Accelerator Design from Start to Finish

ACCELERATOR PHYSICS

MT 2015

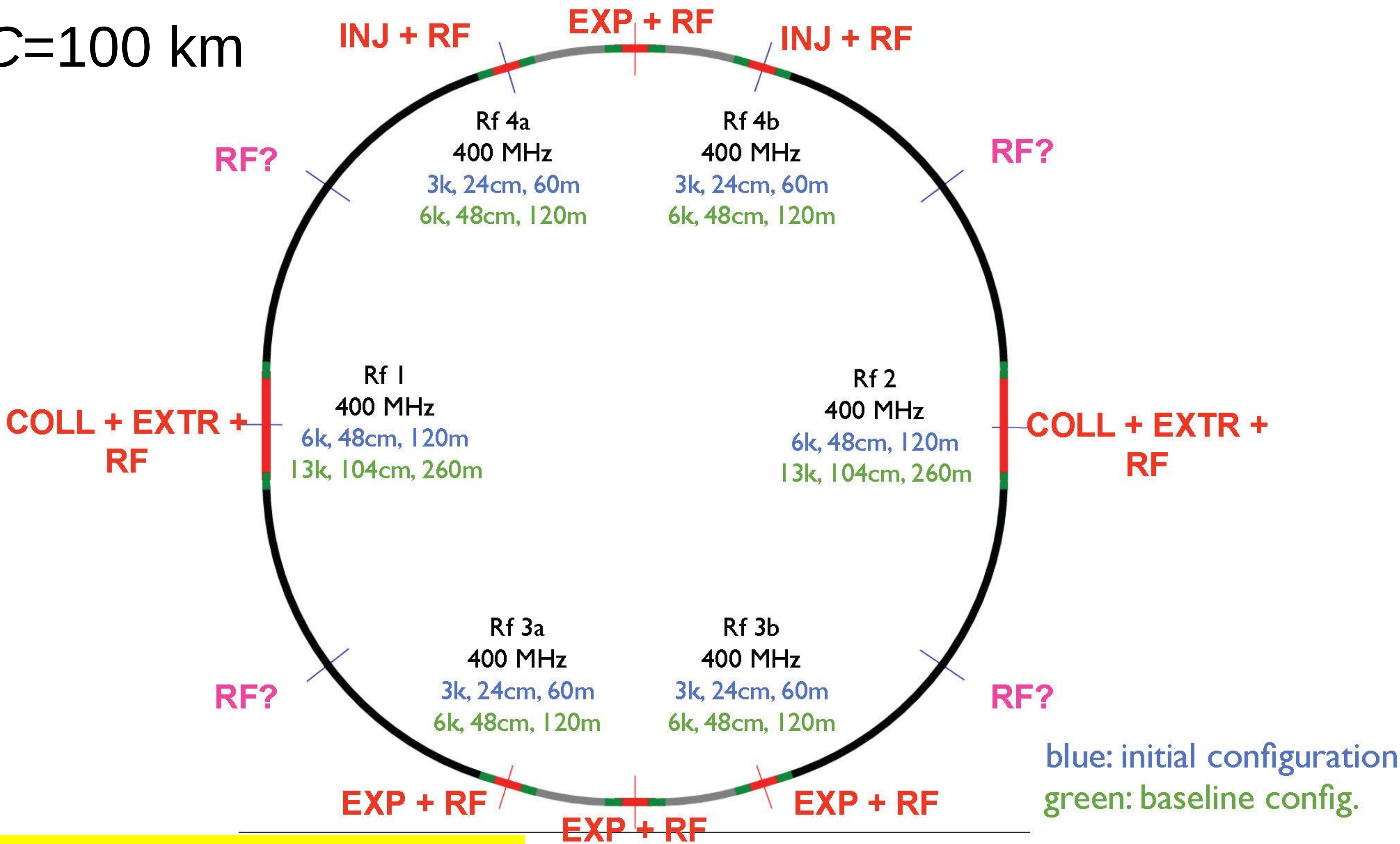
E. J. N. Wilson

Putting "it" together

- The SPS Design Committee get down to business (1971)

FCC-ee preliminary layout

C=100 km

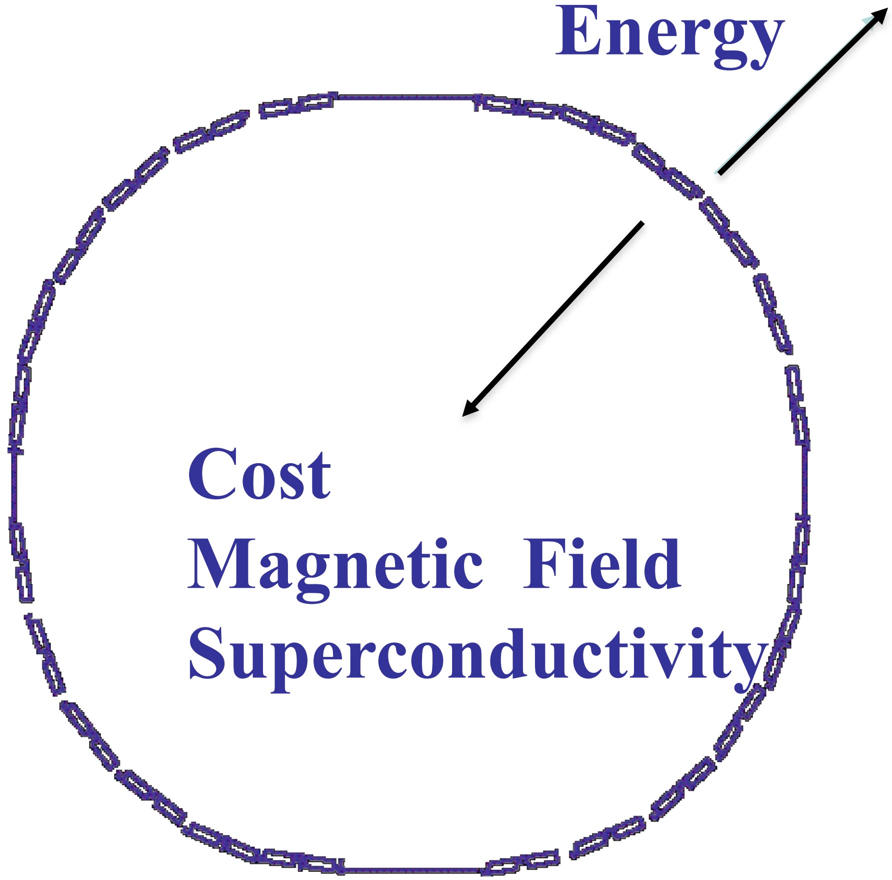


P. Lebrun, J. Osborne, D. Schulte, U. Wienands

- ✓ consistent with *FCC-hh* layout
- ✓ RF staging scenario defined

The compromise between radius and magnetic field

Synchrotron Radiation



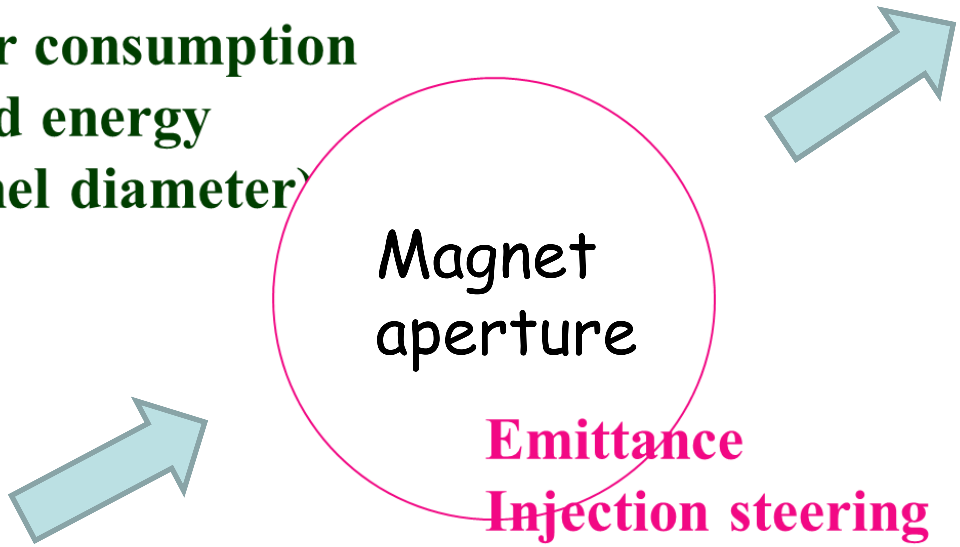
preliminary FCC-ee parameters

parameter	FCC-ee	LEP2
energy/beam	45 – 175 GeV	105 GeV
bunches/beam	**50 – 60000**	4
beam current	**6.6 – 1450 mA**	3 mA
hor. emittance	**~2 nm**	~22 nm
emittance ratio $\varepsilon_y/\varepsilon_y$	**0.1%**	1%
vert. IP beta function β_y^*	**1 mm**	50 mm
luminosity/IP	**1.5-280** x 10^{34} $cm^{-2}s^{-1}$	0.0012 x 10^{34} $cm^{-2}s^{-1}$
energy loss/turn	0.03-7.55 GeV	3.34 GeV
synchrotron radiation power	**100 MW**	23 MW
RF voltage	0.3 – **11 GV**	3.5 GV

- Large number of bunches at Z and WW and H requires **2 rings**.
- High luminosity means short beam lifetime (few mins) and requires continuous injection (**top up**).

Aperture compromise

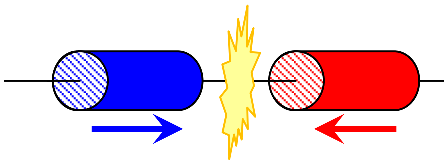
Closer tolerances
Cost
Power consumption
Stored energy
(Tunnel diameter)



Emittance
Injection steering
Space charge
Orbit errors
Dynamic aperture

luminosity scaling: larger E & ρ

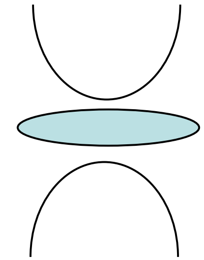
$$e\,f\,k\,N = \text{beam current} \propto \frac{1}{E^4}$$



$$L = \frac{f\,k\,N^2}{4\pi\sigma_x\sigma_y} F\,H$$

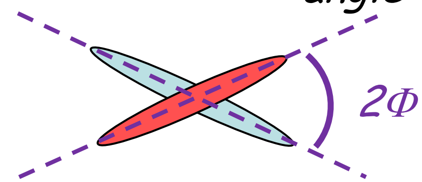
$H \leq 1$

Hour-glass



$F \leq 1$

Crossing angle



$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \leq \xi_y^{\max}(E)$$

Beam-beam parameter

$$L \propto \frac{\rho P_{SR}}{E^3}\,\frac{\xi_y}{\beta_y^*}$$

σ = beam size

k = no. bunches

f = rev. frequency

N = bunch population

P_{SR} = synch. rad. power

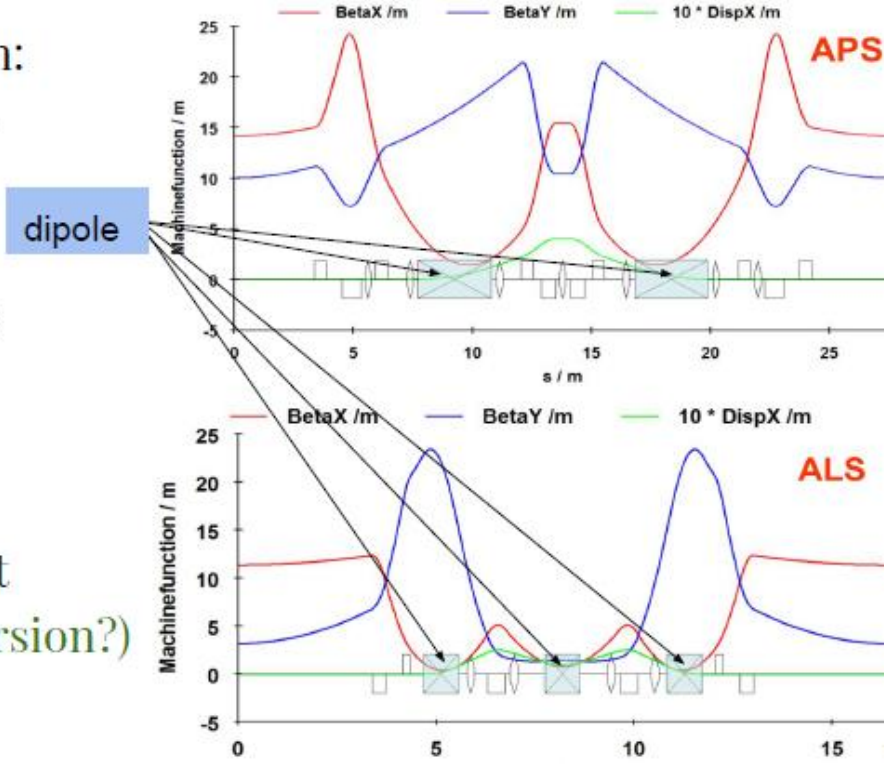
β^* = betatron fct at IP (beam envelope)

J. Wenninger

Low emittance lattices

Examples of Low Emittance lattices

- DBA (Double Bend Achromat), used in:
  - ESRF, ELETTRA, APS, Diamond, SOLEIL...
- TBA (Triple Bend Achromat), used in:
  - ALS, SLS, PLS, ...



.chromat: zero dispersion at long straight

:an you think of why we want zero dispersion?)

Smooth approx. - choosing No. of periods

$$N\mu = 2\pi Q$$

$$\int \frac{ds}{\beta} = \int d\phi$$

$$\frac{2\pi R}{\bar{\beta}} = 2\pi Q$$

$$\therefore \bar{\beta} = \frac{R}{Q} \quad \left(= \frac{\lambda}{2\pi} \right)$$

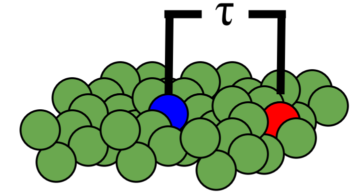
$$\gamma_{tr} \approx Q$$

$$\frac{1}{\gamma_{tr}^{\;2}} = \frac{\bar{D}}{R}$$

$$\therefore \bar{D} = \frac{R}{Q^2}$$

Radiation damping: Longitudinal plane (1/2)

- The synchronous particle is in the bunch centre; $\tau=\Delta s/c>0$ is the time distance for an electron ahead of the synchronous particle



- Assuming changes in ε and τ occur slowly with respect to T_0:

and on average in 1 turn:

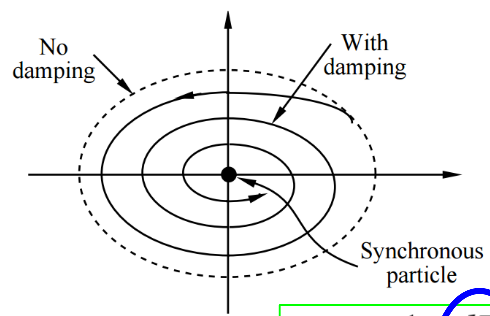
$$\frac{d\tau}{dt} = -\alpha\frac{\varepsilon}{E_0} \qquad \frac{d\varepsilon}{dt} = \frac{eV(\tau) - U(\varepsilon)}{T_0}$$

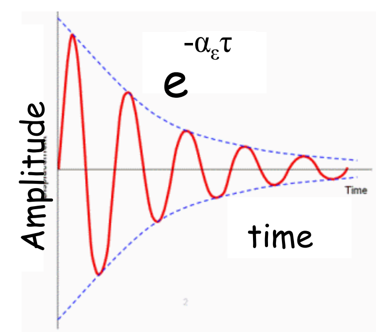
ε and τ decrease **exponentially** with damping time τ_ε:

$$\varepsilon(t) = Ae^{-\alpha_\varepsilon \tau}\cos(\Omega t - \phi)$$

$$\tau(t) = \frac{-\alpha}{E_0\Omega}Ae^{-\alpha_\varepsilon \tau}\sin(\Omega t - \phi)$$

$$\Omega^2 = \frac{e}{T_0}\dot{V}_0\frac{\alpha}{E_0}$$





$1/\tau_\varepsilon=\alpha_\varepsilon$: longitudinal damping factor

$$\alpha_\varepsilon = \frac{1}{2T_0}\frac{dU}{d\varepsilon}$$

let's calculate this!

Radiation damping: Longitudinal plane (2/2)

- Rate of energy loss changes with energy because:
  - it is itself a function of energy
  - orbit deviates from reference orbit and there could be change in path length

$$U(\varepsilon) = \frac{1}{c}\oint P dl$$

: Integral of power radiated over time spent in bendings (both depend on energy of particle)

- P is function of E^2 and B^2:

$$P = P_0 + \frac{2P_0}{E_0}\varepsilon$$

and

$$\frac{dU(\varepsilon)}{d\varepsilon} = \frac{1}{c}\oint \frac{2P_0}{E_0} ds = \frac{2U_0}{E_0}$$

(without taking into account path-lengthening)

Energy distribution of emitted photons

- Energy emitted in quanta; each quantum carries energy u=$\hbar\omega$;
  - n(u): number of photons emi ime with energy in u, u+du
  - u n(u): energy of photons e e with energy in u, u+du

$$N = \int n(u)du = \frac{15\sqrt{3}}{8}\frac{P}{u_c}$$

$$\langle u\rangle = \frac{\int u \; n(u)du}{N} = \frac{P}{N} = \frac{8}{15\sqrt{3}}u_c$$

$$\left\langle u^2\right\rangle = \frac{\int u^2 \; n(u)du}{N} = \frac{11}{27}u_c^2$$

- Total number of photons emitted per

Quantum fluctuations of synchrotron osci[llations]

$$A^2 = \varepsilon^2 + \left(\frac{U_s \omega_s}{\alpha}\right)^2 \tau^2$$

- Invariant longitudinal o[scillation]

$$\varepsilon \to \varepsilon - u \qquad \tau \to \tau$$

- When a photo[n of energy u is e]mitted:

$$\frac{d < A^2 >}{dt} = -\frac{2 < A^2 >}{\tau_\varepsilon} + \left\langle N_\gamma < u^2 >_\gamma \right\rangle$$

radiation damping
quantum excitation

- and the change of A^2 is:

$$< A^2 > = \frac{\tau_\varepsilon}{2} \left\langle N_\gamma < u^2 >_\gamma \right\rangle$$

$$\sigma_\varepsilon^2 = < \varepsilon^2 > = \frac{< A^2 >}{2}$$

$$\frac{\sigma_\varepsilon^2}{E_0^2} = \frac{55}{64\sqrt{3}} \frac{\hbar}{mc} \frac{\gamma^2}{\rho}$$

for synchrotron with separated function magnets

- Average longitudinal invariant decreases exponentially with damping time τ_ε and

Summary of radiation integrals

$$I_1 = \oint \frac{D}{\rho}\, ds$$

$$I_2 = \oint \frac{ds}{\rho^2}$$

$$I_3 = \oint \frac{ds}{|\rho^3|}$$

$$I_4 = \oint \frac{D}{\rho}\left(2k + \frac{1}{\rho^2}\right) ds$$

$$I_5 = \oint \frac{\mathcal{H}}{|\rho^3|}\, ds$$

Momentum compaction factor

$$\alpha = \frac{I_1}{2\pi R}$$

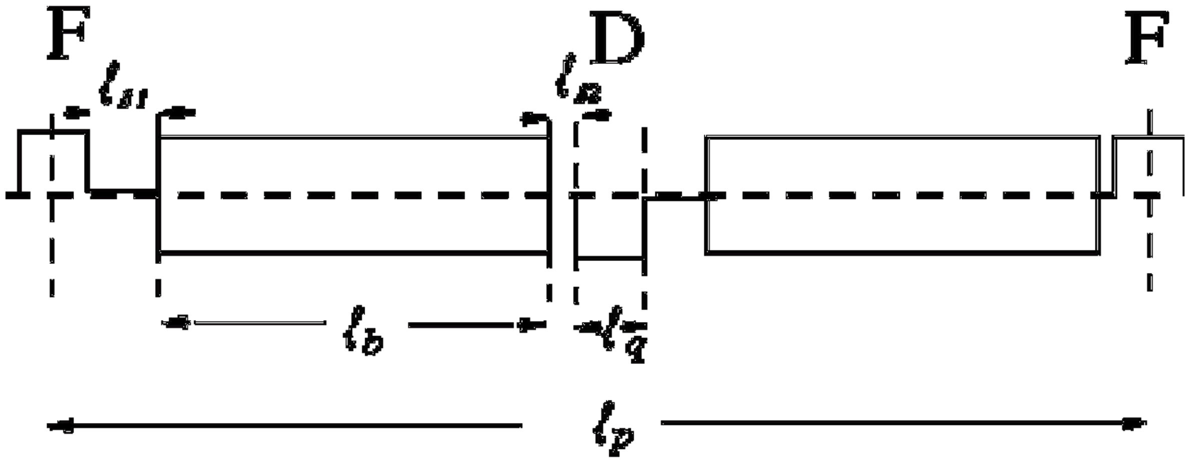
Energy loss per turn

$$U_0 = \frac{1}{2\pi} C_\gamma E^4 \cdot I_2$$

$$C_\gamma = \frac{4\pi}{3} \frac{r_e}{(m_e c^2)^3} = 8.858 \cdot 10^{-5} \left[\frac{\mathrm{m}}{\mathrm{GeV}^3}\right]$$

Period geometry

- Everything must add up for the ring

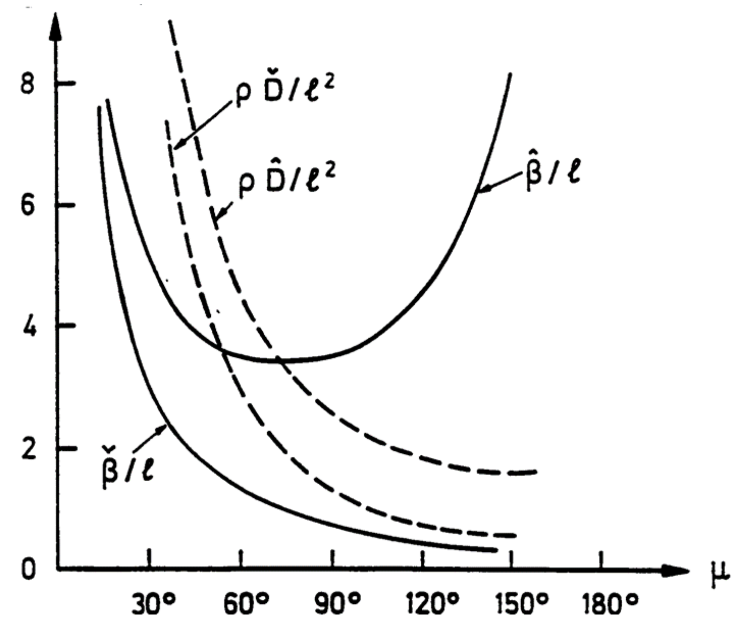


$$\ell_p = 2(\ell_b + \ell_{s1} + \ell_{s2} + \ell_q)$$

$$2\pi R = N_p \ell_p$$

$$2\pi(B\rho) = N_b \ell_b B = 2\pi(3.3356 p[GeV/c])$$

- The beta at the F quadrupole which defines the scale of the apertures goes through a minimum at about 70 deg/cell.
- Other considerations which might lead to close to 90 degrees per cell are
  - Sensitivity to closed orbit errors
  - Ease of locating correctors
  - Schemes for correcting the chromaticity in the arcs without exciting resonances



The lattice and insertions

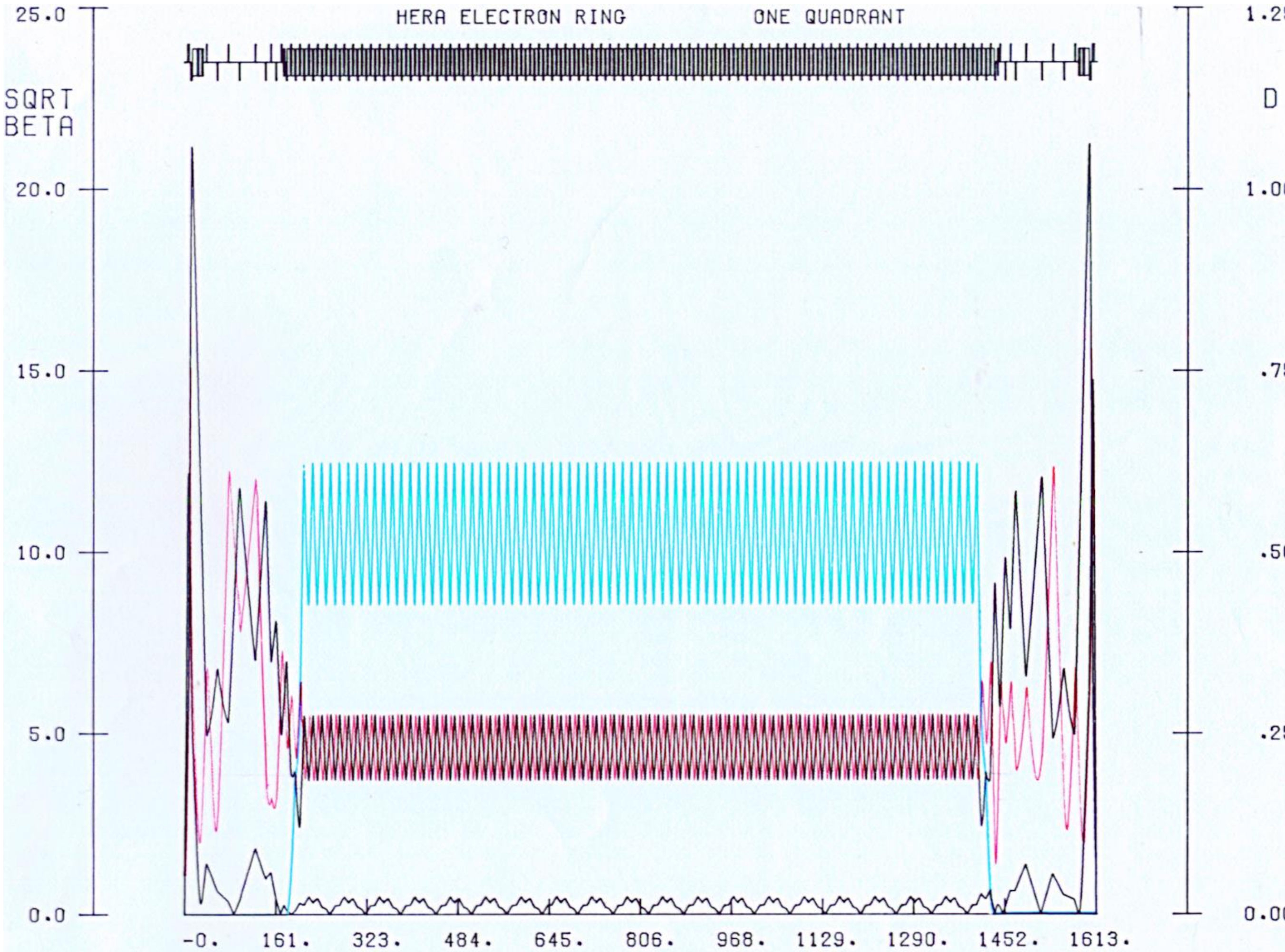
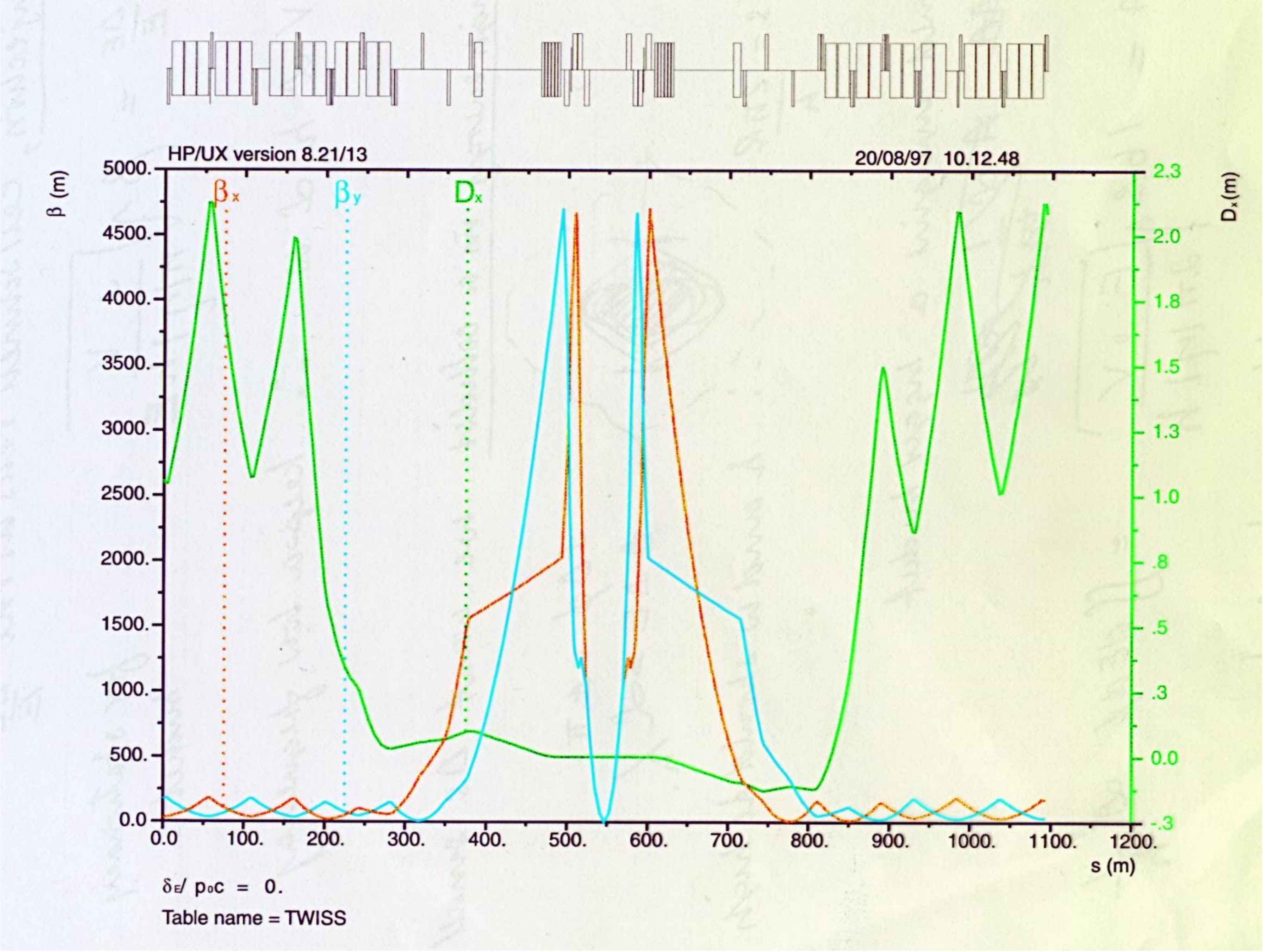


Fig. 3.1 - Electron Lattice with beta functions and dispersion
(β_z in red, β_x in black, D_z in black, D_x in blue)

Insertions


HP/UX version 8.21/13
20/08/97 10.12.48
β (m)
D_x(m)
β_x
β_y
D_x
5000.
4500.
4000.
3500.
3000.
2500.
2000.
1500.
1000.
500.
0.0
2.3
2.0
1.8
1.5
1.3
1.0
.8
.5
.3
0.0
-.3
0.0
100.
200.
300.
400.
500.
600.
700.
800.
900.
1000.
1100.
1200.
s (m)
$\delta_E/\ p_0c\ =\ 0.$
Table name = TWISS

Correction of chromaticity

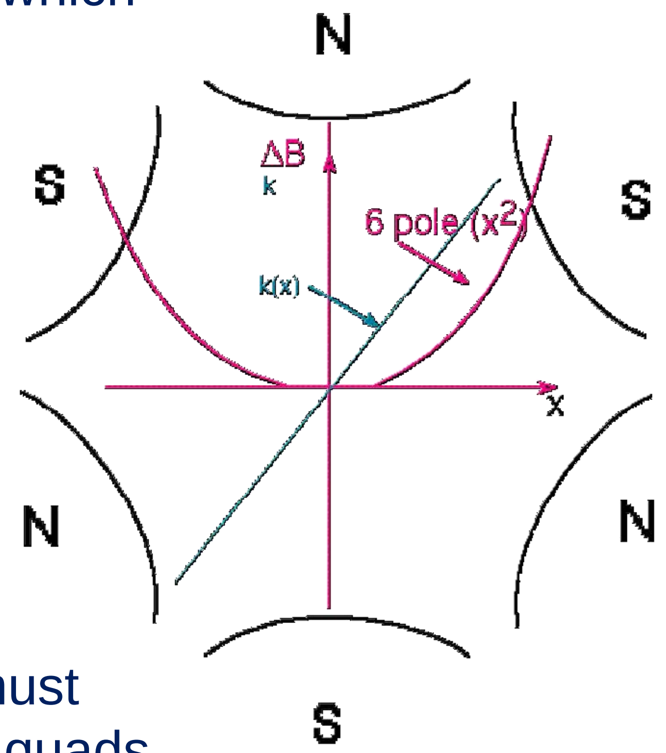
- Parabolic field of a 6 pole is really a gradient which rises linearly with x
- If x is the product of momentum error and dispersion

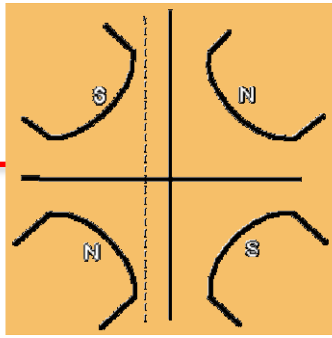
$$\Delta k = \frac{B''D}{(B\rho)}\frac{\Delta p}{p} .$$

- The effect of all this extra focusing cancels chromaticity

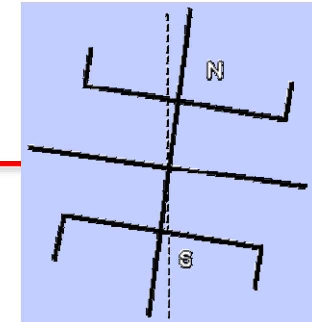
$$\Delta Q = \left[\frac{1}{4\pi}\int\frac{B''(s)\beta(s)D(s)ds}{(B\rho)}\right]\frac{dp}{p} .$$

- Because gradient is opposite in v plane we must have two sets of opposite polarity at F and D quads where betas are different





Sources of distortion



Δy Δ

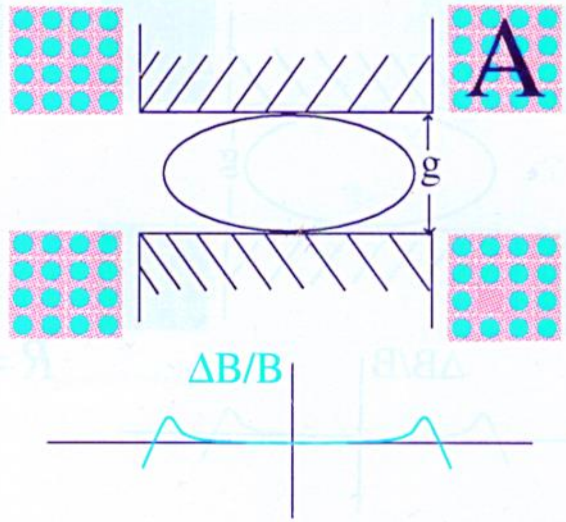
Table 1

Sources of Closed Orbit Distortion

Type of element	Source of kick	r.m.s. value	$\langle \Delta B l / (B\rho) \rangle_{rms}$	plane
Gradient magnet	Displacement	$<\Delta y>$	$k_i l_i <\Delta y>$	x,z
Bending magnet (bending angle = θ_i)	Tilt	$<\Delta>$	$\theta_i <\Delta>$	z
Bending magnet	Field error	$<\Delta B/B>$	$\theta_i <\Delta B/B>$	x
Straight sections (length = d_i)	Stray field	$<\Delta B_S>$	$d_i \langle \Delta B_s \rangle / (B\rho)_{inj}$	x,z

Magnet design

$$\Sigma Bl = 2\pi(B\rho) = 2\pi(3.3356\,pc)$$



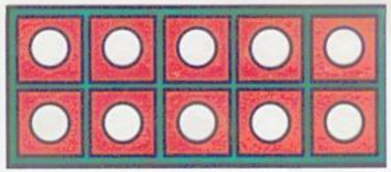
$$NI = \frac{gB}{\mu_o}$$

$$R = \frac{2lN^2\rho}{A}$$

$$\text{Power} = I^2R = \frac{g^2B^2 2l\rho}{\mu_o{}^2 A}$$

Power for given $Bl \propto B$

Magnet configurations



Coil Design/Geometry

Standard design is rectangular copper (or aluminium) conductor, with cooling water tube. Insulation is glass cloth and epoxy resin.

Amp-turns (NI) are determined, but total copper area (A_{copper}) and number of turns (n) need to be decided.

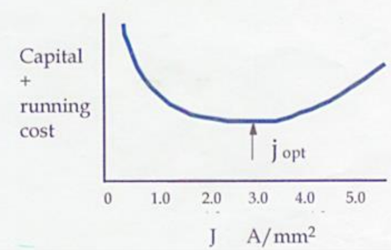
Copper Area. Current density $j = N/A_{copper}$

Optimum j determined from economic criteria.

Some fraction of the magnet capital costs (coil & yoke materials, plus assembly, testing and transport) vary (roughly) as 1/j. Operational costs (price of electrical power over the life of the accelerator) vary as j. So total cost of building and running magnet 'amortised' over life of machine is:

$$\pounds = K + C/j + Rj$$

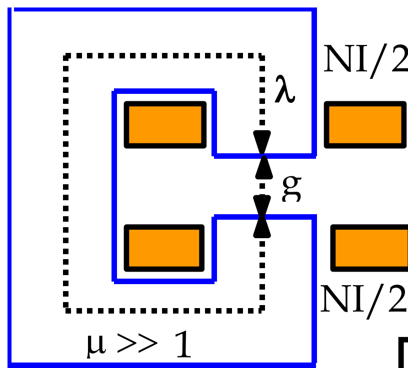
Values of K, C, R and j_{opt} depend on design, manufacturer, policy, country, etc. Values of 3 to 5 A/mm^2 for j_{opt} are typical.



Magnet cross sections

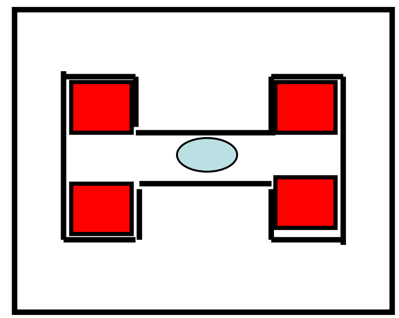
"C' Core:

- Easy access
- Less rig



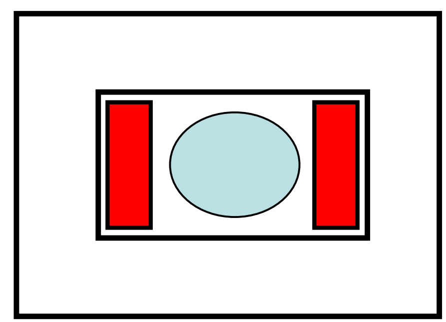
'H core':

- Symmetric;
- More rigid;
- Access problems.

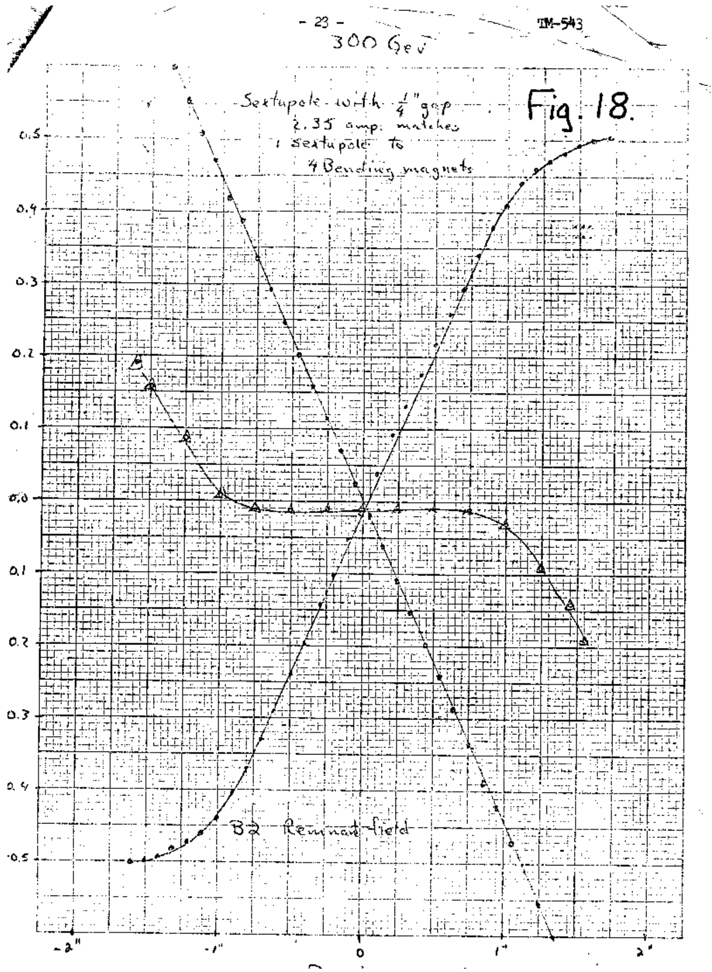


"Window Frame'

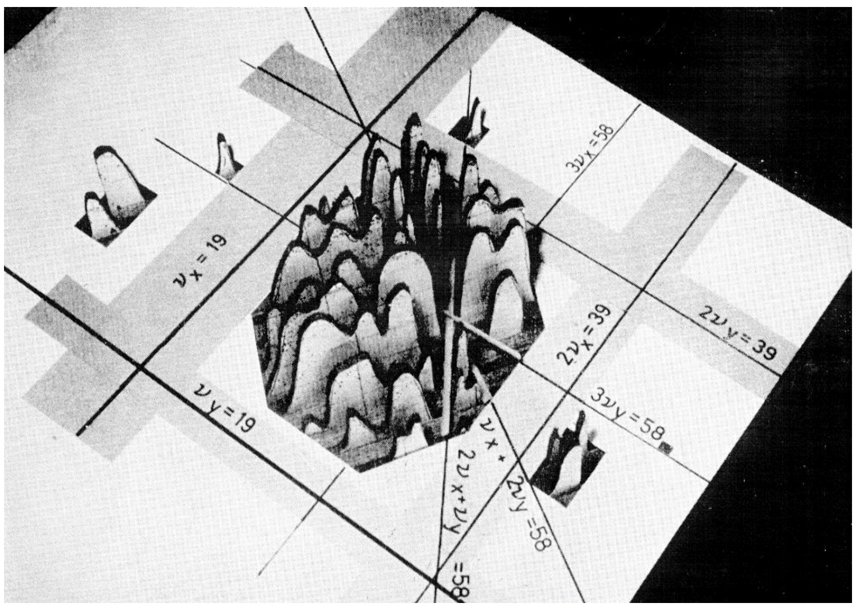
- High quality field;
- Major access problems
- Insulation thickness



How not to measure magnets

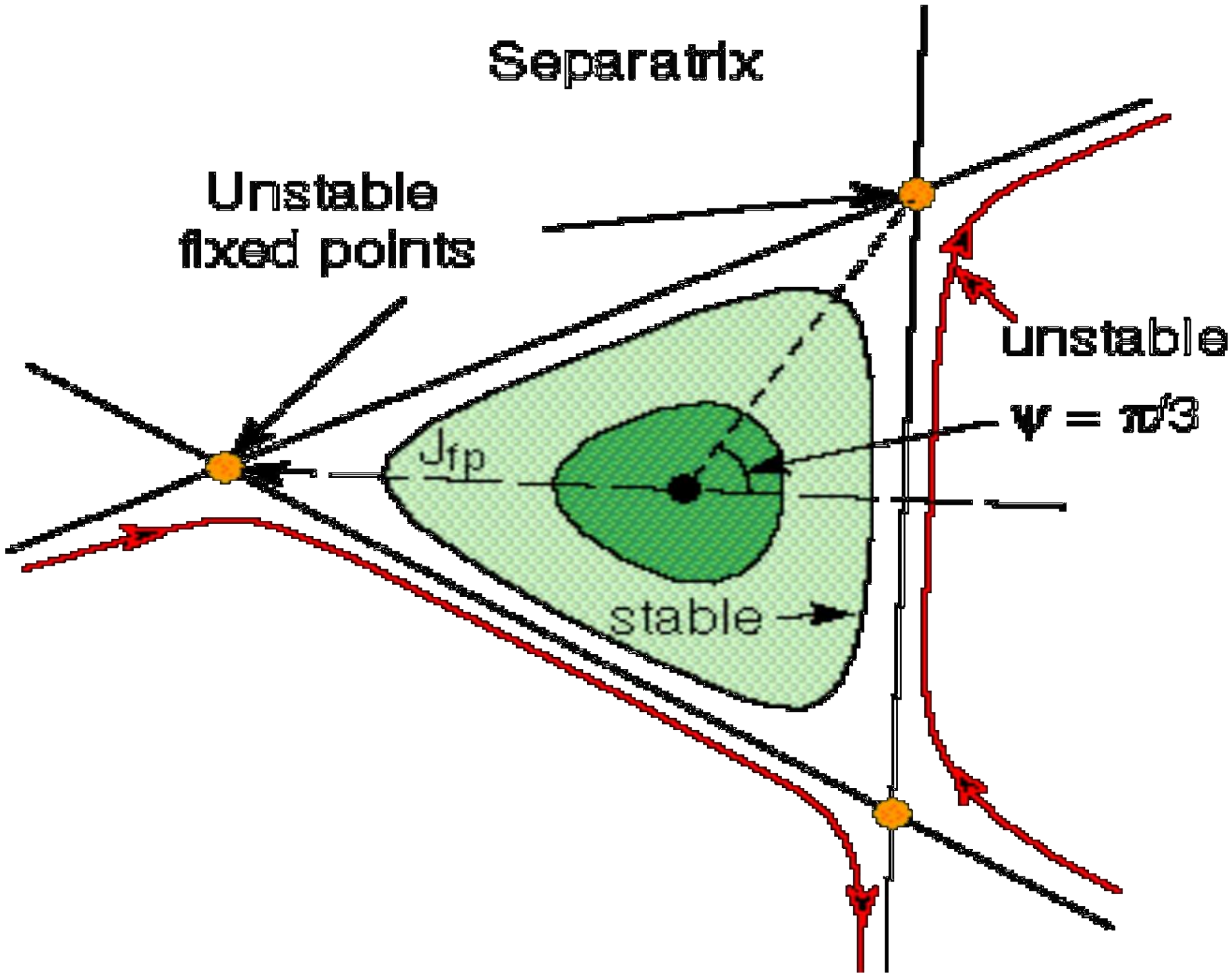


INJECTION STUDIES AT FNAL



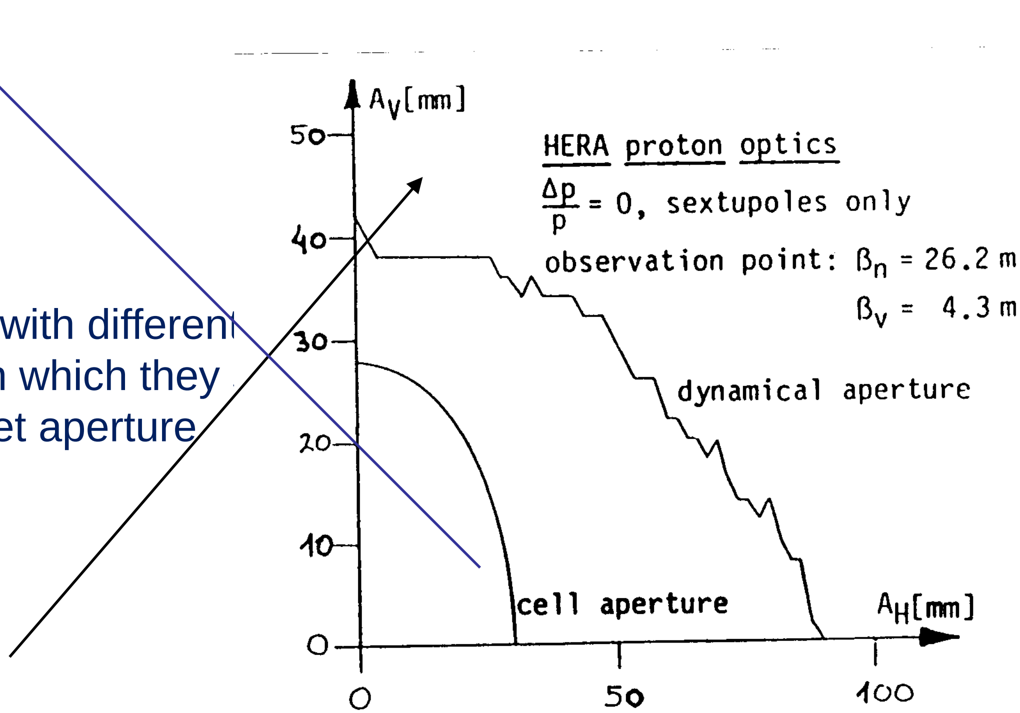
- Remanent sextupole in the FNAL main ring caused serious beam loss due to non-linear resonances.
- This was exacerbated by magnet ripple.
- A three dimensional hill and dale model spanning the Q (or ν) diagram

Magnet tolerances v. aperture (dynamic)



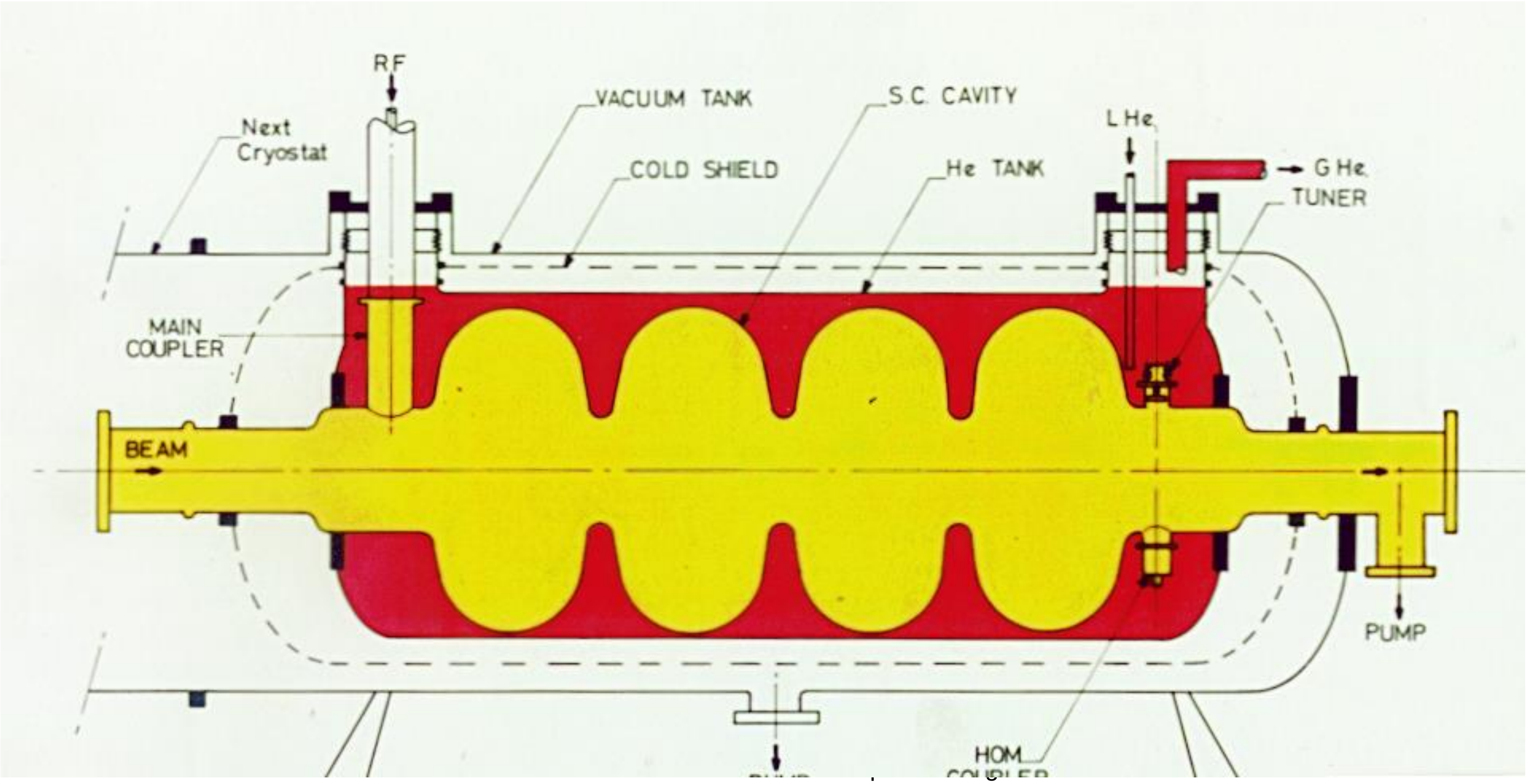
Dynamic Aperture

- Particles launched into simulator with different betatron amplitudes and region in which they turns is compared with the magnet aperture



RF System

- constraint is Voltage per meter and MW of power
- pressure from need to provide a good acceleration rate or large bucket (synchrotron emission in lepton machines)



Synchrotron motion

- This is a biased rigid pendulum

$$\ddot{\phi} = -\frac{2\pi V_0 h \eta f^{2}}{E_0 \beta^2 \gamma}\left(\sin\phi - \sin\phi_s\right)$$

- Synchrotron frequency

$$f_s = \sqrt{\frac{|\eta| h V_0 \cos\phi_s}{2\pi E_0 \beta^2 \gamma}}\, f \; .$$

- Synchrotron “tune

$$f_s = \sqrt{\frac{|\eta| h V_0 \cos\phi_s}{2\pi E_0 \beta^2 \gamma}}\, f \; .$$

- Should be less than 0.05

$$Q_s = \frac{f_s}{f} = \sqrt{\frac{|h| h V_0 \cos f_s}{2 p E_0 b^2 g}} .$$

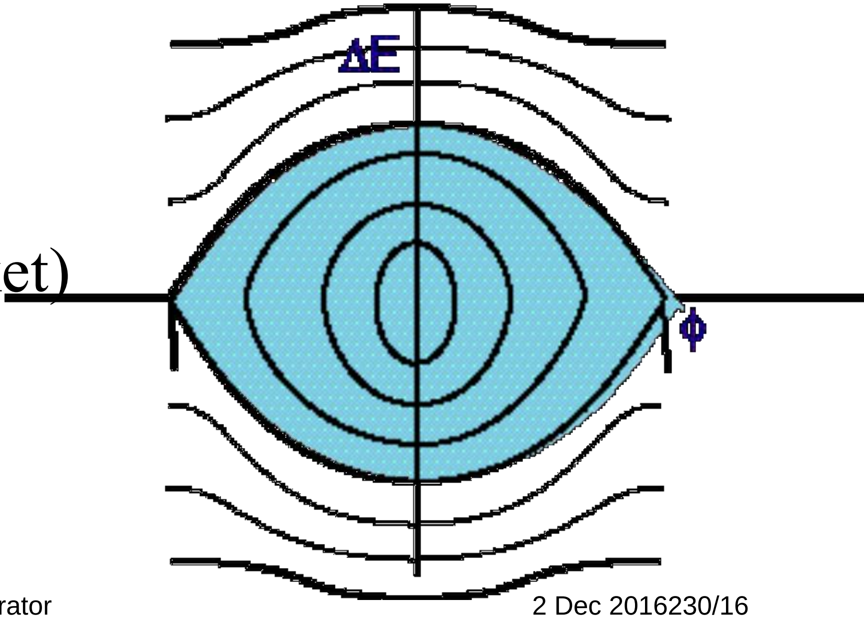
Rf volts to damp instabilities

- During collisions, in order to use the Keil Schnell criterion to combat instabilites we must have enough voltage to reach a threshold value of :

$$\frac{\Delta E}{E} = \beta \sqrt{\frac{eV}{\pi |\eta| hE}}$$

(stationary bucket)

$$V \propto h \propto \omega_{rf}$$

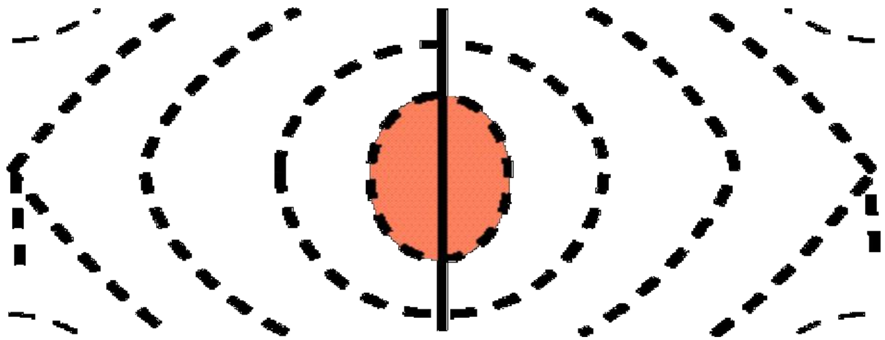


Organising the design work

- A. Lattice
- 1. Establish and update a parameter list
- 2. Choose a lattice http://doc.cern.ch/yellowrep/2005/2005-012/p55.pdf
- 3. Decide phase advance per cell
- 5. Decide period geometry
- 4. Calculate max and min beta and dispersion
- 6. Calculate radiation intyegrals
- 7. Acceptance required
- B. Errors and corrections
- http://preprints.cern.ch/cgi-bin/setlink?base=cernrep&categ=Yellow_Report&id=95-06_v1
- 8. Correction of chromaticity
- C. Magnet and power supply
- http://preprints.cern.ch/cgi-bin/setlink?base=cernrep&categ=Yellow_Report&id=92-05
- 9. The magnet aperture - the most expensive component
- 10. Calculating magnet stored energy
- D. RF
- http://preprints.cern.ch/cernrep/2005/2005-003/2005-003.html
- 11. Choice of RF frequency (scaling)
- 12. Choice of RF voltage (injection)
- 13. Bucket size for capture and acceleration
- E. Collective effects
- 14. Instability thresholds
- http://doc.cern.ch/yellowrep/2005/2005-012/p139.pdf

Short bunches needed for collisions

- When colliding bunches, we want a short bunch



- If h is small, the bucket area must be much bigger

$$A = \iint dE d\phi = 16\beta\sqrt{\frac{EeV}{2\pi|\eta|h}} \propto \frac{h_{snug}}{h}$$

$$V \propto h^3 \quad \text{and} \quad \text{Power} \propto h^6$$

The moment of truth!

Adams, waiting for the first beam in the SPS, asks his team if they have remembered everything.