Accelerator R&D for the Neutrino Factory and muon FFAGs

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Outline

- Introduction.
- Accelerator R&D for the Neutrino Factory within the International Design Study.
- Progress on muon FFAGs.
- Conclusions and future plans.

Standard Neutrino Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Experimental data:

$$\theta_{12} \subset \{32.3^\circ \rightarrow 37.8^\circ\}$$

$$\theta_{31} \subset \{36.9^\circ \rightarrow 51.3^\circ\}$$

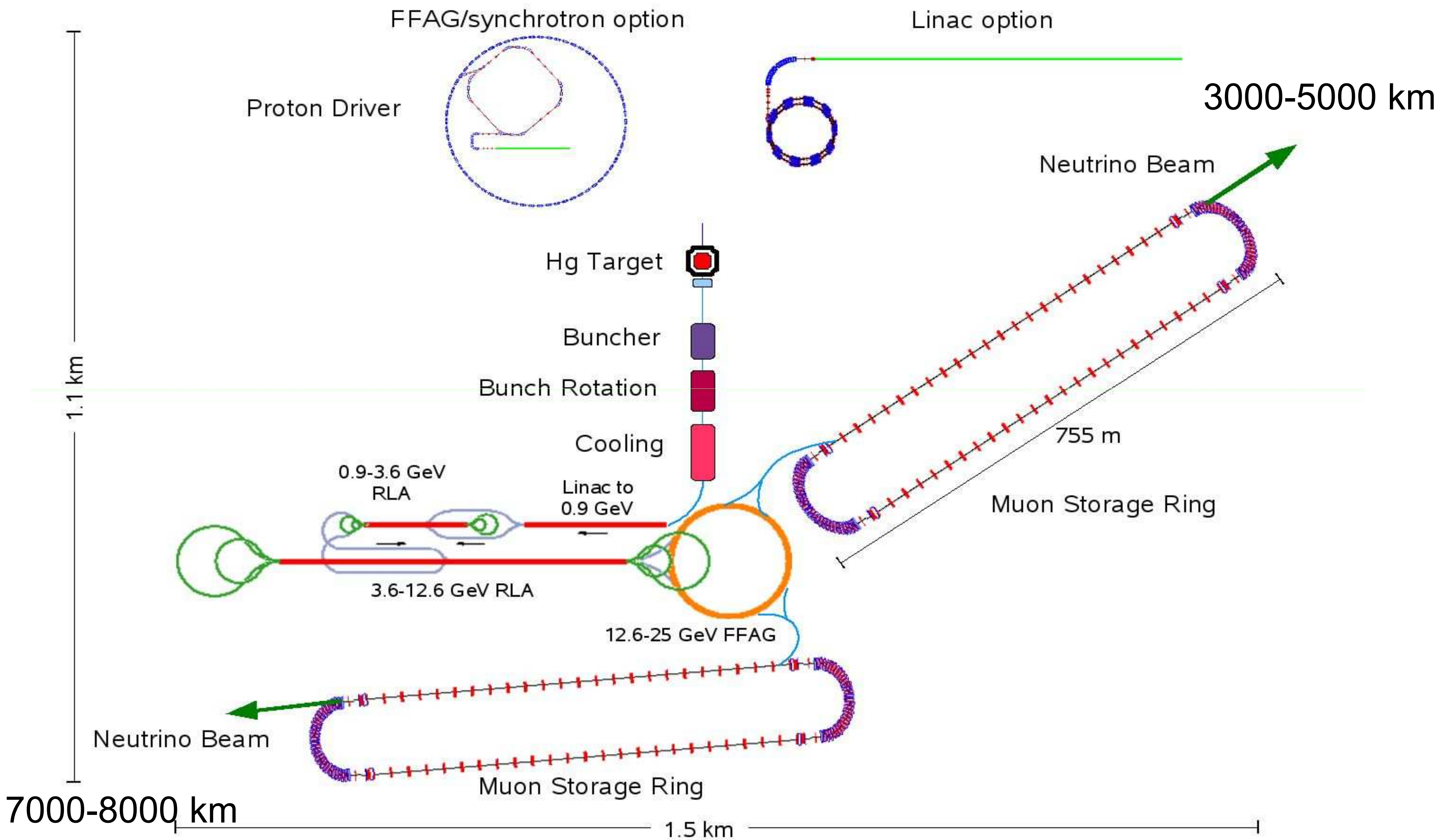
$$\theta_{13} < 10.3^\circ$$

$$\Delta m^2_{21} = (7.66 \pm 0.35) \times 10^{-5}\ \mathrm{eV}^2$$

$$|\Delta m^2_{31}| = (2.38 \pm 0.27) \times 10^{-3}\ \mathrm{eV}^2$$

CP violating phase is unknown!

Neutrino Factory, facility for precision neutrino physics



International Design Study
for the Neutrino Factory (IDS-NF)

IDS-NF Steering Group	
Committee	
A Blondel	Geneva
M Zisman	LBNL
Y Kuno	Osaka
K Long	Imperial (Chair)
Accelerator Conveners	
S Berg	BNL
Y. Mori	Kyoto
C. Prior	STFC
J. Pozimski	Imperial
Detector Conveners	
A Bross	FNAL
P Soler	Glasgow
N. Mondal	Mumbai
A. Cervera	Valencia
Physics and Performance Evaluation Group Conveners	
A Donini	Madrid
P. Huber	CERN
S. Pascoli	Durham University
W. Winter	Universität Würzburg
O. Yasuda	Tokyo Metropolitan University

www.ids-nf.org/

Neutrino Factory parameters

- Proton beam power 4 MW.
- Proton bunch length at the target ± 2-3 ns rms.
- Proton beam energy 5-15 GeV.
- Repetition rate 50 Hz.
- Number of proton bunches per macropulse 3.
- Distance between proton bunches ~160 us.
- Baseline target – Mercury jet.
- Capture system – 20 T solenoid.
- Muon front end – bunching/phase rotation/ionization cooling.
- Muon train length 80 m (52 201 MHz bunches).
- Muon cooling/acceleration RF frequency 201 MHz.
- Number of muons stored in the decay ring ~10^21 per year.

Progress on Accelerator R&D for the Neutrino Factory

- Proton Driver scenarios have been identified (Project X, CERN, RAL, …).
- Feasibility of the mercury jet was demonstrated (MERIT experiment).
- Interesting ideas about altrenative targets were proposed (solid, powder jet).
- Muon front-end improvement (better transmission, shorter in length).
- Mitigation scanarios for the RF breakdown in the magnetic field were proposed (Be cavity, shielded RF lattice, bucked coils, magnetic insullation).
- MTA is progressing on testing the prototype 201 MHz RT cavity for cooling.
- Commissioning of MICE muon beam has been completed.
- Muon accelerator has been designed including some of hardware components (EM design of SC solenoids and SC cavities in the linac etc.)
- Tracking studies are in progress.
- Progress on injection/extraction for the FFAG.
- EMMA circulating beam was established.
- Alternative cost effective acceleration scenario based on scaling FFAG was designed.
- Muon beam diagnostics in the decay ring was simulated.
- …

Main problem:

- energy deposition by primary and secondary particles emitted from the target.

Muon NS-FFAG for NF

Non Scaling FFAG was proposed for the main acceleration of muon beam for the Neutrino Factory as:

- quasi-isochronous lattice enables to use fixed high frequency RF.
- linear fields gives huge DA and allows for simple magnets.
- small orbit excursion – cost effective.

Main problems:

- TOF with amplitude
- injection/extraction

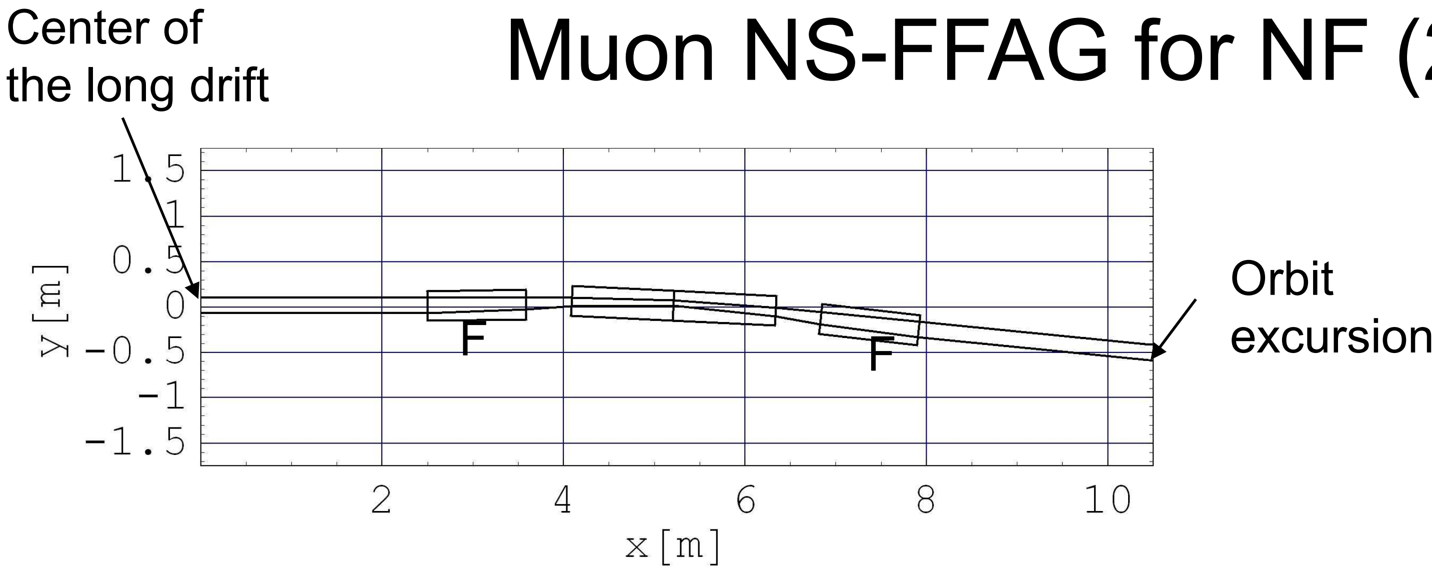
Current Baseline

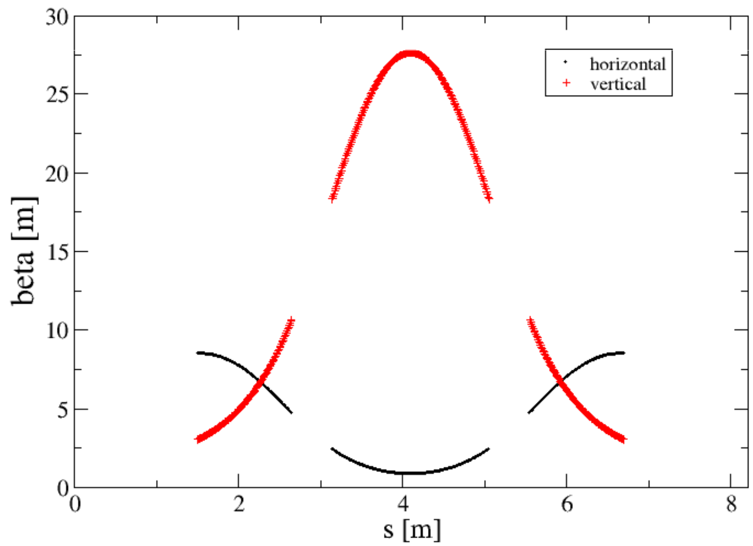
TABLE III. Lattices with cell periods of a half integer number of RF periods.

Long Drift (m)	3.0	3.5	4.0	4.5	5.0
Cells	60	60	64	64	64
D length (m)	1.903800	1.803061	2.214080	2.095687	2.251117
D angle (mrad)	158.881	161.152	152.826	155.343	156.837
D shift (mm)	36.435	35.699	39.256	38.593	41.003
D field (T)	5.02885	5.37290	4.17163	4.46908	4.20784
D gradient (T/m)	-17.75656	-19.69323	-13.83029	-15.25579	-13.55592
F length (m)	1.143172	0.943586	1.232769	1.042002	1.086572
F angle (mrad)	-27.081	-28.216	-27.326	-28.584	-29.331
F shift (mm)	9.700	10.676	11.848	12.773	13.907
F field (T)	-1.24996	-1.55950	-1.15531	-1.41881	-1.39381
F gradient (T/m)	19.22556	24.47768	16.01219	19.75387	18.04570
Cavity cells	88	88	96	96	96
RF voltage (MV)	1090.503	1050.061	1175.028	1144.173	1213.861
turns	12.9	13.4	12.0	12.3	11.6
D radius (mm)	115	117	127	129	137
D max field (T)	7.1	7.7	5.9	6.4	6.1
F radius (mm)	153	145	162	155	163
F max field (T)	4.2	5.1	3.7	4.5	4.3
Circumference (m)	492	492	620	620	667
Decay (%)	5.5	5.7	6.4	6.6	6.7
Cost (A.U.)	167	175	181	188	193

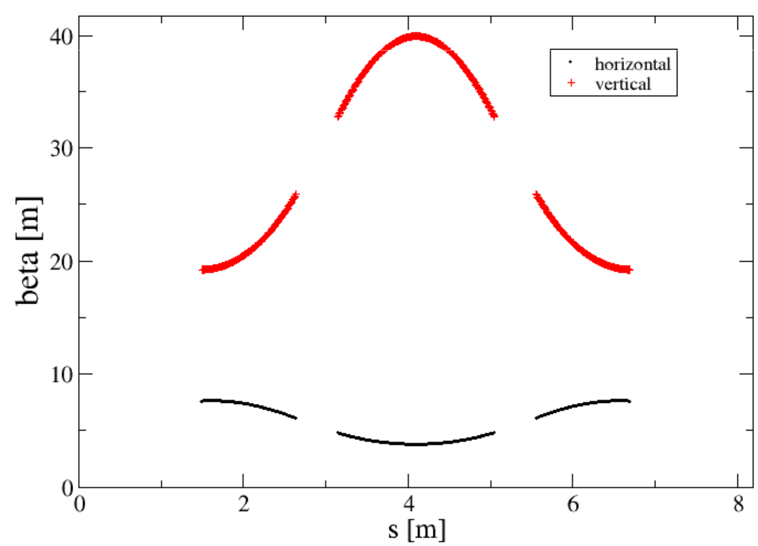
Set of new lattices from Scott Berg, BNL with different drift lengths.

Muon NS-FFAG for NF (2)



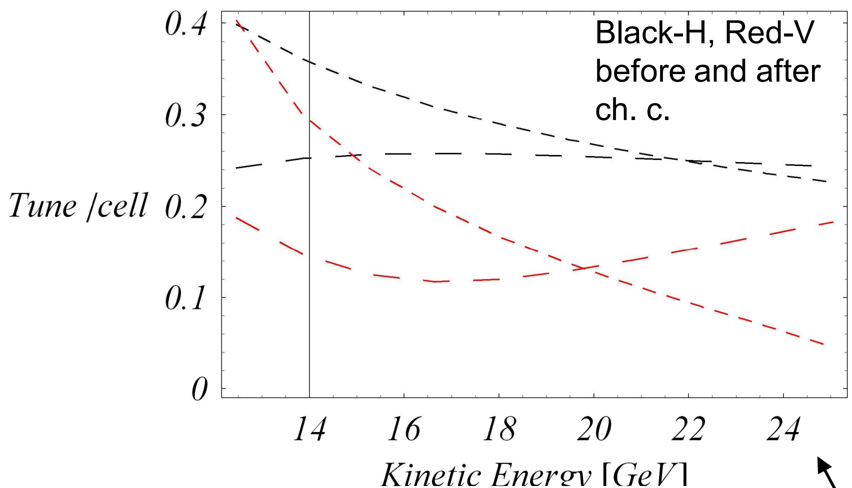


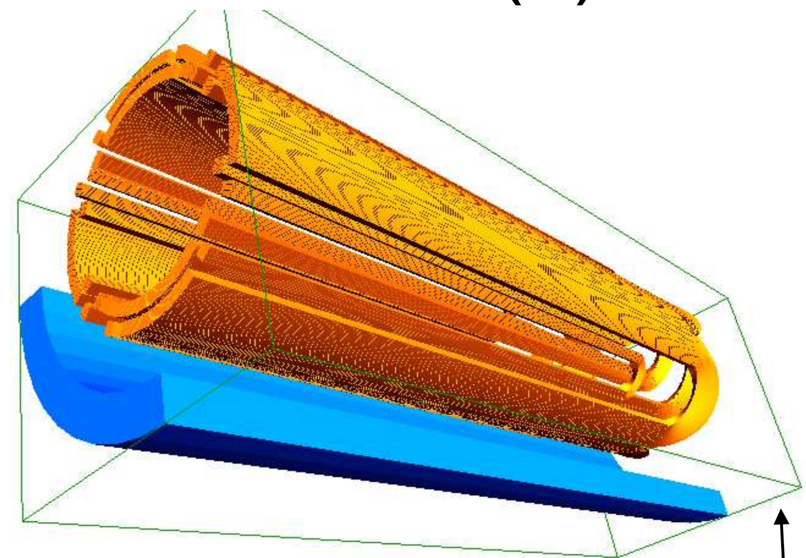
Beta functions at injection

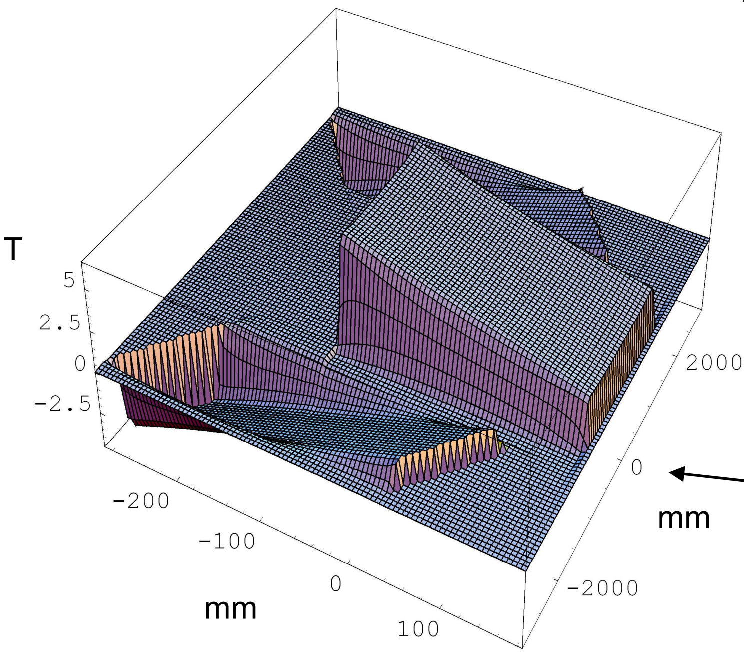


Beta functions at extraction

Muon NS-FFAG for NF (3)



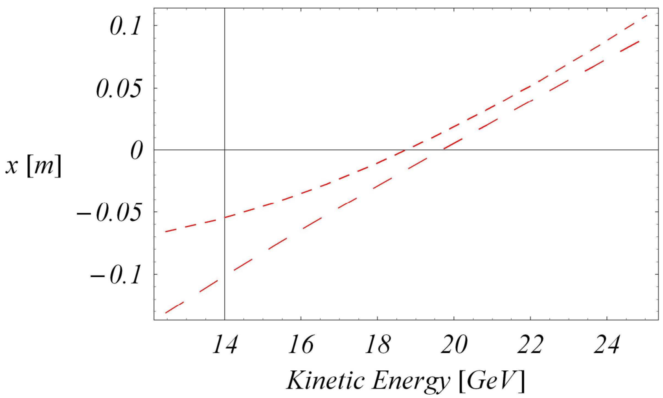


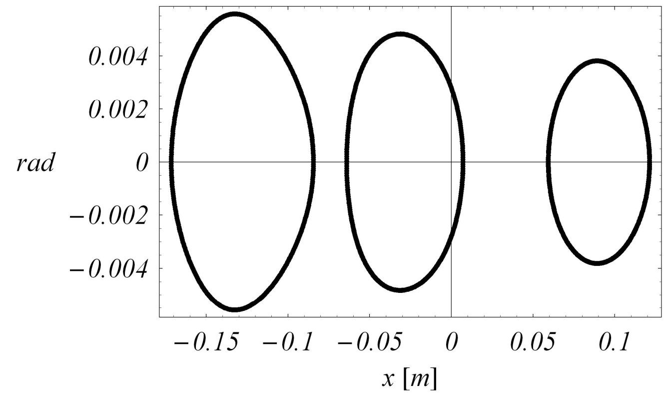


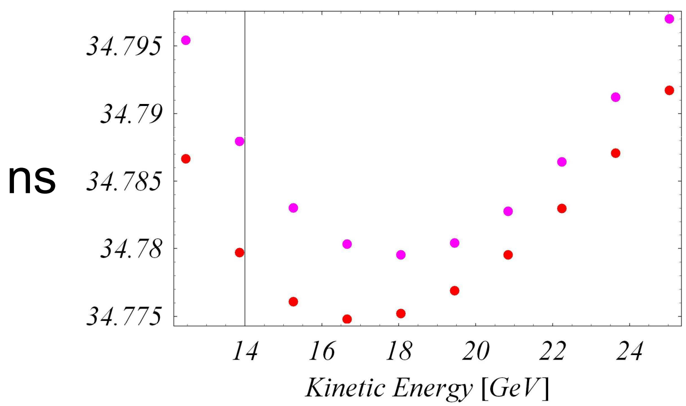
IDS FFAG studies includes:

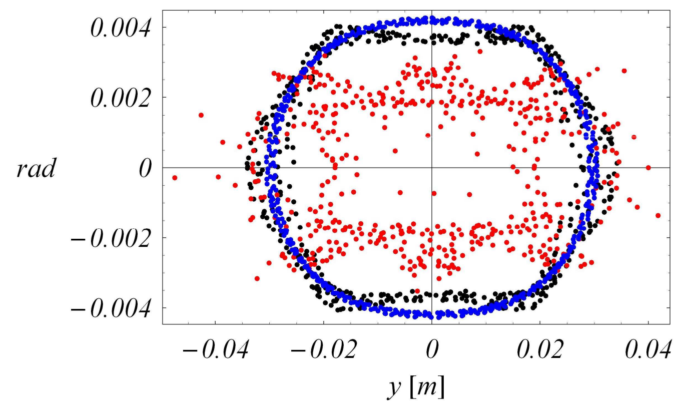
- Chromaticity correction to reduce the TOF problem.
- SC main magnet design using ROXIE code.
- Tracking studies using realistic field maps using Zgoubi code (work in progress).

Effect of chromaticity correction









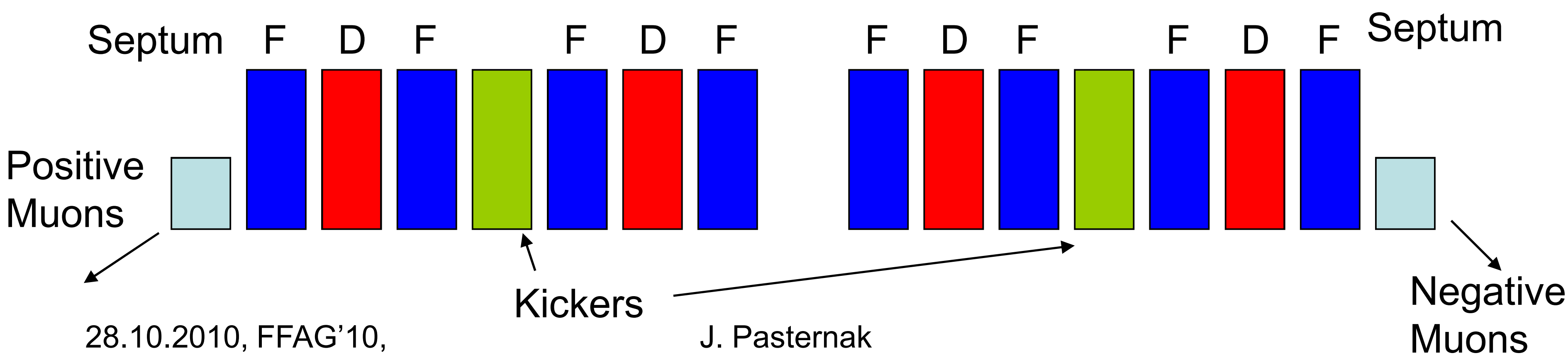
- Only sextupoles are used.
- Orbit excursion becomes a bit larger.
- ToF parabola is a bit shifted and more asymmetric.
- Horizontal DA – no problem for 3 cm normalised emittance (no RF).

- Vertical DA is an issue! The results shows:

1.5 cm norm. acceptance at 12.6 GeV (black),
2.5 cm norm. acceptance at 18 GeV (red).
3 cm norm. emittance tracking at 25 GeV (blue).

Introduction to Injection/Extraction

• Feasible single turn injection/extraction is required for a realistic design of the muon IDS-FFAG operating with 3 Pi cm rad total norm. emittance.
• In order to reduce the kicker strength it is proposed to distribute them in a few cells.
• Kickers are mainly used to supress/create the separation between the „circulating" beam and the injected/extracted beam at the septum.
• Septum is used mainly to clear the beam with respect to the upstream/downstream main magnet (F).
• The septum strength determines the drift length and sets a strong constraint on the lattice design.
• Apply mirror symmetric solution to reuse kickers for both signs of muons.



Injection/Extraction geometries

Injection

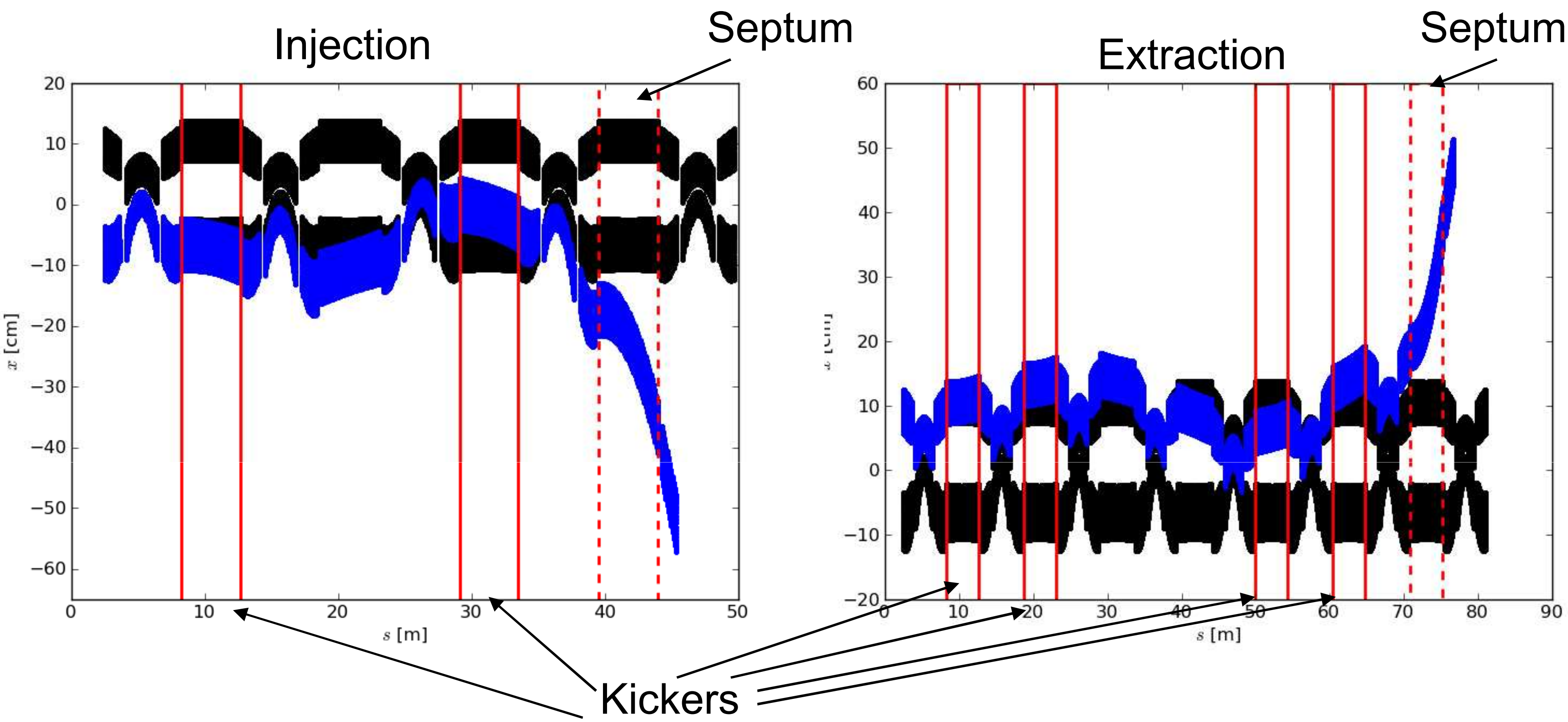
lattice	3m	3.5m	4m	4.5m	5.0m
Plane (H/V)	H	H	H	H	H
No. Kickers	3	3	2	2	2
Kicker field (T)	0.091	0.084	0.104	0.102	0.089
Kicker Polarity	**+-+**	**+-+**	**+0+**	**+0+**	**+0+**
Septum field (T)	2.66	1.90	1.45	1.12	0.92

Extraction

lattice	3m	3.5m	4m	4.5m	5.0m
Plane (H/V)	H	H	H	H	H
No. Kickers	6	6	4	4	4
Kicker field (T)	0.088	0.075	0.087	0.078	0.067
Polarity	**++--++**	**++--++**	**++00++**	**++00++**	**++00++**
Septum field (T)	5.1	3.64	2.77	2.16	1.76

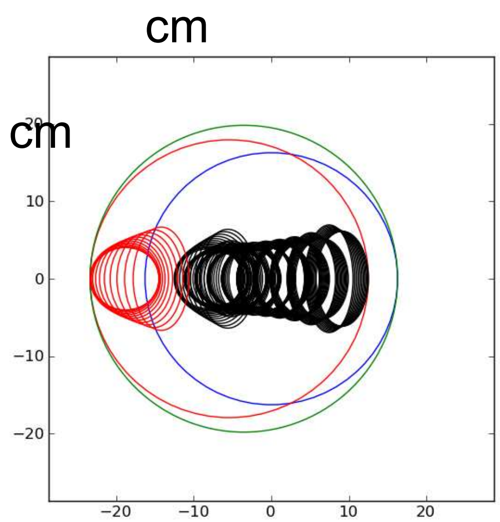
Current Baseline

Injection/Extraction geometries (2)

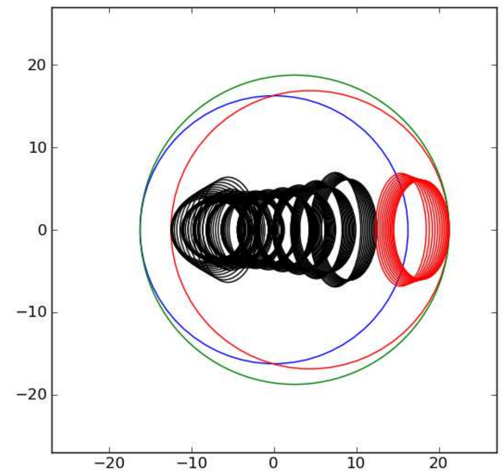


• Both injection and extraction are possible in the horizontal plane.
• Special magnets with larger apertures are needed in the injection/extraction regions.
• Vertical extraction was considered, but it requires special magnets with very large apertures (see next slide).
• With horizontal solutions we can avoid generating the vertical dispersion.

Magnet aperture studies

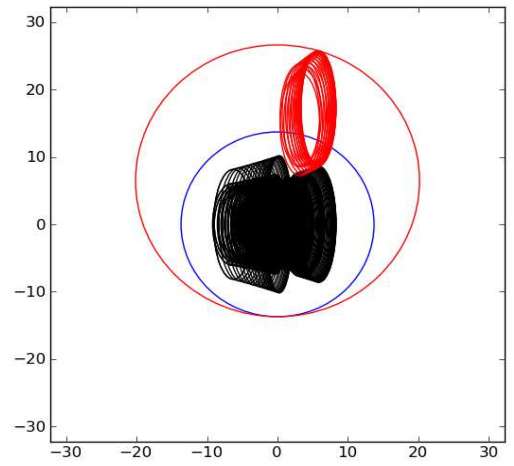


Magnet aperture in F magnet near the injection septum. Blue is the requirement for the circulating beam, red for kicked beam and green is the final special magnet aperture.



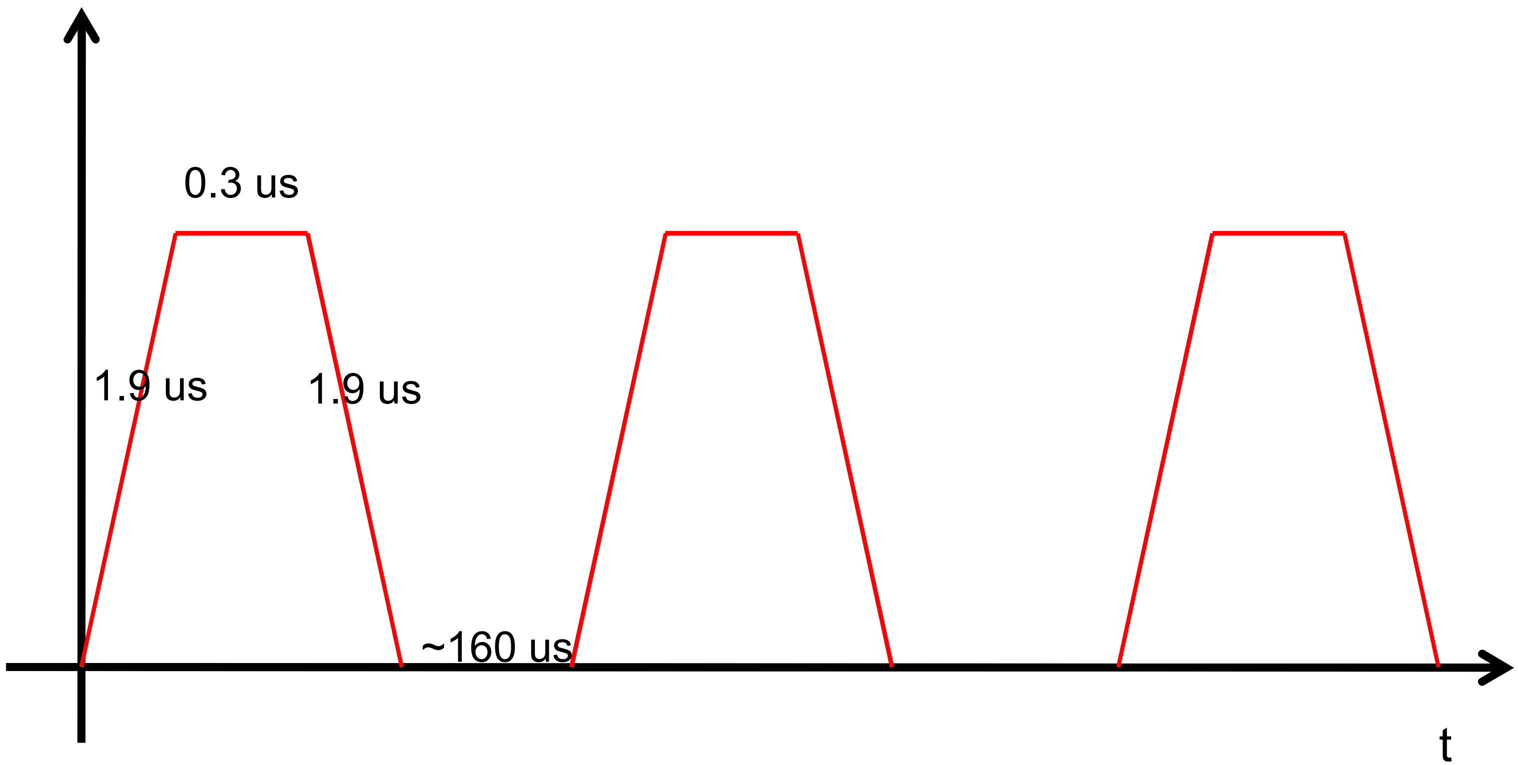
Magnet aperture in F magnet before the extraction septum.

Magnet type	Number of magnets	Radius (cm)
Normal F	116	16.3
Normal D	58	13.7
Injection F	4	20.8
Injection D	4	16.1
Extraction F	8	19.8
Extraction D	2	15.5



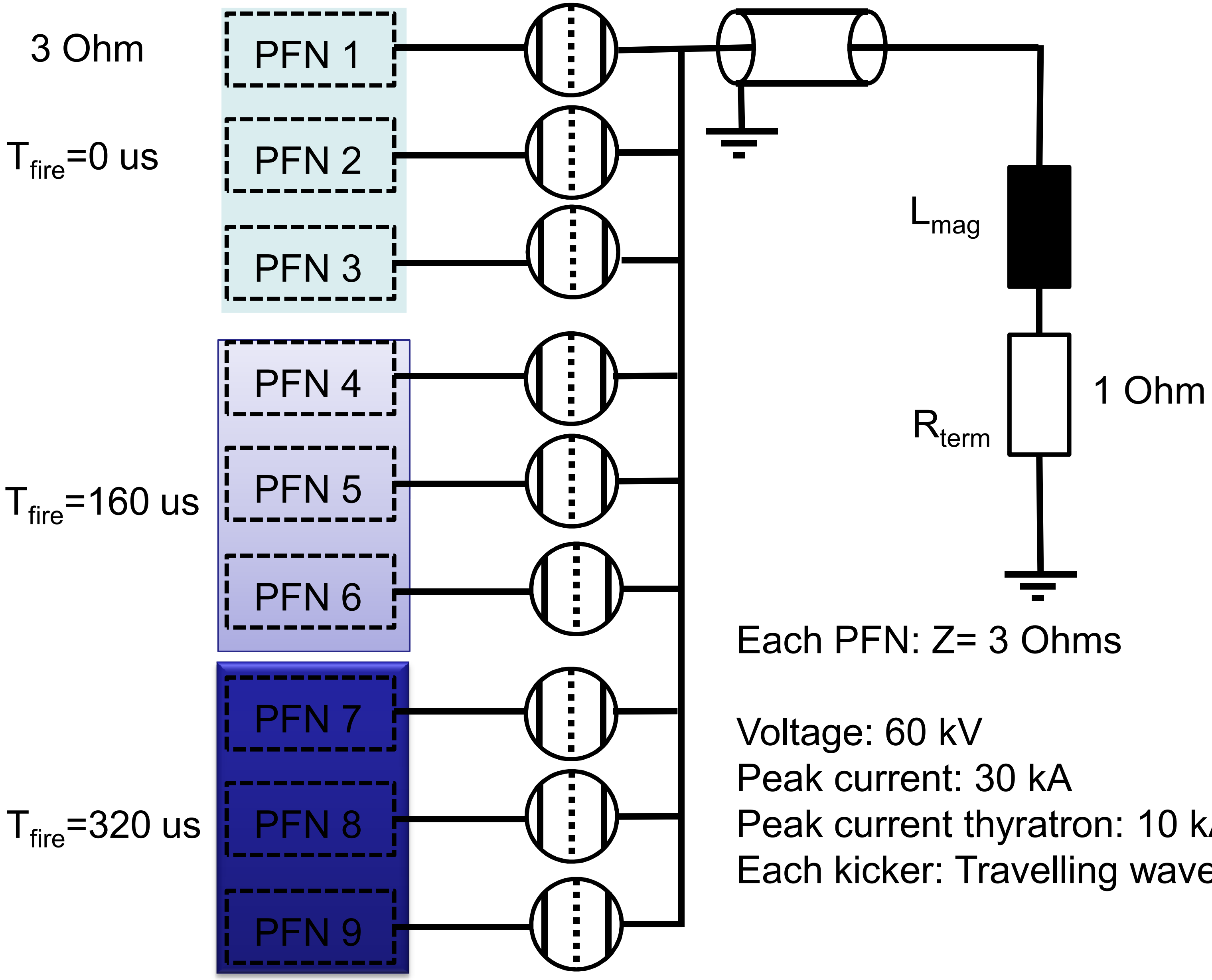
Magnet aperture in D magnet rules out the vertical extraction.

IDS Kicker - Pulses



Here 80 m long muon train was assumed and 2.2 us revolution time in the FFAG. We will still have 3 bunches separeted by 160 us originating from 3 proton bunches at the target.

IDS Kicker System

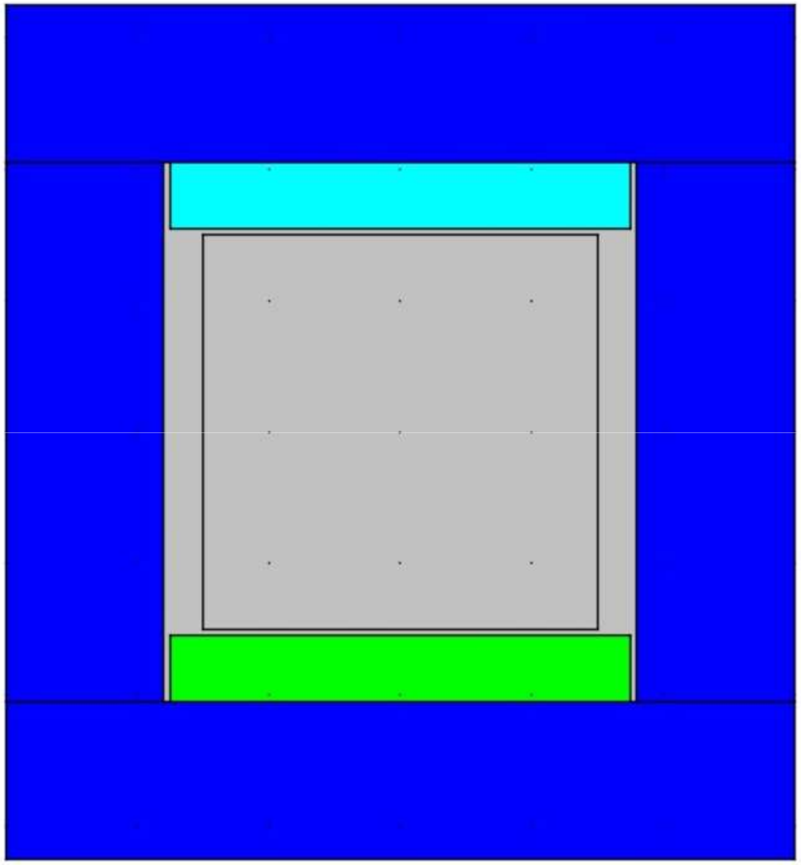


Each PFN: Z= 3 Ohms

Voltage: 60 kV
Peak current: 30 kA
Peak current thyratron: 10 kA
Each kicker: Travelling wave, many sections.

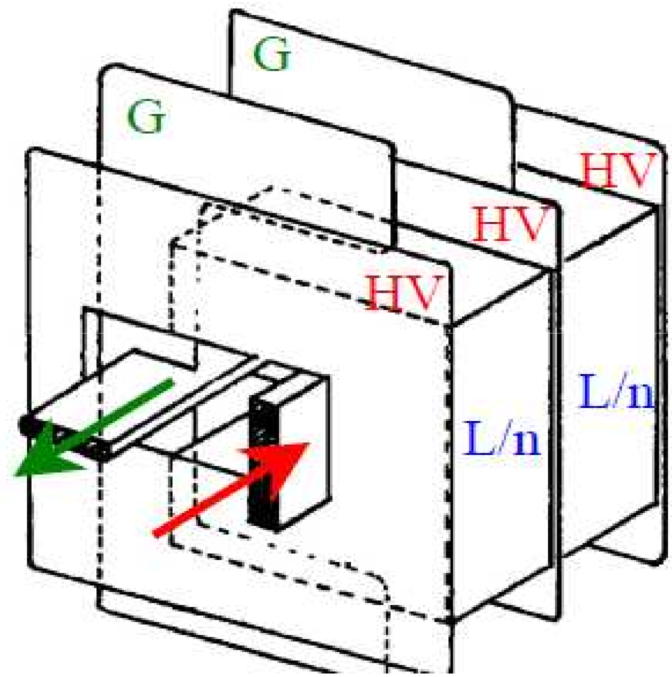
IDS Kicker

- Geometry
  - Aperture: 0.3x0.3 m^2 (needs an update)
  - Yoke: 120 mm
  - Length: 4.4 m
- Field: 100 mT (to add margins)
- Current: 29 kA
- Magnetic energy: 917 J
- Inductance (single turn): 5.1 uH
- Impedance matching
  - Add capacitors



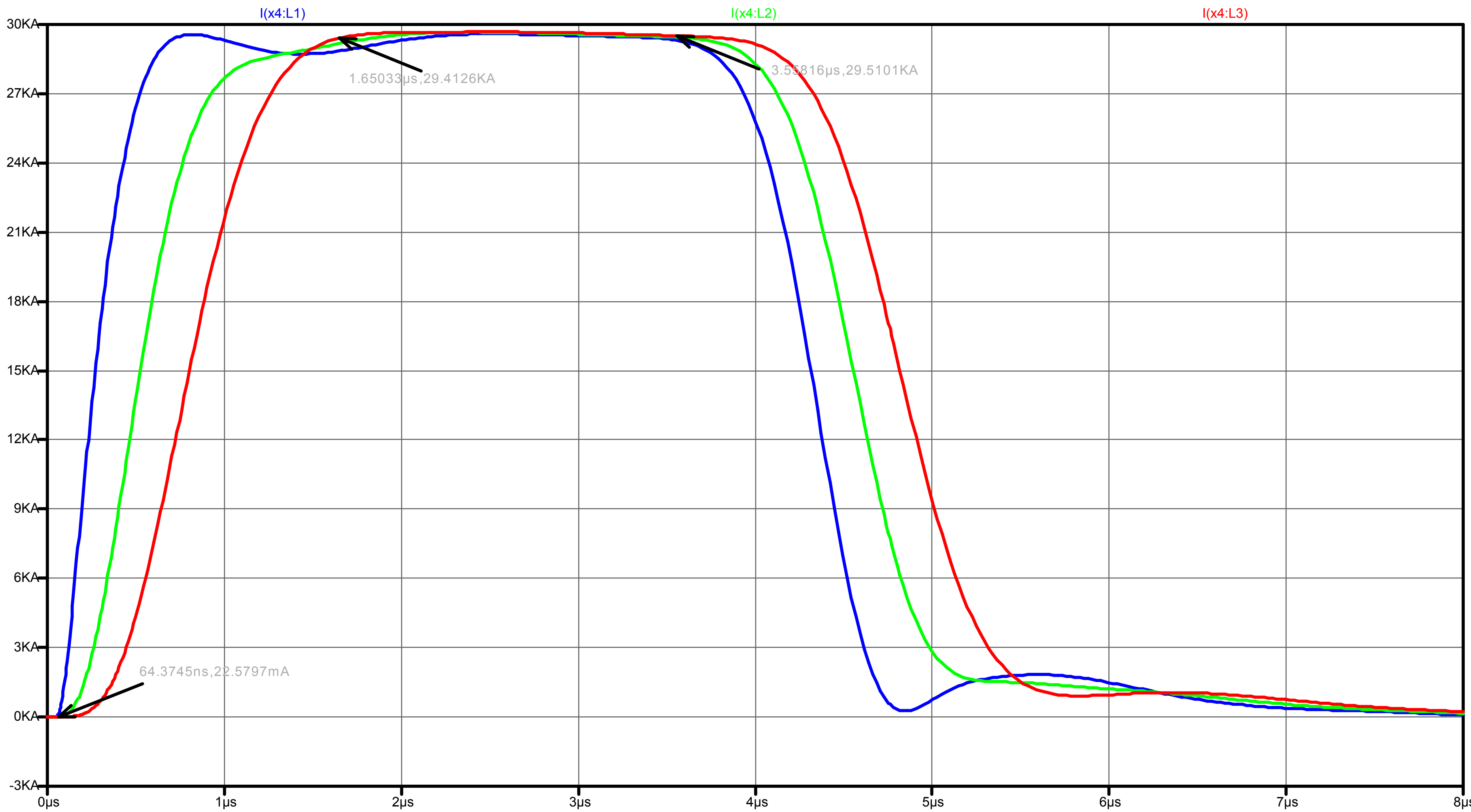
Travelling Wave Kicker

- Need to add capacitance
- Low impedance is required
  - V_{max}=60 kV
  - Current: 30 kA
- Large aperture (long) kicker = large inductance
- Substantial capacitance addition required (by putting plates)
  - Estimate: $C_{1\ Sheet}=1\times10^{-8}$F
  - $C=\varepsilon_0 \cdot S/d$
  - S=1 m^2 (too large?)
  - d=1 mm (too small?)
- You can also add external capacitors.



Realistic kicker design for RDR!

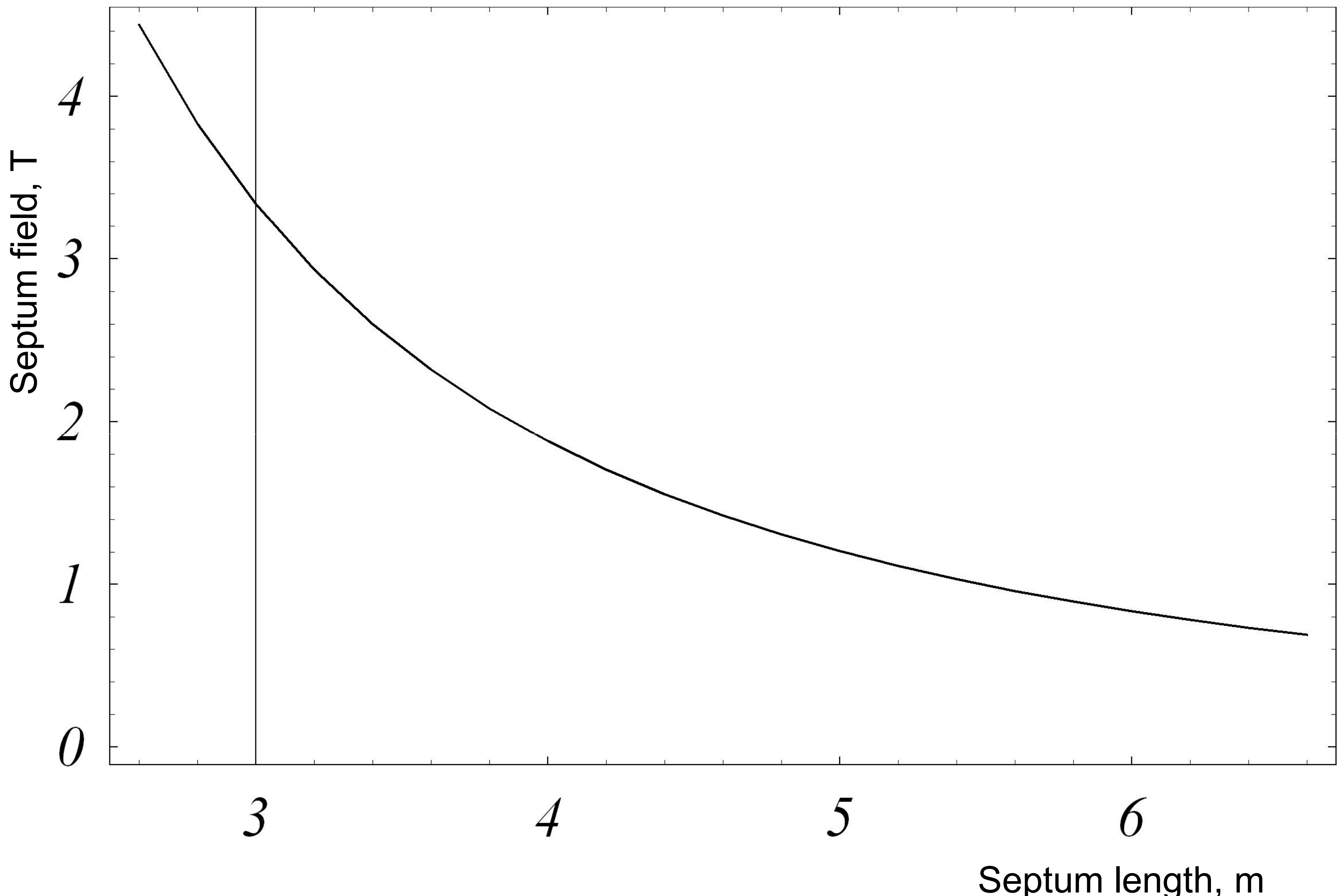
Current pulses in 3 kicker sections – „travelling wave" using PSPice



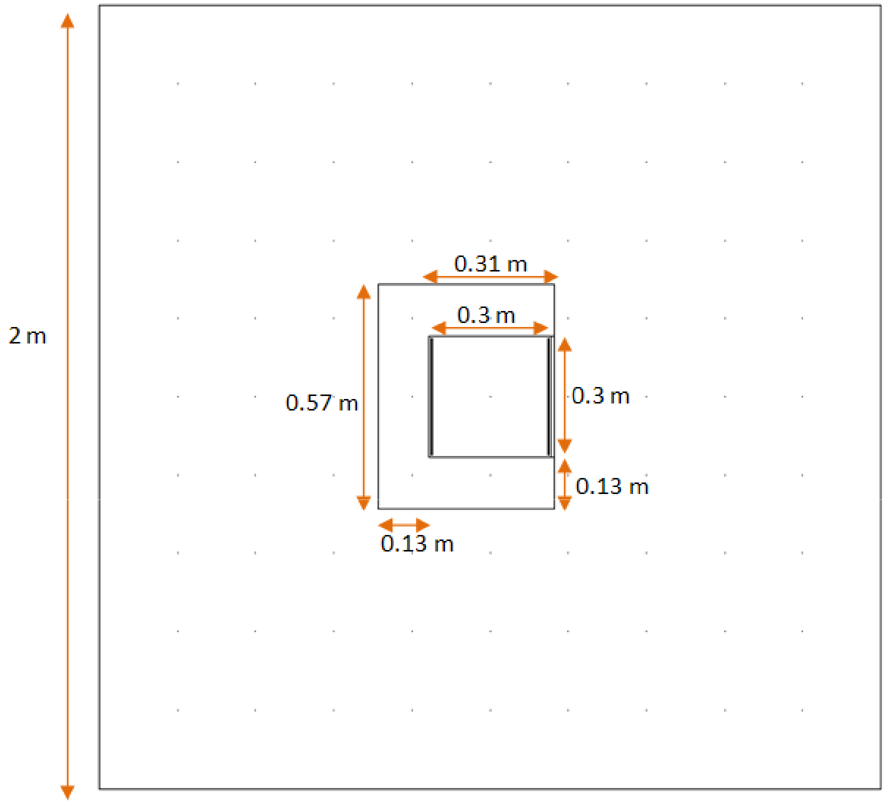
Septum studies

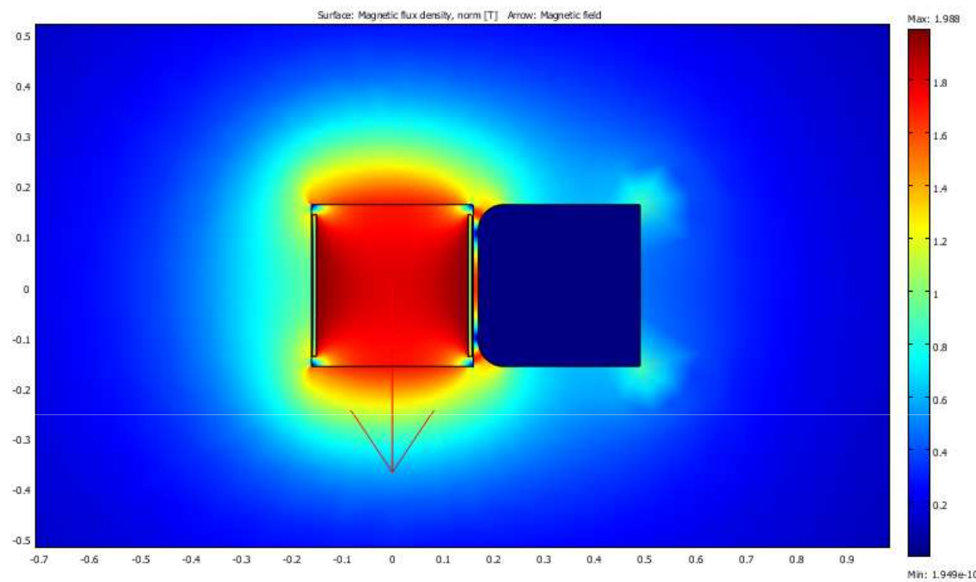
- We are using COMSOL and perform 2D simulations.
- The work started with the basic „window frame” geometry.
- The goal of the study was to limit the field leakage from the septum to the circulating beam region.
- Initial target of 4 T for the septum from beam dynamics studies turned out to be very difficult!
- We studied other schemes with more complicated yoke geometries and different yoke materials.
- The „correcting colil” approach was not very successful.
- The use of the advanced material and yoke shape turned out to be important.

Septum requirements



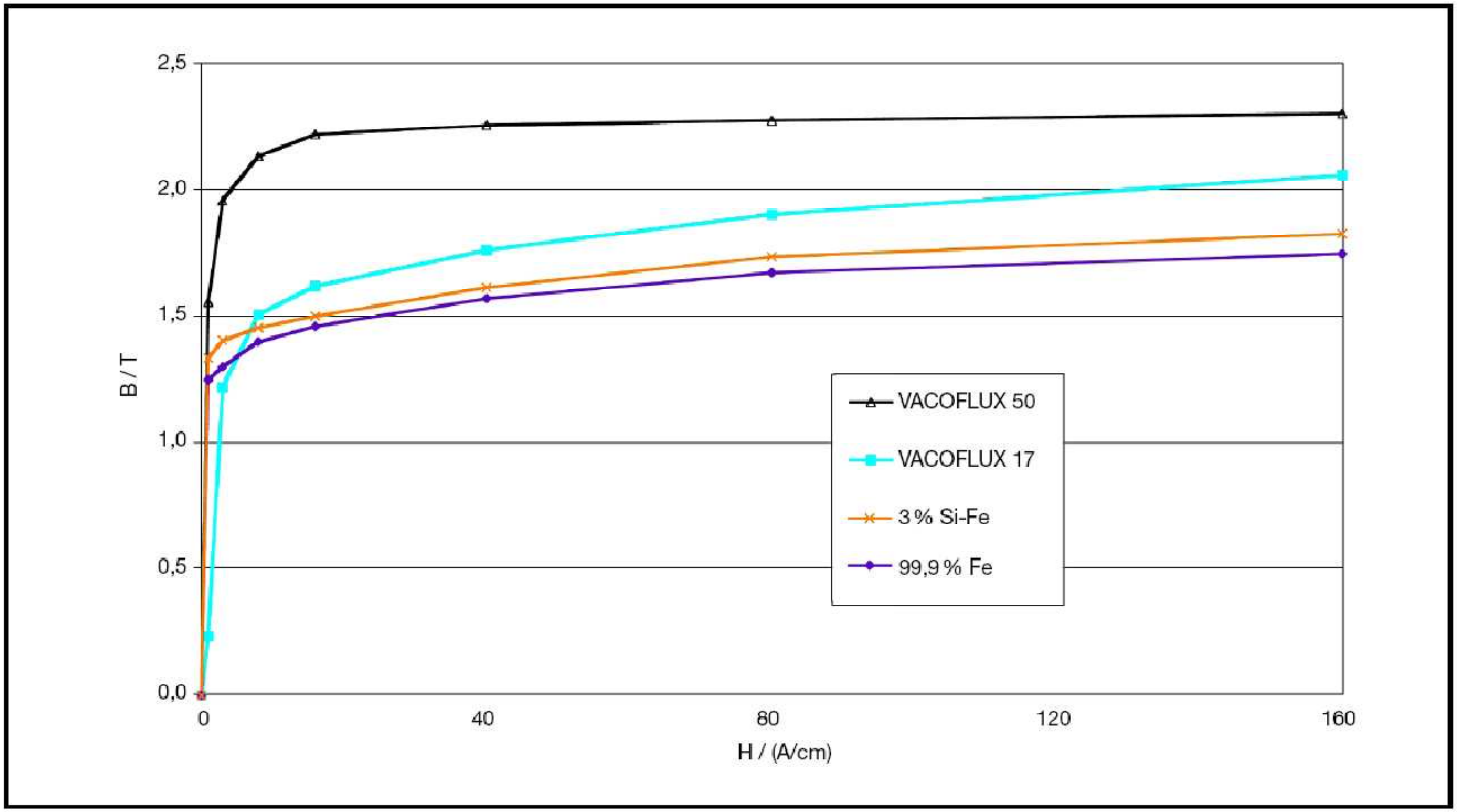
Septum geometry





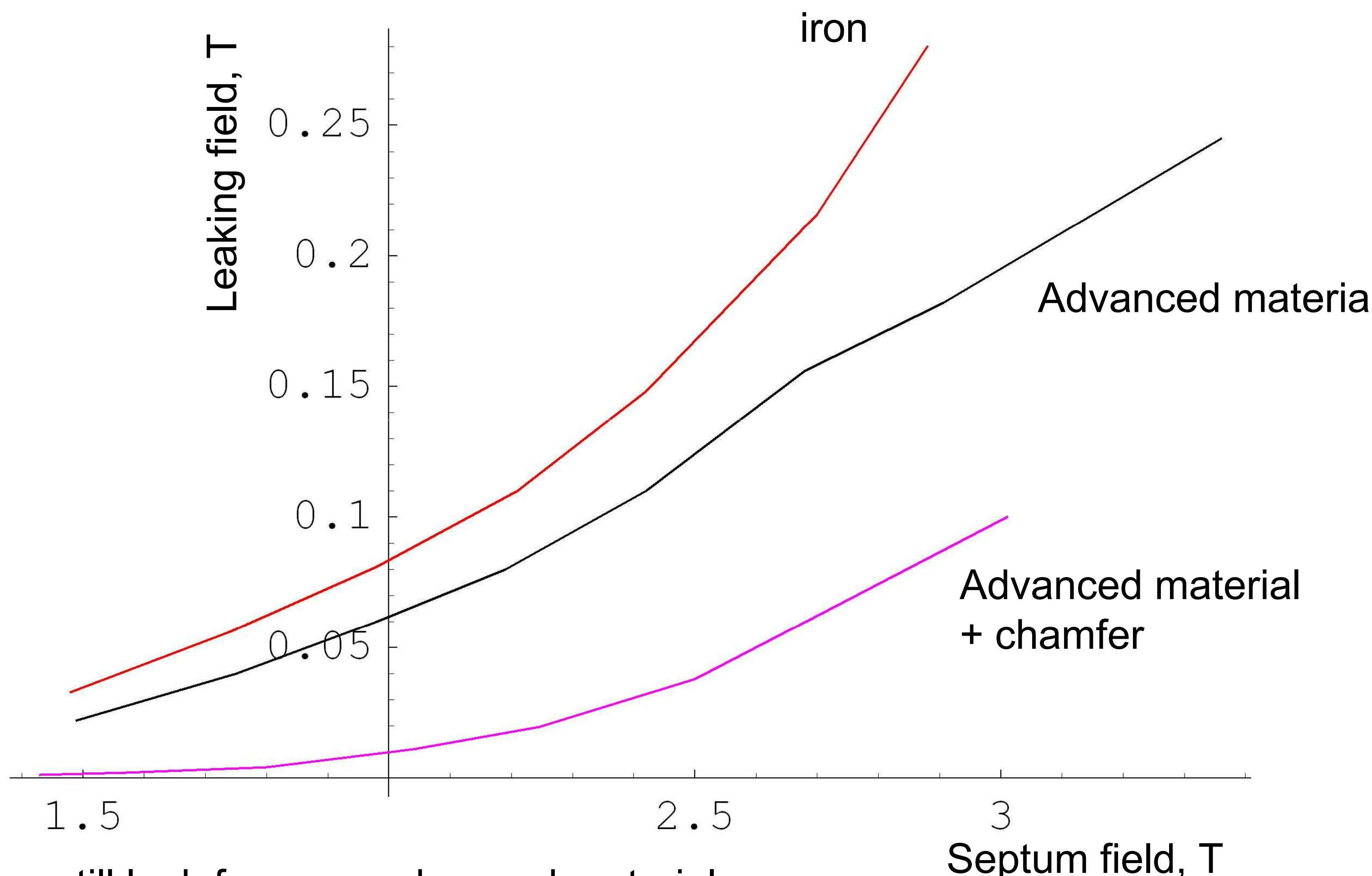
- Starting point of the study was a basic „C-shape" septum magnet.
- Iron was introduced all around the circulating beam.
- Iron was replaced by a special material with high saturation limit (see next slide).
- Chamfer was introduced.

Magnetic Materials for Septum



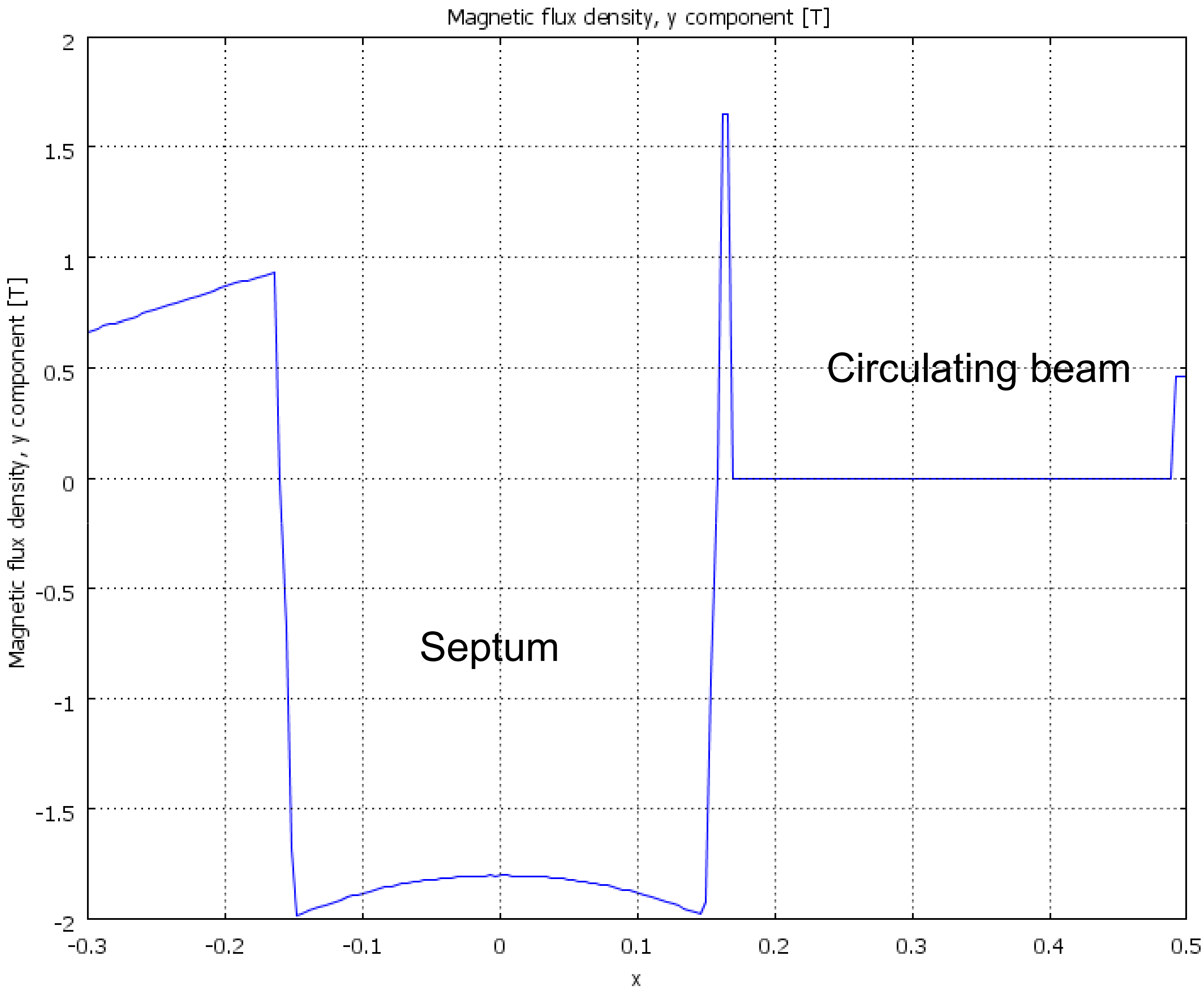
From www.vacuumschmelze.de

Field leakage



- We may still look for more advanced materials.

Field in the septum and the circulating field region



Summary and future plans for IDS FFAG

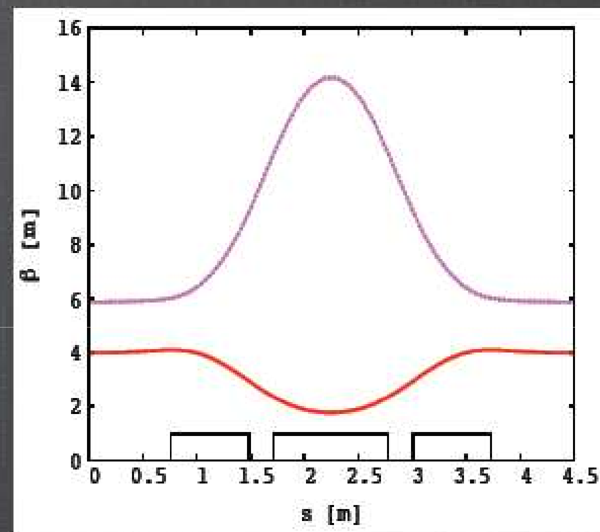
- The Neutrino Factory IDS baseline was updated in order to allow for realistic injection/extraction.
- The drift length (5 m) is dictated by the achievable septum field (~2T).
- Horizontal injection/extraction schemes were selected, as they require smaller increase of aperture in special magnets placed in the injection/extraction regions.
- The kicker system was designed and looks feasible, but the hardware tests would be needed to demonstrate the life-time of critical components (switches, capacitors etc.).
- The realistic design of the kicker is needed.
- 2D simulations of the field leakage from the septum limits the magnetic field to 2 T.
- We need to upgrade to 3D simulations.

Alternative acceleration scenario based on scaling FFAG

Example of a 3.6 to 12.6 GeV muon ring

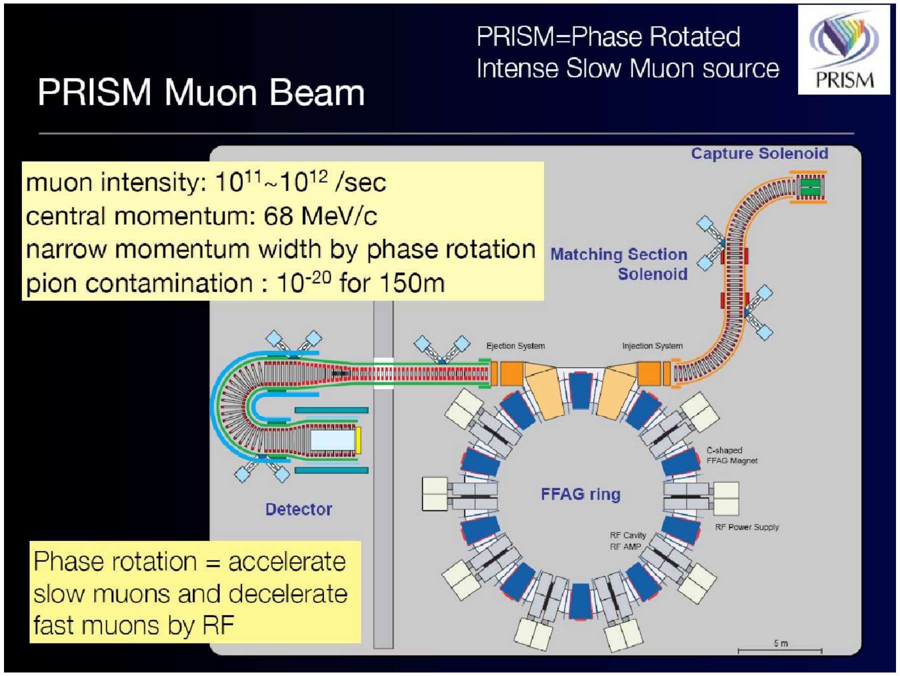
Table 1 - Scaling FFAG muon rings parameters

Lattice type	FDF triplet
Injection (kin) energy	3.6 GeV
Extraction energy	12.6 GeV
rf frequency	200 MHz
Mean radius	$\sim$ 161 m
Synchronous kinetic energy	8.04 GeV
Harmonic number h	675
Number of cells	225
Field index k	1390
Peak rf voltage (per turn)	1.8 GV
Number of turns	6
B_{max} (@ 12.6 GeV)	3.9 T
Drift length	$\sim$ 1.5 m
Horiz. phase adv./cell	85.86 deg.
Vert. phase adv./cell	33.81 deg.
Excursion	14.3 cm

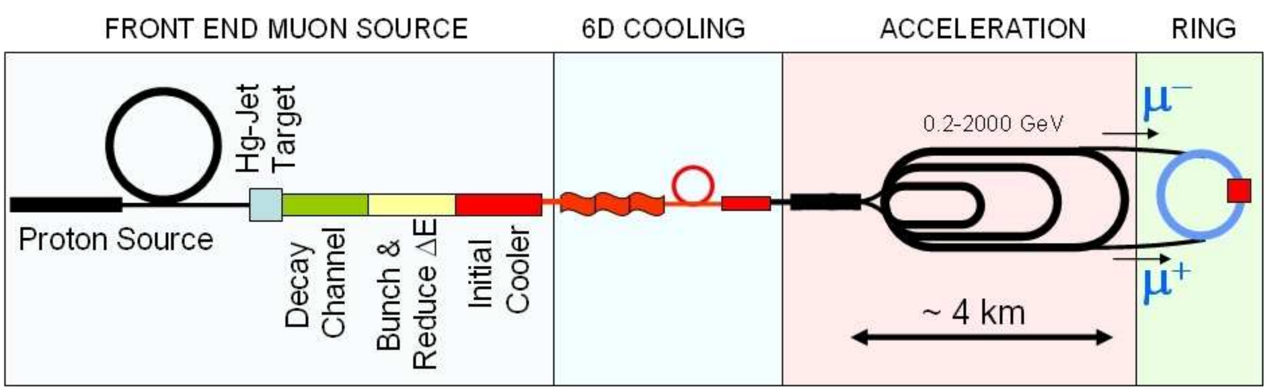


Horizontal (red) and vertical (purple) beta function at 3.6 GeV, calculated using set-wise tracking in soft-edge field model from small amplitude motion around the closed orbit. Position of the magnets effective field boundaries are shown with rectangles.

Physics potentials of muon FFAGs

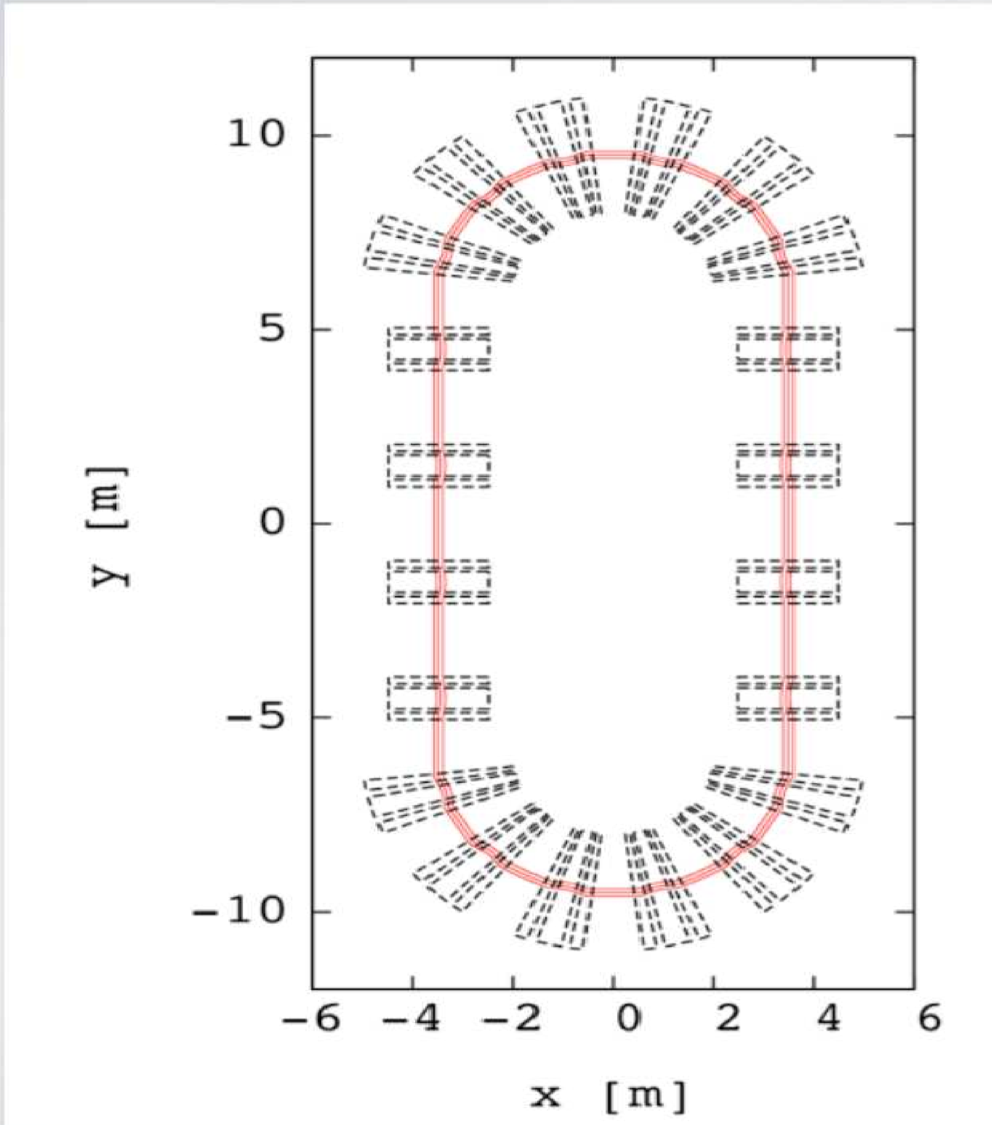


Search for the charge lepton flavor violation via muon to electron conversion at the PRISM/PRIME.



Muon Collider,
the ultimate HEP machine
will likely use FFAGs
or hybride solutions.

New ring designs for PRISM – Advanced FFAG (J-B. Lagrange et al.)



PRISM LATTICE

Bending cell	
k	6.5
Average radius	3.5 m
Phase advances:	
horizontal μ_x	90 deg.
vertical μ_z	90 deg.
Dispersion	0.47 m

Straight cell	
n/ρ	$2.14\,m^{-1}$
Length	$3\,m$
Phase advances:	
horizontal μ_x	24 deg.
vertical μ_z	87 deg.

Conclusions

- Work on the Neutrino Factory is advancing within the IDS-NF.
- The NS-FFAG baseline for the final acceleration was frozen and realistic injection/extraction schemes were designed.
- The alternative low energy acceleration solution to replace RLA II was designed based on scaling FFAG.
- FFAGs are essential for a future muon HEP program (Nufact, PRISM/PRIME, Muon Collider).