Fixed Field Accelerators for Muon Physics and More

J. Pasternak

11/02/2021, IPPP

Outline

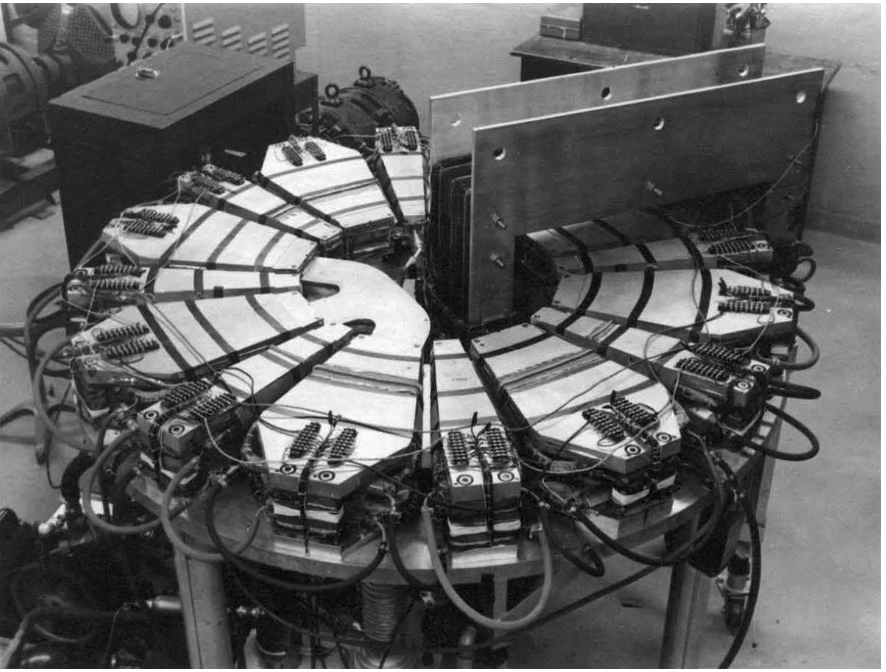
- Introduction: What is FFA?
- nuSTORM
- PRISM
- VFFA
  - For ISIS-II
  - For a Muon Collider
- LhARA
- Conclusions

FFA –Fixed Field Alternating gradient accelerators

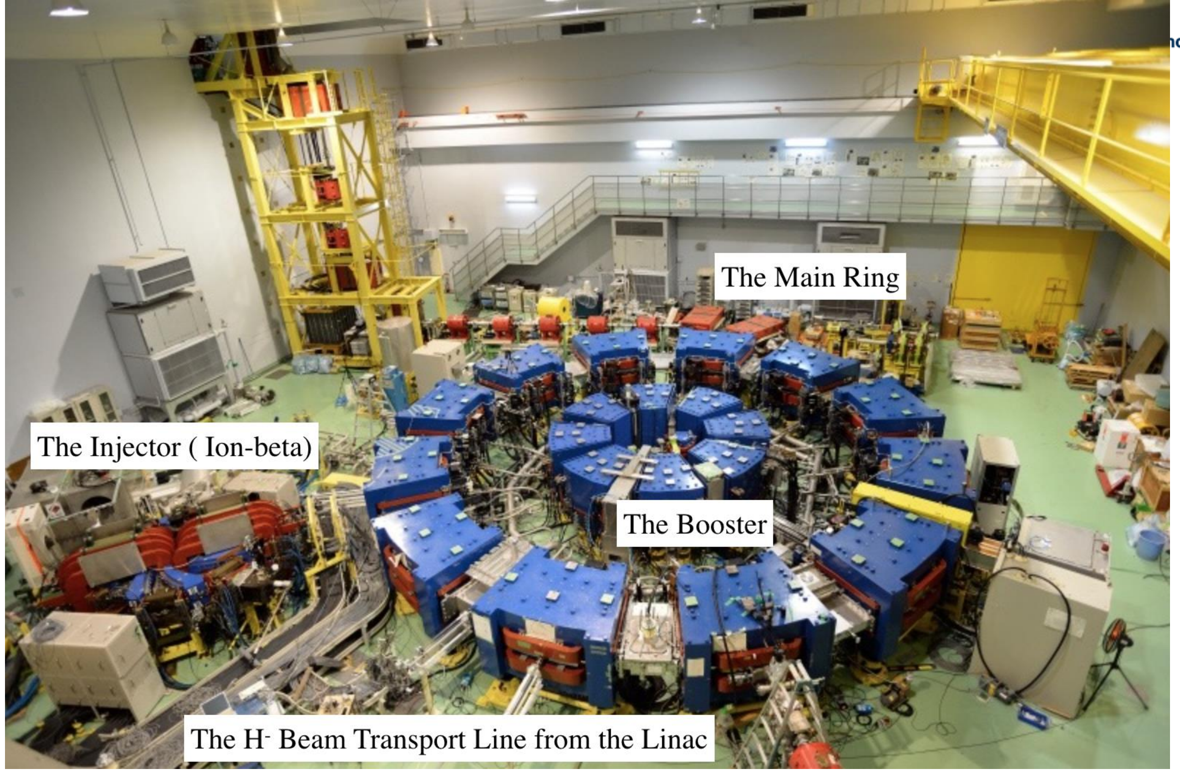
- Invented independently by A. Kolomensky, T. Okhava and K. Symon in 50ties
- They enjoyed rapid developments at the time and almost vanished afterwards
- They came back in 2000 with the first proton FFA developed at KEK by Y. Mori's group

Imperial College London

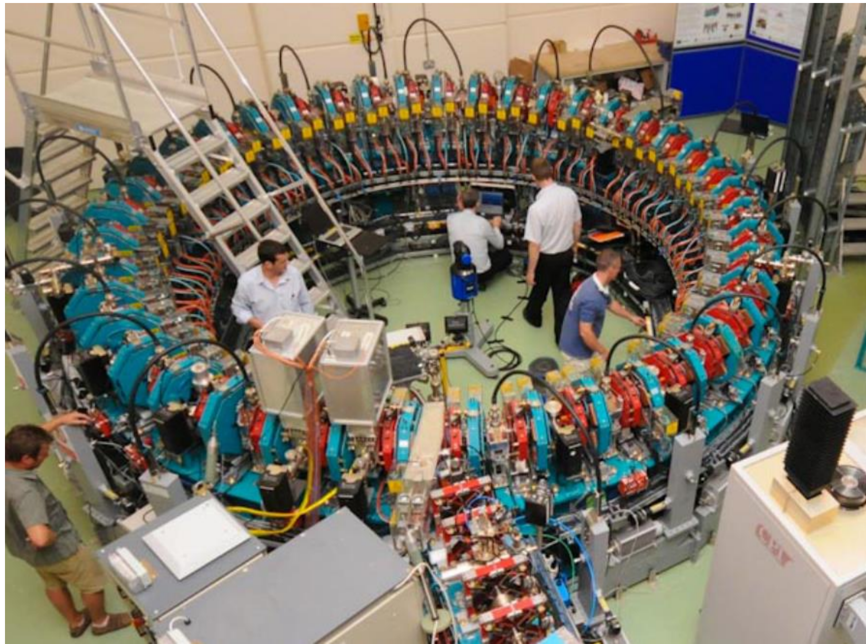
FFA and their properties



Mark I, first FFA



FFA complex at KURNS

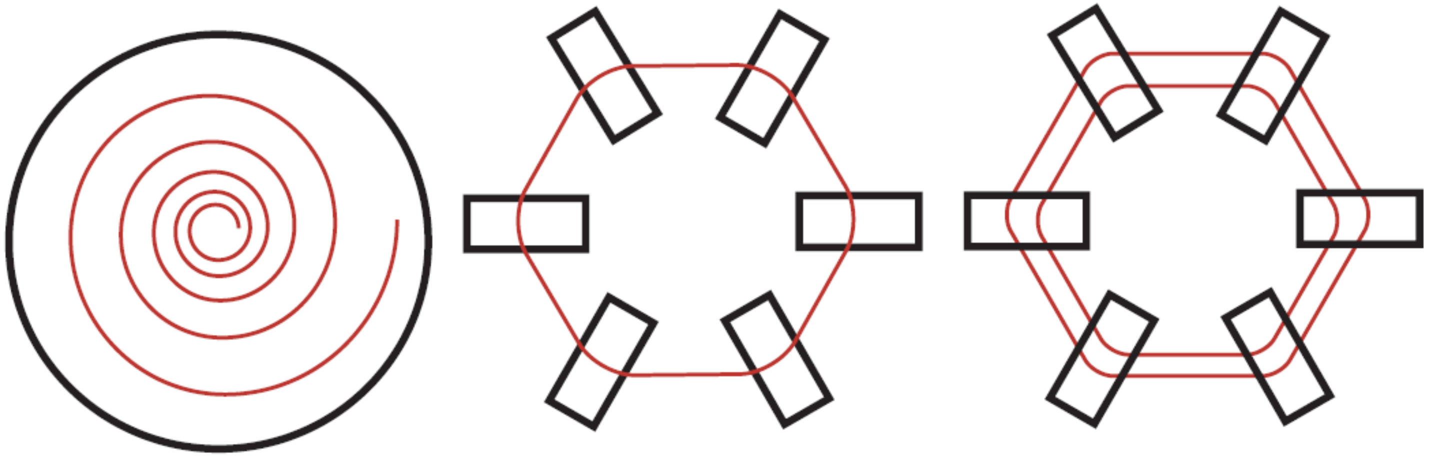


EMMA in DL

Advantages of FFAs for muon accelerators:

- Lack of ramping
- Large intrinsic momentum acceptance
- Typically large transverse acceptance

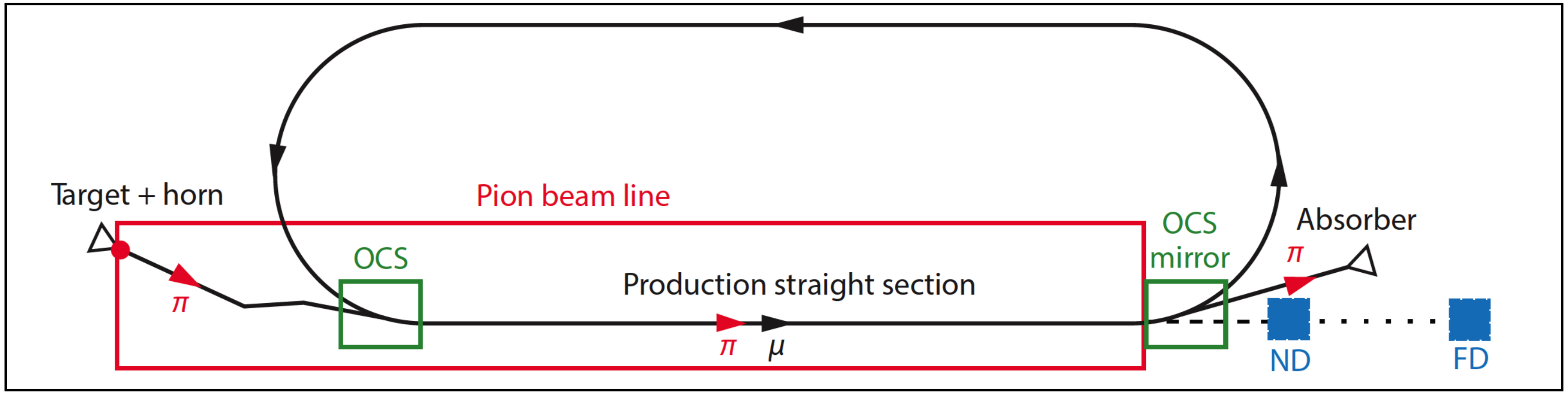
FFA vs other circular machines



Machine	Cyclotron	Synchrotron	FFA
Magnetic field	constant	changing	constant
RF frequency	constant	changing	changing (not always)
Orbit	changing	constant	changing
Tune	changing	constant	constant (not always)

nuSTORM - Origin - Idea

- nuSTORM (`NeUtrinos from STORed Muons') is a facility based on a low-energy muon decay ring.
- Can use existing proton driver (like SPS at CERN)
- Conventional pion production and capture (horn)
  - Quadrupole pion-transport channel to decay ring
  - Direct injection of pions into the decay ring to form circulating muon beam subsequently used as a source of neutrinos w/o a kicker

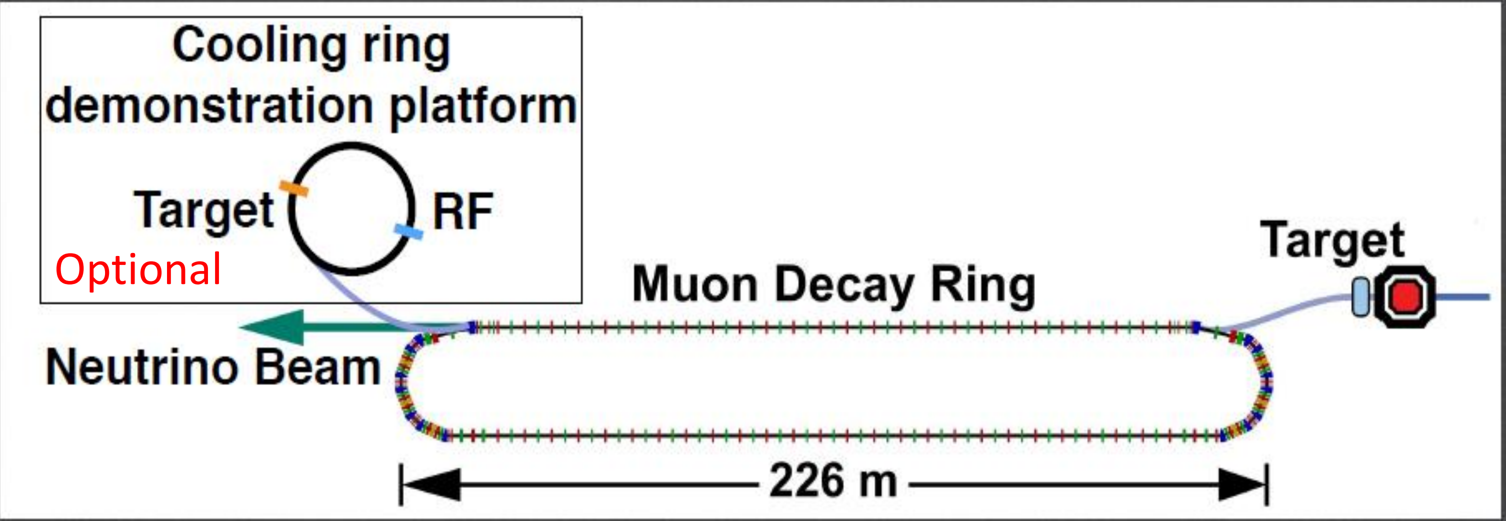


nuSTORM - Motivation

- Neutrino interaction physics – nuSTORM can measure neutrino cross sections precisely
  - Significantly reduce the main source of systematic errors for long base-line oscillation experiments
- Short baseline neutrino oscillation physics – search for sterile neutrinos
- Accelerator and Detector Technology Test Bed
  - Proof of principle for the Neutrino Factory concept
  - Muon Collider R&D platform

νSTORM

nuSTORM Overview



1. Facility to provide a muon beam for precision neutrino interaction physics
2. Study of sterile neutrinos
3. Accelerator & Detector technology test bed
   - Potential for intense low energy muon beam
   - Enables μ decay ring R&D (instrumentation) & technology demonstration platform
   - Provides a neutrino Detector Test Facility
   - Test bed for a new type of conventional neutrino beam

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

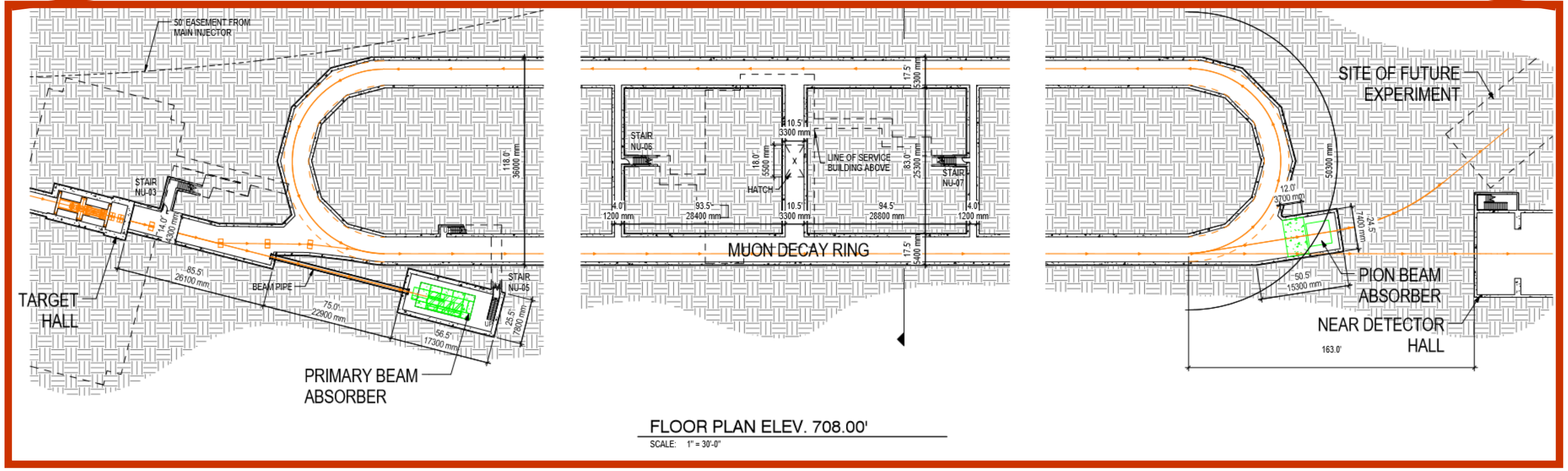
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

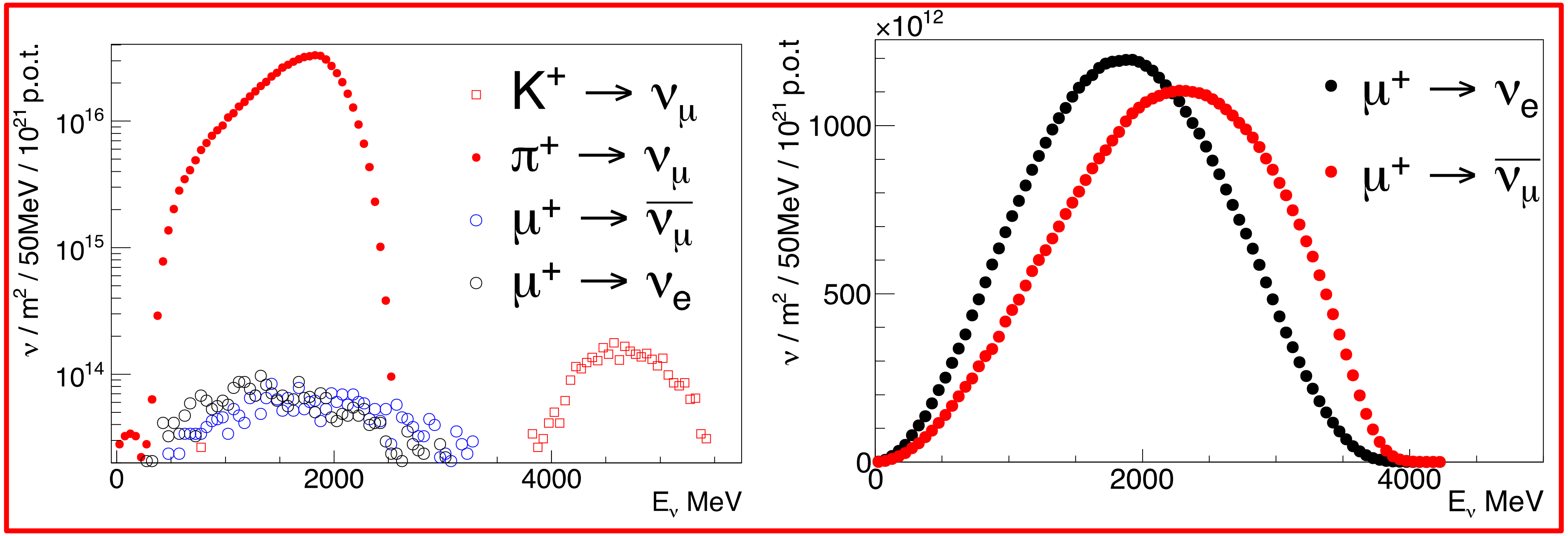
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

nuSTORM @ FNAL

- Serious proposal developed for FNAL
- FNAL taken to project definition report stage

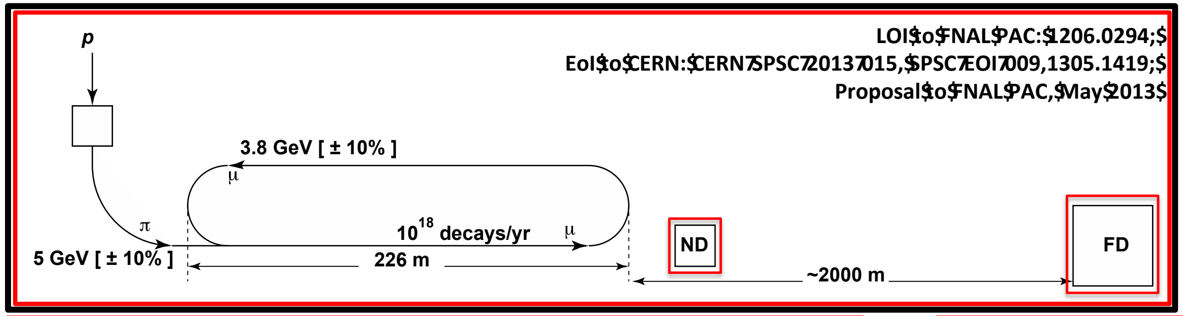


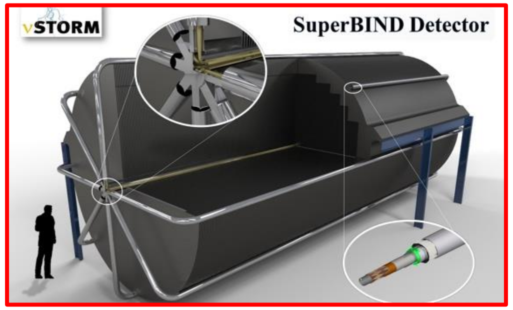
Neutrino Flux

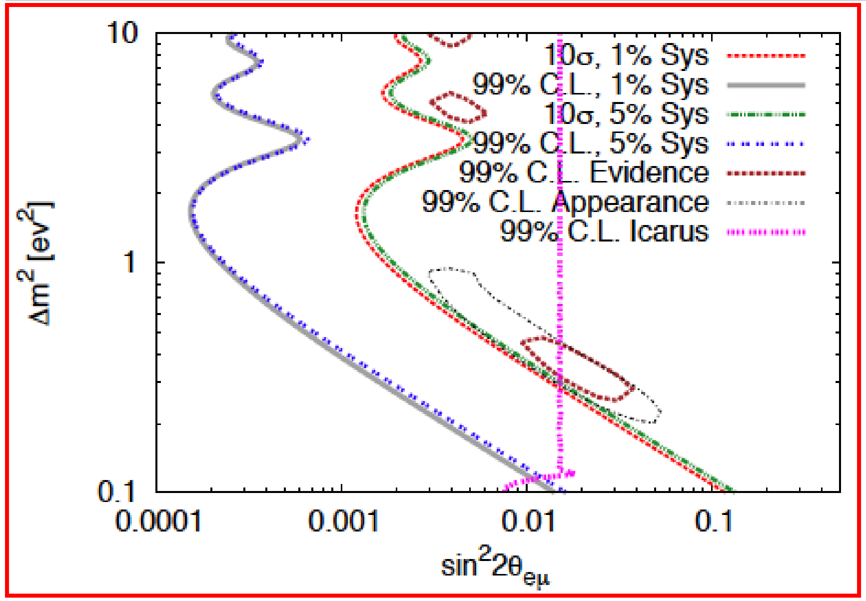


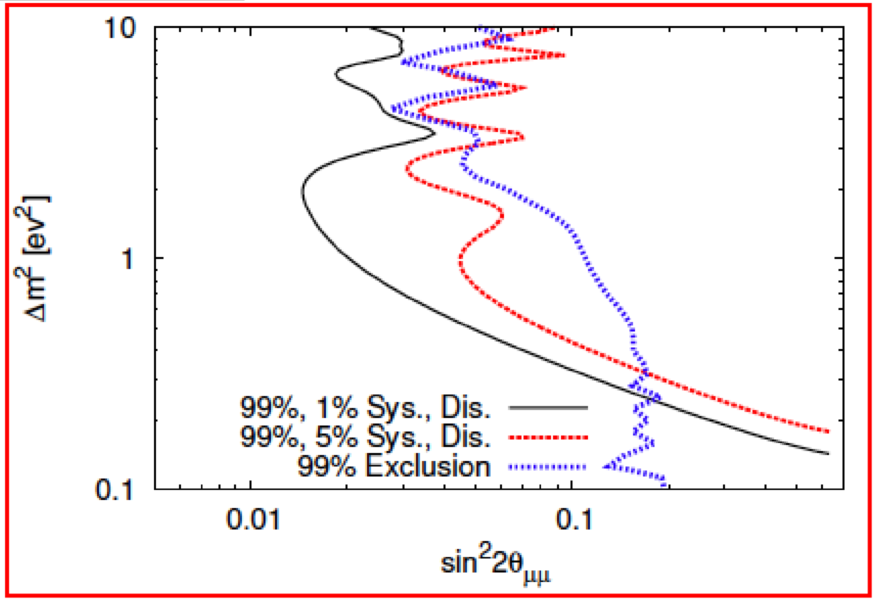
- Multiple channels available
- Good time separation
- Good source of electron neutrinos!
- Polarity of muon beam would be switched

Sterile neutrino search @ FNAL



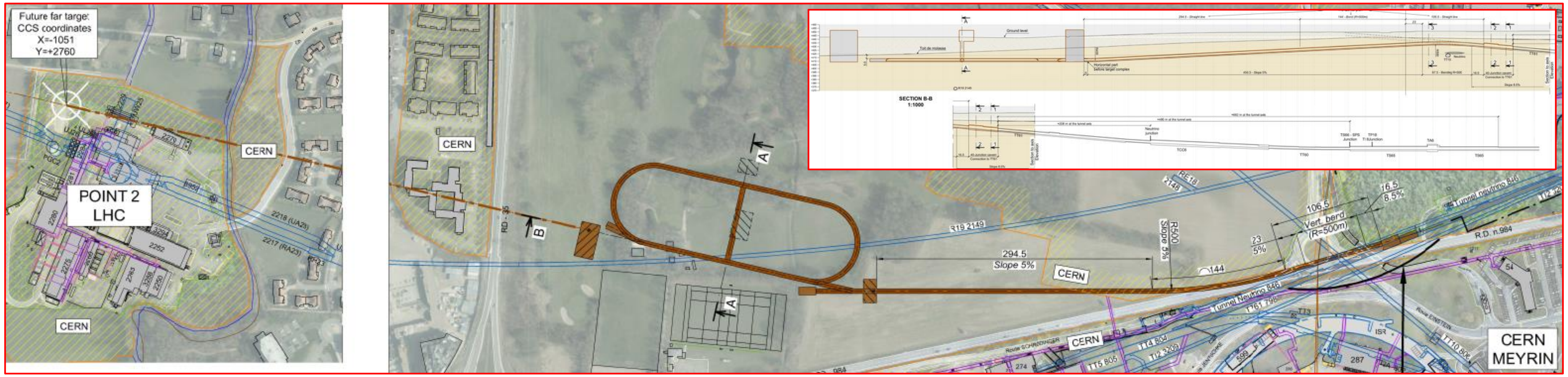






Adey et al., PRD 89 (2014) 071301

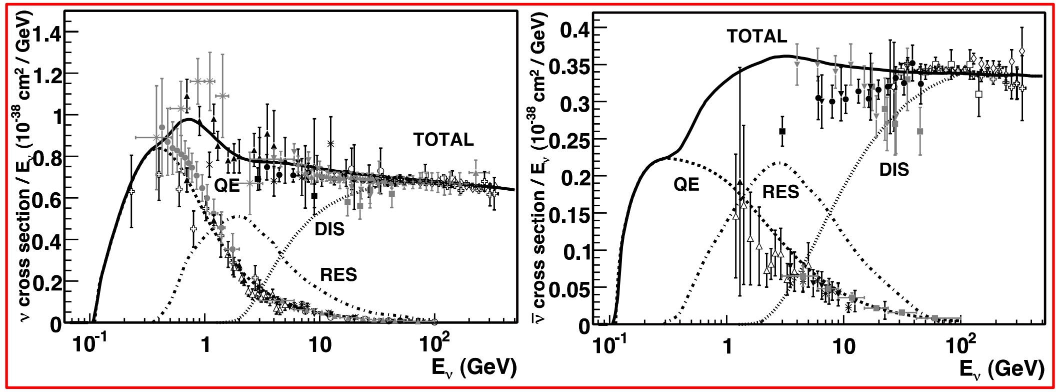
nuSTORM siting at CERN



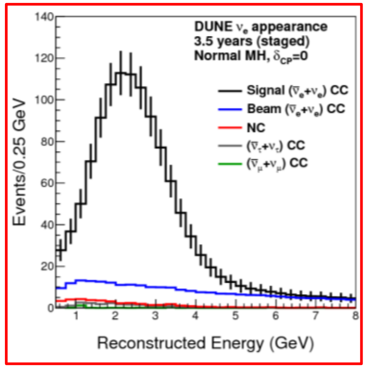
- Extraction from SPS through existing tunnel
- Siting of storage ring:
  - Allows measurements to be made ‘on or off axis’
  - Preserves sterile-neutrino search option

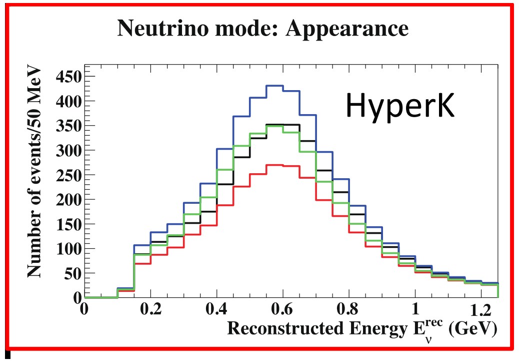
Cross section programme: novel energy range

- Guidance from:
  - Models:
    - Region of overlap 0.5—8 GeV
  - DUNE/Hyper-K far detector spectra:
    - 0.3—6 GeV



- Cross sections depend on:
  - Q^2 and W:
    - Assume (or specify) a detector capable of:
      - Measuring exclusive final states
      - Reconstructing Q^2 and W
    - → $E_\mu < 6$ GeV





- So, stored muon energy range:

$1 < E_\mu < 6$ GeV

Storage ring designs

- FODO design (example: A. Liu's design)
  - Separate-function magnets
  - Relative momentum acceptance ~±9%
  - Large, natural chromaticity, some losses induced by resonances
  - Zero dispersion in the injection/production straight
    - Good efficiency of muon storage and neutrino production
- Full FFA (Fixed Field Alternating gradient) design
  - Combined function magnets
  - Relative momentum acceptance ~±16% or more
  - Zero chromaticity, no resonance crossing
  - Small dispersion and scalope angle in the the injection/production straight
    - Reduced efficiency of muon storage and some effects on the neutrino spectrum
- Hybrid design
  - Combined function magnets in the arcs and in the return straight, quads in the injection/production straight
  - Relative momentum acceptance ~±16%
  - Relatively small chromaticity originating from the injection/production straight
    - Tune spread between integer and half integer lines
    - Some extra correction possible
  - Zero dispersion in the injection/production straight
    - Good efficiency of muon storage and neutrino production

Hybrid design assumptions

- Long straight sections kept at 180m (as in FNAL designs)
- Arc modified to accommodate higher momentum (up to 6.5 GeV/c orbit)
- Dispersion in the arcs is kept smaller to reduce the magnet aperture
- FFA parts (both arcs and straight FFA) were made with a fully transparent optics (both phase advances modulo π).
- For the quad production the solution made of regular cells is selected
- Extra matching sections added in the straight FFA part

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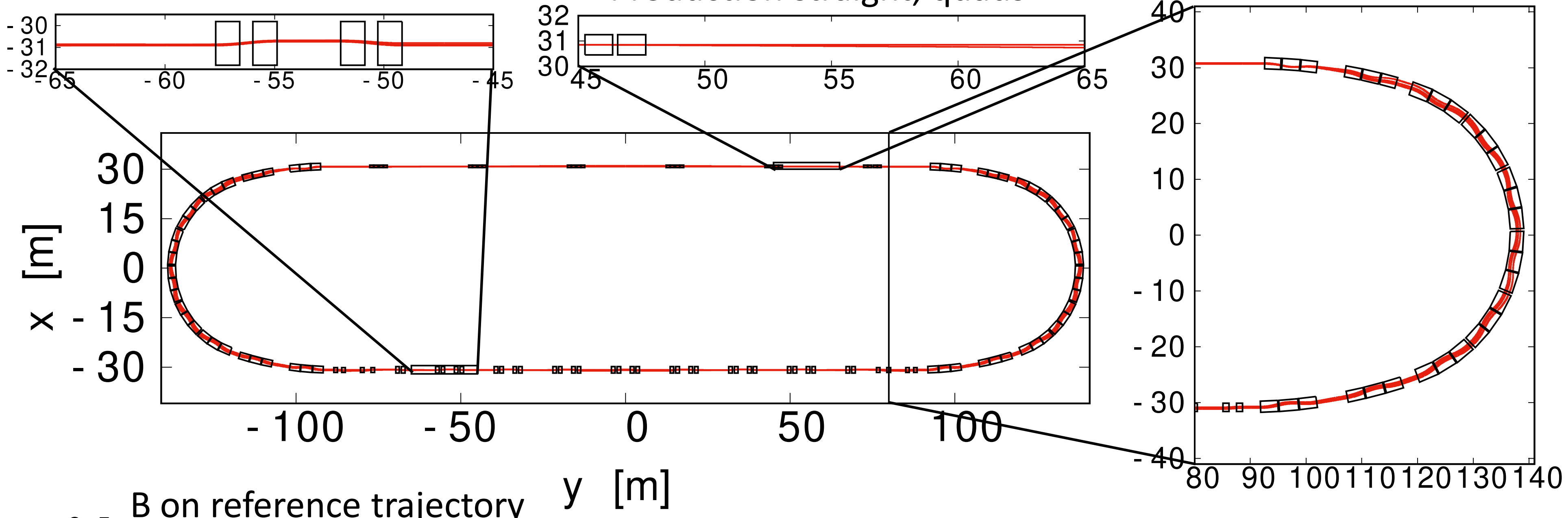
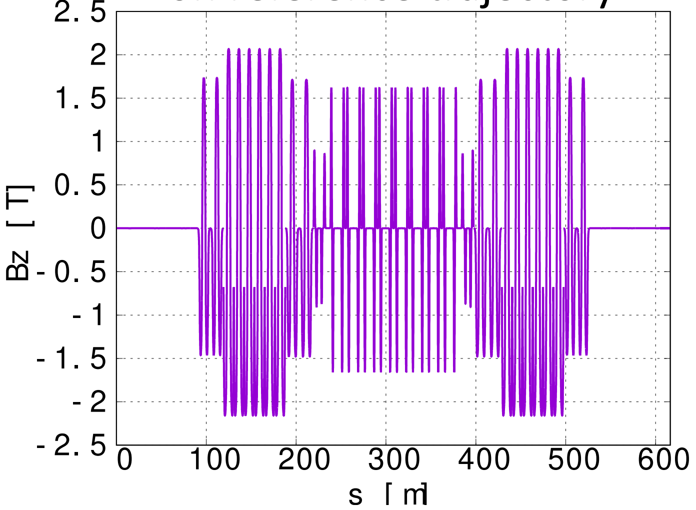
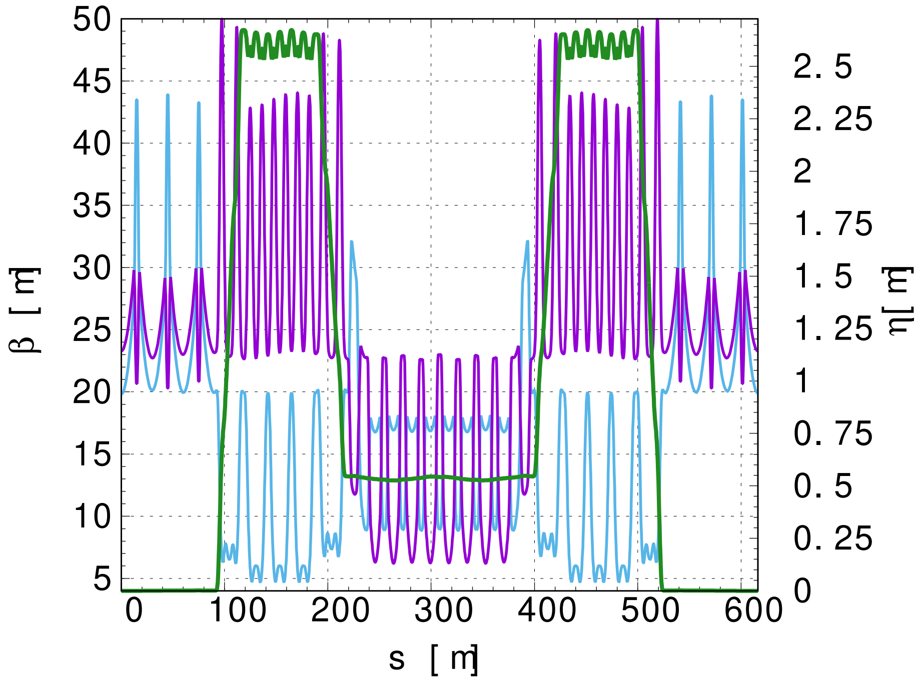
Hybrid design

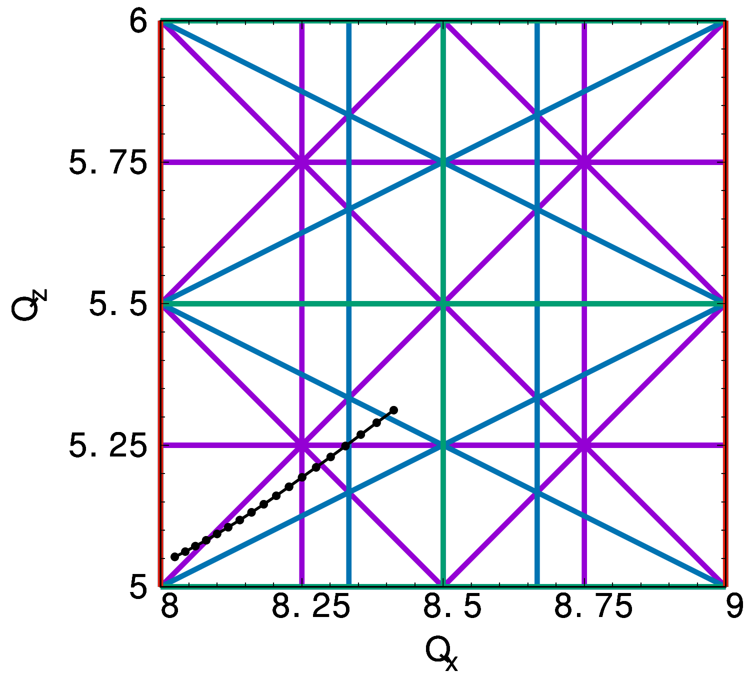




- SC magnets in the arcs
- NC magnets in the straights
- Several types of the lattice cells combined
- Injection in the dedicated straight at the end of the arc

Hybrid optics

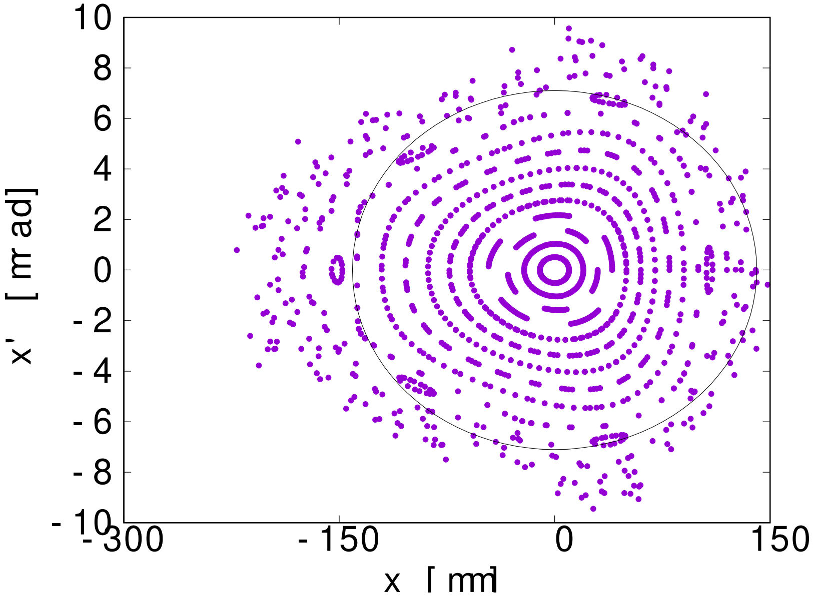


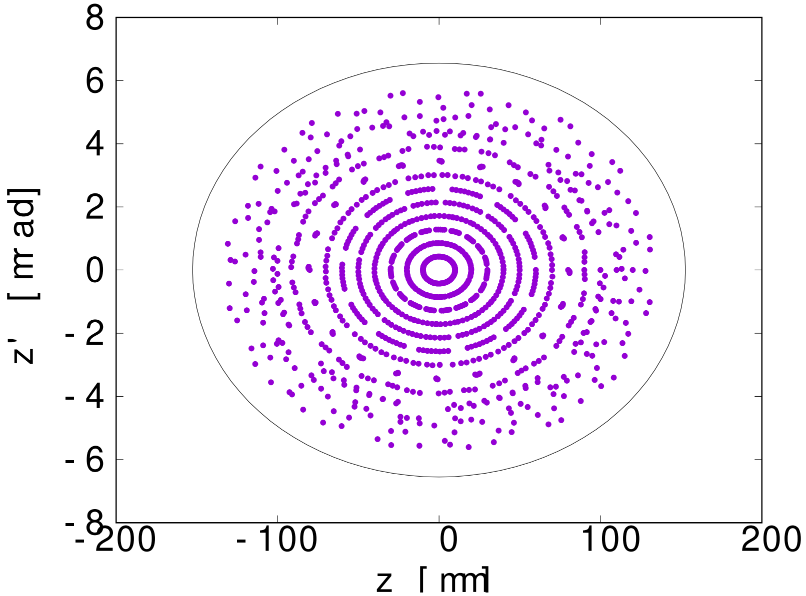


Tune shift for ±16% relative momentum spread

- Good dispersion matching to zero in the production straight
- Relatively large beta functions in the production straight for good neutrino production efficiency

Hybrid ring, tracking





- Good DA in both planes
- Cross check with PyZgoubi (work in progress)
- Tracking with the full beam distribution (next step)

Current focus and near future plans for Hybrid design

- Work on the Hybrid FFA design:
  - Cross check between codes
  - Possibly a modest chromaticity correction to reduce the tune spread to ~0.2
  - Further design work on injection
- Evaluation of the performance: momentum spread, DAs, transmission and the neutrino fluxes, and comparison with other lattices (FODO, full FFA).

Input to the European Particle Physics Strategy Update 2018-2020

European Strategy Update

Americas:	29
Asia:	7
Europe:	81
Total:	***117***

nuSTORM at CERN: Executive Summary

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Abstract

The Neutrinos from Stored Muons, nuSTORM, facility has been designed to deliver a definitive neutrino-nucleus scattering programme using beams of $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ from the decay of muons confined within a storage ring. The facility is unique, it will be capable of storing $\mu^\pm$ beams with a central momentum of between 1 GeV/c and 6 GeV/c and a momentum spread of 16%. This specification will allow neutrino-scattering measurements to be made over the kinematic range of interest to the DUNE and Hyper-K collaborations. At nuSTORM, the flavour composition of the beam and the neutrino-energy spectrum are both precisely known. The storage-ring instrumentation will allow the neutrino flux to be determined to a precision of 1% or better. By exploiting sophisticated neutrino-detector techniques such as those being developed for the near detectors of DUNE and Hyper-K, the nuSTORM facility will:

- Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of $\overset{(-)}{\nu}_e A$ and $\overset{(-)}{\nu}_\mu A$ scattering cross-sections with percent-level precision;
- Provide a probe that is 100% polarised and sensitive to isospin to allow incisive studies of nuclear dynamics and collective effects in nuclei;
- Deliver the capability to extend the search for light sterile neutrinos beyond the sensitivities that will be provided by the FNAL Short Baseline Neutrino (SBN) programme; and
- Create an essential test facility for the development of muon accelerators to serve as the basis of a multi-TeV lepton-antilepton collider.

To maximise its impact, nuSTORM should be implemented such that data-taking begins by ≈ 2027/28 when the DUNE and Hyper-K collaborations will each be accumulating data sets capable of determining oscillation probabilities with percent-level precision.

With its existing proton-beam infrastructure, CERN is uniquely well-placed to implement nuSTORM. The feasibility of implementing nuSTORM at CERN has been studied by a CERN Physics Beyond Colliders study group. The muon storage ring has been optimised for the neutrino-scattering programme to store muon beams with momenta in the range 1 GeV to 6 GeV. The implementation of nuSTORM exploits the existing fast-extraction from the SPS that delivers beam to the LHC and to HiRadMat. A summary of the proposed implementation of nuSTORM at CERN is presented below. An indicative cost estimate and a preliminary discussion of a possible time-line for the implementation of nuSTORM are presented the addendum.

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Addendum to the Executive Summary of nuSTORM at CERN

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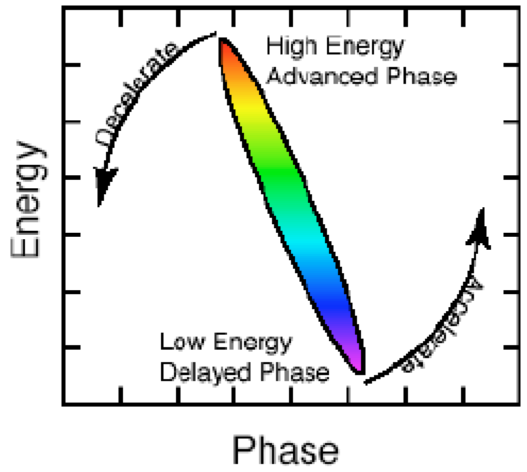
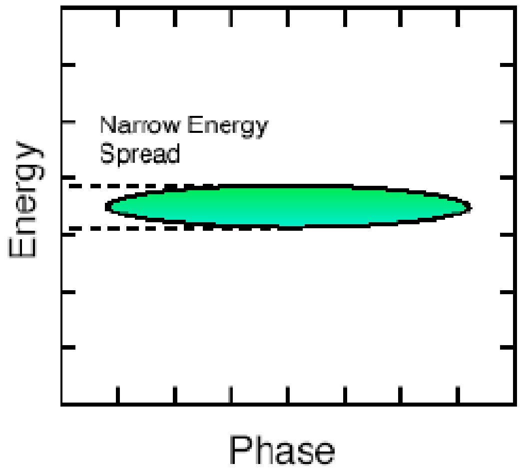
+ Snowmass LOI submitted

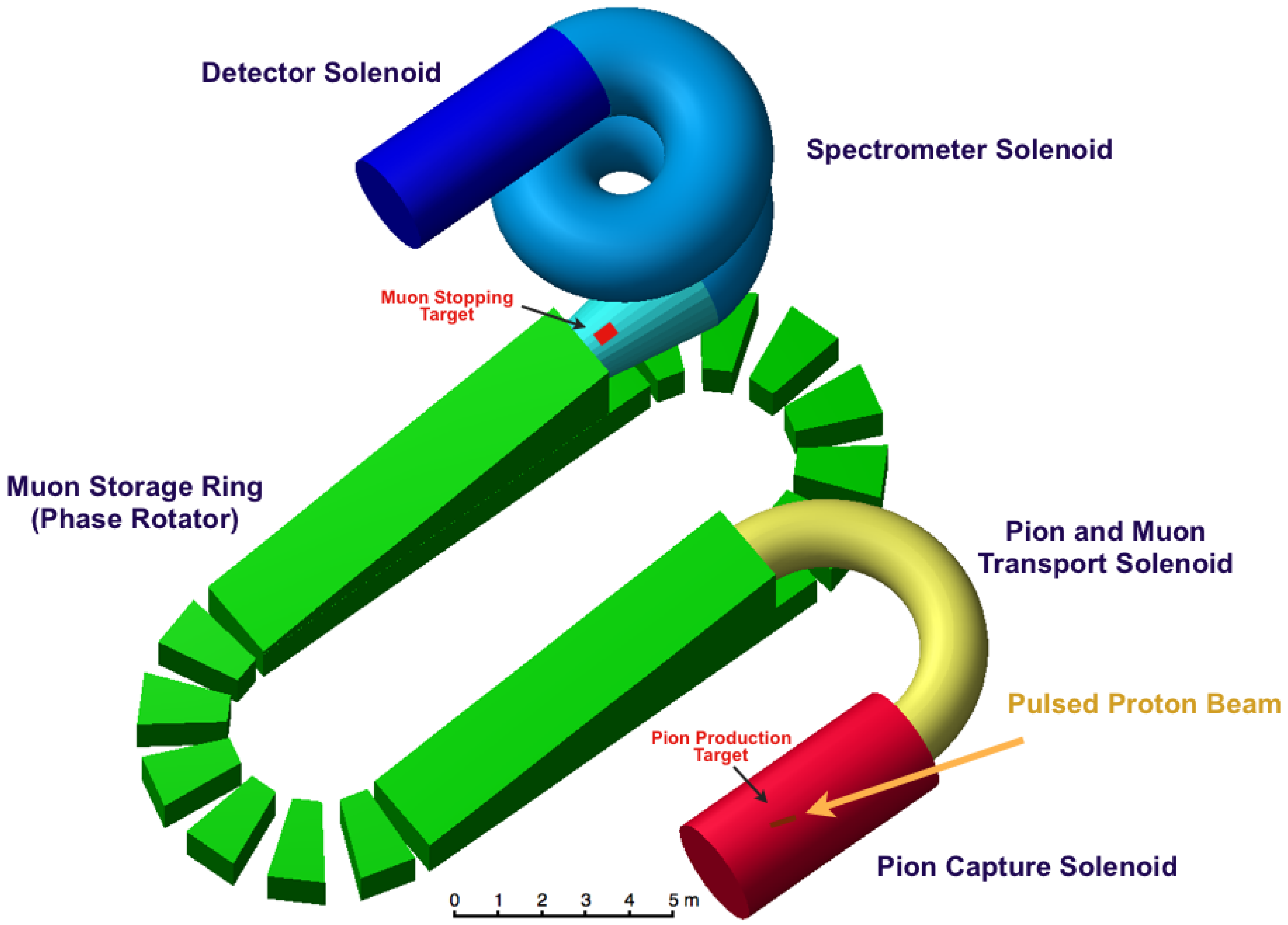
PRISM - Phase Rotated Intense Slow Muon beam

• Charged lepton flavor violation (cLFV) is strongly suppressed in the Standard Model, its detection would be a clear signal for new physics!
• The μ^- + N(A,Z)→e- + N(A,Z) seems to be the most broadly sensitive laboratory for cLFV.
• COMET and Mu2e will seek a signal, but next steps are needed either in the case of a discovery (to further explore a new phenomenon) or further exclusion limits (to continue the search)
• The PRISM/PRIME experiment based on an FFA ring was proposed (Y. Kuno, Y. Mori) for a next generation cLFV search in order to:
 - reduce the muon beam energy spread by phase rotation,
 - purify the muon beam in the storage ring.
• PRISM requires a compressed proton bunch and high power proton beam
• This will provide a single event sensitivity of 3×10^{-19}





Conceptual Layout of PRISM/PRIME



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Challenges for the PRISM accelerator system

- The need for the compressed proton bunch:
  - is in full synergy with the Neutrino Factory and a Muon Collider.
  - puts PRISM in a position to be one of the incremental steps of the muon programme.
  - opportunities to realise in existing proton drivers (like J-PARC) or future ones (like PIP-II at FNAL).
- Target and capture system:
  - is in full synergy with the Neutrino Factory and a Muon Collider studies.
  - requires a detailed study of the effect of the energy deposition induced by the beam in SC solenoids
- Design of the muon beam transport from the solenoidal capture to the PRISM FFA ring.
  - very different beam dynamics conditions.
  - very large beam emittances and momentum spread.
- Muon beam injection/extraction into/from the FFA ring.
  - very large beam emittances and momentum spread.
  - affects the ring design in order to provide the space and the aperture.
- RF system
  - large gradient at the relatively low frequency and multiple harmonics (the “sawtooth” in shape).

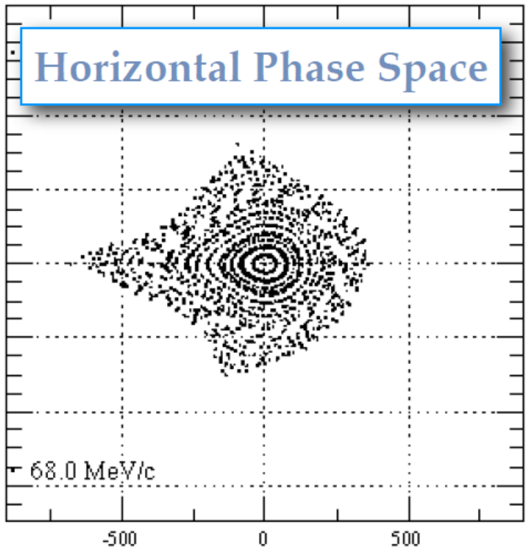
R&D work in Osaka

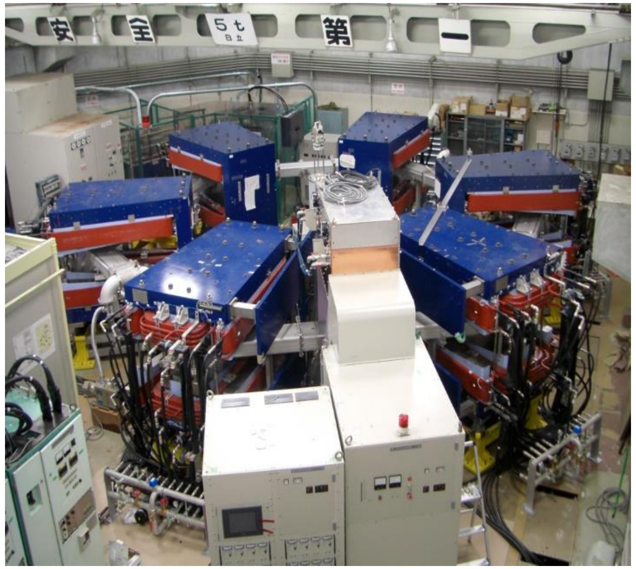
- 10 cell DFD ring has been designed
- FFA magnet-cell has been constructed and verified.
- RF system has been tested and assembled.
- 6 cell ring was assembled and its optics was verified using α particles.
- Phase rotation was demonstrated for α particles.

A. Sato et al., Conf. Proc. C 0806233, THPP007 (2008)

6 cell FFA ring at RCNP

Magnet for FFA cell - design





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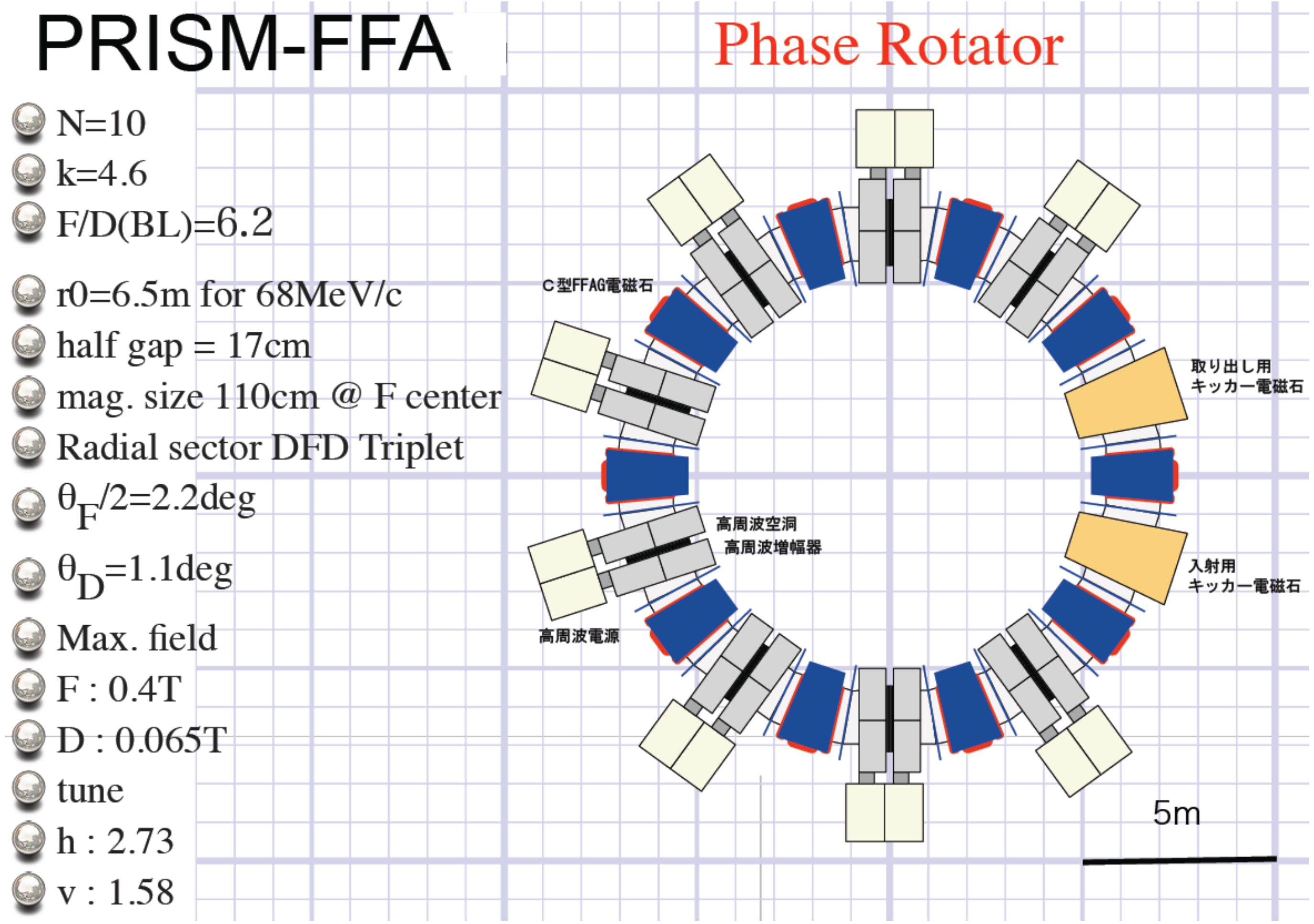
First Design Parameters, A. Sato



V per turn ~2-3 MV

Δp/p at injection = ± 20%

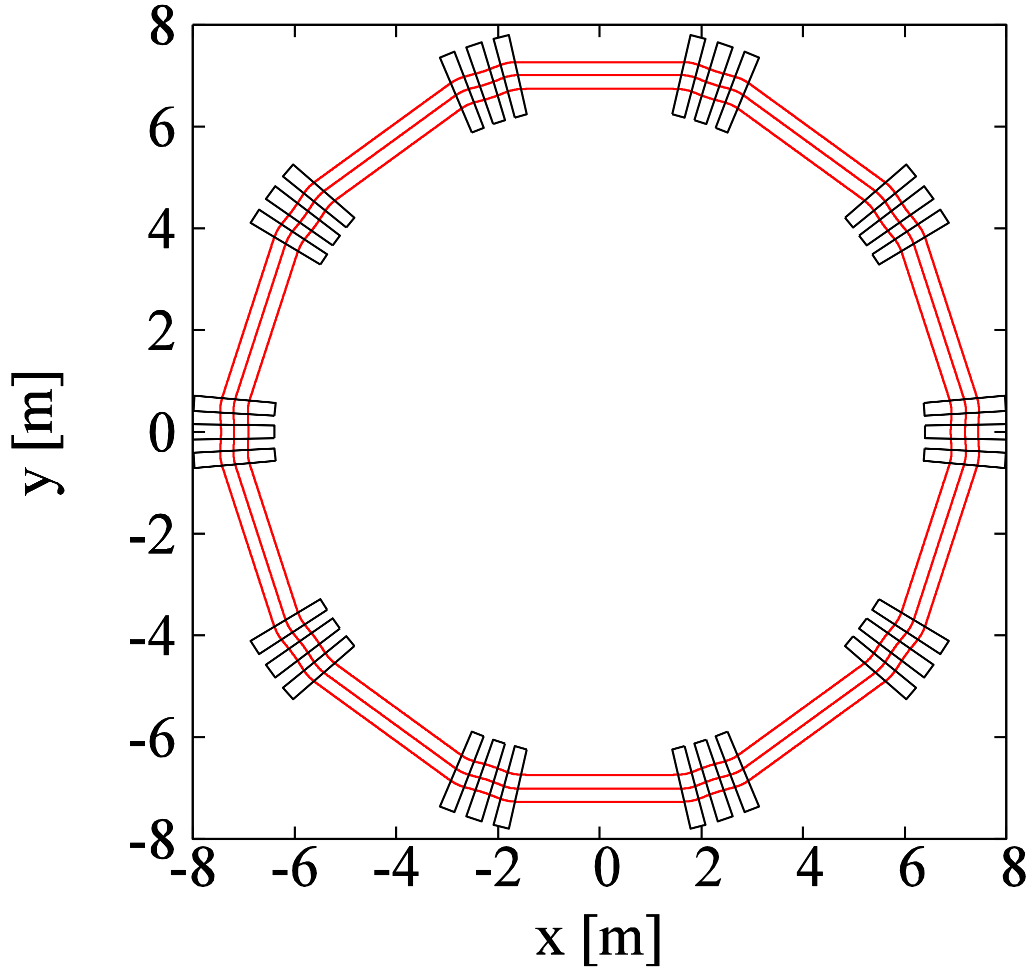
Δp/p at extraction = ± 2% (after 6 turns ~ 1.5 us)

h=1

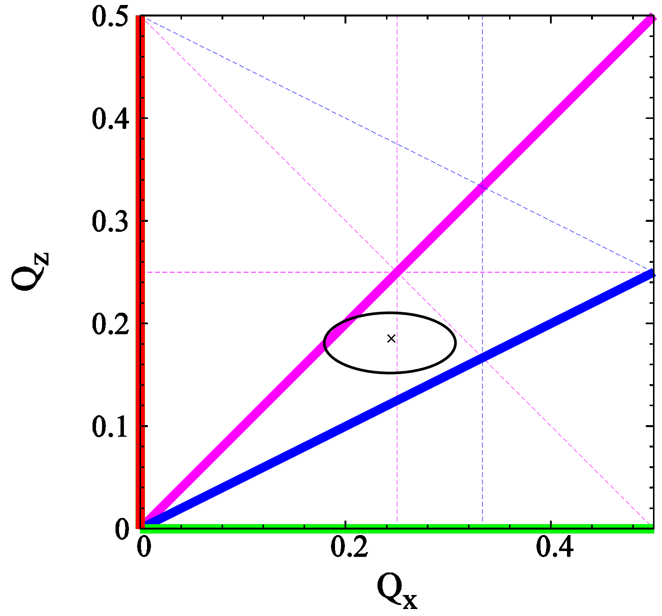
PRISM parameters

Parameter	**Value**
Target type	solid
Proton beam power	~1 MW
Proton beam energy	~ GeV
Proton bunch duration	~10 ns total
Pion capture field	10 -20 T
Momentum acceptance	±20 %
Reference μ^- momentum	40-68 MeV/c
Harmonic number	1
Minimal acceptance (H/V)	3.8/0.5 π cm rad or more…
RF voltage per turn	3-5.5 MV
RF frequency	3-6 MHz
Final momentum spread	±2%
Repetition rate	100 Hz-1 kHz

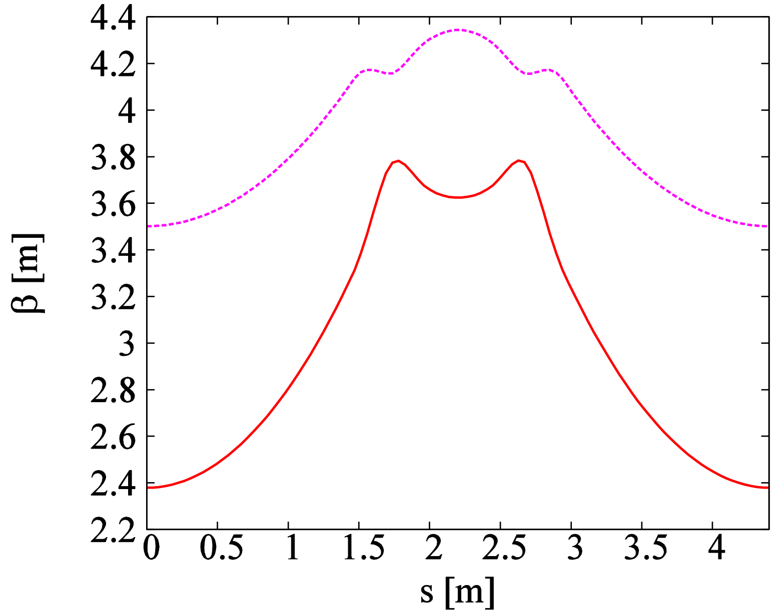
Baseline FDF scaling FFA design

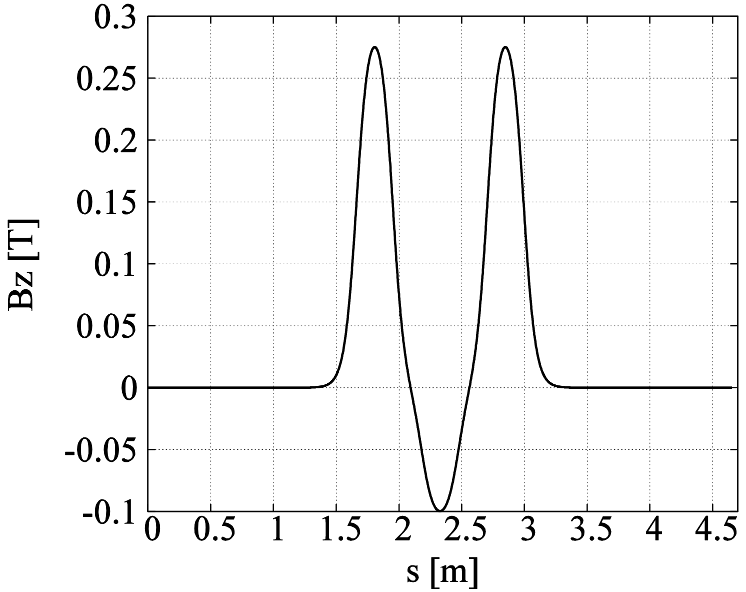


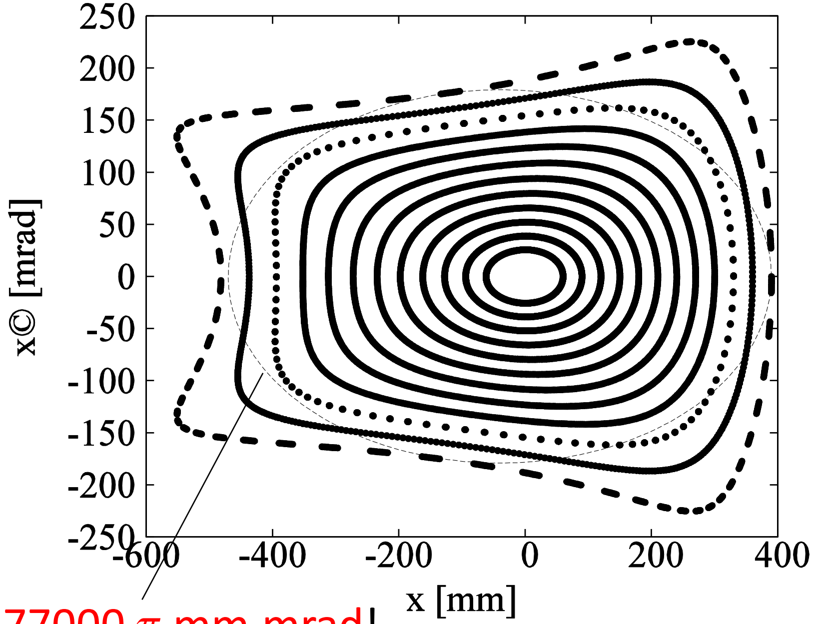
- FDF symmetry motivated by the success of ERIT at Kyoto University
- 10 cells
- k 4.3
- R_0 7.3 m
- (Q_H, Q_V) (2.45, 1.85)
- Minimal drift length 3m



Baseline FDF scaling FFA design (2)







77000 π.mm.mrad!

- Enge field fall-off used to study fringe fields using FixField code
- Enormous horizontal acceptance is achieved in simulations
- Vertical long term stability of ~3000 π.mm.mrad is achieved, however with some optimization ~5000 π.mm.mrad should be stable for a few turns.
- Further optimisation will be performed

Selected Snowmass'21 submissions

- A Phase Rotated Intense Source of Muons (PRISM) for a μ→e Conversion Experiment, SNOWMASS21-RF5_RF0-AF5_AF0_J_Pasternak-096.pdf
- Bunch Compressor for the PIP-II Linac, SNOWMASS21-AF5_AF0-RF5_RF0_Prebys-071.pdf
- SNOWMASS21-RF5_RF0-AF5_AF0_Robert_Bernstein-027.pdf

A Phase Rotated Intense Source of Muons (PRISM) for a $\mu \to e$ Conversion Experiment

R. B. Appleby,[1,2] M. Aslaninejad,[3] R. Barlow,[4] R.H. Bernstein,[5] B. Echenard,[6] A. Gaponenko,[5] D. J. Kelliher,[7] Y. Kuno,[8,9] A. Kurup,[10] J.-B. Lagrange,[7] M. Lancaster,[1] K. Long,[10] K. Lynch,[11] S. Machida,[7] S. Mihara,[12] Y. Mori,[13] B. Muratori,[14,2] J. Pasternak,[10,7,*] E. Prebys,[15] C. R. Prior,[7] A. Sato,[8] D. Stratakis,[5] S. Tygier,[1,2] and Y. Uchida[10]

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(Dated: September 1, 2020)

Letter of Interest: Bunch Compressor for the PIP-II Linac

E. Prebys[1], R. H. Bernstein[2], and J. Pasternak[3]

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[2]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[3]Imerial College London, London SW7 2AZ, UK

August 27, 2020

A New Charged Lepton Flavor Violation Program at Fermilab
(ENIGMA: nExt geNeration experIments with hiGh intensity Muon beAms)

M. Aoki,[1] R.H. Bernstein,[2] L. Calibbi,[3] F. Cervelli,[4] C. Bloise,[5] R. Culbertson,[2] André Luiz de Gouvêa,[6] S. Di Falco,[4] E. Diociaiuti,[5] S. Donati,[4] R. Donghia,[5] B. Echenard,[7] A. Gaponenko,[2] S. Giovannella,[5] C. Group,[8] F. Happacher,[5] M. Hedges,[9] D.G. Hitlin,[7] C. Johnstone,[2] E. Hungerford,[10] D. M. Kaplan,[11] M. Kargiantoulakis,[2] A. Knecht,[12] K. Kirch,[13] M. Lancaster,[14] A. Luca,[2] K. Lynch,[15] M. Martini,[16,*] P. Murat,[2] S. Middleton,[7] S. Mihara,[17] J. Miller,[18] S. Miscetti,[5] L. Morescalchi,[4] D. Neuffer,[2] A. Papa,[4] J. Pasternak,[19] E. Pedreschi,[4] G. Pezzullo,[20] F. Porter,[7] E. Prebys,[21] V. Pronskikh,[2] R. Ray,[2] F. Renga,[22] I. Sarra,[5] D. Stratakis,[2] N.M. Truong,[21] A. Sato,[1] F. Spinella,[4] M. Syphers,[23] and M. Yucel[2]

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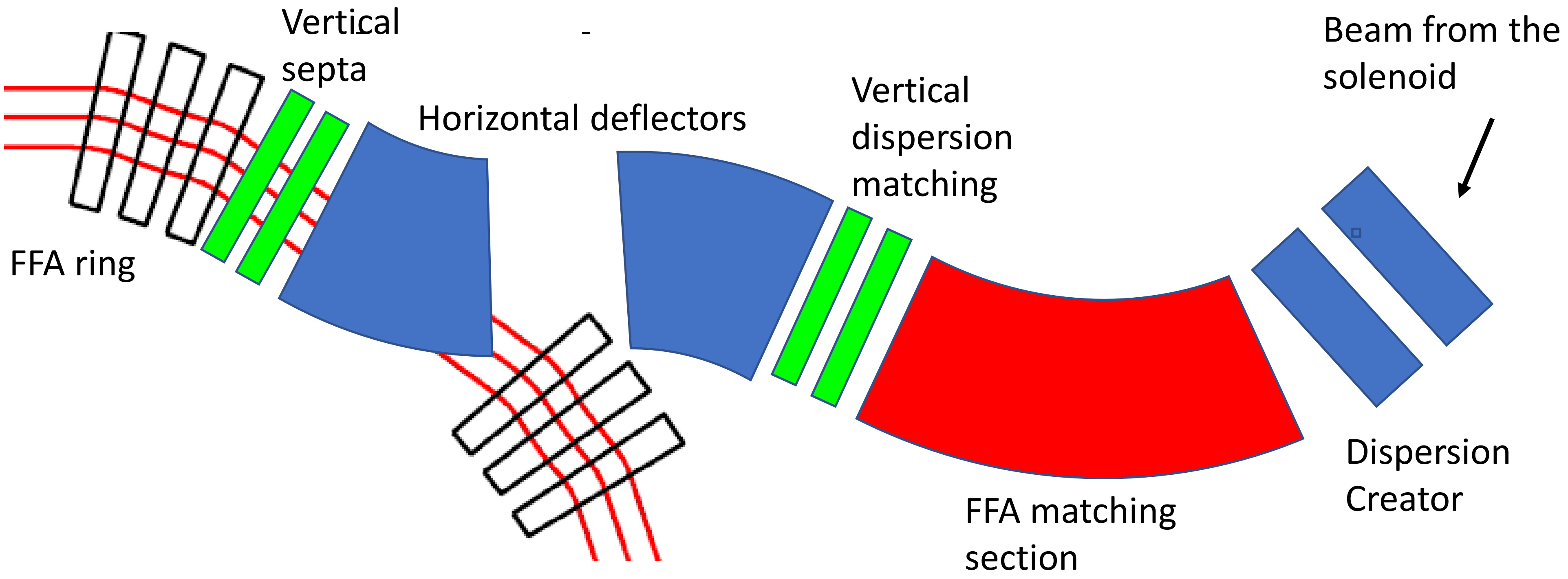
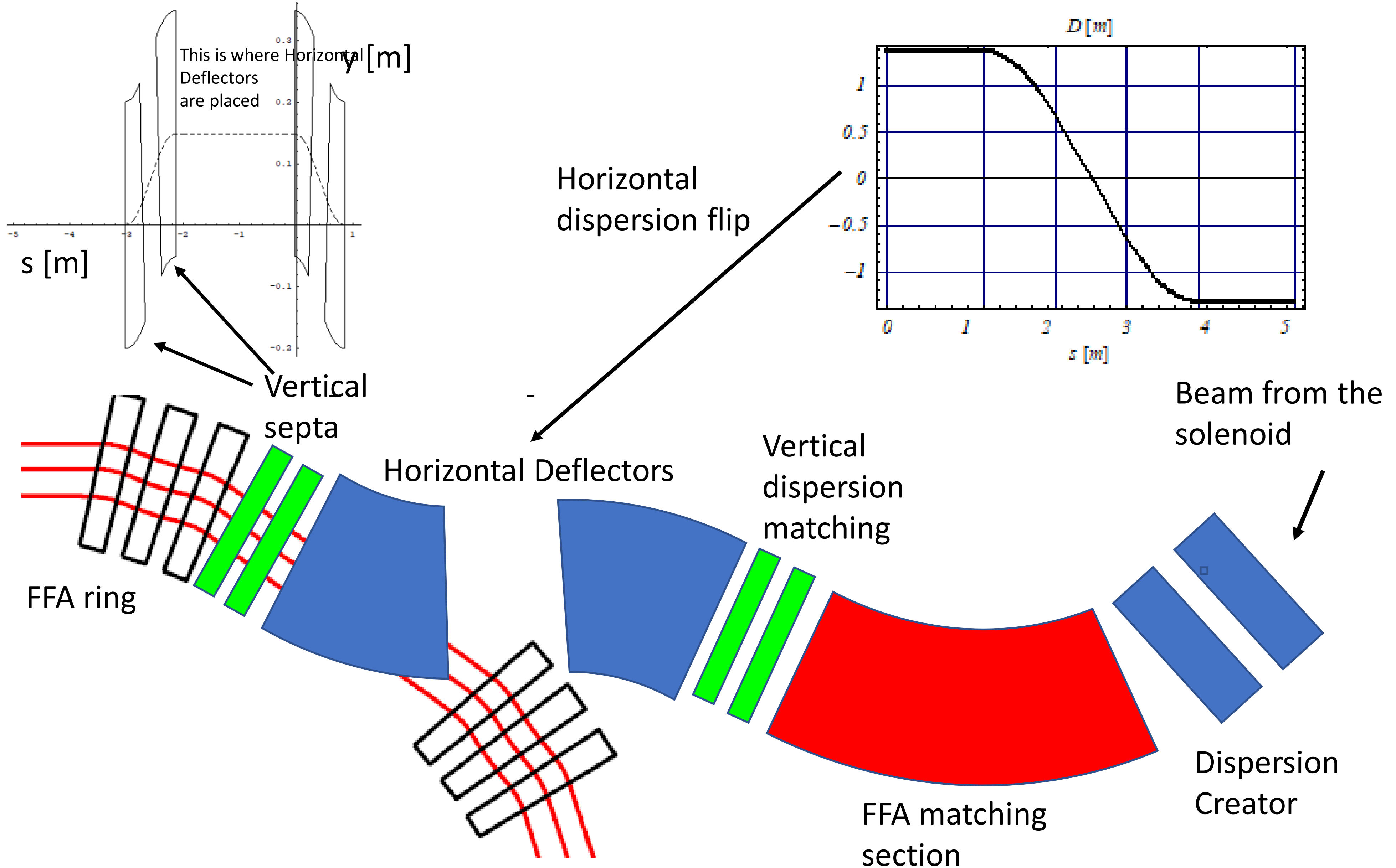
(Dated: August 29, 2020)

New concepts for injection

- Beam from the solenoid enters dispersion creator made of rectangular dipoles
- FFA matching section matches betatron functions, while preserving dispersion
- Horizontal deflectors (two sector bends) allows to pass around the main FFA magnets while entering into the FFA ring
    - Dispersion flips
- Vertical magnets allows to create the necessary gap for the horizontal deflectors and match the vertical dispersion
- System under study/work in progress (R. Feng, IC)



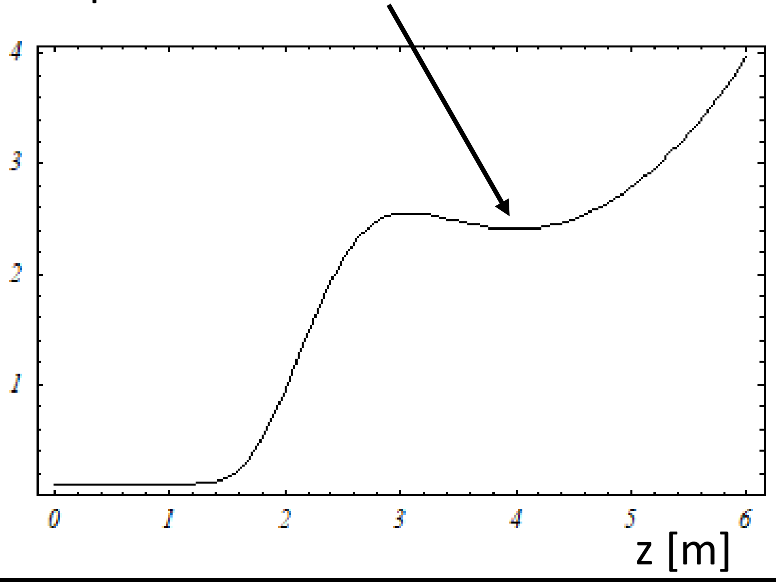
New concepts for injection (2)

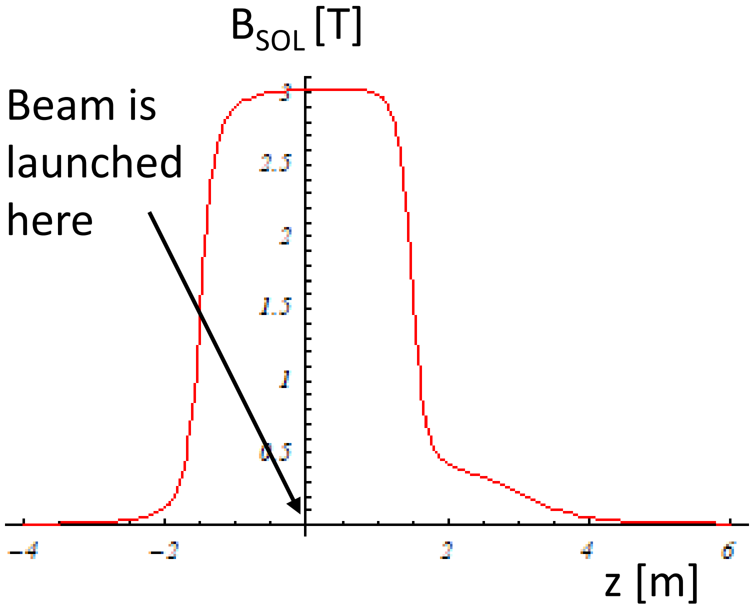


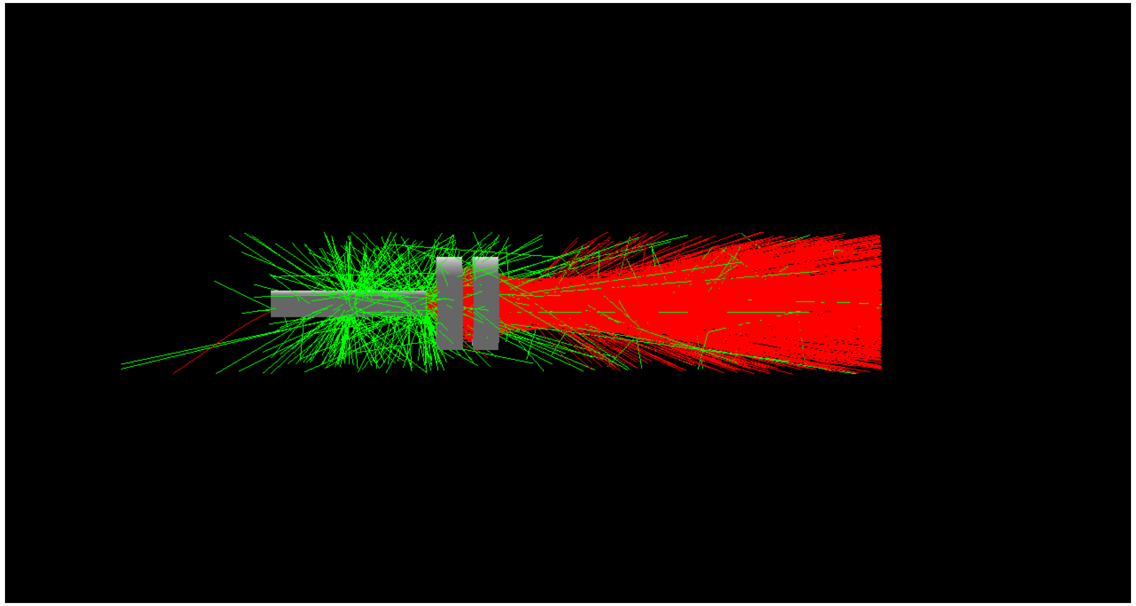
Transition from the solenoid to the AG lattice

- Beam from pion capture/muon decay is transported in ~3T solenoid
  - In G4BeamLine simulation beam is launched matched inside 3T solenoid
  - 45 MeV/c reference momentum is assumed
- Field is switched off adiabatically, while beam is matched transversely to the AG lattice

Dispersion creator starts here

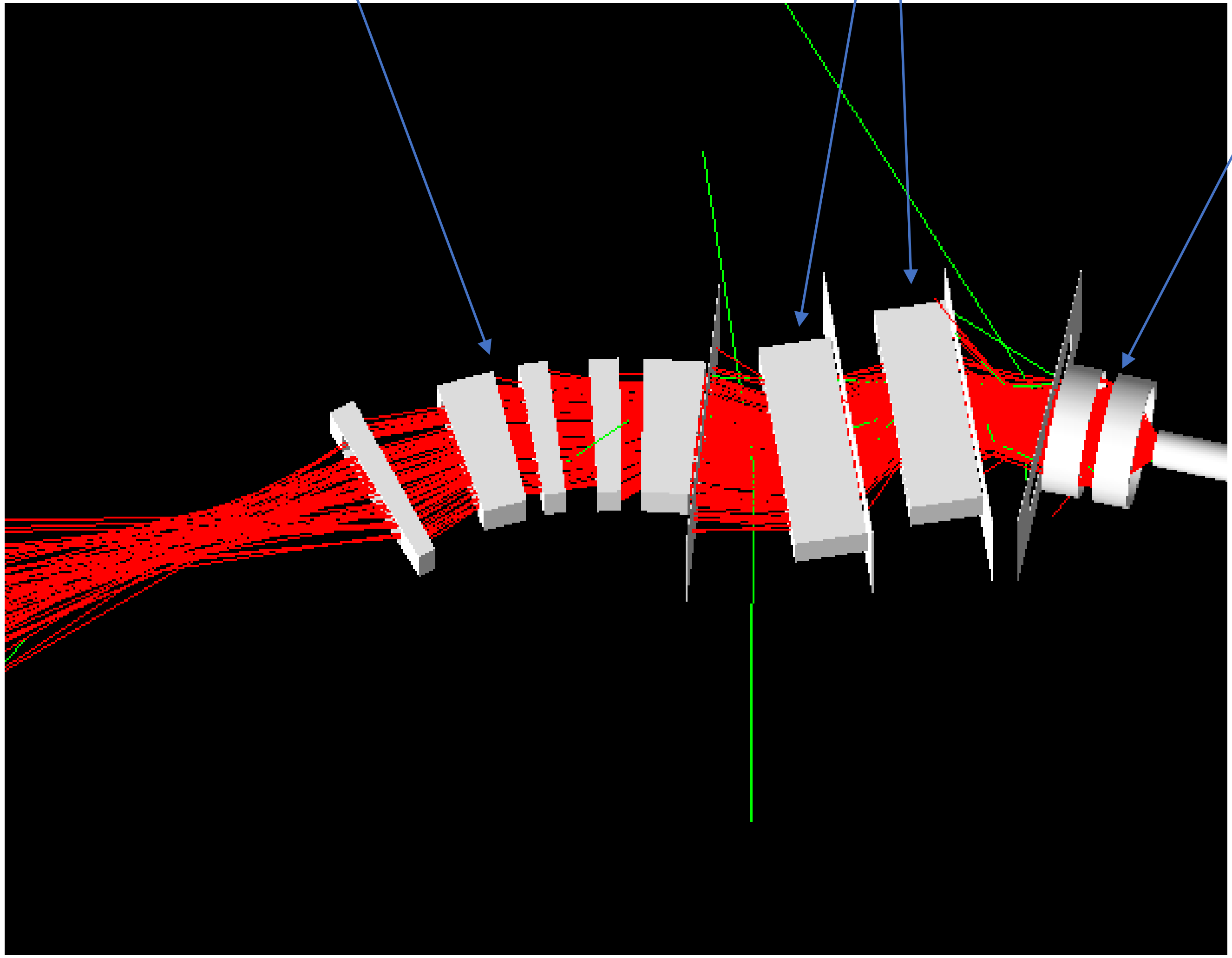






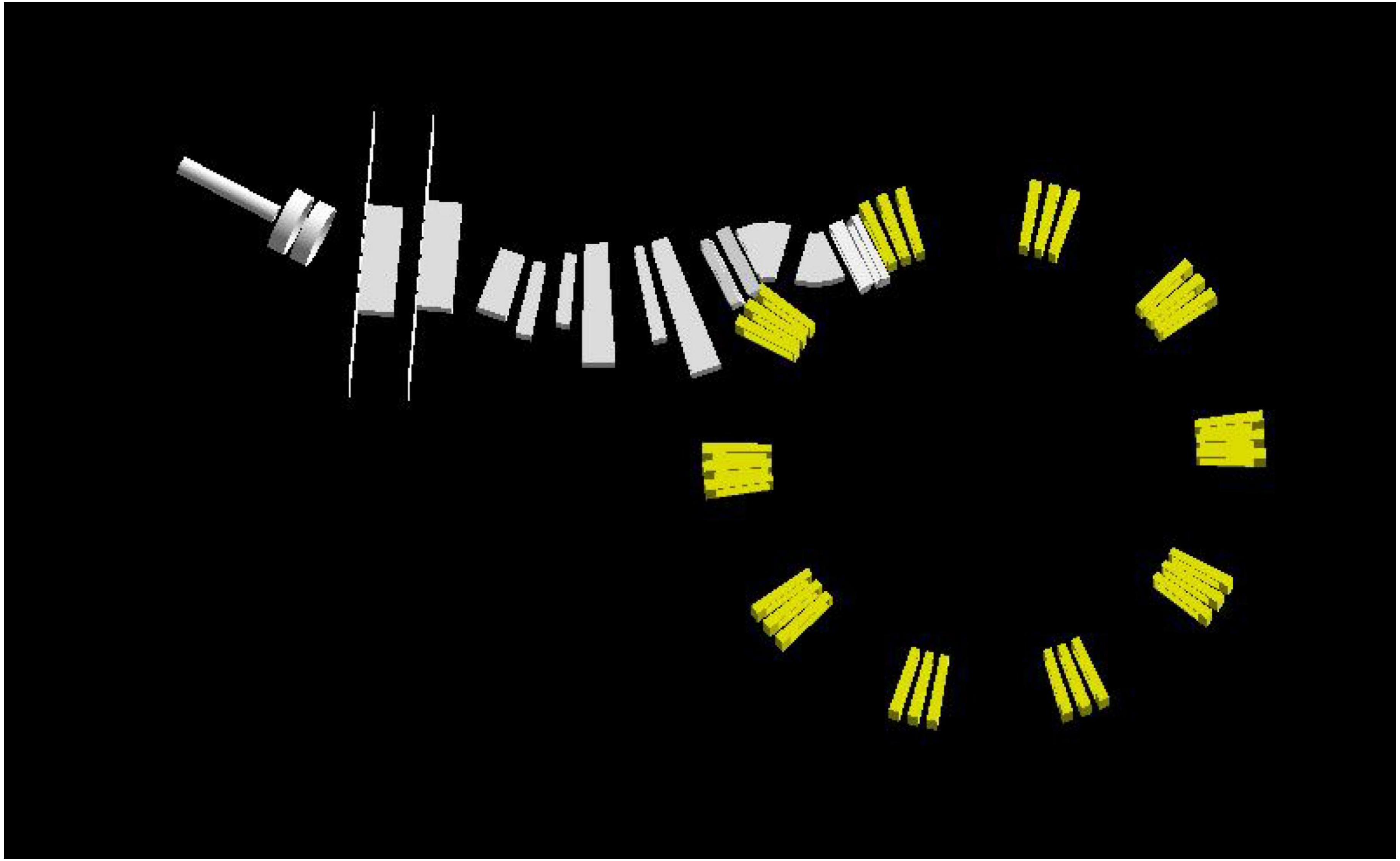
From R. Feng, IC

Preliminary injection line study



From
R. Feng, IC

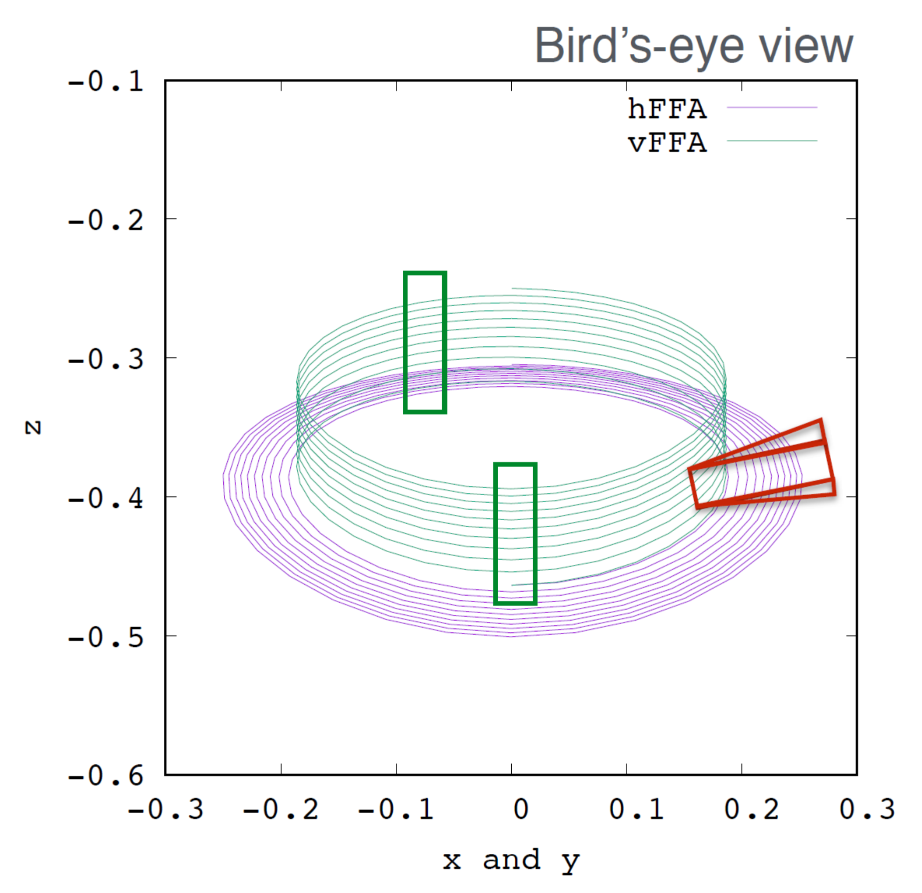
Layout of the injection line and the PRISM ring



From
R. Feng, IC

Vertical FFA

- "Electron cyclotron"
- Beam orbit rises vertically.
- Circumference constant with beam energy.
- Magnetic field increases exponentially vertically.
- Zero-chromatic for any momentum range.



$$B_y(y,\theta) = B_0 e^{m_y(y-y_0)} \mathcal{F}(\theta)$$

Magnetic field law for VFFA

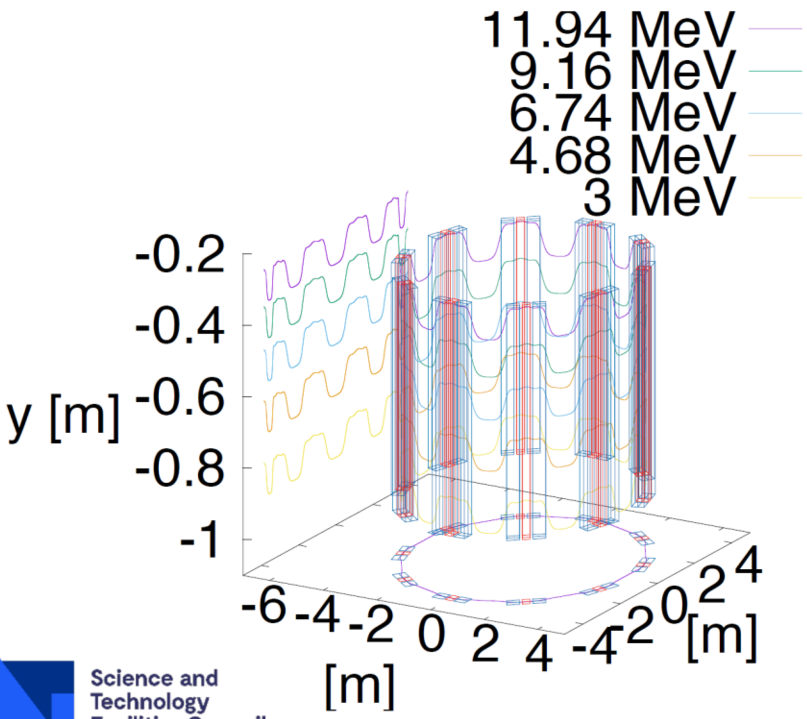
Science and Technology Facilities Council

R&D for ISIS-II

Orbits with acceleration

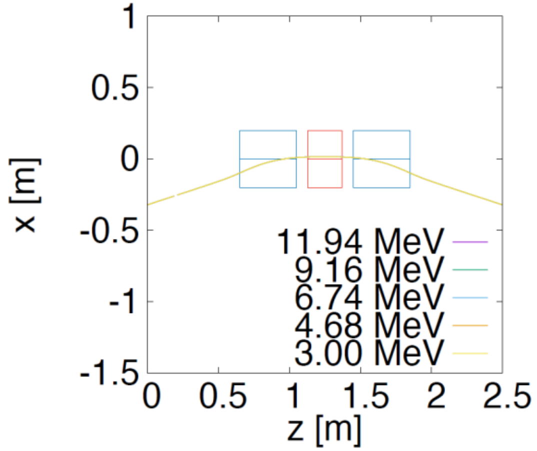
- Separation of orbits reduces logarithmically.

- Proposal for the downscaled test ring using FETS at RAL as an injector
    - To demonstrate VFFA
    - To show high intensity operation
    - To test injection/extraction
- Vertical magnet prototype will be tested first.

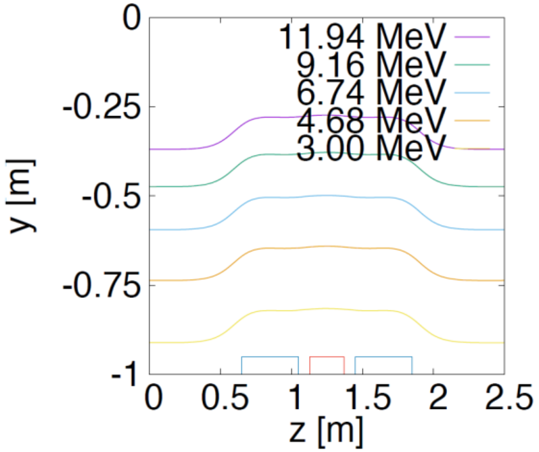


Science and Technology Facilities Council

Top view



Side view



From S. Machida

VFF is an ideal accelerator for relativistic particles like muon as it's momentum compaction factor is zero!

First designs for a Muon Collider are emerging!

First design out of one day work

10 to 300 GeV/c muon accelerator

Momentum range	**10 - 300 GeV/c**
Circumference	**12 km***
Maximum field	**12 T***
Number of cell	**1000**
Radius	**1910 m**
FODO cell length	**12 m**
Length of straight section	**2 m**
Length of magnets	**4 m**
Field index m	**8**
Orbit excursion	**0.425 m**
Tune per cell in decoupled space	**(0.3109, 0.2239)**

* this is simply because the design is not optimised.

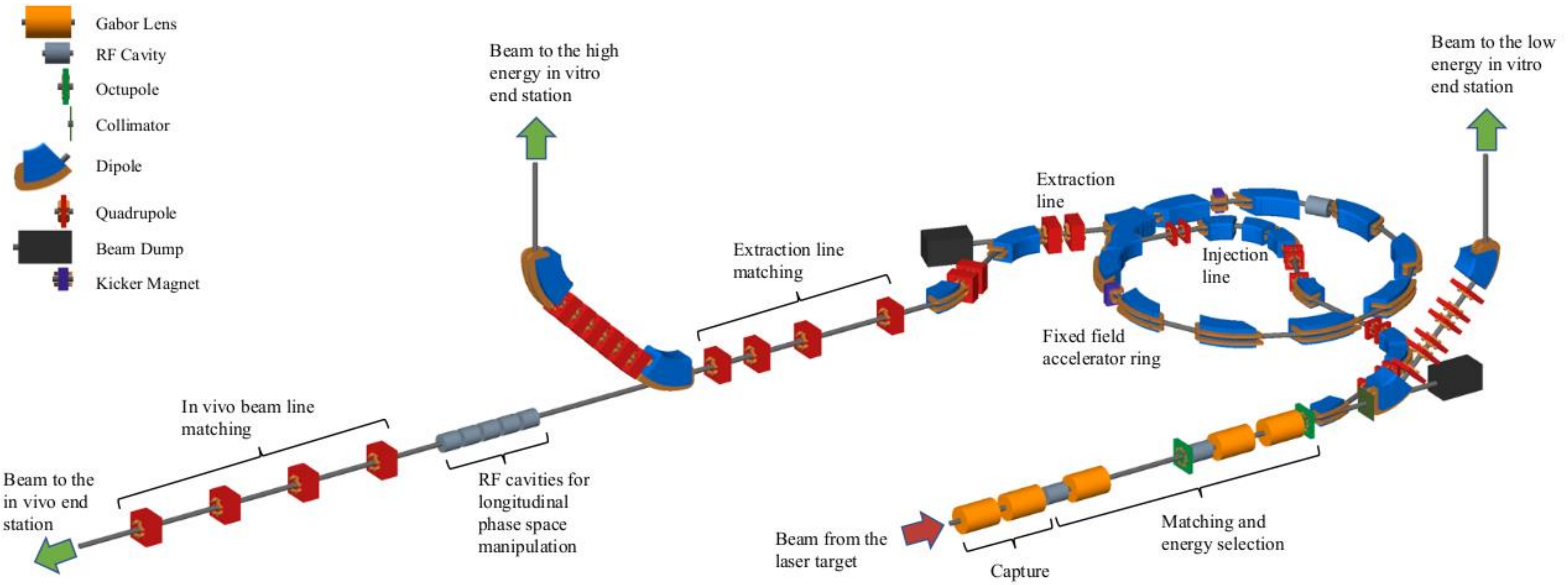
From S. Machida

Imperial College London

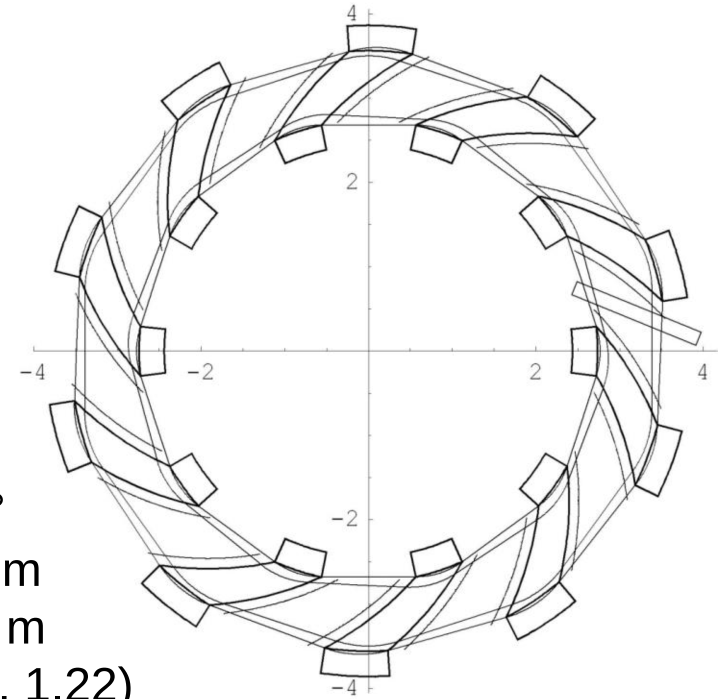
LhARA

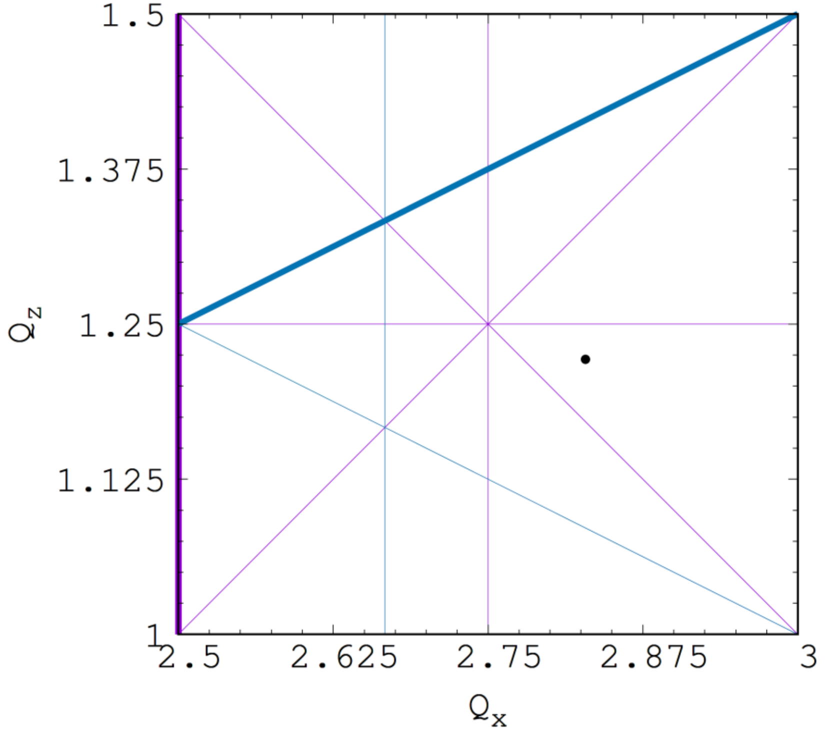
- Laser hybrid Accelerator for Radiobiological Applications (LhARA) was proposed within the Centre for the Clinical Application of Particles (CCAP) at Imperial College London as a facility dedicated to the systematic study of radiobiology.
- It will allow study with proton beams with a flexible dose delivery (including a novel FLASH regime) at Stage 1
- It will open the study to use multiple ions (including Carbon) at Stage2 for both in-vitro and in-vivo end stations.
- It aims to demonstrate a novel technologies for next generation hadrontherapy.

Layout of the full LhARA facility

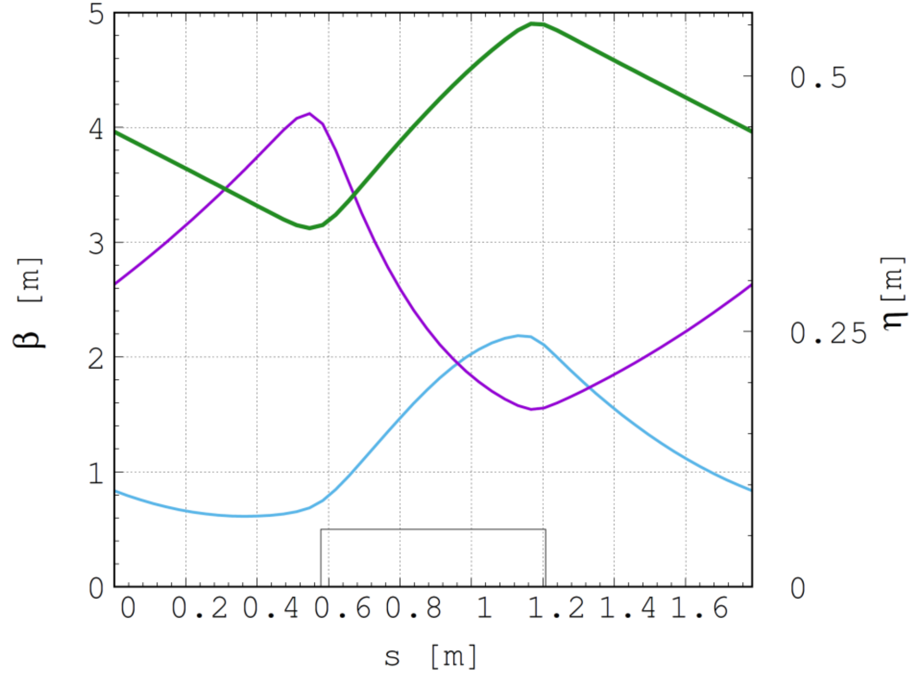


LhARA Ring Parameters





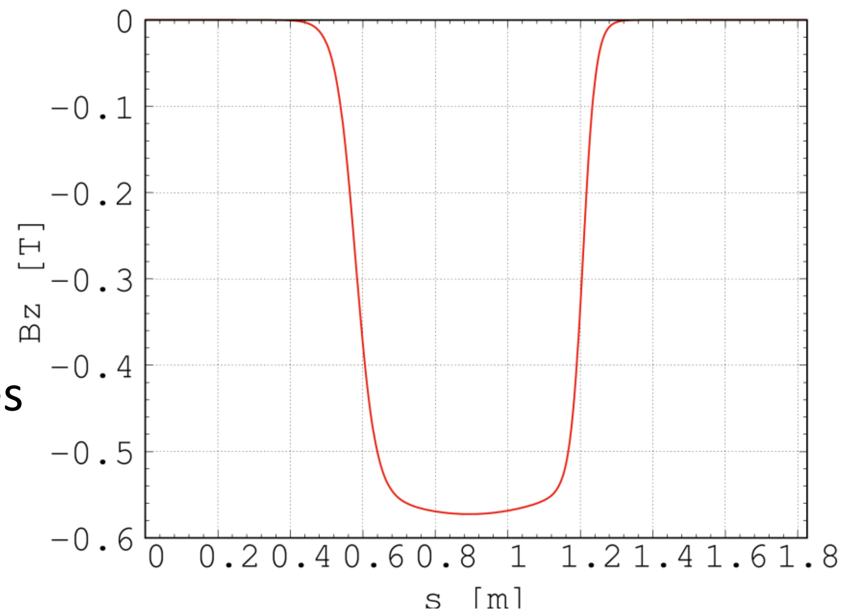
- N 10
- k 5.33
- Spiral angle 48.7°
- R_{max} 3.48 m
- R_{min} 2.92 m
- (Qx, Qy) (2.83, 1.22)
- B_{max} 1.4 T
- p_f 0.34
- Max Proton injection energy 15 MeV
- Max Proton extraction energy 127.4 MeV
- h 1
- RF frequency
  for proton acceleration (15-127.4MeV) 2.89 – 6.48 MHz
- Bunch intensity few×10^8 protons
- Range of other extraction energies possible
- Other ions also possible

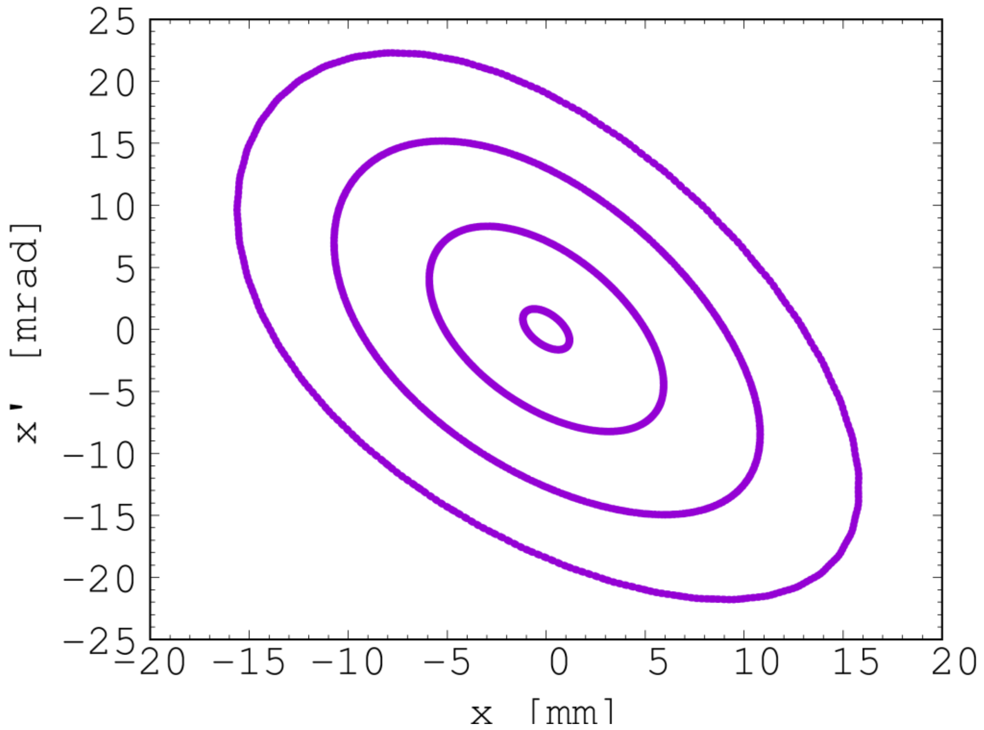


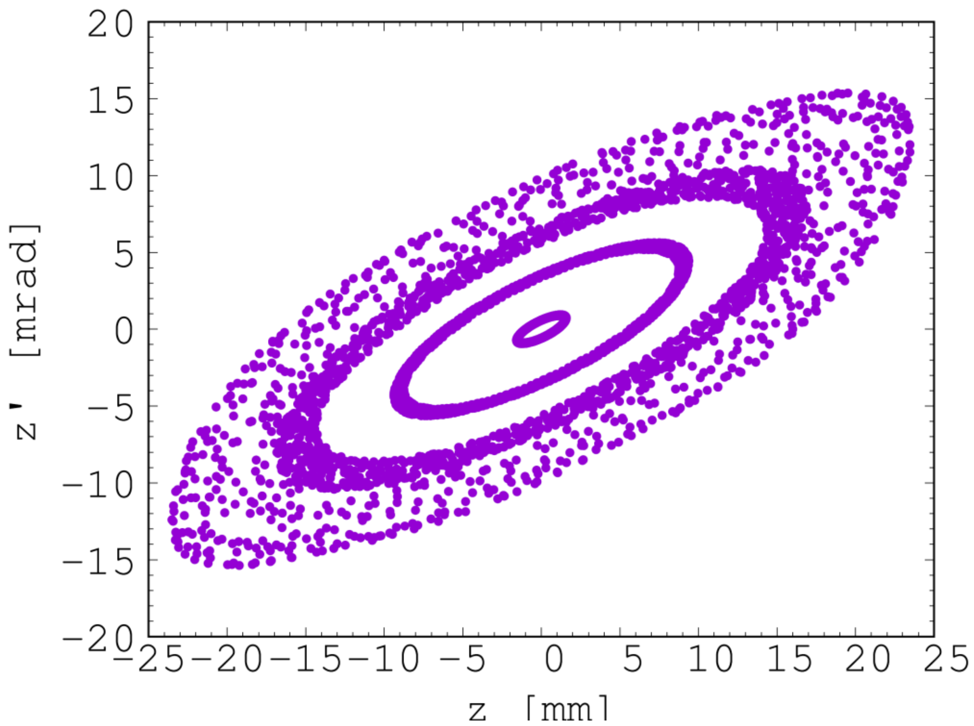
J. Pasternak, IC London

LhARA Ring Tracking

- Performed using proven stepwise tracking code
- It takes into account fringe fields and non-linear field components
- Results show dynamical acceptances are much larger than physical ones
- No space charge effects included yet
- Tracking performed using FixField code

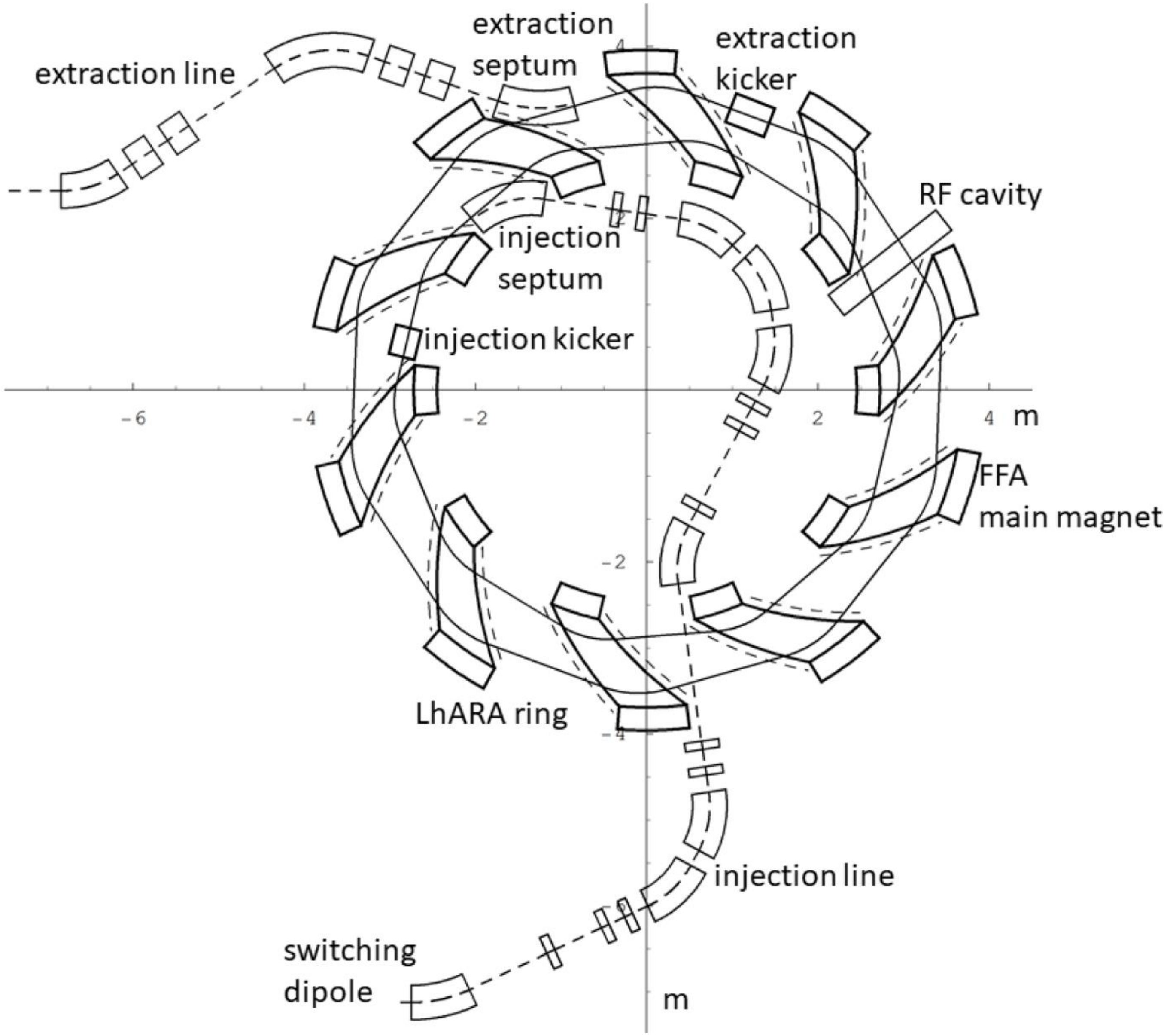






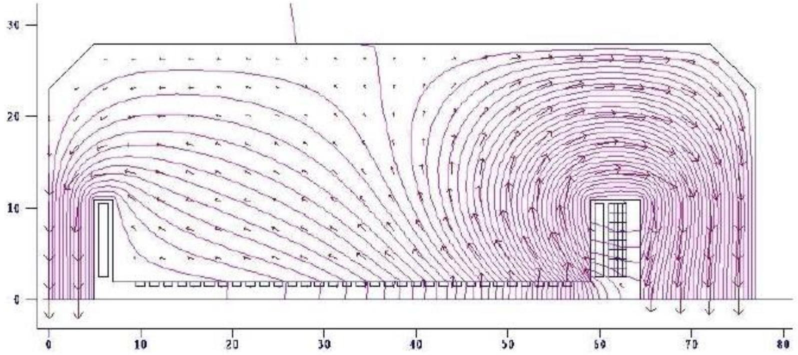
FFA Ring with subsystems

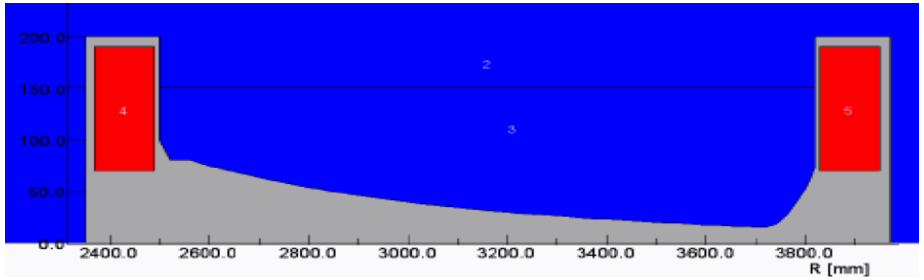
Parameter	unit	value
Injection septum:		
nominal magnetic field	T	0.53
magnetic length	m	0.9
deflection angle	degrees	48.7
thickness	cm	1
full gap	cm	3
pulsing rate	Hz	10
Extraction septum:		
nominal magnetic field	T	1.12
magnetic length	m	0.9
deflection angle	degrees	34.38
thickness	cm	1
full gap	cm	2
pulsing rate	Hz	10
Injection kicker:		
magnetic length	m	0.42
magnetic field at the flat top	T	0.05
deflection angle	mrad	37.4
fall time	ns	320
flat top duration	ns	25
full gap	cm	3
Extraction kicker:		
magnetic length	m	0.65
magnetic field at the flat top	T	0.05
deflection angle	mrad	19.3
rise time	ns	110
flat top duration	ns	40
full gap	cm	2



Essential R&D

Magnet types to be considered





Magnet with distributed conductors:
- Parallel gap – vertical tune more stable,
- Flexible field and k adjustment,

„Gap shaping" magnet:
•Developed by SIGMAPHI for RACCAM project
•Initialy thought as more difficult
•Behaves very well
•Chosen for the RACCAM prototype construction

- For LhARA magnet with parallel gap with distributed windings (but a single current) would be of choice with gap controlled by clamp. Concepts like an active clamp could be of interest too.

- Another important aspect of the R&D is the technology transfer for Magnetic Alloy (MA) loaded RF cavities for the ring

Conclusions

- Thanks to their unique properties, like high acceptance and lack of ramping, FFA accelerators may be ideally suited as muon machines.
- nuSTORM is a serious candidate to serve both neutrino physics and R&D for a Muon Collider
- PRISM may become the next generation flagship programme for lepton flavour violation
- VFFA can be an ideal machine for muon acceleration in a Muon Collider and also serve for ISIS-II. Its technology may be addressed in a prototype ring FETS-FFA.
- FFAs can be applied in radiobiology (LhARA) or in a future hadrontherapy.