Electron beam for research and industrial applications

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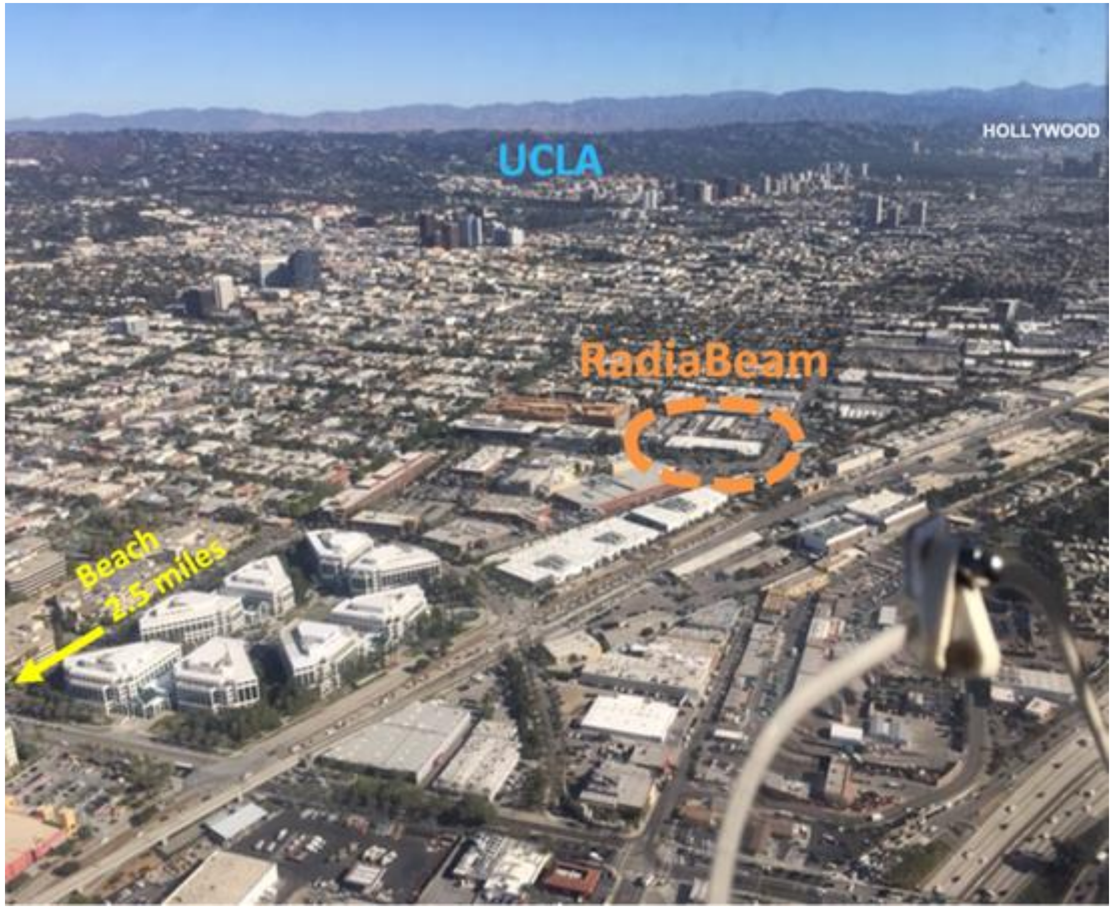
RadiaBeam overview

- Founded in 2004
- 50 employees
  - ~20 engineers, 12 scientists, 10 machinists, 5 technicians
- 35,000 ft^2 headquarters in Santa Monica, CA

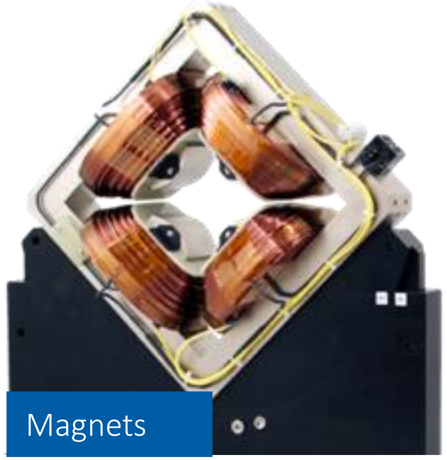
- Accelerator R&D, design, engineering, manufacturing and testing under one roof in a dynamic, small-business setting
- Products: accelerator components (RF structures, magnets, diagnostics), medical/industrial accelerator systems



Products

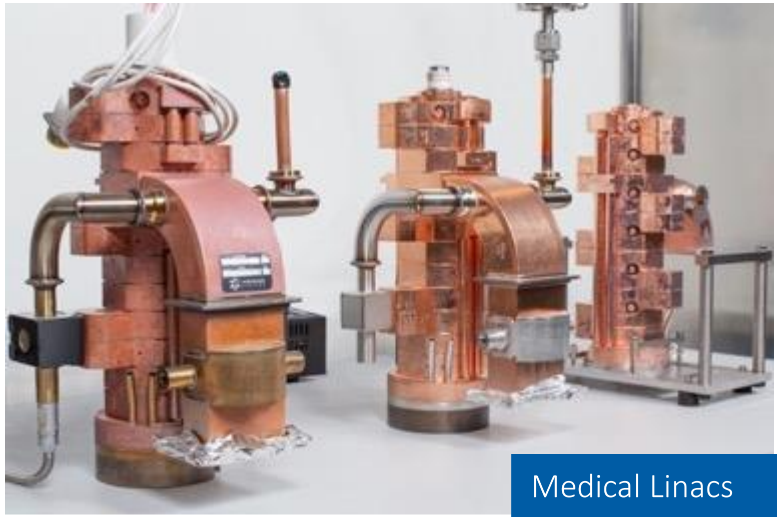
RadiaBeam

- Thousands of products delivered since 2004 with new products every year.


Magnets


Diagnostics


RF Structures


Medical Linacs


Beamlines


Linac Systems

Content

1) Low energy electron beam

2) Irradiation

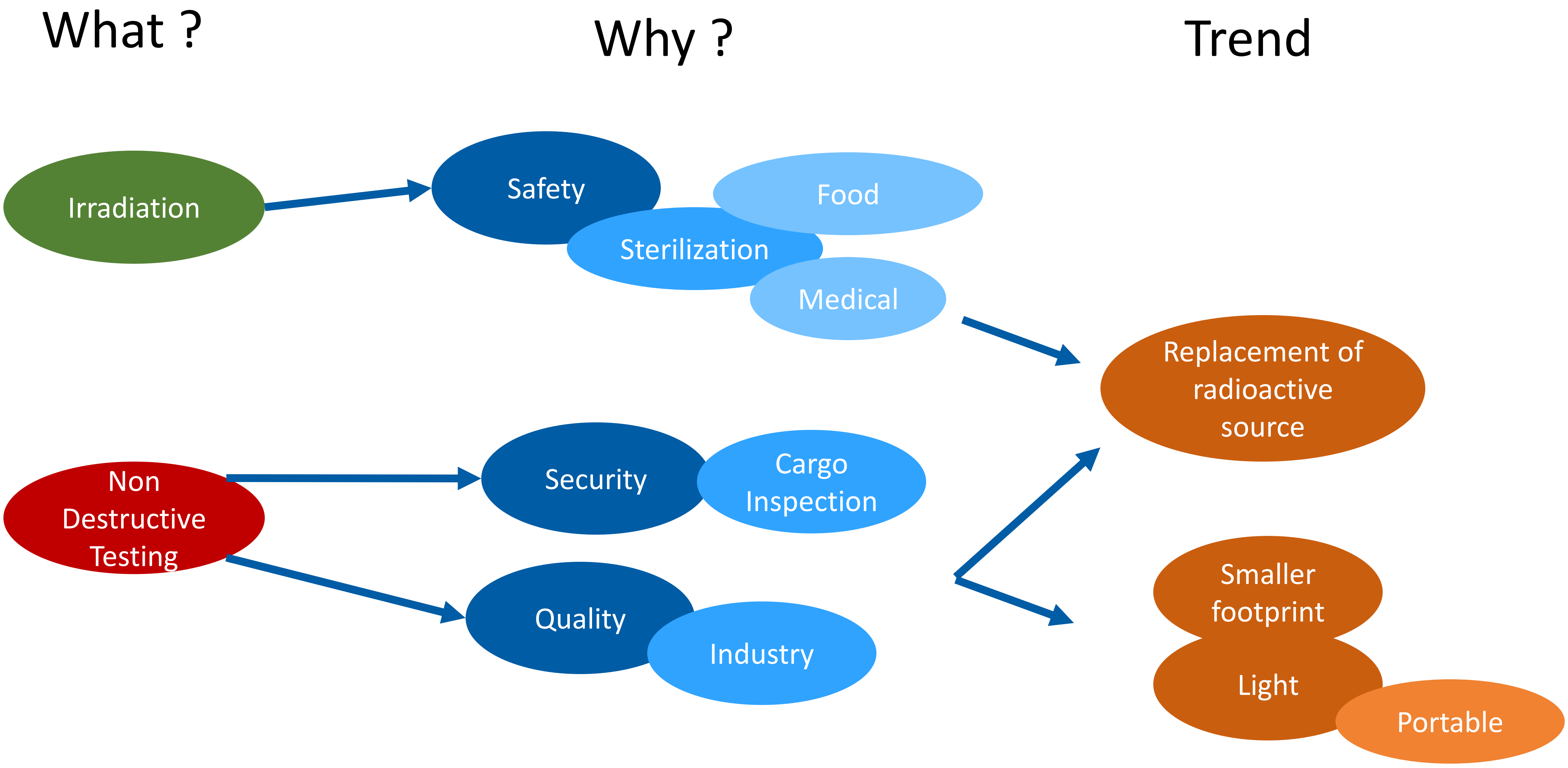
- Safe, High-Throughput, Self-Contained **Irradiator**

3) Non-destructive Testing

- Ultra **Portable X-Ray Source** for Field Radiography

Low energy electron beam

Industrial e-beam trends



Trends

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Replacement of radioactive source

- Why ?
  - Increasing security concern.
  - Restricted supply of Co-60, Cs-137.
  - Challenges in transportation and logistics, radioisotopes lifecycle management.
  - Increasing cost of using radioisotopes.

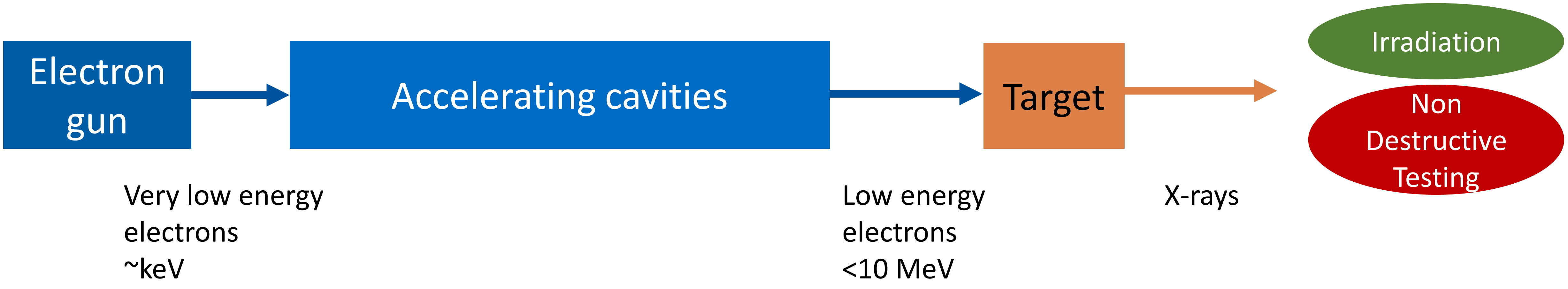
Isotope	Half life	Energy
Yb-169	32 days	145 keV
Se-75	120 days	217 keV
Ir-192	74 days	380 keV
Cs-137	30 y	661 keV
Co-60	5.3 years	1.25 MeV

Small footprint

Light

- Why ?
  - For field use

Linear accelerator



Beam parameters		Irradiation	NDT
Energy	Penetration/material		
Dose rate	Throughput/ test time	As high as possible	As high as possible

Irradiation

- Safe, High-Throughput, Self-Contained **Irradiator**

Motivation

- Replacement of small irradiators (Cs-137, Co-60 in self-contained irradiators)

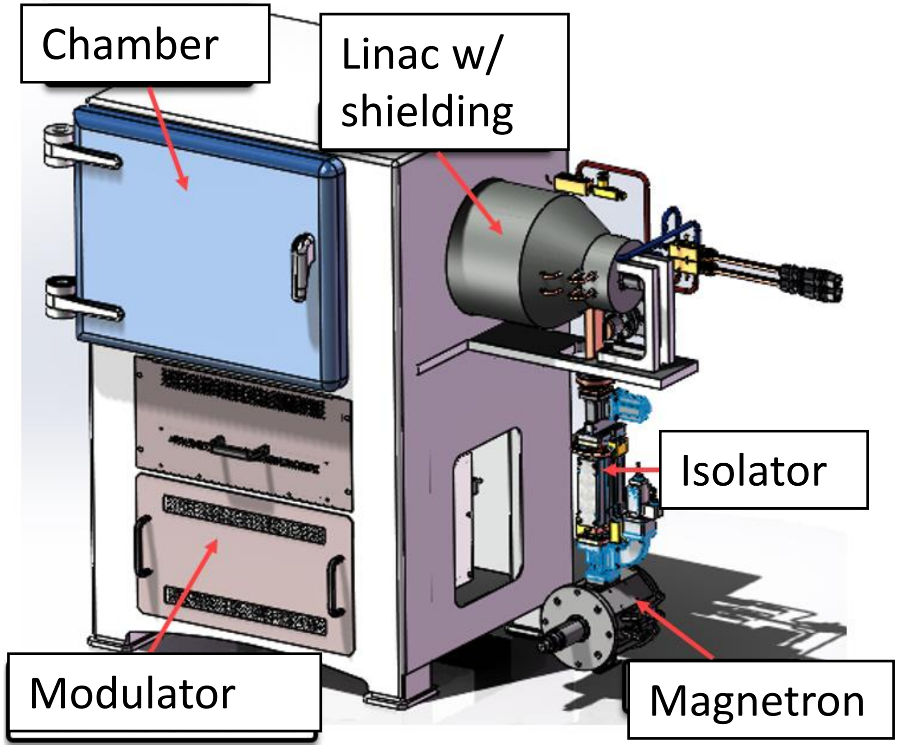
- Sterile insect technique
  - Reduce pest population by releasing sterile insects into the environment
  - Used to control agricultural pests, and disease-bearing pests (E.g. Tse-tse flies in Africa, Med flies in Americas, Zika bearing mosquitos…)

- Other applications (blood irradiation, radiobiological research…)

A. Bakri et al. Sterilizing Insects with Ionizing Radiation, pp. 233-268. In: V.A. Dyck, J. Hendrichs and A.S. Robinson (eds.), Sterile insect technique. Principles and practice in area-wide integrated pest management. Springer, Dordrecht, Netherlands. (2005)

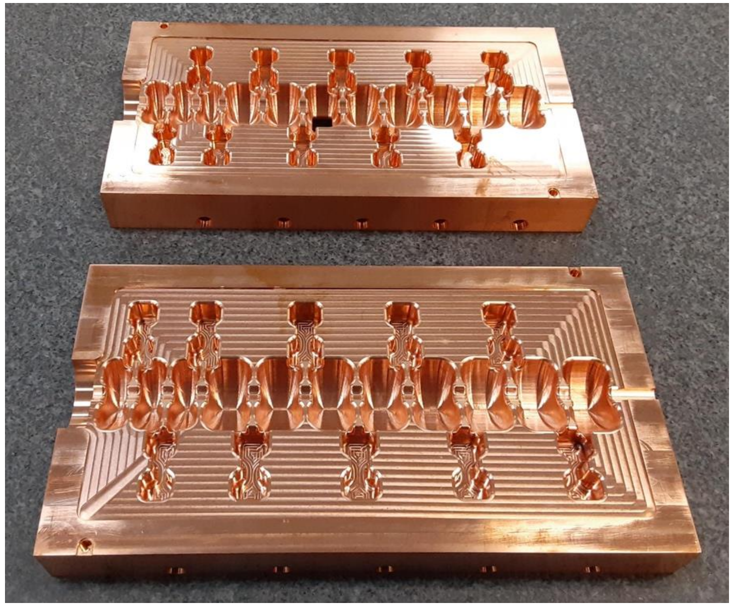
Linac for Sterile Insect Technique

- Energy:
  - Higher energy → higher dose : D ~ E^3
  - RF losses scale with the energy as P ~ E^2
  - Energy of ~ 3 MeV to match Cs-137 (662 keV) or Co-60 (1.25 MeV).
- RF power source: magnetron.
  - Available and reliable.
- Specifications
  - 15 Gy/min dose rate,
  - Throughput: 126 kg/hour
  - Operate in ambient temperature
  - Low dose uniformity ratio
  - Reasonable size/weight
  - Reliability = high level of up time
  - Easy maintenance/service
  - High level of customer support from factory, availability of spares



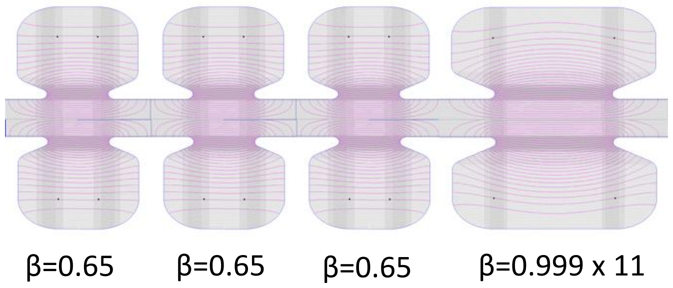
Split Linac Technology

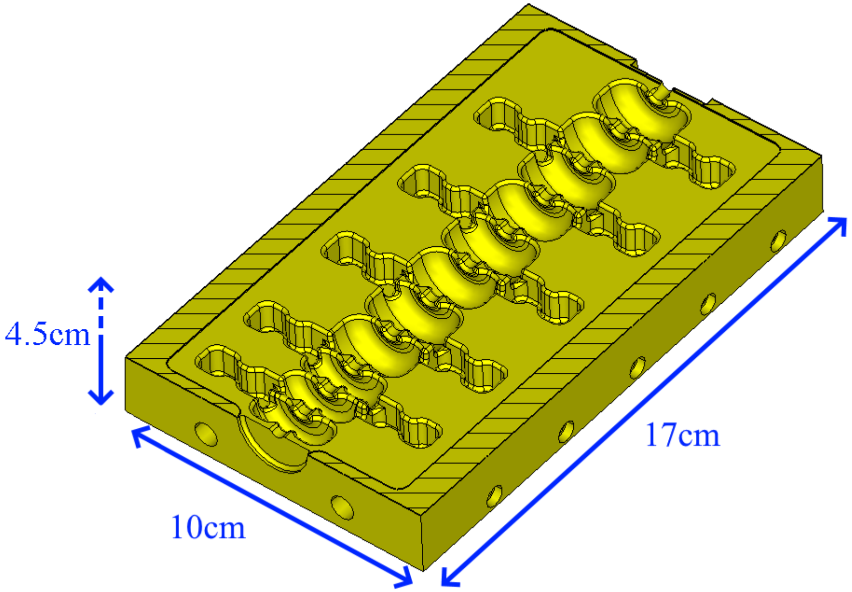
- Linacs are conventionally made from many copper "cells" that are stacked and brazed together
  - Requires precision machining of dozens of parts
  - Brazing introduces additional errors, requires tuning
- Recently, the "split" linac concept has come into vogue
  - Only two parts need to be machined
  - Allows more bonding techniques (e.g. welding, knife-edges)
  - Precision machining can then eliminate need for tuning

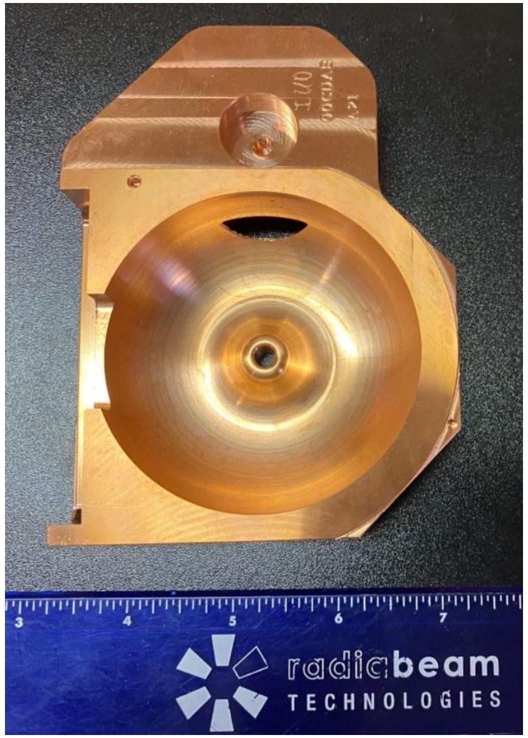


Accelerating structure design

- Side coupled (SCL) standing wave structure
- The integrated bunching section is 3 cells with β=0.65
- 11 accelerating cells structure can accelerate up to 140 mA to 3 MeV with the available power from 1.8 MW magnetron
- Cell geometry was optimized for split structure fabrication approach
- First split SCL made!

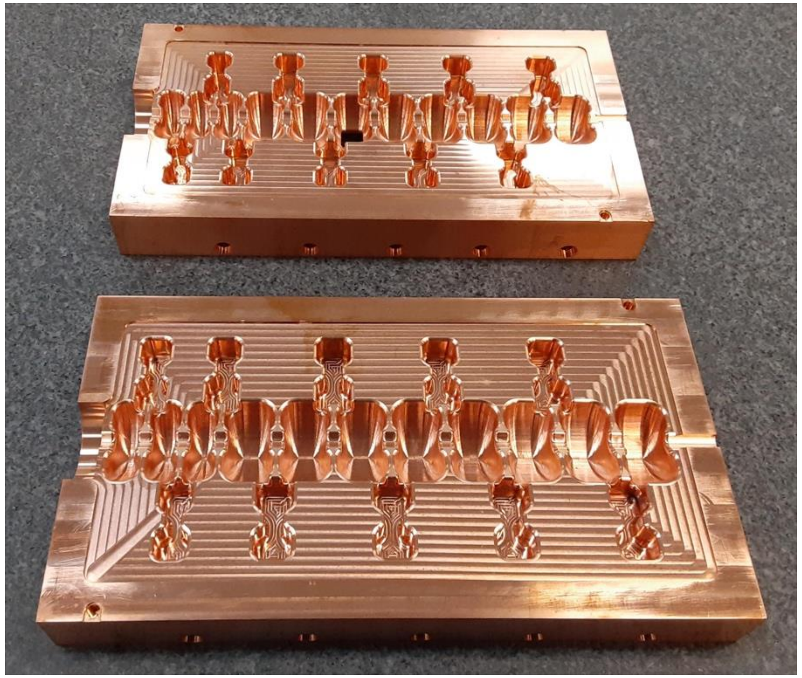


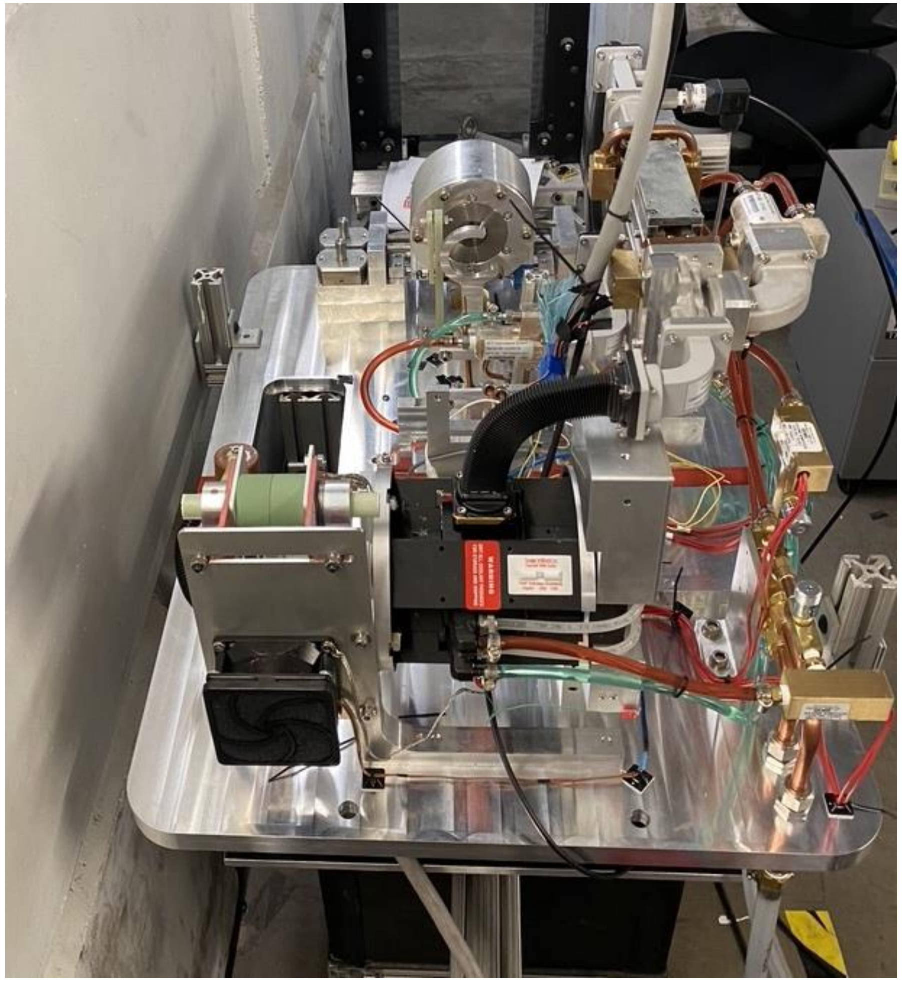




Accelerating structure manufacturing

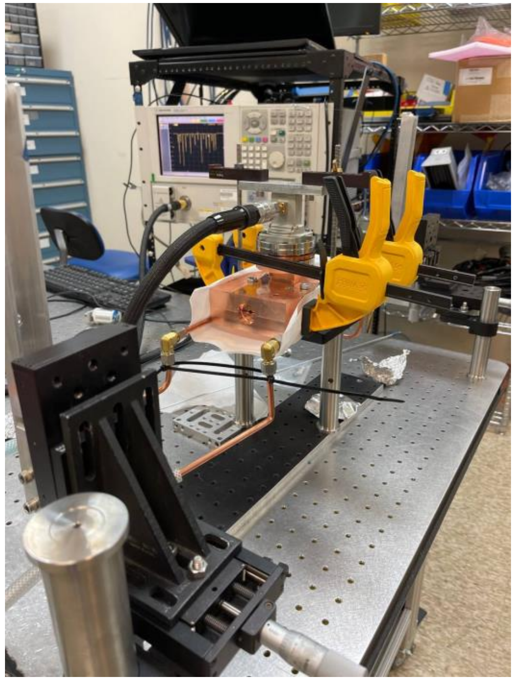
- RF structure for linac machined and cold tested
- Brazing completed
- Test stand set up
- Preparing for final structure operations and hot-testing

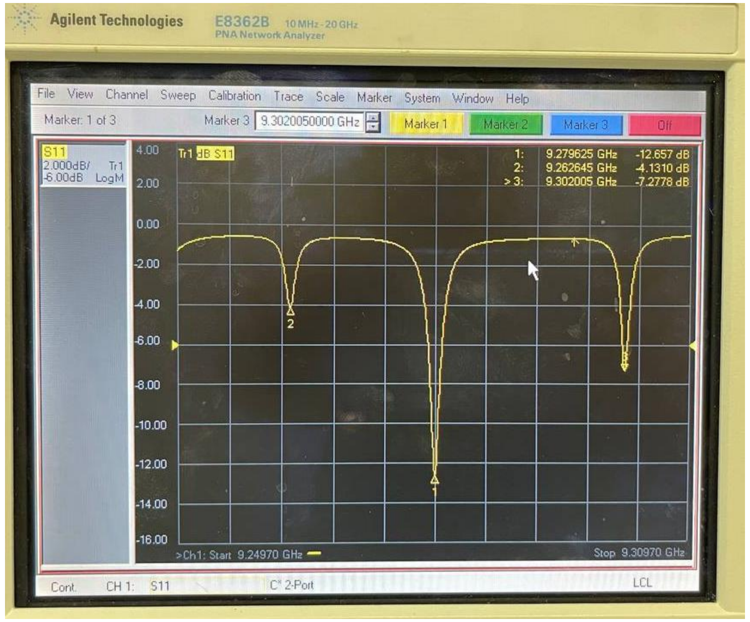


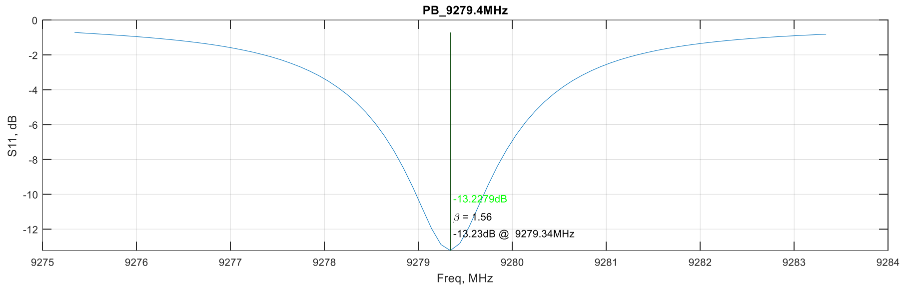


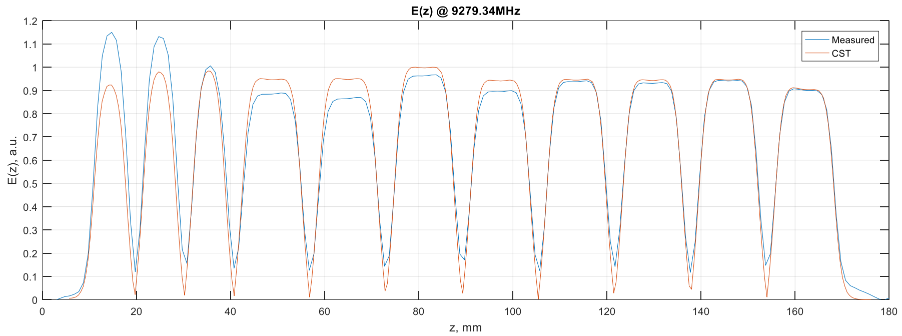
Accelerating structure cold testing

- RF measurements performed before and after brazing
  - Very good agreement of field profiles
  - Frequency shift of -20MHz → can be compensated with the magnetron
  - Can be used with no additional tuning → reduces the costs significantly



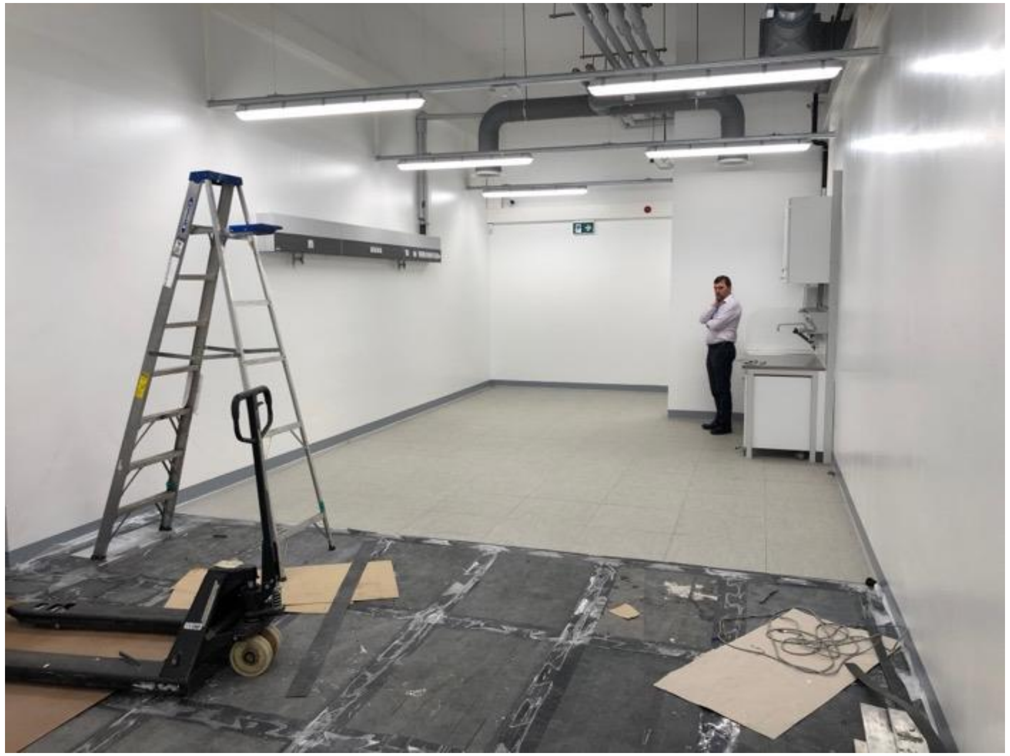






Next steps

- X-ray conversion and irradiation systems are still being designed/built
- Goal is to deliver system to IAEA in 1-2 years timeframe
- Scaling to 4 MeV energy is under consideration



S.V. Kutsaev et al., “Electron Accelerator for Replacement of Radioactive Sources in Insect Sterilization Facilities”, *Physics of Atomic Nuclei, 2021, Vol. 84, No. 10, 2021*

Non-destructive testing

- **Portable X-Ray Source** for Field Radiography

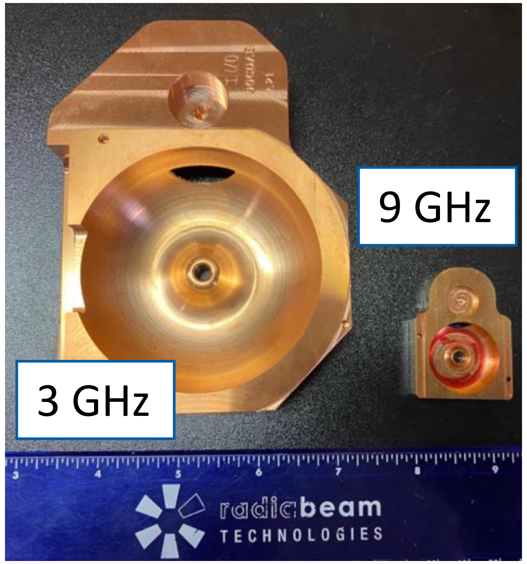
Miniaturization

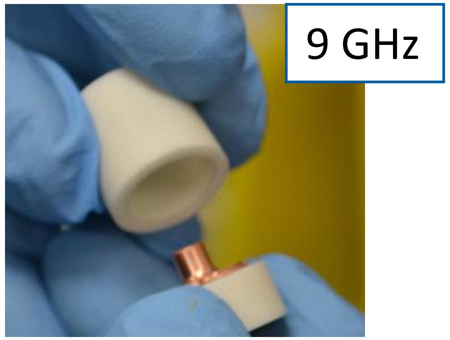
- To replace radioactive sources, used on the field → need to reduce accelerator size

- *Increase* the operating RF *frequency*
  - Transverse dimensions scale as f^{-1}, longitudinal as $f^{-1/2}$
  - The dimensions of peripheral components (and shielding) scale too
  - Limited availability and parameters or high-power RF sources
  - Practically, limited to ~16 GHz (Ku-band) for industrial linacs

- Extreme dimensions can be achieved in *THz* or *laser* accelerators
  - No compact RF sources for these frequencies
  - Beam quality is poor
  - Decades away from industrial applications

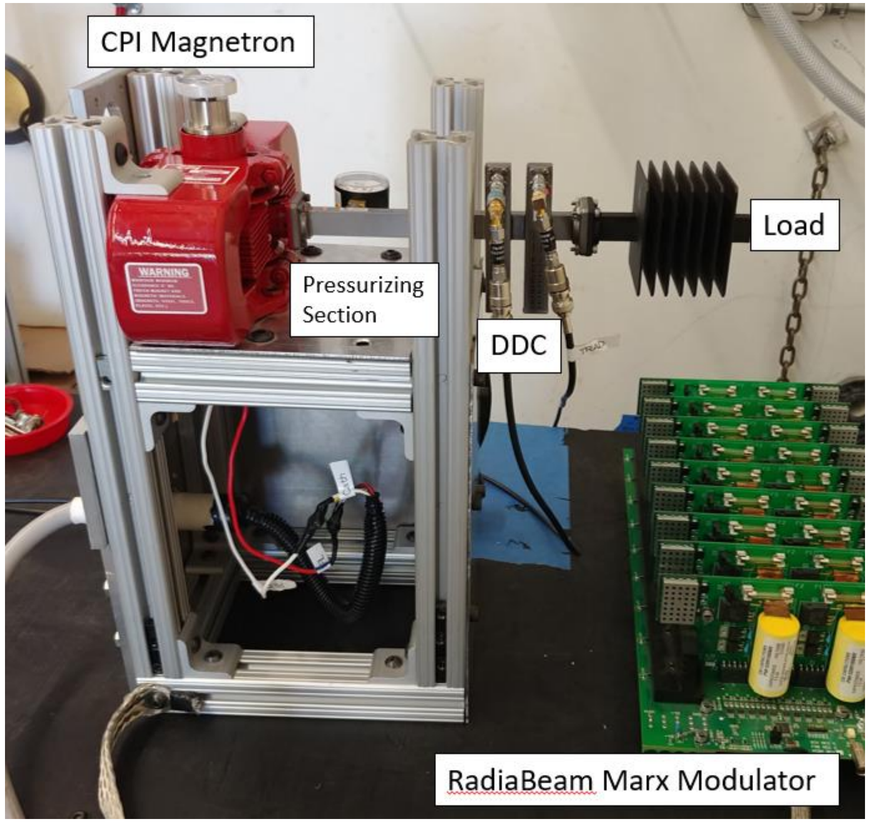
- Dimensions can also be miniaturized by using *dielectric* accelerators
  - Discharge is a problem
  - Requires new dielectric materials
  - Still immature technology





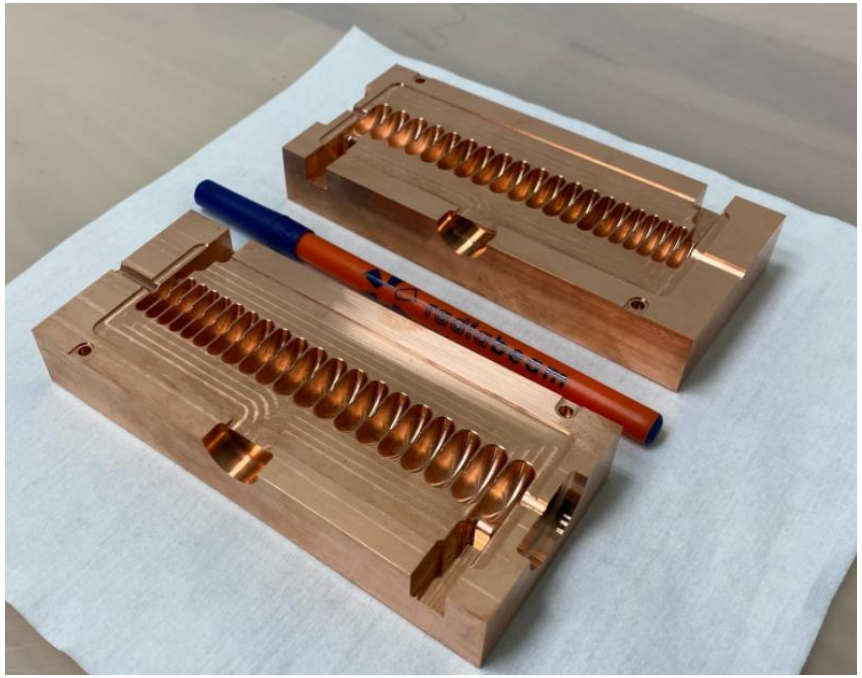
Hand-portable 1 MeV linac

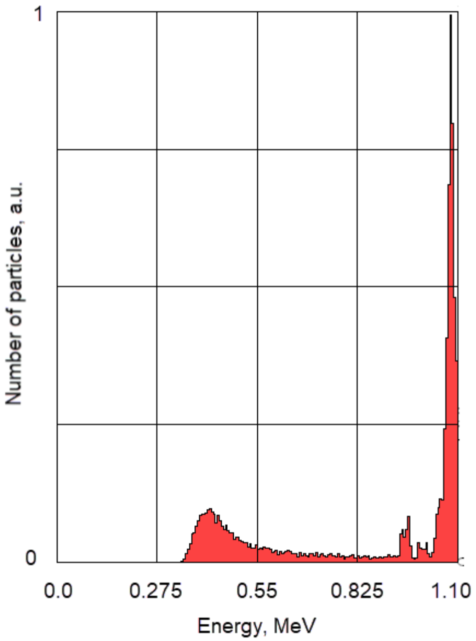
- First-of-its-kind hand-portable Ku-band linac
  - 1 MeV electron energy to replace Ir-192
  - ~ 23 kg, > 1 cGy/min @ 1 m
  - Higher frequencies enabled by “split linac” fabrication technology
  - Compact, lightweight Marx modulator
  - No need for water cooling
  - Can be operated from battery or small generator



Accelerating Structure Design

- 20-cells disk-loaded waveguide section
  - Traveling wave → eliminate circulator and increase bandwidth
    - Less weight, costs + more stable to frequency deviations (environment)
  - Phase velocities range from 0.6 to 0.95: blocks of 5 different cells
    - Optimized for high beam transmission and clean spectrum
    - Less unique cells makes structure cheaper



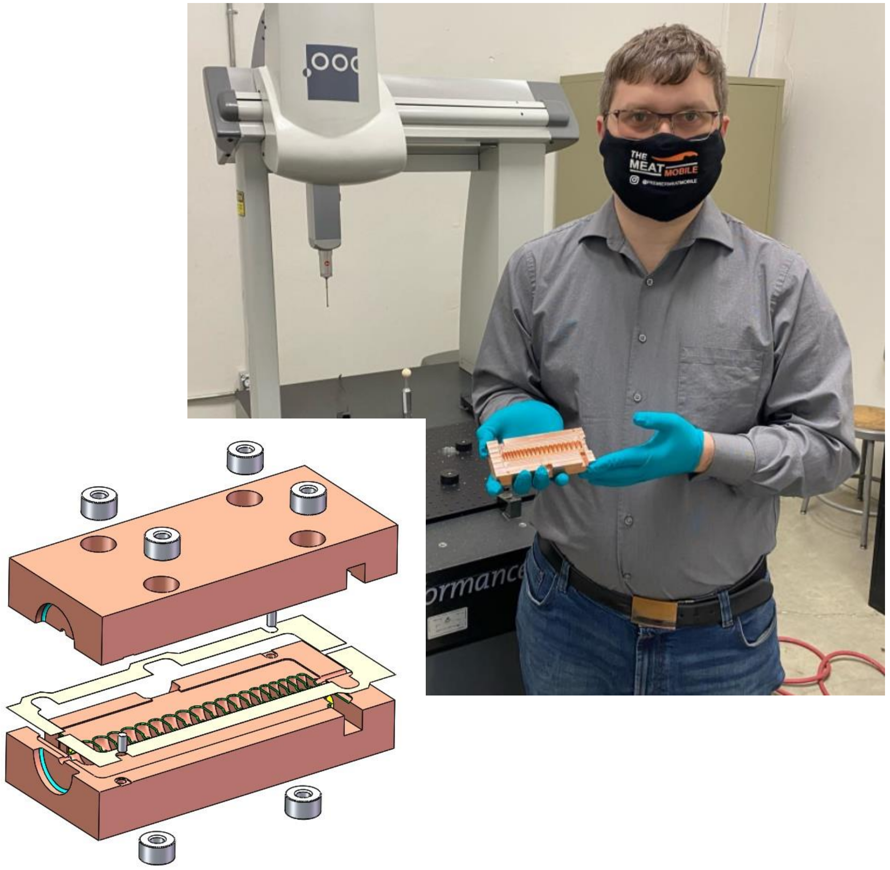


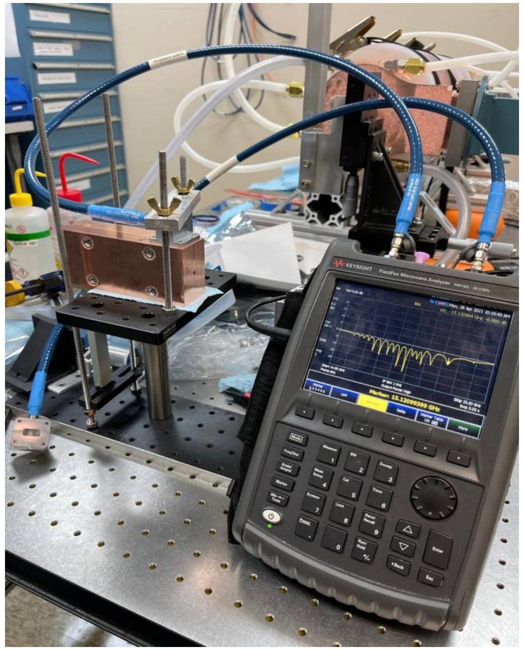
Operating frequency	15.14 GHz
Operating mode	2π/3
Aperture radius	1.188 mm
Structure length	11 cm
Number of cells	20
Maximum beam energy	1.01 MeV
Average beam energy	0.88 MeV
Unused (load) RF power	11.5 %
Filling time	50 ns
Accelerated beam current	113.6 mA
Beam transmission	37.9 %
Energy spread	3.3 %

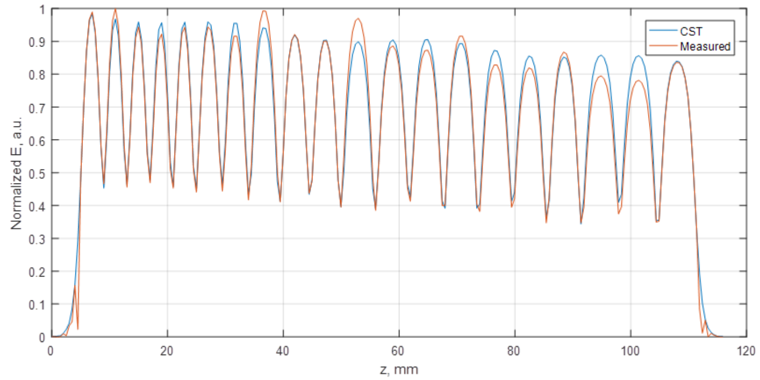
S.V. Kutsaev et al., "Ir-192 radioisotope replacement with a hand-portable 1 MeV Ku-band electron linear accelerator", Appl. Radiat. Isot. 179, 110029, 2022.

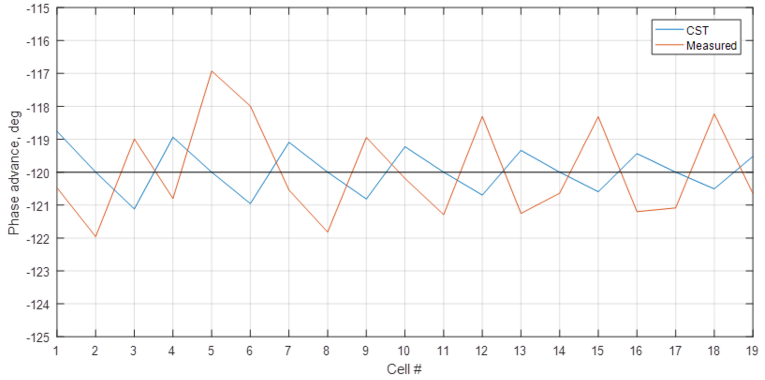
Accelerating Structure Tests

- Complete RF structure was fabricated
  - Machined and brazed
  - RF measurements demonstrate that no additional tuning is required



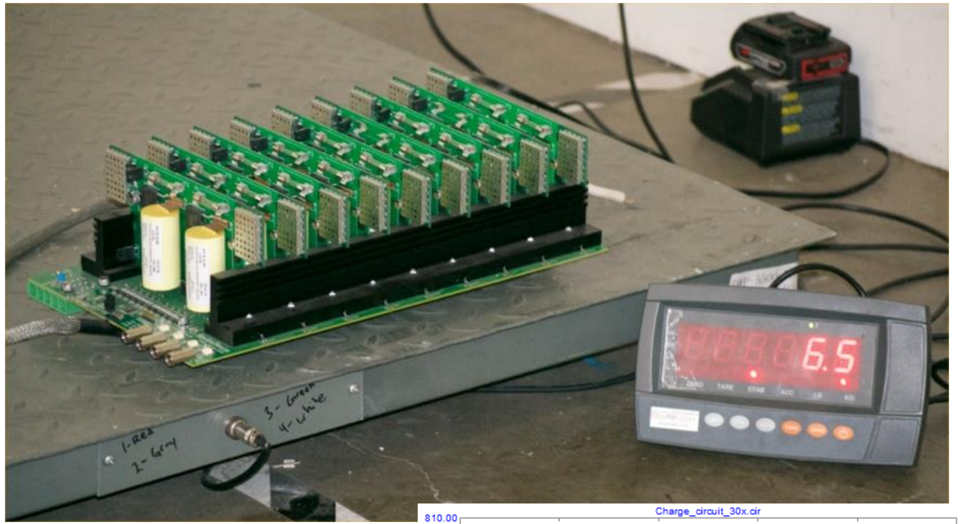


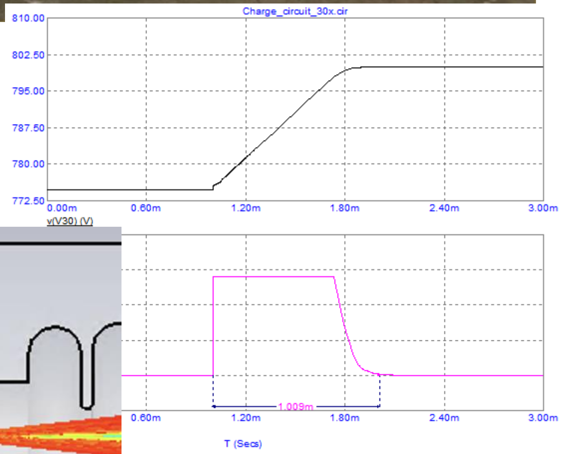


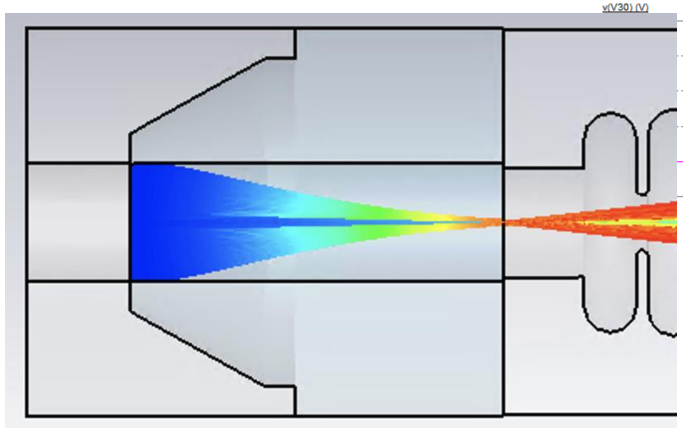


Next steps

- Build a new Marx modulator
  - Compact, carried by a single person
  - Based on solid-state technologies
  - Enough power to drive 250 kW magnetron
  - Fast raising time
- New electron gun
  - Need to design a new compact gun for Ku-band structure
  - Optics must provide good beam transmission
  - Should be driven from the same modulator
- Currently building the first demonstration prototype

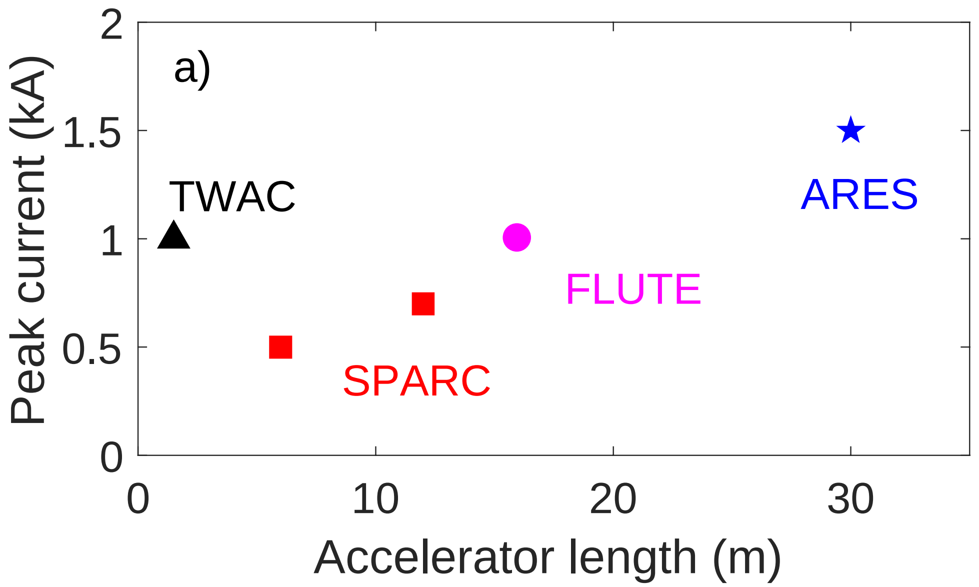






TWAC: Terahertz wave accelerating cavity for ultrafast science

- EIC Pathfinder
- CNRS (IJCLab, PhLAM), DESY, Pécs University, Iteox
- Towards miniaturization: dielectric acceleration.
  - Cm scale accelerating structure
  - High gradient: 100 MeV/m
- Towards ultrafast science
  - Femto second bunch

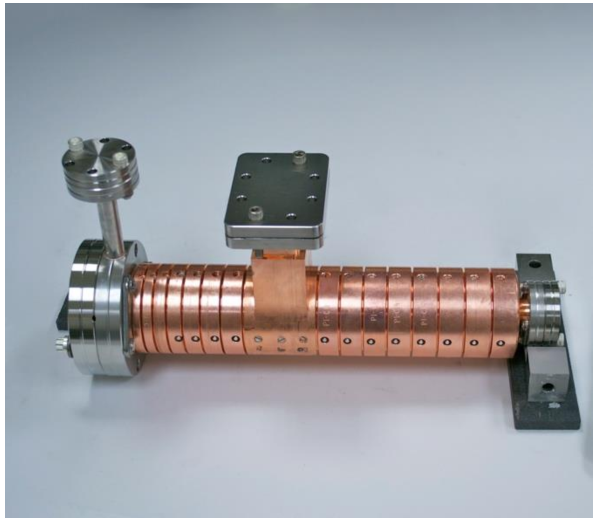


Funded by
the European Union

Conclusion

RadiaBeam

- Currently developing compact X-ray sources as alternatives to radioisotopes such as Ir-192, Cs-137 and Co-60 for irradiation and non-destructive testing.
- Low power systems: cost dominated by accelerating structure manufacturing
  - Our current research is focused on reducing this cost
- Unlikely that accelerator-based alternatives will match price of radioisotopes, at least in near term
  - Some incentives should be provided for users to switch
- Thank you!

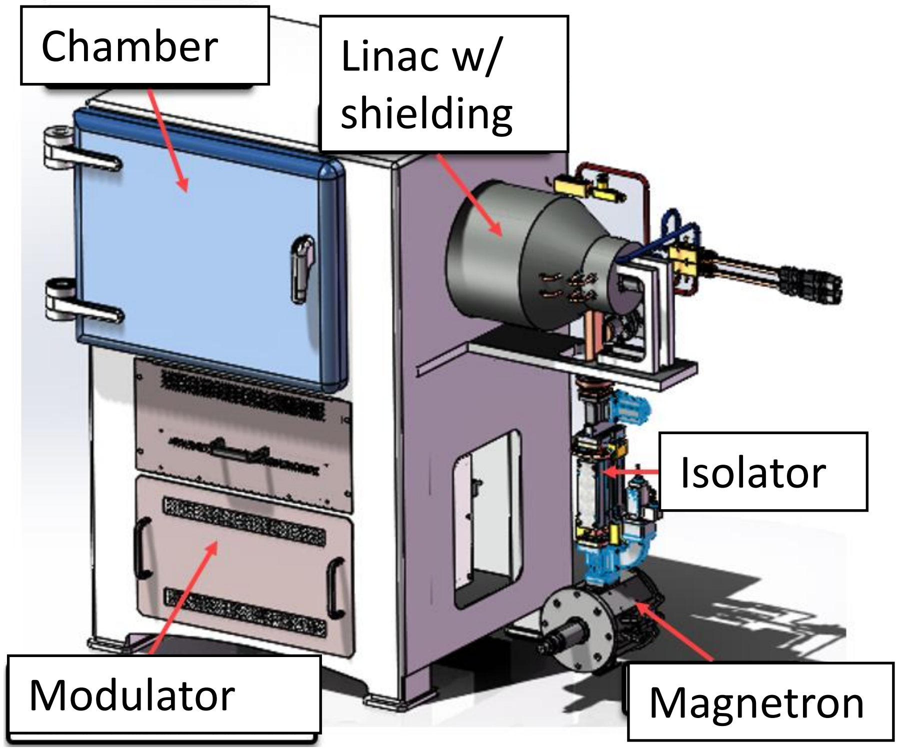


Back-up slides

Full System Design

RadiaBeam

- Direct replacement for Cs-137 irradiators, but with a 3 MeV linac
- Approximately the same size and weight
- 15 Gy/min, 1.3 DUR in 36 cm diameter X 30 cm tall (30 L) canister
- Smaller canisters can of course achieve better DUR!
- For 100 Gy irradiation, throughput for SIT (0.46 g/cm^3) is 126 kg/hour



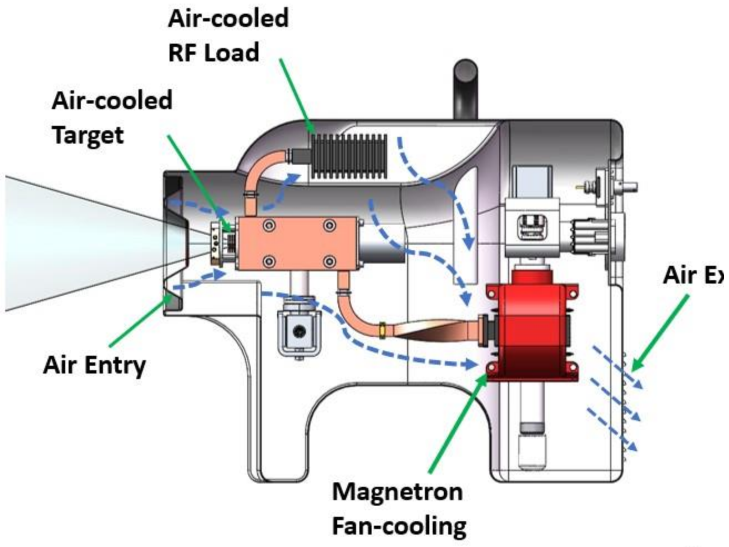
Parameter	Value
Electron Energy	3 MeV
Average Current	100 µA
Dose Rate at canister center	15 Gy/min
Canister Size	30 L (18 cm radius X 30 cm tall)
Dose Uniformity Ratio (30)	1.3
Irradiator System Size	116 cm long x 108 cm tall x 68 cm deep
Irradiator System Weight	3,000 kg
Electrical Requirement	16 kVA (i.e. 400 VAC 20 A 3Ø or 220 VAC 70 A 1Ø)
Room Temperature/Humidity	0˚ – 40˚ C, 0% – 100% humidity
Price Target	**US$ 350,000**

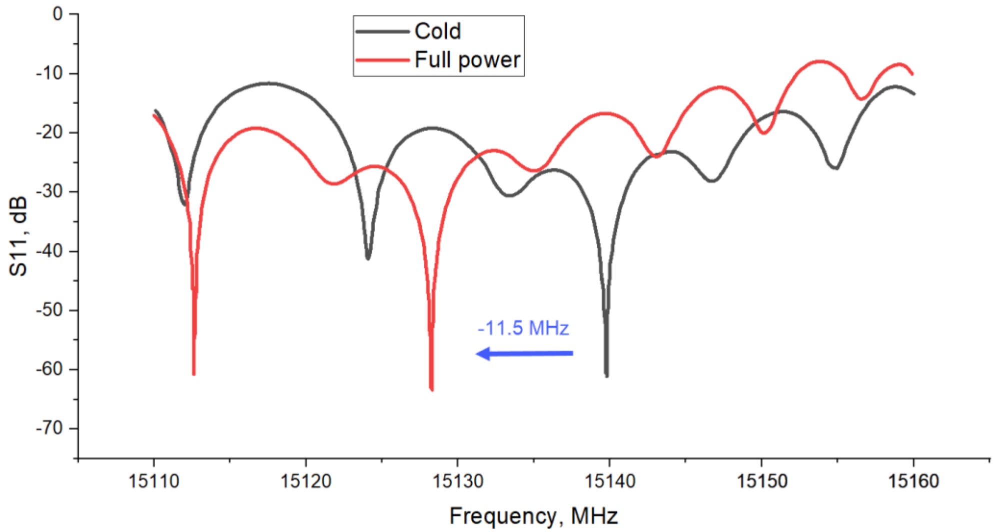
* S. Kutsaev et al., Electron Accelerator for Replacement of Radioactive Sources in Insect Sterilization Facilities, Physics of Atomic Nuclei, 2021, Vol. 84, No. 10 (2021)

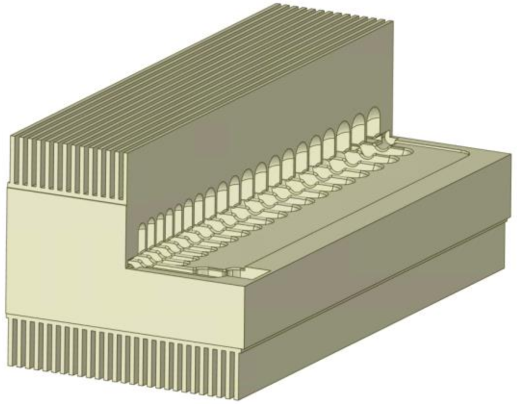
Cooling and frequency stability

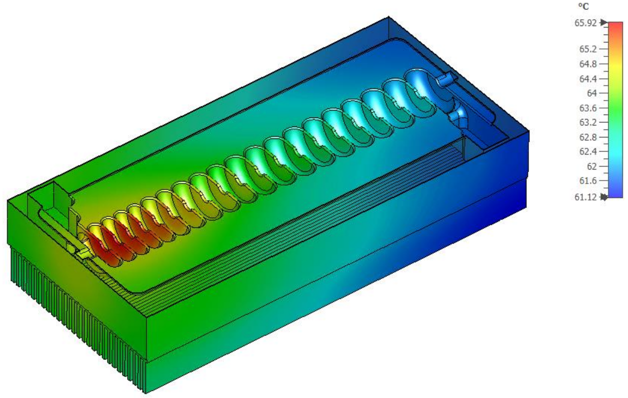
RadiaBeam

- The linac is only cooled by CPU-class fans
  - One for accelerating structure and one for magnetron
  - 2.5 m^3/min air-flow to remove 150 W of power
  - Simulations show the frequency shift of -11.5 MHz with minimal EM field distortions
  - Can be corrected by AFC system (both RF and dose)
  - Allows linac to operate at different environmental conditions





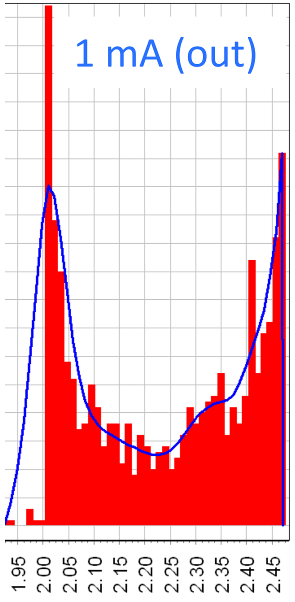


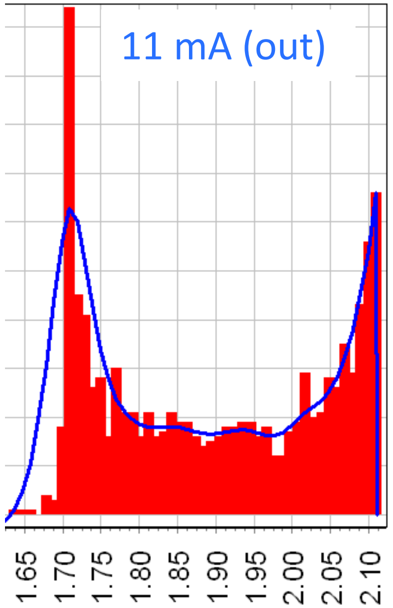


Higher Energies?

RadiaBeam

- We studied the feasibility of a higher energy (up to 2.5 MeV) design
- The energy is limited by RF power availability
- Maximum energy (with 1 mA) can be achieved in 24.5 cm long structure (40 cells)
  - 2 MeV is possible with 11 mA
  - Energy can be adjusted by beam loading



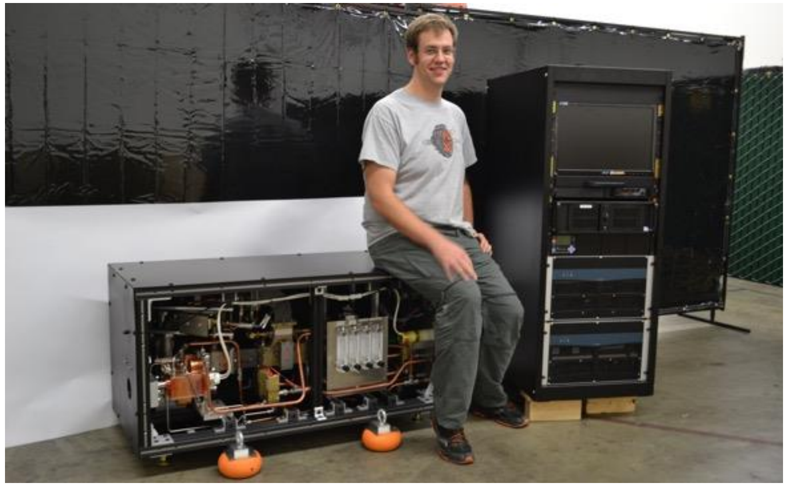


Energy, MeV	1.0	2.0
Replaced radioisotope	Ir-192	Cs-137
Peak beam current, mA	110	11
Average beam power, W	95	15
Estimated dose @ 1m, cGy/min	10.5	5.5
Structure length, cm	8.8	24.5
System weight (+modulator), kg	13.6 (+9)	16.6 (+9)
Linac block dimensions, cm^3	48.6×38.1×26.7	63.3×38.1×26.7
RF pulse length, µs	0.4	
Maximum repetition rate, pps	2500	

A typical Ir-192 source activity for industrial radiography is 100 Ci, which corresponds to a dose rate of 0.8 cGy/min at 1 m.

R&D program

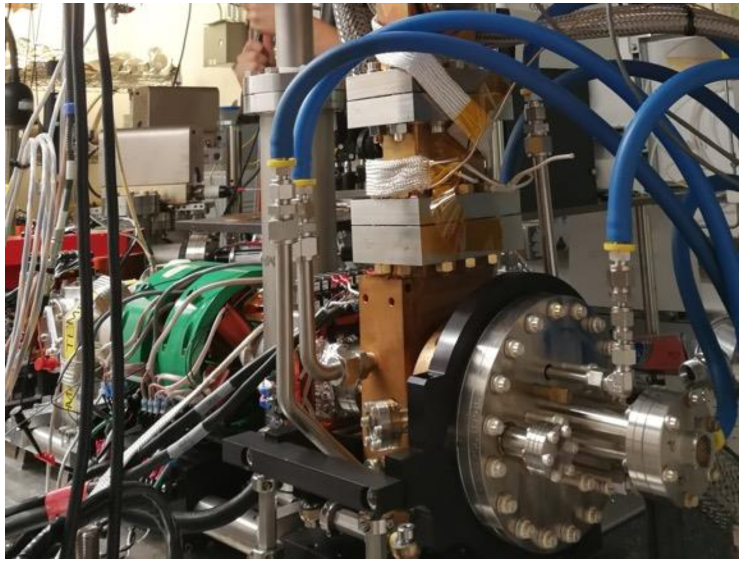
LCLS Dechirper



Industrial linacs

OEM Medical linacs

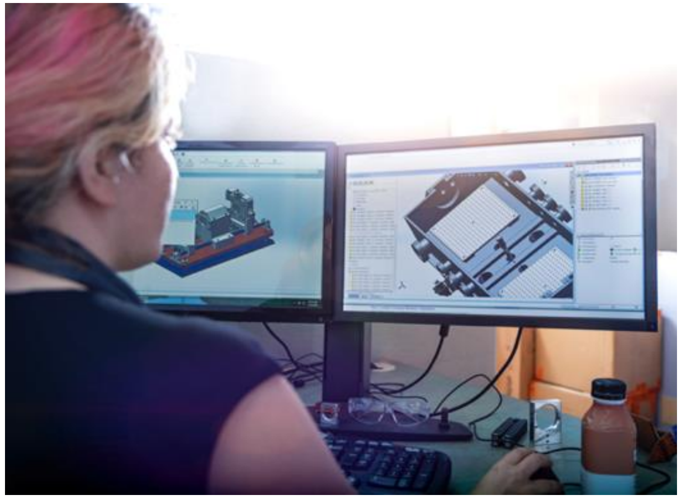
IOTA beamline



APS Gun

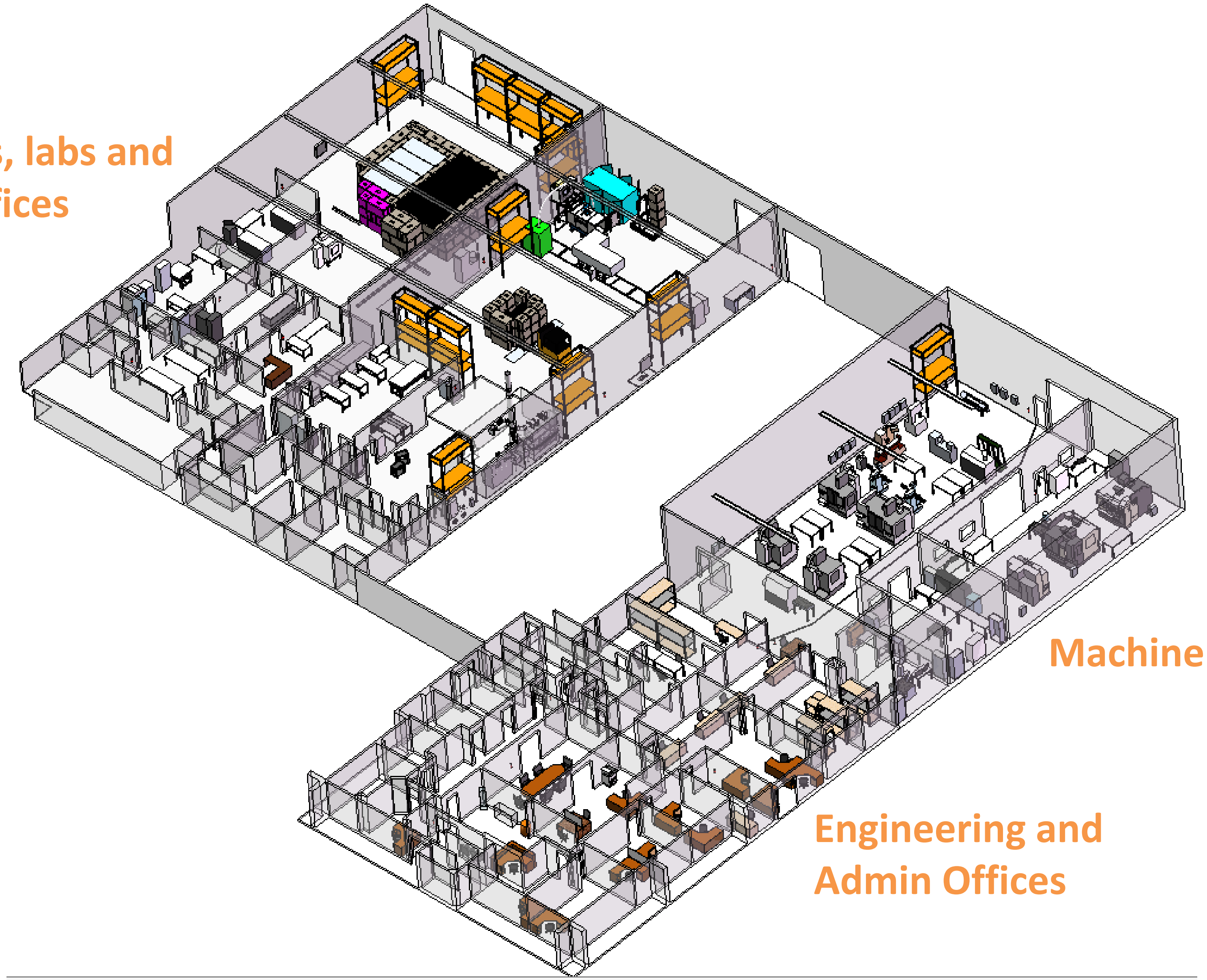
Radiotherapy system (spinoff)

Capabilities



- Physics design and beam dynamics simulations
- RF and mechanical design/engineering
- Manufacturing/in-house machine shop
- Coil winding and epoxy encapsulation
- Precision magnetic testing
- Low-power and high-power RF testing
- Radiation bunkers with RF stations
- E-beam and X-ray measurement equipment

Our facility



Bunkers, labs and R&D offices

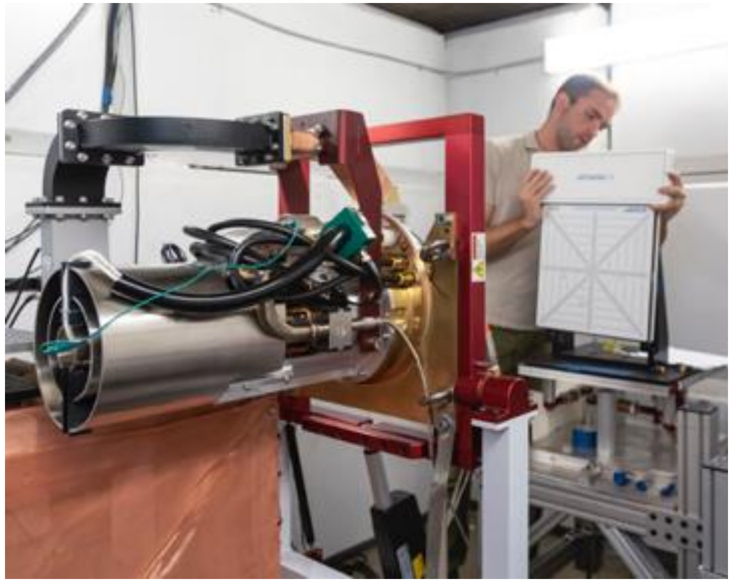
Machine Shop

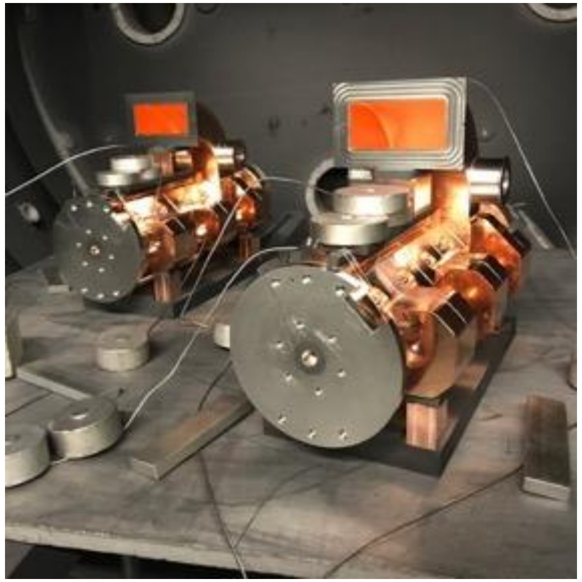
Engineering and Admin Offices

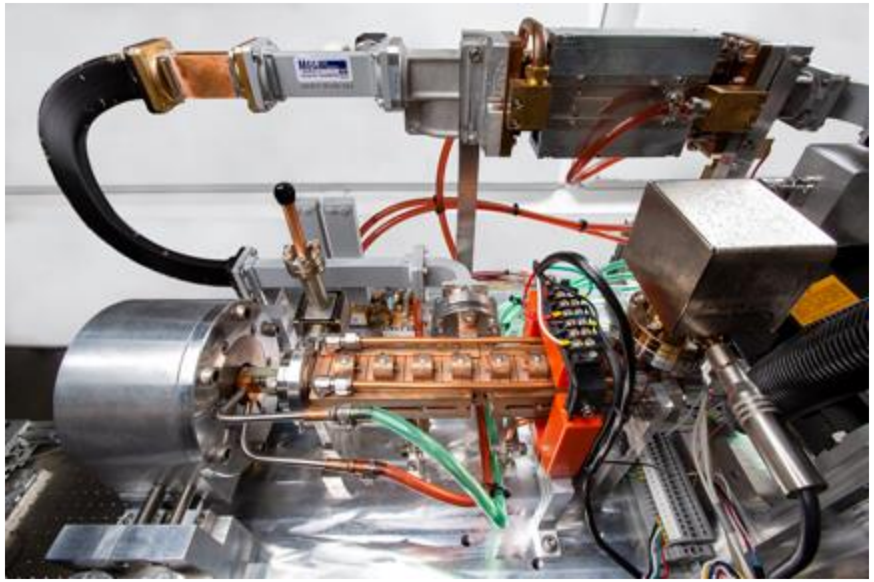
Low power, compact linacs

RadiaBeam

- S- and X-band OEM medical/industrial linacs
- Currently in production at a rate of 20/year
- Linacs conditioned and hot-tested in house, ready for installation at end-user site
- Exceed all performance requirements (dose rate, symmetry, dark current, vacuum, etc.)
- Executed accelerated life testing (10-year lifecycle)

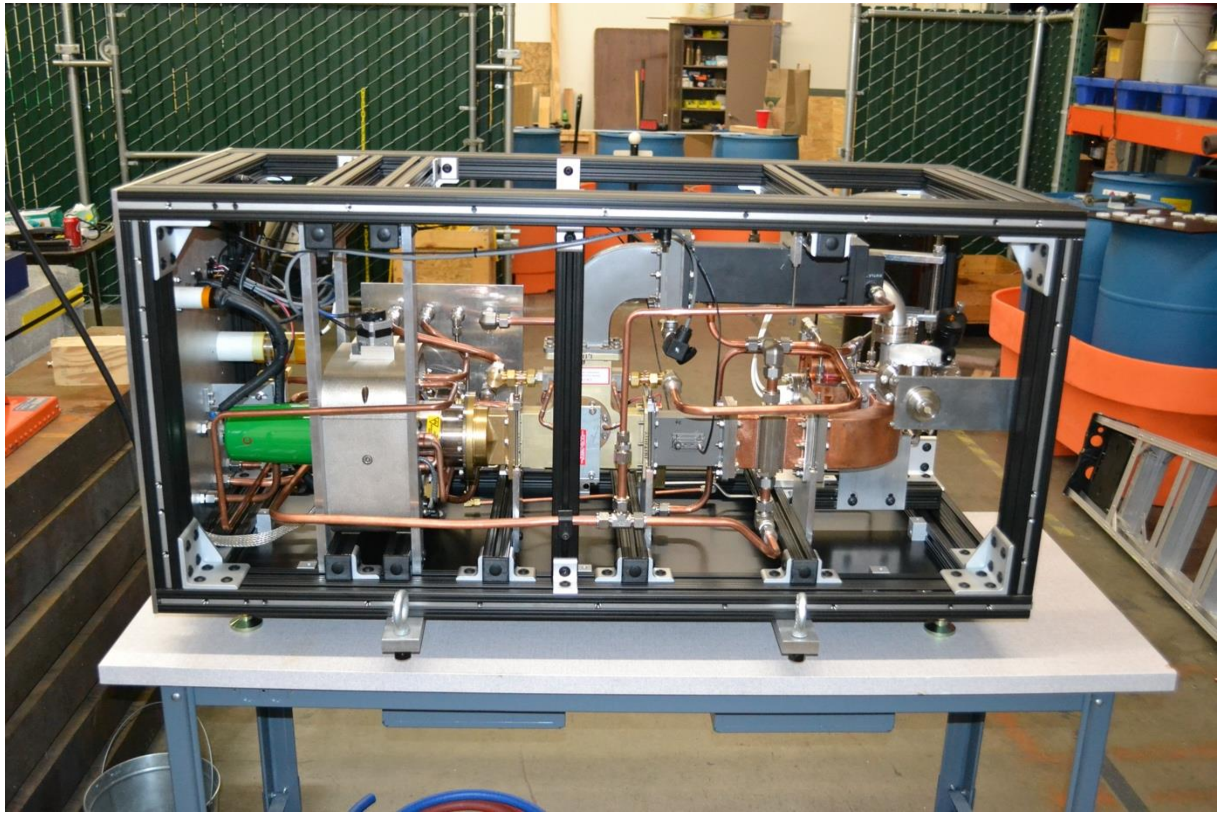


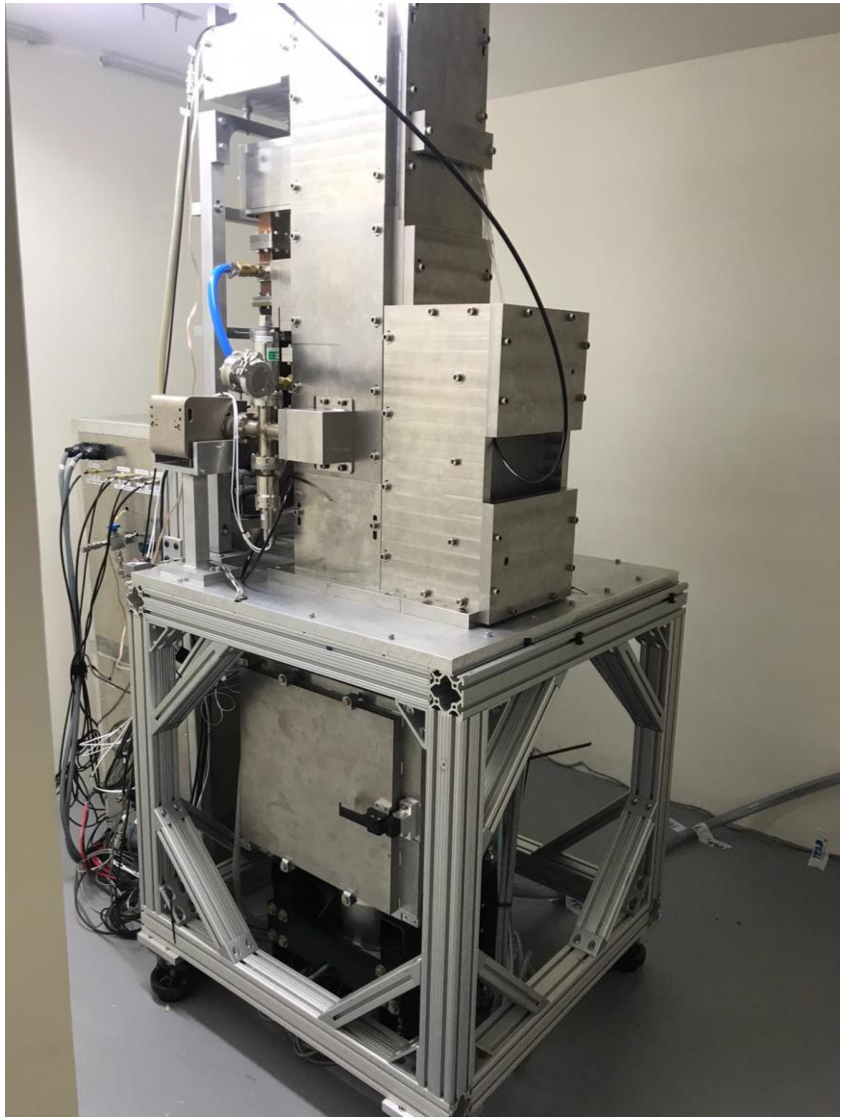




Industrial accelerator developments

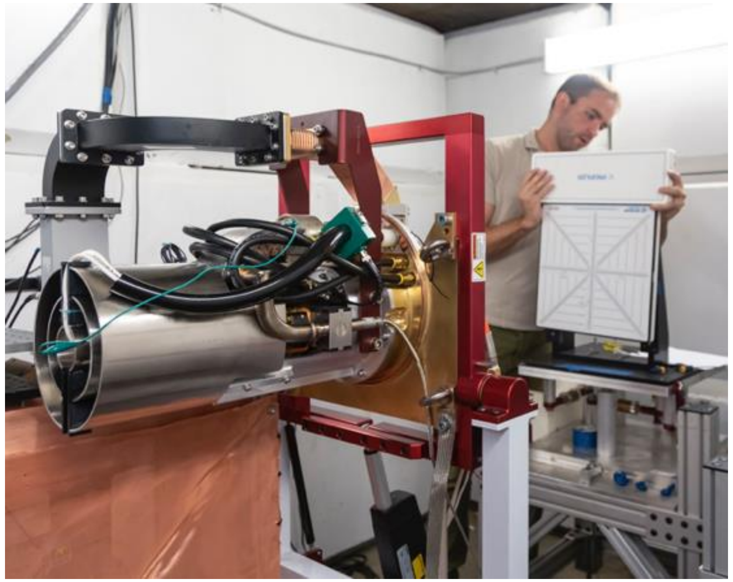
- 2013 – now: Customized industrial linac systems
- 2 – 9 MeV, e-beam or X-ray output
- Wide range of parameters and variability for specialized applications

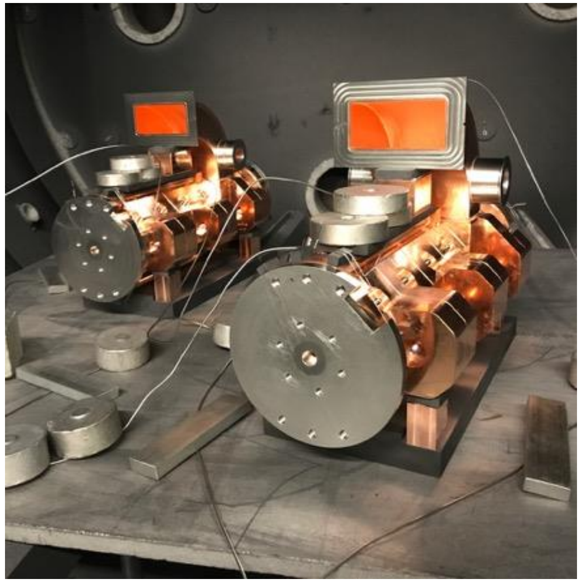


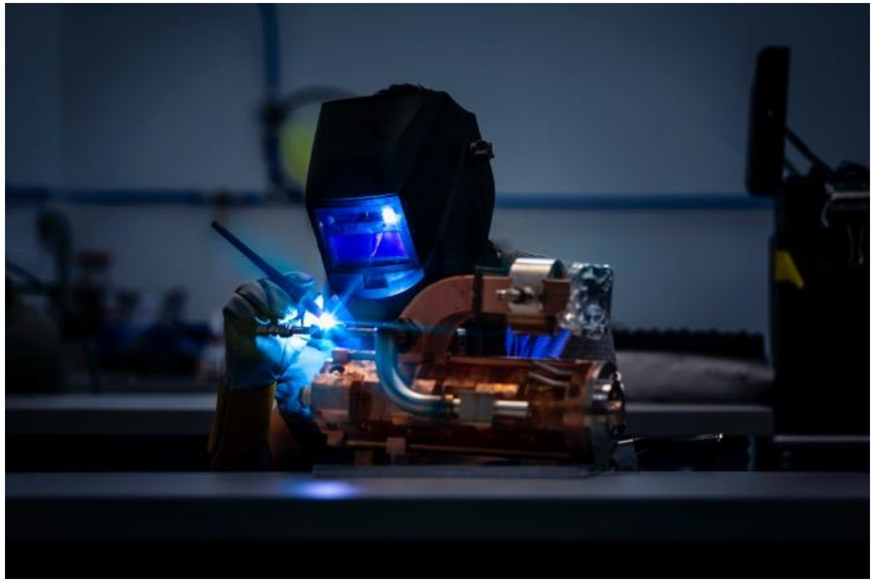


Medical linacs

- S- and X-band OEM medical linacs
- First order in 2017, currently in production at a rate of 20/year
- Linacs conditioned and hot-tested in house, ready for installation at end-user site
- Exceed all performance requirements (dose rate, symmetry, dark current, vacuum, etc.)
- Executed accelerated life testing (10-year lifecycle)

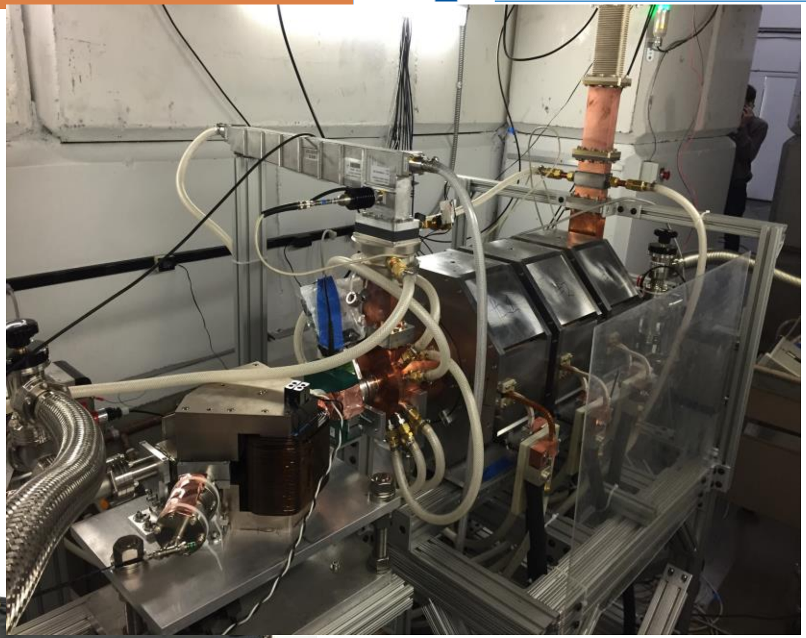




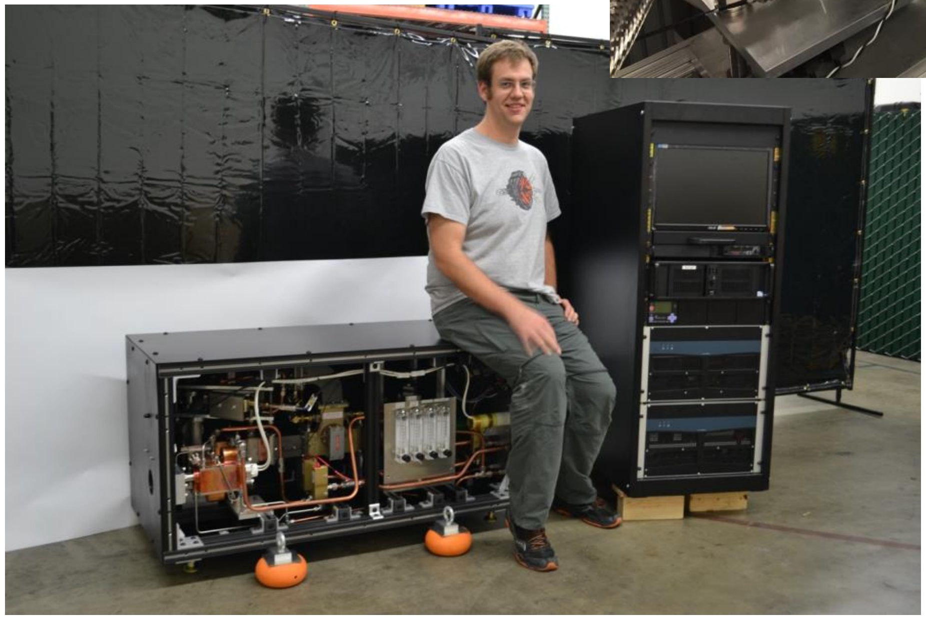


Security linacs

- S- and X-band linacs with variable energy (2-9 MeV, 4/6 MeV)
- Compatible with the requirements for novel adaptive inspection techniques
- Conditioned and hot-tested in house, ready for installation at end-user site



Name	ARCIS	MXS	KuLac
Inspection system	R/road, portal	Mobile	Portal, Mobile
Accelerator	S-band linac	X-band linac	Ku-band linac
Beam energy	2-9 MeV	4/6 MeV	0.5 – 2 MeV
Repetition rate, pps	440 (1000)	200 (500)	2000
Pulse length,	0.1 - 16 µs	1 - 5 µs	0.5 µs
Power source	Klystron	Magnetron	Magnetron

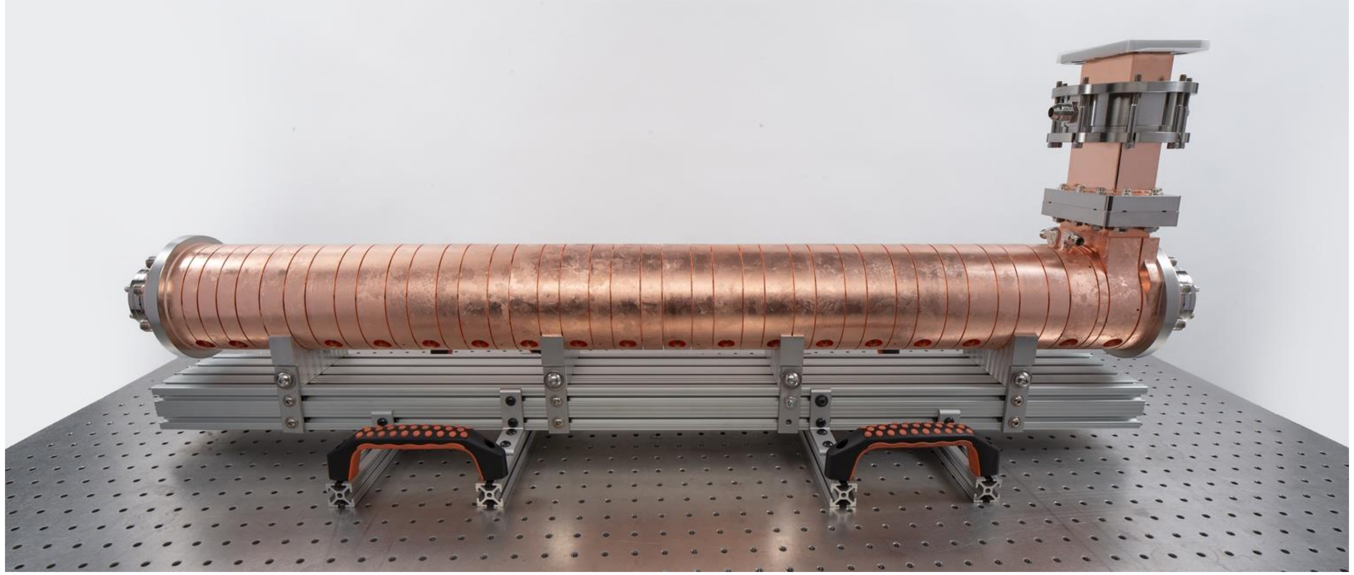


S.V. Kutsaev et al., "Linear Accelerator for Security, Industrial and Medical Applications with Rapid Beam Parameters Variation", *Radiat. Phys. Chem.* **183**, 109398, 2021.
S.V. Kutsaev et al., "Compact X-Band Electron Linac for Radiotherapy and Security Applications", *Radiat. Phys. Chem.* **185**, 109494, 2021.

Newest product: high power linacs

RadiaBeam

- Order in April 2020, first delivery in November 2020
- 10 MeV, 20 kW linacs
- For food irradiation and medical sterilization
- Conditioned at RadiaBeam before delivery to customer



Past radioactive source replacement R&D

- Microlinac (1 MeV) and blood irradiator (2 MeV) (2010 – 2013)
  - Proposed X-band linacs with inexpensive magnetrons/RF power systems
  - Built and tested prototype linacs, but too expensive for application
- Experience was foundation of our commercial accelerator developments