Lecture 6:

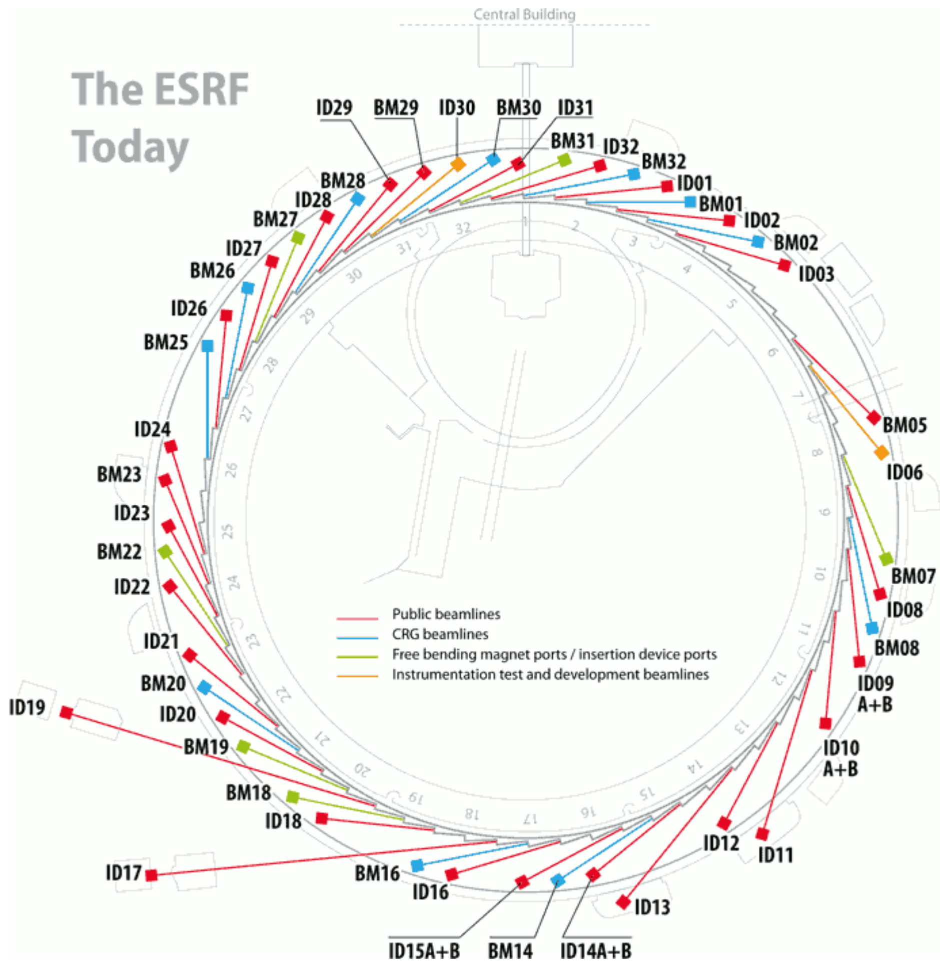
Cell Design

Yunhai Cai
SLAC National Accelerator Laboratory

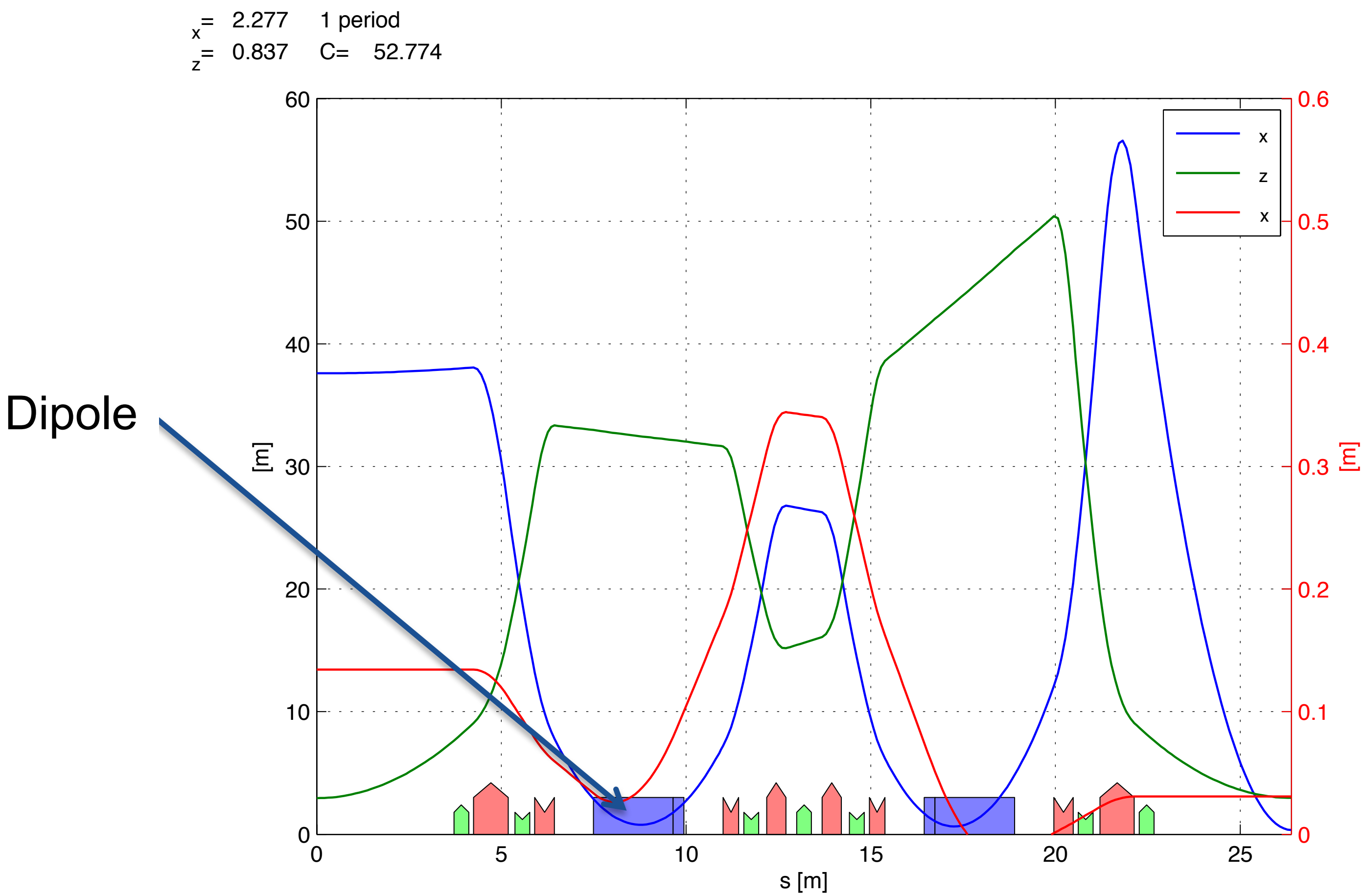
June 13, 2017

USPAS June 2017, Lisle, IL, USA

ESRF at 6 GeV, 32 Cells



ESRF DBA Cell



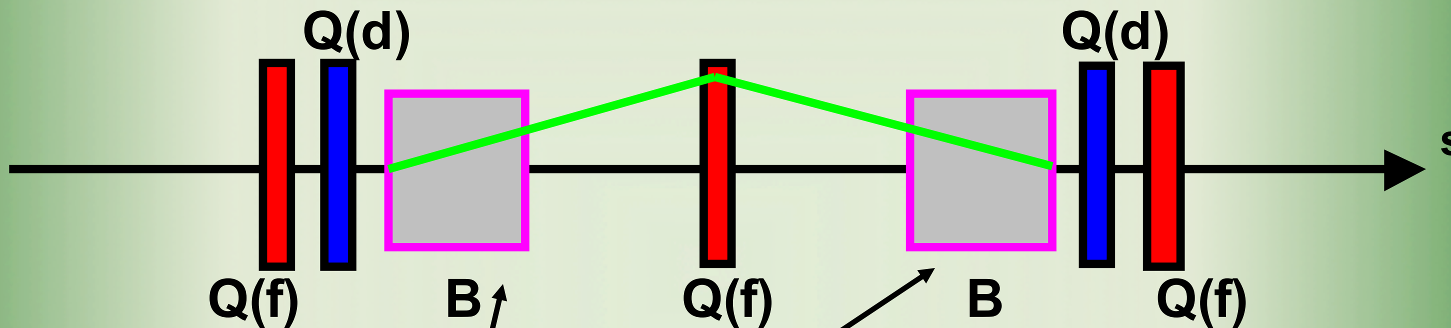
Courtesy of Raimondi

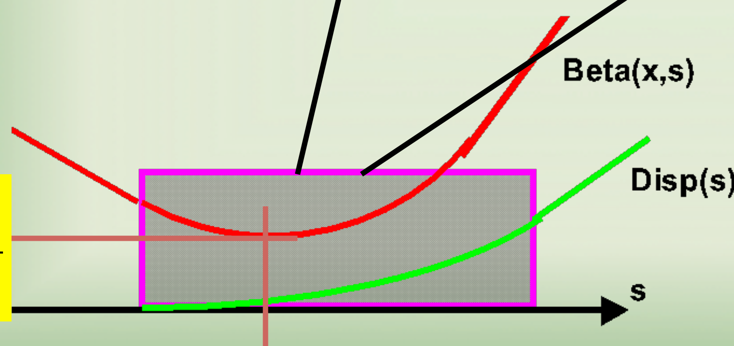
Comments

- Dispersions at the undulator positions are not zero
  - Smaler at lower horizontal beta
- There are dispersions at all positions of sextupole so that local chromatic correction is possible
- Dispersion and horizontal beta are minimized at dipole positions

DBA - Structure

DBA -Lattice





$$\beta_{\min} = L_{mag} \cdot \frac{\sqrt{3}}{8\sqrt{5}}$$

$$s^* = \frac{3}{8} L$$

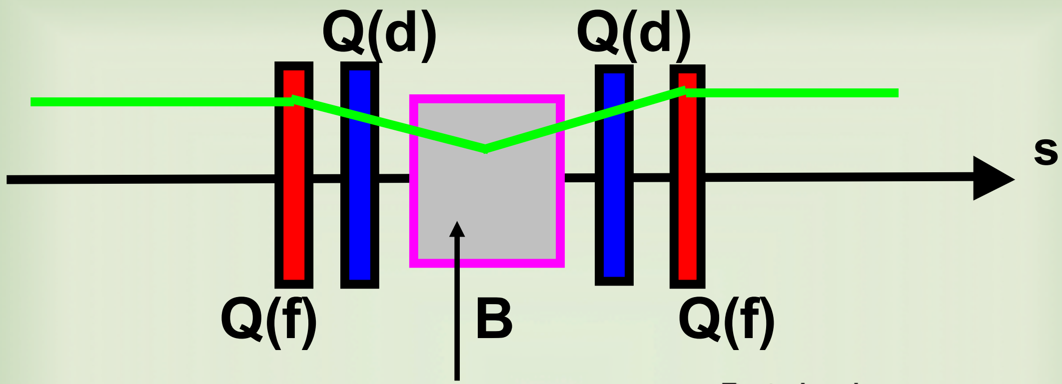
With β_{min} and s* the emittance for the DBA-lattice is:

$$\varepsilon_x = C_q \cdot \gamma^2 \cdot \frac{1}{J_x} \cdot \frac{1}{4\sqrt{15}} \cdot \varphi^3$$

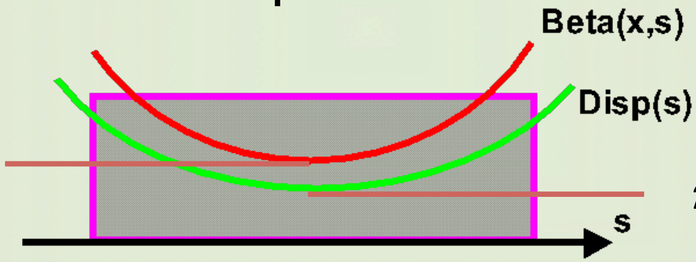
In reality however it is a factor 3 to 4 higher.

TME - Structure

TME –Lattice gives the smallest emittance



$$\beta_{\min} = \frac{L}{2\sqrt{15}}$$



$$\eta_{\min} = \frac{L^2}{24\rho_0}$$

$$\varepsilon_x = C_q \cdot \gamma^2 \cdot \frac{1}{J_x} \cdot \frac{1}{3} \cdot \frac{1}{4\sqrt{15}} \cdot \varphi^3$$

The emittance is by a factor of 3 smaller as for the DBA structure

Introduction to Lattice Design

$$\varepsilon_{horizontal} = \frac{55}{32\sqrt{3}} * \frac{\hbar}{mc} * \gamma^2 * \frac{\langle \frac{1}{\rho^3} H(s) \rangle}{J_x \langle \frac{1}{\rho^2} \rangle}$$

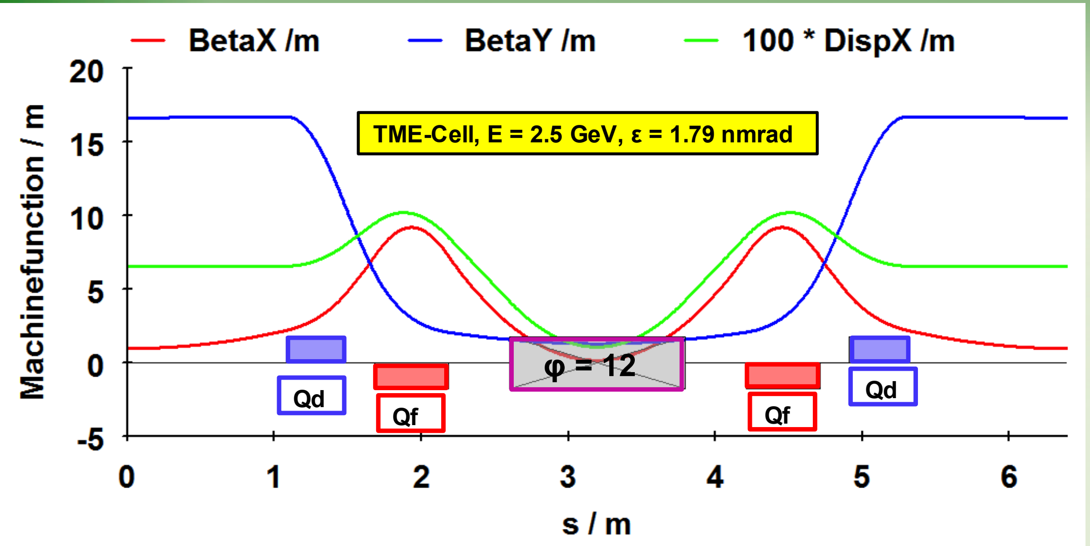
Cq=1.47*10-6 [m/(GeV^2]

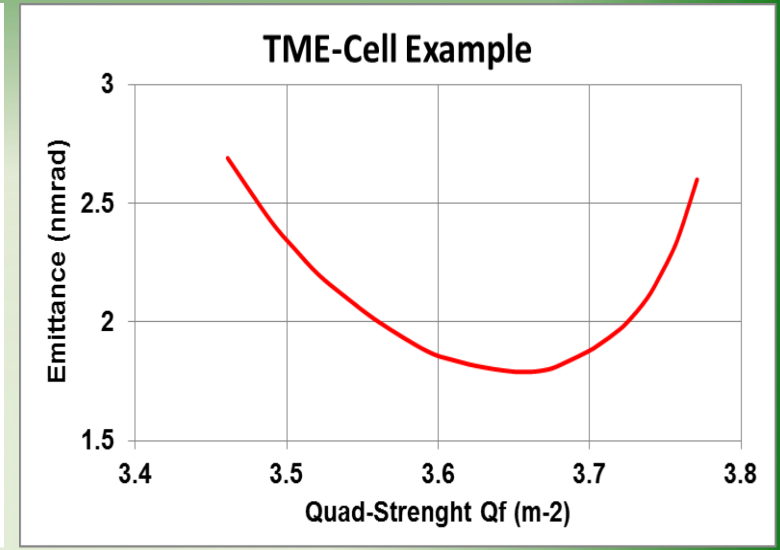
$$H = \beta\eta'\uparrow 2 + 2\alpha\eta\eta' + \gamma\eta\uparrow 2$$

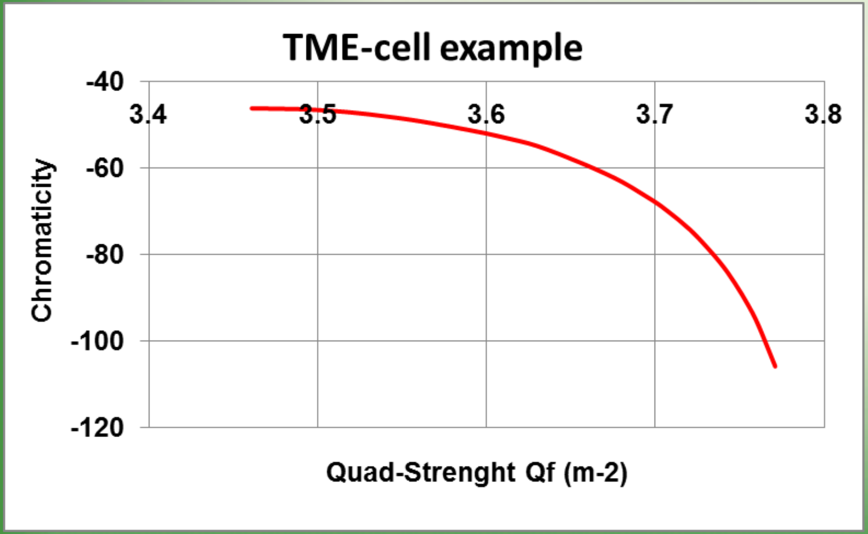
$$\varepsilon_{hor}(nmrad) = 1470 * \frac{(E/GeV)^2}{J_x} * \frac{\Phi^3}{12*\sqrt{15}} * F$$

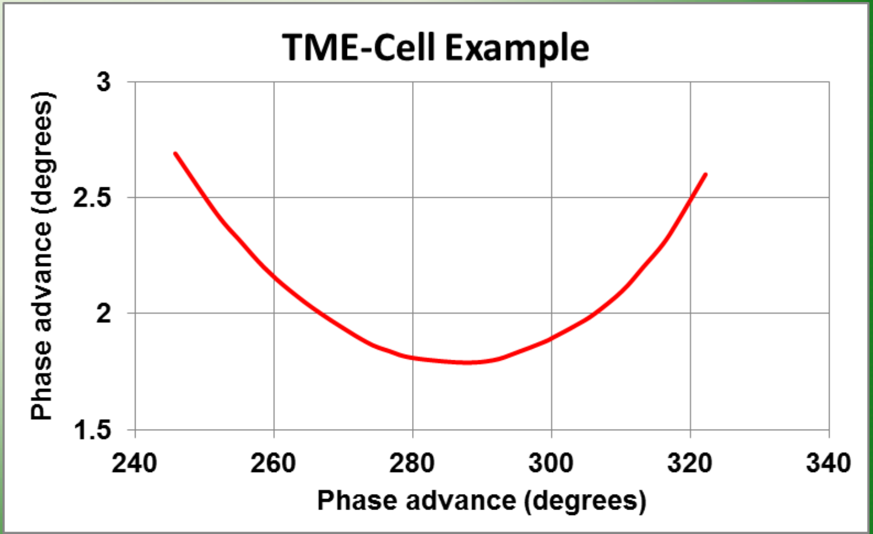
$$\varepsilon_{hor}(nmrad) = 31.63 * \frac{(E/GeV)^2}{J_x} * \frac{\Phi^3}{1} * F$$

Longitudinal Bending Gradient

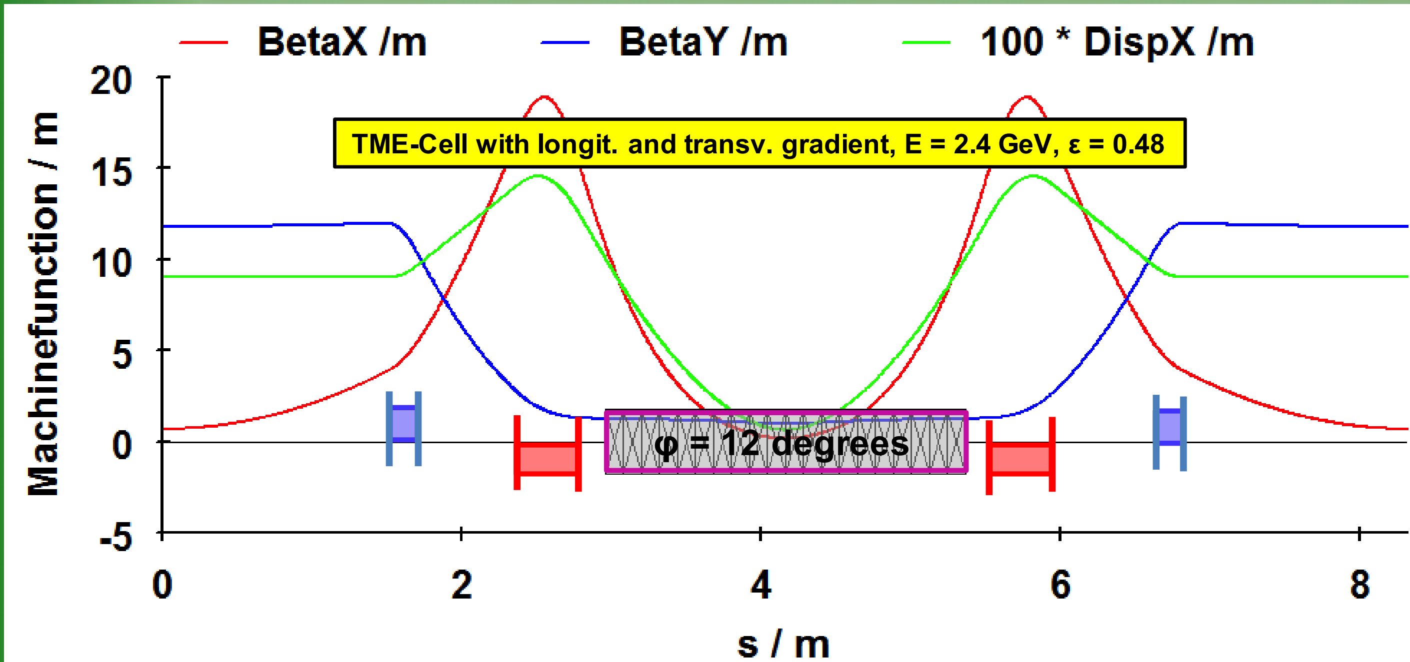


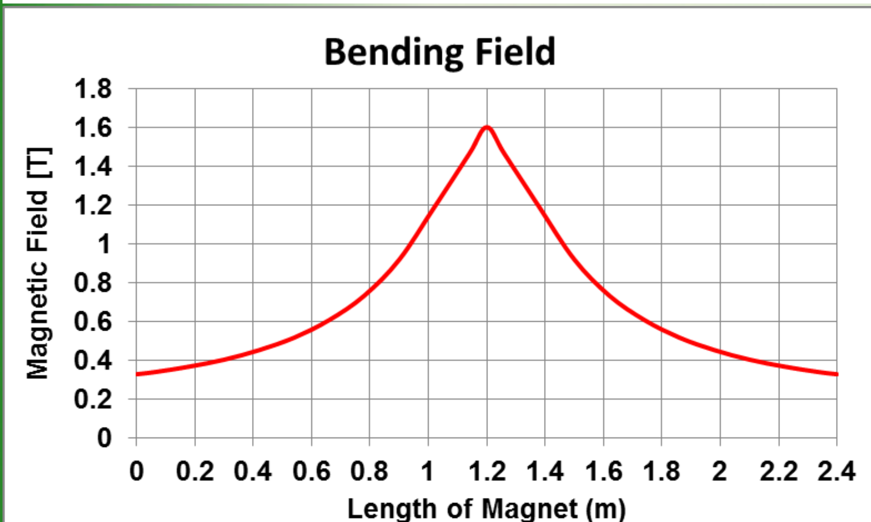


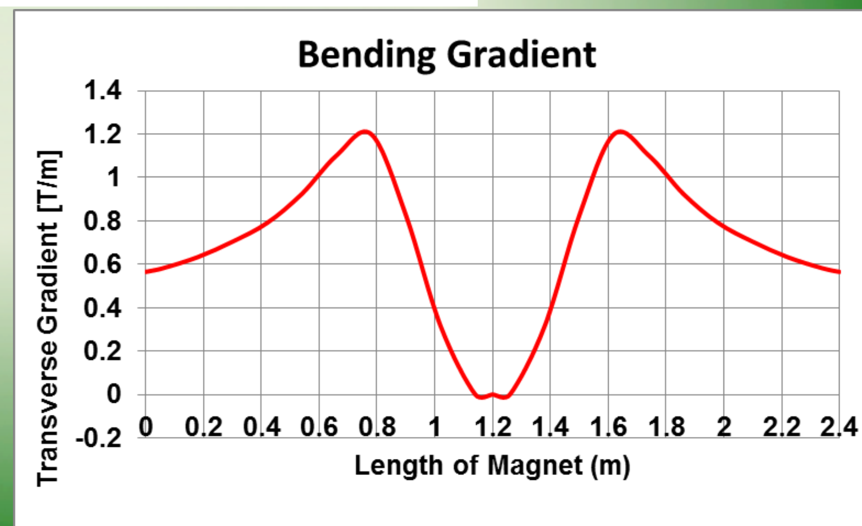




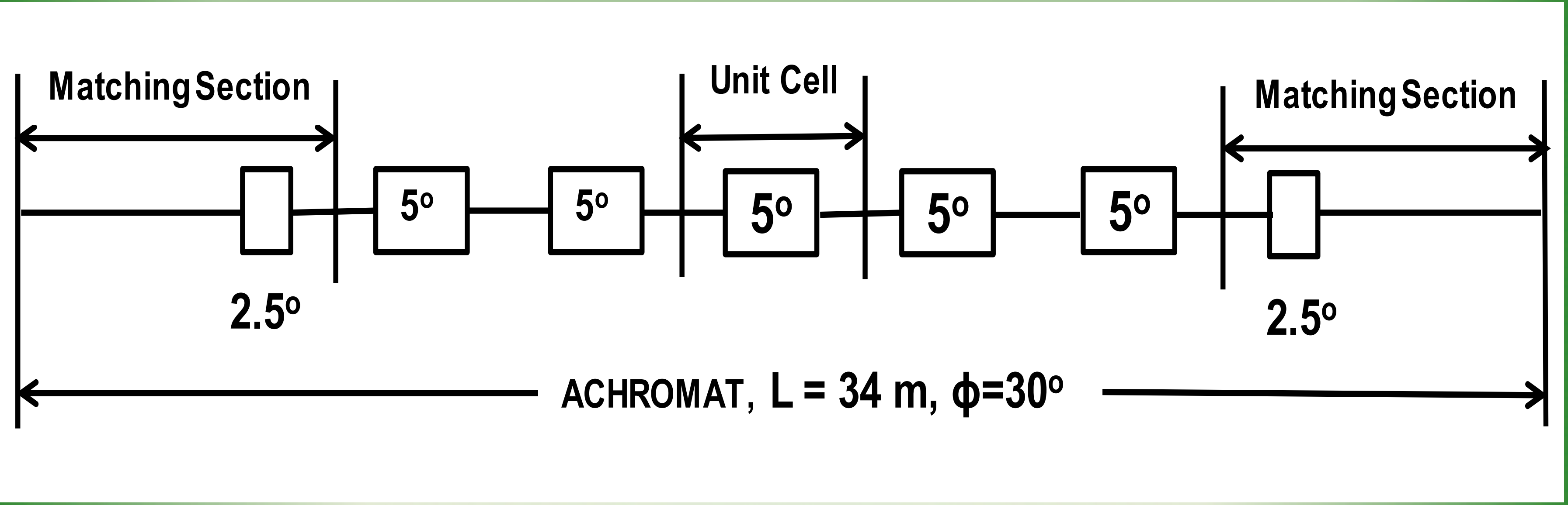
Longitudinal Bending Gradient





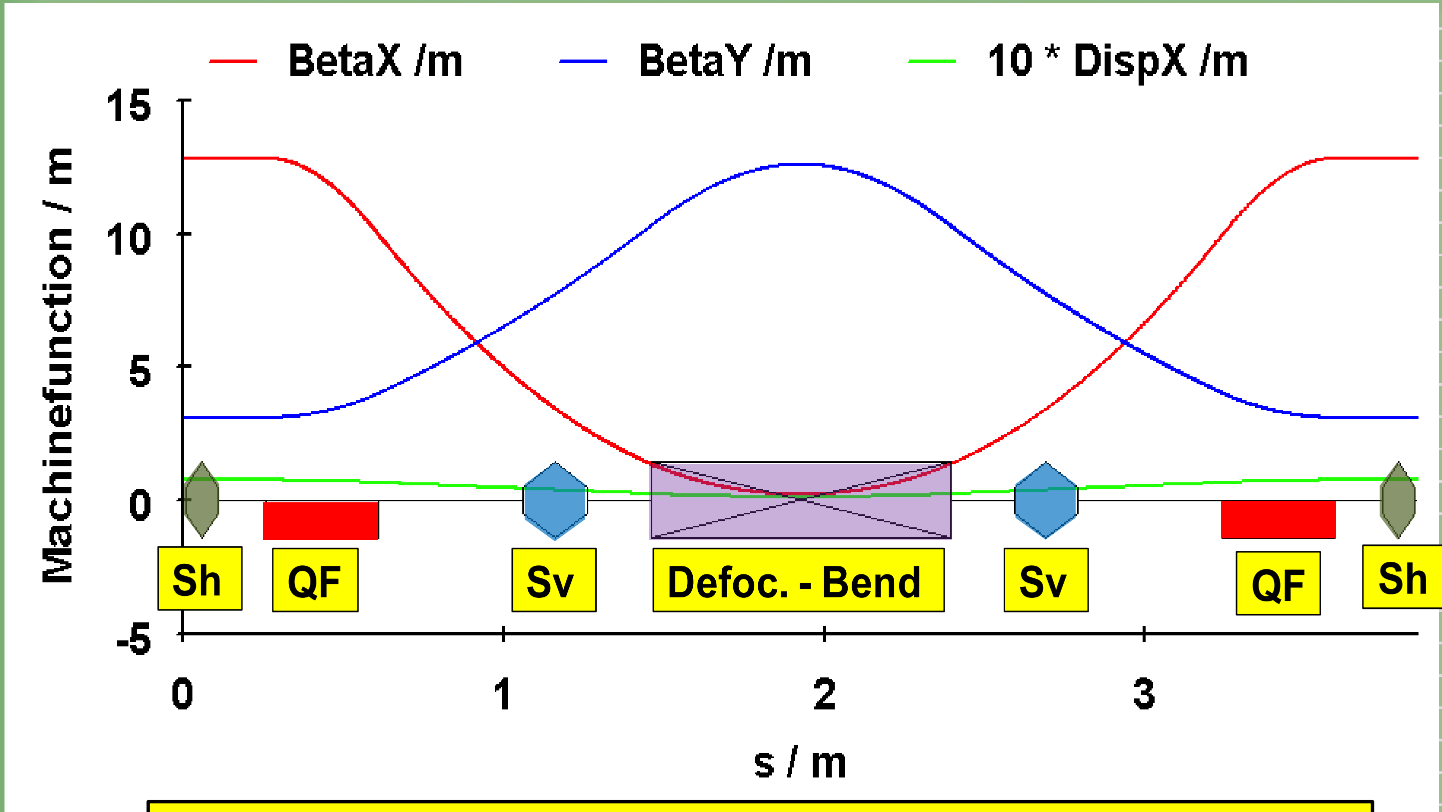


Towards a Diffraction Limited Light Source



The layout for the diffraction limited light source utilizing the MBA structure. The bending magnets in the unit cell with a deflection of 5 degrees and the matching section with an angle of 2.5 degrees. The lattices got the acronym DIFL

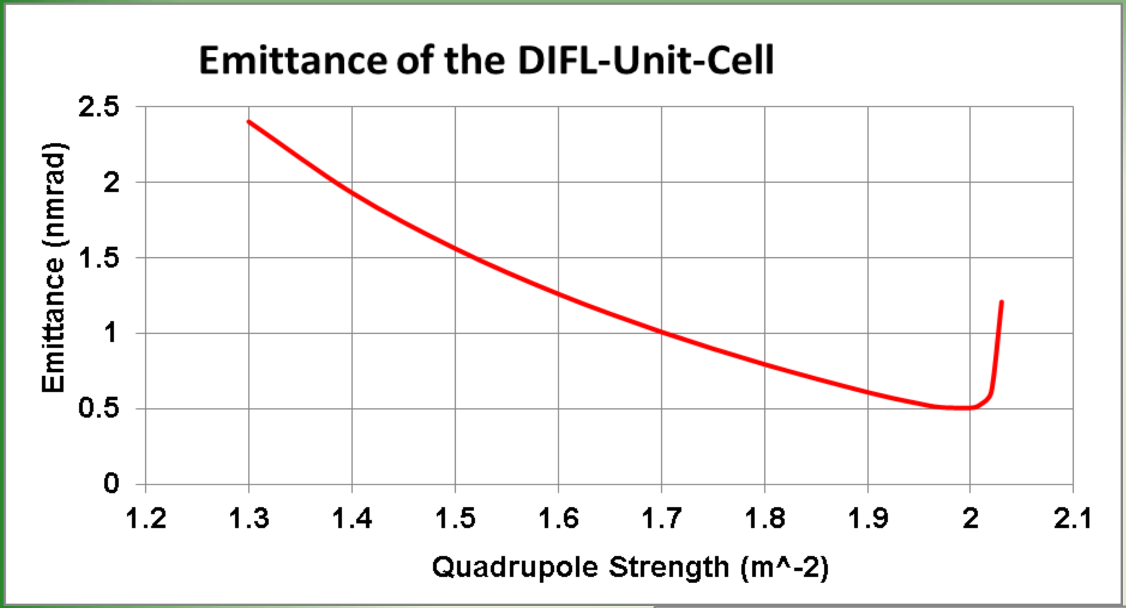
Unit Cell of DIFL-Lattice



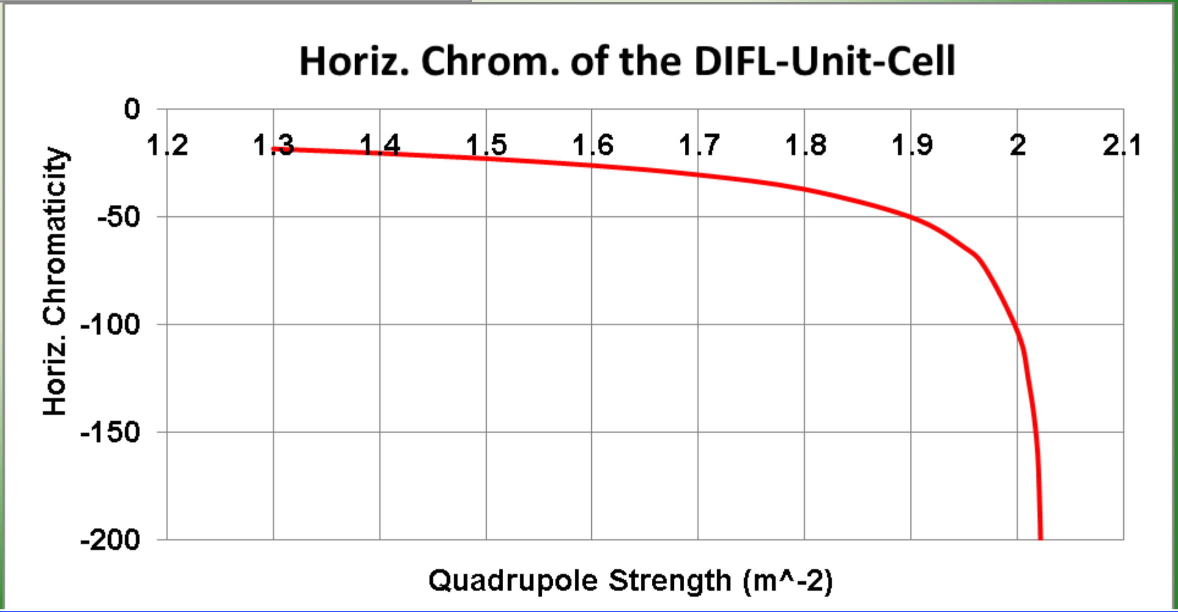
TME Structure, E = 3.0 GeV, ε = 0.5 nmrad, φ = 5 degr.

The arrangements of the magnets within a unit cell of the multi bend Achromat and the corresponding machine functions. The parameters of the magnets are: Bending: L=0.931482 m, ρ=10.674 m, B = 0.93749 T, k=-0.900 m^{-2} ; QF: L =0.35 m, k=1.992 m^{-2}, g=19.92 T/m, g*L = 6.972 T; Sh:L= 0.1 m, m=53.347m^{-3}, ΣSh*L=5.335 m^{-2} ; Sv: L=0.2 m, m = -42.730 m^{-3}, ΣSv*L=8.546 m^{-2}

Characteristics of Unit Cell

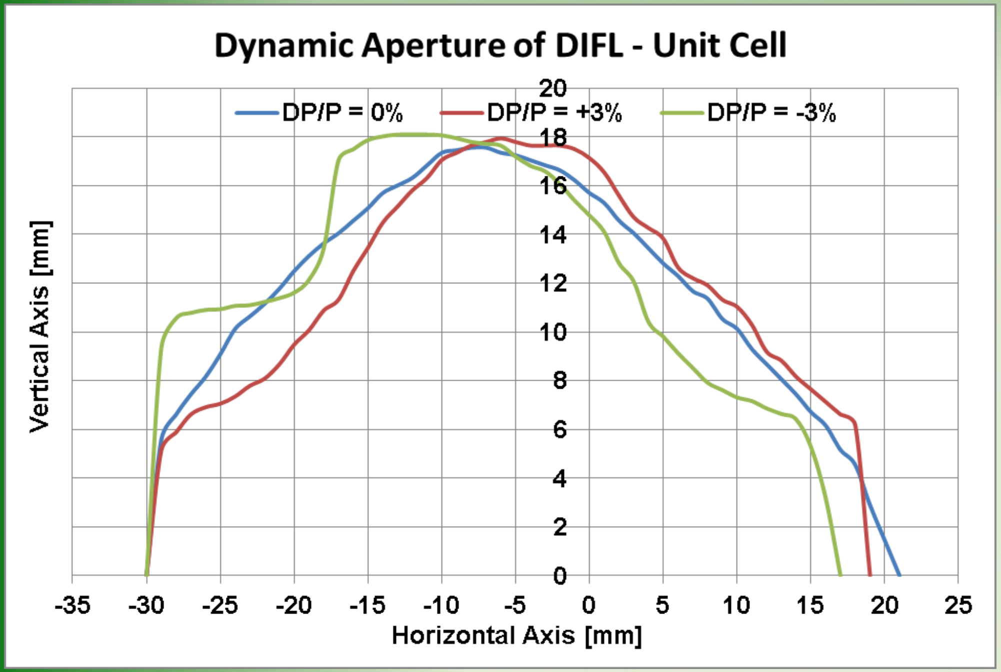


Emittance of the unit cell as a function of the strength of the focusing quadrupole.

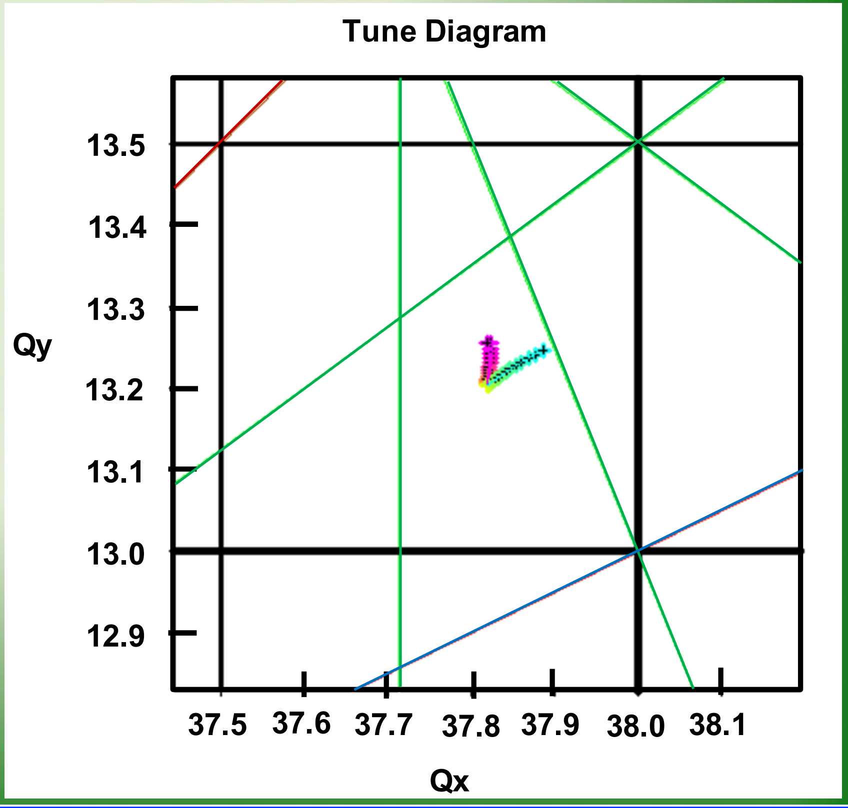


Horizontal chromaticity of the unit cell of the lattice DIFL

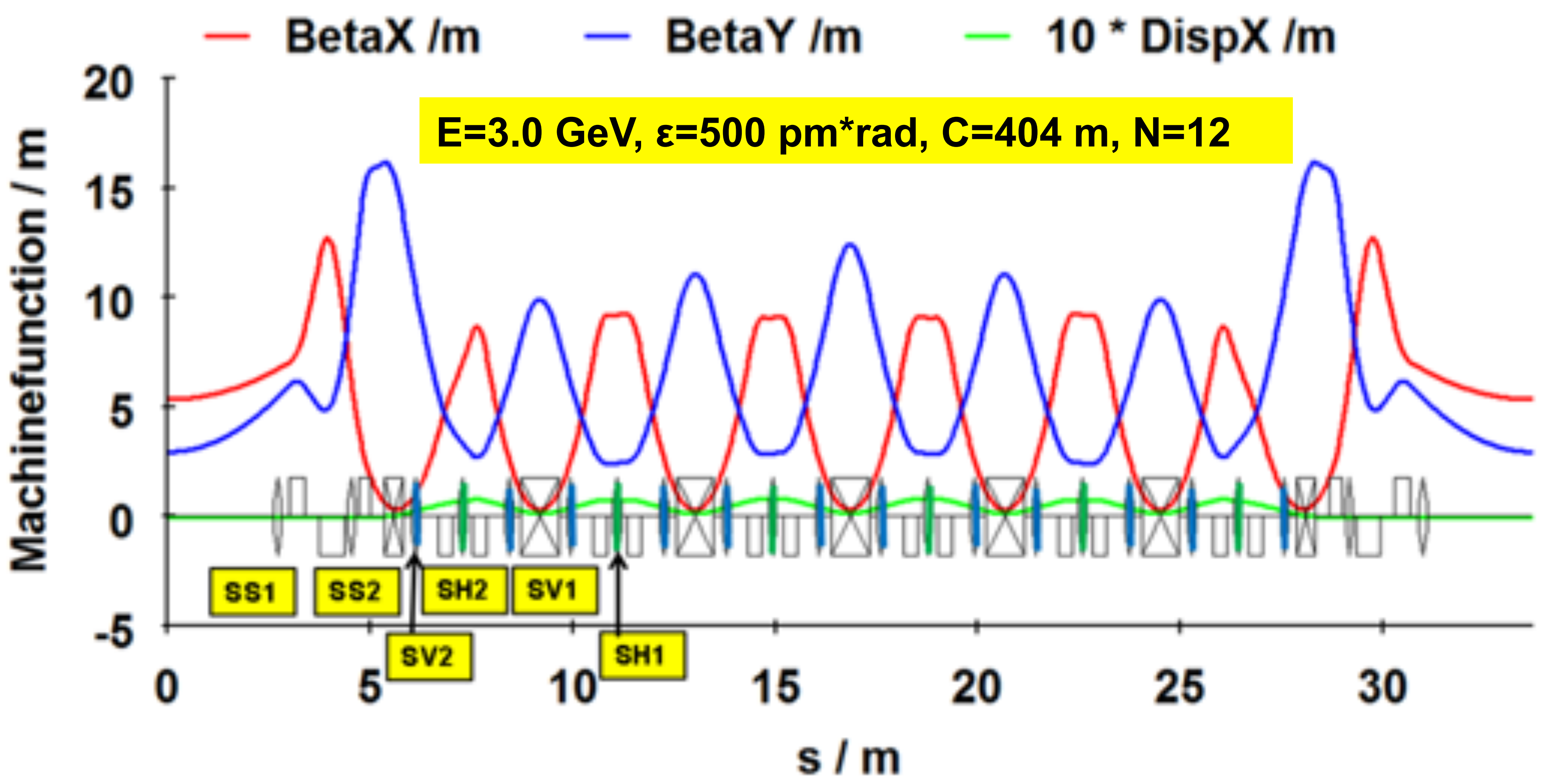
Characteristics of Unit Cell



Dynamic aperture of the unit cell for the energy deviations of Δp/p = -3% (green line), Δp/p = 0% (blue line), Δp/p = 3% (red line).

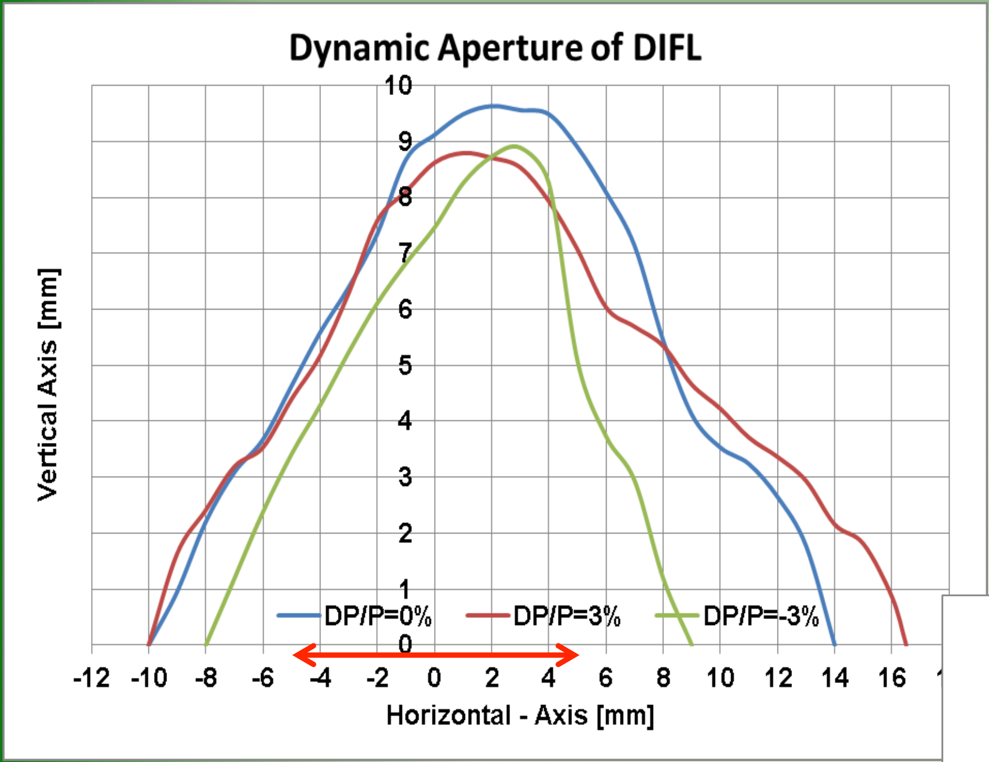


Lattice of DIFL (7BA)



Machine function of the chosen lattice DIFL for the proposed diffraction limited light source

Characteristics of DIFL

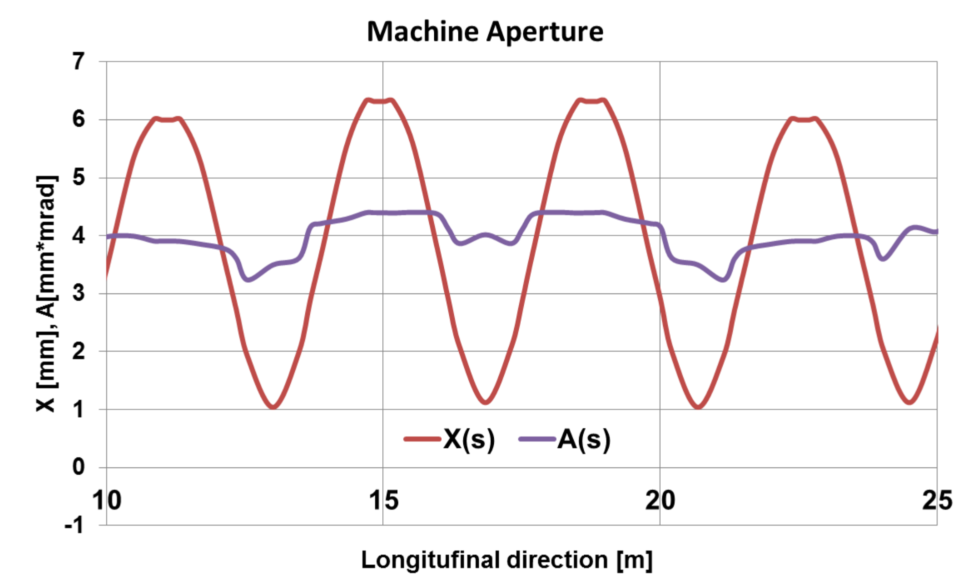


Dynamic aperture of lattice DIFL for the energy deviations of Δp/p = -3% (red line), Δp/p = 0% (black line), Δp/p = 3% (blue line).

X(s)=2*1.33*η(s)*(ΔE/E)

A(s)=(X(s)^2)/ β(s), (ΔE/E)=3%

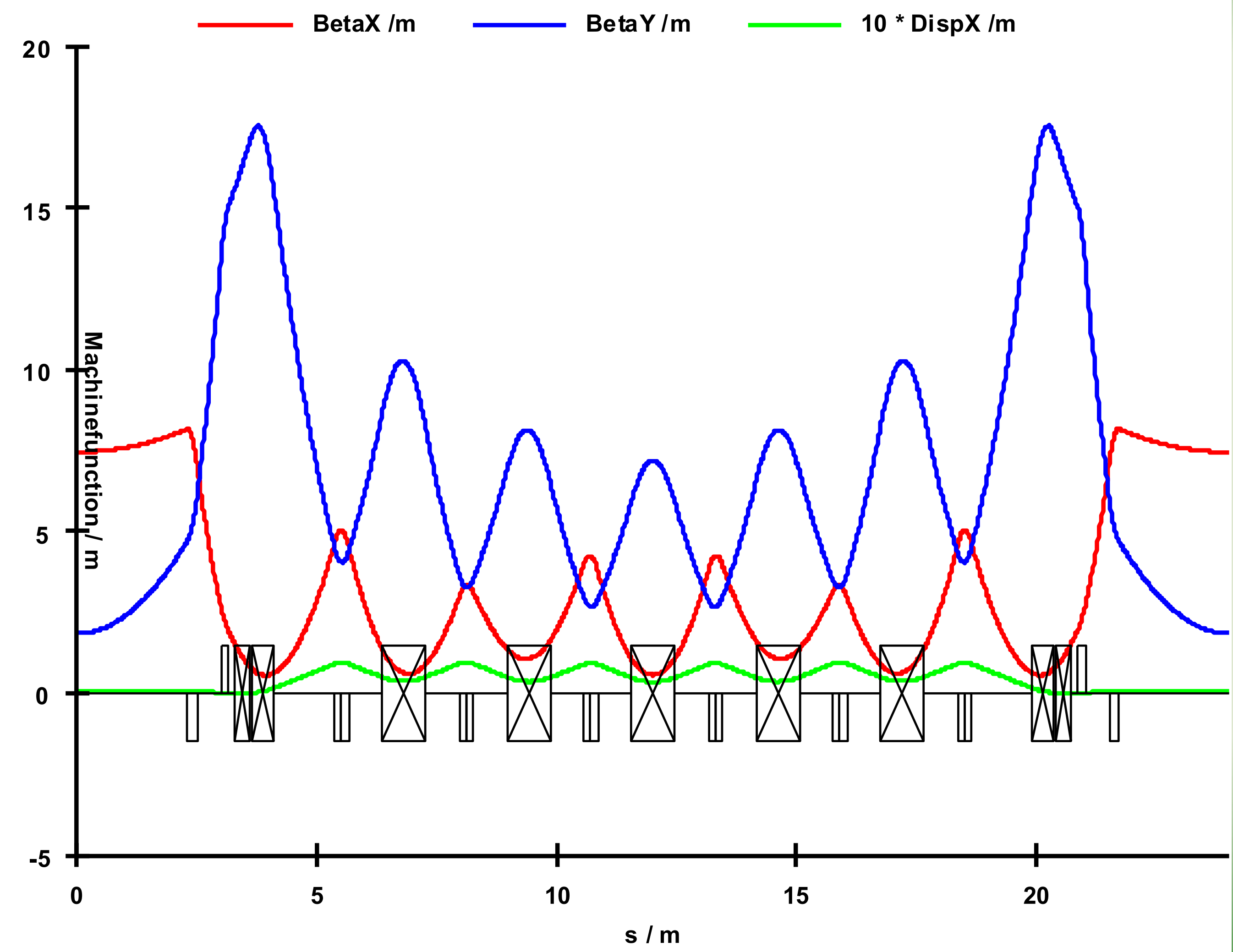
A=5 mm*mrad, β(s=0)=5.2 m/rad
⇉ E(0)= +/- 5.2 mm



Summary (1995)

1995:According to this investigation it should be possible to build Synchrotron Light Sources with an reduction of the emittance by a factor of 10 in comparison to the existing machines.

First proposal of MAX IV (2003)



Parameters:

E = 3.0 GeV

C = 287.2 m

N = 12 fold

φ = 4.67 degr.

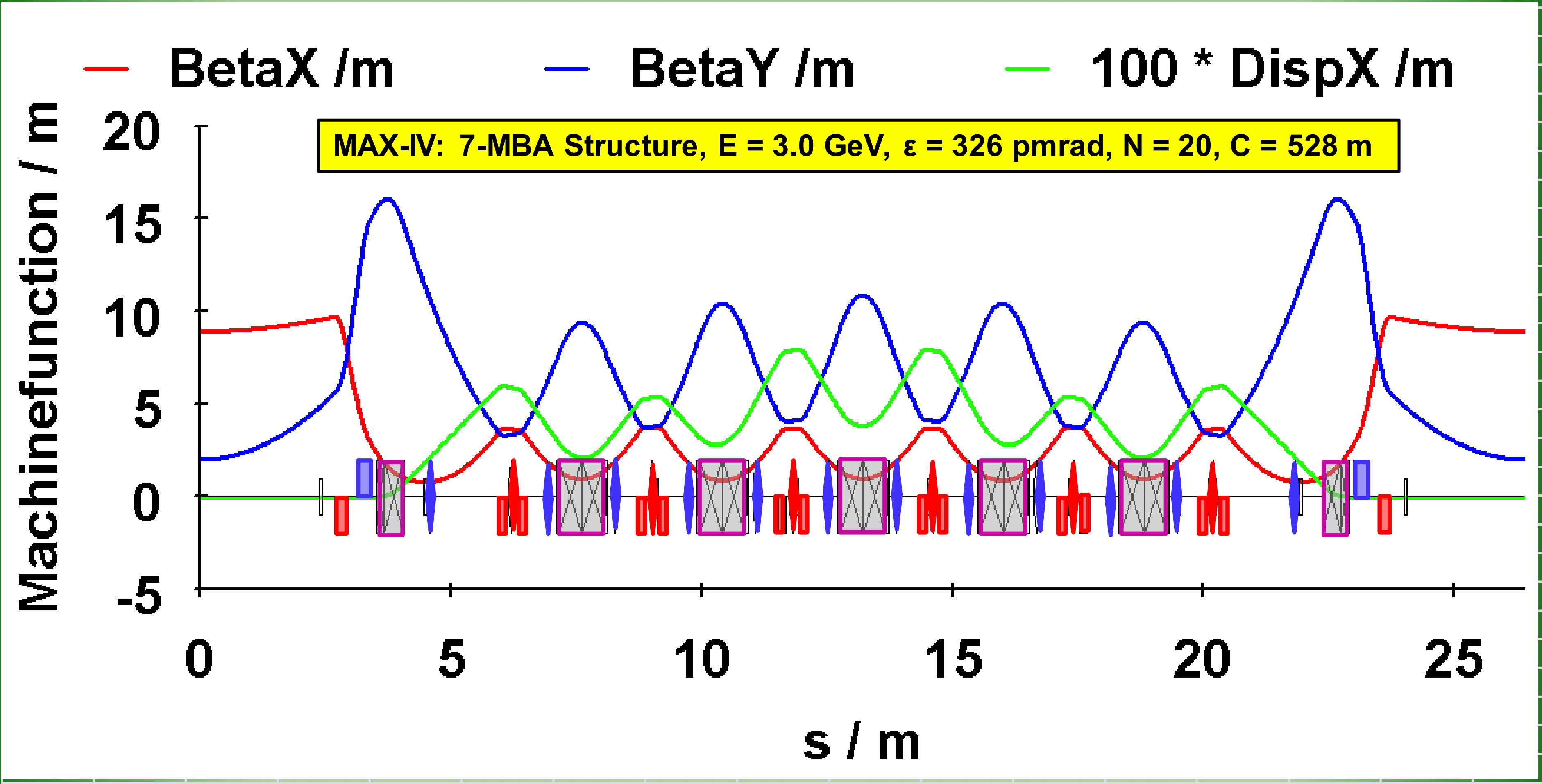
ε_x = 1.2 nmrad

l = 4.6 m

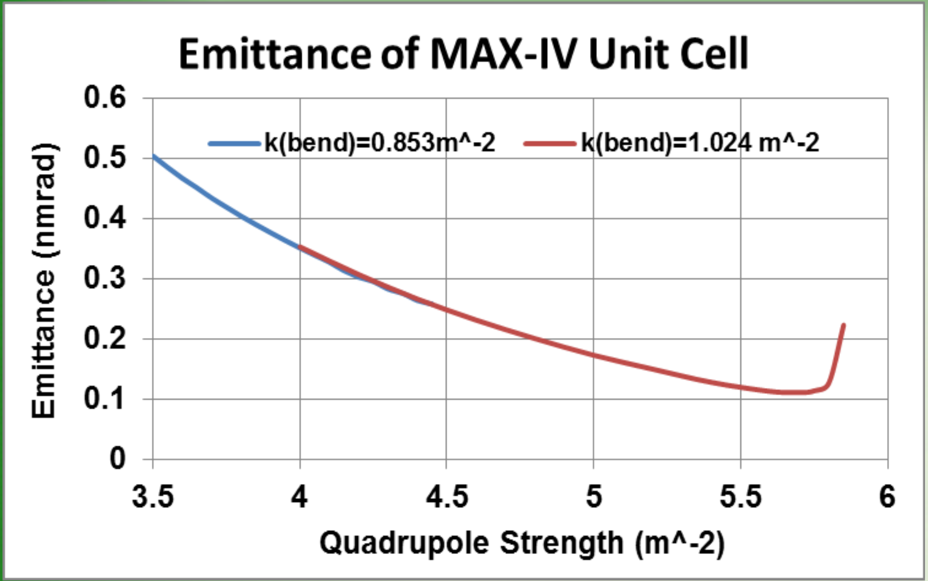
β_x = 7.6 m/rad

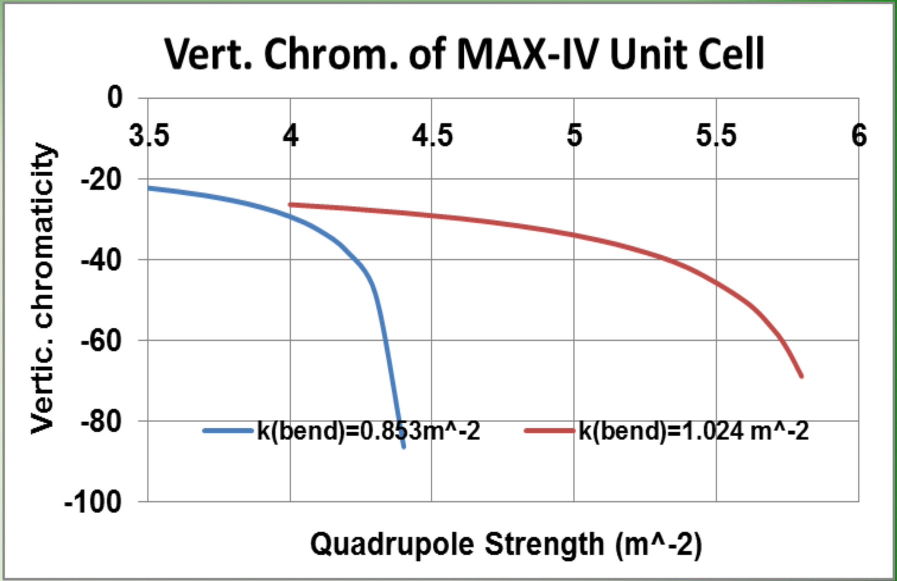
β_y = 1.7 m/rad

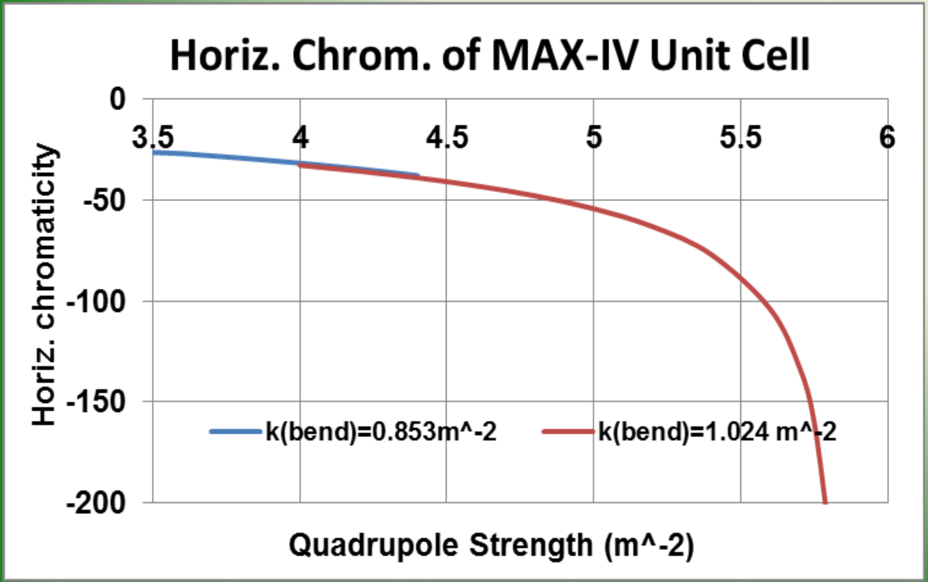
Layout of MAX IV (2014)

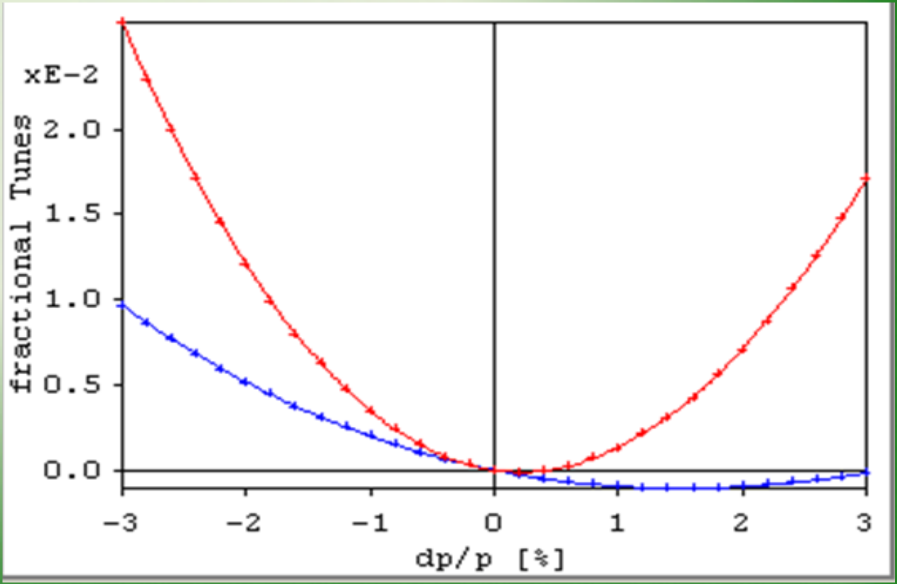


Layout of MAX IV (2014)





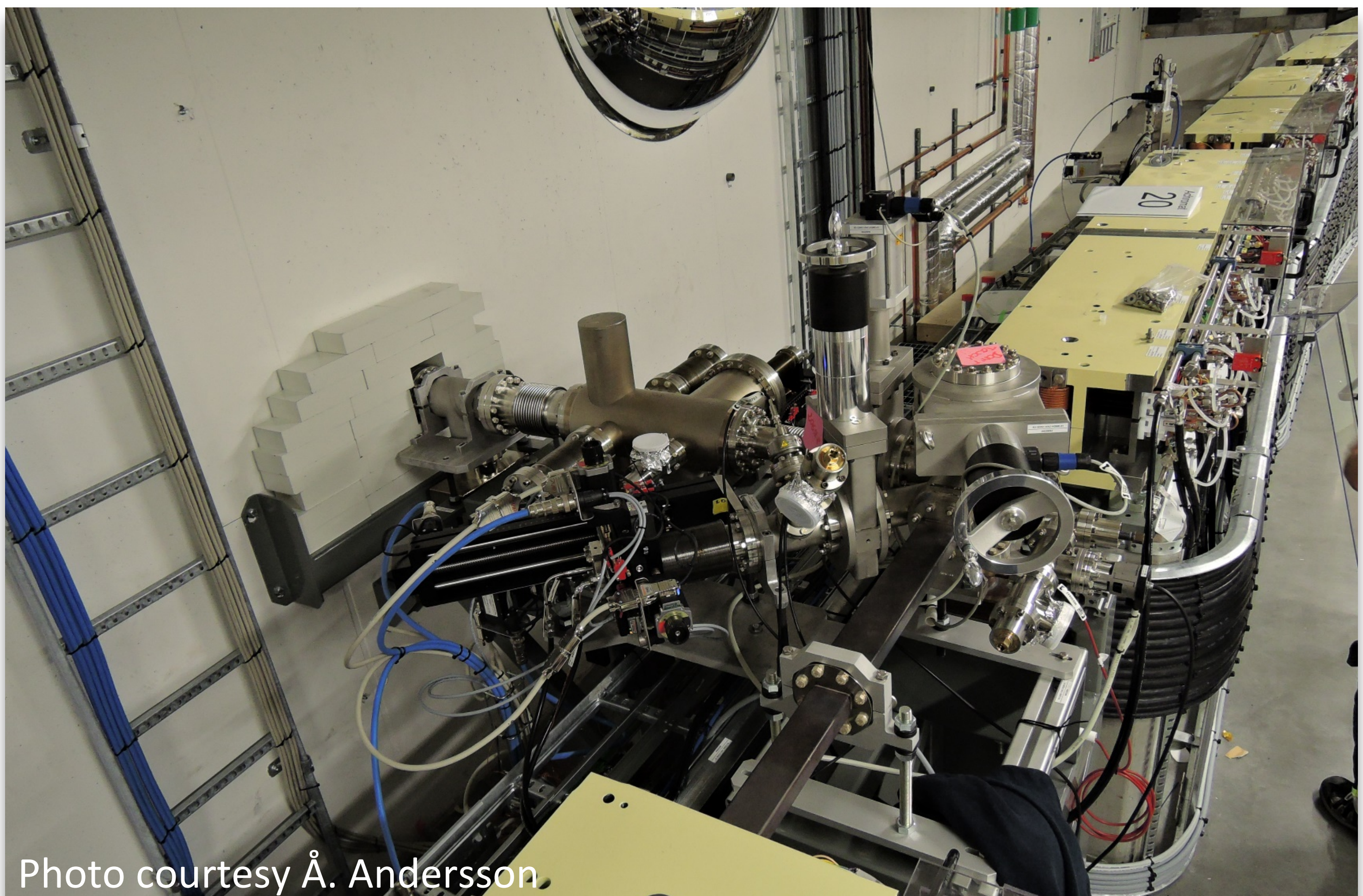


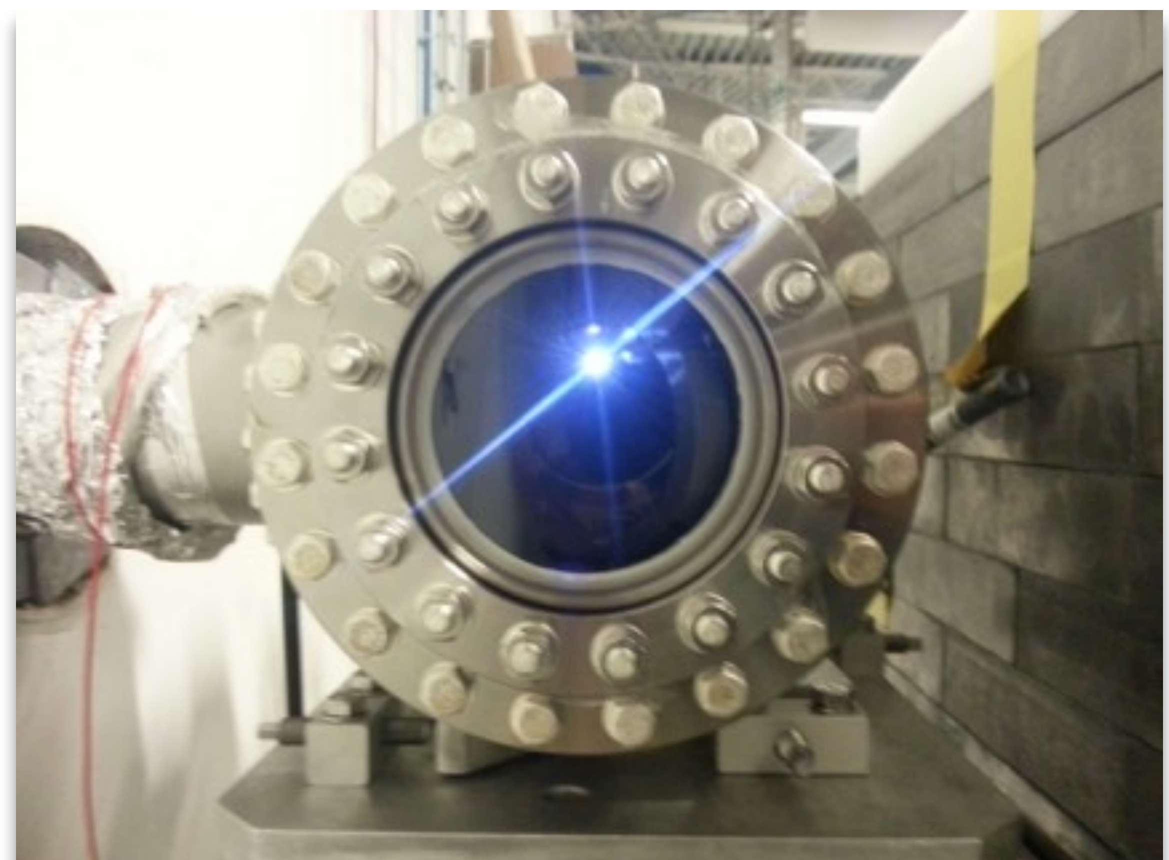


3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

IPAC'**16**, WEPOW034

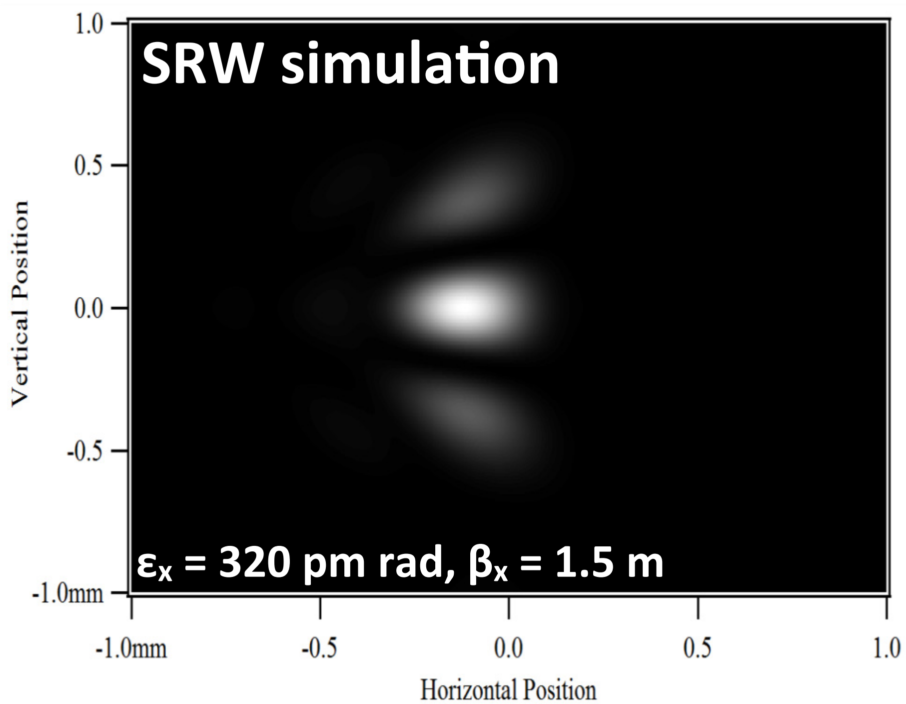


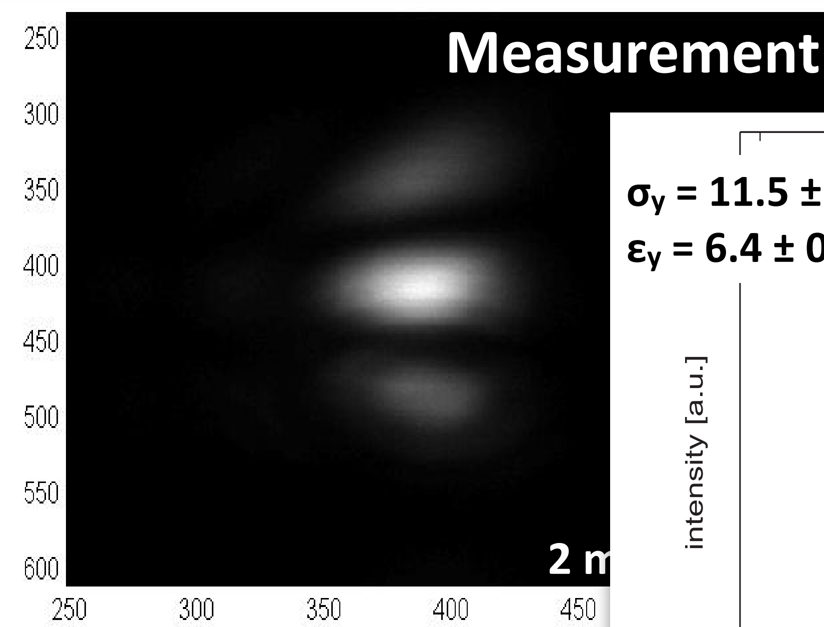


3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

IPAC'**16**, WEPOW034





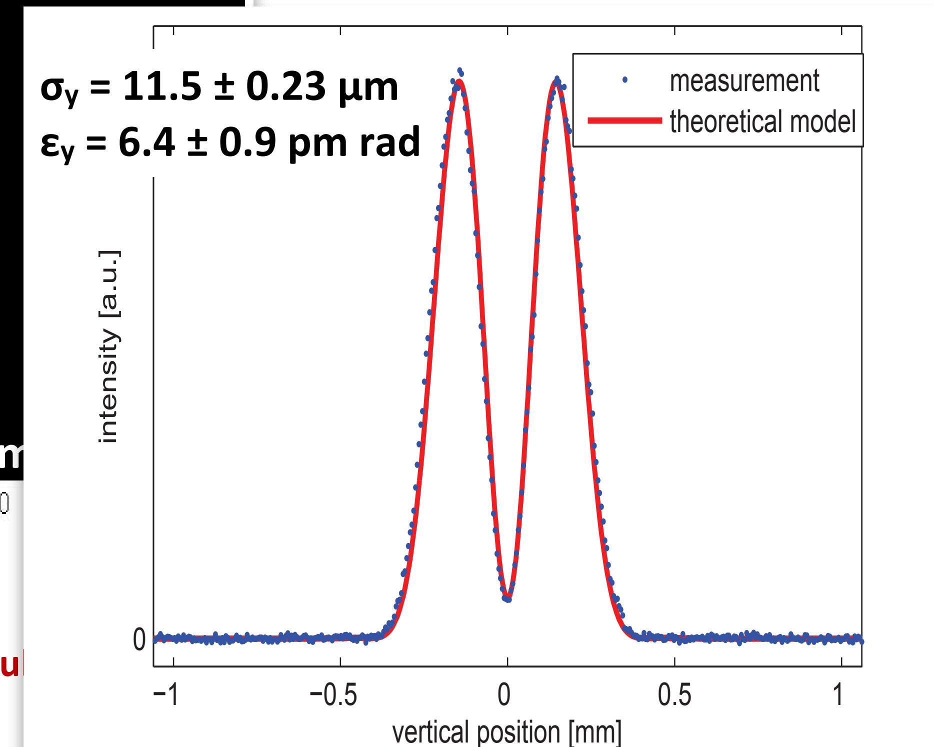


Figure 3: Vertical profile of imaged π-polarized SR at 488 nm wavelength. Measurement (blue dots) and SRW calculation (red lines). The vertical beam size is 11.5 µm.

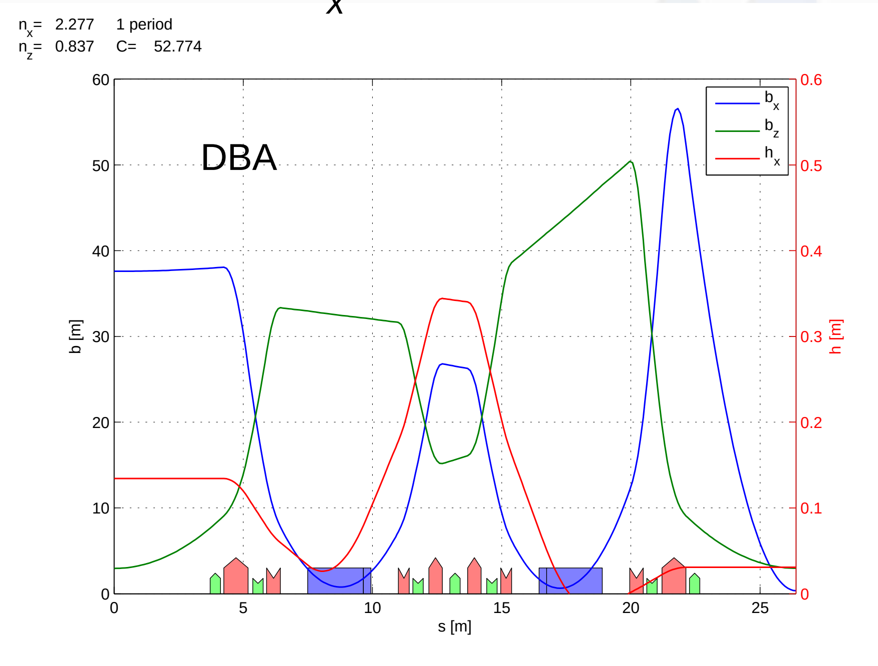
Sigma polarized SR, 632.8 nm, SRW calculation (left) and measured image (right). The simu[…]
done for ε_x = 320 pm rad, β_y = 1.5 m.
Both figures show a 2 x 2 mm^2 area of the image plane.
The fringe pattern is too weak to be visible.

Optical magnification of m=-2.28 is taken into account in the SRW model
Horizontal opening angle: 6 mrad
Vertical opening angle: 8 mrad
Exposure time: 2.9 ms

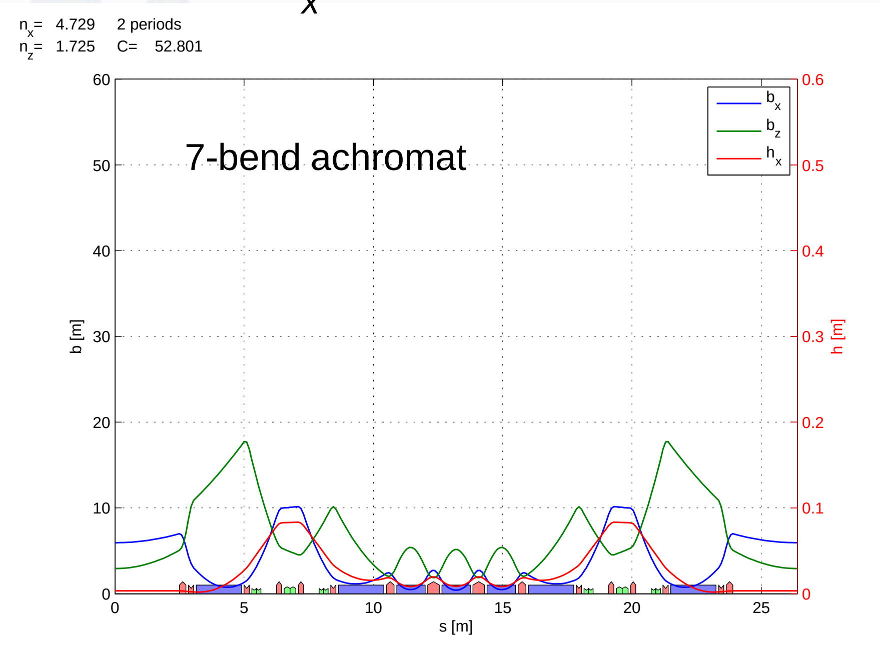
Courtesy J. Breunlin

New lattice

$\varepsilon_x = 4$ nm



$\varepsilon_x = 0.13$ nm

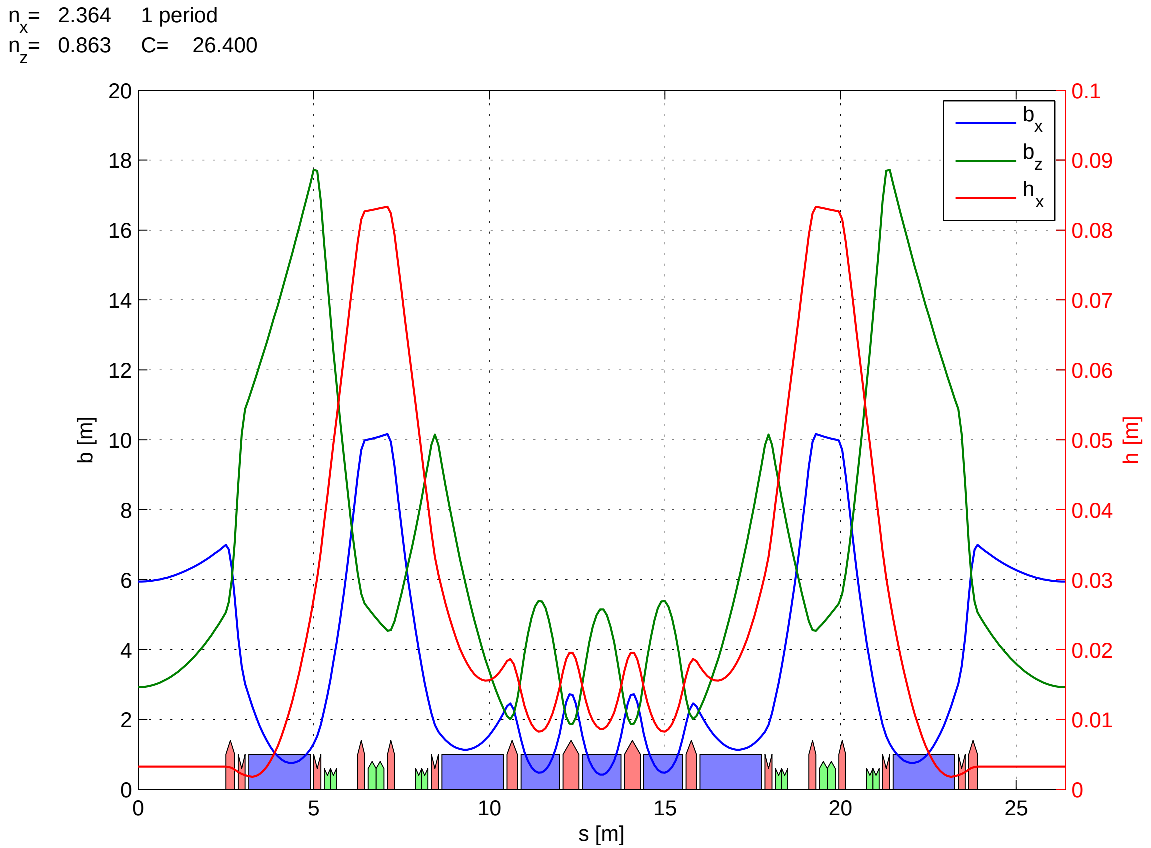


- Cell packed with magnets
- Stronger focusing: tunes 36.44/13.39 → 75.66/27.60
  - Chromaticity: -130/-58 → -102/-75
- Smaller β functions
- Smaller dispersion

} ⇒ { Chromaticity correction needs stronger sextupoles

- Less radiated power (x2 less)

New lattice



Preliminary features:

- 2 dipole families
  - 1 with gradient
- 7 quadrupole families
- 2 sextupole families
- ID straight:
  5 m long instead of
  7.84 m (in “6 m” section)
- No more alternating high- and low-β sections

Electron beam size [μm]		
ESRF		New
High-β	412	28
Low-β	50	

Electron beam divergence [μrad]		
ESRF		New
High-β	11	5
Low-β	107	

New Lattice

	ESRF	New lattice
Dipole [T]	0.86	0.49
Quadrupole [T/m]	17 (25)	112
Sextupole [T/m2]	460	1650

- Weak bending magnet with strong gradient
  - Equivalent to a quadrupole of 33 T/m offset by 1.5 cm
- Strong quadrupoles
- Strong sextupoles
- Dynamic aperture comparable (factor 1-3 smaller) with the present lattice
  - Chromatic correction made with “standard”sextupoles
  - **Total bend length more than doubled => energy lost in synchrotron radiation halved**

Summary

- We have seed how the lattices were evolved from DBA, TME to MBA, HMBA. There are many key innovations, among them,
  - Compact magnets
  - Stronger transverse gradient bends
  - Longitudinal gradient bends
  - “-I” paired chromatic sextupoles
  - Dispersion bumps
  - Harmonic sextupoles
  - Better chromatic corrections
  - Resonance mitigations and cancellations
- Lattice design is also an art. There is its intrinsic beauty.

References

1) M. Sommer, LAL Report No. LAL/RT/83-15, (1983).
2) L.C. Teng, “Minimizating the emittance in designing the lattice of an electron storage ring,” TM-1269, (1984).
3) D. Einfeld et al. “Design of a Diffraction Limited Light Source (DIFL),” PAC proceeding, (1996).
4) S.C. Leemann et al. “Beam dynamics and expected performance of Sweden’s new storage-ring source:MAX-IV,” PRSTAB, **12**, 120701 (2009).
5) D. Einfeld, “MBA designs,” talk at Low Emittance Workshop, Barcelona, Spain 2015.
6) P. Raimondi, “Emittance gymnastic studies,” ESRF, 2012.