RadiaBeam's Projects on Alternative Technologies for Medical and Industrial Applications

NAS Meeting, December 17, 2020

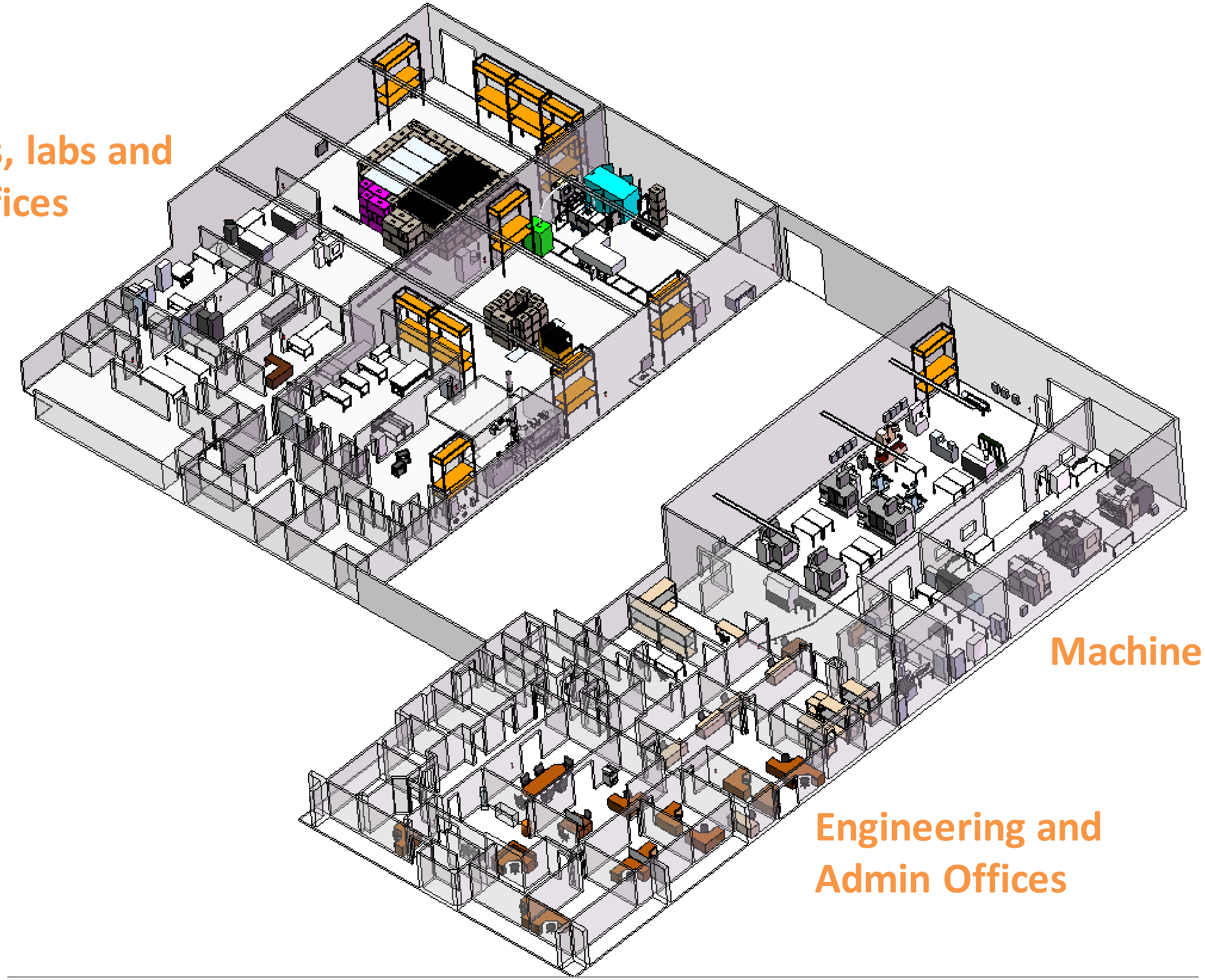
RadiaBeam Overview

- RadiaBeam founded in 2004
- ~50 employees and growing
- 30,000 ft^2 headquarters in Santa Monica, CA

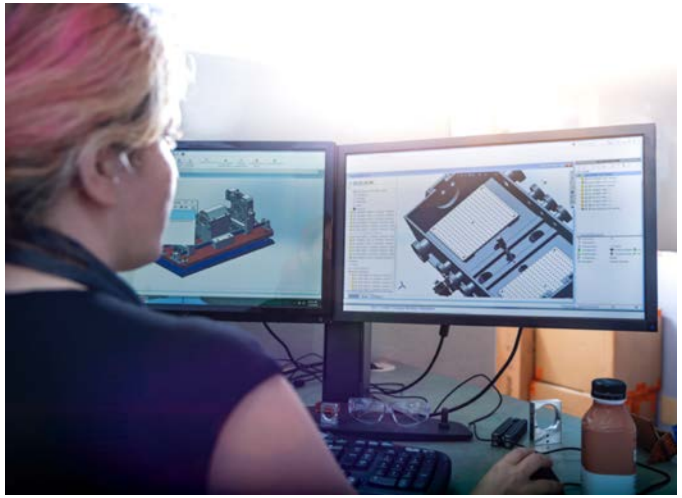
- Accelerator R&D, design, engineering, manufacturing and testing all under one roof in a dynamic, small-business setting
- Products: accelerator components (RF structures, magnets, diagnostics), medical/industrial accelerator systems

Our facility

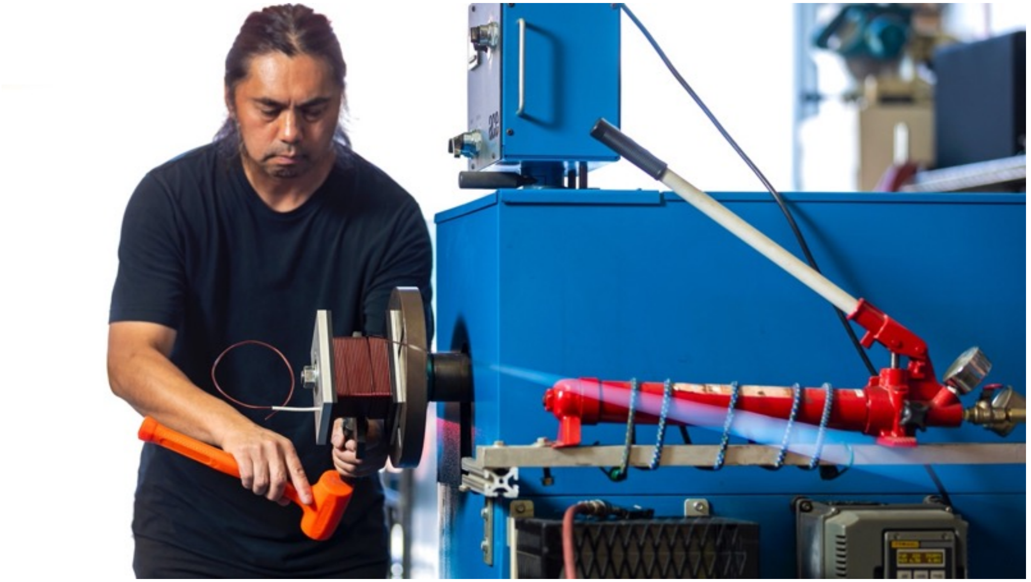
RadiaBeam



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



Products

RadiaBeam

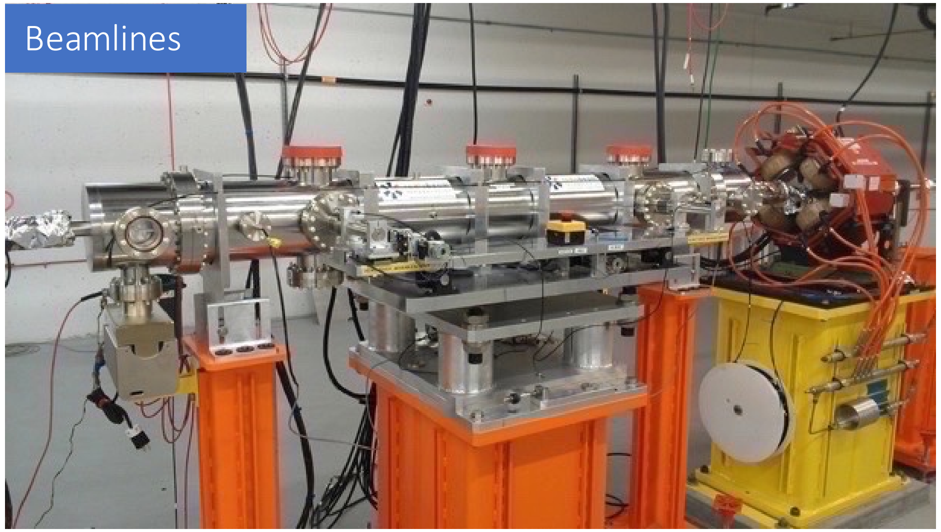
- Thousands of products delivered since 2004 with new products every year.

Magnets

Diagnostics

RF Structures

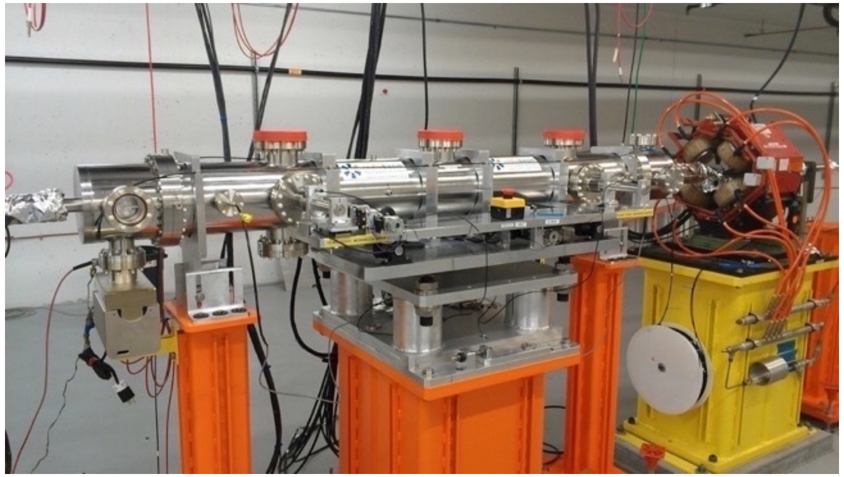
Linac Systems



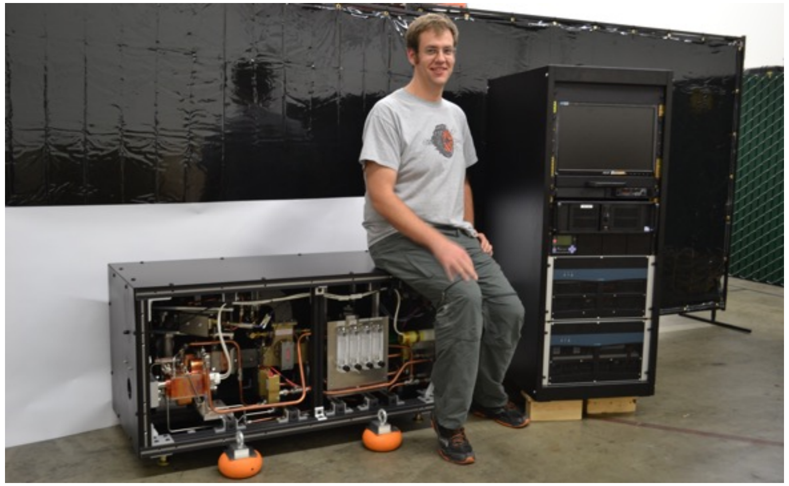
Beamlines

Betatrons

R&D program



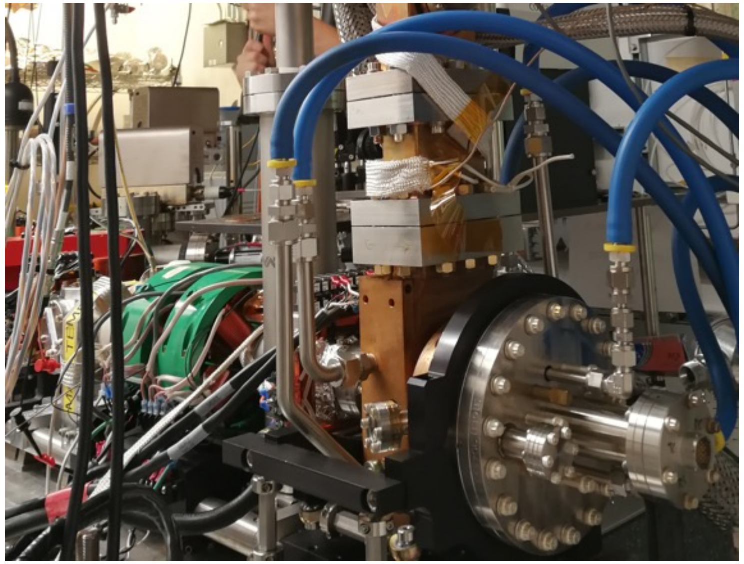
LCLS Dechirper



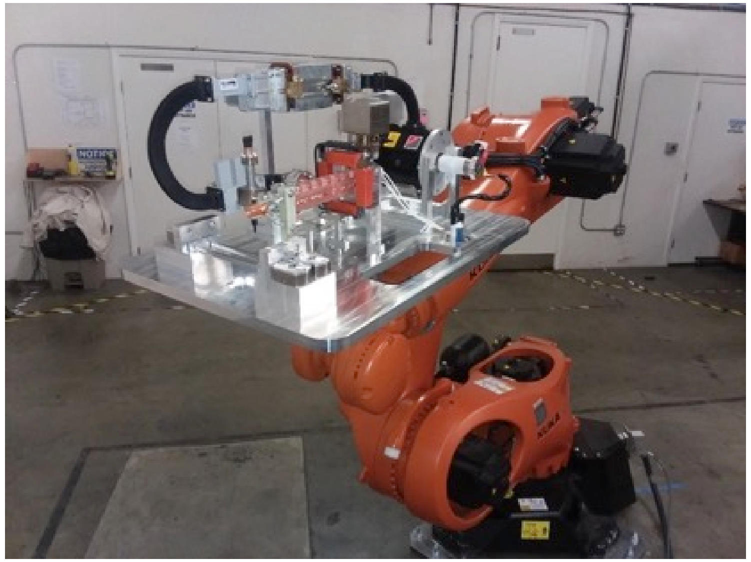
Industrial linacs

OEM Medical linacs

IOTA beamline



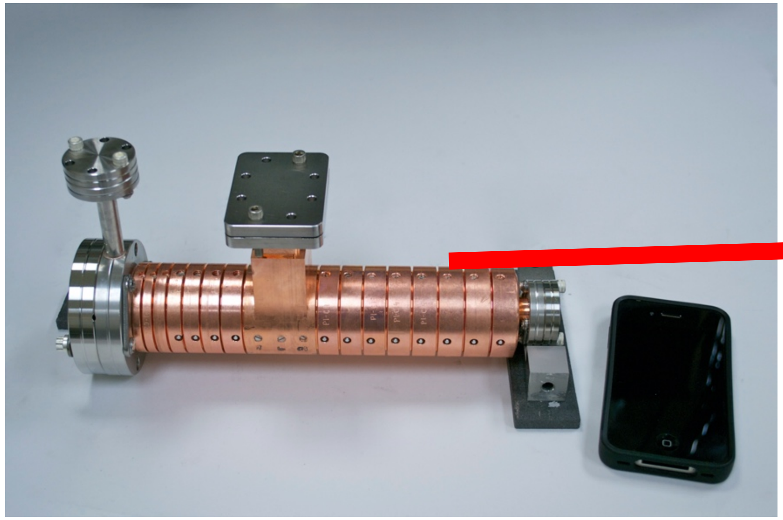
APS Gun

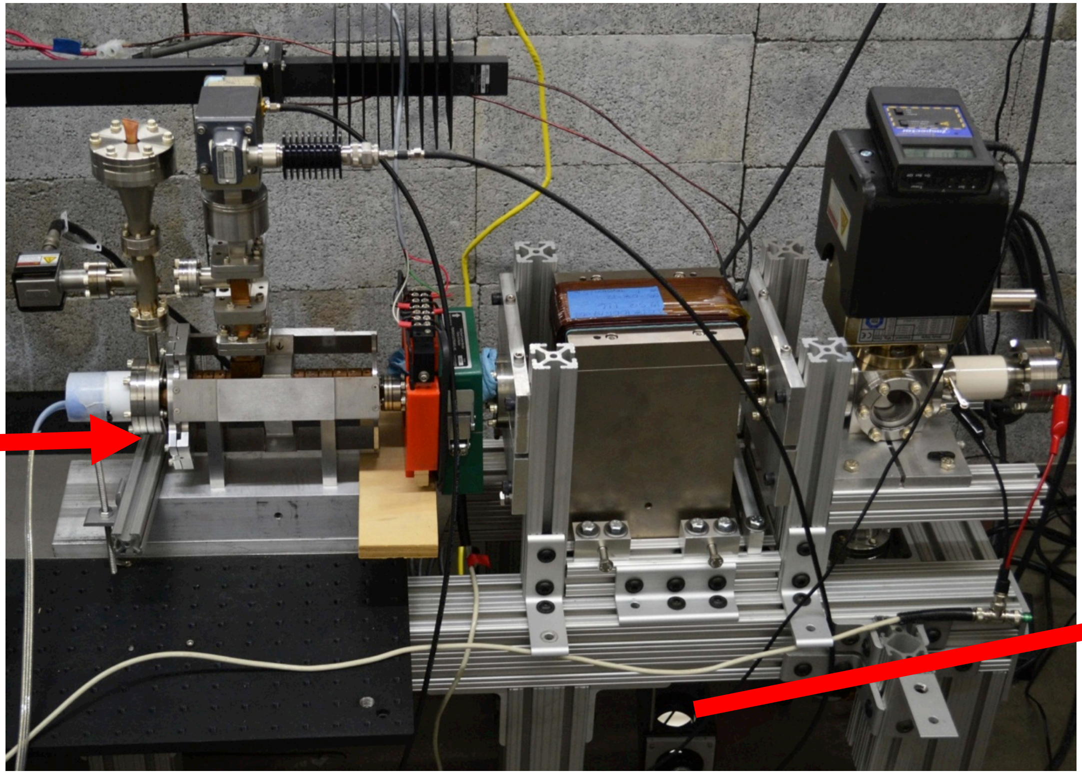


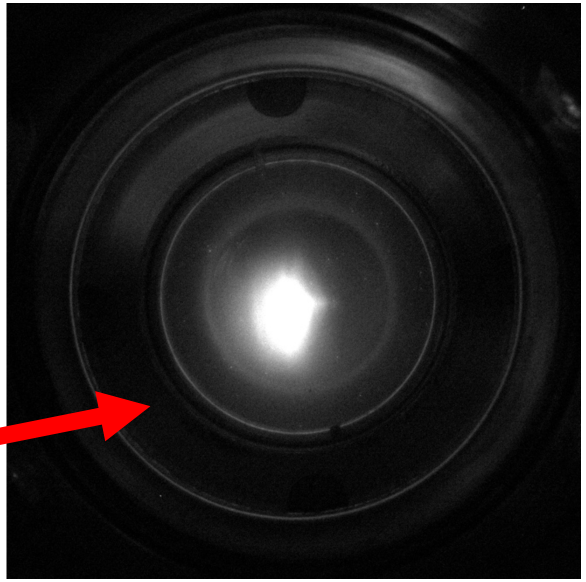
Radiotherapy system (spinoff)

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

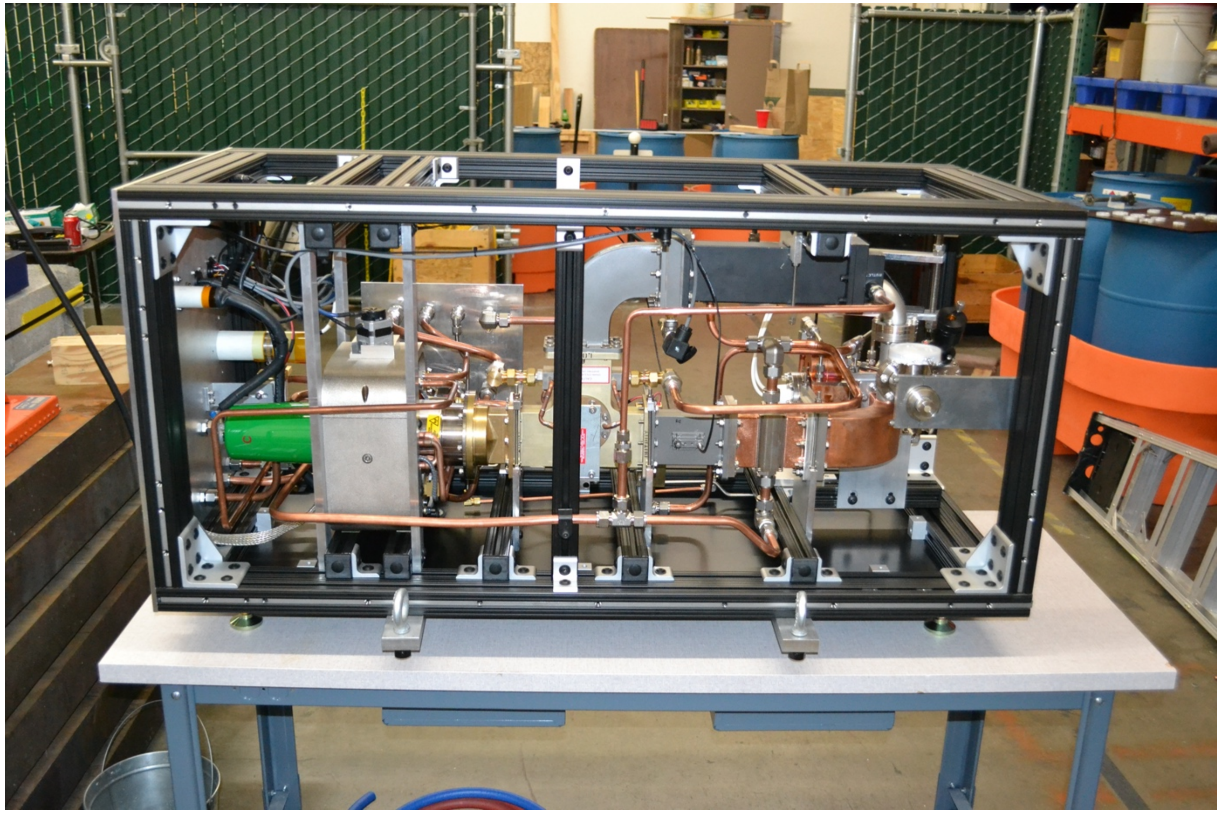


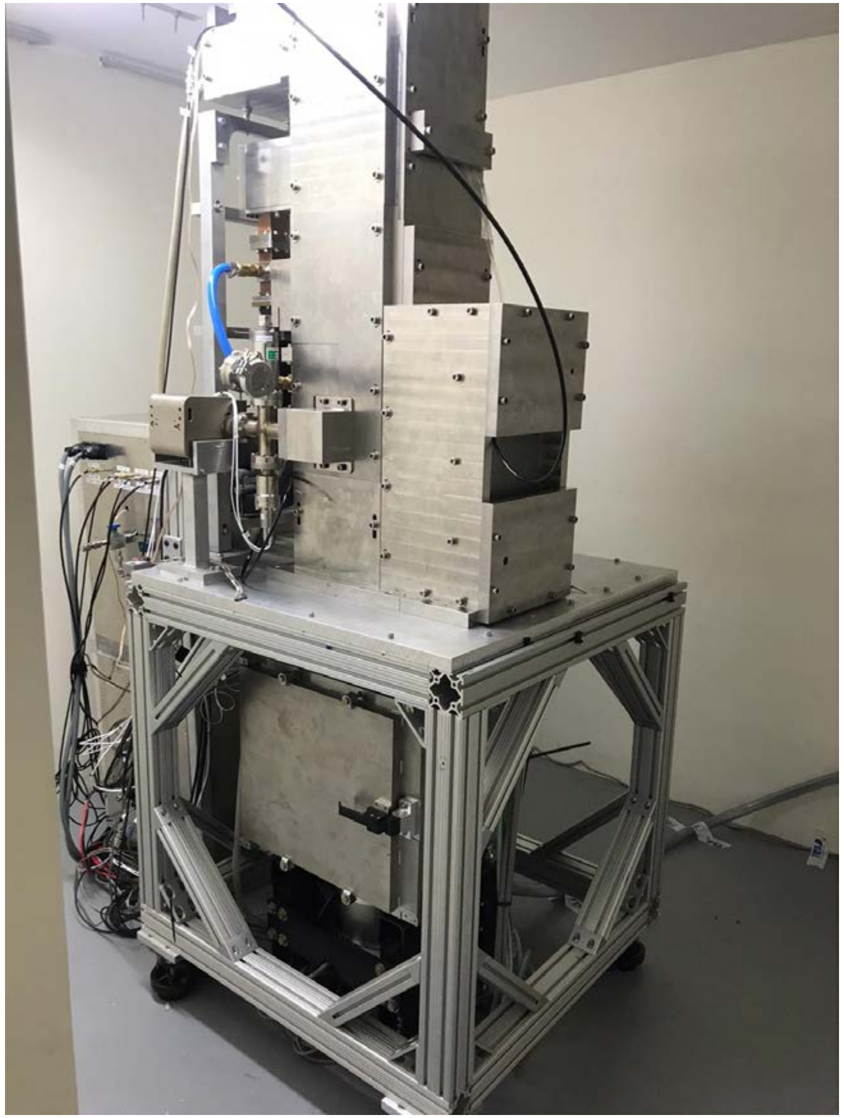




Industrial accelerator developments

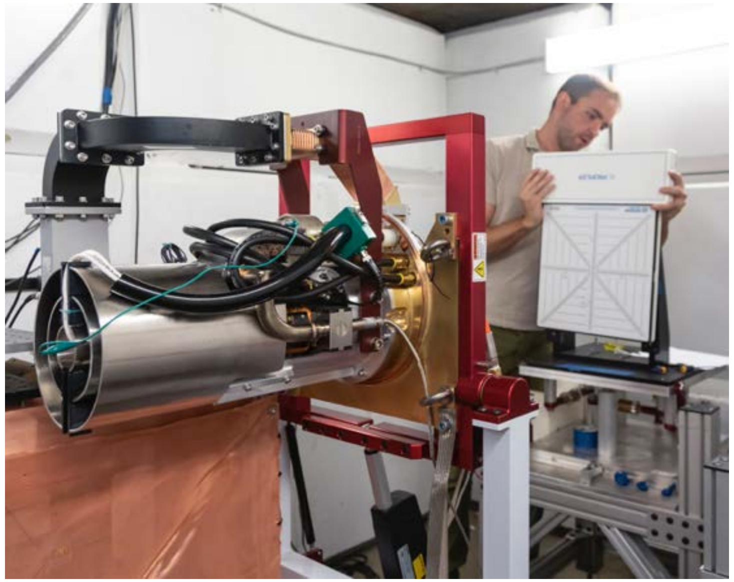
- 2013 – now: Customized industrial linac systems
- 2 – 9 MeV, e-beam or X-ray output
- Wide range of parameters and variability for specialized applications

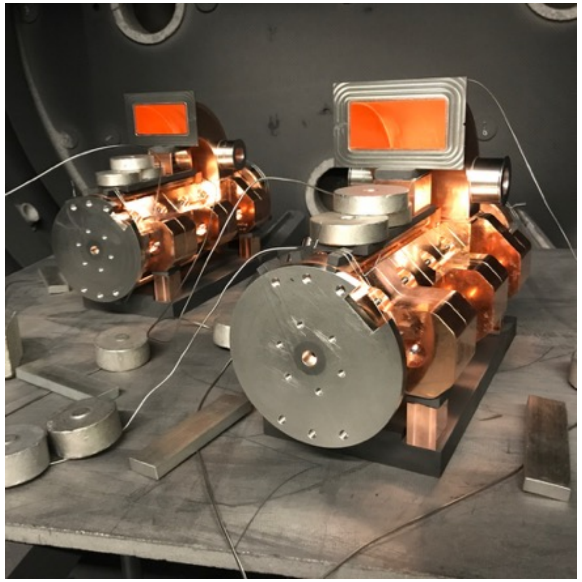


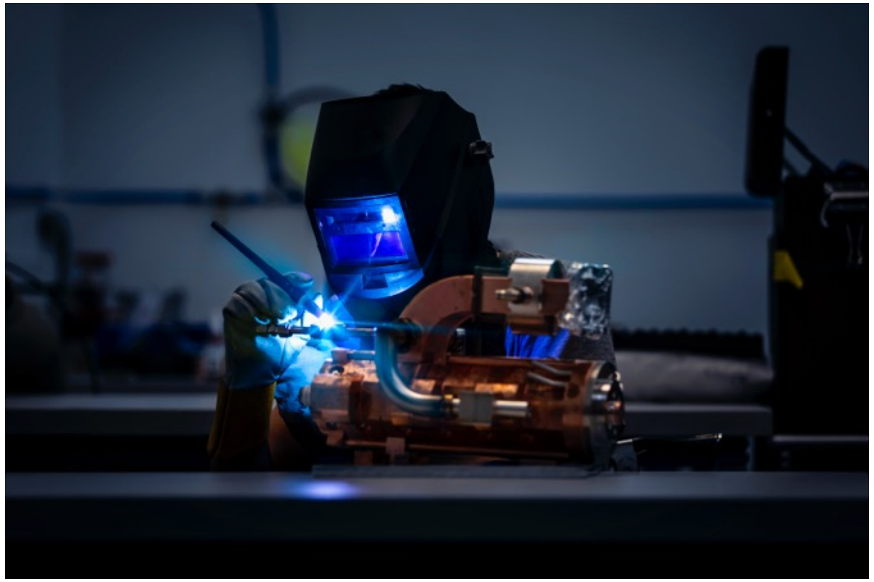


Medical linacs

- 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)

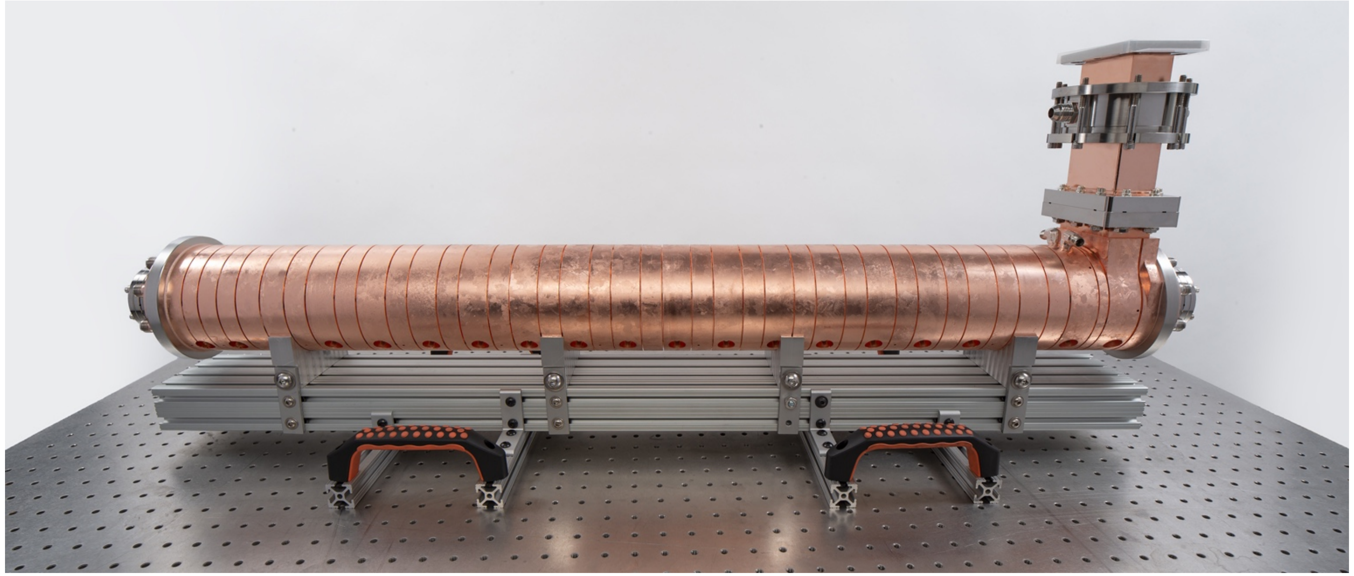






Newest product: high power linacs

- 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



Challenges/lessons learned

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- High power systems: cost dominated by RF power system (modulator)
  - Modulator costs ~$15 per Watt of avg RF power
- Low power systems: cost dominated by accelerating structure manufacturing
  - Fixed cost, ~$100k +/- $50k depending on what's included
  - Our current research is focused on reducing this cost
- Mature solutions and market pull already exists for high power accelerators
- Low power systems are smaller, more cost sensitive, and more diverse
- New accelerator development is expensive and time consuming, often exceeds what can be done in an SBIR project
- Customers don't want to foot the entire bill
- Experience helps, but takes many years and millions of $ to develop

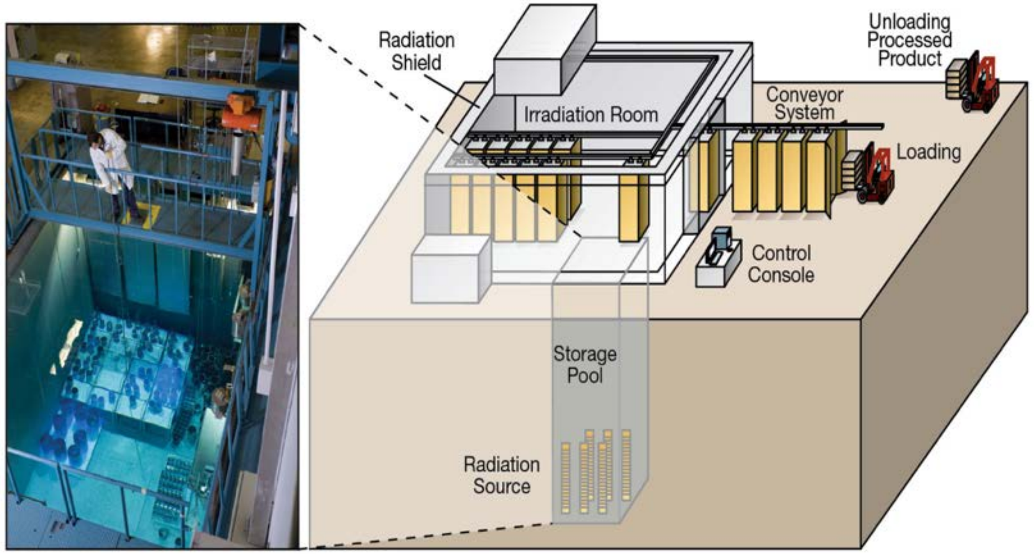
Current SBIR projects

1. Safe, High-Throughput, Self-Contained **Irradiator** (Phase II started 9/2020)
   – Replacement for Cs-137, Co-60 in self-contained irradiators
2. Ultra **Portable X-Ray Source** for Field Radiography (Phase I started 7/2020)
   – Replacement for Ir-192 in field radiography
3. Compact, Improved **Betatron** X-ray Source (Phase I started 7/2020)
   – Replacement for Co-60 in field radiography

	1 - Irradiator	2 – Portable	3 - Betatron
Energy [MeV]	3	1	6
Avg. current [µA]	100	33	0.45
Avg. power [W]	300	33	2.7
X-ray dose rate @ 1 m [cGy/min]	150	1.0	5.4
Size [LxWxH, cm]	125x110x75	30x30x16	70x44x35
Weight [kg]	5,000	20	45

Irradiator - motivation

- Large, panoramic irradiators are currently being replaced by accelerators
- Smaller ones are more difficult to replace, but there are more of them, and they are at higher risk
  - Recent IAEA meeting/report estimates 2,000 – 3,000 worldwide!
- Applications include:
  - Blood irradiation
  - Radiobiological research (e.g. cell cultures, small animals)
  - Radiation effects testing (i.e. space electronics)
  - Detector calibration
  - Space electronics testing
  - Small volume, high value product irradiation (e.g. cannabis and extracts)
  - **Sterile Insect Technique**



Large

Small

Sterile Insect Technique (SIT)

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- Reduce pest population by releasing sterile insects into the environment
- Used to control agricultural pests, and, to a lesser extent, disease-bearing pests
- e.g. Tse-tse flies in Africa, Med flies in Americas, Zika bearing mosquitos

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)

Location of facility	Insect reared	Dose (Gy)[1]	Initial activity (kCi)	Irradiator model (MANUFACTURER)	Source
Argentina	*Ceratitis capitata*[4]	110	20	IMCO-20[2]	Co-60
Canada	*Cydia pomonella*[5]	150	24	Gammacell® 220[2] (NORDION)	Co-60
Chile	*Ceratitis capitata*	120	160	Gammacell® 220[2] (NORDION)	Co-60
Guatemala	*Ceratitis capitata*	100–145	11	Gammacell® 220 E[2] (2 units) (NORDION)	Co-60
			12	Gammacell® 220 R[2] (J. L. SHEPHERD)	Co-60
			42	Husman 521A[2] (ISOMEDIX)	Cs-137
			46	Husman 521[2] (ISOMEDIX)	Cs-137
Mexico	*Anastrepha ludens*[6]	80	35	JS-7400[3] (NORDION)	Co-60
	Anastrepha obliqua[7]	80			
	Ceratitis capitata	100			
Mexico	*Cochliomyia hominivorax*[8]	80	47	Husman 520[2] (3 units) (ISOMEDIX)	Cs-137
Philippines	*Bactrocera philippinensis*[9]	64–104	30	GB 651 PT[3] (NORDION)	Co-60
Portugal	*Ceratitis capitata*	100	20	Gammacell® 220[2] (NORDION)	Co-60
South Africa	*Ceratitis capitata*	90	10	(LOCAL MANUFACTURER)[3]	Co-60
Thailand	*Bactrocera dorsalis*[10]	90	24	Gammacell® 220[2] (NORDION)	Co-60
USA (Hawaii) CDFA[11]/USDA	*Ceratitis capitata*	140	47	Husman 521[2] (2 units) (ISOMEDIX)	Cs-137
USA (Hawaii) ARS/USDA[12]	*Ceratitis capitata*	120	24	Gammacell® 220[2] (NORDION)	Co-60
USA (Texas)	*Anastrepha ludens*	70	38	Husman 521[2] (ISOMEDIX)	Cs-137

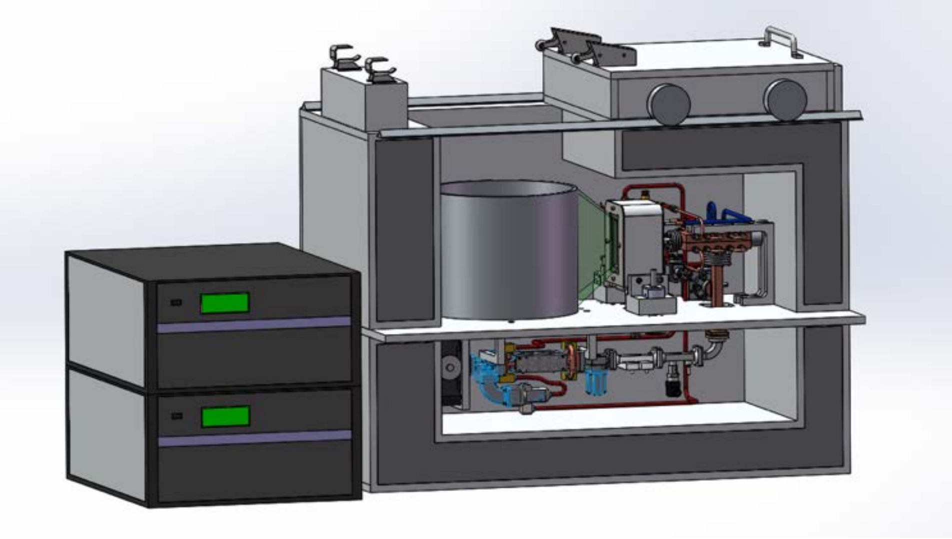
X-ray irradiators for SIT?

- Due to concerns about radioisotopes, X-ray irradiators are being considered
- Recent paper* showed equivalent effectiveness of RS-2400 from Rad Source for SIT
- However low energy (150 kV) limits penetration and throughput
- Not ideal for SIT environment
  - Reports of high maintenance cost, frequent downtime as high-power X-ray tubes need to be replaced often
  - High flow DI chilled water source required
  - Stable electrical power required
  - Limited range of temperature/humidity

* T. Mastrangelo et al., A New Generation of X ray Irradiators for Insect Sterilization, Journal of Economic Entomology, Vol. 103, Issue 1, p. 85-94. (2010)

Linac X-ray irradiator for SIT

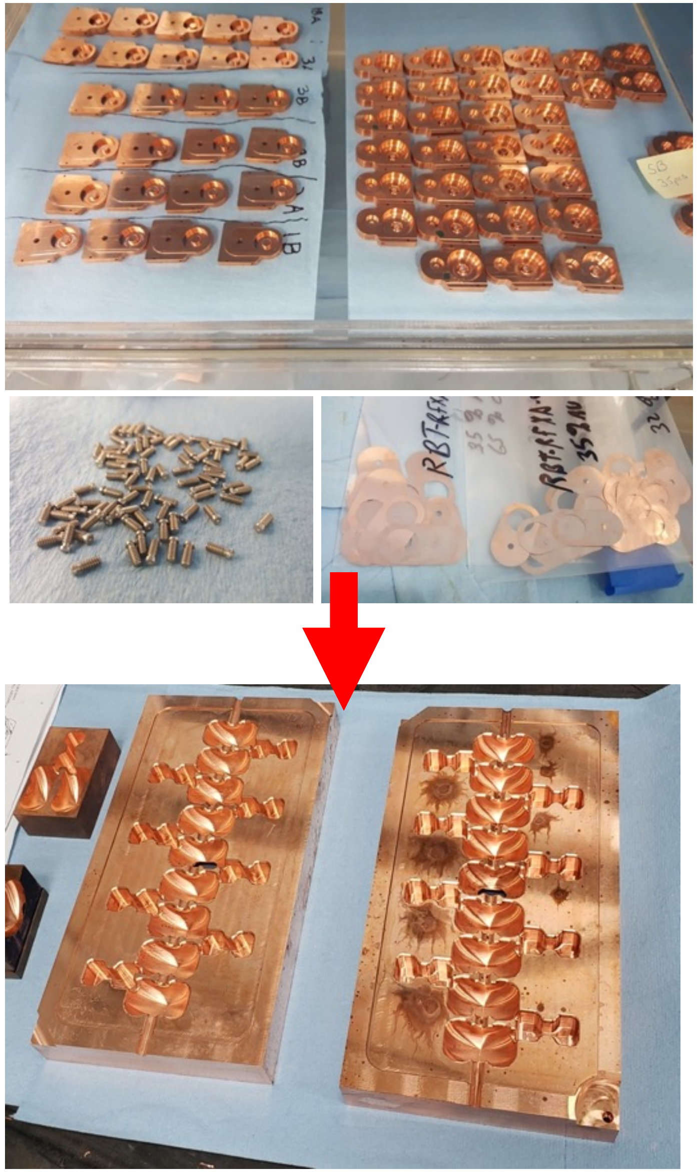
- Self-contained irradiator for sterile insect technique, research, etc.
- Replaces Cs-137 with 3 MV bremsstrahlung from a linac
- High dose rate can be achieved with modest beam currents (~100 µA)
  - Inexpensive, medical/radiography-class linac
- 15 Gy/min, 1.3 DUR in 36 cm diameter X 30 cm tall canister
- 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
Dose Uniformity Ratio	1.3
Canister Size	30 L (18 cm radius X 30 cm tall)
Irradiator System Size	125 cm long x 110 cm tall x 75 cm deep
Irradiator System Weight	5,000 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**

“Split” linac concept

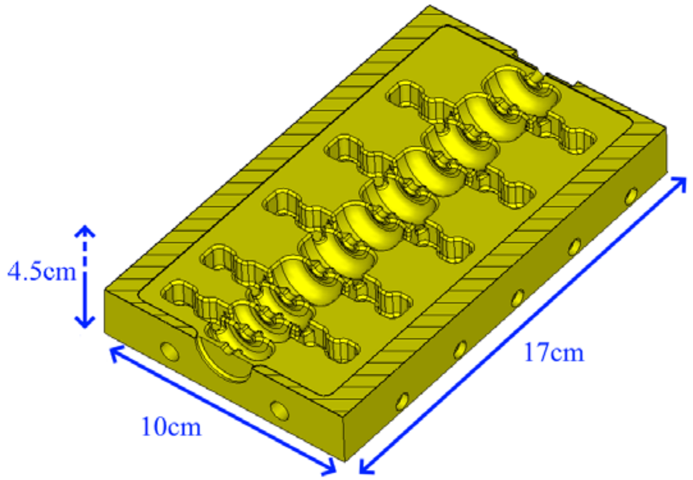
- Linacs are conventionally made from many copper “cells” that are stacked and brazed together
  - Requires precision machining of dozens of parts
  - Brazing introduces additional errors, requires tuning
  - Brazing anneals copper, increasing breakdown rate at high gradients
- Recently, the “split” linac concept has come into vogue
  - Only two parts need to be machined
  - Separates the hermetic joint from the RF surfaces
  - Allows other bonding techniques (e.g. welding, knife-edges)
  - Precision machining can then eliminate need for tuning

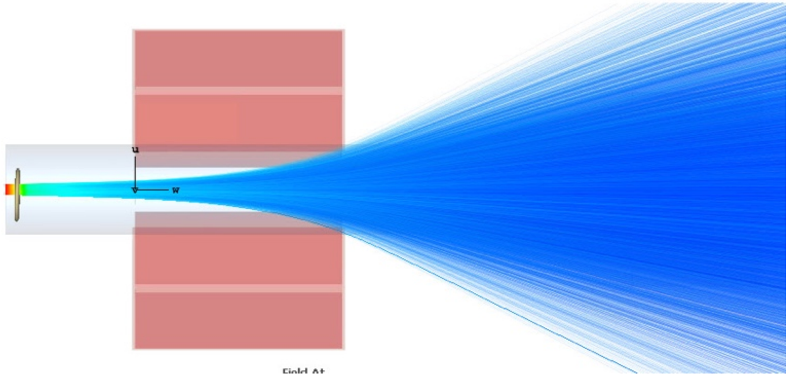


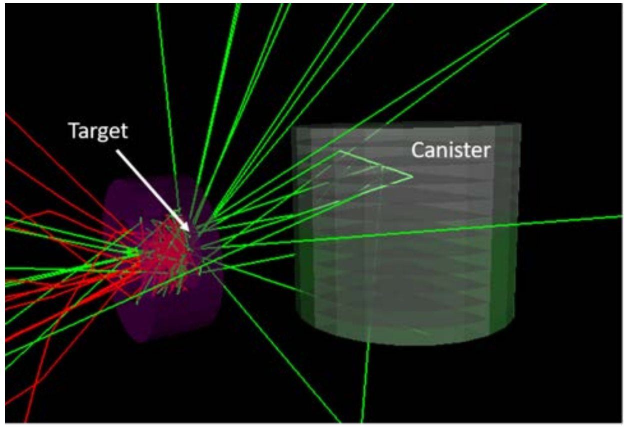
	SCL	S-SCL
Setup/operator time per part	1.5 hours	1.5 hours
Machine time per part	8 hours	20 hours
# of parts	38	2
Total Setup/operator time	57 hours	3 hours
Total machine time	304 hours	40 hours
Setup/operator rate	200	200
Cost of Setup/operator time	$11,400	$600
Machine rate	10	10
Cost of machine time	$3,040	$400
Total machining cost	**$14,440**	**$1,000**

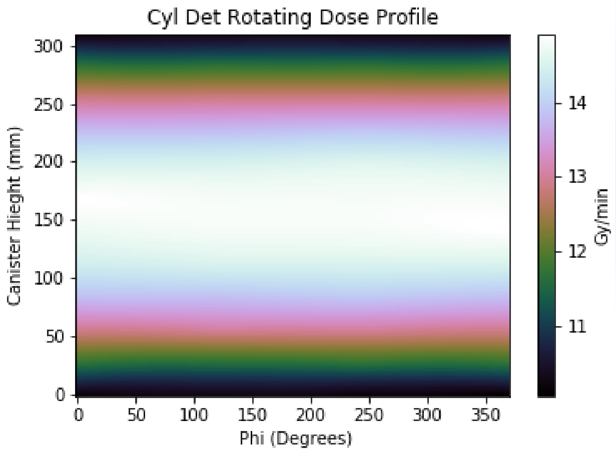
Results so far

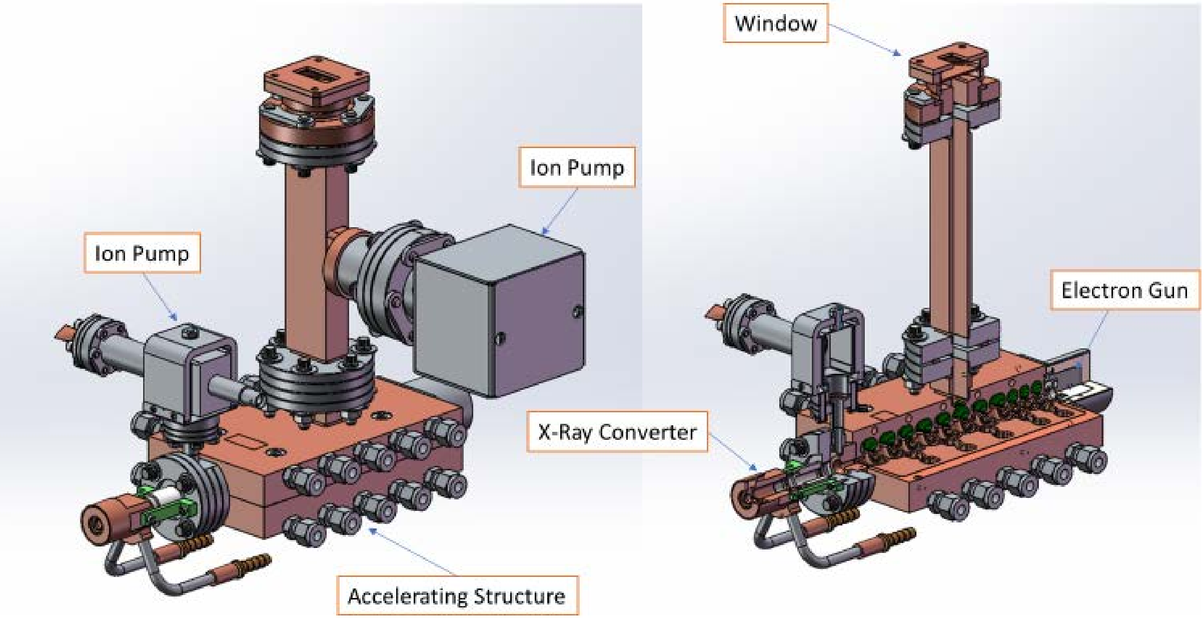
- Linac RF design and beam dynamics optimized
- Defocusing system designed to increase beam uniformity
- Shielding simulated with Monte-Carlo (Geant4)
- Linac and system engineering





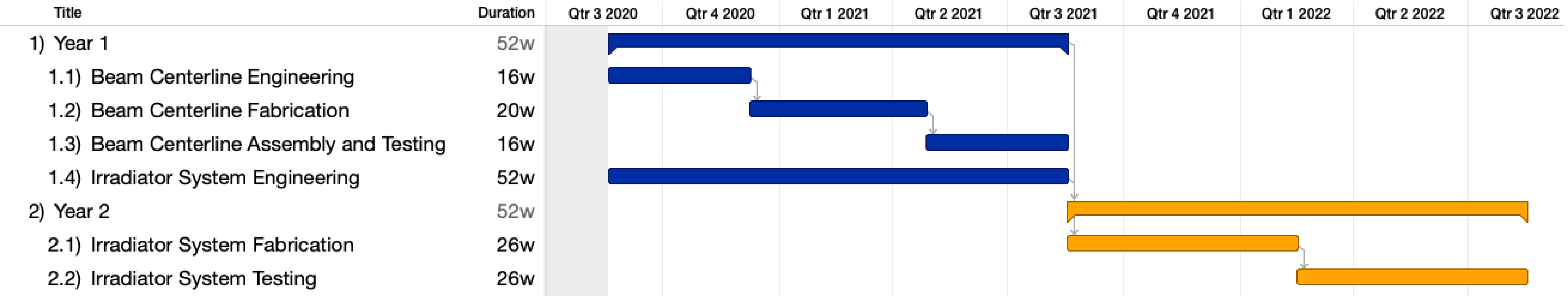






Next steps

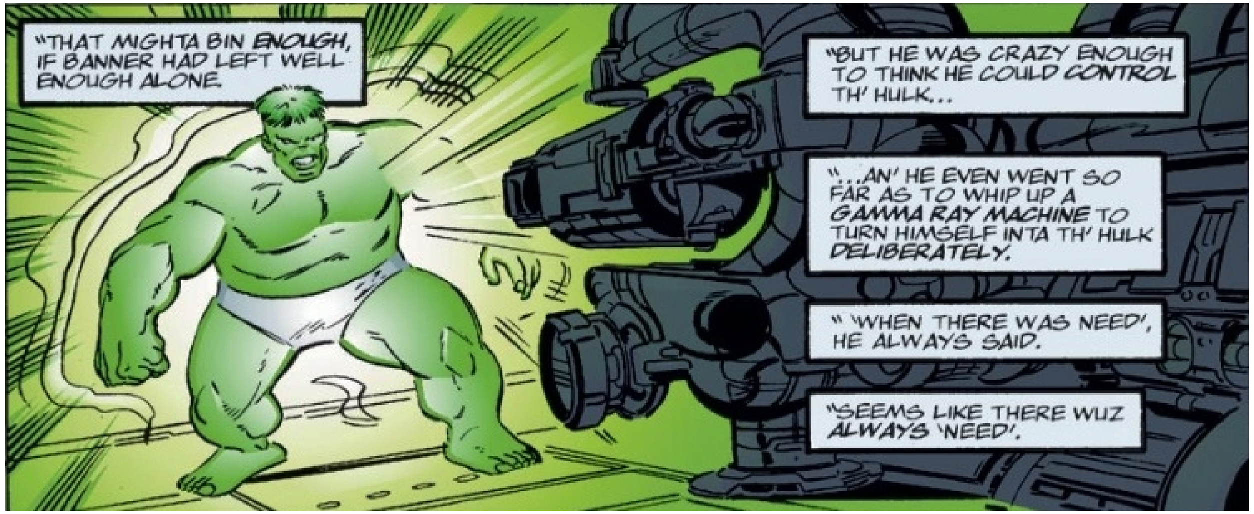
- Complete the engineering of the system, generate manufacturing prints and work instructions
- Fabricate the beam centerline
- Test the beam centerline on a test stand, demonstrating 3 MeV energy and 15 Gy/min
- Fabricate the complete irradiator system, including shielding
- Integrate and demonstrate the complete system, showing 15 Gy/min and < 1.3 DUR in 30 L canister
- *Reach goal: deliver prototype to IAEA*



Portable X-Ray source - motivation

- Radioisotopes are commonly used for field radiography
  - Oil and gas industry, power plants, etc.
  - Also useful for DOE office of emergency response
- But frequent accidents from failure to retract source
- Risk for diversion
- An electronic source would reduce accidents, eliminate diversion threat

Isotope	Half life	Avg Energy	Steel range
Yb-169	32 days	145 keV	6-20 mm
Se-75	120 days	217 keV	10-40 mm
Ir-192	**74 days**	**380 keV**	**20-90 mm**
Co-60	5.3 years	1.25 MeV	40-200 mm

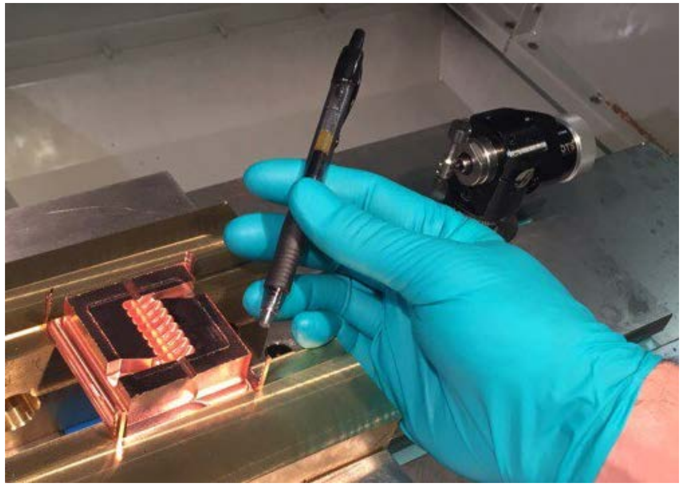


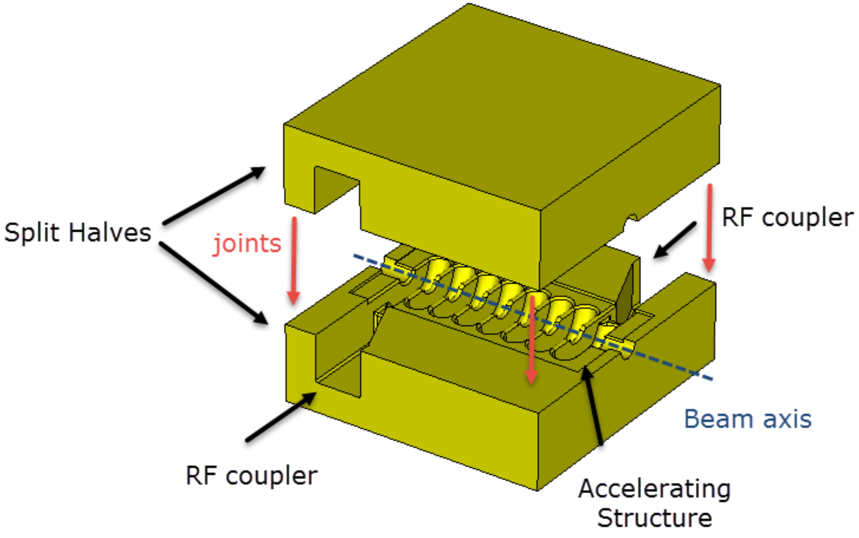
Cartoon gamma projector

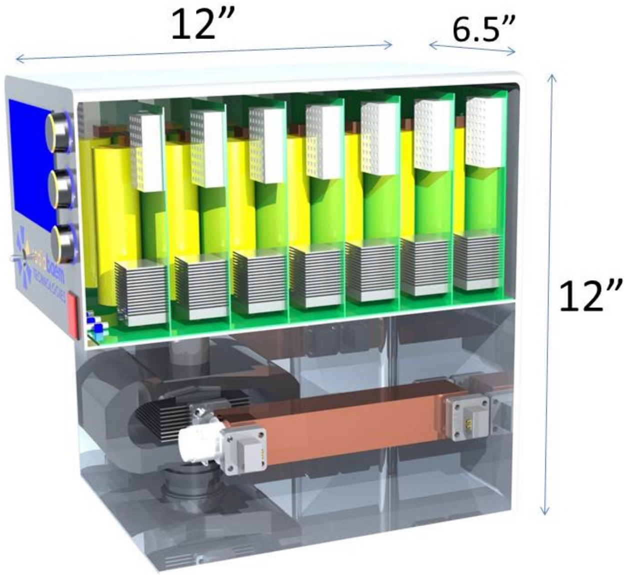
Real gamma projector

Technical approach

- 1 MeV, compact linac to replace Ir-192
  – < 50 lb, > 1 cGy/min @ 1 m
- High frequency Ku-band linac reduces size, power
- Low-power avoids need for water cooling
- “Split linac” approach to reduce manufacturing cost
- Compact, lightweight Marx modulator
- Enable operation from battery



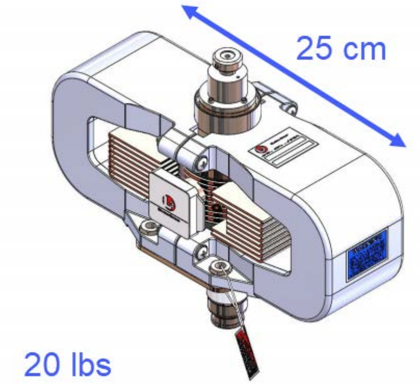


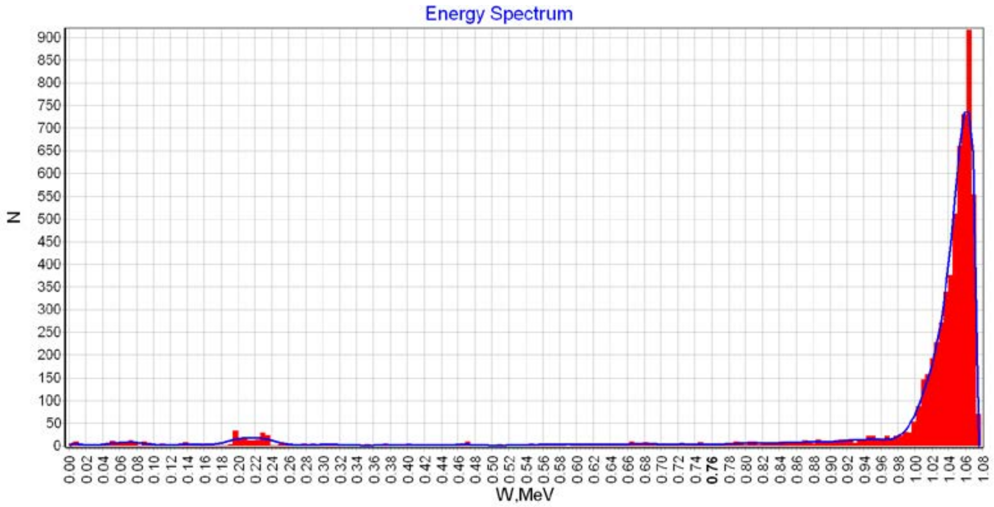


Next steps

RadiaBeam

- Select commercially available magnetron and other components to base the linac design on.
  - Purchased, arriving early next year
- Design and optimize the linac structure through RF numerical simulations to achieve the required energy and current, and to minimize size and cost.
  - Completed; 60 mA peak current at 1 MeV
- Procure RF components and fabricate RF structure for high power tests
  - In progress
- If possible, try to run beam through the structure
- Prepare for Phase II
  - Compact modulator development
  - Better electron gun
  - System engineering

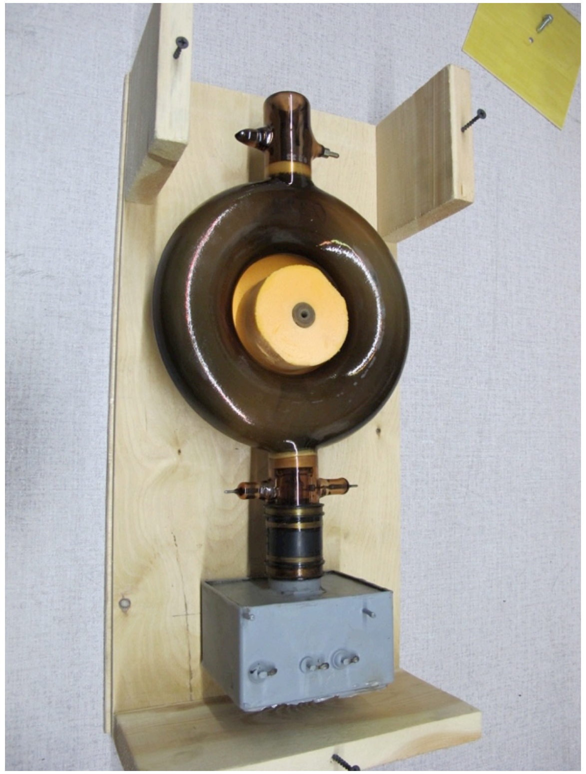




Compact, improved betatron X-ray source

- Betatrons are used for NDT, including for DOE office of emergency response
- They are commercially available only from a manufacturer in Russia (Foton/Tomsk)
  - Concerns about supply chain security
- There is also potential room for improvements in quality, performance and size

JME/Foton Betatron

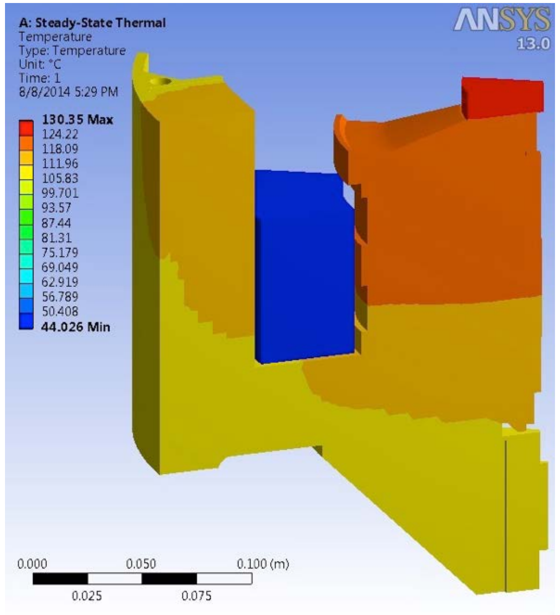


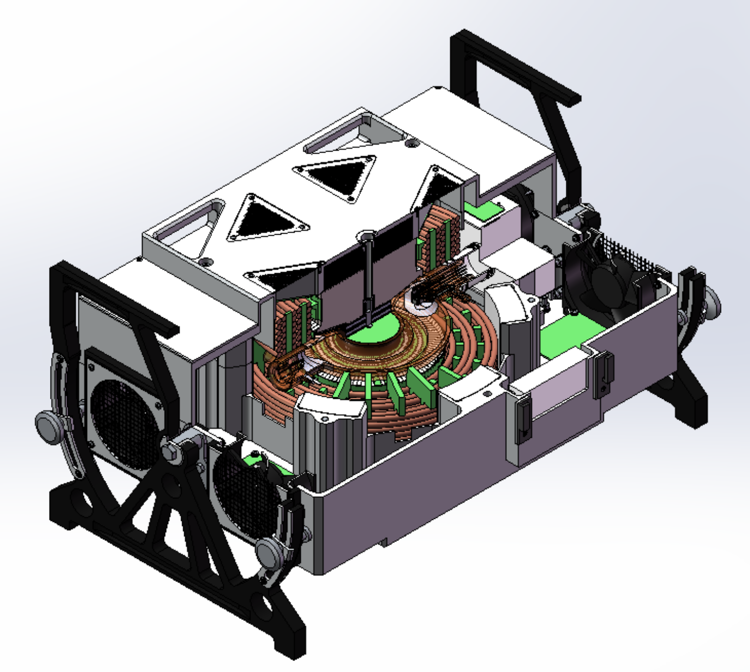
Prior work

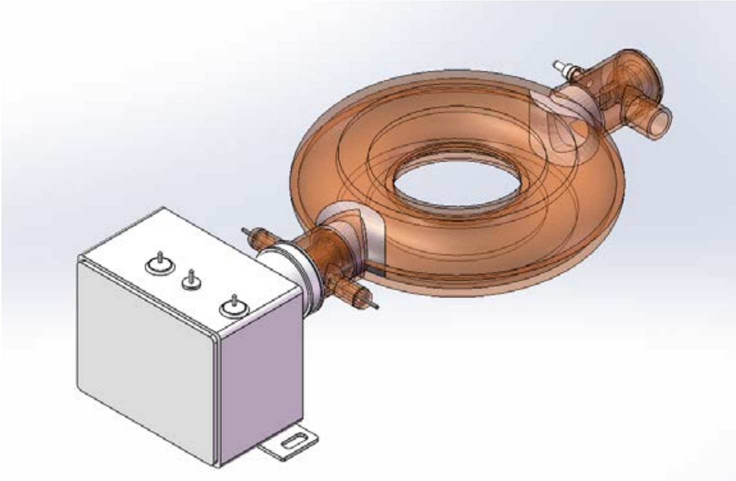
- RadiaBeam built a 9 MeV betatron radiator (magnet) in 2016 for commercial customer (cargo inspection)
  - Tested successfully (15 cGy/min)
- Continued development on manufacturing process, tube and power supply since then
- Initial engineering performed on 6 MeV version

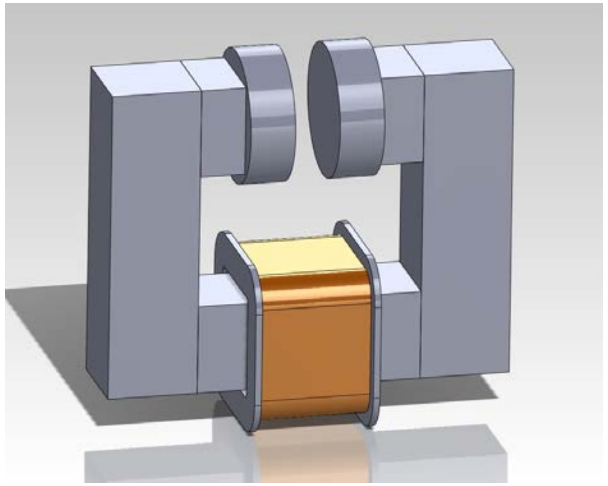
Next steps

- Phase I SBIR started 7/2020
  - Select magnetic material, perform magnetic and thermal simulations
  - Build+test mockup magnet to verify simulations, develop lamination assembly process
  - Design vacuum chamber, explore improvements
  - Design power supply
- Phase II: build and test complete prototype (2021 – 2023)









Conclusion

RadiaBeam

- RadiaBeam specializes in developing specialized accelerators for research, industrial and medical applications
- Currently developing compact high-energy X-ray sources as alternatives to radioisotopes such as Ir-192, Cs-137 and Co-60
- R&D program helped us develop our commercial products
- Accelerator development is challenging, time-consuming and expensive
  - If SBIR is the only funding mechanism available, max budget should be increased to $2 million
- 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!