TIBARAY

CURING CANCER IN A *FLASH*

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

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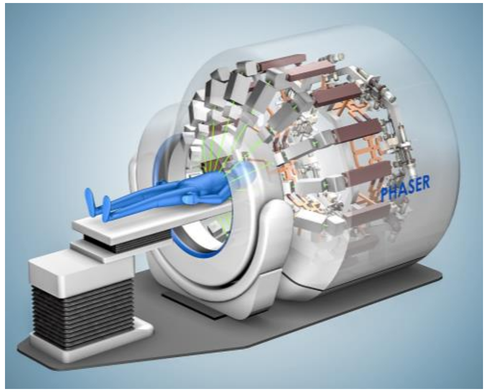
TibaRay, Inc.

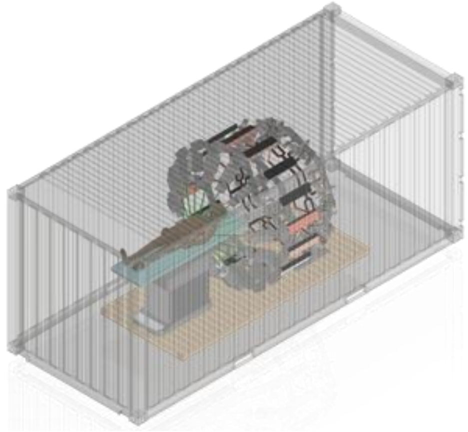
TibaRay Company Introduction

- **Vision – to cure cancer by rebooting radiation therapy**
- **Unprecedented team expertise**
  - World authorities in cancer therapy, medical physics, accelerator science from Stanford & SLAC National Accelerator Lab
  - Experienced business leaders from Siemens and Varian
  - Training/background from world-class institutions
- **Market: Radiation Therapy (RT)**
  - Radiation therapy equipment market >$7B, >6% CAGR
  - Total addressable market $30-50B enabled by our advances
- **Major pain points addressed by TibaRay technology**
  - Collateral damage limits cure of cancer
  - Much of world lacks access to RT
  - Inefficient processes/technology limit clinical throughput
- **TibaRay's solution: PHASER to deliver ultra-rapid "FLASH" RT**
  - 400X faster than state-of-art, motion "freezing" precision & FLASH biological advantages
  - Economical, global access to curative cancer care
  - Enables high throughput with best quality care
- **Established relationships with luminary early adopters**
  - Stanford, MD Anderson, others



Stanford MEDICINE

SLAC NATIONAL ACCELERATOR LABORATORY



TibaRay IP licensing from Stanford

- **Strong IP Position**
- Inventions made at Stanford and the SLAC National Laboratory belong to Stanford
- TibaRay now has **exclusive licenses from Stanford on all relevant IP** on accelerator components and PHASER
  - 13 issued US and international (CN & EP) patents
  - 2 pending US and international (CN & EP) patents
- Additional TibaRay-owned IP in pipeline
- TibaRay has all the elements needed to transfer the licensed technology to commercial products

SBIRs Introduction

- Accelerator technology underlying TibaRay's RT concept can be adapted for other applications
  - Specifically, multi-MeV electron linacs can be used to generate multi-MeV X-rays
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  - Design a 6 MeV novel electron accelerator for use in Radiation Therapy system
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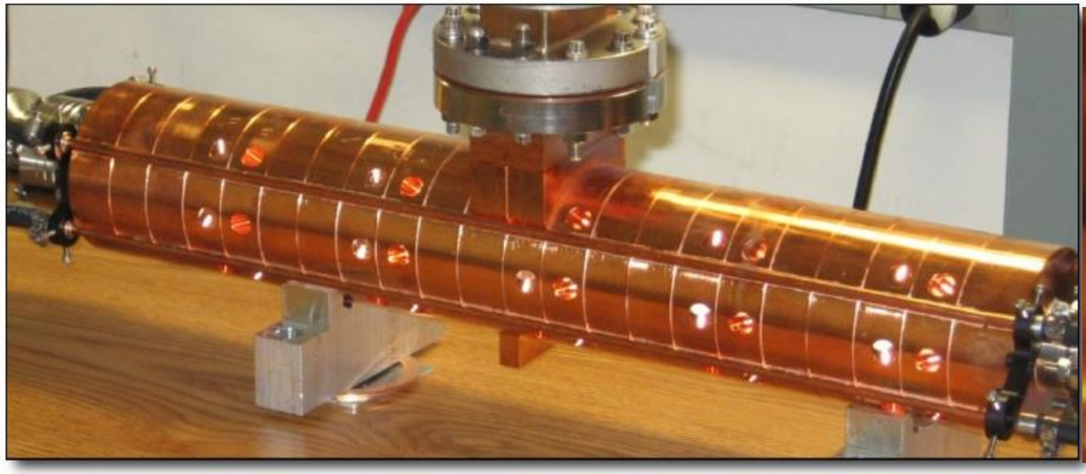
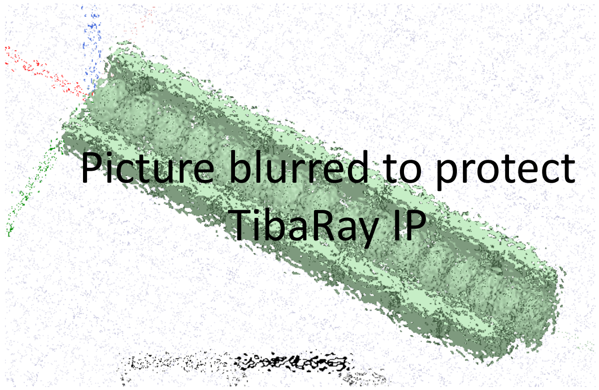
  - Designed for markets that are underserved, in places with less reliable utilities and service capabilities
- SBIR Phase 1: Ultra-Portable X-Ray Source using Novel RF Technology
  - Primary goal is to build a portable, non-radioactive source-based X-ray system for non-destructive imaging in security and inspection applications
  - Design a 2.5 MeV accelerator based novel concepts, 200 kW compact klystron and associated 60 kV portable modulator
  - Optimizing x-ray imaging scintillator for a flat panel detector using existing technology
- These accelerator designs can be adapted for replacements for radiation sources, betatron imaging systems and inspection systems for security, cargo scanning

Existing electron linac designs



- Basic design essentially unchanged for 60 years
- RF power is fed to accelerating cells through the beampipe
- Cells are coupled – modifying any particular cell will affect its neighbors
- Optimizing individual cells is compromised by the need to take into account effects on neighboring cells because of this coupling
- Coupling severely limits the ability to vary RF power from cell-to-cell
- Overall linac performance is therefore limited because of the coupling constraints; typical shunt impedances of 70-90 MΩ/m

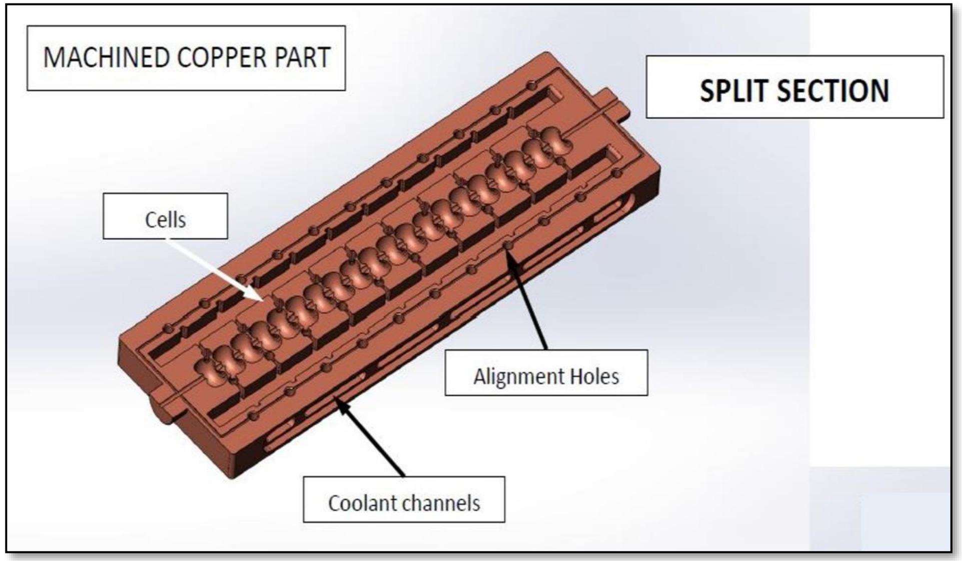
Novel electron linac design



- The design of these novel accelerators is based on new physics and a new invention from SLAC.
- Accelerating cells are NOT coupled, can be optimized individually
- Non-compromised control of RF phase & power going into cells →
  - Superior overall performance (higher shunt impedance ~180 MΩ/m)
  - More compact accelerator form factor

TibaRay implementation:

- Choose 9.3 GHz RF frequency
- Generalized design algorithms developed for
  - optimization of linacs of different energy and power levels
  - Integration techniques with electron source and x-ray production target
- Low-cost manufacturing designed-in at the outset
  - All the cells of a structure are machined in two halves that are brazed instead of brazing cell by cell
  - Cooling and alignment integrated into the two halves and machined at the same time as the cells
- Compact → lightweight radiation and magnetic shielding



Novel Linac Prototypes

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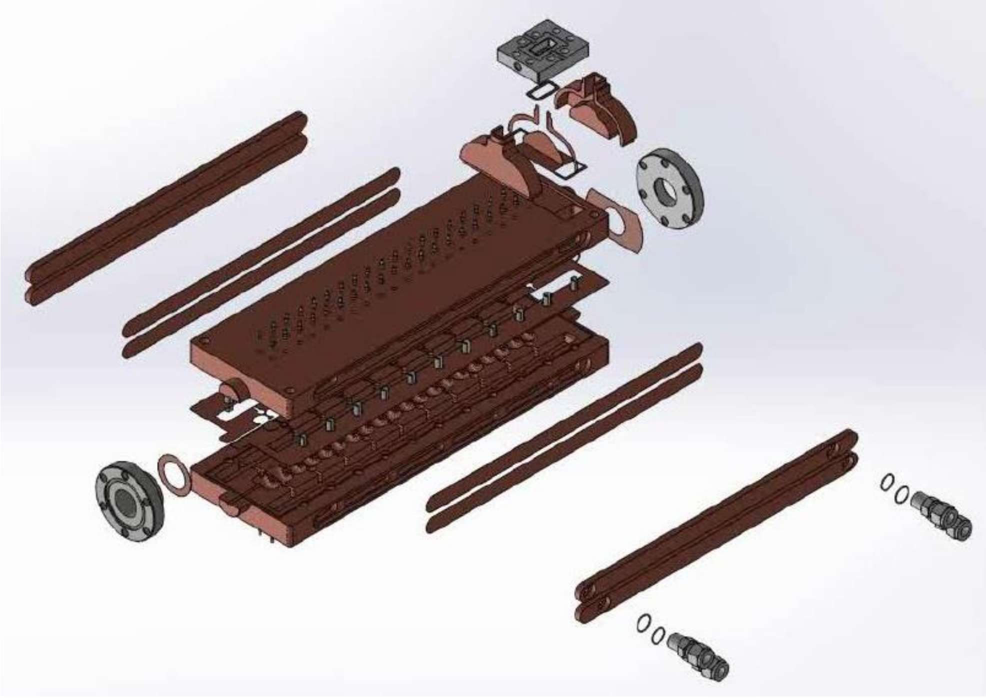
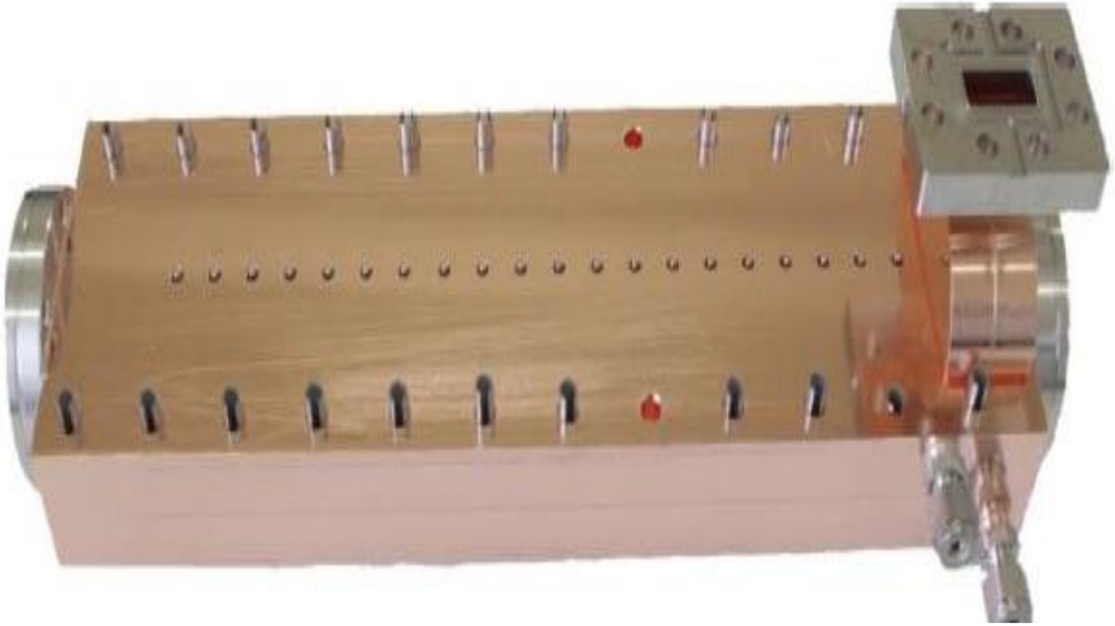
Prototype for Relativistic Electrons: <u>Built & tested – work exactly as designed</u>





- The parts count for final assembly of a linac is greatly reduced
- Lower cost and simple to manufacture

- We are on the ***fourth generation*** of finished β=1 (electron beam is relativistic) linacs.
- We have demonstrated shunt-impedances of 2-3 times higher than conventional linacs
- Need 2-3 times less RF power to establish gradient; 2-3 less heating in the structure

6 MeV “Rugged” Linac

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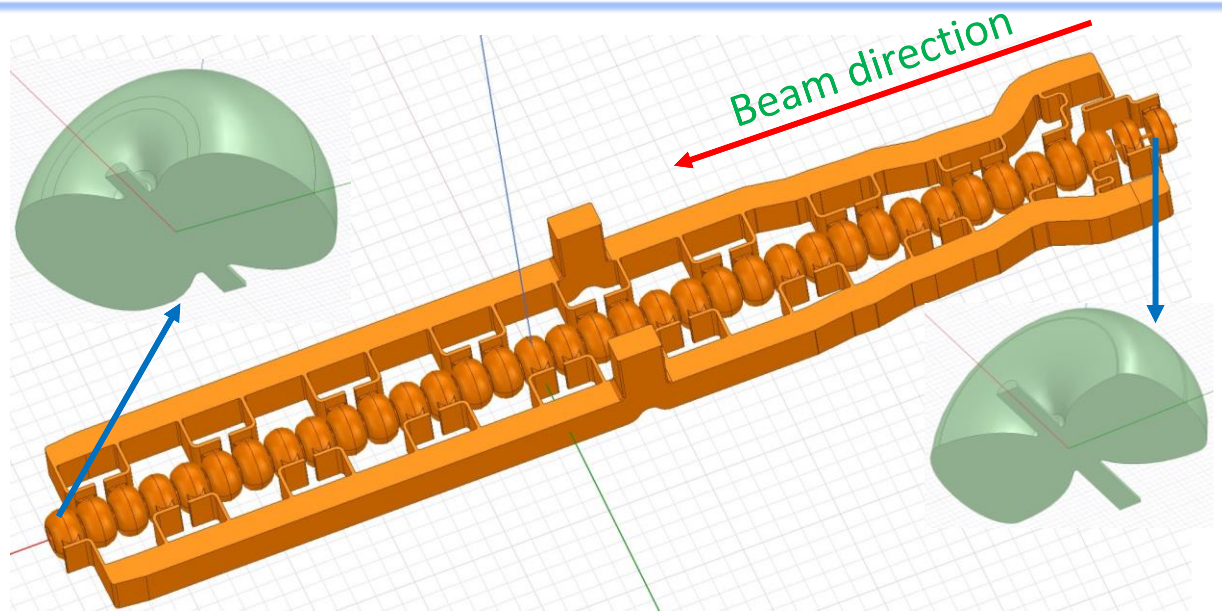
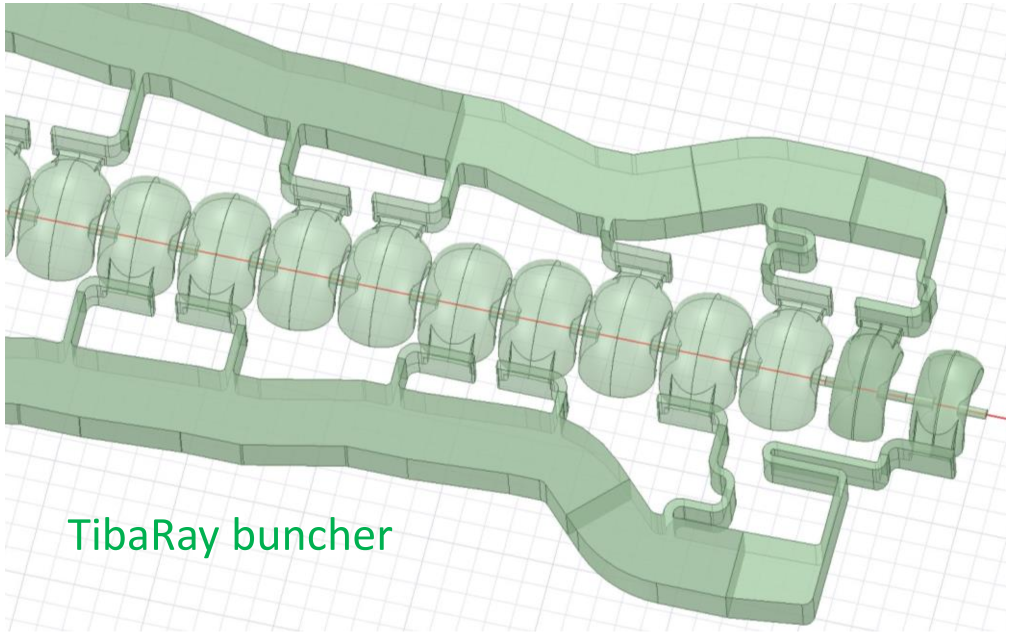
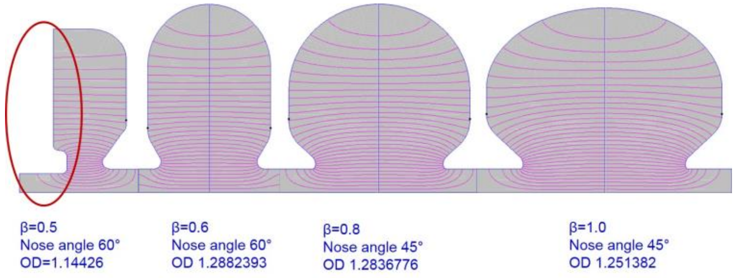
6 MeV Accelerator Design Evolution



two different cell shapes are needed for the TibaRay accelerator



TibaRay buncher

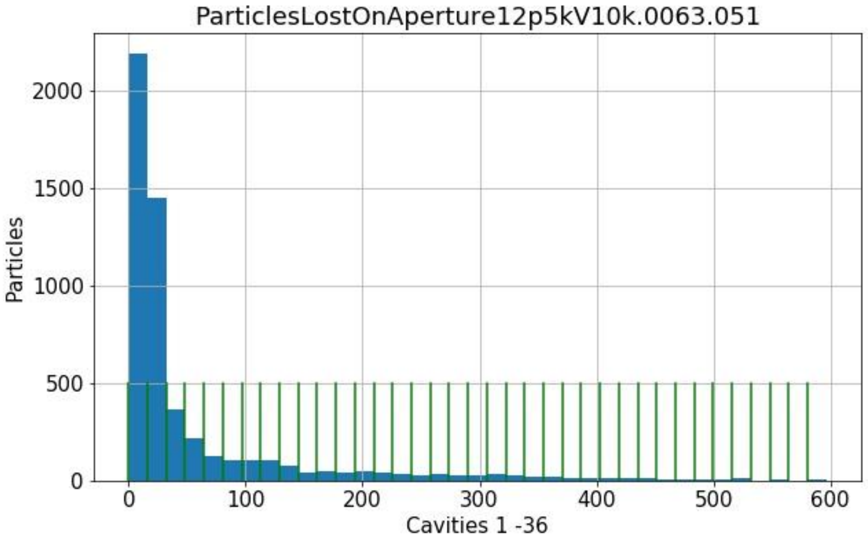


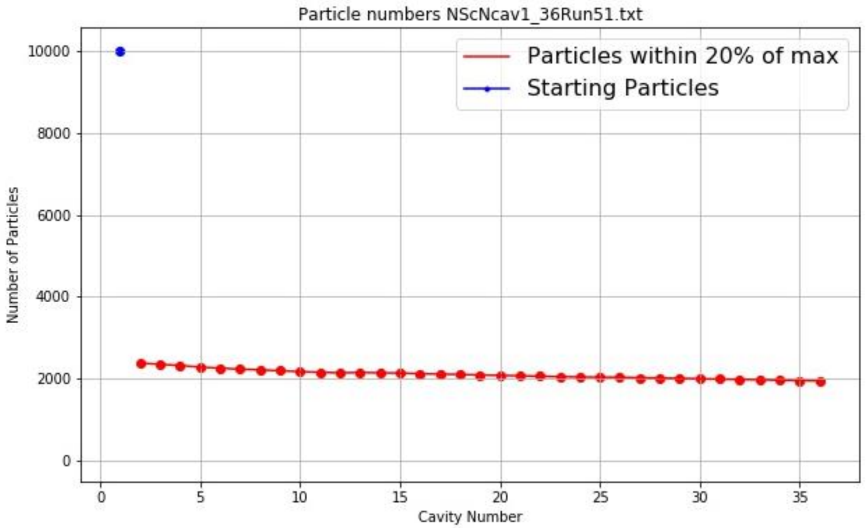
Traditional buncher

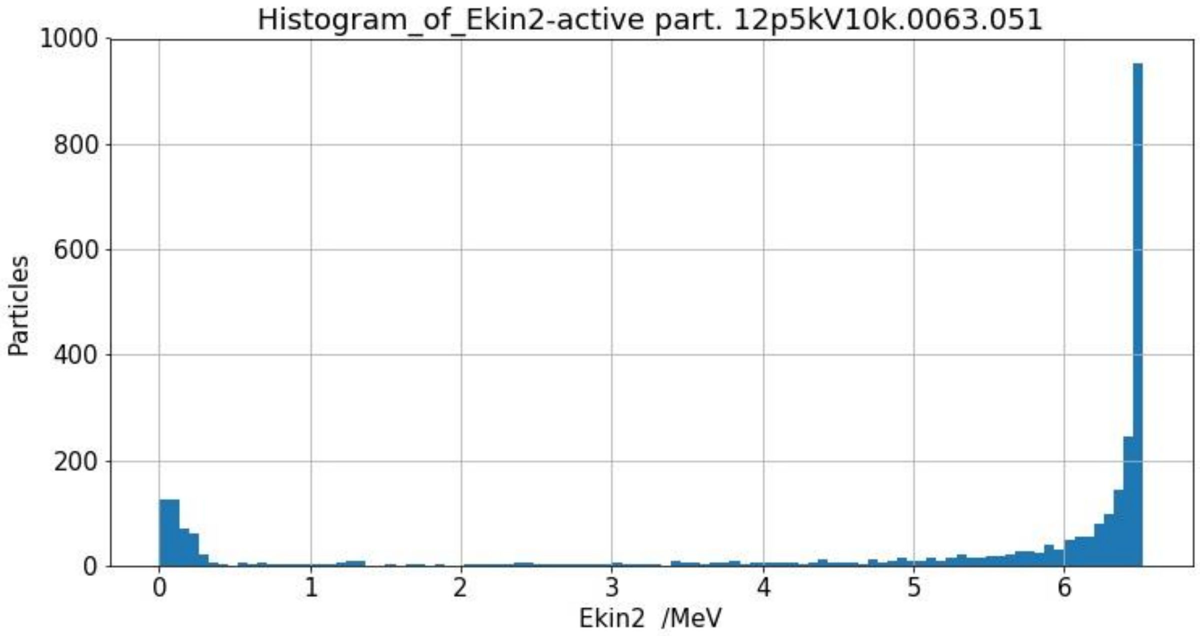
<u>BUNCHER</u>

- Needed at linac beginning to make electron beam relativistic
- In order to improve beam performance, we bunch the beam using the first 12 cells of the accelerator carefully controlling the phase and amplitude of the RF power into each cell. First two identical cells, kW scale power
- Much more efficient but was very hard to design because:
  - ➢ Mixed cavity shapes
  - ➢ Un-uniform, complex manifold shape
- Note* : SLAC approach uses the traditional buncher scheme which consumes much more power

Beam dynamics throughout the Accelerator







- By tuning the power and phase in the 12 buncher cells of the accelerator, we get
  - Reasonable capture efficiency,
  - Most beam lost in the first two cells (low energy)
  - Better than 1% energy spread
  - Better operational stability

Accelerator Manufacture Detail

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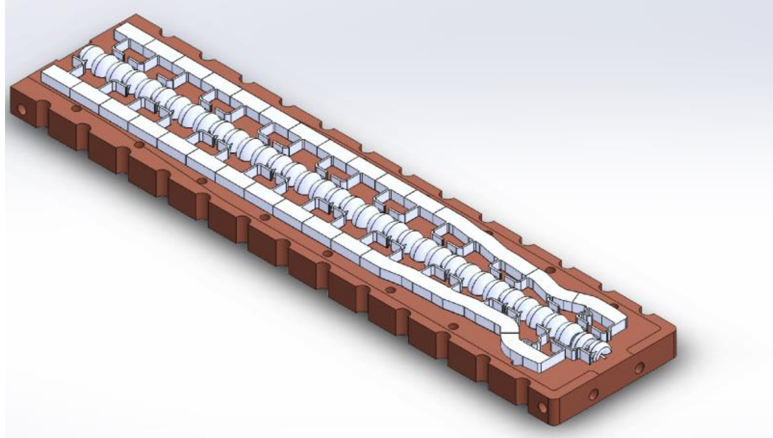
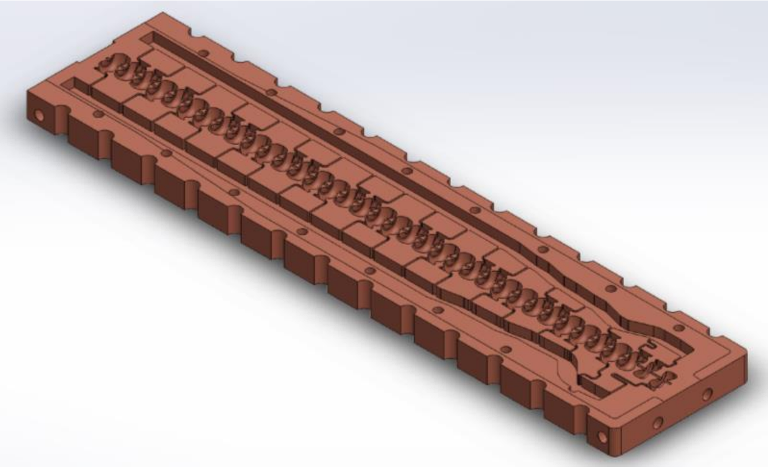
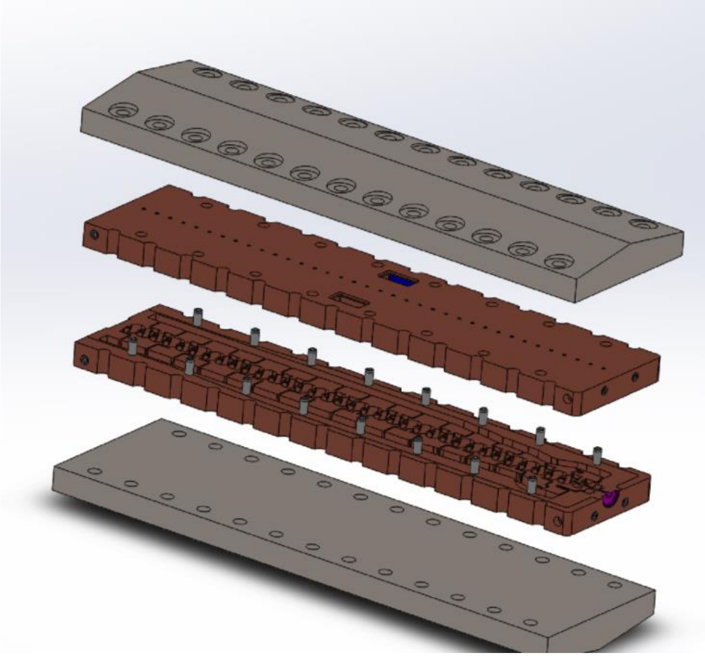
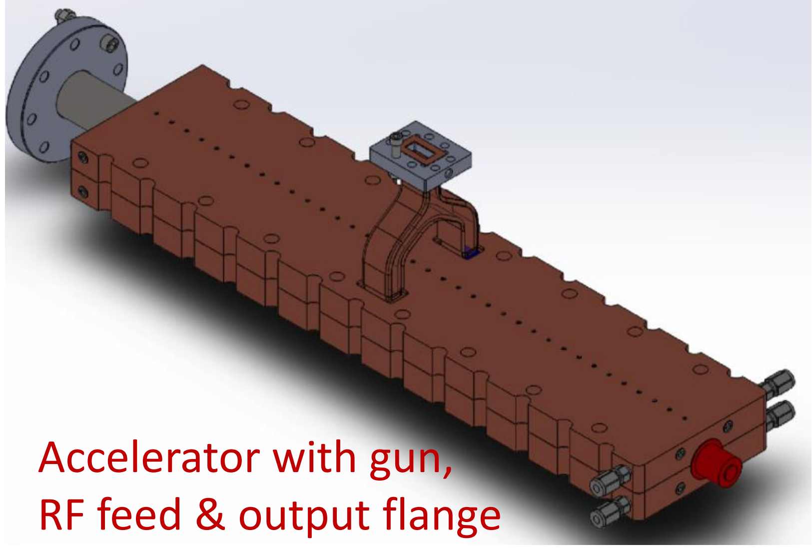


Machine two half blocks

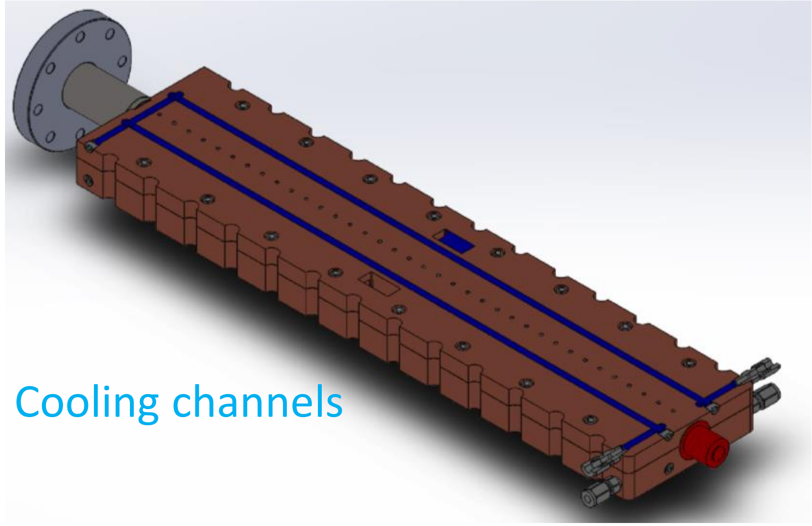




Diffusion bond the two halves
(SLAC development)

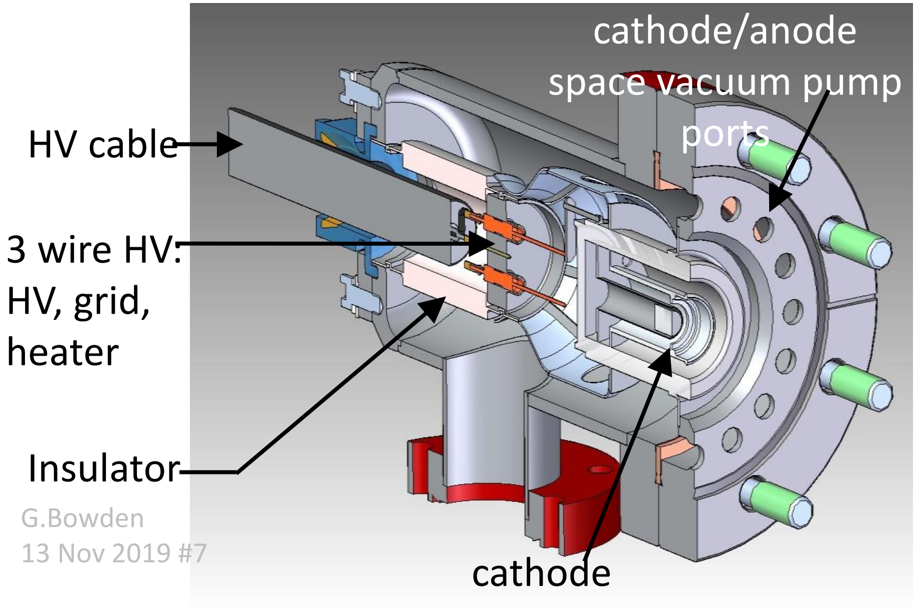


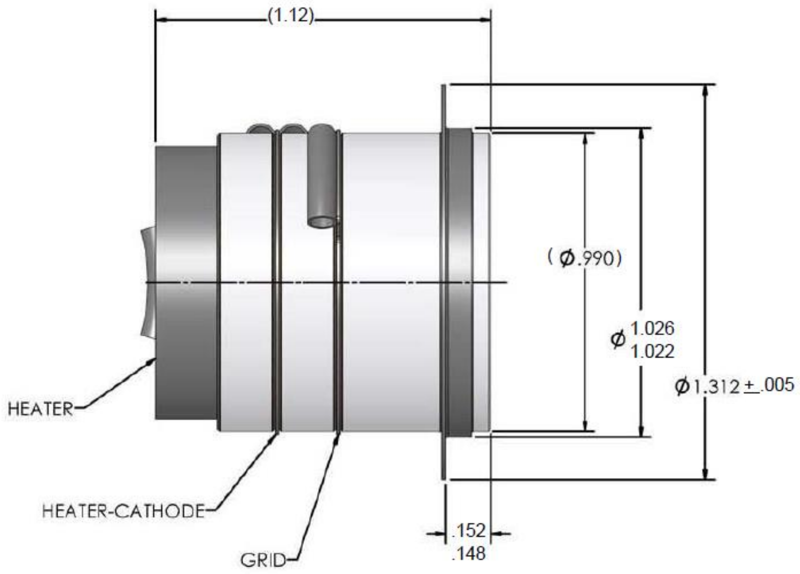
Accelerator with gun,
RF feed & output flange

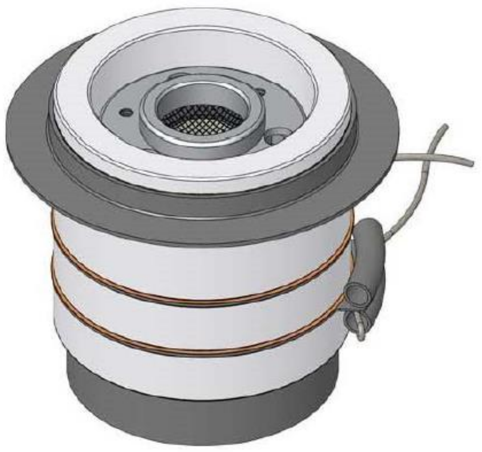


Cooling channels

Linac Design – Gun selection



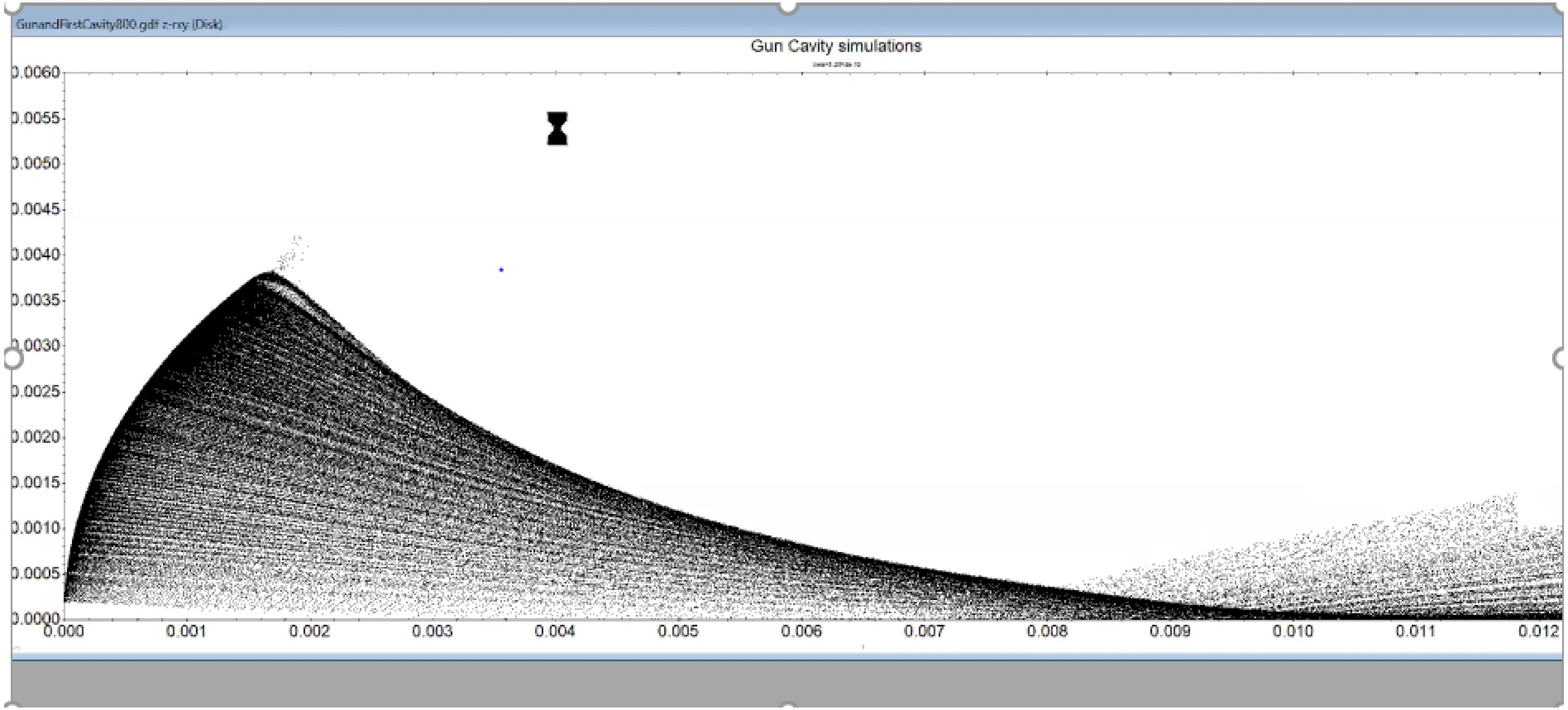




- SLAC egun works at 50 kV requiring ceramic insulator that allows either vacuum or oil contact only.
- The inside chamber is in vacuum and for 50 kV operations, the outside is also put in vacuum. This requires an auxiliary vacuum unit making the gun commercially nonviable because of expense, unreliability and added weight.
- TibaRay solution uses a much smaller 12.5 kV commercial gun. Consequence of this is that the gun and buncher section can be simulated and optimized as a single unit.

Electron bunching and output

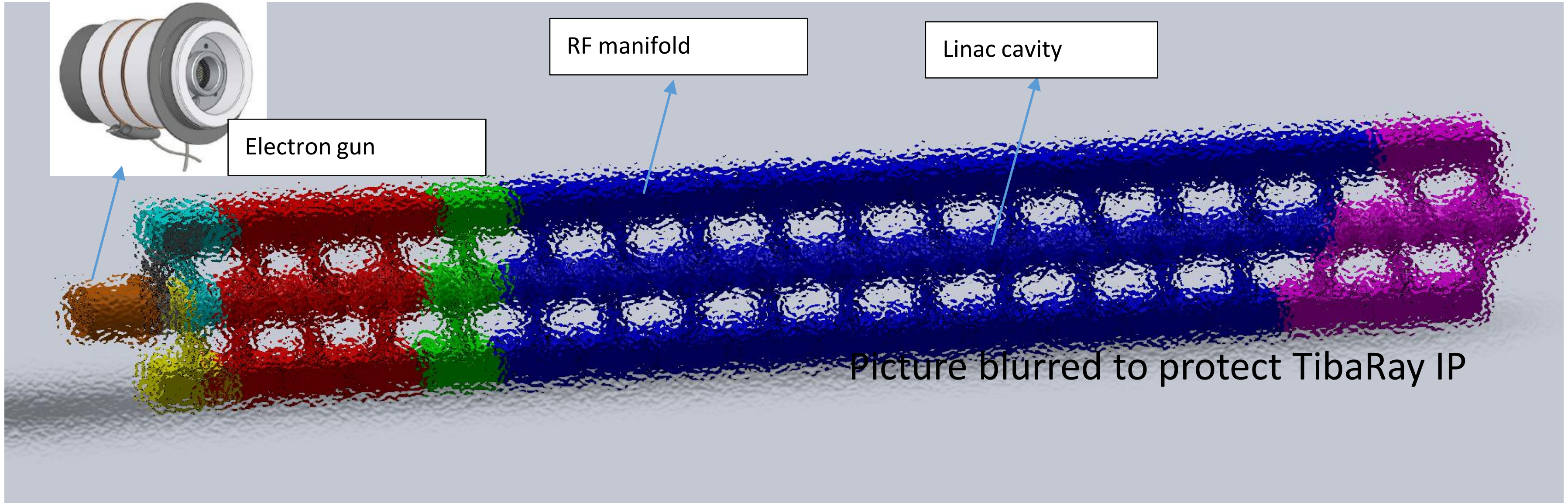
Simulations of electron trajectories from the gun through the first accelerating cell



Electron trajectory showing their interaction with first buncher cavity and resulting bunched electrons

Latest 6 MeV Linac Design

- Linac design is being further optimized for better performance by using more cell shapes
  - More efficient RF Power use
  - Better electron capture from the gun
- More compact RF power distribution manifolds
  - Lighter structures
  - Less copper needed
- Integrate a commercial 12.5 kV electron with the first linac cell design for improved beam parameters



6 MeV Linac Status

- Now
  - Optimizing current accelerator and buncher designs (“rugged” operation)
    - Reduce sensitivity to external conditions (power, phase, temperature).
    - Increase shunt impedance as much as possible
    - New buncher design optimization
    - Progress on TibaRay novel klystron design (different from SLAC design)

- Early 2021
  - Build 6 MV accelerator complete with electron gun and x-ray target
  - Power accelerator using collaborator facility; possible beam operation

- 2021
  - Characterize accelerator beam operation
  - If TibaRay klystron and associated high-voltage modulators developed
    - Power our accelerator with TibaRay klystrons
    - TibaRay modulators have built-in battery backup → standalone operation

6 MeV Linac Summary - 1

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- “Rugged” accelerator designs are well along
  - Much lower RF power requirements allows for RF-source to be de-rated
  - Reduced sensitivity to external conditions (power, phase, temperature)
  - Redundancy – if one cell fails, the accelerator can still adapt to its loss
  - Lower the RF heating of the accelerator, cooling systems de-rated
  - Lower overall power requirements allow battery-backed operation

- RF power source
  - Possibility to adapt to a novel klystron scheme developed at TibaRay
  - Lower voltage modulators are more compact and redundant in operation
  - TibaRay would improve design for more/different commercial applications

- X-ray Radiation output
  - Can produce ~2,000 cGy/minute at 100 cm using a standard 1.5 MW magnetron

6 MeV Linac Summary - 2

- Lower costs to manufacture for volume production
  - Manufacturing cost optimization has started but not yet finished
  - Greater than a factor of two reduction in manufacturing cost expected
  - Newer techniques (e.g., eliminate brazing) will bring price down even lower

- Market
  - Our accelerators can be made as plug-compatible replacements in existing applications with the benefit of less strain on the RF system OR higher beam
  - New applications that can take advantage of higher performance
  - More compact/portable systems are possible (e.g., low dose, low energy)

- Advantages in application
  - "Rugged" medical accelerator – less prone to breakdown, redundant, less expertise needed to fix
  - Various applications using electron linacs, e.g., cargo scanning, limited by price and operational cost. Cheaper machines will encourage more wide-spread use

2.5 MeV X-ray Source

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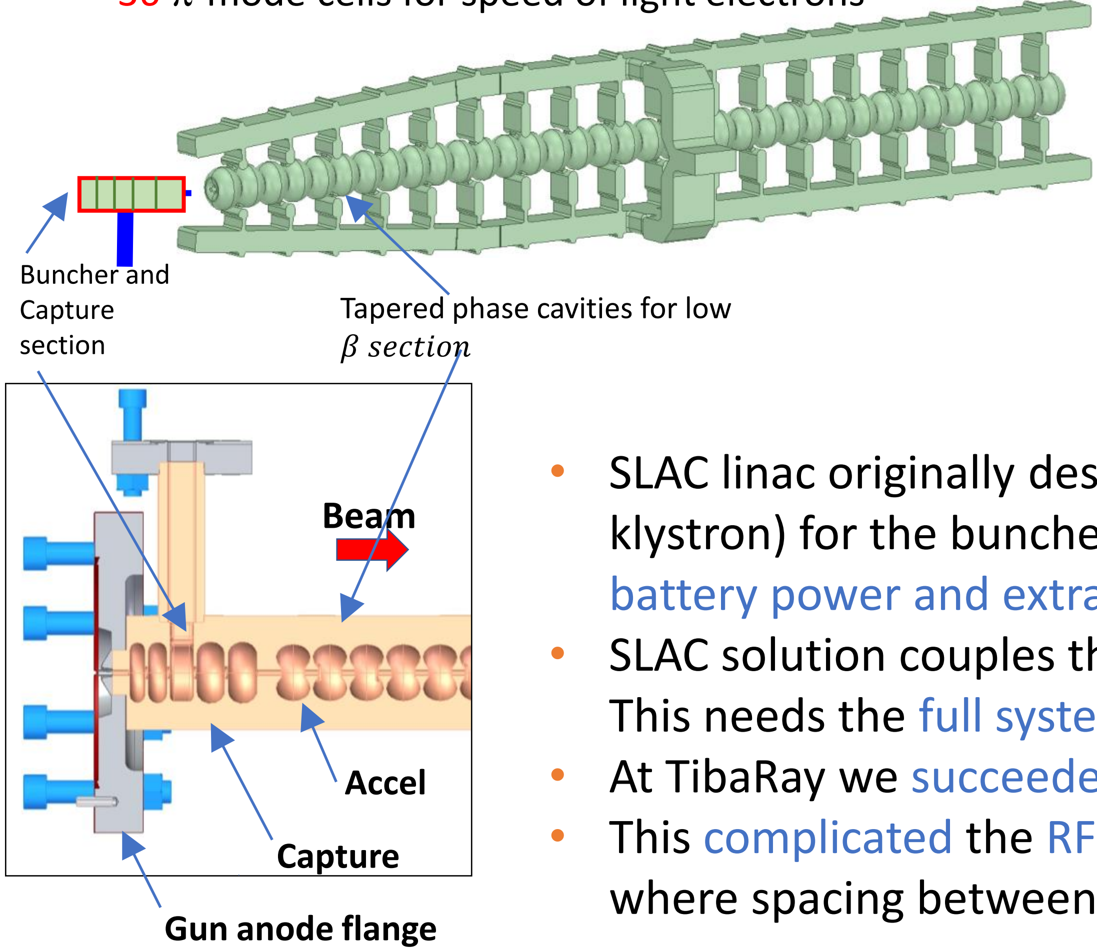
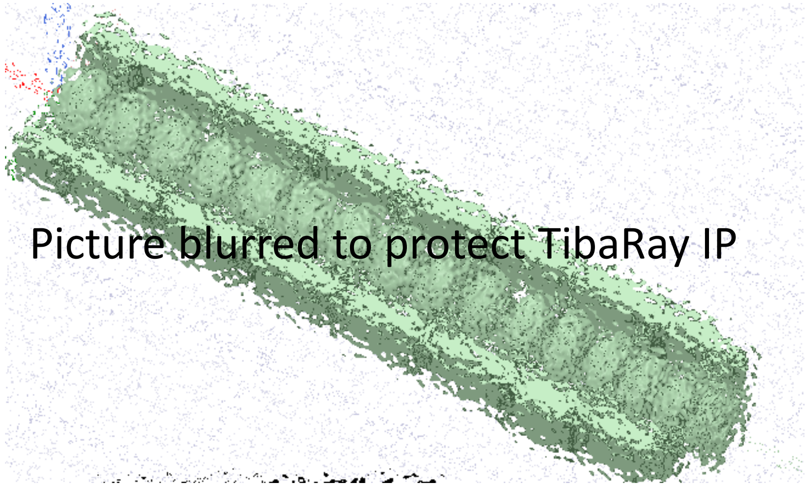
2.5 MeV Linac design progress

SLAC linac design

36 π-mode cells for speed of light electrons

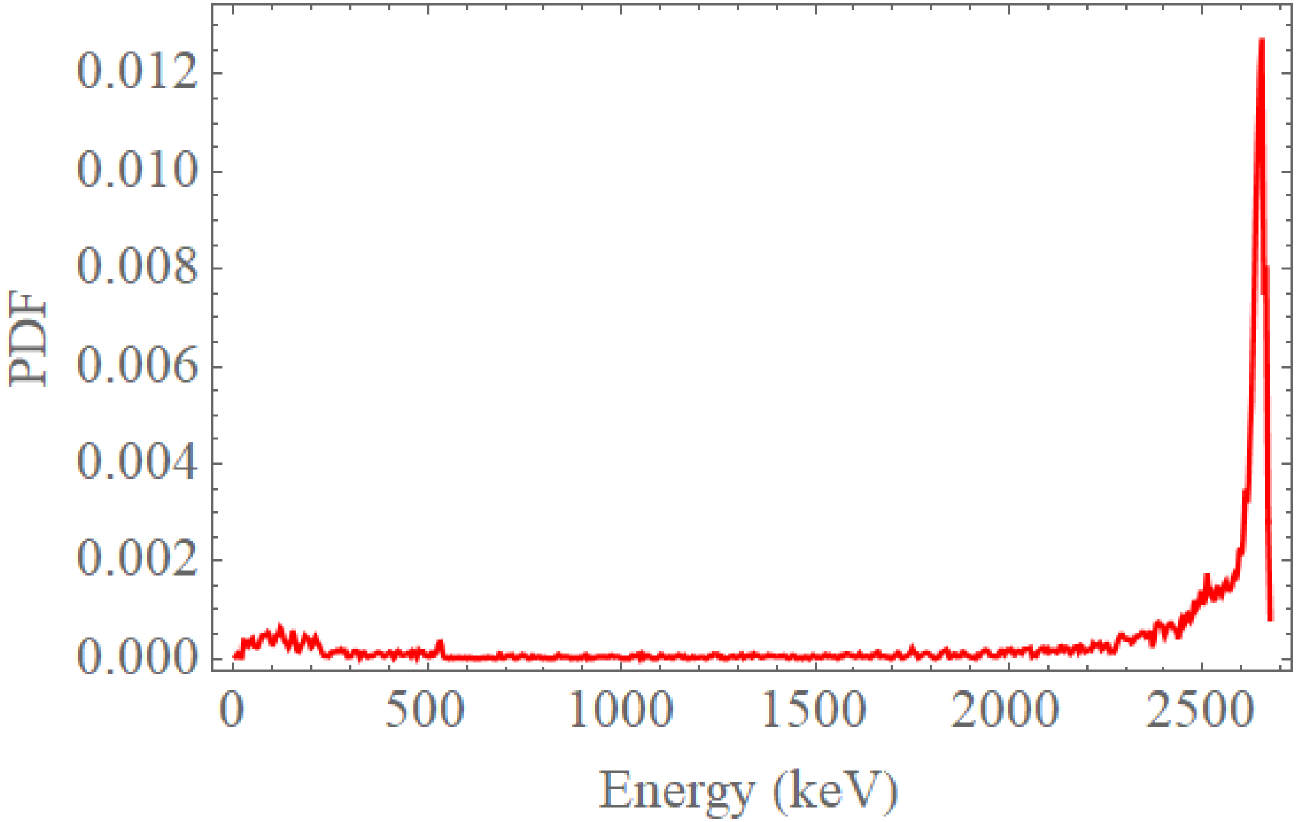


Commercial 12.5 keV eGun used in TibaRay design



- SLAC linac originally designed for variable energy operations, requires ~200 kW (1 full klystron) for the buncher and capture section alone: extra klystron, needs extra battery power and extra weight
- SLAC solution couples the buncher to the rest of the linac in a very complicated way. This needs the full system simulation approach to the design problem.
- At TibaRay we succeeded in designing a single RF feed for the whole system
- This complicated the RF manifold design and we included extra degree of freedom where spacing between cavities was also allowed to change

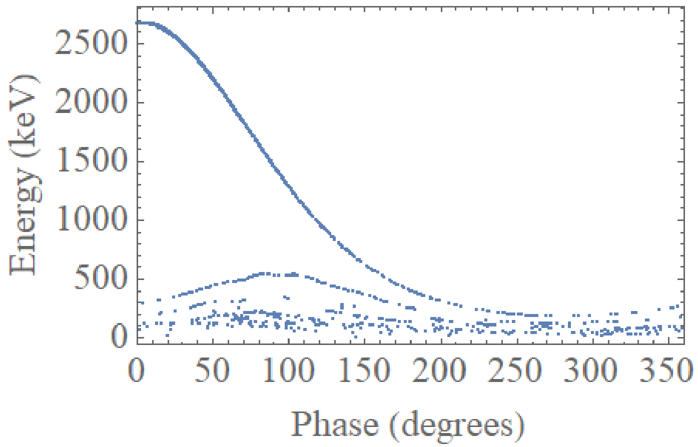
Linac design progress: X-ray output



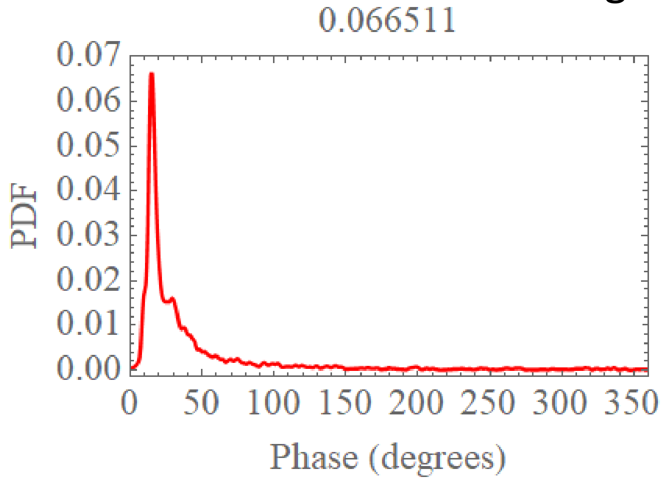
(a) X-ray spectrum from Linac

Max E = 2.65 MeV FWHM = 32 keV (1.2%)

Expected dose rate = ~10 cGy/min at 100 cm



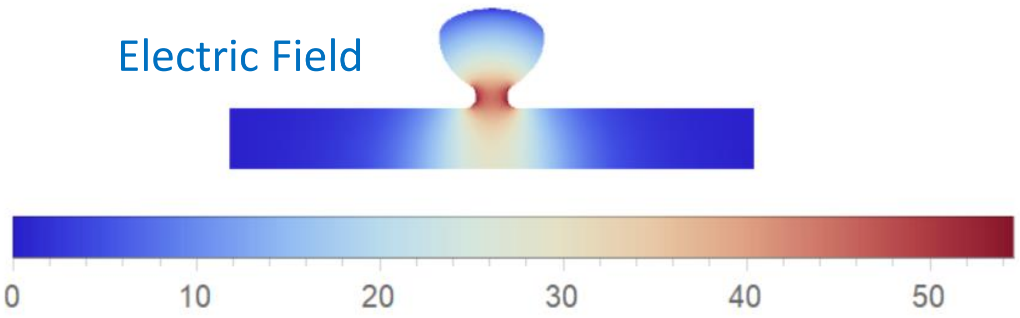
(b) Electron distribution as function of angle and energy

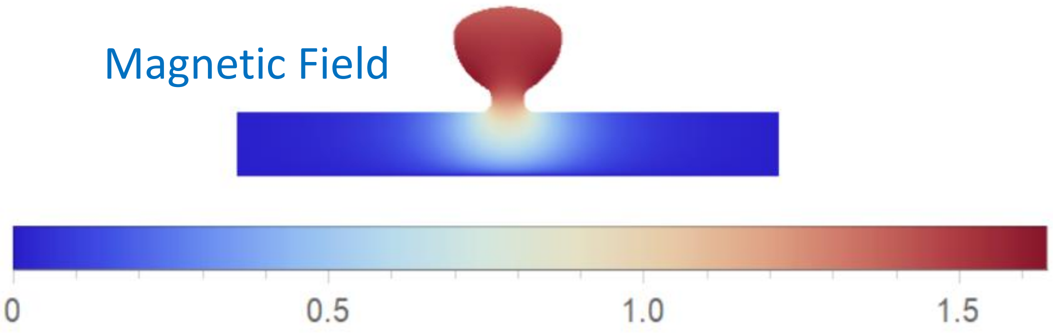


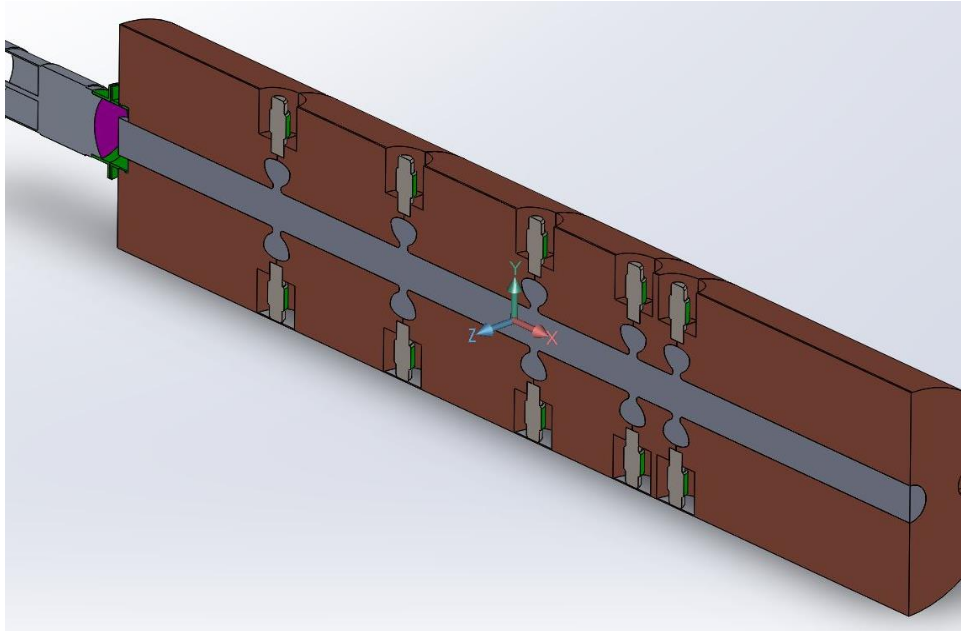
(c) Distribution as function of angle

Novel Klystron Development (Tesla Simulation)

Individual cavity design showing Electric and Magnetic Field



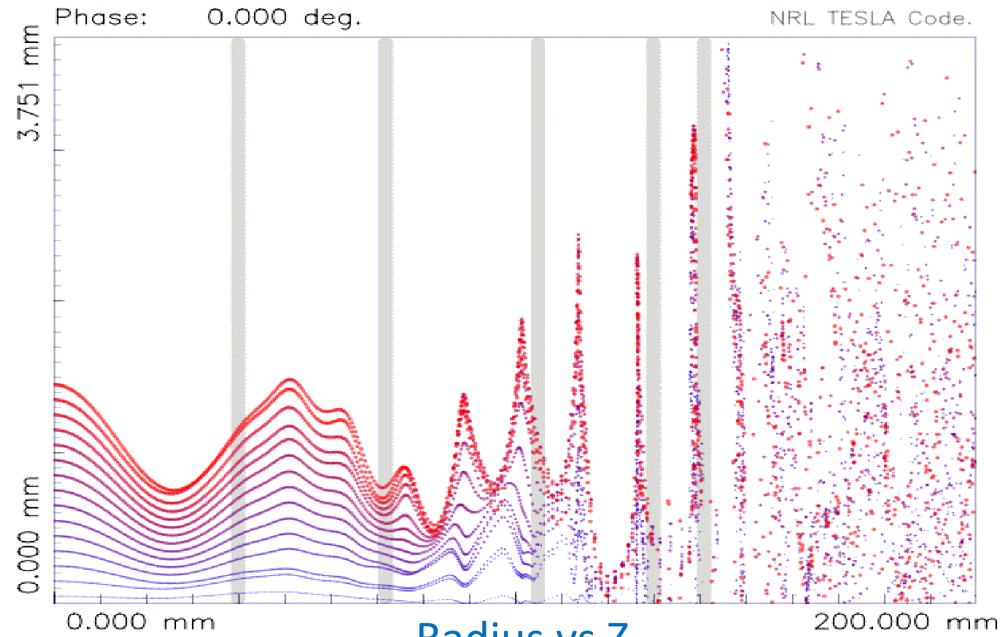




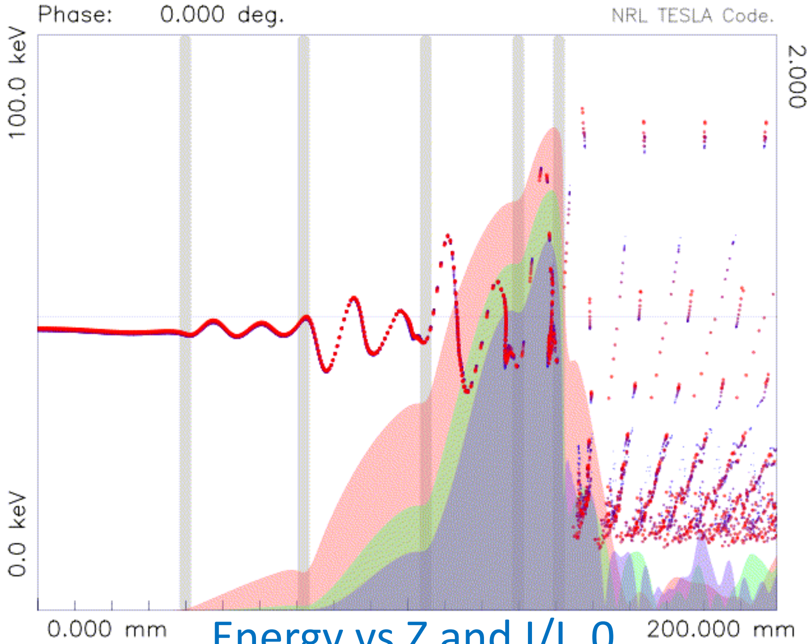
Klystron section schematic showing the five cells

- We used finite element analysis to generate the cavity shapes and fields.
- We used these realistic fields in the Tesla simulations to feed back on the cavity shapes with the goal of optimizing the efficiency.
- With this extremely large beam tunnel radius and low magnetic field we could reach ~ **50% efficiency**.
- The klystron is compact, the interaction circuit **< 15 cm** long, and the **total device length ~ 25 cm**.
- In the mechanical design phase, we will strive to reduce the weight.

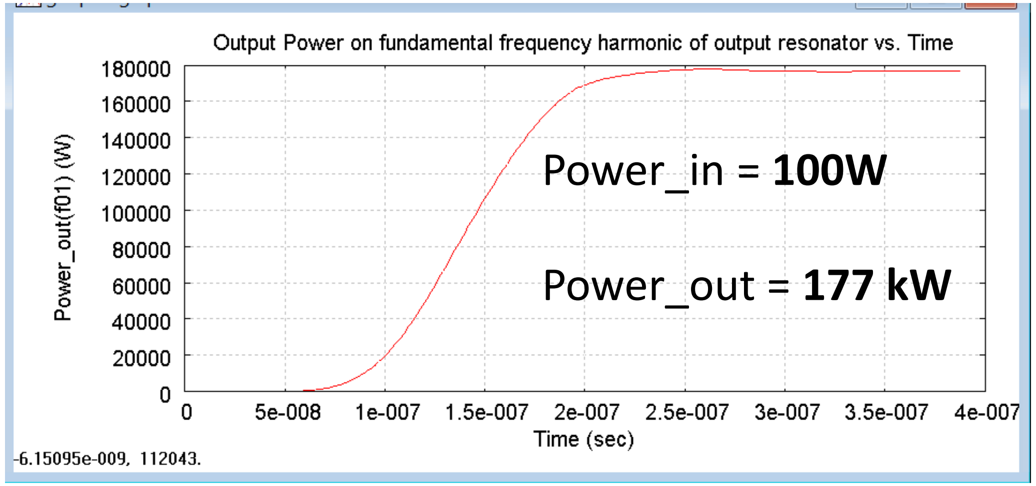
Novel Klystron (Tesla Simulation) – 5 cavity



Radius vs Z



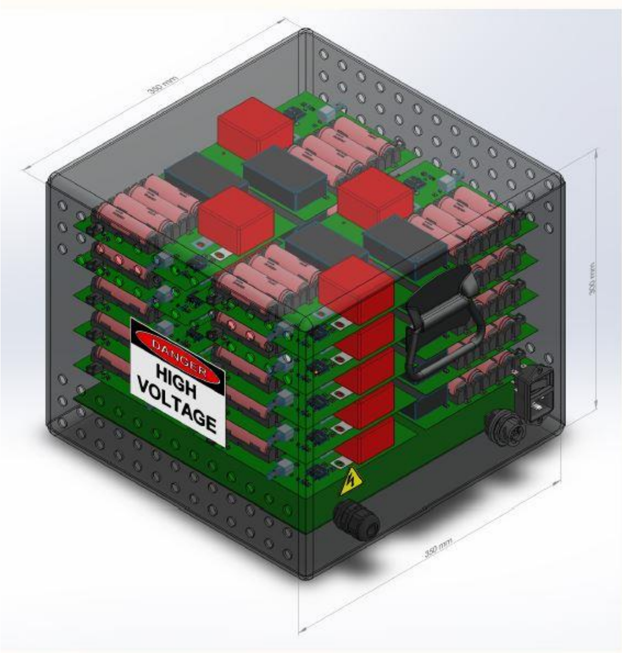
Energy vs Z and I/I_0



- We used very large beam tunnel, and hence the magnetic field required to confine the beam is only 1.3 kG; very compact magnet.
- At tunnel end the beam barely touches the output wall, no body current → thermally stable
- The beam tunnel despite being large is reasonably small compared to the wavelength; the reduction from 11.424 GHz to 9.3 GHz in RF frequency indeed helped.

Battery powered modulator

The overall system size and weight is reduced (eliminates the external power supply and all heavy transformers) dramatically while allowing for battery-based operation



Battery-powered modulator design also showing and stack of 20 HV boards in a protective enclosure. The final product will be <u>~ 1 cu ft and <40 lbs in weight</u>

- Based on Marx capacitor bank
- Uses distributed elements.
- Each board contains it own power supply (battery)
- Each board contain its own high voltage generators
- Architecture eliminates high voltage feeding transformers.
- This architecture eliminates the high frequency external DC power supply needed for the SLAC architecture.

2.5 MeV X-ray Source Summary

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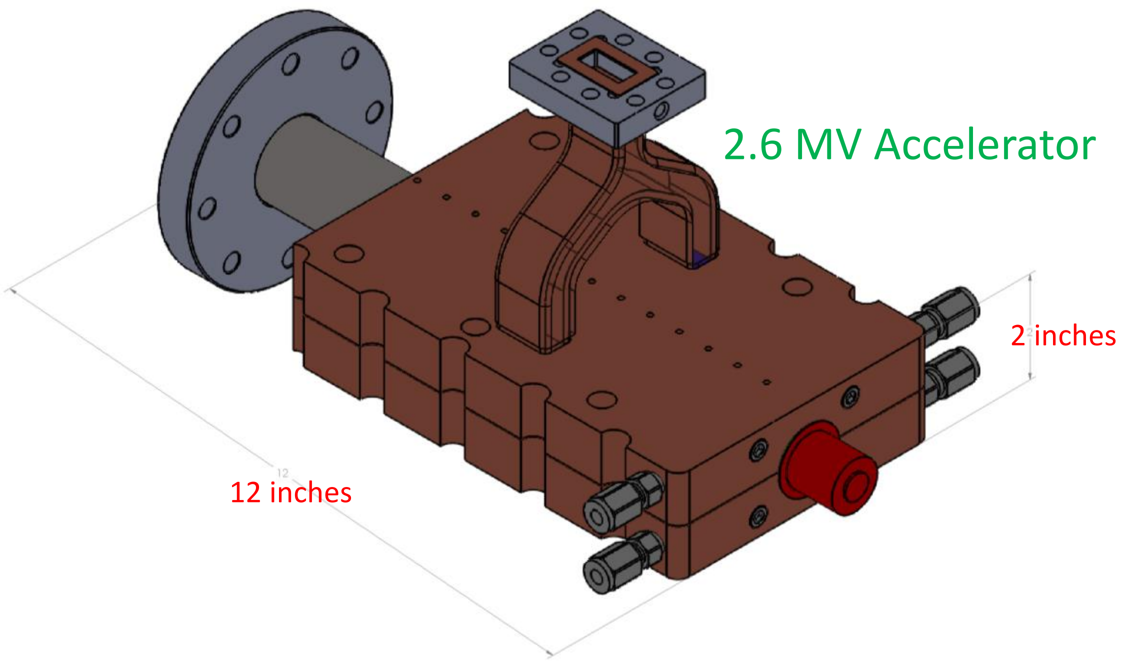
- Significant progress has been made in Phase 1 on all fronts
- System design should be complete by end of Phase 1
- By Phase 2 (if approved) we will build and commission a full commercial system



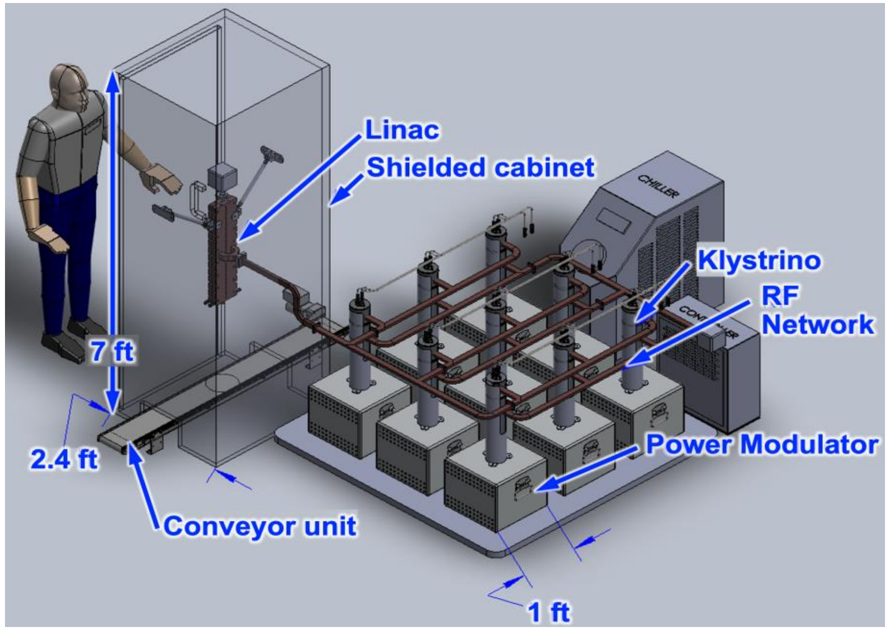
- Approximate dimensions above
- Should be able to make it more compact in width →less weight
- A sample calculation show that this compact accelerator compact with a 200 kW RF Source can make doses of ~10 cGy/minute. It can be used for Radiography

TibaRay Technology Possibilities

TibaRay accelerator/RF technology is a superior solution for:

Cargo scanning
Non-destructive testing/inspection
Food sterilization

Example - Blood Irradiator



Compact **on-site** lab-based system 6.5 kW electron beam power

- Novel compact accelerator & RF power
- Produce ~10% beam power of massive facility, in **lab-based cabinet form factor**
- **High throughput**: deliver sterilizing dose of 25 kGy to **380 units of plasma/hour** (enough to treat ~300 patients with COVID-19), or **similar # PPE**
- Fits in individual blood centers/hospitals at point of care

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