# Decay Ring Design for Long Baseline NF a la NuMAX

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# Outline

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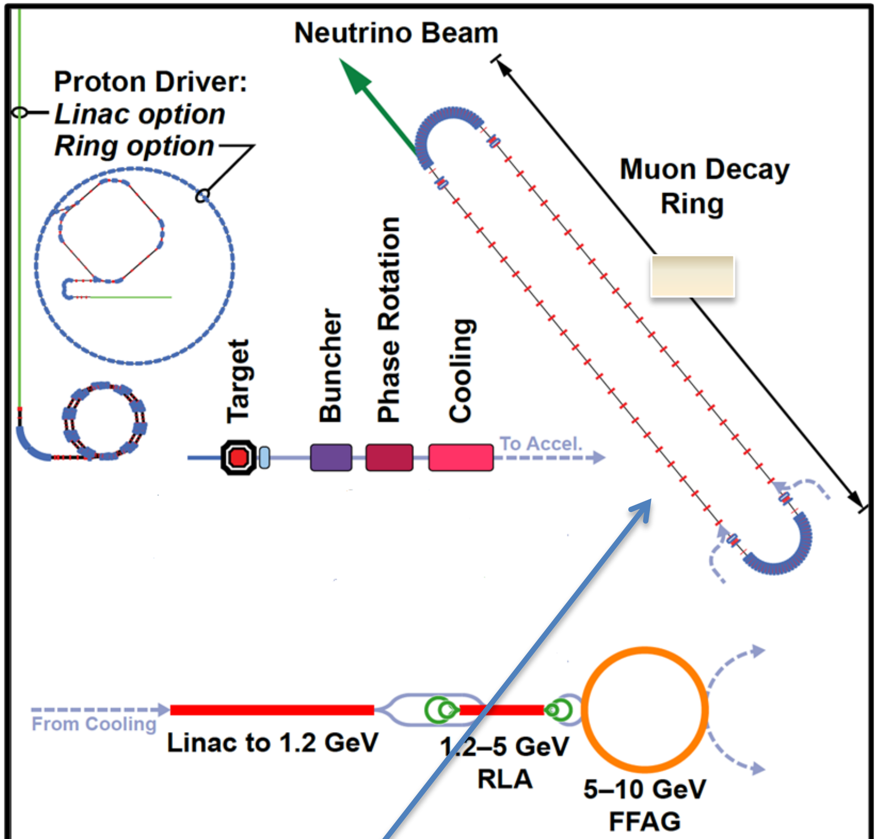
- FDDF ring for NuMax
- FODO ring for NuMax
- Injection considerations
- Neutrino flux calculations
- NuMax/nuSTORM comparison
- Conclusions and future plans

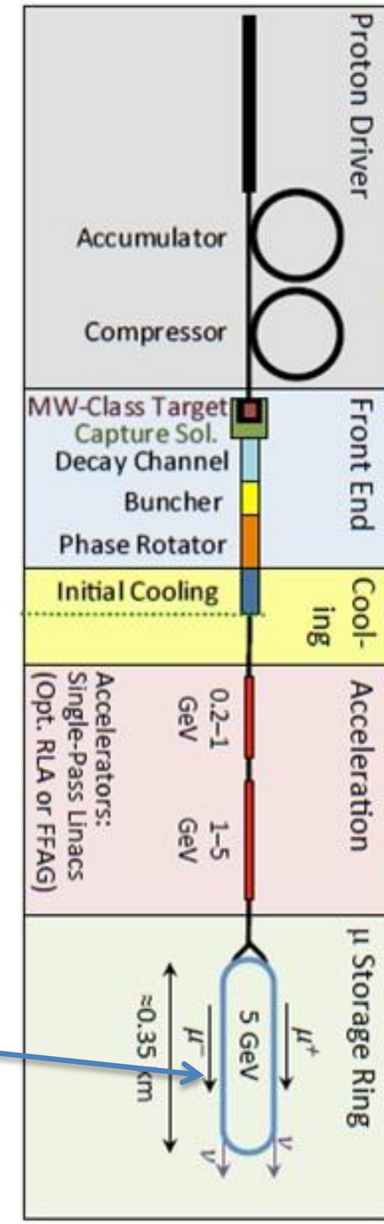
# Introduction




IDS-NF

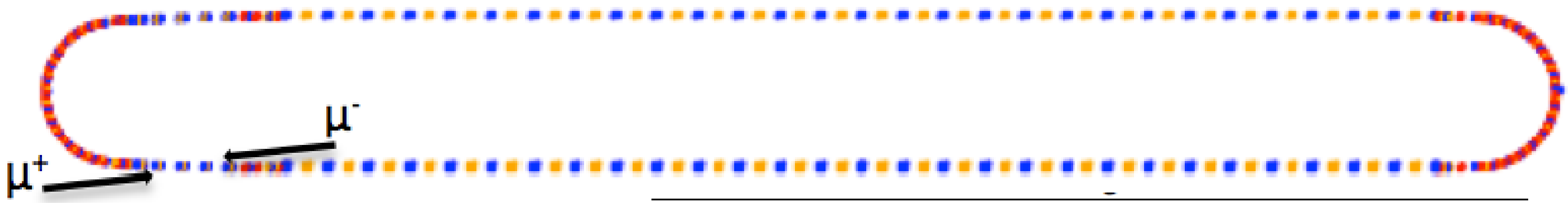
?

We looked at a possible design of the NuMAX decay ring using the IDS-NF decay ring design as a starting point,




NuMAX

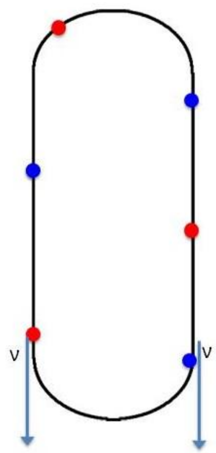
# IDS-NF Decay Ring




•Key assumption for IDS-NF is the need to accommodate 3+3 bunches.

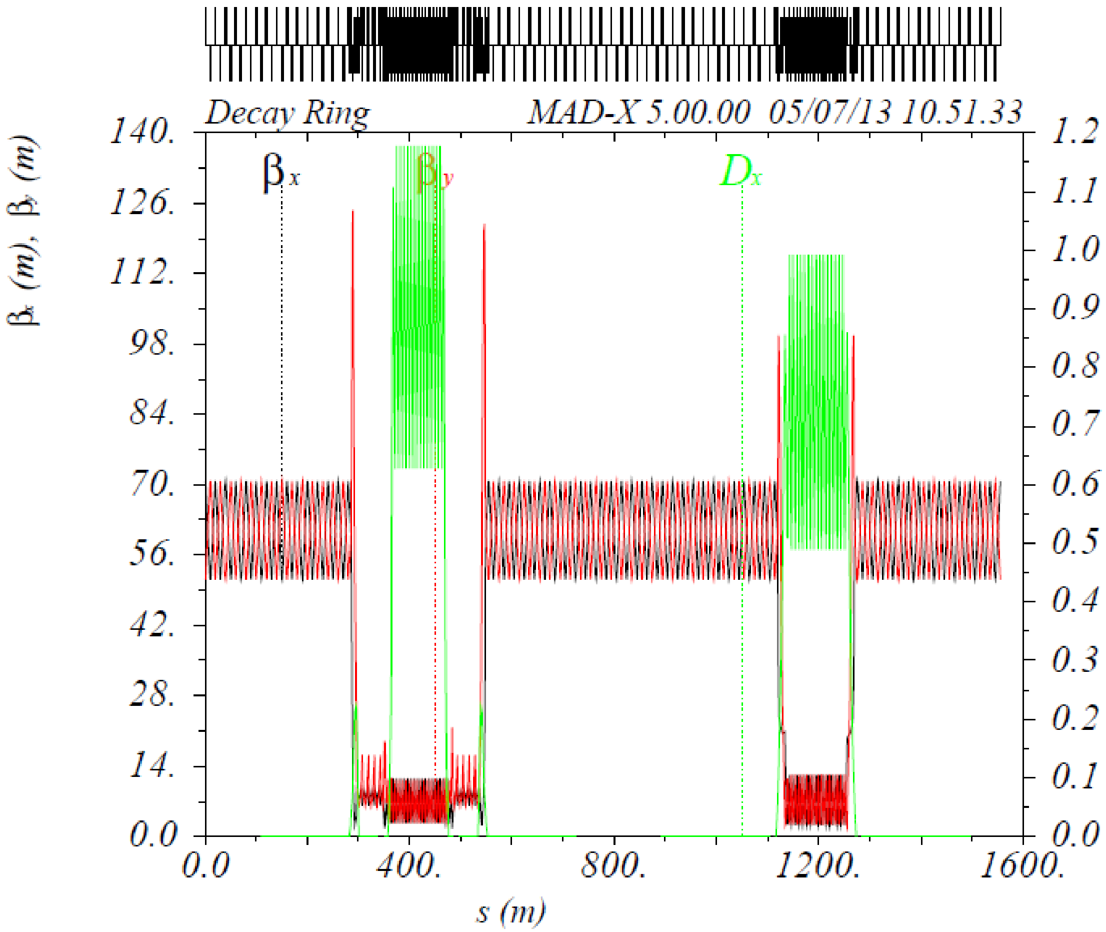
• This makes the injection into the production straight impossible due to the kicker magnet limitations (rise/fall time) and requires a dedicated insertion.

• We have found a solution (dedicated insertion), however it pushes the ring circumference.

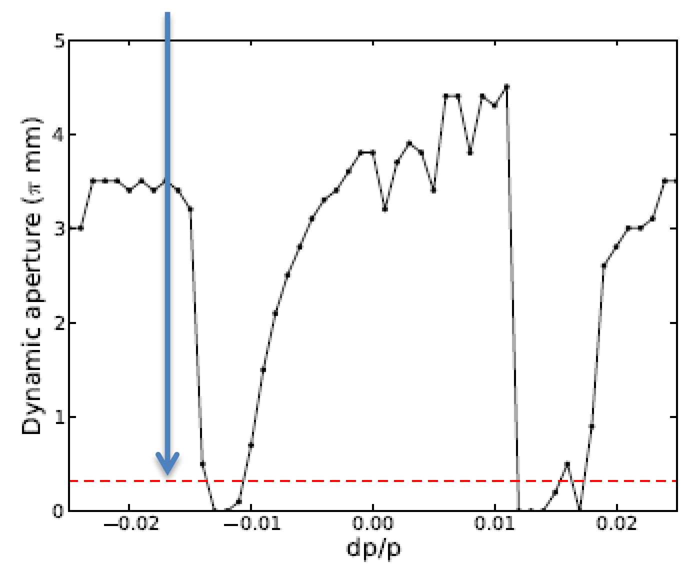



| | | |
|---|---|---|
| Production straight | $562.0 \times 2$ | m |
| Upper arc (incl. disp supp) | 121.155 | m |
| Lower arc | 112.729 | m |
| Insertion | $46.4 \times 2$ | m |
| Matching sections (total) | 104.987 | m |
| Circumference | 1555.672 | m |
| Width of ring | 74.565 | m |
| Length of ring | 737.228 | m |
| Angle of inclination | 10 | deg |
| Maximum depth of ring | 128.02 | m |
| Production efficiency $\eta_p$ | $36.1\% \times 2$ | |
| Total tune (H,V) | 14.77, 13.73 | |
| Chromaticity (H,V) | $-17.11, -20.23$ | |
| Phase slip $\eta$ | $2.8 \times 10^{-3}$ | |
| Turns per mean lifetime | 40.07 | |

# IDS-NF ring (optics and dynamics)




Requirement




You can see the limitations from the integer and half-integer resonances, however it is good enough for the IDS-NF beam!

# IDS-NF vs NuMAX

| | IDS-NF | NuMAX |
|---|---|---|
| Muon energy [GeV] | 10 | 5 |
| Number of bunch pairs | 3 | 1 |
| Bunch train [µs] | 250 | ~170 |
| Normalised acceptance [pi mm rad] | 30 | 20 |
| Ring inclination | 10° | 5.8° |

# Design considerations

| Design Aims |
|---|
| Maximize neutrino production efficiency (η) |
| Low beam divergence in production straight (<0.1/γ) |
| Maintain bunch separation (100 ns) |
| Allow realistic injection scheme |
| Ensure reasonable momentum acceptance |

# Beam divergence in production straight

- Want to keep beam divergence << natural decay cone of neutrinos
- Imposes a minimum beta in the production straight

Beam divergence condition $$x' = \sqrt{\frac{\varepsilon_{rms}}{(\beta_r \gamma_r)\beta}} < \frac{0.1}{\gamma_r} \quad \Rightarrow \quad \beta \propto \gamma_r$$

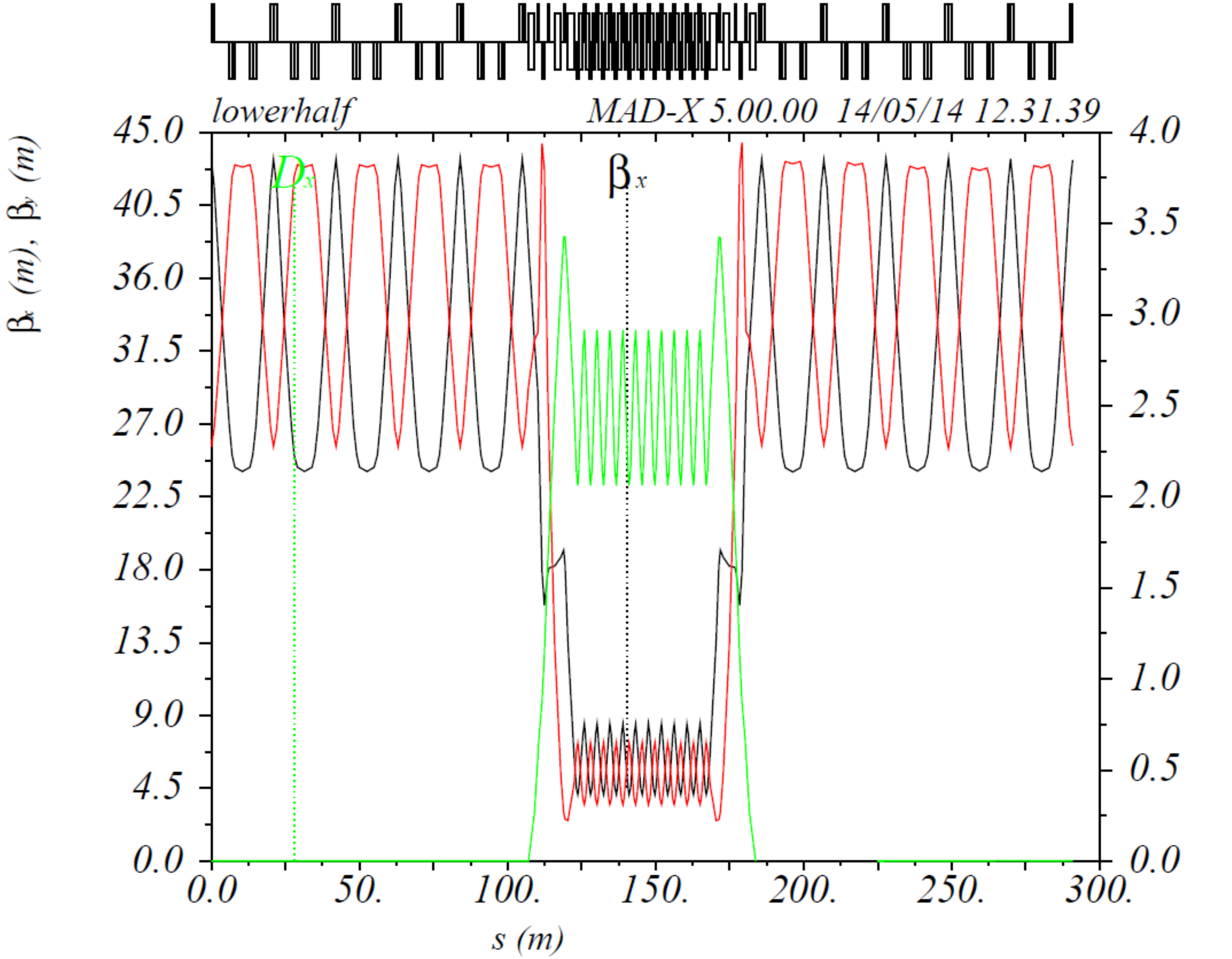
$\varepsilon_{rms}$ =~ 110 π mm mrad (approximately) implies β >~ 25 m

# Lattice overview
# (FDDF in the production straight)

| Section | | Cell No. | Total length (m) |
|---|---|---|---|
| Production | 21 m (cell length) | 10 | 210x2 |
| Matching | - | - | 18.7x4 |
| Arc | 4.34 m (cell length) | 10 | 43.41x2 |
| Ring | - | - | 581.62 |
| Dipole field | 2.4 T | | |
| η | 2x36.1% | | |
| transition gamma | 6.83 | | |
| Ring tune (Qx, Qy) | 5.4, 6.13<br>(needs readjusting) | | |
| Chromaticity (ξx, ξy) | -5.1, - 6.1 | | |

Momentum acceptance is ~0.25/$\xi$~4%

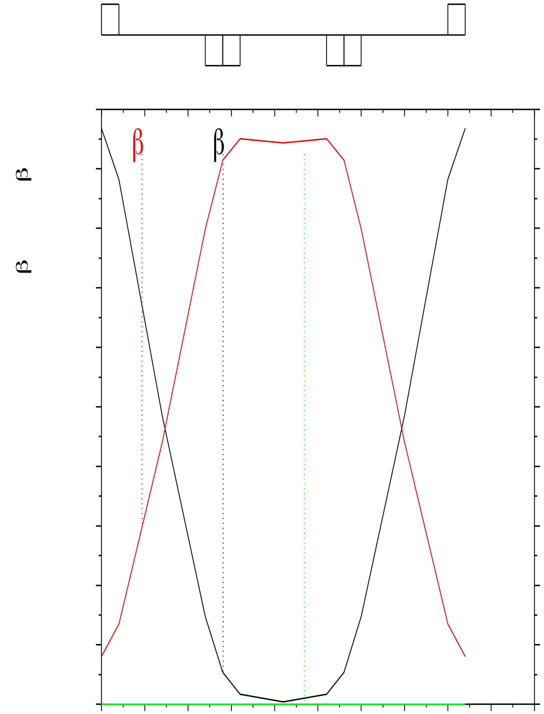
# FDDF optics


lowerhalf
MAD-X 5.00.00 14/05/14 12.31.39
$D_x$
$\beta_x$
$\beta_x$ (m), $\beta_y$ (m)
45.0
40.5
36.0
31.5
27.0
22.5
18.0
13.5
9.0
4.5
0.0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
50.
100.
150.
200.
250.
300.
s (m)

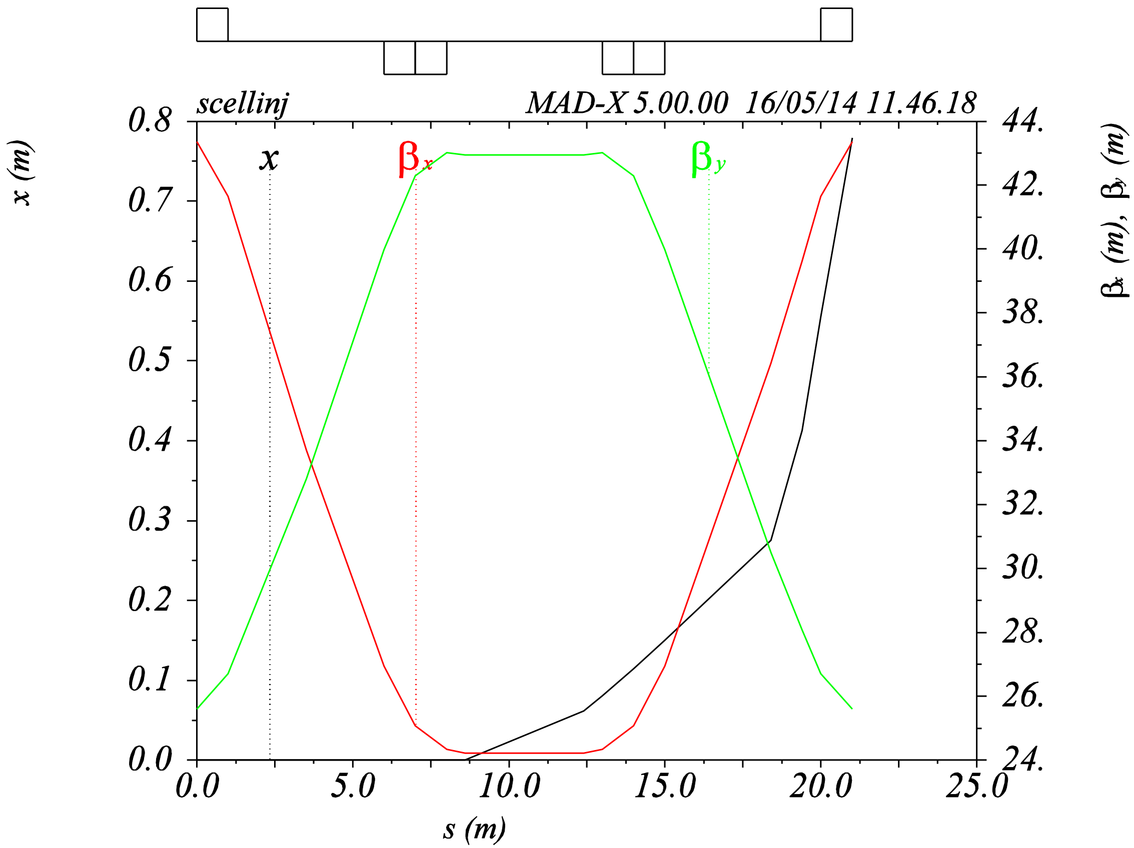
# Production Straight (FDDF)

- FDDF lattice adopted for symmetric injection
- Drift length chosen to reduce variation of beta but allow space for injection elements

| | Length | Field/Gradient |
|---|---|---|
| Drift | 5 m | - |
| QF | 2.0 m | 0.65 T/m |
| QD | 2.0 m | 0.33 T/m |
| Beam envelope in quads | 14.4 cm | - |



# Injection

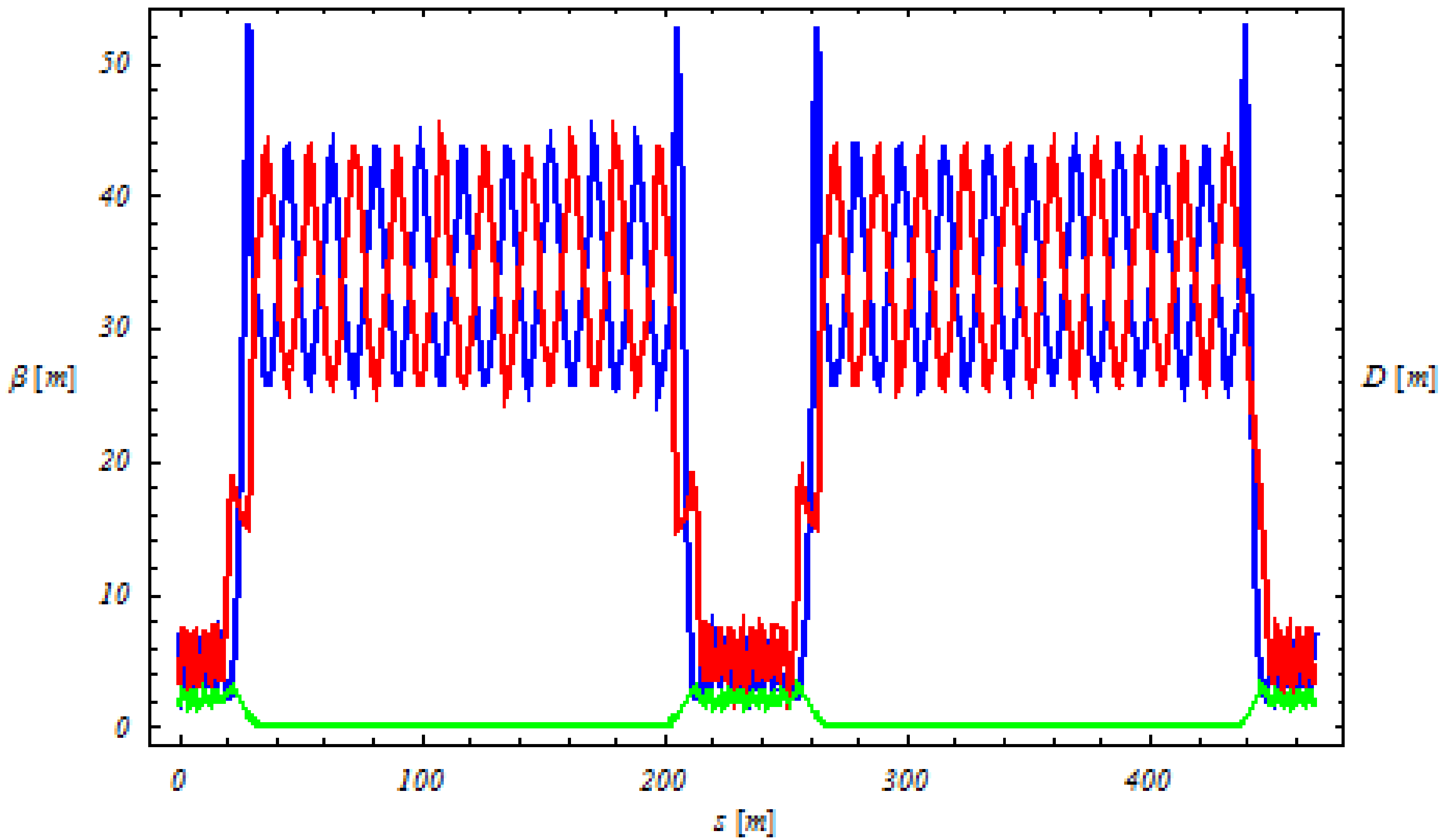



- FDDF allows for symmetric injection of both muon charges.
- Length of the straight section is 5 m.
- Single kicker scenario requires 0.14 T top B field (kicker) -> too much, but distributed kickers may work. Assumed kicker length – 3.8 m (fall time 1.76 $\mu$s)
- Septum 1.67 T, 1m long

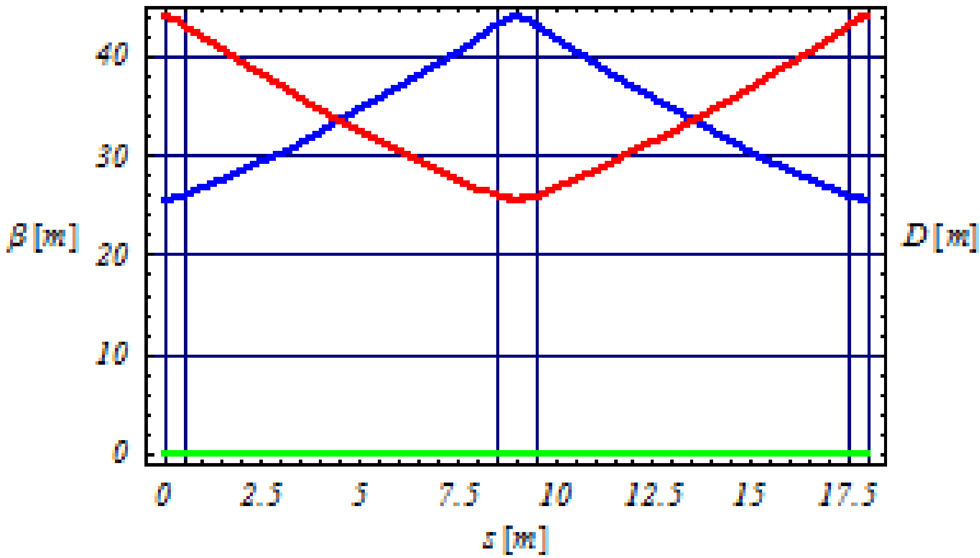
# Lattice overview (FODO in the production straight)

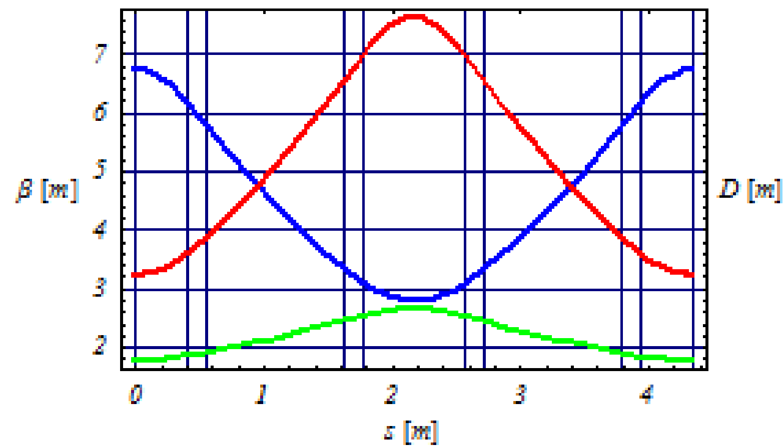
| Section | | Cell No. | Total length (m) |
|---|---|---|---|
| Production | 18 m (cell length) | 9 | 162x2 |
| Matching | - | - | 18.7x4 |
| Arc | 4.34 m (cell length) | 8 | 34.7x2 |
| Ring | - | - | 468.2 |
| Dipole field | 3 T | | |
| η | 2x34.6% | | |
| transition gamma | 6.33 | | |
| Ring tune (Qx, Qy) | 4.65, 5.7 (needs readjusting) | | |

# Preliminary NuMax ring with FODO production straight



# Cells of the ring with FODO-type production straight




FODO Production cell:
- 8 m drift
- Room temperature quads
- Large β
- Zero dispersion

Arc cell:
- Very short drifts
- All magnets SC in the common cryostat.

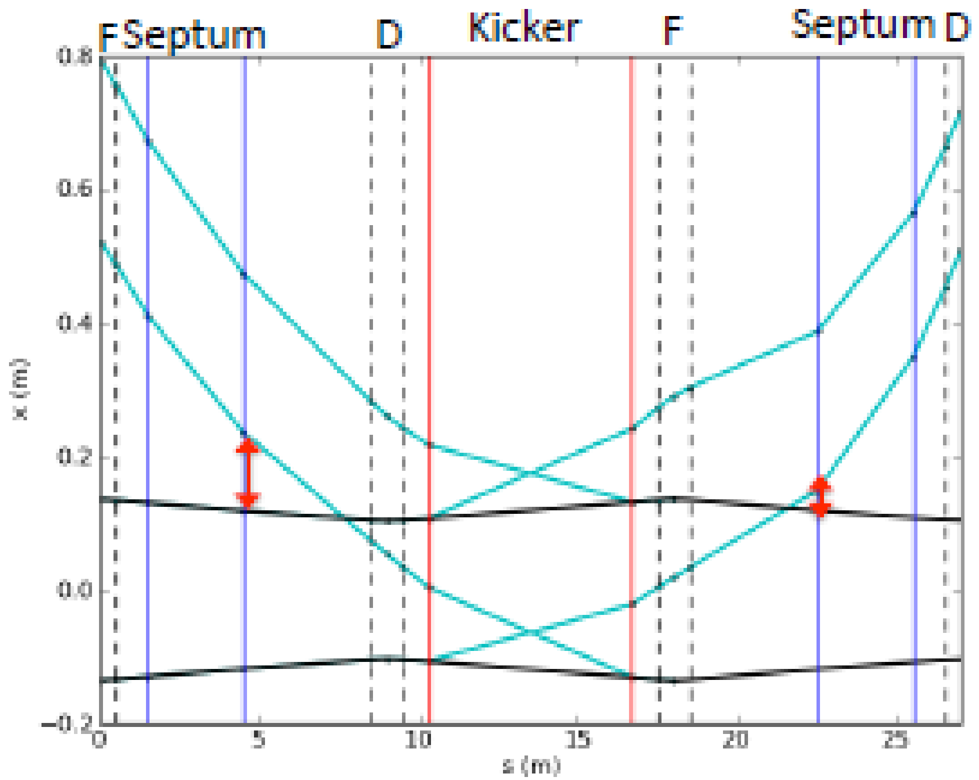
Dipole field 3 T.
- Small β
- Non-zero, but small dispersion
- Now effort is focusing on

a lattice allowing for realistic fringe fields

# FODO injection

- Kickers and septa in consecutive cells.
- 6.8 m kicker with 0.09 T peak field
- 3 m septum with 0.4 and 0.2 T.
- Higher kicker field needed when injecting through the F than the D.

- In the FDDF case, the kicker peak field required is 0.14 T.



# Alternative injection into the FODO ring

- This scheme assumes one empty drift between the kicker and septum
- Kicker approximate parameters:
  - 6.4 m long, subdivided into sub-kickers.
  - 0.05 T top B field
  - Rise/fall time ~1.4 us
  - Aperture ~0.35 m
- Septum – 1.2T, 3m long
- This scheme requires confirmation!

# FODO vs FDDF production straight

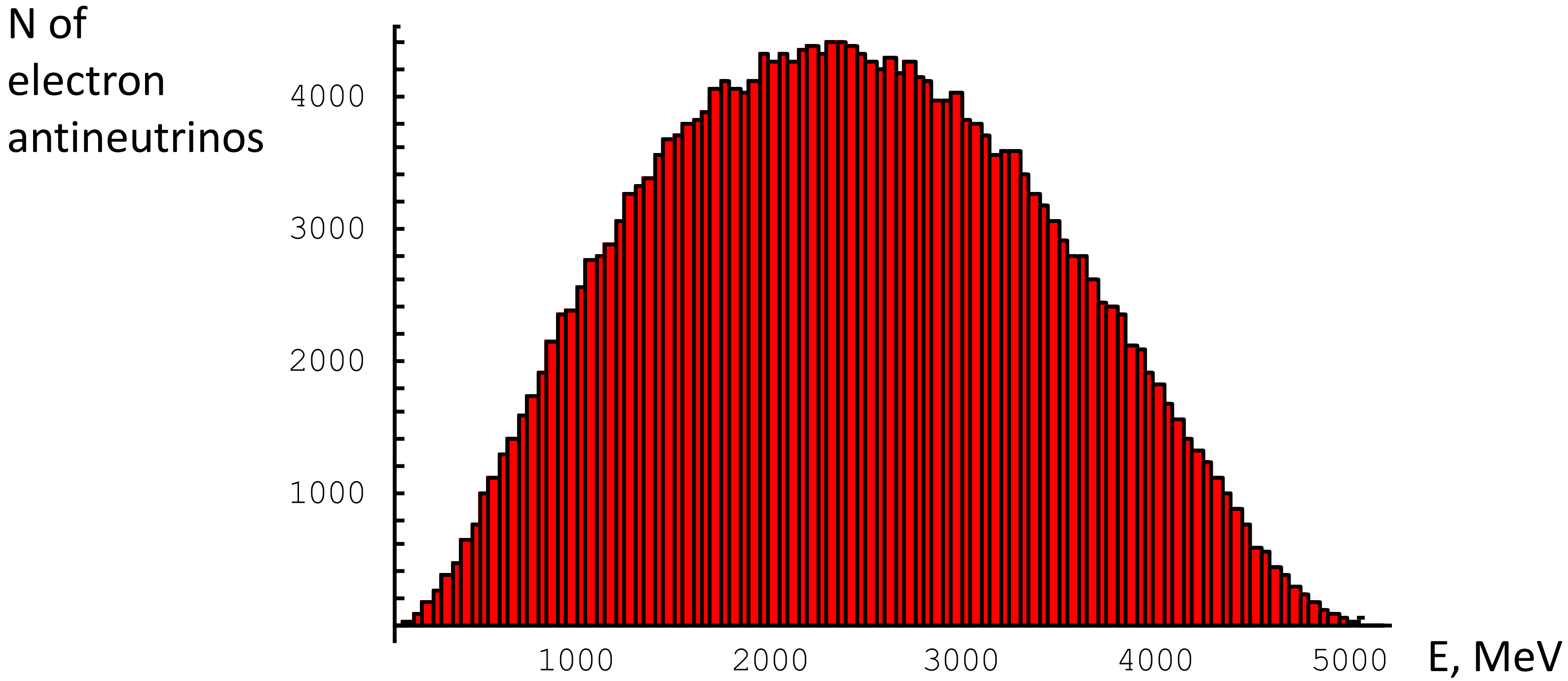
- FDDF considered as it allows symmetric injection of both muon signs.
- However, longer straights possible in FODO easing the peak field kicker requirement.

| | Length (m) | Gradient |
|---|---|---|
| Drift | 8 | - |
| QF | 1 | 1.03 T/m |
| QD | 1 | -1.03 T/m |

| | Length (m) | Gradient |
|---|---|---|
| Drift | 5 | - |
| QF | 2 | 0.65 T/m |
| QD | 2 | -0.33 T/m |

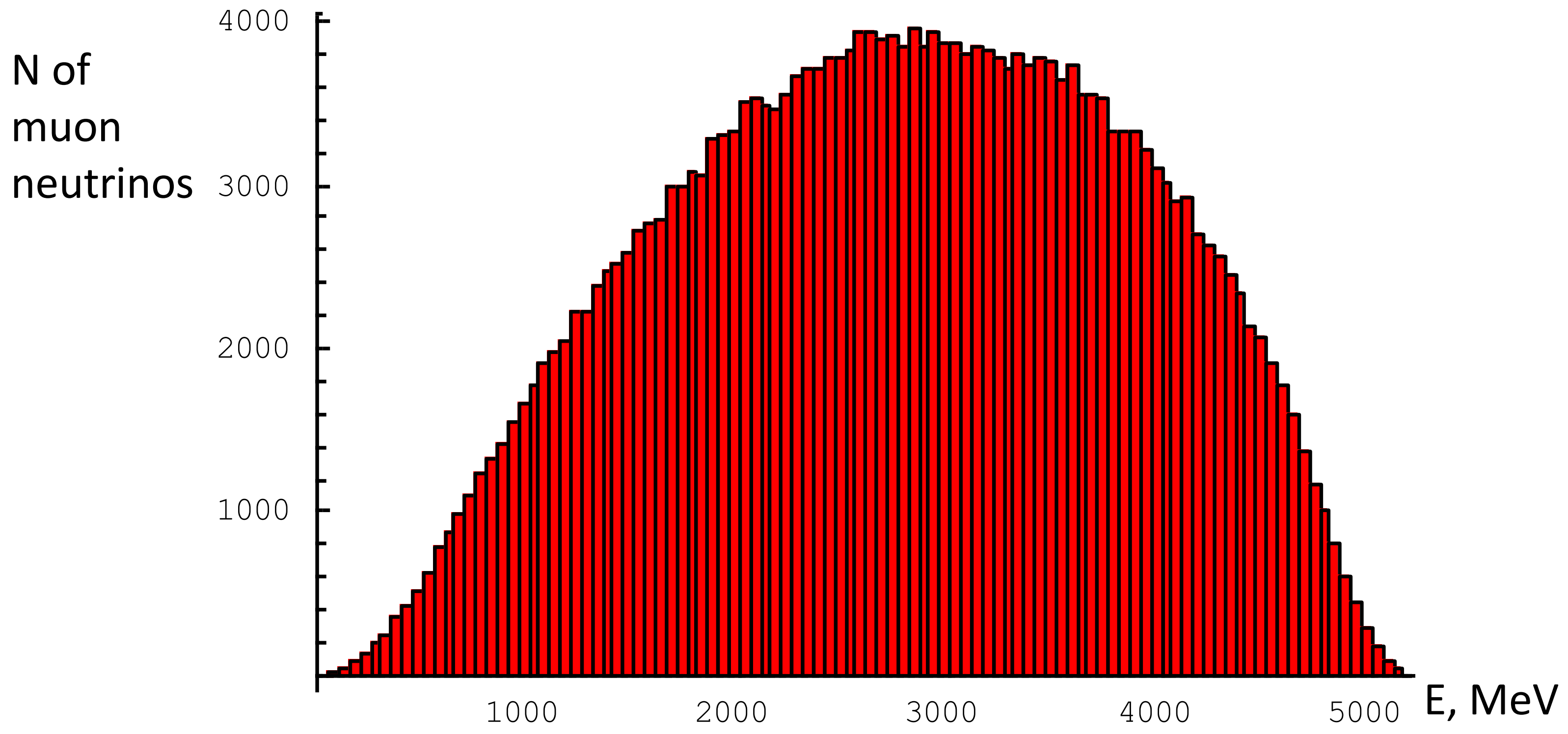
# NuMAX neutrino flux studies (1)

- Near detector: 50m distance, 5m diameter. Results for 1000000 stored muons.

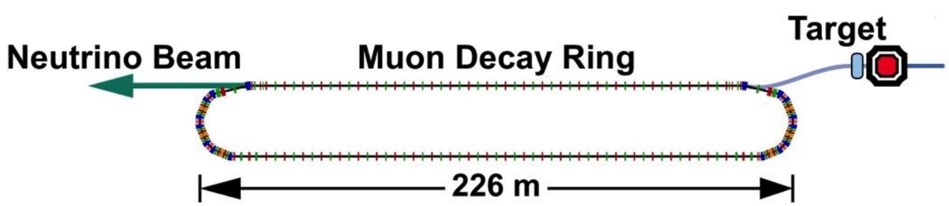


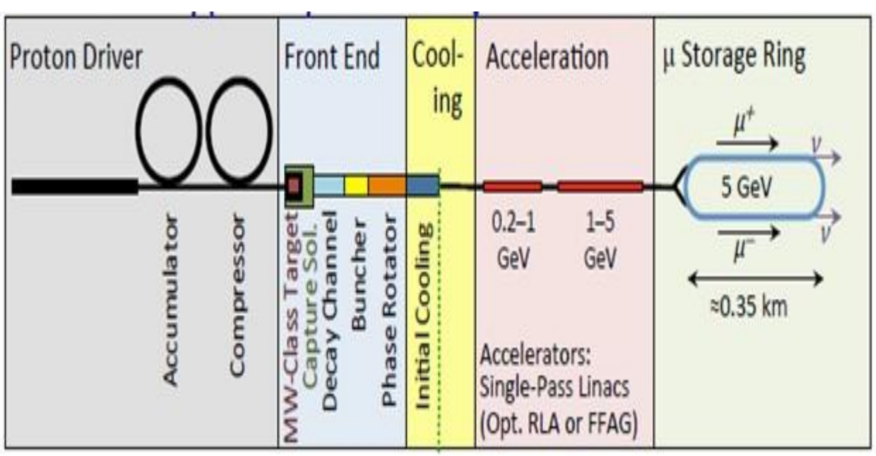
# NuMAX neutrino flux studies (2)

- Near detector:  50m distance, 5m diameter. Results for 1000000 stored muons.



# nuSTORM/NuMAX Global Parameters




| | nuSTORM | NuMax |
|---|---|---|
| Muon Total Energy [GeV] | 3.8 | 5 |
| Bρ [Tm] | 12.675 | 16.674 |
| Geometrical acceptance [$\pi$.mm.mrad] | 3000 | 423 |
| Tilt angle [degree] | 0-1 | 5.8 |
| Momentum acceptance | ±9(19)% | ±6.3% |
| Long baseline length [km] | 2 | 1400 |
| Injection type | Stochastic | Full aperture with kicker |

# Comparison (for fraction of parameters)

| | nuSTORM-FODO | nuSTORM-RFFG | NuMax |
|---|---|---|---|
| Circumference [m] | 480.3 | 500 | 468.2 (582) |
| Dipole B field [m] | 4.14 | 3 (in combined f. mag.) | 3 |
| Dipole total aperture HxV [m] | ~0.3x~0.27 | ~0.96x~0.56 (in c.f.m.) | ~0.42x0.13 |
| Production straight magnet aperture [m] | ~0.6 | ~0.6 m | ~0.35 |

# Common technologies/elements for NuMax and nuSTORM

- SC magnets with large aperture
  - We know we can make them
  - ...but we want to make them efficiently
  
  -> We want magnets with large aperture (including combined function ones -> nuSTORM FFAG option)
- Large aperture room temperature quads (or FFAG-type -> for nuSTORM FFAG option) -> HTS option may be interesting
- Pion/muon beam instrumentation
  - To measure orbit, beam size, current, tune.
- Beam instrumentation for the neutrino beam monitoring
  - To measure divergence
  - To monitor beam energy

# Conclusions

- As NuMax design assumes only 1 bunch/charge, the ring size can be reduced.
- We have two preliminary designs of 581.6 and 468.2 m.
- In both rings production straight and matching can be based on room temperature magnets, but arcs need SC ones.
- Injecting directly into the production straight avoids the need for the dedicated insertion (like in the IDS-NF), which allows to makes the ring smaller.
- Limitation for the size of the ring is again fall time of the kicker.
- A large aperture kicker(s) with modest strength is(are) required, which seems to be feasible (to be confirmed).
- Large aperture quads are needed at injection region.

# Future plans

- Design update
  - Ring optics
  - Injection scheme confirmation
  - Injection line layout/optics
- Tracking studies
  - Using realistic field models
  - Including errors
- Neutrino flux studies -> to motivate neutrino physicists more...

We aim for a journal publication summarizing and properly documenting this effort!

STFC ASTeC

Imperial College London

# Longer term R&D Goals

- Large aperture SC magnets
- Large aperture room temperature magnets
- Muon beam instrumentation
- Beam instrumentation for the neutrino beam monitoring