Rapid Radio-Frequency Beam Energy Modulator for Proton Therapy

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

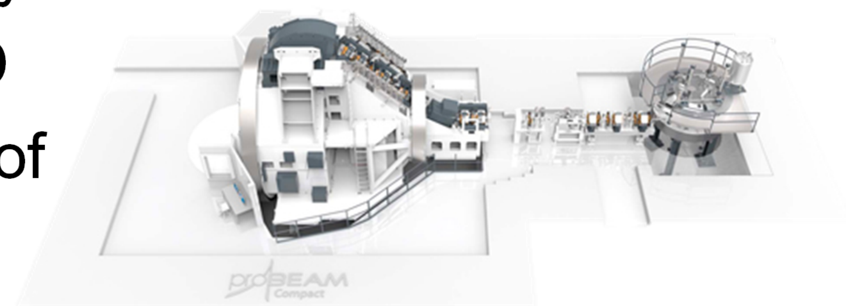
Outline

- Motivation and Background
- Rapid 3D Modulator Gantry Layout
- Cyclotron Beam Format / Bunch Compression
- RF Energy Modulator
  - Design
  - Beam Dynamics
  - Single-Cell Prototype
  - Thermals
- RF Deflector
- Conclusion

Overall Goals for a Rapid RF Beam Energy Modulator

- Develop compact beam delivery system with rapid (seconds) 3D scanning over a tumor volume of up to 4 liters
- Design, fabricate and test major components of the technology: ±30 MeV linac designed for operation at 150 MeV for rapid variation in depth at ~25cm ±6cm and an RF deflector
- High enough dose of >20 Gy/L/s for hypofractionated treatments

Varian ProBeam 360[+]



- 800 nA cyclotron; 70-220 MeV; 12 m height; 261 m^2 total footprint
- Typical treatment: 3 angle exposure; few min each; multiple energies; ~30min per patient

FLASH Treatment (<1s) has the potential to provide both increase in accuracy and biological effects

[+] http://www.attikourismedical.com/product/treatment/oncology/varian-protobeam/

RF Energy Modulation Provides Precision and Speed Required for FLASH Treatment

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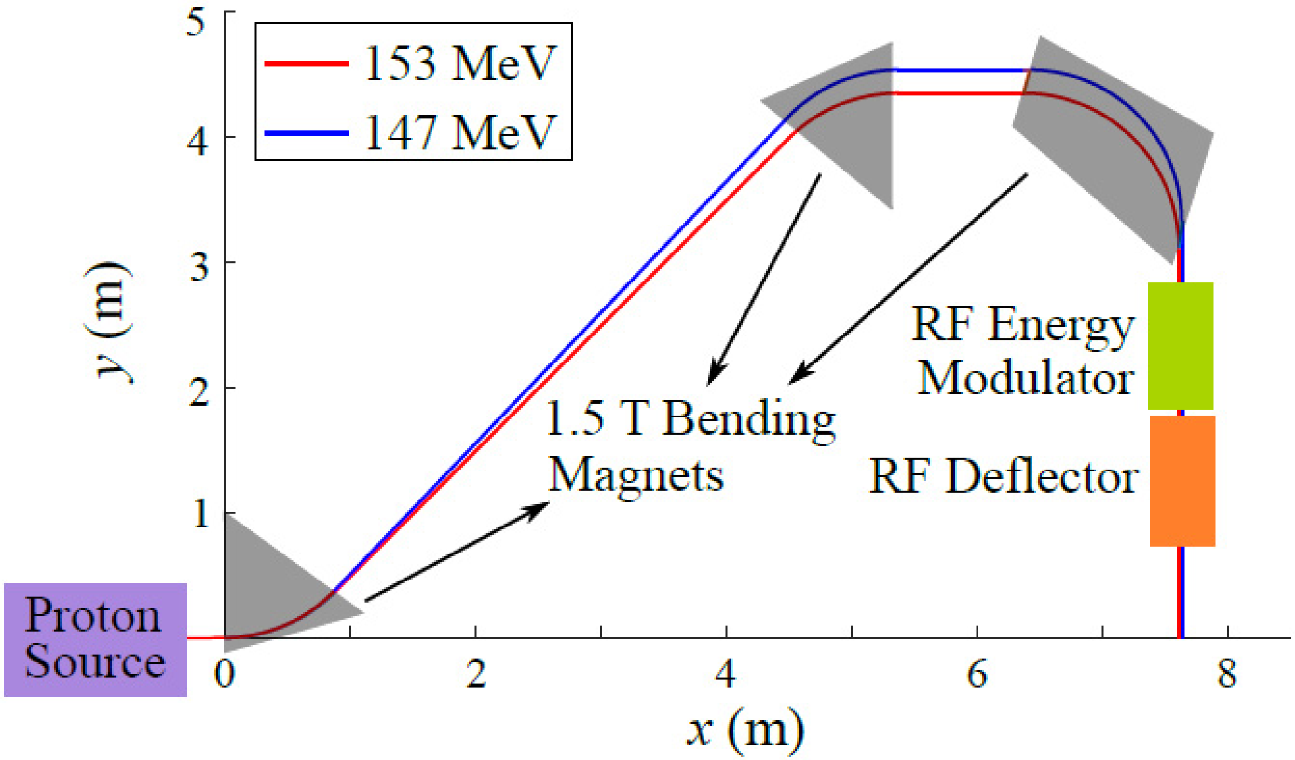
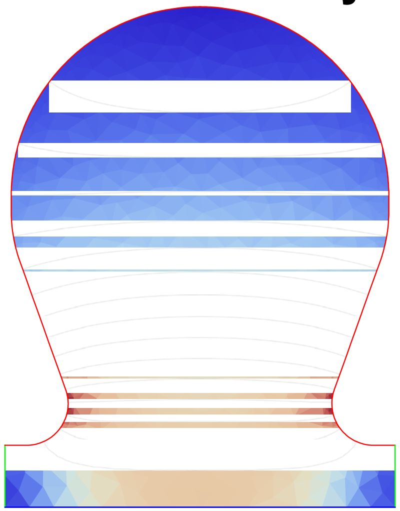
- Schematic of gantry w/ RF energy modulator and deflector
- The gantry is fed by an accelerator delivering a fixed energy hadron beam
  - Allows for permanent or superconducting magnets



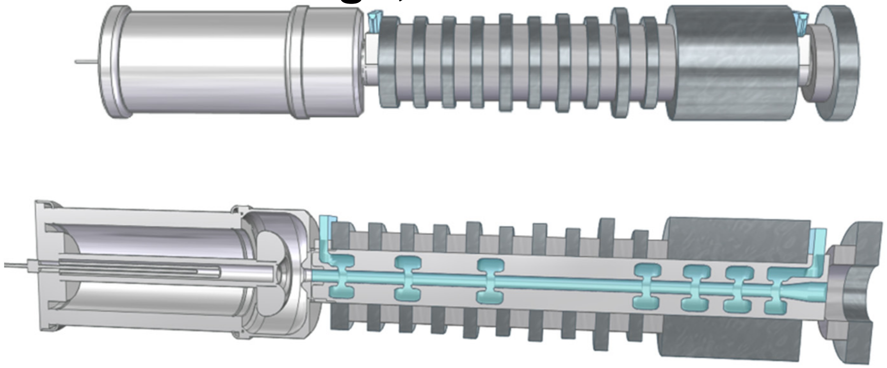
Source Operates at High Duty (Few Percent) Requiring Efficient Structures and Sources

- Aim to operate at high frequency for high shunt impedance
- Powering of the RF structure with one klystron feeding one cell
- Each single unit klystron needs to provide minimum of 400 kW and operates at 60 kV

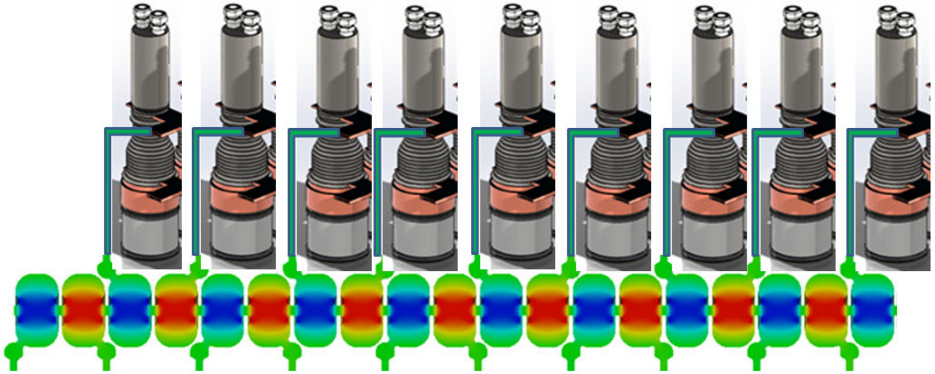
S-Band Cavity



RF Source Concepts in Design, Build and Test



One RF Source per Cell



Franzi et al., LCWS 2018

Bunch Compression Required to Allow for High Frequency S-Band Accelerator and Deflector

- Cyclotron source bunch structure produce long (56 mm), low charge (10s fC) proton bunches
- Target 8X compression with velocity bunching
- Gantry is dispersive and helps with compression
  - <$\pm$450 keV for compressor located immediately prior to gantry

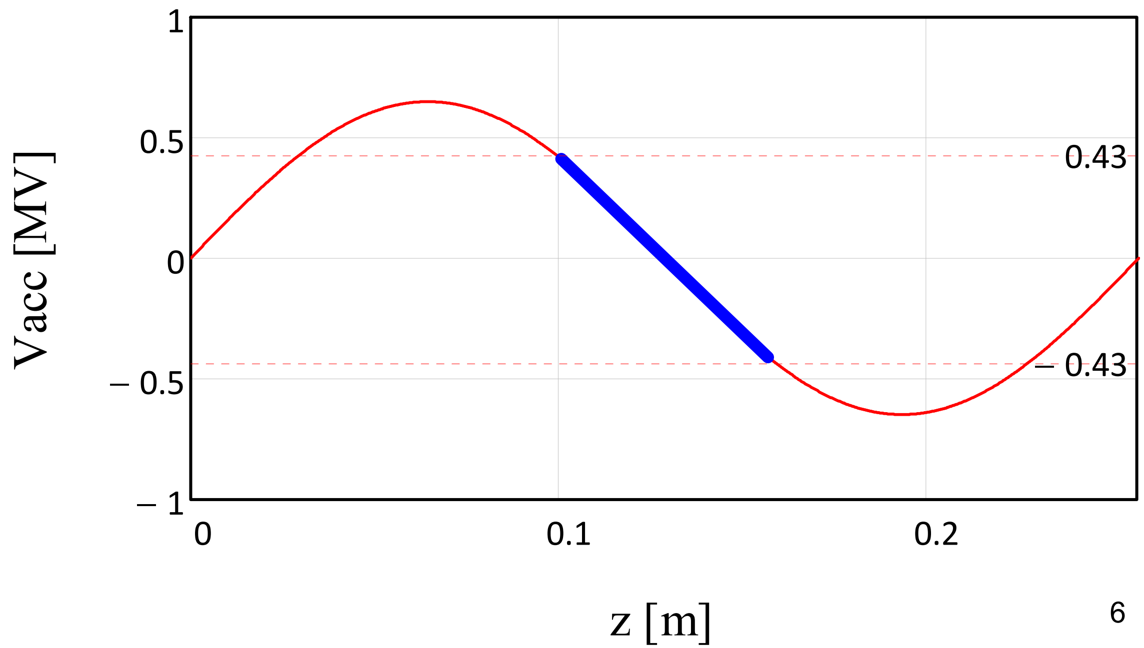
$\lambda = 0.261$ m

f = 582.4 MHz

Vacc = 0.65 MV

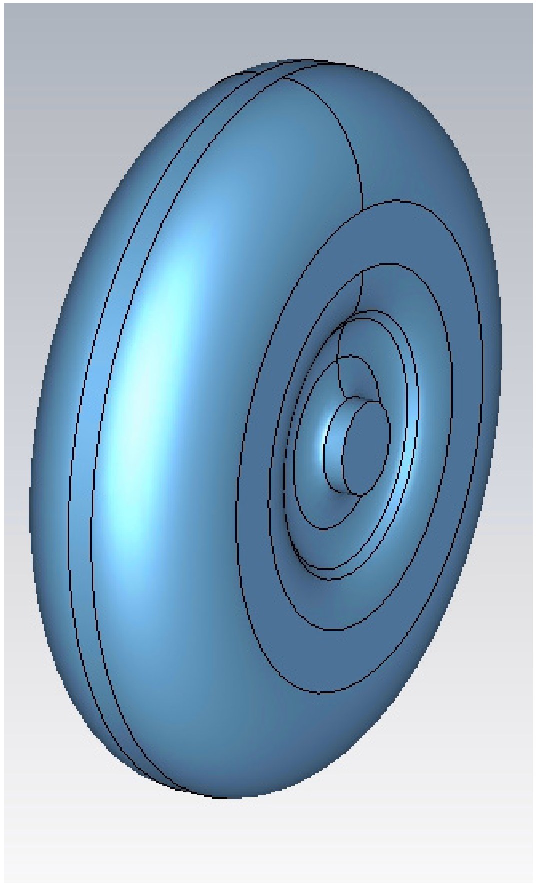
$\sigma z = 56.2$ mm

$\beta = 0.507$

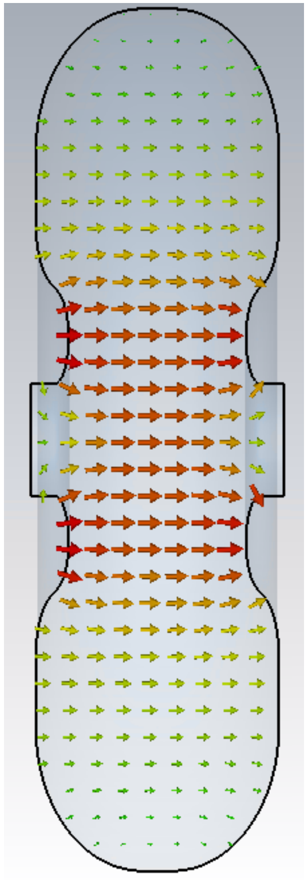


Full Optimization of Linac Cell for the Gantry Requires Distributed Coupling of RF Power

- 30 MV/m gradient achieved with 400 kW per cell



Beam aperture: 1.05 cm



Electric field

Parameter	Value
Frequency	2.856 GHz
Beam aperture (diameter)	1.05 cm
Phase advance per cell	160°
Quality factor Q_0	11936
External quality factor Q_{ext}	11911
Shunt impedance r_s	54.8 MΩ/m
r_s/Q	4.6 kΩ/m
Average gradient E_a	$15\ \mathrm{MV/m} \cdot \sqrt{P/(100\ \mathrm{kW})}$
E_{peak}/E_a	2.26
$H_{peark}Z_0/E_a$	1.25
Pulsed heating temp.	$0.53°\mathrm{C} \cdot [P/(100\ \mathrm{kW}]\sqrt{t_p(\mu s)}$

Full Optimization of Cell Requires Distributed Coupling of RF Power

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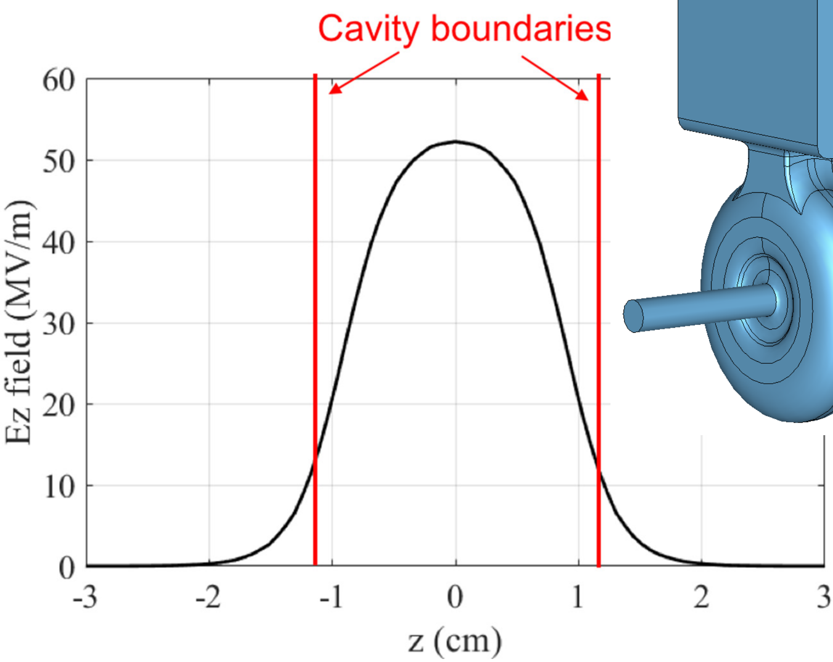

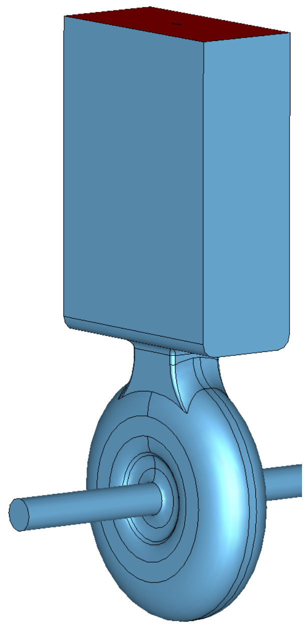

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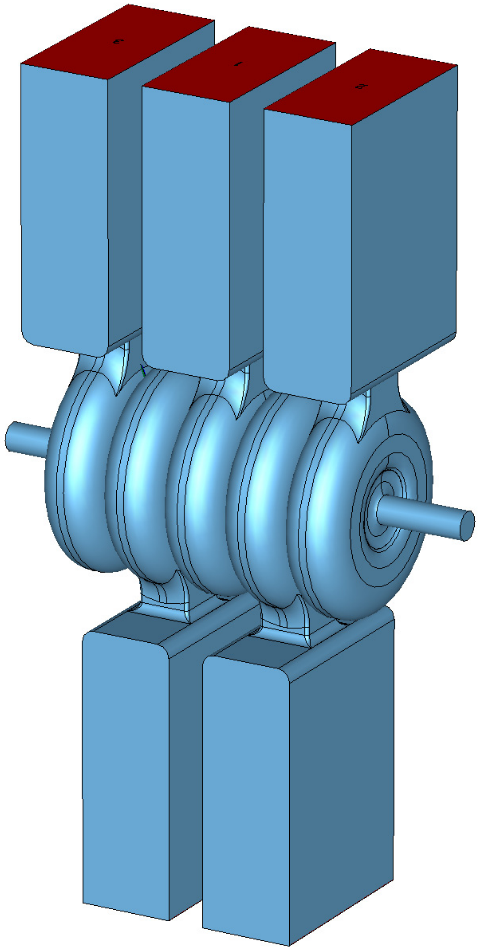
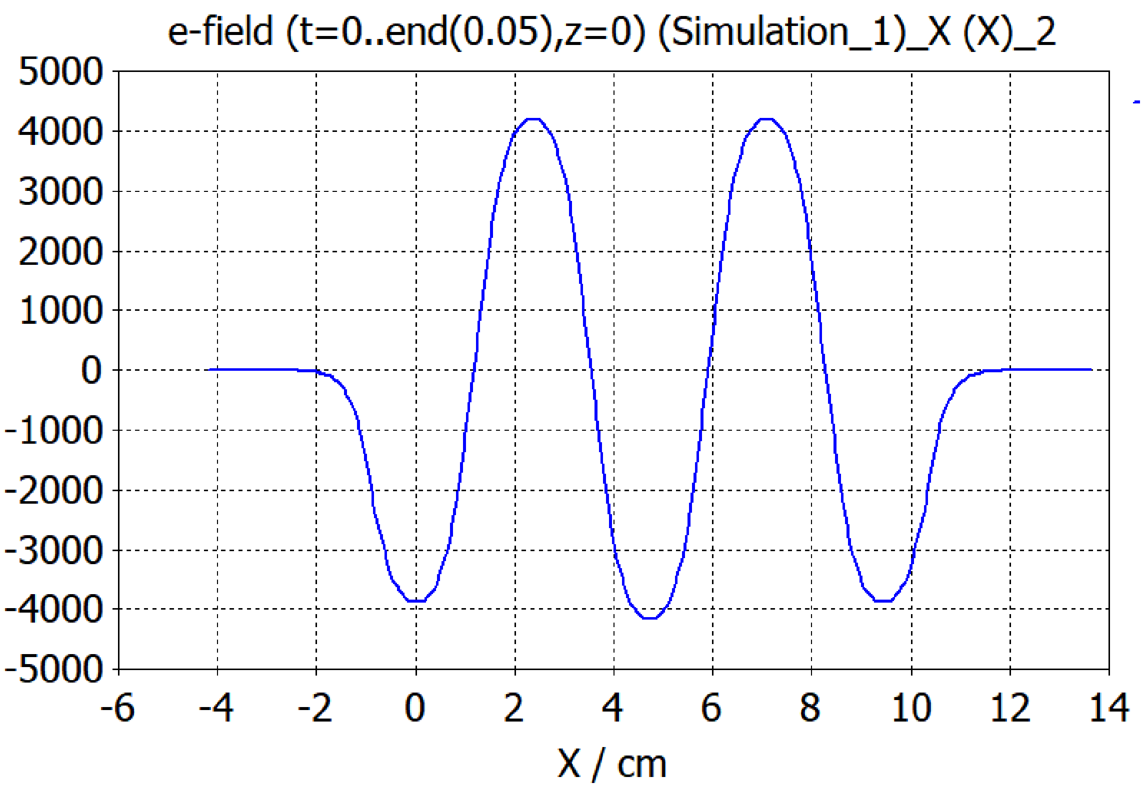
Distributed Coupling Scales to Multi-Cell Geometry without Loss of Efficiency

- Allows for adjusting phase advance along length of linac to account for change in proton velocity



Longitudinal E field on axis (arbitrary unit)

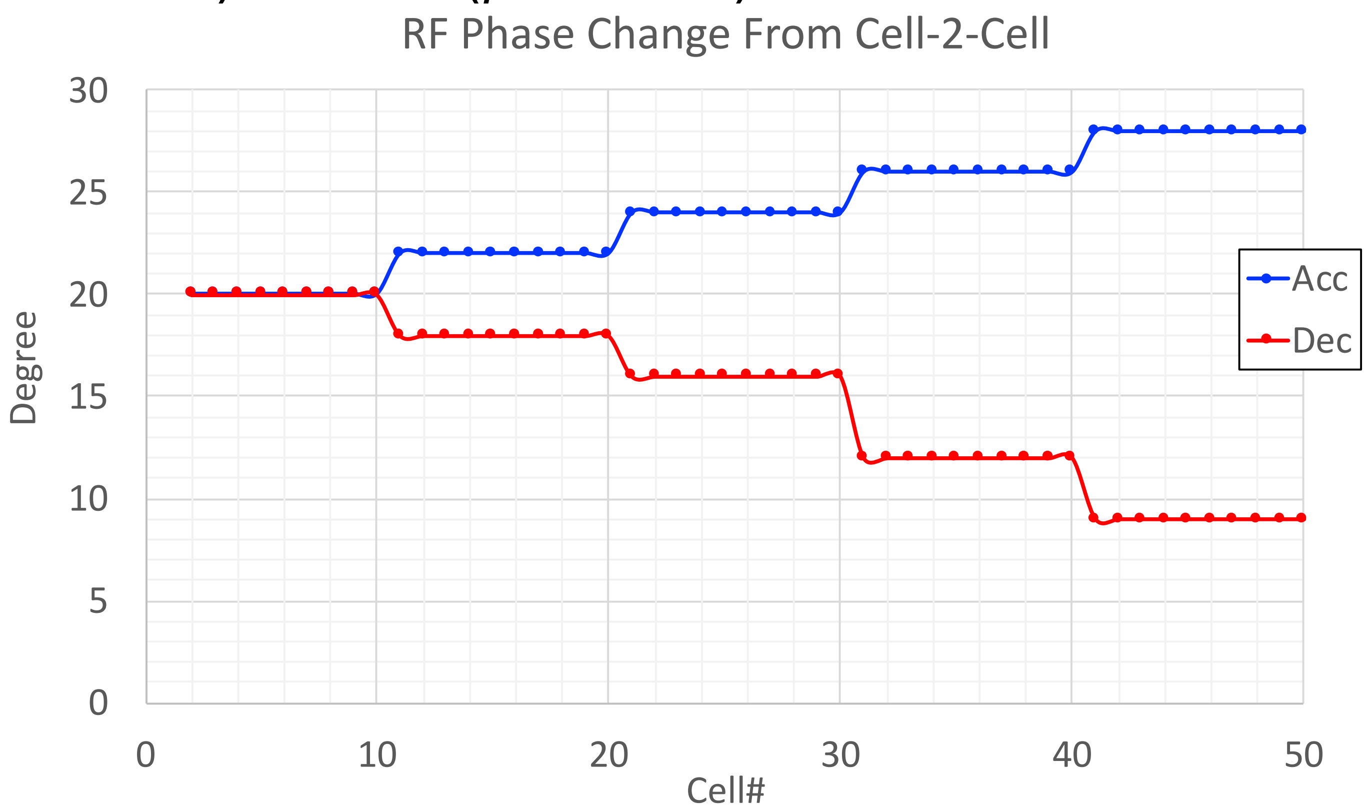


Beam Dynamics: Acceleration / Deceleration

Initial β = 0.5066 (150 MeV)

Target ΔE = 30 MeV

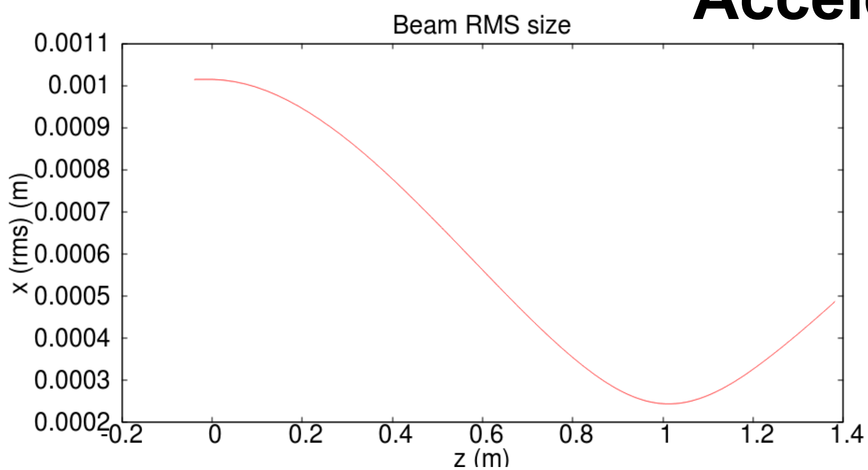
- $\beta\gamma$(180 MeV) = 0.649 (β = 0.544)
- $\beta\gamma$(120 MeV) = 0.522 (β = 0.463)

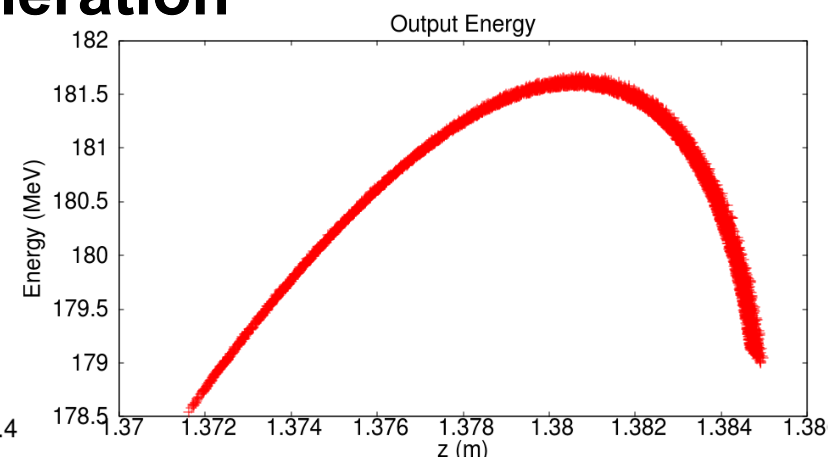


Acceleration and Deceleration Provide Modulation and Transverse Focusing

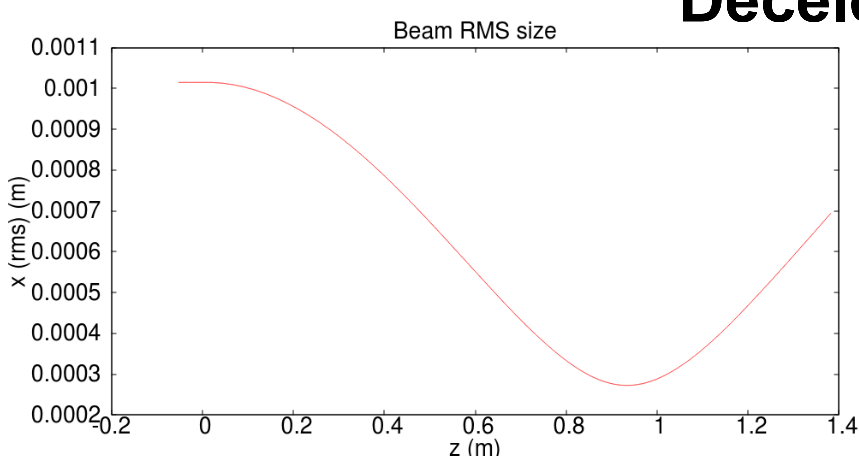
- Initial parameters: 7 mm (full length), β = 0.5066 (150 MeV), beam size (RMS) = 1mm

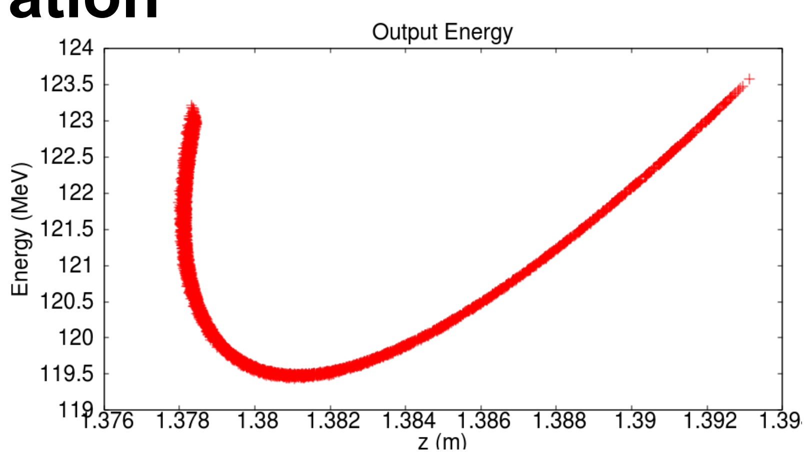
Acceleration





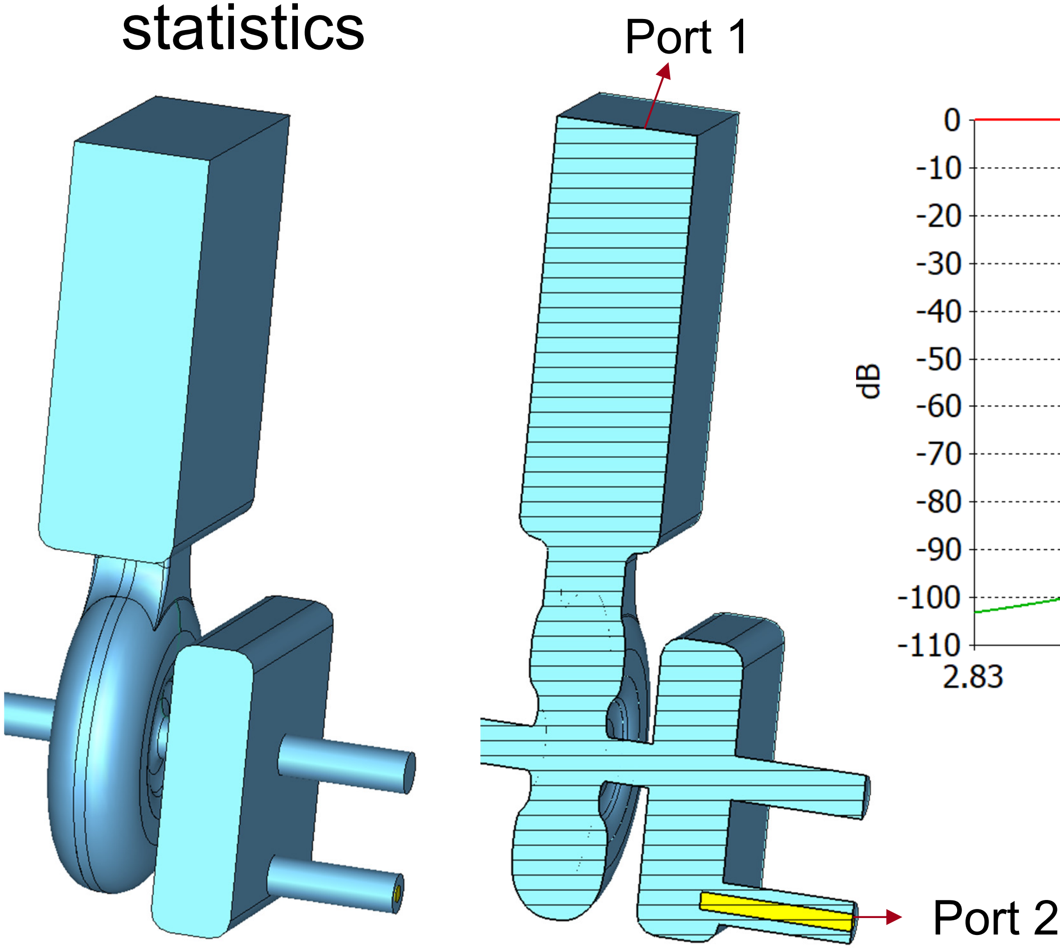
Deceleration

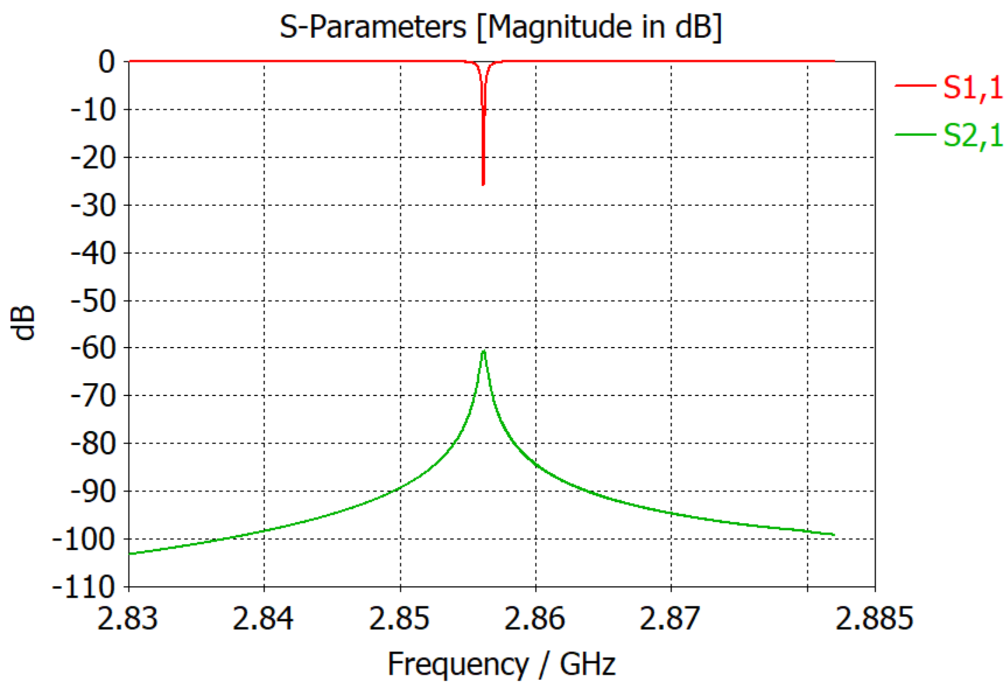




Single Cavity Design Modified to Include Coupling Port to Measure Fields in Cavity

- High gradient in cells (30 MV/m) for S-Band Operation
- Aim to characterize performance and collect breakdown statistics





Mechanical Design Complete and in Fabrication; S-Band Station in Preparation for Experiments at NLCTA

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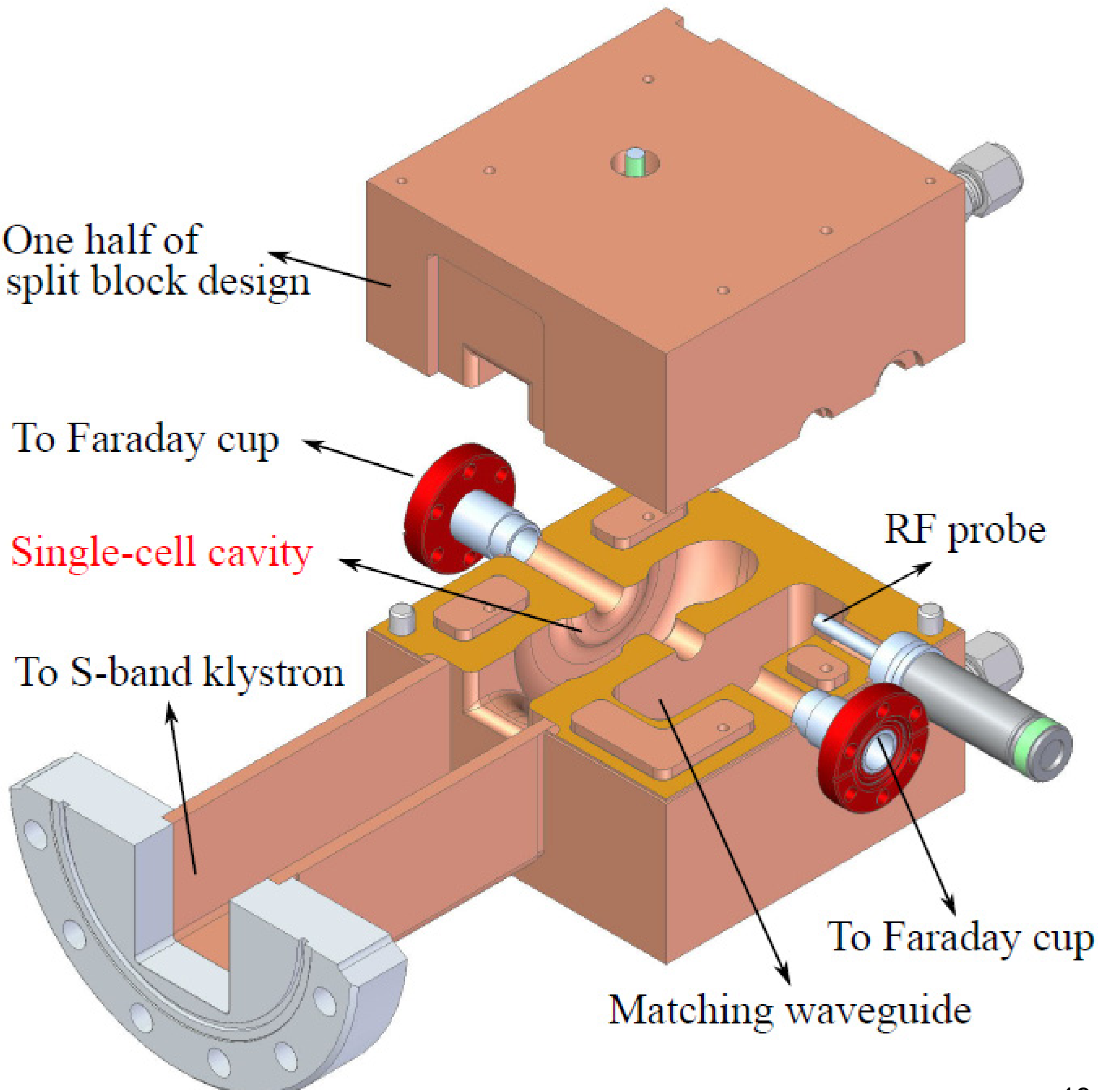
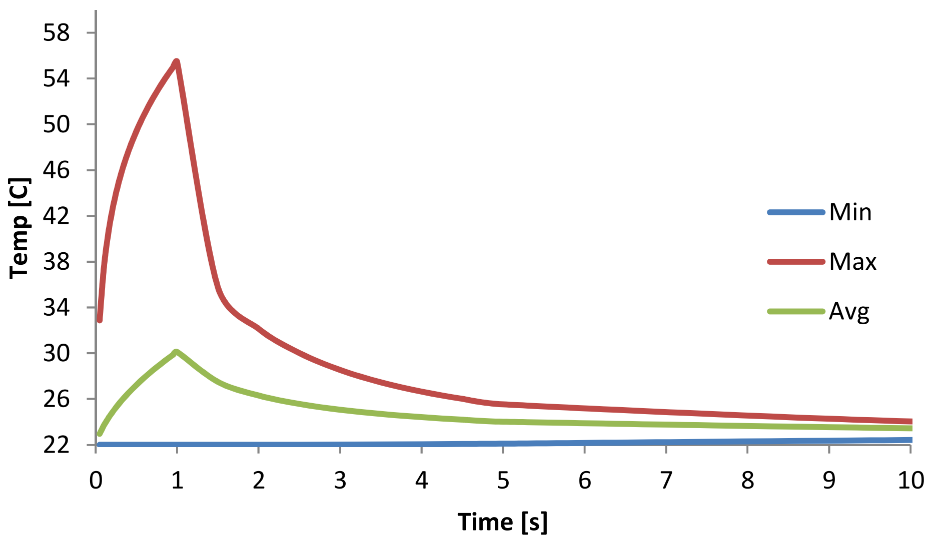
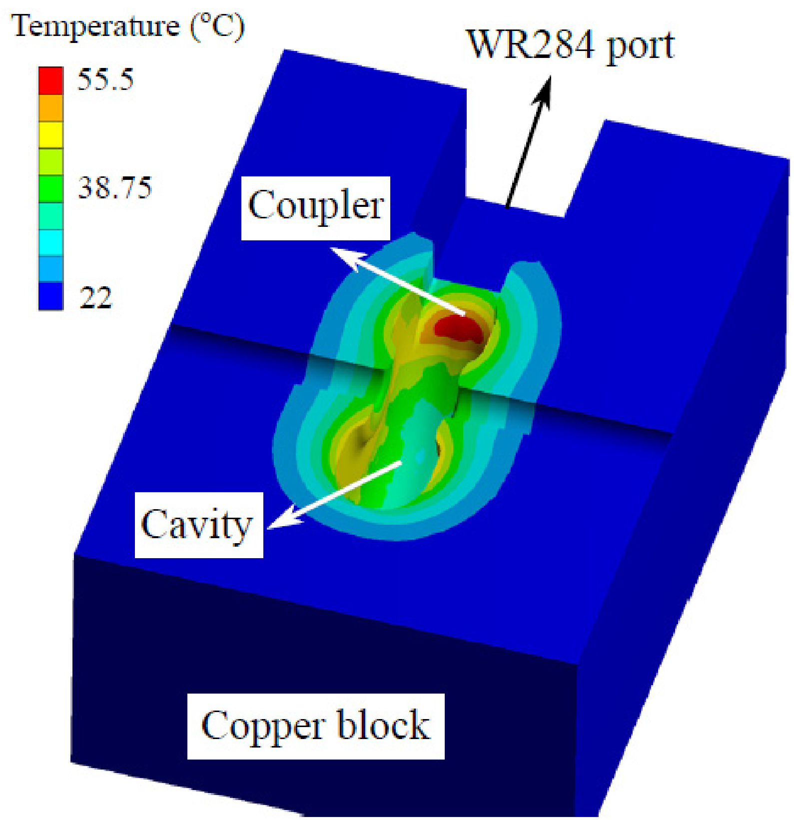
- Mechanical design will test split-block fabrication
  - Plan to test scaling to full length of structure
  - In fabrication at RWI, brazing at SLAC



RF Power During Flash Treatment Delivered for a One Second Burst – No Active Cooling Required

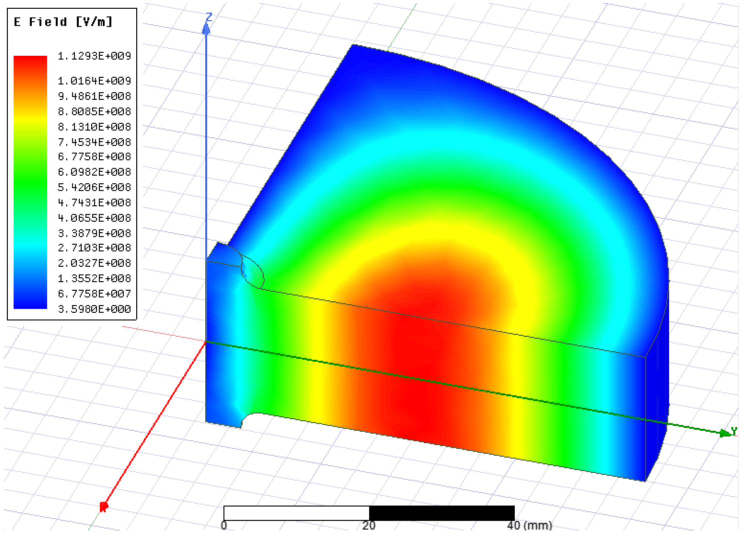
- Input Power: 10 kW average
- Mass: 23.3 kg
- Initial Temp: 22°C
- No cooling applied
- Peak Temp Rise: 33.5°C

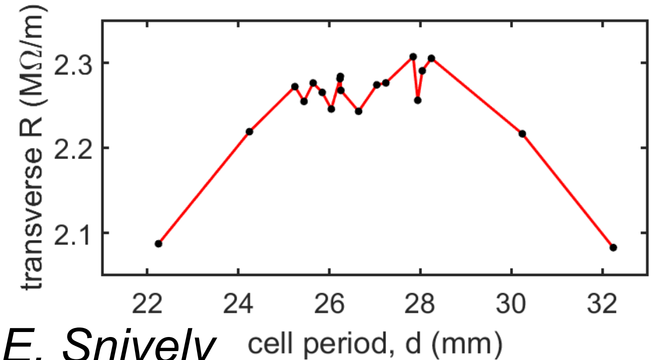




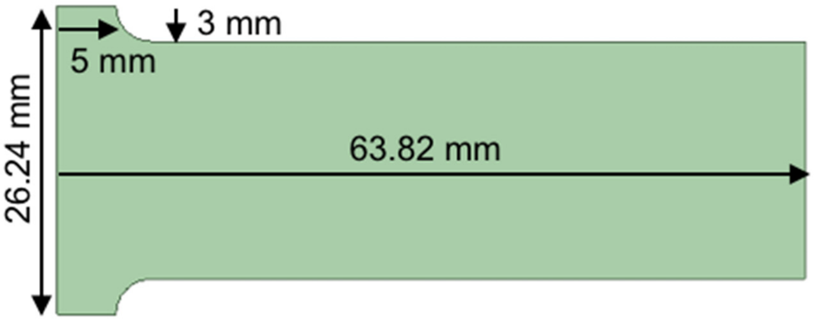
Initial S-band π-mode Deflector Design

- Benchmarking with conventional disk-loaded waveguide structure
  - Will investigate alternate designs
  - Beam aperture increases with length
- Develop comprehensive model to ensure design minimizes aberrations at nonrelativistic energies
- Target: 10 mrad deflection





d = 26.24 mm	
β	.5
Q	12273
R_T	2.265 MΩ/m



E. Snively

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Conclusion

- Completed design of cavity and coupler for RF energy modulator; optimized for 150 MeV protons
- Fabricating single cavity prototype to test performance at nominal 30 MV/m gradient
- Initiated RF deflector design – will proceed through test
- Continue to develop full model from compression through gantry and to target to model beam dynamics
- Target ±30 MeV linac designed for operation at 150 MeV for rapid variation in depth at ~25cm ±6cm
- Develop new technology with high enough dose of >20 Gy/L/s for hypofractionated treatments for FLASH