Fixed Field Alternating Gradient for Muti-turn Superconducting ERL and Medical Applications

An introduction the Fixed Field Alternating (FFA) Gradient accelerators will be provided with pros and cons for accelerating particle beams. A design, installation, and commissioning of the 'CBETA' (**C**ornell University **B**rookhaven National Laboratory **E**RL **T**est **A**ccelerator) is shown. A new and an existing FFA approach for the FLASH proton cancer therapy accelerator and the proton delivery gantry with permanent magnets will be presented. A single beam line ERL LHeC lattice for the future Electron Ion Collider at LHC is shown.

Fixed Field Alternating Gradient for Muti-turn Superconducting ERL and Medical Applications

1. *Brief history of accelerators*
2. *Fixed Field Alternating (FFA) Gradient Accelerators*
3. *Non-Scaling FFA gradient accelerators*
4. *New FFA Superconducting Multiturn ERL – CBETA*
5. *FFA lattice for LHeC*
6. *Permanent and Superconducting Magnet FFA proton and carbon Gantry*
7. *Fast Cycling FFA proton Synchrotron*

BRIEF HISTORY OF ACCELERATORS

Leó Szilárd, Rolf Widerøe, Gustav Ising designed the first linear accelerator (1924)

Ernest Lawrence - 1930 cyclotron built at Berkeley – Nobel Prize in Physics

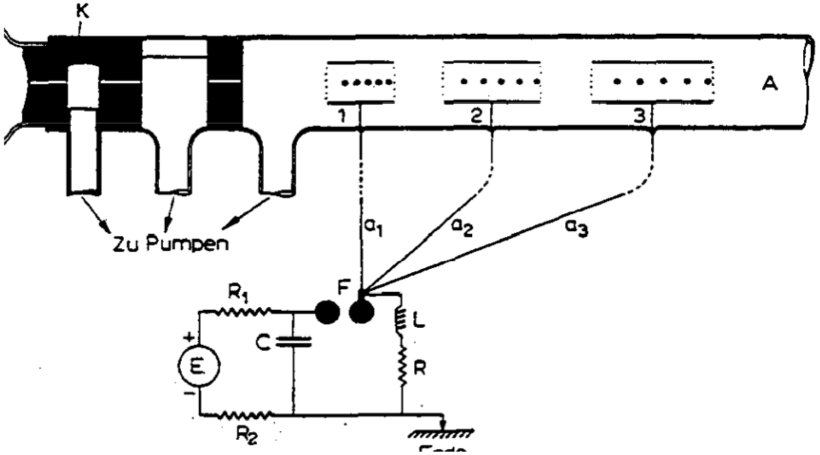
Kolomensky, Ohkawa, Symon and Kerst Fixed Field Alternating Gradient (~1950)

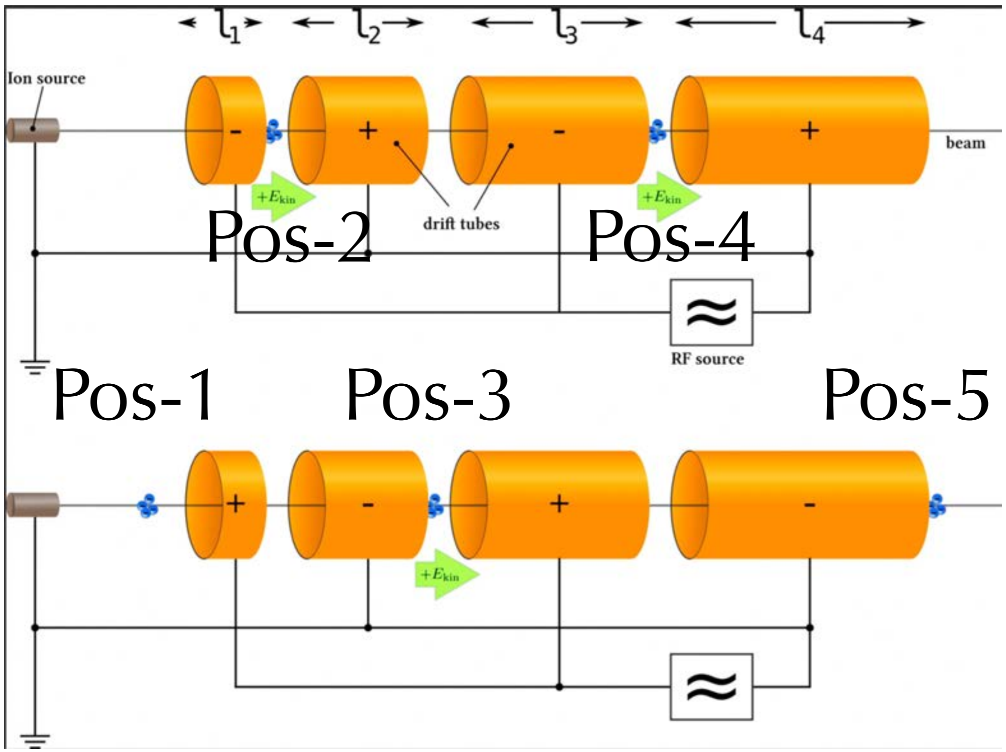
E. D. Courant, M. S. Livingston and H. S. Snyder, The strong-focusing alternating synchrotron (1952) at BNL

Linear Accelerator

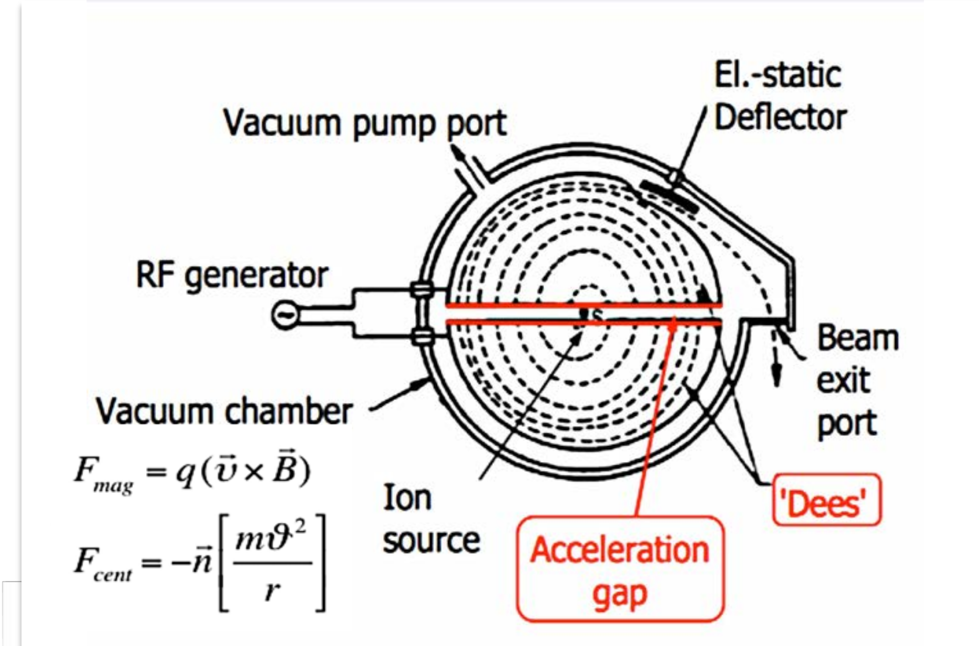
A linear particle accelerator (linac):
Increases the velocity of ions by subjecting them into a series of oscillating electric fields potentials along the beam line.

(invented by Leó Szilárd, patented by Rolf Widerøe 1928, idea fist published by Gustav Ising).

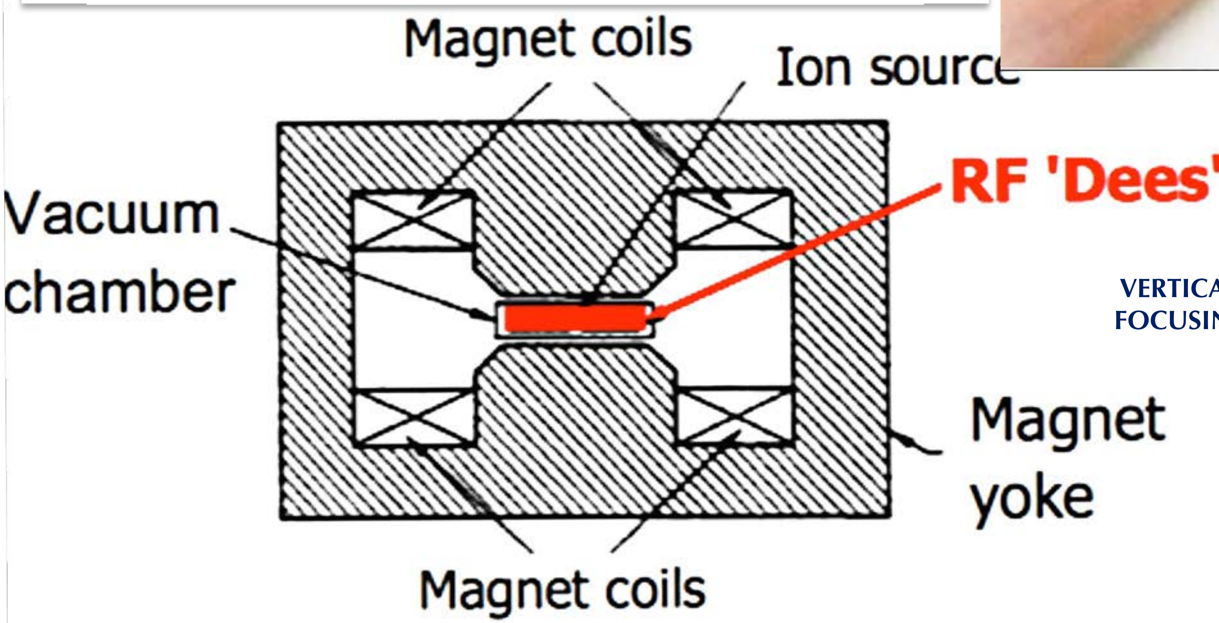




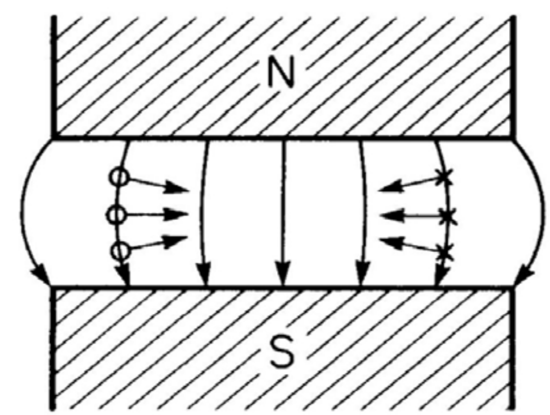
CIRCULAR ACCELERATORS:



Ernest Lawrence and his graduate student Stanley Livingston



VERTICAL FOCUSING

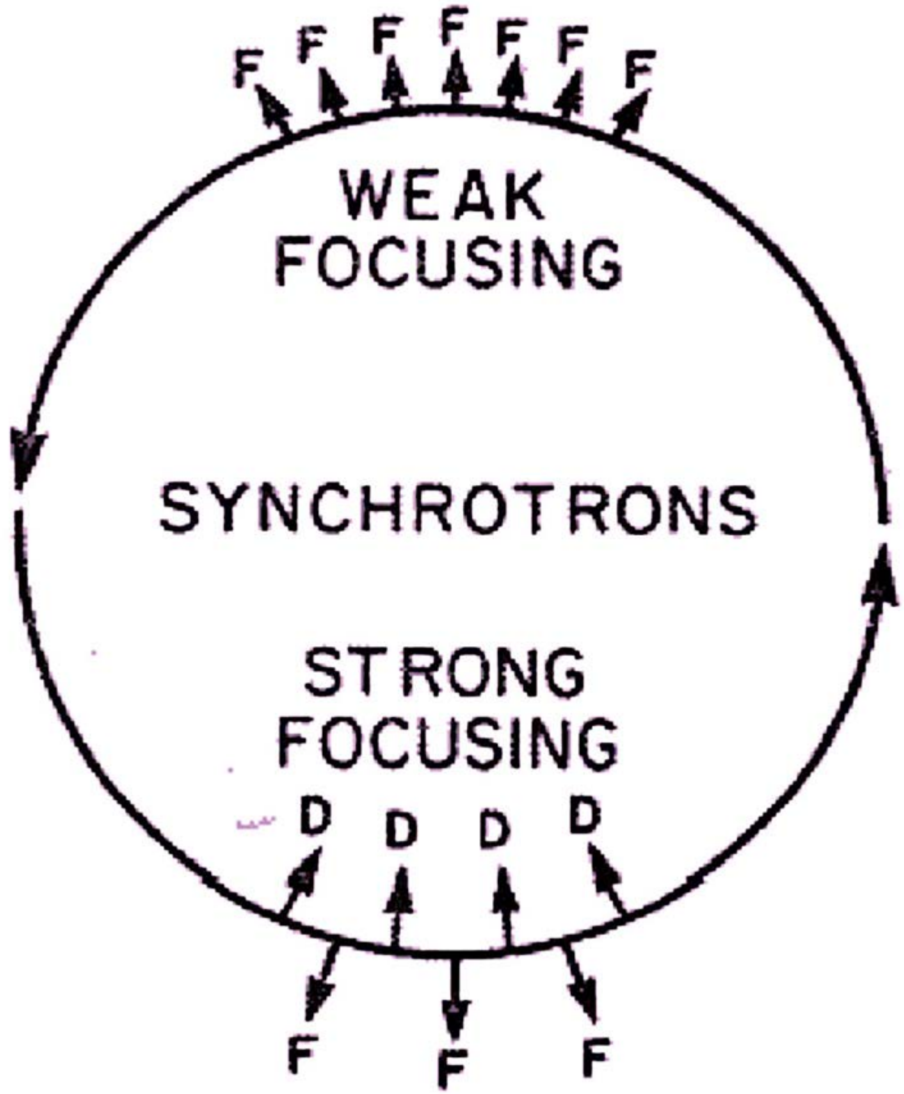


STRONG AND WEAK TRANSVERSE FOCUSING

To build a relativistic cyclotron, the field needs to grow proportional to γ, giving vertical defocusing, and compensate with focusing edges. This is an early form of “strong focusing”.

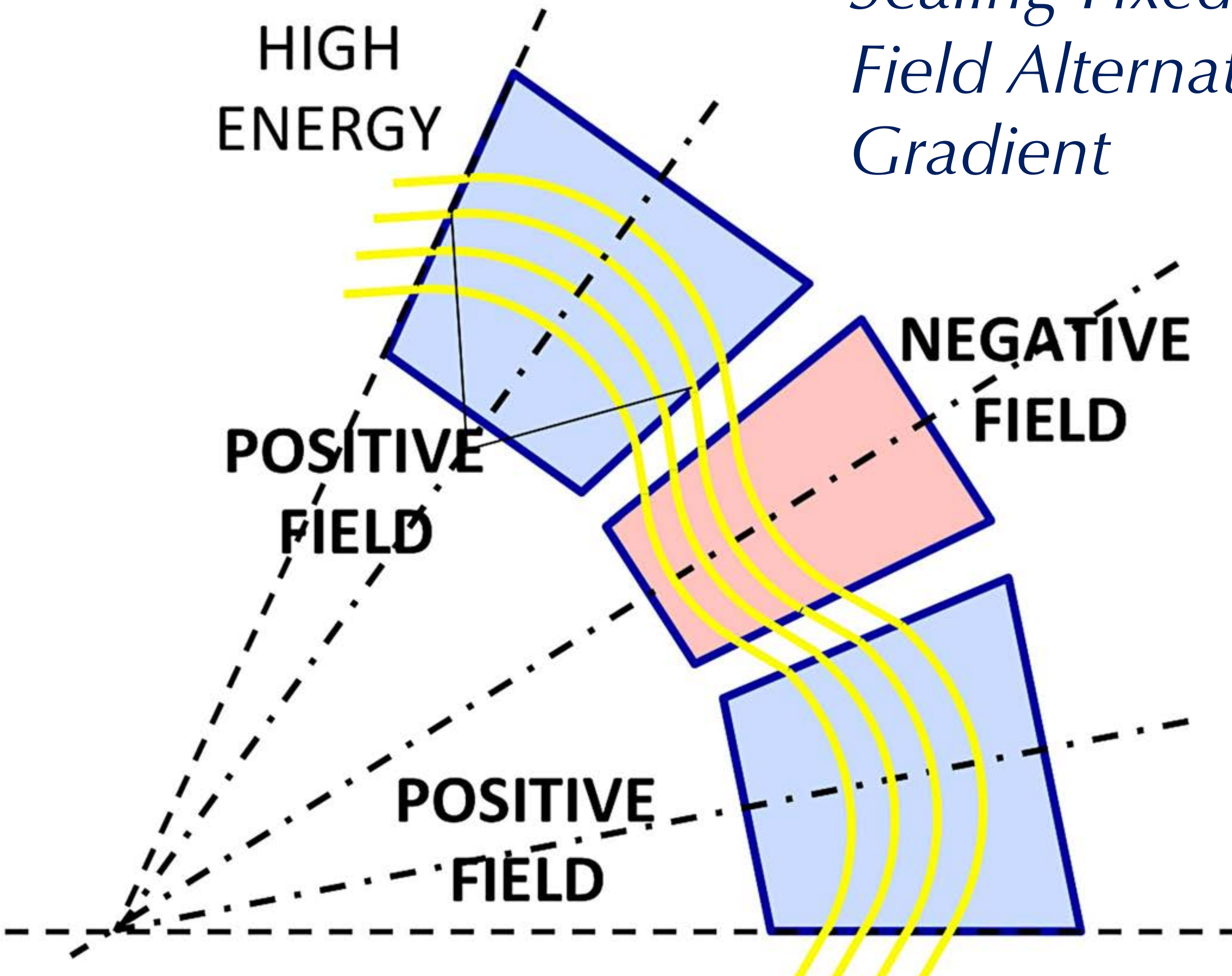
If the focusing was still insufficient the reverse bends are added. That’s how the Fixed-Field Alternating Gradient machine FFAG was invented.

CIRCULAR ACCELERATORS:



CIRCULAR ACCELERATORS:

Scaling-Fixed Field Alternating Gradient



CIRCULAR ACCELERATORS:

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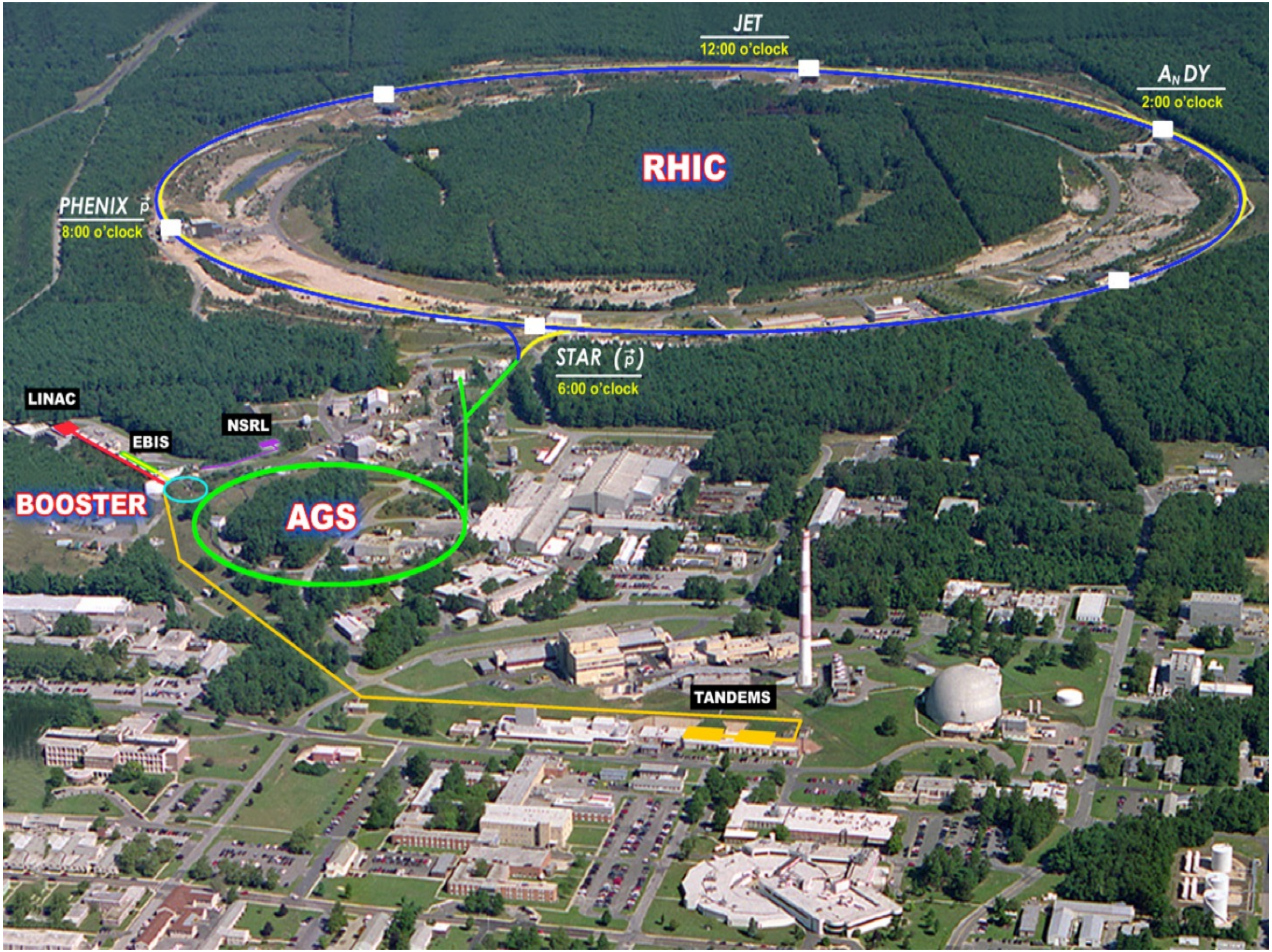

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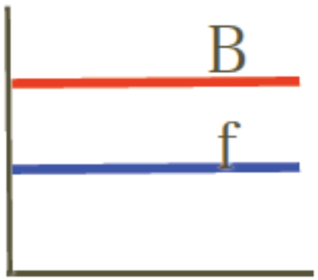
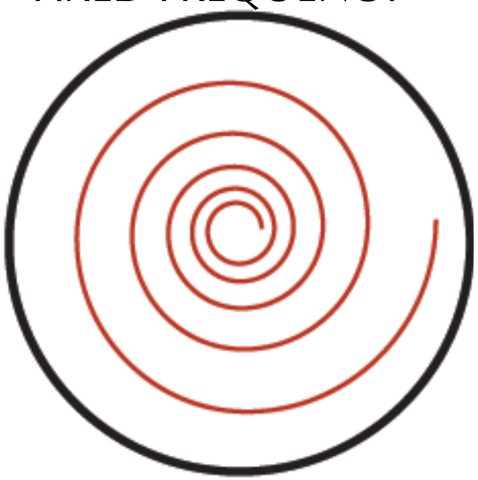


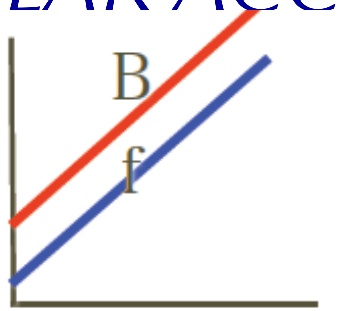
accelerating time

FIXED FIELD
FIXED FREQUENCY



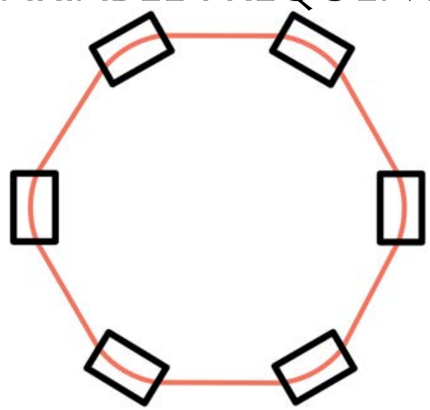
Cyclotron

*isochronous



accelerating time

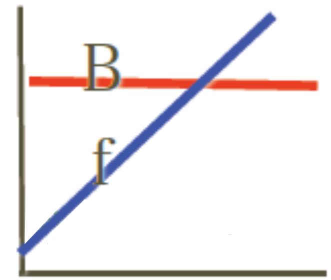
FIXED MAGNETIC FIELD
VARIABLE FREQUENCY



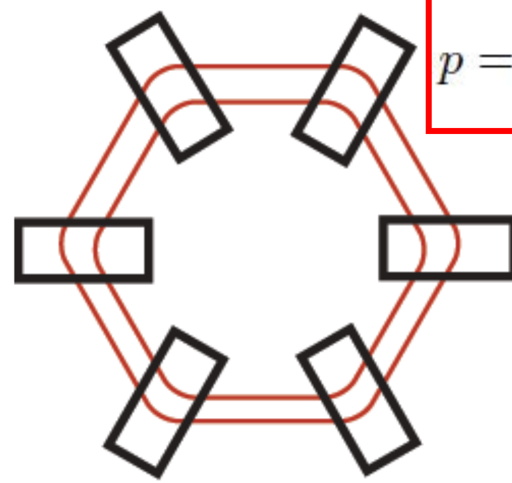
Synchrotron

*const. closed orbit

(varying mag. field)



accelerating time



$$p = p_o \left(\frac{r}{r_o}\right)^{k-1}$$

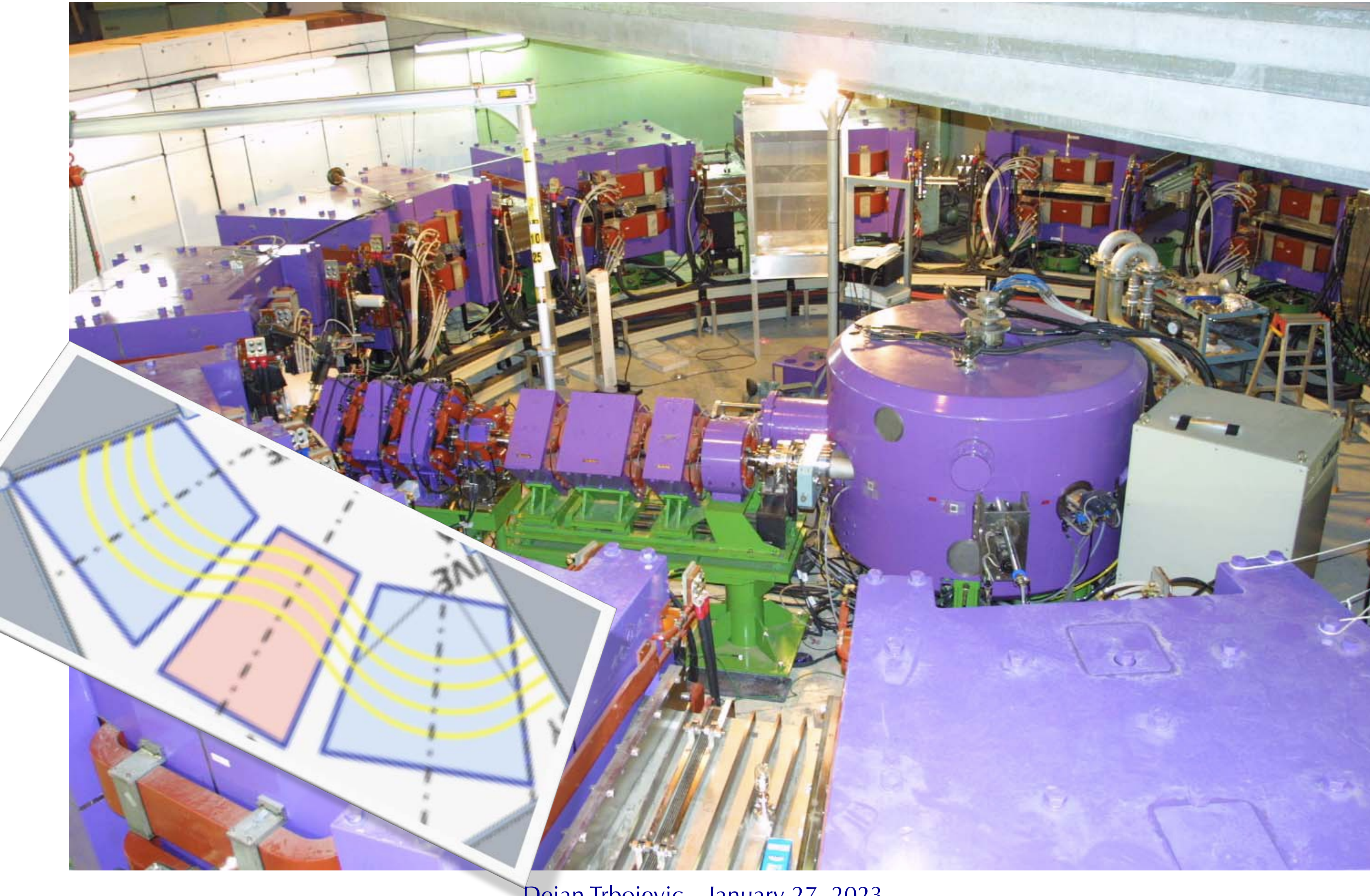
$$B_R = B_o \left(\frac{r}{r_o}\right)^{k} \mu(\Theta)$$

FFAG

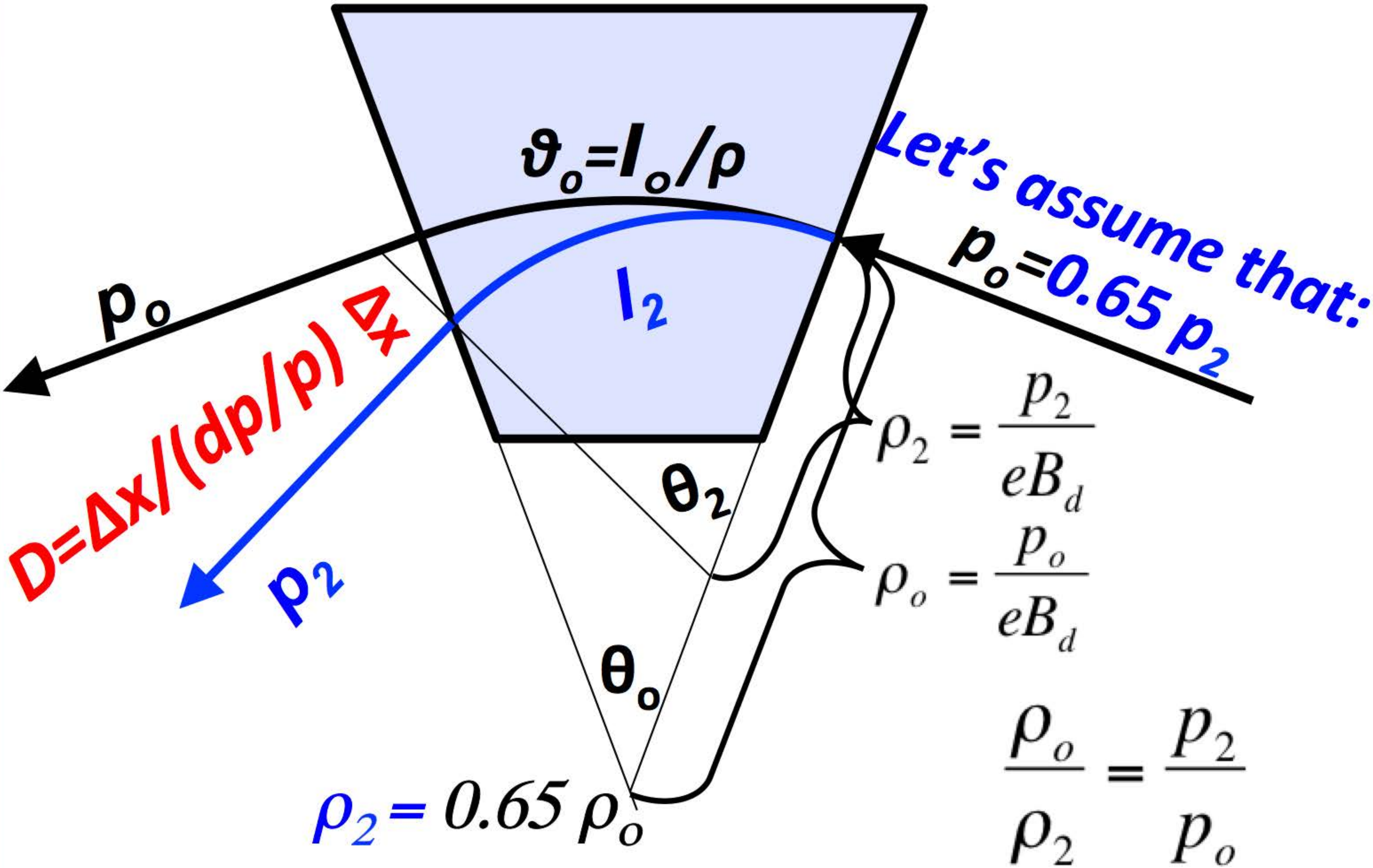
*varying closed orbit

(const. mag. field)

The KEK and KYOTO University 150 MeV Scaling FFA Gradient proton Accelerator



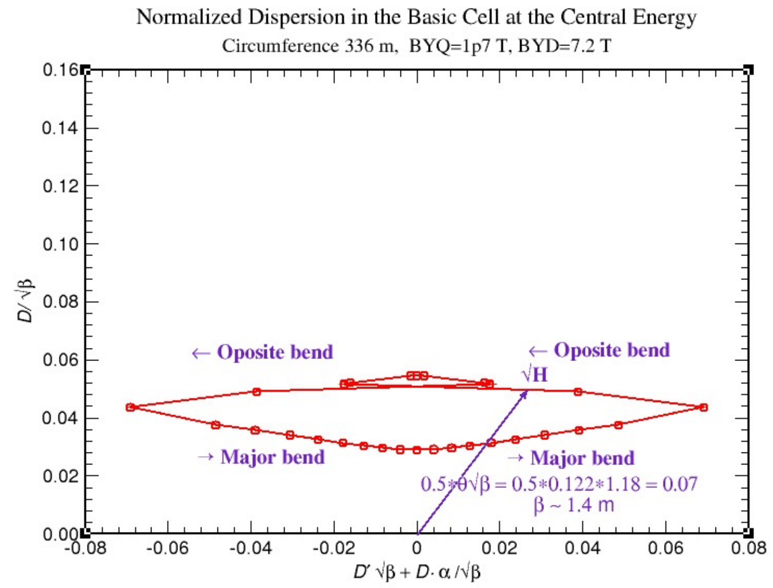
Dispersion Function vs. Momentum



Normalized Dispersion Space

$$\xi = \frac{D}{\sqrt{\beta}} \quad and \quad \chi = D'\sqrt{\beta} + \frac{\alpha D}{\sqrt{\beta}}$$

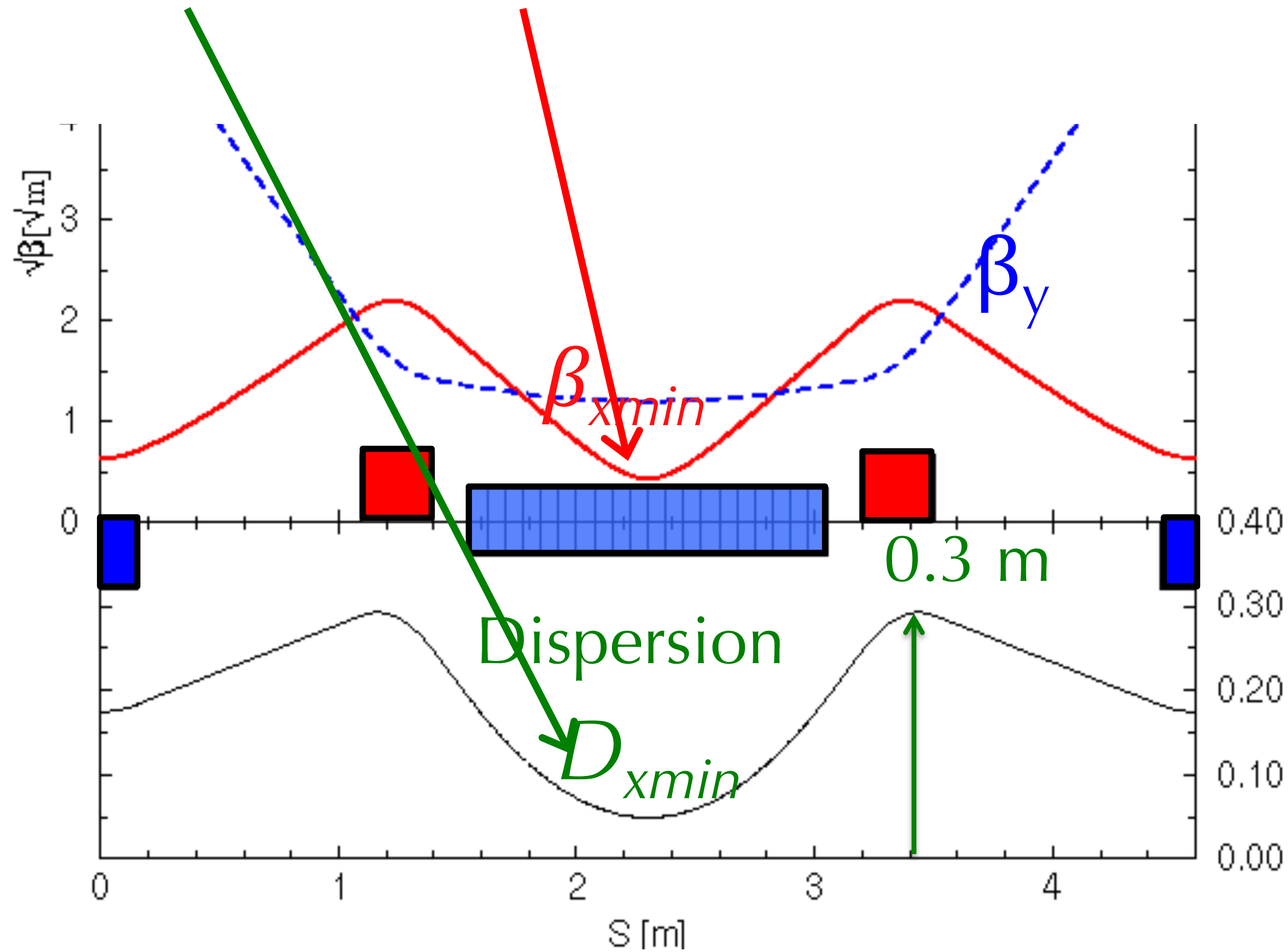
$$H(D,D') \equiv \left(\frac{D}{\sqrt{\beta}}\right)^2 + \left(D'\sqrt{\beta} + \frac{\alpha D}{\sqrt{\beta}}\right)^2 ,$$



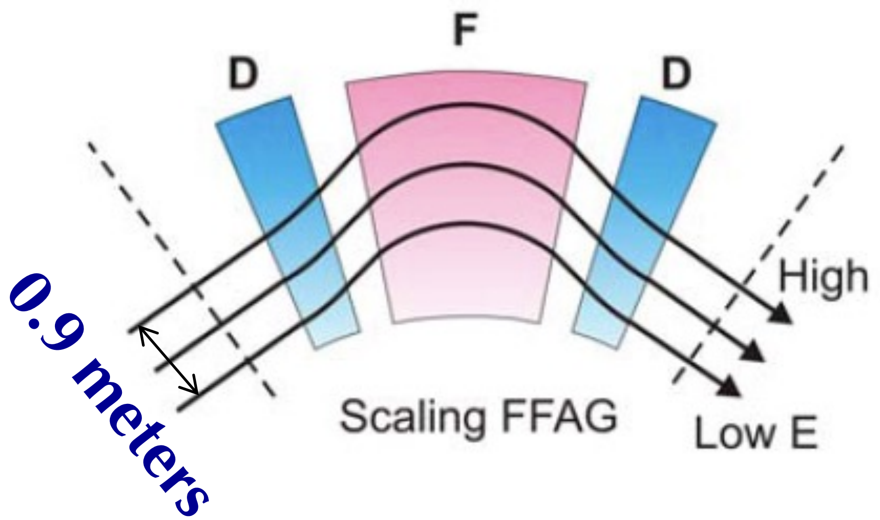
The amplitude value of ***'H'*** is determined within the bending element.
It is enough to minimize ***'H'*** within the dipole to obtain the minimum.
The average value of the ***'H'*** function is always proportional to the :
(ρθ) ^{3} and a merit factor ***F*** in minimization had been previously introduced as:

$$<H> \approx F\ \rho\theta^3 \qquad \frac{d}{dD_o}<H> = 0, \quad \frac{d}{dD_o'}<H> = 0\ , \frac{d}{d\beta_o}<H> = 0$$

To minimized the dispersion function $\mathcal{H}$ the BENDING MAGNET (DEFOCUSING) should be in the middle with minimum of D_{xmin} and β_{xmin} at the center

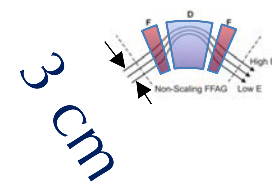


SCALING VS. NON-SCALING FFAG



Linear magnetic field:

$B = B_o + r\, G_o$

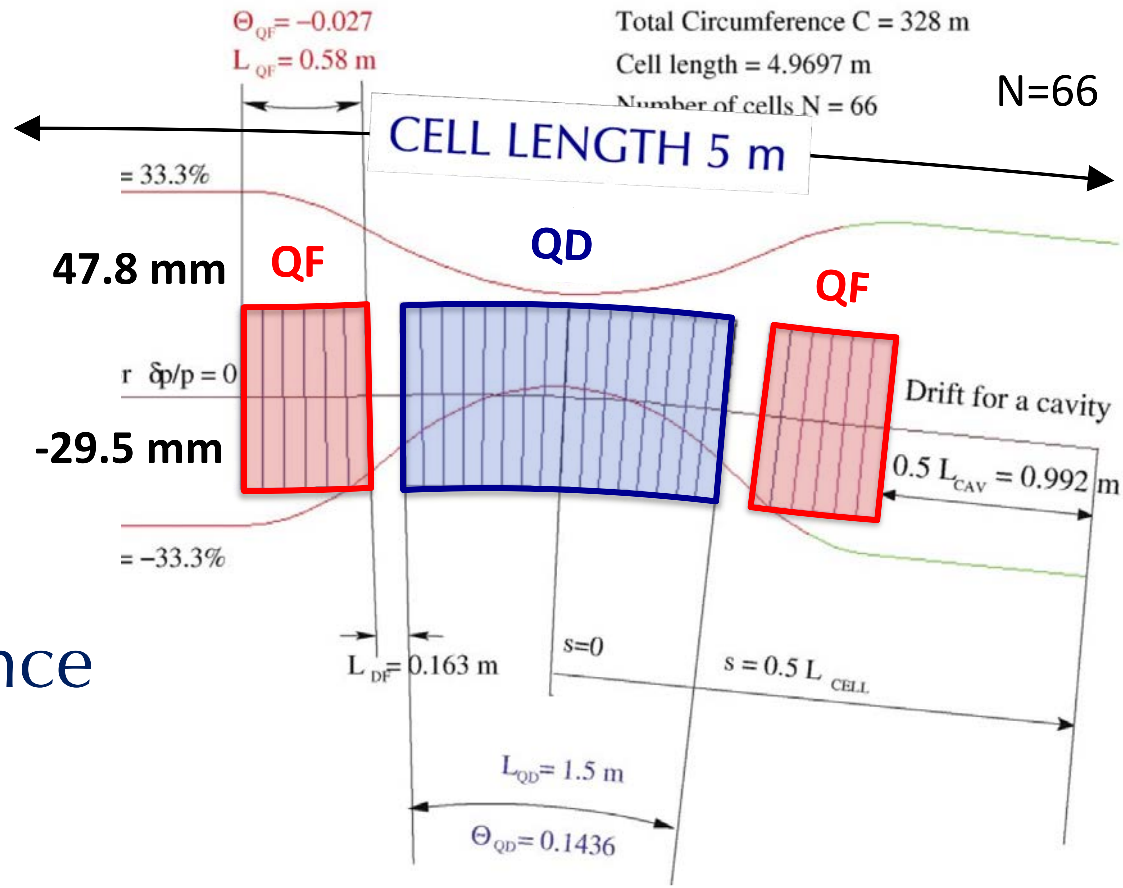


- Orbit offsets are proportional to the dispersion function: $\Delta x = D_x * \delta p/p$
- To reduce the **orbit offsets to ±4 cm range**, for momentum range of **$\delta p/p \sim \pm 50\,\%$** the dispersion function D_x has to be of the order of:

$$D_x \sim 4\ cm / 0.5 = 8\ cm$$

Non-scaling FFAG for Muon Acceleration

- Extremely strong focusing with a small dispersion function
- Tunes vary
- Orbit offsets are small
- Magnets are small
- Large energy acceptance

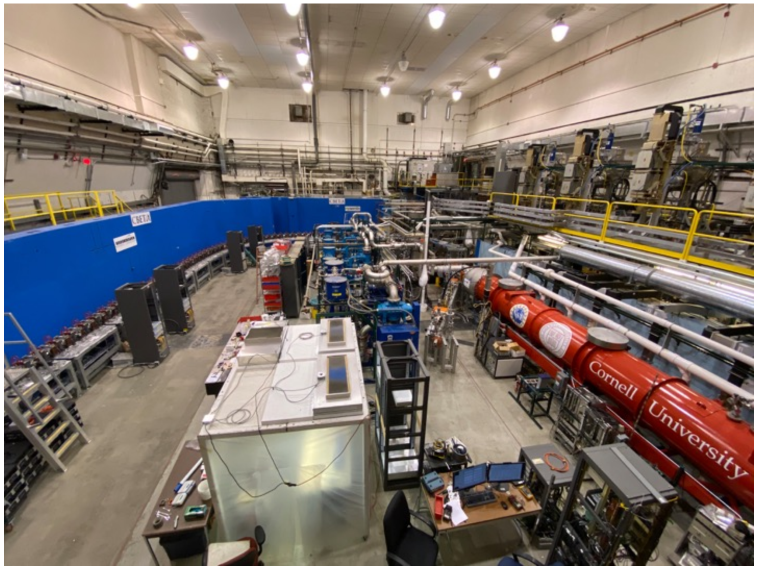


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 050101 (2005)

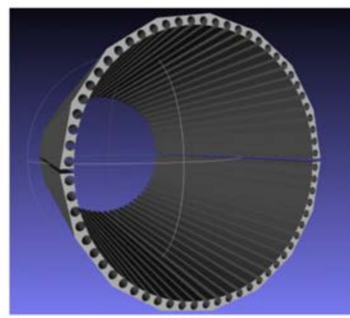
Design of a nonscaling fixed field alternating gradient accelerator

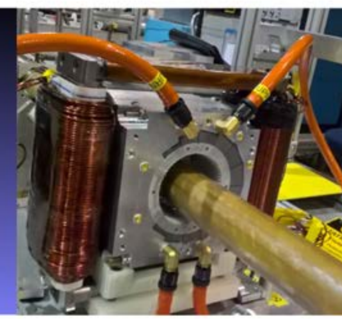
D. Trbojevic,* E. D. Courant, and M. Blaskiewicz
BNL, Upton, New York 11973, USA

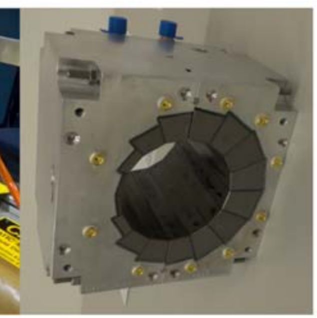
Cornell University Brookhaven National Laboratory Electron Test Accelerator - ***CBETA***

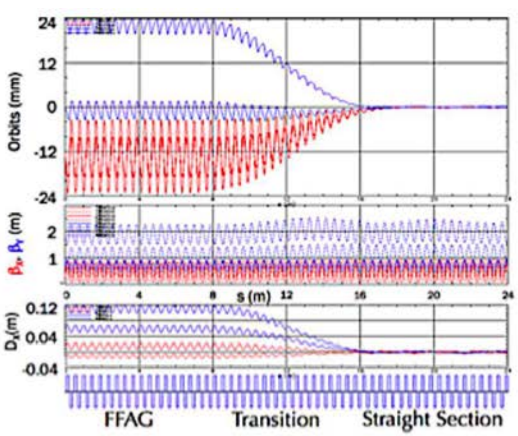


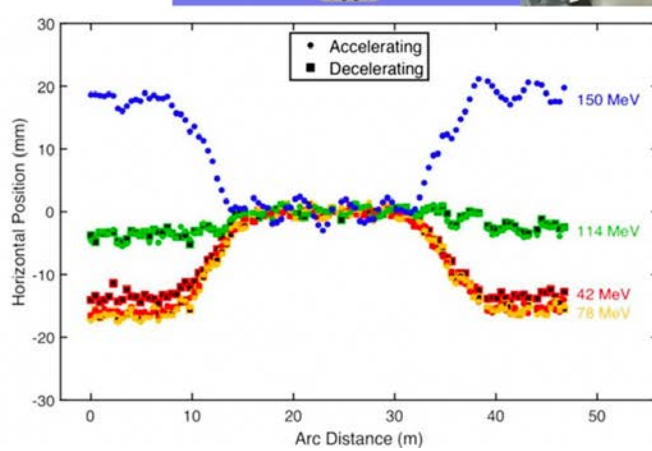
1. *Full proof of principle for the Non-scaling Fixed Field Alternating Gradient*
2. *Merging multiple energy orbits into a single straight-line orbit*
3. *Development of the new permanent magnet technology*

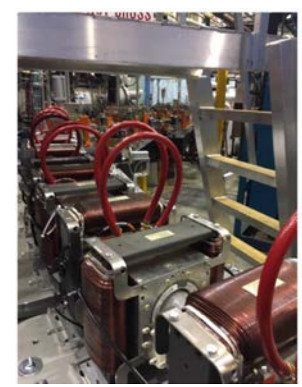






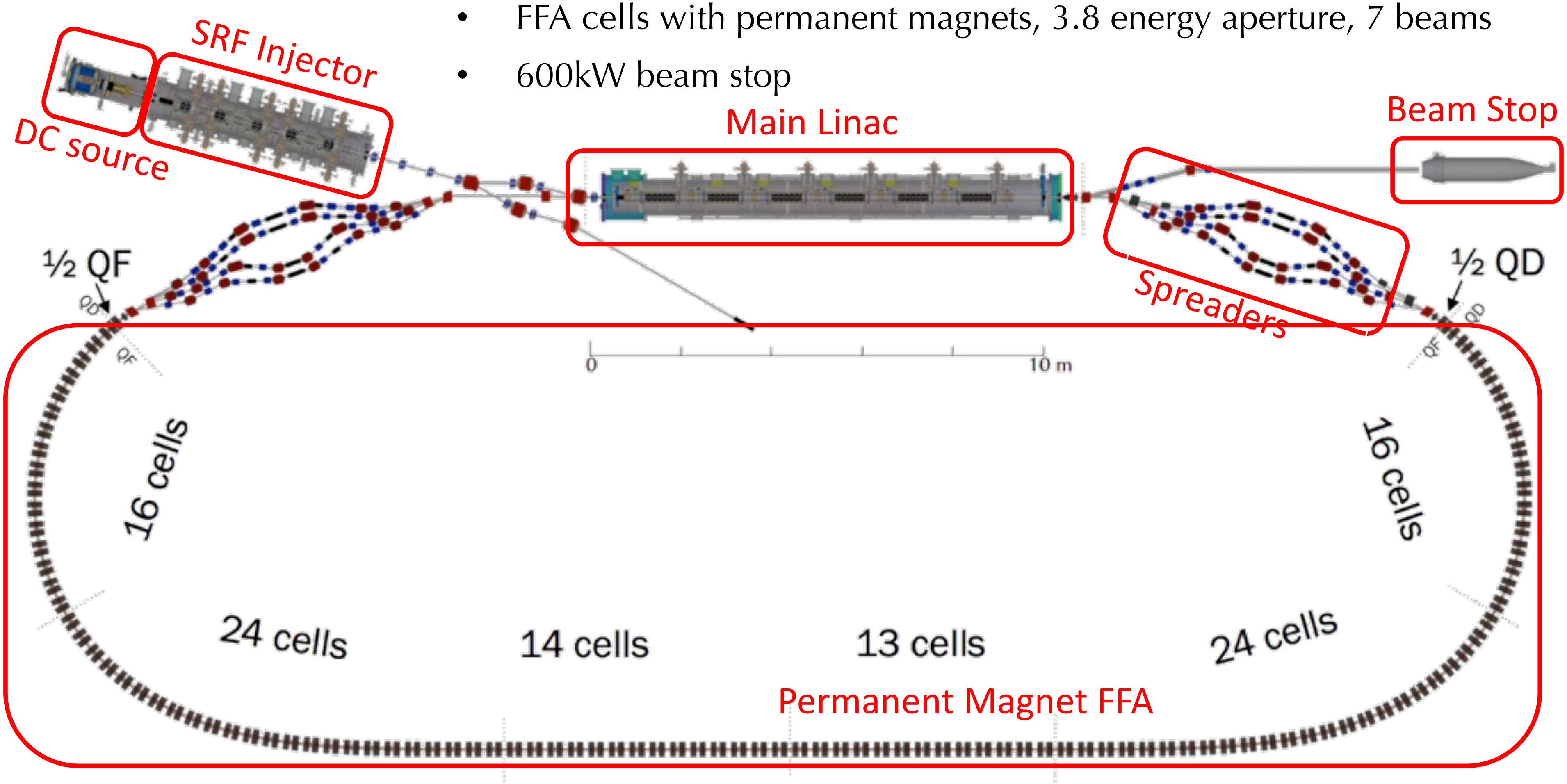






What is 'CBETA'

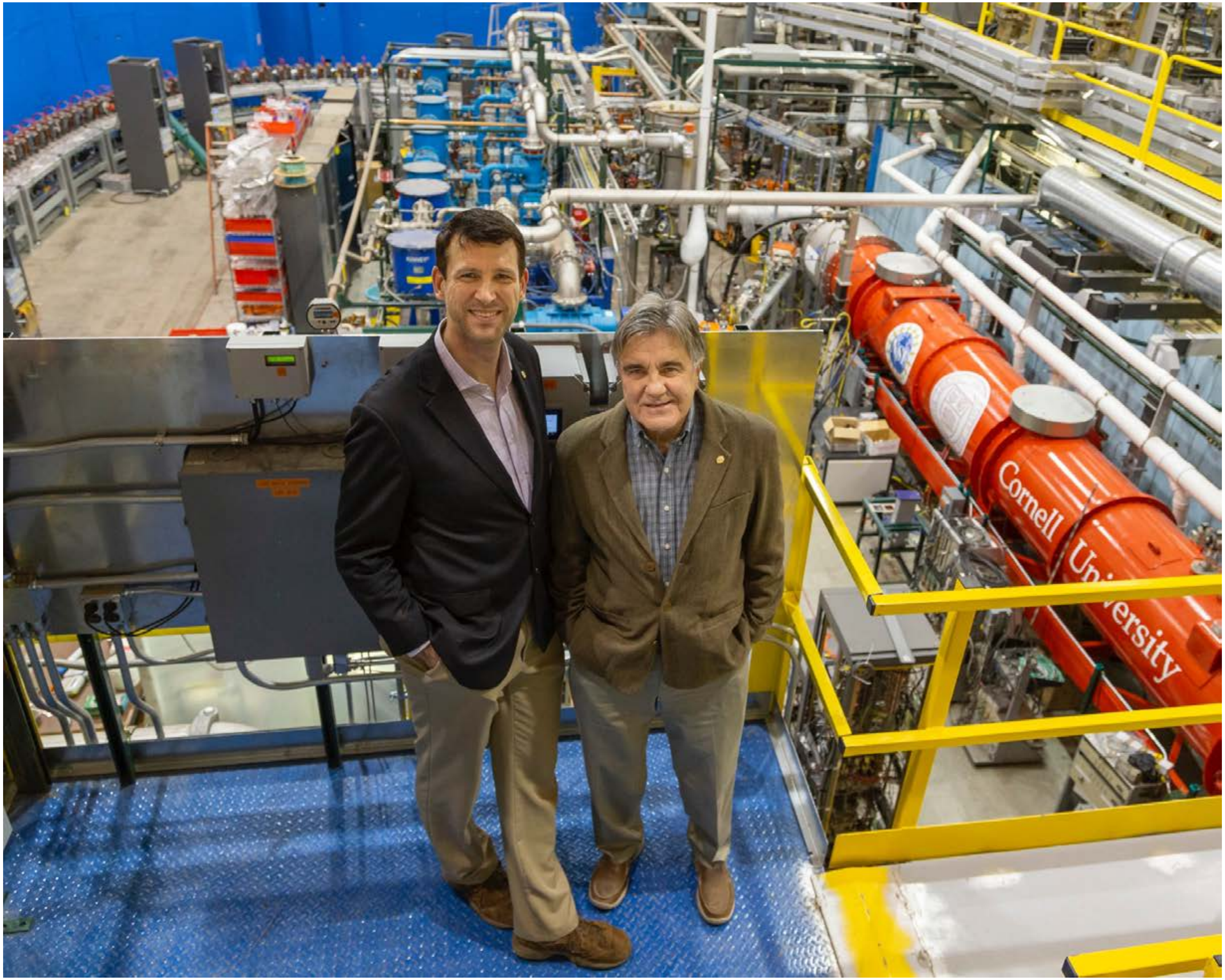
- Cornell DC gun, 2nC peak
- 100mA, 6MeV SRF injector (ICM), 1.3GHz
- 320mA, 6-cavity SRF CW Linac (MLC), 1.3GHz
- 4 Spreaders / Combiners with electromagnets
- FFA cells with permanent magnets, 3.8 energy aperture, 7 beams
- 600kW beam stop



CBETA Preparation Spring 2015

70% of the existing technical-use space was removed for the initial phase

CBETA Spring 2019



Novelties in CBETA

- *ENERGY RECOVERY MULTITURN LINAC WITH WITH 4 TURNS DURING ACCELERATION AND FOUR TURNS DURING THE ENERGY RECOVERY*

- *SUPERCONDUCTING RF : INJECTOR AND MAIN LINAC CRYOMODULE*

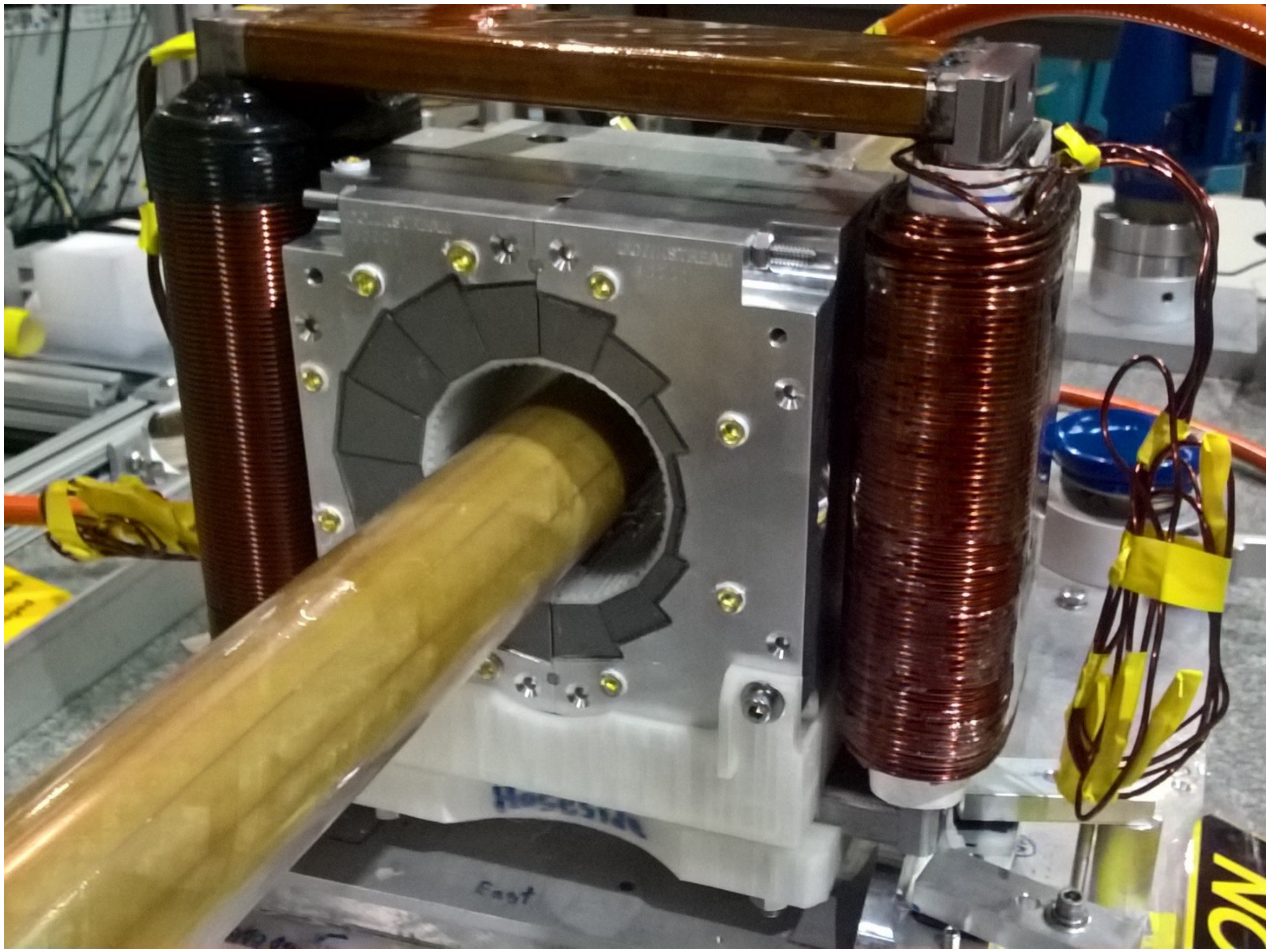
- ***NON-SCALING FFAG – MULTI ENERGY SINGLE BEAM LINE***
  - ***FFAG ARCS***
  - ***TRANSITION FROM ARC-TO-STRAIGHT***
  - ***STRAIGHT SECTION WITH MULTI-ENERGY TRANSFER***

- *PERMANENT HALBACH TYPE COMBINED FUNCTION MAGNETS*

Established new permanent magnet technology




Permanent Combined Function Magnet Design



Halbach design made of NdFeB material

This is a combined dipole+quad

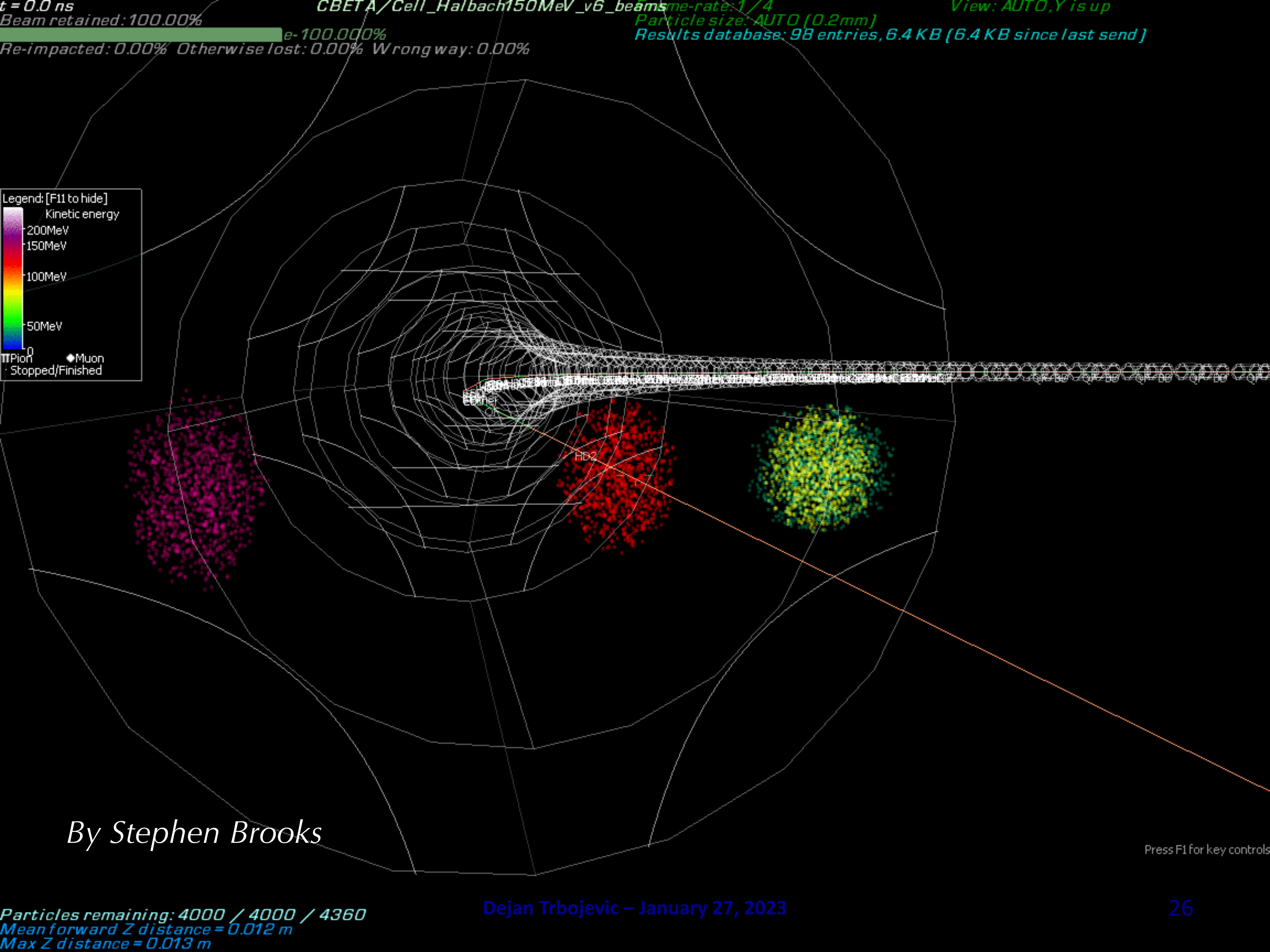
Being measured on rotating coil at BNL

3D printed multipole corrector pack inside

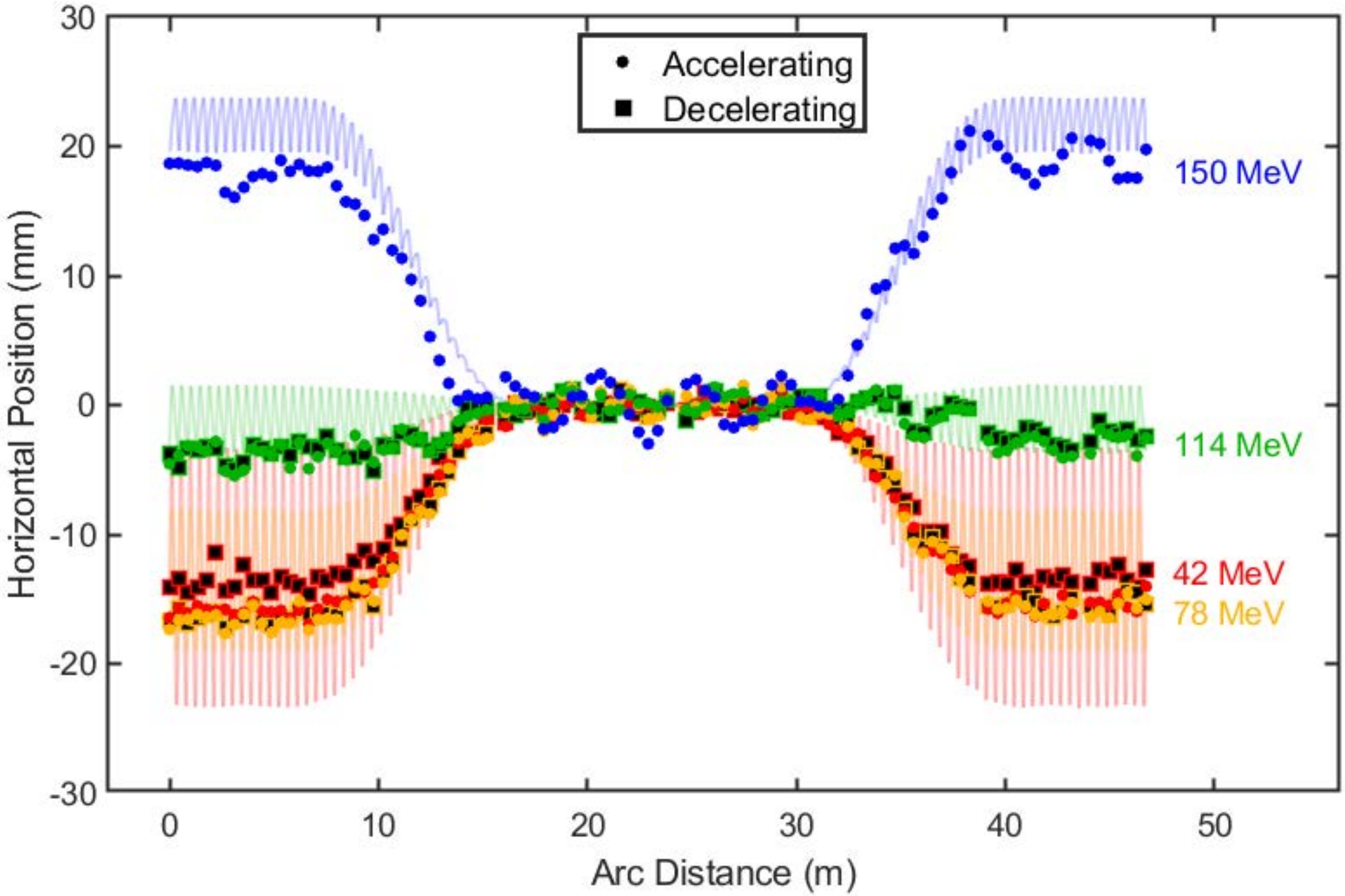
Windo wframe corrector coil outside

Temperature stabilised by water (orange hoses)

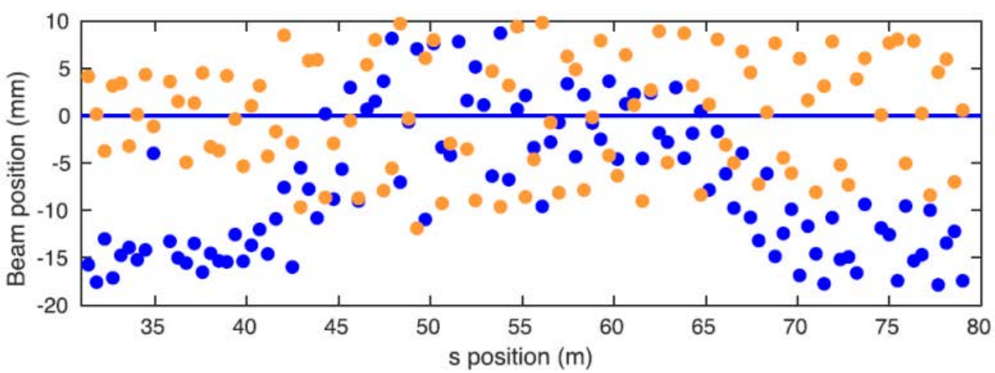
Fixed-Field Return Arc

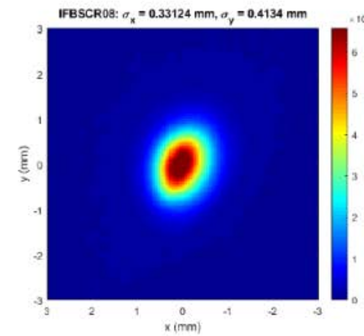

t = 0.0 ns
CBETA/Cell_Halbach150MeV_v6_beams
View: AUTO,Y is up
Beam retained: 100.00%
Particle size: AUTO (0.2mm)
e- 100.000%
Results database: 98 entries, 6.4 KB (6.4 KB since last send)
Re-impacted: 0.00% Otherwise lost: 0.00% Wrong way: 0.00%
Legend: [F11 to hide]
Kinetic energy
200MeV
150MeV
100MeV
50MeV
0
Pion
Muon
Stopped/Finished
By Stephen Brooks
Press F1 for key controls
Particles remaining: 4000 / 4000 / 4360
Mean forward Z distance = 0.012 m
Max Z distance = 0.013 m

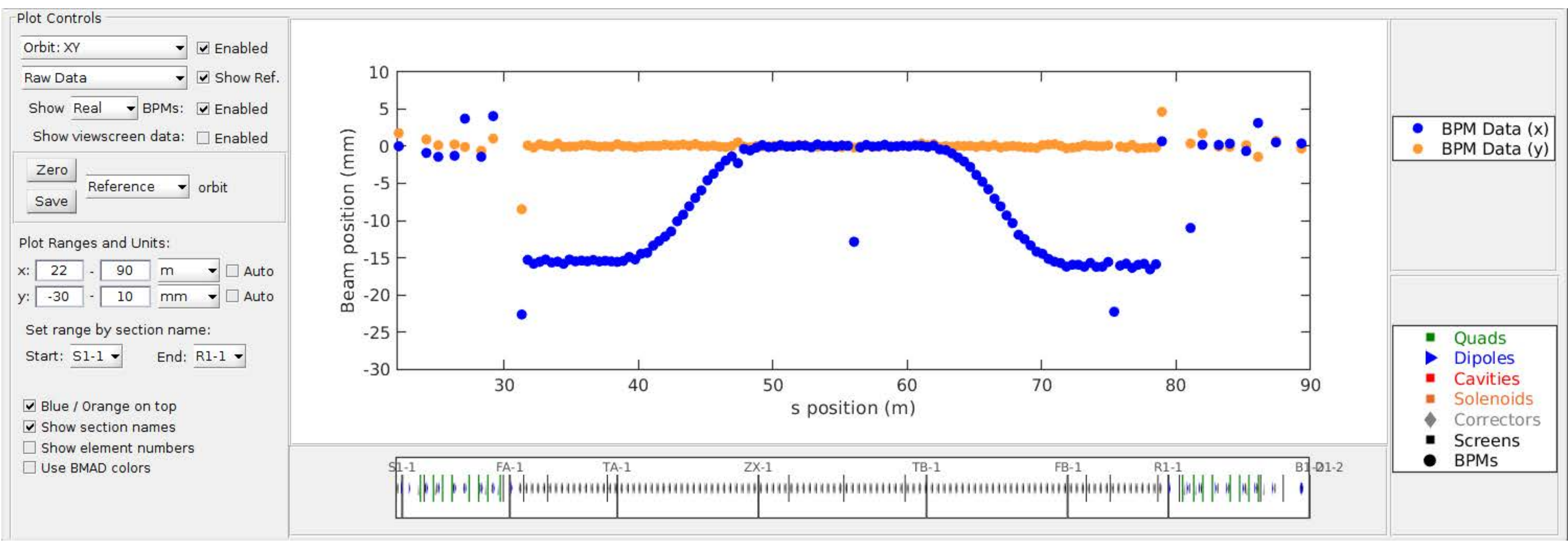
Merging of Multiple Energy Orbits in the arcs to the Straight Section into a Single Orbit



Commissioning results: orbit correction in fixed-field loop

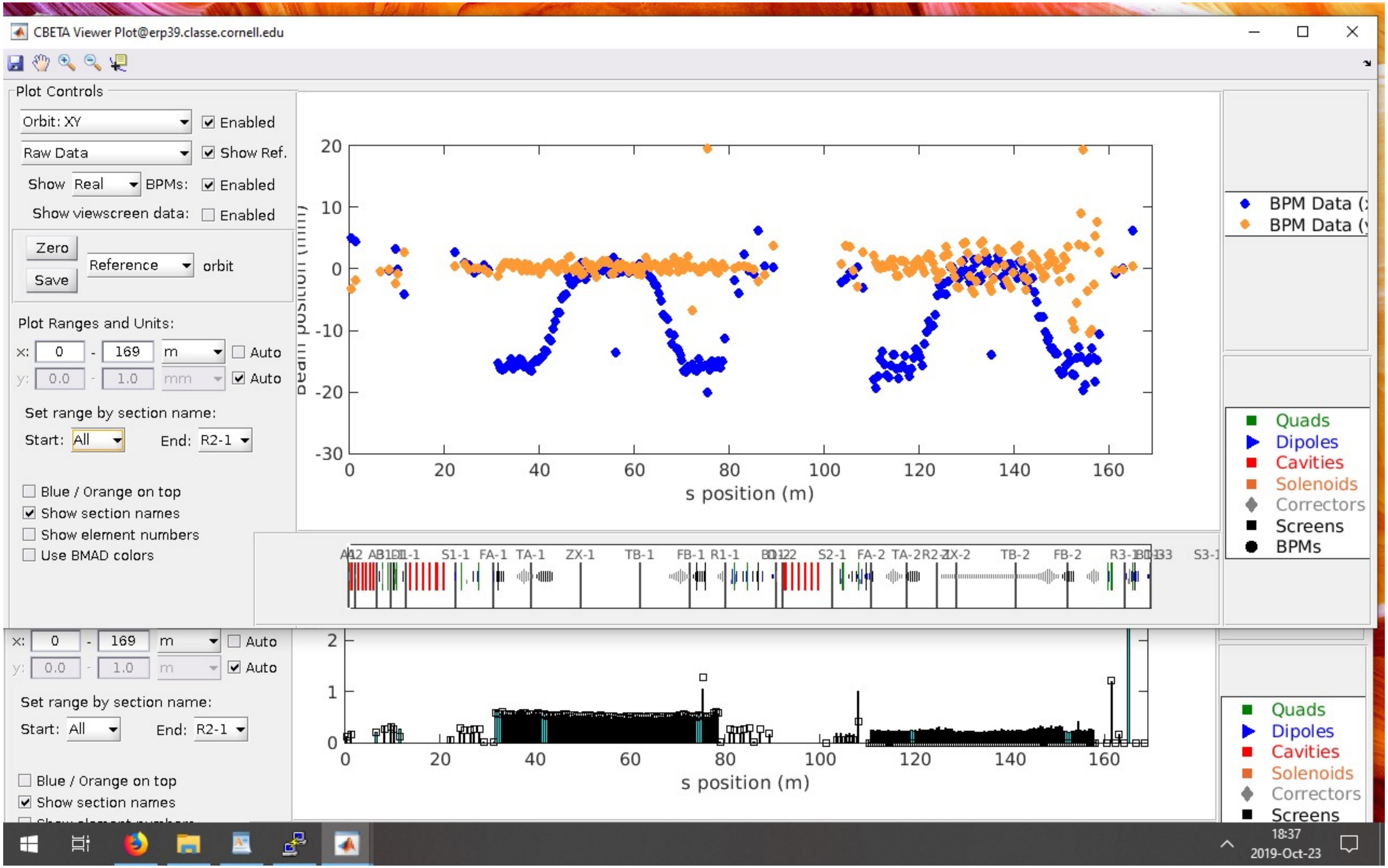




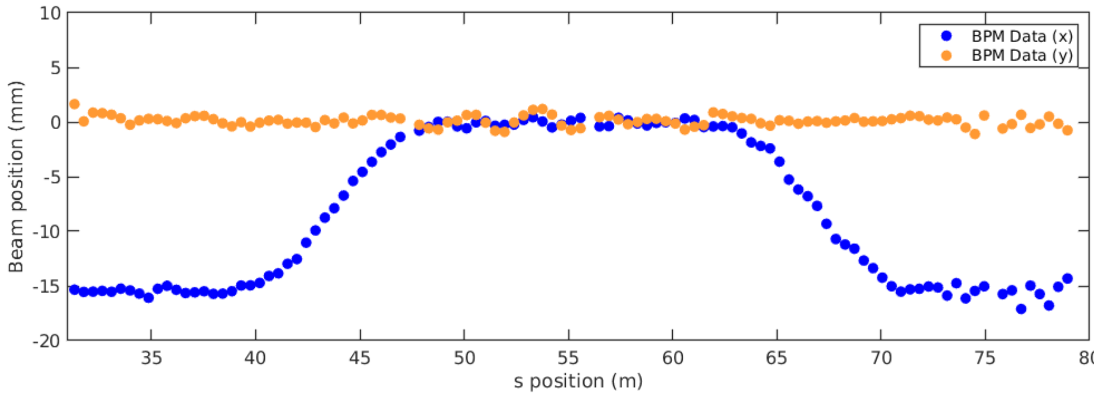


Two Turns with Orbits Uncorrected

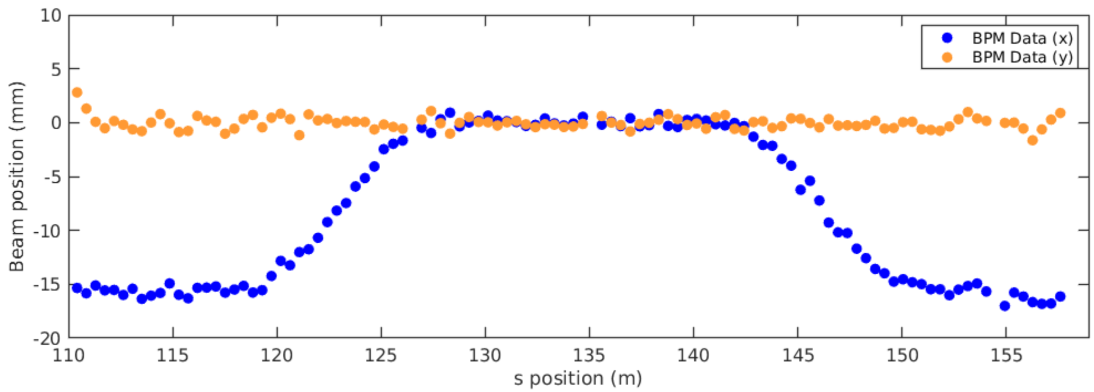
(October 23, 2019)



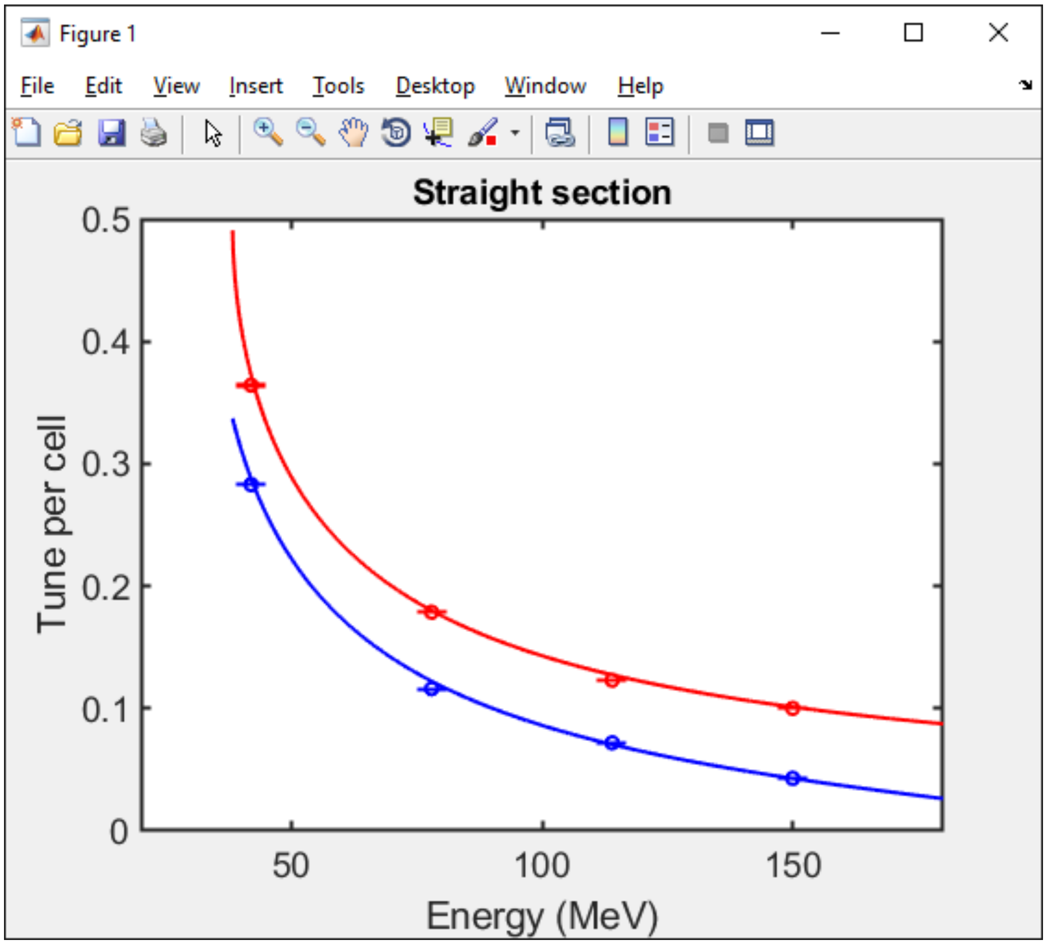
Measured Two Turns with Corrected Orbit

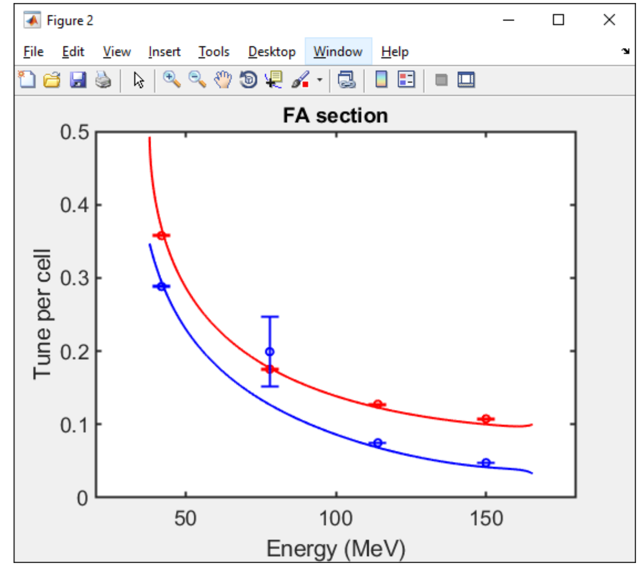


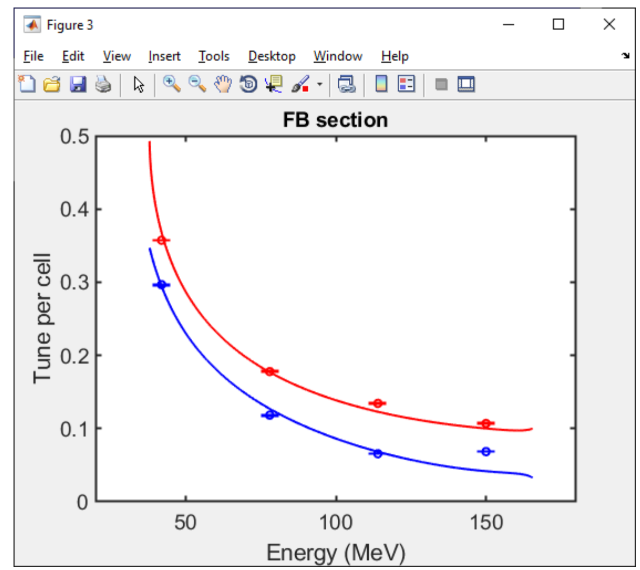
(November 8, 2019)



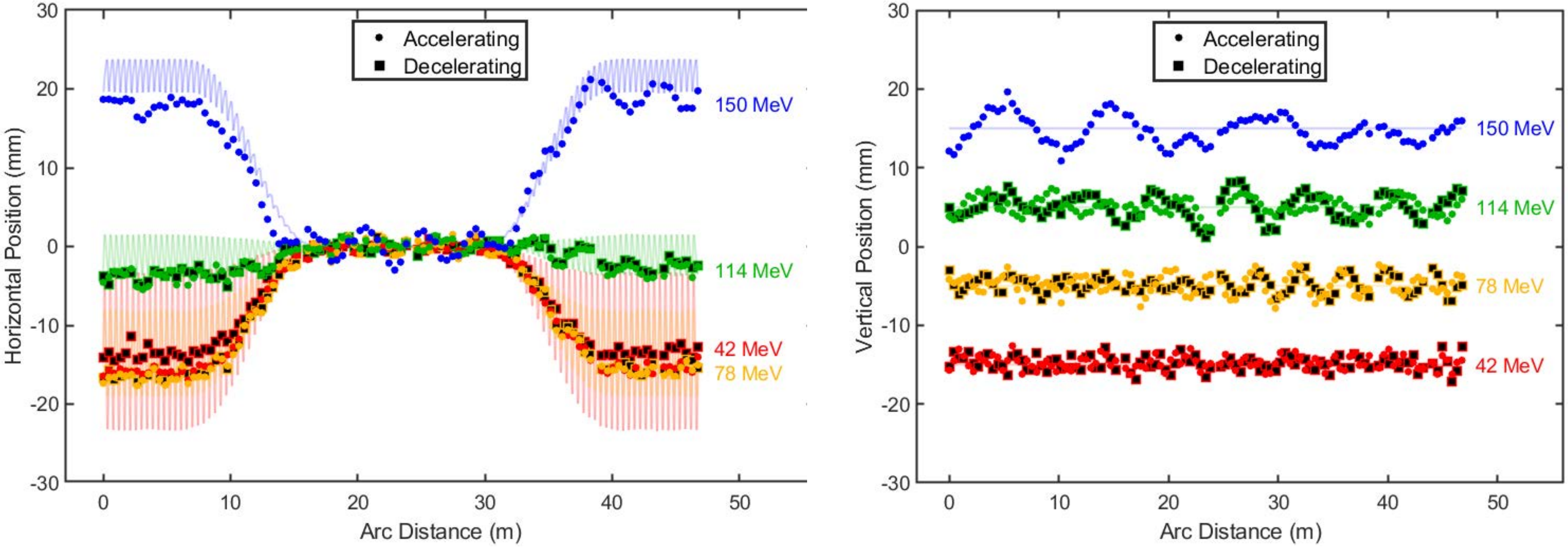
Tunes in FFA part Compared to Model







7-turn ERL operation with corrected turns 1,2,3



Achieved Parameters

Cornell **DC gun**

- 75mA short term, 65mA for hours
- Detailed **phase space diagnostics** for space charge dominated beams.
- Study of 2nC bunch charges

High power **SRF injector linac**

- Tested up to 13.5MeV
- Tested up to 75mA
- Investigation of ion / beam interactions

ERL main SRF linac

- Operated with **1-turn ERL and 99.4% ERL efficiency**
- Operated with **4-turn ERL**
- Detection of **micro bunching**
- 1-turn current limited to 70mu for radiation protection.
- 4-turn current limited to 1nA because of 50% beam loss in the last recovery loop.

FFA return loop

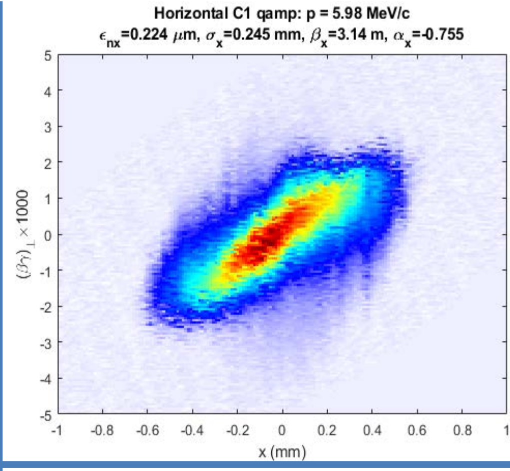
- 7 simultaneous beams (at 42, 78, 114, 150MeV)
- Hardly measurable beam losses in the FFA region

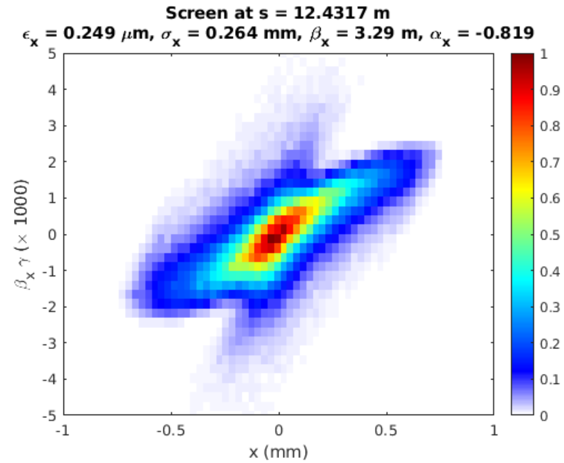
DC gun results

Measured

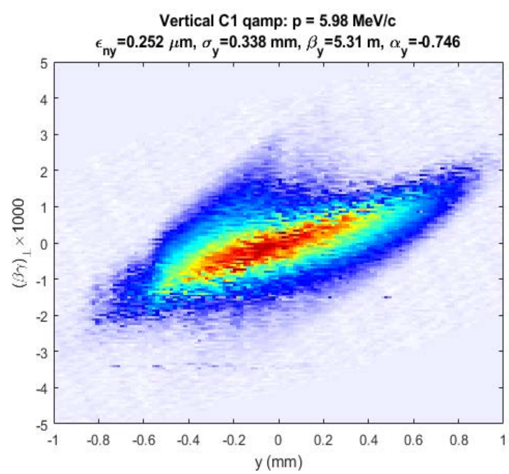
Simulation

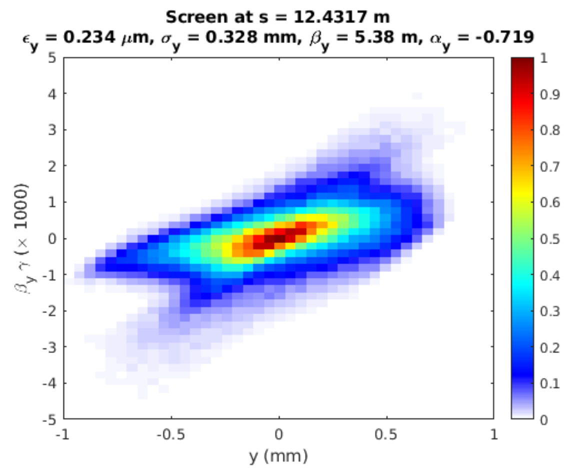
Horizontal





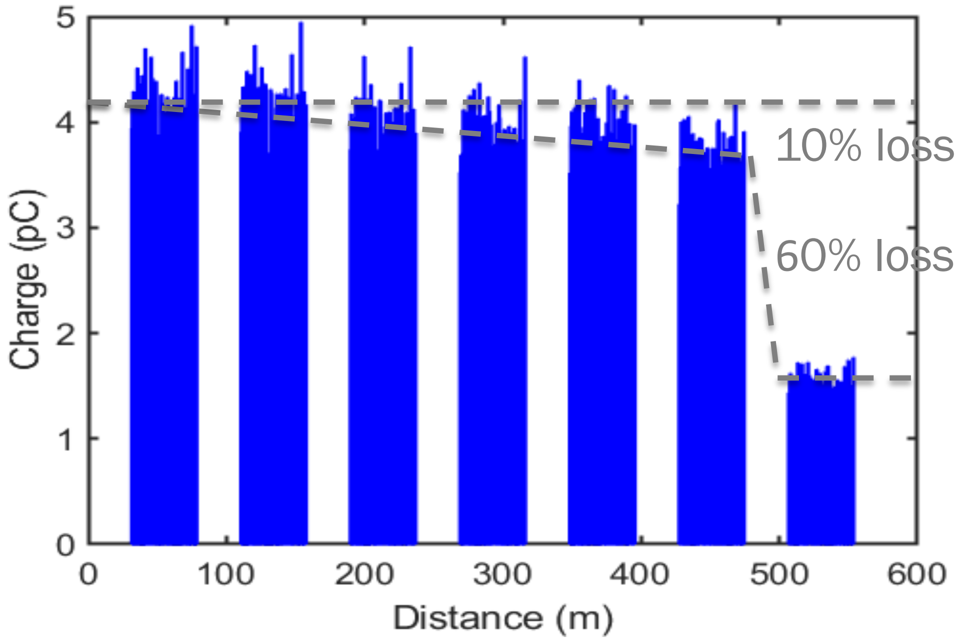
Vertical





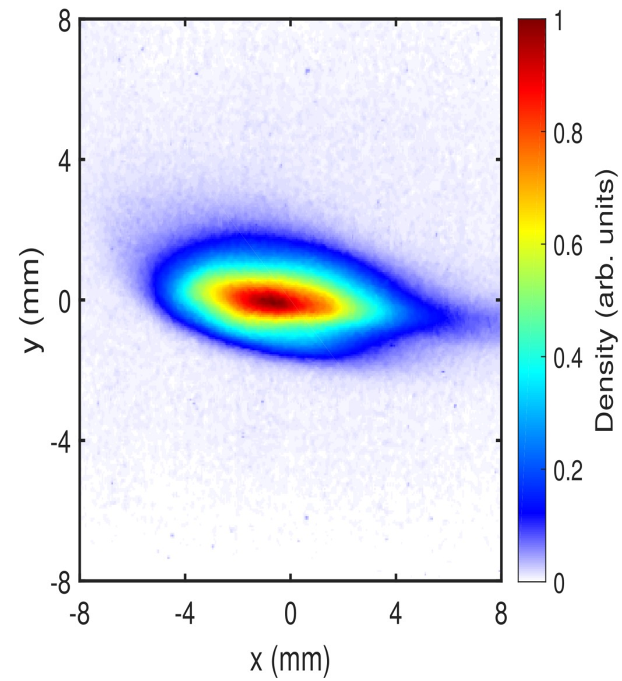
Beam to the Linac lost at the splitters

First beam Dec. 24, 2019.
Multi-turn energy recovery achieved on operated until February 2020.



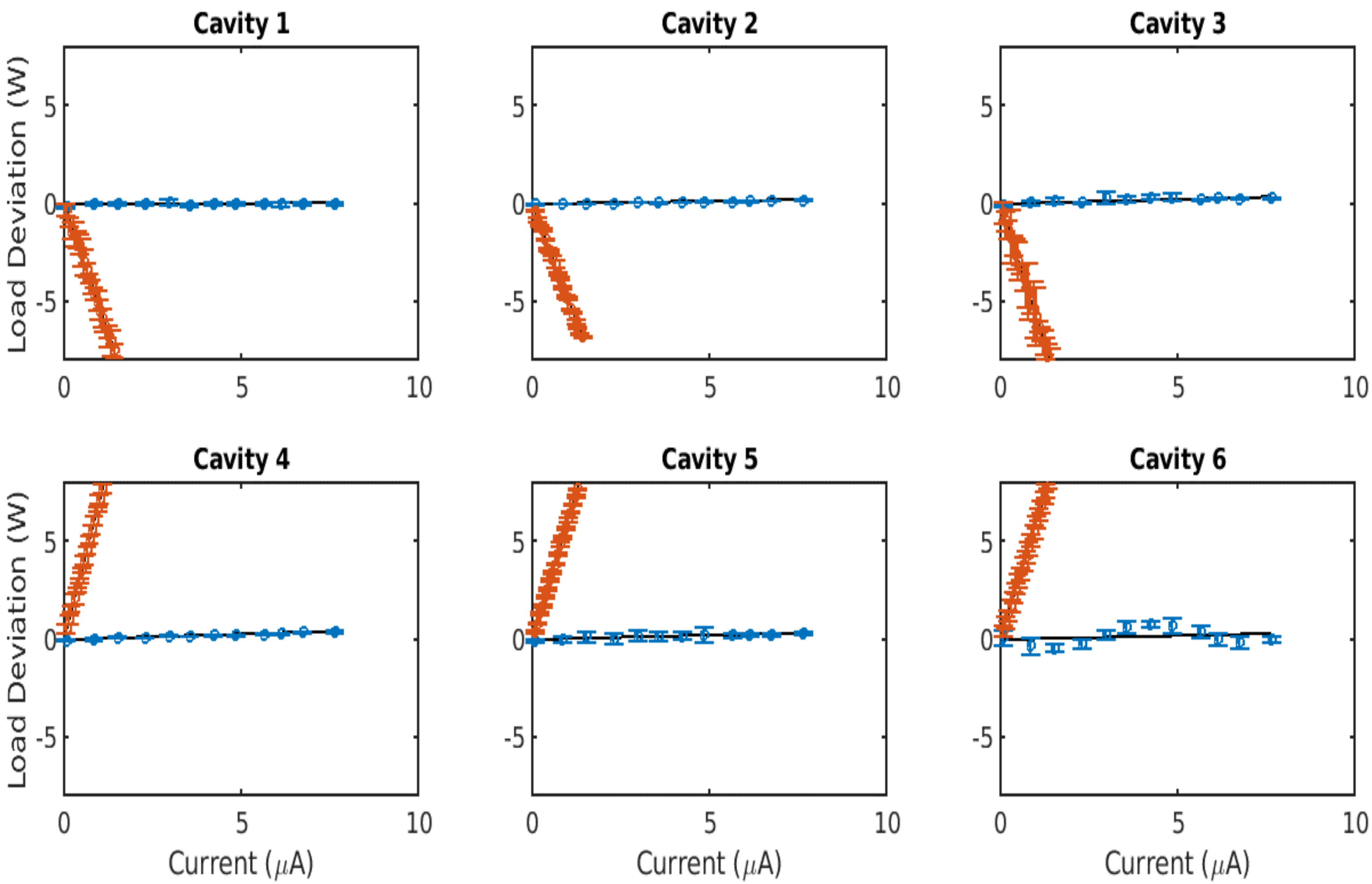
Before the 7th FFA pass there remains an unresolved 60% loss

Beam in the beam stop line



Energy Recovery in every Cavity

- Transmission 99.6 ± 0.1% ; energy recovery > 99.8%
- Measured up to 8 μA
- Each cavity accelerates beam **without** receiving **external power** for it.



SUMMARY

- First multi-turn SRF ERL
- Full Proof of Principle for the Non-Scaling Fixed Field Alternating Gradient Concept
- Proof of Principle for the ARC to Straight Merging
- Established New Technology for the superb quality Halbach-type permanent Combined Function
- Opened door for application to the new electron-positron and electron ion colliders with permanent magnets
- Established energy saving measures: Energy Recovery, SRF, and permanent magnets.

Application of the FFA concept to the possible future energy upgrade of RLA at Jefferson Laboratory from 12 to 22 GeV and alternate FFA DESIGN FOR LHeC

Layout of the LHeC-LHC-SPS

From Oliver Brüning, Andrei Seryi, and Silvia Verdu-Andres
Frontiers in Physics, 25 April 2022, Electron-Hadron Colliders: EIC, LHeC and FCC-e

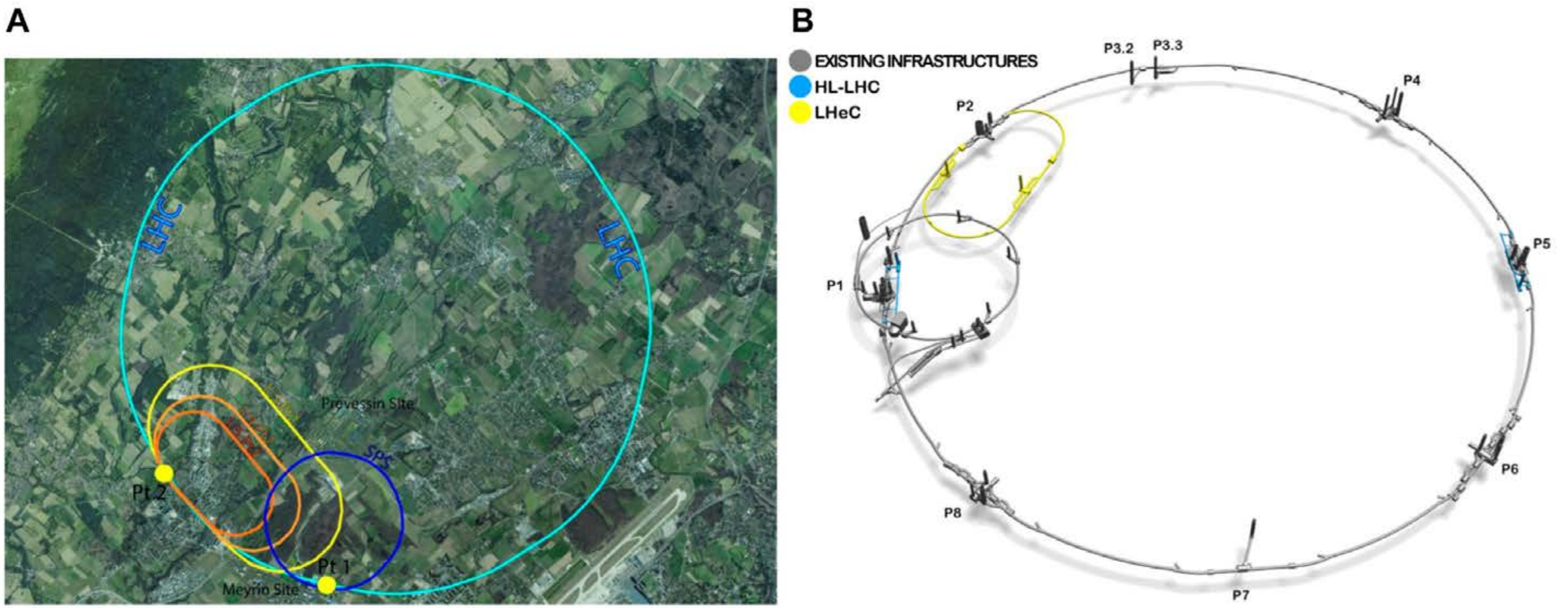
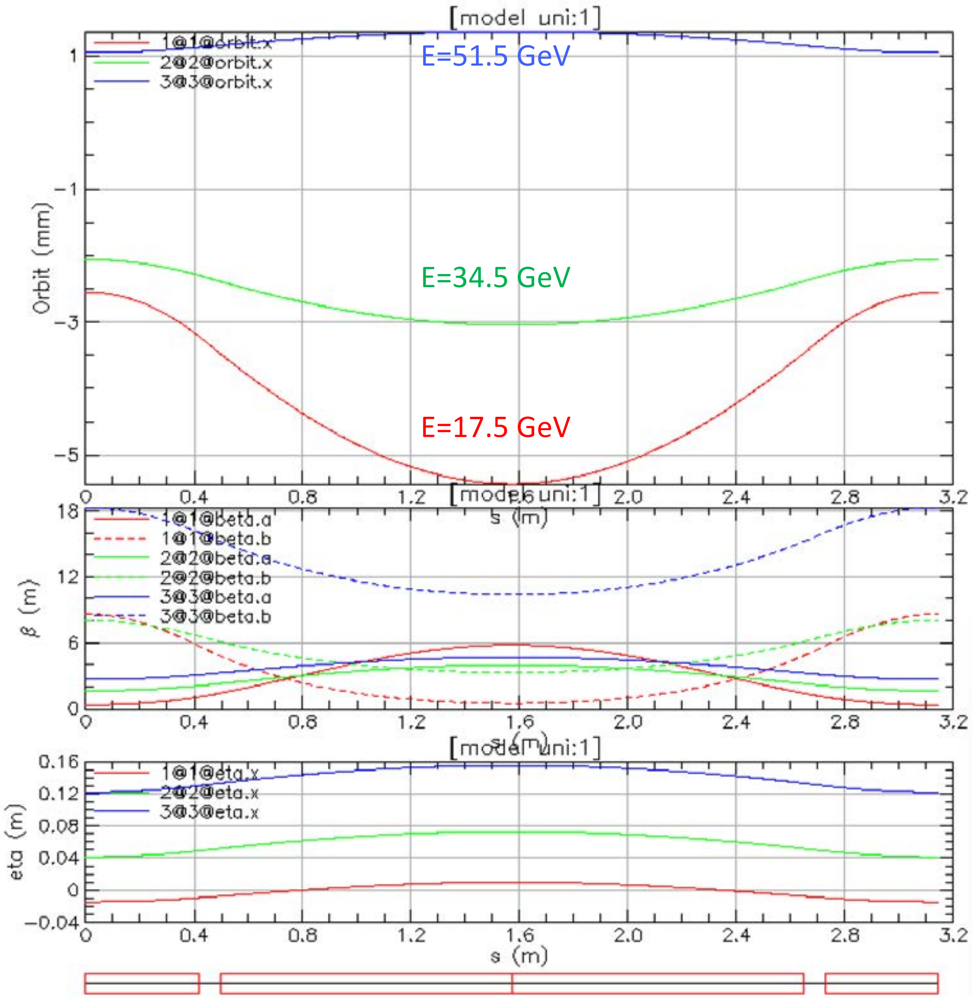
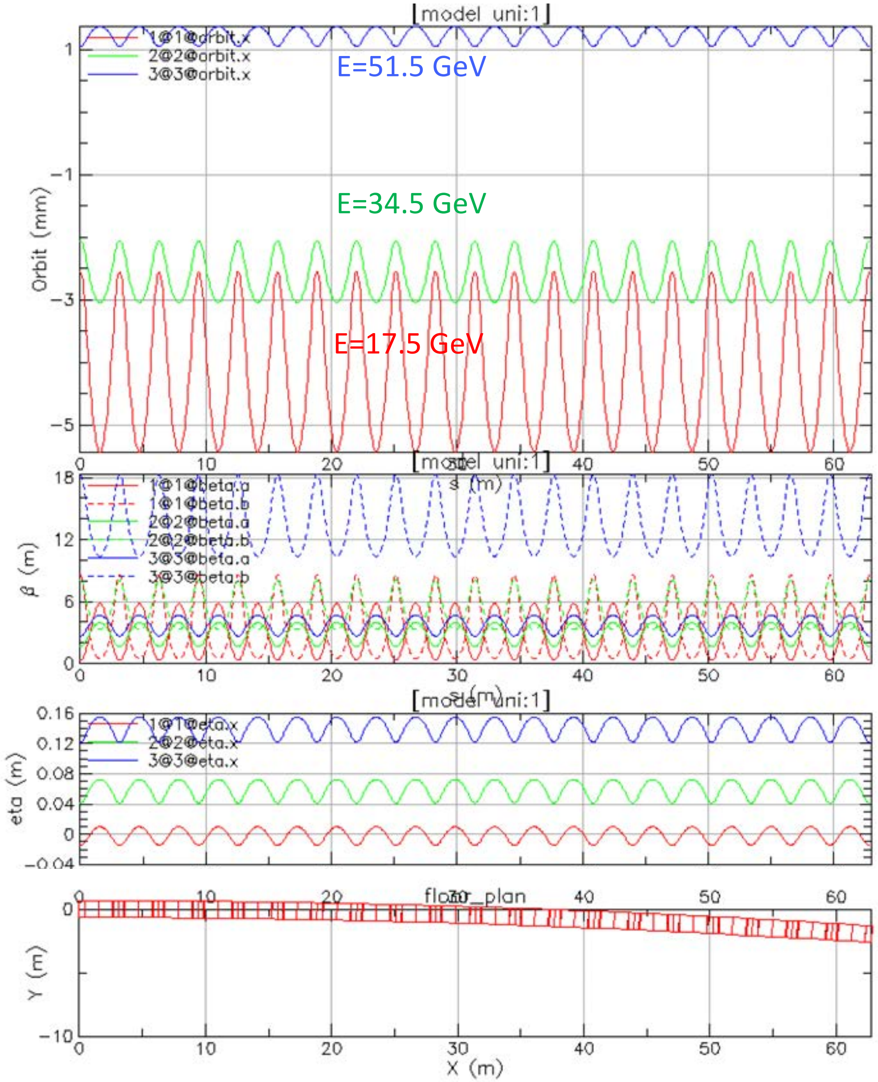


FIGURE 2 | (A) Layout options and footprint of the LHeC in the Geneva basin next to the Geneva airport and CERN. The yellow racetrack corresponds to the LHeC layout that offers optimal performance; in orange, two size variations explored for cost optimization. For reference, the light blue circle depicts the existing tunnel of the LHC; the dark blue circle is the SPS. **(B)** 3D schematic showing the underground tunnel arrangement. The grey sections indicate the existing SPS and LHC tunnel infrastructures and the yellow section the new LHeC installation.

FFA LHeC Recirculator with Energy Recovery

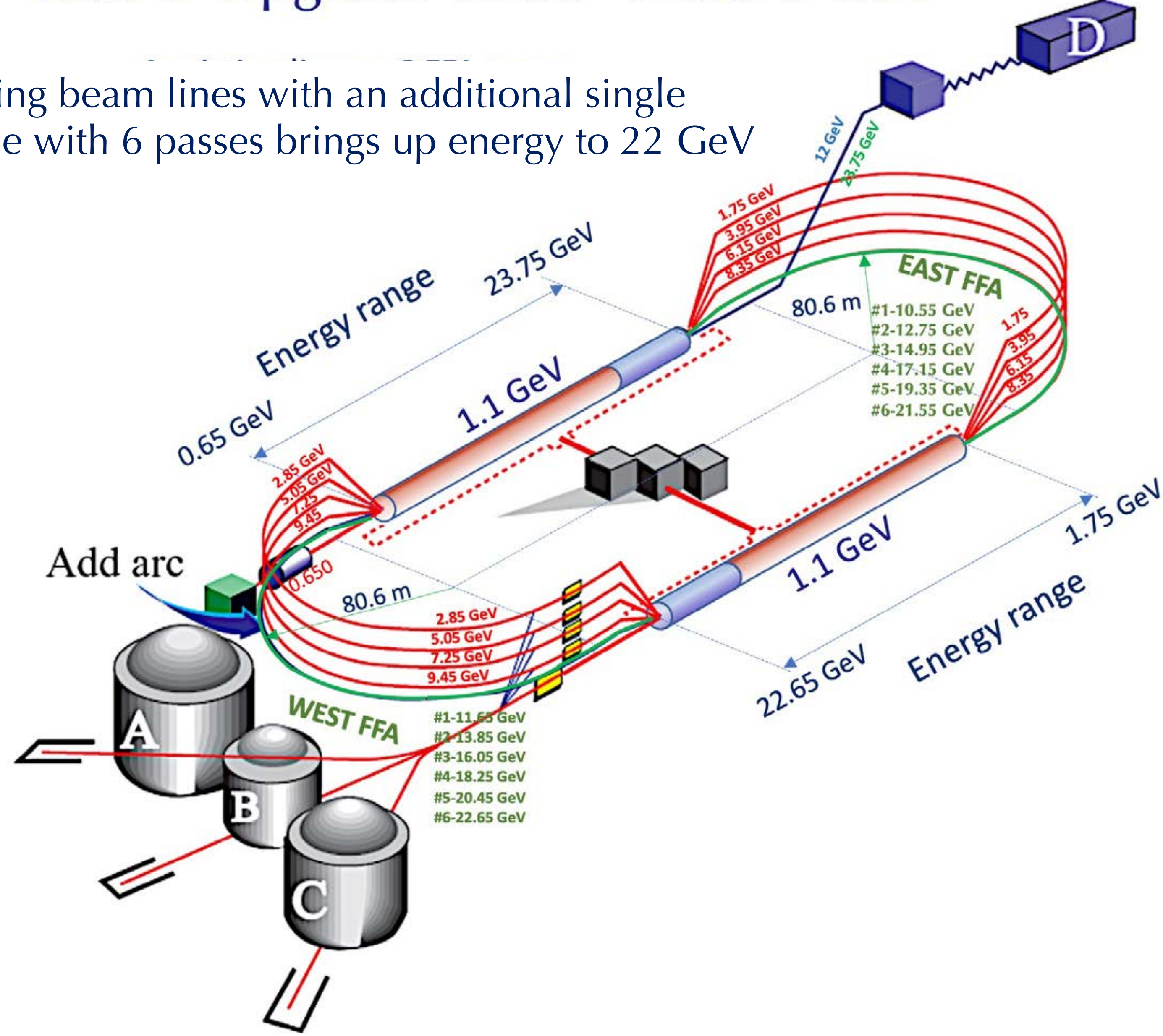
Lattice functions in a single FFA Cell





CEBAF Upgrade 10.55 →23.75 GeV

There 4 existing beam lines with an additional single
FFA beam line with 6 passes brings up energy to 22 GeV



Lattice Functions in a Cell for the WEST-FFA arc

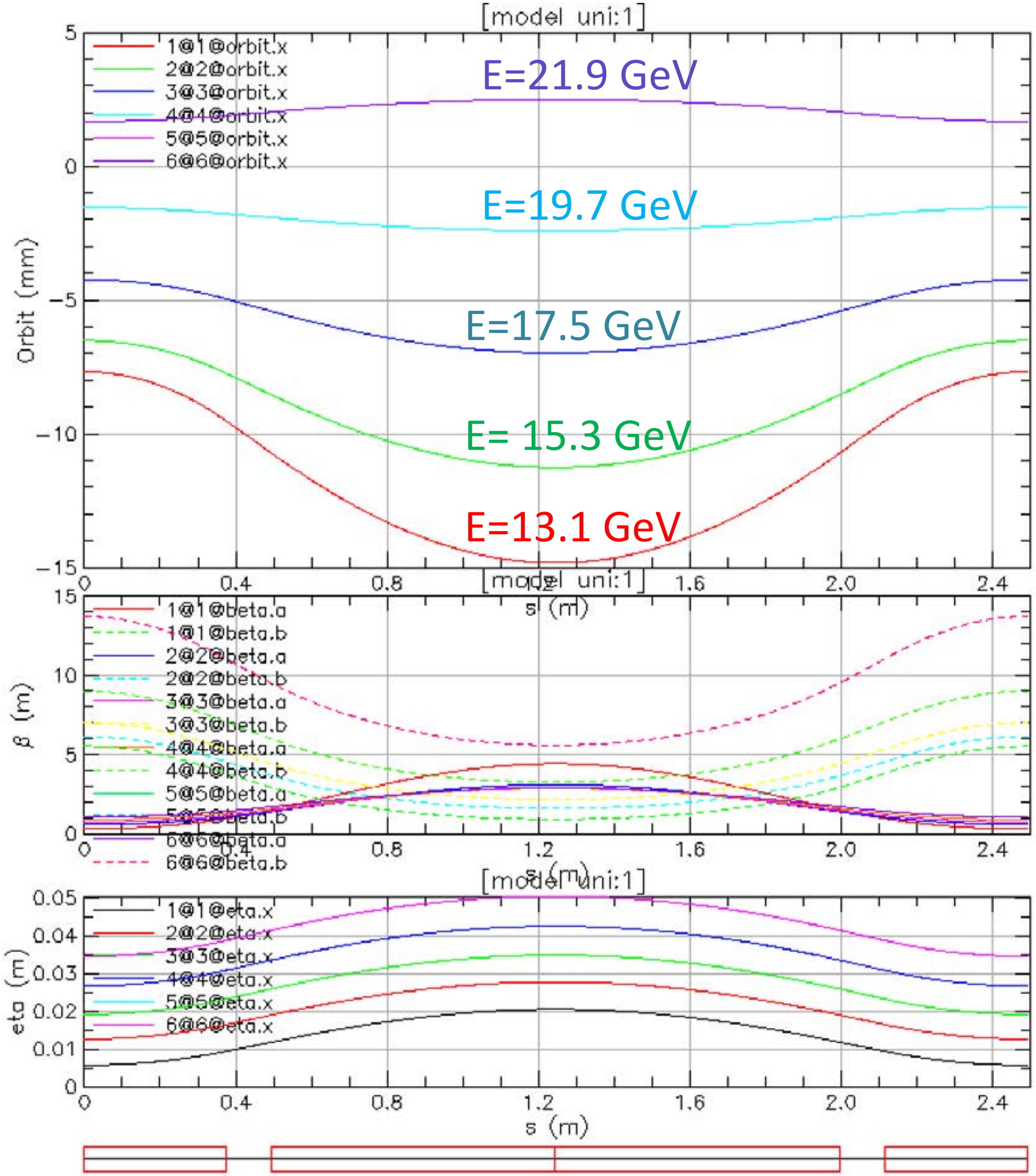
Magnet Properties:

Focusing Magnet QF
GF= -73.26375 T/m
QLF= 1.5 m
θ_F=-0.023180154
B_F=1.07218 T
B_{FMAX}=-1.25 T

Defocusing Magnet BD
GD= -73.26375 T/m
BLD= 0.7511 m
θ_D=-0.023180154
B_D= -0.71375 T
B_{DMAX}=-1.755 T

Total Synchrotron Radiation Lost
In the West Arc from five passes:

E_{LOSS}=373.7 MeV



Lattice Functions in a Cell for the EAST-FFA arc

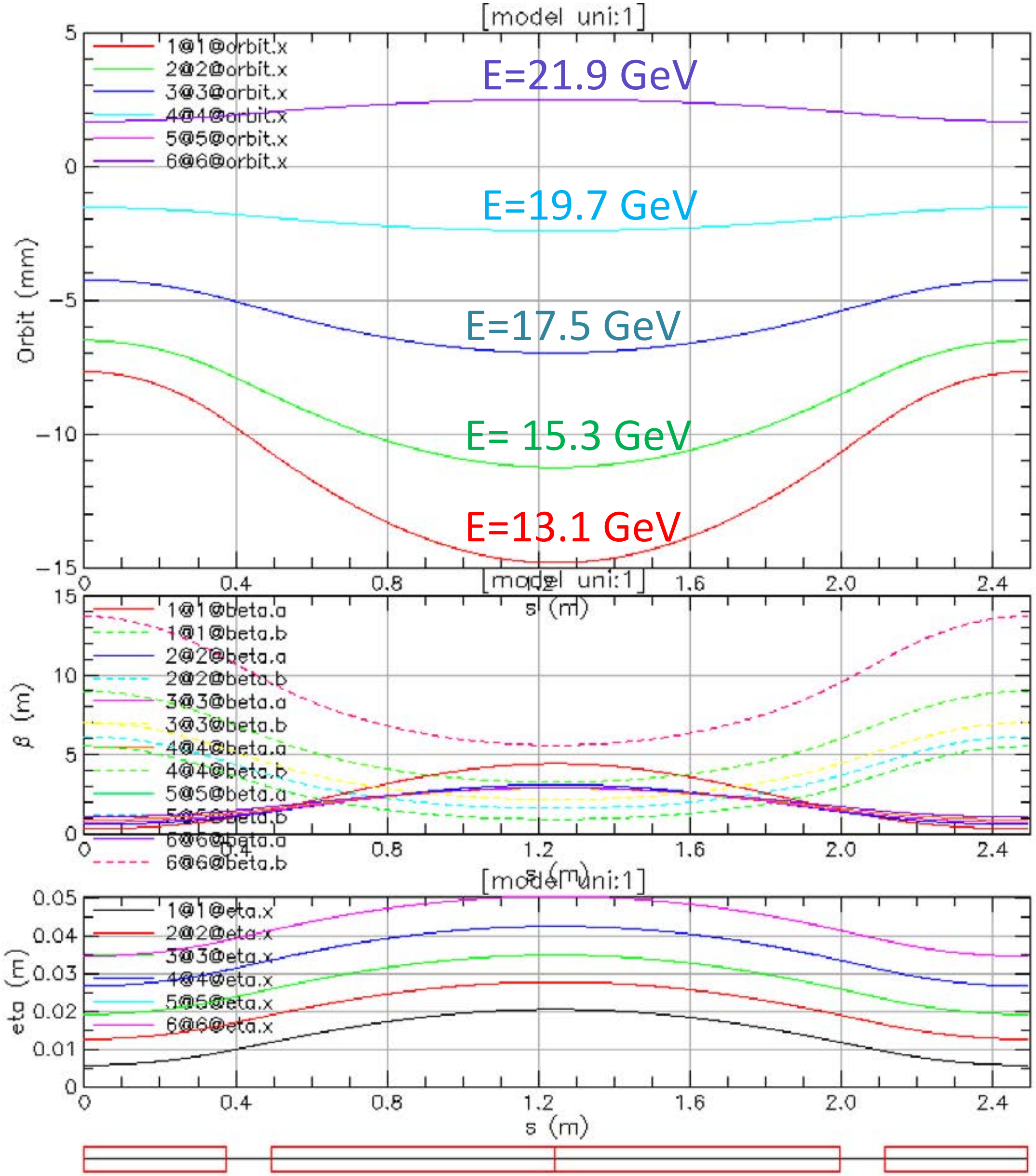
Magnet Properties:

Focusing Magnet QF
GF= -73.26375 T/m
QLF= 1.5 m
θ_F=-0.023180154
B_F=1.07218 T
B_{FMAX}=-1.25 T

Defocusing Magnet BD
GD= -73.26375 T/m
BLD= 0.7511 m
θ_D=-0.023180154
B_D= -0.71375 T
B_{DMAX}=-1.755 T

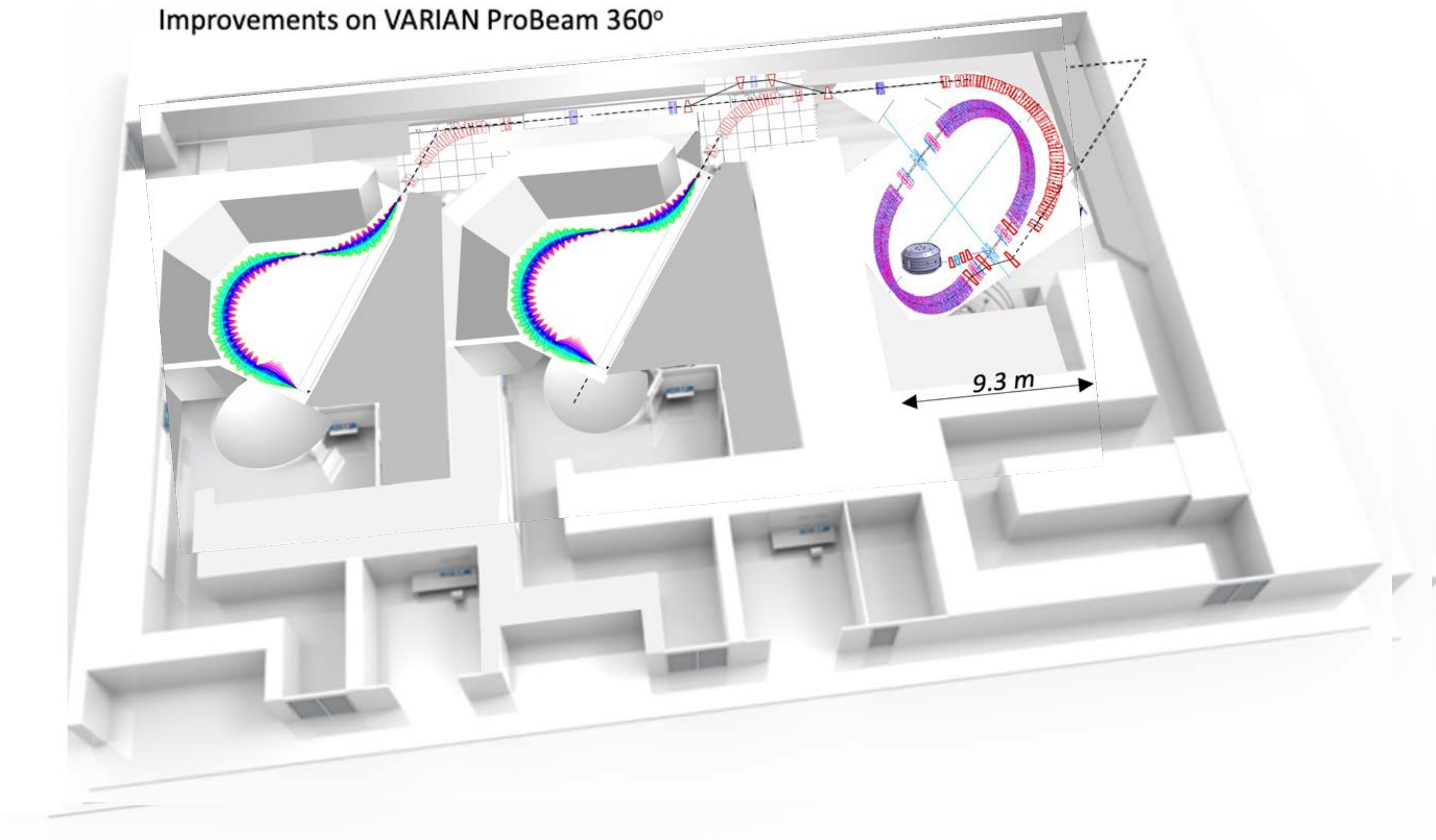
Total Synchrotron Radiation Lost
In the West Arc from five passes:

E_{LOSS}=373.7 MeV

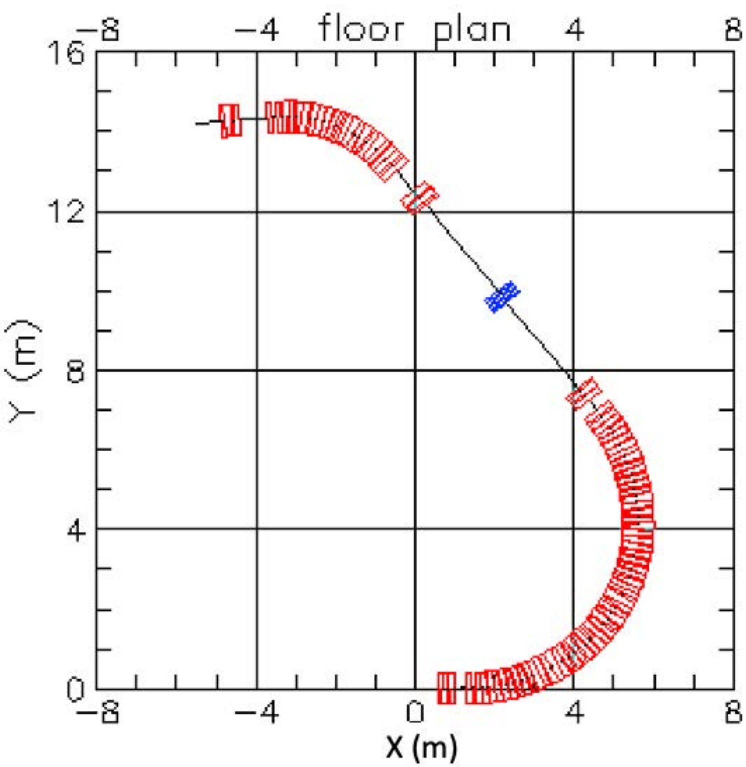


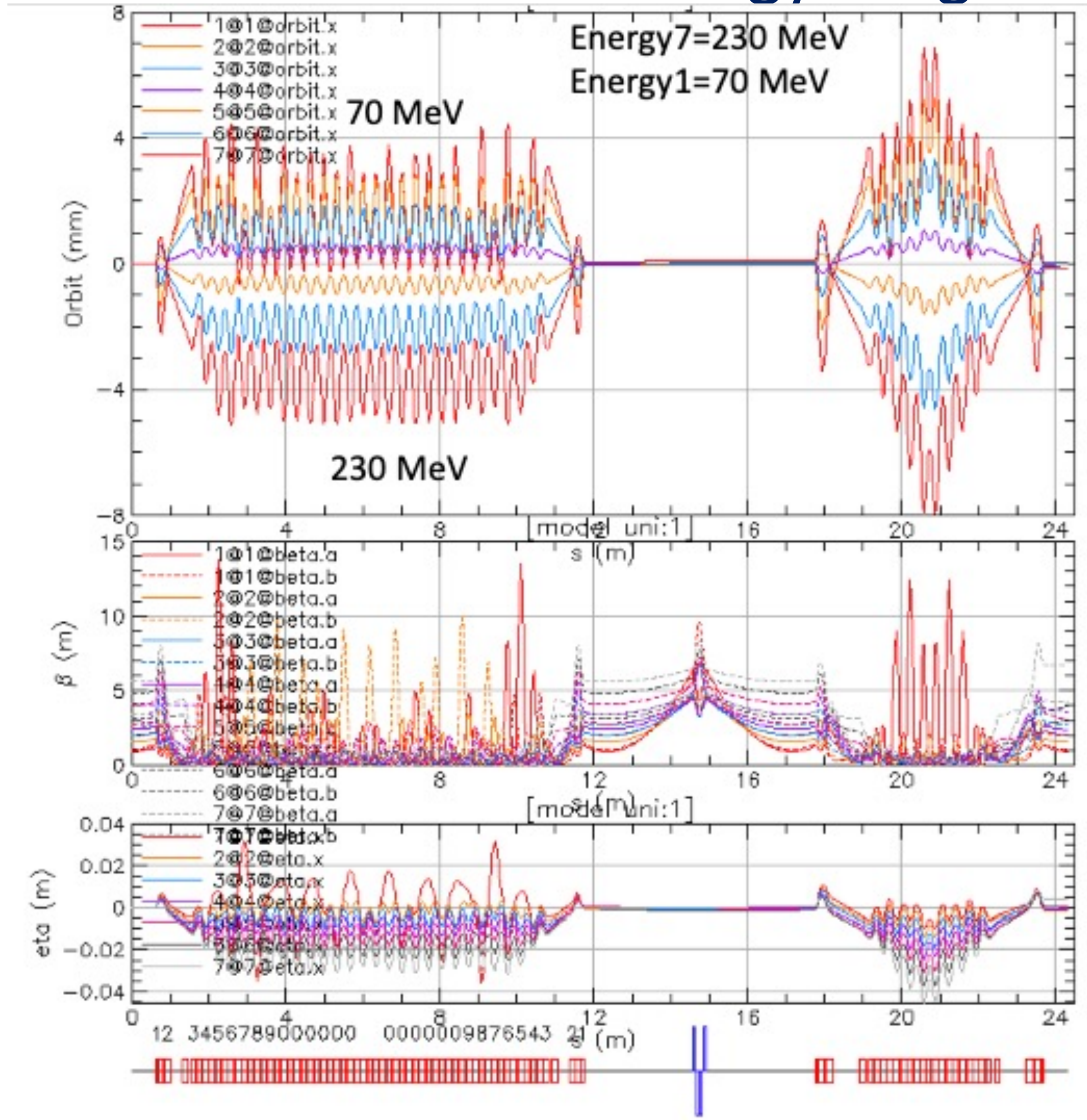
Applications of the FFA concept to the Cancer Radiation Therapy Accelerators, Beam Lines and Gantries

FLASH therapy in the existing proton therapy systems

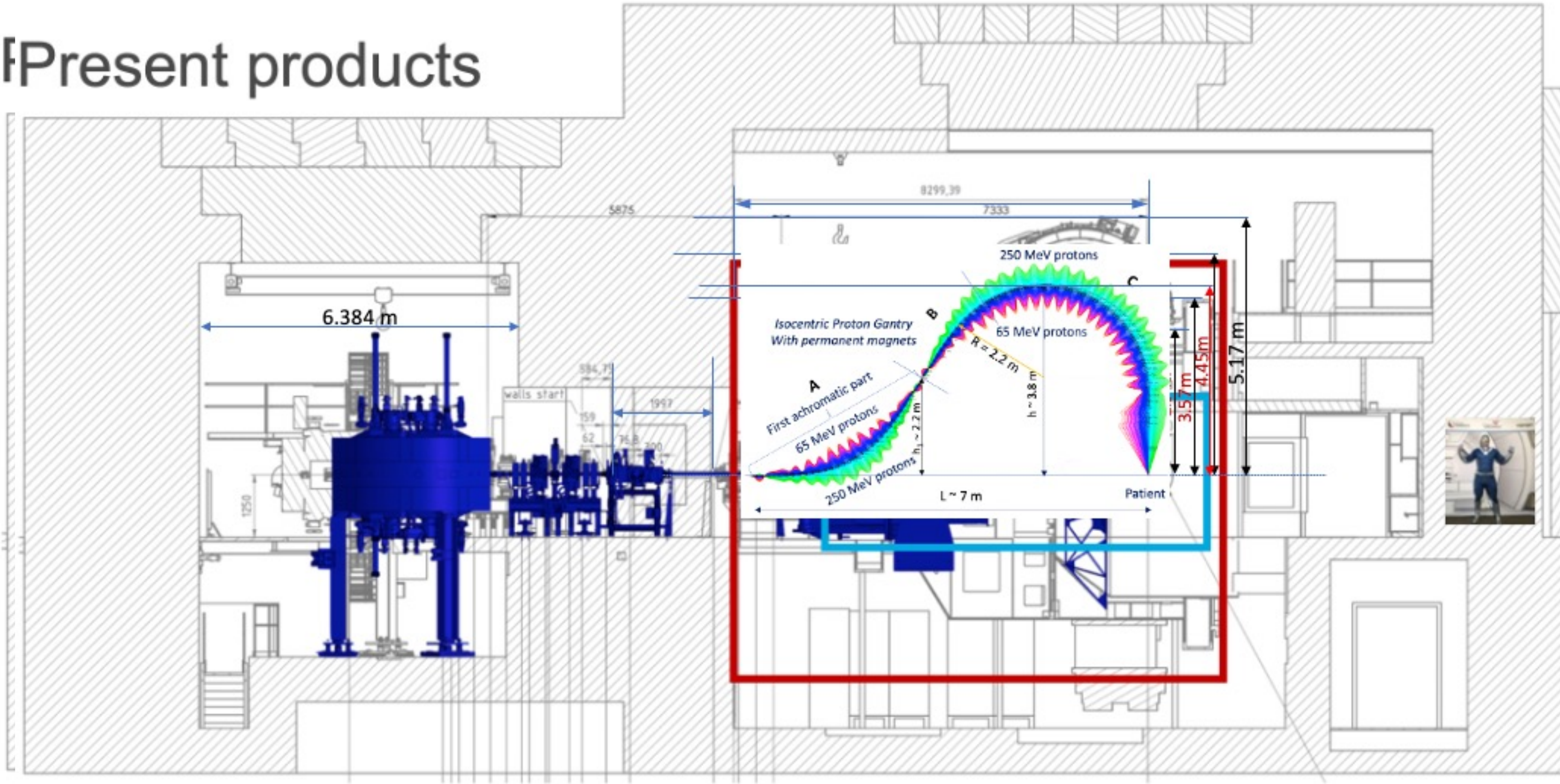


FFA Beam lines with 70—250 MeV kinetic energy range

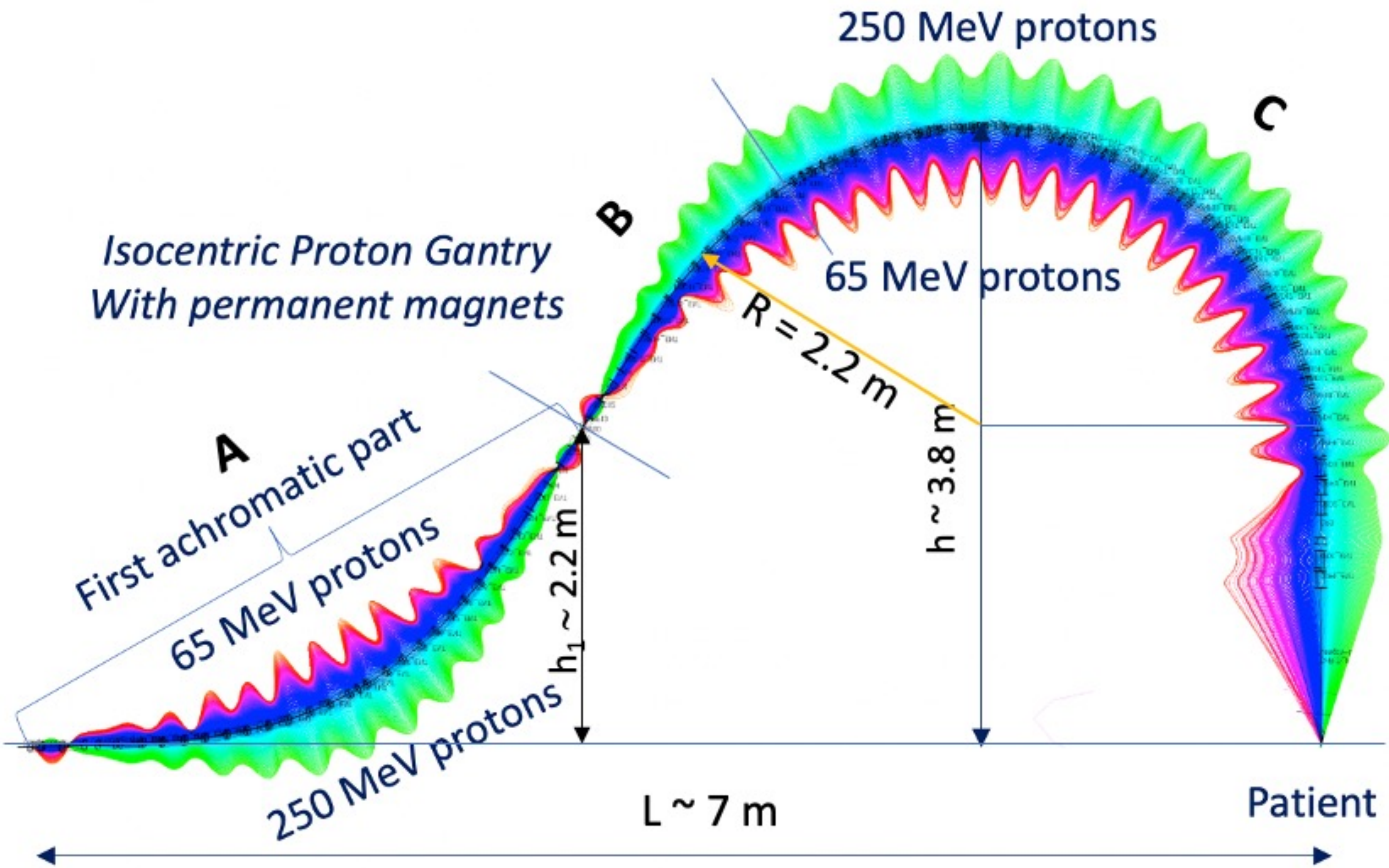




Present VARIAN-SIEMENS gantry

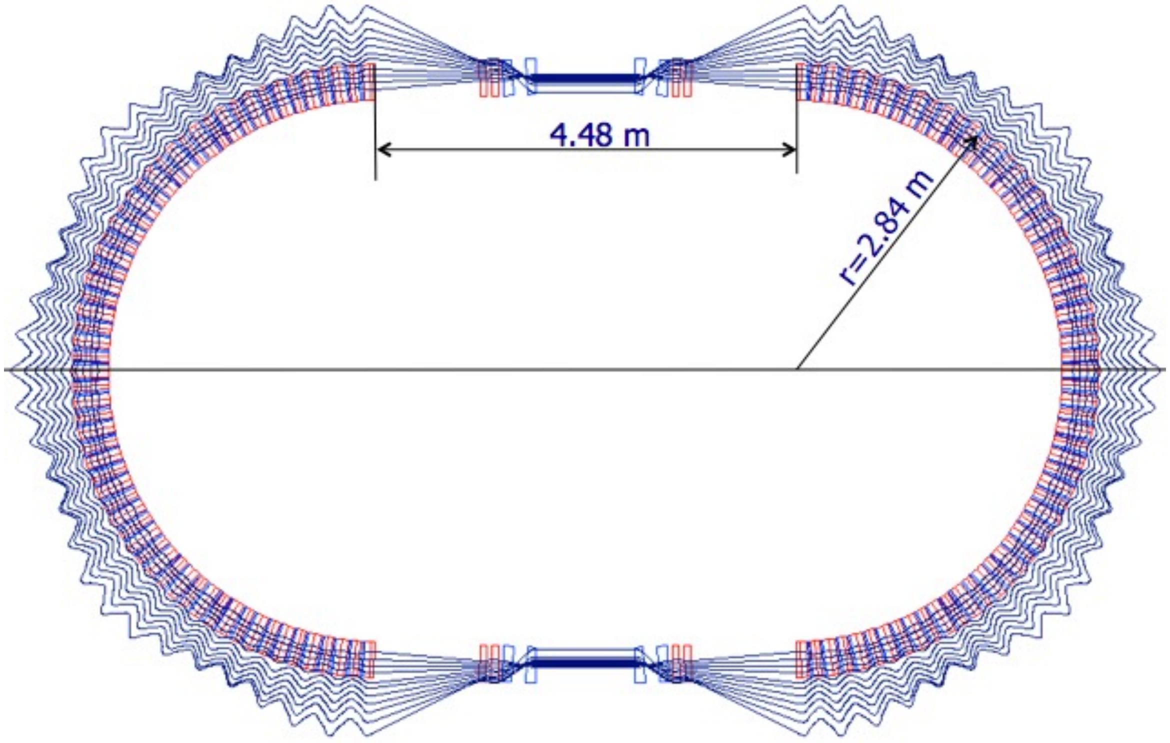


Permanent Magnet Gantry

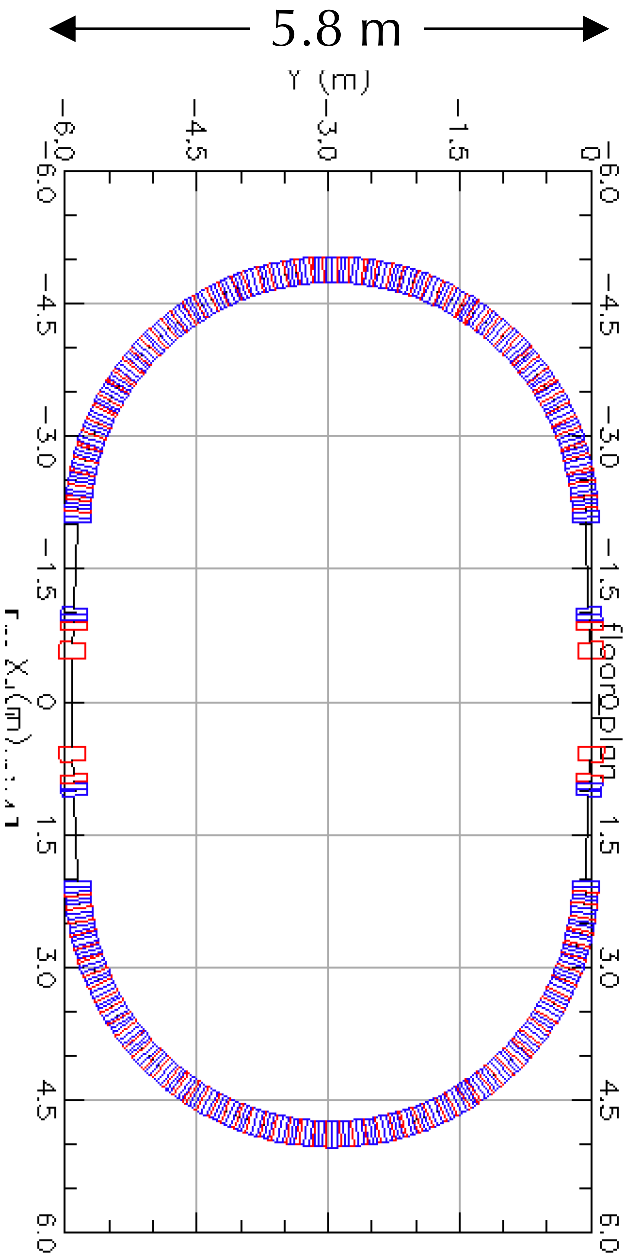


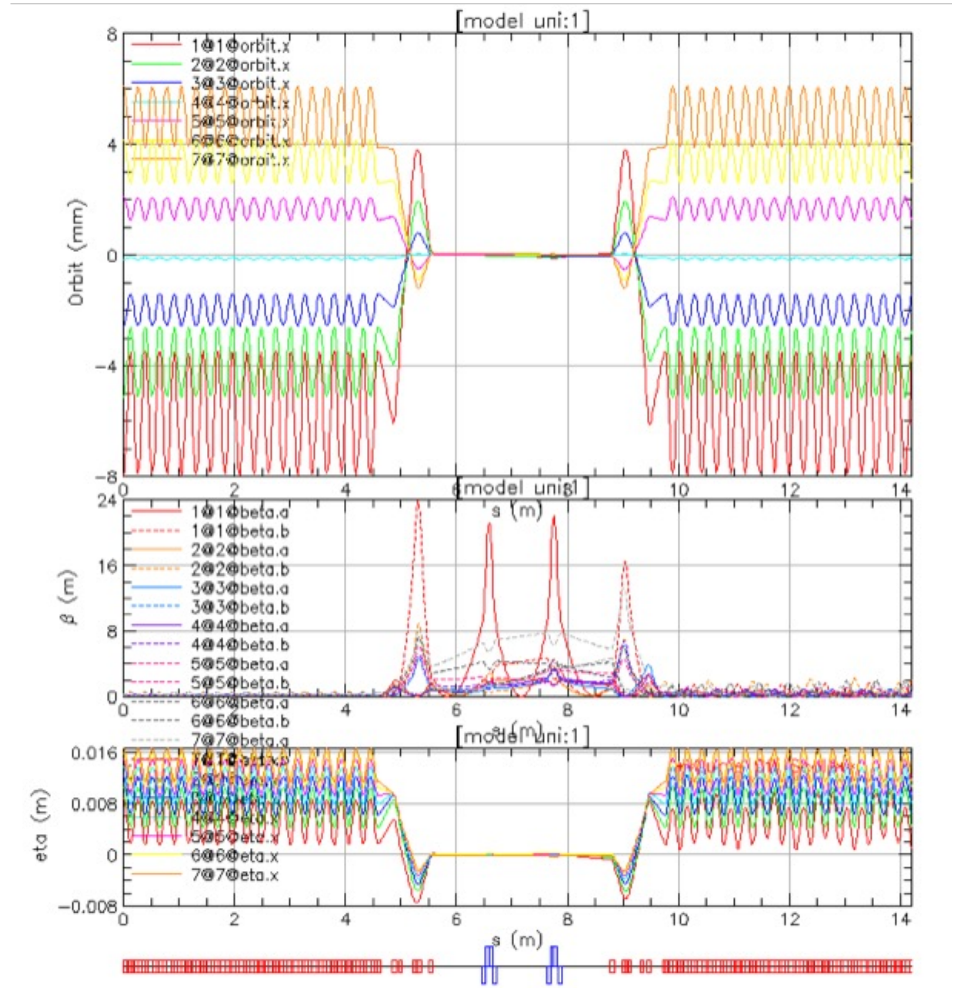
Fast Cycling FFA Synchrotron

The proposal is based on the existing US patent by the PI of this proposal:
D. Trbojevic, Title: "Non-scaling fixed field alternating gradient permanent magnet cancer therapy accelerator", patent number: US 9661737 B2, Date of the patent: May 23, 2017 (belongs to the DOE) .
https://patentimages.storage.googleapis.com/42/5e/92/f7da1cf617d6e3/US9661737.pdf

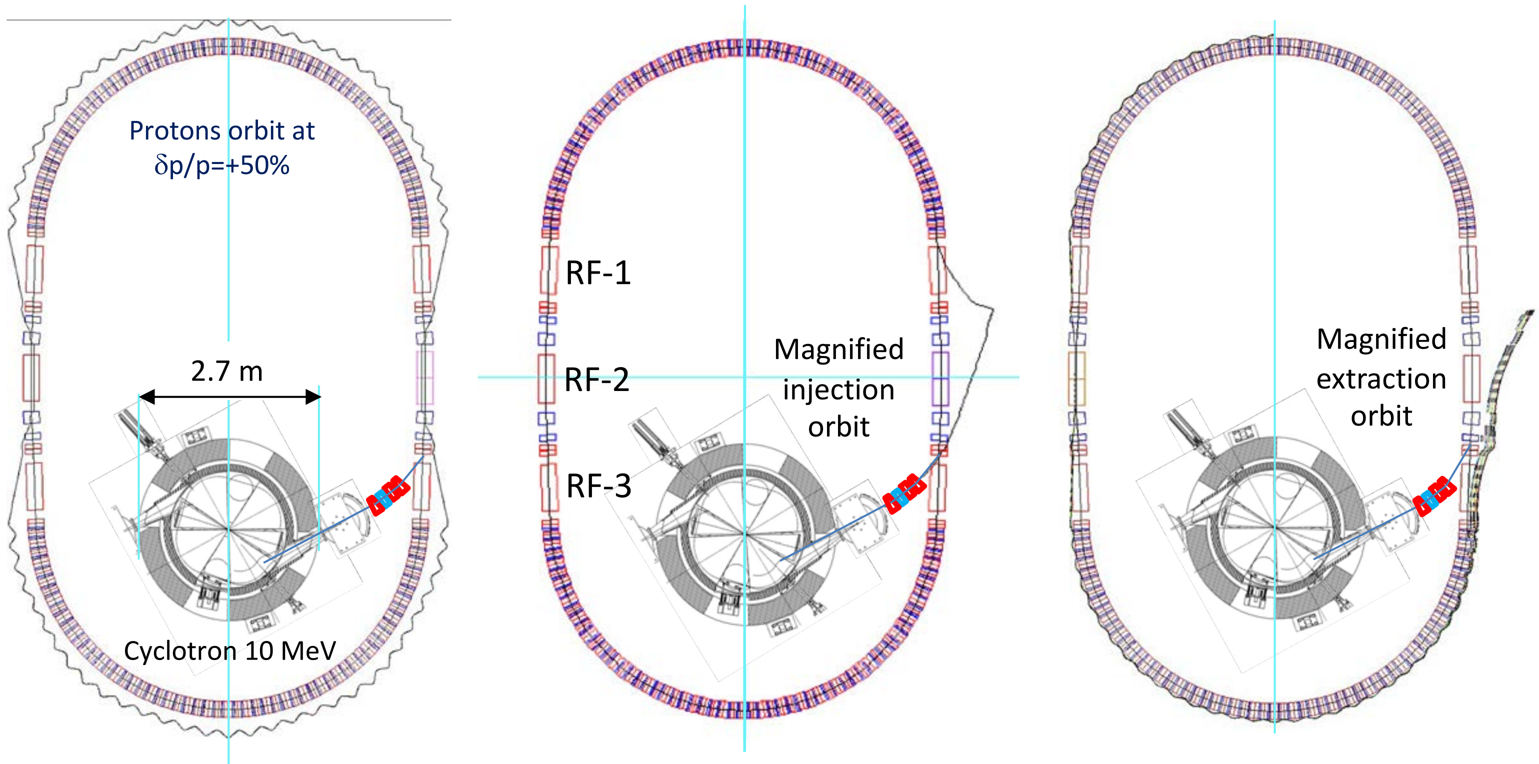


Matching of the Multiple Energy Orbits to the Straight Section





Injection, Extraction and three RF cavities



Synchrotron Beam Size Estimates from the 10 MeV cyclotron

- Input beam is assumed to come from
- the 10 MeV cyclotron
- Measured emittance ~5 π mm mrad

$\beta_x \sim 0.4$ m
$\beta_y \sim 1$ m

At Injection kinetic energy is 10 MeV

γ = *1.010657* $\gamma\beta$*=0.14484*

$$\gamma\beta = \sqrt{\gamma^2-1}\,/\gamma$$

$$\sigma_n = \sqrt{\frac{\beta_{twiss}\varepsilon_n}{6\pi\ \gamma\beta}},\quad 95\%$$

σ_x =1.517 mm

σ_y =2.398 mm

$$\varepsilon_n = \frac{6\pi\ \gamma\beta\ \sigma_n^2}{\beta_{twiss}}$$

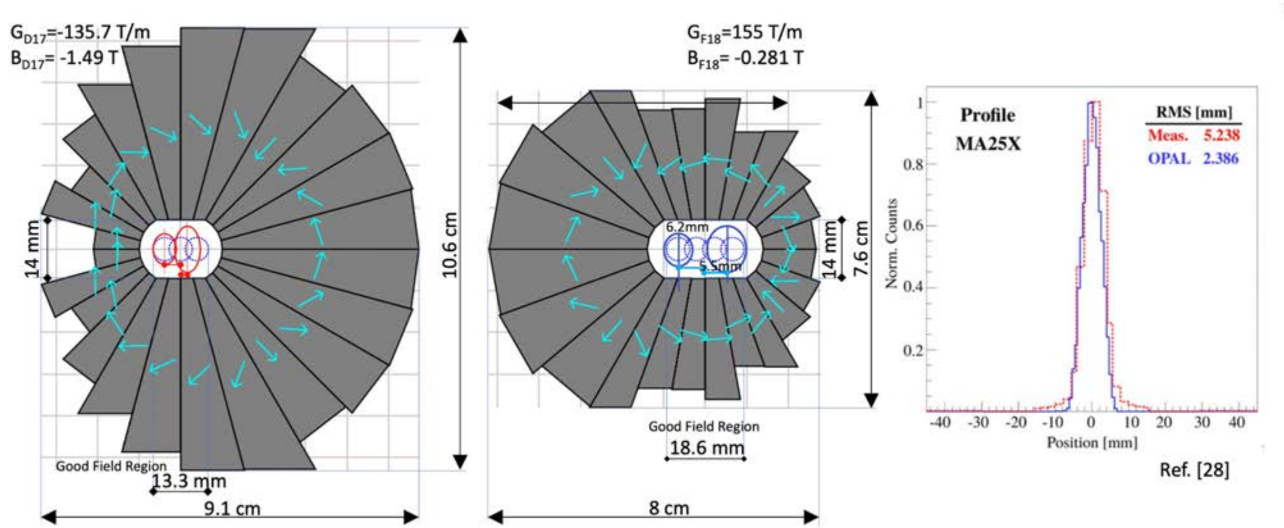
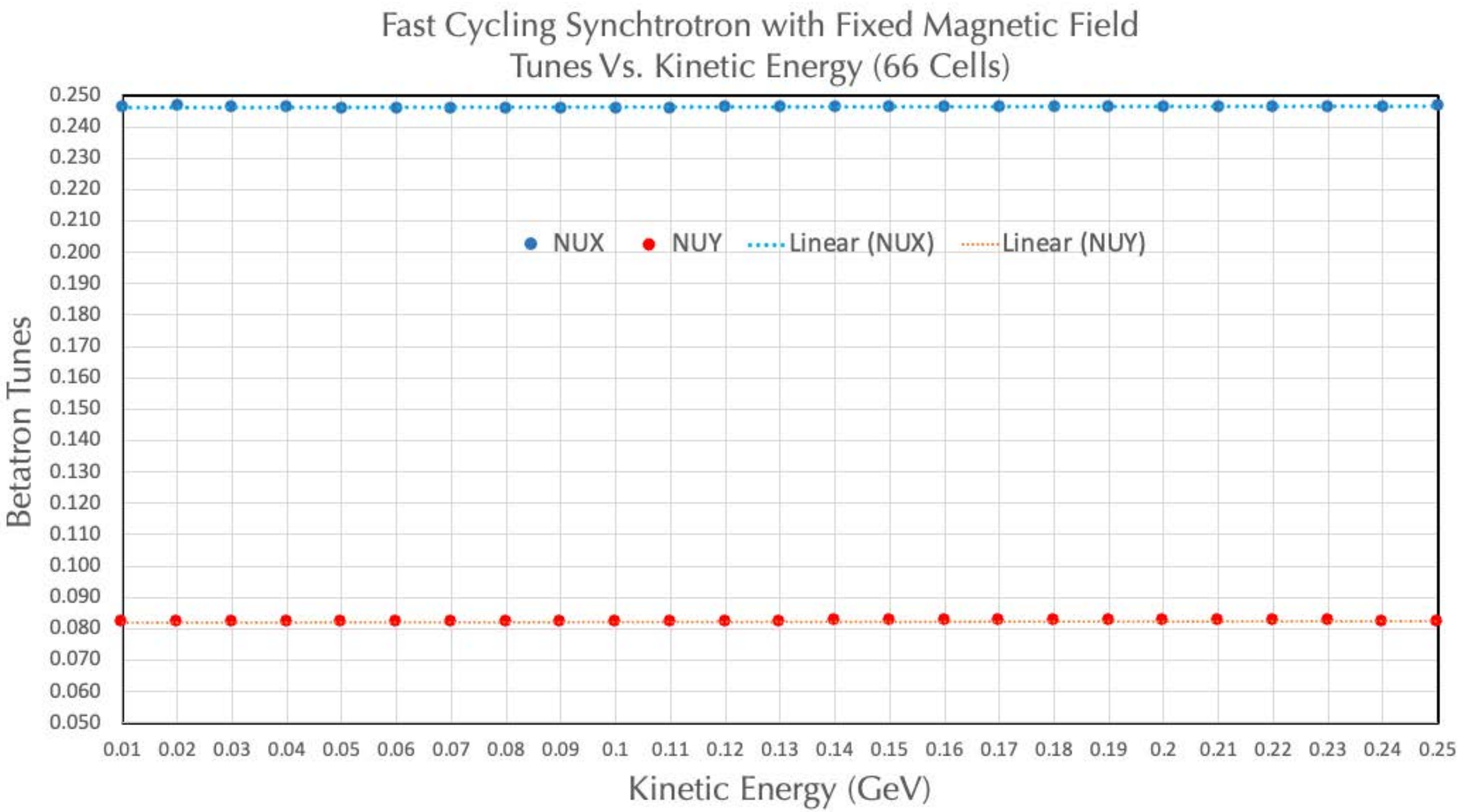
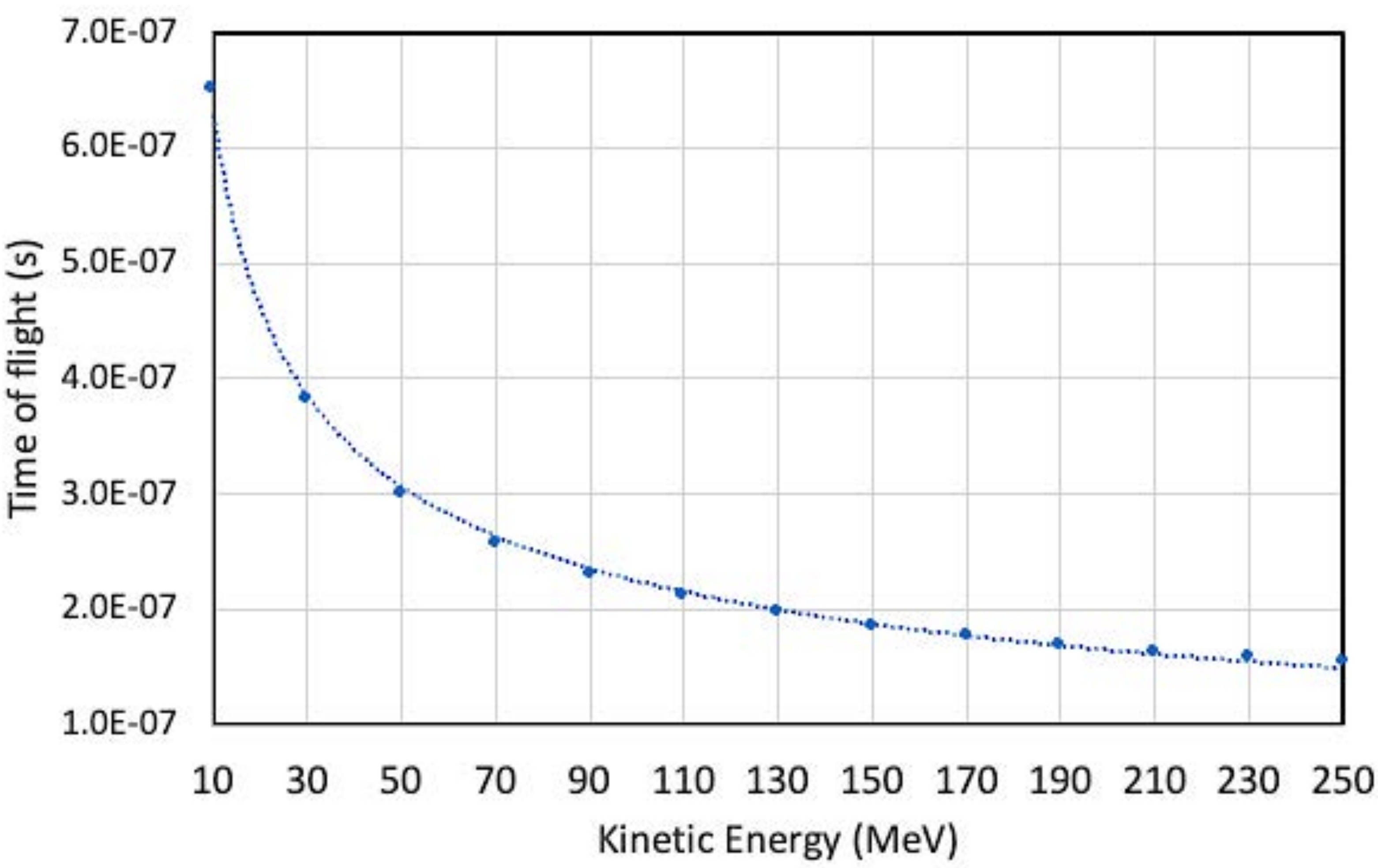


Figure 8: Two oval combined function defocusing (left) and focusing magnet (right) designs of the highest magnetic fields, with beam sizes at both proton kinetic energies of 70 (right side) and 250 MeV (left sides) with the '*PROSCAN*' measured beam profile (right) after the degrader and collimators.

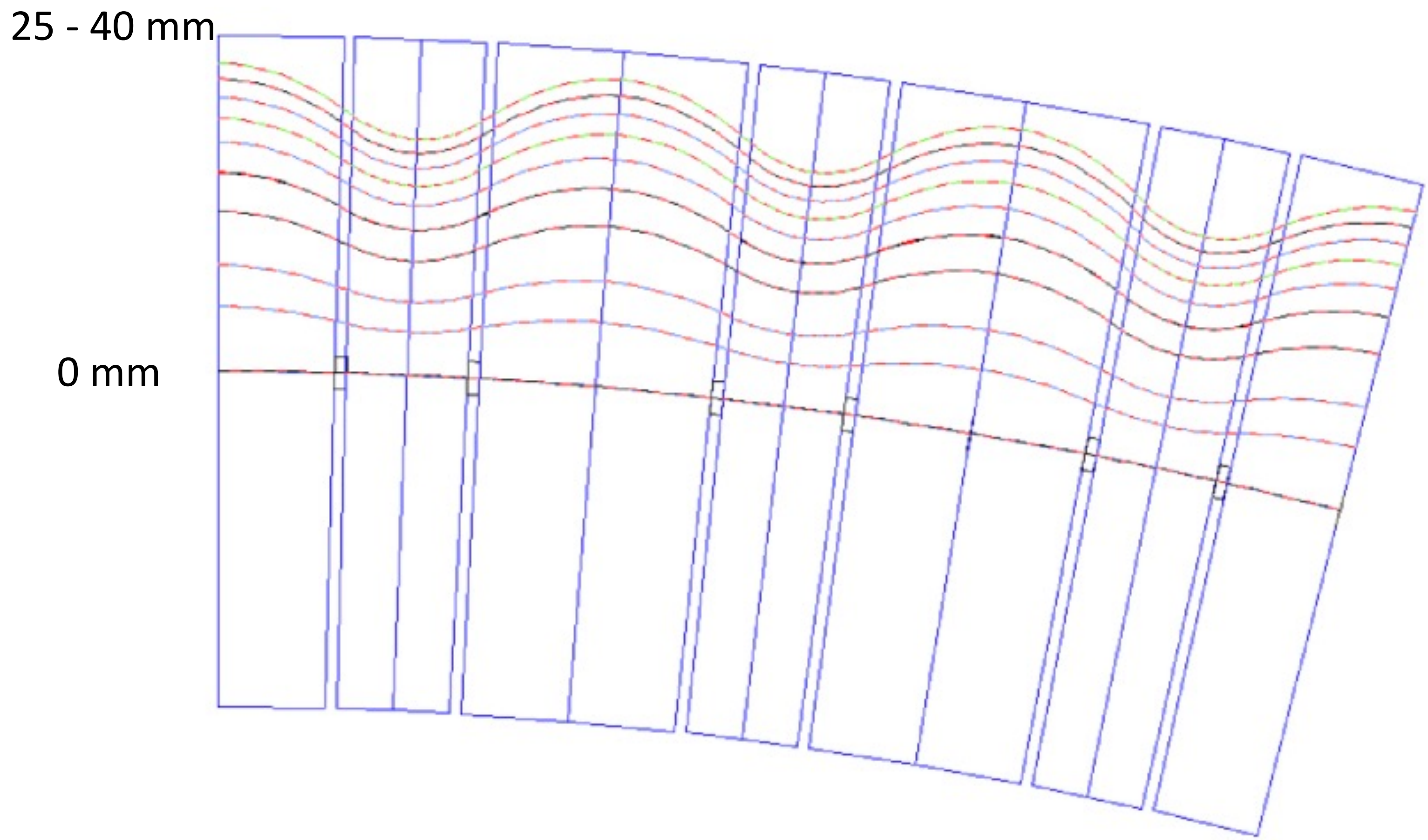
Tunes vs Energy in the FFA Synchrotron



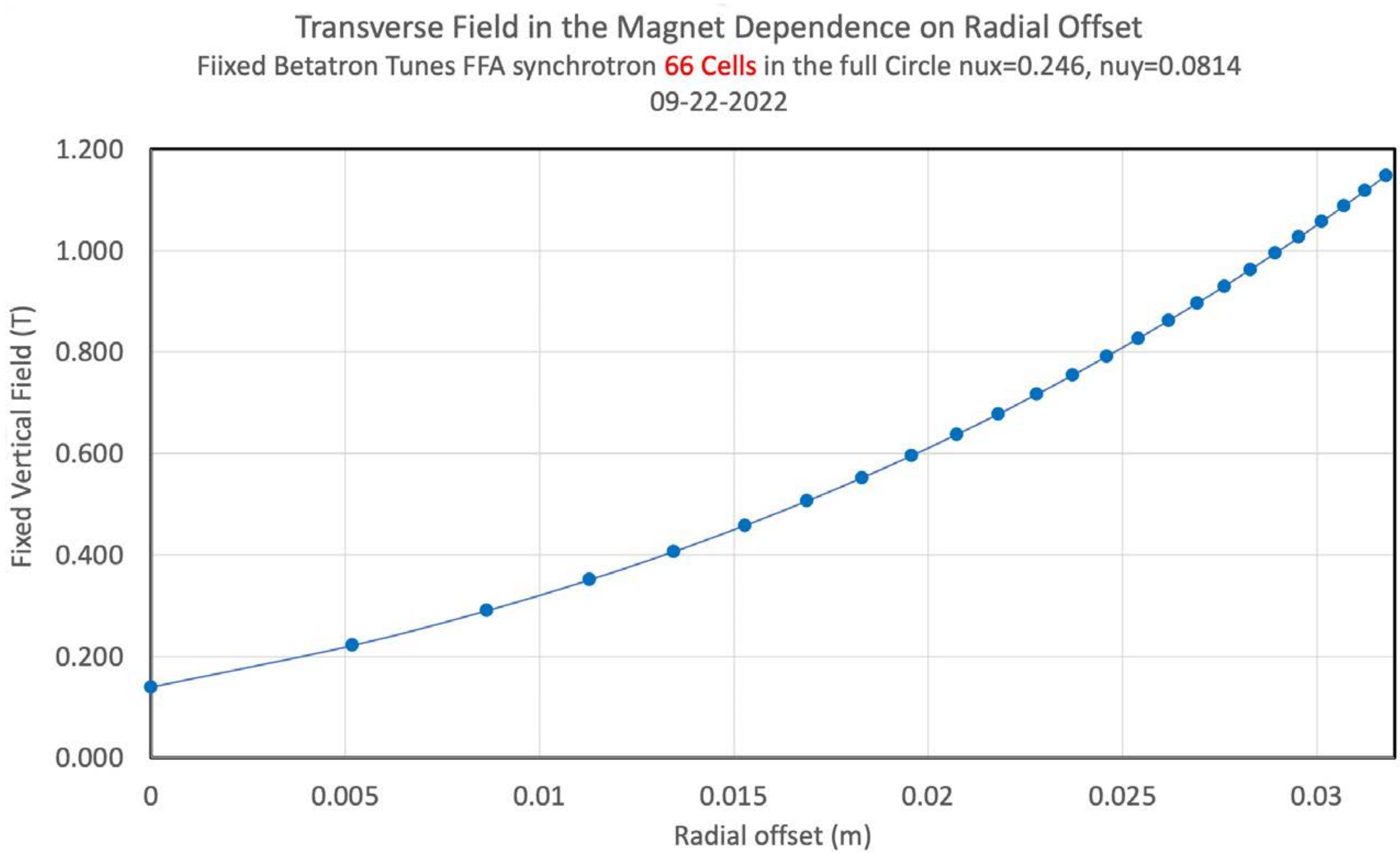
Time of flight dependence during acceleration



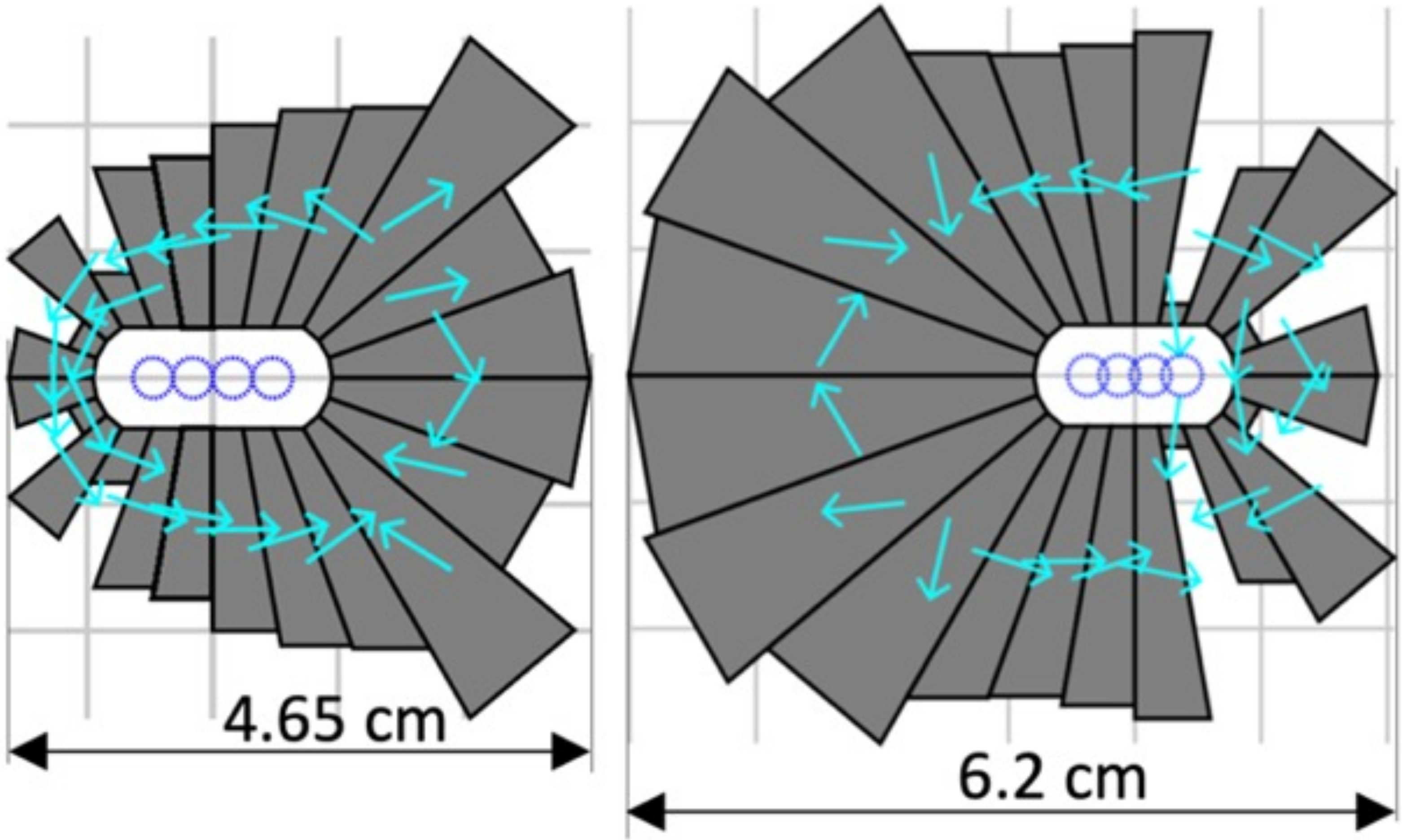
Orbits in the FFA synchrotron After Dynamical Aperture Improvements



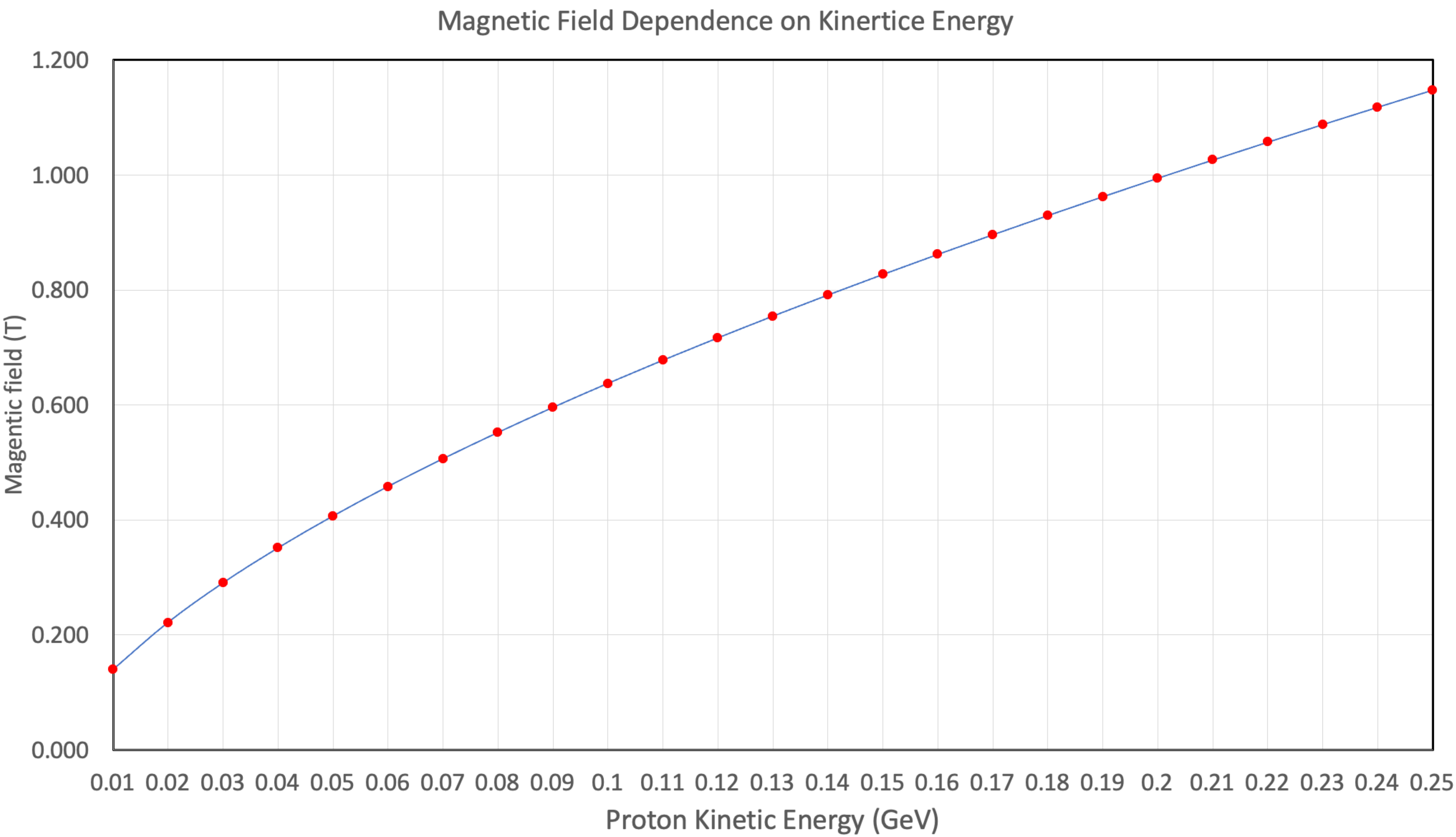
Dynamical Aperture Studies



Permanent Magnets with additional Multipoles



Magnetic field dependence on Energy



Application of Fast-Cycling FFA Synchrotron for Proton Cancer FLASH Radiation Therapy

FLASH cancer therapy: Multiple biological studies and even few patients' treatments around the world in recent years confirmed significant improvements in the cancer treatment results; termed FLASH radiotherapy, involves delivering the same treatment dose *but in much shorter time intervals* — fractions of a second as opposed to minutes — and in far fewer fractions or even a single fraction and therefore at dose rates that are thousands of times higher [1].

The 10 MeV commercially available cyclotron has frequency of 42 MHz and provides 120 mA. This makes $1.8 x 10^7$ protons per bunch. As the synchrotron accelerates 30 bunches this makes per each synchrotron cycle $N_{PROTONS} = 1.15 \times 10^8 \times 30 = 5.4 \times 10^7$. To achieve the 3.8×10^{11} protons for FLASH therapy it is required to run the synchrotron per one FLASH treatment $N = 3.8 \times 10^{11} / 3.23 \times 10^9 \sim 700$. The total time for the FLASH treatment is $t_{FLASH} = 700 \times 898\ \mu s = 632$ ms!

[1] Konrad P. Nesteruk and Serena Psoroulas, "FLASH Irradiation with Proton Beams: Beam Characteristics and Their Implications for Beam Diagnostics", applied sciences, 2021, 11, 2170, https://doi.org/10.3390/app11052170

SUMMARY

- The 10-250 MeV fast cycling proton synchrotron with cycling of 1.3 kHz is the fastest synchrotron proposed. The synchrotron rates are in a range are 15-60 Hz.
- In proton acceleration within the non-relativistic energy range the main problem is the limitation **on the speed of magnetic field response to the change of energy**. This limitation **is now eliminated by using the permanent magnets** for the same energy range.
- One of possible application is in FLASH cancer radiation therapy.
- **This proof of principle accelerator would enable new areas of research using the same principle but building the magnets with multi-layer superconducting wires.**

Advantages:

1. The Fast-cycling permanent magnet synchrotron with 6x10 m area is the best possible synchrotron for the cancer proton FLASH radiation therapy it is cost efficient, does not require electrical power, magnets are very small and light.
2. Small, energy efficient, and fast cycling proton drivers for NPP and HEP.
3. Future Fast cycling synchrotron accelerator driven system (ADS) for transmutation of nuclear waste.