Injection/extraction issues

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I will focus on pulsed machines.

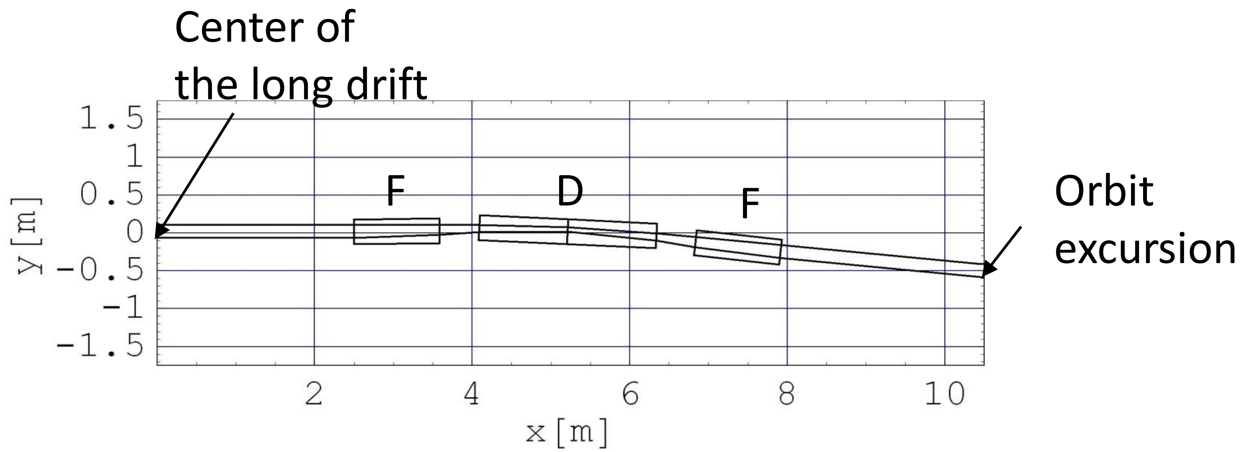
- Pulsed machines operate with certain cycle dictated by the injector, user needs or both
- Pulsed machines are important for:
    i. Fundamental research
        - High intensity drivers (Neutrino Factories, PRISM, Muon Collider, precision measurements with pulsed beams
        - Muon machines feeded by the pulsed for the above drivers
    ii. Medical applications with synchrotron-like beams (bunch-to-pixel scanning)
    iii. Applied science (Neutron Spallation Sources)
    iv. ....
- They may have many potential users and FFAGs may be able to be a cost effective and high performance solution.

- However, yet many sceptical voices can be found about FFAGs in accelerator community and many of them are about injection/extraction.

- Injection/extraction have been treated either in a hurry or as a secondary aspect in our FFAG designs/ commissionings.
- I believe we can improve in a future.

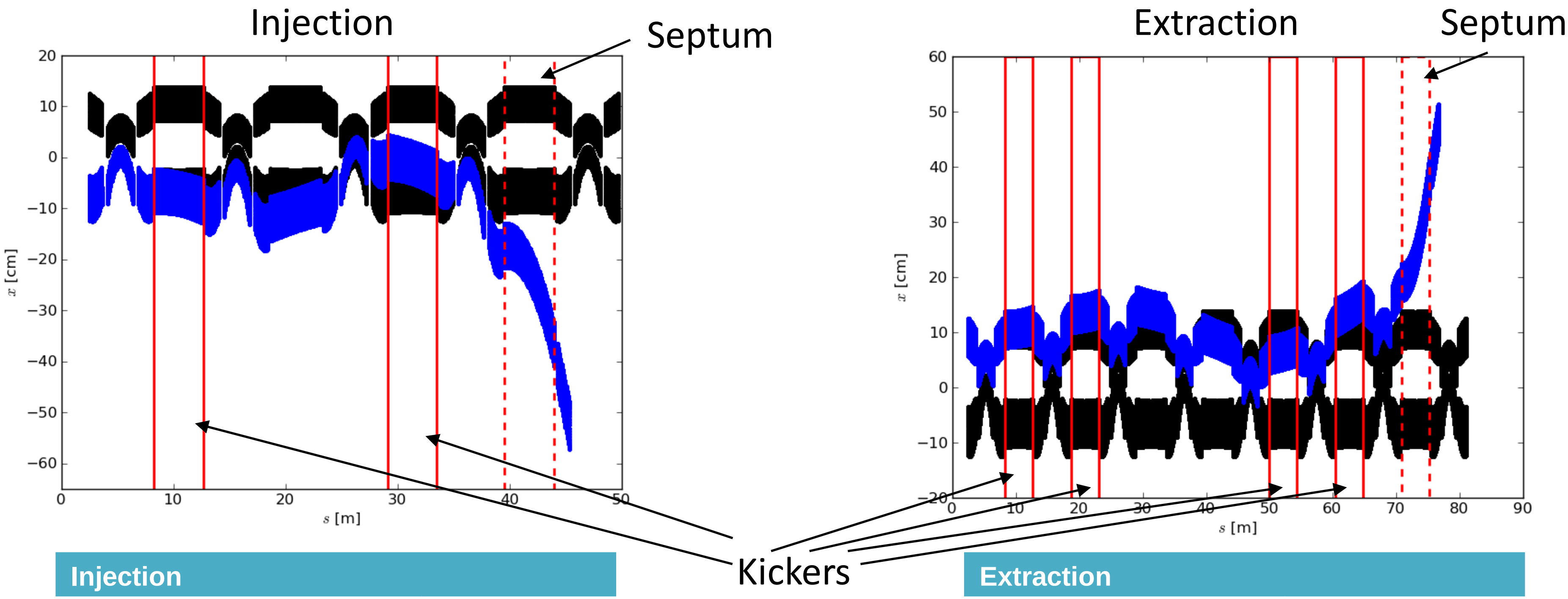
Injection/extraction studies for the Neutrino Factory

Old IDS-NF NS-FFAG design	
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



- We made an attempt to incorporate injection/extraction into the design from the beginning.
- In order to make the injection feasible lattice incorporated 5m long drifts for symmetric injection/extraction.
- This increased the total cost significantly.

Injection/Extraction geometries



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

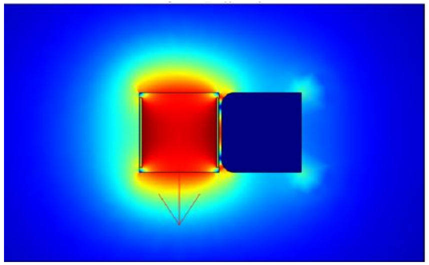
Extraction	
Plane	Horizontal
No. Kickers	4
Kicker field (T)	0.067
Polarity	**++00++**
Septum field (T)	1.76

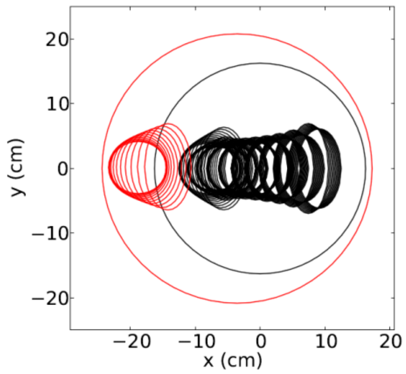
- Septum field was limited to 2 T by the stray fields studies (this dictated the length of the drift)
- Both injection and extraction are in the horizontal plane (minimal additional magnet aperture needed and no generation of the vertical dispersion).

From T. Jones

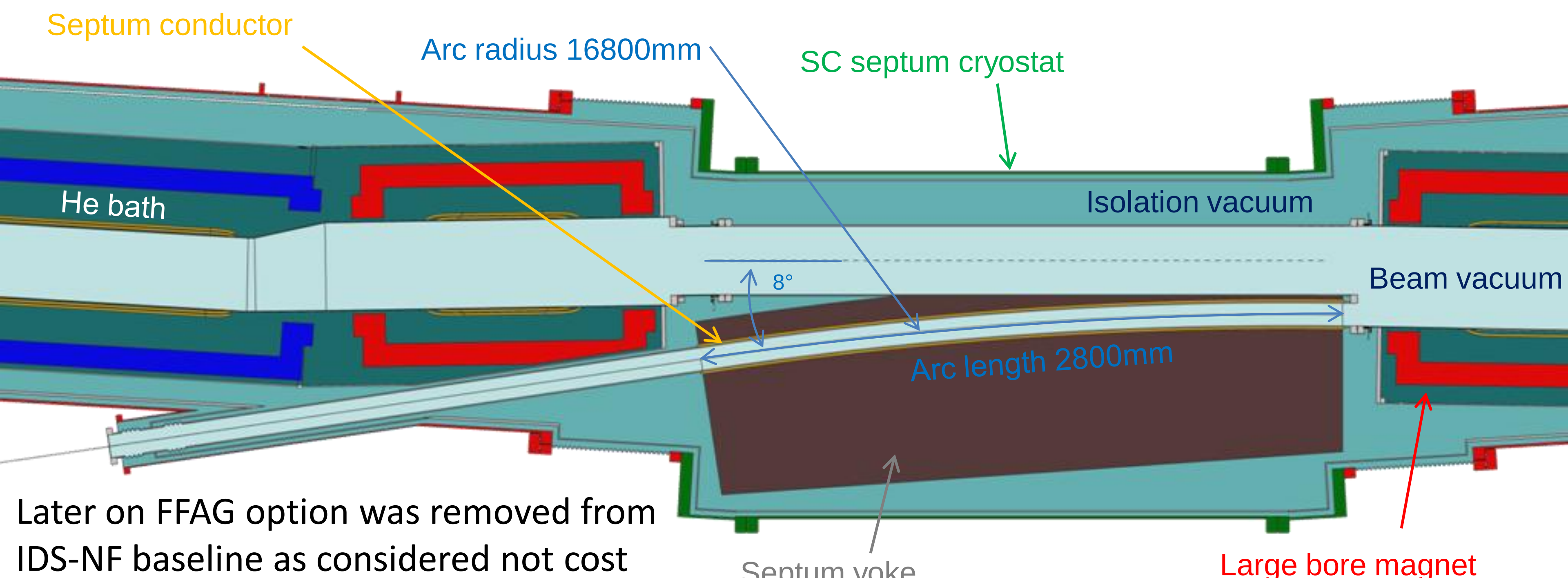
10 GeV version ns-FFAG

- Even when we tried the 10 GeV machine, as the final energy was reduced due to the large θ_{13} the length of the septum was one of the critiacal elemnt.
- Image below is a schematic of superconducting 2T extraction septum. 3D design is required to ascertain feasibility.





Images above and right ref:
NF Interim Design Report



Later on FFAG option was removed from IDS-NF baseline as considered not cost effective enough.

What can we learn?

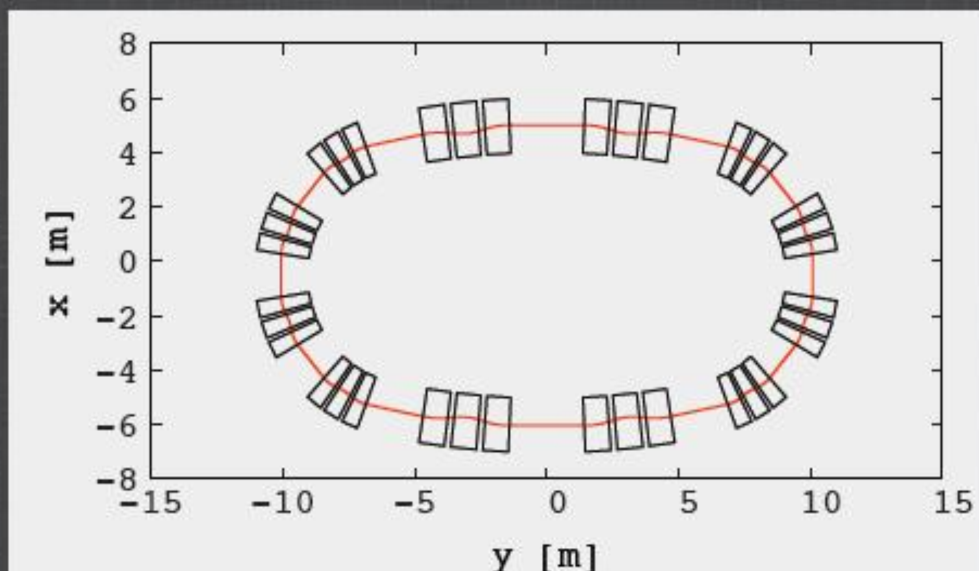
- In IDS-NF case we were forced to keep all cells identical.
- Together with the need for feasible injection/extraction it pushed the cost too high.

- ...However, in other cases we may be able to avoid that problem by switching to a racetrack type solution.

Egg-shape design

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

Large Bending cell FDF triplet	
k-value	28.9503
total bending angle	11.7 deg.
Average radius	30 m
Phase advances:	
Horizontal μ	75 deg.
Vertical μ	81 deg.
Dispersion	1 m



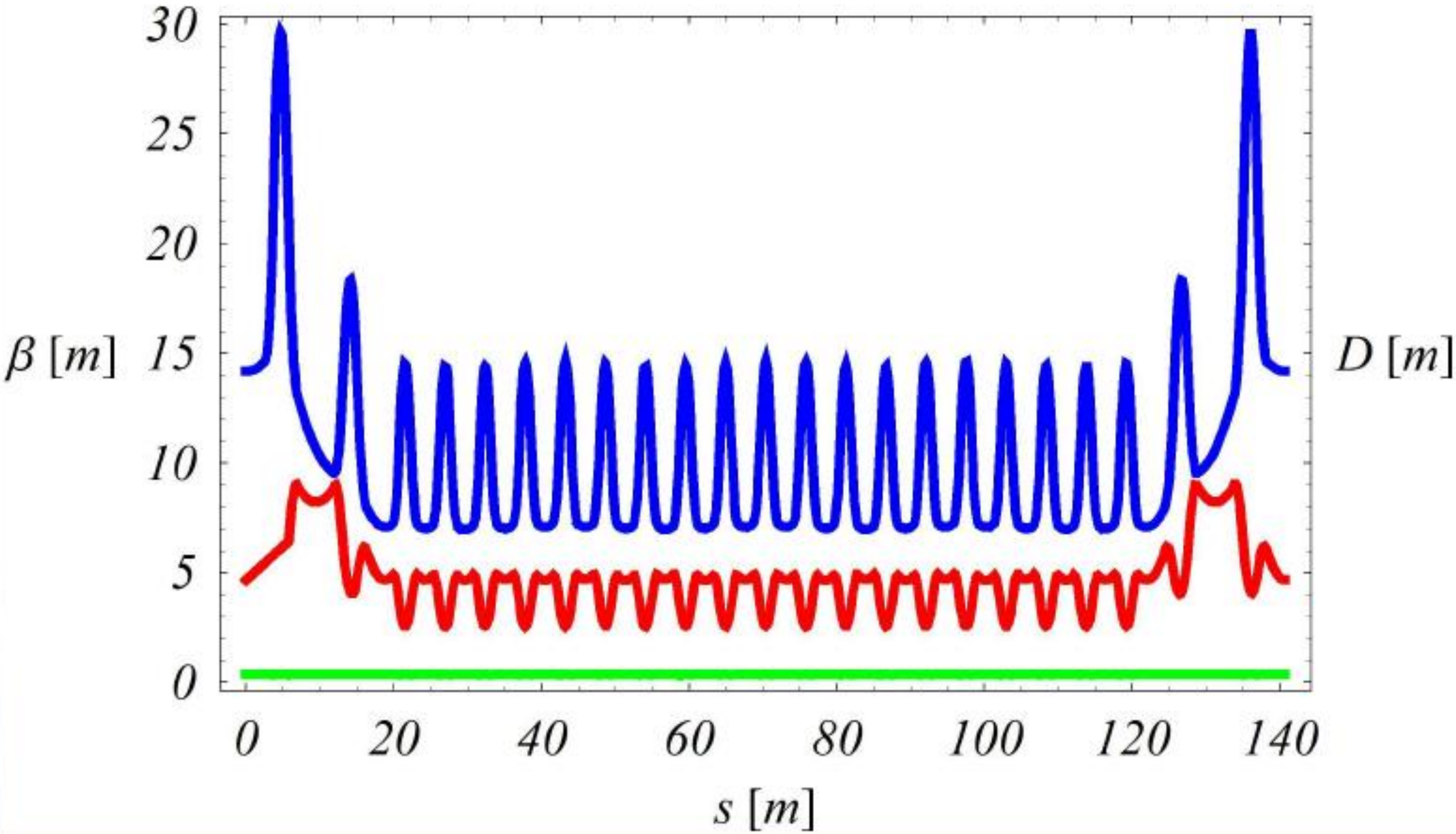
This turned out to be very promising concept (work in collaboration with JB Lagrange).
This work triggered the progress on the nuSTORM FFAG design.

Passed Conceptual Studies for Project-X

Parameters for the Advanced Scaling FFAG

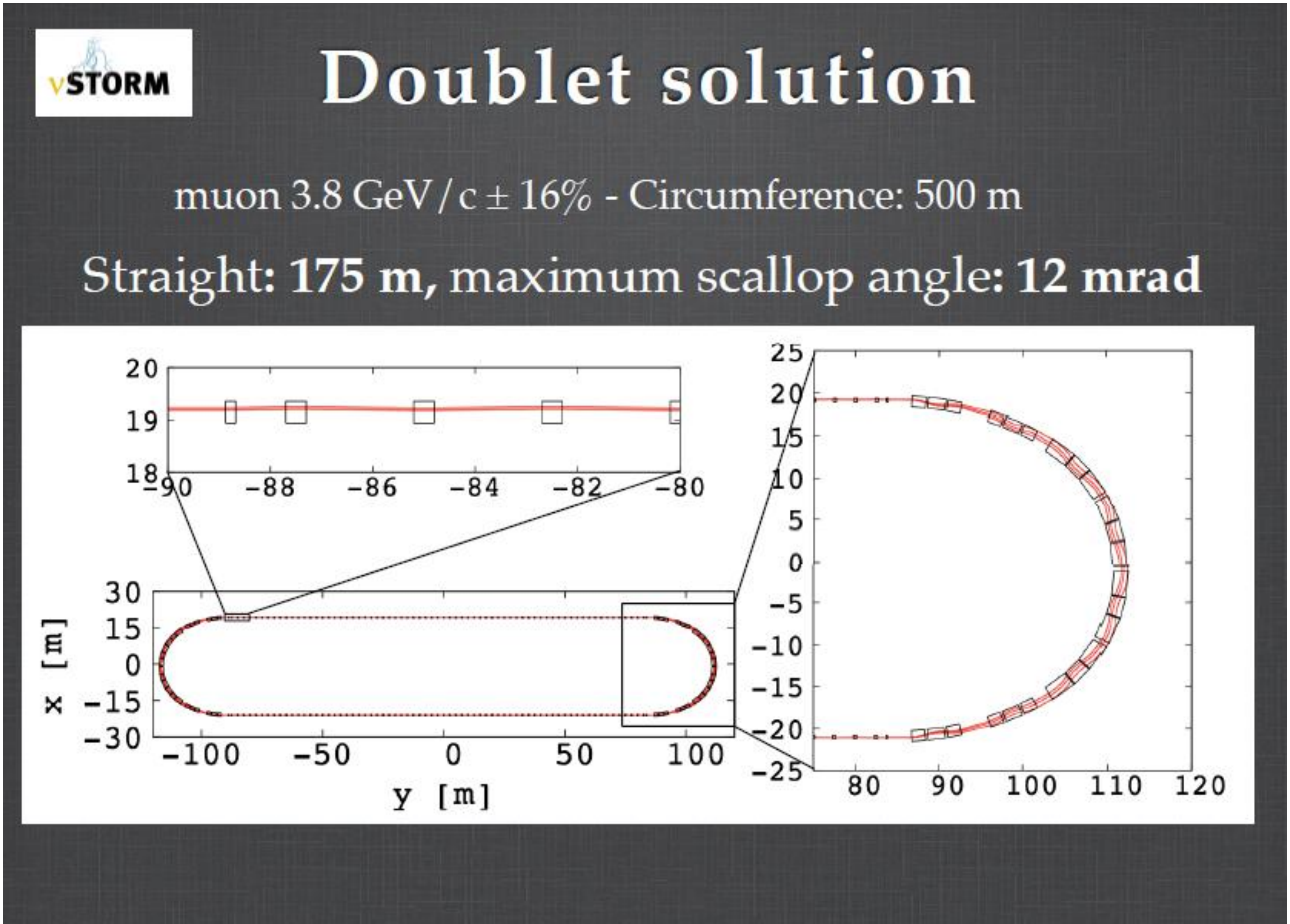
• Circumference	562.7 m
• γ_T	31.7
• Superperiodicity	4
• Number of arc cells	76
• Number of insertion cells	16
(4 insertions with 2π/ π phase advance – H/V)	
• Orbit excursion	0.3 m
• k in the arc/insertion	210.5/515.7
• B max	5.2 T
• R in the arc cells	75.445 m
• R in the insertion	184.1 m
• Drift length in the arc	2 m
• Drift length in the insertion	5 m

Matching in the Advanced Scaling FFAG for the Project-X



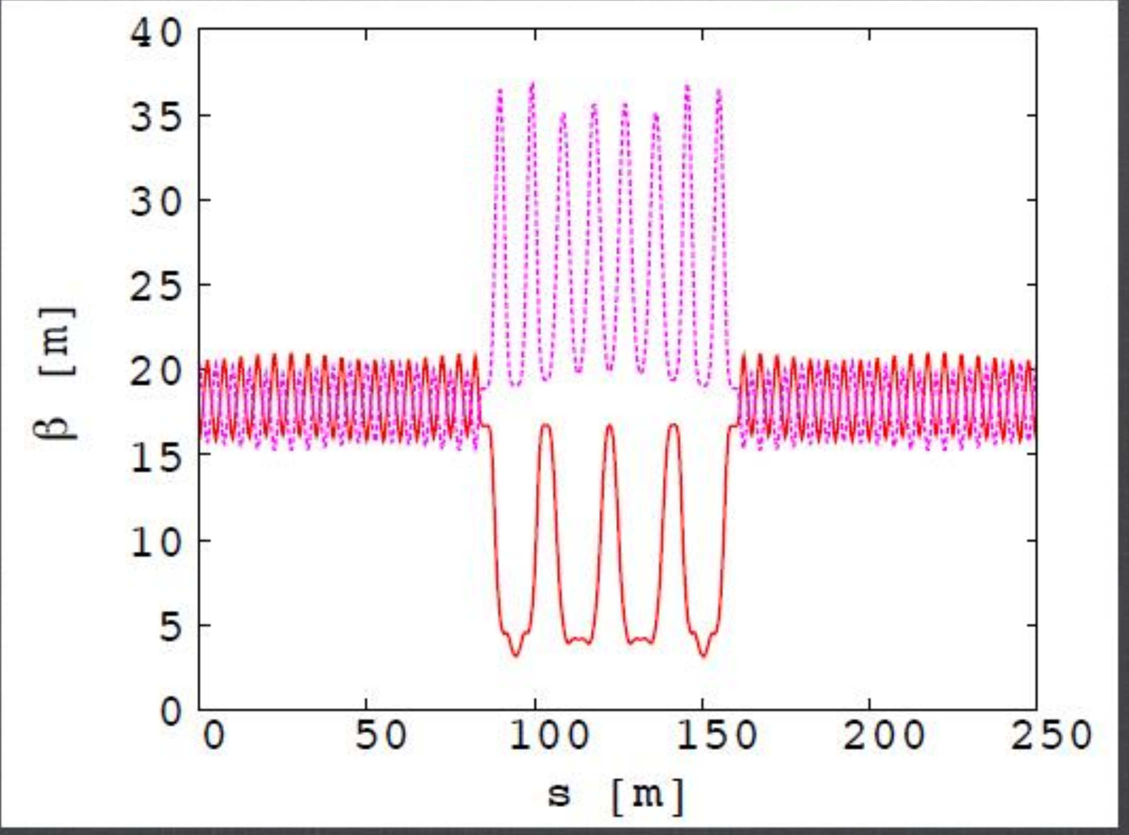
Long drift insertion is well matched to the arc with almost no beta beat!

Advanced lattice design example is the nuSTORM lattice (see JB's talk)



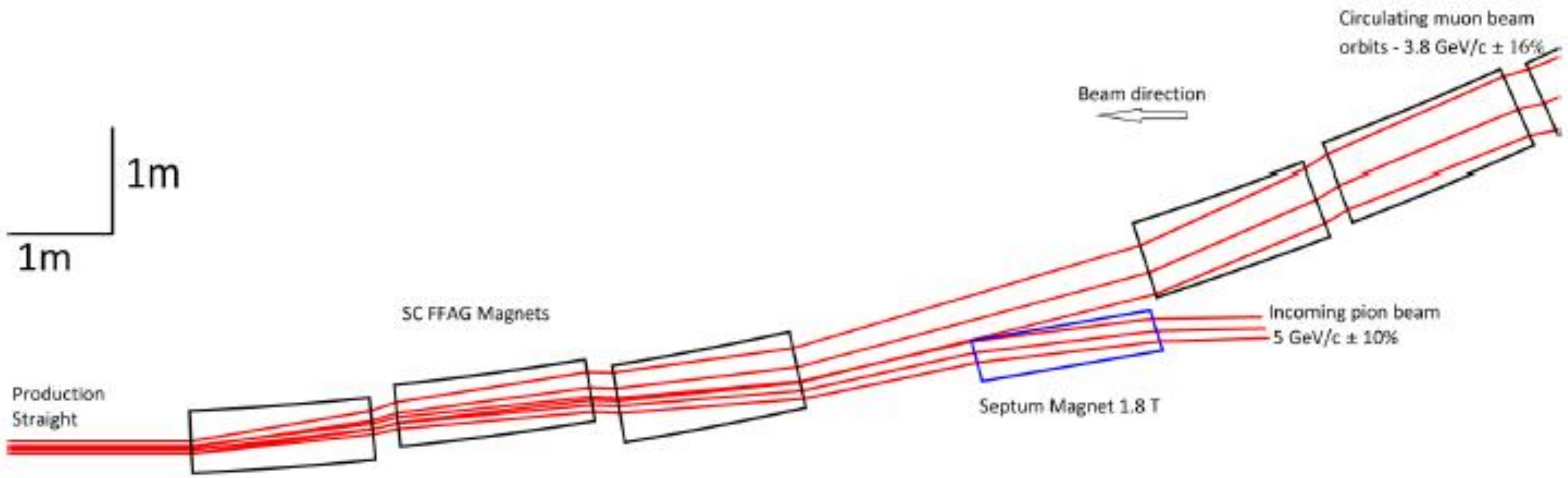
Doublet solution

Beta-functions at matching momentum



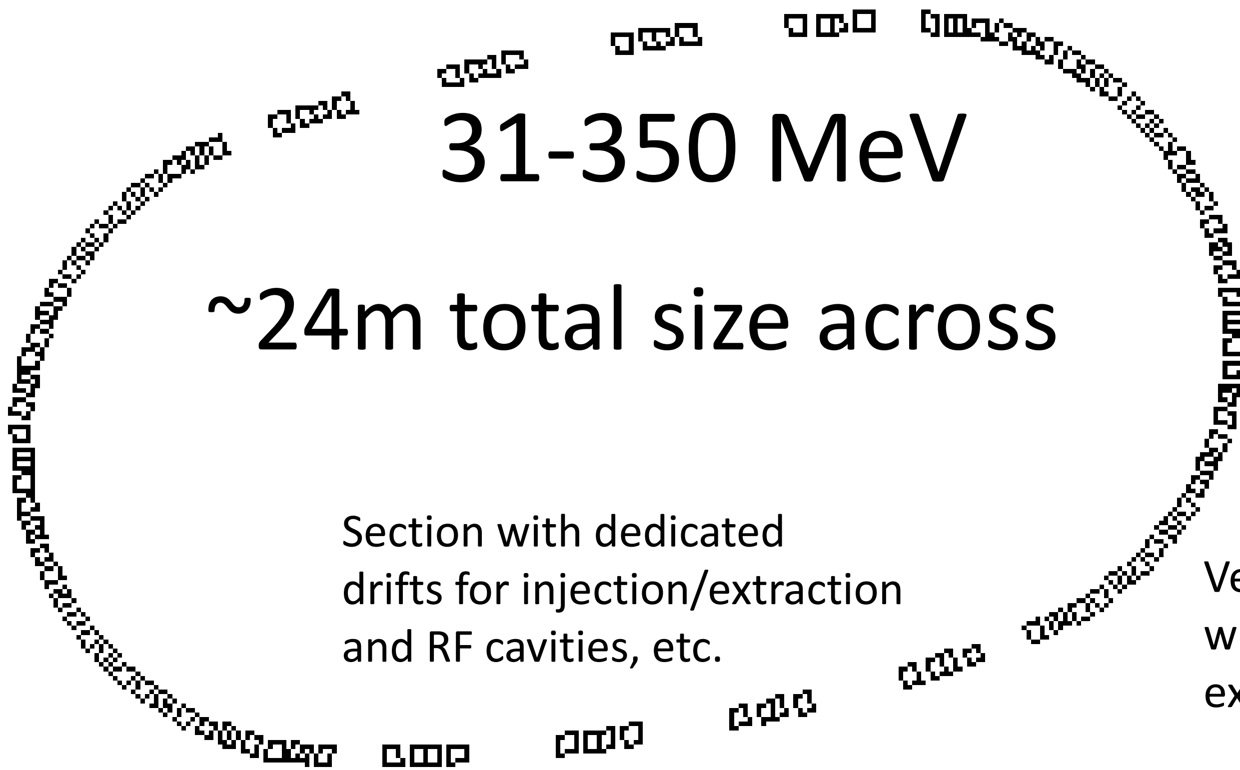
Horizontal (plain red) and vertical (dotted purple) betafunctions for half of the ring.

Injection



Circulating muon beam
orbits - 3.8 GeV/c ± 16%
Beam direction
1m
1m
SC FFAG Magnets
Incoming pion beam
5 GeV/c ± 10%
Production
Straight
Septum Magnet 1.8 T

Egg shape ring for proton radiography, preliminary design to illustrate the principle

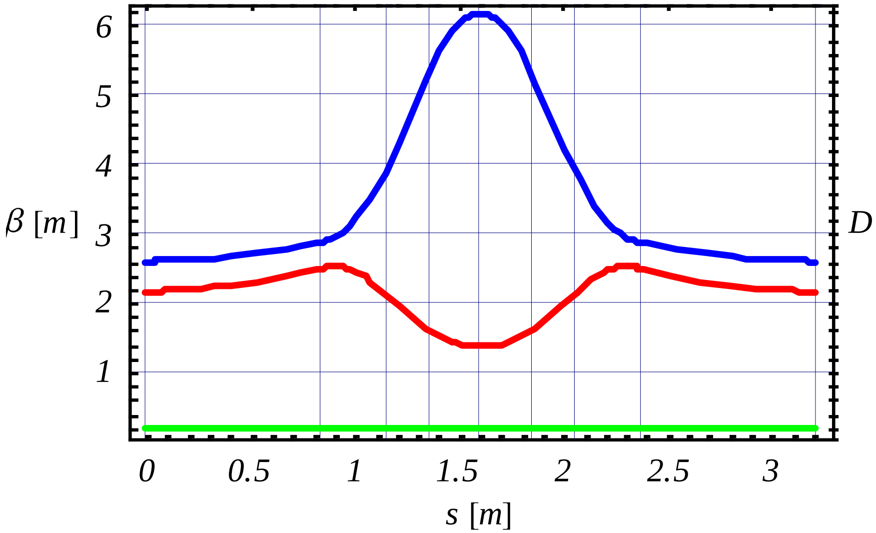


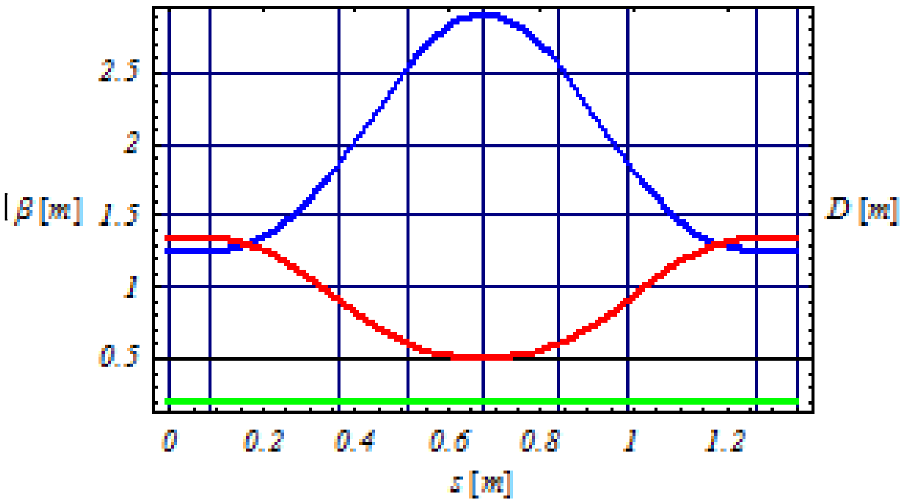
It can be made more compact.

Straight and arc sections

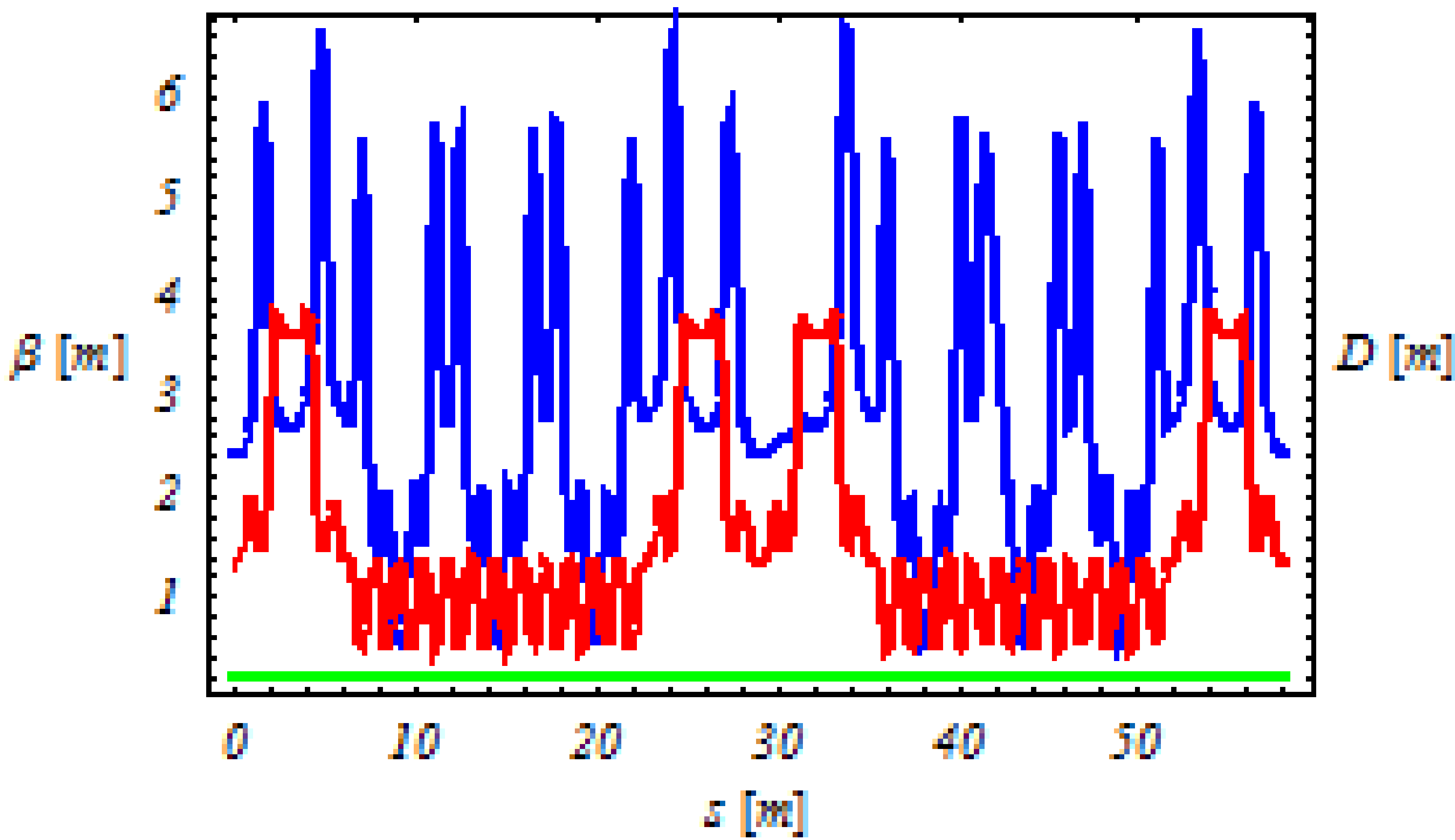
- k=188
- Fields ~1.5,1.4 T
- Orbit excursion 0.25 cm
- Tunes (0.249, 0.158)
- N=8

- k=28
- Fields ~3 T
- Orbit excursion 0.25 cm
- Tunes (0.257, 0.124)
- N= 24





Beta Functions, total tune (8.18/4.24)



Conclusions

- Injection/extraction are one of the most important issue to convinced accelerator and user communities to invest into FFAGs
- We have achieved certain amount of progress and encountered some difficulties.
- Injection/extraction may become much easier

  when using the dedicated design and allowing for dedicated space for kicker/septum hardware
- We should focus on racetrack type solutions.

- I would suggest to make the next research FFAG machine to be of racetrack type!