Orbit control and low emittance operation at Diamond

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Outline

- Introduction to Diamond
- Orbit and linear optics control
- Coupling and small V emittance

  LOCO coupling correction
  closest tune approach and turn-by-turn coupling analysis
  low emittance measurements issues

- Conclusion

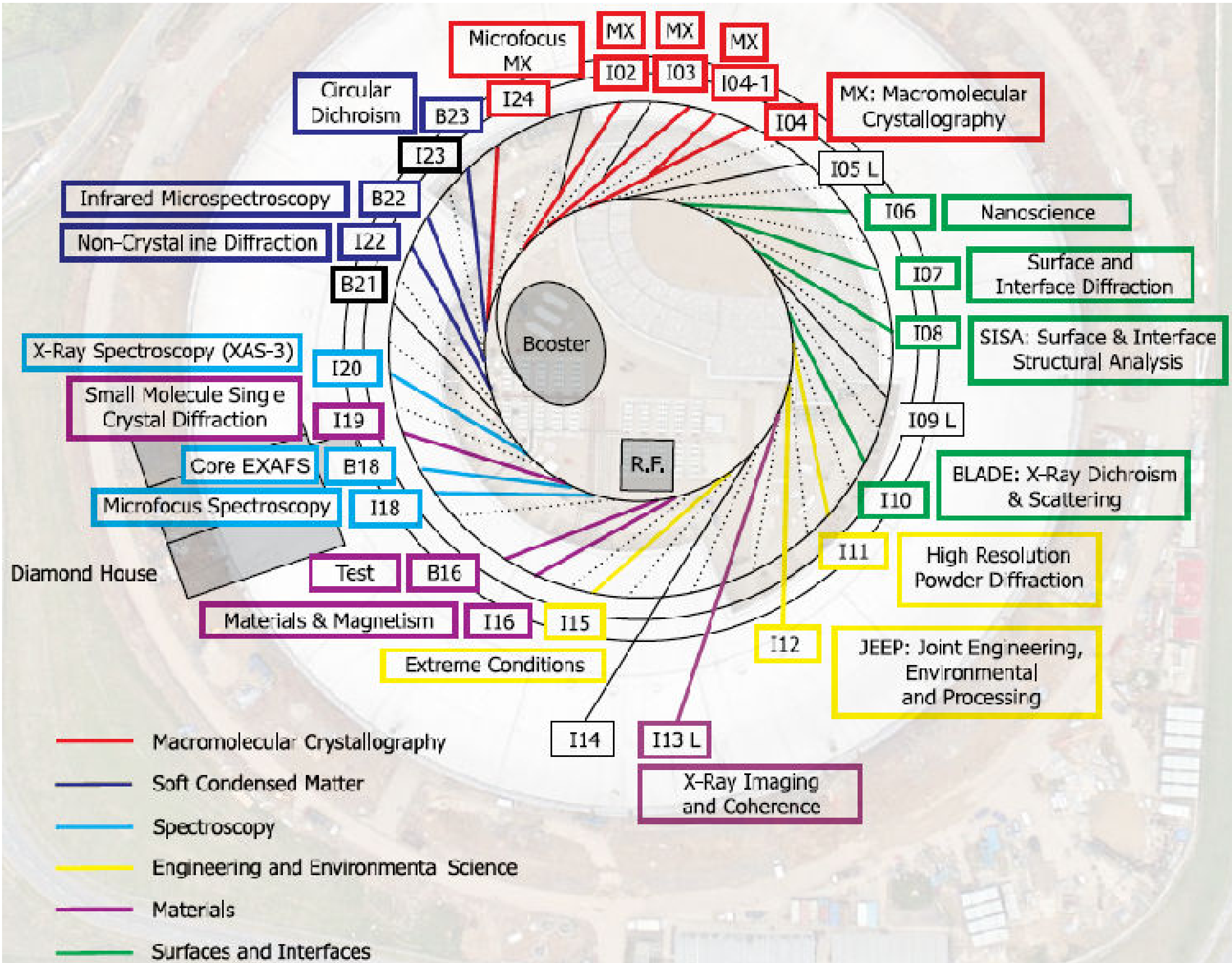
Diamond aerial view

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

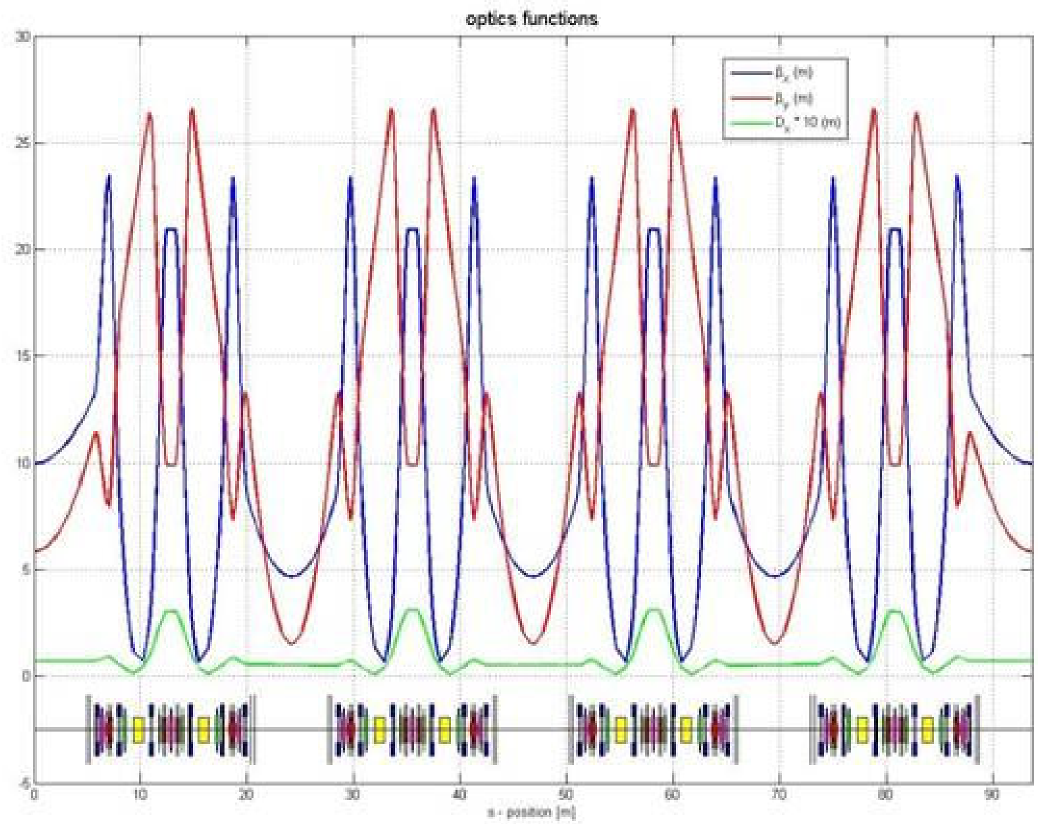
100 MeV LINAC; 3 GeV Booster; 3 GeV storage ring

2.7 nm emittance – 300 mA – 14 beamlines in operation (10 in-vacuum small gap IDs)

Diamond beamlines



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)**

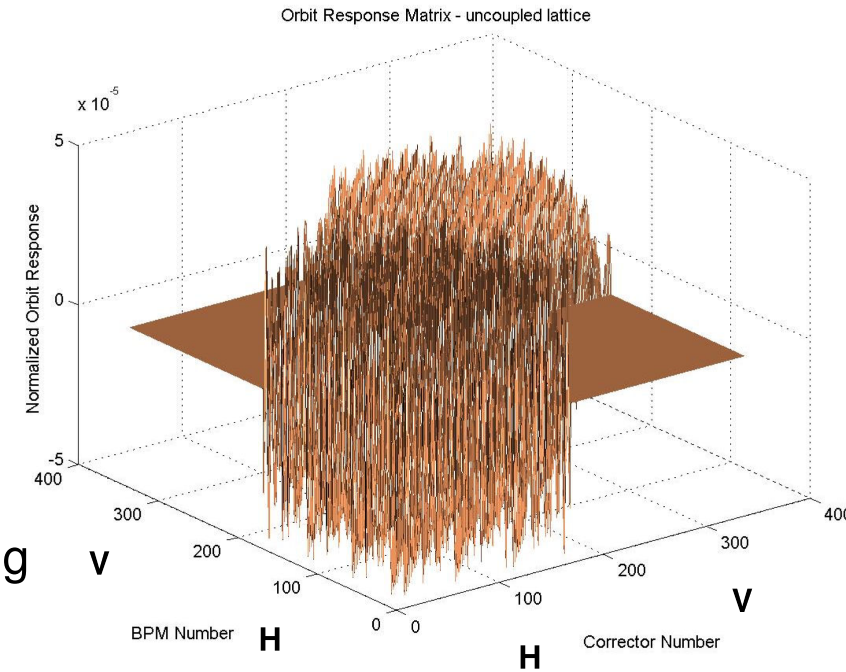
Beam size (h, v)	**123, 6.4 μm**
Beam divergence (h, v) ***(at centre of 5 m ID)***	**24, 4.2 μrad**
Beam size (h, v)	**178, 12.6 μm**
Beam divergence (h, v) ***(at centre of 8 m ID)***	**16, 2.2 μrad**

Orbit control at diamond (I)

Orbit correction is based on the SVD of the orbit response matrix (168 BPMs 168 correctors)

The orbit response matrix R is the change in the orbit at the BPMs as a function of changes in the steering magnets strength

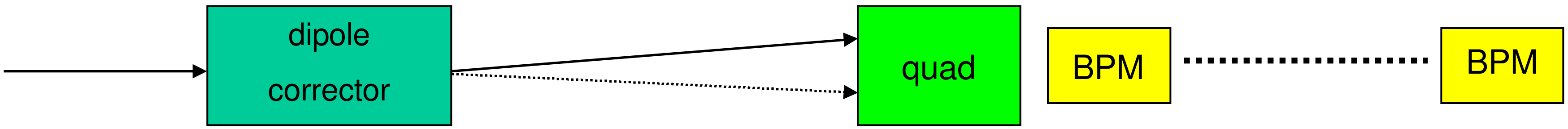
$$\begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} = R_{\substack{\text{model} \\ \text{measured}}} \begin{pmatrix} \bar{\theta}_x \\ \bar{\theta}_y \end{pmatrix}$$



The Response Matrix R can be inverted Using the Singular Value Decomposition (SVD) to correct the closed orbit distortion

Beam Based Alignment

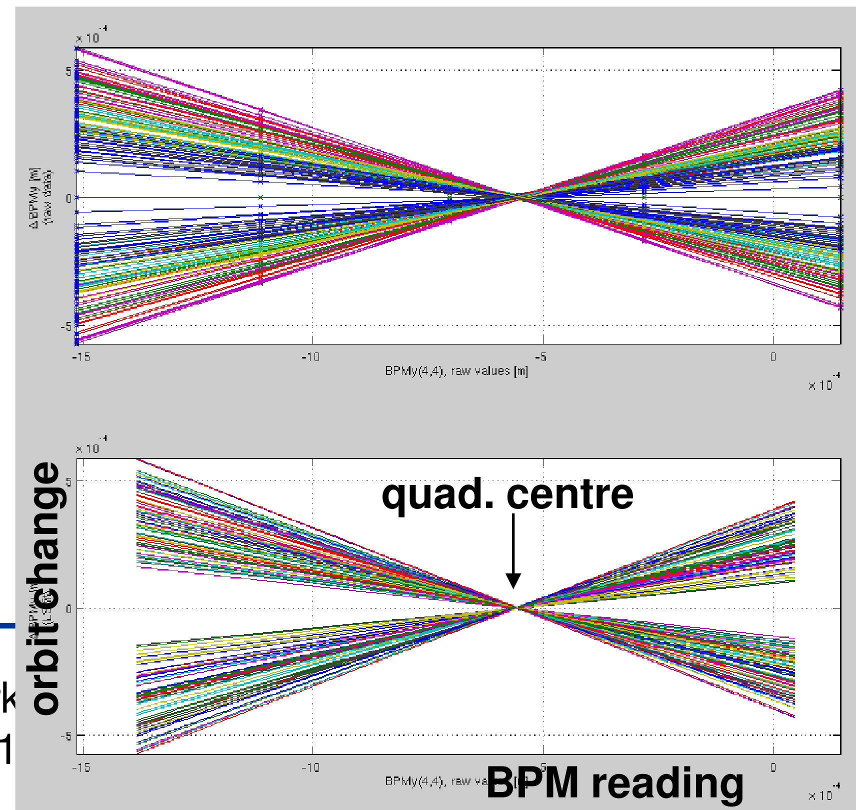
The orbit is corrected to the electrical centre of the BPMs. These are aligned to the centre of neighbouring quads with a BBA procedure



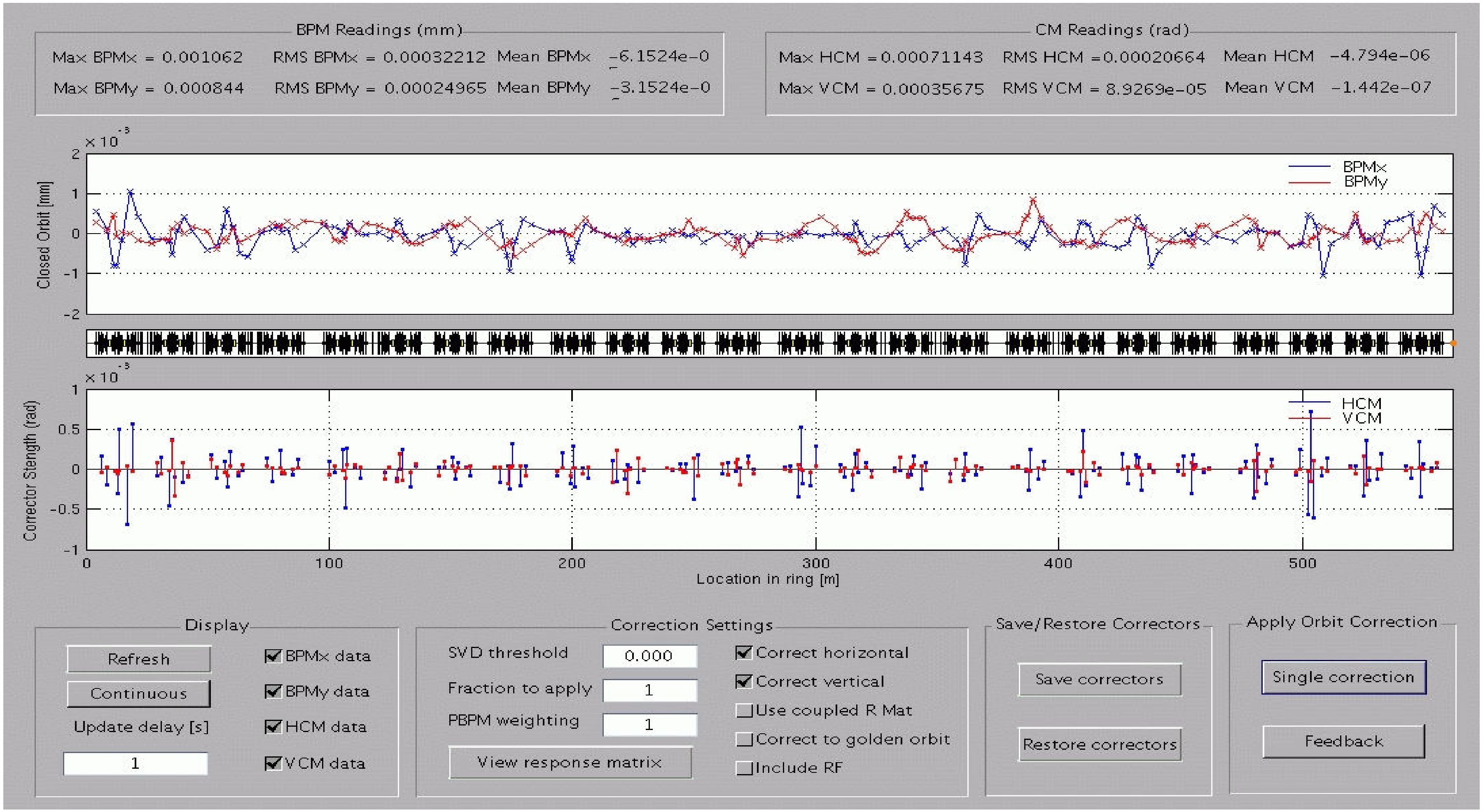
The rms deviation of the electrical centre of the BPM is 330 um rms.

This includes mechanical and electrical offset

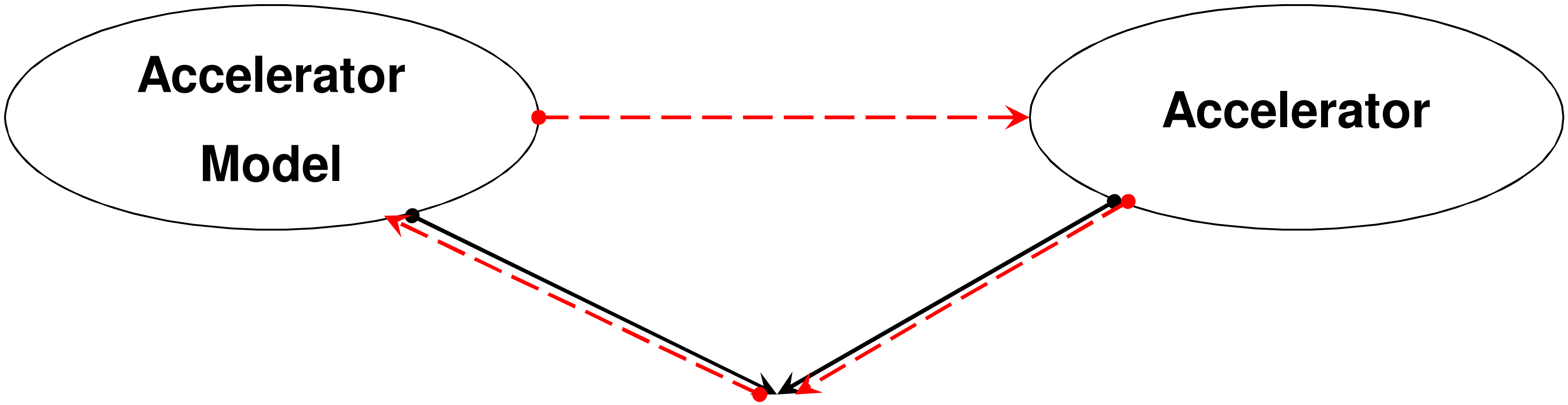
Electrical centres of the BPMs were not calibrated and no accurate mechanical survey was done previously



Storage Ring Closed Orbit < 1μm
(22th October 2006)



Implementation of low emittance optics



Linear Optics

Closed Orbit Response Matrix (LOCO)

Nonlinear Optics

Detuning with amplitude (and momentum)

Apertures and Lifetime

Frequency Map Analysis

Resonance driving terms

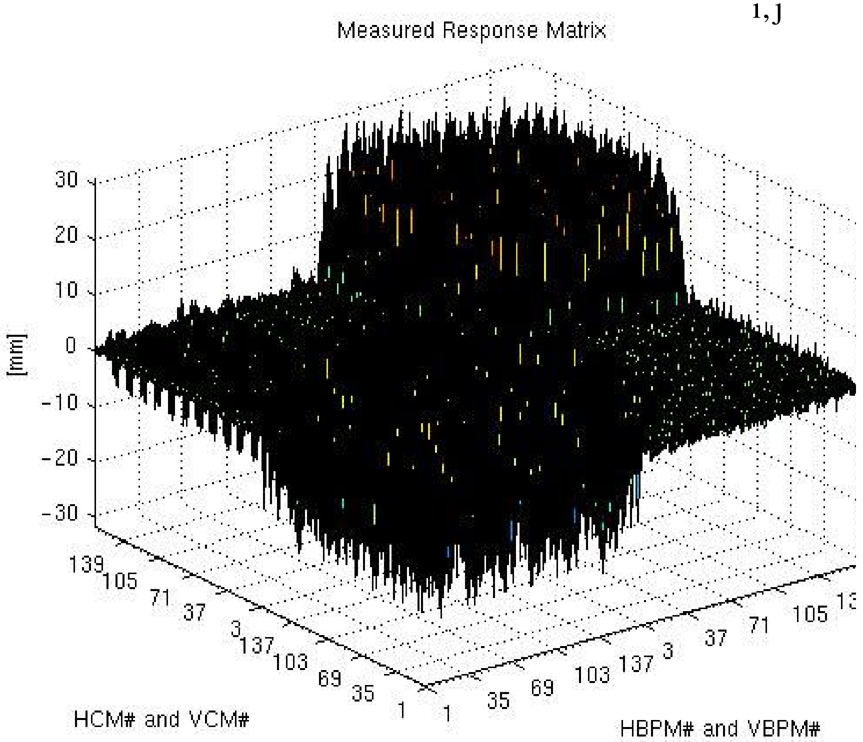
Commissioning of small emittance optics (II)

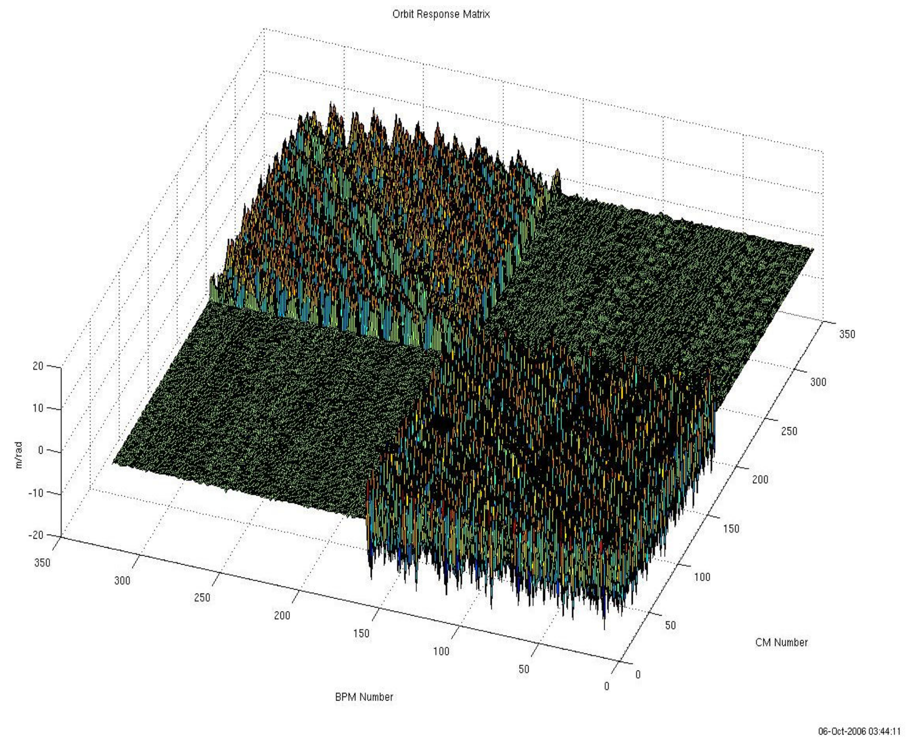
Linear optics studies are based on the analysis of the closed orbit response matrix

The response matrix R is defined by the linear lattice of the machine, (dipoles and quadrupoles), therefore it can be used to calibrate the linear optics of the machine

The quadrupole gradients are used in a least square fit to minimize the distance χ^2

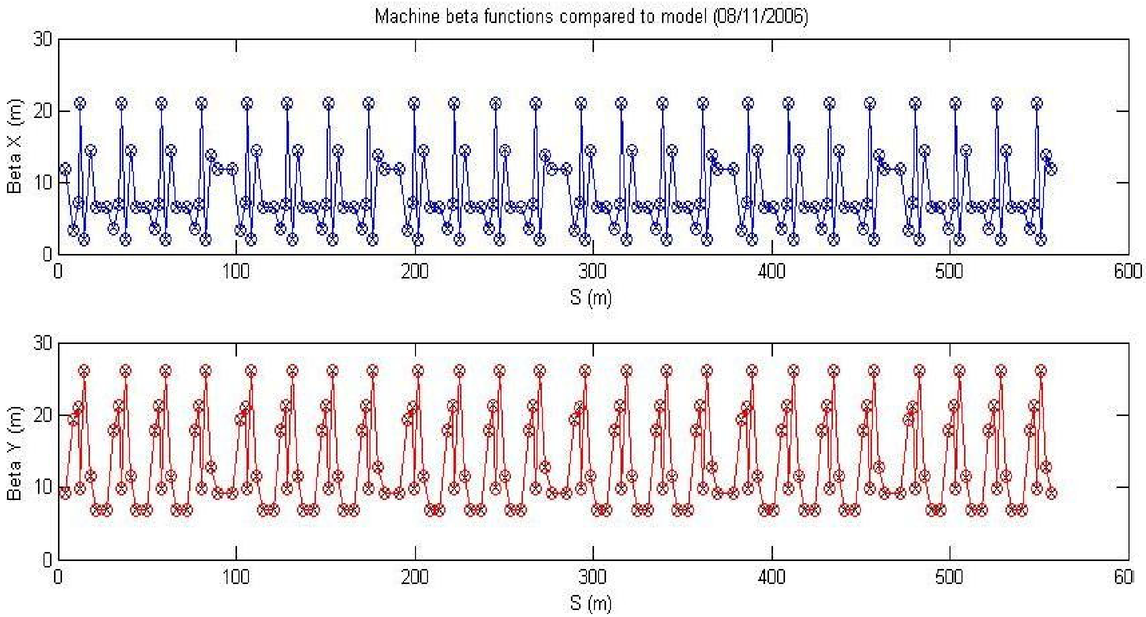
$$\chi^2(\overline{Q},\overline{G}_{BPMs},\overline{k}_{BPMs},...) = \sum_{i,j}\left(R_{ij}^{measured} - R_{ij}^{model}(\overline{Q},\overline{G}_{BPMs},\overline{k}_{BPMs},...)\right)^2$$

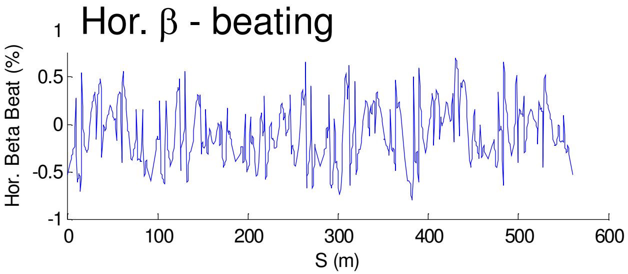


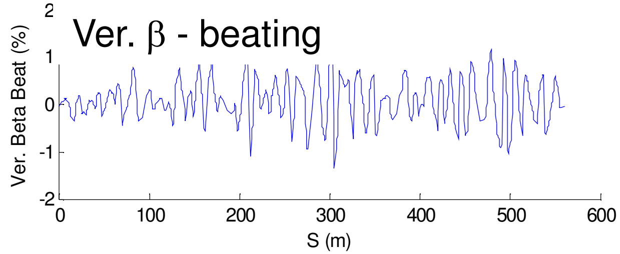


Linear optics modelling with LOCO

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



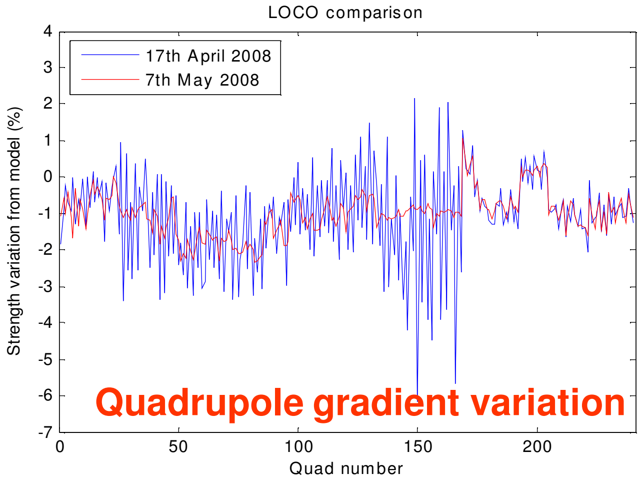




Modified version of LOCO with constraints on gradien variations **(see [ICFA Newsl, Dec'07])**

β - beating reduced to 0.4% rms

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

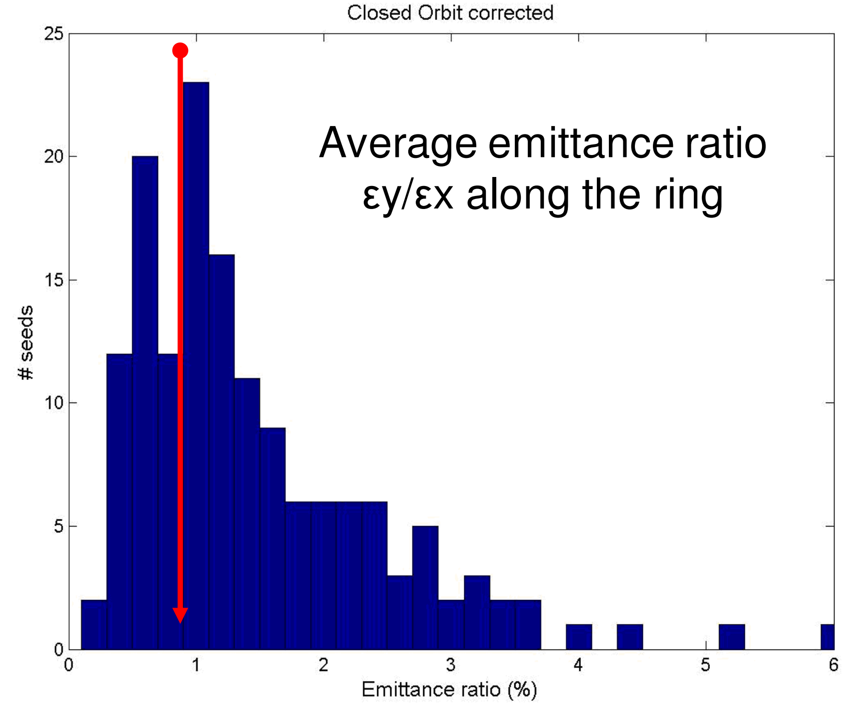


LOCO allowed remarkable progress with the correct implementation of the linear optics

Linear coupling numerical studies: sensitivity to machine errors

Quadrupole transverse displacement	0.1 mm
Sextupole transverse displacement	0.1 mm
Dipole transverse displacement	0.05 mm
Dipole longitudinal displacement	0.05 mm
Dipole Field Errors	0.1 %
Quadrupole roll errors	0.2 mrad
Dipole roll error	0.2 mrad
BPM transverse displacement	0.05 mm
BPM reading	0.5 μm

Coupling dominated by V misalignment of sextupoles (> 60 % of total)



After orbit correction – 150 seeds

Horizontal C.O. r.m.s. (m)	$1.0{\cdot}10^{-4}$
Vertical C.O. r.m.s (m)	$1.1{\cdot}10^{-4}$
Average Linear Coupling (%)	1.5
r.m.s. Linear Coupling (%)	1.0

Measured K = 0.9% with skew quadurpoles off

Numerical correction with crossed orbit response matrix

1) Crossed orbit response matrix

2) Simultaneous minimisation of vertical dispersion

	1)	2)
Horizontal C.O. r.m.s. (mm)	0.10	0.10
Vertical C.O. r.m.s. (mm)	0.11	0.11
Average Linear Coupling χ (%)	0.10	0.03
r.m.s. Linear Coupling (%)	0.11	0.07
r.m.s. H corrector str. (mrad)	0.32	0.32
r.m.s. V corrector str. (mrad)	0.27	0.27
r.m.s. Skew Quad str. (m^{-1})	0.02	0.02

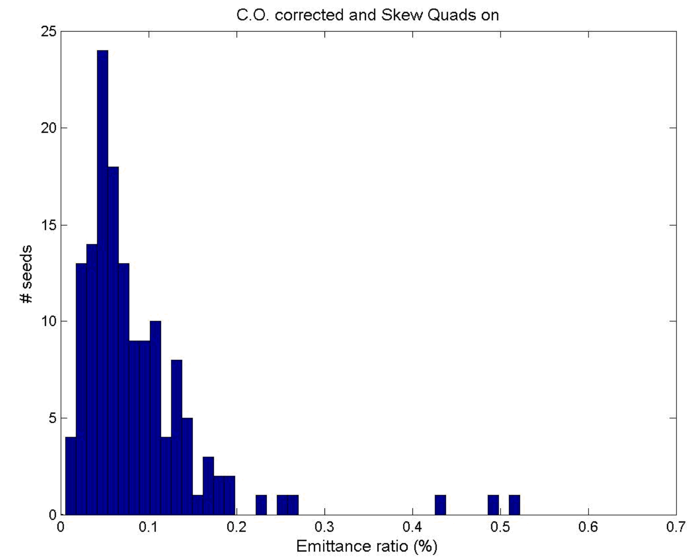
Linear coupling can be reduced

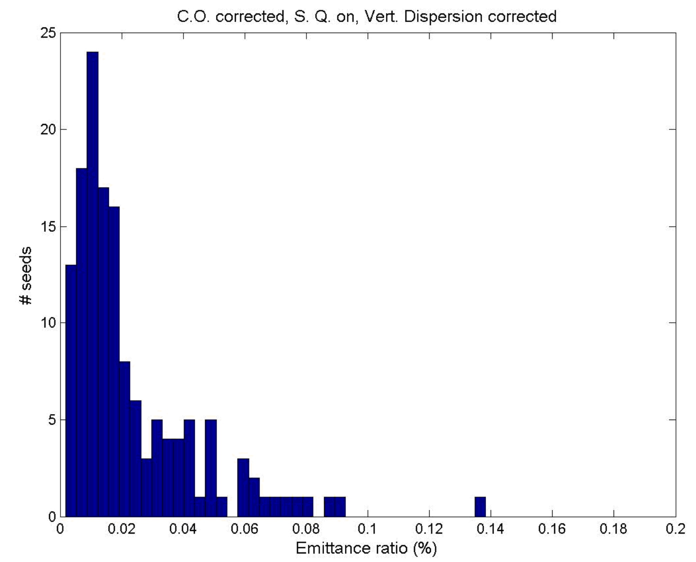
(…on the computer)

to the limit set by the radiation opening angle:

V emittance ~0.6 pm corresponding to K ~ 0.02%

(BETA_LNS code)

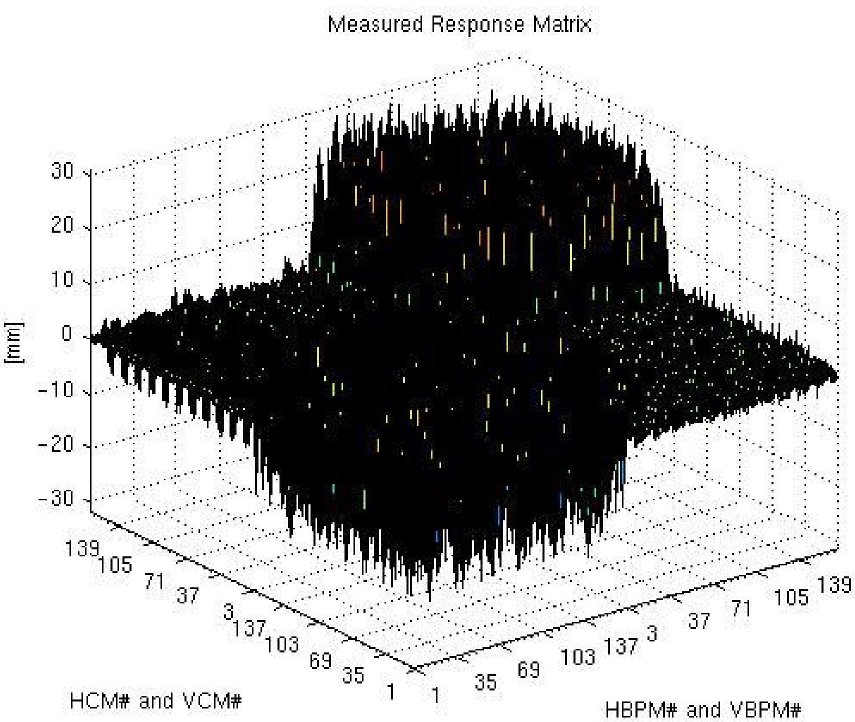


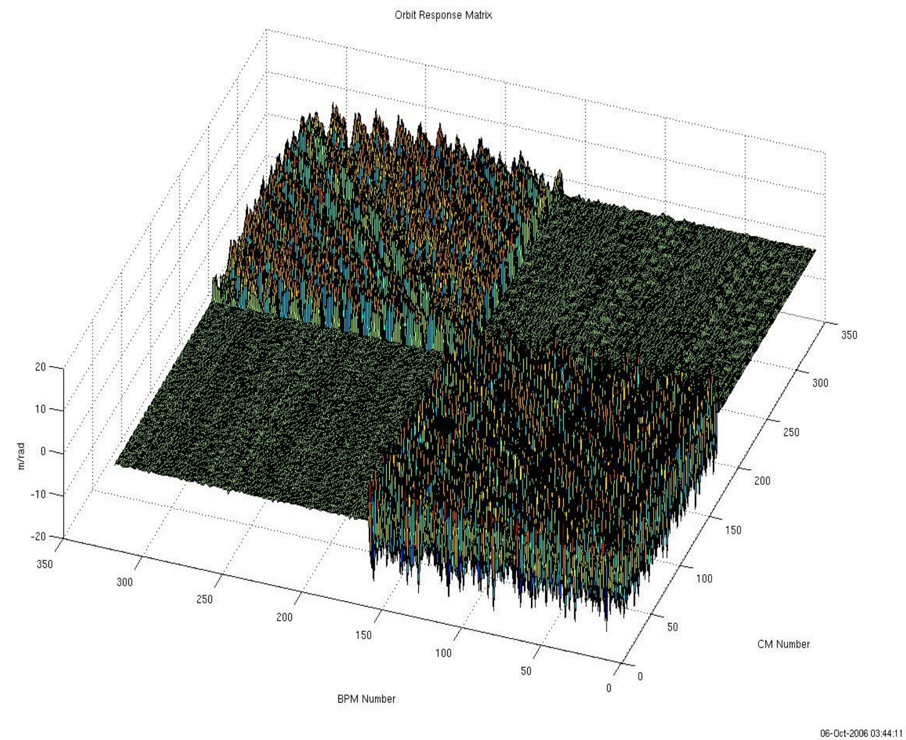


Linear coupling correction with LOCO (II)

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

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

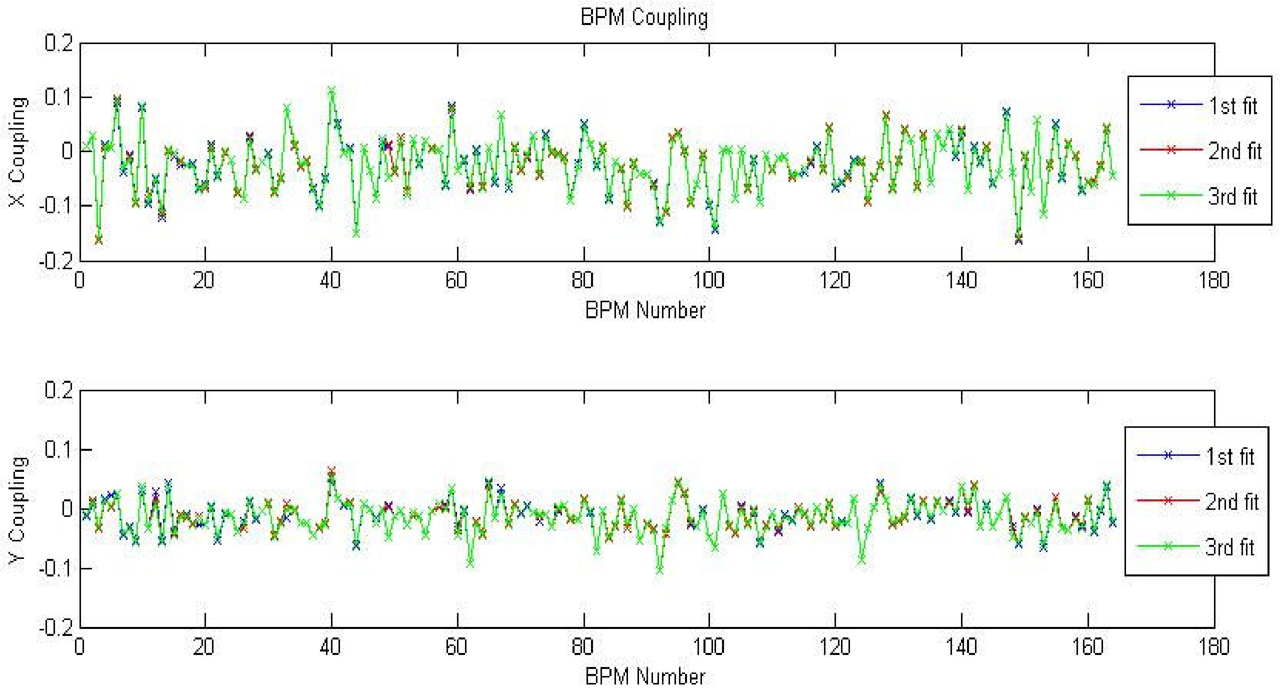




BPMs coupling

LOCO fits also the BPM gain and coupling

BPM coupling includes mechanical rotation and electronics cross talk

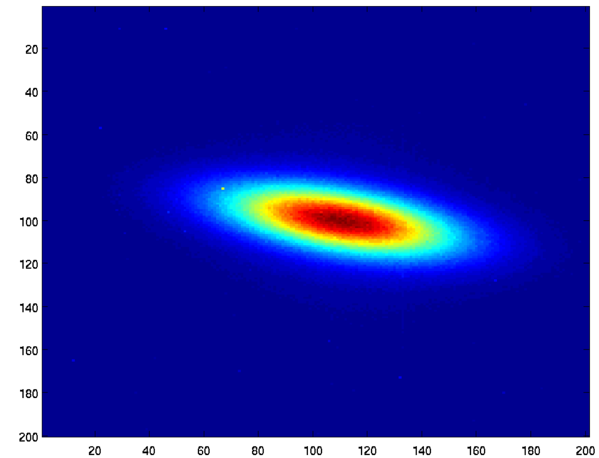


These data are well reproducible over months

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 %)



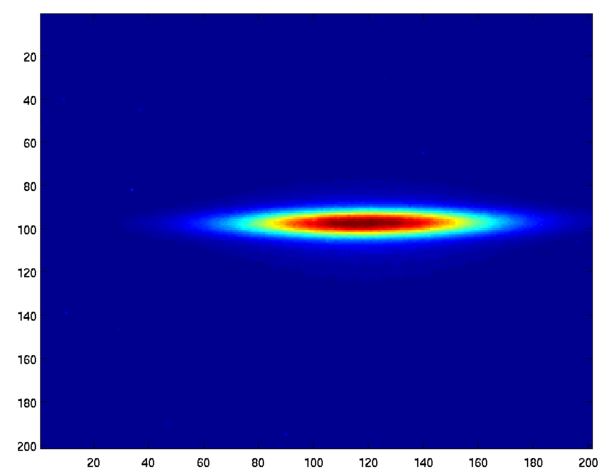
Emittance [2.78 - 2.74] (2.75) nm

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**

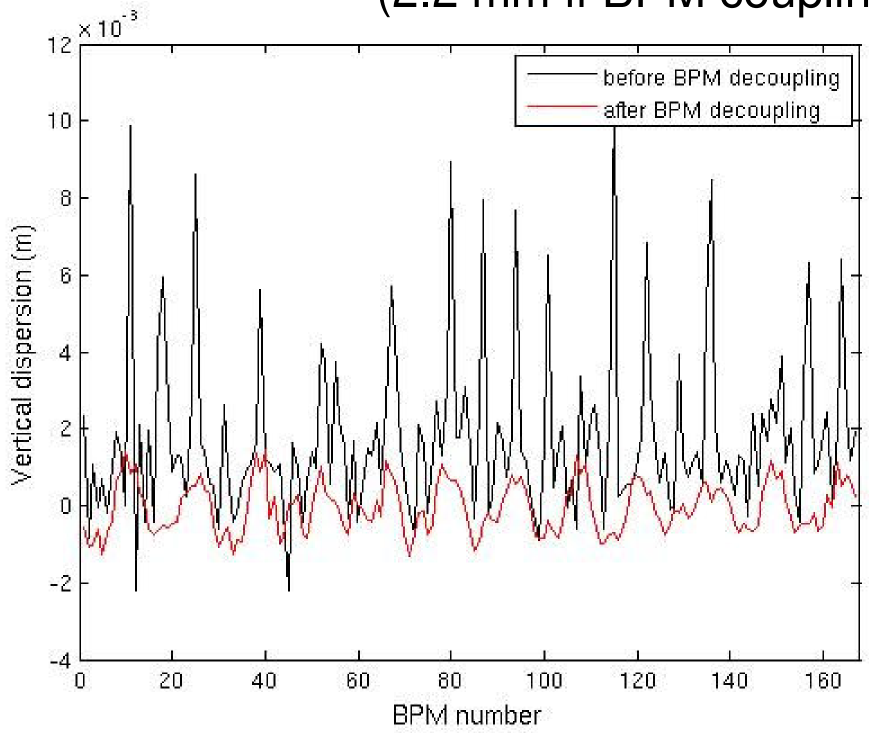
Variation of less than 20% over different measurements

Residual vertical dispersion

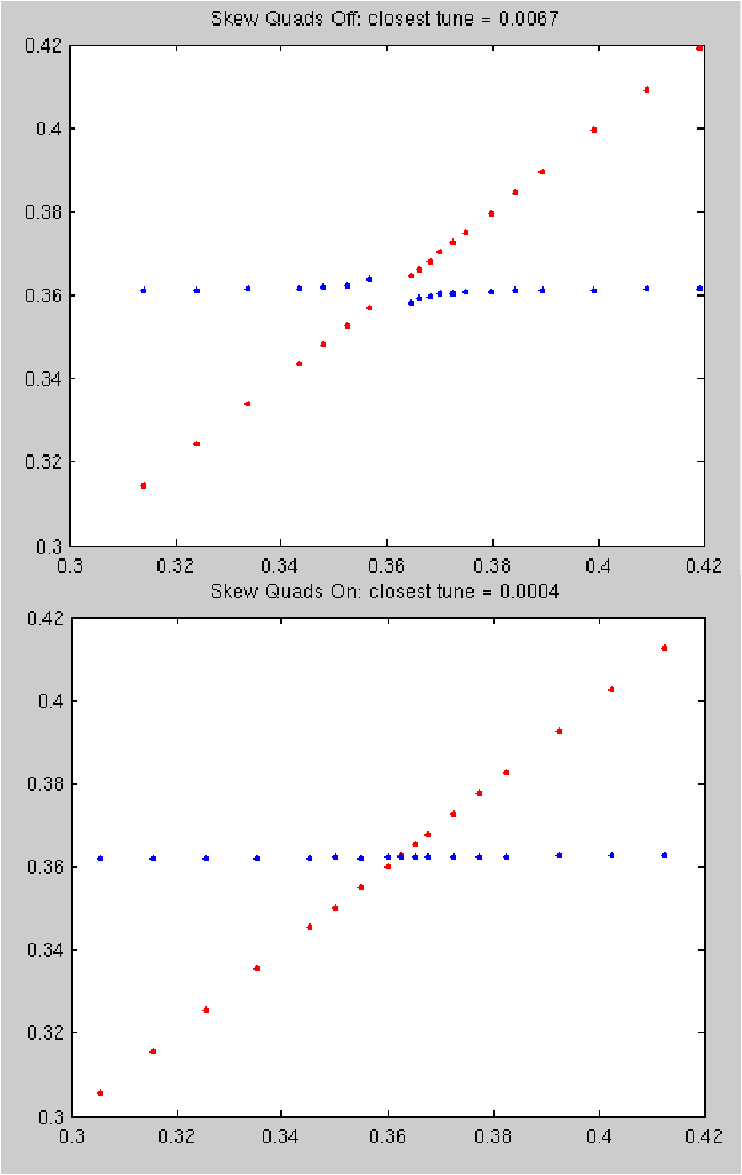
Without skew quadrupoles off r.m.s. Dy = 14 mm

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

(2.2 mm if BPM coupling is not corrected)



Betatron coupling measurement: closest tune approach



The linear betatron coupling (χ) is given by

$$\chi = \frac{\left(c/\Delta\right)^2}{1/2 + \left(c/\Delta\right)^2}$$

C is the minimum separation of the betatron tunes at the resonance is crossed

Δ is the distance of the betatron tunes at the nominal working point

After one LOCO iteration K = 0.15% and C ~ 0

	betatron coupling	emittance coupling
before	0.47 %	1.3%
after	0.002 %	0.15%

Linear coupling correction with turn-by-turn measurements

All BPMs have turn-by-turn capabilities

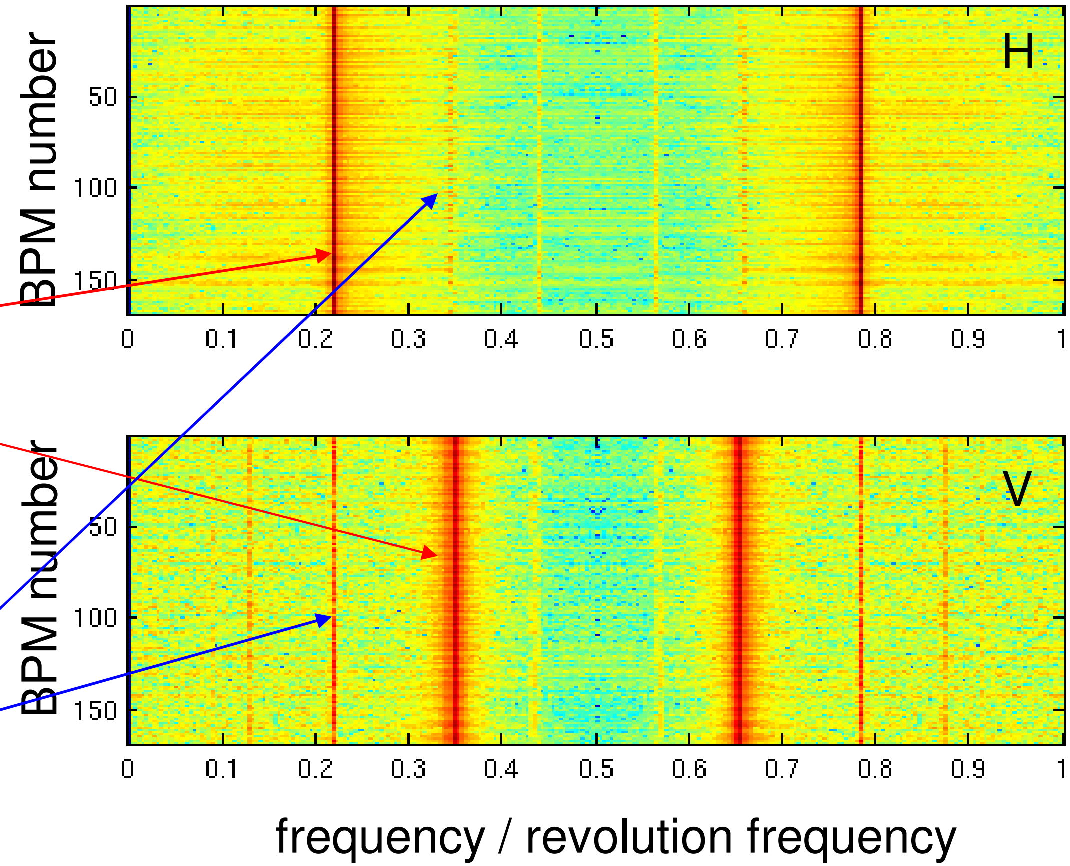
- excite the beam diagonally
- measure tbt data at all BPMs
- colour plots of the FFT

Q_X = 0.22 H tune in H

Q_y = 0.36 V tune in V

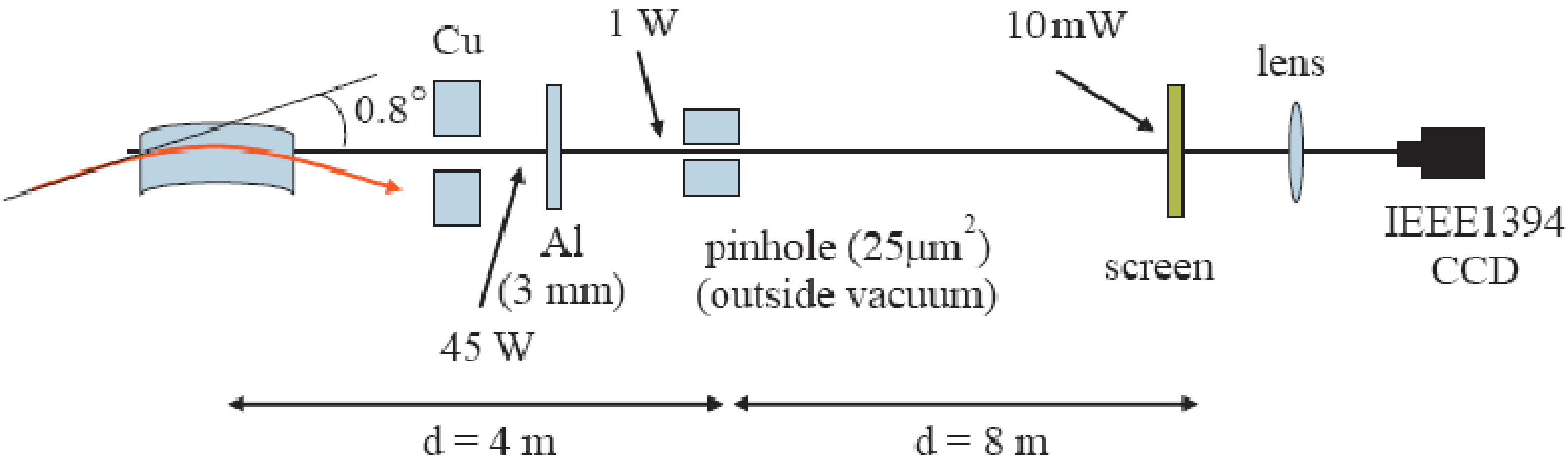
All the other important lines are linear combination of the tunes Q_x and Q_y

$m\,Q_x + n\,Q_y$



Emittance and coupling measurements (I)

Measurements of emittance, energy spread and coupling are made with two **X-rays pinhole cameras** which take the synchrotron radiation from the two dipoles in cell 1



Emittance and emittance coupling are measured indirectly from

measurement of beam spot at the camera

point spread function of the system (→ beam size at the camera)

magnification of the optics (→ beam size at the source point)

electron beam optics functions at the source point (→ emittance)

Emittance and coupling measurements (II)

The point spread function (PSF) Σ_0 is the spot size measured at the camera for a zero emittance electron beam.

$$\Sigma^2 = S^2 + \Sigma_o^2 \qquad \text{if } S = 0 \;\rightarrow\; \Sigma = \Sigma_0$$

The computation of the PSF Σ_0 requires the computation of the diffraction contributions from the square aperture of the pinhole (Fresnel diffraction + spectrum dependence)

$$\Sigma_0^2 = S_{\text{pinhole}}^2 + S_{\text{camera}}^2$$

Σ_0 ~ 15 μm for pinhole 1 and 2 ($CdWO_4$)

The computation of the beam size at the camera S is made with a deconvolution of the PSF Σ_0 assuming Gaussian distributions

The beam size at the source σ is computed from the beam size at the camera S and the magnification m of the X-ray pinhole camera

$$\sigma = \frac{S}{m} = \frac{1}{m}\sqrt{\Sigma^2 - \Sigma_o^2}$$

m = 2.4 for pinhole 1; m = 2.7 for pinhole 2

Emittance and coupling measurements (III)

Experimental confirmation of the contribution of the PSF Σ_0 to the beam size were based on the simultaneous measurements of the

• beam lifetime (Touschek dominated) – proxy for σ_y

and

• measured vertical beam size at the source without/with the deconvolution of the PSF Σ_0

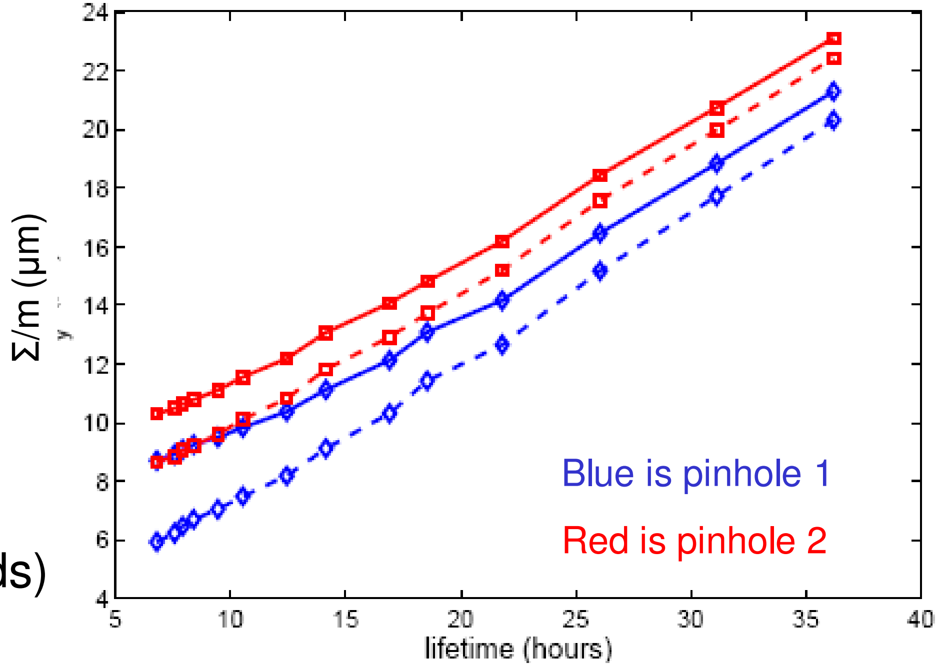
$$\frac{\Sigma}{m} = \frac{1}{m}\sqrt{S^2 + \Sigma_0^2} = \sqrt{\sigma^2 + \frac{\Sigma_0^2}{m^2}}$$

$$\frac{1}{m}\sqrt{\Sigma^2 - \Sigma_o^2} = \frac{S}{m} = \sigma$$

Pinh 1

Σ = 20.9 um Σ_0 = 15.3 um

m = 2.4 σ = 5.9 um



Data with the deconvolution (open diamonds) provide the expected linear relation

The vertical beam size is varied scanning the skew quads taking care that the momentum aperture is unchanged

Emittance and coupling measurements (IV)

The optics functions at the source point can be either inferred from LOCO or measured directly

measure dispersion at the pinhole

added pinhole as a BPM in the LOCO procedure to make sure the optics function at the source point (inside the bending magnet) are correct.

Difference is not significant (good linear model)

The resolution of our system is about 3 μm which is adequate to measure a 6 μm V beam size.

(C. Thomas et al. submitted to PRSTAB – DLS internal note TDI-DIA-OPT-0002)

Conclusions

Diamond is a state-of-the-art third generation light source

Careful alignment and independent power supplies in all quadrupoles have allowed a very good control of the linear optics

Sufficient provision for independently powered skew quads have allows good coupling correction

With LOCO a V emittance of 2.2 pm has been achieved

An intense campaign of Accelerator Physics studies is ongoing to better understand and improve the machine performance

Future work on coupling:

Can we correct the linear coupling better than LOCO?

Is sextupole BBA and realignment necessary to achieve lower V emittance?

(…zero push from users... but damping rings and B-factories are interested)