Challenges related to the design, commissioning and operation of 3rd generation light sources

Amor NADJI

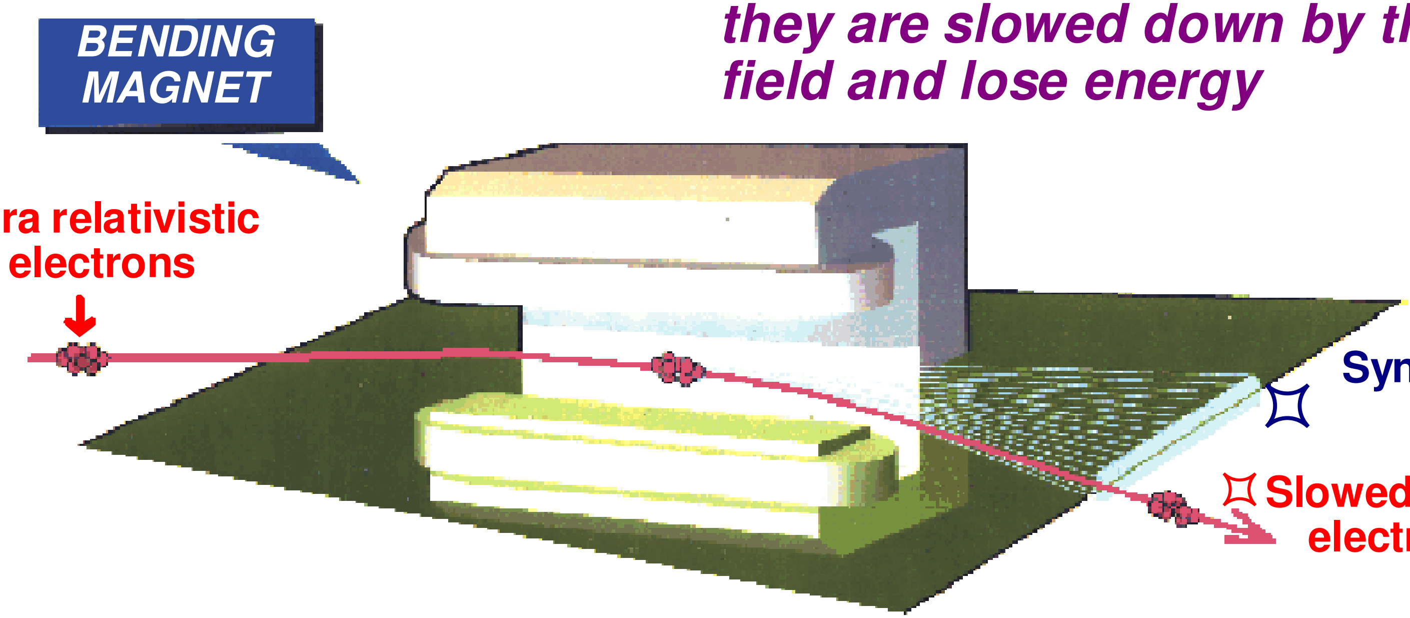
Synchrotron SOLEIL

Content

What is Synchrotron Radiation?

Ultra relativistic electrons can be deviated
by the constant magnetic field of bending magnets
in which their trajectory is an arc of circle

Due to the bending of their trajectory,
they are slowed down by their self
field and lose energy



Ultra relativistic electrons

⌑ Synchrotron Light

⌑ Slowed down electrons

They emit photons in
a direction tangent to their trajectory
This is synchrotron radiation

Such conditions are met in electron Storage Rings

Why Relativistic Electrons ?

- The Radiated Power :

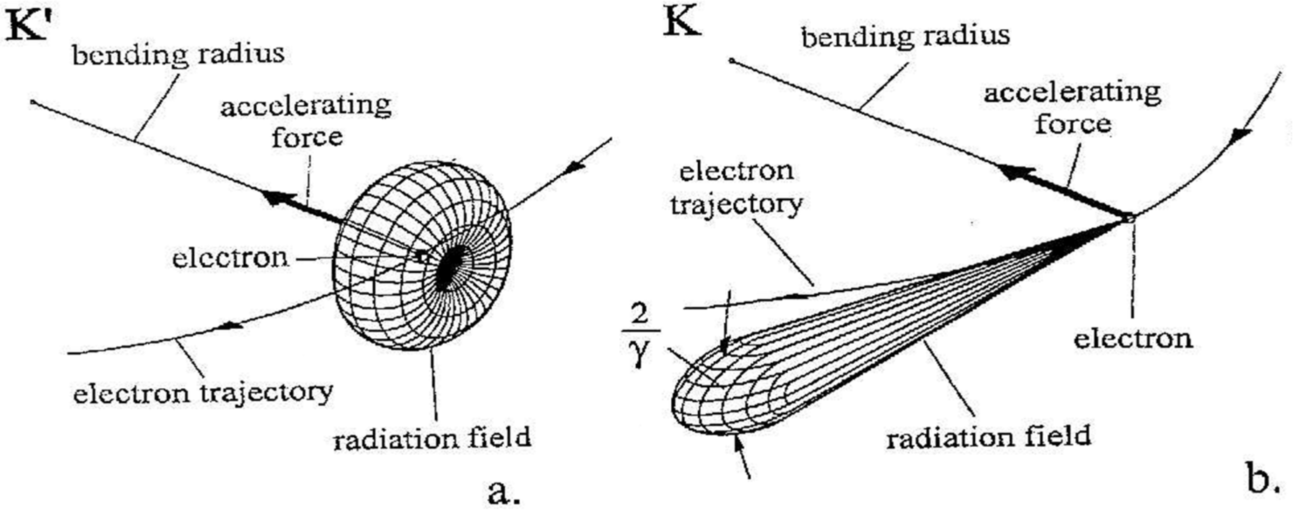
$$\boxed{P_{rad} = \frac{e^2 c}{6\pi\varepsilon_0 \left(m_0 c^2\right)^4} \frac{E^4}{\rho^2}}$$

- Compare the radiation power from an electron ($m_e c^2$ = 0.511 MeV) and from a proton ($m_p c^2$ = 939.19 MeV) with the same energy :

$$\boxed{\frac{P_{rad,e}}{P_{rad,p}} = \left(\frac{m_p c^2}{m_e c^2}\right)^4 = 1.13 \cdot 10^{13}}$$

Why Relativistic Electrons?

The axially-symmetric radiation distribution in the moving frame K' (a.) transforms into a sharply forward peaked distribution in the laboratory frame (b.), with a half opening-angle $\theta=1/\gamma$.



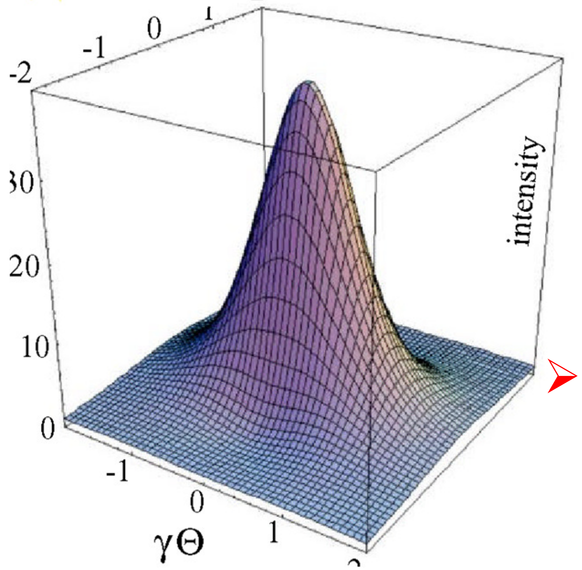
Emission angle

(in the laboratory frame)

$$\tan\theta = \frac{p_y}{p_z} = \frac{p_0'}{\gamma\beta p_0'} \approx \frac{1}{\gamma}$$

This is one of the most useful features of synchrotron radiation.

Some Properties of Synchrotron Radiation

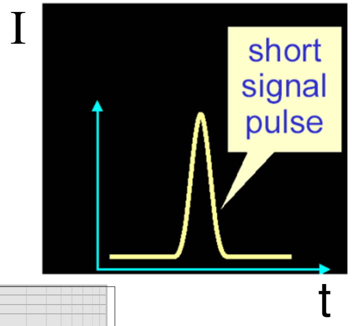


- **narrow cone :**

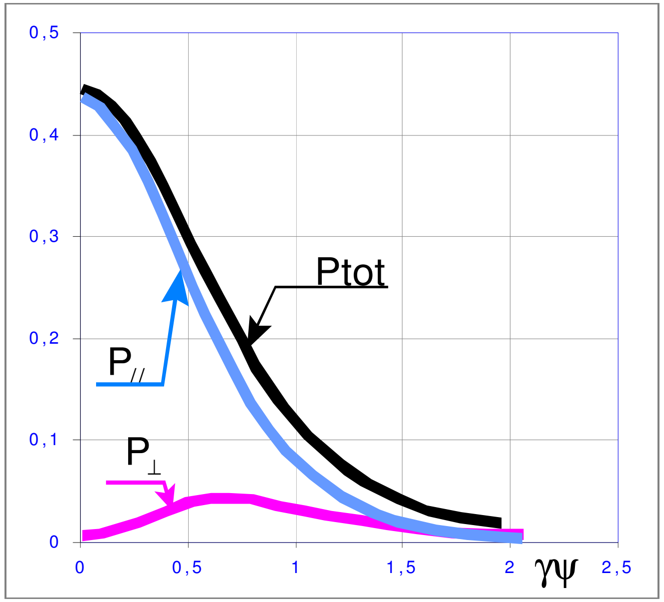
$$\theta_{rms} = \frac{mc^2}{E} = \frac{1}{\gamma}$$

SOLEIL :
E = 2.75 GeV
$\gamma = 5382$
θ_{rms} = 0.186 mrad (0.01°)

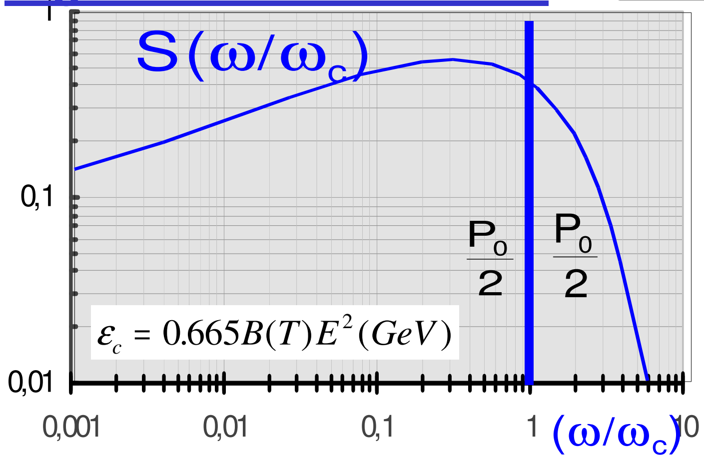
- **pulsed Time Structure**



- **polarisation :**



- **a broad spectrum**
- **High flux and brilliance:**



$$F(\xi,\psi) = \frac{\xi^2}{(1+\gamma^2\psi^2)}\left[K_{2/3}^2(\xi) + \frac{\gamma^2\psi^2}{(1+\gamma^2\psi^2)}K_{1/3}^2(\xi)\right]$$

The σ-mode polarization

The π-mode polarization

Fields of Application

PLURIDISCIPLINARITY

Life Science

21%

Chemistry

15.5%

Cultural Heritage

Earth and Universe Science

15%

Condensed Matter Physics

26%

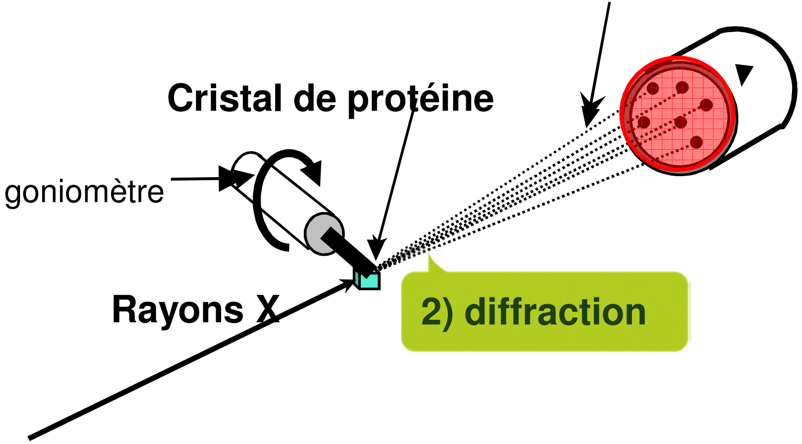
Dilute Matter Studies

15,5%

Industrial applications

Up to 10% of beamtime

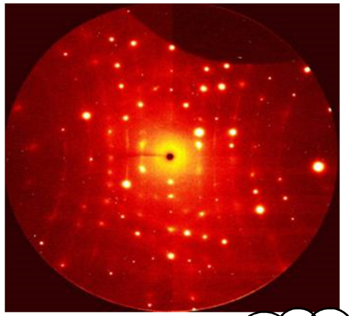
1) Frozen cristal



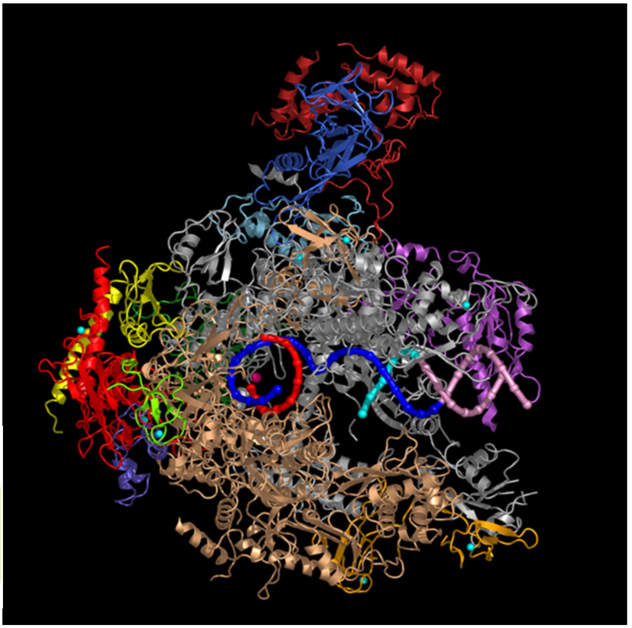
Synchrotron radiation
18-25 keV

2) diffraction

3) Laue patterns recording



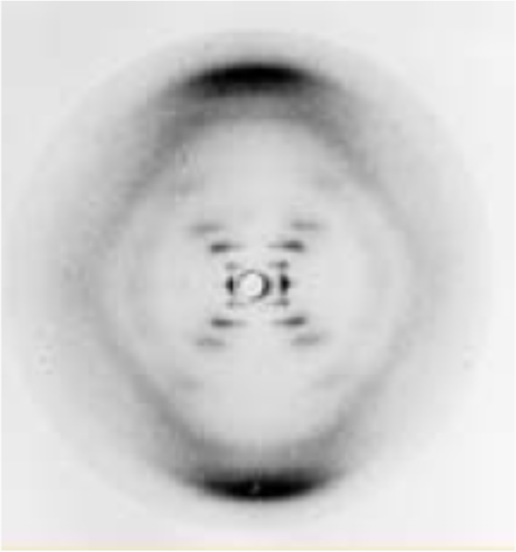
4) Data processing



5) Protein Structure

Millions of atoms !

Life science examples: DNA and myoglobin



Franklin and Gosling used a X-ray tube:

Brightness was 10^8 (ph/sec/mm^2/mrad^2/0.1BW)

Exposure times of 1 day were typical (10^5 sec)

e.g. Diamond provides a brightness of 10^{20}

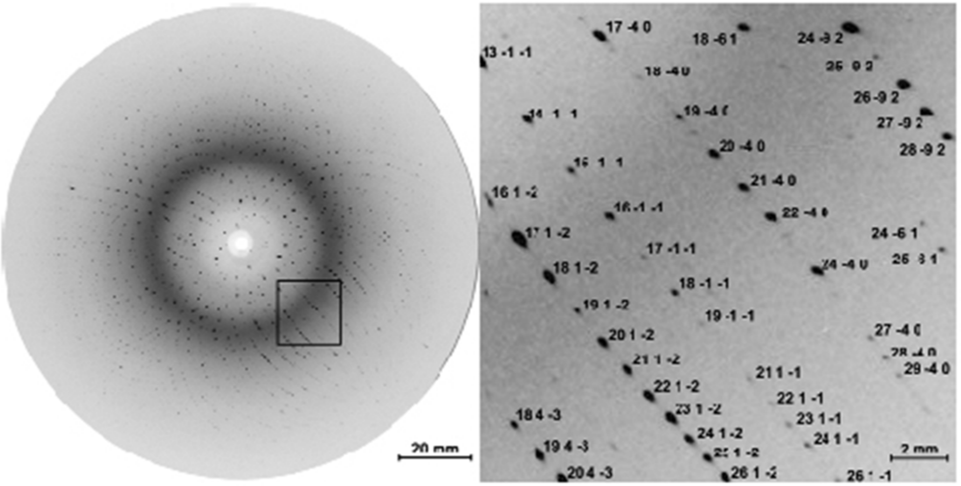
100 ns exposure would be sufficient

Nowadays pump probe experiment in life science are performed using 100 ps pulses from storage ring light sources: e.g. ESRF myoglobin in action

Photograph 51
Franklin-Gosling

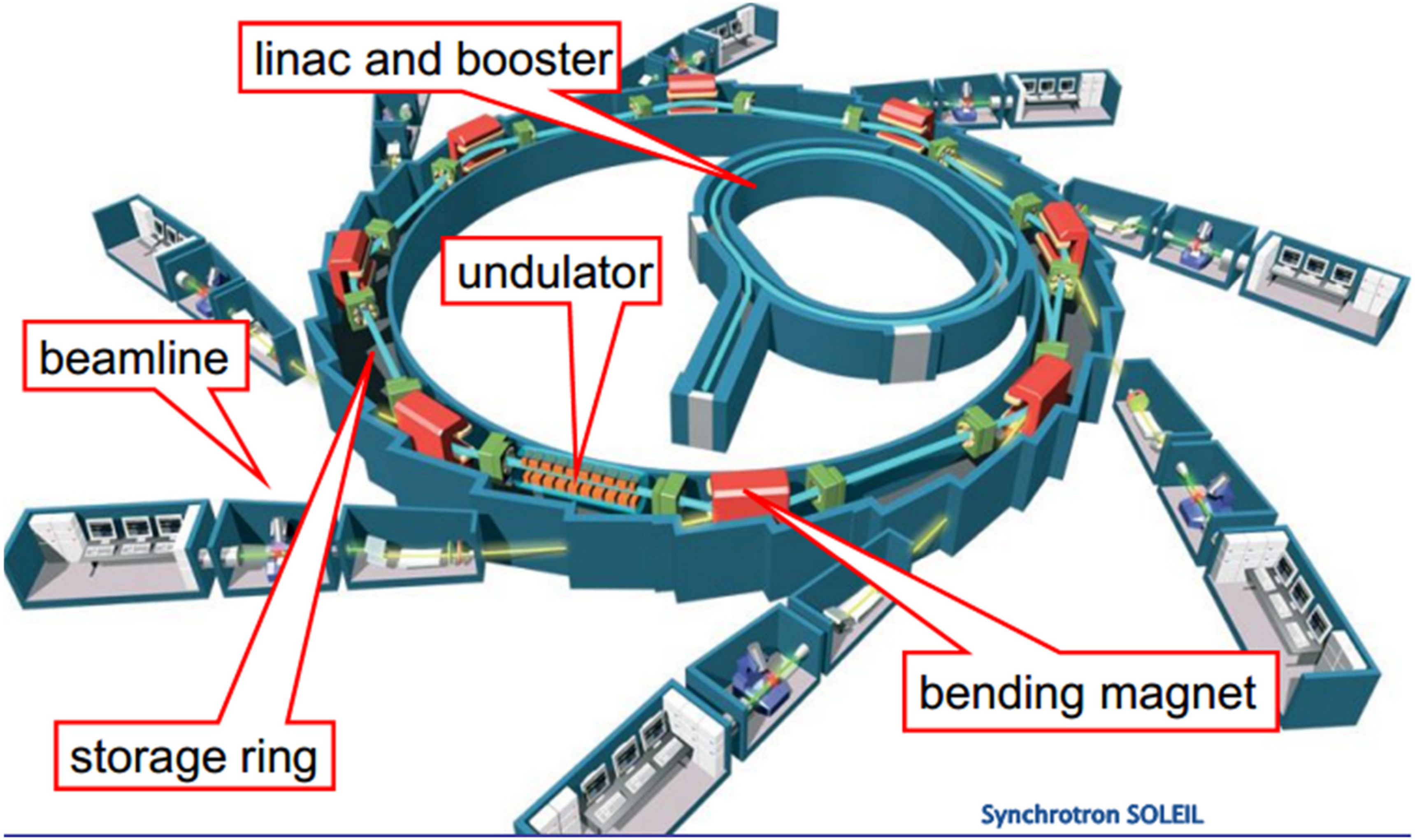
DNA (form B)

1952



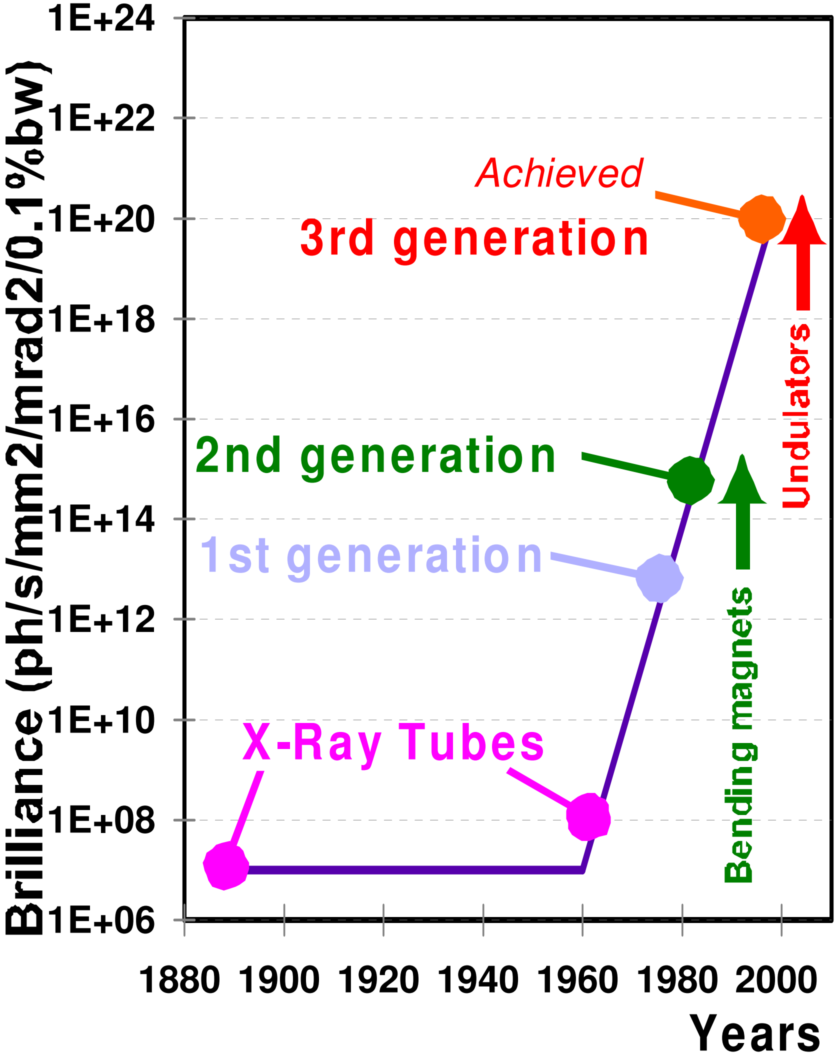
(Courtesy of R. Bartolini))

Synchrotron radiation facility



All beamlines get beam simultaneously

The successive generation of storage ring based sources



1st generation

exploitation of the light from the bending magnets of e+/e- colliders originally built for elementary particle physics

2nd generation

exploitation of the light from the bending magnets and a few insertion devices at a later stage of dedicated storage rings
! lower e beam emittances and
! better optimisation of light extraction
gain of about 1 000

3rd generation

brilliance is the figure of merit
rings designed for very low emittances
priority to undulators
large number of straight sections
gain of about 10 000
moderate gain of about 100 on bending magnet light

Existing 3rd Generation 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	3.5 GeV
2009	**PETRAIII, Germany**	6.0 GeV
2010	**ALBA, Spain**	3.0 GeV

3rd GLS under construction or planned

Under construction

2014	**NSLS-II**, US	3 GeV
2015	**SOLARIS**, Poland	1.5 GeV
2015	**TPS**, Taiwan	3 GeV
2016	**SESAME**, Jordan	2.5 GeV
2016	**MAX-IV**, Sweden	3 GeV

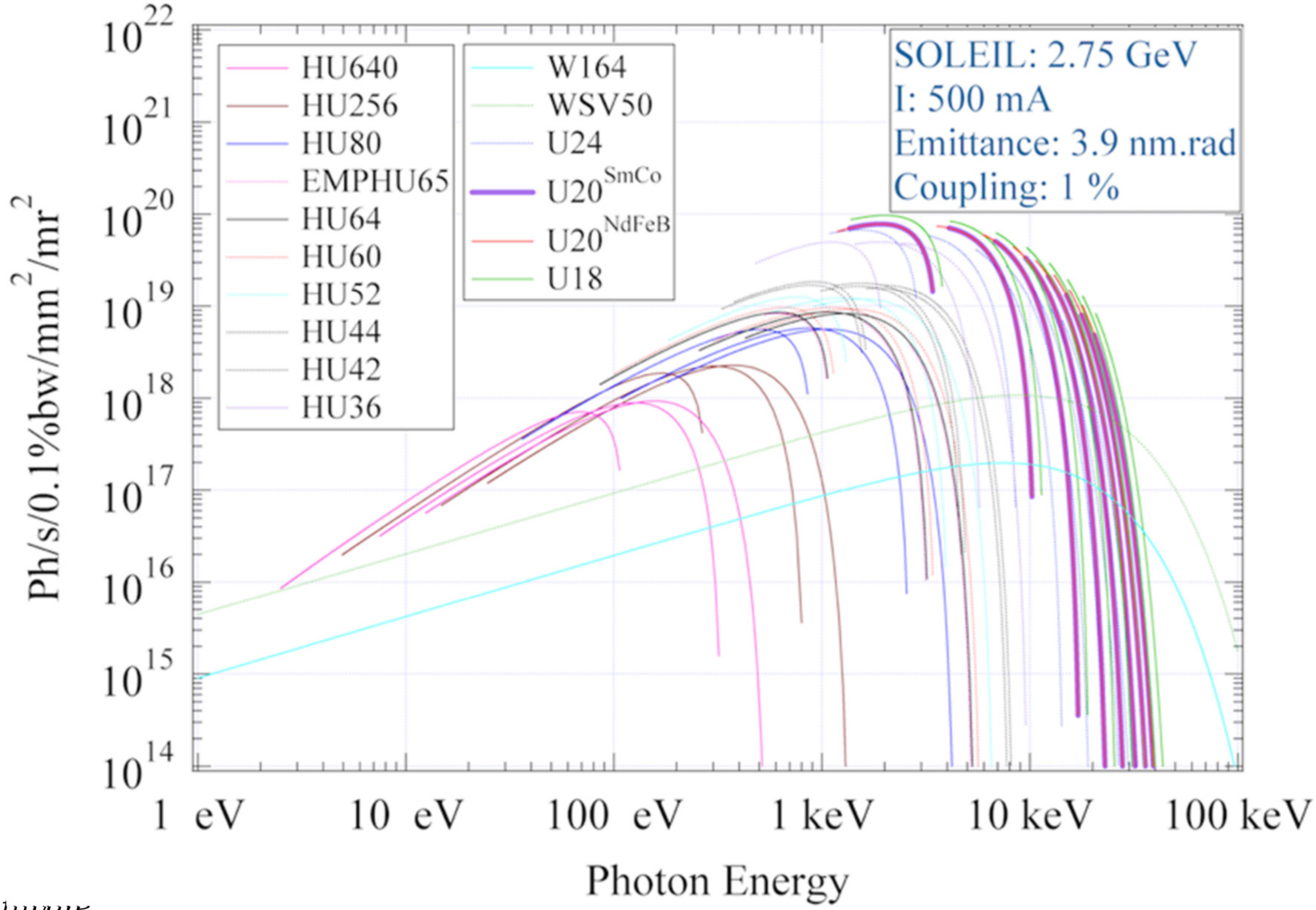
Planned

CANDLE, Armenia	3 GeV
SIRIUS, Brazil	3 GeV

3^{rd} generation Synchrotron light sources

- **Machines optimised for High Brilliance**
- Smaller source sizes, higher current
- Highly performing **insertion devices** matched to the beamline needs
- Beamlines much more accurate (specific scientific use).

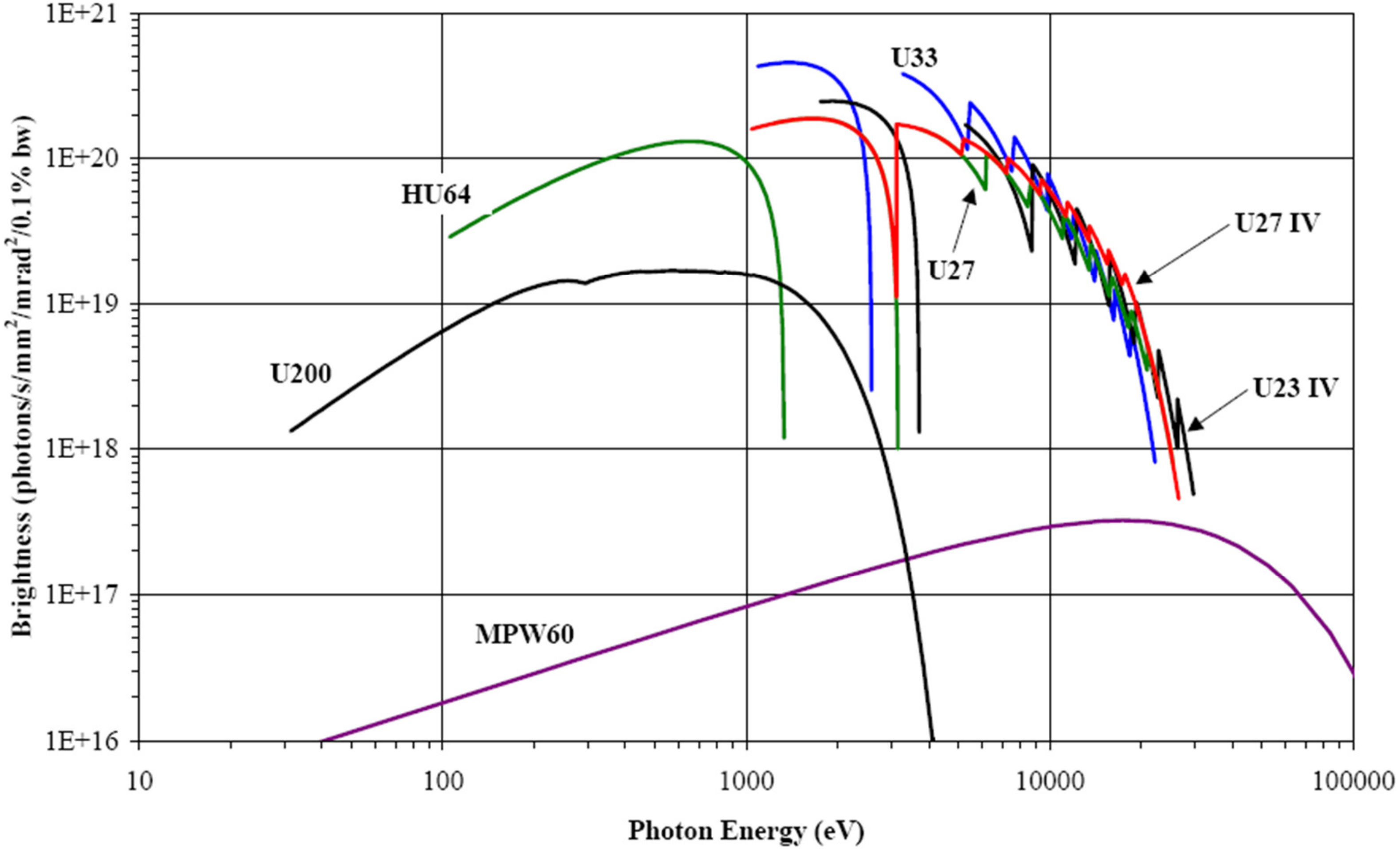
Photon Brilliance at SOLEIL



SOLEIL: 2.75 GeV
I: 500 mA
Emittance: 3.9 nm.rad
Coupling: 1 %

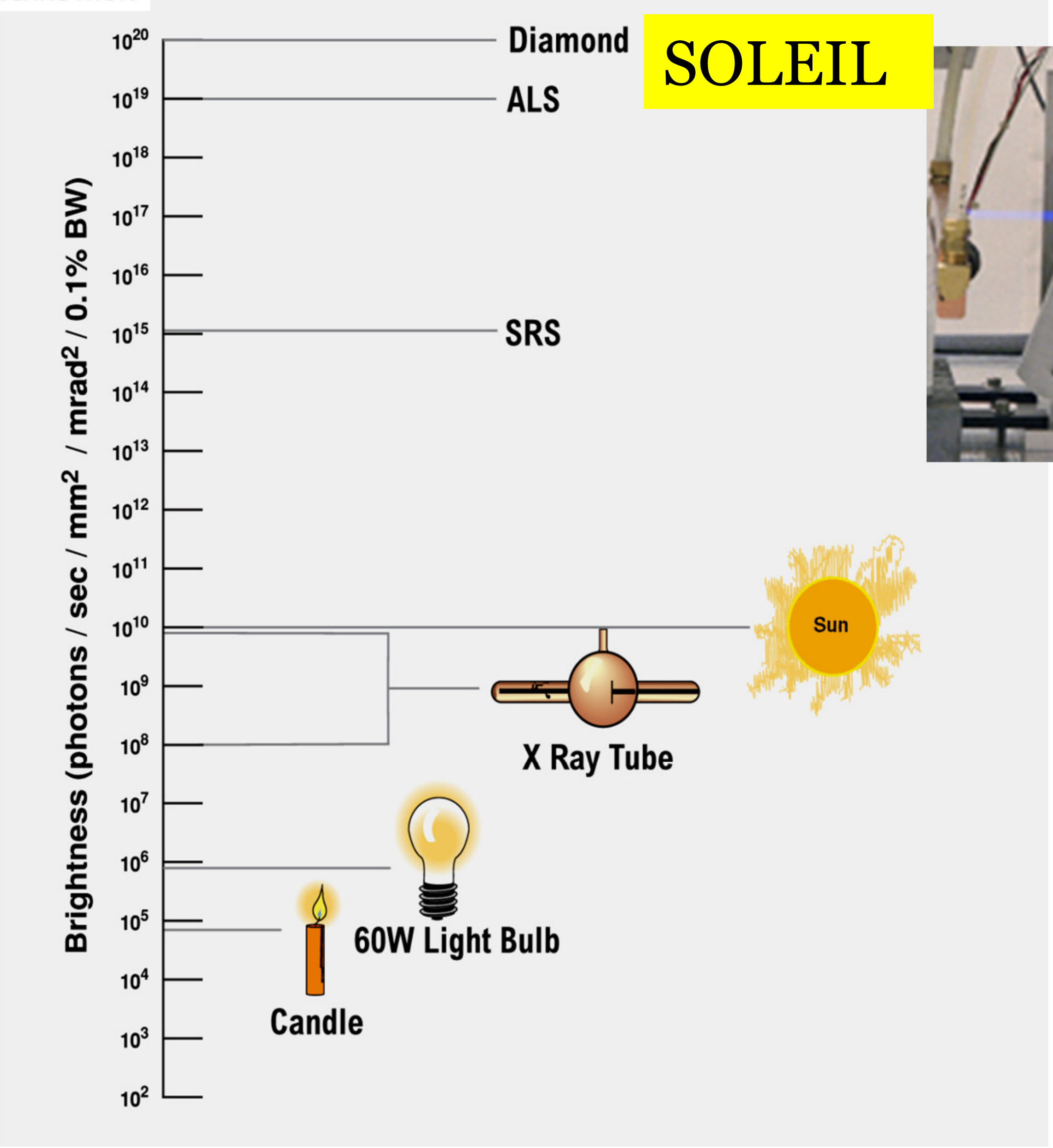
SRW software

Photon Brilliance at Diamond

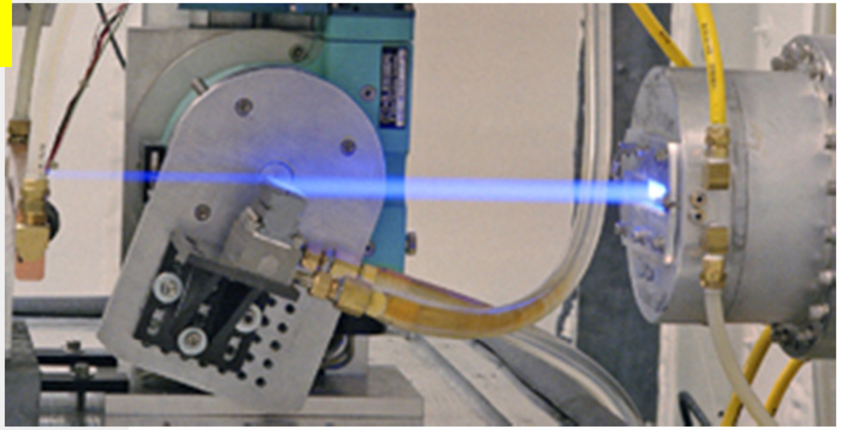


(Courtesy of R. Bartolini))

Brilliance



SOLEIL



High Brilliance

- A parameter of prime importance in experiments with **synchrotron radiation** sources is the spectral **brilliance** (brightness) defined as :

$$\boxed{B = \frac{dN_{ph}}{dA\, d\Omega\, dt\, d\lambda / \lambda}} \qquad \frac{photons\ per\ second}{mm^2\, mrad^2\, 0.1\%b.w}$$

- High intensity, small beam cross section, good focusing of photon beam and high monochromaticity are looked for in order to maximize the photon flux.

- Apart from *diffraction effects*, we have : $\boxed{dA\, d\Omega \approx \varepsilon_x \varepsilon_z}$

ε_x and ε_z are the transverse beam emittances, which are the areas occupied by the beam in horizontal (x,x') and vertical (z,z') phase planes.

HIGH PHOTON BEAM BRILLIANCE ⇨ **LOW** ELECTRON BEAM EMITTANCE and **HIGH** electron beam current.

Horizontal Emittance

Generation of emittance by radiation

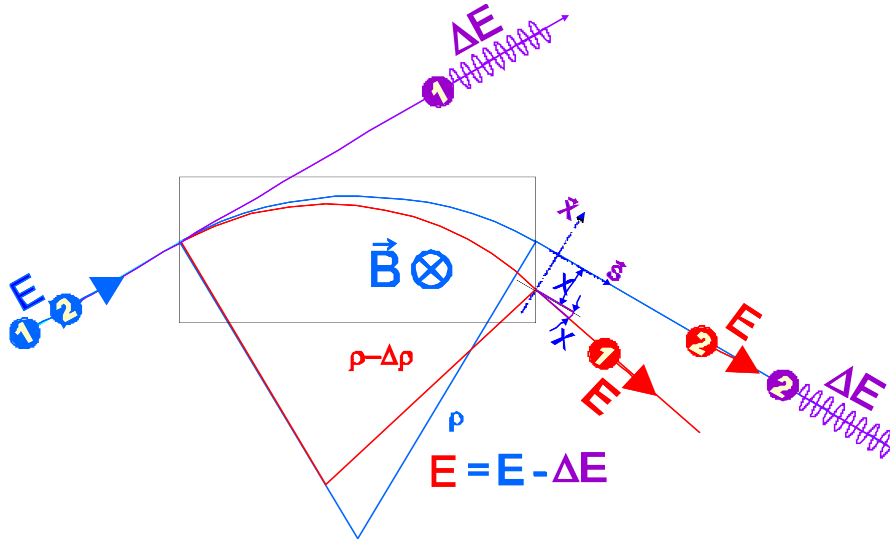
Two e^- with same E and same trajectory at the entrance of the bending magnet (they cannot be distinguished : no e- beam size)

They both radiate ΔE and exit with E-ΔE

1 emits ΔE at the origin, smaller ρ

2 emits ΔE but at the end

They follow different trajectories

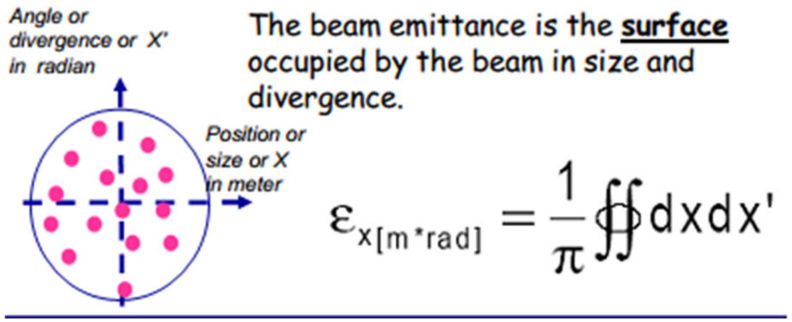


$$dx(s) = \eta(s)\frac{\Delta E}{E} \qquad dx'(s) = \eta'(s)\frac{\Delta E}{E}$$

With η(s) and η'(s) the dispersion function and its derivative

Due to the random aspects of the emission (location, energy), the different electrons exit the bending magnet with different trajectories and different energies. The beam is heated up by the radiation :

⇒ increase of H beam size, H beam divergence and energy spread.

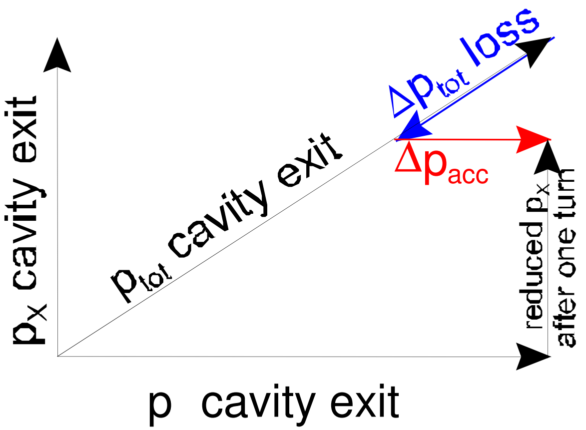


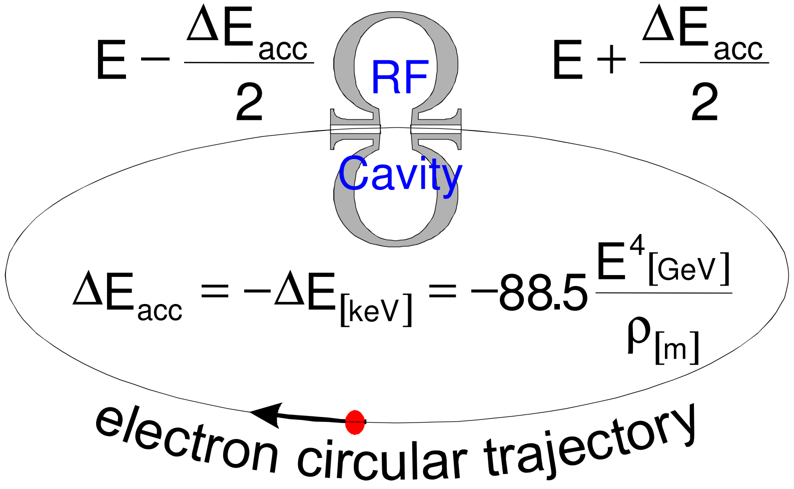
The beam emittance is the <u>surface</u> occupied by the beam in size and divergence.

$$\varepsilon_{x[m*rad]} = \frac{1}{\pi}\iint dx\,dx'$$

Horizontal Emittance

Damping by the RF





$$E - \frac{\Delta E_{acc}}{2} \qquad E + \frac{\Delta E_{acc}}{2}$$

$$\Delta E_{acc} = -\Delta E_{[keV]} = -88.5 \frac{E^4{}_{[GeV]}}{\rho_{[m]}}$$

The heating in the H plane induced by radiation in every bending magnets would lead to a continuous blow up of the H emittance.

However, the restoring of the lost energy by the RF cavity cool down the transverse oscillations in the H plane

The damping time is about the time it would require for the electron to lose its full energy. $\tau \sim E/U_{0.}$ **Memory of initial conditions is totally lost when the RF has restored the total energy of the electron.** ⇨ **Emittance independent of injection conditions**

Equilibrium Beam Emittance

- The natural horizontal emittance for an isomagnetic ring i.e. all bending magnets having same bending radius is :

$$\varepsilon_x = \frac{C_q \gamma^2 \langle H \rangle_{dipole}}{J_x \rho}$$

J_x the horizontal damping partition number.

$J_x \sim 1$ (zero field gradient in bending magnet)
$J_x < 2$ (vertical focusing in bending magnet) :
(potentially) emittance reduction of a factor two

$C_q = 3.83 \times 10^{-13}$ m and γ is the Lorentz factor.
ρ is the bending radius.

H is the so called lattice invariant or dispersion's emittance or H-function

$$H(s) = \gamma_x(s)\eta^2(s) + 2\alpha_x(s)\eta(s)\eta'(s) + \beta_x(s)\eta'^2(s)$$

$\langle \ldots \rangle$ average taken only in the part of the circumference where photons are emitted, (BM and IDs)

- In practical units, ε_x is given by :

$$\varepsilon_x[nm.rad] = 1470\, E[GeV]^2 \frac{\langle H \rangle_{dipole}}{\rho J_x}$$

ε_x is completely determined by the energy, bending field and lattice functions.

Equilibrium Beam Emittance

- After calculation of the <H> value, the natural horizontal emittance for an isomagnetic ring i.e. all bending magnets having same bending radius can be expressed as :

$$\boxed{\varepsilon_x = F\frac{C_q\gamma^2\theta_b^3}{J_x}}$$

J_x the horizontal damping partition number.
θ deviation angle of one bending magnet
ρ bending radius
l_b bending magnet length
N number of bending magnets

$C_q = 3.83 \times 10^{-13}$ m and γ is the Lorentz factor.

$$F = \frac{1}{3}\left[\frac{\beta_0}{l_b} - \frac{1}{4}\alpha_0 + \frac{1}{20}\gamma_0 l_b\right]$$

$\beta_0,\alpha_0,\gamma_0$ twiss parameters at the entry of the BM

It is a general lattice property, <u>there is no assumption on the lattice type</u>.

$$\boxed{\varepsilon_x \propto \frac{1}{N_b^3}}$$

⇒ Should use **many short Bending Magnets** to get **low emittance**

Minimum Emittance (with Achromatic Condition)

The minimum equilibrium beam emittance in an isomagnetic ring with an Achromatic Arc Condition, $\eta_0 = \eta'_0 = 0$, at the entrance of the **BM** :

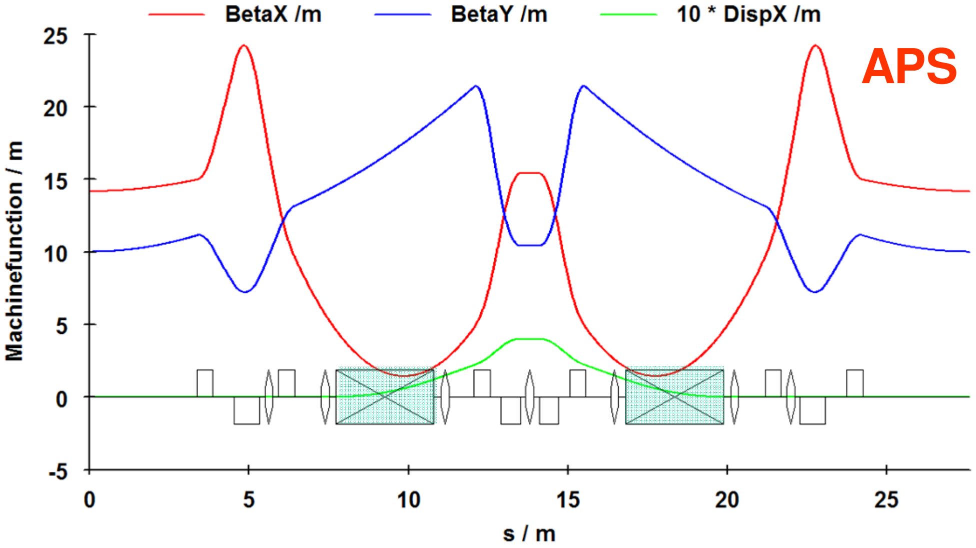
$$\boxed{\varepsilon_{x,\min} = \frac{C_q \gamma^2 \Theta^3}{4\sqrt{15}\, J_x}}$$

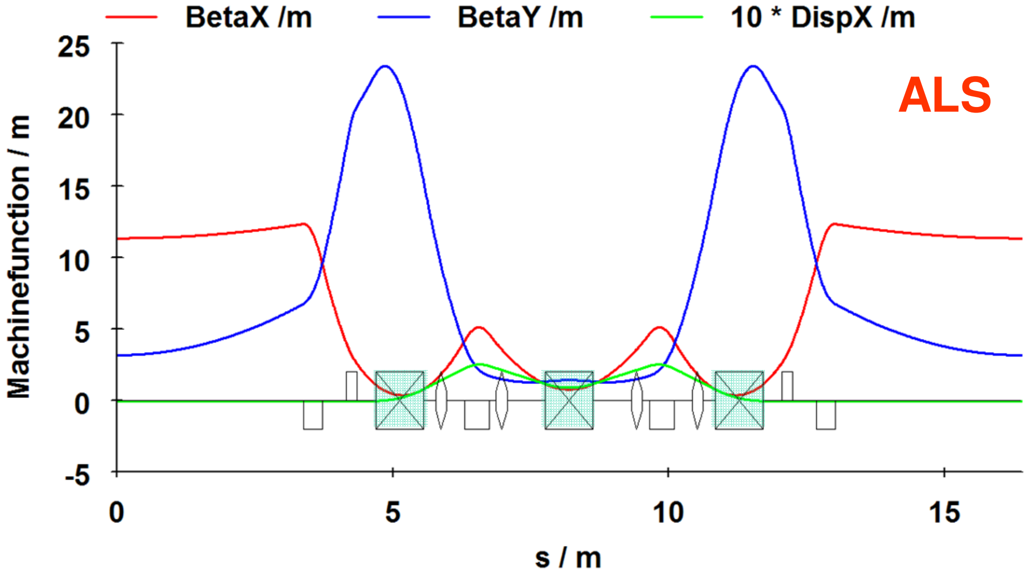
⇒DBA or TBA lattices

(Double/Triple Bend Achromat)

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

TBA used at:
ALS, SLS,
PLS,TLS
…

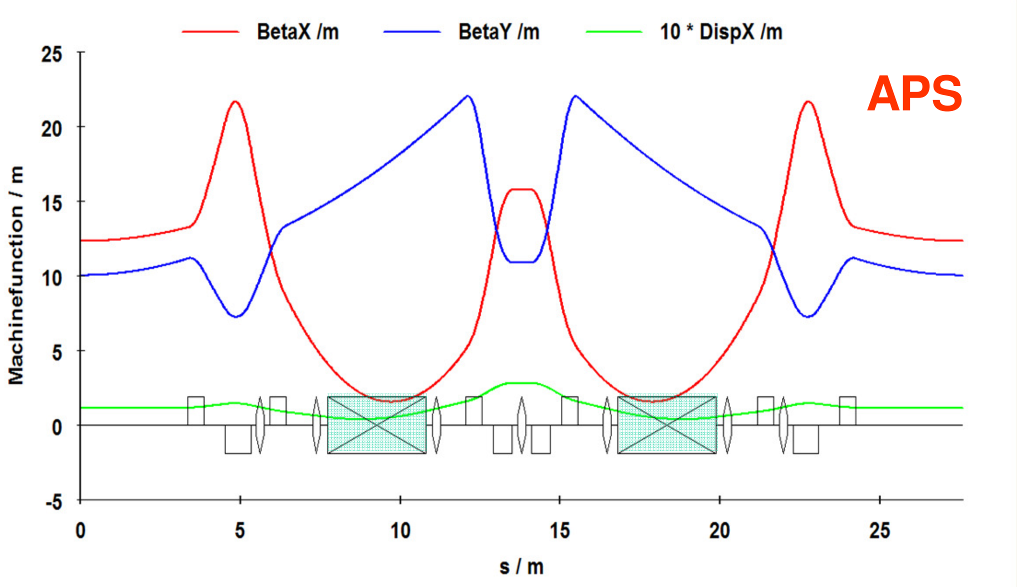




Minimum Emittance (without Achromatic Condition)

By breaking the achromatic condition (non-zero dispersion in straight sections) we can obtain the configuration in which the emittance becomes the smallest.

$$\varepsilon_{x,\min} = \frac{C_q \gamma^2 \Theta^3}{12\sqrt{15}\, J_x}$$



⇒It is smaller **by a factor 3** than in the achromatic arc configuration

Example of Machines which move from Achromatic conditions to non zero dispersion in SS

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

Emittance Achieved

The minimum emittance can't be easily achieved :

Ideal values for SOLEIL and Design values (without achromatic condition) :

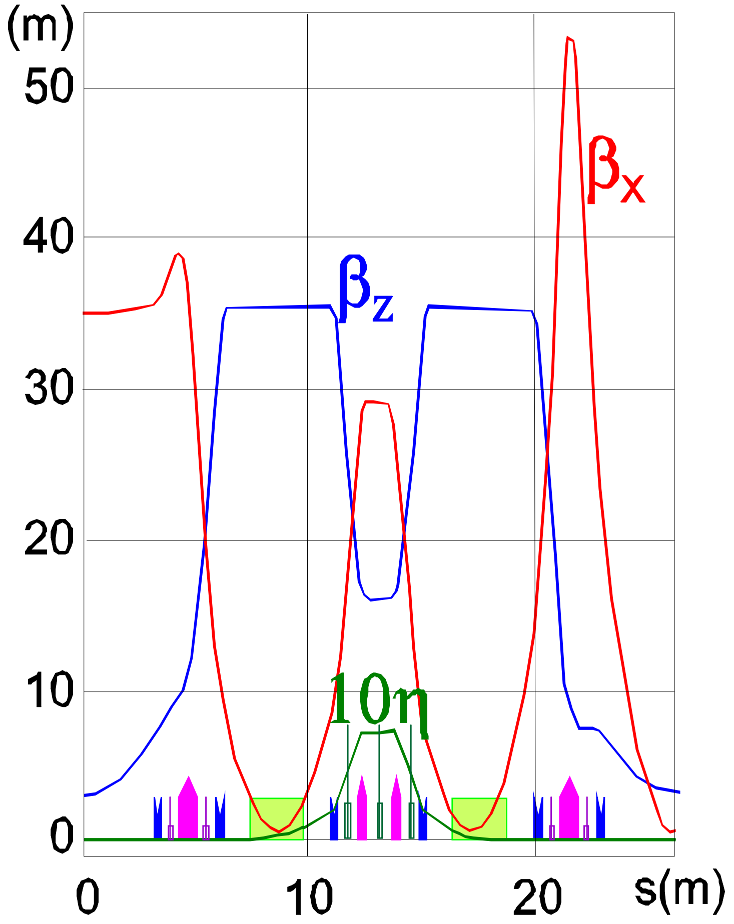
$$\alpha_{0,min} = \sqrt{15} = 3.873 \qquad \alpha_0 = 1.8$$

$$\beta_{0,min} = 2.17 m \qquad \beta_0 = 1.5\, m$$

$$\varepsilon_{x0,min} = 1.8\, nm.rad \qquad \varepsilon_{x0} = 3.7\, nm.rad$$

The ideal value $\alpha_{0,min} = \sqrt{15}$

causes the betatron function to reach a sharp minimum inside the **BM** and then to increase from there on to large values in the quadrupoles, leading to extremely high <u>**chromaticity.**</u>



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Emittance achieved

⇒ Chromaticity has to be corrected for two reasons :

Momentum acceptance : some variation of energy deviation has to be accepted by the storage ring for reasons of **beam lifetime.**

Head tail instability: collective oscillation of electrons in head and tail of the bunch leading to very fast beam loss. ⟹ damped by operating with positive chromaticity

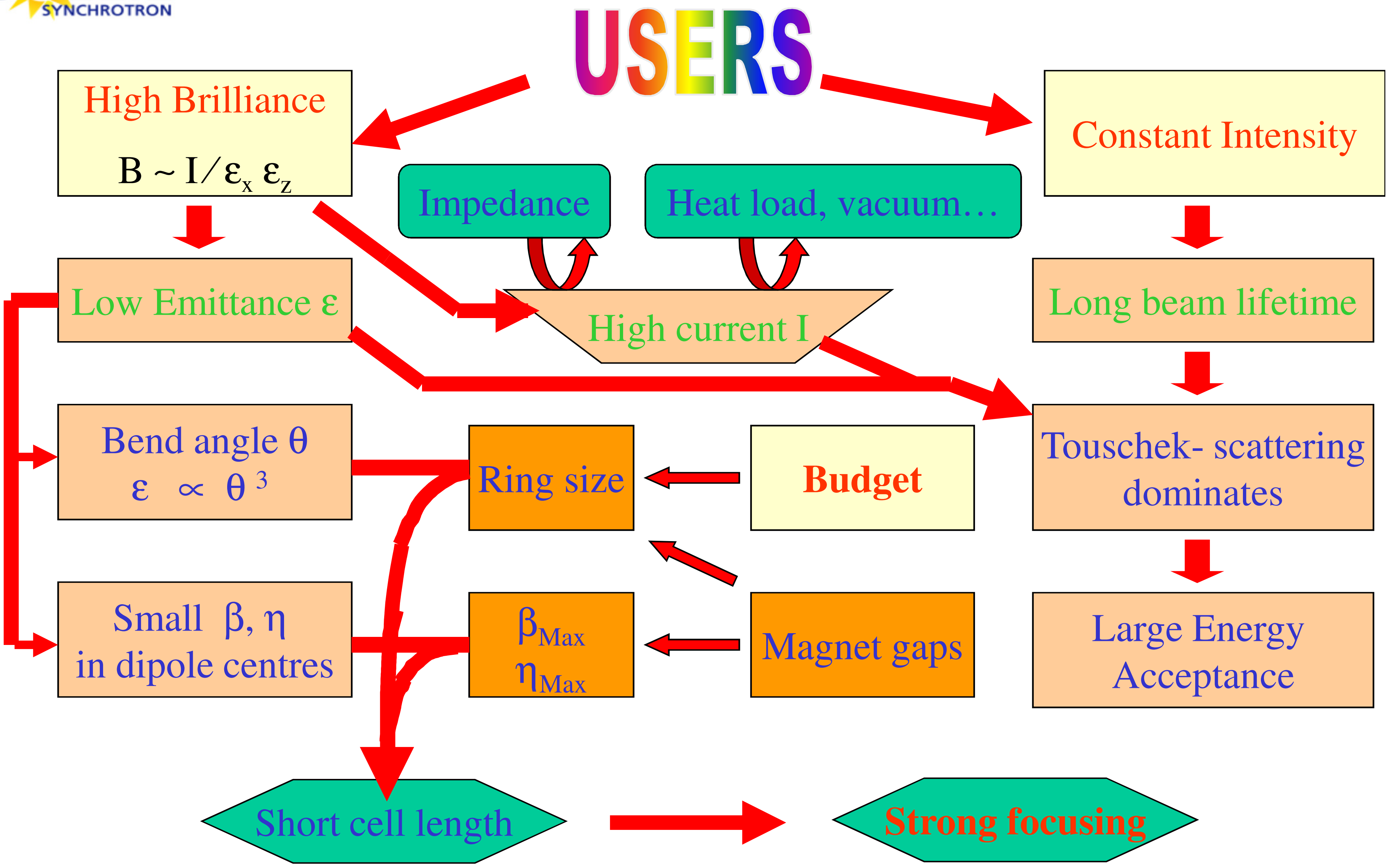
Chromaticity : $\xi \sim \int (- K_Q \beta + m_s \beta \eta) \, ds \geq 0$

quadrupole strength (introduce negative ξ)

sextupole strength (correct the ξ)

Strong chromaticity correction sextupoles reduce the dynamic aperture and this negatively impacts on the beam lifetime.

→ additional sextupoles are required to correct nonlinear aberrations



USERS

High Brilliance

$B \sim I/\varepsilon_x \varepsilon_z$

Impedance

Heat load, vacuum…

Constant Intensity

Low Emittance ε

High current I

Long beam lifetime

Bend angle θ

$\varepsilon \propto \theta^3$

Ring size

Budget

Touschek- scattering dominates

Small β, η in dipole centres

β_{Max}

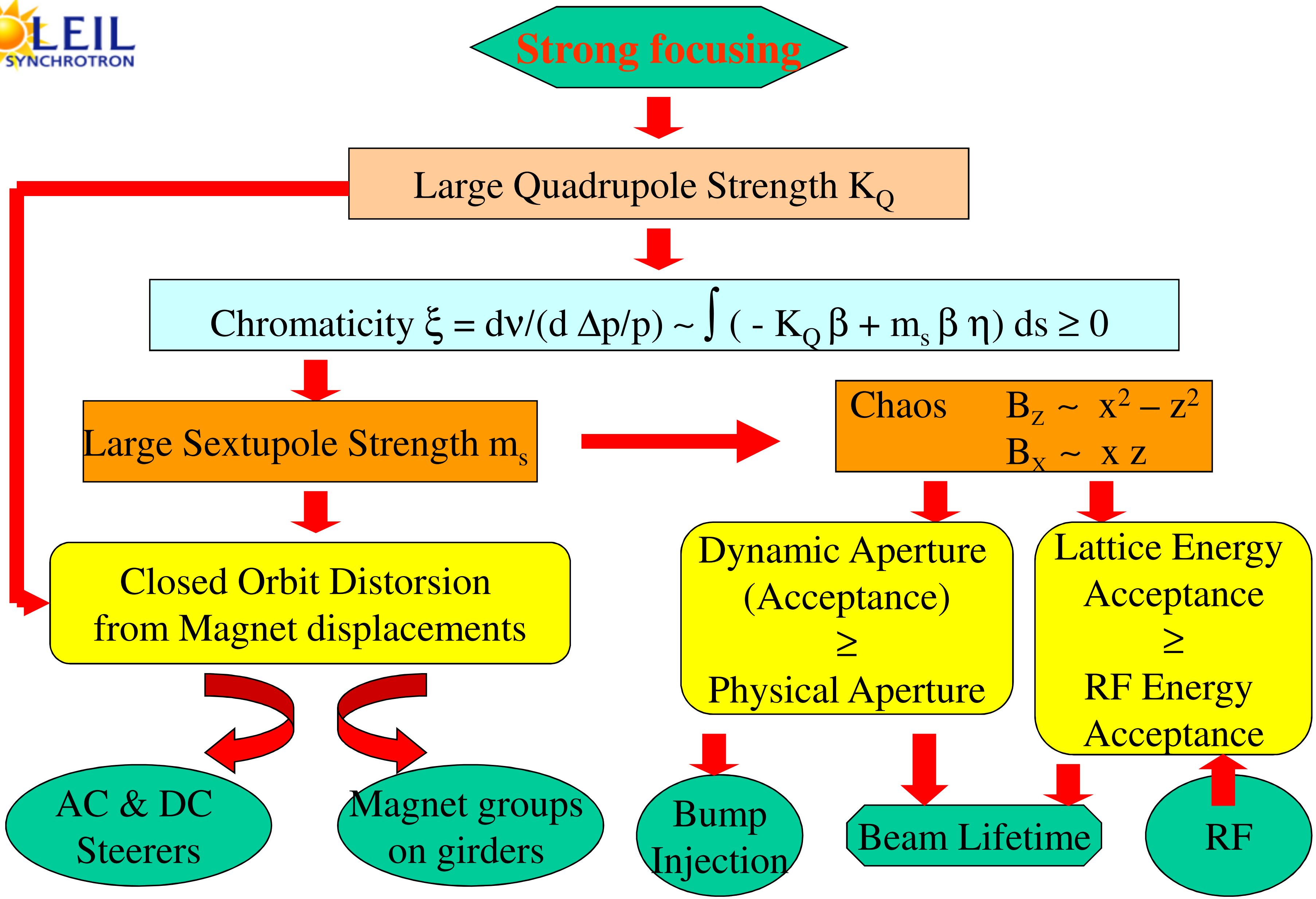
η_{Max}

Magnet gaps

Large Energy Acceptance

Short cell length

Strong focusing



Strong focusing

Large Quadrupole Strength K_Q

Chromaticity $\xi = d\nu/(d\,\Delta p/p) \sim \int (- K_Q \beta + m_s \beta \eta)\, ds \geq 0$

Large Sextupole Strength m_s

Chaos $B_Z \sim x^2 - z^2$

$B_X \sim x z$

Closed Orbit Distorsion from Magnet displacements

Dynamic Aperture (Acceptance) $\geq$ Physical Aperture

Lattice Energy Acceptance $\geq$ RF Energy Acceptance

AC & DC Steerers

Magnet groups on girders

Bump Injection

Beam Lifetime

RF

Low Emittance Lattice: SOLEIL example

Circumference = **354m**

24 straight sections

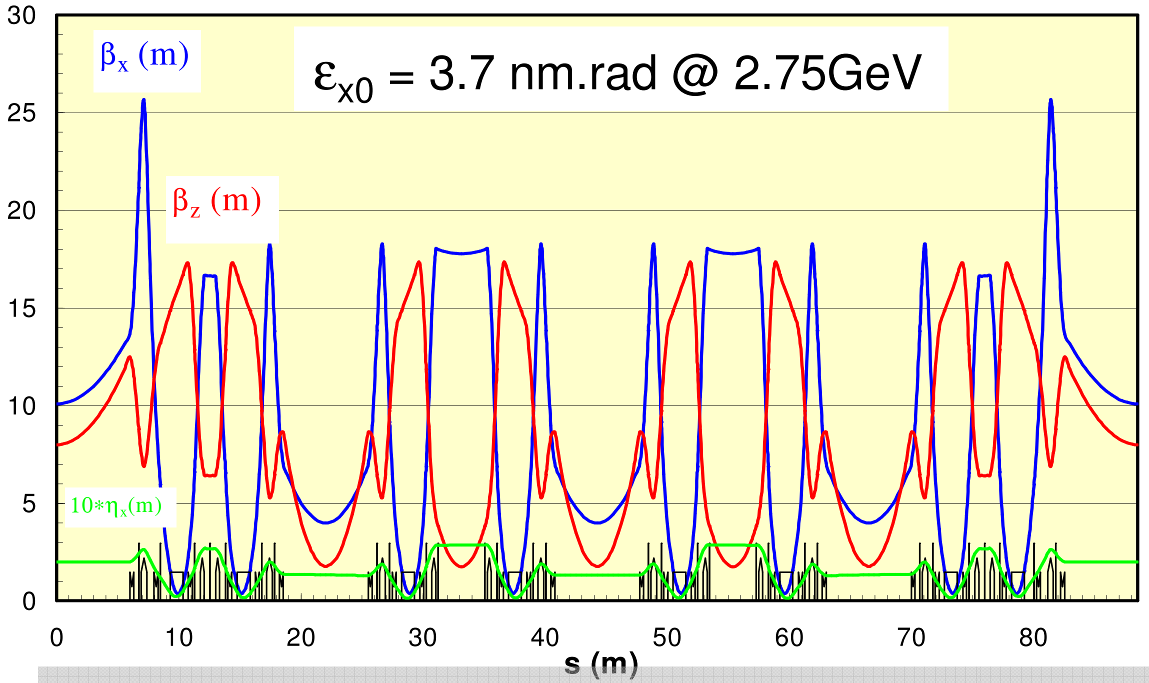
(variable length)

4 x 12 m
12 x 7 m
8 x 3.6m

Strong focusing

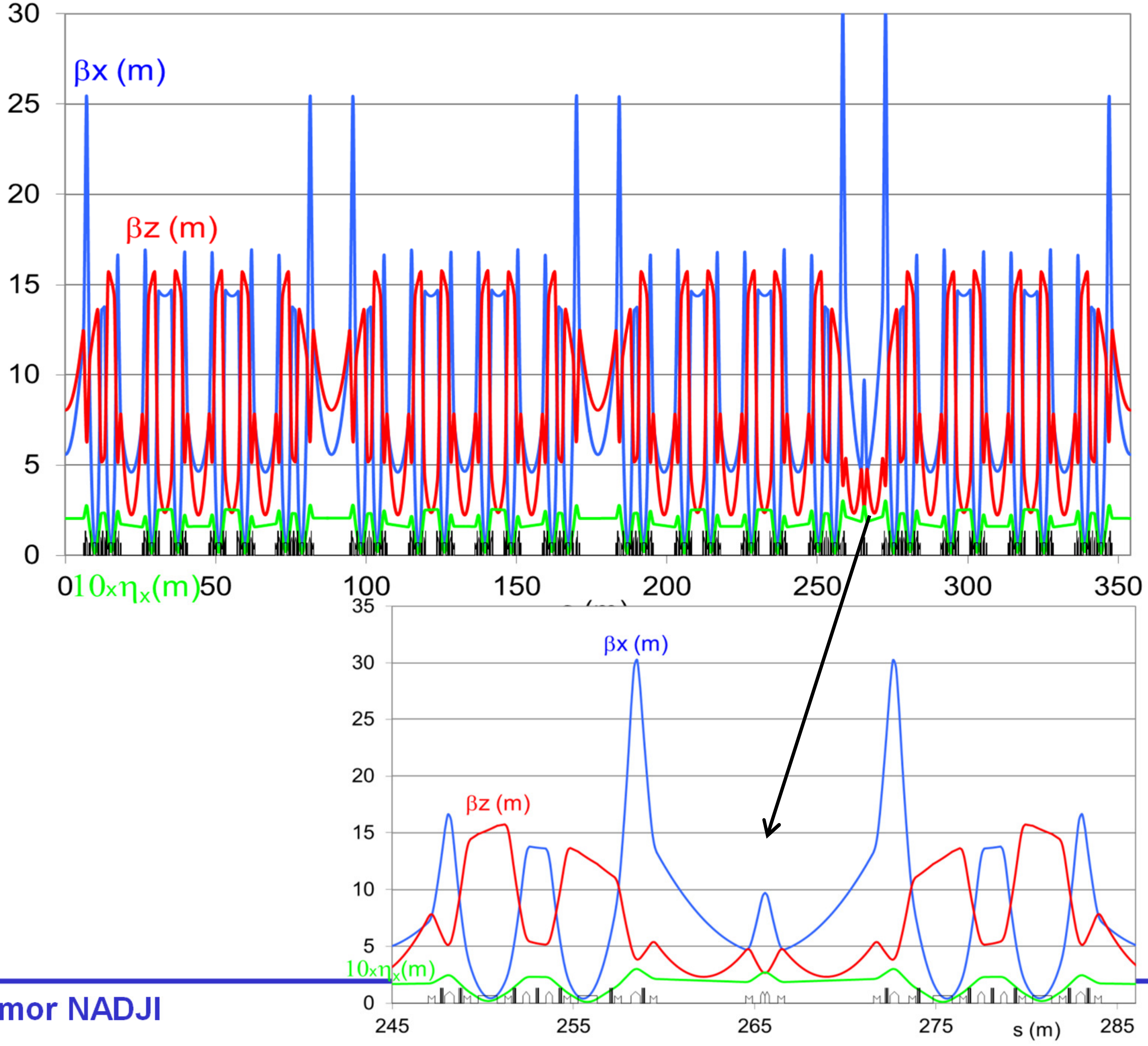
Different β-functions in straight sections

Bunch length = 4mm



Location	σ_x (μm)	σ_y (μm)
Long straight section	270	17
Intermediate straight section	182	8
short straight section	388	8
Bending Magnet	61	43

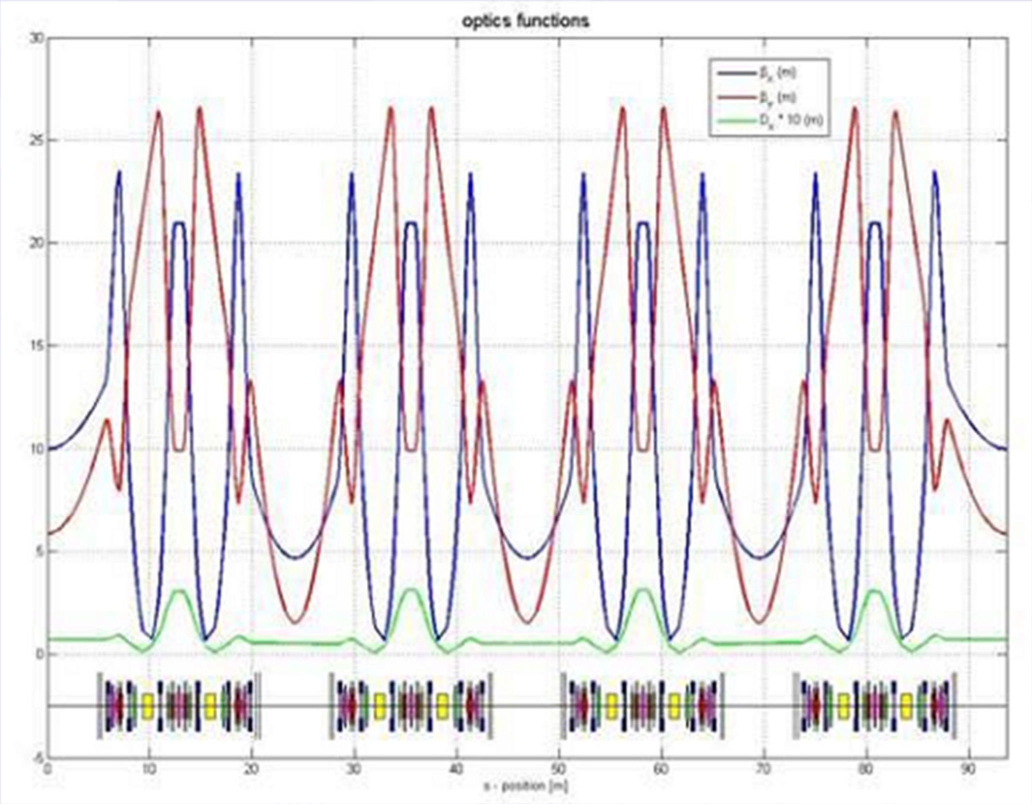
SOLEIL Lattice Modified



Operation with a new optics since January 2012

Two canted 5.5 mm gap in-vacuum undulators

Low Emittance Lattice: Diamond example



nominal, non-zero dispersion lattice

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)	**80, 8 µm**
Beam divergence (h, v) *(at centre of 5 m ID)*	**35, 3 µrad**

(Courtesy of R. P. Walker)

Ultra low emittance Emittance machine

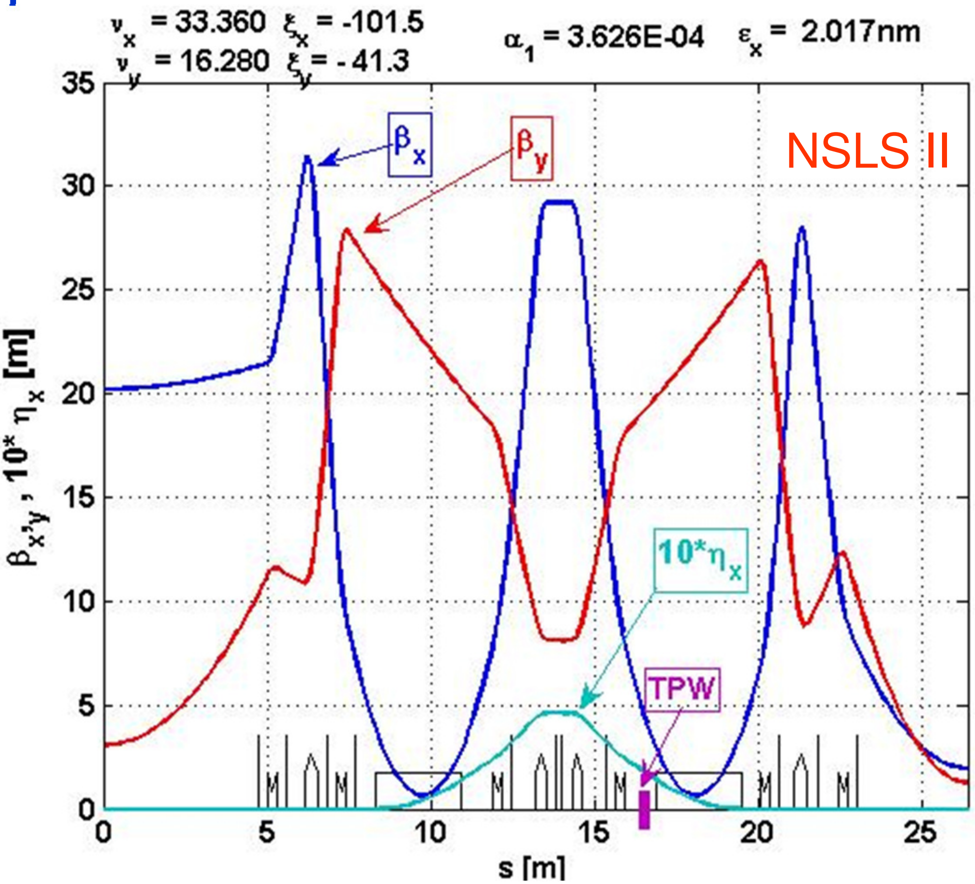
- ☐ **NSLS II (BNL) : under construction**
  DBA (30 cells)

  3 GeV, 792 m, ε_0 = 2 nm.rad

  Low bend field B = 0.4 T
  30 SS for a total of 240 m

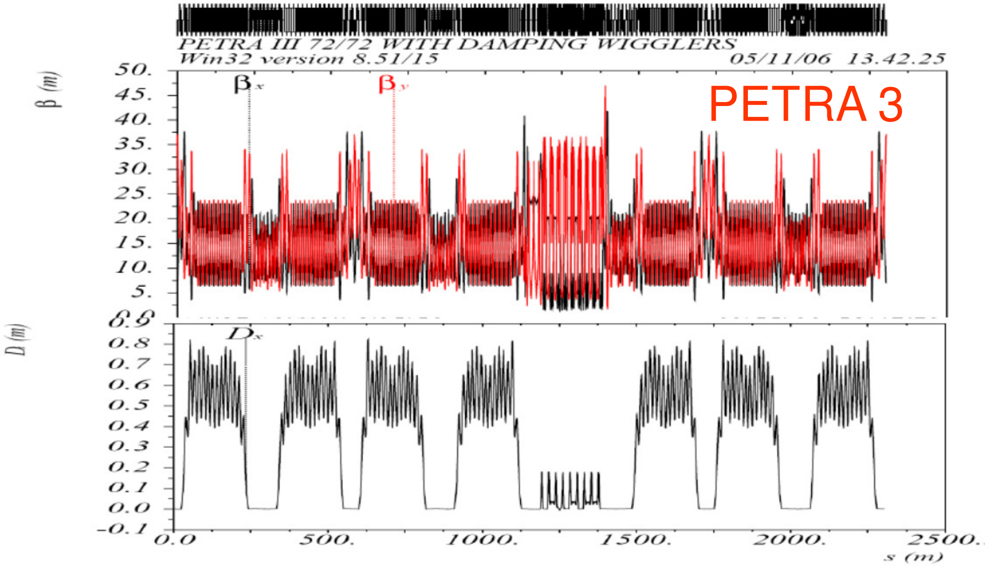
With Damping Wigglers

=> **ε_0 = 0.6 nm.rad**

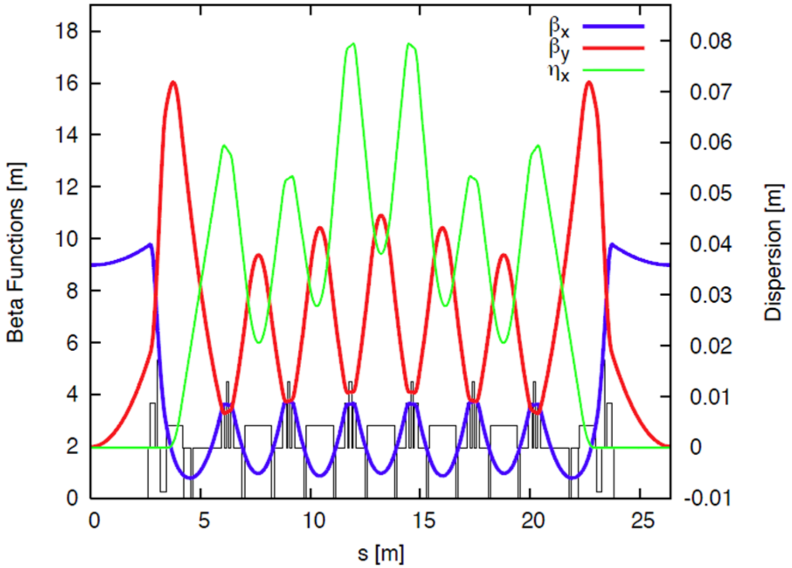


Ultra low Emittance rings

- **PETRA 3 (DESY) : in operation**
  7 old octants FODO + 1 New octant DBA
  6 GeV
  2304 m
  Damping Wigglers
  6 SS for a total of 45 m (14 IDs)
  => Ɛx = 1 nm.rad



- **MAX-IV (Sweden): *under construction***
  7-BA (zero dispersion in SS) 20 cells
  3 GeV
  528 m
  => Ɛx = 0.34 nm.rad



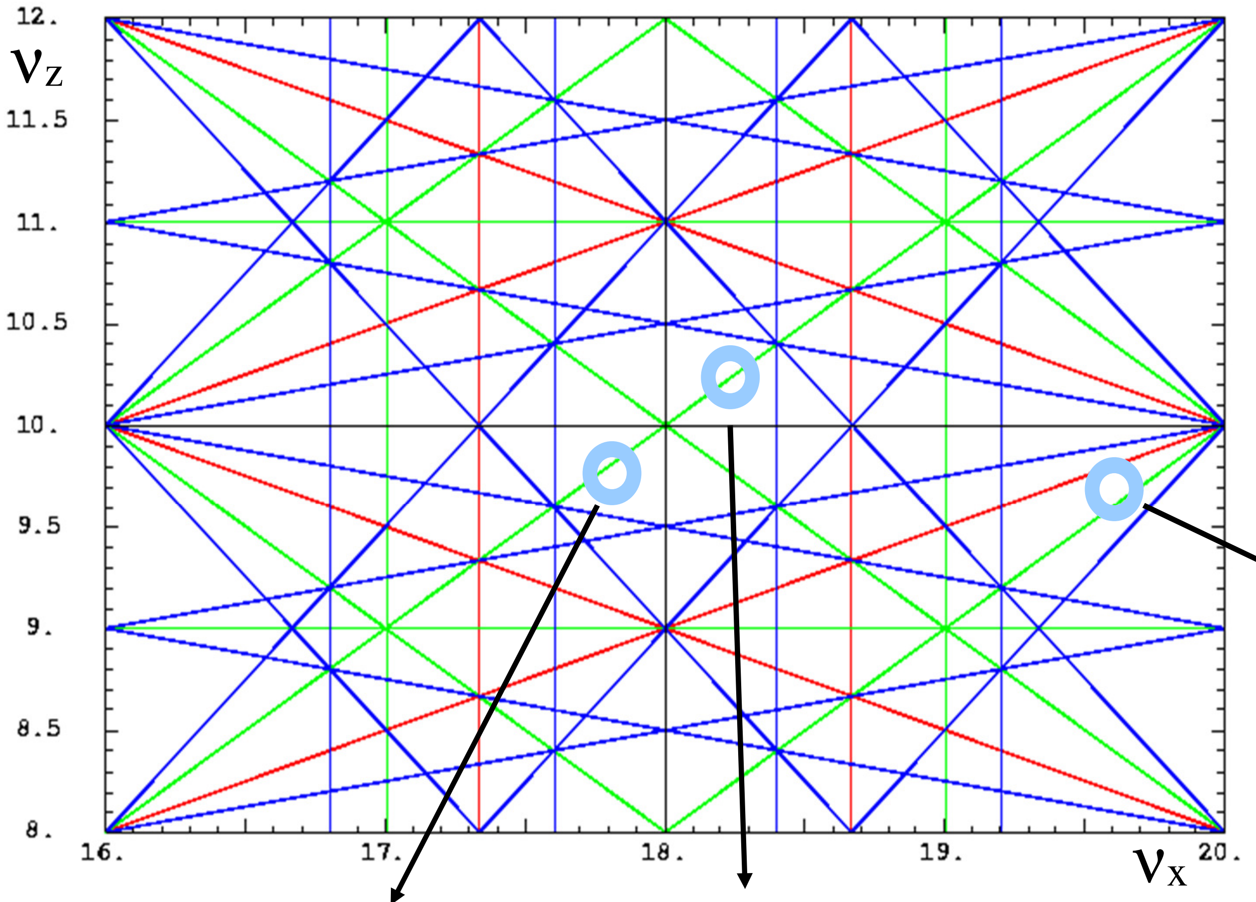
Nonlinear beam dynamics optimisation

It is a complex process where the Accelerator Physicist is guided by

- (semi-)analytical formulae for the computation of nonlinear maps, detuning with amplitude and off-momentum, resonance driving terms
- numerical tracking: direct calculation of non linear tuneshifts with amplitude and off-momentum, **6D** dynamics aperture and the frequency analysis of the betatron oscillations

Many iterations are required to achieve a good solution that guarantees a good dynamic aperture for injection and a good Touschek lifetime

Working point: Tune Diagram



Systematic Resonances

2nd order
3rd order
4th order
5th order

m nx+n nz =p

Smaller dynamic aperture
Lowest emittance

Good Compromise between
dynamic aperture and emittance

Larger dynamic aperture
Higher emittance

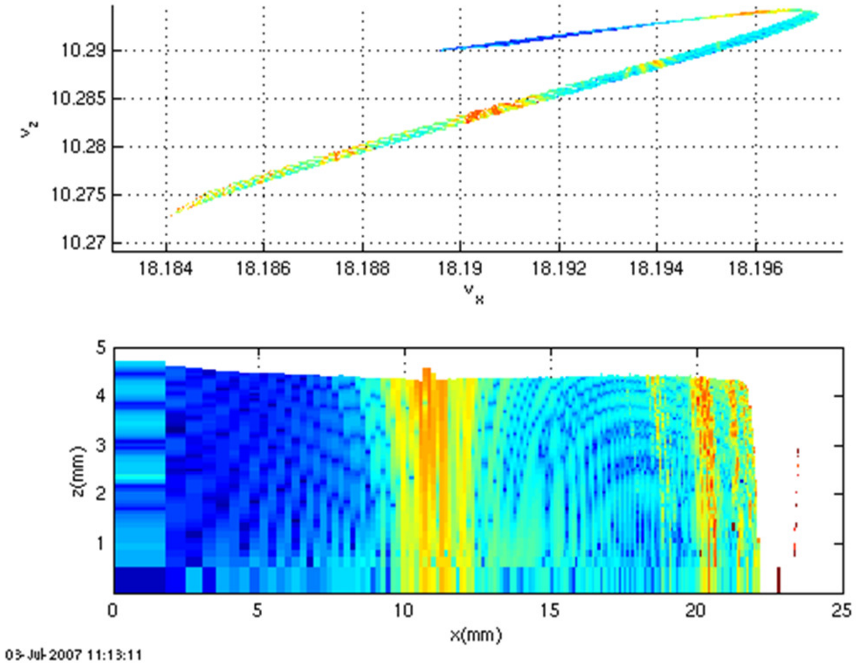
Frequency Map Analysis (NAFF)

Launched particles over a fine X-Z grid plotting

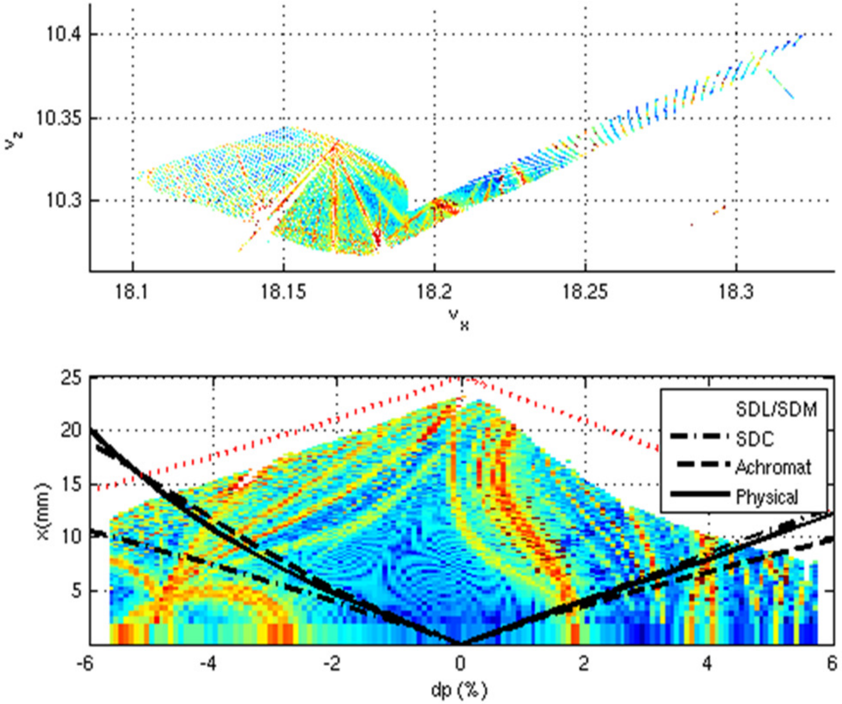
Numerical tunes

Highlighting, nonlinearity (diffusion rate)

On-momentum

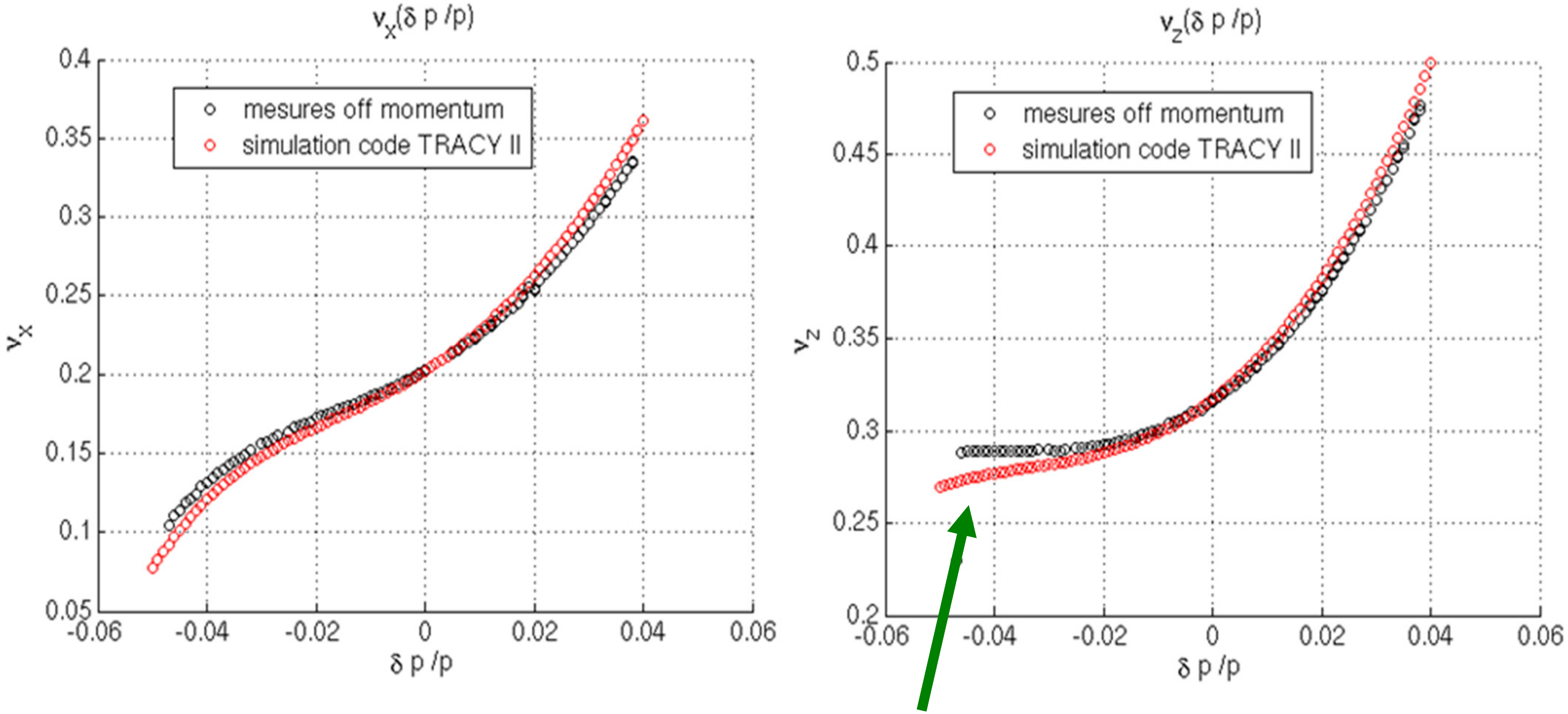


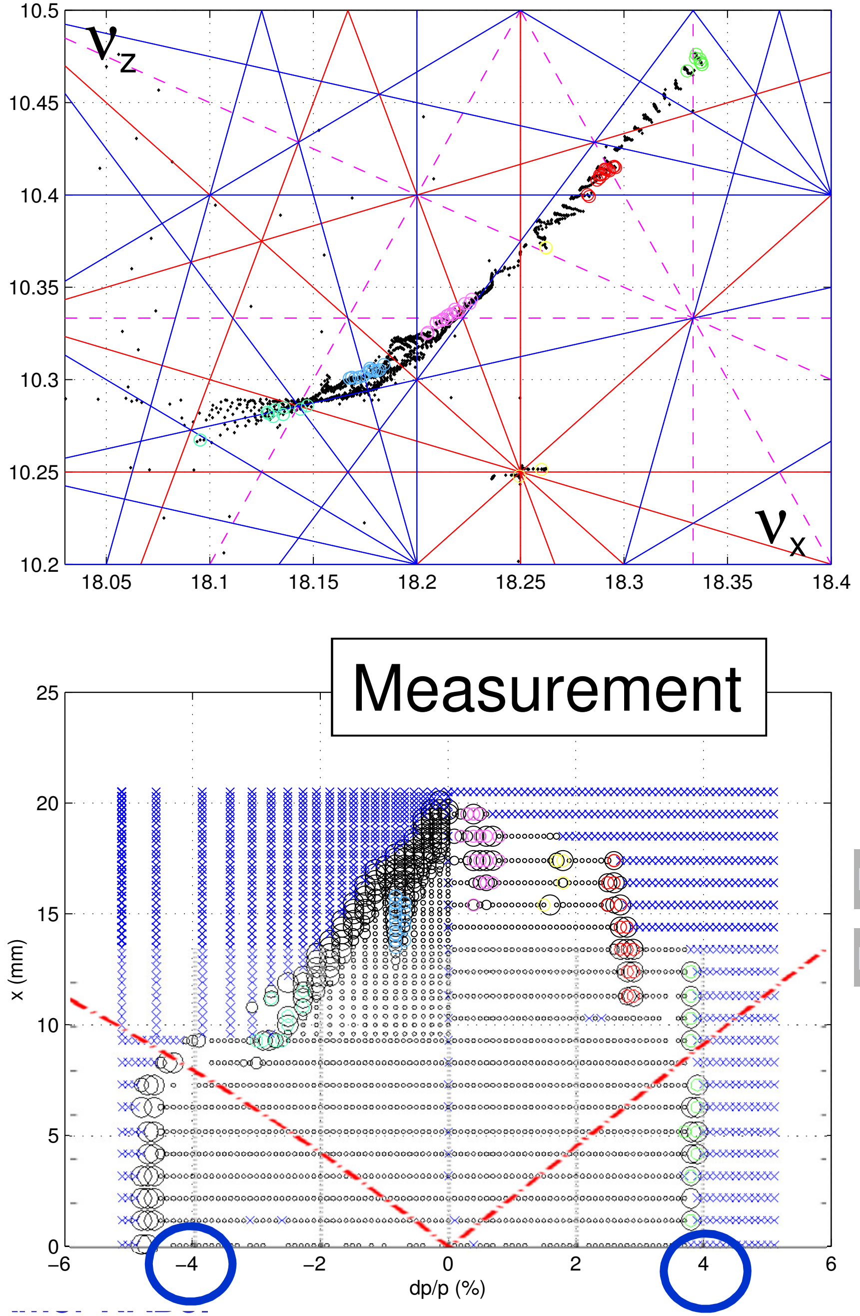
Off-momentum



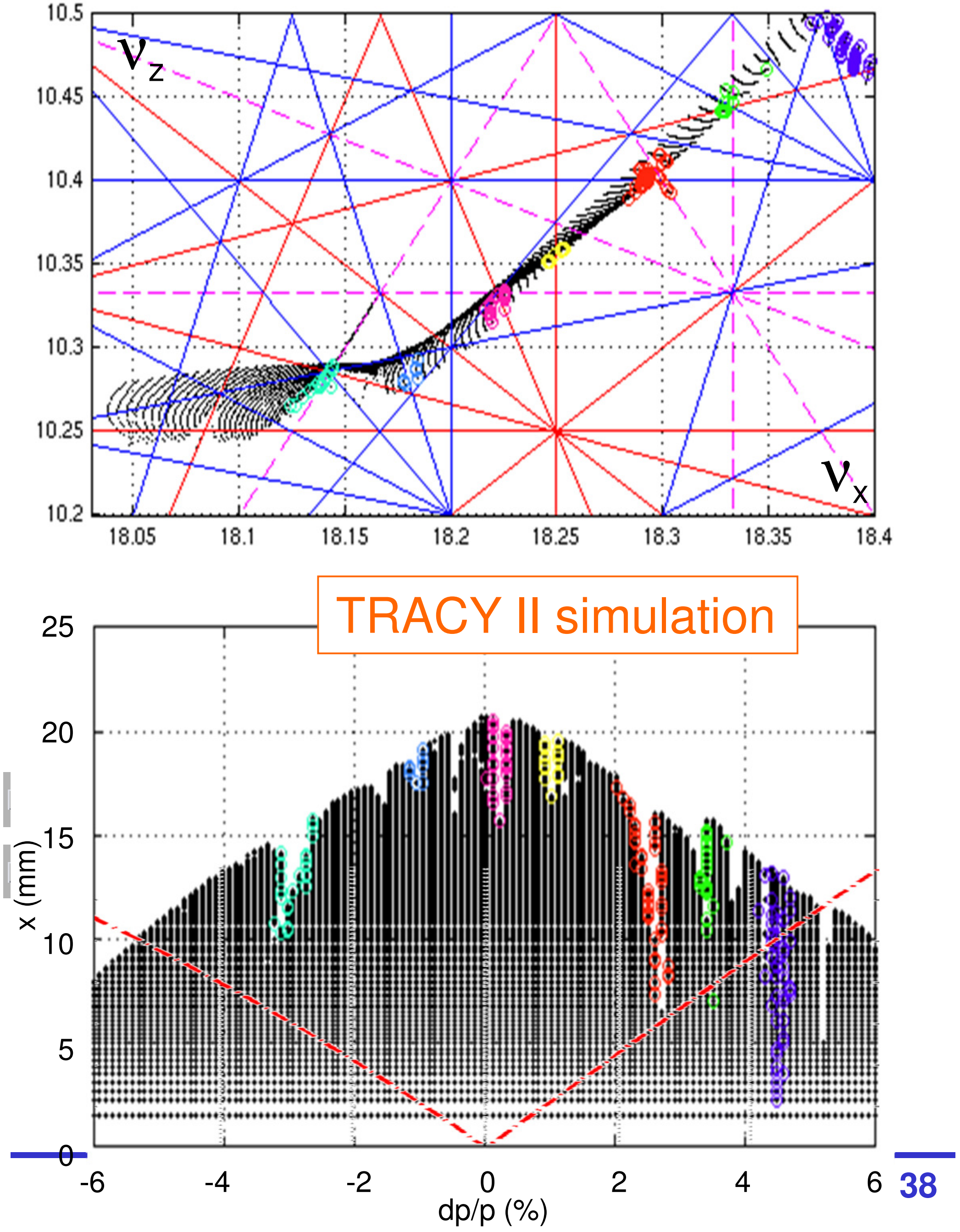
Tunes versus energy

Bare Machine- ν_x=18.202 ν_z=10.317 - chromaticities 2/2





Measurement

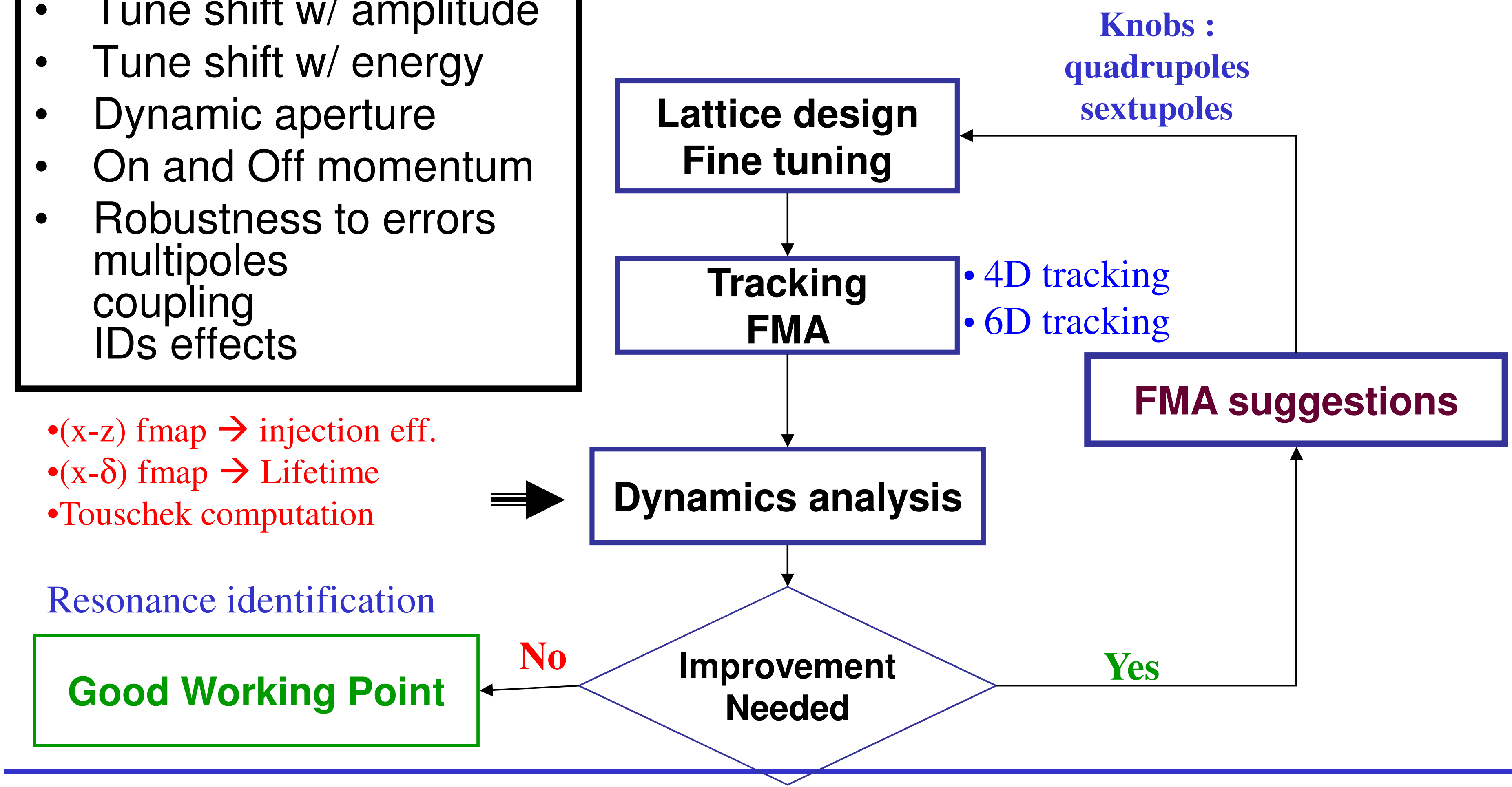


TRACY II simulation

Non linear Optimization Strategy

Quality factors :

- Tune shift w/ amplitude
- Tune shift w/ energy
- Dynamic aperture
- On and Off momentum
- Robustness to errors
  multipoles
  coupling
  IDs effects



Knobs :
quadrupoles
sextupoles

Lattice design
Fine tuning

Tracking
FMA

- 4D tracking
- 6D tracking

FMA suggestions

- (x-z) fmap → injection eff.
- (x-δ) fmap → Lifetime
- Touschek computation

Dynamics analysis

Resonance identification

Good Working Point

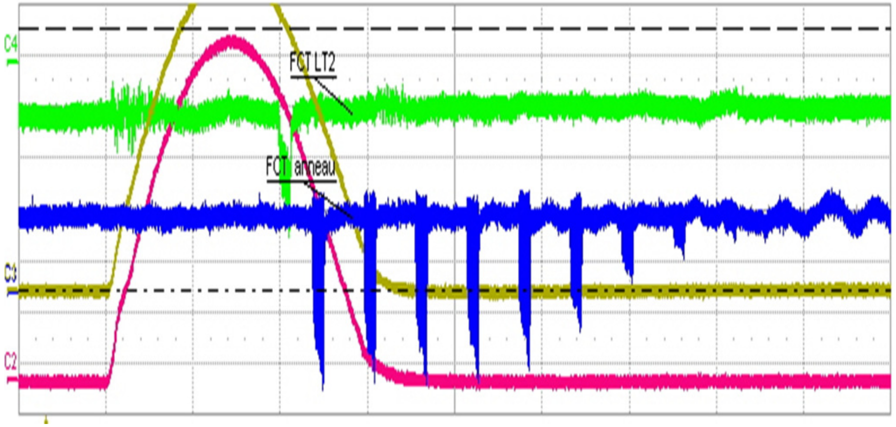
No

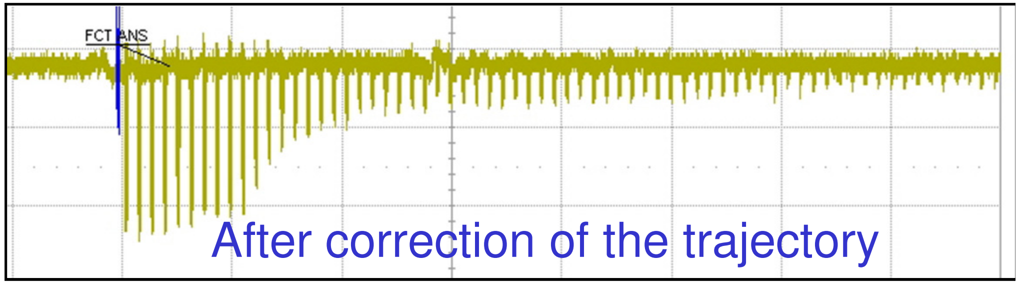
Improvement Needed

Yes

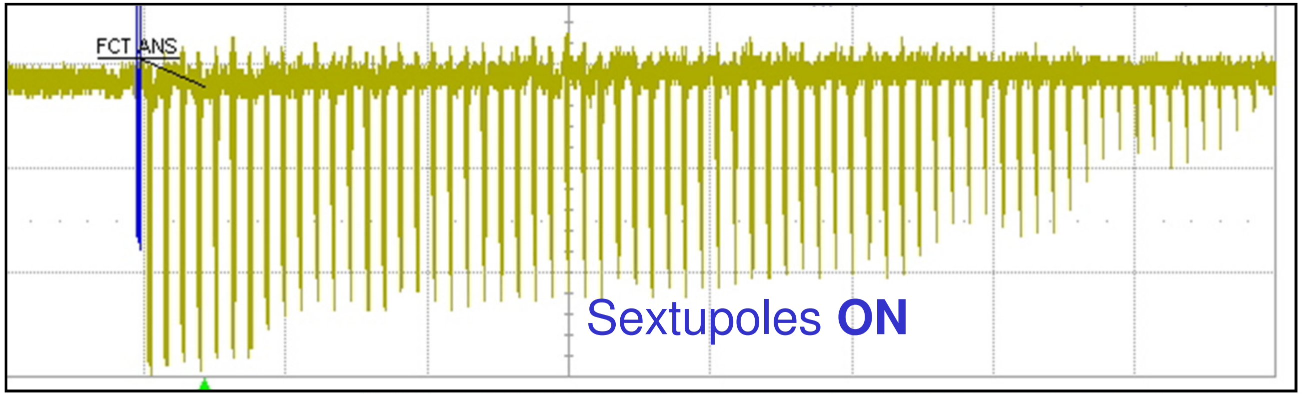
Commissioning with beam

Very first turns



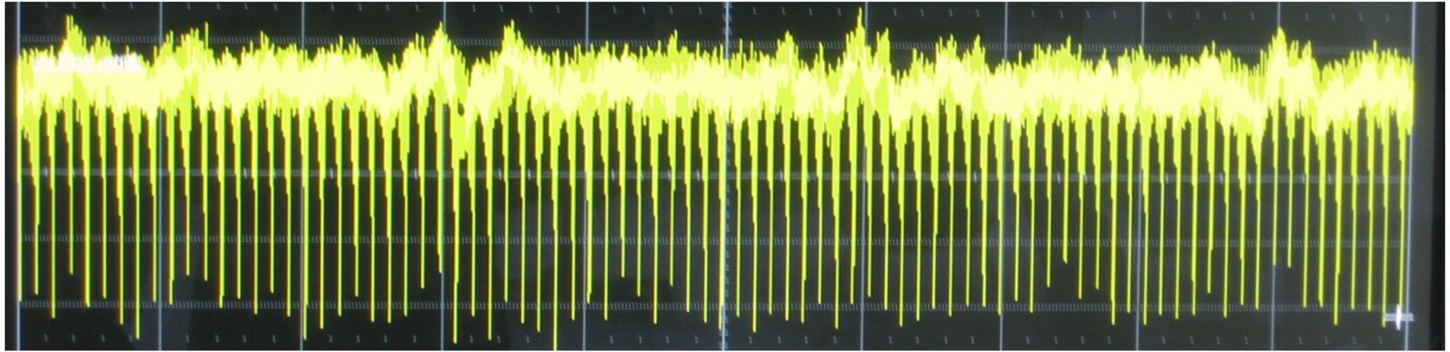


After correction of the trajectory



Sextupoles **ON**

RF **ON**



Electron Beam Current

To reach a high brilliance you need to operate with a high current.
There are 3 main limitations to overcome :

First limitation : the coupled bunch instabilities, which are excited by **H**igher **O**rder **M**odes in the RF cavities (**HOM**).
⇒ increase of the energy spread and bunch length => brilliance reduction
⇒ transverse beam oscillations =>beam losses

Solutions to push the instability thresholds have been experienced and successfully implemented :

- Shifting the mode frequencies to avoid interaction with the bunch spectrum (**temperature control of the cavities**)
- Landau damping : **partial filling or harmonic cavity**
- Reducing the number and impedances of parasitic modes (**superconducting cavities, parasitic mode dampers**)
- **Feedback systems**

Electron Beam Current

Second limitation : the transverse instabilities, resistive wall, ions trapping in multibunch / mode detuning and TMCI in single bunch

⇒ Beam blow-up => brilliance reduction

⇒ transverse beam oscillations => beam losses

Resistive wall is enhanced by the presence of low gap ID vessels

Solutions to push the instability thresholds have been experienced and successfully implemented :

- Shifting the mode spectrum with positive chromaticities
- Landau damping : **partial filling (mainly against ions)**
- Reducing machine impedance (**smooth tapers, no gaps, RF fingers..**)=> at design stage
- **Bunch by bunch transverse Feedback systems (required to achieve high current)**

Electron Beam Current

Third limitation : the thermal load on the vacuum system and front-end
⇒ High heat load with high power density on beam absorbers
⇒ Heating due to RF losses in transitions

Solutions :

- Distributed lump absorbers
- Geometry and material of the absorbers (Glidcop, cooling circuits,..)
- Reduce trapping mode geometry (**smooth tapers, no gaps, RF fingers..**)=> at design stage
- **Require efficient and reliable Machine protection system (thermocouples, flowswitches, Beam position interlocks, instability interlock,..)**

Note : the danger is not coming from the power in the electron beam (Thousands of Joules lost in few microsec) but from the photons beam
⇒ **In case of electron beam mis-steering (without losing it) the photons may reach a part which is not able to sustain the power.**

Electron Beam Current

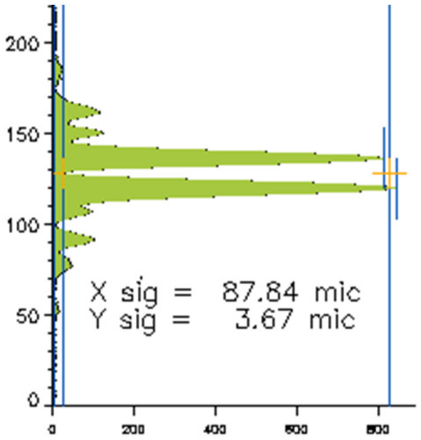
Few figures (reached):

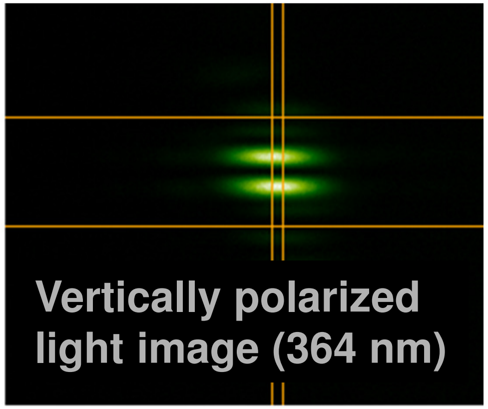
APS,	100 mA
SPRING8	100 mA
ESRF	200 mA
SLS	400 mA
DIAMOND	300 mA
SOLEIL	430 mA => 500 mA (reached in machine development)

SLS achievement: minimum vertical emittance

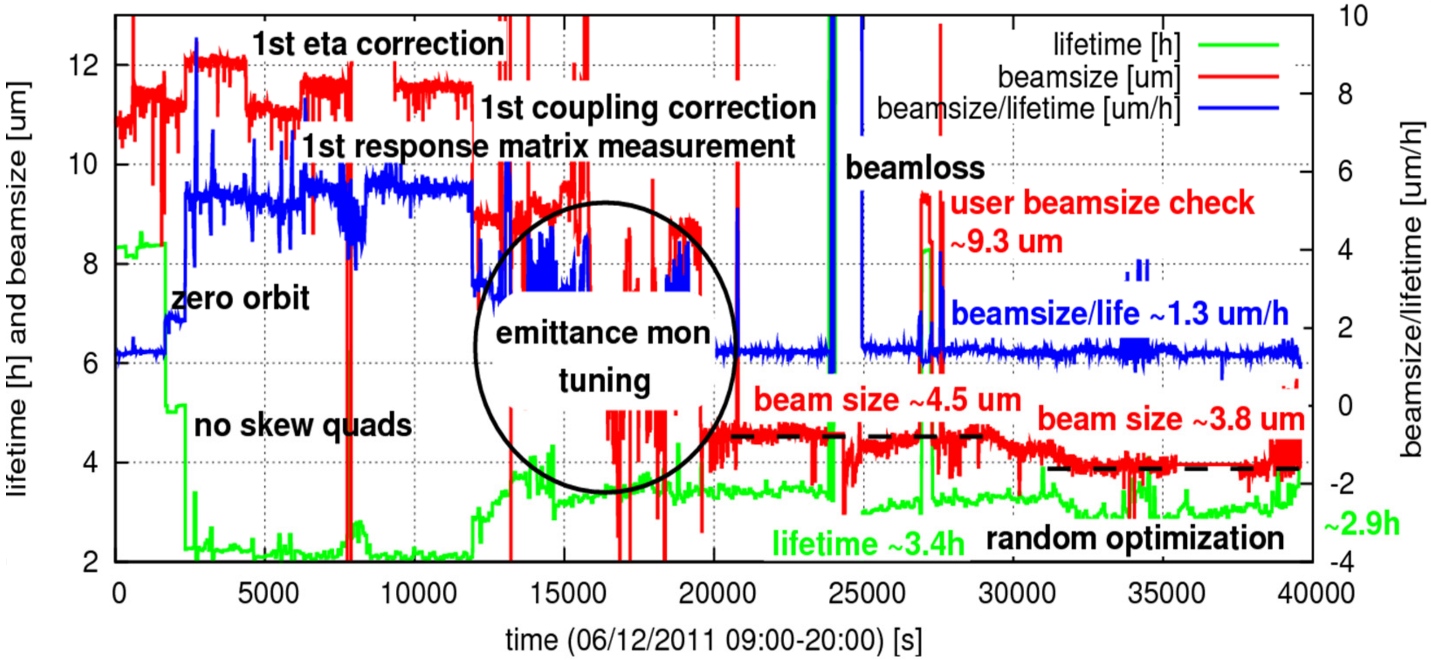
Measures for minimization

- Vertical realignment of storage ring girders with stored beam and orbit feedback running.
- Model dependent optimization: measurements of response matrix and vertical dispersion and calculation of skew quadrupole currents.
- Model independent optimization: random walk of skew quadrupole currents with beam height measurement as target function.
- Fine tuning of emittance monitor to extend its range of measurement .





Vertically polarized light image (364 nm)

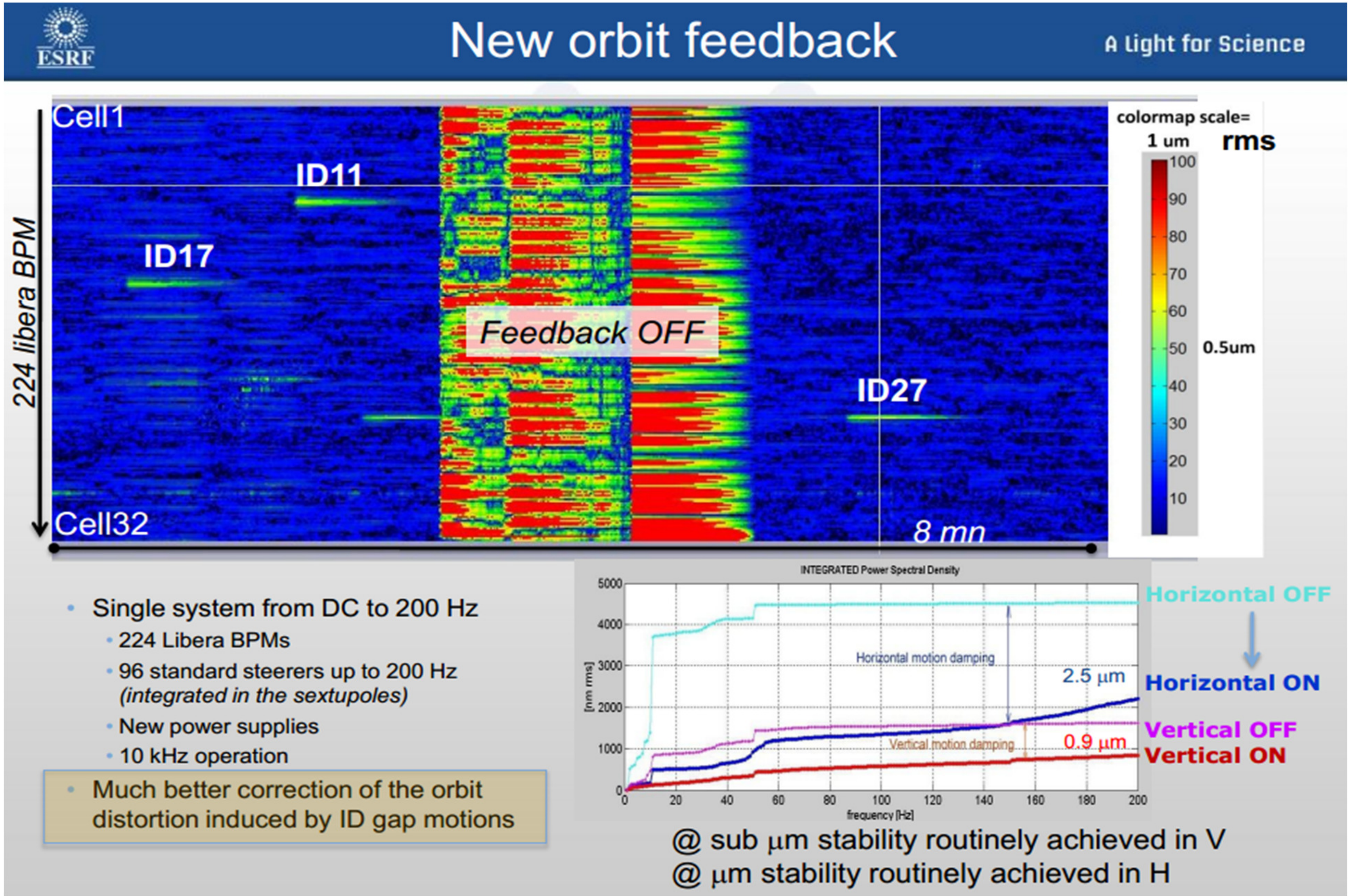


Results

- Record-Value (Dec. 6, 2011) **0.9± 0.4 pm rad**
- Design value 15 pm rad
- Quantum limit 0.2 pm rad

⇨ Nuclear Instruments and Methods in Physics Research A 694 (2012) 133–139

Beam Position Stability



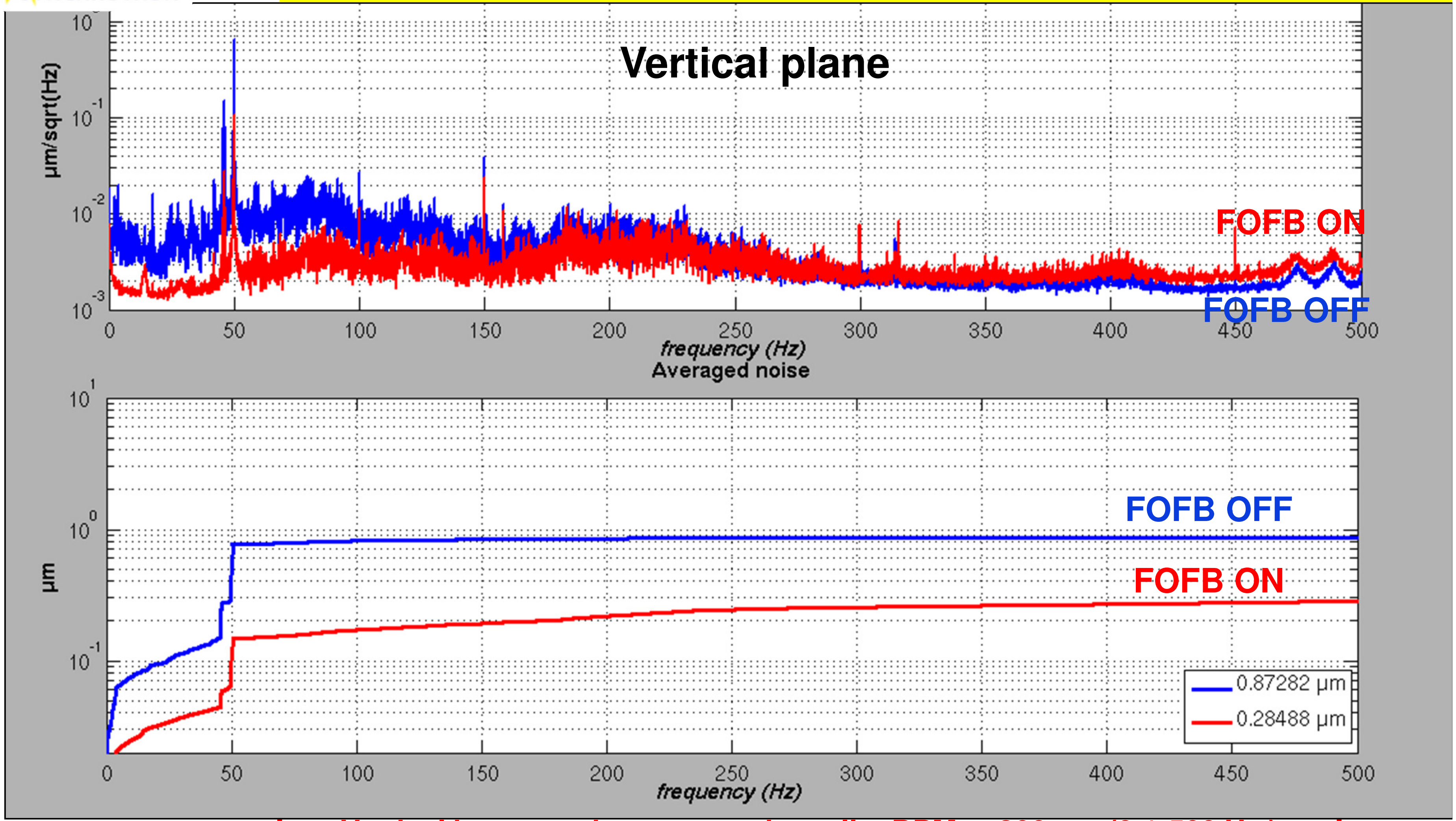
New orbit feedback

- Single system from DC to 200 Hz
  - 224 Libera BPMs
  - 96 standard steerers up to 200 Hz *(integrated in the sextupoles)*
  - New power supplies
  - 10 kHz operation
- Much better correction of the orbit distortion induced by ID gap motions

@ sub μm stability routinely achieved in V

@ μm stability routinely achieved in H

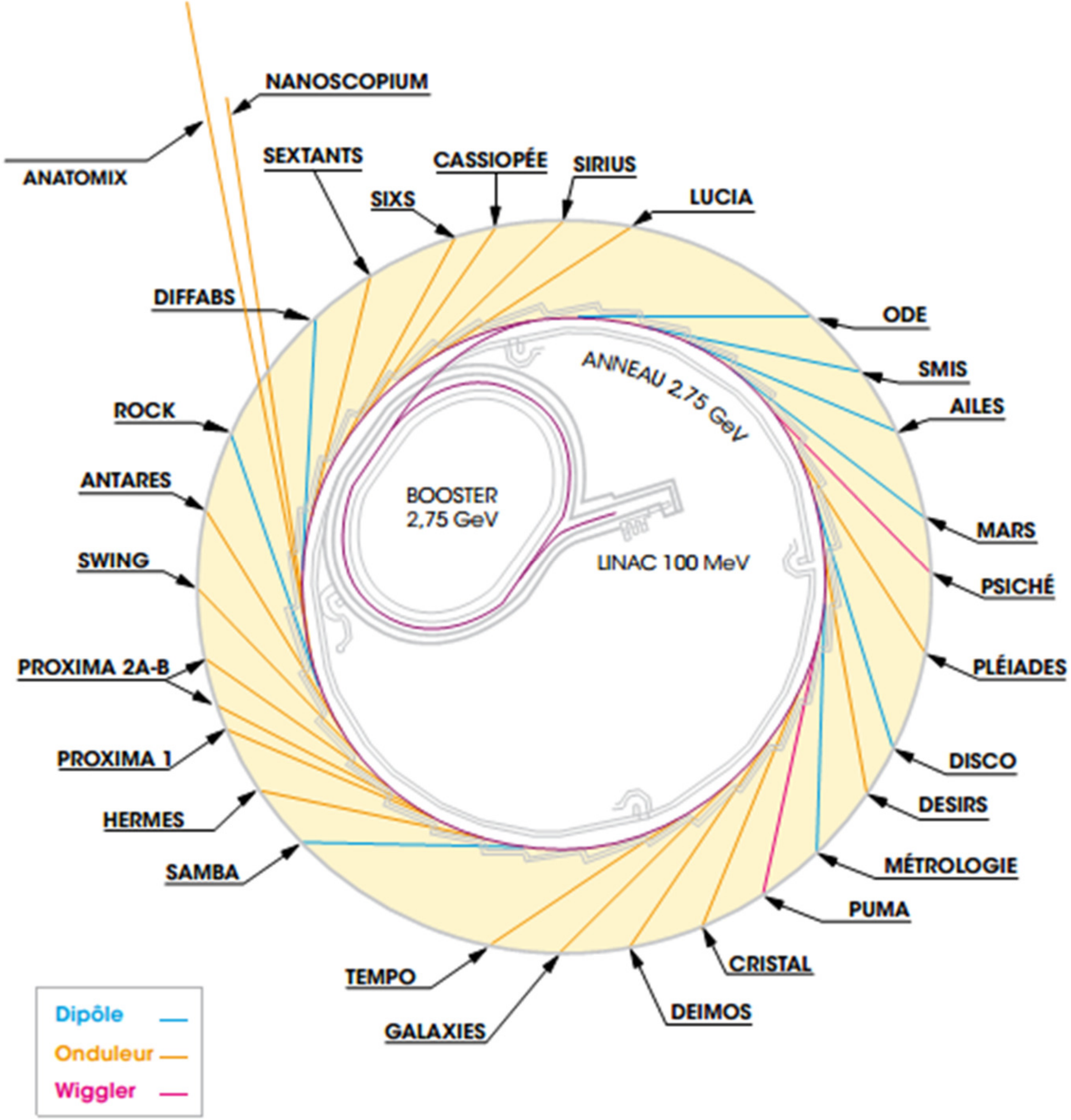
Short Term Beam Position Stability



Vertical beam motion averaged on all e-BPMs ~300 nm (0.1-500 Hz)
It means 200 nm RMS in the middle of the straight sections

SOLEIL Beamlines

Opération:
2008: 11 BL
2009: 14 BL
2010: 17 BL
2011: 20 BL
2013: 25 BL
2014: 26 BL
2016: 29 BL



5 Modes of Operation for the Users

All in Top-up injection

Mode of operation	User Operation	Ultimate performance achieved
Multibunch	430 mA	500 mA
Hybrid	425 mA + 5 mA	425 mA + 10 mA
8 bunch	100 mA	100 mA
1 bunch	12 mA	20 mA
Low α: bunch length and current	4.7 ps RMS and 65 µA per bunch	2.5 ps RMS and 10 µA per bunch

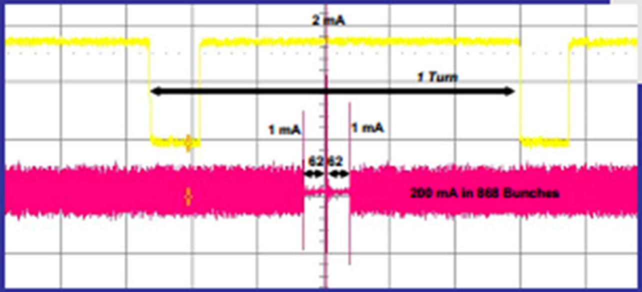
5 feedbacks: TFB, SOFB, FOFB, BTUNE-FB, Coupling-FB

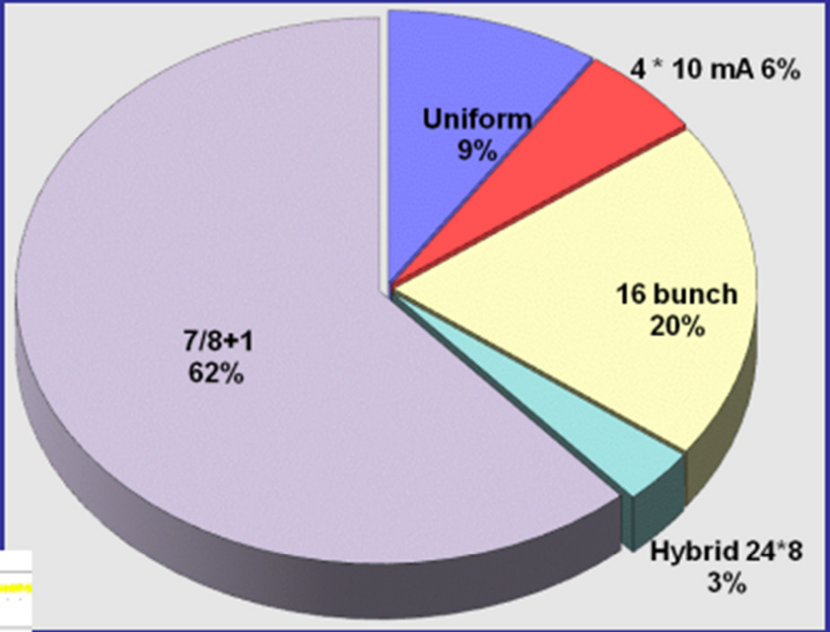
Filling modes

Mode 16 Bunch:
90 mA

Mode 4 Bunch:
40 mA

Mode 7/8+1: 200 mA





91 % of Beamtime
available for Timing
Experiments

Time structure

Many facilities provide specific filling pattern to enable time structure experiments

ESRF : Single bunch, 16 bunch, Hybrid mode (Camshaft),..

SOLEIL : 1 bunch, 8 bunch, hybrid mode

Bunch length are of 10-20 ps (rms)

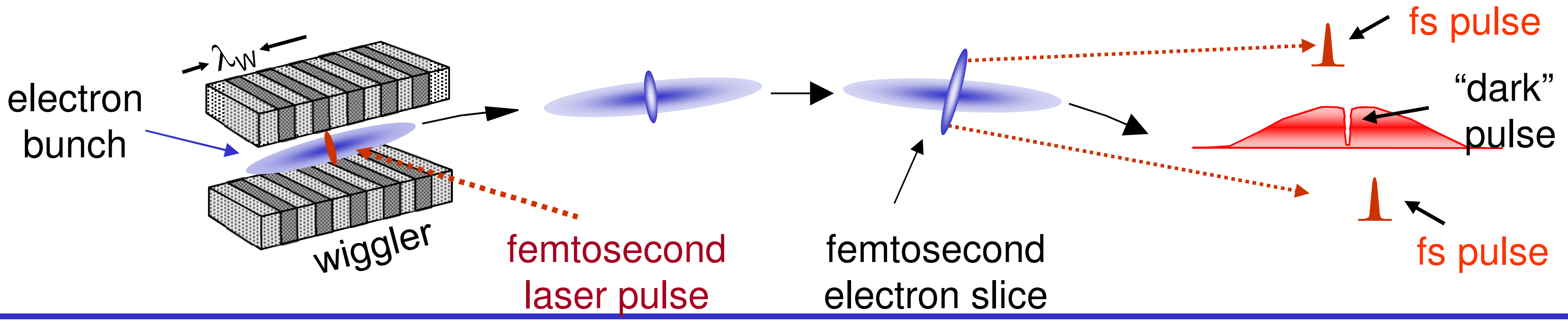
$$\sigma_z = \frac{\alpha c}{2\pi f_s}\sigma_\varepsilon \propto \sqrt{\frac{\alpha \gamma^3}{dV_{RF}/dz}}$$

Request to get shorter bunches

⇒Low alpha lattices provide **ps** bunch length at very low current per bunch (BESSY II, ANKA, ELETTRA, SPEAR3, SOLEIL)

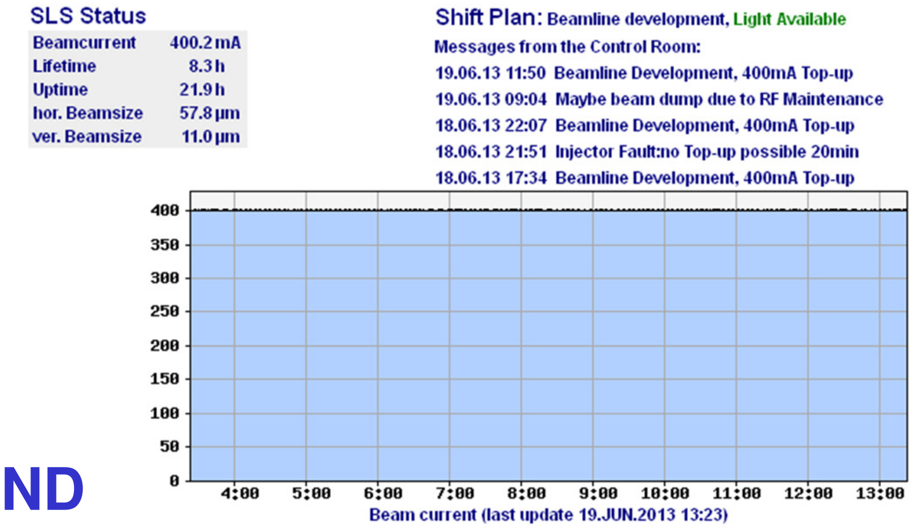
$$\alpha = \frac{1}{L}\oint \frac{D_x}{\rho} ds \approx 10^{-6}$$

⇒ Femto slicing enables to produce **100fs** bunch “slices” using an energy modulation induced by a laser (ALS, SLS, BESSY, and soon SOLEIL). The photon flux is rather weak.



Top-up Operation

SLS



SLS Status

Beamcurrent	400.2 mA
Lifetime	8.3 h
Uptime	21.9 h
hor. Beamsize	57.8 µm
ver. Beamsize	11.0 µm

Shift Plan: Beamline development, Light Available

Messages from the Control Room:

19.06.13 11:50 Beamline Development, 400mA Top-up

19.06.13 09:04 Maybe beam dump due to RF Maintenance

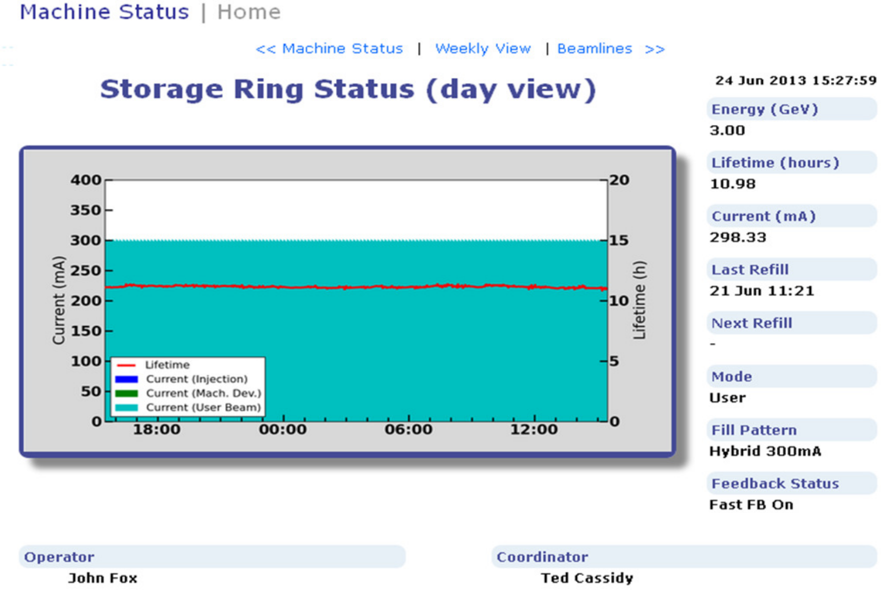
18.06.13 22:07 Beamline Development, 400mA Top-up

18.06.13 21:51 Injector Fault:no Top-up possible 20min

18.06.13 17:34 Beamline Development, 400mA Top-up

Beam current (last update 19.JUN.2013 13:23)

DIAMOND



Machine Status | Home

Storage Ring Status (day view)

24 Jun 2013 15:27:59

Energy (GeV)
3.00

Lifetime (hours)
10.98

Current (mA)
298.33

Last Refill
21 Jun 11:21

Next Refill
-

Mode
User

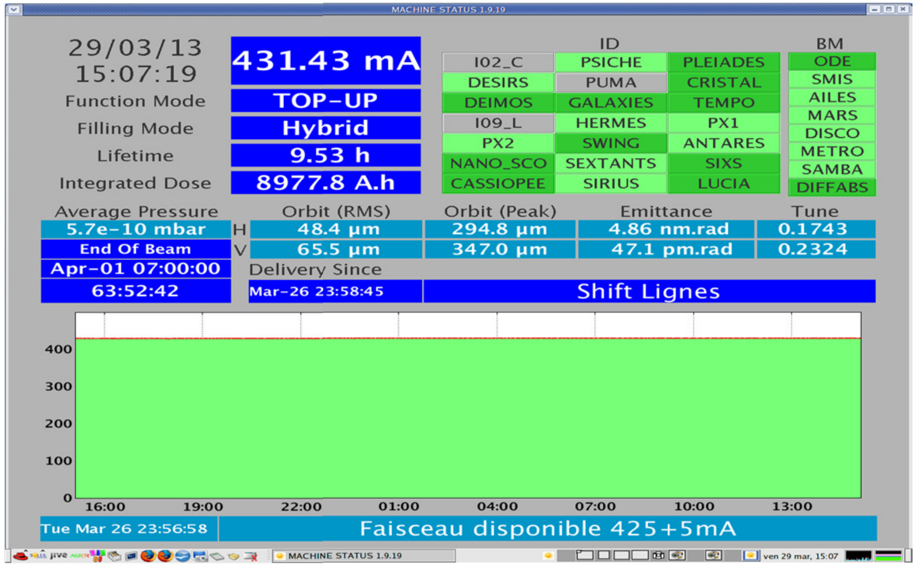
Fill Pattern
Hybrid 300mA

Feedback Status
Fast FB On

Operator
John Fox

Coordinator
Ted Cassidy

SOLEIL



MACHINE STATUS 1.9.19

29/03/13
15:07:19

	431.43 mA
Function Mode	TOP–UP
Filling Mode	Hybrid
Lifetime	9.53 h
Integrated Dose	8977.8 A.h

ID			BM
I02_C	PSICHE	PLEIADES	ODE
DESIRS	PUMA	CRISTAL	SMIS
DEIMOS	GALAXIES	TEMPO	AILES
I09_L	HERMES	PX1	MARS
PX2	SWING	ANTARES	DISCO
NANO_SCO	SEXTANTS	SIXS	METRO
CASSIOPEE	SIRIUS	LUCIA	SAMBA
			DIFFABS

Average Pressure		Orbit (RMS)	Orbit (Peak)	Emittance	Tune
5.7e–10 mbar	H	48.4 µm	294.8 µm	4.86 nm.rad	0.1743
End Of Beam	V	65.5 µm	347.0 µm	47.1 pm.rad	0.2324

End Of Beam
Apr–01 07:00:00
63:52:42

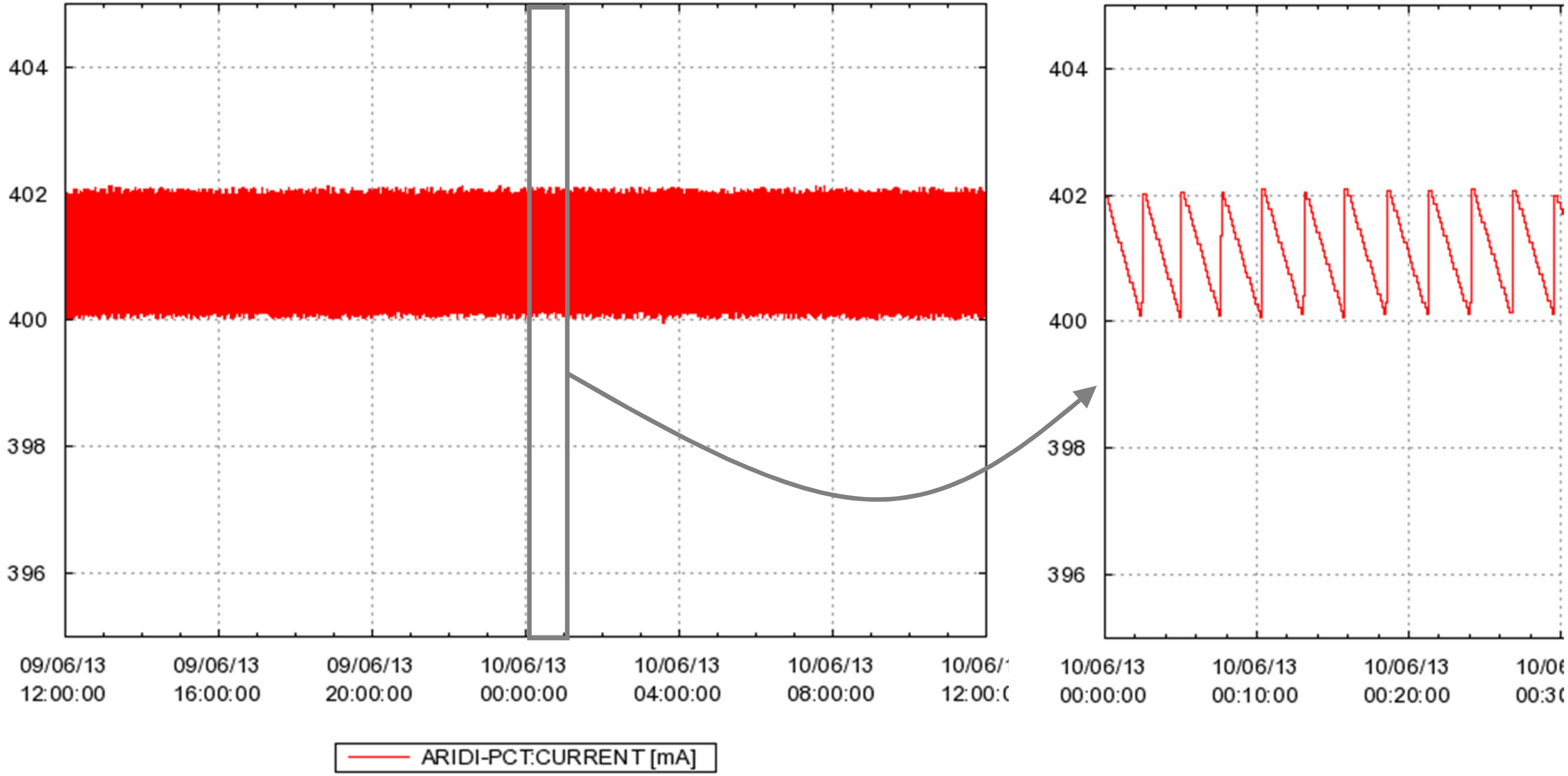
Delivery Since
Mar–26 23:58:45

Shift Lignes

Tue Mar 26 23:56:58

Faisceau disponible 425+5mA

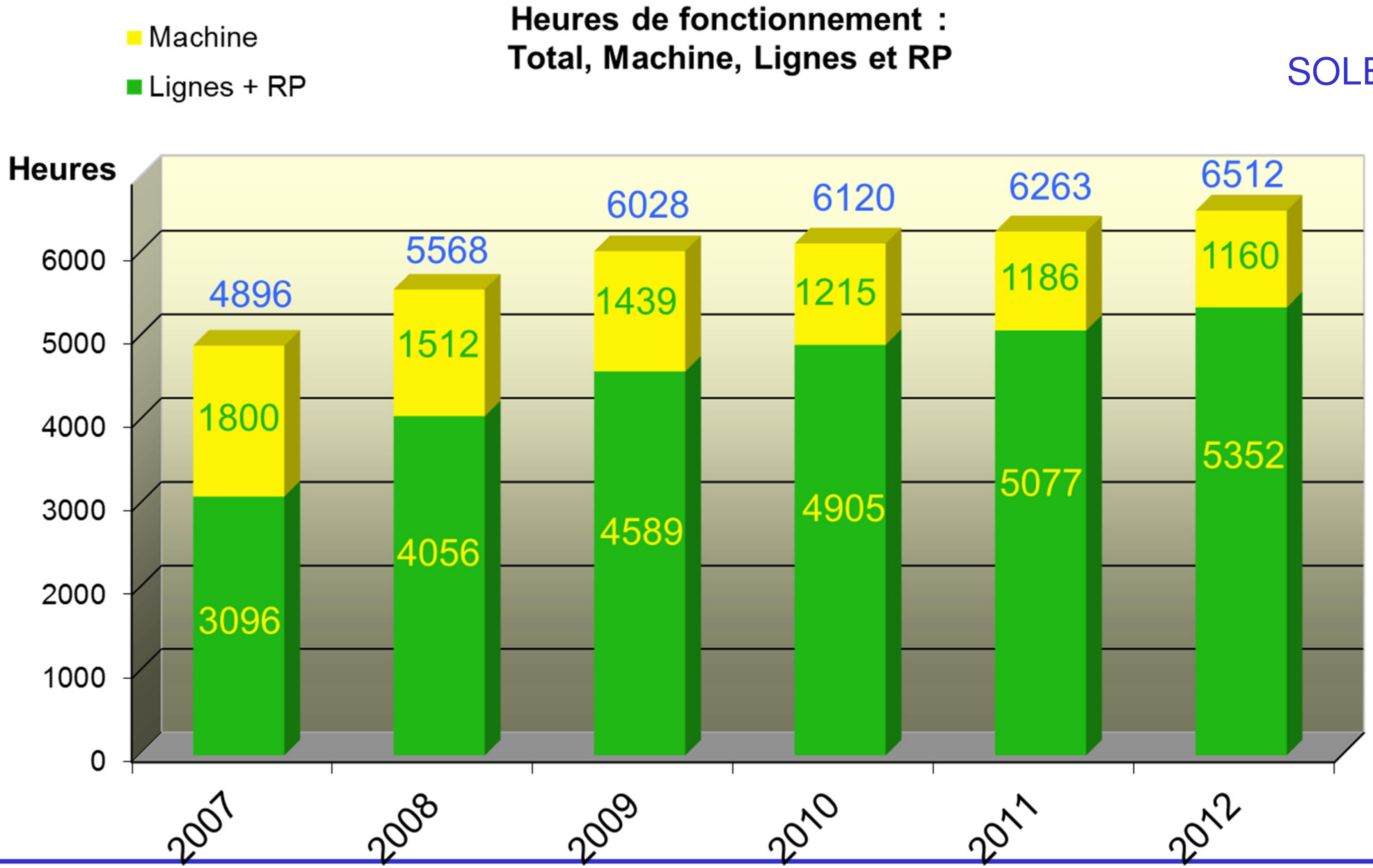
SLS beam current



Typical 24 hours of user operation

Beam schedule

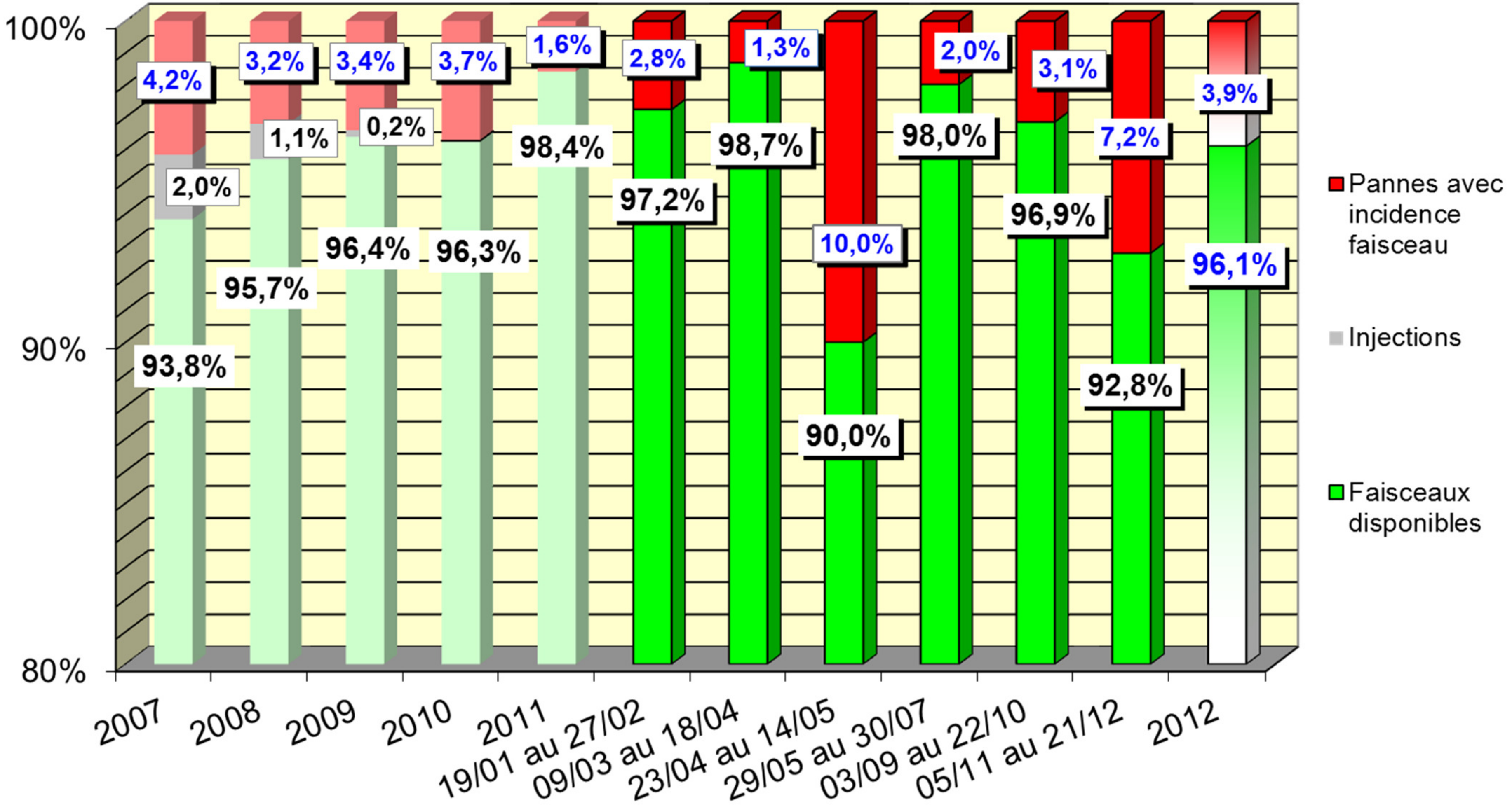
SOLEIL

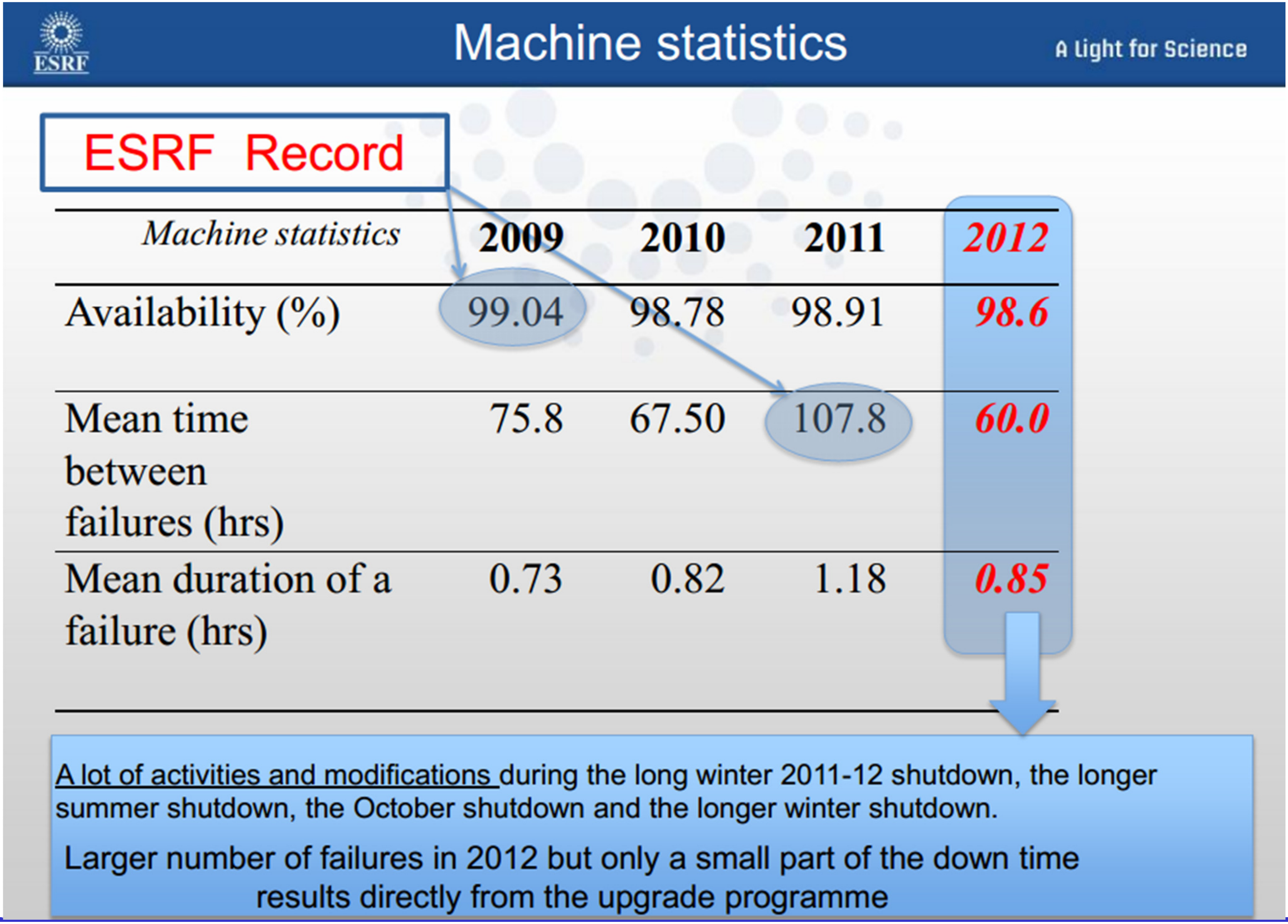


Availability

Efficacité durant les sessions Lignes et RP sur l'année 2012
5133 heures de faisceau ont été délivrées
soit 96,1 % du temps de faisceau programmé

SOLEIL





ESRF

Machine statistics

A light for Science

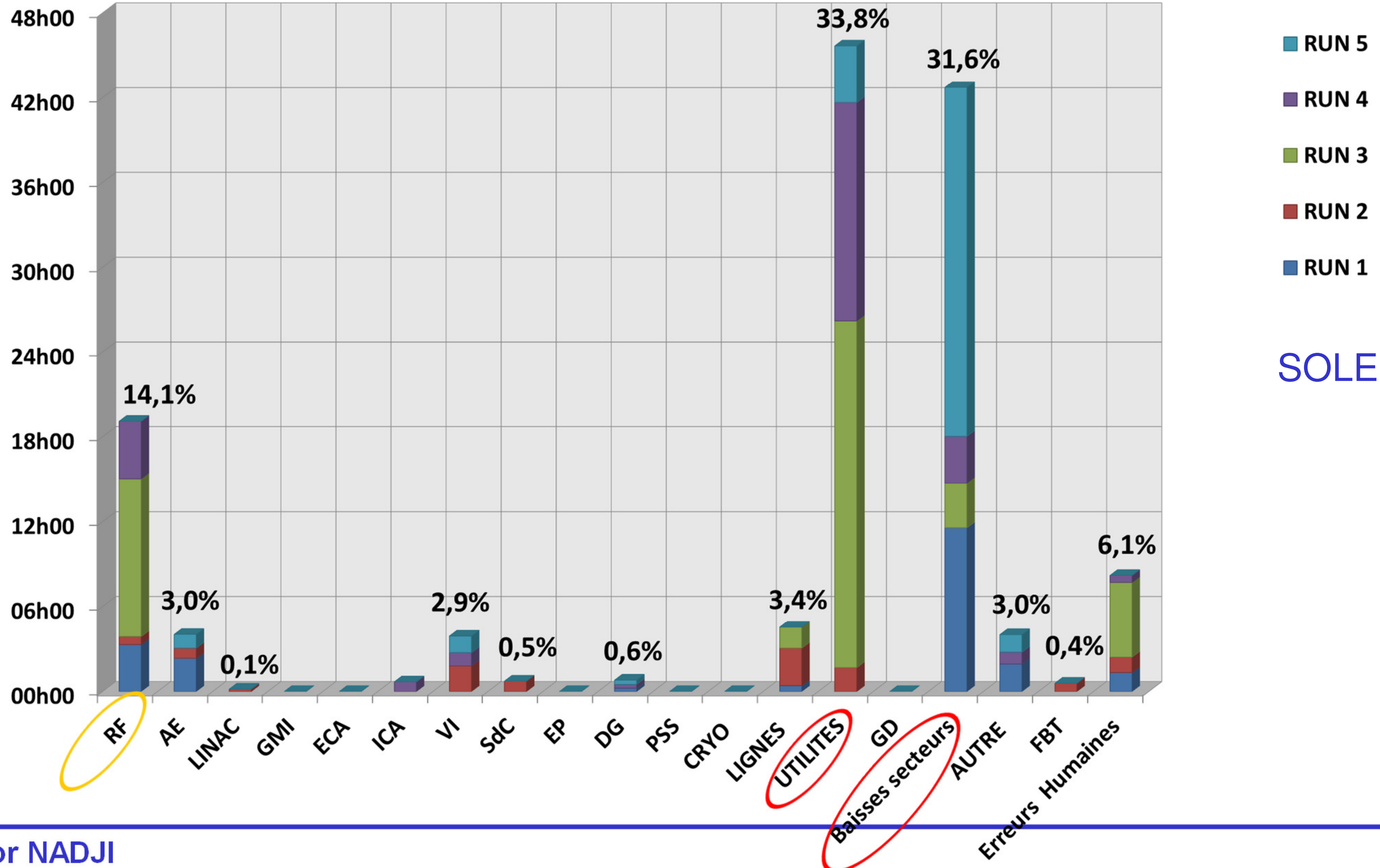
ESRF Record

Machine statistics	**2009**	**2010**	**2011**	***2012***
Availability (%)	99.04	98.78	98.91	***98.6***
Mean time between failures (hrs)	75.8	67.50	107.8	***60.0***
Mean duration of a failure (hrs)	0.73	0.82	1.18	***0.85***

A lot of activities and modifications during the long winter 2011-12 shutdown, the longer summer shutdown, the October shutdown and the longer winter shutdown.

Larger number of failures in 2012 but only a small part of the down time results directly from the upgrade programme

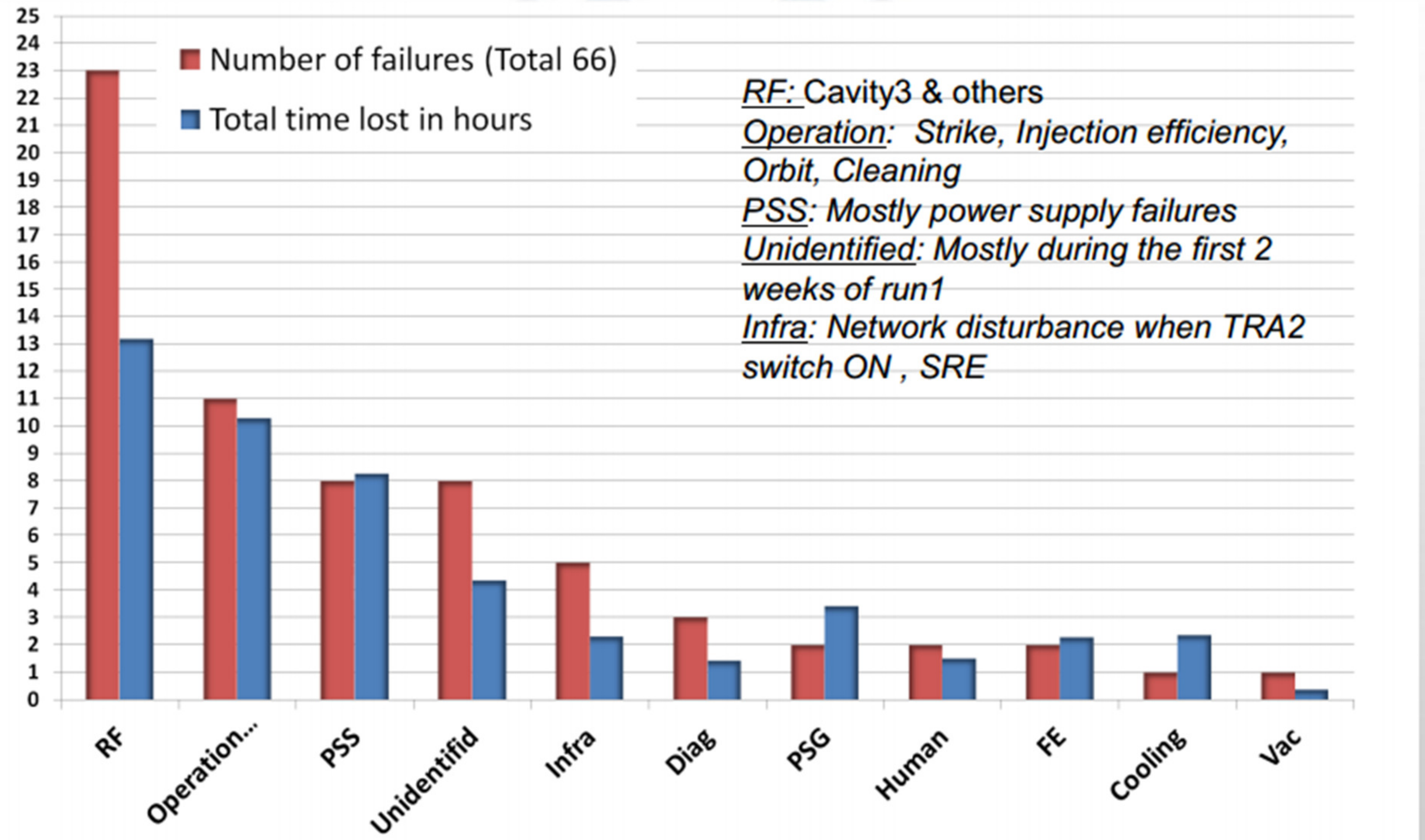
Répartition des 135 heures de pannes avec incidence faisceau stocké (réinjections incluses) par groupe et par RUN, durant les sessions Lignes et RP en 2012, au RUN5



SOLEIL

Machine statistics

A light for Science



RF: *Cavity3 & others*

Operation: *Strike, Injection efficiency, Orbit, Cleaning*

PSS: Mostly power supply failures

Unidentified: Mostly during the first 2 weeks of run1

Infra: Network disturbance when TRA2 switch ON , SRE

MAX IV Magnets

- Pre-series for each type of magnet has been built and approved for mechanical tolerances.

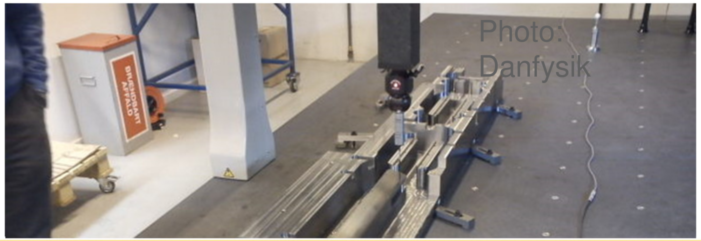


Photo: Danfysik


photo: Anna Olsson, Scanditronix Magnet AB

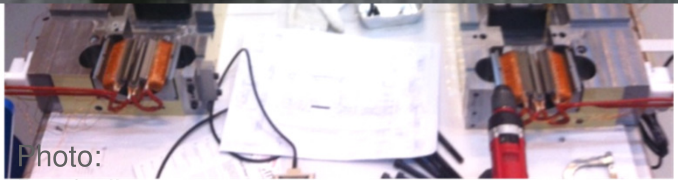


Photo: Danfysik

Assembly

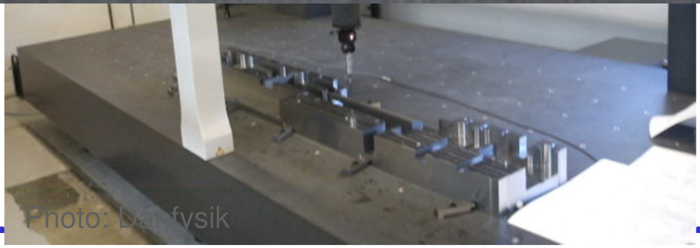
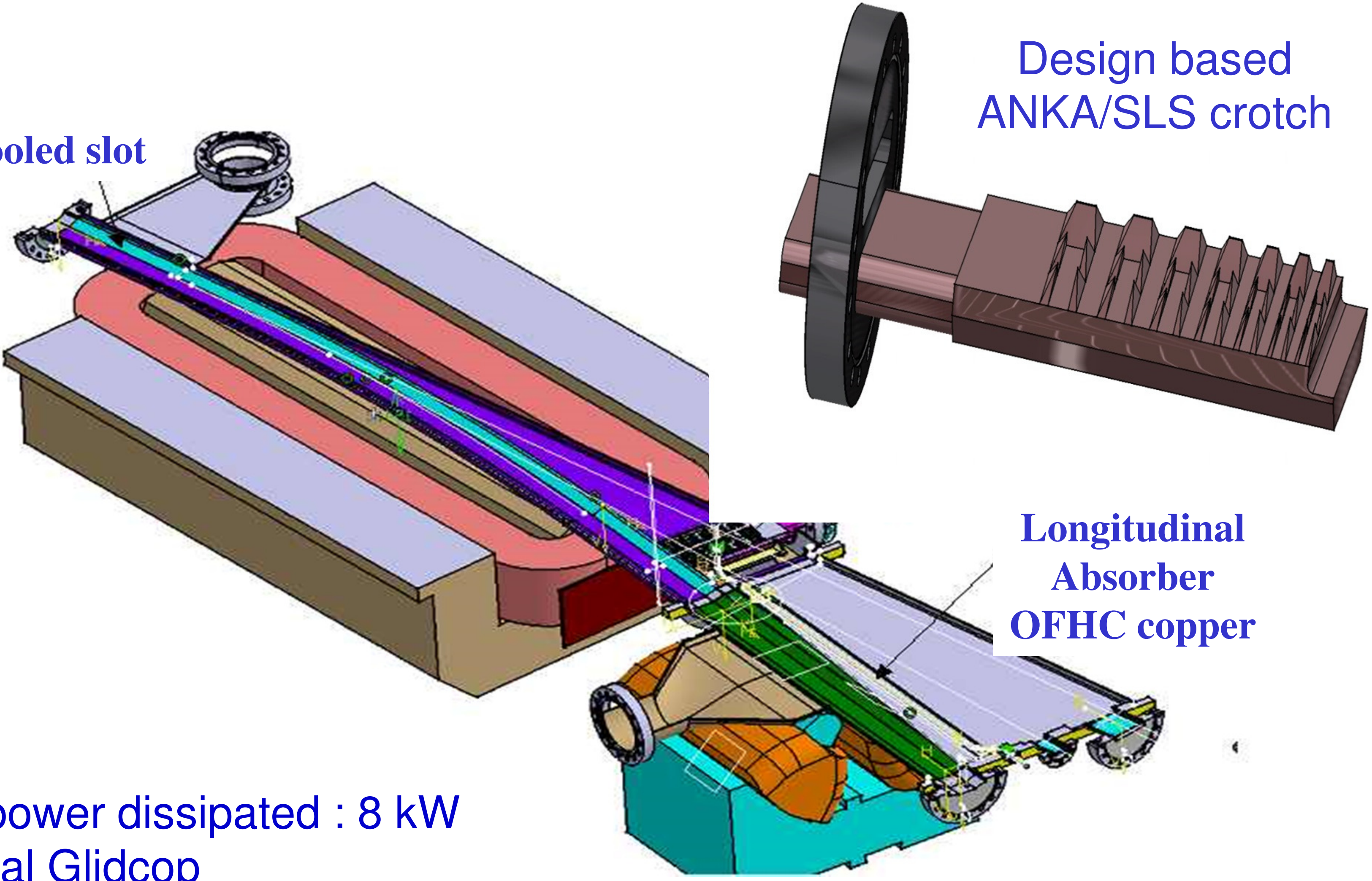


Photo: Danfysik

SOLEIL Dipole Vacuum



Design based ANKA/SLS crotch

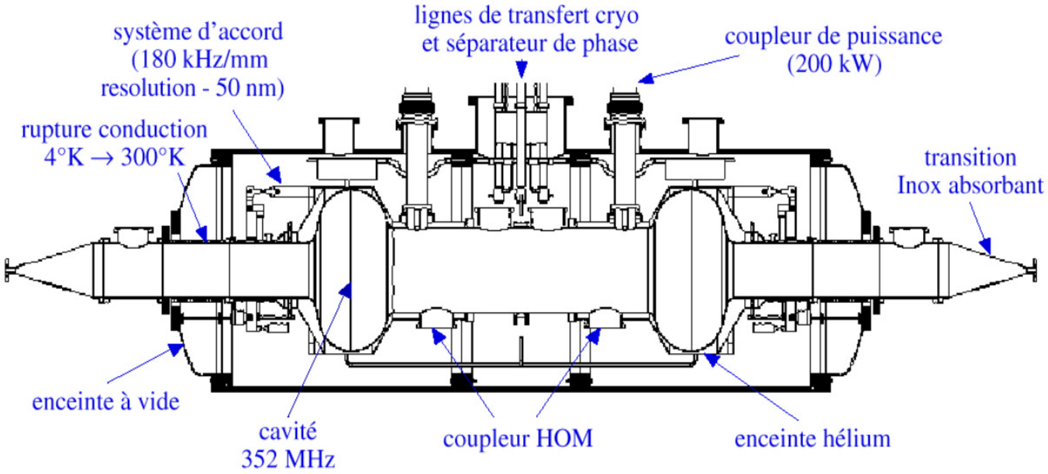
Water cooled slot

Longitudinal Absorber OFHC copper

Total power dissipated : 8 kW
Material Glidcop

RF SYSTEMS : cavities

Superconducting RF cavities : SOLEIL

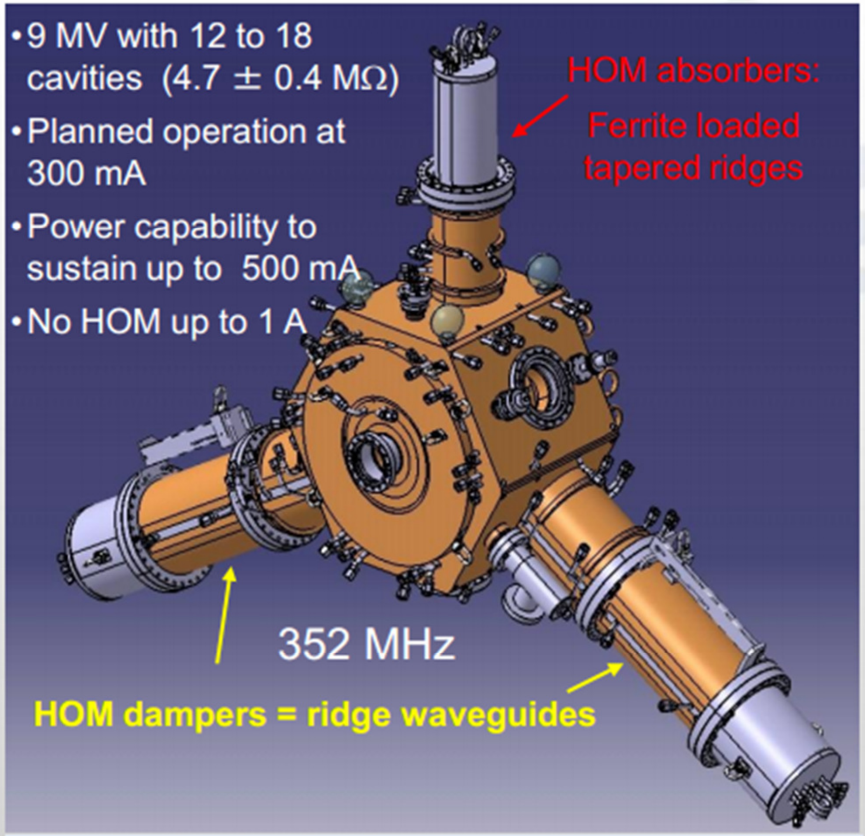


- → **2 cavities @ 352 MHz**
- → **150 kW per cavity (LEP type coupler)**
- → **2MV per cavity**
- → **2 cryomodules installed**
- →**few problems with the cold tuning system**

(Collab CEA/CERN/SOLEIL/ESRF)

Single cell NC HOM damped cavity

A light for Science



- 9 MV with 12 to 18 cavities (4.7 ± 0.4 MΩ)
- Planned operation at 300 mA
- Power capability to sustain up to 500 mA
- No HOM up to 1 A

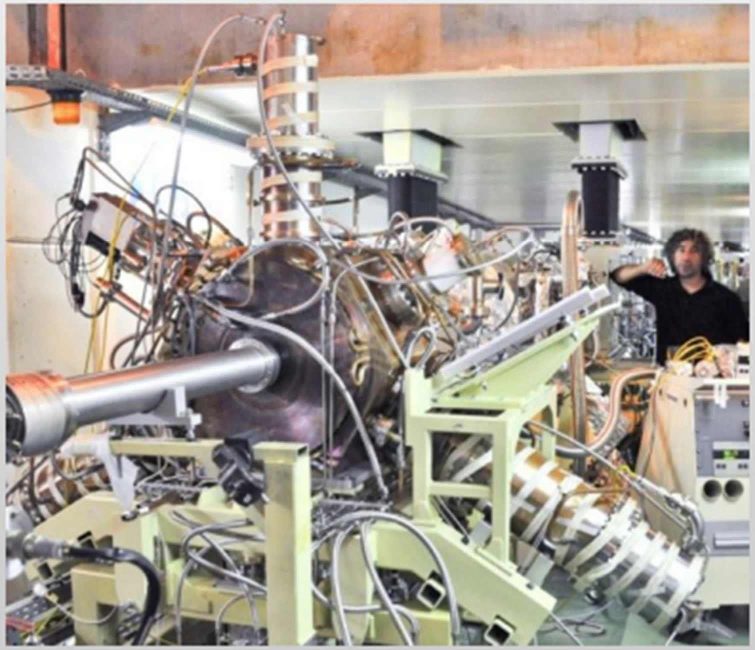
Based on 500 MHz BESSY, MLS, ALBA design [E. Weihreter et al.]

ESRF 352.2 MHz design: several improvements

Goal:

- ➢RF distribution to create new experimental stations
- ➢Prepare future upgrades

➔ 3 Prototypes under test



RF SYSTEMS : Transmitters

IOT's : ELETTRA, DIAMOND, ALBA,..

Solid state amplifier : SOLEIL and more recently ESRF

→ 4x190 kW @ 352 MHz
→ Smooth operation
→ Excellent reliability

190 kW @ 352 MHz
Gain = 52 dB
Overall Efficiency (PS,..) ~60%

BPM Electronic Boards

LIBERA BPM digital electronics provide sub micron resolution, and also :

⇒ simultaneous turn by turn measurement

⇒ slow orbit data

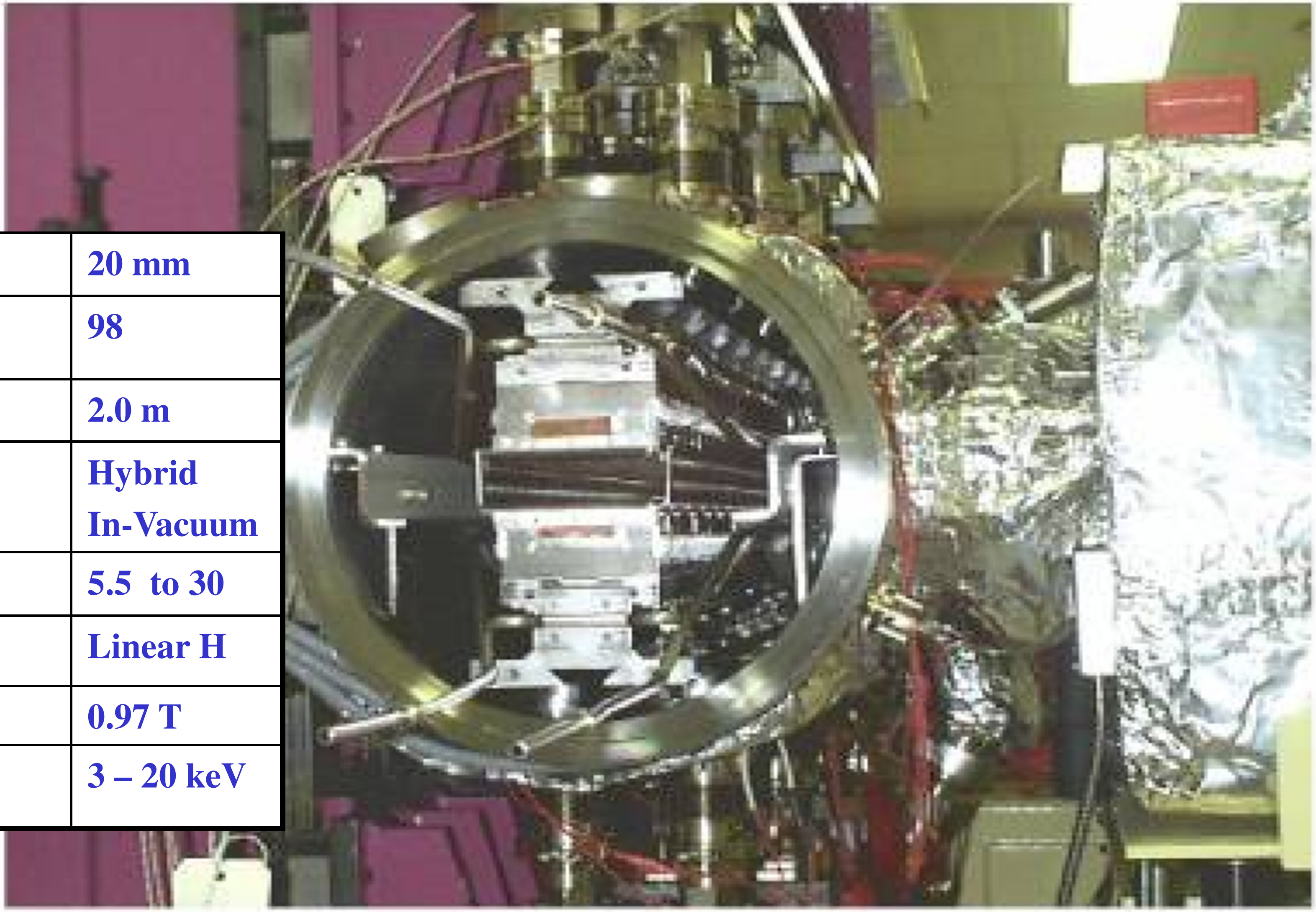
⇒ fast orbit feedback data, and processing

⇒ with low current dependence

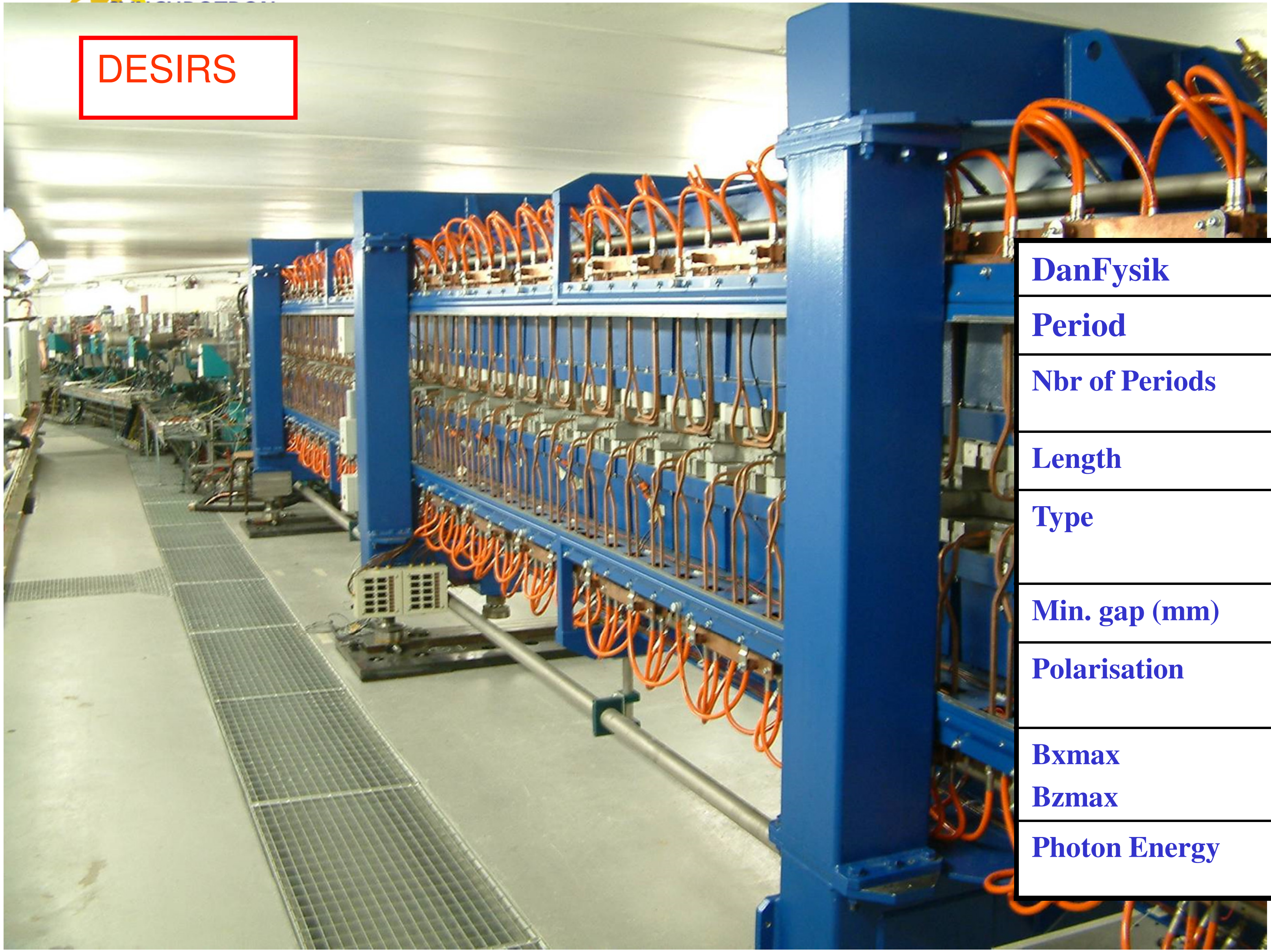
In use at Diamond, SOLEIL, ELETTRA, ASP, ALBA, ESRF, PETRA3,…

Insertion Devices: In-Vacuum undulator U20

Period	**20 mm**
Nbr of Periods	**98**
Length	**2.0 m**
Type	**Hybrid In-Vacuum**
Min. gap (mm)	**5.5 to 30**
Polarisation	**Linear H**
Bzmax	**0.97 T**
Photon Energy	**3 – 20 keV**



Electromagnet Helical Undulator HU640



DanFysik	HU640
Period	640 mm
Nbr of Periods	14
Length	10.0 m
Type	Electro-magnetic
Min. gap (mm)	19
Polarisation	Circ./Lin. adjustable
Bxmax Bzmax	0.09 T 0.11 T
Photon Energy	5 – 40 eV

Apple-II Type Helical Undulator HU80

Period	**80 mm**
Number of Periods	**19**
Length	**1.65 m**
Type	**Apple-II**
Minimum gap (mm)	**15 to 250**
Polarisation	**Circ./Lin.**
Bxmax **Bzmax**	**0.76 T** **0.85 [1.0] T**
Photon Energy	**80 [35] – 1500 eV**

Superconducting Wigglers

Superconducting wigglers are used when a high magnetic field is required 3 - 10 T

They need a cryogenic system to keep the coil superconductive

Nb_3Sn and NbTi wires

SCMPW60 at Diamond

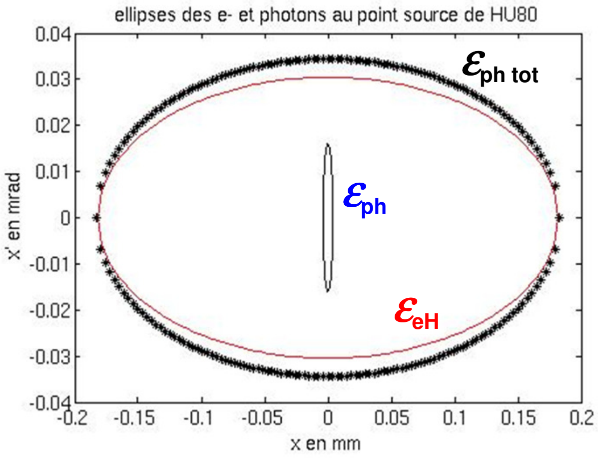
3.5 T coils cooled at 4 K

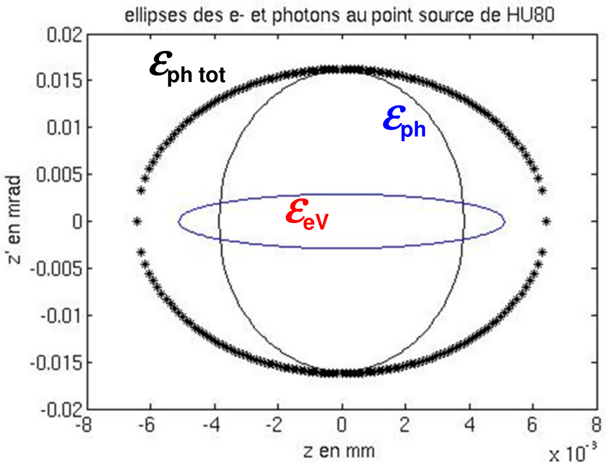
24 period of 64 mm

gap 10 mm

Undulator K = 21

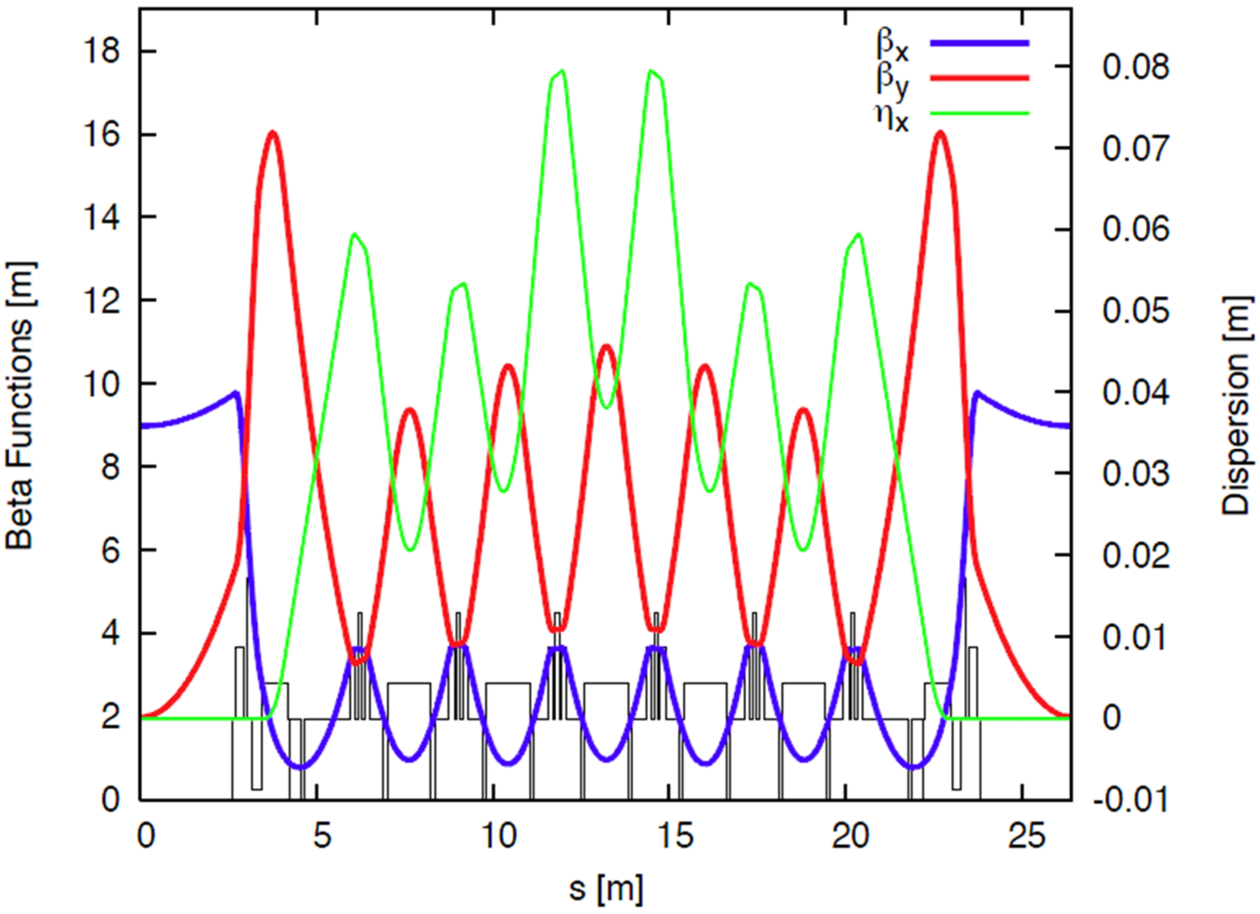
Further decrease of the horizontal emittance





	Electrons beam dimensions		Photons beam dimensions	
	σ_e µm	σ'_e µrad	σ_{tot} µm	σ'_{tot} µrad
Plan H	182	30.4	183	34
Plan V	5.1	2.9	6.5	16

MBA structure



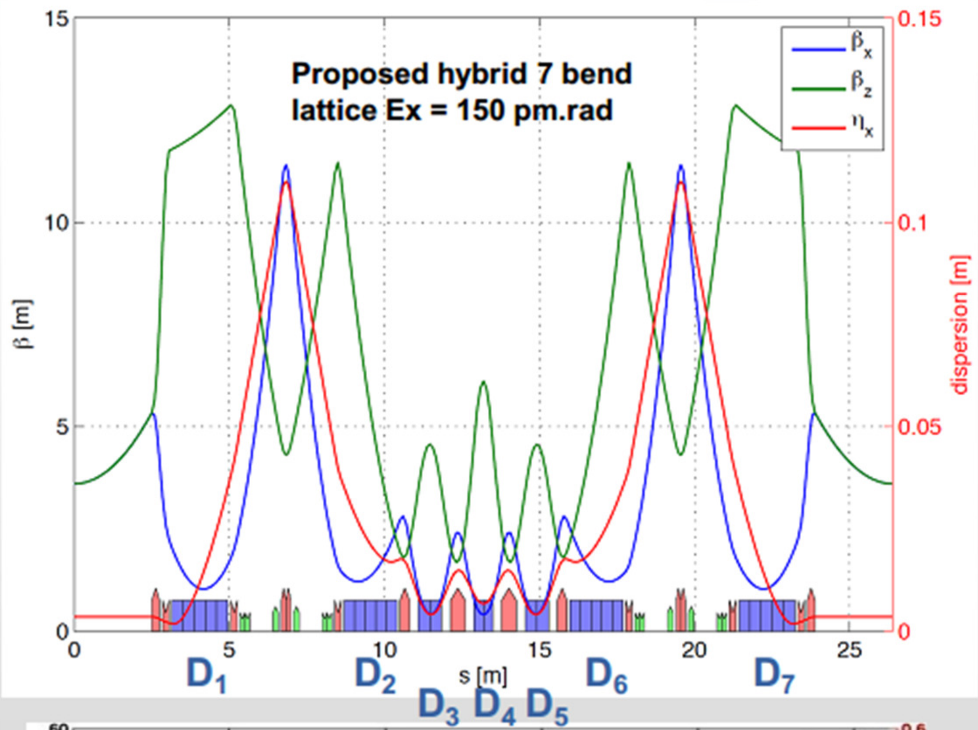
MAX IV

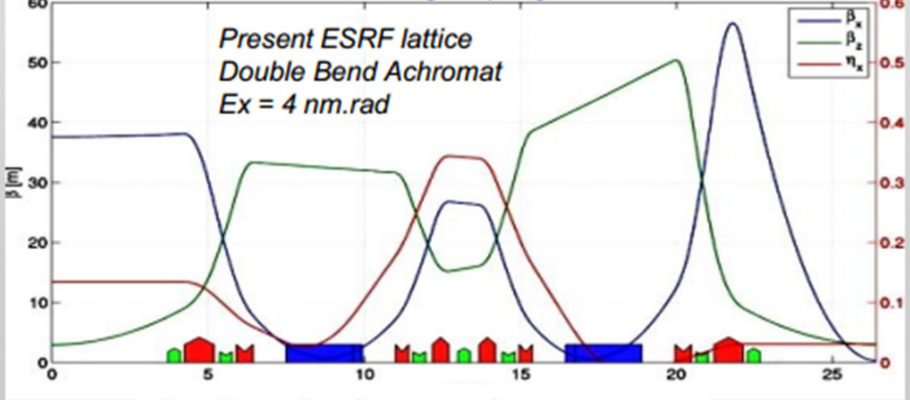
3 GeV
0.34 nm.rad

Under construction

The ESRF low emittance lattice

See: Poster MOPEA008





Bleu: Dipoles Red: Quadrupoles Green: sextupoles

@ 7 bending magnets D_{1to7}
➔ reduce the horizontal emittance

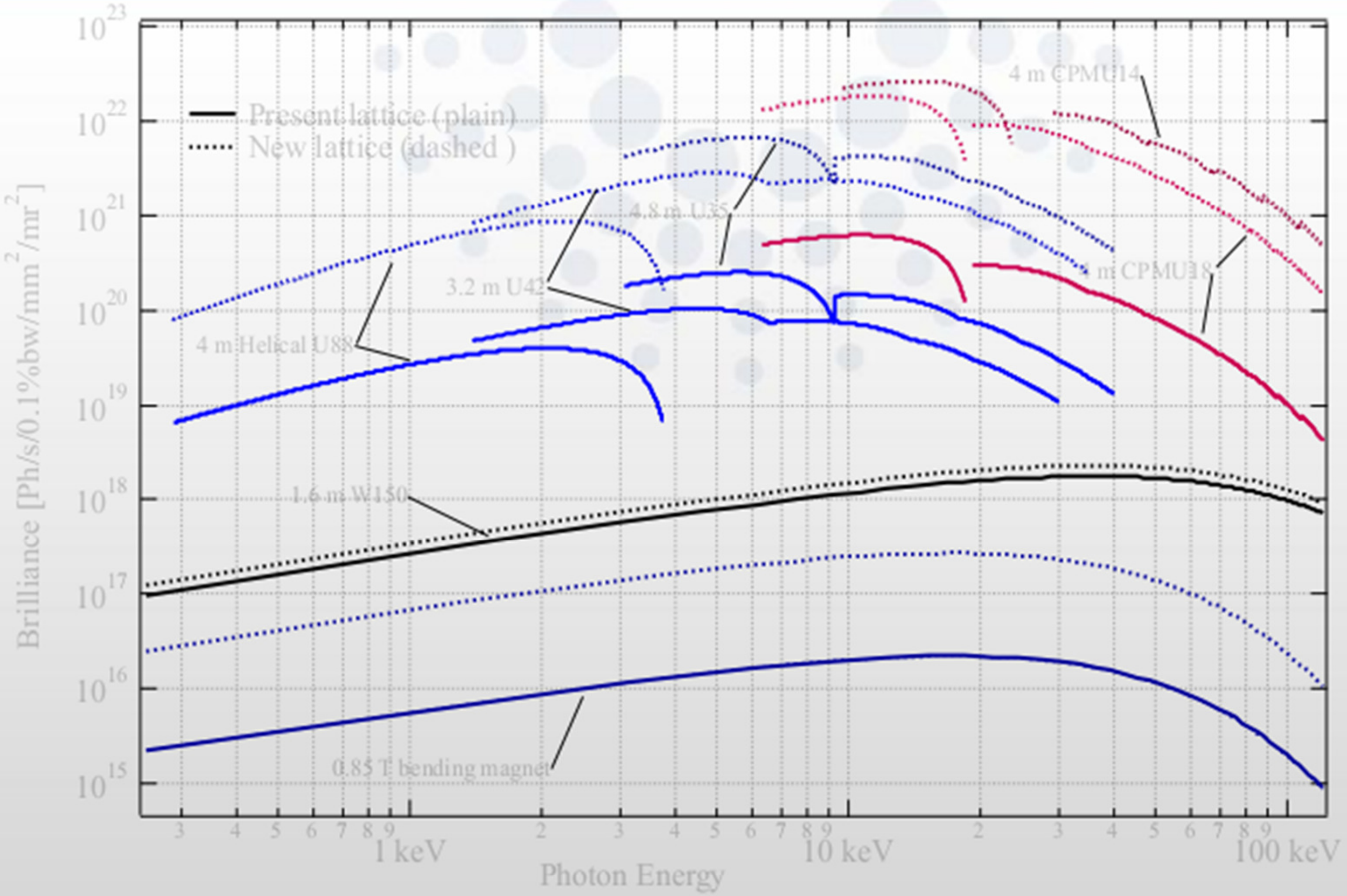
@ Space between D_1-D_2 and D_6-D_7
β-functions and dispersion allowed to growth
➔ chromaticity correction
with efficient sextupoles

@ Dipoles D_1, D_2, D_6, D_7
➔ longitudinally varying field to further reduce emittance

@ Central part alternating
➔combined dipole-quadrupoles$D_{3\text{-}4\text{-}5}$
➔high gradient focusing quadrupoles
@ D_4 (0.34T) and D_5 (0.85T)
➔Source points for BM beamlines

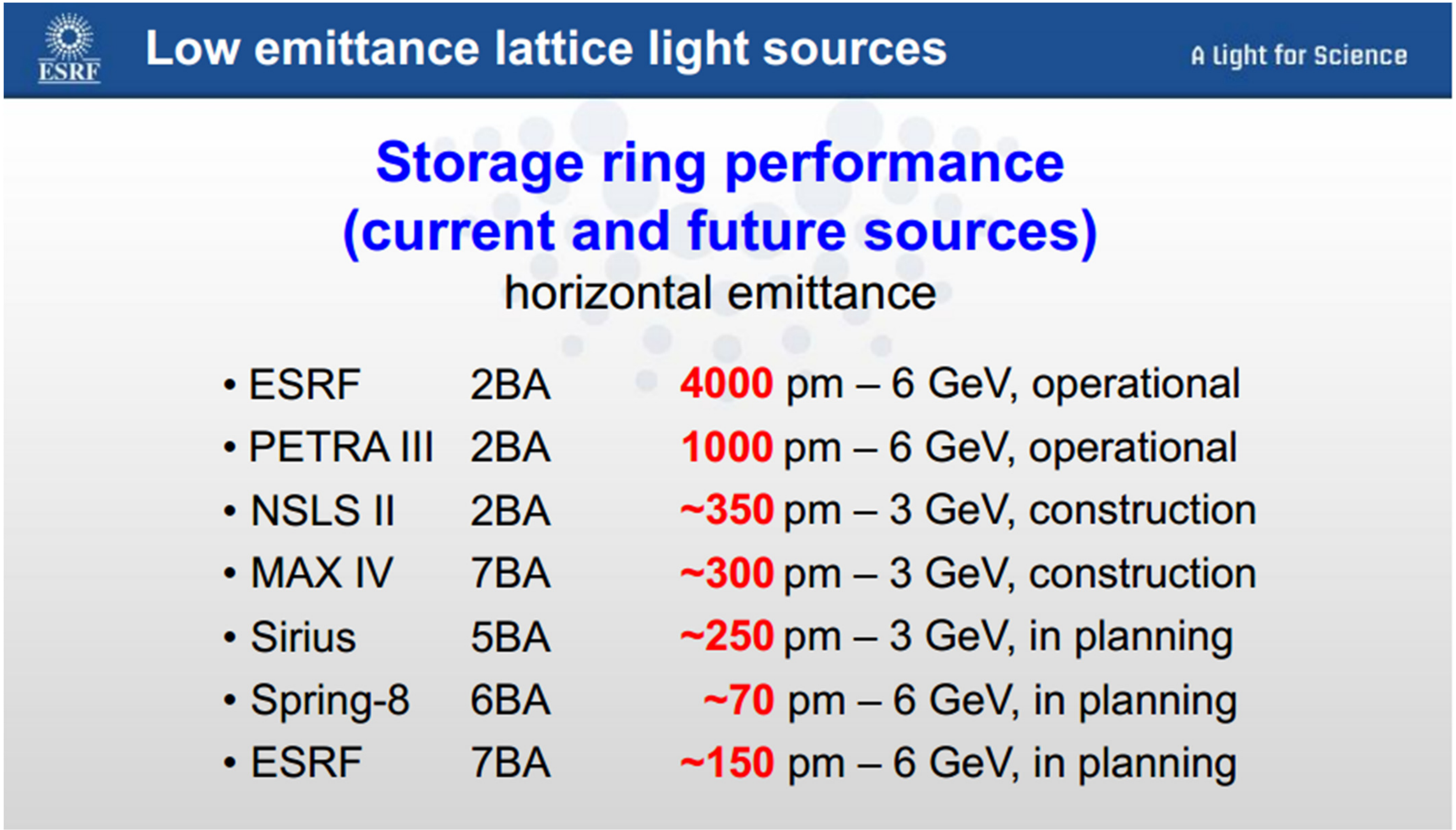
Brilliance at lower horizontal emittance

A Light for Science



Hor. Emittance [nm]	4	0.15
Vert. Emittance [pm]	3	2
Energy spread [%]	0.1	0.09
β_x[m]/β_z [m]	37/3	3.4/2.8

E = 6.04 GeV
I = 200 mA



Low emittance lattice light sources

A light for Science

Storage ring performance (current and future sources)

horizontal emittance

ESRF	2BA	**4000** pm – 6 GeV, operational
PETRA III	2BA	**1000** pm – 6 GeV, operational
NSLS II	2BA	**~350** pm – 3 GeV, construction
MAX IV	7BA	**~300** pm – 3 GeV, construction
Sirius	5BA	**~250** pm – 3 GeV, in planning
Spring-8	6BA	**~70** pm – 6 GeV, in planning
ESRF	7BA	**~150** pm – 6 GeV, in planning

Robinson Wiggler

- Horizontal (natural) emittance: $\varepsilon_{x0} = \dfrac{C_q \gamma^2 \langle H \rangle_{dipole}}{J_x \rho_x}$

- J_x is related to the damping partition D by: $J_x = 1 - D$

$$D = \frac{\oint \frac{\eta_x}{\rho_x^3} ds + \boxed{\frac{2}{B^2 \rho_x^2} \oint \eta_x B \frac{dB}{dx} ds}}{\oint \frac{ds}{\rho_x^2}}$$

If $D = -1$ ➡ $J_x = 2$

The horizontal emittance can be divided by a factor 2

But with an increase of energy spread by a factor $\sqrt{2}$

Such as: $J_x + J_z + J_s = 4$ where $J_z = 1$ and $J_s = 1$

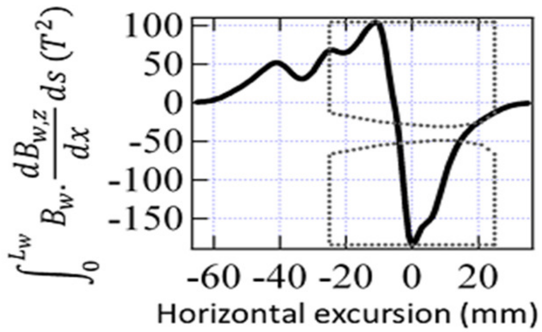
A magnetic element introducing the product ***B*dB/dx*** in a straight section where the dispersion η_x is **non zero** contributes to the modification of D.

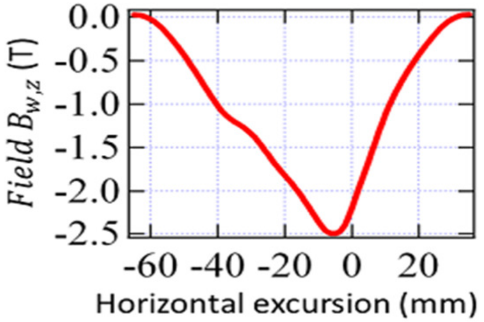
If this magnetic element is such as the field ***(B)*** and the gradient ***(dB/dx)*** are of opposite sign, this contribution is ***negative*** and consequently we can try to find the conditions to make **D =-1**!

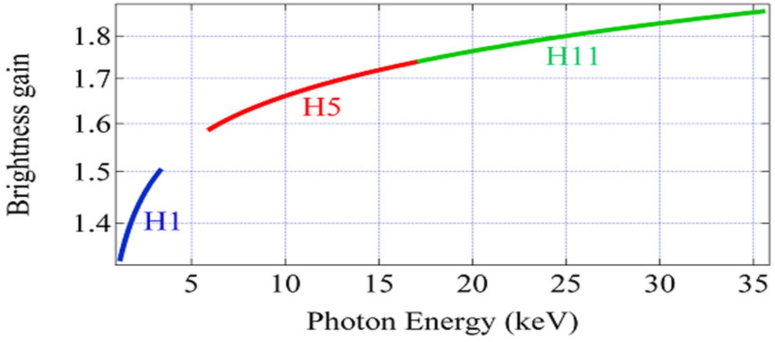
Application to SOLEIL: **(work in progress by a PhD student)**

- In short straight sections of the SOLEIL Storage Ring: $\eta_x = 28$ cm.

$$D \approx 5.6\times10^{-3}\left\langle B_w \frac{dB_{w,z}}{dx}\right\rangle L_w \quad \text{Where} \quad \left\langle B_w \frac{dB_{w,z}}{dx}\right\rangle L_w \approx 193\,T^2 \quad \text{and} \quad L_w \approx 2\,m$$







(see H. Abualrob et al., IPAC'12)

CONCLUSIONS

⇒ **Third generation light sources are very reliable sources of high brilliance, which provide very stable photon beam from IR to hard X-rays.**

⇒ **They operate ~5000 hours/year mostly in Top-up, with > 95% beam time availability.**

⇒ No evidence of under subscription: the demand from the User's community and the number of beamlines per facility is still 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 brilliance and more coherence* => **ultra low emittance ~ 10 – 500 pm**
- ➢ *Technological progress is needed to reach the challenging goal*