Customization of beta functions for user experiments at the APS

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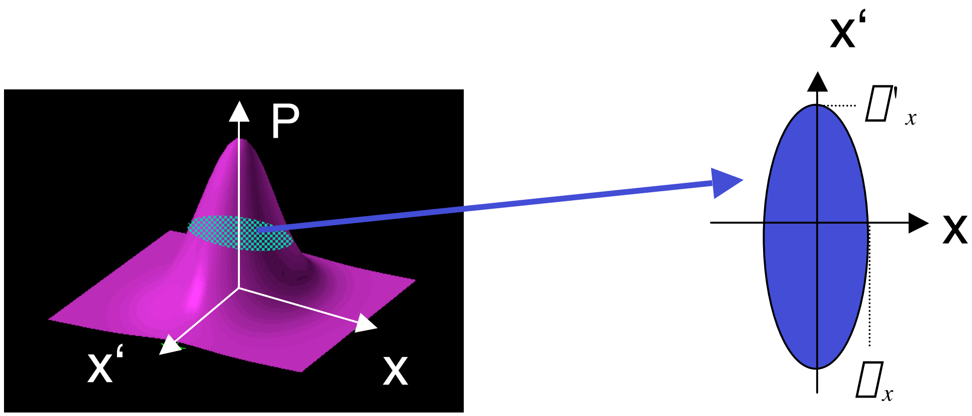
Electron beam phase space

Electrons transverse probability density

$$P(x, x', y, y') = \frac{1}{4\pi^2 \sigma_x \sigma_{x'} \sigma_y \sigma_{y'}} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{x'^2}{2\sigma_{x'}^2} - \frac{y^2}{2\sigma_y^2} - \frac{y'^2}{2\sigma_{y'}^2} \right)$$

Emittance - volume in a phase space



$$\varepsilon_x = \sigma_x \sigma_{x'}$$
$$\varepsilon_y = \sigma_y \sigma_{y'}$$

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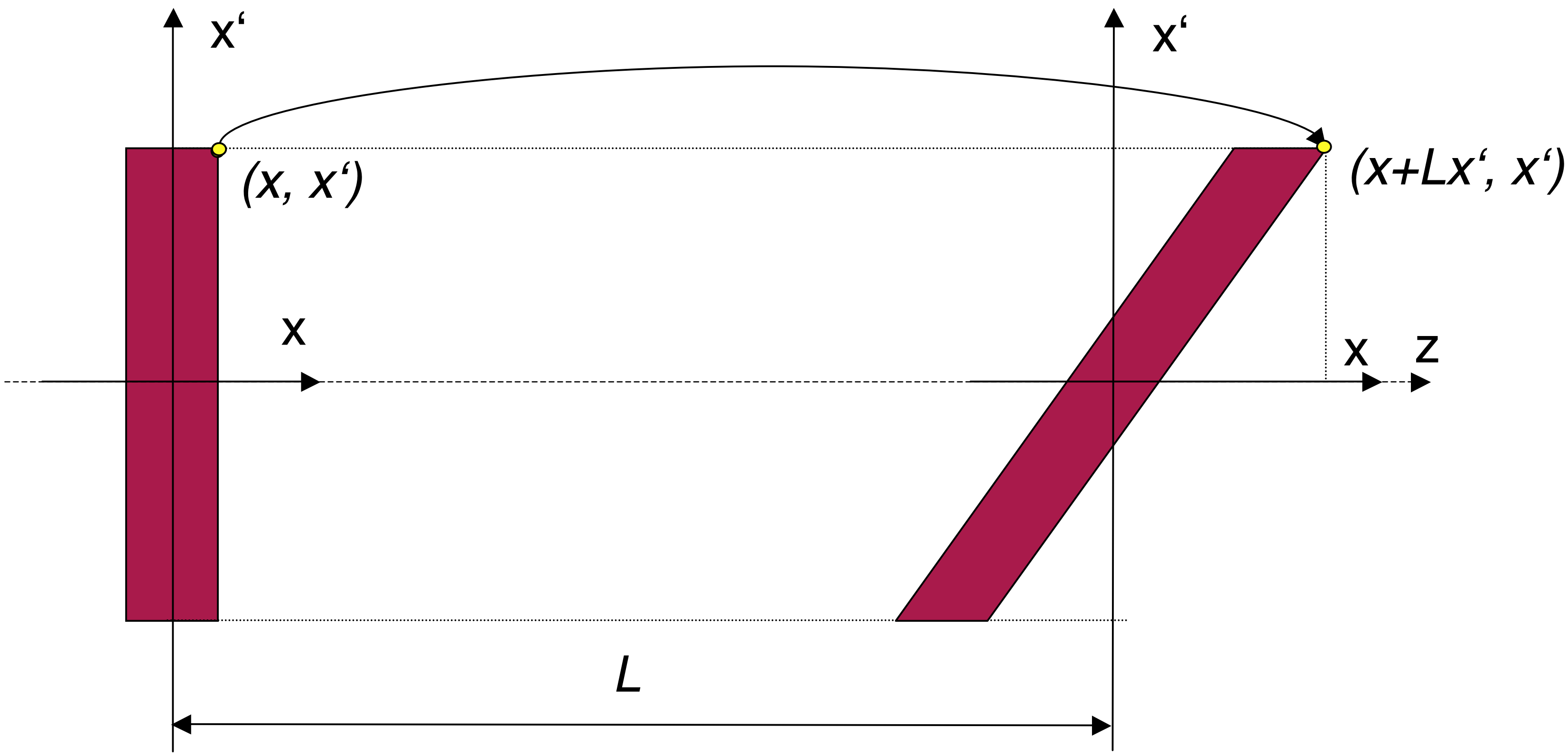
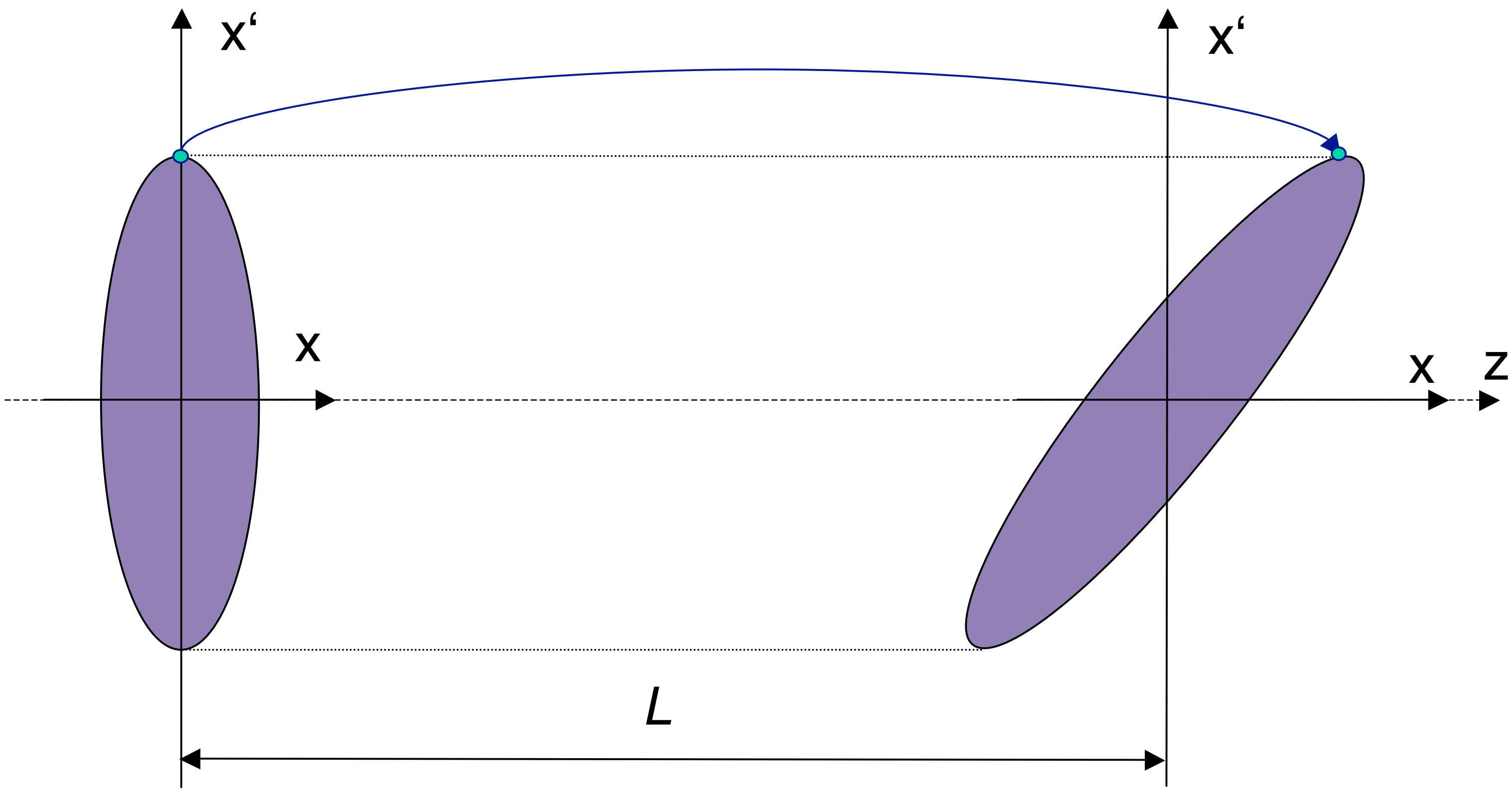
Phase Space Representation

Propagation in free space
Slit



Phase Space Representation

Propagation in free space (cont.)
Phase ellipse



V. Sajaev, P. Ilinski, TWG May 2004

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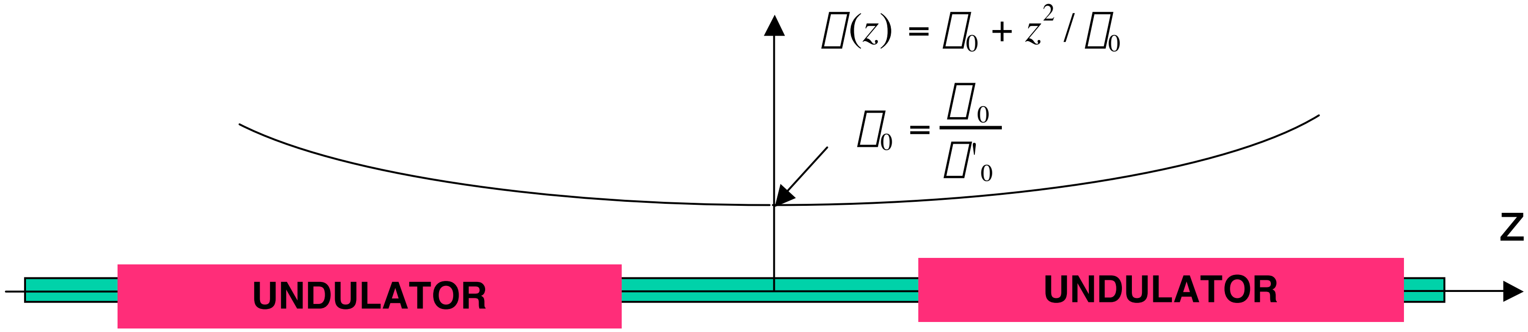
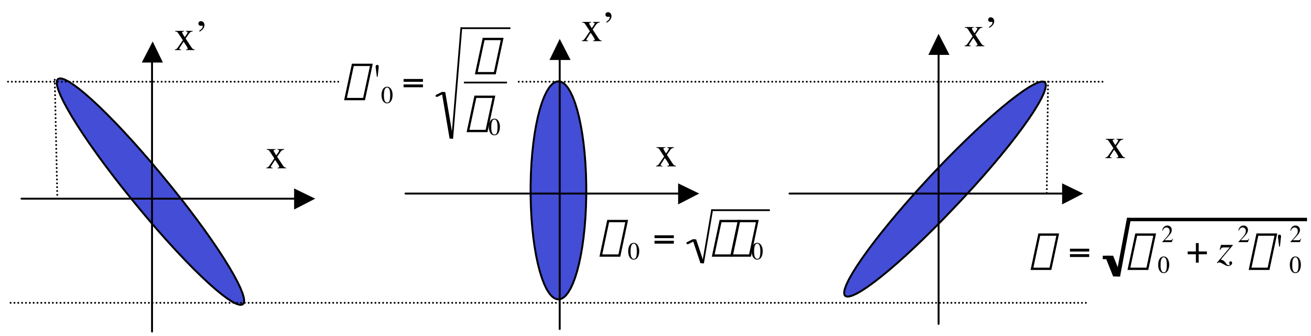
Straight section - free space

Betatron function describes focusing properties

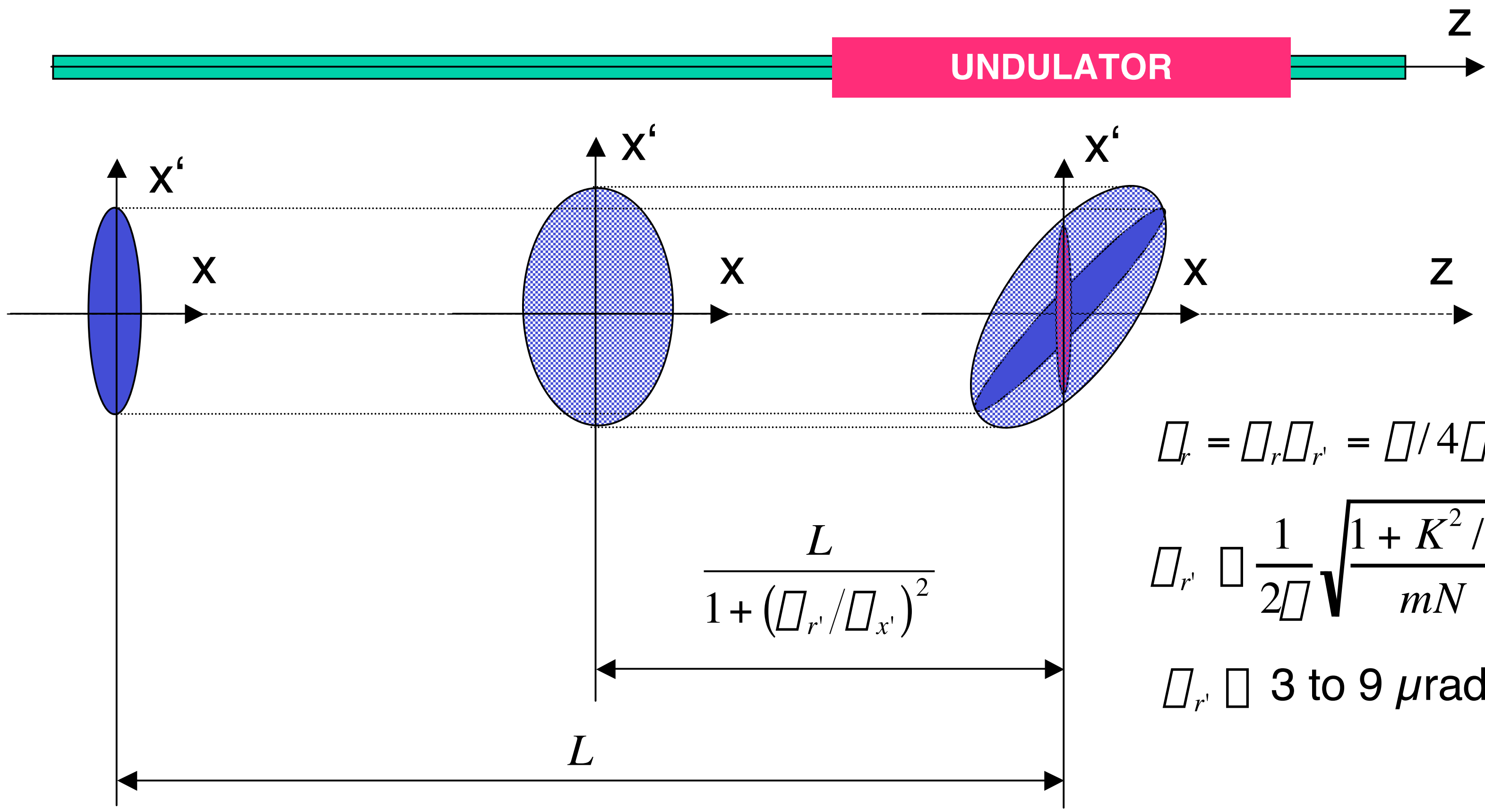


standard deviations σ, σ' can be expressed in terms of the storage ring parameters ε and β



Beta functions are optimized to minimize the effective electron beam emittance while keeping appropriate lifetime and injection efficiency

Photon beam phase space



$$\varepsilon_r = \sigma_r \sigma_{r'} = \lambda / 4\pi$$

$$\sigma_{r'} \approx \frac{1}{2\gamma}\sqrt{\frac{1+K^2/2}{mN}}$$

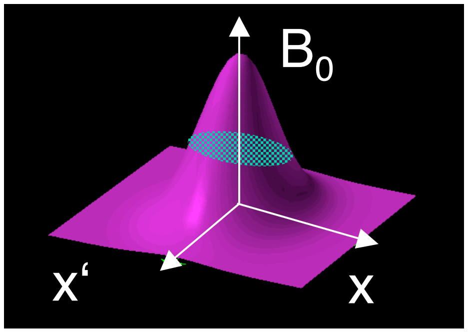
$\sigma_{r'} \approx$ 3 to 9 μrad

σ_x $\qquad$ $\sigma_{Tx} = \sqrt{\sigma_r^2 + \sigma_x^2}$

$\sigma_{x'}$ $\qquad$ $\sigma_{Tx'} = \sqrt{\sigma_{r'}^2 + \sigma_{x'}^2}$

Convolution of undulator radiation from single electron with electron beam

Gaussian beam



Brilliance $$B(\mathbf{x},\theta,z) = B_0 \exp\left[-\frac{1}{2}\left(\frac{(\mathbf{x} - z\theta)^2}{\sigma_r^2} + \frac{\theta^2}{\sigma_{r'}^2}\right)\right]$$

Angular flux density $$\frac{d^2F}{d^2\Omega} = \frac{F}{2\pi\sigma_{r'}^2}\exp\left[-\frac{\theta^2}{2\sigma_{r'}^2}\right]$$

Flux $$F = B_0\left(2\pi\sigma_r\sigma_{r'}\right)^2$$

Coherent phase space $\sigma_r\sigma_{r'} = \lambda/4\pi$ ➡ Coherent flux $F_{coh} = B_0\left(\lambda/2\right)^2$

Undulator radiation in Gaussian beam approximation

On-axis Brilliance $$B_0 = \frac{F}{(2\pi)^2\Sigma_{Tx}\Sigma_{Tx'}\Sigma_{Ty}\Sigma_{Ty'}}$$

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Types of experiments

SR parameters \ Experiment	Source size □= □□	Source divergence □□= □/□	Emittance □=□□□ (B$_0$ ~ 1/□)	Beta Function □=□/□□
Coherence $F_{coh}=B_0$(□/2)^2	small		small (□$_r$=□/4□)	small
Flux density (~ 1/□□)		□□□□$_{r'}$ □□=□□ □		large, depends on optics NA

Coherent experiments

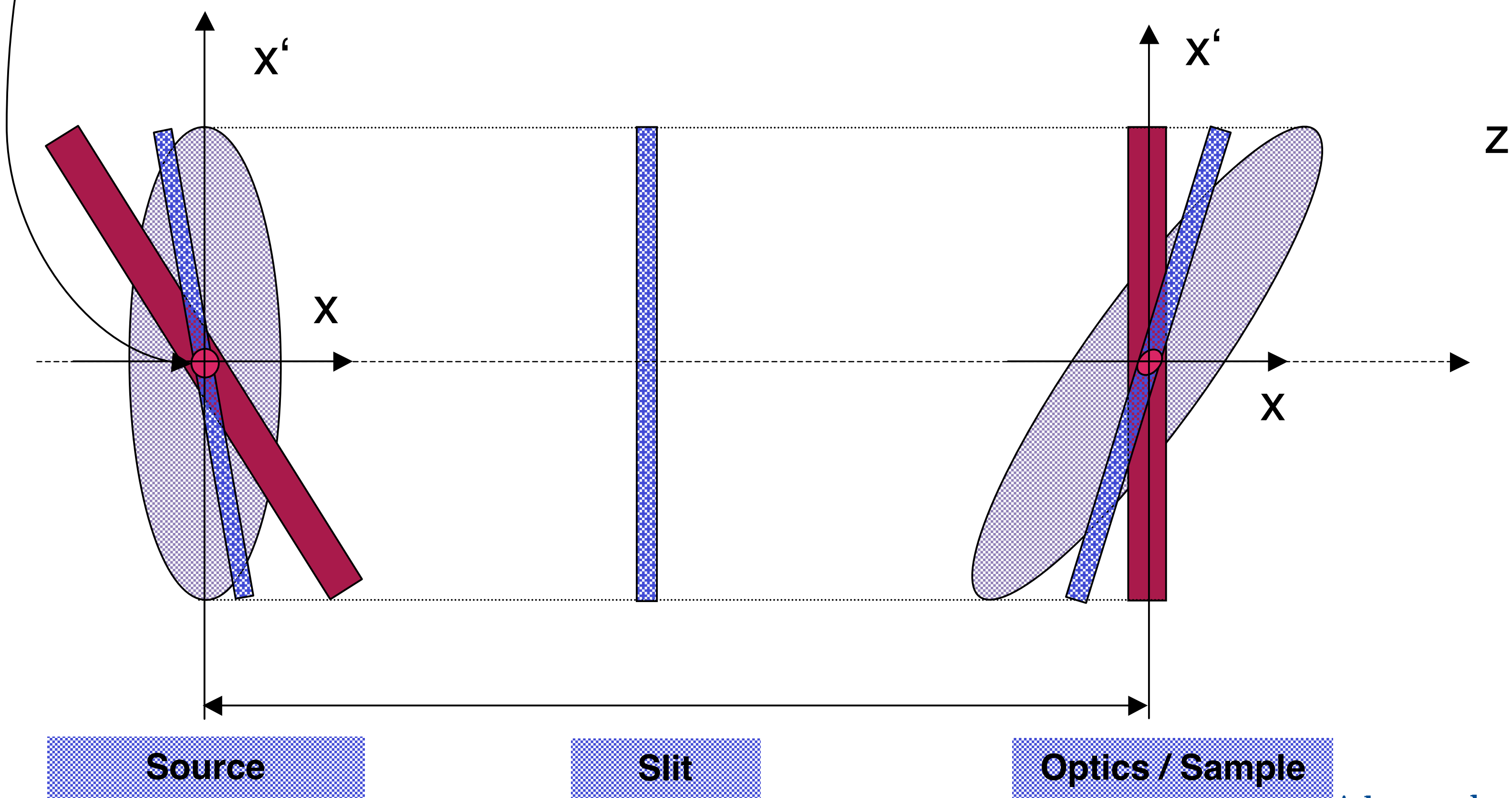
Angular - spatial filtering

Coherent phase space

$$\varepsilon_r = \sigma_r \sigma_{r'} = \lambda / 4\pi$$

$$F_{coh} = B_0 \left(\lambda / 2\right)^2$$

Optical contrast $\sim F_{coh} / F_{Tot}$



Coherent experiments

Beta function customization

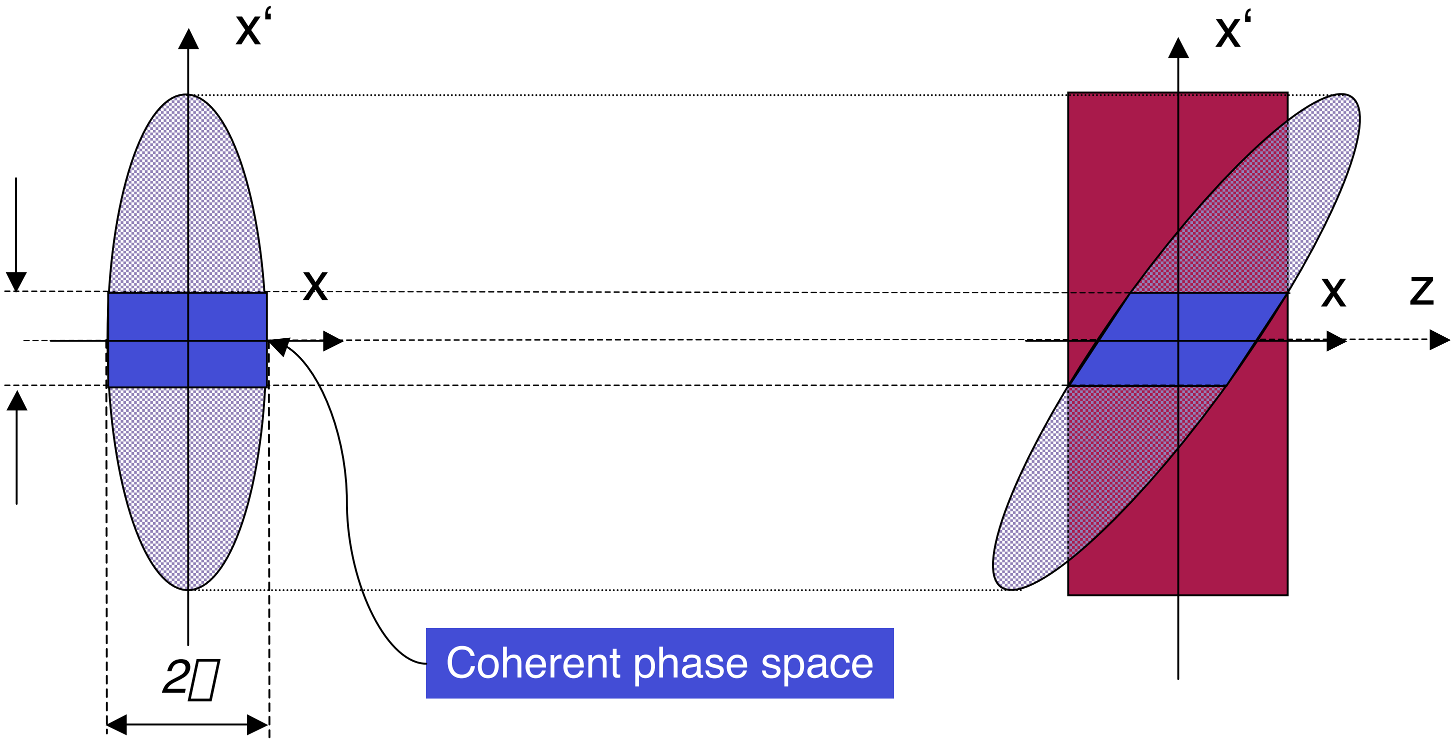
Source

$$F_{coh} = B_0 (\lambda/2)^2$$

Optics / Sample

Optical contrast ~ F_{coh} / F_{Tot}

$$\sigma'_{dif} = \frac{\lambda}{2\pi\sigma}$$

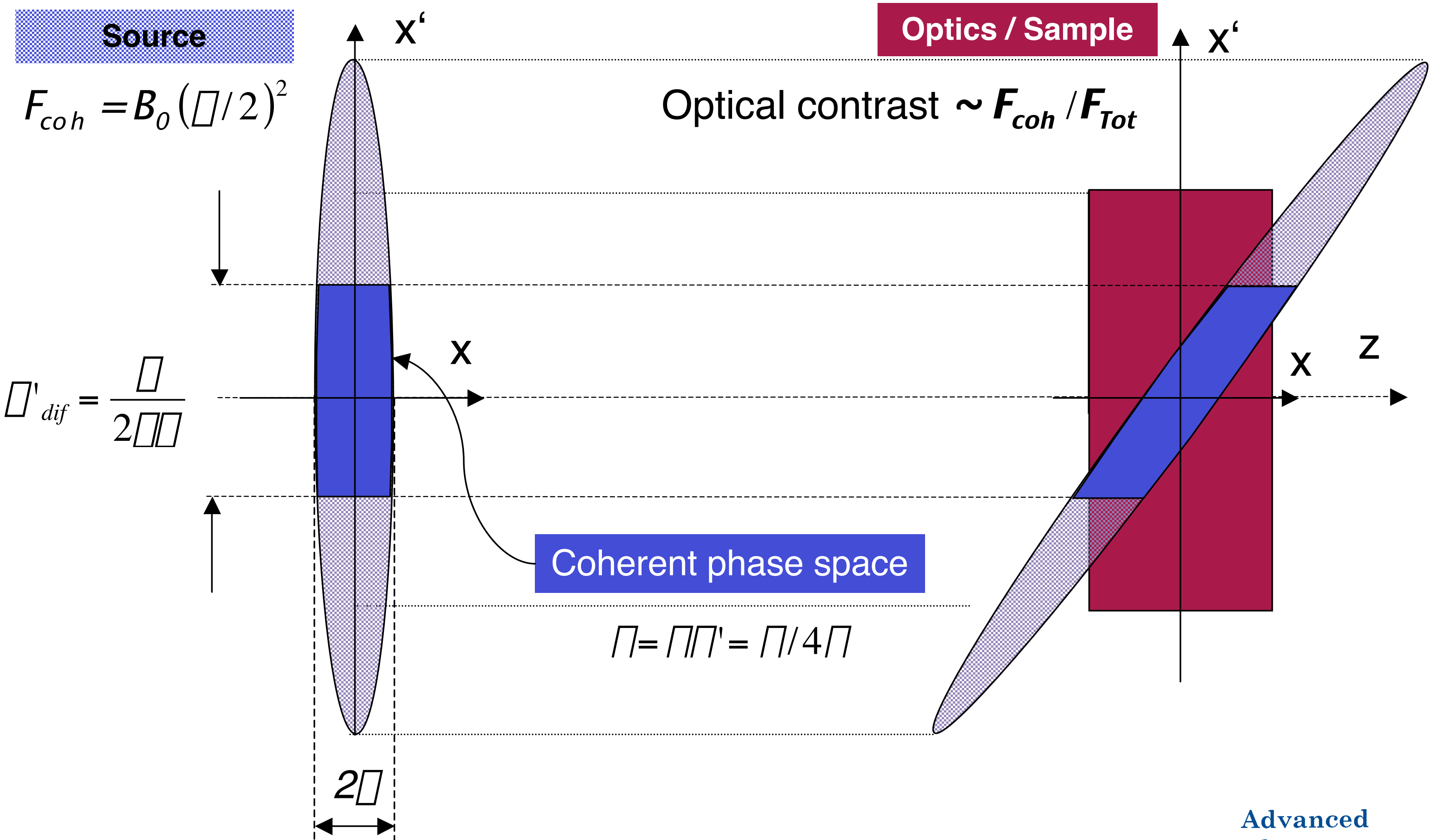


$$\varepsilon = \sigma\sigma' = \lambda/4\pi$$

Coherent experiments

Beta function customization (cont.)

Beta function decreased - Optical contrast $\sim F_{coh} / F_{Tot}$ increased



Optimization of APS Storage Ring Parameters for XPCS Experiments at Beamline 8-ID

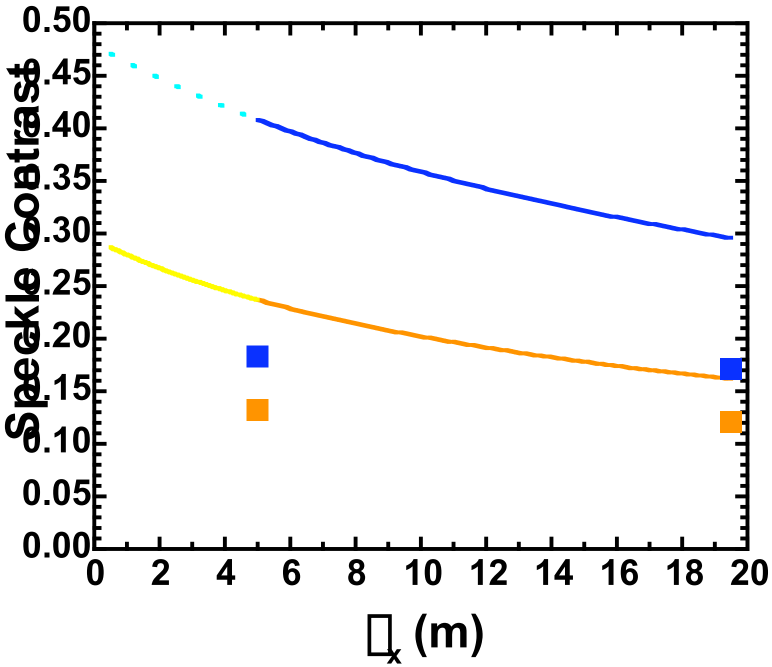
A. R. Sandy, M. Borland, P. Ilinski, L. B. Lurio, S. Narayanan, V. Sajaev

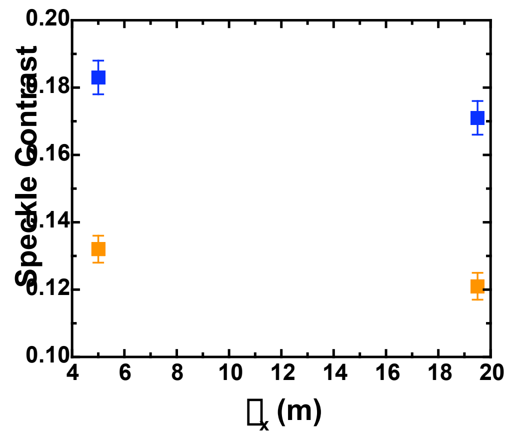
Speckle contrast $A = F_x(L_x/\xi_x)F_y(L_y/\xi_y)$

$L_{x,y}$ - slit size

$\xi_{x,y}$ - coherence length

$$F(x) = \frac{1}{x^2}[\sqrt{\pi}x\,\mathrm{erf}(x) + e^{-x^2} - 1],$$





Calc. Contrast 20 (h) x 20 (v) μm²

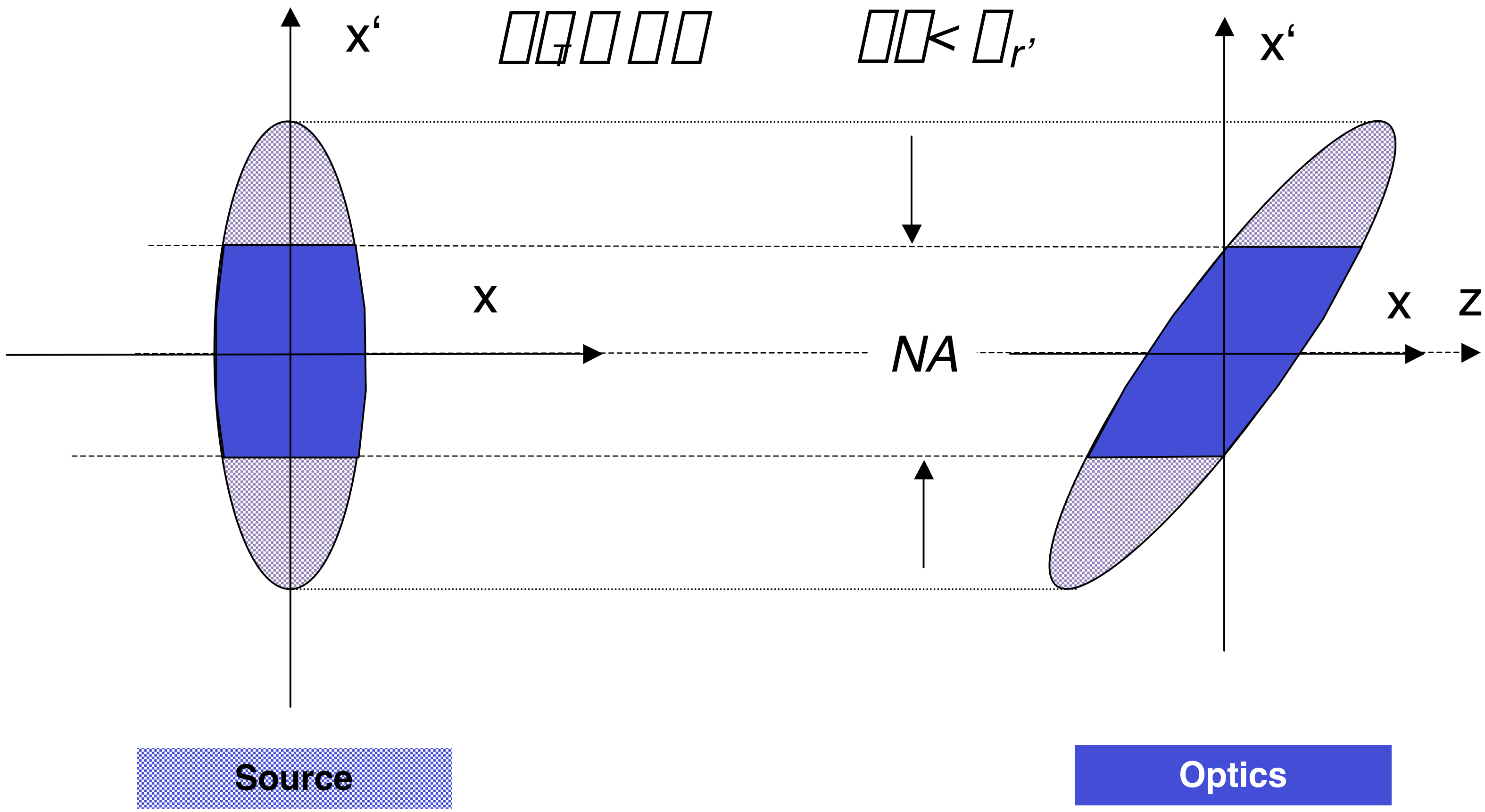
Meas. Contrast 20 (h) x 20 (v) μm²

Calc. Contrast 40 (h) x 20 (v) μm²

Meas. Contrast 40 (h) x 20 (v) μm²

Flux density experiments

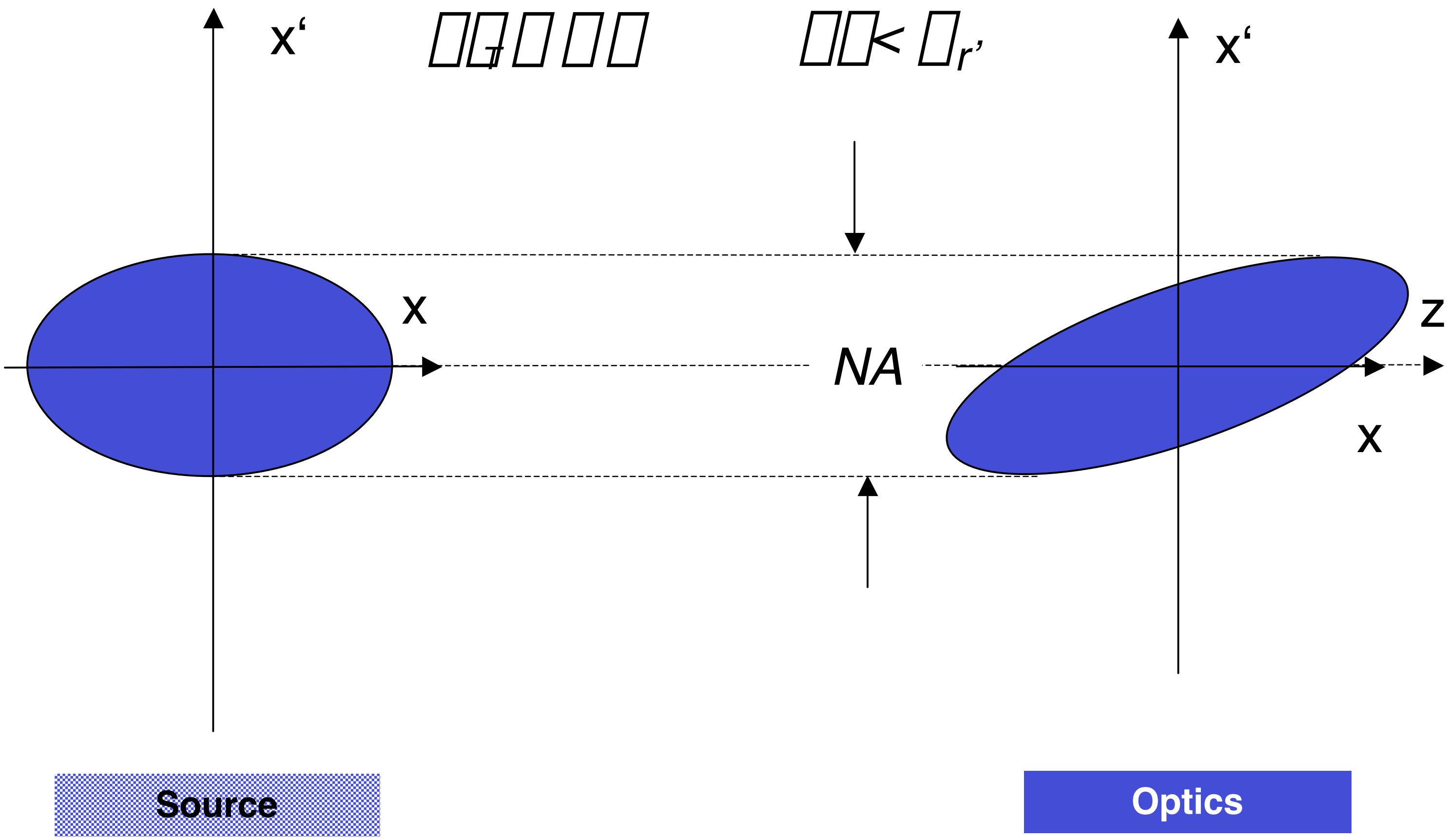
Beta function customization



Flux density experiments

Beta function customization (cont.)

Beta function increased - entire phase space is accepted by optics



Benefits of beta function customization

- For a given emittance
  - experiments that require coherent flux will benefit from having smaller x-ray source size
  - experiments that require high flux density will benefit from smaller x-ray beam divergence
- Electron beam source size or divergence have optimum values for an individual beamline or particular experiment; optimization might be achieved through beta function customization
- Customization of beta function can improve quality of experiments

Is it feasible?

- Smallest possible electron beam emittance or flexible APS lattice, in order to customize beta functions?
- What are the limits for horizontal beta-function?
- What are consequences of beta function customization?
  - emittance
  - lifetime
- How many modes per beamline are possible?
  - a beamline may need different settings of storage ring parameters for different types of experiments
- How often can a mode (APS lattice) be changed?

Beta function manipulations at storage ring

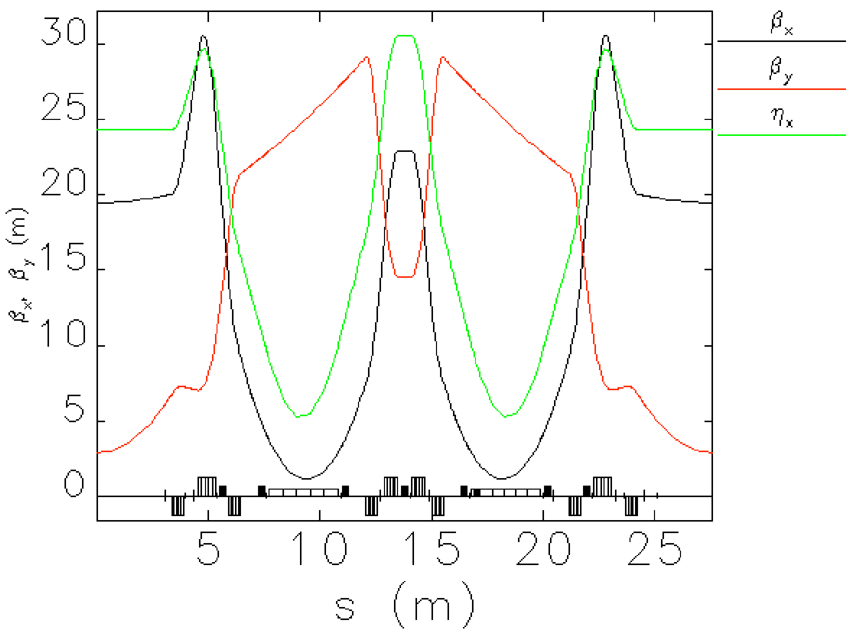
High symmetry lattices

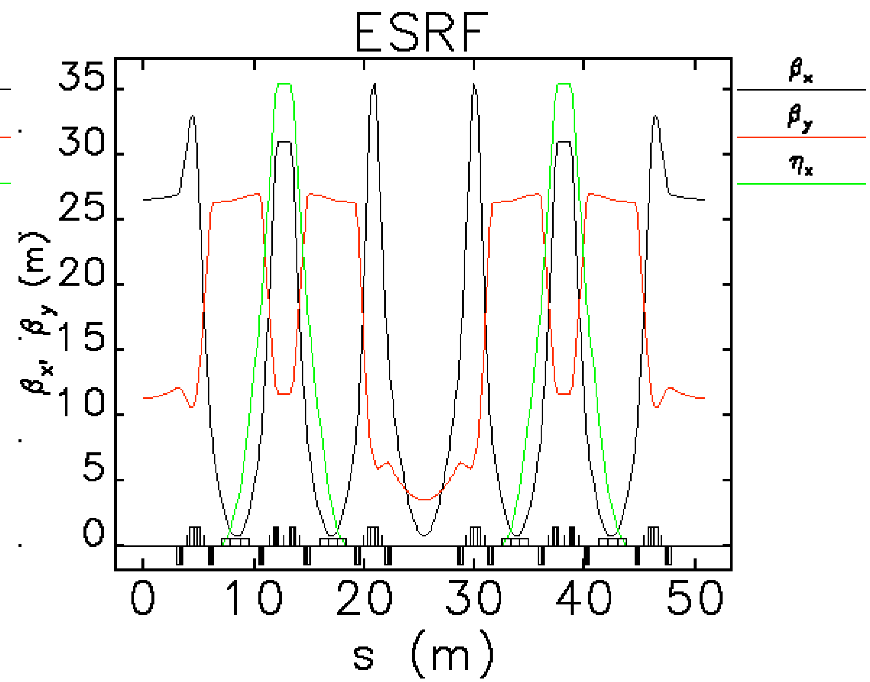
- A highly symmetric lattice is required to achieve low emittance and long lifetime
- Such a lattice has the same electron beam sizes at every undulator location

	N_S	E(GeV)	Number of different ID point
ESRF (France)	32	6	2
APS (ANL)	40	7	1
SPRING-8 (Japan)	48	8	2
ALS (LBL)	12	1.5 (1.9)	1
BESSY-2 (Germany)	16	1.7	2
Elettra (Italy)	12	2.0	1

Two types of radiation points

APS





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Comparison of APS and ESRF source points

□	APS	ESRF (even sectors)	ESRF (odd sectors)
s_x (mm)	274	402	59
s_x’ (mrad)	11.3	10.7	90
s_y (mm)	8.7	7.9	8.3
s_y’ (mrad)	2.9	3.2	3.0
$□_x$ (m)	19.5	35.2	0.5
$□_y$ (m)	2.9	2.5	2.7
Emittance (nm)	3.1	4.2	5.1
Coupling (%)	1	0.6	

APS power supply system is unique

- After the storage ring has been built, it is very difficult to change the beta functions (or source sizes) by considerable amount
- Usually, the quadrupoles that control beta functions are powered in families. This makes it almost impossible to change beta functions at one location
- APS storage ring has a unique power supply system; all quadrupoles are powered by separate power supplies. So we can change beta functions.

Problems arising from local changes

Emittance

- Present lattice is optimized for very small emittance
- Change of beta functions results in emittance increase
- The effect is easy to calculate; we can control emittance during lattice calculation

Problems arising from local changes
(cont.)

Lifetime and injection efficiency

- Present lattice is highly symmetric – no strong resonances close to our working point
- Local change of beta functions breaks the symmetry
- The effect is difficult to quantify – studies required for each lattice change

- There is a number of ways to deal with the lifetime decrease – mainly by increasing number of bunches
- There is no easy way to overcome problems with injection efficiency

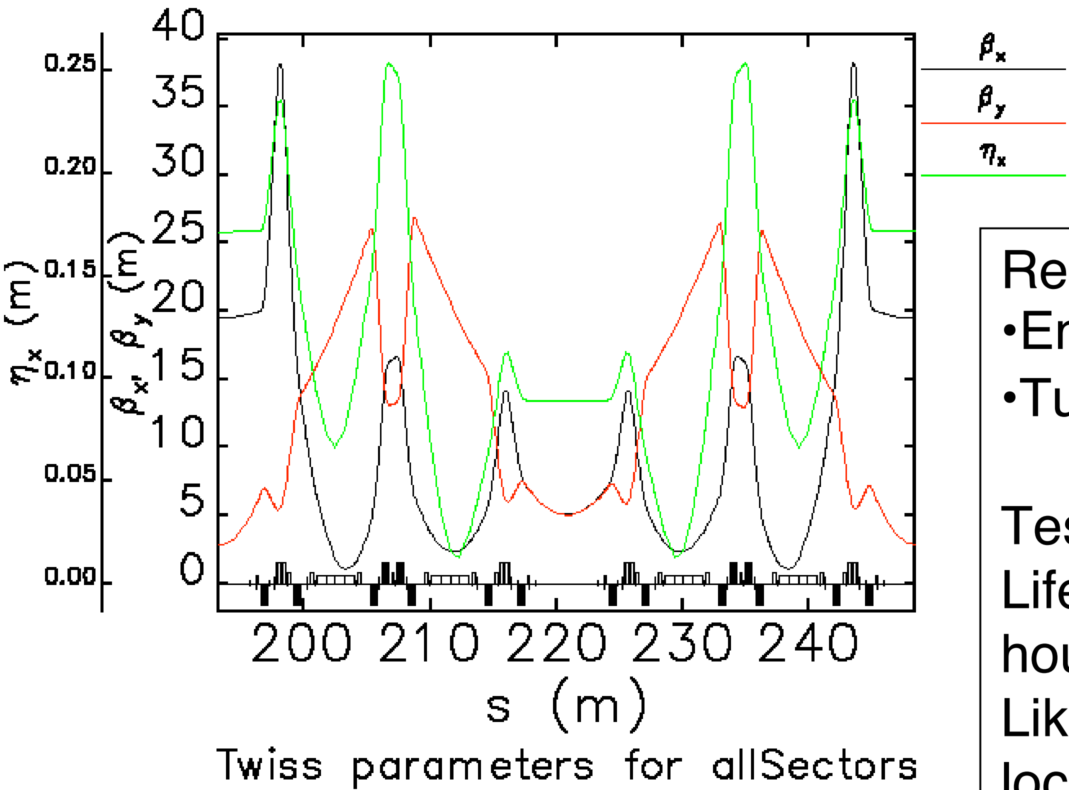
We will present several examples of beta function changes and briefly discuss their effect on the storage ring performance.

When we change beta functions, the constraints are:

- keeping the same emittance
- keeping betatron phase advance per sector (to keep total betatron tunes)

Example 1: beta X is 5 m

(source size is decreased by a factor of 2)

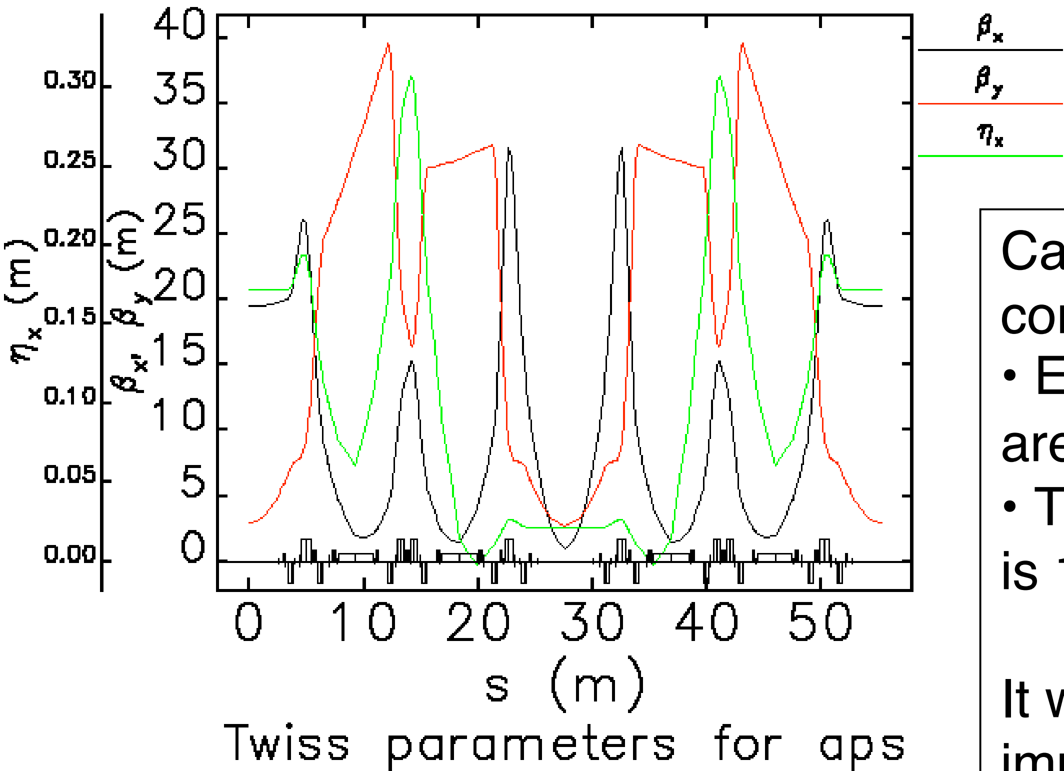


Relatively easy:
- Emittance is constant
- Tunes are constant

Tested at sector 8:
Lifetime is shorter (6 hours vs. 7 hours for normal lattice).
Likely possible to install at several locations

Example 2: beta X is 1 m

(source size is decreased by a factor of 5)



Cannot be achieved under ***both*** constraints:

- Emittance is □ constant – tunes are 0.29 higher
- Tunes are constant – emittance is 16% larger

It will probably be difficult to implement

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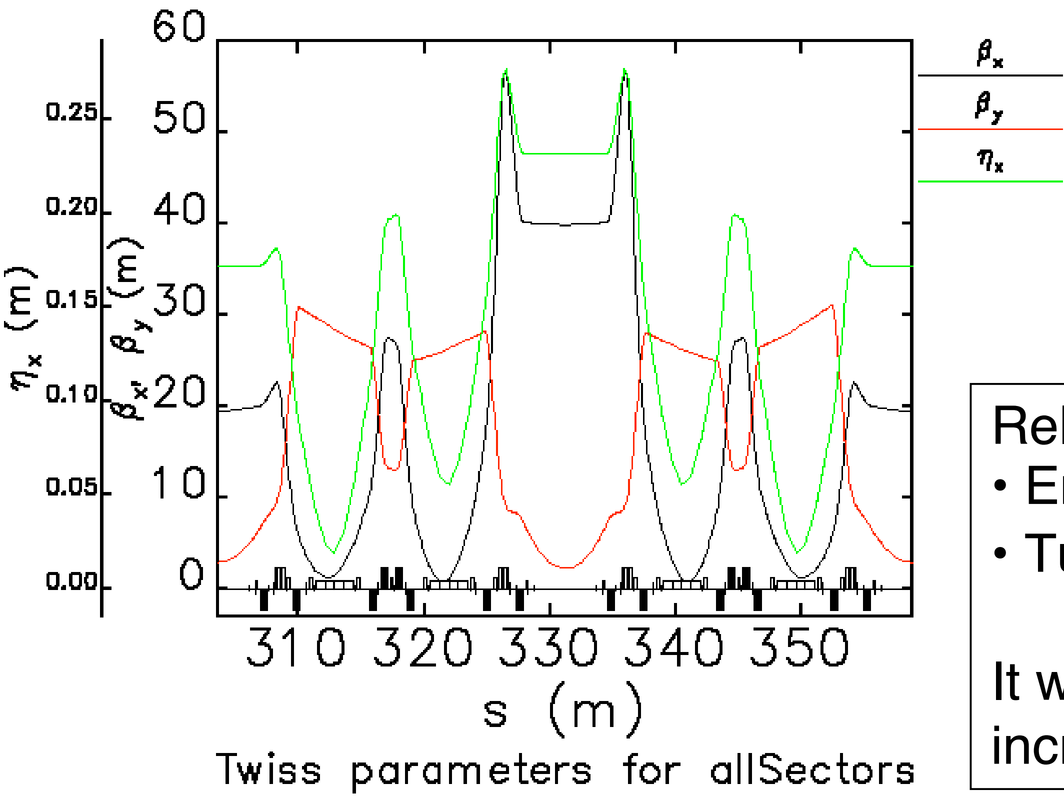
Example 3: beta X is 40 m

(source divergence is decreased by a factor of 1.4)



Relatively easy:
- Emittance is □ constant
- Tunes are constant

It will probably be possible to increase to 60 m

Lattice comparison

□	□ Normal	□ BetaX 5m	□ BetaX 40m	BetaX 1m	
				emittanc e is fixed	tune is fixed
BetaX (m)	19.5	5	40	1	1
Dispersion (m)	0.17	0.09	0.24	0.03	0
Nat.Emittance(nm)	2.50	2.54	2.55	2.59	2.96
s_x (mm)	274	141	390	54	55
s_x' (mrad)	11.3	22.4	7.9	50	55
□$_x$	36.20	36.20	36.22	36.49	36.22
Emittance (nm) at the custom beta location	3.1	3.2	3.1	2.9	3.0
Emittance (nm) at other IDs	3.1	3.2	3.2	3.2	3.6

Is it feasible?

- Customization of beta function in the range of 5 – 50 m seems feasible without serious degradation of storage ring parameters
- Outside of 5 – 50 m range it is not impossible, but requires more analysis due to possible degradation of critical SR parameters
- It would take about a month to create and test a new lattice
- It is only possible to switch lattices during machine intervention/studies
- It is possible to maintain several lattices, but it takes a lot of effort to support all of them