Status of the Diamond Light Source

R. Bartolini

Diamond Light Source Ltd
and
John Adams Institute, University of Oxford

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Outline

- Introduction to Diamond
- Beam optics studies (linear and nonlinear)
- Beam stability
- Low alpha optics and THz emission
- Customised optics

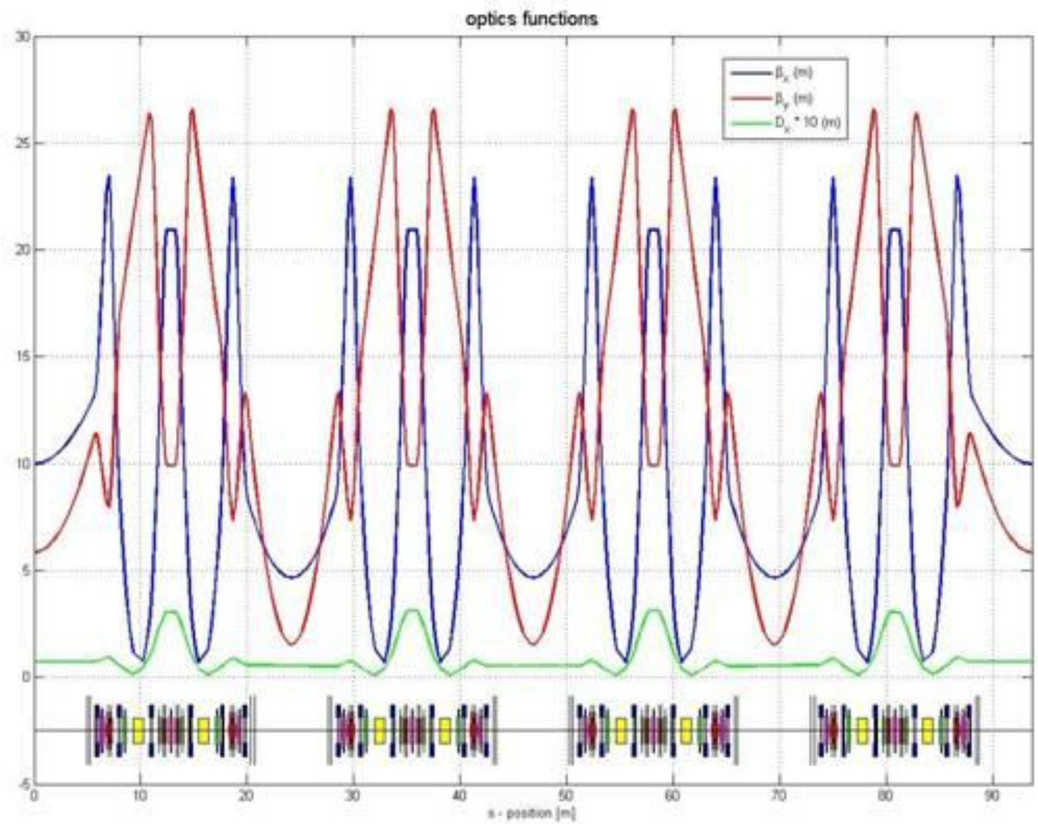
Diamond aerial view

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



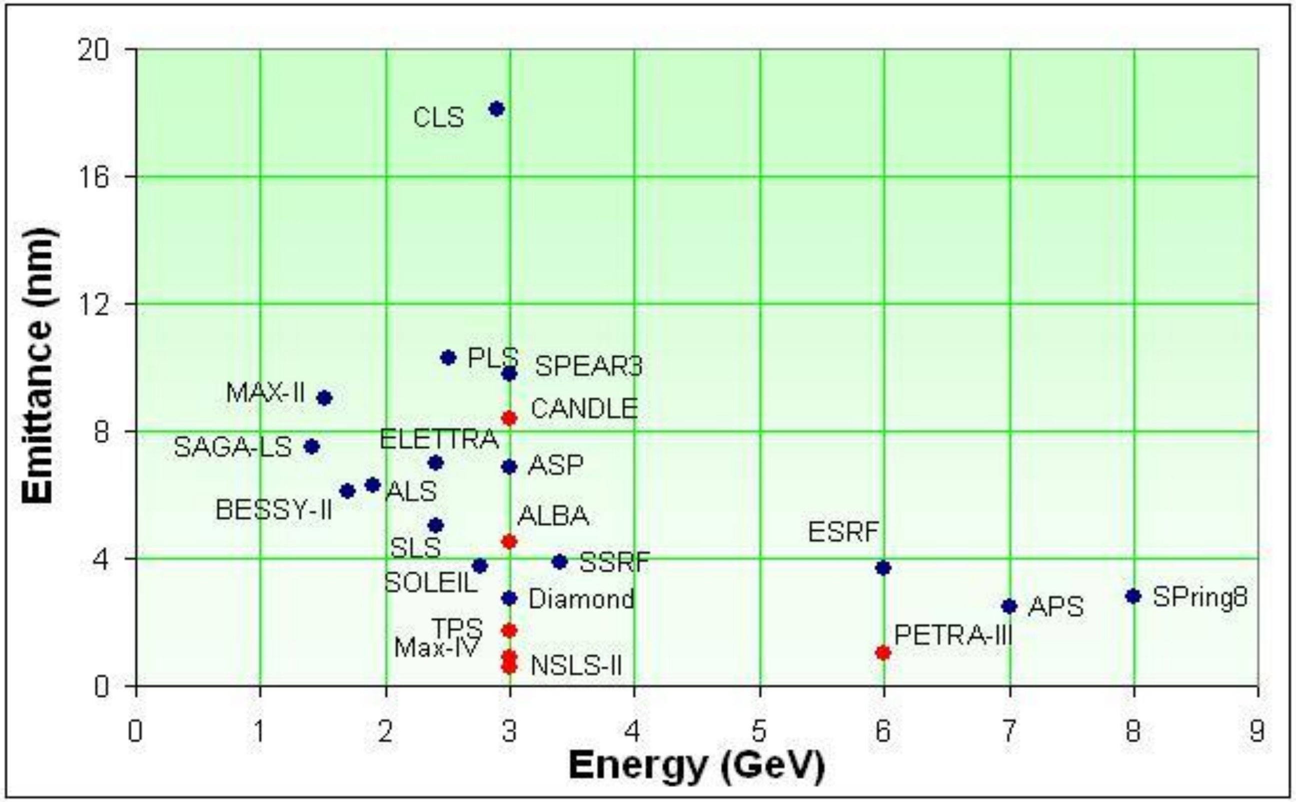
48 Dipoles; 240 Quadrupoles; 168 Sextupoles
(+ H and V orbit correctors + 96 Skew Quadrupoles)
3 SC RF cavities; 168 BPMs

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**

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



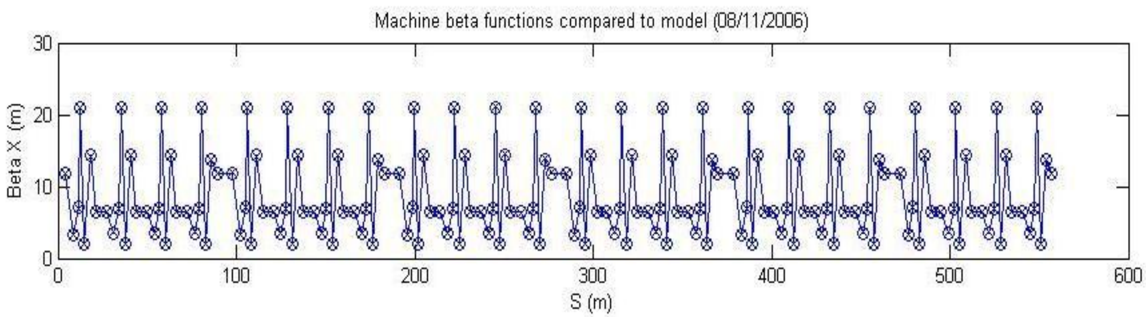
$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

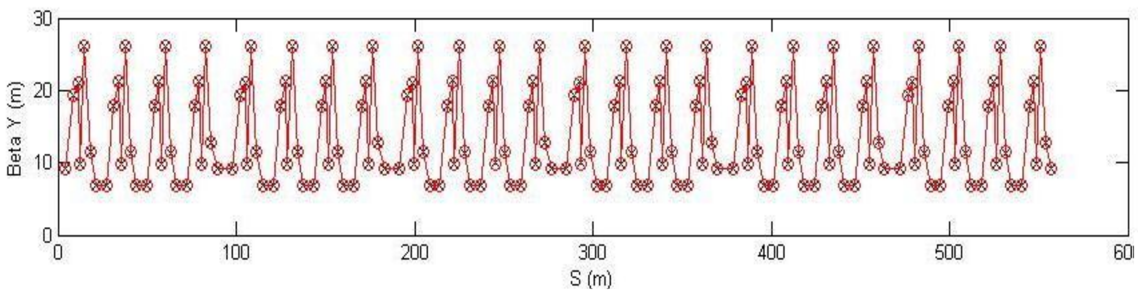
$$\Sigma_x = \sqrt{\sigma^2_{x,e} + \sigma^2_{ph,e}} \qquad \sigma_x = \sqrt{\varepsilon_x \beta_x + (D_x \sigma_\varepsilon)^2}$$

$$\Sigma_{x'} = \sqrt{\sigma^2_{x',e} + \sigma'^2_{ph,e}} \qquad \sigma_{x'} = \sqrt{\varepsilon_x \beta_x + (D'_x \sigma_\varepsilon)^2}$$

Linear optics modelling with LOCO

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

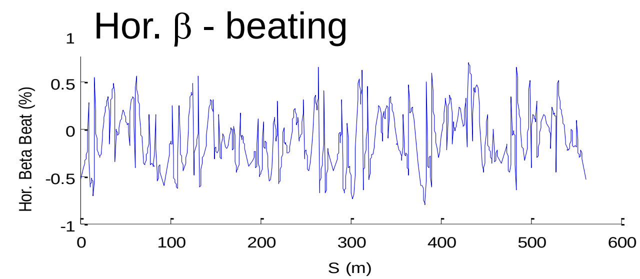


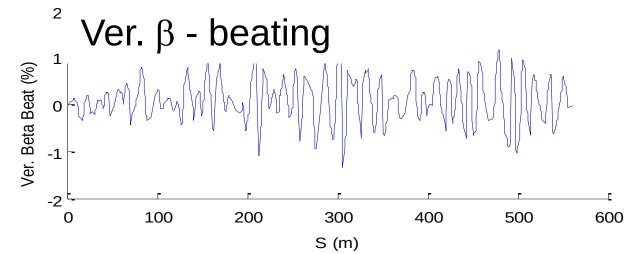


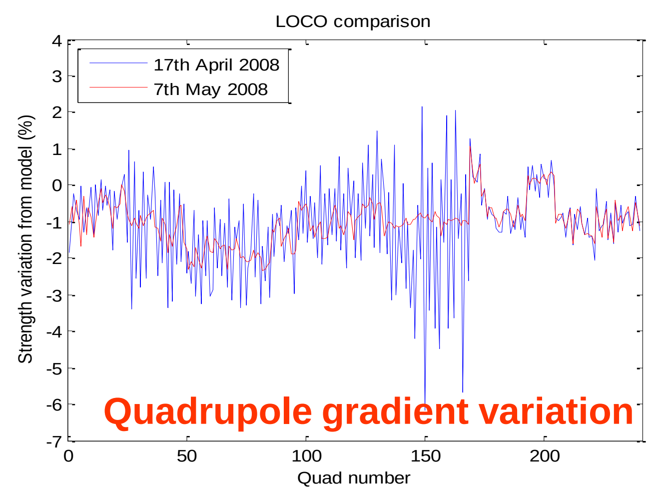
Modified version of LOCO with constraints on gradien variations **(see [ICFA Newsl, Dec'07](#))**

β - beating reduced to 0.4% rms

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





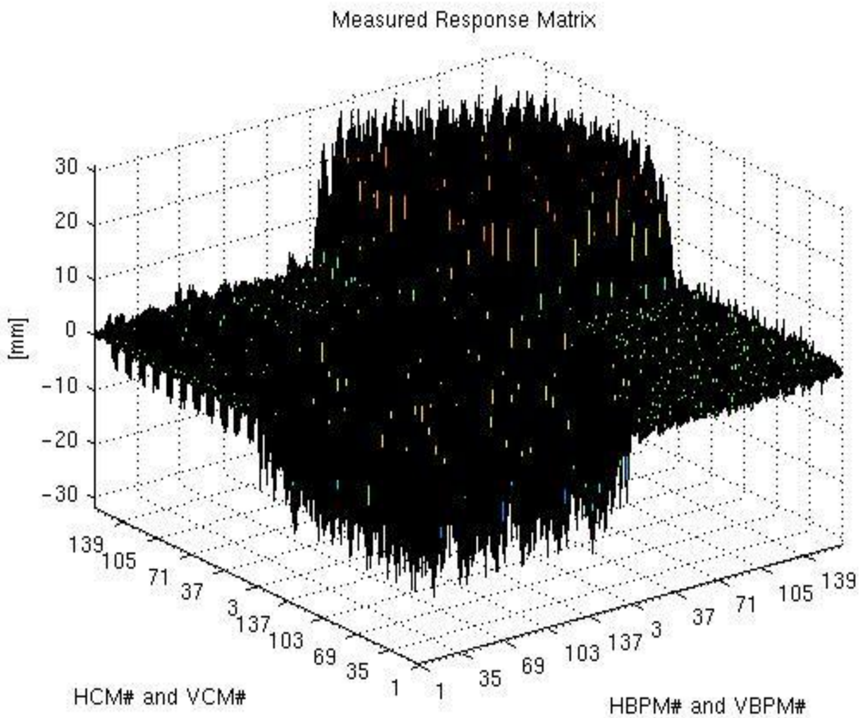


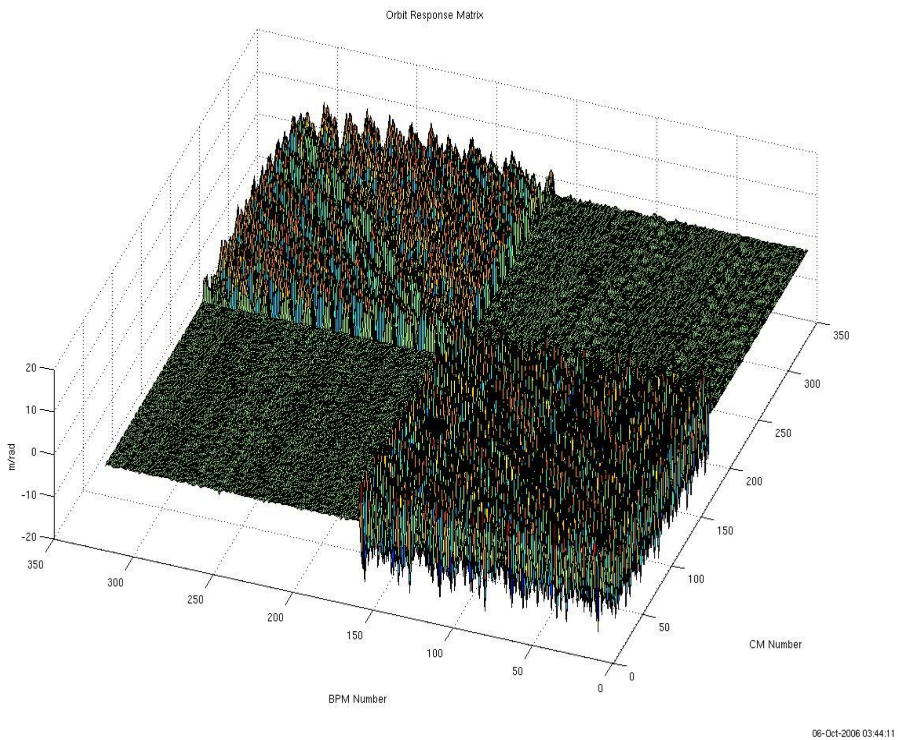
LOCO allowed remarkable progress with the correct implementation of the linear optics

Linear coupling correction with LOCO

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

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



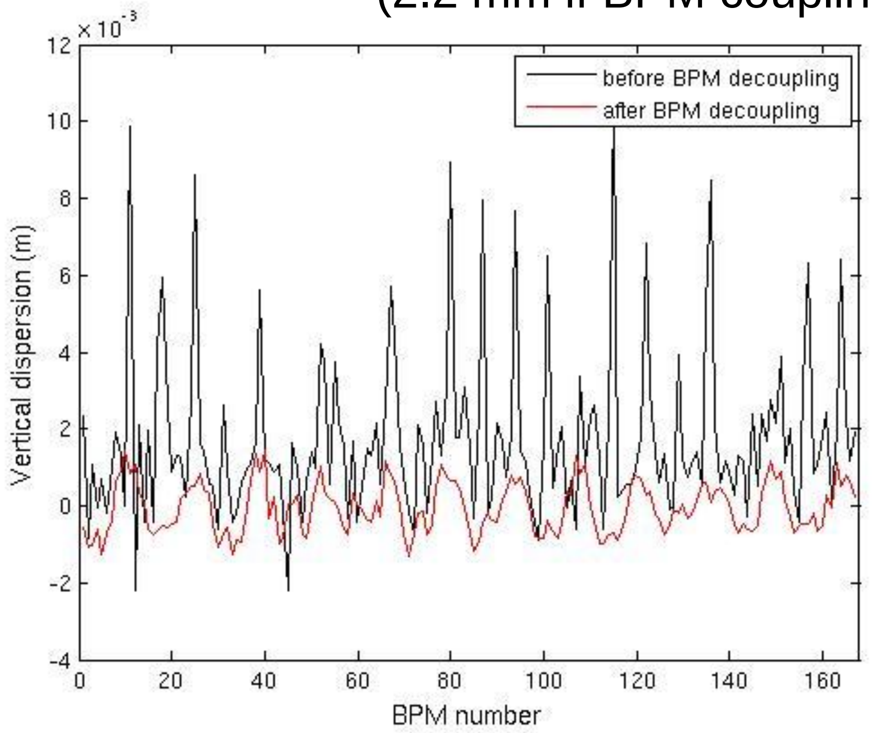


Residual vertical dispersion after correction

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

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

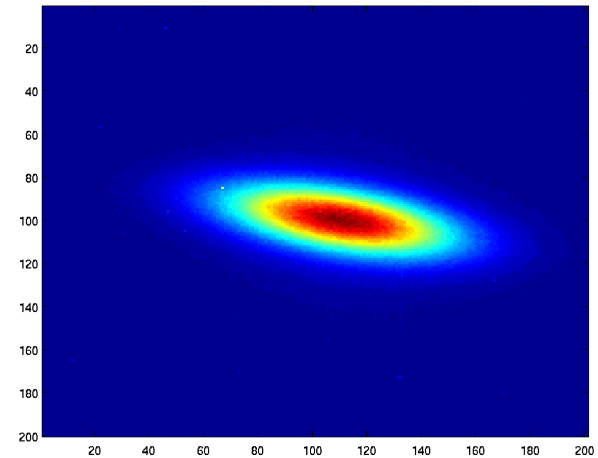
(2.2 mm if BPM coupling is not corrected)



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 %)



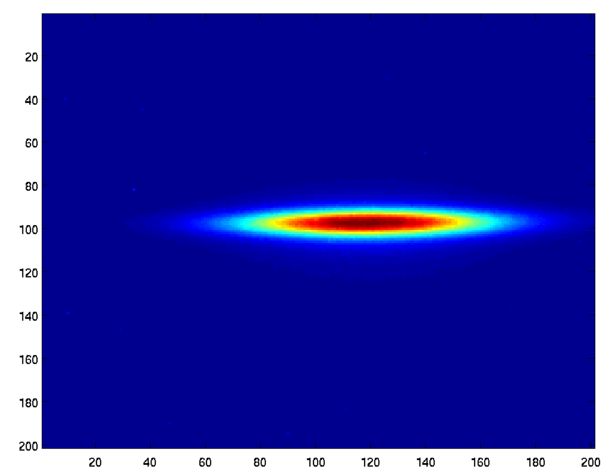
Emittance [2.78 - 2.74] (2.75) nm

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**

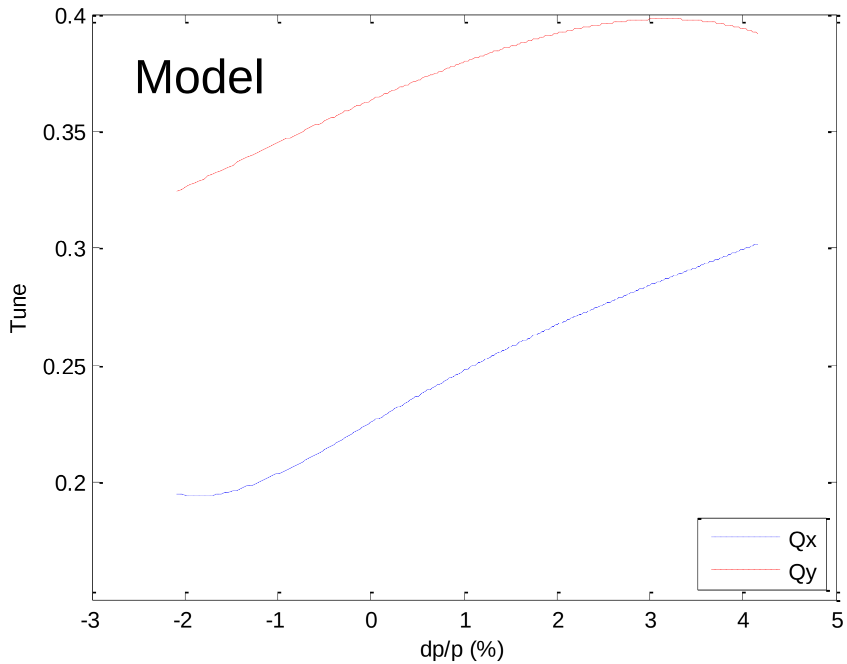
Variation of less than 20% over different measurements

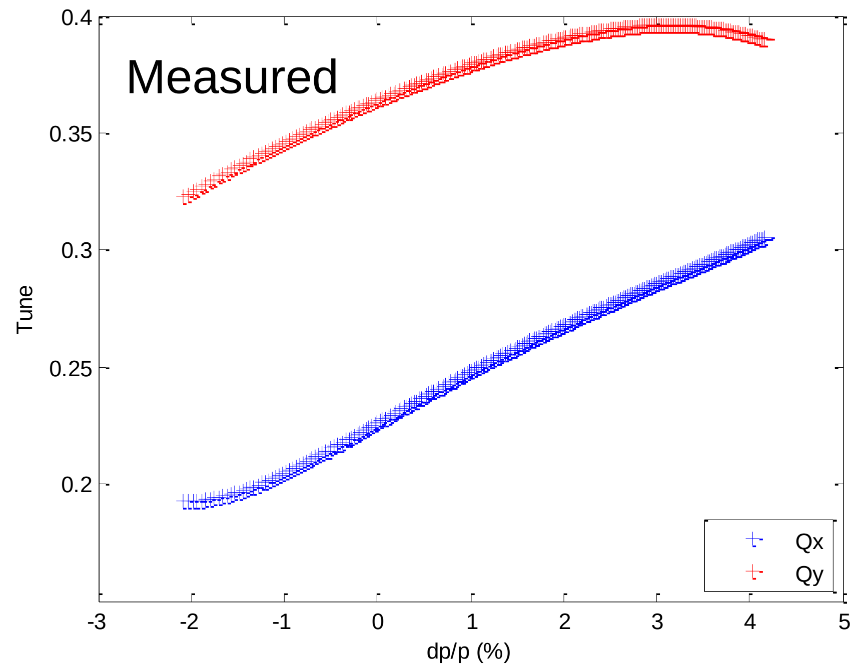
Lowest vertical emittance

	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%	0.25%	5 pm
SLS	5.6 nm	5.4-7 nm	4.5% H; 1.3% V	0.05%	2.8 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

Nonlinear dynamics comparison machine to model (I)

Detuning with momentum: operation at positive chromaticity (2/2)





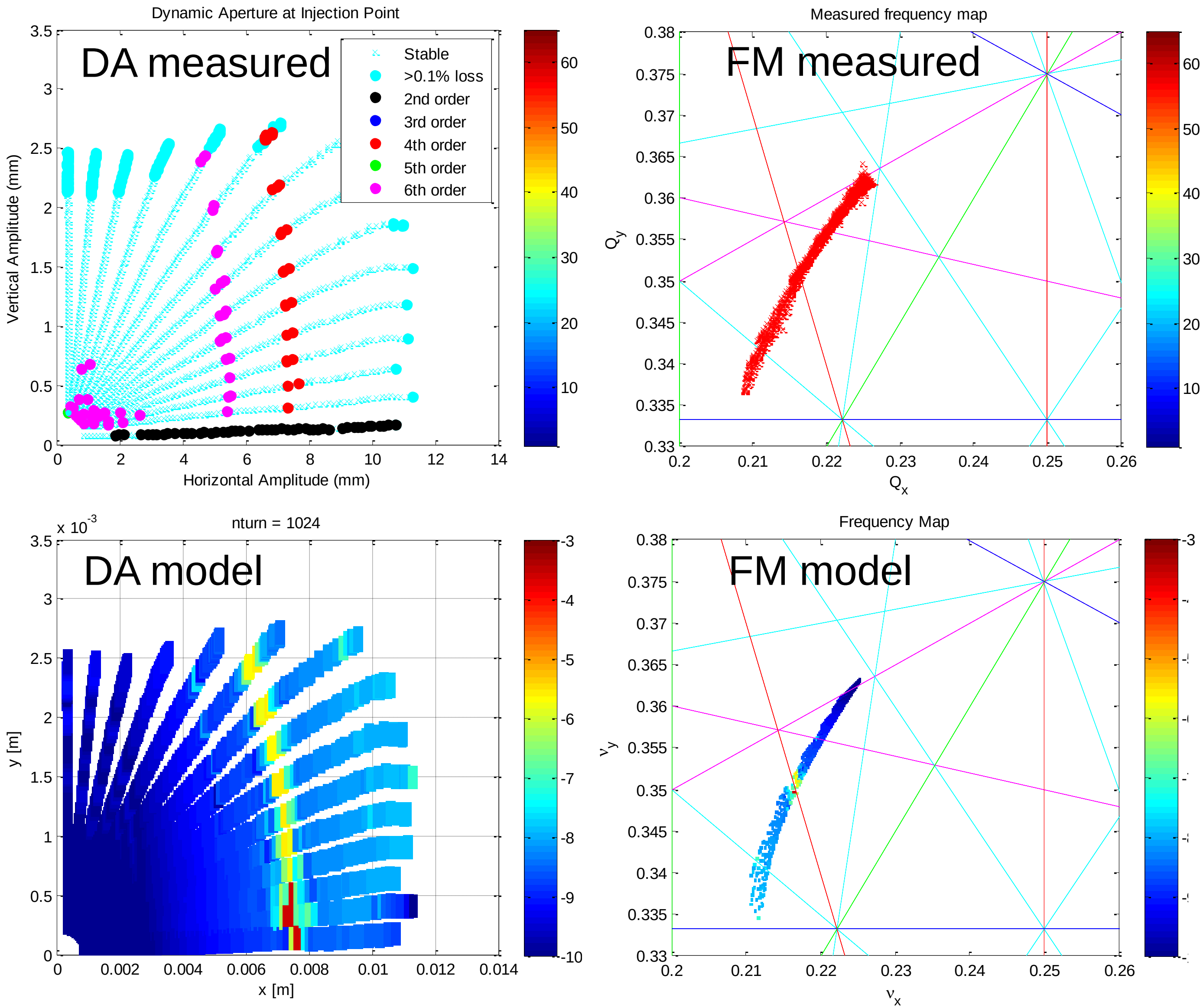
Calibration tables for sextupole families were off by few %

The most complete description of the nonlinear model is mandatory !

Fringe fields in dipoles (2^{nd} order –symplectic integration) and in quadrupoles

Higher order multipoles in dipoles and quadrupoles (from measurements)

Nonlinear dynamics comparison machine to model (II)



1)

Substantial progress after understanding the frequency response of the Libera BPMs

2)

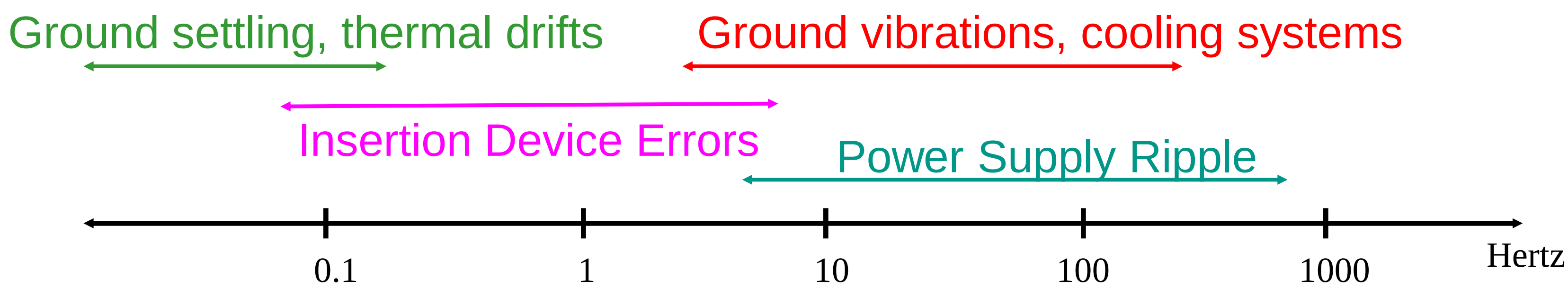
Octupole component in the dipoles reduced by a factor 5

3)

H DA limited by the orbit ILK, not by nonlinearities

(tracking data do not proceed further to larger amplitudes)

Orbit stability: disturbances and requirements



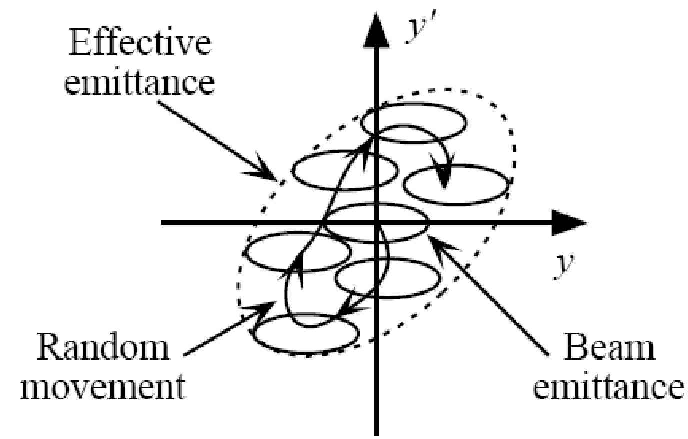
Beam stability should be better than

10% of the beam size

10% of the beam divergence

up to 100 Hz

but IR beamlines will have tighter requirements



<u>for 3rd generation light sources this implies sub-μm stability</u>

- identification of sources of orbit movement
- passive damping measures
- orbit feedback systems

Orbit stability requirements for Diamond

Beam stability should be better than 10% of the beam size

$$\Delta x < 0.1 \cdot \sigma_x \qquad \Delta x' < 0.1 \cdot \sigma_{x'}$$
$$\Delta y < 0.1 \cdot \sigma_y \qquad \Delta y' < 0.1 \cdot \sigma_{y'}$$

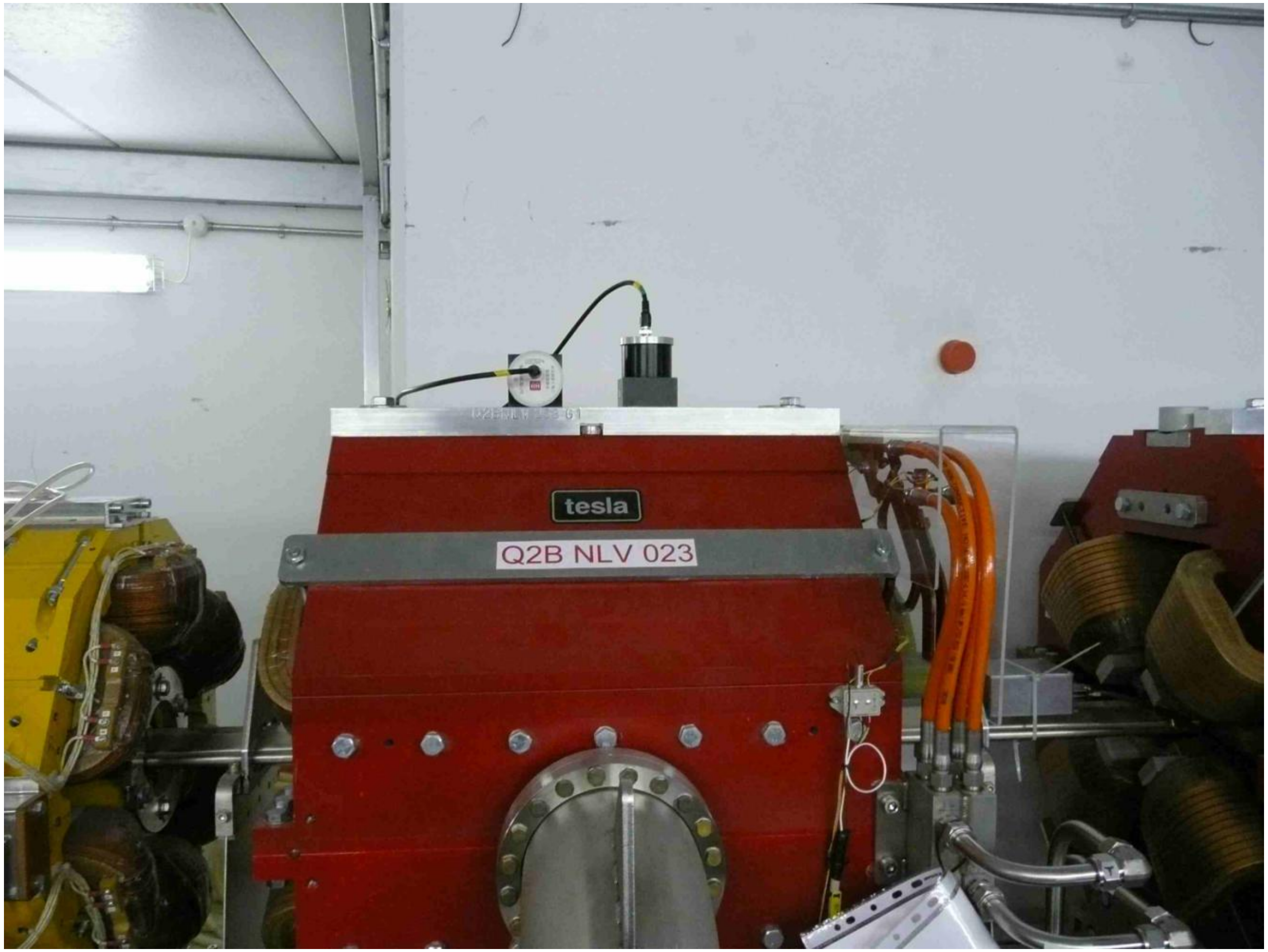
For Diamond nominal optics (at short straight sections)

$$\Delta x < 0.1 \cdot 123\,\mu m = 12.3\,\mu m \qquad \Delta x' < 0.1 \cdot 24\,\mu rad = 2.4\,\mu rad$$

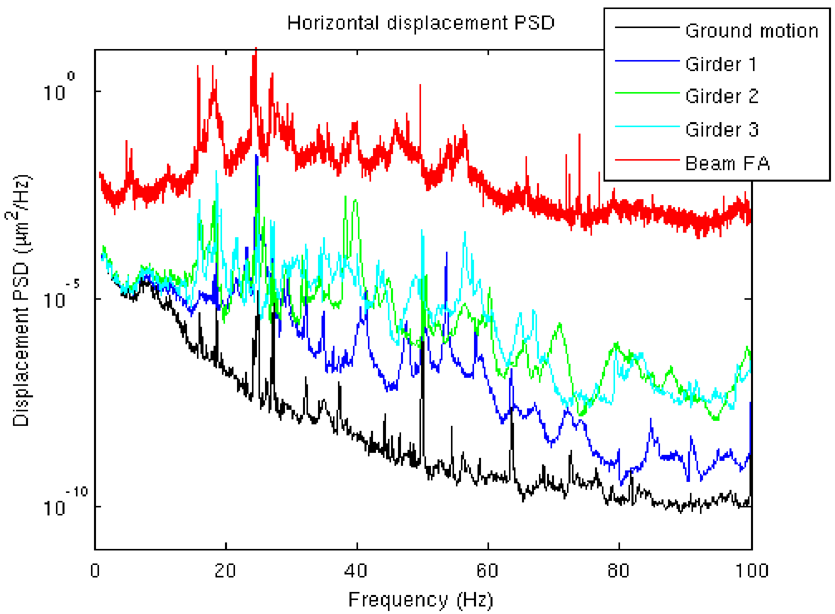
$$\Delta y < 0.1 \cdot 6.4\,\mu m = 0.6\,\mu m \qquad \Delta y' < 0.1 \cdot 4\,\mu rad = 0.4\,\mu rad$$

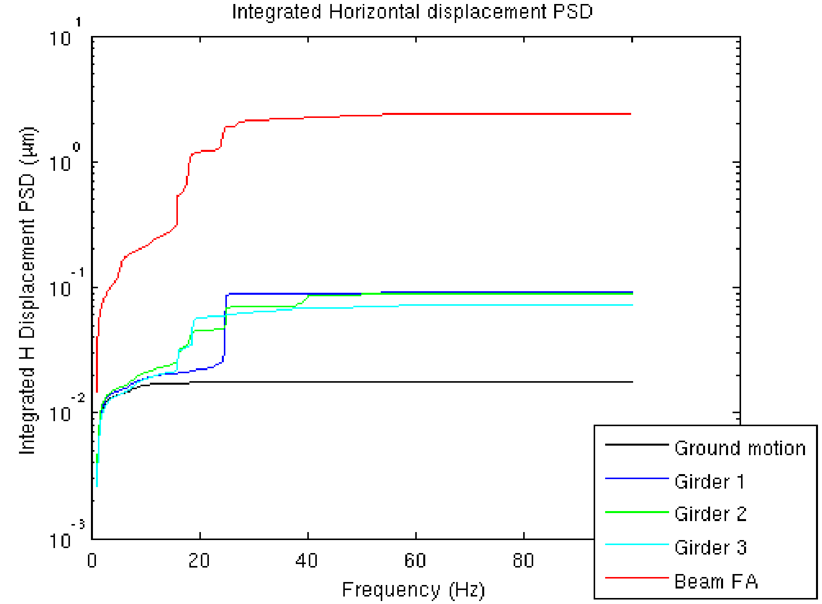
IR beamlines might have tighter requirements

Seismometer mounted on top of a quadrupole



Ground vibrations to beam vibrations: Diamond

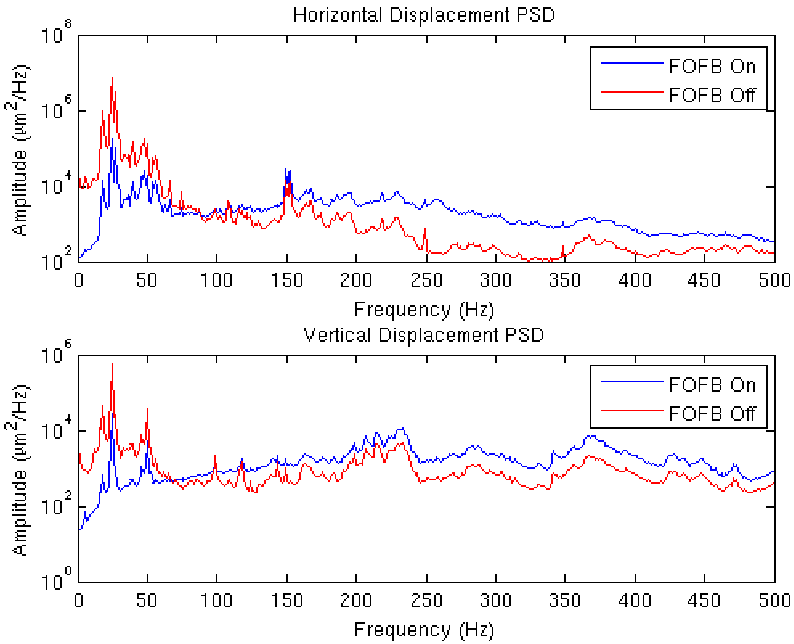


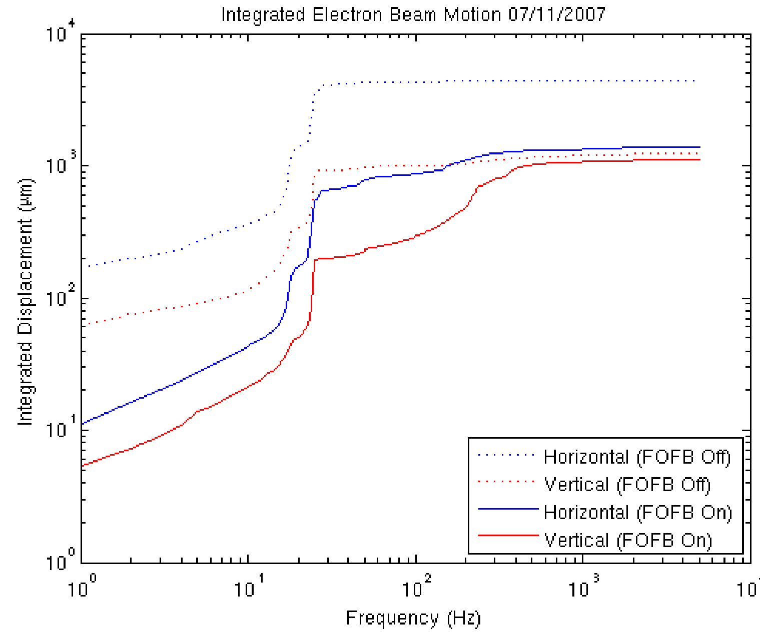


Amplification factor girders to beam: H 31 (theory 35); V 12 (theory 8);

1-100 Hz		Horizontal		Vertical	
		Long Straight	Standard Straight	Long Straight	Standard Straight
Position (μm)	Target	17.8	12.3	1.26	0.64
	Measured	3.95 (2.2%)	2.53 (2.1%)	0.70 (5.5%)	0.37 (5.8%)
Angle (μrad)	Target	1.65	2.42	0.22	0.42
	measured	0.38 (2.3%)	0.53 (2.2%)	0.14 (6.3%)	0.26 (6.2%)

Global fast orbit feedback: Diamond





Significant reduction of the rms beam motion up to 100 Hz;

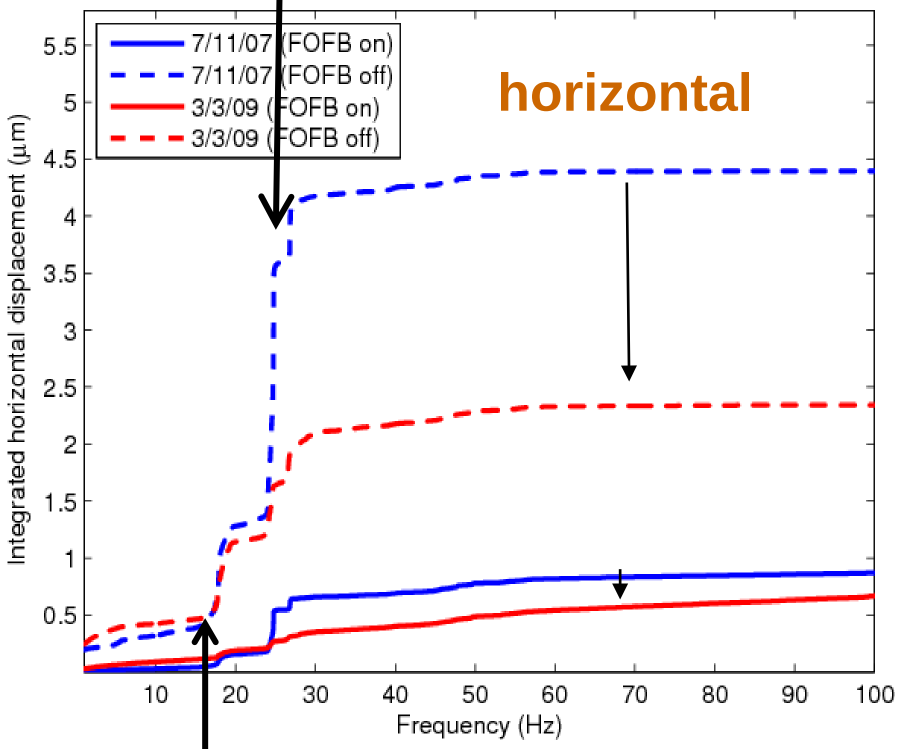
Higher frequencies performance limited mainly by the correctors power supply bandwidth

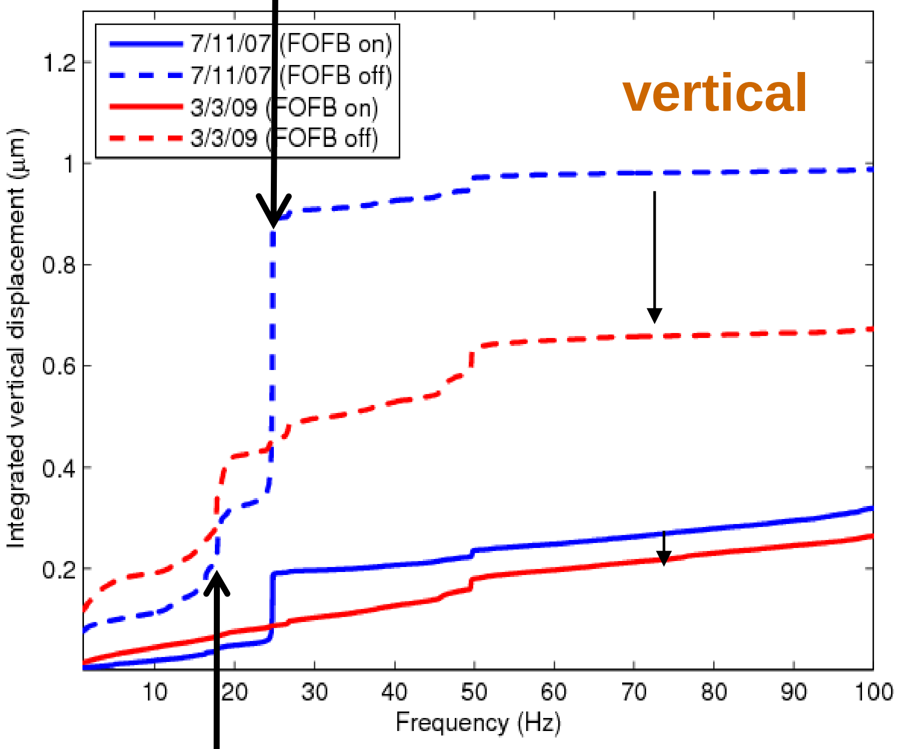
1-100 Hz		Standard Straight H	Standard Straight V
Position (μm)	Target	12.3	0.64
	No FOFB	2.53 (2.1%)	0.37 (5.8%)
	FOFB On	0.86 (0.7%)	0.15 (2.3%)
Angle (μrad)	Target	2.42	0.42
	No FOFB	0.53 (2.2%)	0.26 (6.2%)
	FOFB On	0.16 (0.7%)	0.09 (2.1%)

Passive improvement of orbit stability

Girder vibrations

Elimination of vibrations at 24.9 Hz after fixing water cooling pump mountings





next target: air handling units, 18 Hz

Top-Up motivation

Higher average brightness

- *Higher average current*
- *Constant flux on sample*

Improved stability

- *Constant heat load*
- *Beam current dependence of BPMs*

Flexible operation

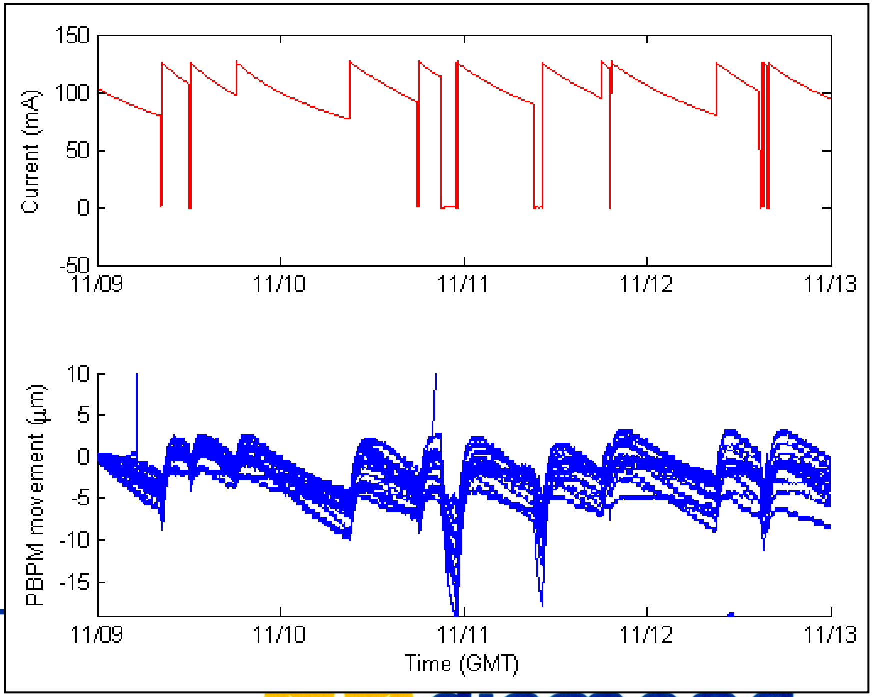
- *Lifetime less important*
- *Smaller ID gaps*
- *Lower coupling*

BPMs block stability

• without Top-Up ~ 10 μm

• with Top-Up < 1 μm

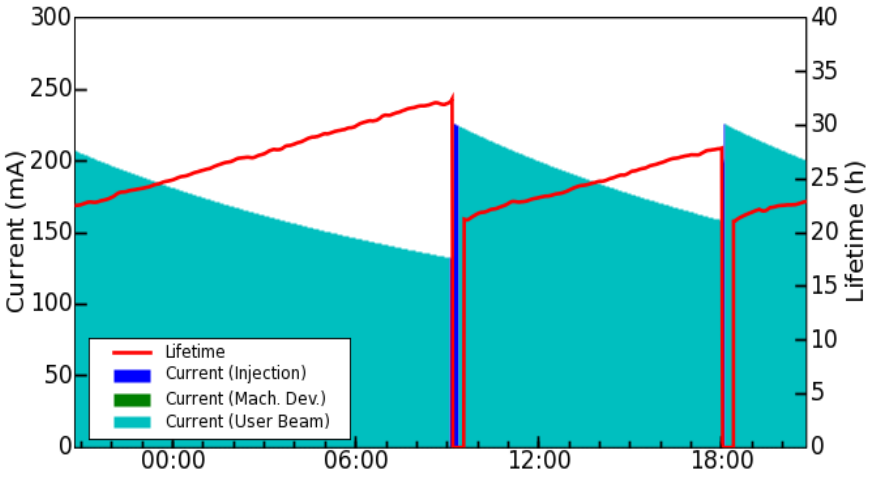
Crucial for long term sub- μm stability

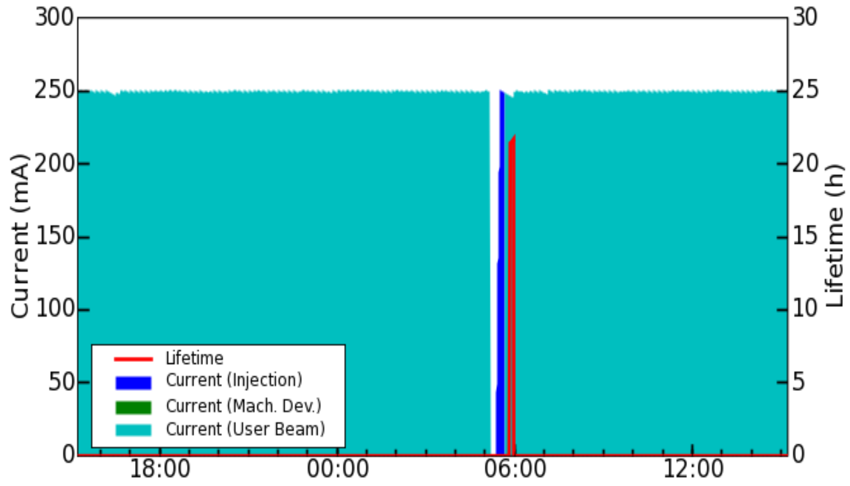


Top-Up mode (I)

First operation with external users, 3 days, Oct. 28-30

Moved from the "Standard" operation: 250 mA maximum, 2 injections/day

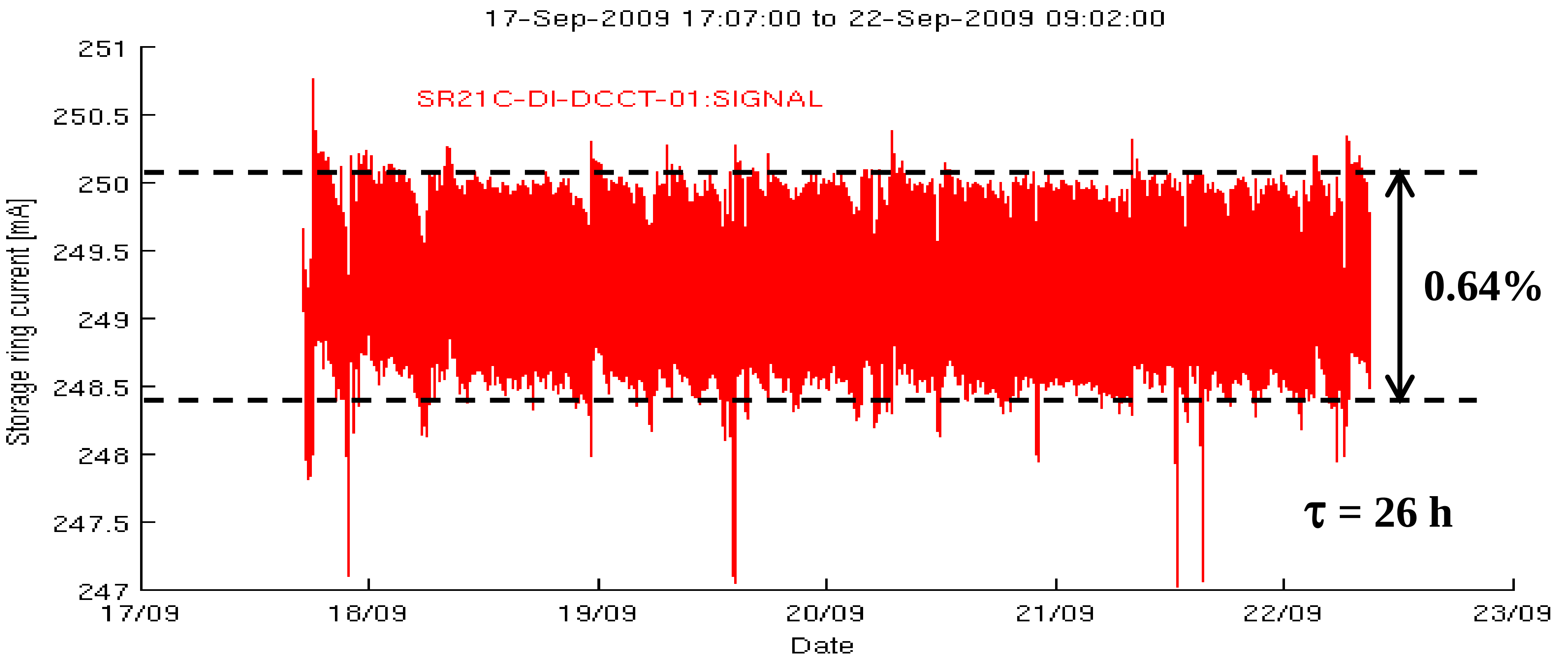




No top-up failures, no beam trips due specifically to top-up

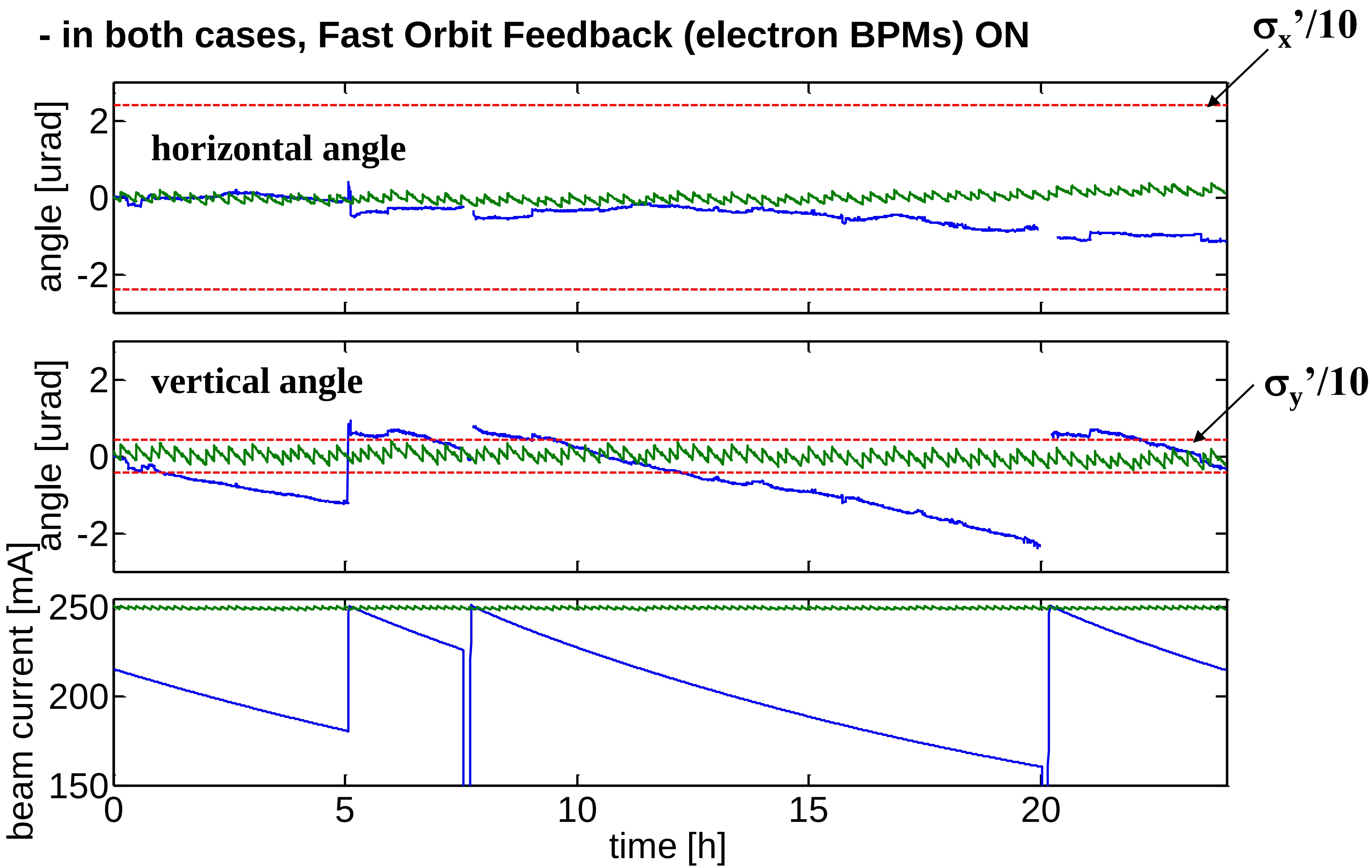
Top-Up mode

❖ **17^{th}-19^{th} September 2009: 112 h of uninterrupted beam:**



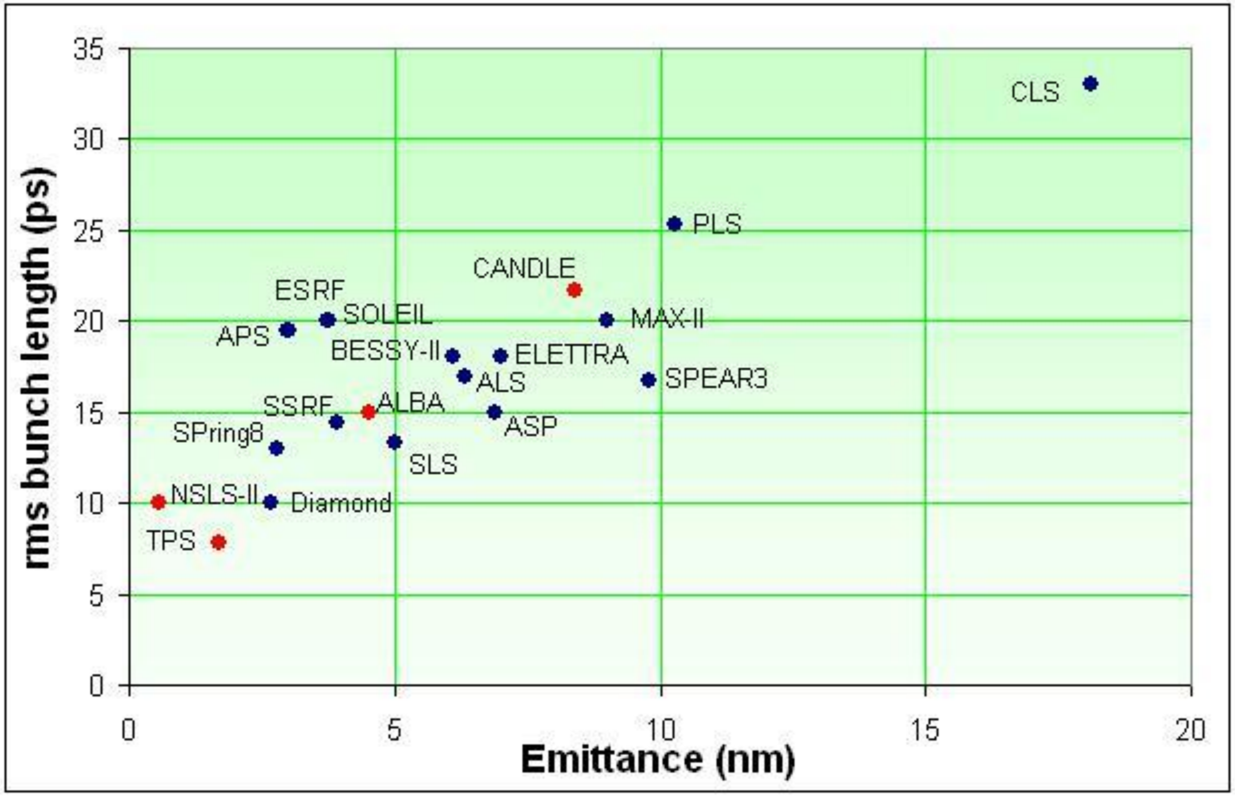
Improvement of orbit stability in Top-Up mode

- measured using one of the photon BPMs (fixed ID gap)
- in both cases, Fast Orbit Feedback (electron BPMs) ON



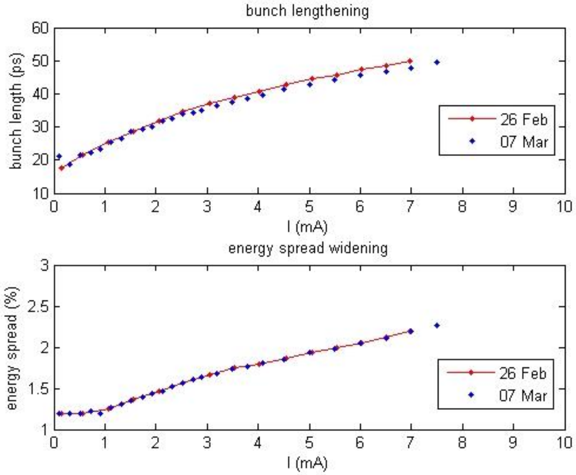
Bunch length in 3rd generation light sources

Time resolved science requires operating modes with single bunch or hybrid fills to exploit the short radiation pulses of a single isolated bunch



The rms bunch length is increases with the stored charge per bunch

(PWD and MI)



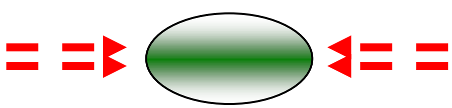
Modern light sources can operate a wide variety of fill patterns (few bunches, camshaft)

Ultra-short radiation pulses in a storage ring

There are three main approaches to generate short radiation pulses in storage rings

e^- bunch

1) shorten the e- bunch

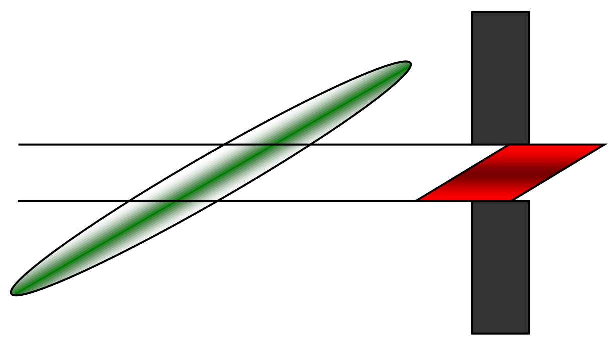


Low – alpha optics

Higher Harmonic Cavities

RF voltage modulation

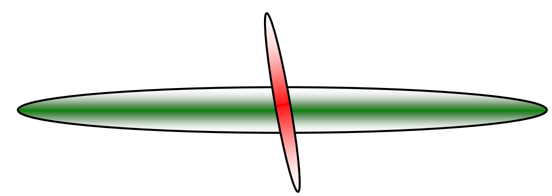
2) chirp the e-bunch + slit or optical compression



Crab Cavities

Synchro-betatron kicks

3) Laser induced local energy-density modulation



Femto–slicing

Short bunches at Diamond

The equilibrium bunch length at low current is

$$\sigma_z = \frac{\alpha c}{2\pi f_s}\sigma_\varepsilon \propto \sqrt{\frac{\alpha \gamma^3}{dV_{RF}/dz}}$$

We can modify the electron optics to reduce α

$$\alpha = \frac{1}{L}\oint \frac{D_x}{\rho} ds \approx 10^{-6}$$

α (low_alpha_optics) $\approx$ α (nominal) /100 ➔ **σ_z(low alpha optics) $\approx$ σ_z(nominal)/10**

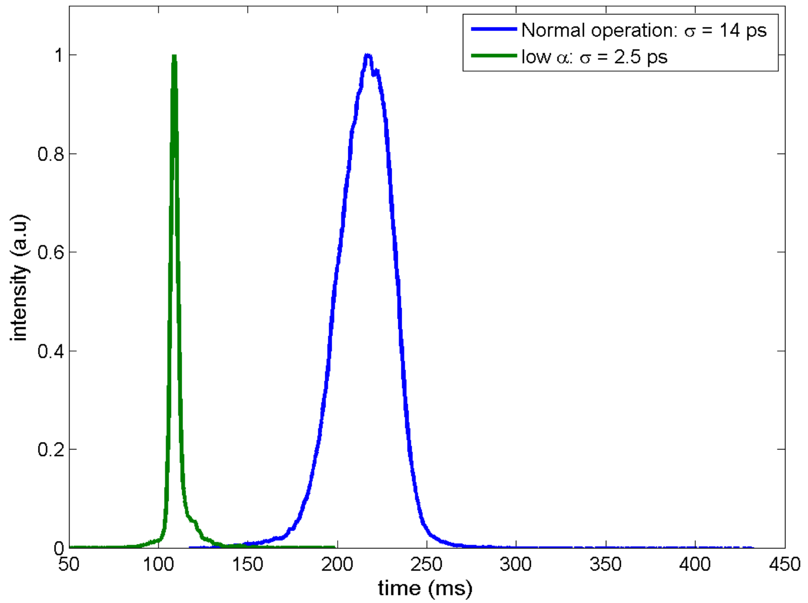
Comparison of measured pulse length for normal and low momentum compaction

2.5 ps is the resolution of the streak camera

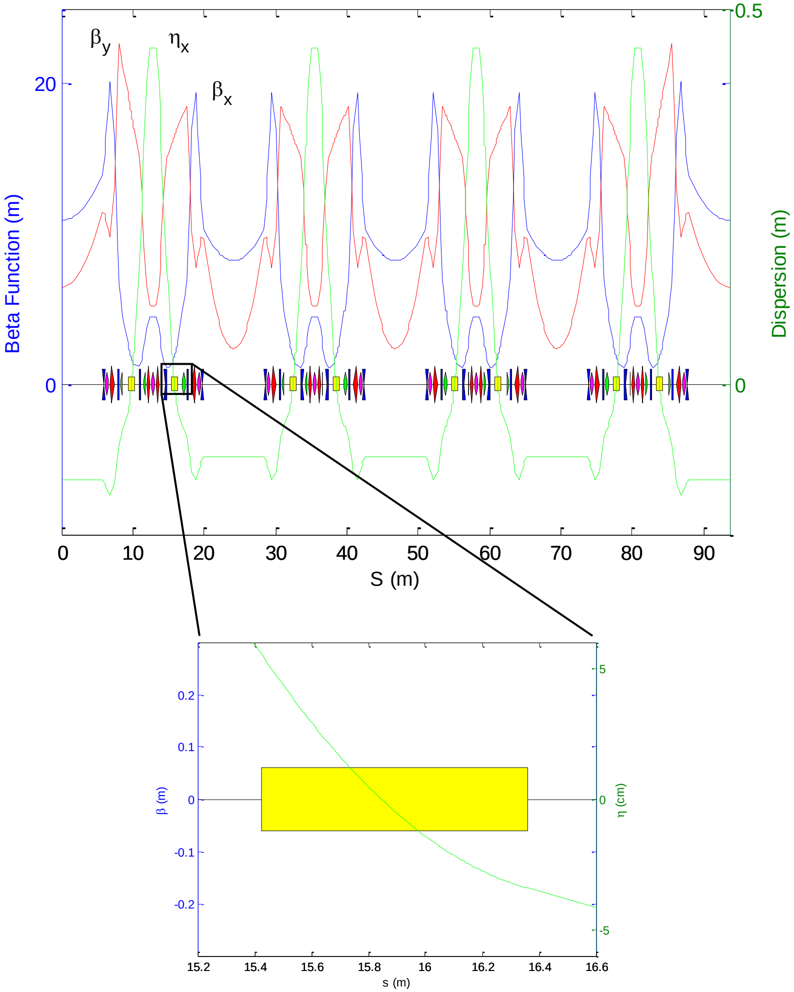
Shorter bunch length confirmed by synchrotron tune measurements

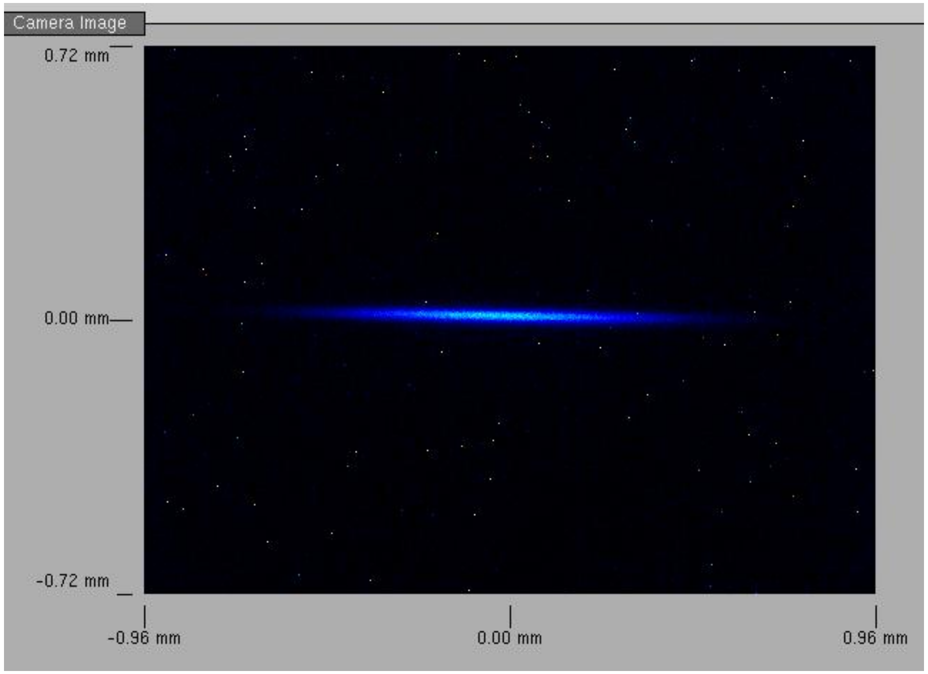
$f_s = 340Hz \Rightarrow \alpha_1 = 3.4\ \ 10^{-6}, \sigma_L = 1.5\text{ps}$

$f_s = 260Hz \Rightarrow \alpha_1 = 1.7\times10^{-6}, \sigma_L = 0.98\text{ps}$



Low alpha lattices at Diamond





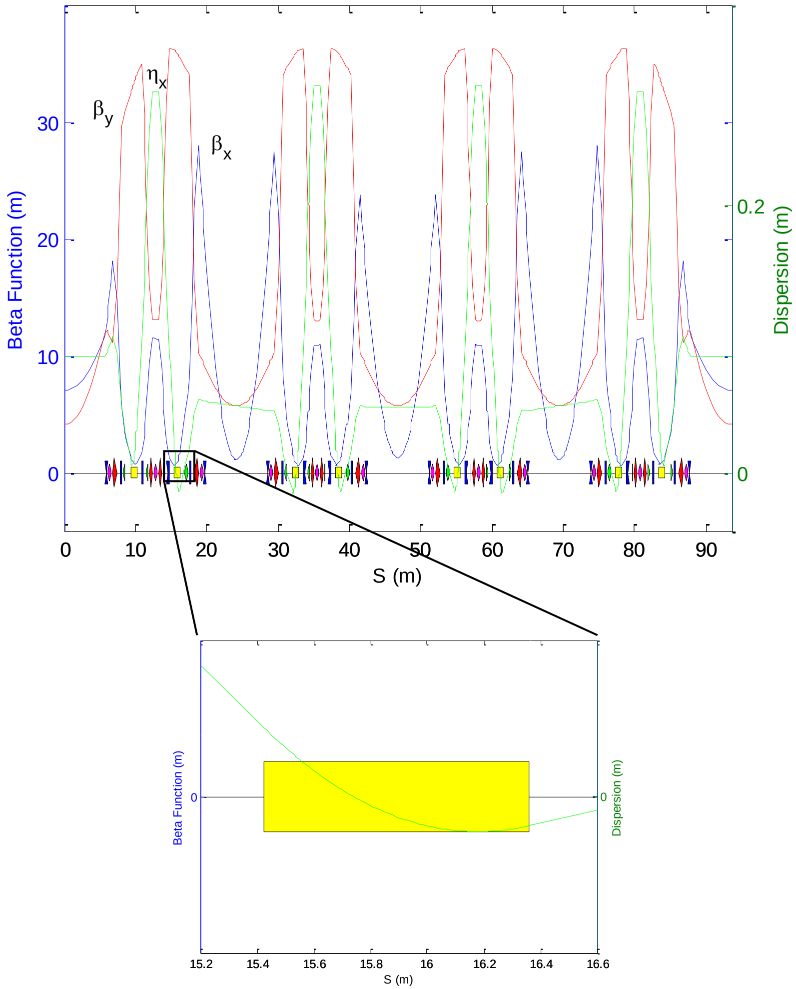
Measured values:

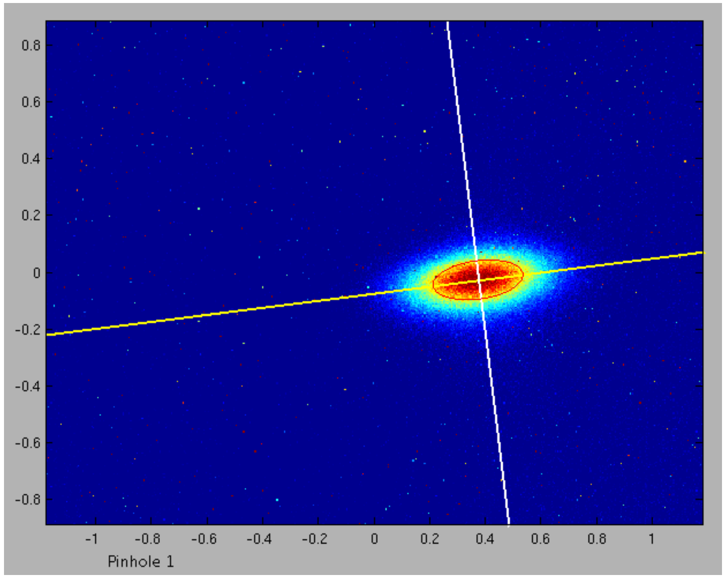
Emittance = 35.1 ± 1.5 nm.rad (34)

En. Spread = 0.13 ± 0.02 %

Coupling = 0.04 0.01%

Low alpha lattices at Diamond





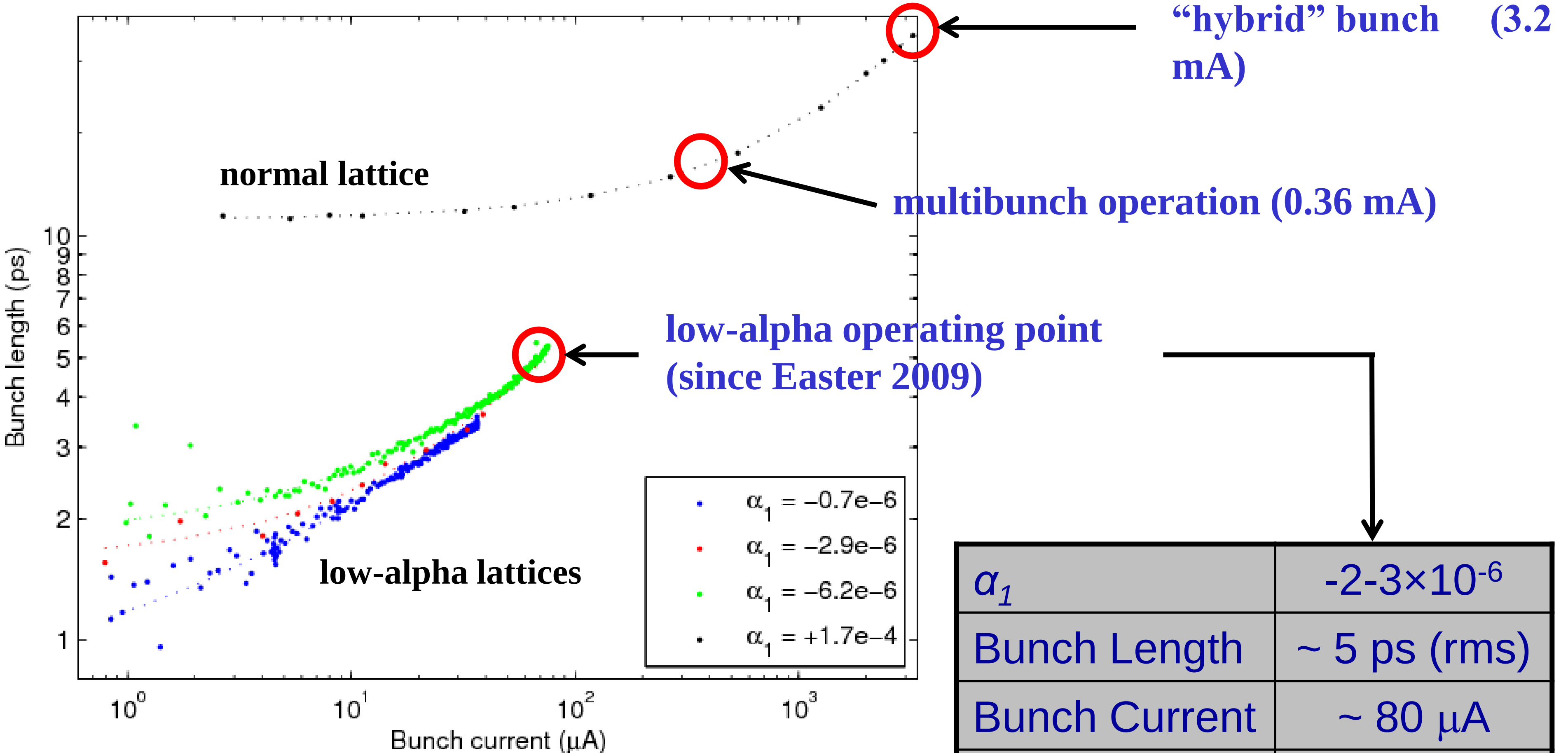
Measured values:

Emittance = ~4 nm.rad (4.2)

En. Spread = ~0.1%

Coupling = ~0.6%

Low-alpha Operation



α_1	$-2\text{-}3\times10^{-6}$
Bunch Length	~ 5 ps (rms)
Bunch Current	~ 80 μA
Lifetime	~ 12 h
Emittance	~ 4 nm.rad
Coupling	< 0.6%

user operation in low alpha in now provided only with the low emittance 4 nm closer to nominal emittance

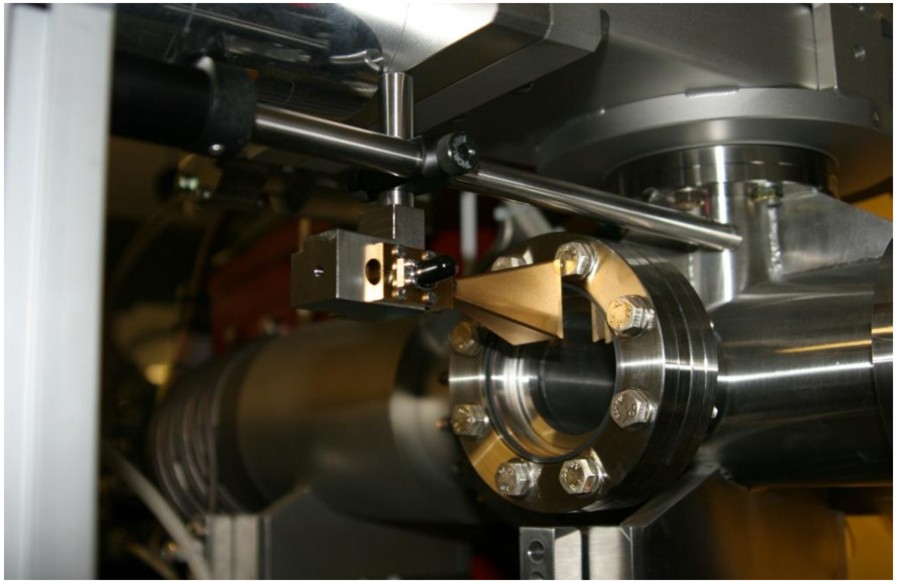
Coherent THz detection @ Diamond

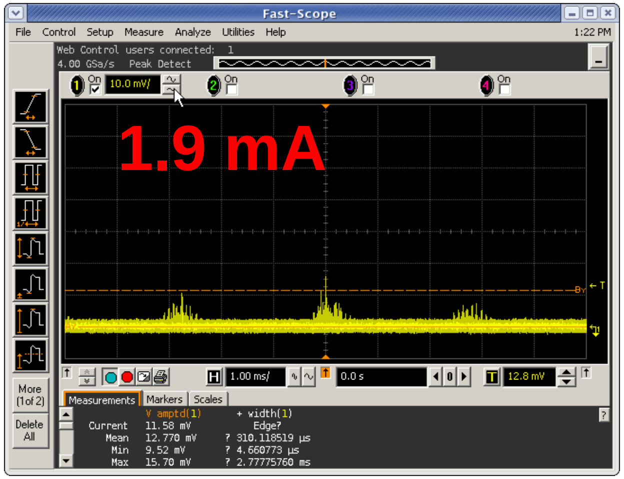
Diamond operates with short electron bunches for generation of Coherent THz radiation

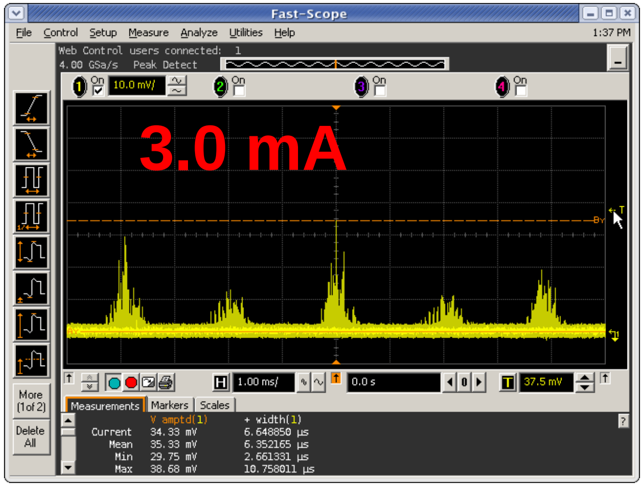
This operating regime is severely limited by the onset of the microbunch instabilities.

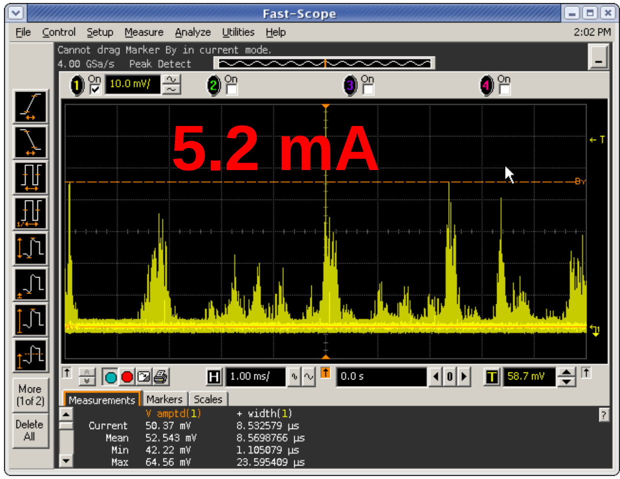
Sub-THz radiation bursts appeared periodically while the beam was circulating in the ring

A ultra-fast Schottky Barrier Diode sensitive to the radiation with 3.33-5mm wavelength range was installed in a dipole beamport;



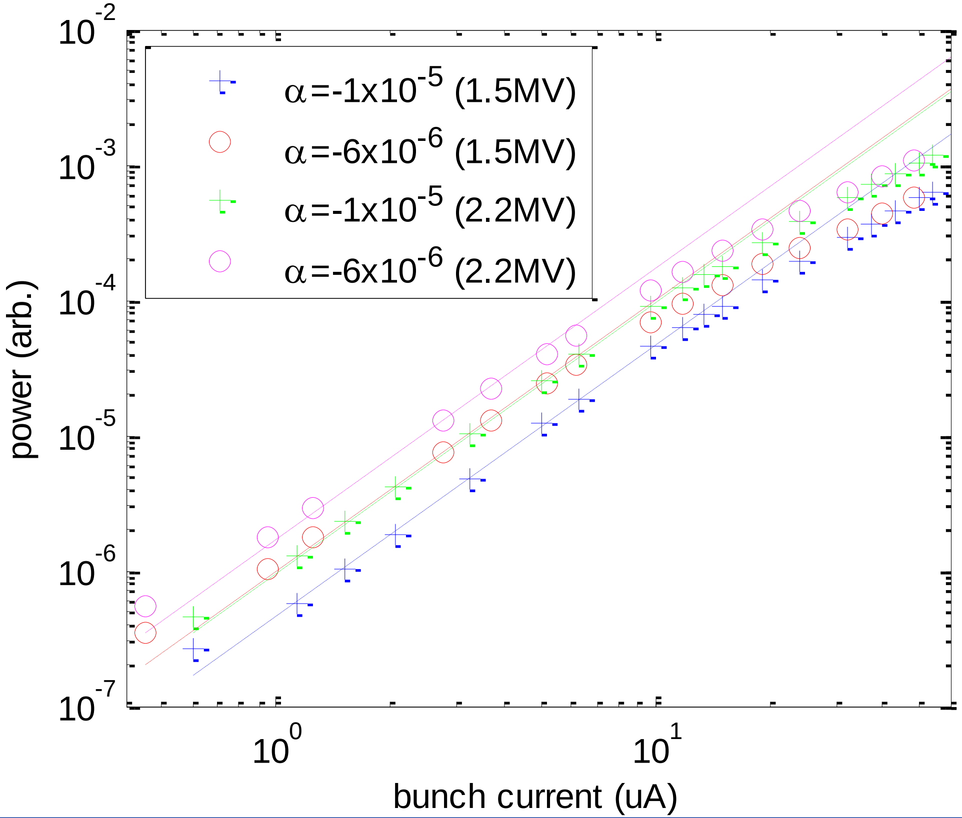




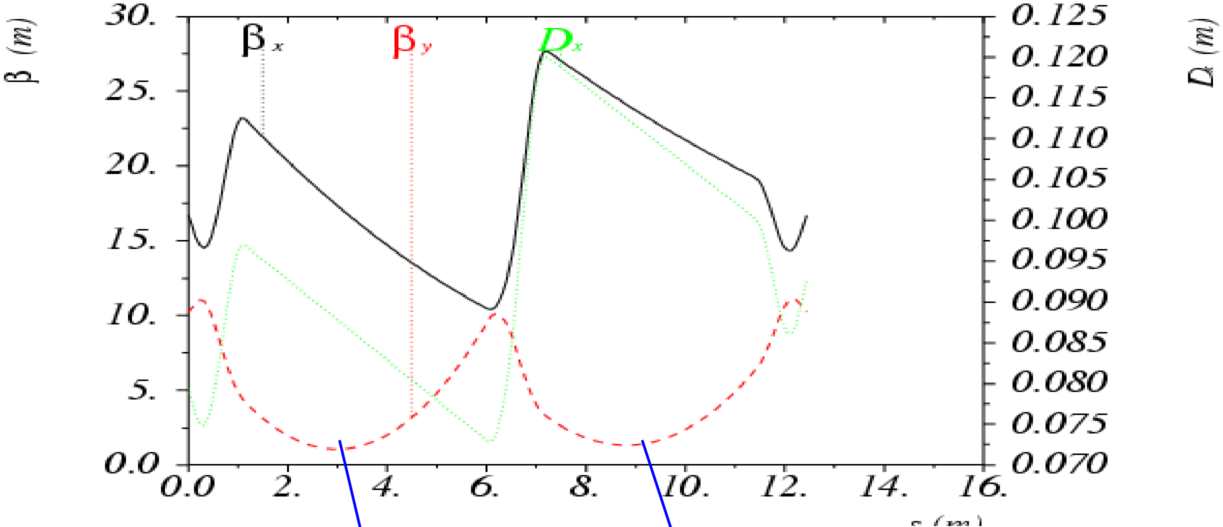


Coherent THz emission

Recent experiments in low-alpha have shown a strong coherent THz emission,
The quadratic dependence of the THz emission with current was clearly detected

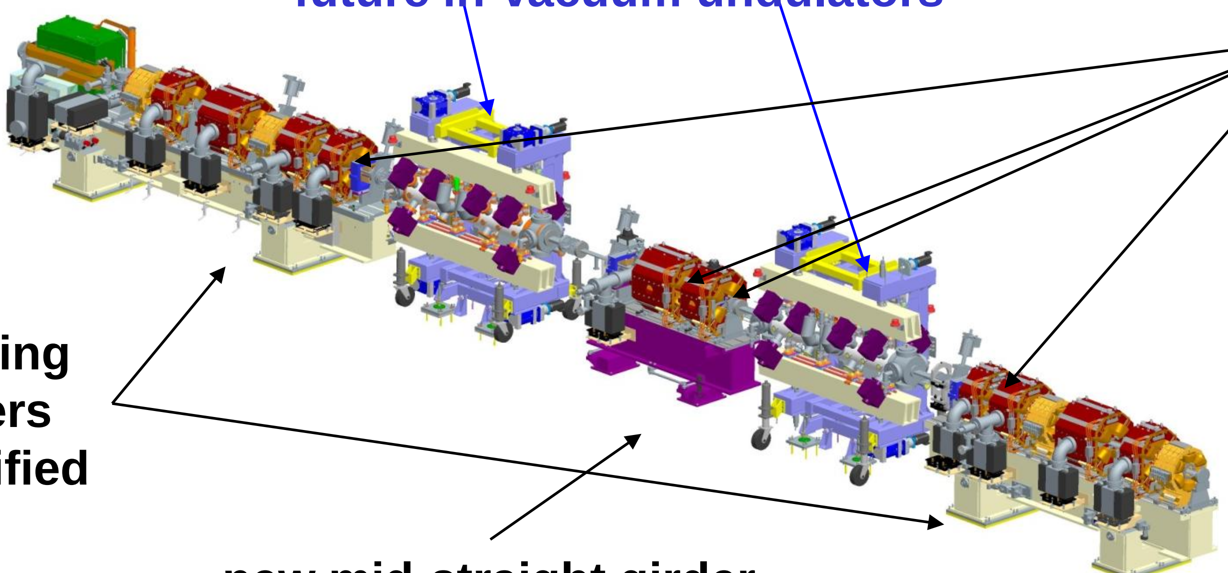


I13: "Double mini-beta" and Horizontally Focusing Optics



future in-vacuum undulators

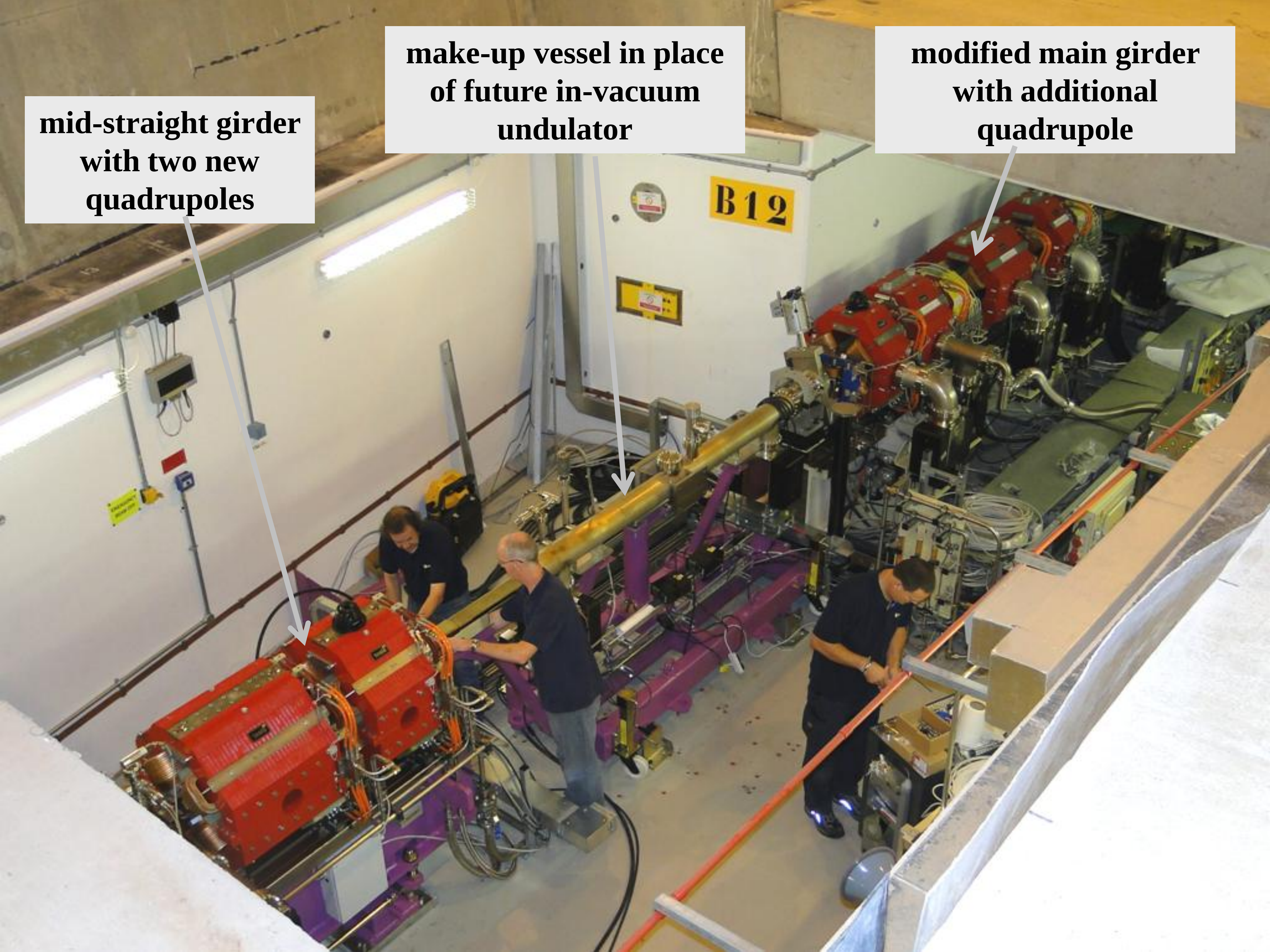
4 new quadrupoles



existing girders modified

new mid-straight girder

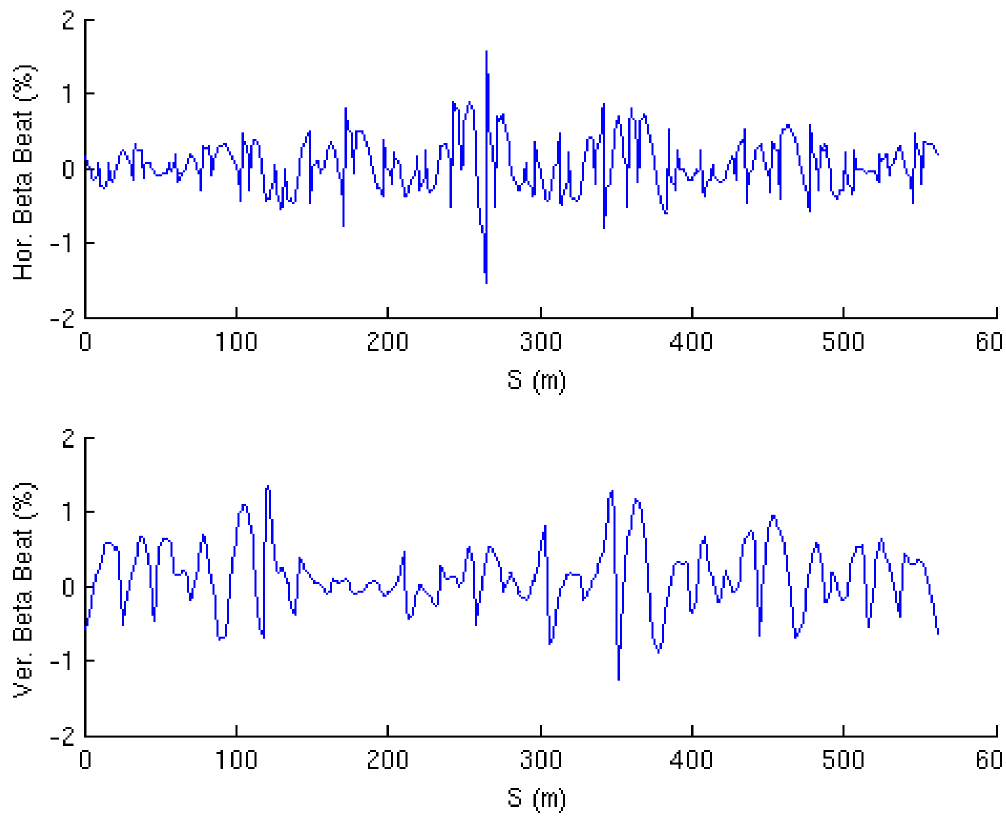
Same again in March 2011 for I09


mid-straight girder with two new quadrupoles
make-up vessel in place of future in-vacuum undulator
modified main girder with additional quadrupole
B12

Customised optics in straight 13

- As regards beam dynamics, the new optics works well and has been well corrected.
- At high current beam instabilities appear which can be overcome, but further work is required to ensure operation is as robust as the nominal optics.
- The aim is to run for users with the new optics before the end of Run #5

Beta-function errors with respect to the model:



Conclusions

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

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

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

Several **very** different optics have all been succesfully operated with residual beta beating of 1% or less., with excellent coupling control.

Two major development programmes already completed: Top Up operation and Low Alpha

Thank you for your attention