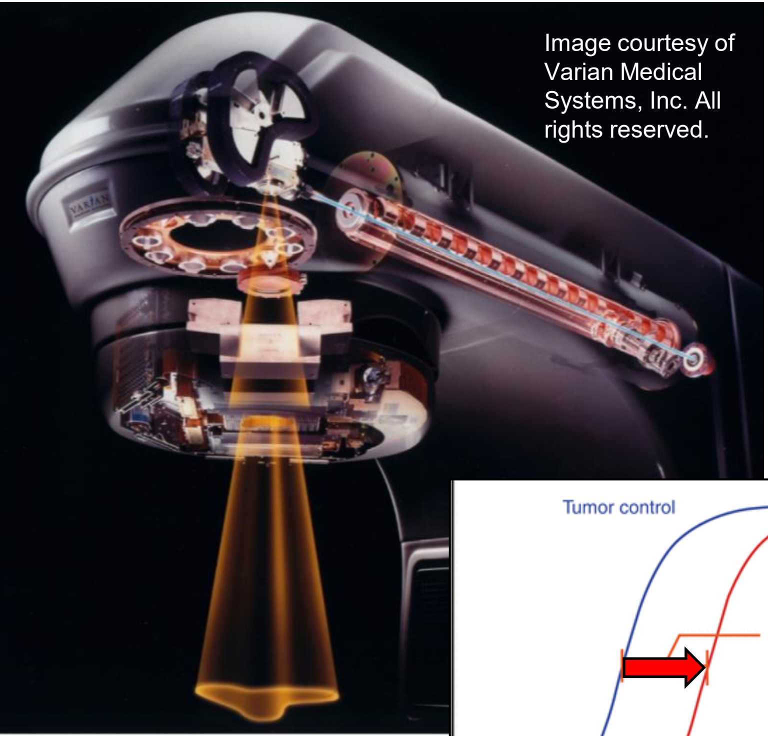
Rapid RF-driven 3D Pencil Beam Scanning for Proton Therapy

Emma Snively, SLAC National Accelerator Laboratory

IPAC’22: Applications of Accelerators, Technology Transfer and Industrial Relations

June 13th, 2022

Improving radiation therapy with new accelerator technology



Increasing the therapeutic window

Minimize dose to healthy tissue ⟶ Shape cross section

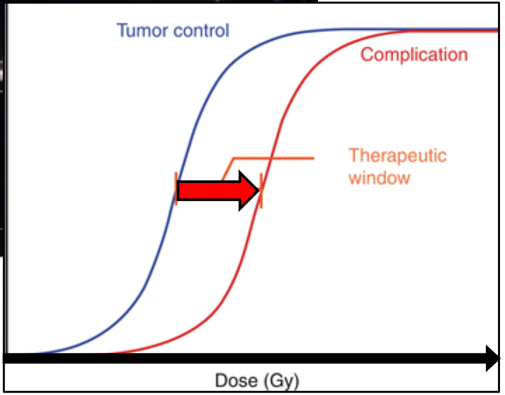
Avoid sensitive organs ⟶ Multiple entry angles

Improving efficiency

Collimators/masks/filters ⟶ Pencil beam scanning

Mechanical motion ⟶ RF phase control

X-ray conversion ⟶ Direct electron therapy

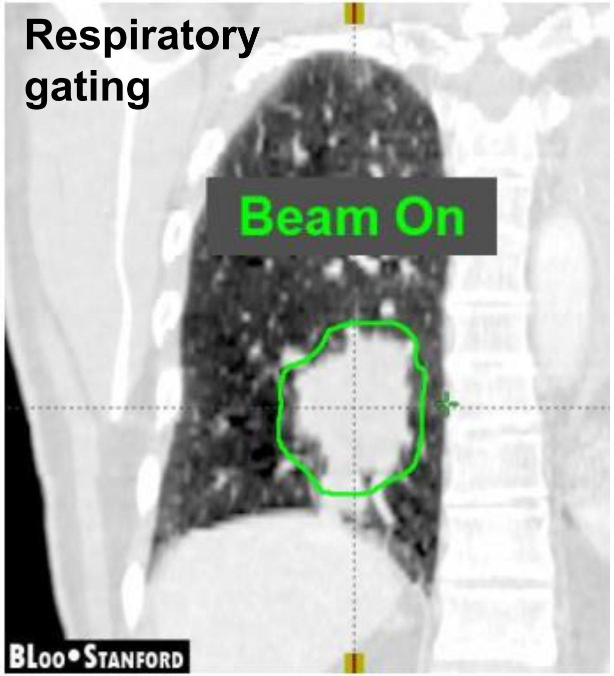


Chang D.S., Lasley F.D., Das I.J., Mendonca M.S., Dynlacht J.R. (2014) Therapeutic Ratio. In: Basic Radiotherapy Physics and Biology.

More compact structures

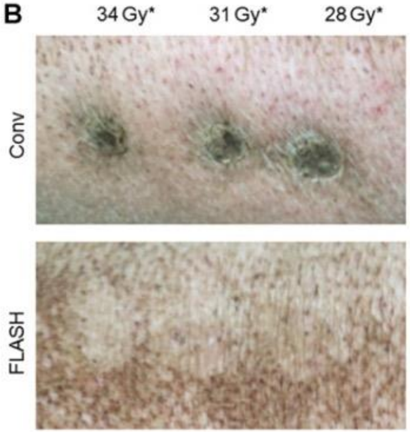
Higher rep rate, higher current

Benefits of Speed



Motion Management

FLASH Therapy

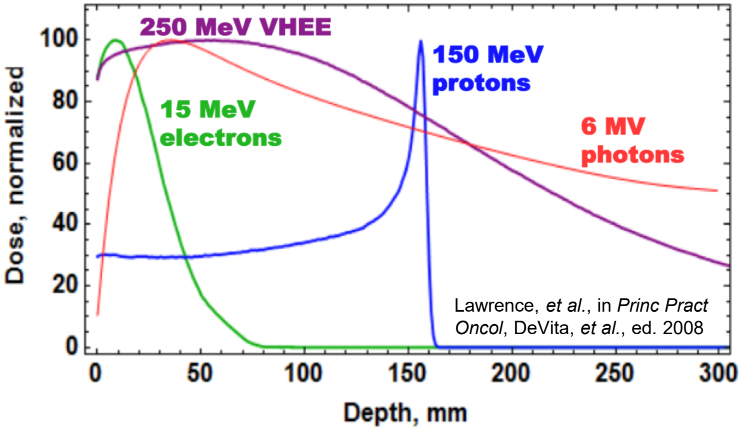


Vozenin, M.C., et al. "The advantage of FLASH radiotherapy confirmed in mini-pig and cat-cancer patients." *Clinical Cancer Research* 25.1 (2019): 35-42.

- Sub-second treatment time appears to improve healthy tissue sparing with comparable tumor control
- Demonstrated in preclinical setting with photons, electrons, and protons
- Requires high dose rate >50 Gy/L/s

Bourhis, Jean, et al. "Treatment of a first patient with FLASH-radiotherapy." *Radiotherapy and oncology* 139 (2019).

Innovation for future proton therapy



Dose profiles for various particle beams in water (beam widths $r = 0.5$ cm)

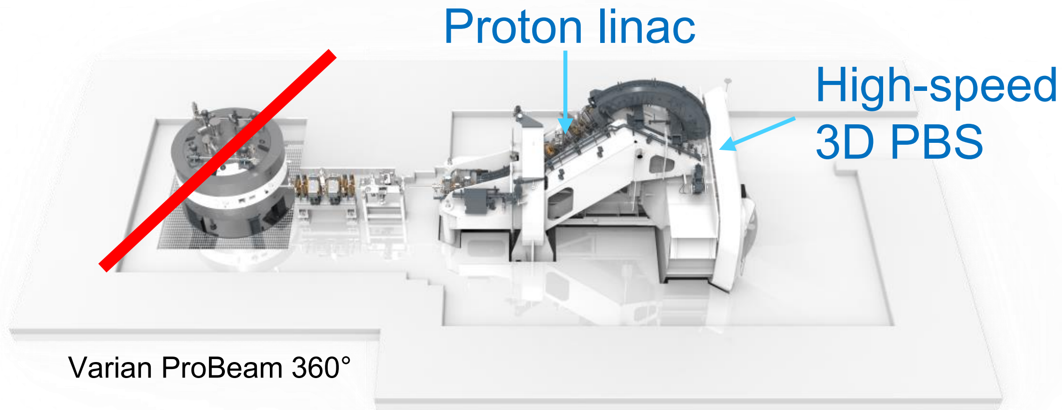
Advantage

- Longitudinal dose shaping

Challenges

- Slow layer switching and steering
- Large expensive facilities

A compact single-room system…



Varian ProBeam 360°

… with FLASH-capable pencil beam scanning.

The development of efficient, inexpensive linacs

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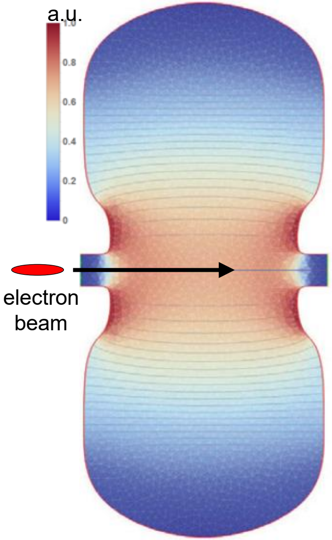
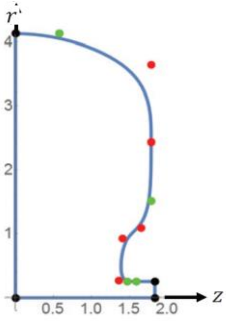
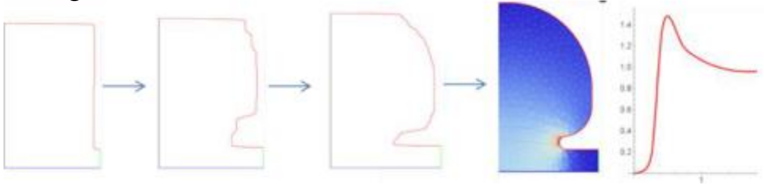
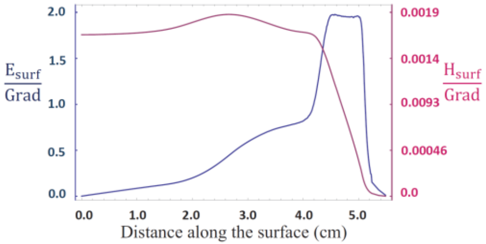




Nasr, M. H., and S. G. Tantawi. ***New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities' Performance***. No. thpmk049. IPAC, 2018.



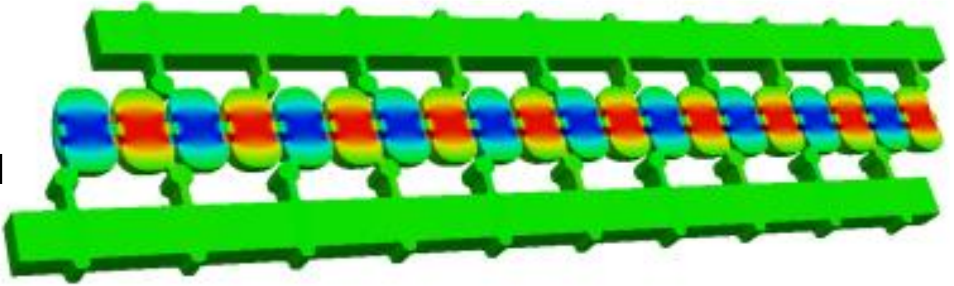
Magnetic field distribution around the cell surface



- Results in a very high shunt impedance, hence very efficient linac structure
- Reduced surface magnetic field enables a very high gradient structure

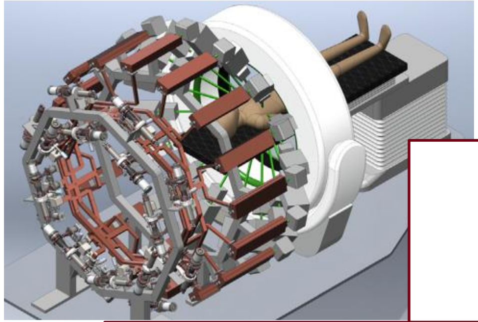
Novel distributed coupling to each cell

- Enables *doubling* RF to beam efficiency and ultra-high-gradient operation!

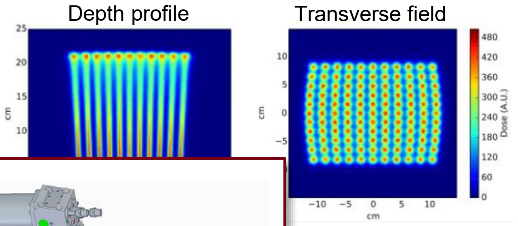


Tantawi, Sami, et al. "Distributed coupling accelerator structures: A new paradigm for high gradient linacs." *arXiv:1811.09925* (2018).

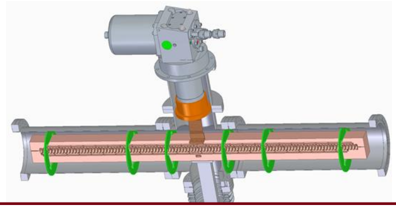
Application to medical accelerators



3D High Speed RF Beam Scanner for Hadron Therapy of Cancer



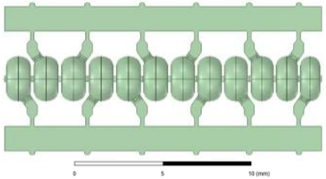
High Energy Compact Cryogenically Cooled Linac System for Very-High-Energy-Electron Radiation Therapy



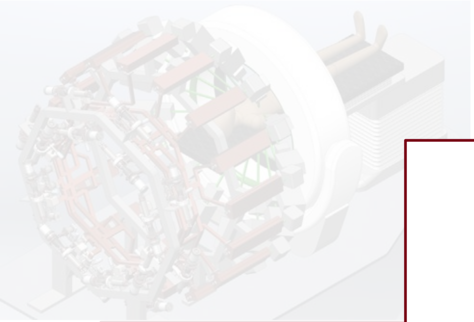
D.O.E. Accelerator Stewards

High Gradient mm-Wave Linac for Very High Energy Electron Therapy

LDRD



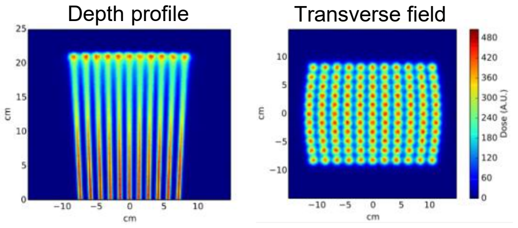
Application to medical accelerators



PHASER

D.O.E. Accelerator Stewardship Program

3D High Speed RF Beam Scanner for Hadron Therapy of Cancer



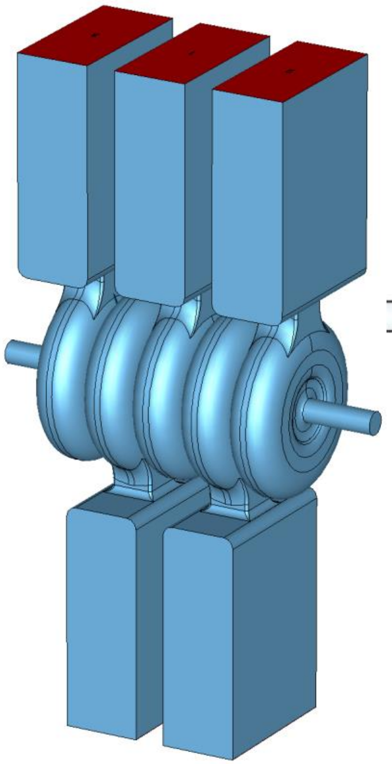
D.O.E. Accelerator
Stewards

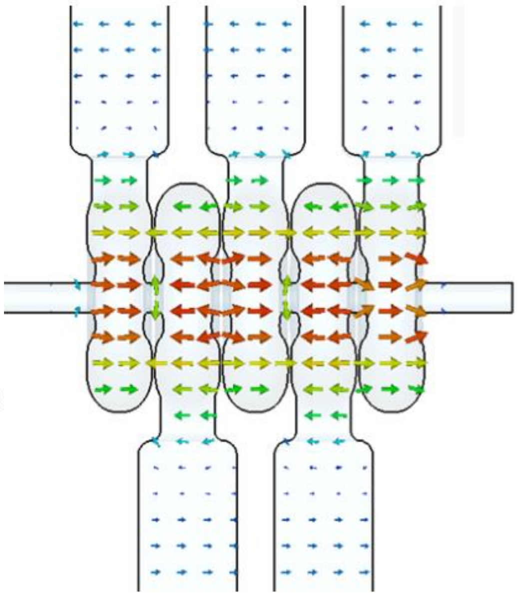
Program Objectives:

Design component technology to cover 4 L volume with >20 Gy/L/s

- Energy modulator providing +/- 30 MeV
- Deflector providing +/- 100 mrad
- System length ≤ 2 m

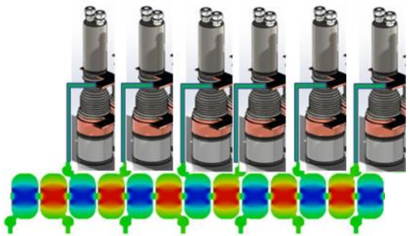
RF energy modulator design

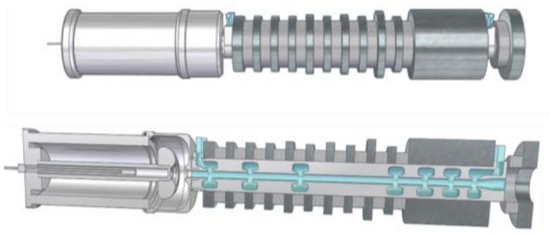




Simulation of 5 cell section

- Each cell fed independently, phased for 160° advance for nonrelativistic protons ($\beta \approx .5$)
- 1 m structure with 30 MeV/m gradient, requires 400 kW per cell

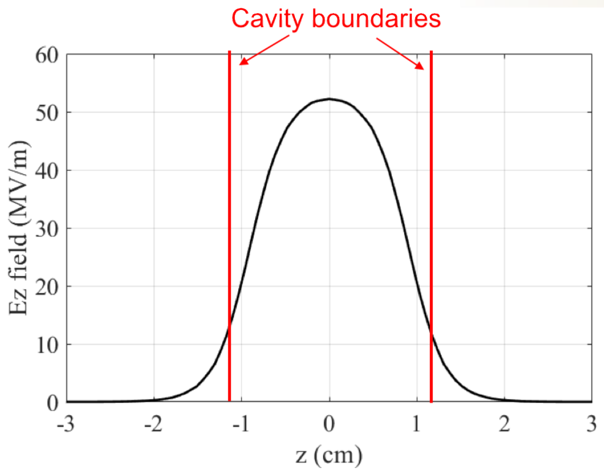




Franzi et al., LCWS 2018

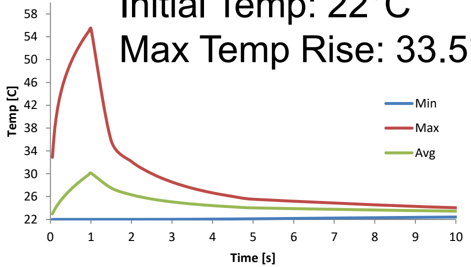
X. Lu

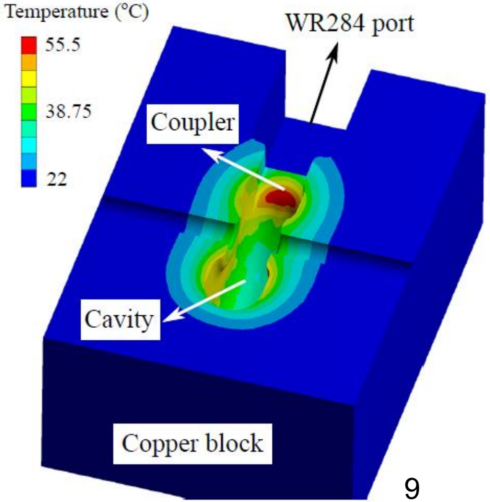
RF energy modulator design



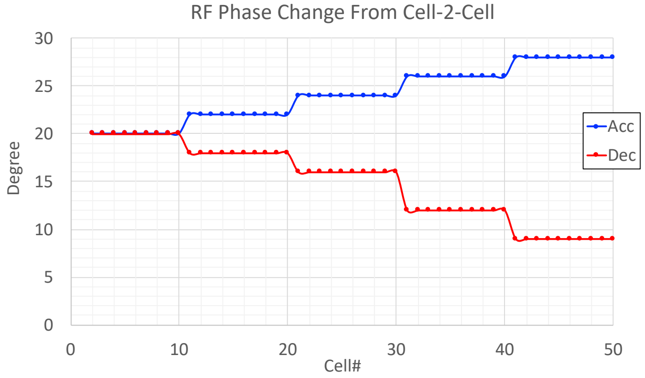
Parameter	Value
Frequency	2.856 GHz
Beam aperture (diameter)	1.05 cm
Phase advance per cell	160°
Quality factor Q_0	11936
External quality factor Q_{ext}	11911
Shunt impedance r_s	54.8 MΩ/m
r_s/Q	4.6 kΩ/m
Average gradient E_a	$15\ \text{MV/m} \cdot \sqrt{P/(100\ \text{kW})}$
E_{peak}/E_a	2.26
$H_{peark}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

10 kW avg input
Initial Temp: 22°C
Max Temp Rise: 33.5°C





- Relative phase along length of linac adjusted for change in proton velocity
- RF power during flash treatment delivered for a one second burst – no active cooling required



X. Lu, Z. Li, A. Sy

RF deflector design

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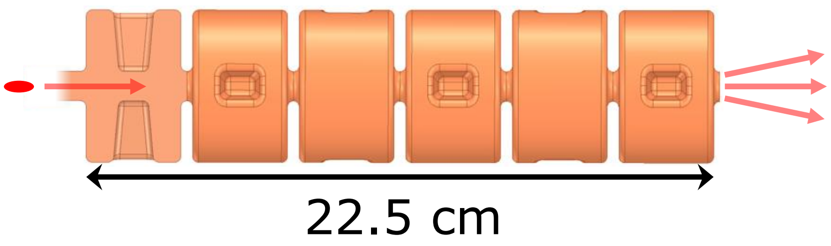
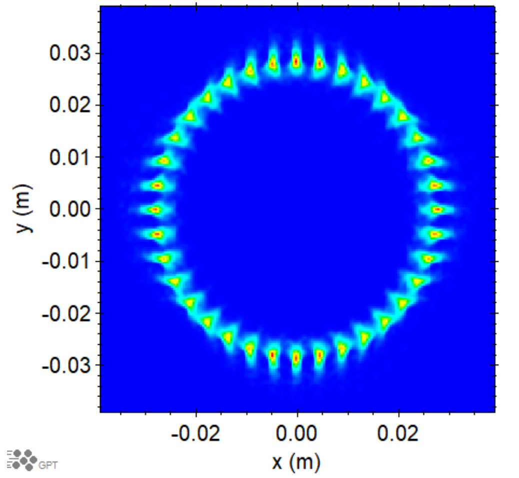
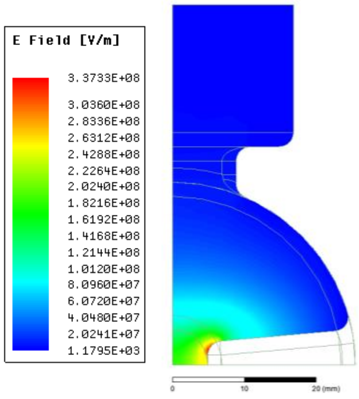
- Design goal: 100 mrad deflection
- TE_{11}–like cavity for high transverse shunt impedance
- Posts protruding into pillbox determine cell polarization

6 cell structure for 15 mrad kick





2 m downstream of deflector entrance



Design parameters	
Frequency	2.856 GHz
Cell period, d	37.5 mm
Q	6996
shunt impedance	66.8 MΩ/m
Dissipated power	800 kW
Integrated V_y	1.415 MV
Kick	37.73 MeV/m

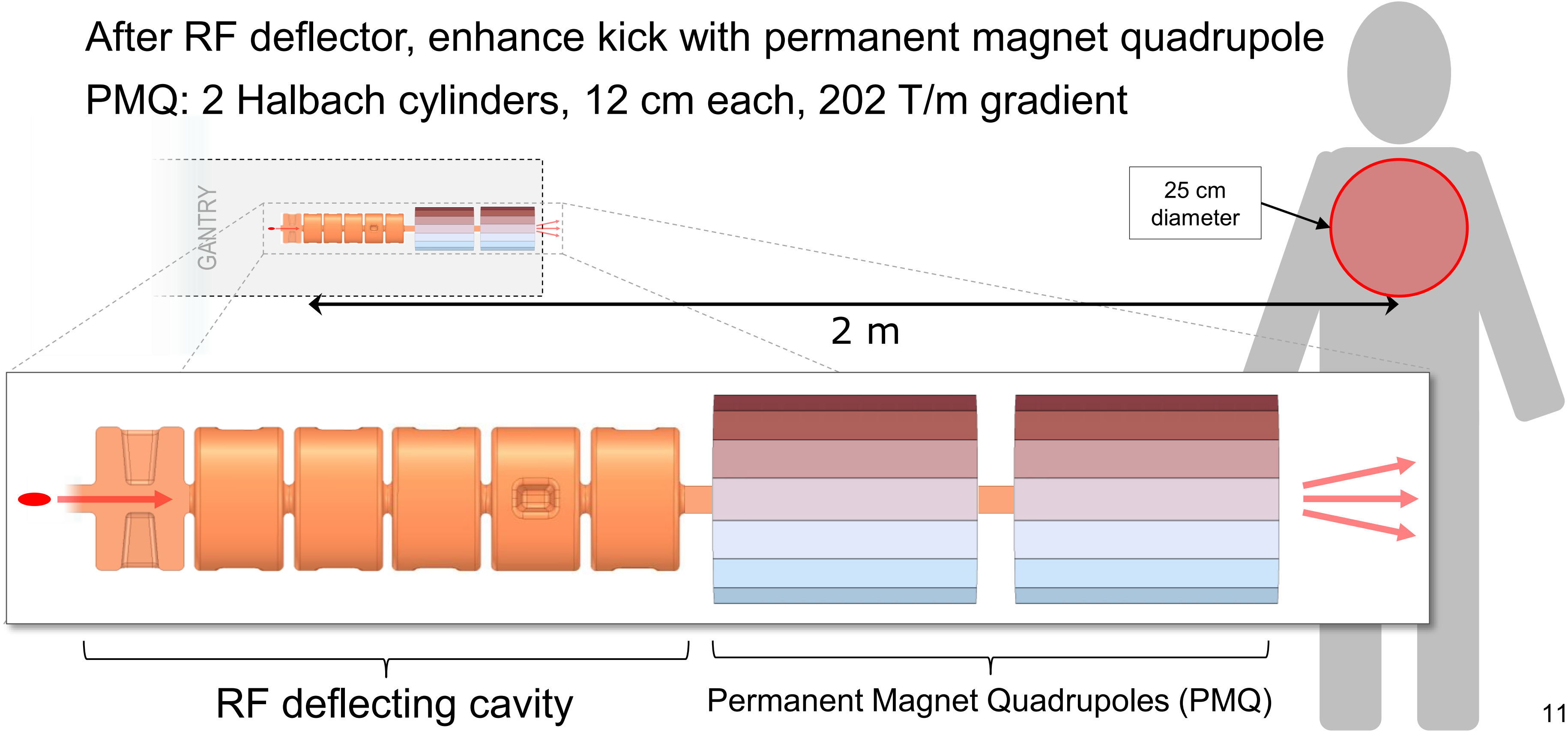
Improving performance?

- 20 cell tapered structure at room temp for up to 46 mrad kick
- Cooling to 40 K in 10 cell structure for up to 48 mrad kick

Magnifying the RF steering

After RF deflector, enhance kick with permanent magnet quadrupole

PMQ: 2 Halbach cylinders, 12 cm each, 202 T/m gradient

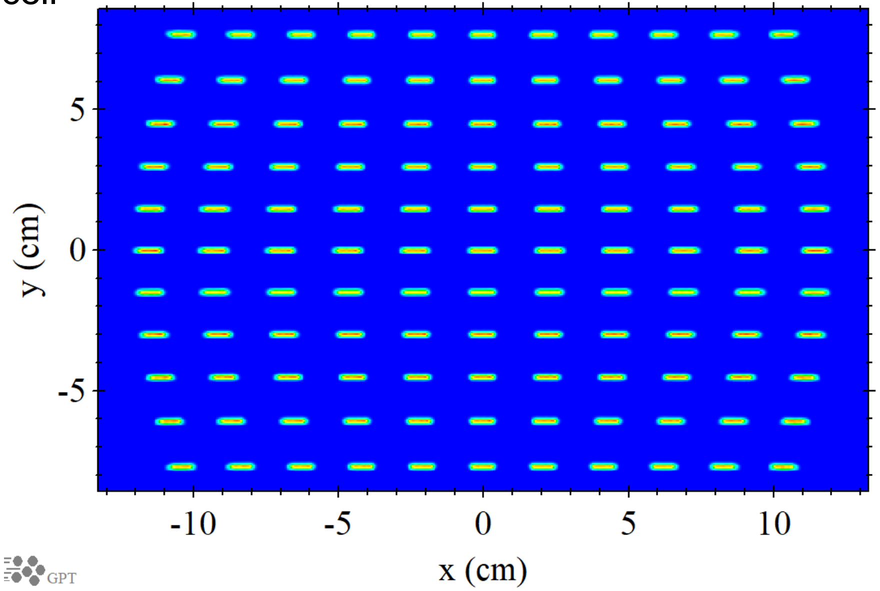


Beam distributions at isocenter

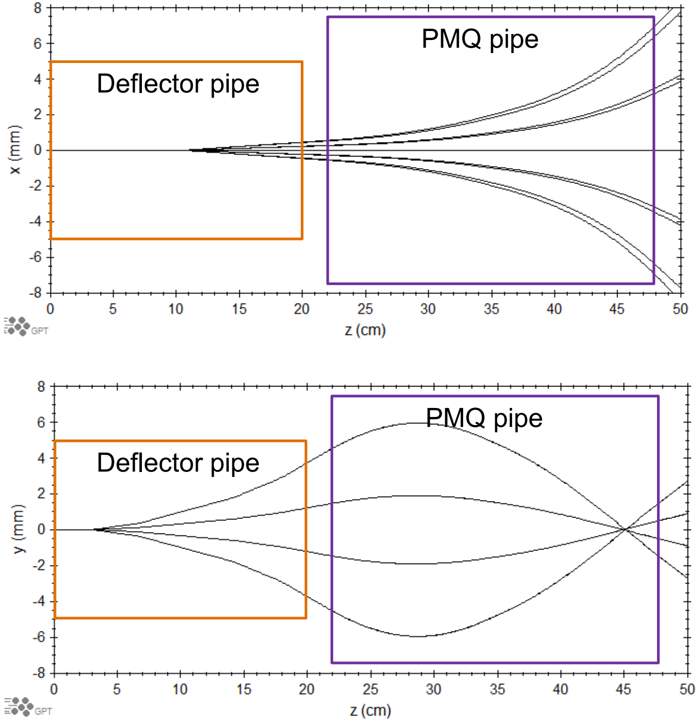
Aperiodic deflector structure: 6 cell Y-Y-Y-Y-X-Y, 22.5 cm total length

Simulations performed using General Particle Tracer (GPT)

Using a proton energy of 180 MeV and operating at 45 K with 400 kW per cell

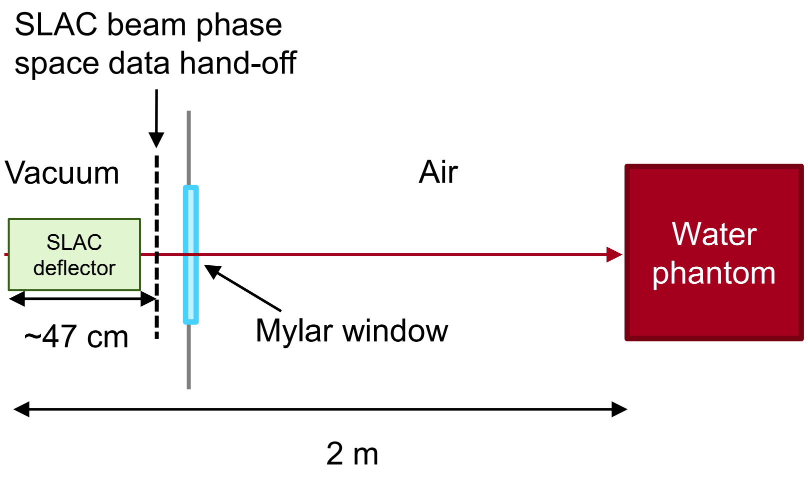


Beam trajectories

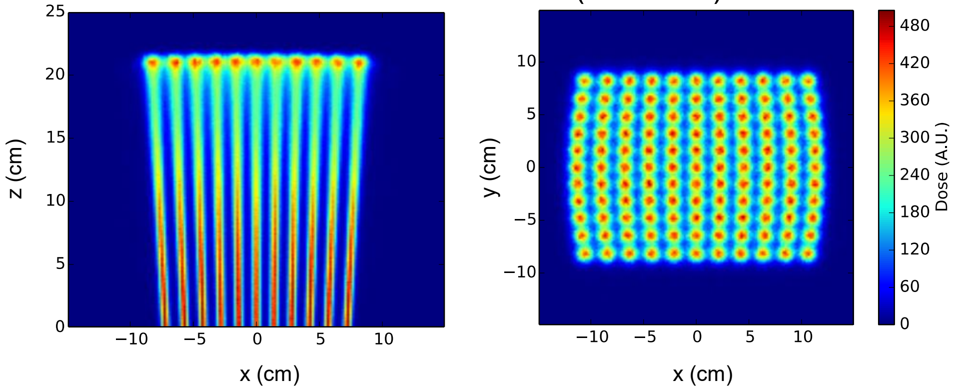


Rastered beam distribution showing 121 cumulative shots covering an area of roughly 23 x 16 cm.

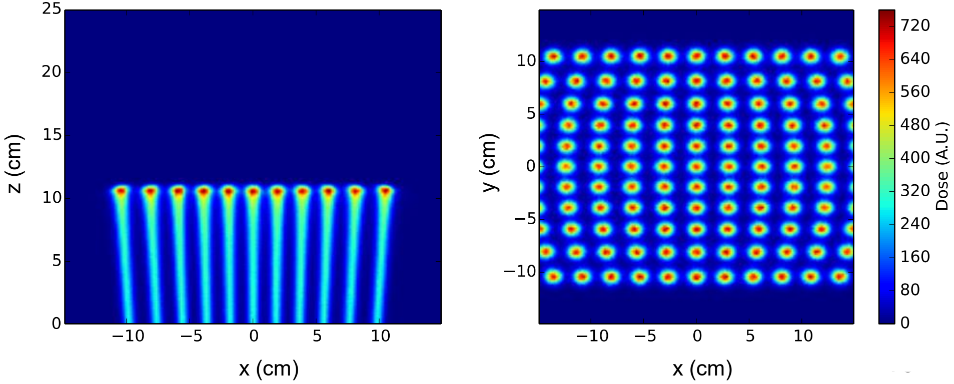
Dose deposition study (J. Mendez, UCSF)



Accelerated beam data (180 MeV)

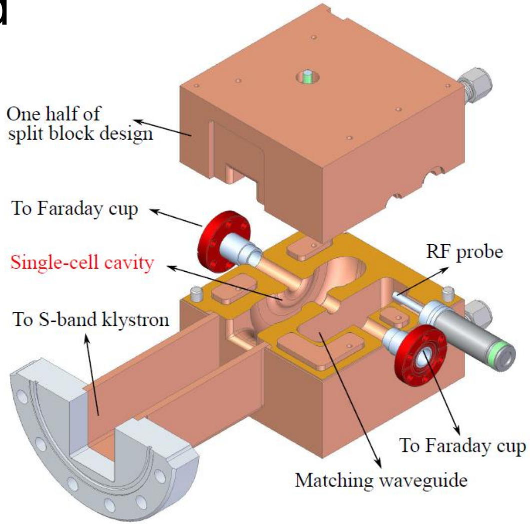


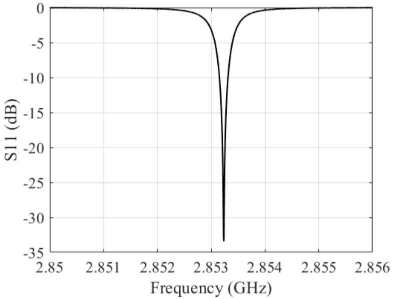
Decelerated beam data (120 MeV)



Cold tests of fabricated prototypes

Single-cell S-band energy modulator prototype

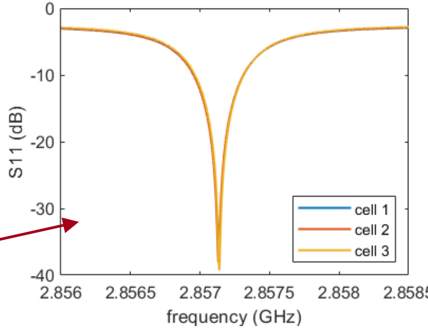




	Design	Cold Test
f (GHz)	2.856	2.853 Cu-Ag, 2.854 Cu
Q0	11936	12014 Cu-Ag, 12197 Cu
Coupling β	1.0021	1.04 (both)

Three-cell S-band deflector prototype

After tuning



On-going high-power testing at NLCTA

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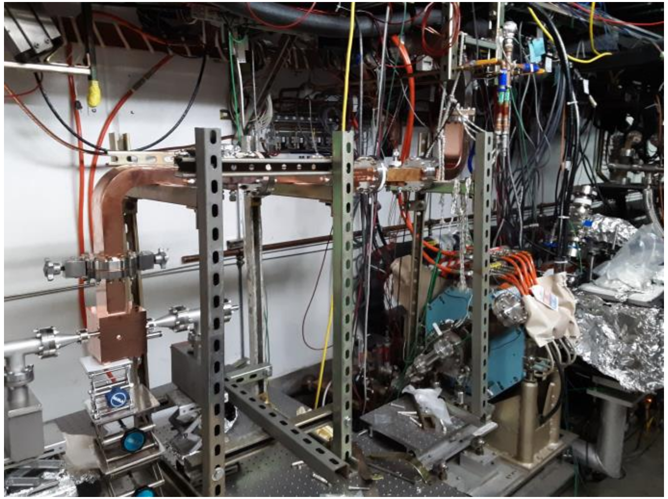
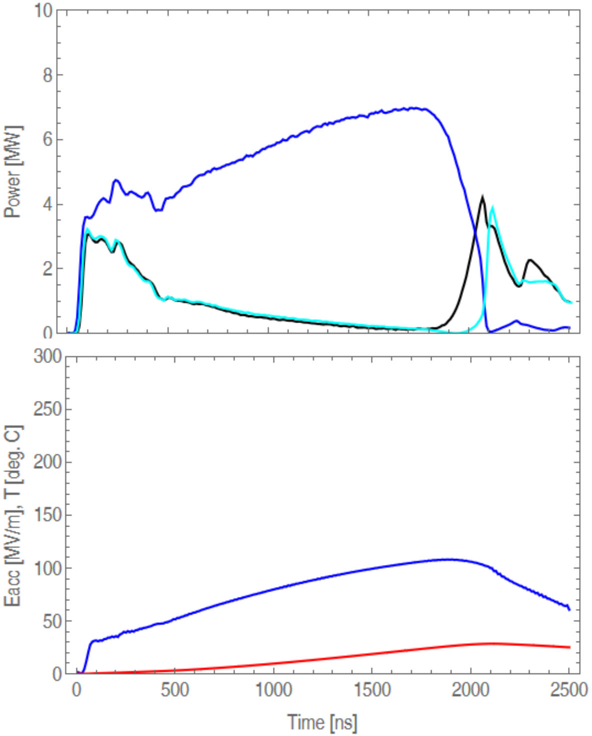
Single cell energy modulator prototype

-nominal input 400 kW, 30 MV/m

- Achieved 1 MW, 50 MV/m before observing breakdowns, now testing up to 6 MW





Measured forward and reflected power. Estimate of reflected power.

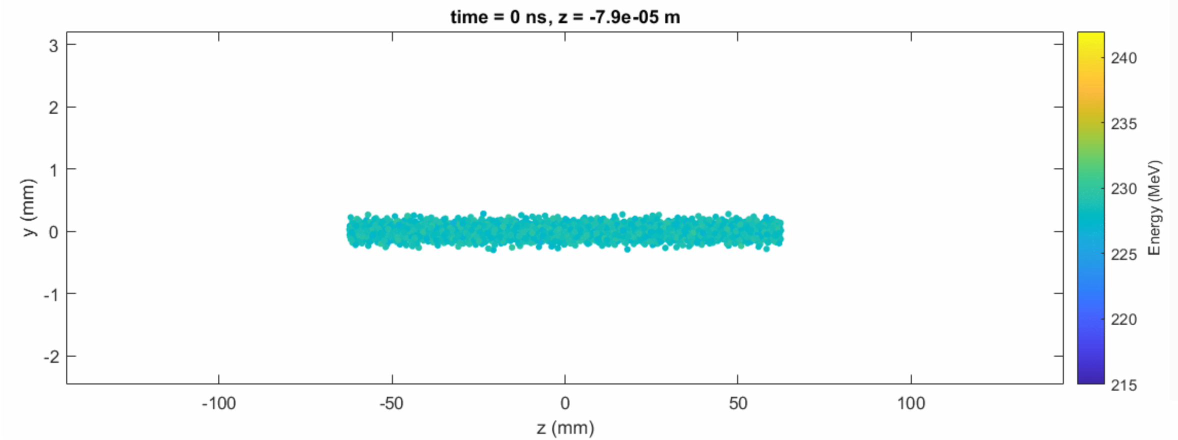
Calculated acceleration gradient and temperature rise

Today's poster session: "High Gradient Conditioning and Performance of C-Band ß=0.5 Proton Normal-Conducting Copper and Copper-Silver Radio-Frequency Accelerating Cavities" (**TUPOMS060**)

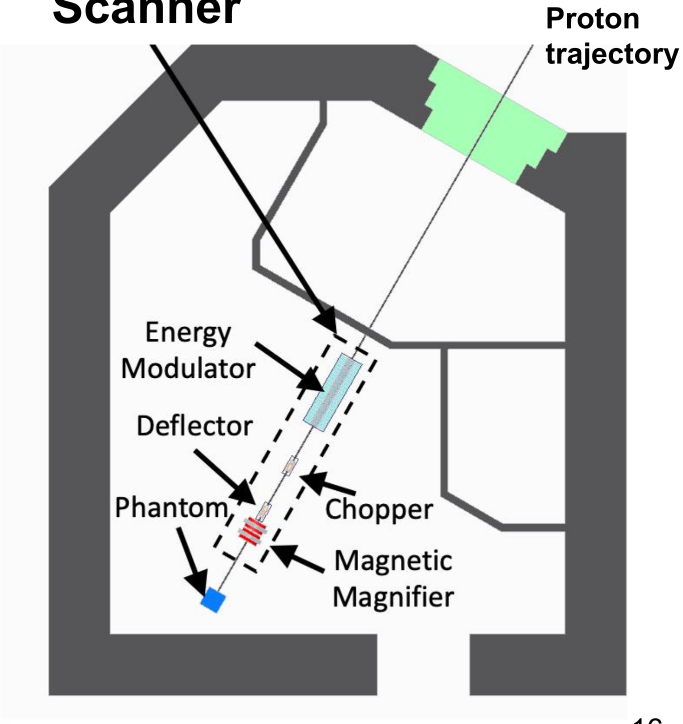
Proposed beam test at treatment facility

Challenges:

- Match the bunch structure needed for the deflector while maximizing dose
  - Add energy chirp for compression
  - Bunch selection with RF chopper

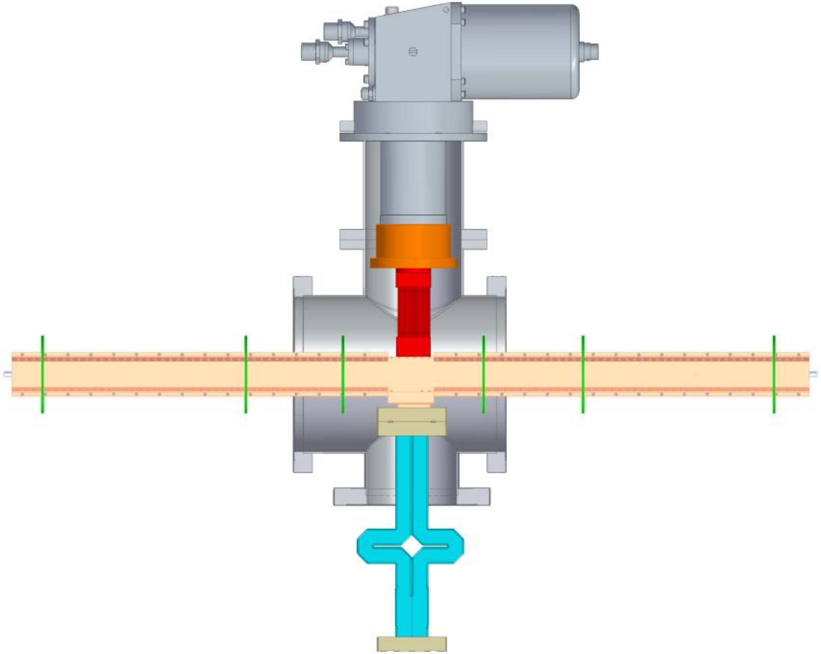


Rapid 3D Scanner

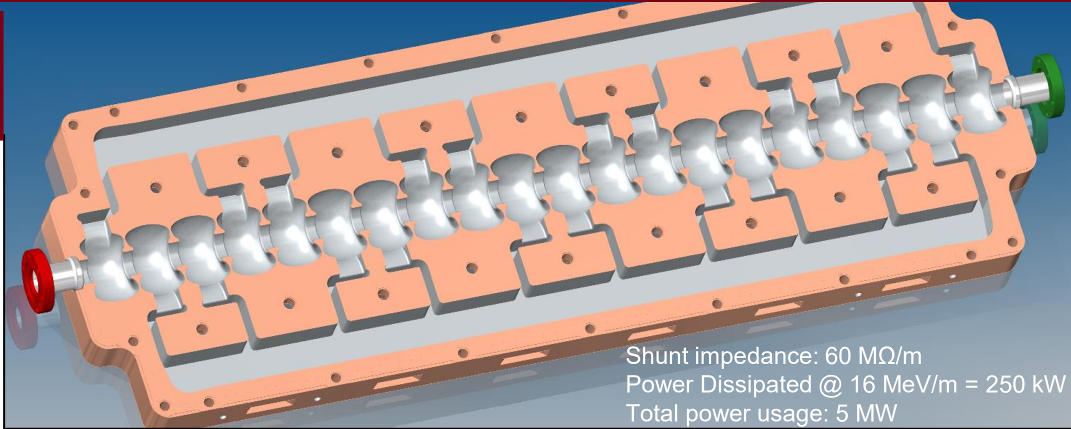


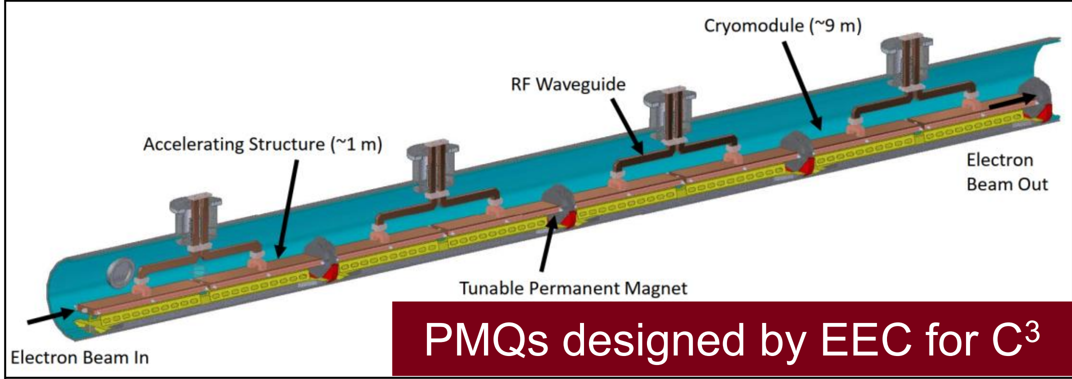
Outlook: leveraging current SLAC research

VHEE cryostat assembly designed for accelerator operation in medical facility



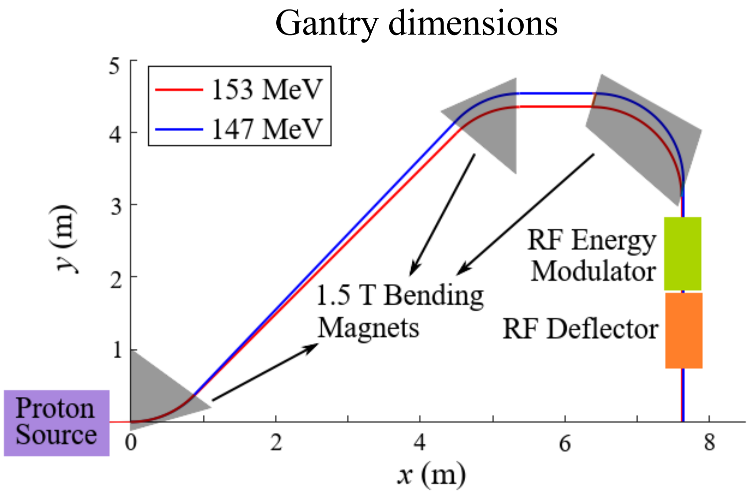
S-band π-mode distributed linac in fabrication for EIC





PMQs designed by EEC for C^3

3D High Speed RF Beam Scanner for Hadron Therapy of Cancer



- Overall system under 2 meters
- Energy modulator ±30 MeV, equivalent to +6 cm to -5 cm depth range
- Deflector steers over a ±10 cm range

SLAC

Emma Snively
Xueying Lu
Zenghai Li
Valery Dolgashev
Gordon Bowden
Ann Sy
Greg Le Sage
Brad Shirley
Dennis Palmer
Mitchell Schneider
Sami Tantawi
Andy Haase
Emilio Nanni

Stanford Medical

Billy W. Loo Jr.

Loma Linda University

Reinhard Schulte

Northwestern Proton Center

Mark Pankuch

UCSF

Bruce Faddegon
Jose Mendez
Jhonatan Carrasco Hernandez

Accelerator Stewardship Program