Synchrotron Radiation

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- Radiation of accelerated charge
- Energy Spectrum
- Energy loss per turn; per meter; per radian
- Damping of oscillations
- Quantum Excitation of Betatron Oscillations
- Equilibrium beam emittances
- Storage Rings and Light Sources

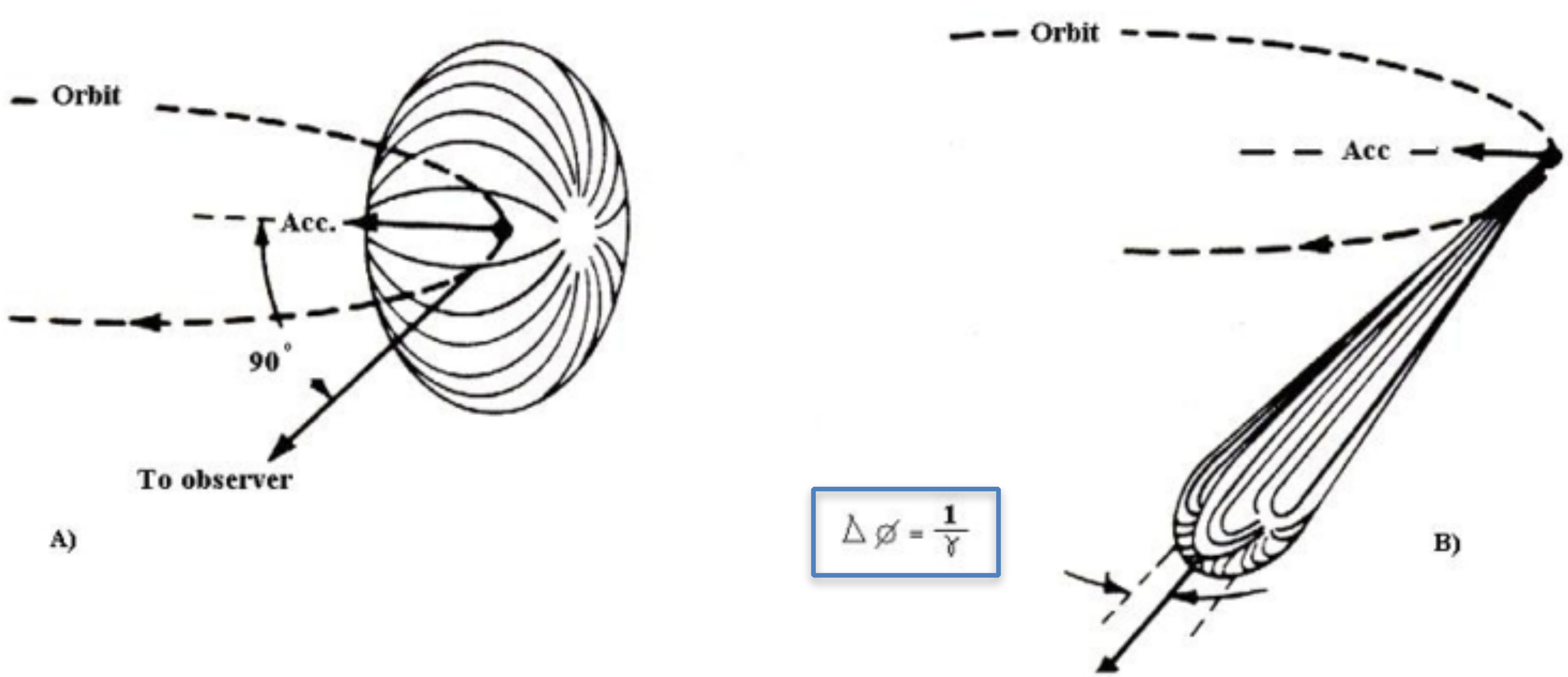
Radiation of an Accelerated Charge

- Larmor showed that the power radiated by a charged particle being accelerated is

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3} \qquad \text{if relativistic:} \quad P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4$$

- If the acceleration is transverse to the particle's direction of motion, then $a = v^2/r$, and due to bend field:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2c}{\rho^2}\gamma^4$$



Energy Spectrum of Radiation

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$$\omega_0 = 2\pi f_0 = c/\rho$$

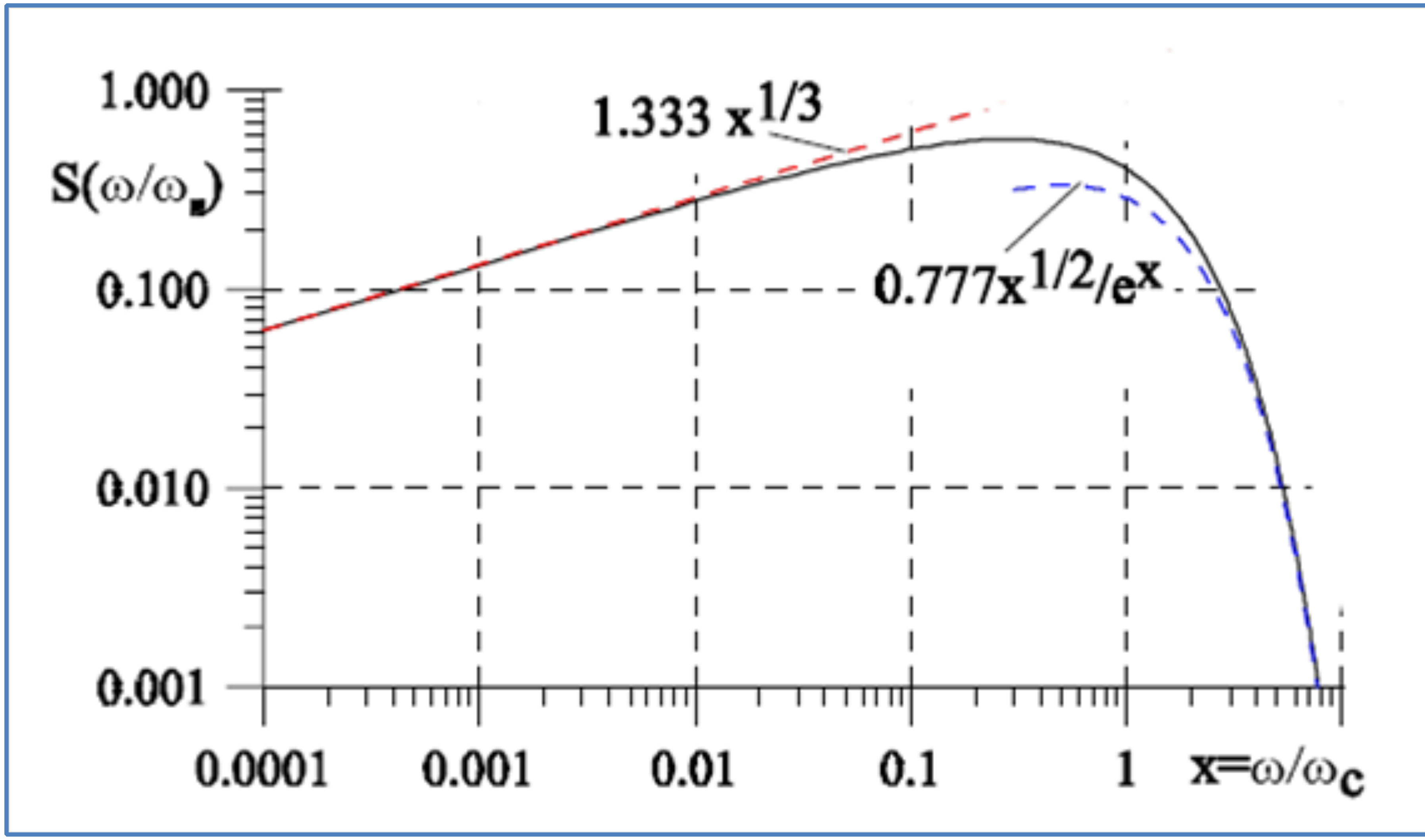
$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2 c}{\rho^2}\gamma^4$$

$$w_c \equiv \frac{3}{2}\gamma^3\hbar\omega_0$$

$$\langle w \rangle = \frac{8}{15\sqrt{3}} w_c$$

$$\langle w^2 \rangle = \frac{11}{27} w_c^2$$

$$\frac{dP(w)}{dw} = \frac{P}{w_c/\hbar} S(w/w_c)$$



Energy Loss per Revolution

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- Note: In terms of field *B* and energy *E*:

$$P = \frac{1}{6\pi\epsilon_0} \frac{e^4}{m^4 c^5} B^2 E^2$$

- Integrate the power loss around the circumference of the ring:

$$U_0 = \frac{e^2}{6\pi\epsilon_N}\gamma^4 \int_0^{2\pi R} \frac{1}{\rho^2} ds \longrightarrow U_0 = C_\gamma \frac{E^4}{\rho}$$

- C_γ = 8.85 x 10^{-5} m/GeV^3 (electrons)
- = 7.8 x 10^{-18} m/GeV^3 (protons)

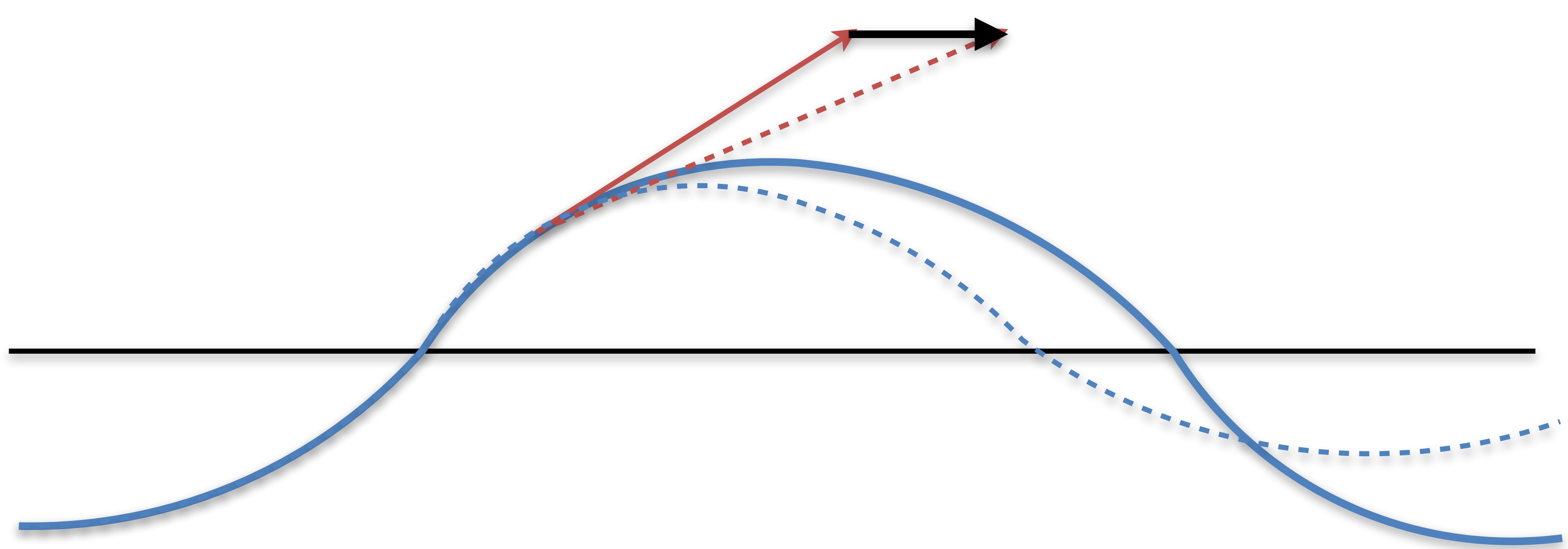
$$\left(\frac{0.511}{938}\right)^4 \quad !!$$

$$C_\gamma \equiv \frac{4\pi}{3} \frac{r_0}{(mc^2)^3} \qquad r_0 \equiv \frac{e^2}{4\pi\epsilon_0 mc^2}$$

Note: $\langle P \rangle = f_0 U_0$

Photon Emission

- Photons are emitted in direction of the particle's motion, which likely is not along the ideal trajectory; however, energy **is** restored (by RF) in the *s*-direction



- This creates the possibility of damping; similar to the adiabatic damping that occurs during acceleration

Adiabatic Damping from Synchrotron Radiation

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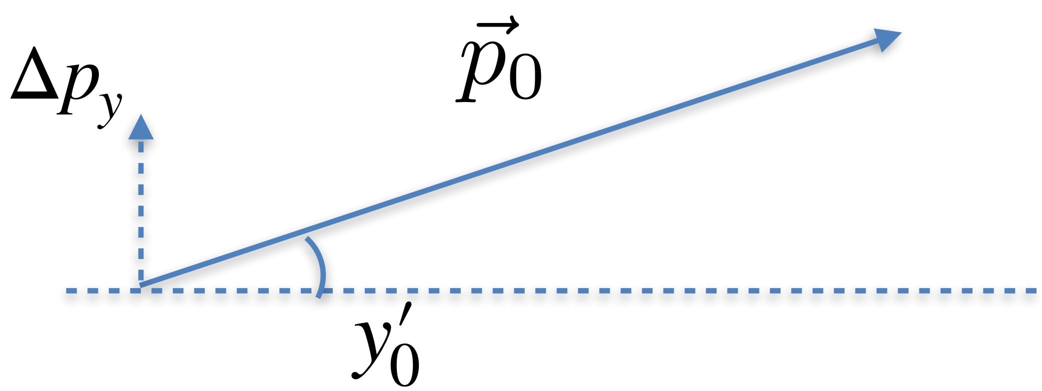
look at vertical betatron oscillations…



The particle will lose energy due to the emission of photons, but the energy will be replenished by the RF system in the ring.

However, the RF accelerates in the *s* direction, whereas the radiation can occur at arbitrary angles *y'*

$$\Delta y' = -y_0' \frac{\Delta p}{p}$$

magnitude of the loss

Note: particles at peak of their betatron oscillation will have little/no change in *y'*, while particles with large transverse angles will have their *y'* affected most

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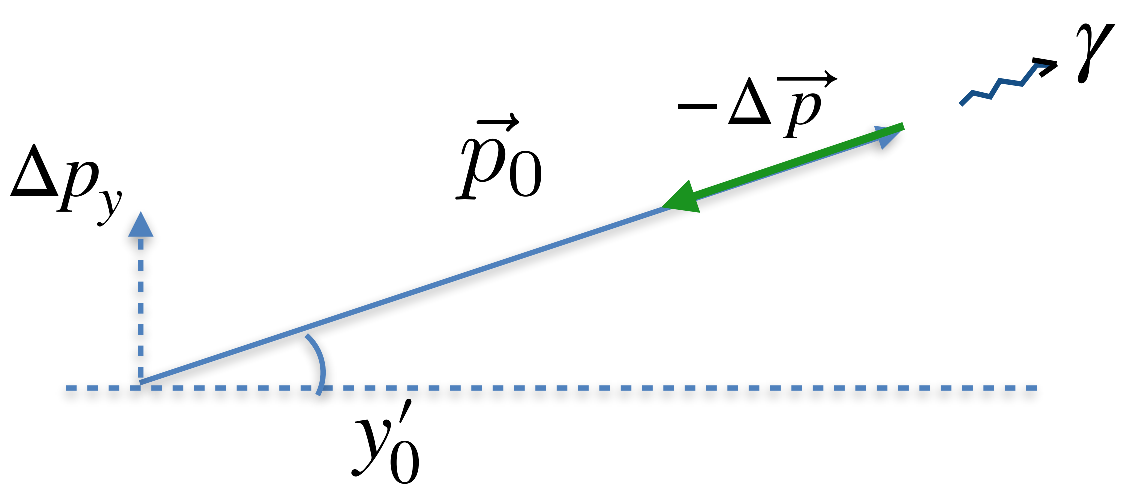

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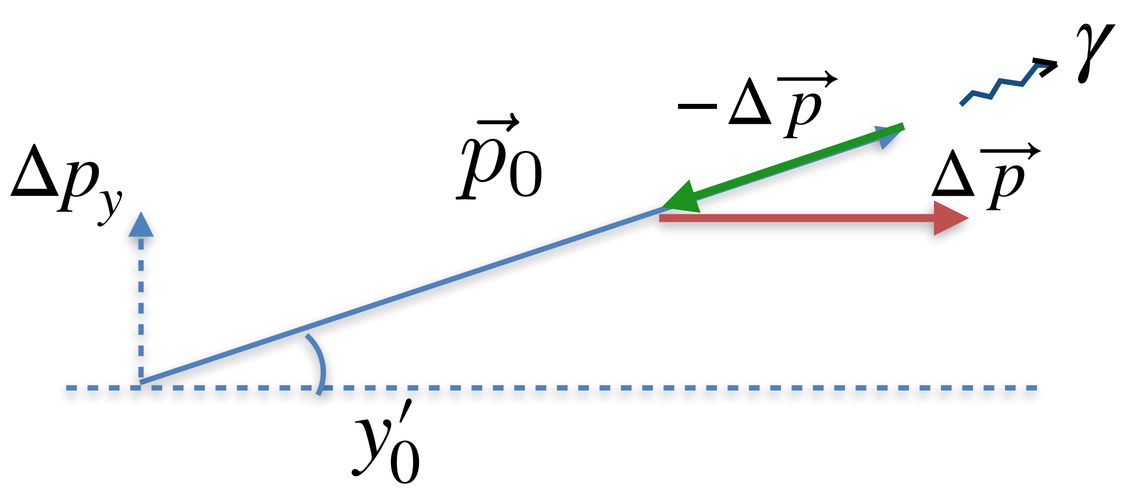

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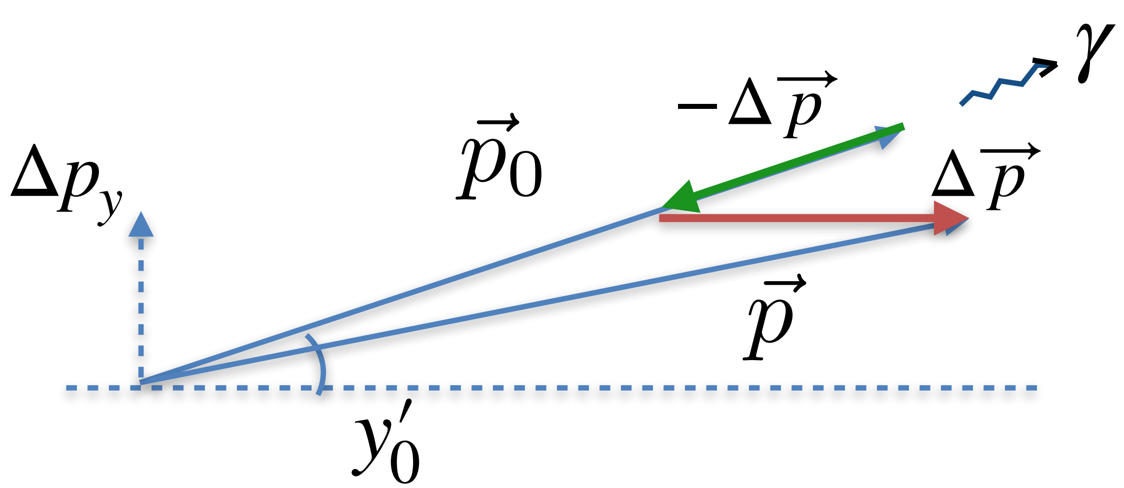

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Damping of Vertical Oscillations

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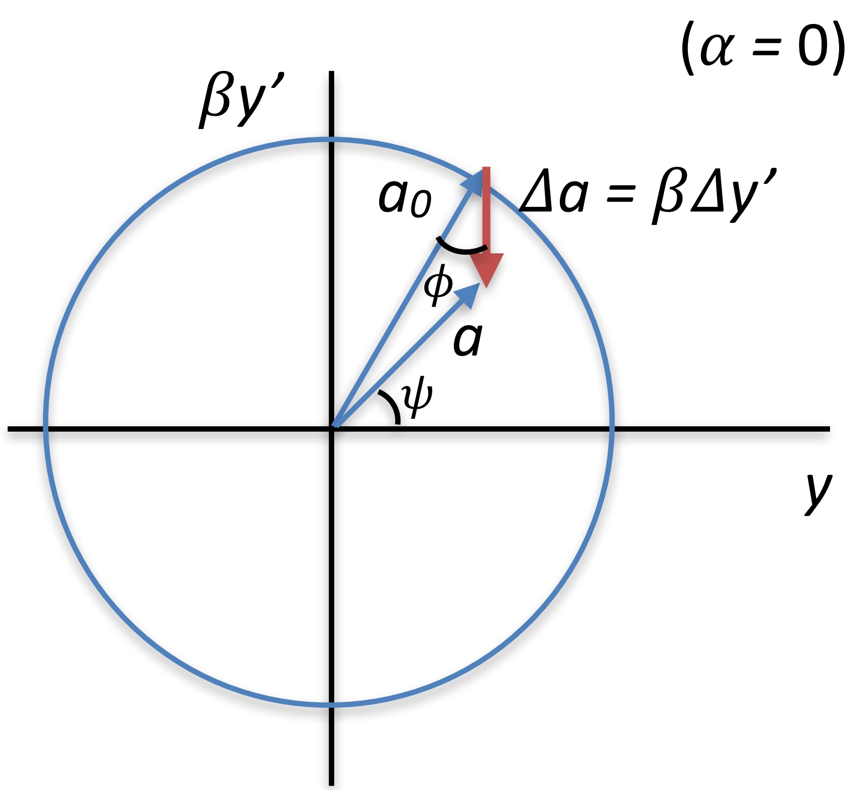
Now assuming that the incremental change in momentum is small compared to the overall momentum, and that the changes occur gradually on time scales large compared to those of the betatron motion…



$$\begin{aligned} a^2 &= a_0^2 + \Delta a^2 - 2\Delta a\, a_0 \cos\phi \\ &= a_0^2 + \Delta a^2 + 2\Delta a\, a_0 \sin\psi \\ &= a_0^2 + \Delta a^2 + 2\Delta a\, \beta\, y_0' \\ &= a_0^2 + (-\beta y_0' \frac{\Delta p}{p_0})^2 + 2(-\beta y_0' \frac{\Delta p}{p_0})\beta y_0' \\ &= a_0^2 + (\beta y_0')^2 (\frac{\Delta p}{p_0})^2 - 2(\beta y_0')^2 \frac{\Delta p}{p_0} \end{aligned}$$

$$\Longrightarrow \quad \langle a^2 \rangle = \langle a_0^2 \rangle - 2\langle (\beta y_0')^2 \rangle \frac{\Delta p}{p_0}$$

Note: $2\langle (\beta y')^2 \rangle = 2\langle y^2 \rangle = \langle a^2 \rangle$

So, $\Delta\langle a^2 \rangle = -\langle a_0^2 \rangle \frac{\Delta p}{p_0}$ $\quad \frac{\Delta\epsilon}{\epsilon} = -\frac{\Delta p}{p} \approx constant =$ average *dp/p* = *dE/E* loss per turn, due to synchrotron radiation…

Damping of Vertical Oscillations

$$\frac{\Delta\epsilon}{\epsilon} = -\frac{\Delta p}{p} \quad \longrightarrow \quad \frac{d\epsilon_y/dn}{\epsilon_y} = -U_0/E \quad \longrightarrow \quad \epsilon_y = e^{-(U_0/E)n} = e^{-t/\tau_0}$$

Since $\epsilon_y \sim \sigma_y^2$, then $\sigma_y \sim e^{-t/\tau_y}$ where $\tau_y \equiv 2\tau_0$

and $\tau_0 \equiv \frac{E}{P} = \frac{E}{f_0 U_0}$

While even the "ideal" particle loses energy, according to

$$U_0 = C_\gamma \frac{E^4}{\rho}$$

it re-gains energy from the RF system;

we now look at how the synchrotron oscillations of nearby particles will also damp…

Energy Loss Relative to Ideal Particle

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- While all particles will be accelerated the same, on average, a particle near the ideal, synchronous particle might lose more/less energy

  - could pass through different B fields and/or through longer field path, due to dispersion; in summary, to lowest order (see textbook):

$$\frac{d\Delta E}{dn} = -\Delta E \int_0^T \frac{P}{E}\left[2 + \frac{D}{\rho} + 2D\frac{B'}{B}\right] dt$$

path length difference due to D

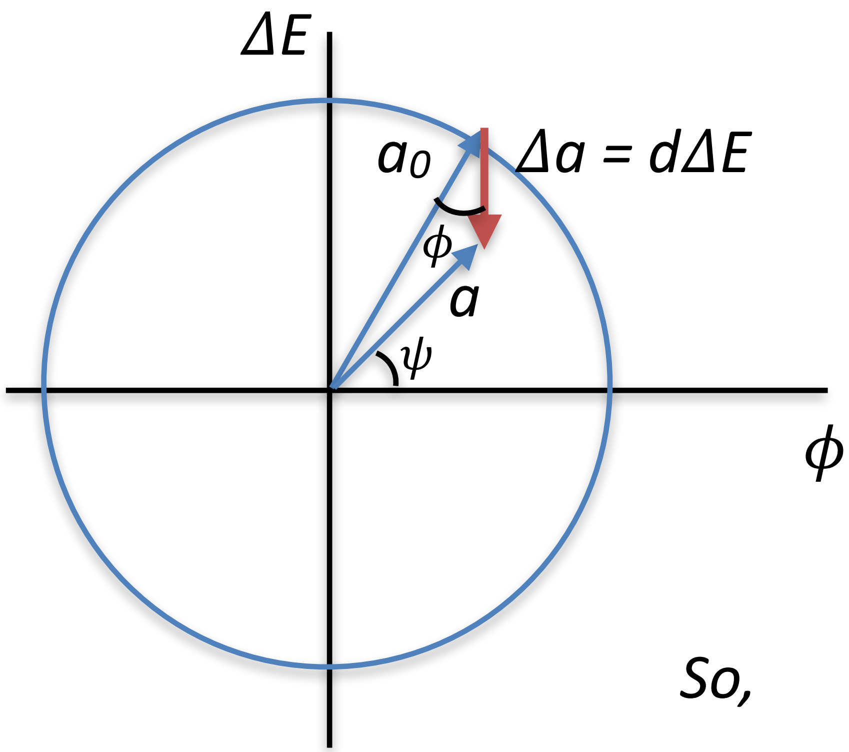
$\Delta B = B'x = B'D(\Delta E/E)$

$$d\Delta E = -\frac{2+\mathscr{D}}{f_0\tau_0}\Delta E \qquad \textit{per turn}$$

$$\mathscr{D} \equiv \frac{\langle \frac{D}{\rho^2}\left(\frac{1}{\rho} + 2\frac{B'}{B}\right)\rangle}{\langle \frac{1}{\rho^2}\rangle}$$

Damping of Synchrotron Oscillations

As in the *vertical* case…



$$a^2 \approx a_0^2 - 2\left(\frac{2+\mathscr{D}}{f_0\tau_0}\Delta E\right)\Delta E$$

$$\langle a^2\rangle = \langle a_0^2\rangle - 2\frac{2+\mathscr{D}}{f_0\tau_0}\langle \Delta E^2\rangle$$

$$2\langle \Delta E^2\rangle = \langle a^2\rangle \qquad \longrightarrow \Delta\langle a^2\rangle = -\frac{2+\mathscr{D}}{f_0\tau_0}\langle a^2\rangle$$

So,

$$\frac{d\epsilon_s/dn}{\epsilon_s} = -\frac{2+\mathscr{D}}{f_0\tau_0} \approx constant$$

$$\frac{d\epsilon_s}{\epsilon_s} = -\frac{2+\mathscr{D}}{\tau_0}dt$$

Hence,

$\epsilon_s \sim e^{-2t/\tau_s}$ *and* $\Delta E \sim e^{-t/\tau_s}$ *where*

$$\boxed{\tau_s = \frac{2\tau_0}{2+\mathscr{D}}}$$

Energy Loss Relative to Ideal Particle

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$$\Delta E \sim e^{-t/\tau_s} \qquad \tau_s = \frac{2\tau_0}{2+\mathcal{D}} \qquad \mathscr{D} = \frac{\langle \frac{D}{\rho^2}\left(\frac{1}{\rho} + 2\frac{B'}{B}\right)\rangle}{\langle \frac{1}{\rho^2}\rangle}$$

- Note: In a standard FODO-style lattice, there is no gradient, *B*', in regions where there is bending, *B*

- thus, in this case, $\mathscr{D} \approx \langle D/\rho \rangle = \alpha_p = 1/\gamma_t^2$ (a small number)
- hence,

$$\mathscr{D} \ll 2 \longrightarrow \tau_s \approx \tau_0$$

- In a combined function ring (like the AGS at Brookhaven, the Booster and Recycler rings at Fermilab), where *B'* is present along with *B*, then this function ($\mathscr{D}$) can actually be large

Robinson's Theorem[1]

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[1] K. W. Robinson, "Radiation Effects in Circular Electron Accelerators," Phys.Rev. 111, No. 2 (1958).

- over distance *ds*,

$$\begin{pmatrix} x \\ x' \\ y \\ y' \\ \phi \\ \Delta E \end{pmatrix} = dM \begin{pmatrix} x \\ x' \\ y \\ y' \\ \phi \\ \Delta E \end{pmatrix}_0 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-du/E & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-du/E & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-2du/E \end{pmatrix}_0 \begin{pmatrix} x \\ x' \\ y \\ y' \\ \phi \\ \Delta E \end{pmatrix}_0$$

$$\det dM = 1 - 4\, du/E$$

to lowest order, for one revolution: $\det M = 1 - 4\, U_0/E$

But, too, the determinant of M is the product of its eigenvalues which are, for oscillatory motion, in the form of e^{γ_k} and the six γ_k's come in conjugate pairs. So, taking only the real parts α_k (for damping), the decrements per turn are:

$$\alpha_x + \alpha_x + \alpha_x = -(4U_0/E)/2$$

or, in terms of time:

$$\frac{1}{\tau_x} + \frac{1}{\tau_y} + \frac{1}{\tau_s} = \frac{2}{\tau_0}$$

- Thus, from the other damping times found above,

$$\tau_x = \frac{2\tau_0}{1 - \mathscr{D}}$$

Damping of Oscillations — Summary

- Characteristic Damping Time: $$\tau_0 \equiv E/\langle P \rangle = \frac{E}{f_0 U_0}$$
- Vertical Betatron Oscillation Damping Time: $$\tau_y = 2\tau_0$$
- Longitudinal Oscillation Damping Time: $$\tau_s = \frac{2\tau_0}{2 + \mathscr{D}}$$
- Robinson's Theorem: $$\frac{1}{\tau_x} + \frac{1}{\tau_y} + \frac{1}{\tau_s} = \frac{2}{\tau_0}$$
- Horiz. Betatron Oscillation Damping Time: $$\tau_x = \frac{2\tau_0}{1 - \mathscr{D}}$$

These are damping times of oscillation amplitudes; damping of *emittances* are twice as fast

Quantum Excitation of Oscillations

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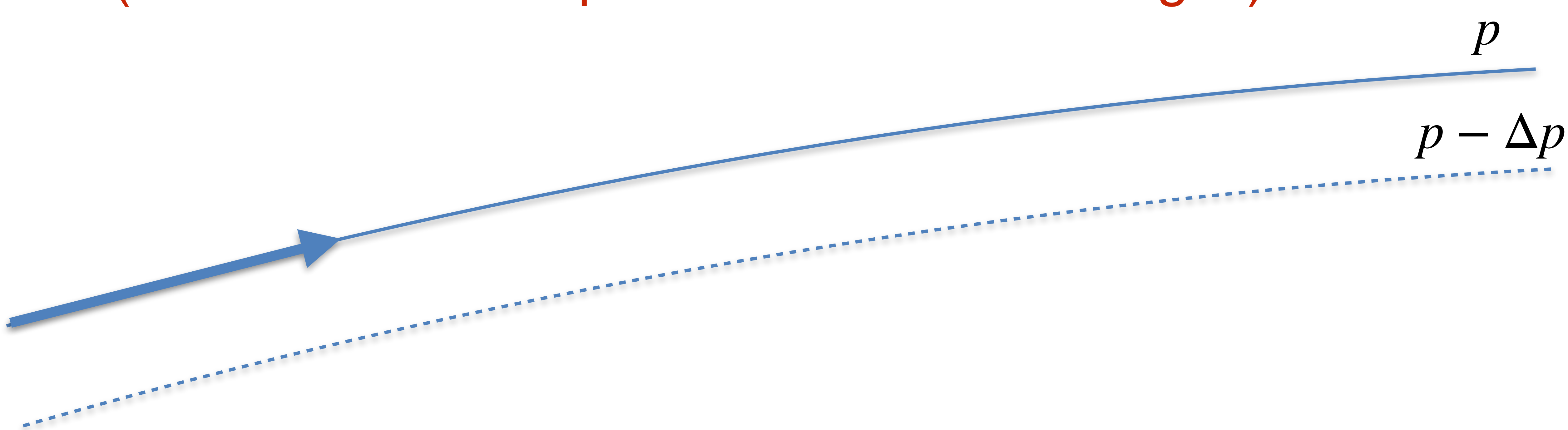
- We see that the oscillation amplitudes decay with time; but there is an opposing process:
  - Quantum fluctuations in regions of dispersion
    - excites synchrotron oscillations
    - excites betatron oscillations in horizontal plane
    - only important in horizontal plane
      - » (unless vertical dispersion exists in the ring…)



This "growth" of oscillation amplitude will compete with the decay of the oscillation from above, until an equilibrium horizontal beam size is reached…

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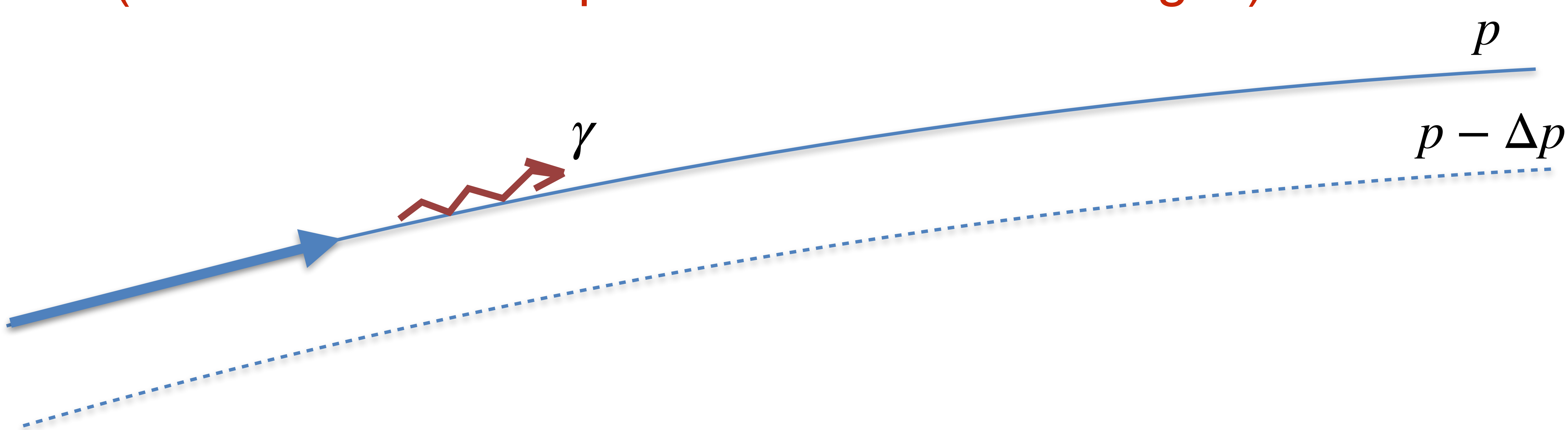

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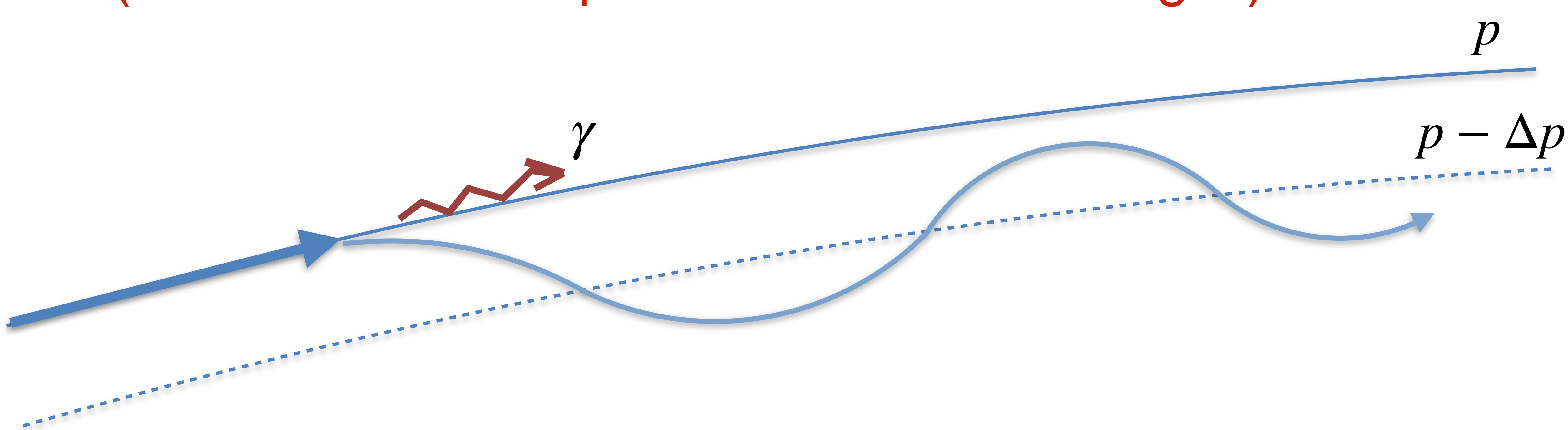


This "growth" of oscillation amplitude will compete with the decay of the oscillation from above, until an equilibrium horizontal beam size is reached…

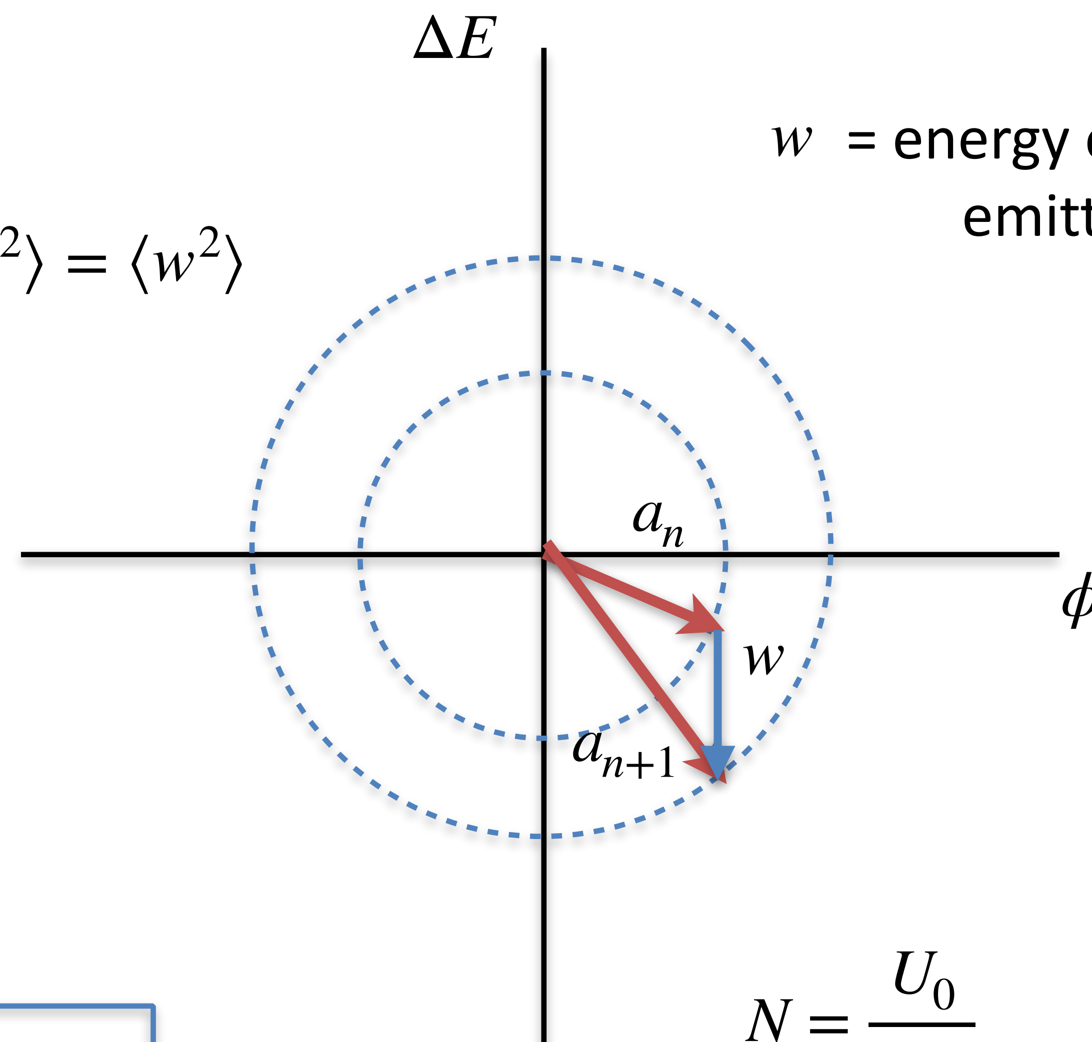
Excitation of Energy Oscillations

- Longitudinal Phase Space Picture:

$$a_{n+1}^2 = a_n^2 + w^2 - 2wa_n \cos\phi \longrightarrow \Delta\langle a^2\rangle = \langle w^2\rangle$$

$$\langle a^2\rangle = 2\sigma_E^2$$

$$\Delta\sigma_E^2 = \frac{1}{2}\langle w^2\rangle$$



w = energy of emitted photon

So, in total…

$$\frac{d\sigma_E^2}{dt} = -\frac{2}{\tau_s}\sigma_E^2 + \frac{1}{2}Nf_0\langle w^2\rangle$$

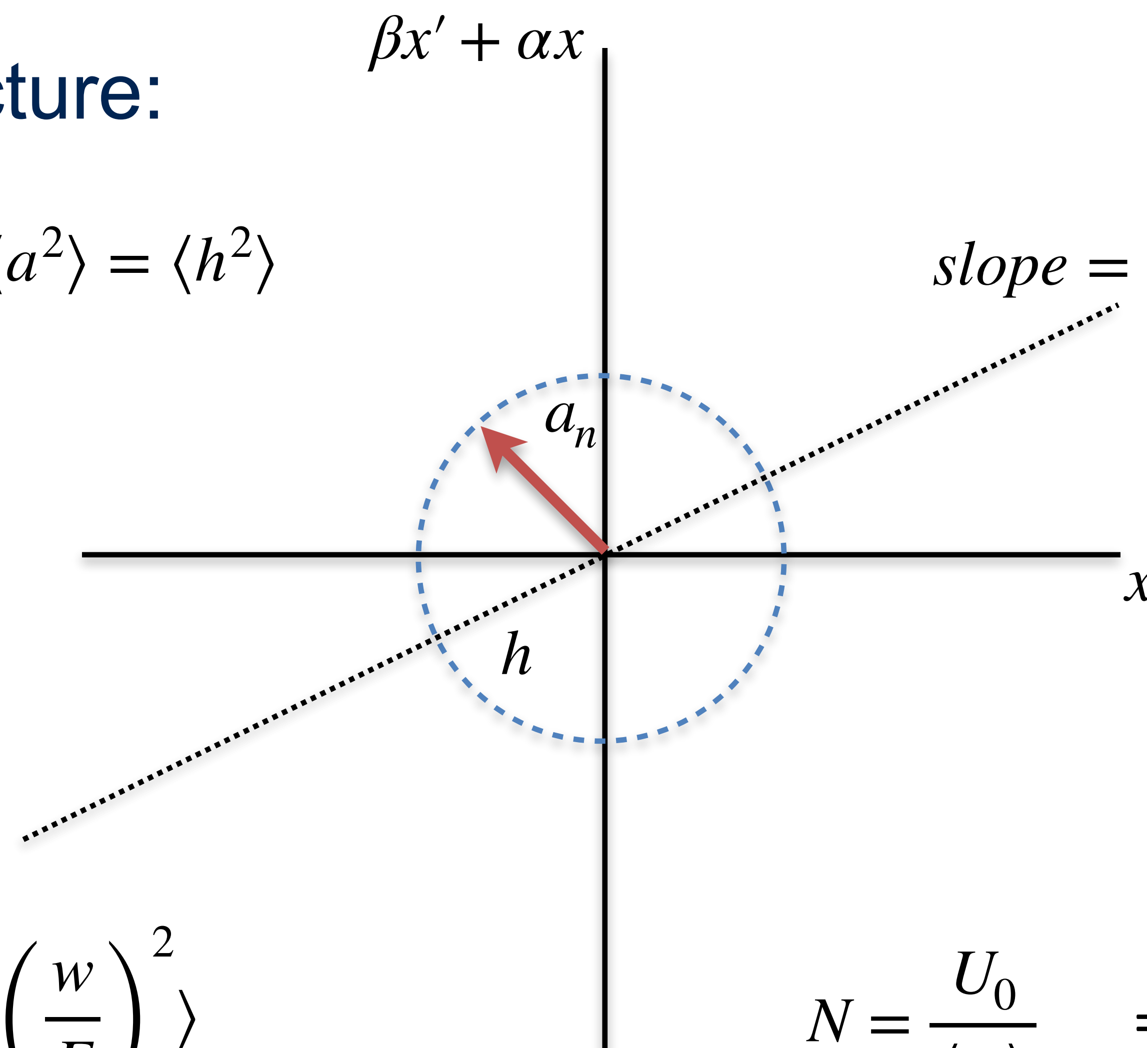
$$N = \frac{U_0}{\langle w\rangle}$$ # photons/turn

f_0 = revolution frequency

Excitation of Betatron Oscillations

- Transverse Phase Space Picture:

$$a_{n+1}^2 = a_n^2 + h^2 - 2ha_n\cos\phi \longrightarrow \Delta\langle a^2\rangle = \langle h^2\rangle$$



$$slope = \frac{\alpha D + \beta D'}{D}$$

$$\langle a^2\rangle = 2\sigma_x^2$$

$$\Delta\sigma_x^2 = \frac{1}{2}\langle h^2\rangle = \frac{1}{2}[D^2 + (\beta D' + \alpha D)^2]\langle\left(\frac{w}{E}\right)^2\rangle$$

$$N = \frac{U_0}{\langle w\rangle}$$ = # photons/turn

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So, in total…

$$\frac{d\sigma_x^2}{dt} = -\frac{2}{\tau_x}\sigma_x^2 + \frac{1}{2}Nf_0\langle\mathscr{H}\rangle\beta_x\frac{\langle w^2\rangle}{E^2}$$

$$\mathscr{H} = \frac{D^2 + (\beta D' + \alpha D)^2}{\beta_x}$$

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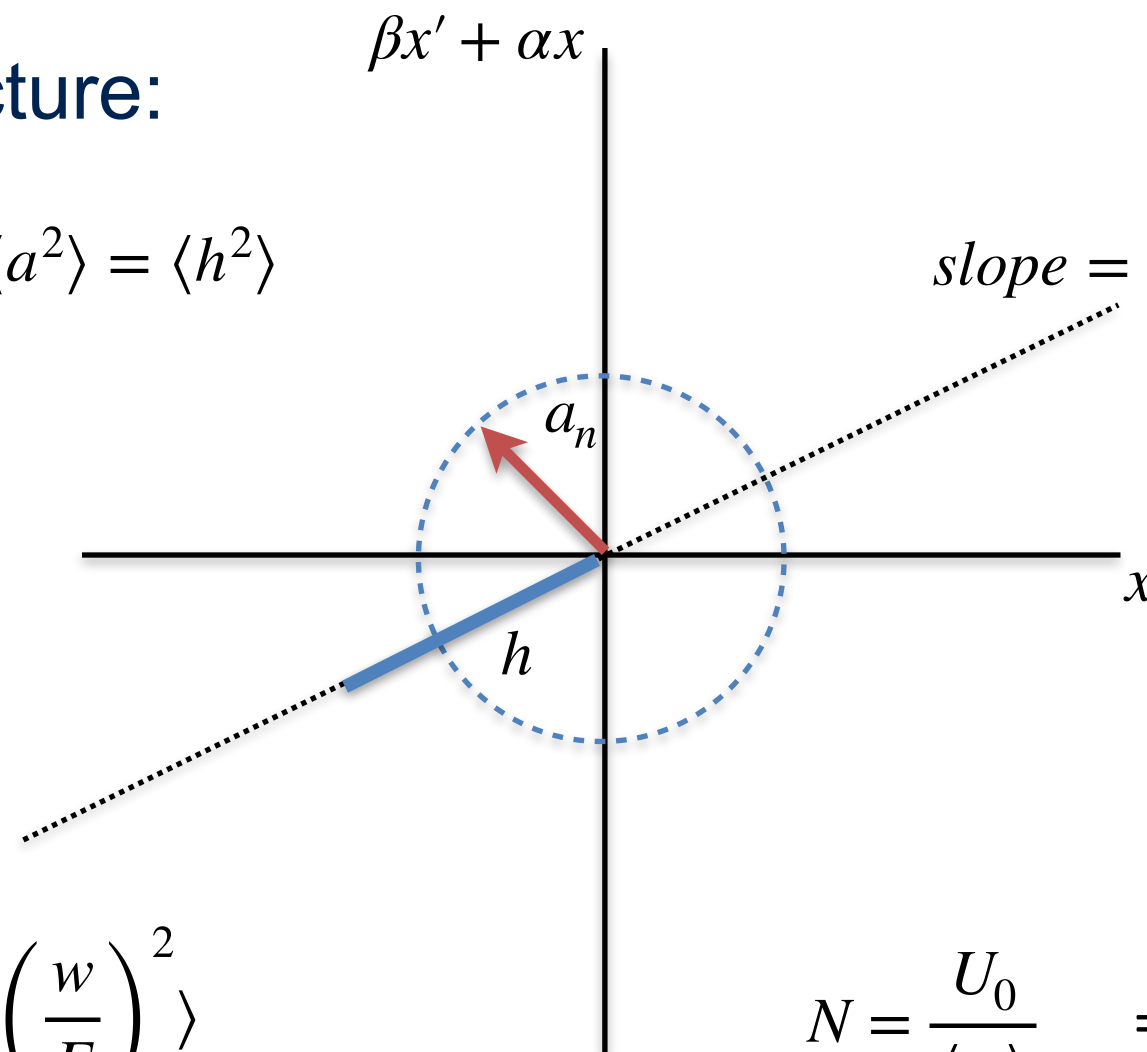

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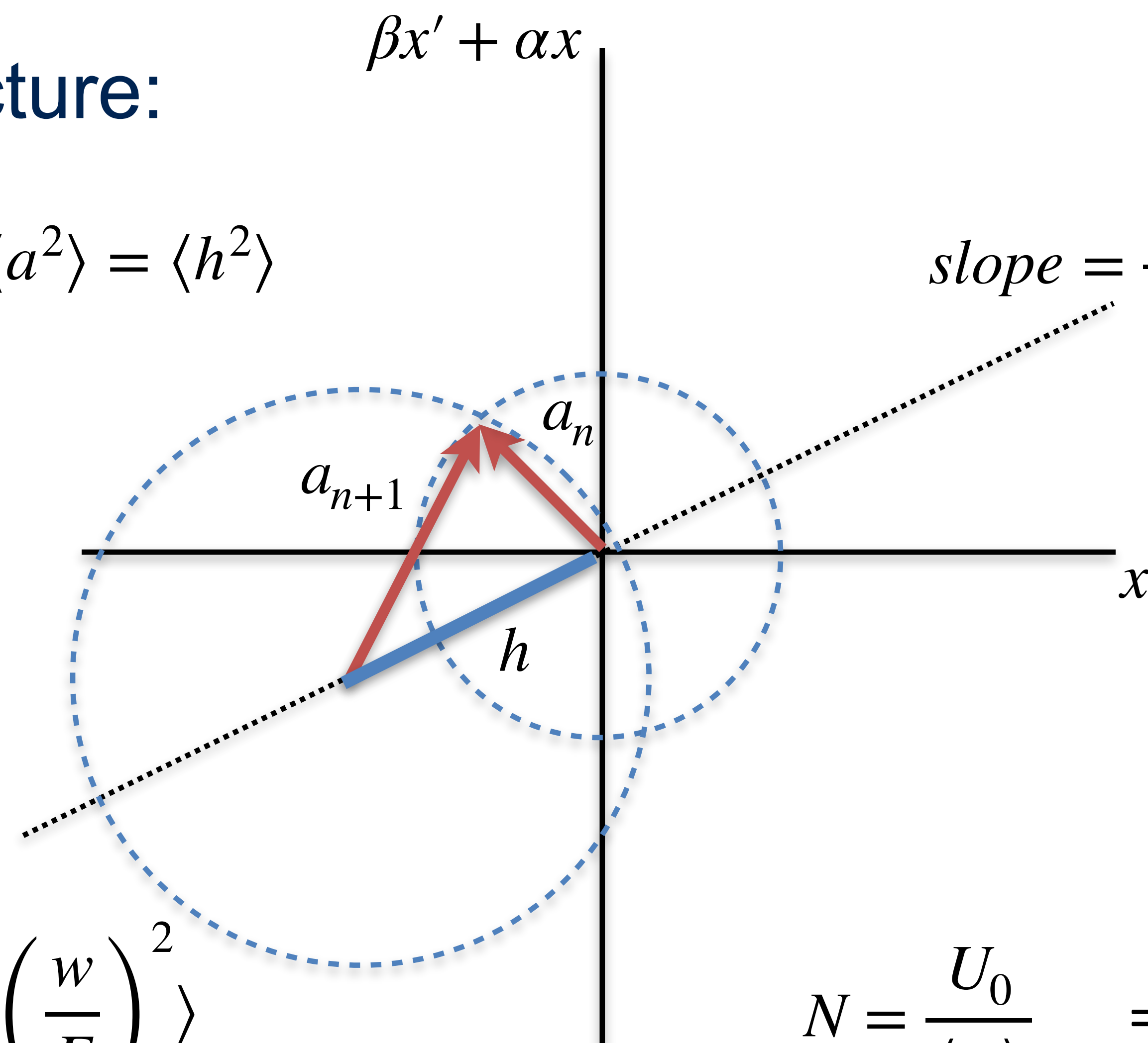

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Equations of Motion for Beam Variances

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- At equilibrium, the derivatives are zero:

$$\frac{d\sigma_E^2}{dt} = -\frac{2}{\tau_s}\sigma_E^2 + \frac{1}{2}Nf_0\langle w^2\rangle = 0$$

$$\frac{d\sigma_x^2}{dt} = -\frac{2}{\tau_x}\sigma_x^2 + \frac{1}{2}Nf_0\langle\mathscr{H}\rangle\beta_x\frac{\langle w^2\rangle}{E^2} = 0$$

$$\frac{d\sigma_y^2}{dt} = -\frac{2}{\tau_y}\sigma_y^2 = 0$$

$$\sigma_E^2 = \frac{\tau_s}{4}Nf_0\langle w^2\rangle$$

$$\sigma_x^2 = \frac{\tau_x}{4}Nf_0\langle\mathscr{H}\rangle\beta_x\frac{\langle w^2\rangle}{E^2}$$

$$\sigma_y^2 = 0$$

ideally, no source of vertical excitations; only damping

$$\sigma_E^2 = \frac{1}{2}\,\frac{1}{2+\mathscr{D}}\,\frac{\langle w^2\rangle}{\langle w\rangle}\,E$$

$$\sigma_x^2 = \frac{1}{2}\,\frac{\langle\mathscr{H}\rangle}{1-\mathscr{D}}\,\frac{\langle w^2\rangle}{\langle w\rangle}\,\frac{\beta_x}{E}$$

$$\sigma_y^2 = 0$$

at equilibrium, which is reached on a time scale of $\sim few \times \tau_0$

Example

- E = 10 GeV, electron beam

$$U_0 = 8.85 \times 10^{-5} \cdot 10^4/1000 \text{ GeV} = 0.885 \text{ MeV}$$

- $2\pi R$ = 1 km —-> f_0 = 300 kHz

$$\tau_0 = E/(f_0 U_0) = 10^4/(3 \times 10^5 \cdot 0.885) \text{ s} = 39 \text{ ms}$$

  - ω_0 ~ 2 MHz
  - ω_c = (3/2)(20,000)^3(6.58e-22)(2e6/sec) MeV-sec = 16 keV

- $\langle w \rangle$ = 5 keV, $\sqrt{\langle w^2 \rangle}$ = 10 keV
- let $\mathscr{D} \approx 0$, $\mathscr{H} \approx D^2/\beta \approx$ (2 m)^2/(40 m) = 0.1 m
- then, $\sigma_x \rightarrow$ 2 mm, $\sigma_y \rightarrow 0$, and $\sigma_E/E \rightarrow 7 \times 10^{-4}$

- Note that the horizontal emittance would be $\epsilon_N = \gamma\sigma^2/\beta \rightarrow$ 2000 mm-mr
  - very large numerical values, compared to proton beam emittances, but mostly just due to the high values of γ

Summary

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radiated energy per turn, power:

$$U_0 = C_\gamma \frac{E^4}{\rho} \qquad \langle P \rangle = f_0 U_0$$

C_γ = 8.85 x 10^{-5} m/GeV^3 (electrons)
= 7.8 x 10^{-18} m/GeV^3 (protons)

photon properties:

$$\omega_0 = 2\pi f_0 = c/\rho$$

$$w_c \equiv \frac{3}{2}\gamma^3 \hbar\omega_0$$

$$\langle w \rangle = \frac{8}{15\sqrt{3}} w_c$$

$$\langle w^2 \rangle = \frac{11}{27} w_c^2$$

$$\sigma_E^2 = \frac{1}{2}\frac{1}{2+\mathscr{D}}\frac{\langle w^2\rangle}{\langle w\rangle} E$$

$$\sigma_x^2 = \frac{1}{2}\frac{\langle \mathscr{H}\rangle}{1-\mathscr{D}}\frac{\langle w^2\rangle}{\langle w\rangle}\frac{\beta_x}{E}$$

$$\sigma_y^2 = 0$$

equilibrium quantities

$$\mathscr{D} = \frac{\langle \frac{D}{\rho^2}\left(\frac{1}{\rho} + 2\frac{B'}{B}\right)\rangle}{\langle \frac{1}{\rho^2}\rangle} \qquad \mathscr{H} = \frac{D^2 + (\beta D' + \alpha D)^2}{\beta_x}$$

Summary

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- Synchrotron radiation is emitted by charged particles “bending” through a magnet
- Radiation is emitted within a cone of angle $\sim \pm 1/\gamma$
- For separated-function lattices (FODO, etc.), all oscillations will damp toward equilibrium emittance values; can be tailored by the lattice design
  - by varying β_x, D_x, $\mathscr{H}$, *etc.*
- The final vertical emittance won’t become zero in reality, will be determined by residual vertical dispersion and/or other error terms — but, it is typically much, much smaller than the horizontal emittance
  - very flat beams!
- Damping implies that operation of the synchrotron is often not as sensitive to resonances, injection errors, etc. as for a proton accelerator

Cornell University -- CESR

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Cornell Electron Storage Ring

LEP, Geneva -- 1990's

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European Organization for Nuclear Research (CERN) -- LEP tunnel (= LHC tunnel!)

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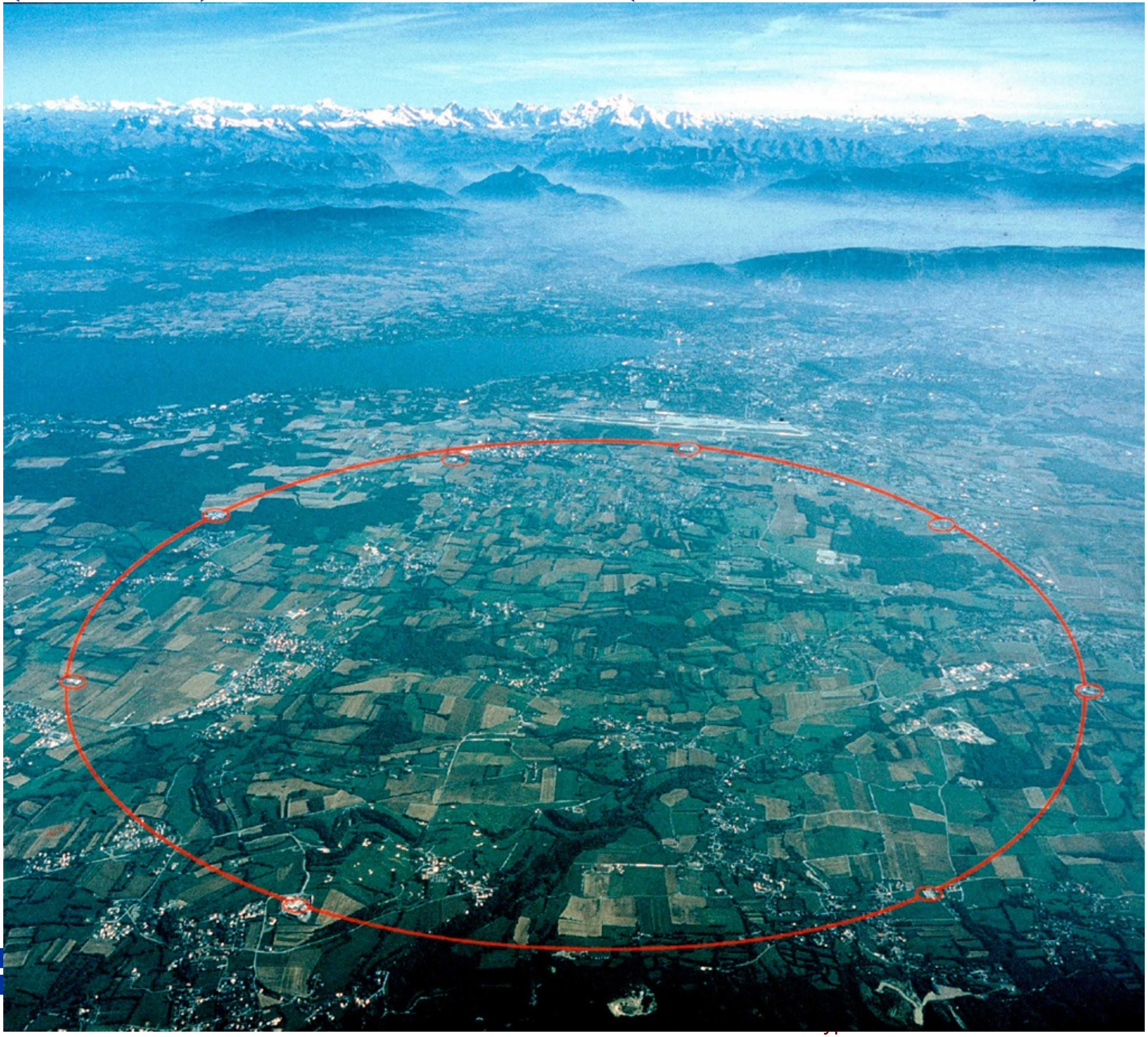
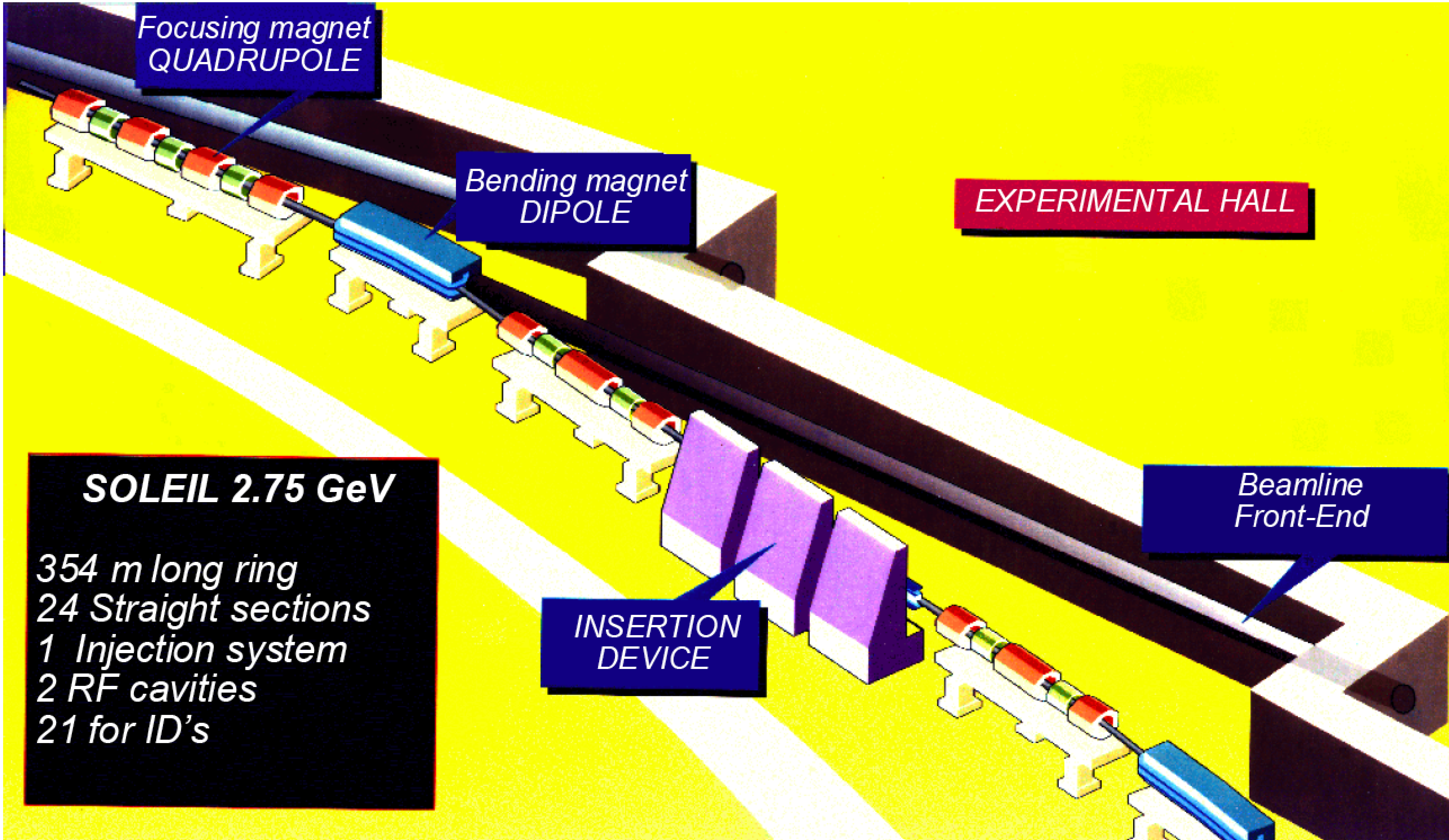


A typical lattice for a storage ring



Courtesy Y. Papaphilippou

Light Source Lattices

- Chasman-Green
- Triple-bend achromats
- Minimum emittance lattice
- Bunch compression
- Coherent SR
- Insertions for wigglers/undulators

Chasman-Green cell

Northern Illinois University

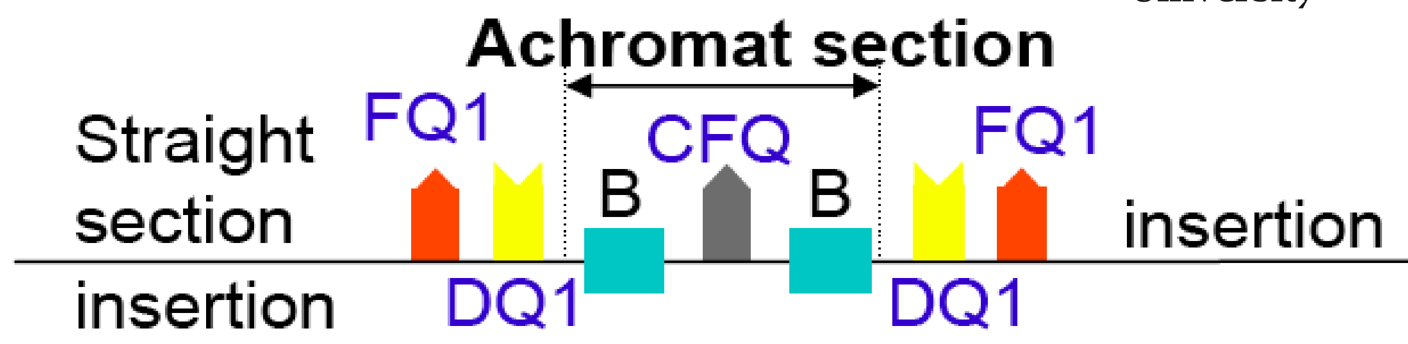
- Double bend achromat with unique central quadrupole
- Achromatic condition is assured by tuning the central quadrupole
- Minimum emittance with a quadrupole doublet in either side of the bends
- The required focal length of the quad is given by

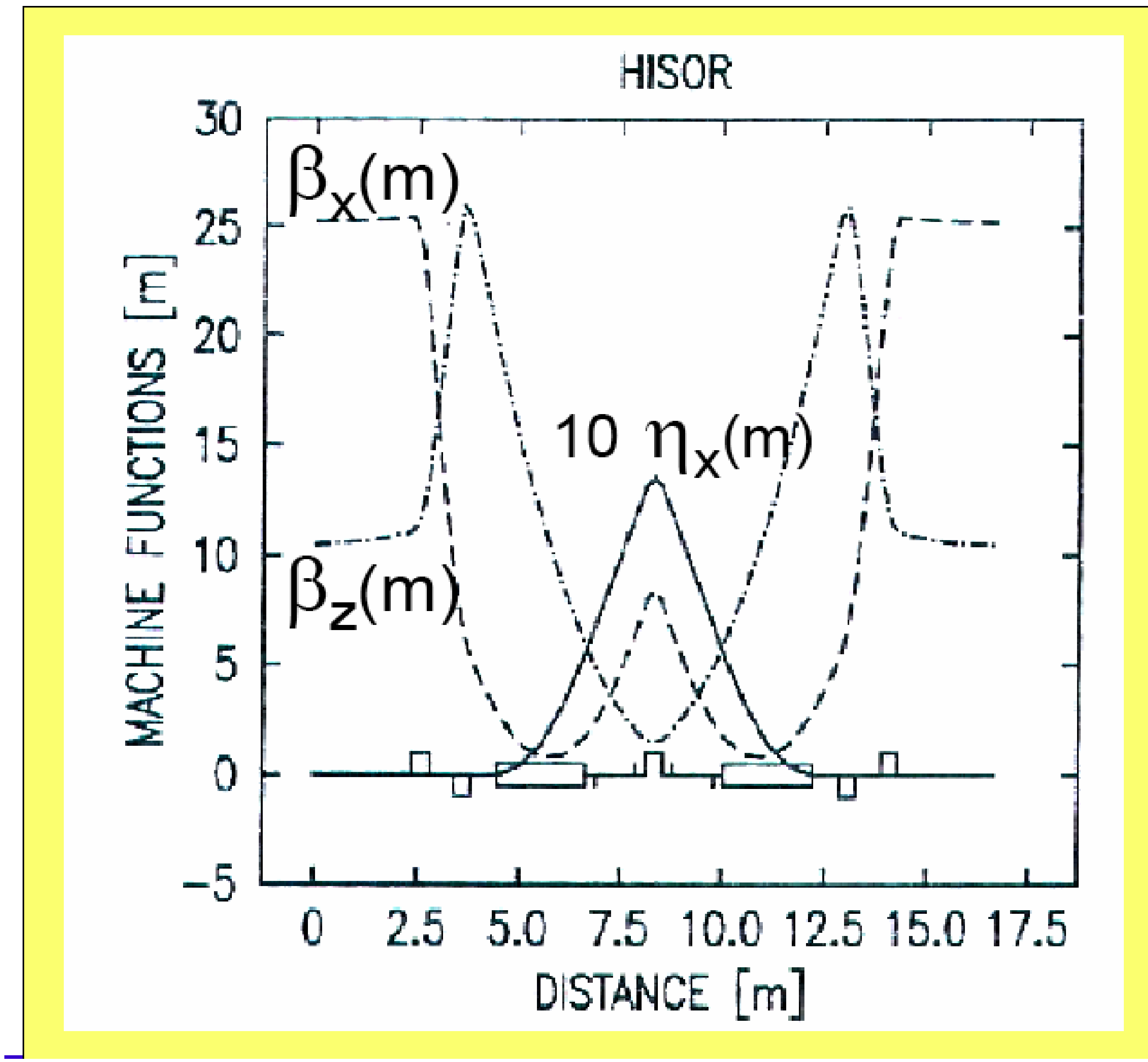
$$f = \frac{1}{2}(L_{\text{drift}} + \frac{1}{2}L_{\text{bend}})$$

and the dispersion

$$D_c = (L_{\text{drift}} + \frac{1}{2}L_{\text{bend}})\theta$$

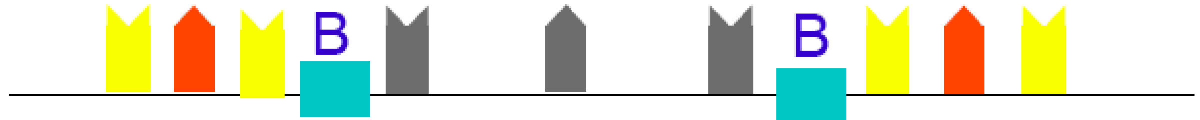
- Disadvantage the limited tunability and reduced space



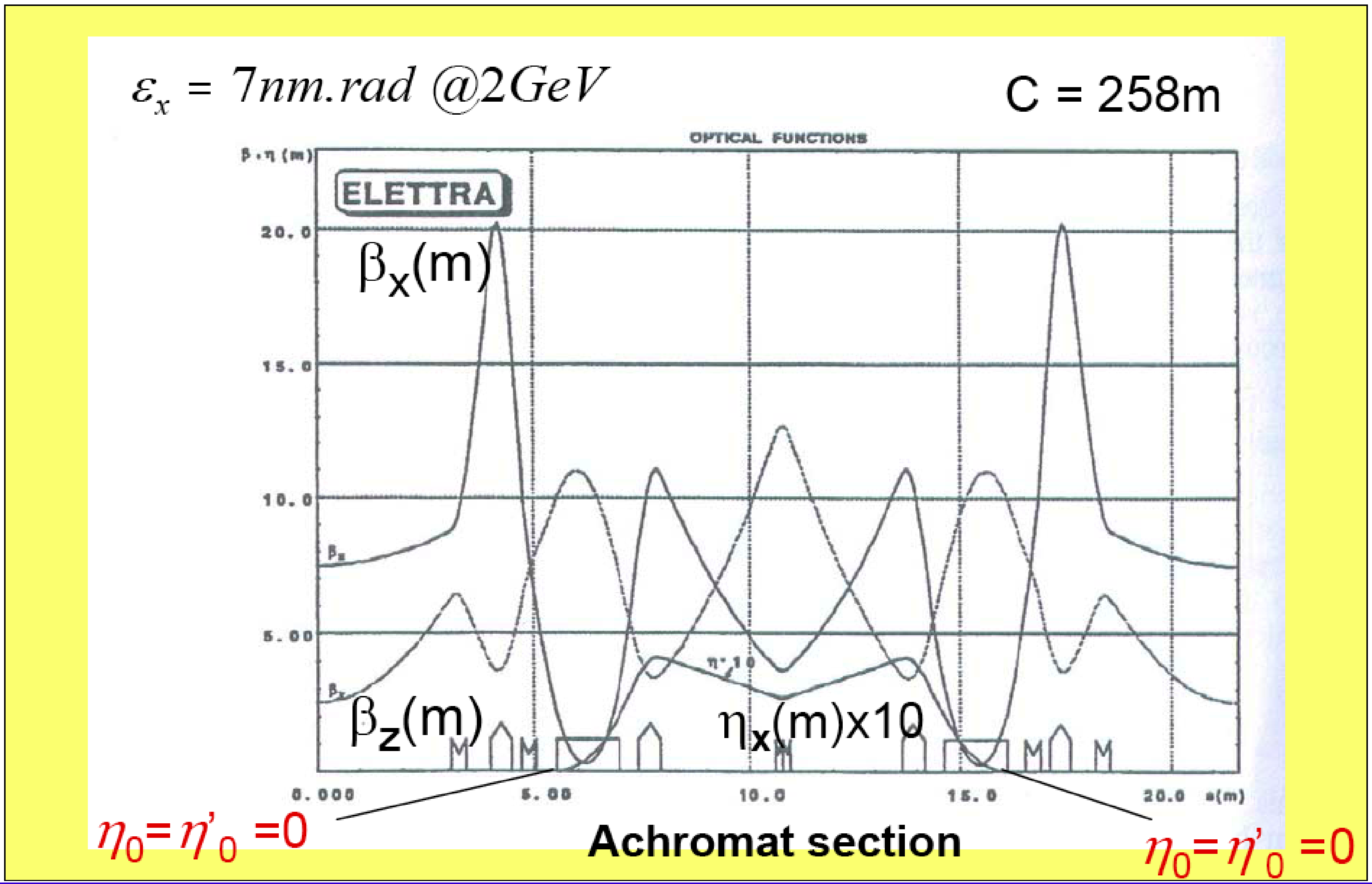


Courtesy Y. Papaphilippou

DBA with triplet



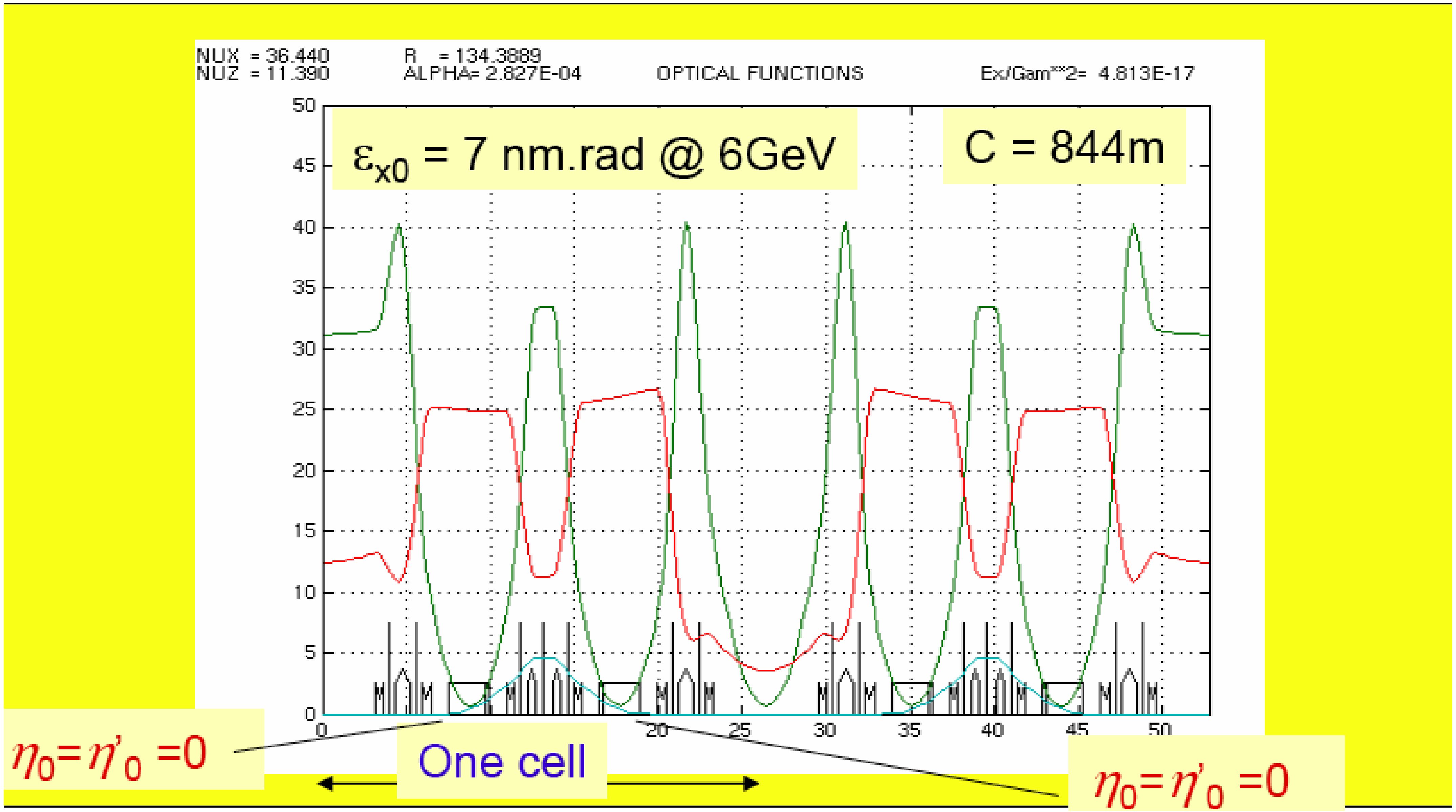
Achromat section



- Central triplet between the two bends and two triplets in the straight section to achieve the minimum emittance and achromatic condition
- Elettra (Trieste) uses this lattice achieving almost the absolute minimum emittance for an achromat
- Disadvantage the increased space in between the bends

Courtesy Y. Papaphilippou

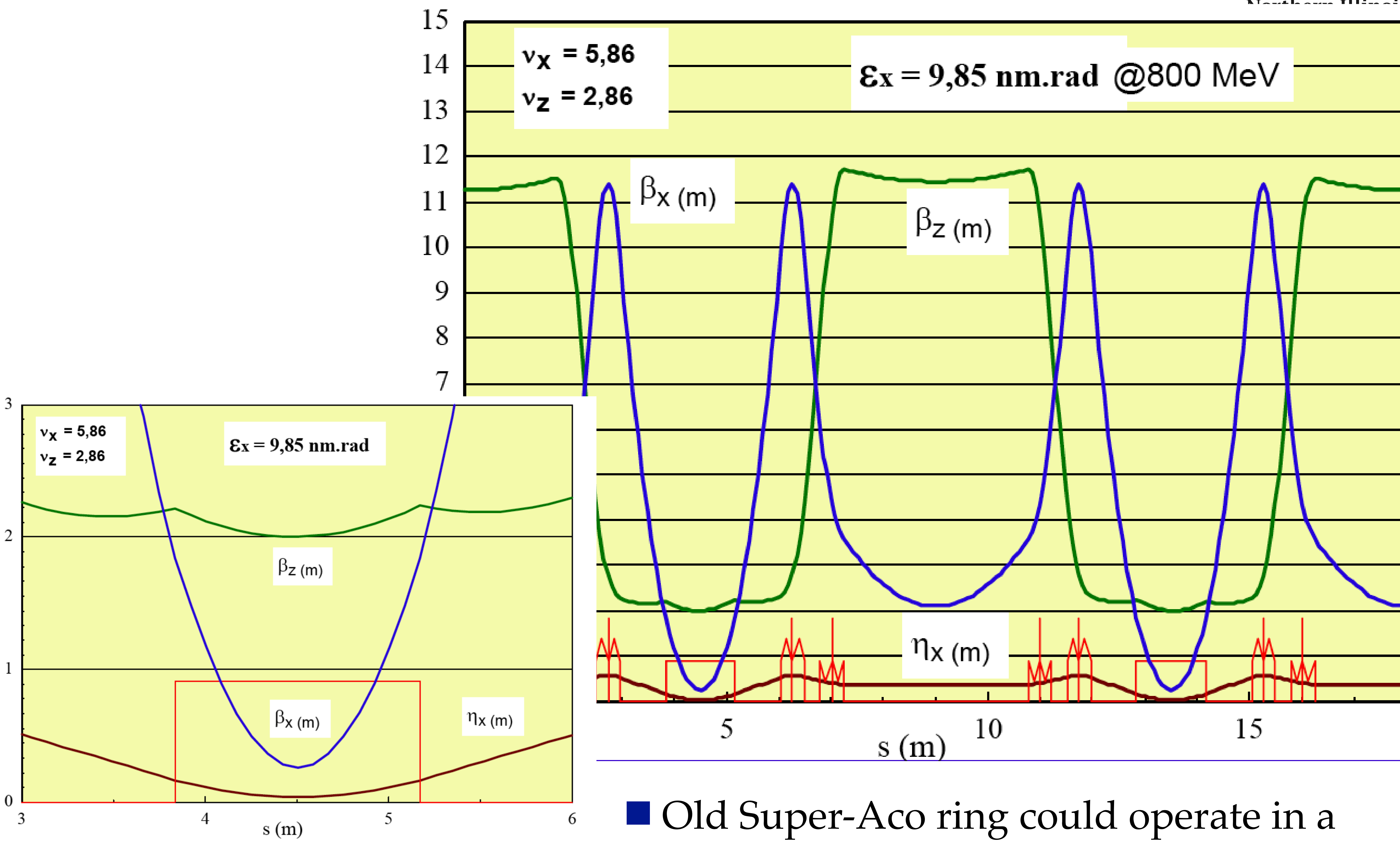
Expanded DBA II



- Original lattice of ESRF storage ring, with 4 quadrupoles in between the bends
- Alternating moderate and low beta in insertions

Courtesy Y. Papaphilippou

Theoretical minimum emittance optics

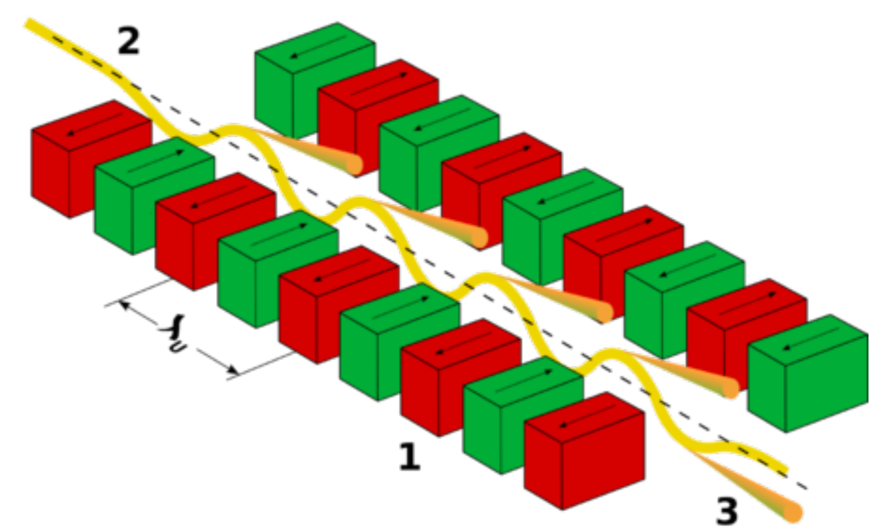


Courtesy Y. Papaphilippou

- Old Super-Aco ring could operate in a theoretical minimum emittance optics
- Structure mostly used in damping rings

Synchrotron Radiation Insertion Devices

- Radiation from a bending magnet is "incoherent"
  - i.e., each particle radiates independently from any other; can happen anywhere along the path of the magnet
- Using "wiggler" magnets, or undulators, with *N* very short periods, the power will go up ~ N^2 compared to bending dipole
- Undulator Strength Parameter:



$$K = \frac{eB\lambda_u}{2\pi mc}$$

  - K << 1: small oscillations, and gives narrow energy bands
  - K >> 1: large oscillations ("wiggler") and broad energy band

Free Electron Laser

- Use of higher-energy electron beams in undulator arrangement (*K* <<1)
- If the SR is very strong (sometimes augmented by a laser beam), transverse electric field of the radiation interacts with the transverse electron current created by the sinusoidal wiggling motion
  - causes some electrons to gain and others to lose energy to the optical field, creating *micro-bunching*
  - this creates much more *coherent* radiation — many orders of magnitude stronger radiation than usual undulator

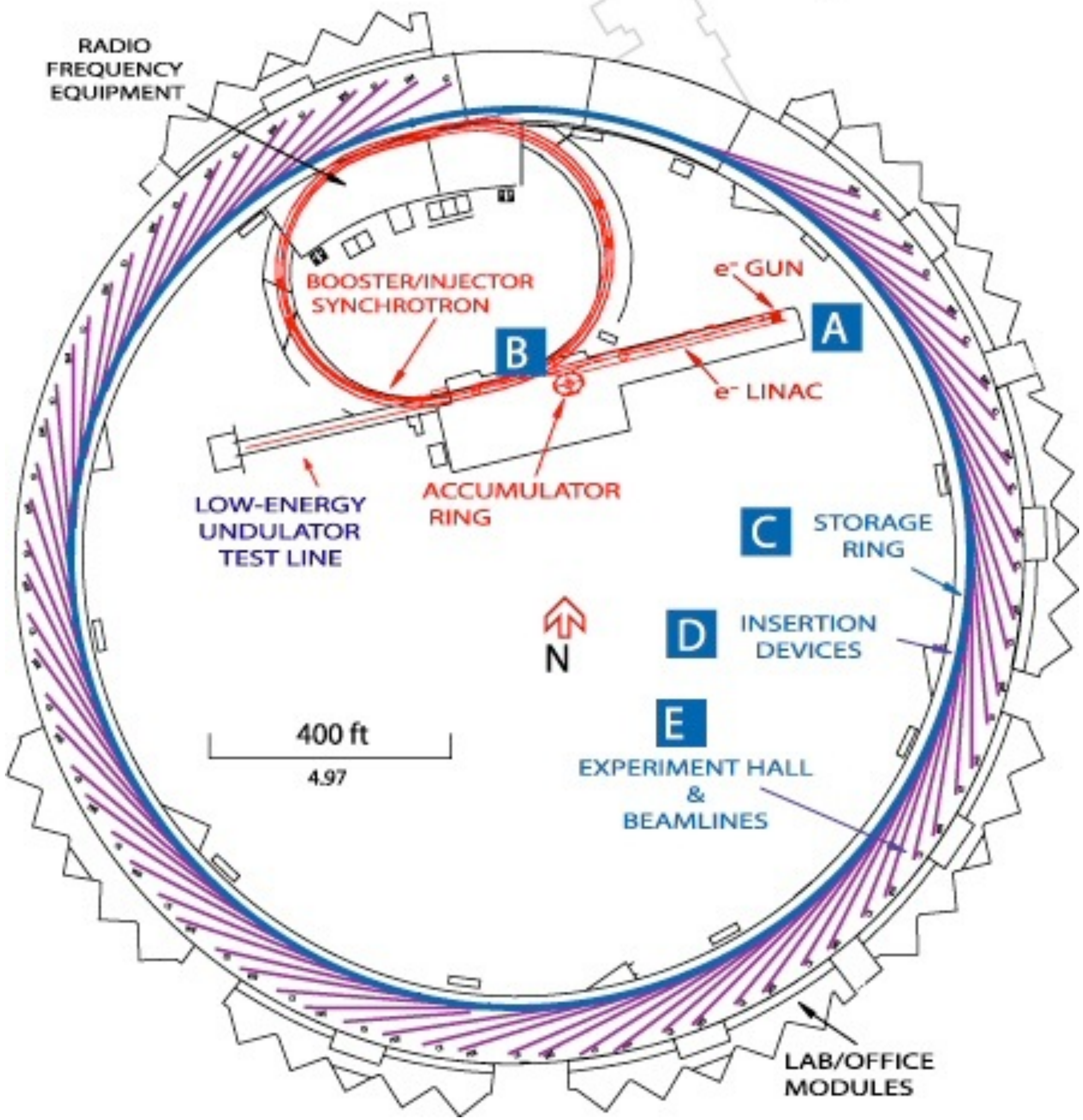
$$\lambda_{rad} = \frac{\lambda_u}{2\gamma^2}(1 + K^2)$$

ex: 1 cm undulator period can produce 1 nm X-rays, for γ ~ 2000

Advanced Photon Source (APS) -- Argonne National Laboratory

Northern Illinois University

The Advanced Photon Source



Undulator at the APS

LHC?   FCC??

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