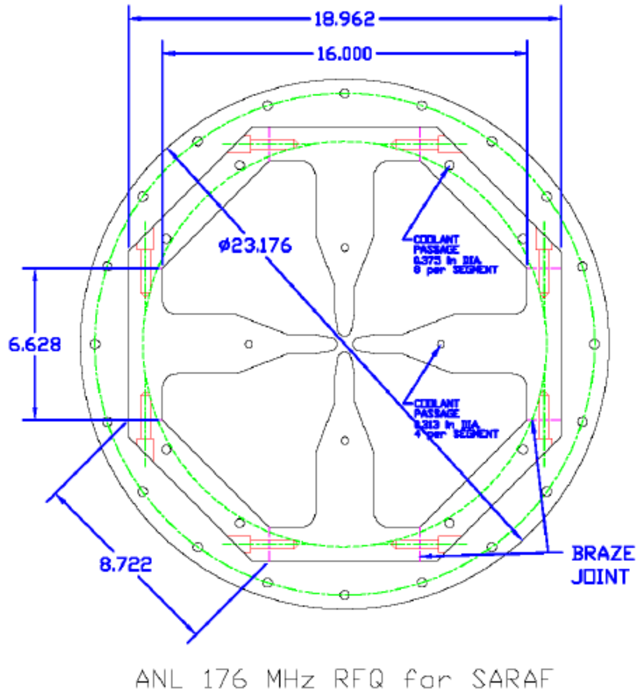
- Reliable CW protons and deuterons operation
- Beam formation with extremely low longitudinal halo
- Moderate peak fields to avoid any possible breakdowns and avoid long conditioning of the resonator. In particular, the peak electric fields should be below $1.8E_K$ (E_K=Kilpatrick criterion)
- High acceleration efficiency (>97%) for 5 mA
- No transverse rms emittance growth through the RFQ



The 4 vanes 176 & 109 MHz CW RFQ



109 MHz

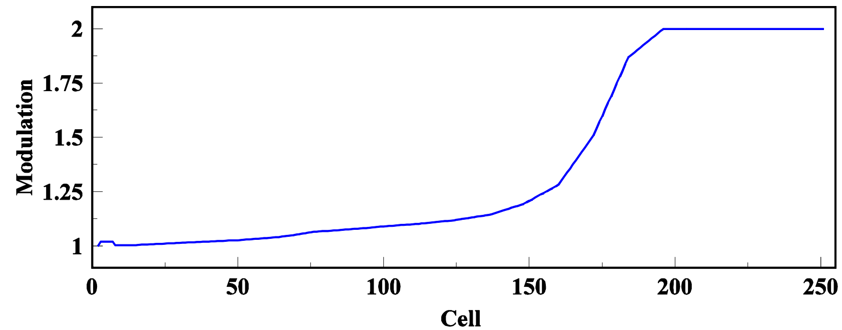


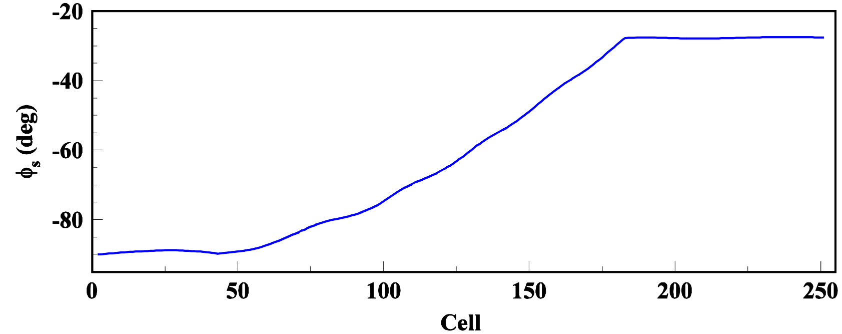
176 MHz

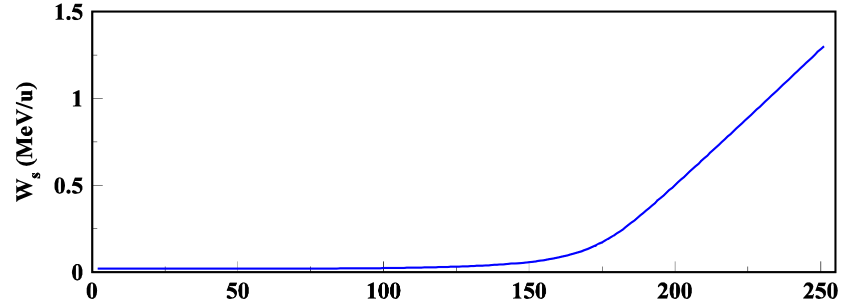
4-vane structure was chosen to reduce RF power as compared to 4-rod or even 4-vane structure with "windows"

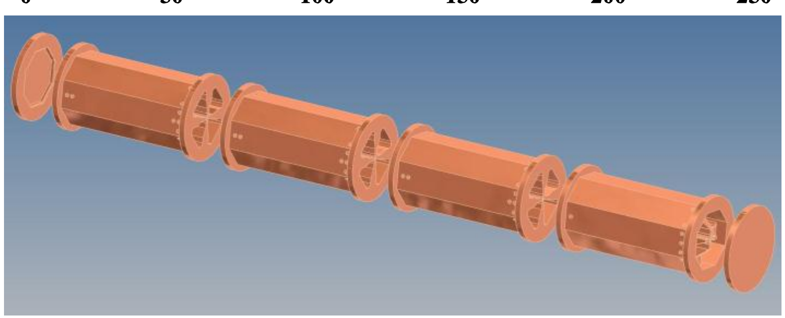
176 MHz CW RFQ: Beam Dynamics Optimized Design

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	$3 \cdot 10^{-3}$	$1 \cdot 10^{-3}$







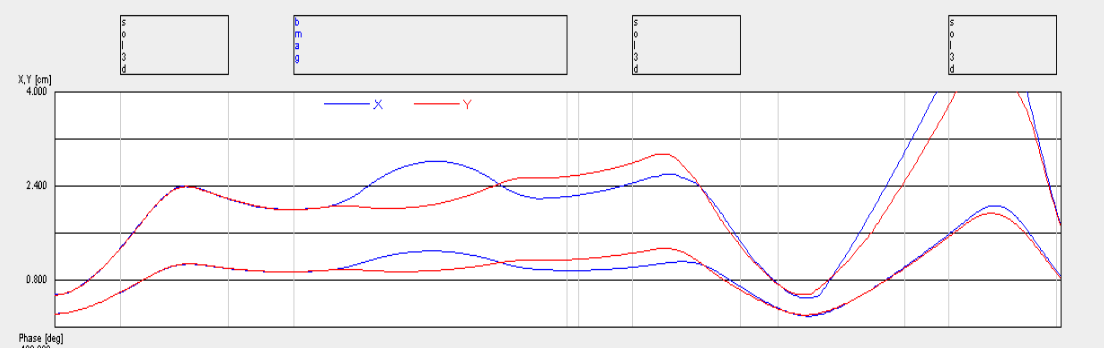


Two Important Design Features

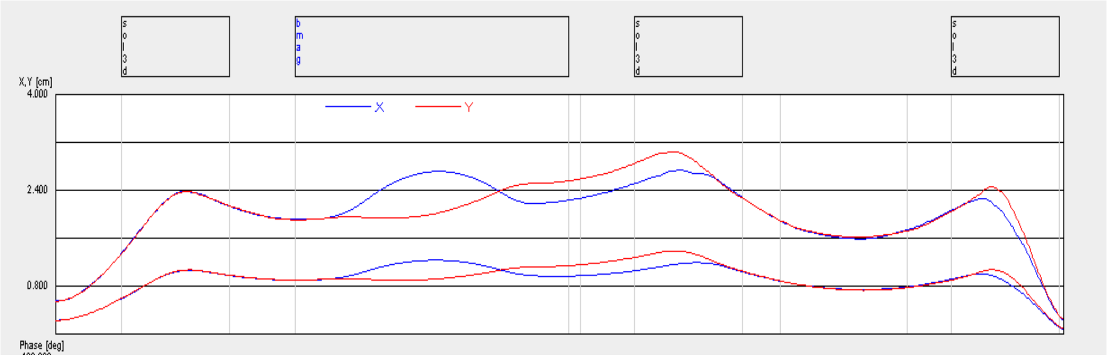
- Approaches 100% transmission
- Input matcher to reduce emittance growth

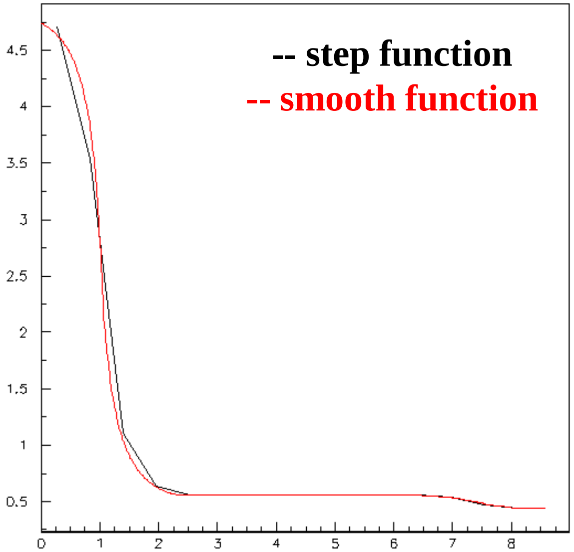
A Smooth Two-Step Input Matcher

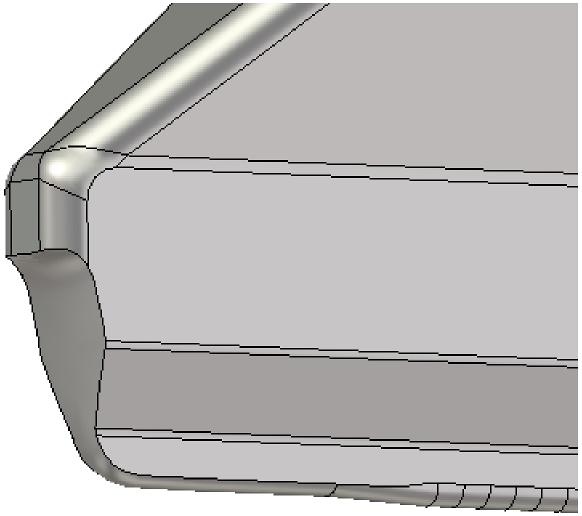
LEBT with RFQ original 6 cell input matcher: α ~ 1.5



LEBT with RFQ special 15 cell input matcher: α ~ 0.25





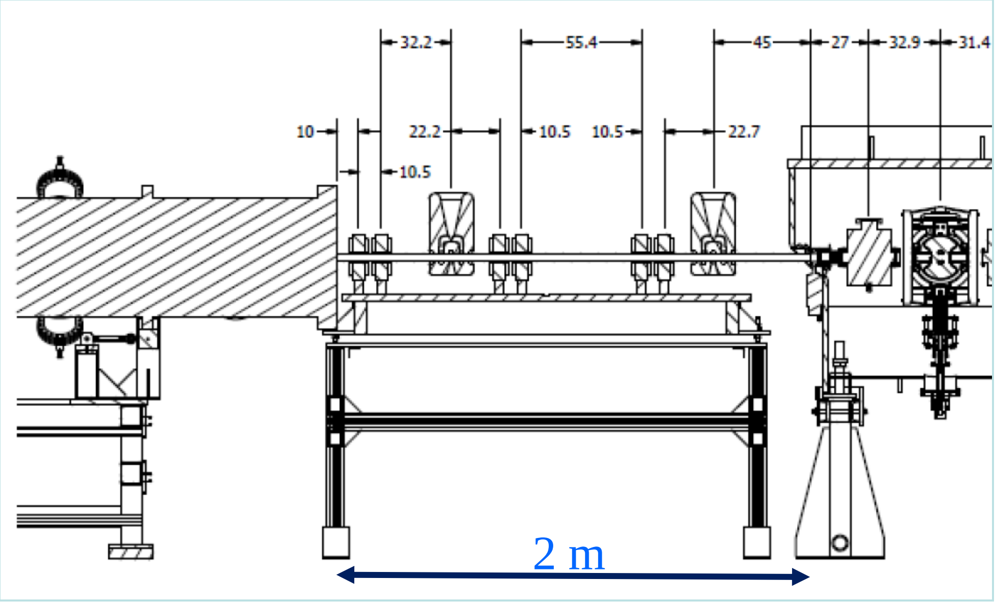


MEBT primary functions

- Match either a proton or a deuteron beam into the 6D acceptance of the SC linac;
- Avoid emittance growth and formation of beam halo;
- Provide space for beam diagnostics and cold trap

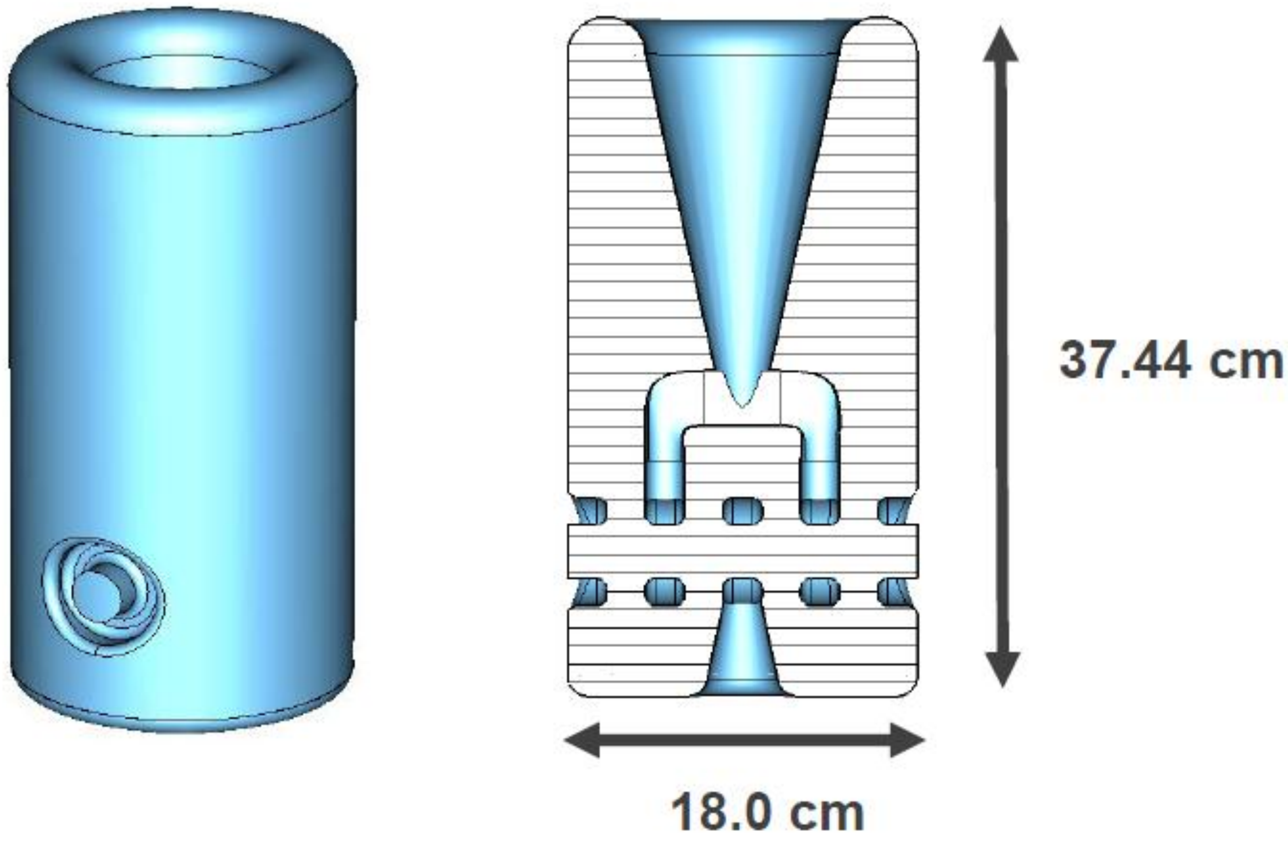
Matching of the RFQ beam to the SC acceptance is not a trivial task

- The available accelerating gradient of the SC structures is appreciably higher than that of the RFQs;
- The MEBT forms a radial beam for injection into the SC linac;



176 MHz Room Temperature Buncher

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

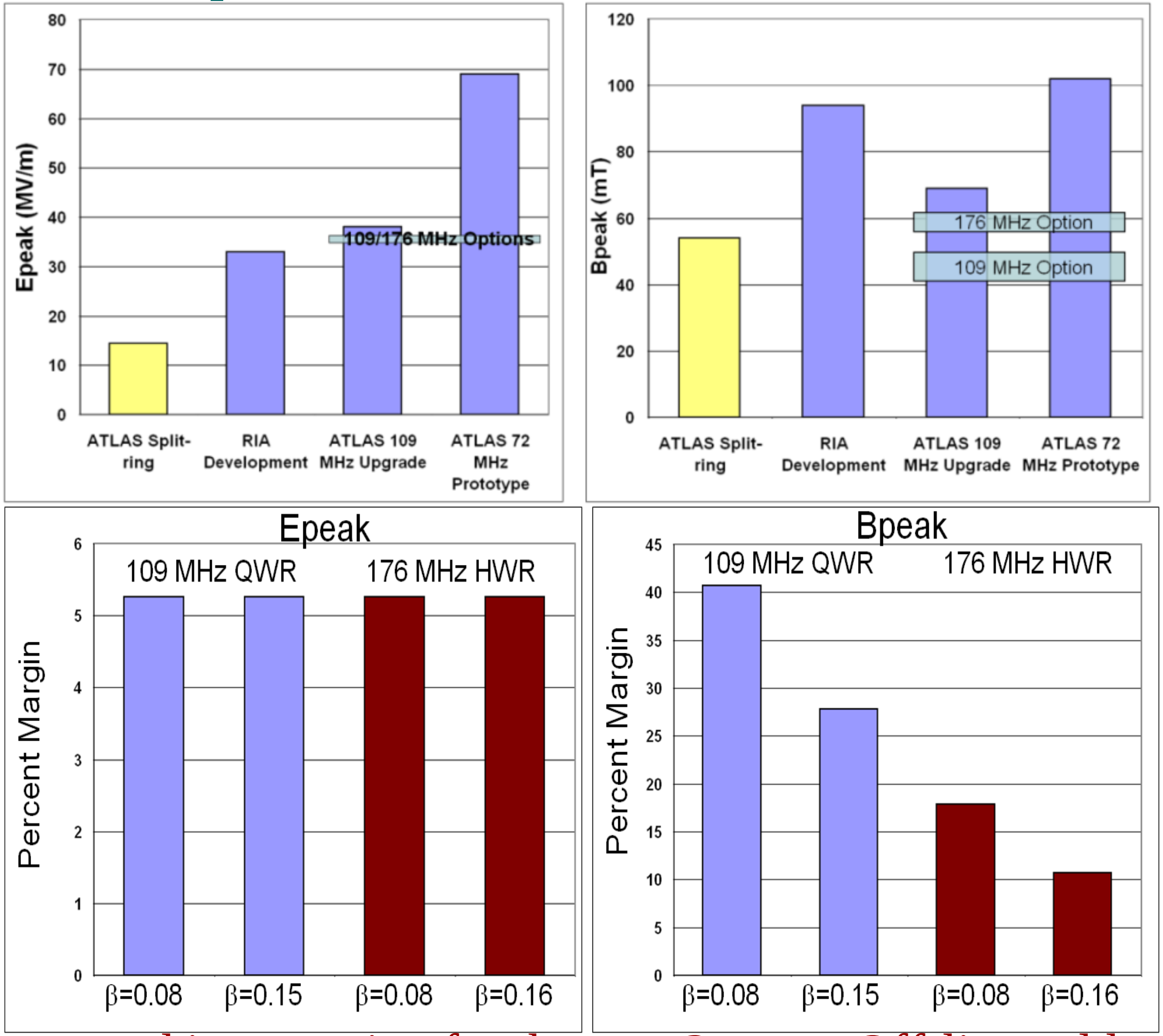


SC cavity main EM parameters Selection

- Based on the demonstrated performance of TEM-class cavities at ANL.

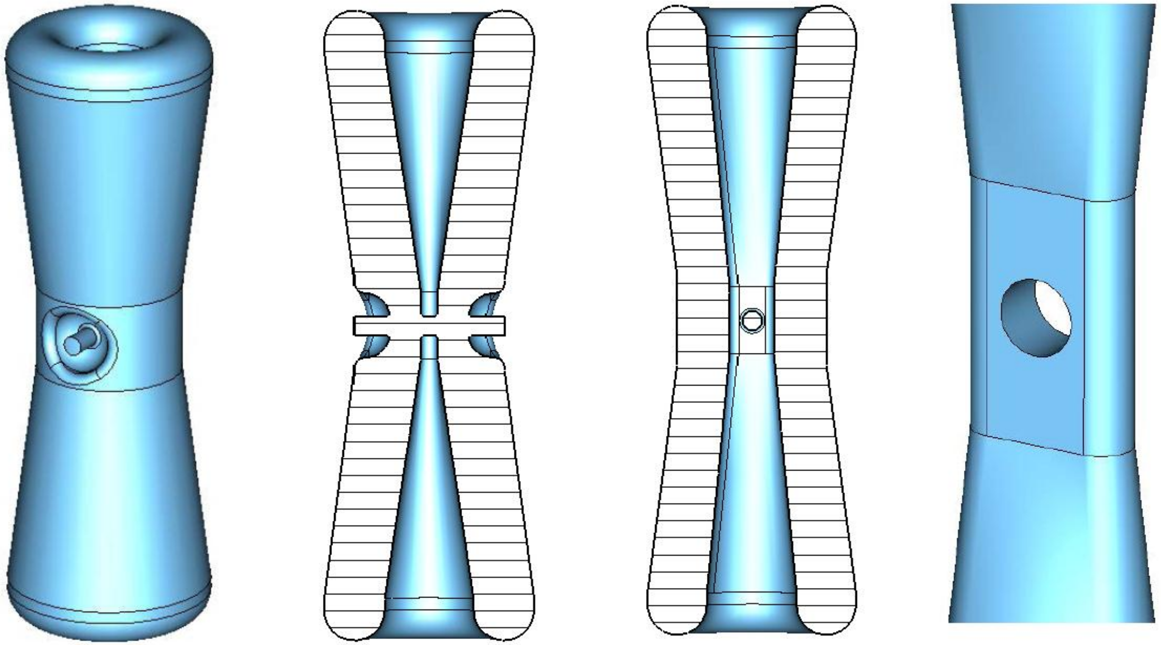
[M.P. Kelly et al, MOPB073 these proceedings]

- Weighted toward maintaining E_{PEAK} at or below 36 MV/m.



- These parameters were demonstrated in operation for the past 3 years. Off-line cold test of NEW 72 MHz cavities demonstrated >70 MV/m in all 4 tested cavities.

EM optimization of HWRs



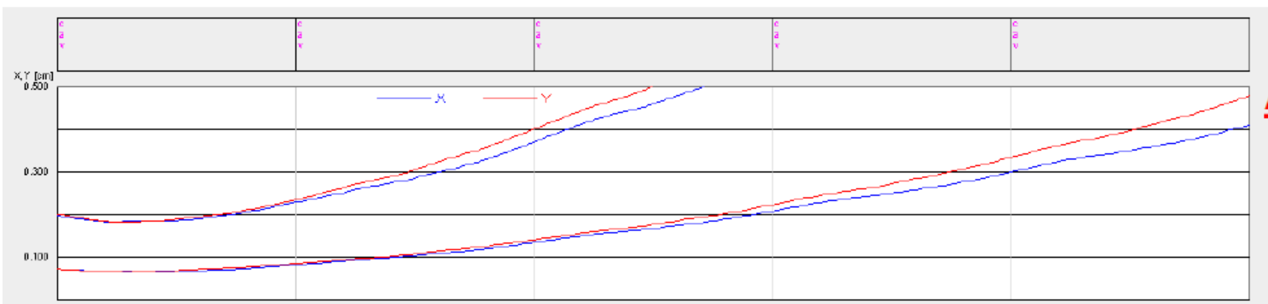
Three steps optimization to the Race-Track center conductor design to reduce magnetic field and the transverse beam asymmetry :

- Elliptical aperture.
- Intermediate round loft.
- Change the geometry to “donut” shape.

Elliptical aperture

The elliptical aperture reduces the quadrupole effect caused by the asymmetric geometry

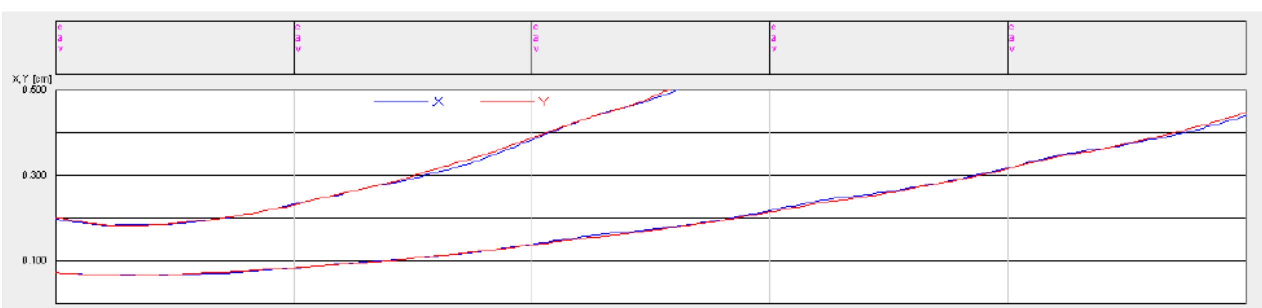
Round Aperture



Asymmetry

[B. Mustapha et al, HIAT-2012]

Elliptical Aperture



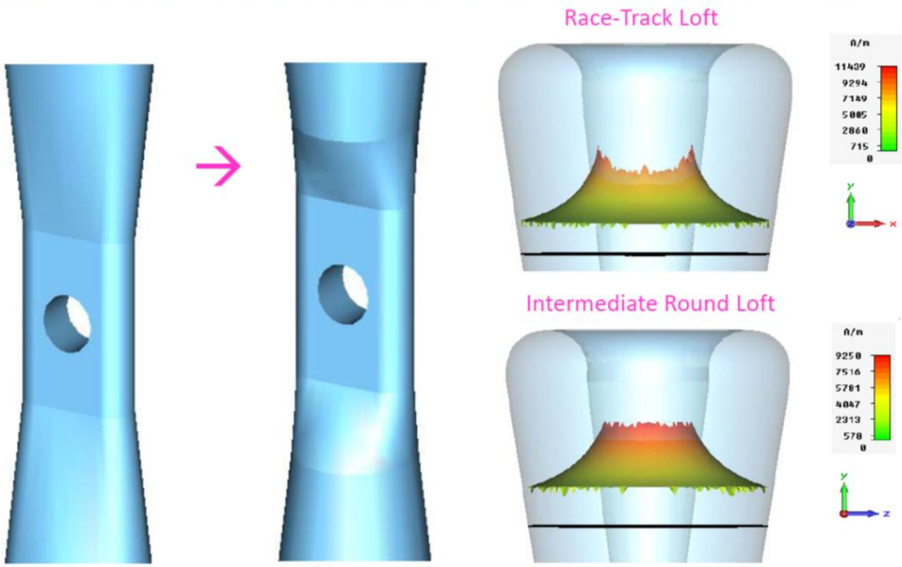
Asymmetry Gone

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

HWR EM fields optimization

Intermediate round loft **Change the geometry** **to donut shape**

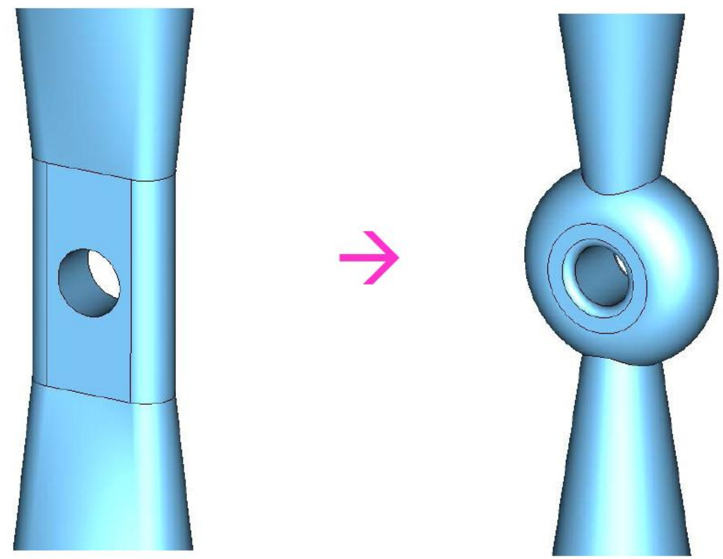
Race-Track versus Round Loft in the Center Conductor



- **The intermediate round loft reduces the peak magnetic field**

[B. Mustapha et al, IPAC-2012]

Replacing the Race Track with a donut-shaped

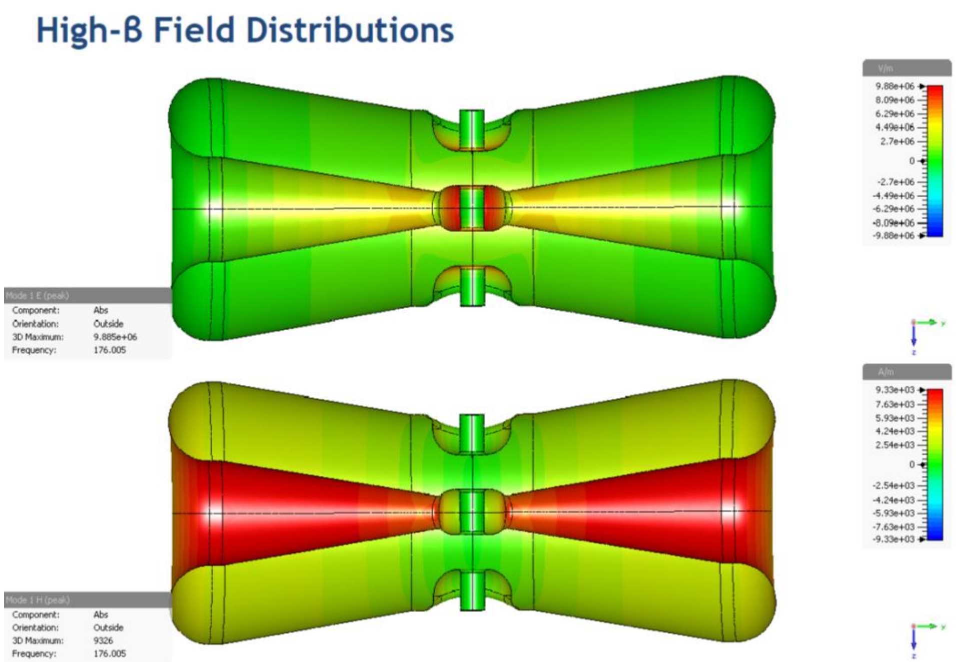


- **The donut-shaped cavity has a slightly higher E-peak, a much lower B-peak, and a higher shunt impedance.**

[CST MWS]

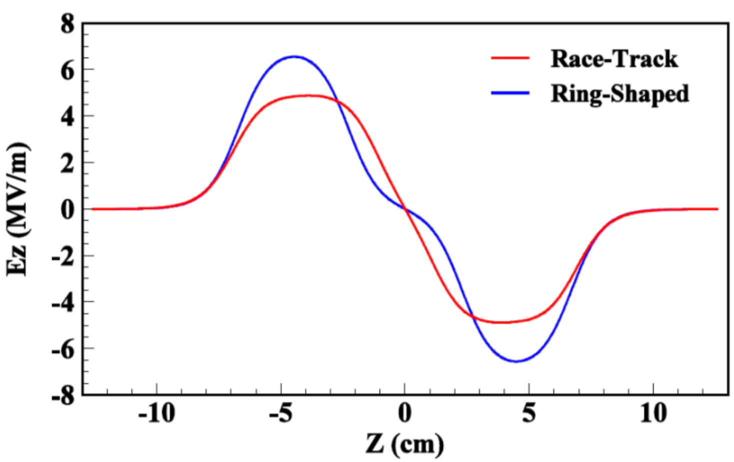
The final donut shape CST EM fields

CST EM Fields



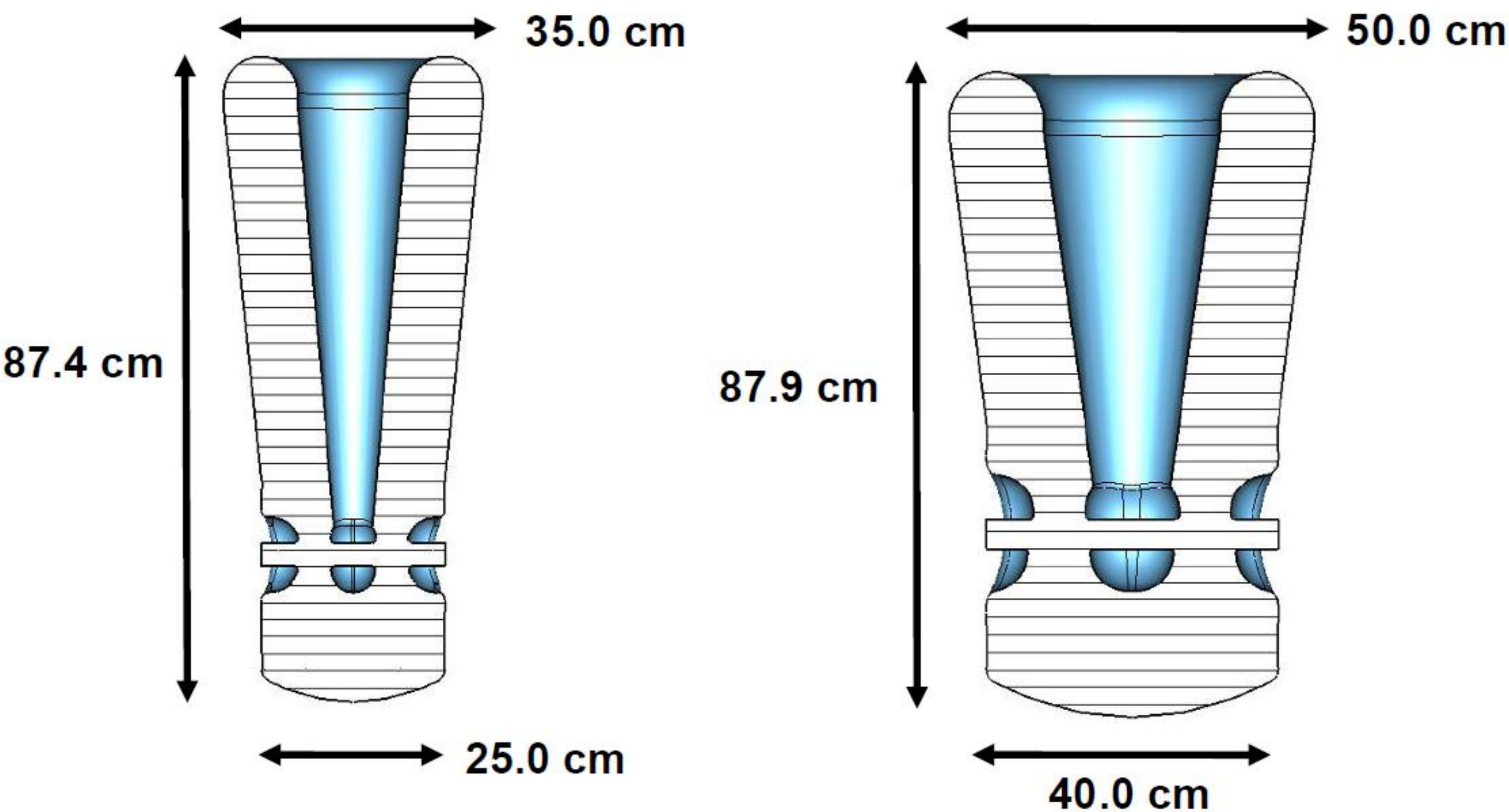
Donut-Shaped vs. Race Track design: Shunt Impedance

R/Q = V^2/ωU, ωU is the same in MW-Studio → R/Q α V^2



- The Donut-Shaped has a 32% higher shunt impedance due to the narrower acceleration gaps (a better transient time factor)
- The donut-shaped cavity is capable of delivering 2.1 MV at 36 MV/m and 43 mT or 3.4 MV at 59 MV/m and 70 mT

Final designs of the 109-MHz QWRs



Geometries and dimensions for the low-β (left) and the high-β (right) cavities

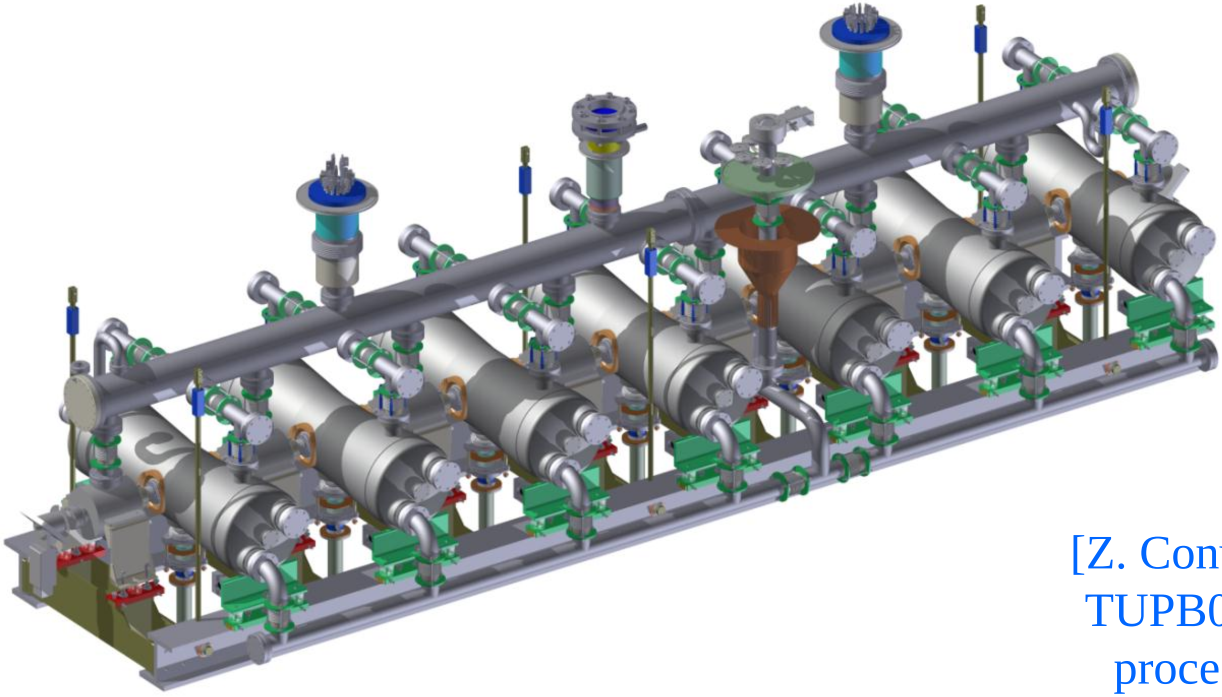
The steering correction is achieved by introducing a drift tube face tilt angle to compensate the QWR non-symmetric magnetic component.

Physics design of high-intensity linacs

- The transverse and longitudinal wave numbers, κ_{T0} and κ_{L0}, for zero beam current must change adiabatically along the linac
- This feature minimizes the potential for mismatches and helps to assure a current-independent lattice and its tune.
- The wave numbers of particle oscillations are expressed as $\kappa_{T0}= \sigma_{T0}/L_f$, $\kappa_{l0}= \sigma_{l0}/L_f$, where σ_{T0} and σ_{L0} are the zero-current transverse and longitudinal phase advances per focusing period of length L_f .
- An adiabatic change of the real-estate accelerating gradients and focusing fields is required to fulfill these conditions. Fulfillment of these conditions results in a current-independent tune of the SC linac section.
- In the proposed lattice design for both frequency options we follow this concept very closely with a focus on minimizing the number of cavities and solenoids for cost efficiency.

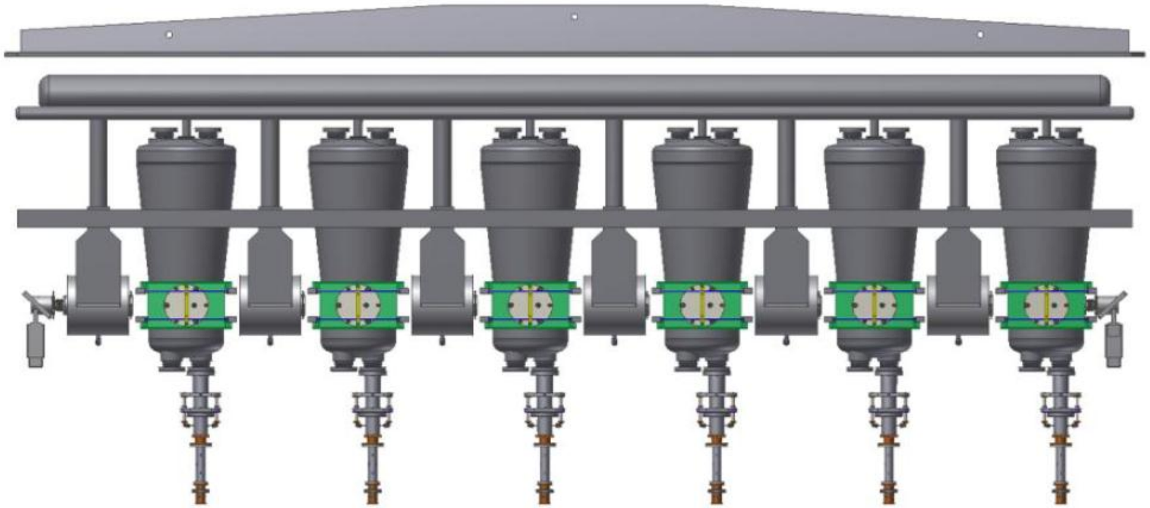
176 MHz Cryomodule Design

- First low-β cryomodule: BPM, Solenoid, Cavity per focusing period
- High-β cryomodule: 3 focusing periods, 2 HWRs each, and 1 HWR in the 4th period.

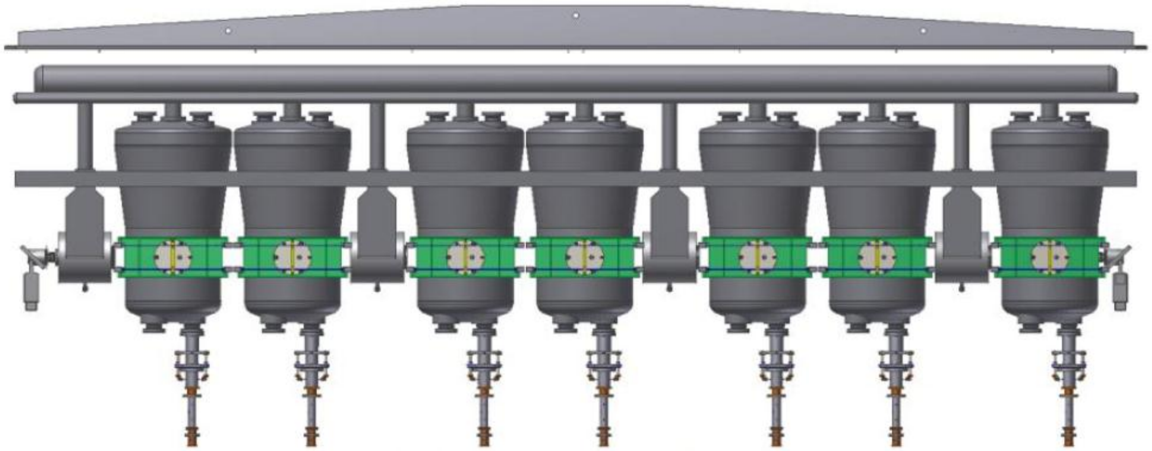


[Z. Conway et al, TUPB068 these proceedings]

The 109 MHz SC modules



109 MHz Low-Beta Cryomodule Lid with Cavity String



109 MHz High-Beta Cryomodule Lid with Cavity String

low-β (top) and high-β (bottom) lattice design

109 MHz Linac vs. 176 MHz linac

- 109 MHz requires one cryomodule less but a new RFQ
- Apertures can be made larger
- Higher shunt impedance
- Requires new RF system
- 176 MHz is a more familiar frequency; the RF system can be made domestically
- In terms of beam dynamics they are very similar

176 MHz Lattice Beam Dynamics & Errors Study

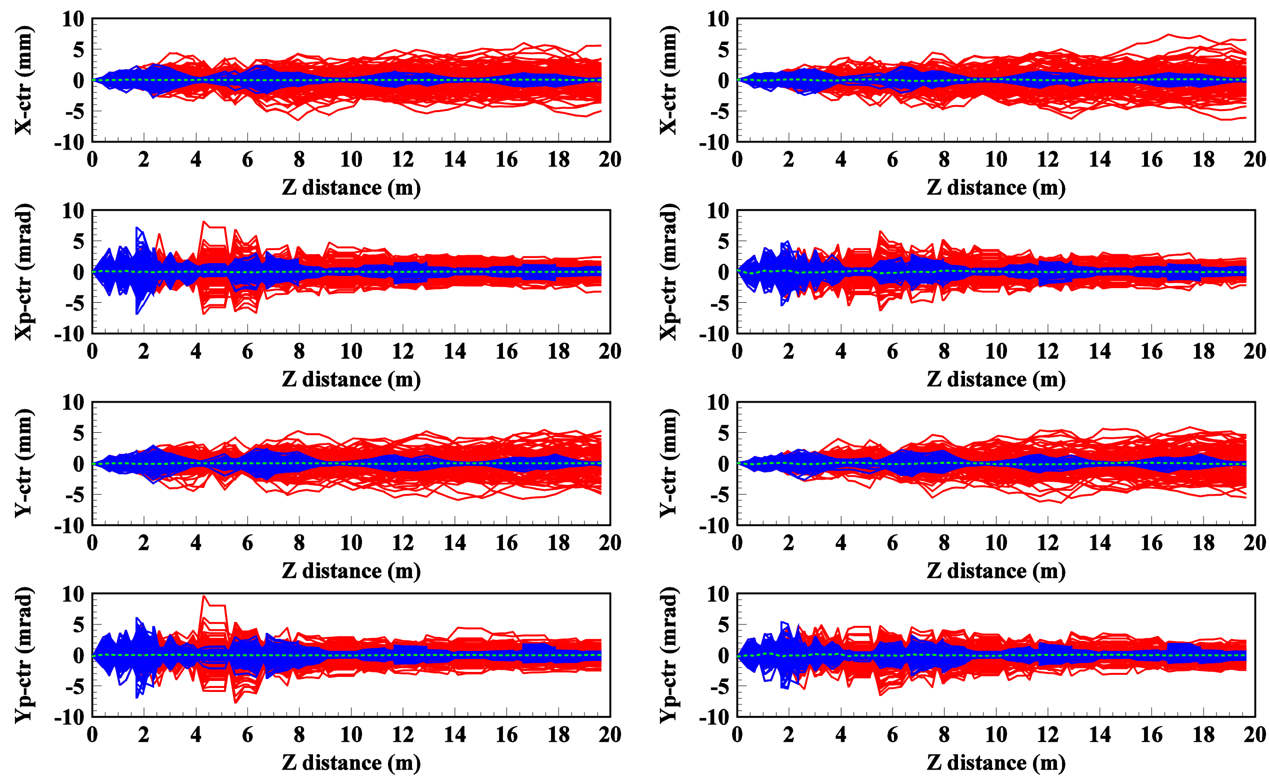
- A 5 mA proton/deuteron beam reaches 40 MeV with 28 HWRs
- The normalized rms emittance growth for a typical run, is a few percent
- No losses were found in 100 runs with errors and 100k macro particles

Applied Errors:

Cavity & Solenoid Misalignments: 500 µ

Cavity Phase: 0.5 deg

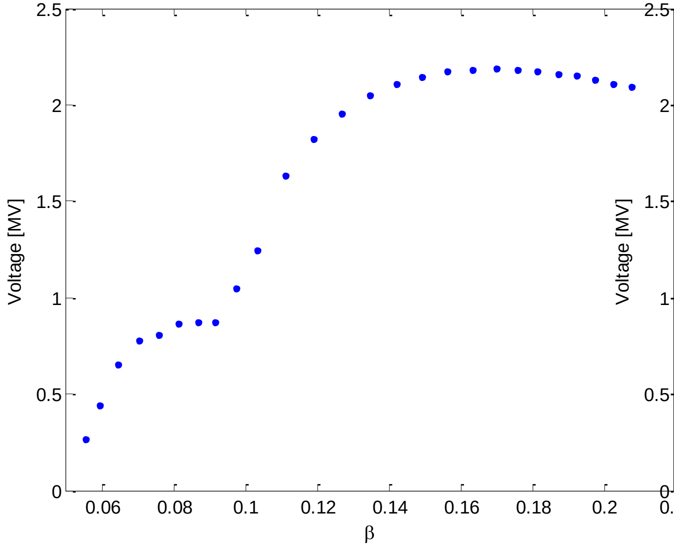
Cavity Field: 0.5 %



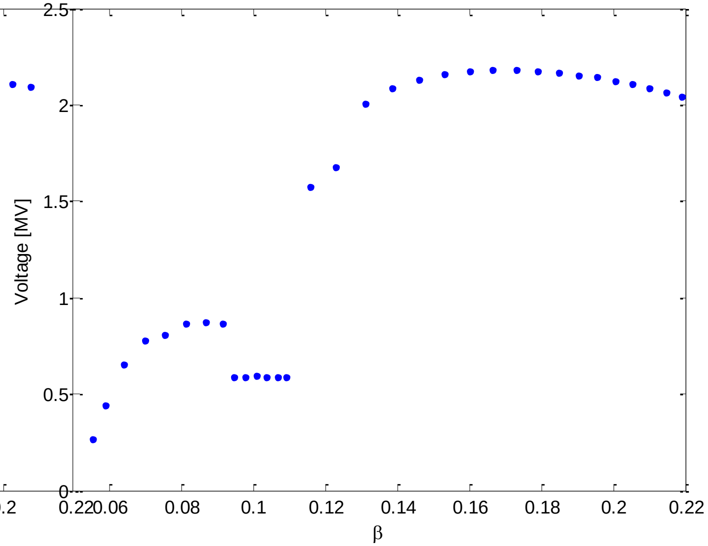
Centroid motion along the linac before (Red) and after (Blue) correction. The correction uses only 2 correctors and 2 monitors per cryomodule.

INTEGRATING SARAF PSM IN SARAF PHASE II LATTICE

- The existing SARAF Phase-I prototype SC module (PSM) can be used as a second low-β cryostat in Phase II.
- The PSM cavities were set at 600 kV, 70% of their original design voltage.
- The result is an additional 5 MeV energy gain for deuteron
- 3 MeV are gained at the PSM
- 2 additional MeV are the result of a better velocity matching downstream of the PSM

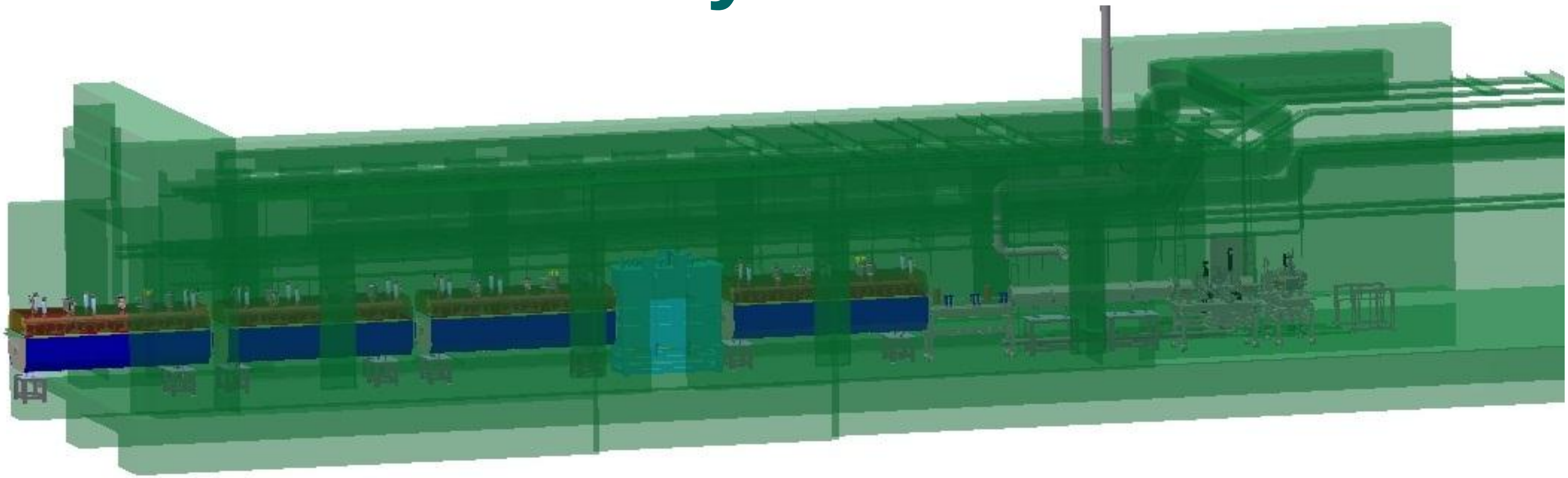


Phase II

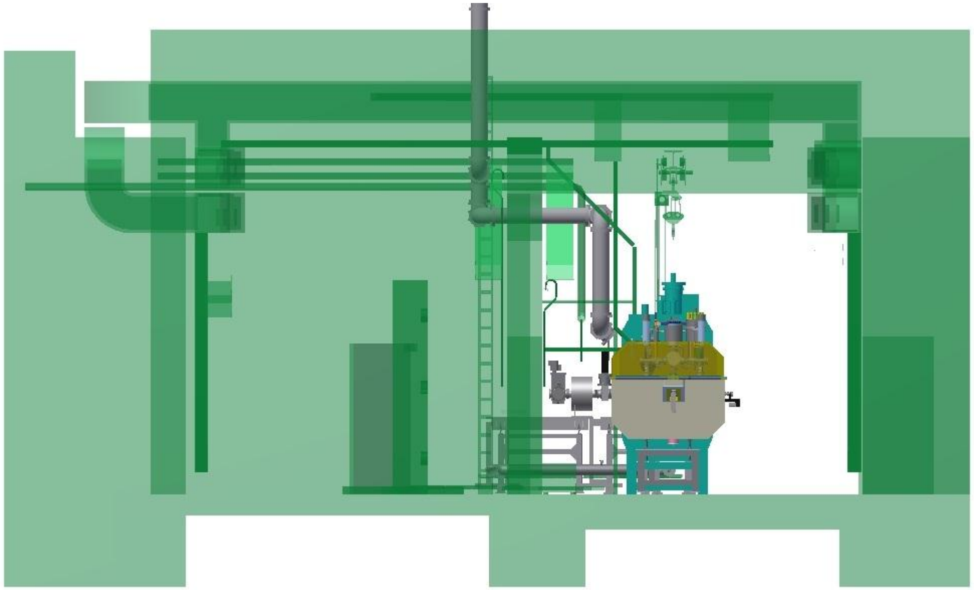


Phase II with the PSM

Accelerator Layout with the PSM

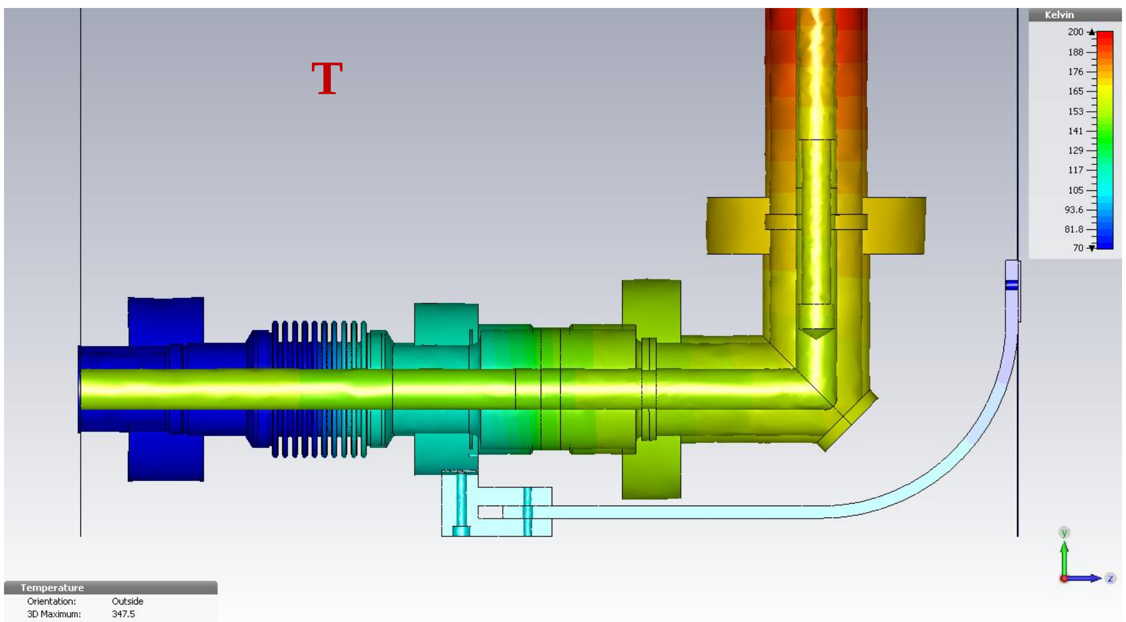


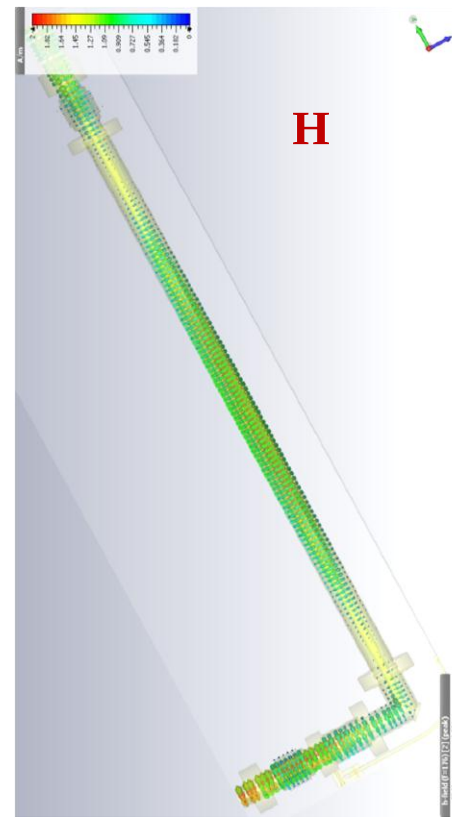
- The ion source and LEBT are in the original position.
- New RFQ, MEBT, and superconducting linac.
- PSM included.



Analysis of the PSM coupler

- RF thermal co-simulation analysis of the PSM HWR coupler cold window temperature rise during 4kW beam operation is essential for integrating the PSM in Phase II





[CST Multi Physics]

Summary

- Two linac options based on 109 MHz QWRs and 176 MHz HWRs capable to deliver 5 mA, 40 MeV proton and deuteron beams have been studied.
- Extensive end-to-end beam dynamics simulations iterated with the engineering design show that both options can hold the hands-on maintenance criterion which is vital for a high intensity machine.
- As there are only slight differences between both options, the SARAF project adopted the 176 MHz HWR linac since it will be a smooth transition from phase I.
- Furthermore, with some modifications, the current SARAF PSM can be included in the Phase II lattice