Design and optimisation strategies of the non-linear beam dynamics in diffraction limited synchrotron light sources

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John Adams Institute
for Accelerator Science

diamond

Outline

- **Diffraction limited light sources**
  - motivations
  - present landscape

- **Optics design strategies**
  - TME and (quasi-)diffraction limited rings
  - linear optics and nonlinear optics
  - deterministic algorithms
  - numerical algorithms

- **Examples**
  - MBA, Hybrid MBA, DDBA/DTBA, Antibends
  - (MAX IV, Pep-X, ALS U, ESRF-EBS, APS U, Diamond-II, SLS-II)

Diffraction limited light sources

Photon flux and brilliance and coherent fraction

$$\mathrm{flux} = \frac{N_{ph}}{\Delta T \cdot \Delta\omega / \omega} \qquad \mathrm{brilliance} = \frac{\mathrm{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \qquad F = \frac{\lambda^2 / (4\pi)^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

Σ's are the convolution of electrons and photon beam size and divergence

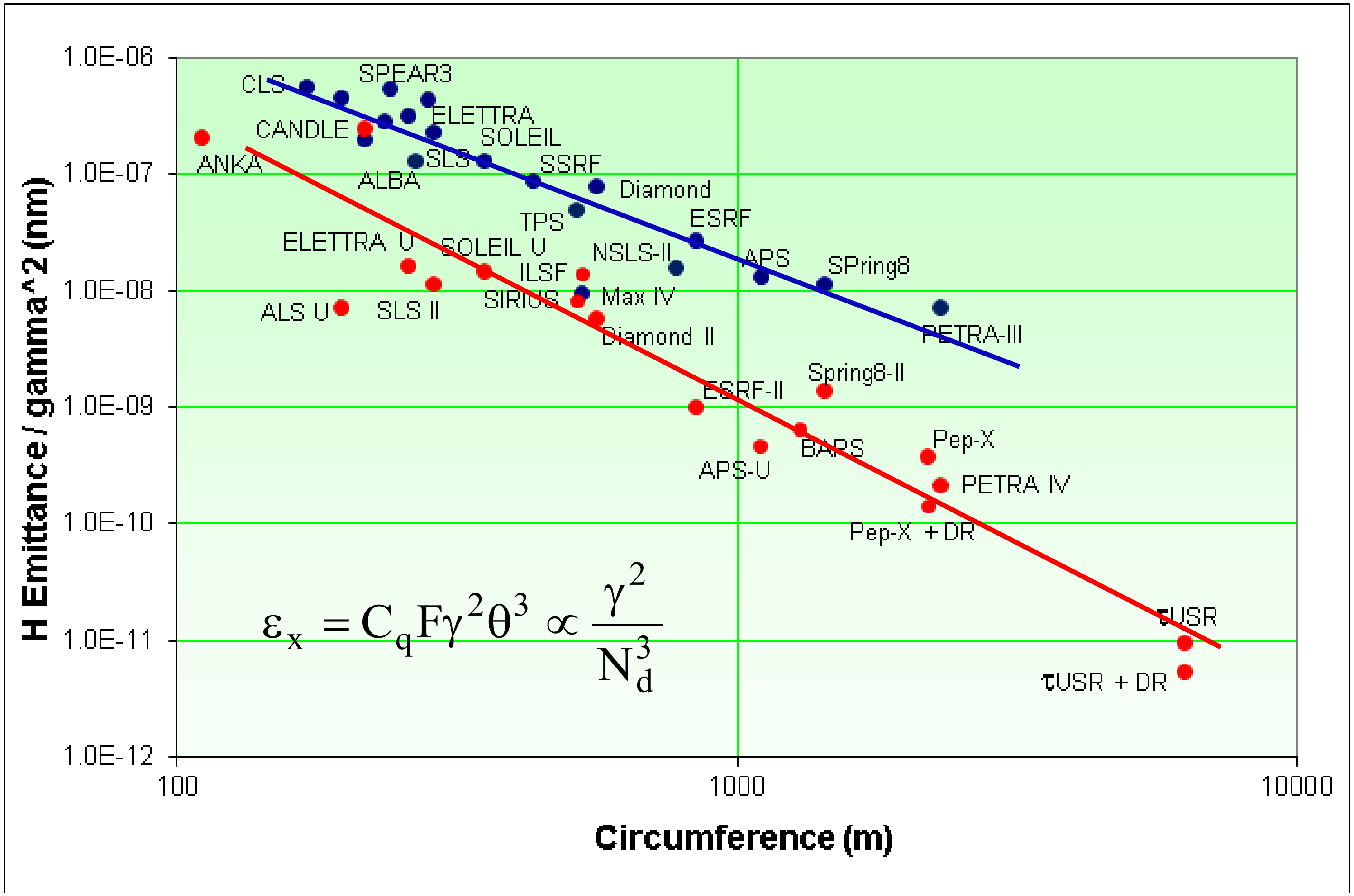
$$\Sigma_x = \sqrt{\sigma^2_{x,e} + \sigma^2_{ph}} \qquad \Sigma_{x'} = \sqrt{\sigma^2_{x',e} + \sigma'^2_{ph}}$$

Brilliance and coherent fraction are maximised for smaller electron beam emittances until the diffraction limit is reached

$$\varepsilon_{e^-} \le \varepsilon_{ph} = \frac{\lambda}{4\pi}$$

~10 pm for diffraction limit at ~1 Angstron (12.4 keV)
~100 pm for diffraction limit at ~ 1nm (1.24 keV)

Survey of low emittance lattices for light sources



$$\varepsilon_x = C_q F \gamma^2 \theta^3 \propto \frac{\gamma^2}{N_d^3}$$

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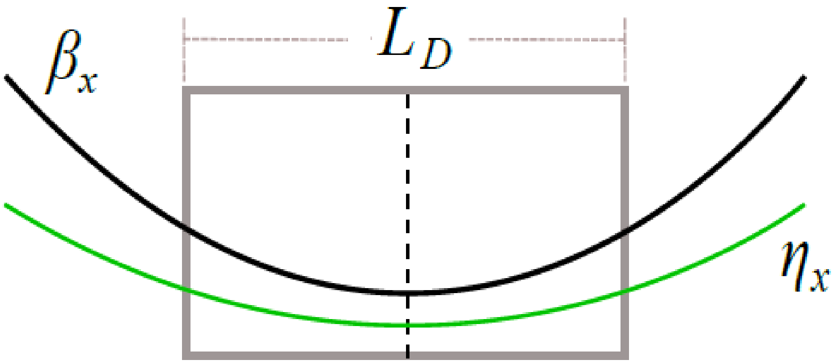
From Theoretical Minimum Emittance (TME) to MBA cells

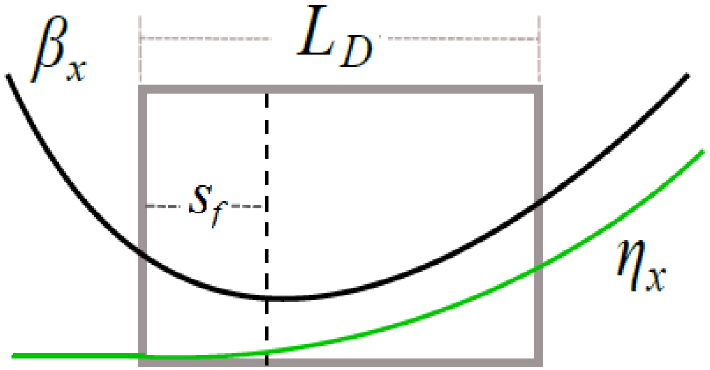
Low emittance lattices are built using the concept of Multibend Achromats (MBA)

$$\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\langle H_{inv} \rangle_{dip}}{\rho}$$

Minimise the contribution of the dipoles to the emittance



$$\beta_c = \frac{L}{2\sqrt{15}} \qquad D_c = \frac{L^2}{24\rho}$$

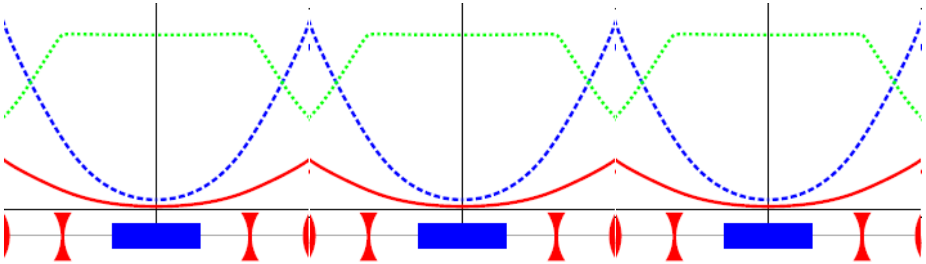


$$\beta_0 = 2L\sqrt{\frac{3}{5}} \qquad \alpha_0 = \sqrt{15} \qquad s_f = \frac{3}{8} L_D$$

These conditions provide the theoretical minima for the emittance generated in dipoles (for constant B)

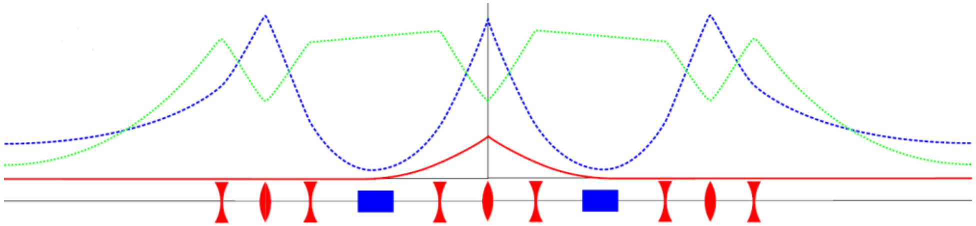
from TME to MBA cells

TME



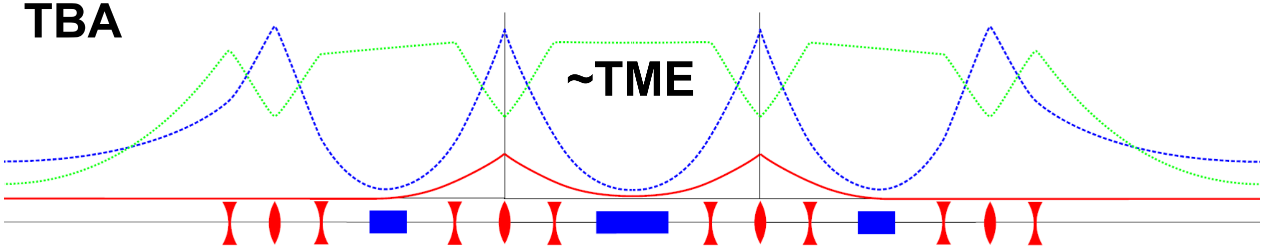
$$\varepsilon_{\mathrm{TME}} = \frac{C_q}{12\sqrt{15}}\gamma^2\theta^3$$

DBA



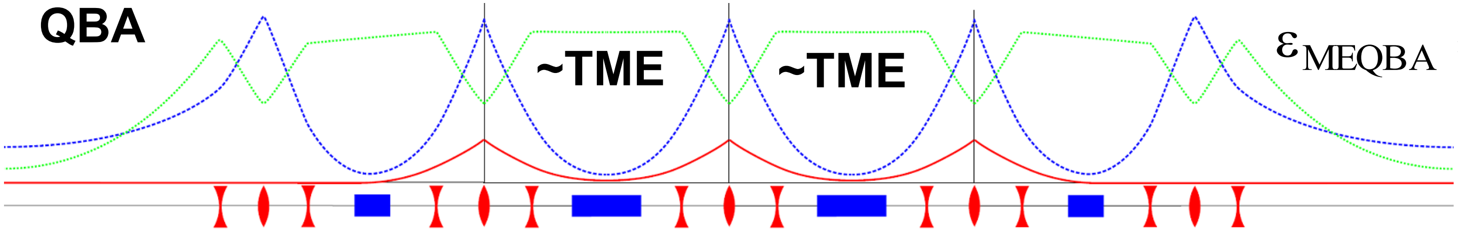
$$\varepsilon_{\mathrm{MEDBA}} = \frac{C_q}{4\sqrt{15}}\gamma^2\theta^3$$

TBA



$$\varepsilon_{\mathrm{METBA}} \approx 0.66\,\varepsilon_{\mathrm{MEDBA}}$$

QBA

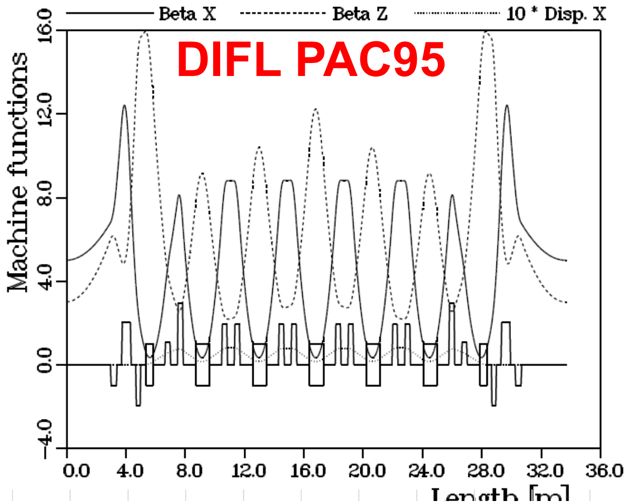


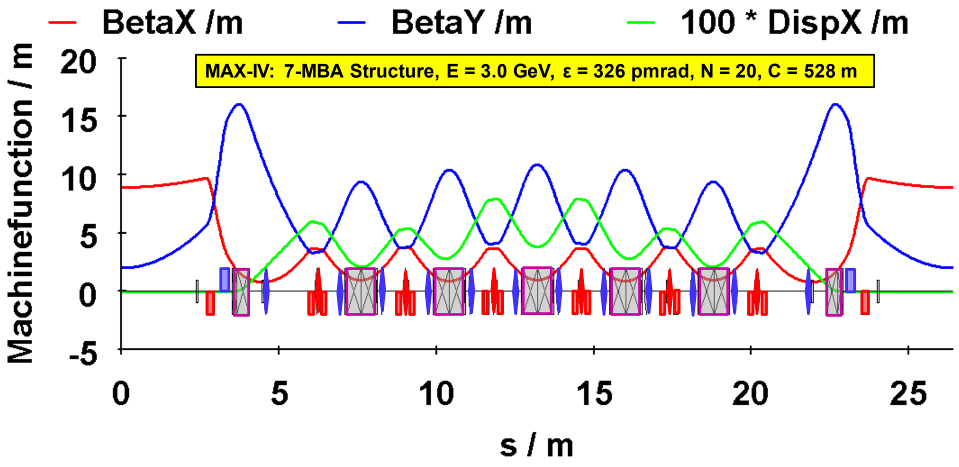
$$\varepsilon_{\mathrm{MEQBA}} \approx 0.55\,\varepsilon_{\mathrm{MEDBA}}$$

$$\varepsilon_{\mathrm{MEMBA}} = C_q F \gamma^2\theta^3$$

S.Y. Lee, PRE 54, 1940, (1996)
S.Y. Lee, Accelerator Physics, World Scientific

DIFfraction Limited light source (DIFL)





~20 years from the first proposal

- **D. Einfeld et al. NIMA 1993**
  PAC1995

to the first beam

- **M. Eriksson et al. IPAC 2016**

About 20 new / upgrade projects
Renaissance of storage ring LS due to

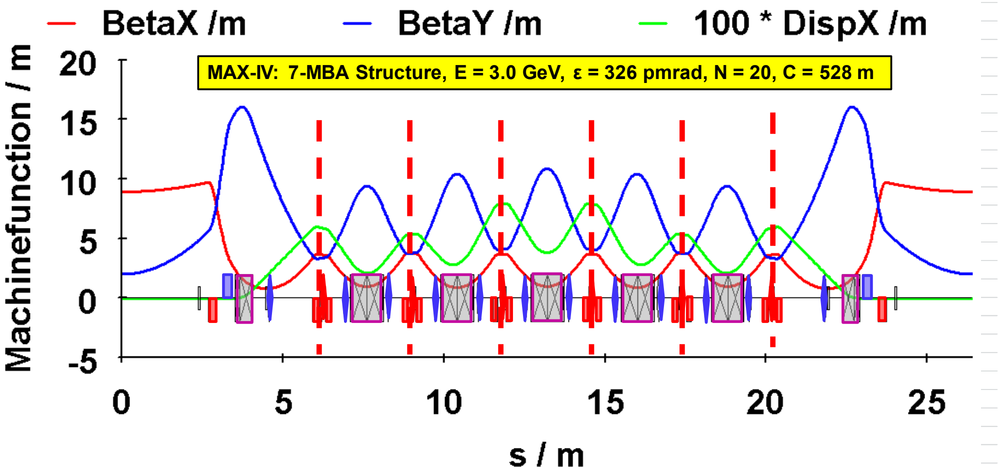
- **science case improved**
- **technology of subsystems**
- **success of 3rd GLS**

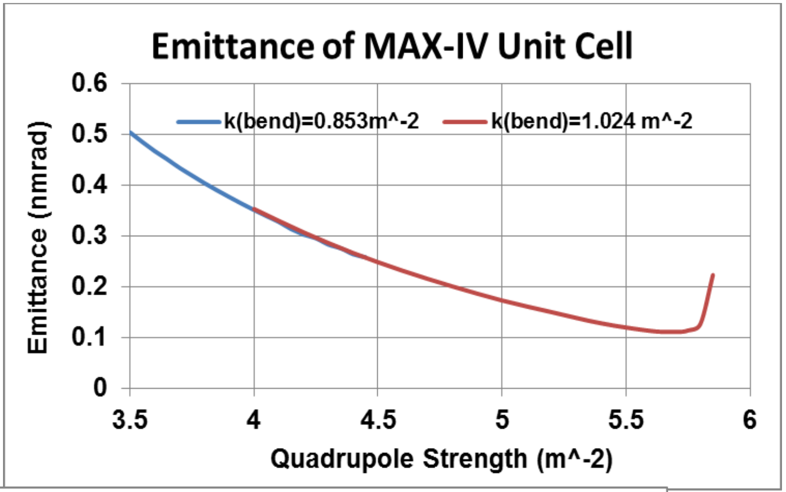
and

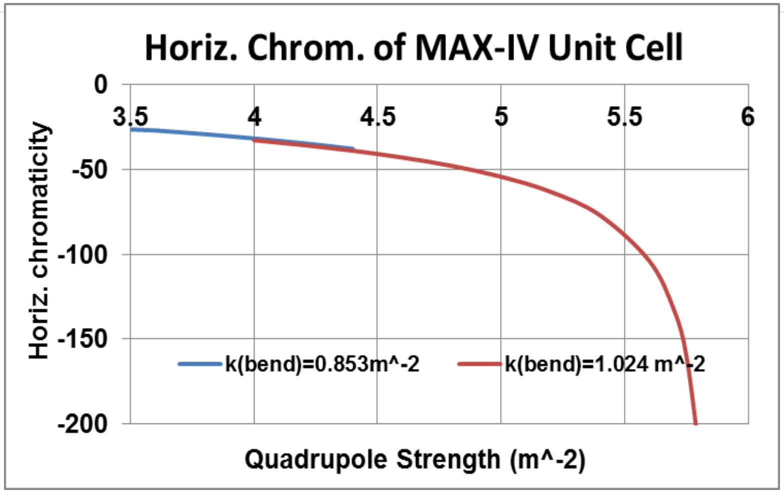
- ***beam dynamics optimisation***

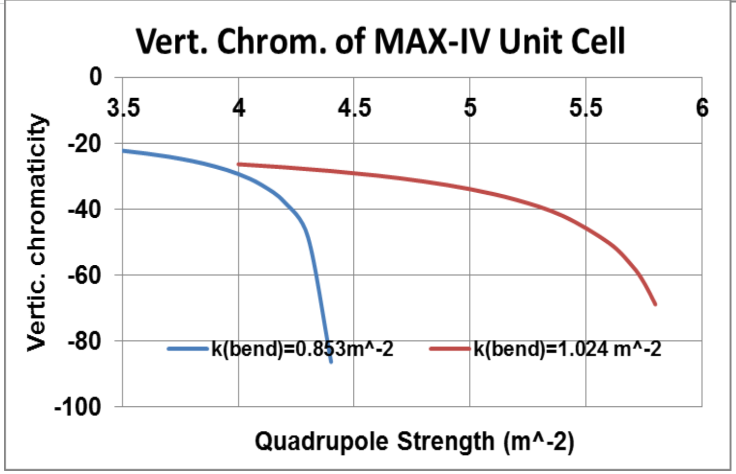
e.g. MAX IV-like TME unit cell

TME cells generate strong focussing and large chromaticity







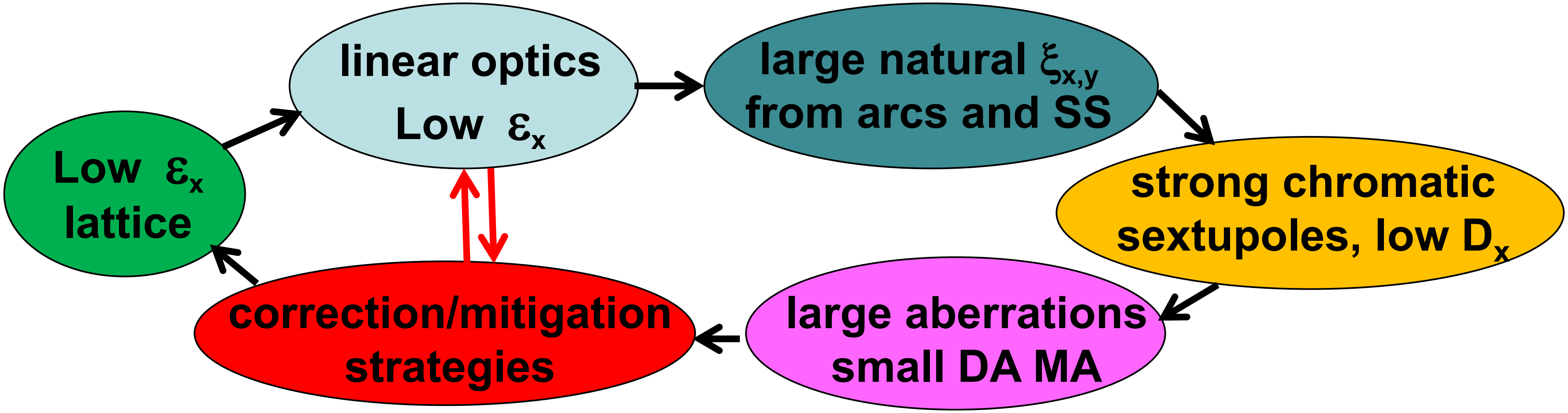


The natural chromaticity increses sharply for low emittance (chromaticity wall)

Nonlinear dynamics optimisation

strong sextupoles are required to correct the chromaticity

$$\xi_{x,y} = -\frac{1}{4\pi}\oint_{C} \beta_{x,y}(s)[K_{x,y}(s) - S_{x,y}(s)D_{x}(s)]ds$$



Low ε_x lattice

linear optics Low ε_x

large natural $\xi_{x,y}$ from arcs and SS

strong chromatic sextupoles, low D_x

large aberrations small DA MA

correction/mitigation strategies

Injection efficiency, beam lifetime (Touschek), control of beam losses

Off axis injection

- **~ 10 mm Dynamic Aperture**
- **few per cent Momentum Aperture**

On axis (swap-out) injection

- **allows more aggressive desing – (like Top Up)**
- **reduced DA requirements but still needs a good MA**

Optimisation tools

Based on perturbative theory of betatron motion

- resonance driving terms (and detuning terms)
- cancellation rules - symmetries

Based on numerical tracking

- detuning with amplitude, momentum, driving terms, FMA, ...
- direct evaluation of DA, MA
- direct evaluation of injection efficiency
- effect of errors (magnets, misalignment, ...) and IDs

Tracking tools: MADX-PTC, elegant, AT, Tracy-II(-III), OPA, ...

Deterministic algorithms

Based on perturbative theory of Hamiltonian of betatron motion

- sextupole resonance driving terms
- first order cancellations

  in a cell
  over N cells
  via symmetry

- sensivity matrices driving terms ↔ sextupoles (and SVD)

- extension to higher order magnetic multipoles
- extension to higher order perturbative terms

Hamiltonian of betatron motion

$$H=\frac{p_x^2+p_y^2}{2(1+\delta)}-\frac{x\delta}{\rho(s)}-\frac{1}{2}\frac{x^2}{\rho^2(s)}+\frac{b_2^2(s)}{2}(x^2-y^2)+\frac{b_3^2(s)}{3}(x^3-3xy^2)+O(4)$$

$$h_{jklmp}(s)=\sum_{s_i} b_N(s_i)\beta_x^{\frac{j+k}{2}}(s_i)\beta_y^{\frac{l+m}{2}}(s_i)\delta^p e^{i(j-k)\mu_x(s_i)}e^{i(l-m)\mu_y(s_i)}$$

$$j+k+l+m+p=N$$

A. Schoch, CERN 57-23 (1958);
R. Ruth, SLAC-pub 4103, (1986);
J. Bengtsson, CERN 88-04 (1988);

Resonant driving terms

complex coefficients s-dependent
each multipole contributes to definite resonant driving terms
e.g. sextupoles contribute to
2 chromaticities, 3 chromatic and 5 geometric driving terms
(unavoidable 16 additional terms after correcting the chromaticity)
phase relations may enhance or cancel their contribution

$h_{11001}=h_{11001}^{*}\rightarrow\xi_x$

$h_{00111}=h_{00111}^{*}\rightarrow\xi_y$

$h_{20001}=h_{02001}^{*}\rightarrow 2Q_x$

$h_{00201}=h_{00021}^{*}\rightarrow 2Q_y$

$h_{10002}=h_{01002}^{*}\rightarrow Q_x$

$h_{30000}=h_{03000}^{*}\rightarrow 3Q_x$

$h_{21000}=h_{12000}^{*}\rightarrow Q_x$

$h_{10110}=h_{01110}^{*}\rightarrow Q_x$

$h_{10200}=h_{01020}^{*}\rightarrow Q_x+2Q_y$

$h_{10020}=h_{01200}^{*}\rightarrow Q_x-2Q_y$

all $\propto b_3$

…then higher order multipoles $\propto b_4$; $\propto b_5$; …

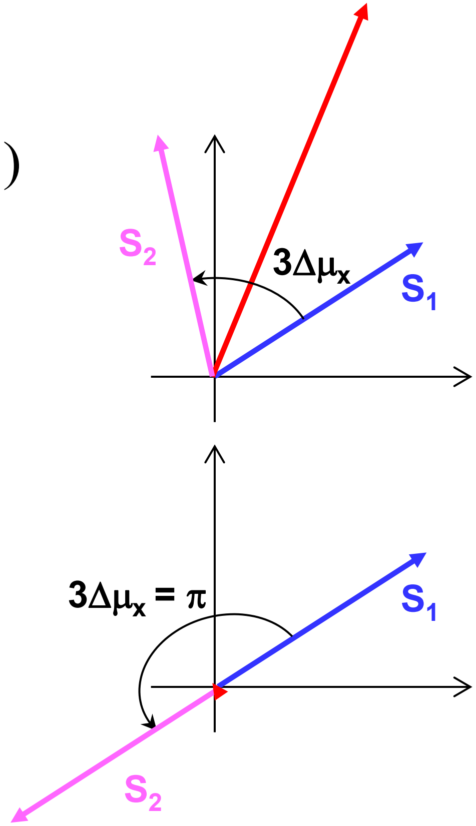
…then higher perturbative orders $\propto b_3b_3$; $\propto b_3b_4$; …

Compensation rules in first order

Simple rules can be establish to compensate the contribution of two sextupoles to a given resonant driving term, e.g. for (3,0)

$$h_{30000} \propto b_3 L \beta_x^{\frac{3}{2}} [\overset{S_1}{e^{i3\mu_{xi}}} + \overset{S_2}{e^{i3(\mu_{xi}+\Delta\mu_x)}}] = b_3 L \beta_x^{\frac{3}{2}} e^{i3\mu_{xi}} (1 + e^{i3\Delta\mu_x})$$

$$e^{i3\Delta\mu_x} = -1 = e^{i(2n+1)\pi}$$



We can set the phase advance to target specific resonances or, even better, to cancel the contribution to all normal sextupoles geometric resonances terms by

$\Delta\mu_x = (2n+1)\pi$ $\Delta\mu_y = n\pi$

Normal and skew sextupoles resonances are cancelled by

$\Delta\mu_x = (2n+1)\pi$ $\Delta\mu_y = (2n+1)\pi$

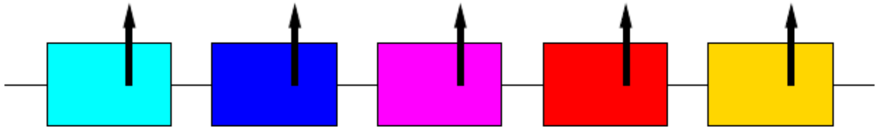
Compensation rules in N cells

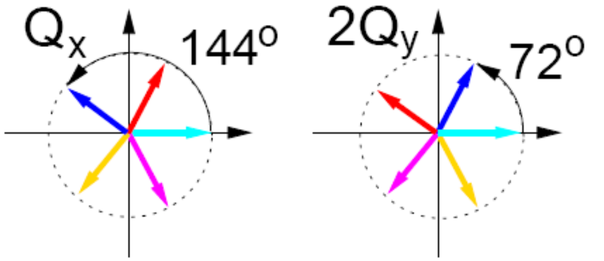
If the contribution of two sextupoles cannot be compensated within a cell some compensation can be obtained after N cells, e.g. for (3,0)

$$h_{30000} \propto b_3 L \beta_x^{\frac{3}{2}} \sum_{k=0}^{N-1} e^{i3\Delta\mu_x k} = b_3 L \beta_x^{\frac{3}{2}} \frac{1-e^{i3\Delta\mu_x N}}{1-e^{i3\Delta\mu_x}} = b_3 L \beta_x^{\frac{3}{2}} e^{i3\Delta\mu_x (N-1)/2} \frac{\sin(3\Delta\mu_x N/2)}{\sin(3\Delta\mu_x /2)}$$

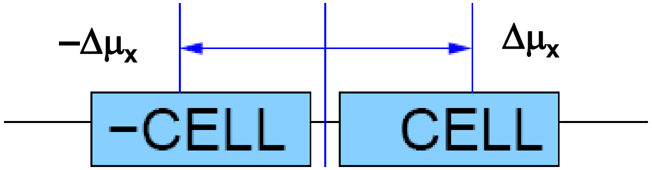
e.g. for N = 5 we can choose Q_x = 2/5 and Q_y = 1/10
e.g. for N = 7 we can choose Q_x = 3/7 and Q_y = 1/7
and so on… will cancel all third order resonances

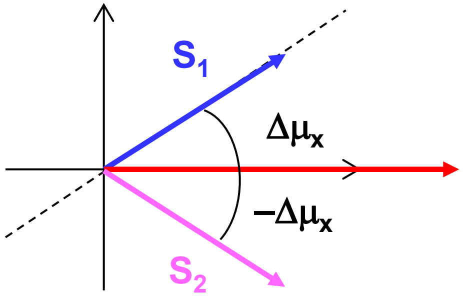
$Q_x = \Delta\mu_x/2\pi$ $Q_y = \Delta\mu_y/2\pi$





Role of symmetry:
Cancellation of imaginary part of driving terms occur if the cell is symmetric





Re-adapetd from A. Streun

sensitivity matrices (and SVD inversion)

Linear relations between resonance driving terms and multipole gradients

$$\begin{pmatrix} \searrow & & \vdots & & \swarrow \\ \cdots & \sum\limits_{n\in m_m} & \beta_{xn}^{(j+k)/2}\beta_{yn}^{(l+m)/2}\eta_n^p \mathrm{e}^{\mathrm{i}\{(j-k)\mu_{xn}+(l-m)\mu_{yn}\}} & & \cdots \\ \nearrow & & \vdots & & \nwarrow \end{pmatrix}_{9\times M_{\mathrm{sext}}} \cdot \begin{pmatrix} \vdots \\ (b_3L)_m \\ \vdots \end{pmatrix}_{M_{\mathrm{sext}}\times 1} = \begin{pmatrix} \vdots \\ \sum\limits_{n}^{N_{\mathrm{quad}}} (b_2l)_n \cdots \\ \vdots \end{pmatrix}_{1\times 9}$$

using M_{sext} sextupoles for N driving terms **J. Bengtsson, SLS 97-9, (1997)**

Linear relations can be extended to octupoles, to compensate resonances or amplitude detuning terms, e.g.

$$\delta\vec{\nu}_{\mathrm{oct}} = \mathbf{B}_{\mathrm{oct}}\vec{b}_4$$

$$\begin{pmatrix} \partial Q_x/\partial J_x \\ \partial Q_y/\partial J_y \\ \partial Q_y/\partial J_x \\ \partial^2 Q_x/\partial\delta^2 \\ \partial^2 Q_y/\partial\delta^2 \end{pmatrix} = \frac{3}{8\pi}\begin{pmatrix} (\beta_x)_1^2 & \cdots & (\beta_x)_{N_{\mathrm{oct}}}^2 \\ -2(\beta_x\beta_y)_1 & \cdots & -2(\beta_x\beta_y)_{N_{\mathrm{oct}}} \\ (\beta_y)_1^2 & \cdots & (\beta_y)_{N_{\mathrm{oct}}}^2 \\ 4(D_x^2\beta_x)_1 & \cdots & 4(D_x^2\beta_x)_{N_{\mathrm{oct}}} \\ -4(D_x^2\beta_y)_1 & \cdots & -4(D_x^2\beta_y)_{N_{\mathrm{oct}}} \end{pmatrix}\begin{pmatrix} b_{4,1} \\ \\ \\ \\ b_{4,N_{\mathrm{oct}}} \end{pmatrix}$$

using N_{oct} octupoles for 5 detuning terms **S. Leemann et al., PRSTAB 14, (2011)**

Numerical algorithms

Based on numerical search of parameter space

- **GLASS (GLobal Search of All Stable Solutions)**
- **gradient search, symplex, least square, ...**
- **genetic algorithms, MOGA, particle swarm, (or just random search ☺)**

Accurate numerical calculation of the objectives (tracking-based)

- **dynamic aperture, momentum aperture (s-dependent)**
- **FMA, detuning terms, diffusion rates, RDT, lifetime, injection eff.**
- ***verified experimentally: Diamond, SOLEIL, ESRF, SPEARIII, NSLS-II, ...***

Realistic models can be used *directly in the optimisation stage*

- **engineering apertures, IDs, full 6D motion with RF, radiation damping**
- **errors in magnets: fringe fields, systematic and random multipoles**
- **misalignments: girders, individual magnets, BPMs**

Parallelised on clusters (large throughput)

MOGA

The use of MOGA in the optimisation of synchrotron light sources was pioneered by M. Borland and colleagues and implemented in elegant/pelegant

Objectives: simultaneous optimisation of **multiple objectives**, particularly apt to cases where objectives are conflicting

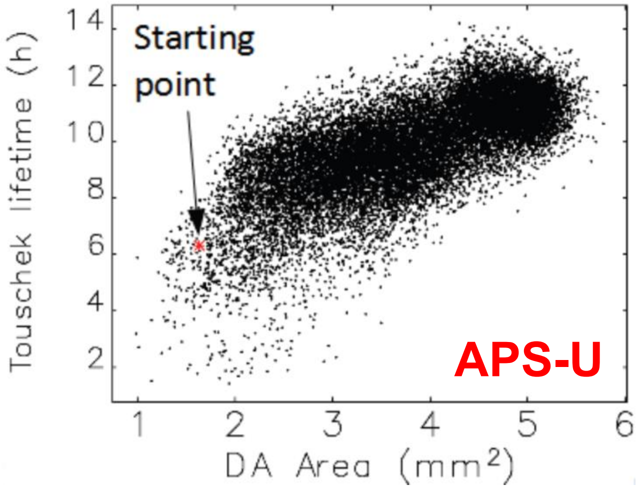
Parameters: suitable for large dimension parameter spaces ensuring the search of **global minimum**

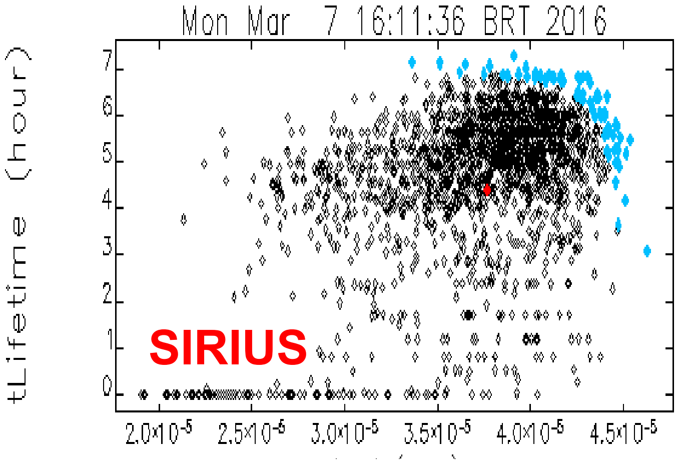
Populations choice: a **population** evolves over a number of **generations**. Mating techniques and selection criteria mimic evolutionary processes: mutations (i.e. crossover, inversion, …) selection of dominant solutions (dominant individuals)

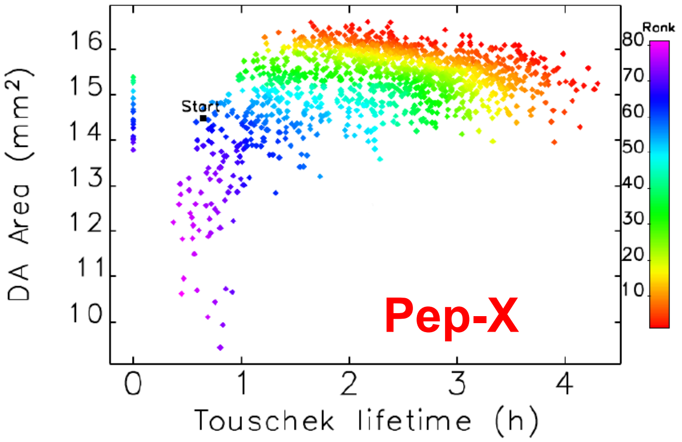
Results: indicates the best trade-off between objectives in the **Pareto-front**

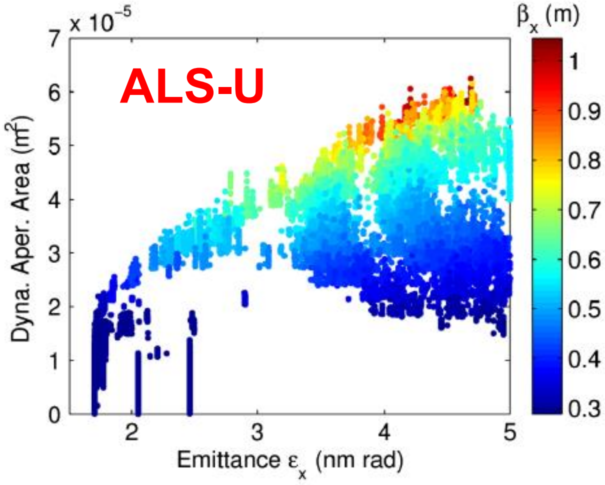
Parallel implementation of genetic algorithm and sorting (NGSA-II) are available. Explore **large portion** of the parameters space with **high accuracy.**

MOGA optimisation





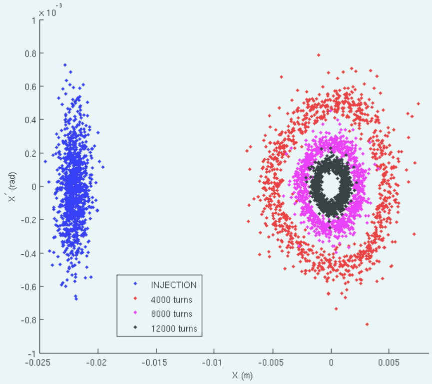


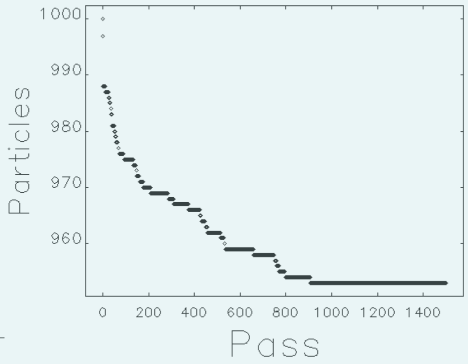


Further objectives in MOGA

Many objectives have been trialled: objective choice ranges from the injection efficiency computed with 6D tracking of injected beam (slow computation!) to proxies of the DA given by driving terms (fast computation!)

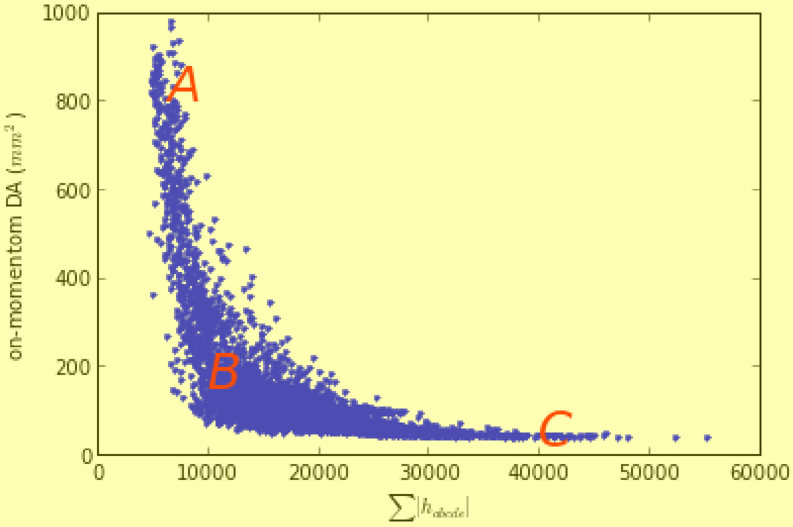
injection tracking in phase space and captured particles vs turns





full simulation of the injection process (6D) takes into account DA and MA for injection

correlation DA ↔ RDT



Not perfect but large DA always corresponds to small RDT

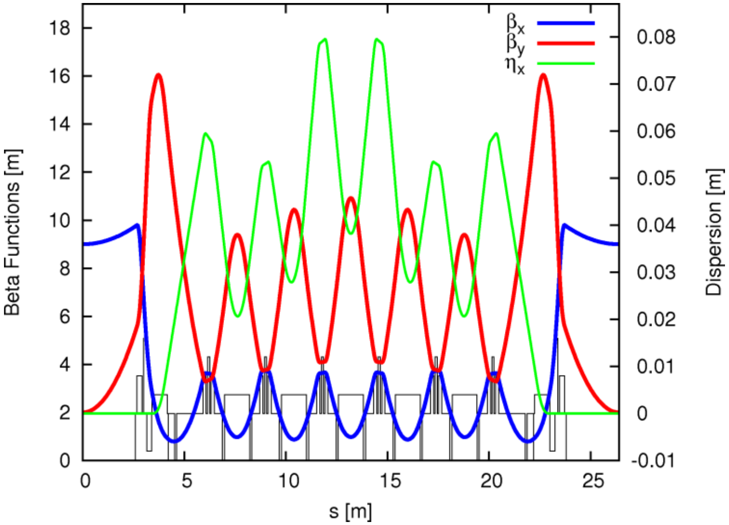
Y. Li et al, PRSTAB, 14, 045001,(2011)

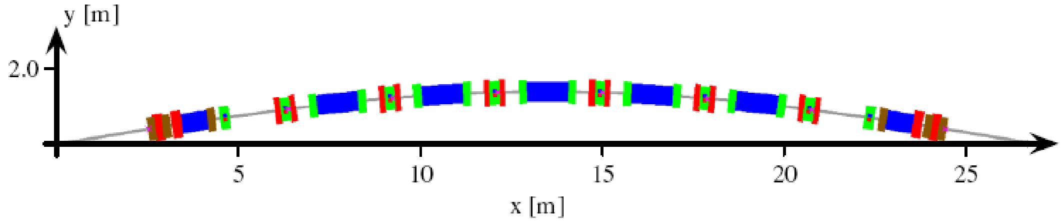
Examples

MBA		
	MAX IV, Pep-X, ALS-U Sirius, Elettra U, ILSF, ...	detuned TME cells with small Dx
Hybrid MBA		
	ESRF, APS U, HEPS	LGB + D_x bump + paired sexts.
DDBA-DTBA		
	Diamond-II	mid-straigth section in MBA arcs (M even)
Reverse bends		
	SLS-II	cells with reverse bends

MBA: MAX IV

MAX IV is the first low emittance light source based on 7BA lattice





528 m, 330 pm bare lattice (20 cells)
5 detuned TME cells and two matching cells
distributed sextupoles in the arc for chromatic correction

Nonlinear dynamics optimisation based on

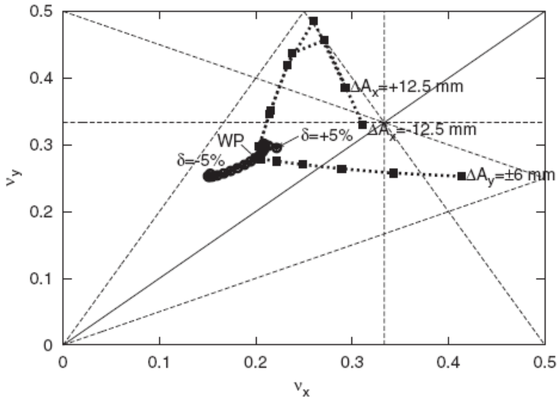
minimisation of detuning with amplitude terms → weak octupoles
minimisation of resonance driving terms via SVD of sensitivity matrix
numerical evaluation of lattices based on FMA and direct tracking

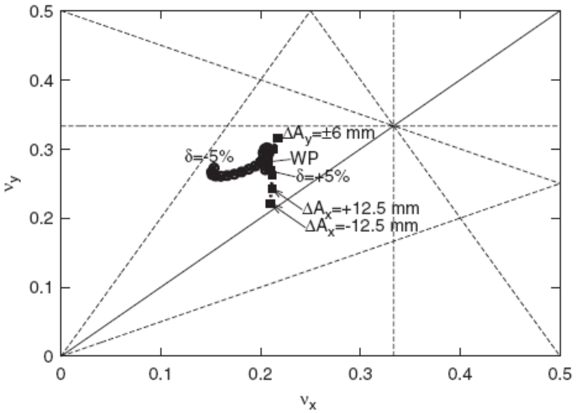
MAX IV – detuning and diffusion maps

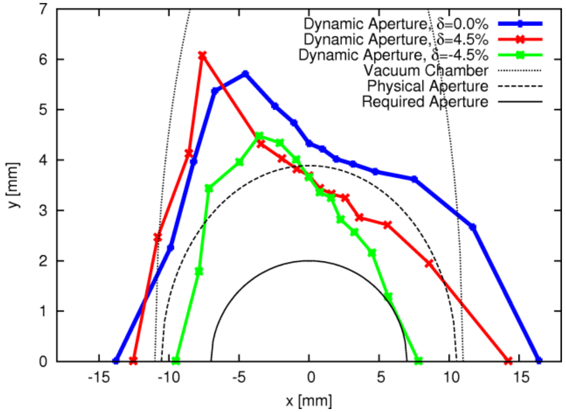
Driving terms minimisation with

5 sextupoles families distributed sextupoles

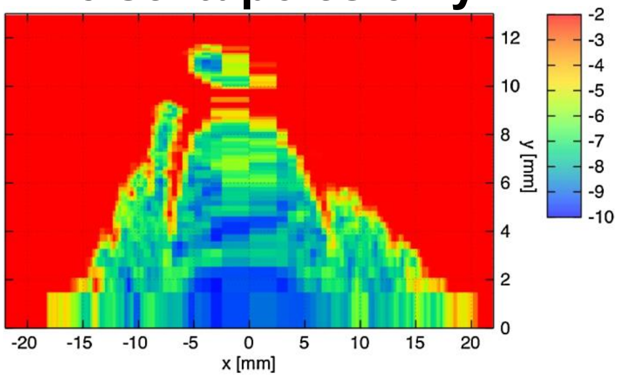
3 octupoles families to control amplitude dependent tuneshift



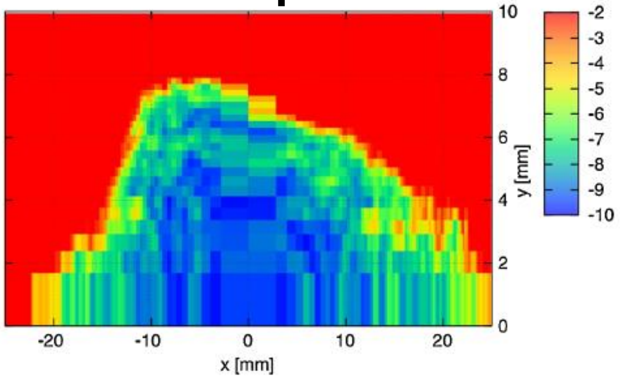


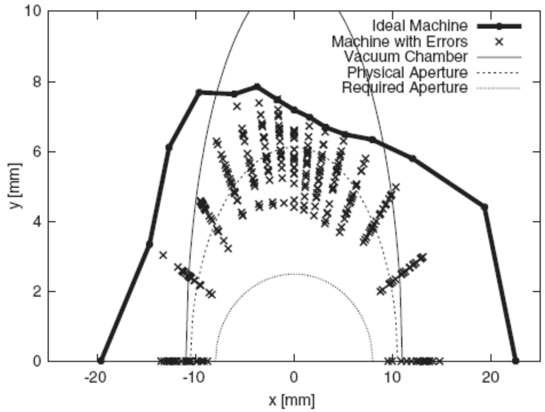


5 sextupoles only



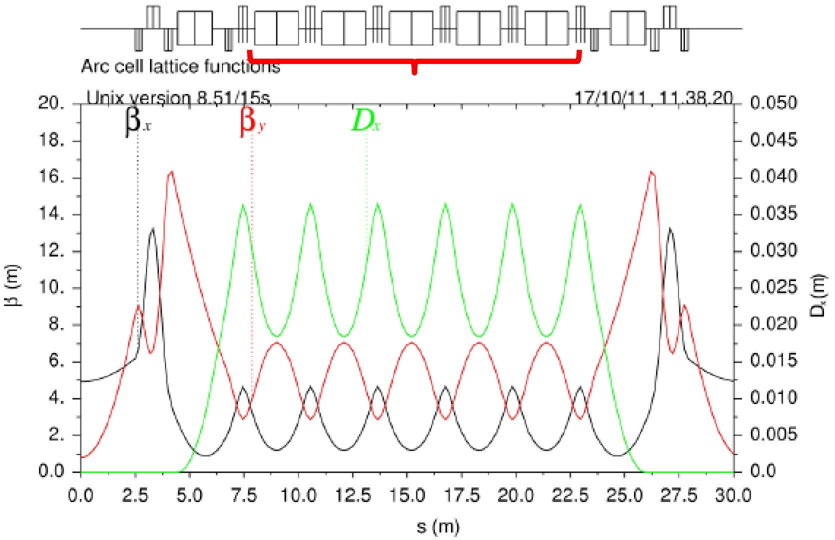
with octupoles





FMA used to study tune footprint, FM folding, resonance crossing and diffusion rates. Direct tracking with errors for robustness check

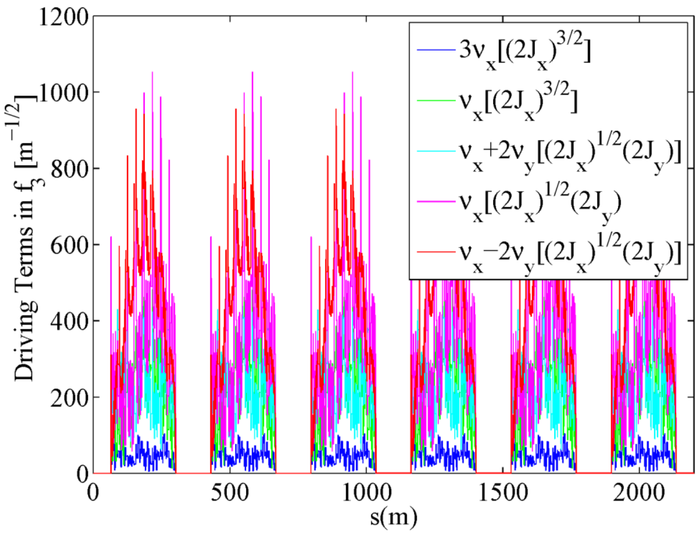
Pep-X: 7BA achromat

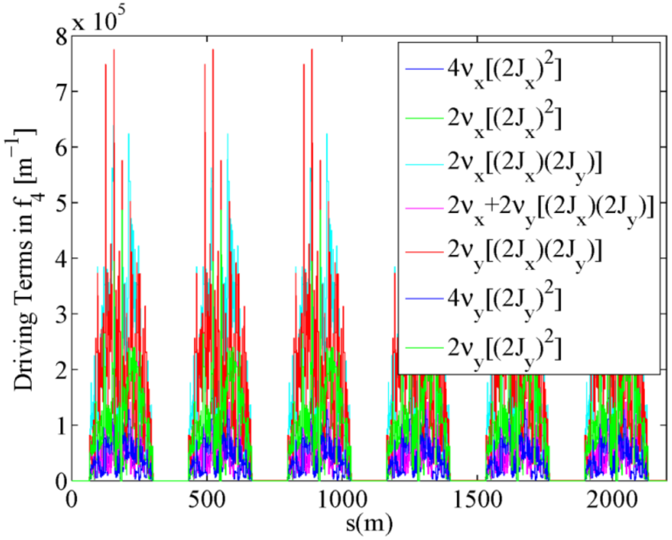


Nat. emittance 29 pm-rad (4.5 GeV)
5TME unit cells
Cell phase advances: μ_x=(2+1/8) x 360^0, μ_y=(1+1/8) x 360^0

Compensation of driving terms achieved after 8 cells
10 mm DA in high beta section

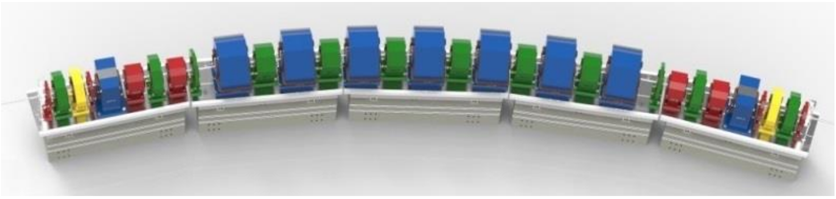
All Geometrical 3rd and 4th Resonances compensated except $2\nu_x$-$2\nu_y$ targeted explicitly using additional sextupoles (Y. Cai et al. PRSTAB 15, (2012))

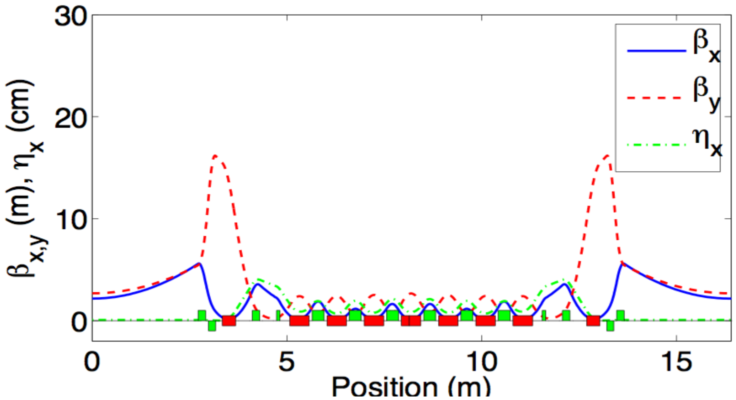


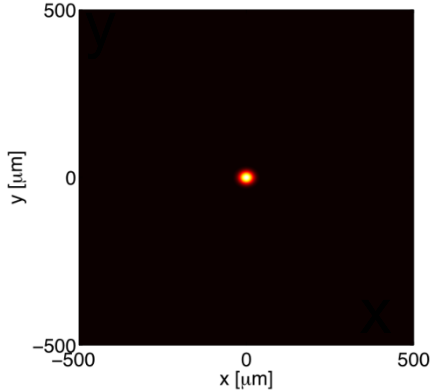


MBA: ALS-U

ALS-U: 9BA @2 GeV







with full coupling:

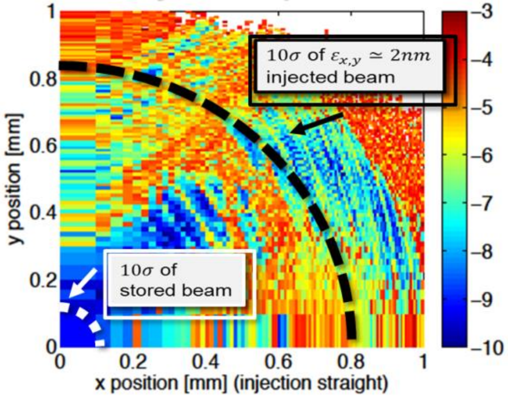
$\varepsilon_x \simeq 50\ pm$

$\varepsilon_y \simeq 50\ pm$

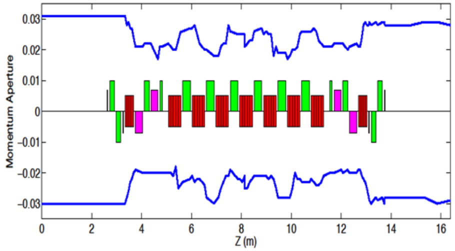
Courtesy C. Steier, C. Sun, M. Venturini

12 cells 9BA lattice (100 pm) has quad components in all bendings and 2 families of chromatic + 2 families of harmonic sextupoles

Frequency map analysis & Dynamic Aperture



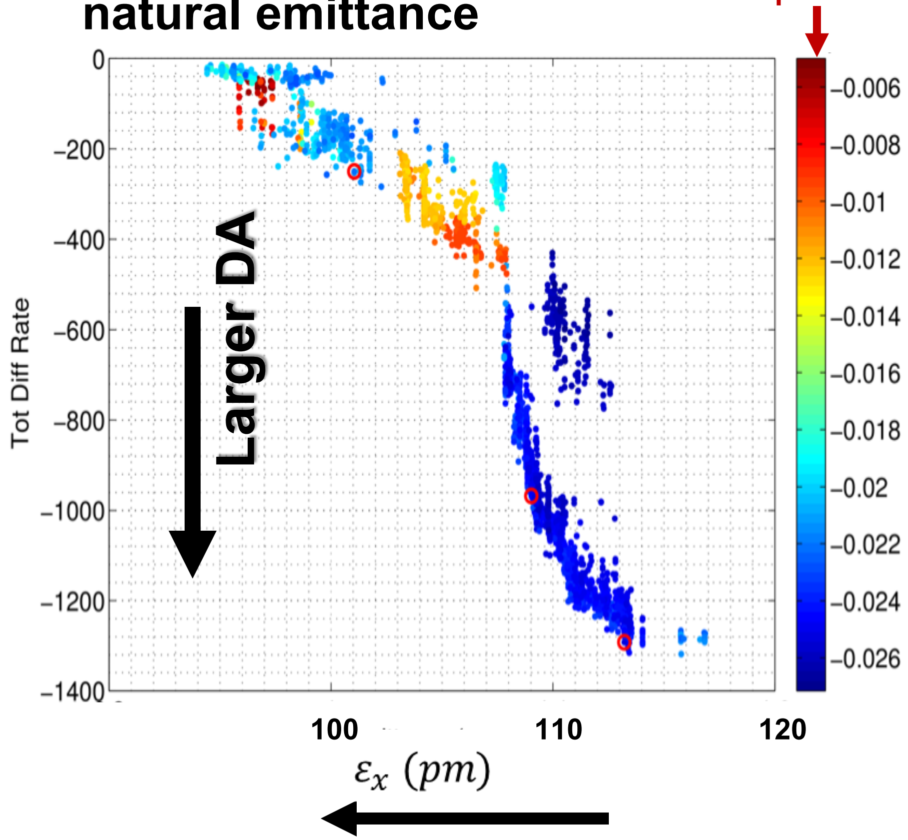
Momentum acceptance in 2-3% range



- **Lattice design work still in progress**
- **Options to use antibends are considered (20% reduction in ε_x)**
- **Small DA requires on-axis injection and small-emittance injected beam**

ALS-U: extensive use of MOGA

Trade-off between DA and natural emittance



Momentum Aperture

Larger DA

Smaller emittance

**Natural emittance in the absence of radiation effects from IDs*

<u>Three</u> objectives

- natural emittance
- weighted average diffusion rate
- momentum aperture

Integrated optimisation linear/nonlinear

Independent variables

- gradient of all focussing elements
- strength of harmonic sextupoles

DA calculations include normal and skew gradient errors
(stated emittance refer to no-error uncoupled lattice)

Constraints

$\beta_{x,y}$ < 3 m in straight sect.
g < 100 T/m

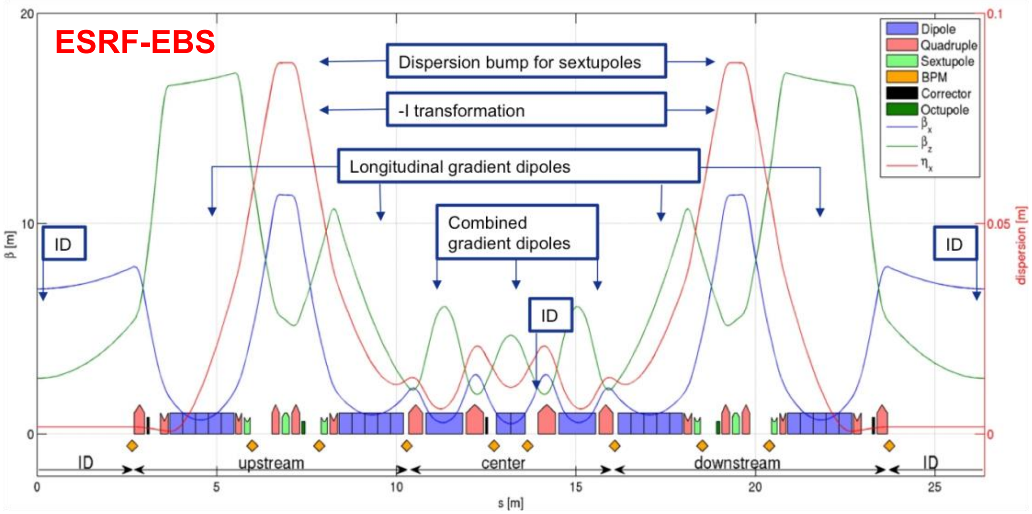
MOGA tends to push the H phase advance between the chromatic sext. to 5π

Hybrid MBA

Hybrid 7BA cell pioneered at ESRF-EBS (130pm) and adapted to APS U (67 pm)

HEPS (60 pm)

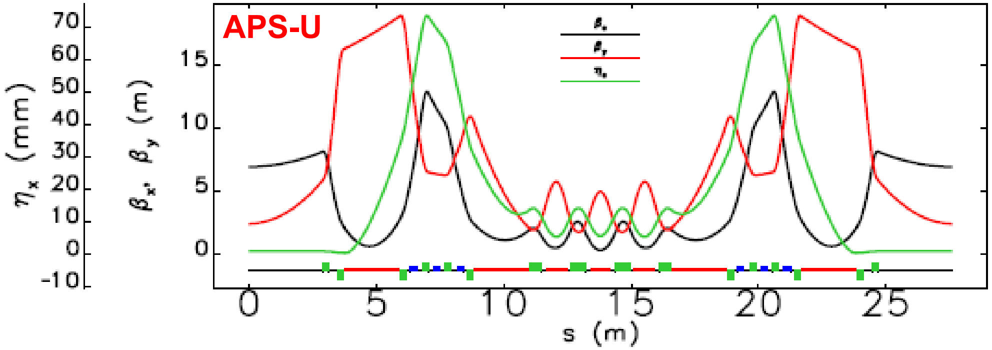
- **Dispersion bump for chromatic sextupoles;**
- **3π / π phase advance for cancellation of sextupole driving terms;**
- **Longitudinal gradient bend for emittance minimisation**
- **high beta section for injection at ESRF-EBS – swap out inj. at APS-U, HEPS**

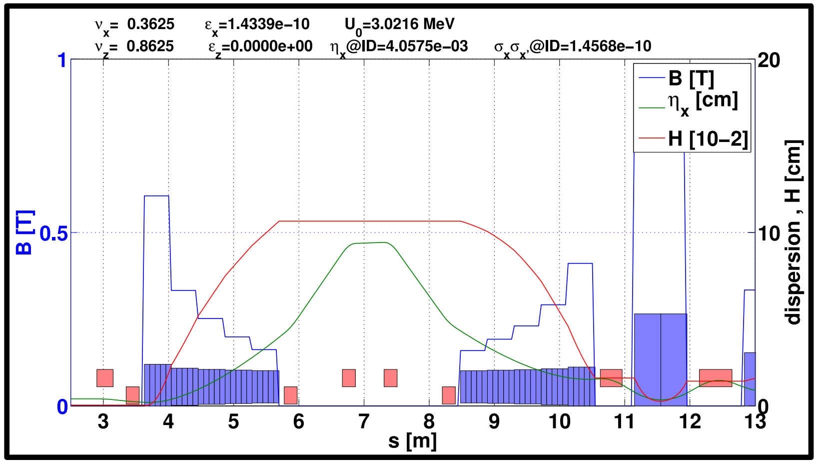


longitudinal gradient dipoles:

- **to reduce the emittance via bending where H_{inv} is small**
- **increase the dispersion in bump**

$$\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\left\langle H_{inv} / \rho^3 \right\rangle_{dip}}{\left\langle 1 / \rho^2 \right\rangle_{dip}}$$

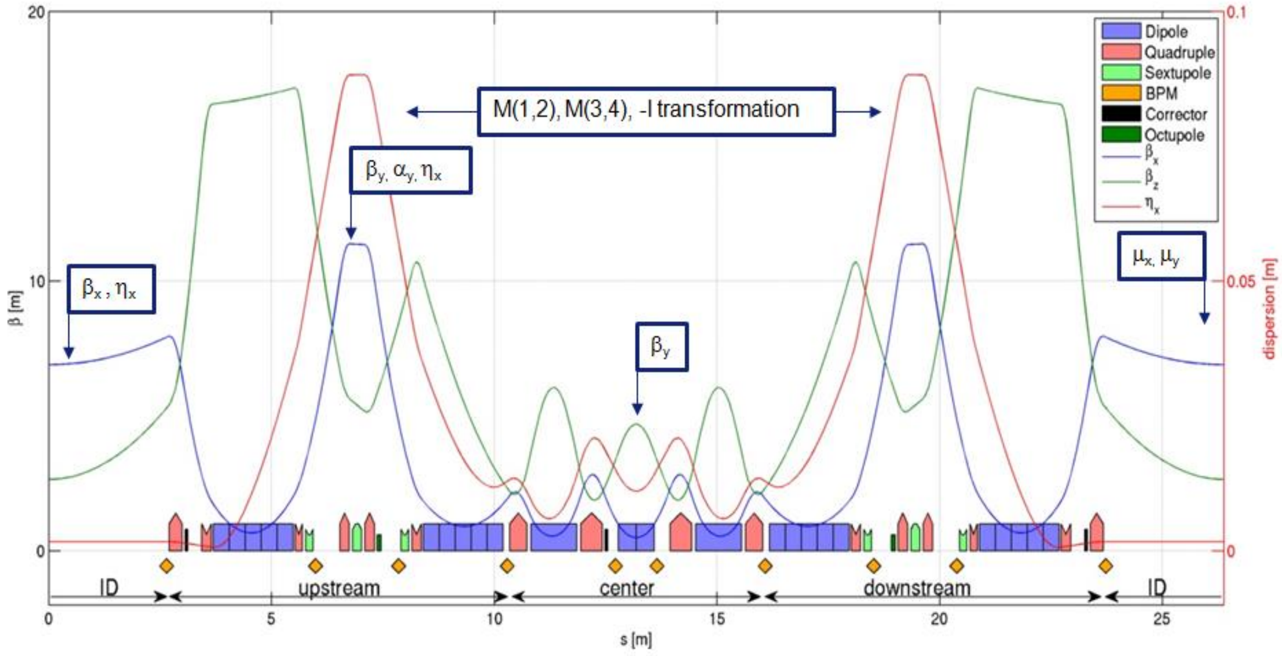




HMBA optimisation strategy

Combined linear – nonlinear optics optmisation: fine readjustment of the linear optics are used to target non-linear dynamics objectives

Linear optics parameters are modified while keeping the chromaticity corrected with two sextupole families in the dispersive bump. Effect on DA and Lifetime is checked. Nonlinear elements (1 sext. and 1 oct.) are also included



Parameter	**main target**
μ_y (SF-SF)	DA
M_{12} (SF-SF)	dQ_y/dJ_x
M_{34} (SF-SF)	dQ_x/dJ_x
α_y @ SF	dQ_y/dJ_y
β_x @ SF	$\varepsilon_{x,}$ nat. $\xi_{x,y}$
D_x @ SF	trade off ε_x and ξ_x
β_x @ ID	σ_x , ε_x

Nine quadrupole per half cell set nine optics parameters selected after the assessment of the effect of each of them on the nonlinear optics.
(Such choice is initially empirical, then optimised using MOGA)

HMBA: MOGA

MOGA is then further used to

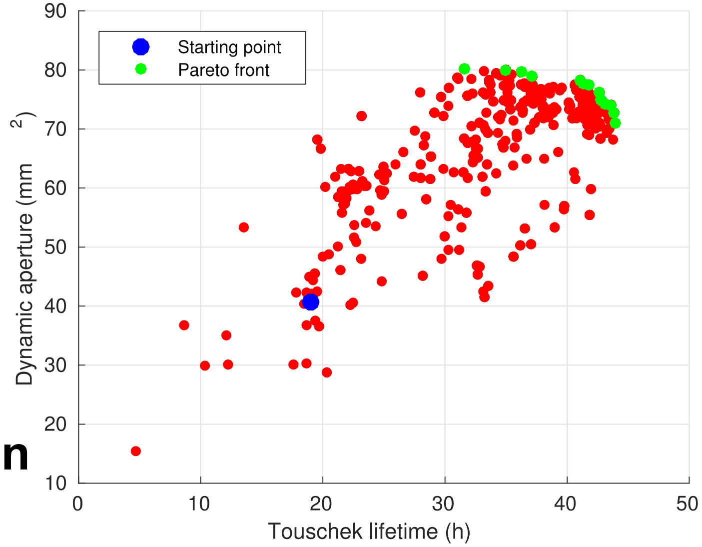
control the quadrupoles and the optics functions (at fixed chromaticity)
control the sextupoles

Objective functions

On-momentum dynamic aperture (special high beta injection cell)
Touschek lifetime computed with Piwinski formula

e.g. MOGA at ESRF-EBS has been used with
6 sextupoles
and 2 octupoles over two cells
then reduced to
3 sextupole
and 1 octupole over two cells

Effect of errors is fully included (10 seeds),
misalignments, BPM, multipoles and their correction

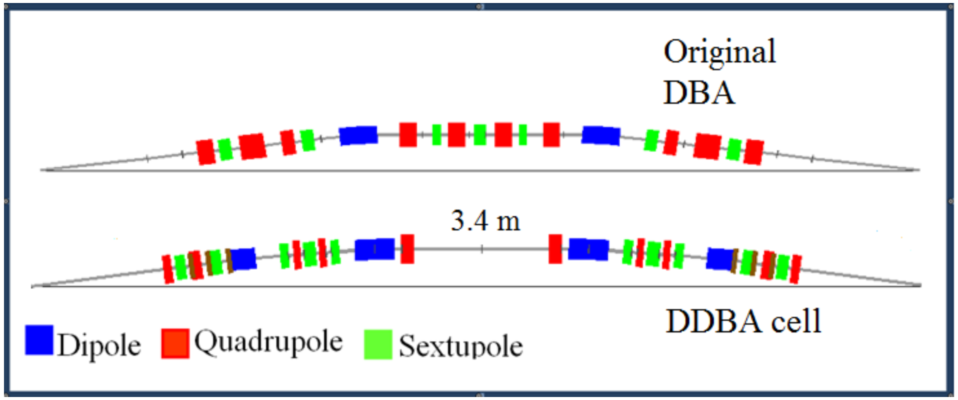


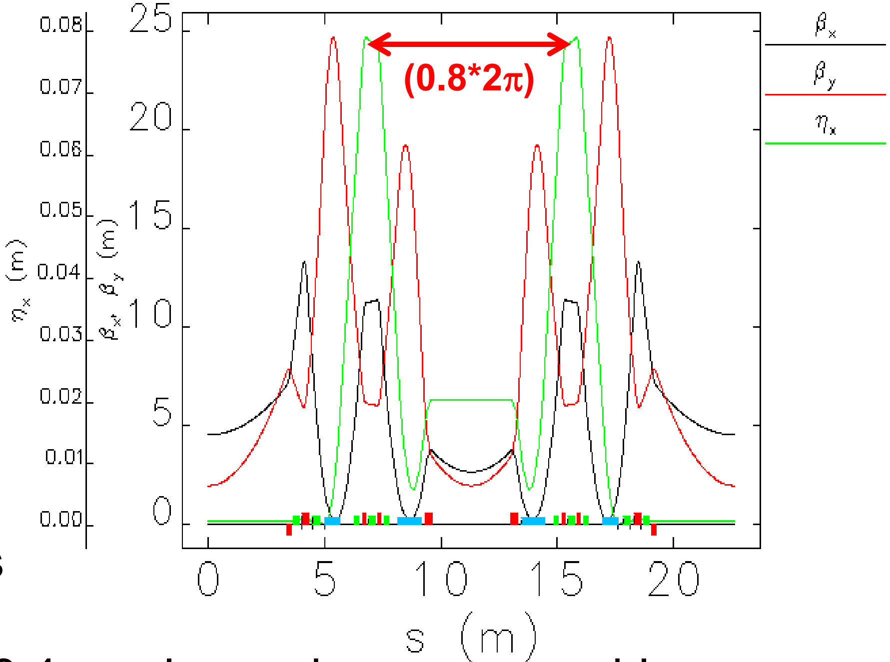
Large chromaticities [e.g. (6,4)] show better dynamics

Diamond II: DDBA cell – 270 pm

The 4BA cell can be modified to introduce an additional straight in the middle of an arc while keeping the emittance small.

doubling the capacity of the ring



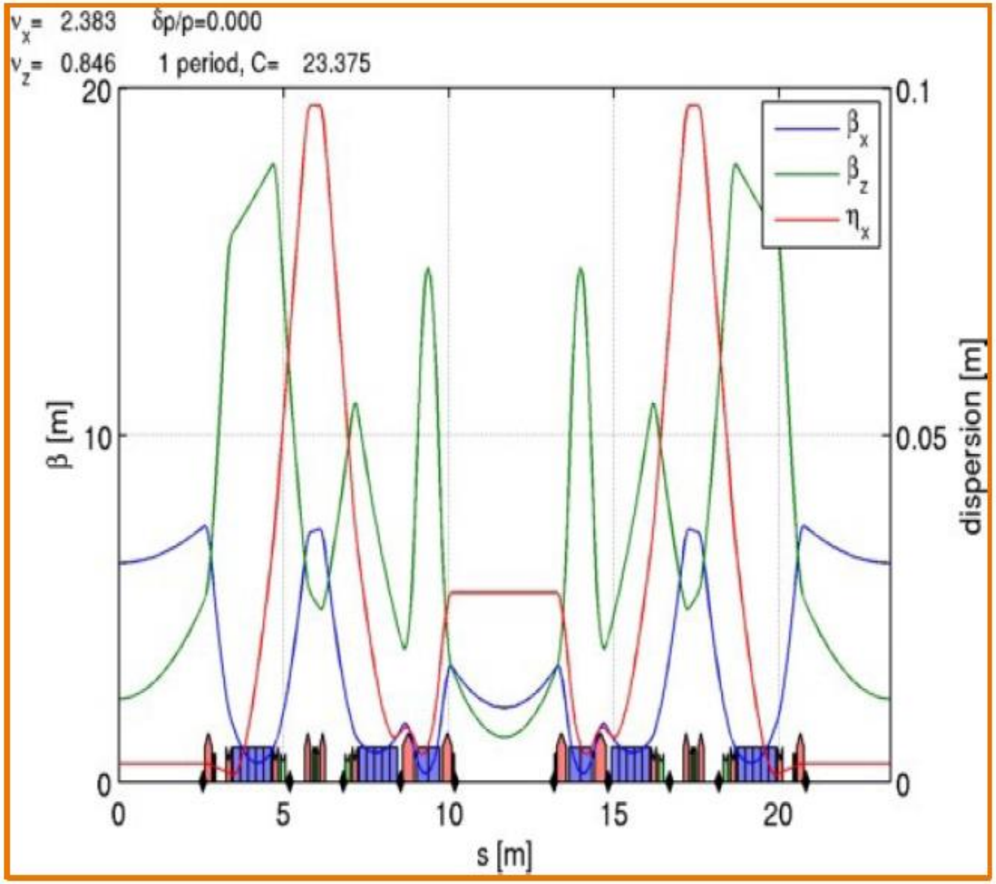


- Increase dispersion at chromatic sextupoles
- removed sextupoles in the new straight
- Longer mid-cell straight section from 3m to 3.4 m – longer is unmanageable
- Problem with horizontal phase advance between chromatic sextupoles (0.8 *2π)
- DA ~ ± 5 mm after extensive MOGA runs

Diamond II: DTBA cell

A more aggressive design has been proposed that merges the ESRF HMBA concept with the Diamond DDBA mid straight section taking the best of both

Use the ESRF cell (7BA with longitudinal gradient dipoles) – removing the mid dipole to make it a 6BA with a straight at the centre



Promising design:

Emittance 120 pm
~ 10mm DA
~ 3 h lifetime

short straight sections ~5m
long straight sections ~8 m
mid-straight section ~3 m

Large beta x for injection under investigation

Diamond II: DTBA cell optimisation

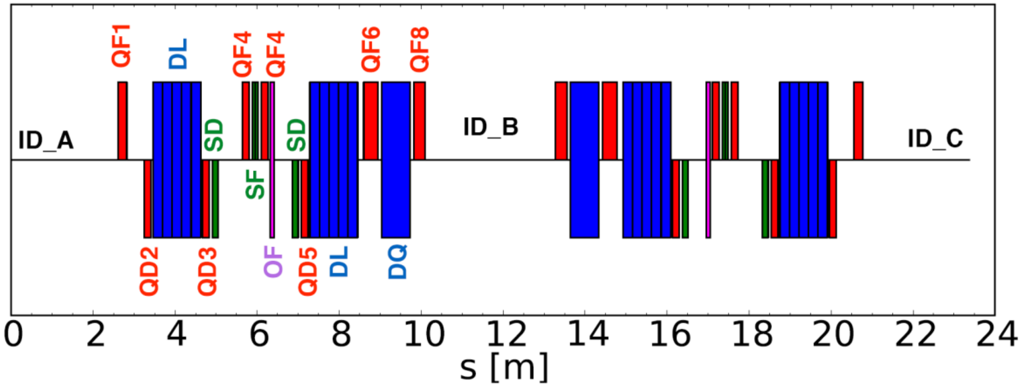
Following the ESRF approach we start with a linear ↔ nonlinear optimisation make a thorough scan of the linear optics parameters that provide the best DA and MA (for a fixed chromaticity)

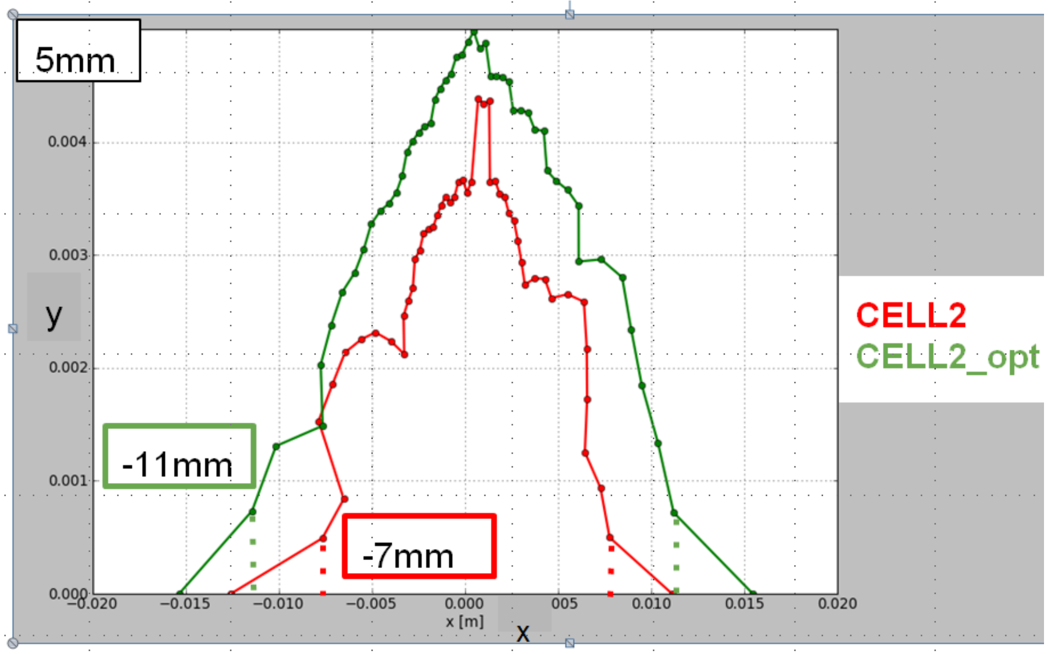
Only quads are changed

Parameter	**main target**
α_y@SF	dQ_y/dJ_y
Octupole	dQ_x/dJ_x
μ_y (SF-SF)	dQ_y/dJ_x
β_x@ID	ε_x
β_x@SF	ε_x and nat. $\xi_{x,y}$
D_x@ (ID)	ε_x and nat. $\xi_{x,y}$

MOGA is then used to optimise 6 sextupole families in two cells.

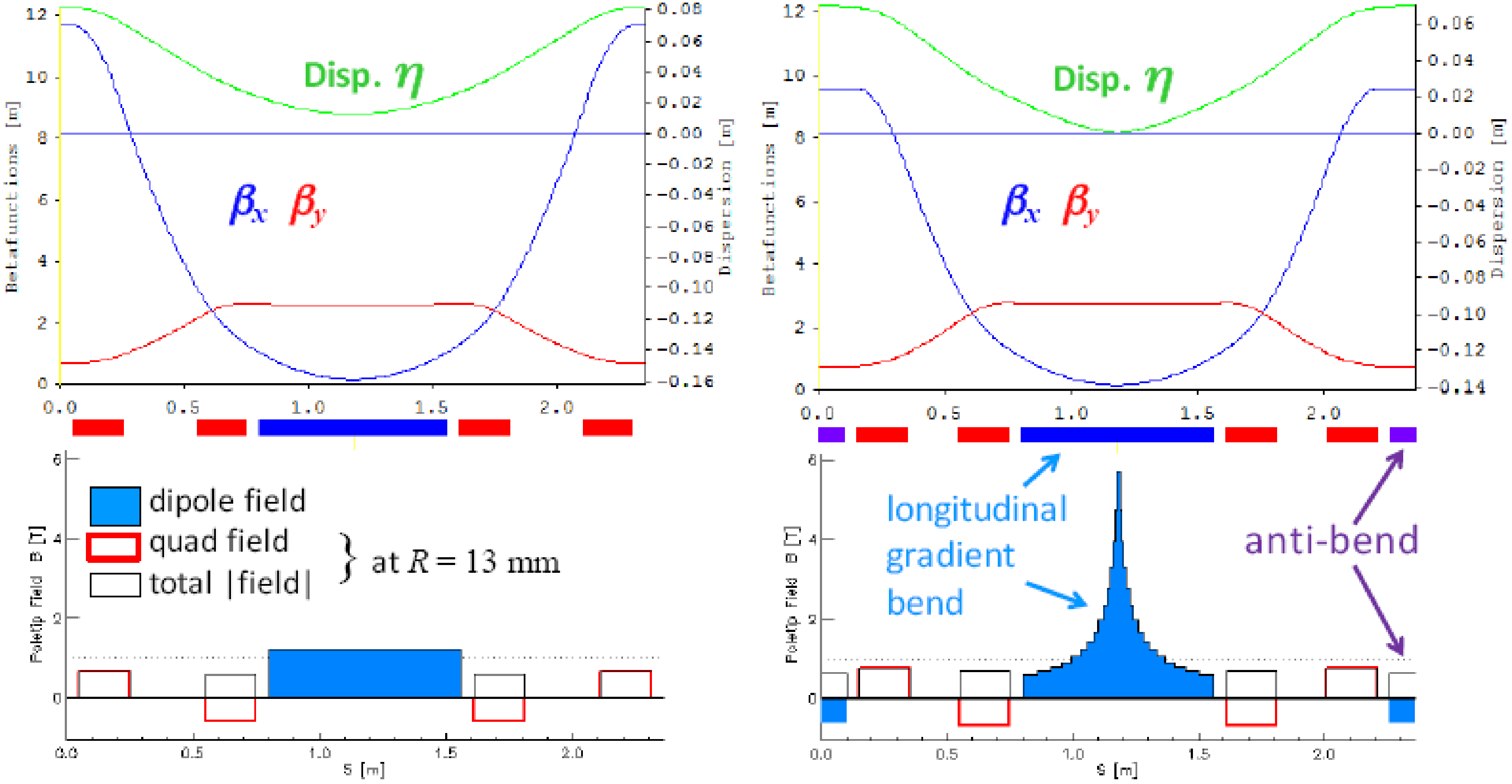
A. Alekou et al, in WEPOW044





SLS II – reverse bends

Combining longitudinal gradient bends and reverse bends to reduce the emittance



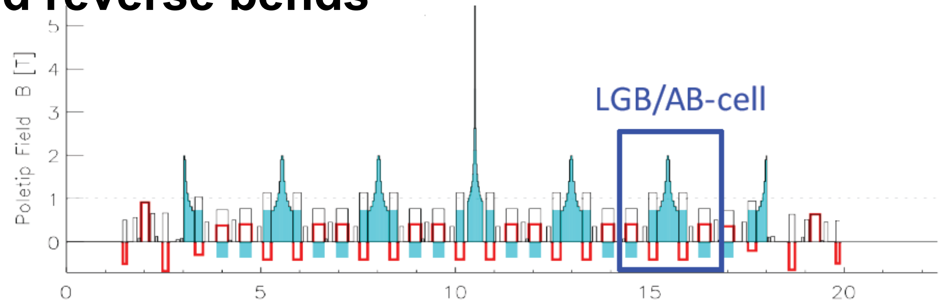
conventional: $\varepsilon = 990\ \mathrm{pm}\ (F = 3.4)$

LGB/AB: $\varepsilon = 200\ \mathrm{pm}\ (F = 0.69)$

Courtesy A. Streun

SLS II - optimisation

SLS-II is the based on a 7BA lattice with longitudinal bends, superbend in the mid-dipole and reverse bends

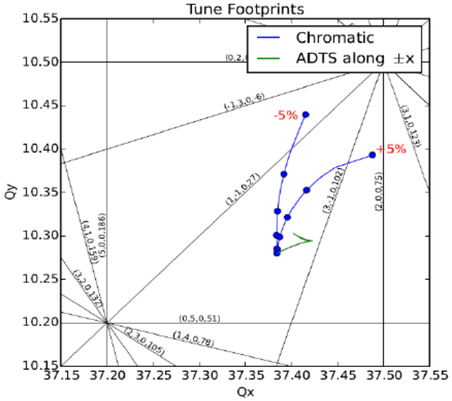


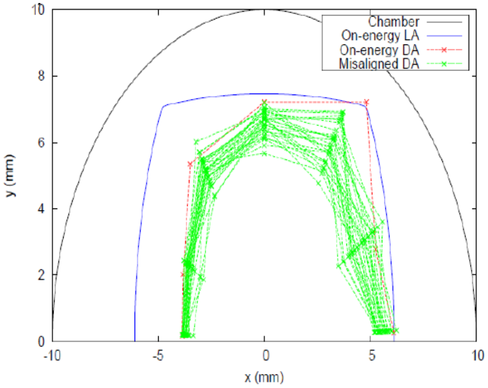
288 m, 140 pm bare lattice (12 cells)
distributed sextupoles in the arc for chromatic correction
4 chromatic; 9 geometric; 10 octupoles

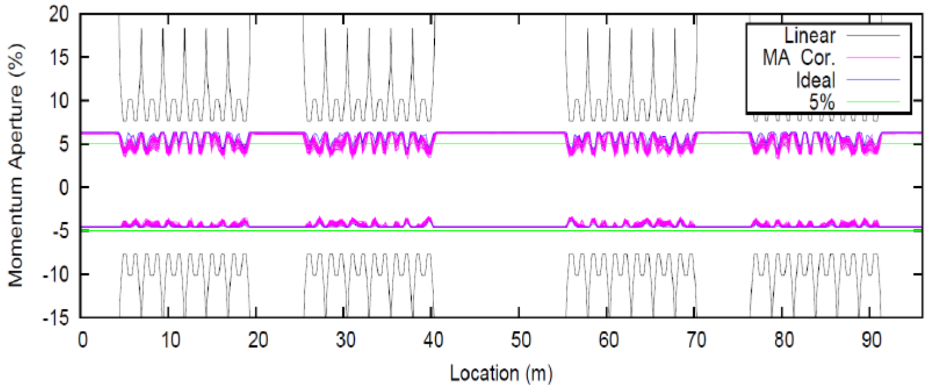
Nonlinear dynamics optimisation based on

- **minimisation of driving terms via phase cancellation in 1st order**
- **minimisation of amplitude dependent tuneshift using octupoles**
- **and some 2nd order driving terms**
- **tracking with errors**
- **MOGA used for DA on momentum and DA at ±dp/p=3% (three obj.)**

DA -4mm/5mm; MA almost 5% (4.5 h)







Conclusions

Since the approval of MAX IV in 2009

ESRF was funded in 2012 (commissioning 2020)
SIRIUS is under construction (commissioning 2018)
many upgrade programmes and new rings proposal developed based on **MBA design with many variants**

Many key drivers: but a crucial one is

growing confidence on nonlinear dynamics optimisation strategies

deterministic algorithms and numerical algorithms (MOGA) provide good solutions

+

accurate calculation of key physical quantities (and expt. agreement)

+

robust optimisation includes the effect of errors

The development of ultra low emittance rings is now seriously tackled by a large community, in EU, US and Asia.

Low emittance ring community

The last IPACs counted about 20 new studies around the world

The LOWεRING network sponsored by EuCARD2 is playing an important role in fostering these developments

- **ICFA Low Emittance Rings Workshops (LowERing 2010, 2011)**
- **XDL 2011 Workshops for ERLs and DLSRs, Cornell, June 2011**
- **Beijing USR Workshop, Huairou, October 2012**
- **DLSR Workshop, SPring-8, December 2012**
- **Low Emittance Ring Workshop, Oxford, July 2013**
- **DLSR Workshop, SLAC, December 2013**
- **Workshop on collective effects (TWIICE), Paris, 2014**
- **Workshop on Low Emittance Rings Technology (ALERT), Valencia, 2014**
- **Low Emittance Rings Workshop (LER2014), Frascati, September 2014**
- **DLSR Workshop, Argonne, November 2014**
- **Workshop on Low emittance ring design, Barcelona (2015)**
- **Low Emittance Rings Workshop (LER2015), Grenoble, September 2015**
- **Workshop on collective effects (TWIICE-2), Abingdon (UK), 2016**
- **DLSR workshop, Hamburg, (2016)**
- **Workshop on Low Emittance Rings Technology (ALERT-2), Trieste, 2016**

- **WP6: low emittance rings**
- **Y. Papahilippou (CERN)**
- **S. Guiducci (INFN)**
- **R. Bartolini**

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