Future Trends in Cyclotrons

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Today you've already hear about science, technology and application of cyclotrons to medicine, from some of the world's leading experts: M.Schippers, W.Kleeven and S. Brandenburg

I aim to repeat little of what they have already presented...

Instead, I'd like to give you a glimpse of what is possible, and what is revolutionary, in the cyclotron domain, mid-2015.

Cyclotrons in general:

- Can Accelerate all ions: H^+,H^-,H_2^+ and highly charged heavy ions
- Intensities: highly charged heavy ions to ~ 1 mA and H^+,H^- to ~few mA
- Advanced cyclotrons are possible in all three Cyclotron Flavors: Lawrence, Synchronous, Isochronous

Key Characteristics of Cyclotron Flavors:

- Lawrence and Synchrocyclotrons are weak focusing and have longitudinal phase stability like synchrotrons and linacs

- Isochronous are strong focusing (AVF) and have no relation between period and momentum (sit at the synchronous transition energy –momentum and period are not related)

- Isochronous share many key beam physics properties with FFAGs (they are derived from the same set of equations)

How the Cyclotron Flavors scale with Energy and Field:

- Lawrence have a simple uncritical field scaling but energy is limited to 20 MeV or less by an accumulating ion phase error (with respect to acceleration gap crossing)
- Synchrocyclotrons - share the same field scaling simplicity with Lawrence but have unlimited final energy – the frequency synchronously declines with increasing mass-energy
- Isochronous $T \sim r^2$ has no limit but you have to simultaneously solve the vertical focusing limit in the AVF field that scales as $1/B^2$

Cyclotron Flavors and Intensity:

- Lawrence no real limit but with internal ion sources a few hundred microamps have been demonstrated

- Synchrocyclotrons – low intensity (enA): Low duty factor ~1000 acceleration cycles per second, with a full acceleration cycle of order few hundred microsecond and the same ‘bucket’ space charge limits as the other flavors

- Isochronous are the highest intensity CW ion accelerators – milliamps protons at both low energy and high energy have been achieved

Me: These days, in Hampton, on the seacoast of New Hampshire (45 mi north of Boston), I represent:

- *Antaya Science and Technology*- my ‘flat’ boutique accelerator design firm / new technology incubator
- *Antaya Foundation for Science and Technology* - supporting secondary school science and engineering education
- *AMMDX* - a medical device manufacturing company
- *Antaya Proton Therapy* – developing advanced low cost local PT centers

A major theme in all this for me is a mixture of advanced cyclotron beam dynamics and’ what is next possible’ superconductivity-

Compact High Field Superconducting Cyclotrons

Compact High Field Cyclotrons in general:

- Are necessarily about going to high magnetic guide field: $p/q=rB$
  - This scaling characteristic is shared with synchrotrons (also betatrons and microtrons)
  - Synchrotrons operate essentially on one fixed equilibrium orbit by ramping B
  - Cyclotrons contain a nested set of EOs from T=0 to $T=T_{final}$ in a fixed B field

- Can Accelerate all ions: H^+,H^-,H_2^+ and heavy ions

- Are possible in all three Cyclotron Flavors: Lawrence, Synchronous, Isochronous

Why high field? *We found already with the K500 that a 2x increase in average field results in a facility cost (cyclotron, vault, services) decrease of 3X*

Compact High Field Superconducting Cyclotron Development Timeline:

- 1982 - K500 at MSU was the first compact high field superconducting Cyclotron
  - It is Isochronous with B~3-5T and fully saturated AVF poles (very important)
  - With iron AVF poles high energy and focusing are not compatible
  - Heavy ion acceleration represents a 'sweet spot' where both work well enough
  - Demonstrated that when you double B the cost declines by $/3

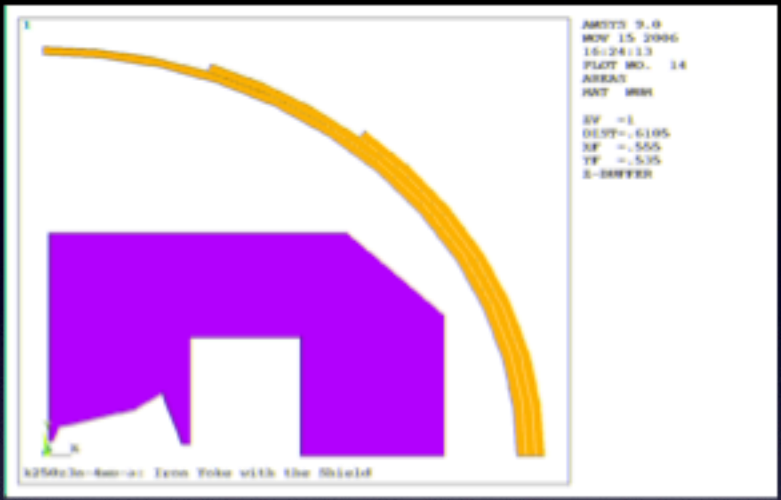
- 1980s-1990s - Many Compact Heavy Ion Superconducting Cyclotrons for heavy Ions were built- only 1, AGOR, could also accelerate protons directly.

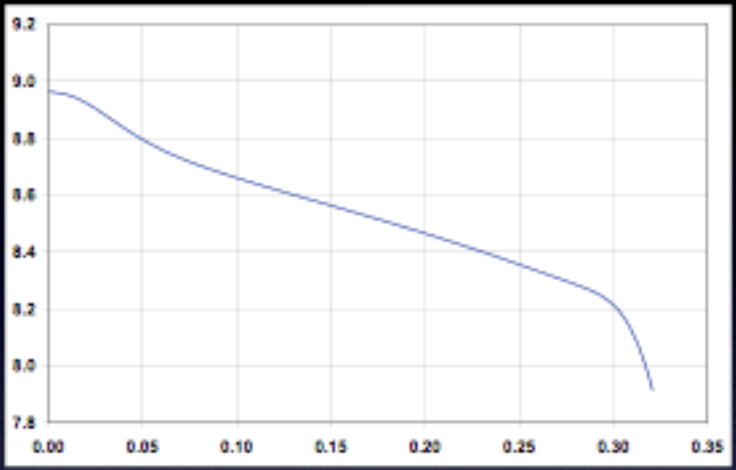
Compact High Field Superconducting Cyclotron Development Timeline (cont'd):

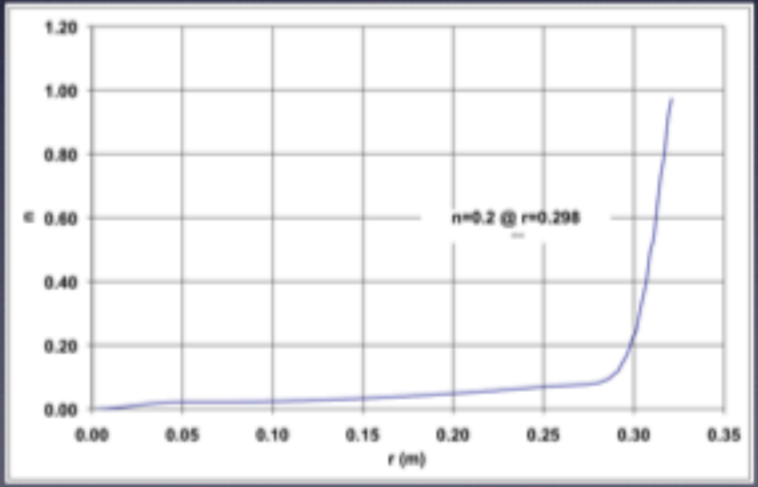
- 2003-2007 – MIT High Field Synchrocyclotron commercialized by Mevion
  - It is the highest field particle accelerator B_0~ 9T
  - T=250 MeV and I~40 enA
  - It was my first attempt to make a compact proton therapy machine using superconducting magnet technology
  - The field scaling solution came in 2004
  - The full quantitative beam dynamics solution with self-extraction was achieved in 2007

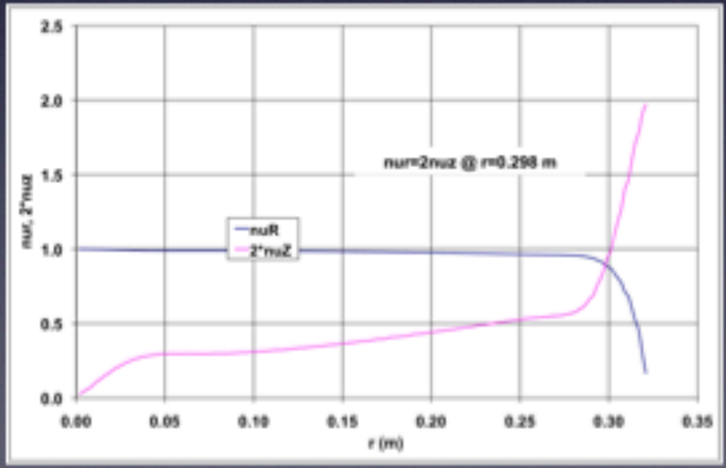
- For Single room PT, to date, Mevion has orders for about 10 installations

Beam Dynamics scaling to high fields (Antaya 2004)









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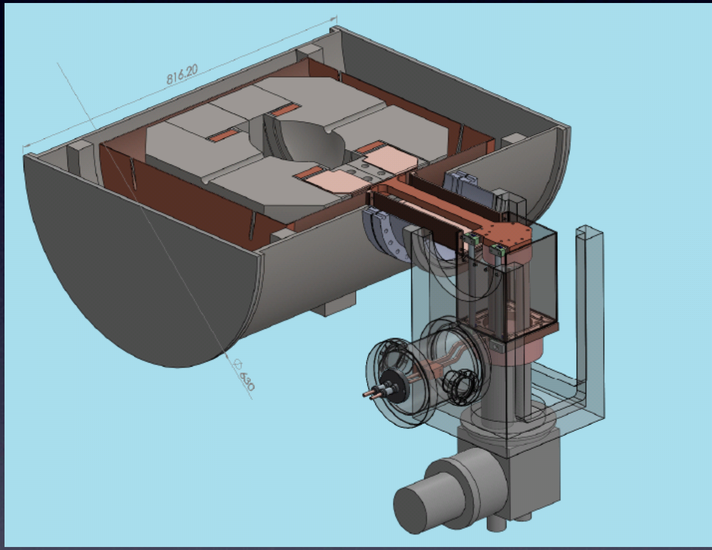
Compact High Field Superconducting Cyclotron Development Timeline (cont'd):

- 2008-2011 MIT Nanotron Design Studies
  - Lawrence B_0~ 6T
  - Portable, transportable weak focusing cyclotron for Active Interrogation
  - Simple field, RF and T~10 MeV

- Above 6T the radial and axial cold mass thermal (and decentering load) supports begin to dominate the design envelope

- The Nanotron solved this by including the iron inside the cryostat with the Sc coils

- Also, it features dry conduction cooling



Compact High Field Superconducting Cyclotron Development Timeline (cont'd):

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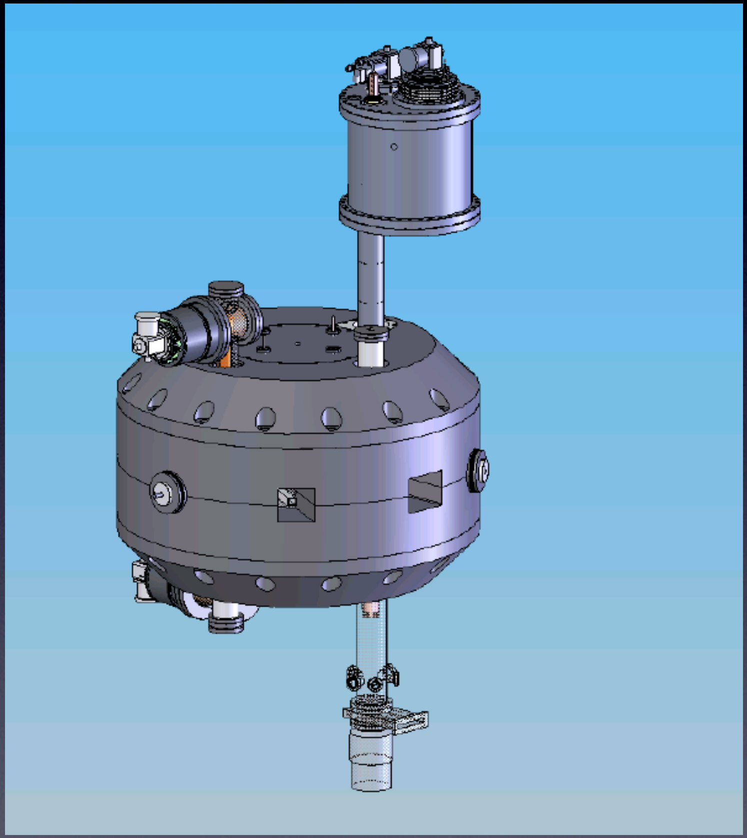
- 2010-2012 MIT Megatron Design Studies
  - B_0~ 4.5T .. my first attempt at scaling Isochronous proton cyclotrons to high field
  - High intensity (mA), Long Standoff Active Interrogation
- Featured Rare Earth Ferromagnetic Flutter Poles to generate the AVF Field
- Beam Dynamics solution at 250 MeV achieved in 2011



Future Trends in Cyclotrons #1

"AMIT Compact High Field H^- Cyclotron for PET Isotopes"

Accelerator Unit, Division of Electrical Engineering, CIEMAT (Spain)

High Field Superconducting Cyclotron Development Timeline (cont'd):

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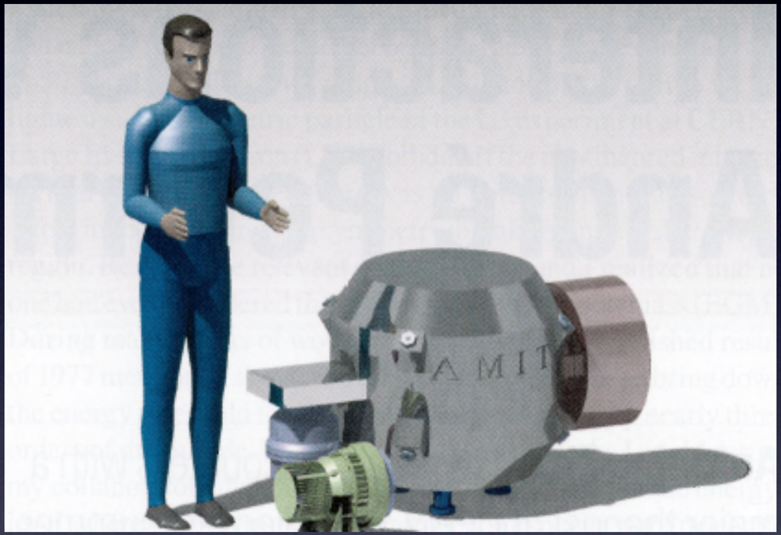
- 2009-2012 MIT / CIEMAT Design Studies for a weak focusing compact isotope generator
  - CIEMAT approached me and others to propose new accelerator initiatives for them to develop
  - I proposed high field cyclotrons and this is in fact the accelerator class they chose for development
  - But MIT Nanotron IP limited what they could do with compact high field H^+ cyclotrons



- I had felt that H^- at high field, missed by others, was possible, and this would give CIEMAT a unique 'space' of their own to develop
  - 1T is no real hard limit for probabilistic Lorentz Stripping
  - D. Obradors came to MIT and we found a H^- solution ~4T at ~10 MeV in early 2010

- C. Oliver also came to MIT and began the quantitative Beam Dynamics effort

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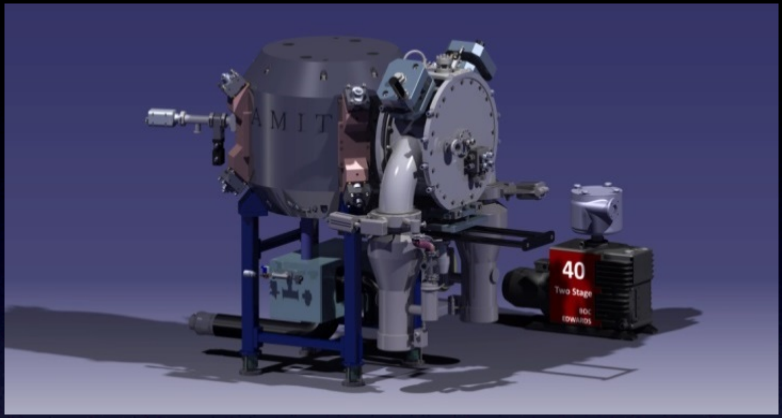
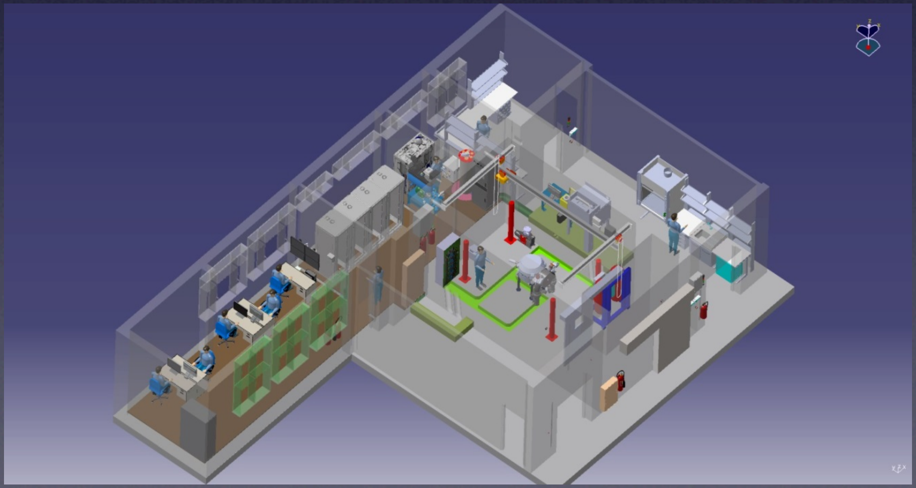
Highest Field H^- Compact Superconducting Lawrence Cyclotron:

- CIEMAT AMAT in 2015 is now well underway...
  - Complete systems design for a stand alone isotope generation is a hospital has been completed
  - T>8.5 MeV and I~10 eμA
  - For C11 and F18 radioisotopes

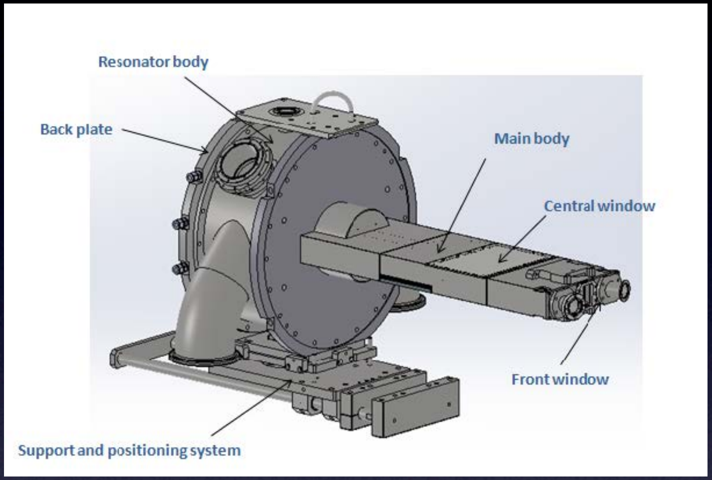


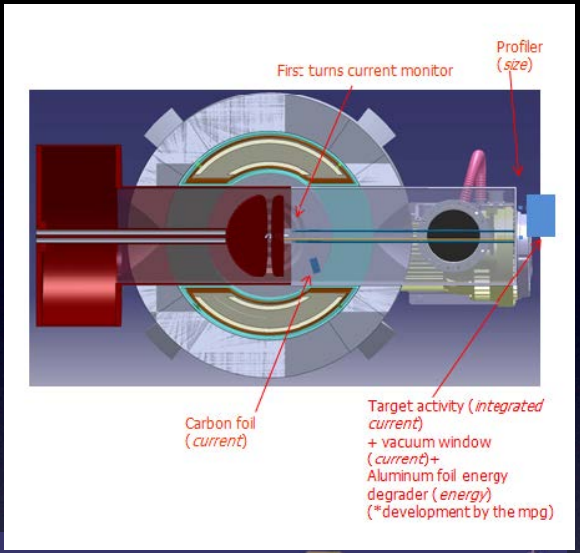
- It is an impressive large & successful collaboration: 10 companies, 14 Research Labs

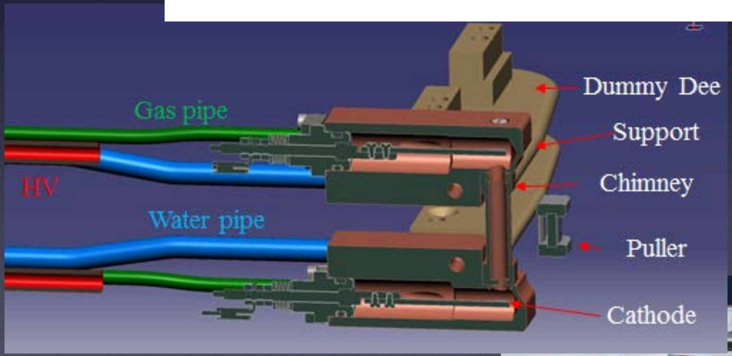
- It has a ‘beautiful’ quantitative weak focusing cyclotron beam dynamics design (C. Oliver and collaborators)



Some CIEMAT AMAT Hardware:







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Future Trends in Cyclotrons #2

"ION-12^{SC} Portable, Self-Shielding High Field N13 Ammonia PET Isotope Generator"

Ionetix Corporation (USA)

High Field Superconducting Cyclotron Development Timeline (cont'd):

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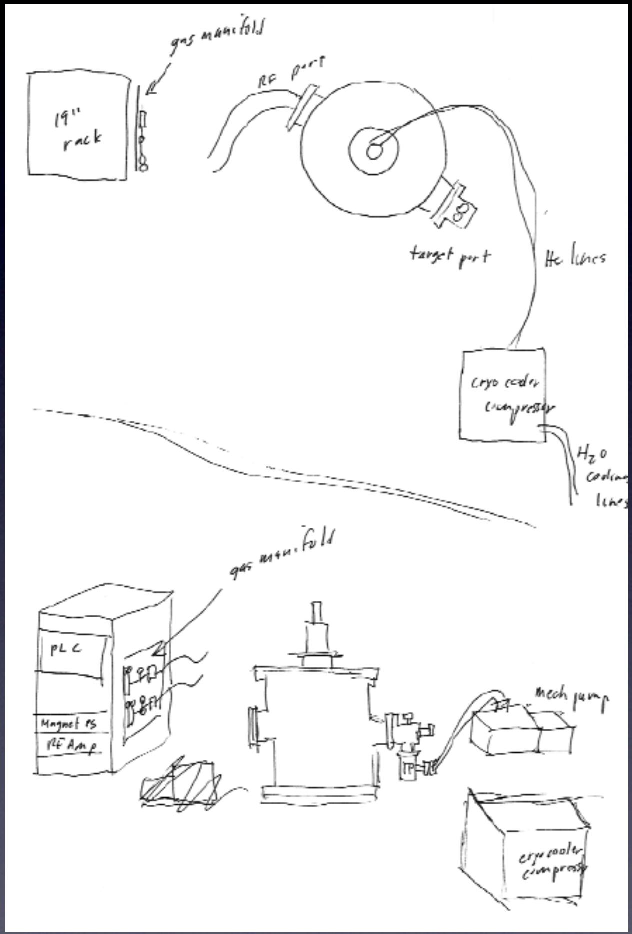
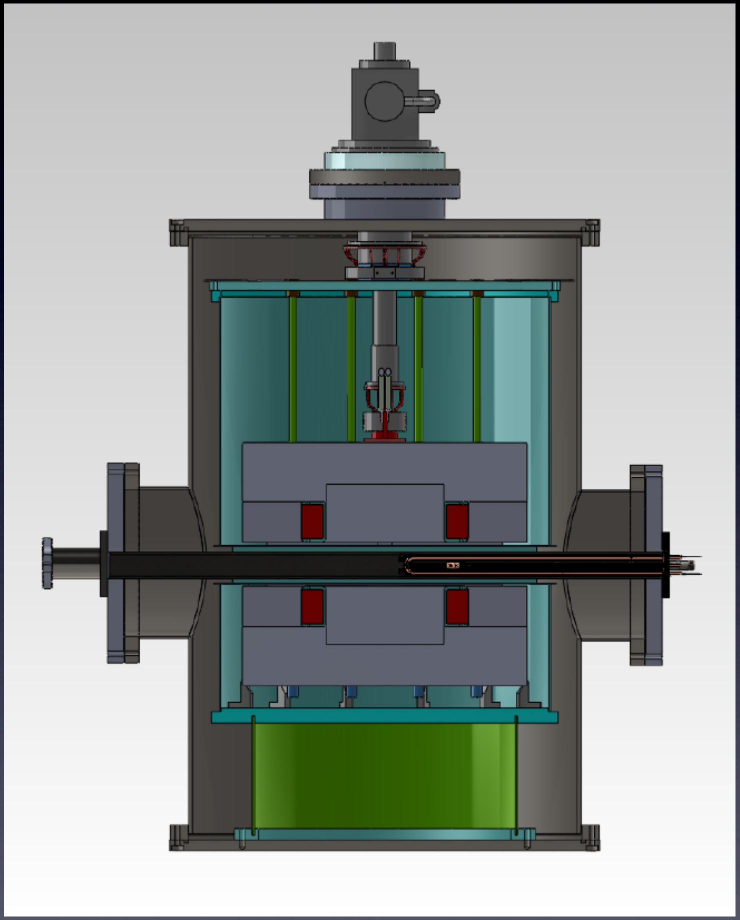
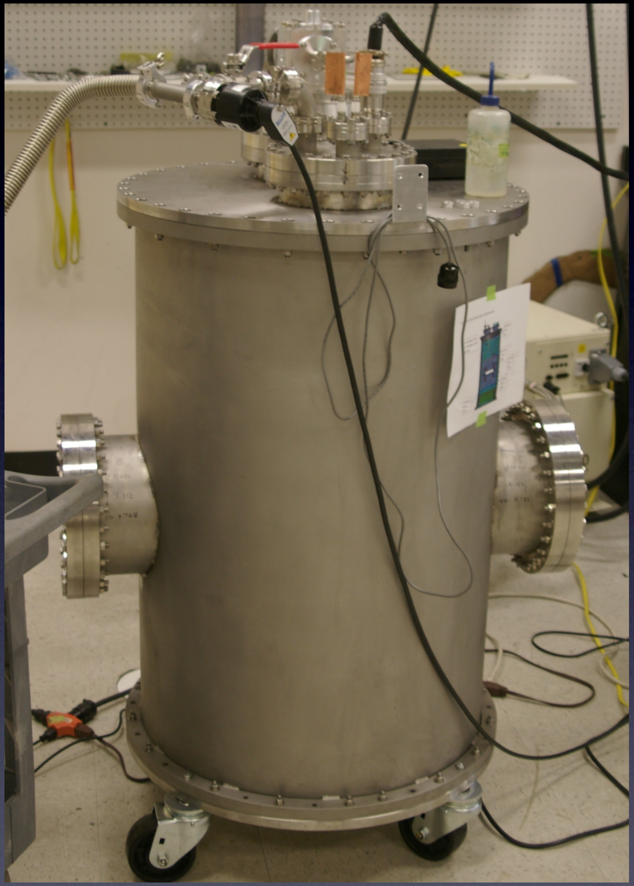
- 2012-2015 Ionetix Isotron for N13 Ammonia for Injection
  - Tc-99m is the most commonly used imaging isotope in the US with only a one week in hand stock at any given time
  - It is derived from Mo-99m decay
  - Mo-99m is made by fissioning ^{235}U in a high flux reactor
  - In May 2010 both HFR and NRU had emergency shutdowns and the US was essentially out of Tc-99m for SPECT cardiac perfusion imaging
  - I started getting calls at MIT..
- Many Folks/Labs/Orgs began looking at new reactor and accelerator Tc-99m supply concepts
- But there is a better imaging agent- lower dose, high resolution imaging: N13 Ammonia but... $T_{1/2}$ is only 10min
- I founded Ionetix to put N13 generators in a clinic next door to PET Cameras!



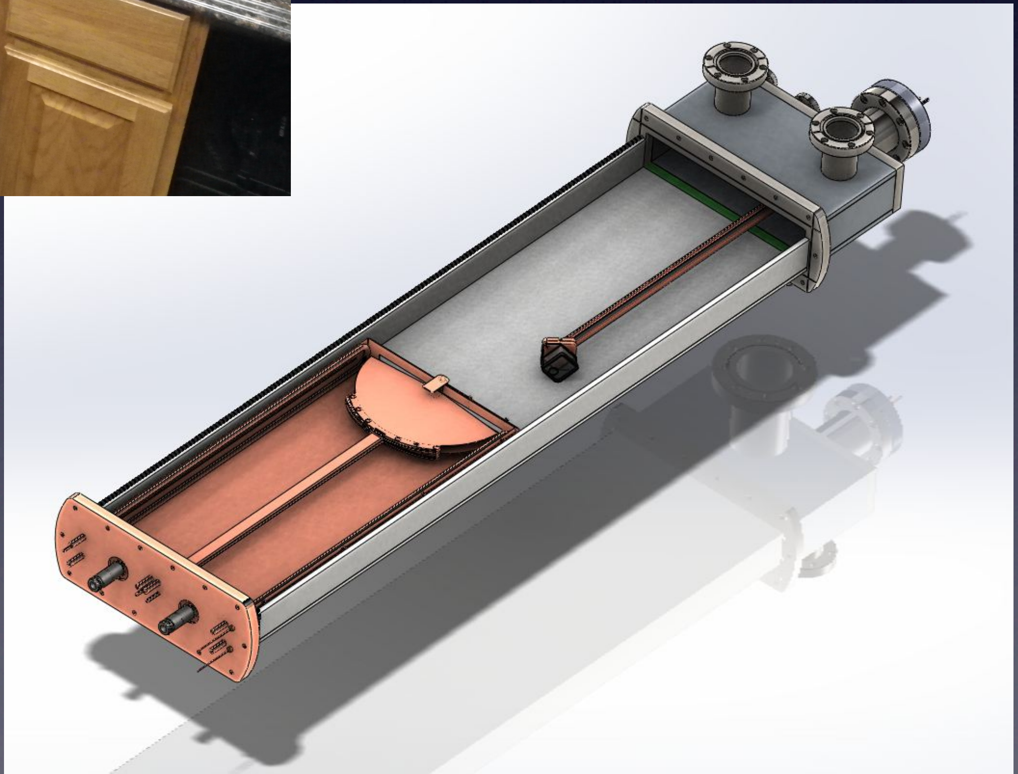
Isotron Prototype Topology





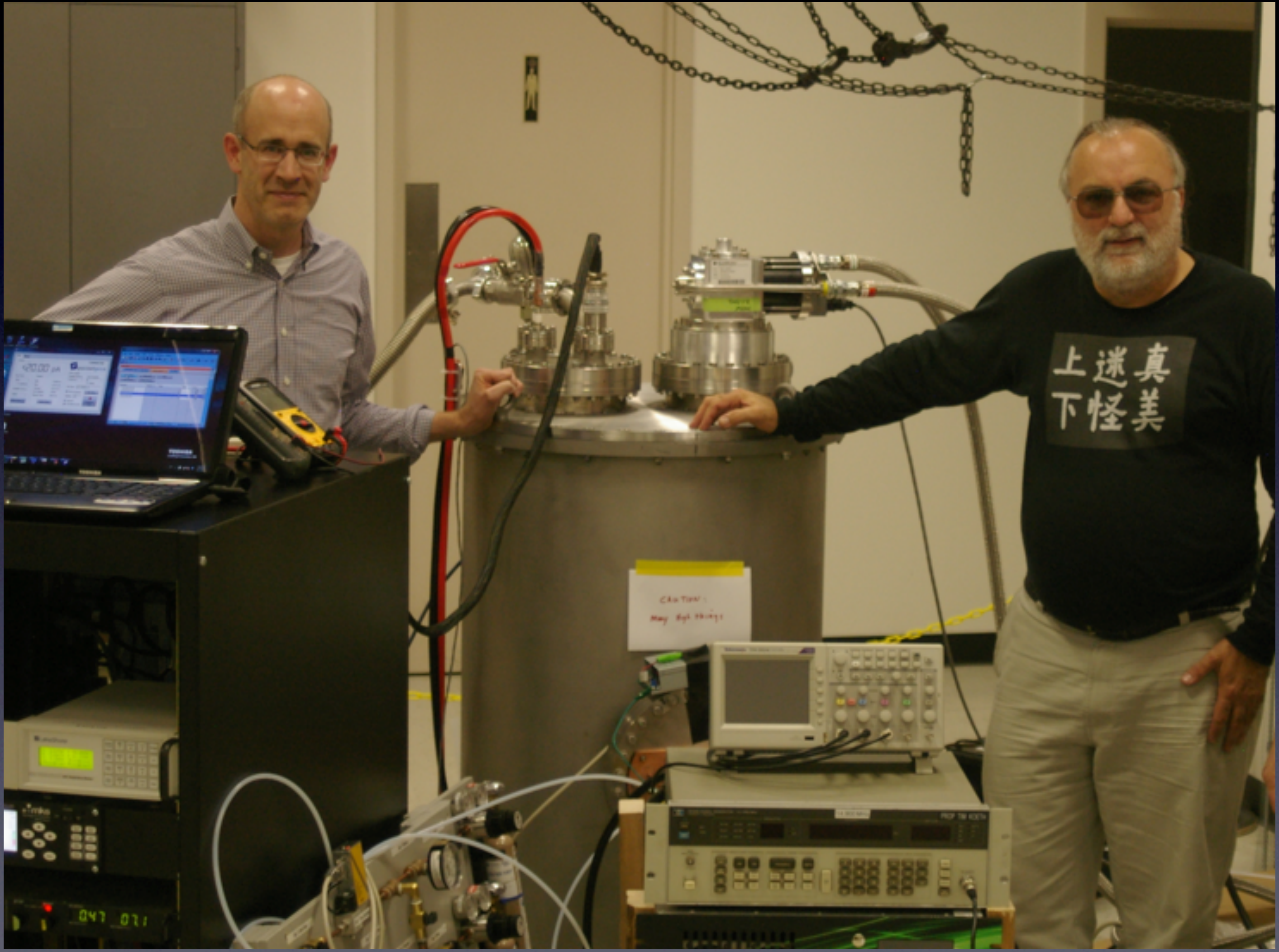
Isotron scale?

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



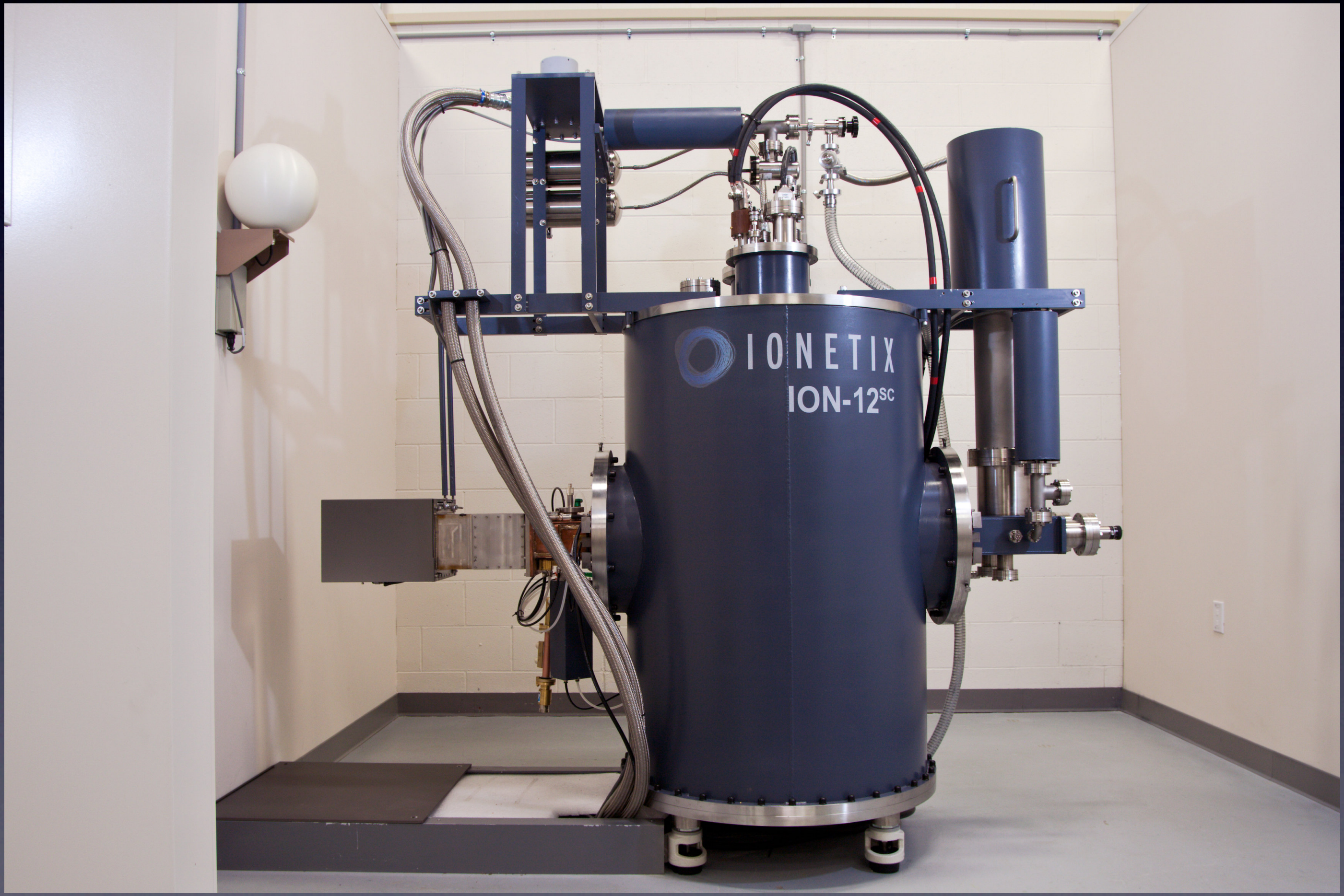
Isotron Dee / Resonator

Isotron Prototype First Beam



Ionetix production model ION-12^{SC}

12 MeV 1800 kg cyclotron + target + chemistry self-shielding unit dose



Ionetix N13 Ammonia Generator Status – 3 installs so far planned in 2015:

- First ION-12^{SC} is going to the University of Michigan Medical School Cardiology Department
- Second system is to be installed on the fourth floor offices of a 15 doctor cardiology practice in Sarasota Florida ... this is what I was trying to do
- The third to Wisconsin where it will be installed in a track and moved around to medium size hospitals

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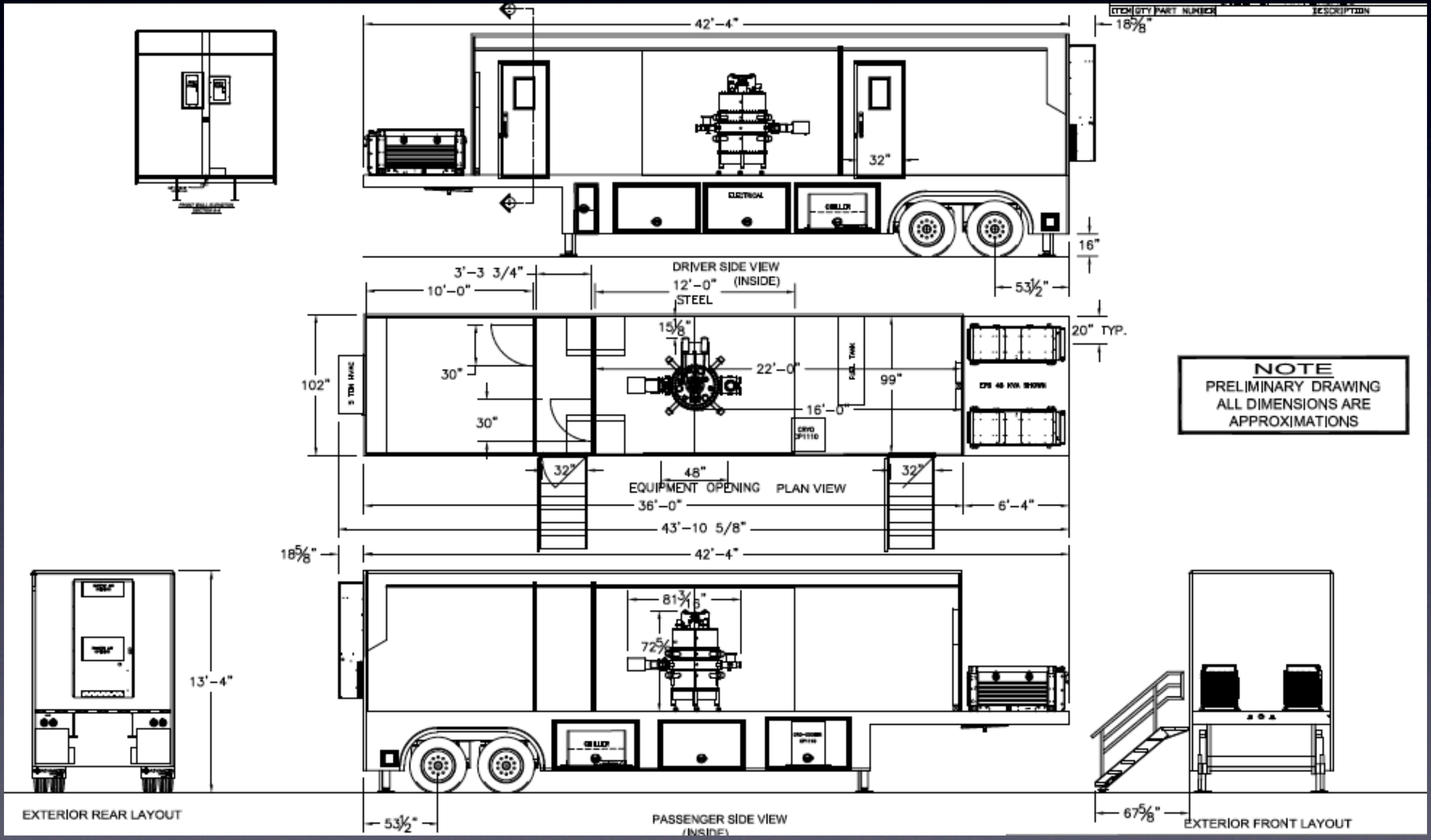
Ionetix ION-12^{SC} is fully portable and transportable:



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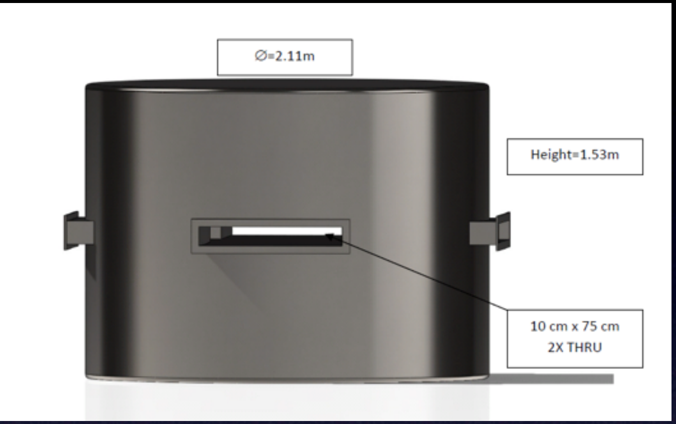
Future Trends in Cyclotrons #3

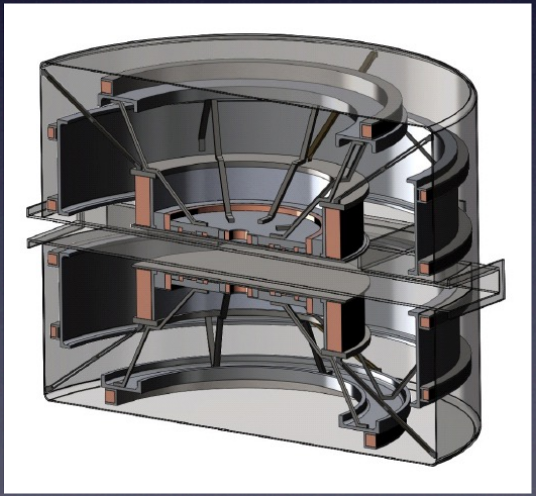
"Variable Energy Air Core Synchrocyclotron for Proton Therapy"

Massachusetts Institute of Technology (USA)

High Field Compact Superconducting Cyclotron Development Timeline (cont'd):

- 2011-2014 MIT Iron Free Variable Energy High Field Synchrocyclotron (4 tonnes!)
    - Origins were also in the Megatron campaign at MIT
    - A. Radovinsky found a clean solution for a self-shielded iron free design with a straight-forward optimization in 2011
    - Later variable energy was added – the field is linear with current and B_0 sets T_{final} exactly
- It has been licensed by MIT to ProNova for PT but in principle can be built at any energy
- Has the low duty factor and intensity characteristic of synchrocyclotrons





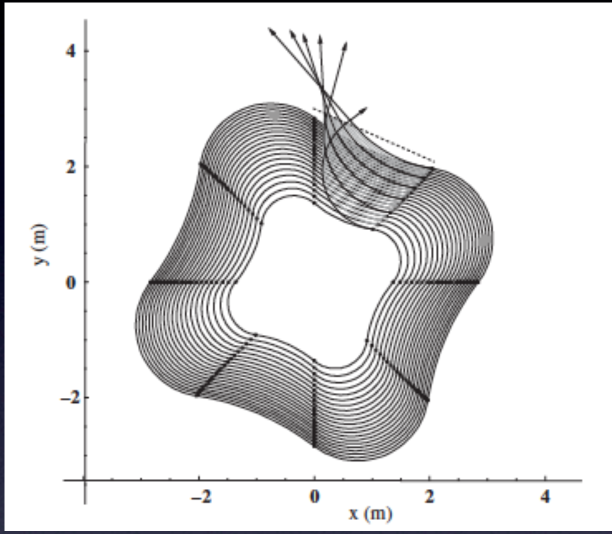
Future Trends in Cyclotrons #4

"High Intensity Variable Energy H_2^+ Cyclotron-FFAG for Proton Therapy and Isotope production"

Paul Scherrer Institute (Switzerland)

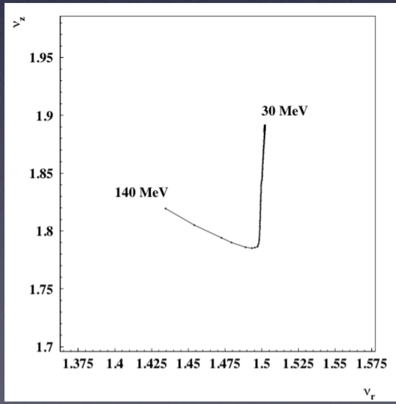
Very Novel Alternating Gradient H_2^+ Cyclotron:

- 2015 Cyclotrons with Fast Variable and/or Multiple Energy Extraction
  - C.Baumgarten, PSI
  - See PhyRevSTAB_16_2013_100101
  - H_2^+ stripping extraction in the reverse bends



- FFAG magnet configuration- edge crossing solution was the key development

- Applicable low to high energy- isotopes, PT, & ADS



- Note q/m=0.5 and reverse field alternating sectors always makes it bigger than AVF isochronous cyclotrons for a given B_0 but this is a very interesting concept!

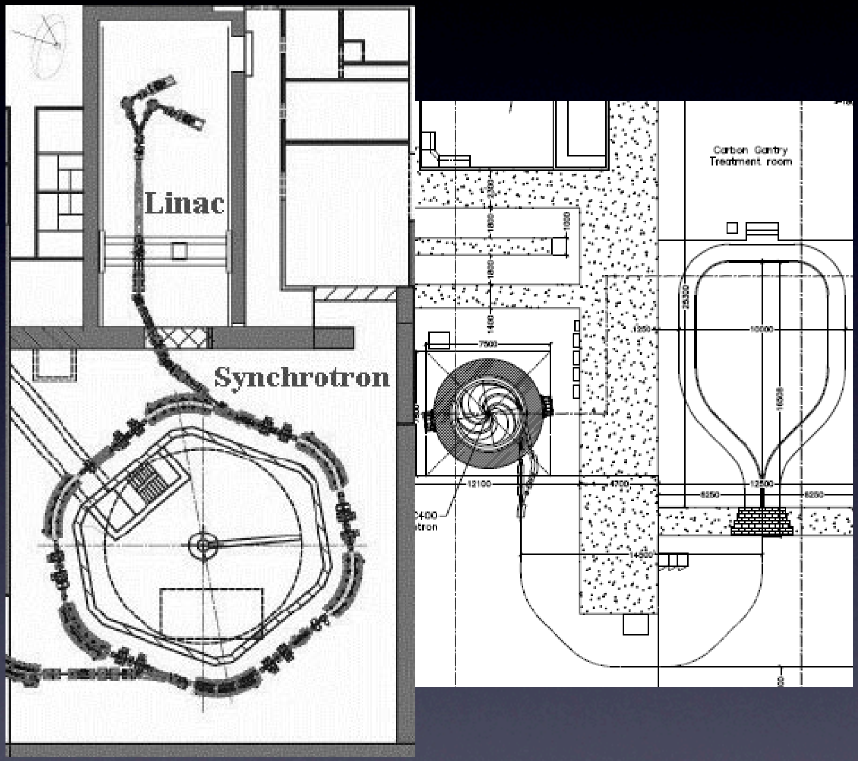
Future Trends in Cyclotrons #5

"IBA C400 for Carbon Therapy"

Ion Beam Applications (Belgium)

High Field Compact Superconducting Cyclotron Development Timeline (cont'd):

- 2011-2015 IBA C400 Carbon Cyclotron
  - K=1600, 7m diametr, tonnes
  - Carbon @ 400 MeV/n
  - H_2^+ stripping extraction to get protons at MeV
- Green sheet design campaign- much new ground has been broken:
  - Beam Dynamics
  - Extraction
  - Ion sources & high intensity
  - Magnet Design and analysis
  - RF
- It is ready to go...



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Future Trends in Cyclotrons #6

"TAAC Compact High Field Isochronous Cyclotron for Ultra-Fast Pencil Beam Scanning Proton Therapy"

Antaya Science and Technology (USA)

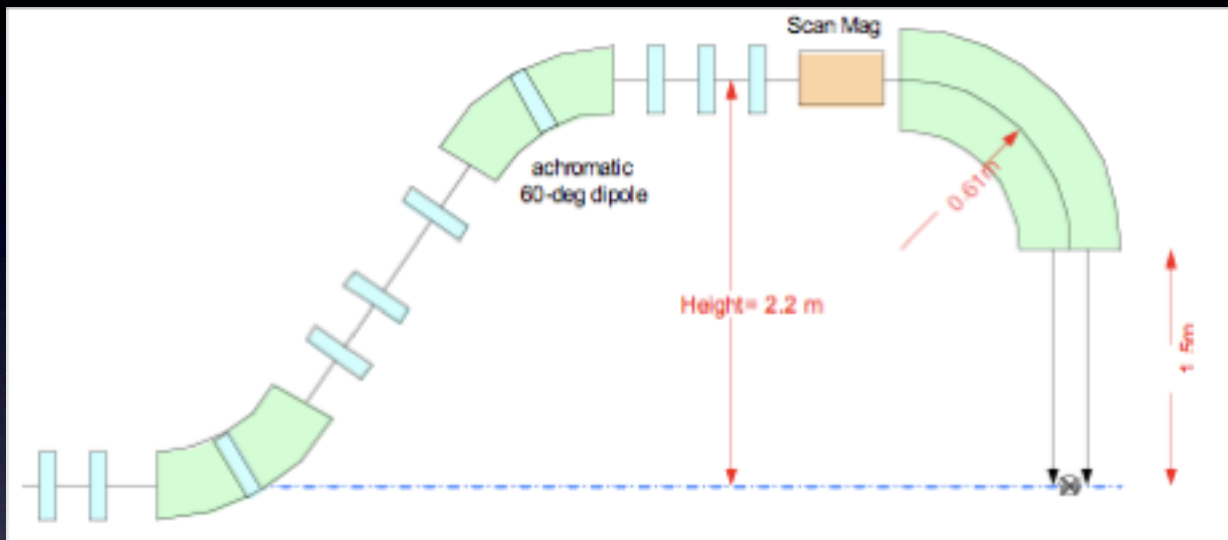
AS&T Technically Advanced Affordable Cyclotron

- Origins of this Cyclotron:
  - General problem of the cost of PT
  - The challenging problem of Organ Motion that obscures PT precision

- January 2103 NIH Experts Meeting in Bethesda
  - Many researchers were at this meeting were looking for ways to track organ motion (MR, CT, in patient PET, proton radiography)
  - As a development path this ‘felt’ hard to me
  - Still, with so many good people looking at tracking organ motion, it seemed this development path was properly ‘covered’

- What should I look at?
  - Everyone knows how to hold their breath for a few seconds- So I put up a nice challenge for my team at AS&T
  - Could we develop a system (cyclotron and fast gantry) that could treat a 10x10x10 cm^3 tumor in the rest portion of a single breath hold?

The Compact Superconducting Gantry was already well under way...



- Procure Double Bend Achromat Gantry (Cameron, Anferov and Antaya)
  - Each bend is independently an achromat
  - Field level 2-4 T
  - Cryogen Free
- ProCure licensed to ProNova in 2013

Compact High Field Superconducting CW Isochronous Cyclotron for Ultrafast Pencil beam Scanning

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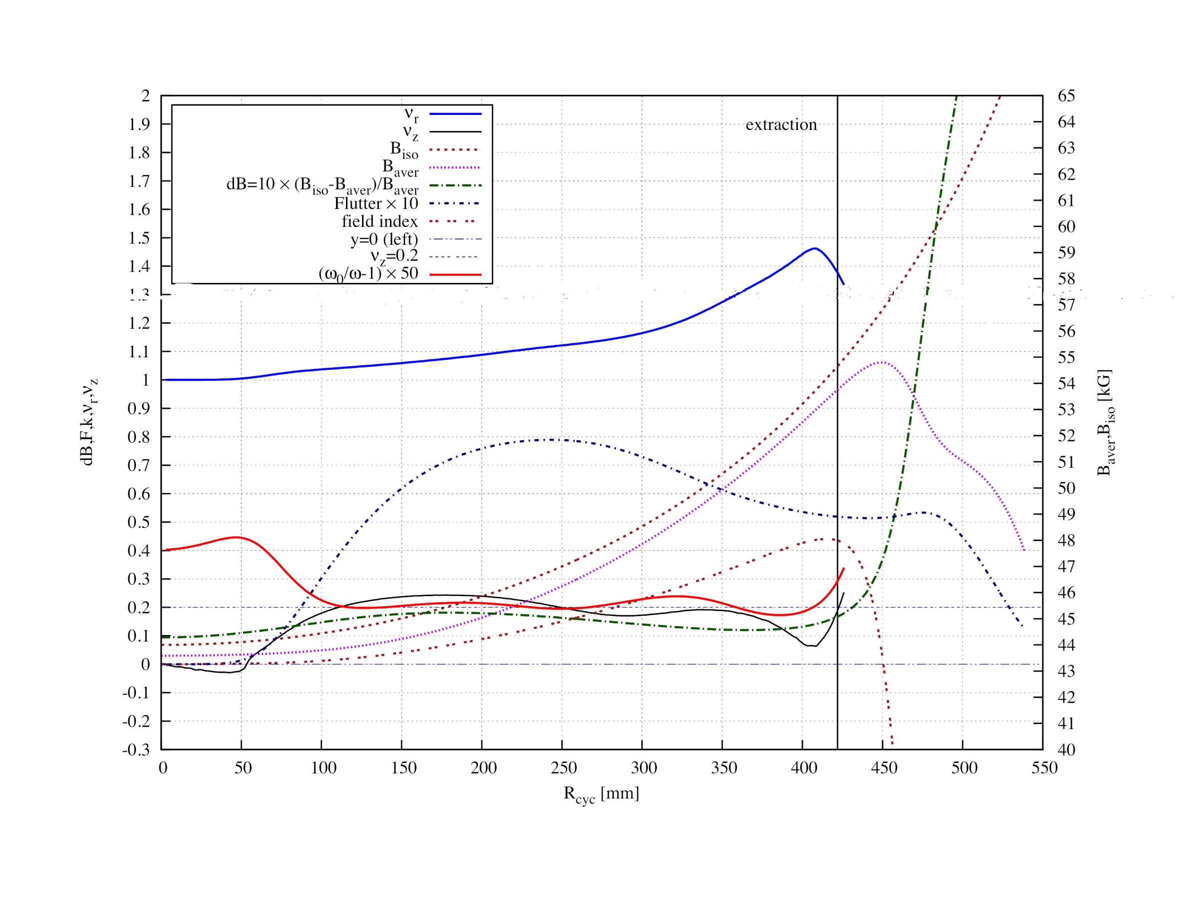
A 2X increase in B field over existing proton cyclotrons to get $/3 cost reduction while making Ultra-fast Pencil beam scanning possible?

- Solve the problem of scaling the Isochronous AVF Flutter field to High Energy for very compact proton cyclotrons while preserving isochronism, minimizing the integral phase error for acceptable betatron tunes

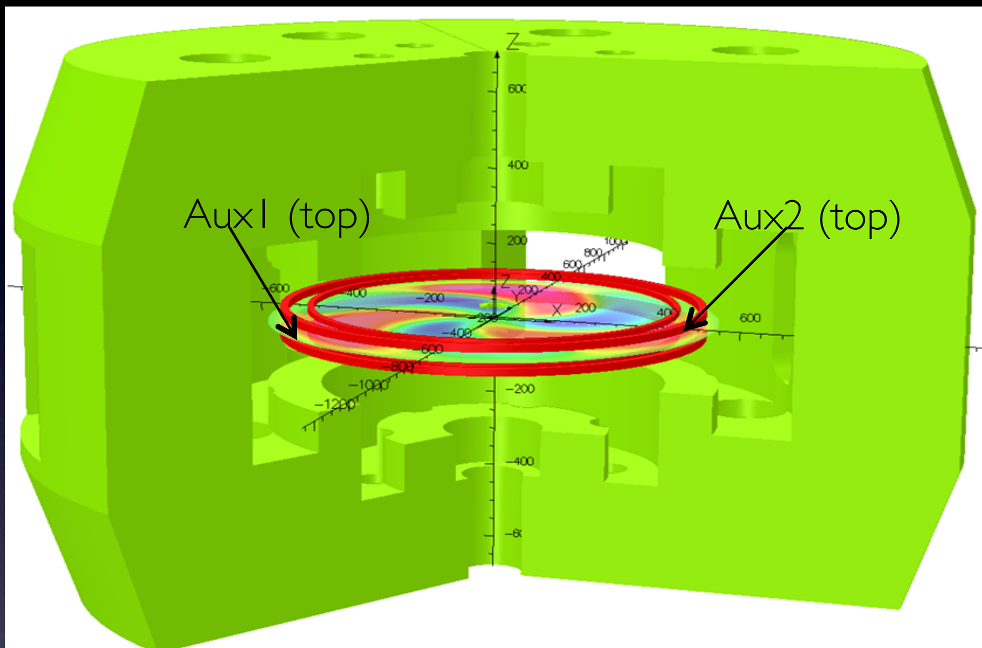
- Sort out how to do high extracted beam intensities and gfast time bases intensity modulation in high field conduction cooled compact superconducting cyclotrons

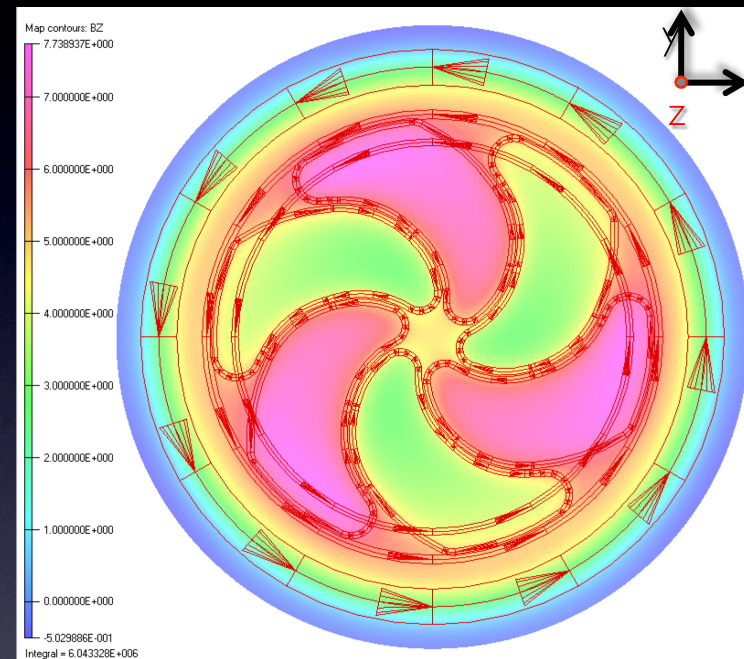
TAAC Tune Diagram...



Isochronous, 3 Sector, 230 MeV, 0.42 m extraction radius

TAAC Field design:





Simple return yoke, superconducting coils, modest spiral, average field 4-7T

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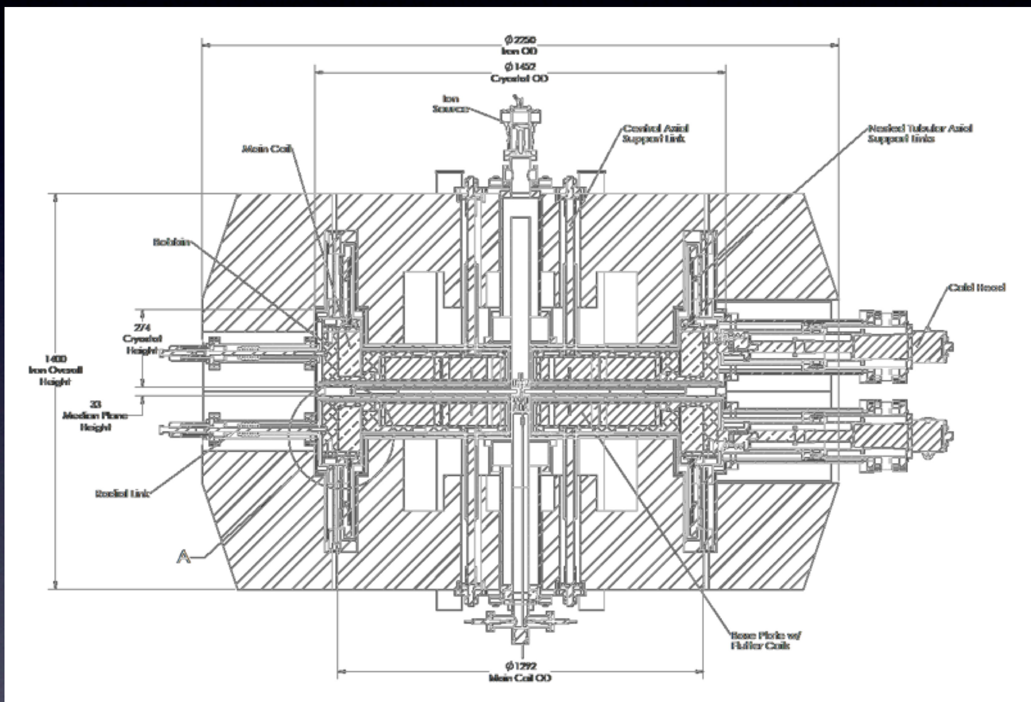
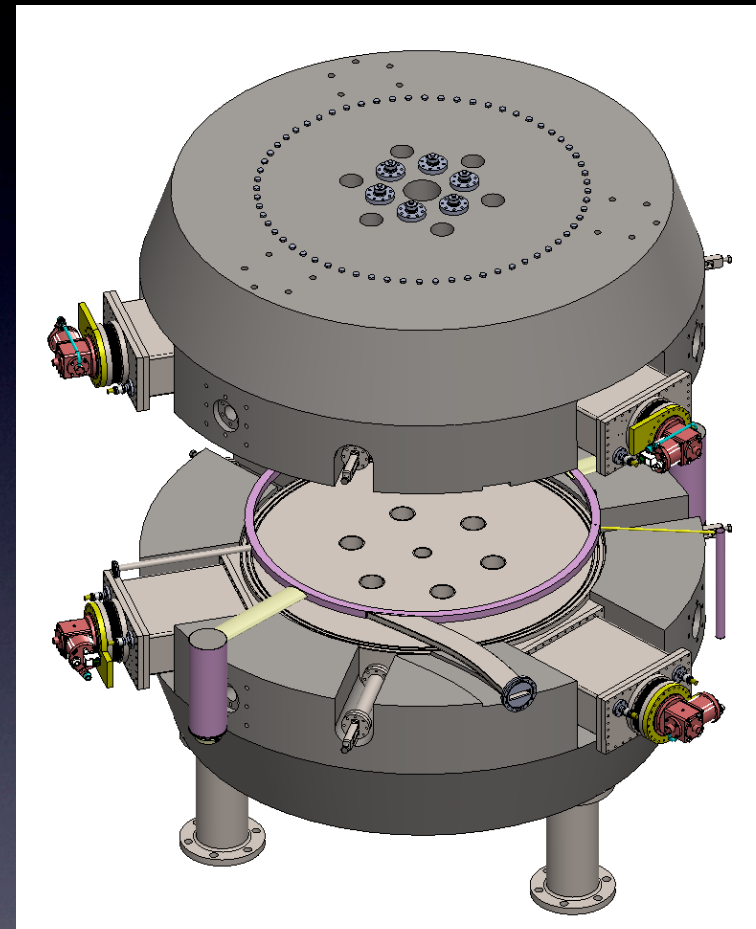
TAAC engineering design:





2.2m diameter, 1.6m tall, 30 tonnes, dry cryo-cooled, warm median plane- key technology proof-of-concept demonstrations (magnet, RF, high intensity injector) are now in progress

Future Trends in Cyclotrons #7

"Honorable Mention:
High Intensity H_2^+ Separated Sector Driver Cyclotron"

INFN LNS (Italy)

Muon Production using a High Power Separated Sector Superconducting Cyclotron:

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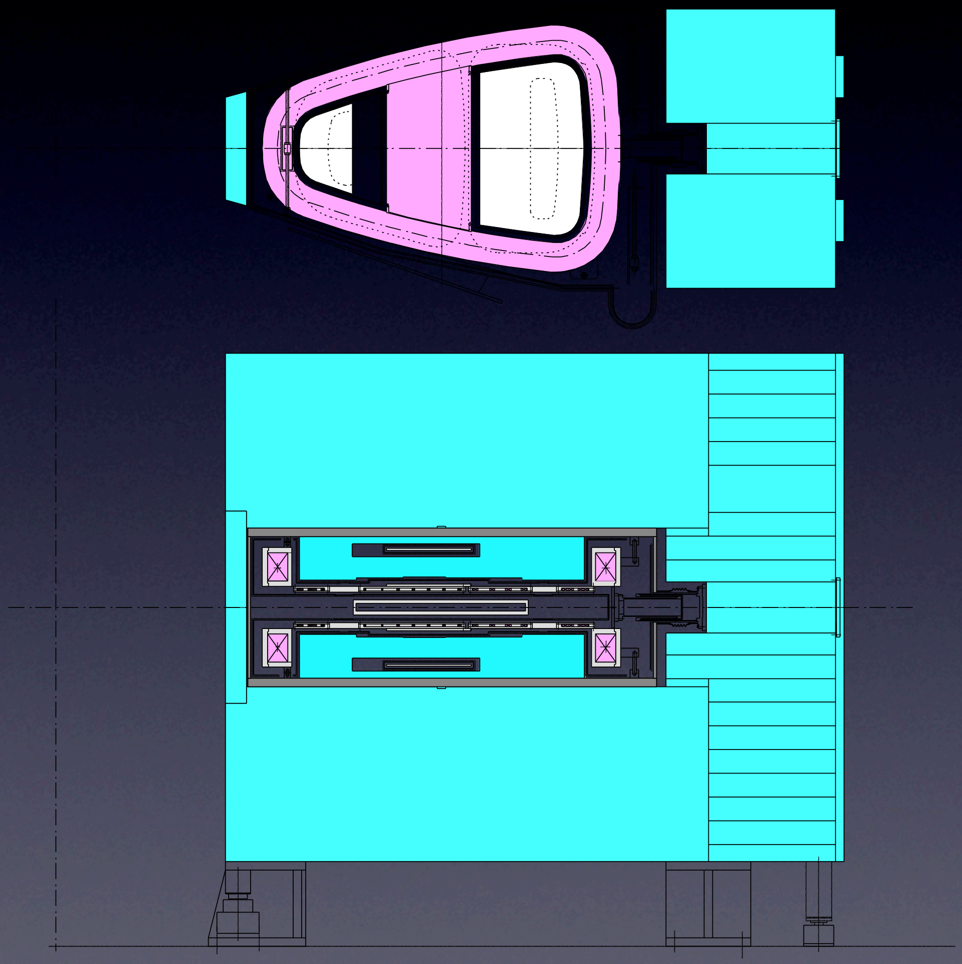
- 2012-2015 INFN LNS Catania and collaborators
  - K=3200, 14m diameter, 830 tonnes
  - q/m=0.5 @ 800 MeV/u
  - H_2^+ stripping extraction to get protons at 800 MeV
- Mostly a demonstrated technology- much in common with PSI and RIKEN ring cycs
- Also applicable to Accelerator Driven Systems sub-critical nuclear reactors



Thank you. Onward. TAA