Imperial College
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Science & Technology Facilities Council
ISIS

CERN
Physics
Beyond
Colliders

Design of nuSTORM facility for a potential implementation at CERN

J. Pasternak,

on behalf of nuSTORM study team

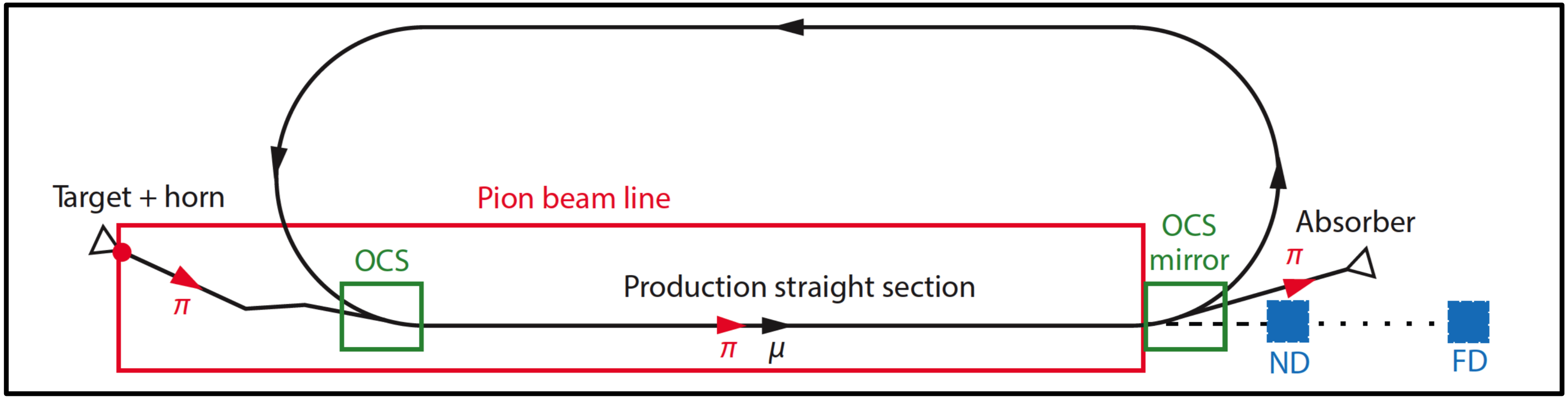
Daegu, 30/08/19, nufact’19

Outline

- Origin
- Motivation
- FODO design for nuSTORM (FNAL)
- Advanced FFA concept
- Studies of siting at CERN
- Studies of hybrid FFA solution
- Summary and future plans

Origin - Idea

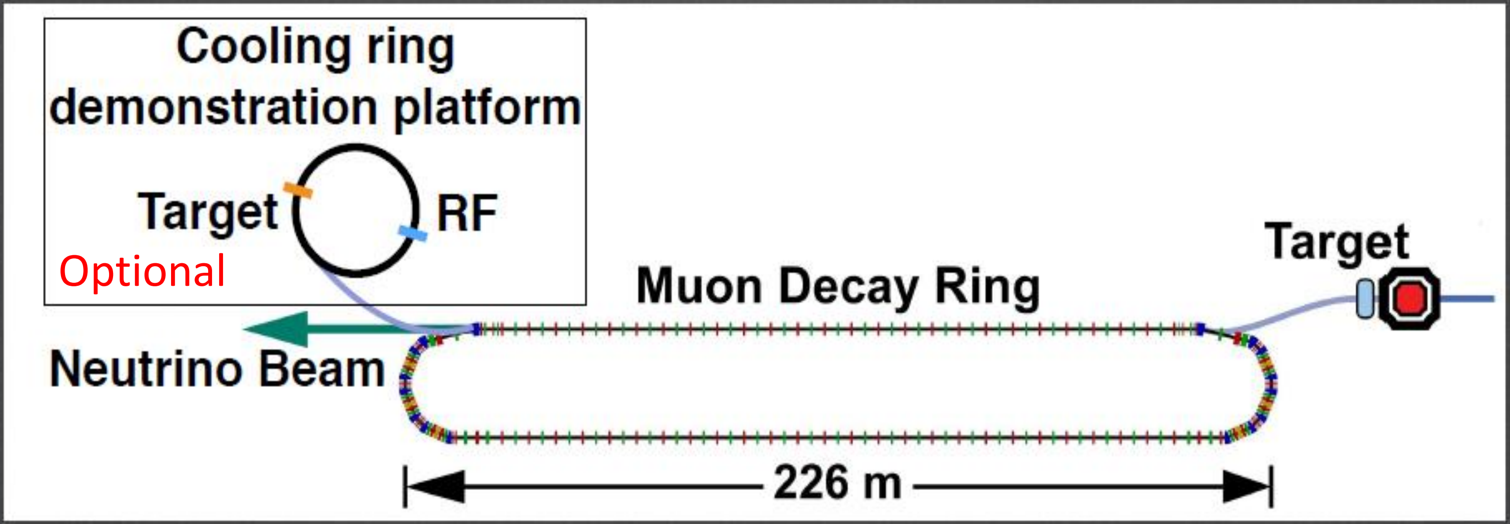
- nuSTORM (`NeUtrinos from STORed Muons') is a facility based on a low-energy muon decay ring.
- Can use existing proton driver (like SPS at CERN)
- Conventional pion production and capture (horn)
  - Quadrupole pion-transport channel to decay ring
  - Direct injection of pions into the decay ring to 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

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

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

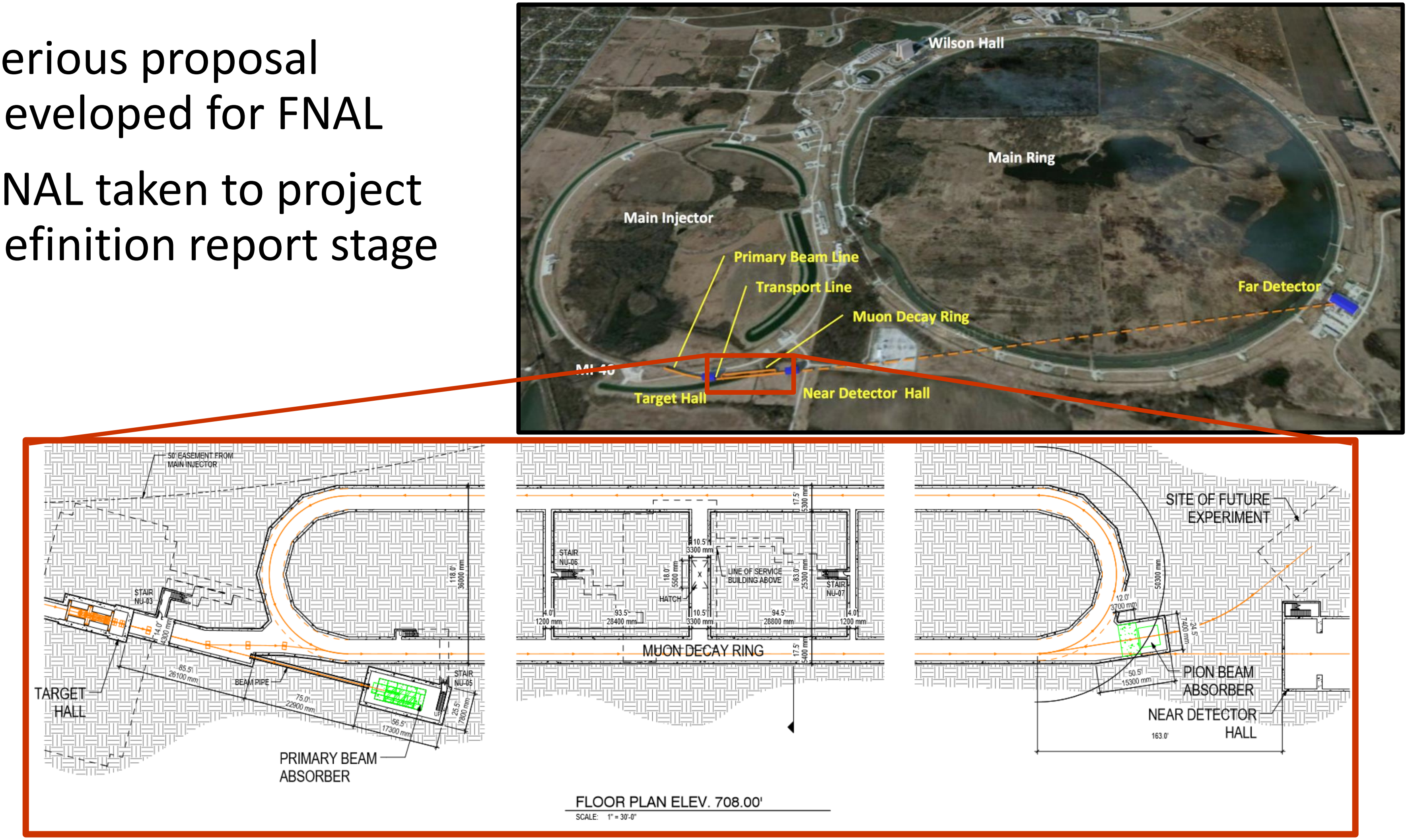
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

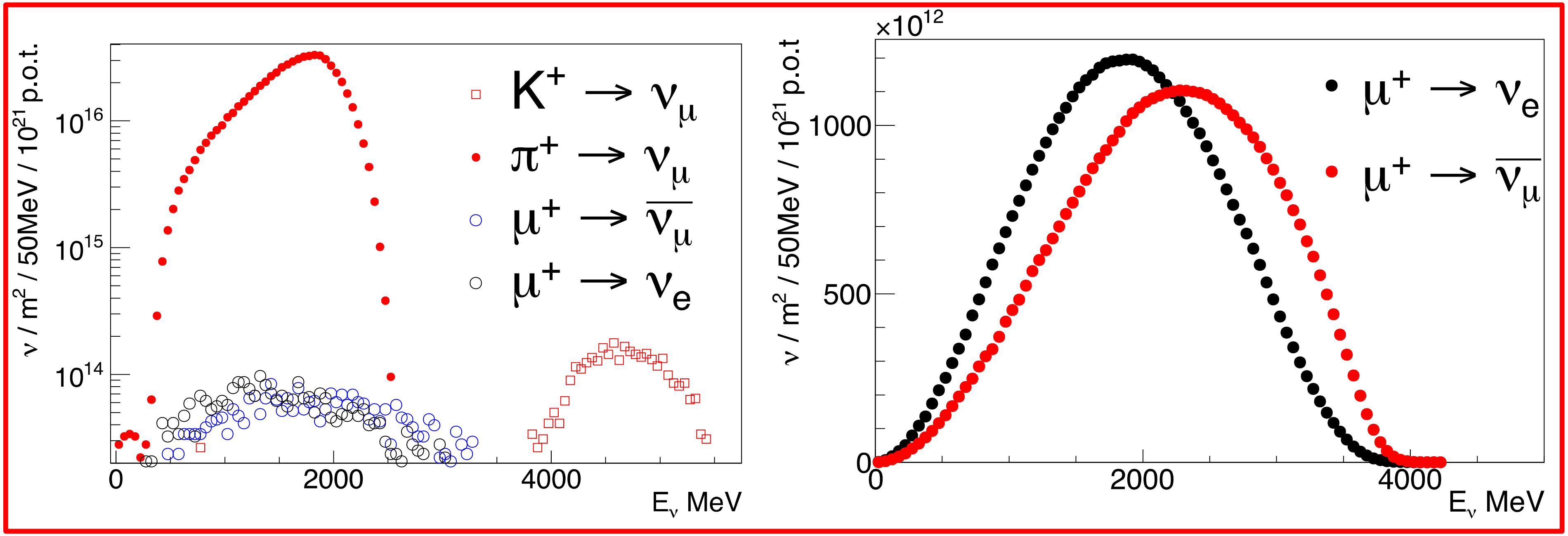
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

Existing Work - FNAL

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

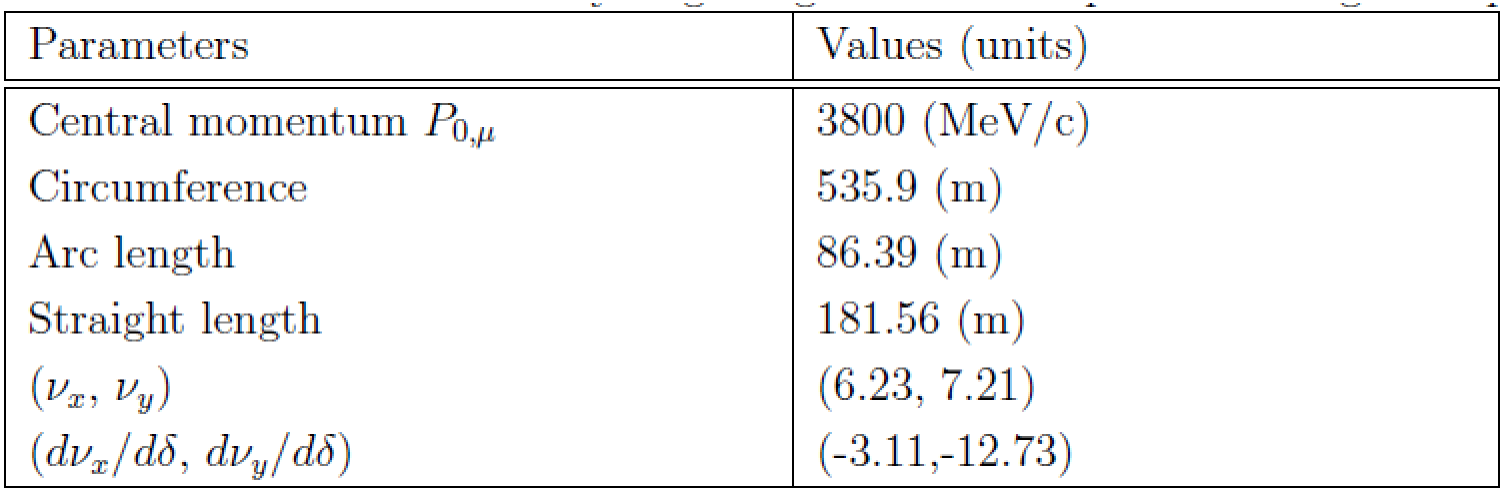


Neutrino Flux



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

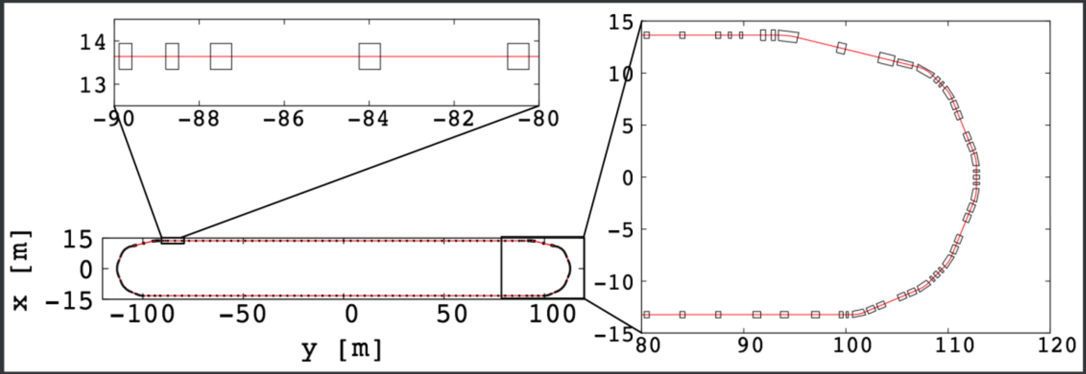
FODO design, A. Liu

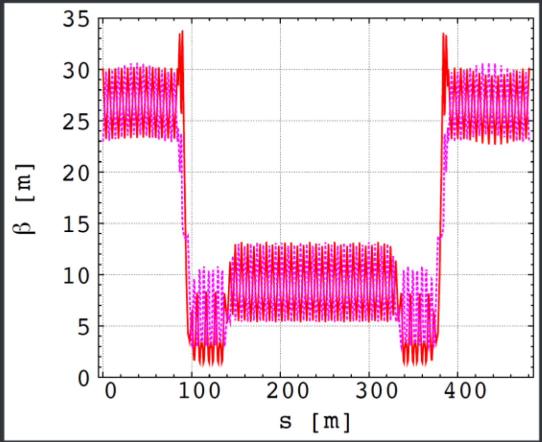


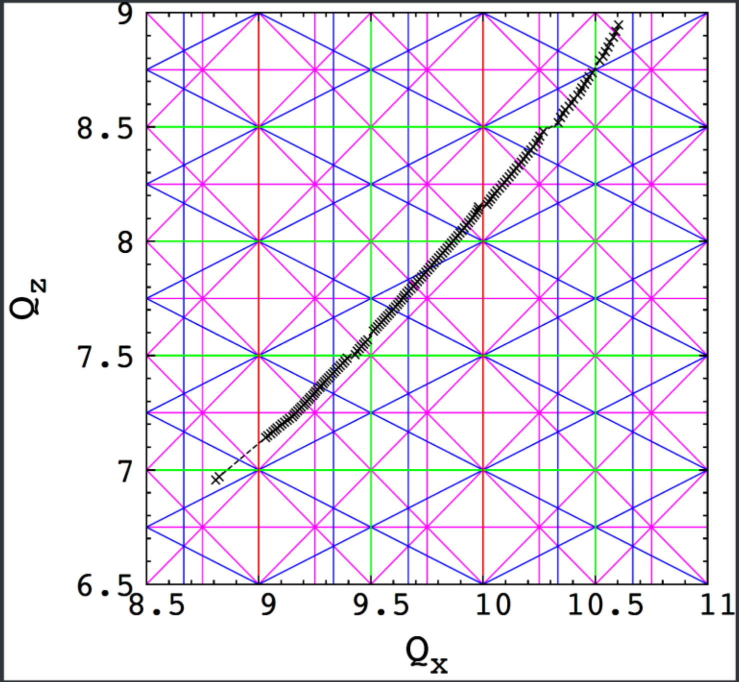
Parameters	Values (units)
Central momentum $P_{0,\mu}$	3800 (MeV/c)
Circumference	535.9 (m)
Arc length	86.39 (m)
Straight length	181.56 (m)
(ν_x, ν_y)	(6.23, 7.21)
$(d\nu_x/d\delta, d\nu_y/d\delta)$	(-3.11,-12.73)

- Based on separated function AG lattice, well known technology
- Partial chromaticity correction with sextupoles was studied

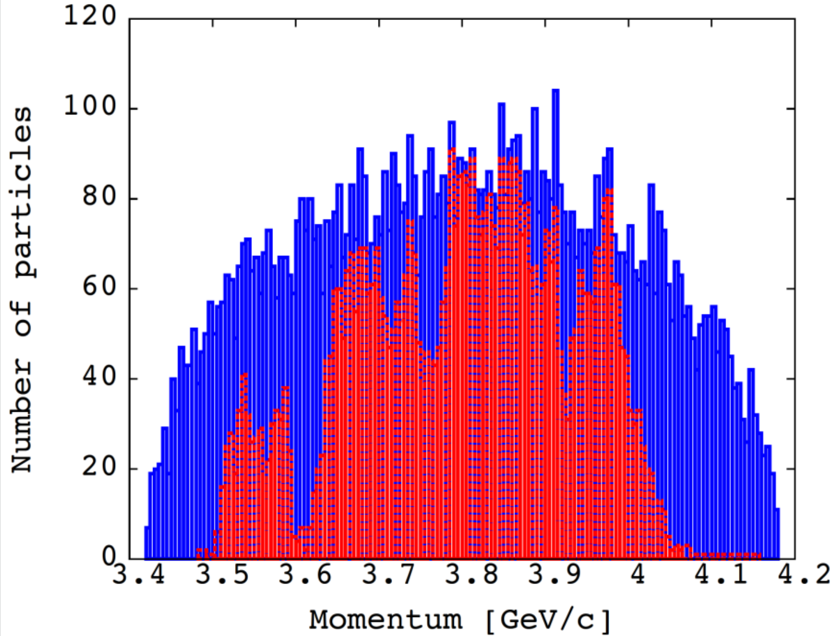
FODO losses





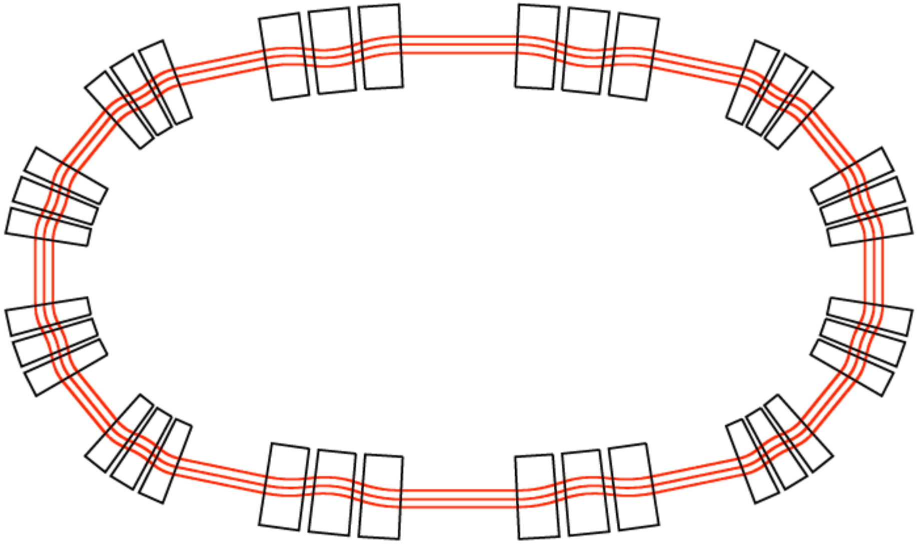


Tune spread for -8% and +9% momentum, p_0 (9.71, 7.83)

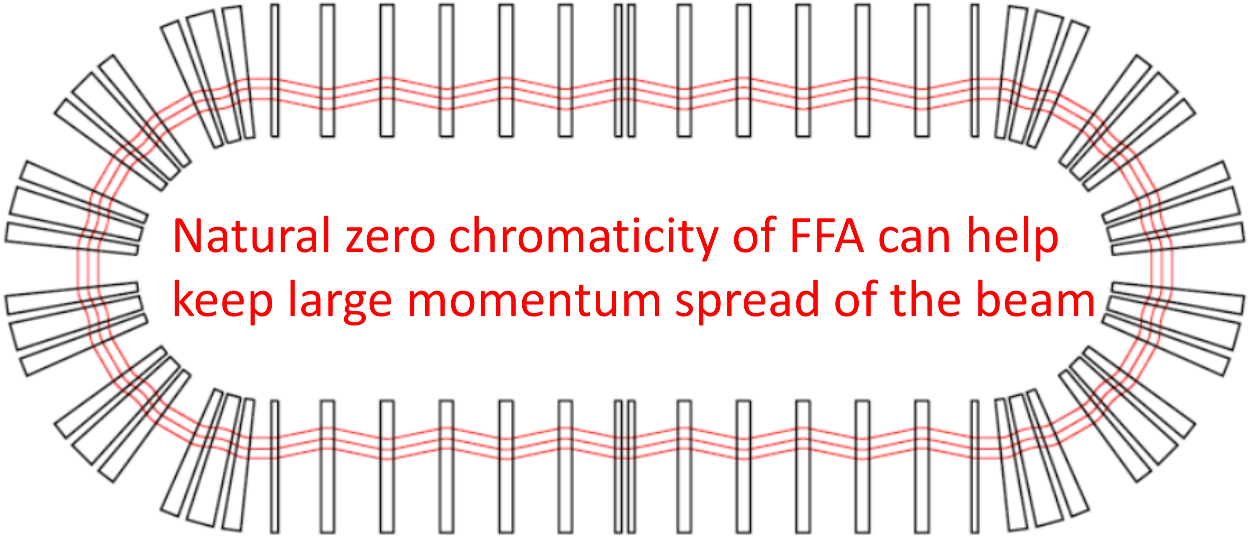


Losses from waterbag distribution (ε=2 mm)

Advanced Fixed Field Alternating gradient (FFA) – can read Fixed Field Accelerator

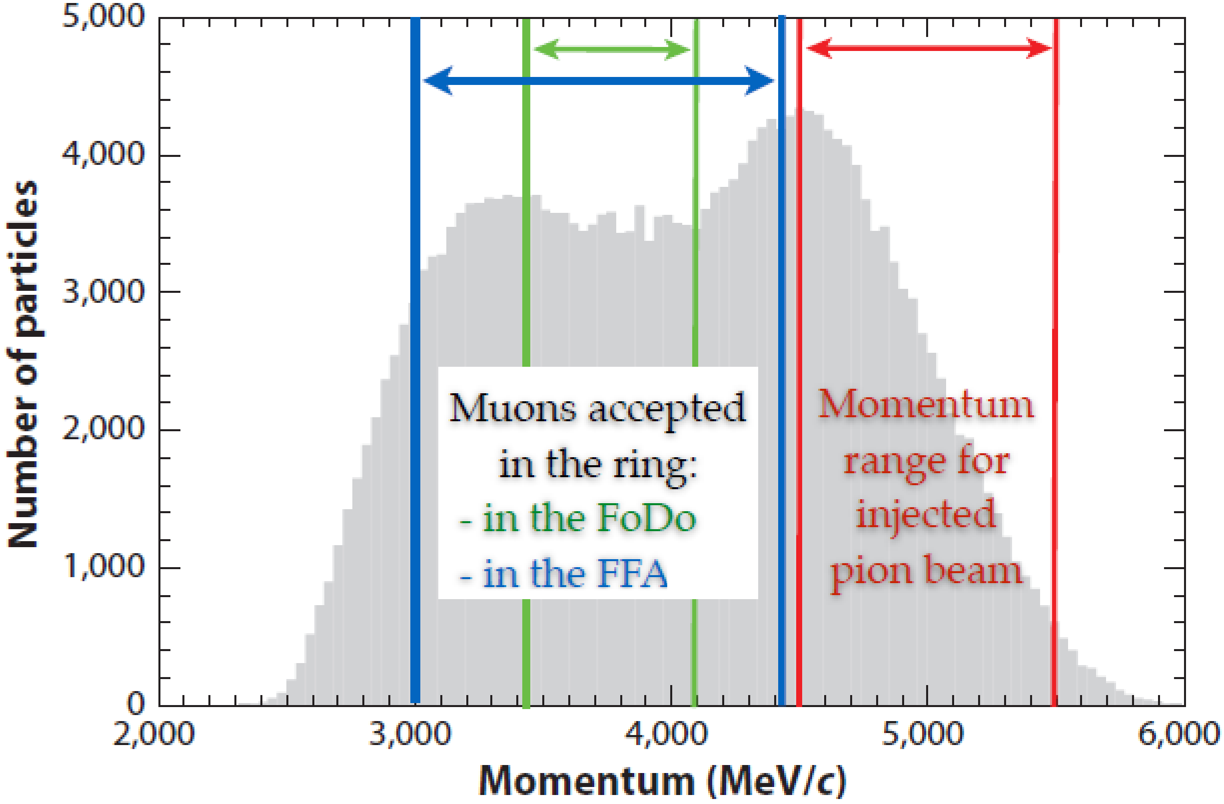


By combining cells with different radius
or arcs with straight cells, long straight sections can be created and neutrino beam can be formed along them.



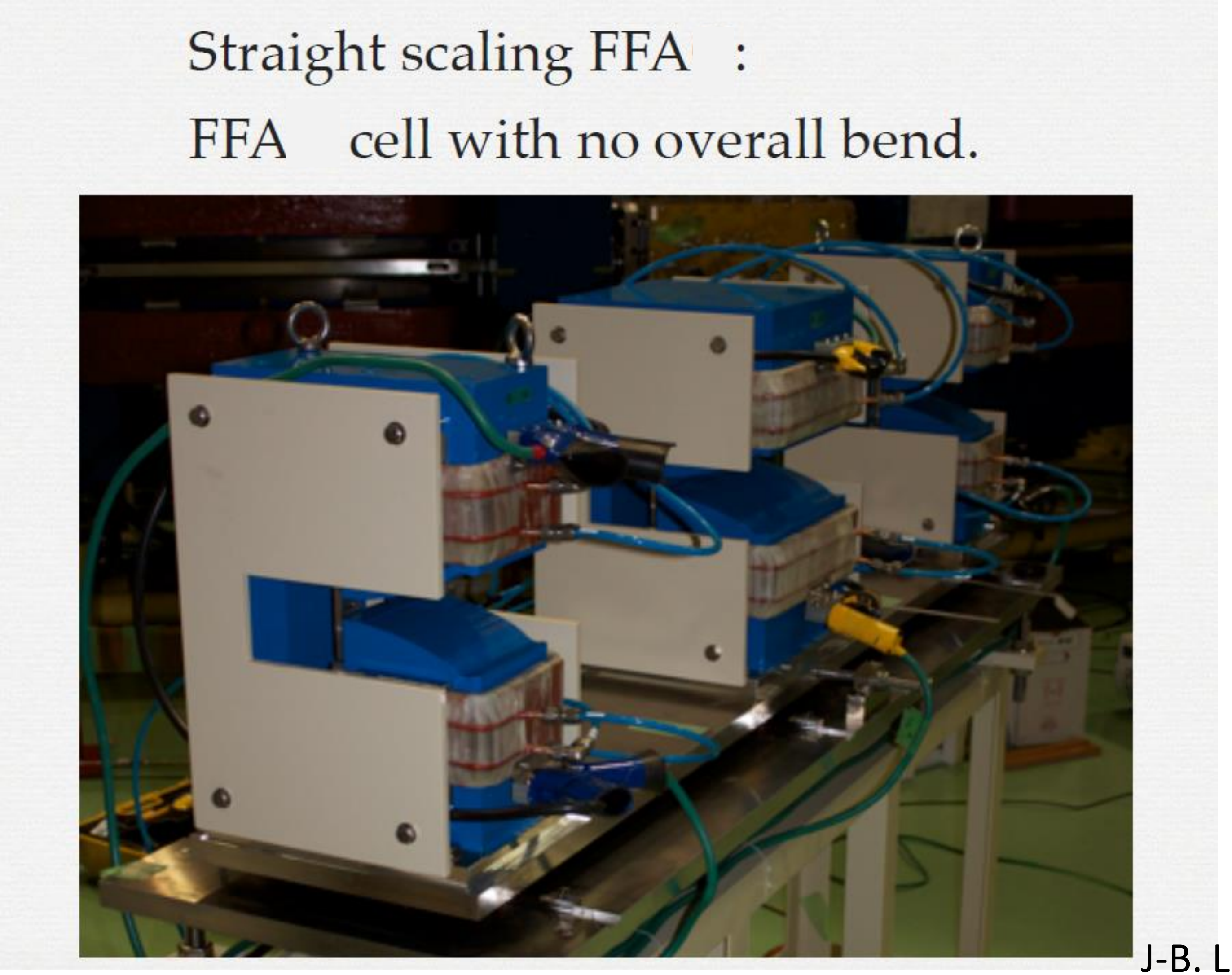
Natural zero chromaticity of FFA can help keep large momentum spread of the beam

Advantage of FFA: large momentum acceptance



- FFA can accept ±16% (triplet) or ±19% total momentum spread.
- FODO - ±9% with 58% efficiency (67% with sextupoles)

How to make straight cell?

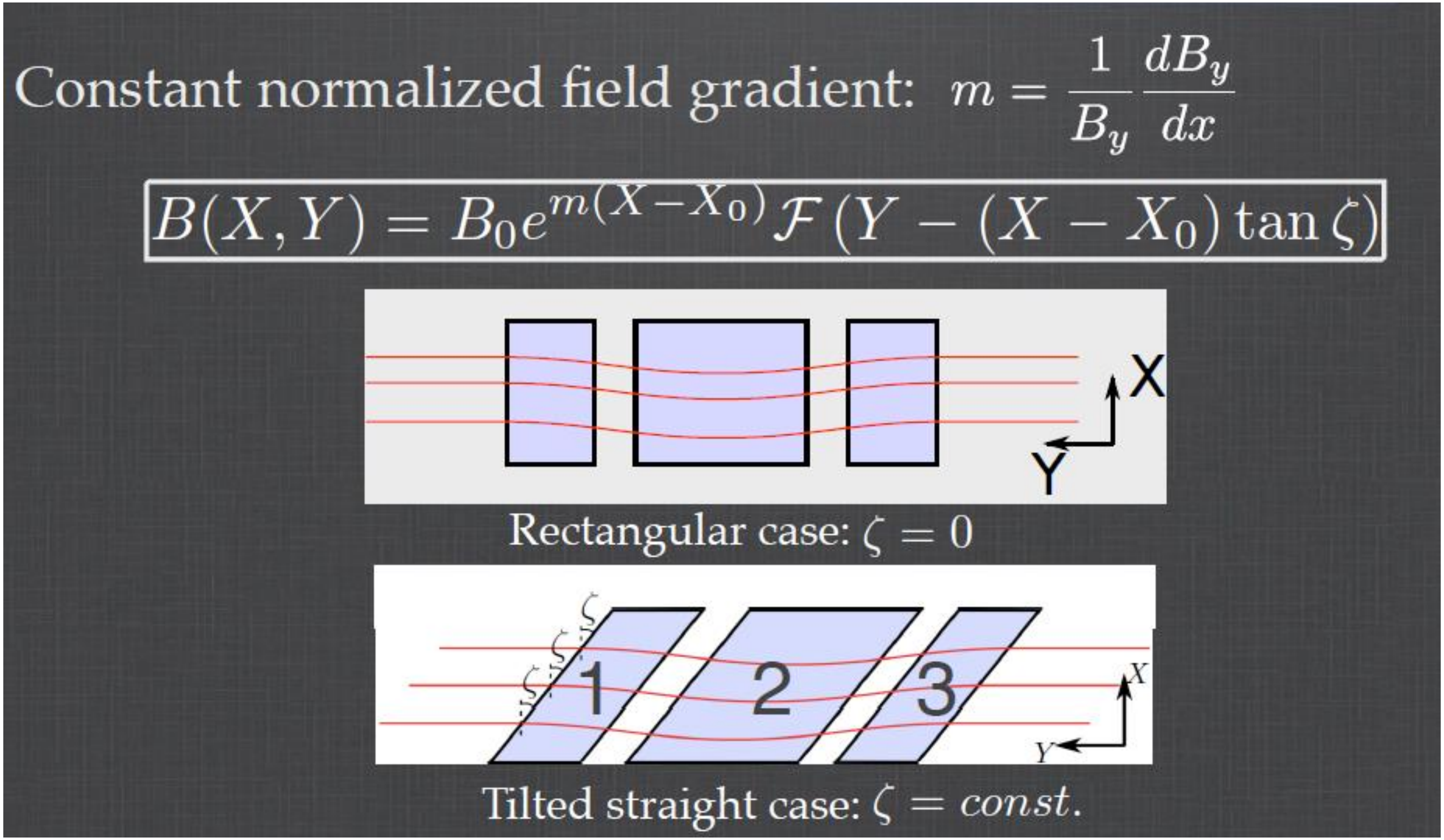


Straight scaling FFA :

FFA cell with no overall bend.

J-B. Lagrange’s thesis

Straight FFA (principles)



Constant normalized field gradient: $m = \frac{1}{B_y}\frac{dB_y}{dx}$

$$\boxed{B(X,Y) = B_0 e^{m(X-X_0)} \mathcal{F}\left(Y - (X - X_0)\tan\zeta\right)}$$

Rectangular case: $\zeta = 0$

Tilted straight case: $\zeta = const.$

...however orbit scallop angle is present!

νSTORM Racetrack FFA

Constraints:

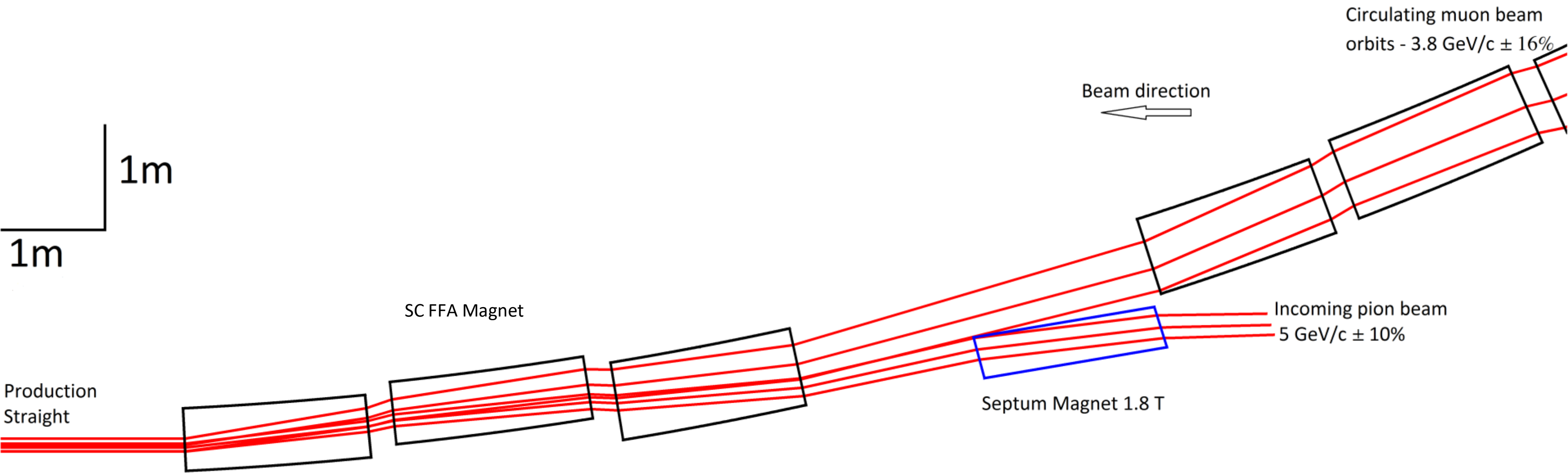
- in the straight part, the **scallop effect** must be as small as possible to collect the maximum number of neutrinos at the far detector.

- **Stochastic injection**: in the dispersion matching section, a drift length of 2.6 m is necessary to install a septum.

- to keep the ring as small as possible, **SC magnets in the arcs** are considered. **Normal conducting magnets in the straight part** are used.

- **large transverse acceptance** is needed in both planes: 1 (2) π mm.rad.

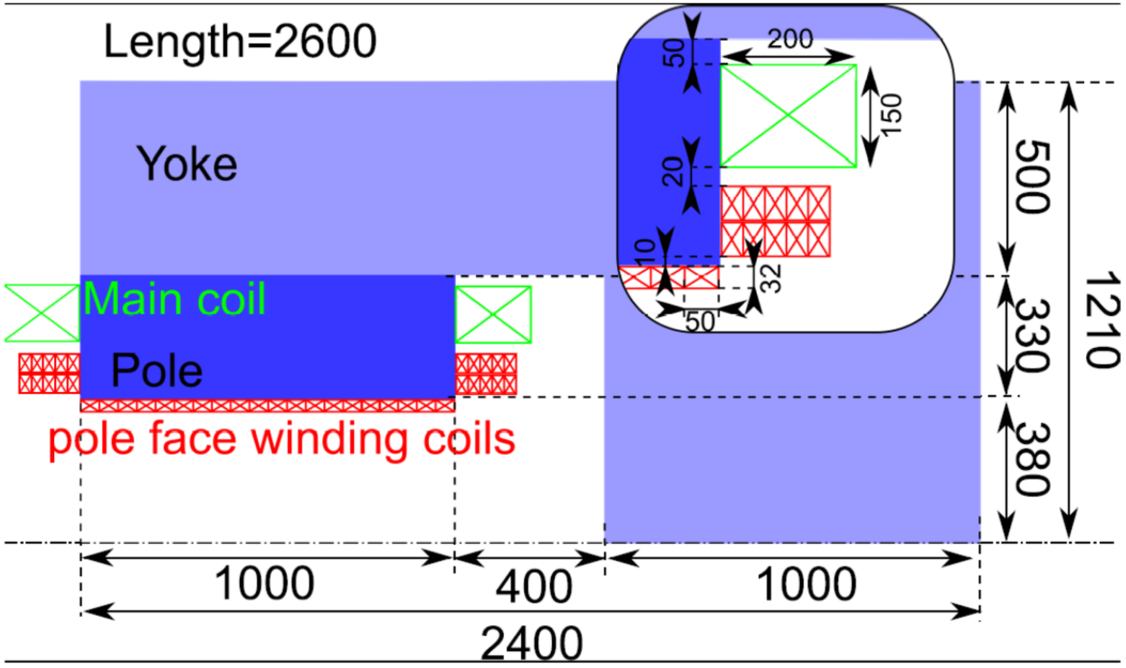
Injection section



- Injection system will use septum magnet and NO kicker (stochastic injection)
- Special optics allows to introduce a sufficient straight section length

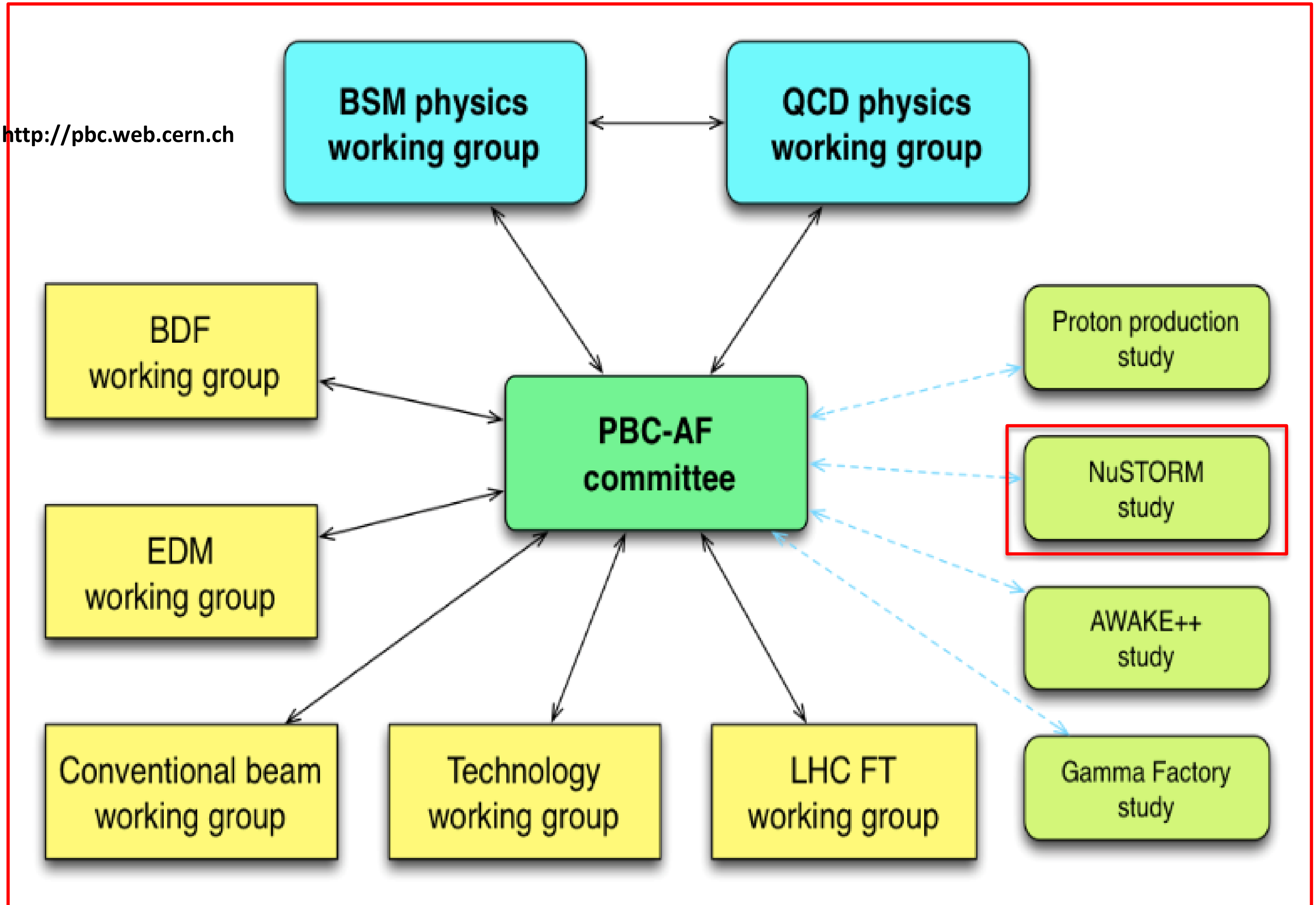
FFA arc magnet concept

- Superferric type, 3T
- Main coil combined with distributed coils to create the FFA required field



Physics Beyond Colliders study group

http://pbc.web.cern.ch



BSM physics working group

QCD physics working group

BDF working group

PBC-AF committee

Proton production study

EDM working group

NuSTORM study

AWAKE++ study

Conventional beam working group

Technology working group

LHC FT working group

Gamma Factory study

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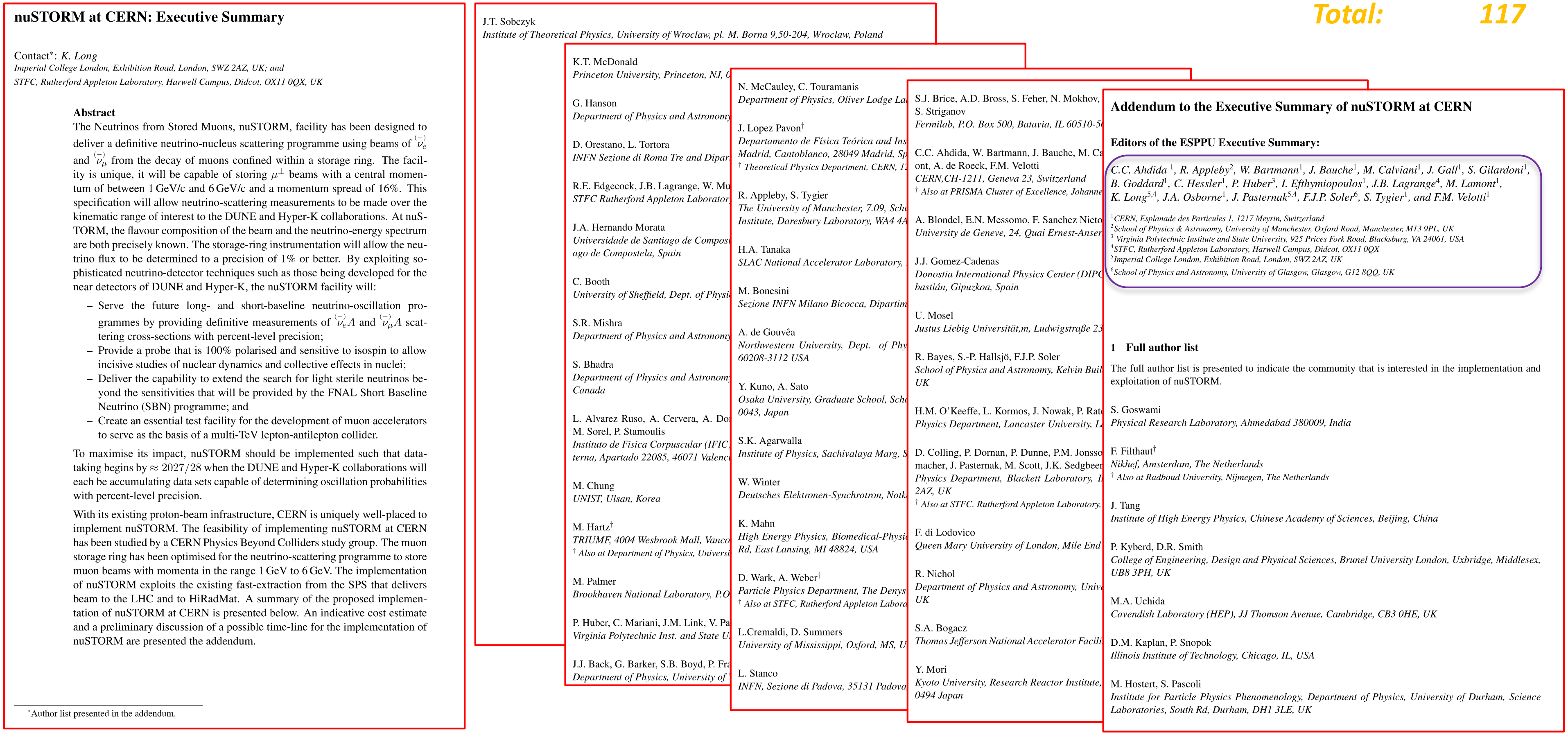
Input to the European Particle Physics Strategy Update 2018-2020

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 $\approx 2027/28$ 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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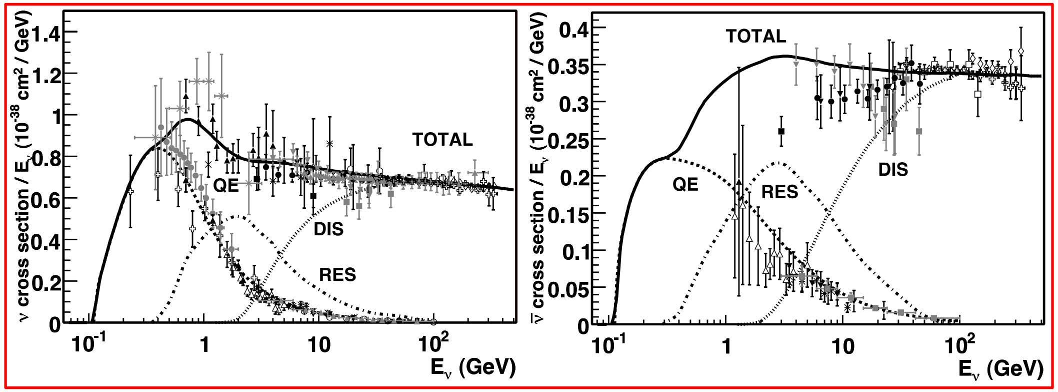
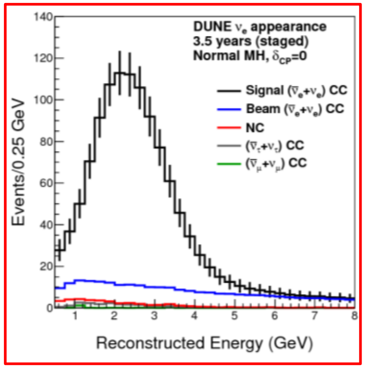
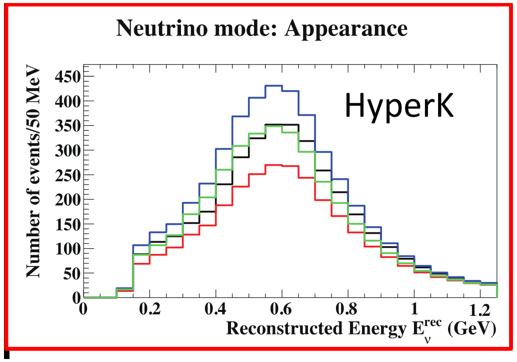
Novel specification: energy range

- 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

See WG1 talk by A. Bross on Tuesday

nuSTORM @ CERN

- Initial proposal for siting at CERN to look at:
  - Muon energy range
  - SPS requirements
  - Fast extraction, beam-line
  - Siting
  - Target and target complex
  - Horn
  - Civil engineering
  - Radiation-protection implications

nuSTORM for νN scattering @ CERN — proton beam parameters

- New specification!
  - Design update:
    - $1 < E_\mu < 6$ GeV
  - Challenge for accelerator design!
  - Benefit:
    - Calibration via energy spectrum
    - Statistical ‘mono-energetic beam’

- SPS requirements table

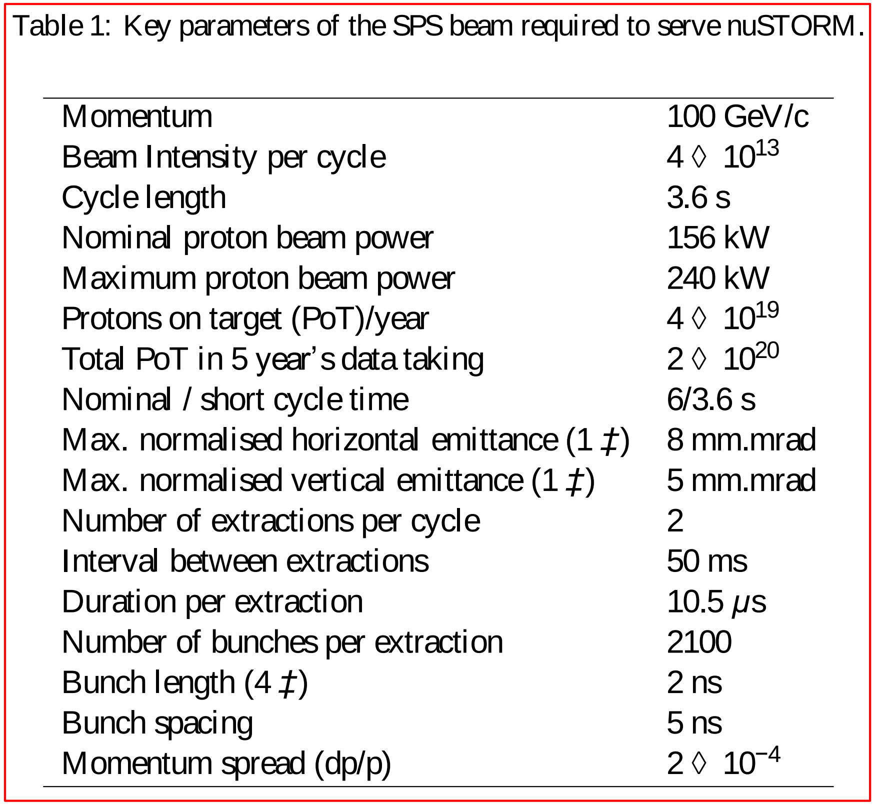
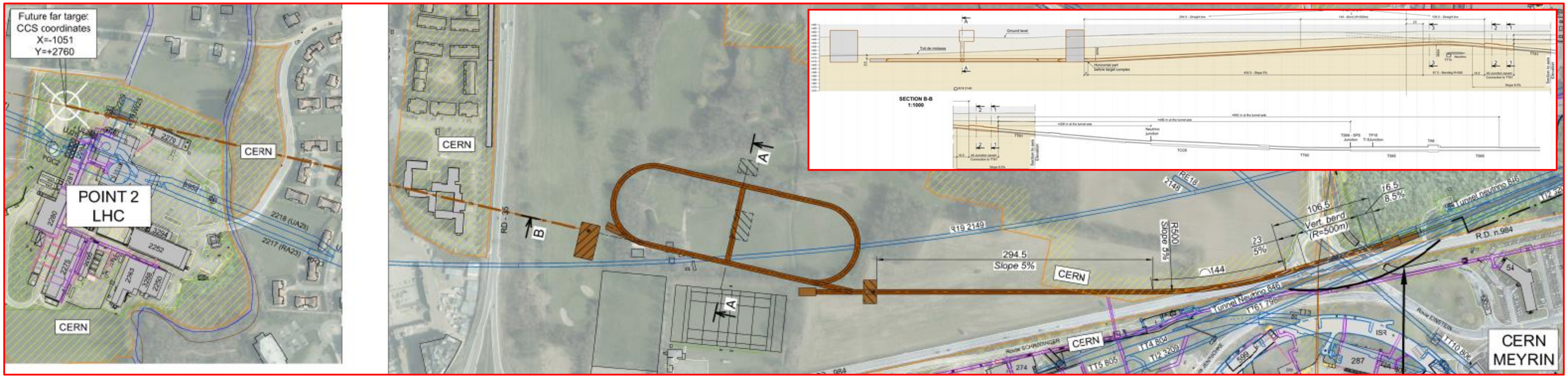


Table 1: Key parameters of the SPS beam required to serve nuSTORM.

Momentum	100 GeV/c
Beam Intensity per cycle	4 ◊ 10^{13}
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	4 ◊ 10^{19}
Total PoT in 5 year’s data taking	2 ◊ 10^{20}
Nominal / short cycle time	6/3.6 s
Max. normalised horizontal emittance (1 ‡)	8 mm.mrad
Max. normalised vertical emittance (1 ‡)	5 mm.mrad
Number of extractions per cycle	2
Interval between extractions	50 ms
Duration per extraction	10.5 μs
Number of bunches per extraction	2100
Bunch length (4 ‡)	2 ns
Bunch spacing	5 ns
Momentum spread (dp/p)	2 ◊ 10^{-4}

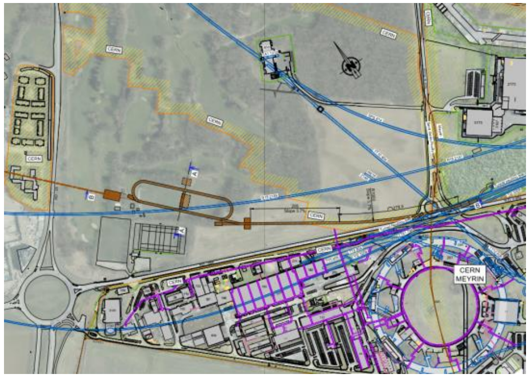
nuSTORM siting at CERN

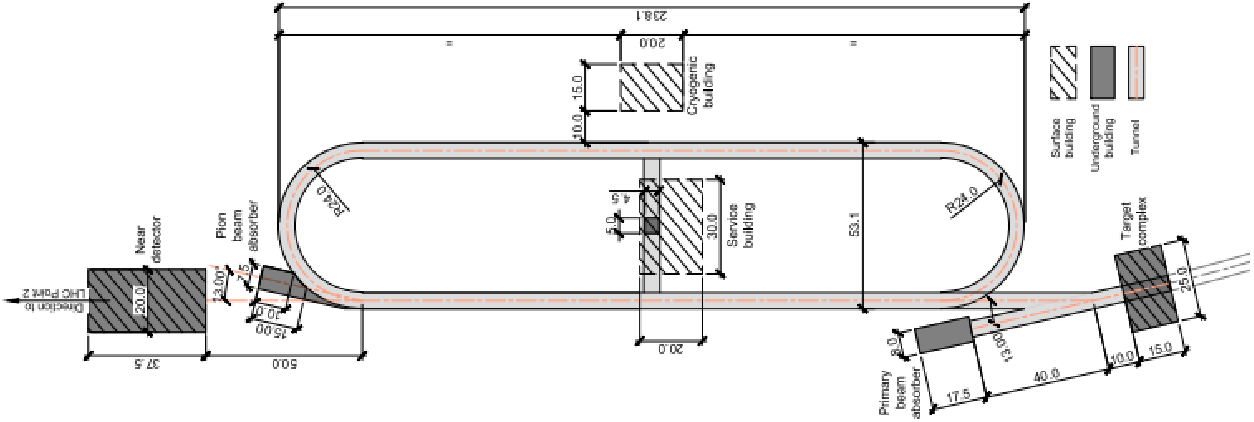


- Extraction from SPS through existing tunnel
- Siting of storage ring:
  - – Allows measurements to be made 'on or off axis'
  - – Preserves sterile-neutrino search option

Progress on CE Design

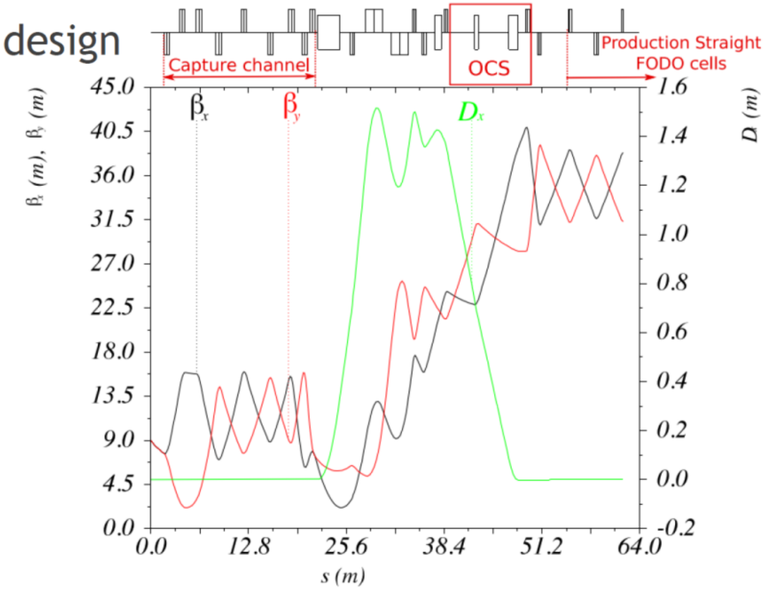
- Location changed to fit current design
- Buildings added to include all needs as per FNAL design
- Simple open cut building construction allowed for



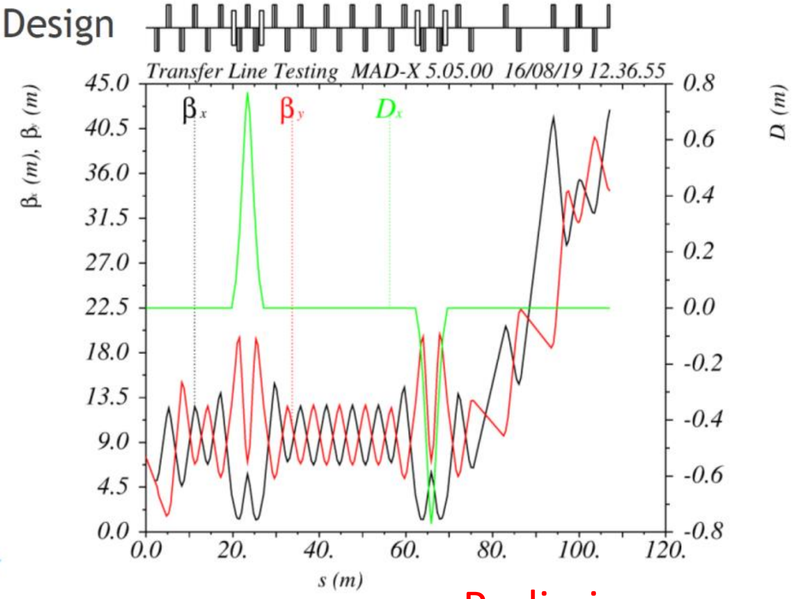


Novel study of the pion transport line at CERN, C. Hunt

Original design



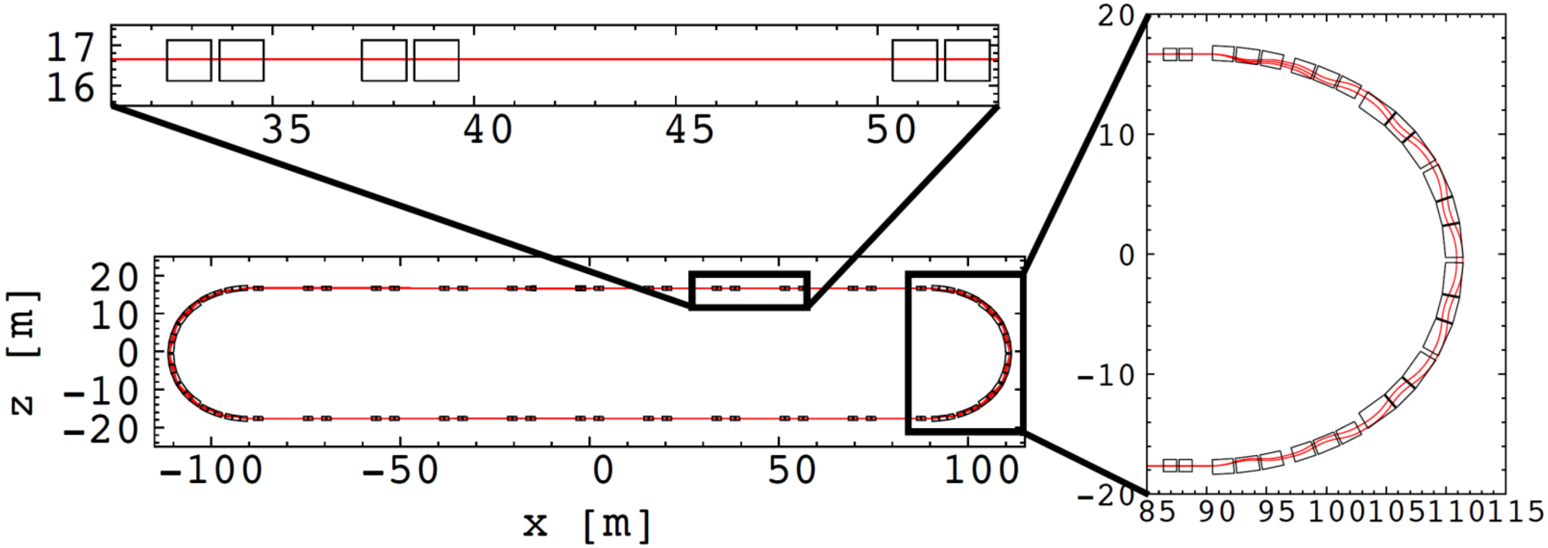
Novel Design



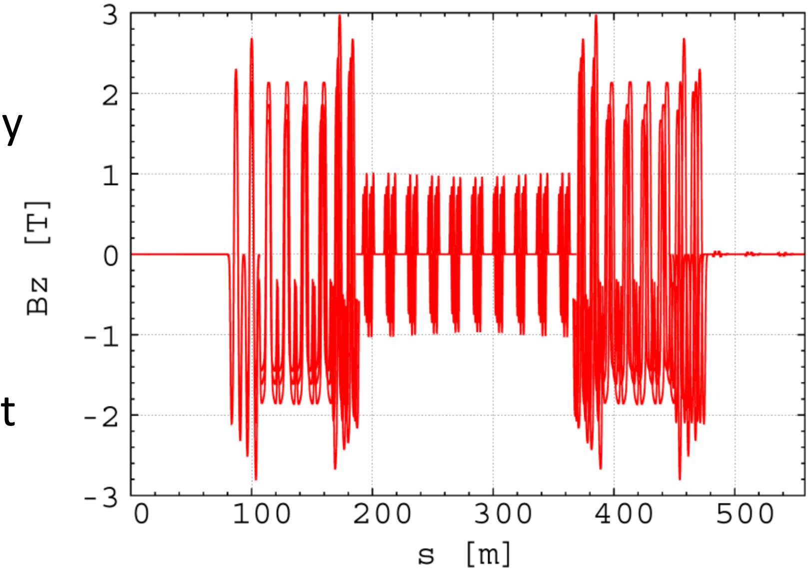
Preliminary

- Novel design focuses on minimising ring irradiation by incorporating two achromatic bending sections
- Flexibility allows to perform matching and to adjust the length
- Tracking studies are planned to check the performance
- Details for matching into OCS still to be defined

Hybrid FFA solution

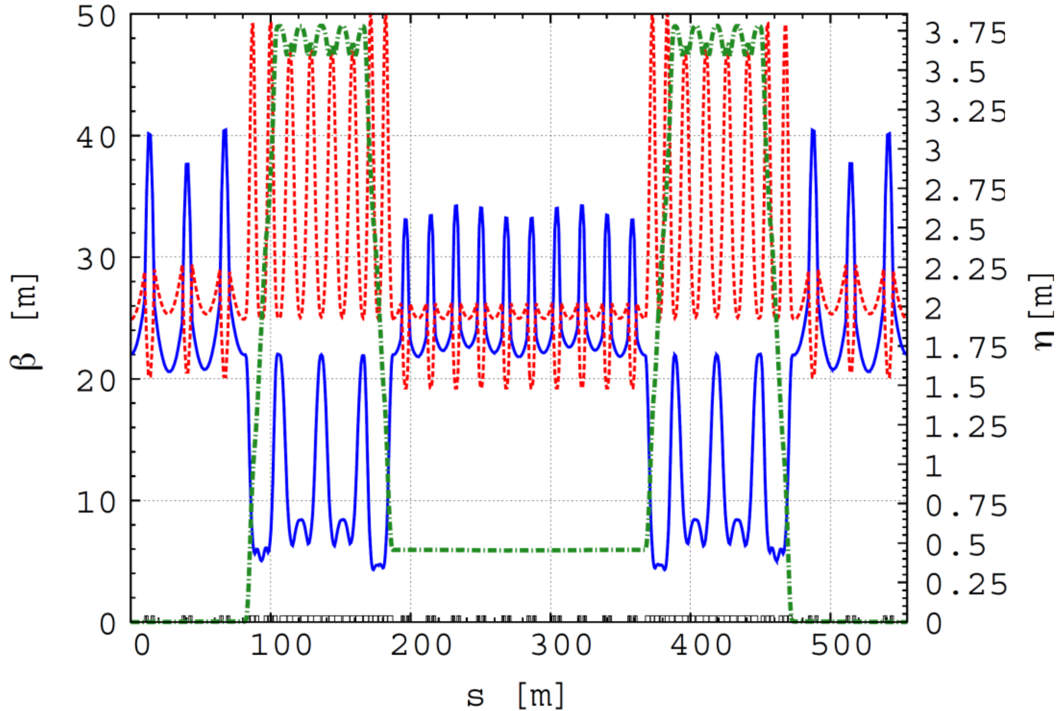


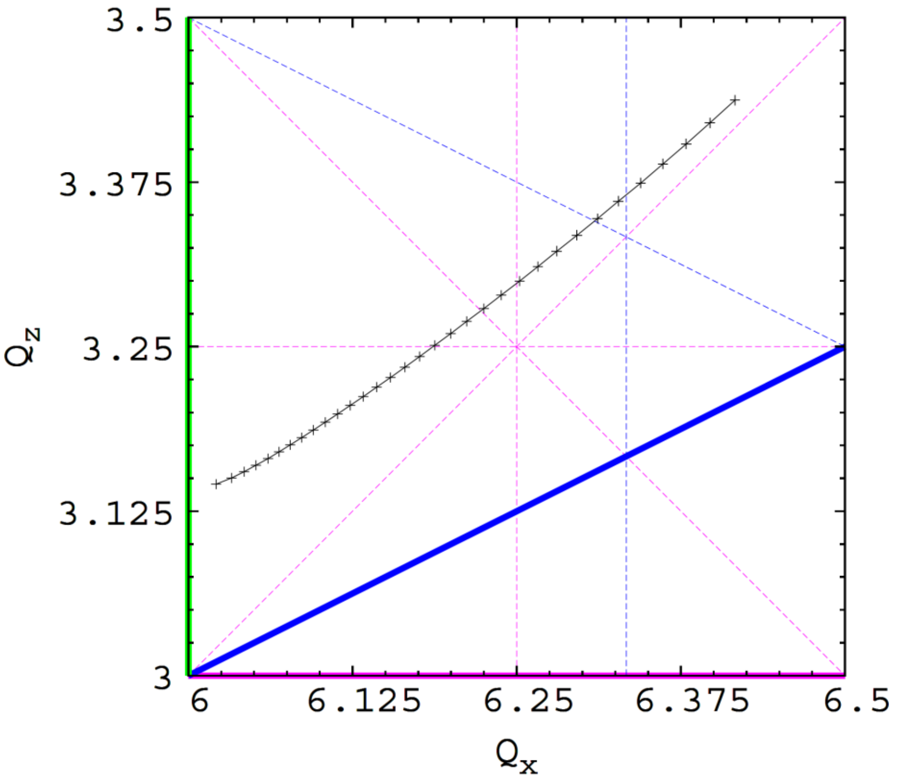
- Hybrid FFA to merge benefits for superior lattice:
  - Zero dispersion and no scallop angle (from FODO) for improving muon capture efficiency and neutrino flux
  - Large DA and momentum acceptance (from scaling FFA)
- Lattice contains:
  - Zero dispersion quad injection/decay straight
  - Zero-chromatic arc
  - Zero-chromatic FFA straight (can be used for experiments too)



Initial Hybrid FFA solution (2)

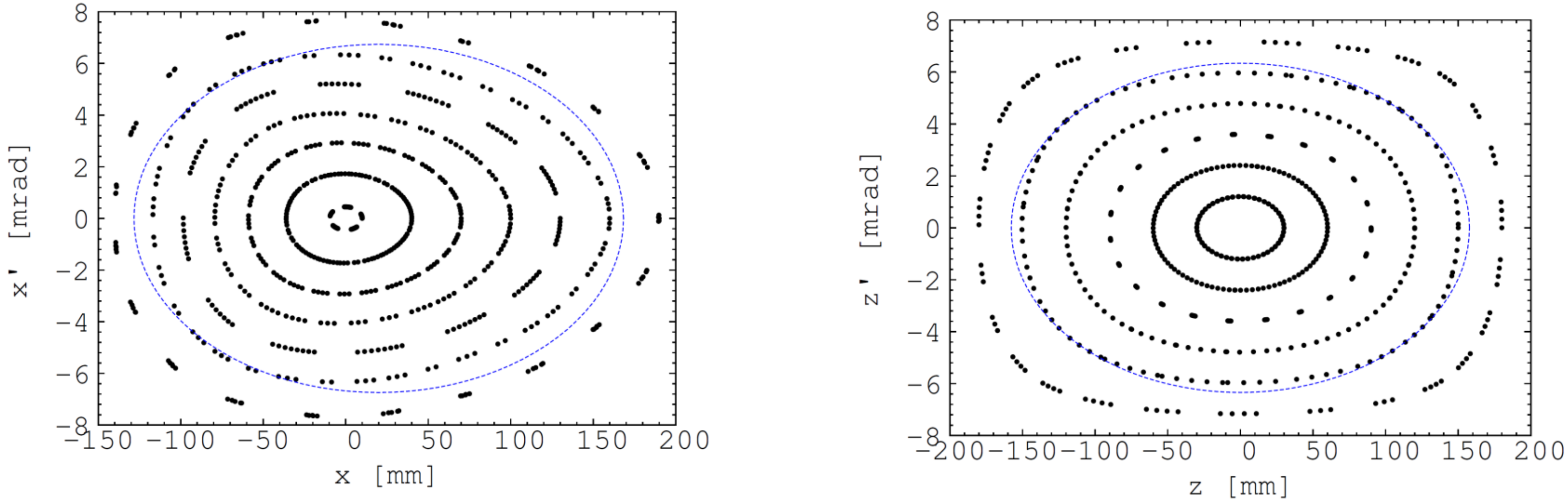
- Optics incorporating sections with different optical properties has been successfully combined using FFA matching cells at the end of the arc
- Zero dispersion section will maximise the muon accumulation efficiency
- Beam with the large momentum spread remains stable





- Tune spread generated by the large momentum acceptance stays between integers and half integers (much the same way as high intensity machines with space charge)

Initial Hybrid FFA solution (3)

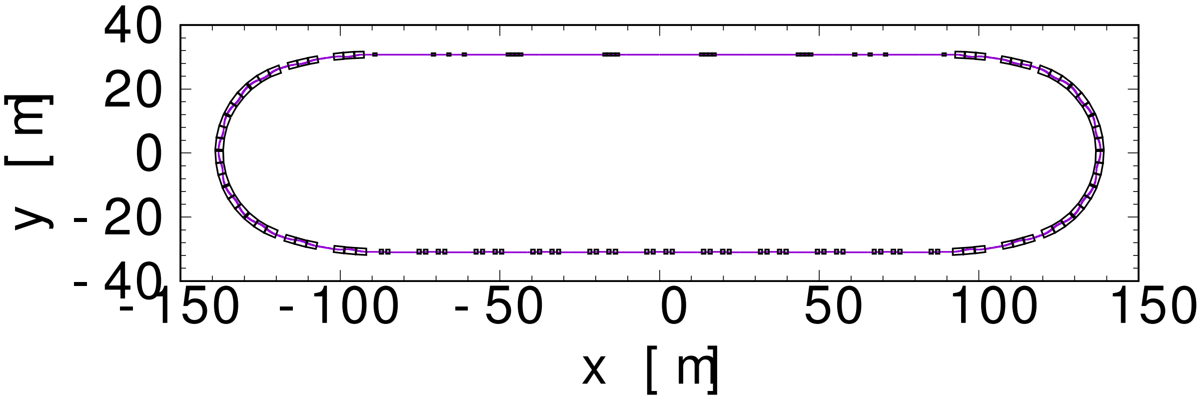


- Large DA on momentum has been achieved.
- However large dispersion would require large magnet aperture

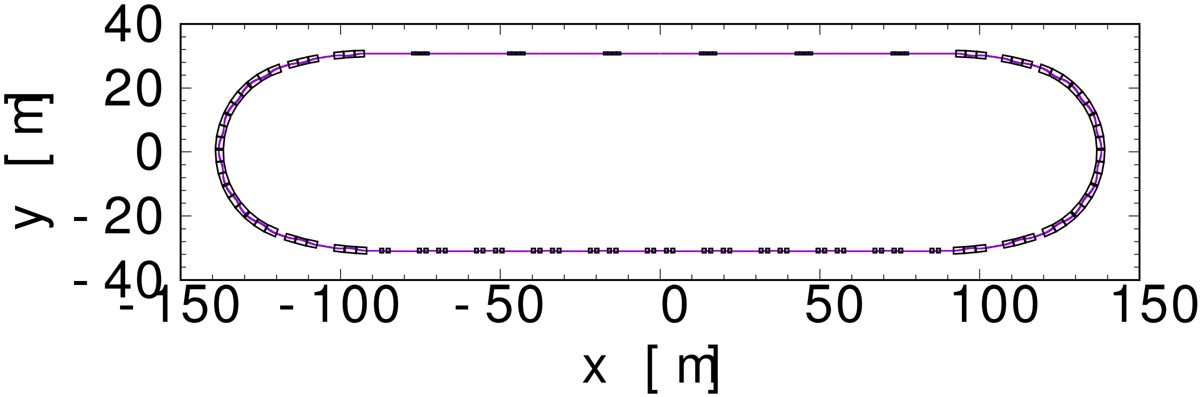
Next iteration in Hybrid FFA solutions (1)

- Long straight sections kept at 180m
- 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 straight two solutions considered:
  - With matching section added
  - Made of regular cells

Next iteration in Hybrid FFA solutions (2)



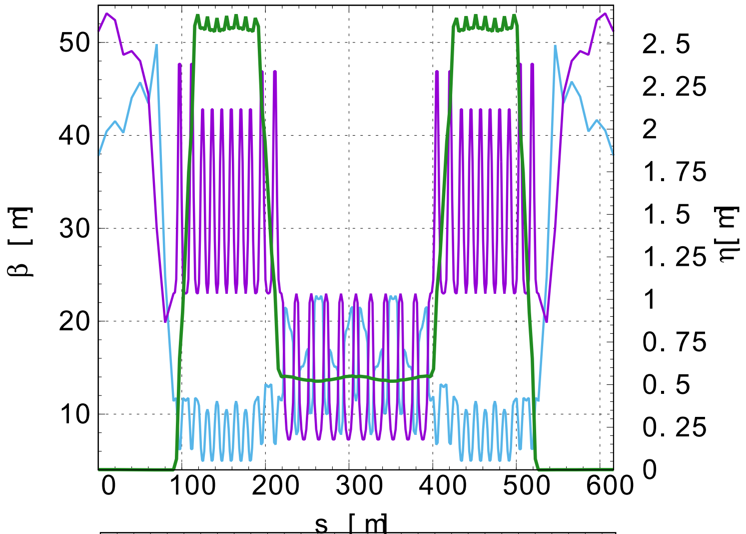
Solution with
matching section
in the quad straight
(the layout)



Solution with
regular cells only
(the layout)

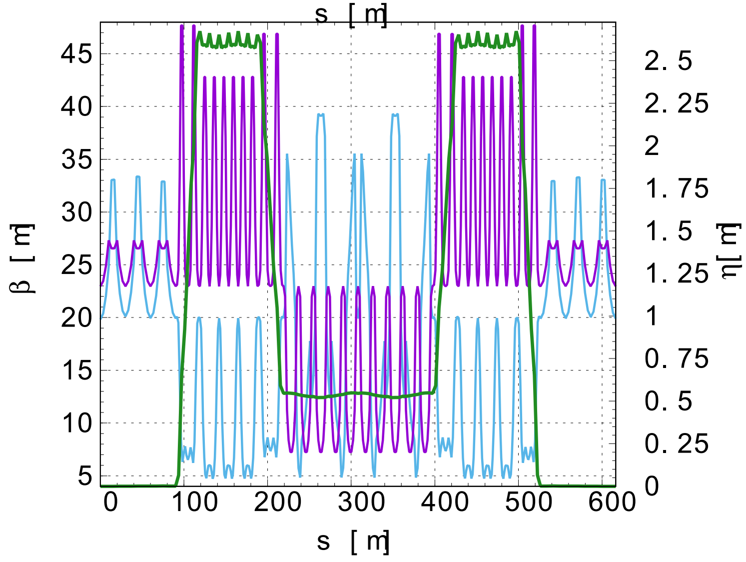
Next iteration in Hybrid FFA solutions (3)

Some mismatch in horizontal plane in the straight FFA, irregular behaviour in the quad section



Solution with matching section in the quad straight (blue β_H , violet β_V , green dispersion)

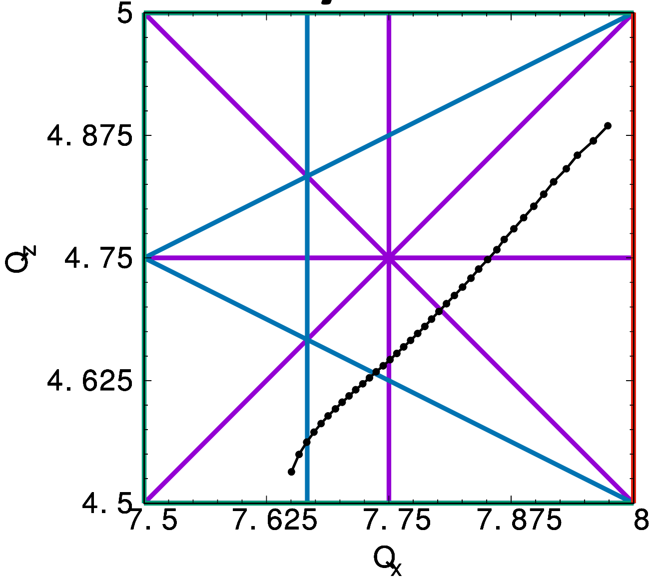
Strong mismatch in horizontal plane in the straight FFA, regular behaviour in the quad section



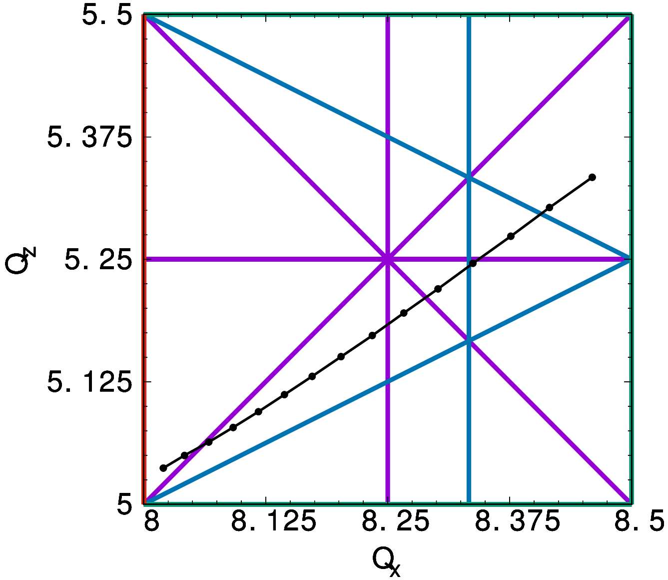
Solution with regular cells only (blue β_H , violet β_V , green dispersion)

Next iteration in Hybrid FFA solutions (4)

Large momentum spread can be accommodated between integer and half-integer lines (±16%), however some non-linear resonances may influence dynamics.

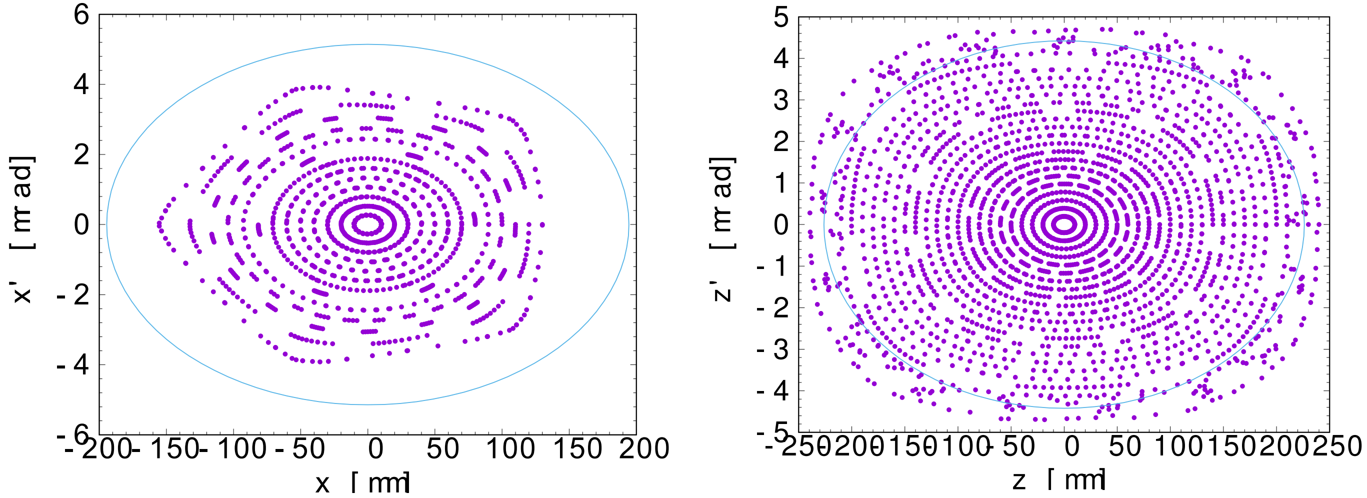


Solution with matching section in the quad straight (tune diagram)

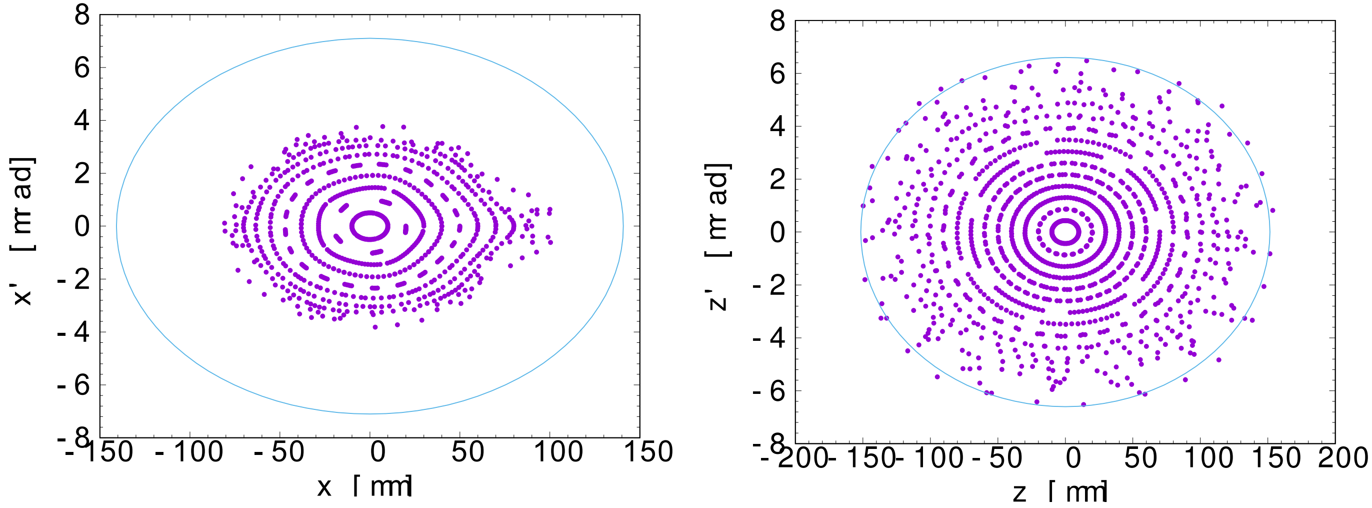


Solution with regular cells only (tune diagram)

Next iteration in Hybrid FFA solutions (5)



Solution with matching section in the quad straight (DAs)



Solution with regular cells only (DAs)

Both solutions do not have a sufficient horizontal DA (the requirement is 1mm). This needs to be improved.

Current focus and near future plans for Hybrid FFA

- Improve the Hybrid FFA design:
    - Modify matching
    - Modify straight FFA
    - Change the working point
    - Possibly introduce a modest chromaticity correction to reduce the tune spread to 0.2
- Evaluate the performance: momentum spread, DAs and calculate the neutrino fluxes.

Summary

- nuSTORM can measure neutrino interaction precisely, which can reduce systematic errors of neutrino oscillation experiments seeking CP violation signal and can contribute to the sterile neutrino search.
  - Can also serve as the R&D test bed for muon accelerators (like the Muon Collider or the Neutrino Factory) and neutrino detectors
- Solid designs exist and could be implemented straightaway (FODO or FFA)
- FFA design allows to substantially increase the ring’s momentum acceptance (and so the neutrino flux), while maintaining a very large transverse acceptance

☐ Novel Hybrid FFA shows very promising results and we are working to demonstrate its performance.

- Siting at CERN option was identified (within PBC) and civil engineering study shows no show-stoppers.

- ‘nuSTORM, the next steps’ workshop is being organised at CERN in October (21-22 October 2019, see https://indico.cern.ch/event/837890/).