Accelerator Physics

Mike Syphers

- Approach to design and layout
- Stage 1 -- 20 TeV
- Stage 2 -- 175 TeV
- R & D items

Approach to Design

- 2 Clusters (IR, inj/ext, RF, etc.) & 2 arcs
- Low field -- *gradient magnets*; High field -- separated function, *FODO* cells
- Common cell lengths (Stages 1 &2)
- Dispersion Suppression -- SSC-style
- Modules -- lengths in units of half-cell length, *L*

Approach -- 2 Rings in 1 Tunnel

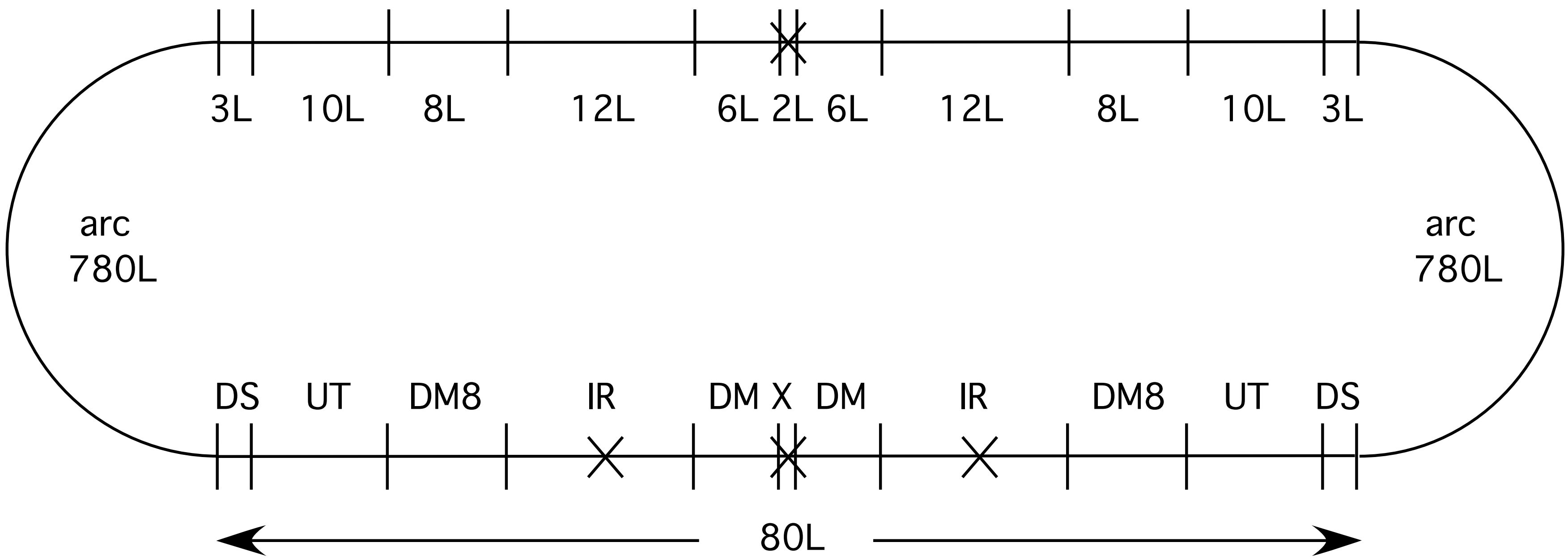
- Geometry
  - Common average radius of curvature
  - Common dispersion suppression scheme
  - Arc ← low field
  - Straight ← high field

Use "virtual survey monuments"

- Focusing
  - Common β_{max} locations
  - Common phase advance (dispersion suppression)
- Circumferences of low field inner/outer rings must be equal (lattice issue)

Approach -- Layout of Collider

- Schematic layout of collider modules, emphasizing the straight section functions…

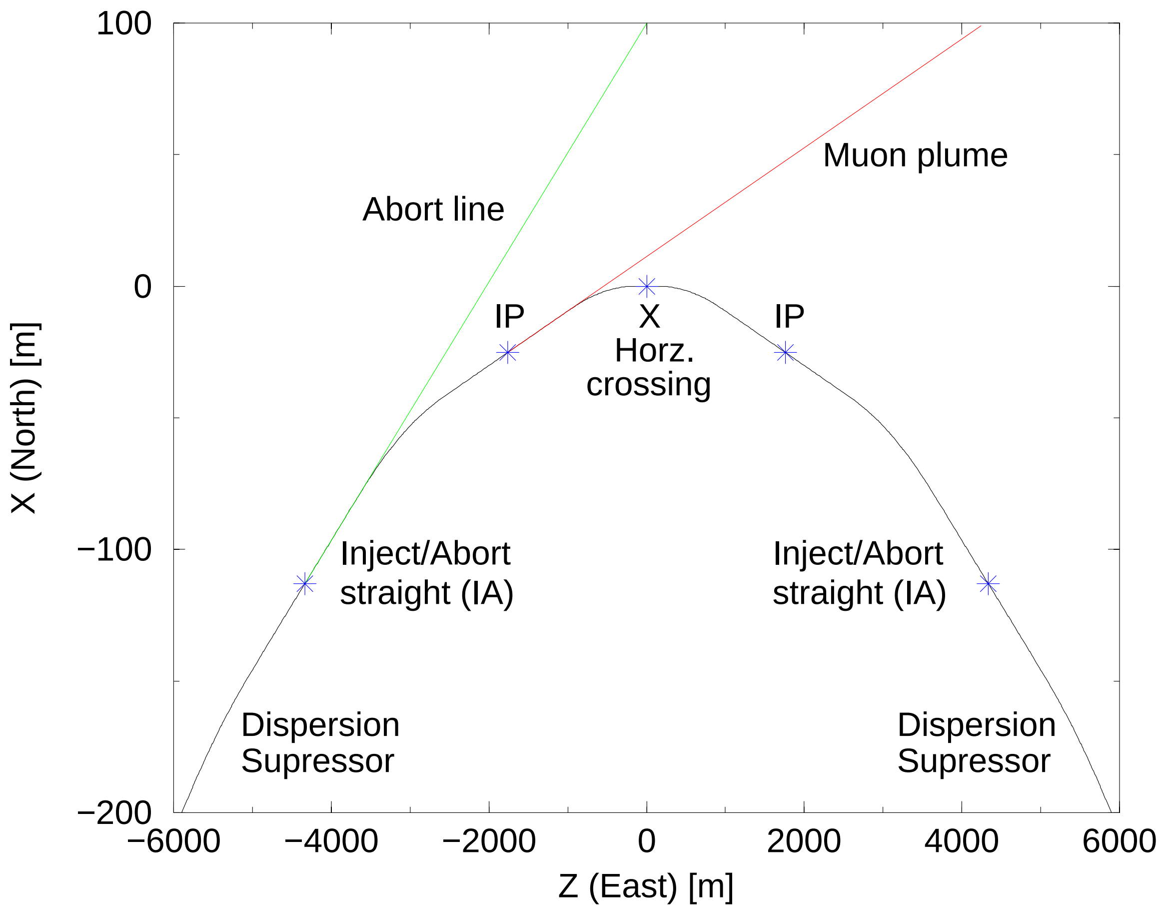


Development of Lattice Parameters

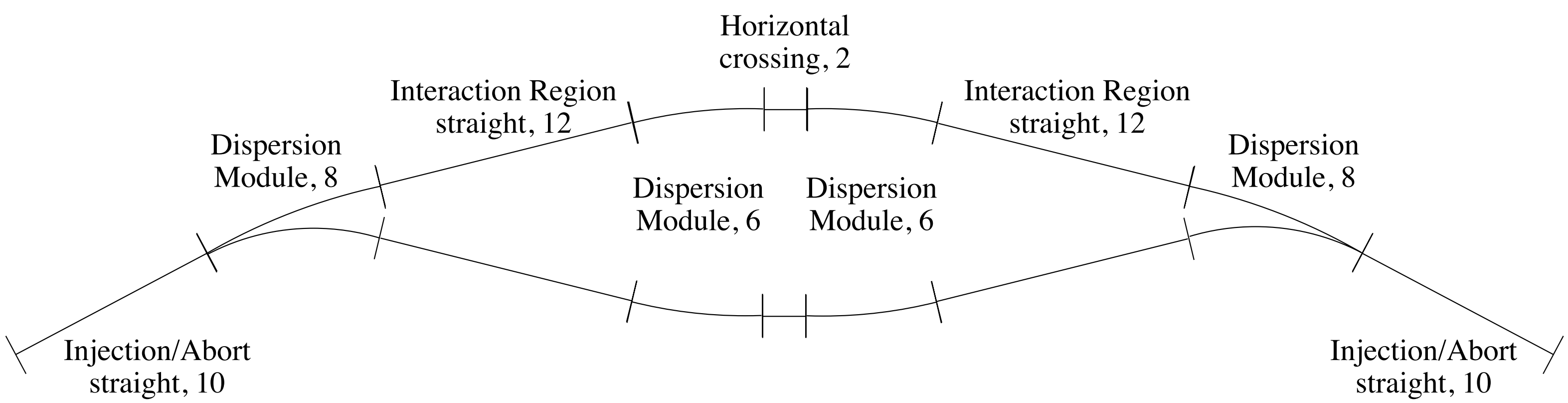
- Modules: units of half-cell length
- Half-cell: units of bunch spacing
- Bunch spacing: Tevatron
- 2 IR's @ FNAL site
- … & 2 UT's:
  - injection, abort, RF, etc.
- Far-side cluster -- FODO cells in IR/UT "slots"

N_λ	L_{hc} (m)		Common Factors
18	101.6149	2*3*3	2 3 6 9 18
20	112.9054	2*2*5	2 4 5 10 20
22	124.1959	2*11	2 11 22
24	**135.4865**	**2*2*2*3**	**2 3 4 6 8 12 24**
26	146.7770	2*13	2 13 26
28	158.0676	2*2*7	2 4 7 14 28
30	169.3581	2*3*5	2 3 5 6 10 15 30
32	180.6486	2*2*2*2*2	2 4 8 16 32
34	191.9392	2*17	2 17 34

Cluster Region close-up



Bypass Option (future)



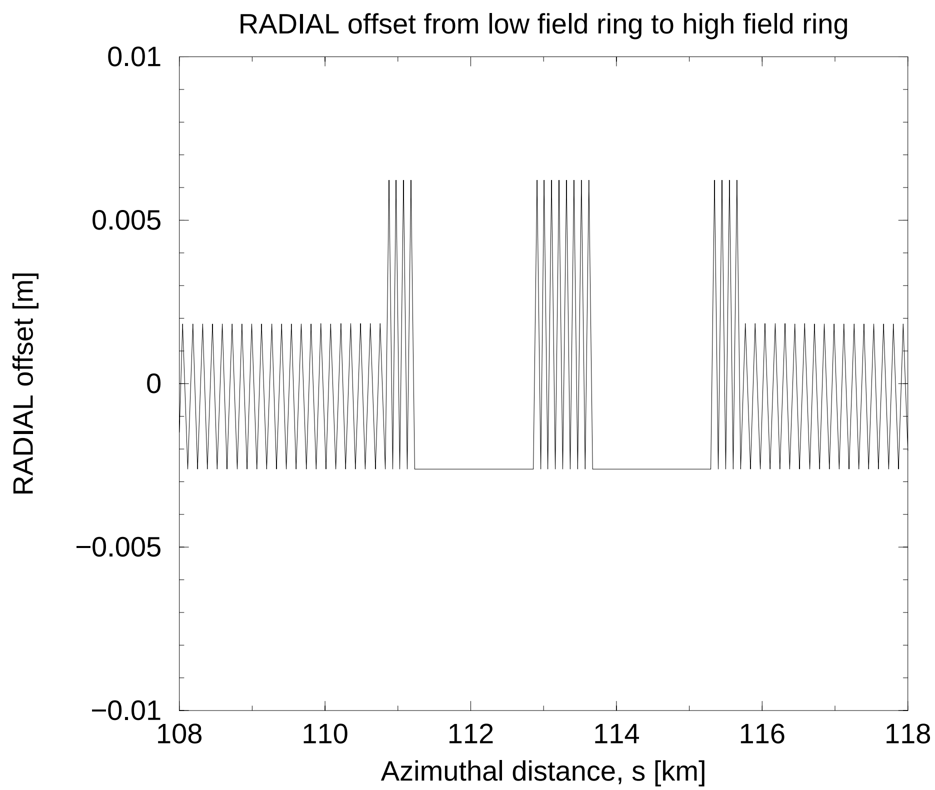
Lengths (eg "6") are in units of the arc half cell length

Lattice parameters common to both Stages

Circumference, C	233.037	km
Average arc radius, R	35.0	km
Number of interaction points	2	
Half cell length, L_{hc}	135.486	m
Half cell bend angle, θ_{hc}	3.875	mrad
Half cell count	1720	
Half cell harmonic, n_λ	24	
Bunch spacing (53.1 MHz), S_B	5.645	m
or,	18.8	ns
Number of buckets	41280	
Number of bunches, M	37152	
Phase advance per cell	90.0	deg
Revolution frequency	1.286	kHz
Revolution period, T	0.778	ms
Harmonic number, h	371520	
RF frequency (9×53.1)	478.0	MHz

Two colliders in one tunnel

Typical radial offset of Stage 2 ring relative to Stage 1 ring is a few millimeters, with maxima occurring in the dispersion suppressor regions…

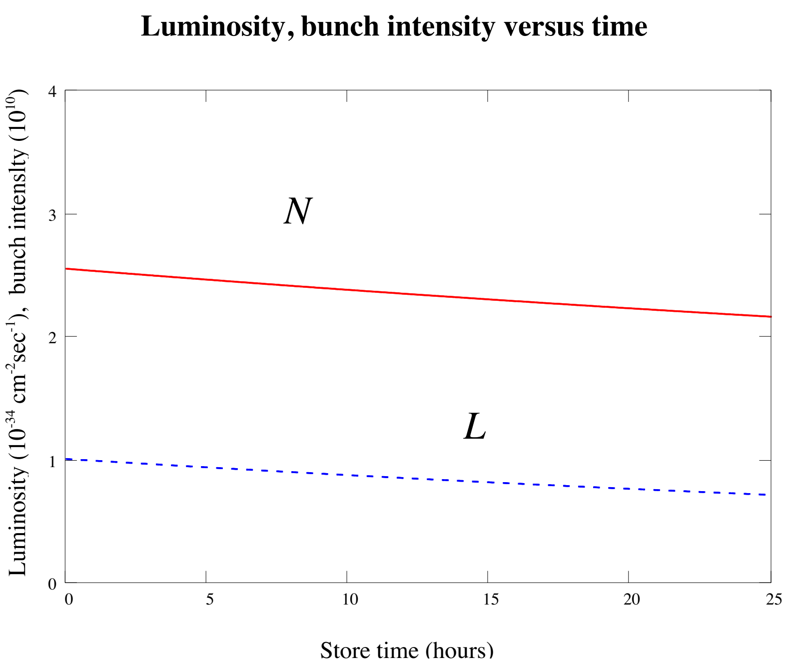


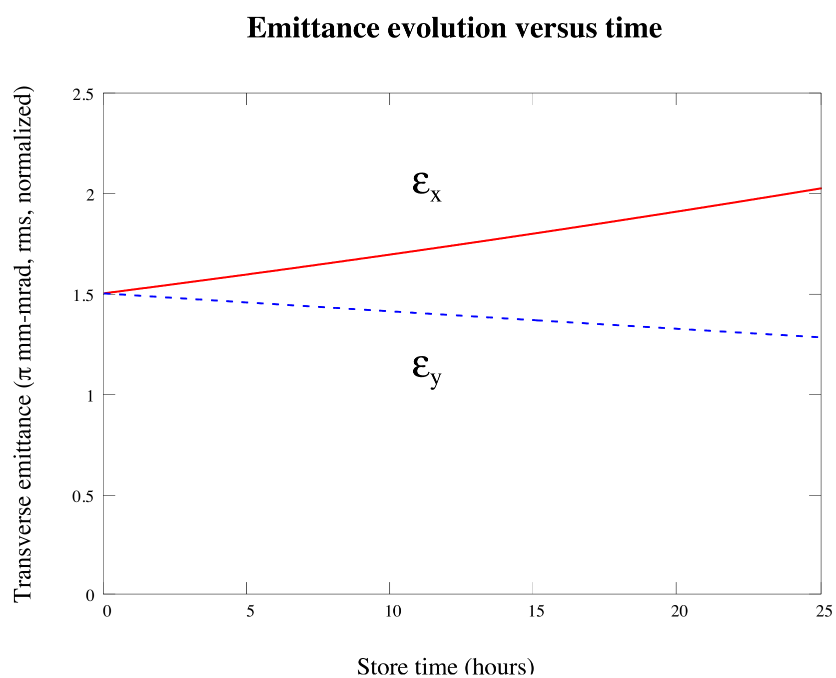
Stage 1 -- Nominal Store Parameters

Storage energy	20	TeV
Peak luminosity	10^{34}	$cm^{-2}sec^{-1}$
Packing fraction	89	%
Injection energy	0.9	TeV
Emittance, rms		
(H&V, inject)	1.5 π	μm
Initial bunch intensity	2.6×10^{10}	
Average beam current	195	mA
Stored energy per beam at collision	3.0	GJ
Bend field at storage	2.0	T
Bend magnet gradient	9.0	T/m
Phase advance per cell	90.0	deg
Max RMS arc beam size (inject)	1.2	mm

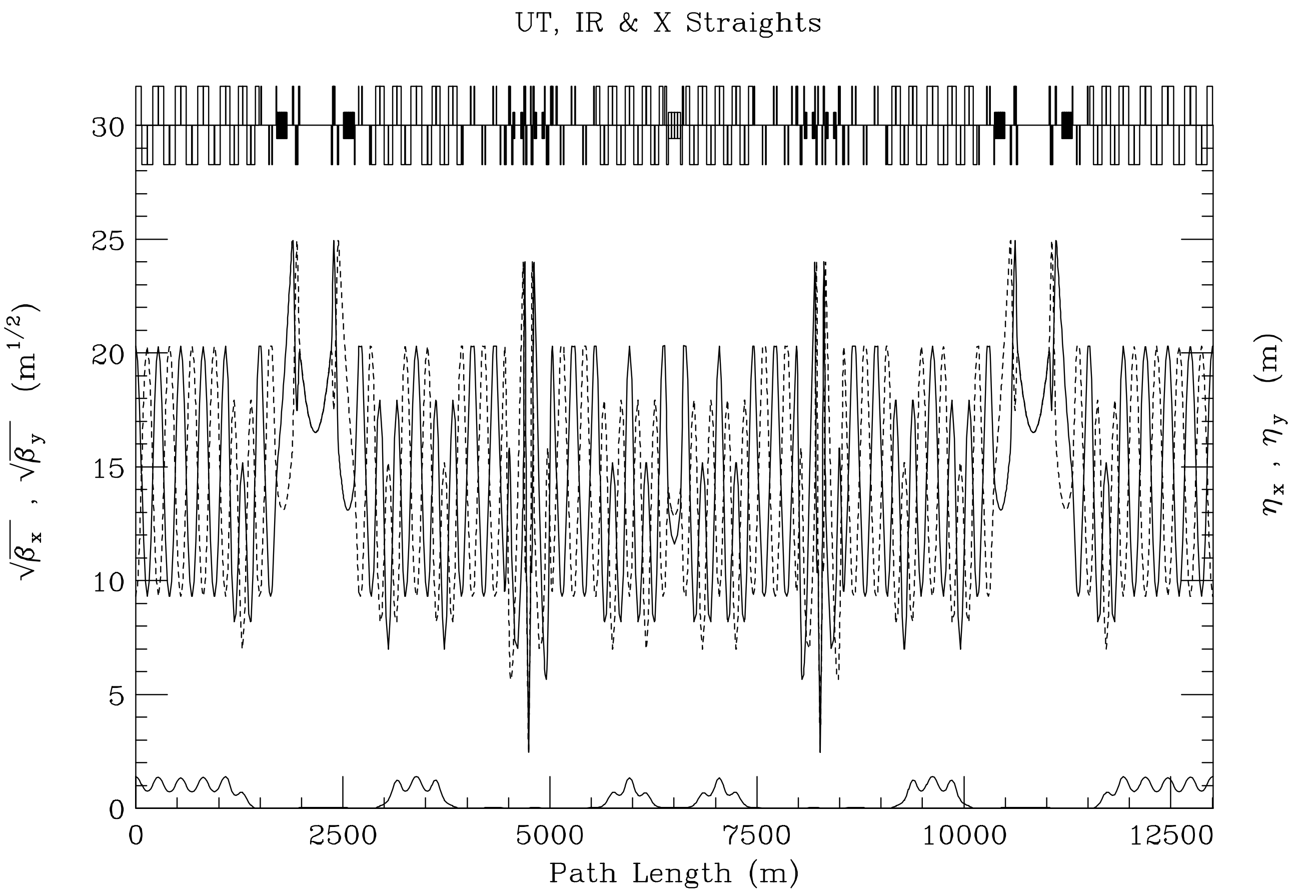
Bunch spacing (53.1 MHz)	5.645	m
or,	18.8	nsec
Bunch length	30	mm
Longitudinal emittance, rms (inject)	0.4	eV-s
RF voltage at storage	50	MV
Fill time	60	min
Acceleration time	1000	sec
Beam size (rms) at IP (storage)	4.6	μm
Total crossing angle (10σ)	153	μrad
Distance from IP to first magnet	21	m
β^* at IP (H & V)	0.3	m
Maximum interactions per crossing	20	
Debris power at IP (each direction)	3	kW
Energy loss per turn per particle	38	keV
Radiation damping time, τ_0	100	hr
(anti-damping in H plane)		

Stage 1 -- Parameter Evolution





Lattice Functions through Cluster Region

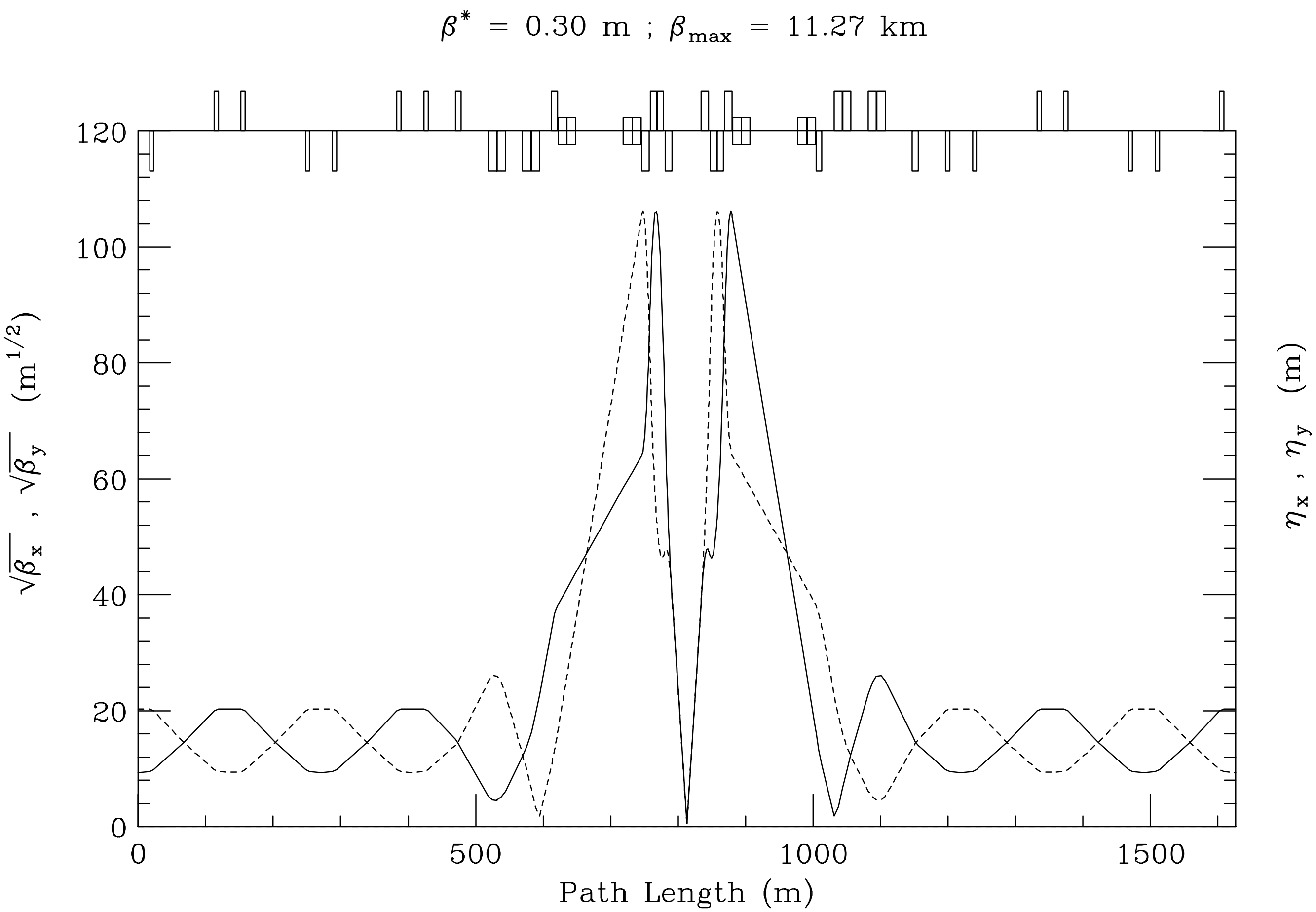


Cell and Magnet parameters

Stage 1 @ 20 TeV/c

Cell Type	Cell Length (m)	Magnet Type	L_{mag} (m)	#/cell	B (T)	B’ (T/m)
Arc	270.973	GF / GD	65.75	4	1.966	± 9.278
Suppressor	203.230	GSF / GSD	48.81	4	1.766	± 16.687
Straight	270.973	QF / QD	6.10	4	0	± 69.333

Stage 1 Collision Optics



IR Magnet parameters

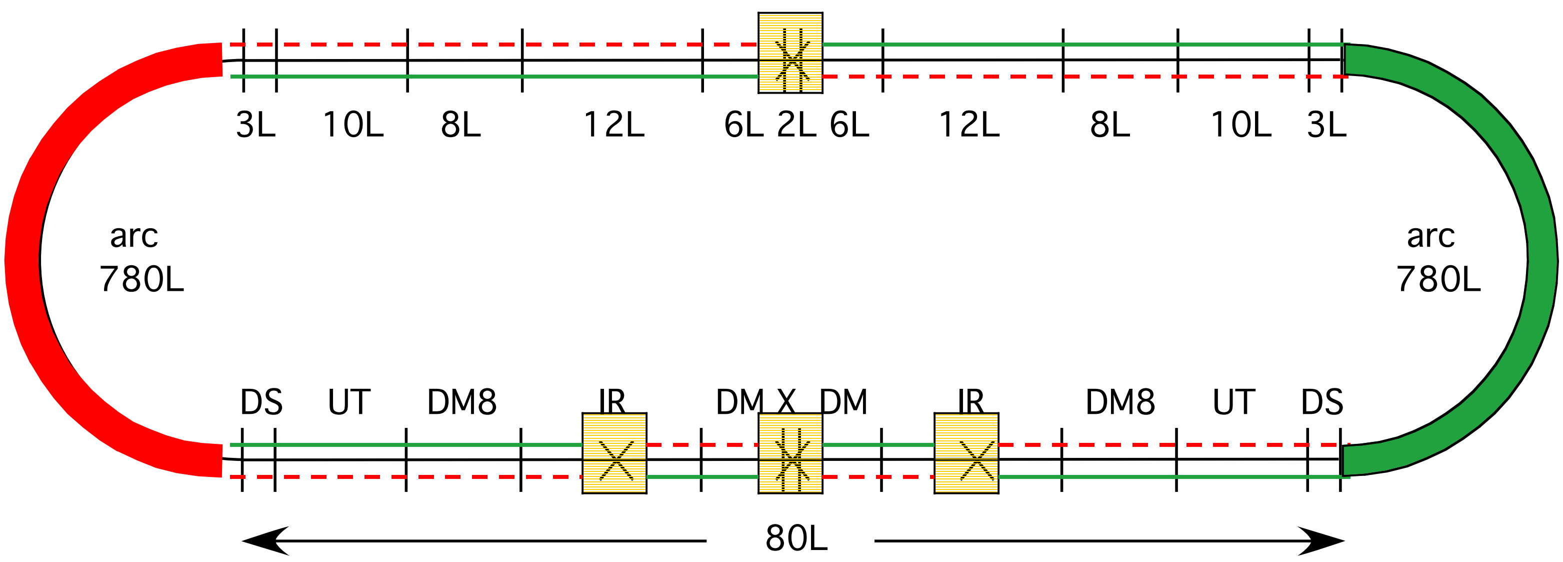
Stage 1 @ 20 TeV/c

Quad #	L_{mag} (m)	B' (T/m) β^* = 6.0 m β_{max} = 575 m	B' (T/m) β^* = 0.3 m β_{max} = 11.3 k m
1	10.90	-301.5	-298.2
2a & 2b	9.22	+304.3	+294.5
3	10.90	-301.5	-298.2
4	12.19	+51.11	+62.40
5a & 5b	12.19	+69.44	-65.51
6a & 6b	12.19	-62.00	-65.51
7	7.62	+0.802	+66.69

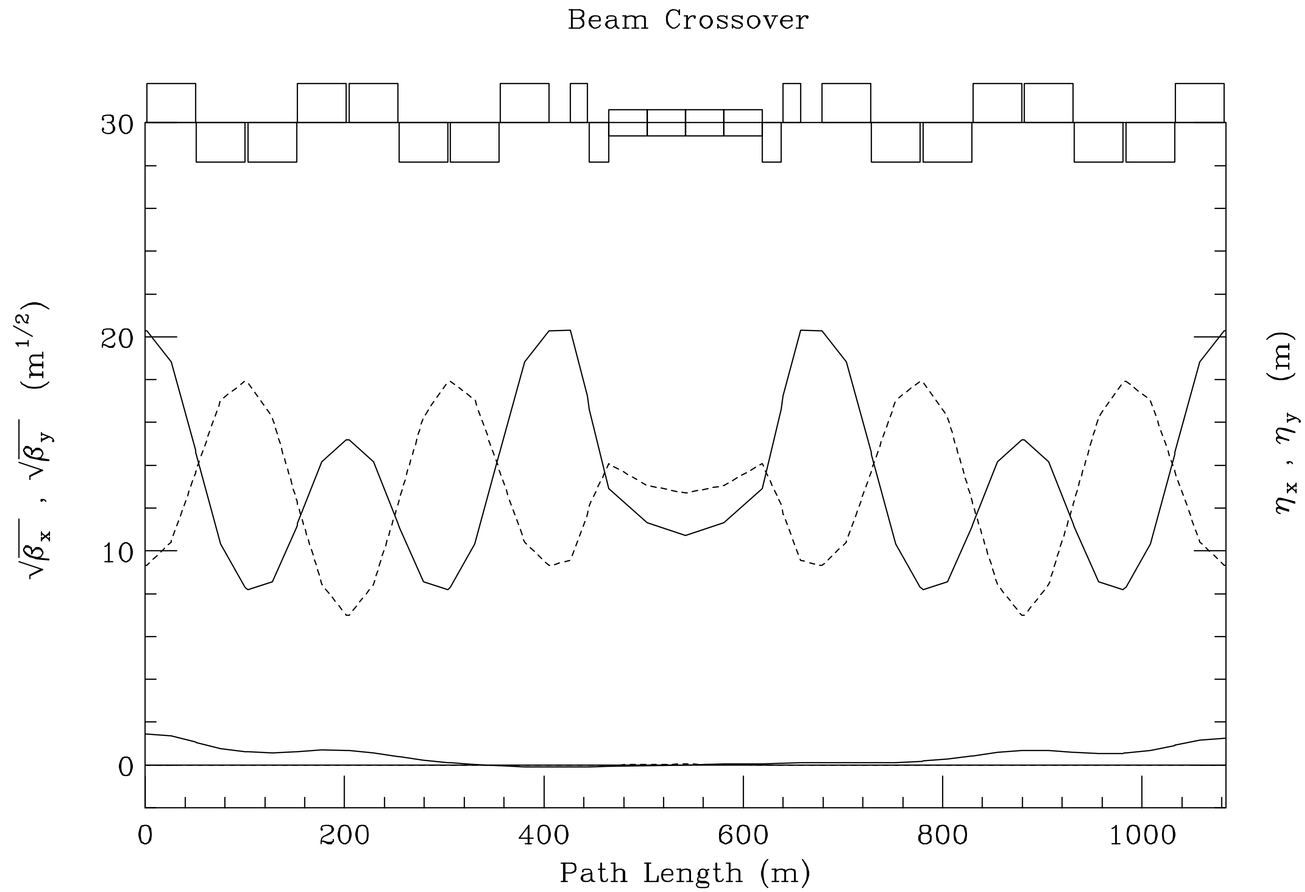
Changes polarity

Beam Crossings

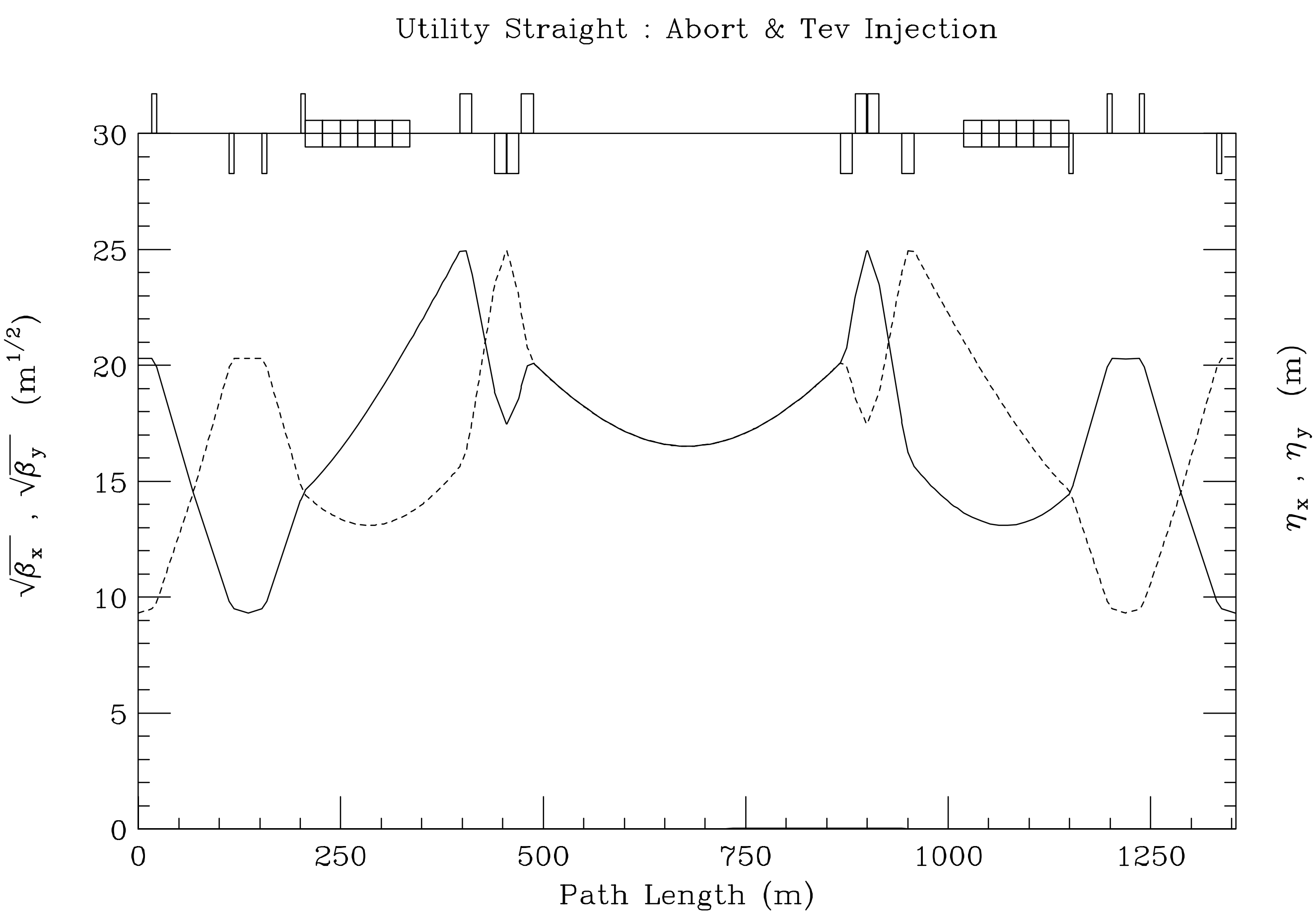
- Beams are separated horizontally
- To keep same path length, cross each other even number of times and alternate inside/outside paths in arcs



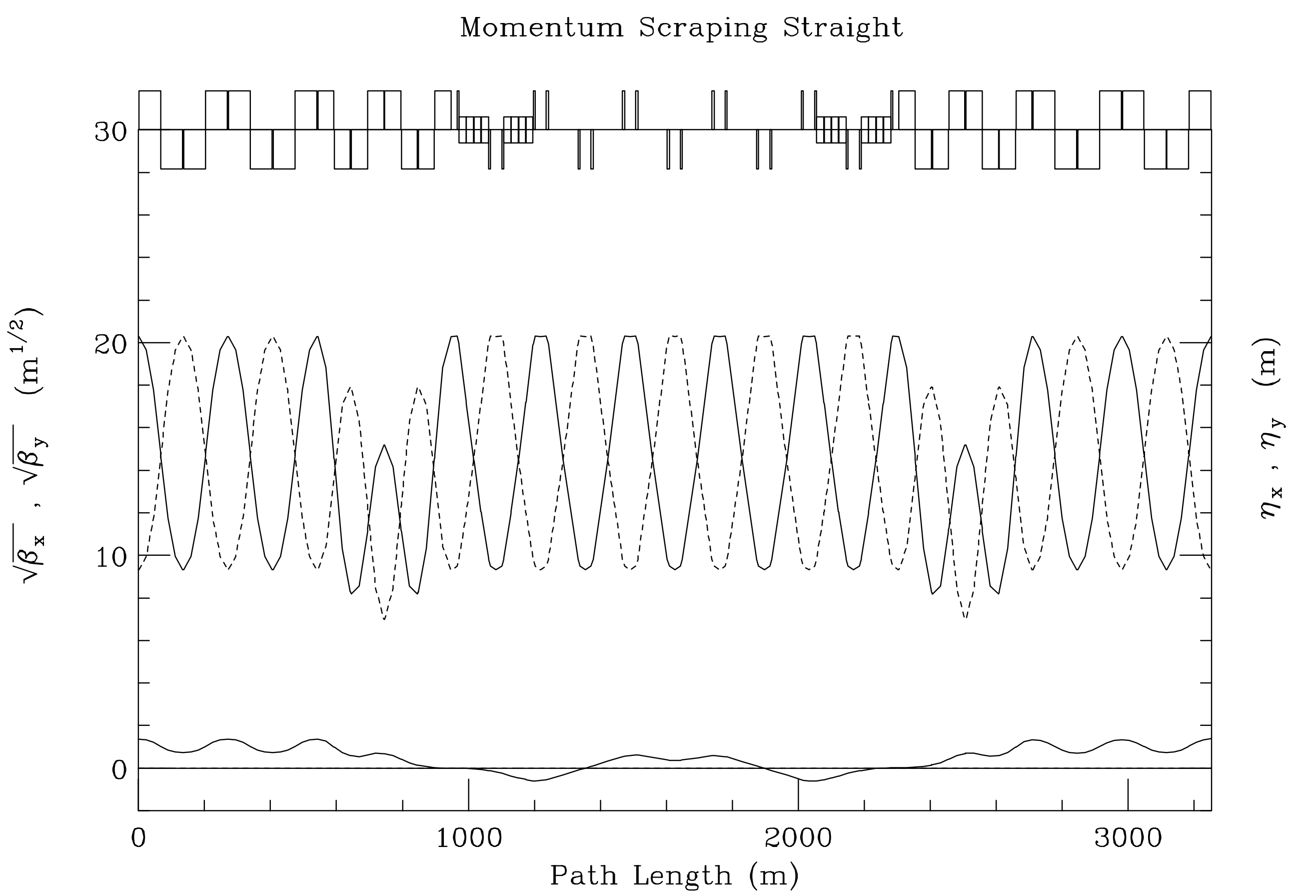
Beam Cross-over Region



Utility Straight Region



Momentum Scraping Region



Stage 1 -- Injection Tracking input

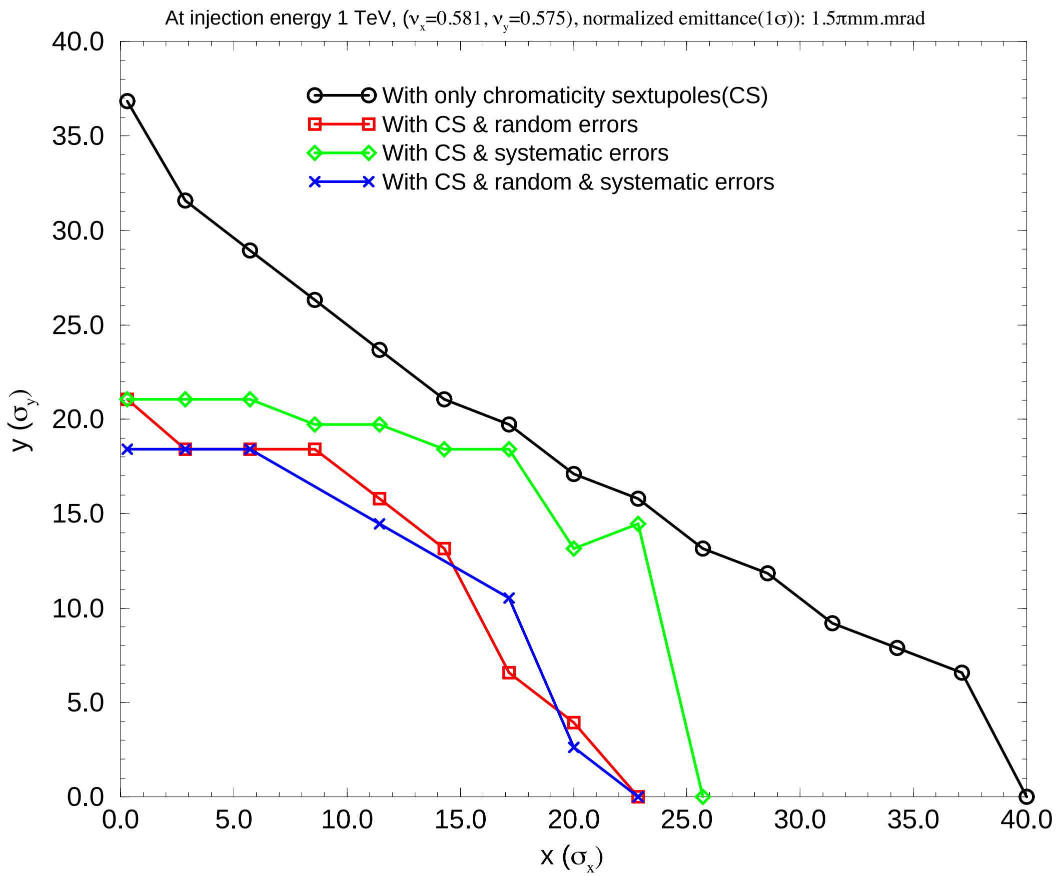
Multipole harmonics used in Injection tracking
Scaled from Main Injector data (w/ skews = 0)

Order, n	$\langle b_n \rangle$	$\langle a_n \rangle$	$\sigma\langle b_n \rangle$	$\sigma \langle a_n \rangle$
2	-0.600	0.000	0.600	0.200
3	0.000	0.000	0.149	0.300
4	0.300	0.000	0.300	0.150
5	0.000	0.000	0.100	0.500
6	0.000	0.000	0.250	0.250

10^{-4} @ $R_{ref} = 10$ mm

Stage 1 -- Dynamic Aperture -- injection

Dynamic Aperture of VLHC Low Field Lattice



- 1000 turn data shown here
- 10000, 100000 turn data similar results

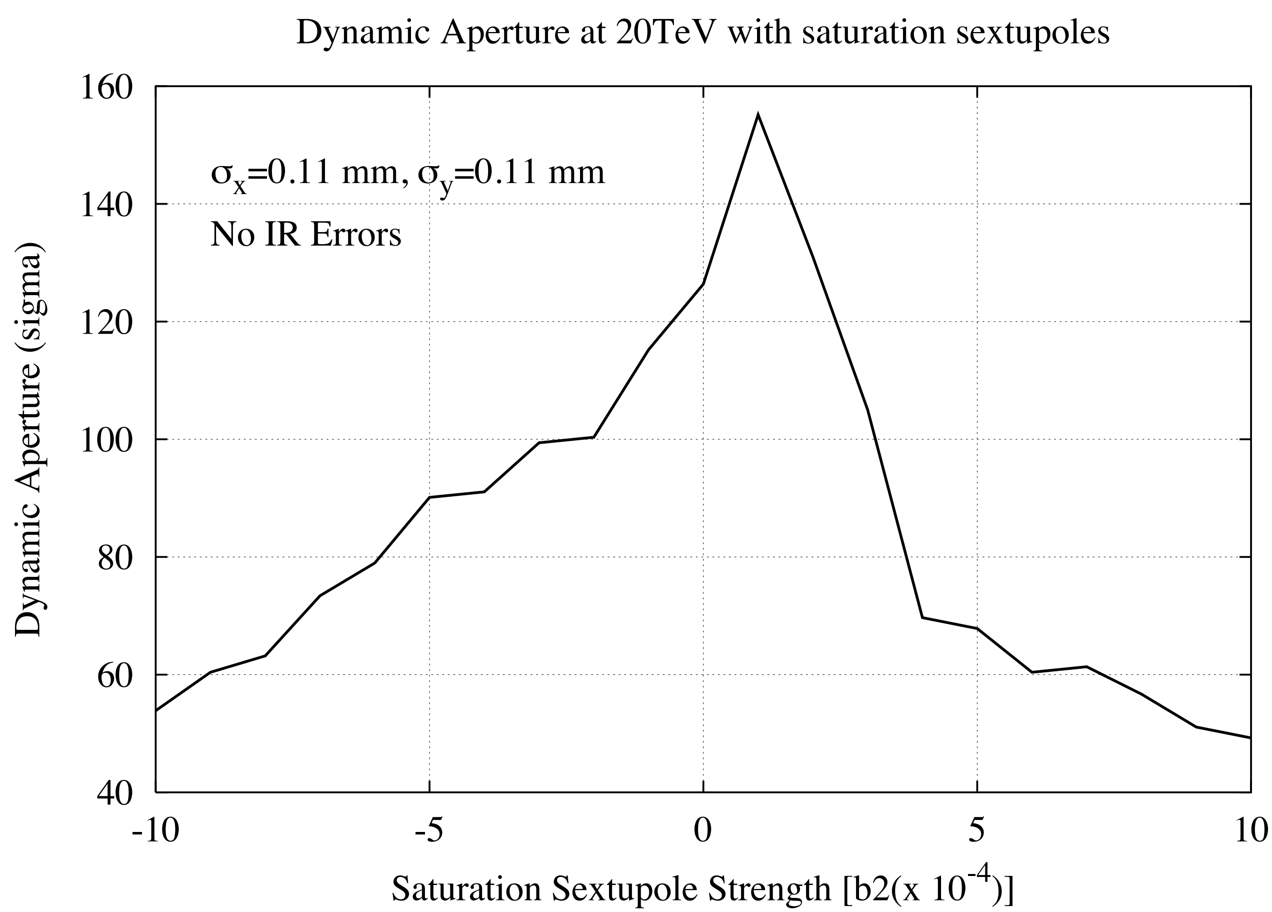
Stage 1 -- 20 TeV Tracking input

Multipole harmonics of IR Quadrupoles used in 20 TeV tracking *(based on FNAL - LHC experience)*

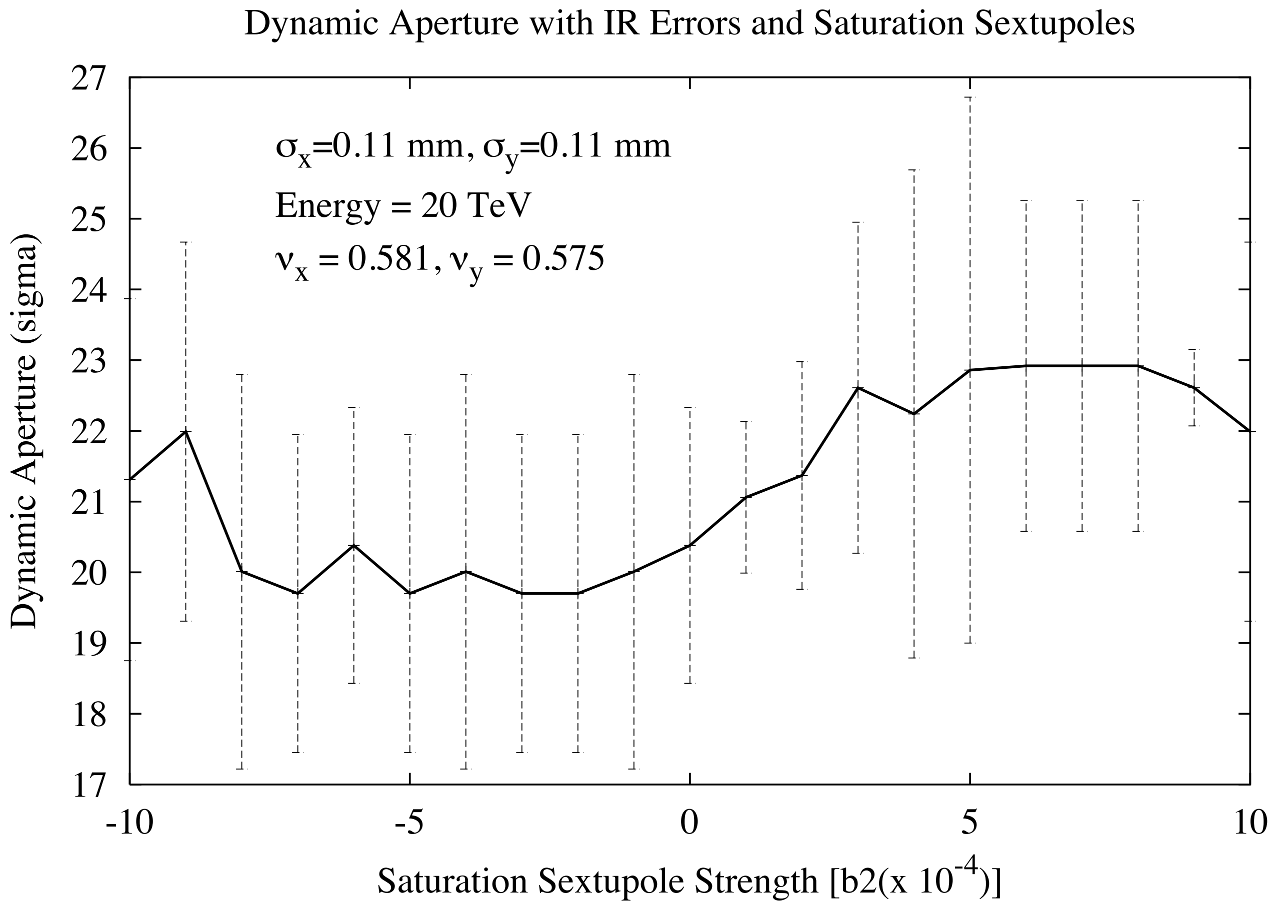
Order	<b_n>	<a_n>	d<b_n>	d<a_n>	σ<b_n>	σ <a_n>
2	0	0	0.5	0.5	0.9	0.9
3	0	0	0.1	0.1	0.3	0.3
4	0	0	0.05	0.05	0.06	0.06
5	0.015	0	0.1	0.1	0.1	0.05
6	0	0	0.005	0.005	0.005	0.005
7	0	0	0.002	0.002	0.003	0.003
8	0	0	0.0005	0.0005	0.001	0.001
9	0.0002	0	0.001	0.0003	0.0005	0.0005

10^{-4} @ $R_{ref} = 10$ mm

Stage 1 -- 20 TeV tracking, w/o IR errors



Stage 1 -- Dynamic Aperture w/ IR errors



Collective Effects Workshop

- *VLHC Instability Workshop, March 2001*
  http://www.slac.stanford.edu/~achao/VLHCWorkshop.html
  - **Transverse mode coupling instability**
    - **Safety factor N_{thr}/N_b: LF → 0.5, HF → 8**
  - **Resistive wall multi-bunch instability**
    - **Increments: LF ~1 turn, HF ~5 turns**
  - **Incoherent and coherent tune shifts**
    - **dQ_{LF} = -0.3, dQ_{hF} = -0.02**
- **Not expected to be serious:**
  - **Electron cloud instability LF – 0.25 s, HF – 0.5(10?) s**
  - **Longitudinal microwave instability safety factor ~ 20**
  - **Coherent synchrotron tuneshift safety factor ~ 10**
  - **Ground motion and dB/B effects can be suppressed by a feedback**

Stage 1 issue -- instabilities

- Resistive wall instability
  - Requires feedback system -- doable
- Transverse Mode Coupling Instability (TMCI)
  - Growth time less than one turn at 2.6 x 10^{10}/bunch

$$N_{thr} = 1.85 \cdot 10^{10} \cdot \frac{E_{inj}}{1TeV} \cdot \frac{\nu_s}{0.01} \cdot \left(\frac{a}{9mm}\right)^3 \cdot \frac{232km}{C} \cdot \frac{250m}{<\beta>} \cdot \sqrt{\frac{\sigma_s}{10cm}}$$

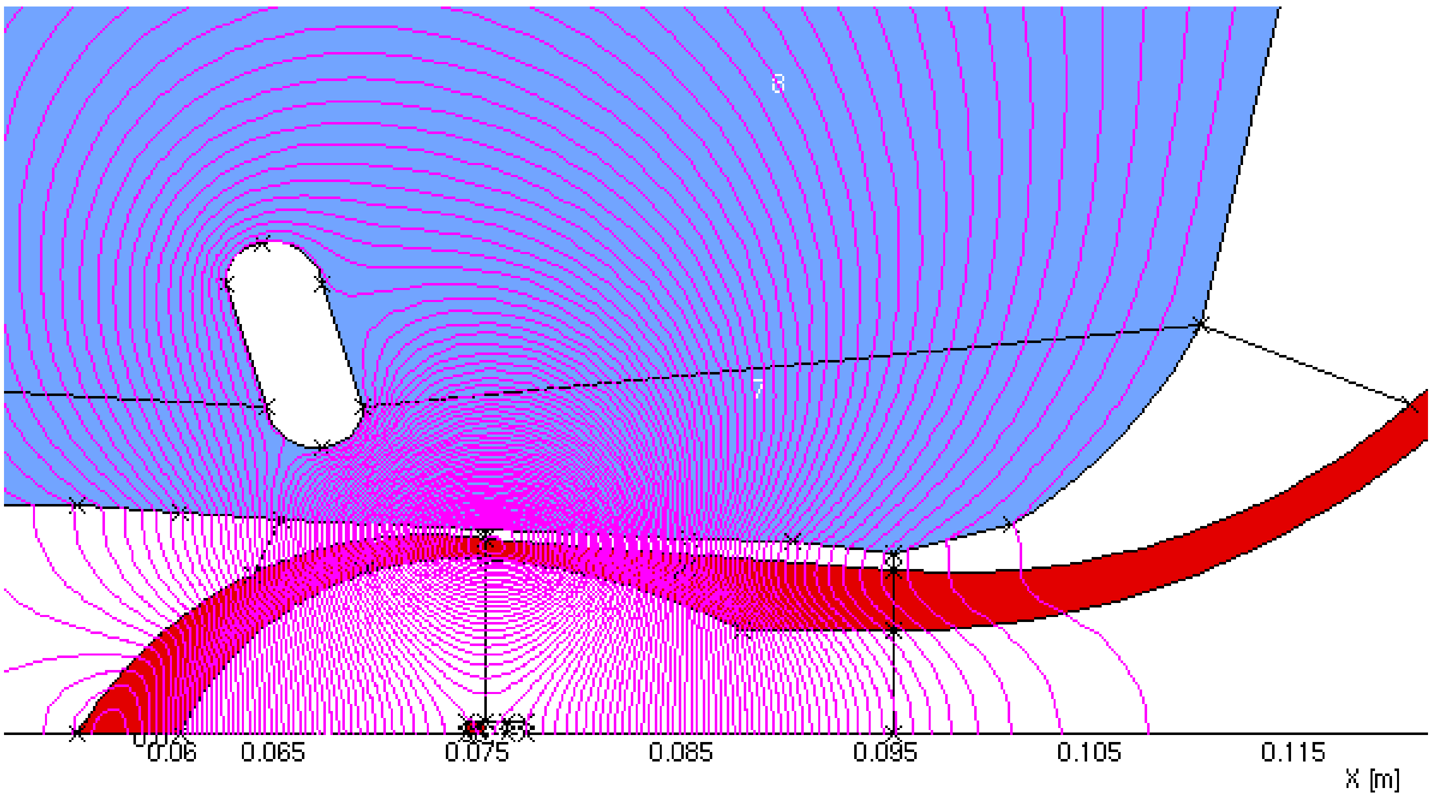
  - The TMCI has been observed in many electron rings (PETRA, PEP, VEPP-4, LEP), but not in proton machines.
  - Deal with by injecting low intensity bunches, and coalescing at higher energy (3-5 TeV, say) where threshold is higher.

Coherent and Incoherent Tune Shifts

- Coherent tuneshift variation along partially filled ring
- Incoherent tune shift due to detuning Resistive Wall wakes
- Laslett tune shift due to the dc image currents in the poles of the magnets
  - $\delta\nu_{LF}$ = -0.3 $\delta\nu_{HF}$ = -0.2

Tune shift from eddy currents

Magnetic field distribution caused by beam pipe eddy currents after ten bunches with current 0.19 A



Courtesy Vladimir Kashikhin.

Stage 1-- instabilities (cont'd)

- Cures:
  - RW: feedback system
  - Tune shifts: inject bunches more evenly to minimize lower harmonics
  - TMCI: coalescing
- Coalescing requires new RF system in injector chain (same f_{RF} as in Collider), and a second, lower frequency (53.1 MHz) system (2-3 MV) in the Stage 1 collider.
  - Yet to look at impact on injector chain RF systems

Ground Motion Issues..

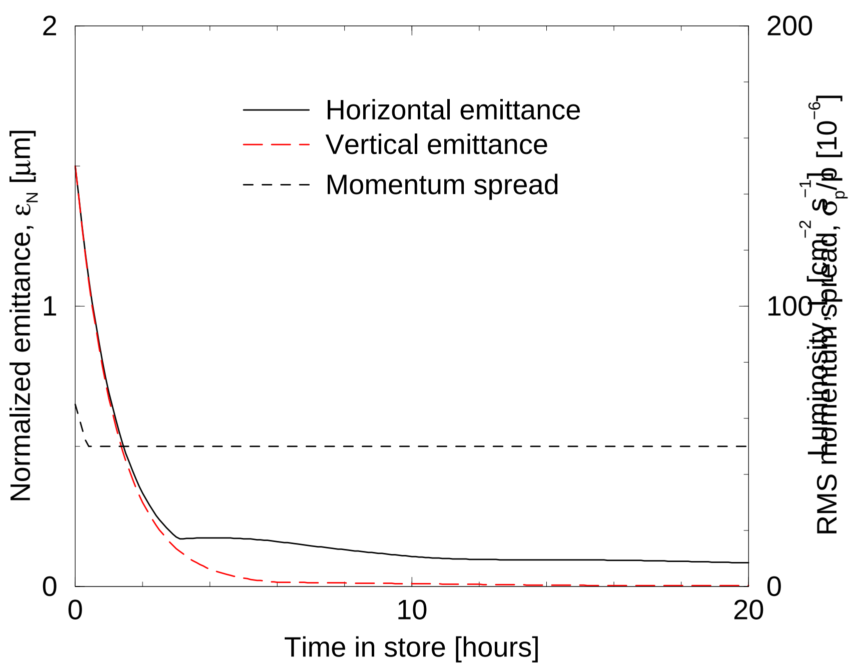
- Fast disturbances -- dealt with by using feedback systems
- Slow movements: ATL rule…
  - $\Delta \langle x^2 \rangle = (7\times10^{-7}\ \mu m^2/m/s)(\pi \times 10^7\ s)(135\ m)$
    $= (60\ \mu m)^2$ after one year
  - Leads to maximum closed orbit excursions $= 9\ mm/yr^{1/2}$
  - Align few magnets (outliers) per year

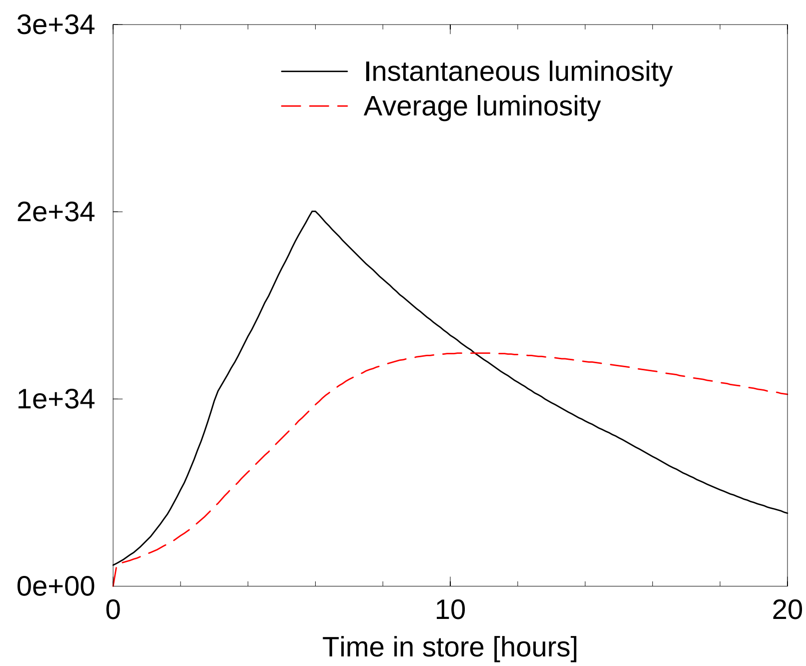
Stage 2 -- Nominal Store Parameters

Storage energy	87.5	TeV
Peak luminosity	2×10^{34}	$cm^{-2}sec^{-1}$
Packing fraction (arc)	85.5	%
Injection energy	10	TeV
Transverse Emittance, rms (H&V, inject)	1.5 π	μm
Natural Transverse Emittance, rms	0.04 π	μm
Initial bunch intensity	7.5×10^9	
Average beam current	57	mA
Stored energy per beam at collision	3.9	GJ
Bend field at storage	9.8	T
Phase advance per cell	90.0	deg
Max RMS arc beam size (inject)	0.42	mm
Synch. Rad. Power (per beam)	0.9	MW
Dipole linear heat load	4.7	W/m

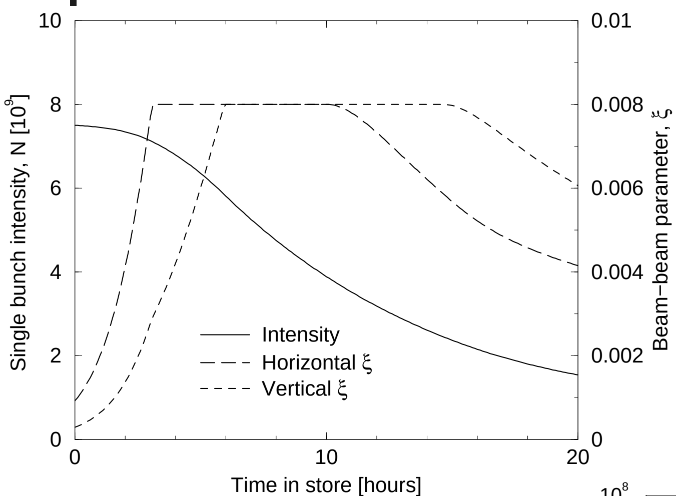
Bunch spacing (53.1 MHz)	5.645	m
or,	18.8	nsec
Bunch length (rms)	82	mm
Longitudinal emittance, rms (inject)	2.0	eV-s
RF voltage at storage	50	MV
Fill time	30	sec
Acceleration time	2000	sec
Beam size (rms) at IP (storage) - H	2.5	μm
- V	0.25	μm
Total crossing angle (10σ, inj.)	57	μrad
Distance from IP to first magnet	30	m
β^* at IP (H / V)	3.7 / 0.37	m
Maximum interactions per crossing	50	
Debris power at IP (each direction)	36	kW
Energy loss per turn per particle	16	MeV
Radiation damping time, τ_0	1.2	hr

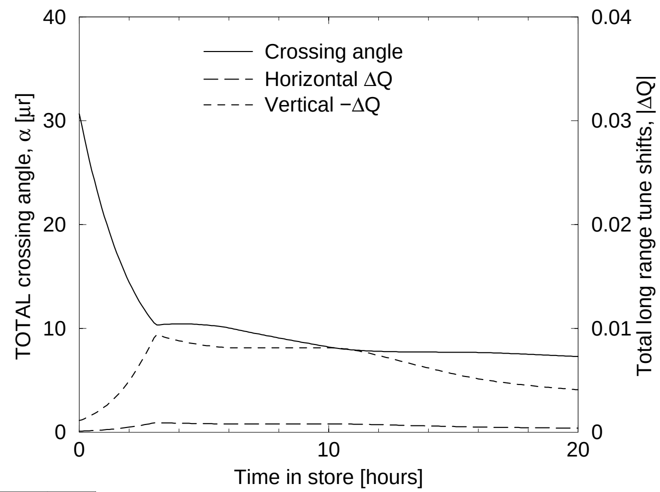
Stage 2 -- Parameter Evolution

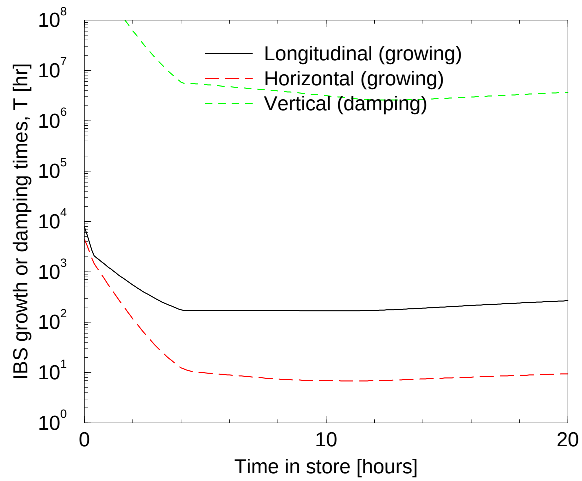




Stage 2 -- Parameter Evolution (cont’d)







Stage 2 -- Operational Considerations

Adjusting beam parameters to **respect a cryogenic power limit** makes the average luminosity depend on the beam energy *E* :

$$L_{ave} < \frac{P_{cryo}}{E}\left(\frac{1}{N_{IP}\sigma_{tot}}\right)\left(\frac{T_0}{T_{store}}\right)$$

T_{store} is much larger than T_{damp}, to take advantage of radiatively damped beam sizes. It is safe to estimate that

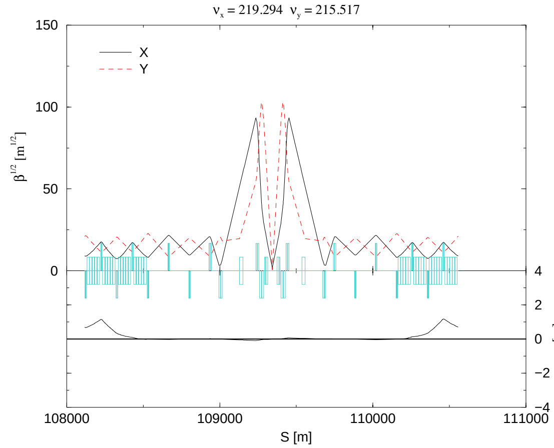
$$\frac{T_0}{T_{store}} \approx 0.2$$

Similarly, if the ***beam stored energy*** per ring $U = NME$ must be kept below a maximum value then

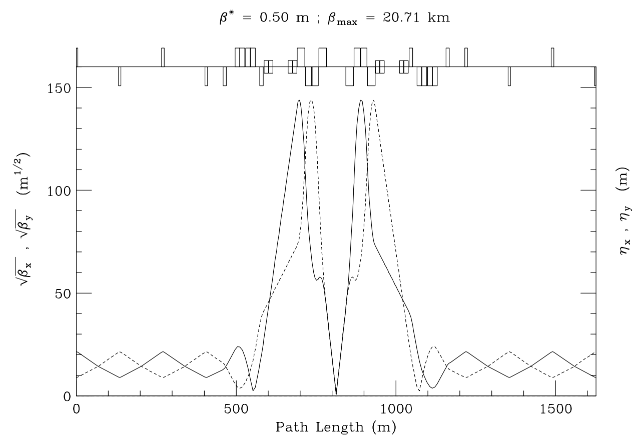
$$L_{ave} < \frac{U_{\max}}{E}\left(\frac{1}{N_{IP}\sigma_{tot}}\right)\left(\frac{1}{T_{store}}\right)$$

Stage 2 -- Lattice

- Standard FODO cells, etc.
- IR optics:
  - Doublet Optics (flat beams)
  - vs. Triplet Optics (round beams)



Doublet Optics



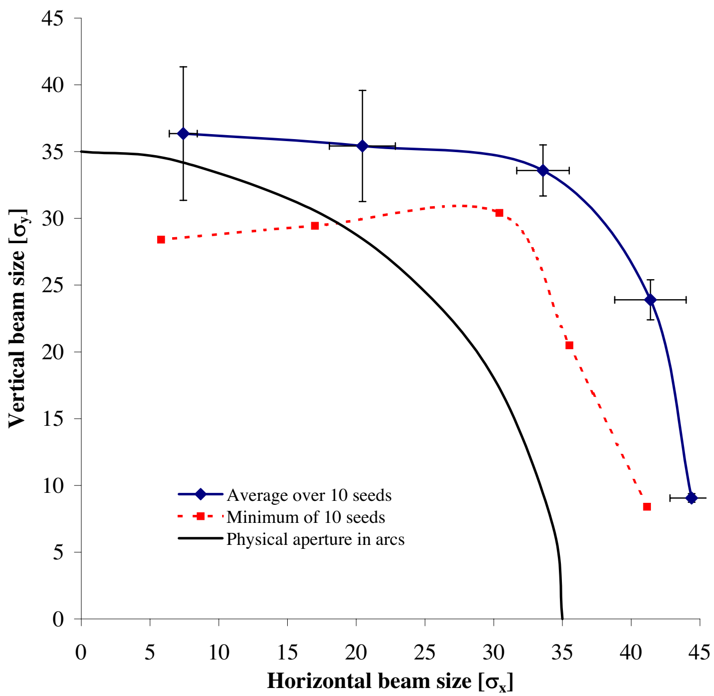
Triplet Optics

Round vs. Flat beams at the IP

- **Flat beams**:
  - Order of magnitude increase of β^*_x, and reduction of β_{max} in doublet quadrupoles. β_{max} - V & H -- both reduced
  - Fewer parasitic collisions per IR, reducing long-range tune shift (especially horizontal)
- **However,**
  - Designs of first quad and splitting dipole are difficult
  - Neutral particles from IP aim head-on for conductor located at center of first 2-in-1 quadrupole
  - Need for careful tuning to keep vertical emittance small; however, routinely achieved in electron rings.

Round beam case -- with IR magnet designs and optics -- is in hand.
Flat beam scenario is a promising upgrade. Studies will continue…

Stage 2 -- Injection Dynamic Aperture



Error bars = rms of 10 seeds

- 1000 -turn tracking
- Errors:
  - Quad offsets 0.3 mm
  - Dipole roll 0.5 mrad
  - Field errors 0.05%
  - Multipoles in dipoles
- Orbit corrected to zero in BPMs (0.2 mm rms)
- Chromaticity corrected

Stage 2 issues

- **Energy deposition**
  - The power of debris products exiting the collision point goes far beyond current experience. **Is there an acceptable engineering solution?**
- **Operational aperture**
  - **How far can the closed orbit move** before beam is lost? Is feedback necessary on closed orbits, tunes, and chromaticities in order to accelerate beam to top energy?
- **Instabilities**
  - HF -- higher rigidity --less susceptible to instability issues, but still a concern.
- **Diffusion**
  - Operational scenario assumes beam emittances decrease by order of magnitude or more, with a damping time of ~2.5 hours (10^7 turns). Basic understanding of slow diffusion mechanisms does not preclude the **possibility that this is fundamentally impossible**.

VLHC Accelerator Physics R&D items

- Instabilities
  - Impedance budget and estimate; superpipe model/test?
  - TMCI excitation (using Tevatron e^- lens?)
  - Collective feedback system specs.
- Diffusion
  - Ground motion, modulational diffusion, Intra Beam Scattering, Beam-Beam induced diffusion, etc.
- Lattice Design
  - IR optics (doublet & triplet), LF to HF transfer line, vertical dispersion suppression, beam abort, collimation, crossing angles/planes, optimum half cell length.

VLHC R&D items (cont'd)

- Simulation/Scaling
  - Particle tracking, energy deposition, dynamic optics. Is the operational aperture more critical than the dynamic aperture? Feedback on closed orbits, tunes, and chromaticities. Arc and IR correction schemes.
  - Luminosity versus energy, cryogenic power load, IR energy deposition,number of events per crossing, and capital or operating costs.
- Beam experiments
  - Beam-beam
  - Diffusion
  - Intra-Beam Scattering
  - …