Low emittance tuning in light sources

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Jesus College, Oxford 18th May 2011

Outline

- Introduction to 3rd generation light sources

    Low emittance lattices

- Beam optics studies

    linear optics
    nonlinear optics

- Further techniques for low emittance control

    optics and coupling control with spectral lines analysis
    dispersion and couplign free steering

3rd generation storage ring light sources

1992	**ESRF**, France (EU)	6 GeV
	ALS, US	1.5-1.9 GeV
1993	**TLS,** Taiwan	1.5 GeV
1994	**ELETTRA**, Italy	2.4 GeV
	PLS, Korea	2 GeV
	MAX II, Sweden	1.5 GeV
1996	**APS**, US	7 GeV
	LNLS, Brazil	1.35 GeV
1997	**Spring-8**, Japan	8 GeV
1998	**BESSY II**, Germany	1.9 GeV
2000	**ANKA**, Germany	2.5 GeV
	SLS, Switzerland	2.4 GeV
2004	**SPEAR3**, US	3 GeV
	CLS, Canada	2.9 GeV
2006:	**SOLEIL**, France	2.8 GeV
	DIAMOND, UK	3 GeV
	ASP, Australia	3 GeV
	MAX III, Sweden	700 MeV
	Indus-II, India	2.5 GeV
2008	**SSRF**, China	3.4 GeV
2009	**PETRA-III**, D	6 GeV
2011	**ALBA**, E	3 GeV

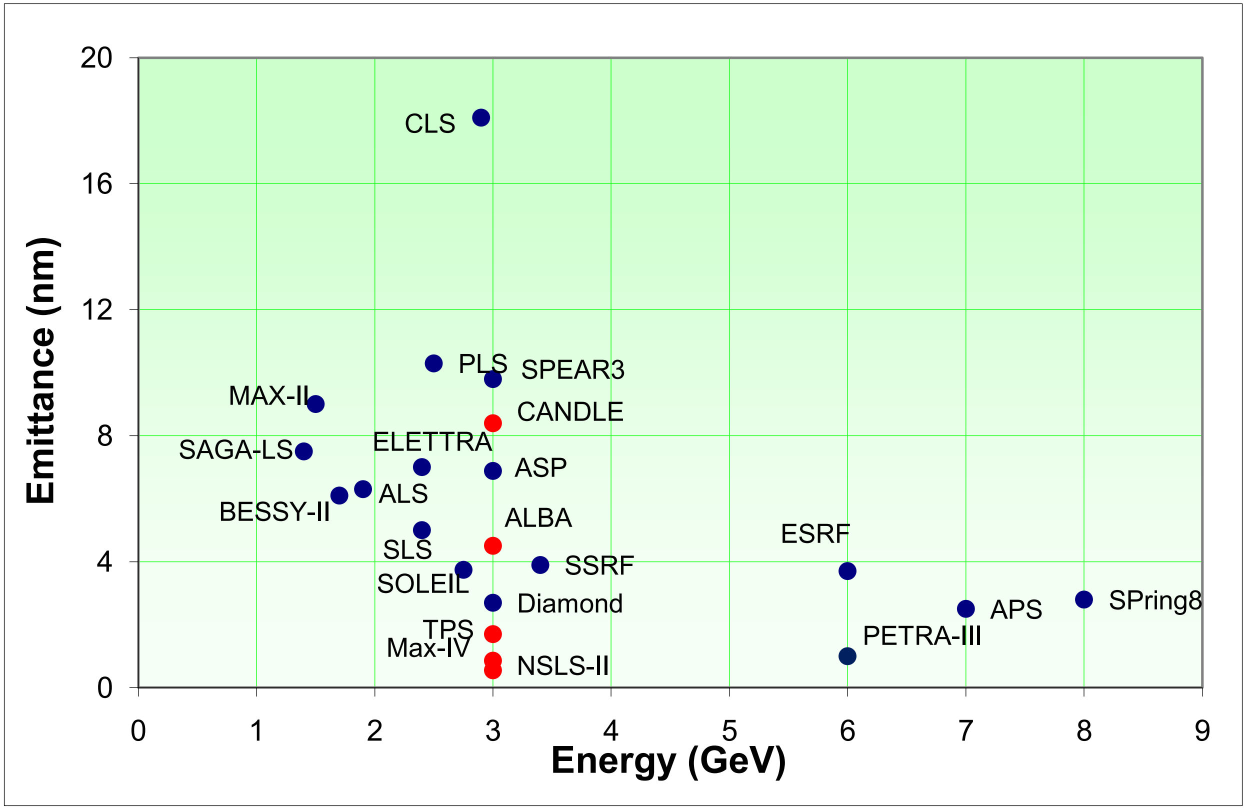
3rd generation storage ring light sources

under construction or planned

> 2011	**NSLS-II**, US	3 GeV
	SESAME, Jordan	2.5 GeV
	MAX-IV, Sweden	1.5-3 GeV
	TPS, Taiwan	3 GeV
	CANDLE, Armenia	3 GeV

Brilliance and low emittance

The brilliance of the photon beam is determined (mostly) by the electron beam emittance that defines the source size and divergence



$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

$$\Sigma_x = \sqrt{\sigma_{x,e}^2 + \sigma_{ph,e}^2}$$

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

$$\sigma_{x,e} = \sqrt{\varepsilon_x \beta_x + (D_x \sigma_\varepsilon)^2}$$

$$\sigma_{x',e} = \sqrt{\varepsilon_x \gamma_x + (D'_x \sigma_\varepsilon)^2}$$

Low emittance lattices

Lattice design has to provide **low emittance** **and** **adequate space in straight sections** to accommodate long Insertion Devices

$$\varepsilon_x = \frac{\gamma^2}{J_x \rho} < H >_{\text{dipole}} \qquad H(s) = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Minimise β and D and be close to a waist in the dipole

Zero dispersion in the straight section was used especially in early machines

avoid increasing the beam size due to energy spread
hide energy fluctuation to the users
allow straight section with zero dispersion to place RF and injection
decouple chromatic and harmonic sextupoles

DBA and TBA lattices provide low emittance with large ratio between

$$\frac{\text{Length of straight sections}}{\text{Circumference}}$$

Flexibility for optic control for apertures (injection and lifetime)

DBA and TBA

Double Bend Achromat (DBA)

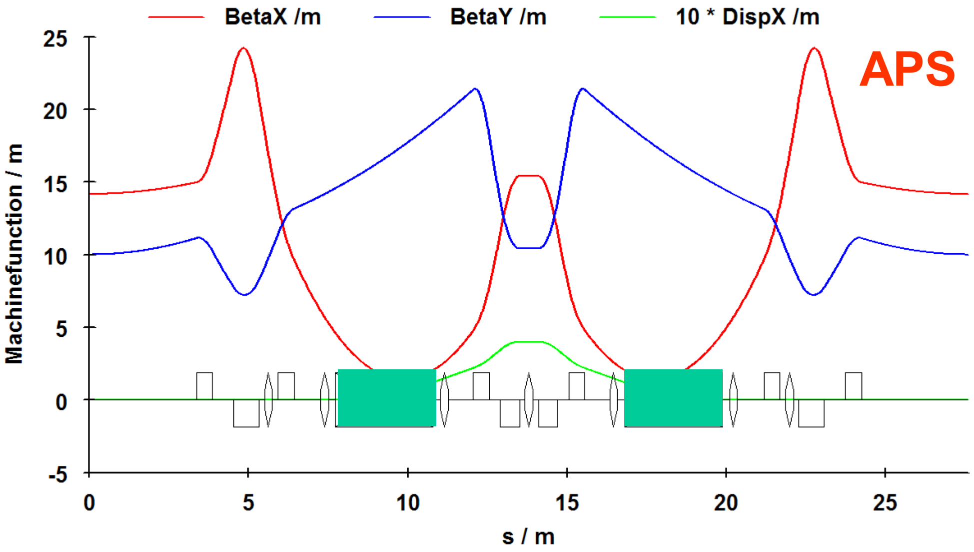
Triple Bend Achromat (TBA)

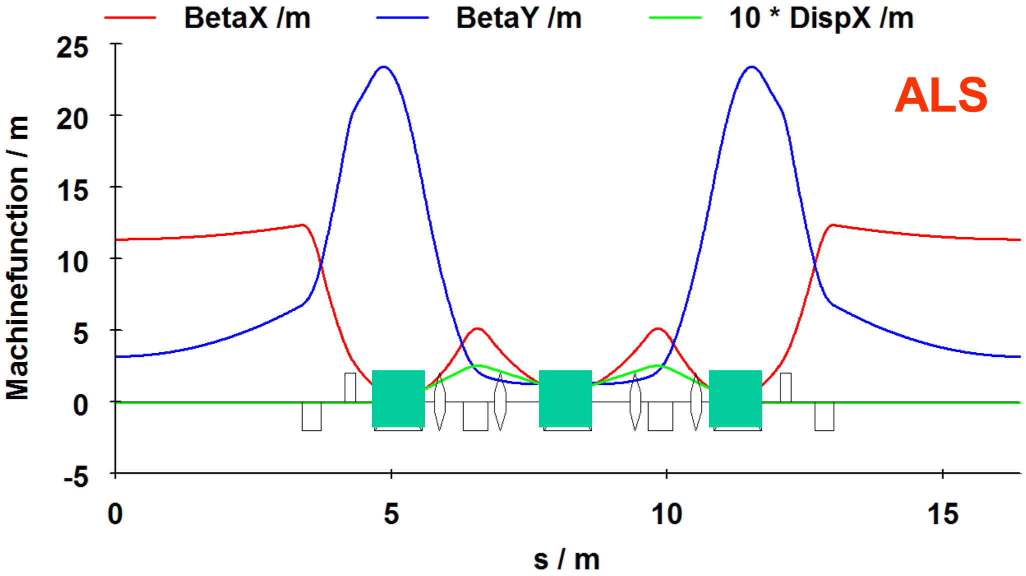
DBA used at:
ESRF,
ELETTRA,
APS,
SPring8,
Bessy-II,
Diamond,
SOLEIL,
SPEAR3
...

TBA used at
ALS,
SLS,
PLS,
TLS
…

$$\varepsilon_x = F\frac{C_q\gamma^2\theta_b^3}{J_x} \propto \frac{1}{N_b^3}$$

$$F_{MEDBA} = \frac{1}{4\sqrt{15}} \qquad \mathrm{F}_{\mathrm{METBA}} = \frac{7}{9}\mathrm{F}_{\mathrm{MEDBA}}$$





Breaking the achromatic condition

Leaking dispersion in straight sections reduces the emittance

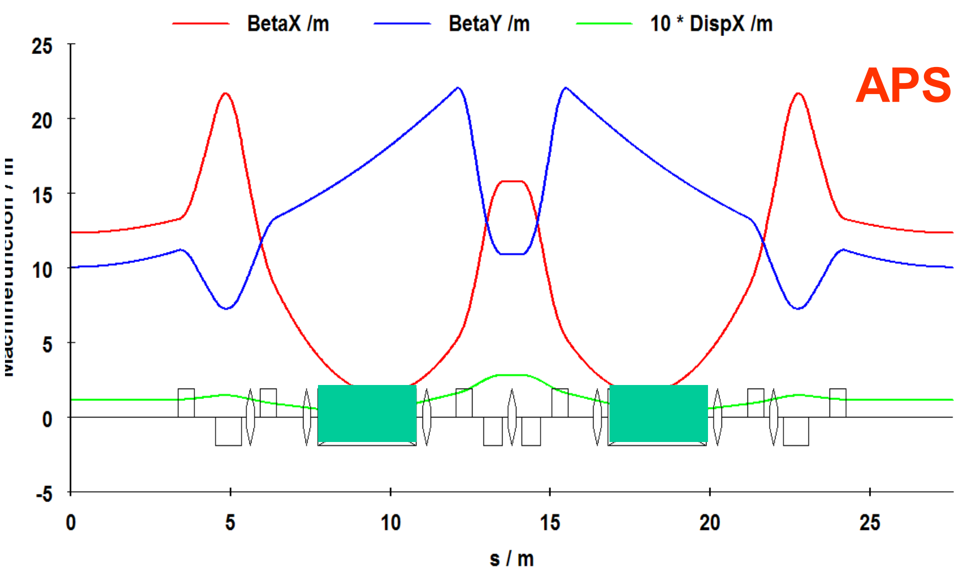
ESRF	7 nm → 3.8 nm
APS	7.5 nm → 2.5 nm
SPring8	4.8 nm → 3.0 nm
SPEAR3	18.0 nm → 9.8 nm
ALS (SB)	10.5 nm → 6.7 nm

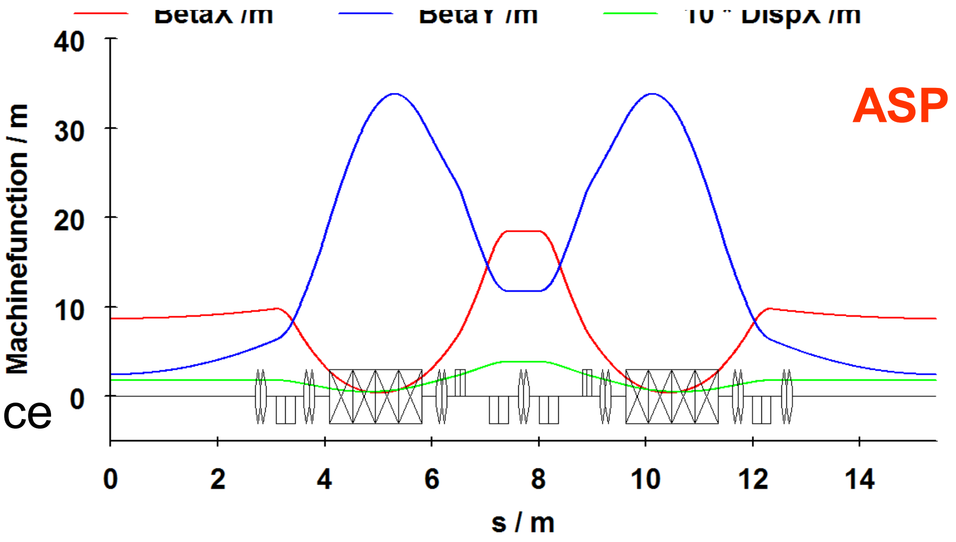
$$F_{MEDBA} = \frac{1}{4\sqrt{15}} \qquad F_{MEDBA-disp} = \frac{1}{12\sqrt{15}}$$

The emittance is reduced but the dispersion in the straight section increases the beam size

$$\sigma_x = \sqrt{\varepsilon_x \beta_x + (\sigma_E D_x)^2}$$

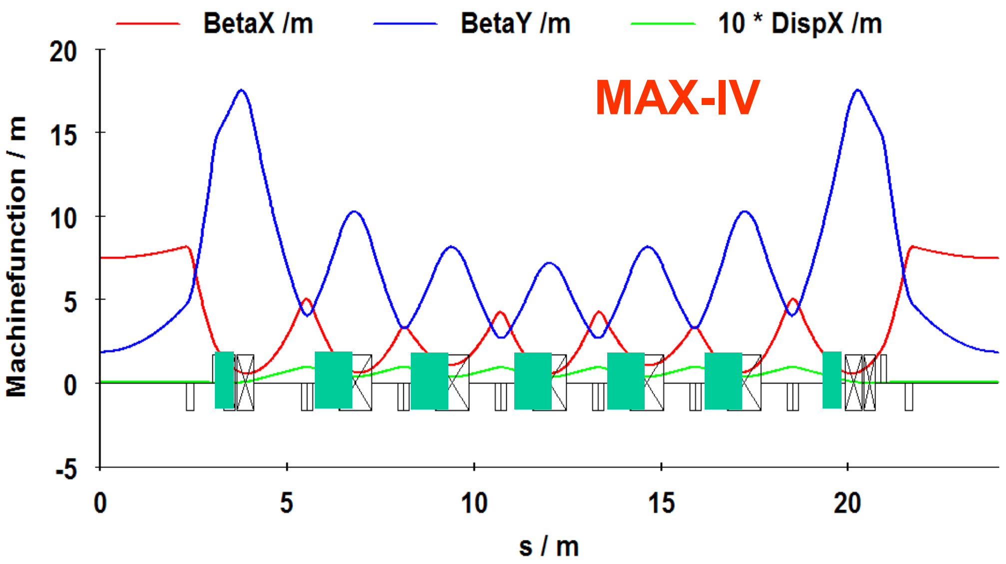
Need to make sure the effective emittance and ID effects are not made worse





Low emittance lattices

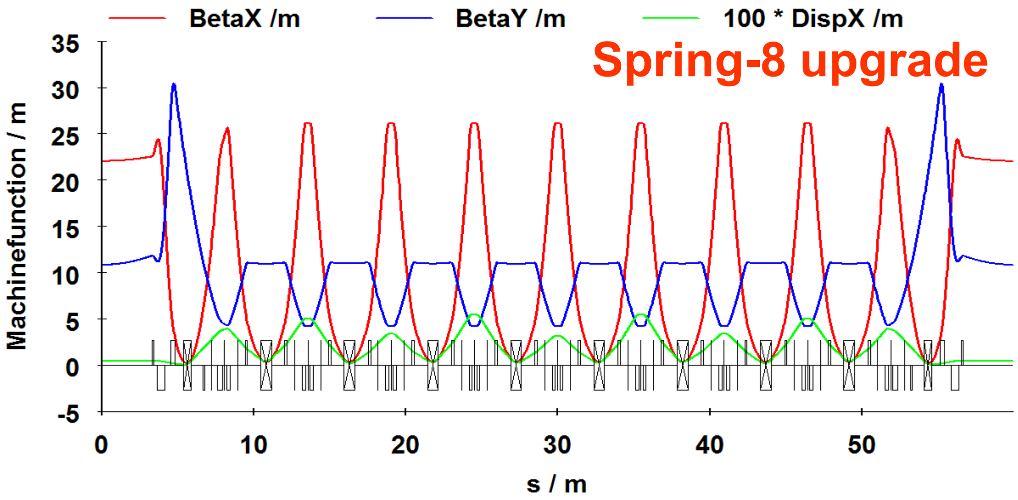
New designs envisaged to achieve sub-nm emittance involve



Damping Wigglers
Petra-III: 1 nm
NSLS-II: 0.5 nm

MBA
MAX-IV (7-BA): 0.5 nm
Spring-8 (10-BA):160 pm

10-DBA abandoned because no DA, reverted to a QBA



Diamond aerial view

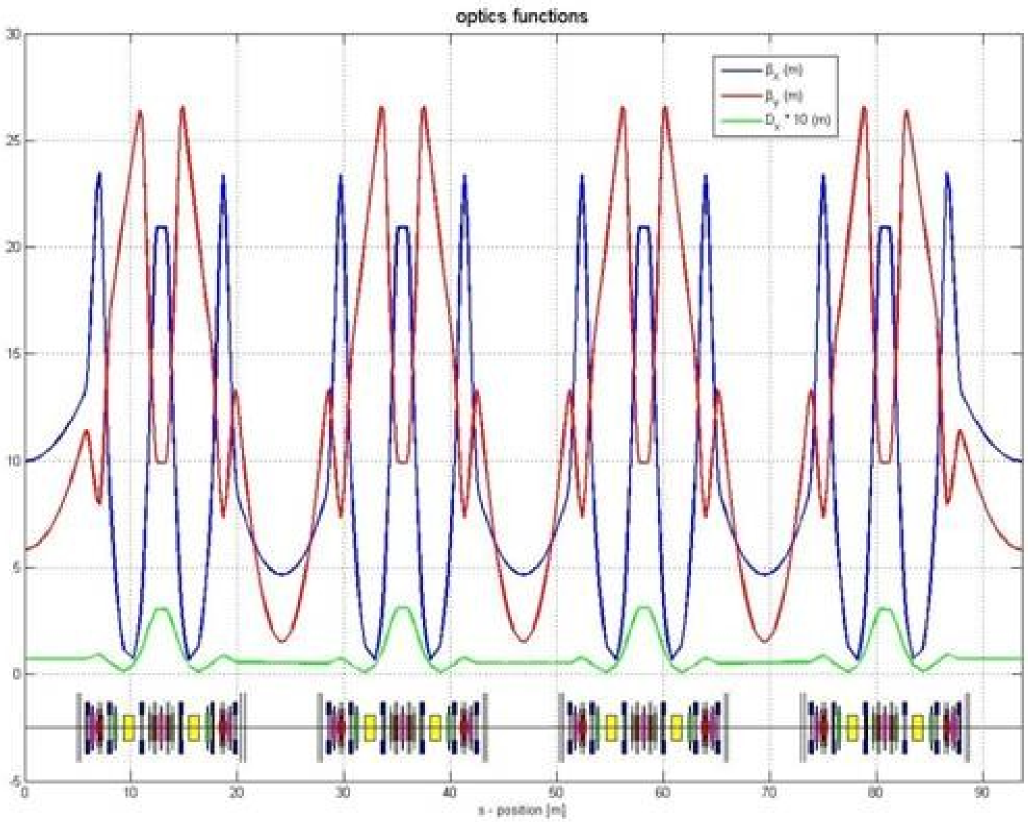
Diamond is a third generation light source open for users since January 2007

100 MeV LINAC; 3 GeV Booster; 3 GeV storage ring

2.7 nm emittance – 300 mA – 18 beamlines in operation (10 in-vacuum small gap IDs)

Diamond storage ring main parameters

non-zero dispersion lattice



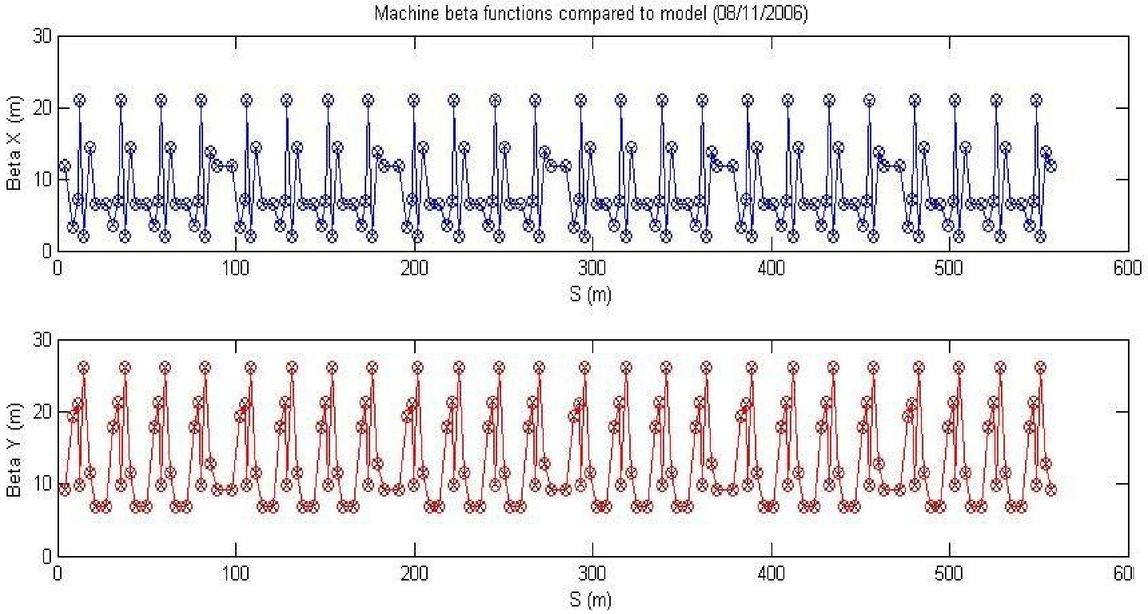
48 Dipoles; 240 Quadrupoles; 168 Sextupoles
(+ H and V orbit correctors + 96 Skew Quadrupoles)
3 SC RF cavities; 168 BPMs

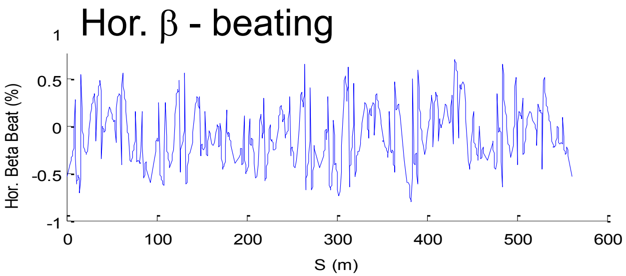
Quads + Sexts have independent power supplies

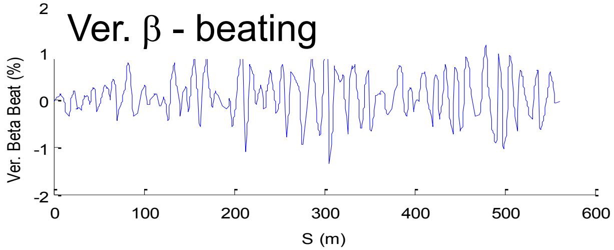
Energy	**3 GeV**
Circumference	**561.6 m**
No. cells	**24**
Symmetry	**6**
Straight sections	**6 x 8m, 18 x 5m**
Insertion devices	**4 x 8m, 18 x 5m**
Beam current	**300 mA (500 mA)**
Emittance (h, v)	**2.7, 0.03 nm rad**
Lifetime	**> 10 h**
Min. ID gap	**7 mm (5 mm)**
Beam size (h, v)	**123, 6.4 μm**
Beam divergence (h, v) ***(at centre of 5 m ID)***	**24, 4.2 μrad**
Beam size (h, v)	**178, 12.6 μm**
Beam divergence (h, v) ***(at centre of 8 m ID)***	**16, 2.2 μrad**

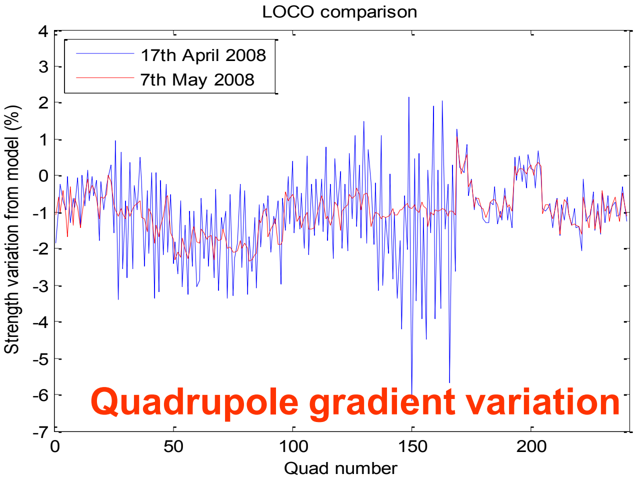
Linear optics modelling with LOCO

Linear Optics from Closed Orbit response matrix – J. Safranek et al.


Machine beta functions compared to model (08/11/2006)


Hor. β - beating


Ver. β - beating


LOCO comparison

Quadrupole gradient variation

Modified version of LOCO with constraints on gradien variations **(see ICFA Newsl, Dec'07)**

β - beating reduced to 0.4% rms

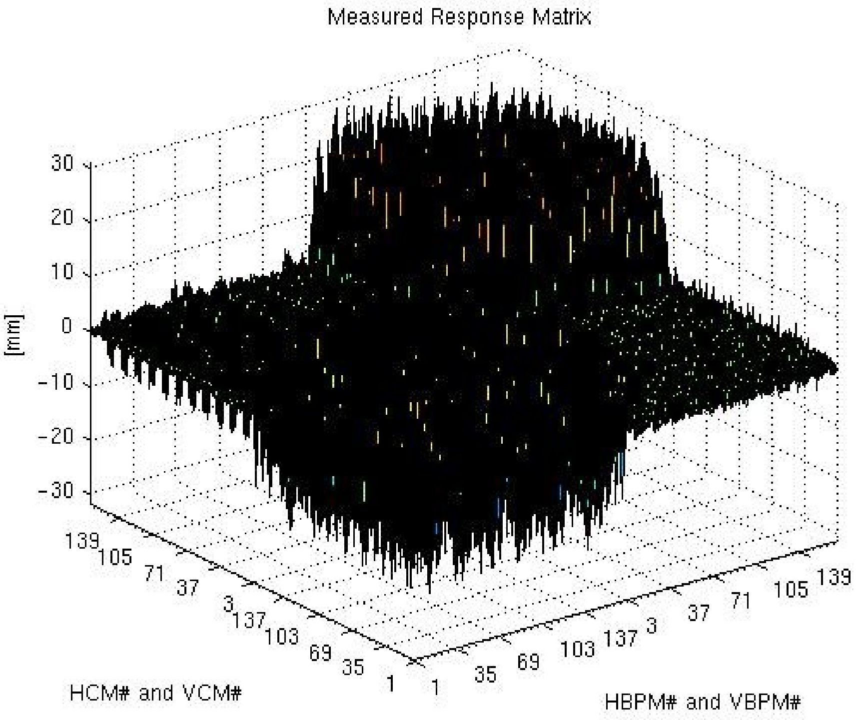
Quadrupole variation reduced to 2%
Results compatible with mag. meas. and calibrations

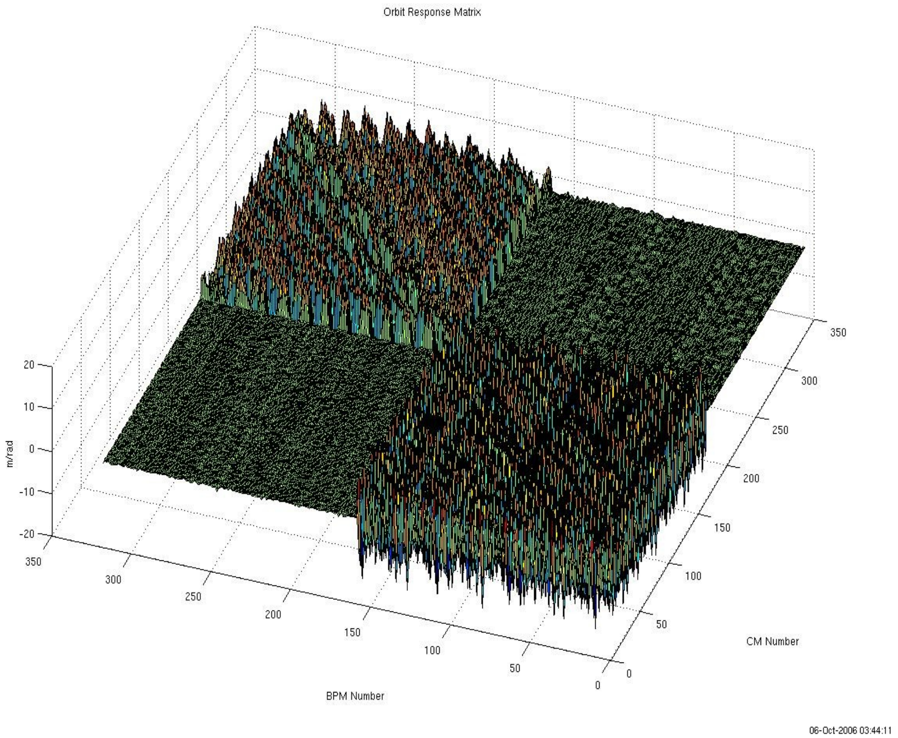
LOCO allowed remarkable progress with the correct implementation of the linear optics

Linear coupling correction with LOCO (II)

Skew quadrupoles can be simultaneously zero the off diagonal blocks of the measured response matrix and the vertical disperison

$$\chi^2(\overline{Q},\overline{G}_{\mathrm{BPMs}},\overline{S}_q,\overline{k}_{\mathrm{BPMs}},\ldots)=\sum_{i,j}\left(R_{ij}^{\mathrm{measured}}-R_{ij}^{\mathrm{model}}(\overline{Q},\overline{S}_q,\overline{G}_{\mathrm{BPMs}},\overline{k}_{\mathrm{BPMs}},\ldots)\right)^2$$

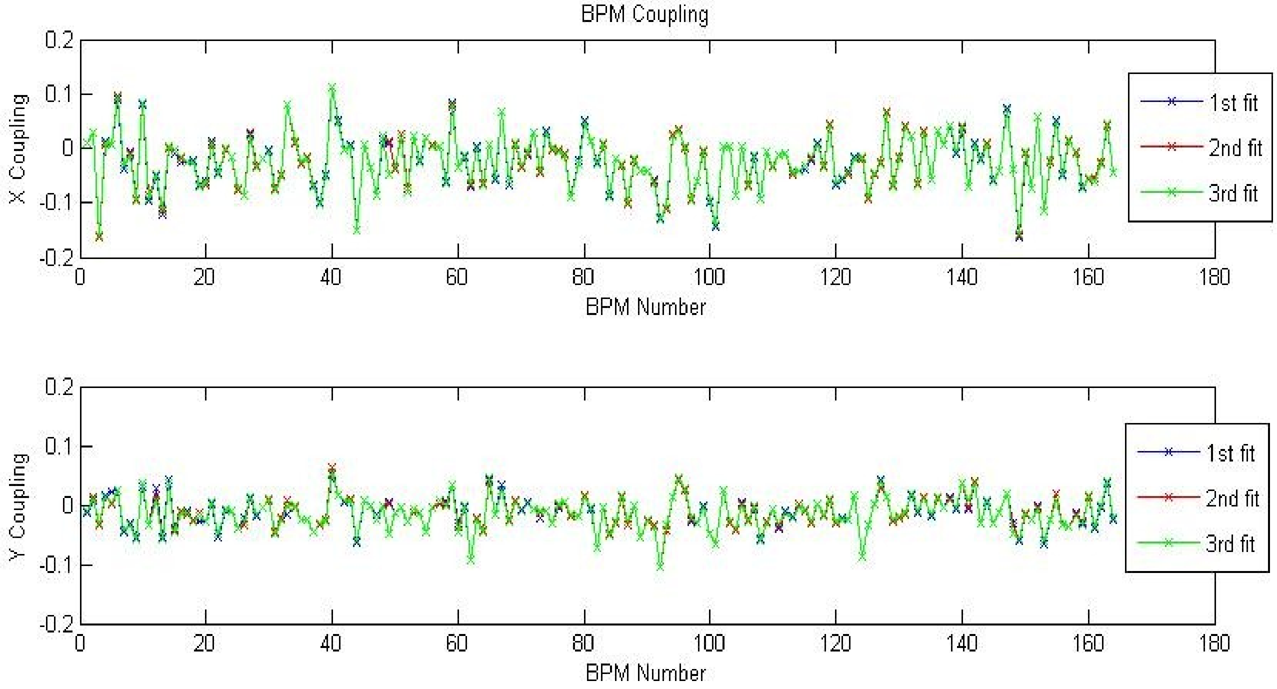




BPMs coupling

LOCO fits also the BPM gain and coupling

BPM coupling includes mechanical rotation and electronics cross talk



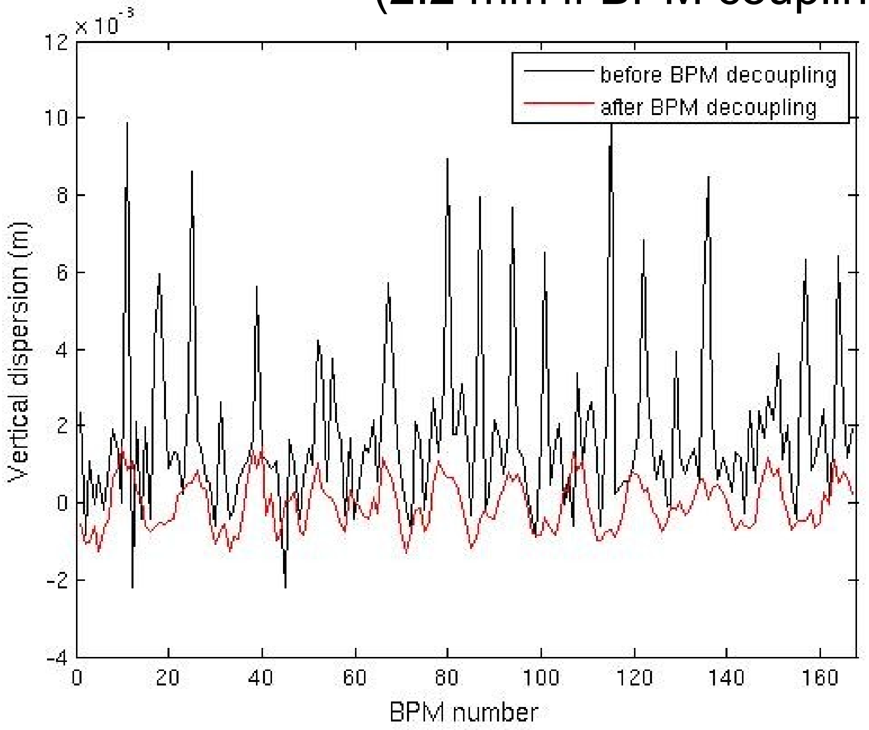
These data are well reproducible over months

Residual vertical dispersion

Without skew quadrupoles off r.m.s. Dy = 14 mm

After LOCO correction r.m.s. Dy = 700 µm

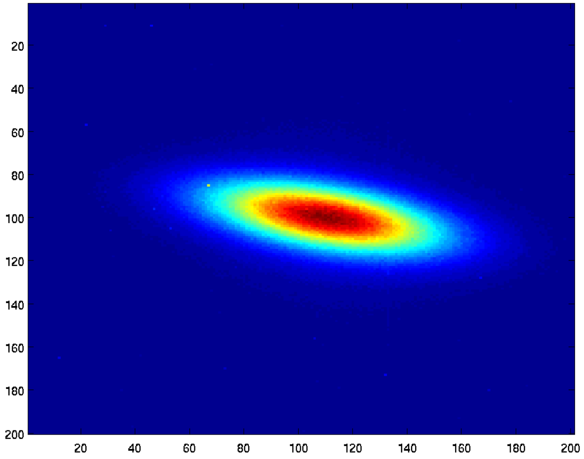
(2.2 mm if BPM coupling is not corrected)



Measured emittances

Coupling without skew quadrupoles off K = 0.9%

(at the pinhole location; numerical simulation gave an average emittance coupling 1.5% ± 1.0 %)



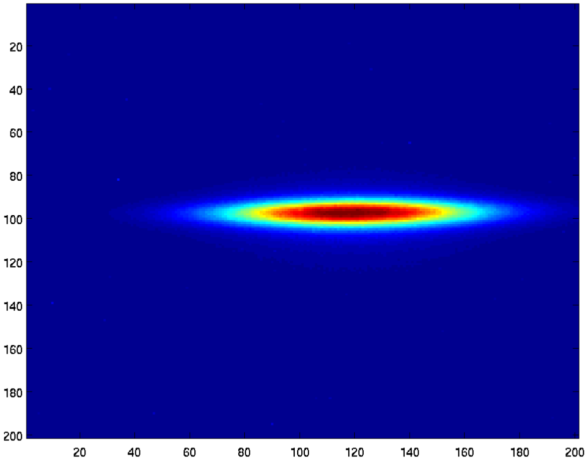
Emittance [2.78 - 2.74] (2.75) nm

Energy spread [1.1e-3 - 1.0-e3] (1.0e-3)

After coupling correction with LOCO (2*3 iterations)

1st correction K = 0.15%

2nd correction K = 0.08%



V beam size at source point 6 µm

Emittance coupling 0.08% → **V emittance 2.2 pm**

Variation of less than 20% over different measurements

Comparison machine/model and Lowest vertical emittance

	Model emittance	Measured emittance	β-beating (rms)	Coupling* ($\varepsilon_y / \varepsilon_x$)	Vertical emittance
ALS	6.7 nm	6.7 nm	0.5 %	0.1%	4-7 pm
APS	2.5 nm	2.5 nm	1 %	0.8%	20 pm
ASP	10 nm	10 nm	1 %	0.01%	1-2 pm
CLS	18 nm	17-19 nm	4.2%	0.2%	36 pm
Diamond	2.74 nm	2.7-2.8 nm	0.4 %	0.08%	2.2 pm
ESRF	4 nm	4 nm	1%	0.1%	4.7 pm
SLS	5.6 nm	5.4-7 nm	4.5% H; 1.3% V	0.05%	2.0 pm
SOLEIL	3.73 nm	3.70-3.75 nm	0.3 %	0.1%	4 pm
SPEAR3	9.8 nm	9.8 nm	< 1%	0.05%	5 pm
SPring8	3.4 nm	3.2-3.6 nm	1.9% H; 1.5% V	0.2%	6.4 pm
SSRF	3.9 nm	3.8-4.0 nm	<1%	0.13%	5 pm

* best achieved

Non-linear optics optimisation and control with low emittance lattices

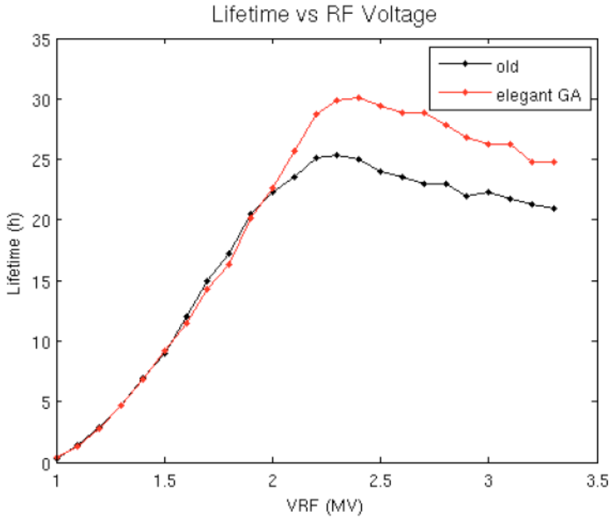
Low emittance → Large Nat. Chromaticity with Strong quads and Small Dispersion → Strong SX → Small Apertures (Dynamic and Momentum apertures)

Usually the phase advance per cell is such that low resonance driving terms are automatically compensated (to first order)

Numerical optimisation is however unavoidable

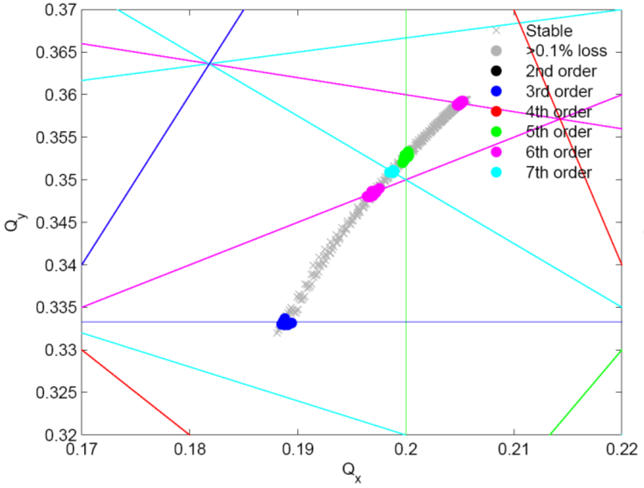
need 6D tracking (watch out alpha_2)
use DA and FM plots
use MOGA !

MOGA in elegant to optimise 8 sextupole families at Diamond improved the Touschek lifetime by 20 %

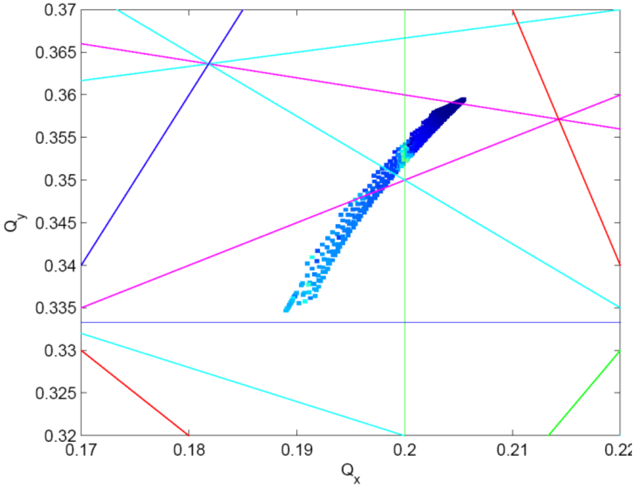


Frequency map and detuning with momentum comparison machine vs model (I)

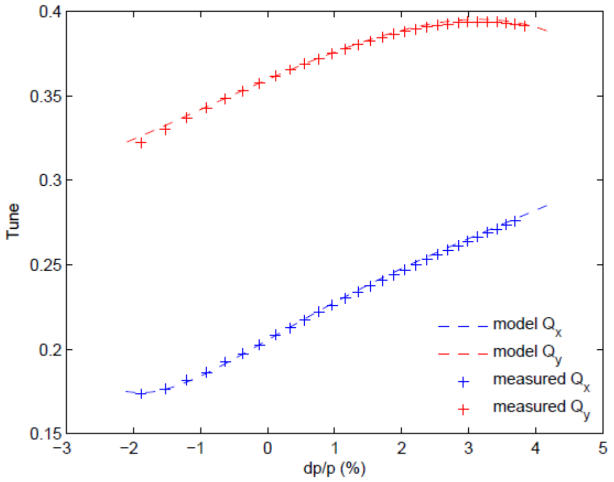
FM measured



FM model



detuning with momentum model and measured



Sextupole strengths variation less than 3%

The most complete description of the nonlinear model is mandatory !

Measured multipolar errors to dipoles, quadrupoles and sextupoles (up to b10/a9)

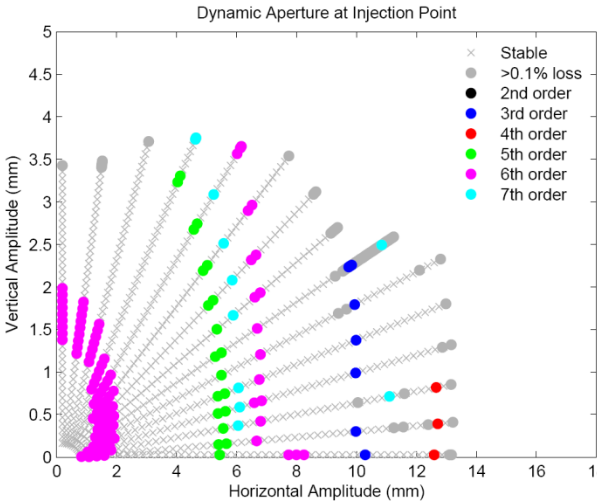
Correct magnetic lengths of magnetic elements

Fringe fields to dipoles and quadrupoles

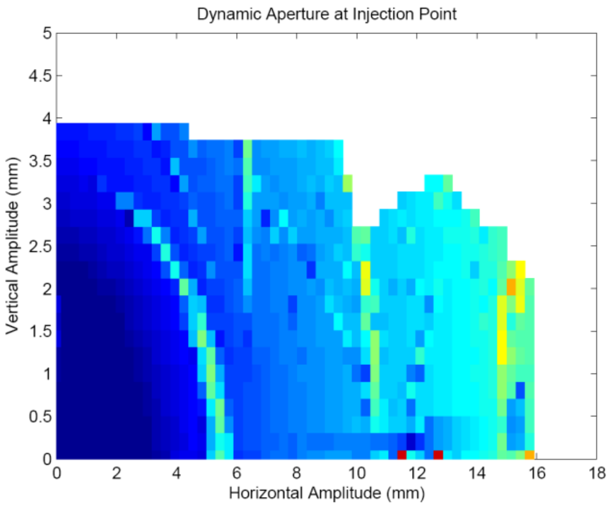
Substantial progress after correcting the frequency response of the Libera BPMs

Frequency map and detuning with momentum comparison machine vs model (II)

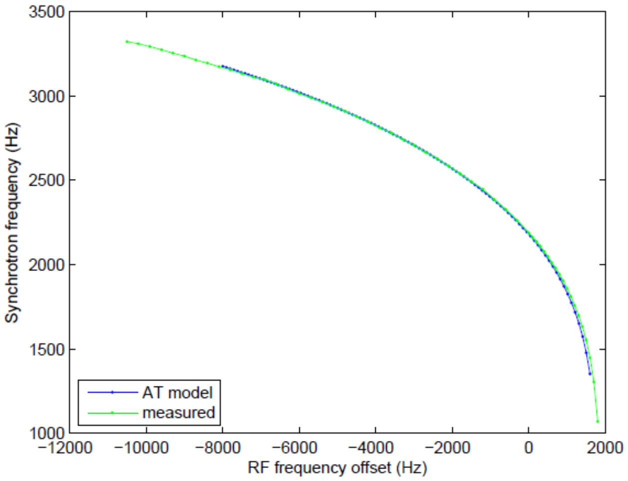
DA measured



DA model



Synchrotron tune vs RF frequency

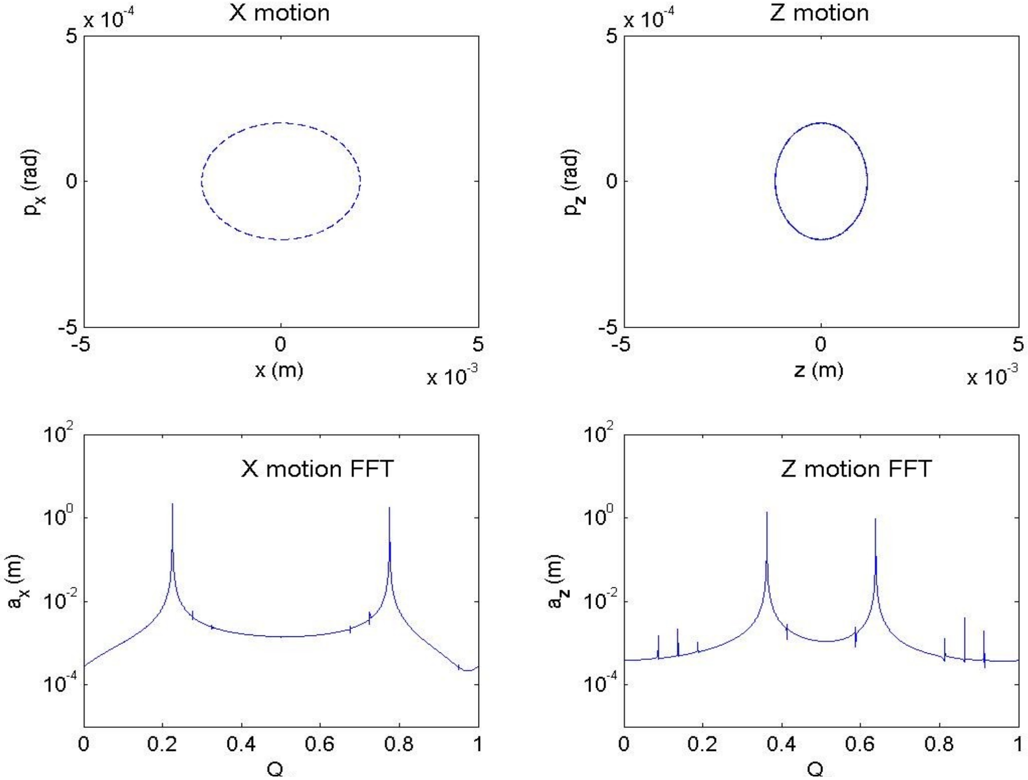


The fit procedure based on the reconstruction of the measured FM and detunng with momentum describes well the **dynamic aperture**, the **resonances excited** and the dependence of the **synchrotron tune vs RF frequency**

R. Bartolini et al. Phys. Rev. ST Accel. Beams 14, 054003

Frequency Analysis of betatron motion

Example: Spectral Lines for tracking data for the Diamond lattice



Spectral Lines detected with SUSSIX (NAFF algorithm)

e.g. in the horizontal plane:

• (1, 0)	$1.10\ 10^{-3}$	horizontal tune
• (0, 2)	$1.04\ 10^{-6}$	$Q_x + 2\ Q_z$
• (–3, 0)	$2.21\ 10^{-7}$	$4\ Q_x$
• (–1, 2)	$1.31\ 10^{-7}$	$2\ Q_x + 2\ Q_z$
• (–2, 0)	$9.90\ 10^{-8}$	$3\ Q_x$
• (–1, 4)	$2.08\ 10^{-8}$	$2\ Q_x + 4\ Q_z$

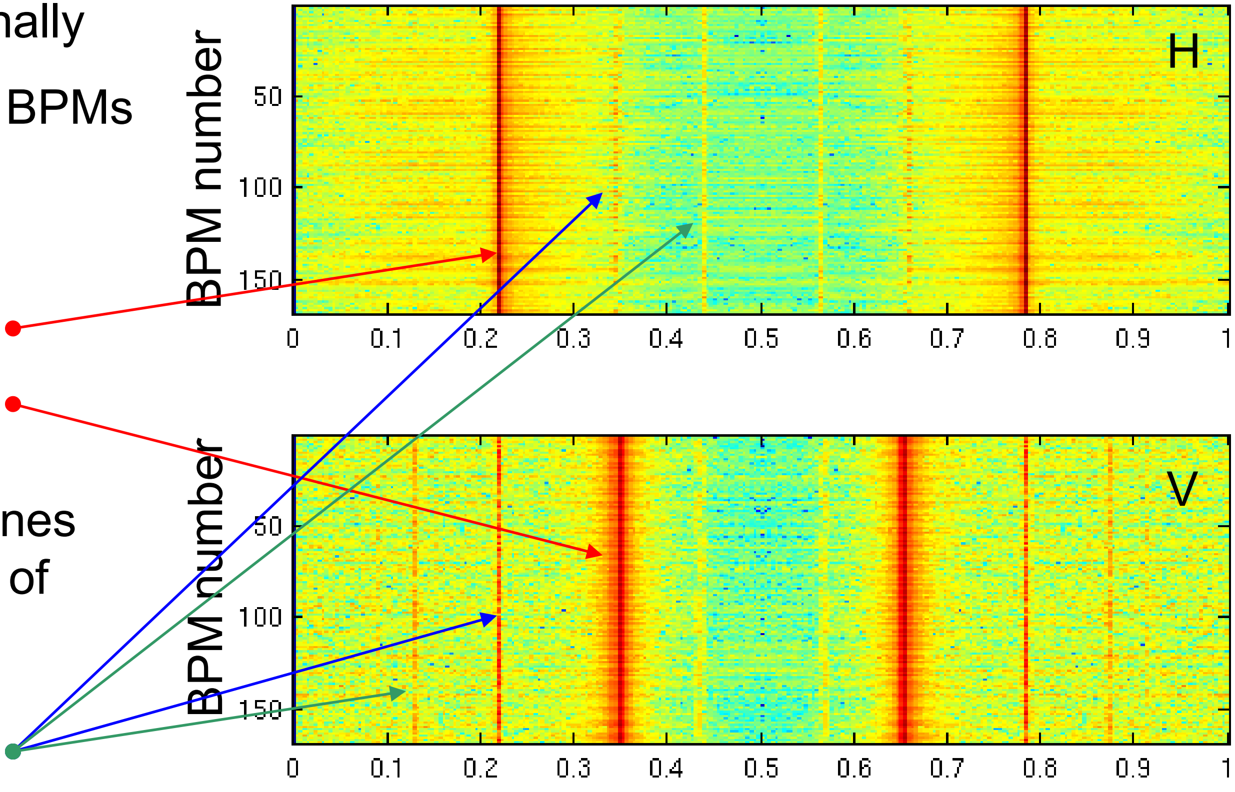
Each spectral line can be associated to a resonance driving term

J. Bengtsson (1988): CERN 88–04, (1988).
R. Bartolini, F. Schmidt (1998), Part. Acc., 59, 93, (1998).
R. Tomas, PhD Thesis (2003)

Nonlinear dynamics from betatron oscillations

All BPMs have turn-by-turn capabilities

- excite the beam diagonally
- measure tbt data at all BPMs
- colour plots of the FFT



Q_X = 0.22 H tune in H

Q_y = 0.36 V tune in V

All the other important lines are linear combination of the tunes Q_x and Q_y

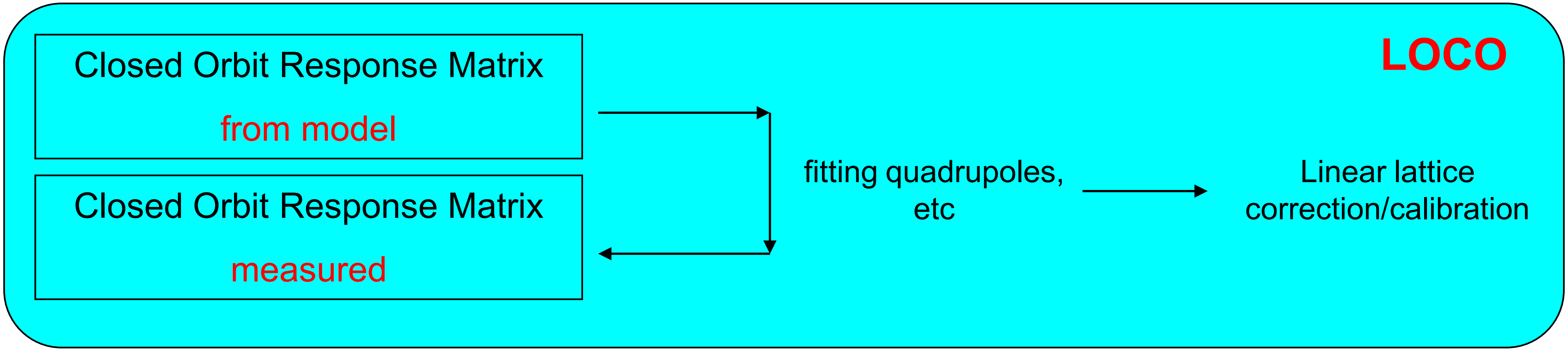
$m\,Q_x + n\,Q_y$

frequency / revolution frequency

See also R. Bartolini et al. Phys. Rev. ST Accel. Beams 11, 104002 (2008)

ongoing work

Frequency Maps and amplitudes and phases of the spectral line of the betatron motion can be used to compare and correct the real accelerator with the model



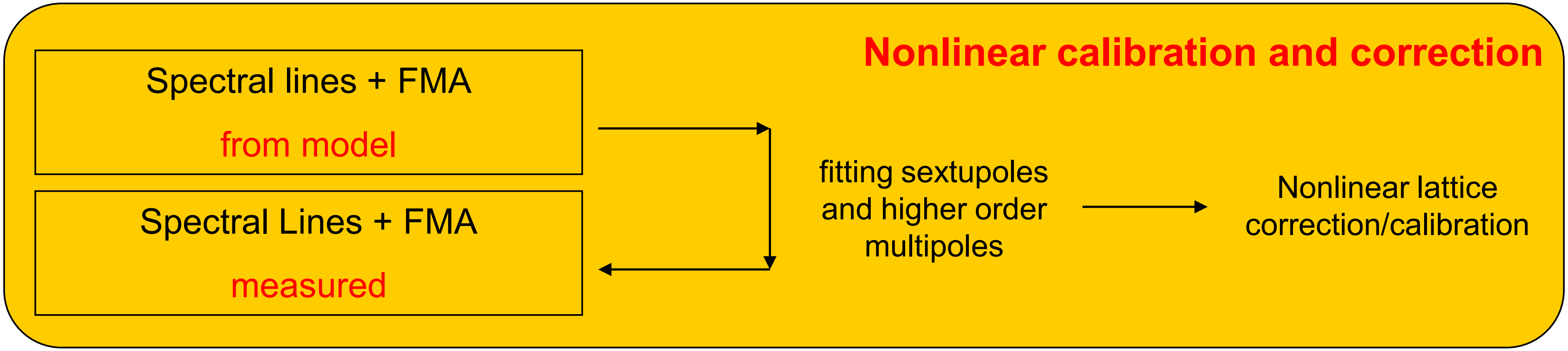
LOCO

Closed Orbit Response Matrix
from model

Closed Orbit Response Matrix
measured

fitting quadrupoles, etc

Linear lattice correction/calibration



Nonlinear calibration and correction

Spectral lines + FMA
from model

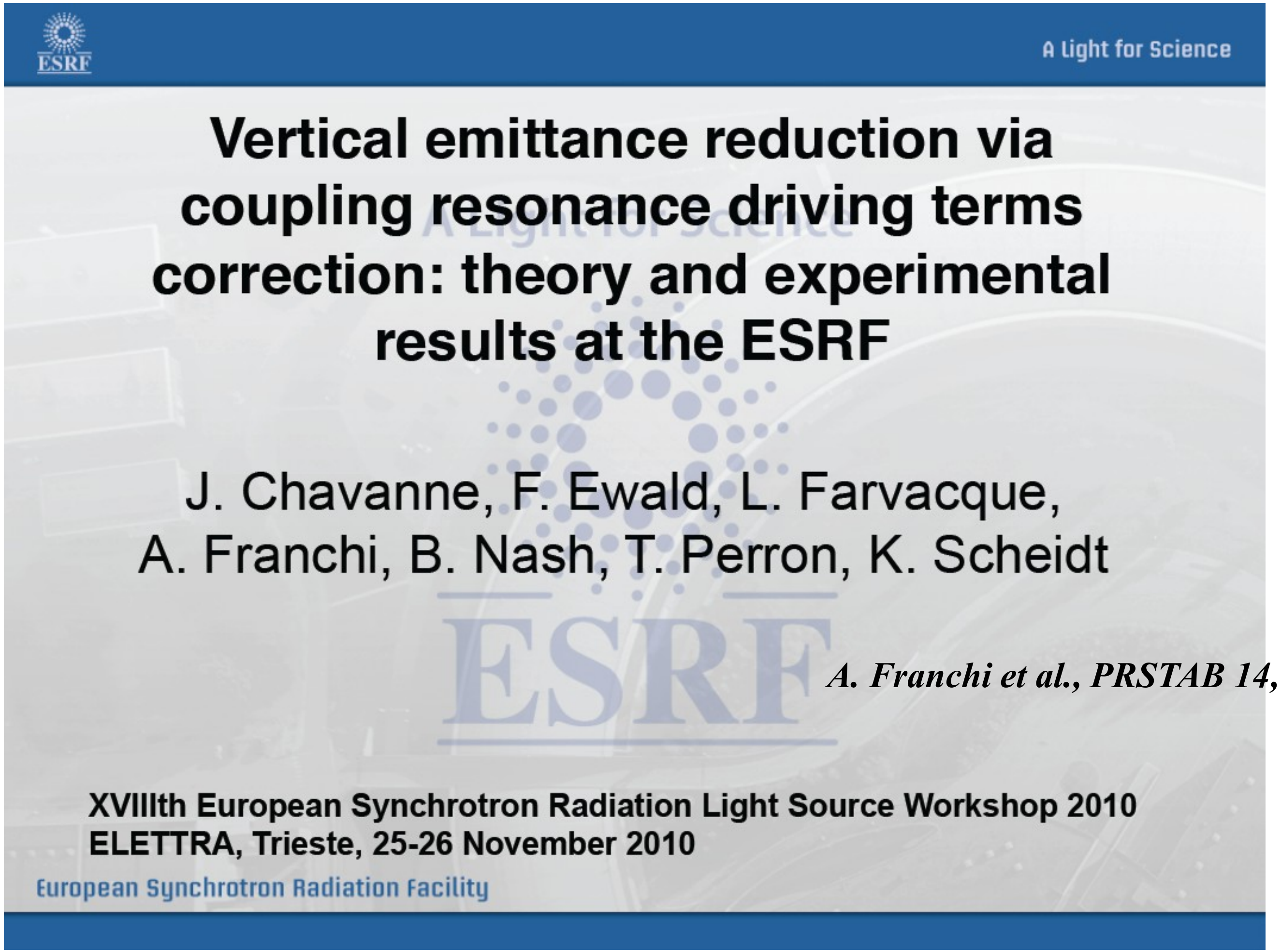
Spectral Lines + FMA
measured

fitting sextupoles and higher order multipoles

Nonlinear lattice correction/calibration

Combining the complementary information from FM and spectral line should allow the calibration of the nonlinear model and a full control of the nonlinear resonances

Further techniques



A Light for Science

Vertical emittance reduction via coupling resonance driving terms correction: theory and experimental results at the ESRF

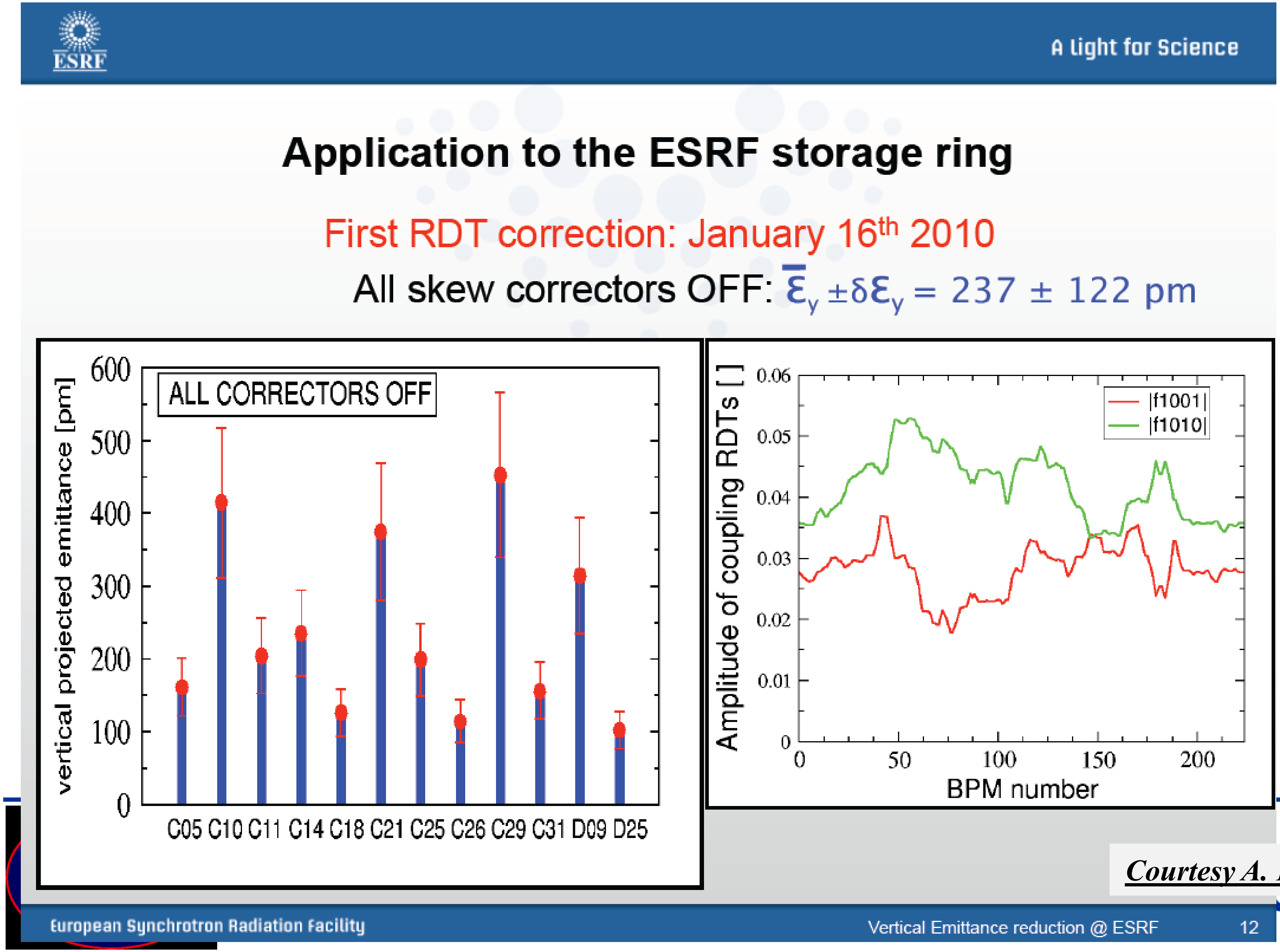
J. Chavanne, F. Ewald, L. Farvacque,
A. Franchi, B. Nash, T. Perron, K. Scheidt

XVIIIth European Synchrotron Radiation Light Source Workshop 2010
ELETTRA, Trieste, 25-26 November 2010

European Synchrotron Radiation Facility

A. Franchi et al., PRSTAB 14, 034002 (2011)

ESRF coupling correction with spectral lines (I)



A light for Science

Application to the ESRF storage ring

First RDT correction: January 16th 2010

All skew correctors OFF: $\bar{\varepsilon}_y \pm \delta\varepsilon_y = 237 \pm 122$ pm

European Synchrotron Radiation Facility

Vertical Emittance reduction @ ESRF

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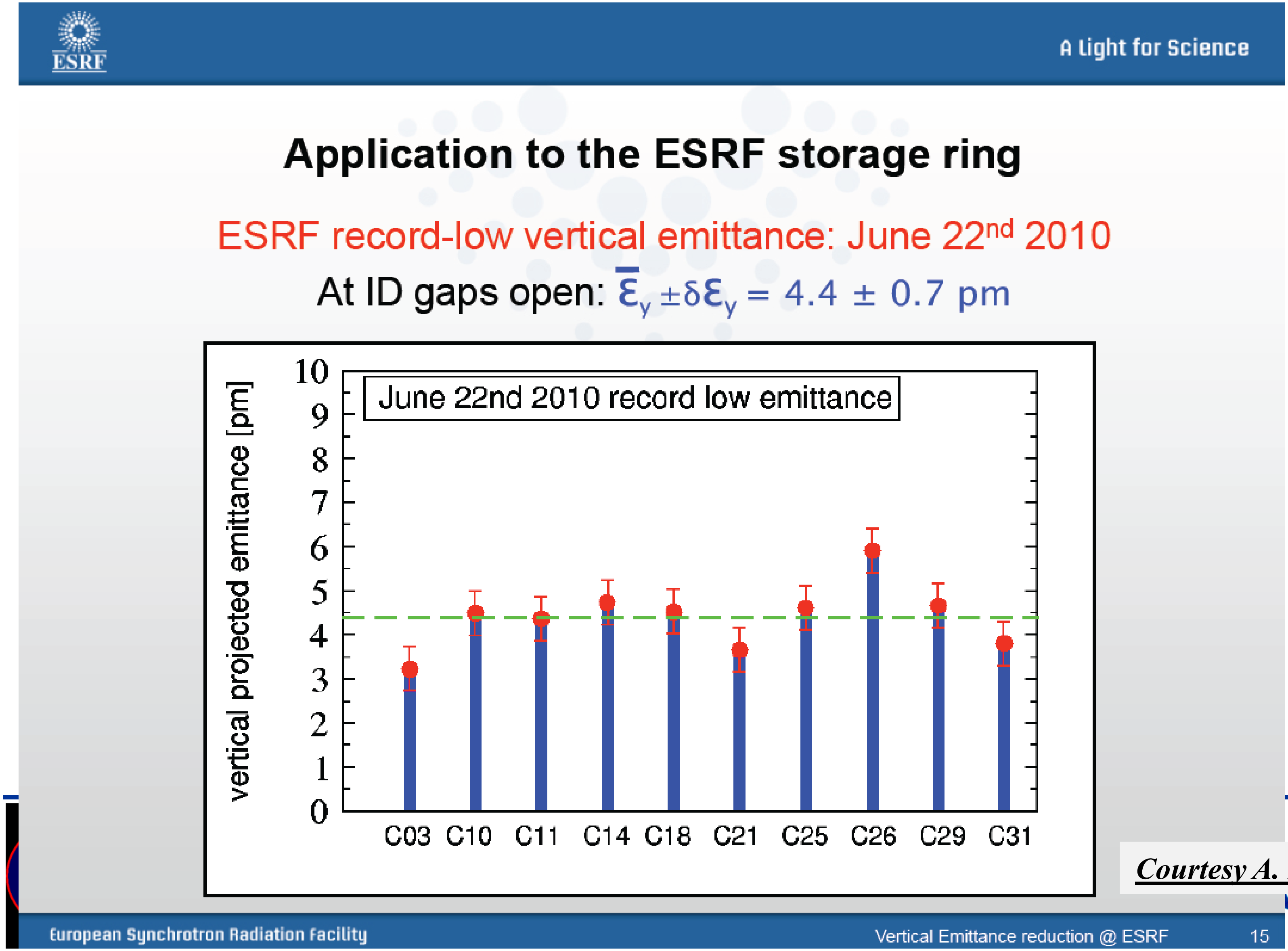
Courtesy A. Franchi

ESRF coupling correction with spectral lines (II)



A Light for Science

Application to the ESRF storage ring

ESRF record-low vertical emittance: June 22nd 2010

At ID gaps open: $\bar{\varepsilon}_y \pm \delta\varepsilon_y = 4.4 \pm 0.7$ pm

European Synchrotron Radiation Facility

Vertical Emittance reduction @ ESRF

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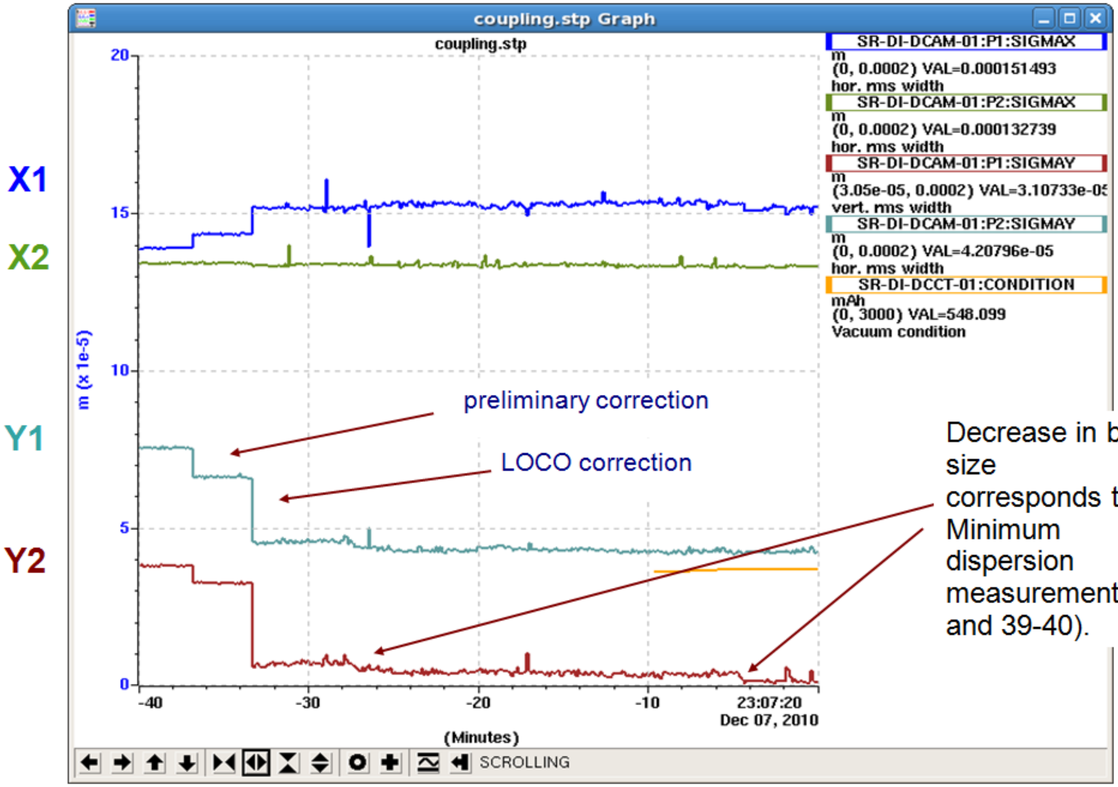
Courtesy A. Franchi

Low emittance tuning at Diamond for SuperB

Last year results on low emittance tuning and the achievement of a vertical emittance of 2.2 pm have sparked quite some interest from the Damping ring community (CLIC and ILC) and from the Super B

In collaboration with the SuperB team (P. Raimondi,. M. Biagini, S: Liuzzo) Diamond has been used as a test-bed for new techniques for low emittance tuning based on **dispersion free steering and coupling free steering.**



preliminary correction

LOCO correction

Decrease in beam size corresponds to Minimum dispersion measurements (30 and 39-40).

4 MD shifts at DLS
November - February

New JAI PhD student to start in October

Conclusions

Third generation light sources provide a very reliable source of high brightness, very stable X-rays

The agreement wit excellent for the linear optics and improvements can be foreseen for the nonli s

At Diamond several **very** differe ave all been succesfully operated with residual beta beating of 1% or less, w nt coupling control.

Careful alignment and independent power su ll quadrupoles and sextupoles have allowed a very good control of th d nonlinear optics

Diamond is an ideal test-bed for testing low emitta g techniques relevant for SuperB

Anyone interested is most welcome to join these studies.

Thank you for your attention !