Best® Cyclotron Systems, Inc.

Resonator System for the *BEST* ®70MeV Cyclotron

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OVERVIEW

BEST 70MeV Cyclotron is developed for radioisotope production and research purpose.

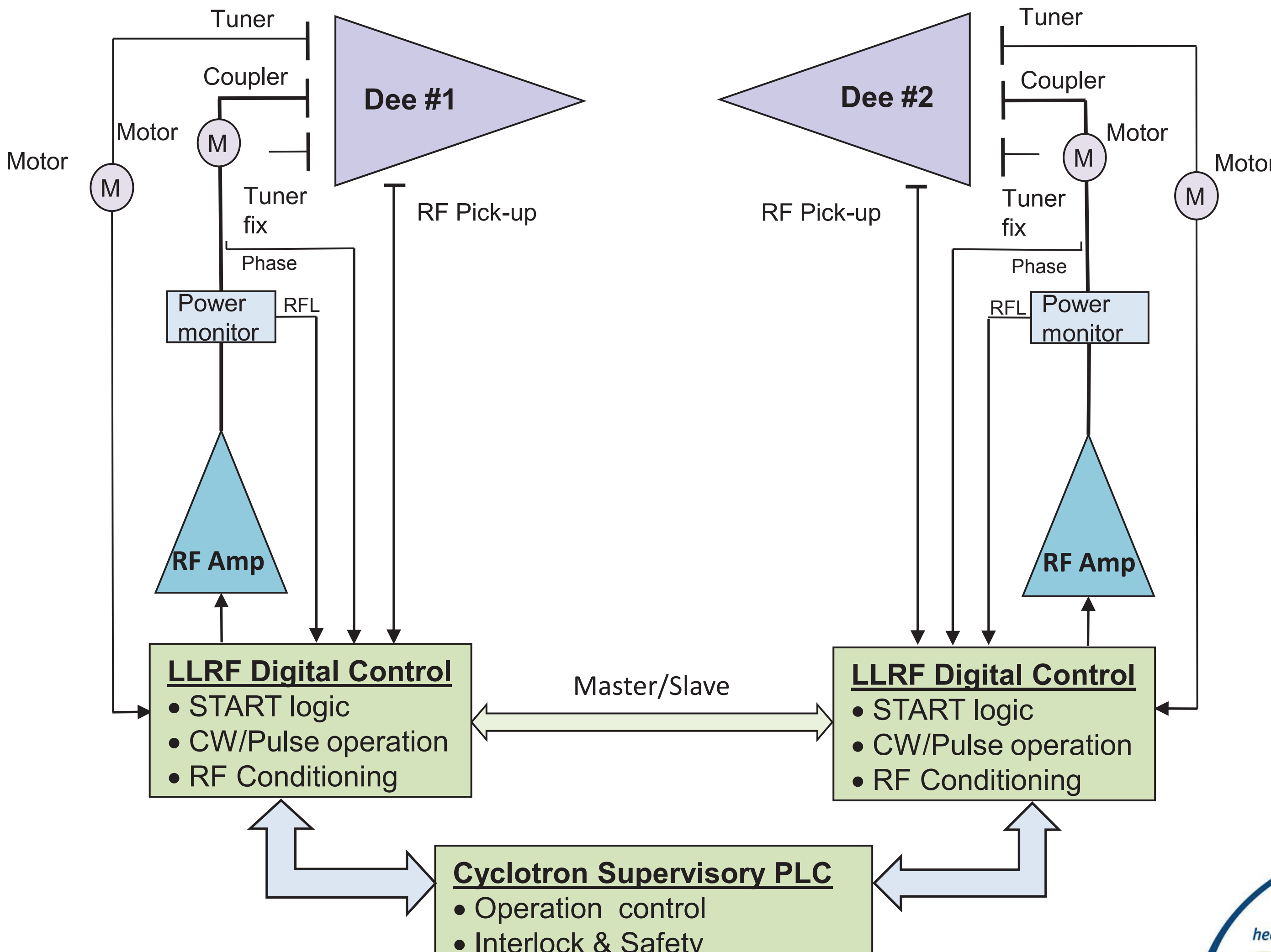
- General description
- Resonator System
  - Electromagnetic simulations
  - Mechanical model
  - Cold test set-up
- RF Power Amplifier
- LLRF Control

General description

The RF system has been designed for the following cyclotron characteristics:

- Maximum acceleration energy of 70MeV
- Beam intensity of 700μA of negative hydrogen ions
  - Beam power minimum 49kW
- Two separated RF Systems

General description



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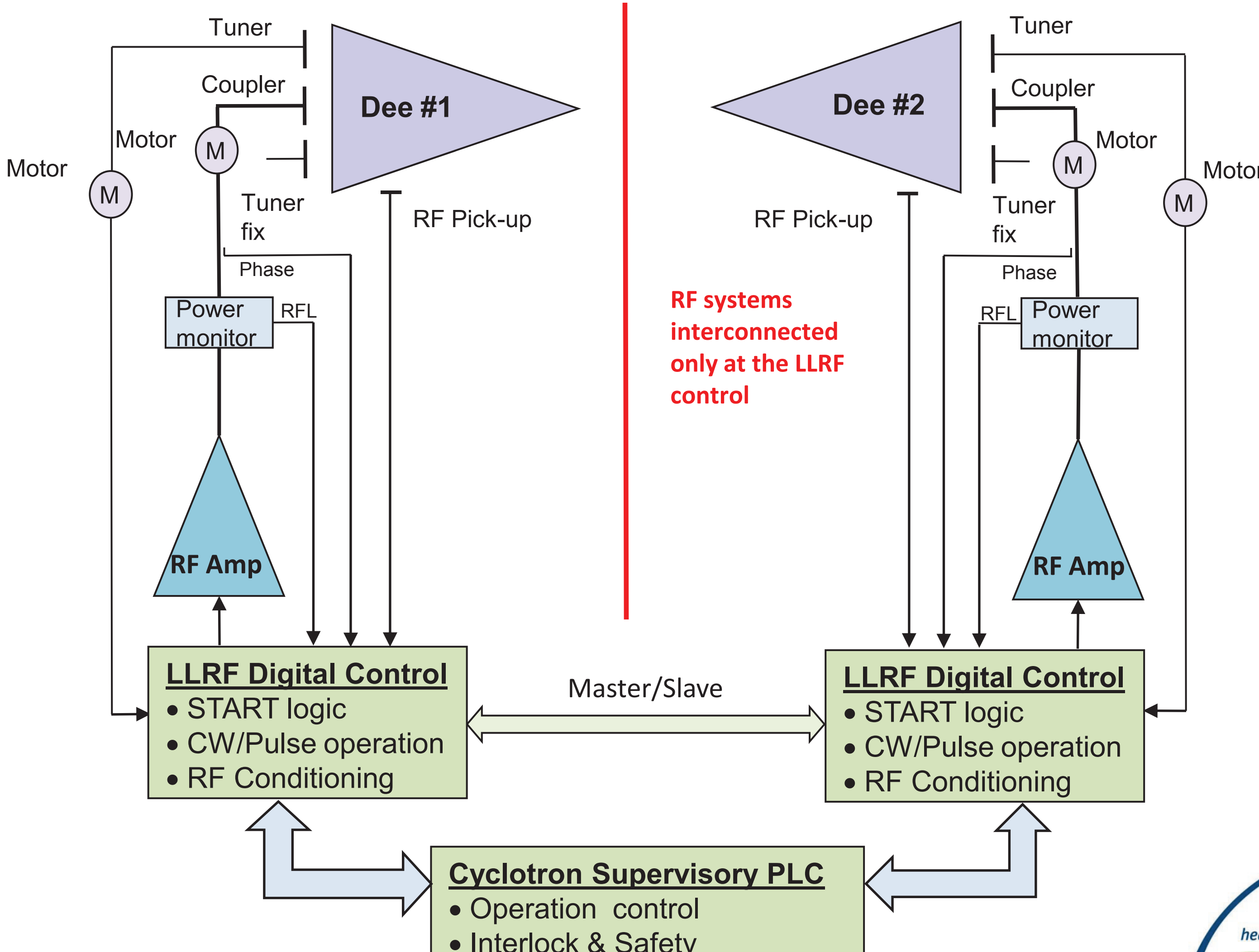
General description



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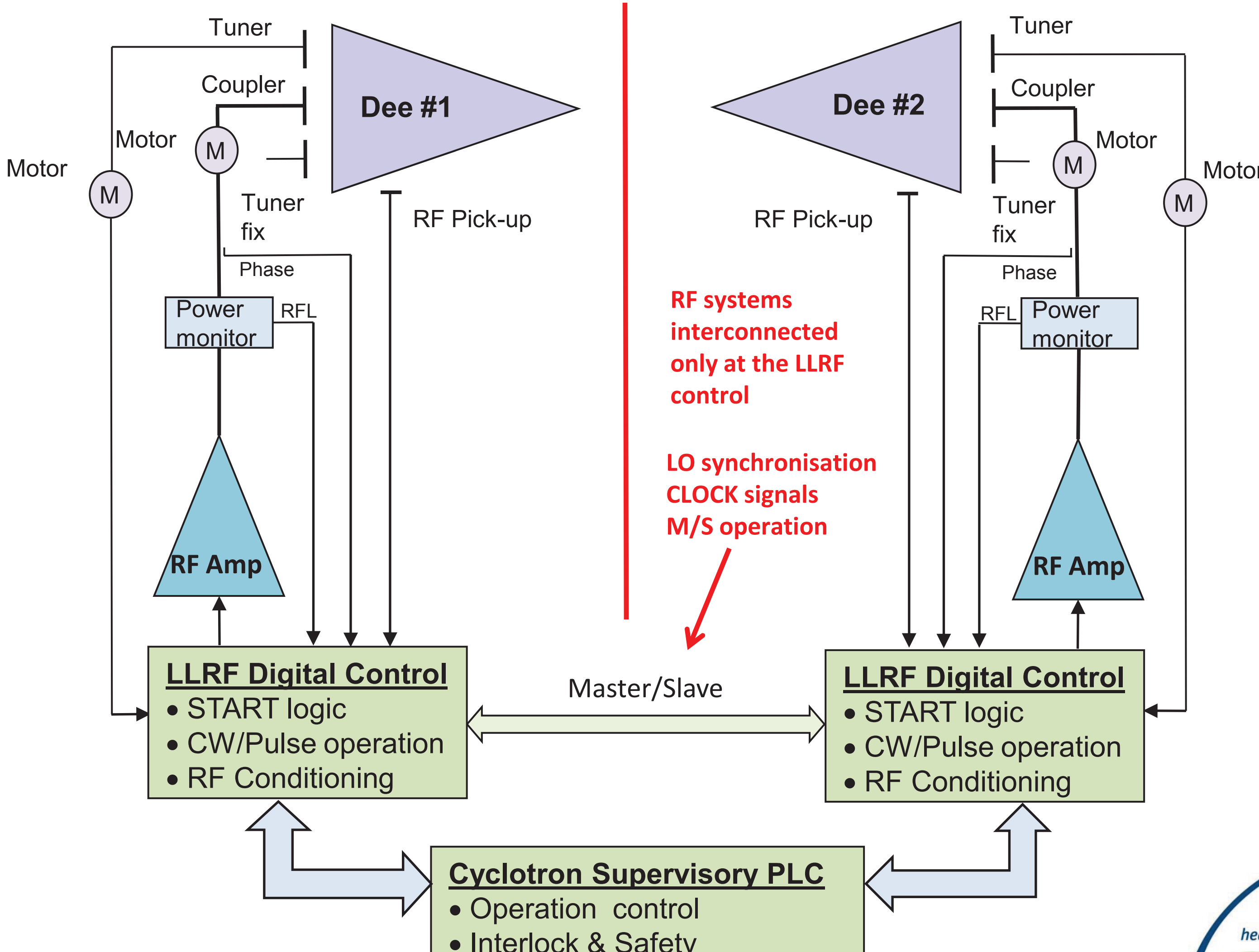

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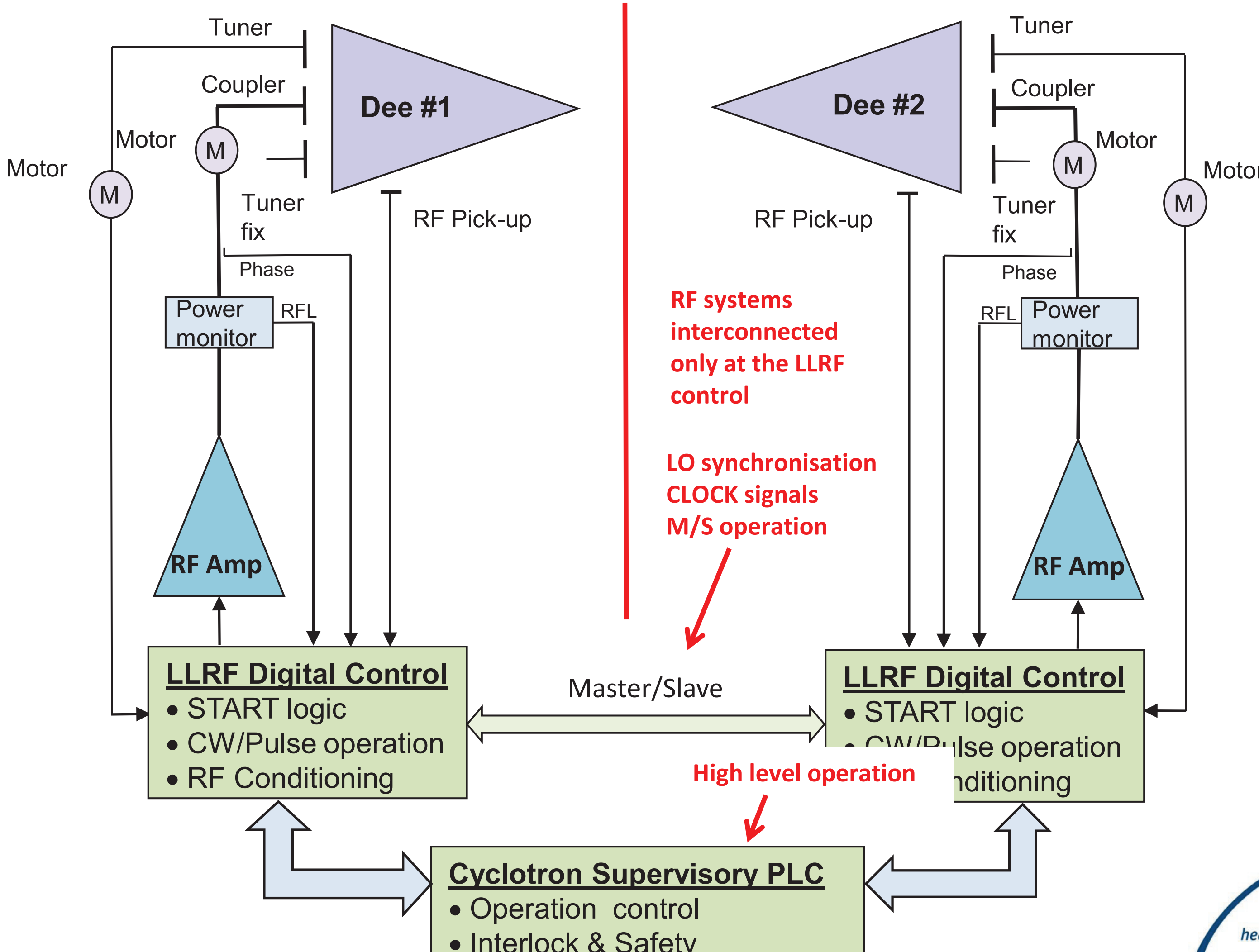

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General description

Advantages of separated resonator design:

- Symmetrical dee voltage distribution
- Reduced coupling power per cavity, coupler design less critical
- Reduces cavity mismatch with beam loading, lower VSWR
- Allows beam intensity control through phase and amplitude modulation of the accelerating field between the dees.

Initial requirements

Parameter	Value
Number of dees	Two λ/2 resonant cavities placed in opposite valleys shielded at the tip
Frequency	56.2MHz (4th harmonic)
Center region accep.	±25 degrees
Dee angle	30 degree dee tip 36 degree to dee end
Quality Factor	8000 to 12000
Average shunt impedance	150kΩ minimum
Dissipated power	12 to 15kW (per cavity)
Dee voltage	60kV dee tip, increasing to outer radius
Amplitude stability	5×10^{-4}
Phase stability	±0.1 degree

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Latest simulation results

Parameter	Value
Number of dees	Two λ/2 resonant cavities placed in opposite valleys shielded at the tip
Frequency	56.2MHz (4^{th} harmonic)
Center region accep.	±25 degrees
Dee angle	30 degree dee tip 36 degree to dee end
Quality Factor	6800
Average shunt impedance	103kΩ minimum
Dissipated power	17.3kW (per cavity)
Dee voltage	60kV dee tip, 70.4kV to outer radius
Amplitude stability	5×10^{-4}
Phase stability	±0.1 degree

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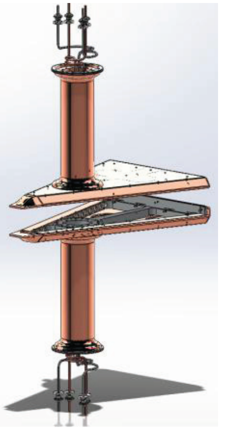
Resonator system

- Two λ/2 resonant cavities, single stem design
- Each cavity equipped with:
  - Capacitive coupling, movable coupler for beam load compensation
  - Movable tuning for phase loop control
  - Fix tuner for cavity resonant frequency compensation between the different dee tip configuration
  - Thermal probes, three probes per cavity placed close to the high current density locations



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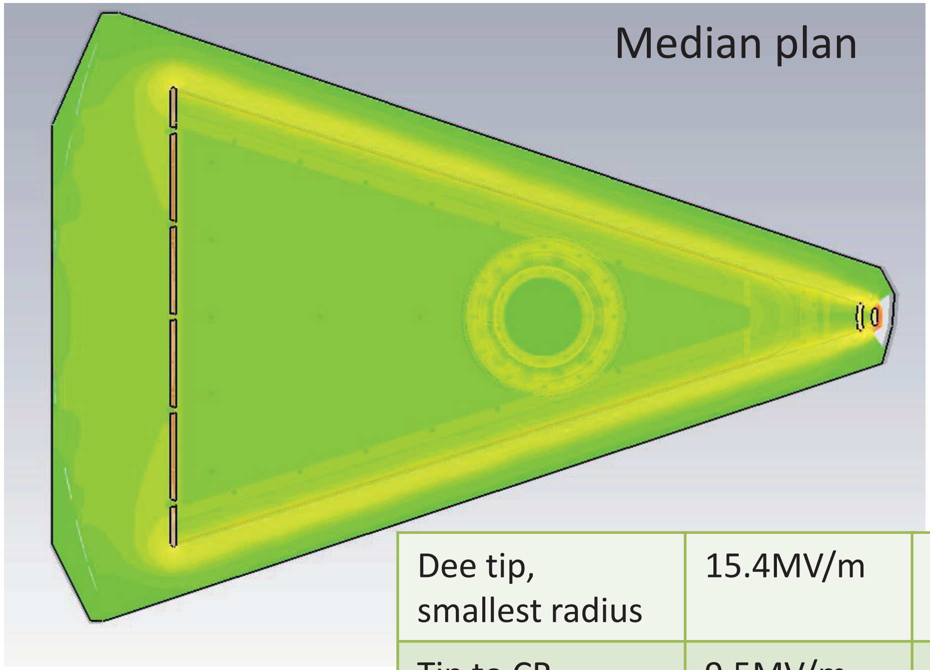
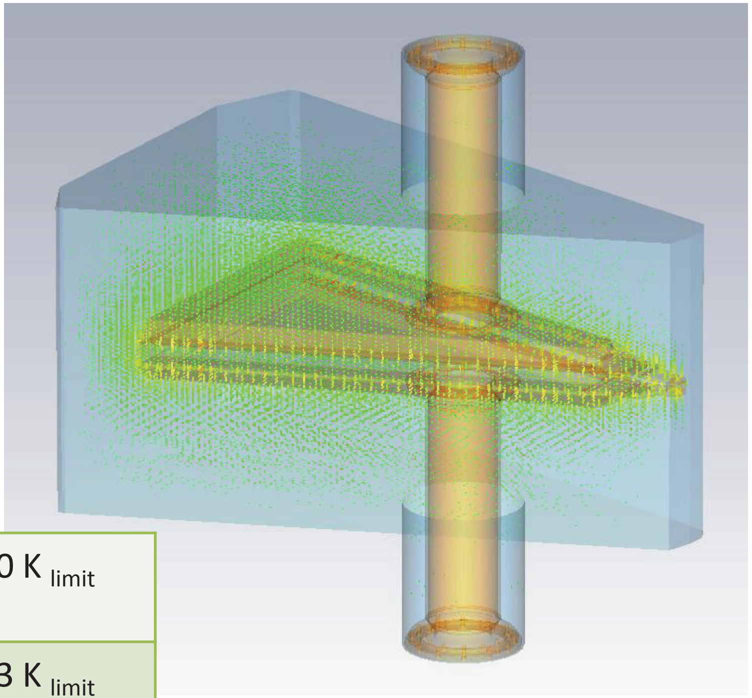
Electromagnetic model simulations

Electric field distribution





Dee tip, smallest radius	15.4MV/m	1.70 K $_{limit}$
Tip to CR	9.5MV/m	1.03 K $_{limit}$
First turn	9.9MV/m	1.07 K $_{limit}$
Middle	3.1MV/m	0.34 K $_{limit}$
End	5MV/m	0.54 K $_{limit}$

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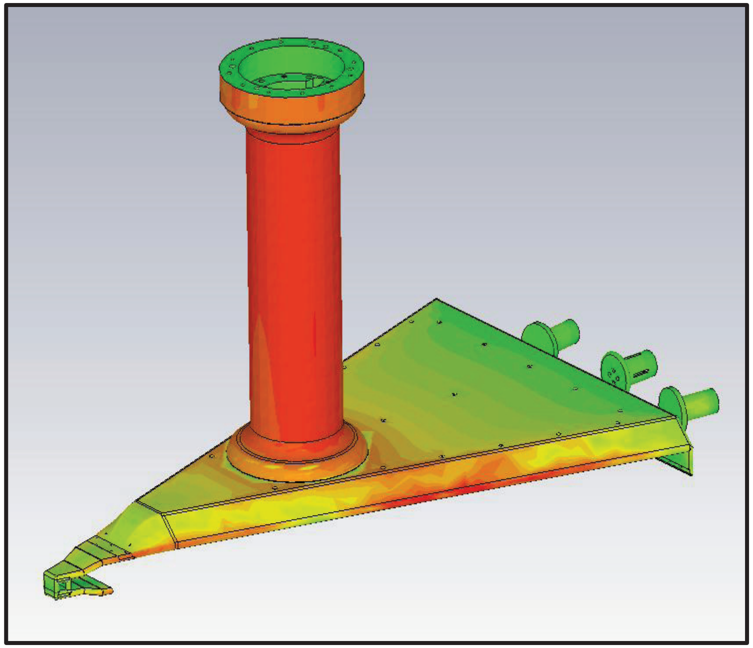
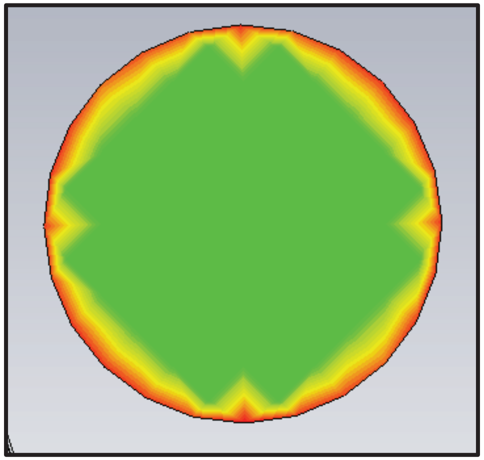
Electromagnetic model simulations

Surface currents distribution



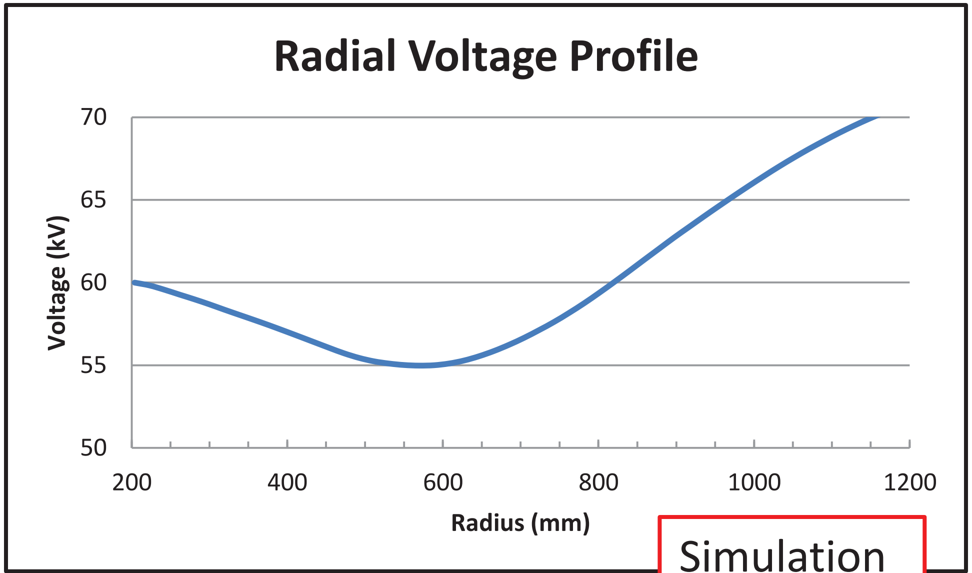
Surface currents on the resonator and stem, maximum 5200 A/m



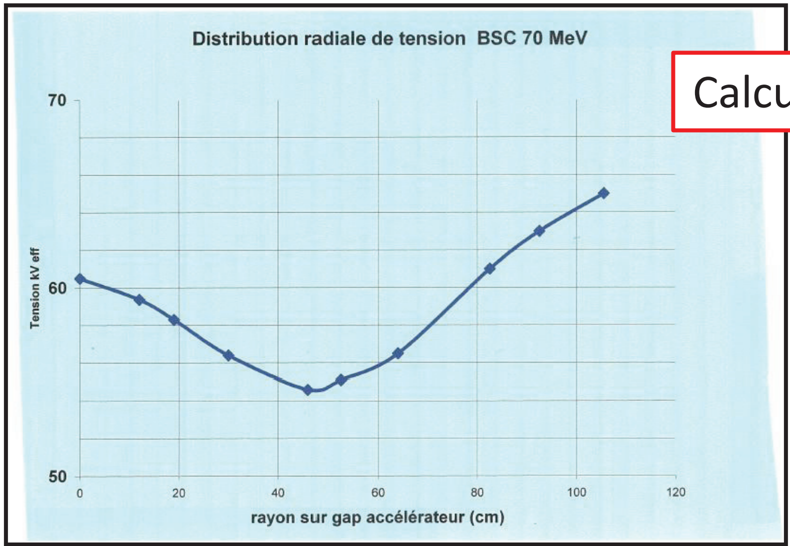
Surface currents on the ground plate, maximum 3200 A/m

Dee voltage profile

Freq (MHz)	56.2
Power (kW)	17.3
Q factor	6800
Shunt Impedance (kΩ)	103
V_tip (kV)	60.0
V_outer (kV)	70.3



Simulation



Calculated

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Power estimate

Total Simulated Power Loss (kW)	17.30

Total Theoretical Power Loss (kW)	14.00
Extraction side	1.85
Injection side	1.60
Stems (top and bottom)	9.85
Short circuit	0.40
Coupling mismatch	0.15
Other unevaluated losses	0.15

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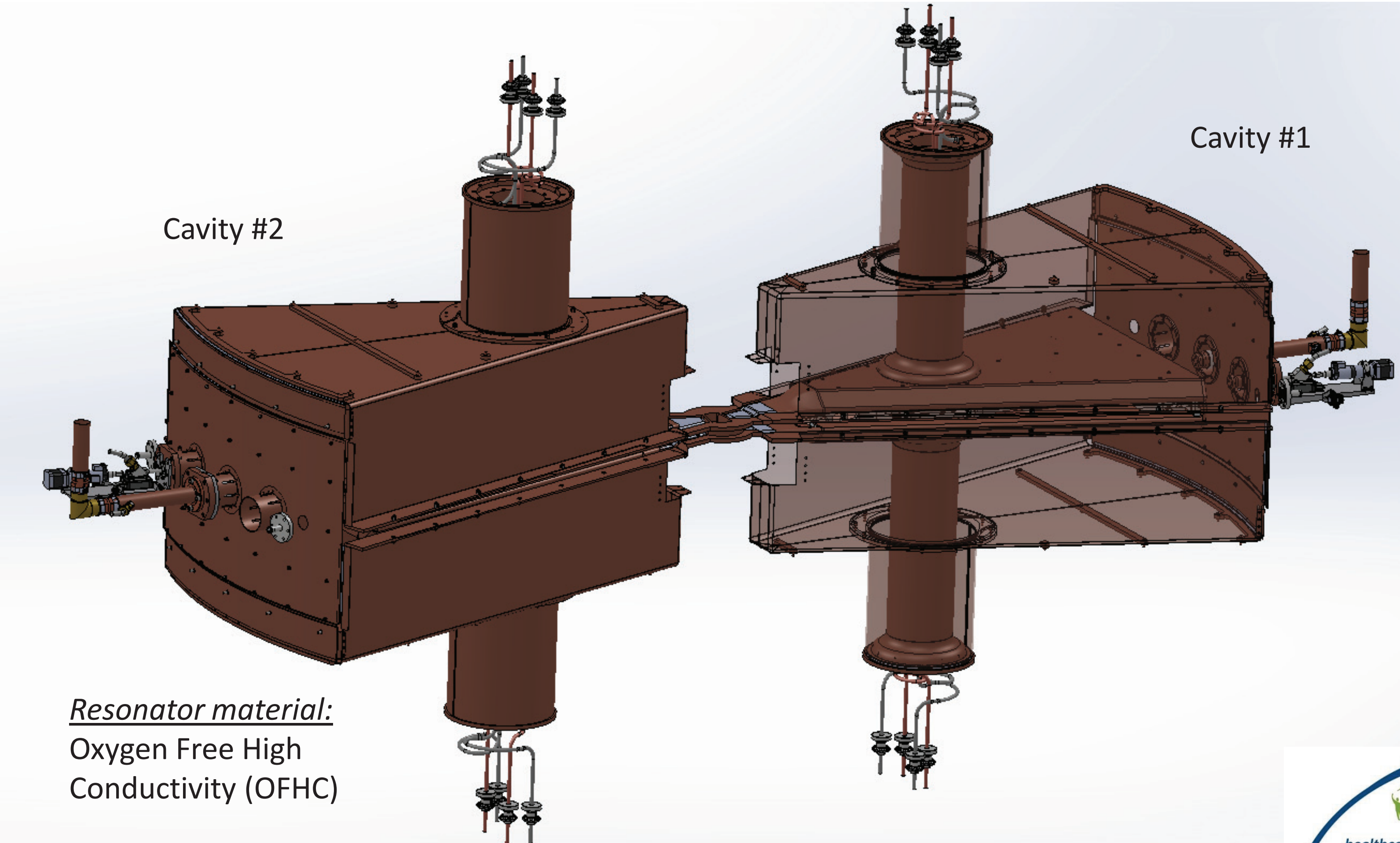
Mechanical model



Resonator material:
Oxygen Free High
Conductivity (OFHC)

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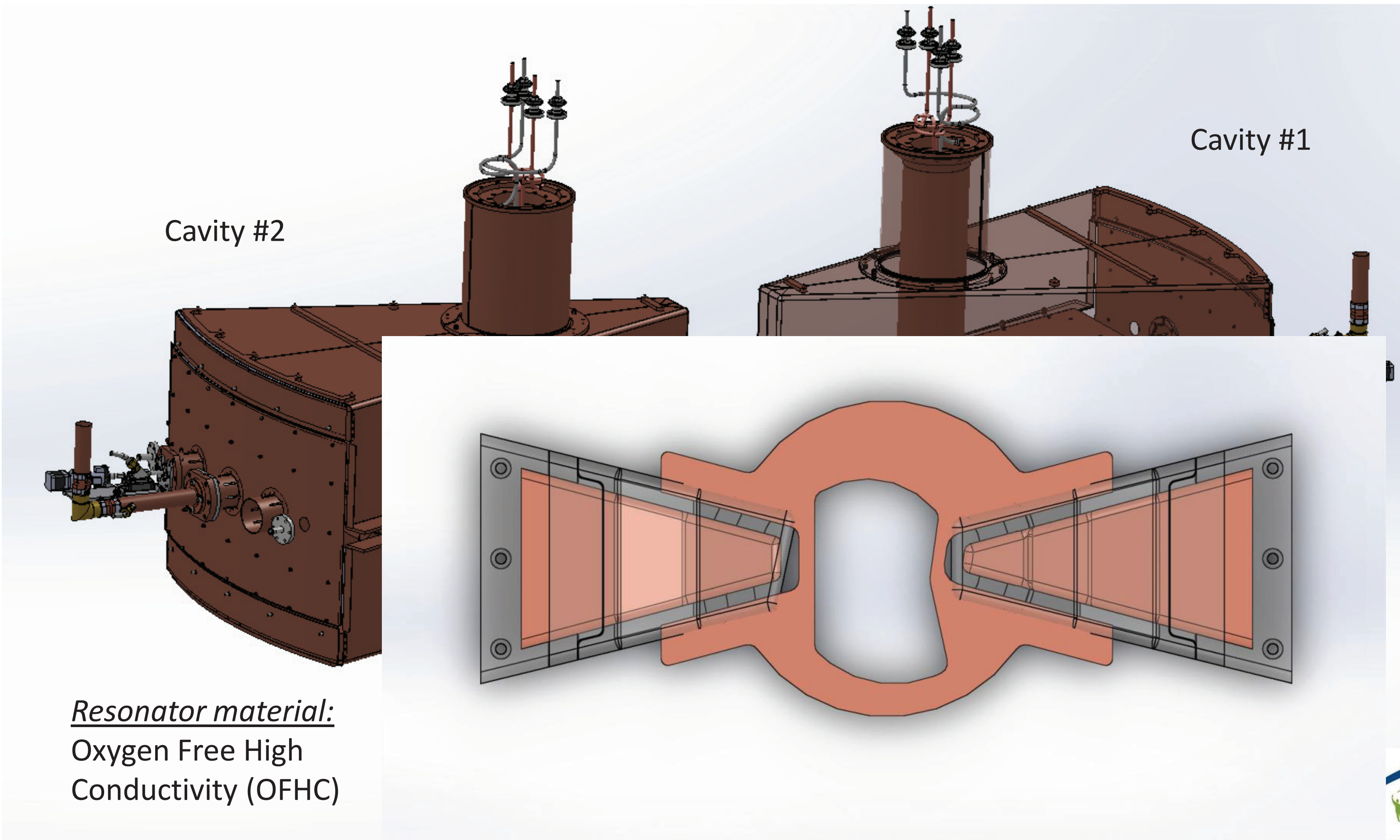
Mechanical model



Resonator material:
Oxygen Free High Conductivity (OFHC)

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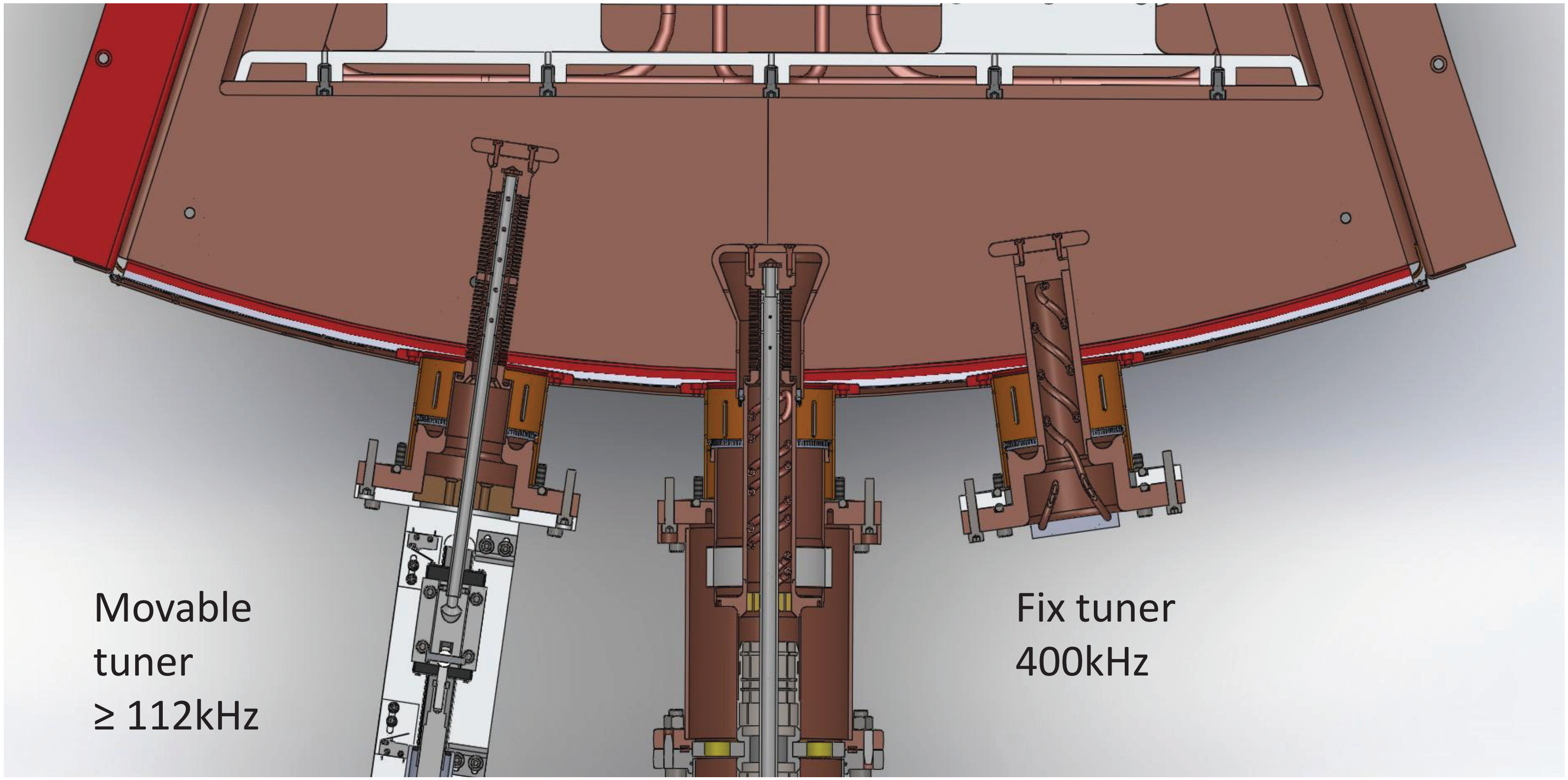
Coupling and tuning mechanisms



Movable coupler

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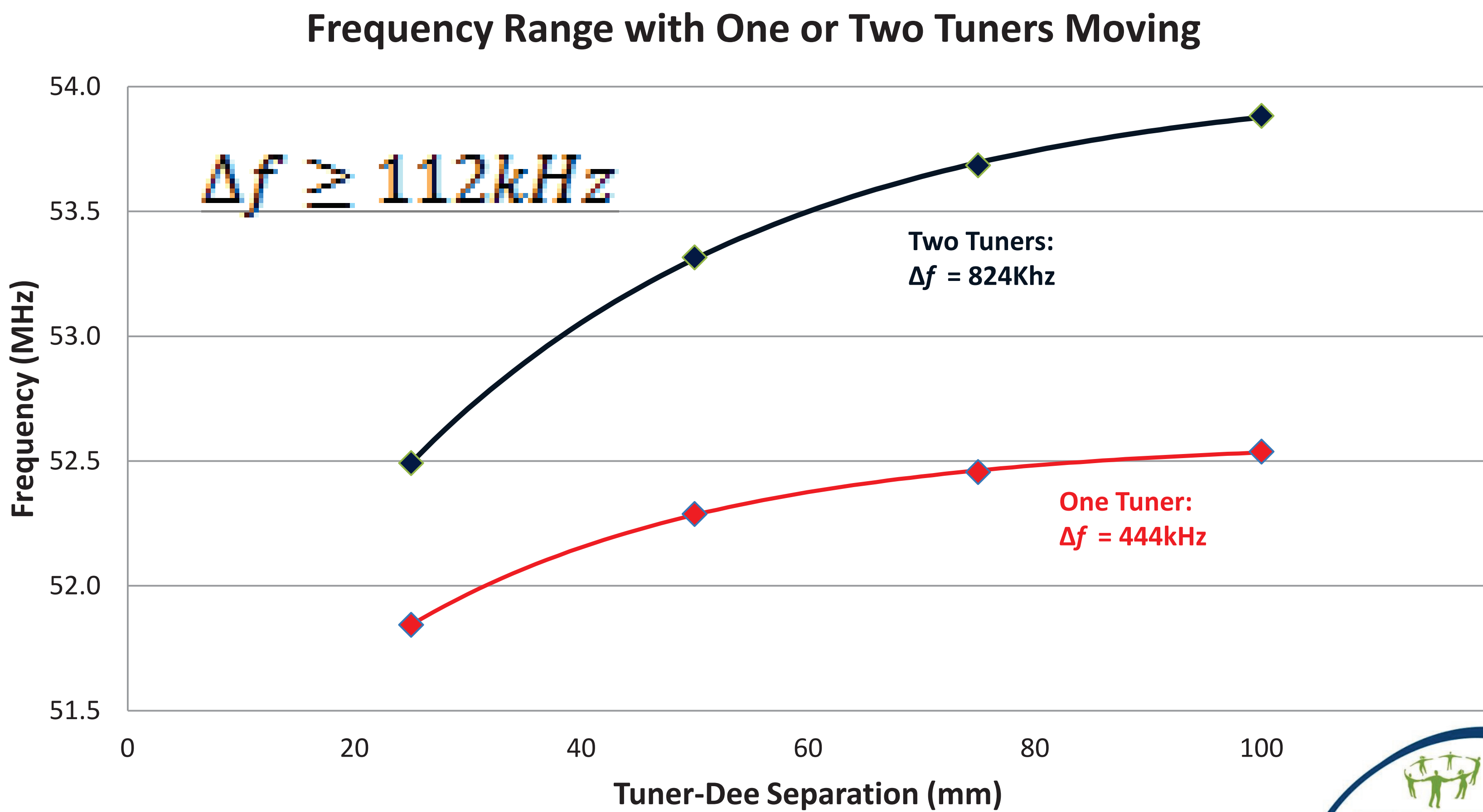
Tuning range



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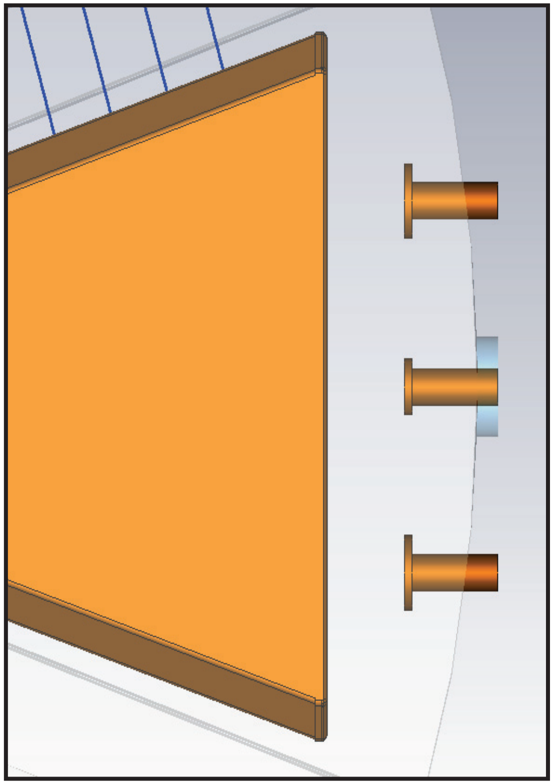
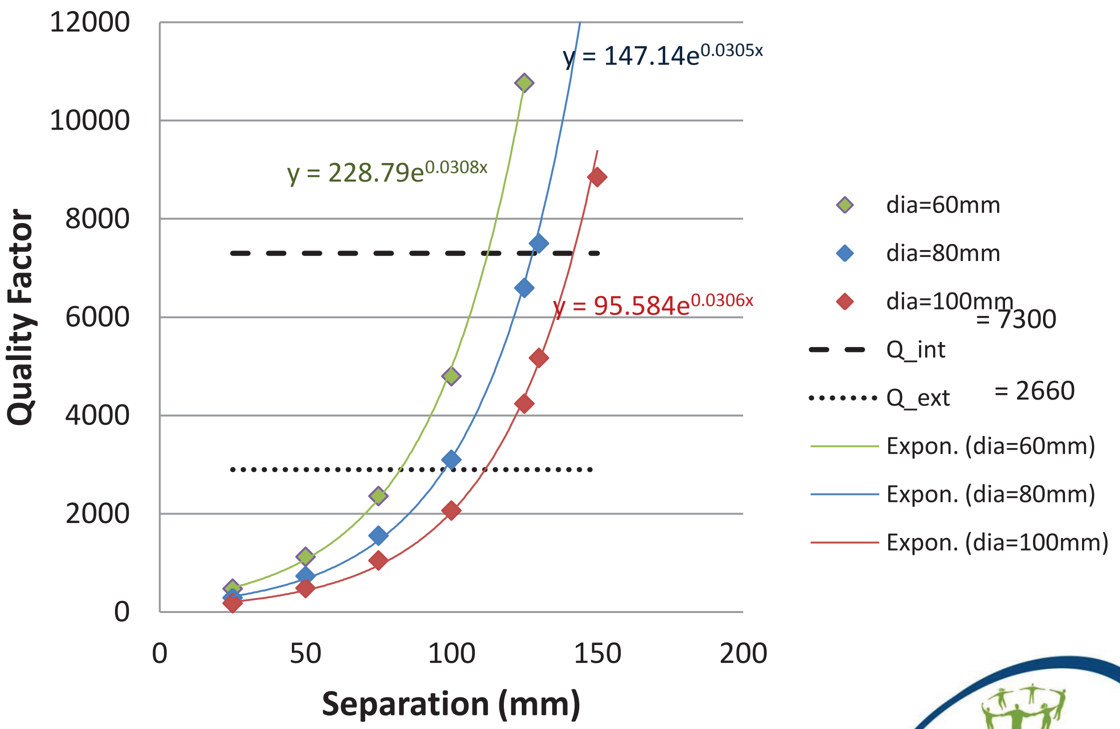
Coupler matching

P_{cavity} = 14kW,
P_{beam} = 24.5kW (700μA beam)





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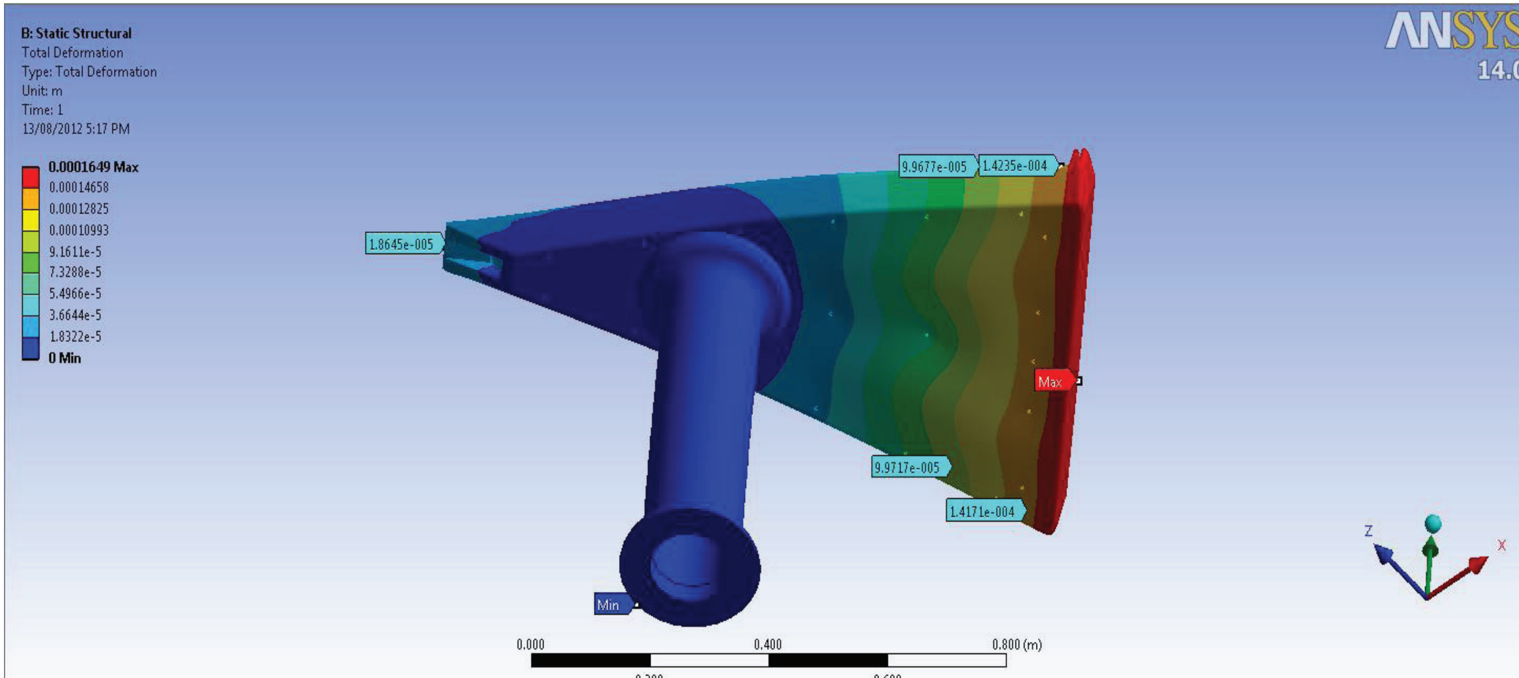
Mechanical deflection



Maximum deflection of 0.16mm at the end of the dee plate assembly where an additional distributed load of 2kg has been added to make up for the contact finger pressure coming from the upper plate

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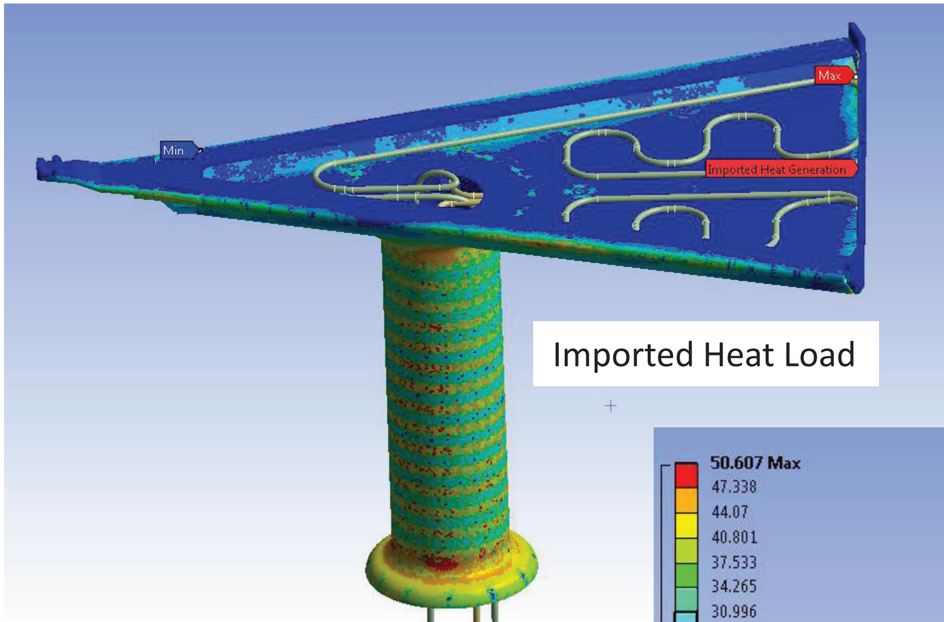
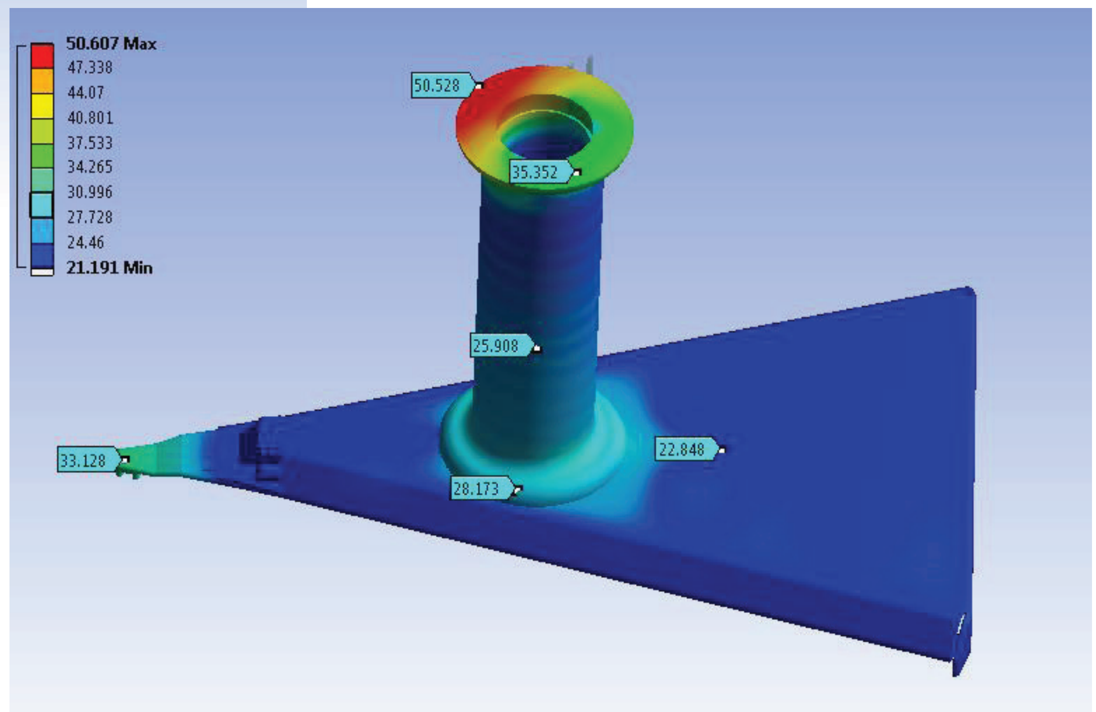
Thermal simulation



- 7.6 kW input power
- 2.4 kW cooled on dee plate
- 5.2 kW cooled in stem



- imported CST surface currents
- 20deg DI water supply
- turbulent flow, 12 L/min per circuit

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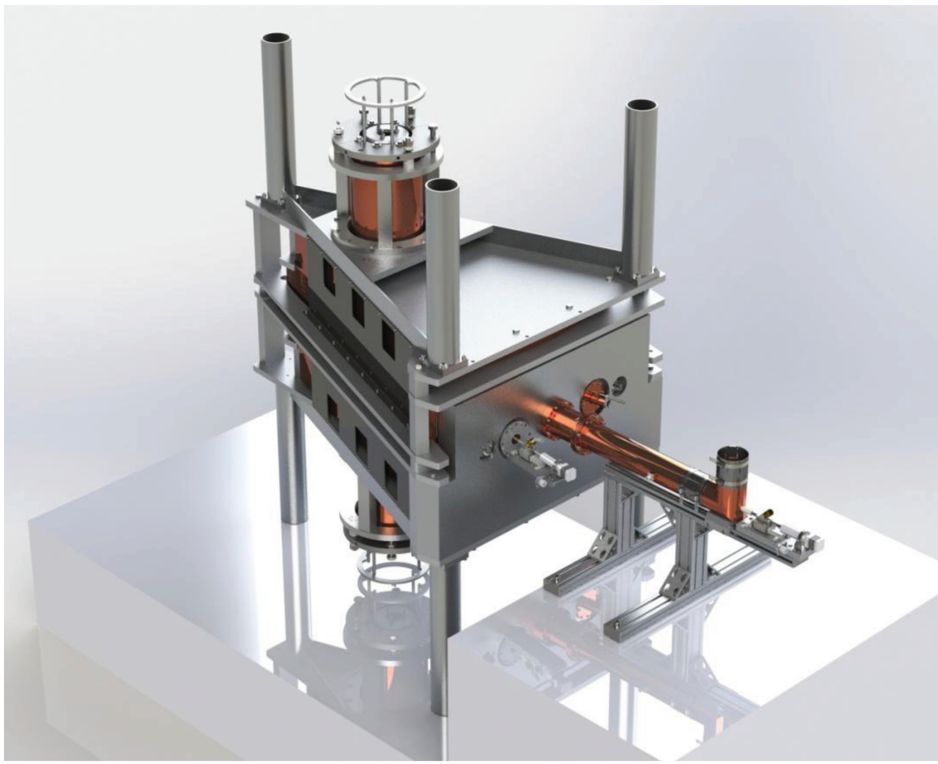
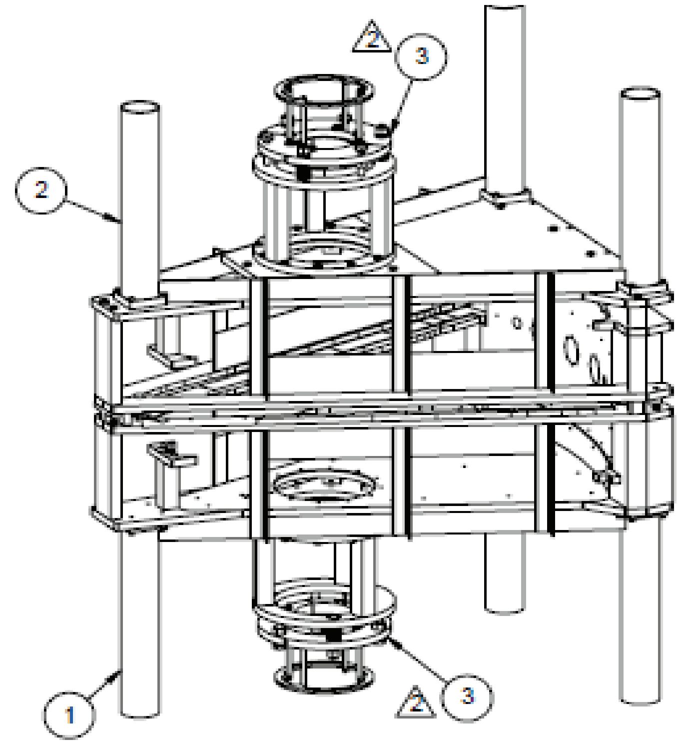
Frequency cold test set-up

Cold test frame (aluminum structure)





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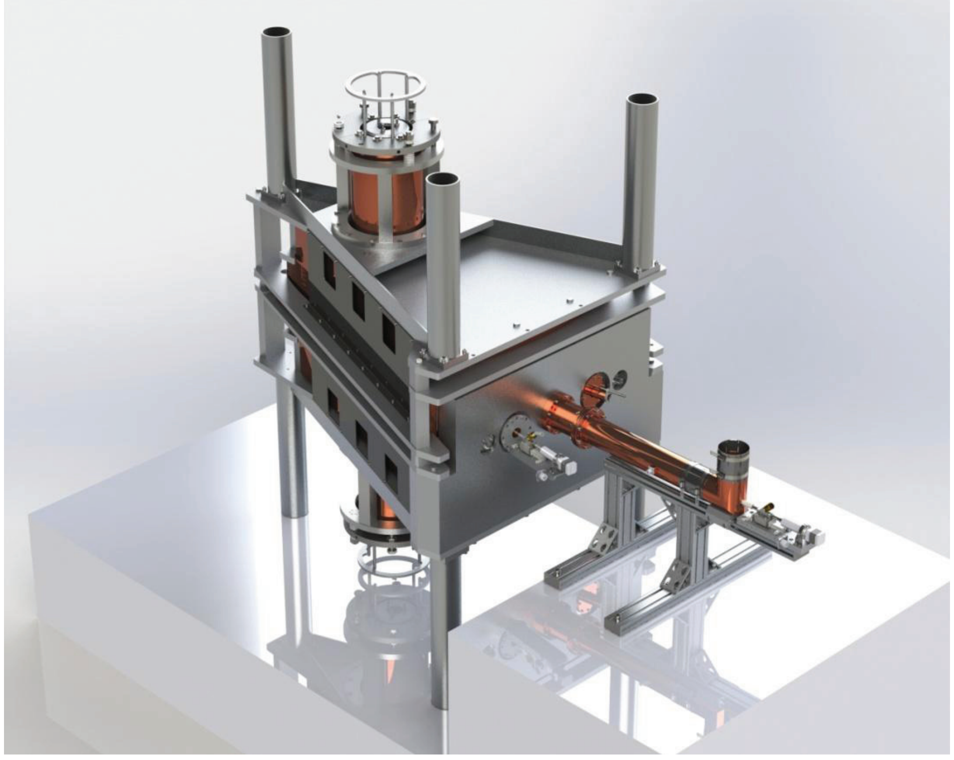

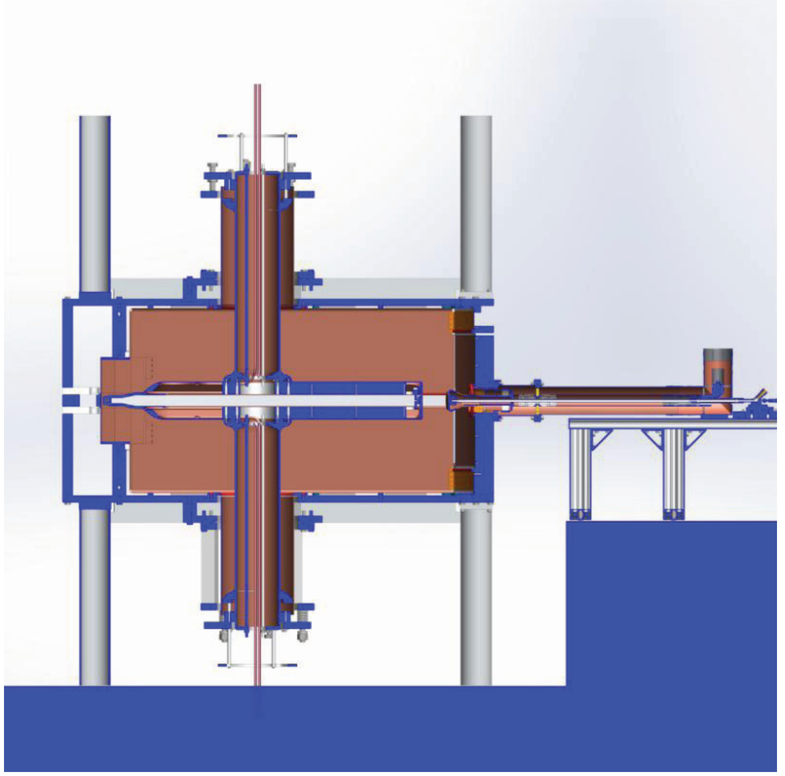

RF Power amplifier

- Resonator dissipated power: $P_{res} \approx 14kW$ (x 2)
- Beam power: $P_{beam} = 700\mu A \times 70MV = 49$ kW
- Total power: $P_t = 77kW$
- Adding 20% safety margin: $P_{operational} = 92.4kW$
- Two 55kW separate amplifiers
- Local/Remote control monitoring – Cyclotron PLC system

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Amplifier characteristics

Item	Value
Power Output	55kW (tunable to 65kW)
Stability	Better than ±10% over 8 hours @ 55kW
Modulation	CW, Pulse
Frequency	56.0MHZ (2MHz bandwidth)
Cavity	Strip line
Efficiency	Approx. 62% (final stage)
Water cooled tube	3CW40000A7, high μ triode
Harmonic content	-25dBc (all harmonics)
Output connector	4-1/16" EAI flange

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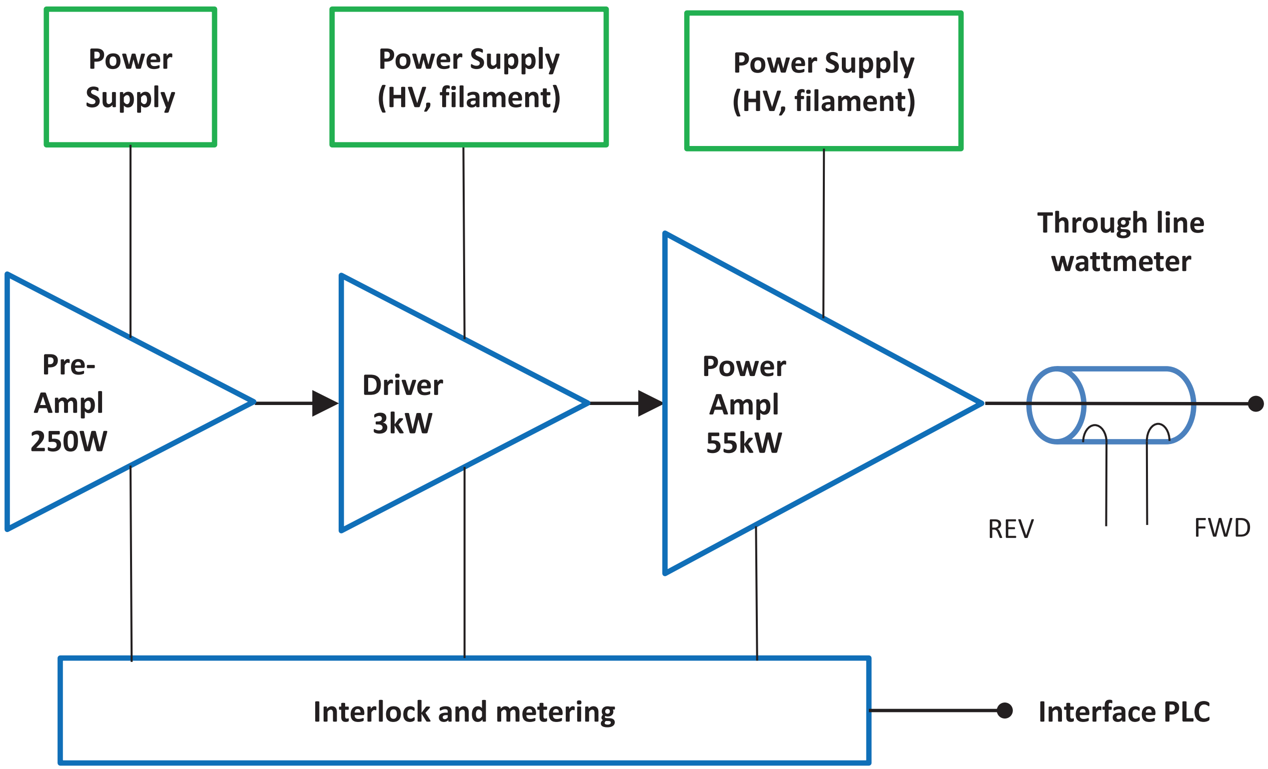
Amplifier block diagram



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Amplifiers successfully tested

- 48 hours endurance test at full operational power of 55kW

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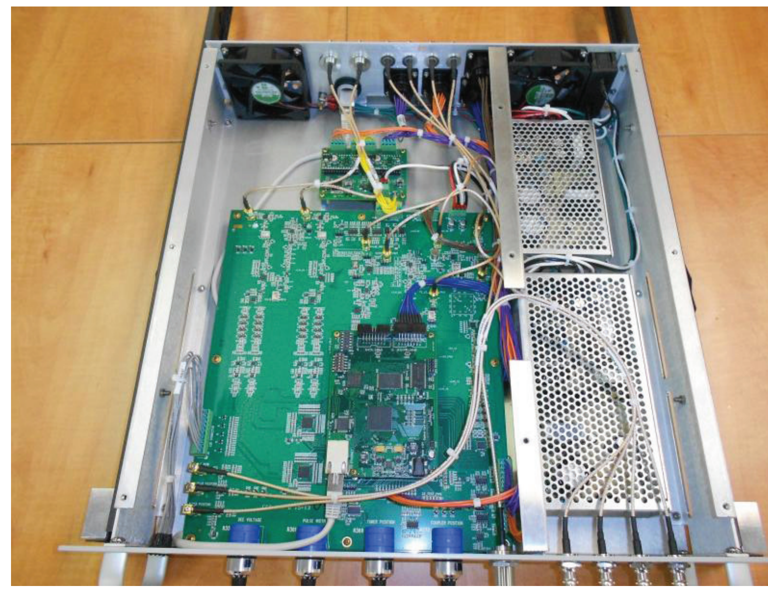
LLRF Control

Poster TUPPT024

- Versatile digital LLRF control for the full range of BEST Medical cyclotrons
- Frequency selectable 49-80 MHz depending on system
- Single or double resonator configuration
- Optional addition of buncher control
- System successfully integrated on a single resonator 73 MHz cyclotron



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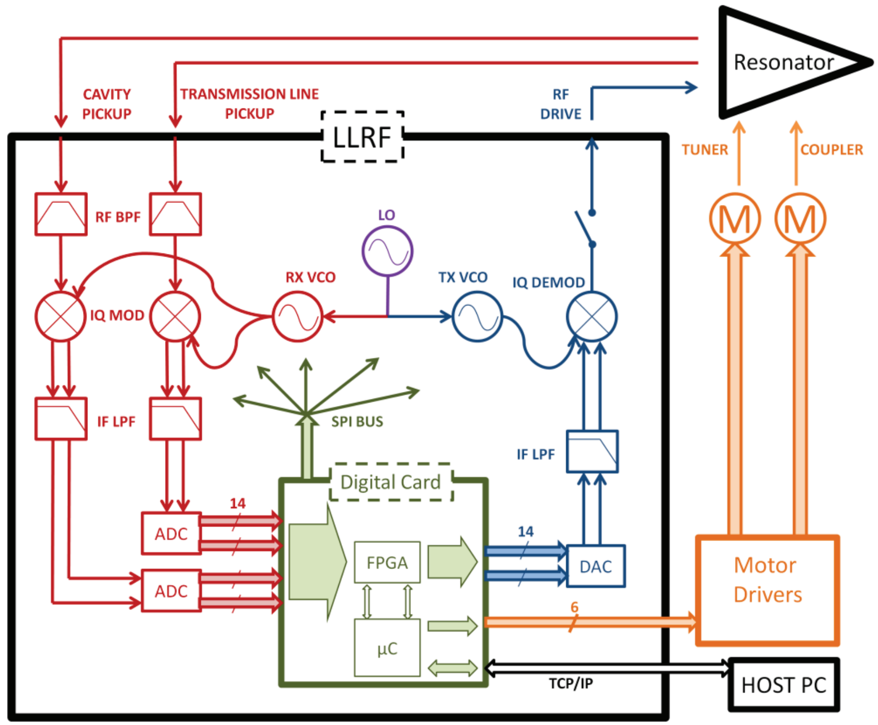
LLRF Control architecture

Poster TUPPT024

- Analog RF front- and back-end
- Digital Control Card
- Motor drives
- Power supplies



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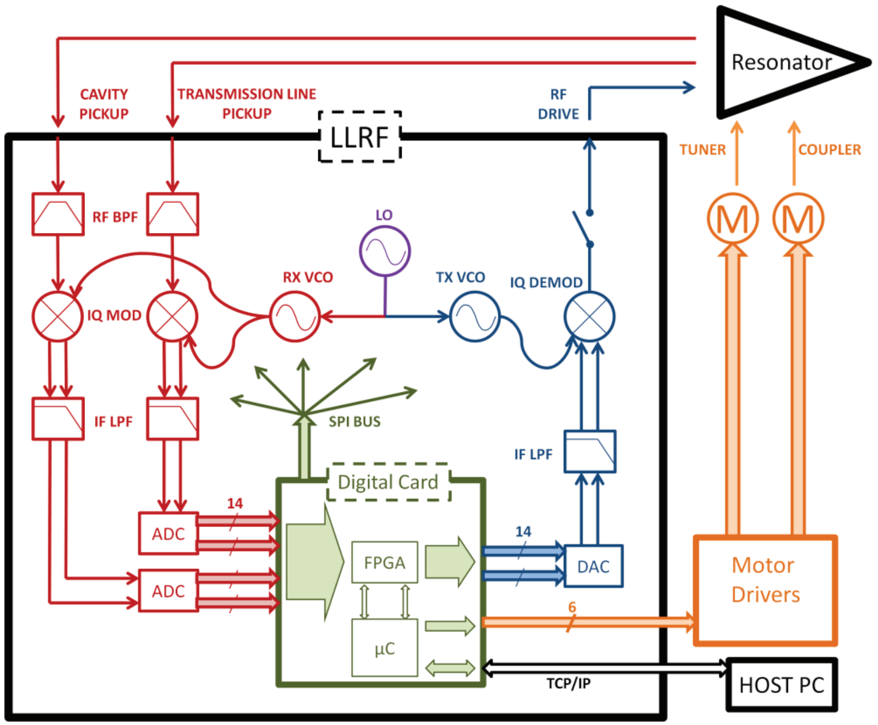
LLRF Control architecture

Poster TUPPT024

- Analog RF front- and back-end
- Digital Control Card
- Motor drives
- Power supplies

- Frequency mixing down to constant IF
- I/Q modulation and digitization
- Digital signal processing
- I/Q digital output
- Frequency mixing up to operating frequency



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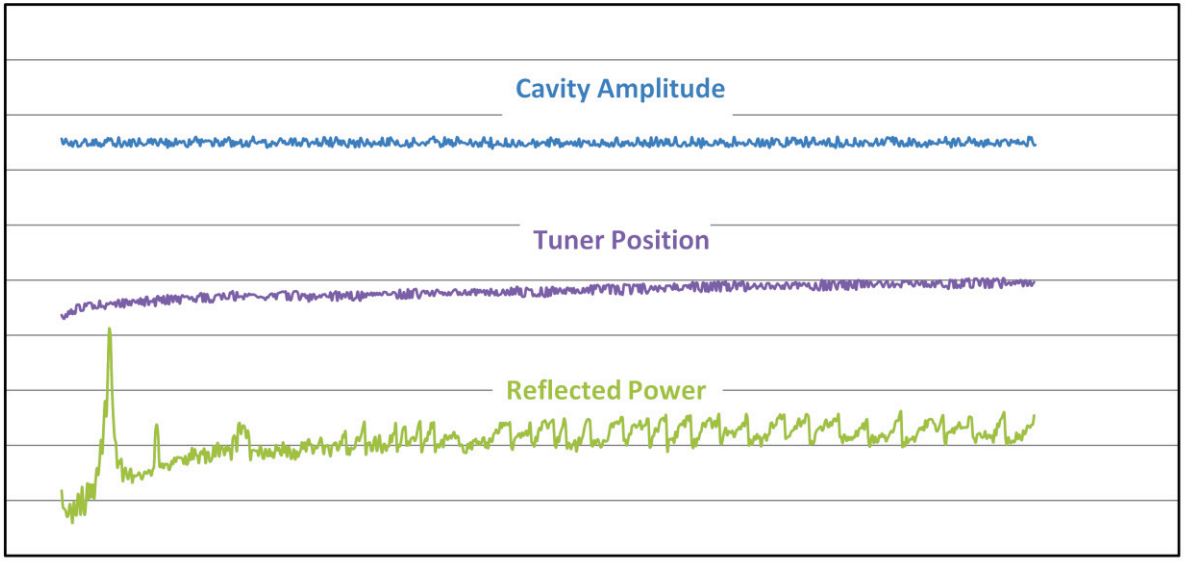
LLRF Control performance test

Poster TUPPT024

Digital LLRF Stability Test



- The design and production of a fully digital LLRF controller has been completed
- Integration testing on a single resonator cyclotron shows good initial results
- Double resonator cyclotron integration in progress
- Beam pulsing techniques using resonator phase modulation will be developed

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