A New Center for Heavy Ion Research in the US

Cancer Center Perkins&Will

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CENTER FOR PARTICLE THERAPY & RESEARCH
MASTER PLAN - WACO, TEXAS Perkins&Will

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Abstract

Progress in cancer therapy with ions heavier than protons, i.e., helium, carbon, oxygen and even neon, requires research and development capability. Ion research activity, however, is limited from the absence of U.S. accelerator facilities offering ion beams for therapy – placing the U.S. significantly behind Europe and Asia. A new center for ion therapy research is under development in Waco, TX, in collaboration with established accelerator entities, both academic and industrial, along with medical partnerships. The advanced technologies will produce both clinical and research beams, offering a complete range of ions, intensities and energies required by the medical community, including the capability to perform groundbreaking, ultra-high dose (FLASH) therapy research.

With dramatic advances in beam delivery, patient treatment, and next generation accelerators,

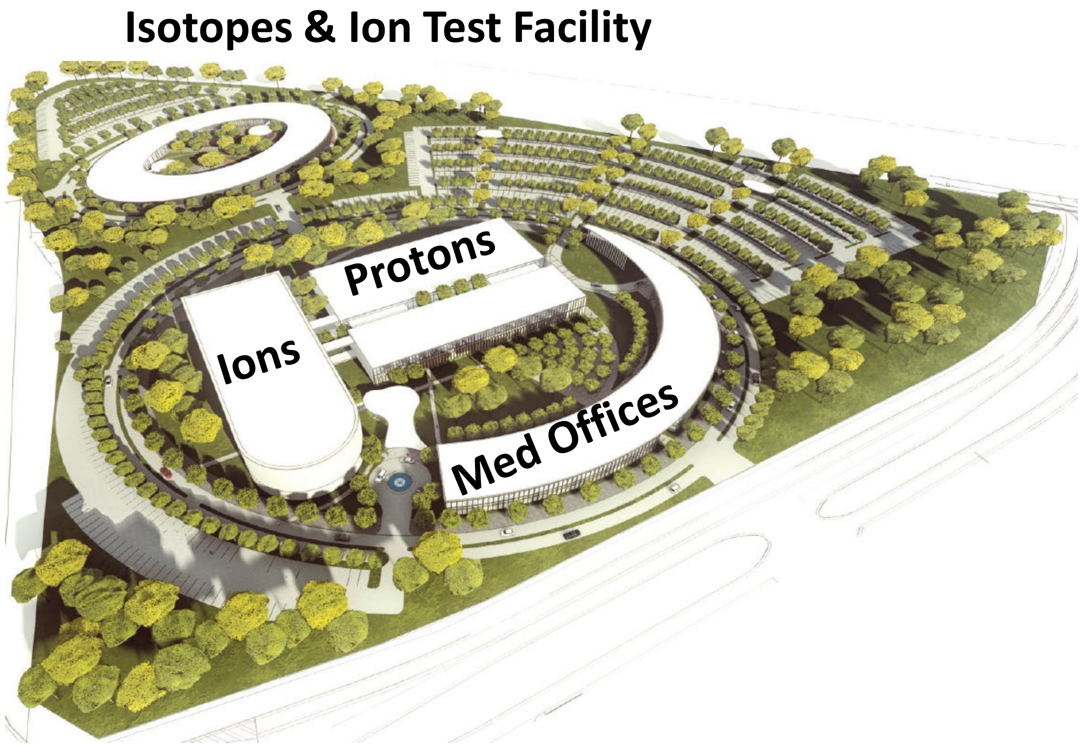
THIS UNIQUE FACILITY will restore US leadership in CANCER therapy and research.

Collaborating Institutions: MDAnderson, Fermi National Accelerator Lab, Brookhaven National Lab, Crocker Nuclear lab, Lawrence Berkeley National Lab, UCDavis, Michigan State University, Baylor University, Particle Accelerator Corporation, Radiabeam Technologies, TechSource

Optimizing a broad-community ion user facility

The Ion Campus - Overview

- ***Proton and Heavy Ion Radiotherapy***
  - Protons in a separate facility (230 MeV therapy cyclotron)
  - Heavy Ion Beam Facility
    - All therapy ions supported – including protons - oxygen and neon
    - Priority: *helium and carbon therapy (deuterons for imaging)*
    - FLASH capable
    - Ions for material science (DOD, DARPA, Space applications)
  - Operation:
    - Turnkey, min operational overhead
    - Low maintenance and low health risk
- ***Theranostics Radioisotope production & Ion Test Facility***
  - Commercial radioisotope machines
  - Future area reserved for dedicated ion beam R&D facility



Outline

1. Proton and Heavy Ion Radiotherapy including FLASH radiotherapy
2. Theranostics therapy and radioisotopes – discussed in a separate FFA23 presentation
3. Intro to Accelerators and operating parameters (conventional)
4. Staged Approach to support broad-community therapy and research
    1. Multi-ion Source (two or more sources with different ions)
    2. Radio Frequency Quadrupole (RFQ) ultra-low energy module – for cell research
    3. Low Energy Stage (compact cyclotron) – for Radiobiology research
    4. Medium Energy Stage (cyclotron) – Radiotherapy for eye and skin cancers
    5. Ion Therapy Stage (Fixed Field Gradient Accelerator, FFGA) – Heavy ion radiotherapy
5. Center for Particle Beam Therapy
    1. Facility layout
    2. Renderings
6. Summary

Conventional Accelerators for ions (KE/nucleon)

Synchrotrons *(>100 MeV – TeV/n energies)*

- Pulsed: changing magnetic fields (0.5-50Hz rep rate)
- Swept-frequency accelerating systems
- Current limited by size
- Variable energy

Cyclotrons *(~10 MeV – 100 MeV/n CW)*

- Fixed magnetic fields
- For CW beams, fixed-frequency accelerating system
- Higher energies:
    - ***Very large at higher energies for CW beam or***
    - ***Pulsed synchrocyclotron for compact footprint (swept freq RF)***
- mA currents for CW; *fixed energy (per charge to mass)*

Linacs *(any energy)*

- Largest footprint, most costly
- Ultra-high currents – 100 mA
- Variable energy @ *synchrotron duty cycles*

Gradient Cyclotrons/FFGAs (~10 MeV – 2 GeV/n)

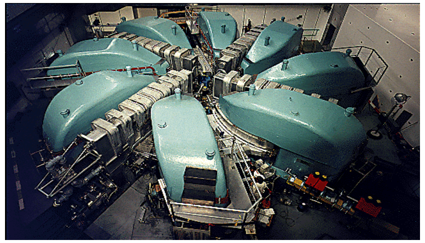
- Fixed magnetic fields, (Fixed Field Gradient Accelerator, FFGA)
- CW (fixed freq RF) or kHz pulsed beams to high energy
- Most compact @≥100 MeV/n
- High current , *FFGA can support variable energy extraction*

Synchrotron

Low Current (<mA), High Energy, Hz pulsed

Cyclotron

High Current (<Amp) Low Energy (600MeV), CW or kHz pulsed

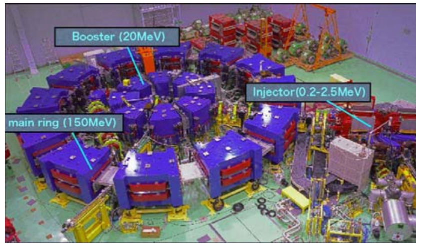


Linac

High Current, High Energy, Pulsed or CW: Large, expensive, high power if not superconducting

FFGA

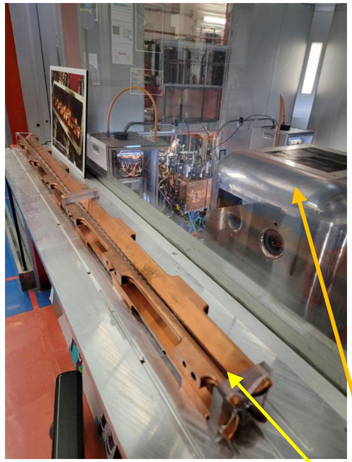
High Current (<Amp), High Energy (GeV), CW or pulsed, compact



Energy Reach of Ion Accelerator Types (approximate)

- Ion therapy energies require up to 250 MeV/nucleon for helium and 430 MeV/nucleon for carbon
- Beyond ~150 MeV/nucleon, the size & cost of a cyclotron increases dramatically. The next-generation Fixed Field Gradient accelerator developed for this facility reduces the size and cost of the therapy machine by half compared to cyclotrons. (Current commercial ion therapy machines are low dose synchrotrons without FLASH capability.)

< MeV/n



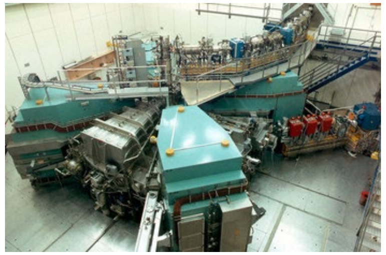
Tandems (large), RFQs, Cockcroft Waltons (very large)

few MeV/n

CW/pulsed:
Drift Tube linac
Lowest losses
Cyclos have high central region losses (40-80%) for CR vertical axis injection

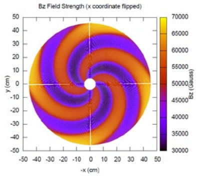
≤50 MeV/n

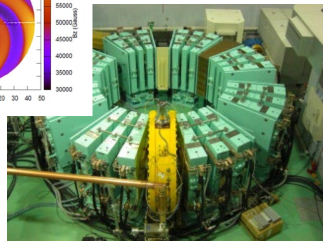
CW:
Sector iso-cyclotron (PSI Injector)



≤150 MeV/n

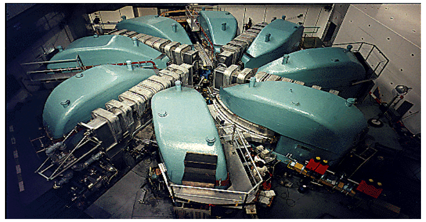
CW:
AVF cyclotrons and gradient cyclotrons
Pulsed:
synchrocyclotrons and conventional FFGAs





≤1 GeV/n

CW:
AVF cyclotrons (very large),
FFGAs (nonscaling, compact)
Pulsed:
synchro- cyclotrons and scaling FFGAs

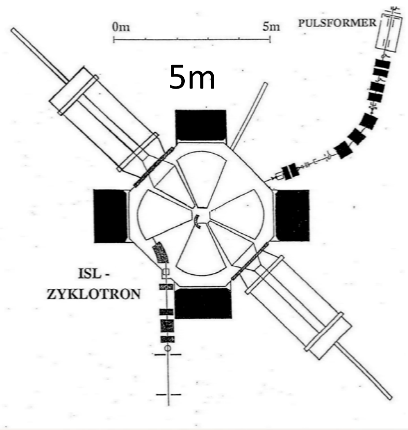


Multi-GeV – TeV/n

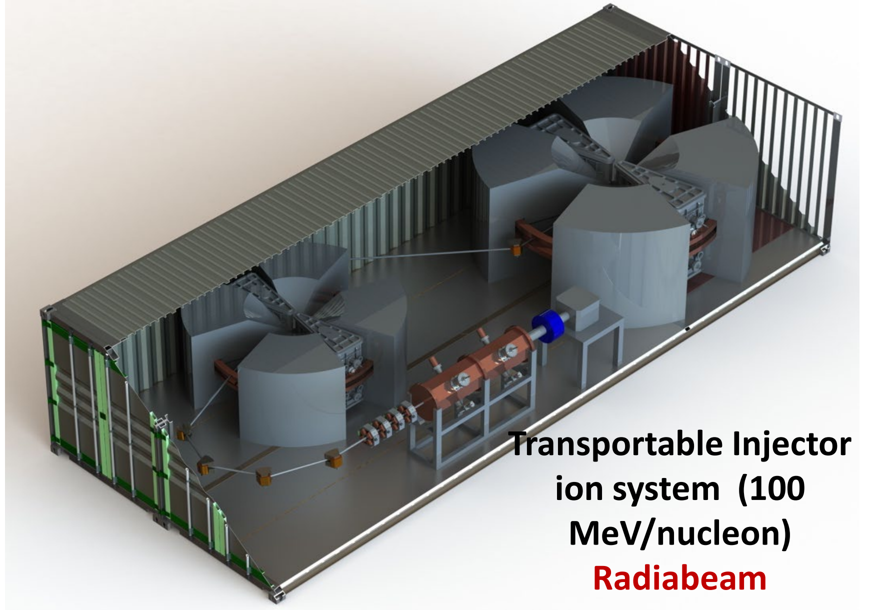
Pulsed:
Synchrotrons (<100 Hz duty cycle)

Staged Approach to Accelerator Systems

- ***Multi-ion CW Beam*** *(eliminates synchrotrons)*
  - **q/m=1/2** supports all therapy ions without significant retuning
    - 10^{6-9} ions/RF bunch (μAmp currents)
- ***Compact stages*** *(eliminates NC linacs)*
- ***Low-loss*** *(eliminates AVF/compact cyclotrons)*
  - **High gradient acceleration** to separate orbits @extraction
    - Fixed-frequency RF (broadband has lower acceleration gradients)
  - **Horizontal injection** (vertical axial injection is very high loss)
    - Requires injection energy (~4 MeV/nucleon for q/m=1/2)
- ***Turnkey*** *– min complexity (SC eliminated)*
  - **Stages:** *RFQ, low energy, high energy cyclotron, therapy FFGA*
    - Simplifies accelerator operation and the design of each stage
    - User beamlines can be supported from each stage (no retuning)
    - Restricts relativistic effects to HE cyclotron and therapy machine
    - Standalone 100 MeV/nucleon transportable Injector (supports heavier ions)



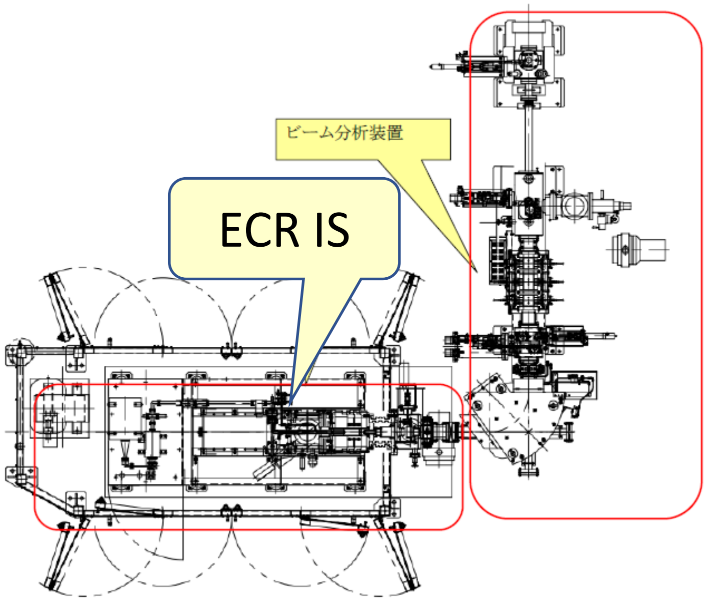
HZB ion cyclotron:
10 m diameter with broadband RF tuner

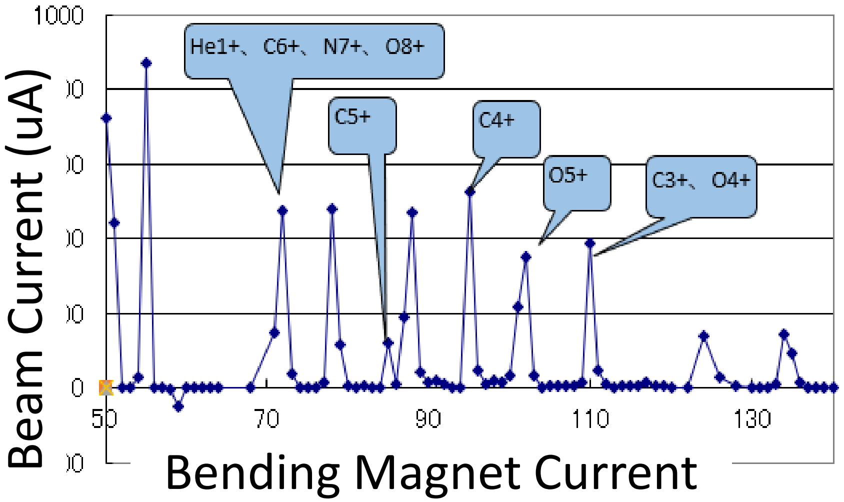


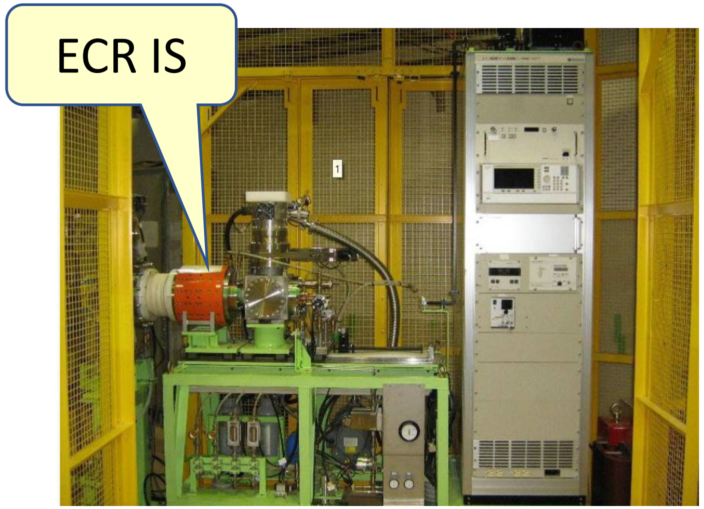
Transportable Injector ion system (100 MeV/nucleon)
Radiabeam

Electron Cyclotron Resonance Ion Source (ECRIS)

Compact ECRIS and Analyzing Magnet Layout







Compact ECRIS (Sumitomo) ion species output and installation

Elimination of contaminants will be required in Low Energy Beam Transport. Two sources may reduce contamination.

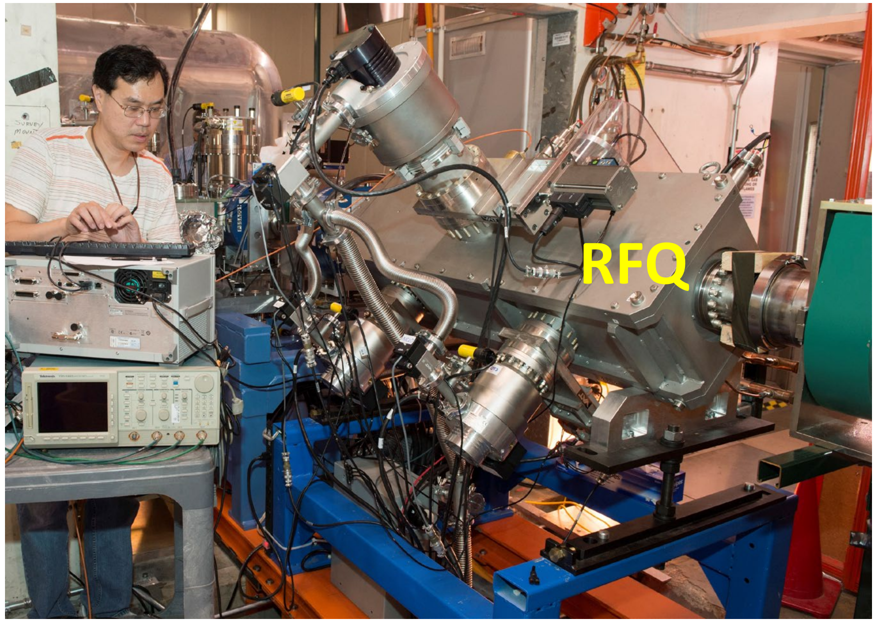
Compact ECRIS (Sumitomo) Two Sources:

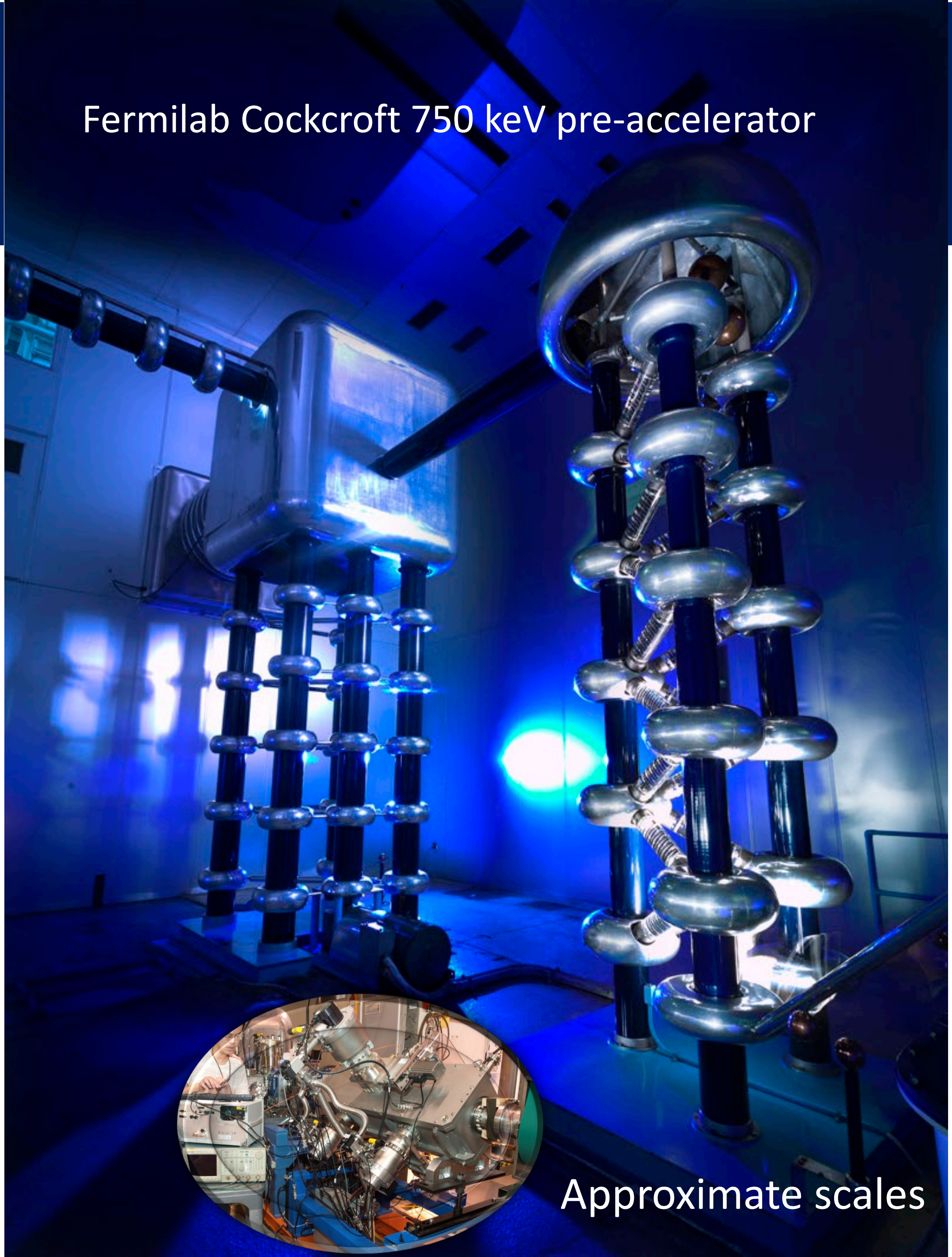
1^{st}: Therapy Ions: $_{12}C^{6+}$ and $_{4}He^{2+}$

2^{nd}: Diagnostic Source: H_2^+, D^+

RFQ vs Cockcroft Walton pre-accelerator

Precursor to low-loss compact accelerators





RFQ Stage:
CW 85-120 MHz, ion dual RFQ (2 RFQs)
special thank you to Andrea Denker (HZB)

Two independently tunable RFQs in single module
Originally injector to HZB cyclotron, Berlin (formally ISL)
Capable of accelerating therapy and heavier ions

Cyclotrons will be operated at half the RFQ frequency
Pre-RFQ chopping to fill every other RF bucket followed by re-bunching/rotation prior to injection into LE cyclotron

Provides ultra-low energy ion beams for cell research
FLASH and conventional dose capability and independent research beamline

Length (split into two stages)	[m]	3
diameter	[m]	0.5
number of stems per stage		10
minimum aperture	[mm]	2
min/max Ein	[keV/u]	15.16/29.72
min/max Eout	[keV/u]	178.35/355.09
charge-to-mass-ration		1/8 - 1/2
frequency	[MHz]	85 - 120
duty factor		100% (cw)
max power consumption p. stage [kW]		20

Table 1: ISL-VE-RFQ parameters

Radiobiology, Eye/skin, Therapy Stages

Low Energy Iso-cyclotron	High Energy Iso-cyclotron	Therapy Iso-FFGA
Sector Cyclotron 4 – 24 MeV/nucleon (q/m=1/2)	Sector Cyclotron 24 – 100 MeV/nucleon (q/m=1/2)	Fixed Field Gradient Accelerator (FFGA) 100-25 MeV/nucleon (q/m=1/2)
low-loss horizontal injection	Low loss horizontal injection	Nonlinear, alternating gradient strong focusing isochronous racetrack lattice
RF ~50 MHz, 8th harmonic for q/m=1/2	RF identical to LE Cyclotron 8th harmonic for q/m=1/2	Long straight for variable energy extraction *(no energy degrader)*
Booster accelerator required between RFQ and cyclotron	Cyclotrons RF matched and cogged (8th harmonic)	Long straight for high-gradient acceleration modules
Dual Extraction: Radiobiology beamline	Dual extraction: Eye/skin therapy line and clinical research	Gantry and Leo Chair for beam delivery

Low Energy Cyclotron - Research

Low energy ion beams for Radiobiology research

Both FLASH and conventional dose capability and dedicated beamline for Radiobiology cancer research

Conventional cyclotron design

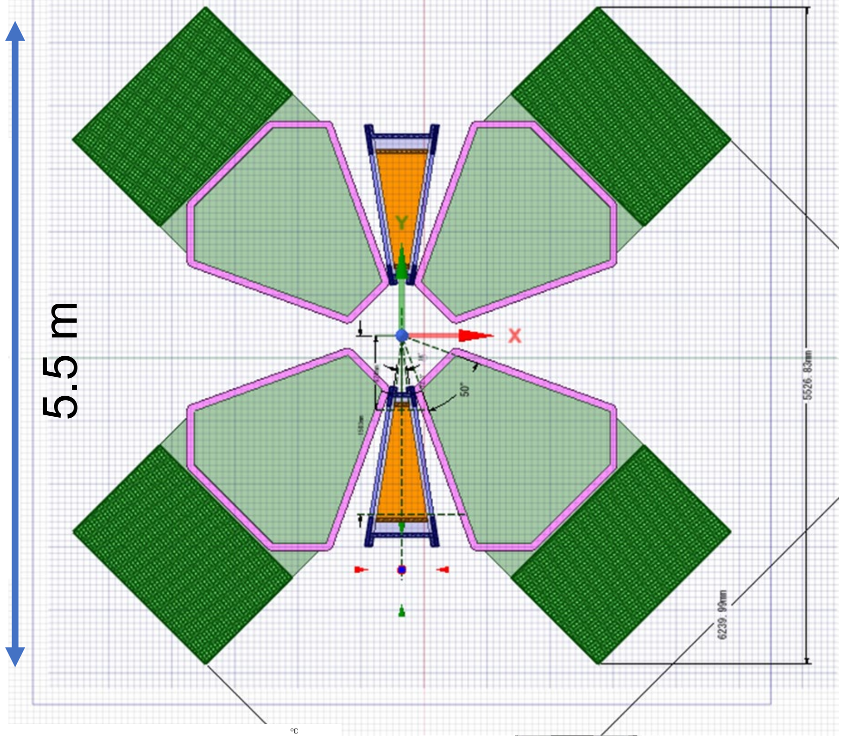
Turnkey, continuous-beam operation; 24 MeV/nucleon max ion energy. Magnet and RF engineering in progress.

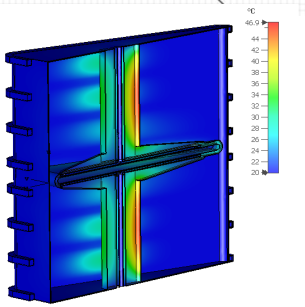
Strategic heavier ion species supported – see table

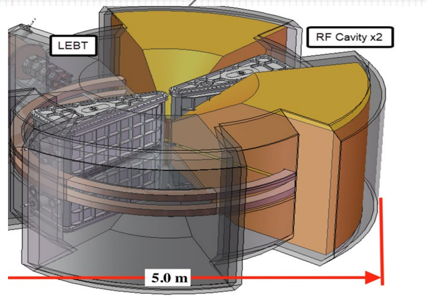
Critical for radiation performance testing of electronics and materials (DOD/DARPA/Aerospace Industries)

Energy per nucleon	q/A	harmonic	Ions
2.6 MeV	1/6	24	TBD B^{2+}, C^{2+}, $^{30}Si^{5+}$, $^{36}Ar^{6+}$, Co^{10+}, Cu^{11+}, Kr^{14+}, Xe^{22+}
6 MeV	1/4	16	He^{1+}, B^{3+}, C^{3+}, O^{4+}, Ne^{5+}, Si^{7+}, S^{8+}, Ca^{10+}, $^{36}Ar^{9+}$, V^{13+} Co^{15+}, Cu^{16+}, Kr^{22+}, Xe^{33+}
10.7 MeV	1/3	12	B^{4+}, C^{4+}, N^{5+}, O^{5+}, Ar^{6+}, Al^{9+}, Ne^{7+}, Cl^{12+}, Si^{10+}, V^{17+}, Co^{20+}, Cu^{21+}, Kr^{29+}, Xe^{44+},
24 MeV	1/2	8	H_2^{+}, He^{2+}, N^{7+}, O^{8+}, Ne^{10+}, Si^{14+}, $^{32}S^{16+}$, $^{36}Ar^{18+}$, Ca^{20+}

Layout and mechanical design of LE stage







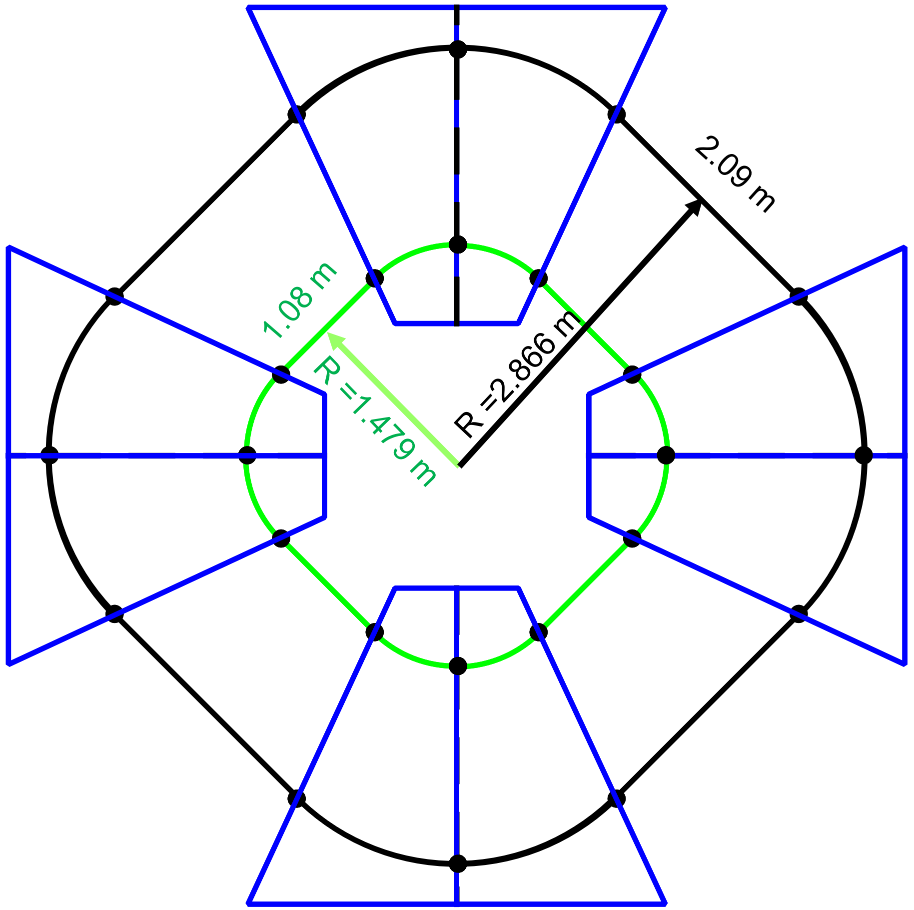
HE cyclotron – low energy radiotherapy

Medium energy ion beams for eye/skin therapy and research
Both FLASH and conventional dose capability and dedicated beamline for shallow cancer therapy and research.

Advanced gradient cyclotron design
Turnkey, continuous-beam operation @100 MeV/nucleon (q/m=1/2,~50.6 MHz, 8th harmonic). Hardware systems under development. Controls and operation integrated with Low Energy cyclotron Module. Significantly smaller machine components and cost than a combined LE/ME single machine.

Strategic high energy ion beams for radiation hardness testing
Higher energy ion test beams specifically targeted for development by DOD/DARPA/Space agencies. Currently pulsed high energy ion beams only available at Brookhaven National Lab from the AGS synchrotron. Beam time costly and oversubscribed.

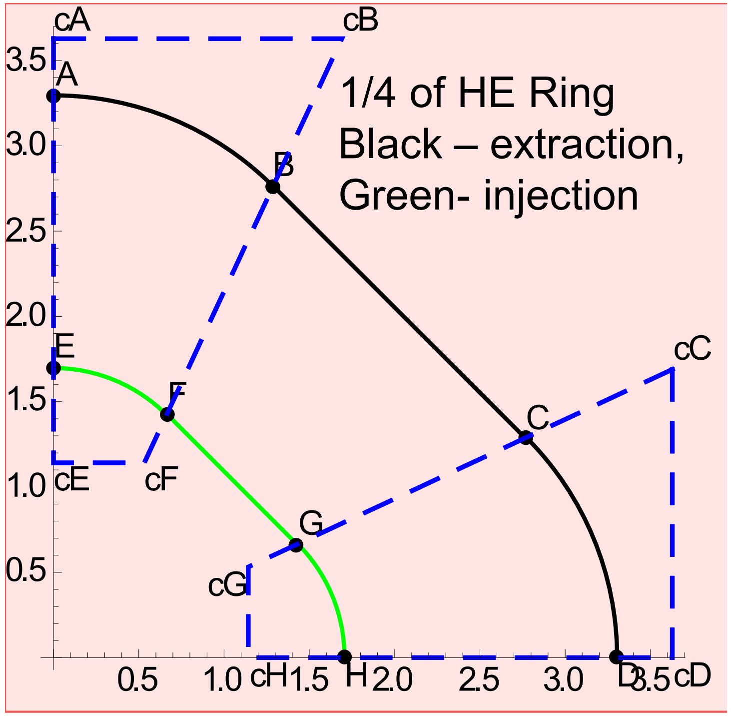
Note: Very heavy ions not supported due to relativistic effects – target is to accelerate Xe to 50 MeV/nucleon.



Preliminary geometry of HE ring

HE Cyclotron – Hard edge Design
24 -100 MeV/n for q/m = 1/2 .

- HE Ring will dictate the RF frequency
- Relativistic effects on momentum 10%@extraction and 2.4%@ injection
- Significant space for clean injection and extraction – for transport a backleg may be removable
- Isochronous to 10^{-7} (ideal field)

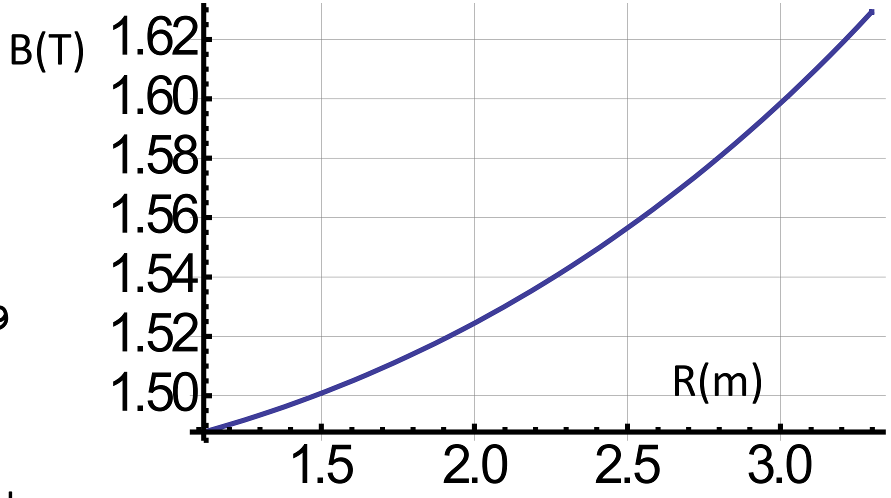


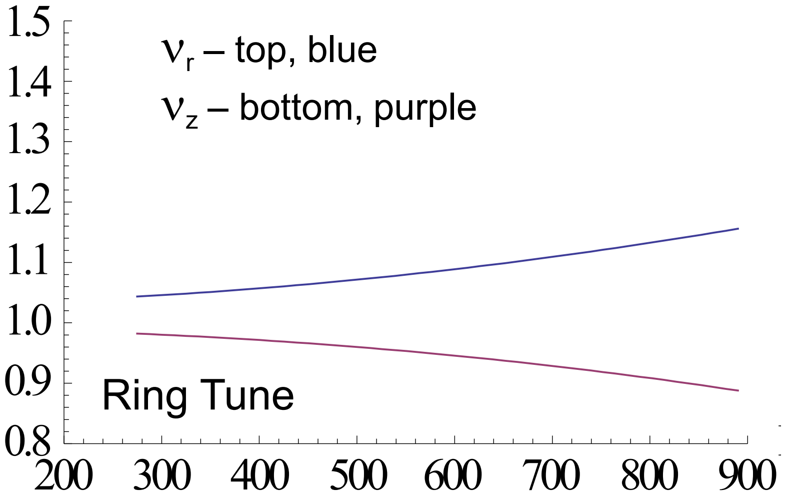
Field Profile:

`Bf(r)= 14.9252-0.487832 r+0.33809 r²-0.0755392 r³+0.0281412 r⁴-0.00513183 r⁵ +0.000529662 r⁶`

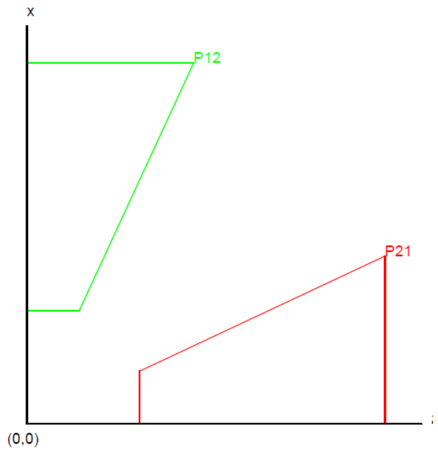
$$Bf(r) = 14.9252 - 0.487832\, r + 0.33809\, r^2 - 0.0755392\, r^3 + 0.0281412\, r^4 - 0.00513183\, r^5 + 0.000529662\, r^6$$

Trajectories	Magnet Edges
A: (0, 3.29849)	cA: (0,3.62834)
B: (1.2875,2.76519)	cB: (1.68939, 3.62834)
C: (2.76519, 1.2875)	cC: (3.62834, 1.68939)
D: (3.29849, 0)	cD: (3.62834, 0)
E: (0, 1.70263)	cE: (0,1.14188)
F: (0.664592, 1.42735)	cF: (0.531675,1.14188)
G: (1.42735, 0.664592)	cG: (1.14188, 0.531675)
H: 1.70283, 0)	cH: (1.14188,0)



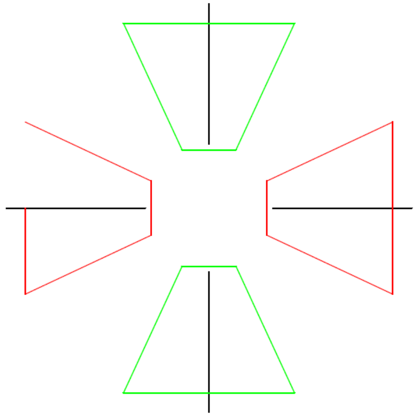


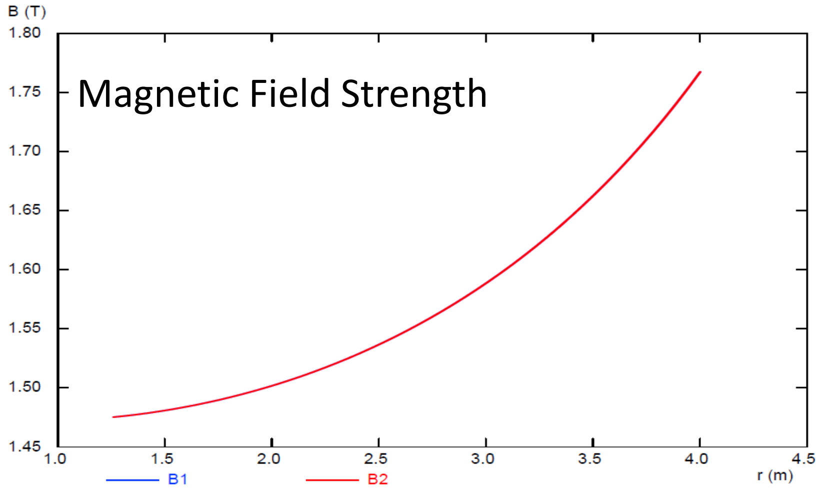
HE Cyclotron – high-order performance with Enge fringe fields

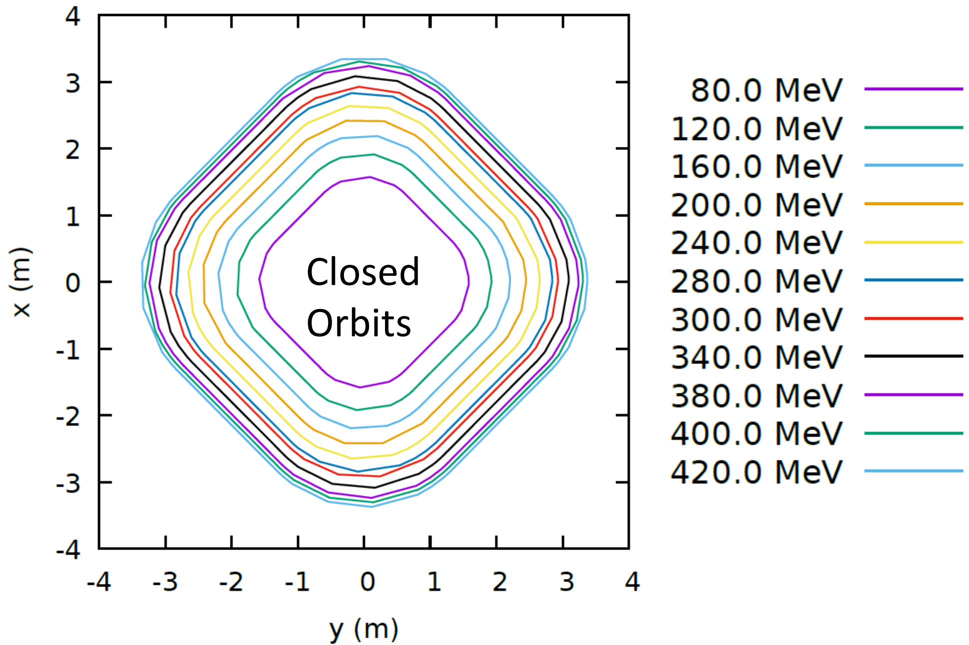


P12
from (x,z)= (1.1418800 m, 0.5316750 m)
(r,th)= (1.2595905 m, 24.9673331 de
to (x,z)= (3.6283400 m, 1.6893850 m)
(r,th)= (4.0023584 m, 24.9670749 de

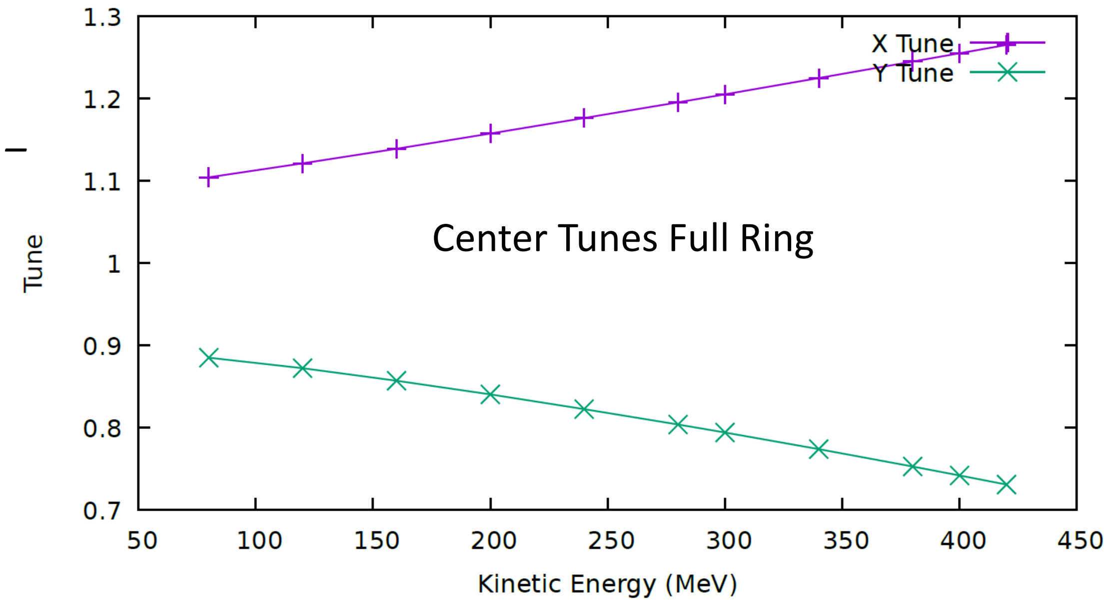
P21
from (x,z)= (0.5316750 m, 1.1418800 m)
(r,th)= (1.2595905 m, 65.0326669 de
to (x,z)= (1.6893850 m, 3.6283400 m)
(r,th)= (4.0023584 m, 65.0329251 de





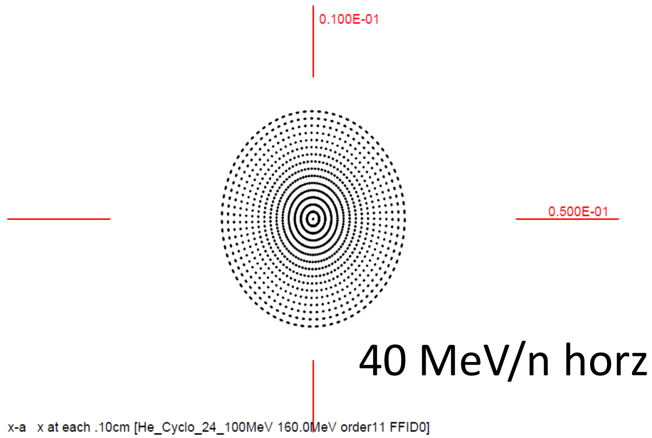


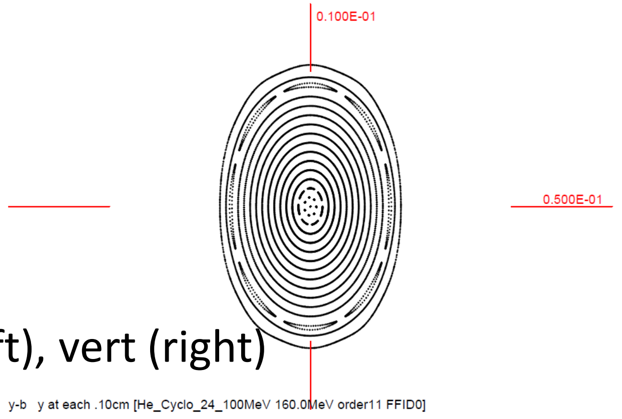
For He^{2+} <24 to >100 MeV/n. No integer or half integer crossings – stable beam at all energies



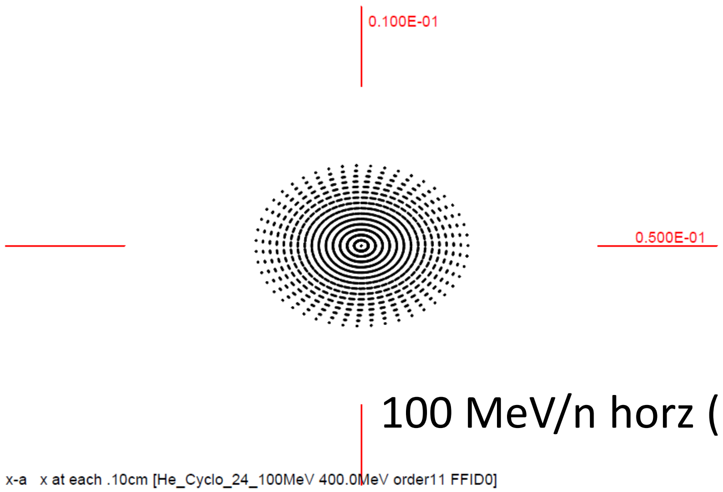
HE Cyclotron– Tracking and Field Maps

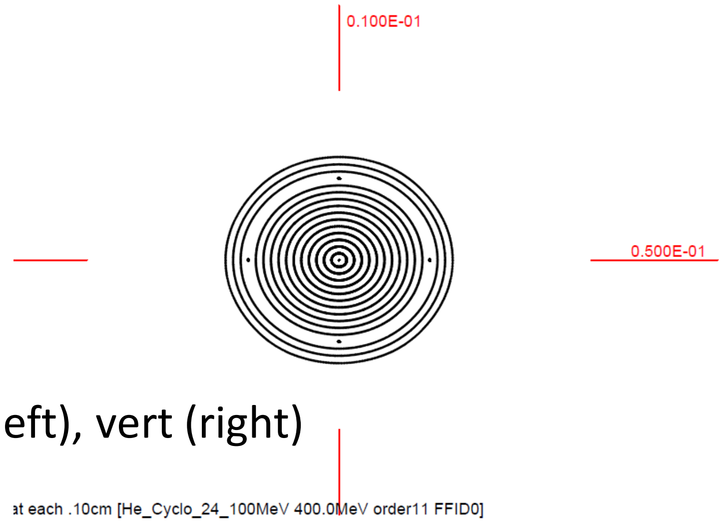
- x-y tracking in 1 mm steps
- Enormous >10cm aperture stability
- No resonance or unstable beam observed



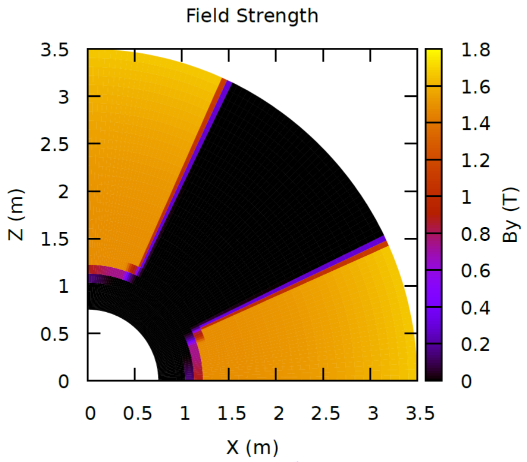


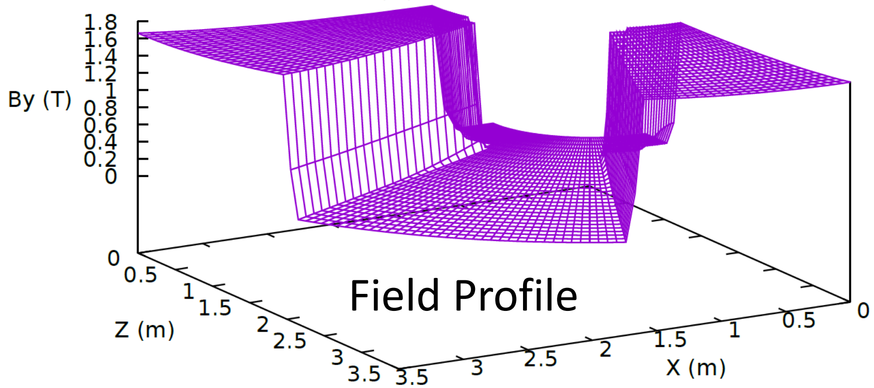
40 MeV/n horz (left), vert (right)





100 MeV/n horz (left), vert (right)

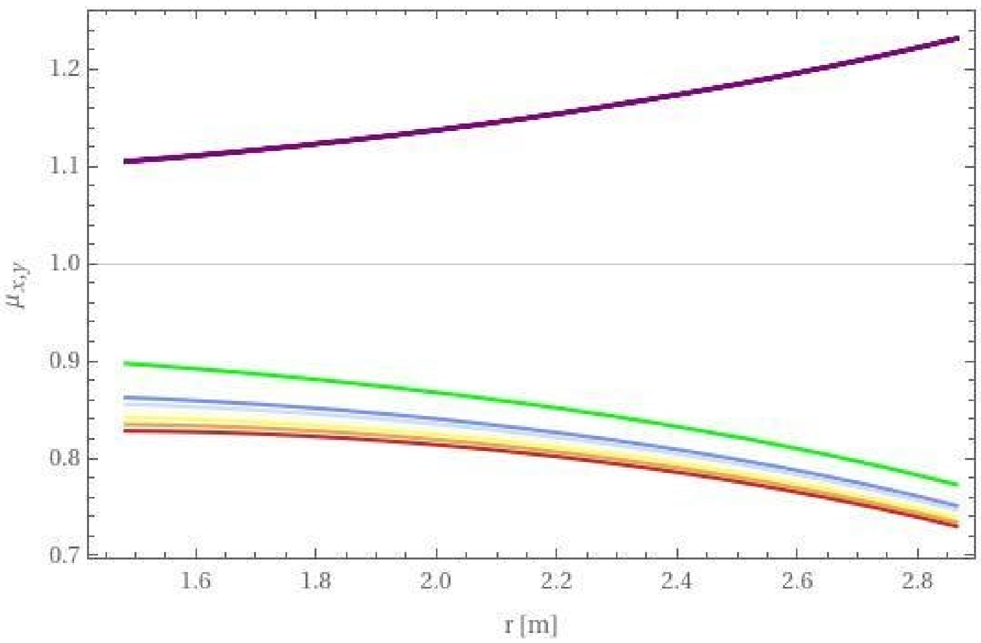


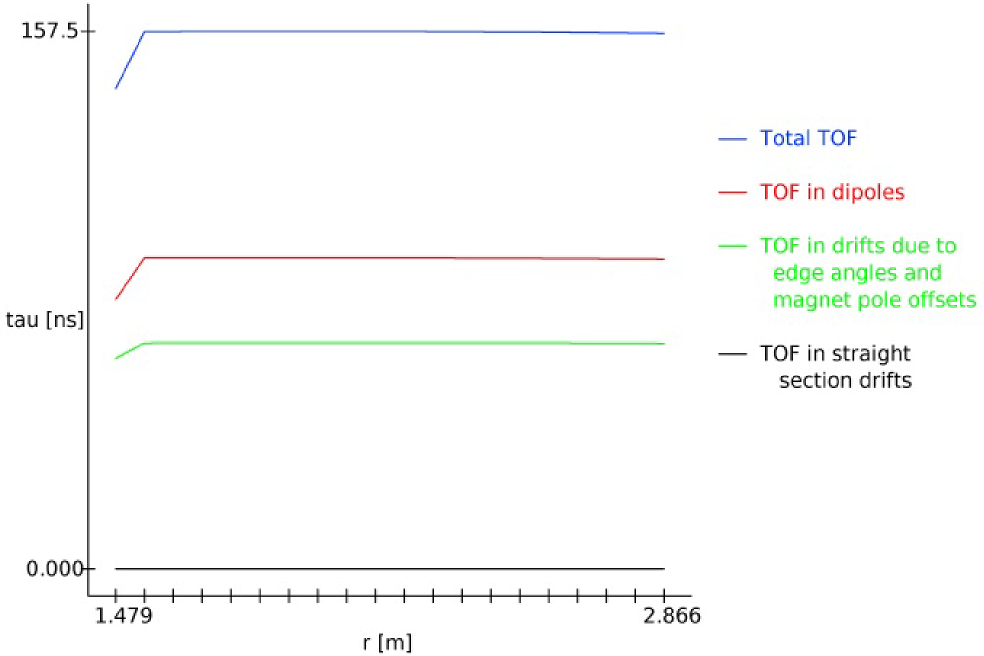


HE Cyclotron– COSY (MSU) Iso- Performance Studies

Horizontal (top, purple) and vertical tunes (bottom, differing colors) for varying fringe field falloff speeds. While the lower curves are broadly similar to each other, they are noticeably offset relative to each other, leading to different resonances being crossed and thus a differing behavior of vertical dynamics.

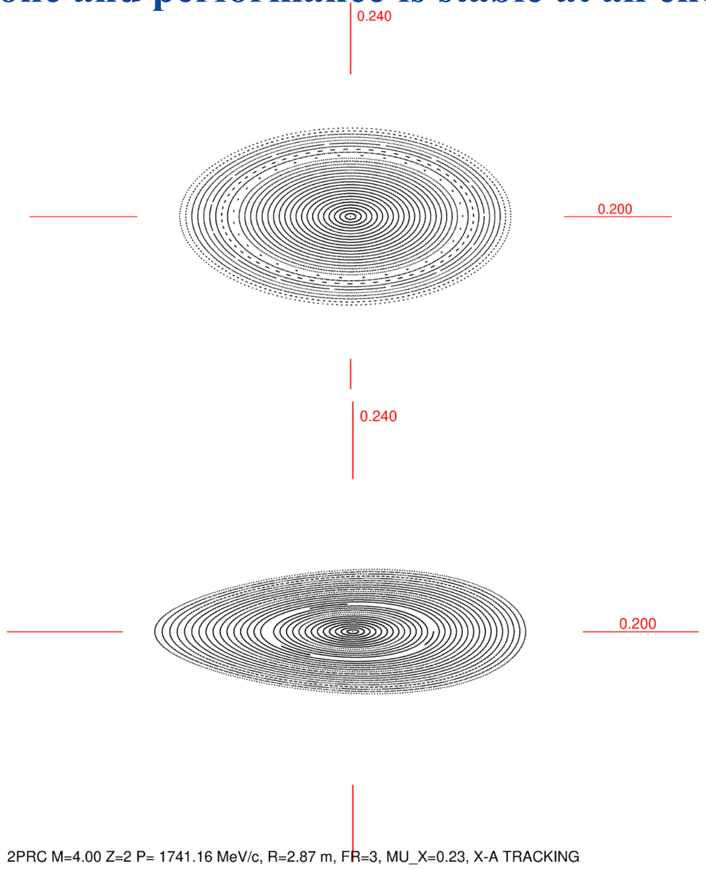
Isochronicity of the layout as a function of radius. . The total time of flight (TOF) needs to be kept relatively constant as this limits the acceptable longitudinal acceptance of the cavities, which especially for high-harmonic operation needs to be carefully understood. This figure does not depend markedly on whether fringe fields are used or not, and so only the figure with soft edge fringe fields is shown.

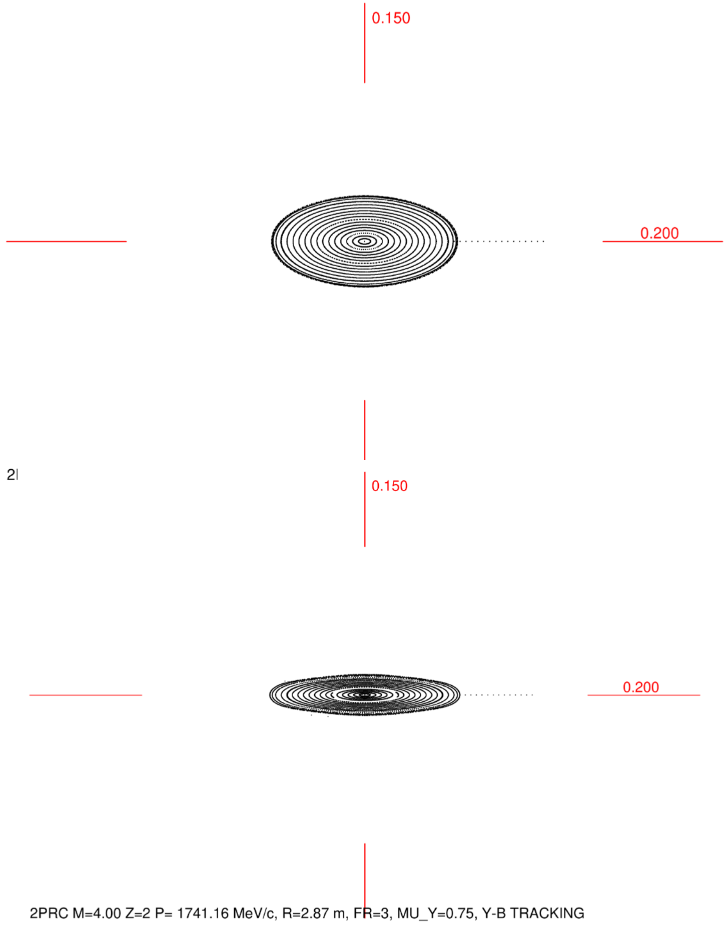




HE Cyclotron– COSY (MSU) Iso- Performance Studies

Horizontal (left) and vertical (right) tracking of the innermost (upper) and outermost (lower) reference orbit radii. The largest stable vertical rays are limited by nonlinearities arising in the fringe fields, which shows the importance of their detailed modelling. A more extensive set of tracking pictures for ten radii across the full tune space has been done and performance is stable at all energies

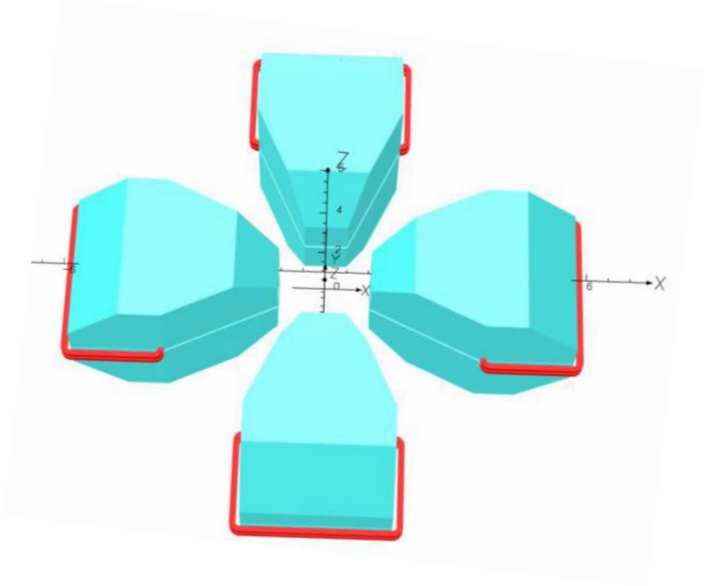


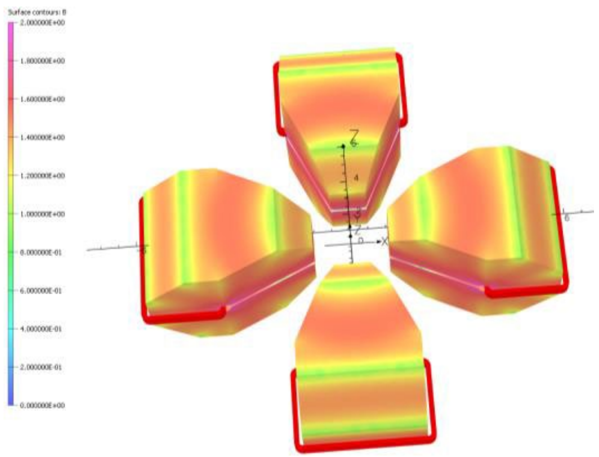


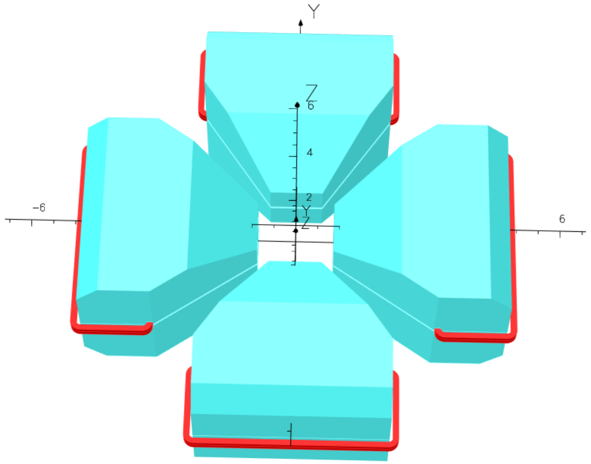
HE Cyclotron – Coil and Magnet Design

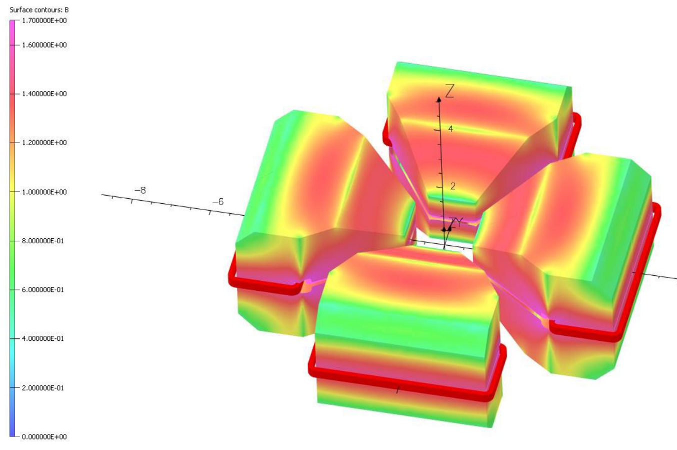
The magnet has a 60 mm gap and to obtain the specified field the total current in the coil should be 50 kA. However, the parts of the iron core saturated to the field above 2 T for the 1.7 peak field version (left pictures).

Reducing the peak field in the gap to 1.35 T reduced the saturation to <1.7T and reduced the outer radius of the yoke (right pictures).

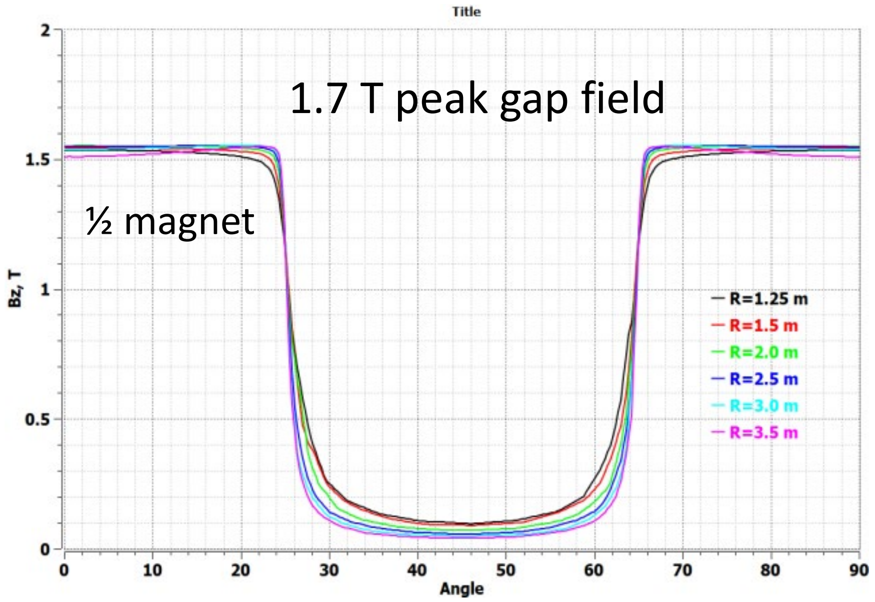


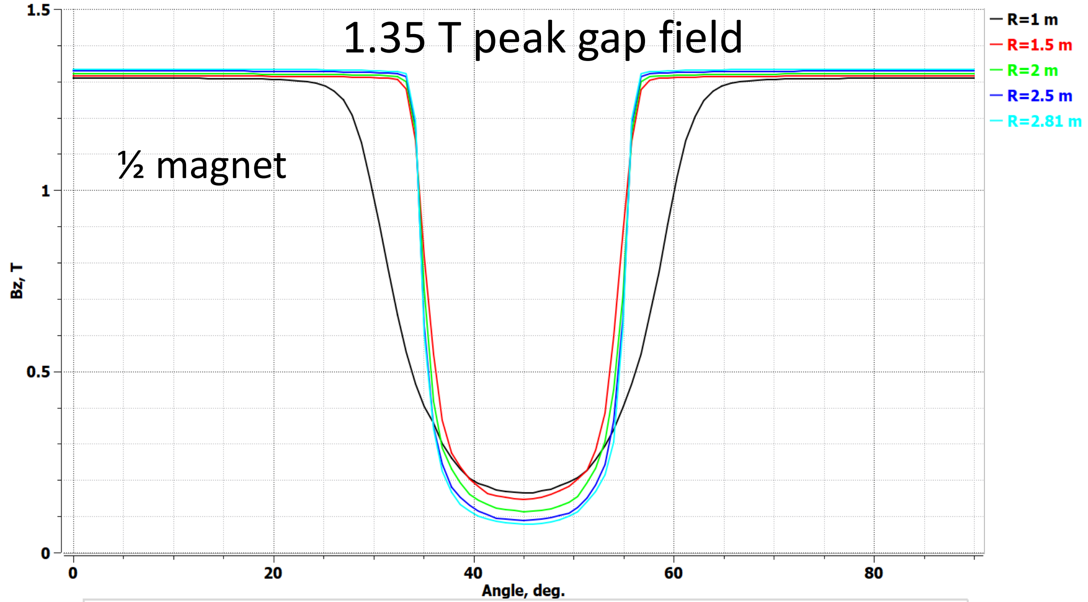


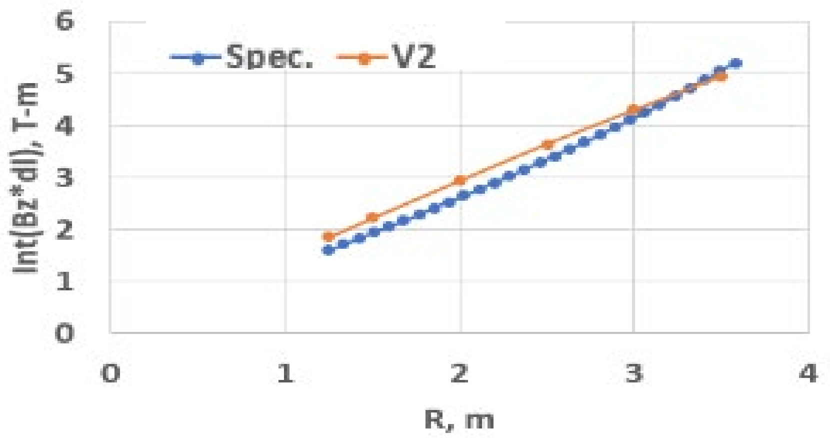


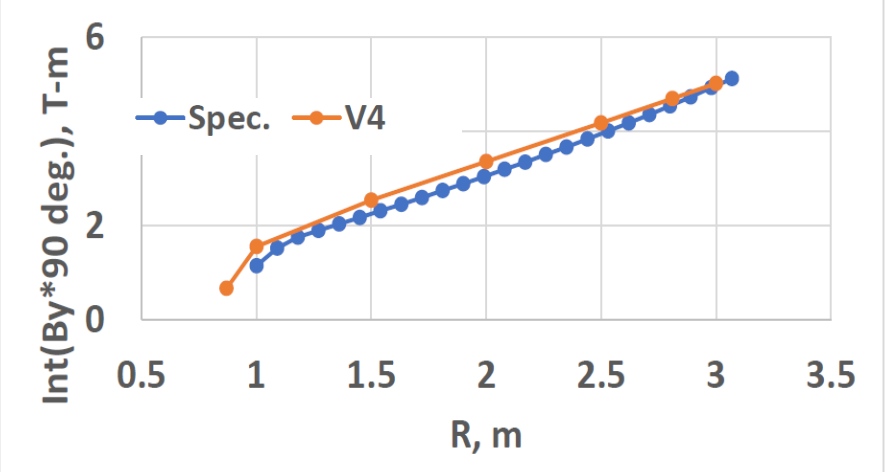


HE Cyclotron – low energy radiotherapy



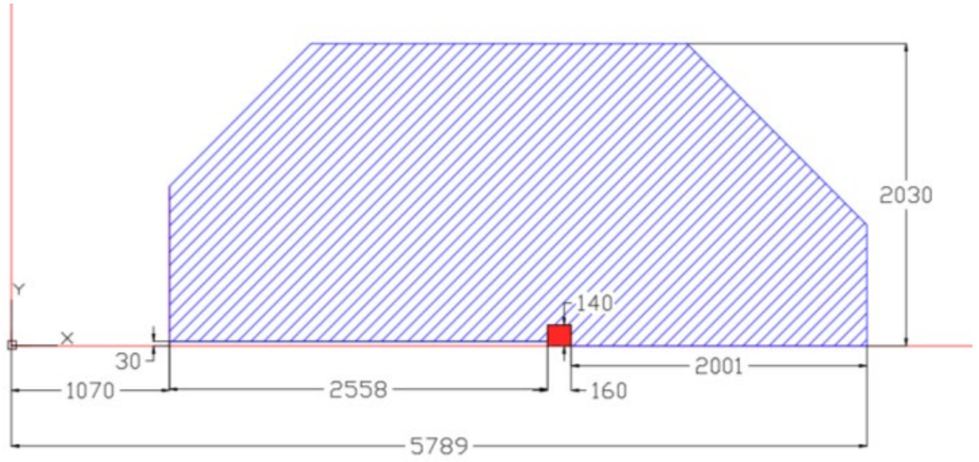


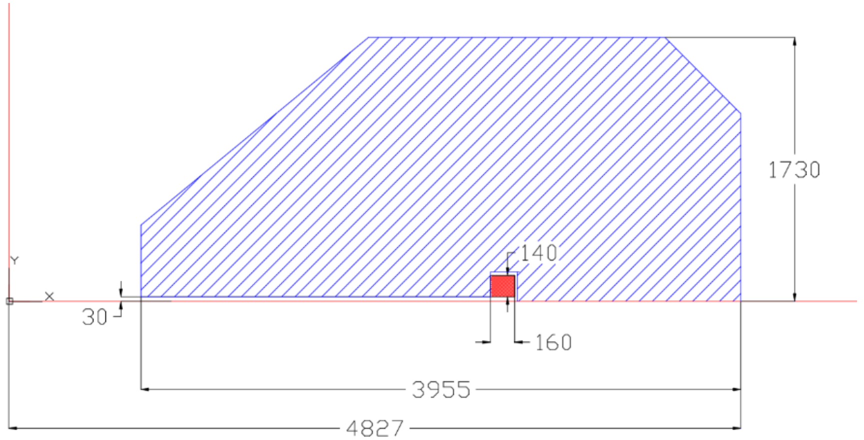




HE Cyclotron – upper pole cross section

1.7 T peak gap field

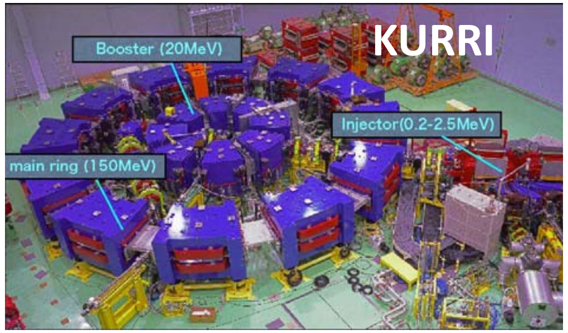




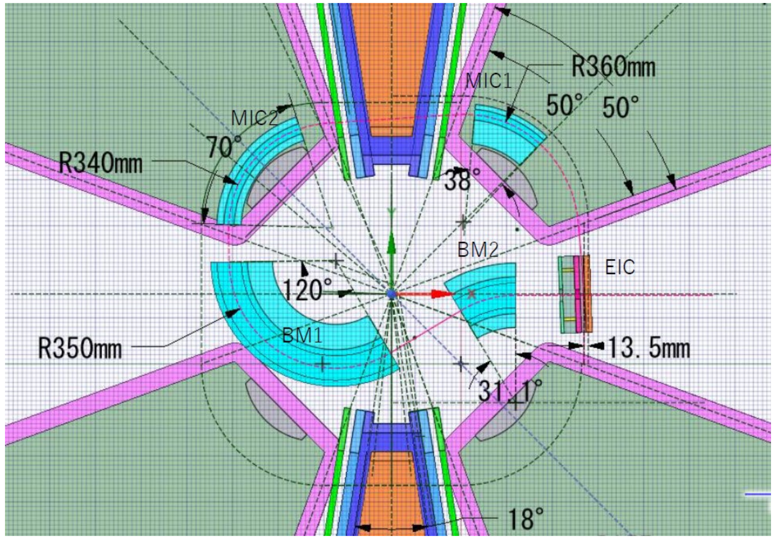
1.35 T peak gap field

Staging iso-Cyclotrons vs single 100 MeV/n

- **Staging develops compact accelerator systems through lower energy range.**
  - Isochronous orbits (CW) requires radius to scale with velocity
  - Cost significantly reduced for smaller magnets (~aperture or ΔR) – field tolerances relaxed
  - High vacuum, lower losses, reduced maintenance costs
- **Cyclotrons with identical RF frequency can be “cogged” in time**
  - RF controls simplified and identical for both cyclotrons



Potentially nest rings



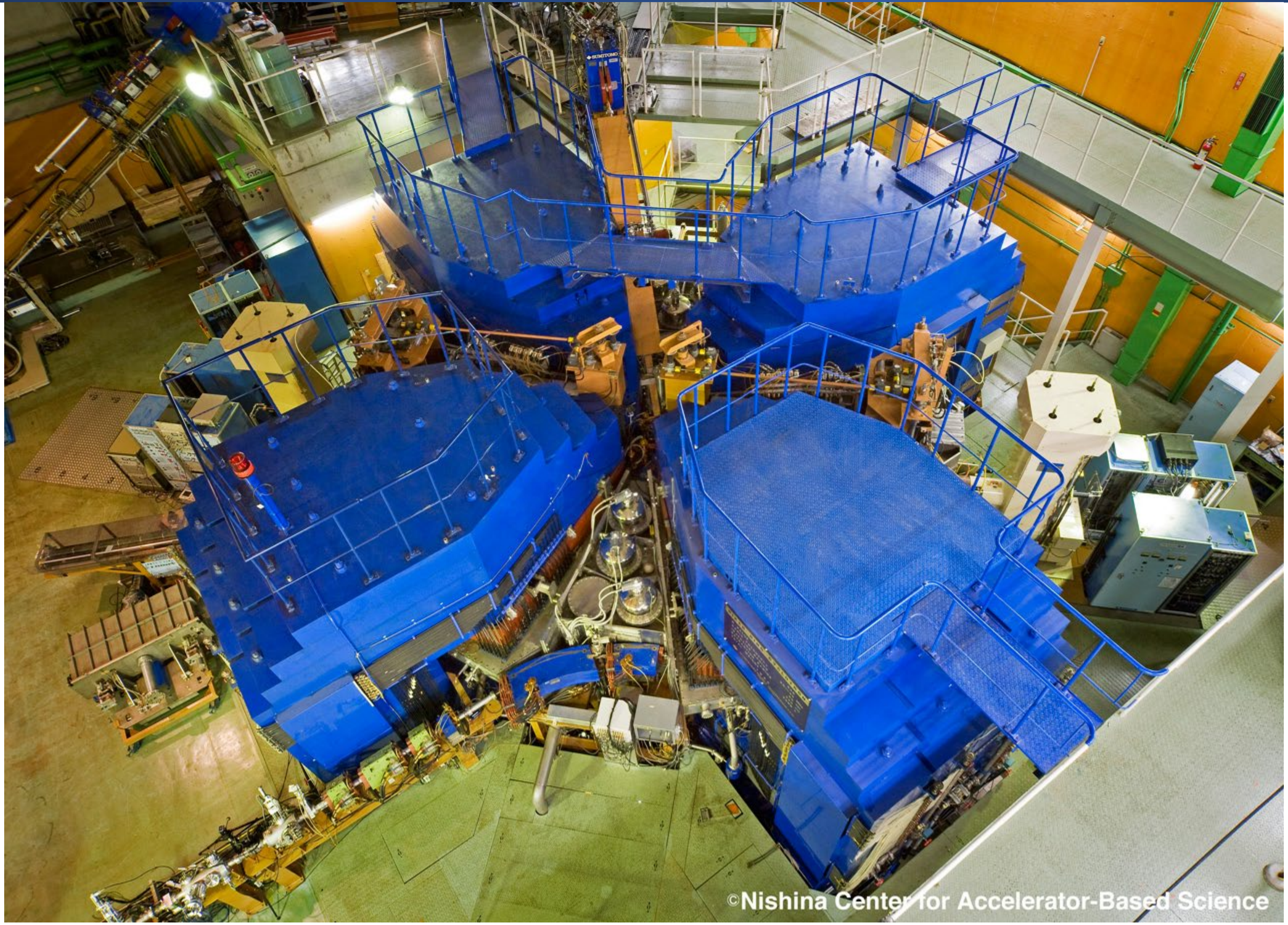
Example of a central region for low-loss horz axial injection for ions

Energy/nucleon Range	Velocity (c)	Orbit radius factor	Aperture 0.34 m injection radius (m)
4 – 24 MeV/n	0.09 - 0.22	2.4	~0.5 m
24 – 100 MeV/n	0.22 - 0.43	1.9	~0.7 m
4 – 100 MeV/n	0.09 - 0.43	4.65	~1.2 m

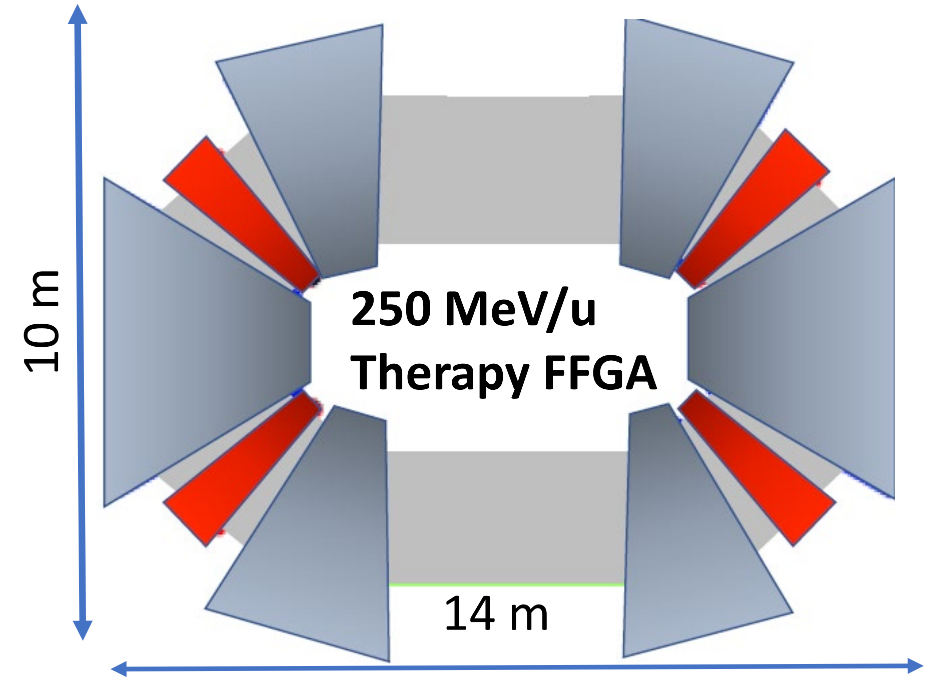
Aperture based on a 0.34 m injection radius LE Cyclotron

RIKEN – ~4-100 MeV/n normal conducting cyclotron

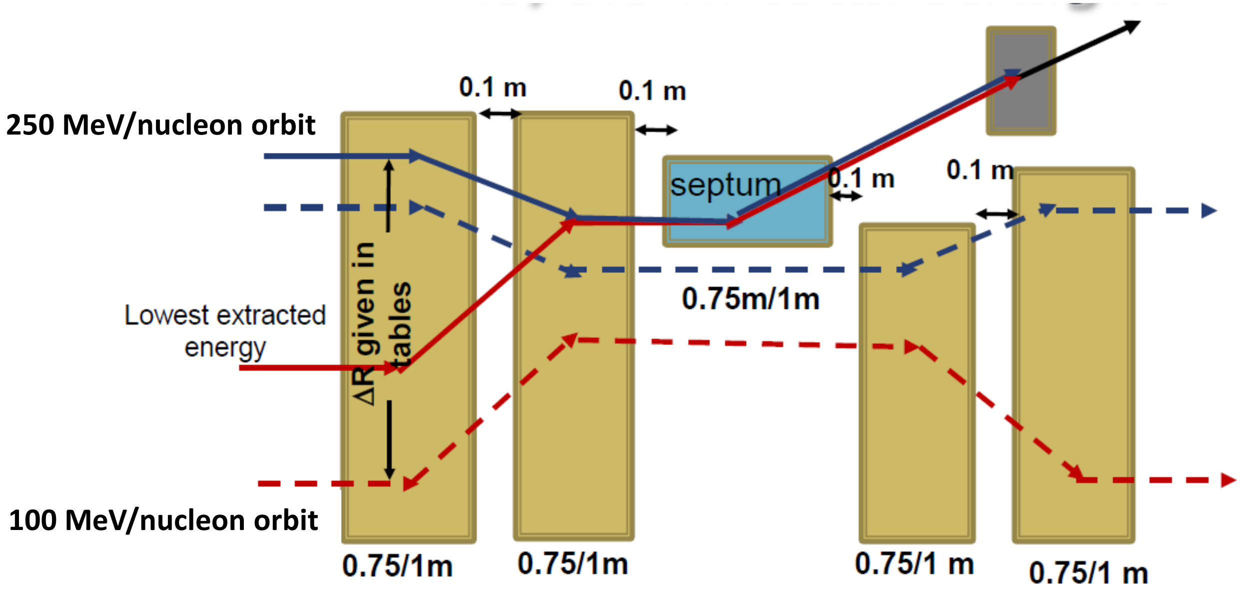
A single unit cyclotron becomes massive with significant operational overhead versus the modular approach proposed.



The 100-250 MeV/nucleon Therapy System



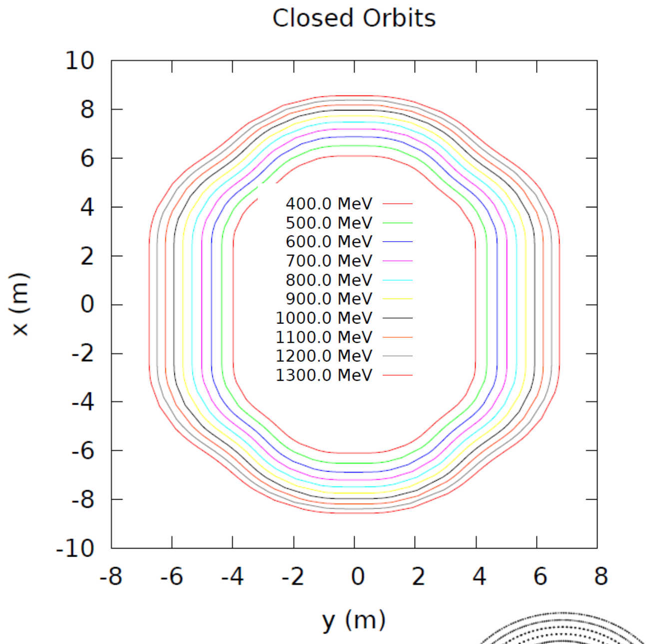
Normal Conducting Therapy FFGA: Footprint of fixed-field alternating gradient, variable energy therapy accelerator. Continuous CW beam, FLASH capable. Superconducting footprint ~half.

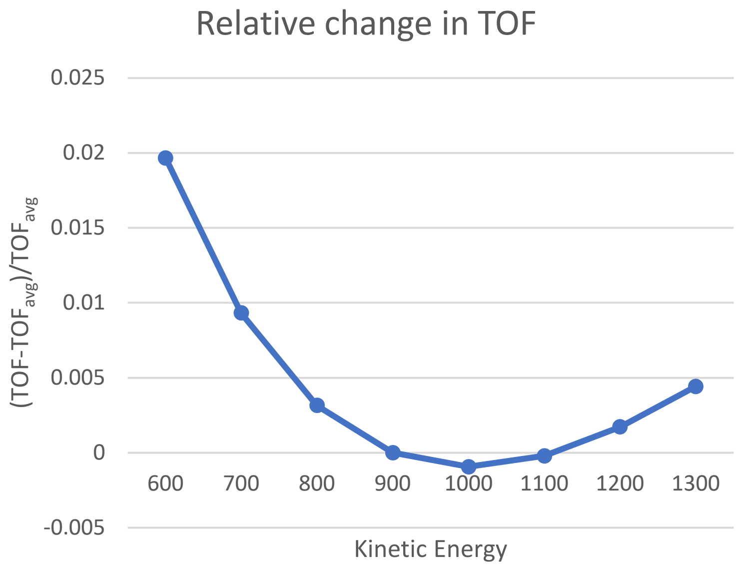


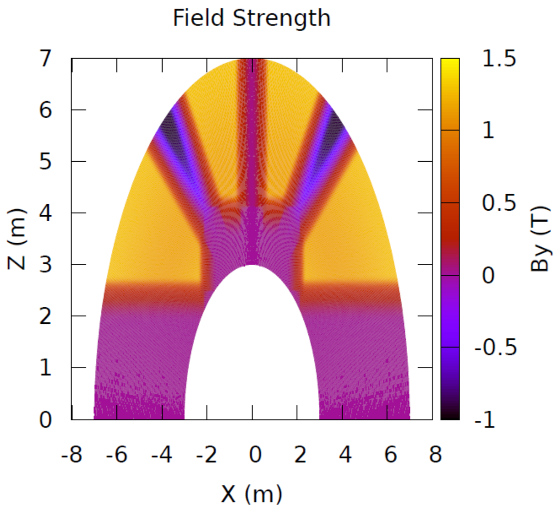
Variable Energy extraction: Layout of a ramped, bipolar magnet system that selects the orbit & energy for extraction through a septum. Inner, lower-energy orbits are returned to their respective closed orbits for continued acceleration.

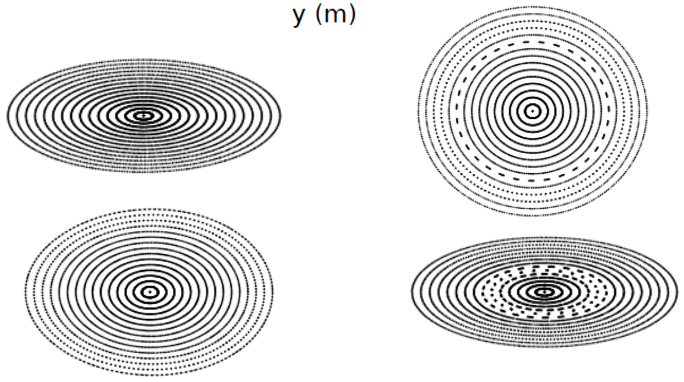
Therapy FFGA – Phase Space Tracking and TOF

- Full fringe fields
- High order simulations
- Large DA





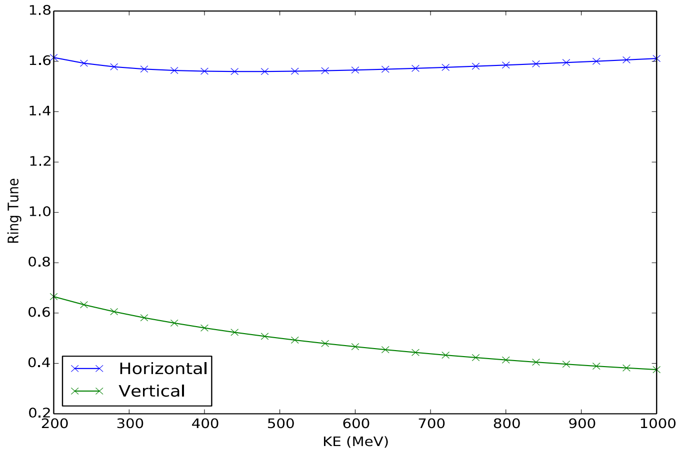


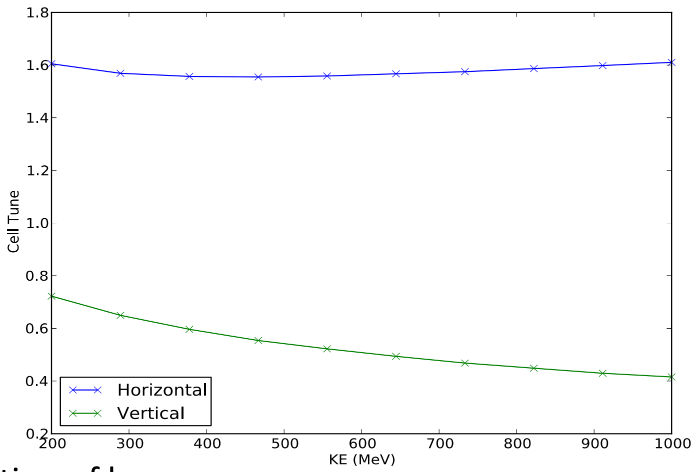


Phase space tracking (500 turns) 100 MeV/μ (top) 330 MeV/ μ in 1mm steps - >±1.5 cm (horz, left, vert, right)

TOF <±1% - typical starting value for cyclotron design – field can be "adjusted" for <10^{-6} tolerance. In practice poles are tracked and shimmed

Therapy FFGA – Machine Tune and DA





Machine tunes for the 2m ring (left) and the mini-racetrack FFAGs (right) as a function of beam energy..

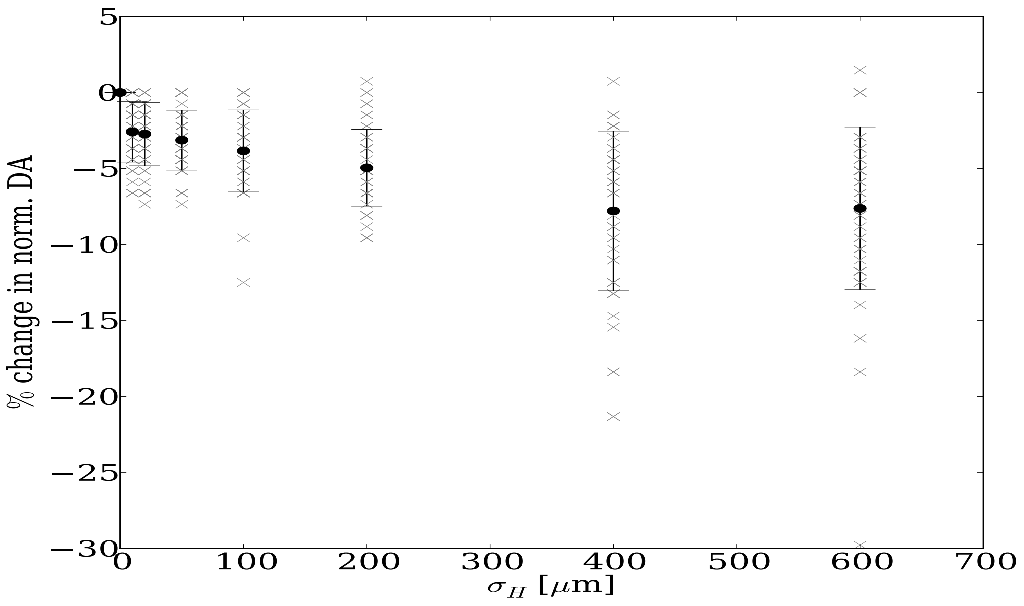
Dynamic aperture	Horizontal π.mm.mrad	Vertical π.mm.mrad
200 MeV 40 turns	74700	107
200 MeV 200 turns	72600	91
800 MeV 40 turns	156300	364
800 MeV 200 turns	155100	356

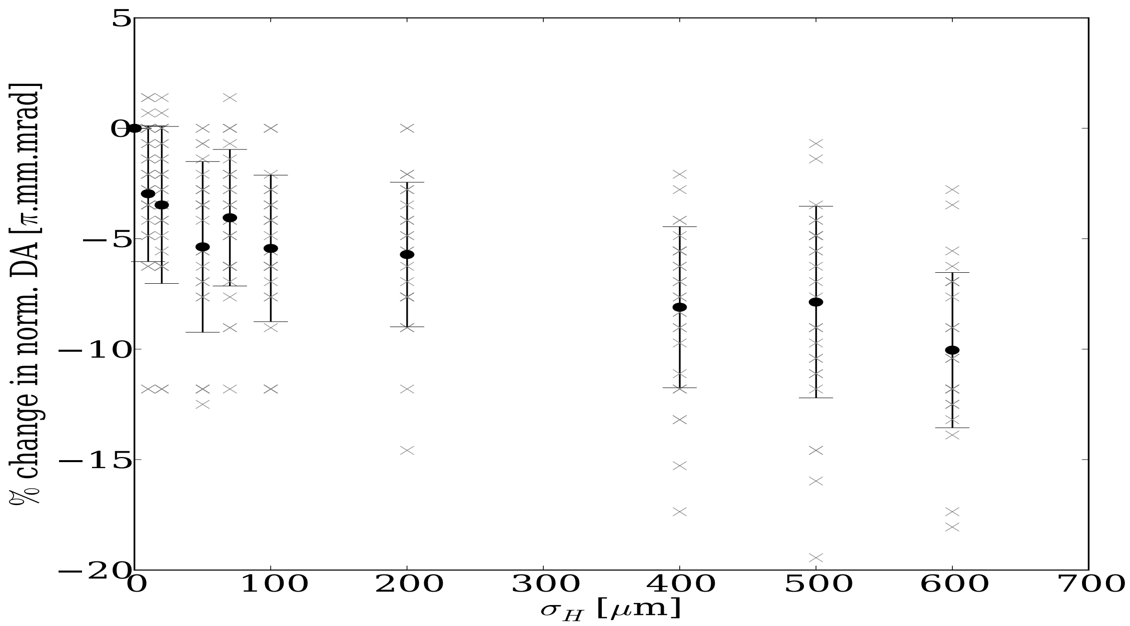
Dynamic aperture	Horizontal π.mm.mrad	Vertical π.mm.mrad
200 MeV 40 turns	25000	46
200 MeV 200 turns	23700	43
800 MeV 40 turns	63000	277
800 MeV 200 turns	63000	223

Unnormalized DA for circular (left) and racetrack (right) computed with PyZoubi – R. Appleby

Therapy FFGA – Alignment Error Study

- Stability to misalignments and errors – studied up to 600 microns





The relative drop in dynamic aperture as a function of misalignment for the circular 2m straights FFAG (left and the 4m straights racetrack (right) computed with PyZgoubi – R. Appleby

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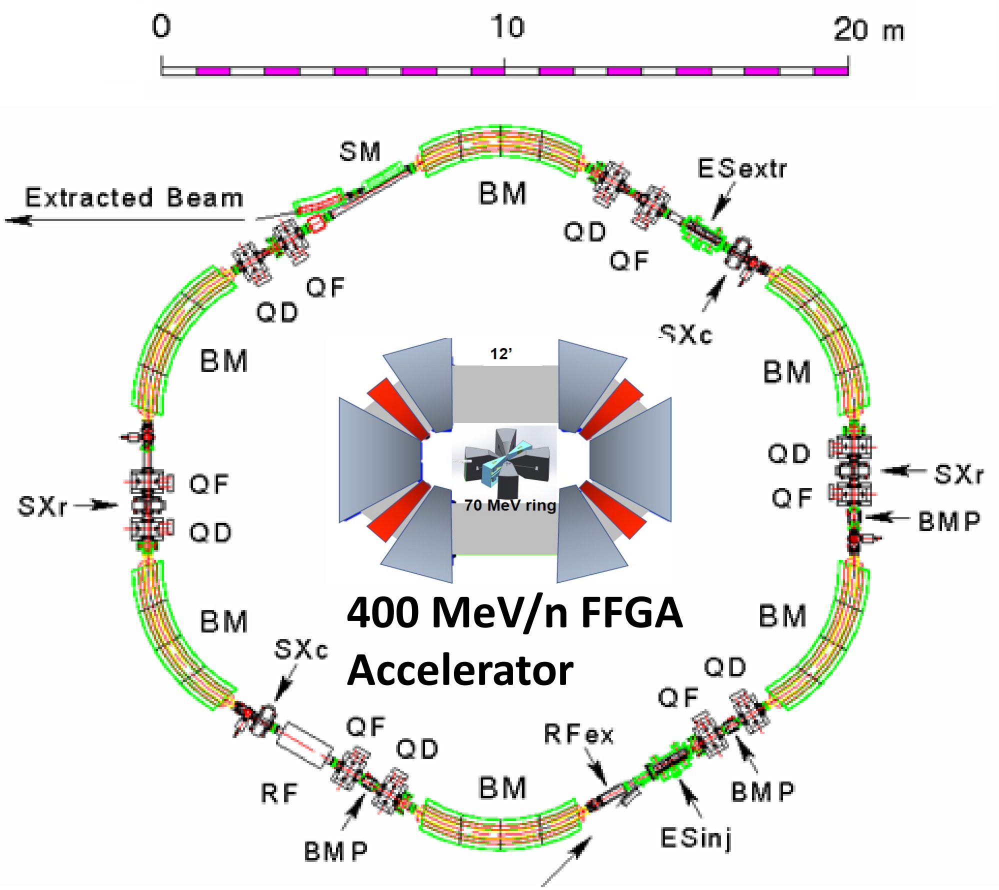
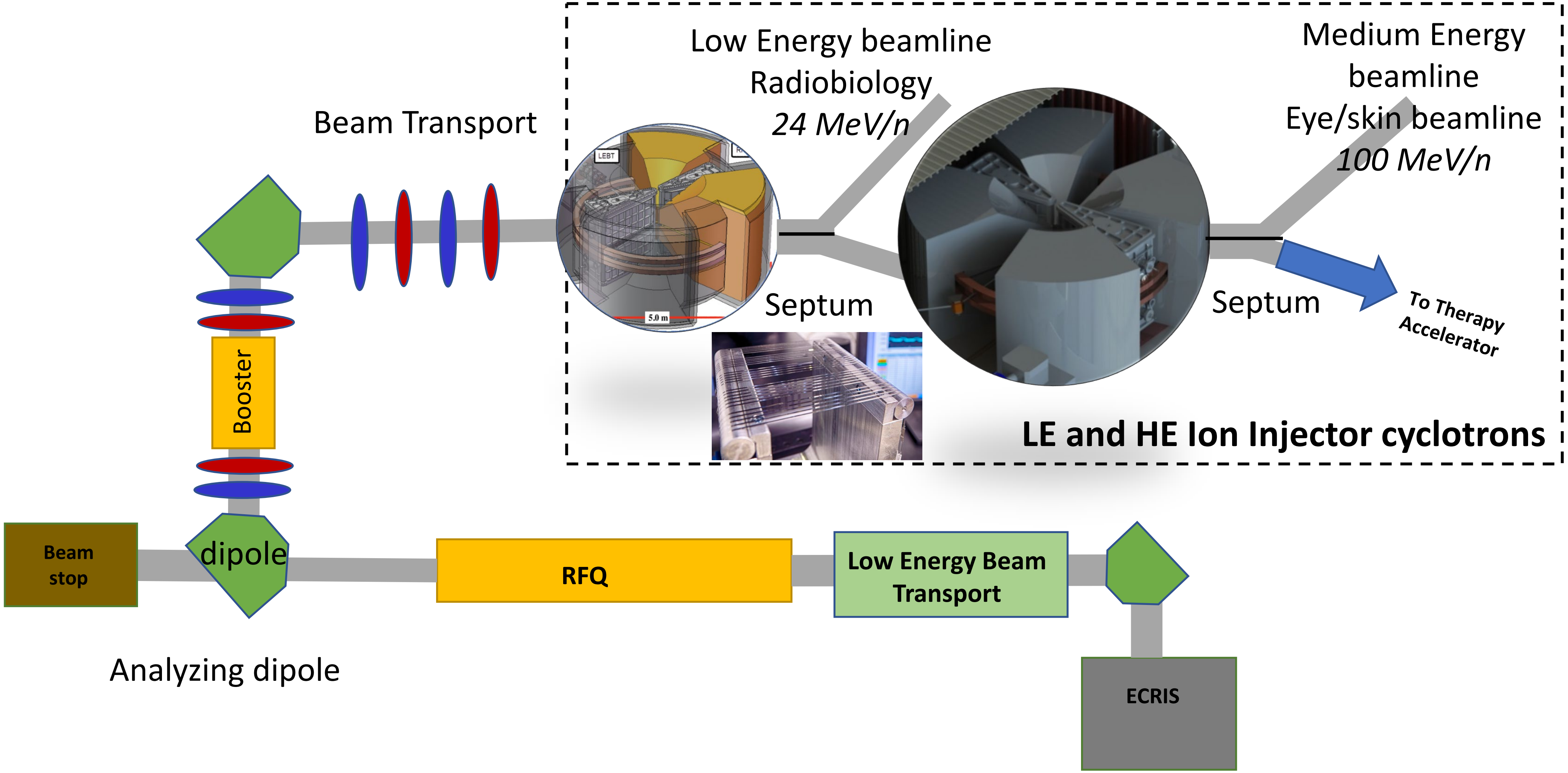
NEXT-generation FLASH-capable Compact Ion Therapy FFGA

- Footprint compared to synchrotron
  - Half the size, half the cost, more powerful
- Variable Energy – unlike cyclotron
  - Critical for ion R&D, especially FLASH
- Multi-ion beam capability
  - Real time imaging with therapy
  - Intense Ion beams for FLASH
- Concept developed at National & International Accelerator Labs
  - Turn-key operation
  - Does not require "national lab" level of staffing

Heidelberg Ion Therapy (HIT) synchrotron



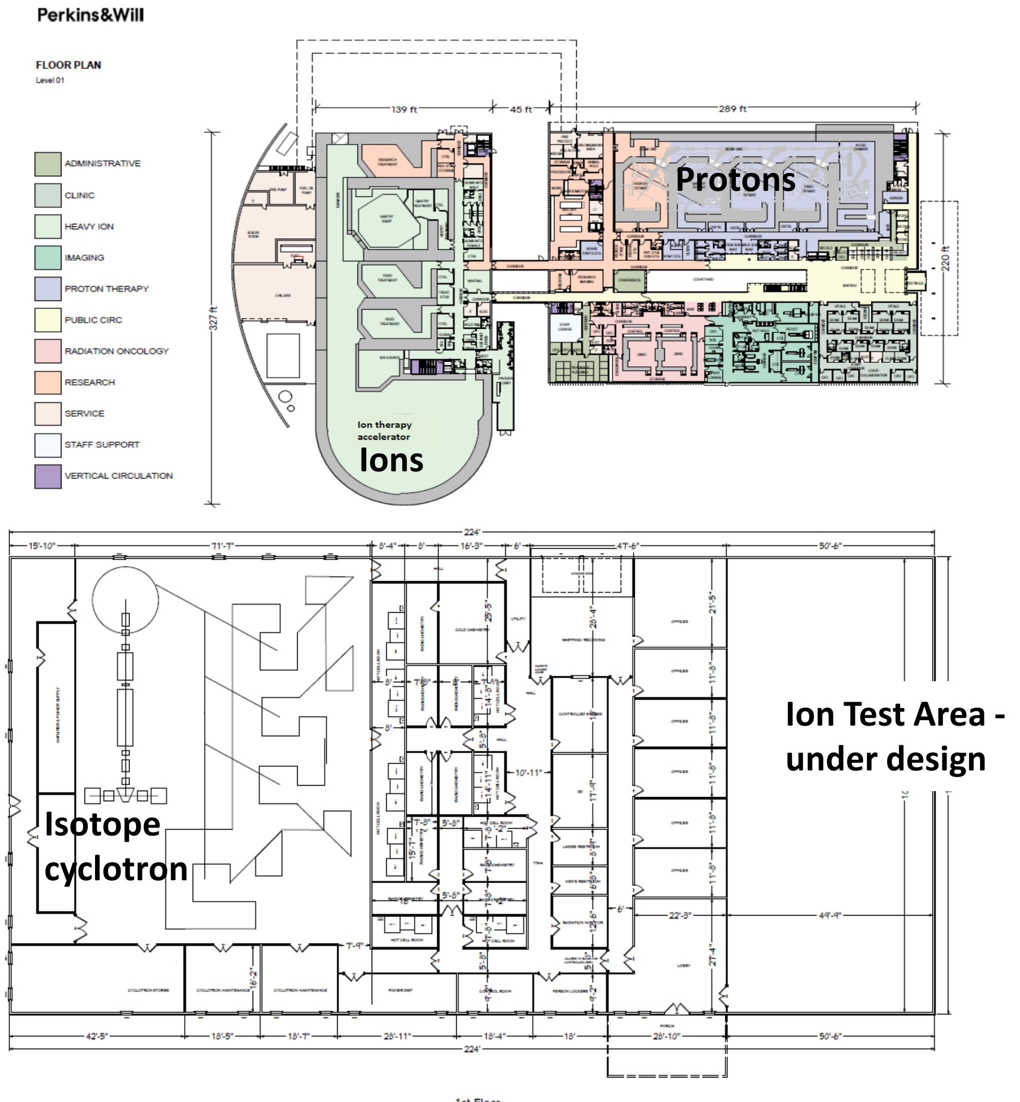
Layout of Pre-therapy Modules



Center for Particle Beam Research: Facility Layout

Isotope & Ion Test Facility

Therapy Facility



Master Ion Complex(left), Proton & Ion Therapy (top, right) and Isotope/Ion Test Facility (right)

Center for Particle Beam Therapy and Research

Center for Ion therapy and research
Chisholm, Landing, Waco, TX

- Site preparation and construction underway
- The center will incorporate state-of-the-art accelerator technologies
- Collaboration with internationally recognized accelerator entities: national laboratories, academic and industry have been established and clinical partners

Rendering of architectural plan drawings for Medical Office Building (top), Center for Particle Beam Therapy and Research

Summary of Staged Approach for Multi-Energy/CW Ion Beams – Multi-user facility

- **RFQ accelerates a specific charge to mass state from multi-ion source (ECR IS)**
  - Injection and ion(s) selection is performed prior to RFQ and/or injection into LE cyclotron stage
    - Chopping/matching/rebunching required to match cyclotron RF
  - *Extraction line for ultra-low energy ions – 0.2-0.4 MeV/n is supported (**cell radiobiology**)*
  - Contaminant control to LE cyclotron
- **LE Cyclotron Stage**
  - Beam automatically matched to HE stage
  - *Extraction line for low energy ions: 24 MeV/n (**Radiobiology including FLASH**)*
    - Multi-species ion beams including heavier ions possible from this stage
- **HE Cyclotron Stage**
  - *Extraction line for medium energy ions: 100 MeV/n (Eye/skin treatment line)*
- **Therapy Stage**
  - *Variable energy extraction line for therapy energy ions: ~100-250 MeV/n*
    - *30 cm depth for He, 11 cm for C*
- **Simultaneous Beam delivery and new technologies (Leo Chair)**
  - Separate beamlines: multi-user, multi-energy support capability (septum beam splitter)
  - Turn-key –
    - different ion species can be delivered without retuning the accelerator chain

Concluding Remarks

1. Each stage (4) provides standalone clinical and research ion beams without reconfiguration
    1. Cell radiobiology (0.4 MeV/nucleon)
    2. Ion radiobiology (FLASH and conventional dose beams, 24 MeV/nucleon)
    3. Skin and Eye therapy lines and research (FLASH and conventional dose beams, 100 MeV/nucleon)
    4. Heavy Multi-ion therapy (including FLASH intensities & variable energy up to 250 MeV/nucleon)
        - ❖ *Translates into full 30 cm penetration for helium and 11 cm for carbon*
2. Supports unprecedented broad Medical and Research User Community
    - ➢ Centrally located in a medical and research epicenter
        - ❖ *MDAnderson, Baylor, Scott & White, Aerospace industries, top medical and research universities . . .*
3. Strategic high energy heavy ions for DOD/DARPA/Aerospace Industries
    - ➢ Significantly higher energies than existing CW heavy ion cyclotron facilities
        - ❖ *Lawrence Berkeley , Crocker Nuclear and Texas A&M cyclotron facilities*

This facility is critical to reinstate the US in a leadership role in cancer and strategic ion research

THANK YOU