μ Storage Ring for ν beam

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Fermilab f

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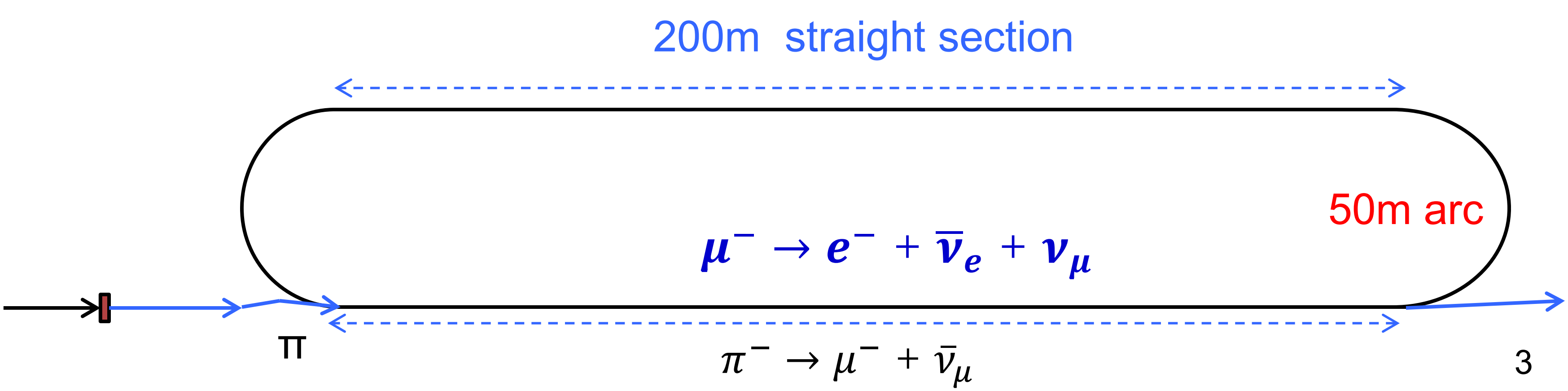
Outline

- Scenario Overview
- Stochastic injection
- Storage ring options
  - Superconducting
  - Normal
- Current Studies

Neutrinos from μ Storage Ring

- Intense Proton beam on π production target
- Collect forward π's; transport into ring
  - Li lens or horn
- π decay in injection Straight Section produces μ's
  - 50% of 5GeV π decay in 200m SS

- μ's accepted by ring; circulate for ~100 turns
  - Decay : $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ produces neutrino beams
  - C =~500m



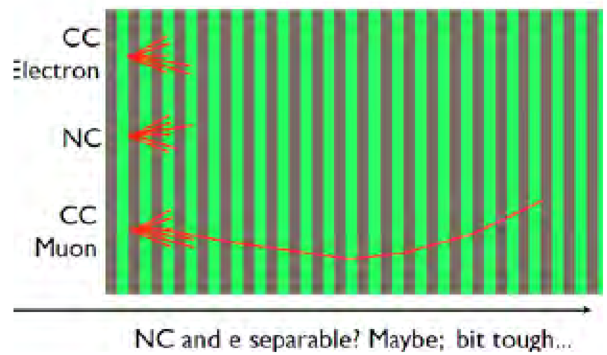
Parameter Choices

- **Need ~GeV neutrino beams**
  - searching for L/E = 1km/GeV ν_e, $\bar{\nu}_e$ oscillations

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

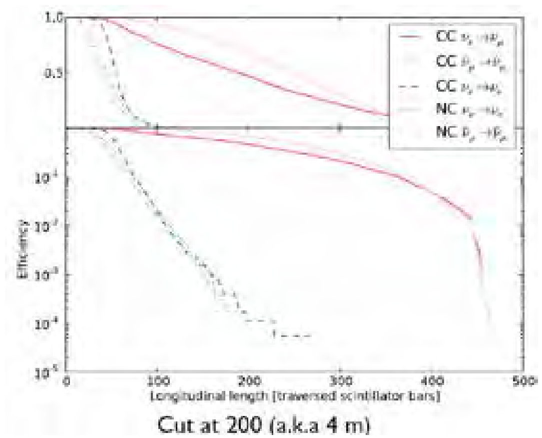
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- **Need to cleanly separate μ^+ from μ^-**
  - magnetized detector – MIND
    - iron/scintillator detector
  - needs >~2 GeV neutrinos for clean separation

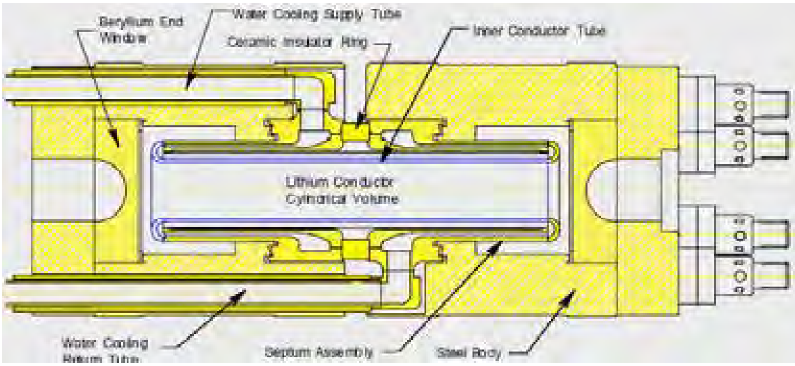


C. Tunnell

- **Need ~3.8 GeV μ storage ring**
  - Requires ~5 GeV π's
  - requires ~50+ GeV Main Injector Proton source



Li lens or magnetic Horn or?



Ø *~ Li Lens (pbar)*

Ø $B(r) = \mu_0 \dfrac{I_0 r}{2\pi r_0^2}$

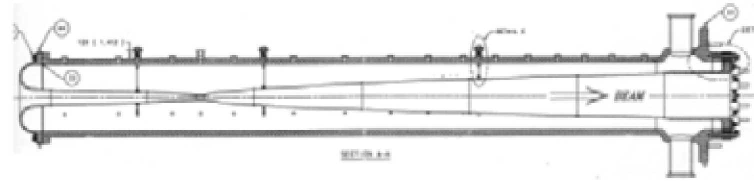
§ r_0=1cm; L_{active} =15cm

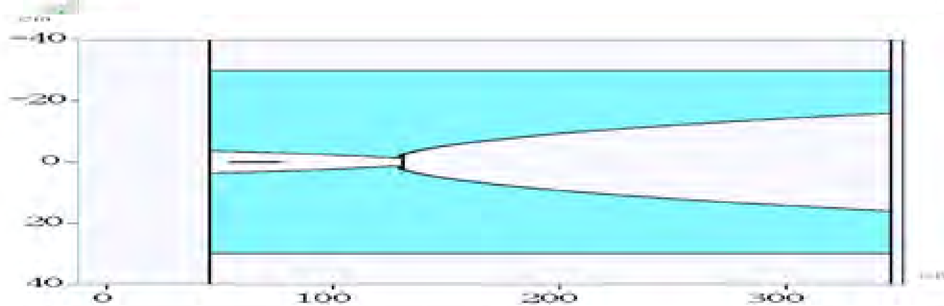
§ I_0 à 500kA

§ B = 10T

- for 20cm focal length,3GeV,
- want ~167kA (3.33T)
- ~50 mrad acceptance

§ can get 100 mrad with r_0=2cm





Ø *~ NuMI Horn*

Ø $B = \mu_0 \dfrac{I_0}{2\pi r}$

§ r_{min}=1.35cm; r_{max}=15cm

§ I_0 à 200kA

§ B = 3T à 0.2T

- nonlinear optics

π à μ Injection

- Ø **Separate Transport for π à**
  - § kick into storage ring after decay
    - Requires fast kicker, can only use part of MI/spill
- Ø **Injection of π into straight section, accept μ in ring acceptance.**
  - § “stochastic injection”
    - stochastic was popular in 1980
    - stochastic cooling, stochastic extraction, …
  - § no kickers; phase space of injected π and circulating μ are separated
  - § **Circumvents Liouville’s Theorem**
- Ø **Could also inject into target inside ring**
  - § π’s within acceptance decay
  - § μ’s within acceptance stored
    - circulating beam passes through target
    - collection of beam off target more limited

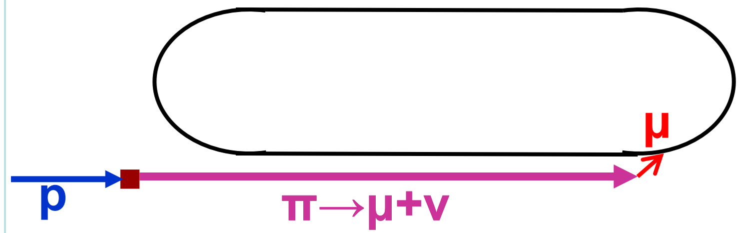


FIGURE 2A
"STOCHASTIC INJECTION" WITH NON-CIRCULATING π BEAM.

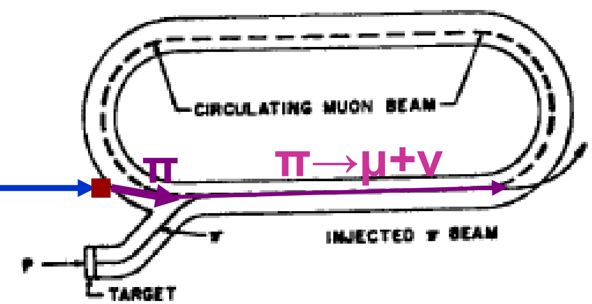
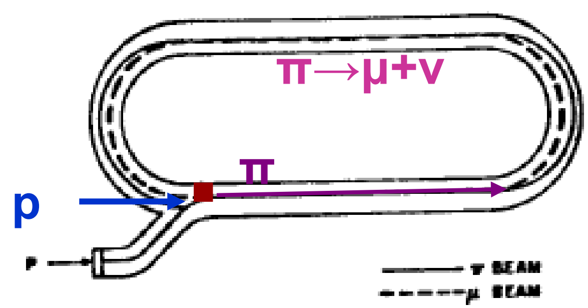
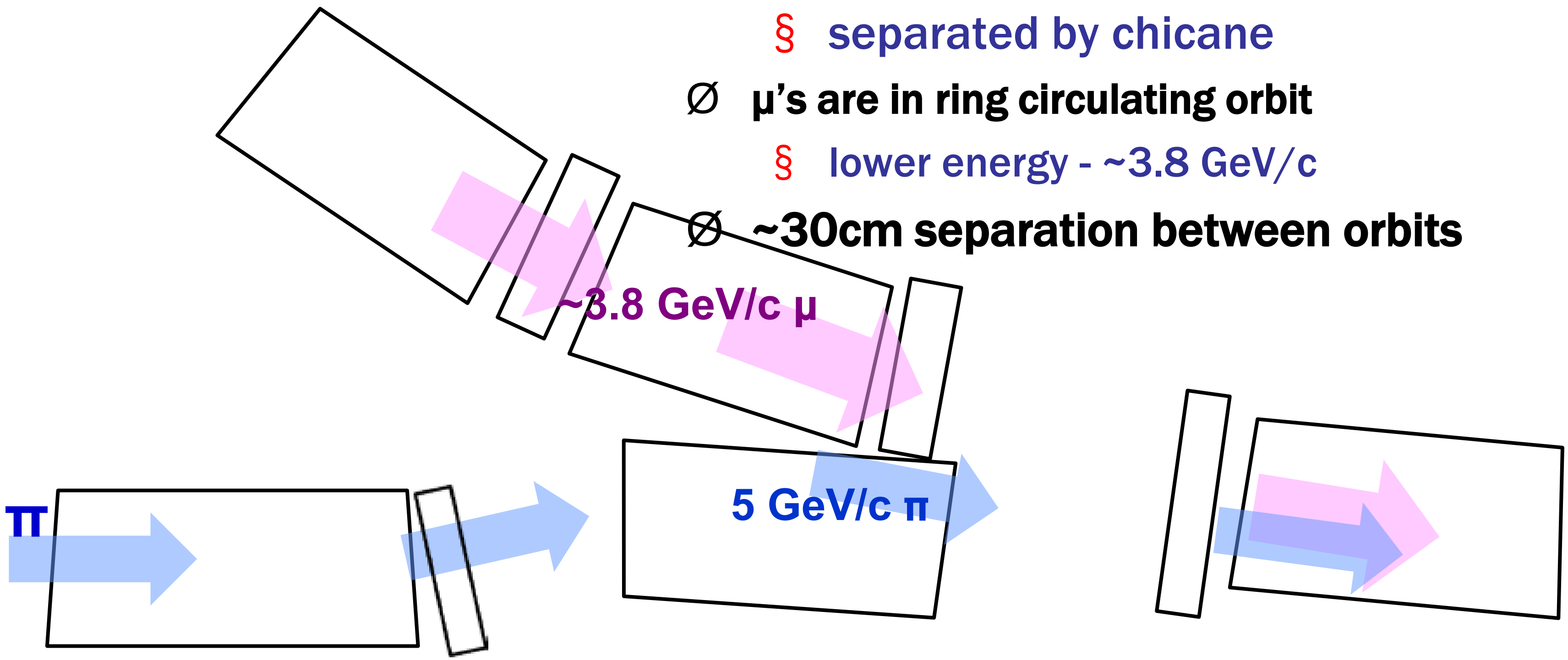


FIGURE 2B
"STOCHASTIC INJECTION" WITH SEPARATE π AND μ ORBITS.



Overview of stochastic injection

- π's are in injection orbit (~5 GeV/c)
  - separated by chicane
- μ's are in ring circulating orbit
  - lower energy - ~3.8 GeV/c
- ~30cm separation between orbits

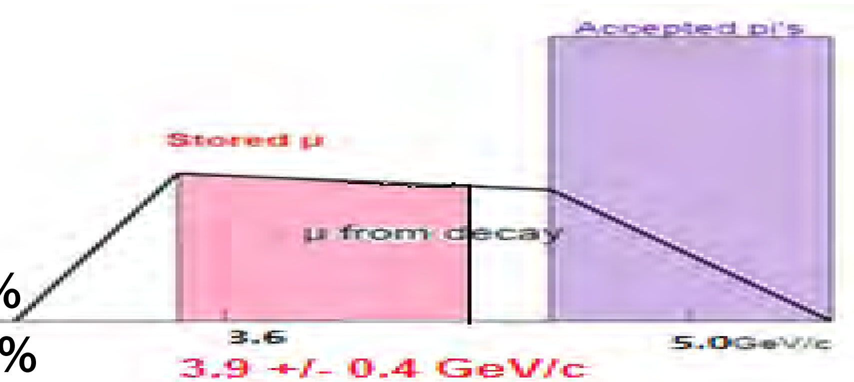


$$\pi \rightarrow \mu + \nu$$

$$P_\pi\left(1-\frac{{m_\mu}^2}{{m_\pi}^2}\right) < P_\mu < P_\pi$$

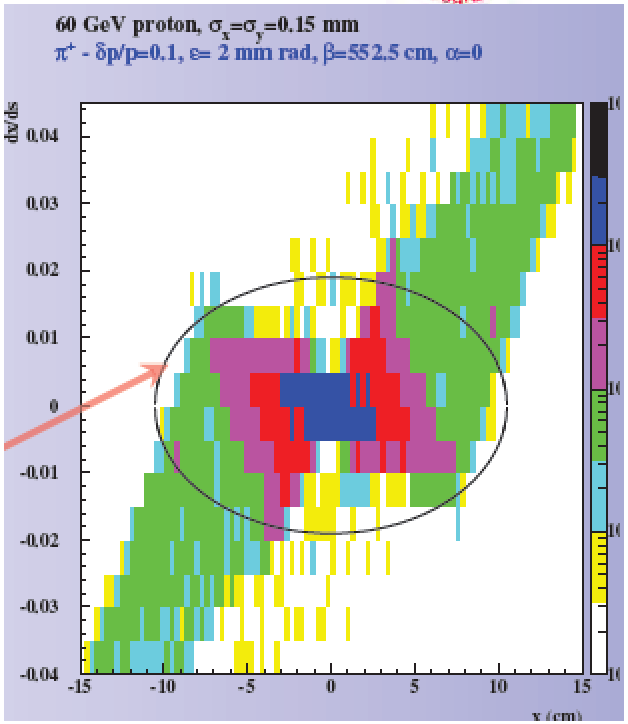
Injection Line accepts 5 GeV/c ± 10%

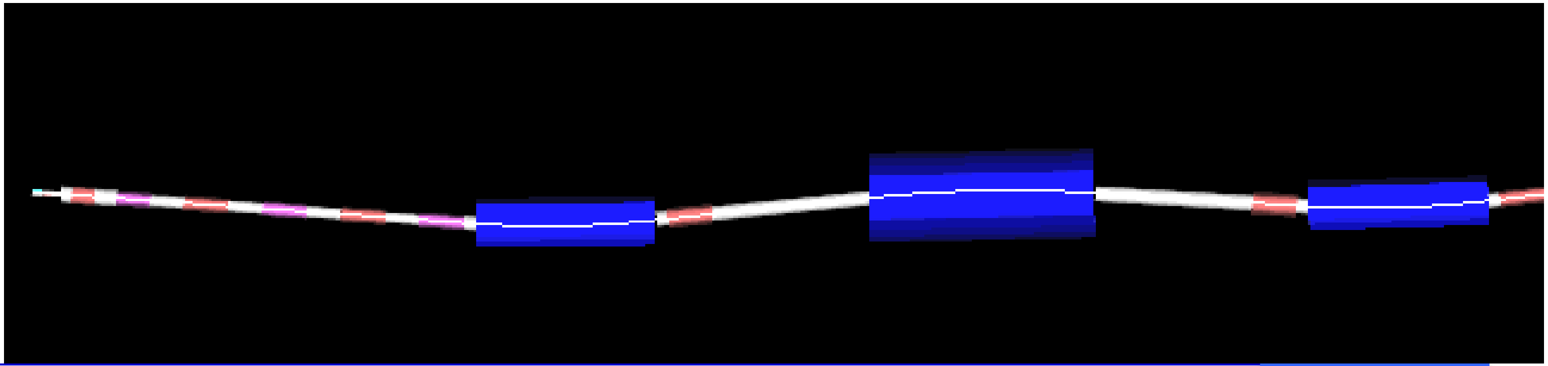
Storage Ring accepts 3.8 GeV/c ± 10%



Transport into Ring

- **Horn has greater acceptance than Li lens**
  - more established technology (nuMI)
    - large aperture Li lens requires R&D
- **Sequence of quads from Li lens into Ring (A. Liu)**
  - good acceptance of transport
  - ~0.1 π / p into ring ~5±0.5 GeV
    - ~0.01 μ/p stored in ring

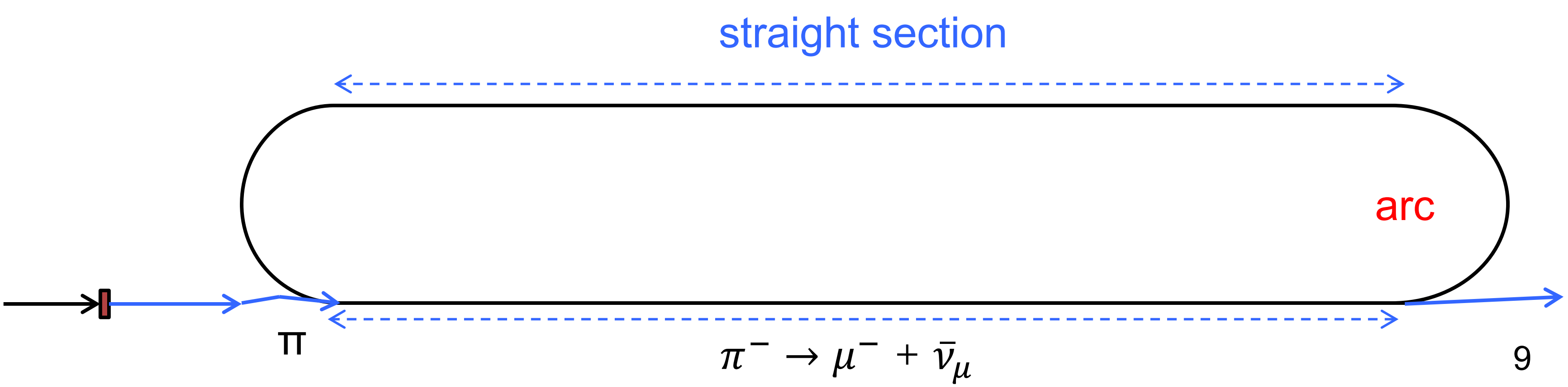




Q1 Q2 Q3 Q4 Q5 Q6 B1 Q7 Q8 B2 Q9 Q10 B3

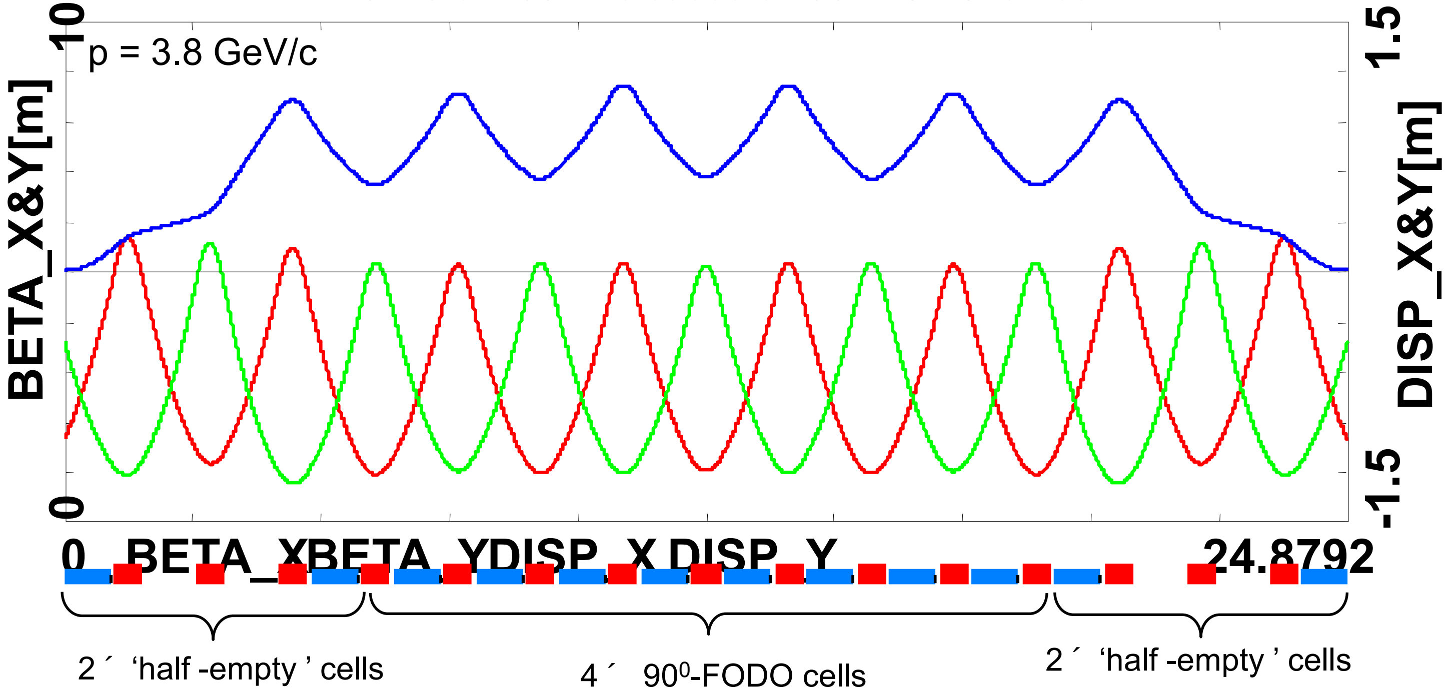
Lattices for storage rings

- **FODO Lattices**
  - Superconducting
    - B à 4T
    - A. Bogacz
  - Normal conducting
    - B<2T
  - Goal: ±10% momentum acceptance, 0.002m "emittance" acceptance
- **FFAG Lattices**
  - A. Sato, Y.Mori



Arc Optics- High Field

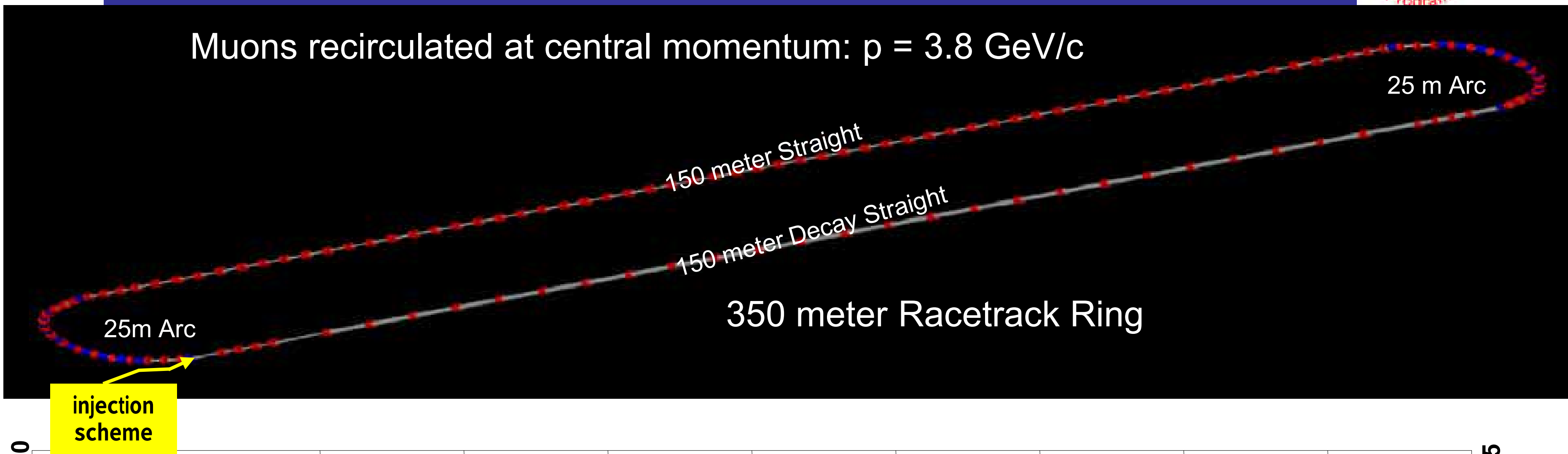
25 meter 180^0 Arc based on 90^0-FODO lattice

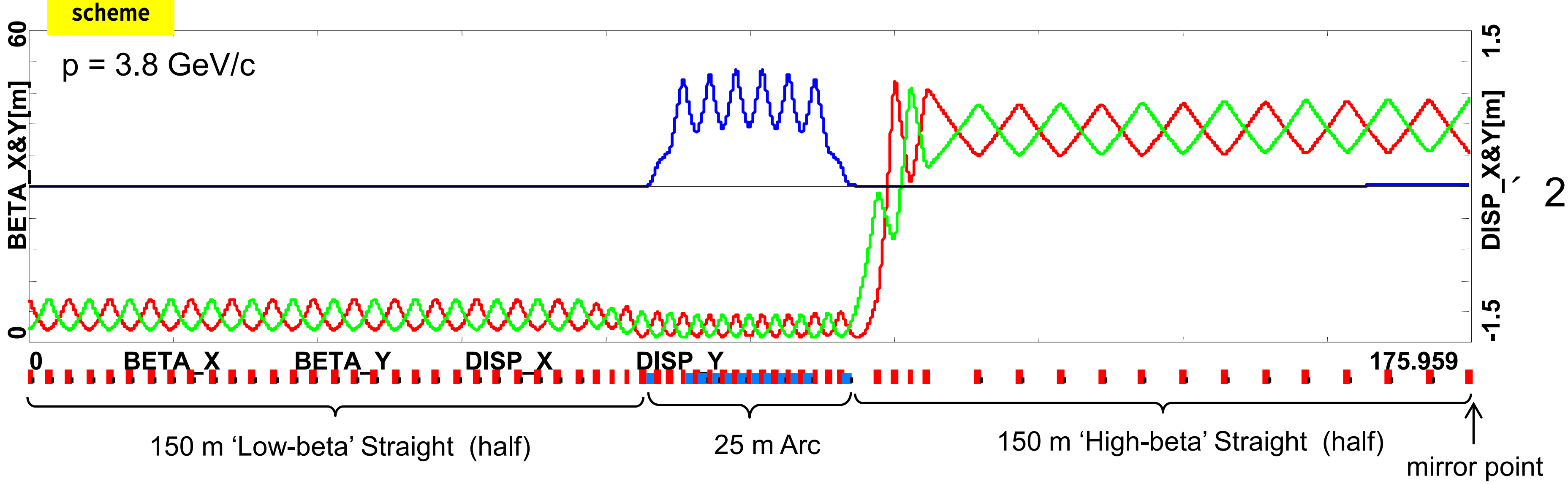


Aperture radius: r = 15 cm

12 ´ Dipoles:	field: **3.9 T**esla	length: 85 cm
15 ´ Quads:	gradient : 25 Tesla/m (3.8 Tesla at the pole)	length: 50 cm

Decay Ring – 3.8 GeV μ





Magnet Cost Estimate

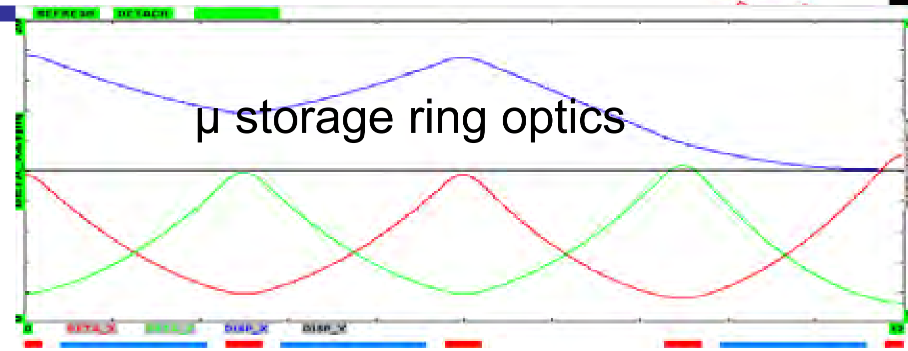
Strauss & Green Costing Model

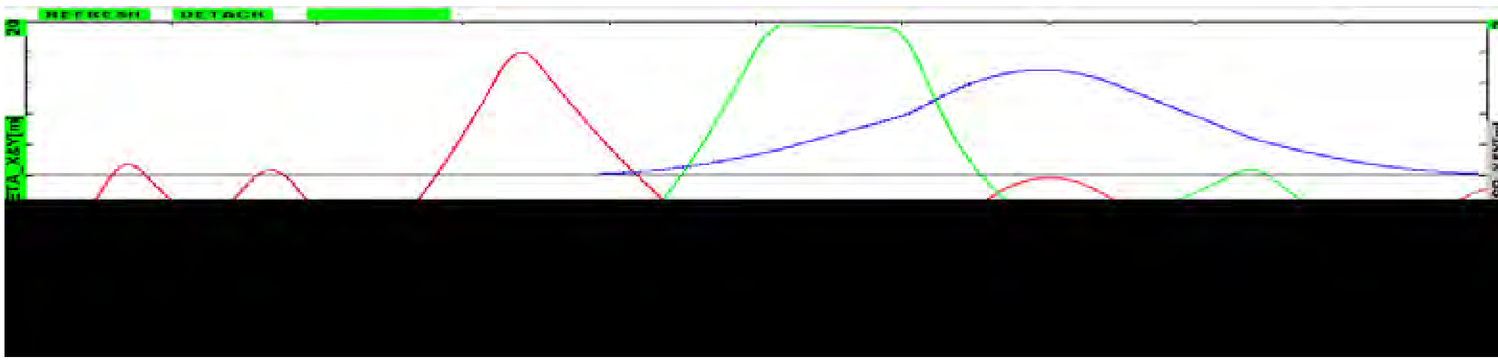
nuStorm Superconducting Magnets cost estimation June 28, 2012														
		Pole field	Eff. Length	Length	Int. strength	Aperture	Quantity	Gradient	Magnet Cost*	Total cost		3.142	Cryo	Cryo/magnet 65k$
Name	Type	Bp, T	Leff, m	Lm, m	T - m, or T	Diameter, m	Qty	G, T/m	C, M$	Total C, M$			Cr,M$	
D1	Dipole	3.9	0.85	0.55	3.32	0.3	24	0	0.3933	9.439			1.56	
Q1	Quadrupole	3.75	0.5	0.35	12.50	0.3	30	25.00	0.1730	5.191			1.95	
Q2	Quadrupole	1.65	0.6	0.45	6.60	0.3	63	11.00	0.1143	7.198			4.095	
Q3	Quadrupole	0.33	0.6	0.3	0.66	0.6	33	1.10	0.0988	3.261			2.145	
							150			25.1	M$		9.8	
* - magnet cost calculated using the magnetic field energy volume where Lm is the magnet physical and Leff- effective length														

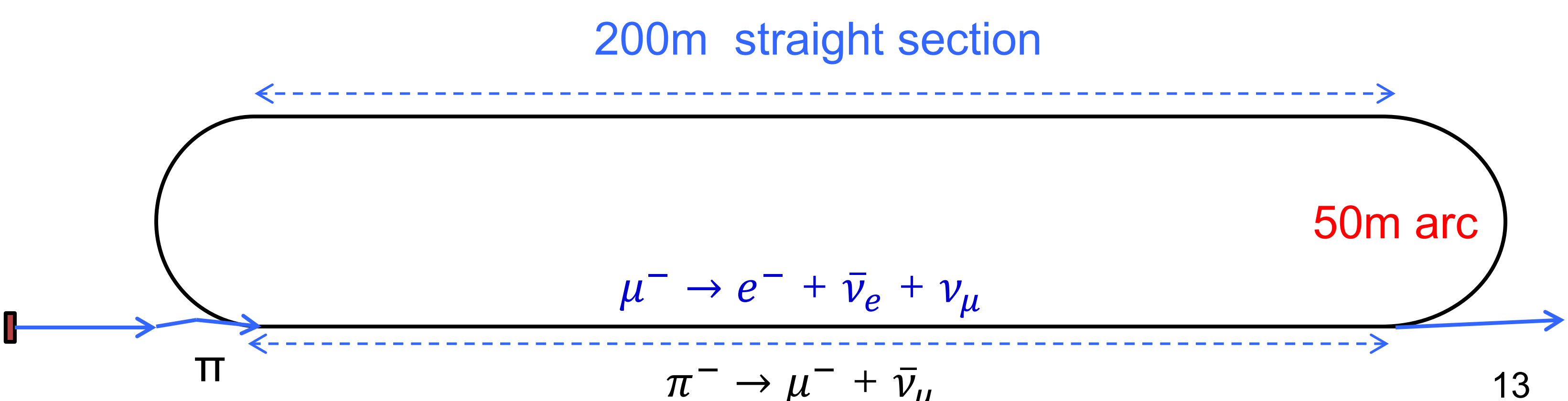
Vladimir Kashikhin

Alternate FODO lattice

- **Lower field**
  - not superconducting
- **Match into ring**



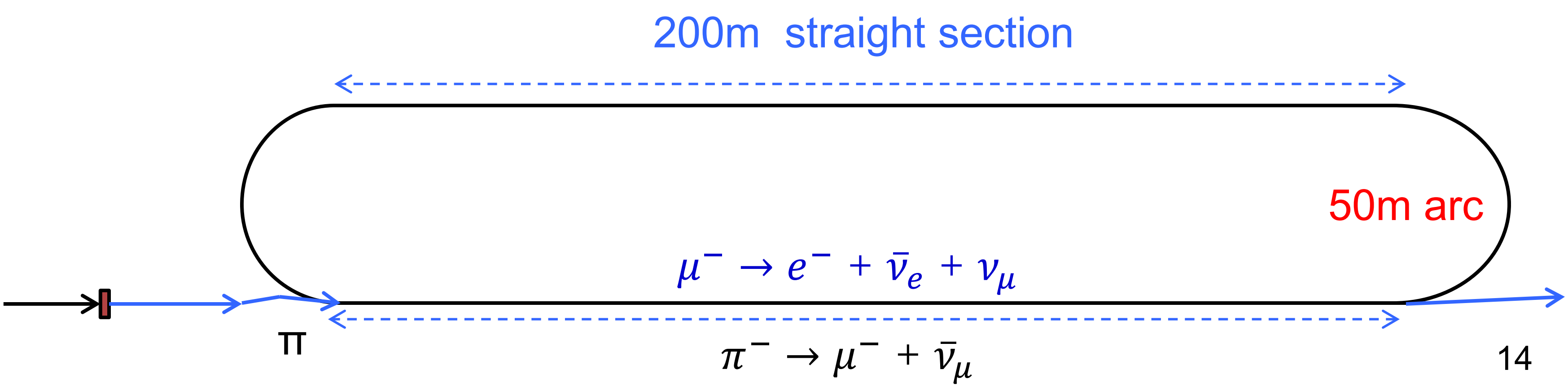




Alternate Low-field Storage ring

- **Inject ~5GeV π into Straight section to produce μ's from decay**
  - 50% of 5GeV π decay in 200m SS (60% in 250m)
  - Lower field à longer arc

    B<2T
  - longer quads to keep gradient lower
- **Straight section for π à μ capture and μ decay ν production**
  - decay channel must keep π beam confined to capture μ's from decay
- **Neutrino opening angle ~1/γ ~0.03**
  - beam transport angles ~0.005
    - $\theta_{rms} = \sim (\varepsilon_{rms}/\beta^{*})^{1/2}$
    - $\Delta\varepsilon_T = \sim (\beta^{*}\Theta_{decay}^{2})/2$
      - $\Theta_{decay} \sim 30/5000$



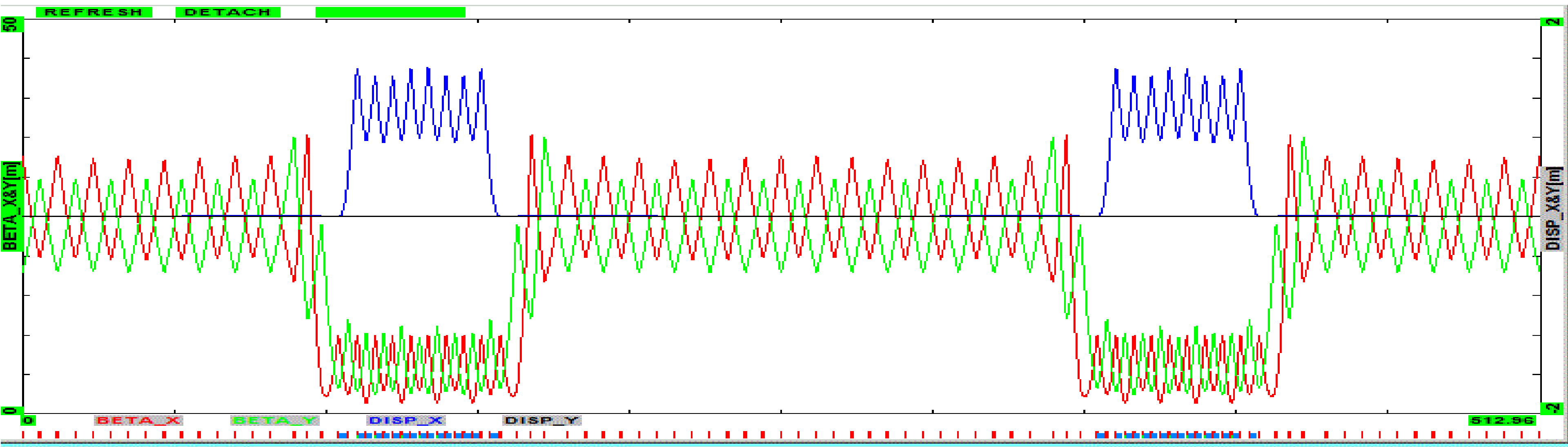
Lattice Parameters Low-Field

Parameter	Symbol	Value	Unit ∅
Cell length	L	6	m
Max β	β_{max}	10	m
Dispersion	η_{max},	1.2	m
Quad	B’, L	12T/m	0.5m
Dipole	B	1.2T	2.0m
β range in straight	β_{ss}	20/30	m

Low-Field (<2T) magnets

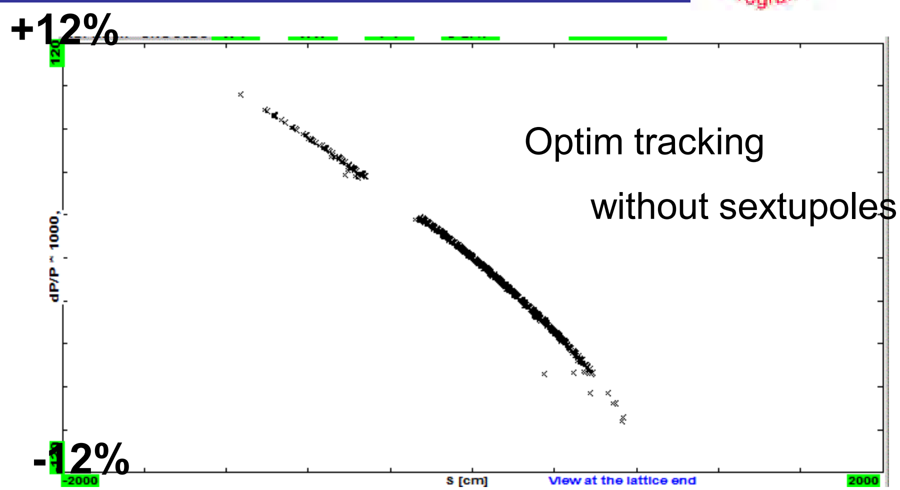
Arc quads would have r<0.15m

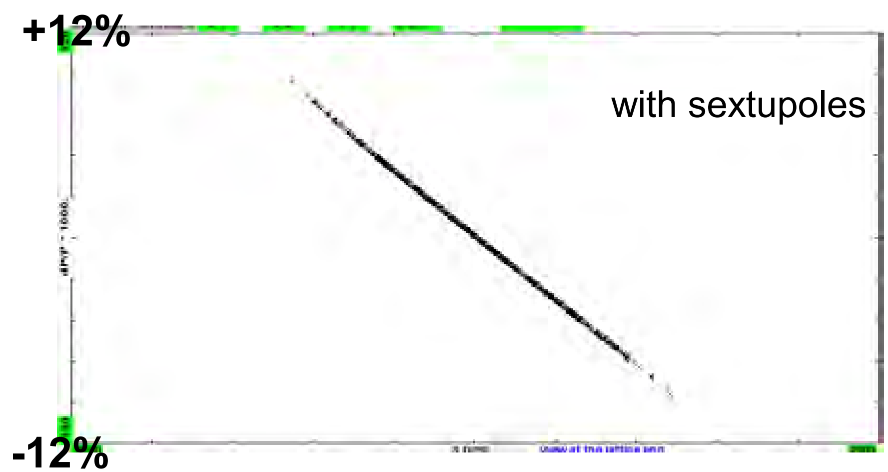
- $\varepsilon_{acc} = 0.15^2/10 = 0.002$m
- $\varepsilon_{acc,N} = \sim 0.08$m
  - $\varepsilon_{acc,N,rms} = \sim 0.015$m
- $\delta p/p = \pm 10\%$
- $\theta_{rms} = \sim 0.005$ (at $\beta_\wedge = 30$m)
- Angle from π-decay
  - 30 MeV/5000 -~0.006



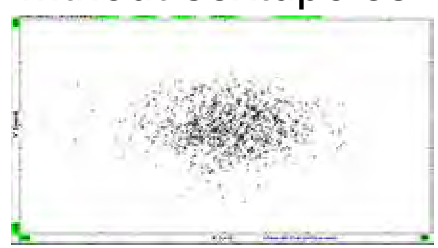
Lattice development

- **Momentum spread of ±10% crosses resonances**
  - beam loss at resonance momenta
  - sextupole reduces loss from resonances
    - increases nonlinear orbit distortion
  - optimization
    - vary tunes,
    - sextupoles to reduce chromaticity





without sextupoles



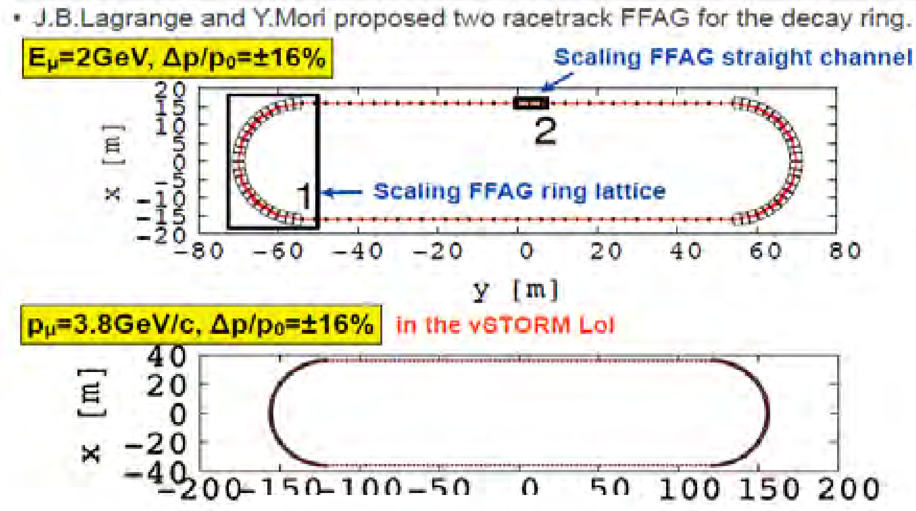
with sextupoles

Variations

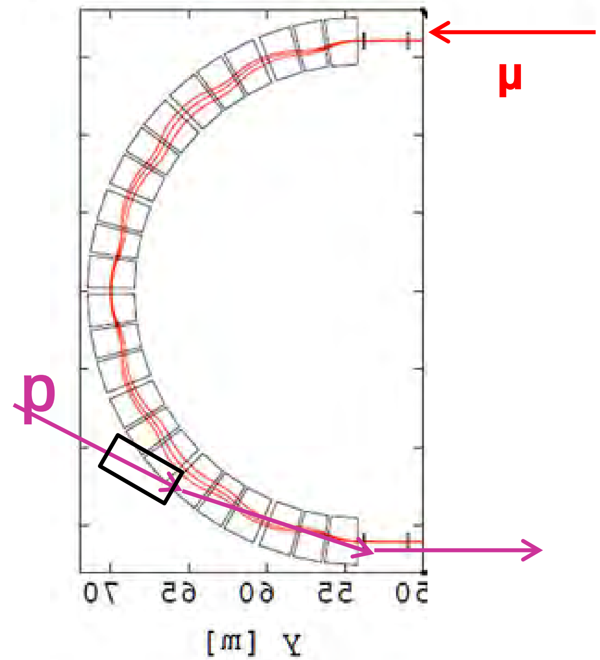
- **Ring Design**
  - Use FFAG-style lattice
  - must add injection
    - dispersion bump + septum

could have better acceptance

- FODO probably not best .



- **Inject**
  - In Space between cells-
    - increase space
  - Insert septum/separator magnet



Summary

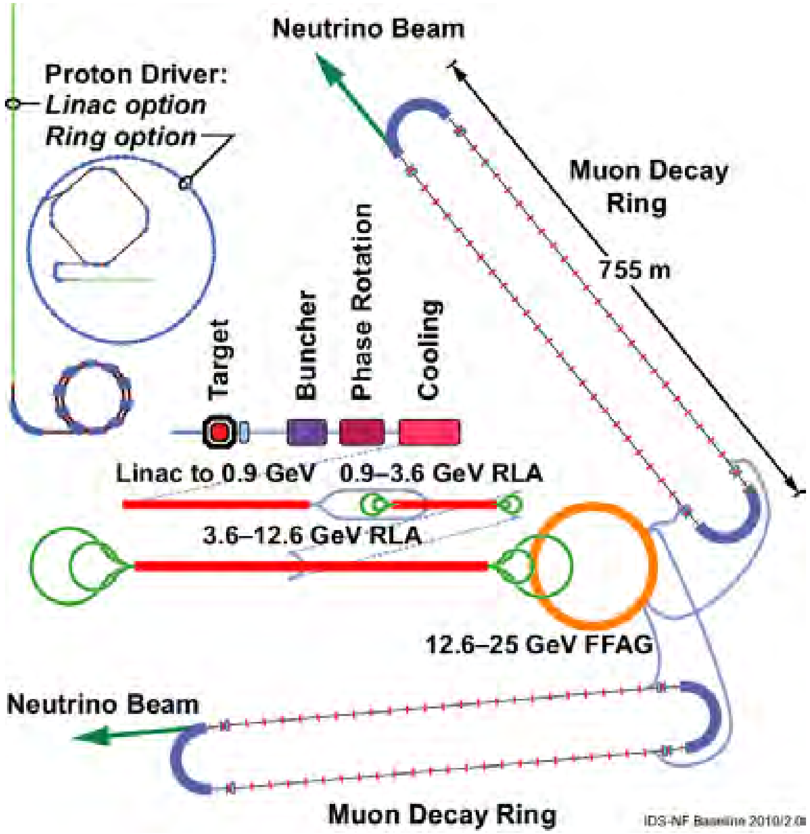
- **Presented a nuSTORM Storage ring overview**

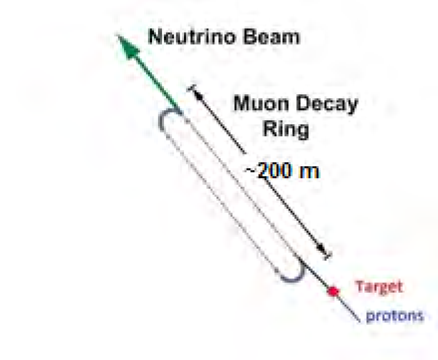
- **“stochastic” Injection of muons into storage ring**

- **Questions?**

Comparison of facilities

Ø IDS neutrino factory





Low-luminosity Neutrino Factory
nuSTORM