Stationary CT Design for Real-Time 4D Imaging

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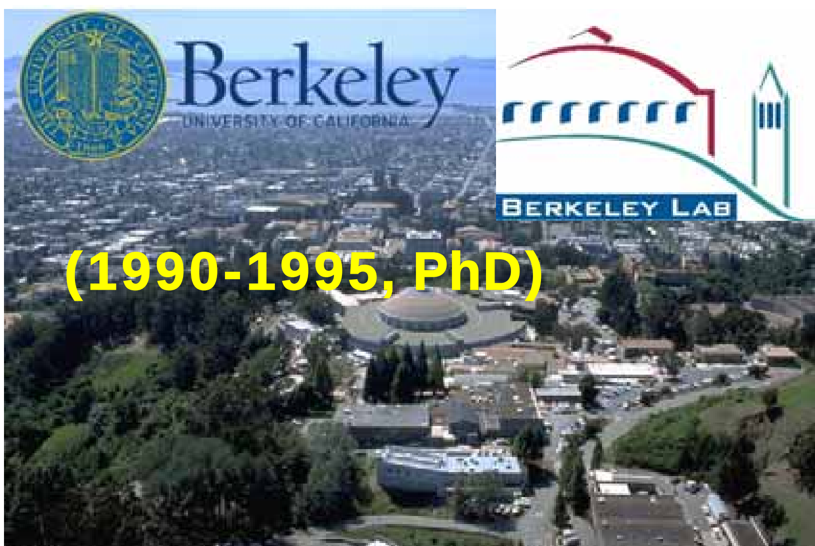
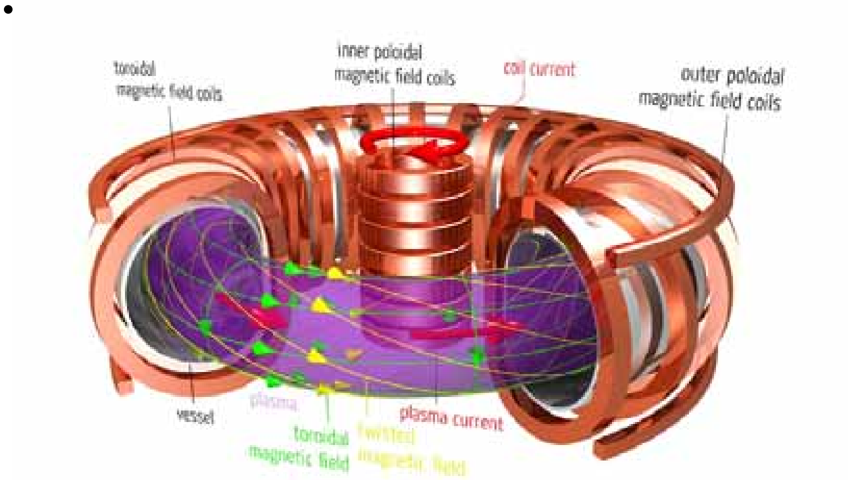
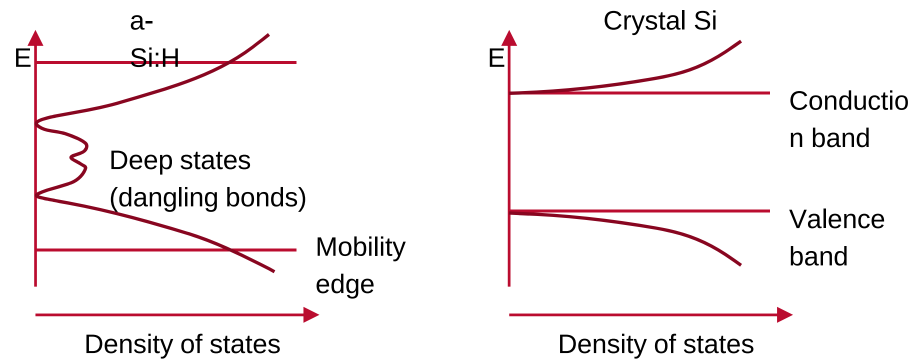
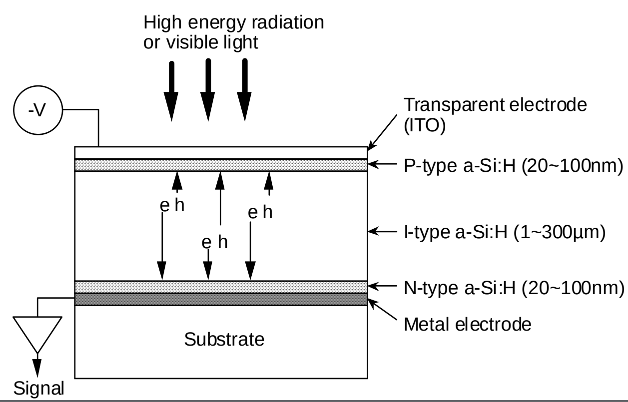
A little bit about myself…





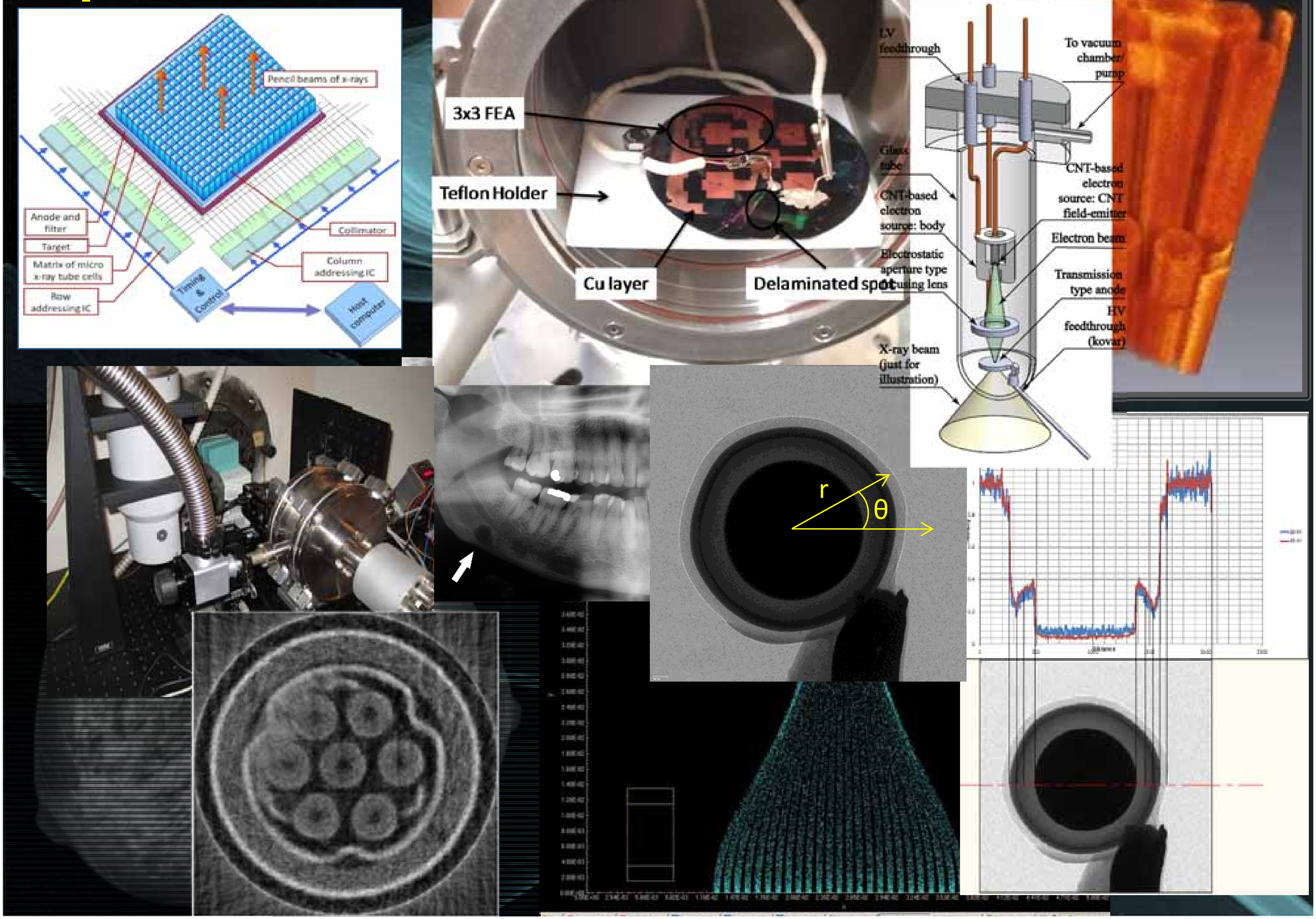





가톨릭대학교
THE CATHOLIC UNIVERSITY OF KOREA
The Korea Herald
I was somewhere around here... (1995-2009)

doing these...

Expanded research areas…



Research Interests at UNM

- Nuclear Imaging for medical, nuclear nonproliferation, and homeland security
  - Gamma rays
  - X-rays
  - Neutrons
- Stationary 4D CT for Cardiac and Traumatic Brain Injury Applications
- Algorithms for CT Reconstruction Image Processing, and Image Analysis
- Machine Learning for Imaging

Introduction

- Traumatic Brain Injury (TBI) is a major cause of death and disability
  - Approximately 153 deaths/day in the U.S.
- “There is often confusion about the mechanical etiology of concussions”
  - The many different head motions that can occur when an impact force is acting on the head is a major factor of this confusion.
  - Key to understanding the immediate impairment of TBI is determining the effects of causal forces on the blood vessels and cellular networks within the brain.

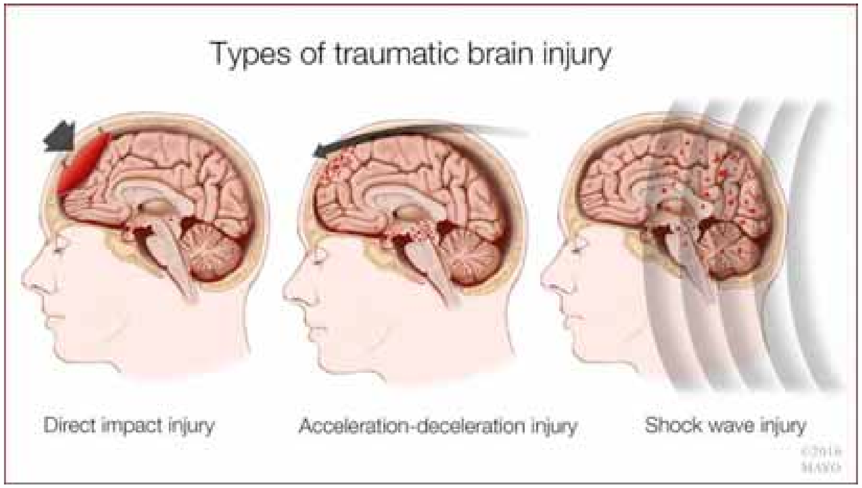
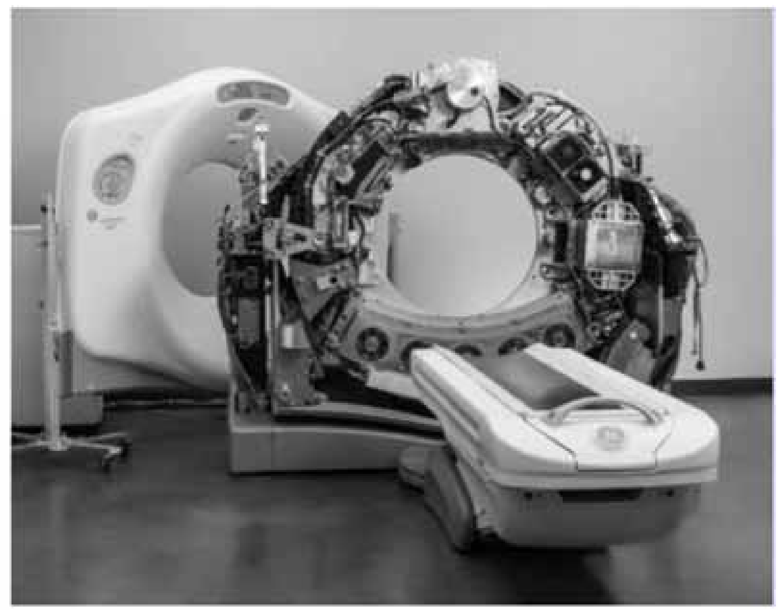


Image credit: Mayo Clinic 2016

TBI and Computed Tomography (CT)

- Real-Time CT is integral to aid in the design of TBI prevention gear.
  - CT would have a temporal resolution of around 30 milliseconds.
  - Immediately useful in identifying accurate strain/deformation thresholds for TBI
  - Development of a real-time CT may lead to advancement of research toward better TBI detection.
- Current state-of-the-art CT systems use a rotation gantry.
  - Gantry rotation time of approximately 270 milliseconds leads to a temporal resolution of the same time.
  - Mechanical limitations on the gantry prevent the system from reaching the desired 30 millisecond temporal resolution.



Typical gantry of a conventional CT system with covers removed (photograph of GE Light Speed VCT®).

Our Approach

- To reach a temporal resolution of 30 millisecond, we are investigating a stationary CT architecture.
  - Removes the rotating gantry by electronically sweeping one or more x-ray beams across the field-of-view.
  - A gantry ring of more than one hundred x-ray sources will produce the x-ray beams sequentially
  - A second gantry ring houses the detector elements to cover 360 degrees.

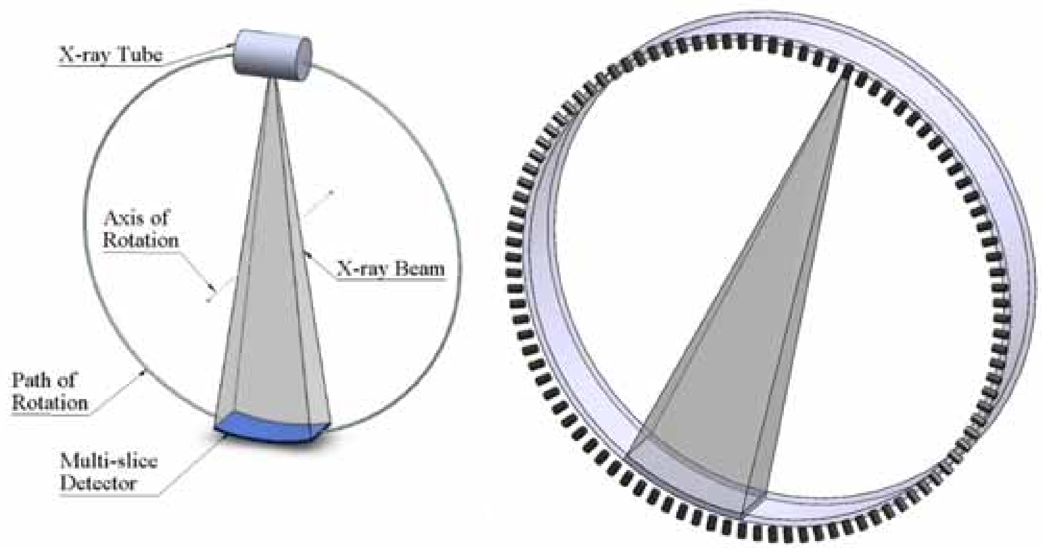
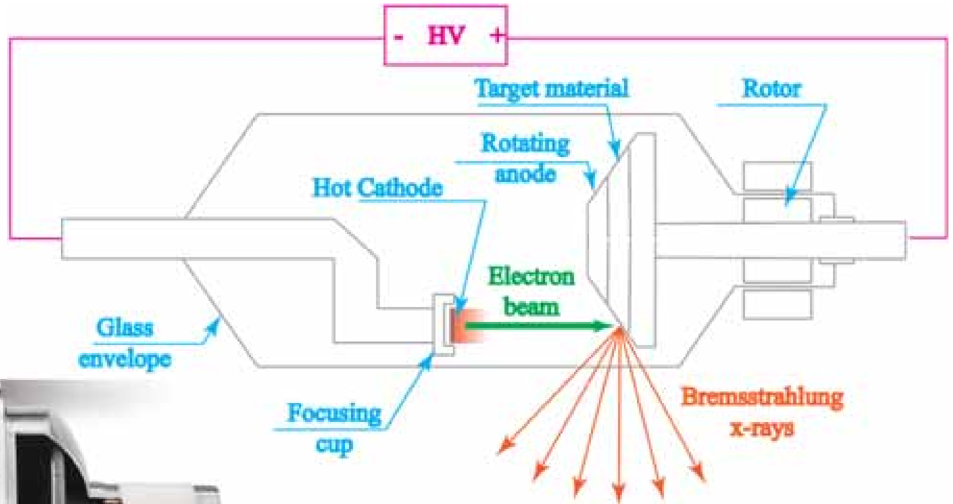
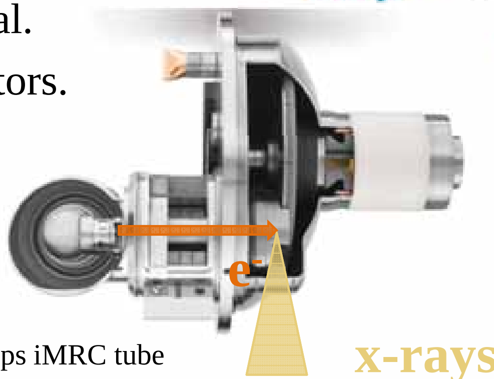


Figure 1: Schematic Illustrations of conventional CT architecture (left) and stationary CT concept (right)

Current X-ray Tube for CT

- Electron source:
  - Hot cathode/filament emits electrons by thermionic emission.
- Anode:
  - Anode is kept at higher potentials than the cathode → electrons are accelerated toward the anode.
  - A tungsten target is attached/deposited on the anode.
  - High energy electrons strike the target→ bremsstrahlung x-ray spectrum.
  - Reflection type anode.
- Electron focusing:
  - Focusing cup.
- Vacuum envelope:
  - Common materials:
    - Glass + metal,
    - Only metal.
  - Ceramic insulators.



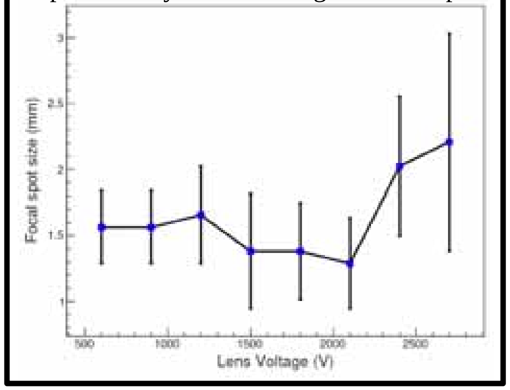


Philips iMRC tube

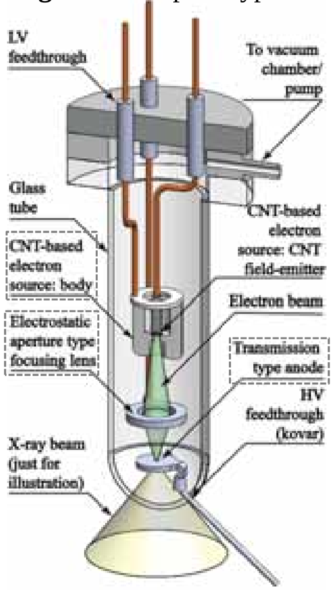
Compact X-ray Tube for Stationary CT

- We need:
  - More than at least 200 projections for a medical CT reconstruction using an iterative CT reconstruction algorithm.
  - An array of closely spaced x-ray sources,
    - individually addressable,
    - capable of producing x-ray pulses with less than 0.165 msec pulse width
- Development of a compact x-ray tube that fits these requirements.

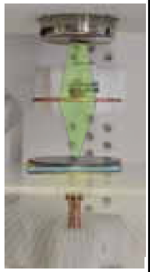
Focal spot size can be controlled by lens potential by the following relationship.

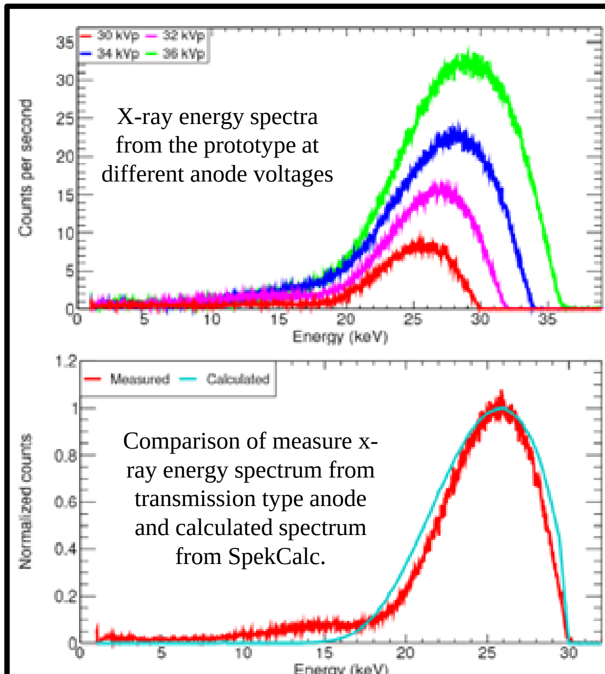


Schematic of the **first-generation** prototype



First-generation prototype





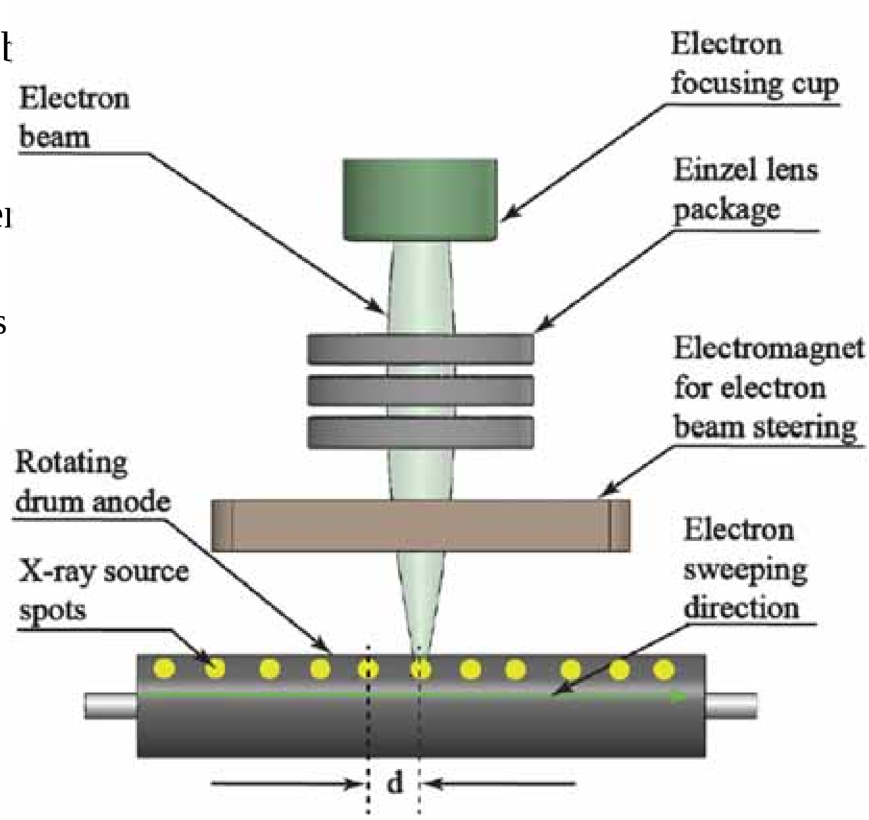
Issues with the first-generation prototype:

1. Target on transmission type anode melts at high currents.
2. CNT source had frequent arcing between the cathode and the extraction grid.
3. Electron emission current from the CNT source was not uniform.
4. CNT source was frequently getting damaged from high-voltage breakdowns.

- A. Avachat, W. Tucker, C. Castano, **H. Lee**, *"Particle-in-cell simulations of electron focusing for a compact x-ray tube comprising CNT-based electron source and transmission type anode,"* IEEE Trans. Electron Devices, accepted, 2019.

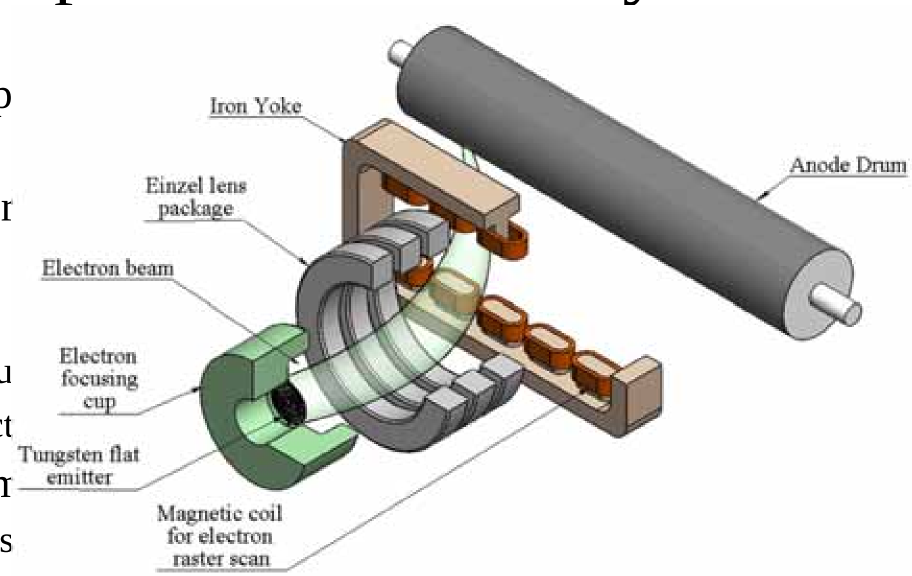
Initial Challenges

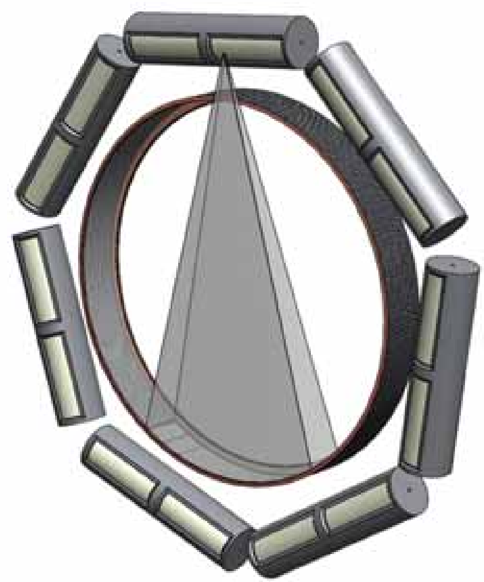
- Compact enough to fit ~180 x-ray spot sources in a ~800 mm ϕ ring
  - ~25 mm space between x-ray focal spots
- Fast enough to sweep one or more x-ray t
  required projections
  - ~150 μsec/pulse
- Be able to generate an x-ray beam with er
  production.
  - Technique Factors: 120 kVp and 340 mAs



Components for Compact and Fast X-ray Tube

- Conventional types of primary comp
requirements.
- We propose using the following alter
  - Tungsten flat emitter cathode
  - Rotating drum anode
  - Electrostatic lenses for electron focu
  - Electromagnets for steering the elect
- The tube must also avoid the vacuum
  - Damage to cathode or anode renders

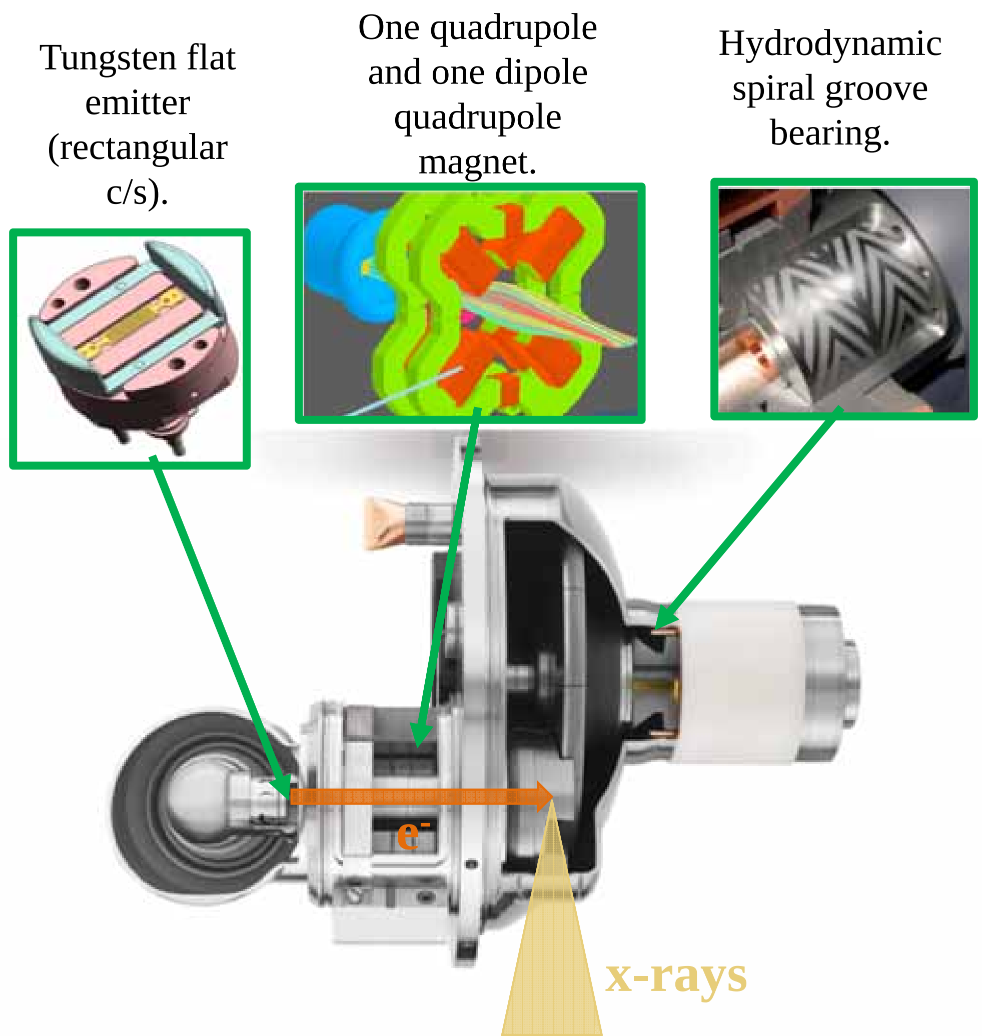




Why These Components?

- Tungsten Flat Emitter Cathode
  - Extensively studied
  - Improved focal spot quality
- Rotating Drum Anode
  - Allows for electron beam sweeping
  - Shares same advantages of disc anodes
- Electron Beam Focusing and Steering
  - Previously studied electrostatic focusing lens
  - Incorporating magnetic sweeping reduces heat generation

e.g. Philips iMRC® tube for CT



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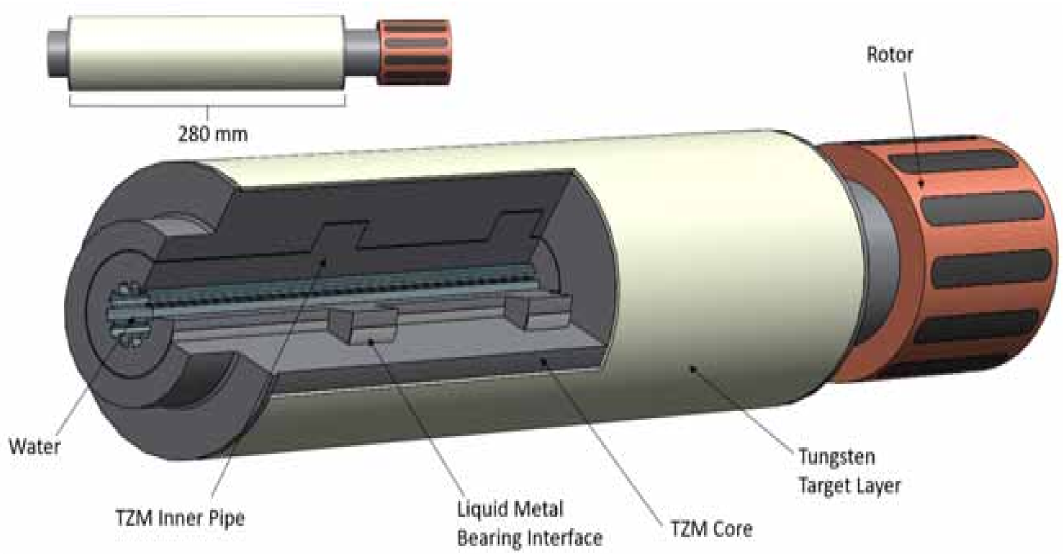
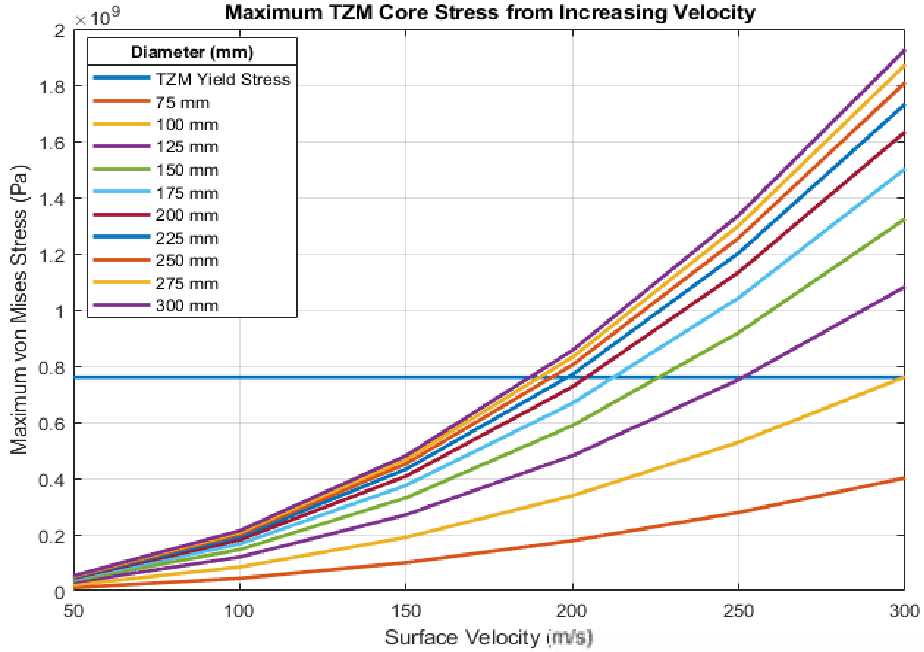
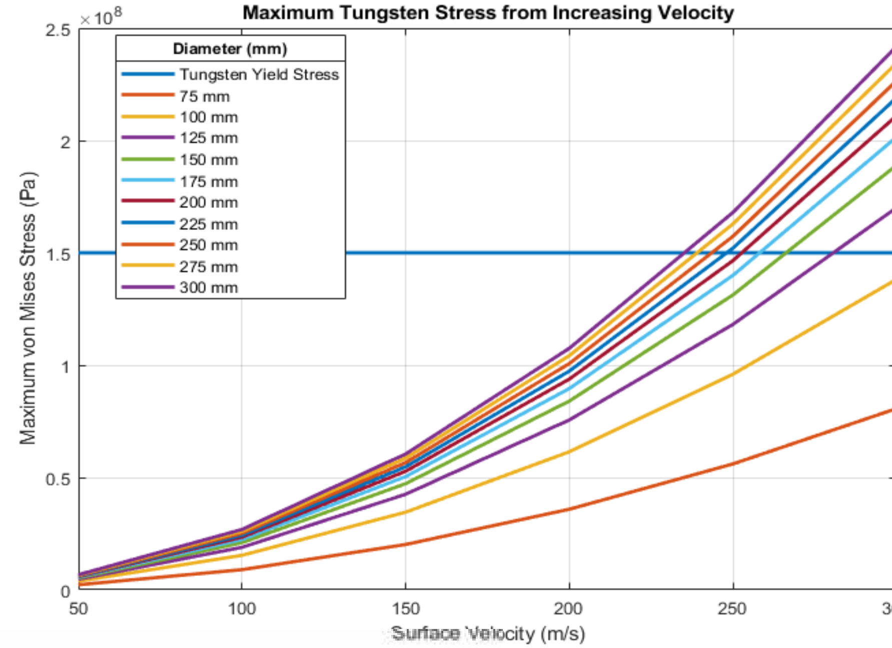
Simulating the Drum Anode

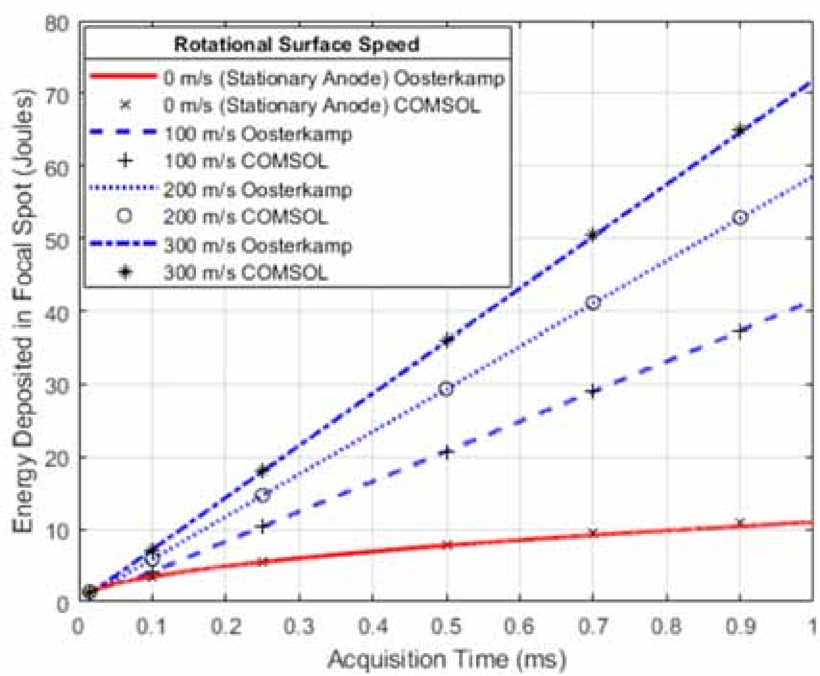
- Drum Anode must be able to rotate quickly enough to dissipate heat, but also sustain the stress imposed on the materials due to rotation.
- TZM core chosen for heat transfer properties
- Tungsten target layer for x-ray production
- Liquid metal bearing interface chosen as they do not wear out.
- COMSOL simulations were performed to determine the rotation speed
- Surface temperature of 2600 °C
- Assumed focal spot size of 1mm x 7mm
- Anode is able to operate safely under load.



CAD render of the drum anode

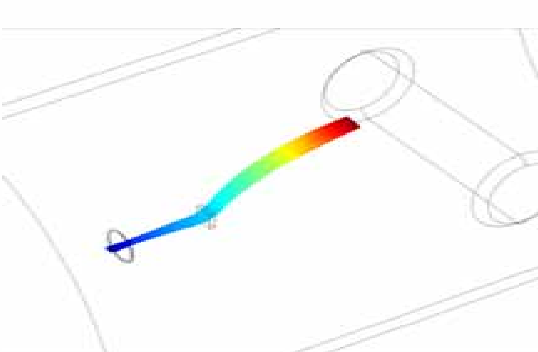

Maximum TZM Core Stress from Increasing Velocity
Diameter (mm)
TZM Yield Stress
75 mm
100 mm
125 mm
150 mm
175 mm
200 mm
225 mm
250 mm
275 mm
300 mm
Maximum von Mises Stress (Pa)
×10^9
Surface Velocity (m/s)

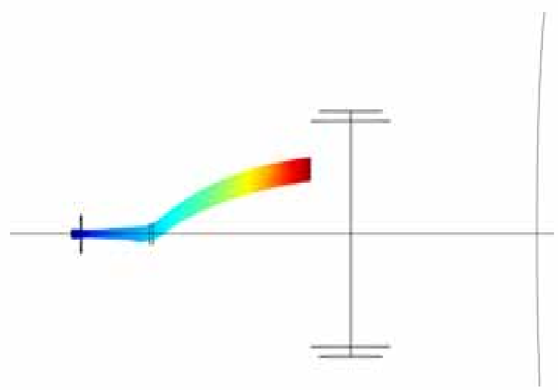

Maximum Tungsten Stress from Increasing Velocity
Diameter (mm)
Tungsten Yield Stress
75 mm
100 mm
125 mm
150 mm
175 mm
200 mm
225 mm
250 mm
275 mm
300 mm
Maximum von Mises Stress (Pa)
×10^8
Surface Velocity (m/s)

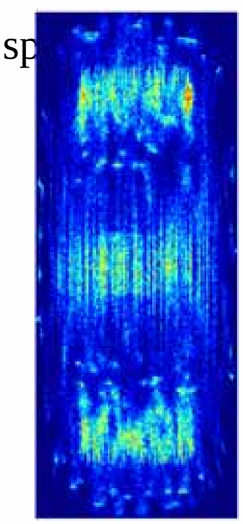

Rotational Surface Speed
0 m/s (Stationary Anode) Oosterkamp
0 m/s (Stationary Anode) COMSOL
100 m/s Oosterkamp
100 m/s COMSOL
200 m/s Oosterkamp
200 m/s COMSOL
300 m/s Oosterkamp
300 m/s COMSOL
Energy Deposited in Focal Spot (Joules)
Acquisition Time (ms)

Controlling the Electron Beam

- Electron focusing has been studied previously
  - Einzel lens package performed better than conventional electrostatic lenses
  - Lest amount of chromatic and spherical aberrations
- Magnet steering is used in newer x-ray tube designs
- Studying the combination of focusing and steering effects on the focal spot of the electron beam
- Using COMSOL software to simulate the electron beam.
  - Beam is easily steerable using a uniform magnetic field.
- Current task is to correct the electron focusing to create a uniform beam of the correct size and shape.
- Determine the effects that the magnetic steering has on the focused focal sp







Isometric view of electron beam steering (left). Top-Down view of electron beam steering (center). Image from particle counter of focal spot, note the non-uniform distribution (right).

Vacuum Discharge

- Vacuum discharge (arcing) hinders the development of x-ray technology since the technology began.
- Multiple factors compound together to lead to a discharge
  - Distance between electrodes (primary contributor)
  - Surface roughness of electrodes
  - Vacuum pressure
  - Purity of vacuum and electrodes
- Discharges can cause damage to electrodes that render tube inoperable.
  - Termination of exposure
  - Worsen image quality (missing projections)
  - Destroy the tube

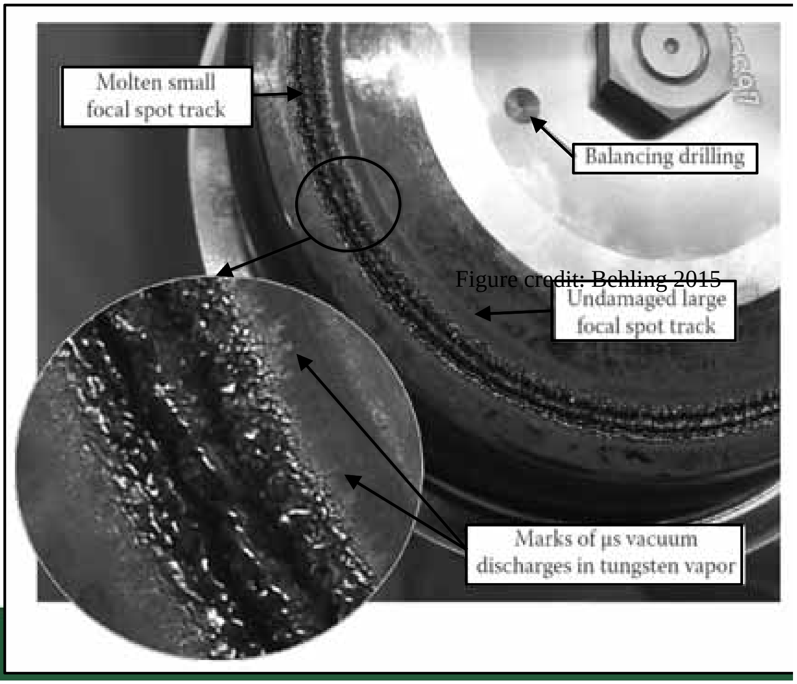
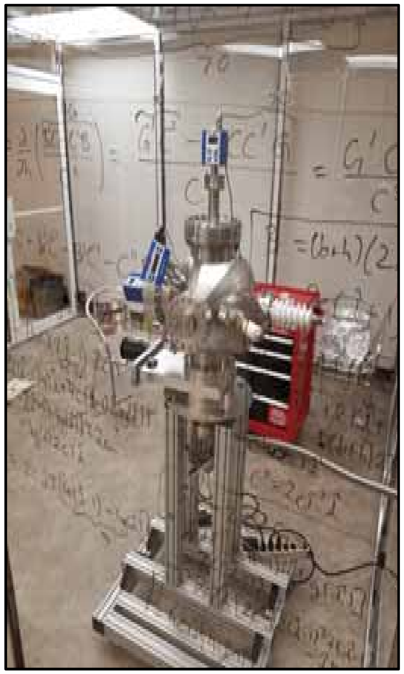
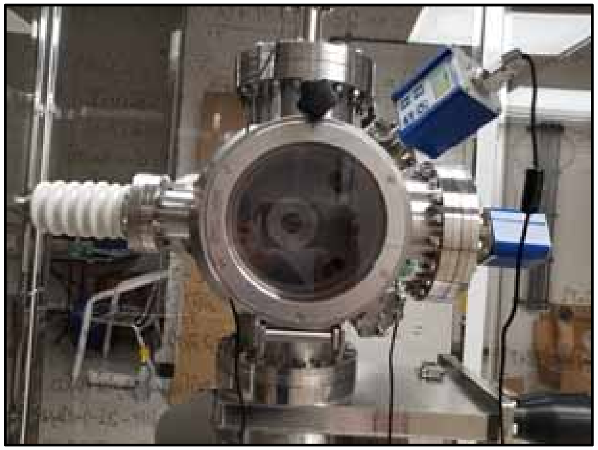


Figure credit: Behling 2015

Current Progress – Vacuum Discharge

- Experiments are being set up at the University of Missouri Science and Technology lab
- ISO Class 7 Cleanroom constructed to reduce contaminants in vacuum and on electrode surfaces
    - Materials are prepared and cleaned inside the room before being placed in the chamber.
    - Assist in controlling for vacuum discharge conditions
- Determine effects of distance between electrodes on vacuum discharge probability.





Did We Accomplish Our Goal?

Vendor	Scanner Model	Source Mode	Gantry rotation time (ms)	Intrinsic Temporal Resolution (ms)	X-ray Generator Power (kW)	Assumed Power Efficiency	Energy deposited per projection (Joules)
GE	Optima 660	Single	350	175	72	0.62	7.81
	Revolution HD/GSI	Single	350	175	107	0.62	11.61
	Revolution CT	Single	280	140	103	0.62	8.94
Philips	Ingenuity	Single	420	210	80	0.62	10.42
	iCT Elite	Single	270	135	120	0.62	10.04
	IQon Spectral CT	Single	270	135	120	0.62	10.04
Siemens	Somatom Definition Edge Stellar	Single	280	142	100	0.62	8.80
	Somatom Definition Flash Stellar	Dual	280	75	100	0.62	9.30
	Somatom Force	Dual	250	66	120	0.62	9.82
Toshiba	Aquilion PRIME	Single	350	175	72	0.62	7.81
	Aquilion ONE	Single	350	175	72	0.62	7.81
	Aquilion ONE Vision	Single	275	137	100	0.62	8.49
TuckAvaLee	Cylinder Single	Single	N/A	**33**	77	0.62	**7.50**
	Cylinder Dual	Dual	N/A	**33**	77	0.62	**15.00**

Future work

- Prototyping
  - A fast and compact x-ray tube based on the drum anode.
  - A preliminary 4D CT
- Validate the stationary CT imaging for TBI phantoms.