FFAGs for muon acceleration for the Neutrino Factory and a Muon Collider

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Outline

- Introduction.
- NS-FFAG for the old baseline 25 GeV
- Designs for new baseline of 10 GeV
- RDR baseline decision.
- Conclusions

Introduction

New IDS-NF baseline.	
Number of cells	67 m
Circumference	669 m
RF voltage	1.1956 GV
Max field in F magnet	4.4 T
Max field in D magnet	6.2 T
F magnet radius	16.1 cm
D magnet radius	13.1 cm
Muon decay	7.1 %
Injection energy	12.6 GeV
Extraction energy	25 GeV

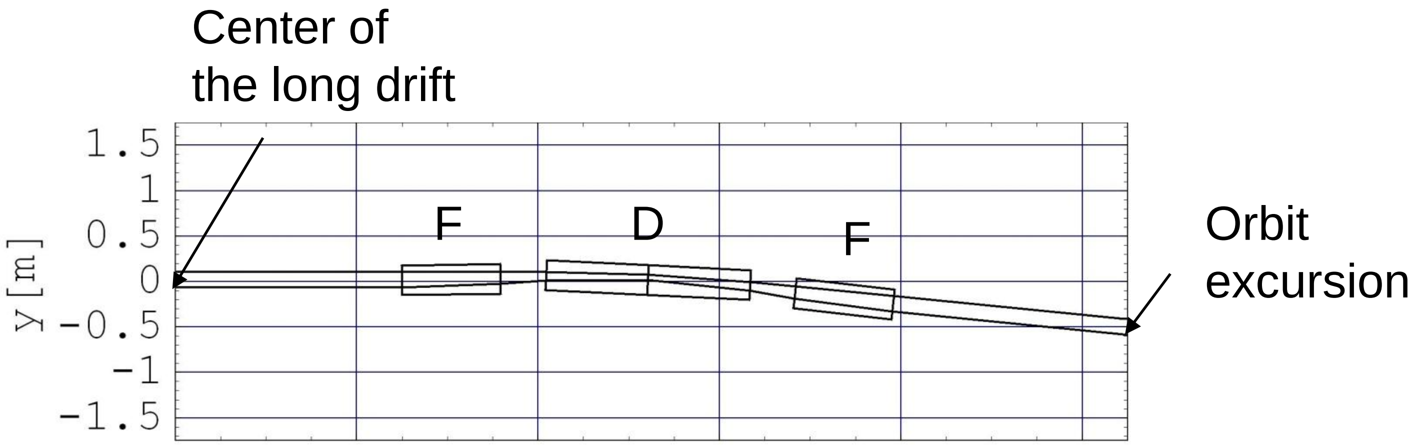
Non-scaling FFAG is selected for the final muon acceleration at the Neutrino Factory.

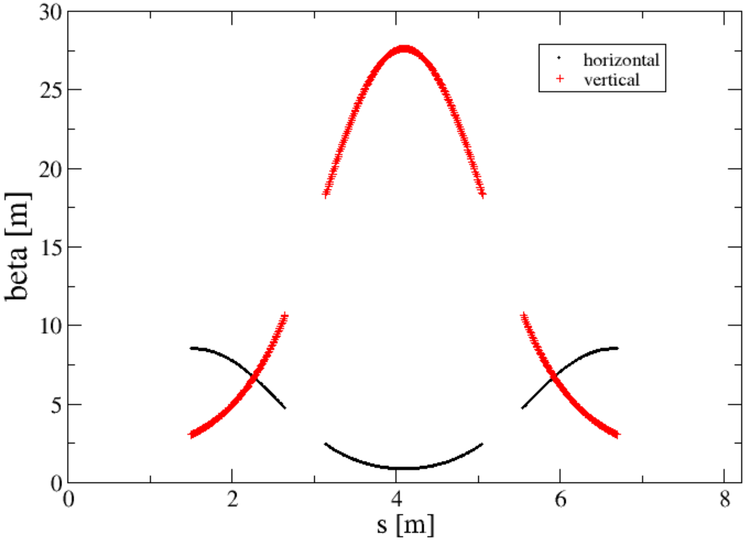
Advantages include:

- Allows very fast acceleration (~12 turns).
- Large dynamic aperture due to linear magnets + high degree of symmetry.
- More turns than in RLA – more efficient use of RF – cost effective.
- Quasi-isochronous – allows fixed frequency RF system.
- Orbit excursion and hence magnet aperture smaller than in the case of a scaling FFAG – cost effective.
- Principles of NS-FFAG are now being tested during ongoing EMMA commissioning.

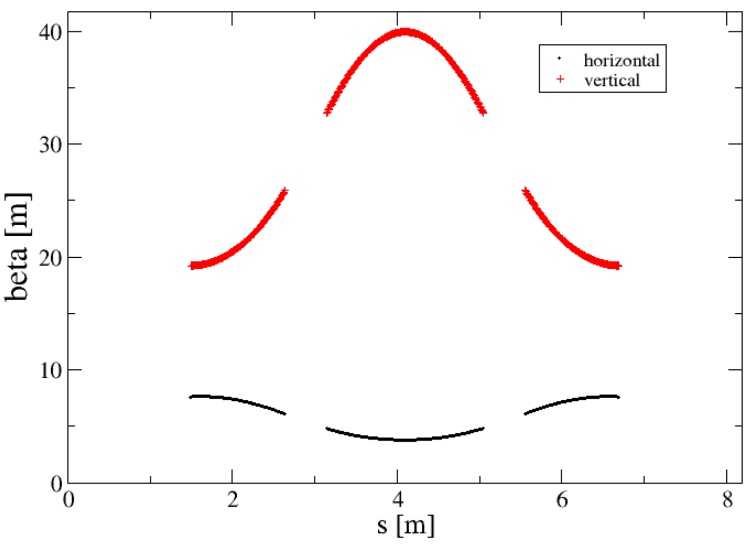
•Lattice was updated to incorporate 5m long drifts for symmetric injection/extraction.
•Injection/extraction geometries.
•Kicker/septum studies.
•Preliminary design of the main magnets.

Layout and optics



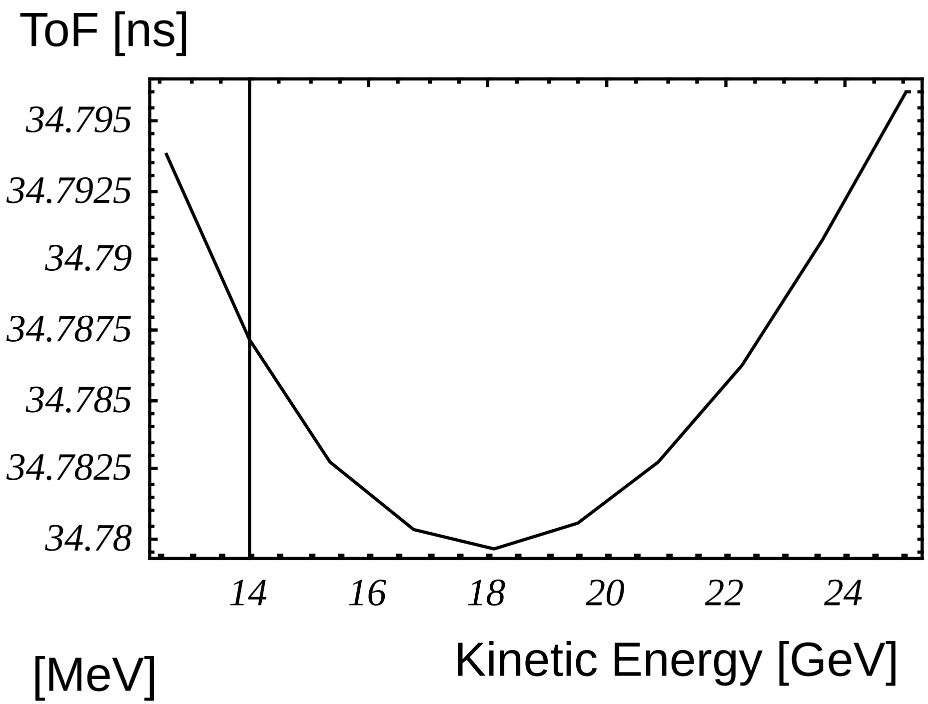


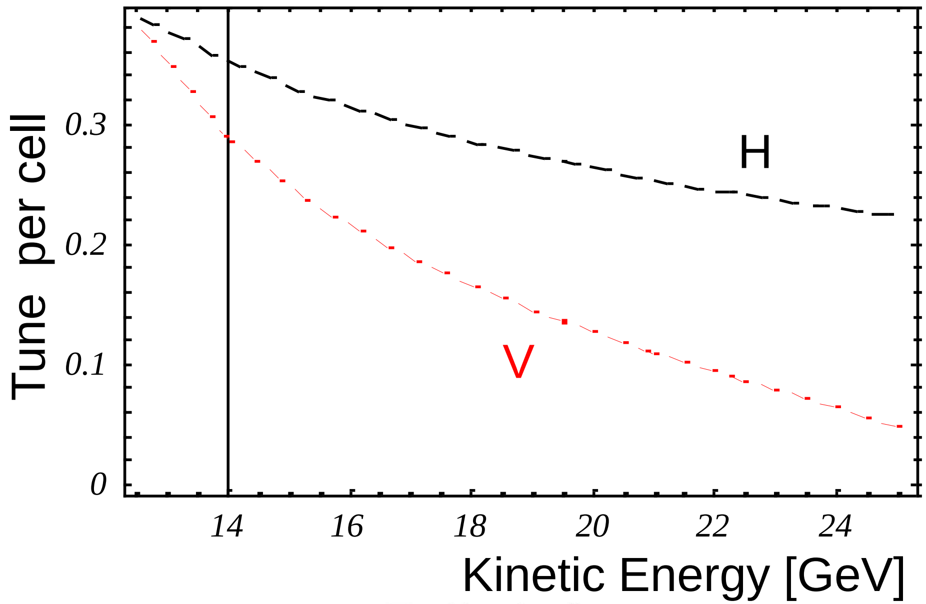
Beta functions at injection

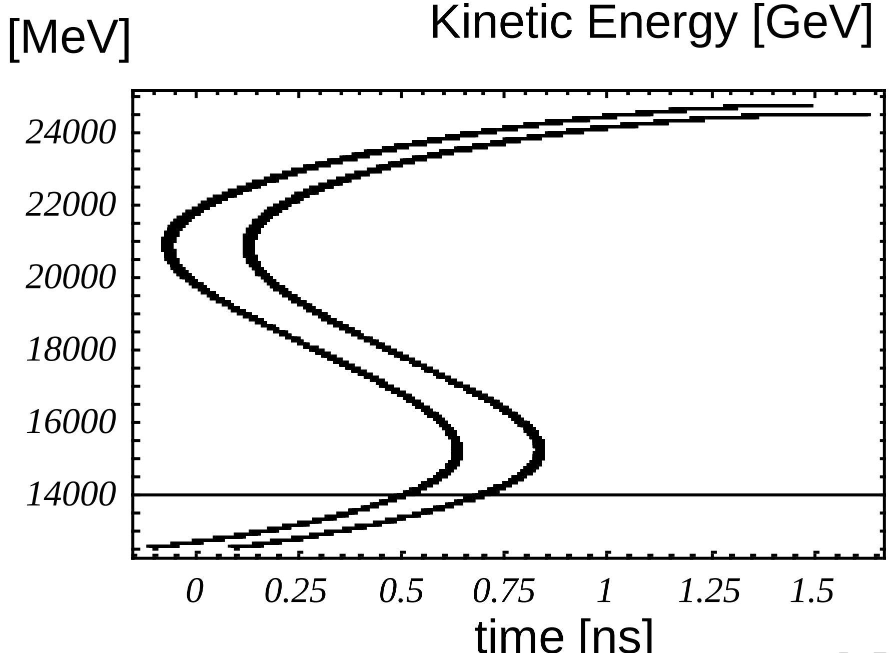


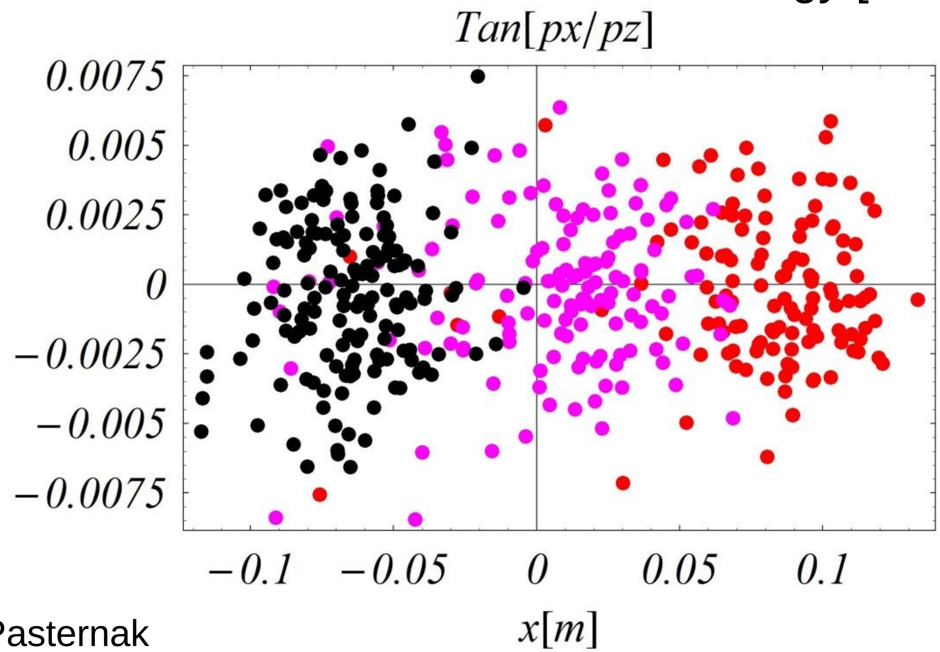
Beta functions at extraction

Beam Optics and Acceleration









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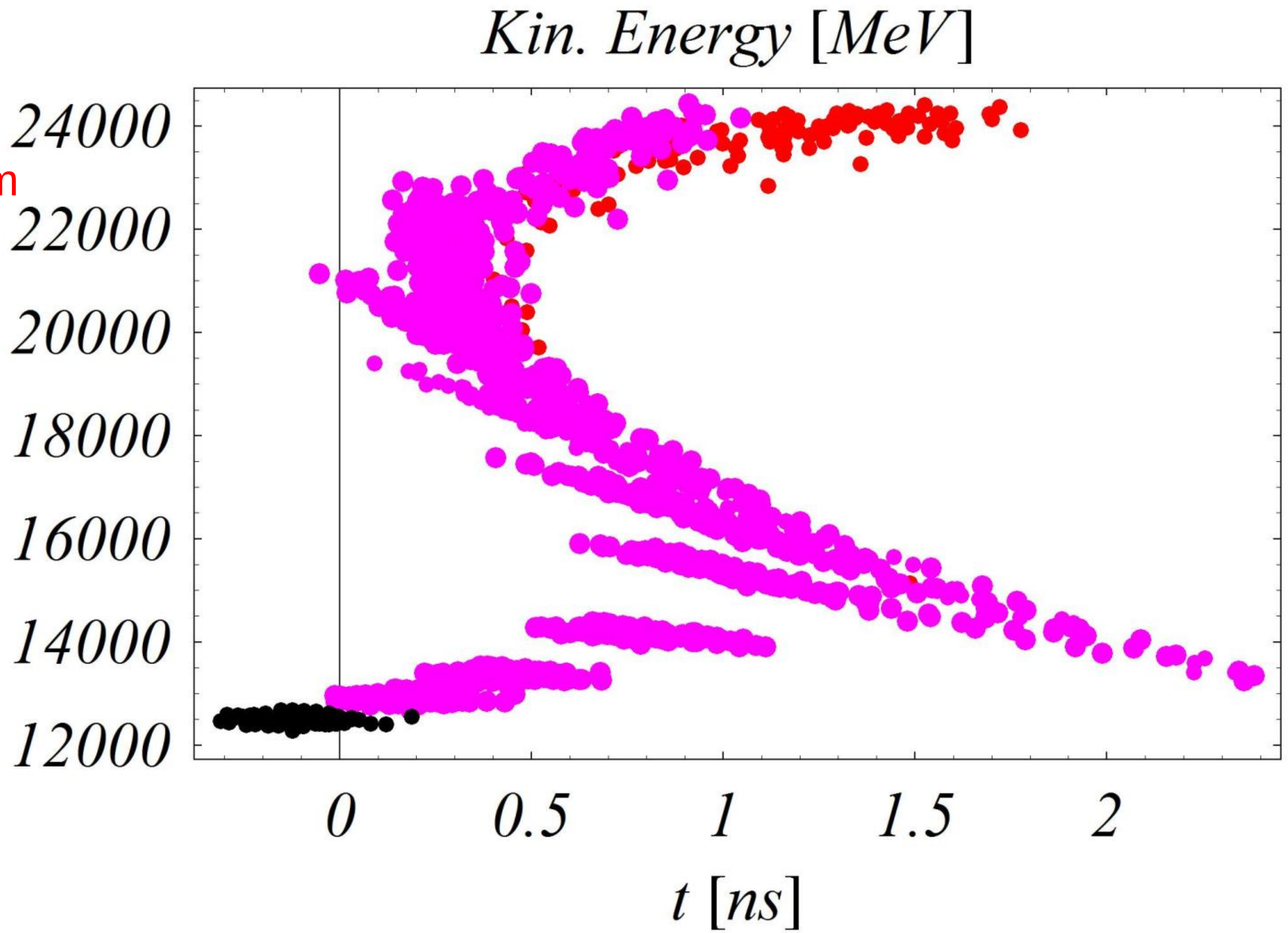
Acceleration studies:
6D tracking, full transverse emittance, Gaussian distribution, RF synchronization at 21 GeV

Muons with a large momentum spread!

Potential problem for the septum operation!



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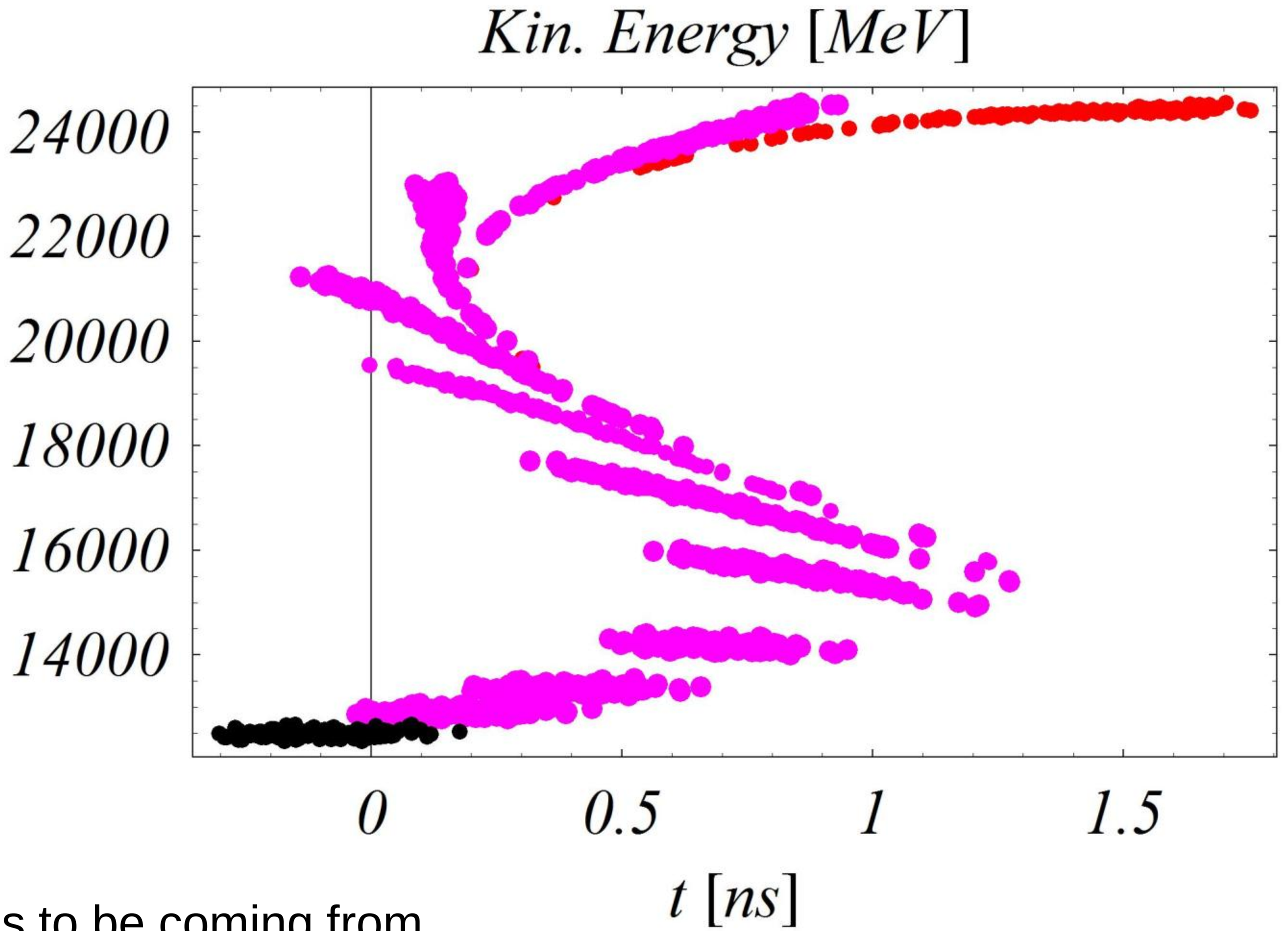
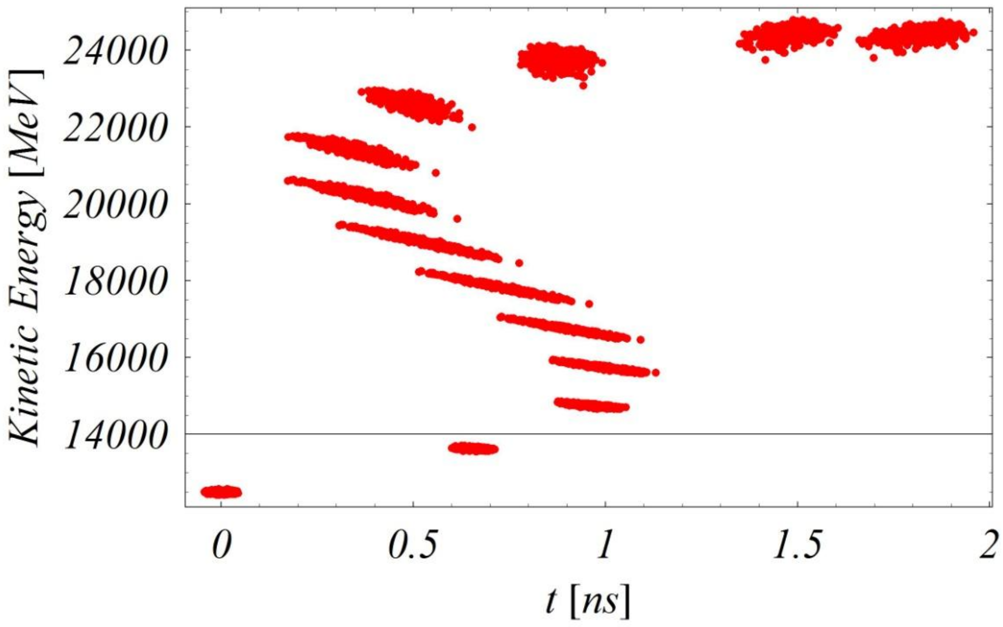
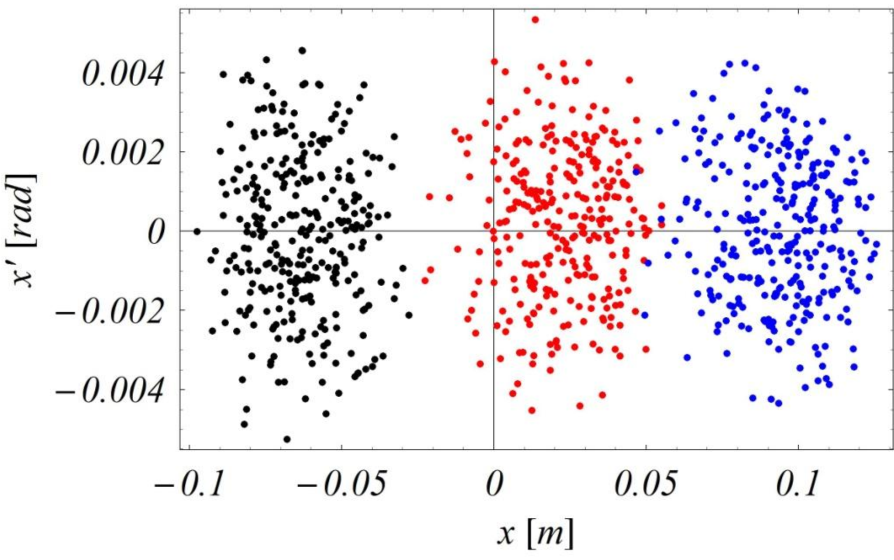
Acceleration studies (2):
6D tracking, small transverse emittance, Gaussian distribution, RF synchronisation at 21 GeV



The effect seems to be coming from
Non-zero chromaticity (ToF varation with the transverse amplitude) + distortion of the serpentine channel (to be further investigated).

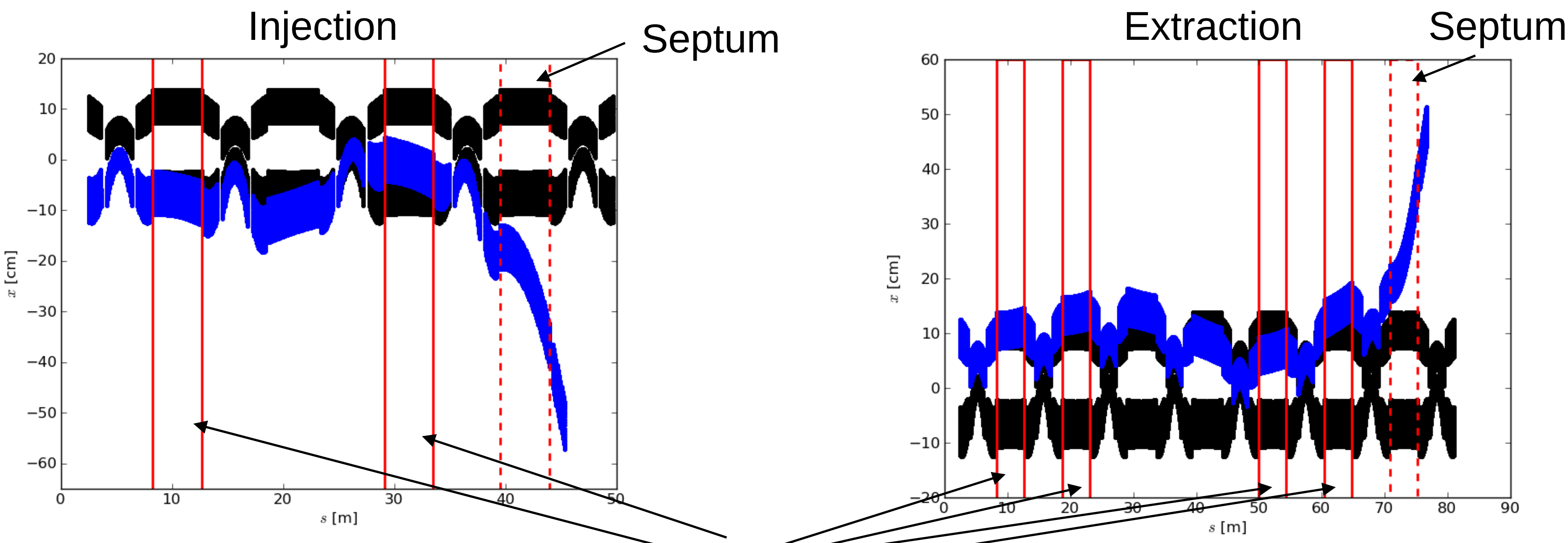
Recent progress on acceleration in 25 GeV machine, for the EUROnu report





- Longitudinal emittance growth is visible, but low energy tails has been removed (potential problem for extraction).
- This gives a hope to recover quality in FFAG!

Injection/Extraction geometries



Injection	
Plane	Horizontal
No. Kickers	2
Kicker field (T)	0.089
Kicker Polarity	**+0+**
Septum field (T)	0.92

Extraction	
Plane	Horizontal
No. Kickers	4
Kicker field (T)	0.067
Polarity	**++00++**
Septum field (T)	1.76

- Septum field was limited to 2 T by the stray fields studies (see next slides).
- Both injection and extraction are in the horizontal plane (minimal additional magnet aperture needed and no generation of the vertical dispersion).
- Larger apertures in the special magnets witch are needed have been calculated.

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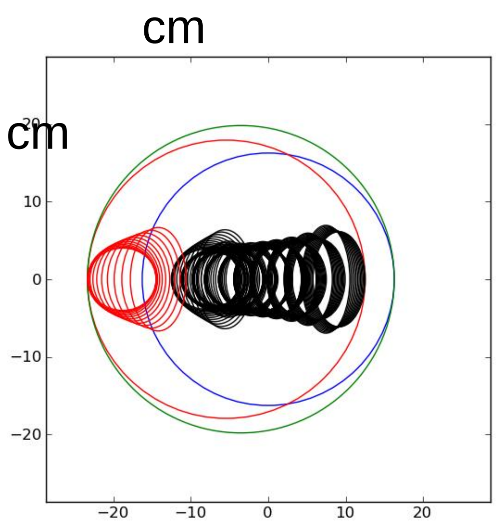
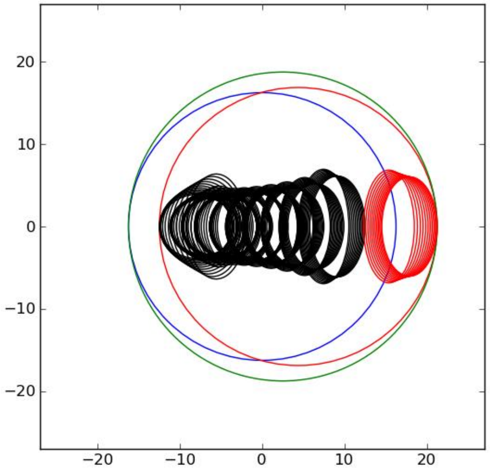
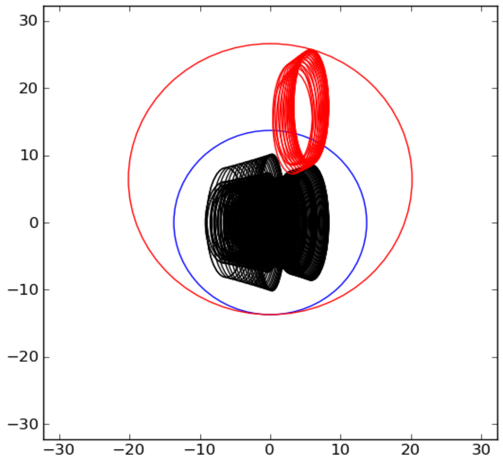
Magnet aperture studies



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.



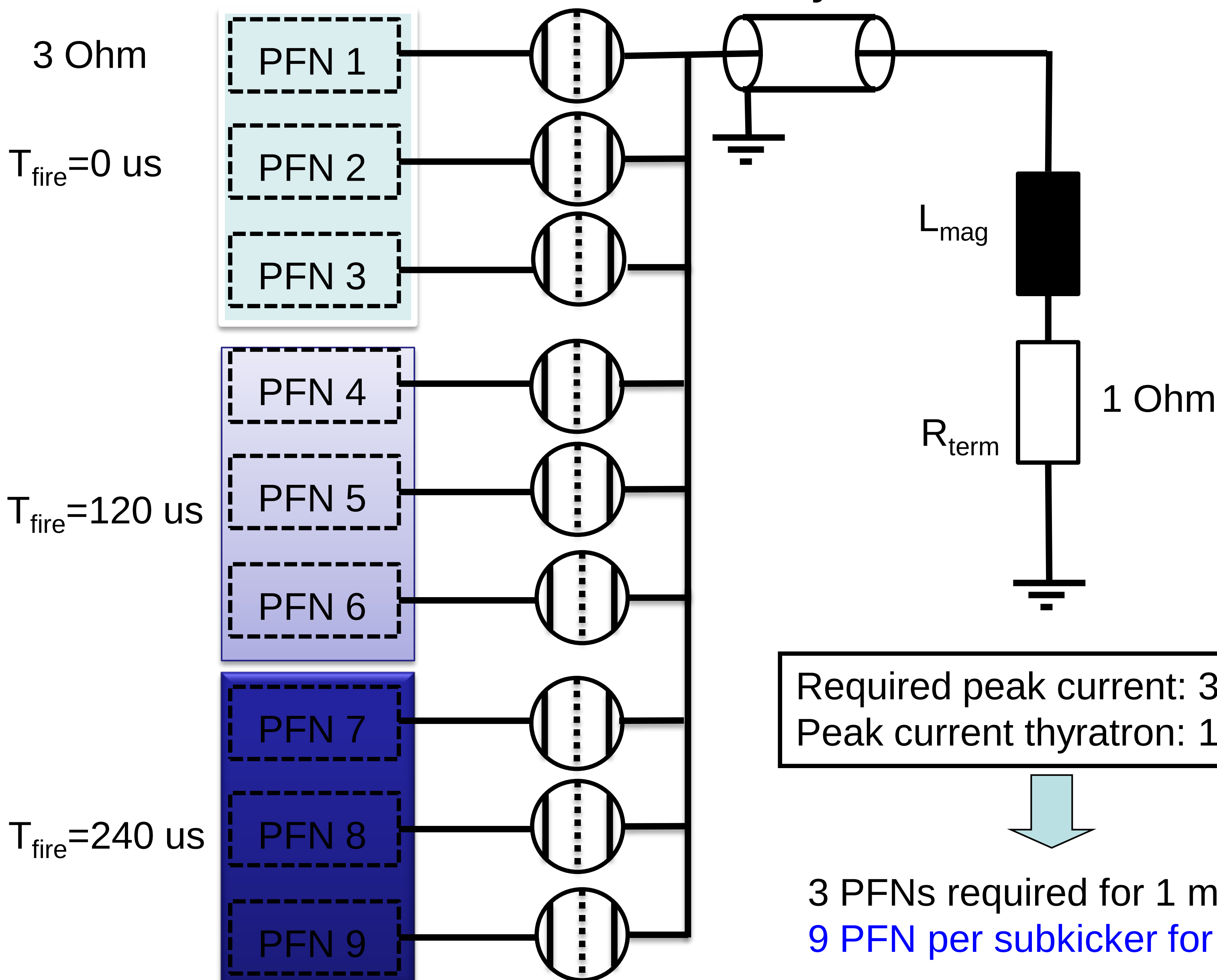
Magnet aperture in F magnet before the extraction septum.



Magnet aperture in D magnet rules out the vertical extraction.

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

IDS Kicker System



Required peak current: 30 kA
Peak current thyratron: 10 kA

3 PFNs required for 1 muon bunch train.
9 PFN per subkicker for 3 trains!

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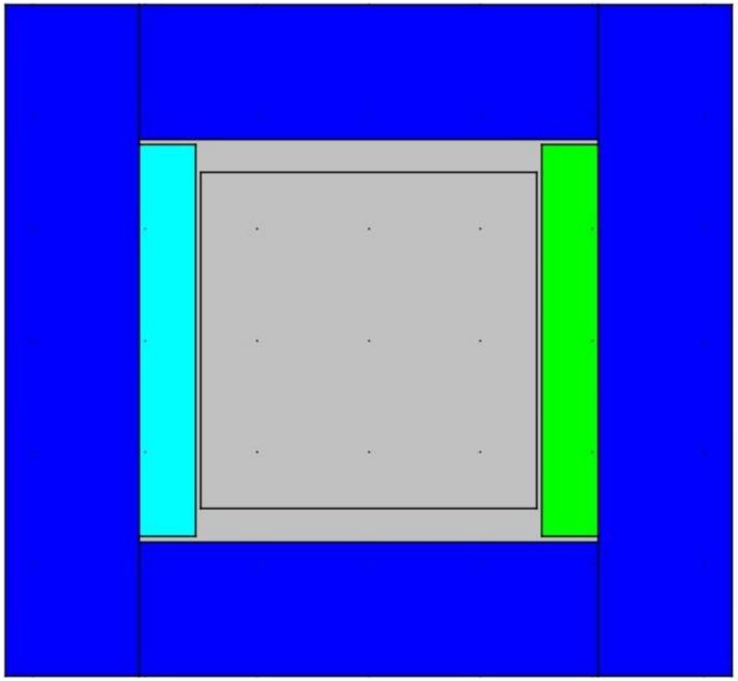
Kicker magnet

- Travelling wave type.
- Geometry
  - Aperture: 0.3x0.3 m^2 (recent update ~0.32x0.22)
  - Yoke: 120 mm
  - Length: 4.4 m
- Field: 100 mT (to add margins)
- Current: 29 kA
- Voltage 60 kV
- Magnetic energy: 1700 J
- Inductance (single turn): 5.1 uH
- Subdivided into 4 smaller kickers (36=9x4 PFNs and switches per magnet).
- Rise/fall time 2.2 us.
- Impedance matching
  - Add capacitors



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

Update needed to match the new short muon train.

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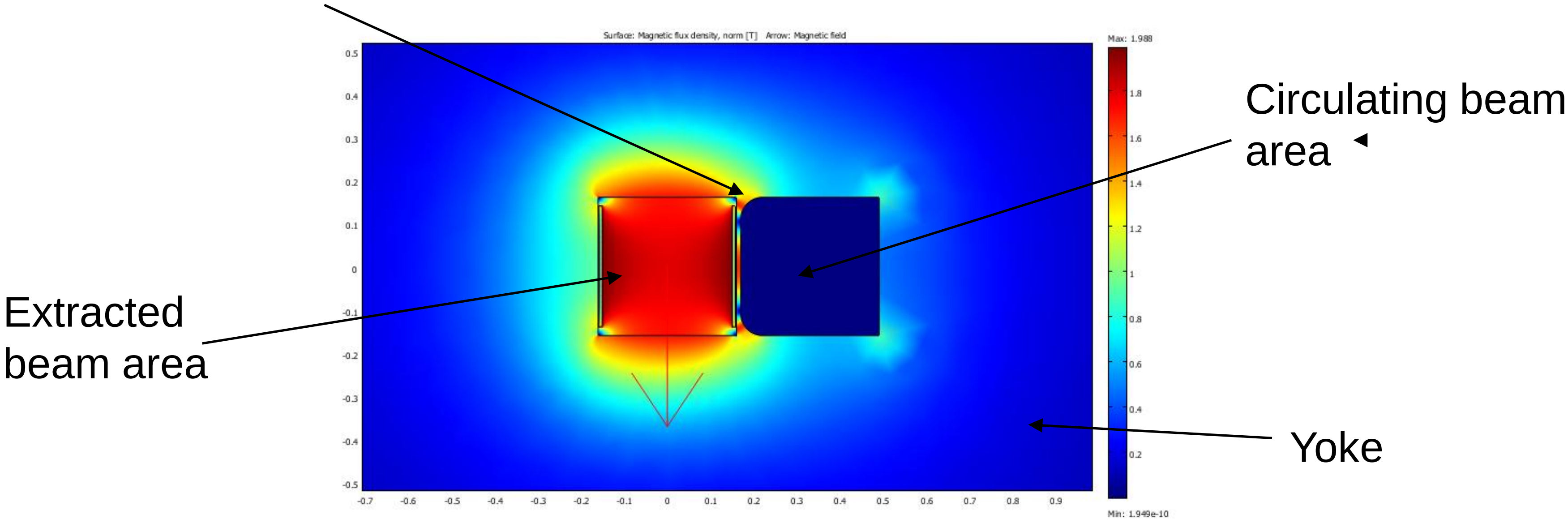
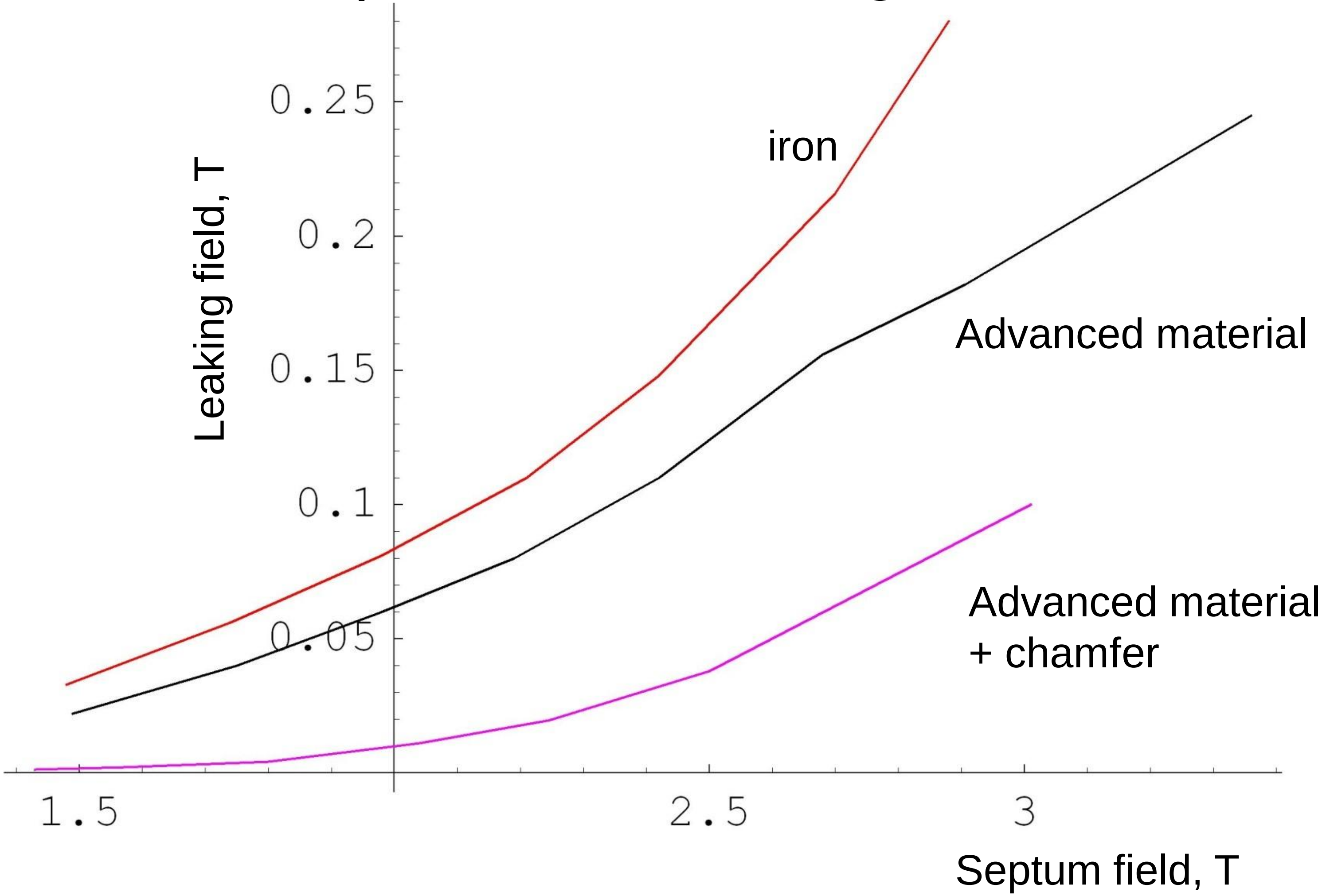
Septum geometry

- The goal of the study was to limit the field leakage from the septum to the circulating beam region.
- We were using COMSOL and performed 2D simulations.
- Starting point was a basic „C-shape" septum magnet.
- Iron was introduced all around the circulating beam.
- Iron was replaced by the soft magnetic cobalt-iron-alloy with high saturation limit.
- Chamfer was introduced.



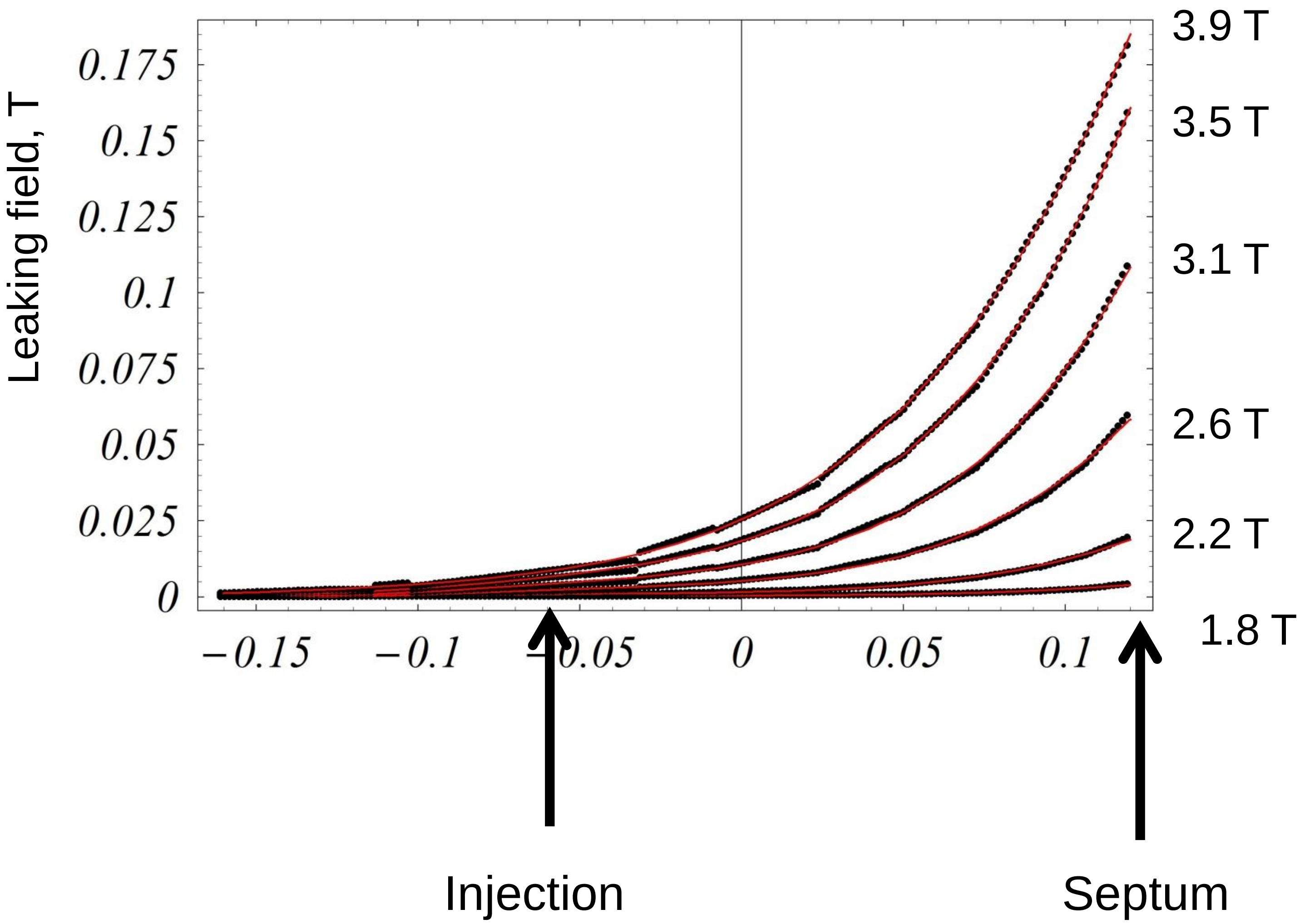
Septum Field Leakage



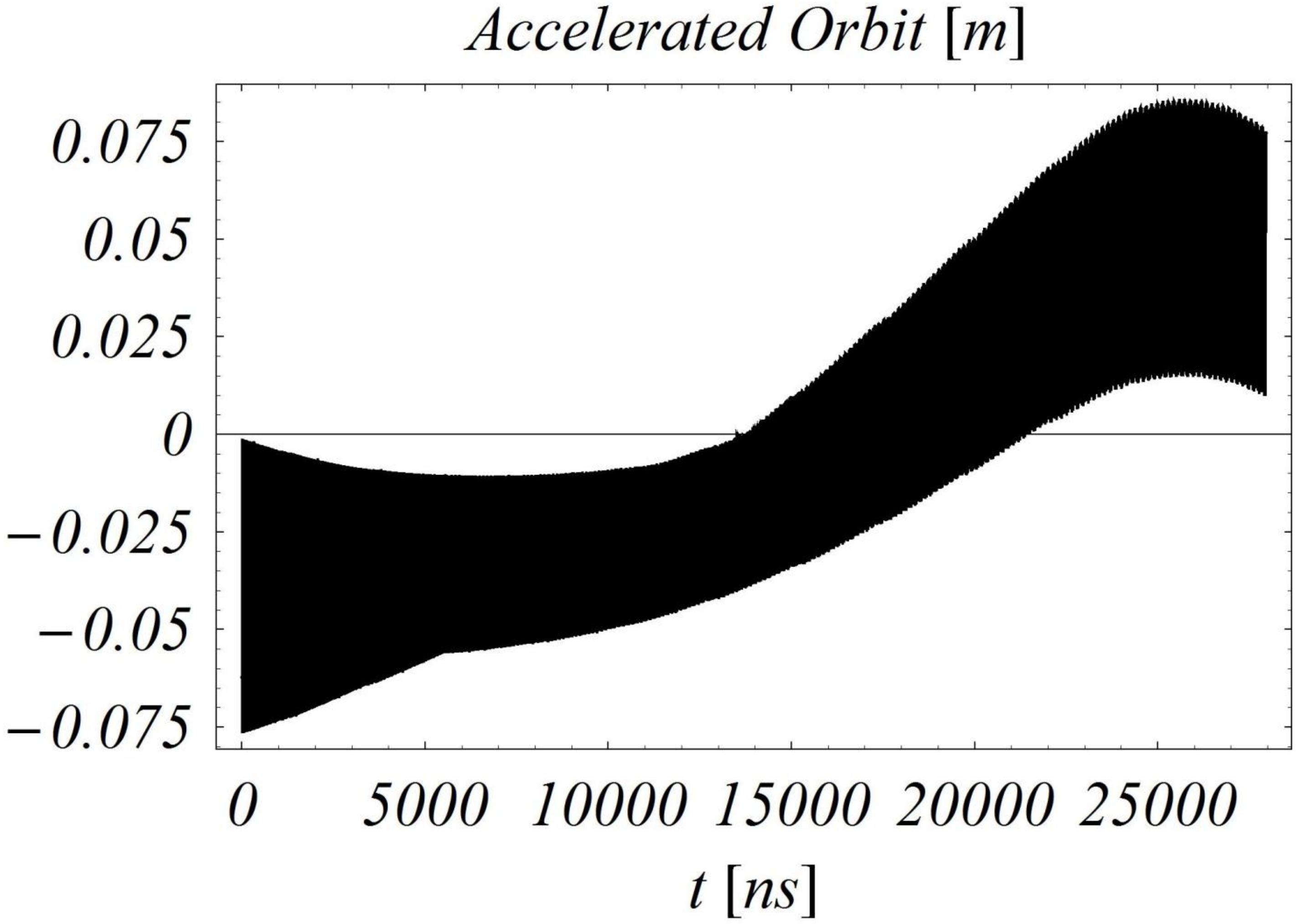
- The advanced material is the soft magnetic cobalt-iron-alloy (VACOFLUX 50 from www.vacuumschmelze.de)
- We may still look for more advanced materials.

Effect of Septum Field Leakage

- Stray fields have been generated using COMSOL
- Multipoles have been fitted to the numerical points up to the decapole.

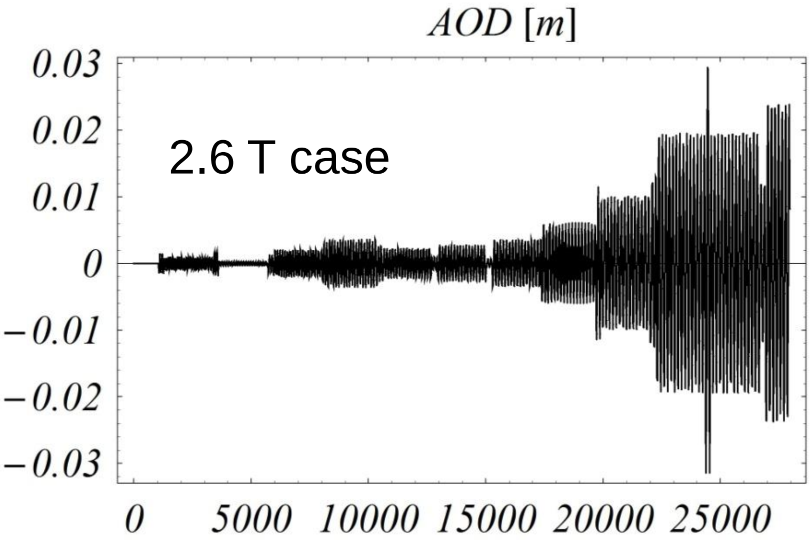


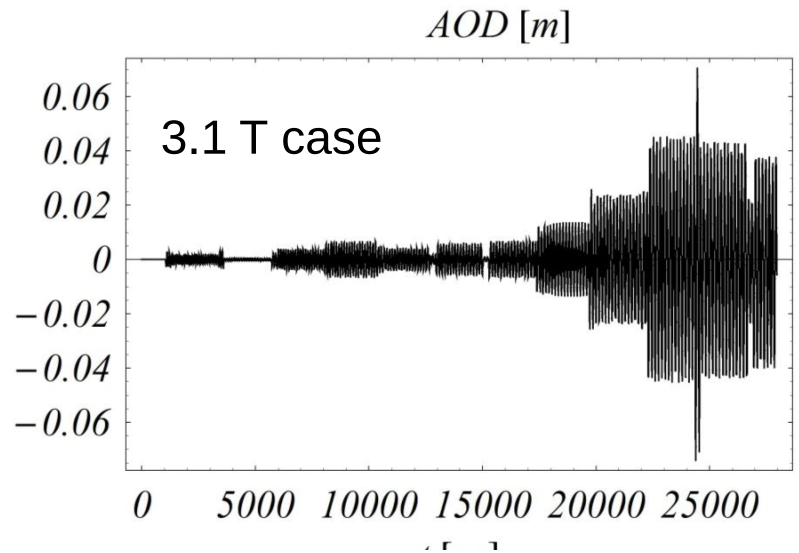
Effect of Septum Field Leakage (2)

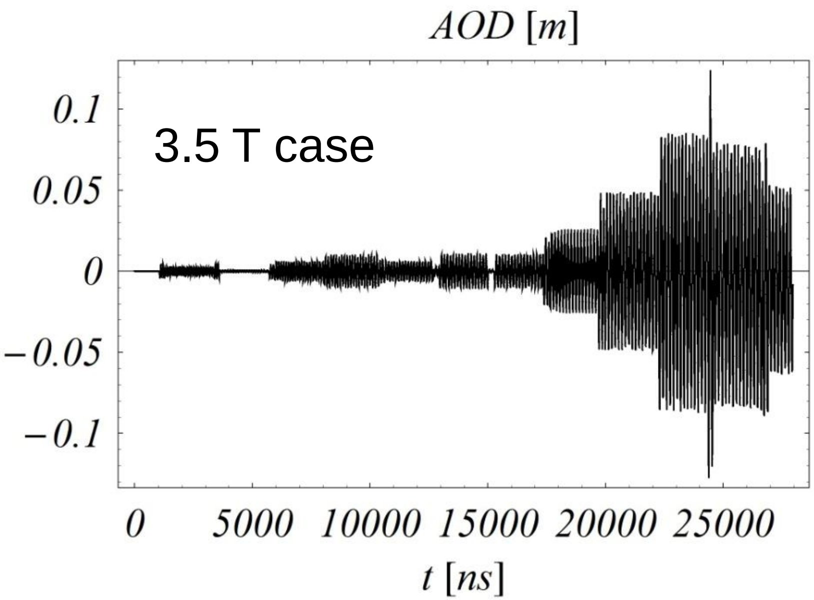


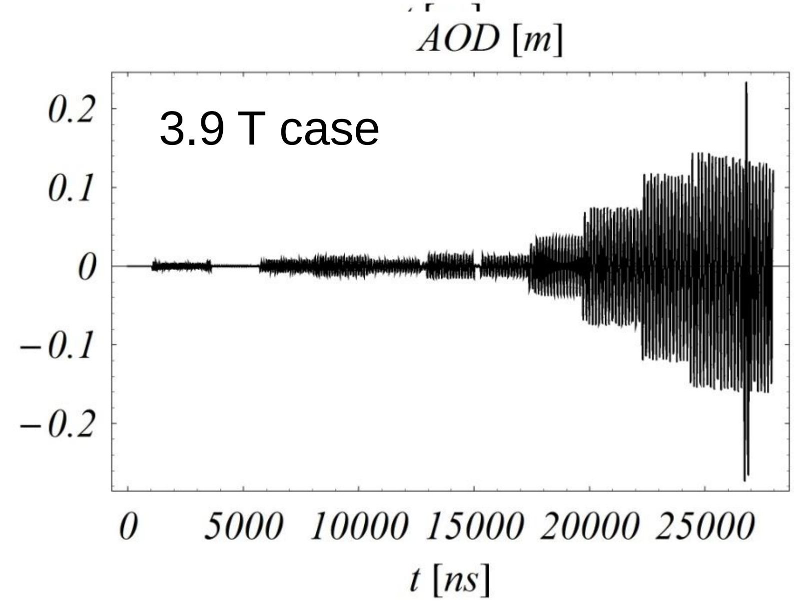
Septum field zero, no leakage.

Effect of Septum Field Leakage (4)









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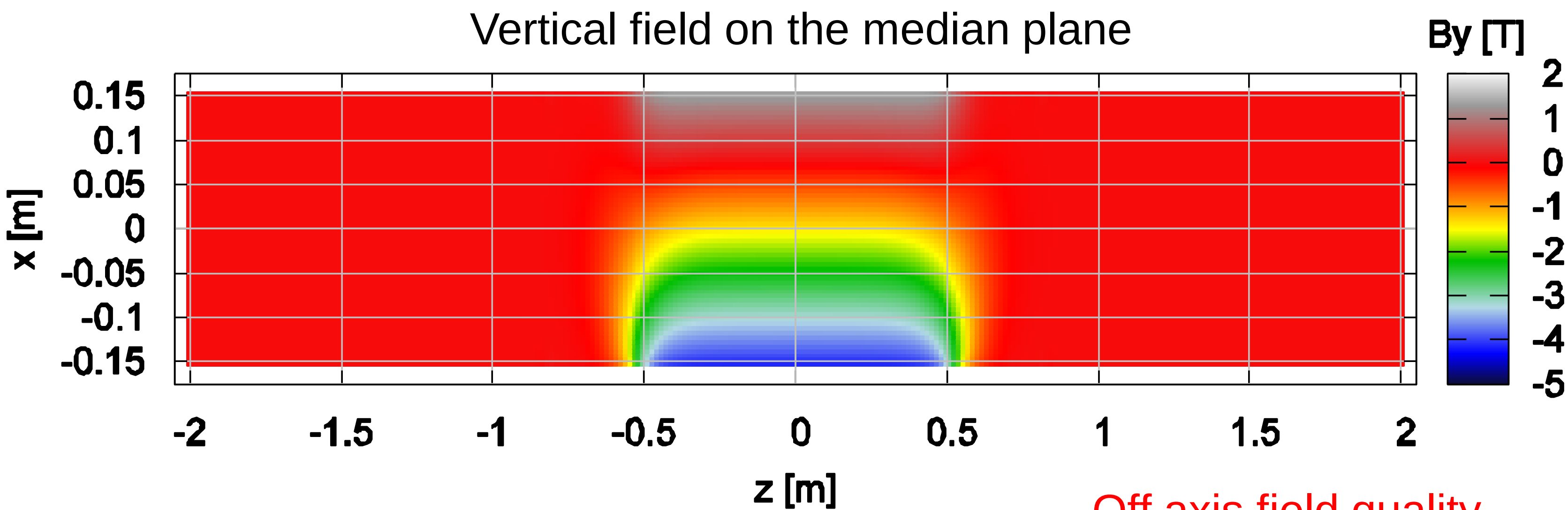
Main magnet design

The current design effort:

- Focuses on the conventional „Cos-Theta” with separate layers for dipole and quadrupole components.
- This is motivated by simplicity and in addition a possibility of a flexible optics tuning.
- Design is performed using the CERN ROXIE code.
- Work on F magnet is more advanced (included in the IDR).



Off axis field quality needs to improved!

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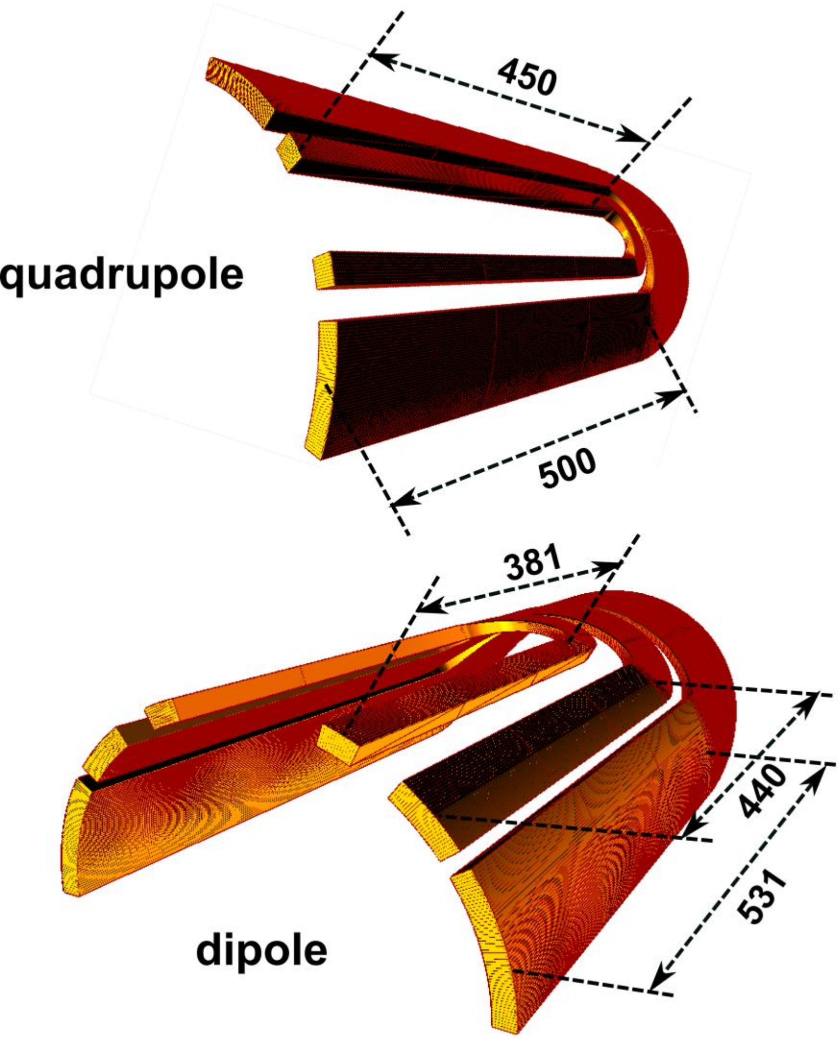
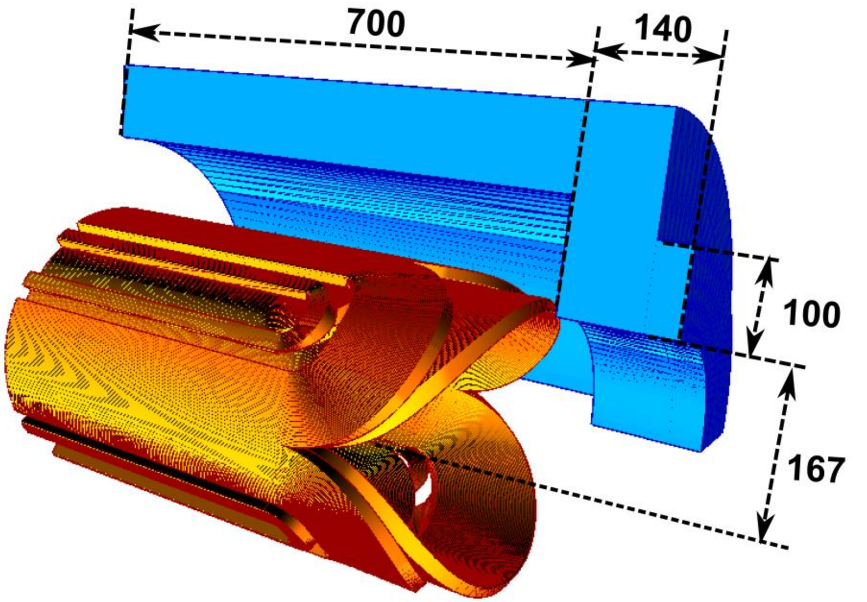
F magnet geometry





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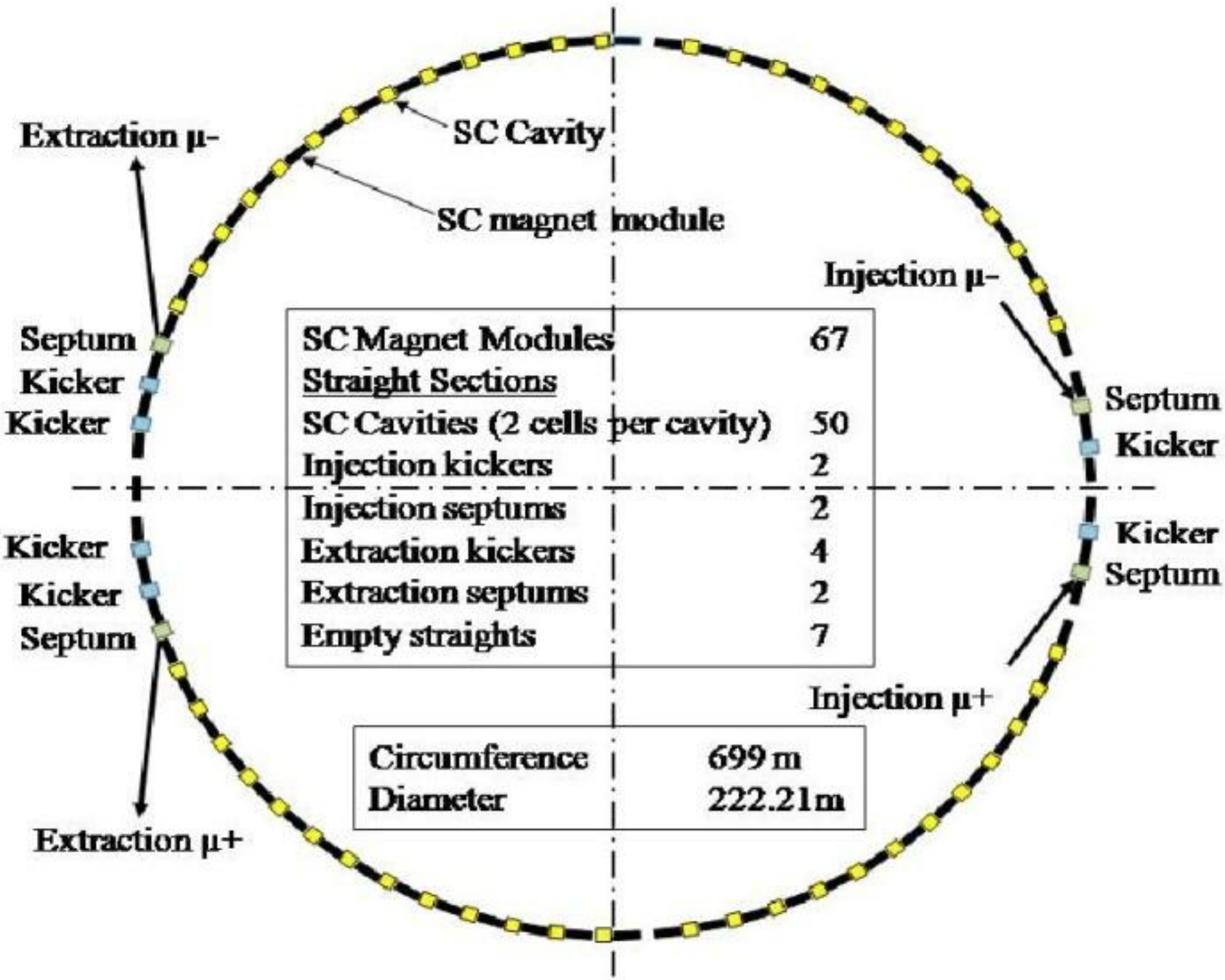
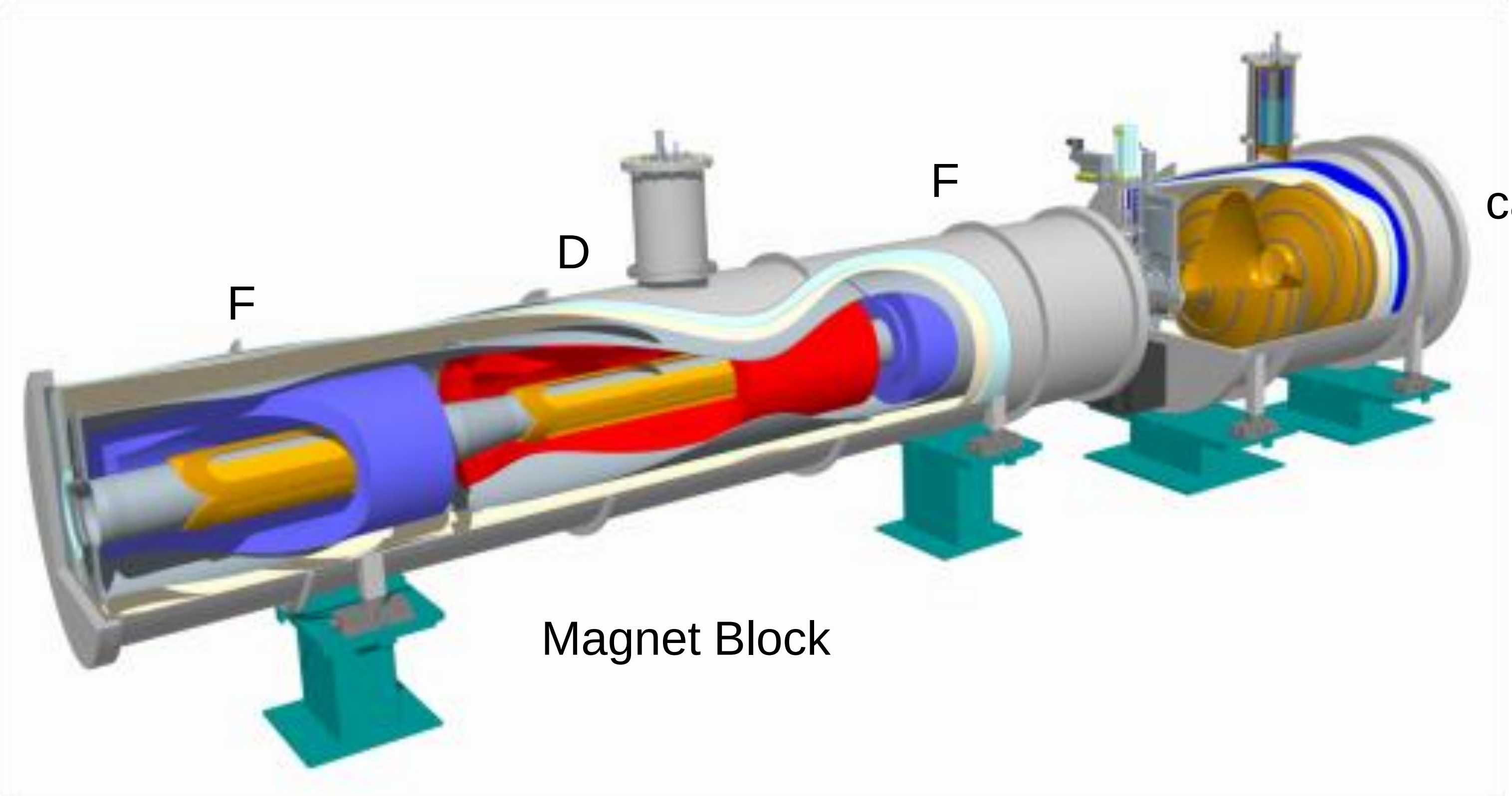
Ring Layout (12.6 -25 GeV NS-FFAG)

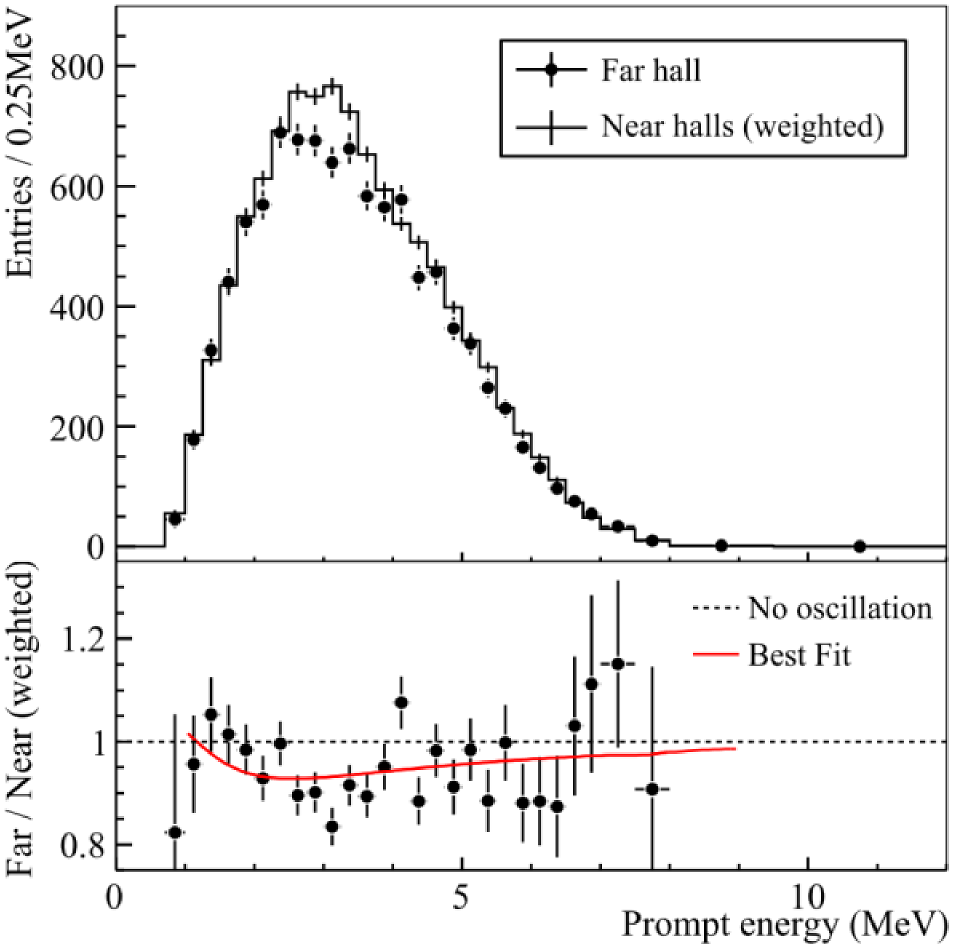


Towards engineering design



- Start of the engineering effort!
- Effective drift length reduced to 4m
(due to space for the cryostat and flanges).
- Kicker field increased 0.106 T
- Extraction septum field to 1.94 T.
- Injection/extraction still feasible!

Discovery of the large θ_{13} in reactor experiments

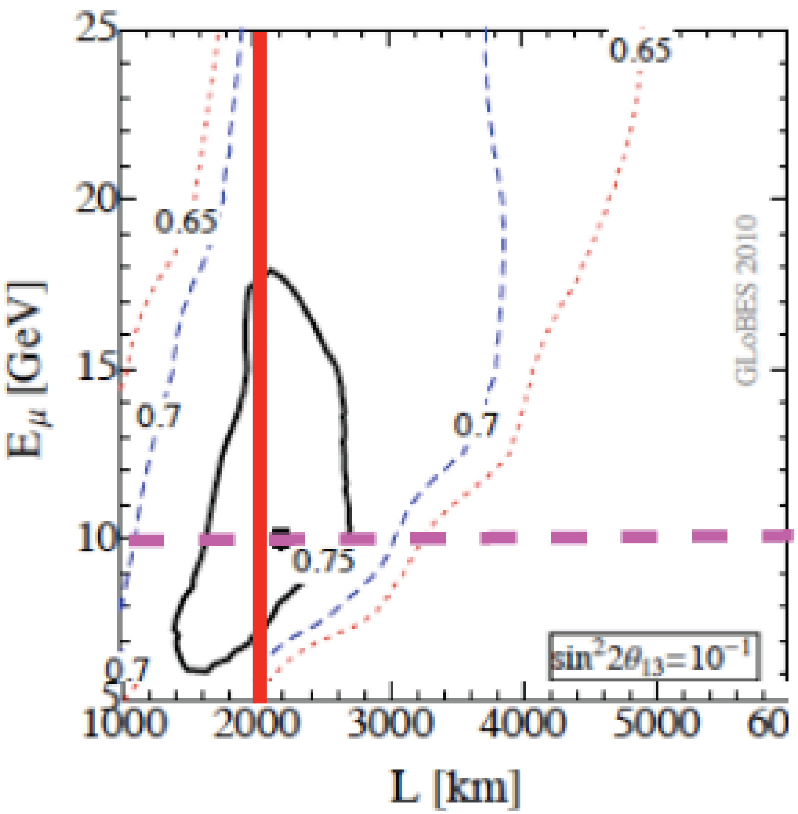


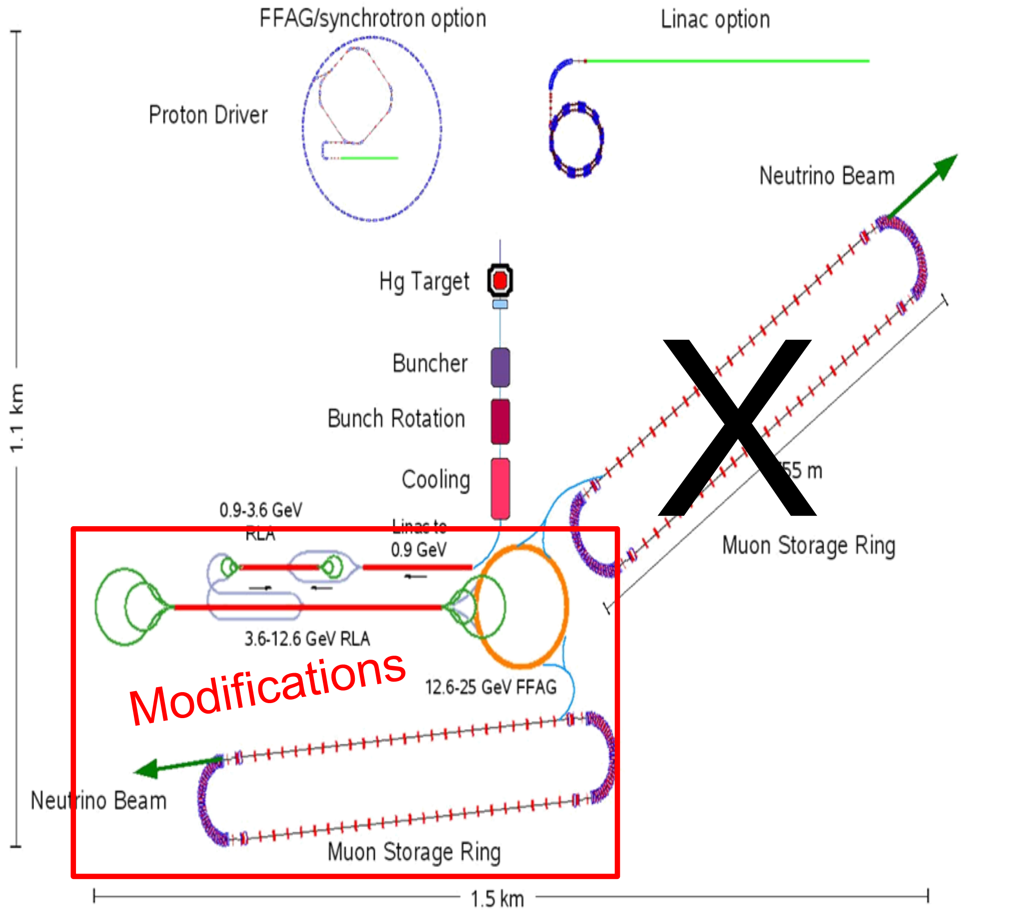
Daya Bay oscillation result, from arXiv: 1203.1669v2 [hep-ex] 2 April 2012

PMTs in the Daya Bay detector, (from Nature News)

	$\sin^2 2\theta_{13}$		
	Value	Statistical	Systematic
D-Chooz	0.086	0.041	0.030
Daya Bay	0.092	0.016	0.005
RENO	0.113	0.013	0.019
Mean	***0.098***	***0.013***	

Baseline modifications due to the large θ_{13}





Detectable CP-violation fractions as a function of muon energy in the storage ring and a baseline length, from S. Pascoli's talk at IDS-NF meeting in Glasgow

Effects of large θ_{13} on the baseline:

- Only one decay ring needed with reduced energy/circumference/cost (see David's talk).
- Modifications in the muon acceleration scheme (only 10 GeV needed).

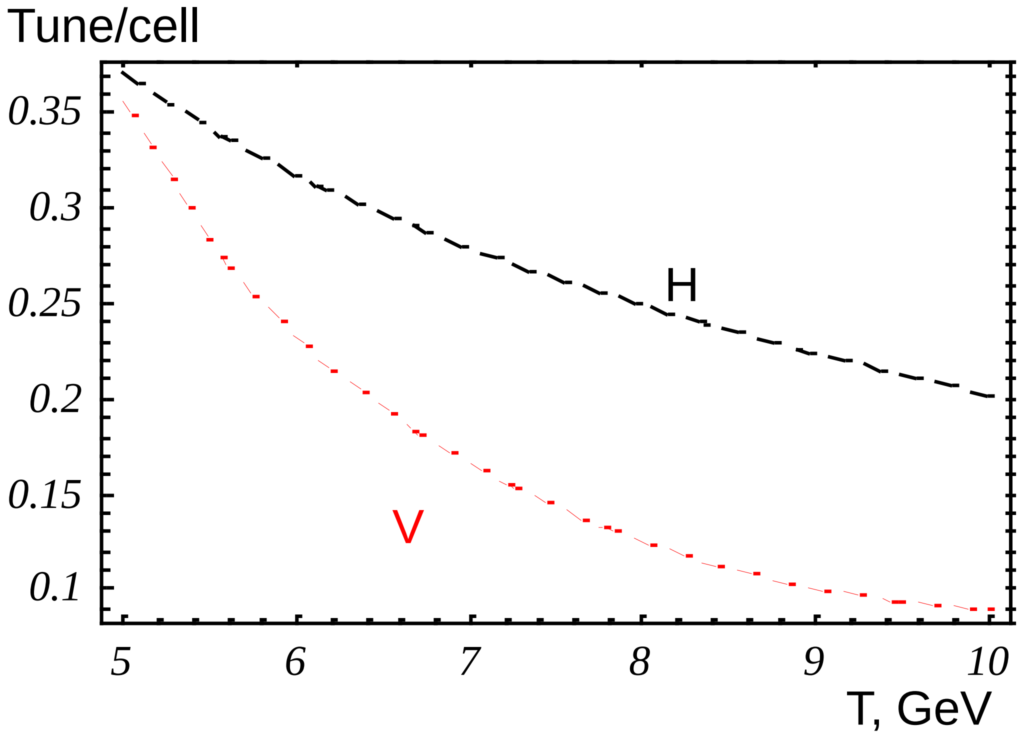
FFAG Designs Comparison

	25 GeV machine	10 GeV machine Scott (preliminary)	10 GeV machine Jaroslaw (preliminary)
Circumference [m]	669	434	369.9
Nomber of RF cavities	50	36	26
RF voltage [MV]	1196	864.8	~625
Number of turns	11.6	6.7	8.5
Number of cells/magnets	67/201	53/159	49/147
Drift length [m]	5	3.8	3.8
Magnetised length [m]	~263	~153.1	~108.3

The large θ_{13} scenario, NS-FFAG 5-10 GeV (preliminary)

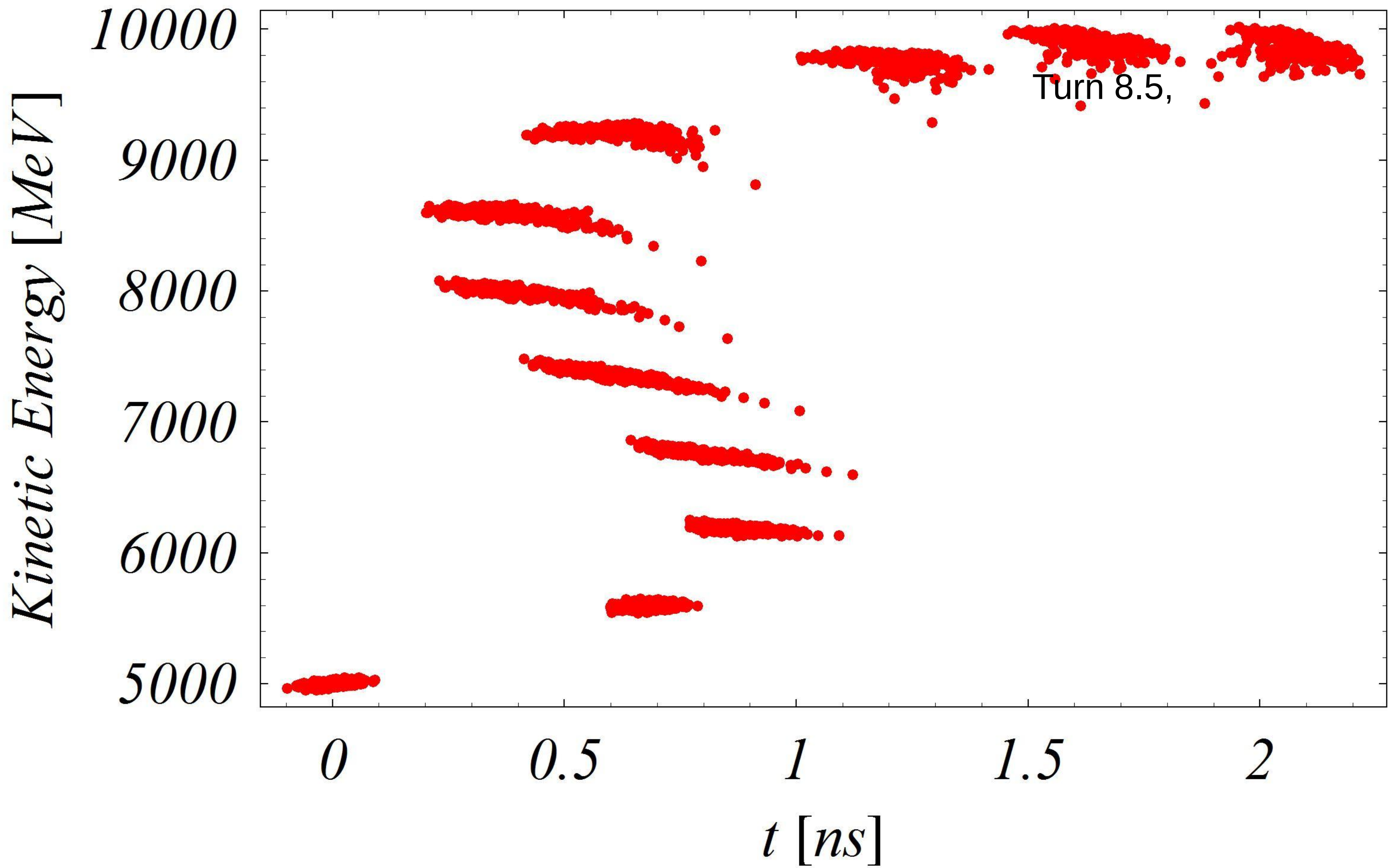
- Assumption:

Use the same technology as in 25 GeV machine (B field levels, RF, apertures, etc.).

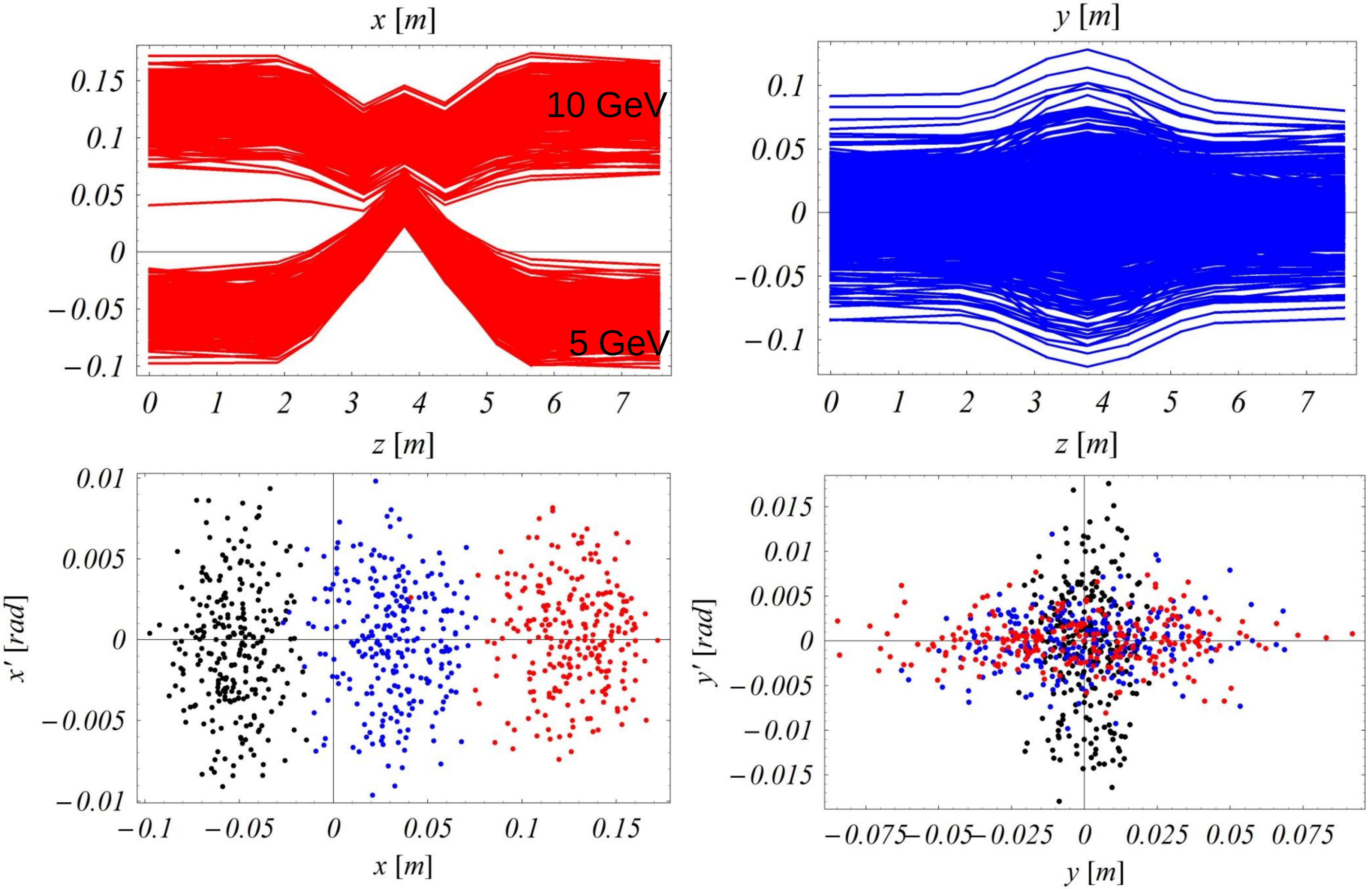


- FDF triplet
- Drift length 3.8 m
- Assumed double cell 201 MHz cavity in a drift.
- B max 6.3 T
- N cells 49
- Small level of chromaticity correction assumed (to improve the off-momentum stability and partially improve the ToF problem).
- This seems to allow for more turns.
- Machine seems to have a sufficient DA.

Preliminary acceleration study in the ring with sextupoles (not yet optimised)

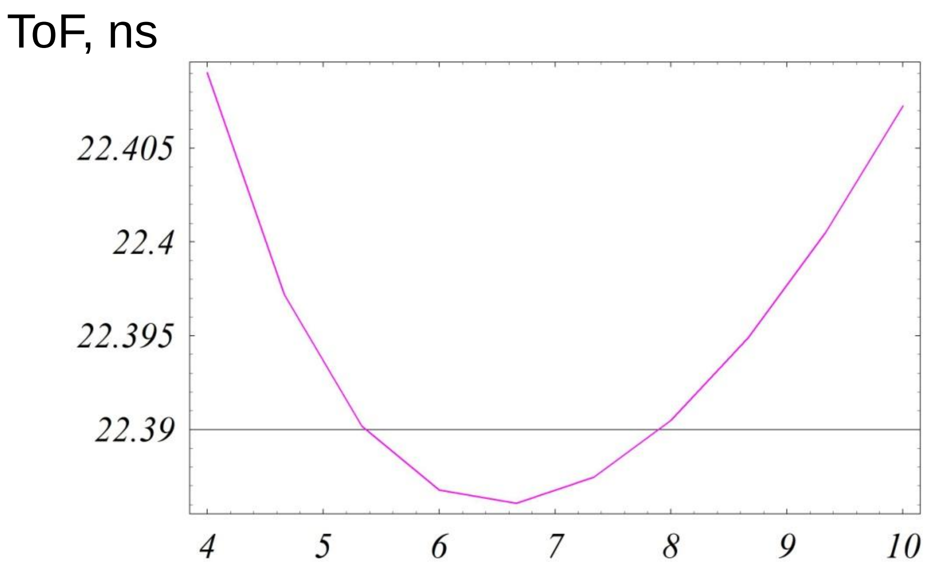


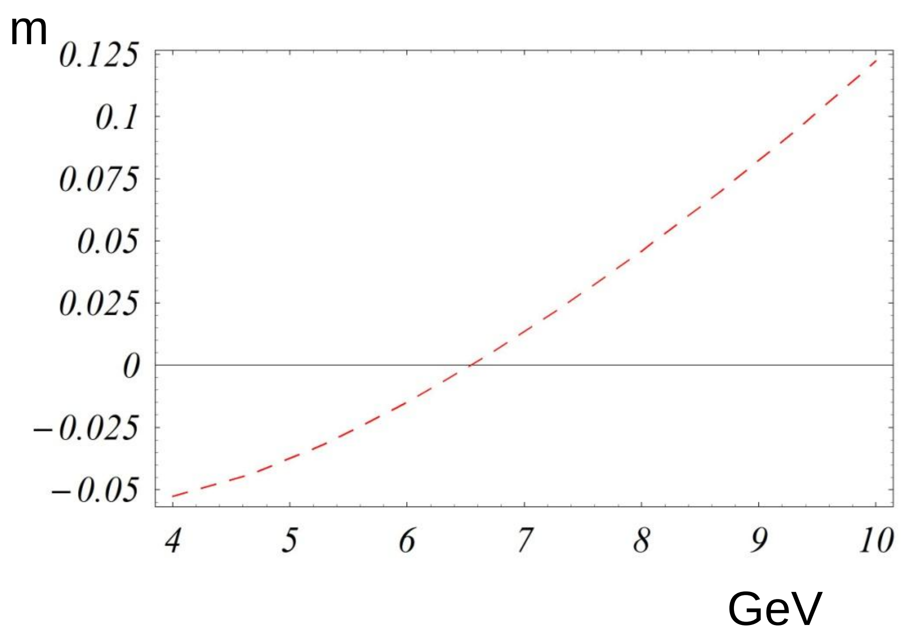
Apertures and phase spaces

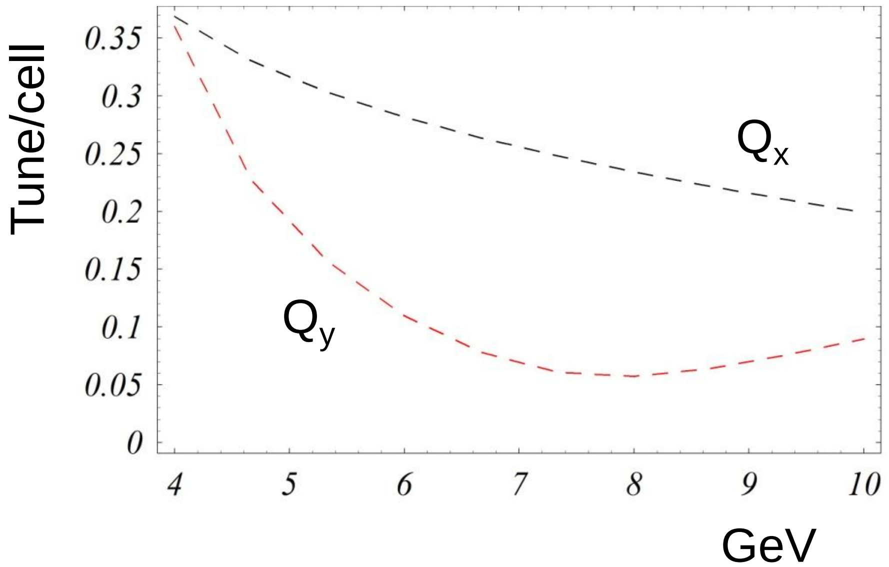


Apertures a bit larger than in 25 GeV machine!

Preliminary results for 4-10 GeV machine (factor 2.5 in acceleration)





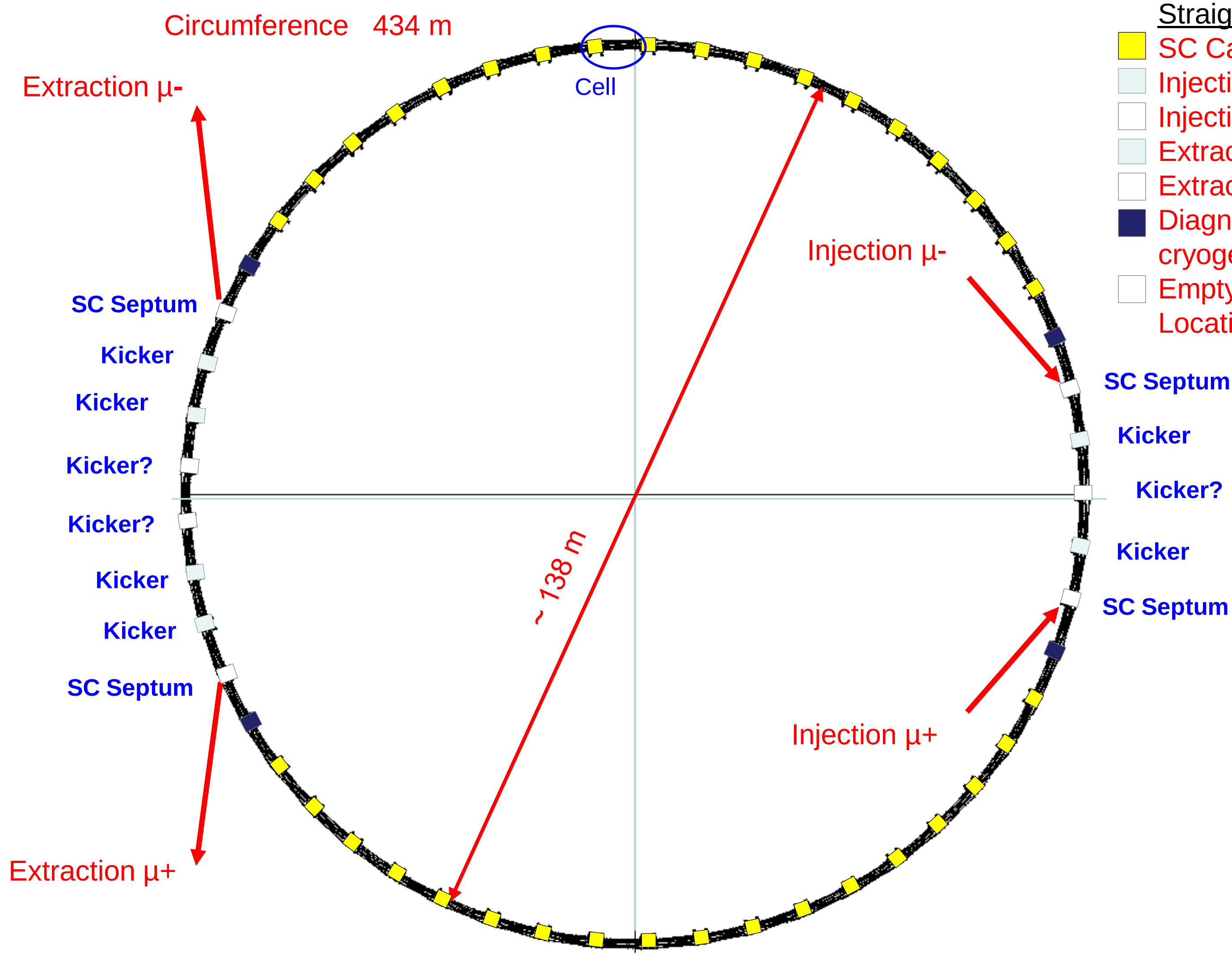


- 63 cells
- 423 m in circumference
- Orbit excursion close to the 25 GeV machine
- Short cells
- Drift length of 3.5 m
- 15 % chromaticity correction

to improve the tune behaviour and ToF

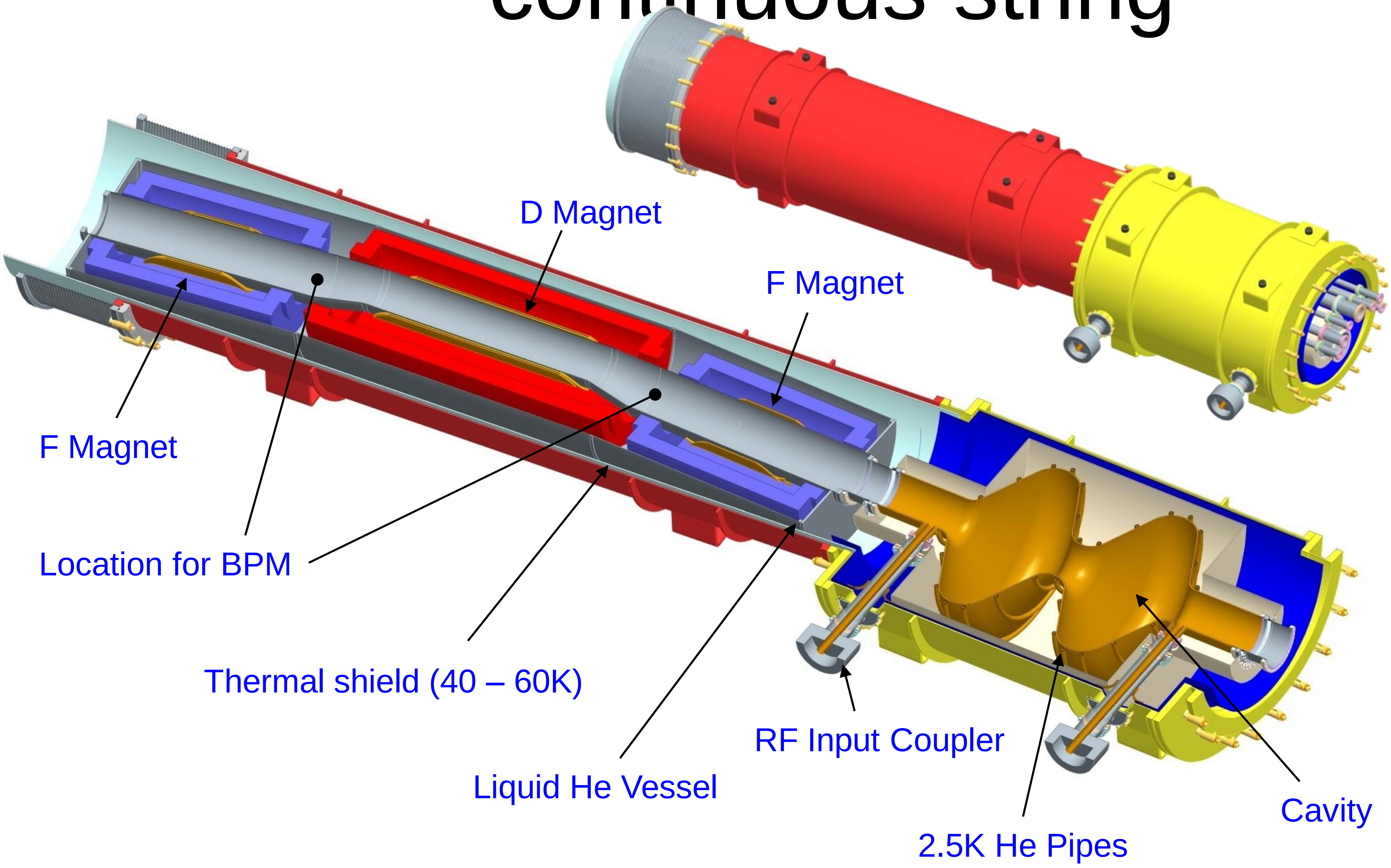
- Please mind machine is non-linear.

ns-FFAG Layout with continuous cryomodules

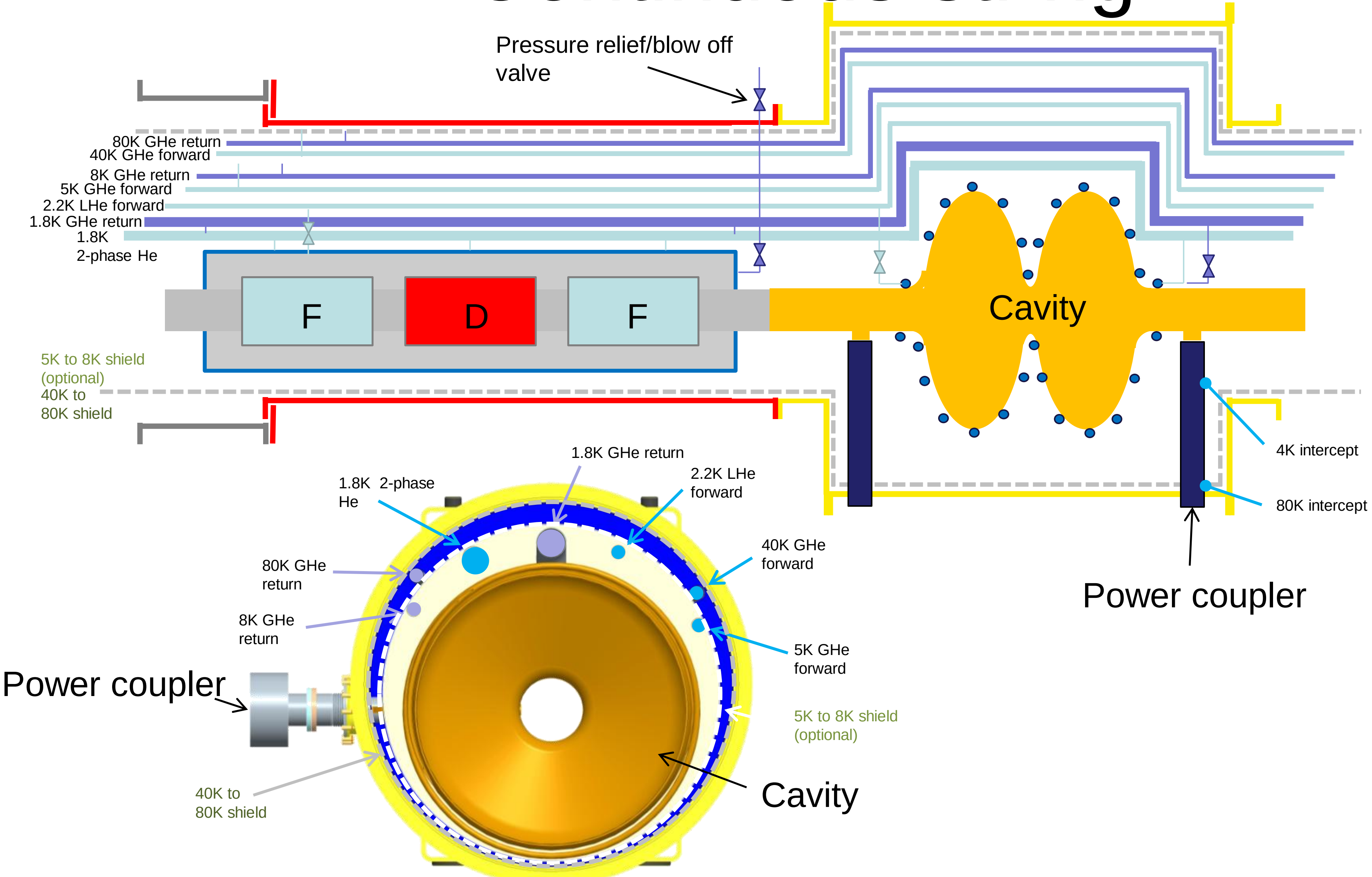


■	SC Magnet Modules	53
	Straights Sections	
■	SC Cavities (2 cells per cavity)	36
□	Injection kickers	2
□	Injection SC septums	2
□	Extraction kickers	4
□	Extraction SC septums	2
■	Diagnostics, pumping and cryogenic service stations	4
□	Empty straights/Possible Kicker Locations.	3

ns-FFAG cell in a continuous string



Cryogenic schematic – Continuous string

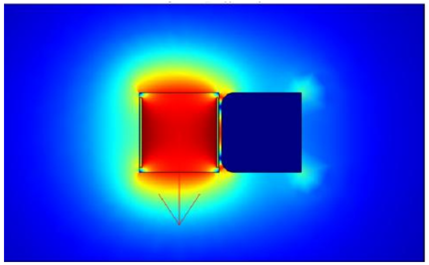


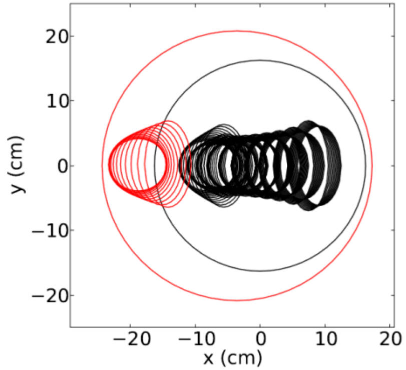
From T. Jones

Septum magnet – NF ns-FFAG

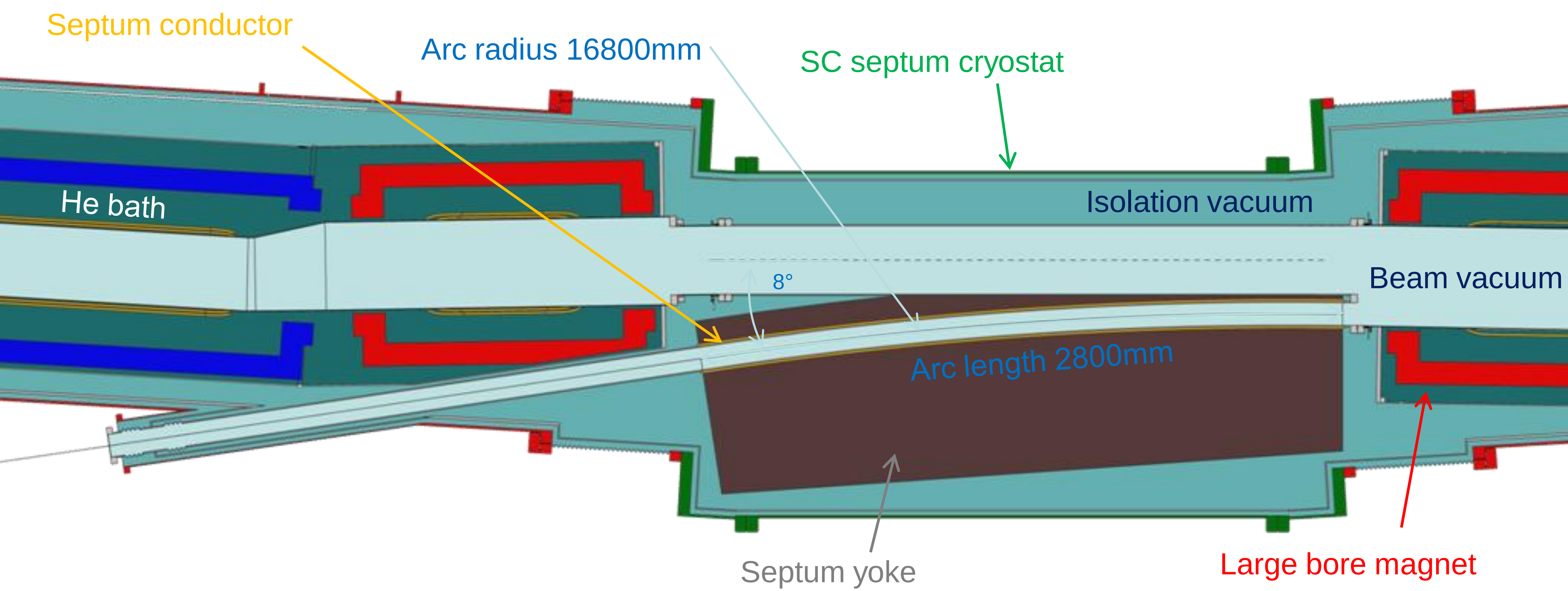
• Septum design on-going.

• Image below is a work in progress schematic of superconducting 2T extraction septum. 3D design is required to ascertain feasibility.

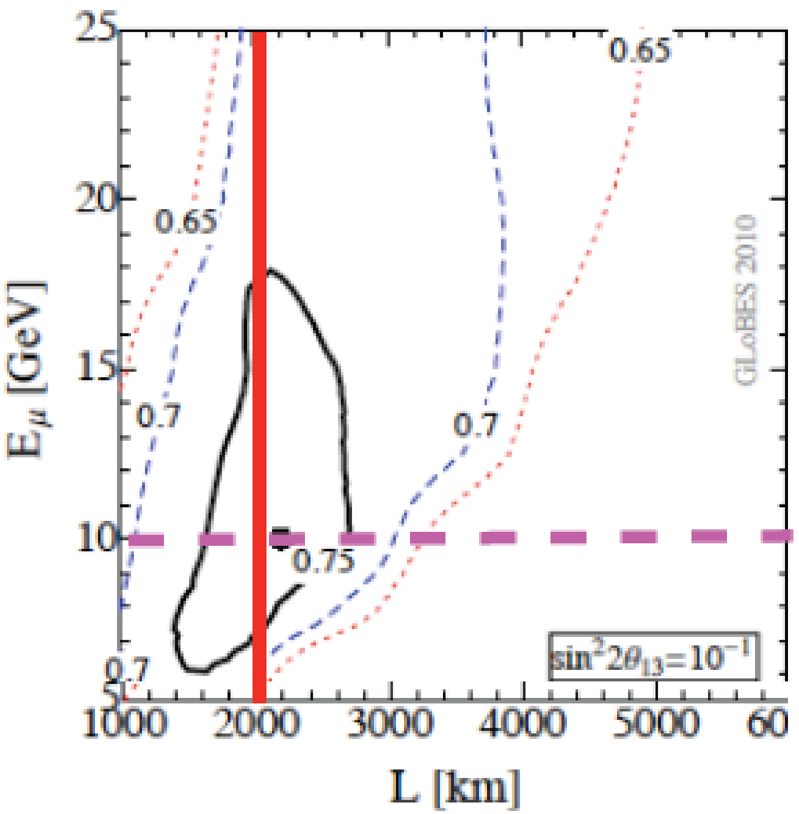


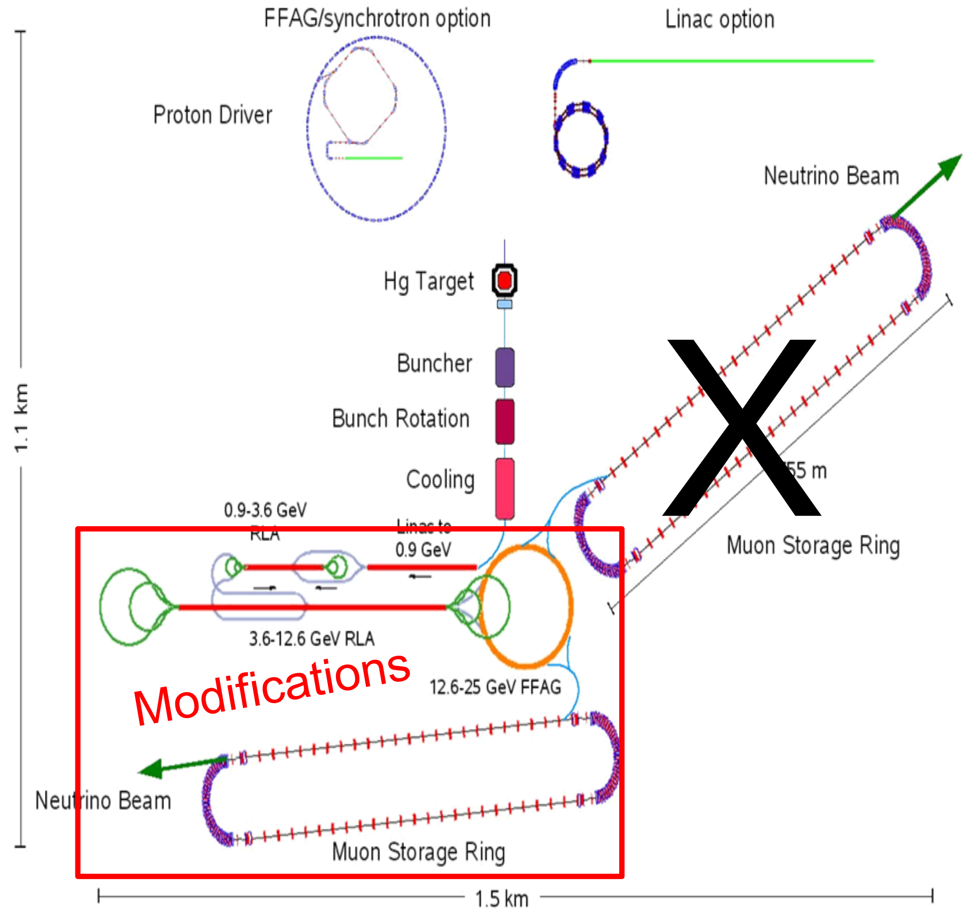


Images above and right ref: NF Interim Design Report



Baseline modifications due to the large θ_{13}





Detectable CP-violation fractions as a function of muon energy in the storage ring and a baseline length, from S. Pascoli's talk at IDS-NF meeting in Glasgow

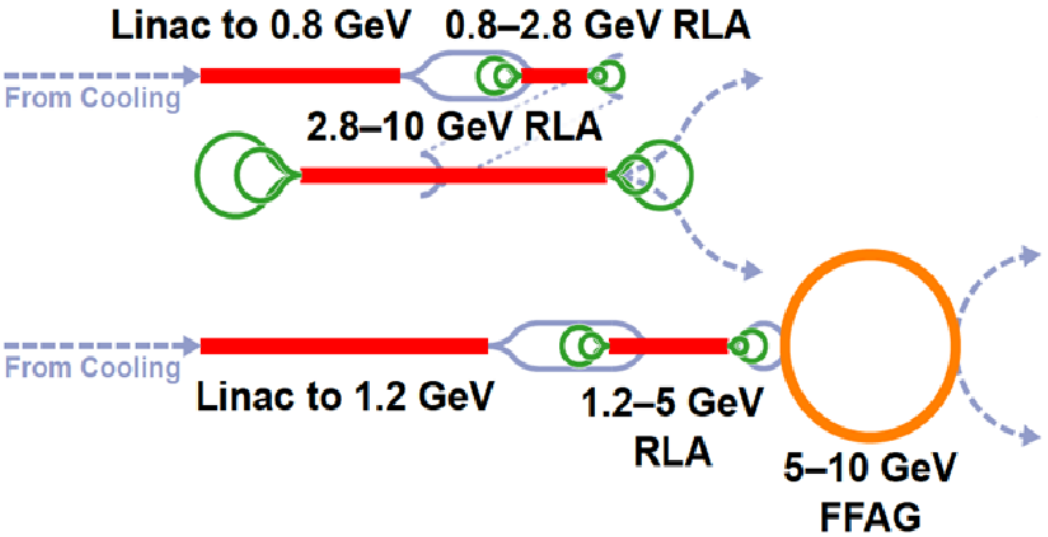
Effects of large θ_{13} on the baseline:

- Only one decay ring needed with reduced energy/circumference/cost (see David's talk).
- Modifications in the muon acceleration scheme (only 10 GeV needed).

10 GeV acceleration scenarios due to large θ_{13}
Argument at NuFact'12

Option I

Option II



For 10 GeV muon acceleration two options have been proposed:

- **Option I:** using linac and two Recirculating Linear Accelerators (RLAs) – it is very similar to the previous baseline part up to 12.6 GeV

- **Option II:** using linac+RLA+ Nonscaling Fixed Field Alternating Gradient (NS-FFAG) ring – NS-FFAG could use the same technology developed for 12.6-25 GeV ring.

Option II was selected at the Nufact'12 due to 5 GeV breaking point, which was favoured as better for an intermediate staging for physics at that time.

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Muon Acceleration Baseline Decision

- There is no need for any intermediate energy stage for the NF (no cost advantage due to a different baseline length specification, a different decay ring design and a detector location).
- According to the current cost exercise both options perform very similar .
- NS-FFAG is a new type of accelerator with some operational risk

- Take Option I (without FFAG and 2 RLAs to 10 GeV) or even modify the old 12.6 GeV option with 2 RLAs.

But...

- According to the current cost exercise both options perform very similar.

The error bars are huge, especially as the RLA cost model is scaled from the FFAG one. Are we sure we want to remove a possibility to have options in the system, which is the clear cost driver?

- NS-FFAG is a new type of accelerator with some operational risk

The proof of principle has been demonstrated
during the EMMA commissioning at Daresbury Lab.

RF budget for muon acceleration in the NF

Back of envelope calculations (very crude)

Efficiency Factors

- Old 25 GeV scenario:

$(0.9-0.15)/1 + (12.6-0.9)/4.5 + (25-12.6)/10.3$ [GeV/e] = ~4.5 GV

LINAC RLAs FFAG

- New 10 GeV scenario, Option I

$(0.8-0.15) + (10-0.8)/4.5$ [GeV/e] = ~2.7 GV

LINAC RLAs

Both equal up to error bars

- New 10 GeV scenario, Option II

$(1.2-0.15) + (5-1.2)/4.5 + (10-5)/9$ [GeV/e] = ~2.5 GV

LINAC RLAs FFAG

Conclusion:

- both scenarios have approximately the same cost,
- Are they ideal?

Summary

- The IDS baseline was updated and the NS-FFAG was removed.

- NS-FFAG will be only in the appendix of the RDR!

- In my personal view there is still a room for better and more cost effective designs and it is still worth to consider new options for the Neutrino Factory (racetrack, advanced etc.)!

- NS-FFAGs are still important for a Muon Collider and a Higgs Factory.