“Superconducting Magnet needs for cutting edge Medical and Security Applications

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Present Situation

- ODD Paradox:

  - Particle accelerators are clearly important in society and are being used to do many good things that affect people
    - Isotope production for cardiac, body and brain imaging
    - X-ray radiotherapy for Oncology
    - X-rays for cargo and container screening

  - However, the Accelerator Technologies being used for these applications were developed in the 1960s and 1970s
    - H- cyclotrons (and even the front end of the LANSE accelerator at LANL)
    - Electron accelerators producing Bremsstrahlung Photons
    - Unsaturated iron magnets at low magnetic field, high mass and power consumption

Starting from scratch now, we wouldn't make the same technology decisions and outcomes would be better

Meanwhile…

- There has been great progress in all areas of particle accelerator science and technology:
  - Beam codes are sufficient quantitative to model phase space evolution, space charge and non-linear beam-beam interactions
  - Field design codes are good to ~10-100 ppm
  - Materials databases and analysis tools have benchmarks across a wide range of challenging projects and devices
  - There have been several major world-wide engineering campaigns (SSC, ITER, LHC…) that unite science, engineering, technology to solve a hard problem
  - …

And y'all here at LBNL (and the Bay Area) have been a big part of this progress over the past 3 decades

Upfront: Role of LBNL in all this

- **Universities** make the most sense to me when they are doing fundamental research with students
  - That rhythm makes it hard to meet sprogrammatic deadlines
  - Collision with companies and agencies over publishing results
  - Fundamental research is expensive and high risk
- **Companies** are best at product development
  - People must perform now
  - Regulatory requirements of commercial products require specialized infrastructure (Quality, Iso, CGMP, …)
  - Science infrastructure then gives way to incremental product development (hard to be science based, just a few do it well)
- **National Labs** simply put, for me, bridge this divide
  - Large research facilities set the tone for Science based applications (needed to move accelerator based apps forward)
  - Centers combining specialized engineering and test facilities with unique world-class expertise develop ‘organically’

Accelerator *Science* based Applications of Interest in this talk:

Ion Beam Radiotherapy

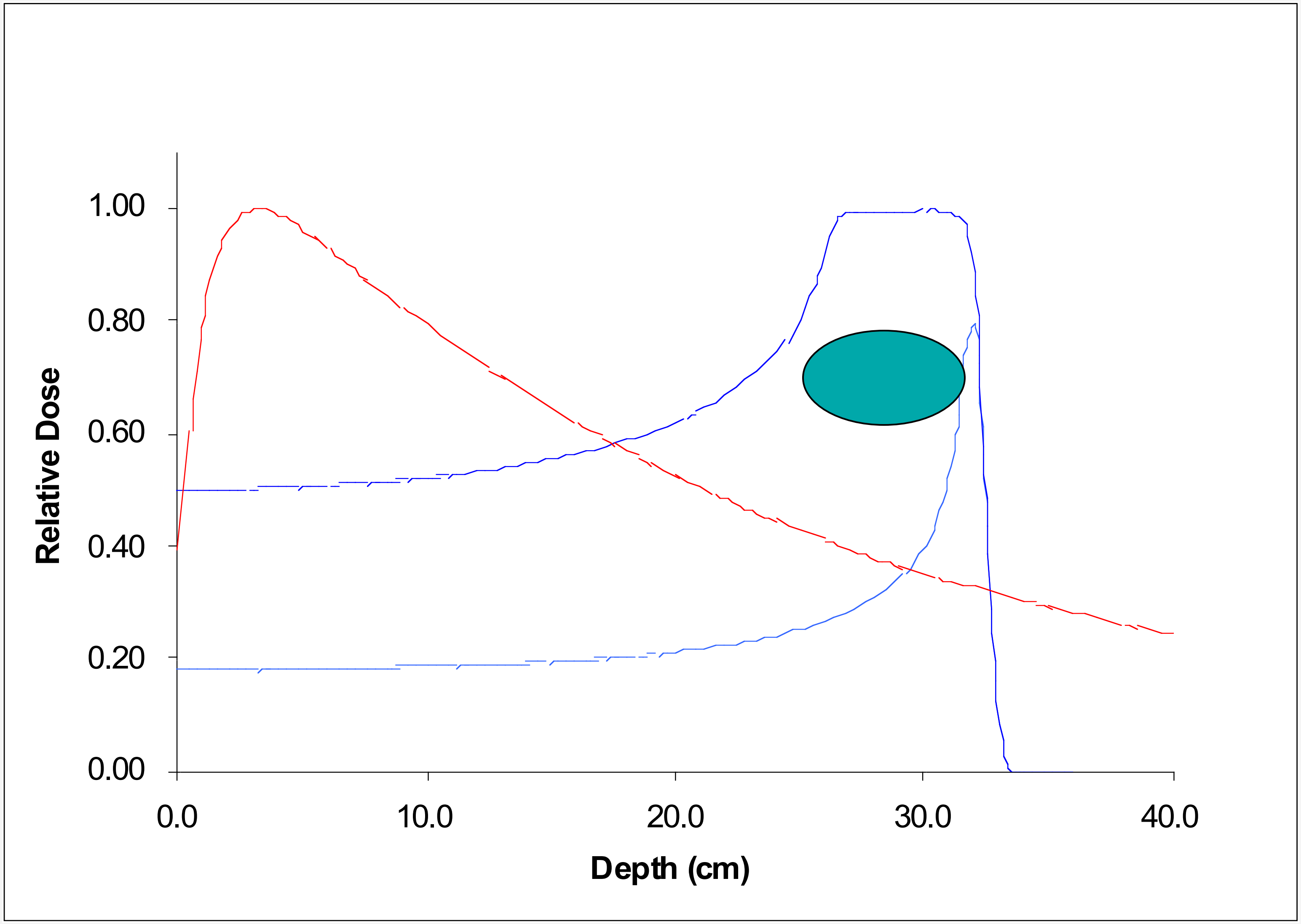
Short Lived PET Isotopes

Proton Active Interrogation

Ion Beam Beam Radiotherapy

- Around a million people each year in the US and also in Europe are treated with X-rays to destroy tumors
  - That's a few thousand electron accelerators spread around the US
- The 'Science' of radiotherapy (killing tumors with radiation) says that Ion Beams (Protons, Heavy Ions) are better than Photons
  - No exit dose allows precise conformal mapping of tumors
  - Subsequent lower overall radiation dose means less damage to healthy tissue
  - Mounting evidence also suggests that long term secondary cancer likelihoods are more than an order lower than with photons
- Yet, there are at present ~10 PBRT centers in the US treating around 50,000 patients/year (5%)

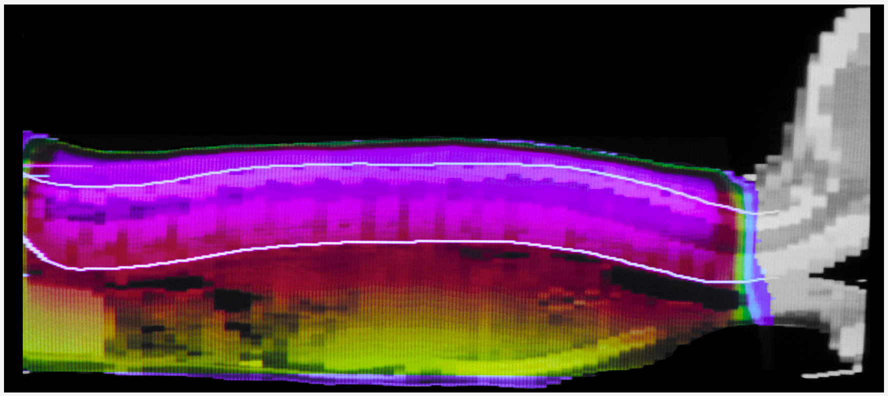
Physics… Bragg Curve Stopping of Protons in Water

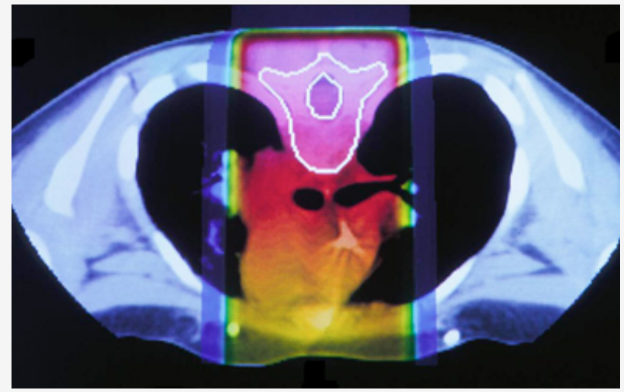


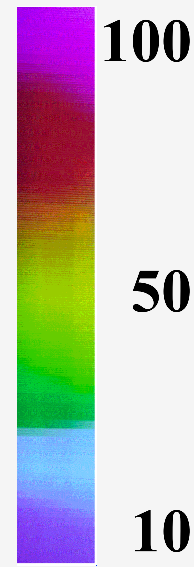
Opportunity… Proton Beam Radiotherapy

Pediatric Medulloblastoma- with protons the dose is highly localized with low collateral damage and risk

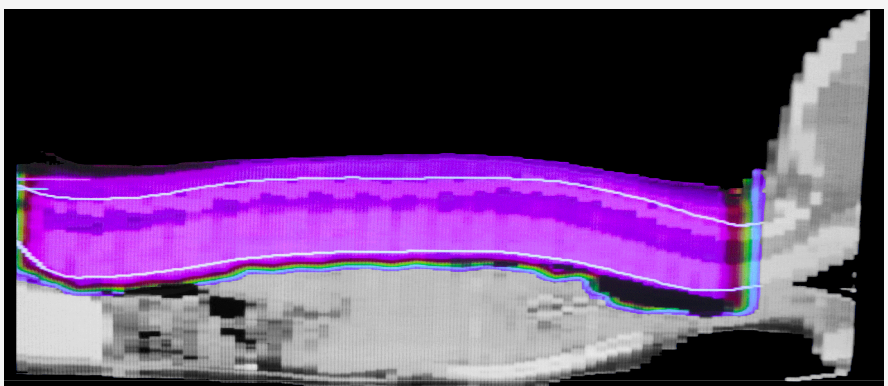
X-RAYS

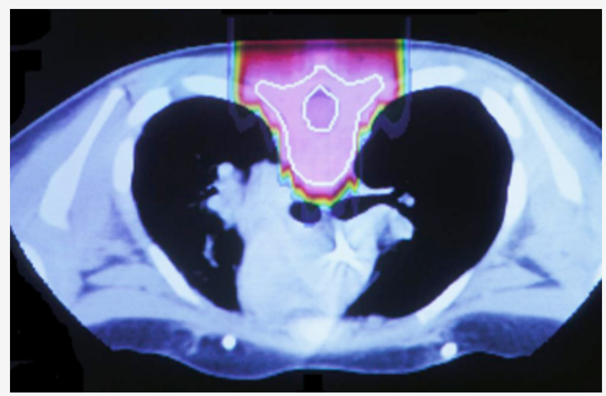






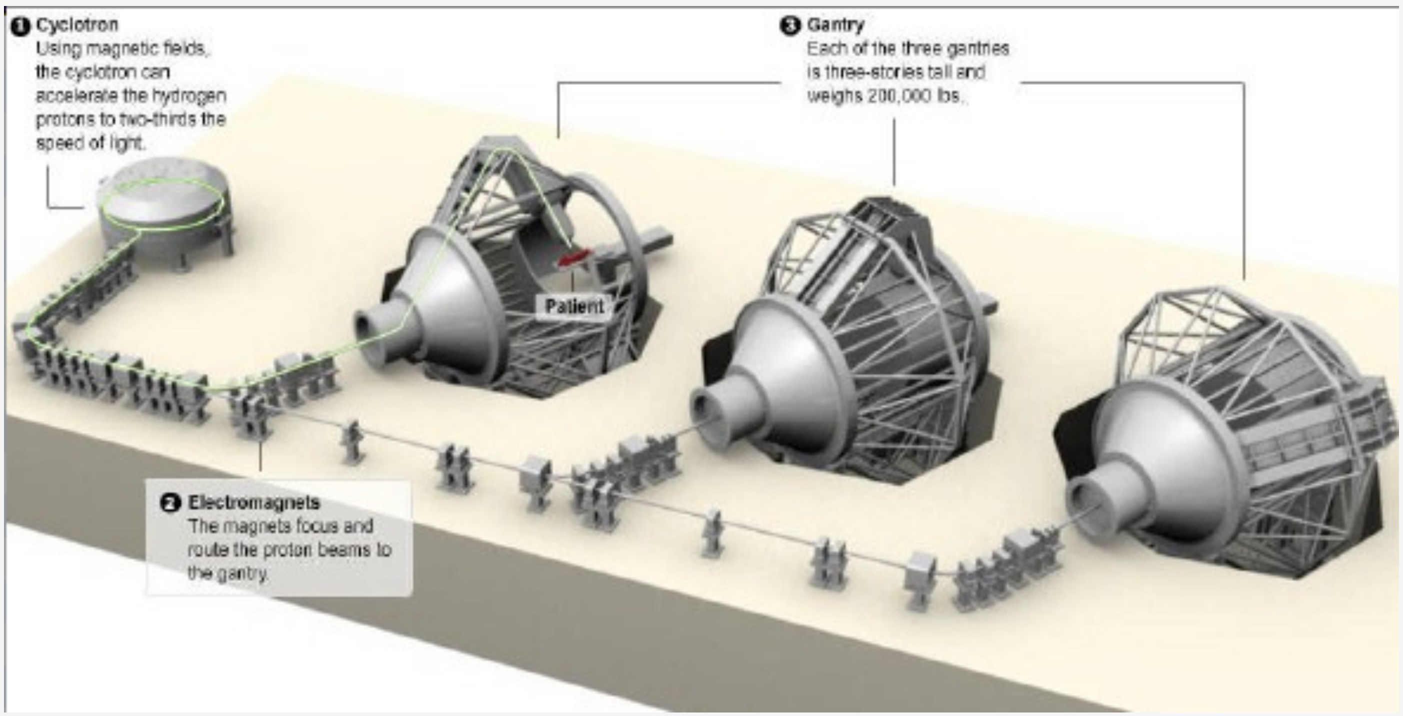
PROTONS





Challenge… Proton Facilities are very expensive relative to Photons

- Protons are 20x the cost of X-Rays
  - 1 room ~$50M
  - 3 rooms (IBA Jacksonville below) $150M



Sc Synchrocyclotrons for PBRT

- Guide field B is a *very simple,* azimuthally symmetric and falls about 10% from the center to the effective pole edge (r_{max})
  - Axial motion is weak focusing ($0<n<1$)
  - Acceleration is phase stable (number of orbit are arbitrary)
- If we set $\omega_{rf}=\omega/\gamma$ then the *RF frequency will fall synchronously as the ions get heavie*r so that gap crossings are at the right times and acceleration is preserved:
  - 6 Tesla 250 MeV Synchrocyclotron: 90 MHz ➔ 60 MHz
  - 9 Tesla 250 MeV: 140 MHz ➔ 100 MHz
- Consequences
  - Variable frequency on a fast time scale (microseconds) is required
  - Acceleration has a low duty factor – the RF can only be reset a few hundred times per second

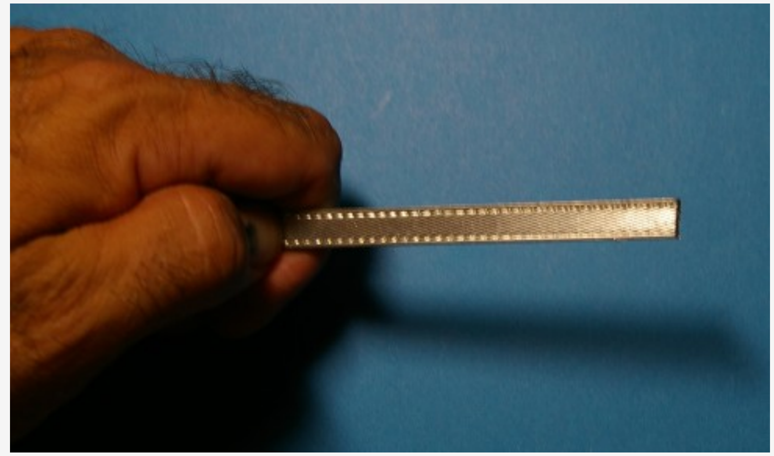
It is therefore a low intensity accelerator but it scales nicely to high magnetic field with very small form factors (Antaya 2004)

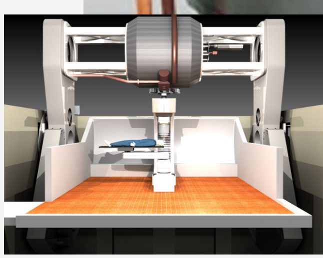
Compact High Field Synchrocyclotrons

- Mevion Monarch
  - Mounted on a gantry for rotation about the patient
  - $B \sim 9T$, $B_{coil} \sim 11T$
  - 254 MeV protons
  - Barnes Jewish Hospital St Louis, operating, FDA approved

- IBA S2C2
  - Fixed at ground level feeding beams to one or two treatment rooms
  - 6T 230 MeV or 250 MeV
  - First Operation 2013

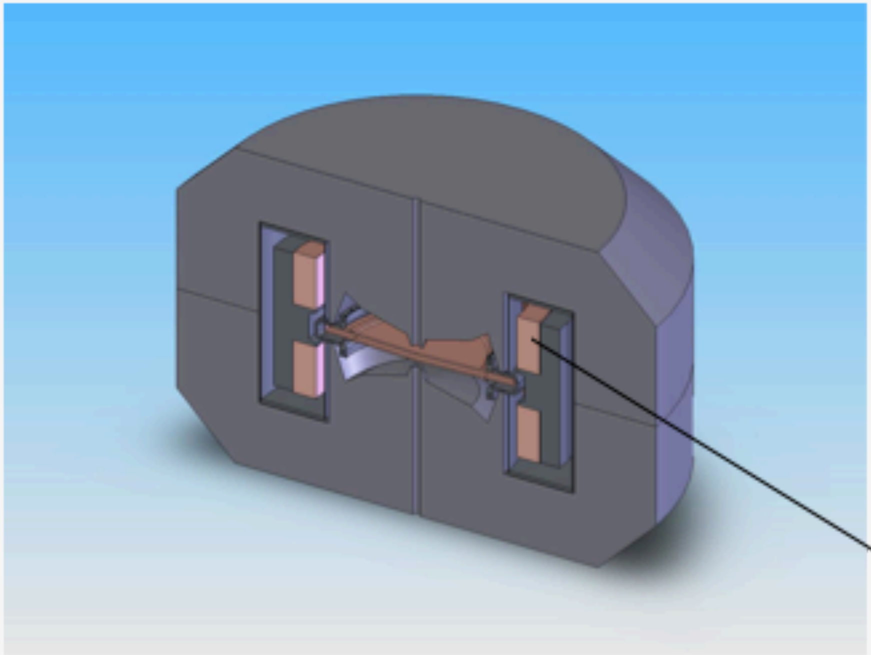
Mevion Monarch: about the size and cost of a modern 18 MeV PET Cyclotron





- Nb3Sn Coils:
- High Jc strand- ~3000 A/mm^2 (Oxford)
- Conductor is derived from DOE HEP Conductor Development Program extensively vetted by US LARP
- Wind & React, Cable in Channel
- Follows a conductor concept developed shown above for the US DOE OFES Levitated Dipole Experiment (Minervini et al/MIT)
- MIT design under sponsored research agreement with Mevion 2004-2007

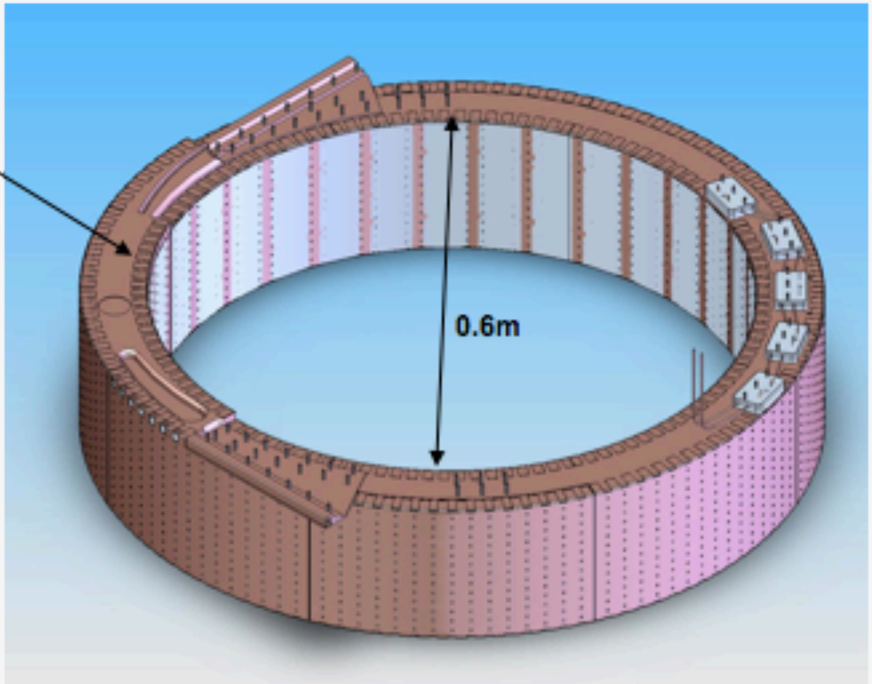
Sc Coils- react & wind Rutherford Cable with Nb_3Sn strand



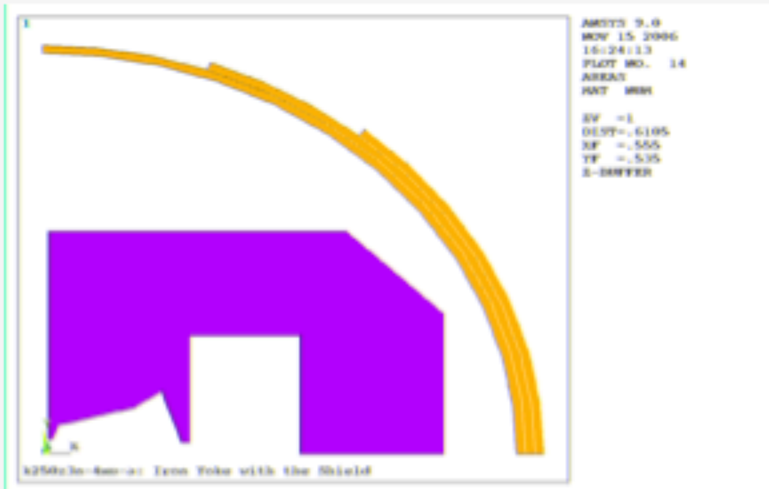
Coils Use 3.2 km of Conductor in layered winding: 49 turns x 26 layers

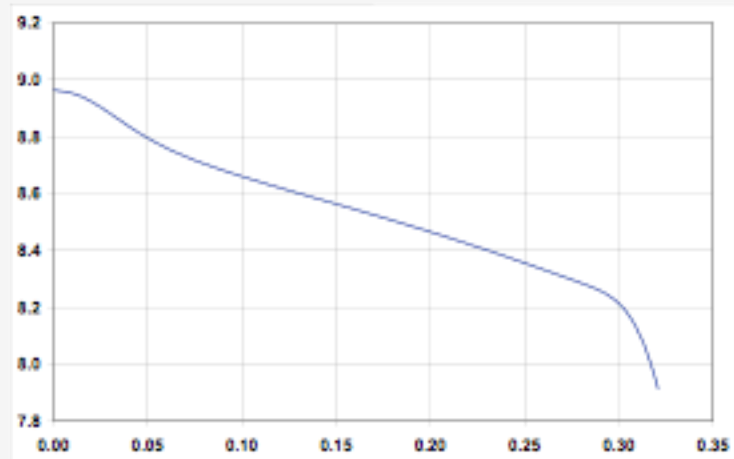
Conductor is not graded

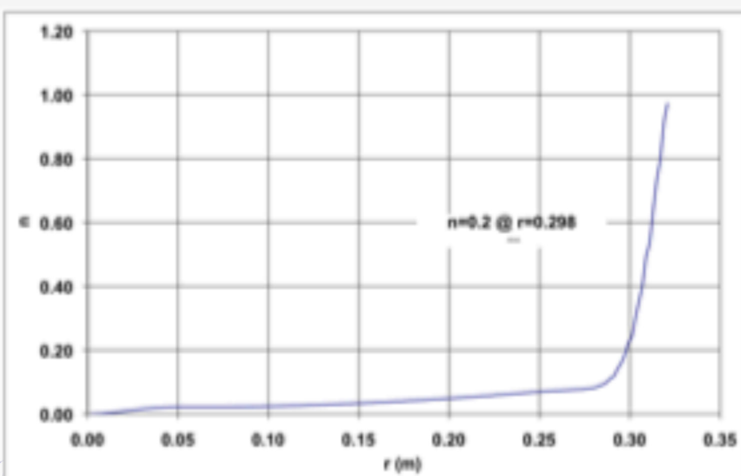
Coils designed for 800m lengths and 5 splices

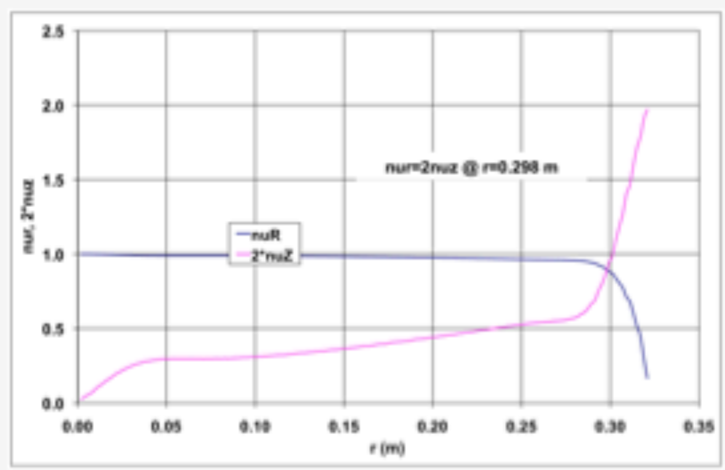


Beam Dynamics scaling to high fields (Antaya 2004)







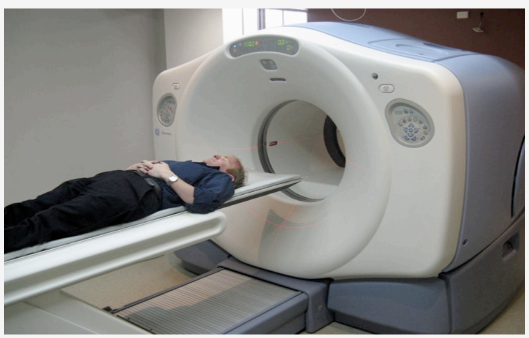


Diagnostic Nuclear Medicine

Nuclear imaging is an effective, non-invasive and painless diagnostic commonly used in oncology, cardiology and neurology

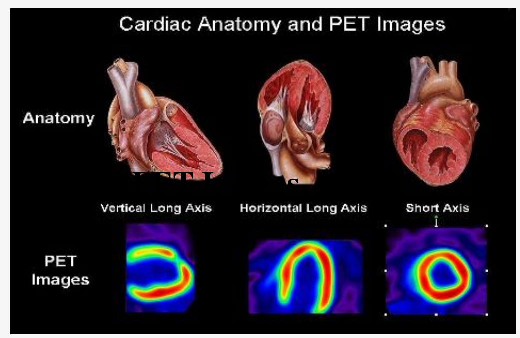
Procedure:

- Radioisotope is injected into or inhaled by patient
- Positron emission tomography (PET) or single photon emission computed tomography (SPECT) scanner is used to detect gamma rays produced by radioisotope
- Scanner measures the amount of metabolic activity at the site in the body and a computer reassembles the signals into images
- Provides information about function and metabolism of body's organs unlike CT or MRI



PET Scanner

Source: *ABC News*



Source: *Cardiac PET Solutions*

Benefits of PET over SPECT: Science says it is better medicine

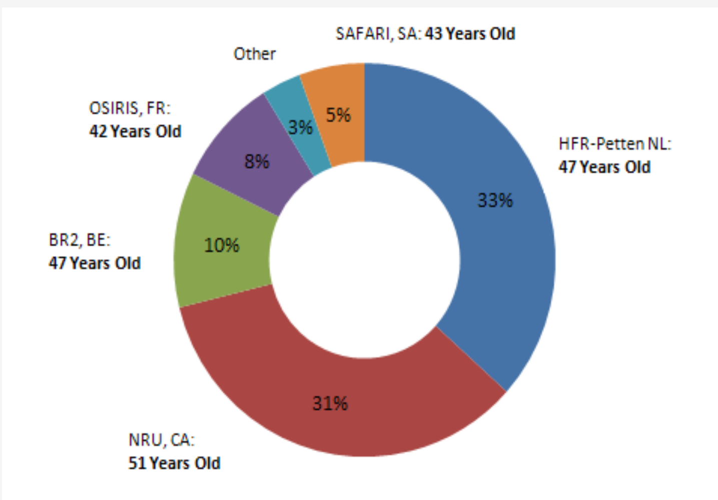
SPECT currently dominates cardiac imaging (95%), however PET is widely considered the future of cardiac imaging due to several advantages:

- Improved accuracy, irrespective of body mass index and gender
  - Better resolution and less attenuation
  - Improved patient outcomes
  - Lower false positive rate
- Lower radiation exposure to patient
  - Up to five times lower effective dose
- Valuable data about both cardiac blood flow and heart tissue viability

[1]Journal of Nuclear Medicine [2]ASNC

IS PET's DAY FINALLY HERE? SPECT SUPPLY challenges

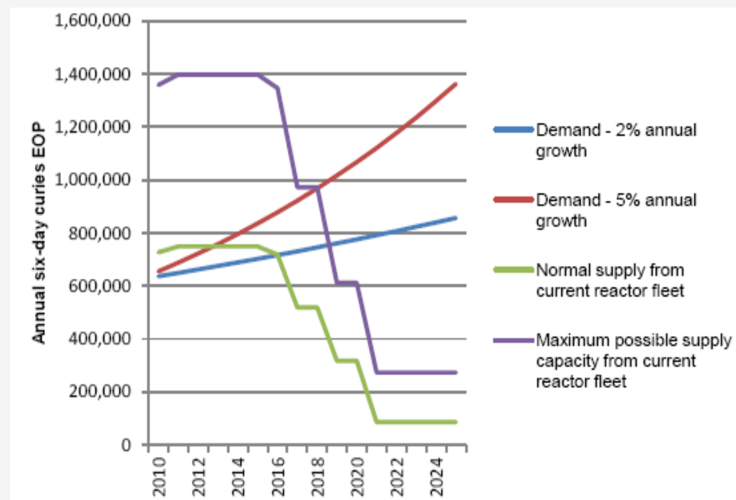
- Entire U.S. supply of ^{99m}TC is imported and Chalk River reactor (provides 50% of U.S. supply) will shut down in 2016[1]
- There have been frequent disruptions in the supply chain since 2007, largely due to the aging of the five major reactors - all are over 40 years old
- There will be a significant global shortage within 5 years without additional capacity



[1]International Atomic Energy Agency

Source: Triumf

Global Mo-99 Supply and Demand Projections



Source: Nuclear Energy Agency

PET with ^{13}N for cardiac imaging

Superior imaging, leading to better patient outcomes:

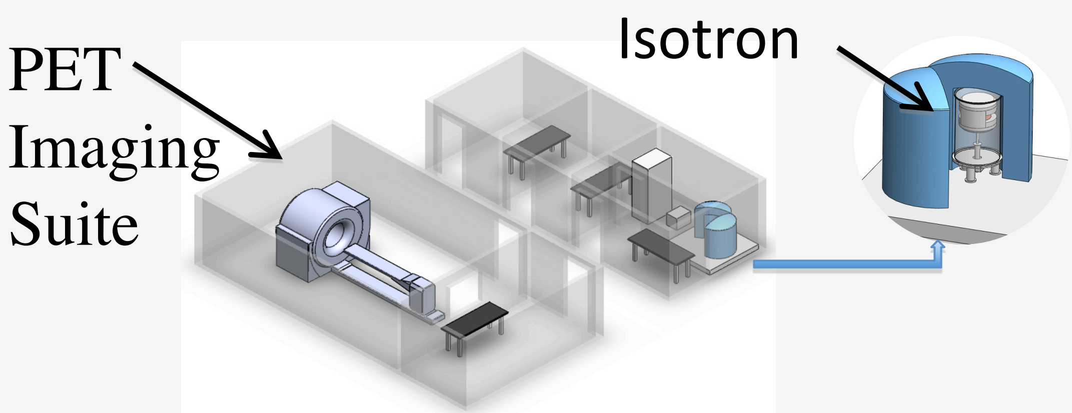
- Half life of 10 minutes
  - Fast patient throughput
  - Low radiation to patient and technician

- Reliable supply of radioisotope
  - Frequent supply interruptions for SPECT and PET alternatives, ^{99m}TC and ^{82}Rb
  - Recent recall of rubidium-82 generators after radiation exposure detected at border crossings

[Note that one can construct entirely the same science based case for $^{11}C0_2$ brain imaging for trauma medicine and Alzheimer's Disease diagnosis.]

^{13}N SOLUTION in a compact Sc cyclotron

- Despite significant advantages over alternatives in SPECT and PET, ^{13}N has had two main limits to adoption:
  - Half-life is only 10 minutes so you have to make it where you will use it
  - However, few medical facilities have on-site cyclotrons due to size and cost
- Ultra-compact high field superconducting cyclotron system to provide superior blood flow imaging by enabling PET imaging agent ^{13}N availability directly in a clinical setting

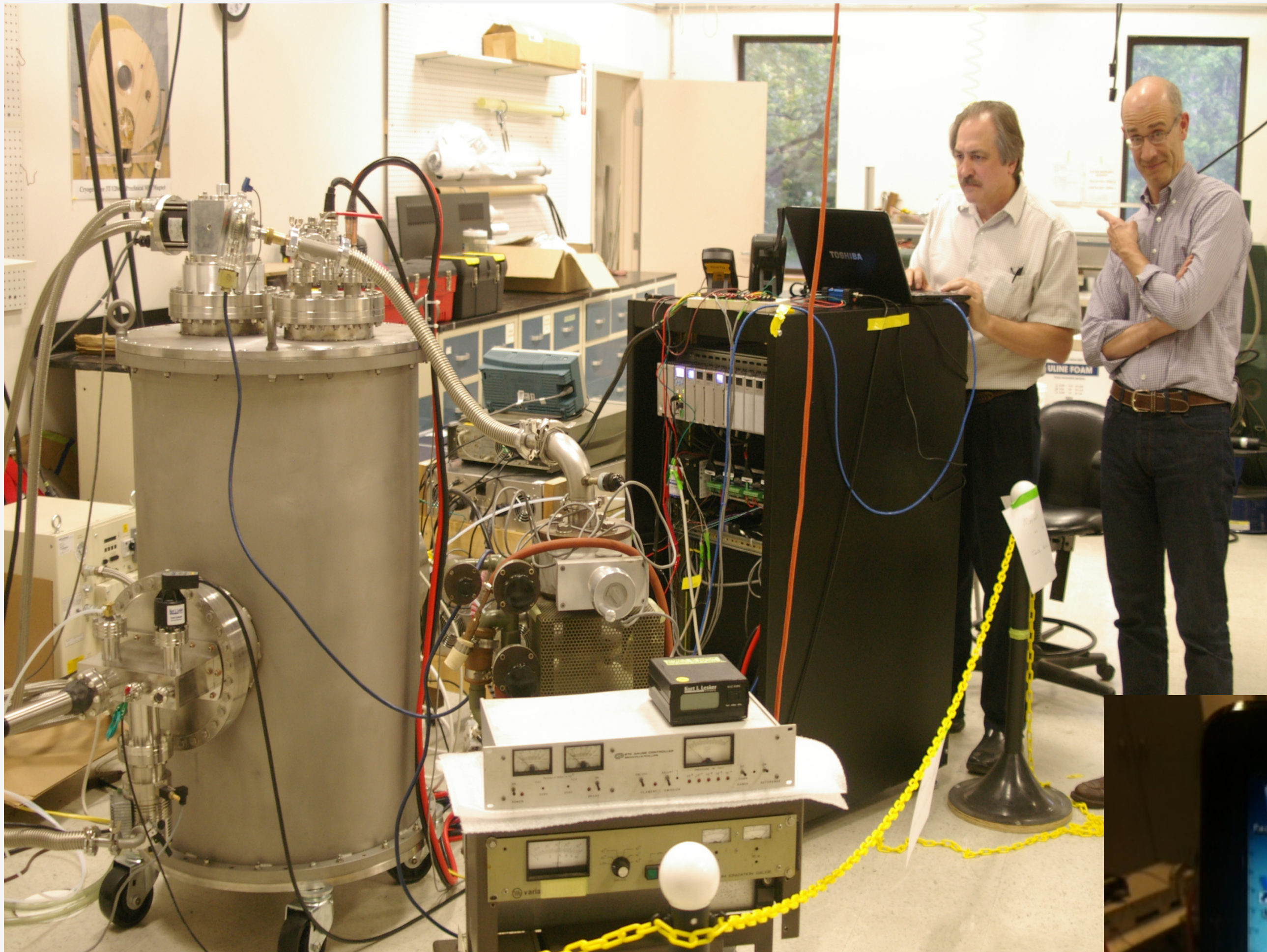


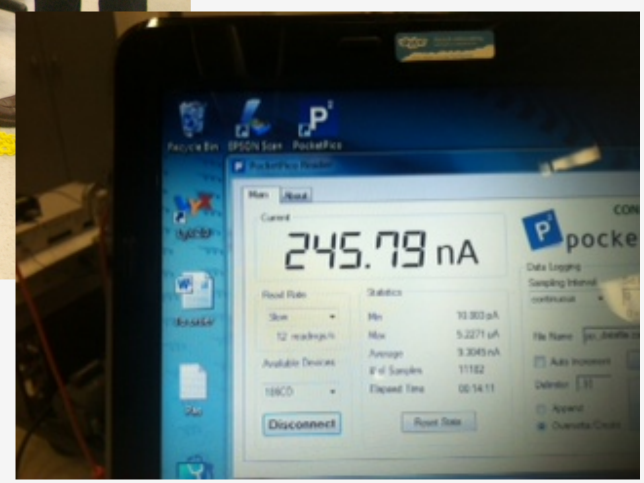
Compact High Field Classical Cyclotrons for N13?

- Ionetix Isotron ^{13}N Cyclotron
  - H+ ions with internal target
  - Final energy 12.5 MeV
  - First Operation late may 2012

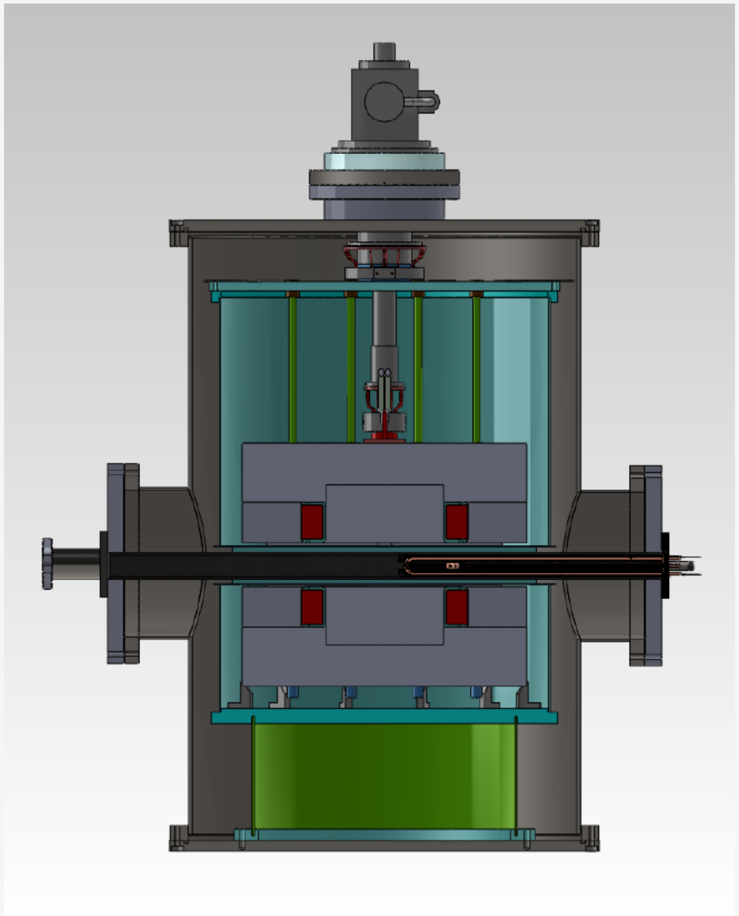
- CIEMAT AMIT ^{11}C Cyclotron
  - H- ions with stripping extraction
  - Final energy ~11 MeV
  - ~4T guide field
  - Final Design and R&D in progress
  - First operation ~late 2013

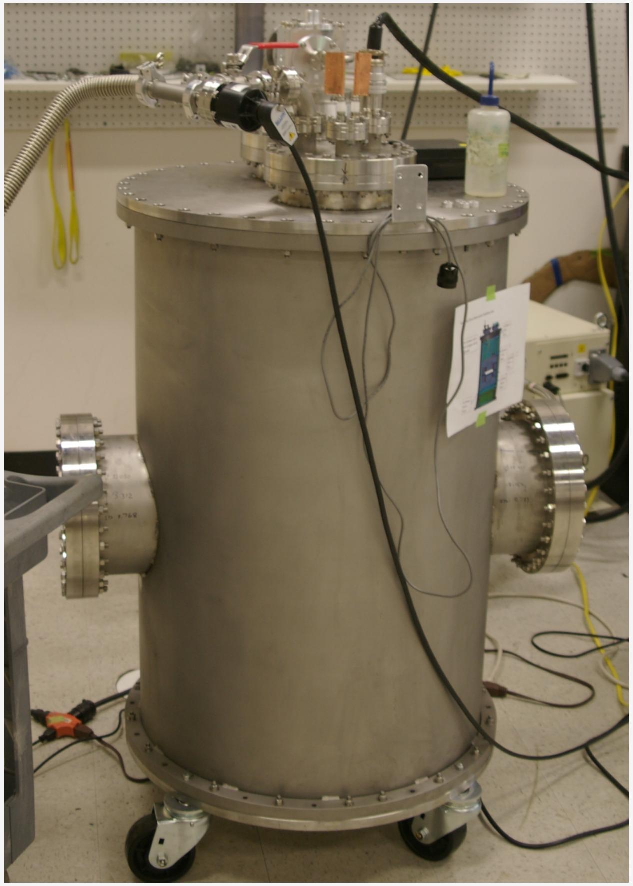
Isotron N13 Demo Cyclotron- First beam 2 June 2012





Isotron Topology

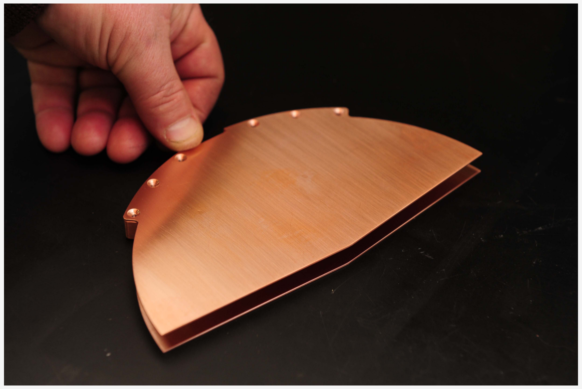


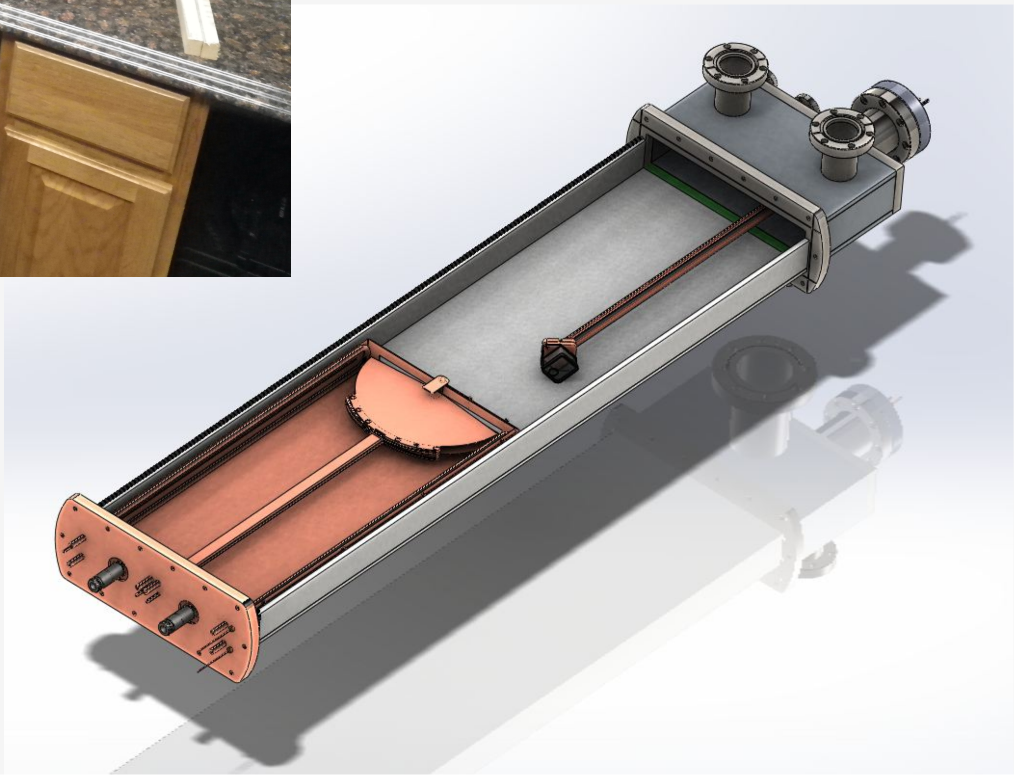


Isotron scale?

- About the same pole size as the 1932 Cyclotron but 160 times higher final proton energy

Isotron Dee/Resonator





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CIEMAT AMIT ^{11}C Cyclotron at 4T is similar in scale

Source: CERN Courier

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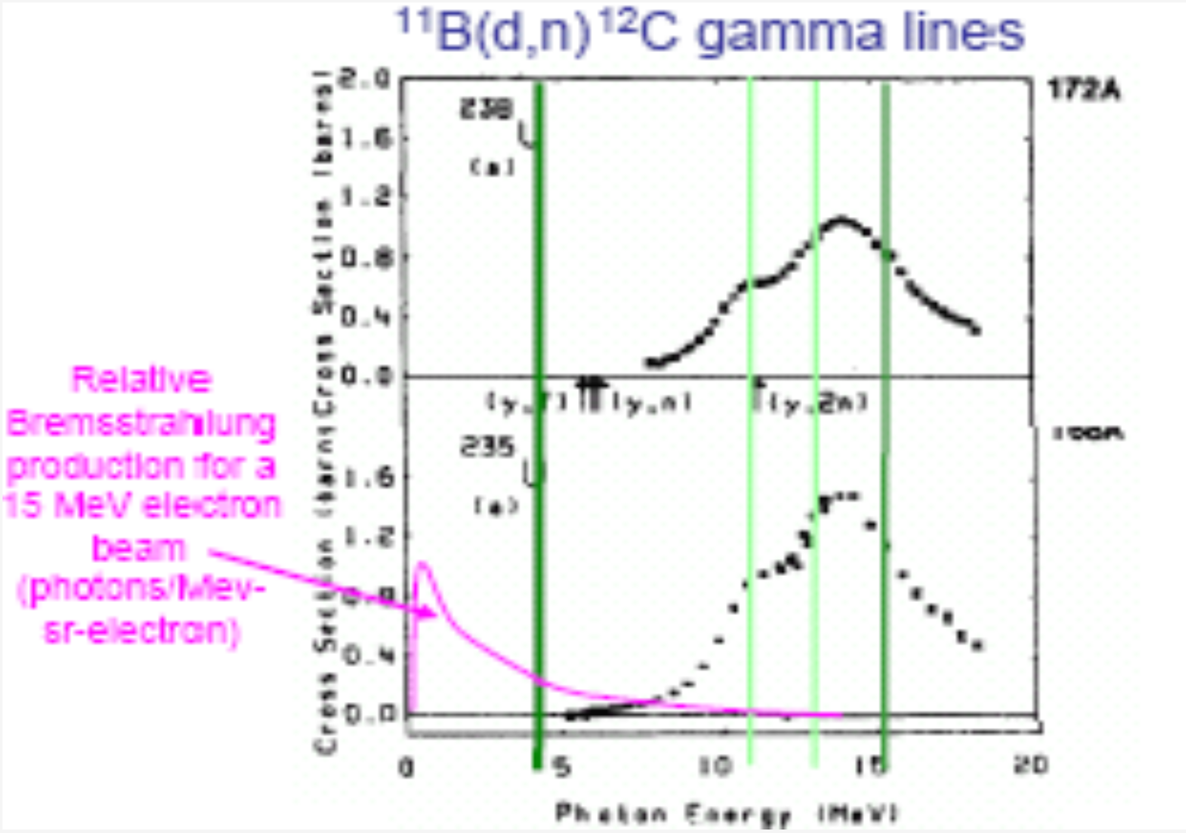
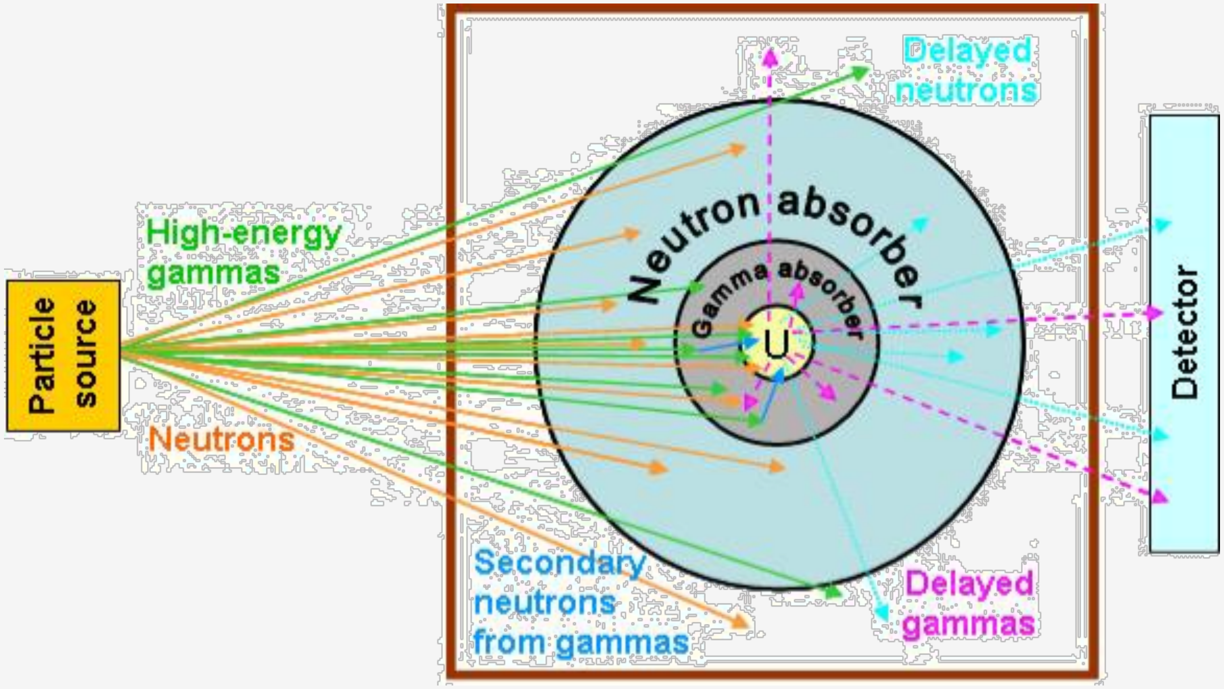
Near Proximity Proton Active Interrogation

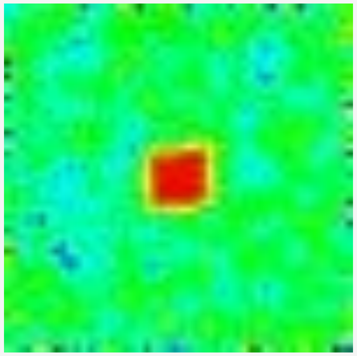
Physics… Photofission of ^{235}U



Near Proximity Active Interrogation- concept



100 cc U cube in 40 cm Fe block imaged with 15.1 MeV gammas (MCNPX simulation)



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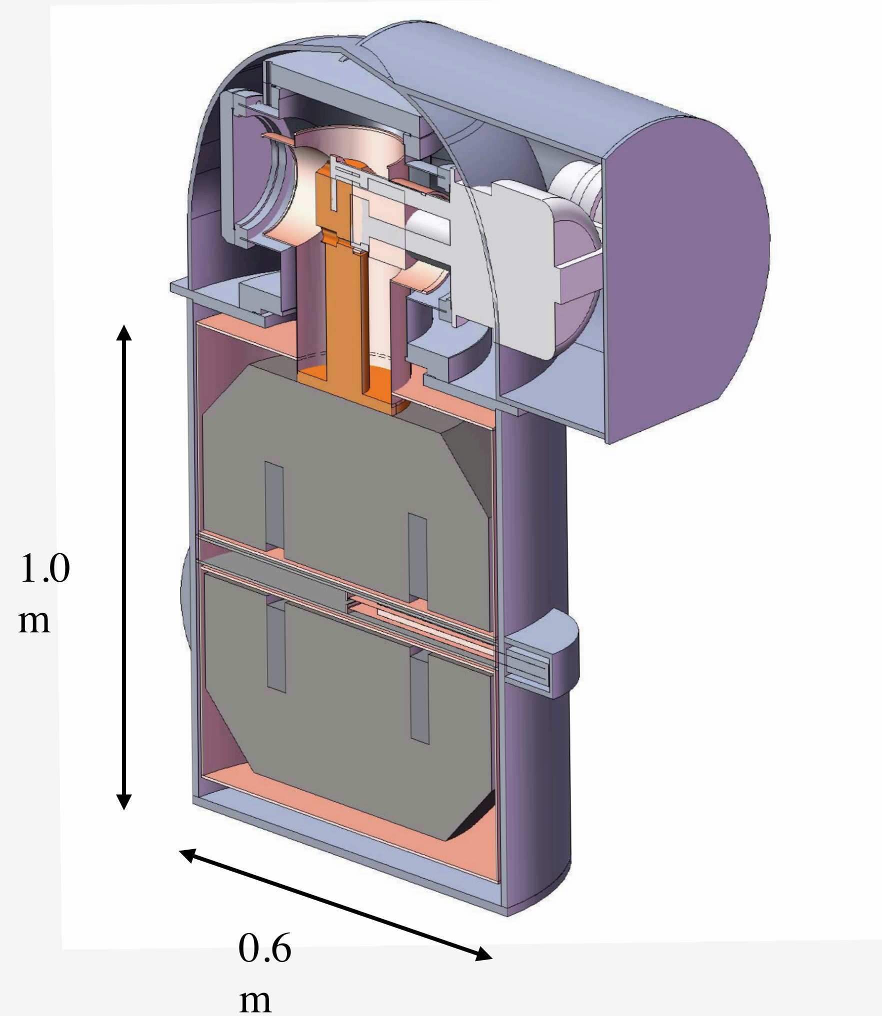
Basically Same Topology as the N13 cyclotron, slightly lower energy, a little more compact would be good (higher field)

- $^{11}B[d,n\gamma]^{12}C^*$ with deuterons at 4.5 MeV (essentially a 9 MeV proton cyclotron)
- Proof of Concept this Fall with the Isotron at MIT
- Later- maybe better $^{12}C[p,\gamma]^{12}C^*$ at 19 MeV



Isotron Setup for High Power Operation
MIT, October 2012

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Cryogen Free Sc Magnets

- An absolute necessity for all of the applications discussed
- For systems with tight RAM requirements ,e.g. medical apps, built in cooling redundancy is necessary
  - This is best understood for PBRT- 24h is desired/48h is ‘tolerated’
  - Other apps? Won’t fly if high field magnets prove unreliable
- To make the system reasonable to deploy for LTS conductors- practically we are obliged to design for 1-1.5 watts of heat load at 4.2K
  - There may still be 2-3 cryocoolers in the design baseline: one is essential, one is required for redundancy/recovery, one dedicated to the HTS leads
  - Conduction path/ heat removal may be complex, affecting the overall structural design, and leading to failures

Big Challenges

- Cool down of a dry winding with Cryocoolers
  - Hard for magnet development:
    - Cycle times are of order a month
    - Cool downs are difficult to model and predict (structures are complex, databases insufficient at low temp)
    - Progress is slow if you get anything wrong
    - Testing with LHe is not useful
  - Recovery after a fault is measured in weeks- this is bad for a critical application

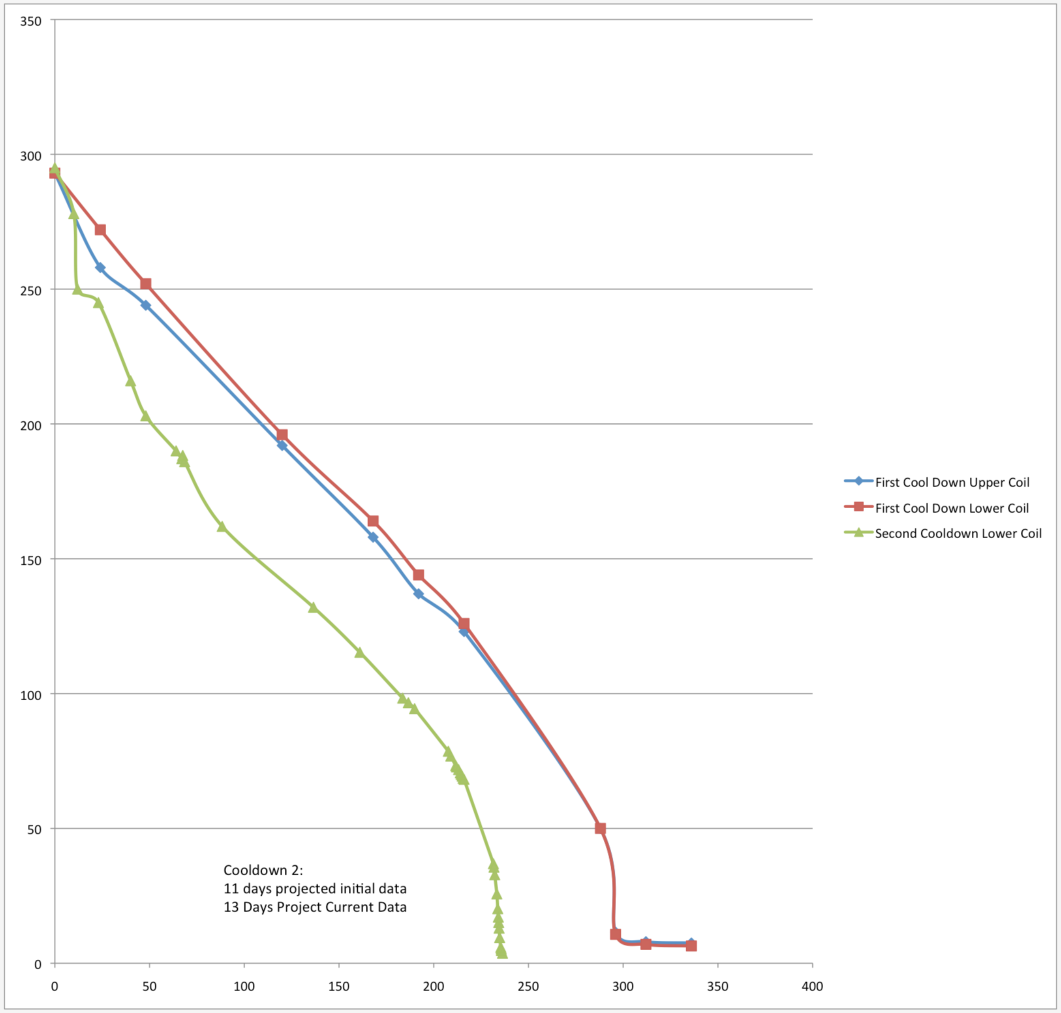
- Heat transfer- everything (heat capacities, thermal conductivities, cooling capacity) are racing to zero

- Training-
  - Force distributions favor free coils
  - Cooling favors a tightly bound coils

Heat Conduction in a Cryocooled Sc Magnet

- dH/dt = -kA dT/dx :
  - residual heat at low temperature cannot be removed where ΔT is small
  - Gaps and joints in the heat conduction ‘pathway’ reduce ΔT at the lowest temperatures
  - At low temperature, helium has the highest thermal conductivity – this leads to some hybrid cryocooler/thermal siphon helium cooling systems
- Analysis/Modeling of the cooldown and steady state operation
  - Complexity of the cold mass structure and contact resistances within the structure limit the effectiveness of thermal modeling
  - Thermal sensors on the cold mass are limited to reduce heat loads
  - Testing has a long time constant and can be frustrating- if the system does not cool down what when wrong?

Same System- small conduction adjustments
(1800 lbs of mass cooled with one 1W CC)



Coil Training and Peak Stresses

- Peak fields of order 7-8T for NbTi or 10-11T for Nb_3Sn in the windings

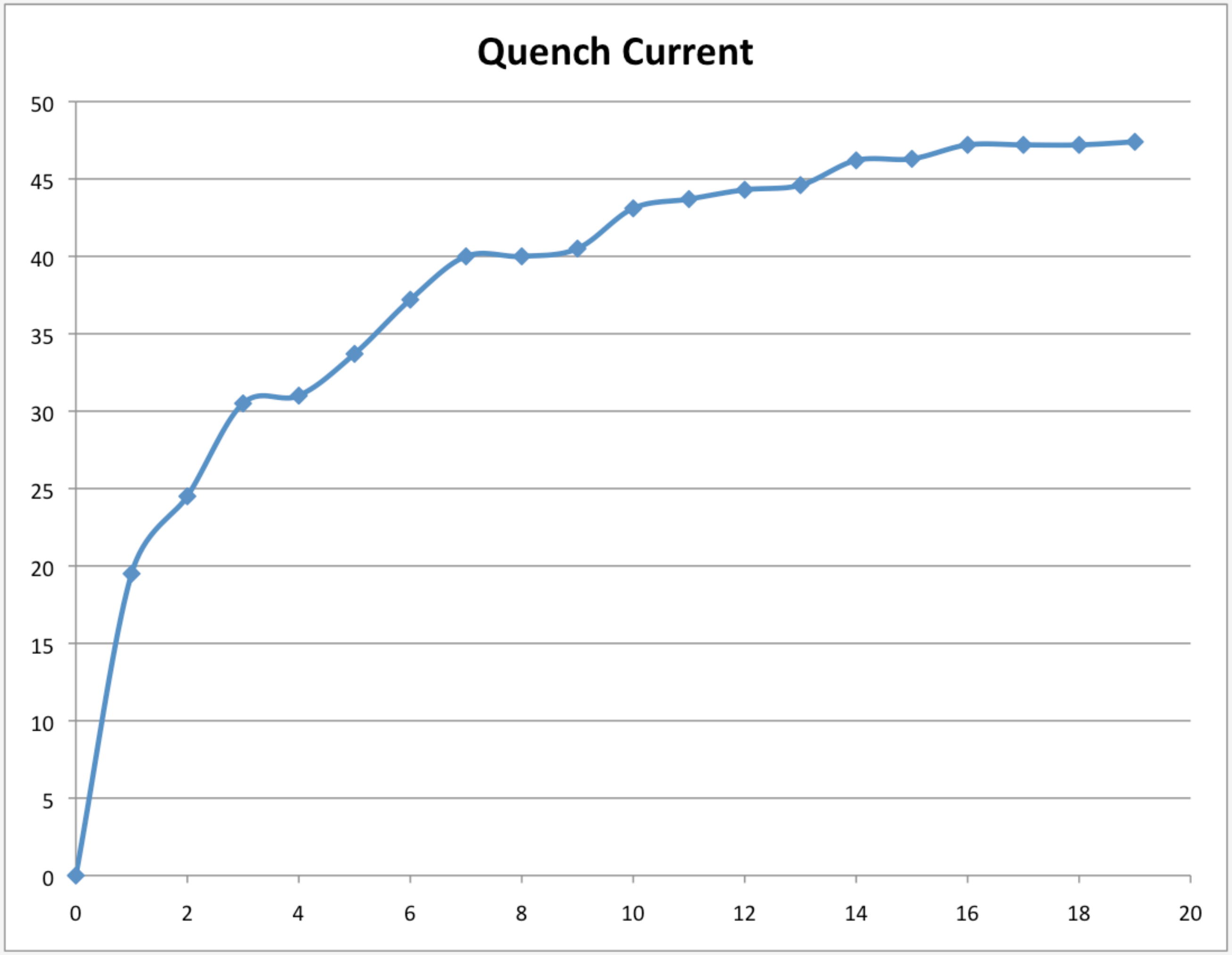
- High engineering current densities of order 10-20 kA/cm^2 in the winding are preferred for fast quench propagation

- With coil radii 0.2-0.5m, coils easily reach peak hoops stresses of order few hundred MPa (9T synchrocyclotron 800 MPa)

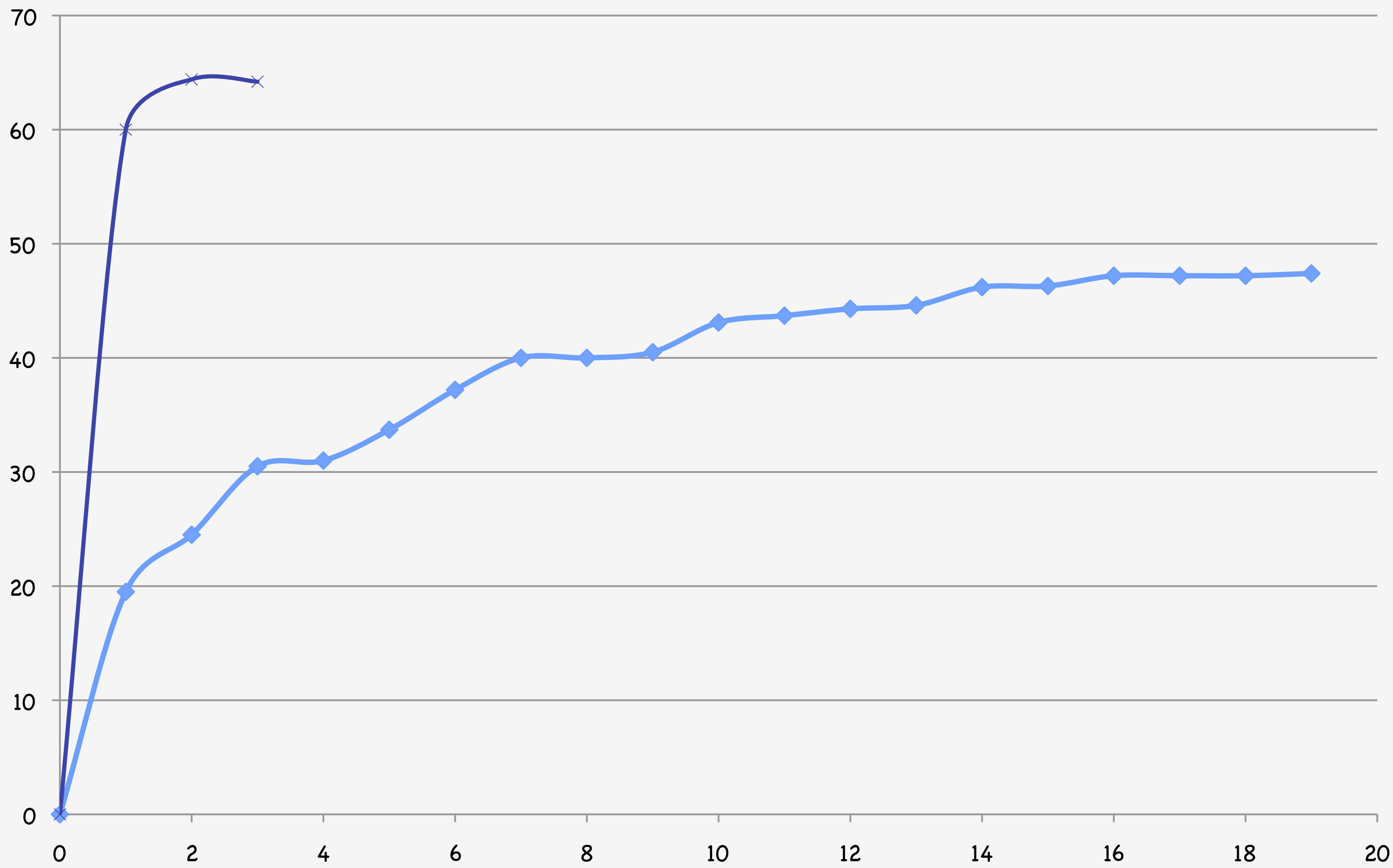
- Winding packs are compact (this is deliberate) and epoxy-glass composite structures are the preferred engineering solution

Coil Training is likely!

And Painful!
(Thermally bonded, high turn number, 0.5mm wire solenoid pair)



Suppose instead we opt for a ‘free coil’:



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2 October 2012

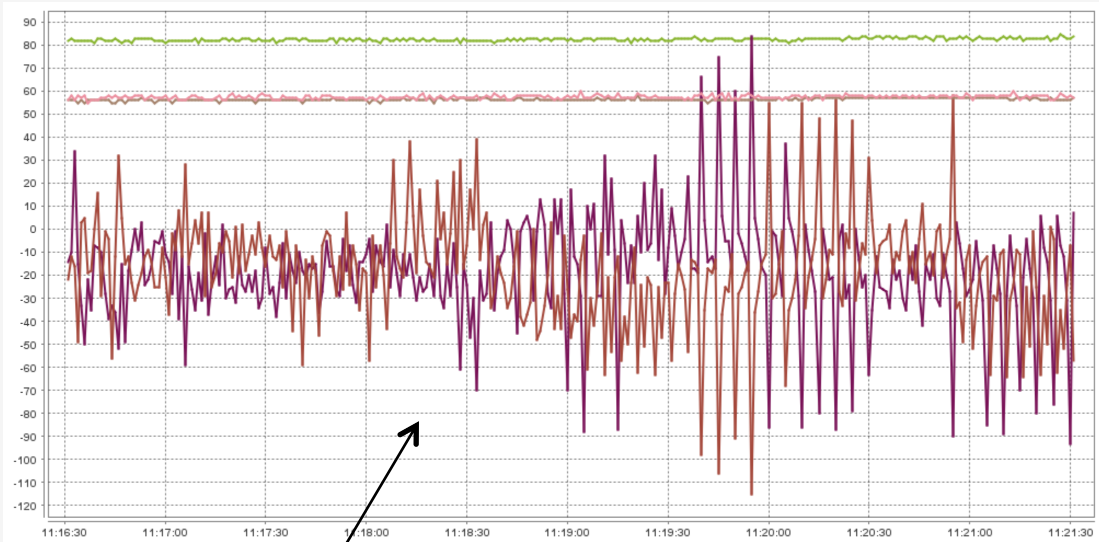
TA Antaya

Cryocooler Mechanical Coupling is Non-trivial

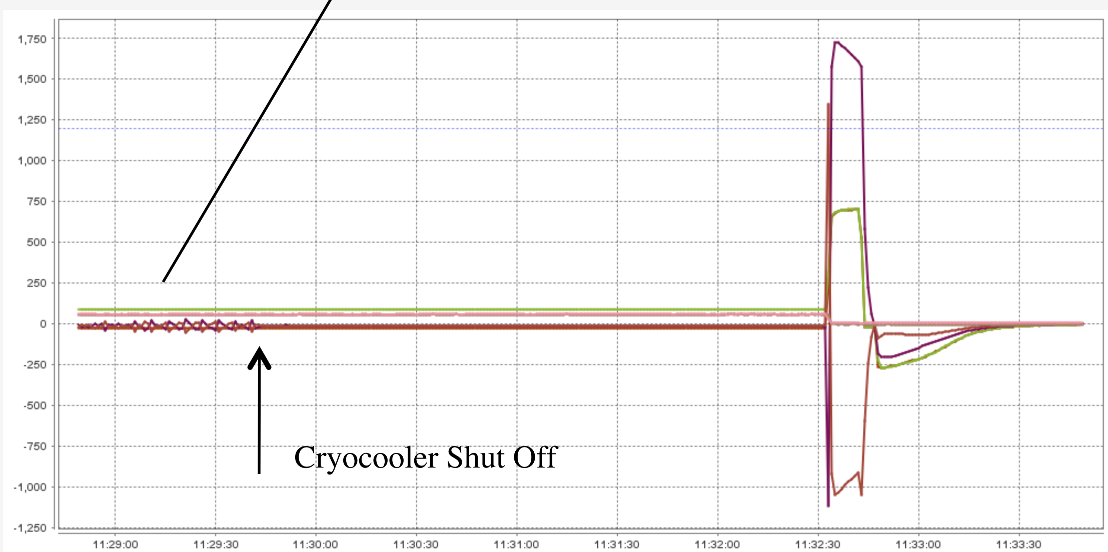
Power Supply

HTS Leads

Coils



Voltage Drops (mV)



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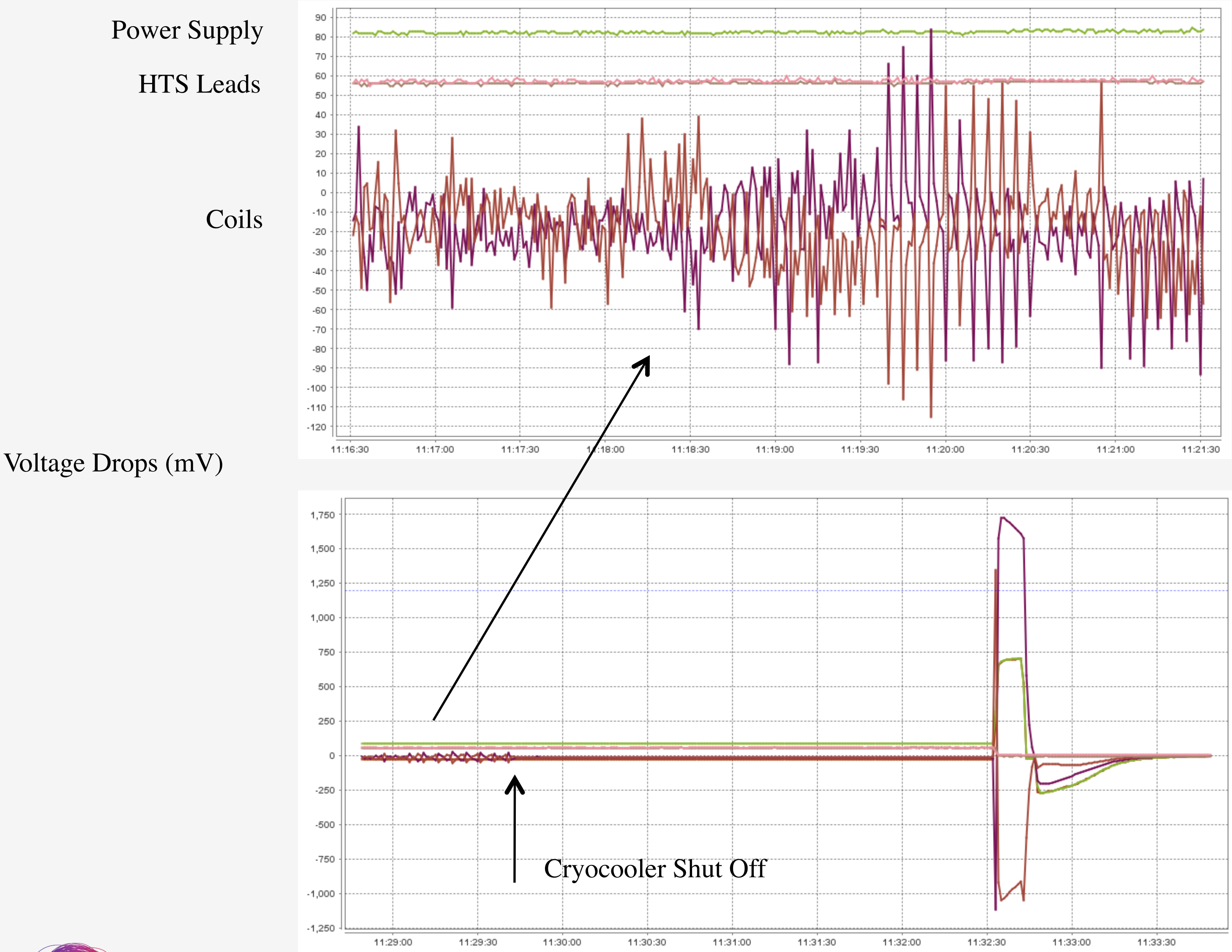
Cryocooler Mechanical Coupling is Non-trivial

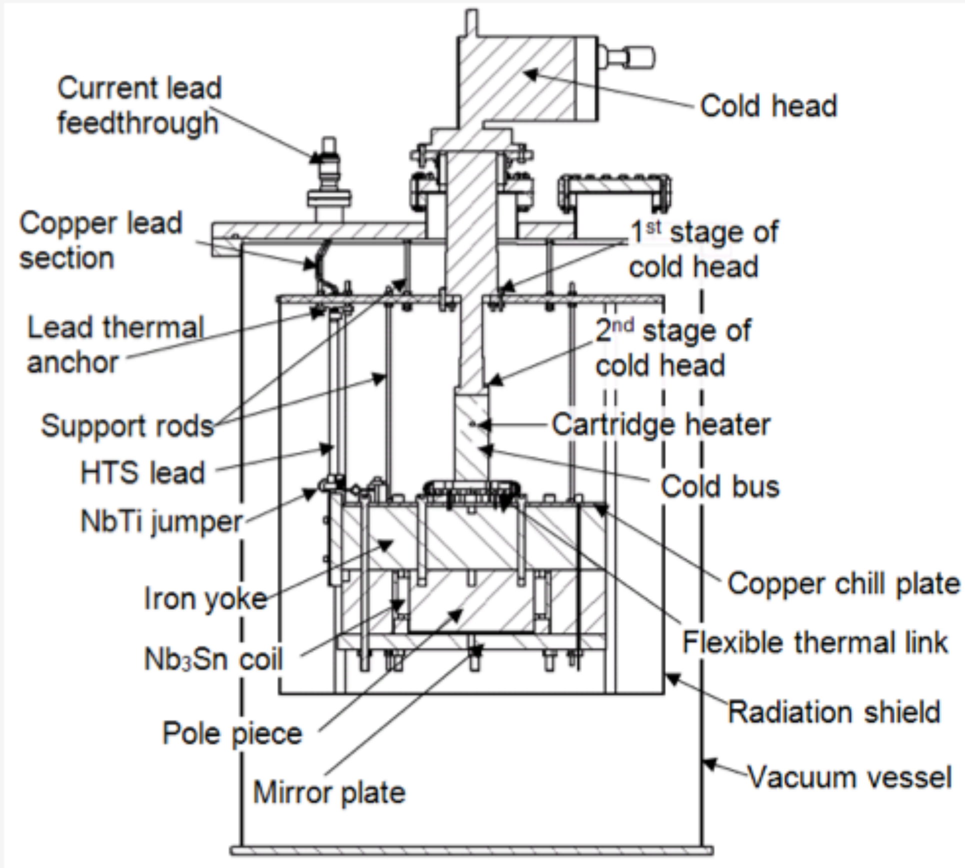


My Wish List to make these Applications Fly

- Faster Cool down with a single installed cryocooler → higher temperature operation
- Fast ramp capability in high inductance systems → Higher Cooling capacity,
- Higher Cooling Capacity → Single stage cryocoolers
- Single Stage Cryocoolers → higher temperature Sc magnets

Dry winding- small solenoid, racetrack and 2θ, j_{eng} ~20 kA/cm_2, B~4T, dB/dT ~0.1T/s, T~30K, jBr ~150 MPa, predictable training, quantitative thermal structures

Starting in that direction- 2 Stage CC, single coil Nb3Sn wind and react solenoid coil test completed recently: 236A, no training at 4K → ~100A @ 10K which would work for small cyclotrons



What can LBNL Do?

- 30-35K, 4T, conductor, cable, winding pack development
- Set of 'Case Studies'-
  - standardized solenoid, race track, 2θ coils
  - self-consistent mechanical and thermal conducting structural designs with know training in the range of 4-8T
  - For standard manufacturing methods and materials selections
- Publish and maintain a self-consistent low temperature materials dB
- Coupled analyses as a service; training materials development for winding pack modeling and sub-modeling in ANSYS and other FEA codes
- Better CC coupling structures – zero ΔT but vibration suppression
- Replace Cu with He thermo-siphon 'cells' for heat conducting at low temperature; high heat removal w/o eddy currents

Why would this be important?

- Helping directly couple advanced science and engineering into real work applications of some fair societal importance
- Meaningful efforts for staff where they can see the impact of what they are doing in non-esoteric terms
- You have key international resources in hand: people, facilities, codes, analysis methods, material databases, test facilities, benchmarks- in particular Nb_3Sn, MgB_2 and high force/stress mitigation; accelerator folks in near proximity to couple to

Thank you for giving this opportunity to help start this discussion

Backup Slides

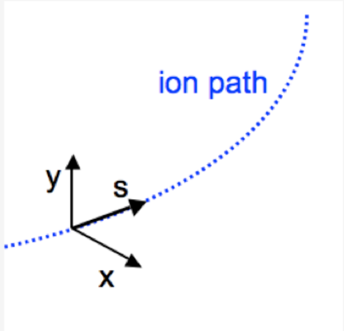
Cyclotrons

- Are *Circular Particle Accelerators*:
  - Ion rotation frequency $\omega = QB/m$ where Q is the ion charge
  - Ion Momentum $p = QBr$
- Energy Range… 1 MeV - 1200 MeV
- Ions accelerated… H^-, protons, molecular ions to Uranium
- Intensities: picoamps to ~10 milliamps
- Particle orbits in the guide field… ~a few to ~20,000
- Energy Gain per orbit… few KeV to ~ 1 MeV
- Acceleration in one stage is possible, CW operation possible

Cyclotrons and Special Relativity

- $\omega = QB/m$ … note that $m = \gamma m_0$
  - 10 MeV proton $\gamma = 1.01$
  - 250 MeV proton $\gamma = 1.26$
  - 1200 MeV proton $\gamma = 2.3$
- Ignore γ? … Classical (Lawrence) Cyclotron
- Compensate for γ
  - Allow the ion rotation to slow down by lowering the acceleration frequency … Synchrocyclotron
  - Hold the ion rotation frequency constant by raising the guide field … Isochronous Cyclotron

Cyclotron Orbit Stability



- Beam Coordinates (Frenet-Serret)
- Cyclotrons- cylindrical coordinates are such a coordinate sys
  - x➔r y➔z s➔ϕ
  - Guide magnetic field **B** is taken in the z direction
- To accelerate for 100 or even 20,000 orbits means that the motion in r and z is bounded… as best this means *sinusoidal*
  - r: let r=<r> + x and the radial motion is $x'' + (1-n)\omega^2 x=0$
  - z: $z'' + n\omega^2 z=0$
- Generally you can show that the radial (x) motion is stable in cyclotrons so it comes down usually to axial (z) stability relative to the height of the magnet gap

Cyclotron Acceleration Frequency

- Acceleration Frequency depends on the guide field B
- Ion rotation frequency ω=QB/m as before
- Take f=ω/2π Q=Ze and m=Au
- f=15.36 MHz × Z/A × B with B in Tesla
  - Protons 1 Tesla f=15.4 MHz
  - Protons 6 Tesla f=108 MHz
- Note that ions can accelerate on multiples of the fundamental frequency $\omega_{rf}=h\omega$ where h=1,2,3,….

Cyclotron Final Energy (T), Field (B) and Size (r)

- Cyclotron Final Energy to zero order:
  - $T_{max} = KZ^2/A$;
- Where
  - $K = e^2 r_{max}^2 B_{max}^2/2u = 48.3\ \text{MeV} \times r_{max}^2 B_{max}^2$
- This is how we make cyclotrons compact:
  - Resistive Magnet Technology B_{max} ~1-3T
  - NbTi Sc Magnet Technology B_{max} ~4-6T
  - Nb_3Sn Sc Magnet Technology B_{max} ~8-10T

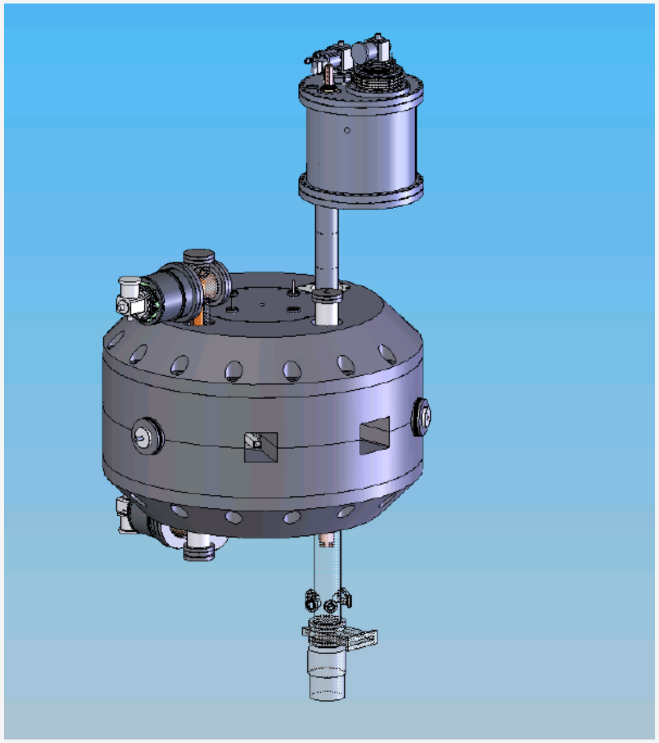
IONETIX

Cyclotrons and Superconductivity?

- Usual Sc challenges: heat loads, conductor stability, quench & protection…
  - Cryocoolers have made it easier to deploy Sc cyclotrons
  - Close Loop Helium Thermo-siphon with multiple cryocoolers in a satellite dewar: Mevion maybe, Varian Proscan, IBA S2C2
  - Dry winding with a single cryocooler: Ionetix Isotron
- In addition cyclotron systems must be fit in:
  - vacuum chamber, RF, ion source, probes & diagnostics, beam extraction systems
  - many of these systems must pass thru the cryostat wall in the radial direction
- Scaling to High Field?
  - Current density and magnetic field in the coils goes up
  - High force densities, stored energy and decentering forces

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



Classical Cyclotrons (ignore relativity)

- First Cyclotrons in the 1930s-1940s
- Final Energy is limited by the frequency error
  - Let Φ be the angular difference between when the ion crosses and acceleration gap and when it *should* cross to gain the maximum energy
  - $\Delta\Phi \sim \omega_{rf}/\omega - 1$
  - 1% mass increase representsan ion crossing a gap late by 3.6°
  - 90° phase shift takes just 25 turns
- Max Final Energy ~20 MeV; practical limit (dee voltage) ~13-14 MeV; ion phase space is large (weak focusing)
- High Field Classical Cyclotron @6 Tesla reintroduced in 2012

Isochronous Cyclotrons

- Most widely used cyclotron type
  - All ion species including being able to do variable ion species and variable final energy in one machine
  - High intensity, CW operation
- Let $B=\gamma B_0$ where B0 is the value near the center
  - then $\omega = QB/m = Q\gamma B_0/\gamma m_0 = QB_0/M_0$ is a constant and independent of mass change
- Are a variation on strong focusing circular particle accelerators:
  - That B increases with radius ***unbounds*** the simple axial motion of classical and synchrocyclotrons
  - The field must vary azimuthally (flutter) to correct this axial beam blow up
  - Flutter is inversely proportional to the average field

Are the hardest to scale to high field but we are working on that…

Compact High Field Isochronous Cyclotrons? Not Yet!

Close

- Harper Grace Neutron Therapy Cyclotron (MSU, 1992)

- Varian 250 MeV Proton Beam Radiotherapy Cyclotron
  - 1992 MSU design study – 250 MeV 2T average field
  - Commercialization started by ACCEL in 2001; machine install at PSI in 2005- first beam 2006
  - First patients treated with PSI machine in 2007
  - Second machine built for Reineker Center in Munich- patients treated in 2009
  - Machine 3-8 under construction near Cologne Germany with #3 going to San Diego now