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

C Johnstone, FNAL, F Meot, CEA, & G H Rees, RAL

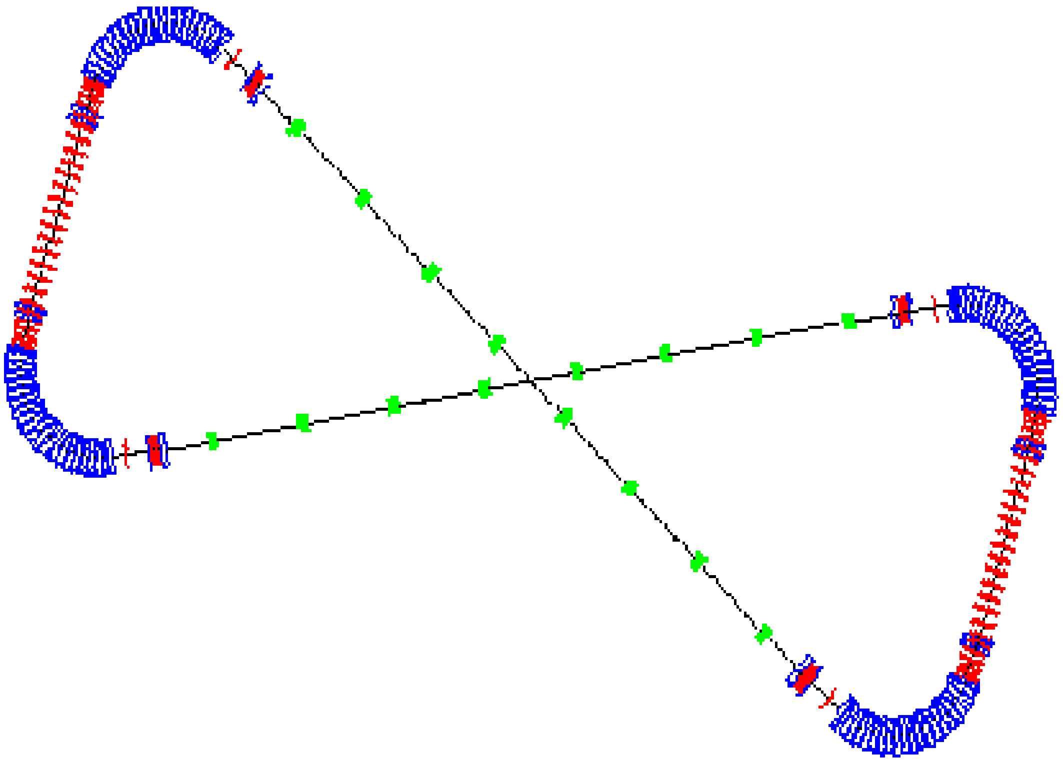
Decay Ring Tunnels

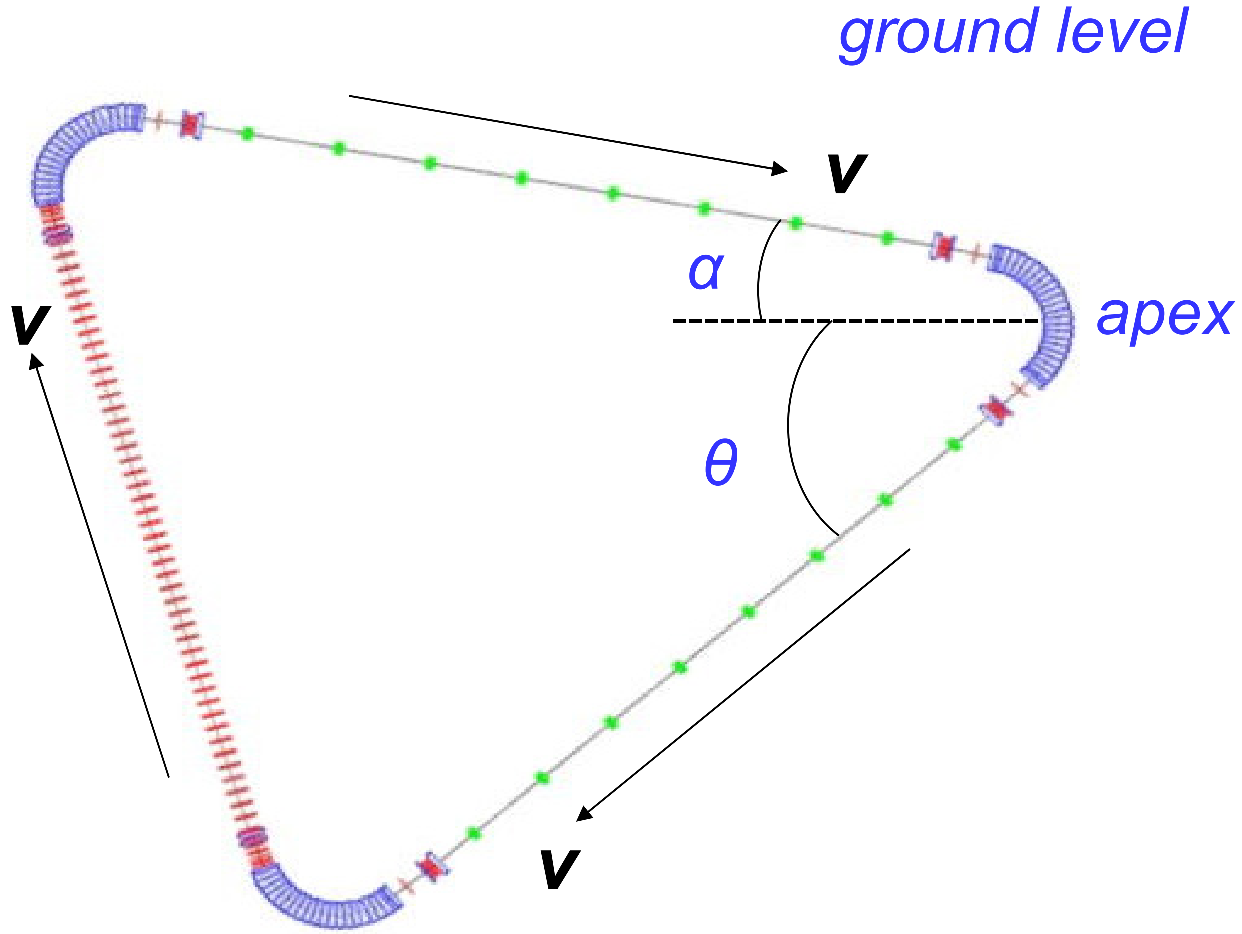
- *Assume neutrino detectors at 7500 and ~ 3500 km*

- *The isosceles Δ and bow-tie designs have μ^+ & μ^- beams in two adjacent rings, all in a common tunnel*
- *Each ring has two production straights, and each of the detectors takes neutrinos from both μ^+ & μ^- rings*

- *The racetrack ring designs use separate tunnels and this eases the task of finding suitable detector sites*
- *Each racetrack ring has just one production region, so that each ring is aligned to its own neutrino detector*

Bow-tie Decay Ring





$\sin\alpha = L_1/2R$

L_1, L_2 detector distances

$\sin\theta = L_2/2R$

R the equatorial radius

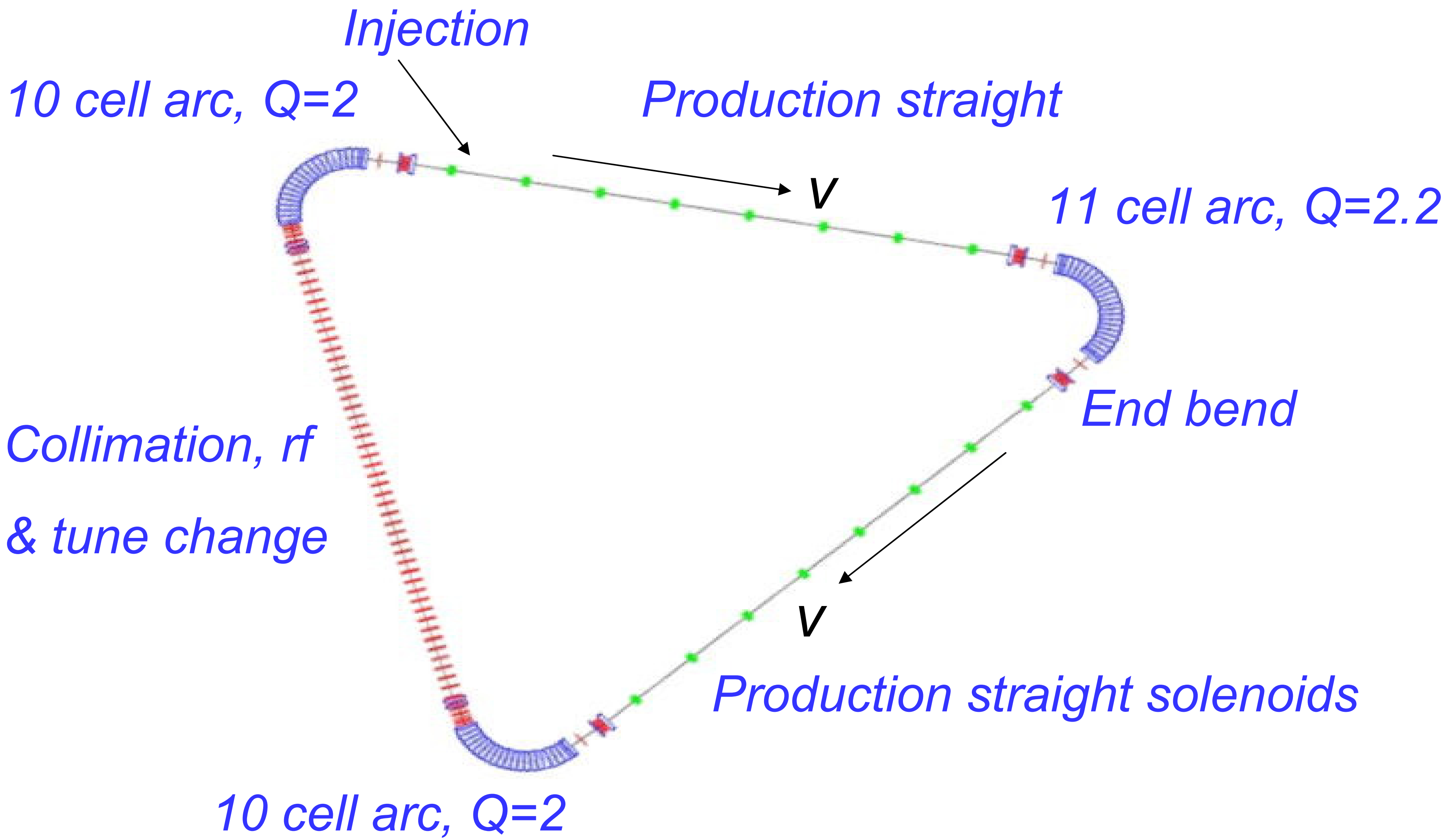
Vertical Plane Layout for 2 Isosceles Triangle Rings

Triangle Ring Production Efficiencies

Best for ν-production efficiency are vertically aligned, adjacent, triangular rings of minimum apex angle, with two detectors in opposite directions, in gnomonic projection. Some inclination to a vertical plane is expected for most pairs of detector sites:

For an RAL Neutrino Factory with two, 1608.8 km circumference decay rings, and neutrino detectors at Carlsbad (7513 km) and:

2nd detector site	*Vertical tilt*	*Apex angle*	*Production Efficiency*
Baksan (3375 km)	*30.6°*	*60.2°*	*2 x 23.9 %*
Cyprus (3251 km)	*9.7°*	*51.7°*	*2 x 25.0 %*
Crete (2751 km)	*0.9°*	*48.6°*	*2 x 25.4 %*



Schematic Plan of Triangle Ring

Triangle Apex Angles

- The number of arc cells sets the apex angle of triangle
- Smallest apex angle is for a triangle in a vertical plane
- Detectors at 7500 & 3500 km need ~ 50° apex angles.
- Groups of five cells are used for control of chromaticity

Arc cells	Apex angles	Circumf.	Prod. straight	Efficiency
10+10+10	~60.0°	1608.8 m	383.7 m	2 x 23.9 %
10+10+11	52.8°	1608.8 m	398.5 m	2 x 24.8 %
10+10+12	~45.4°	1608.8 m	415.3 m	2 x 25.8 %
10+10+16	~22.4°	1608.8 m	482.0 m	2 x 30.0 %

Features of Triangle & Bow-tie Rings

- Designed for MW intensities: $\beta\gamma A = 30\ (1.5)^2\ \ (\pi\ \mathrm{mm\ r})$
- Uses a beam loss collection system for the muons
- Uses combined not separated function magnets in arcs
- Uses solenoid focusing in the two production straights
- Uses bend units at the ends of the production straights
- Uses box-car stacking for trains of 80 μ^+ & μ^- bunches
- Uses matching section bends to suppress dispersion (these influence the production straight orientations).
- Lattice is modified when upgrading from 20 to 50 GeV (Some magnets changed & ring re-aligned for 50 GeV).

Production Straight Focusing

- *A figure of merit for lattice focusing is: $1 / (\gamma\beta_{max})$*
  For a FODO thin lens: $\gamma\beta_{max} = 2/(1 - \sin \mu/2) > 2$

- *For an OSO lattice of weak solenoids: $\gamma\beta_{max} \approx 1$*
  So, β_{max} (OSO) may be one half of β_{max} (FODO)

- *Eight, 4.8 m solenoids in 398.5 m straight sections:*
  At 20/50 GeV, $\beta_{max} \approx 99/163$ m for 4.3/6.4 T solenoids

Production Straight End Bends

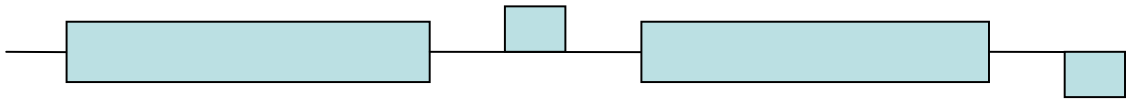
- *Neutrinos, from $\mu^{\pm}$ beyond the bends, miss detectors. Bends introduce dispersion, however, into the lattice.*
- *Matching of dispersion to arcs requires further bends, which are different for the 20 and the 50 GeV lattices.*
- *Small changes in the arc bend angles are required to preserve the orientation of the 2 production straights.*
- *Dispersion in the third straight is also affected and so modified matching is needed for the 50 GeV upgrade.*

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	0.10	0.12
Number of solenoids	8	8
Solenoid fields (T)	4.27	6.37
Length of solenoids (m)	4.75	4.75
Half of inter space (m)	21.1	21.1
β value at beam waist (m)	~94.3	~160.3
β (max) in solenoid (m)	~99.1	~163.1

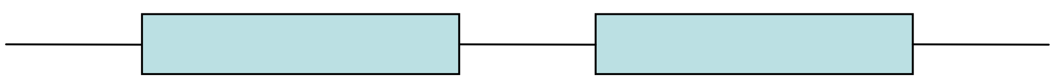
Arc Cell Design

Old CERN 10,10,10 FODO design:



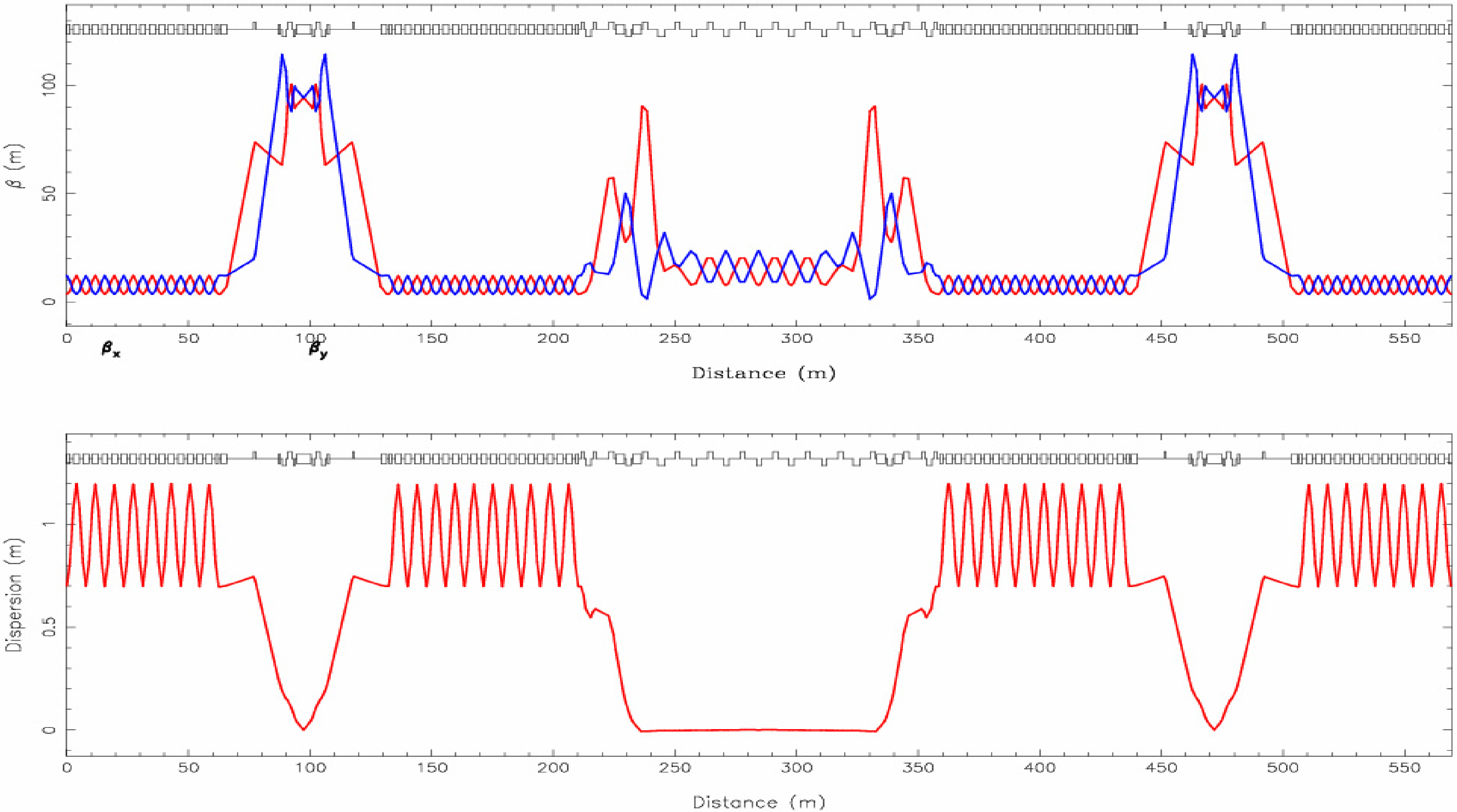
Lengths = 9.703, 0.7 m, $\mu = 90°$, $\beta_{max} = 16.6$ m, $D_{max} = 1.4$ m.

New 10,10,11 (BF)O(BD)O design:

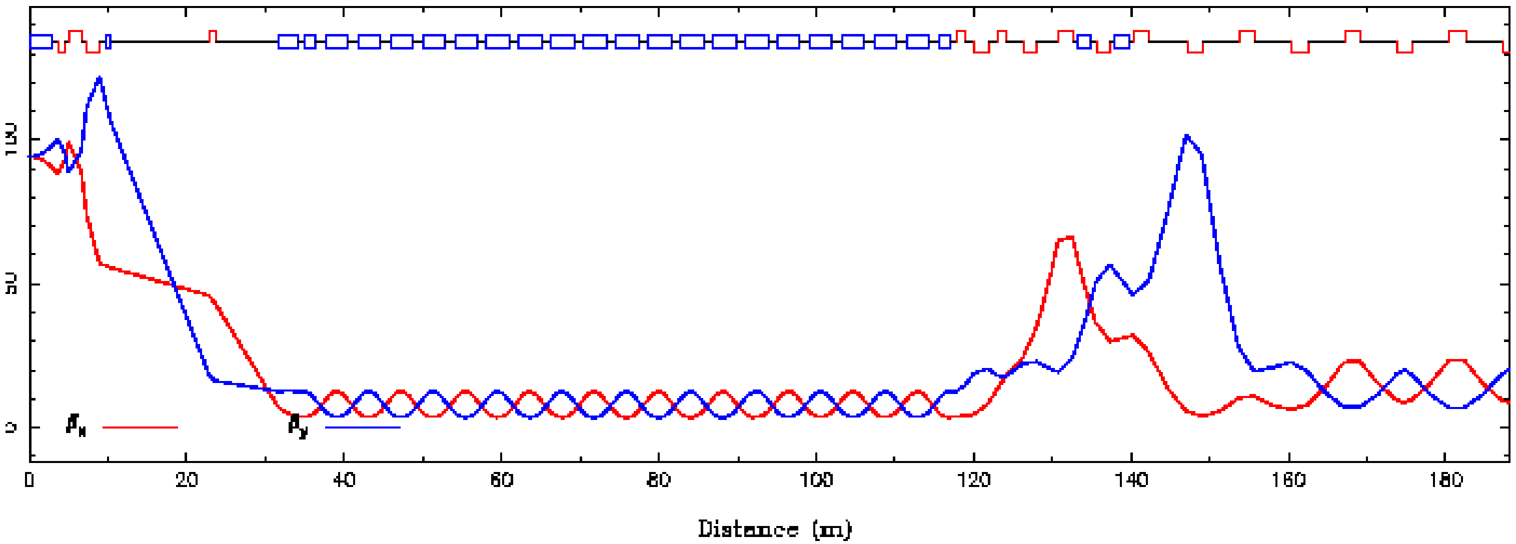


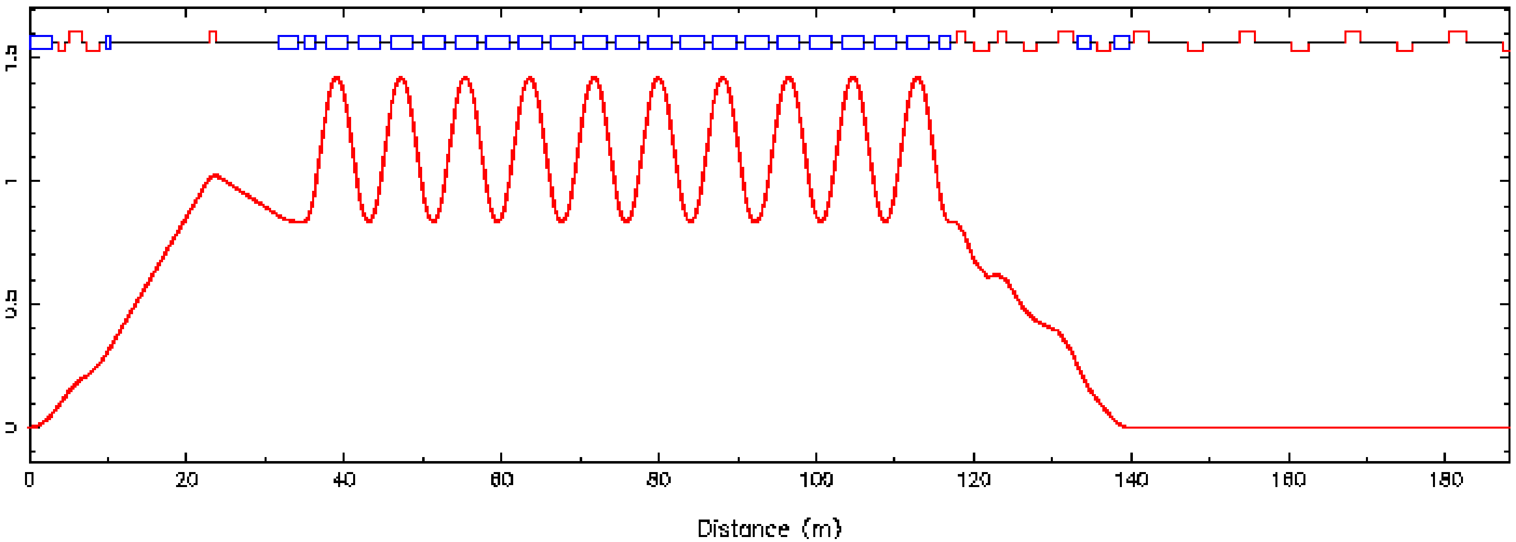
Lengths = 8.200, 1.2 m, $\mu = 72°$, $\beta_{max} = 12.7$ m, $D_{max} = 1.4$ m.

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



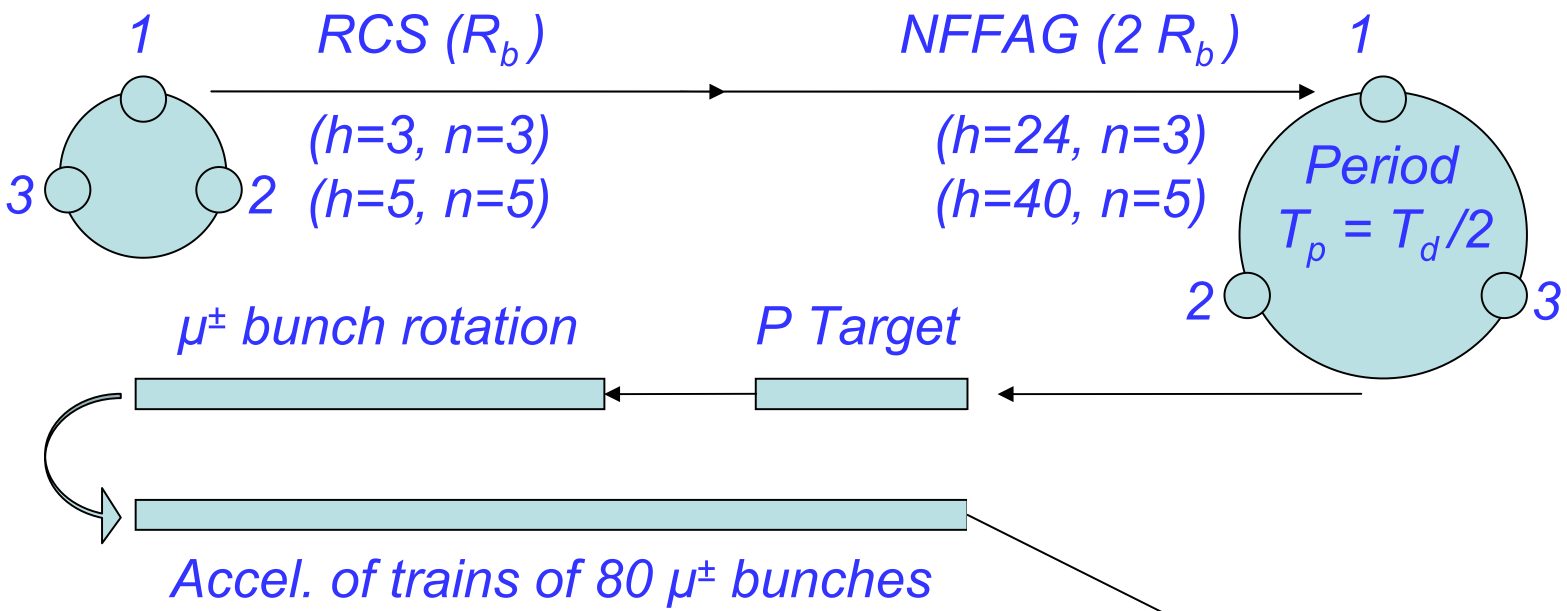
Triangle ring lattice functions outside production straight.

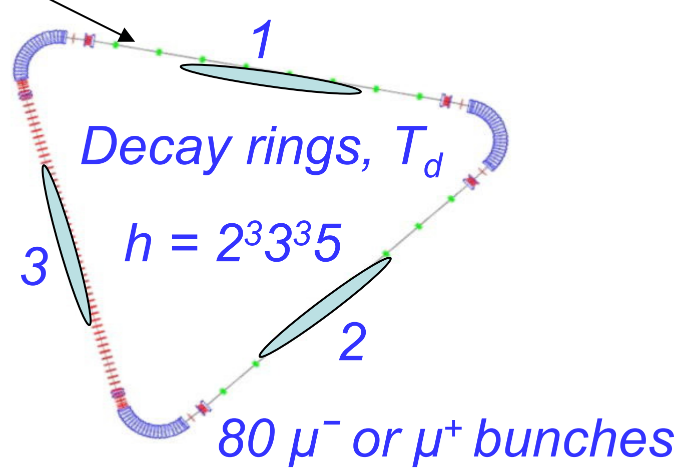




Bow-tie lattice functions outside production straight

Bunch Train Injection



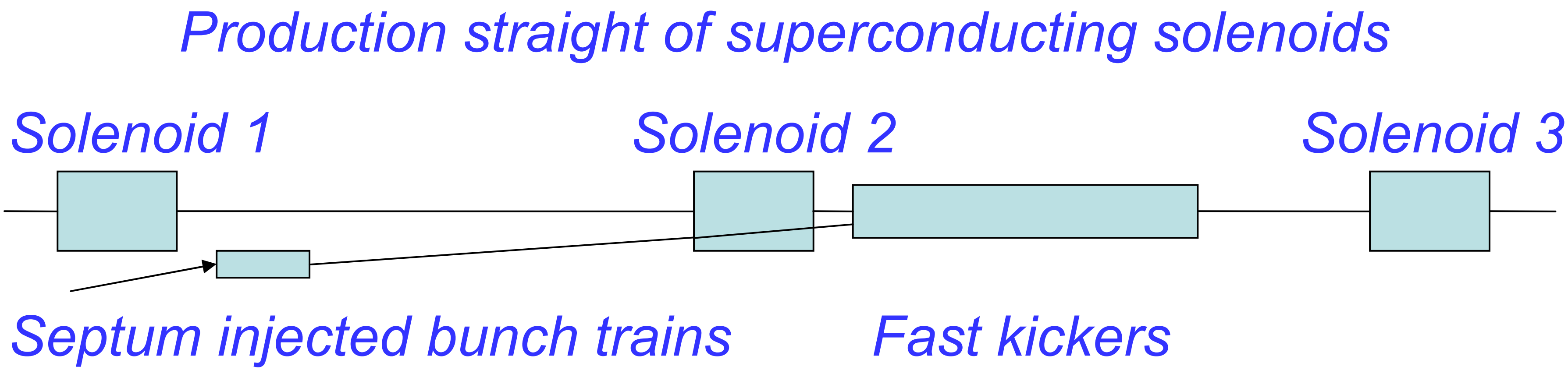


NFFAG ejection delays:
$(p + m/n)\ T_d$; m = 1 to n (= 3,5)

Pulse < 40 μs for liquid target

Pulse > 60 μs for solid targets

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



R & D is needed for the high stored energy & power, pulsed kickers, with n (5 or 3) injected bunch trains per 50 Hz cycle. Rise & fall times are ~650 ns for the large acceptance rings.

Injection Parameters

$\theta_k \approx \surd\, \beta_k\, (\surd A + \surd \varepsilon + t_s / \surd \beta_s) / (\beta_k \sin \Delta\mu + ½\, NL \cos \Delta\mu)$

NLI (number, length, current) = $2\, (B\rho)\, \theta_k \surd(A\, \beta_v) / \mu_o$
NTV (number, rtime, voltage) = $2\, (B\rho)\, \theta_k \surd(A\, \beta_k)$

At 20 GeV, for A, ε = 354.7, 157.7 mm mr, t_s = 15 mm
$\beta_s \approx \beta_k \approx \beta_v \approx$ 95.0 m, $\Delta\mu \approx 25°$, $B\rho$=67.06 T m, T= 460 ns:

Use 7, shorted, 3m, 10 Ω delay line, push pull K with
14 x [50 kV PFN, 5 kA pulsers & 10 Ω feeders] /ring.

NL = 24 m, θ_k = 6.47 mr, I = 5000 A, NTV ~ 0.18 V s

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). and ring acceptances are: $\beta\gamma A = 30\,(1.5)^2$ (π mm r).*

RF System to Contain Bunch Structure

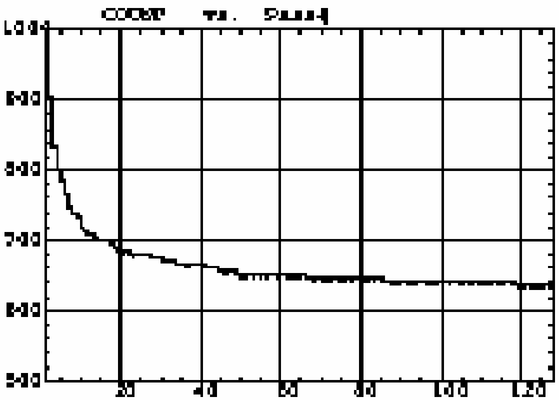
- *An RF system is needed only if $n = 5$ & $\Delta p/p > \pm 2.5$ %*
  Injected bunches may expand in phase until $\Delta\varphi = \pm 90°$

- *The inductive wall fields are defocusing as γ is > γ-t*
  The required net RF containing field scales as $(\Delta p/p)^2$

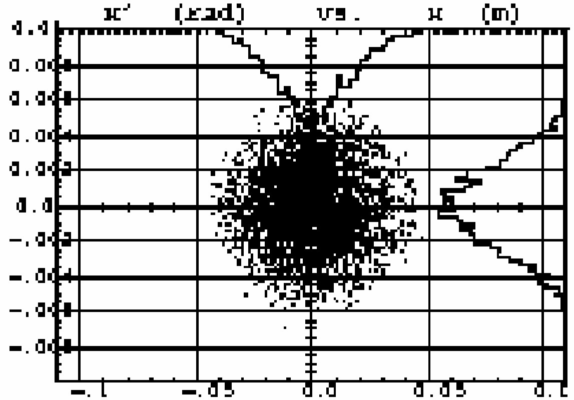
- *30 MV, 201 MHz containing fields/ring for $\Delta p/p = \pm 1\%$*
  3 cavities, 2x1 MW input couplers for ~ 5.4 MW per ring

- *Cavities on tune; loading alters with each injected train*
  Reflected power is dissipated in the circulator loads

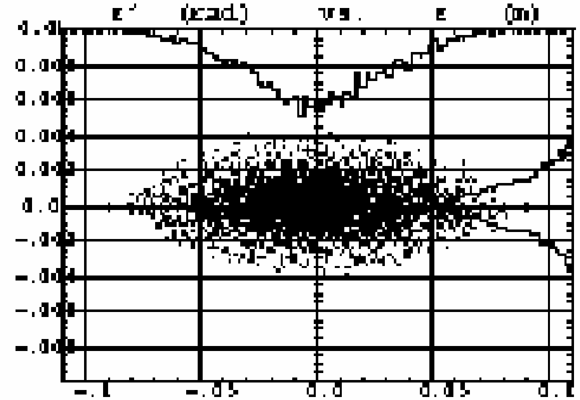
- *The dynamic aperture improves for lower $\Delta p/p$ beams*



Survival (ε=60 (π) mm r, Δ=±4%)



Horizontal phase space



Vertical phase space

Tracking of $\mu^{\pm}$ with sextupoles in the triangle ring arcs.

Tracking the linear machine shows very weak coupling and well-behaved transverse motions for $\Delta p/p$ = ± 4%. The effect of machine errors is next to be determined.

Parameters for 52.8° Apex Angle Triangle Rings

- *Circumference of decay rings:* 1608.8 m
- *Length of production straights:* 398.5 m
- *Production straight efficiency:* 2 x 24.8 %
- *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:* 120.0 m
- *Max β in the ring at 50 GeV:* 184.0 m
- *Q_h and Q_v values at 20 GeV:* 13.37, 13.18
- *Q_h and Q_v values at 50 GeV:* 13.19, 12.82

Triangle Design Summary

- *An outline design has been made for 2, isosceles triangle, 20 (potentially 50) GeV, $\mu^{\pm}$ storage rings*
- *The MW rings have large βγA, at 30 $(1.5)^2$ (π mm r). C = 1609 m, L = 398 m, ξ = 2 x 24.8%, 52.8° apex Δ.*
- *Production straight solenoids give lower beam sizes. μ to ν angle ratios are 0.10 & 0.12, at 20 & 50 GeV.*
- *Injection difficult for uncooled (45 π mm r) $\mu^{\pm}$ beams. F Meot is tracking to find dynamic aperture with errors.*

Vertical Bow-Tie Decay Rings

Advantages:

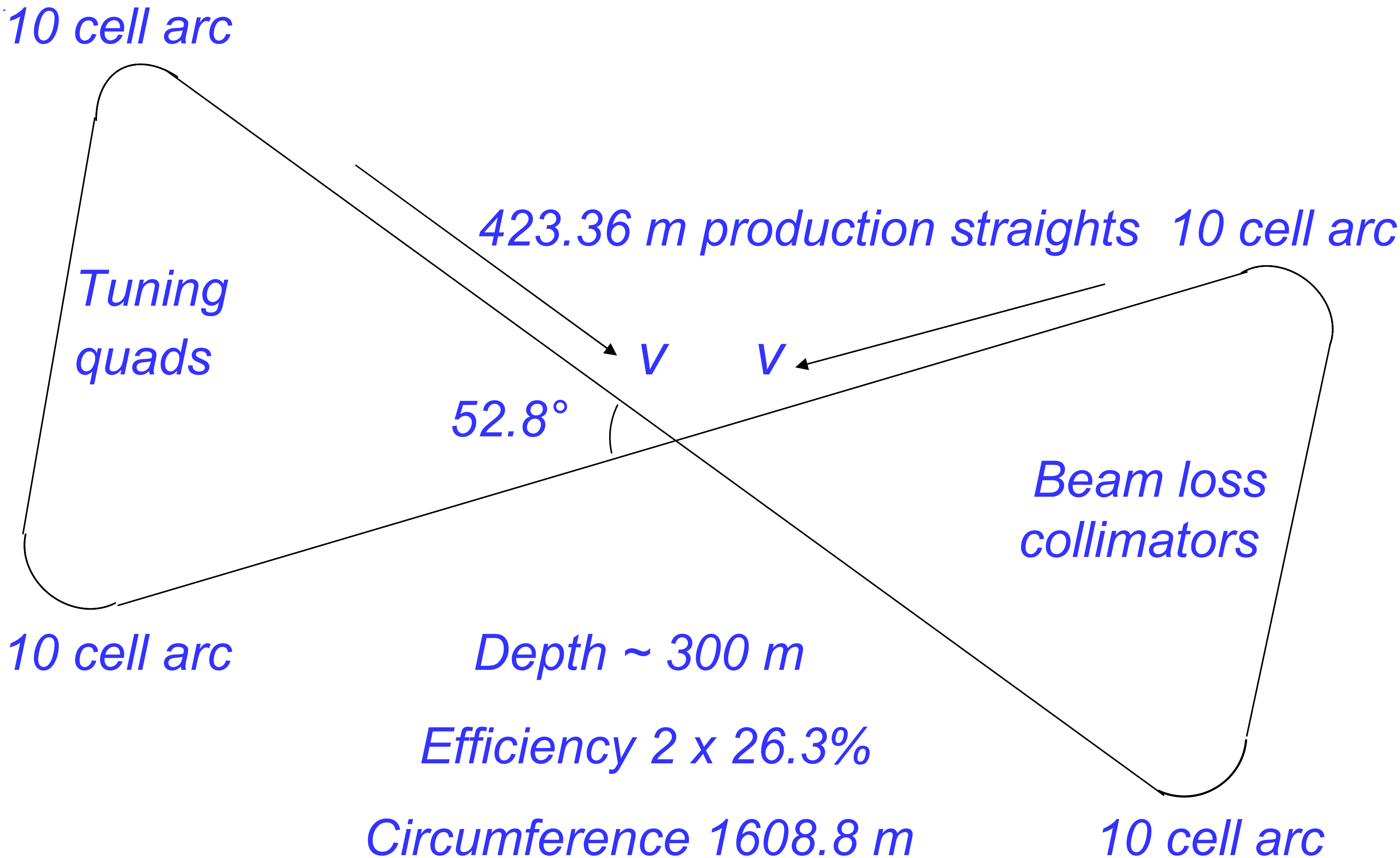
- *A reduced vertical tunnel depth of ~ 300 m (~ 435 m for triangular and racetrack rings)*
- *A higher ν production efficiency of 52.6% (49.6% for triangular rings and 38.2% for racetracks)*
- *A greater choice of the opening angle around 50°*

Disadvantages

- *A larger number of main bend cells are required (40) (31 for comparable isosceles triangle, shaped rings)*

Solenoids to give decay of the muon polarisation?
Possibility to sit on intrinsic depolarising resonance

Vertical Bow-Tie Decay Rings



Relative Costs

Ring designs have arcs, match sections & production straights all interchangeable (in principle). Thus, the cost issues are:

The additional bending and fewer quads for the bow-tie rings.
The reduced depth of the tunnel needed for the bow-tie rings.
The additional tunnel (smaller diameter) for the racetracks.
The extra beam lines and services for the racetracks.

For equivalent yield racetracks, power increases needed are:
38% for proton driver (4 to 5.5 MW) and for $\mu^{\pm}$ accelerators.

Ring Comparisons

1. *If suitable detector sites can be found, the triangle or bow-tie shapes are favoured.*
2. *If suitable detector sites are not available, racetracks in separate tunnels are needed.*
3. *If designs 1 and 2 are both proposed, the former has the following advantages:*

   the need for only one tunnel and a larger neutrino production efficiency (which is > the gain of adding μ^- beams).