PXIE RFQ Design Overview

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Outline

- **Overview**
- **PXIE RFQ Design**
  - Beam dynamics
  - RF *EM*/structure studies and design
  - Engineering design, thermal and structure analyses
- **Key fabrication tests**
  - Tools and fixtures
  - Brazing and fabrication techniques
- **Summary**
  - Milestones and schedule

Overview of the Design

- Beam dynamics design meets the design requirements in intensity, emittance growth, TWISS parameters and transmissions (PARMTEQ)
  - Low vane tip-tip voltage while maintaining good beam dynamics
    - Lower CW RF power requirement
  - The RFQ beam dynamics design has been optimized and simulated using the measured beam distribution , including LEBT optics.
- RFQ structure design
  - RF simulations in collaboration with Fermilab (3-D CST MWS)
    - Mode separation (pi-rods)
    - Cut-backs (including radial matcher) at both ends
    - Field perturbation due to pi-mode rods, tuners, cut-backs
    - Tuner location and sensitivity
    - RF coupler
  - Engineering and mechanical design
    - Thermal management
    - Mechanical structure
    - Vacuum and water cooling system

PXIE RFQ Design Requirements

Parameters	PXIE	Unit
Design requirements		
Ion Type	H-	
Output Energy	2.1	MeV
Duty factor	100	%
Frequency	162.5	MHz
Beam current	5 (nominal); 1-10	mA
Transverse Emittance	< 0.25 (norm. rms)	πmm-mrad
Longitudinal Emittance	0.8-1.0	keV-nsec
Input energy	30	kV
Emittance Growth	10	%
Transmission	95	%
TWISS Parameter αs	Less than 1.5	

Beam Dynamics Design @ I = 5 mA

Beam distribution derived from ion source emittance measurements;

Transmission:

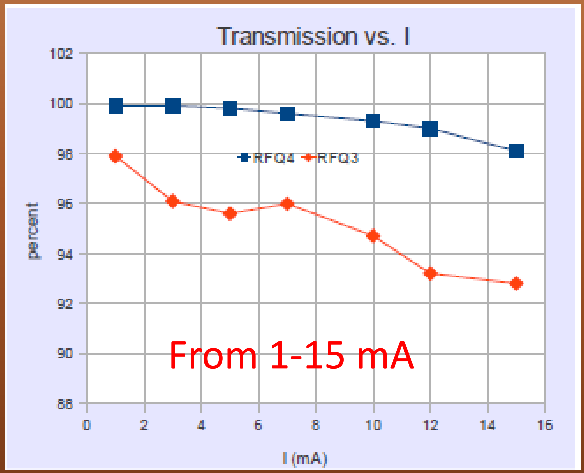
99.8 % at 5 mA;

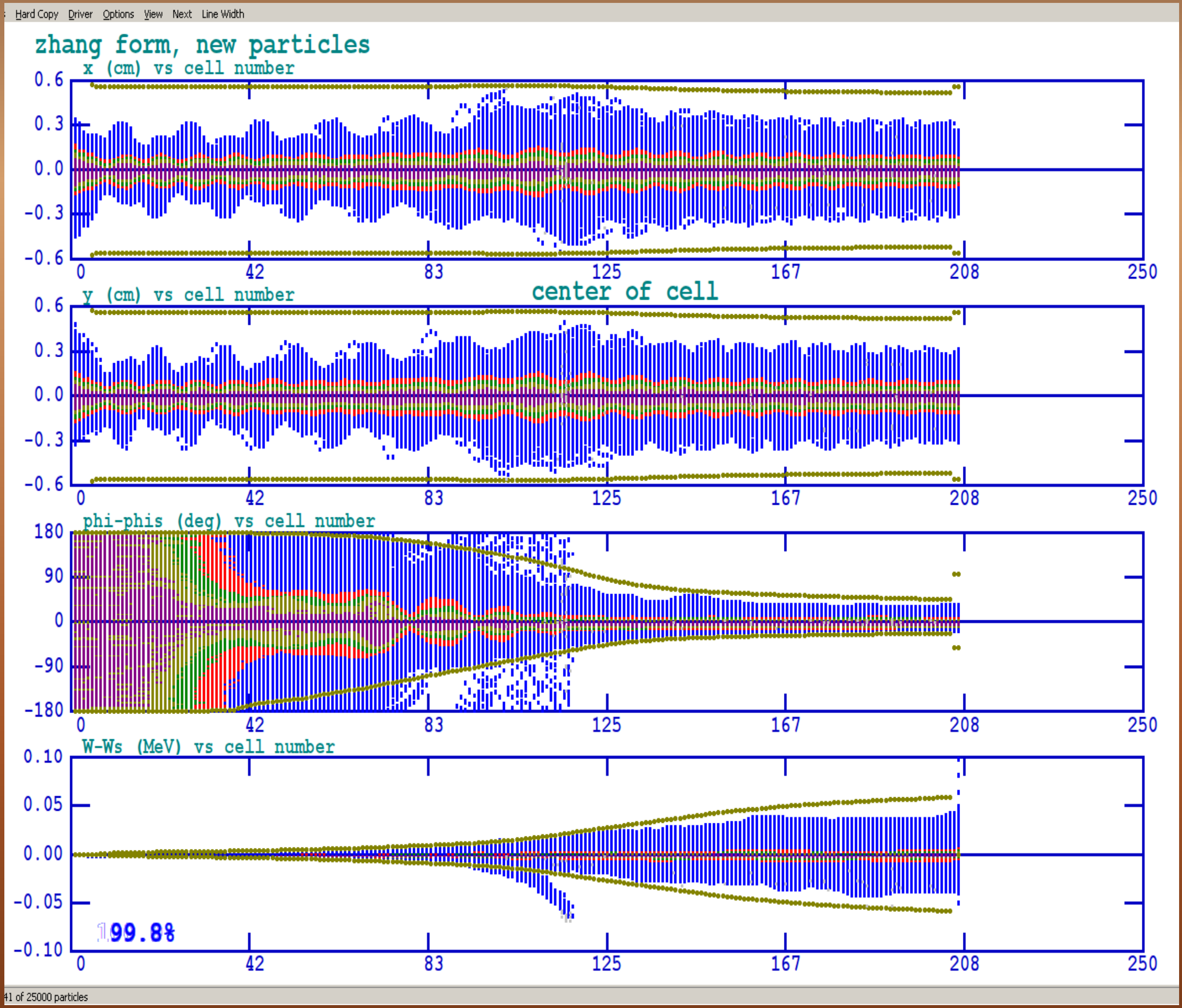
Transverse output emittance:

0.15 pi mm-mrad

Longitudinal emittance:

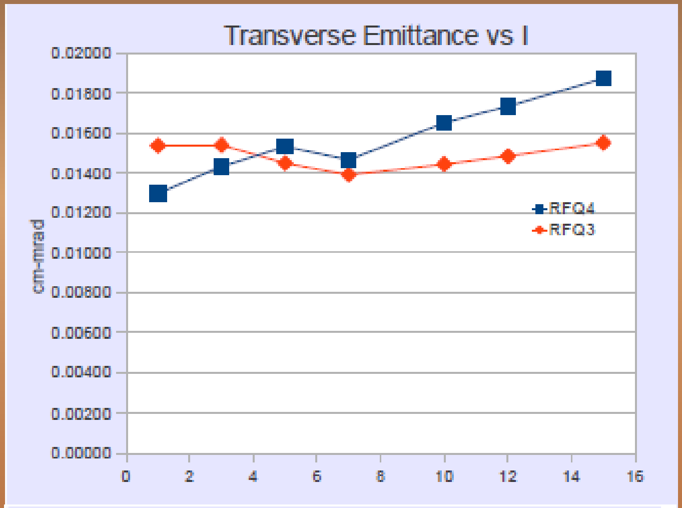
0.64 keV-nsec

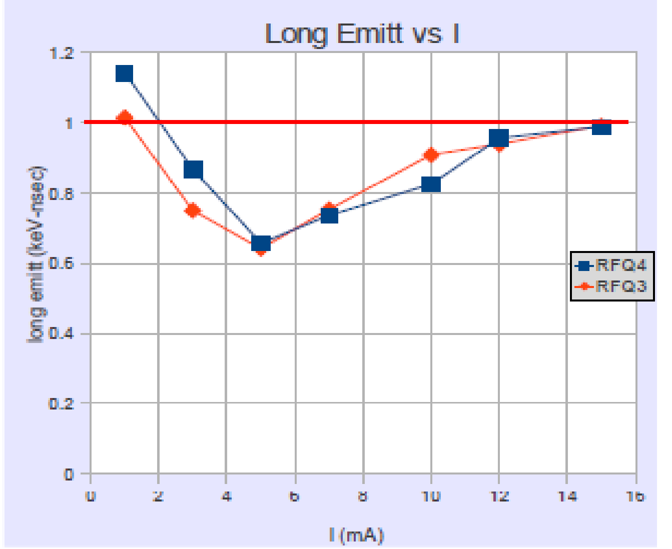




Beam Dynamics Design (cont'd)

Parameters	Value	Unit
Vane Tip Voltage	60	kV
RFQ Length	4.45	m
Transmission	99.8	%
Transverse Emittance	0.15	πmm-mrad
Longitudinal Emittance	0.64	keV-nsec
TWISS Parameters α_x, α_y	-1.17, 1.41	
Minimum longitudinal r	1.029	cm
Max. modulation index m	2.3	
Total # of cells	208	

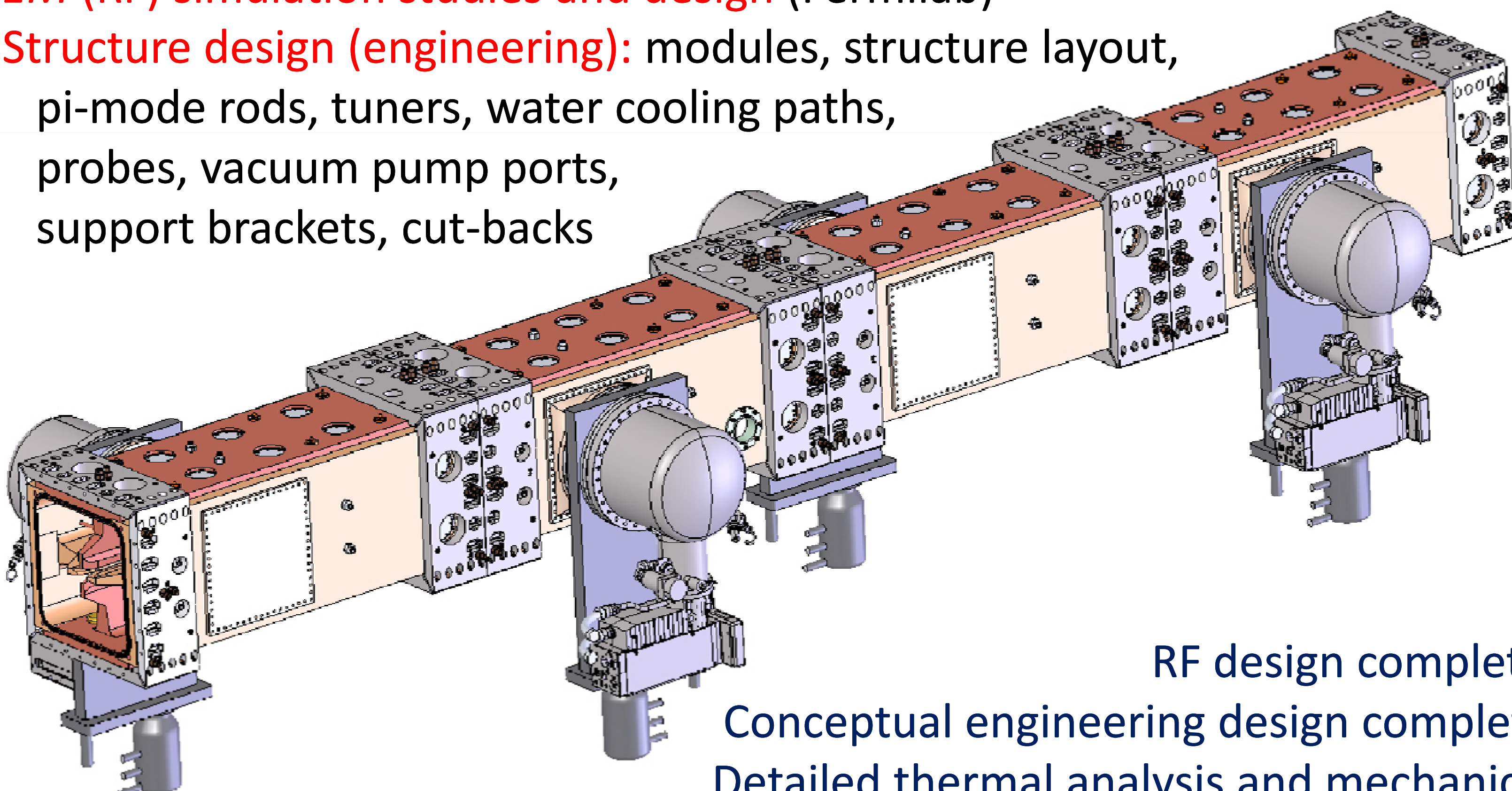




PXIE RFQ: RF Structure Design

EM (RF) simulation studies and design (Fermilab)

Structure design (engineering): modules, structure layout, pi-mode rods, tuners, water cooling paths, probes, vacuum pump ports, support brackets, cut-backs



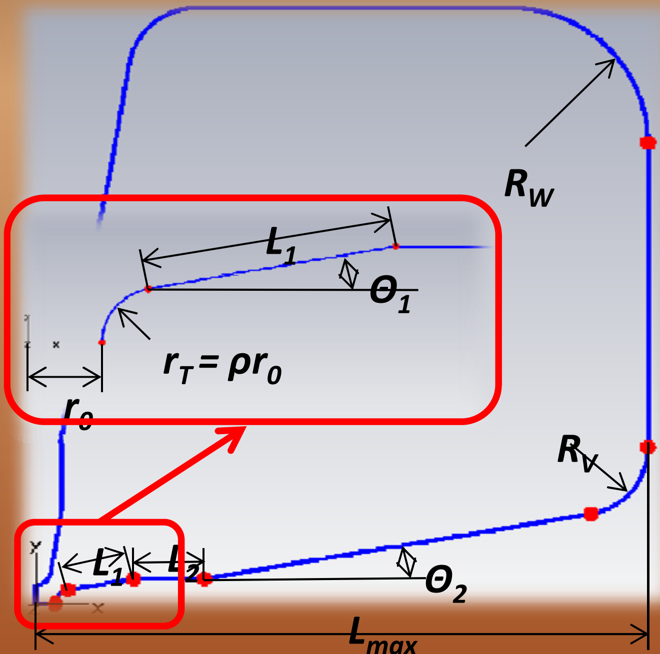
RF design complete

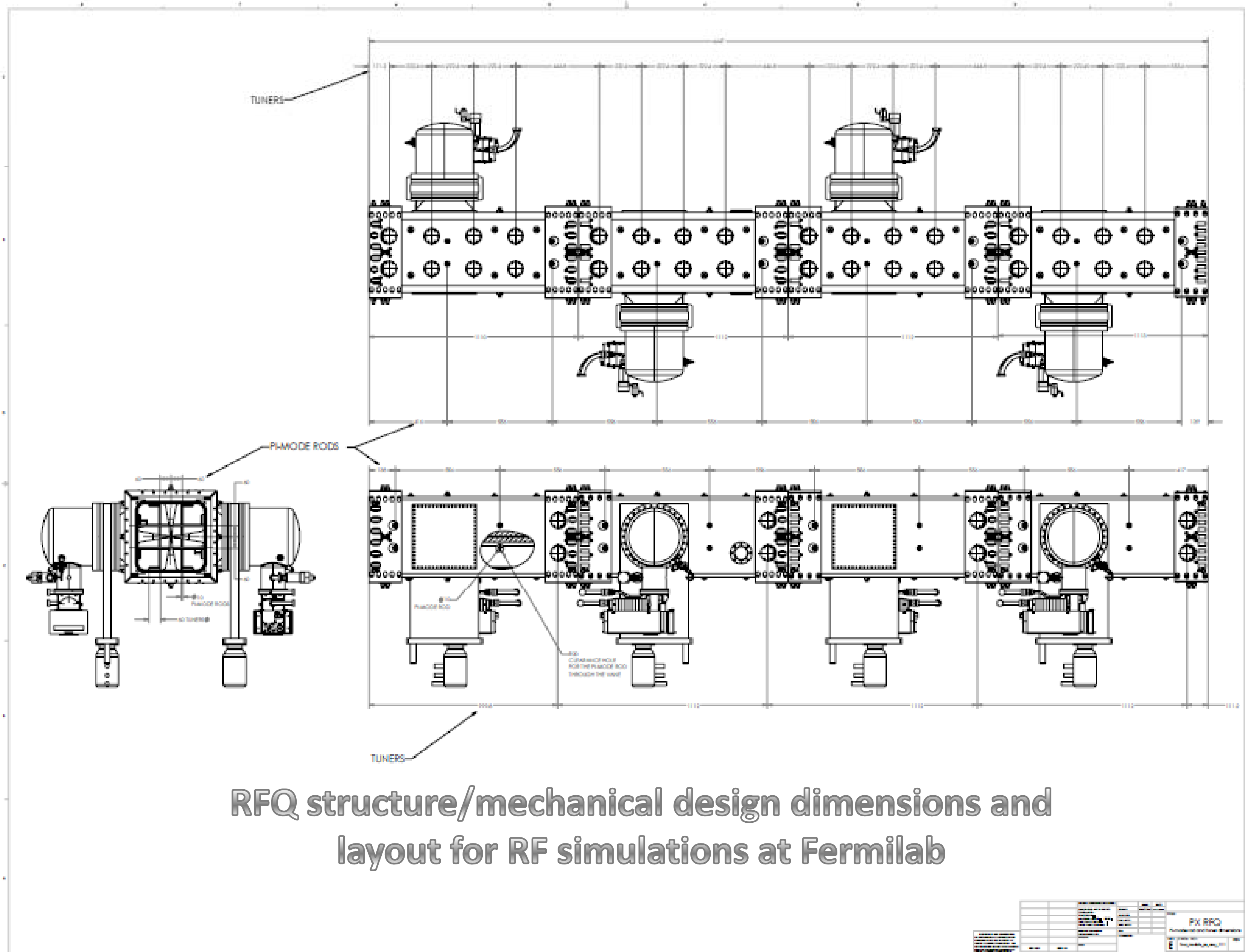
Conceptual engineering design complete

Detailed thermal analysis and mechanical design in progress

RF Simulation/Structure Design

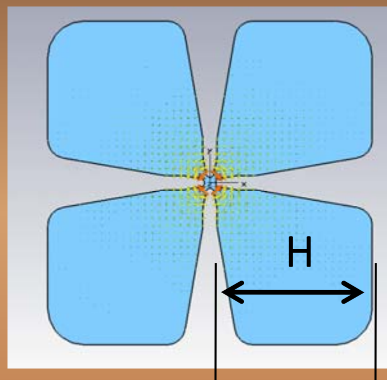
- **Collaboration with Fermilab**
  - **2D SUPERFISH simulations**
    - Frequency (cross-section), RF power density
    - Parameterized 2D model
  - **3D CST MWS simulations**
    - Mode stabilization schemes
    - VCR versus PI-mode stabilization rods
    - Field perturbation due to rods, tuner, …
    - Power dissipation (3D)
    - Thermal calculations
  - **RFQ termination**
    - Cut-back and radial matcher at entrance
    - Cut-back at exit
  - **Tuners**
- Bench-marking, measurements and simulations using SLAC's Omega-3P code

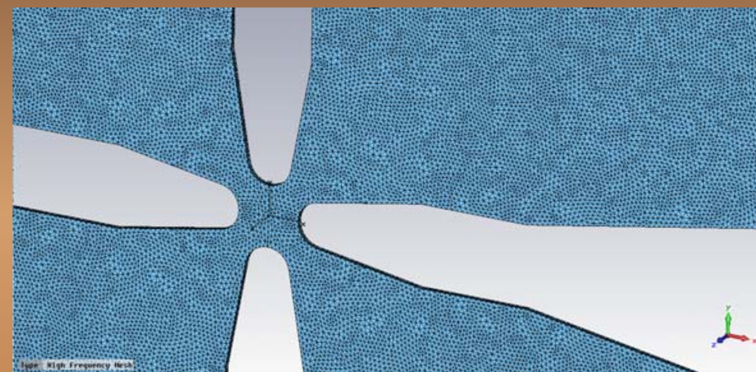




RFQ structure/mechanical design dimensions and layout for RF simulations at Fermilab

2D RF Simulation Results

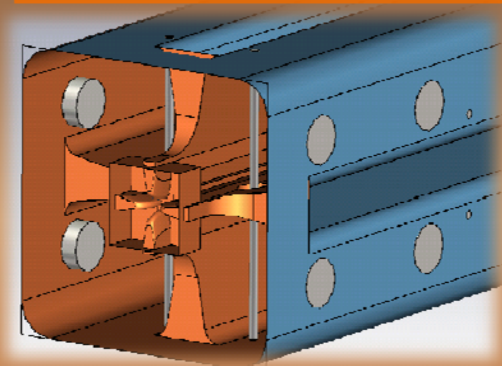




Parameters	IMP	PXIE	Unit
Quadruple frequency	162.57	162.49	MHz
Q factor	16863	16813	
Power loss per length	132.4	133.0 (59.2kW)	Watts/cm
Peak electric field	15.75	13.4	MV/m
Dipole mode frequency	157.55	157.5	MHz
Tuning sensitivity ΔF/ΔL	1.04	1.04	MHz/mm
H		176.59	mm

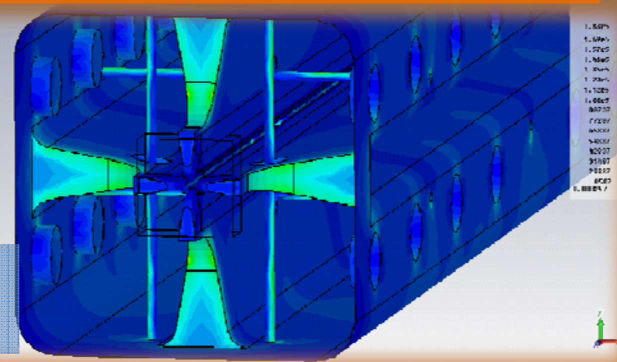
The 2D cross section is tuned to operating frequency of 162.5 MHz at H=176.59

3D RF Simulation Results



The model includes:

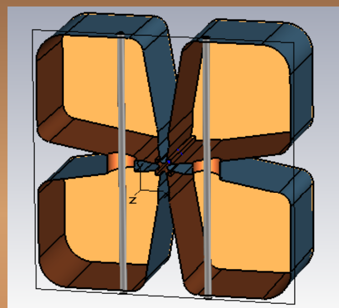
- Pi-mode stabilization rods
- Radial matcher and two terminations
- Tuners

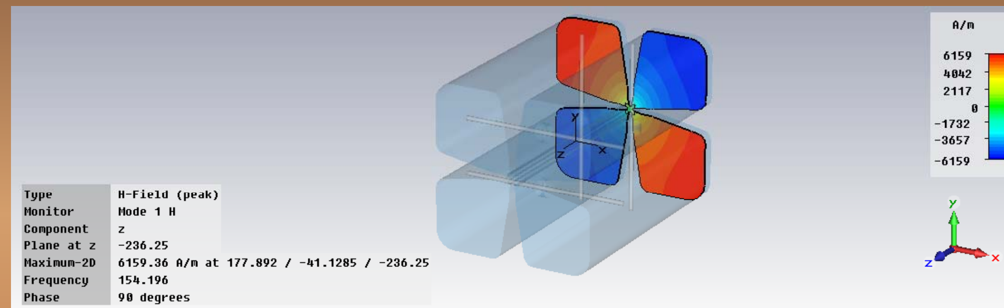


Power loss density distribution

Parameters	**PXIE-T**	**Units**
Frequency	162.493	MHz
Frequency of dipole mode	181.99	MHz
Q factor	14660	
Q factor drop due to everything	-14.7	%
Power loss per cut-back (In/Out)	336/389	watts
Max power loss density at cut-back	7.9	W/cm^2
Total power loss	73.8	kW
H	172.73	mm

Perturbation from Pi-rod Stabilization



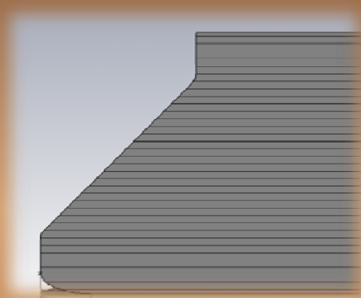
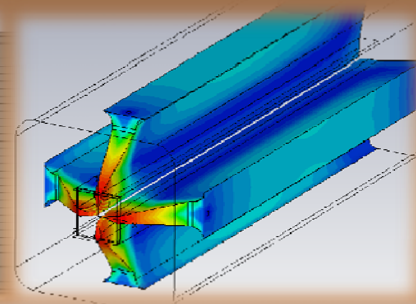
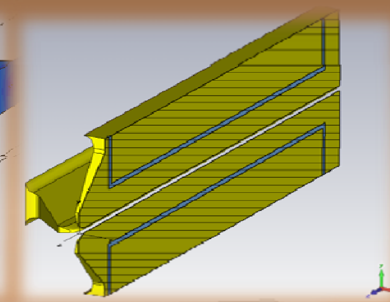
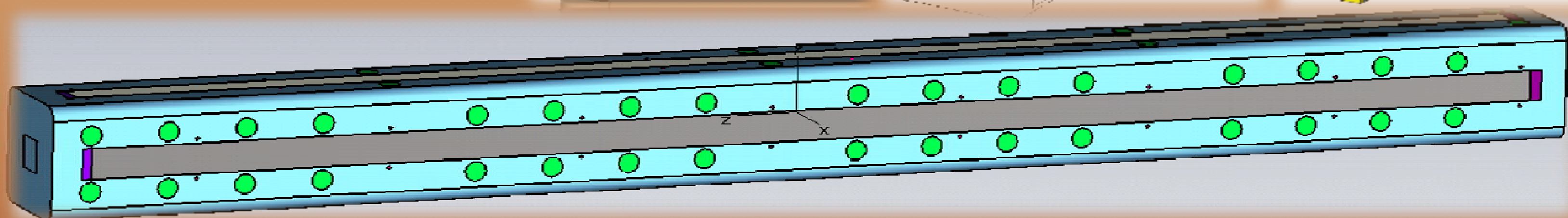
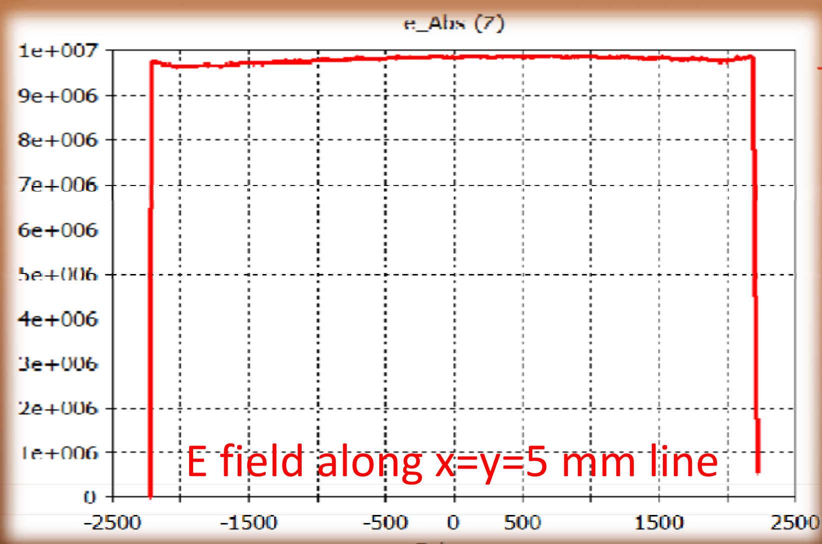


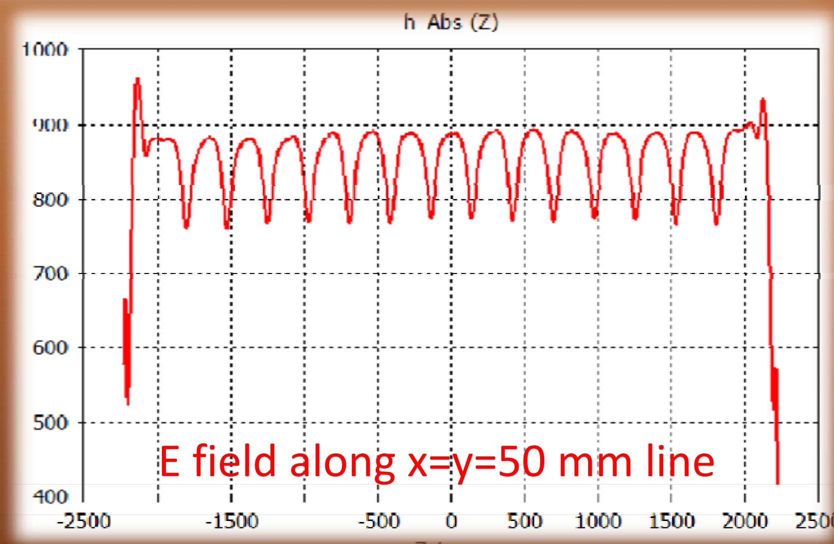
Parameters	PXIE	Unit
Frequency	162.486	MHz
Quad. frequency shift due to Pi-mode rods	-5.56	MHz
Q factor	15333	
Q factor drop due Pi-mod e rods	-9.65	%
Power loss per Pi-mode rod	188	Watts
Dipole mode frequency	179.6	MHz
Dipole mode shift	22.1	MHz
Field perturbation at x=y=5 mm	0.3	%
H	171.44 (176.59)	mm

RF Termination Design

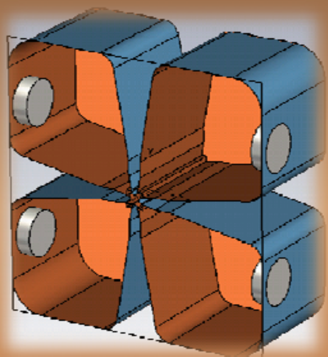
Termination design:

- Maintain field flatness by adjusting cut-back geometry and minimize power density.

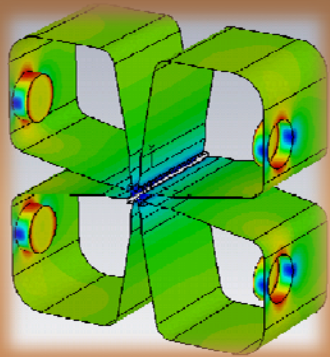


Tuner Studies



Current Design:

- 80 tuners in total and each tuner has 60 mm in diameter with 20 mm intrusion (nominal position)
- Simulations of tuners in a structure period



Parameters	PXIE-T	Unit
Frequency	162.495	MHz
Frequency shift due tuners	1.334	MHz
Q factor	16115	
Q factor drop due tuners	-4.1	%
Power loss per tuner	57.7	Watts
Tuning sensitivity	16.7	kHz/mm
Nominal tuner intrusion	20	Mm
H	177.84	mm

Summary of RF Power Requirements*

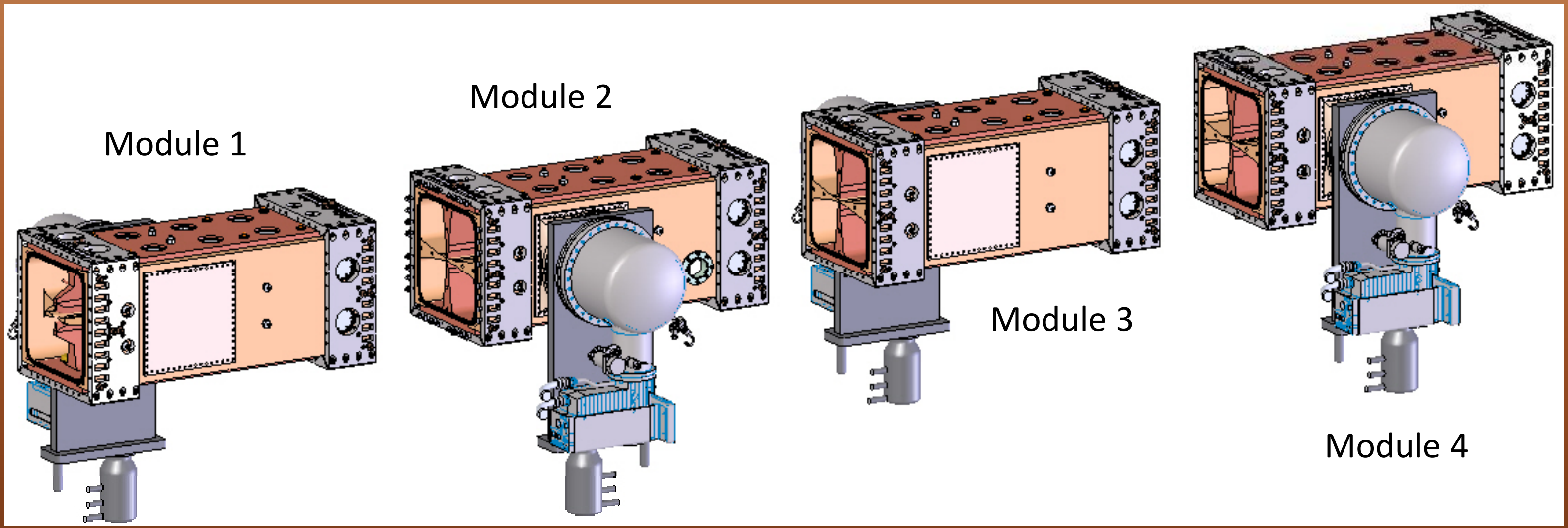
Section	Total, kW	Per unit, W
Walls	29.5	-
Vanes, 4 units	31	7764
Input cut-backs, 4 units	1.34	336
Output cut-backs, 4 units	1.56	389
Pi-mode rods, 32 units	5.53	173
Tuners, 80 units	4.79	59.9
Sub-total	73.72	
Beam power at 5 mA	10.5	
Total	84.22	

*Based on 3D RF simulation results.

RF Structure (Mechanical) Design

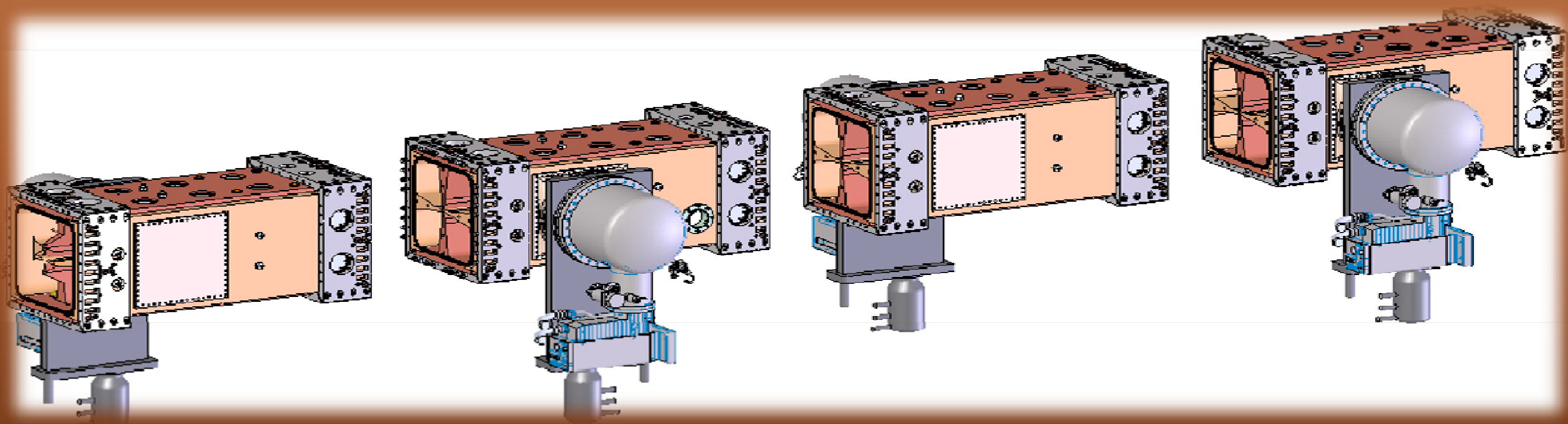
Summary of the IMP RFQ design:

- RFQ: 4.45 meters long consists of four modules;
- 32 Pi-mode stabilization rods;
- 2 RF power couplers;
- 80 plug-tuners (20 per module);
- 48 RF probes;
- Preliminary termination (cut-back) design (RF) complete.



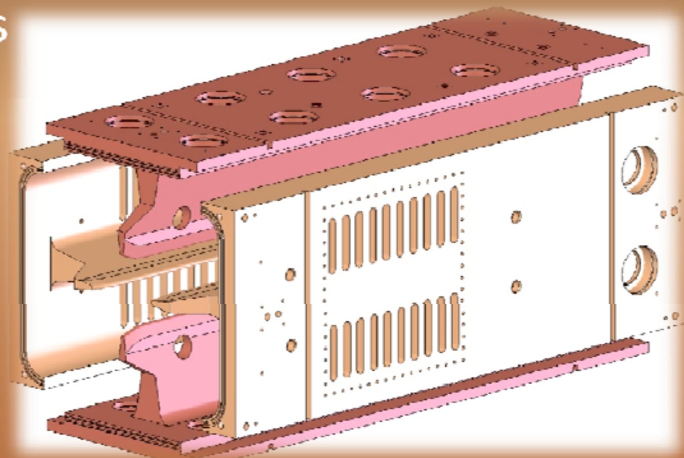
PXIE RFQ Design Approach

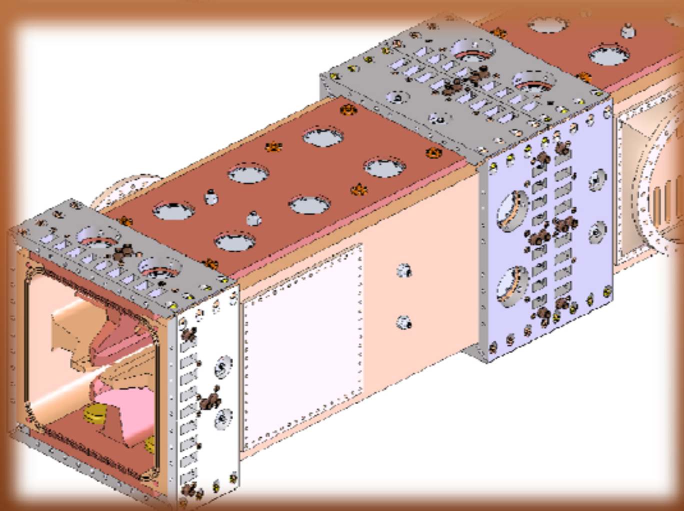
- **Develop the PXIE design based on past LBNL RFQ experience**
- **Use proven, low risk techniques from the SNS RFQ design**
  - Four vane copper-to-copper braze
  - Fly cut modulated vane tips
  - Brazed, water cooled pi-mode rods
  - Low profile, bolted module joints
  - Removable fixed slug tuners



PXIE RFQ Module Design Features

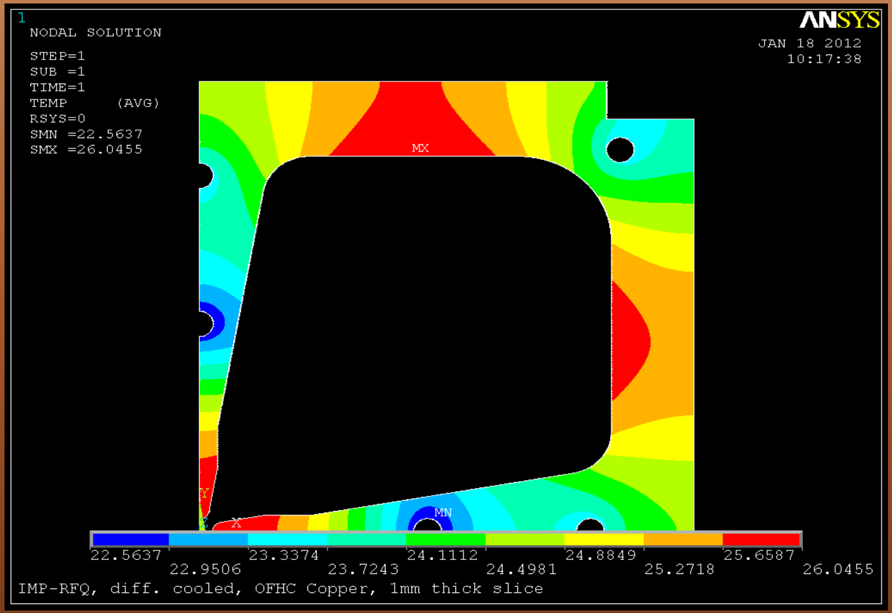
- Each module consists of four separately machined vanes
- Gun drilled vane and outer wall cooling passages
- Precision ground mating surfaces
- High reliability copper-to-copper braze forms cavity module
- 20 fixed slug tuners/module
- 8 pi-mode stabilizing rods per module
- 12 field sensing loops per module
- RF power feed through two loop couplers
- Two vacuum pumping ports per module
- Separate wall and vane cooling circuits provides active tuning capability
- Sealing provided by RF and O-ring seals at bolted joints

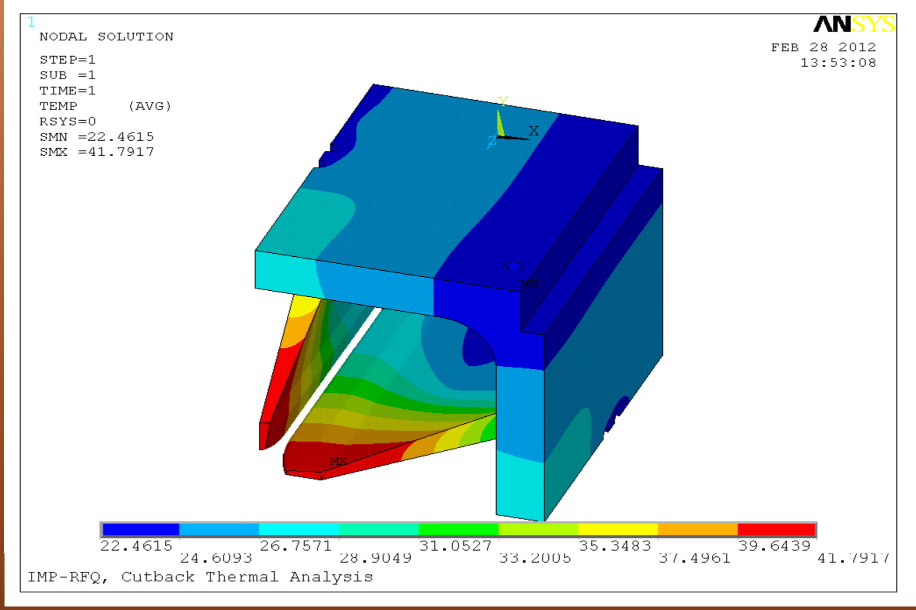




Mechanical Analyses

- Numerous engineering analyses carried for design validation
- Cavity body thermal analysis using ANSYS to calculate RF field, power dissipation density, compared well with SUPERFISH output
- Stress analysis using converted ANSYS thermal model
- Water temperature tuning analysis using a separate ANSYS model
- Calculation of area properties for body stiffness analysis



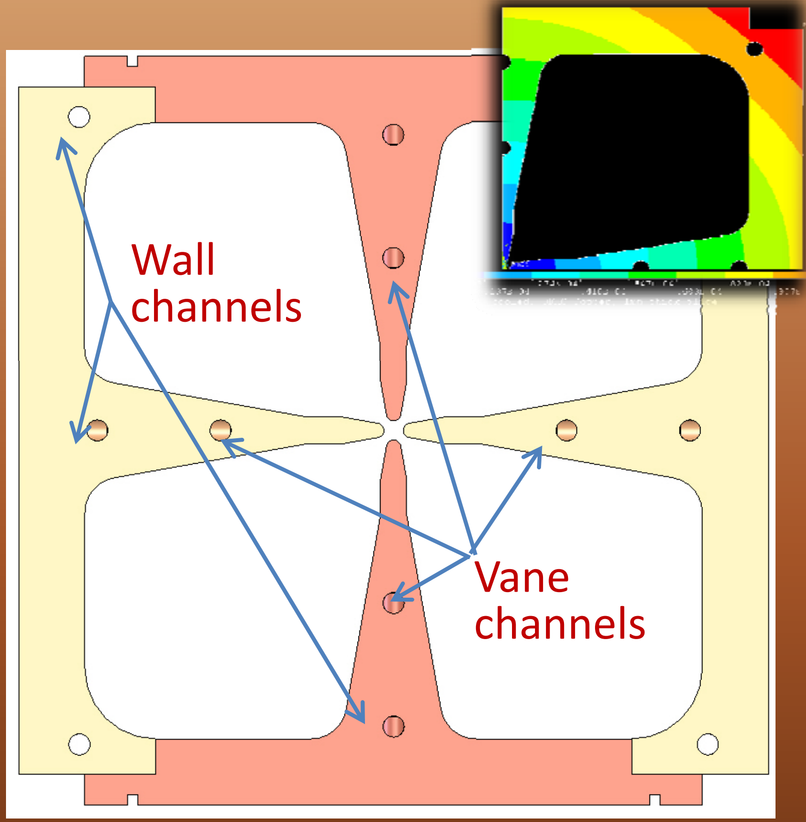


Frequency Tuning Analysis

- The RFQ cavity resonant frequency can be shifted by altering the cooling water temperature
- Due to the sensitivity of the frequency to the vane tip spacing, a wider tuning range can be achieved by varying only the vane water temp.
- Displacements from the structural analysis are used in an ANSYS RF model to predict tuning performance
- Analysis results:

PXIE Frequency Shift	Shift
Overall (kHz/°C)	-2.80
Vane (kHz/°C)	-16.70
Wall (kHz/°C)	13.90
Sum of Vane and Wall (kHz/°C)	-2.80
Theoretical Shift (kHz/°C)	-2.91
% Error	3.8%

- ~ 200 kHz tuning range possible

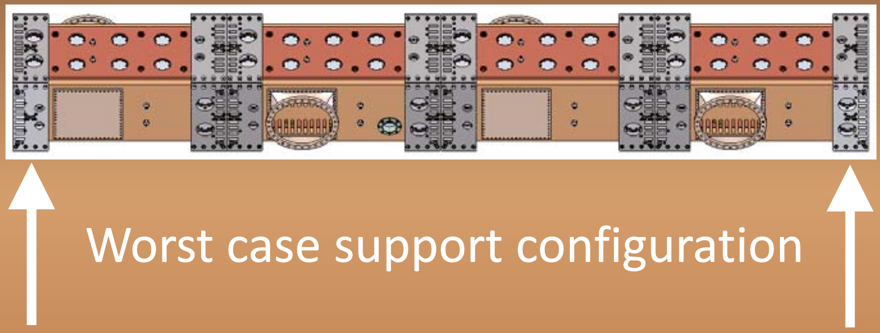


RFQ Stiffness/Strength Analysis

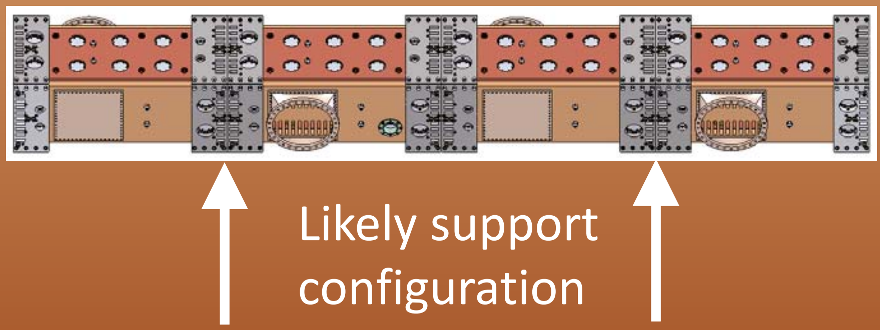
- **When bolted together, the four modules form a single, stiff structure that can be analyzed as a beam**
- **The large cross section of the 162.5 MHz RFQ is heavy, but extremely stiff in bending. Calculated parameters are:**
  – Cross section area: ~ 794 cm^2
  – Weight/length: ~ 6930 N/m (~ 785 kg/module – body only)
  – Moment area of inertia: ~ 1.59×10^5 cm^4
- **Maximum stress and deflection of the RFQ due to its own weight is dependent on the design of the support system**
- **Worst case analysis helps to determine the type of support needed**

Stiffness/Strength Analysis (cont'd)

- For worst case, the results are:
  - Maximum stress: 2.0 MPa
  - Maximum deflection: 0.15 mm



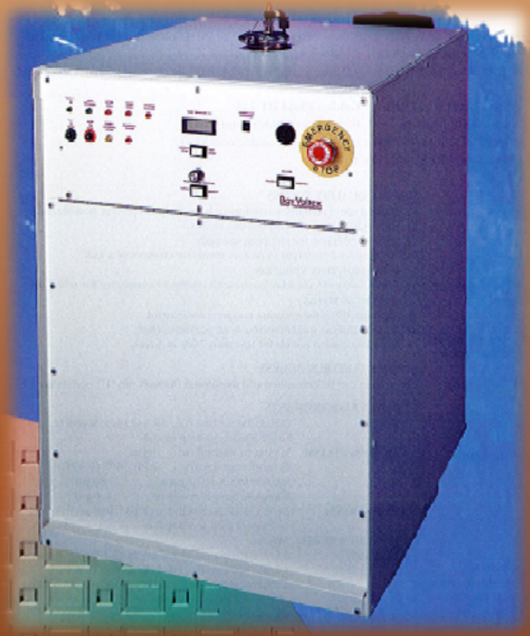
- For likely support points:
  - Maximum stress: 0.13 MPa
  - Maximum deflection: <0.01 mm



- The yield stress of the fully annealed copper can be as low as 25 MPa, but the stress due to support and handling are very low
- The SNS RFQ was supported using a 6-strut system

RFQ Cooling System

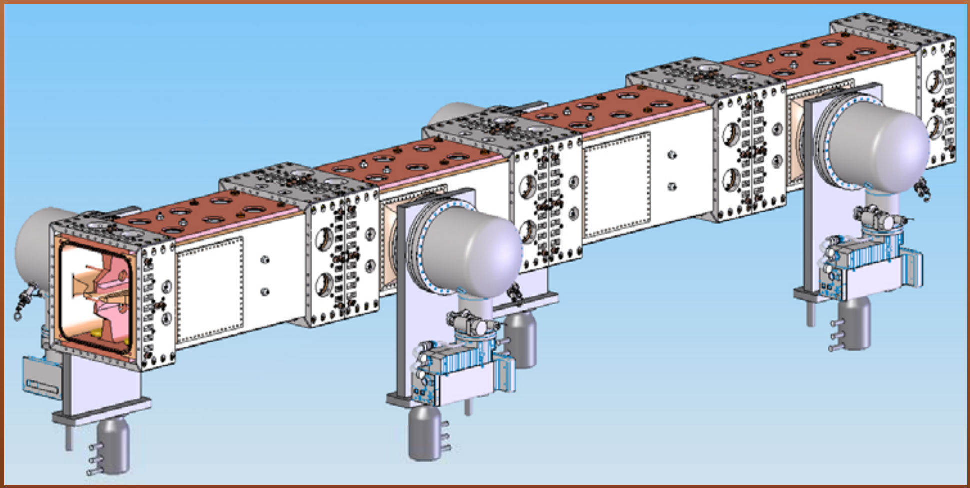
- **Each module has 12 cooling channels (8 wall, 4 vane)**
- **12 mm diameter channels flow 0.26 l/s at 2.29 m/s velocity**
  - Reynolds number is 25,900 (turbulent flow)
  - Maximum flow to prevent Cu erosion is 4.57 m/s
  - Lower flow rate used to reduce chiller size
- **Total system flow: 8.3 l/s wall, 4.1 l/s vane**
  - Nominal water temperature rise is 1.9 ^{o}C
  - Commercial closed-loop chillers that meet system requirements are readily available
  - Two units needed (one for vanes, one for walls)
- **Small flow in pi-mode rods (.04 l/s each) necessary to limit axial thermal stresses**



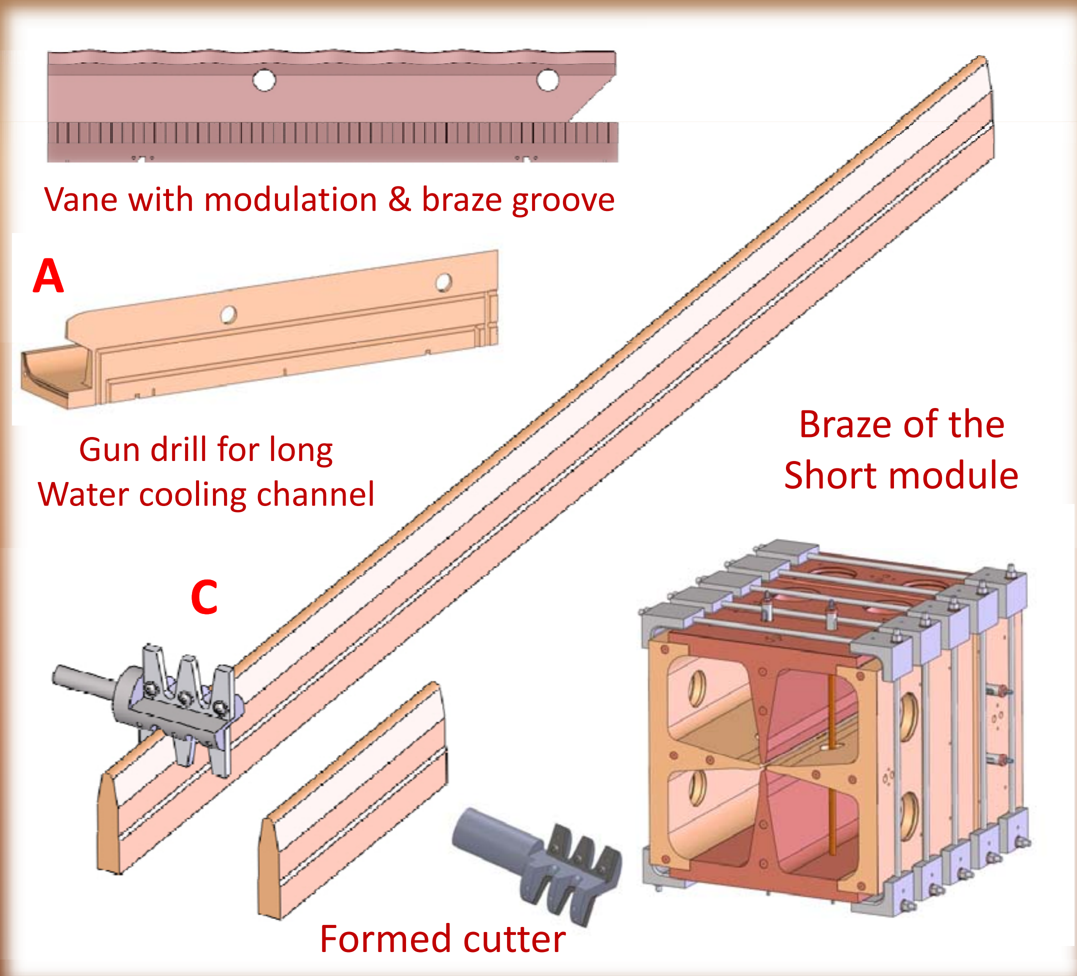
Commercial chiller example

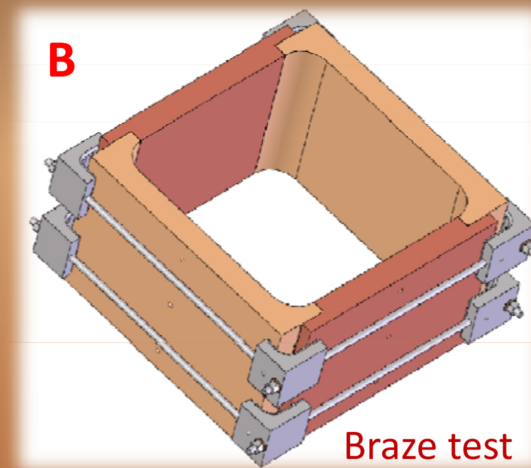
RFQ Vacuum System

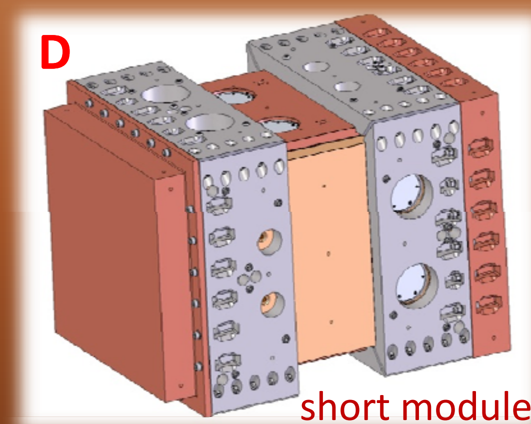
- Primary gas loads are: module joint and tuner O-rings, cavity wall out-gassing and gas from LEBT
- RFQ body has 8 vacuum ports (2 per module)
- Vacuum could be achieved by four 10" Trubo- or cryo- pumps (two per RFQ side)
- Additional 4 vacuum ports are blanked off
- Cavity walls only need to be detergent cleaned (no baking)
- Viton O-ring seals are to be pre-baked and ungreased
- More detailed analysis will be required – possible that 8" pumps can be used



Key Fabrication Test







Summary

- **Milestones and schedule**
  - Beam dynamics design complete and frozen;
  - RF *EM* design complete, including RFQ structure & terminations;
  - Preliminary engineering design complete:
    - RFQ layout, dimensions of RFQ cross-section, cut-backs, pi-mode rods, tuners, module joints, water cooling channels;
    - Thermal and mechanical structure analyses complete, including RFQ body and cut-backs;
    - Fixtures for machining, brazing, lifting and handling.
  - Drawings for fabrication testing in progress:
    - Material for formed cutter ordered;
  - Initial analyses of water cooling system and vacuum system complete;
  - First PXIE RFQ design review scheduled on April 12, 2012 at LBNL;
  - Fabrication drawings expect to be delivered by September 30, 2012