Light Sources performance, trends and design issues in low emittance rings

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Outline

- Introduction

  user's requirements and accelerator physics challenges
  design issues in low emittance rings

- Overview of the performance of 3rd generation light sources

  comparison of design with achieved parameters
  brightness – linear and nonlinear optics
  stability – orbit feedbacks

- Trends and Improvements

  top up
  short pulses
  customised optics for canted beamlines

- Conclusions

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, Australia3 GeV	
	MAX III, Sweden	700 MeV
	Indus-II, India	2.5 GeV
2008	**SSRF**, China	3.4 GeV

3^{rd} generation storage ring light sources

under commissioning

2009	**Petra-III**, Germany	6 GeV

under construction or planned

2010	**ALBA**, Spain	3 GeV
> 2010	**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

Synchrotron radiation sources properties

Broad Spectrum which covers from microwaves to hard X-rays

High Flux: high intensity photon beam

Flux = Photons / (s • BW)

High Brilliance (Spectral Brightness): highly collimated photon beam generated by a small divergence and small size source (partial coherence)

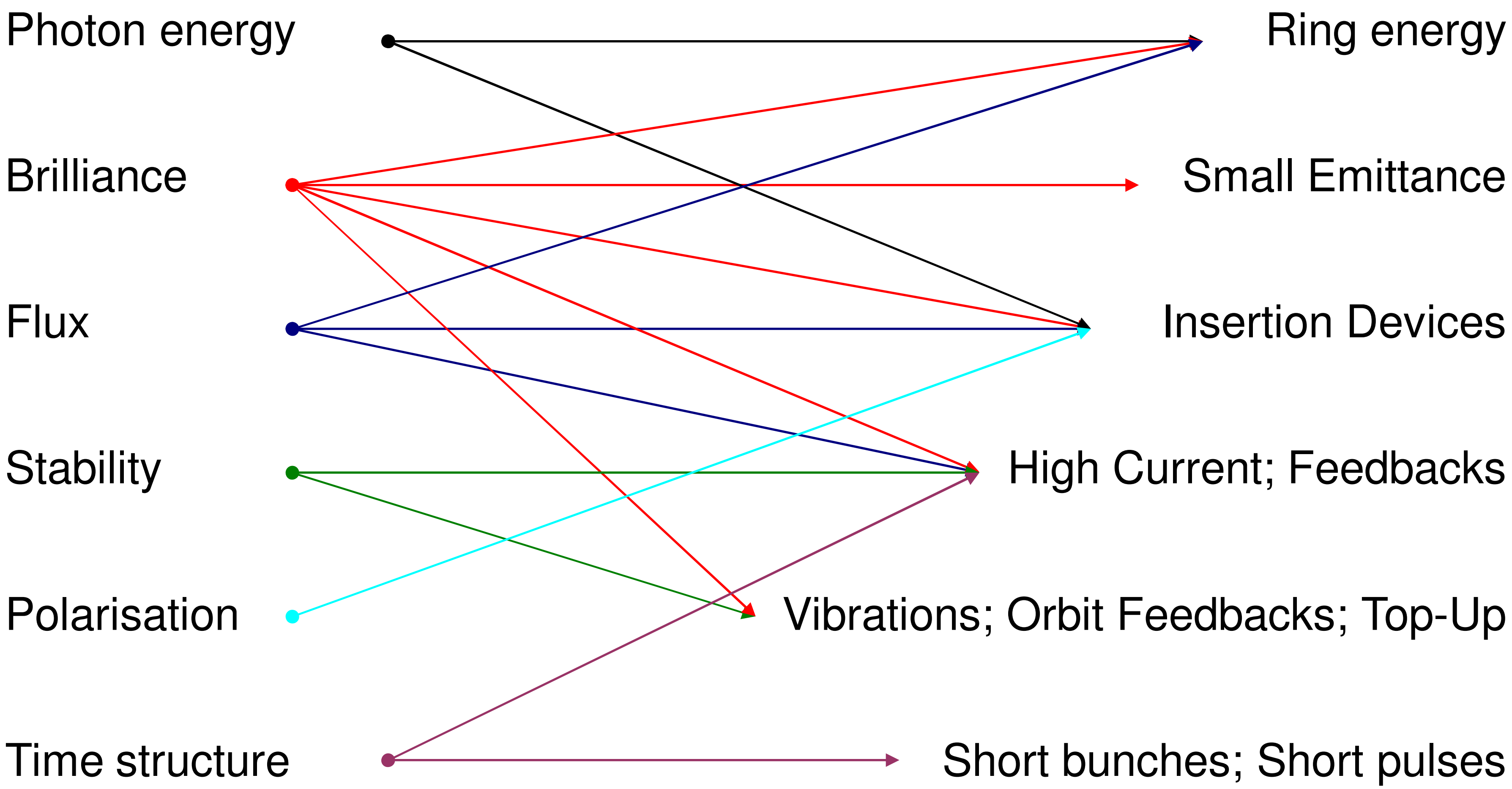
Brilliance = Photons / (s • mm^2 • mrad^2 • BW)

High Stability: submicron source stability

Polarisation: both linear and circular (with IDs)

Pulsed Time Structure: pulsed length down to tens of picoseconds

Accelerator Physics challenges



Photon energy

Brilliance

Flux

Stability

Polarisation

Time structure

Ring energy

Small Emittance

Insertion Devices

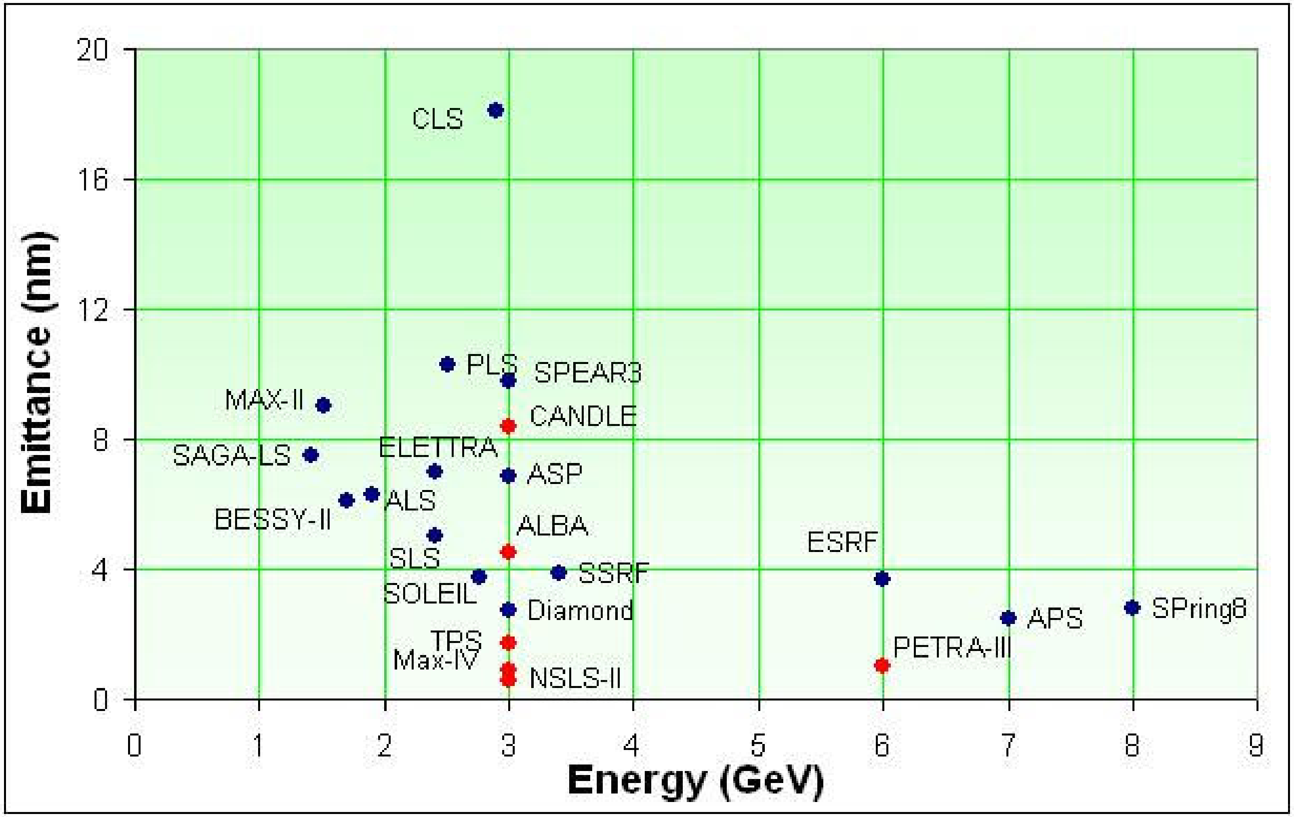
High Current; Feedbacks

Vibrations; Orbit Feedbacks; Top-Up

Short bunches; Short pulses

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



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

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

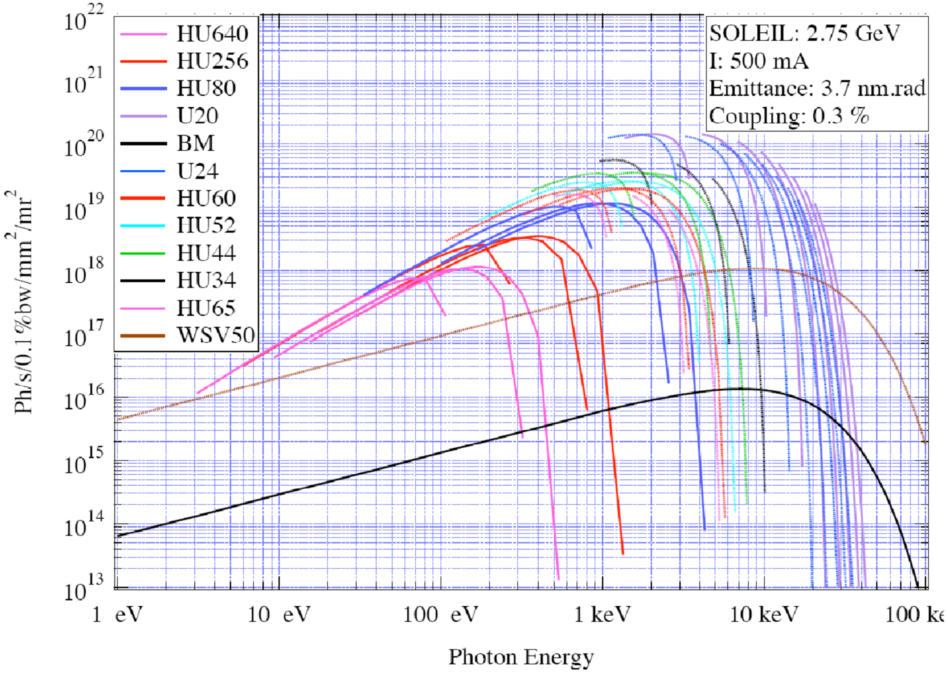
$$\Sigma_{x'} = \sqrt{\sigma_{x',e}^2 + \sigma'^2_{ph,e}}$$

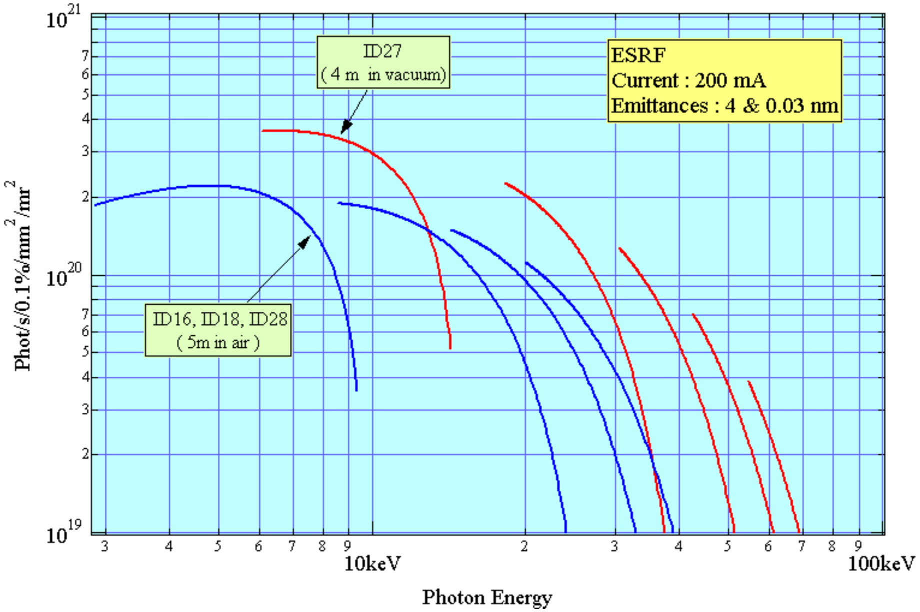
$$\sigma_x = \sqrt{\varepsilon_x \beta_x + (D_x \sigma_\varepsilon)^2}$$

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

Brilliance with IDs

Thanks to the progress with IDs technology storage ring light sources can cover a photon range from few tens of eV to tens 10 keV or more with high brilliance





Medium energy storage rings with In-vacuum undulators operated at low gaps (e.g. 5-7 mm) can reach 10 keV with a brilliance of 10^{20} ph/s/0.1%BW/mm^2/mrad^2

Courtesy M.E. Couprie (SOLEIL)

Low emittance lattices

Low emittance and adequate space in straight sections to accommodate long Insertion Devices are obtained in

Double Bend Achromat (DBA)

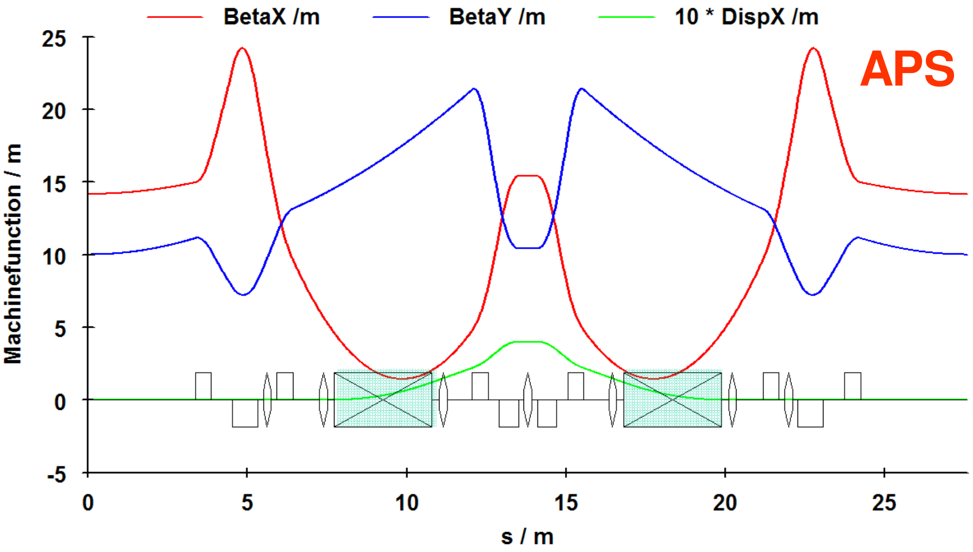
Triple Bend Achromat (TBA)

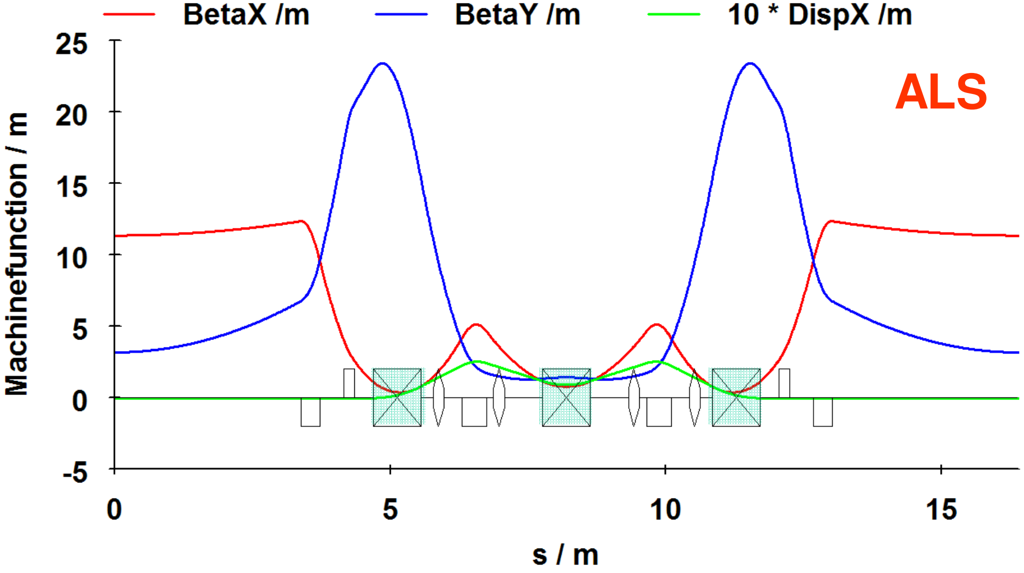
DBA used at:
ESRF,
ELETTRA,
APS,
SPring8,
Bessy-II,
Diamond,
SOLEIL,
SPEAR3
...

TBA used at
ALS,
SLS,
PLS,
TLS
…

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

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

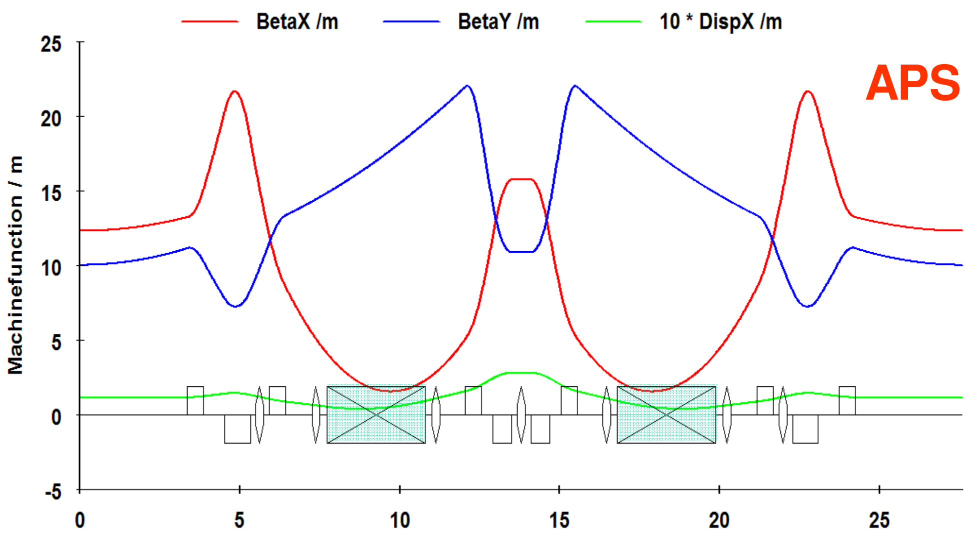




Low emittance lattices

The original achromat design can be broken, leaking dispersion in the straight section

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



New designs envisaged to achieve sub-nm emittance involve

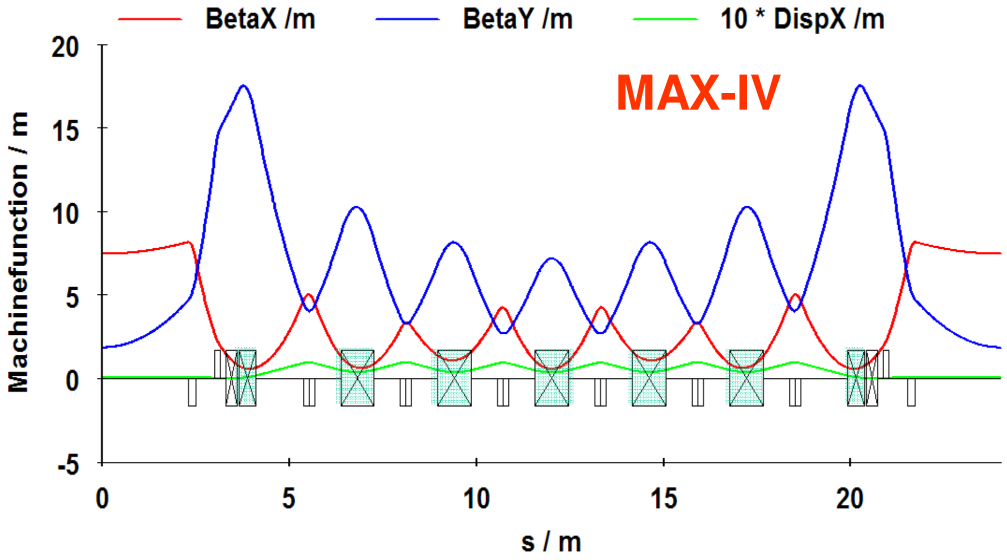
MBA

MAX-IV (7-BA): < 1nm S. Leemann's talk

Damping Wigglers

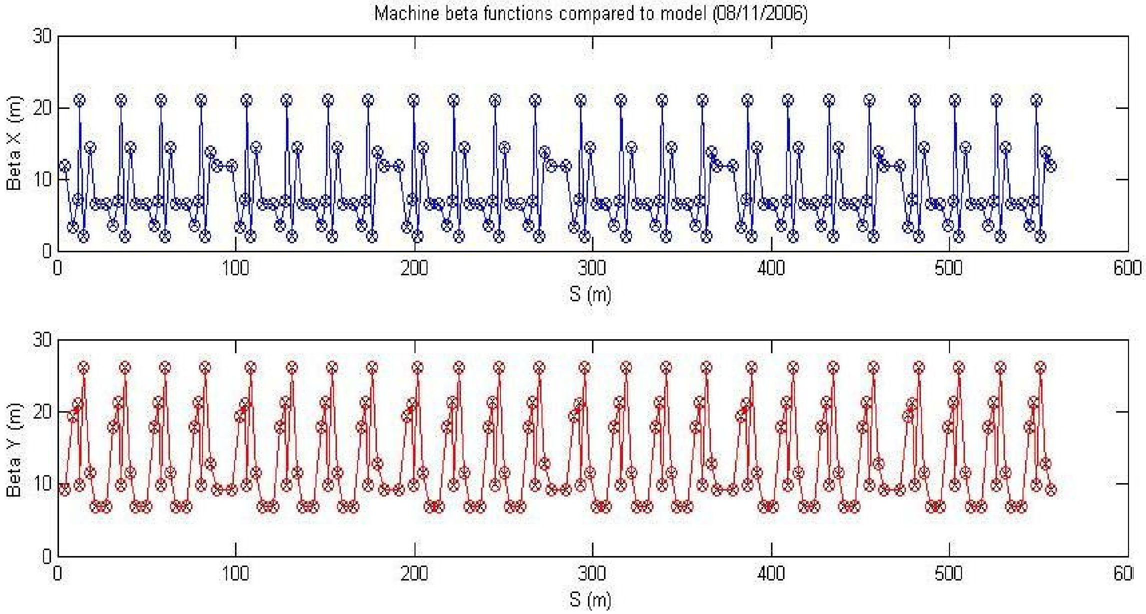
NSLS-II: < 1nm

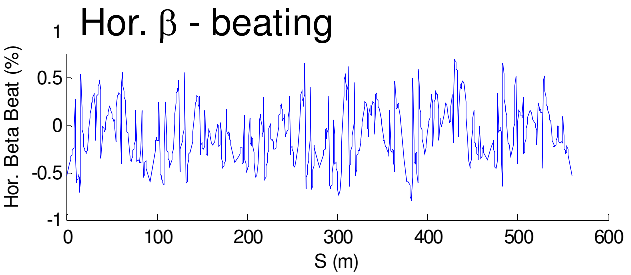
Petra-III: 1 nm

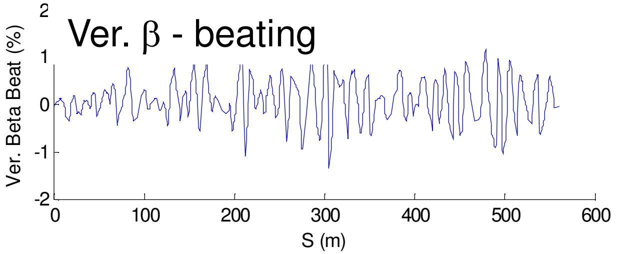


Linear optics modelling with LOCO

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



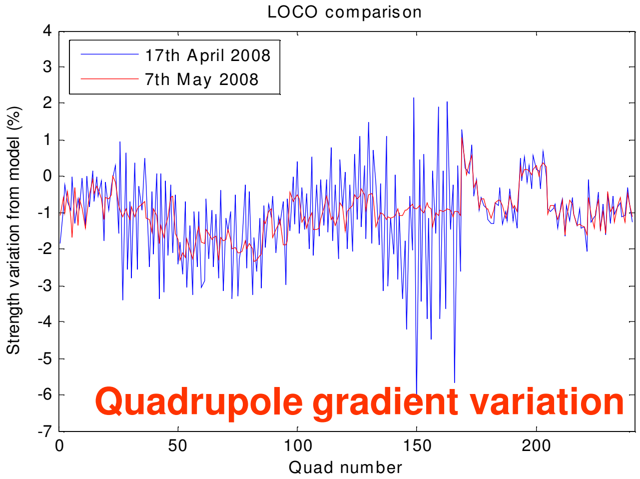




Modified version of LOCO with constraints on gradien variations **(see [ICFA Newsl, Dec'07](#))**

β - beating reduced to 0.4% rms

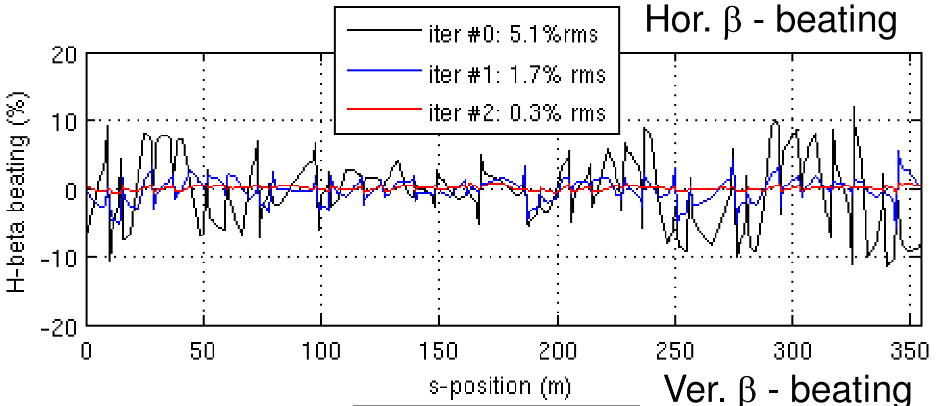
Quadrupole variation reduced to 2%
Results compatible with mag. meas. and calibrations

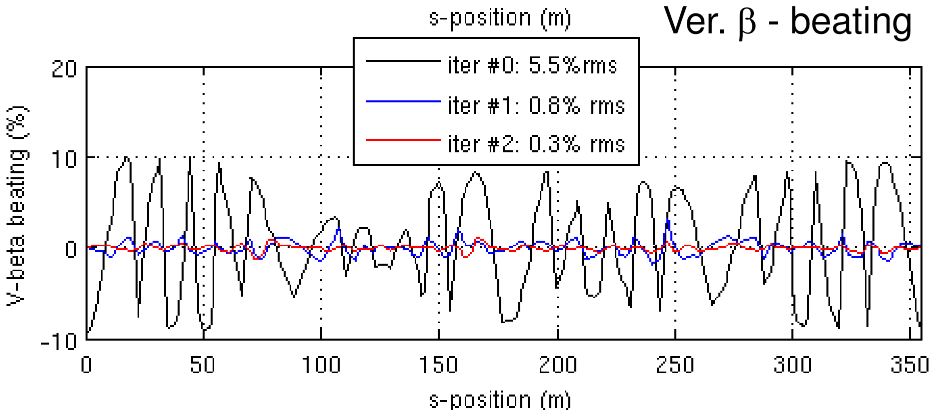


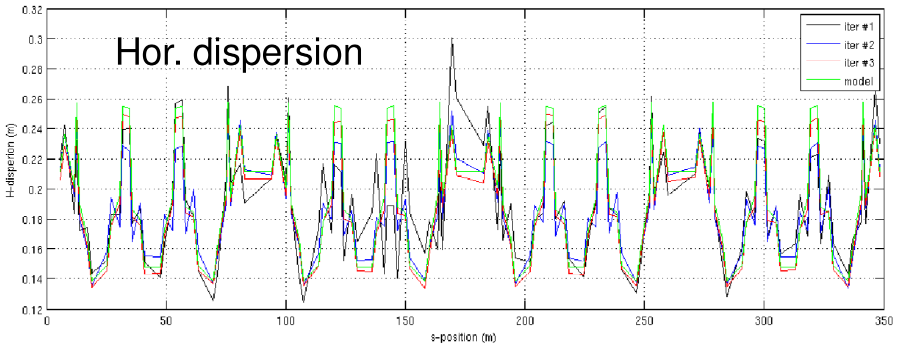
Quadrupole gradient variation

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

Linear optics modelling: SOLEIL


Hor. β - beating

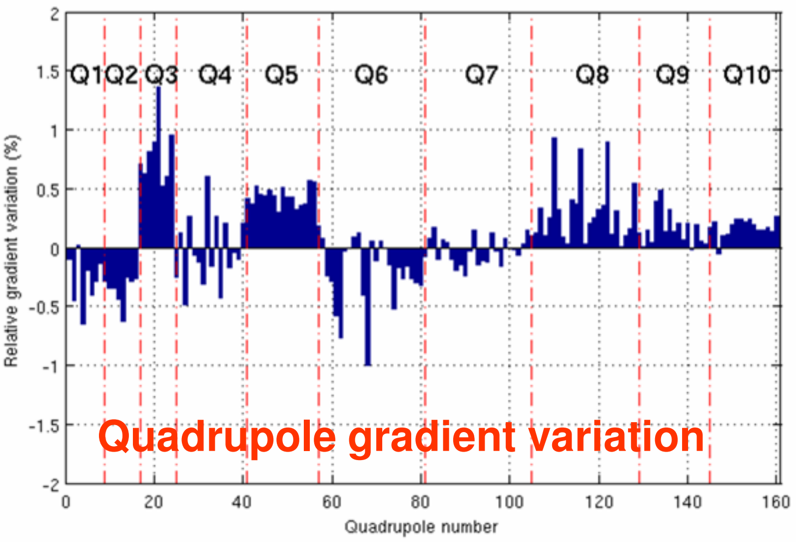

Ver. β - beating


Hor. dispersion

Modified version of LOCO with constraints on gradient variations

β - beating reduced to 0.3% rms

Results compatible with mag. meas. (10^{-3} gradient identity, Brunelle *et al.*, EPAC'06) and internal DCCT calibration of individual power supply

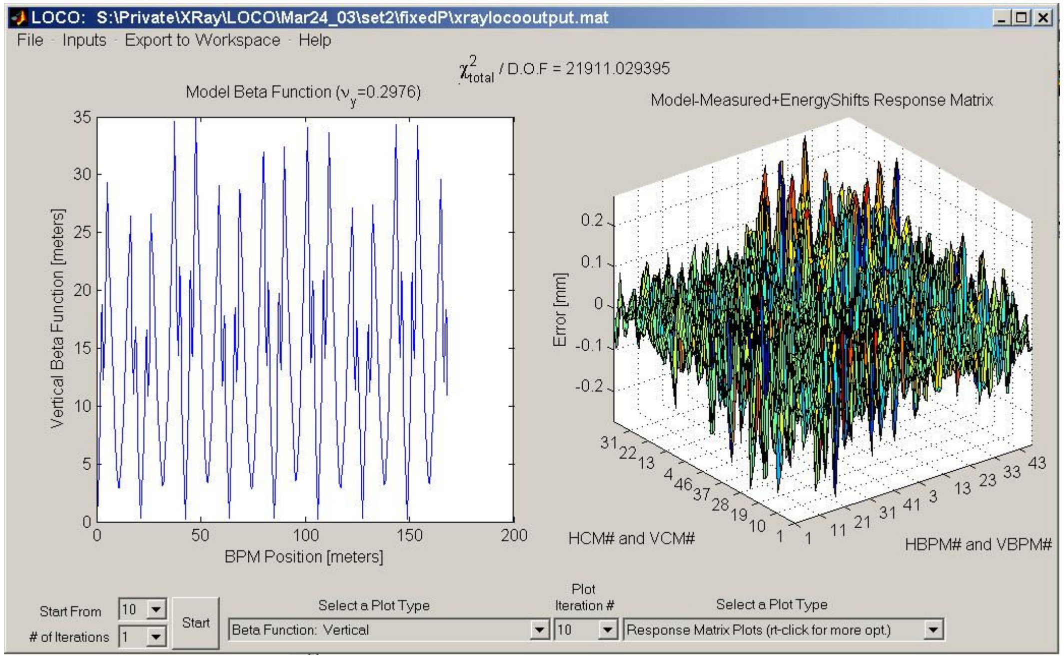

Quadrupole gradient variation

Courtesy A. Nadji (SOLEIL)

MATLAB LOCO and Middlelayer

LOCO: Linear Optics from Closed Orbit

- Calibrate/control optics using orbit response matrix
- Determine quadrupole gradients
- Correct coupling
- Calibrate BPM gains, steering magnets



LOCO: S:\Private\XRay\LOCO\Mar24_03\set2\fixedP\xraylocooutput.mat

χ^2_{total} / D.O.F = 21911.029395

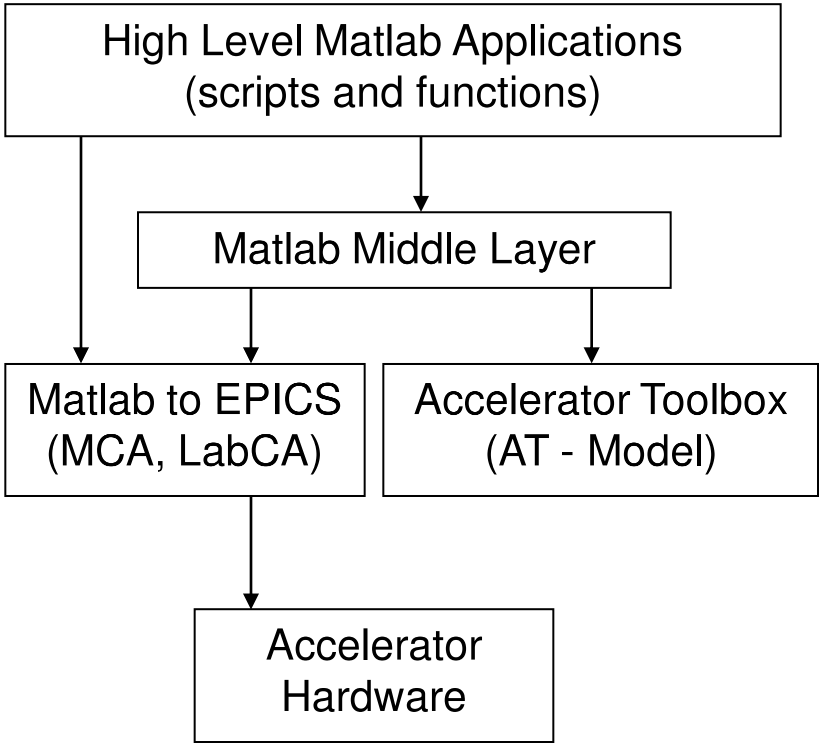
Start From: 10

# of Iterations: 1

Select a Plot Type: Beta Function: Vertical

Plot Iteration #: 10

Select a Plot Type: Response Matrix Plots (rt-click for more opt.)



High Level Matlab Applications (scripts and functions)

Matlab Middle Layer

Matlab to EPICS (MCA, LabCA)

Accelerator Toolbox (AT - Model)

Accelerator Hardware

LOCO and Middlelayer are used at

ALS
Spear3
CLS
PLS
SOLEIL

Diamond
ASP
SSRF
ALBA
NSLS-II

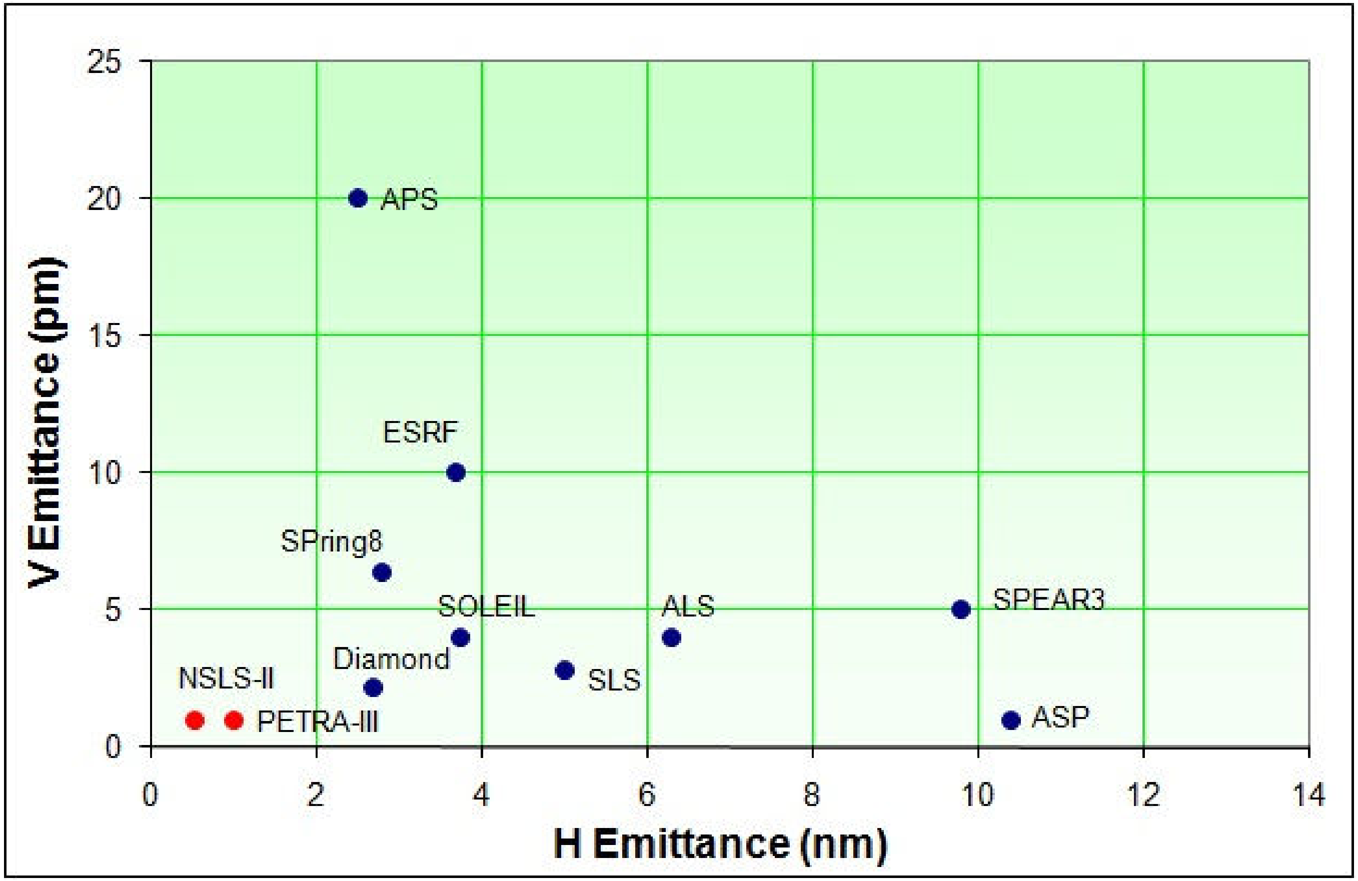
Courtesy J. Safranek (SSRL), G. Portmann (ALS)

Comparison model/machine for linear optics

	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 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%	10 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

* best achieved

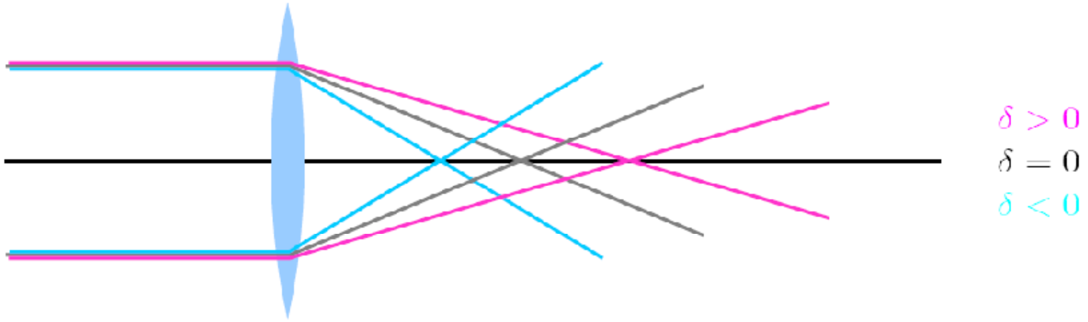
Vertical Emittance in 3rd generation light sources



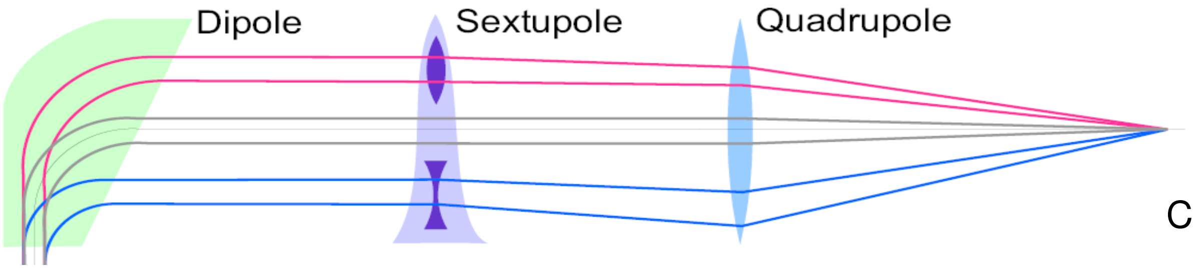
Best achieved values – not operational values
Assuming 10^{-3} coupling correction , the V emittance of the new projects can reach the fundamental limit given by the radiation opening angle;
Measurements of such small beam size is challenging !

Small emittance and nonlinear beam dynamics

Small emittance → Strong quadrupoles → Large (natural) chromaticity



→ strong sextupoles (sextupoles guarantee the focussing of off-energy particles)



Courtesy A. Streun

→ additional sextupoles are required to correct nonlinear aberrations

Strong sextupoles reduce

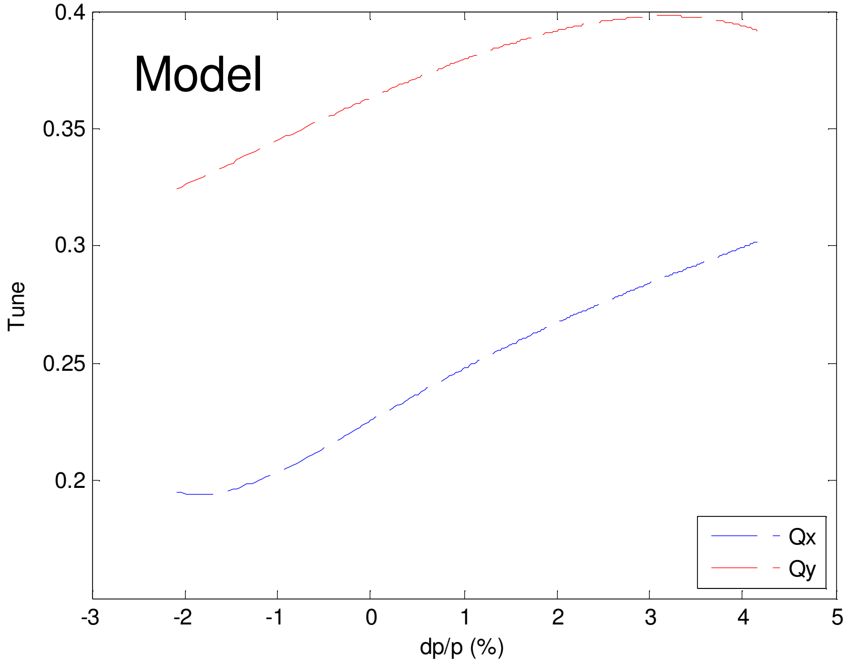
the dynamic aperture (impact mainly the injection efficiency)

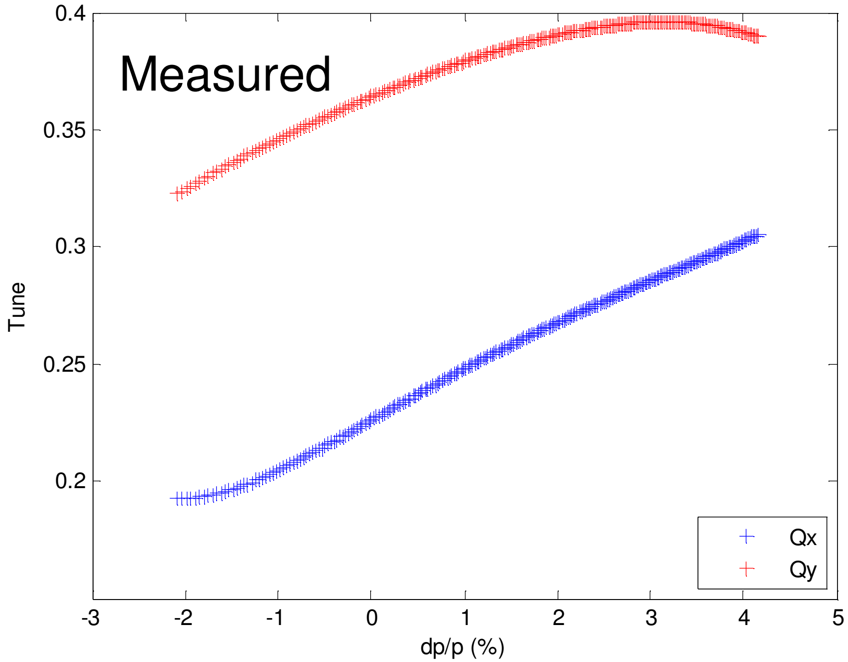
the momentum aperture (impact mainly the Touschek lifetime)

[+ consider the effect of realistic errors + watch out α_2]

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 available of the nonlinear model is mandatory !

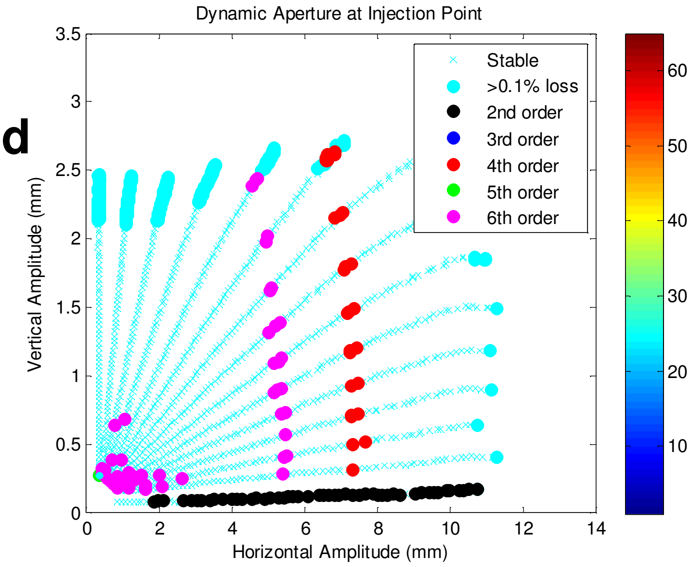
Fringe fields in dipoles (2nd order –symplectic integration) and in quadrupoles

Higher order multipoles in dipoles and quadrupoles (from measurements)

Nonlinear dynamics comparison machine to model (II)

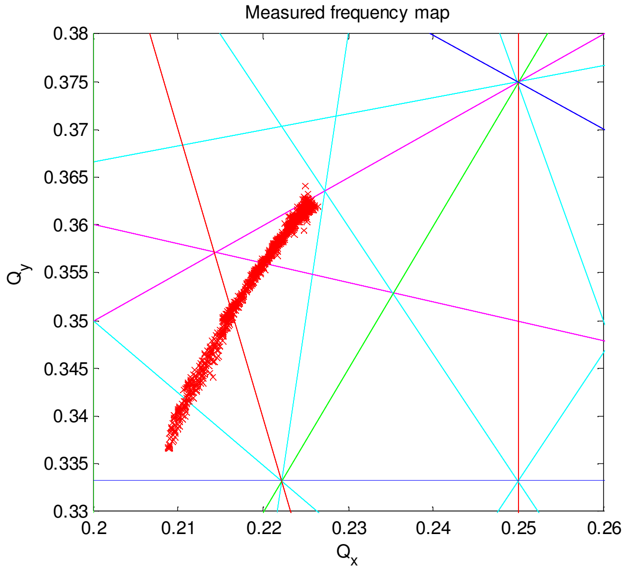
DA

measured



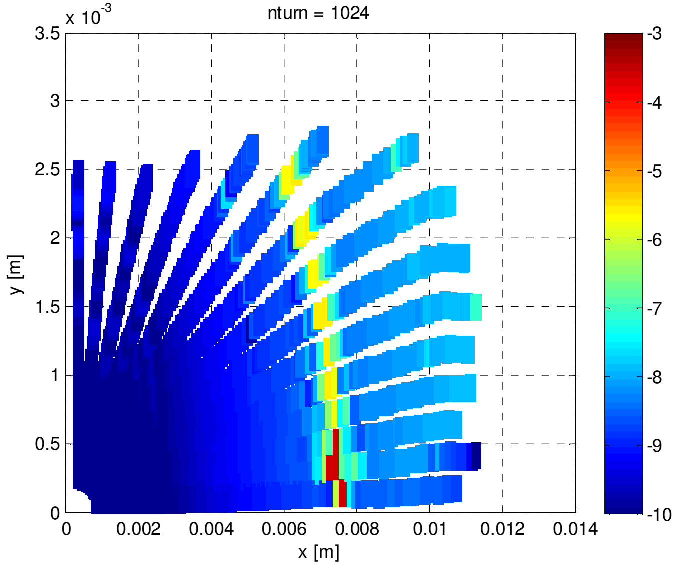
FM

measured



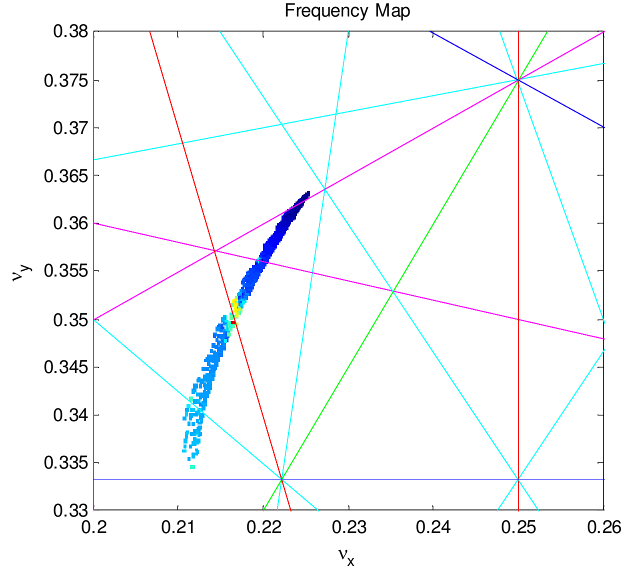
DA

model



FM

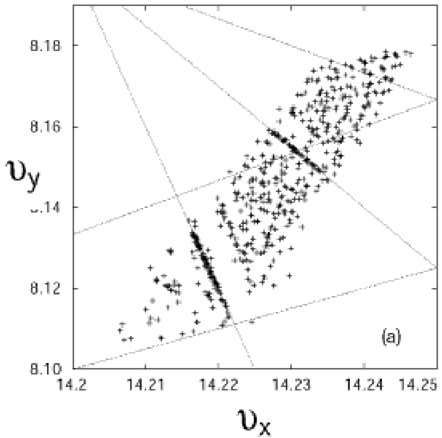
model



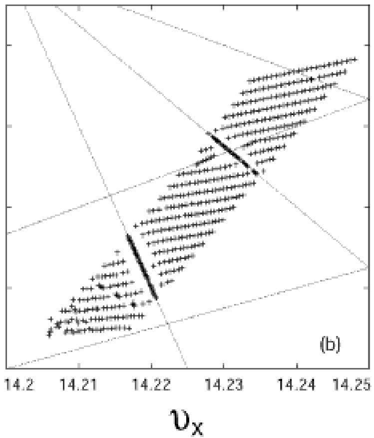
Frequency Map Analysis: ALS and BESSY-II

ALS linear lattice corrected to
0.5% rms β-beating

FM computed including residual
β-beating and coupling errors

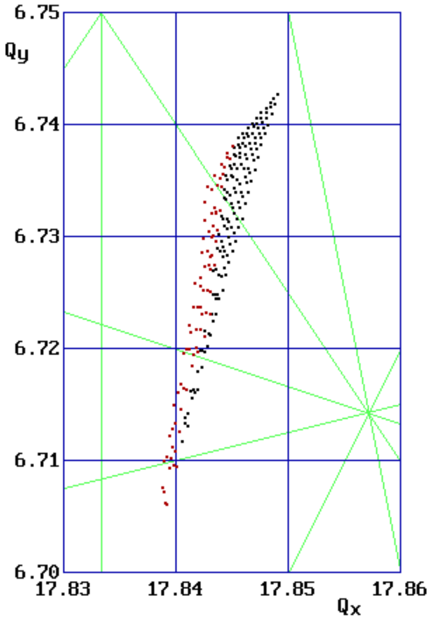


ALS measured

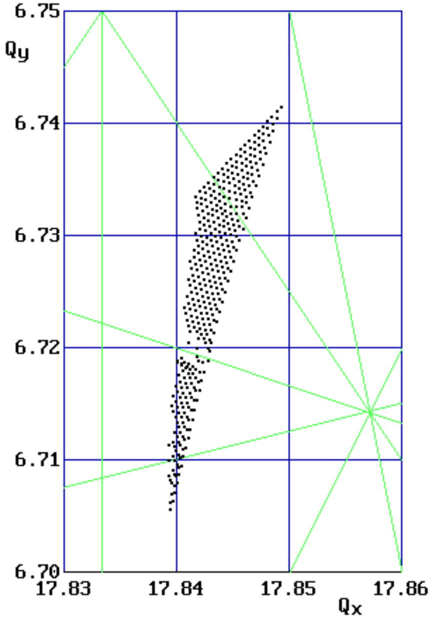


ALS model

BESSY-II with harmonic sextupole
magnets, chromaticity, coupling



BESSY-II measured



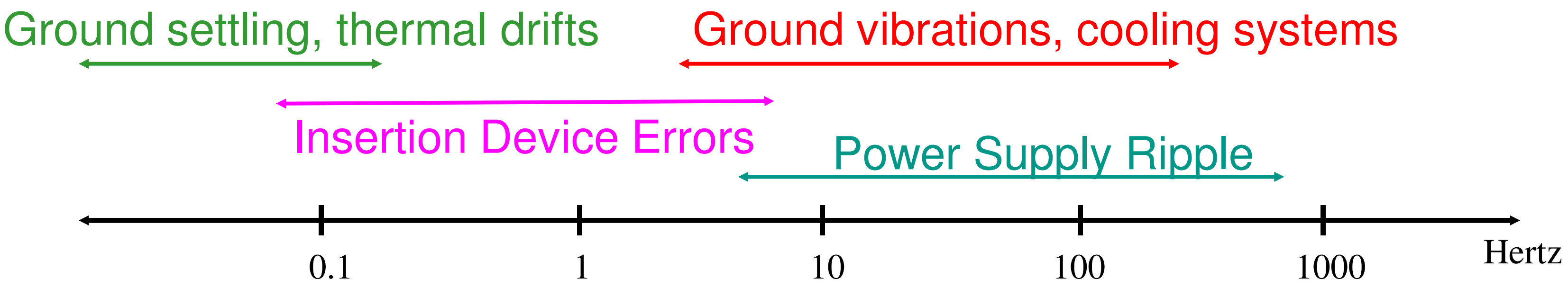
BESSY-II model

A very accurate description of machine model is mandatory

- fringe fields: dipole, quadrupole (and sextupole) magnets
- systematic octupole components in quadrupole magnets
- decapoles, skew decapoles and octupoles in sextupole magnets

Courtesy C. Steier (ALS) P. Kuske (BESSY-II)

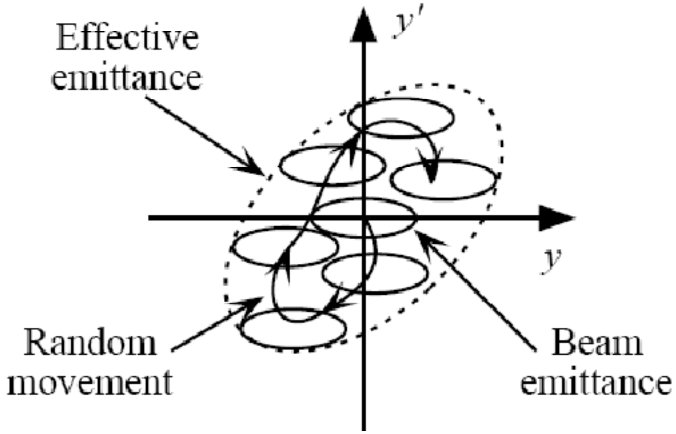
Orbit stability: disturbances and requirements


Ground settling, thermal drifts

Ground vibrations, cooling systems

Insertion Device Errors

Power Supply Ripple



Beam stability should be better than

10% of the beam size

10% of the beam divergence

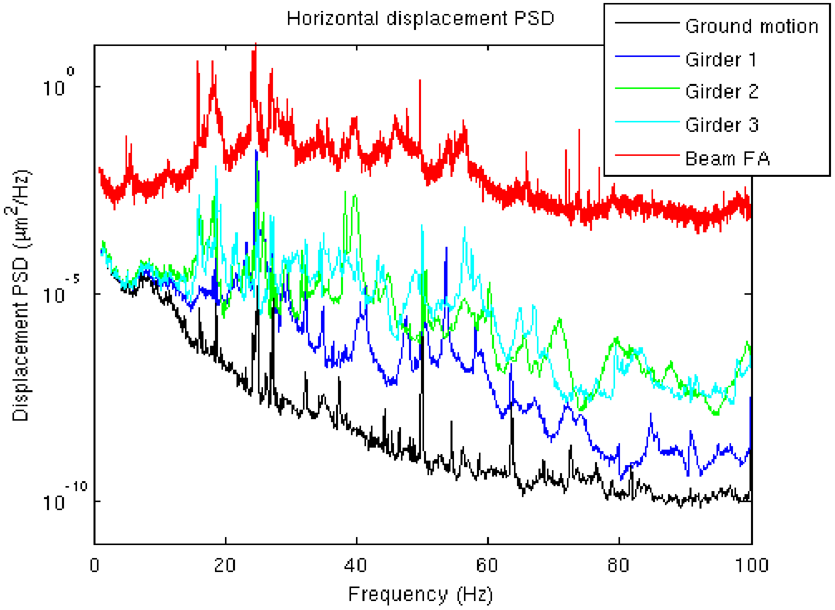
up to 100 Hz

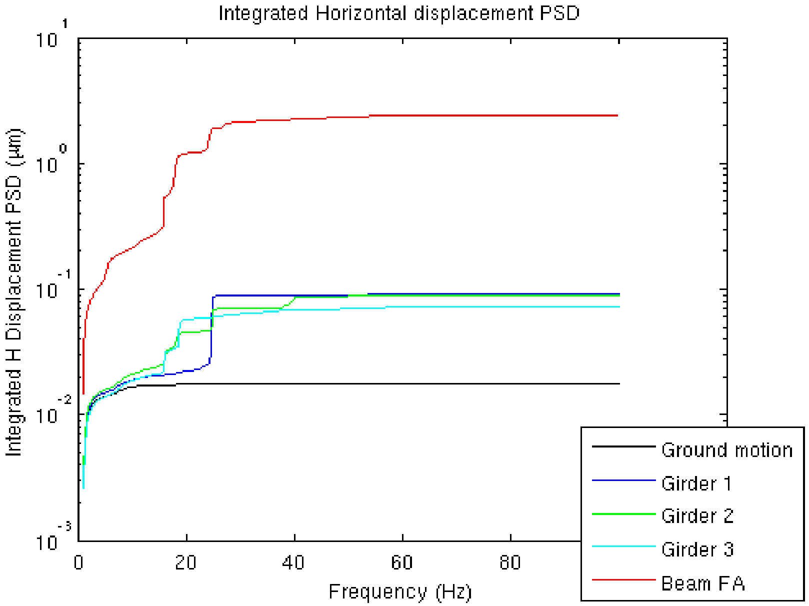
but IR beamlines will have tighter requirements

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

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

Ground vibrations to beam vibrations: Diamond

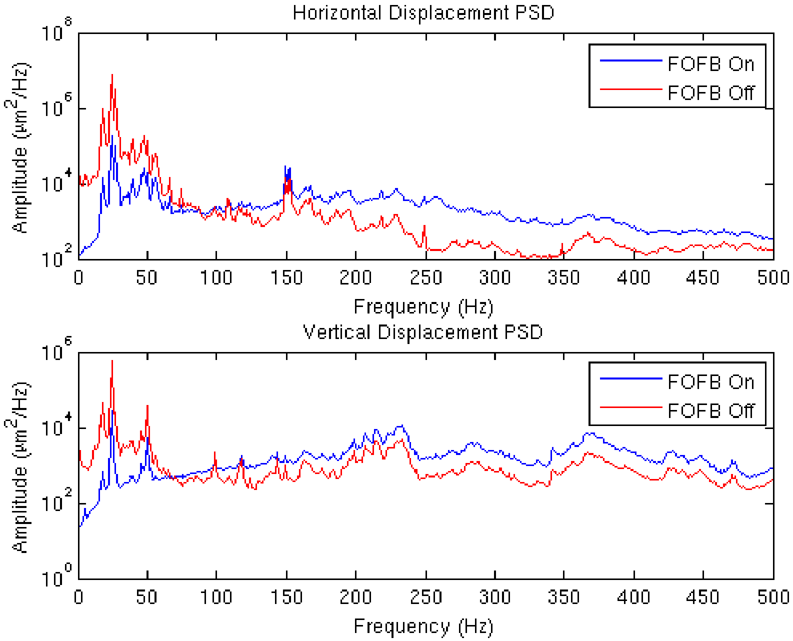


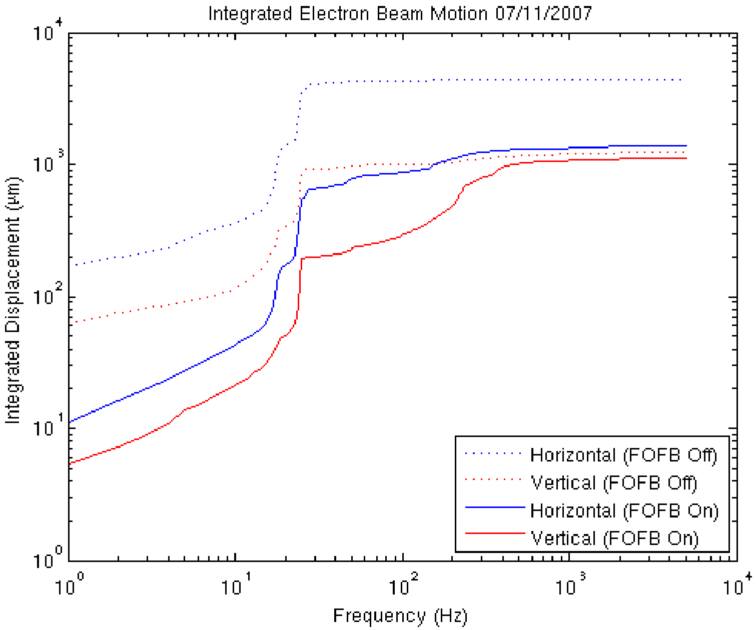


Amplification factor girders to beam: H 31 (theory 35); V 12 (theory 8);

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





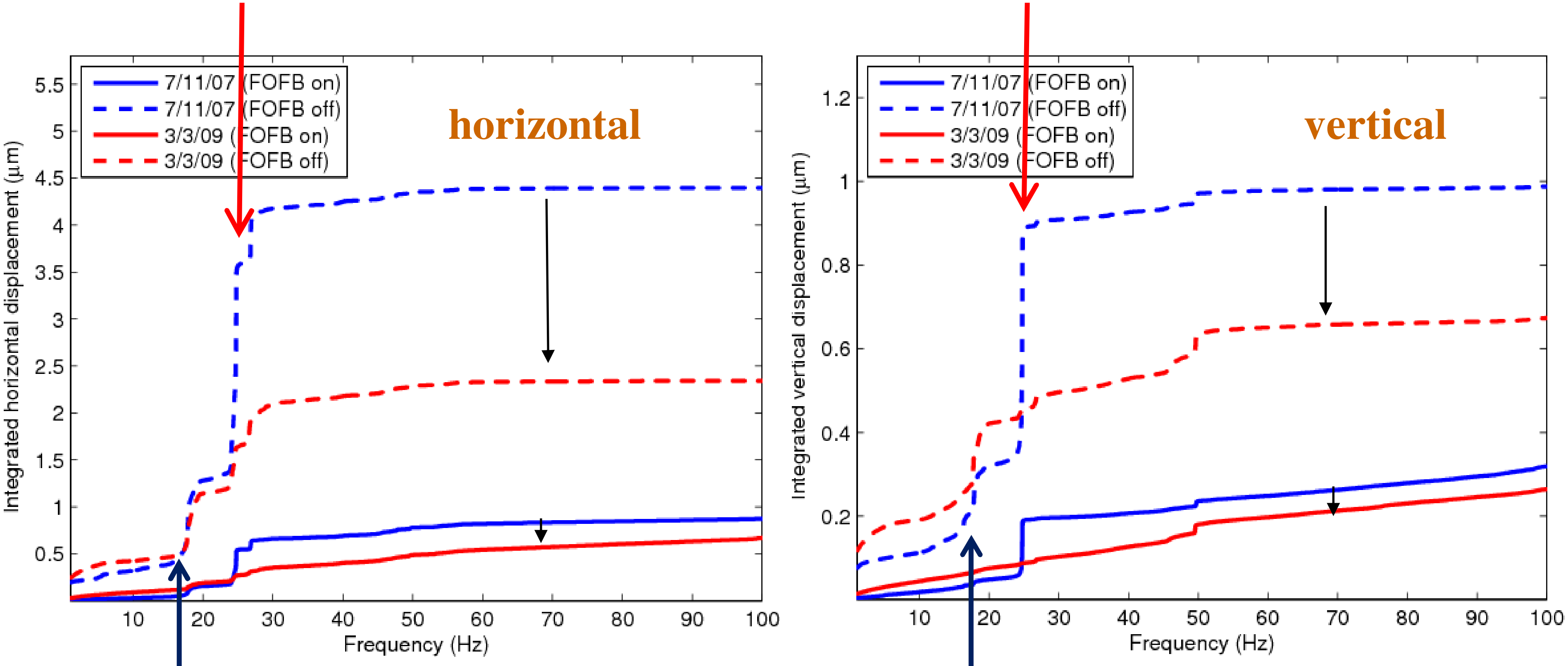
Significant reduction of the rms beam motion up to 100 Hz;

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 damping of ground vibrations at diamond

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



next target: air handling units, 18 Hz

Overview of fast orbit feedback performance

Summary of integrated rms beam motion (1-100 Hz) with FOFB
and comparison with 10% beam stability target

	FOFB BW	**Horizontal**	**Vertical**
ALS	40 Hz	< 2 μm in H (30 μm)*	< 1 μm in V (2.3 μm)*
APS	60 Hz	< 3.2 μm in H (6 μm)**	< 1.8 μm in V (0.8 μm)**
Diamond	100 Hz	< 0.9 μm in H (12 μm)	< 0.1 μm in V (0.6 μm)
ESRF	100 Hz	< 1.5 μm in H (40 μm)	~ 0.7 μm in V (0.8 μm)
ELETTRA	100 Hz	< 1.1 μm in H (24 μm)	< 0.7 μm in V (1.5 μm)
SLS	100 Hz	< 0.5 μm in H (9.7 μm)	< 0.25 μm in V (0.3 μm)
SPEAR3	60Hz	~ 1 μm in H (30 μm)	~ 1 μm in V (0.8 μm)

* up to 500 Hz

** up to 200 Hz

Trends on Orbit Feedback

- restriction of tolerances w.r.t. to beam size and divergence
- higher frequencies ranges
- integration of XBPMs
- feedback on beamlines components

Trends and improvements (I)
Top-Up Operation

Top-Up operation consists in the continuous (very frequent) injection to keep the stored current constant – <u>with beamline shutters open</u>.

$\Delta I/I \sim 10^{-3}$

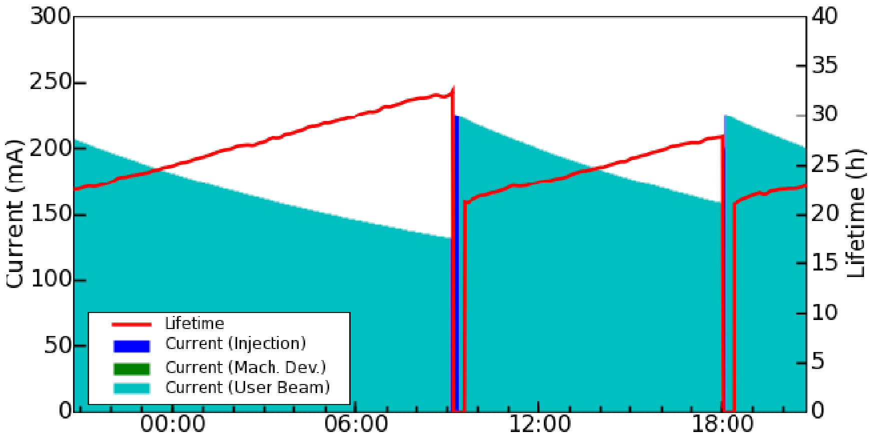
Already in operation at APS, SLS, SPring8, TLS

New machines such as Diamond, SOLEIL are also operating Top-Up

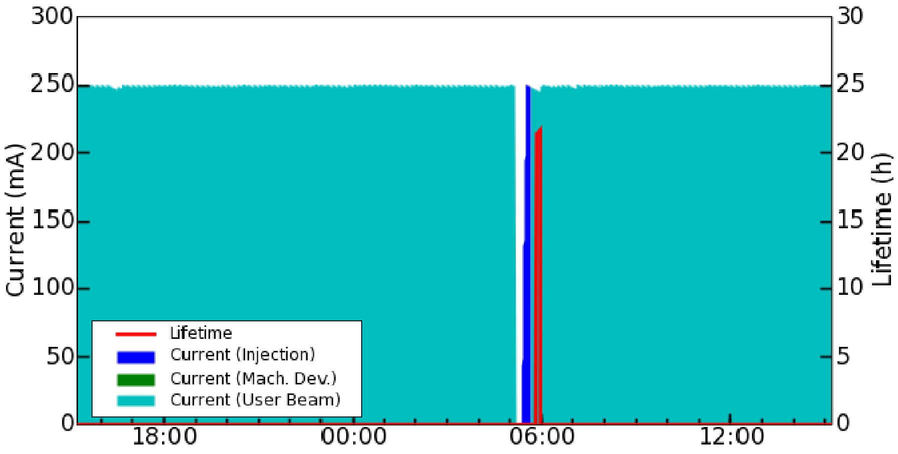
Retrofitted in ALS, SPEAR3, ELETTRA, BESSY-II, ESRF (few bunches mode)

Operating modes are machine specific (frequency of injection, # of shots, charge)

Standard decay mode



Top-Up mode



Advantages of Top-Up Operation: stability

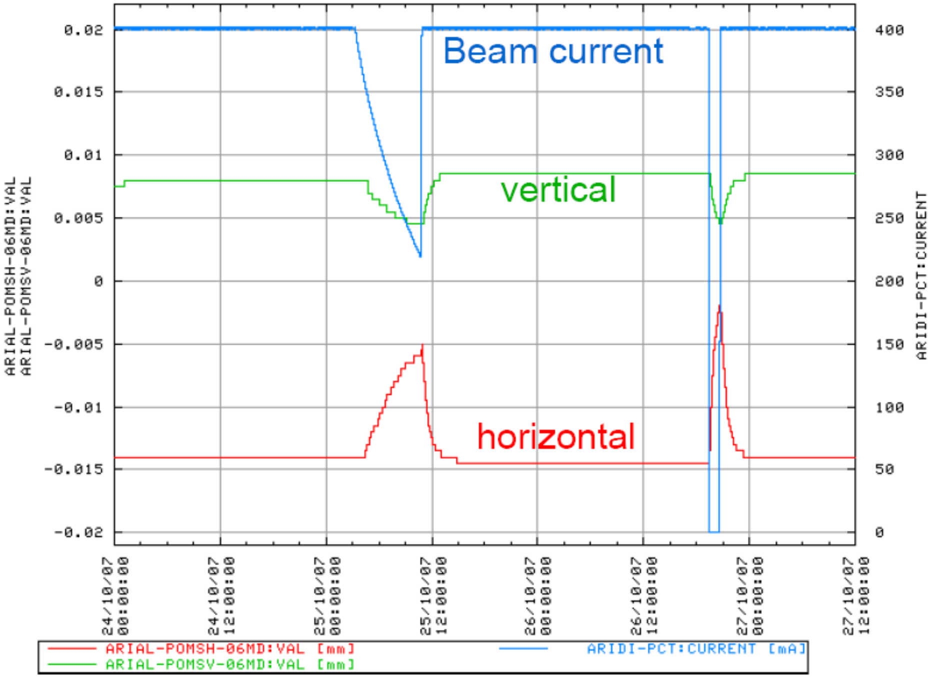
Top-Up improves stability:

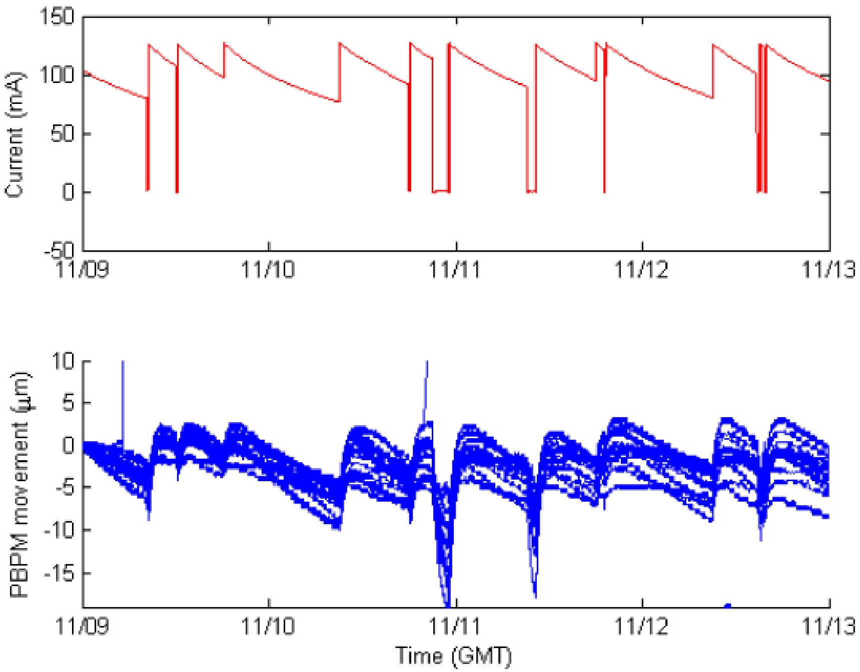
- constant photon flux for the users
- higher average current
- constant thermal load on components

BPMs block stability

- without Top-Up ~ 10 μm
- with Top-Up < 1 μm

Crucial for long term sub- μm stability

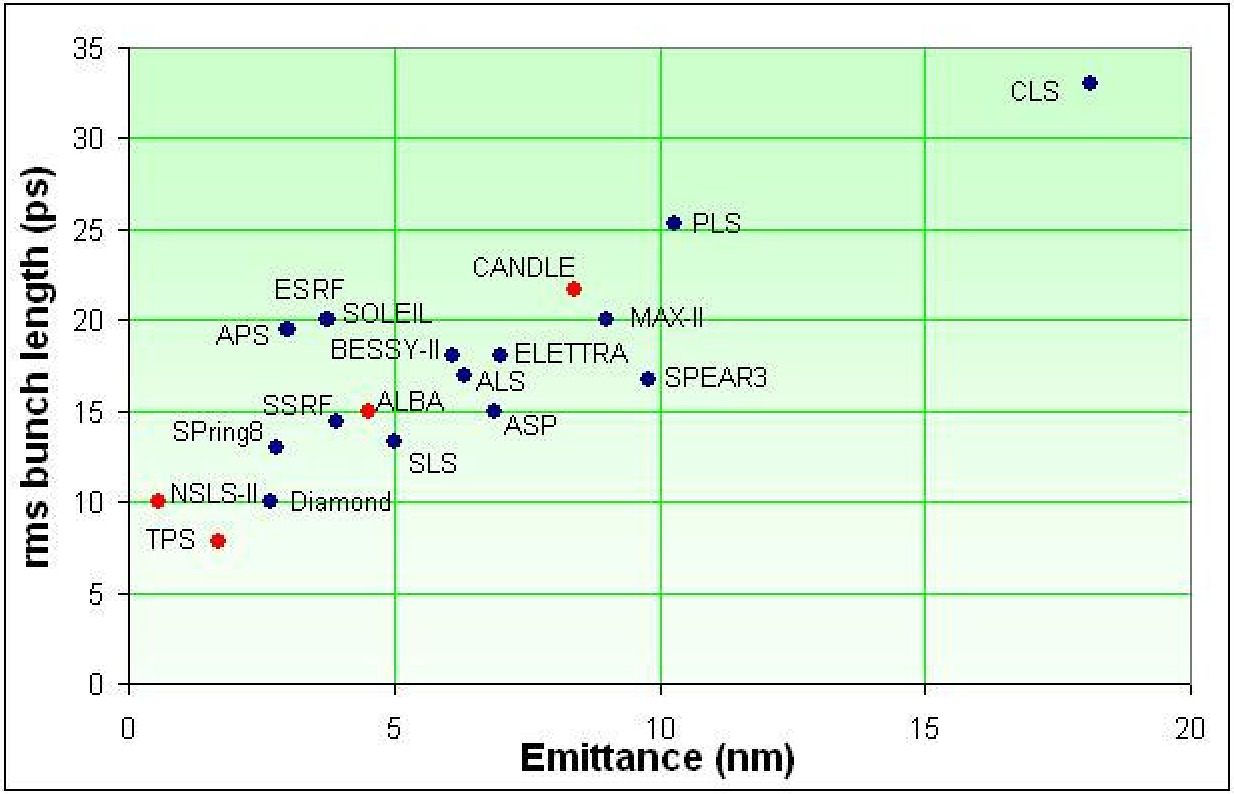




Courtesy M. Boge (SLS)

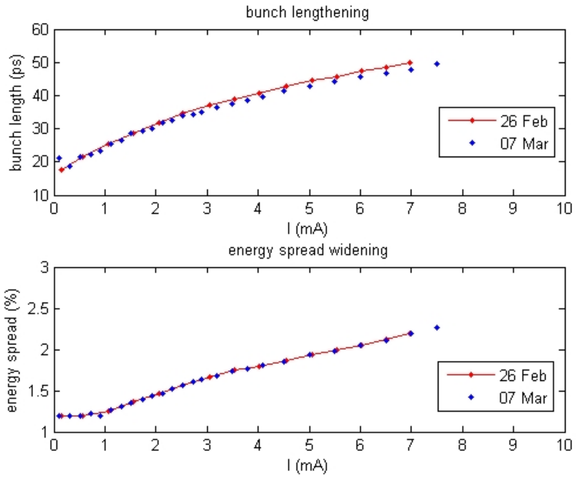
Trends and Improvements (II)
Time Structure

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

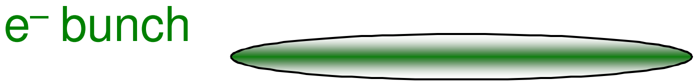
(PWD and MI)



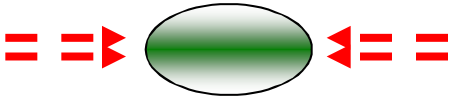
Modern light sources can operate a wide variety of fill patterns
(few bunches, camshaft)

Ultra-short radiation pulses in a storage ring

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



1) shorten the e- bunch

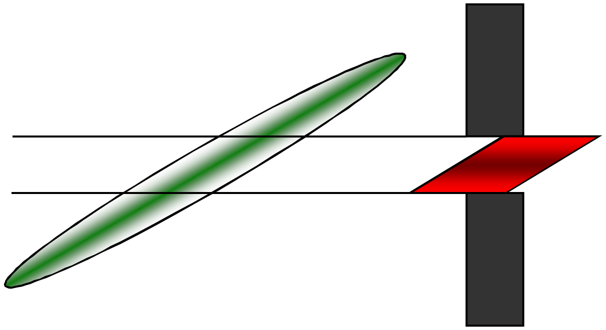


Low – alpha optics

Higher Harmonic Cavities

RF voltage modulation

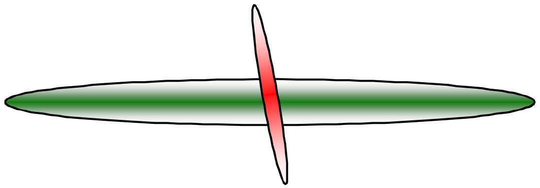
2) chirp the e-bunch + slit
or optical compression



Crab Cavities

Synchro-betatron kicks

3) Laser induced local
energy-density modulation



Femto–slicing

Bunch length (low current)

The equilibrium bunch length is due to the quantum nature of the emission of synchrotron radiation and is the result of the competition between quantum excitation and radiation damping. If high current effects are negligible the bunch length is

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

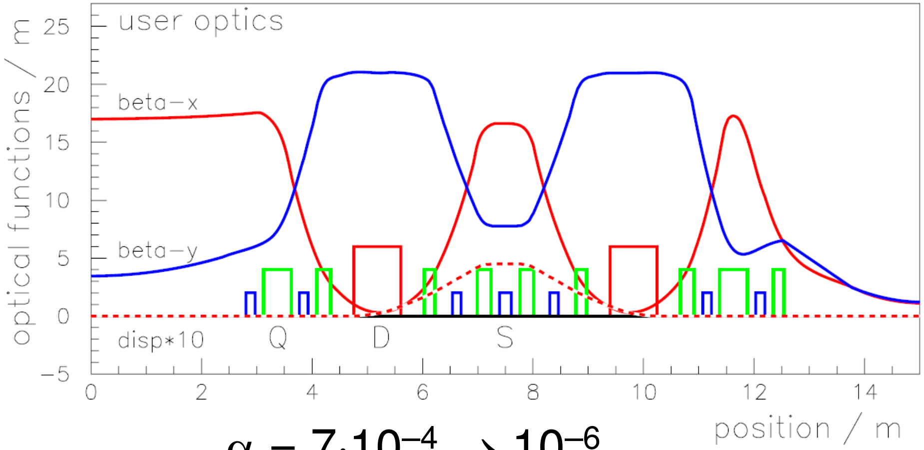
We can modify the electron optics to reduce α

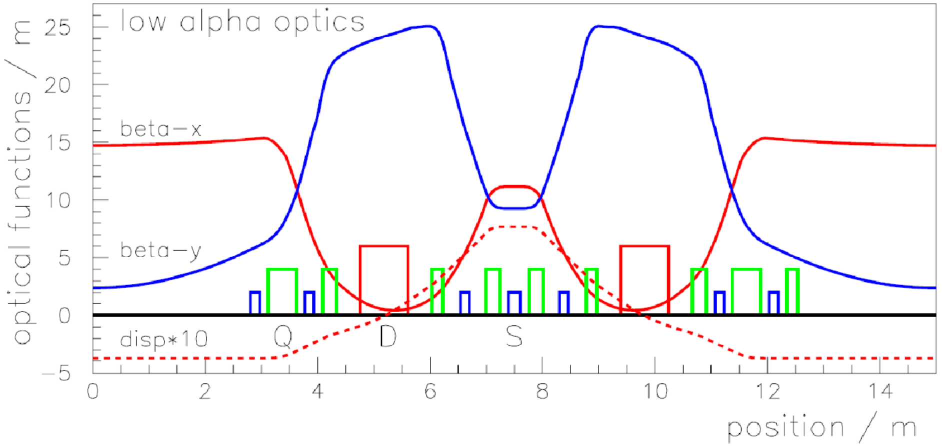
$$\alpha = \frac{1}{L}\oint \frac{D_x}{\rho} ds \approx 10^{-6}$$

α (low_alpha_optics) ≈ α (nominal) /100 → **σ_z(low alpha optics) ≈ σ_z(nominal)/10**

Bessy-II, ANKA, ELETTRA, diamond, SOLEIL, SLS and SPEAR3 have successfully demonstrated low-alpha operation with few ps bunches for Coherent THz radiation or short X-ray pulses

Low alpha optics: BESSY-II





$\alpha = 7\cdot 10^{-4} \rightarrow 10^{-6}$

$\sigma_z = 12$ ps (rms) $\rightarrow 0.7$ ps

$\varepsilon_x = 6$ nm $\rightarrow 30$ nm

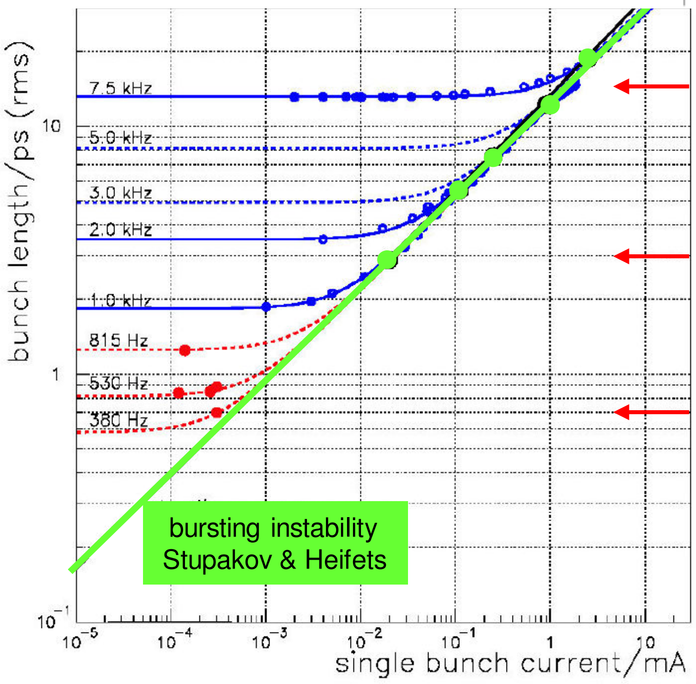
When the bunch is too short CSR generates chaotic bursts of THZ radiation

Microbunch instability (Stupakov-Heifets)

$$I_{th} \propto \sigma_z^{a} \frac{dV_{RF}}{dz}$$

a = 7/3 theory

a = 8/3 experiment



user optics
13 ps

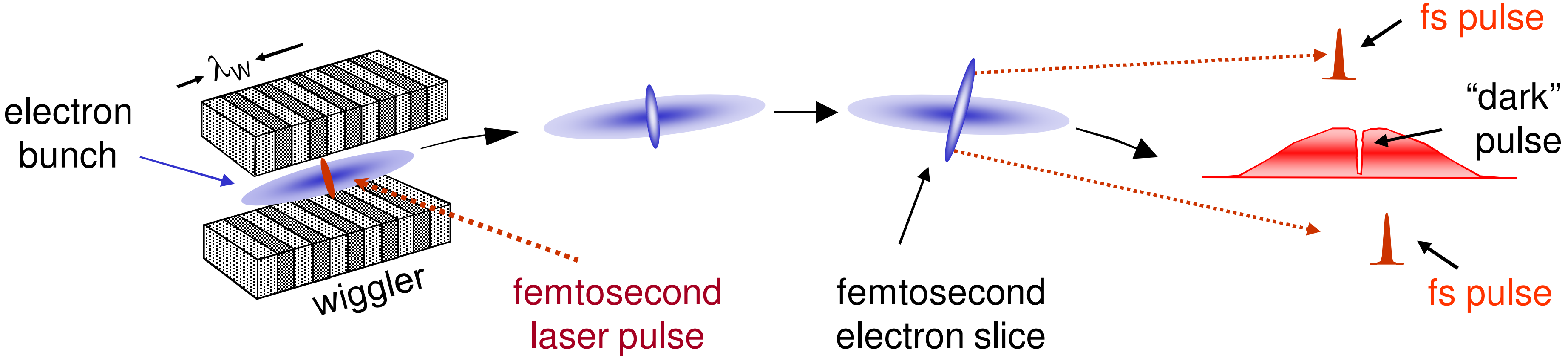
THz optics
3 ps

sub-ps optics
700 fs

Courtesy: BESSY-II

Femtosecond slicing

A.A. Zholents and M.S. Zolotorev, Phys. Rev. Lett. 76 (1996) 912.



λ_W

electron bunch

wiggler

femtosecond laser pulse

femtosecond electron slice

fs pulse

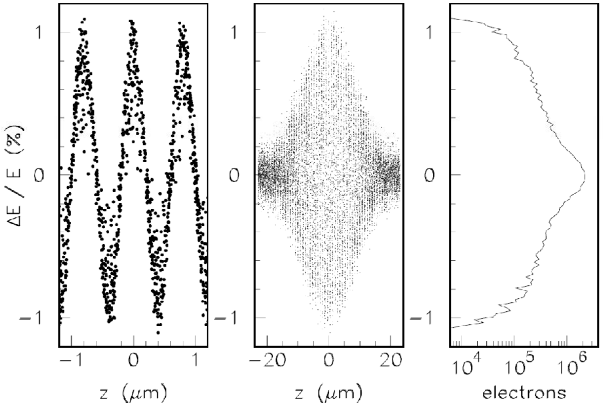
“dark” pulse

fs pulse

electron-laser interaction in the modulator

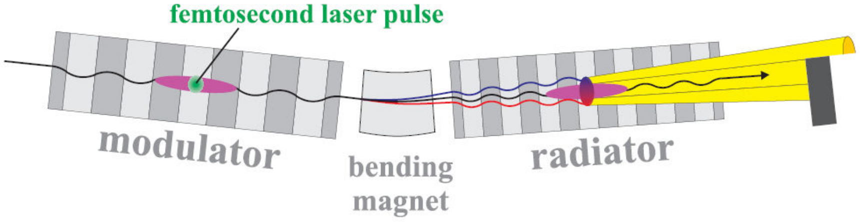
spatial or angular separation in a dispersive section

fs radiation pulses from a radiator



natural energy spread ~0.1%

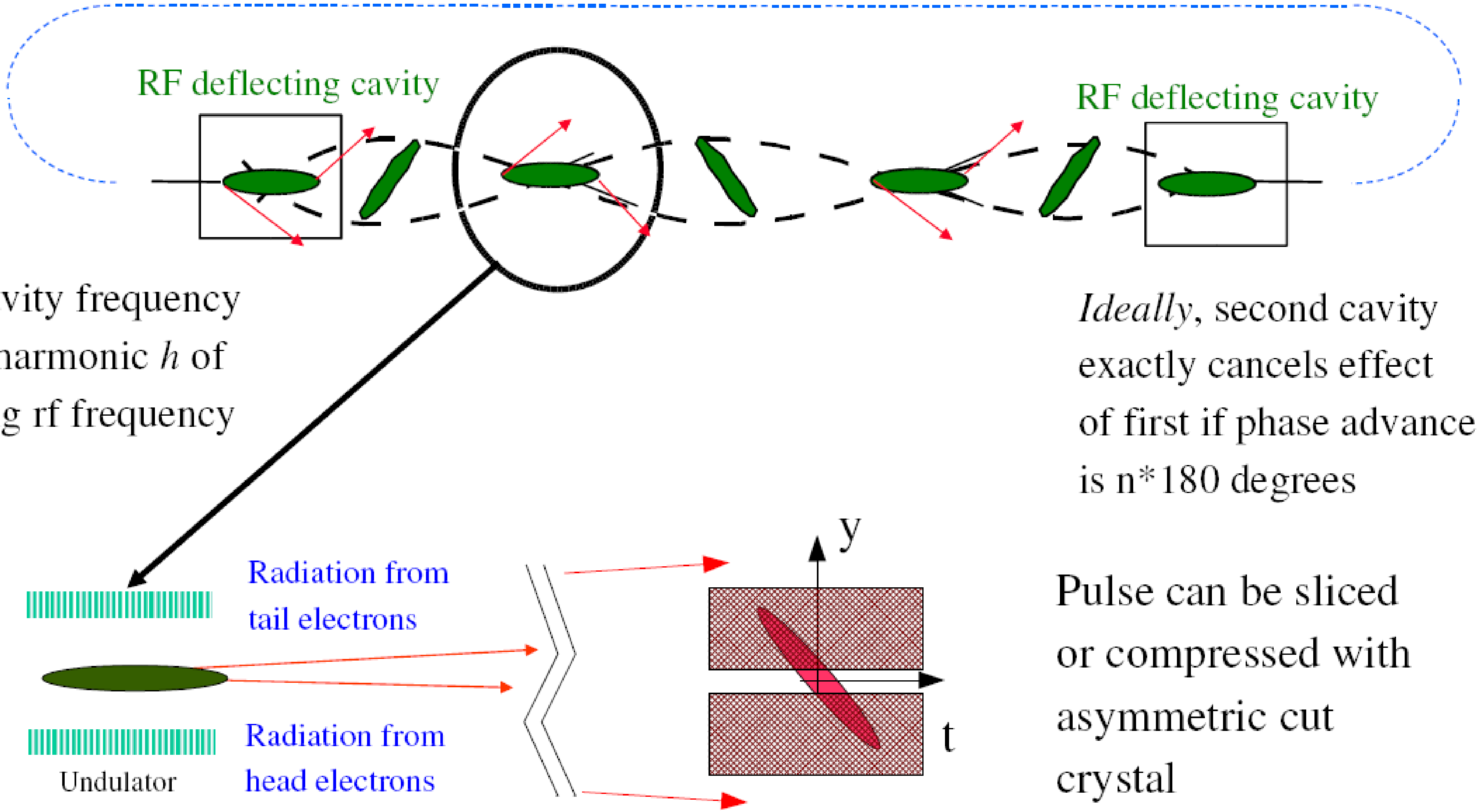
induced energy modulation ~1.0%



BESSY-II, ALS and SLS have successfully demonstrated the generation of X-ray pulses with few 100 fs pulse length, tunable and synchronised to an external laser for pump-probe experiments

Crab Cavities for optical pulse shortening

A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425 (1999)



Cavity frequency is harmonic *h* of ring rf frequency

Ideally, second cavity exactly cancels effect of first if phase advance is n*180 degrees

Pulse can be sliced or compressed with asymmetric cut crystal

Courtesy M. Borland (APS)

Comparison of options for short radiation pulses

	Low-alpha	Crab cavity	femtoslicing
Pulse length	~1 ps	~1 ps	~100 fs
Photon flux	poor	good	very poor
synchronisation	no	no	yes
Hardware upgrade	easy	difficult	manageable
Compatibility with normal users operation	no	yes	yes
Rep rate	MHz	MHz	KHz

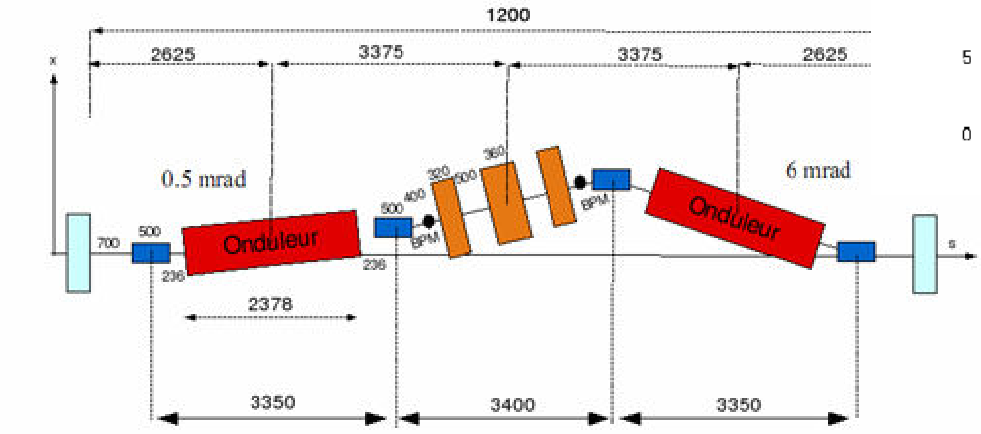
Trends and improvements (III)
Customised optics for special beamlines

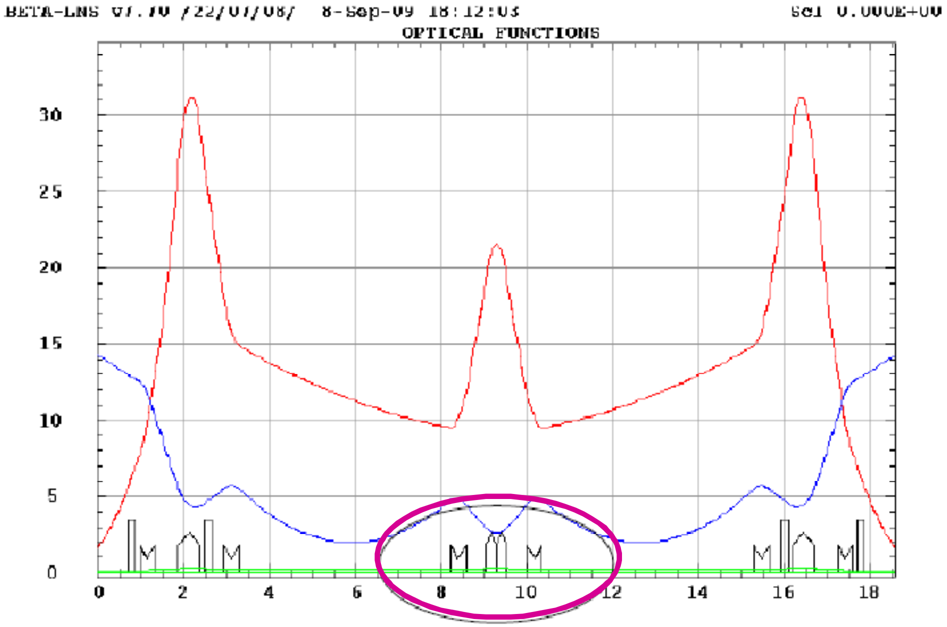
Many storage ring light source have implemented two canted undulators in the same straight to increase the number of beamlines.

Many of these have also speical optics in the straight sections, e.g. APS, ESRF, Bessy, SLS; Diamond, Soleil,

2 mini-β_z (8 m → 2 m) to host two low-gap IDs and a chicane

(quadrupole triplet tested. Further Commissioned + breaking of the 4-fold symmetry)





Courtesy L: Nadolski (SOLEIL)

Conclusions

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

No evidence of under subscription: user's community and the number of beamlines per facility is increasing;

The agreement with model is excellent for the linear optics and improvements can be foreseen for the nonlinear optics

Future developments will target

higher brightness	even lower emittance < 1 nm, lower coupling
higher stability	Top-Up, sub-μm over few hundreds Hz
short pulses	< 1 ps
higher current	~ 500 mA
larger capacity	more undulator per straights (canted undulators)

Technological progress is expected to further improve brightness and stability (IDs, RF, BPMs, DPS, …)

Thanks to many colleagues which have provided the material for this talk

and

thank you for your attention.