Seminar at CEA/Saclay

Accelerator R&D for CW Ion Linacs

P.N. Ostroumov

June 29, 2015

Content

- CW ion and proton linacs
- Example of a normal conducting CW RFQ
- Cryomodule design and performance
- High performance quarter wave and half wave SC resonators
- RF couplers, tuners
- SC solenoids
- Applications of CW linac technology

Abstract

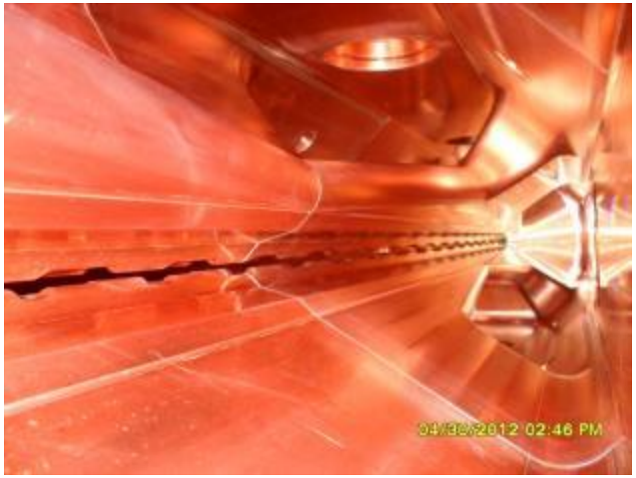
- Substantial research and development related to continuous wave (CW) proton and ion accelerators is being performed at ANL. This includes both normal conducting and SC accelerating structures. Primary focus of this talk will be on technologies which we apply for the development of RFQ, quarter-wave and half-wave resonators for the ATLAS upgrade and FNAL Proton Improvement Plan. Application of these technologies to FRIB driver linac and 40-MeV deuteron linac will be also discussed.

Superconducting CW Ion Linear Accelerators

- Only SC technology can support CW ion linacs if required beam energy is above several MeV/u
- Heavy-ion linacs, beam space charge is not significant beyond the ion sources
- Linacs for light ions: Protons, H-minus and deuterons. Beam space charge is significant
- SC Linac always includes normal conducting front end
- Heavy ion Linacs: 300-500 keV/u
  - High accelerating gradients can be effectively used due to m/q>1
- Light ion Linacs (protons, H-minus, deuterons): 2-7 MeV
  - Higher energy is better to suppress space charge effects, however it is limited by complexity and cost of a NC RFQ
- In the SC section (low and medium energies) compact accelerating-focusing structures are required
  - Short focusing periods to control strong RF defocusing and space charge
  - Possibility to apply high accelerating gradients
  - Avoid long drift spaces to minimize amplification of phase errors

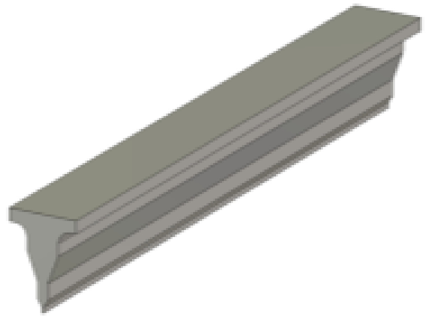
ATLAS 60.625 MHz CW RFQ

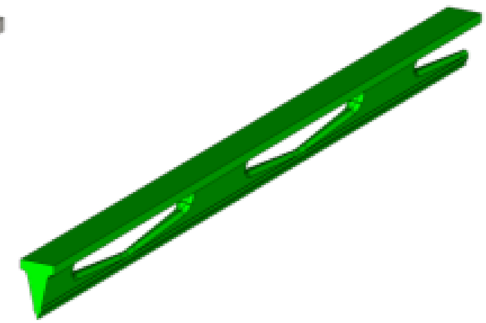
	Parameter	Value
1	Duty cycle	100%
2	q/A	1/7 to 1
3	Input Energy	30 keV/u
4	Output Energy	295 keV/u
5	Average radius	7.2 mm
6	Vane Length	3.81 m
7	Inter-Vane Voltage	70 kV
8	RF power consumption	60 kW

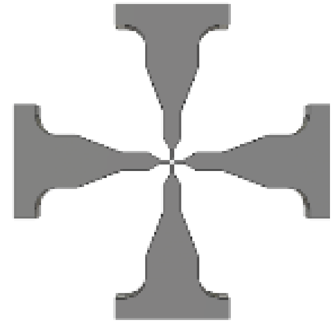


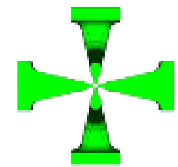
RF Structure

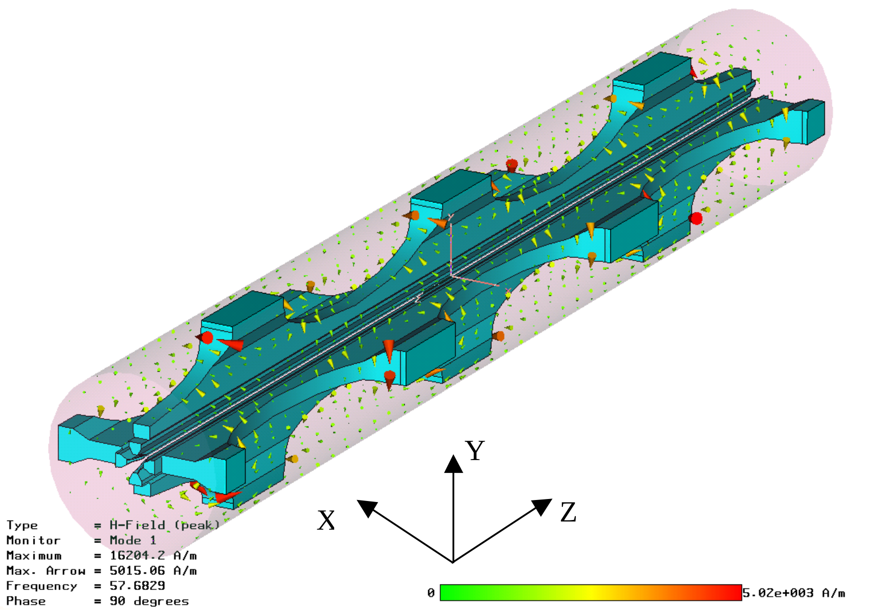
- Multi-segment split-coaxial RFQ
  - Relatively small transverse dimensions
  - Strongly coupled structure
  - Non-operational frequencies far away from the operational one

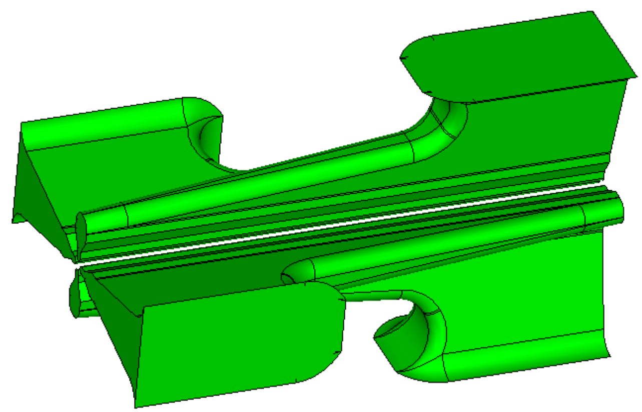






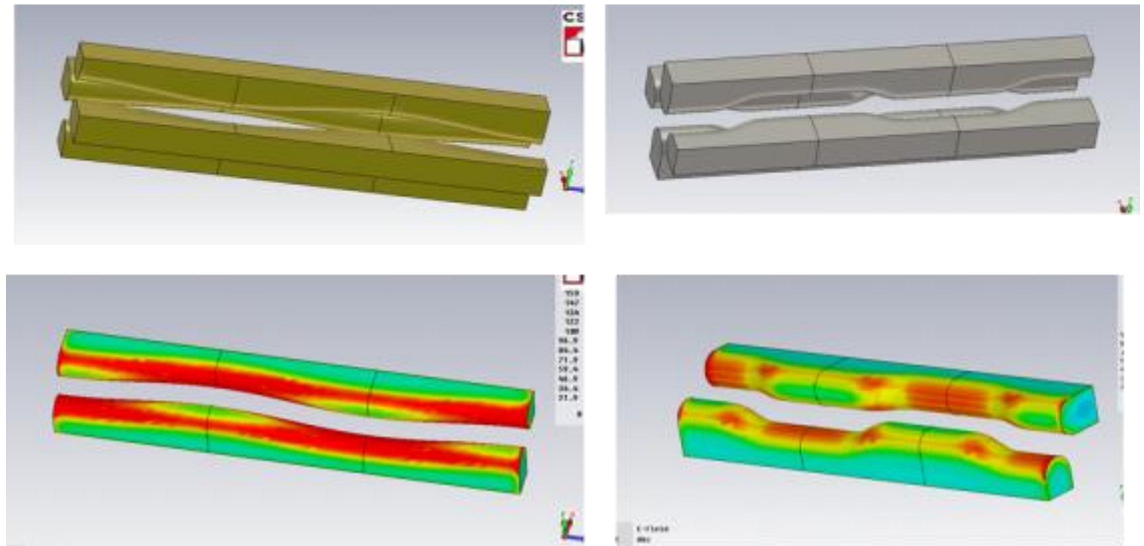


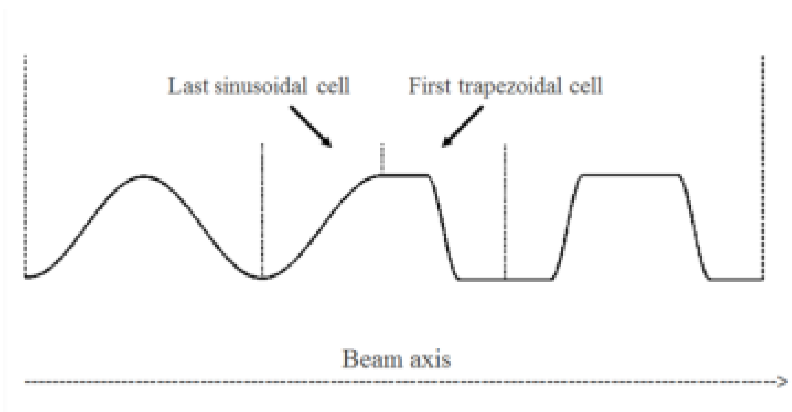


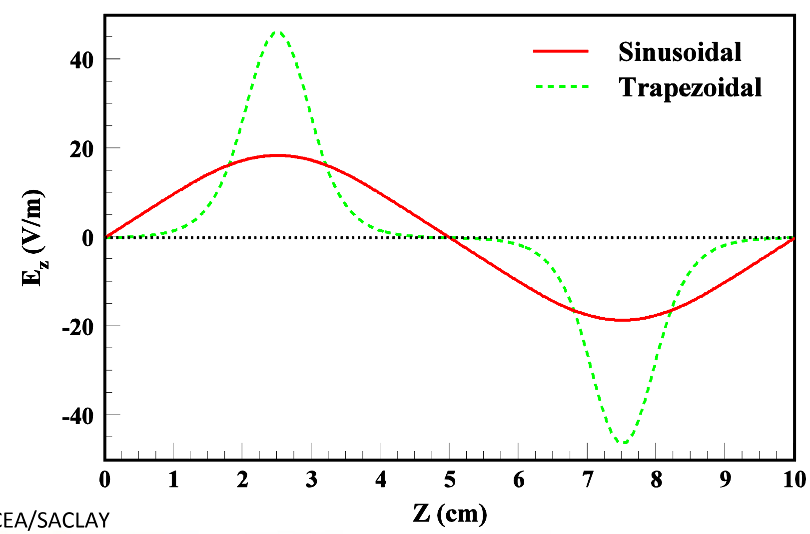


Trapezoidal Vane Tip Modulation

- Increased acceleration efficiency due to higher transit time factor

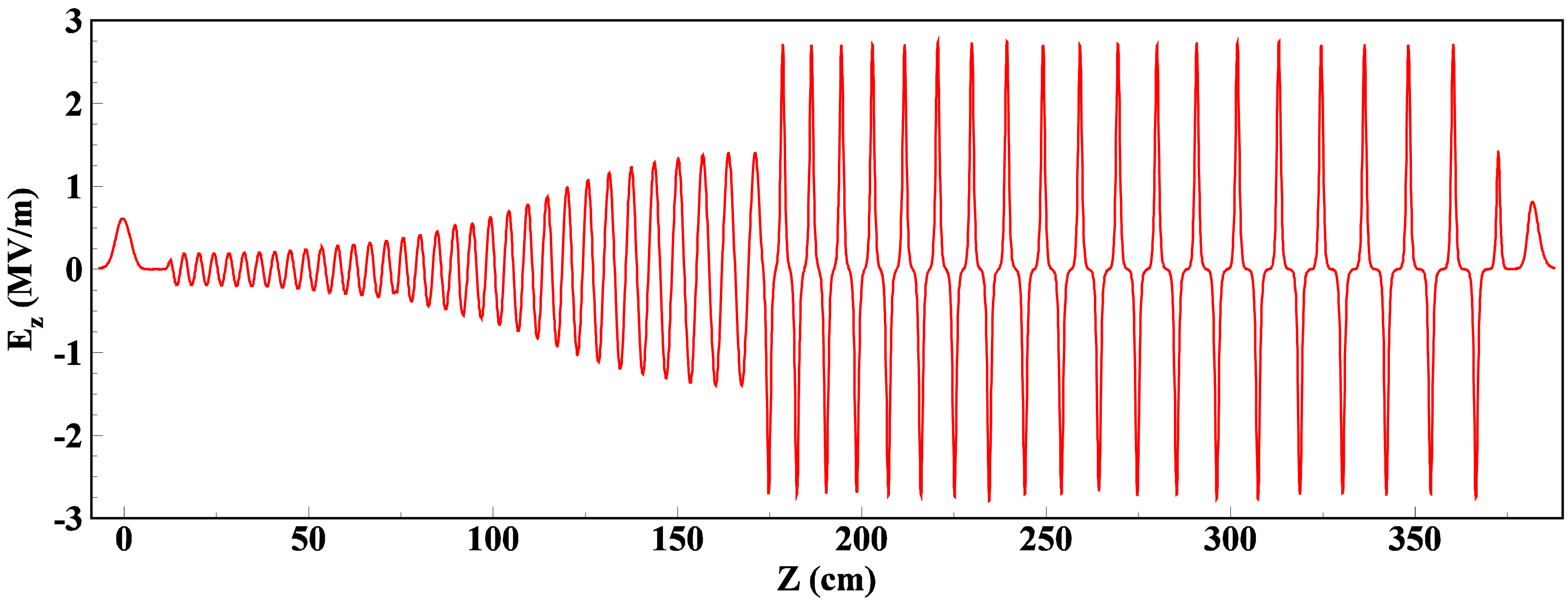






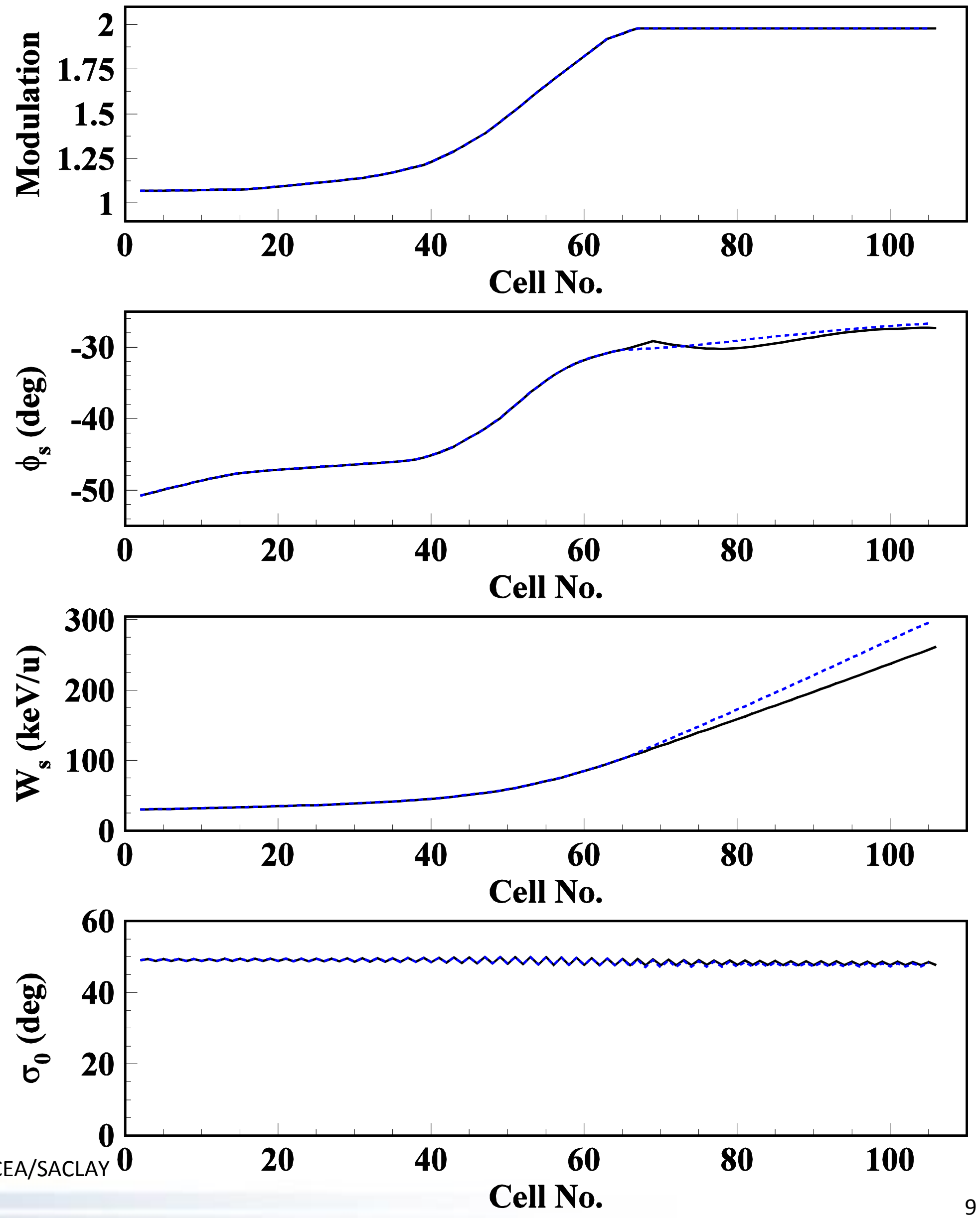
Accelerating Field Distribution Along the RFQ

- Sinusoidal modulation   Trapezoidal modulation



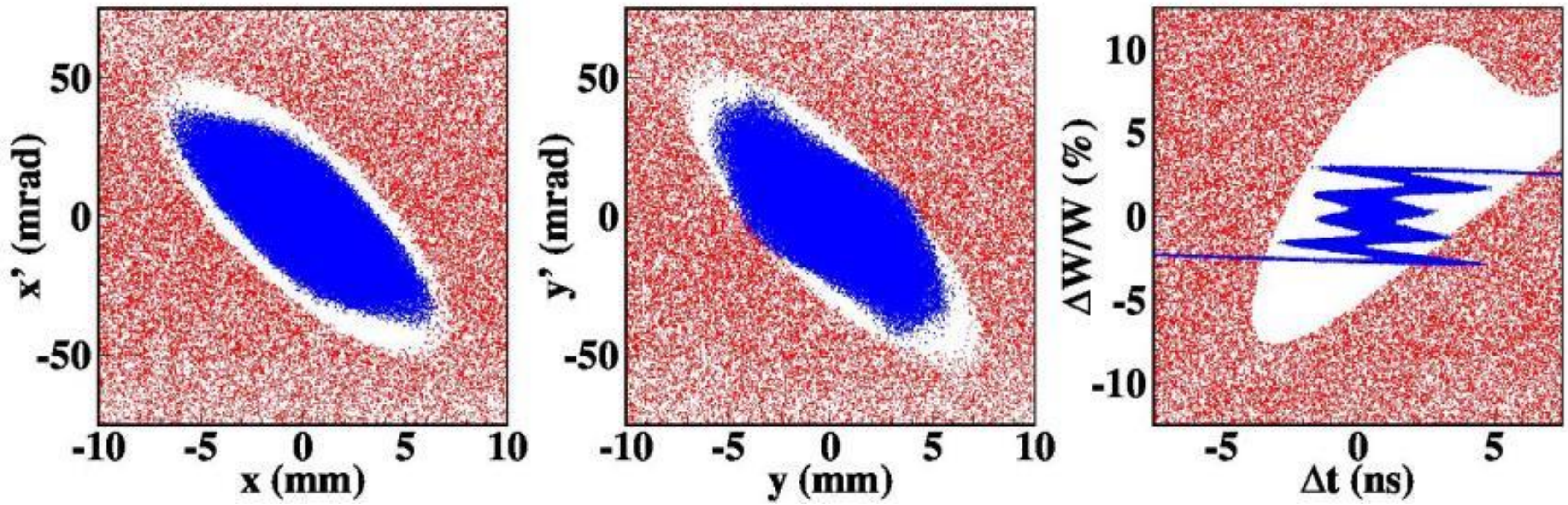
RFQ Parameters

- Comparison of fully sinusoidal and trapezoidal modulations
- Trapezoidal in the acceleration section only



Beam Dynamics

- RFQ is designed to provide very low longitudinal emittance
- 4-harmonic pre-buncher is used
  - 12.125 MHz is the fundamental frequency of bunching
- Extensive beam dynamics studies were reported in PRST-AB
  - 2-term potential
  - 8-term potential
  - Fully 3D from CST EM and MWS studio



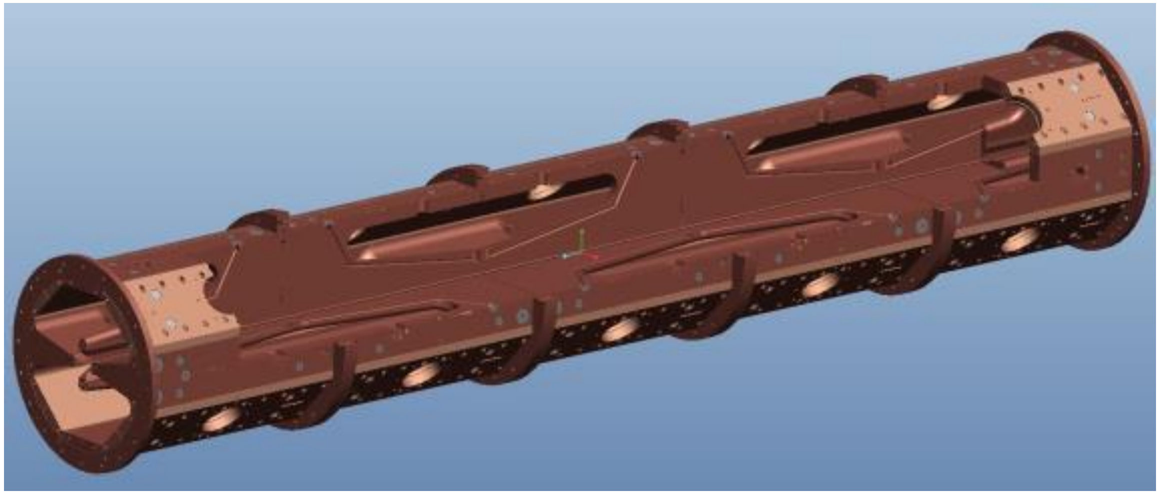
ANL RFQ Highlights

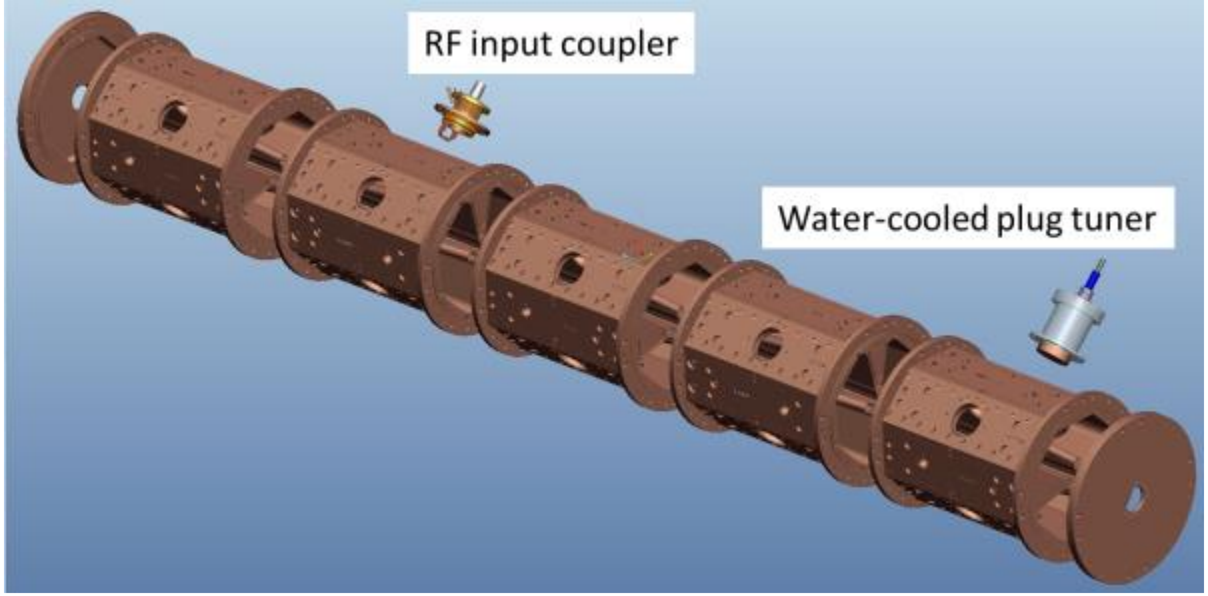
- Highly coupled EM structure
  - "flat" field distribution, non-operational modes are separated more than by 10 MHz
  - "bead-pull" tuning is not required
- Conservative design, peak field is 1.5 Kilpatrick, 1.8 Kilpatrick at very small spots in the section with trapezoidal modulation
- Trapezoidal modulation
  - Increases shunt impedance by 60%
- A short output radial matcher to form axially-symmetric beam
- Fabrication:
  - Precise machining, no alignment necessary
  - 2-step brazing in a high temperature furnace
- No "cold model"– was directly built from CST MWS geometry
- Measured Q-factor is ~94% of the MWS calculated Q_0 for annealed oxygen free copper

Fabrication Technology

- The RFQ is designed as a 100% OFE copper structure including flanges and end caps, fabrication process
  - Delivery of raw copper. Copper samples are checked for low oxygen content.
  - Preliminary machining of vanes, quadrants, and end caps; drilling of water cooling channels; and high-temperature furnace brazing of water channel plugs using a 35-65 Au Cu alloy in a hydrogen atmosphere.
  - Hydrostatic pressure testing of the cooling channels.
  - Final machining of all parts, including vane tip modulation, cleaning
  - Fabrication of the fixture required for segment assembly, lifting, and transportation. Fabrication of the cavity support fixture to be used in the furnace.
  - Assembly of each segment; pre-braze machining to install end flanges. Frequency check of individual segments. Disassembly of segments and cleaning of all parts in a heated Citranox bath. Assembly and preparation to load into the furnace in vertical orientation.
  - Final brazing using CuSil alloy in a hydrogen atmosphere.
  - Post-brazing final machining. RF measurements and final cleaning of segments in a heated Citranox bath. Vacuum leak check of segments.
  - Assembly of the segments and end flanges. Installation of external water-cooling pipes, water-cooled tuners, pick-up loops, driving loops, RF transmission line, and vacuum system components.

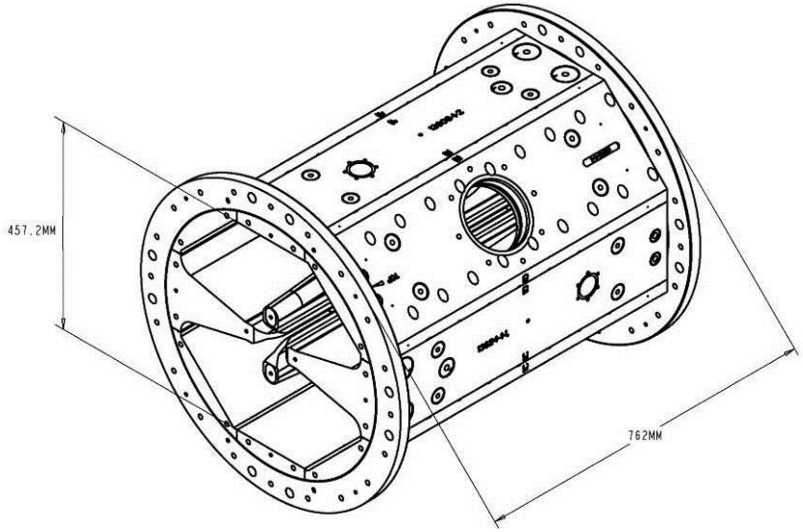
Mechanical Design: 5 Segments Bolted Together



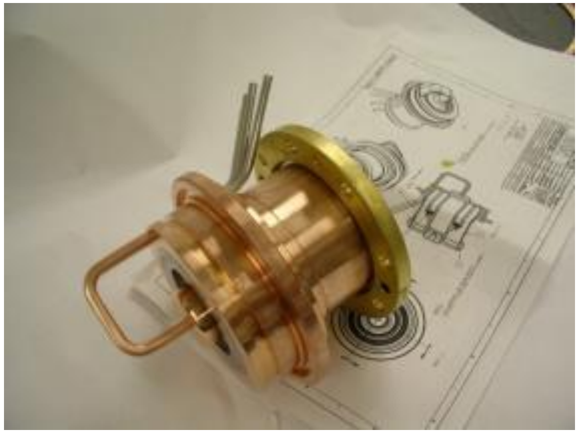


Components

- The first segment



Vacuum “grill”



- RF coupler

Fabrication Steps

Copper Ingots

Machining

First Vane

ANL Inspection During Manufacturing

Second (Final) Brazing

- Final brazing alloy is CuSil (28% copper, 72% silver)

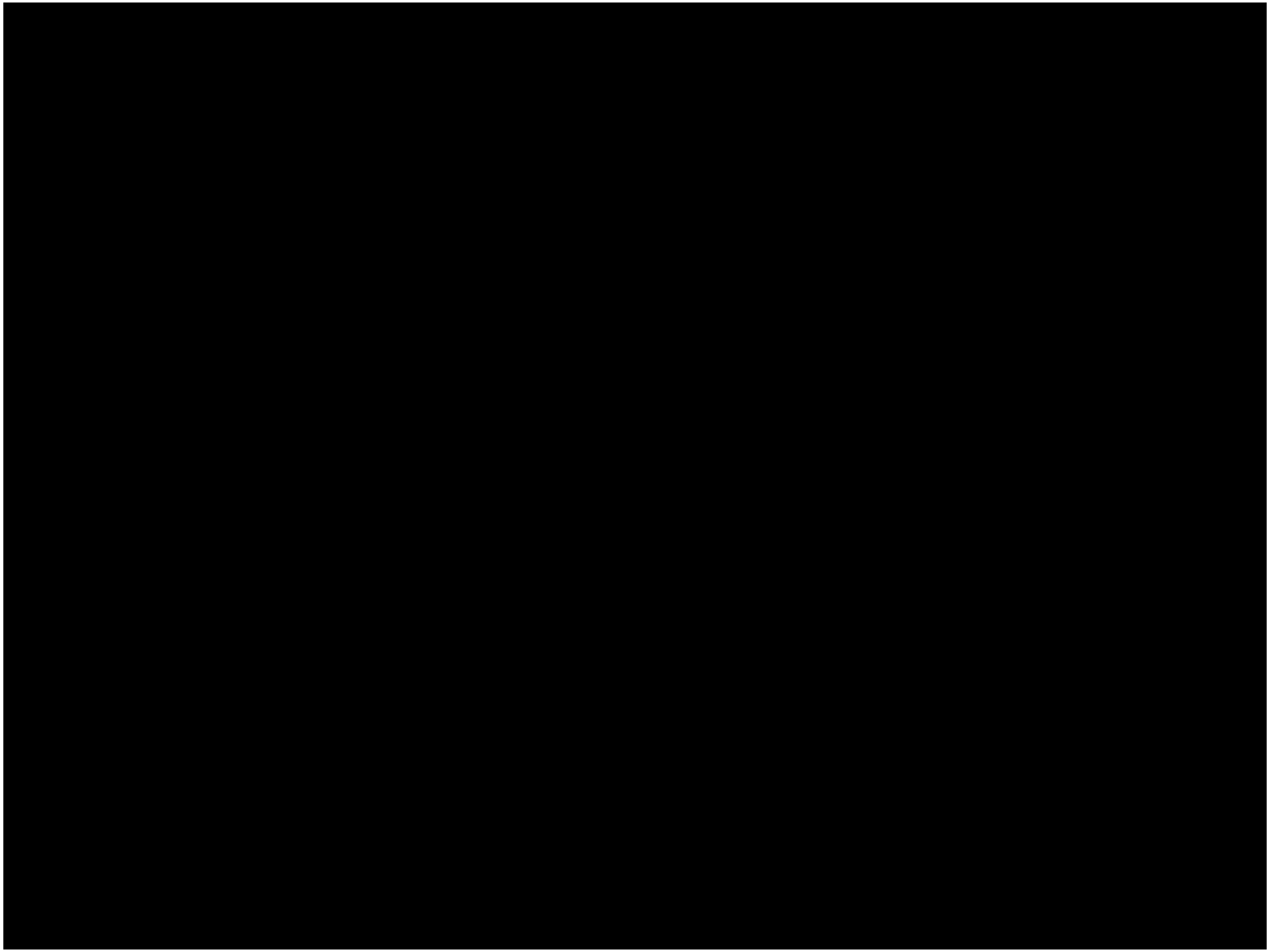
Brazing in California

Segment #1

- Pre-brazed assembly

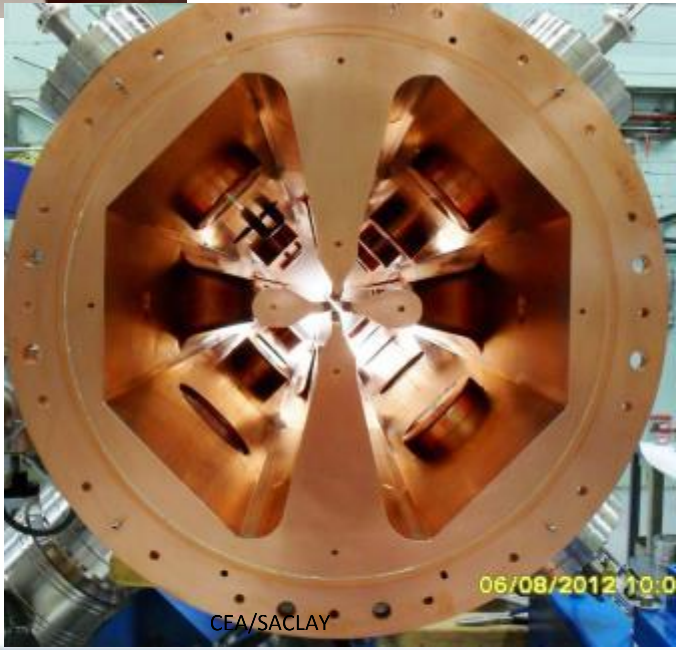
After the brazing

Pin Drop



RFQ assembly after installation of tuners, RF couplers, pick-up loops, vacuum pumps, and vacuum gauges.

Internal Views of the RFQ After Completed Assembly



Off-Site Beam Test (July 2012)

1—All permanent magnet ECRIS installed on HV platform;

2—LEBT;

3—pepper-pot emittance probe;

4—matching quadrupole triplet;

5—RFQ,

6 —RF amplifier;

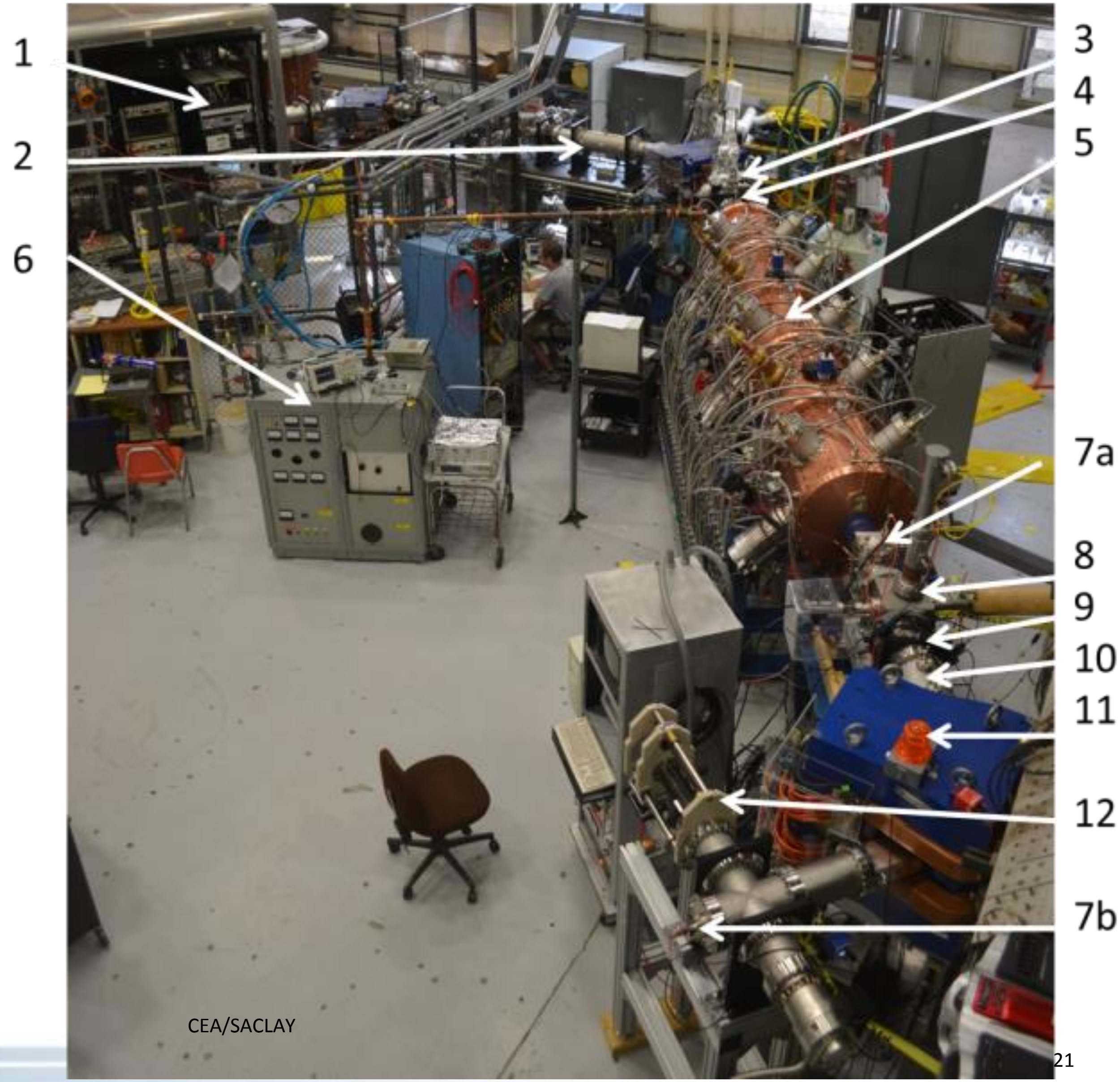
7a, 7b—water cooled Faraday cup;

8—bunch shape monitor;

9—rotating wire scanner;

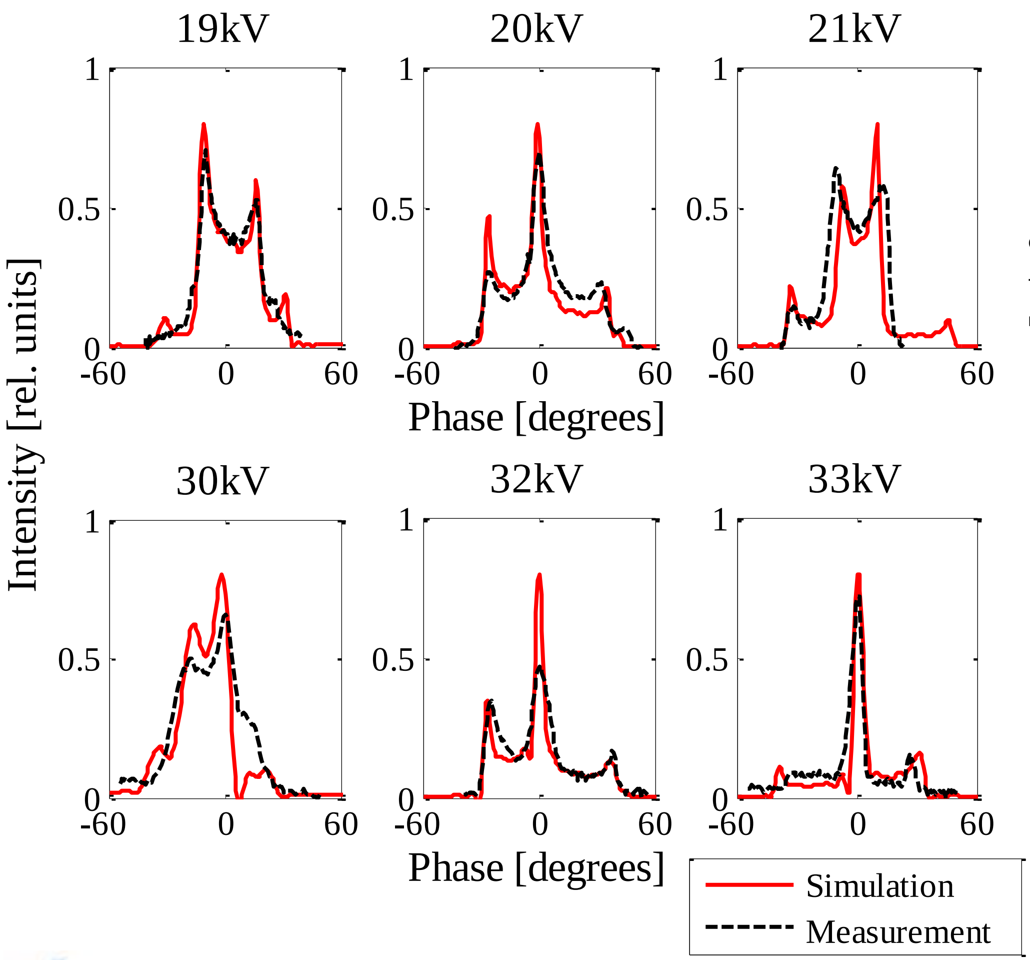
10—electrostatic doublet; 11—70° bending magnet;

12—water cooled movable horizontal jaw slits.

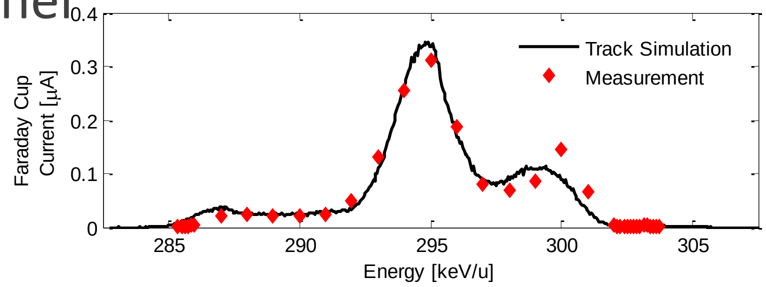


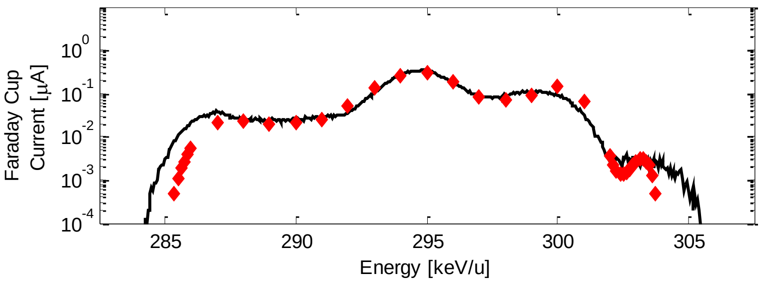
Bunch Shape, Energy Spread and Transverse Profile

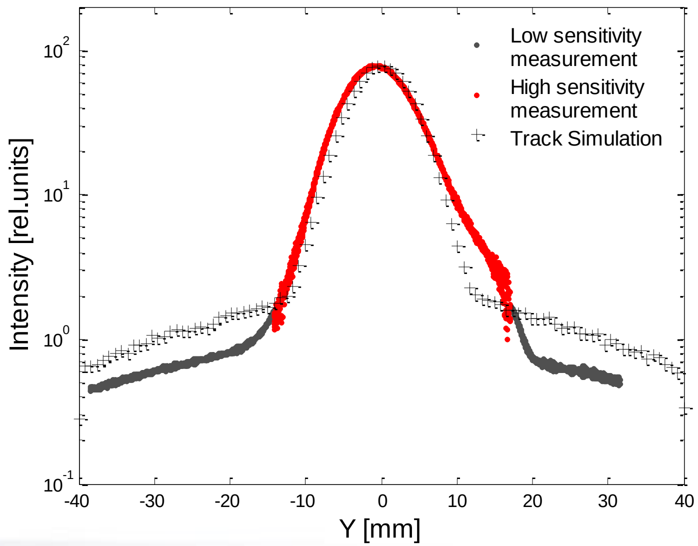
- Off-line testing without external buncher
- Simulation with TRACK code



CEA/SACLAY

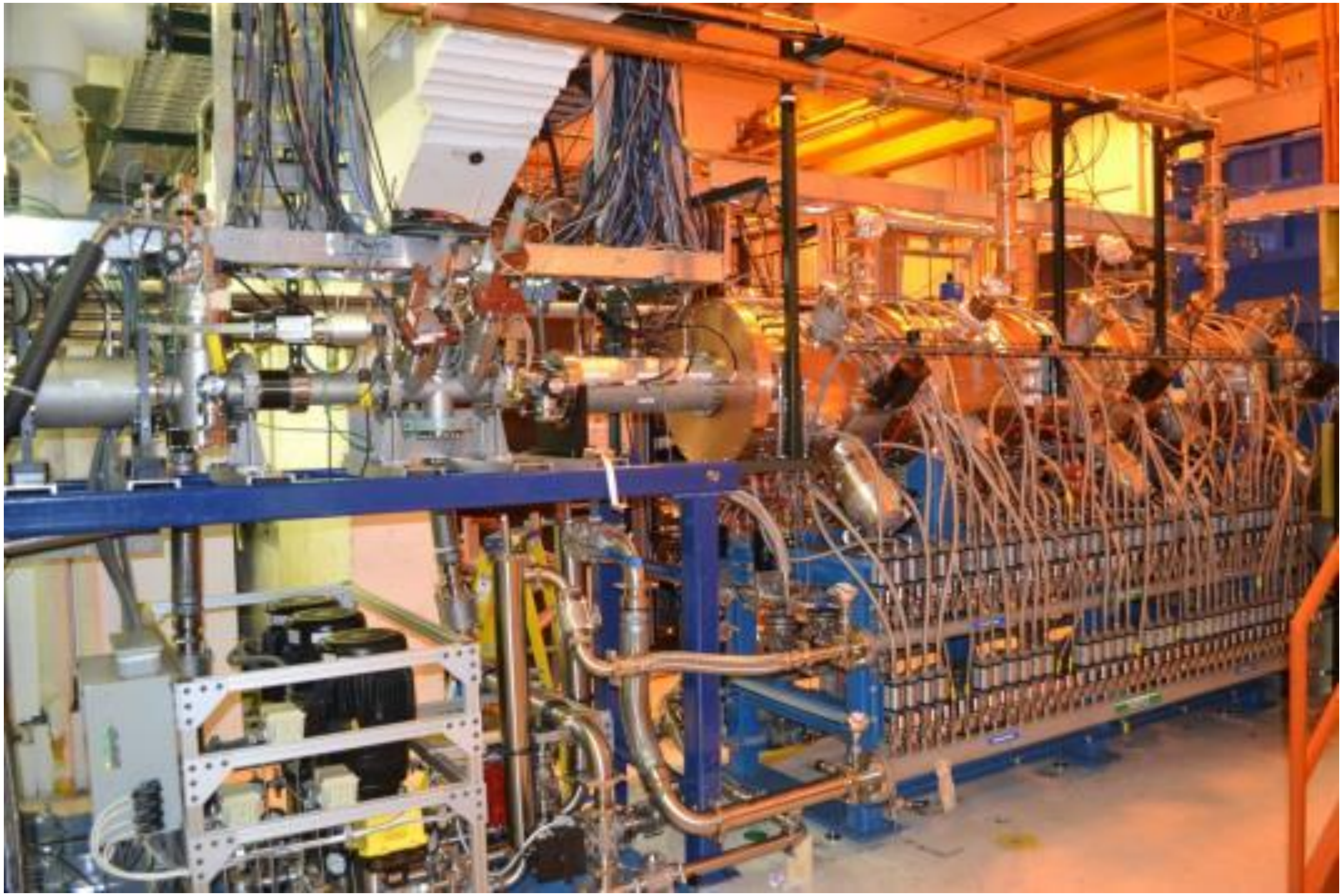






ATLAS with New CW RFQ

- 100% beam transmission to the physics experiments
- Efficiency is in creased by factor of 2



Water pumps and mixer

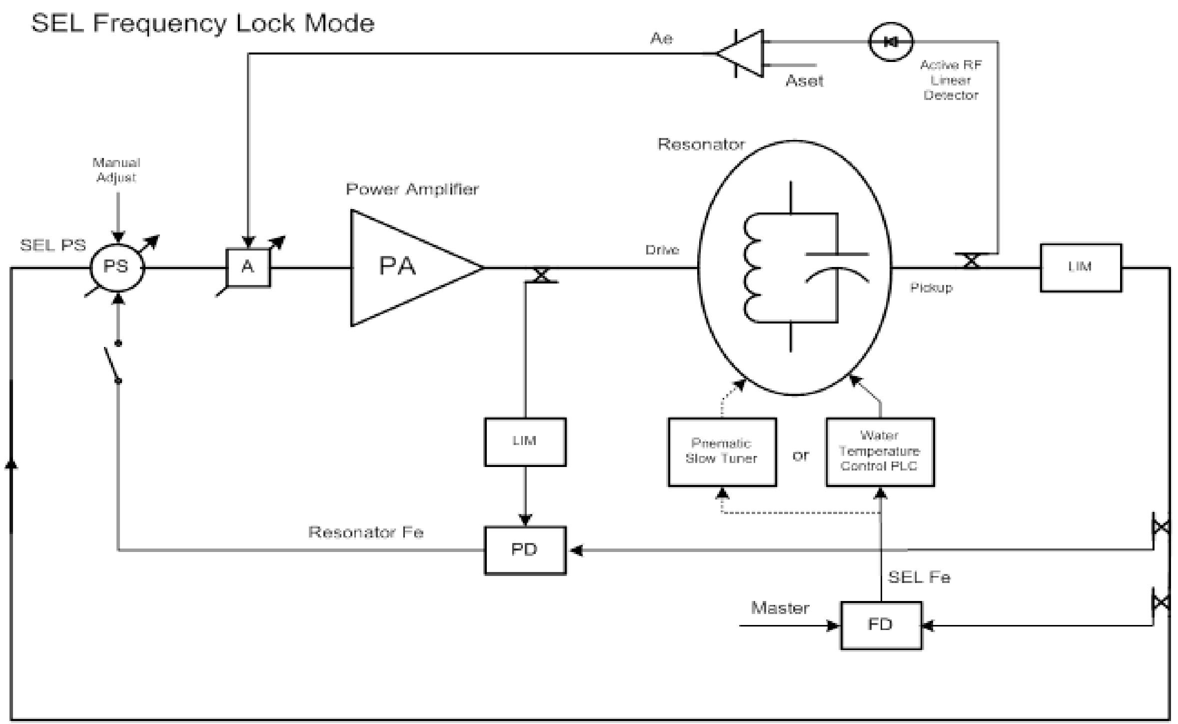
RF System

- Two 60-kW tetrode amplifiers

RF circulators

RFQ RF Control System – Multiple Modes

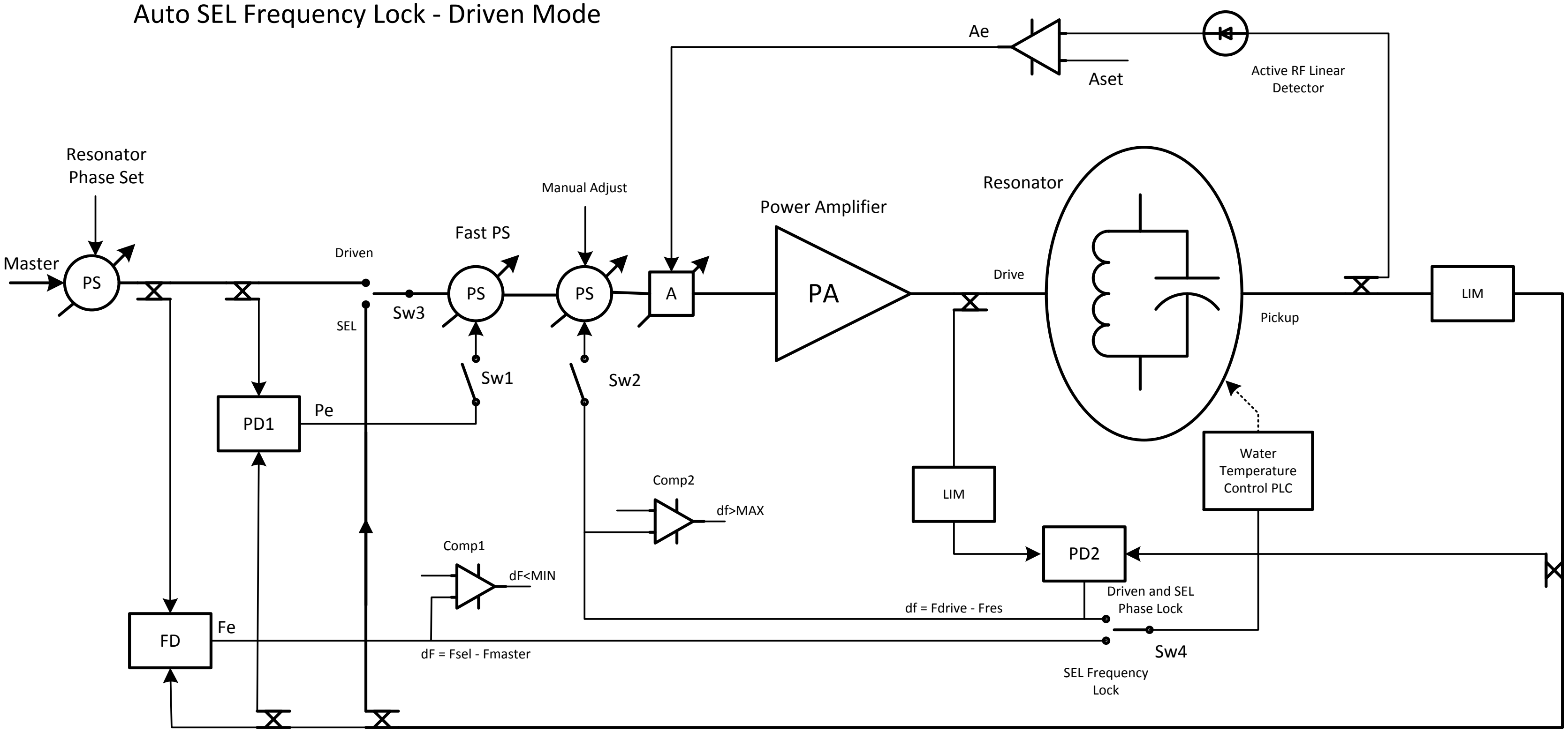
- Self-excited Loop-Frequency Lock Mode
  - provides shortest resonator "on-frequency tune" time
  - allows resonator detuning range, defined by Frequency Detector bandwidth (> 10 resonator bandwidths), while maintaining a matched condition for the 60kW amplifiers
  - does not phase lock the cavity for beam acceleration



RFQ RF Control System – Multiple Modes

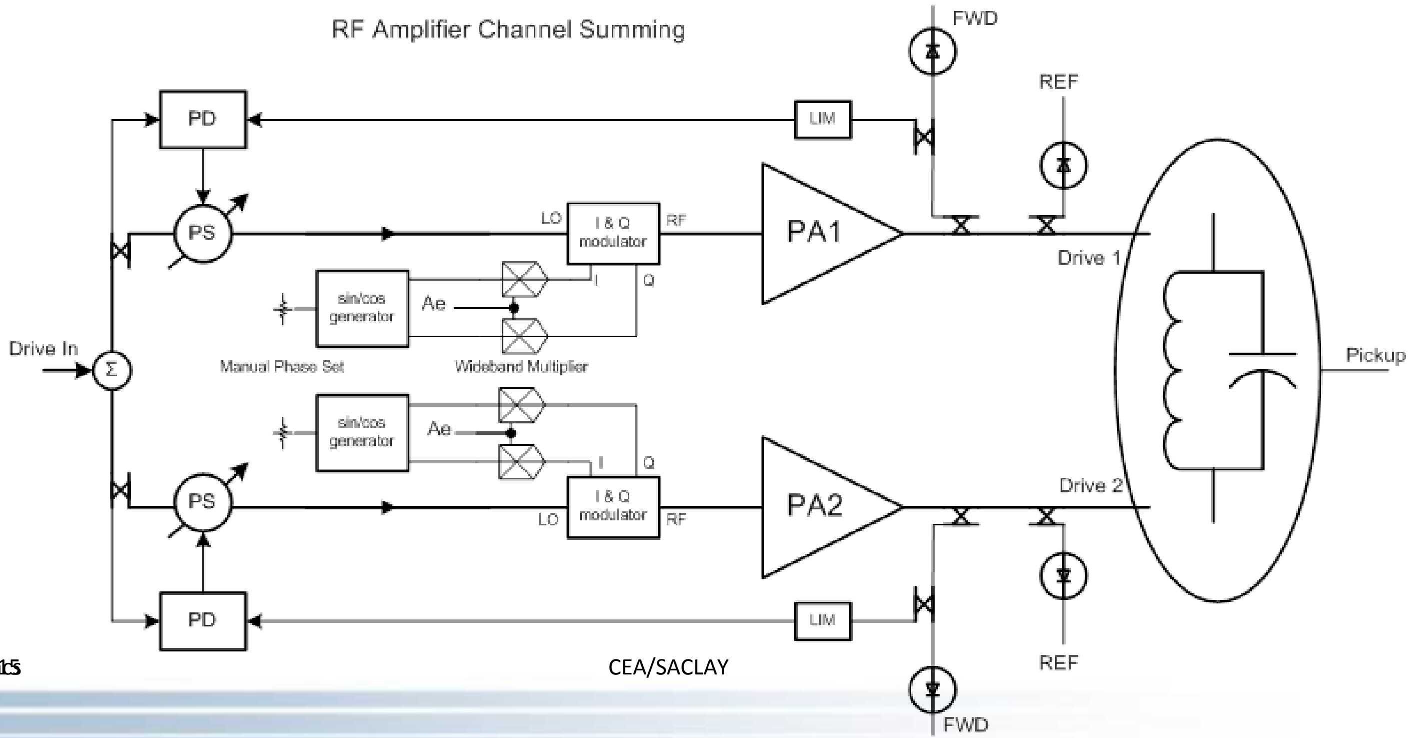
- Driven Mode
  - Power amplifiers are driven at the Master Oscillator frequency
  - allows phase lock mode for beam acceleration
  - has a limitation of 2kW for reflected power (before the installation of the circulator)

Auto SEL Frequency Lock - Driven Mode



Summing Two RF Amplifiers for ATLAS RFQ

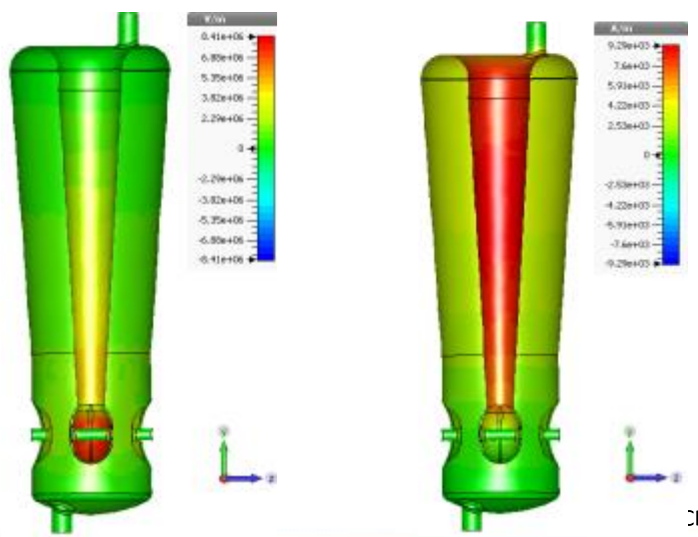
- Two individual phase stabilization loops
- I&Q modulator used as 360 degrees phase shifter and fast amplitude regulator
- VSWR Trip Protection and other protection and recovery modes
- The RFQ has two power couplers each driven by a 30 kW amplifier
- This reduces the maximum power requirements of the drive couplers
- Also reduces the maximum power output of each amplifier



QWRs and HWRs

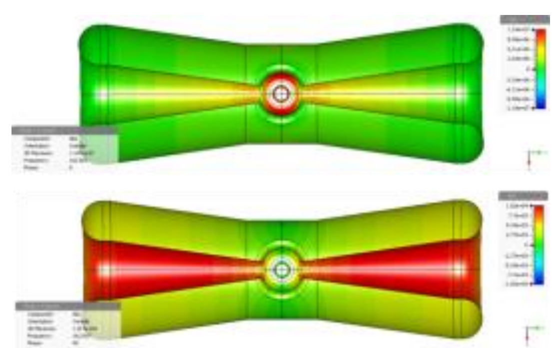
- New approach in the EM design and optimization
  - Conical shape to reduce peak magnetic field
  - Minimized RF losses: high shunt impedance and geometry factor
  - Integrated with the fabrication, processing and cleaning plans
  - Correction of dipole and quadrupole components
- Efficiently uses available space in the cryostat keeping the longitudinal dimension very compact

	QWR	HWR
Frequency, MHz	72.75	162.5
Optimal beta	0.077	0.112
V_{design}, MV	2.5	2.0
E_P /E_{ACC}, MV/m	5.16	4.7
B_P/E_{ACC}, mT/MV/m	7.6	5.0
G, Ohm	26	48
R_{sh}/Q, Ohm	575	271



CW

:EA/SACLAY



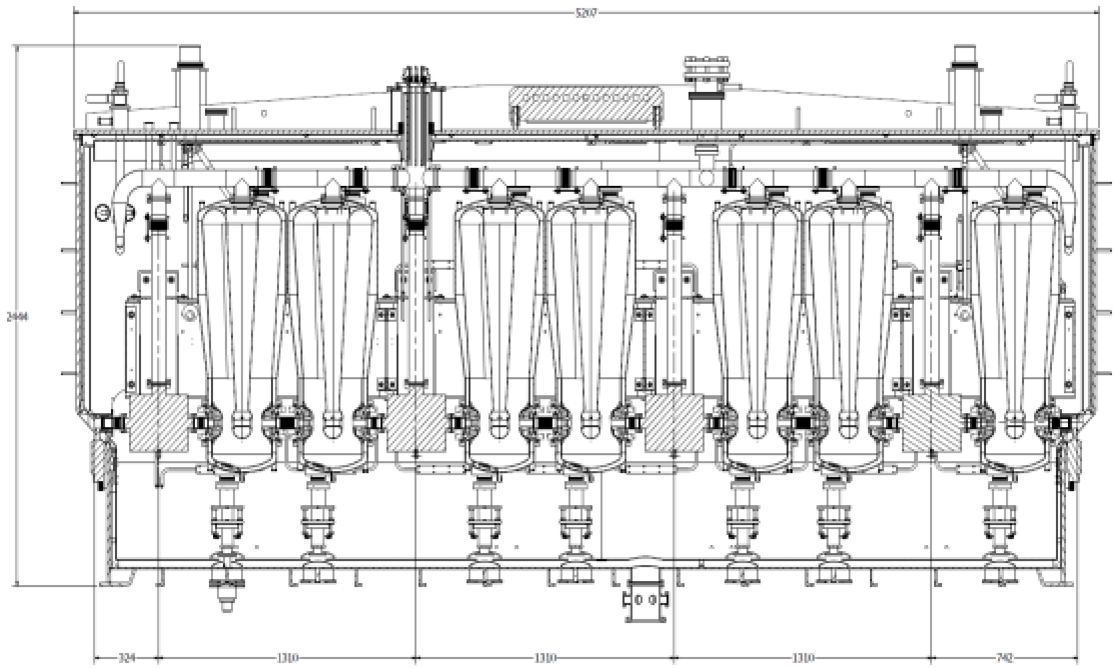
E-field

B-field

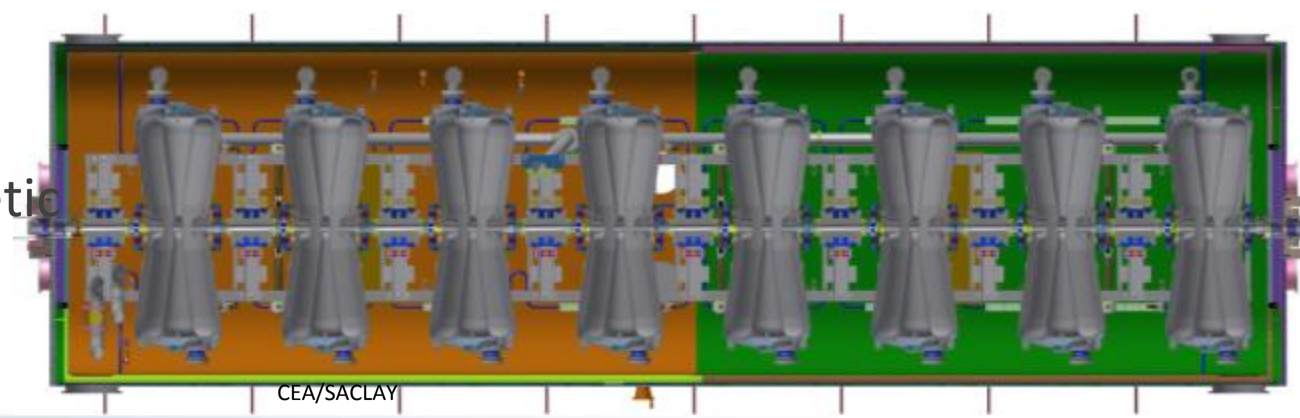
Compact Cryomodule Design

- Long cryomodule
  - Reduced drift spaces
  - Reduced heat load
- High packing factor
  - Reduced drift spaces
  - Short focusing period
- Separate vacuum
  - Clean RF space
- Titanium strongback
  - Facilitates easy alignment
- SS vessel, room temperature magnetic and thermal shield

Seven 72.75 MHz QWRs and 4 solenoids

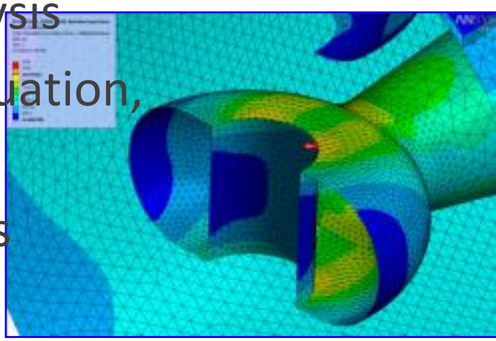


Eight 162.5 MHz HWRs, 8 solenoids and 8 BPMs

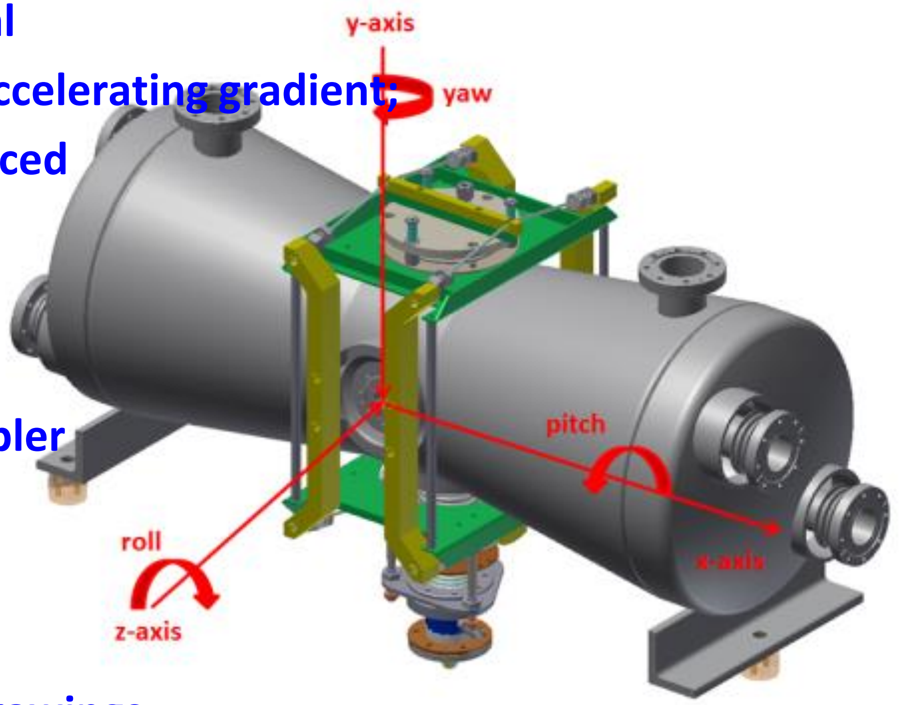


Engineering Analysis of Jacketed Cavity and Mechanical Design

- Mechanical stresses and displacements in niobium and SS vessel, compliance with pressure vessel code, safety analysis
- Minimization of frequency sensitivity to He pressure fluctuation, df/dP
- FEA analysis of the slow tuner, stresses and displacements



- In addition:
  - **Provide an overall compact mechanical design to maintain a high real estate accelerating gradient;**
  - **Provide coupling ports enabling advanced RF surface processing techniques;**
  - **Integrate a coupling port;**
  - **Facilitate the integration of several cavities and their sub-systems (RF coupler and tuners) into the cryomodule;**
  - **Provide a means for cavity alignment in the cryomodule;**
  - **Create a complete set of fabrication drawings.**

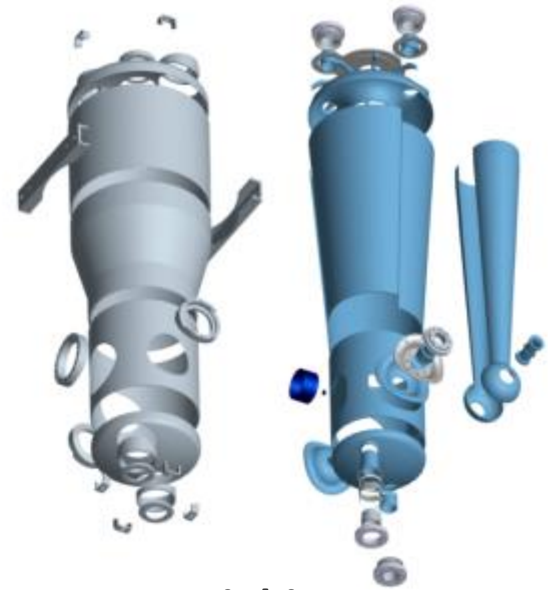


HWR - Fabrication Steps

- Forming of niobium parts (Deep drawing, hydroforming, die forming, machining)
- Wire EDM of EBW surfaces
- Electron beam welding
- Final wire EDM of the beam aperture
- Niobium-SS brazed transitions
- Installation of stainless steel helium vessel
- Cleaning, EP
- 625C baking
- Light EP, HPR
- Ready for cold testing

QWR

SS parts Niobium

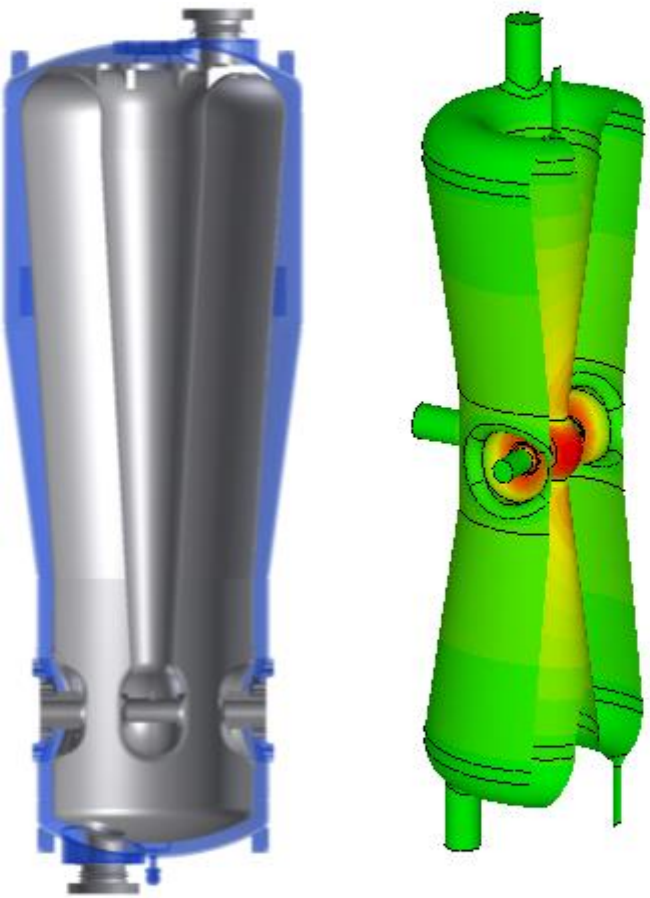


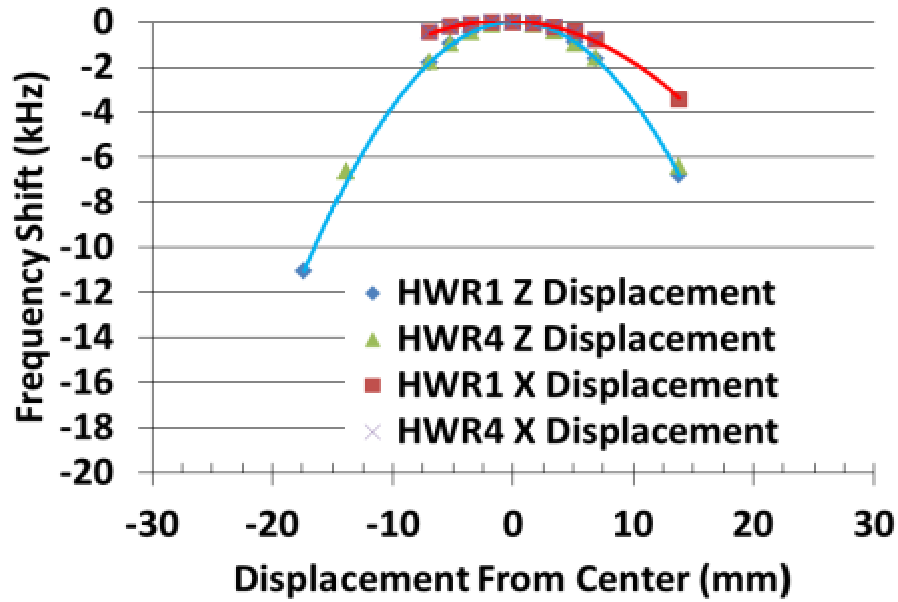
HWR Niobium parts

HWR (and QWR) Beam Aperture Alignment

- Design beam aperture = ϕ33.0 mm.
- Wire-EDM bore of the beam aperture gives very accurate results:
  - Aperture diameter tolerance ±0.04 mm.
  - Aperture Pitch and Yaw tolerance <0.1°.
- Wire-EDM is done prior to helium jacketing. This is expected to perturb the Pitch and Yaw alignment by <0.1 °.

Minimize Microphonics by Centering of Drift Tube in both QWRs and HWRs



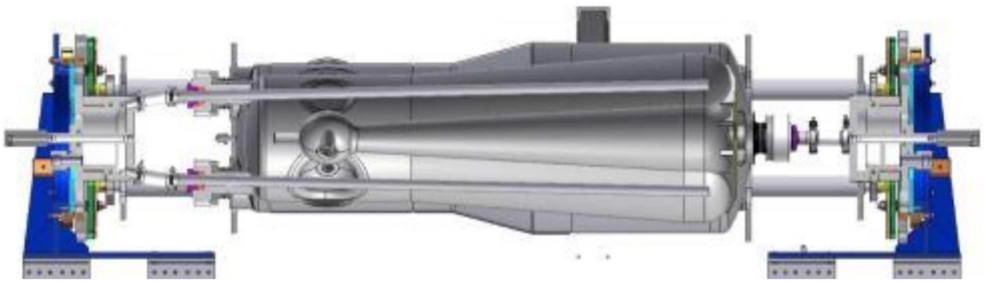


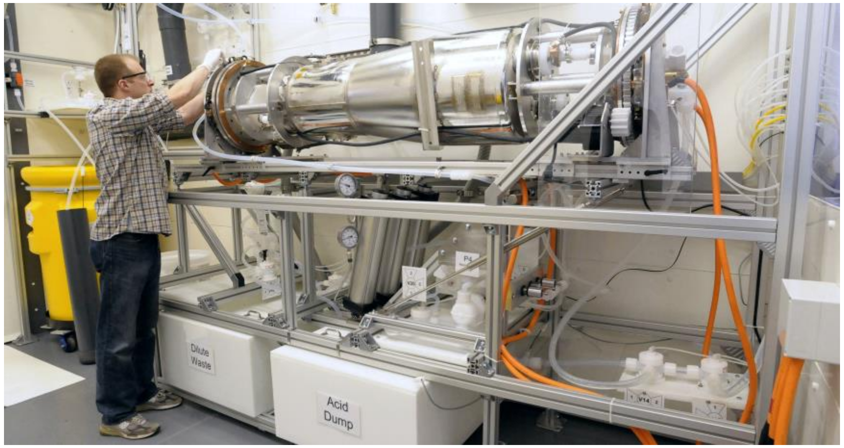
Reduce microphonic frequency variations due to pendulum-like motion of inner conductor.

- J.R. Delayen, NIMA A259 (1987) 341
- Practically accomplished by electromagnetic centering of the inner conductor. Maximize the cavity frequency. No position measurements required.

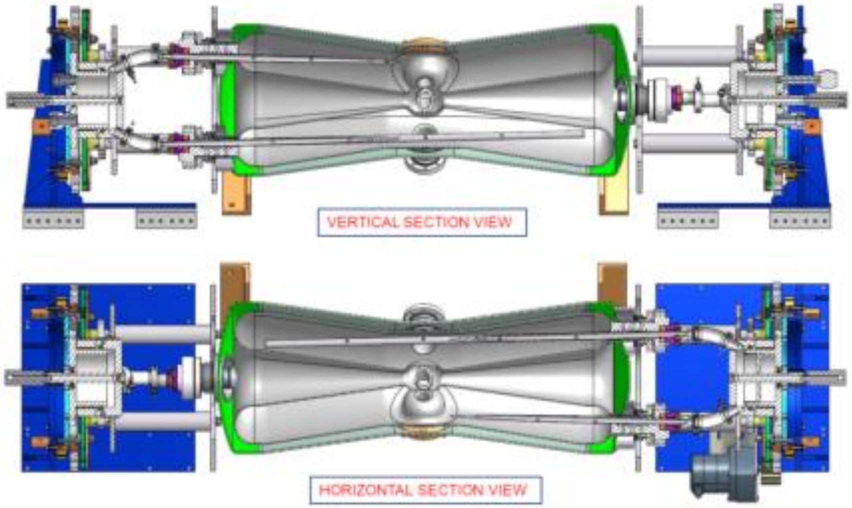
Electropolishing

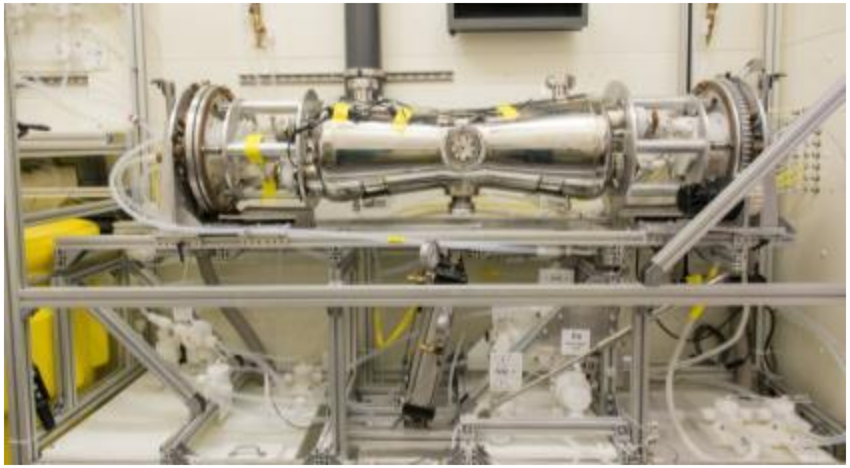
Electropolishing is performed after all mechanical work including stainless steel helium vessel has been complete





Cathode is parallel to the central conductor. Cooling through the He jacket

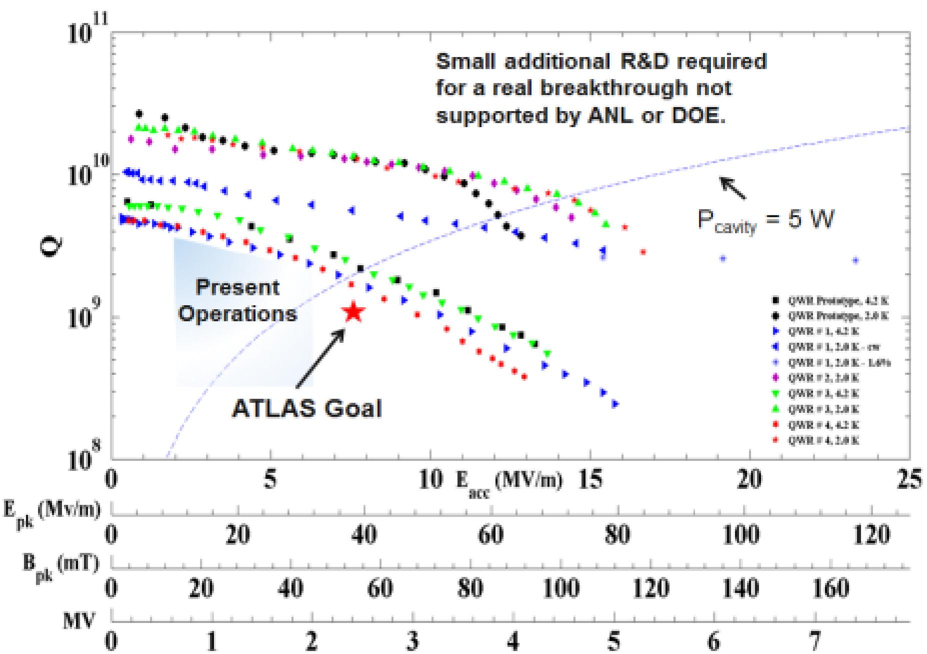




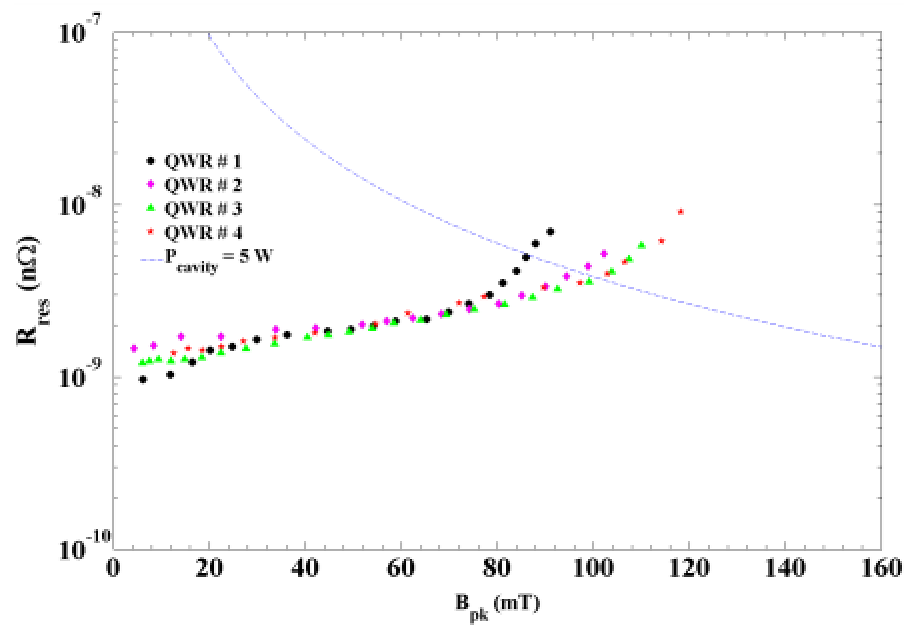
Measured 72 MHz QWRs Performance

- 5 cavities can operate at 62 MV/m and produce at least 3.75 MV accelerating voltage
- Operation at 2K is more economical
- No significant X-ray radiation at operational gradients

Off-line 4.5K and 2K

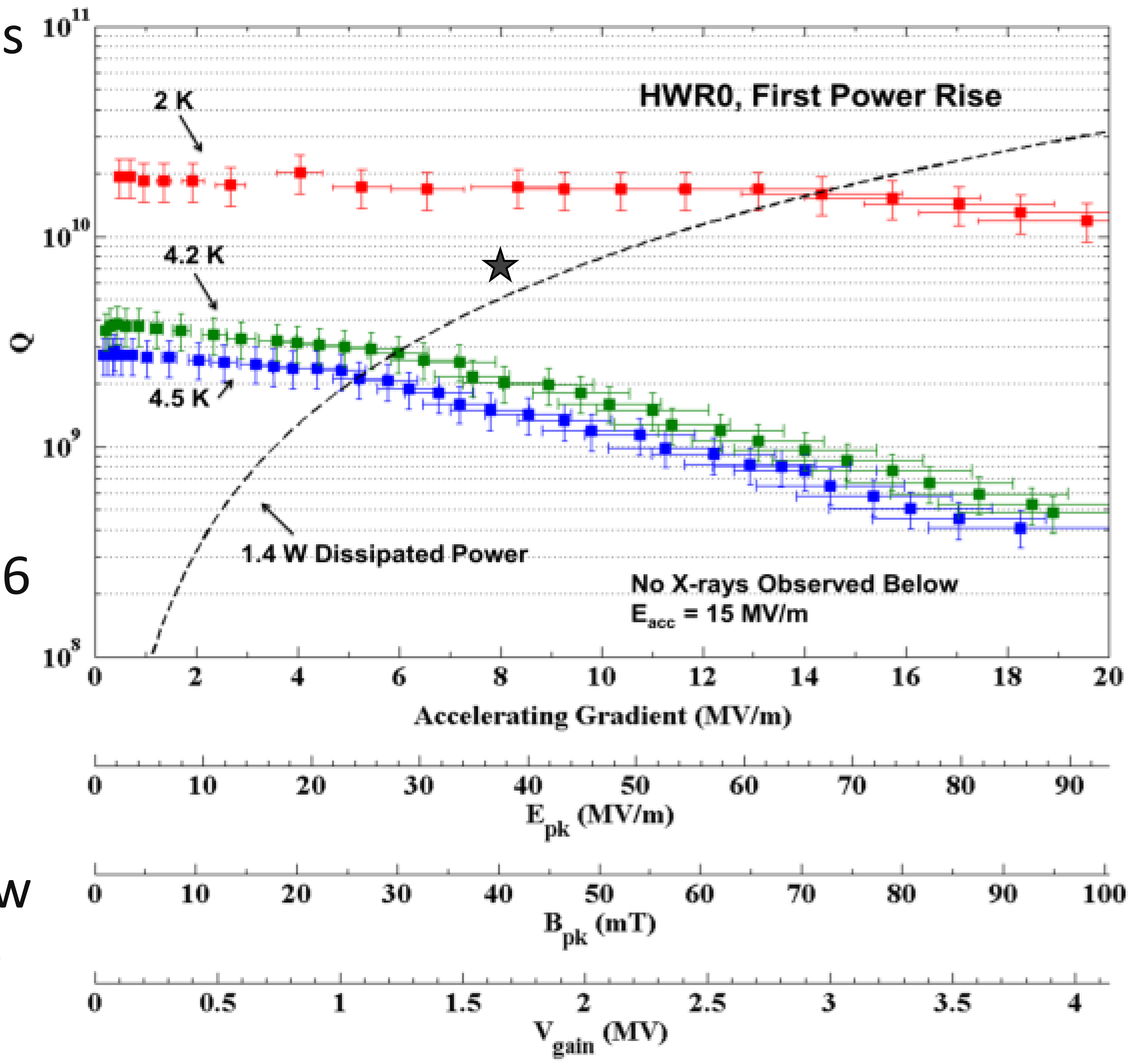


Residual resistance

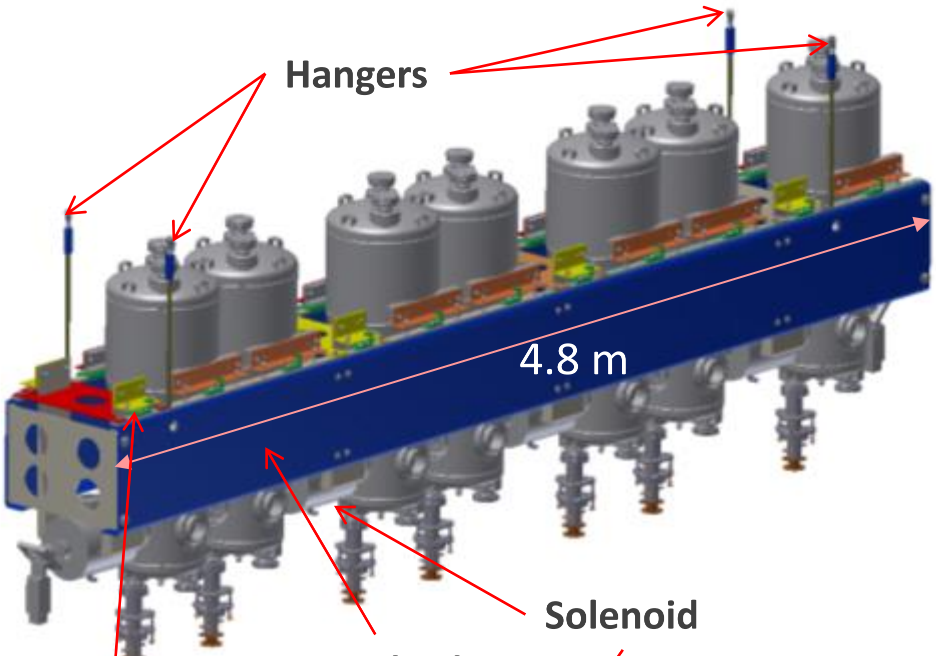


HWR Cold/RF Testing

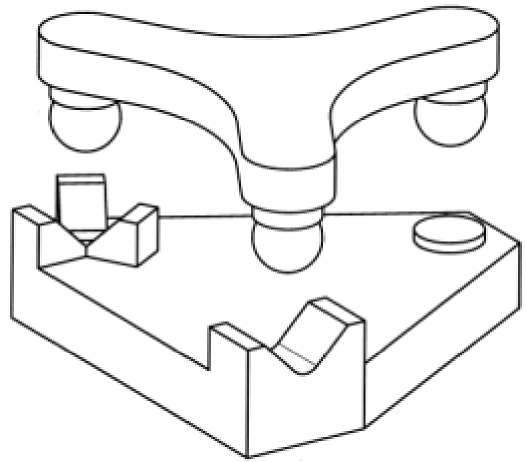
- Performance sets a new world record in TEM-class cavities
- The star is the design specification
- Testing was done with adjustable coupler at critical coupling
- Residual resistance is <2.6 nΩ up to 14 MV/m
- Design field is 8 MV/m, $Q_0=7\times10^9$
- No X-rays observed below E_{ACC}=15 MV/m, or E_P= 70 MV/m

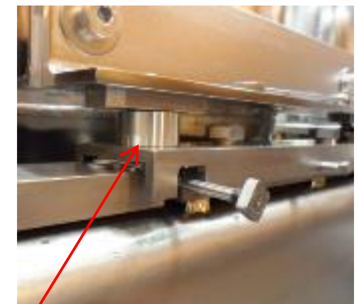


Kinematic-Alignment Hardware

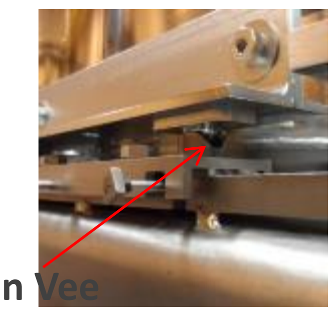


Kelvin Type Kinematic Coupling for Solenoid/Cavity Mount





Ball in Ring



Ball on Vee

Ball on Flat Surface

Alignment Results in Cryomodule at 4.5 K

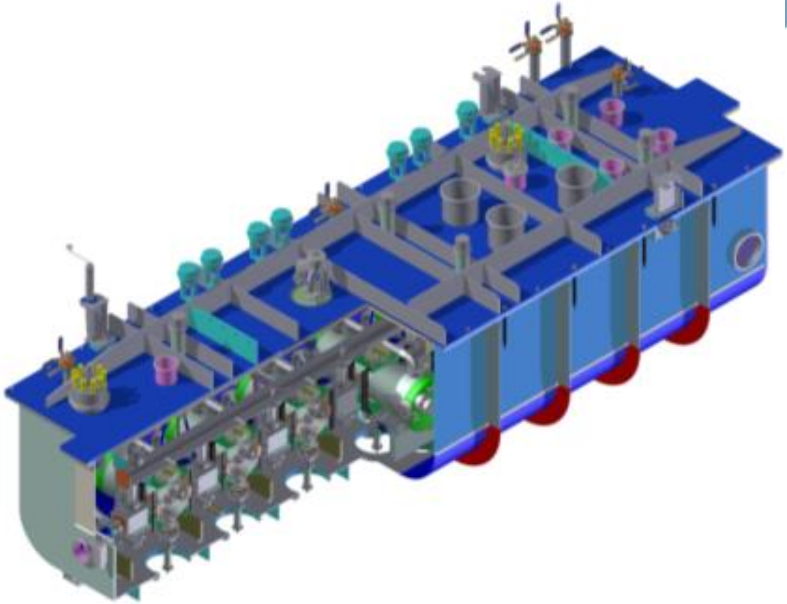
(RMS deviations from the fitted beam axis)

	Solenoids	Cavities*
Horiz.	0.12 mm	0.50 mm
Vertical	0.18 mm	0.28 mm

HWR Cryomodule

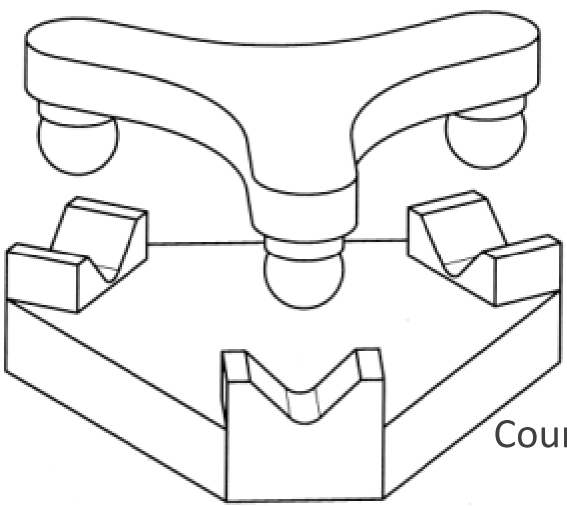
- 8 cavities 8 SC solenoids, 8 BPMa
- Compact design to handle high beam current up to ~20 mA protons
- SC solenoids equipped with return coil and 2-plane steering coils
- Off-line cold testing – 2016
- Installation at FNAL –early 2017
- Beam commissioning – end of 2017

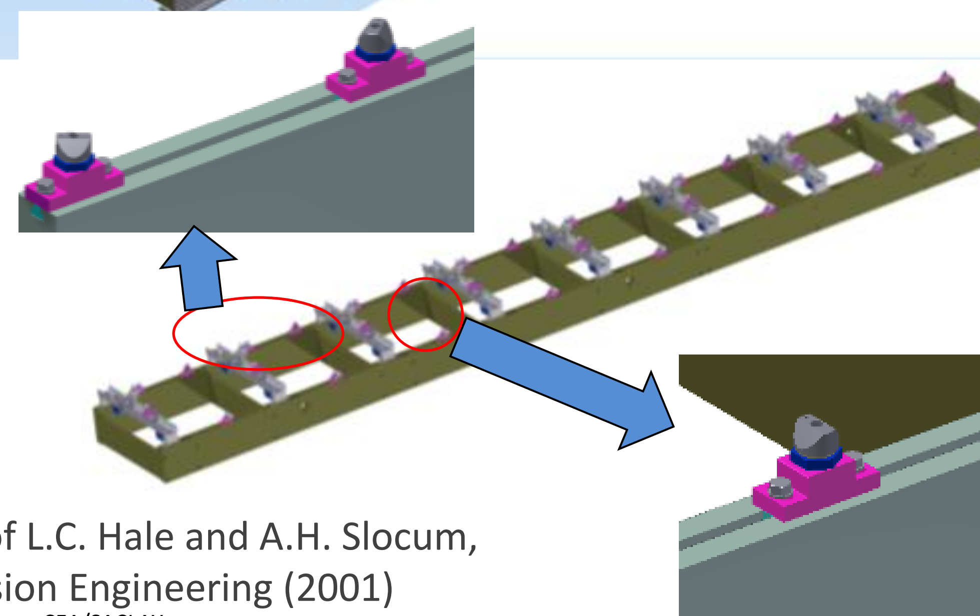
Parameter	Value
Length (beam ports)	5.93 m
Length (overall)	6.3 m
Width	2.1 m
Height	2.2 m



Alignment of cavities and solenoids in HWR Cryomodule

- 3-groove kinematic coupling (Maxwell-type)
- Cavity or solenoid center in the horizontal plane remains unchanged after cool down



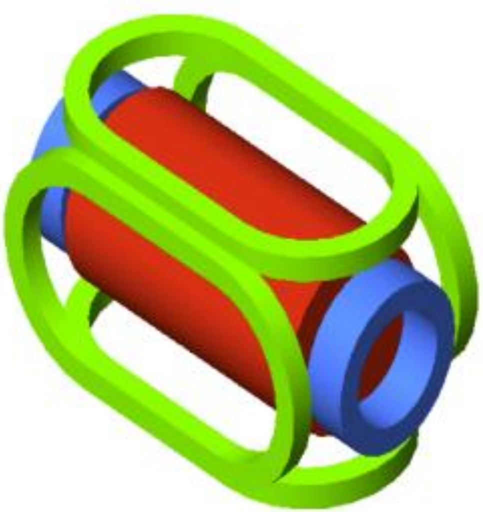


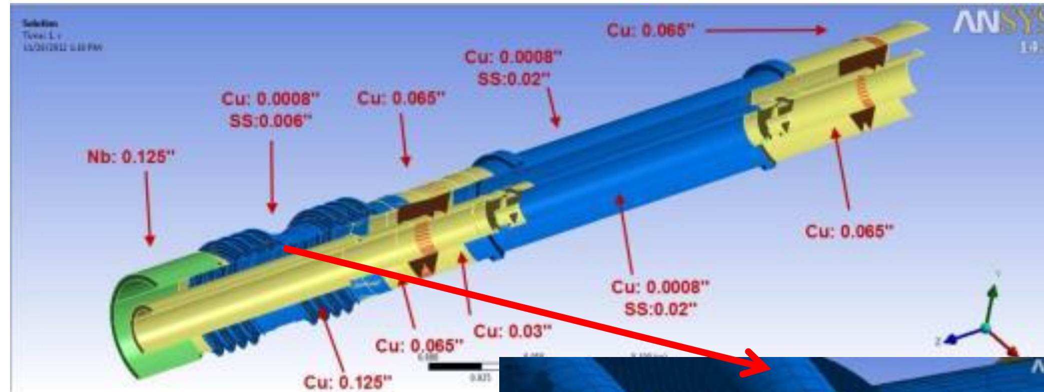
Courtesy of L.C. Hale and A.H. Slocum, Precision Engineering (2001)

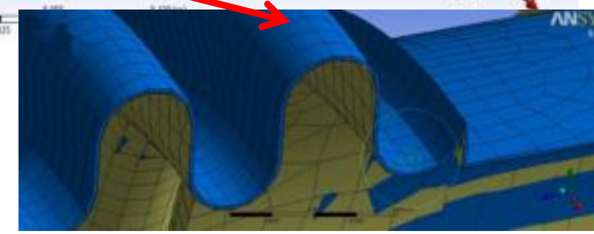
Sub-Systems

15 kW adjustable RF input coupler. Adjustable, includes cold and warm ceramic disk windows

SC solenoid 3D model, includes main coil, bucking coils and X-Y steering coils. Proposed in Linac 2002 paper

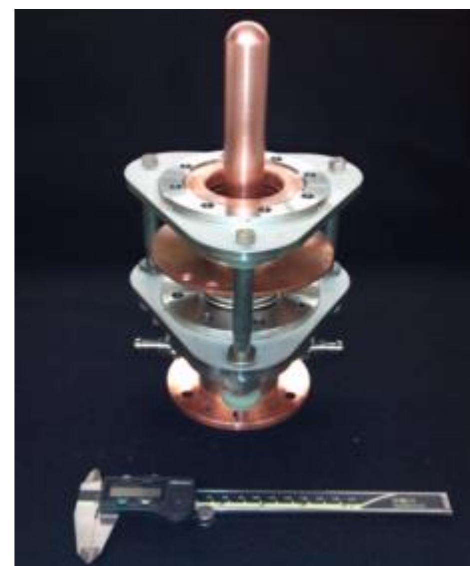






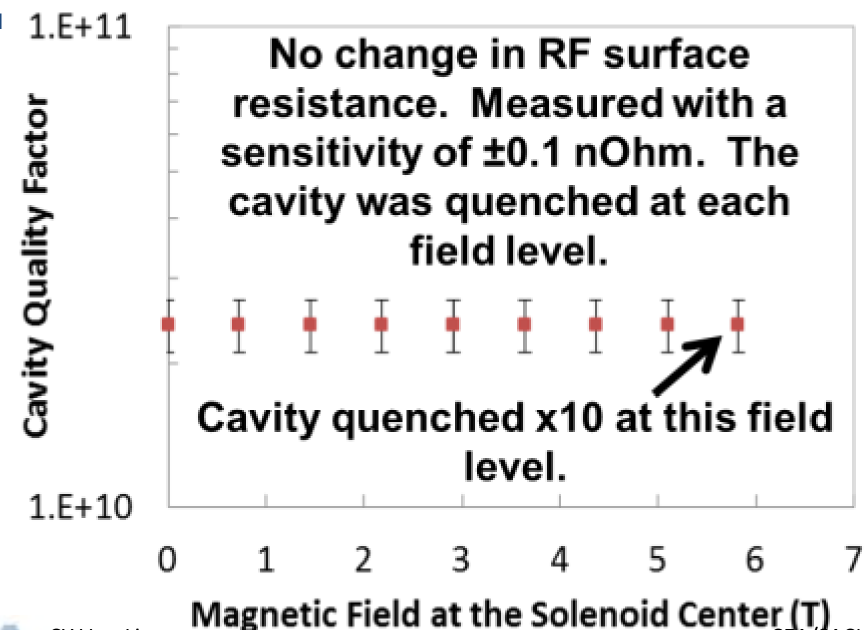
0.006" SS bellows with 0.0007" Cu

SC solenoid in helium vessel.

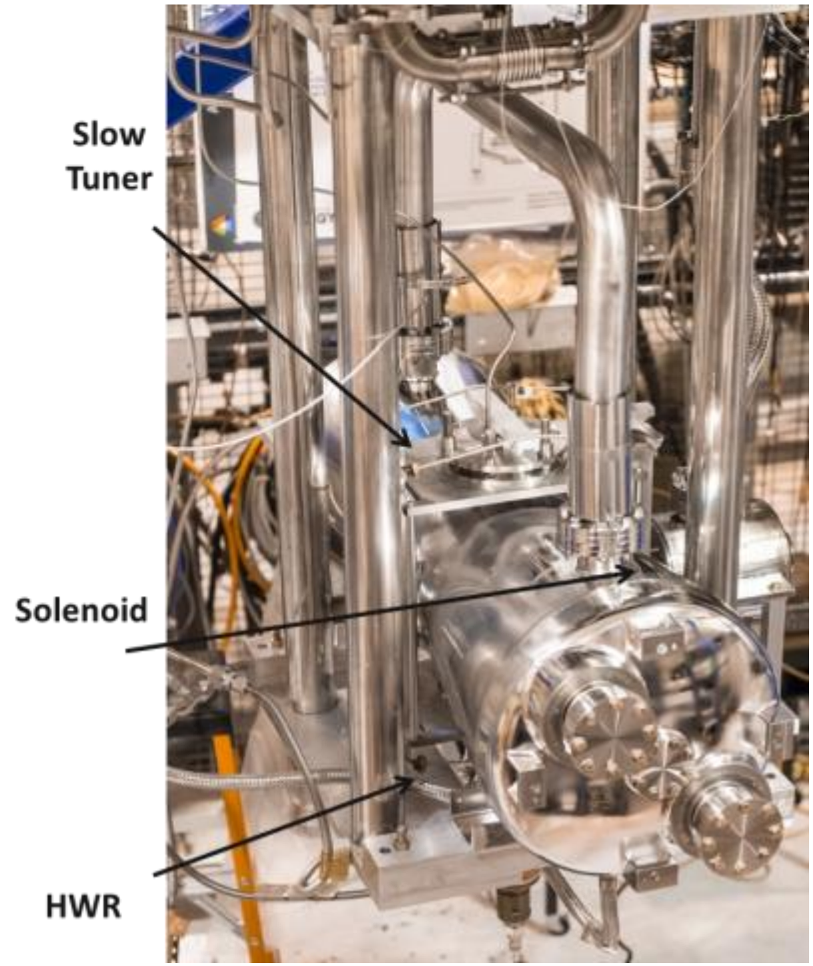


Solenoid focusing facilitates a short focusing period

Cold Testing of HWR with Solenoid

- To decrease the accelerator lattice length we have integrated x-y steering coils into the focusing solenoid package.
- Important design issue:
  - Minimize stray field @ the RF cavity to prevent performance degradation due to trapped magnetic flux.
- 

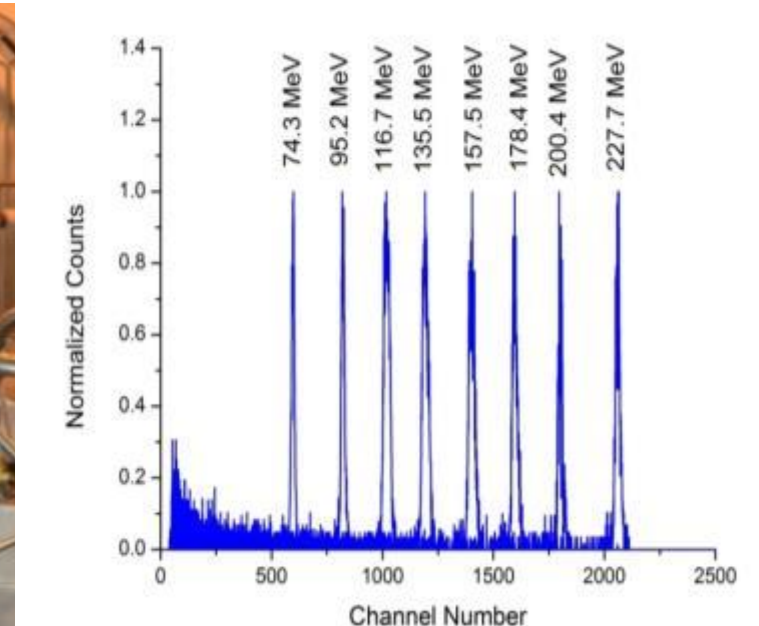
Half-Wave Cavity Assembled for Testing



Cryomodule Assembly and Testing

- 4K cryomodule has been built and commissioned off-line, July 2013
- Installed into the accelerator tunnel and in operation since April 1, 2014
- 2.5 MV average voltage per cavity in CW mode
- 17.5 MV total voltage

In Operation since April 1, 2014



Average	Operational	Available
V_{EFF}	2.5 MV	3.75 MV
E_{PEAK}	40 MV/m	60MV/m
LHe, 4.5K	5 W	12 W

RF System

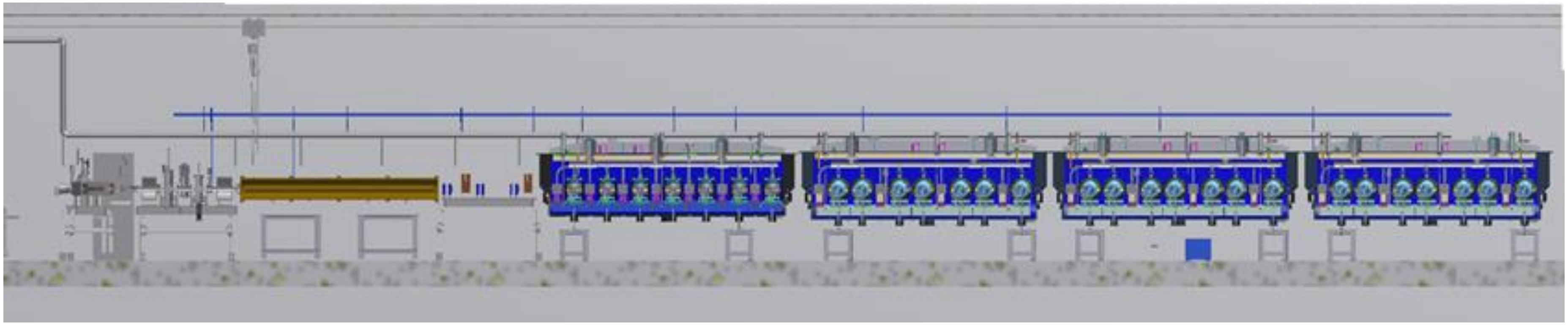
- Beam current up to 50 eμA
- 4 kW solid-state amplifiers
- Adjustable RF input couplers
- Currently 1.5-2.0 kW are sufficient to provide stable operation at 2.5 MV
- Bandwidth is in the range from 20 Hz to 25 Hz

RF transmission line

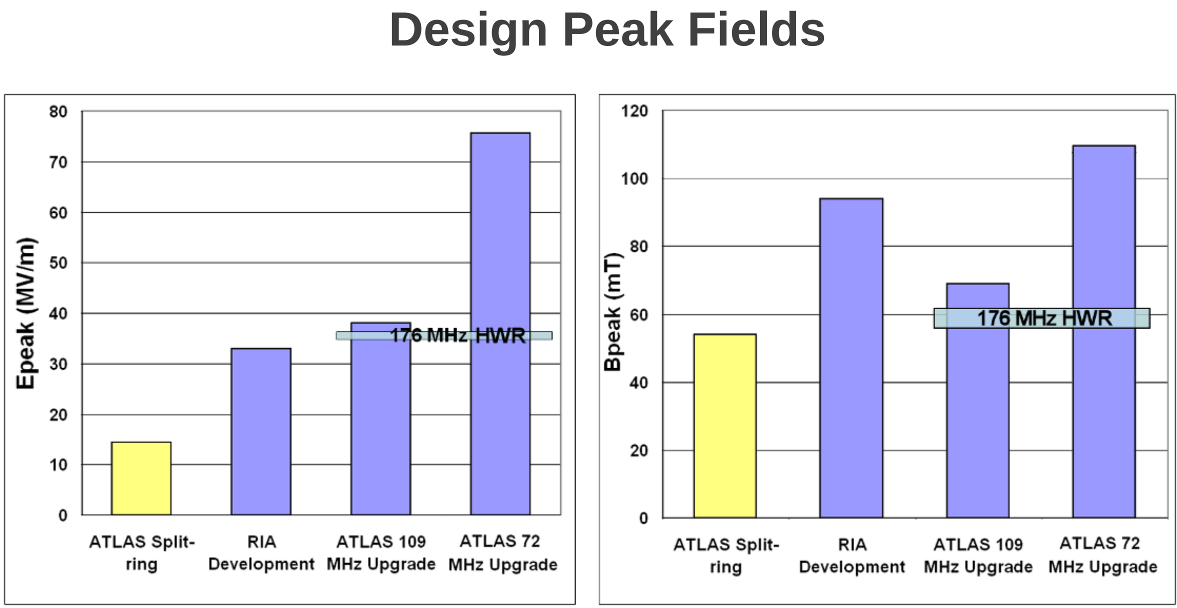
Directional coupler,
circulator,
dummy load

Applications

Conceptual Design of a 40 MeV Deuteron linac, 2012



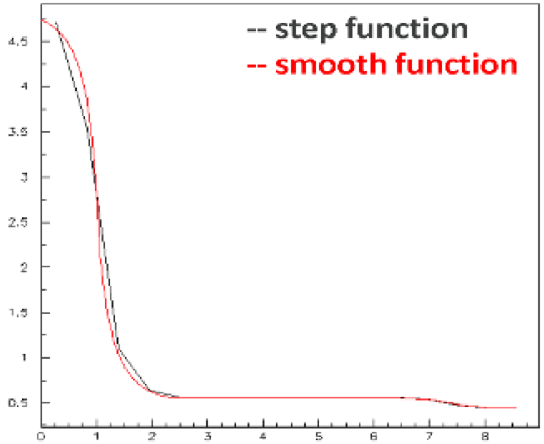
- RFQ, 3.8 m length, 1.3 MeV/u
- One cryomodule with 7 HWRs, β =0.09
- Three cryomodules with 21 HWRs, β=0.16

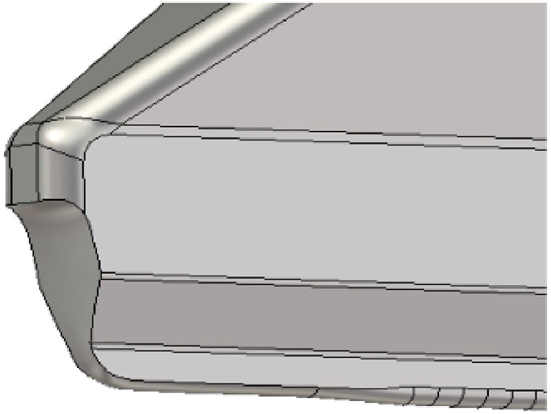


Preliminary Design of a 176 MHz CW RFQ

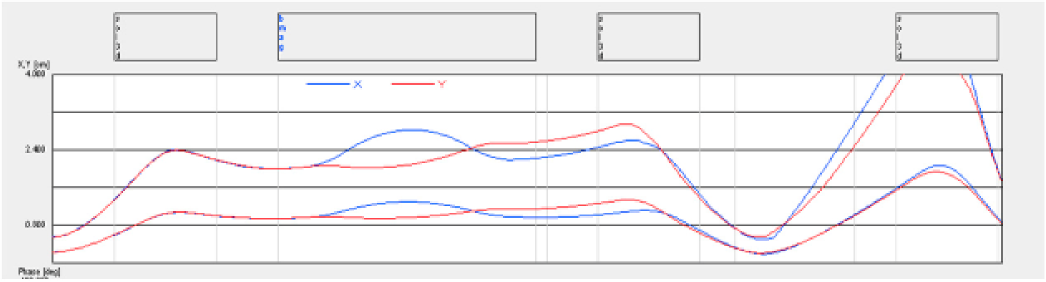
Parameter	Value
Lowest q/A	½
Input energy, keV/u	20
Output energy, keV/u	1300
Frequency, MHz	176
Voltage, kV	75
Design current, mA	5
Power, kW	125
Average radius, mm	4.4
Max. modulation	2
Min. transverse phase advance, deg	33
Norm. trans. acceptance, π mm·mrad	2.2
Peak surface field, Kilpatrick units	1.6
Number of cells	250
Length, m	3.8

Input Matcher

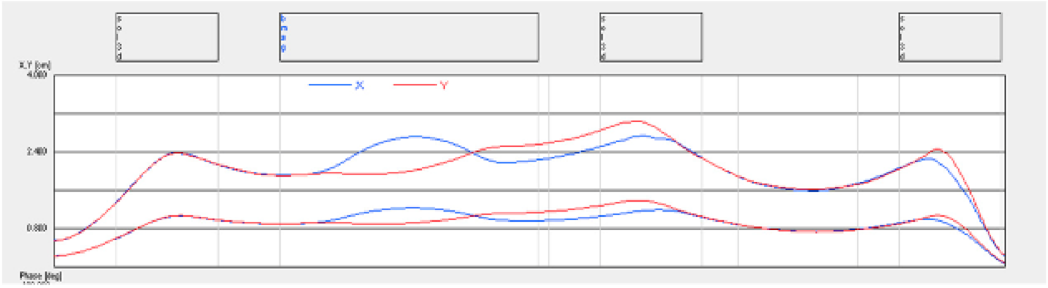




LEBT with original 6 cell input matcher: α ~ 1.5



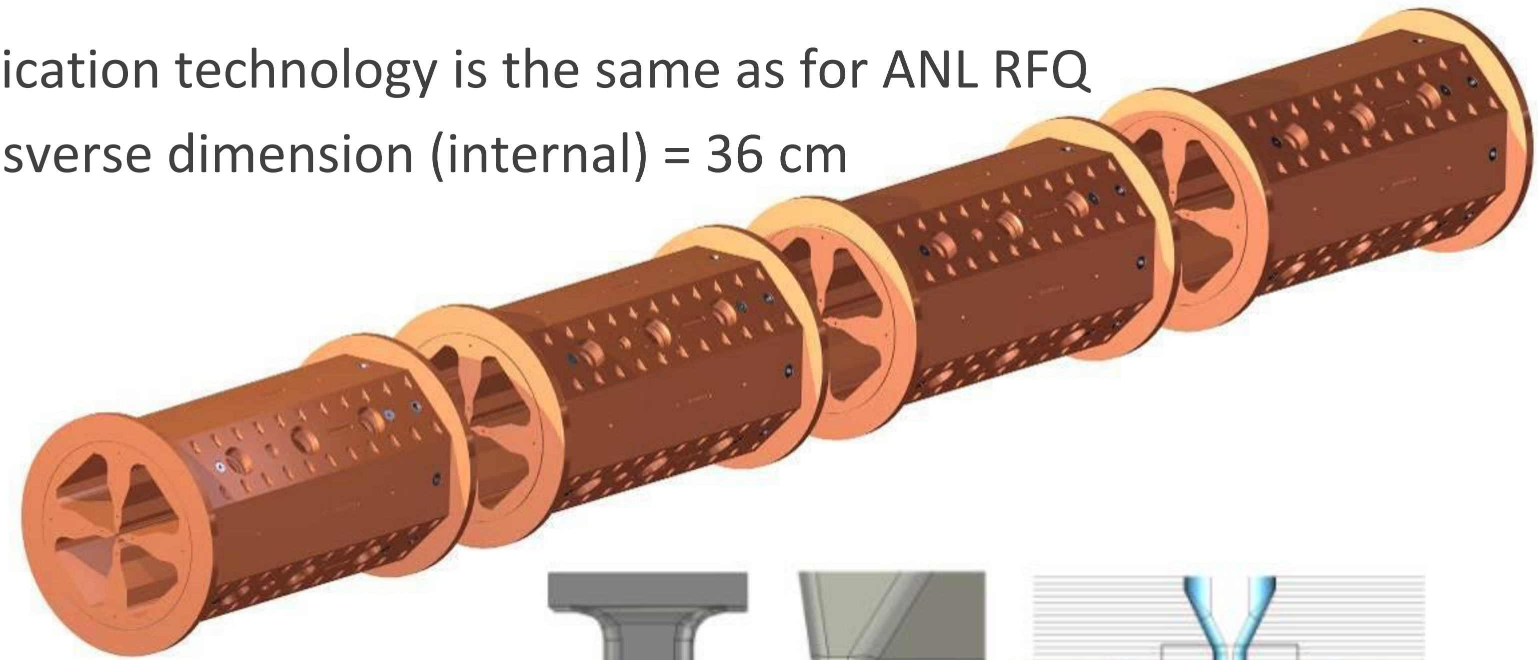
LEBT with special 15 cell input matcher: α ~ 0.25



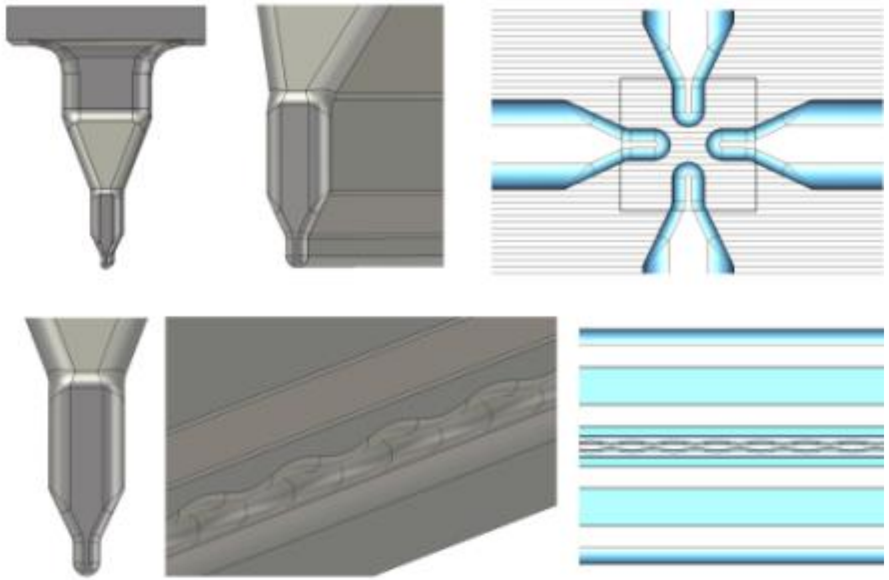
Emittance growth in LEBT reduced from 50% to 10%

4-Vane Structure, 4 Segments

- Fabrication technology is the same as for ANL RFQ
- Transverse dimension (internal) = 36 cm

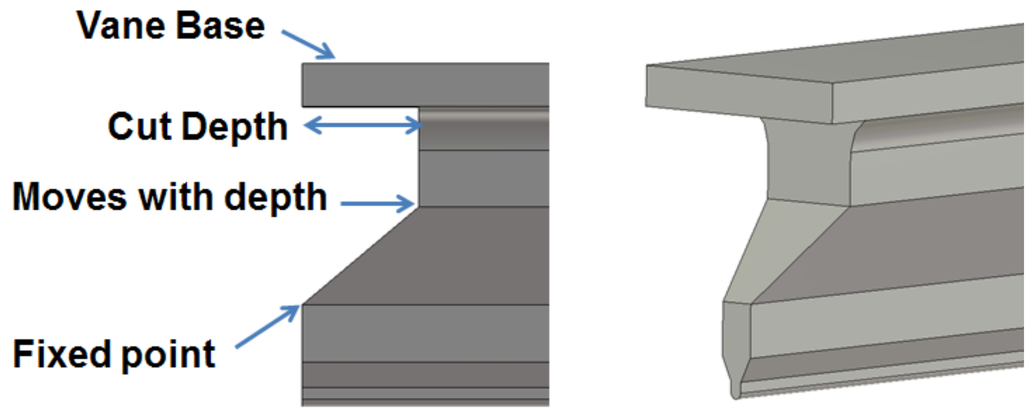


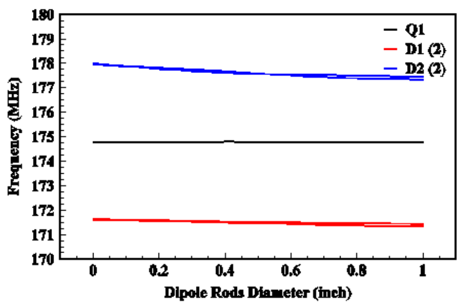
CST model includes
Vane tip modulation

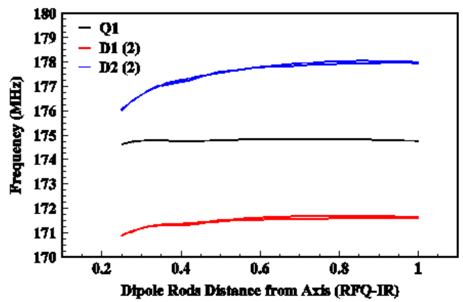


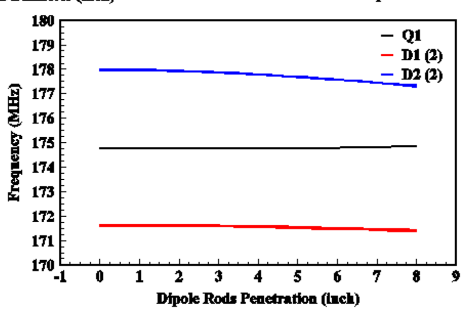
Uniform Voltage Along z

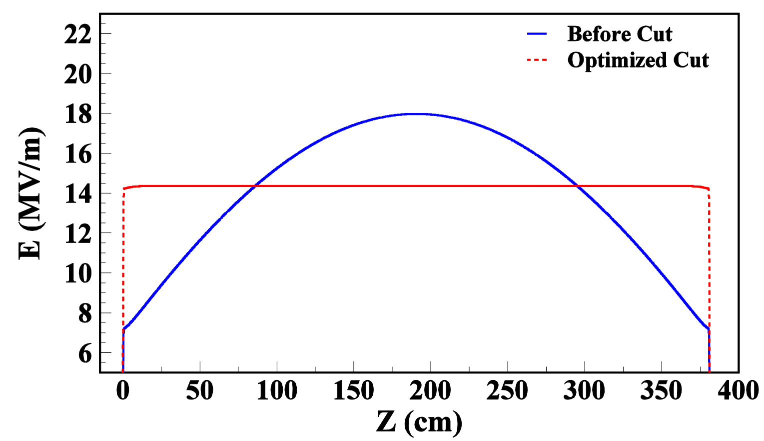
- Study of dipole rods



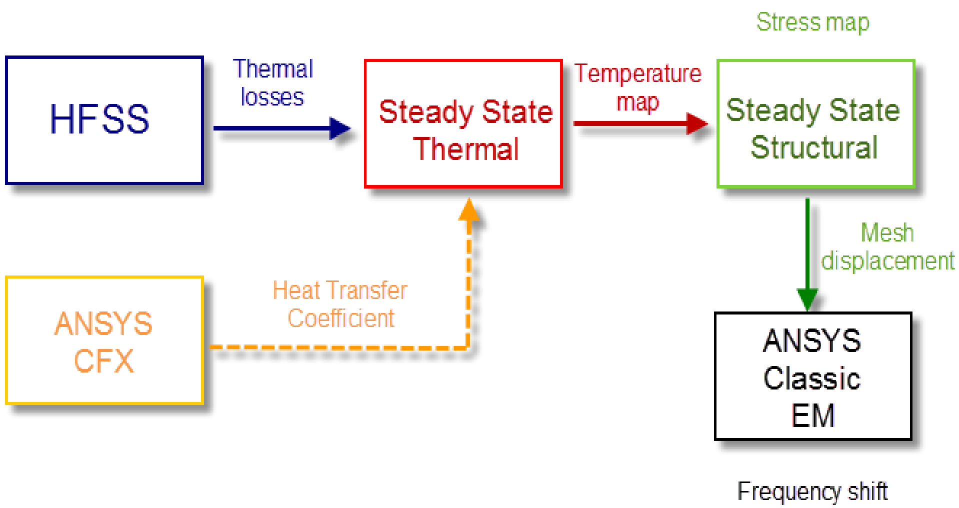


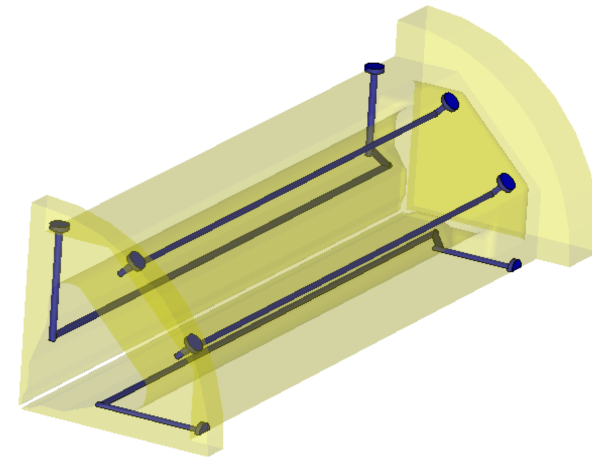


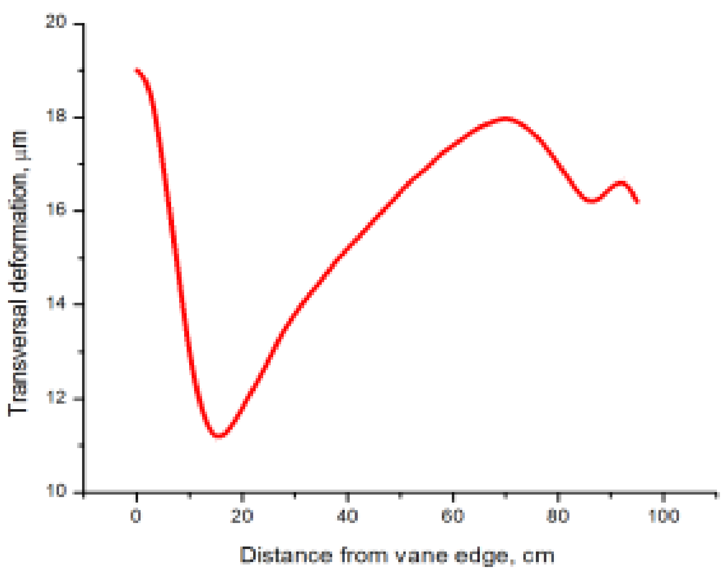




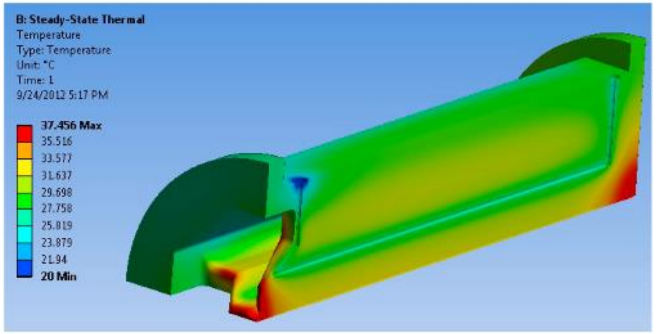
Water Cooling, Optimized



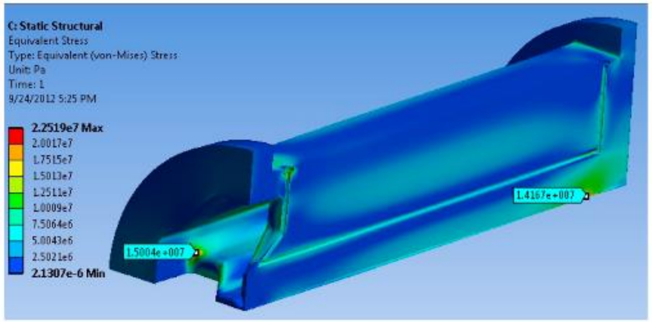




- Temperature Map



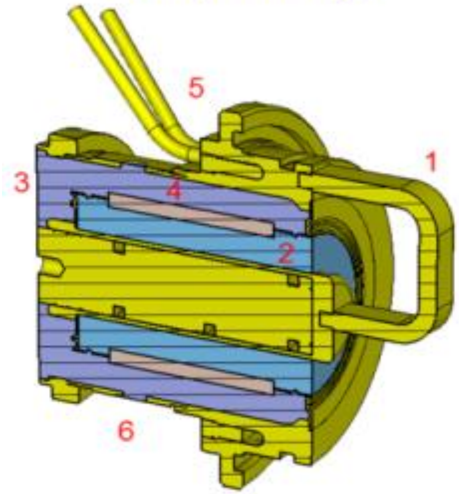
- Von Mises Stress Map



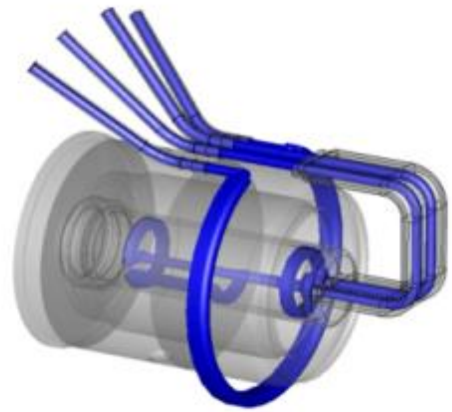
RF Coupler

- The same design as for 60 MHz RFQ

Coupler Design



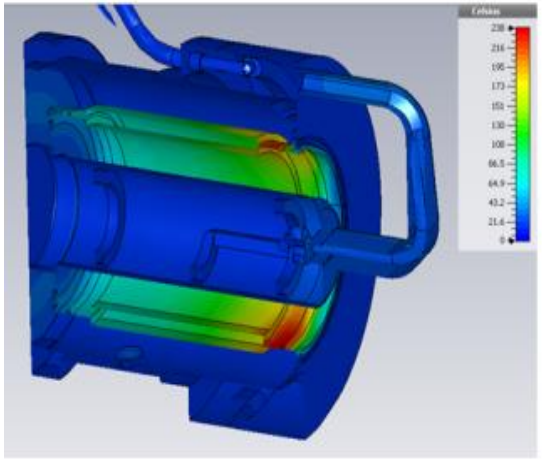
Cooling Channels



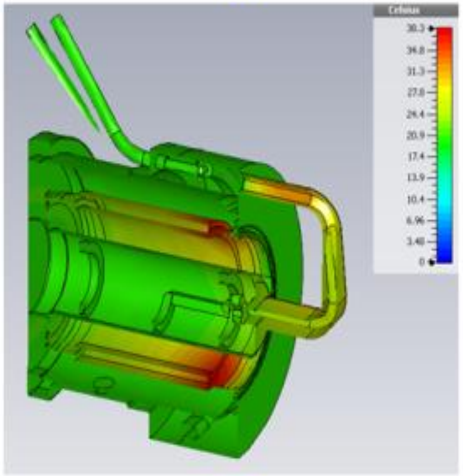
1- Coupling loop, 2-Vacuum, 3-Air,
4- Ceramic window with cuffs,
5- Water cooling channels,
6-Hole for air cooling flow

- Significant reduction of heat load for the coupler with copper cuffs

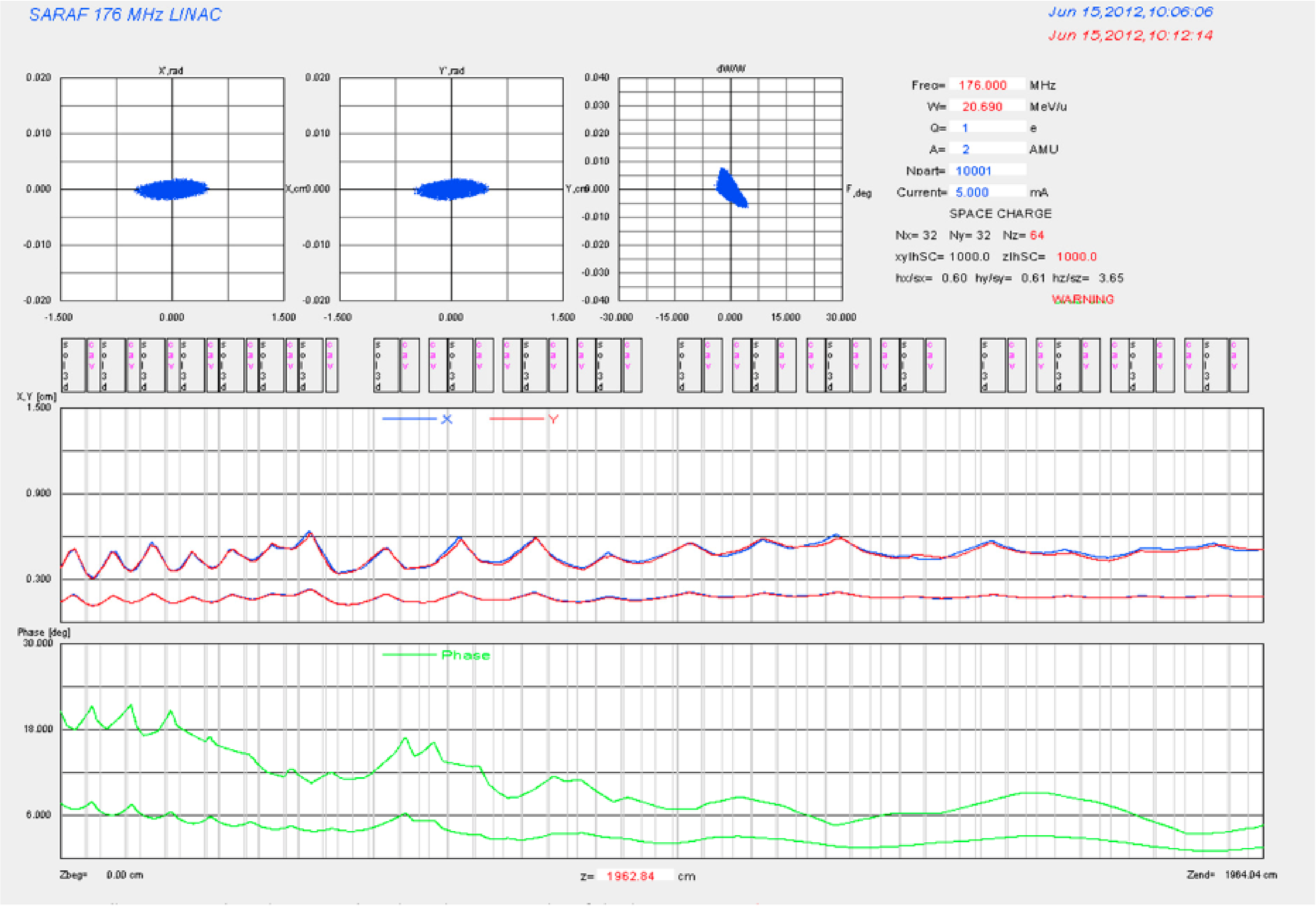
With steel cuffs



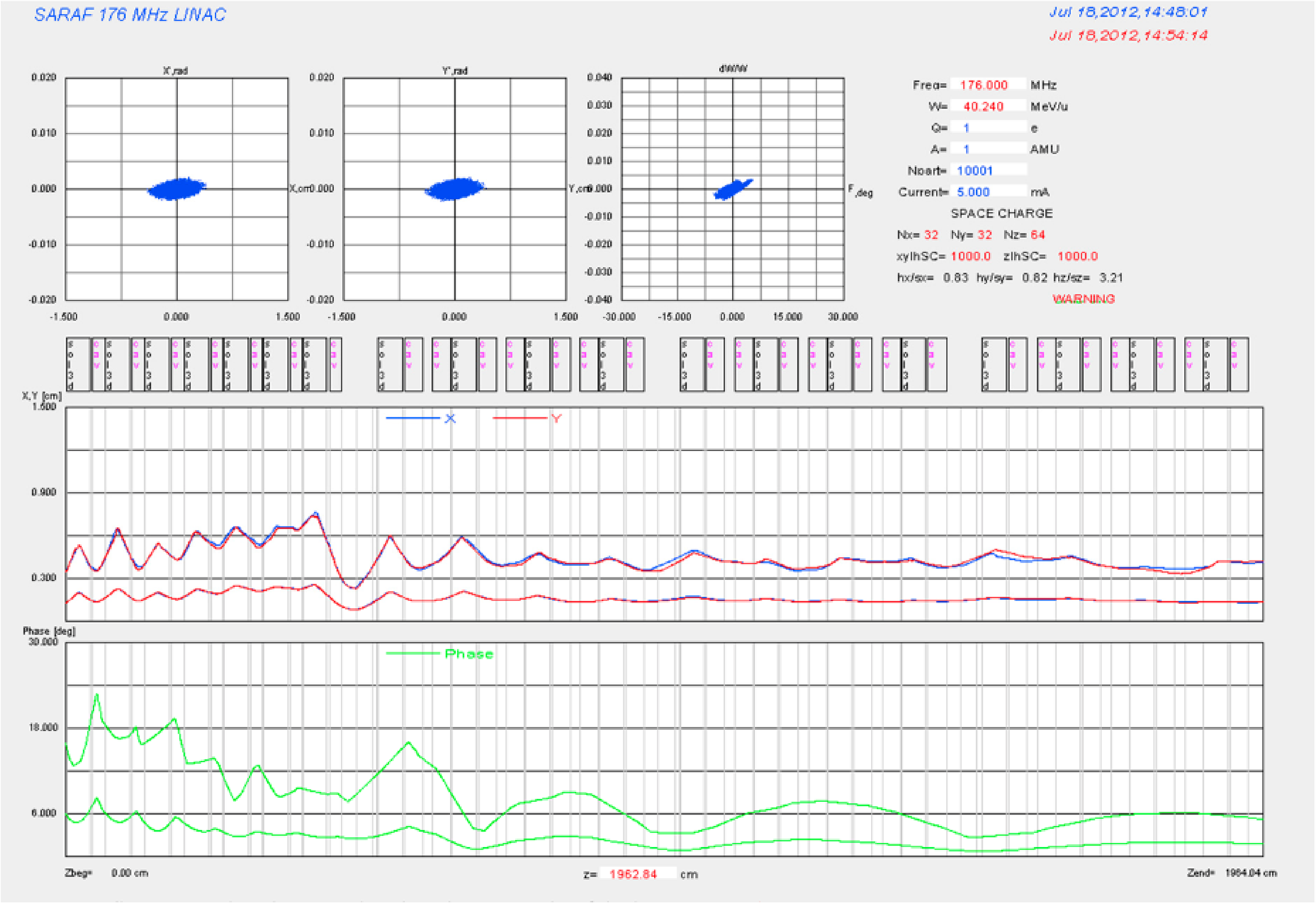
With copper cuffs



5-mA Deuteron Beam



5-mA Proton Beam



Emittance Growth and Beam Losses

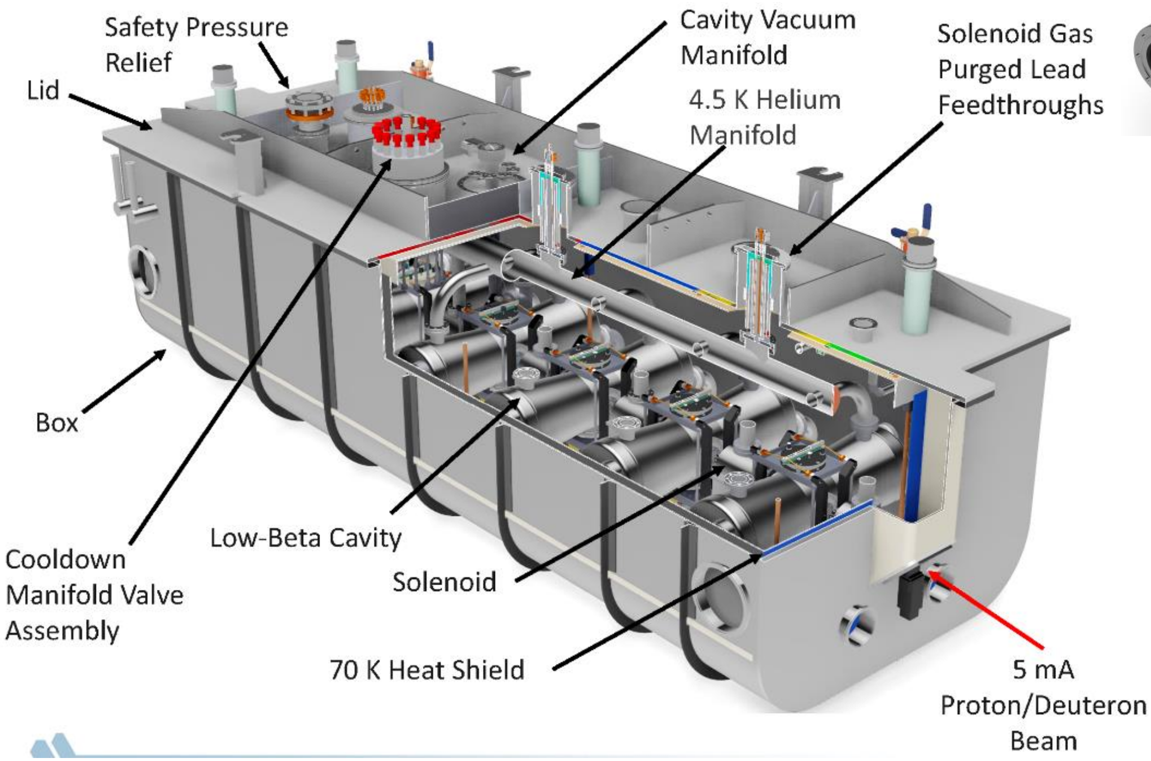
DEUTERON BEAM: GOOD MATCHING THROUGHOUT the LINAC				
Section	ε(t,n) - rms	ε(l,n) – rms	ε(t,n) – 99%	ε(l,n) – 99%
LEBT	10 %	-	34 %	-
RFQ	3.5 %	-	22 %	-
MEBT	5 %	0 %	18 %	0 %
LINAC	0 %	4 %	5 %	23 %
PROTON BEAM: NOT MATCHED in the LEBT (ASSUMED a 50% EMITTANCE GROWTH)				
Section	ε(t,n) - rms	ε(l,n) – rms	ε(t,n) – 99%	ε(l,n) – 99%
LEBT	50%	-	50%	-
RFQ	0 %	-	10 %	-
MEBT	1 %	1 %	7 %	0 %
LINAC	9 %	16 %	55%	52 %

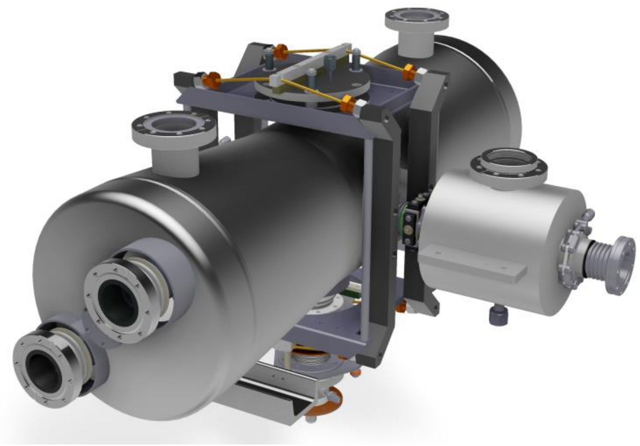
- Beam losses before and after correction of beam center
- 100 random seeds with 3 sets of errors

Error Set	Misalignment (mm)	Phase (deg)	Amplitude (%)
1	0.3	0.5	0.5
2	0.5	0.5	0.5
3	1.0	1.0	1.0

DEUTERON BEAM		
Error Set	**Fraction lost before correction**	**Fraction lost after correction**
1	0	0
2	0	0
3	2E-4	0
PROTON BEAM		
Error Set	**Fraction lost before correction**	**Fraction lost after correction**
1	0	0
2	4E-7	2E-7
3	2E-4	0 (*)

Engineering Model of the 162.5 MHz β=0.09 HWR Cryomodule for SARAF





Developments for FRIB: Optimized Design of HWR

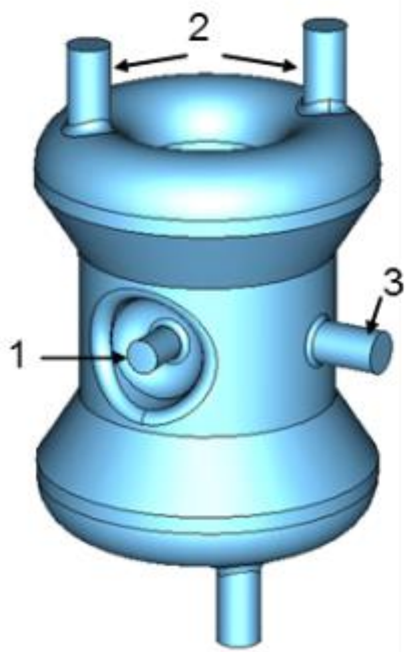
- β_{OPT}=0.29, f=322 MHz
- The work was completed in June 2011
- Even the proposed option was not selected as a FRIB baseline, the results were used for optimization of the current FRIB cavities

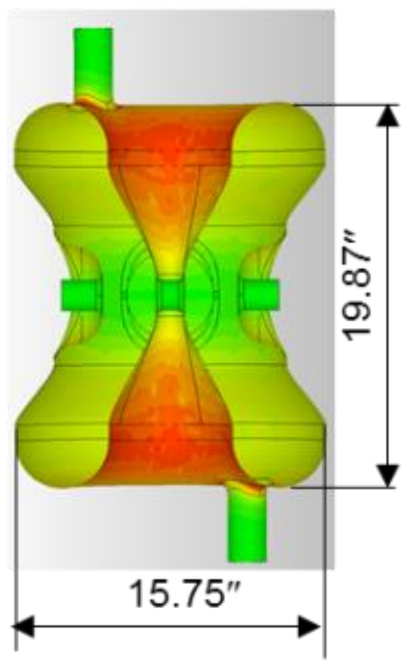
Suggested operational parameters for the HWR (2011):

Voltage = 2.5 MV

E_{peak} = 41.5 MV/m

B_{peak} = 73.6 mT



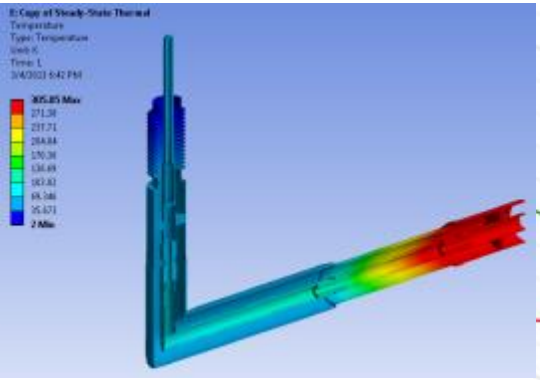


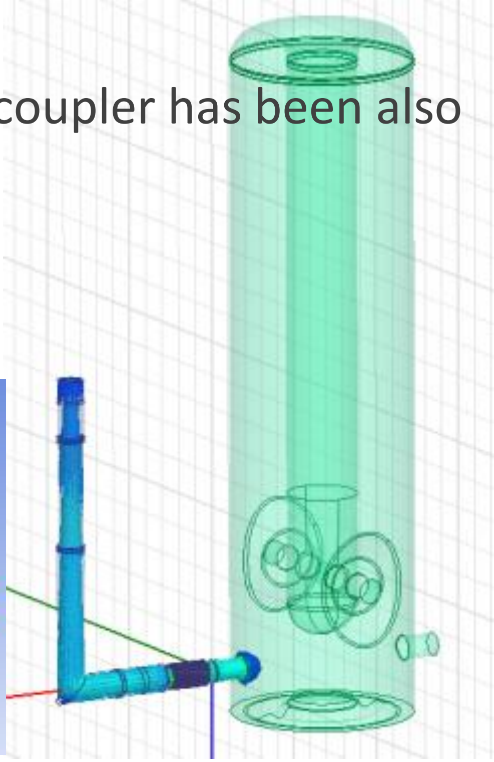
CEA/SACLAY

S.S. Helium Jacket

FRIB RF Couplers for QWRs

- High power RF couplers for SC cavities
  - Design spec is 2.5 kW
  - Tested up to 3 kW without any heating
  - 90-deg angle coupler has been also developed





Developments for FRIB: Slow Tuners for HWRs

- Pneumatic slow tuner
  - All SC cavities are equipped with this tuner
- Increase reliability of operation in high radiation environment
- Facilitate easy assembly outside the clean room

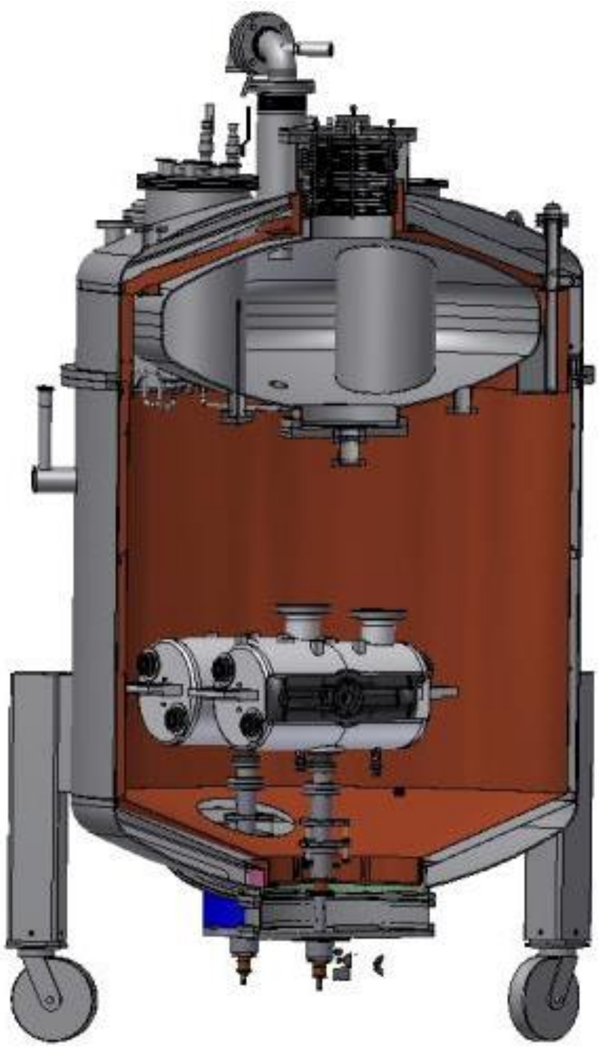
Beta=0.53 resonator with the slow tuner installed

162.5 MHz beta=0.11 resonator with the slow tuner installed

Work for FRIB: RF Surface Processing and Certification of HWRs

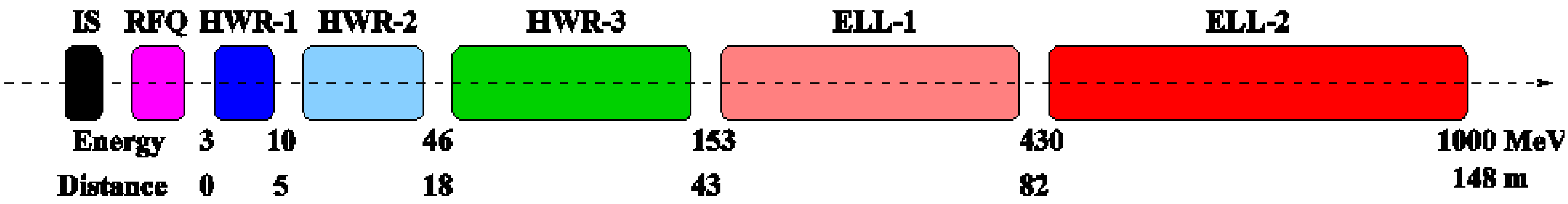
- Ultrasonic cleaning
- Coupling Check
- Bulk Etching
- Custom Etch
- Frequency Check
- 625C Heat Treatment
- Leak Check
- Light etch
- High pressure rinsing
- Low Temperature Bake
- Cold RF testing

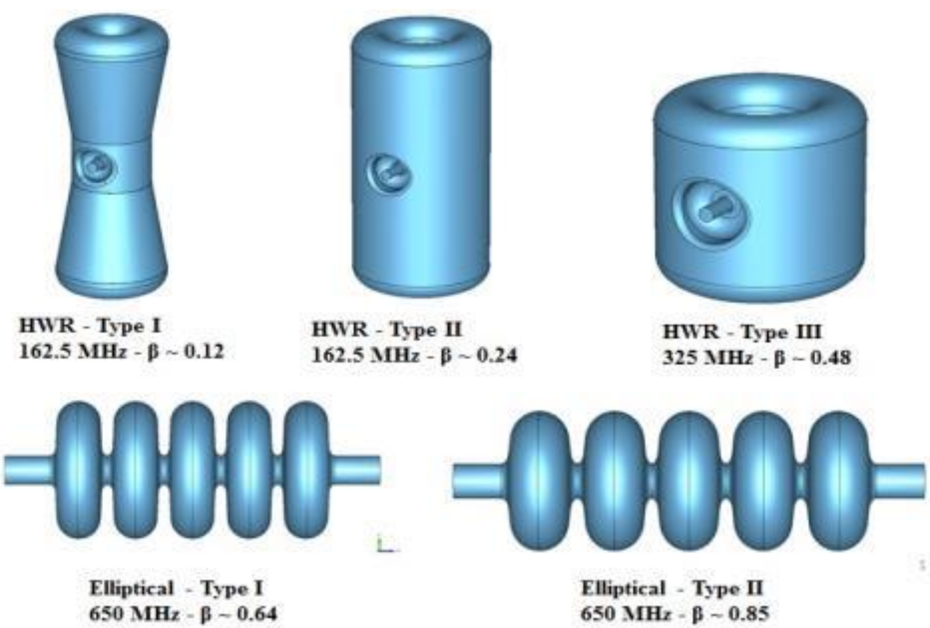
Test cryostat with 2 beta=0.29 FRIB resonators



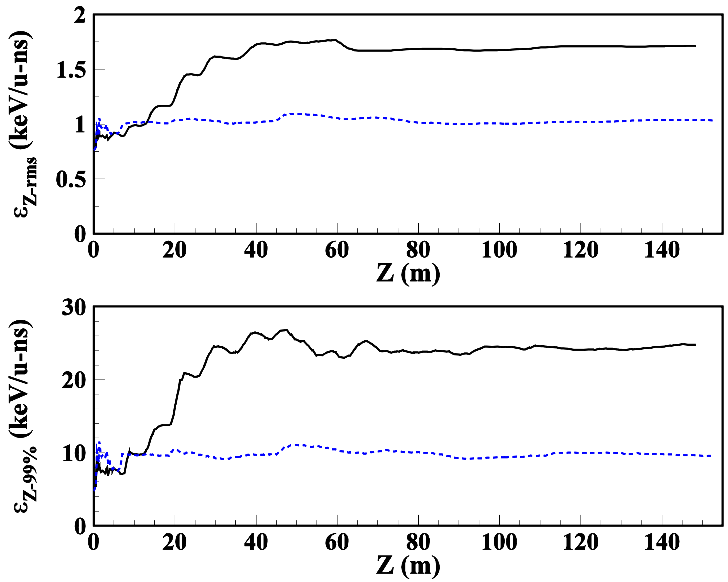
25 mA 1 GeV Linac for ADS

- 3 MeV RFQ, 3 types of HWRs and 2 types of elliptical cavities
- 121 SC cavities (E_P=40 MV/m and B_P=70 mT) and 55 SC solenoids in 19 Cryomodules





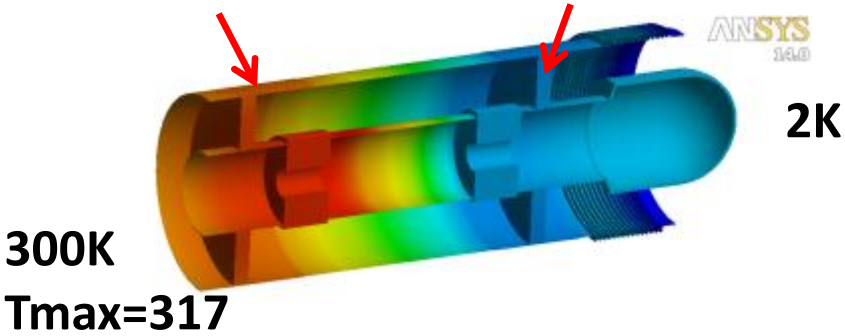
RMS and 99% emittance growth before and after optimization



75 kW RF Coupler Design for HWRs

- Similar to 15 kW RF coupler
- 75kW average power
  - Based on 6 1/8’’ coax
  - Warm and cold disk windows
  - Reflections less than -30dB

Thermal performance at resonance



Parameter	Value		
Material	**AL 300**	**AL 300**	**AL 995**
Thickness, in	**0.5**	**0.25**	**0.25**
Max temp., K	**316.9**	**303.9**	**302.0**
Heat to 2K, W	**7.8**	**7.2**	**6.6**
Heat to 55K, W	**72.5**	**54.0**	**47.6**
Heat to 300K, W	**24.1**	**11.2**	**3.0**

Summary

- Advanced technologies developed at ANL are available for both normal conducting and superconducting accelerating structures for application in CW hadron linacs. These technologies are being applied for various applications.
- A CW RFQ providing high quality ion beams has been in operation for several years with high reliability.
- The performance of the QWRs and HWRs is remarkable and sets a new world record both in terms of accelerating gradients and residual resistance (cryogenics load).
- The first cryomodule with 2K TEM-class cavities will be operational with beam in 2 years. The cryomodule is being developed and built and ANL, will be installed at FNAL and commissioned with beam
- Limited R&D is required for the development and construction of a 25 MW driver linac for ADS or for transmutation of spent nuclear fuel.