Neutrino Factory, $\mu^{\pm}$ Decay Rings

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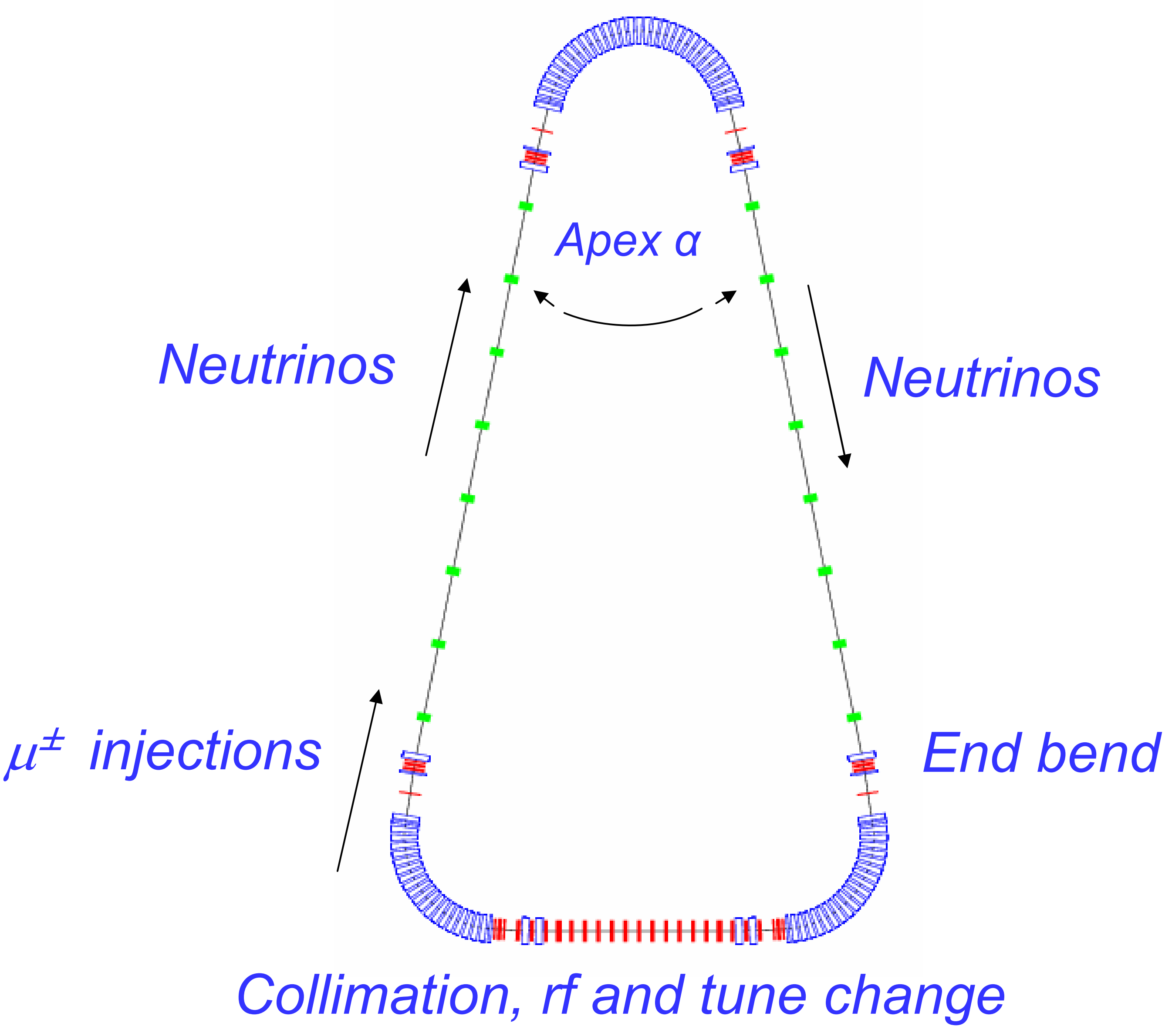
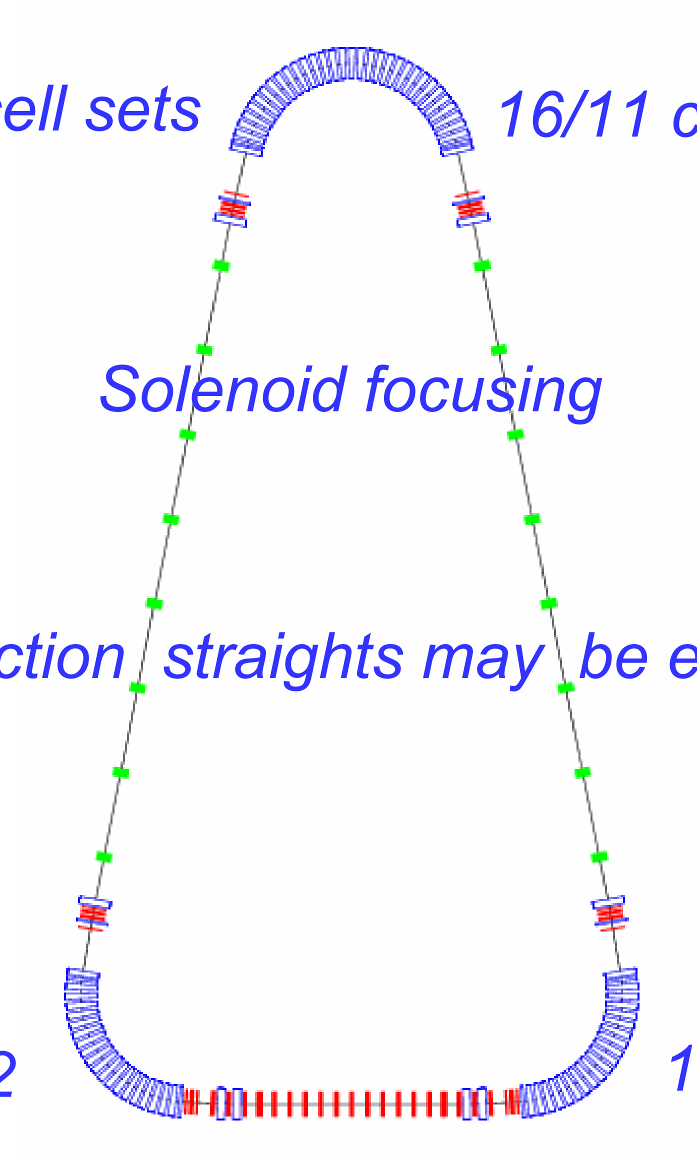
20 GeV Isosceles Triangle Rings (2)



50 GeV Isosceles Triangle Rings (2)



Triangle Ring Design Changes

- *Change from equilateral to an isosceles triangle ring.*
- *Design for MW intensities:* $\beta\gamma A = 30\ (1.5)^2\ (\pi\ mm\ r)$
- *Use box-car stacking for trains of 80* μ^+ *&* μ^- *bunches.*
- *Introduce a beam loss collection system for muons.*
- *Use combined not separated function magnets in arcs.*
- *Use solenoid focusing in the two production straights.*
- *Use bend units at the ends of the production straights.*
- *Use matching section bends to suppress dispersion*
- *(these influence the production straight orientations).*
- *Modify the lattice when upgrading from 20 to 50 GeV.*
- *Change some magnets and re-align ring for 50 GeV.*

Decay Ring Triangle Apex Angles

Numbers of arc cells determine triangle apex angles.
Five cell groups are used for the chromaticity control.

Arc cells	Apex angles (º)	Circ. (m)	Prod. st. (m)	RF harmonic (h)	Efficiency (%)
10+10+10	~60.0	1573.05	364.0	2^5 x3 x11	2 x 23.1
10+10+11	~52.8	1573.05	378.0	2^5 x3 x11	2 x 24.0
10+10+12	~45.0	1525.38	388.0	2^{10}	2 x 25.4
11+11+15	~34.5	1525.38	412.2	2^{10}	2 x 27.0
10+10+16	~22.4	1573.05	465.5	2^5 x3 x11	2 x 29.6

Note: Detectors at 7500 & 3500 km need apex angles of ~ 50°.

Proton and Muon, n =5, 50 Hz Bunch Trains

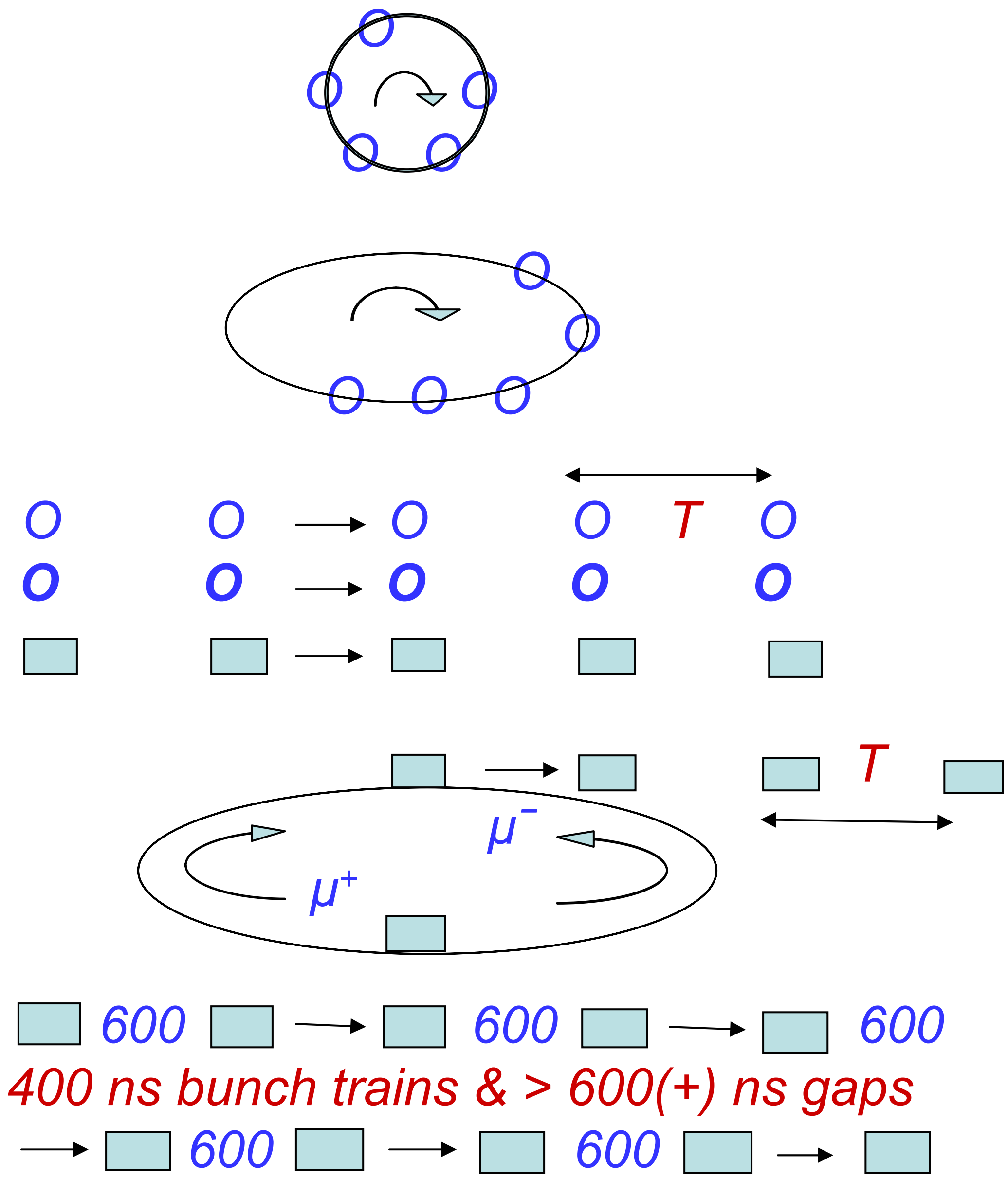
Proton booster (n=5, h=6)

Proton driver (n=5, h=36)

Proton bunches at target
Pion bunches after target
Muon, 400 ns bunch trains

(n-1)T< 60 μs (liquid target)
T > 60 μs (for solid targets)
20 GeV μ^+ & μ^- accelerator

20/50 GeV μ^+ decay ring
C>1500 m circumference
20/50 GeV μ^- decay ring



Ring Harmonic Numbers

Rings	Beta	Circ (m)	h	RF (MHz)	N_b /Ring
50 GeV μ Decay	0.9999977	1573.0691	1056	201.250	5x80
20 GeV μ Decay	0.9999861	1573.0509	1056	201.250	5x80
8-20 GeV $\mu^{\pm}$ Acc	0.9999861	1135.0991	762	201.250	10x80
3.2-8 GeV $\mu^{\pm}$ Acc	0.9999150			201.250	10x80
1-3.2 GeV $\mu^{\pm}$ Acc	0.9994890			201.250	10x80
3-10 GeV P Driver	0.9963143	801.44744	36	13.079-13.417	5
			216	80.500	5
			540	201.250	5
0.18-3 GeV Booster	0.9712057	400.72372	6	2.4422-4.3595	5

Box-car Transfer of μ^+ & μ^- to Decay Rings

The 20 GeV decay rings, 8-20 GeV $\mu^\pm$ acc & P driver, of periods T_d, T_a, T_p, all have 201.25 MHz as a harmonic. The integers p (= 1,2,3 ,4), n and m are chosen so the proton bunch delays are a good approximation to:

$$(n \pm p/5)\ T_d \approx (m \pm 1/12)\ T_p$$

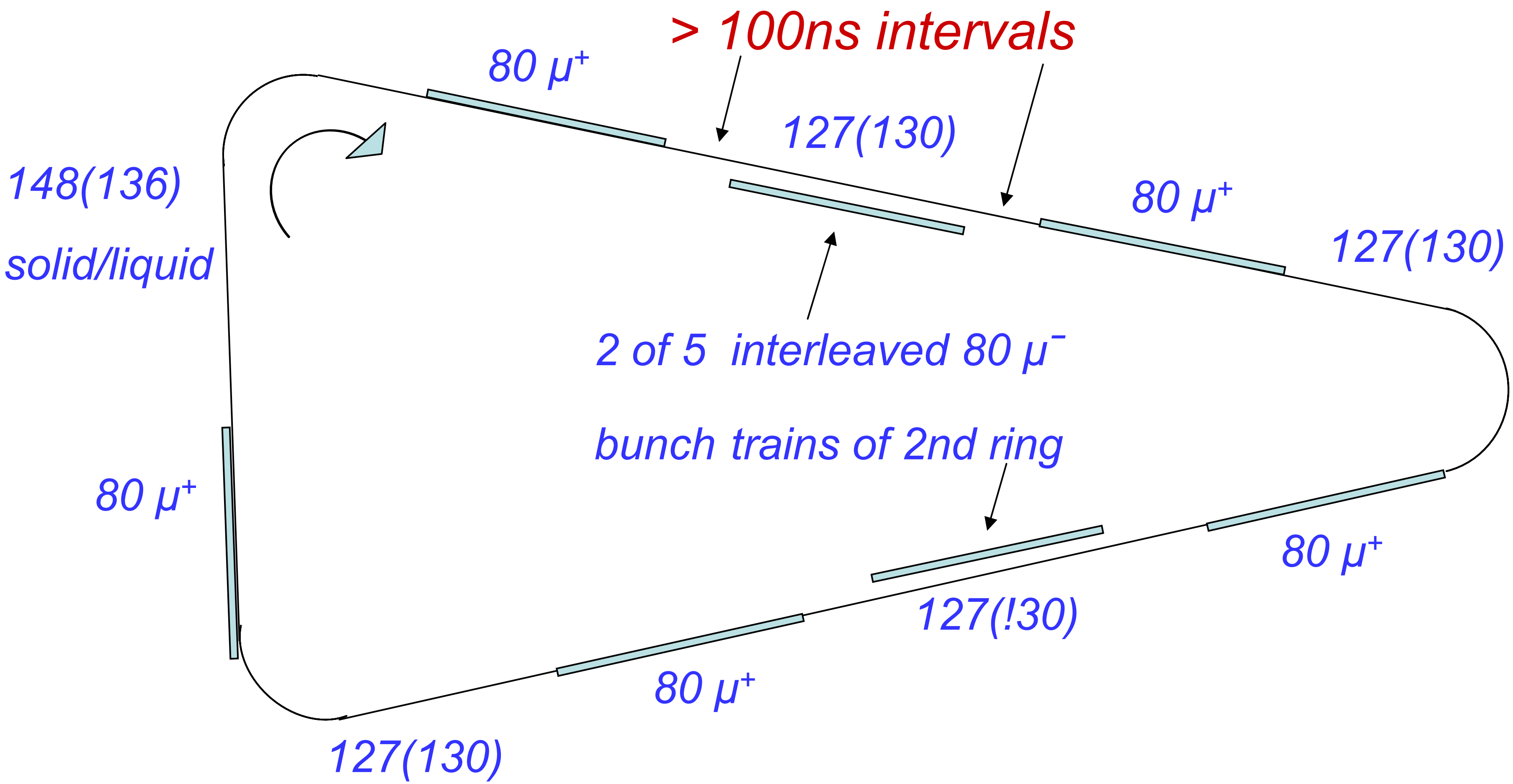
T_d, T_a, T_p = 5.2472044, 3.7863345, 2.6832296 μs, (T_d / T_p) = 1.9555554

Target	m	n	p	(m ± 1/12)	$(n \pm p/5)\ (T_d / T_p)$	|Difference|
Solid	23	12	-1	23 + 0.083333	23.075553	0.007780
Liquid	5	3	-2	5 + 0.083333	5.084444	0.001111

For solid target: $(m + 1/12)\ T_p = n\ T_d - 207\ T_b$ (RF period T_b)

For liquid target: $(m + 1/12)\ T_p = n\ T_d - 423\ T_b$

N=5, Muon Bunch Pattern in Decay Rings



80 full and 127 (or 130) empty RF buckets

Other Triangle Ring Options

1. A wider range of apex angles may be obtained by adding half cells in one or more of the arcs.
2. Production straights may have different lengths, but ξ gain of longer is < loss in ξ of the latter.
3. For specified detector distances, the smallest apex angle is for a triangle in a vertical plane.
4. Smaller circumference rings may be considered with n reduced from 5 to 4, 3 or 2 bunch trains.

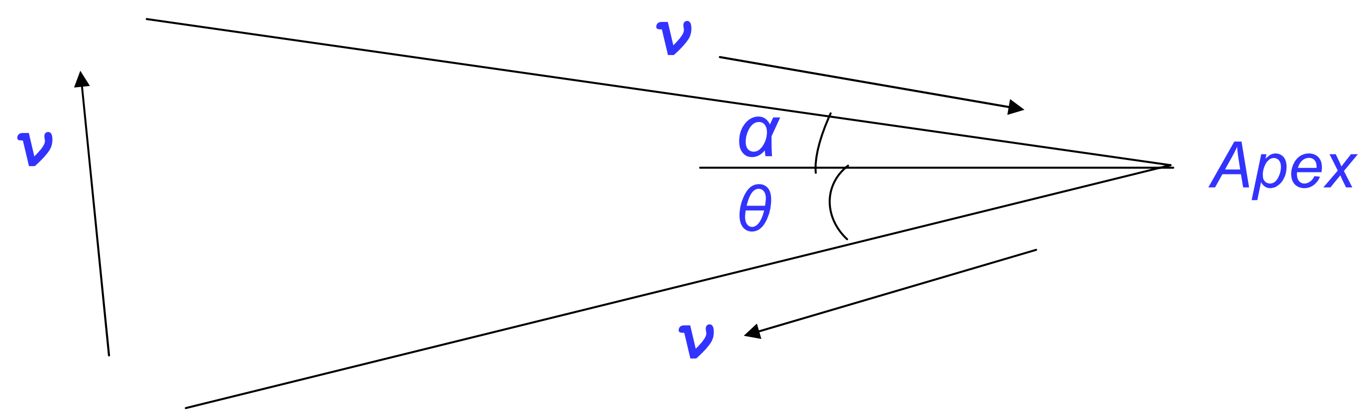
Efficiencies for Smaller Decay Rings

Circumference (m)	Prod St (m)	Efficiency	Racetrack
1573.05	2 x 378.0	48.0%	38%
1258.44	2 x 268.0	42.6%	35%
943.83	2 x 156.9	33.2%	30%
629.22	2 x 14.8	4.7%	20%

Each reduction in circumference lowers the efficiency and, for the last case, a racetrack is the more efficient.

There is concern for the > 400 m depths of triangle and racetrack rings, at the circumference of 1573 m.

Vertical Plane Triangle Ring



$\sin\alpha = L_1/2R$ $\sin\theta = L_2/2R$

L_1, L_2 detector distances R the equatorial radius

L1	L2	Apex angle $(\alpha + \theta)$
3500 km	7500 km	~ 52.0°
2500 km	7500 km	~ 47.5°

Site Examples

NuFact	Detector 1	Detector 2	Apex α	Vert. tilt
BNL	Carlsbad (2883 km)	Arlit (7369 km)	48.4°	0.9°
RAL	Carlsbad (7513 km)	Baksan (3375 km)	60.2°	33.9°
		Cyprus (3251 km)	51.7°	10.7°
		Crete (2751 km)	48.6°	1.0°

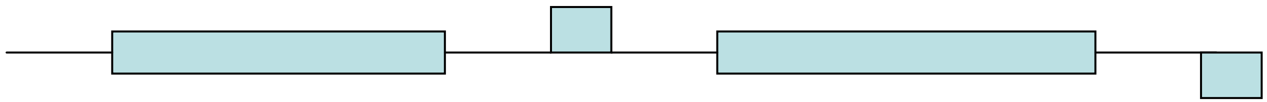
Muon Beam Loss Collection

Due to the $e^{\pm}$ losses after $\mu^{\pm}$ decays, the warm bores of S/C arc magnets have to be cooled, & clad with Pb. (The cladding absorbs > 80% of the $e^{\pm}$ beam power.) Direct $\mu^{\pm}$ wall loss also leads to magnet heating, and to minimise this, $\mu^{\pm}$ loss collection is proposed, with primary and secondary collimators in 4 FODO cells at the centre of the short straight section of the ring,

Primary collimators are set for : $\beta\gamma A = 30$ (π mm r).
The ring acceptances are: $\beta\gamma A = 30\,(1.5)^2$ (π mm r).

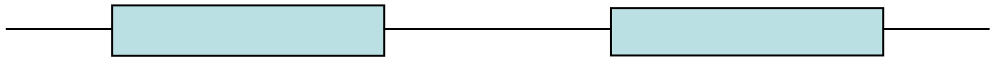
Arc Cell Design

CERN 10,10,10 FODO design:



Lengths = 9.703, 0.7 m, $\mu = \pi/2$, β_{max} = 16.6 m, D_{max} = 1.4 m.

New 10,10,16 BFOBDO, FFAG design:



Lengths = 7.80, 1.4 m, $\mu = 2\pi/5$, β_{max} = 12.1 m, D_{max} = 1.2 m.

(space for cryostat ends, valves, correctors, diagnostics, vacuum & cooling)

Production Straight Focusing

A figure of merit for lattice focusing is: $1 / (\gamma\beta_{max})$

For a thin lens FODO: $\gamma\beta_{max} = 2/(1 - \sin \mu/2) \quad > 2$

For an OSO lattice of weak solenoids: $\gamma\beta_{max} \approx 1$

So, the OSO cell has a 50% lower value for β_{max}.

For 52.8°, use 8, 4.75 m units in 378.0 m straights:

At 20 GeV, $\beta_{max} \approx 99$ m for solenoids with 4.3 T.

At 50 GeV, $\beta_{max} \approx 163$ m for solenoids with 6.4 T.

Neutrino Production Straights

	20 GeV	50 GeV
Muon norm rms emitt (π mm r)	4.80	4.80
μ to ν divergence angle ratio, R	0.098	0.119
Number of solenoids	8	8
Solenoid fields (T)	4.272	6.369
Length of solenoids (m)	4.75	4.75
Half of inter space (m)	16.8	16.8
β value at beam waist (m)	~94.3	~160.3
β (max) in solenoid (m)	~99.1	~163.1

Effect of Production Region End Bends

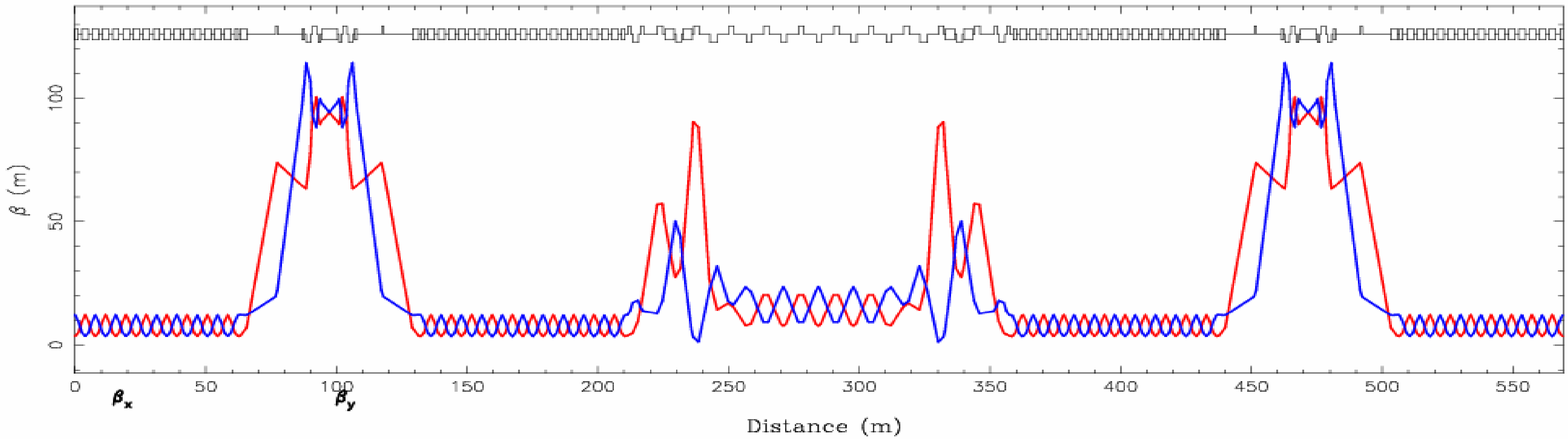
Neutrinos, from $\mu^{\pm}$ beyond the bends, miss detectors.
Bends introduce dispersion, however, into the lattice.

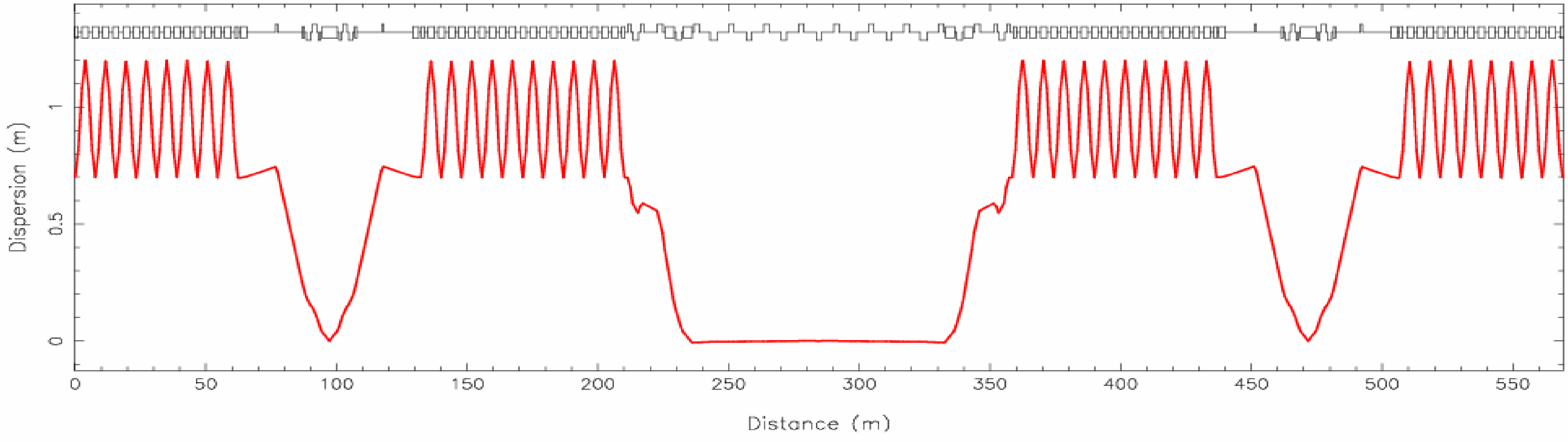
Matching of dispersion to arcs requires further bends, which are different for the 20 and the 50 GeV lattices.

Small changes in the arc bend angles are required to preserve the orientation of the 2 production straights.

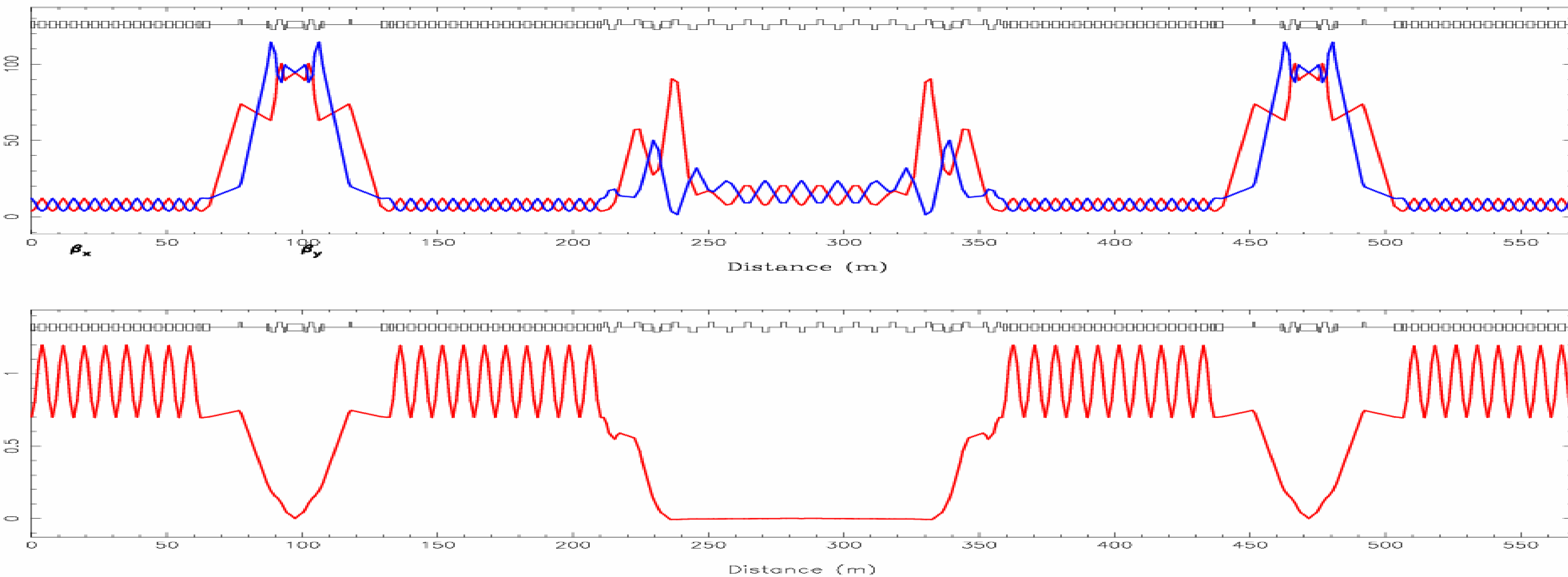
Dispersion in the third straight is also affected and modified matching is needed for the 50 GeV upgrade.

20 GeV Lattice Functions outside Production Straights





Production to Collimation Straight Matching



Storage Ring Parameters

Efficiencies for 22.4° apex Δ:	2 x 29.6 %
Efficiencies for 52.8° apex Δ:	2 x 24.0 %
Production straights of above:	465.5, 378.0 m
Decay rings' circumference:	1573.1 m
μ to ν angle ratio at 20 GeV:	0.098
μ to ν angle ratio at 50 GeV:	0.119
Max β in the ring at 20 GeV:	117.0 m
Max β in the ring at 50 GeV:	184.0 m
Q_h and Q_v values at 20 GeV:	13.367, 13.184
Q_h and Q_v values at 50 GeV:	13.187, 12.817

First Tracking of 22.4°, 1170.8 m, 20 GeV Ring

On-momentum muons:

Horizontal ε_n = 60 (π) mm rad only, Q_h = 10.79 -10.80

Vertical ε_n = 60 (π) mm rad only, Q_v = 11.147 - 11.155

Hor. & vert. ε_n = 30 (π) mm rad, Q_h ,Q_v= 10.81, 11.166

Effect of the solenoid (+-+-+-+-) coupling is small.

Off-momentum muons:

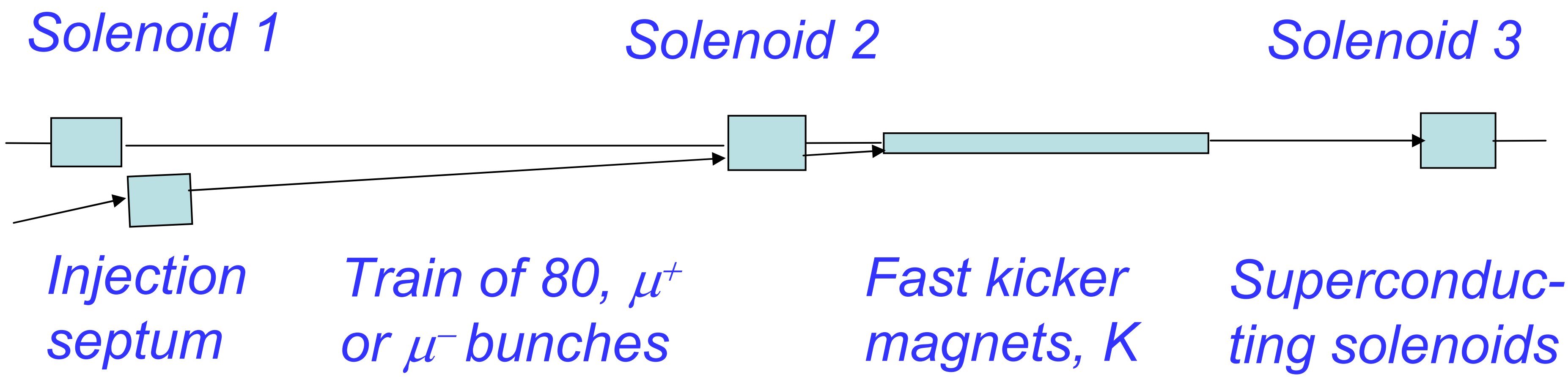
$\Delta p/p$ = 0.5%, hor. & vert. ε_n = 60 (π) mm rad; stable.

$\Delta p/p$ = 1.0%, h. & v. ε_n = 45 (π) mm rad; just unstable.

Q_v decreases to 11.0, in agreement with ξ_v estimates.

Injection of n Trains of 80 $\mu^{\pm}$ Bunches

Long neutrino production straight section



K stored energy/power is large due to the big acceptance & the ~ 600 ns rise & fall times for the 1573.1 m circumference ring, which has n (= 5) injected bunch trains per 50 Hz cycle. Induction kickers may be needed for the upgrade to 50 GeV.

Injection System Parameters

Inject at upstream end of long straight nearest surface.

$\theta_k \approx \sqrt{\beta_k}\,(\sqrt{A} + \sqrt{\varepsilon} + t_s/\sqrt{\beta_s}) \,/\, (\beta_k \sin \Delta\mu + \tfrac{1}{2}\, NL \cos \Delta\mu)$

NL I (number, length, current) $= 2\,(B\rho)\,\theta_k \sqrt{(A\,\beta_v)}\,/\,\mu_o$

NT V (number, rtime, voltage) $= 2\,(B\rho)\,\theta_k \sqrt{(A\,\beta_k)}$

At 20 GeV, for $A, \varepsilon = 354.7, 157.7$ *mm mr,* $t_s = 15$ *mm,*

$\beta_s \approx \beta_k \approx \beta_v \approx 95.0$ *m,* $\Delta\mu \approx 25°$, $B\rho = 67.064$ *T m,* $T = 435$ *ns:*

Use 8, shorted, 3m, 10 Ω delay line, push pull K with 16, 50 kV PFN; 16, 5 kA pulsers and 16, 10 Ω feeders.

$NL = 24$ *m,* $\theta_k = 6.47$ *mr,* $I = 5000$ *A,* $NT\,V = 0.16$ *V s*

Longitudinal Motion and RF

RF needed to keep 100 ns gaps if $n=5$, but not if $n<5$.
Injected bunch trains are tilted in longitudinal phase space & rotate in RF cavity & wall impedance fields.

Injected bunches are allowed to expand in phase until

$$\Delta\varphi = \pm\, \pi/2 \text{ rad, for } \Delta p/p = \pm\, 0.01$$

Required are 30 MV, 201 MHz containing fields/ ring.

The required net RF containing field scales as $(\Delta p/p)^2$ and the dynamic aperture also improves at lower $\Delta p/p$.

RF System for Rings

Inductive wall fields are defocusing as $\gamma > \gamma_t$.
Fields become small after the bunches expand.

Reactive beam loading comp.; cavities on tune.
Loading alters after each injected bunch train.
Reflected power dissipated in circulator loads.

The peak power for n = 5 is ~ 5.4 MW per ring.
So, for 2x1 MW input couplers: 3 cavities/ring.

Design Summary

An outline design has been made for 2, isosceles triangle, 20 (potentially 50) GeV, $\mu^{\pm}$ storage rings.

For a single detector, 2 racetrack rings are preferred.
For 2 detectors, 2 vertical triangle rings have higher ξ.

C = 1573.1 m, L = 378 m, ξ = 2 x 24.0%, 52.8° apex Δ.
C = 1258.4 m, L = 268 m, ξ = 2 x 21.3%, 52.8° apex Δ.
The MW rings have large βγA, at 30 $(1.5)^2$ (π mm r).

Production straight solenoids give lower beam sizes.
μ to ν angle ratios are 0.10 & 0.12, at 20 & 50 GeV.

F Meot is tracking to find dynamic aperture with errors.
Injection difficult for uncooled (45 π mm r) $\mu^{\pm}$ beams.