Physics Potentials and accelerator challenges of Phase Rotated Intense Source of Muons (PRISM)

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on behalf of PRISM Task Force and
Snowmass’21 Study Group

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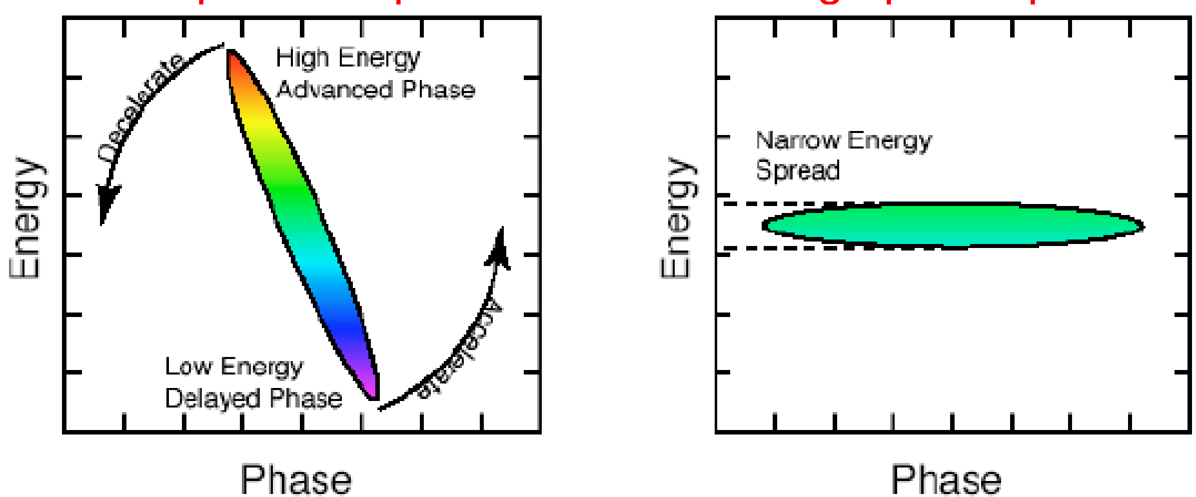
Outline

- Introduction and motivation
- Challenges of PRISM
- R&D at Osaka
- Current FFA baseline
- Proposal for Advance Muon Facility at FNAL (Snowmass'21)
  - Beam for PRISM from PIP-II
- New injection concepts
- Conclusions

Introduction and motivation

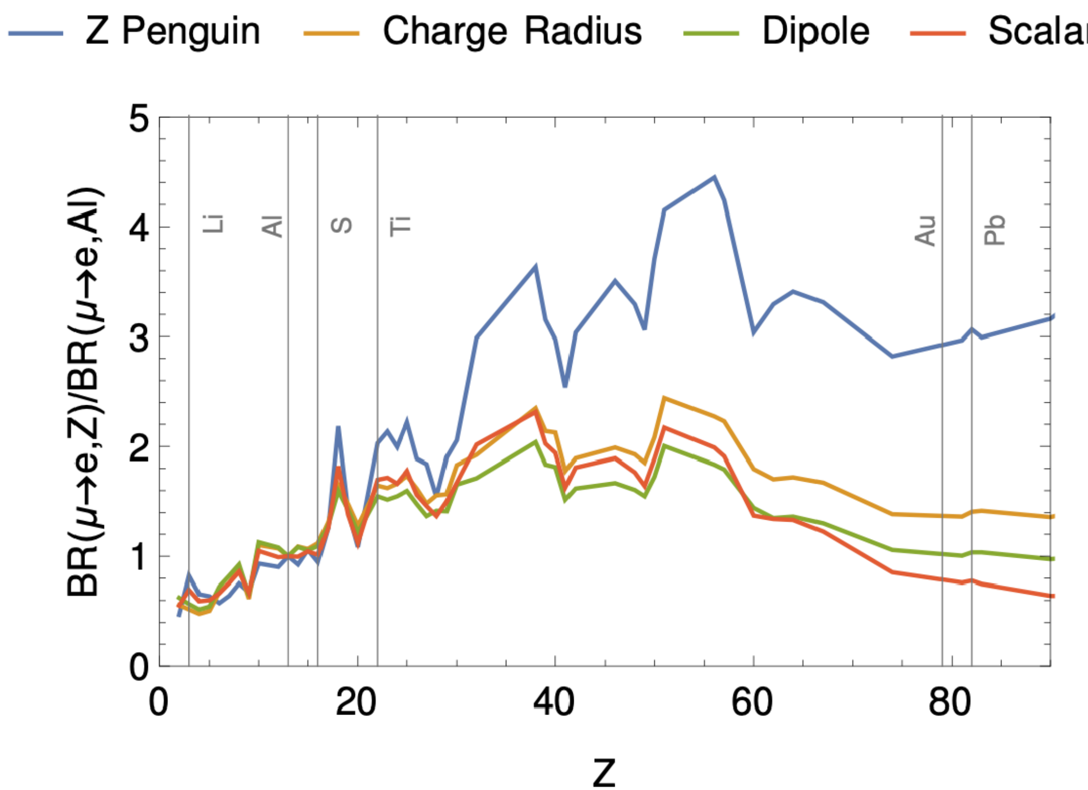
PRISM - Phase Rotated Intense Slow Muon beam

- Charged lepton flavor violation (cLFV) is strongly suppressed in the Standard Model, its detection would be a clear signal for new physics!
- The $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$ 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 Fixed Field Alternating gradient (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



Introduction and motivation (2)

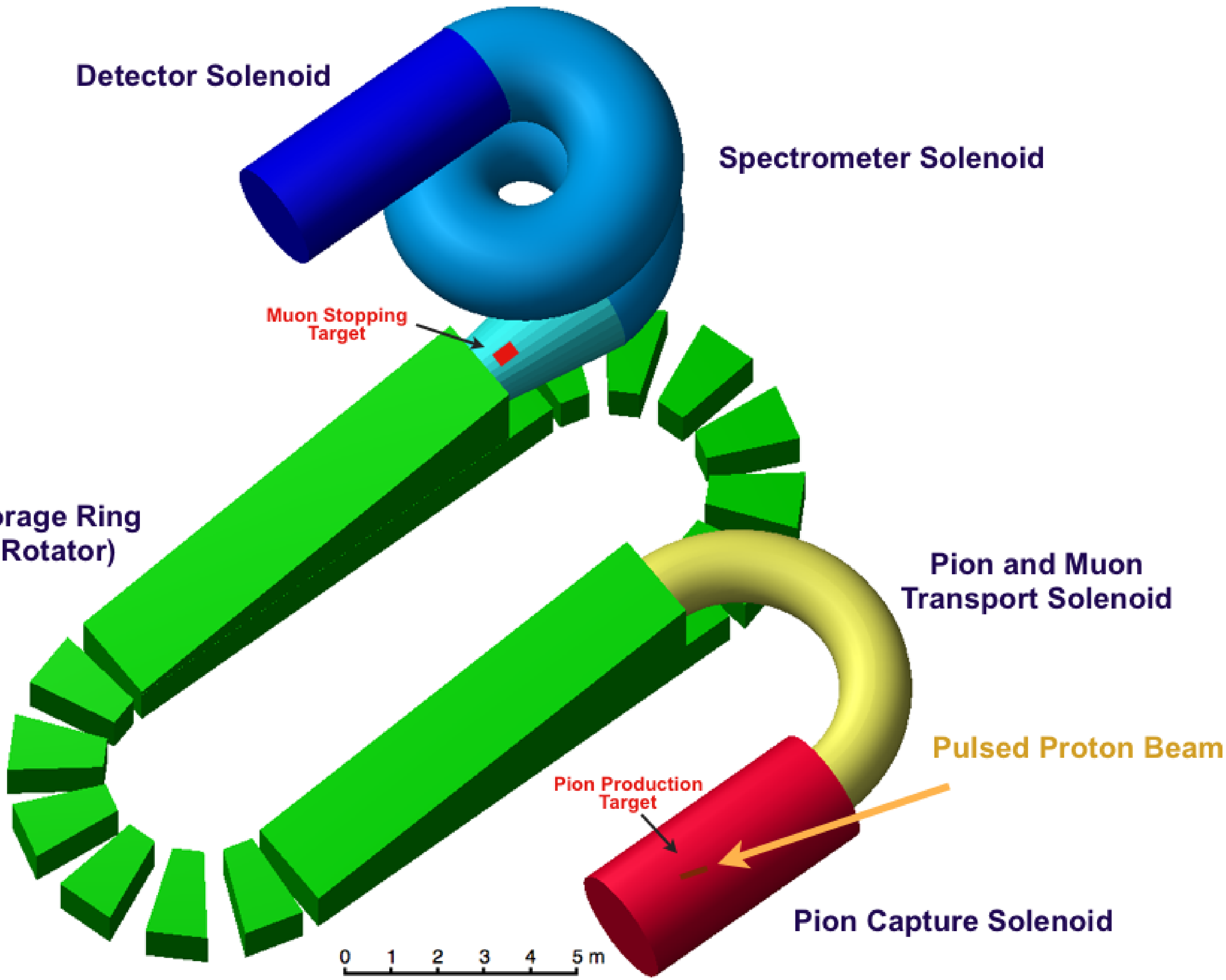
• In case of the discovery of the signal in the current generation of experiments PRISM can probe the structure of the New Physics signal using different Z conversion target materials



arXiv: 2203.08278v1

• In case of the lack of positive evidence from the current generation experiments, PRISM will provide a single event sensitivity of 3×10^{-19}

Introduction and motivation (3)



Conceptual Layout of PRISM/PRIME

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Challenges for the PRISM accelerator system

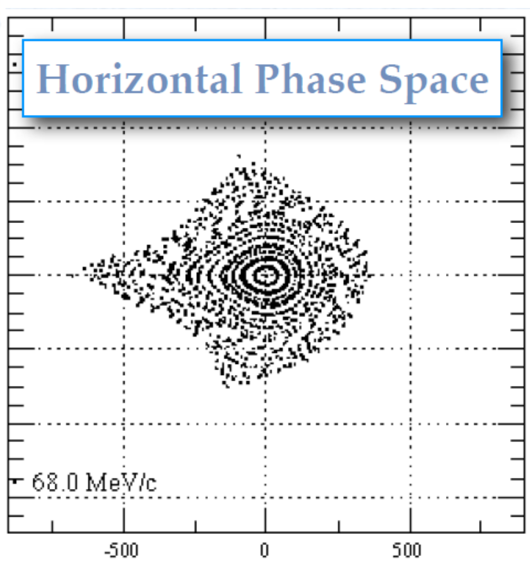
- The need for the compressed proton bunch:
  - is in full synergy with the Neutrino Factory and a Muon Collider.
  - puts PRISM in a position to be one of the incremental steps of the muon programme.
  - opportunities to realise in existing proton drivers (like J-PARC) or future ones (like PIP-II at 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
  - Short rise/fall times for the kickers
  - Septa with large aperture
  - 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)

Magnet for FFA cell - design



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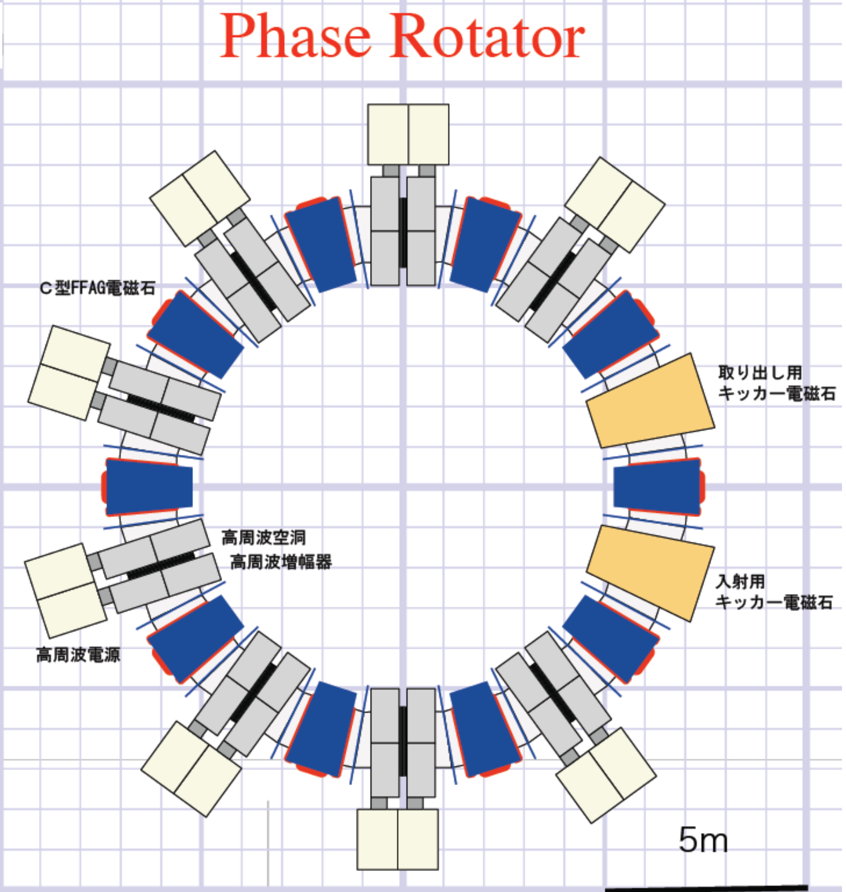
6 cell FFA ring at RCNP

First Design Parameters, A. Sato

PRISM-FFA

- N=10
- k=4.6
- F/D(BL)=6.2
- r0=6.5m for 68MeV/c
- half gap = 17cm
- mag. size 110cm @ F center
- Radial sector DFD Triplet
- $\theta_F/2$=2.2deg
- θ_D=1.1deg
- Max. field
- F : 0.4T
- D : 0.065T
- tune
- h : 2.73
- v : 1.58



V per turn ~2-3 MV

p/p at injection = ± 20%

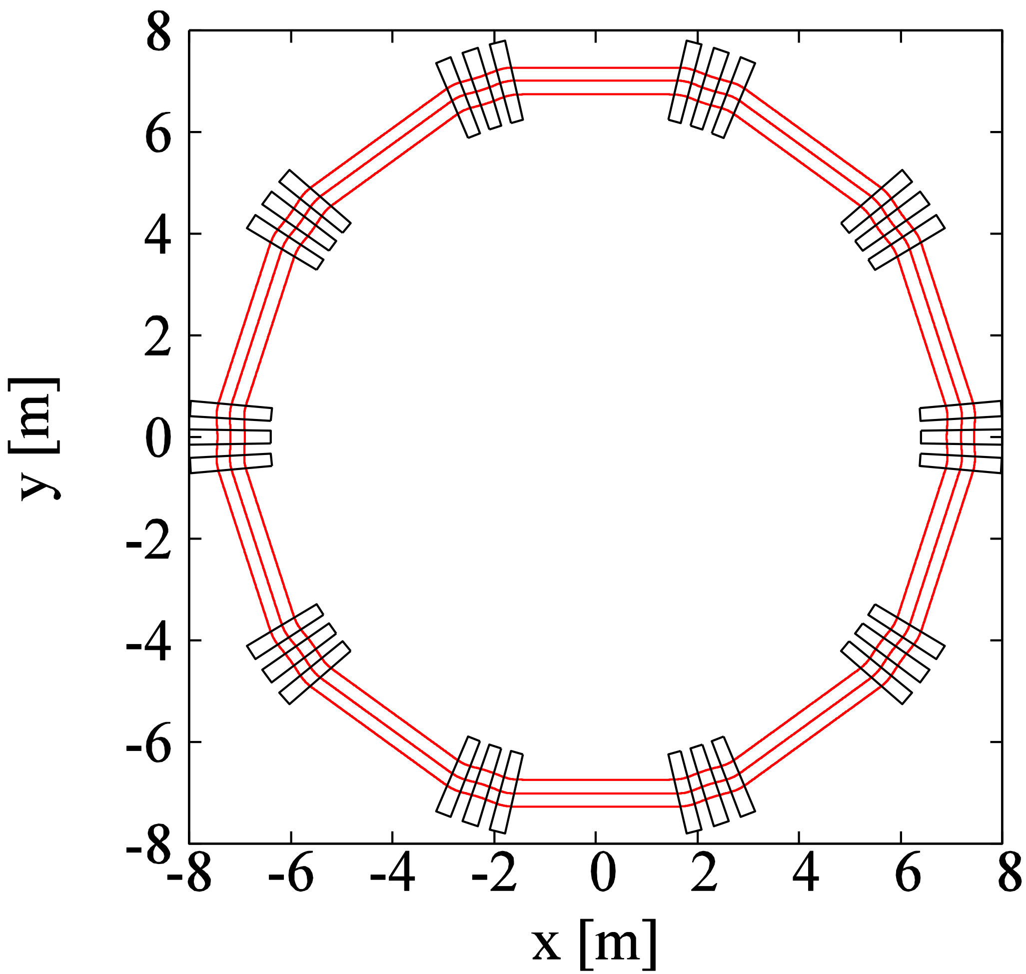
p/p at extraction = ± 2% (after 6 turns ~ 1.5 us)

h=1

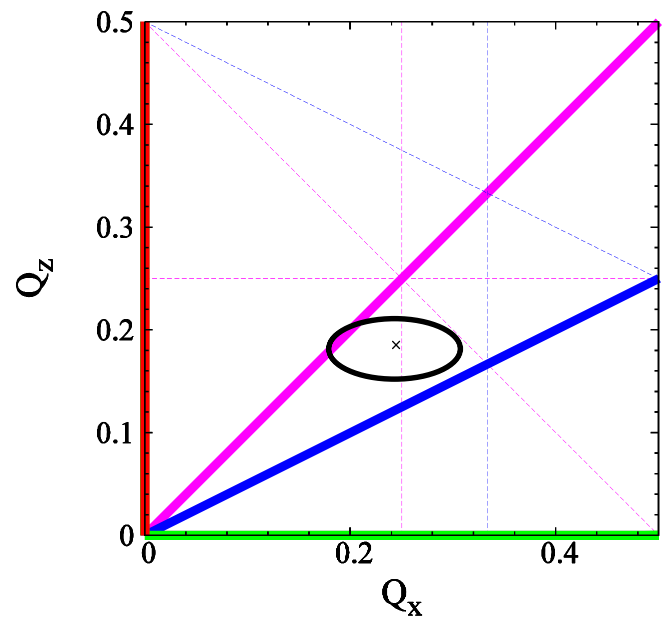
PRISM parameters

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	45 MeV/c (aiming for ~20 MeV/c, the induction linac could be used after extraction from the FFA)
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

Current 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



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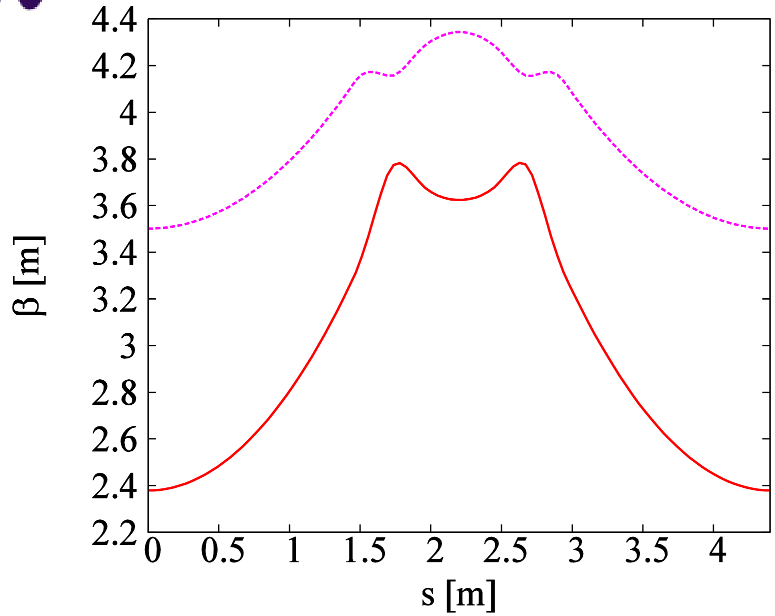
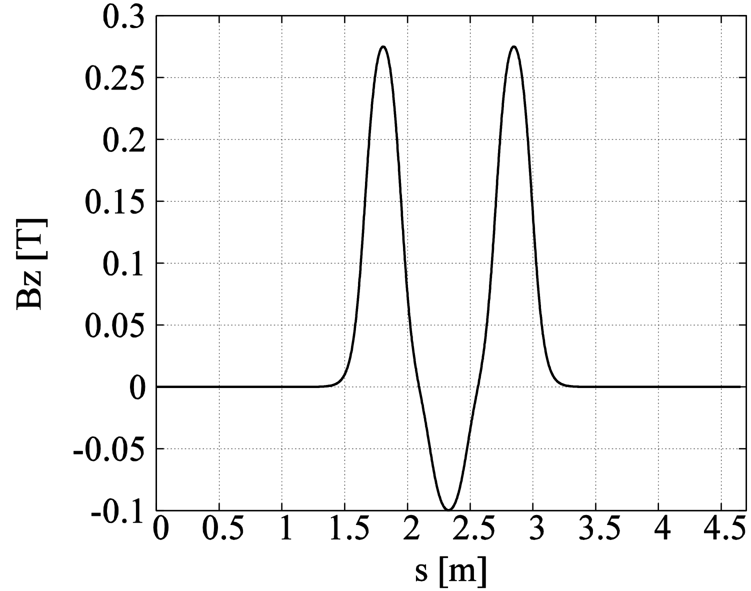
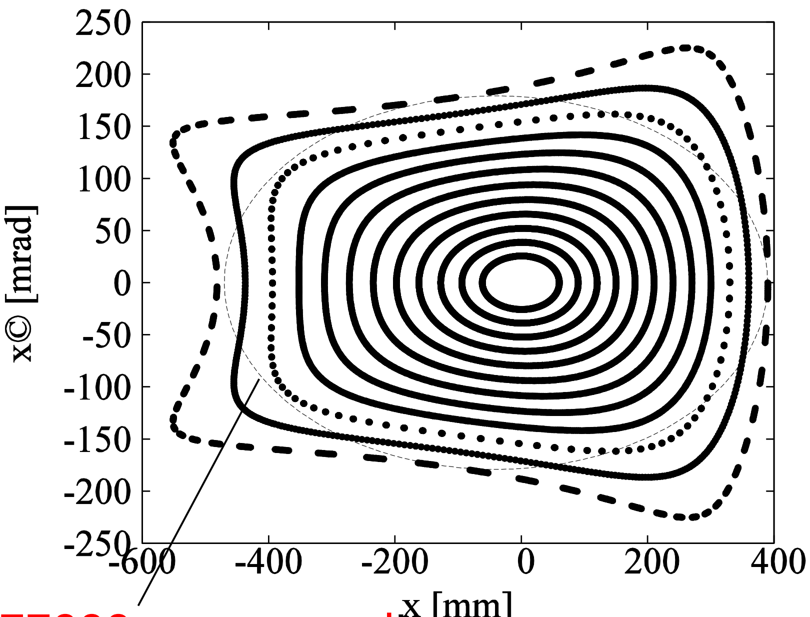
Current Baseline: FDF scaling FFA design (2)







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

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Advanced Muon Facility at FNAL

arXiv: 2203.08278v1

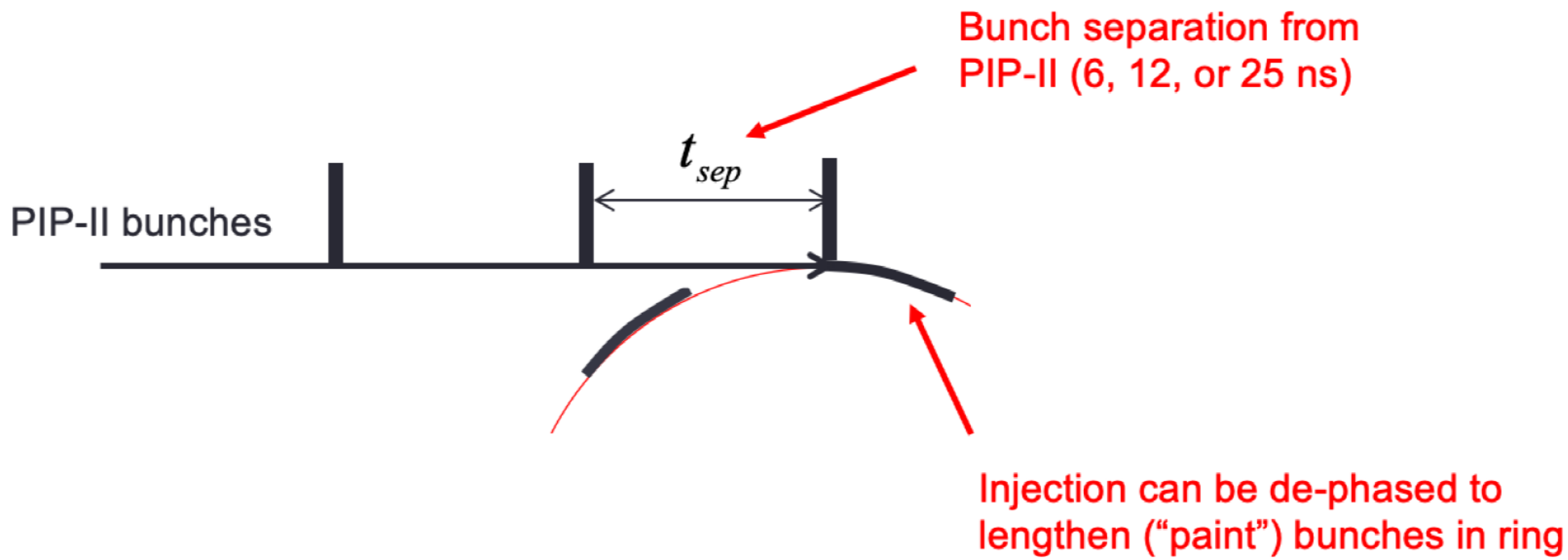
A New Charged Lepton Flavor Violation Program at Fermilab

M. Aoki,[1] R. B. Appleby,[2,3] M. Aslaninejad,[4] R. Barlow,[5] R.H. Bernstein,[6] C. Bloise,[7] L. Calibbi,[8] F. Cervelli,[9] R. Culbertson,[6] André Luiz de Gouvêa,[10] S. Di Falco,[9] E. Diociaiuti,[7] S. Donati,[9] R. Donghia,[7] B. Echenard,[11] A. Gaponenko,[6] S. Giovannella,[7] C. Group,[12] F. Happacher,[7] M. T. Hedges,[13] D.G. Hitlin,[11] E. Hungerford,[14] C. Johnstone,[6] D. M. Kaplan,[15] M. Kargiantoulakis,[6] D. J. Kelliher,[16] K. Kirch,[17] A. Knecht,[18] Y. Kuno,[1,19] A. Kurup,[20] J.-B. Lagrange,[16] M. Lancaster,[21] K. Long,[20] A. Luca,[6] K. Lynch,[22] S. Machida,[16] M. Martini,[23,*] S. Middleton,[11] S. Mihara,[24] J. Miller,[25] S. Miscetti,[7] L. Morescalchi,[9] Y. Mori,[26] P. Murat,[6] B. Muratori,[27,3] D. Neuffer,[6] A. Papa,[9] J. Pasternak,[20] E. Pedreschi,[9] G. Pezzullo,[28] T. Planche,[29] F. Porter,[11] E. Prebys,[30] C. R. Prior,[16] V. Pronskikh,[6] R. Ray,[6] F. Renga,[31] C. Rogers,[16] I. Sarra,[7] A. Sato,[1] S. L. Smith,[27,3] F. Spinella,[9] D. Stratakis,[6] M. Syphers,[32] N.M. Truong,[30] S. Tygier,[2,3] Y. Uchida,[20] and M. Yucel[6]

Submitted to Snowmass'21 process

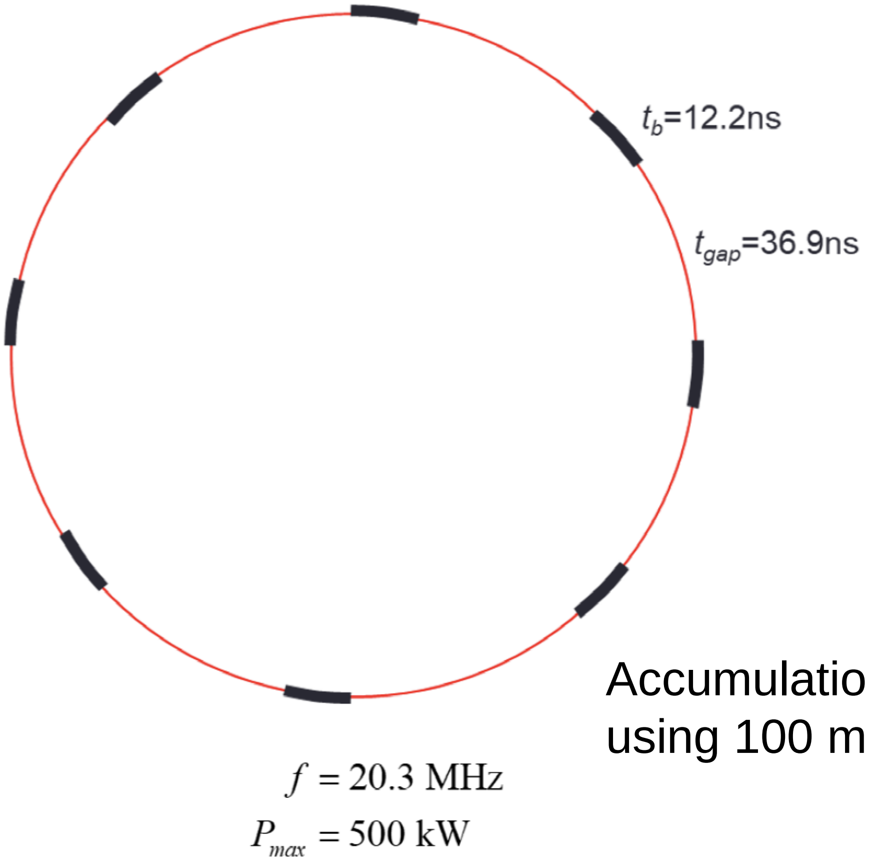
Realising compressed bunches using PIP-II linac at FNAL

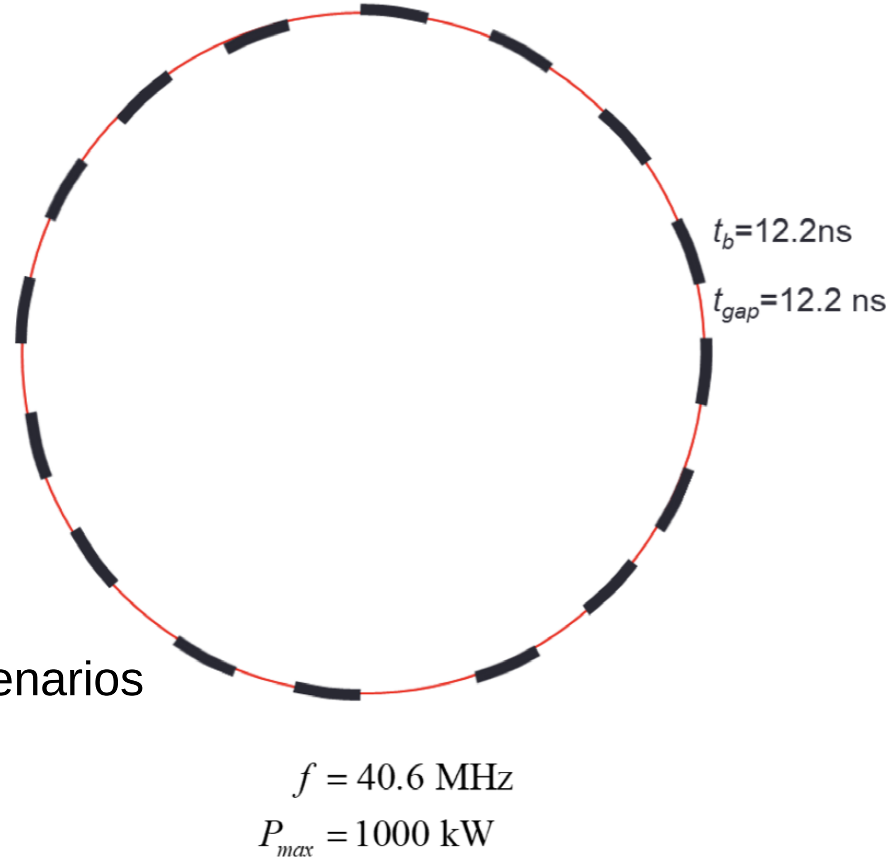
- PIP-II linac can be used to generate the compressed bunches
  - The neutrino program will use less than 1% of its capacity
  - Other upgrade scenarios can be also considered
- Compressor ring needs to be added



arXiv: 2203.08278v1

Realising compressed bunches using PIP-II linac at FNAL (2)





Accumulation scenarios using 100 m ring

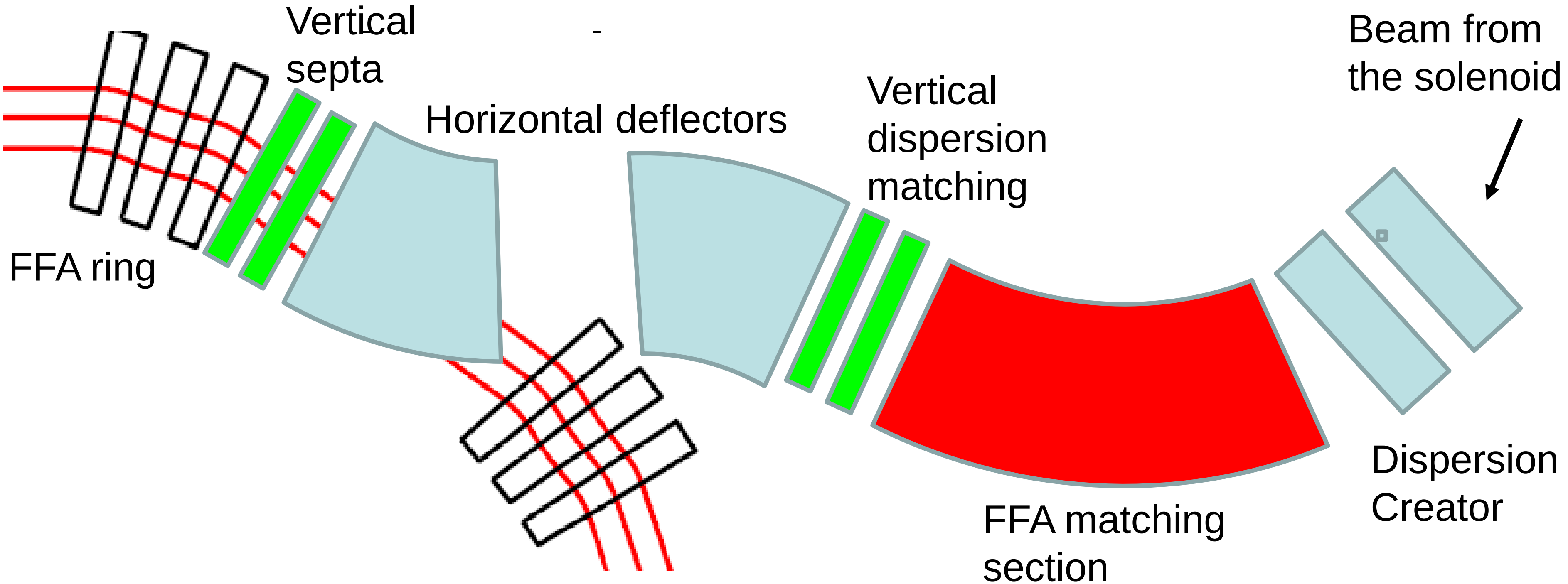
	C=100 m			C=500 m (BSR)		
Power [kW]	100	500	1000	100	500	1000
N_b $[10^{12}]$	7.8	39.1	78.1	7.8	39.1	78.1
ϵ_N [π-mm-mr]	54	268	536	268	1339	2678
radius ($\beta_\perp = 20$m) [mm]	26	58	83	58	131	185

Parameters for 100m and 500m compressor rings

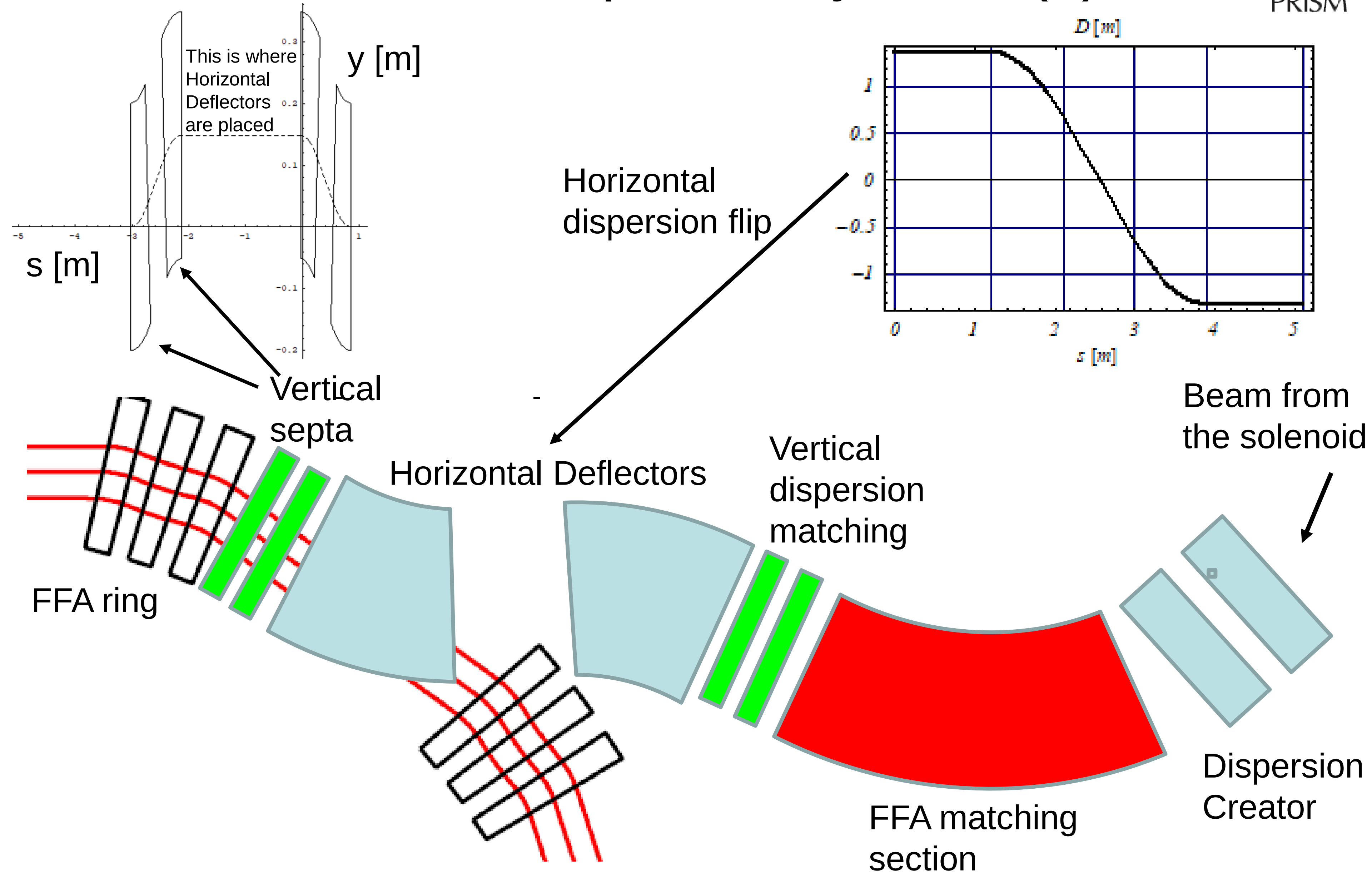
arXiv: 2203.08278v1

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 including the Lambertson-type septum and match the vertical dispersion to zero
- Finally, the vertical kickers bring the beam on the circulating orbit



New concepts for injection (2)



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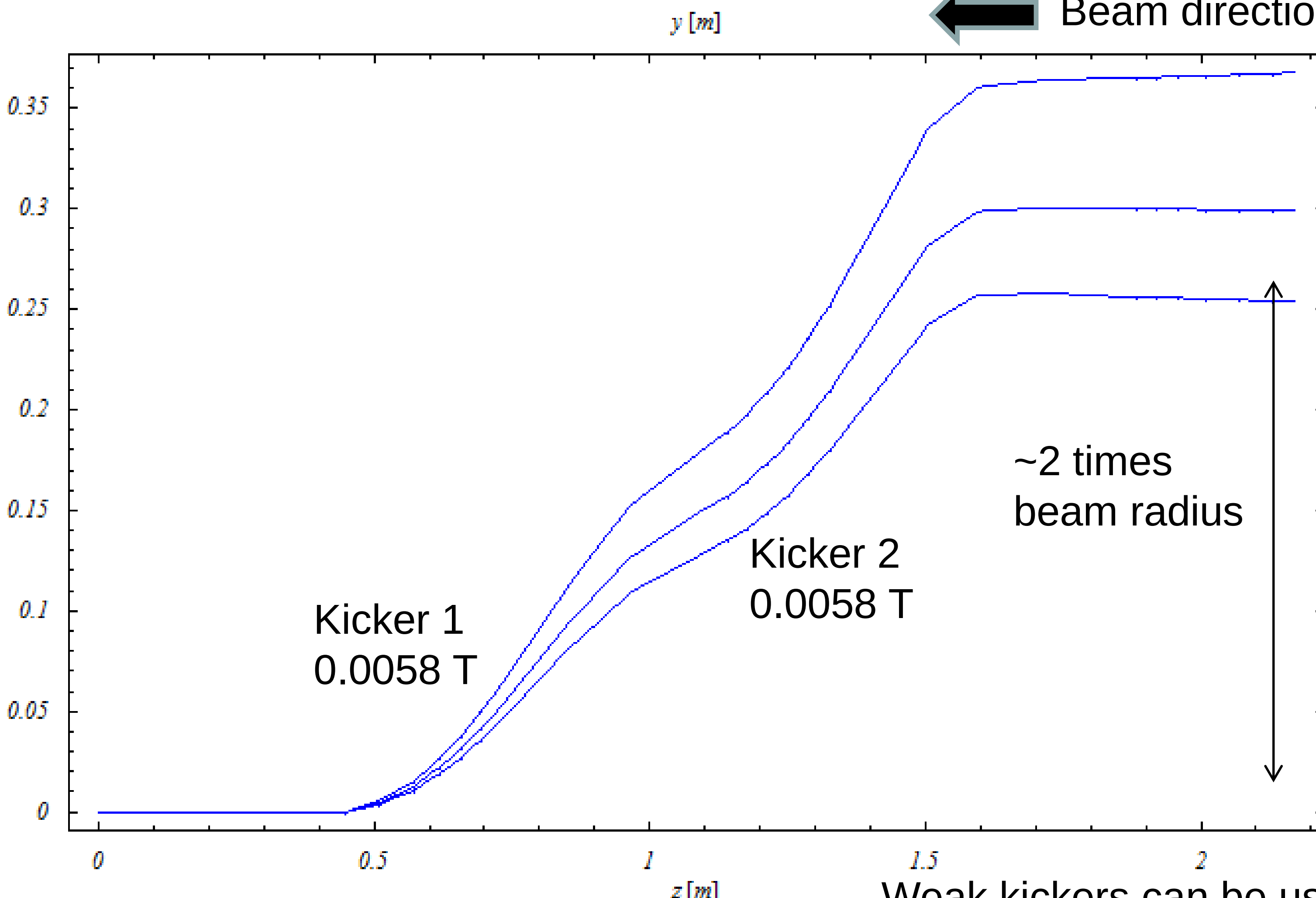
Vertical injection into FFA

Orbit separation with 2 kickers

Beam direction



Weak kickers can be used!

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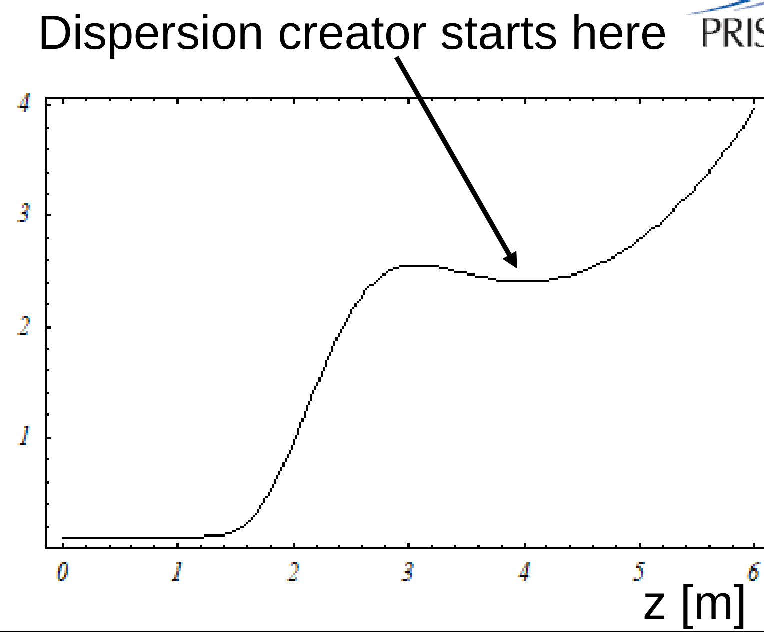
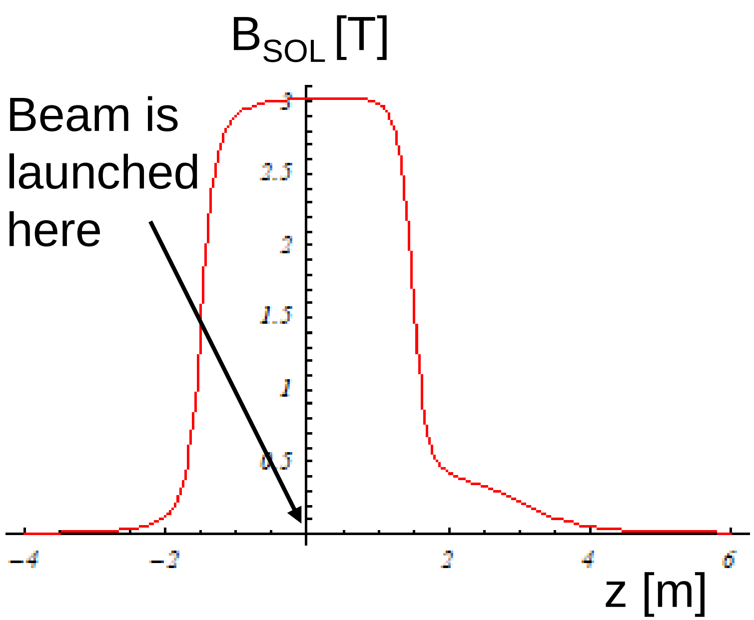
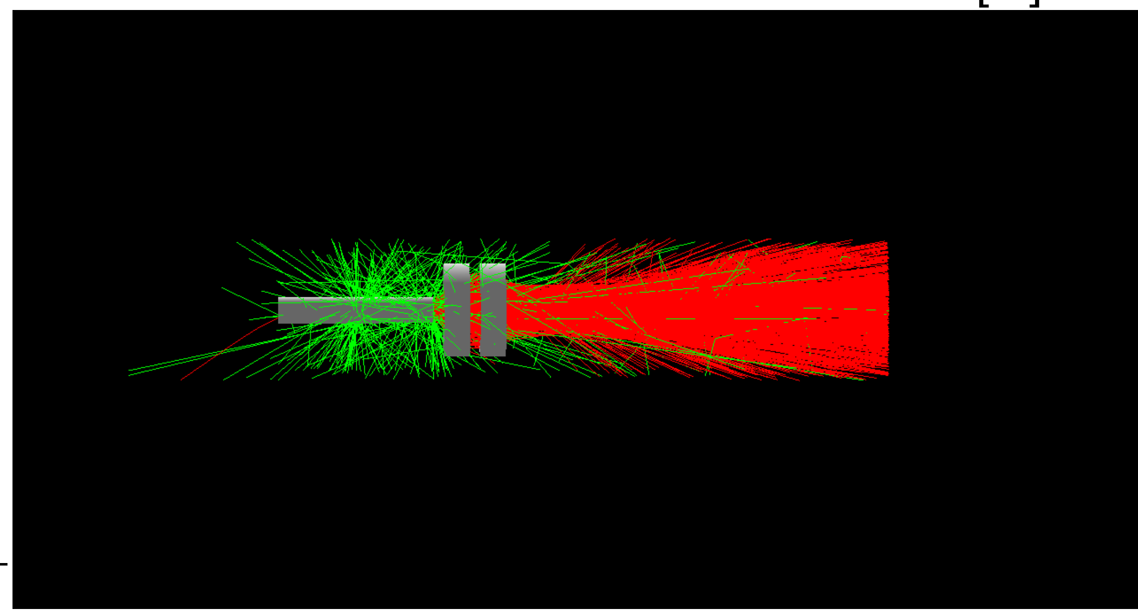
Transition from the solenoid to the AG lattice

- 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 reduced to zero gradually, while beam is matched transversely to the Alternating Gradient (AG) lattice







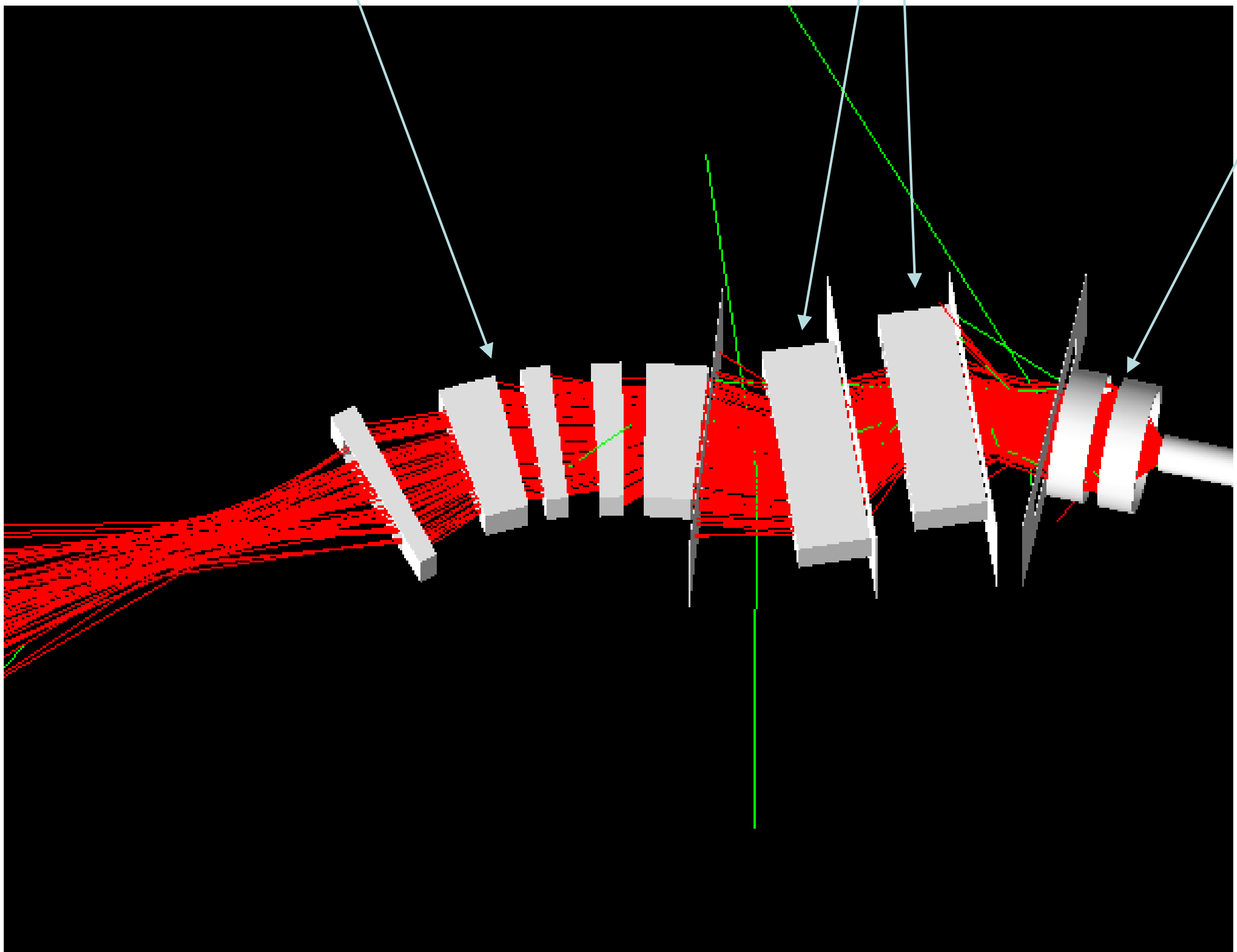
From R. Feng, IC

Preliminary injection line study

Dispersion Creator

Part of the FFA matching section

Solenoidal matching coils



Beam from the solenoid

From R. Feng, IC

Preliminary injection line study, work is progressing (2)

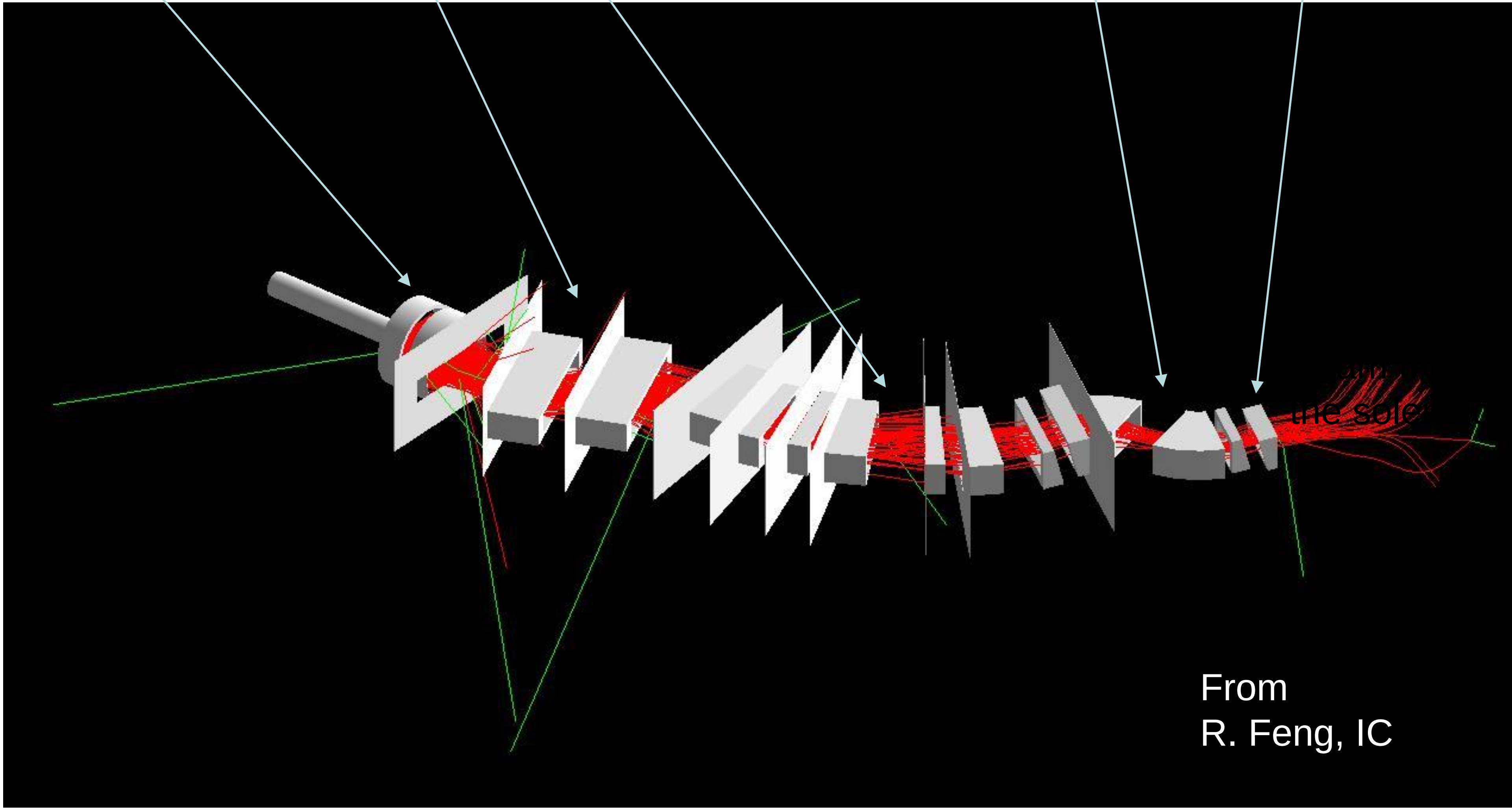
Dispersion Creator

Solenoidal matching coils

FFA matching section

Horizontal deflectors

Vertical septum



Conclusions

- We aim to make further progress on defining the PRISM system in a near future
  - 3D field maps are in the process of creation to be used in G4BeamLine (or BDSIM) simulation of injection
    - Study in synergy with nuSTORM

- We hope the Snowmass process will lead to P5 endorsing the PRISM system and to prepare the route for its funding

- Compressed bunches needed for PRISM can be generated using PIP-II linac and further upgrades of the FNAL chain or at J-PARC
  - We plan further studies on generating the compressed bunches

- PRISM is a serious choice for the next generation cLFV experiment
- Please join us!

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