Optical Design: Components and Techniques

Northern Illinois University

- First Key Question:
  - What is the purpose of the accelerator / beamline?
    - » sets requirements on particle energy, luminosity/brilliance, beam size, acceleration rate, particle targeting rate, ...
    - » ...which sets requirements for B, B', …
- Next Questions:
  - key parameters?
    - » aperture, final focus, momentum acceptance, momentum manipulations, high intensity, ...
  - special requirements?
    - » slow spill, e- stripping, diagnostic sections, collimators/halo removal, beam cooling, ...
  - also, number of users, or number of experiments:
    - » 10-100? (Light Source) 1-10? (HEP facility) 1-2? (medical), etc.

Optical Design [2]

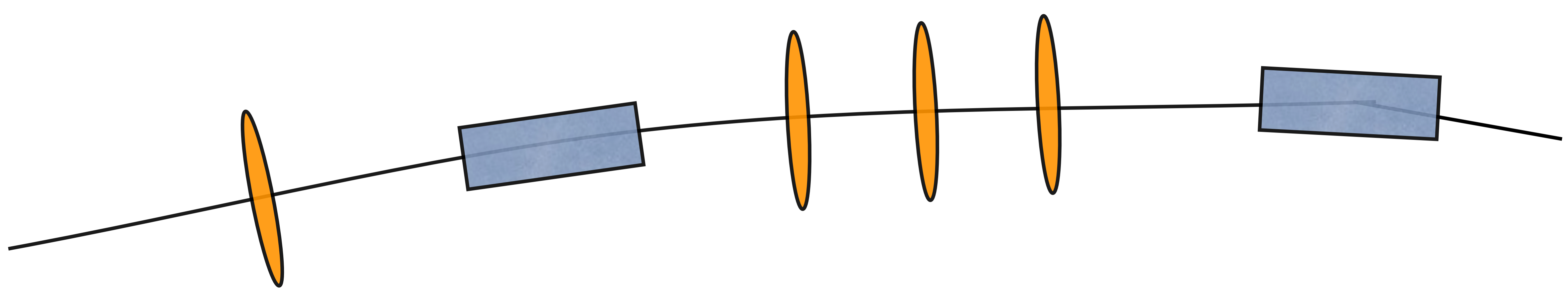
Northern Illinois University

- Further…
  - choice(s) of technology?
    - » maximum field strengths, straight sections lengths, apertures, …
    - » power consumption, real estate, …
  - system constraints?
    - » geometrical -- existing tunnel(s), beam line direction/orientation, accommodation of surface features, geological, ...
    - » components -- existing magnets, existing power supplies, diagnostics, accelerating cavities, ... COST! …
  - source(s) of particles?
  - charge state(s), injection energy, emittances of existing beams, …

Ex: Light Source

- Synchrotron Radiation due to bending
  - want low dispersion function in the bending magnets
  - --> produces smaller equilibrium emittances

- Typically, lower energy (~1-10 GeV) electrons; many users!
  - thus, can tolerate lower "packing fraction":
    - » $2\pi\rho/C <$ ~50%



Ex: HEP Synchrotron

Northern Illinois University

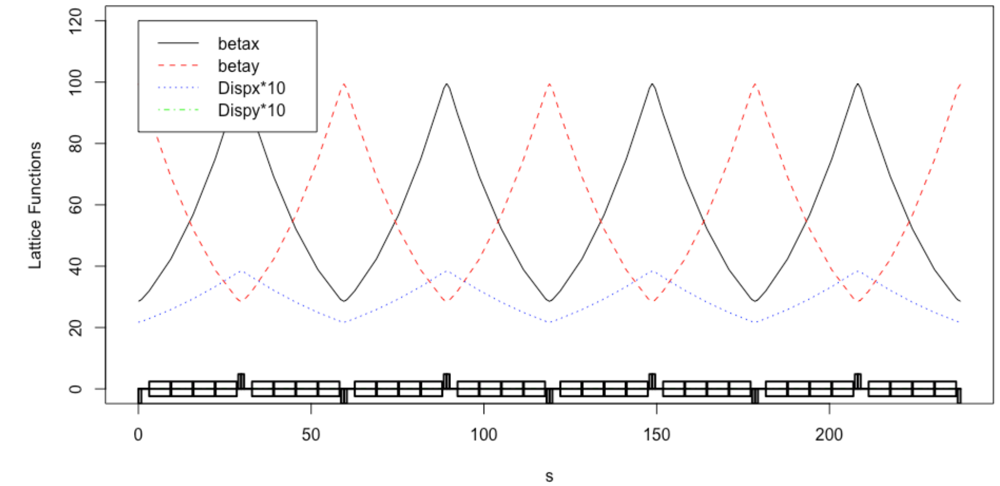
- Here, typically very high energy, few experiments (though still MANY users!)
  - need lots of bending, perhaps less need for free space in the system
  - may look like mostly FODO cells, with space for RF accelerating cavities, injection/extraction, etc.
  - here, typically much larger packing fraction (~80% or higher in the arcs)

Optical Modules

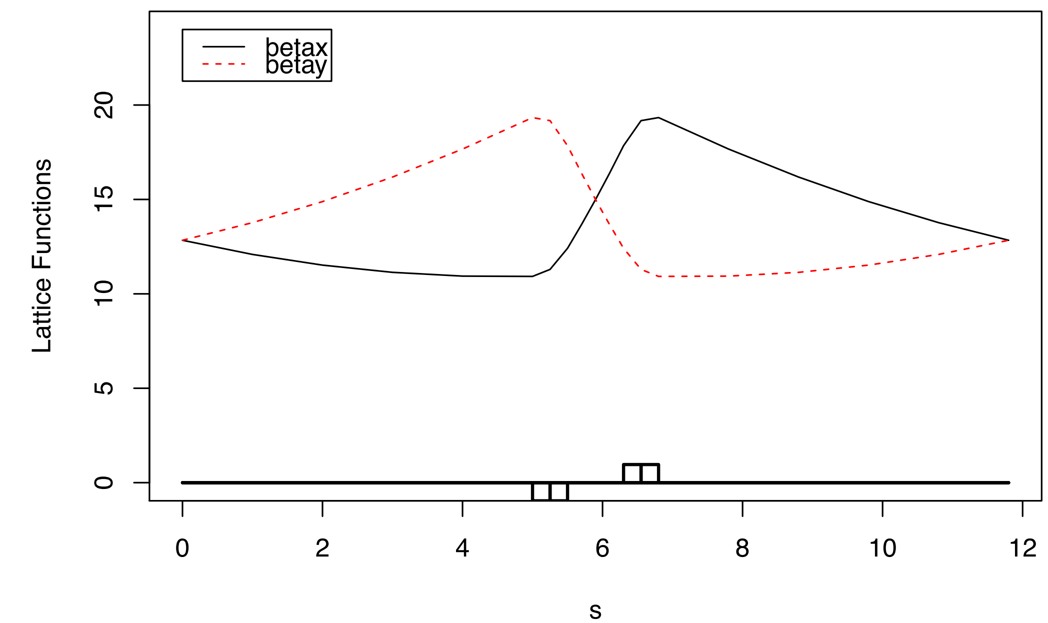
- Very often useful to think of optical systems in terms of modules
- Each module has a purpose and/or special conditions to be met
  - general beam transport; achromatic; large dispersion for momentum selection, charge selection; small dispersion for isochronous transit; final focus onto target; long drift space for equipment; compact bending; etc. ...
- Large/long systems are best generated with (stable!) periodic lens systems -- may or may not have bending
- Often need longer spaces for instrumentation, RF, switching magnets, experiments, etc.
- May need to match one focusing structure into a different focusing structure (e.g., change of cryomodule lengths, etc.)
- Simultaneously trying to control $(\alpha, \beta, D, D')_{x,y}$ [and sometimes $\psi_{x,y}$] as well as X,Y,Z and X',Y' of the ideal trajectory along the beam line!
  - *various computer programs are good at this*

Doublets and Triplets

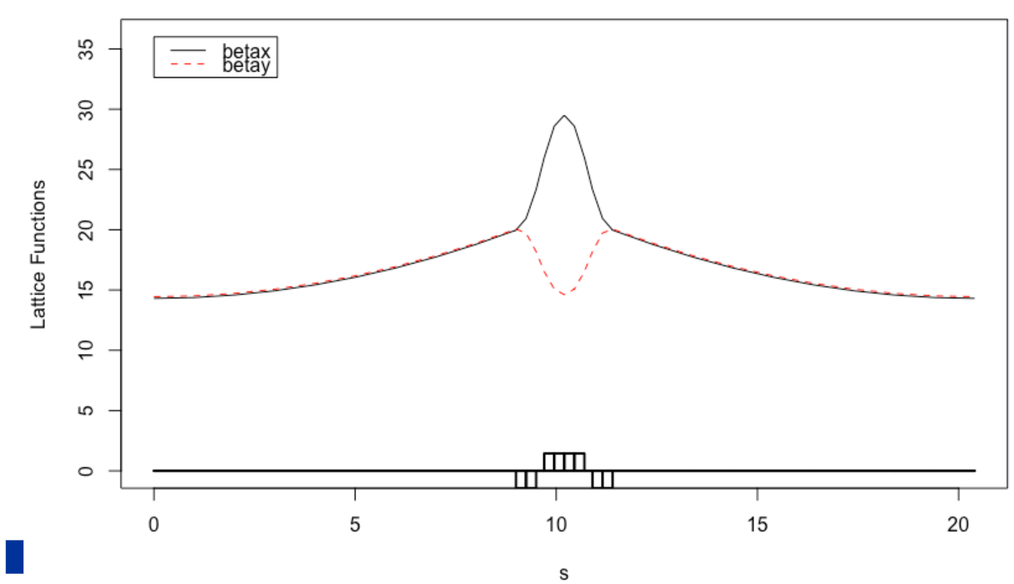
- FODO Cells
  - basic transport; equal spacing; easy analysis

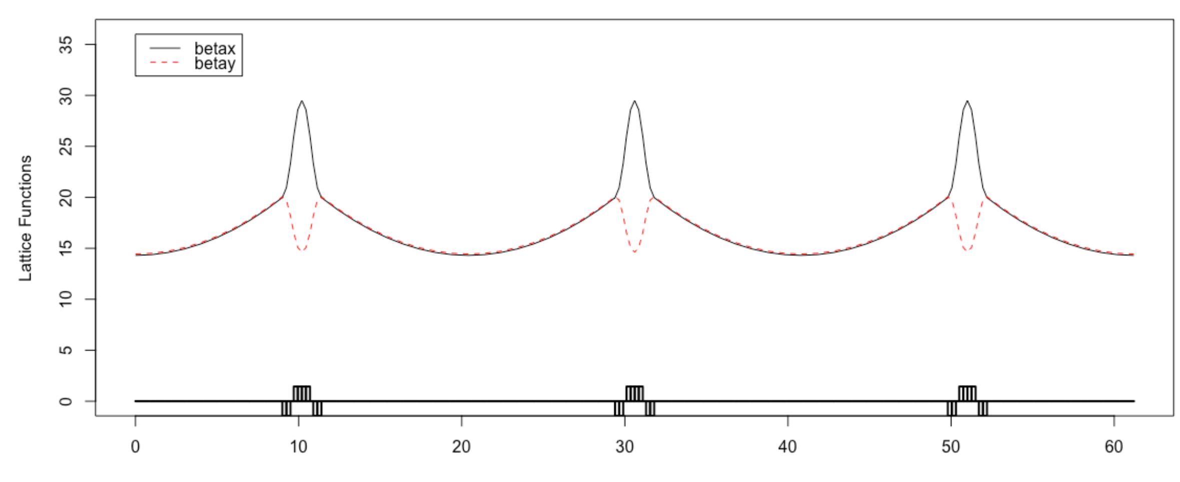


- Doublets
  - can be used to generate more space



- Triplets
  - can be used to keep beam “round”

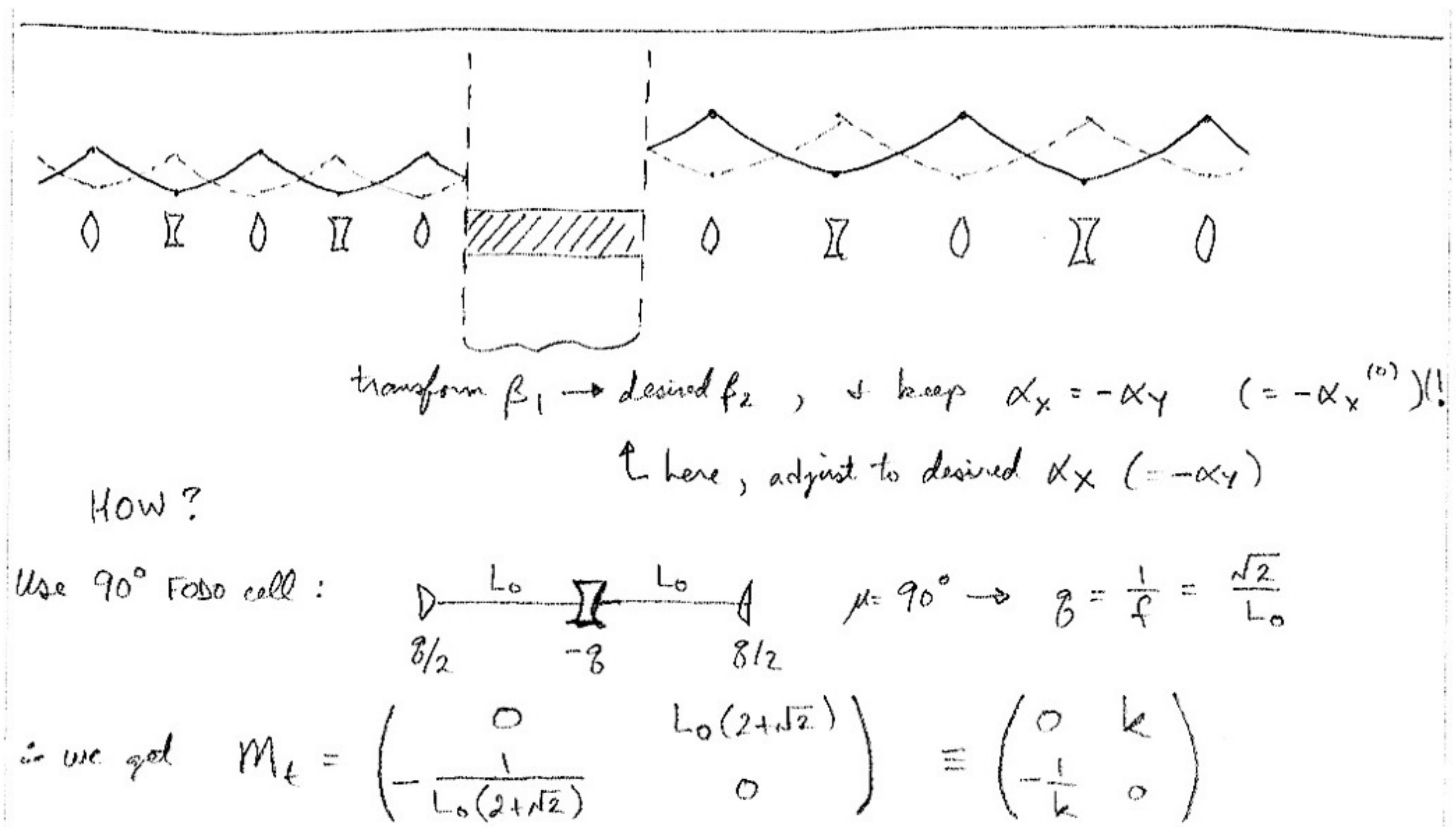




Quarter-Wave Transformer

Northern Illinois University

- Suppose want to transform from one focusing pattern to another...

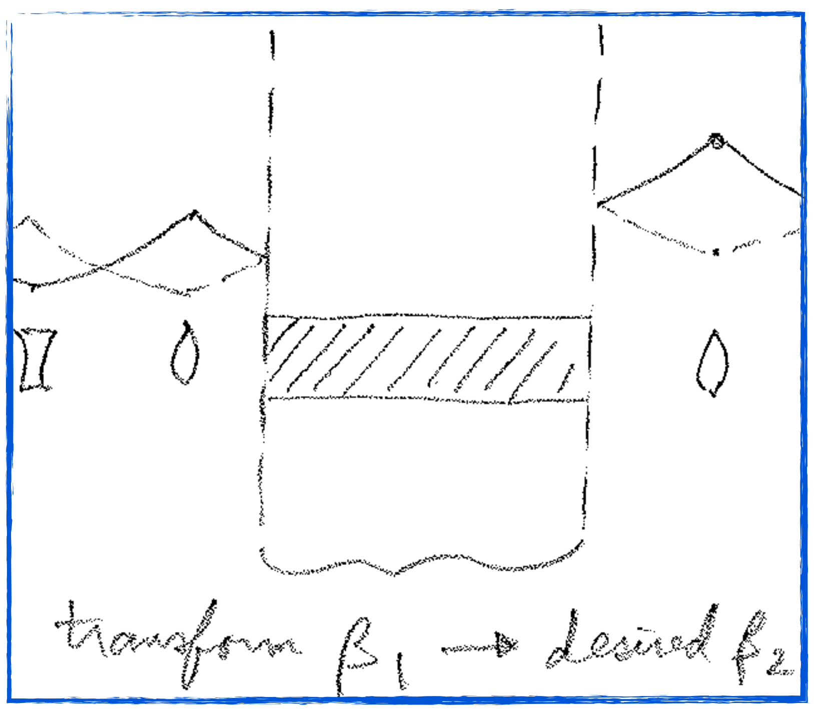


$$\begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}_2 = \begin{pmatrix} 0 & k \\ -\frac{1}{k} & 0 \end{pmatrix} \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}_1 \begin{pmatrix} 0 & -\frac{1}{k} \\ k & 0 \end{pmatrix} = \begin{pmatrix} k^2\gamma_1 & \alpha_1 \\ \alpha_1 & \beta_1/k^2 \end{pmatrix}$$

Quarter-Wave Transformer [2]

- So, adjust k (i.e., L_0 and f) to get the desired β_2
- Then, re-adjust $q/2$ at the end to get the desired α_2

$$\alpha_2 = -\alpha_1, \quad \beta_2 = k^2\gamma_1 \quad \Rightarrow \quad \frac{\beta_2}{\beta_1} = \left(\frac{k}{\beta_1}\right)^2 (1+\alpha_1^2)$$



Once have b2, may not have the *desired* α2 needed for the match into the new FODO cells; so, re-adjust α2 by adjusting the last quad of the transformer:

$$\Delta\alpha_2 = \beta_2 \cdot \Delta q$$

Note: since start with $\beta_x = \beta_y$ @ pt. 1, then get $\beta_x = \beta_y$ @ pt. 2

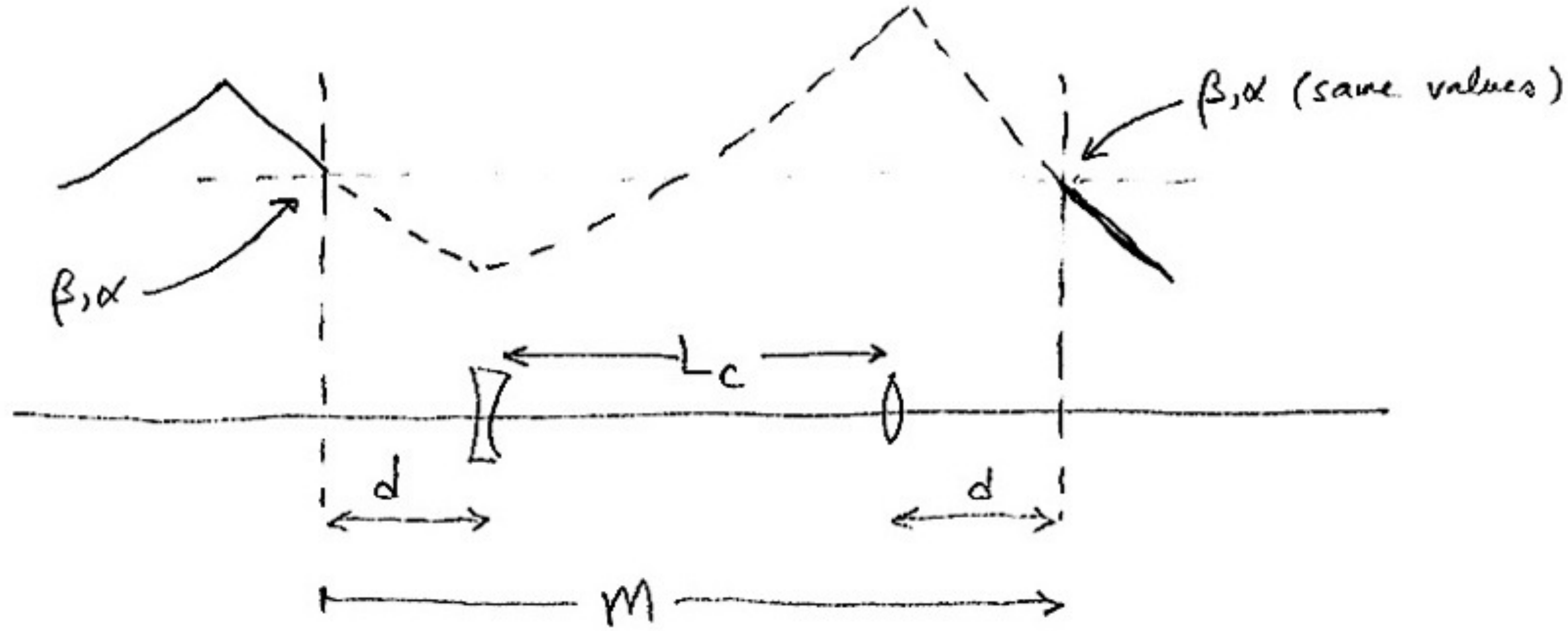
AND $\alpha_x = -\alpha_y$ @ pt. 1 —> $\alpha_x = -\alpha_y$ @ pt. 2

AND when re-adjust, $\Delta\alpha_x = \beta_x \Delta q = -\beta_y \Delta q = -\Delta\alpha_y$

which automatically maintains $\alpha_x = -\alpha_y$ condition at pt. 2

Collins Straight Section

Northern Illinois University



$$M = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -q & 1 \end{pmatrix}\begin{pmatrix} 1 & L_c \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ q & 1 \end{pmatrix}\begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 + qL_c(1-dq) & 2d + L_c(1-d^2q^2) \\ -q^2 L_c & 1 - qL_c(1+dq) \end{pmatrix}$$

$$= \begin{pmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu & \cos\mu - \alpha\sin\mu \end{pmatrix}$$

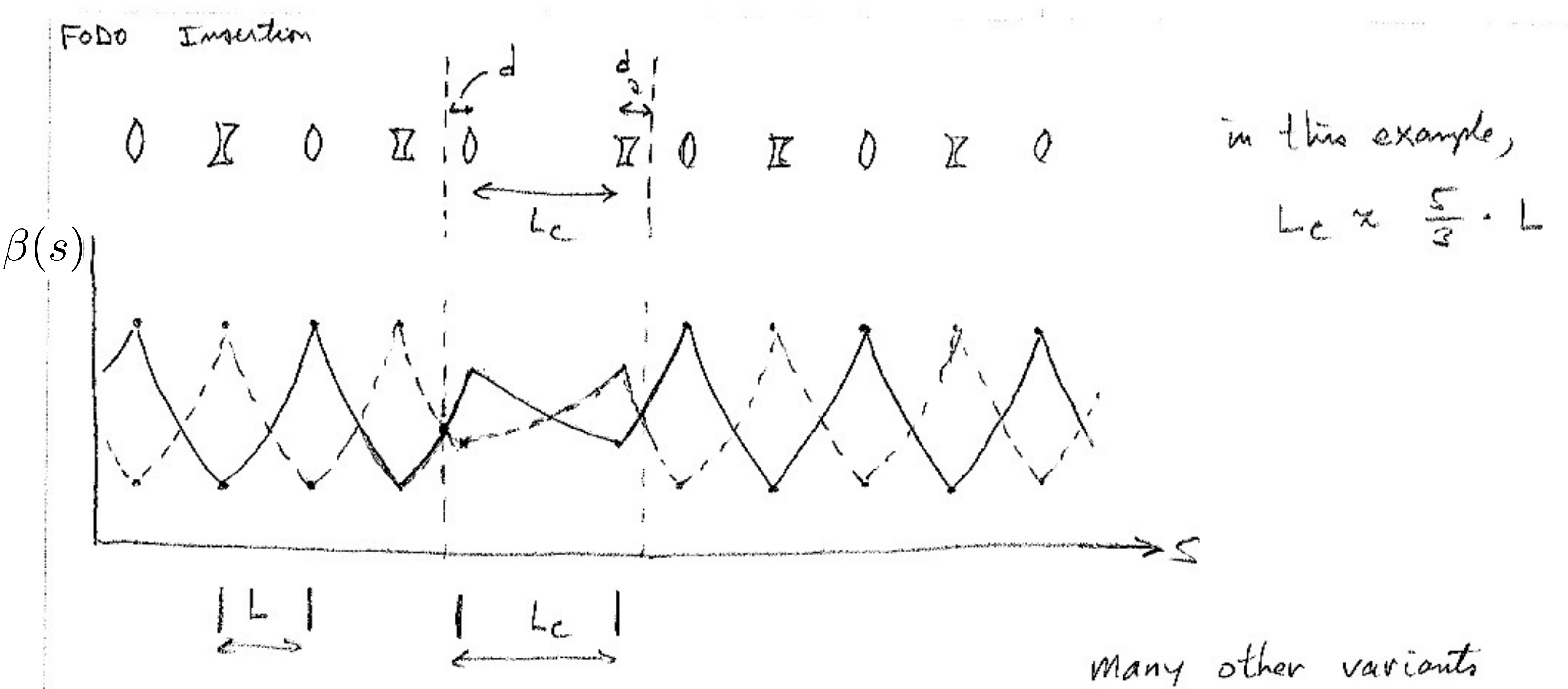
$$\Rightarrow \left.\begin{aligned} 2\alpha\sin\mu &= 2qL_c \\ \text{and} \quad \gamma\sin\mu &= q^2 L_c \end{aligned}\right\} \quad q = \frac{1}{f} = \frac{\gamma}{\alpha}$$

$$\hookrightarrow L_c = f^2\gamma\sin\mu = \frac{\alpha^2}{\gamma}\sin\mu \quad \text{and} \quad d = \frac{1}{\gamma}\tan\mu/2$$

if choose $\mu = \pi/2 \Longrightarrow L_c = \frac{\alpha^2}{1+\alpha^2}\cdot\beta$, $f = \frac{\alpha}{1+\alpha^2}\beta$, $d = \frac{1}{1+\alpha^2}\beta$

Collins Straight Section [2]

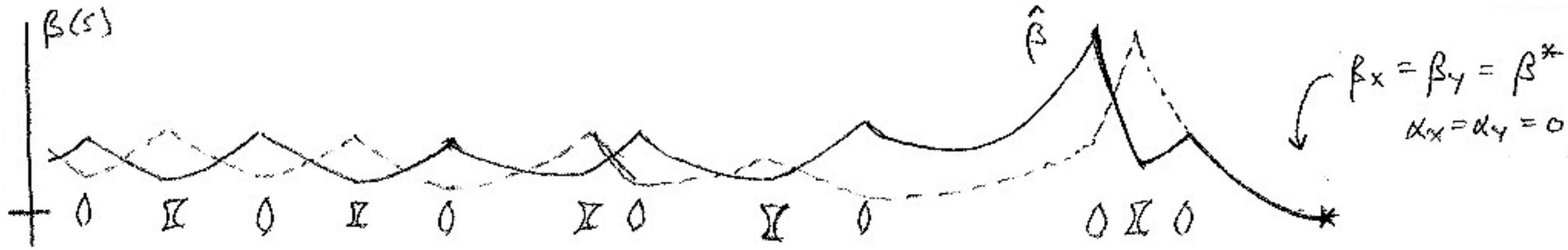
- Note: in order to match H and V optics *simultaneously*, we want $\alpha_x = -\alpha_y$ and $\beta_x = \beta_y$ at the match point(s).
  - this occurs in the middle of a FODO cell…



Final Focus

Northern Illinois University

$$\beta(s) = \beta^* \left[1 + (s/\beta^*)^2\right]$$



target

transport	adjust/tune	final focus
telescope-like:	"eyepiece"	"objective"

$\leftarrow L^* \rightarrow$

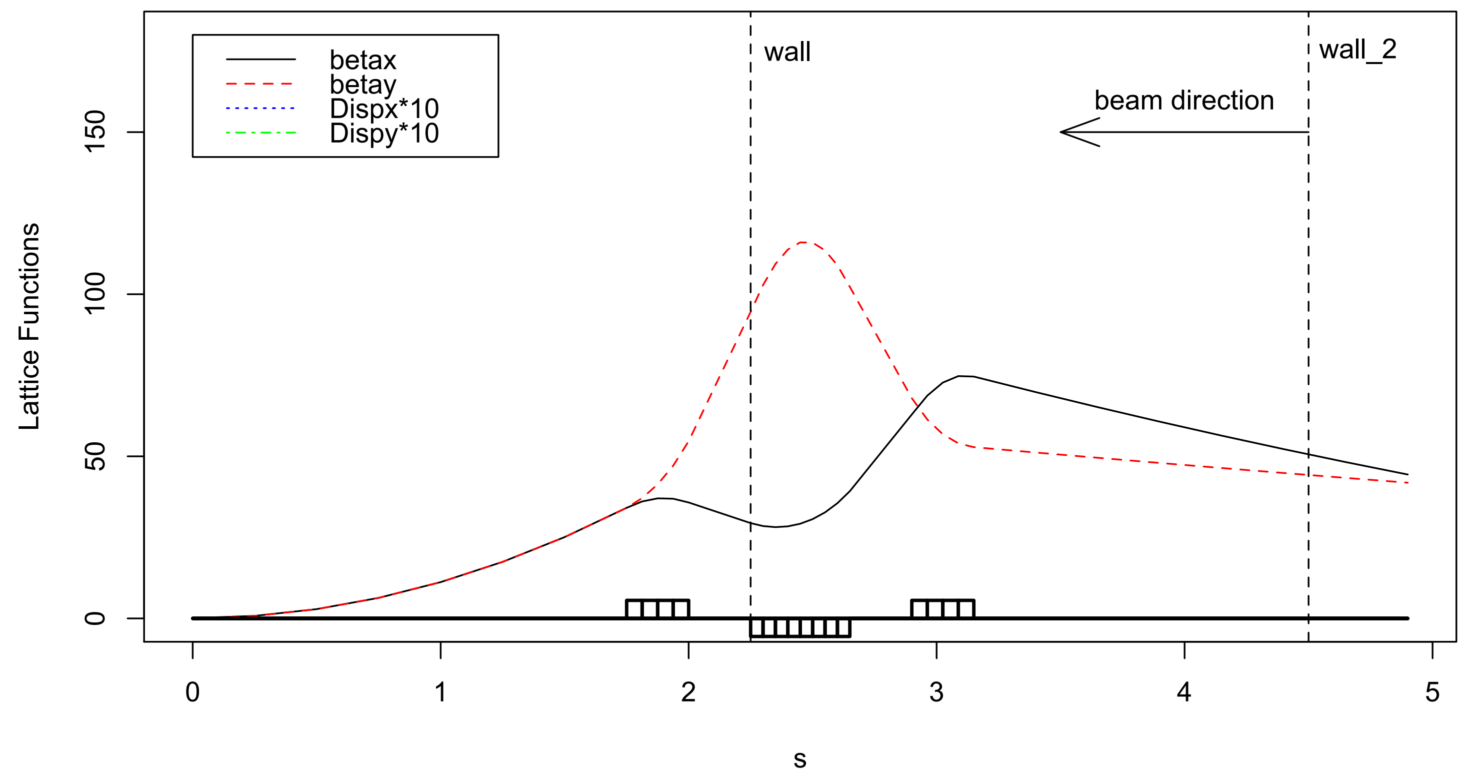
To tune, consider starting at the target with a desired $\beta = \beta^*$, and $\alpha = \alpha^* = 0$, and working backward to find values for tuning quads that match β_x, β_y back into the transport region

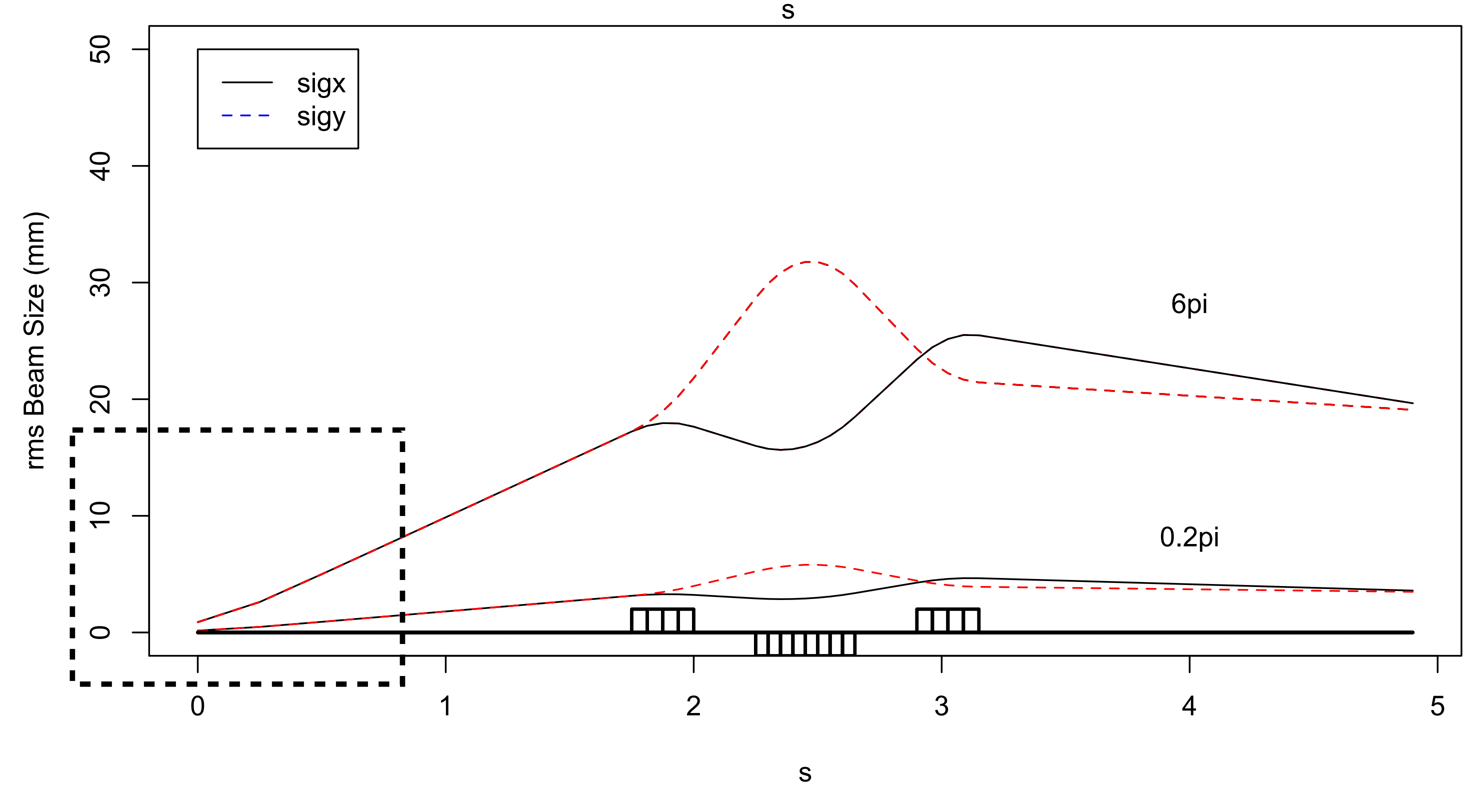
$$\hat{\beta} \approx \frac{L^2}{\beta^*}$$

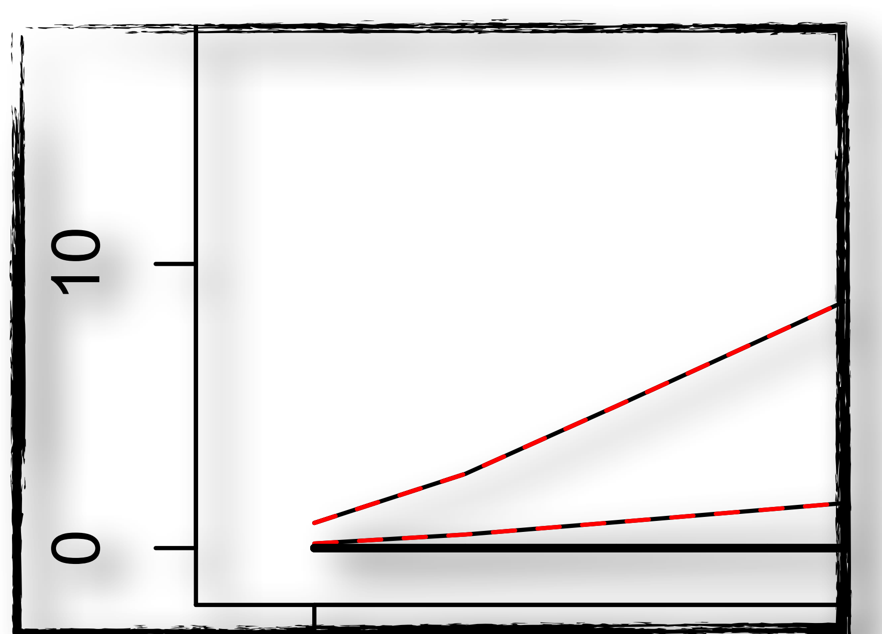
tune 4 quads to match 4 parameters $(\beta, \alpha)_{xy}$

Final Focus [2]

- FRIB Final Focus:
- Beam size max/min
  - max/min ~ 35
  - max(linac)/min(target) ~ 10



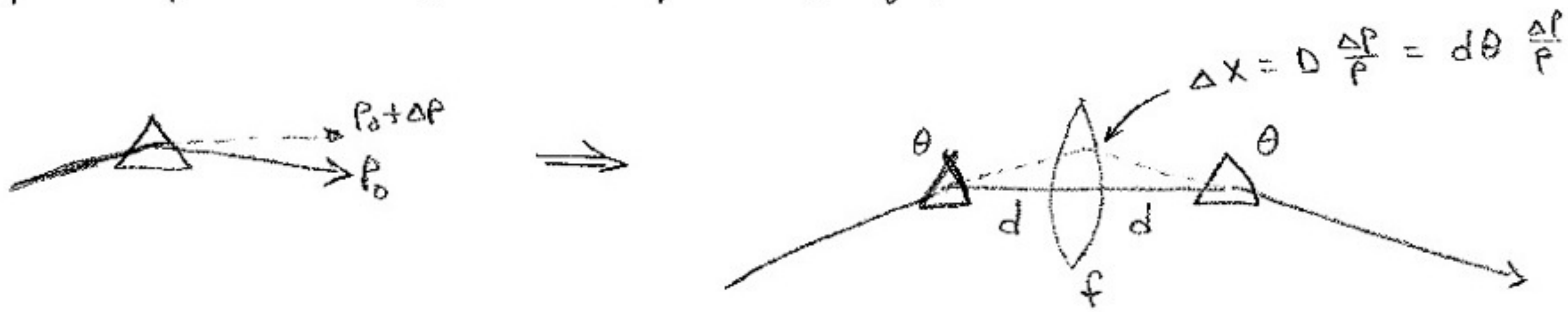




Double-Bend Achromat

Achromat: enter / exit w/ $D = D' = 0$ (D = dispersion)

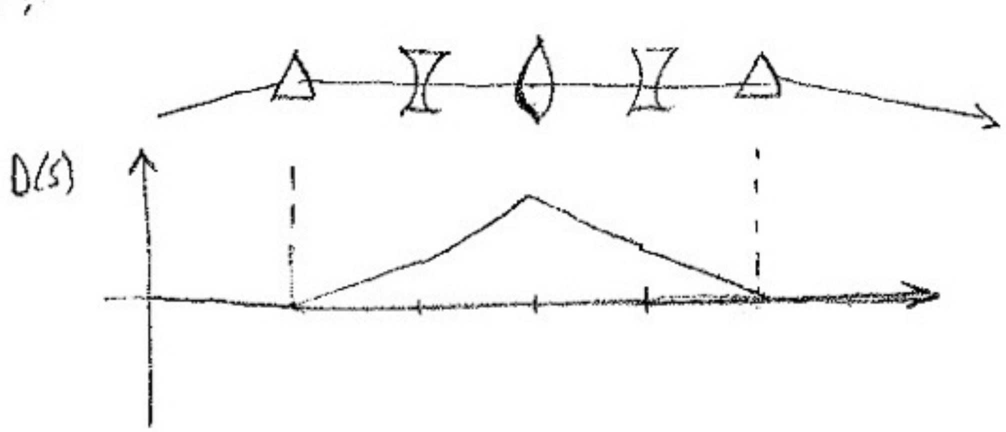
simple concept: use 2 bend magnets w/ quad(s) in between



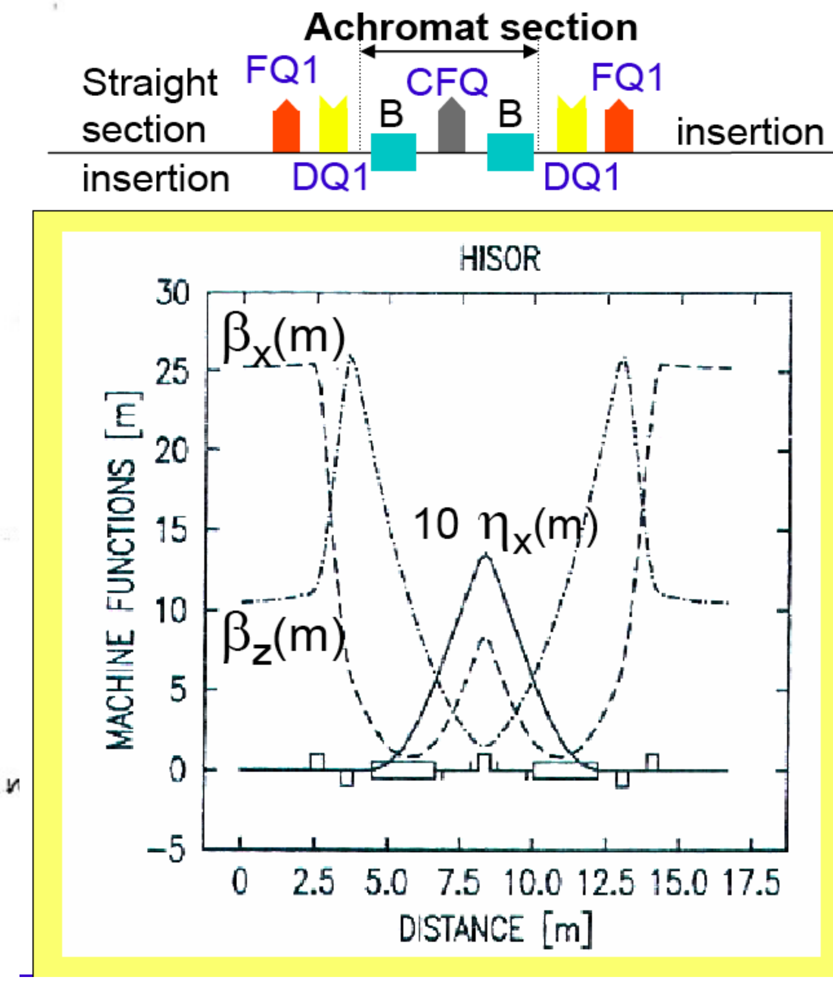
if $d = 2f$, then $\Delta D'$ at lens: $\Delta D' = -\frac{d\theta}{f} = -2\theta$

Note: since lens focuses in x, defocuses in y,

can use a triplet:



Chasman-Green lattice

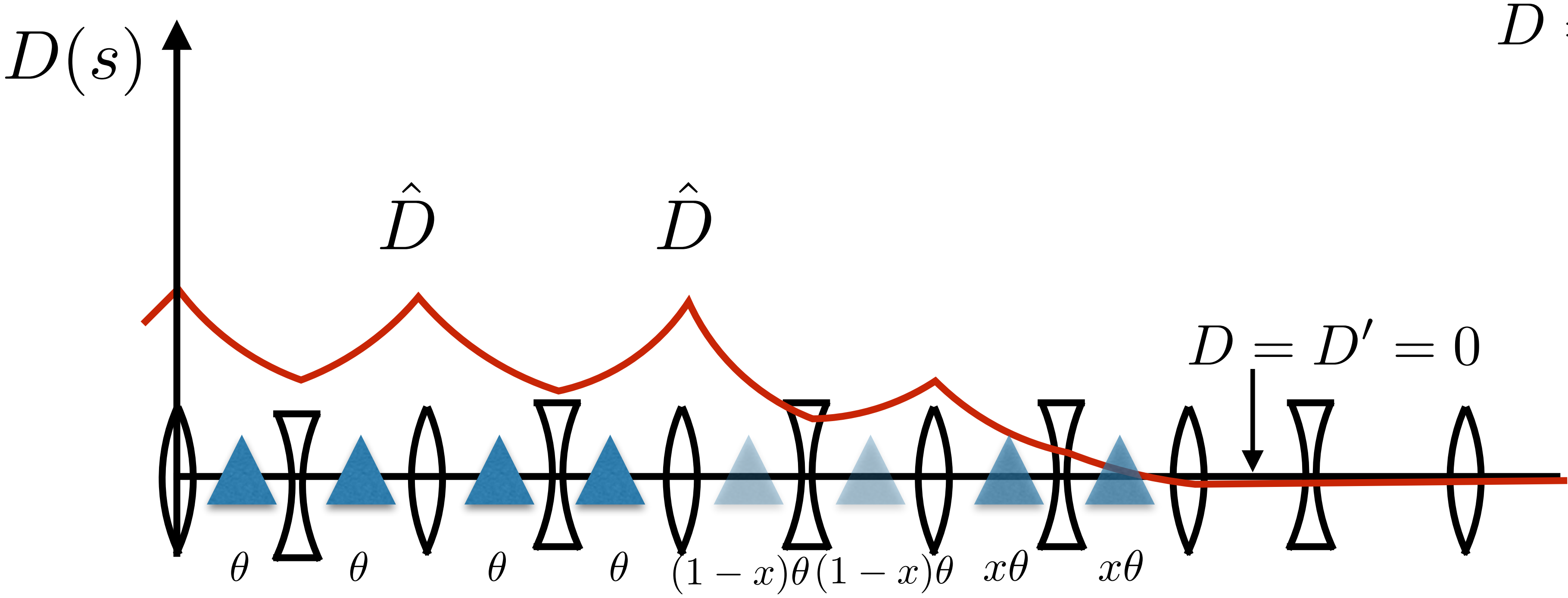


Dispersion Suppressor

used in rings or large bending segments to bring the periodic dispersion of the FODO cells to zero

$$\hat{D} = \frac{L\theta}{\sin^2\frac{\mu}{2}}\left(1 + \frac{1}{2}\sin\frac{\mu}{2}\right)$$

μ = phase advance per FODO cell



What value of *x* will bring *D*, *D*' both to zero?

Let periodic dispersion be: $\vec{D}_0 = \begin{pmatrix} D_0 \\ D'_0 \end{pmatrix}$ and $M_0 = \begin{pmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu & \cos\mu - \alpha\sin\mu \end{pmatrix}$

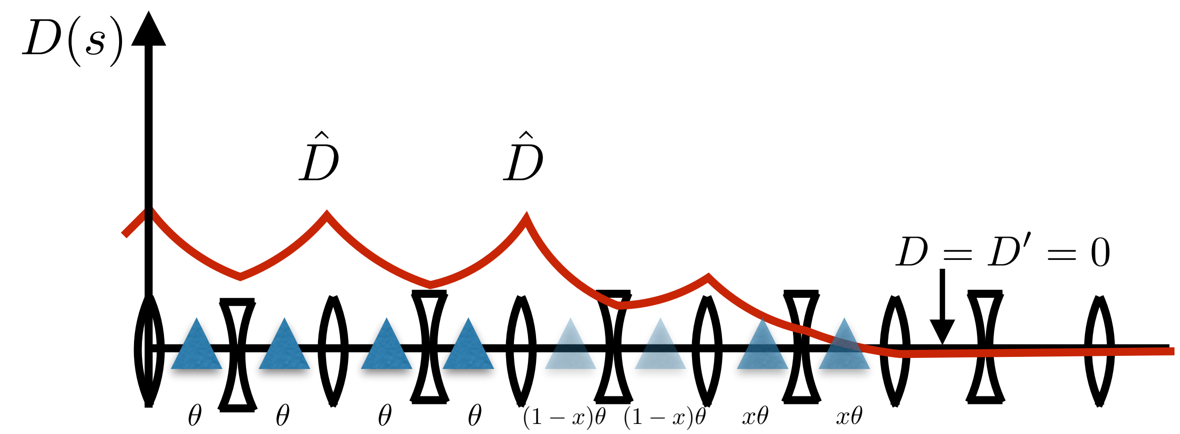
Then, using 3x3 matrix approach:

$$\begin{pmatrix} \vec{D}_0 \\ 1 \end{pmatrix} = \begin{pmatrix} a & b & e \\ c & d & f \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \vec{D}_0 \\ 1 \end{pmatrix} = \begin{pmatrix} M_0 & (I - M_0)\vec{D}_0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \vec{D}_0 \\ 1 \end{pmatrix}$$

Dispersion Suppressor

Northern Illinois University

So, we transport through a cell with bending reduced by factor (1-*x*) followed by a cell with bending reduced by factor *x*; since *D* ~ θ, then the matrix elements scale accordingly and hence…



final dispersion = 0

$$\begin{pmatrix} \vec{0} \\ 1 \end{pmatrix} = \begin{pmatrix} M_0 & x(I - M_0)\vec{D}_0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} M_0 & (1-x)(I - M_0)\vec{D}_0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \vec{D}_0 \\ 1 \end{pmatrix}$$

initial periodic values

which, upon simplification, yields $\vec{0} = \left[(1-2x)I + x(M_0^{-1} + M_0)\right] M_0 \vec{D}_0$

Noting that $M_0^{-1} + M_0 = trace(M_0)I = (2\cos\mu)I$

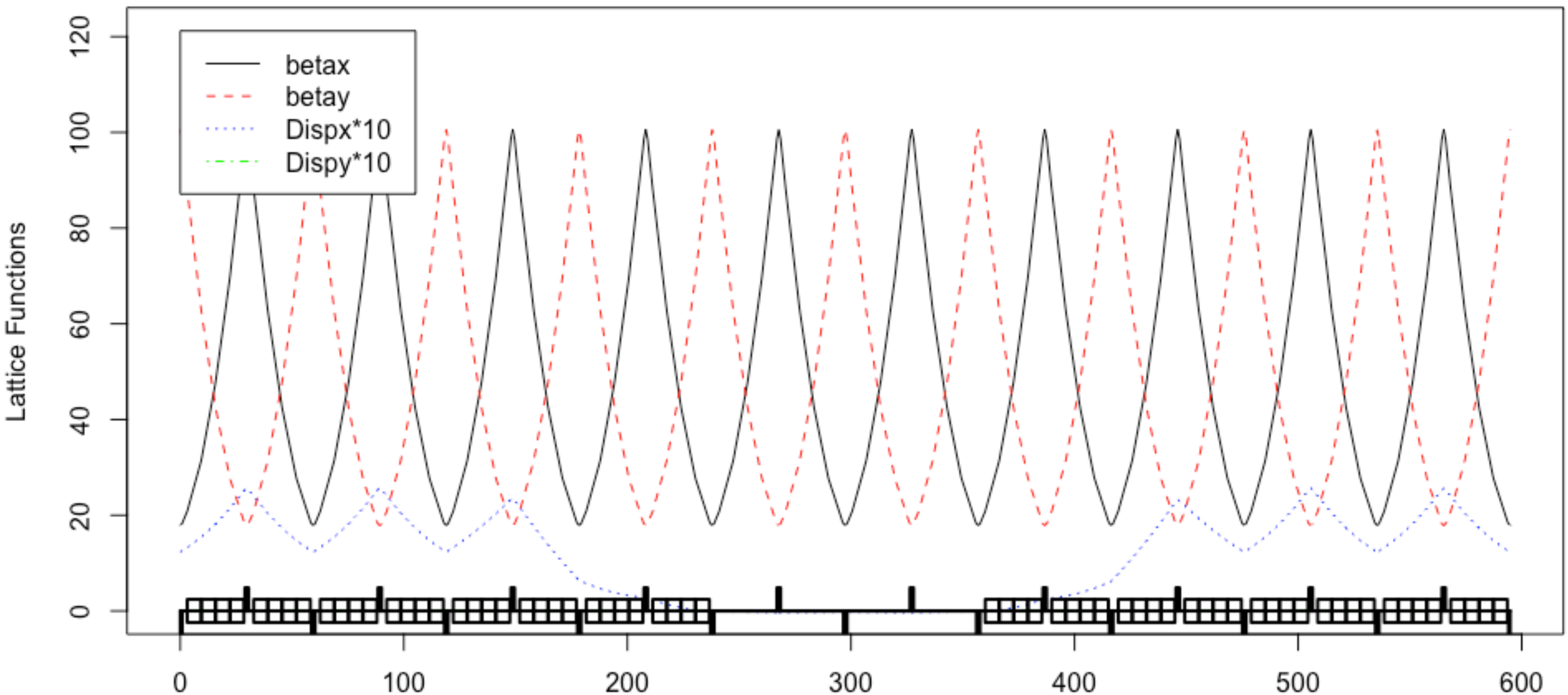
then our equation is satisfied if

$$x = \frac{1}{2(1-\cos\mu)}$$

μ	x	1-x
60°	1	0
90°	1/2	1/2

Dispersion Suppressor Example

$\mu = 90^\circ$

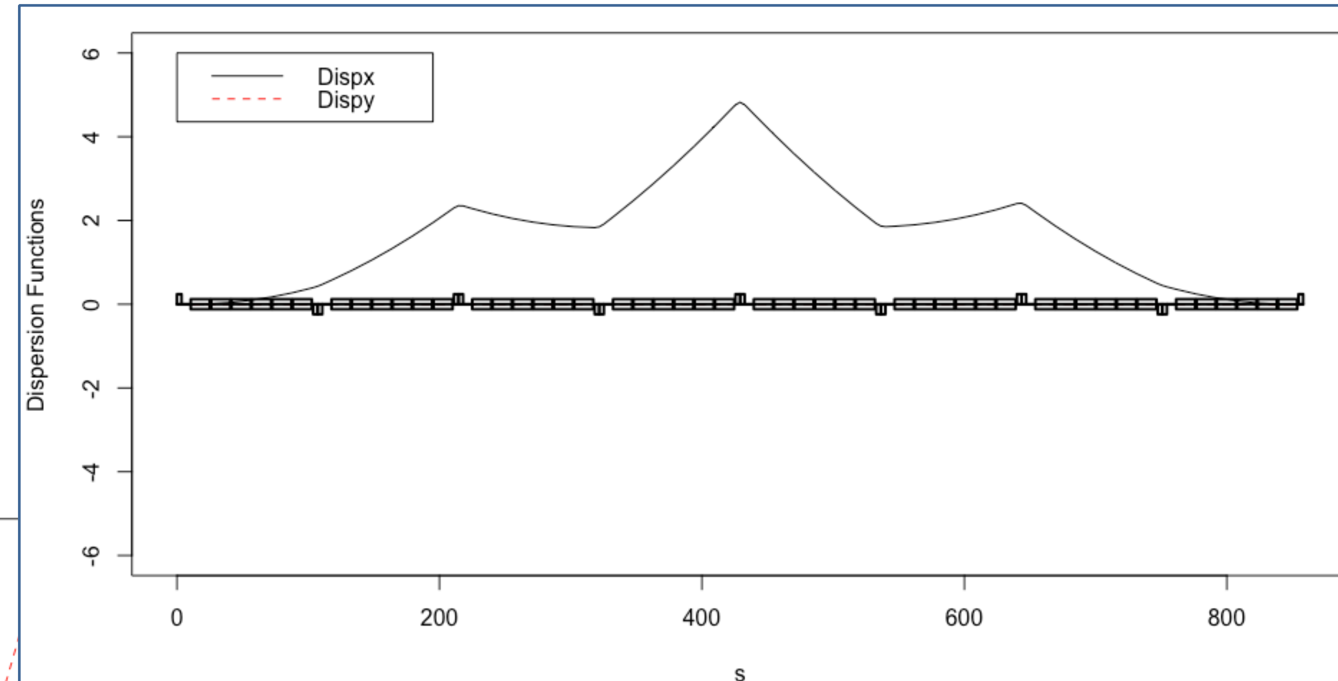


$$\theta \quad \theta \quad \theta \quad \theta \quad \frac{\theta}{2} \quad \frac{\theta}{2} \quad \frac{\theta}{2} \quad \frac{\theta}{2} \qquad\qquad \frac{\theta}{2} \quad \frac{\theta}{2} \quad \frac{\theta}{2} \quad \frac{\theta}{2} \quad \theta \quad \theta \quad \theta \quad \theta$$

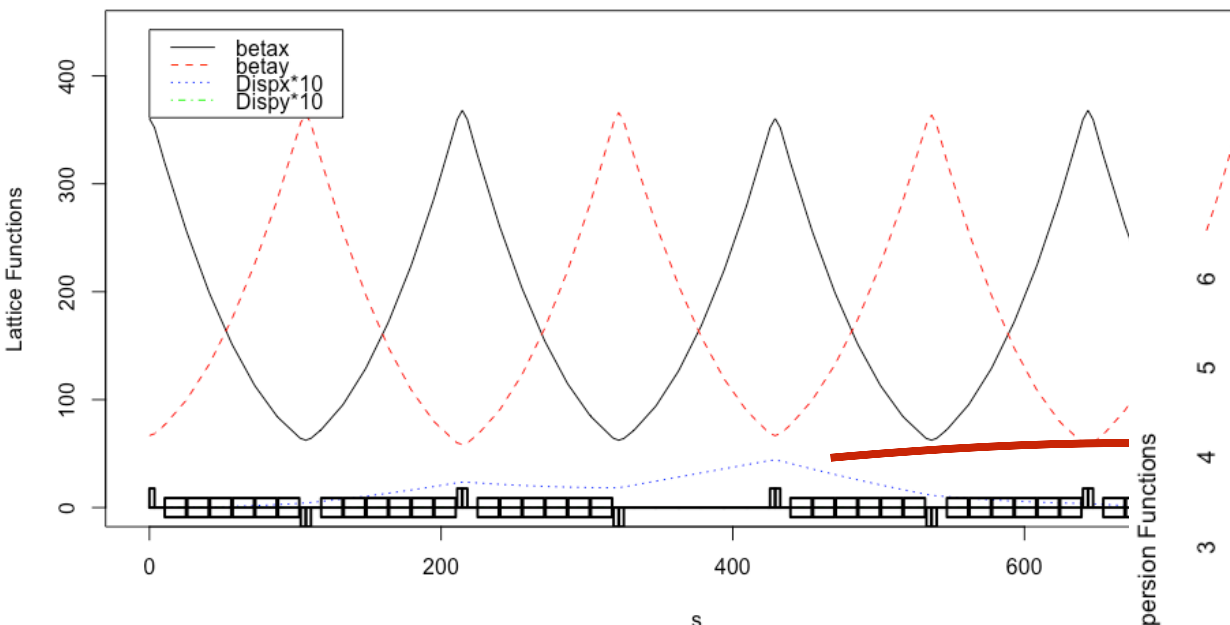
FODO Achromatic Bend Sections

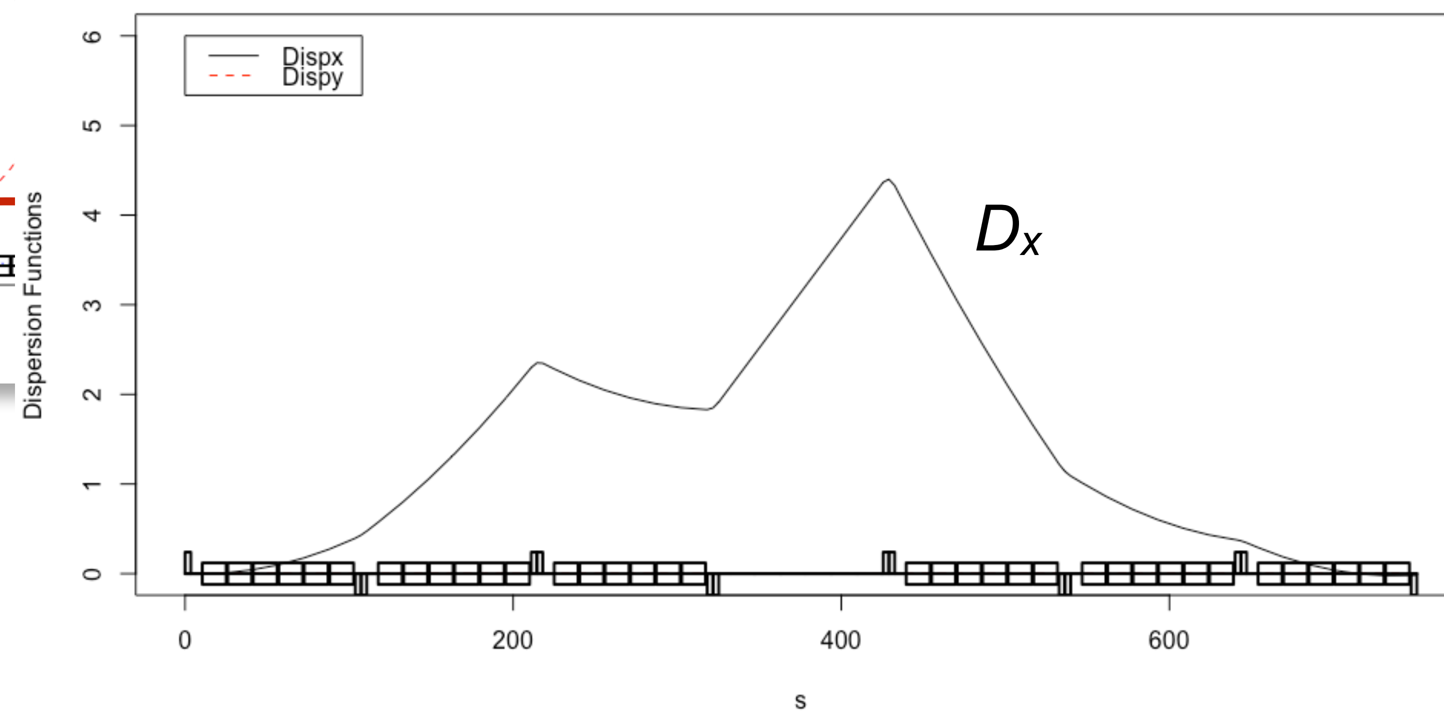
Northern Illinois University

for μ = 90°/cell, use 4 cells;
back-to-back dispersion suppressors —



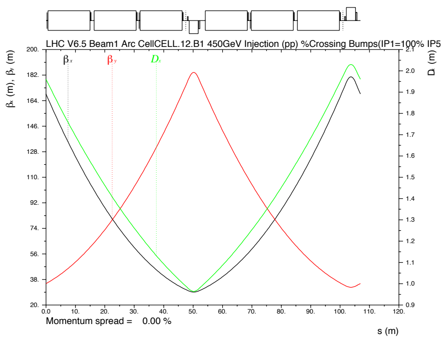
here, μ = 90°, but
with empty half-cell in middle:



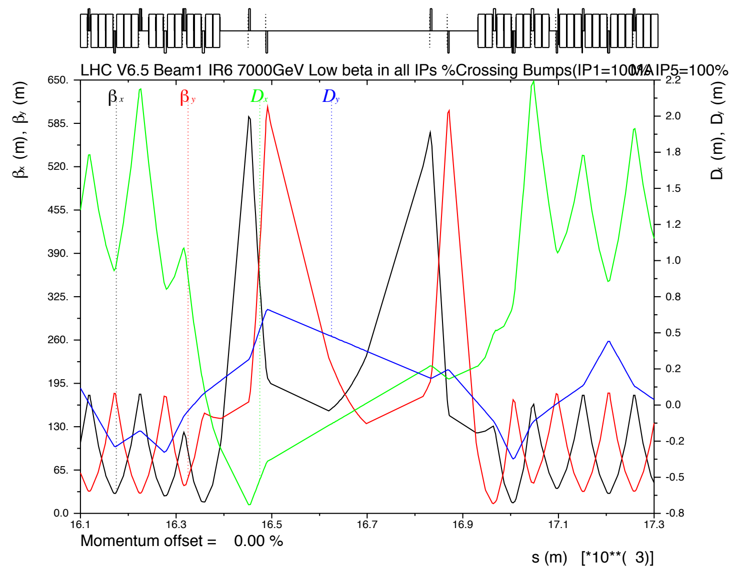


LHC Straight Sections

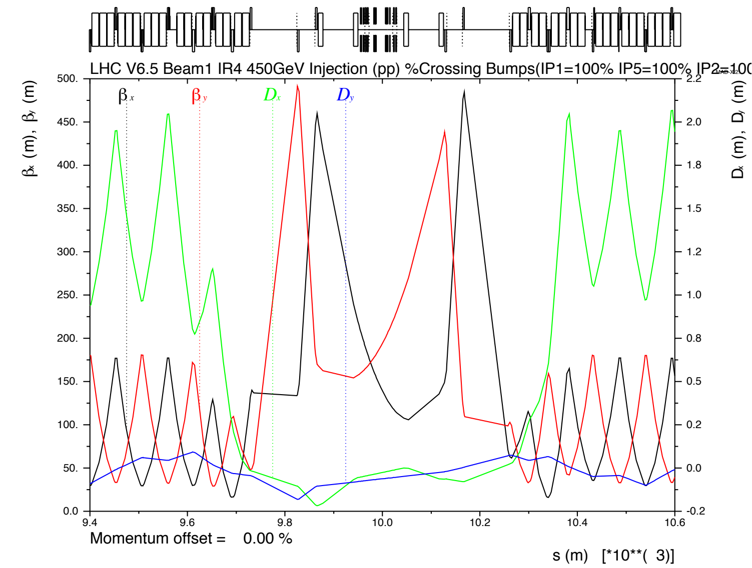
Standard Cell



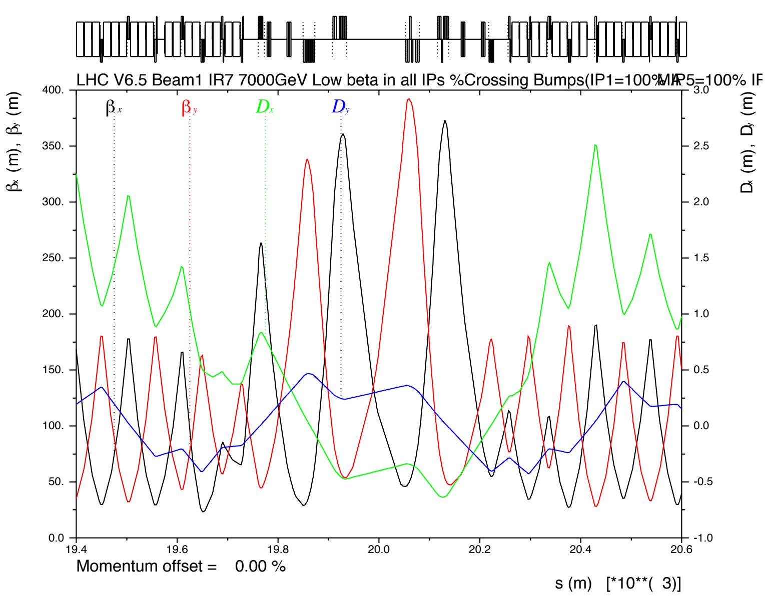
Acceleration Region



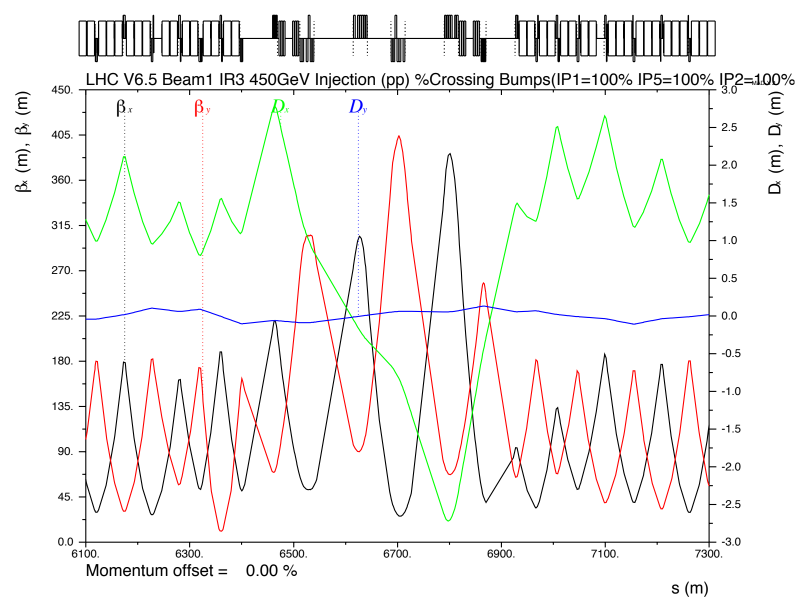
Extraction Region



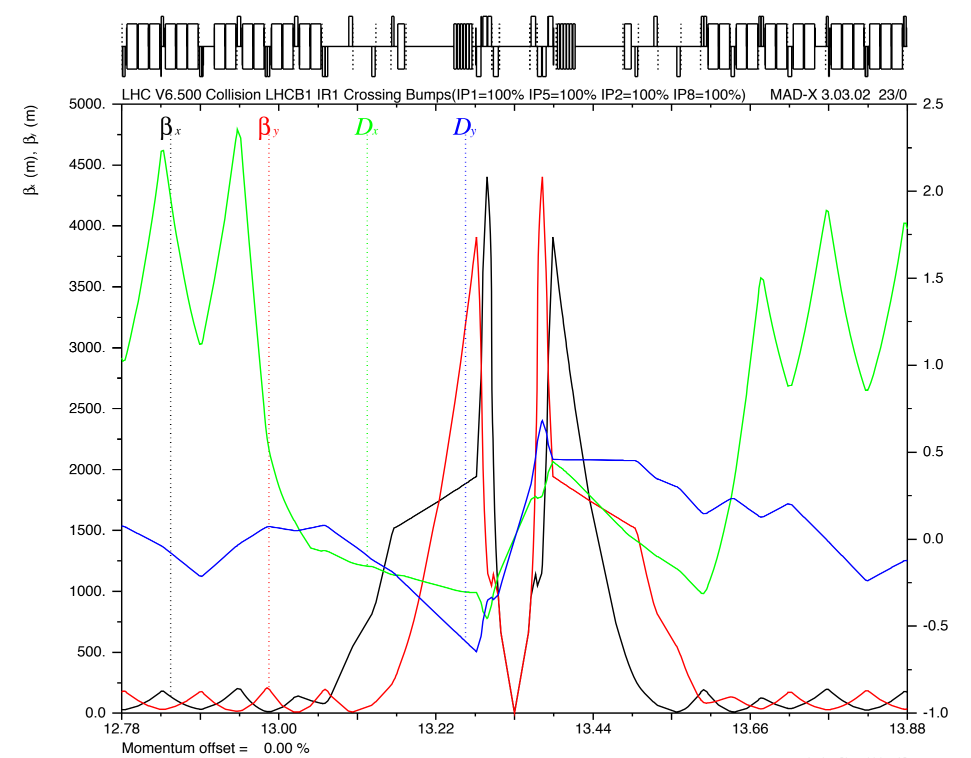
Emittance Cleaning



Momentum Cleaning



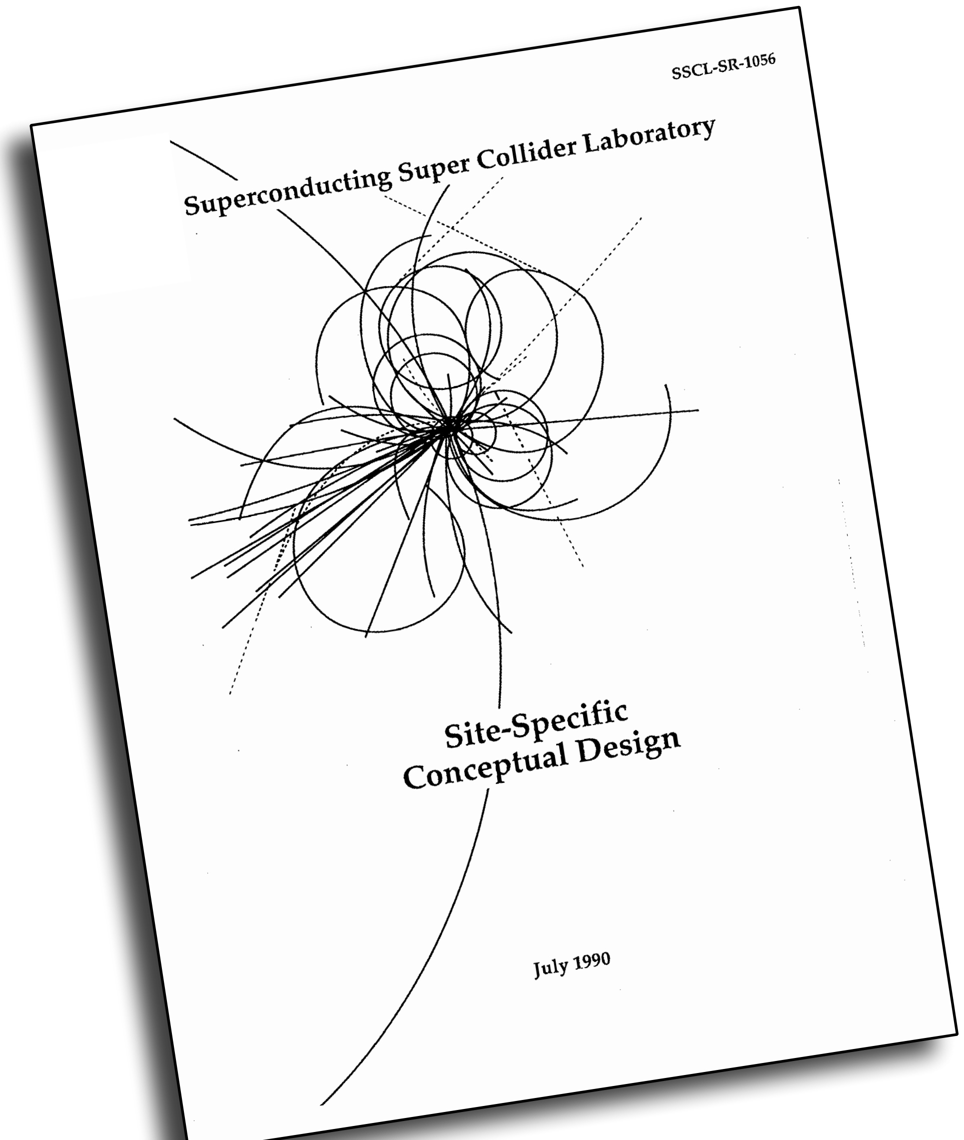
Interaction Region



The Superconducting Super Collider

- The "White Book" (Site-Specific Conceptual Design)

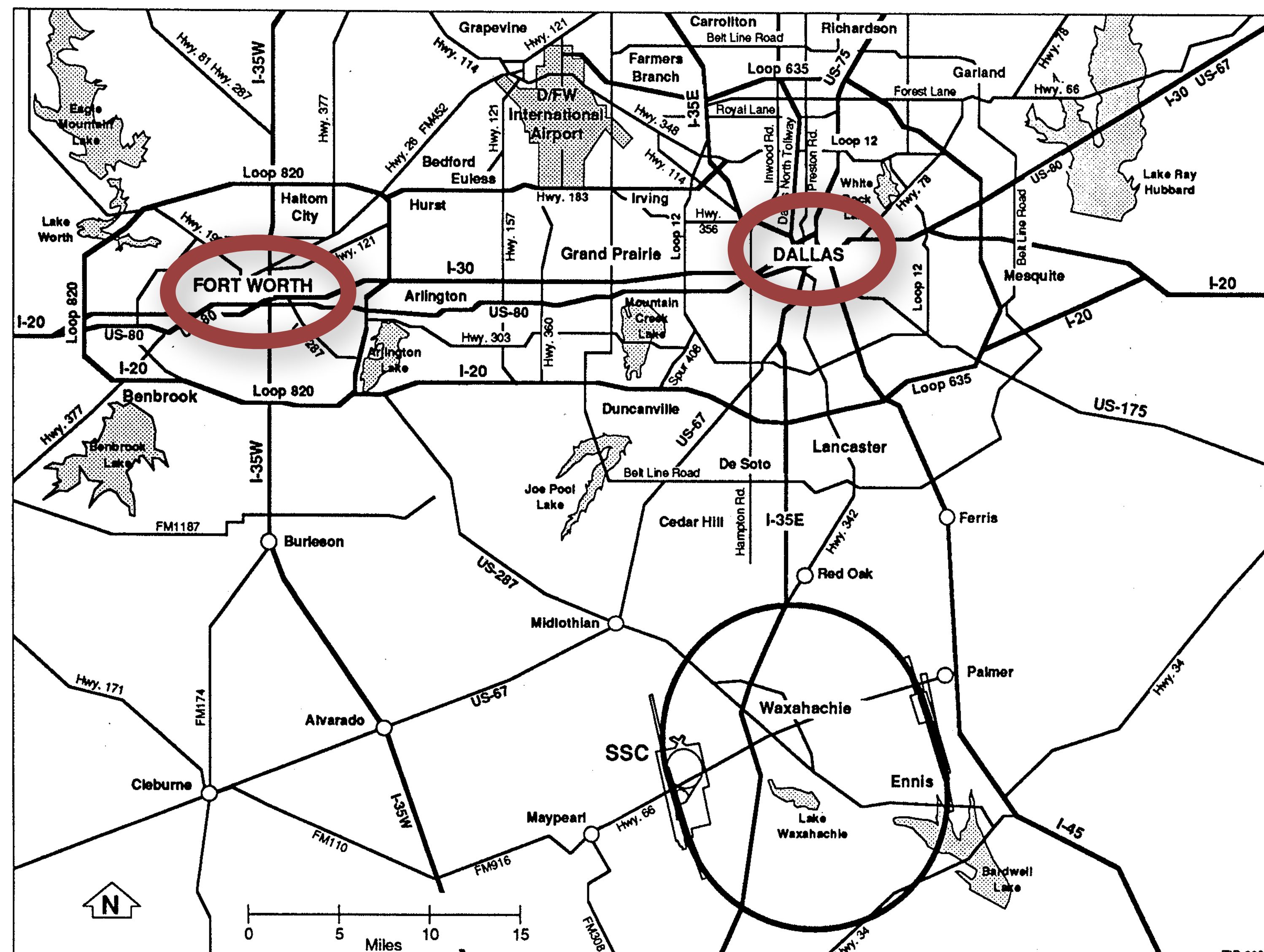
(*~1990…*)


SSCL-SR-1056

Superconducting Super Collider Laboratory

Site-Specific Conceptual Design

July 1990



Superperiodicity

Northern Illinois University

- Racetrack vs. multiple superperiods

from CDR (1986)

However, the clustered scheme is more cost effective because of considerations concerning the conventional facilities and so was recommended for the SSC conceptual design.

Generally speaking, evenly distributed IRs permit a higher superperiodicity and thus fewer resonances in the tune space. For the case of SSC, this means a superperiodicity of 6, if the utility sections and crossings are ignored. Realization of the consequences of high superperiodicity requires correlation of particle motion in magnets that are separated by 1/6 of the ring circumference, i.e., about 14 km. Because of various magnet field and alignment errors, correlation over this long distance is not likely to be maintained. The superperiodicity is thus broken in reality and all low-order resonances, systematic and accidental, need to be avoided.

The fact that a high superperiodicity is not very important for the SSC is demonstrated by particle tracking using the programs PATRICIA [4.2-8] and RACETRACK [4.2-9] on

eral was found to deteriorate as compared with the two-family scheme.

There is a potential optical advantage of IR clustering. Compared with distributed IRs, clustered IR lattices have one more variable to control the optical quality, namely, the betatron phase advance μ between adjacent IPs in a cluster. The optimum value of μ is found to be an odd multiple of $\pi/2$ [4.2-7, -11, -12]. By pairing IRs in a cluster and setting μ to the optimum value, one minimizes the chromatic aberrations of particle motion. This optimum phase also helps to reduce the orbit effect from long-range beam-beam interactions and to suppress some of the incoherent beam-beam resonances.

To be more specific, the tune dependence on momentum is described to first order by

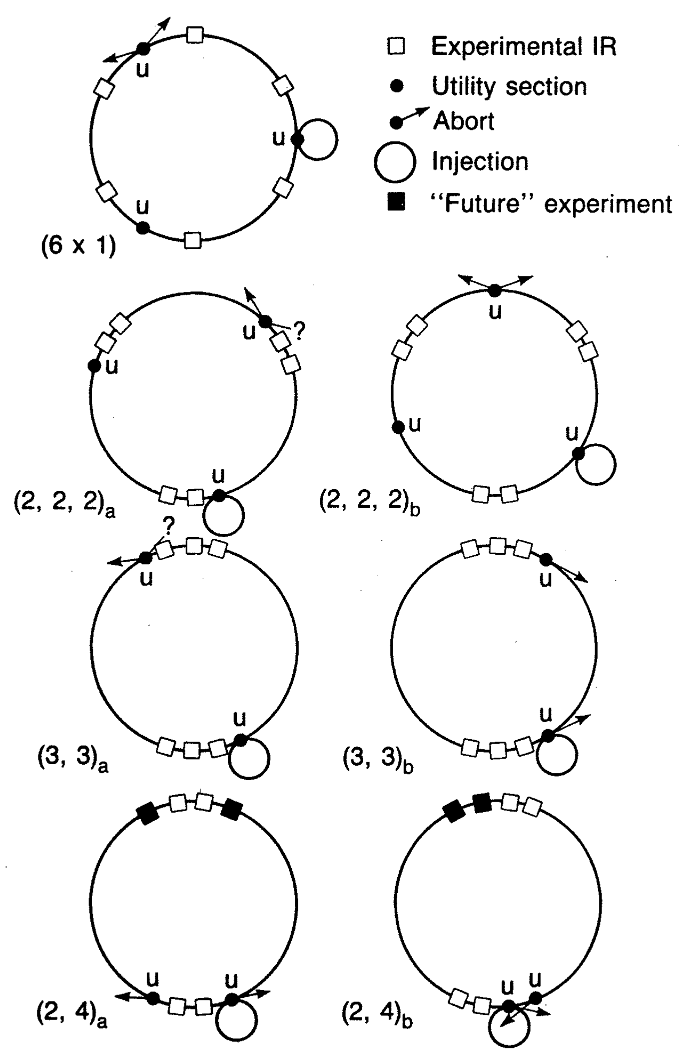


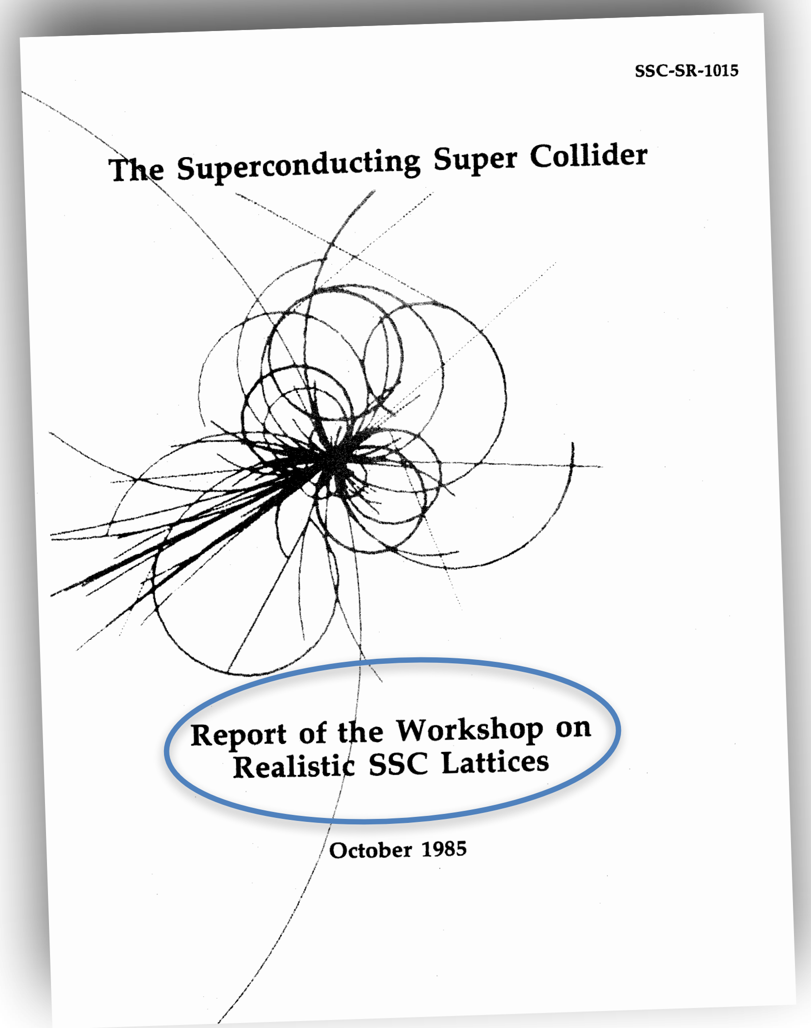
Figure 4.2-1. Various possible IR clustering arrangements for the SSC.

FNAL: original Main Ring had $P = 6$;
Tevatron: $P = 1$!

Magnet Arrangement: 2-in-1 / 1-in-1 / H / V

Northern Illinois University

- Vertical 1-in-1 chosen for the SSC, following extensive studies and workshops



The beams are separated vertically by 70 cm in the arcs. The magnets in the arcs are arranged in an over-under configuration rather than side by side. The 70 cm separation allows the magnets of the two rings to be decoupled cryogenically as well as magnetically. The over-under arrangement has the advantages that the tunnel space can be utilized more effectively and that the path lengths between collision points in the two rings can be more easily equalized. The decoupled magnets allow separate operation of the two rings. This makes it possible to perform accelerator physics studies on one ring when the other ring is not available [4.2-3].

In a side-by-side arrangement, the horizontal dispersion introduced by the separation section can be removed by the horizontal dispersion suppressor already incorporated in the lattice. In an over-under arrangement, the vertical dispersion caused by the vertical separation section has to be compensated by an additional vertical dispersion suppressor. This can be done in two ways, depending on whether the beam separation starts immediately after the IR triplets (the early separation scheme) [4.2-2] or about 200 m after the triplet (the late separation scheme) [4.2-4]. The former allows more flexibility for operating and making corrections on the two rings separately and it minimizes the long range beam-beam perturbations. Early separation also makes it easier to remove the forward secondary particles that are generated by beam collisions. The latter has the advantage that the beta functions are more easily controlled, giving smaller beta function values in the matching quadrupoles beyond the main triplets.

The present conceptual design adopts the early separation scheme. The vertical dispersion suppression is accomplished by dividing the 70 cm separation into two steps and then introducing a FODO section which has 180 degree phase advance between the two steps. The vertical dispersion contributions from the two steps cancel outside the separation region.

Collider Parameters

- From the SCDR

Table 4.1.1-1
SSC Parameters

Energy	20 TeV
Particles/bunch (N)	0.75×10^{10}
Circumference	87,120 m
No. of bunches (B)	17,424
NB	1.3×10^{14}
f_{rot}	3.4 kHz
$f_{collisions}$	60 MHz
S_b	5.0 m
ε_N (σ)	1 π mm-mrad
β*	1/2 m
σ* (μm)	5
Luminosity ($\mathcal{L}$)	1×10^{33} cm^{-2} s^{-1}
$\mathcal{L}$/hit	1.6×10^{25} cm^{-2}
$\Delta\nu_{HO}$ (total)	0.003
$\Delta\nu_{LR}$ (total)	0.004
Sync. rad. power at $NB = 1.3\times10^{14}$	8.75 kW/ring

Collider Lattice Parameters
(Footprint Version)

Energy: injection, collision (TeV)	2	20
Magnetic radius (m)	10187.1896	
Magnetic field (T)	6.55	
Rigidity (T-m)	66712.8	
Gradient (T/m)	205.6	
Circumference (484 cell lengths) (km)	87.12	
Arc length, cluster length (km)	35.28	8.28
Half-cell length, arc sector length (m)	90	4320
Long straight section length, bypass length (m)	1350	4770
Drift lengths at IP: low-β, medium-β IRs (m)	±20	±120
Drift lengths in utility straight: center, ends (m)	500	161
IP-IP distance: inner, outer (m)	2160	2520
IP-IP bending angle (mrad)	40	
Minimum IP to muon beam clearance (m)	34	
Vertical beamline separation (m)	0.80	
Cell phase advance (deg)	90	
Betatron tune: outer, inner bypass branch	123.28	123.78
Phase advance between IPs: outer, inner branch	$4.25 \times 2\pi$	$3.75 \times 2\pi$
Chromaticity: collision, injection optics	–250	–173
Transition energy-γ_T	105	
Momentum compaction (α)	0.000091	
Crossing angle (μrad)	<150	
Bunch spacing (m)	5	
rf wavelength (m)	0.8333	
Lengths of cell dipole, quadrupole (effective)* (m)	12.7	5.2
Bend radius, average arc radius (km)	10.187	12.032
Bend angle per arc, per cluster (deg)	168	12
Maximum number of IRs: simultaneous, total	5	9
Cells per arc, cluster length in equivalent cells	196	46
Number of dipoles per cell, per ring (outer)	12	5040
Number of dipoles per arc, per cluster (outer)	2352	168
Number of dipoles per bypass inner branch	104	
β_{max}, β_{min} in arc (m)	305	53
η_{max}, η_{min} in arc (m)	1.82	0.8
β* in low-β IR: injection, collision (m)	8	0.5
β* in medium-β IR: injection, collision (m)	60	10
β_{max} in low-β, medium-β IRs (collision) (m)	7990	2657
β_{center}, β_{max} in utility straight (m)	300	970

*See Tables 4.1.1.1-3 and 4.1.1.1-7.

Modularity

- Length of Standard Half-Cell was ir
  - *L* = 90 m, for example
- Then, Utility Regions, IRs, *etc.*, eac
- By adding *L* at ends of straight sect symmetry of optics

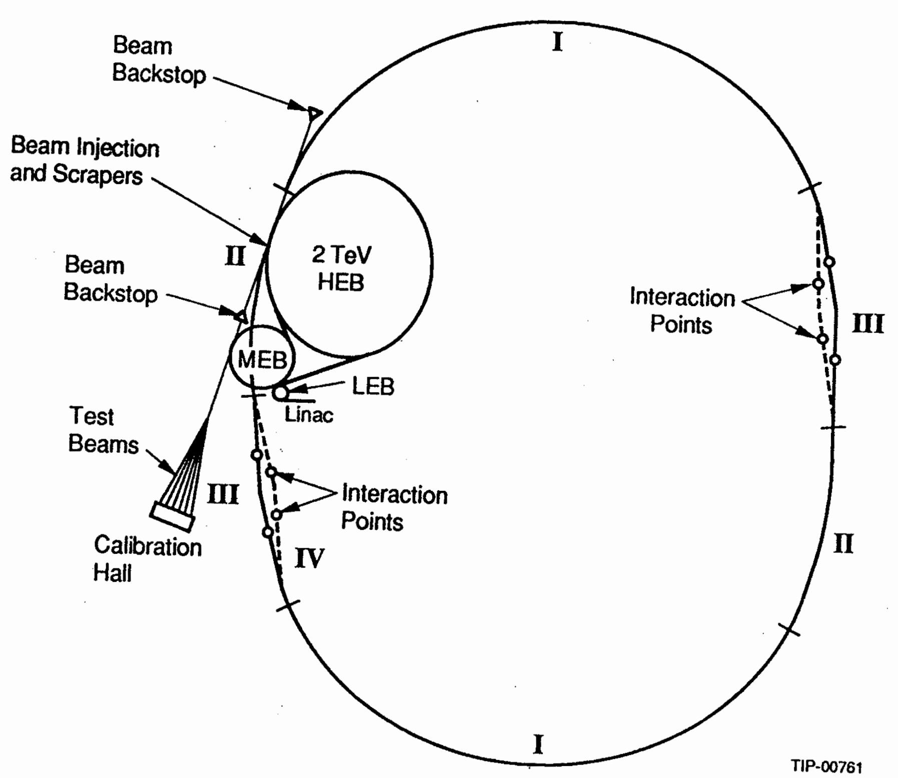
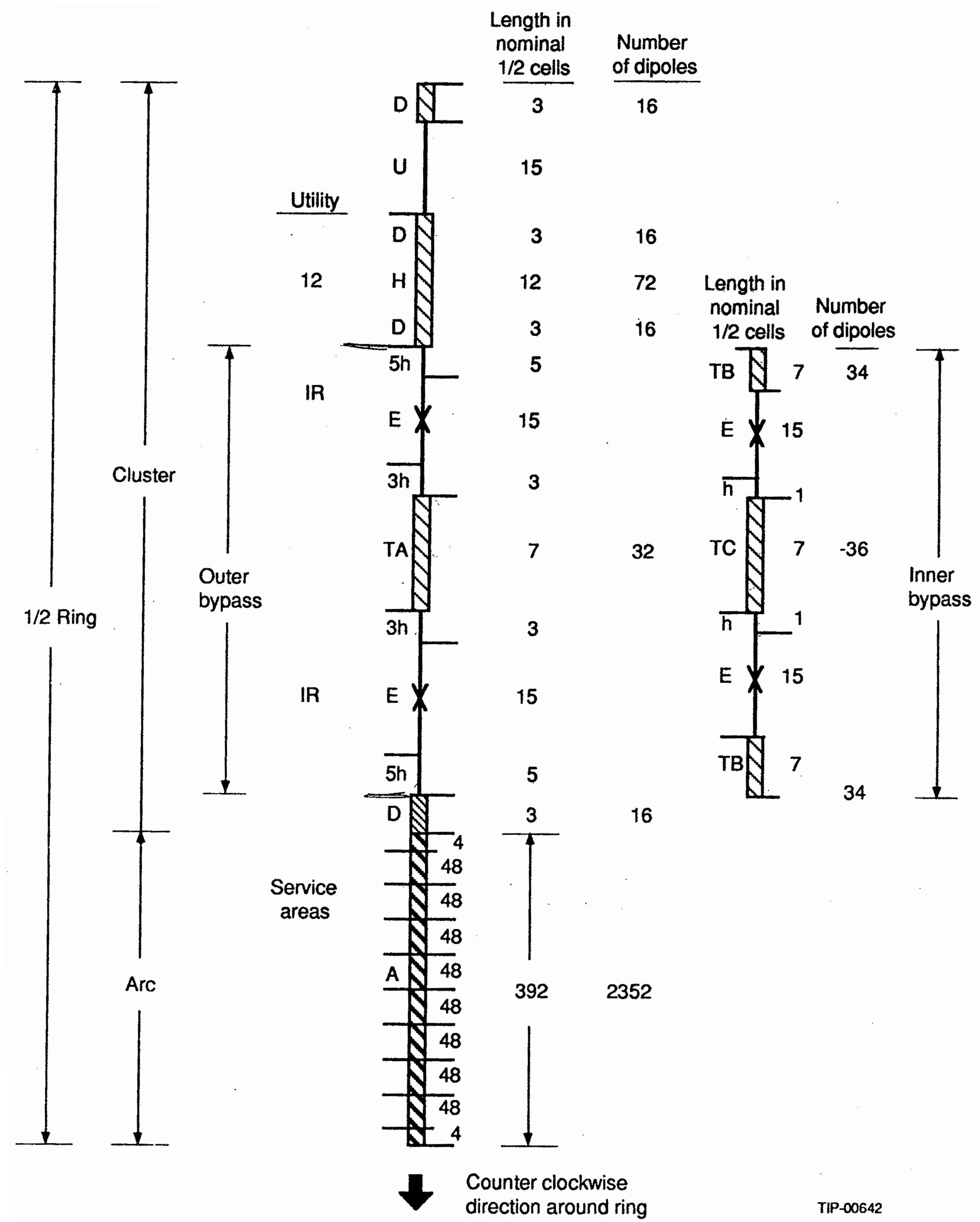


Figure 4.1.1.1-4. Schematic layout of SSC.

Modular Approach:



Utility Region

Northern Illinois University

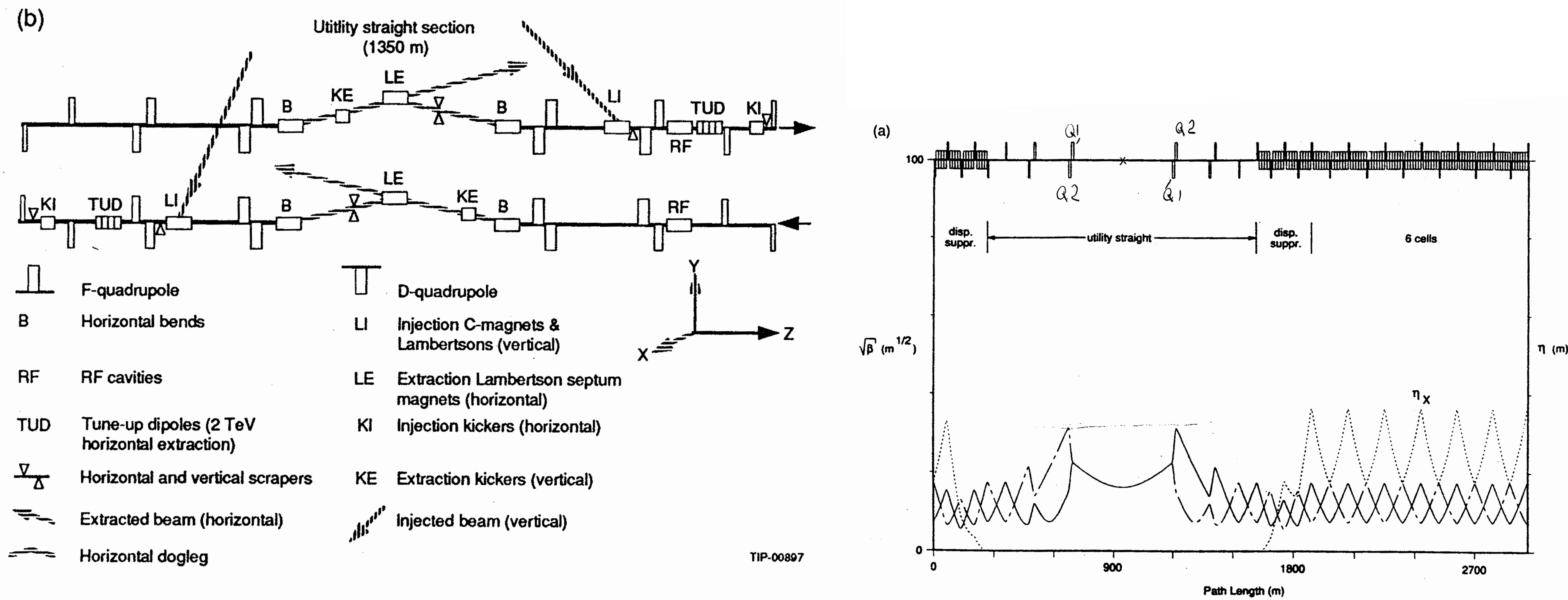


Figure 4.1.1.1-9. Utility straight section: (a) lattice and orbit functions and (b) functional elevation-view schematic.

Injection/Collision Regions

Northern Illinois University

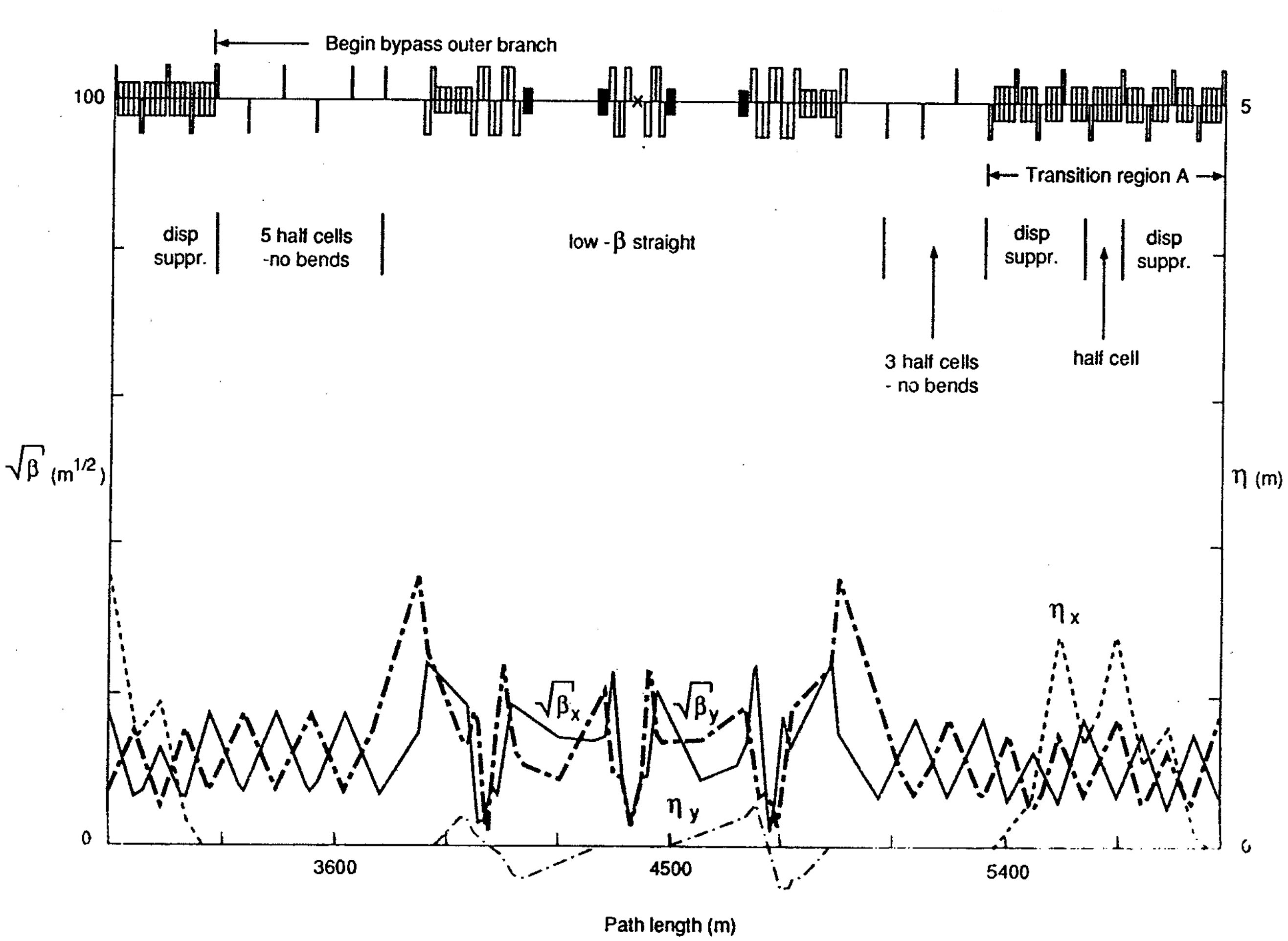


Figure 4.1.1.1-12. Lattice and orbit functions of low-β IR in injection optics.

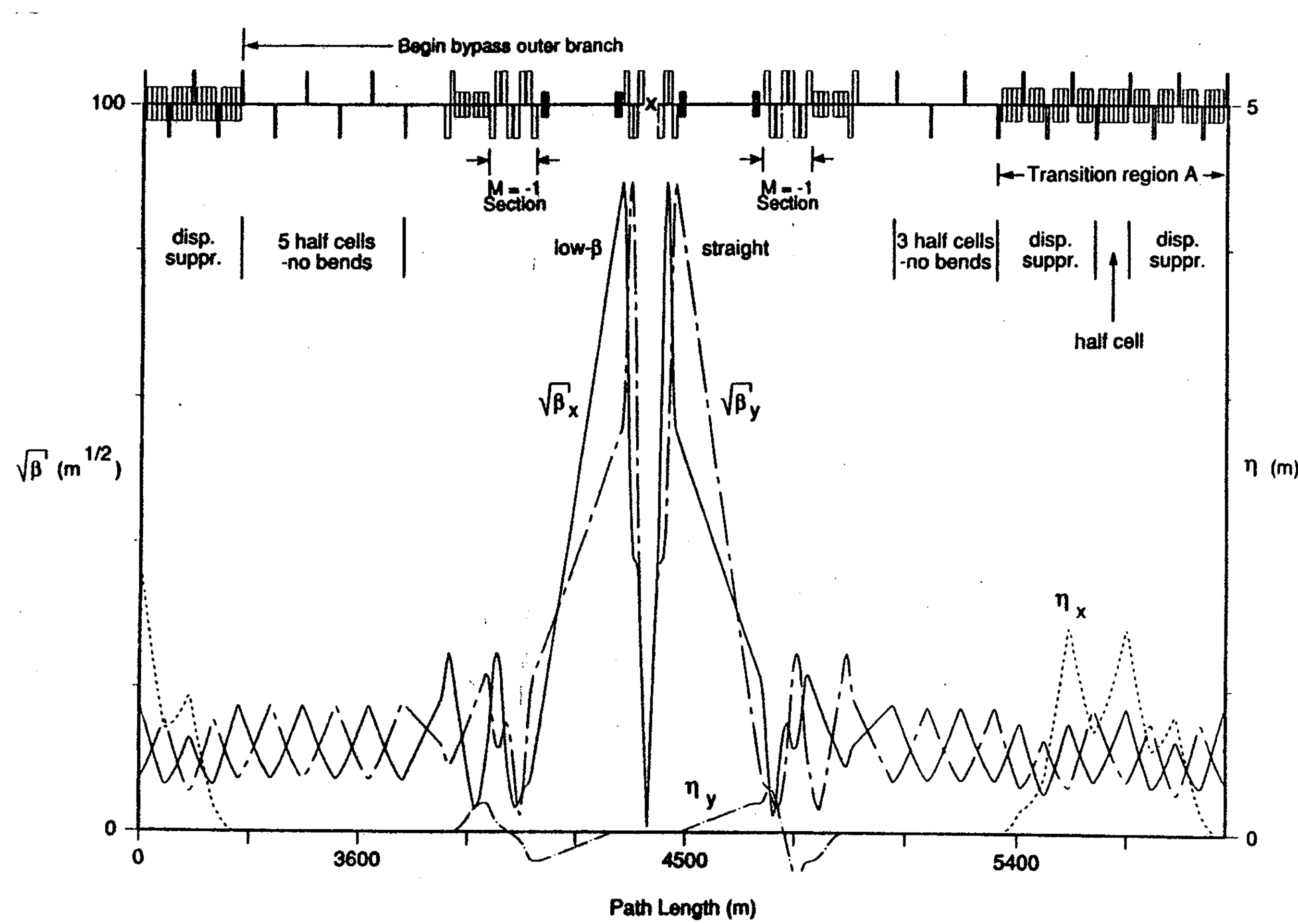


Figure 4.1.1.1-11. Lattice and orbit functions of low-β IR in collision optics.

The Diamond Bypass

Northern Illinois University

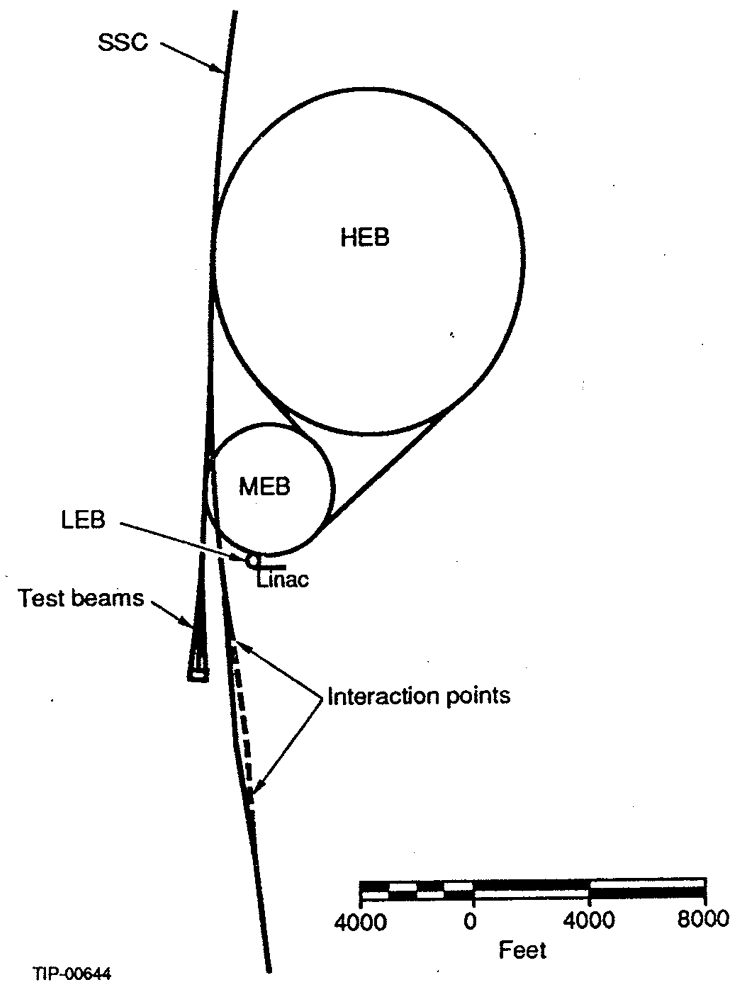


Figure 4.1.1.1-2. Layout of west campus region.

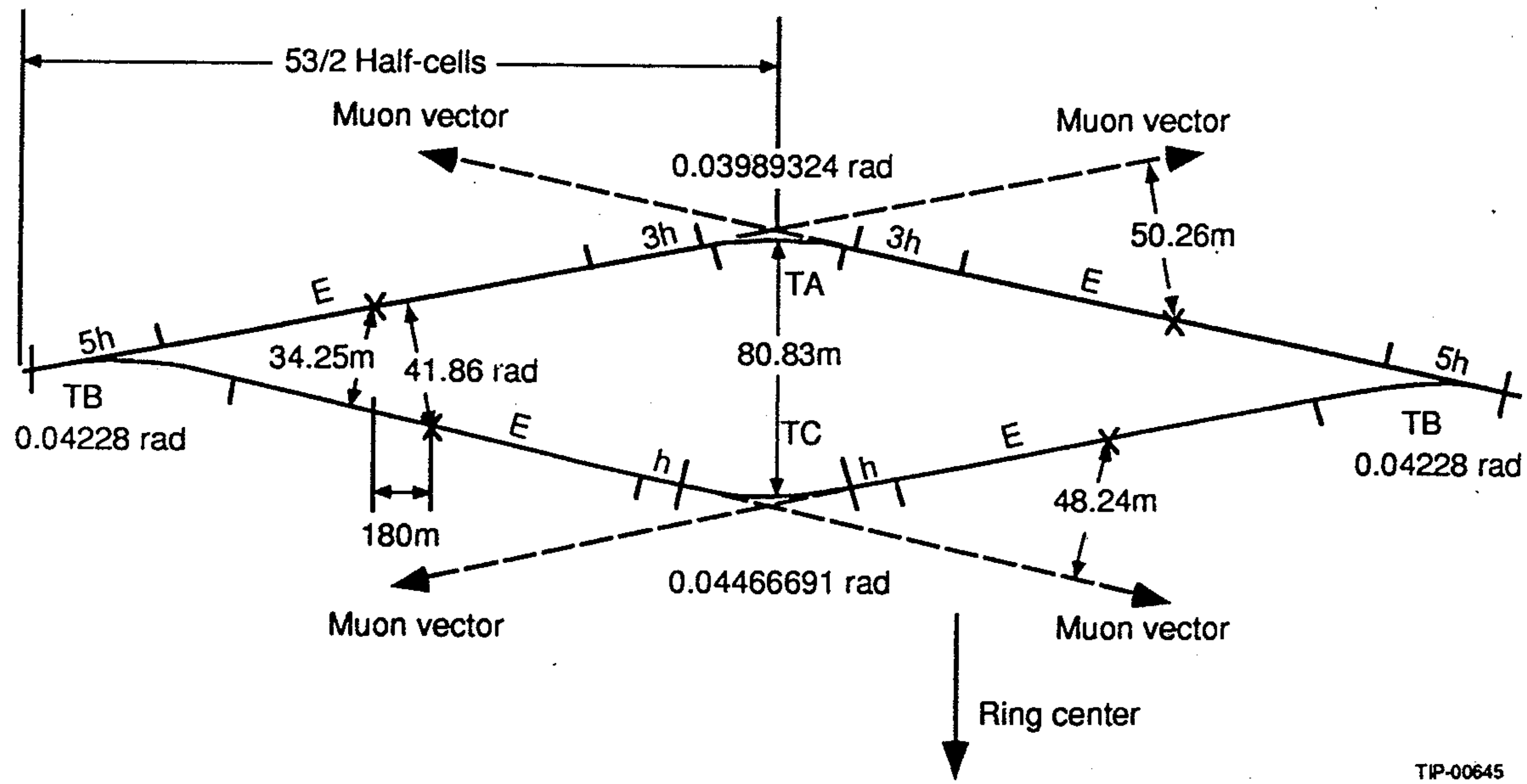


Figure 5.2.1 The diamond bypass arrangement. In the initial configuration, the outer legs (farther from ring center) will be instrumented.

Lattice Decisions

- 1-in-1 assured can operate one ring without the other
  - *except*: the IR triplets were "shared" by both
  - desire was to be able to commission one ring if the other was not ready
  - Vertical "-*I* " beam lines made IR tuning transparent
- IR designs were still being finalized at project end
  -

Nuclear Instruments and Methods in Physics Research A 346 (1994) 448–460
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Principles of interaction region design in hadron colliders and their application to the SSC

Y. Nosochkov *, T. Sen, E. Courant [1], A. Garren, D.M. Ritson [2], R. Stiening, M.J. Syphers
[a] *Superconducting Super Collider Laboratory* [+], *2550 Beckleymeade Avenue, Dallas, TX 75237, USA*

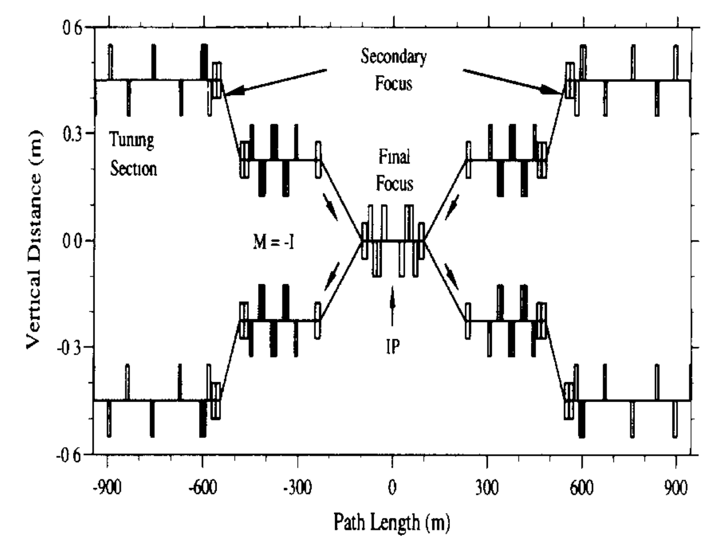


Fig. 1. Vertical view of an IR.

Dispersion Suppressor

Northern Illinois University

keep $L\theta = \frac{1}{2}$ for 90° dispersion suppression by making $L = 3L_o/4$ and $\theta = 2\theta_o/3$

Required second length of dipole magnet

Later, this magnet was also used at power feed locations to create extra space
(every six cells throughout an arc)

$\theta_d = 2\theta_0/3 = \theta_0 \times 4/5 \times 5/6$

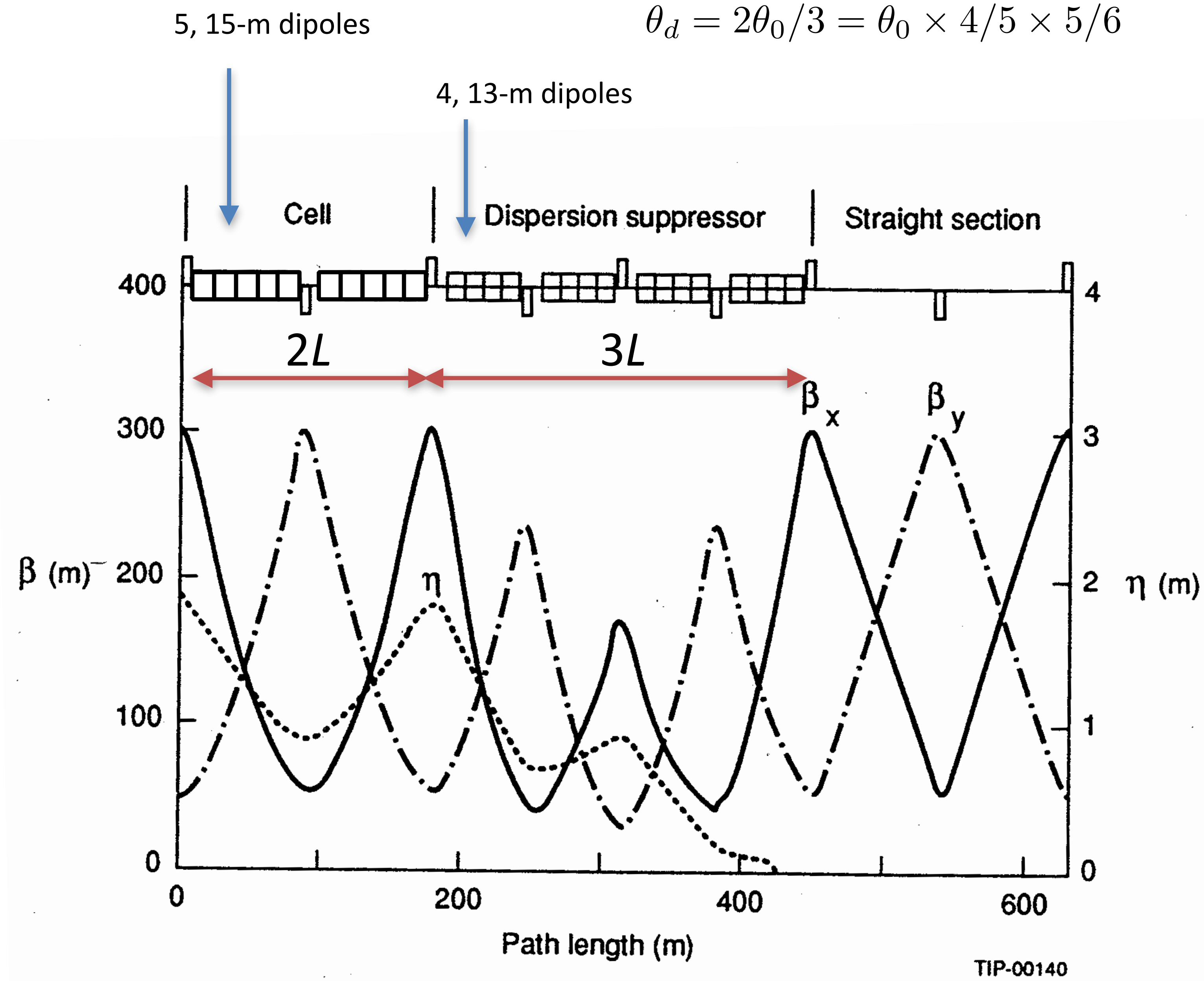
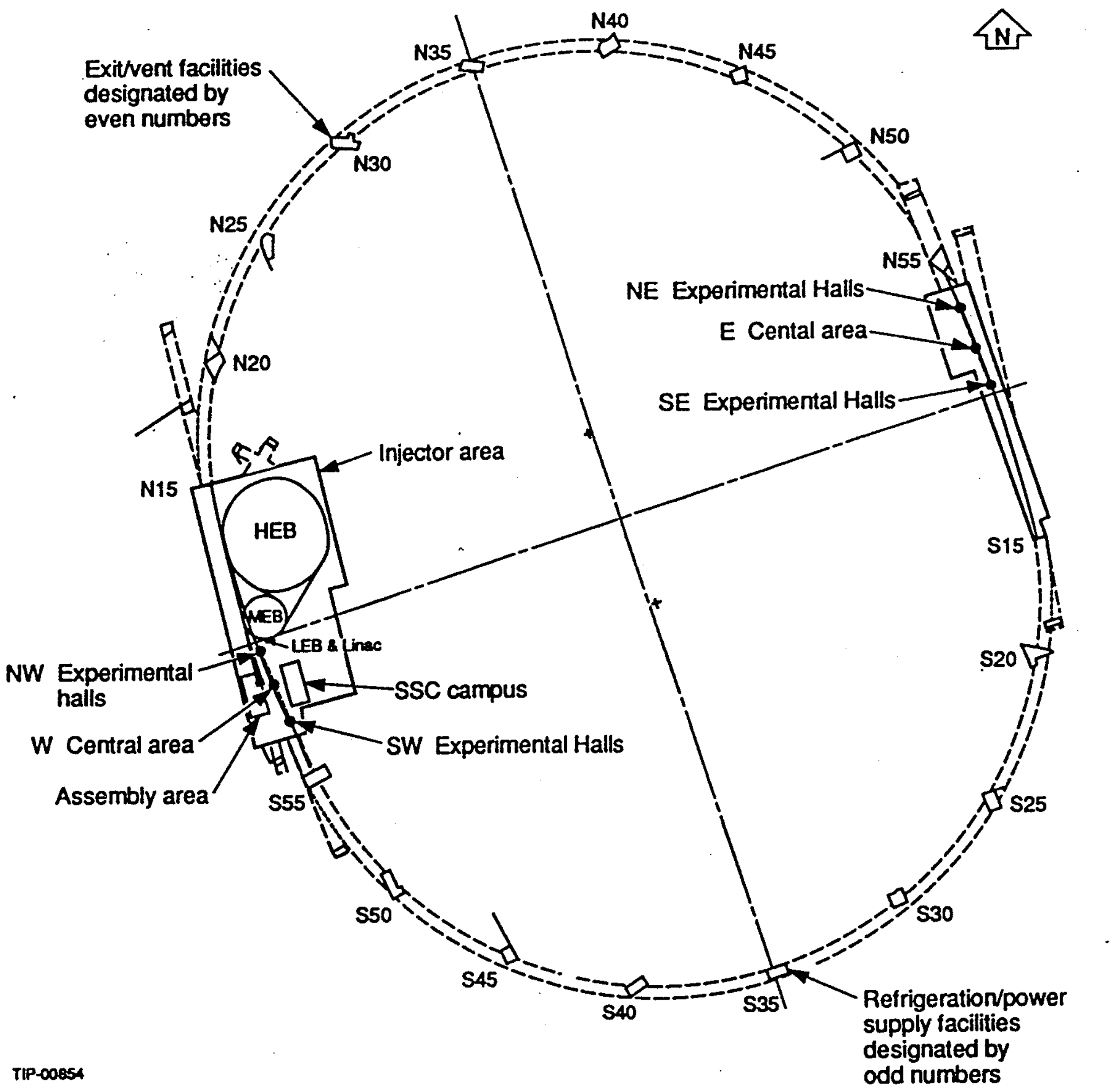


Figure 4.1.1.1-8. Lattice functions of the normal cell *C*, the dispersion suppressor *D*, and empty cell *CO*.

The "10F" Lattice

i.e., Version 10, sub-version F (1993)

- "holes", and the role of modularity in the final layout



- "free space" created in arcs
  - "missing" dipoles in cells

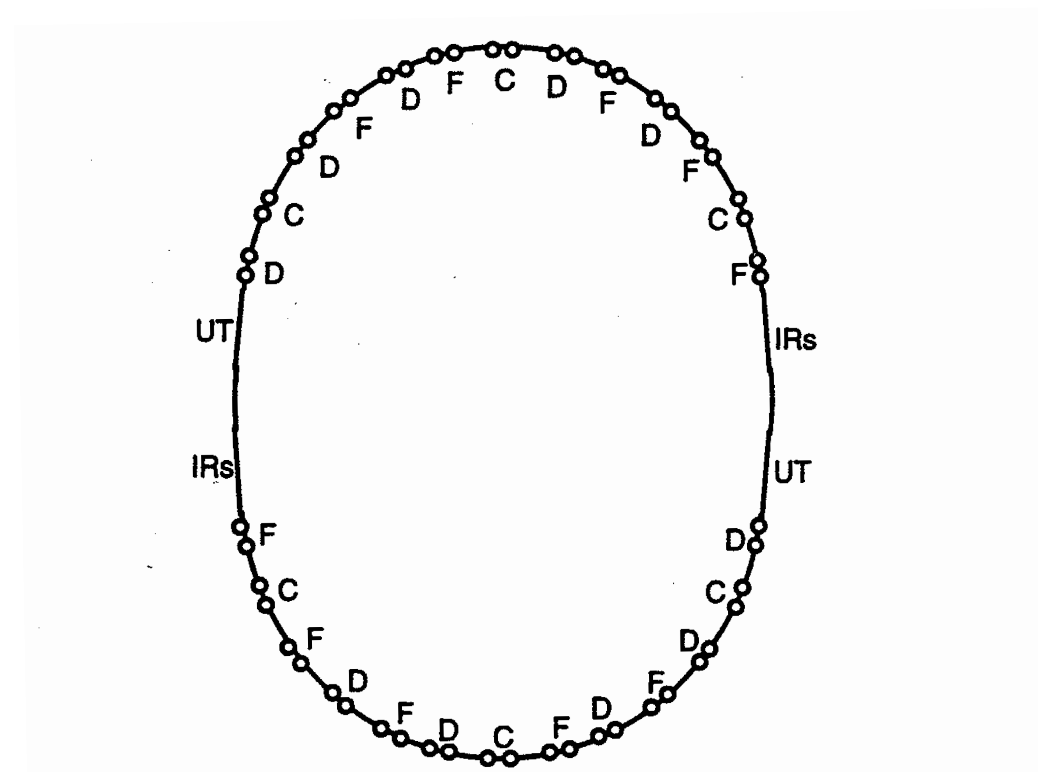


Figure 7-1. Schematic Layout of the Free Space in the Collider.

Modularity and "free space"

Northern Illinois University

- Modularity and "free space" became very useful when finalizing the exact locations of shafts, utilities and service buildings