Status of muon FFAGs

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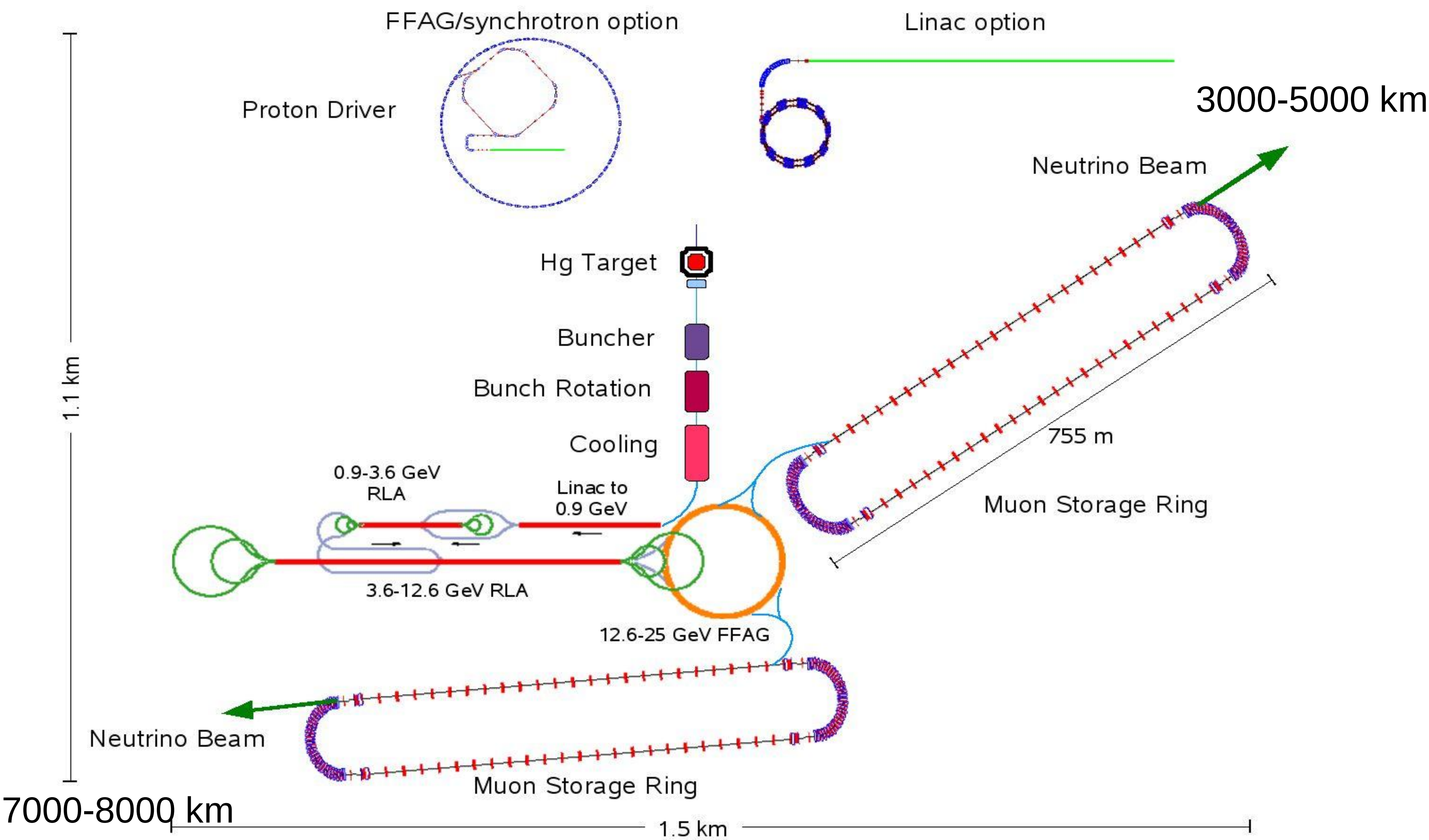
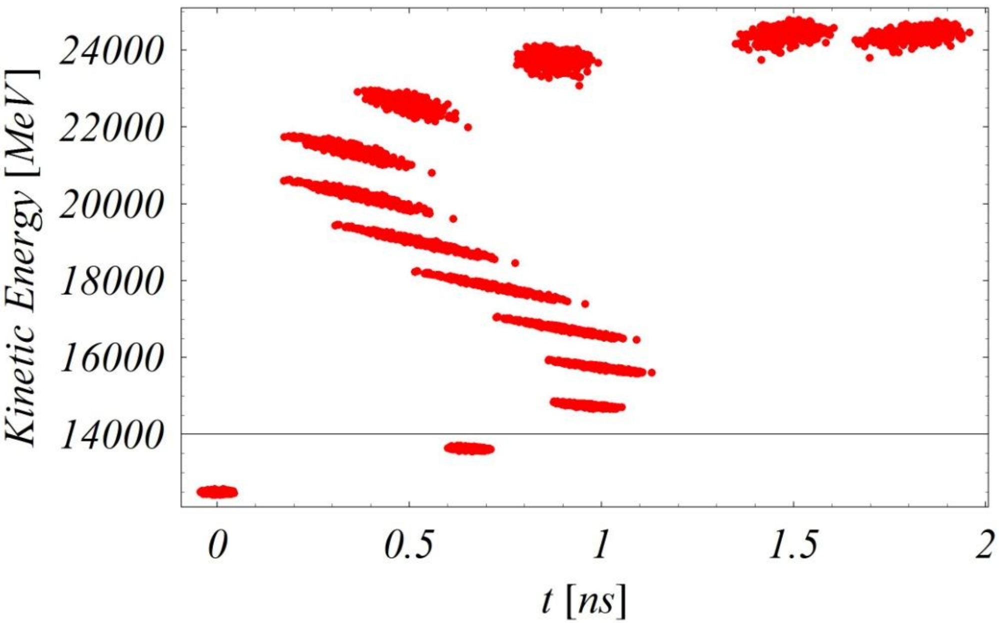
Outline

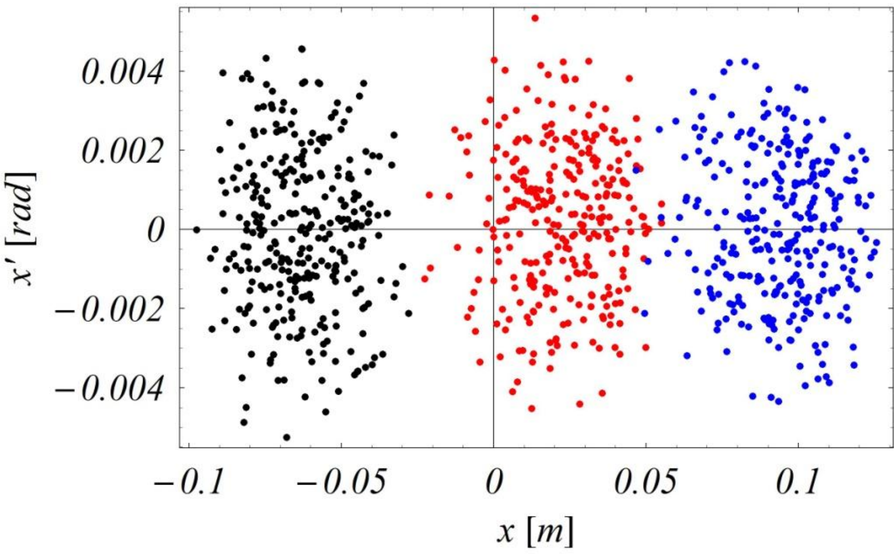
- FFAGs for the Neutrino Factory
- nuSTORM
- PRISM
- Conclusions

IDS-NF Neutrino Factory Baseline (before April 2012)



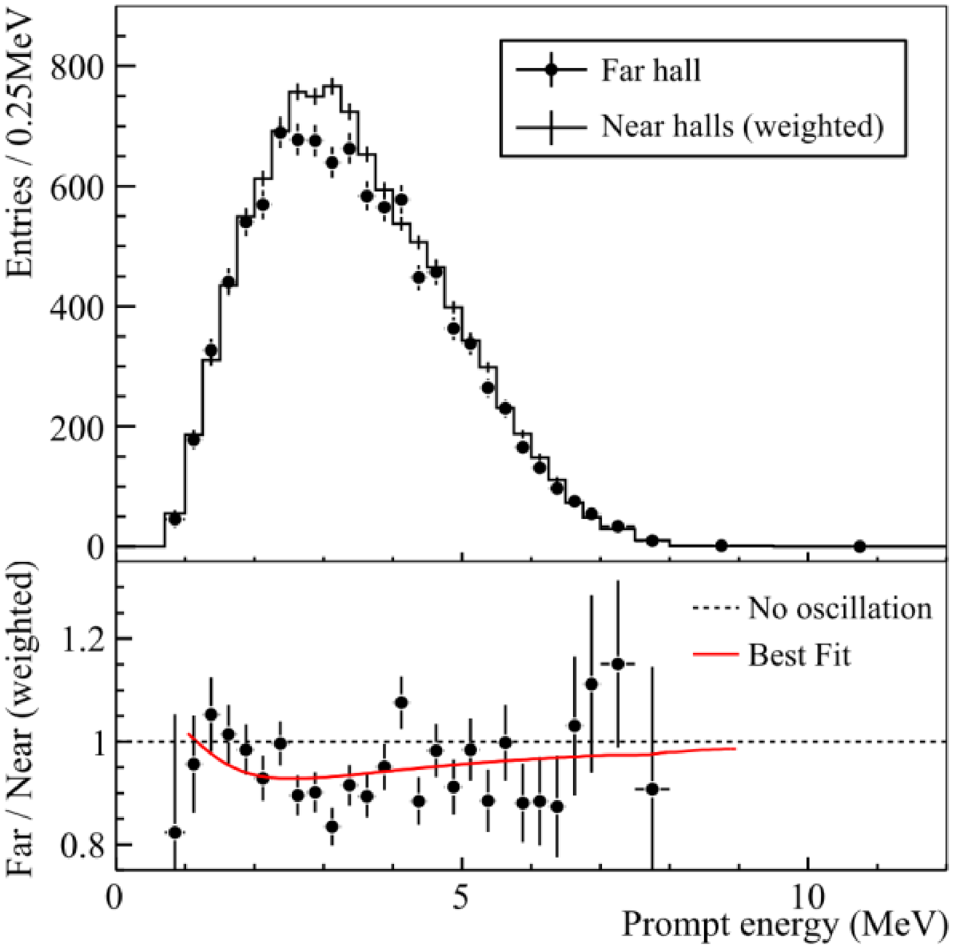
Huge progress on acceleration in 25 GeV machine, for the EUROnu report





- Longitudinal emittance growth is still visible, but low energy tails has been removed (a potential problem for extraction)
- This was very encouraging path towards the required quality in FFAG!

Discovery of the large θ_{13} in reactor experiments (status as in 2012)

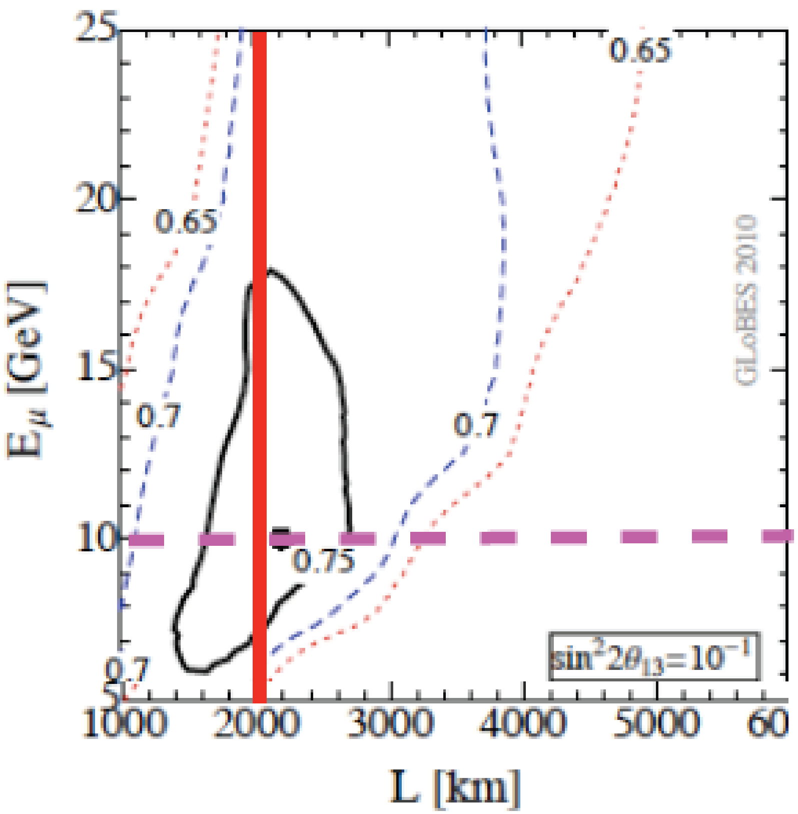


Daya Bay oscillation result, from arXiv: 1203.1669v2 [hep-ex] 2 April 2012

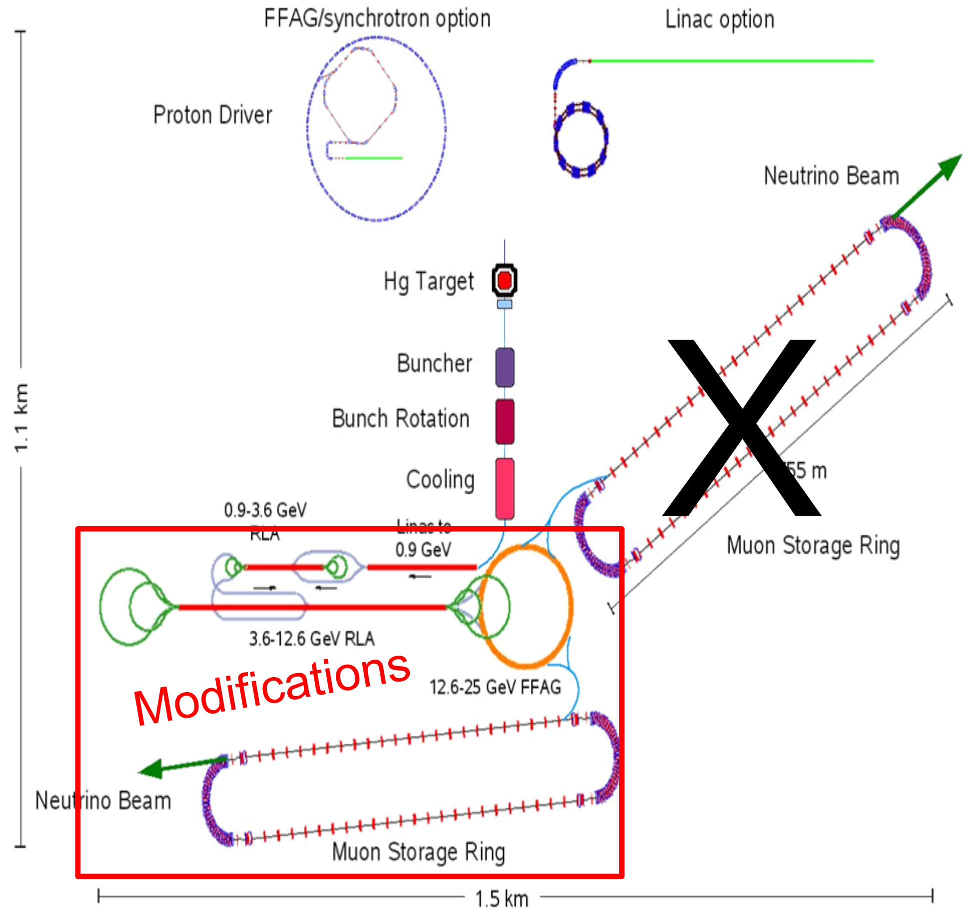
PMTs in the Daya Bay detector, (from Nature News)

	$\sin^2 2\theta_{13}$		
	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)



Effects of large θ_{13} on the baseline:

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

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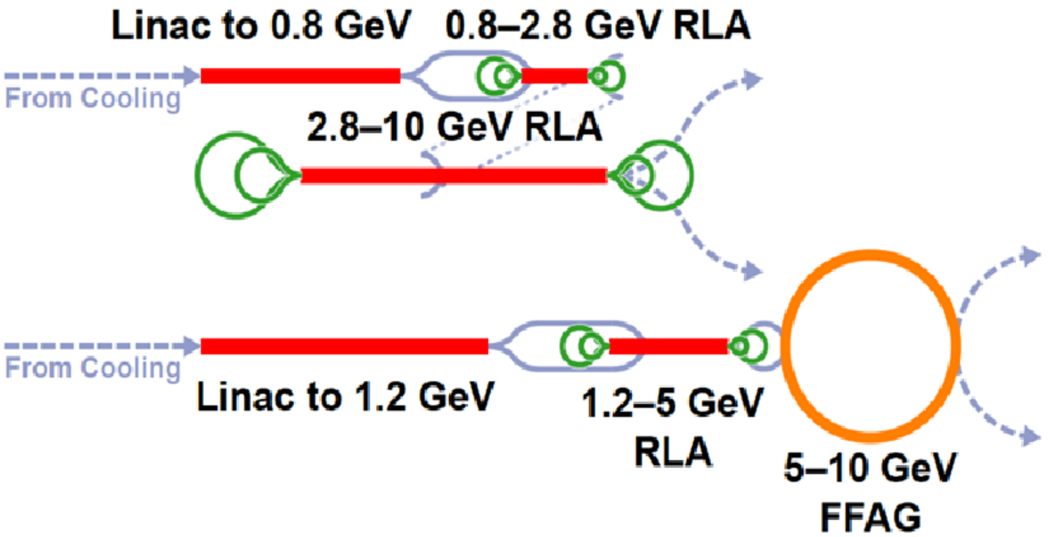
10 GeV acceleration scenarios due to large θ_{13} Argument at NuFact'12

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.

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.

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)

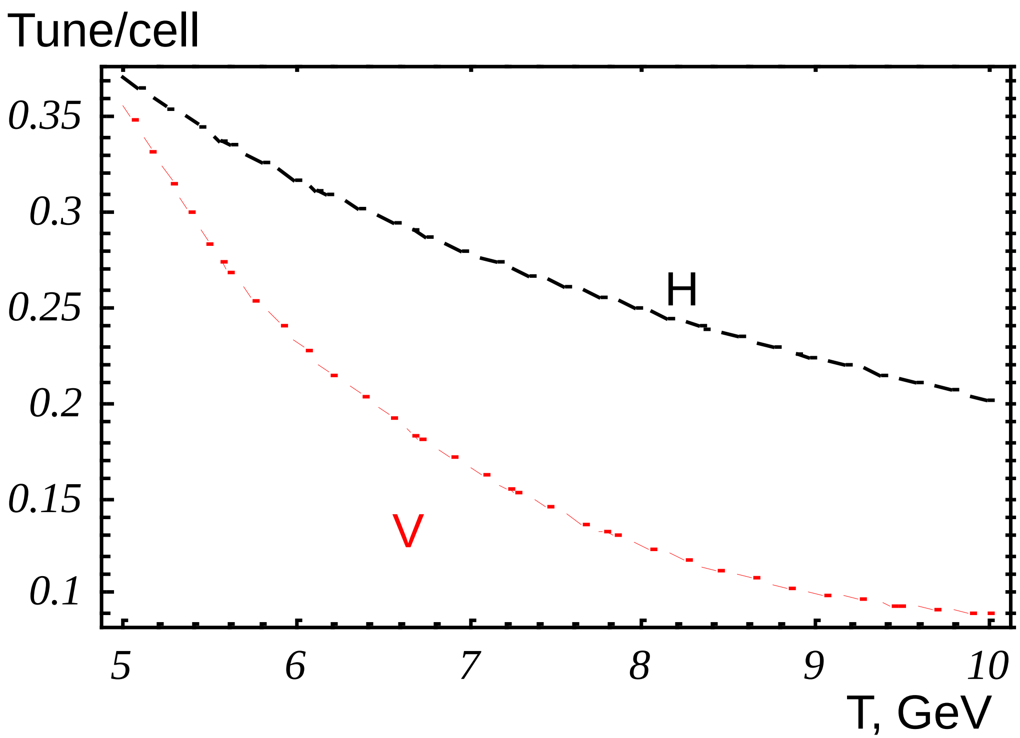
FFAG Designs Comparison

	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)

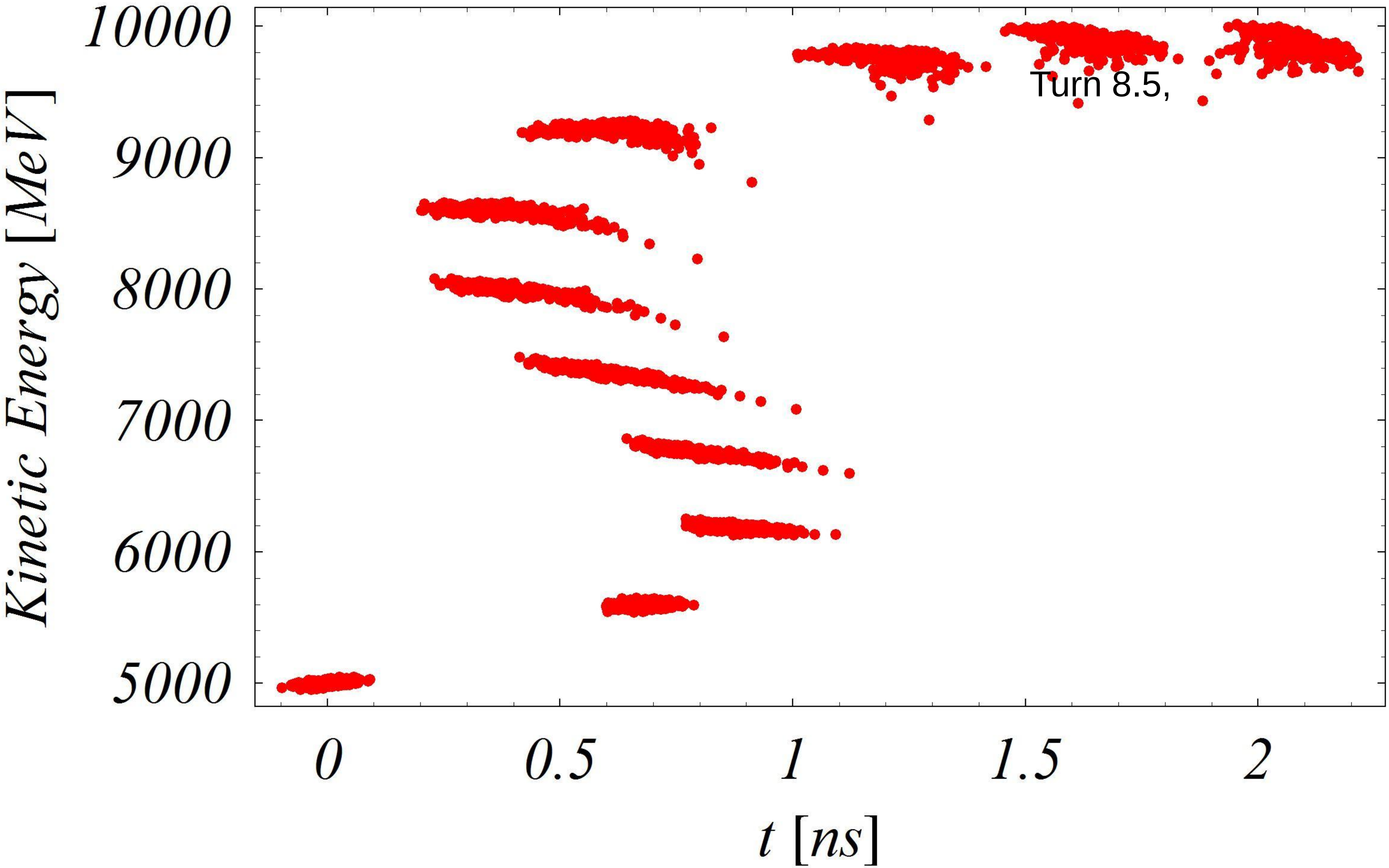
- Assumption:

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

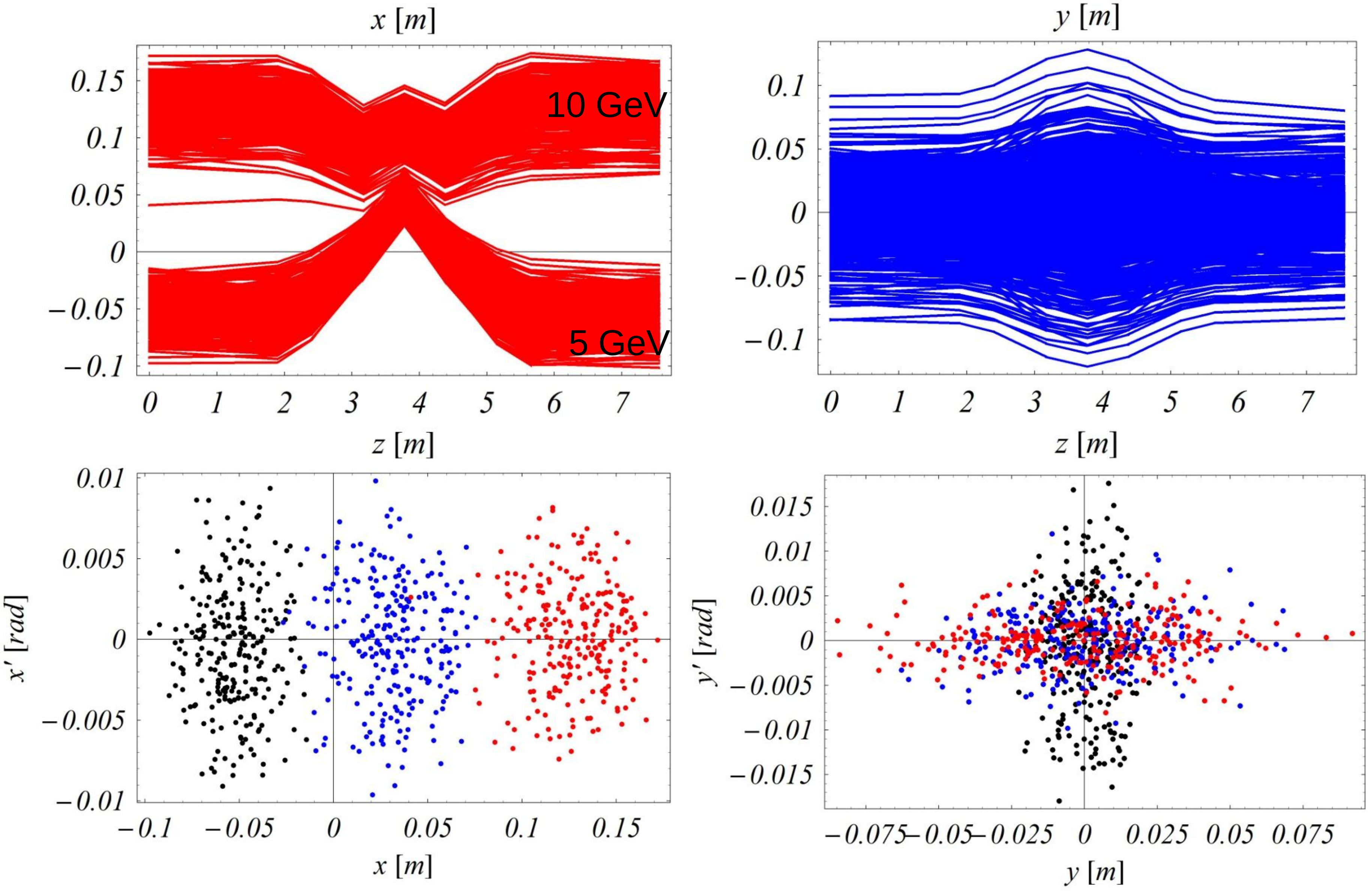


- FDF triplet
- Drift length 3.8 m
- Assumed double cell 201 MHz cavity in a drift.
- B max 6.3 T
- N cells 49
- Small level of chromaticity correction assumed (to improve the off-momentum stability and partially improve the ToF problem).
- This seems to allow for more turns.
- Machine seems to have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

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

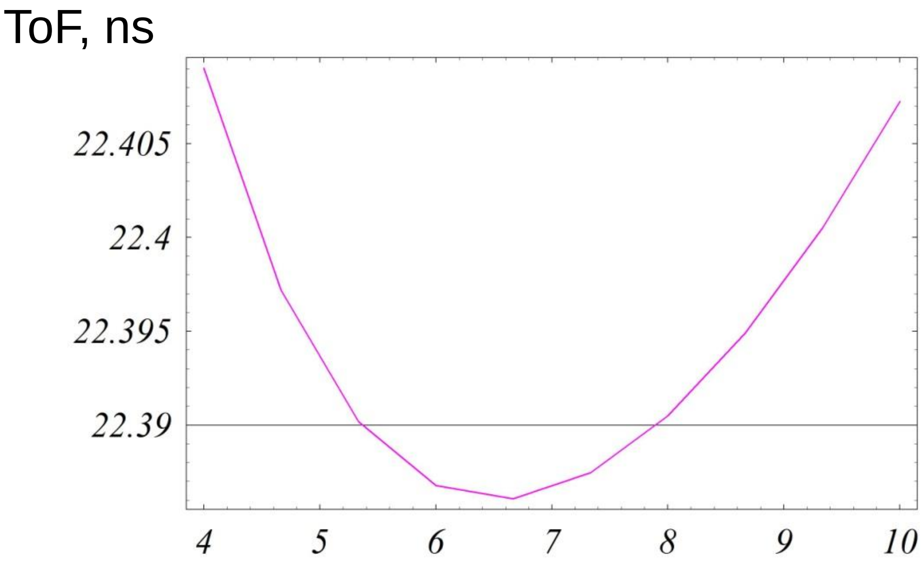


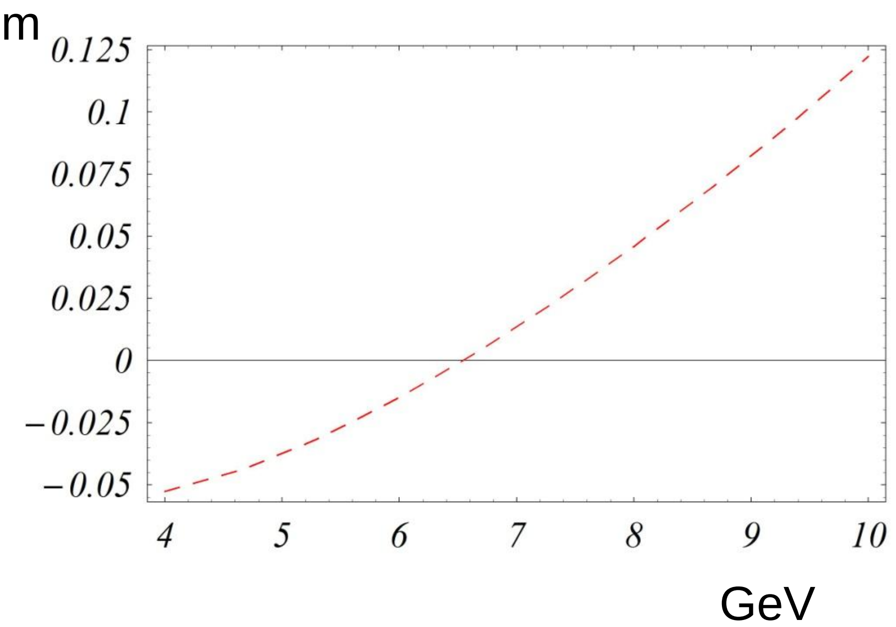
Apertures and phase spaces

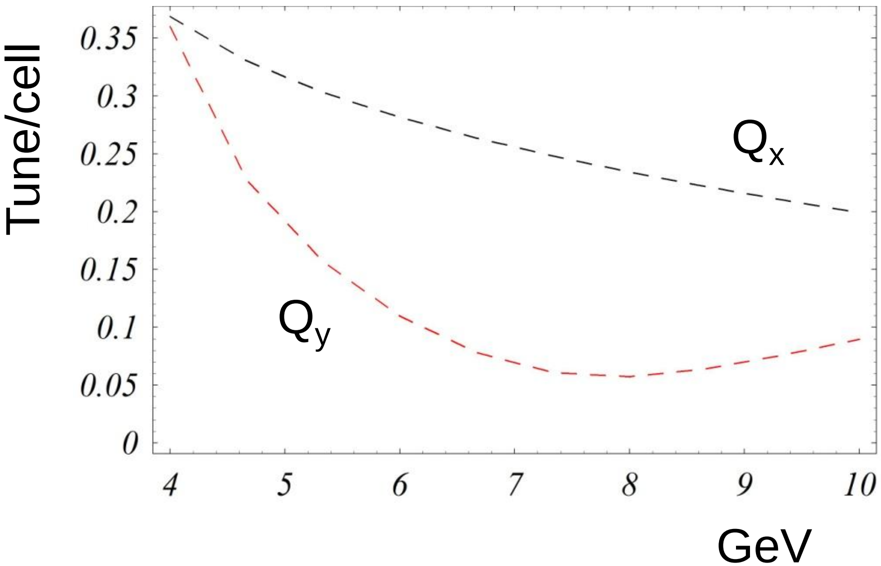


Apertures a bit larger than in 25 GeV machine!

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.

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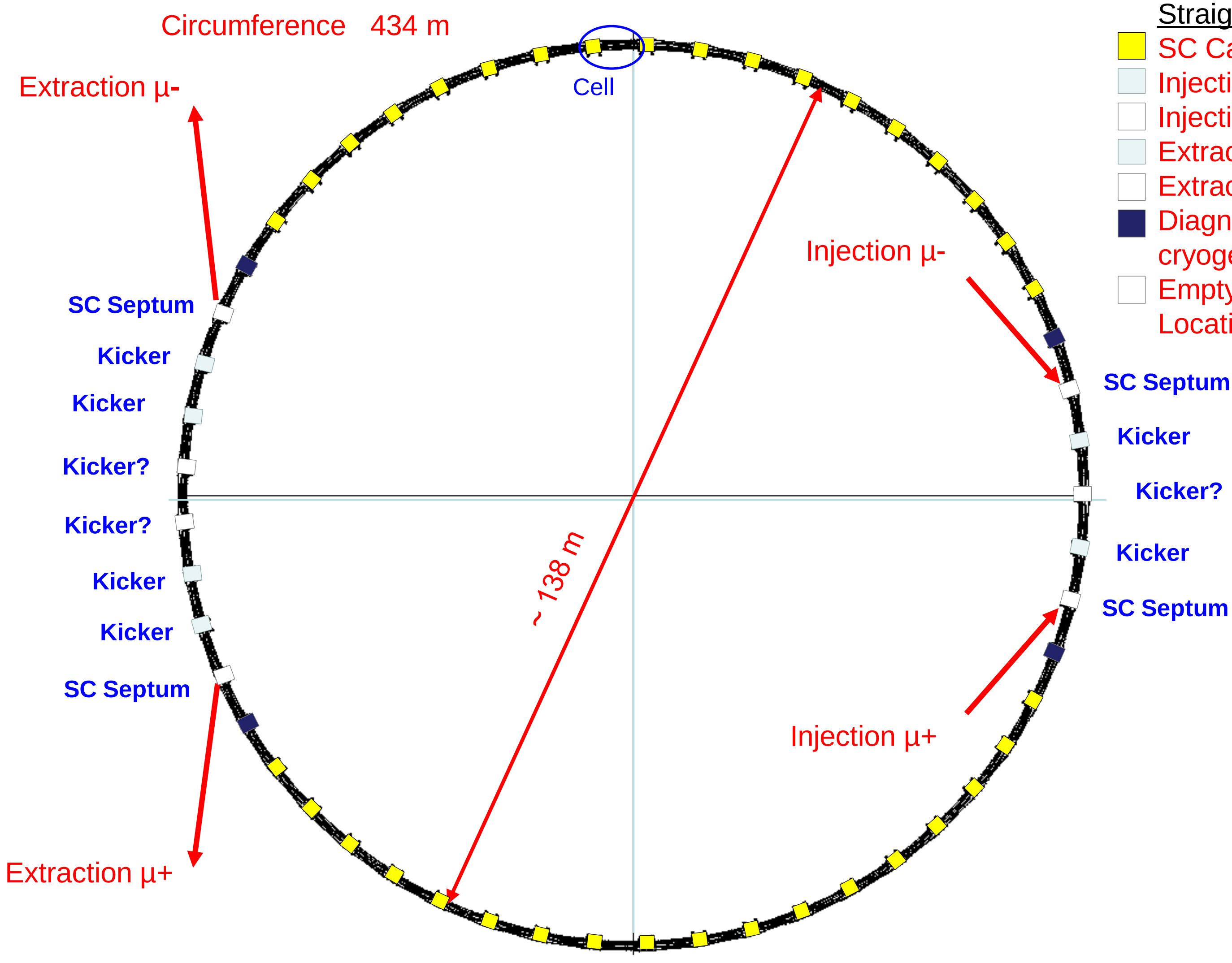
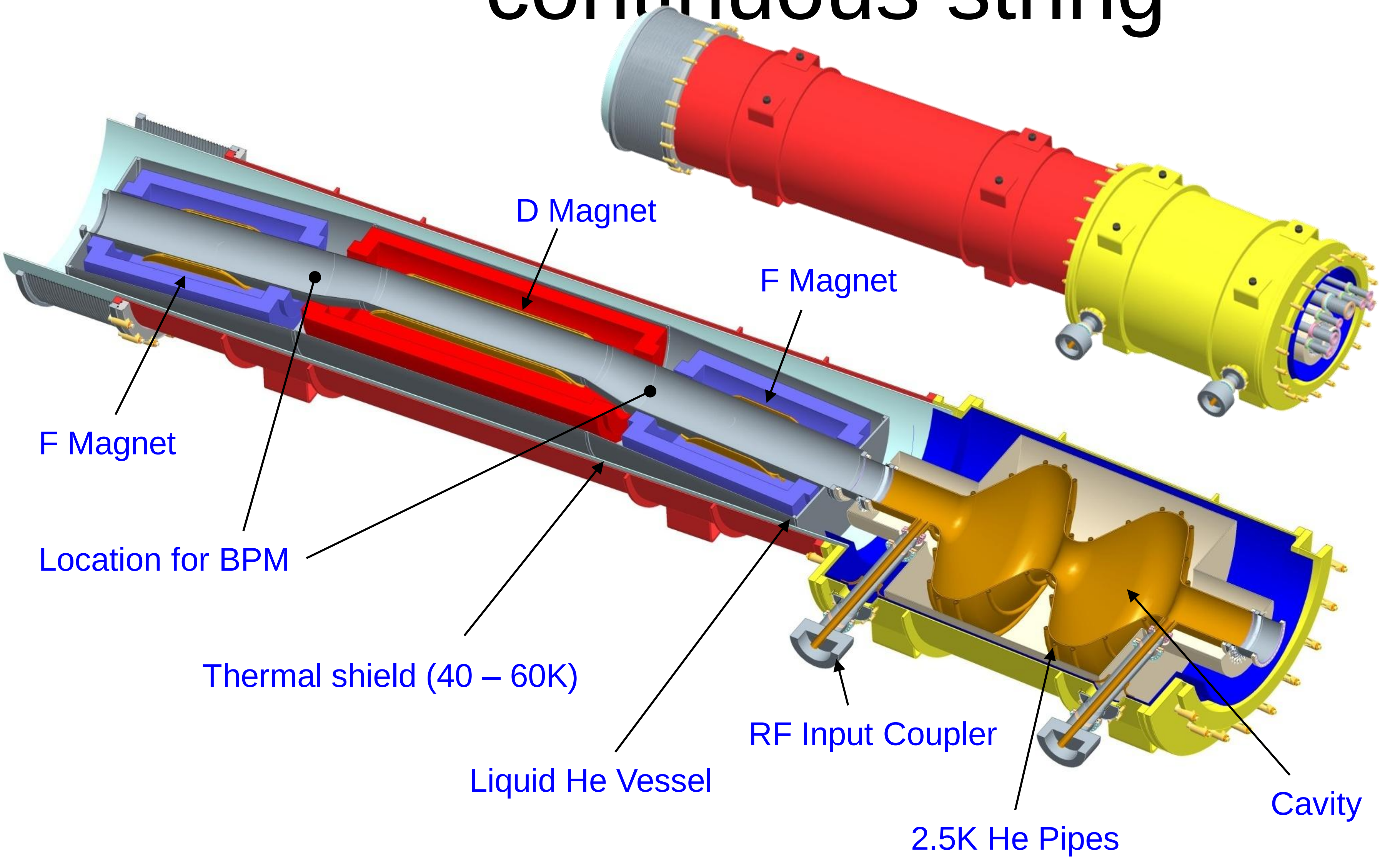
ns-FFAG Layout with continuous cryomodules

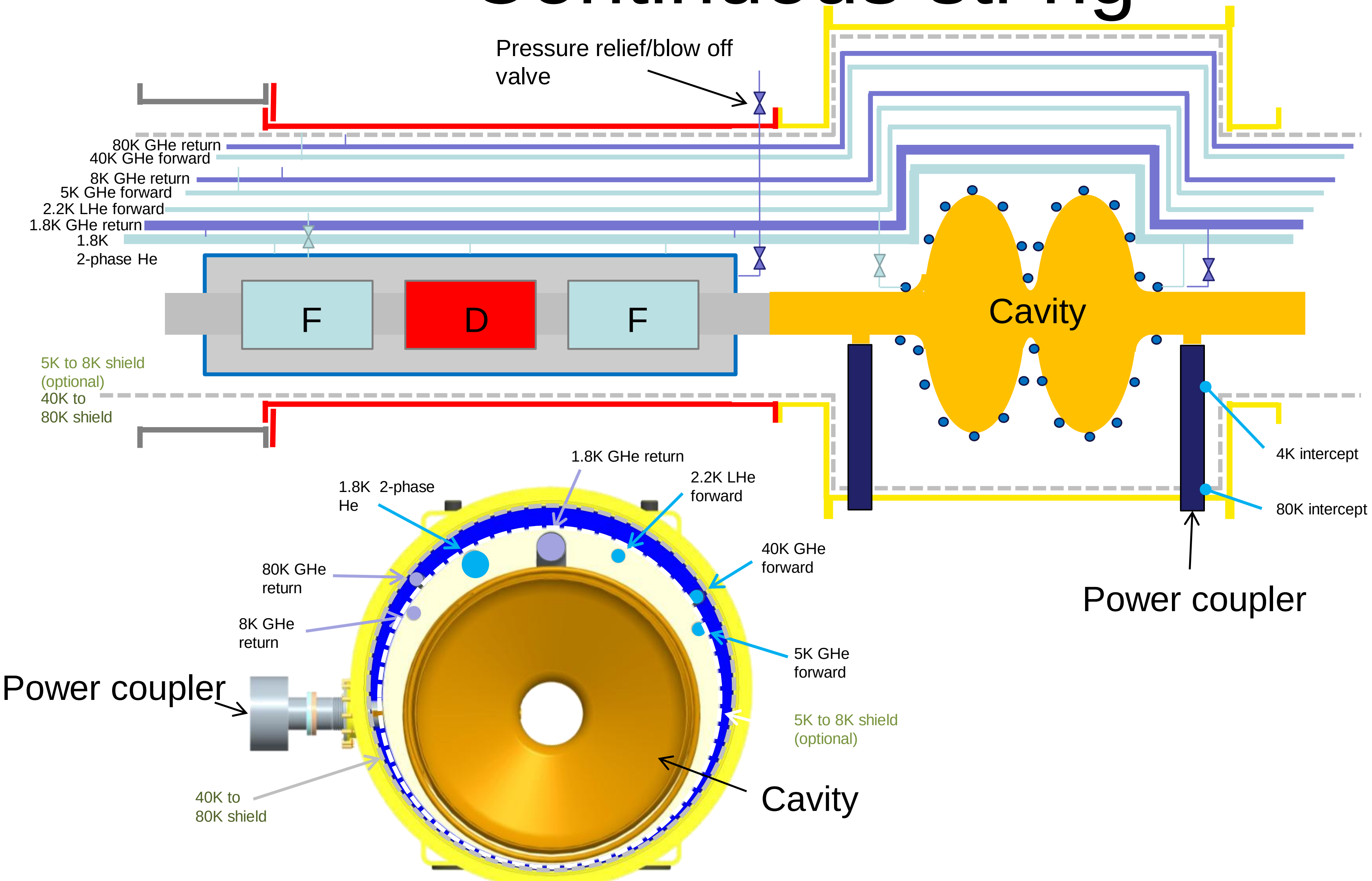


SC Magnet Modules	53
Straights Sections	
SC Cavities (2 cells per cavity)	36
Injection kickers	2
Injection SC septums	2
Extraction kickers	4
Extraction SC septums	2
Diagnostics, pumping and cryogenic service stations	4
Empty straights/Possible Kicker Locations.	3

ns-FFAG cell in a continuous string



Cryogenic schematic – Continuous string

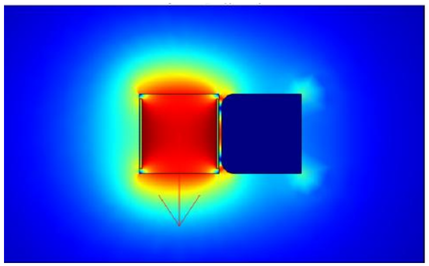


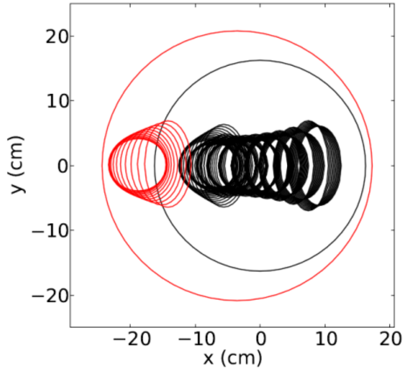
From T. Jones

Septum magnet – NF ns-FFAG

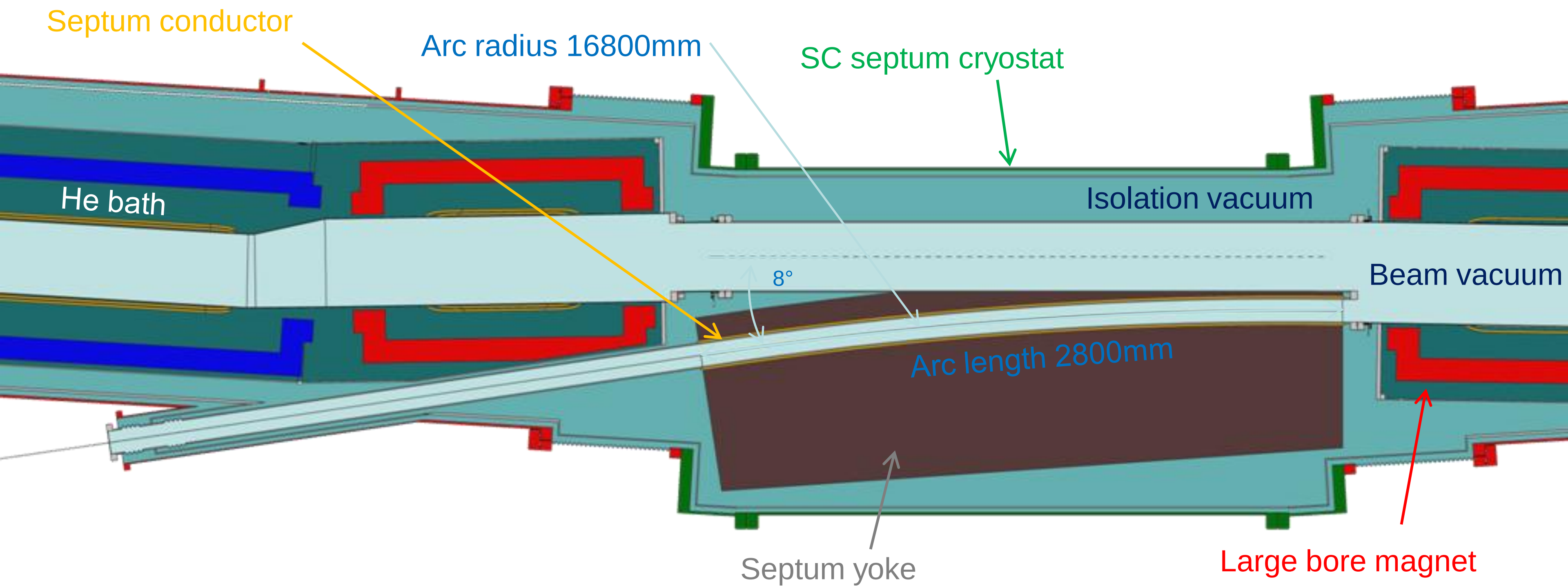
• Septum design on-going.

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





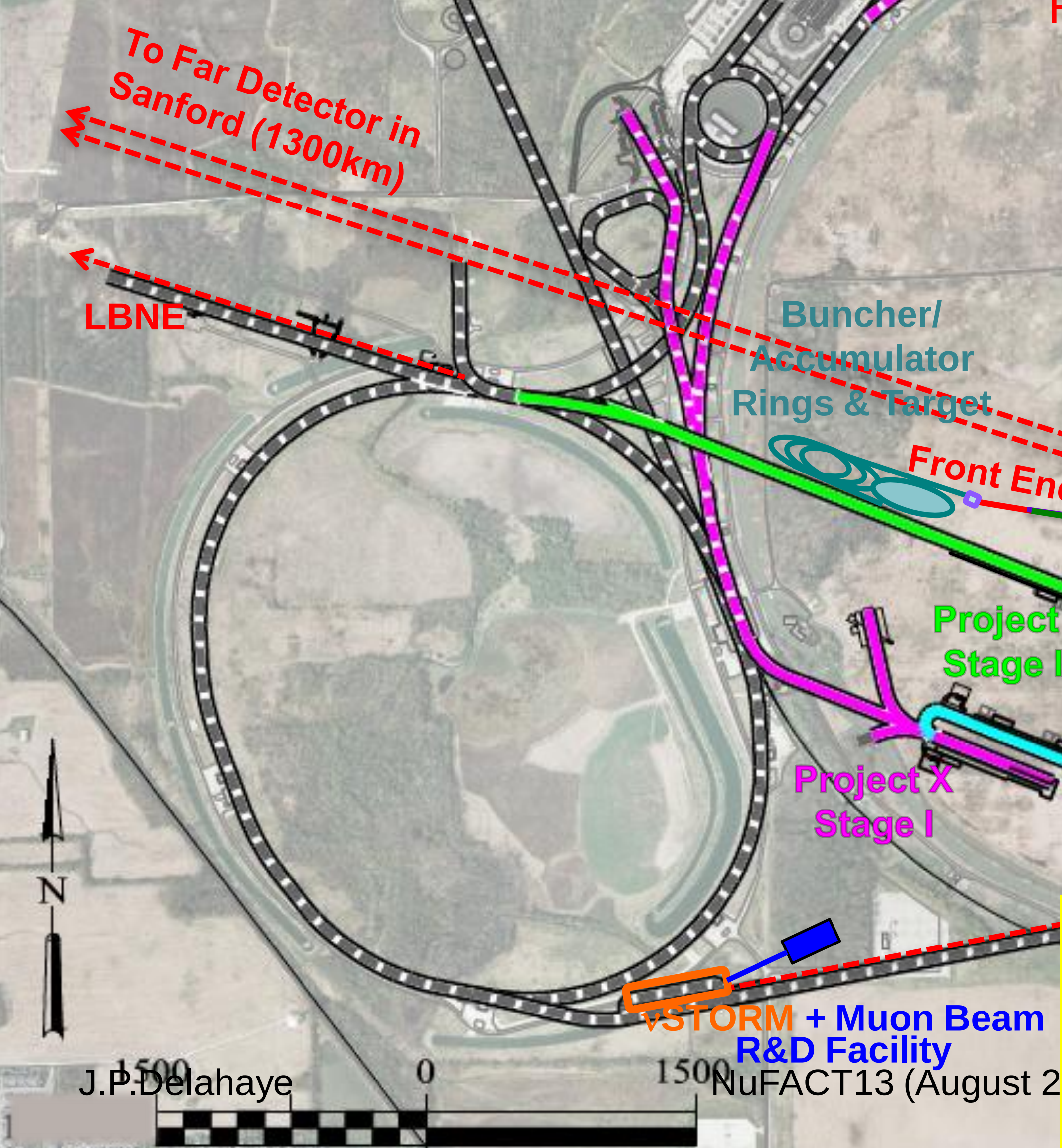
Images above and right ref:
NF Interim Design Report



Incremental scenario for muon accelerators at FNAL

Preliminary (collab. project X)

Presented by M. Palmer at nufact'13

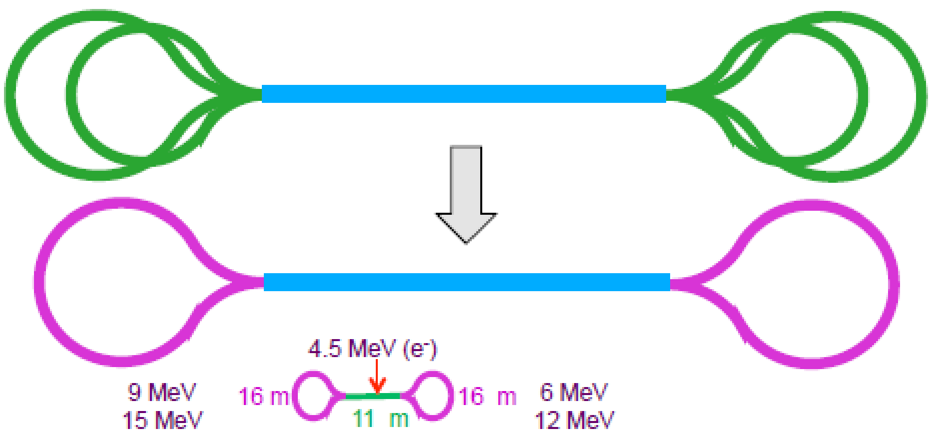


Later upgradable to a Muon Collider with Tevatron size at 6 TeV

Muon acceleration question for Nufact’14

- What is the optimum muon acceleration scheme for the Neutrino Factory with respect to feasibility, performance and cost (FFAG, RLAs with FFAG arcs, linac)?

Example:



RLA with FFAG arcs

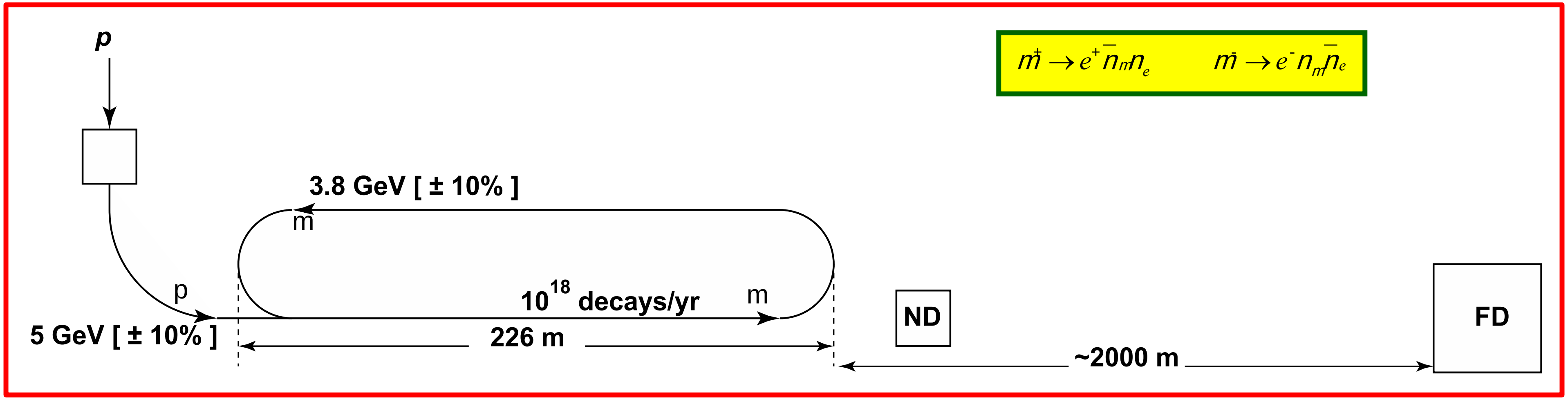
JEMMRLA

Design goals for muon FFAG accelerators for NF and MC

- To seek for a solution for 5 GeV final energy (what is the injection energy?)
- To be compatible with higher frequency (325 MHz at the current studies)
- To try the option of racetrack geometry
- To be upgradable to 10 GeV and/or to the Higgs Factory (final energy of 65 GeV).
- To develop an FFAG scenario for a Muon Collider

EMMA experiment is essential!

nuSTORM concept:



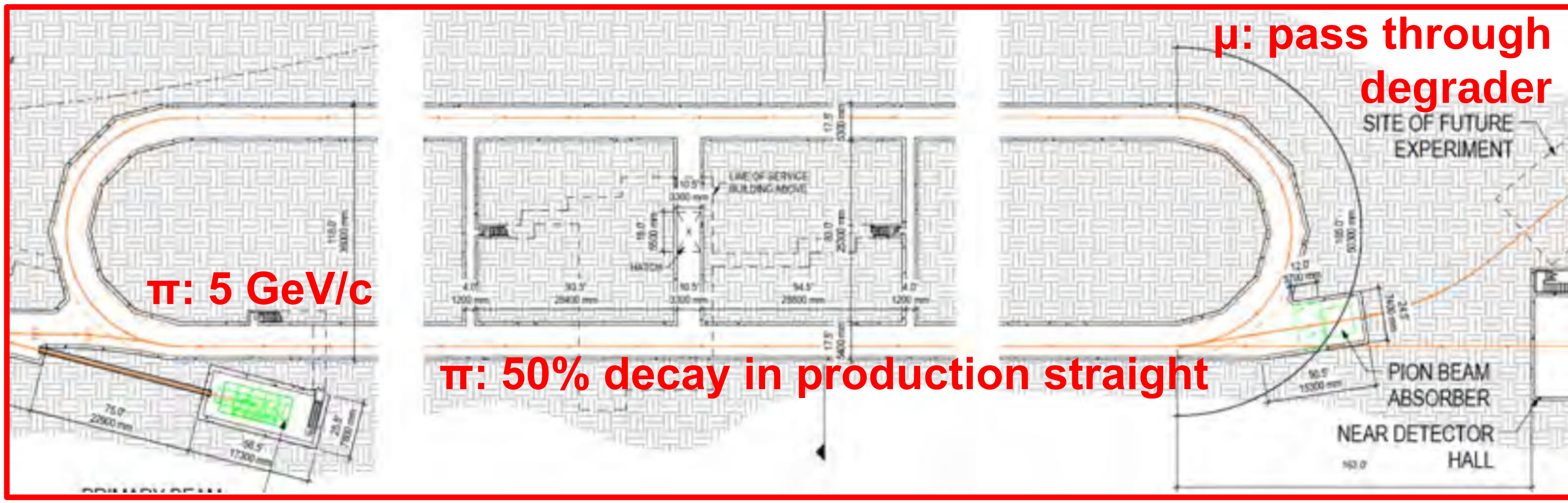
- Neutrinos from decay of stored muon beam:
  - Precisely known flavour composition;
  - Precisely known energy distribution

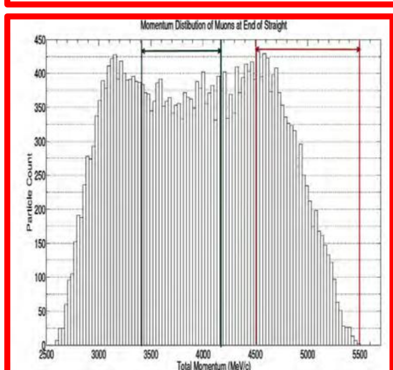
The case for nuSTORM:

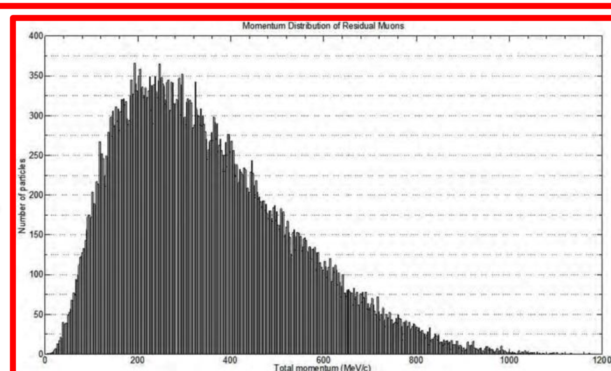
- The nuSTORM facility will:
  - Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of $\nu_e N$ and $\nu_\mu N$ scattering cross sections with percent-level precision;
  - Allow searches for sterile neutrinos of exquisite sensitivity to be carried out; and
  - Constitute the essential first step in the incremental development of muon accelerators as a powerful new technique for particle physics.

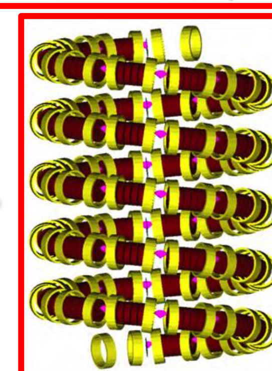
6D ionization cooling experiment:

- Reduction of 6D phase space of muon beam essential for future Muon Collider
  - MICE will provide proof of the ionization cooling principal in 4D using a single-particle technique
- nuSTORM will provide the pulsed, high-flux muon beam required for the development of ionization cooling



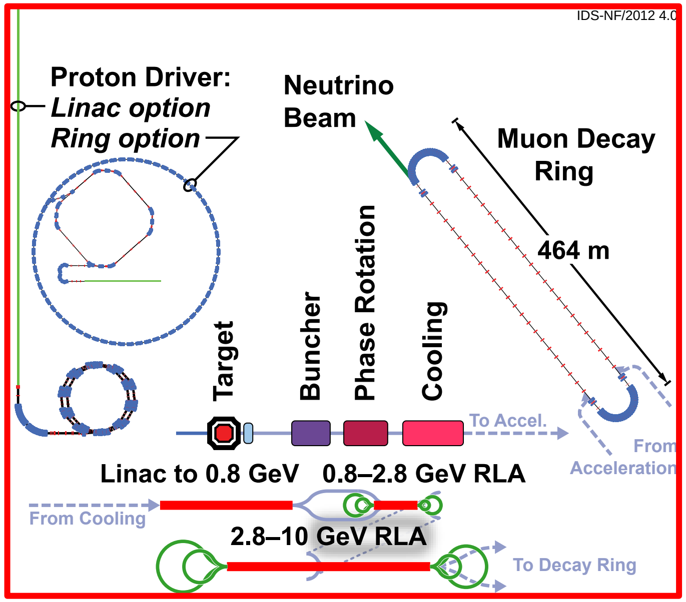


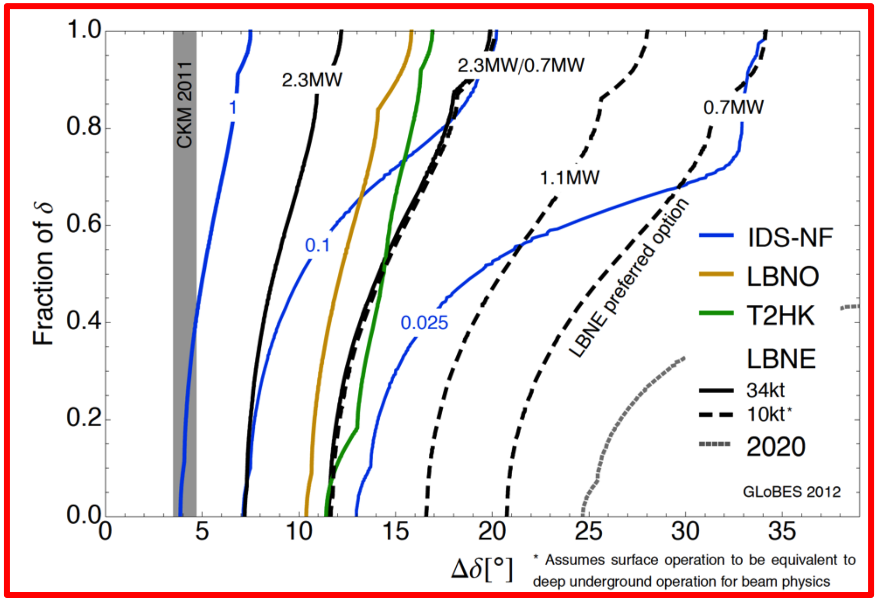




nuSTORM and muon accelerators for PP:

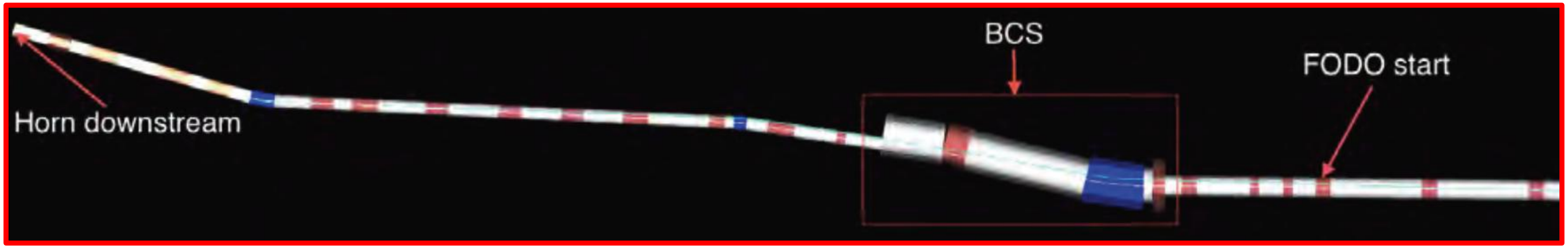
- Muon accelerators have the potential to:
  - Make definitive measurements of neutrino oscillations at the Neutrino Factory;
  - Provide multi-TeV lepton-antilepton collisions at the Muon Collider
- Incremental development of the Neutrino Factory programme offers exquisite sensitivity and precision:





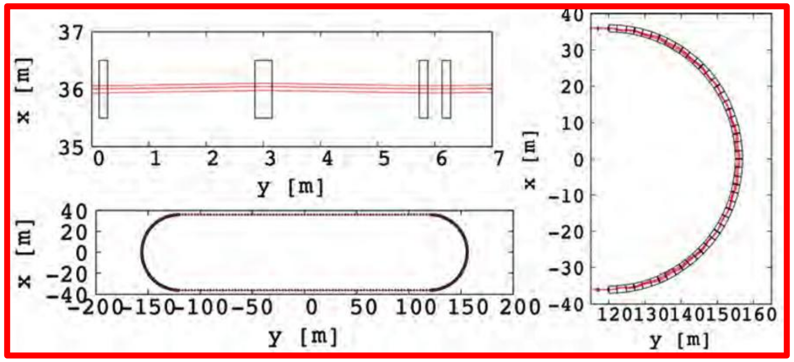
- nuSTORM is the essential first step in the incremental progamme:
  - Can be implemented “today” using known technologies
    - For the accelerator and the detectors
  - Capable of delivering a first-rate neutrino-physics programme *and* the R&D required to prepare the subsequent step

π injection and decay ring:



- Beam Combination Section (BCS) designed to deliver π-beam at start of straight
- Large aperture quad-focusing ring adopted as baseline
  - FFAG ring is an attractive option with very strong potentials (see JB's talk)

Parameter	FODO	RFFAG
$L_{straight}$ (m)	185	240
Circumference (m)	480	606
Dynamic aperture A_{dyn}	0.6	0.95
Momentum acceptance	$\pm$ 10%	$\pm$ 16%
π/POT within momentum acceptance	0.094	0.171
Fraction of π decaying in straight (F_s)	0.52	0.57
Ratio of $L_{straight}$ to ring circumference (Ω)	.39	.40
Relative factor ($A_{dyn} \times \pi$/POT $\times F_s \times \Omega$)	0.011	0.037



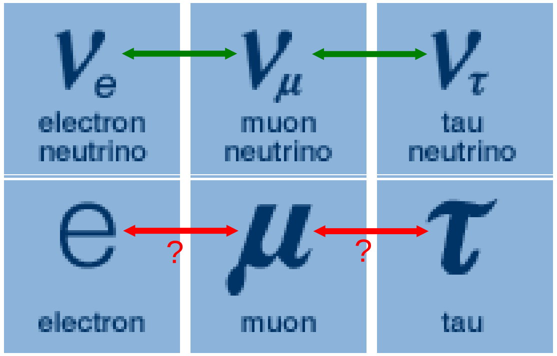
Implementation, at FNAL:

- Benefits from existing extraction tunnel;
- Ideal baseline from storage ring to D0 assembly building:
  - Space and infrastructure for SuperBIND and LAr detector;
- Space and access for near detector

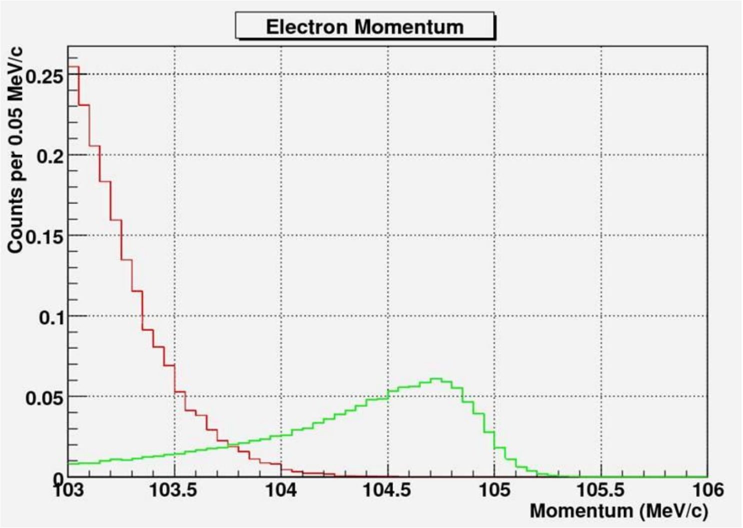
There is also a scenario for CERN.

PRISM, Motivation

- Charge lepton flavor violation (cLFV) is strongly suppressed in the Standard Model, its detection would be a clear signal for new physics!
- Search for cLFV is complementary to LHC.
- The μ- + N(A,Z)→e- + N(A,Z) seems to be the best laboratory for cLFV.
- The background is dominated by beam, which can be improved.
- The COMET and Mu2e were proposed and PRISM/PRIME is the next generation experiment.



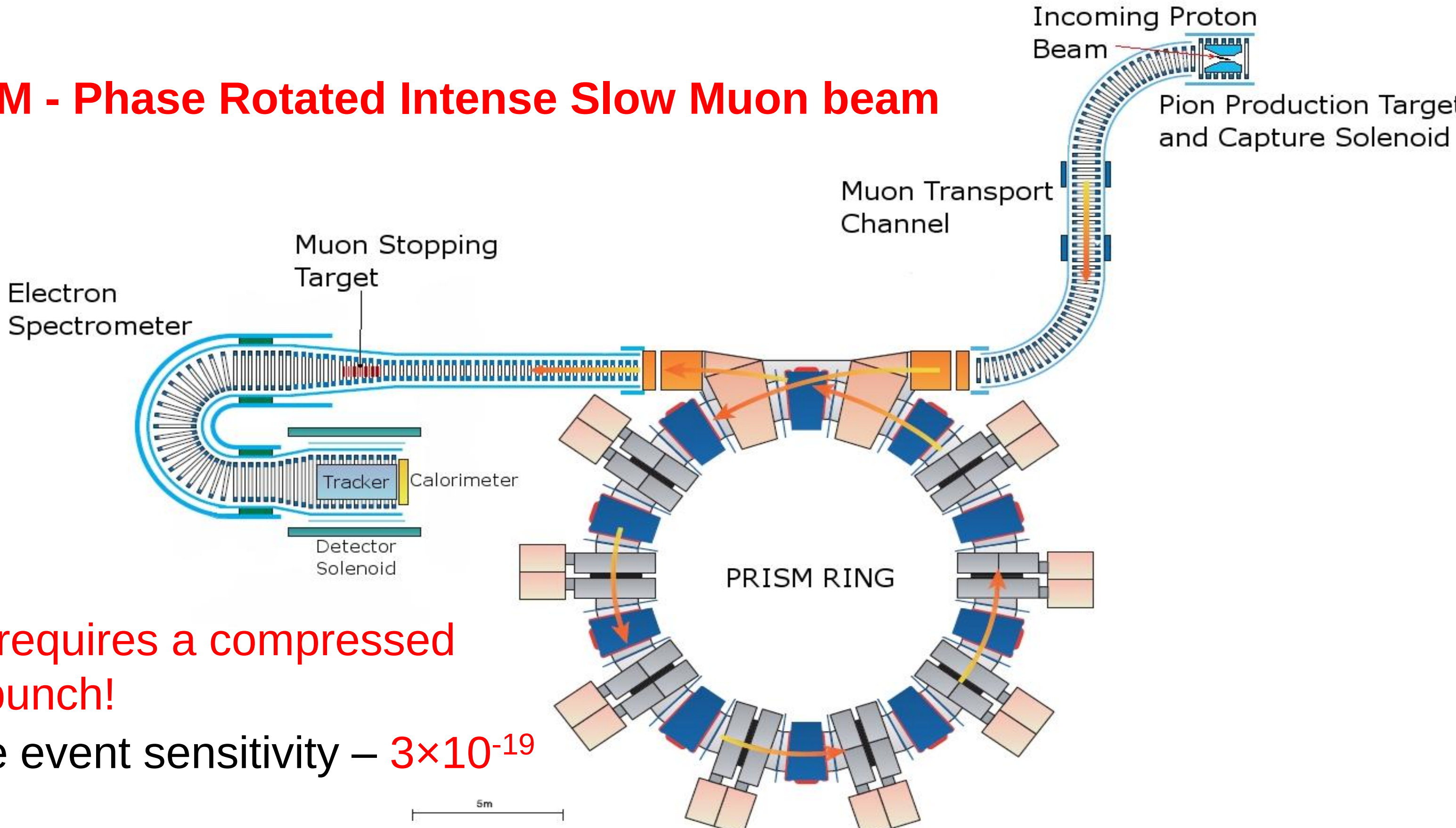
Does cLFV exists?



Simulations of the expected electron signal (green).

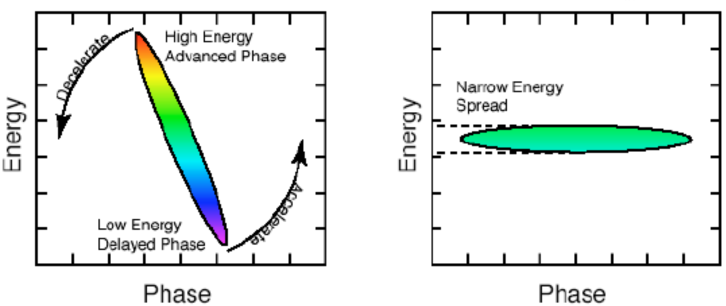
Layout of the PRISM/PRIME

PRISM - Phase Rotated Intense Slow Muon beam



PRISM requires a compressed proton bunch!

Single event sensitivity – 3×10^{-19}



The PRISM/PRIME experiment based on FFAG ring was proposed (Y. Kuno, Y. Mori) for a next generation cLFV searches in order to:

- reduce the muon beam energy spread by phase rotation,
- purify the muon beam in the storage ring.

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PRISM Task Force

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The aim of the PRISM Task Force:

- Address the technological challenges in realising an FFAG based muon-to-electron conversion experiment,
- Strengthen the R&D for muon accelerators in the context of the Neutrino Factory and future muon physics experiments.

The Task Force areas of activity:

- the physics of muon to electron conversion,
- proton source,
- pion capture,
- muon beam transport,
- injection and extraction for PRISM-FFAG ring,
- FFAG ring design including the search for a new improved version,
- FFAG hardware systems R&D.

Members:

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M. Lancaster, UCL, London, UK

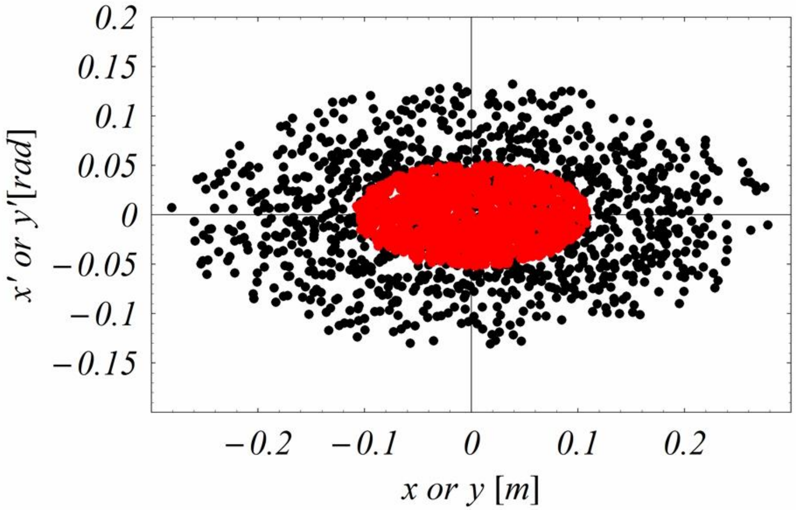
You are welcome to join us!

PRISM parameters

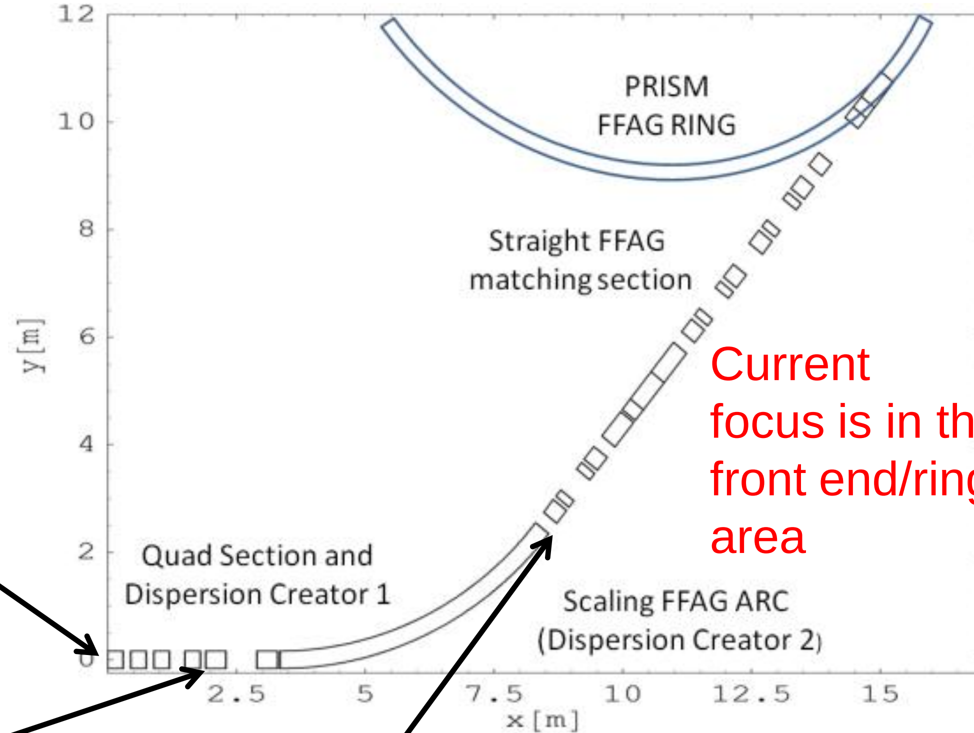
Parameter	Value
Target type	solid
Proton beam power	1-4 MW
Proton beam energy	multi-GeV
Proton bunch duration	~10 ns total (in synergy with the NF)
Pion capture field	4-10 T
Momentum acceptance	±20 %
Reference μ^-momentum	40-68 MeV/c
Harmonic number	1
Minimal acceptance (H/V)	3.8/0.5 π cm rad
RF voltage per turn	3-5.5 MV
RF frequency	3-6 MHz
Final momentum spread	±2%
Repetition rate	100 Hz-1 kHz

Matching to the FFAG

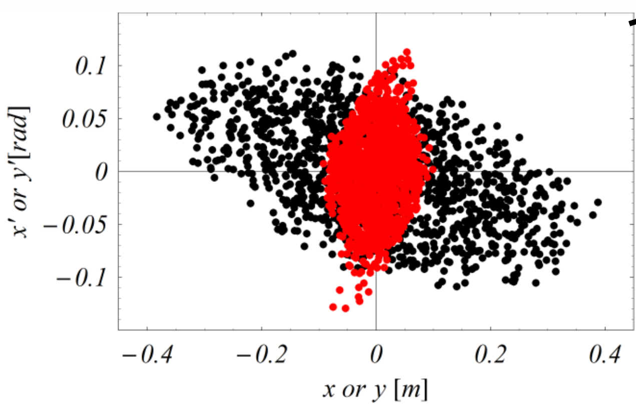
- Tracking status (work in progress)



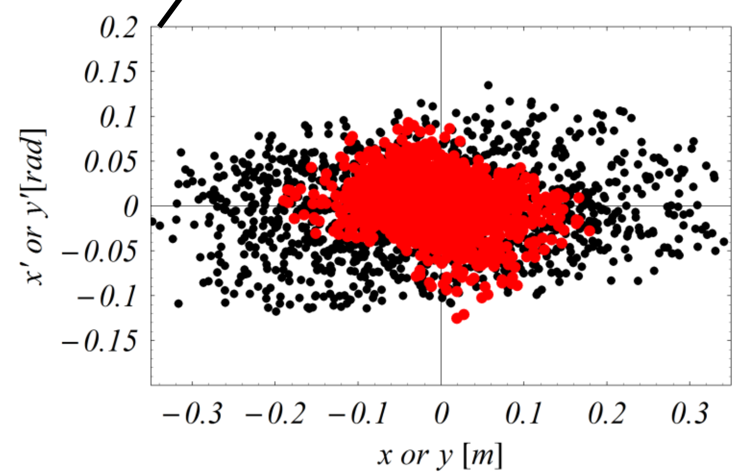
Horizontal (black) and vertical (red) phase spaces at the input to the AG part of the PRISM muon front end.



Current focus is in the front end/ring area



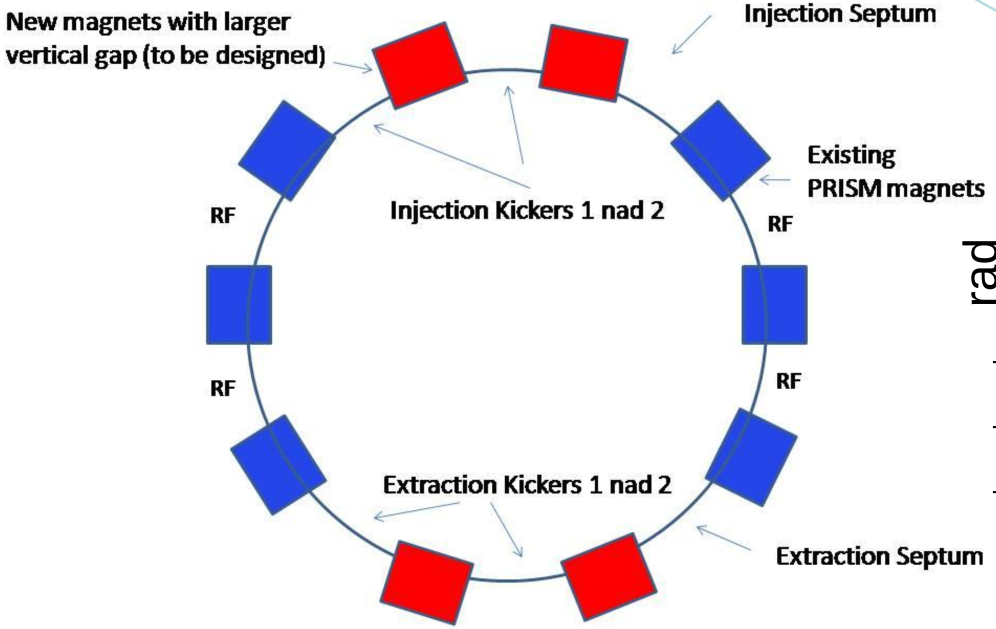
At the end of the quad Channel

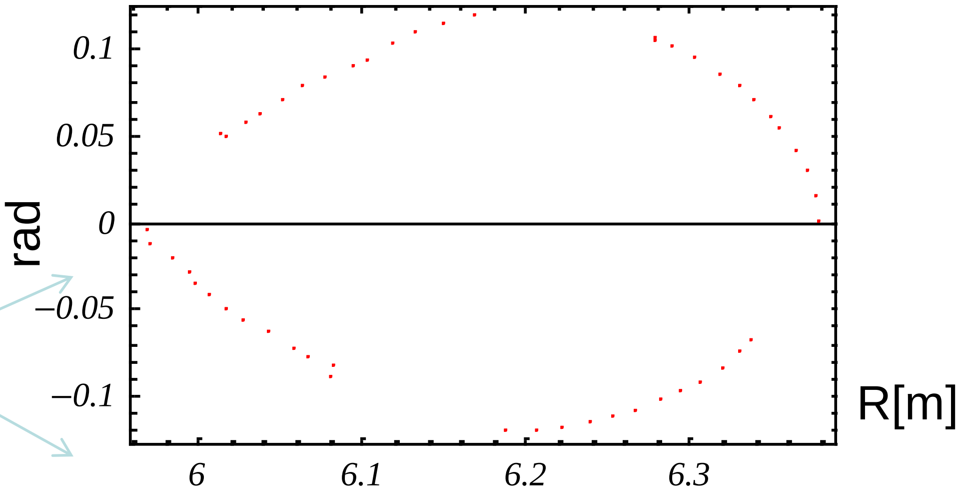


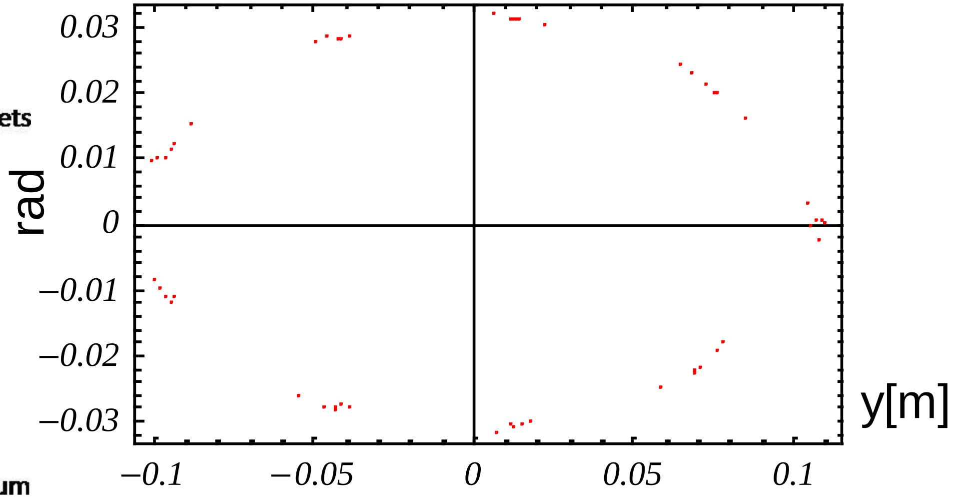
At the end of the horizontal dispersion creator (transmission 97%)

Reference design modifications for Injection/Extraction

- In order to inject/extract the beam into the reference design, special magnets with larger vertical gap are needed.
- This may be realised as an insertion (shown in red below).
- The introduction of the insertion breaks the symmetry but this does not limits the dynamical acceptance, if properly done!







PRISM Injection Challenge

- Requires a simultaneous injection of entire momentum spread (±20%)

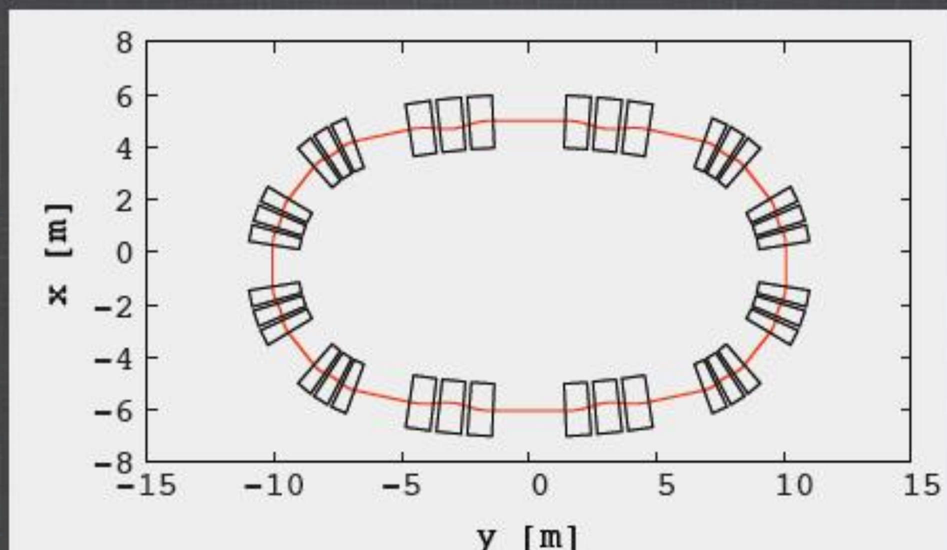
- Needs to perform for huge emittance.

- Calls for new magnet designs with very large acceptance.

- Currently:
  - -vertical scheme seems the only possible
  - -kicker strength can be relaxed (realised) with 2 long kickers.
  - -the major challenge is a realistic beam optics match from the front end (well away from the ring) to the ring (including betatron functions and both horizontal and vertical dispersions

Egg-shape design

Small Bending cell FDF triplet		Large Bending cell FDF triplet	
k-value	3.82	k-value	28.9503
total bending angle	39.15 deg.	total bending angle	11.7 deg.
Average radius	5 m	Average radius	30 m
Phase advances:		Phase advances:	
Horizontal μ_x	90 deg.	Horizontal μ	75 deg.
Vertical μ_z	60 deg.	Vertical μ	81 deg.
Dispersion	1 m	Dispersion	1 m



The most promising proposal for an alternative ring,
work in collaboration with JB Lagrange.
This work triggered the progress on the nuSTORM FFAG design
(the arc to straight matching)

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Summary

- The IDS baseline was updated and the NS-FFAG was removed from 10 GeV machine (to be presented in the Reference Design Report soon).
- Options to go for even lower energy (5 GeV) are being discussed.
- 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., vertical FFAG, etc.)!
- NS-FFAGs are still important for a Muon Collider and a Higgs Factory.
  EMMA experiment is essential!
- The next step for muon accelerators is the nuSTORM and FFAG option is very attractive! More studies are needed!
- PRISM has a lot of synergies with nuSTORM FFAG design. The major challenge remains the injection geometry.