Unit 10 - Lecture 15

Advanced Cyclotron and Synchrocyclotron Designs

MIT 8.277/6.808 Intro To Particle Accelerators

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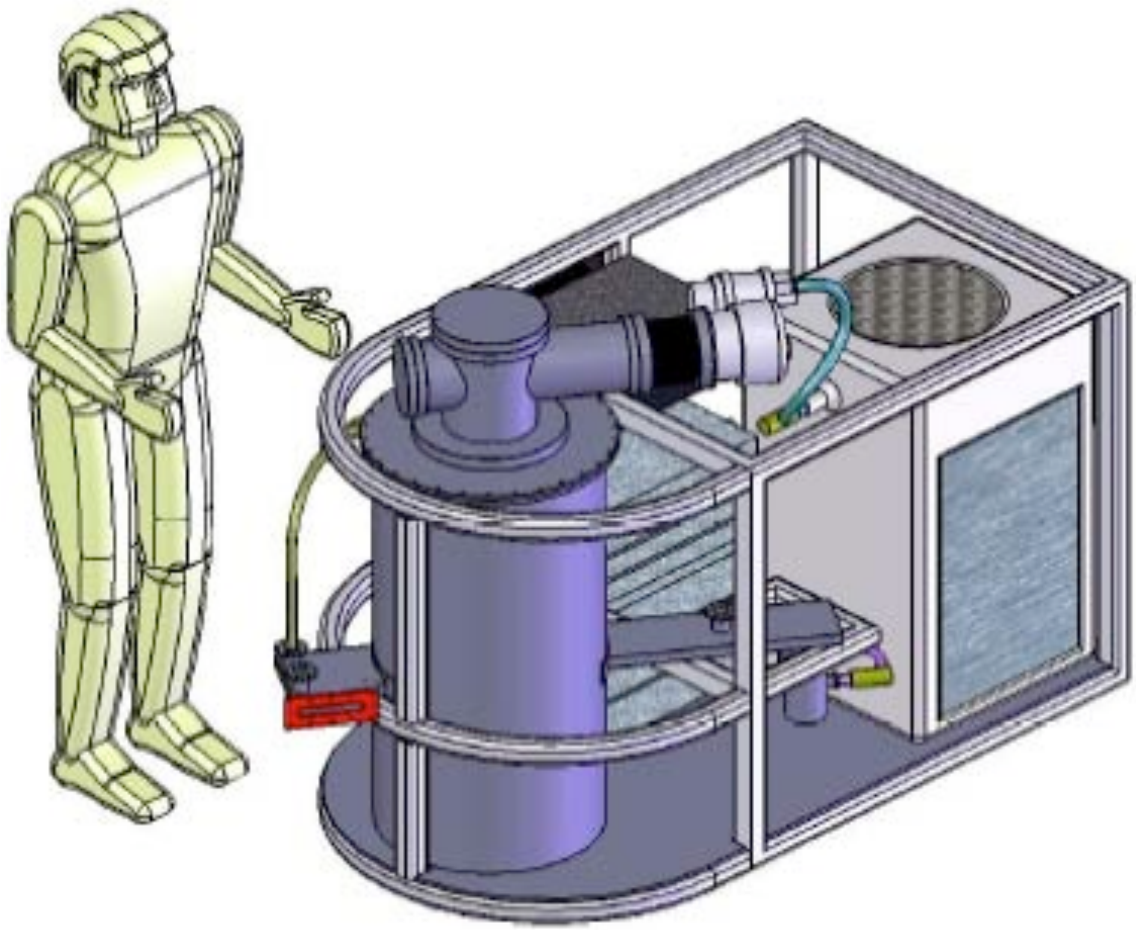
Nanotron

An advanced classical cyclotron

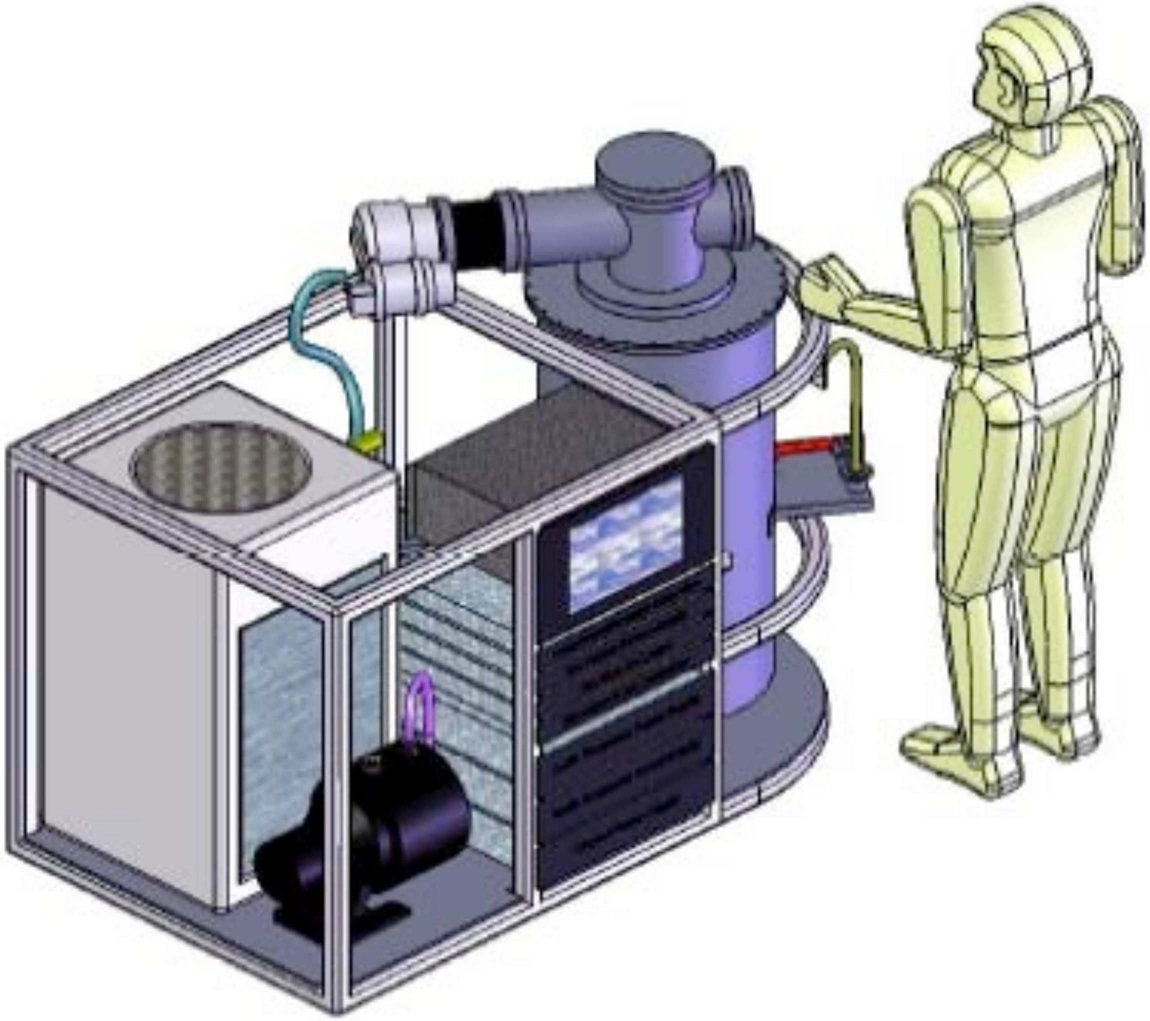
The Application

- Strategic Nuclear Materials Absolute Verification
  - Enriched Uranium- smuggled in small quantities by people, or in shipping containers (sea, air)
  - Would like to do cargo inspection *anywhere*
  - U is not very radioactive- easily shielded by iron
  - Have other methods (metal detectors, xrays) to *suggest* weapons materials but false positives are high
  - Also the required Xray doses (from bremsstrahlung sources) may be too high for personnel
- Absolute Verification
  - Create a mono-energetic radiation beam: neutrons or γ-rays to fission suspected materials
  - D + 11B at a deuteron energy of 5 MeV would work
- Need a portable, simple high intensity acceleration at 5-10 MeV
  - Most likely candidate- small RFQ is still 4m long and high gradients are not simple
  - Can this be done with a cyclotron?

~20 MeV P-O-P Cyclotron - Front

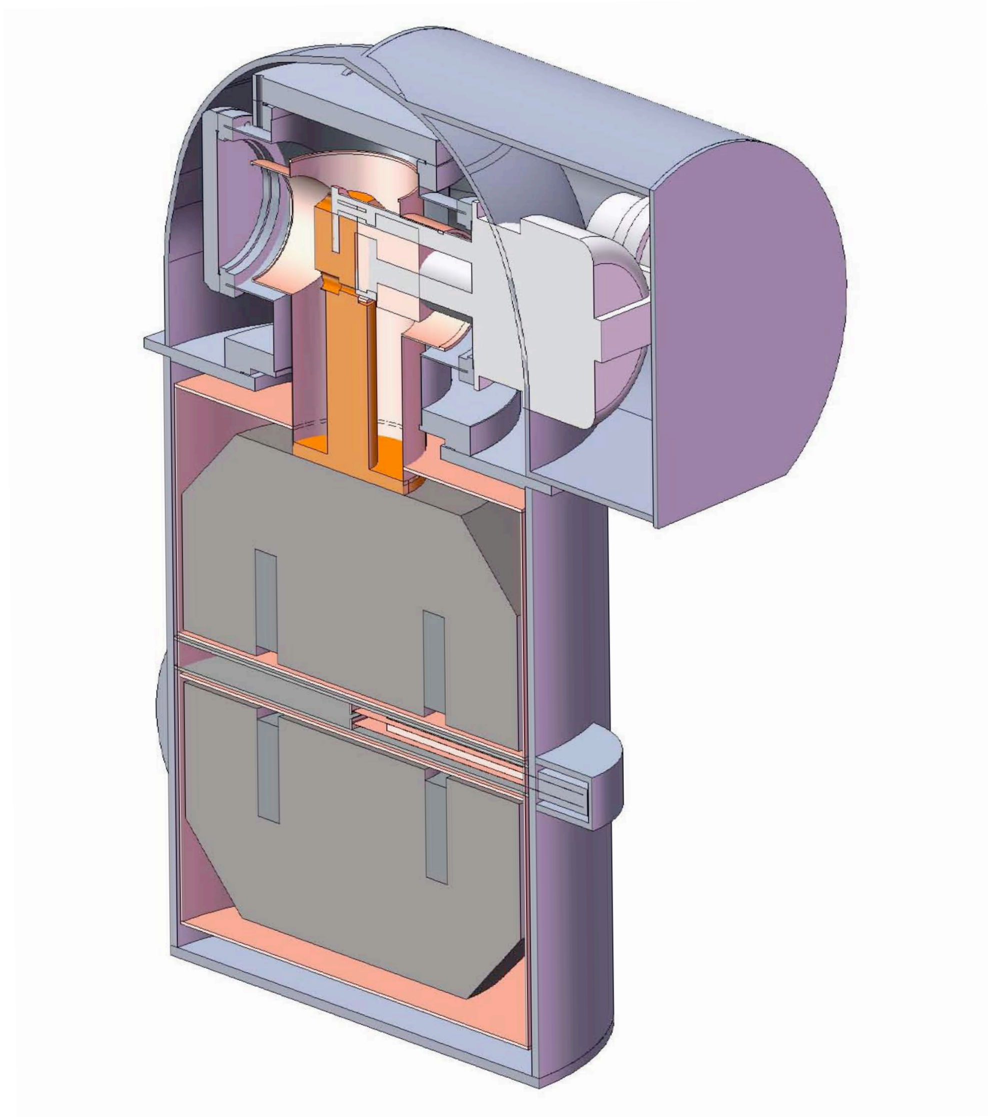


~20 MeV Cyclotron- Back

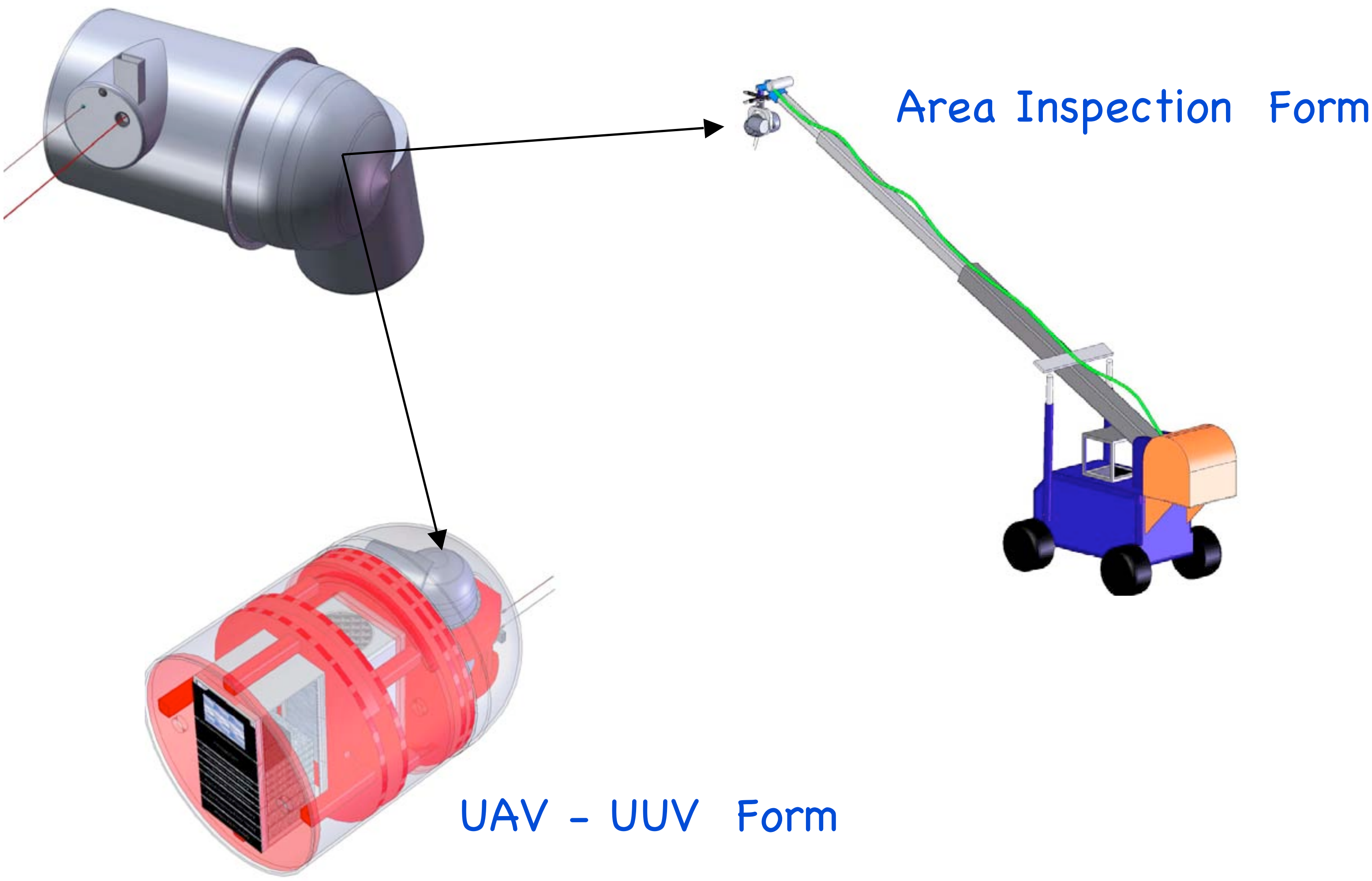


Nanotron Elevation Section View

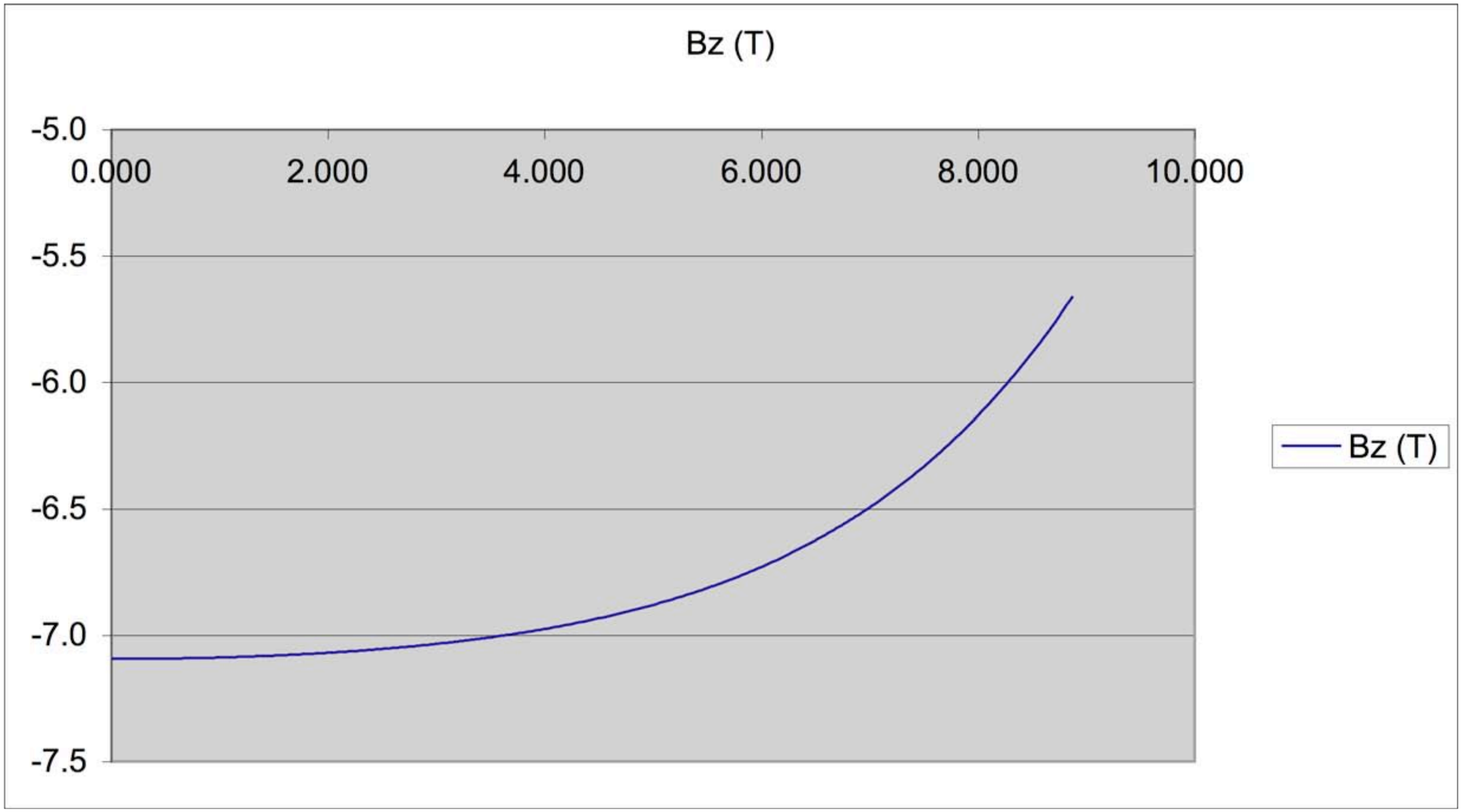
- Nanotron:
  - superconducting
  - cold iron
  - cryogen free
  - ‘portable’
- Proton Energy ~10 MeV
  - Also accelerates deuterium (on 2nd harmonic of the RF frequency) to 5 MeV



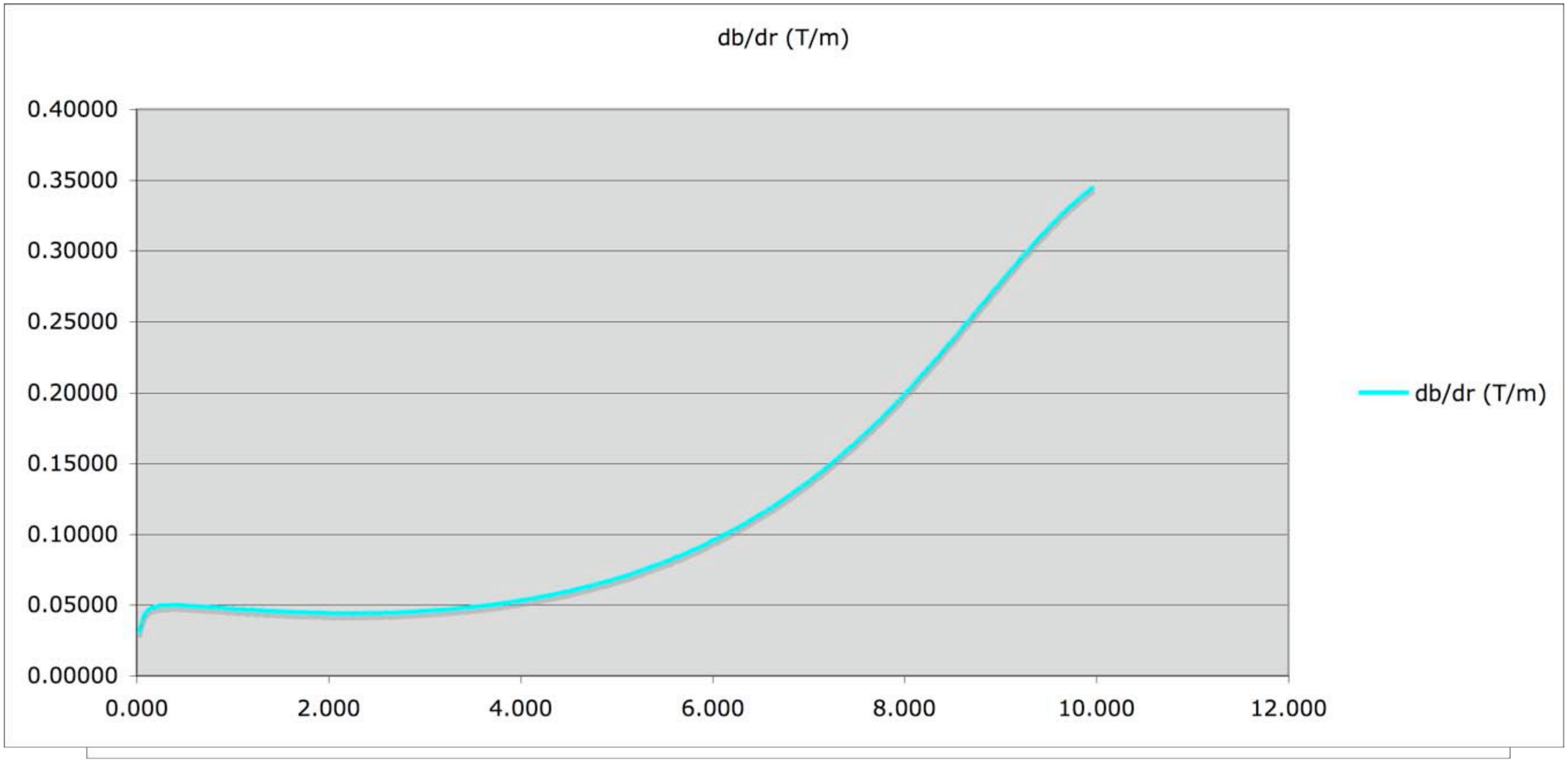
Nanotron 'head' can be separated



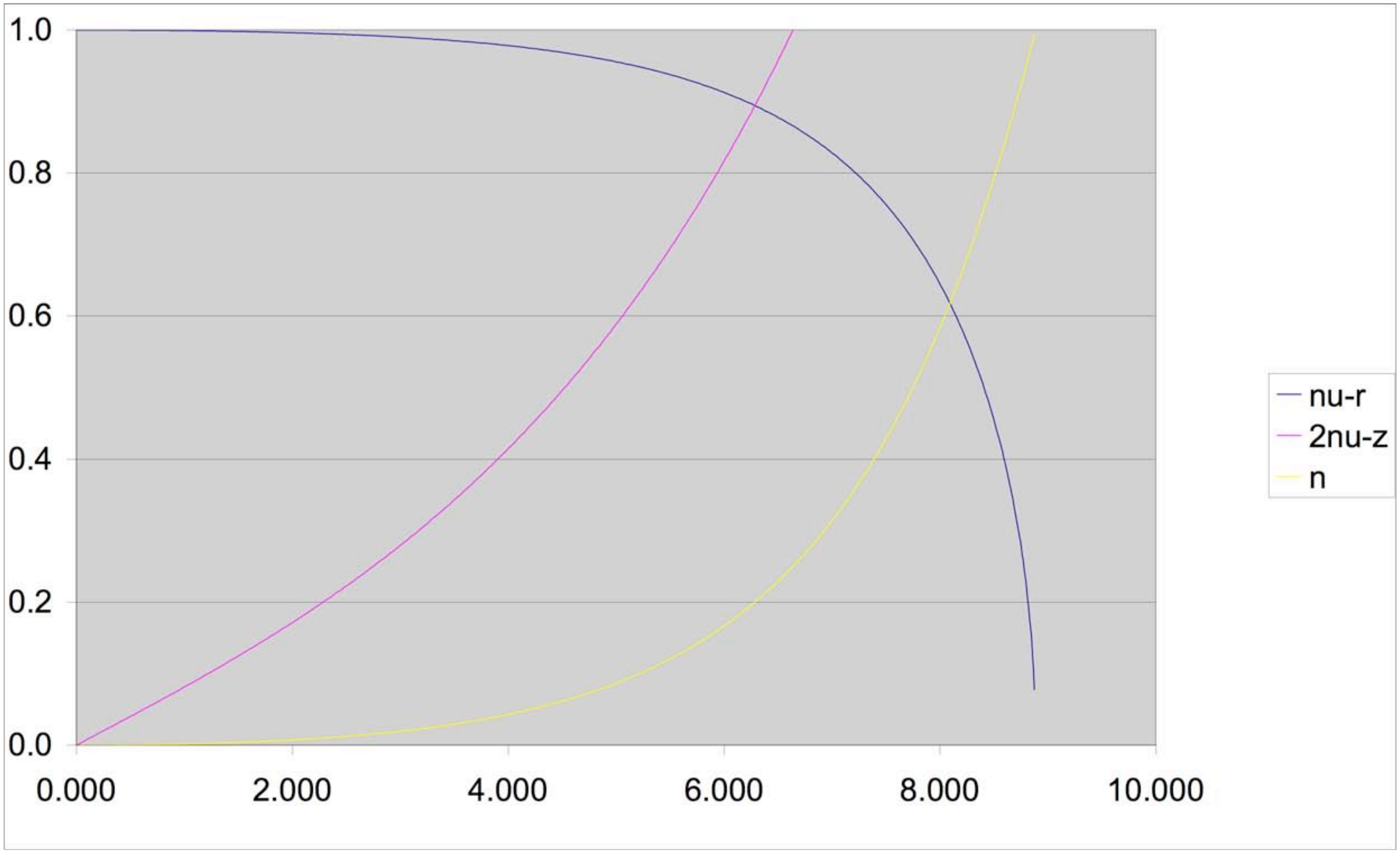
B_z (T)



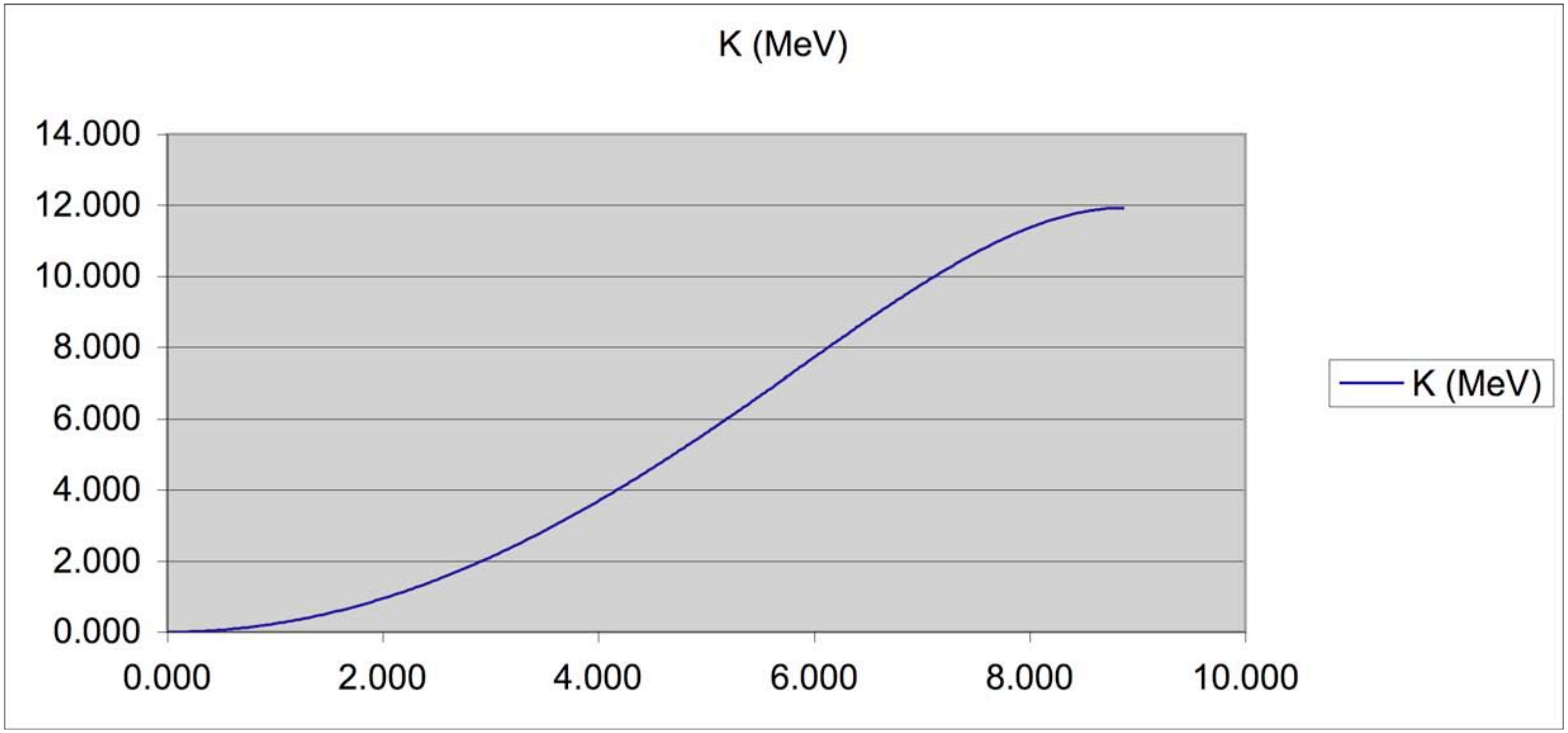
Axial Field Gradient (T/m)



Field Index and Tunes



Ion Energy (MeV)



Synchrocyclotrons

- Weak focusing
- Phase stability
- Intensity limited by low duty factor

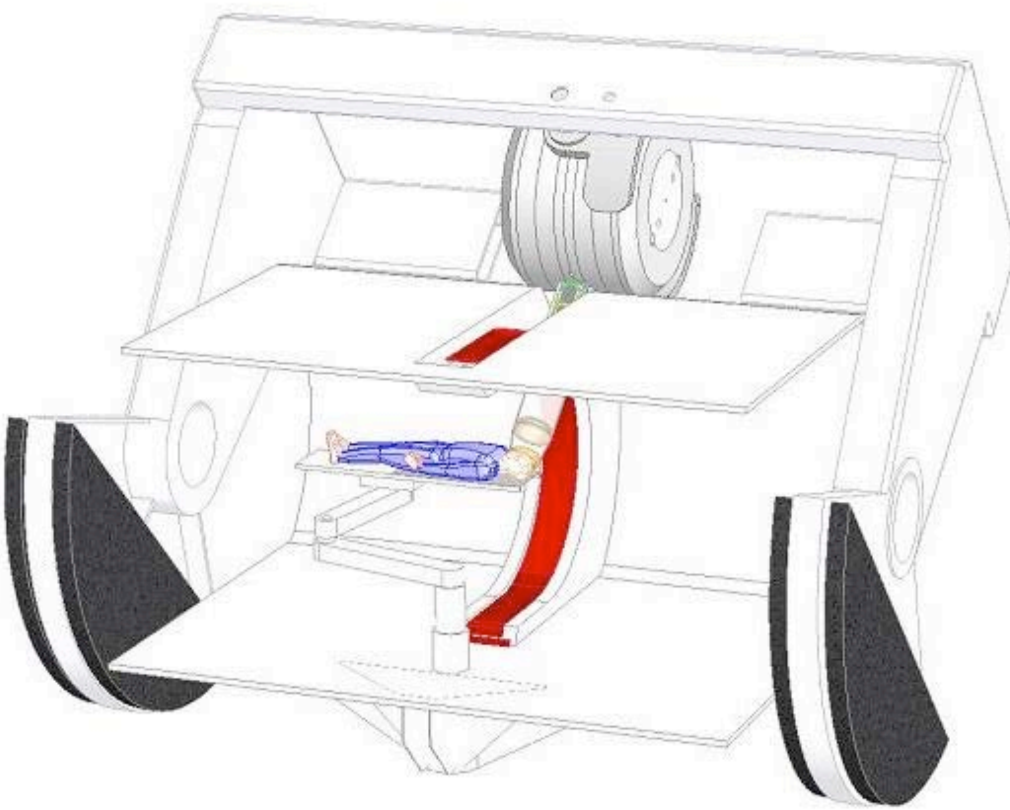
Relativistic Limit on Classical Cyclotrons has several solutions:

- The mass in $\omega = qB/m$ is the relativistic mass $m=\gamma m_0$
- $\omega \approx$ **constant** only for very low energy cyclotrons:
- Example: proton mass increases 25% when accelerated to 250 MeV
  - *Classical 'Lawrence' cyclotrons work to ~25 MeV*
- Variable beam-radius accelerator (cyclotron) there are two general solutions:
  - (a) *synchrocyclotron:* $\omega=\omega_0/\gamma(t)$
  - (b) *isochronous cyclotron:* $B=\gamma(r)B_0$
- Fixed beam-radius accelerator (Synchrotron): B(t) and ω**(t) req'd.**

Synchrocyclotron Key Features

- Weak Focusing axial restoring force (same as classical cyclotrons)
- Phase Stable Acceleration (same as classical cyclotrons)
- Variable Acceleration Frequency
  - 250 MeV protons at 9T require about a 40% frequency swing
  - typ. 3/4λ resonator requires about 3x capacitance swing- still best achieved with a rotator capacitor
  - solution favors small dees with low voltages (<10 kV)
- Low voltage Acceleration means close radial orbit spacing at full energy (~10μm) (same as classical cyclotrons)
- Final energies to 1 GeV (γ≈2 for protons) (same as isochronous cyclotrons)

9T Clinatron Synchrocyclotron



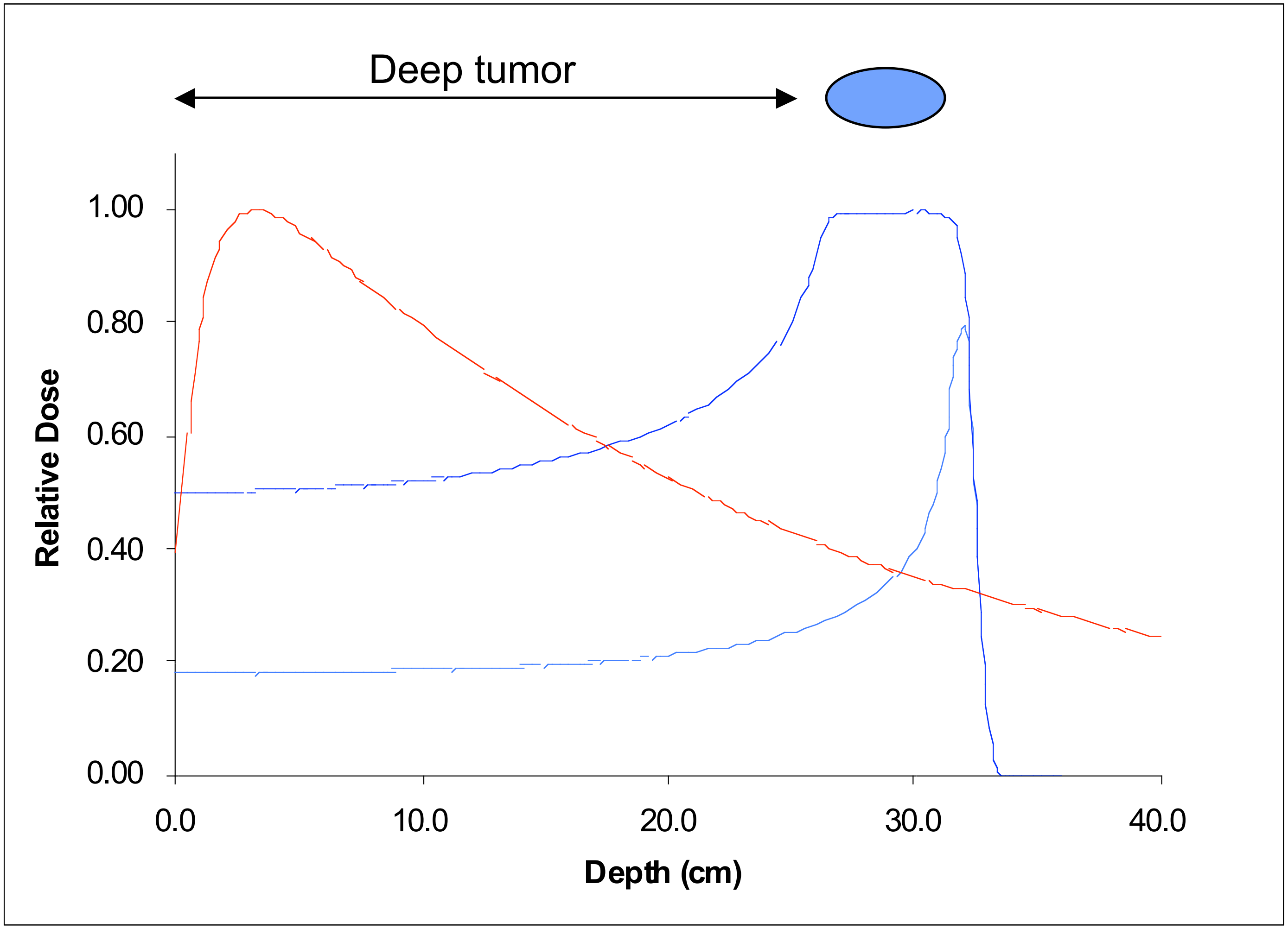
- Still River Systems 9 Tesla, 250 MeV, synchrocyclotron for Clinical Proton Beam Radiotherapy

Application: Radiotherapy

- About 2 million people are diagnosed with cancer each year
- Treatment Choices:
  - Chemotherapy
  - Surgery
  - Radiation
- Treatments typically have 2 or more of the above modalities
- About 50% receive radiation
- Radiation- Xrays (bremsstrahlung) from a 9 MeV electron Linac

XRAY Advantage - an affordable clinical device

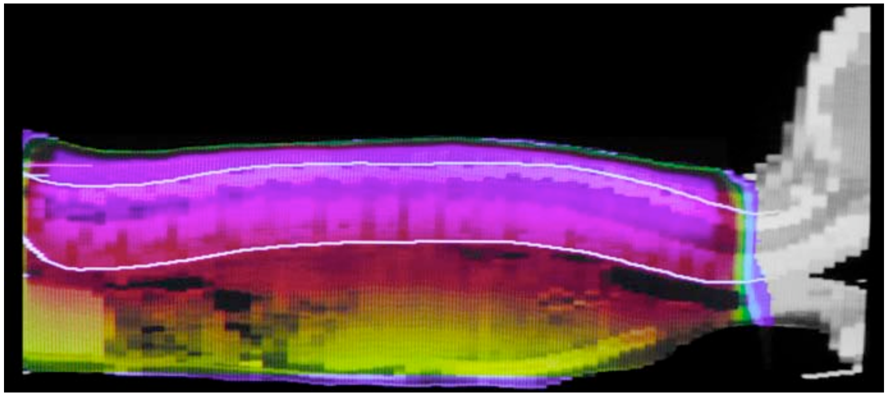
Xrays versus Protons- protons are better

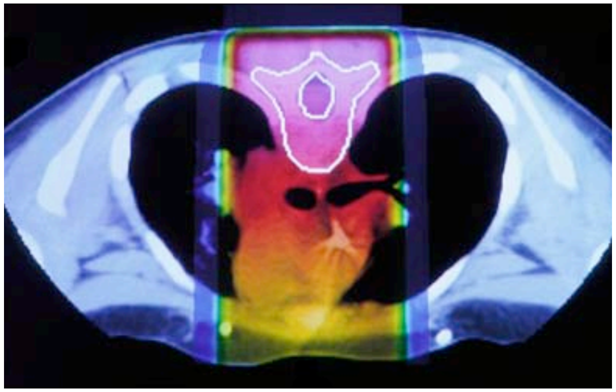


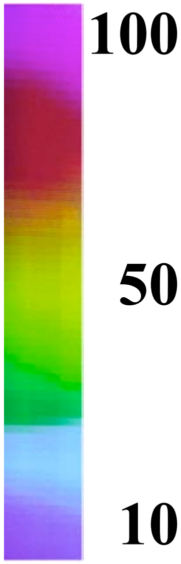
Proton Clinical Benefit – dose is highly localized

Pediatric Medulloblastoma

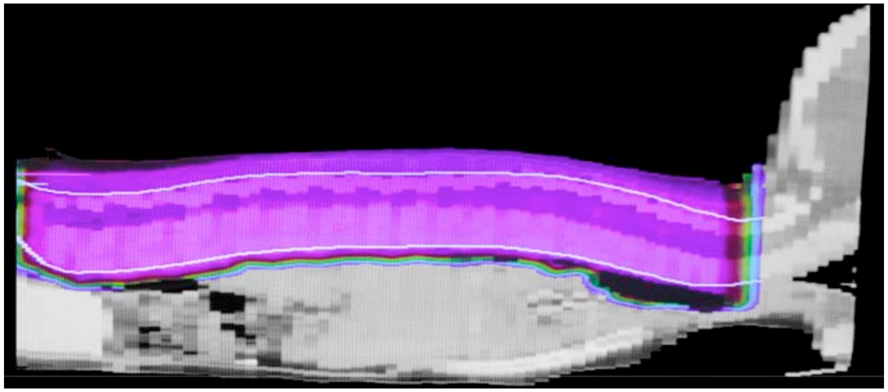
X-RAYS

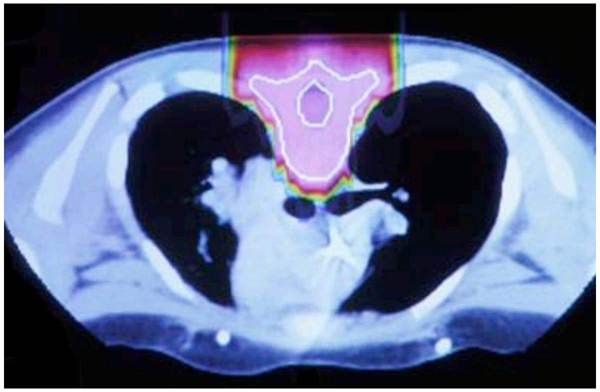




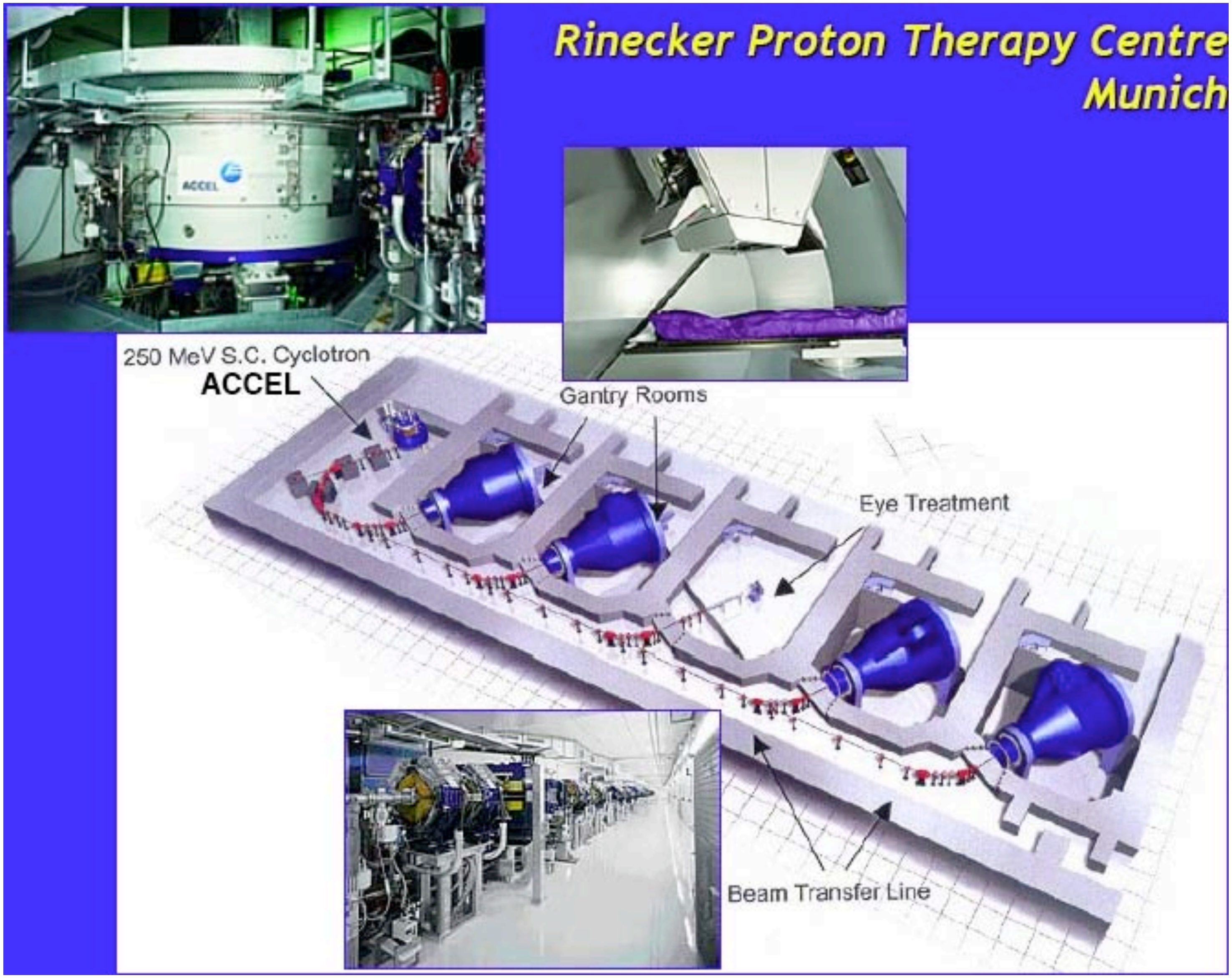


PROTONS





Compare to Conventional PBRT



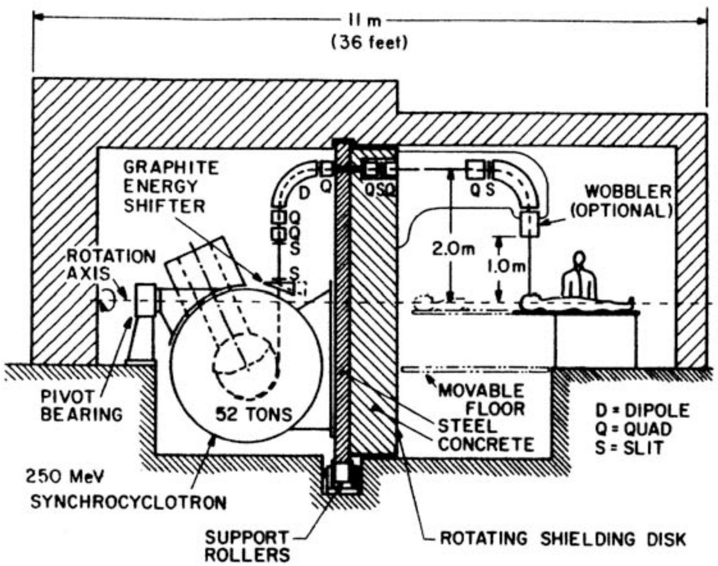
Other Required Features for clinical application

- Mounted on a rotating gantry
- Operated by a clinician: 24/7, 52 weeks/yr, 20y lifetime
- Safety is very important
- Universal Deployment

} **Suggests attempting a Cryogen Free Magnet as an integral element of the baseline design** (applies to the two items above)

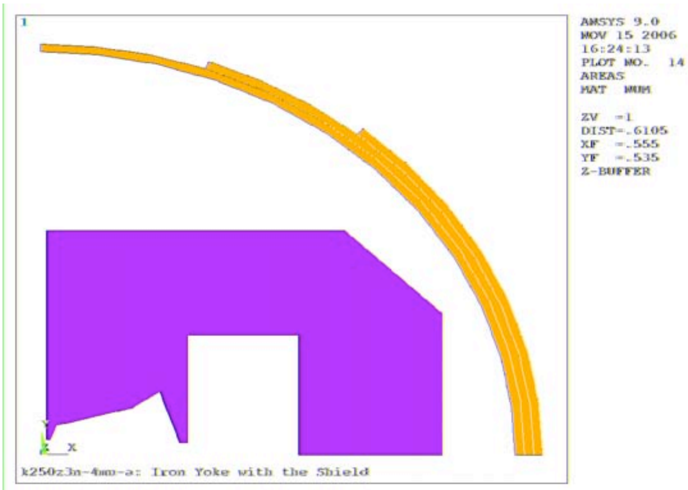
- Highly desirable to suppress the Fringe Field at Patient (8T to .0005T in 2m)

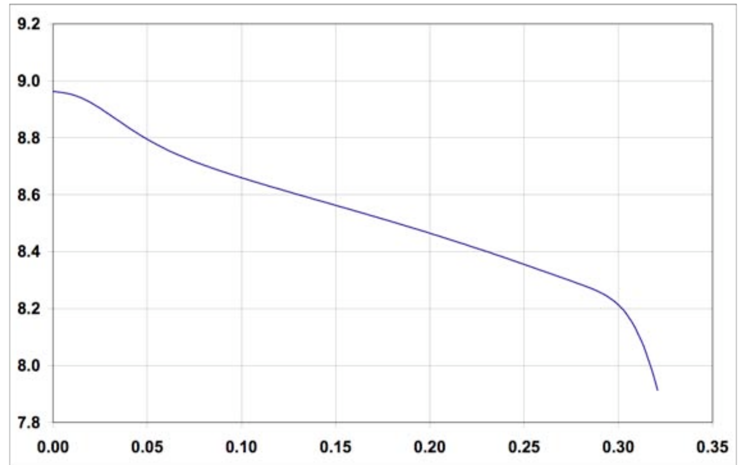
MSU K250 Synchrocyclotron Design Study

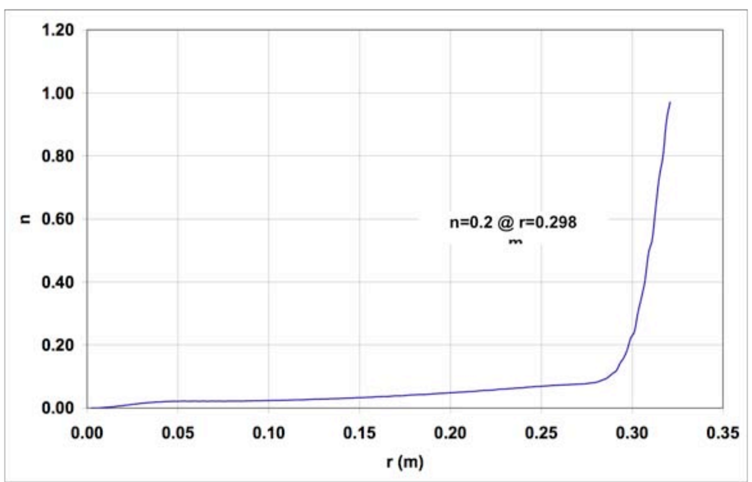


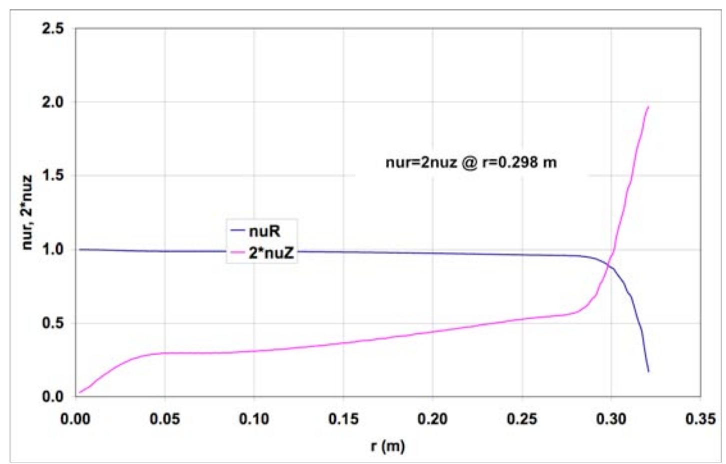
- Motivation was to exploit less complex cyclotron given PRT beam intensity requirements
- Specs
  - 100 enA
  - 5.53 Tesla Field
  - Pole radius 21 in.
  - 6250 turns
  - Mass 65 tons
  - F: 84.3-61.75 MHz
  - Dee voltage 20 kV
  - 1 kHz modulation
- Reasonable set of beam studies performed- all design requirements met

Extension to even higher fields (Antaya 2004…)

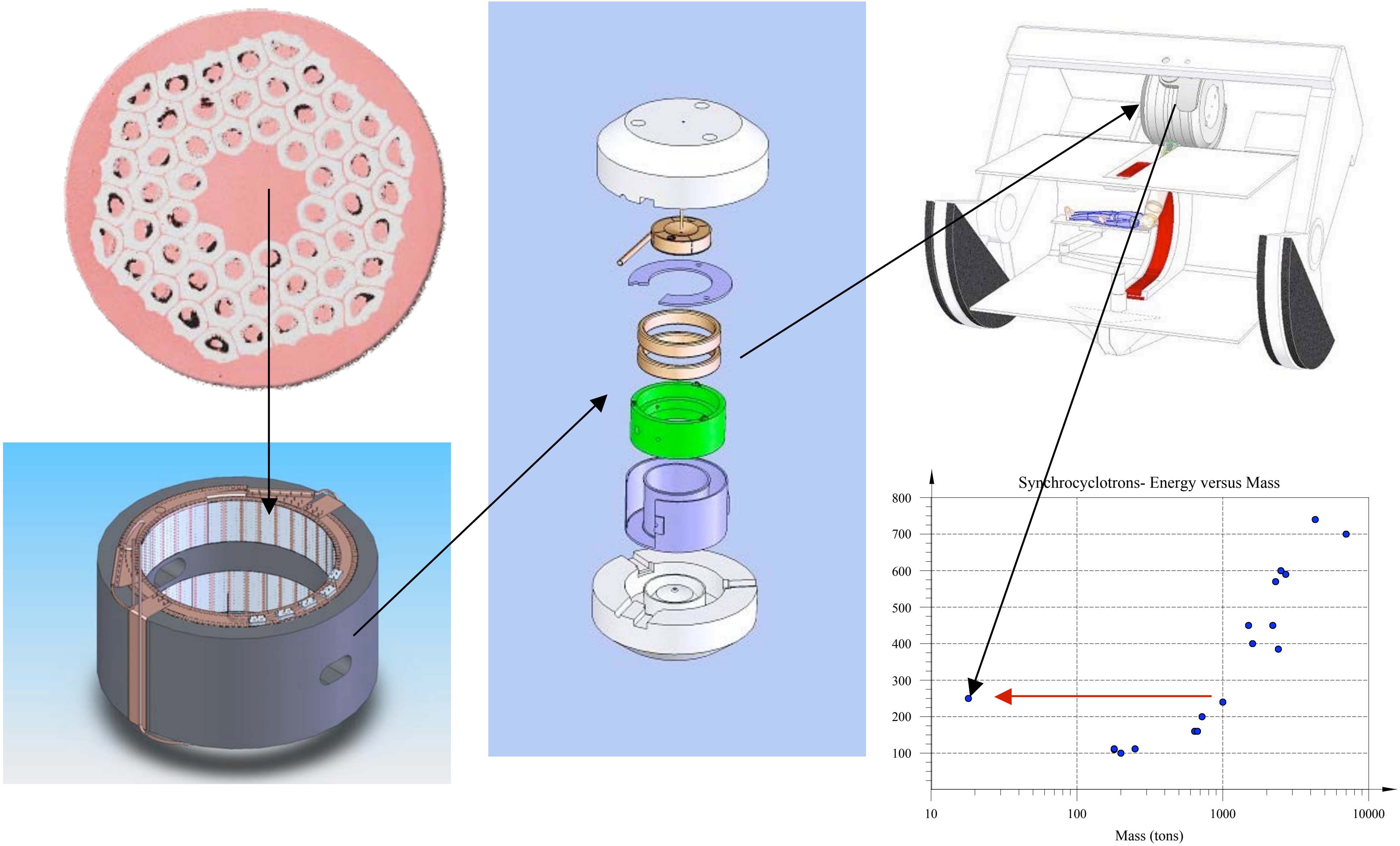




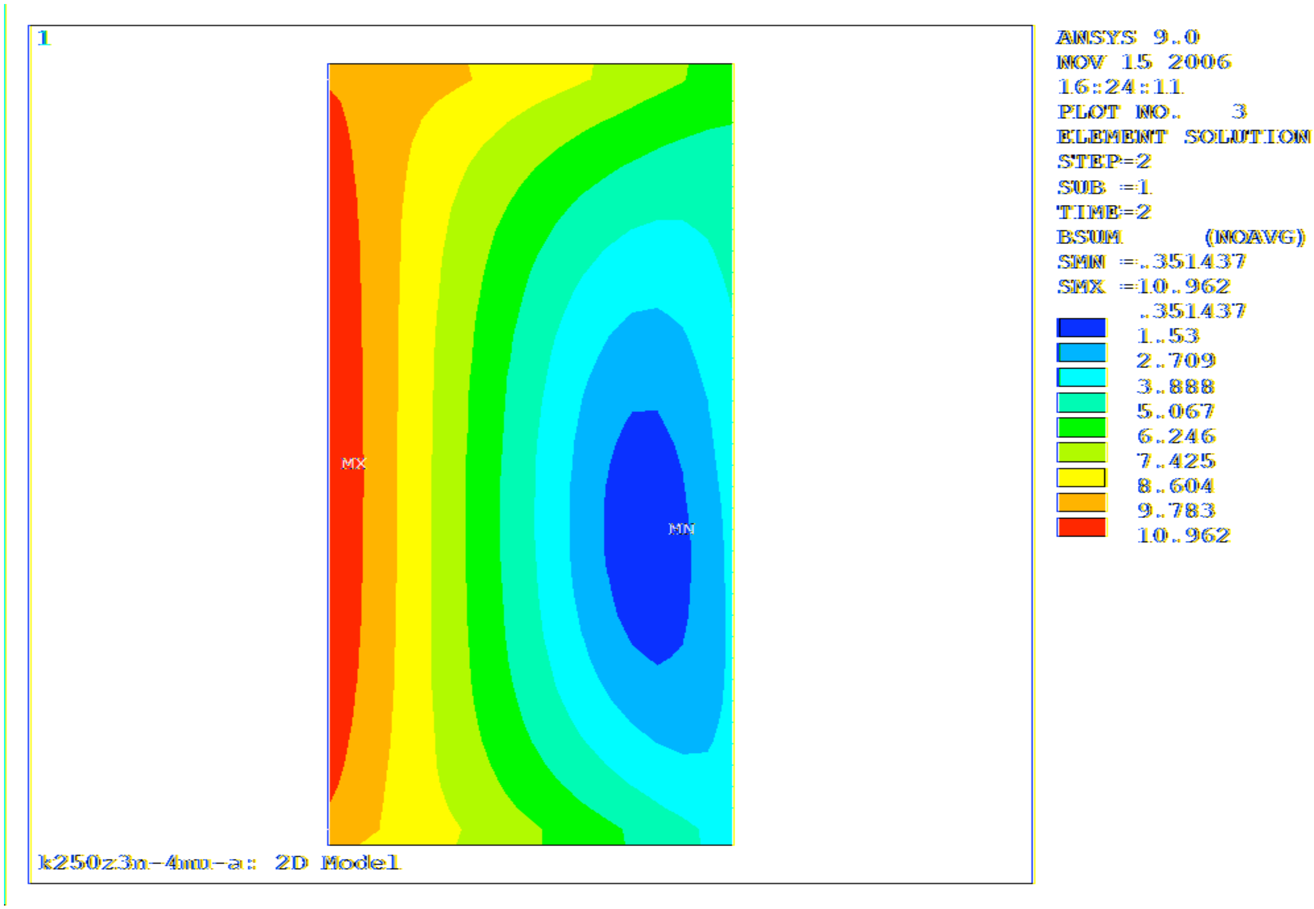




Compact High Energy Cyclotrons can result…



High field scaling is not without challenges



Consequences for the Superconducting Magnet

- Current Density must increase while the total magnetic flux and required amp-turns decrease

- Forces are large- both the field and current density are increasing - *this is a limiting engineering constraint*

- Stored Energy density scales with B^2- *this is also a significant challenge*

- >70% of req'd. field comes from the coils- *this is more feasible for the synchrocyclotron than an isochronous cyclotron*

- Full iron return yoke is essential
  - cyclotron systems issues 'prefers' warm iron
  - force distribution then adds the complexity of large de-centering forces to the overall engineering challenge

Cyclotron Coils- Force Density Limit

- The elemental force dF on a volume element carrying a current density j is given by

$$d\vec{F} = \vec{j} \times \vec{B} d^3 x$$

- The total *required* magnetic flux Φ has a peculiar scaling with final energy in cyclotrons- flux and amp-turns decrease:

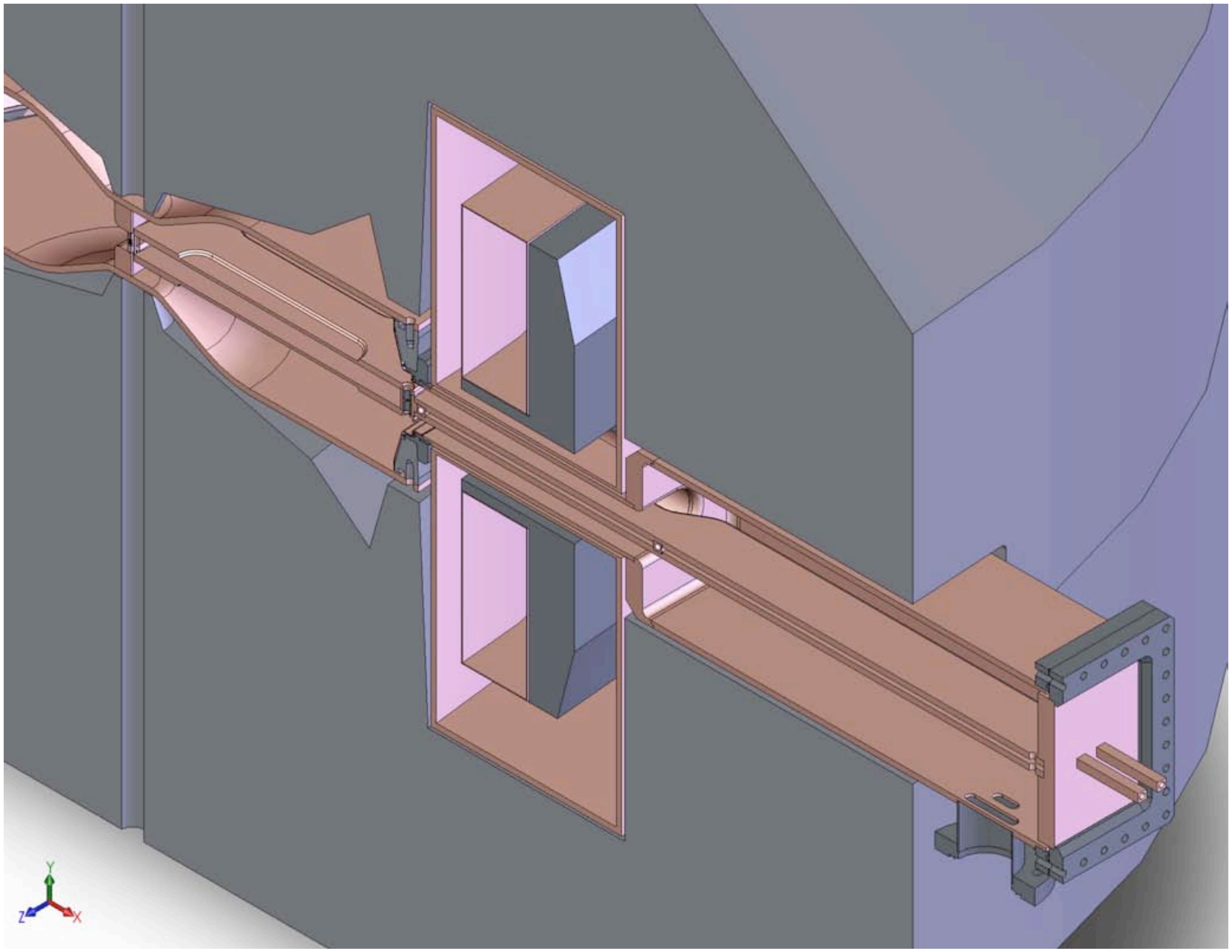
$$\Phi = \int \vec{B} \cdot d\vec{a} \cong E_{final} / B_{final}$$

- Optimized Current Density in solenoids however still increases:

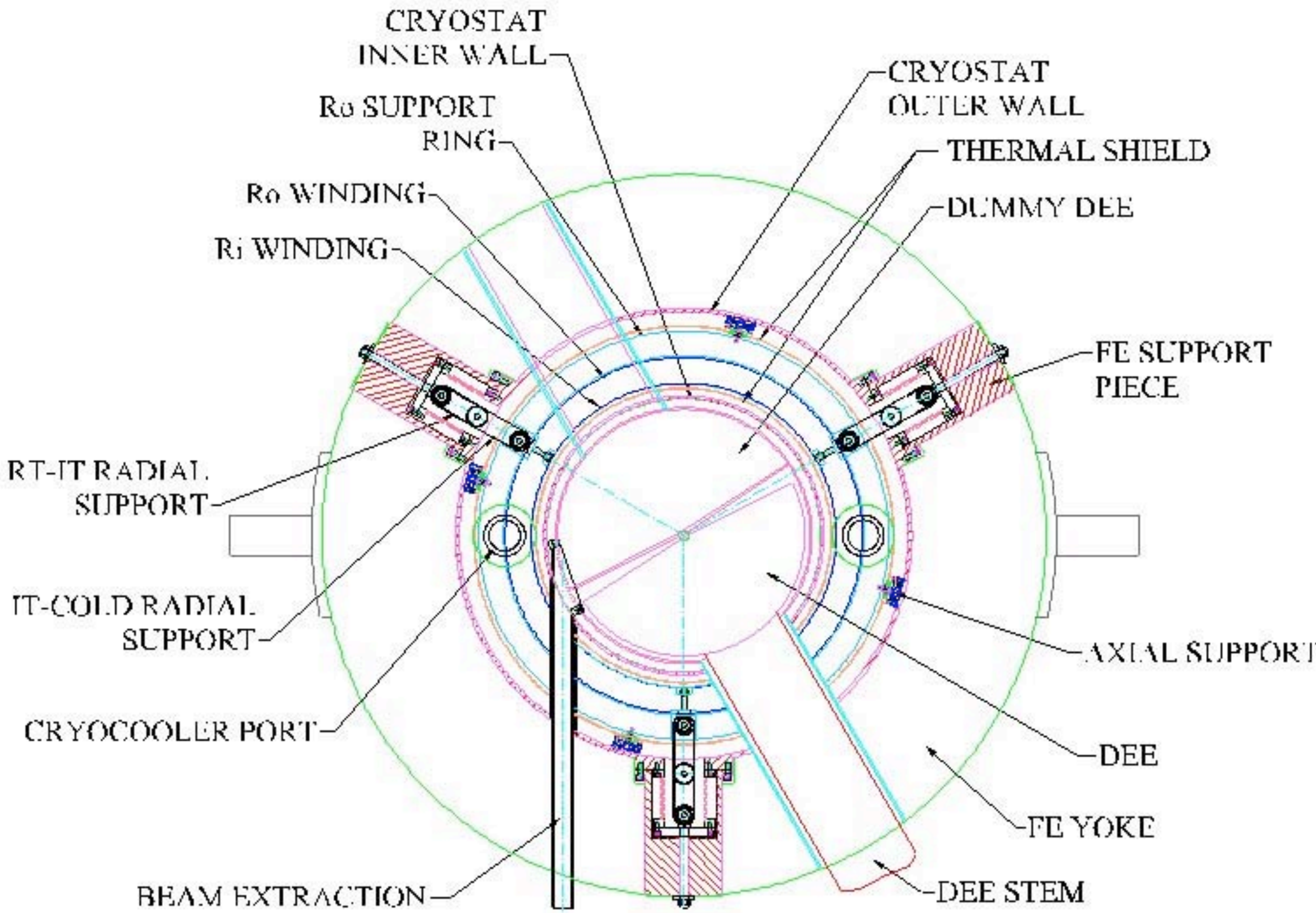
$$\left|\vec{j}\right| = \frac{B_0}{\mu_0 \rho_{in} F(\alpha,\beta)}$$

Hence both the field and current density rise as the radius of the cyclotron decreases- at 10T hoop stress $[jB\rho]_{max}$~800 MPa.

Compact Configuration itself- An Engineering Systems Challenge



Plan View 250 MeV Clinatron



Isochronous Cyclotrons

- Sector Focusing
- Not Phase Stable
- Limited by Focusing and Resonances

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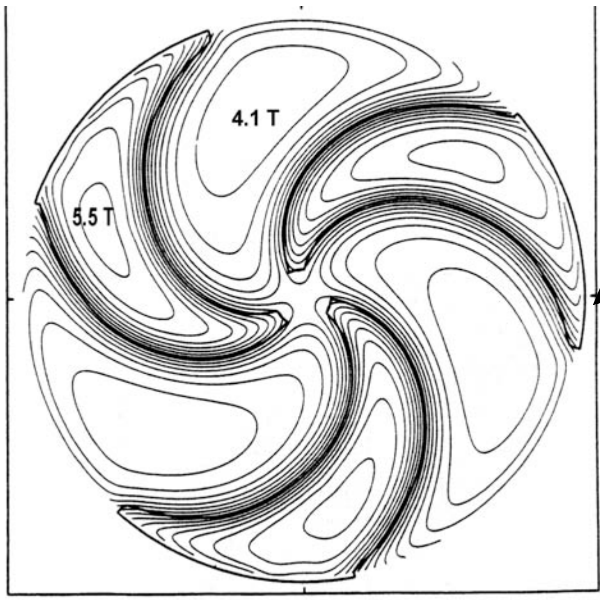
Isochronous Cyclotron Key Features

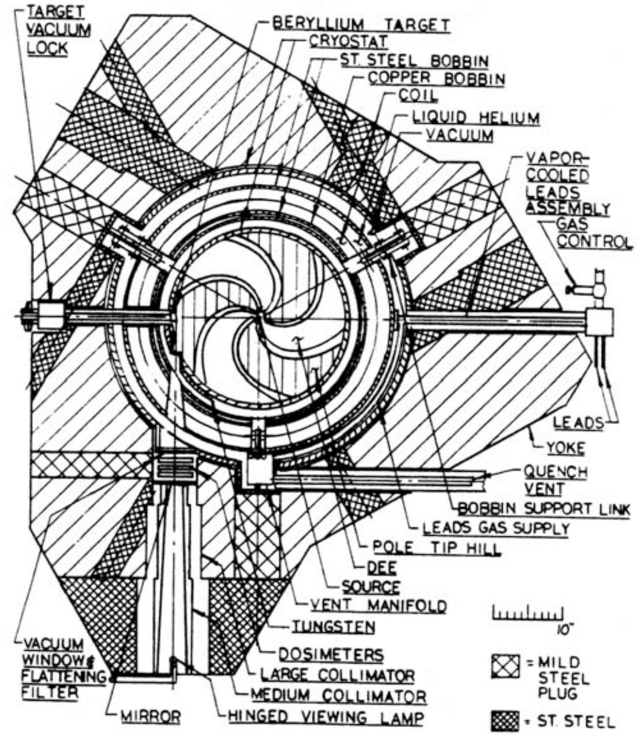
- Weak Focusing does not work (n<0) since B increase with r
  - Strong focusing is introduced
  - Increases resonant interaction of radial and axial motions
- Not Phase Stable Acceleration
  - $\alpha=\gamma^2$ so $d\tau/\tau=0$
  - Energy gain per turn must be programmed into the design- orbit pattern is fixed for a give ion and final energy
- Fixed Acceleration Frequency; CW operation
- Generally high acceleration voltage
  - radial orbit spacing at full energy large (few mm)
  - Permits 'single turn extraction'
- Final energies to 1 GeV ($\gamma\approx2$ for protons)
  - Variable final energy and ion species possible by changing the frequency and making a field profile adjustment
  - Ions from H+ to U, intensities to mA

Isochronous Cyclotrons & Flutter



- Flutter F - required for focusing in Isochronous Cyclotrons

$$F(r) = \frac{1}{2}\sum_{m}[B_m(r)/B_0(r)]^2$$



$$B(r,\theta) = B_0(r) + \sum_{m} B_m(r)\cos[m\theta + \zeta_m(r)]$$

- High azimuthal Symmetry

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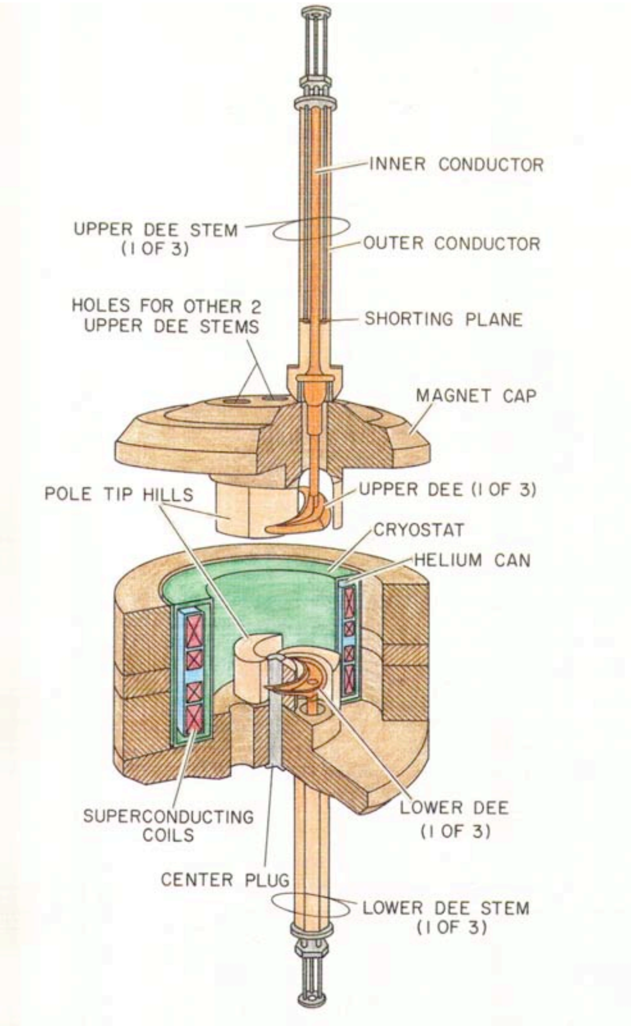
Superconducting Isochronous Cyclotrons have established Important Technological Limits @5T

- MSU K500 – 1982
  - Solved field design problem
  - Solved 3-phase RF
  - Solved beam extraction
- MSU K1200 – 1988
  - highest energy CW accelerator
- TAMU K500 – 1988
  - improved RF mech. design
- MSU K100 – 1989
  - Solved gantry rotation with pool boiling cryogens
  - C.R. w/ separated cathode PIG
- Orsay/Groningen K600 - 1996
- Milan/Catania K800 - 1994
- Accel/MSU K250s- PBRT 2005



Flutter Limit- Present SC Isochronous Cycs

- The flutter must be high to compensate the negative axial focusing strength to a positive number.
- The since amplitude of the any component of the azimuthally varying field cannot exceed about half of 2.2T, then *flutter falls rapidly towards zero as the average field is raised.*
- At ~5T average field, and using iron for field shaping, the flutter is about 5%, and care is needed to meet focusing requirements for high energy acceleration (high γ) without going to separated sectors.
- At the average field levels under consideration in the present effort, ~9T, the flutter in a simple ferromagnetic circuit would be negligible
- Non-simple structures required (this is a nice thesis project)
- Ferromagnetic materials other than Iron (gadolinium) would also work

Summarize:

- We understand (to 9T):
  - Beam Dynamics Scaling: high fields, low acceleration voltages & passive extraction systems
  - Magnet Engineering Challenges: peak fields, stresses and stored energy
  - Systems Engineering Subtleties: to accommodate required sub-systems & achieve reasonable design margins
- And have developed:
  - a comprehensive set of quantitative & predictive tools- beam dynamics, field design, conductor…
  - Coupled structural-field, thermal, hydraulic engineering methods to support such efforts

What's next?

We are going to look at the Physics and Engineering of ultra compact:

- Nanotron: Classical weak focusing (10 MeV) cyclotrons
- Isotron: Isochronous Cyclotrons to ~100 MeV
  - Protons or heavy ions
  - Isotope production
  - Direct radiation sources
- Compact High Energy Cyclotrons (~1 GeV) for protons or muons - long stand off nuclear materials detection

- With
  - Fields 8-14T, conventional and HTS conductors
  - Cold magnetic structures (iron and rare earth poles)
  - And unusually application packaging

What's required:

Fundamental

- Axial Injection at High Field
- Non-linear space charge forces at low velocity in the center
- Full acceleration phase space evolution
- …

Engineering

- Nb_3Sn at higher fields, HTS at low temps and high fields, HTS at Intermediate temps
- Compact acceleration structures
- Isochronous 'flutter' solution at high field
- …

Application Specific Optimization

- App. drivers are primarily in medicine and security for these ultra compact machines

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