

Use of High Gradient NCRF Accelerating Structures in Small Industrial Accelerator Systems

GARD RF Roadmap Update - NCRF Meeting

January 20, 2026

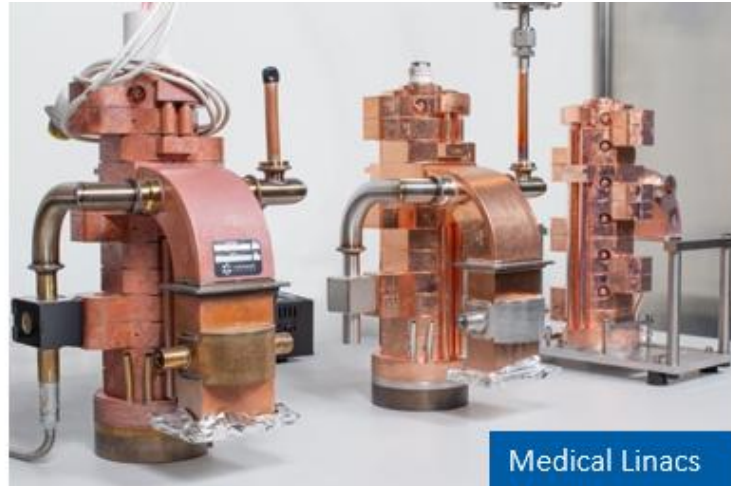
Sergey V Kutsaev

- RadiaBeam is a small business company, located in Santa Monica, CA that specializes on accelerator components, instruments, and industrial accelerator systems

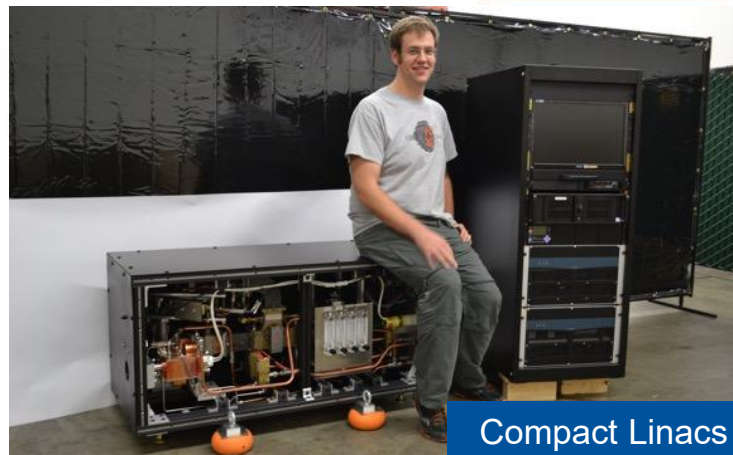
RF Structures



1/20/2026



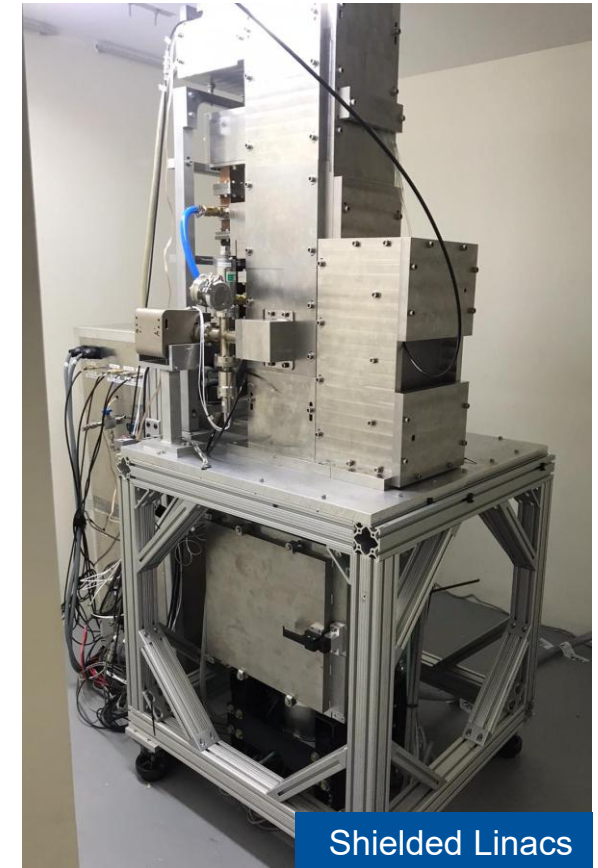
Medical Linacs



Compact Linacs



Security Linacs



Shielded Linacs

Use of High Gradient NCRF Accelerating Structures in Small Industrial Accelerator Systems

- Most of RadiaBeam's accelerators are sold for conventional applications and are NOT high-gradient!

Application	Beam Energy, MeV	Beam Power, kW	Gradient, MV/m	Main Requirement
Industrial Irradiation	7-10	10-30	~10	Max beam power
Radiotherapy	6	0.5-1	~20	Min cost
FLASH Radiotherapy	9-12	>10	~10	Max instantaneous dose
Small-Sample Irradiation	1-3	0.5-2	~15	Low-cost with self-shielding
NDT	0.15-2	<1	<10	Compactness

- Customers and applications prefer high beam power, reliability and low costs over compactness
- Even compact accelerators benefit from low-energy/low-gradient regimes due to the RF power source, shielding, cooling and other critical contributors to the SWaP characteristics

- Higher gradients = Higher RF losses
- Higher RF losses = Less beam power
- Higher RF losses = More powerful RF sources
 - More expensive

Linac cost breakdown

	Low Power	High Power
RF Peak Power	3 MW	5 MW
Beam Power	1.5 kW	20 kW
Linac Cost	\$150,000	\$2,000,000
RF System Cost	\$70,000	\$700,000
Fabrication Cost	\$50,000	\$150,000
Linac Cost per Watt	\$100	\$100

$$P_{RF} = \left(\frac{V^2}{R \cdot L} = \frac{E \cdot V}{R} \right) + I \cdot V$$

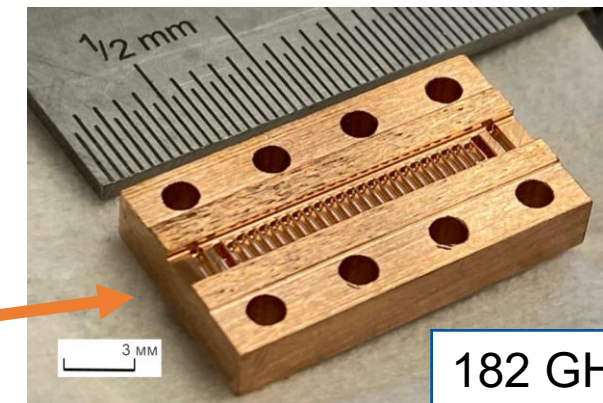
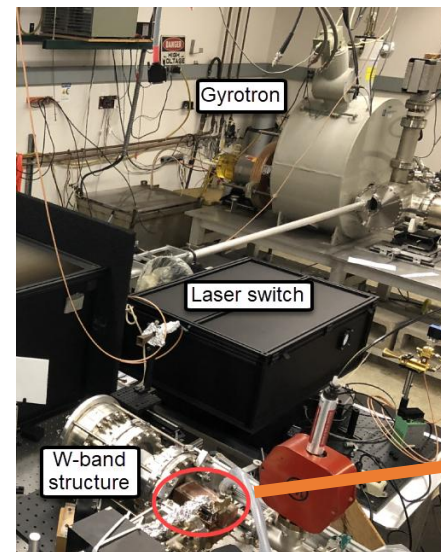
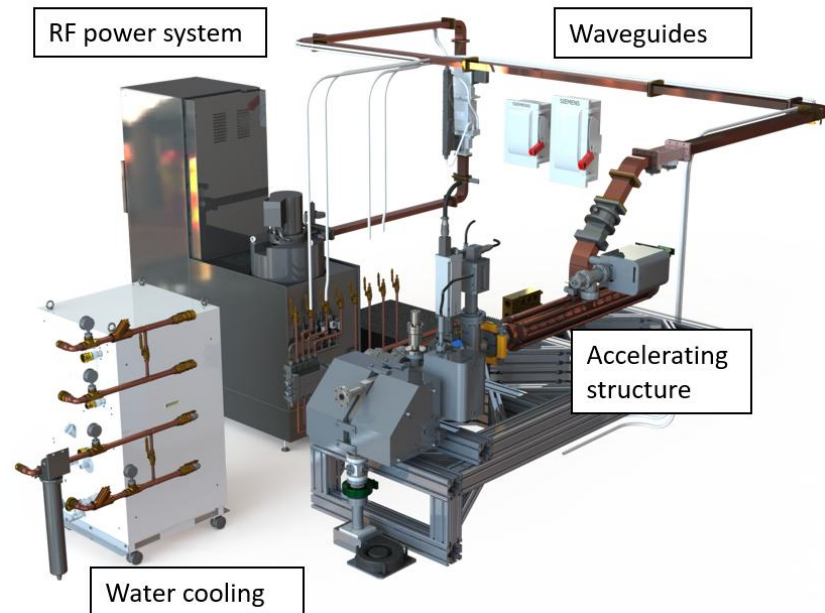
V, MeV	E, MV/m	L, cm	P _{rf} MW	P _{beam} kW
10	10	100	5	35
10	25	40	5	14
10	50	20	10	28?
2	10	20	2.7	2.4
2	25	8	2.7	2
2	50	4	2.7	1.3.

RF source	Frequency	Peak Power, MW	Average Power, kW	Price, k\$
Klystron	S-band	5	36	200
Klystron	S-band	50	9	350
Magnetron	S-band	3.1	4.5	30
Klystron	X-band	5	18	200
Klystron	X-band	50	0.5	>300
Magnetron	X-band	1.7	1.5	>30

$$P_{RF} = \left(\frac{V^2}{R \cdot L} = \frac{E \cdot V}{R} \right) + I \cdot V$$

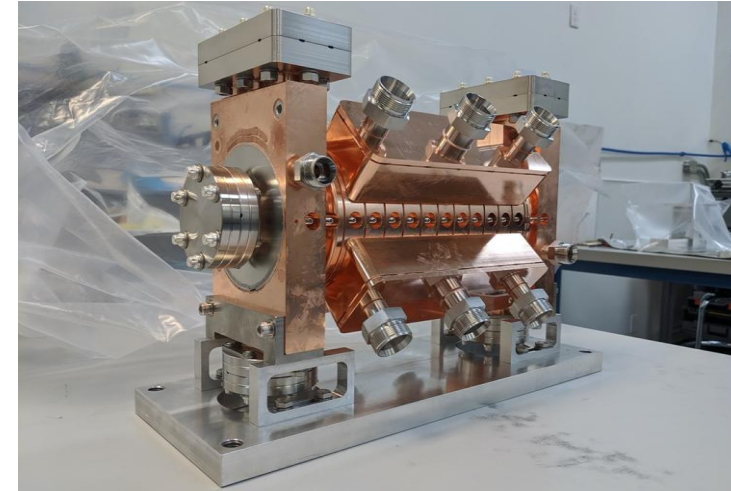
- Higher gradients = Higher RF losses
 - More cooling
- Higher RF losses = Less beam power or more RF power
- For the energies of ~10 MeV and less, the reduction of linac length doesn't reduce the system size
 - In extreme cases power source can become much larger than the accelerator

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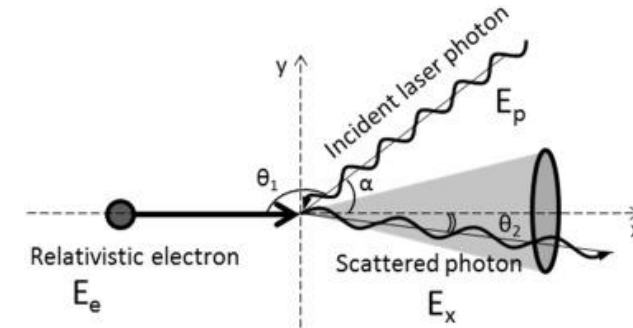
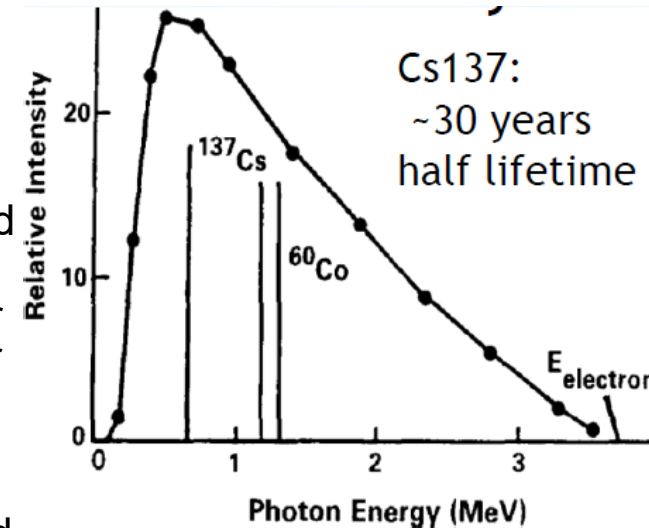


$$P_{RF} = \left(\frac{V^2}{R \cdot L} = \frac{E \cdot V}{R} \right) + I \cdot V$$

- High gradients start to make sense when high-energy beams are required
 - i.e. when **V** and/or **L** are more important than beam power
 - Or when performance (emittance) scales directly with gradient, not length
- Emerging applications:
 - Hadron therapy linacs (250 – 1000 MV, nA beams)
 - VHEE radiotherapy (50-200 MeV, μ A beams)
 - Compact light sources (100-500 MeV, room-size requirements)
 - Neutron and Isotope production (40-150 MeV, size constrains)
 - Ultrafast electron systems (several MeV, very small emittances)
- RadiaBeam's involvement in these projects is currently limited at R&D or prototype stages
 - Not commercial sales yet



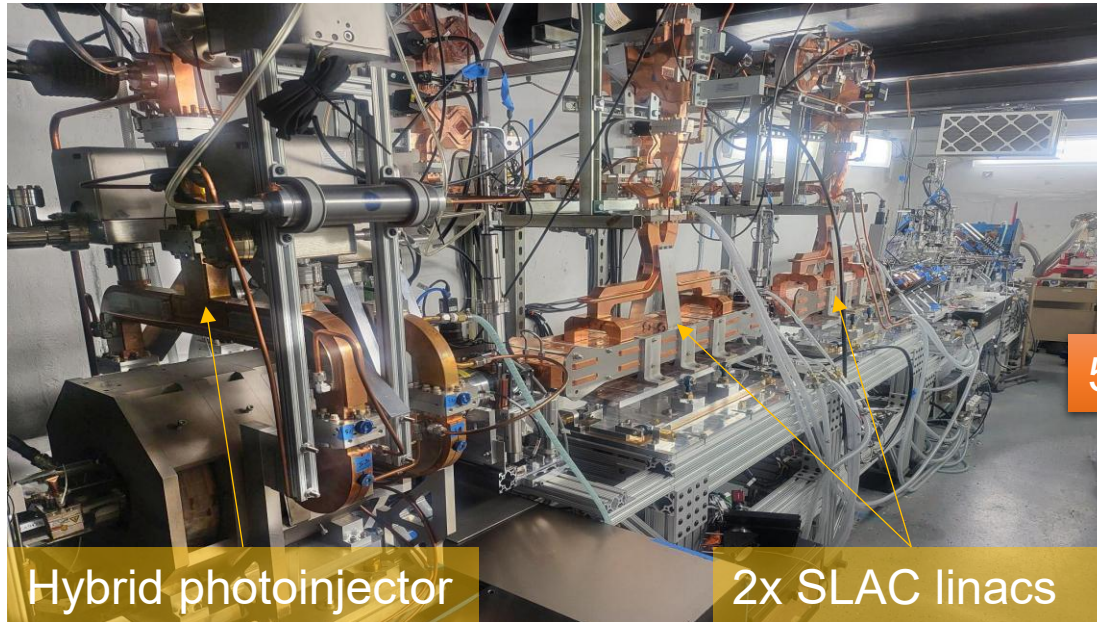
- Monochromatic X-ray sources could enable high-resolution imaging and precise material discrimination
 - For accurate detection of explosives, narcotics, and shielded special nuclear materials.
 - High spectral brightness and directionality allow for deployment of compact ICS hard X-ray sources for advanced detection and metrology applications
 - At higher (MeV) photon energies, ICS sources uniquely enable compact and high brightness tunable sources for nuclear photonics research and applications
- Conventional X-ray security systems utilize Bremsstrahlung with continuous spectrum
- Conventional quasi-monochromatic light sources are huge and not applicable for **mobile** deployment
- Inverse Compton Scattering (ICS) sources are promising solution for compact and flexible quasi-monochromatic X-ray sources



- The Gamma Ray Interrogation Technique (GRIT) program focused on the development high flux hard X-ray compact ICS sources
- The system's main components:
 - Magma 25 laser system (collaboration with Amplitude)
 - High gradient, 100 MeV, 5712 MHz linac (collaboration with SLAC)
 - Hybrid C-band photoinjector (collaboration with UCLA)



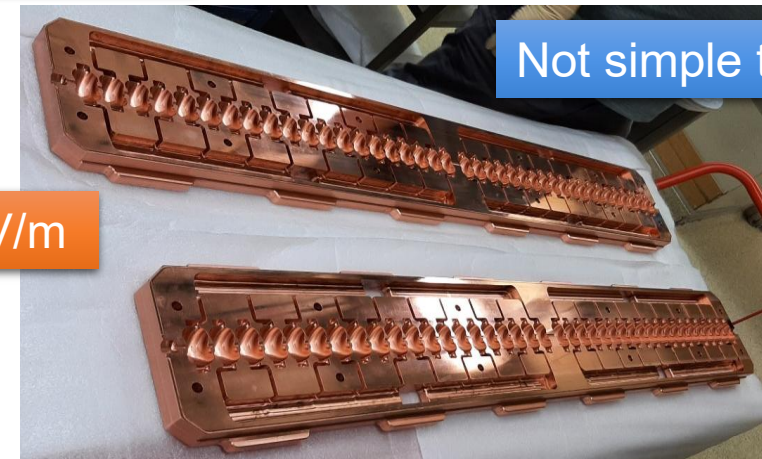
5.7 GHz



Hybrid photoinjector

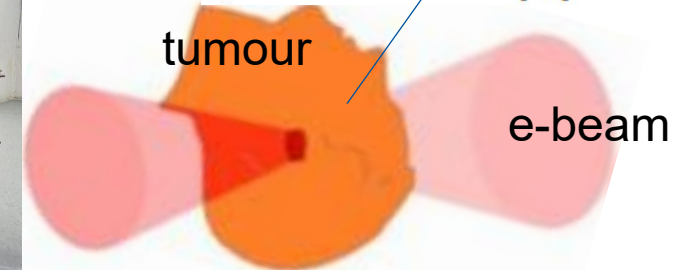
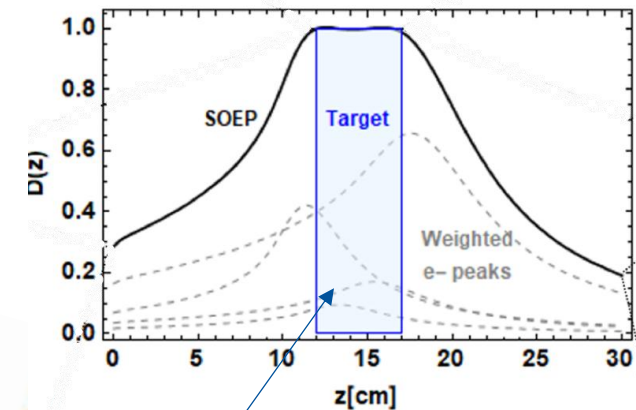
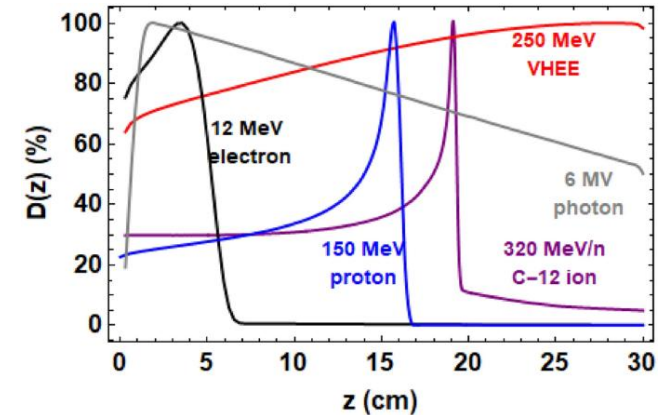
2x SLAC linacs

50 MV/m

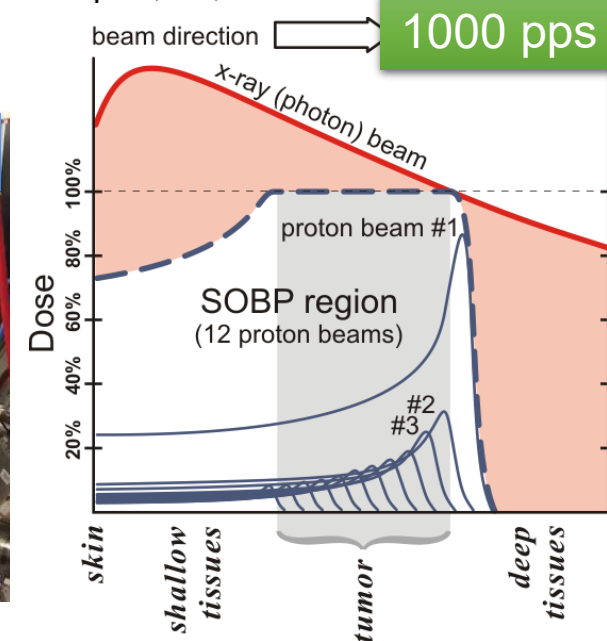
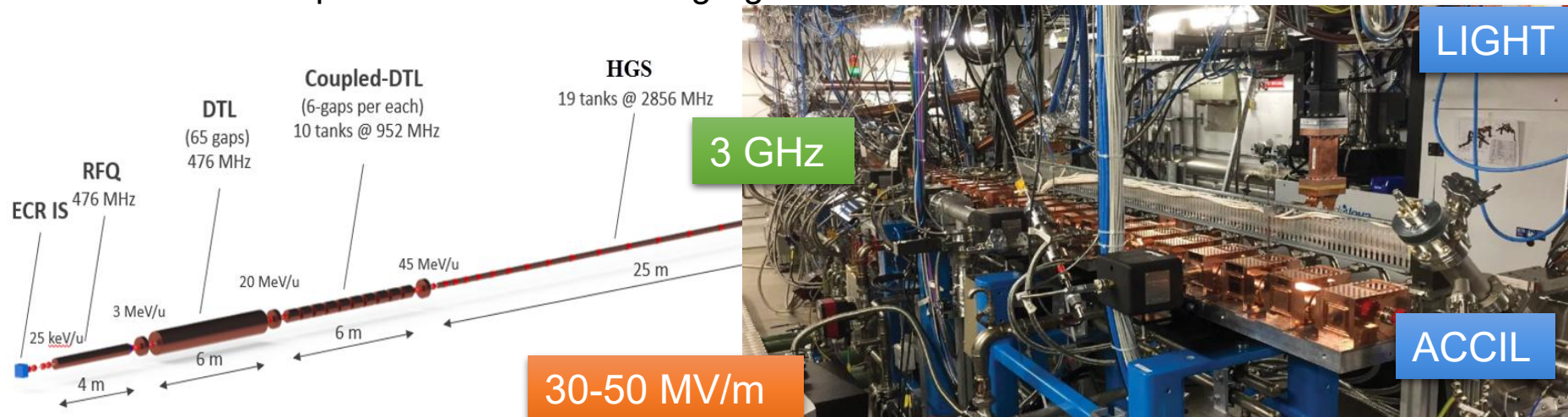
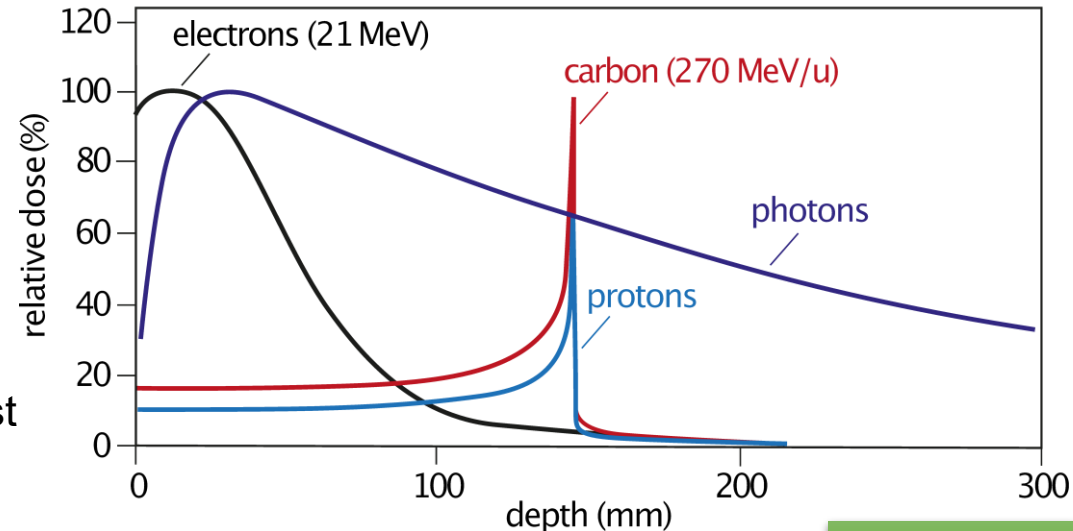


Not simple to fabricate

- Compact high-energy electron linacs can also be used for VHEE radiotherapy:
 - Electrons are easier to accelerate than hadron
 - Easier to produce high doses than X-rays
 - Most successful in demonstrating the FLASH effect
- To achieve tumor depths of 30 cm requires electron energies of **200-250 MeV**
 - 3D scanning can be achieved by the energy variation and focusing
- Conventional 200 MeV electron linacs are neither compact nor cheap
- Similar linac (as for ICS) can be used for VHEE
 - With the modifications trading off beam size for intensity



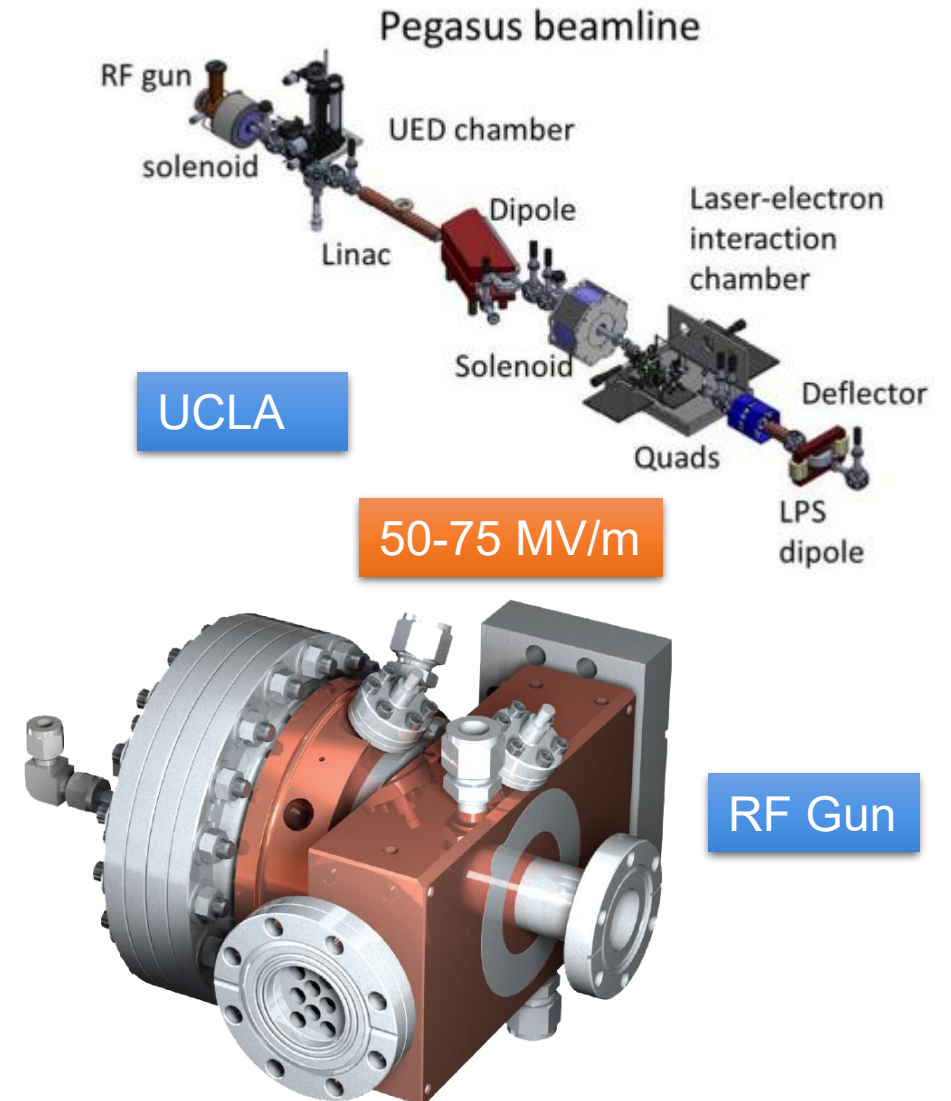
- Hadron therapy provide promising advances
 - Bragg peak enables better localization of dose
 - able to treat “radioresistant” tumors
 - biological efficiency of the dose is higher
 - can treat the tumor as 3D-printed with energy variation (SOBP)
- US insurance companies are not very excited with their size and cost
- Competitive accelerators must be compact and cost-efficient
 - 250 MeV for protons, 450 MeV/u (900-1080 MV) for carbon ions
- New developments are based on high-gradient accelerators



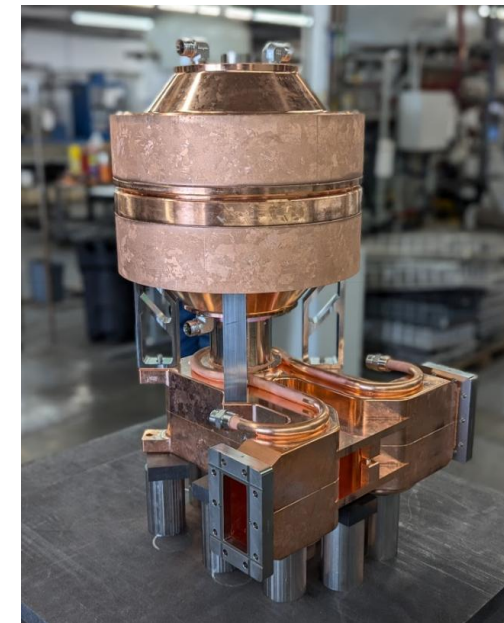
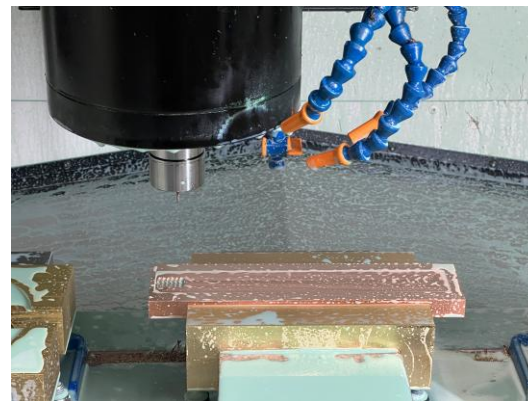
- 40-100 MeV electron beams find their use for neutron and isotope production
 - Novel medical radioisotope production (Ac-225 et al.) at 40+ MeV
 - There are active projects to use 100 MeV electron linacs as a driver for compact ADS reactors for data centers
 - Rensselaer Polytechnic Institute builds a high-gradient L-band linac for neutron and isotope research
 - RadiaBeam is fabricating L-band 40 MV/m MHz accelerating structures for RPI
- These linacs need high-gradient operation because neutron and isotope production must be achieved at tens of MeV within a *small, heavily constrained shielded vault*, while maintaining beam power, energy tunability, and hands-on maintenance limits.
 - Beam loading is also a key parameter!



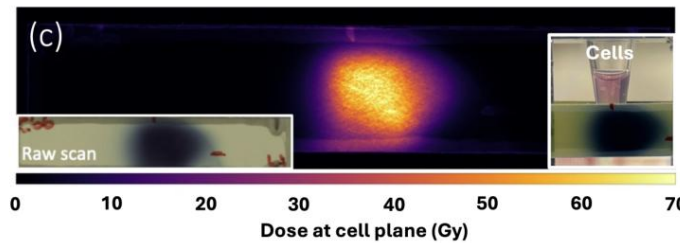
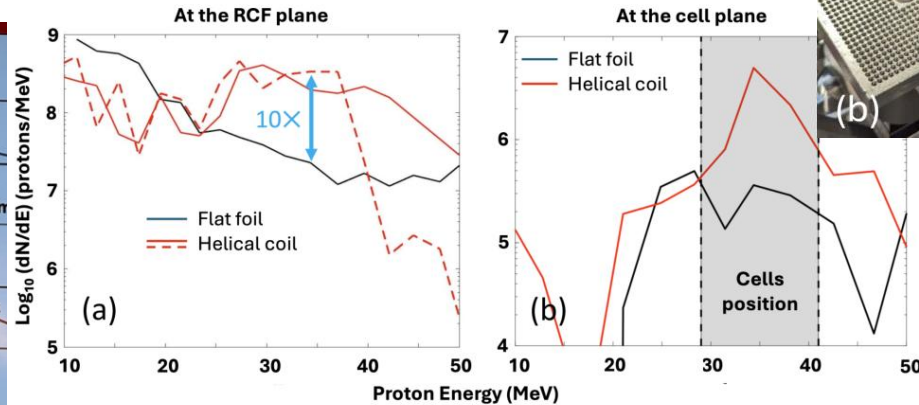
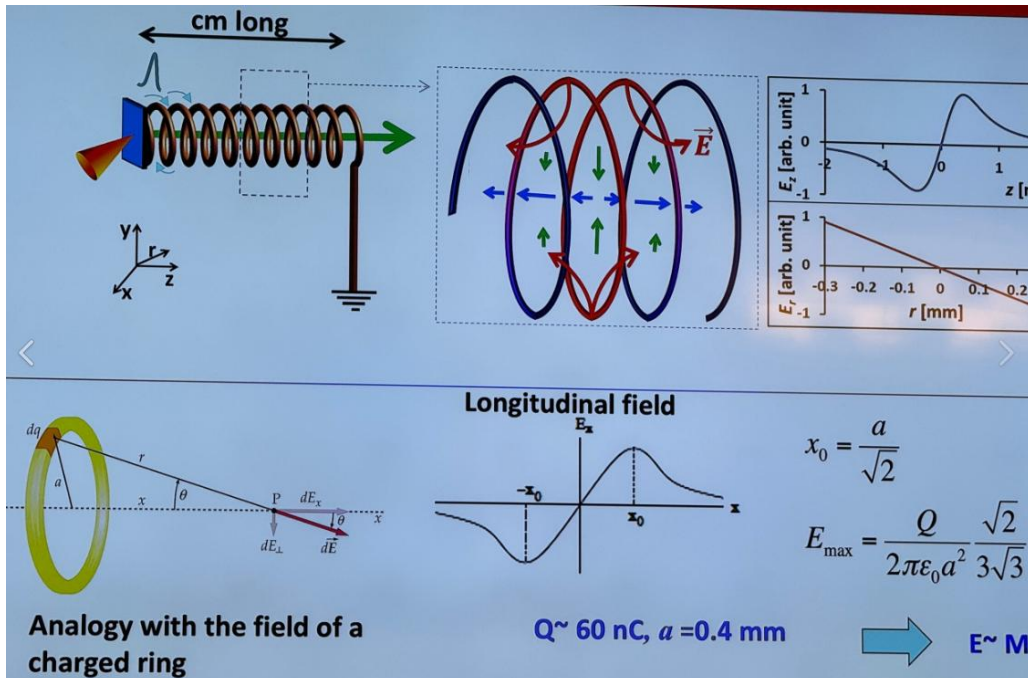
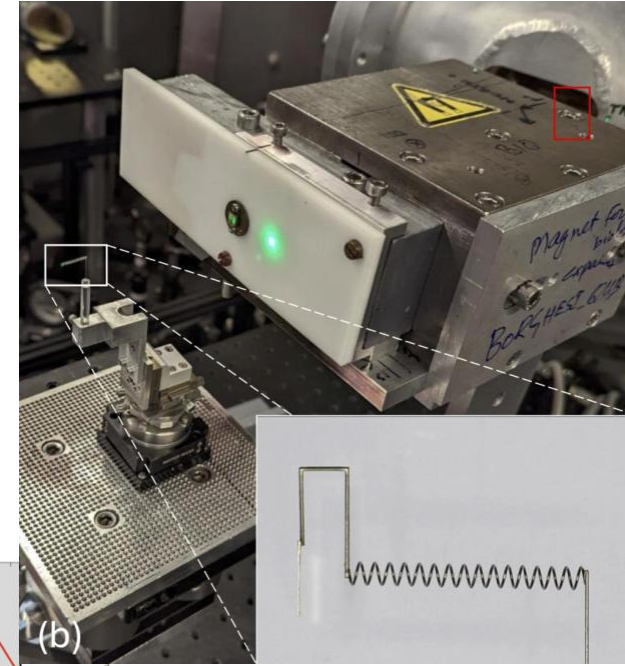
- High-gradient structures can be used for time-resolved radiation chemistry and radiobiology or in ultrafast electron microscopes
- The need for high gradient is **not driven by energy**, but by **time structure and beam physics constraints**
 - Very large dose delivered in ultrashort time (ns to fs)
 - Peak dose rates orders of magnitude above clinical or industrial norms
- Ultra-high peak dose rate + high beam current + nanosecond timing + space-charge suppression cannot be achieved simultaneously at conventional systems



- Beam efficiency
 - High gradients = High RF losses
 - Develop structures with lower RF losses
- RF power sources
 - High peak power RF sources are large, expensive and provide low average power
 - Develop new RF sources, or efficient pulse compressors
- Fabrication challenges
 - High gradient structures are not easy/cheap to fabricate
 - Complex topology, strict tolerances, surface roughness etc.
 - Design simpler structures or fabrication protocols



- fs-Laser-driven spiral wire with spaced loops
 - Proposed by S. Kar from
 - 1 fs * 10 Hz * 1 kA = 10 nA
 - 50 MeV demonstrated?
 - 60 Gy doses are enough for radiotherapy



Queen's University
Belfast

- Most of the commercial industrial linacs are used for conventional applications and operate at low gradients ($\sim 10\text{-}20$ MV/m)
 - Higher gradients = more RF losses
 - Beam power and system costs are more important than the dimensions
 - For ~ 10 MeV or lower energies accelerator length reduction doesn't lead to the system size reduction
- High-gradient accelerators start to play a critical role in the high-energy emerging applications when beam energy and linac size are critical
 - Hadron therapy, VHEE, compact light sources, isotope production, UEM etc.
- In order to be attractive for the industrial applications the following R&D is required
 - Development of cheap high peak and average power sources
 - Fabrication simplification
 - Novel low-loss materials
 - Novel accelerator types?

