



MIT Plasma Science and Fusion Center



## Advanced Compact Particle Accelerator Research at MIT

Faculty and P.I.s: Timothy Antaya, Ron Ballinger, Dick Lanza, Joe Minervini and Dennis Whyte

Students: Mark Artz, Robert Block, Heidi Baumgartner, Zachary Hartwig, Tyler Sordelet and Jiexi Zhang

Engineering Staff: Anthony Bistany, Ermin Citirik, Val Fishman and Phillip Michael, Alexi Radovinsky, Brad Smith and Alex Zhukovsky

# Collaborations and Sponsors

- Dan Merdes, Eric Little, Simon Miller, Dennis Wess, Mike Yukich, Mike Zuger, Penn State University Applied Research Laboratory, under US DOD sponsorship:

*7T Transportable Classical Superconducting Cyclotron*

*250 MeV Superconducting Proton Isochronous Cyclotron*

- Luis Garcia, Concepcion Oliver, Diego Obradors, Fernando Toral, Cristina Vazquez, CIEMAT Accelerator Research Department, under Government of Spain sponsorship:

*4T H- Compact Superconducting Cyclotron for  $^{11}\text{C}$  based Imaging Compounds*

- John Cameron and Vladimir Anferov, ProCure Imaging Centers under NIH sponsorship:

*4T Double Bend Achromat Sc Gantries for PBRT based on "Supraferric" Magnets*

- Brandon Blackburn and Mike Hynes, Raytheon IDS under US DOD sponsorship:

*60 MeV Linac for an Integrated Stand-off Inspection System*

# Overview

- The Compact Superconducting Cyclotron Research Group at MIT Plasma Science and Fusion Center (PSFC) and MIT NSE
- Co-located with a very good Large Scale Superconductivity Group lead by Joe Minervini
- With close collaboration with Dick Lanza's Nuclear Detector Research Program in the Nuclear Science and Engineering Department at MIT

Theme is maybe something like:

*“Directed use of energetic charged particle beams”*

- The *primary purpose* of this program is *Educational- 5 thesis students supported at present and 3 more anticipated Fall 2011*
- Generally what we create will be built and operated by others having little accelerator

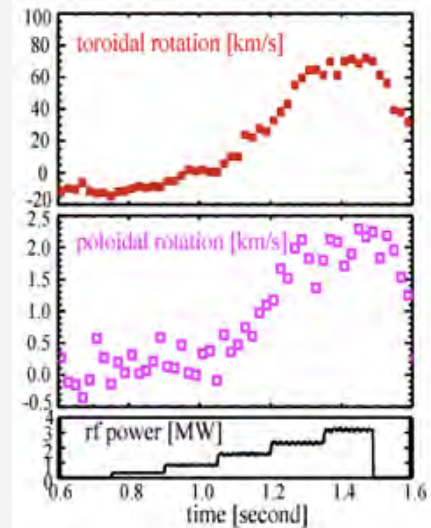
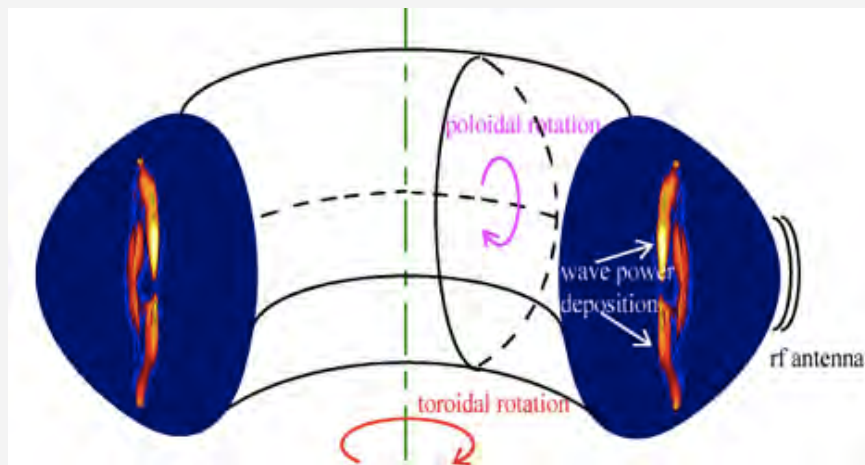
## We are mindful of Important Societal Forces so we try to contribute where we can:

- Detection of Concealing Shielded Strategic Nuclear Materials- *proton active interrogation both near proximity and long stand off*
- Stable Isotope Supply- *particularly very short lived isotopes*
- Affordable Ion Beam Radiotherapy- *low cost and non-technical*

And we strive to make possible the ability for doing all of this... *Anywhere!*

# The MIT PSFC is an international Fusion Science research facility, most known recently for:

- Mode conversion experimental studies on the Alcator C-Mod Tokamak (Y.Lin)
  - A 'first': significant toroidal and poloidal plasma flows can be achieved with RF Waves
  - these flows suppress instabilities which improves the confinement time and increase plasma pressure
- This is fundamentally important for understanding tokamak plasmas and also very important for fusion energy production in magnetically confined plasma reactors



# The Technology & Engineering Division is a first-of-a-kind Capable large scale Superconducting Device Development Group:

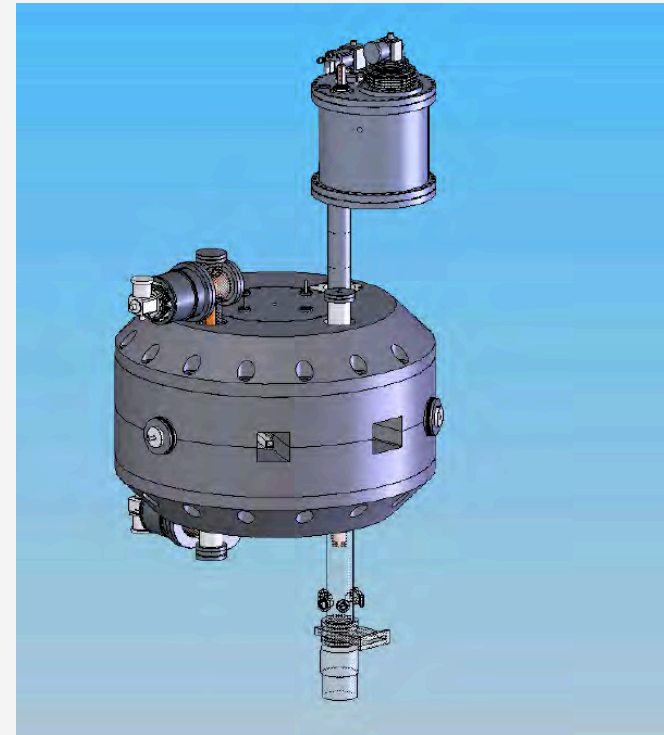
- Fully equipped superconductor characterization laboratory
- Fully equipped materials characterization laboratory including load testing at elevated or cryogenic temperatures
- Set of test probes for superconducting component studies under extreme conditions
- Several large scale test facilities and magnetic field 'sources' for prototype development
- A large set of benchmarked methods and analyses codes for first of a kind large scale superconducting engineering
- Which have enable studies and development of:
  - magnetically confined fusion devices of all types
  - inertial confinement fusion beam transport systems
  - large scale superconducting devices for HEP and other basic science applications, medicine and industry
  - launchers, levitation and maglev systems
- And most recently: DC superconducting power distribution systems and compact superconducting cyclotrons

## For doing advanced research the PSFC is also:

- Largest on campus laboratory at MIT
- Full Lab infrastructure:
  - personnel, financial, purchasing, shipping & receiving, safety
  - instrumentation and fabrication shops
  - a number of specialty engineering groups
  - Excellent library and research report system
- Research Divisions: Plasma Theory, Alcator Experiment, Waves and Beams, High Density Physics and *Technology & Engineering*
- Linked to MIT Departments: EECS, MSE, ME, NSE and Physics
  - relevant fundamental educational courses and multi-disciplinary engineering courses
  - UROP undergraduate and graduate thesis students

# Compact Superconducting Cyclotrons beyond 6T ...

- Compact (a few cubic meters)
- Transportable (minimize the mass and power)
- Not tethered to a helium liquefier- cryo-coolers; HTS leads; many conductor types
- Full acceleration in 1 accelerator stage
- High Field Superconducting Cyclotron (>6T): all 3 types are in play
- T= 10 - 1000 MeV protons and heavy ions

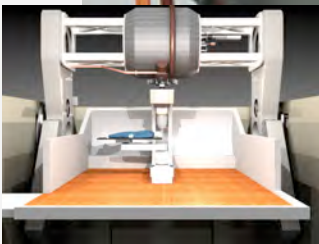




# Compact Superconducting Cyclotron Research

- work started in late 2002
- Initial focus- compact cyclotrons to enable low cost Proton Beam Radiotherapy
- 9T Synchrocyclotron was designed (2006), commercialized (2007), and first system operated 2010
- Now we are working on several machines for basic science and advanced applications

# Next Gen PBRT: Still River Monarch 250 – a 250 MeV Proton Synchrocyclotron about the size and cost of a modern 18 MeV PET Cyclotron

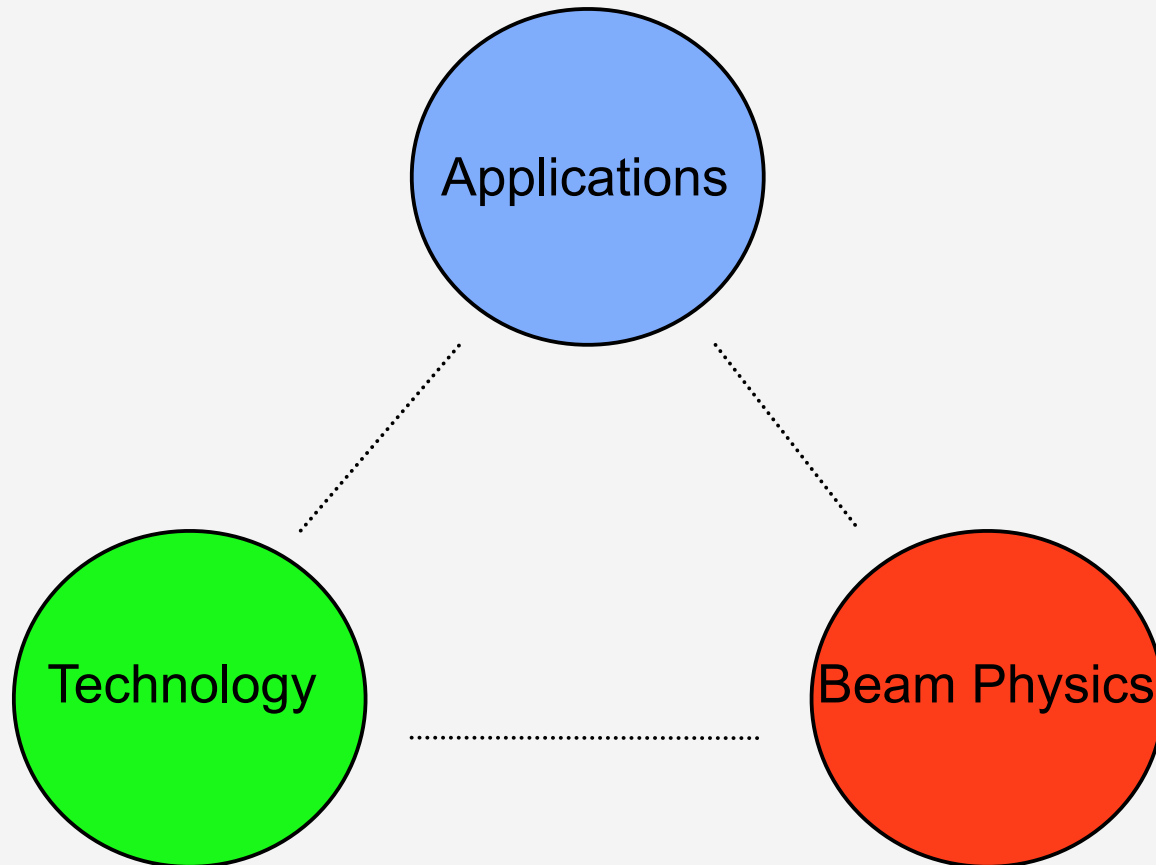


- Nb<sub>3</sub>Sn Coils:
- High J<sub>c</sub> strand- ~3000 A/mm<sup>2</sup> (Oxford)
- Conductor is derived from DOE HEP Conductor Development Program extensively vetted by US LARP
- Wind & React, Cable in Channel (Luvata)
- Follows a conductor concept developed for the US DOE OFES Levitated Dipole Experiment (Minervini et al/MIT)
- 5 Patents awarded; another half dozen under examination

First- delivery to Barnes Jewish in 2011; around 5 under construction, around 17 ordered

Accelerator Science is an rich mix of beam physics, advanced technology and important applications, so students have many study areas to choose from and many potential career paths:

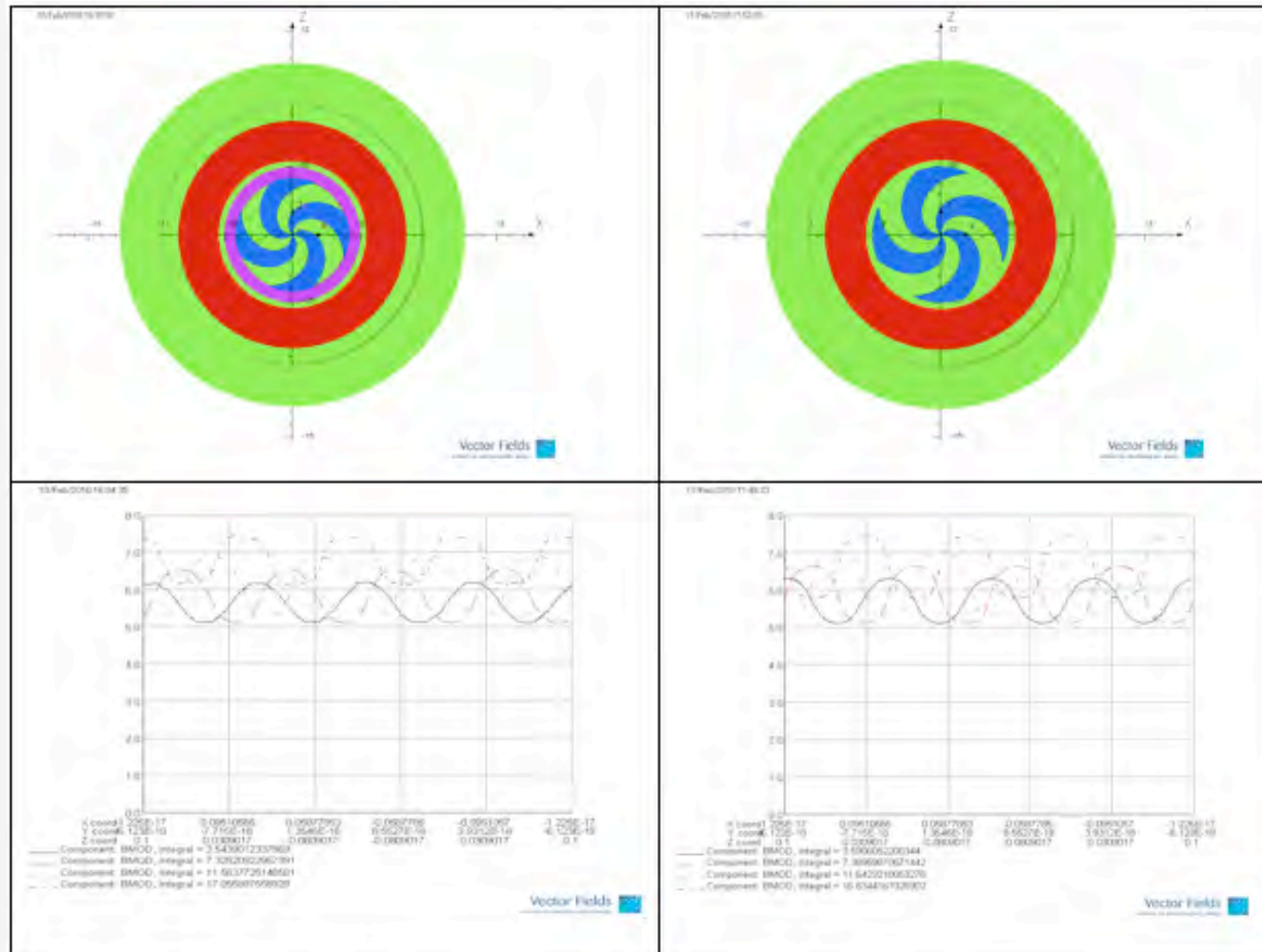
Basic Science, medicine, security...



Magnets, RF, HV, Ion sources ...

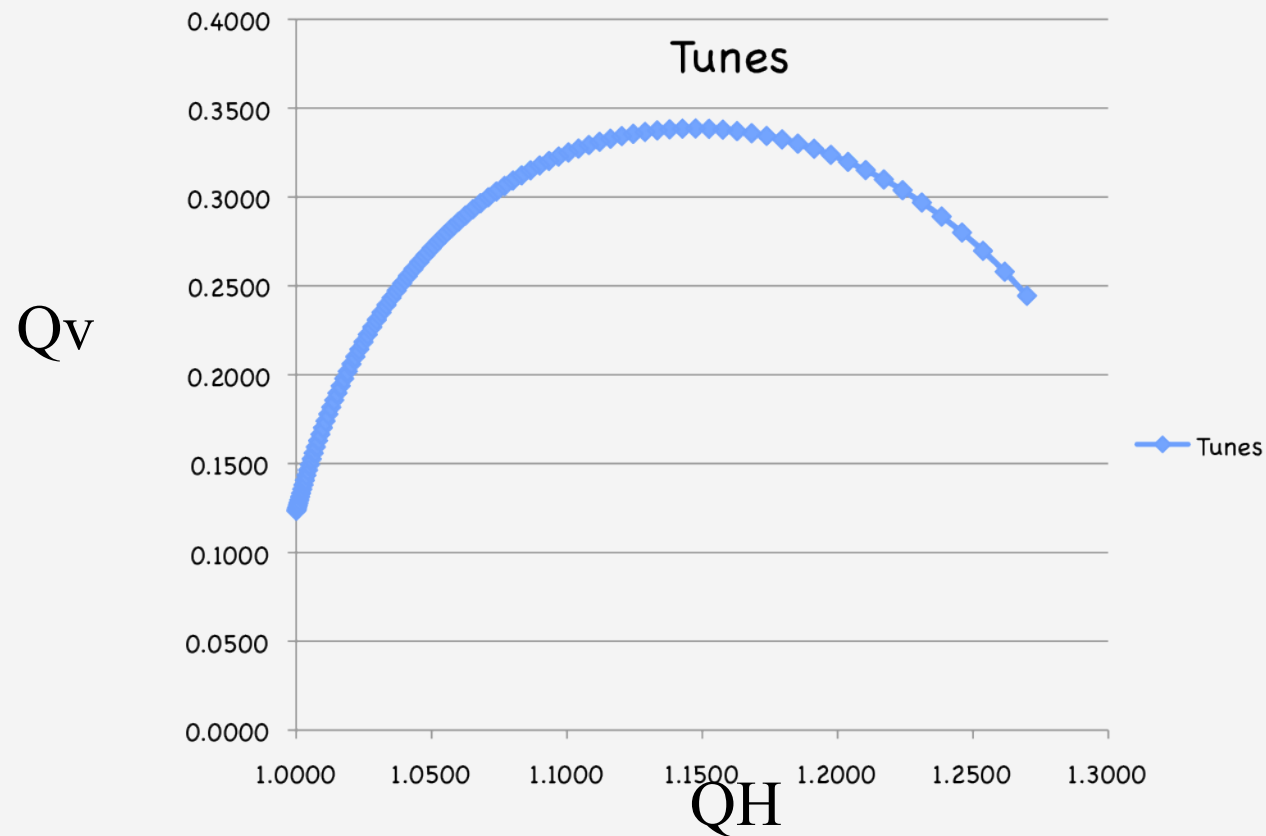
Tunes, Phase Space Evolution,  
Space Charge ...

# Electromagnetic Computations: 250 MeV Megatron CSC



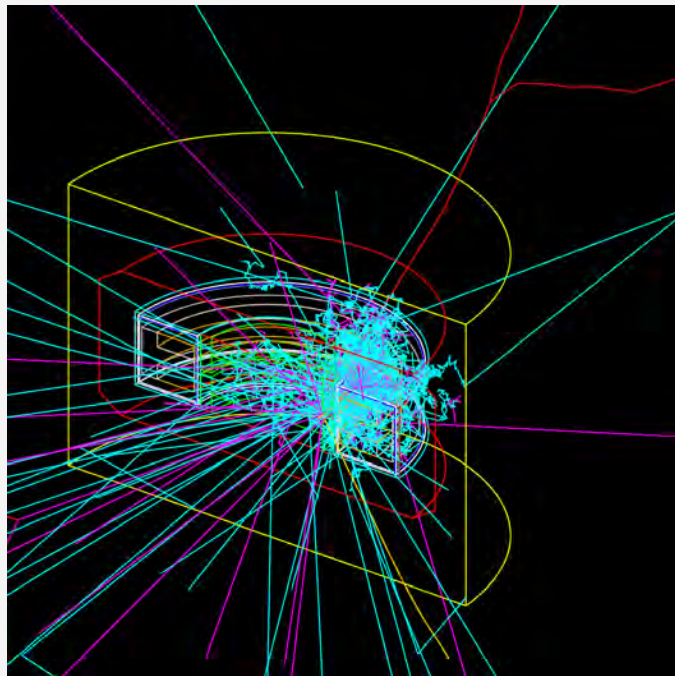
All of the students are trained to be highly skilled with the key computational tools

# Circular Particle Accelerators: EO Orbit Analysis

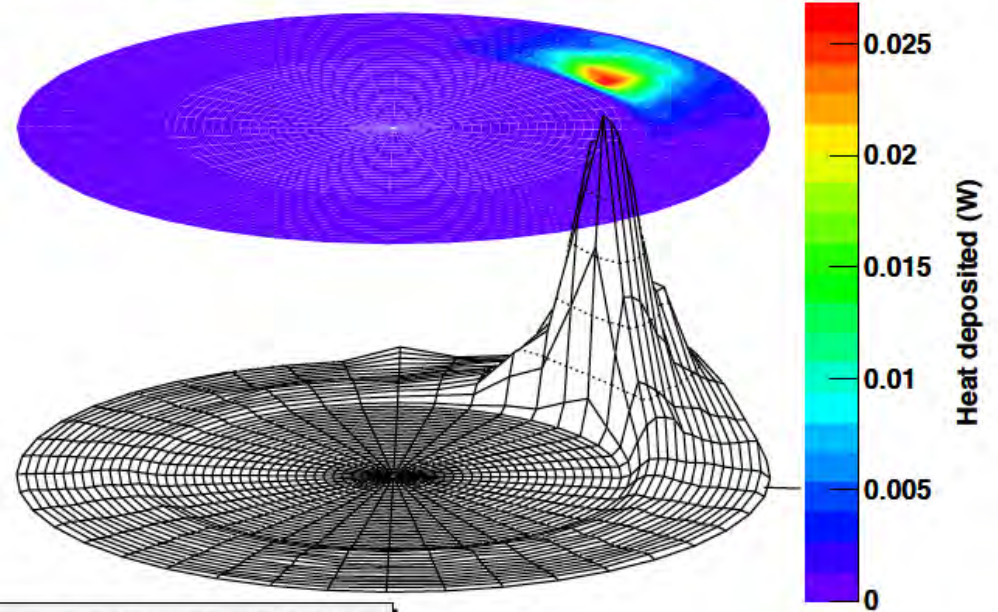


High field cyclotron beam dynamics- Ph.D. Thesis Student Jiexi Zhang

# Lost ion beam radiation simulation in a cyclotron- Power dissipation at the Sc coils



Heat Deposited in SC Coil by Secondary Particles



Total heating in SC coil: 1.94676 Watts

GEANT4, fully parameterized incl. virtual He3 detector, 3D, 100 nodes on comp. cluster, benchmarking in progress... (Z.Hartwig, Ph.D. student, NSE)

# Other Codes Under Development with Students

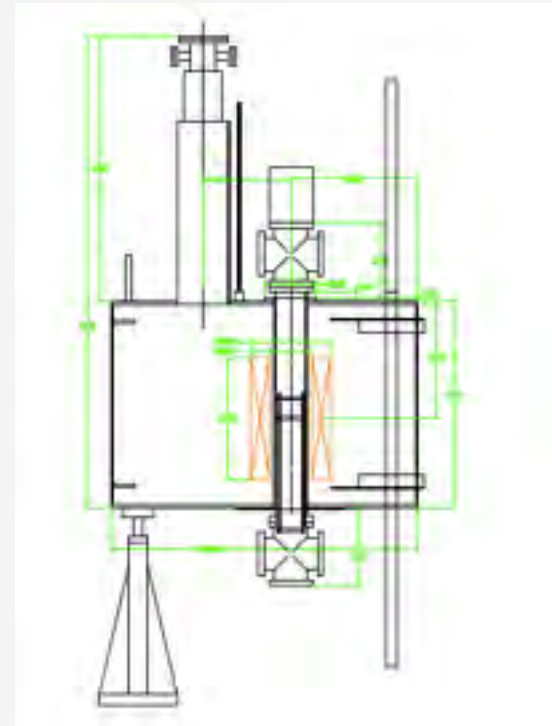
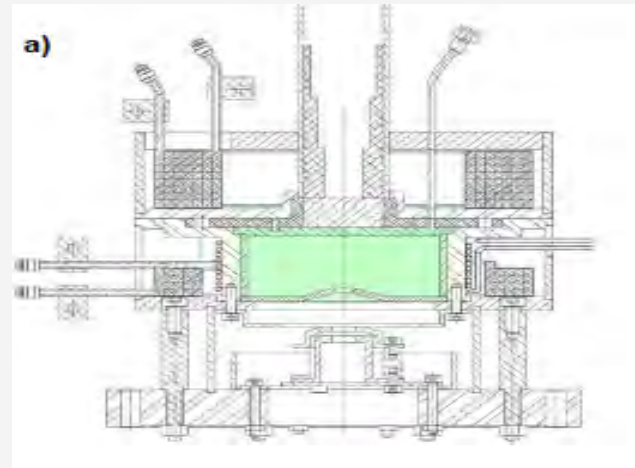
- VPAC: Time domain particle tracking codes for weak focusing cyclotrons
- Z3Cyclone: Isochronous Cyclotron Central Region Problem
- PYBEAM\*: 1D beam optics with space charge for rapid layout of beam beam optics systems
- FASTCYC\*: isochronous cyclotron axial and flutter field generator for rapid survey of the orbit properties design space of a new machine
- BEAM3D : ECRIS Extraction With Space Charge

\*(These codes are part of a new Accelerator Science and Engineering graduate student curriculum now being developed at MIT NSE)



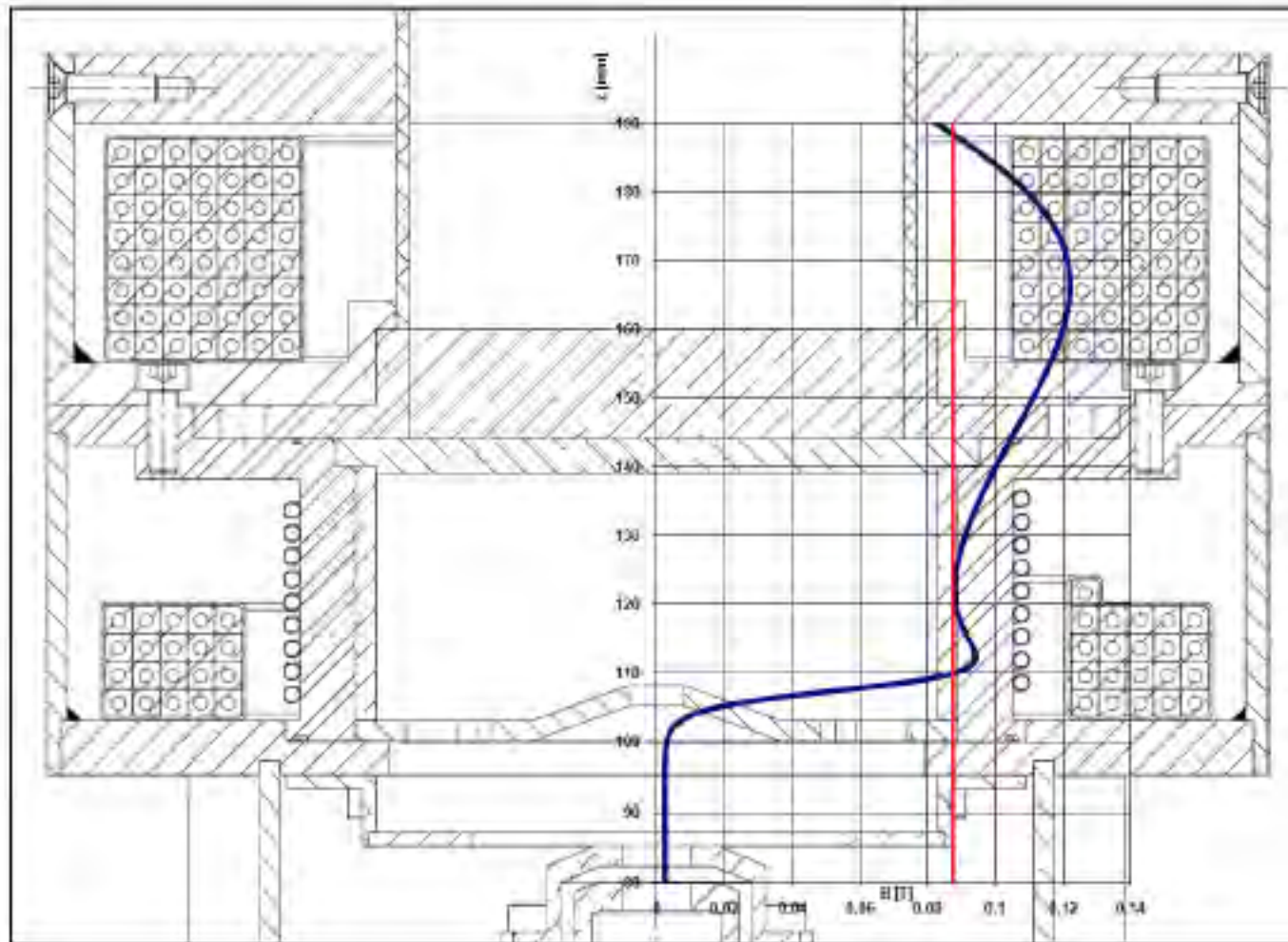
# High Brightness (ECR) Ion Sources

- DTRA Development (Frontiers Study)-  
Master's Thesis, Jordi Reig, MIT Spring  
2010
- 2.45 GHz ECH heating frequency
- 20 mA, 20 kV, 0.1mm-mrad norm.  
emittance
- Design complete; dwg package &  
component selection complete
- Fully analyzed including beam formation  
w/space charge
- Ion source fab and 9T test stand  
assembly in progress-Mark Artz SM  
Summer 2011

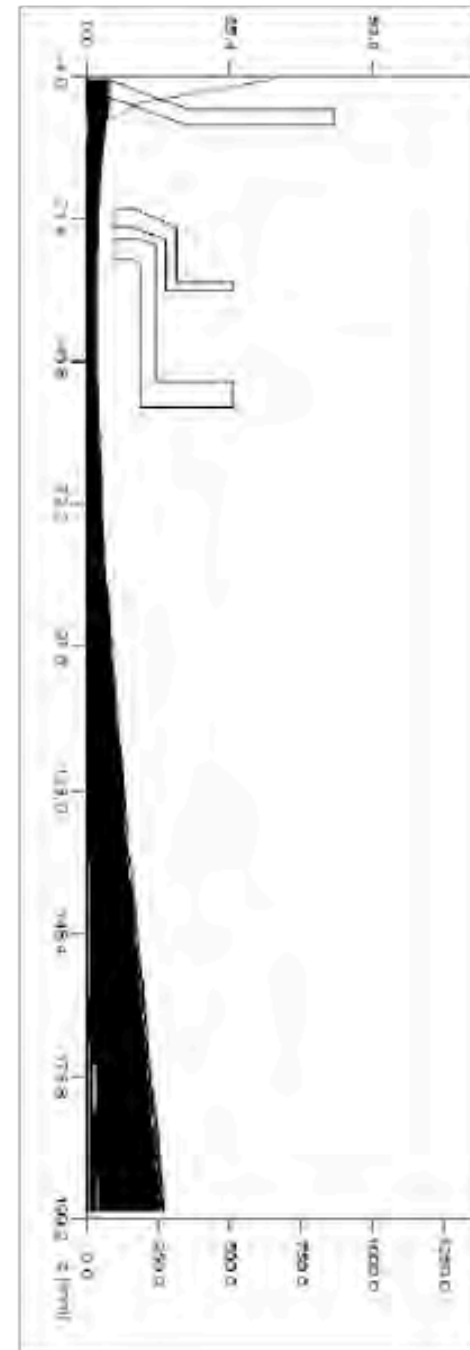
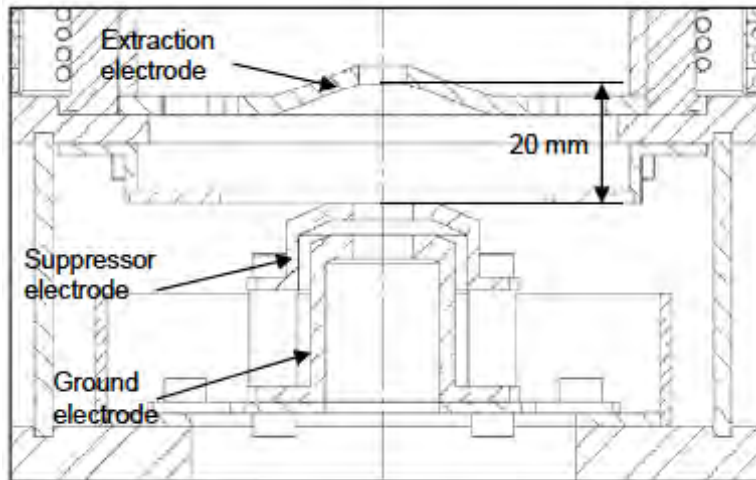
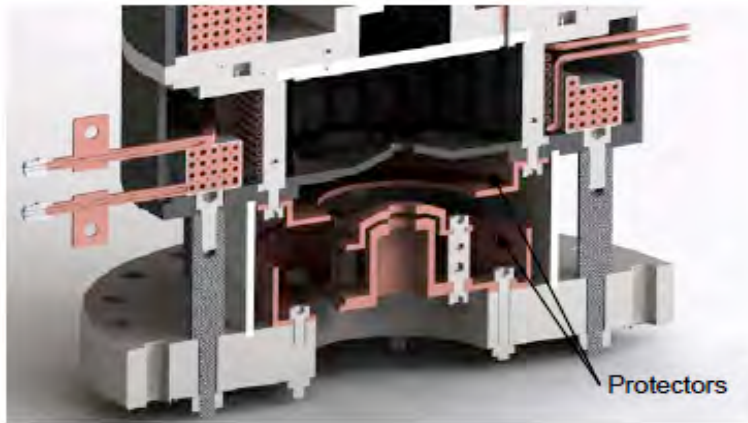




# ECR: Tunable Axial Tandem Mirror



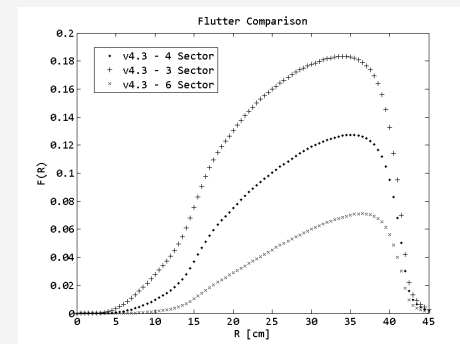
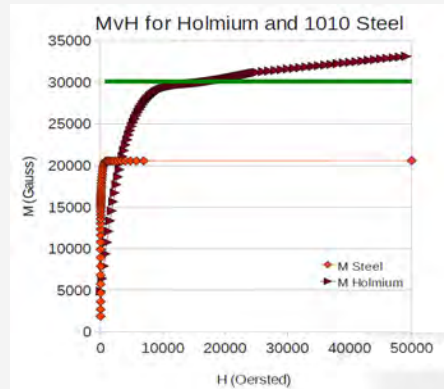
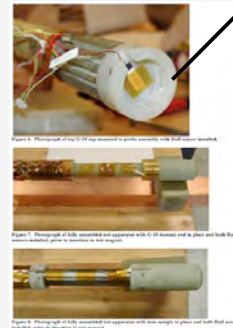
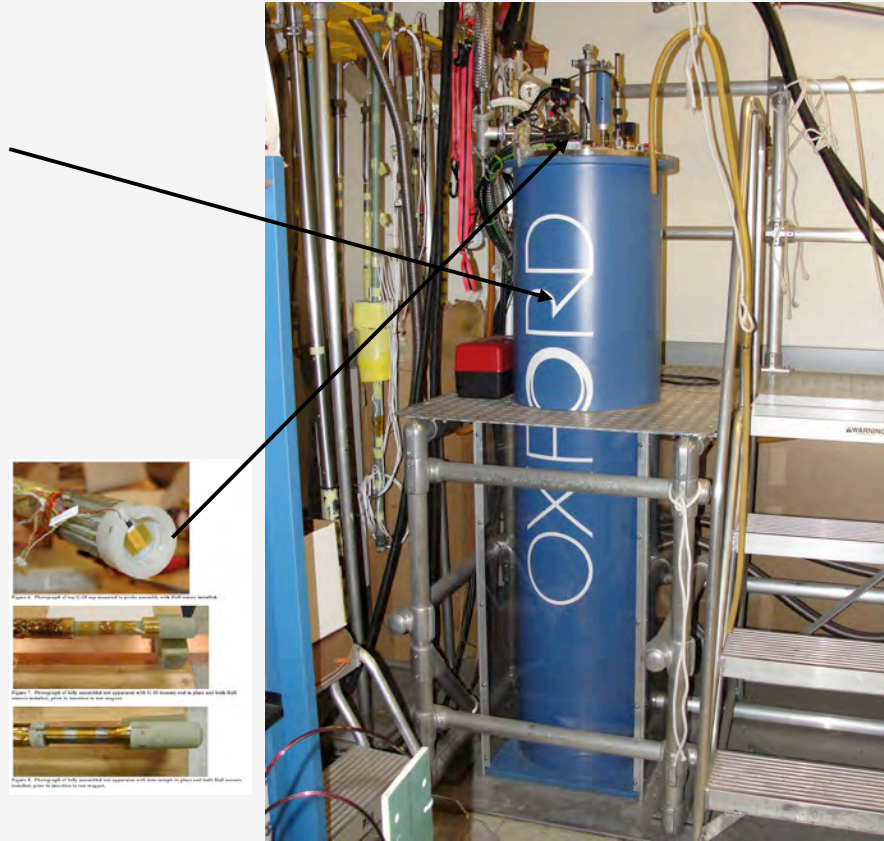
# 20 mA DC Extraction with Space Charge



# Extending Ferromagnetic Structures beyond iron: 4.2K

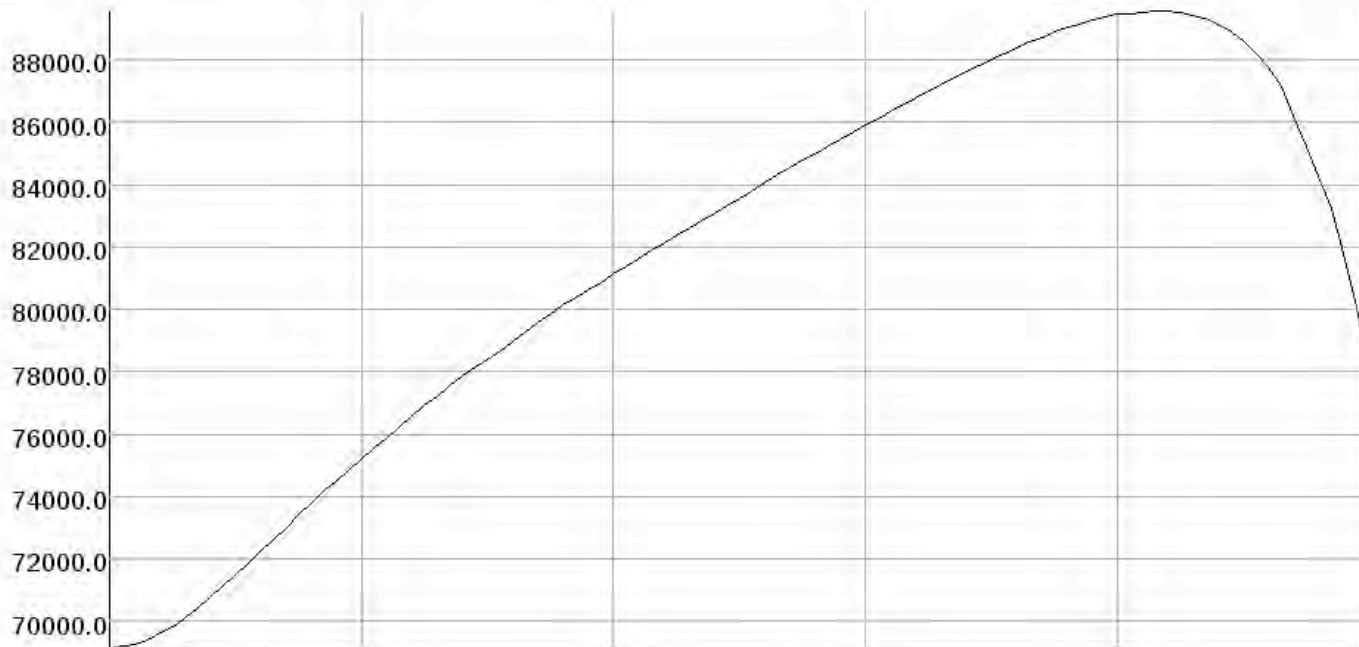
## Measurement of Saturation Magnetization of Gd and Ho

- Holmium- Mark Norsworthy MIT SM Degree June 2010
- Use an existing cold bore 14T magnet normally used to measure properties of new superconductors
- 4.2K Cold Specimen holder design
- Gadolinium- Fall 2010- Spring 2011 Heidi Baumgartner UROP undergraduate student
- We are already using these results to design advanced cyclotrons



# Megatron: Holmium Pole Tips at 4K- the most significant advance in Flutter in more than 30y

30/Aug/2010 14:42:44



X coord	0.0	6.36396103	12.7279221	19.0918831	25.4558441	31.8198052
Y coord	0.0	6.36396103	12.7279221	19.0918831	25.4558441	31.8198052
Z coord	0.0	0.0	0.0	0.0	0.0	0.0

Component: BZ, from buffer: Line, Integral = 3.6773276597E+06

Energy J  
Mass g

**MODEL DATA**  
 cyc014-db.op3  
 TOSCA Magnetostatic  
 Nonlinear materials  
 Simulation No 1 of 1  
 1334168 elements  
 366951 nodes  
 1 conductor  
 Nodally interpolated fields  
 Activated in global coordinates  
 Reflection in XY plane (X+Y fields=0)  
 Reflection in YZ plane (X field=0)  
 Reflection in ZX plane (Y field=0)

**Field Point Local Coordinates**  
 Local = Global

**FIELD EVALUATIONS**

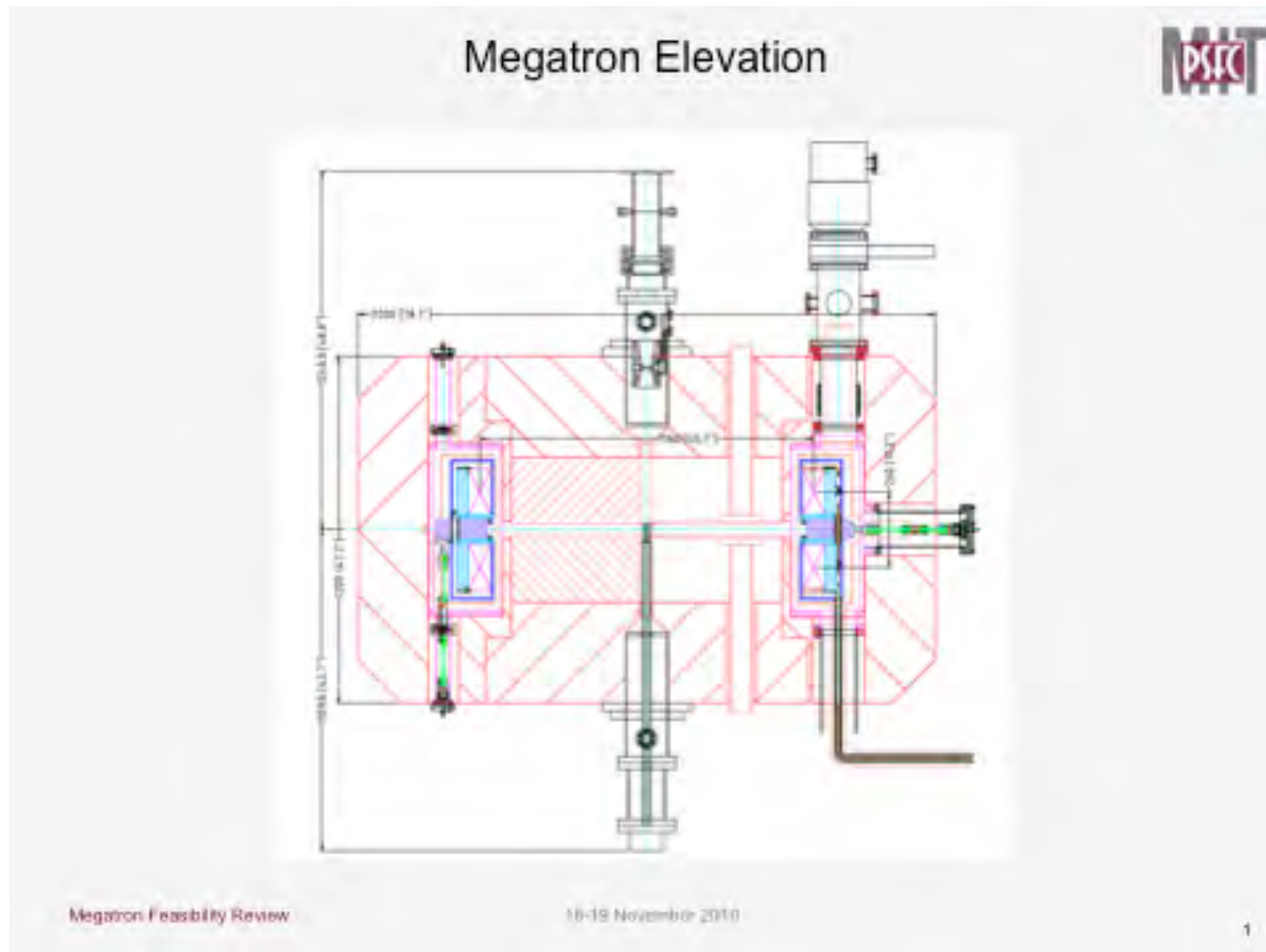
Line	LINE	101	Cartesia
	(nodal)		n
	x=0.0	y=0.0	z=0.0
	to	to	
	31.819	31.819	
	81	81	
Polar	POLAR	100x10	Cylindric
	(nodal)	0	al
	r=0.0 to	theta=0.0	z=0.0
	45.0	to 90.0	



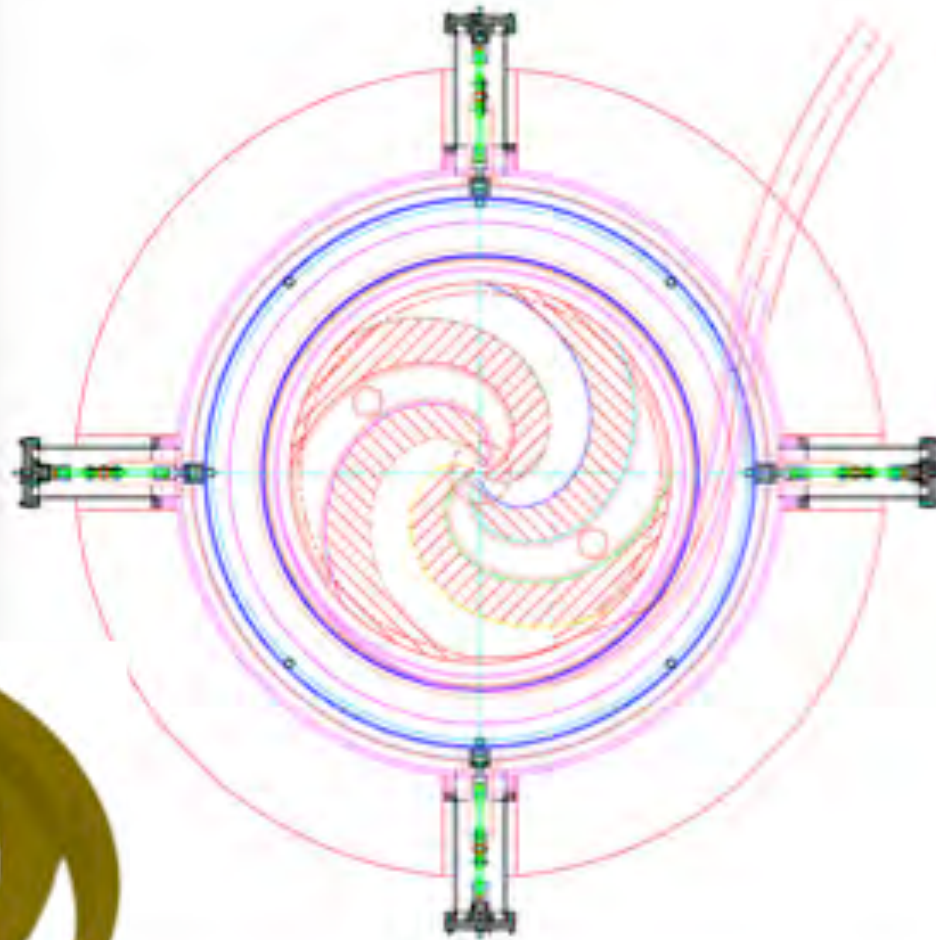
Hill centerline magnetic field



# Transportable 250 MeV Proton Cyclotron for Long Stand-off Active Interrogation Demonstration- *design and fab in progress*



# Megatron Plan View

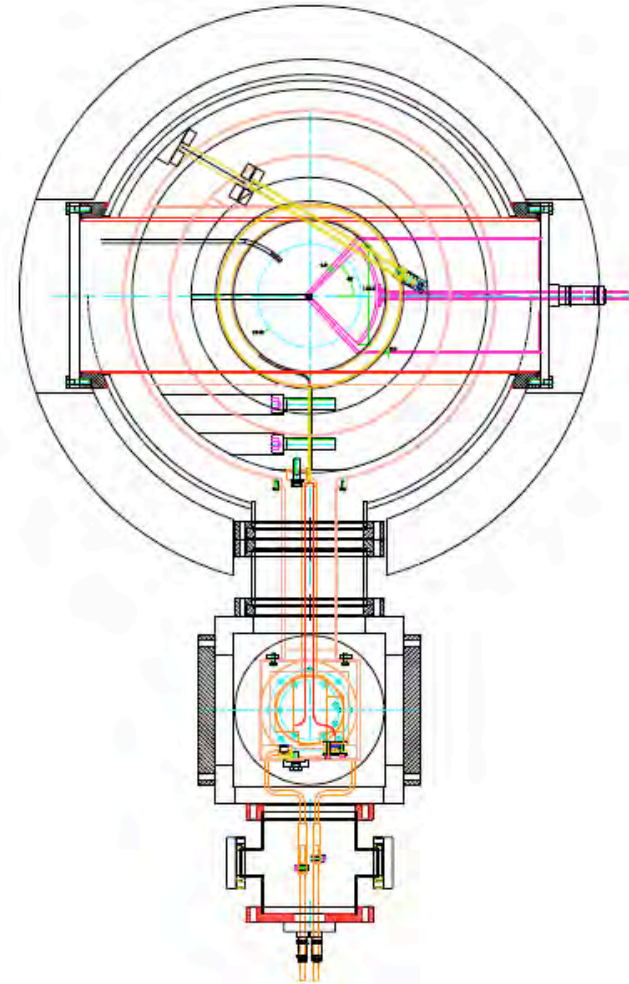
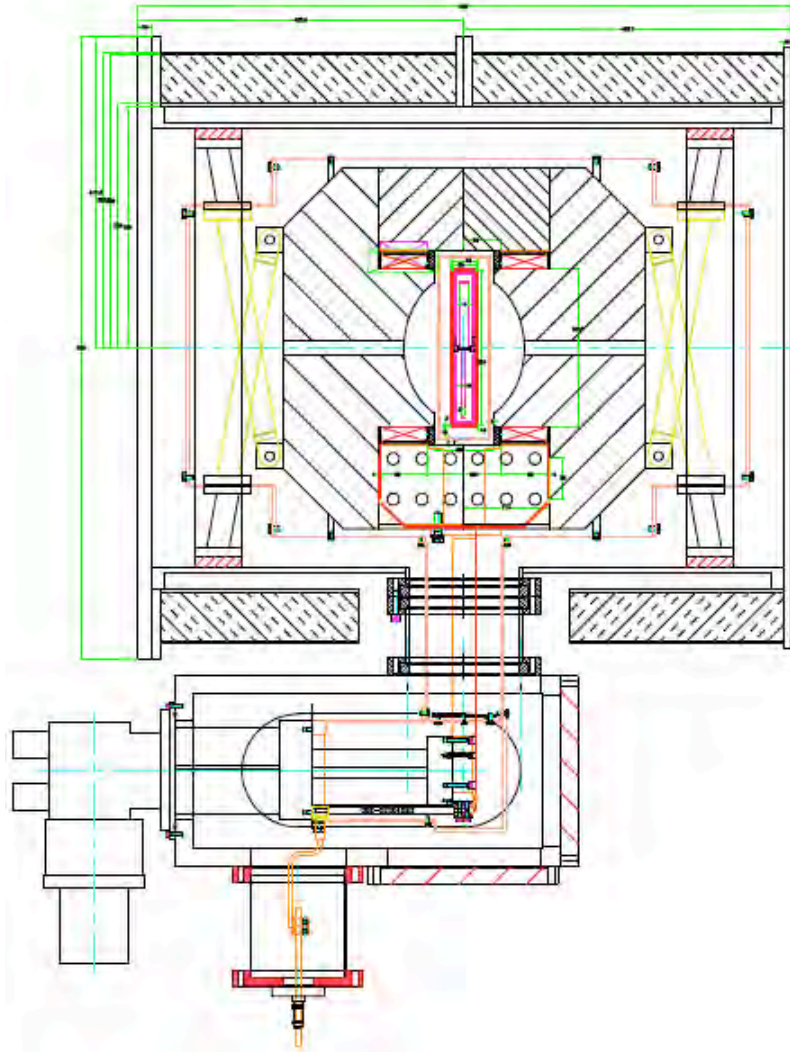


16-18 November 2010

How does the Megatron compare with existing 250 MeV Proton Isochronous Cyclotrons? We are looking at 2 configs. *...both are almost as compact as the 9T synchrocyclotron*

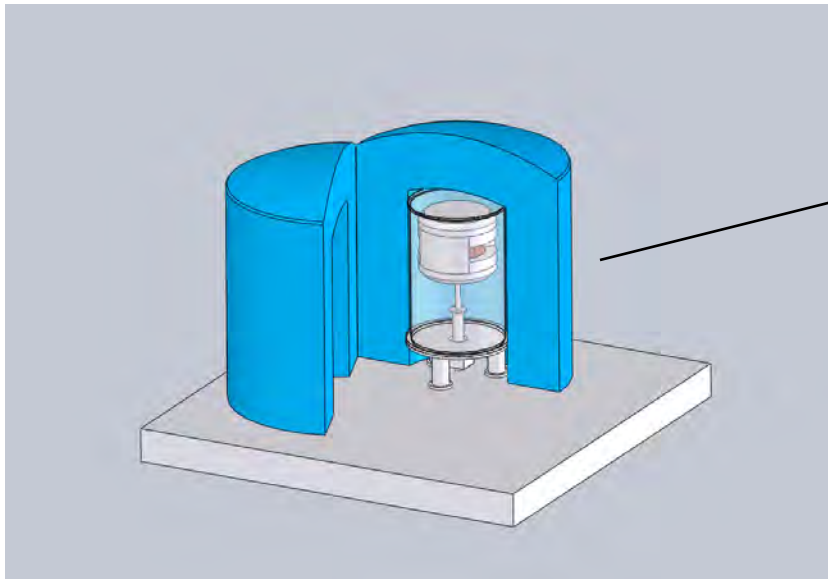
	Still River Monarch	Megatron (018)	Megatron (406)	Varian <u>Proscan</u>	IBA C230
R pole (m)	0.34	0.52	0.6	0.8	1.05
D yoke (m)	1.8	2.2	2.4	3.1	4.3
Height (m)	1.2	1.2	1.2	1.6	2.1
B <sub>0</sub> (T)	8.9	4.2	3.6	2.4	2.2
B <sub>f</sub> (T)	8.2	5.4	4.7	3.1	2.9
M (tonnes)	20	30	40	100	250
<u>T<sub>f</sub></u> (MeV)	254	267	272	250	235

# Nanotron: Demo for an Ultra-portable weak focusing cyclotron for Proton Active Interrogation

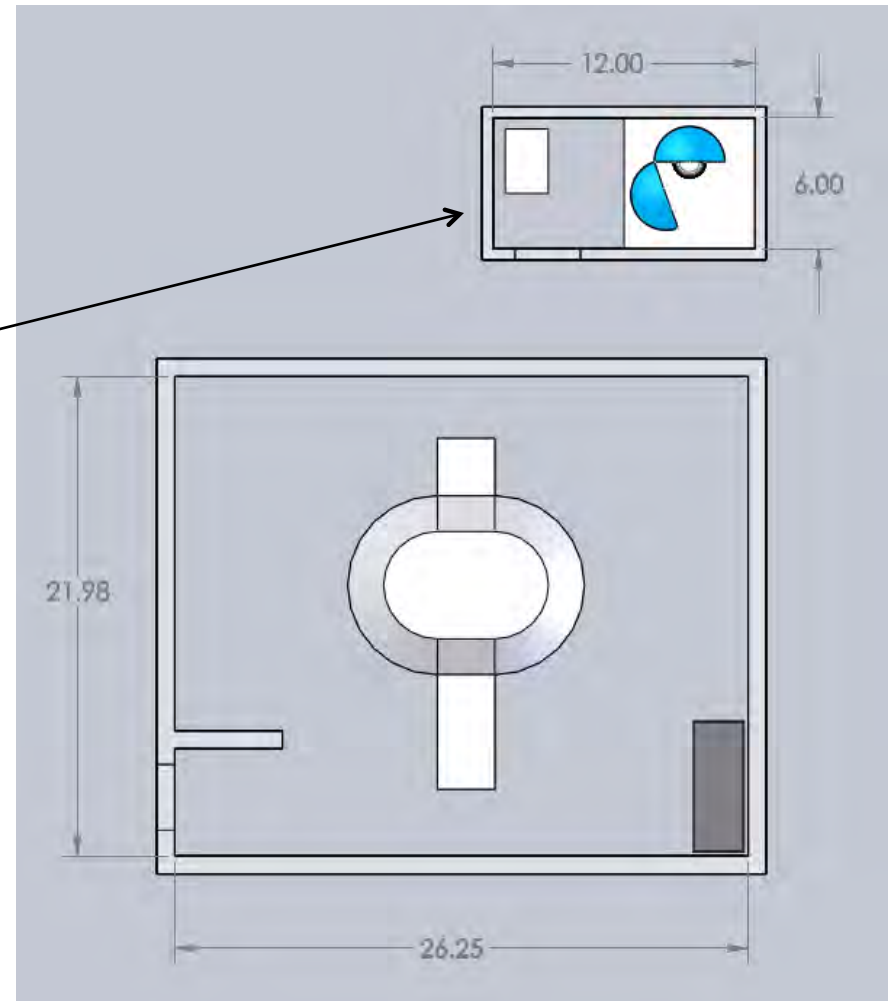




# Compact Cyclotron for On demand production of very important Short Lived PET Isotopes ( $^{11}\text{C}$ , $^{13}\text{N}$ and $^{15}\text{O}$ ) that can be *co-located with the PET Imaging Systems*



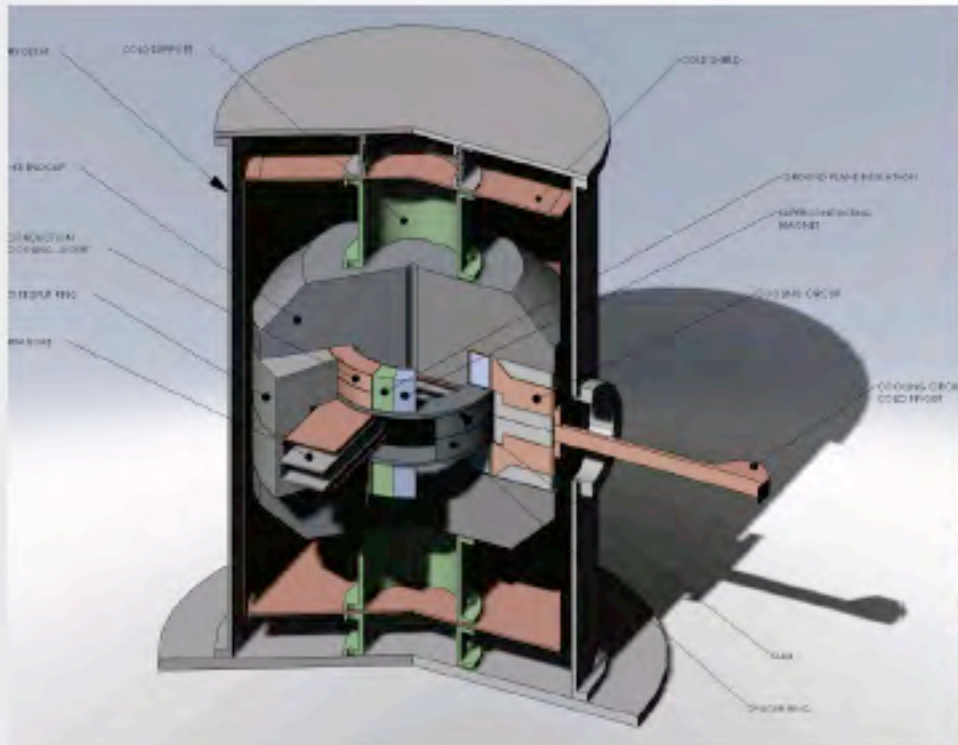
12.5 MeV PET Cyclotron: 3 kW and 2 tons total mass incl. shielding



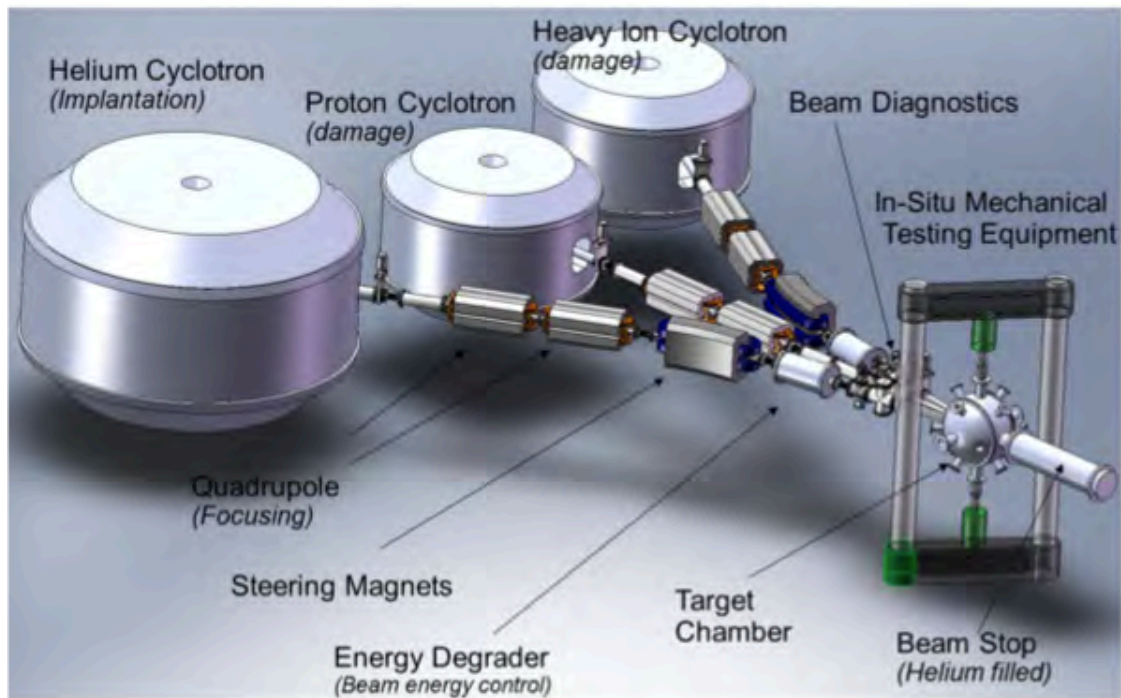
Conventional Pet Cyclotron: 200kW wall plug power, 20 tons + 25 tons of shielding

(New startup company Ionetix- 2011)

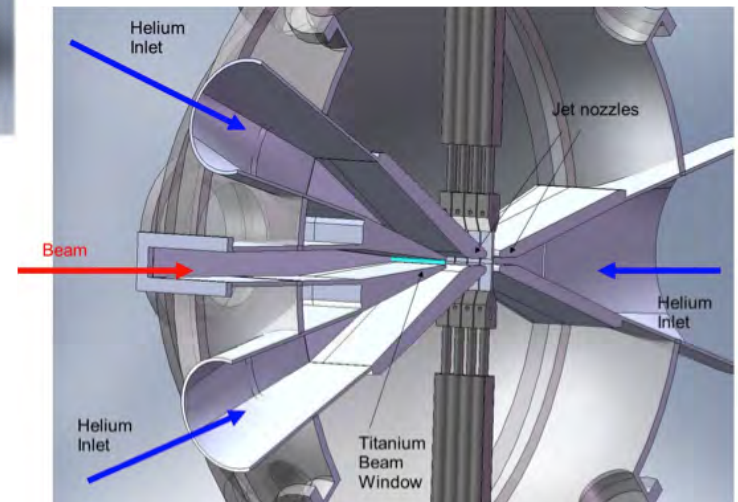
# DEMONSTRATION N13 GENERATOR MAGNET TEST



# Under Study at MIT NSE : Facility for High DPA rates for Fission and Fusion Materials Characterization



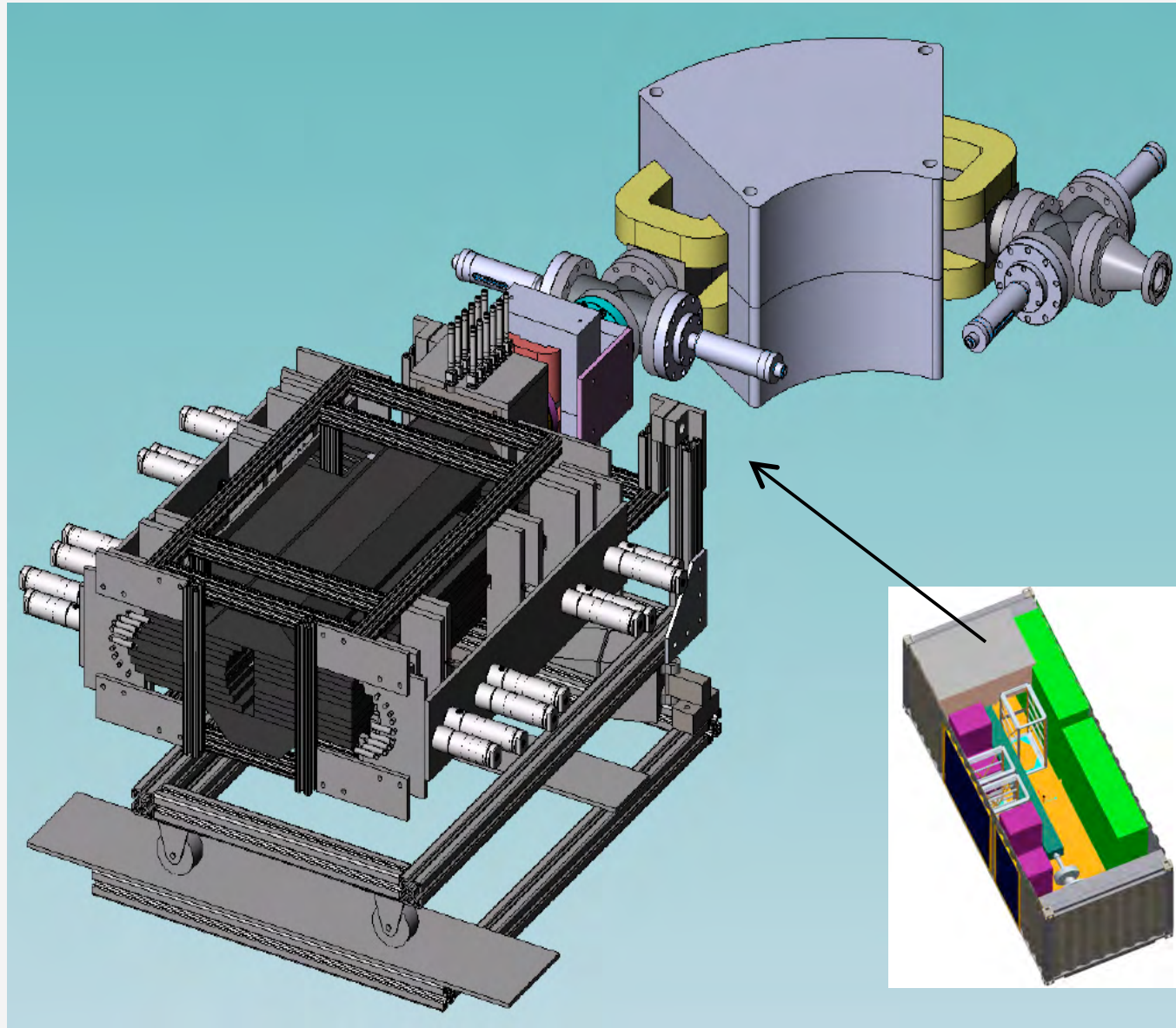
Fall 2010 - initial design study was work performed by 4 senior undergraduates !  
Tyler Sordelet, SM NSE Fall 2011



**Some other Accelerator Projects underway in my  
group...**

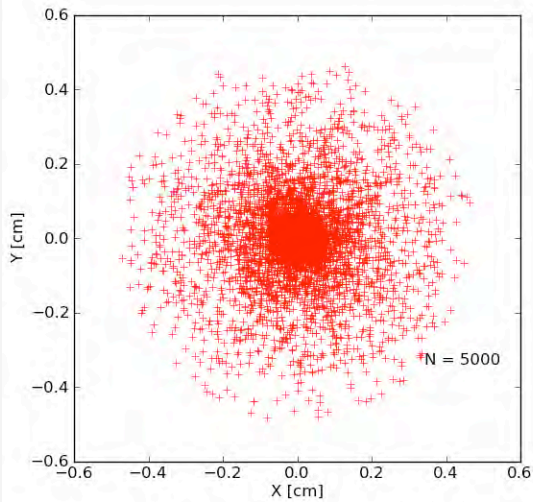


# MIT Bremsstrahlung Beam Generation System for ISIS

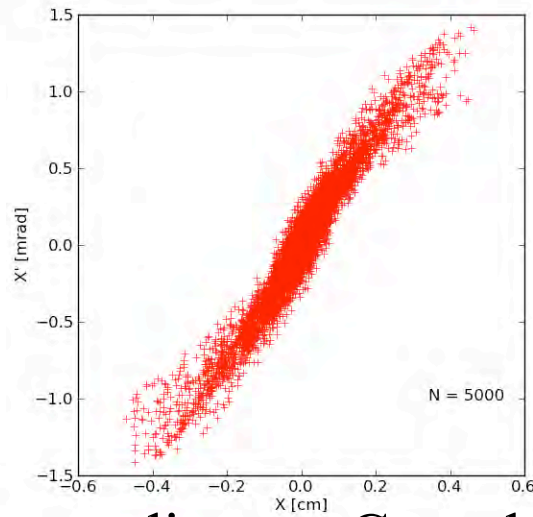


# 60.7 MeV Electron Beam Characteristics (RE Block SM Spring 2011)

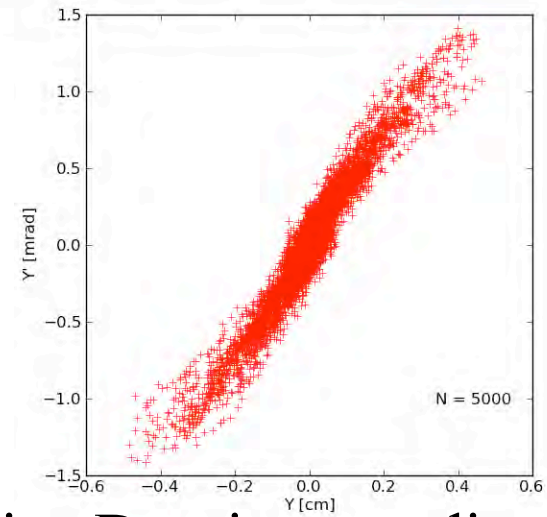
(x,y)



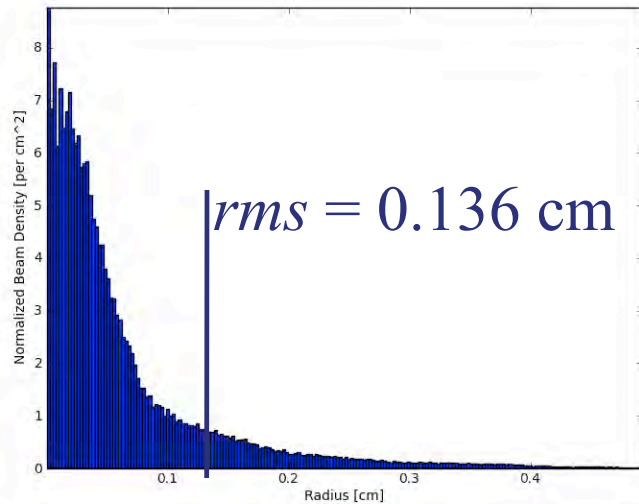
(x,x')



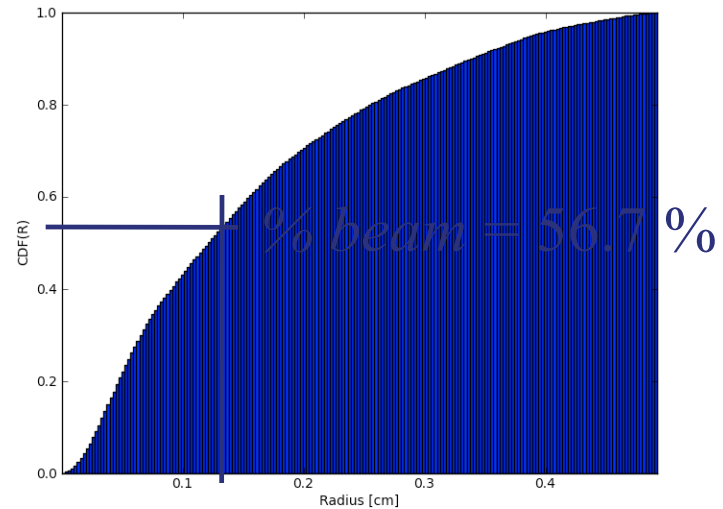
(y,y')



Beam Density vs radius



Cumulative Density vs radius

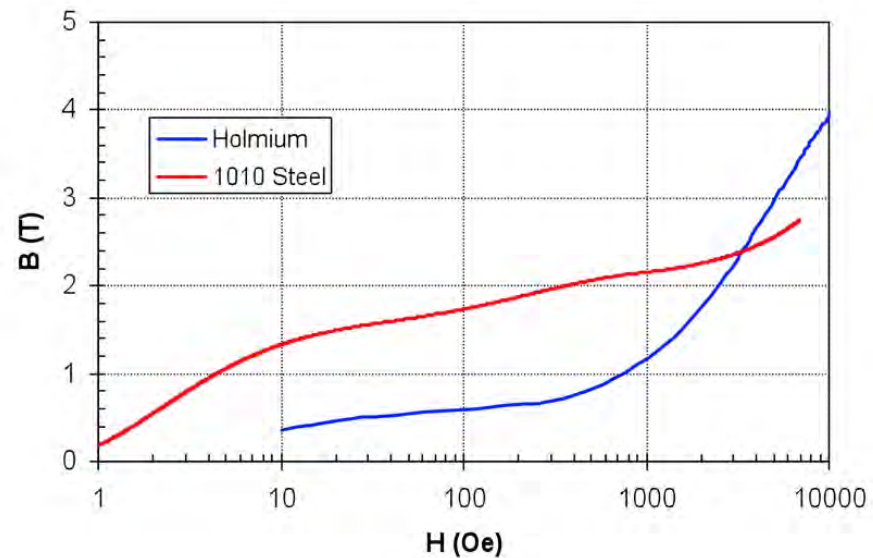
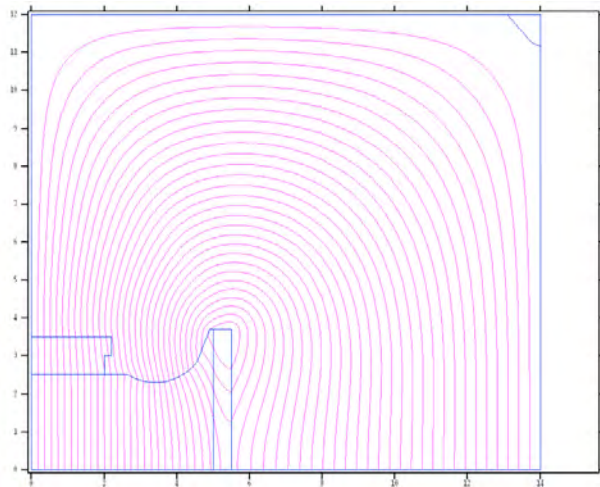


## A new Class of Superconducting Magnets: “SUPRAFERRIC”

Use the fact that the REFs are hard to magnetize and in particular are hard to saturate to get:

Superconducting magnets that are linear over a wide dynamic range without complex higher order correction coils or massive iron yokes (super-ferric) result

(Antaya, Norsworthy, Anferov, Cameron, Block patent pending)



(Antaya, Norsworthy, Anferov, Cameron, Block- patent pending)

Thank you!