Fermi National Accelerator Laboratory

Project X

FNAL RFQ Studies for Project-X

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Talk Outline

Project X

- **Basic requirements for RFQ**
- **Short table of existing CW RFQ parameters**
- **RFQ design**
- **Beam dynamic simulation**
- **On choice of RFQ cavity cross-section, RFQ vanes and length, input/output matching**
- **Conclusion and plans**

Initial requirements for design

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The requirements as they were on 1/24/2011

Ion	Proton
Frequency	162.5 MHz
Duty factor	100%
Average beam current	5.0 mA
Output energy	2.5 MeV
Injected beam transverse emittance, rms	≤ 0.25 π mm mrad
Output beam longitudinal emittance, rms	.7 …1.0 keV·nsec
Total structure length	≤ 4.5 m
RF power losses	≤ 150 kW

Special attention should be paid to:

- Power losses – because it's CW
- Longitudinal emittance – because of frequency jump
- Beam losses inside cavity – accumulation of harmful things

Existing CW RFQ designs

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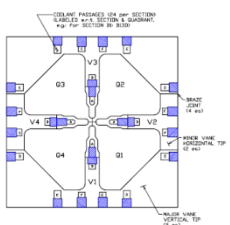
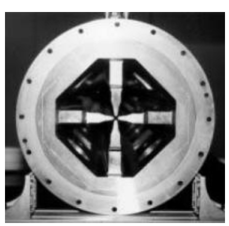
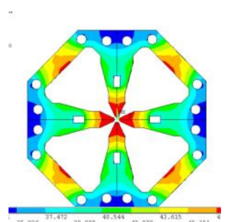
Project	Freq., MHz	E_{in}/E_{out}, keV/Mev	Length, m	Power, kW	R0, aver. aperture
LEDA	350	75/6.7	8	1200	variable
KOMAK	350	50/3	3.25	350	variable
Indian ADS	350	?/4.5	6.52	428	const
IPHI	352	95/5	7.9	1150	variable
TRASCO	352	80/5	7.13	580	variable
IFMIF	175	100/5	9.78	522	variable



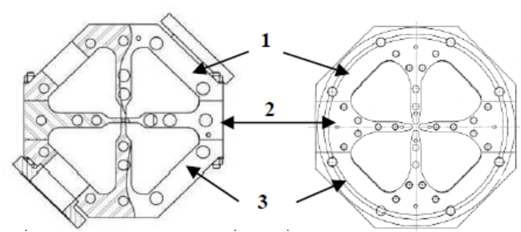
LEDA



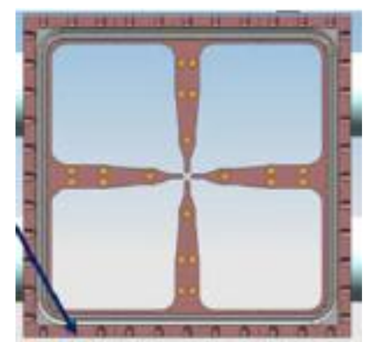
KOMAK



Indian ADS



TRASCO IPHI



IFMIF

Only LEDA successfully operated several months at full power. There is a number of routinely operated CW RFQ for energies ≈ 1 MeV and below.

RFQ parameters

Basic design parameters	
Input energy	40 keV
Voltage	85.0 kV
Average radius	6.0 mm
Vane tip curvature radius	5.4 mm
Synchronous phase	-90° …-28°
Modulation	1.02 …2.0

We have done several design studies of the RFQ for Project X at Fermilab for frequencies of 325 and 162.5 MHz (S.Rao, A.A.Kolomiets). The presented design by A.A. Kolomiets (ANL) is the latest and the most developed.

Calculated RFQ parameters	
Aperture, min	4.0 mm
Cell length	8.55 – 67.1 mm
Cell number	203
RFQ length	4572 mm
Transverse phase advance @ I=0	57^0 - 50^0
Normalize transverse envelope	1.29 – 1.33
Maximum field at vane surface	27 MV/m
Norm. transverse acceptance	4.89 mm mrad
Longitudinal phase advance @ I=0	23^0 – 40^0 – 13^0
Power losses	202 kW/141 kW

Comments on choice of the basic RFQ parameters

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•RF power losses mainly depend on **intervane voltage**. So, the voltage was chosen relatively low U=85 kV

•Focusing parameter is proportional to voltage. Relatively low voltage has been compensated by decreasing of $\mathbf{R_0}$.

$$B=\frac{Ze}{A}\frac{U}{E_0}\left(\frac{\lambda}{R_0}\right)^2$$

•However $\mathbf{R_0}$ has to be big enough to provide required transverse acceptance ***A*.** It was accepted in this design that $\boldsymbol{A/\varepsilon_{in}}\geq 4$.

•Additionally to provide design emittance / acceptance ratio, the maximum value of modulation coefficient has been limited ***m* = 2**.

$$A=\frac{\gamma}{\lambda}\left(\frac{2}{m+1}\frac{R_0}{\rho_{max}}\right)^2$$

•**Maximum field** at electrode surface for flat electrodes with pole curvature radius ***R*e** and voltage between adjacent electrodes ***U*** can be expressed as

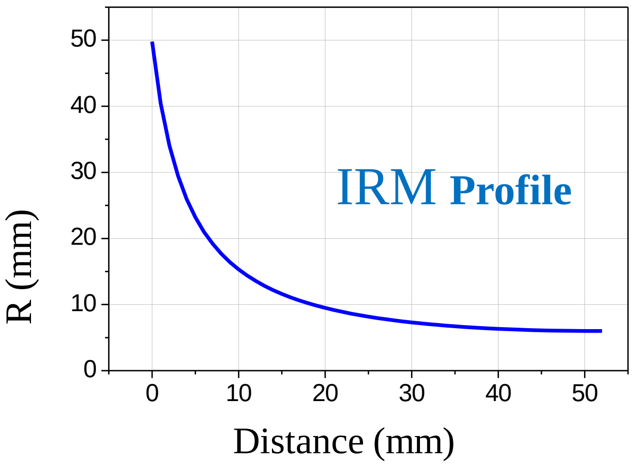
$$E_{max}=\frac{U}{R_0}\chi$$

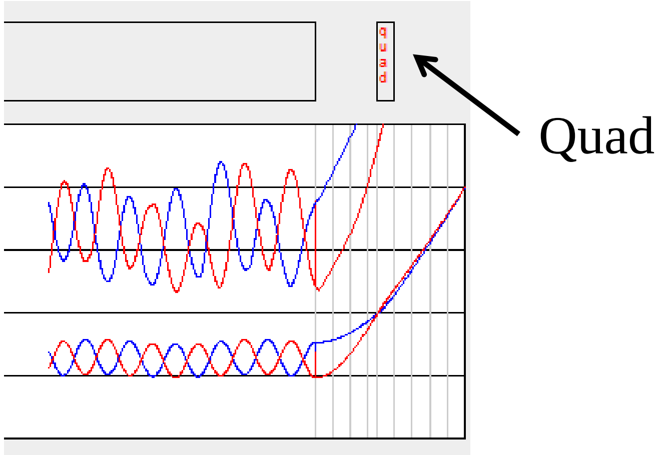
where field enhancement factor $\chi=\sqrt{\frac{1}{2}\left(1+\frac{R_e}{R_0}\right)^2+\left[\frac{2T}{\pi}k\,R_0\,I_0\left(k\frac{R_0+R_e}{\sqrt{2}}\right)\right]^2}$

•**Maximum field** in this design is relatively low (27 MV/m compare to 33 MV/m for LEDA), the ratio **Re/R0** has been chosen close to 1 (0.9 in fact).

Input/Output radial matching

The code DESRFQ is used for further RFQ design. It calculates accelerating-focusing channel parameters for given basic parameters. Input/output matching are designed separately. The final verification of beam dynamic are performed with multiparticle code TRACK.

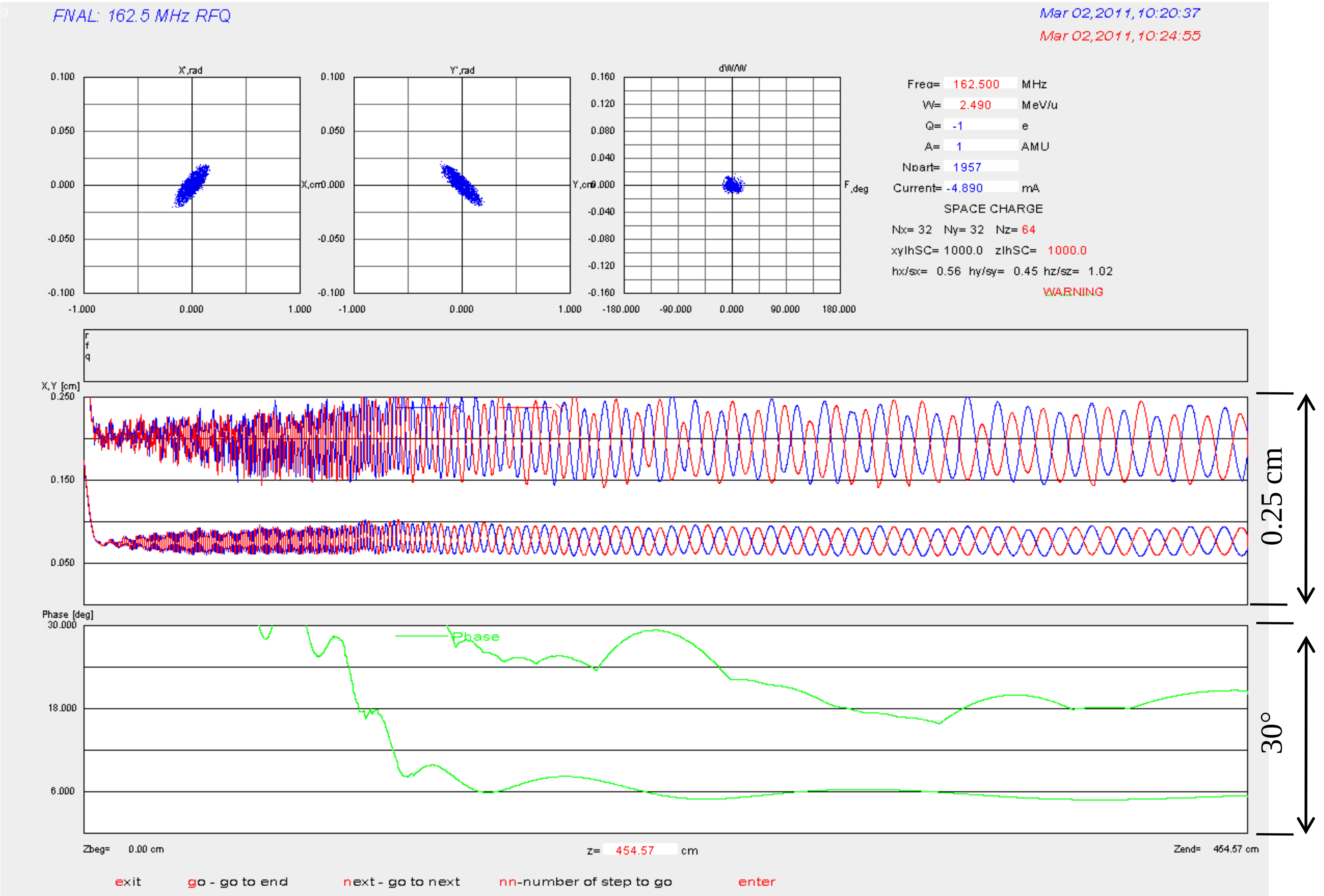




The simple 6 cell length Input Radial Matcher is used in this design. It provides acceptable matching for computer simulation. IRM can be redesigned later to provide optimized bean dynamics in LEBT and RFQ. Current matched input beam parameters are $\alpha_{x,y}$ = 1.4 and $\beta_{x,y}$ = 6.2 cm/mrad.

Final RFQ cell length is adjusted to provide the condition when bunch leaves vanes at maximum field amplitude. The beam has in this case crossovers in both transverse planes. Transverse envelopes became equal at about 15 cm after RFQ. Short quadrupole placed in this position equalize envelope angles and produces axial symmetric beam.

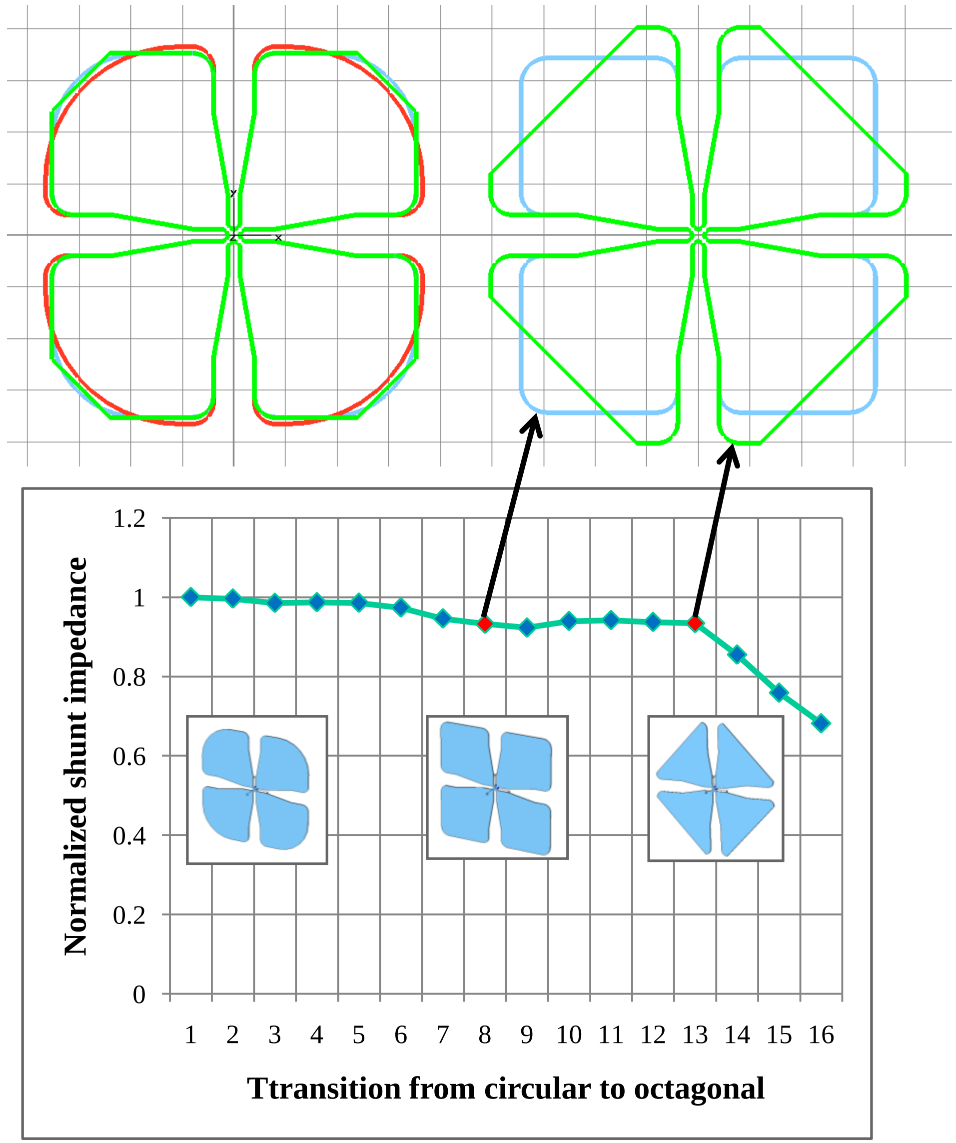
TRACK simulation



Simulated beam parameters for I = 5 mA

Particle loss inside structure	< 0.3 %
Transmission	> 98%
Transverse emittance, rms	0.025 π cm·mrad
Transverse emittance growth, rms	1
Transverse emittance @ 99.5% particles	0.157 π cm·mrad
Transverse emittance growth @ 99.5% particles	1.093
Longitudinal emittance, rms	0.825 keV·nsec
Longitudinal emittance @ 99.5% particles	13.4 keV·nsec

Cross-section



The shunt impedance of RFQ is relatively insensitive to the shape of cross-section. For chosen shapes the drop of shunt impedance is ≈ 7% compare to the circular shape.

Length of RFQ

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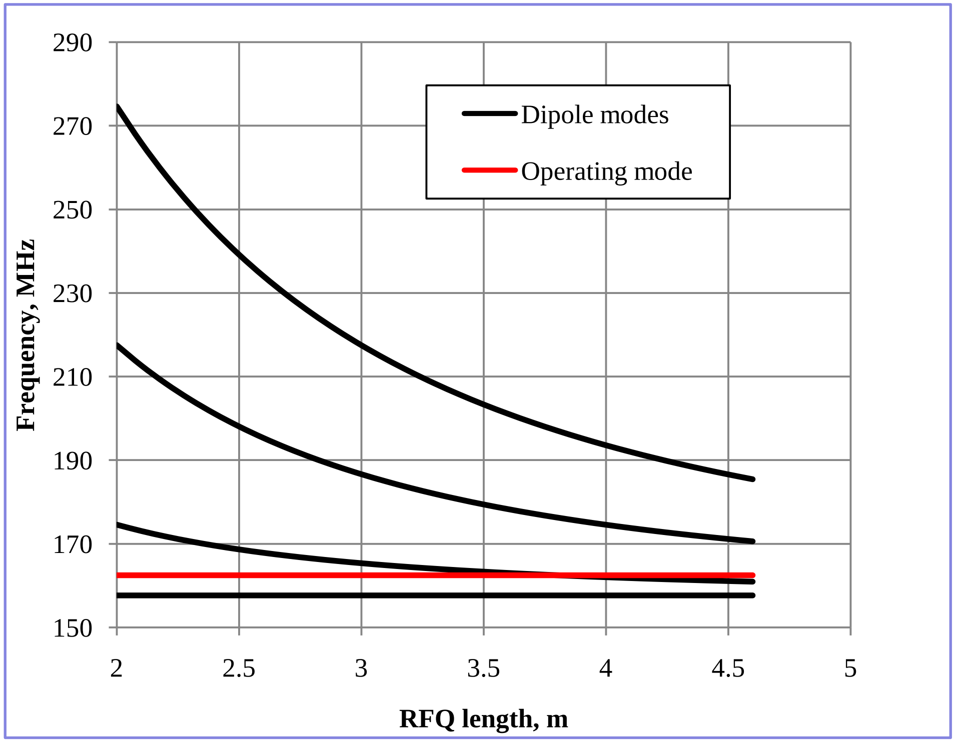
The long electrical length produces longitudinal and azimuthal field distribution instability. For L=4.5 m the dipole modes are too close.



Dipole mode frequencies vs RFQ length. The RFQ terminations are perfect.

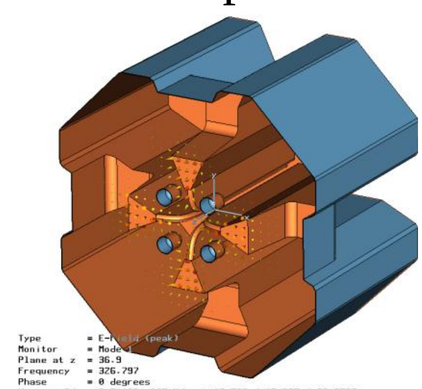
<u>Solutions:</u>

Use resonantly coupled ≈ 2.25 m long sections of RFQ structure

OR

- Make RFQ ≈4.75 m long
- Use end-wall tuners to lower nearest dipole frequencies
- Place power couplers at ≈1/4 and ≈ 3/4 of RFQ length to suppress excitation of the nearest dipole modes.

A real RFQ termination



Vane design

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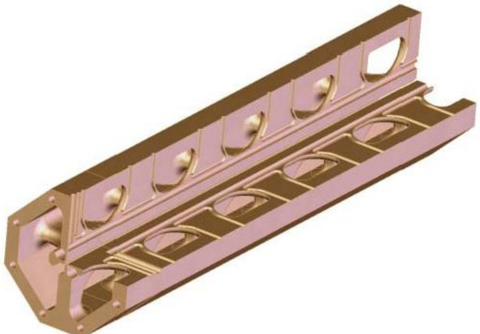


Vanes with windows,
"four ladder" cavity

Traditional vane (HINS RFQ)

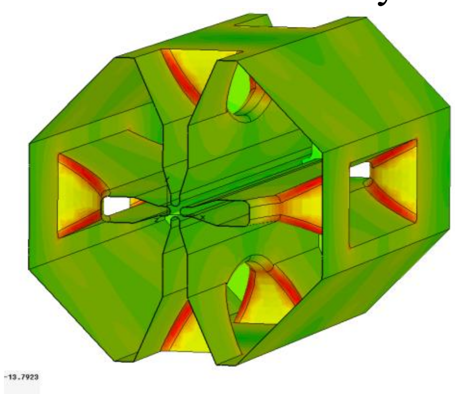
"Four ladder" structure

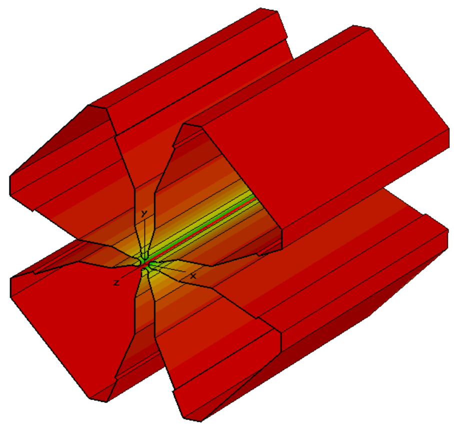
<u>Pros</u>:

- No problem with dipole modes, high azimuthal stability.
- Smaller transverse dimensions

<u>Cons:</u>

- Less effective than traditional
- Non-uniform RF losses, "hot" spots in very inconvenient places.





Surface magnetic field distribution

H_{max} = 15640 A/m
P = 202 kW

H_{max}=2954 A/m
P = 141 kW

F = 162.5 MHz
V = 85 kV
L = 4.5 m (without ends)

Conclusion and plans

We are in the very beginning of the design. The further plans are:

- **Physics and beam dynamic**
  - **Further improvement of RFQ performance**
  - **Consequences of beam losses due to mismatching, tuning errors etc**
  - **Multipactor simulation**
  - **Matching LEBT, RFQ and MEBT**
- **RF design**
  - **Make a final choice and optimization of cavity design**
  - **Study the longitudinal and azimuthal stabilization of the field**
  - **Segmentation in conjunction with field stability and manufacturing**
  - **Power coupler RF design**
- **Mechanical design**
  - **Design and optimization of cooling scheme**
  - **Coupled thermal and stress analyses**
  - **Mechanical design of power couplers, tuners, probes**
  - **Development of production flow, resolve manufacturing issues**