Performance and Trends of Storage Ring Light Sources

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Outline

- Introduction
  - user's requirements and accelerator physics challenges
- Overview of the performance of 3rd generation light sources
  - comparison of design with achieved parameters
  - brightness, stability and time structure
- Trends and Improvements
  - review of the upgrades of existing facilities
  - technological developments
- 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, Australia	3 GeV
	MAX III, Sweden	700 MeV
	Indus-II, India	2.5 GeV
2008	**SSRF**, China	3.4 GeV

3rd generation storage ring light sources

under construction or planned

2009	**ALBA**, Spain	3 GeV
	Petra-III, Germany	6 GeV
> 2009	**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)

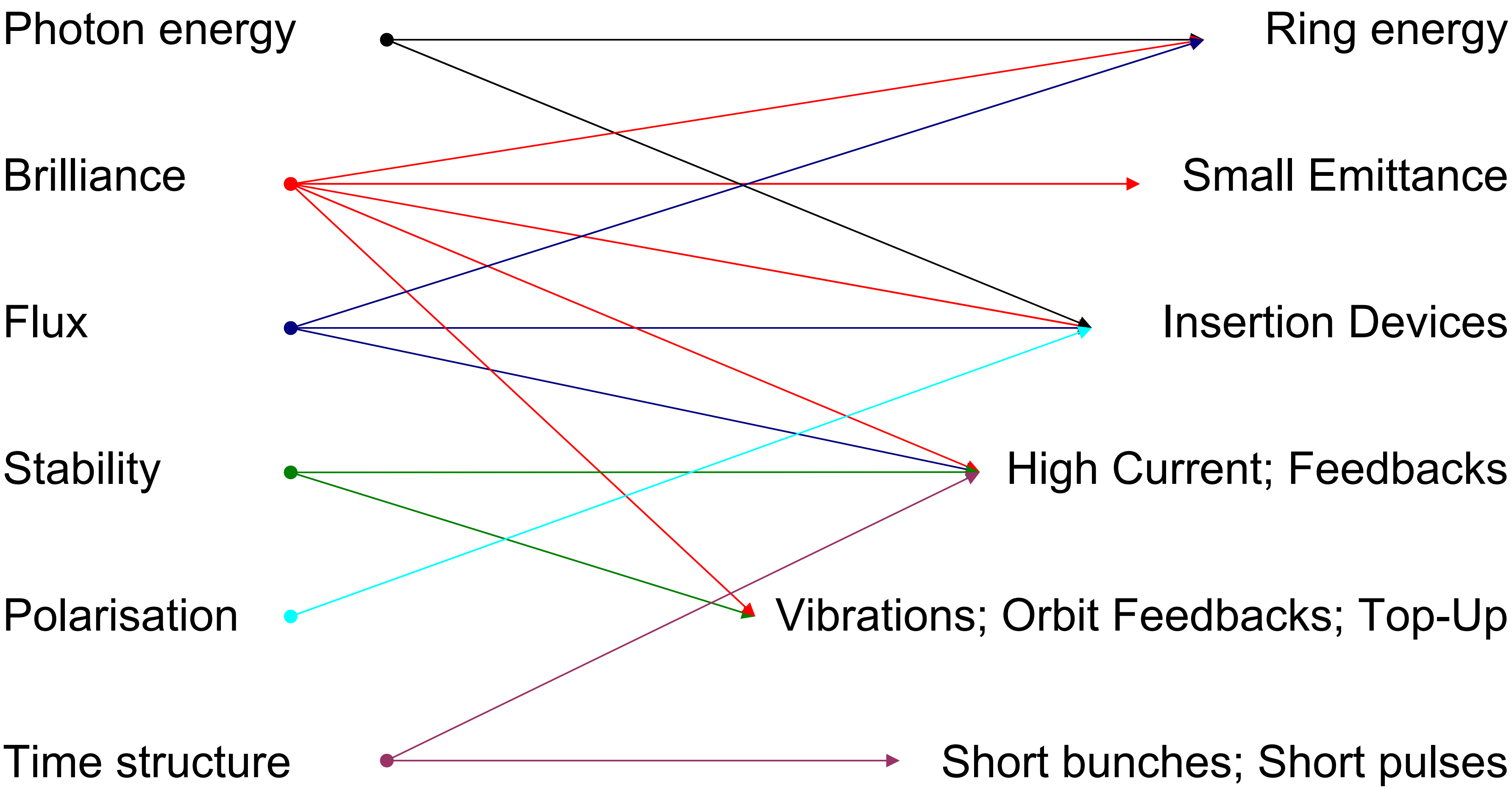
Brilliance = Photons / (s • mm^2 • $mrad^2$ • BW)

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

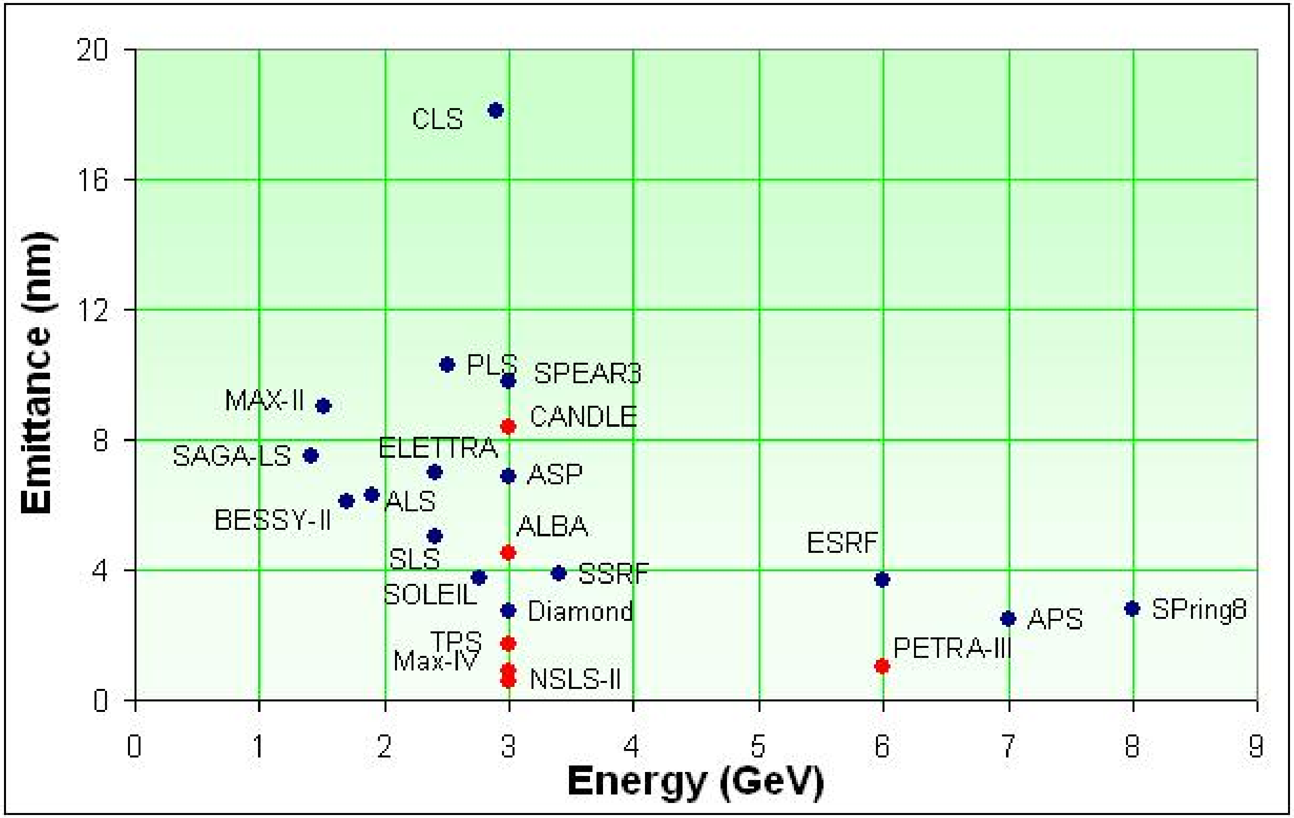
High Current; Feedbacks

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



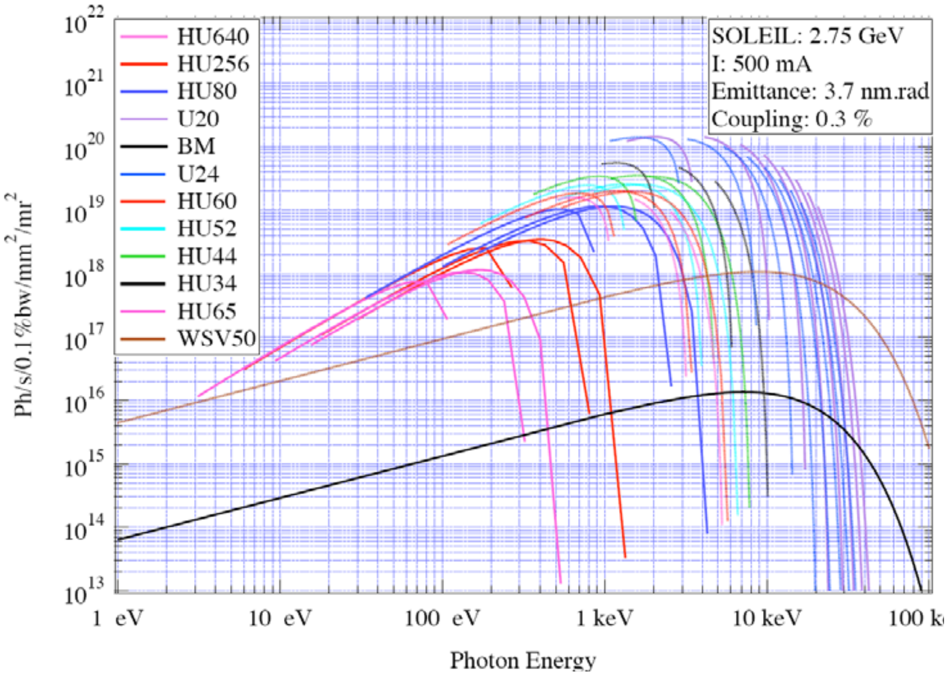
$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

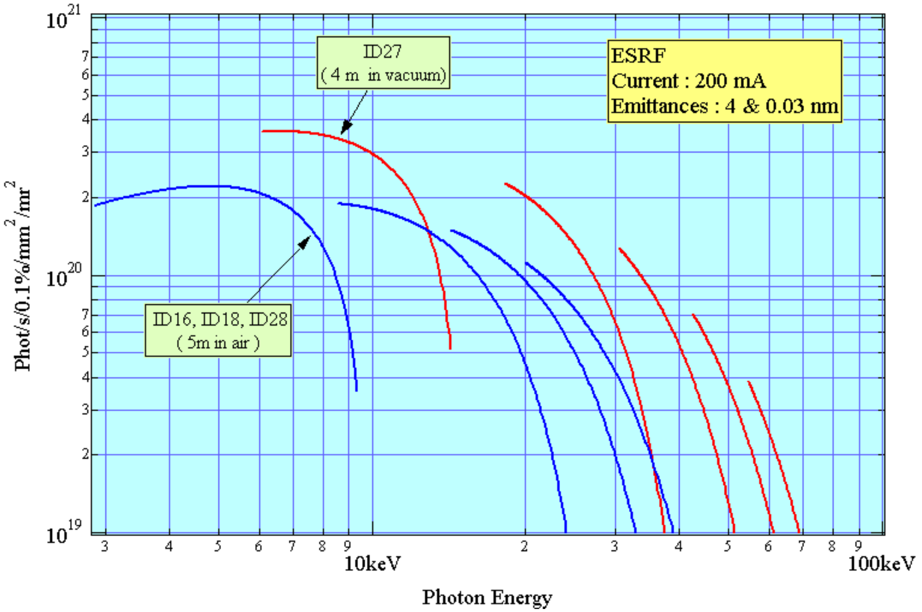
$$\Sigma_x = \sqrt{\sigma_{x,e}^2 + \sigma_{ph,e}^2} \qquad \sigma_x = \sqrt{\varepsilon_x \beta_x + (D_x \sigma_\varepsilon)^2}$$

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

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)

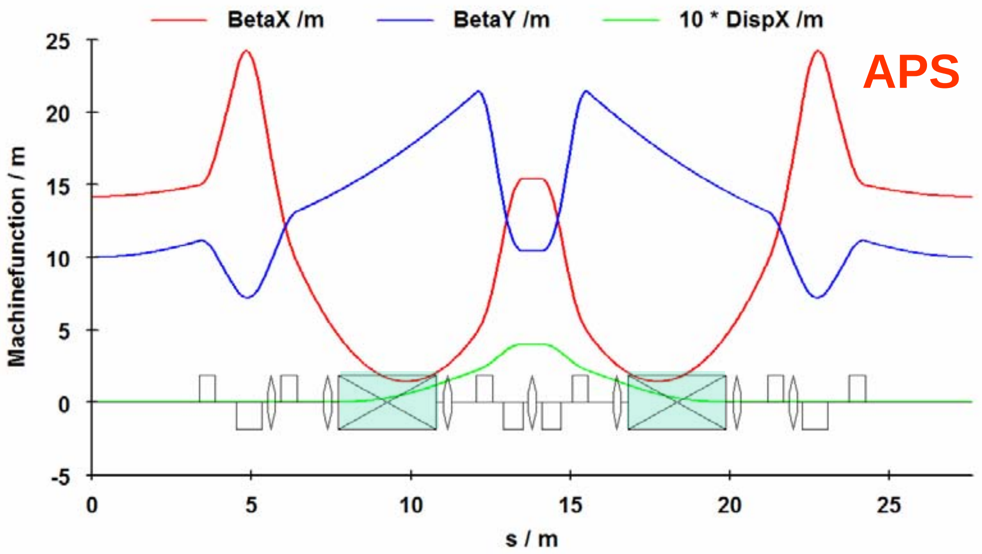
Triple Bend Achromat (TBA)

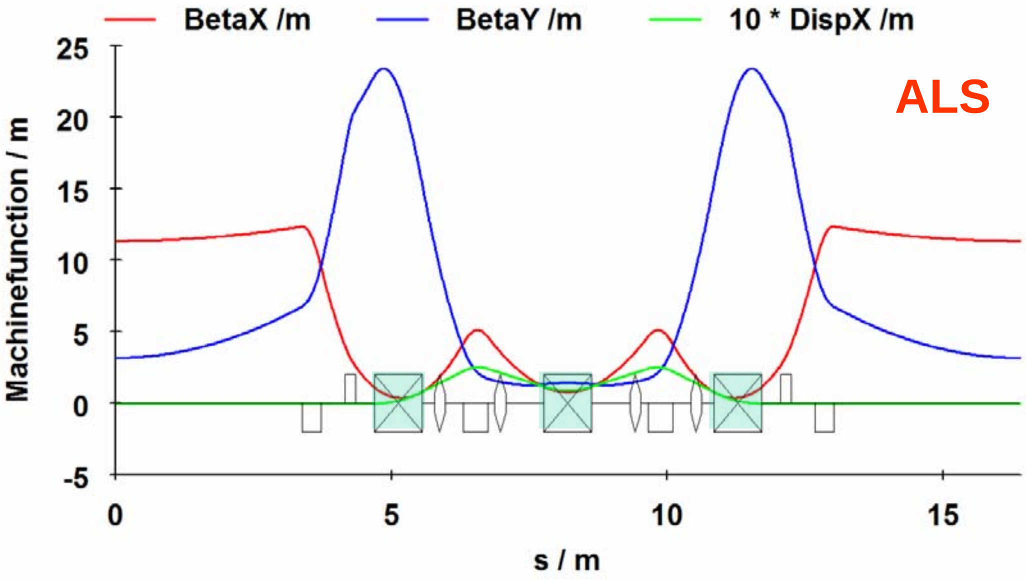
DBA used at:
ESRF,
ELETTRA,
APS,
SPring8,
Bessy-II,
Diamond,
SOLEIL,
SPEAR3
...

TBA used at
ALS,
SLS,
PLS,
TLS
…

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

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

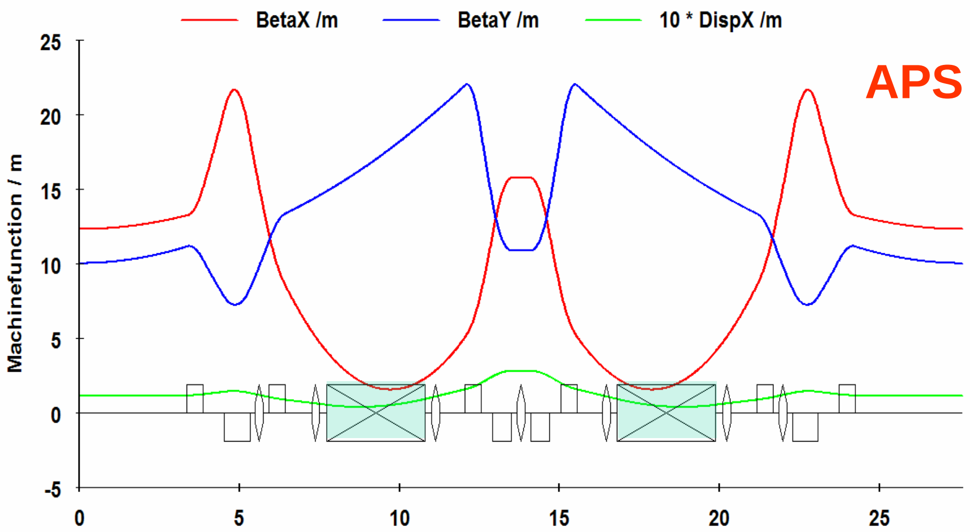




Low emittance lattices

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

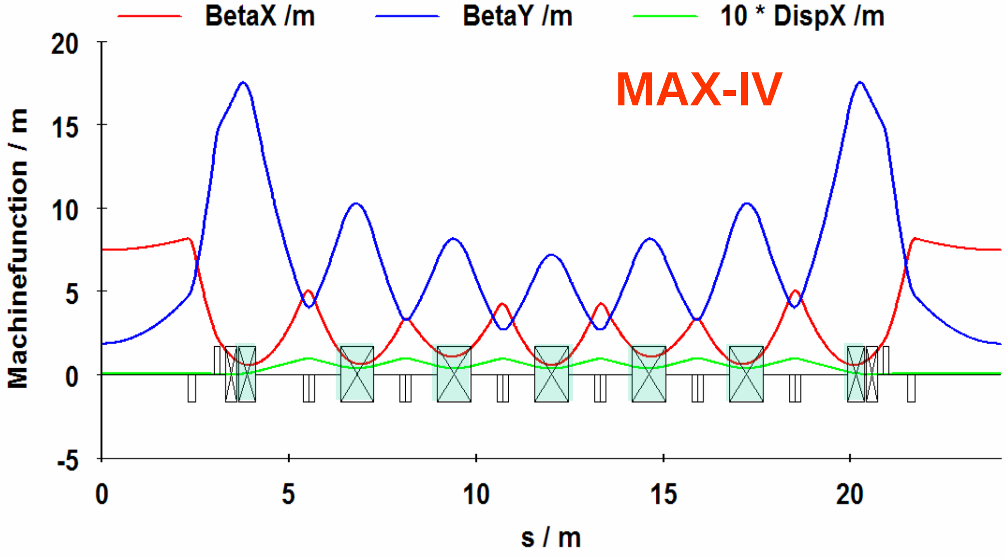
MBA

MAX-IV (7-BA): S. Leemann WEPC011

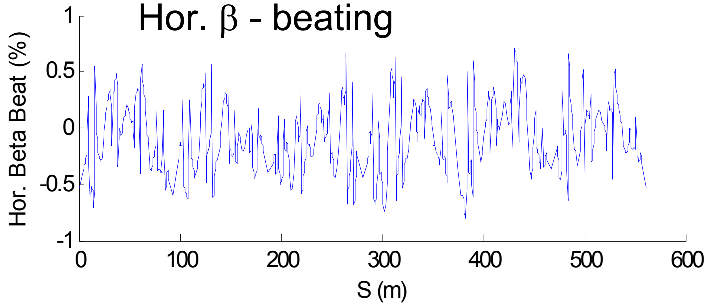
Damping Wigglers

NSLS-II: J. Bengtsson this session

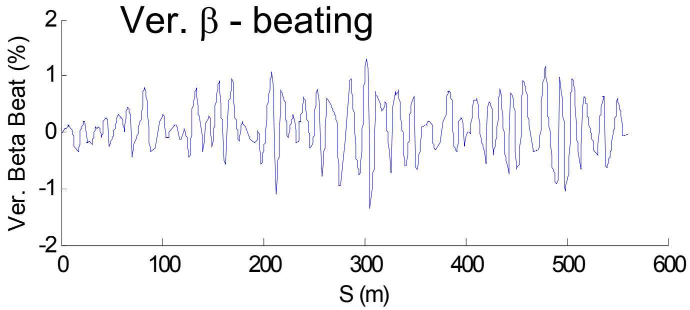
Petra-III: K. Balewski WEPC001



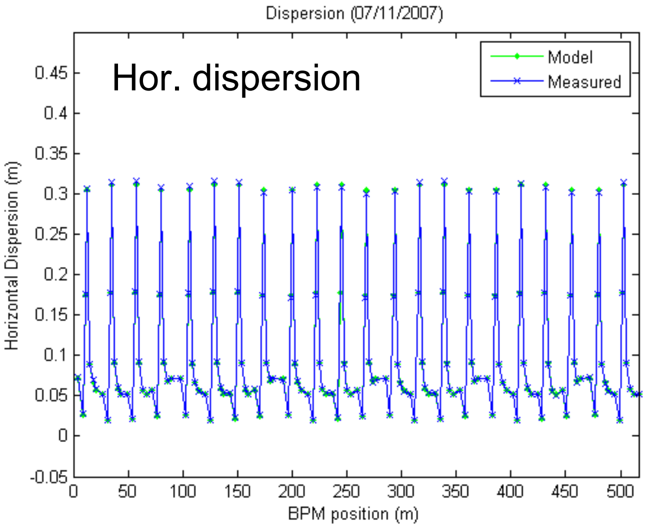
Linear optics modelling: Diamond



Hor. β - beating



Ver. β - beating



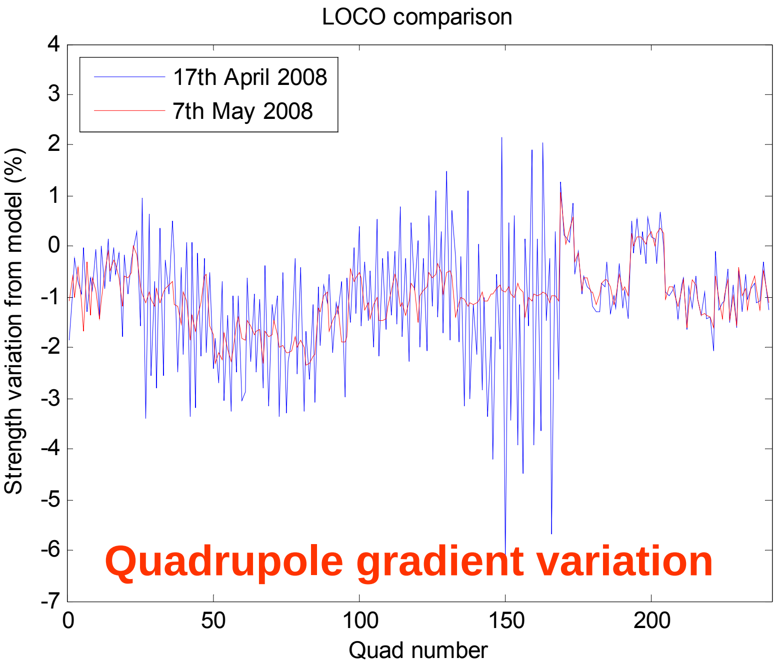
Dispersion (07/11/2007)

Hor. dispersion

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

β - beating reduced to 0.4% rms

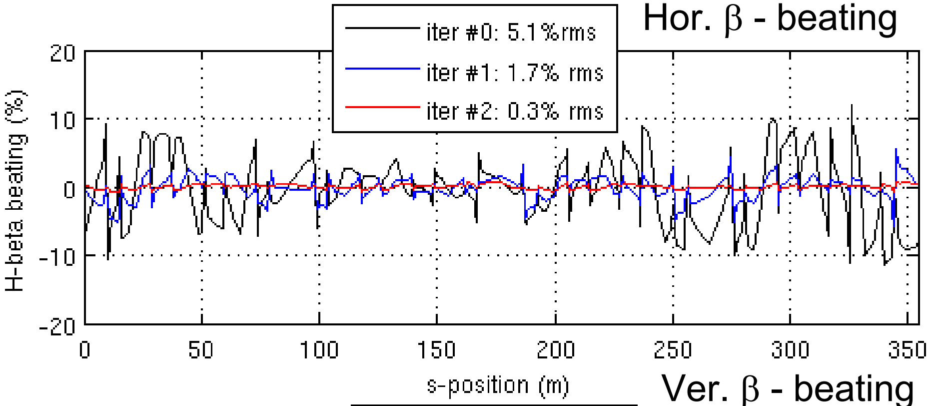
Quadrupole variation reduced to 2%
Results compatible with mag. meas.

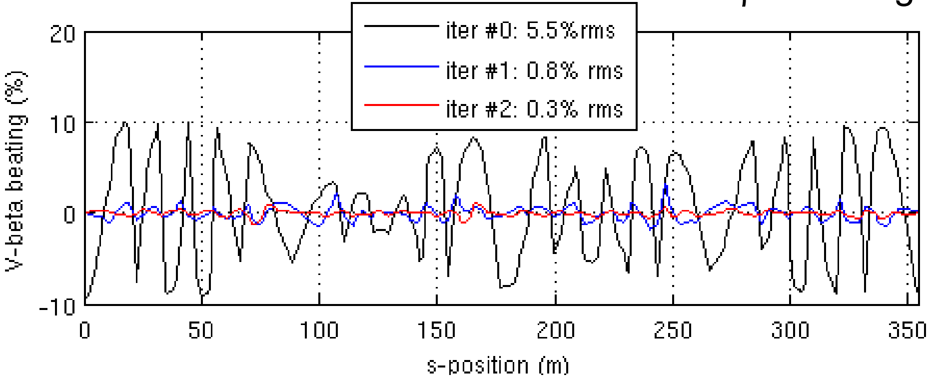


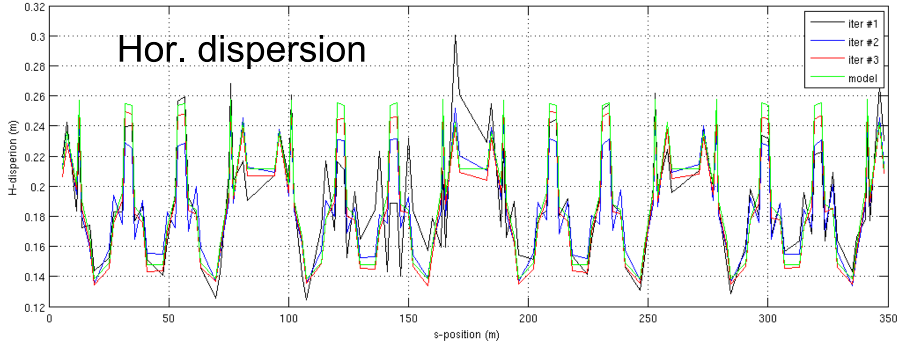
LOCO comparison

Quadrupole gradient variation

Linear optics modelling: SOLEIL



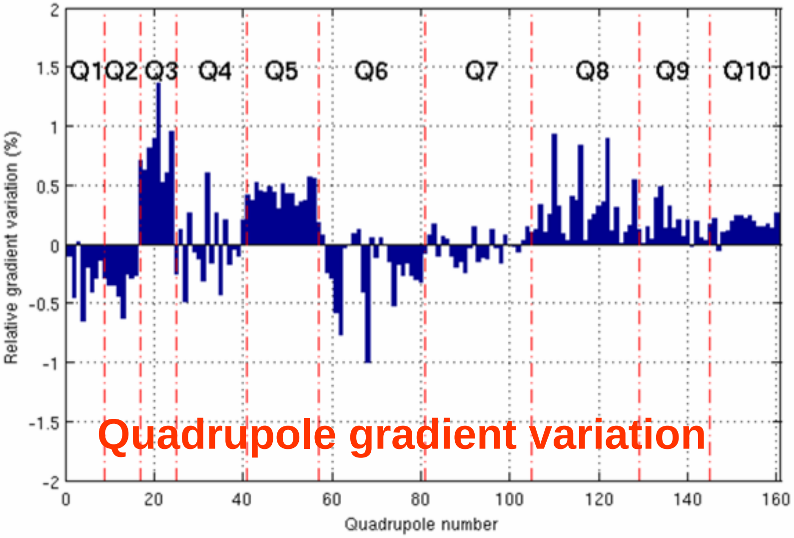




Modified version of LOCO with constraints on gradient variations

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



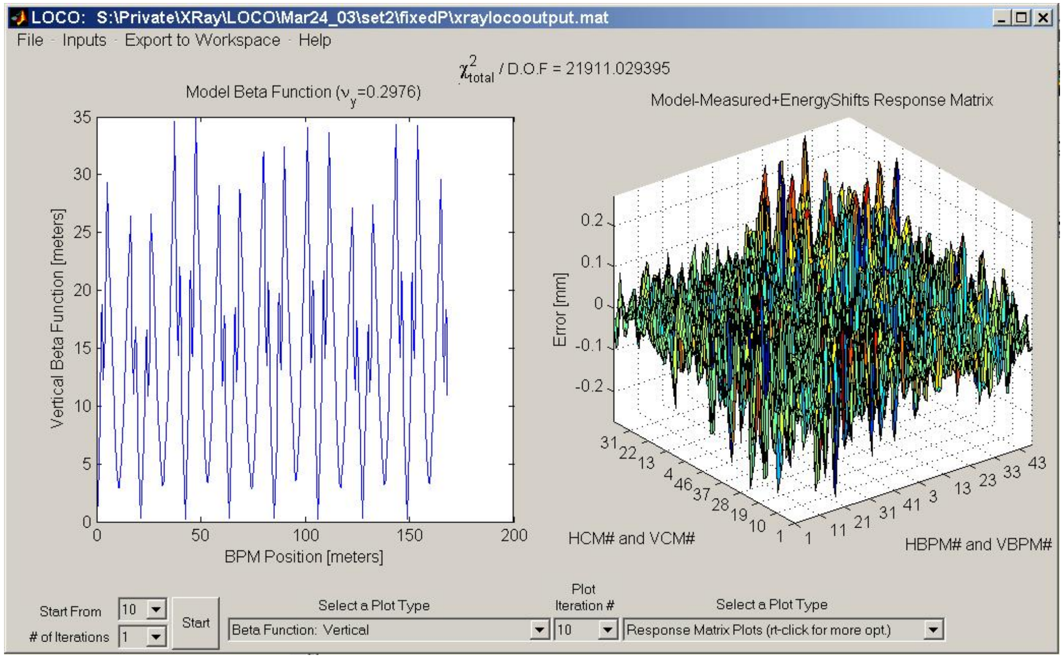
Quadrupole gradient variation

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

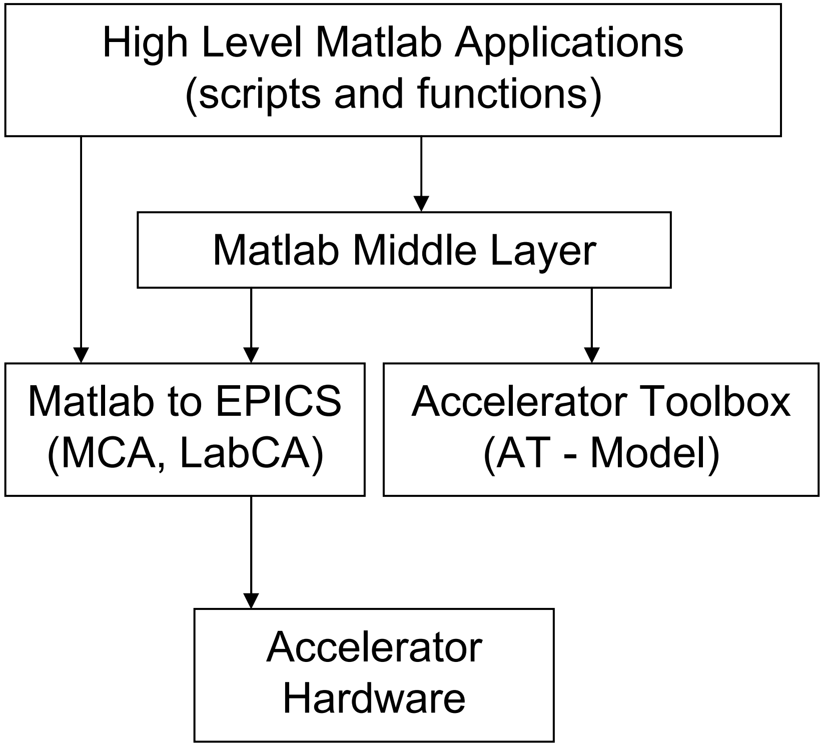
Start From: 10

\# 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	Diamond
Spear3	ASP
CLS	SSRF
PLS	ALBA
SOLEIL	NSLS-II

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

Summary of comparison model/machine for linear optics

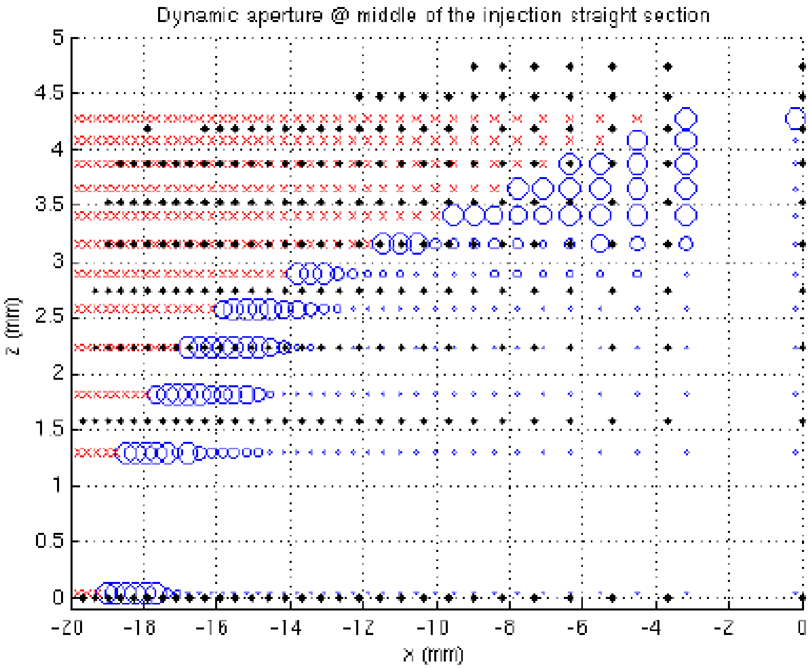
	Model emittance	Measured emittance	β-beating (rms)	Coupling* ($\varepsilon_y / \varepsilon_x$)	Vertical emittance
ALS	6.7 nm	6.7 nm	0.5 %	0.1%	4-7 pm
APS	2.5 nm	2.5 nm	1 %	0.8%	20 pm
CLS	18 nm	17-19 nm	4.2%	0.2%	36 pm
Diamond	2.74 nm	2.6-2.9 nm	0.4 %	0.15%	4 pm
ESRF	4 nm	4 nm	1%	0.25%	10 pm
SLS	5.6 nm	5.4-7 nm	4.5% H; 1.3% V	0.05%	3.2 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

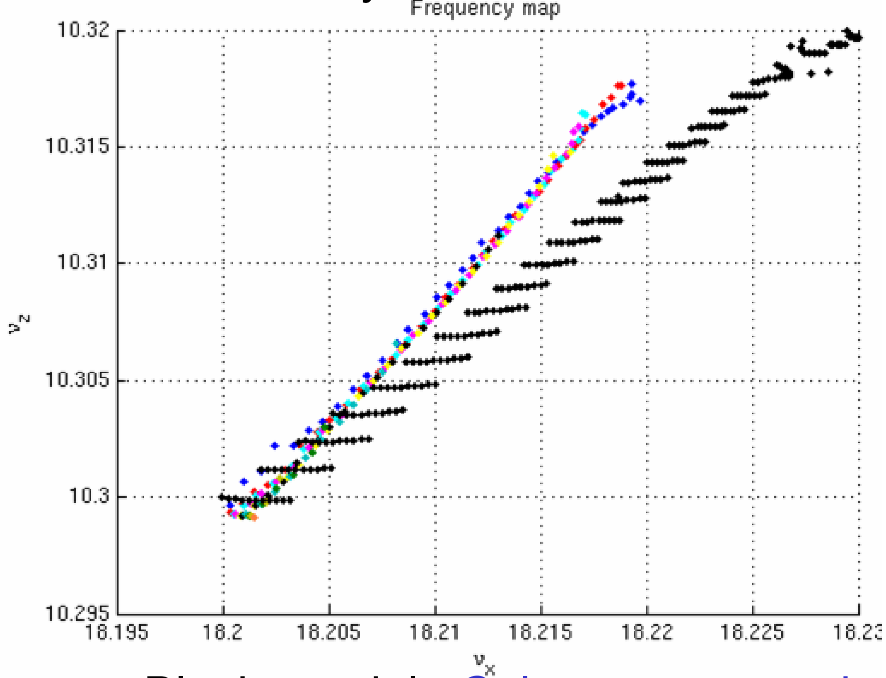
M. Boge: WEPC003 Coupling Control at the SLS

Dynamic Aperture

SOLEIL bare lattice at zero chromaticity



Black–model; Blue–loss rate; Red unstable



Black–model; Colours measured

Tracking includes

Systematic multipole errors

Dipole: up to 14-poles
Quadrupoles: up to 28-poles
Sextupoles: up to 54-poles
Correctors (steerers): up to 22-poles
Secondary coils in sext. → strong 10-pole term

From magnetic measurements:
Dipole: fringe field, gradient error, edge tilt errors

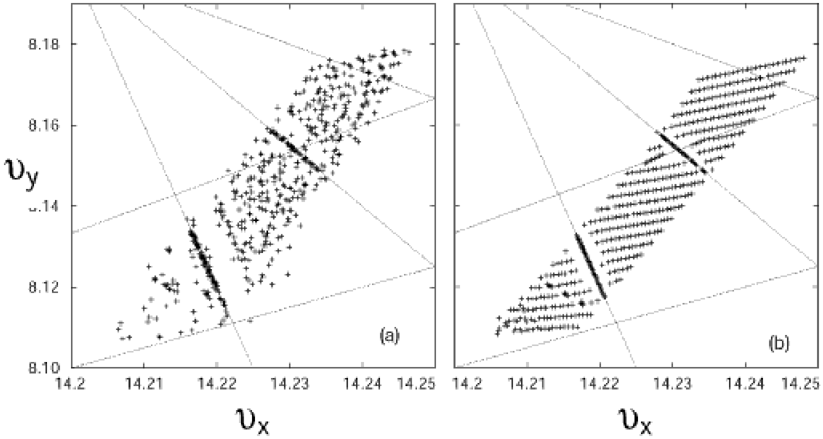
Coupling errors (random rotation of quadrupoles)
No quadrupole fringe fields

Courtesy A. Nadji (SOLEIL)

Frequency Map Analysis: ALS and BESSY-II

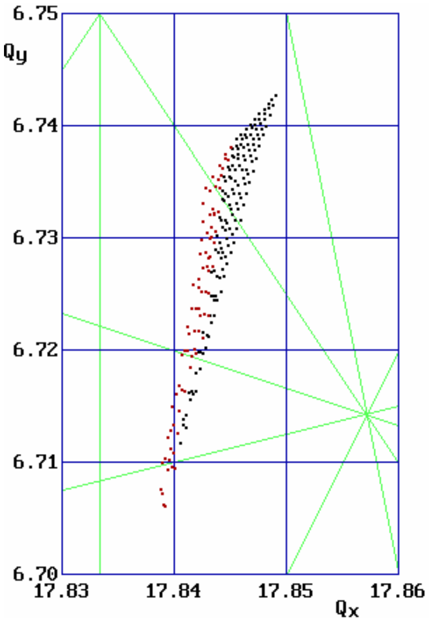
ALS linear lattice corrected to
0.5% rms β-beating

FM computed including residual
β-beating and coupling errors

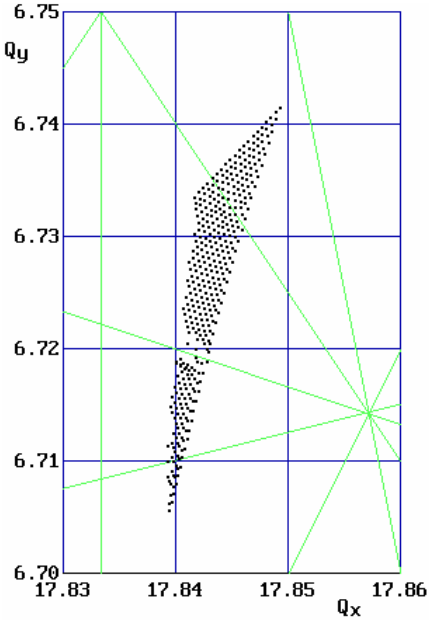


ALS measured ALS model

BESSY-II with harmonic sextupole
magnets, chromaticity, coupling



BESSY-II measured



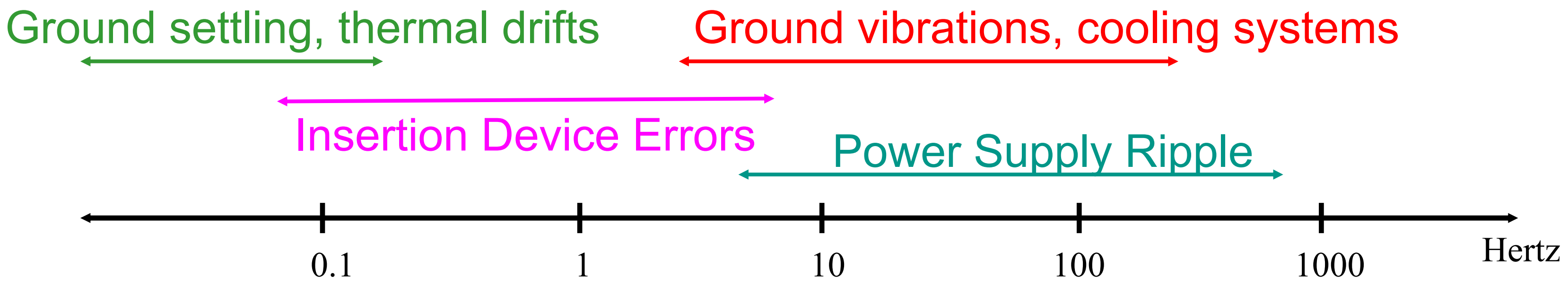
BESSY-II model

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

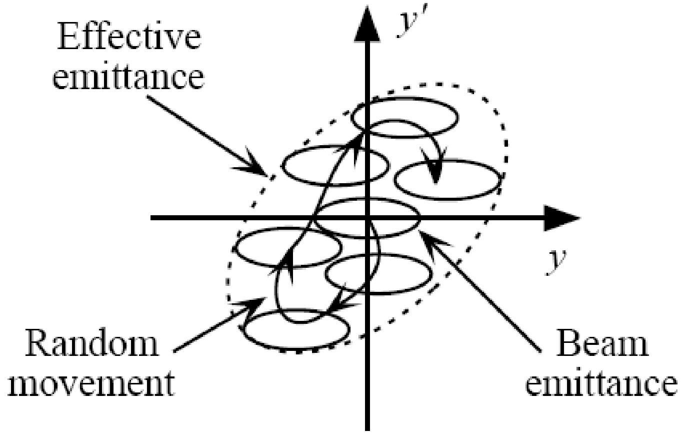
Beam stability should be better than

10% of the beam size

10% of the beam divergence

up to 100 Hz

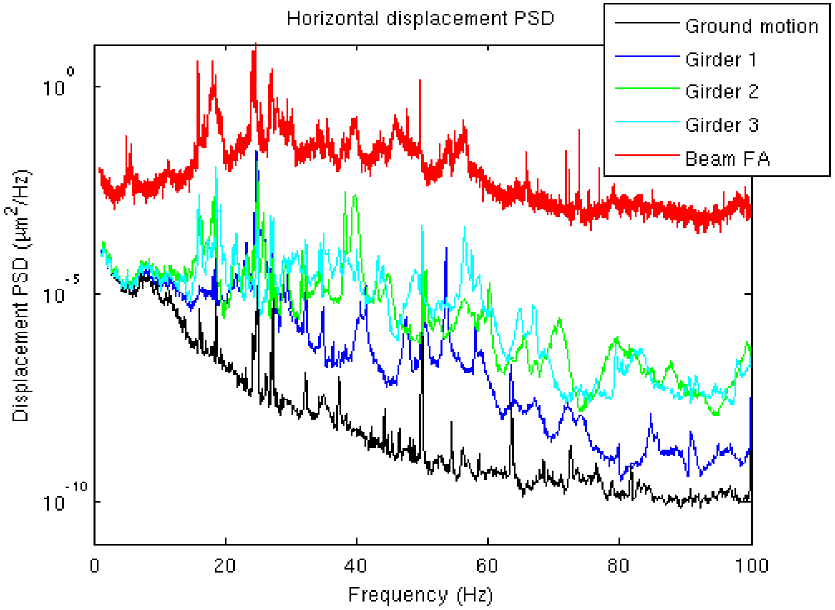
but IR beamlines will have tighter requirements

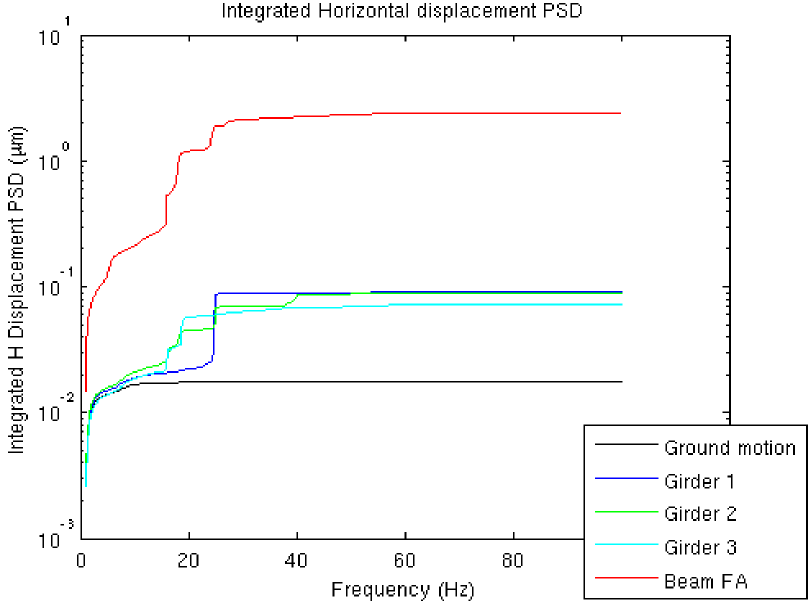


<u>for 3rd generation light sources this implies sub-μm stability</u>

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

Ground vibrations to beam vibrations: Diamond

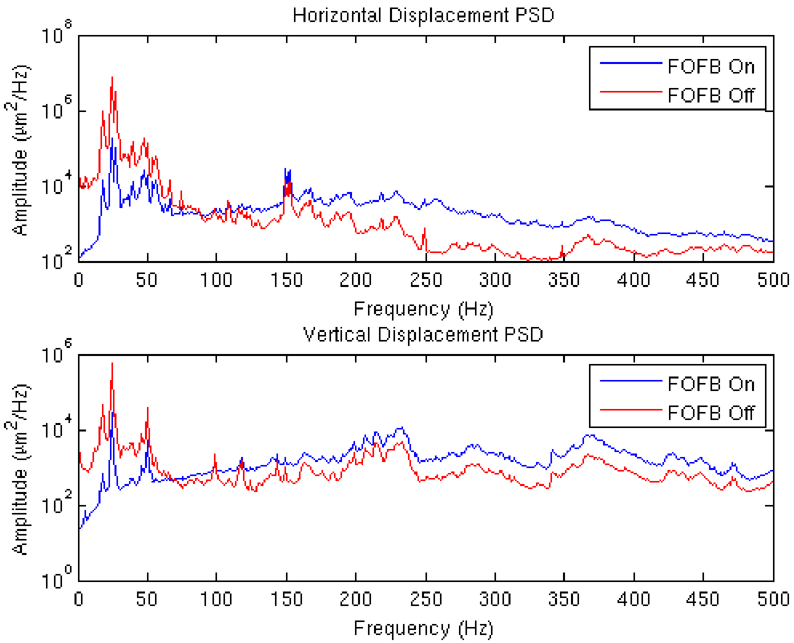


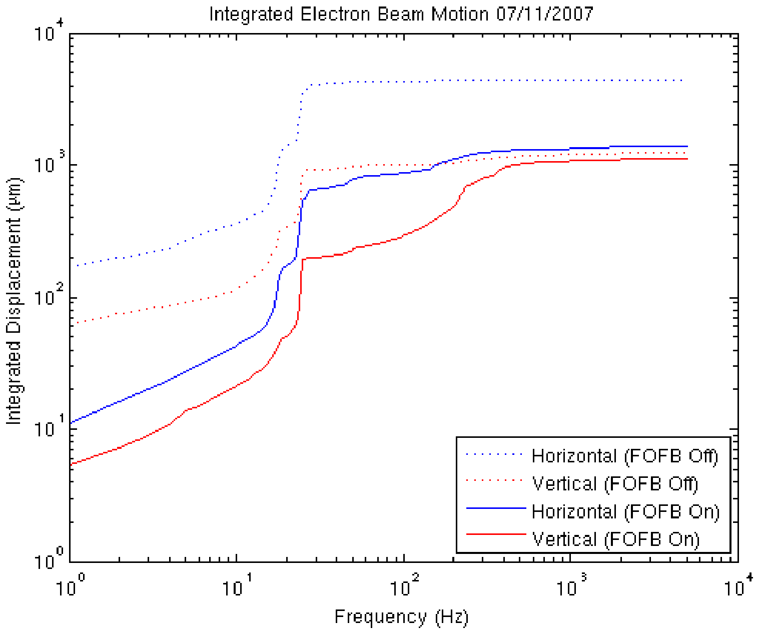


Amplification factor girders to beam: H 31 (theory 35); V 12 (theory 8);

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

M. Heron (DLS): THPC118

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%)**

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

Top-Up Operation

Top-Up operation consists in the continuous (very frequent) injection to keep the stored current constant

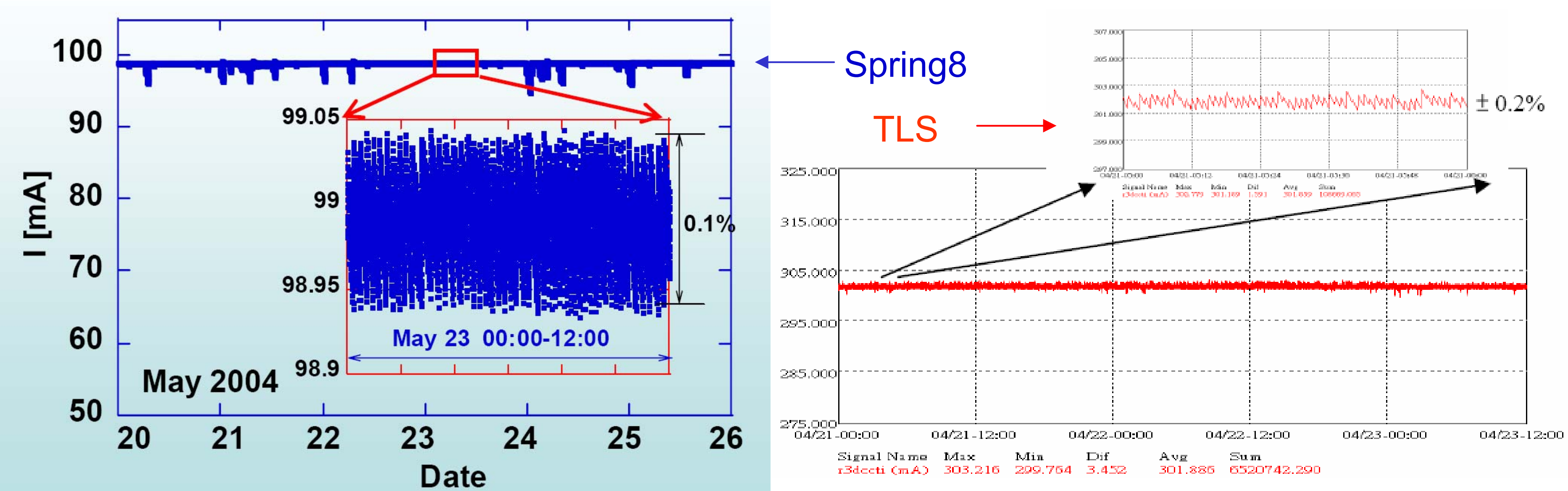
$\Delta I/I \sim 10^{-3}$

Already in operation at APS, SLS, SPring8, TLS

New commissioned machines Diamond, SOLEIL are undergoing tests and will operate Top-Up soon

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

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



Advantages of Top-Up Operation: stability

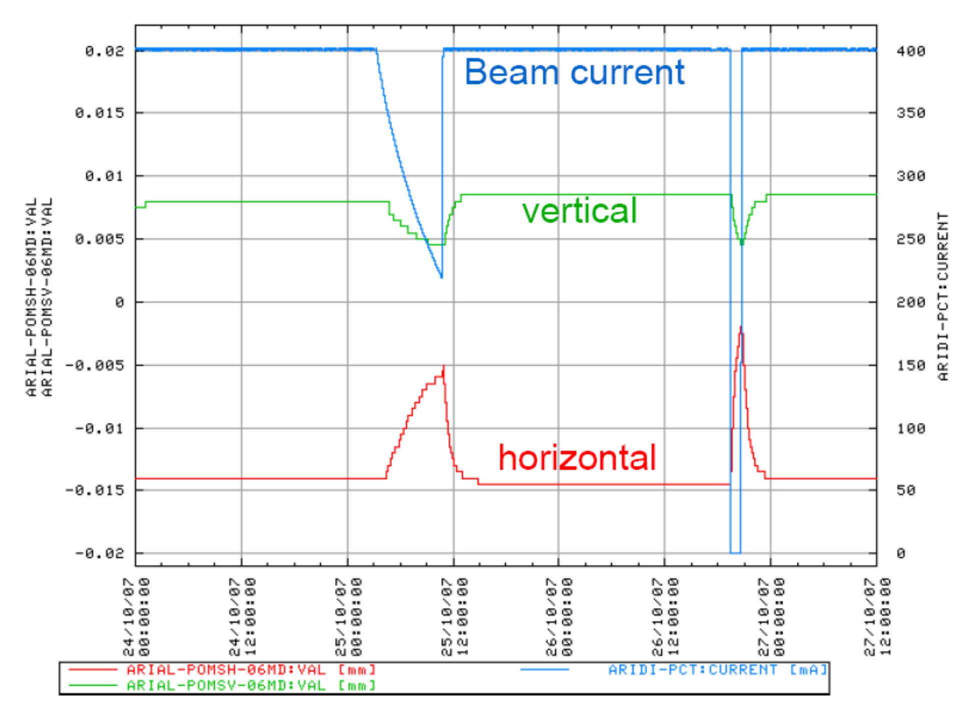
Top-Up improves stability:

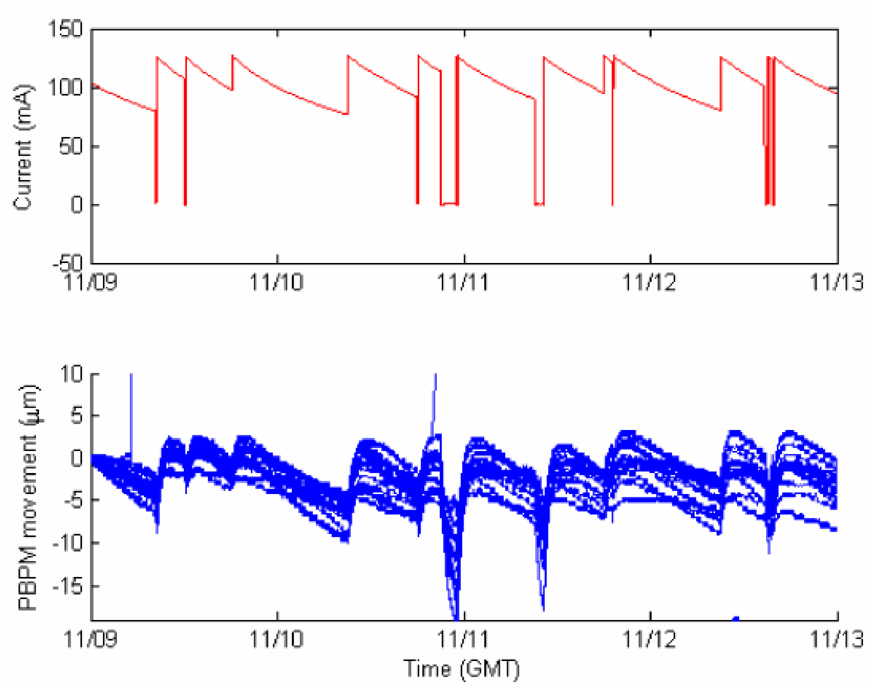
- constant photon flux for the users
- higher average current
- constant thermal load on components

BPMs block stability

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

Crucial for long term sub- μm stability

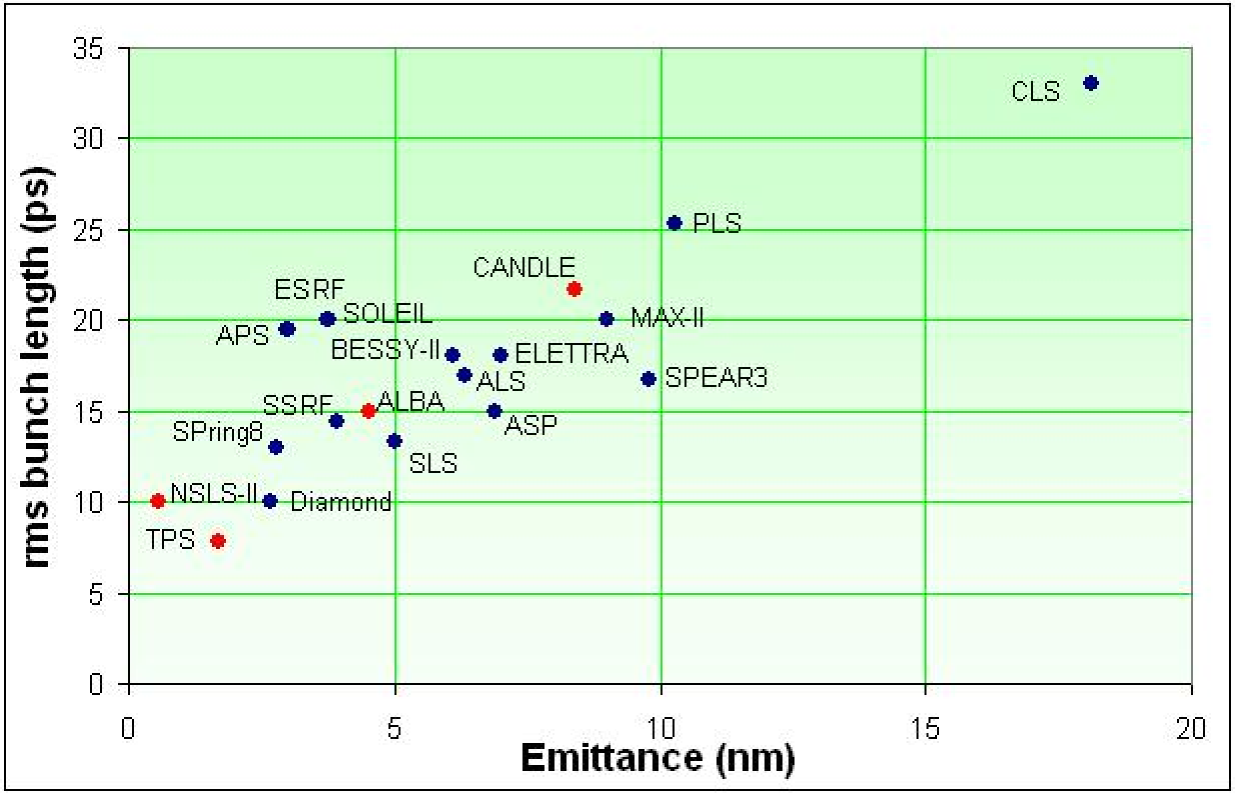




Courtesy M. Boge (SLS)

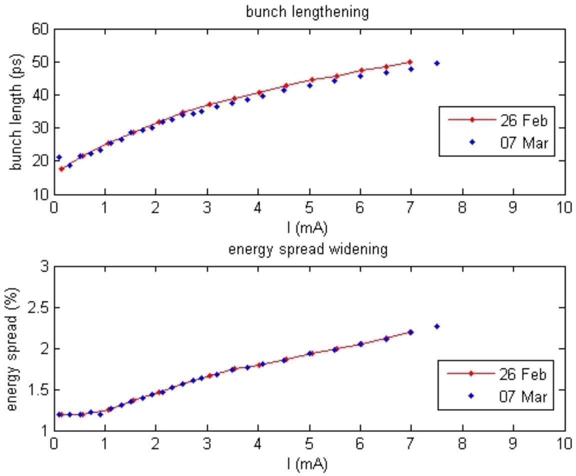
Time Structure

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)

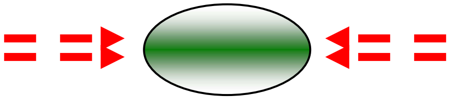


Modern light sources can operate a wide variety of fill patterns (few bunches, camshaft)

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

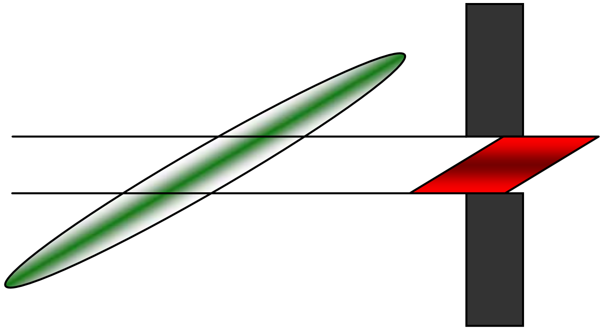


Low – alpha optics

Higher Harmonic Cavities

RF voltage modulation

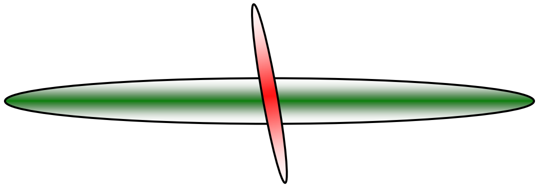
2) chirp the e-bunch + slit
or optical compression



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

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

We can modify the electron optics to reduce α

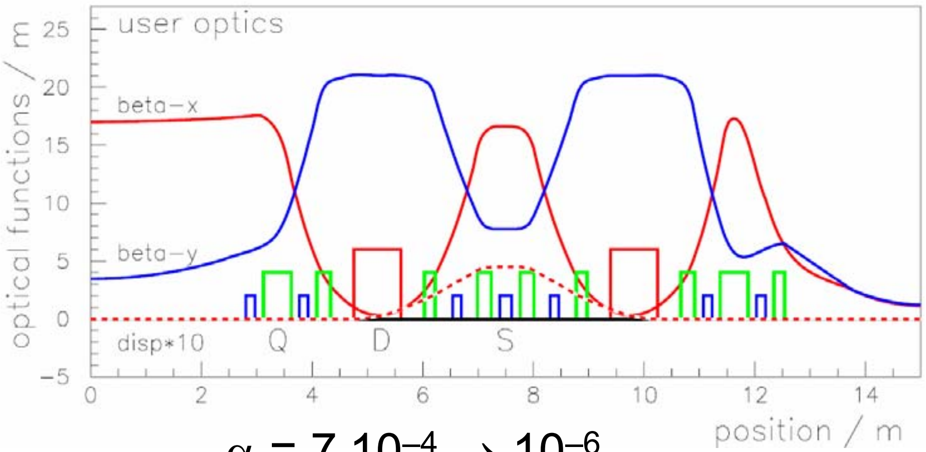
$$\alpha = \frac{1}{L} \oint \frac{D_x}{\rho} ds \approx 10^{-6}$$

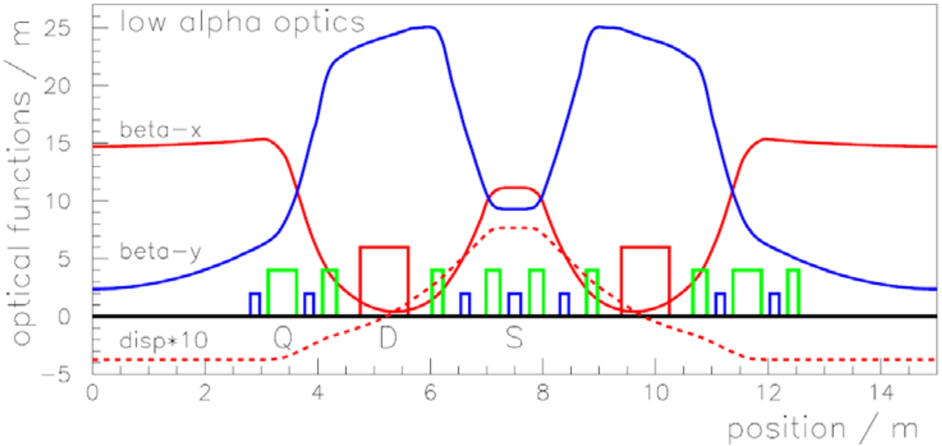
α (low_alpha_optics) $\approx$ α (nominal) /100 ➔ **σ_z(low alpha optics) $\approx$ σ_z(nominal)/10**

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

G. Wuestefeld: MOZAG02 Coherent Synchrotron Radiation and Short Bunches in Electron Storage Rings
S.A. Muller: WEPC046 Characterising THz Coherent Synchrotron Radiation at the ANKA Storage Ring
E. Karantzoulis: WEPC027 Coherent THz Radiation at ELETTRA

Low alpha optics: BESSY-II





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

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

ε_x = 6 nm $\rightarrow$ 30 nm

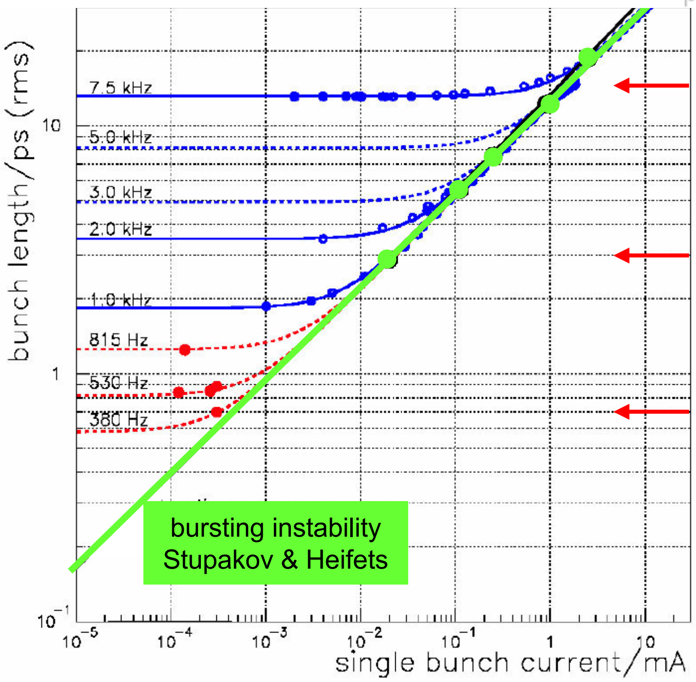
When the bunch is too short CSR generates chaotic bursts of THZ radiation

Microbunch instability (Stupakov-Heifets)

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

a = 7/3 theory

a = 8/3 experiment



user optics
13 ps

THz optics
3 ps

sub-ps optics
700 fs

Courtesy: BESSY-II

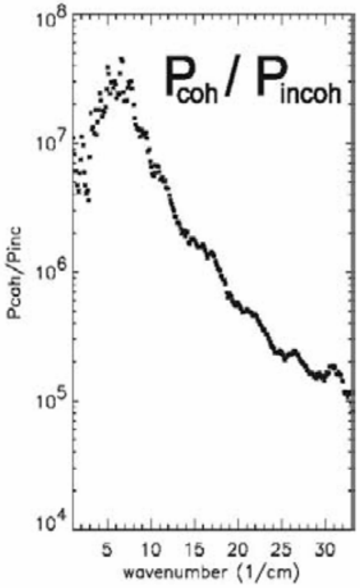
Performance and possible upgrades

At BESSY-II coherent radiation is offered to user 4 times a year in dedicated shifts of 3 days

σ_z = 3 ps rms

15mA in 400 bunches (37.5 μA per bunch)

stable emission: P (coherent) / P (incoherent) ~ 10^7

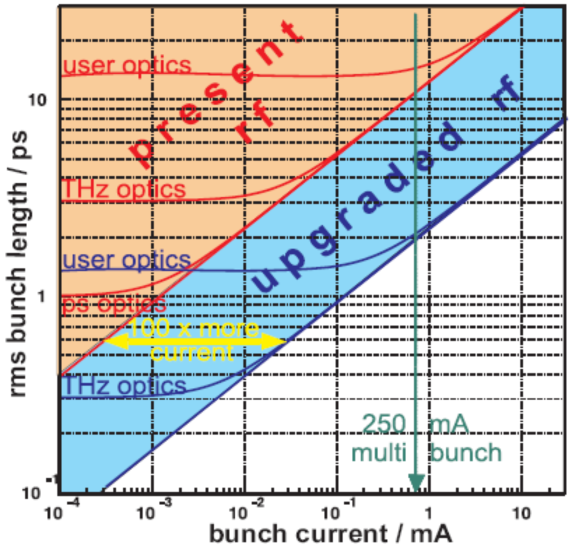


Possible upgrade based on the combination of low-alpha with a 3HC SC cavity in bunch shortening mode

50 MV - 1.5 GHz giving 100 higher RF gradient can allow

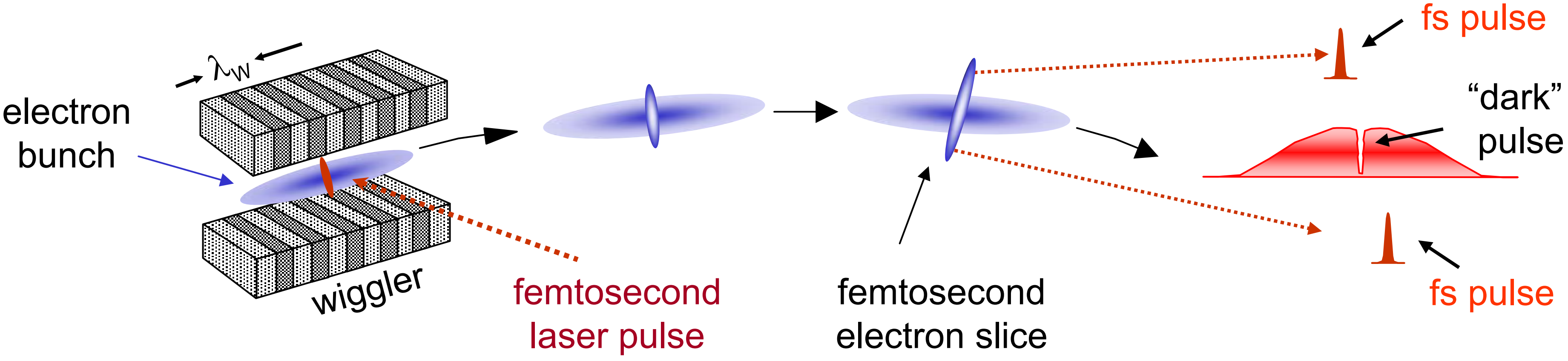
1.3 ps, 0.5 mA per bunch in nominal optics

300 fs, 17 μA per bunch in the low-alpha optics



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

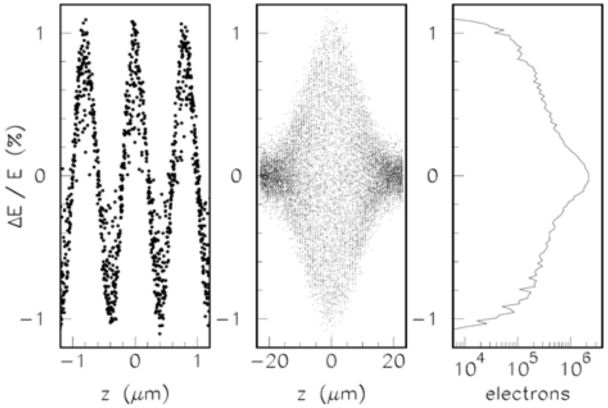
“dark” pulse

fs pulse

electron-laser interaction in the modulator

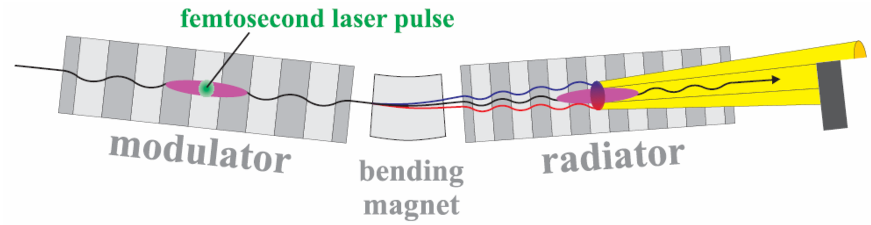
spatial or angular separation in a dispersive section

fs radiation pulses from a radiator



natural energy spread ~0.1%

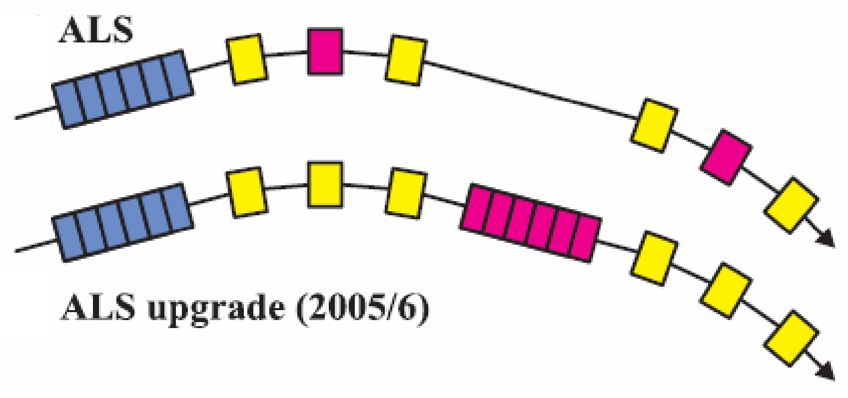
induced energy modulation ~1.0%

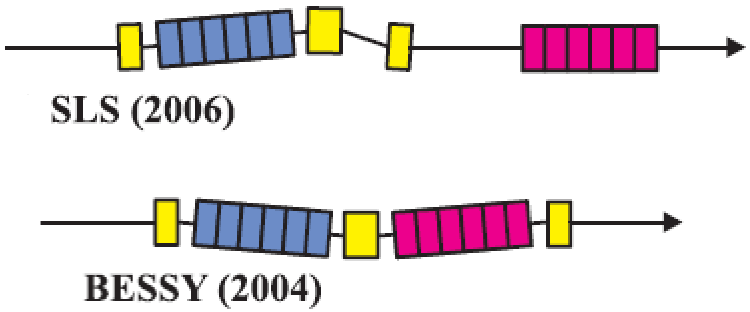


BESSY-II, ALS and SLS have successfully demonstrated the generation of X-ray pulses with few 100 fs pulse length, tunable and synchronised to an external laser for pump-probe experiments

Femto-slicing summary

	ALS	ALS upgrade	BESSY-II	SLS
Ph. energy	0.5 – 7 keV	0.2 – 10 keV	0.4-1.4 keV	5-8 keV
Ph/sec/0.1% BW	$3 \cdot 10^4$	$2 \cdot 10^6$	10^6	$4 \cdot 10^5$
Pulse length (fwhm)	140 fs	200 fs	100-150 fs	110-170 fs
Rep rate	1 kHz	20 kHz	1-2 kHz	2 kHz
Modulator	wiggler 16 cm	wiggler 11.4 cm	planar 13.9 cm	wiggler 13.8 cm
Radiator	Bending	In-vac U30; 5.5 mm gap	UE56;	In-vac U19; 5 mm gap
Laser	0.7 mJ; 50 fs	1.5 mJ; 100 fs	5 mJ; 70 fs;	5 mJ; 70 fs;
separation	H spatial	V spatial	angular	angular



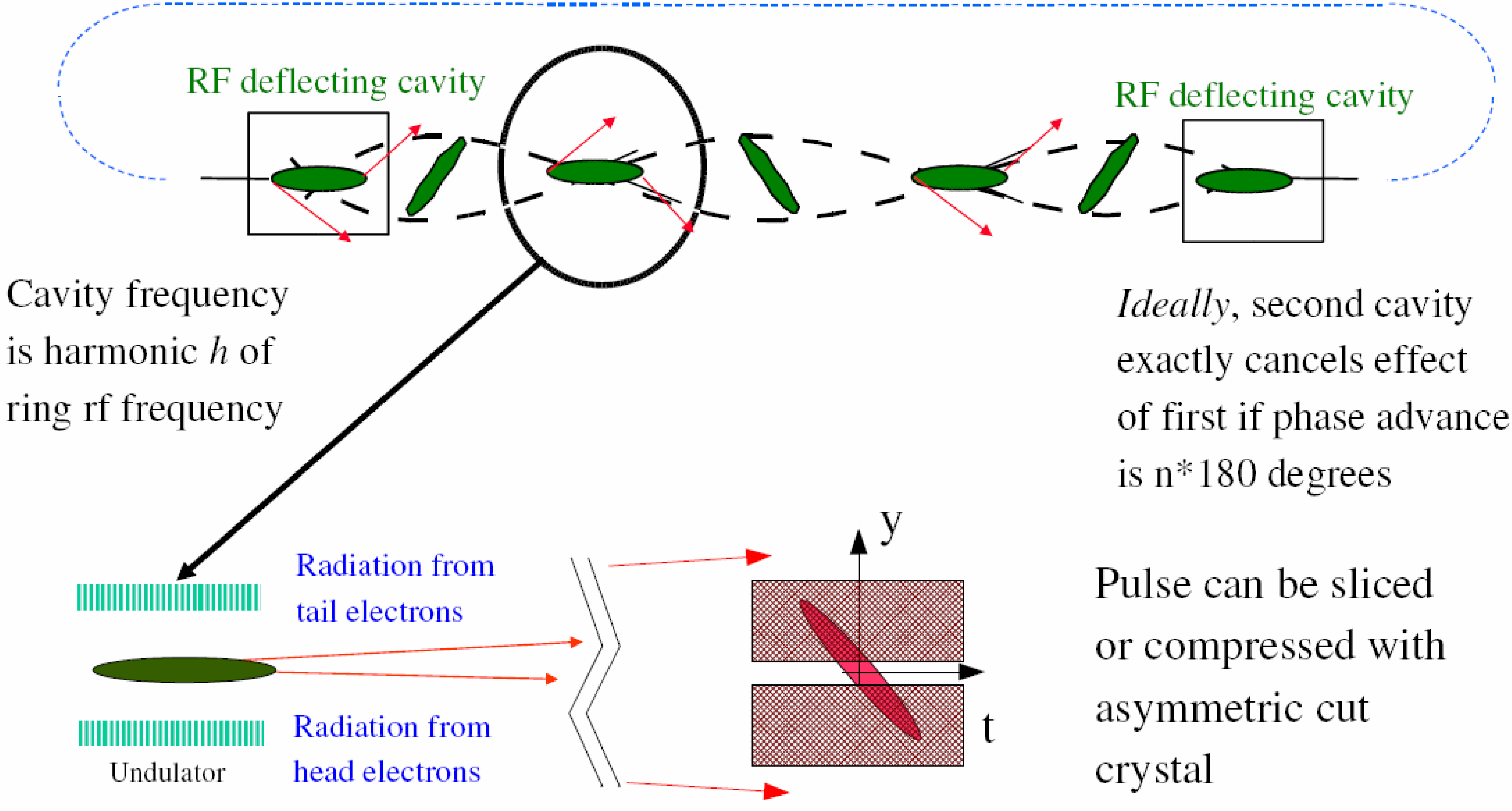


T. Quast (Bessy-II): MOPC046

Adapted from S. Khan (U. Hamburg)

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)

APS crab cavity predicted performance

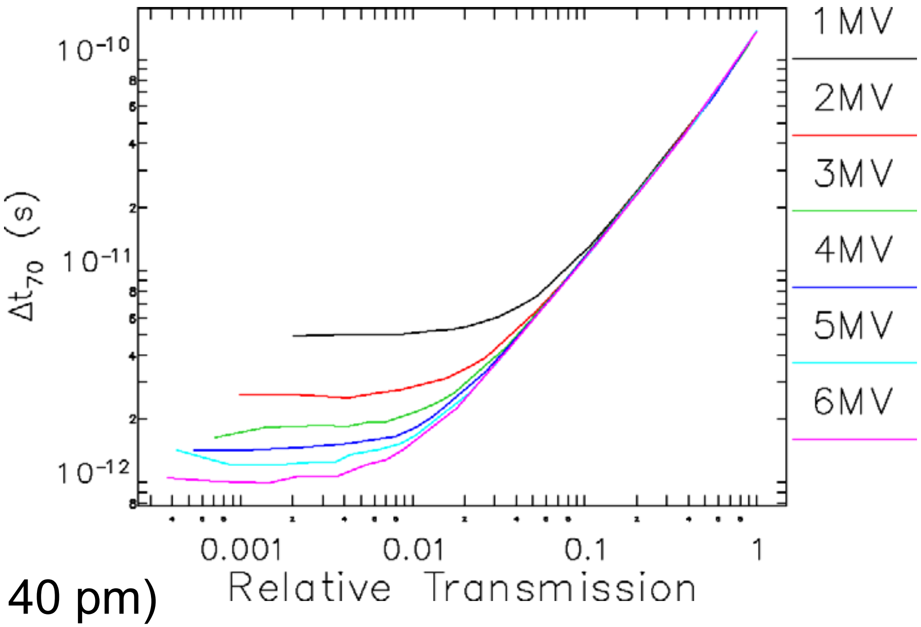
Several schemes based on Superconducting RF or Pulsed Normal conducting RF were investigated

The presently proposed scheme is based on a Superconducting RF option with

2815 Hz (8th harmonic of the main RF) 4 MV

The systems delivers

- x-ray pulses with lengths 1-2 ps FWHM
- Photon energies of 4 keV or greater
- photon energy tunability
- $10^4 – 10^6$ photon per pulse
- 1% of nominal intensity
- high repetition rate (many MHz)
- acceptable vertical emittance growth (20 > 40 pm)



R&D required to damp LOM and HOM in SC RF structures

Courtesy A. Nassiri (APS)

Comparison of options for short radiation pulses

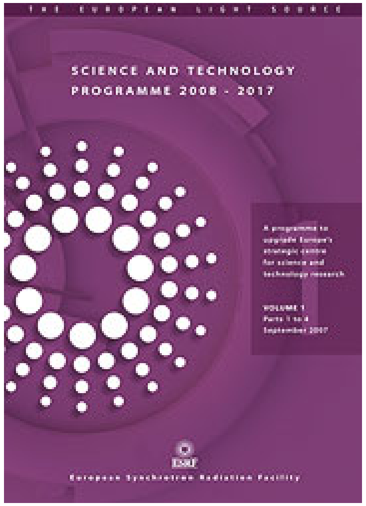
	Low-alpha	Crab cavity	femtoslicing
Pulse length	~1 ps	~1 ps	~100 fs
Photon flux	poor	good	very poor
synchronisation	no	no	yes
Hardware upgrade	easy	difficult	manageable
Compatibility with normal users operation	no	yes	yes
Rep rate	MHz	MHz	KHz

Trends and upgrades: ESRF

ESRF has already undergone a number of machine performance improvements since commissioning in 1992 with an emittance of 7 nm at 6 GeV

- Distributed dispersion → Emittance of 3.8 nm
- higher current (100 mA to 200 mA)
- Vertical beta tuned to 2.5 m in all ID straight to allow for small ID gap.
- One more family of chromatic sextupoles
- global FOFB

A new upgrade program is proposed for funding (“The purple Book”)



SCIENCE AND TECHNOLOGY
PROGRAMME 2008 - 2017

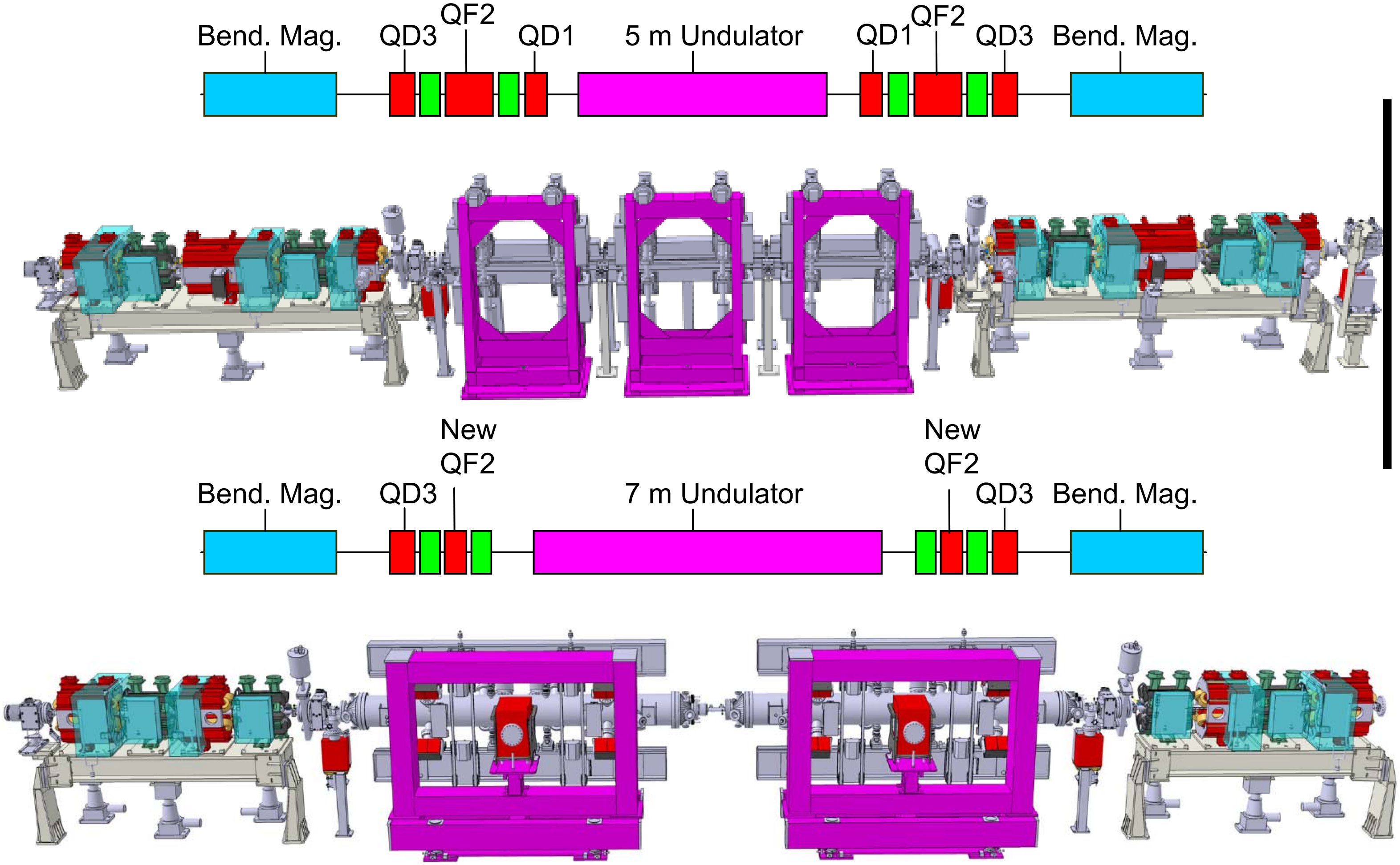
European Synchrotron Radiation Facility

- Lower vertical emittance (lower coupling)
- Longer straight sections (longer IDs or canted Ids)
- Higher current (from 200 mA to 300 mA)
- Top Up for 16 and 4 bunches modes
- Cryogenic Permanent Magnet undulators

New technology: BPMs, RF NC HOM free cavities..

P.Elleaume WEPC010: Upgrade of the ESRF Accelerator Complex

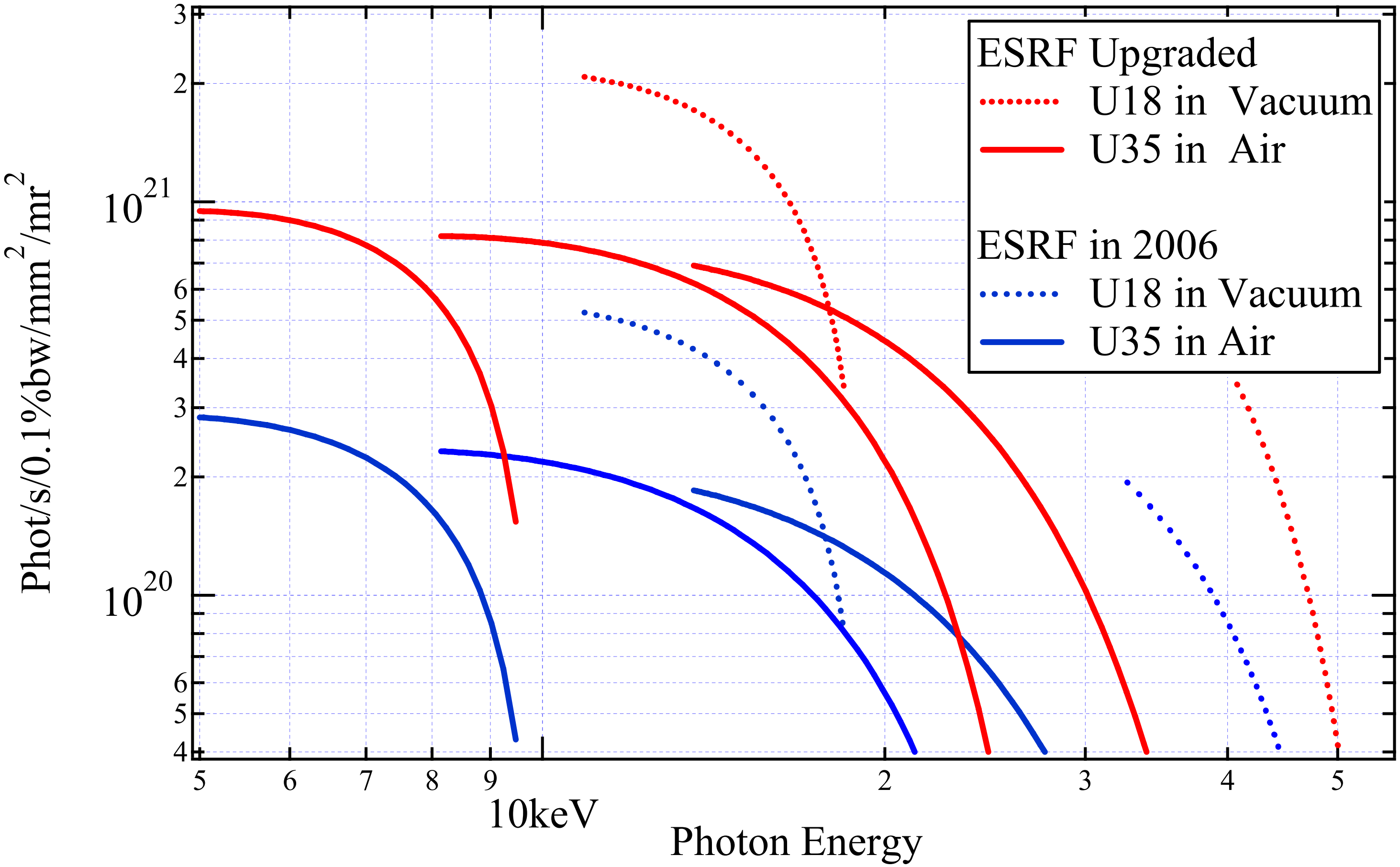
Trends and upgrades: ESRF



Longer straight section allow for longer IDs or canted schemes serving more beamlines

Trends and upgrades: ESRF

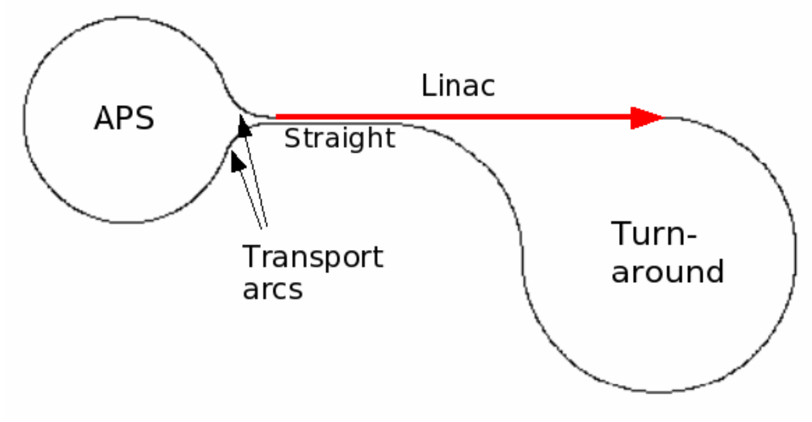
ESRF Increased brightness with longer IDs, lower coupling, higher current



Trends and upgrades: APS

APS upgrade since commissioning in 1995 with an emittance of 7.5 nm at 7 GeV

- Distributed dispersion → effective emittance of 3.1 nm (natural emittance 2.5 nm)
- FOFB (60 Hz BW)
- Top-Up
- Canted undulators



The current upgrade concepts include an ERL upgrade option

Intermediate upgrades options have been explored (not precluding the ERL option):

- Longer straight sections (longer IDs, customized optics, canted Ids)
- Higher current (from 100 mA to 200 mA)
- Short pulses programme with crab cavities,
- Increase BW of orbit feedback system to achieve sub-μm stability up to 200 Hz

Courtesy M. Borland, G. Decker (APS)

Trends and upgrades: Diamond and Soleil

Diamond since the start of user operation:

- FOFB run in user operation
- TMBF under commissioning
- Top-Up
- 300 mA for users
- low-alpha
- canted undulators, customised optics
- CMPU

Soleil since the start of user operation :

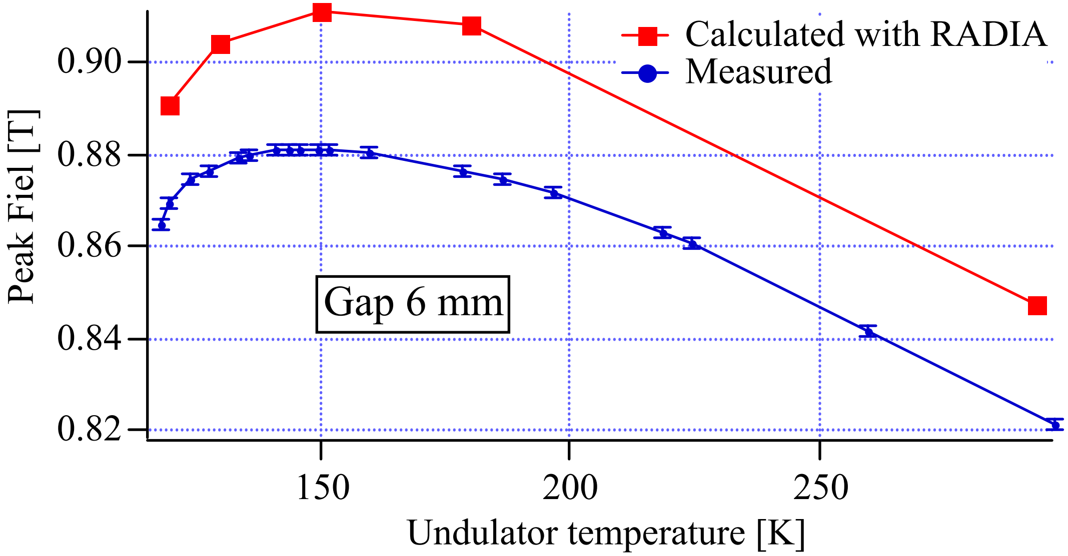
- TMBF run in user operation
- FOFB under commissioning
- Top-Up
- 500 mA for users; 100 mA in 8 bunches
- low-alpha first test started; femtoslicing considered
- new IDs, CPMU

J. M Filhol (SOLEIL): WEPC016

Technological developments

Insertion Devices

- EPU and APPLE-II
- Small gap in-vacuum ~5 mm
- Superconducting wigglers
- Cryogenic Permanent Magnets Undulator (ESRF, SOLEIL, Diamond)
- Superconducting undulators (ANKA)



Higher field allows higher flux on harmonics

Shorter undulators allow canted beamlines from the same straight

Better resistance to radiation

CMPU: J. Chavanne (ESRF): WEPC105, C. Benabderrahmane (SOLEIL) WEPC098
SC undulators: Rossmanith (ANKA) WEPC125

Technological developments

RF systems:

- Superconducting RF-system (CLS, TLS, SOLEIL, Diamond,…)
- Normal Conducting HOM damped structures (BESSY-II, ALBA, ESRF)
- HHC: SC @ Elettra, SLS, TLS; NC @ ALS, BESSY-II
- IOTs (Diamond, ALBA, Elettra), Solid State Amplifiers (Soleil)

BPMs:

- Digital BPM electronics: simultaneous t-b-t, fast orbit feedback data, slow orbit data (Diamond, SOLEIL, ELETTRA, ASP, ALBA, …)
- sub-μm resolution (few μm in turn-by-turn mode)

Power Supplies:

- Digital Power Supply controllers (SLS, Diamond, SSRF, Elettra, PLS)

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.