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

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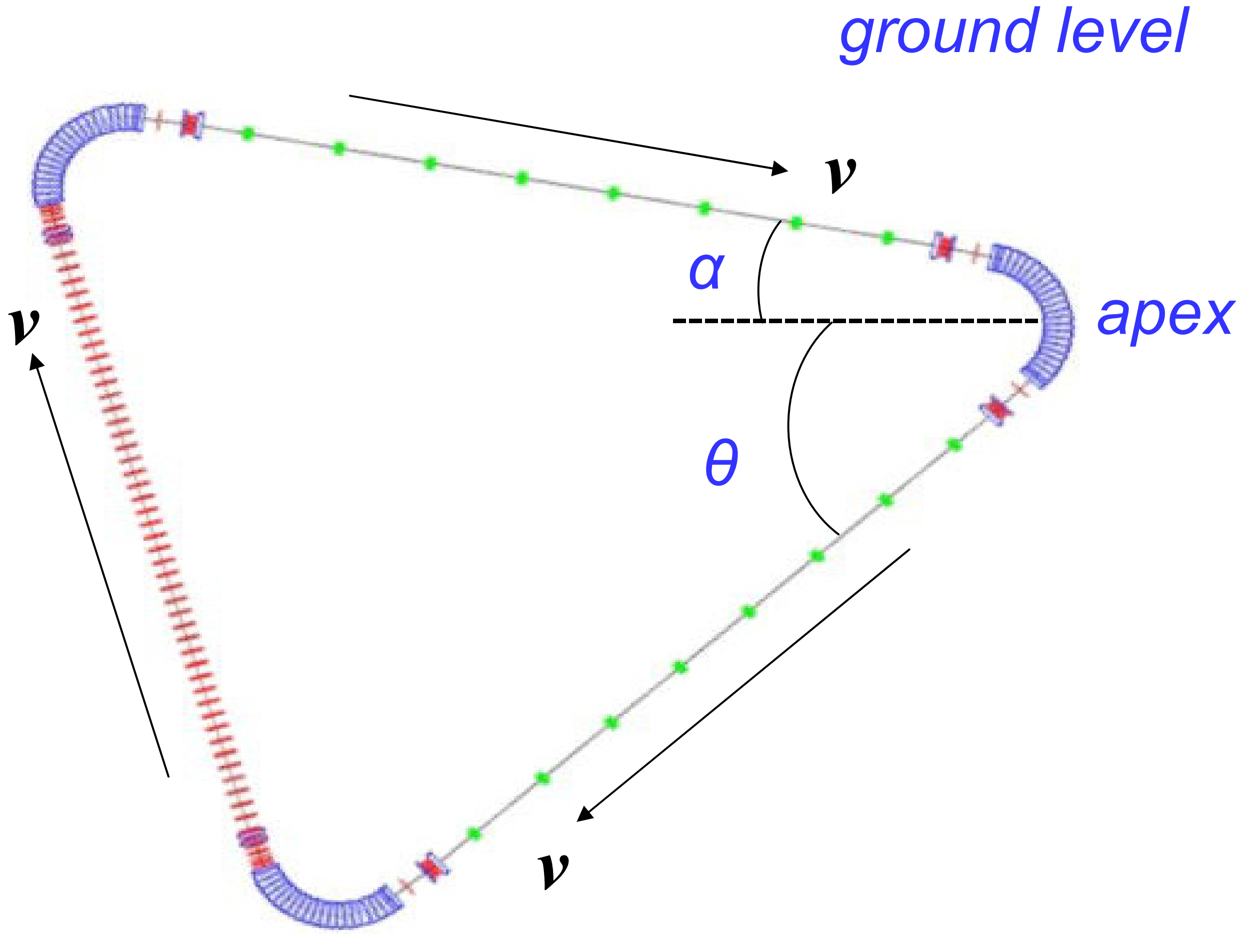


$\sin\alpha = L_1/2R$

L_1, L_2 detector distances

$\sin\theta = L_2/2R$

R the equatorial radius

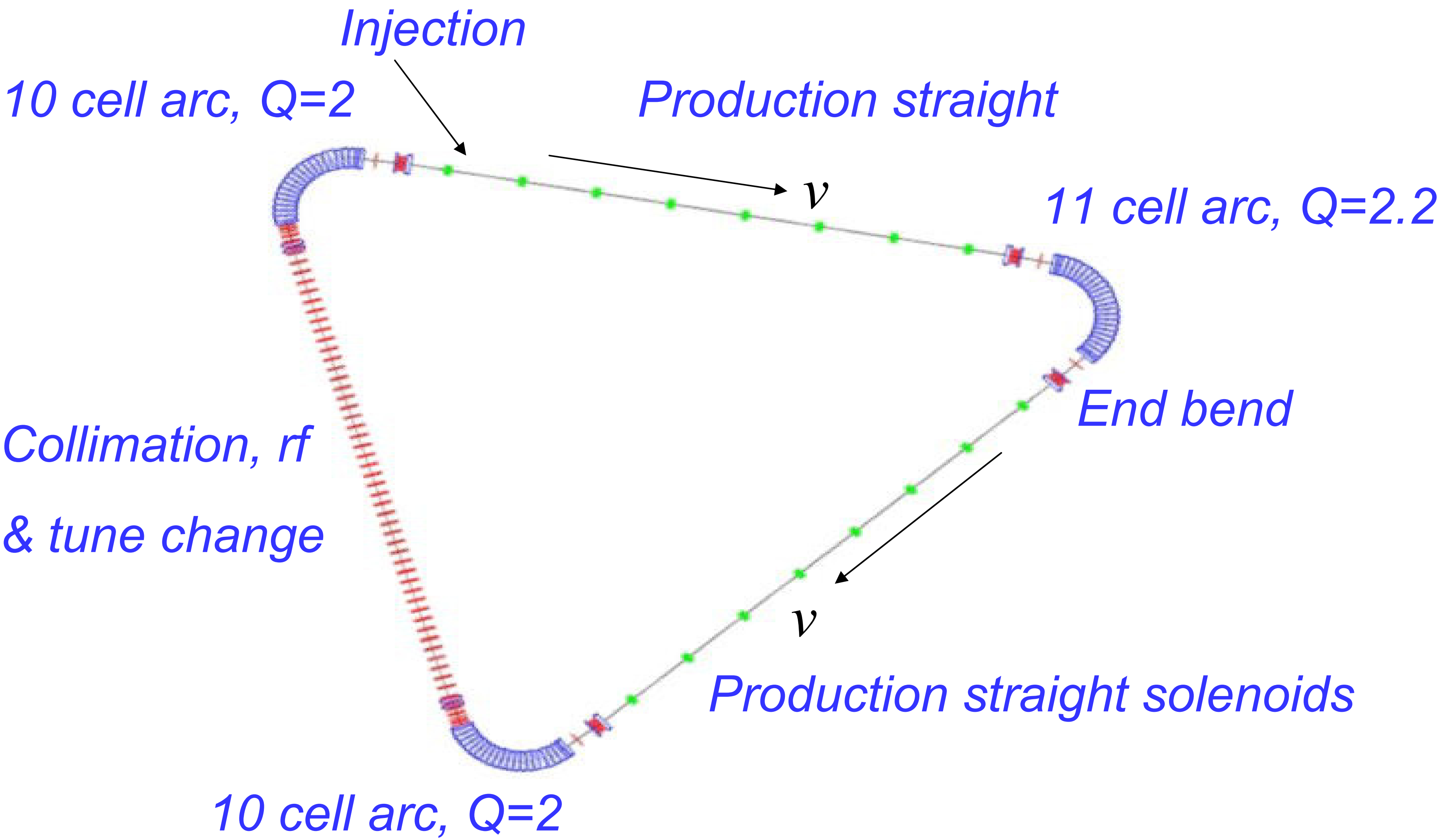
Vertical Plane Layout for 2 Isosceles Triangle Rings

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:

2^{nd} 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 Isosceles Triangle Rings

- *Designed for MW intensities:* $\beta\gamma A = 30\ (1.5)^2\ (\pi \text{ mm r})$
- *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 398.4 m straight sections:*
  At 20/50 GeV, $\beta_{max} \approx 99/163$ m for 4.3/6.4 T solenoids

Production Straight End Bends

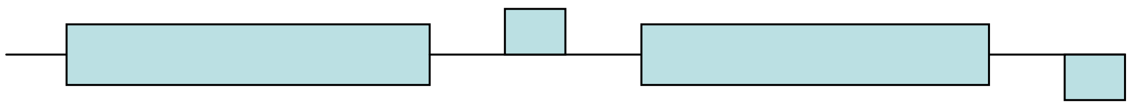
- *Neutrinos, from $\mu^{\pm}$ beyond the bends, miss detectors. Bends introduce dispersion, however, into the lattice.*
- *Matching of dispersion to arcs requires further bends, which are different for the 20 and the 50 GeV lattices.*
- *Small changes in the arc bend angles are required to preserve 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

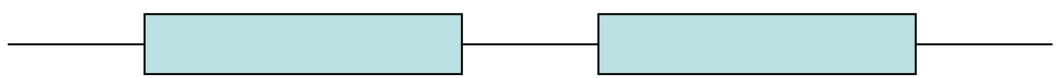
Arc Cell Design

Old CERN 10,10,10 FODO design:



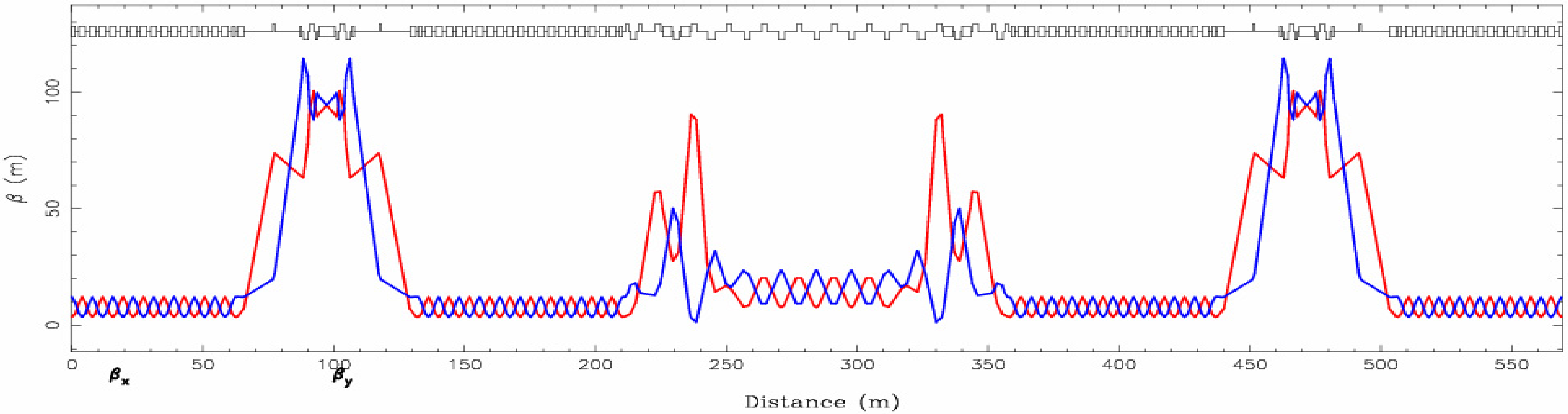
Lengths = 9.703, 0.7 m, μ = 90°, β_{max} = 16.6 m, D_{max} = 1.4 m.

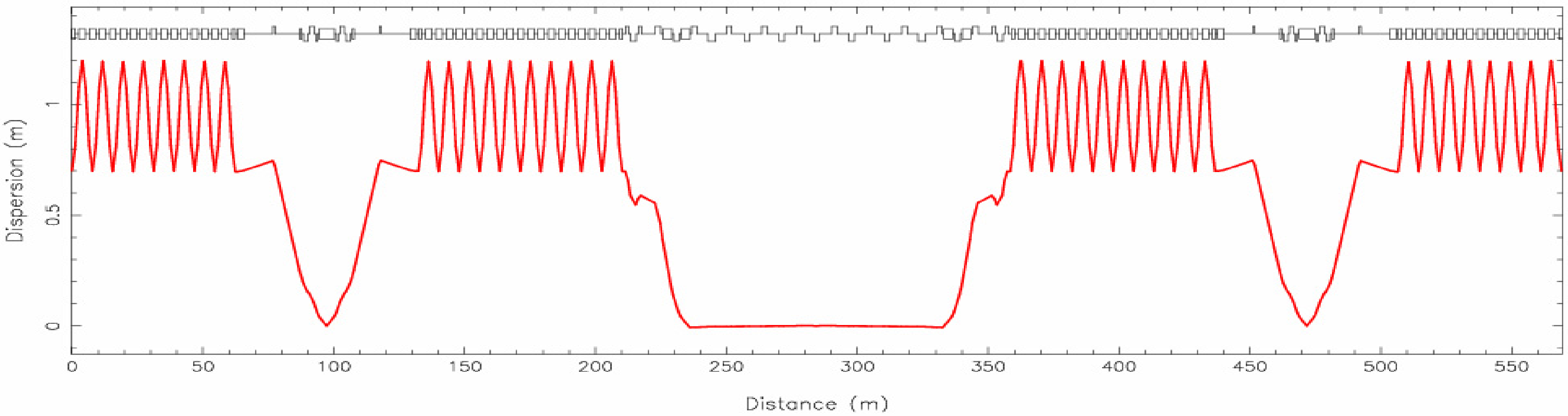
New 10,10,11 (BF)O(BD)O design:



Lengths = 8.200, 1.2 m, μ = 72°, β_{max} = 12.7 m, D_{max} = 1.4 m.

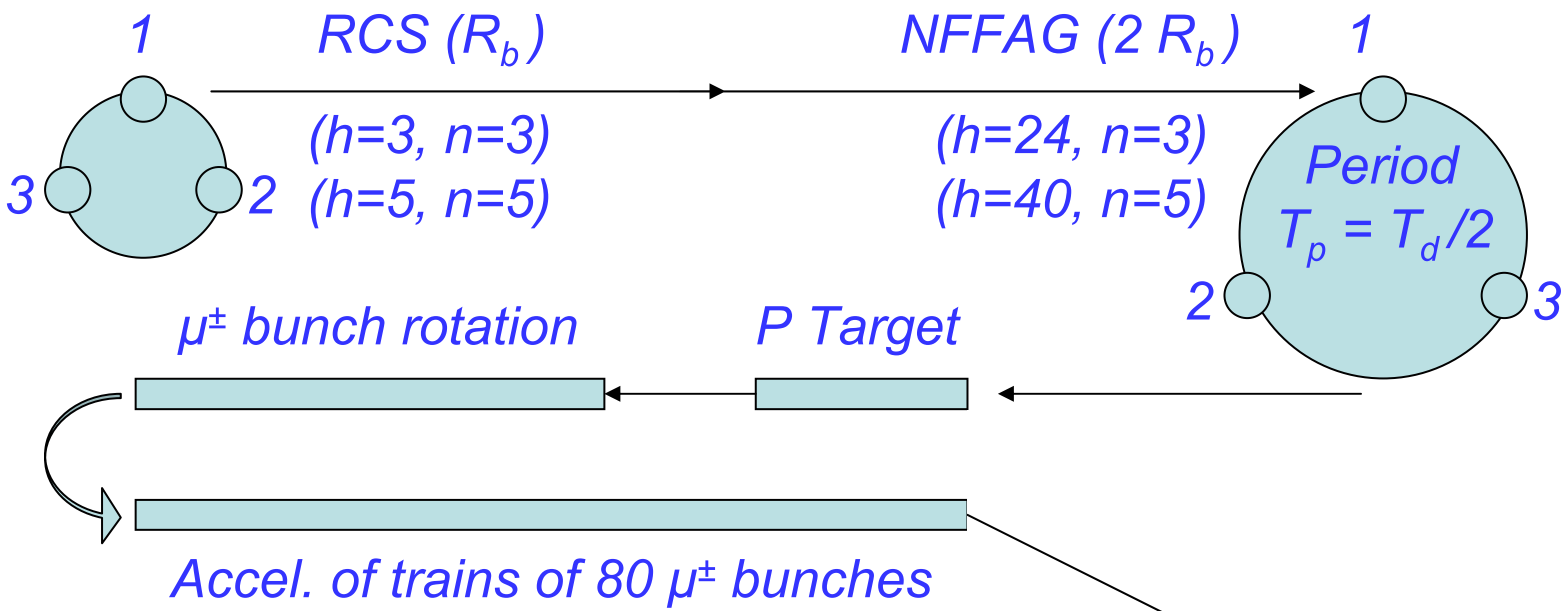
(space for cryostat ends, valves, correctors, diagnostics, vacuum & cooling)





Triangle ring lattice functions outside production straight.

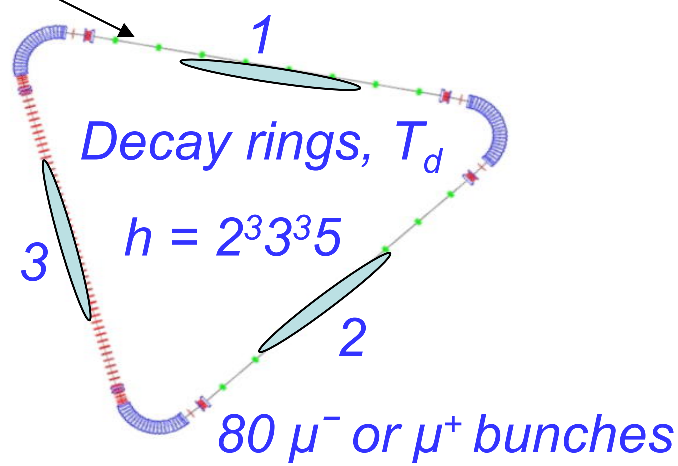
Bunch Train Injection



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

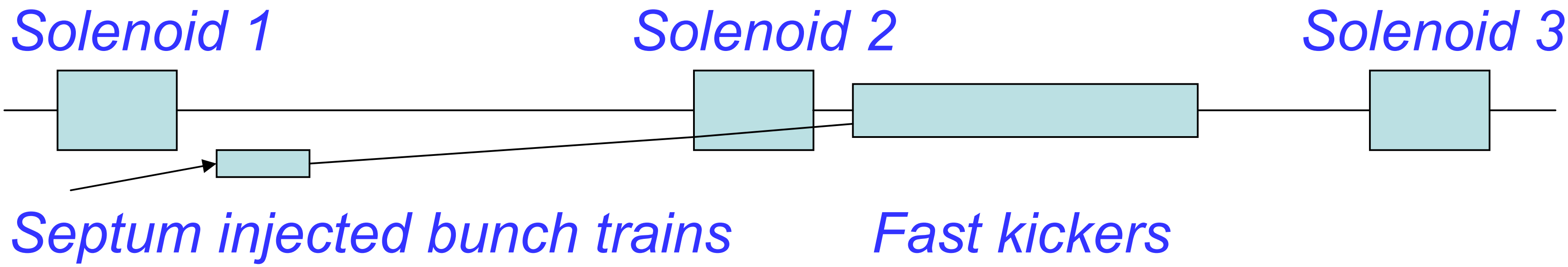
Pulse < 40 μs for liquid target

Pulse > 60 μs for solid targets



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

Production straight of superconducting solenoids



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

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

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

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 8, 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

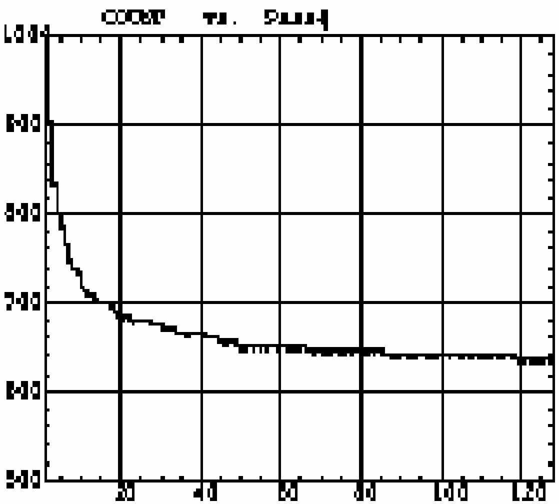
- *An RF system is needed only if n = 5 & Δp/p > ± 2.5 %*
  Injected bunches may expand in phase until Δφ = ±90°

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

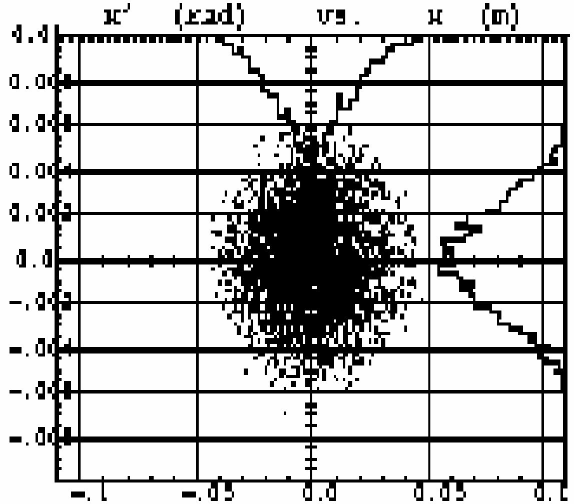
- *30 MV, 201 MHz containing fields/ring for Δp/p = ±1%*
  3 cavities, 2x1 MW input couplers for ~ 5.4 MW per ring

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

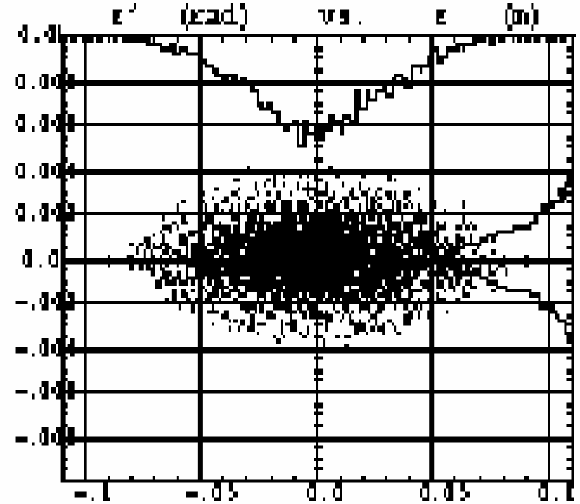
- *The dynamic aperture improves for lower Δp/p beams*



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 $\Delta p/p = \pm 4\%$. 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*

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 $\beta\gamma A$, 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:

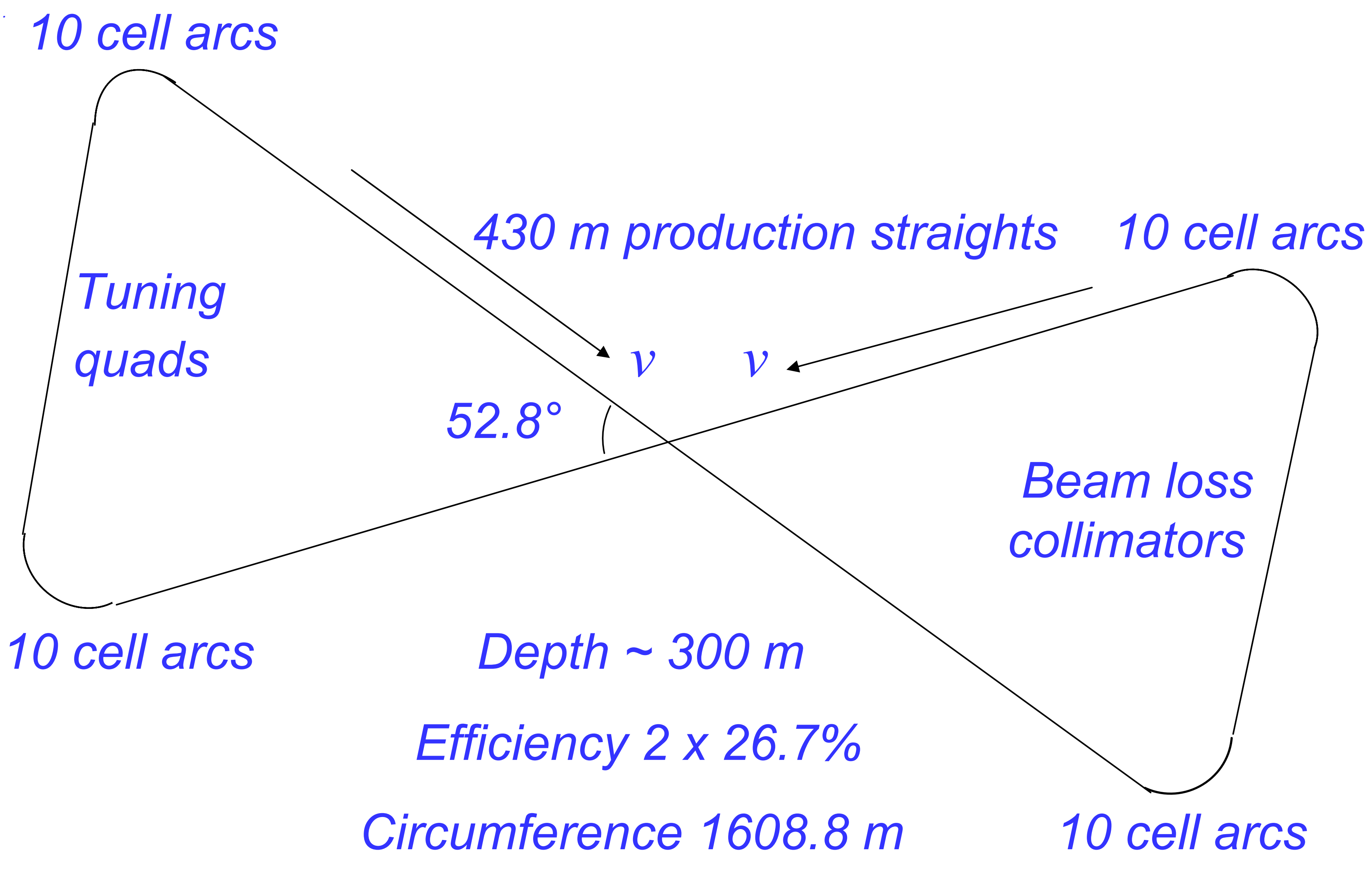
- *a reduced vertical tunnel depth of ~ 300 m (~ 435 m for triangular and racetrack rings);*
- *a higher ν production efficiency of 53.4% (49.6% for triangular rings and 38.2% for racetracks);*
- *a greater choice of the opening angle around 50°.*

Disadvantages

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

Polarisation retained?

Vertical Bow-Tie Decay Rings



Depth ~ 300 m

Efficiency 2 x 26.7%

Circumference 1608.8 m

Relative Costs

The three ring designs have the arcs, the matching sections and the production straights all interchangeable (in principle). Thus the cost issues reduce to the following:

The additional bend cells & fewer quads for the bow-tie rings.
The reduced depth of the tunnel for the bow-tie rings.
The additional tunnel (smaller cross section) for the racetracks
The additional services and beam lines for the racetracks.

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).*