ACCELERATOR GROUP
European Physical Society

IPAC23

14th International Particle Accelerator Conference

IPAC '23

7 - 12 May 2023

VENICE, ITALY

Hosting institutions

Elettra Sincrotrone Trieste

INFN
Istituto Nazionale di Fisica Nucleare

Student Tutorials 5,6 May

Synchrotron Light Sources: how do they work? And what about Inverse Compton Scattering?

Student Tutorials, 6 May 2023 IPAC 2023, Venice, Italy
Ryutaro Nagaoka
Synchrotron SOLEIL

Outline:

- **I. How were the storage ring-based light sources born?**
- **II. Characteristics of the 3rd Generation Light Sources**
- **III. Towards the 4th GLSs (or what are called Diffraction-Limited Storage Rings)**
- **IV. What are the “Ring-based Inverse Compton Scattering Light Sources”?**
- **V. Summary and Perspectives**

Acknowledgement

RN thanks his colleagues in the Accelerator Physics group of SOLEIL for their help in preparing this talk

Part I

How were the storage ring-based light sources (LS) born?

Subjects Treated:

- **Origin of storage ring-based synchrotron radiation sources**
- **Characteristics of synchrotron radiation (SR)**
- **Evolution of LS rings from 1st to 2nd and 3rd generations**

Origin of ring-based SR sources

◊ Why are electron storage rings such as SOLEIL serving today as light sources?

◊ History of accelerator development:

Initial non-circular straight accelerators

⇓

Cyclotrons

⇓

Synchrotrons

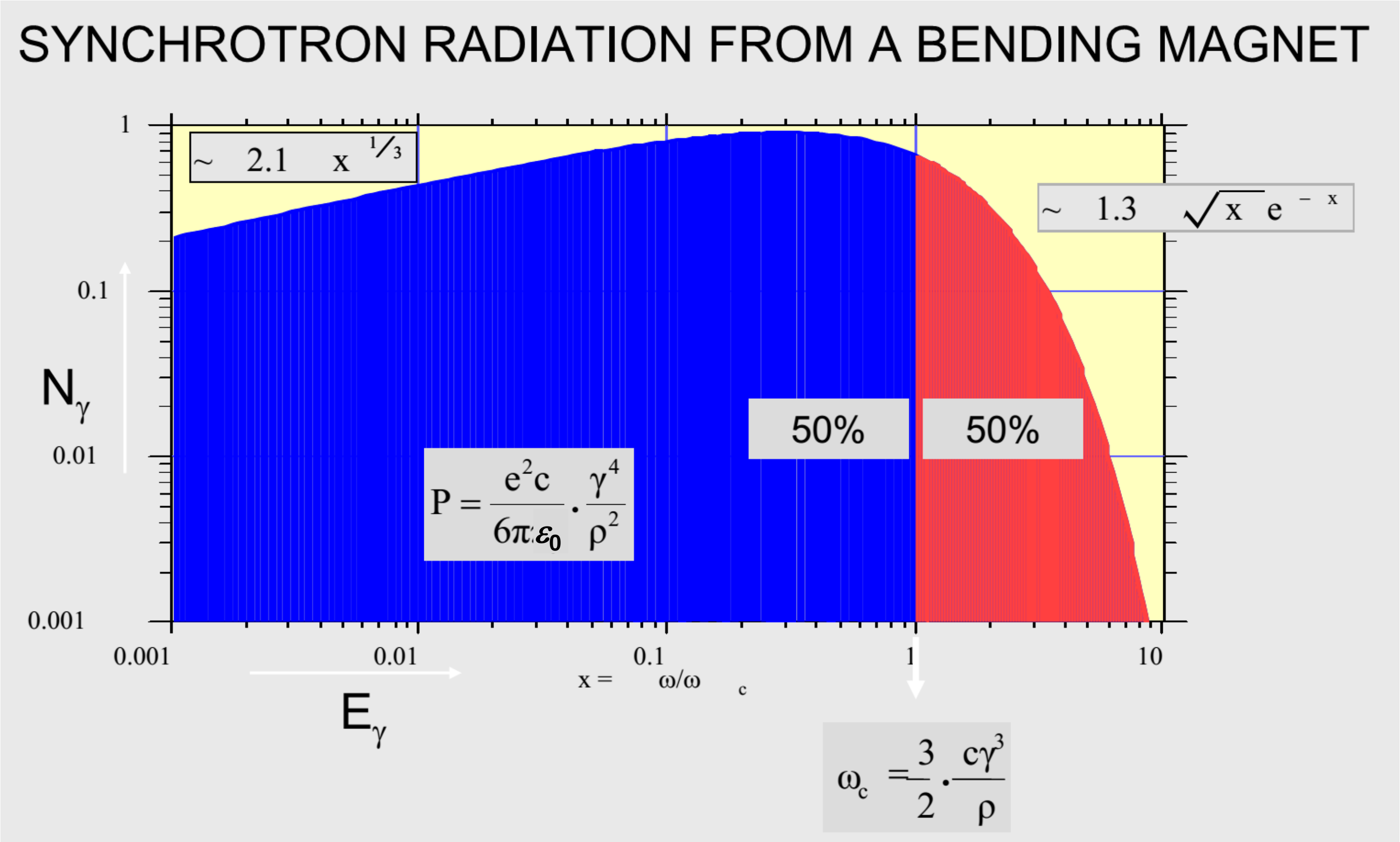
⇓

Synchrotron radiation (SR) as a major obstacle for high energy physics experiments

⇓

Discovery of the good properties of synchrotron radiation for material science and ***parasitic*** use of SR in high energy physics synchrotrons (1st generation) in 1960s

Characteristics of SR (1/2)

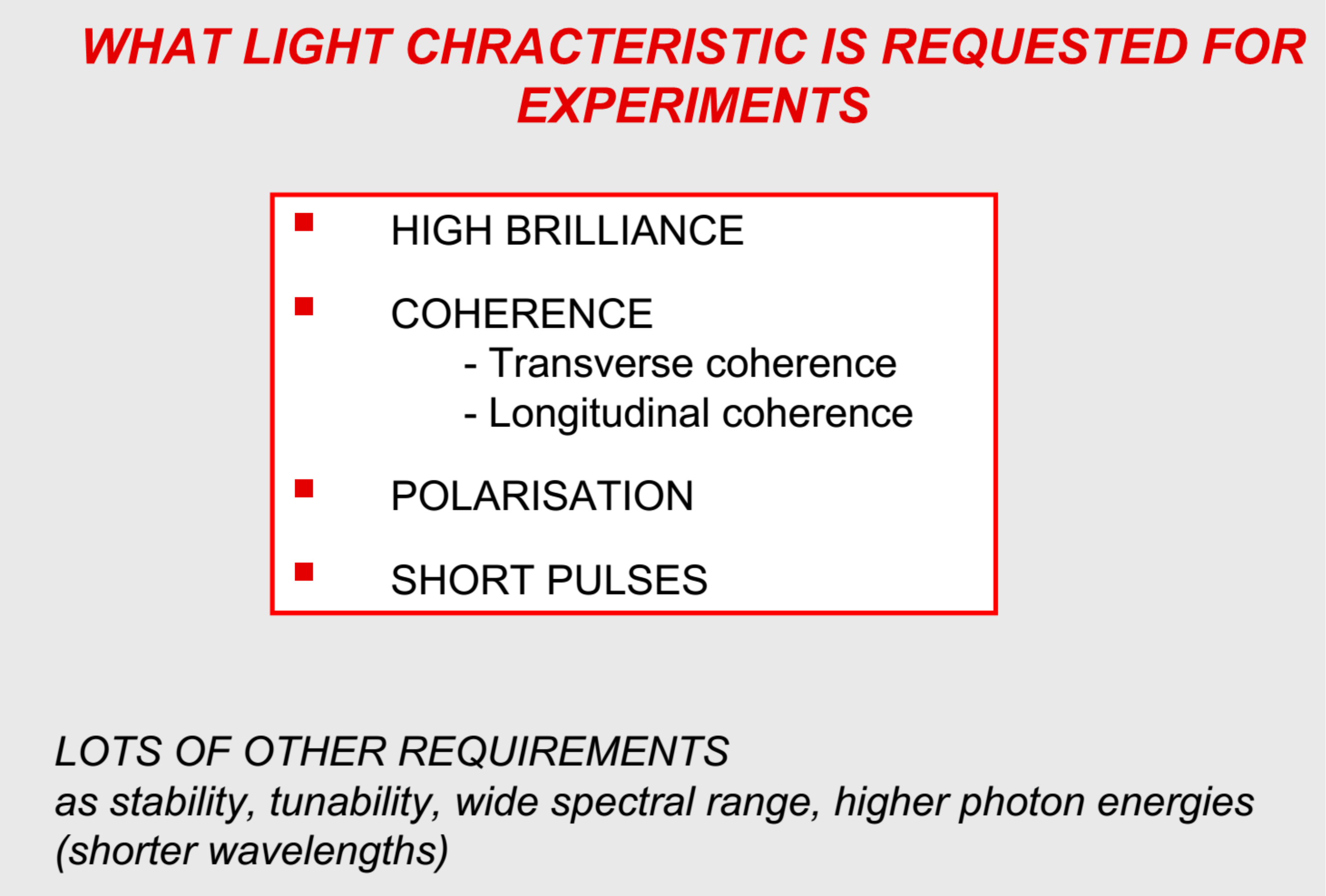


$$P = \frac{e^2 c}{6\pi\varepsilon_0} \cdot \frac{\gamma^4}{\rho^2}$$

$$\omega_c = \frac{3}{2} \cdot \frac{c\gamma^3}{\rho}$$

(taken from a lecture given by Albin Wrulich (PSI) at CERN Accelerator School in 2004)

Characteristics of SR (2/2)



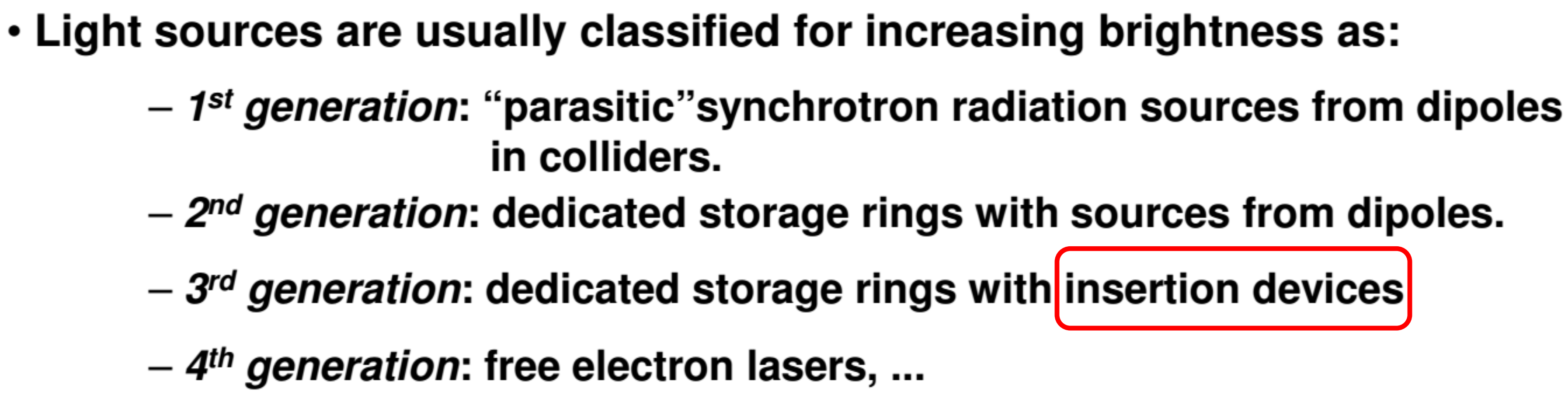
WHAT LIGHT CHRACTERISTIC IS REQUESTED FOR EXPERIMENTS

- HIGH BRILLIANCE
- COHERENCE
  - Transverse coherence
  - Longitudinal coherence
- POLARISATION
- SHORT PULSES

LOTS OF OTHER REQUIREMENTS
as stability, tunability, wide spectral range, higher photon energies (shorter wavelengths)

(taken from a lecture given by Albin Wrulich (PSI) at CERN Accelerator School in 2004)

Evolution from 1^{st}, 2nd to 3^{rd} GLSs (1/3)



- **Light sources are usually classified for increasing brightness as:**
  - **1^{st} *generation*: "parasitic"synchrotron radiation sources from dipoles in colliders.**
  - **2^{nd} *generation*: dedicated storage rings with sources from dipoles.**
  - **3^{rd} *generation*: dedicated storage rings with insertion devices**
  - **4^{th} *generation*: free electron lasers, ...**

(taken from a lecture given by Fernando Sannibale (LBL) at Univ. New Mexico in 2014)

Evolution from 1st, 2nd to 3rd GLSs (2/3)

L12: Ring-Based
Light Sources
F. Sannibale

Examples of Existing Ring Based Light Sources

SLS (2002) 2.4 GeV
ε_x= 3.9 nm, ε_y=72 pm, I=300 mA

ALS (1993) 1.9 GeV
ε_x= 2.0/2.5 nm, ε_y=30 pm, I=500 mA

LNLS (1997) 1.37 GeV
ε_x= 100 nm, ε_y ~ 1nm, I=250 mA

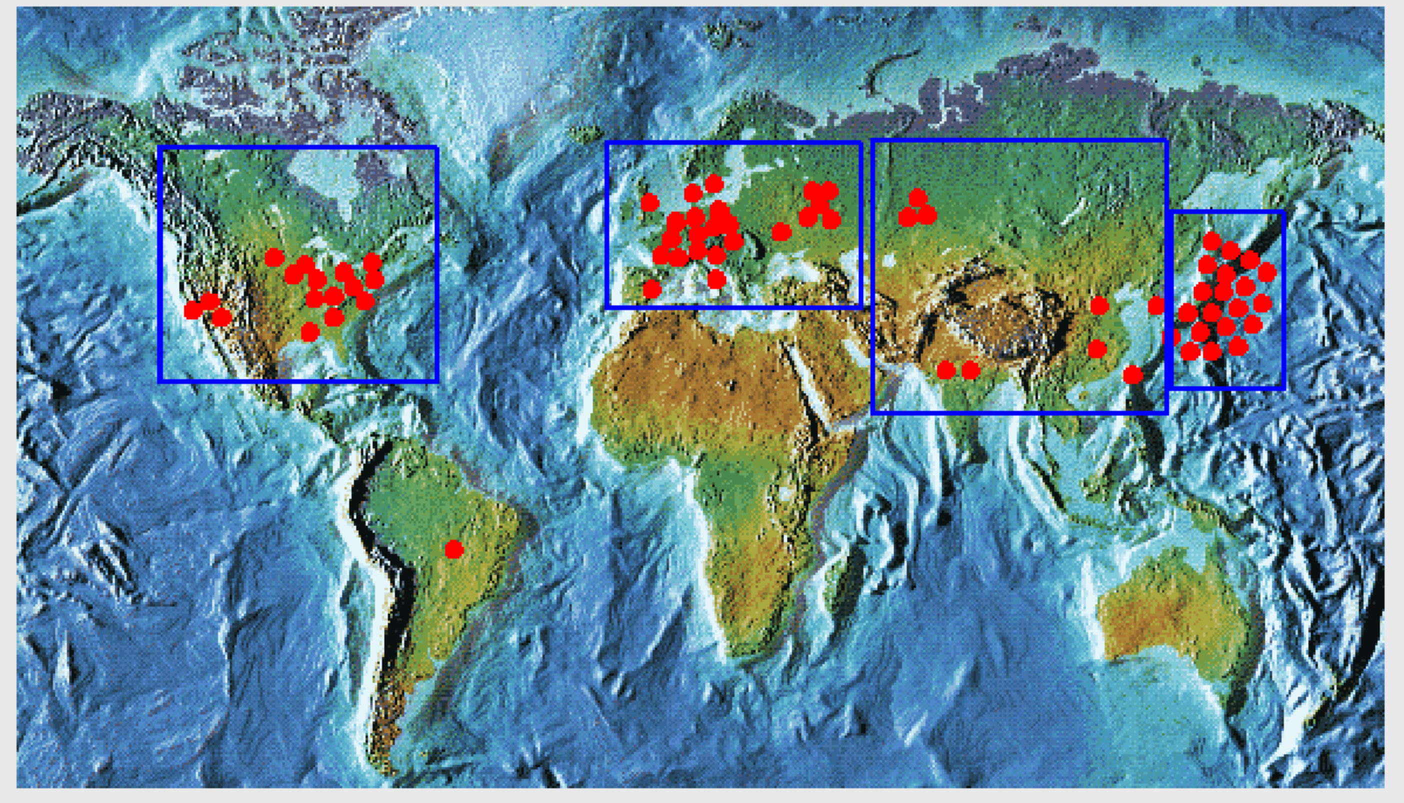
Soleil (2006) 2.75 GeV
ε_x= 3.7/5.6 nm, ε_y=37 pm,
I=400(500) mA

APS (1995) 7 GeV
ε_x= 2.5/3 nm, ε_y=30 pm, I=100 mA

Diamond (2007) 3 GeV
ε_x= 3.0 nm, ε_y= 30 pm, I=300(500) mA

(taken from a lecture given by Fernando Sannibale (LBL) at Univ. New Mexico in 2014)

Evolution from 1st, 2nd to 3rd GLSs (3/3)



(taken from a lecture given by Albin Wrulich (PSI) at CERN Accelerator School in 2004)

Part II

Characteristics of 3rd Generation Light Sources (GLSs)

Subjects Treated:

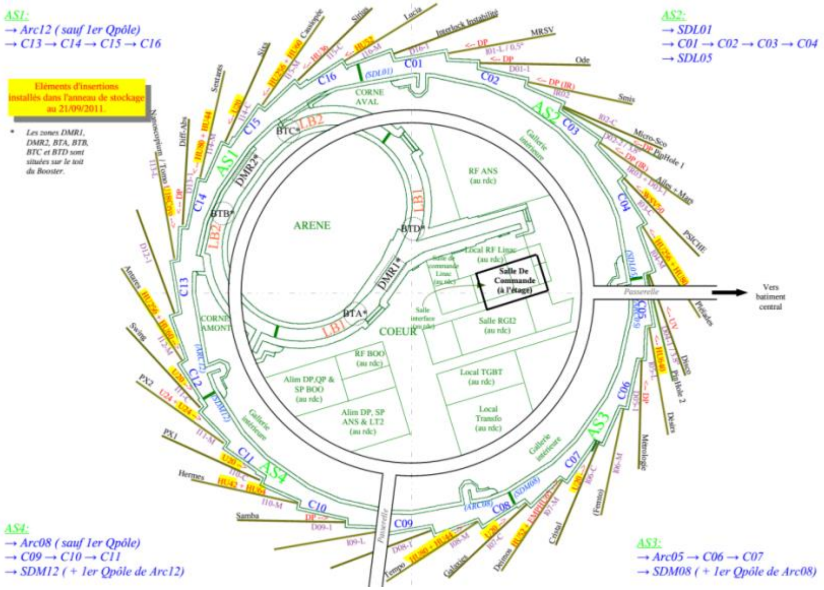
- **Design goals**
- **Ring structure**
- **Beam dynamics issues**
- **Operational aspects**

Design goals (1/2)

Goals and the target performance of 3rd Generation Ring-Based Light Sources (3GLSs):

Constant delivery of a high quality, intense and stable photon beam to a large number of beamlines

<u>Currently running 3GLSs</u>:
Many free straights for IDs (Insertion Devices). IDs and dipoles used for photon beamlines.
Ring magnet lattice elaborated to provide a low emittance electron beam with a large ratio (free straight sections)/ circumference



29 beamlines (22 IDs + 7 dipoles) at SOLEIL

Design goals (2/2)

High quality and intense photon beams: Often characterized in terms of

$$Brilliance = \frac{Photons}{Second \cdot mrad^2 \cdot mm^2 \cdot 0.1\%BW} \propto \frac{I}{\varepsilon_x \varepsilon_y}$$

I : Beam current, ε_u : Transverse emittance

$\Rightarrow$ Two major axes in increasing Brilliance:

1) Lowering the transverse emittances ε_x and ε_y
2) Increasing the beam intensity I

Ring structure

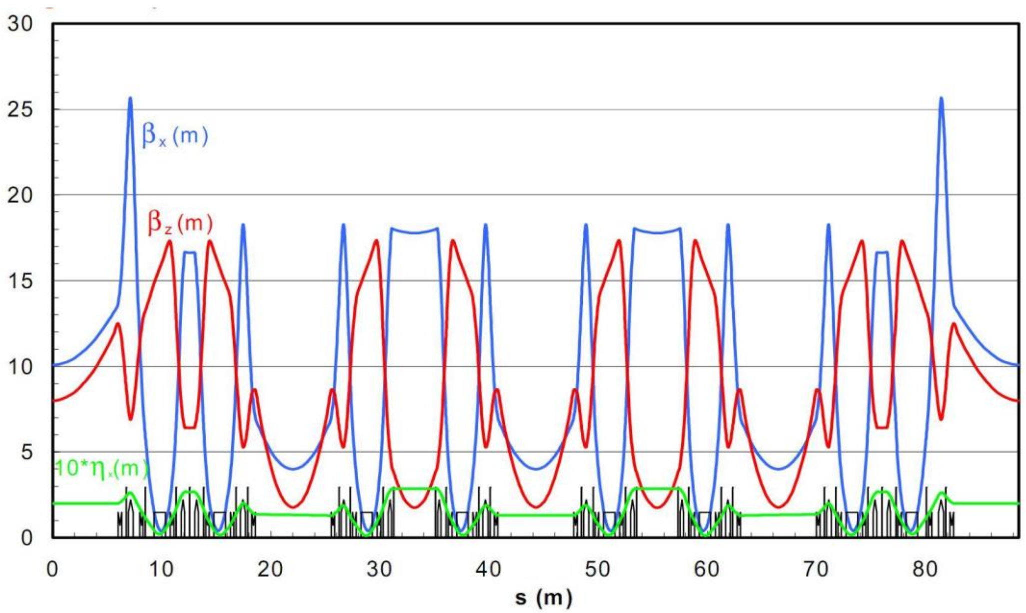
- There are two reasons to want to have the ring composed of many identical cells:
  1) To introduce many free straight sections for insertion devices (IDs)
  2) To avoid dangerous structural resonances occurring on particle motions

- In 3GLSs, a Double-Bend (DB) cell is popular since it allows designing a low-emittance optics in a compact structure, thus leaving longer distance for free straight sections

One quarter of the ring composed of 4 Double-Bend (DB) cells for SOLEIL.

⇓

24 straights (4×12 m + 12× 7 m + 8× 3.6 m) over 354 m of circumference, i.e. ***45%*** *availability at SOLEIL, in a DB lattice*



Beam dynamics issues

◊ In following the “two axes” mentioned earlier to improve the storage ring performance as a light source, serious beam dynamics issues emerge due to the effort of lowering the emittance:

Issues related to single particle dynamics:

Strong focusing with quadrupoles to approach the theoretical minimal emittance condition

→ Large chromaticities
→ Strong sextupoles to correct the chromaticities
→ Strong limitation of the stability of particle motions (i.e. small “dynamic apertures”)
→ Injection and beam lifetime limitations and large sensitivity of the optics to imperfections

Issues related to collective beam dynamics:

Strong focusing with quadrupoles to approach the theoretical minimal emittance condition

→ Smaller magnet bore radii
→ Narrower vacuum chamber (VC) apertures
→ Higher coupling impedance (larger EM interactions with electrons and VCs)
→ High intensity beam becoming more unstable collectively

Operational aspects (1/2)

- One another important performance of a ring-based LS is to store an electron beam in ***different filling modes*** to satisfy those users who are utilizing the time structure of SR in their experiments (so called ***time-resolved experiments***)

- In addition, if the ring is capable of storing a short electron bunch (normally in several picosecond order), it may satisfy users that request longitudinal coherence in SR

Mode of operation Bunch filling patterns	User Operation in 2016	Ultimate performance achieved
Multibunch	500 mA	500 mA
Hybrid/camshaft mode	425 mA + 5 mA	425 mA + 10 mA
	+ Slicing on high intensity bunch	Slice length < 200fs FWHM
8 bunches	100 mA	110 mA
1 bunch	16 mA	20 mA
Low-α: Hybrid mode	4.7 ps RMS for 65μA	< 3.2 ps RMS for 15 μA

Five modes of operation provided by SOLEIL to its users

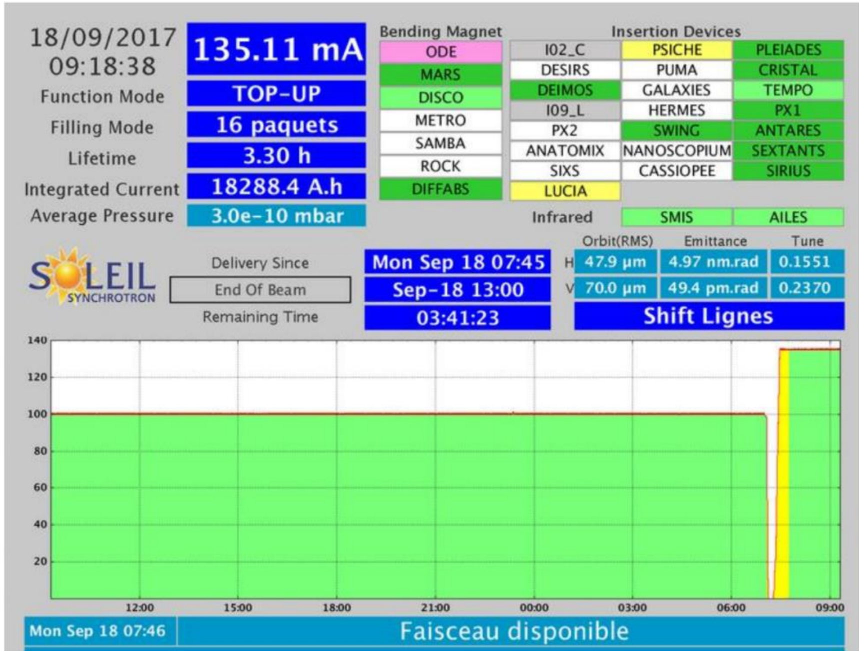
Operational aspects (2/2)

◊ For the constant delivery of stable beam, the following efforts are made:

- Construction of a ring on solid foundation and drill pillars into the ground to stabilize the floor
- Development of a fast and accurate (μm level) orbit correction system
- Topping-up to keep the beam intensity constant (see the graph below)
- Permanent running of a number of feedback systems to keep the machine and the beam stable

◊ Many 3GLSs are operated 24h/24 and over 5000 hours/year for users

◊ As the beam availability is crucial, great efforts are constantly made to keep the availability close to 100%, maximize the Mean Time Between Failures (MTBF) and minimize the Mean Time To Recover (MTTR).



18/09/2017
09:18:38
135.11 mA
Function Mode: TOP-UP
Filling Mode: 16 paquets
Lifetime: 3.30 h
Integrated Current: 18288.4 A.h
Average Pressure: 3.0e-10 mbar

Bending Magnet

ODE
MARS
DISCO
METRO
SAMBA
ROCK
DIFFABS

Insertion Devices

I02_C	PSICHE	PLEIADES
DESIRS	PUMA	CRISTAL
DEIMOS	GALAXIES	TEMPO
I09_L	HERMES	PX1
PX2	SWING	ANTARES
ANATOMIX	NANOSCOPIUM	SEXTANTS
SIXS	CASSIOPEE	SIRIUS
LUCIA		

Infrared: SMIS, AILES

Delivery Since: Mon Sep 18 07:45
End Of Beam: Sep-18 13:00
Remaining Time: 03:41:23

	Orbit(RMS)	Emittance	Tune
H	47.9 µm	4.97 nm.rad	0.1551
V	70.0 µm	49.4 pm.rad	0.2370

Shift Lignes

Mon Sep 18 07:46
Faisceau disponible

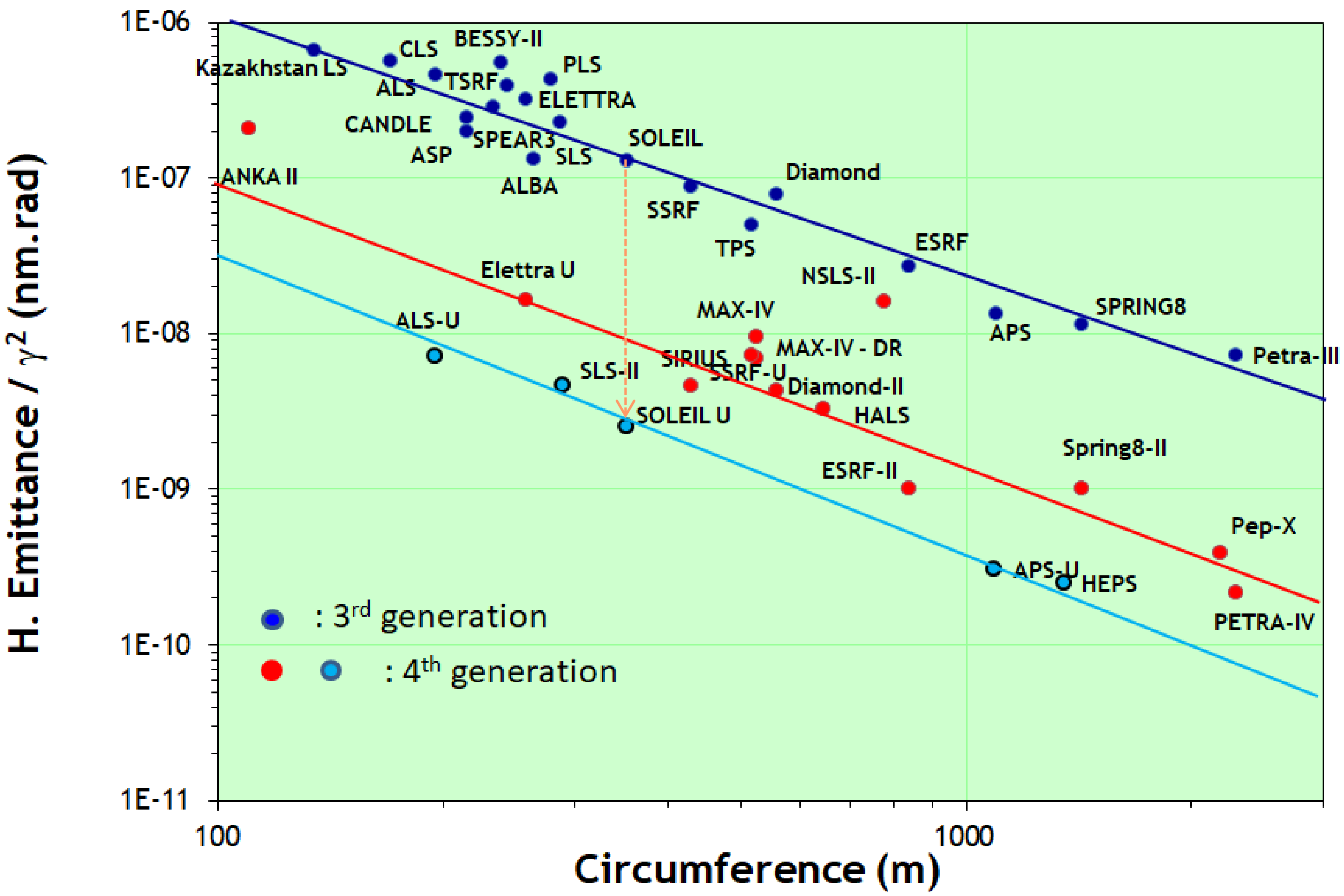
Part III

Evolution towards 4th GLSs (or what are called DLSRs)

Subjects Treated:

- **Currently arising global trend to construct them**
- **Key towards 4GLSs: “MBA” lattice**
- **Major beam dynamics and technological challenges**

Global trend constructing 4GLSs

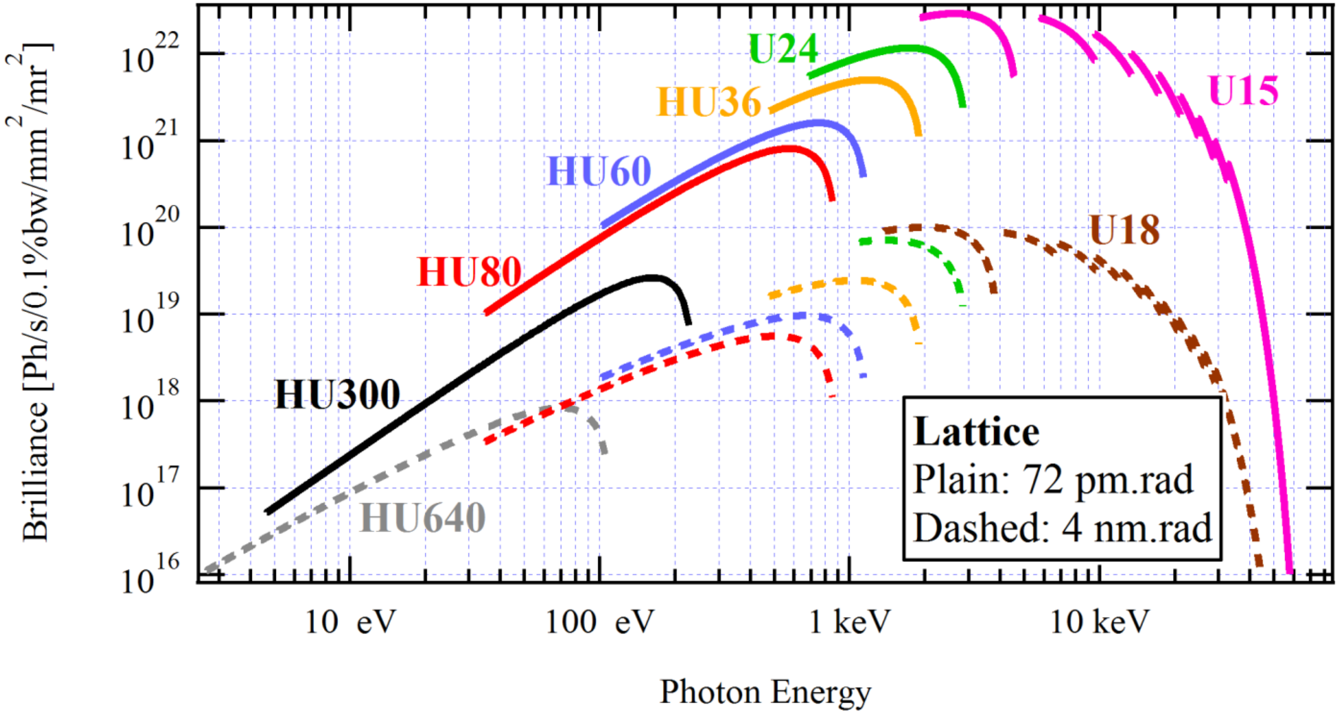


(Riccardo Bartolini's plot updated)

Why we think they are 4GLSs …

Brillance des photons

$$B_n(\lambda) = \frac{F_n(\lambda)}{4\pi^2\left(\varepsilon_x \otimes \varepsilon_R(\lambda)\right)\left(\varepsilon_z \otimes \varepsilon_R(\lambda)\right)}$$

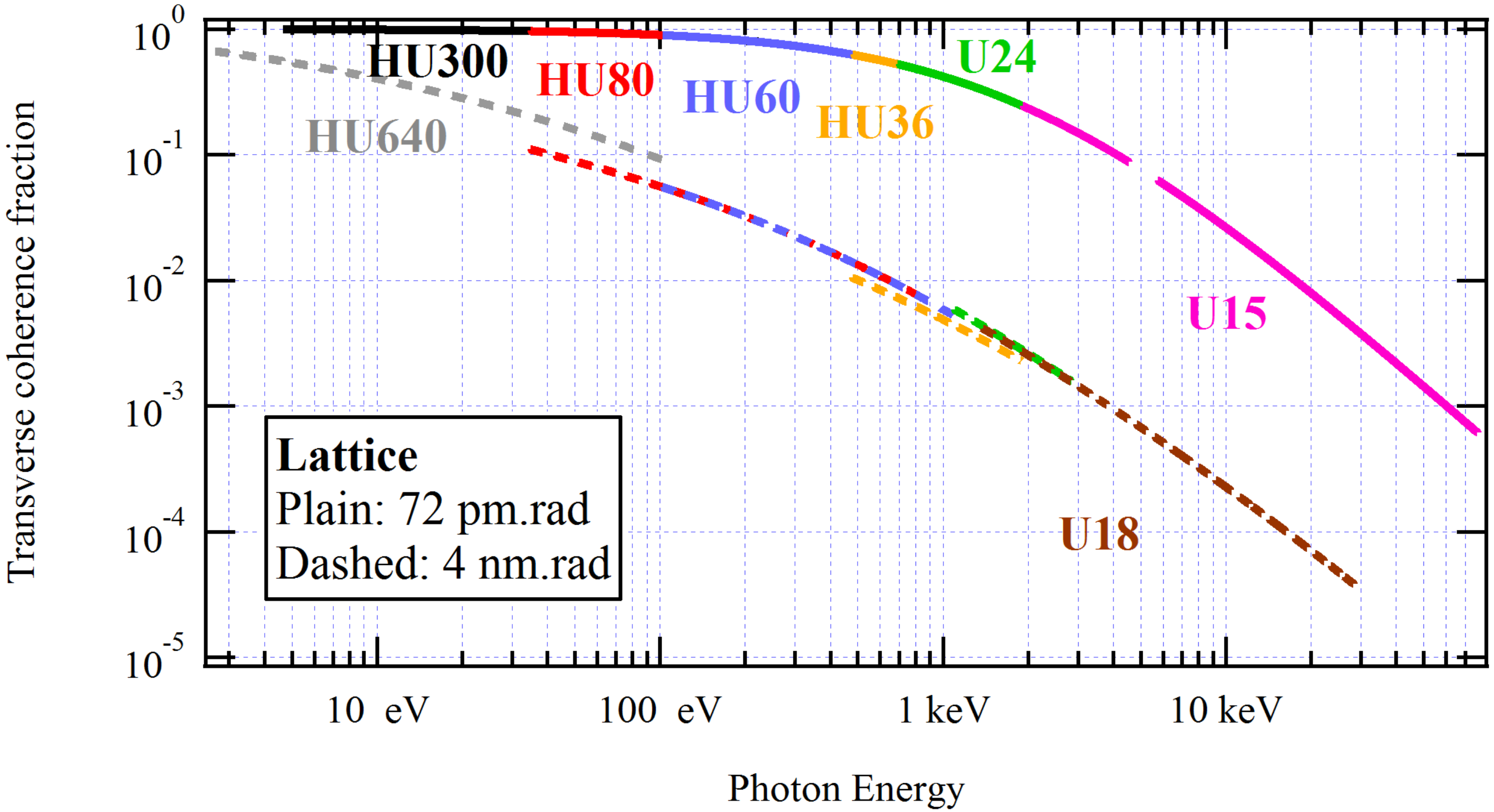


Increase of brilliance attains ***two orders of magnitude*** in the range of interest: Namely from 1 to 3 keV, exceeding the value of 10^{22} photons/s/mm^2/mrad^2/0.1%b.w. Brilliance reaches 10^{20} photons/s/mm^2/mrad^2/0.1%b.w. at 40 keV!

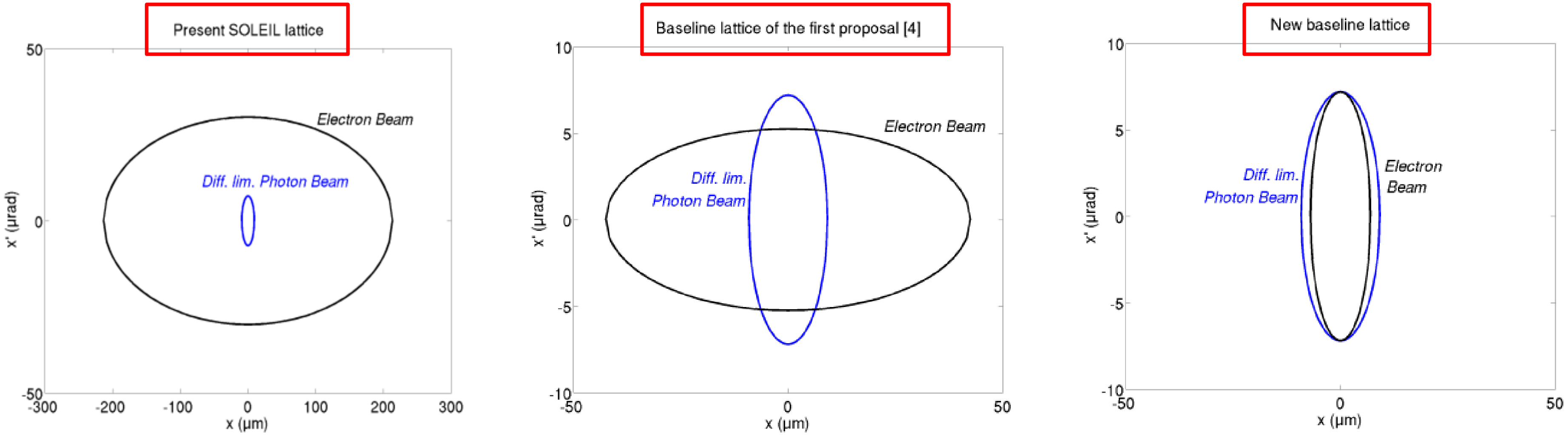
Why we think they are 4GLSs …

Transverse coherence

$$f_c(\lambda) = \frac{\varepsilon_R(\lambda)}{\varepsilon_R(\lambda) \otimes \varepsilon_x(e^-)} \frac{\varepsilon_R(\lambda)}{\varepsilon_R(\lambda) \otimes \varepsilon_z(e^-)}$$



They are also called DLSRs



Electron and photon beam emittances are the importance of matching between the two

Key to 4GLS: MBA lattices

Analytical expression for the horizontal emittance

$$\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\oint H(s)/\rho(s)^3 ds}{\oint ds/\rho(s)^2} = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2},$$

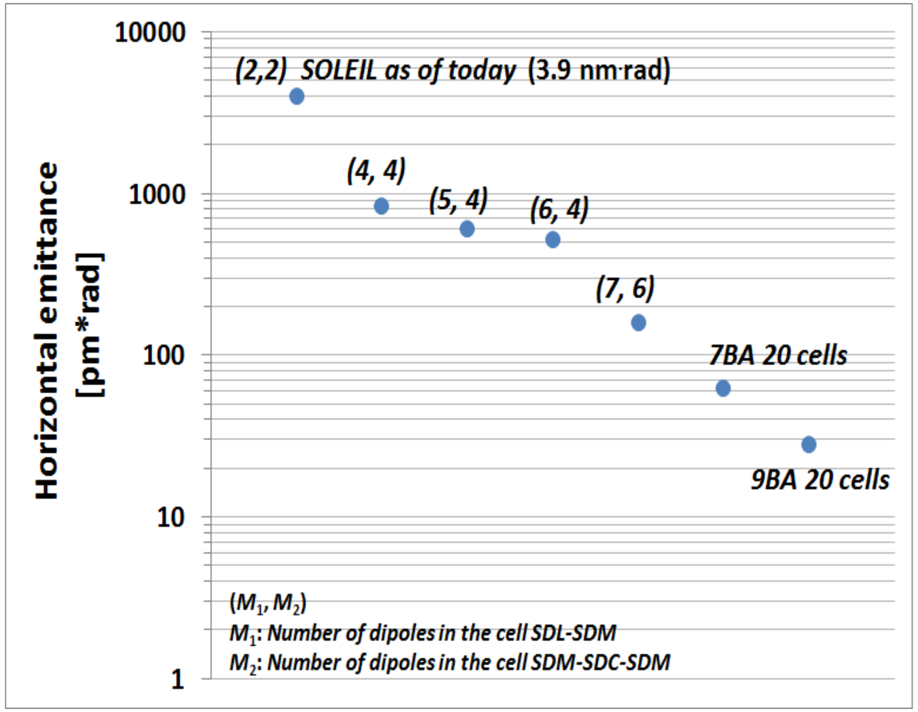
$$\Downarrow$$

Dependence of Theoretical Minimal Emittance on

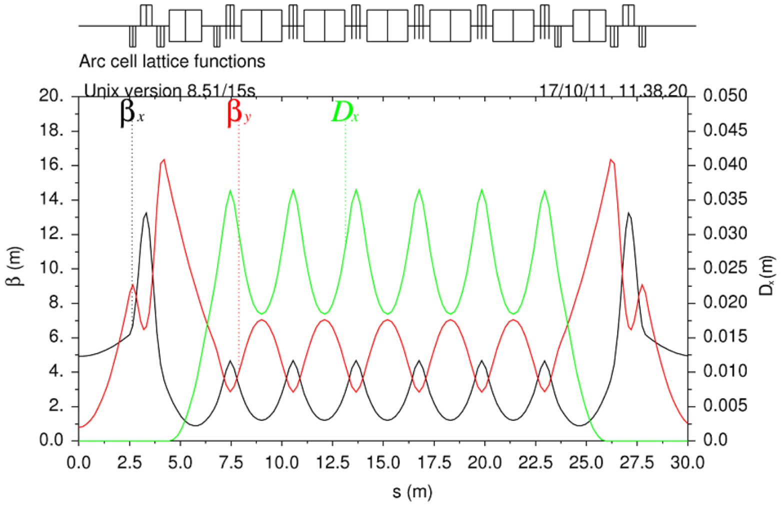
E: Energy of the machine

N: Number of dipoles

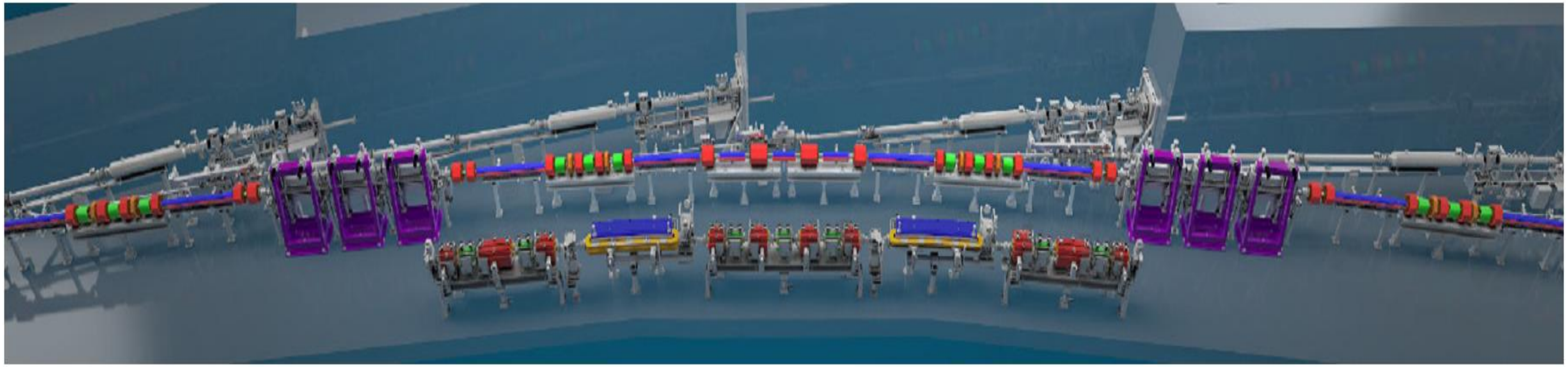
$$\boxed{\varepsilon_x \approx F(lattice)\frac{E^2}{N^3}}$$



Characteristics of MBAs

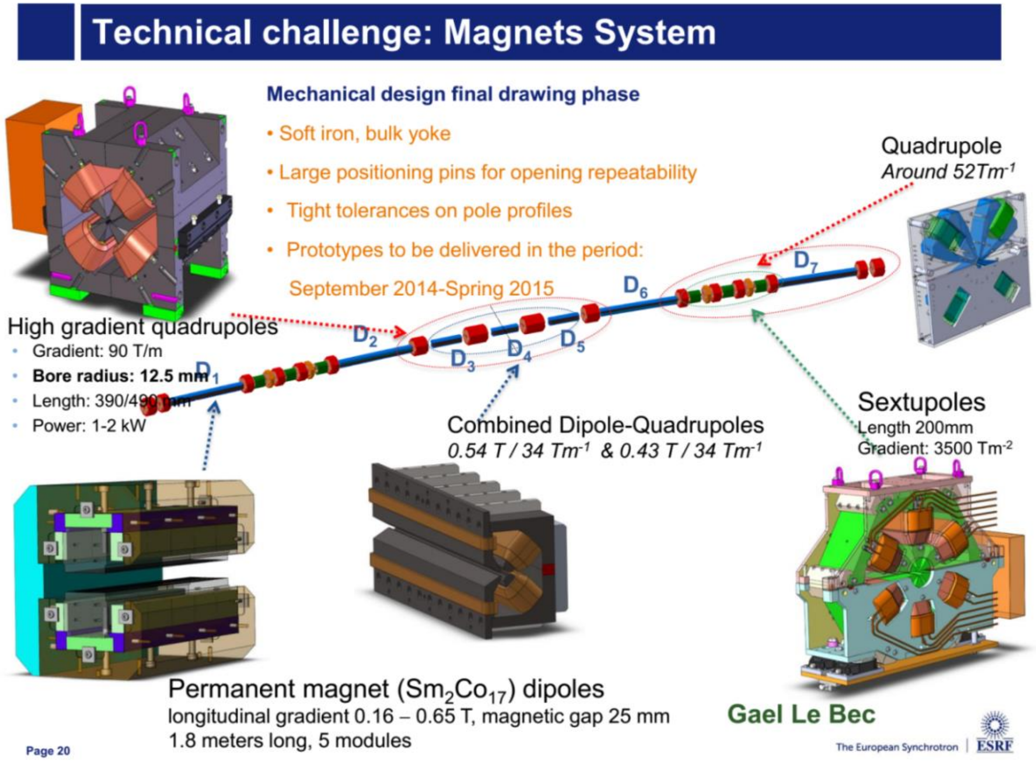


7BA lattice optimized for PEP-X (Y. Cai et al., SLAC)



(taken from J.-L. Revol et al., “ESRF Upgrade Phase II”, IPAC2013)

Characteristics of MBAs



Technical challenge: Magnets System

Mechanical design final drawing phase

- Soft iron, bulk yoke
- Large positioning pins for opening repeatability
- Tight tolerances on pole profiles
- Prototypes to be delivered in the period: September 2014-Spring 2015

High gradient quadrupoles

- Gradient: 90 T/m
- **Bore radius: 12.5 mm**
- Length: 390/490 mm
- Power: 1-2 kW

Quadrupole

Around 52Tm^{-1}

Combined Dipole-Quadrupoles

0.54 T / 34 Tm^{-1} & 0.43 T / 34 Tm^{-1}

Sextupoles

Length 200mm

Gradient: 3500 Tm^{-2}

Permanent magnet (Sm_2Co_{17}) dipoles

longitudinal gradient 0.16 – 0.65 T, magnetic gap 25 mm

1.8 meters long, 5 modules

Gael Le Bec

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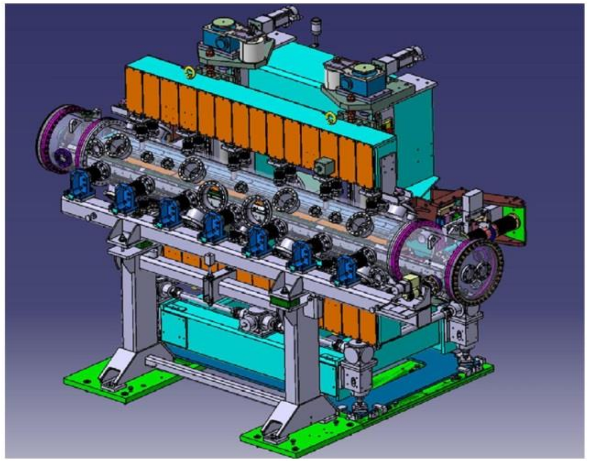
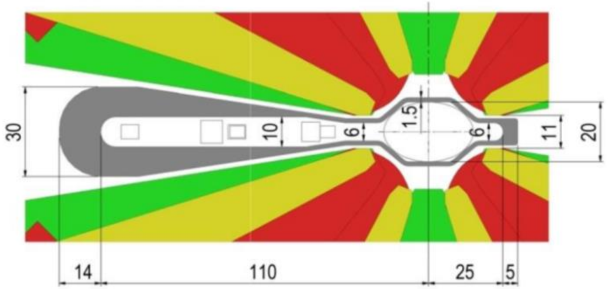
The European Synchrotron | ESRF

(Special magnets developed for the ESRF upgrade: taken from P. Raimondi, LERD2015, April 2015)

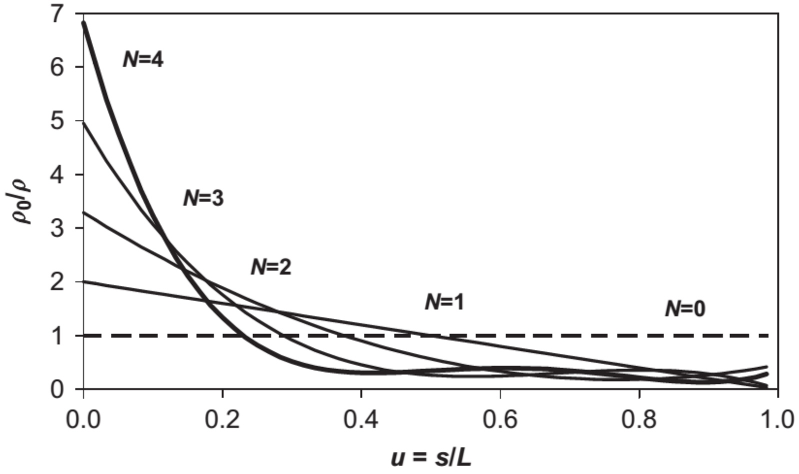


Cryogenic in-vacuum undulator developed at SOLEIL



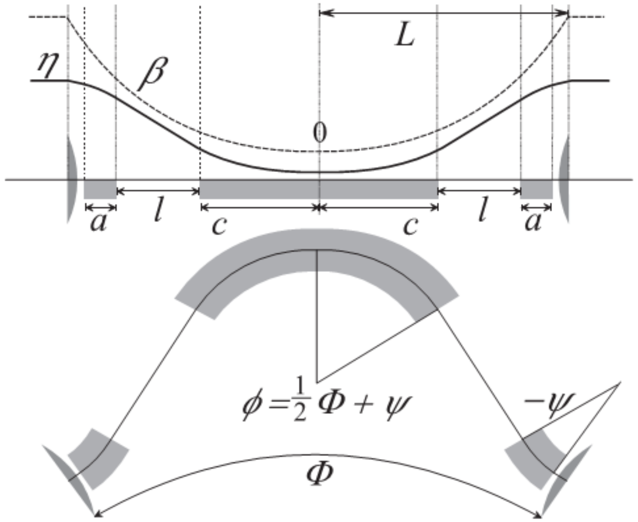
(New vacuum chamber design for the ESRF upgrade: taken from J.-L. Revol et al., "ESRF Upgrade Phase II", IPAC2013)

Associated recipes developed



Application of "Longitudinal gradient bends"

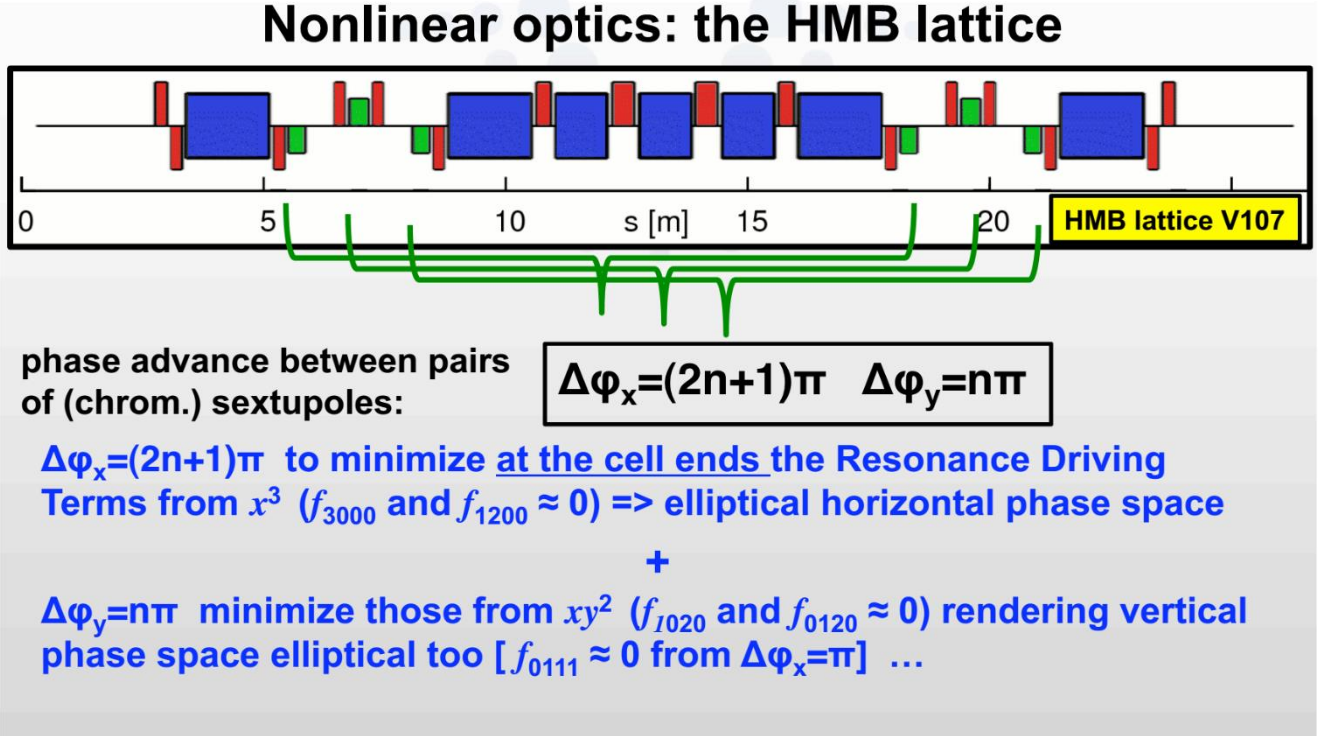
*(taken from R. Nagaoka, A. Wrulich, NIM **A575** (2007) 292)*



Combination of "Longitudinal gradient bends" with "reverse-bends

*(taken from A. Streun, NIM **A737** (2014) 148)*

Associated recipes developed



Nonlinear optics: the HMB lattice

phase advance between pairs of (chrom.) sextupoles: $\Delta\varphi_x=(2n+1)\pi \quad \Delta\varphi_y=n\pi$

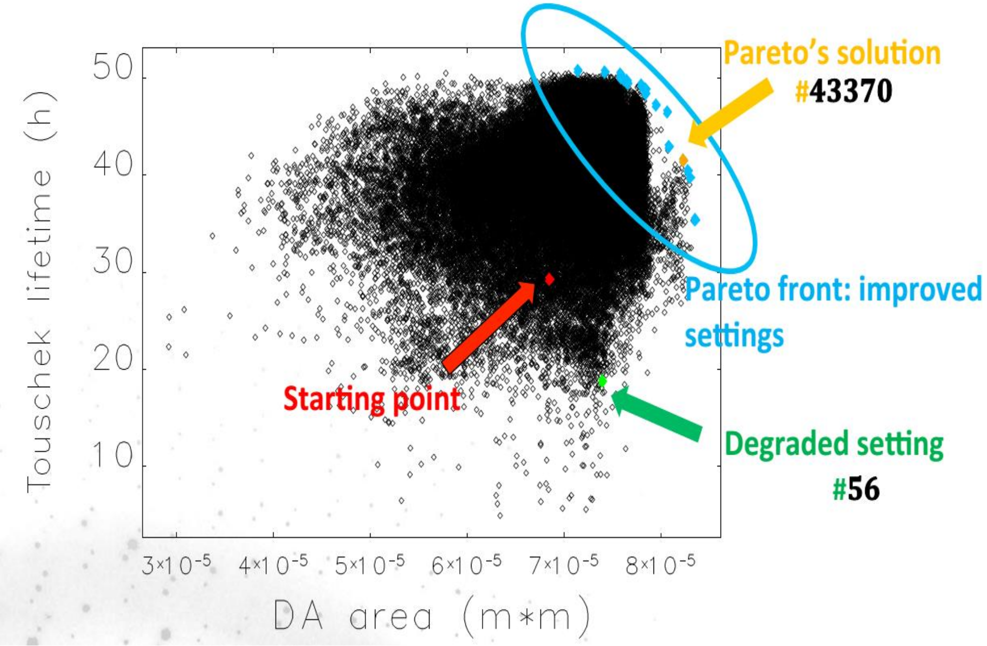
$\Delta\varphi_x=(2n+1)\pi$ to minimize at the cell ends the Resonance Driving Terms from x^3 (f_{3000} and $f_{1200} \approx 0$) => elliptical horizontal phase space

+

$\Delta\varphi_y=n\pi$ minimize those from xy^2 (f_{1020} and $f_{0120} \approx 0$) rendering vertical phase space elliptical too [$f_{0111} \approx 0$ from $\Delta\varphi_x=\pi$] …

Principle of (-I) sextupole compensation scheme illustrated for the ESRF-EBS lattice (A. Franchi, workshop USR, Beijing 2012)

Associated recipes developed



DA area and Touschek lifetime for the MOGA optimized solutions. Present (starting point), improved and degraded lattices are blue, red, and green marks respectively (L. Nadolski et al., LERD2016, Lund)

Associated recipes developed

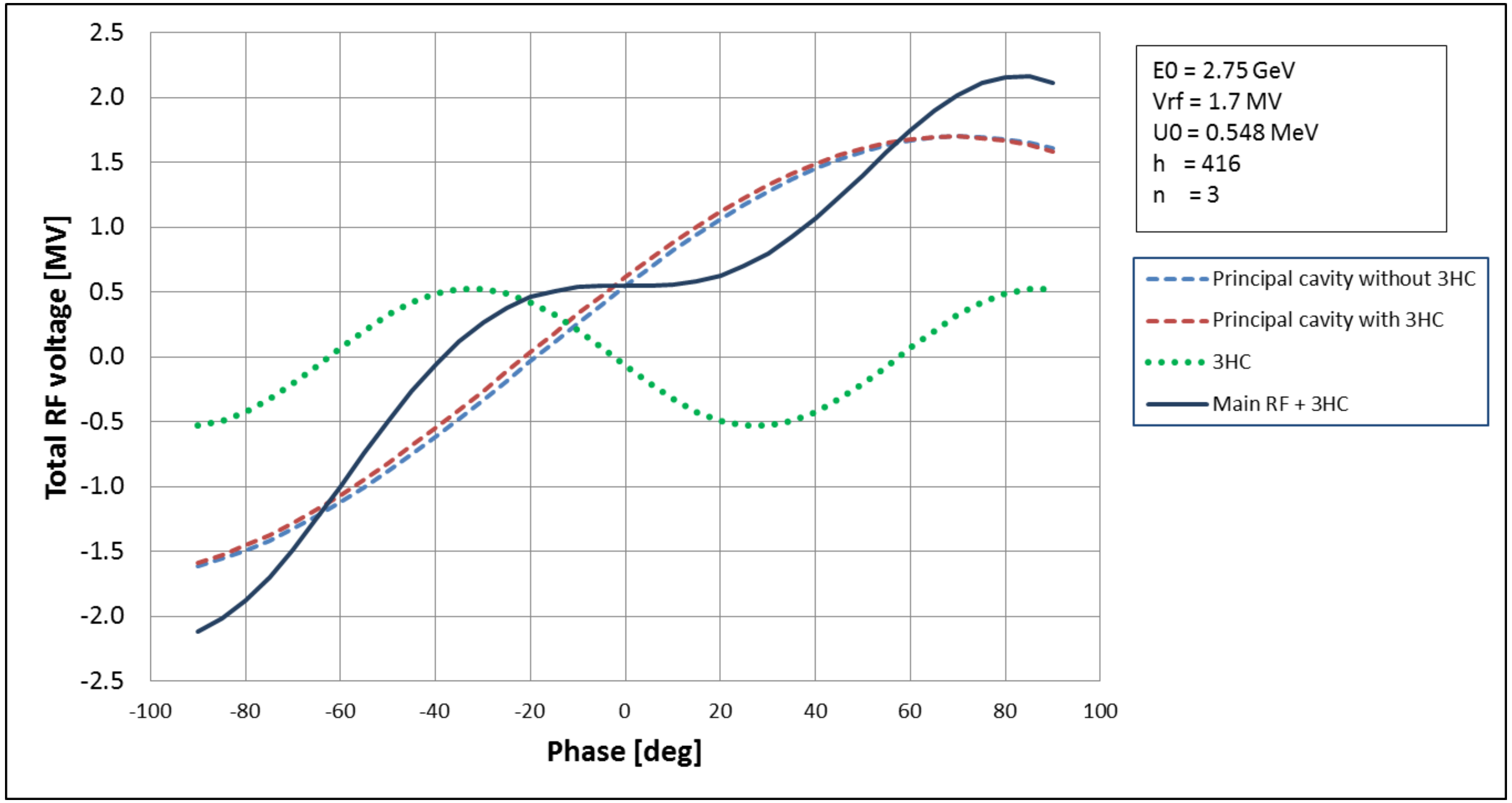
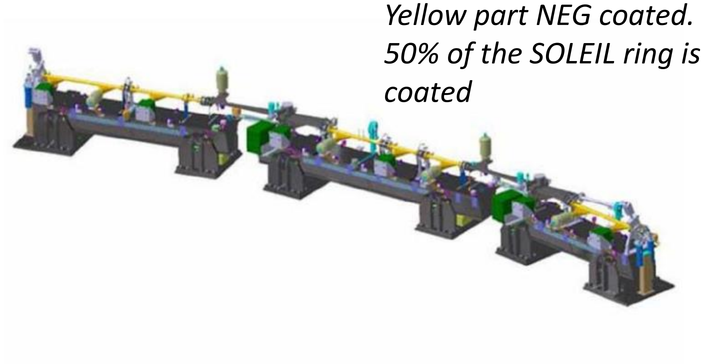
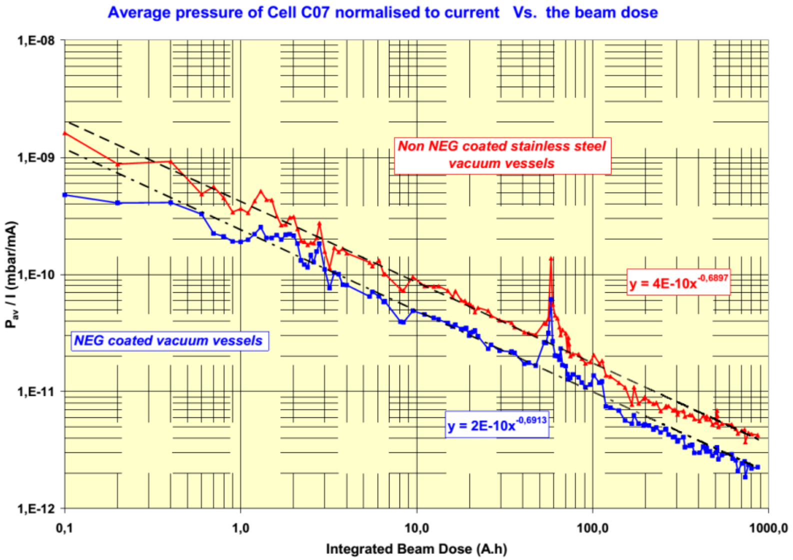


Illustration of a flat RF potential achieved by adding a component from a third harmonic cavity on top of the original RF voltage

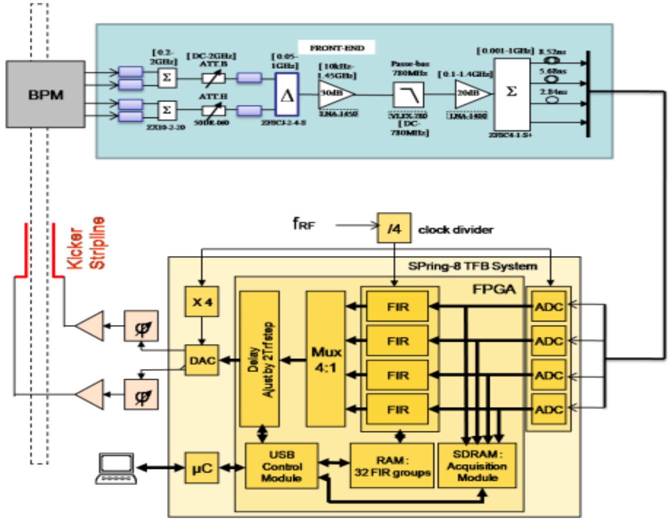
Associated recipes developed



Yellow part NEG coated. About 50% of the SOLEIL ring is NEG coated



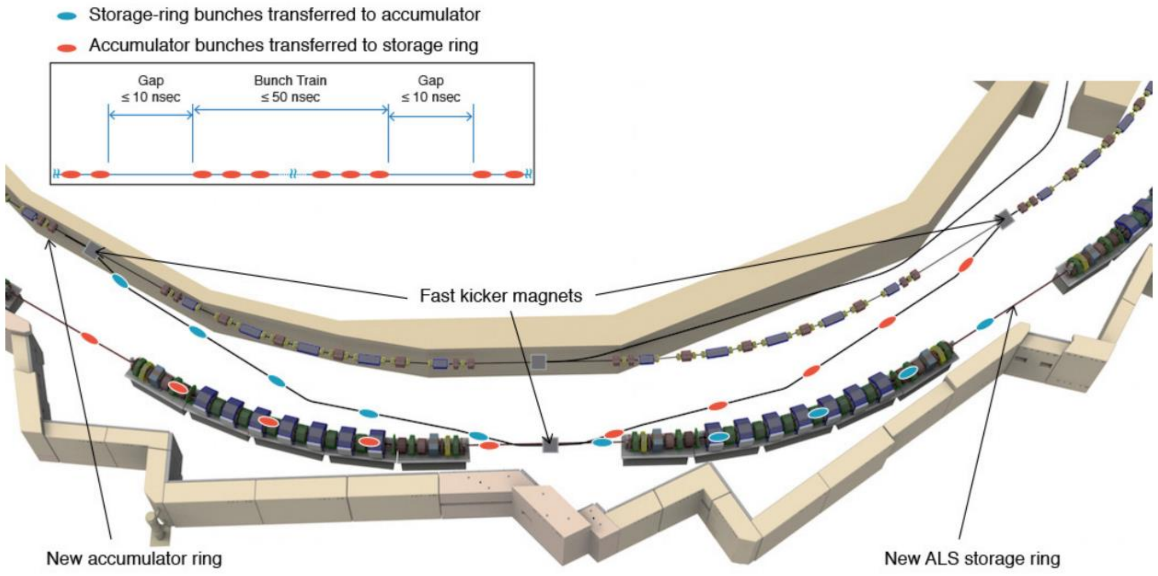
(taken from C. Herbeaux et al., "Vacuum conditioning …", EPAC08)



Layout of bunch-by-bunch transverse feedback system developed at SOLEIL

Non-standard injection schemes (1/2)

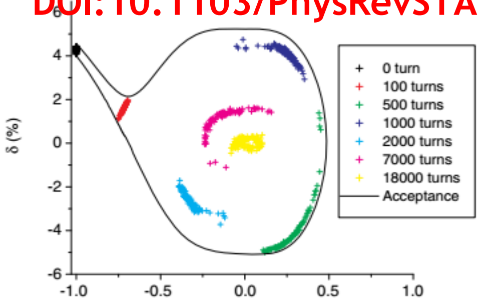
Swap injection scheme is being developed for APS-U and ALS-U in the US

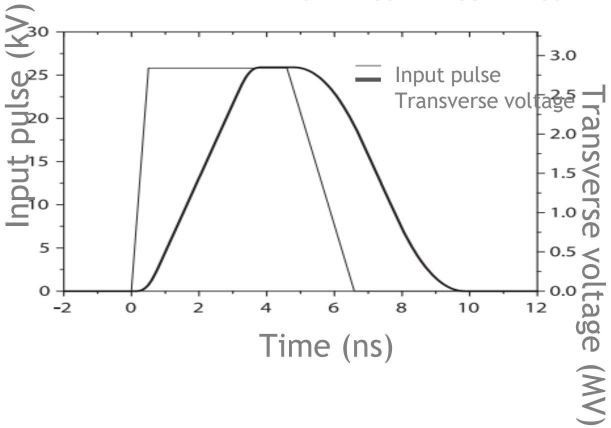


(taken from C. Steier et al., "On-axis swap-our R&D for ALS-U", IPAC2017)

Non-standard injection schemes (2/2)

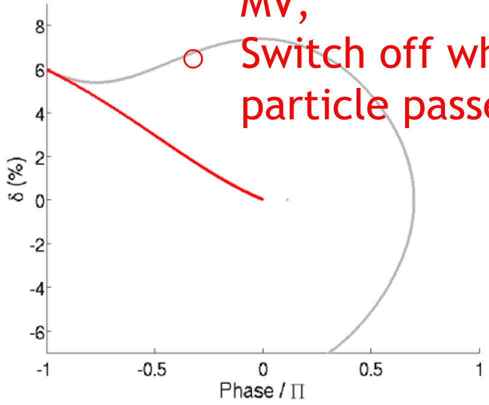
M. Aïba et al., PRST AB 18, 020701 (2015)
DOI:10.1103/PhysRevSTAB.18.020701





Two longitudinal on-axis injection schemes developed for DLSRs

Particle with zero betatron amplitude

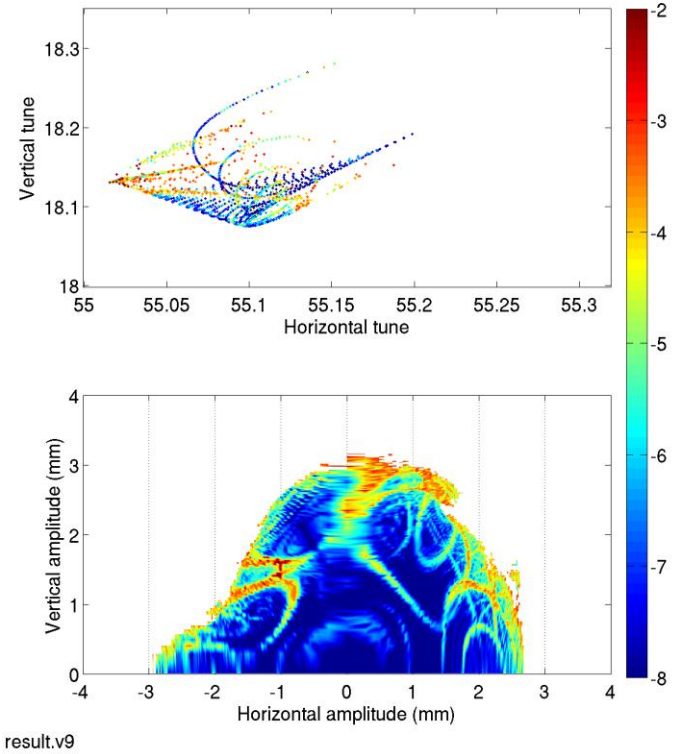


- Switch on $V_{RF\ add}$ = 1 MV,
- Switch off when particle passes φ_s

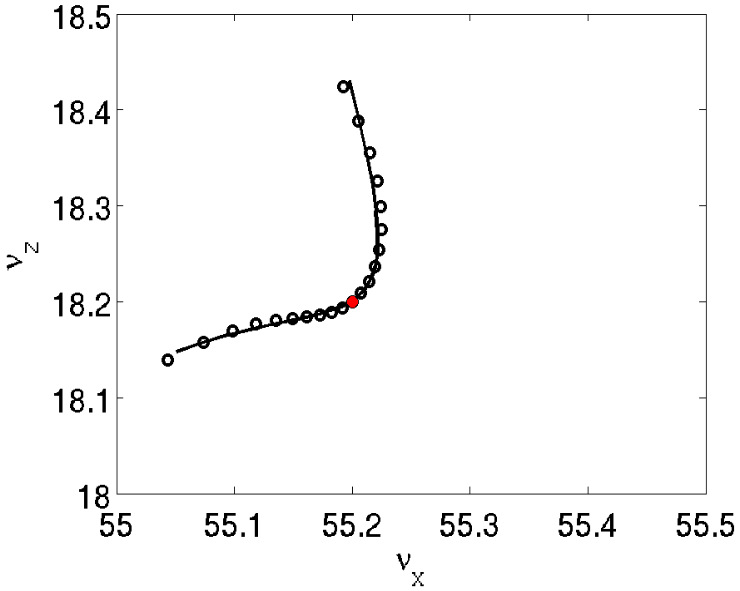
(taken from M.-A. Tordeux et al., "Longitudinal injection …", ESLS-XXV, 2017)

Beam dynamics issues (1/2)

◊ Studies of transverse single particle motions which are severely limited in DLSR are of utmost importance

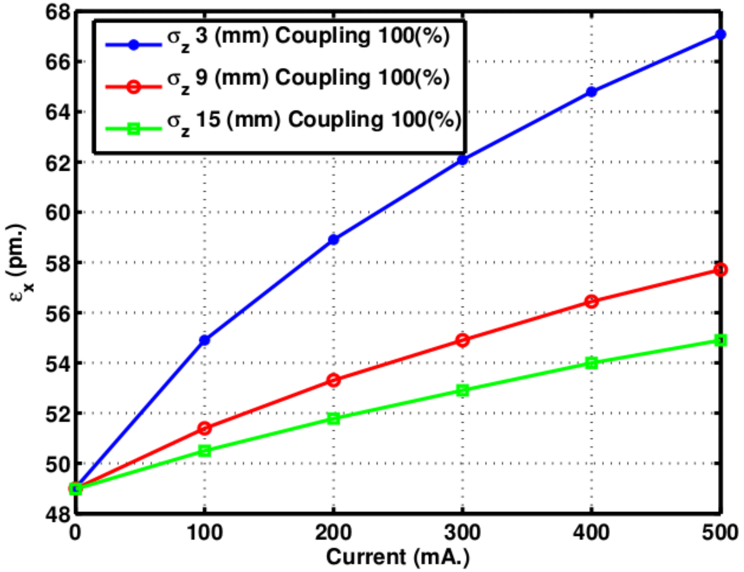


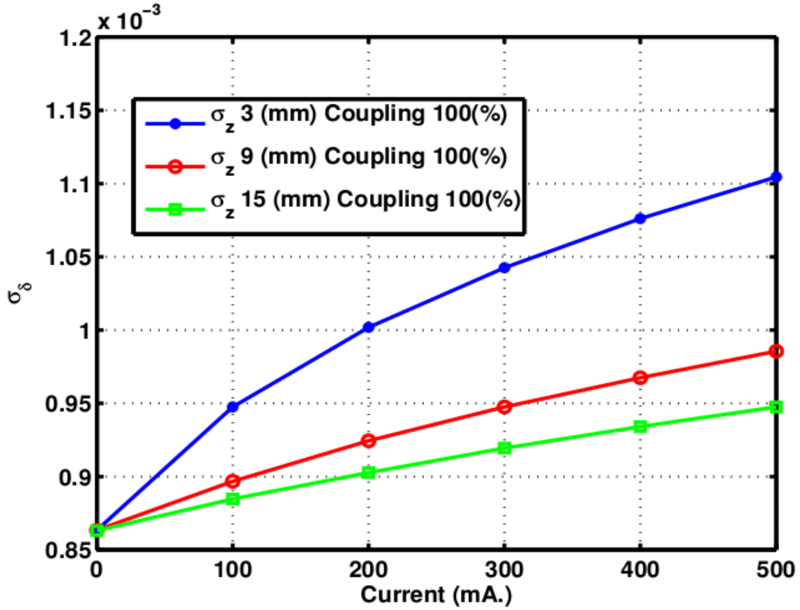
On-momentum transverse stability



Tune shift with energy deviation

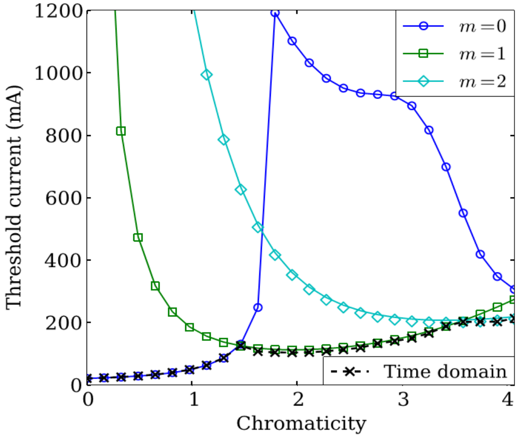
Beam dynamics issues (1/2)

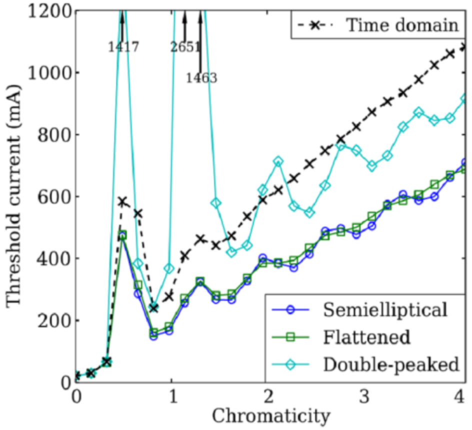




Due to extremely small beam sizes, scattering of electrons (Intra Beam Scattering and Touschek scattering) within a bunch due to their Coulomb fields becomes a serious threat in achieving the ultra-low emittance

Beam dynamics issues (1/2)

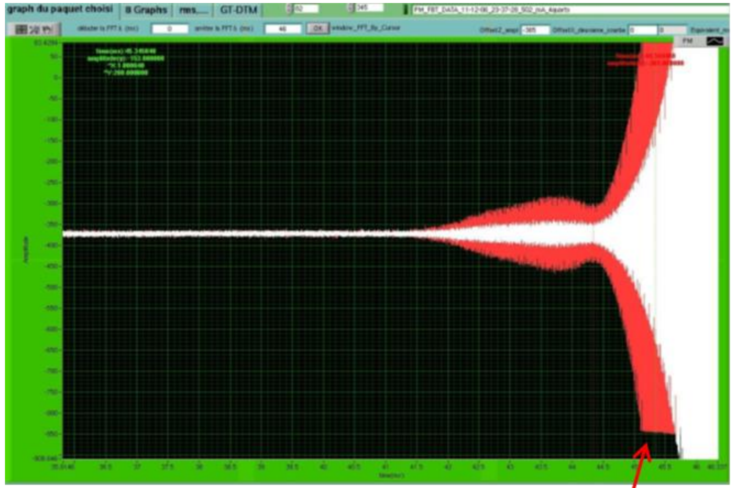




Time domain results give ~50% higher thresholds

*(F. Cullinan et al., PRAB **19**,124401 (2016))*

Fast beam-ion instability encountered and studied at SOLEIL

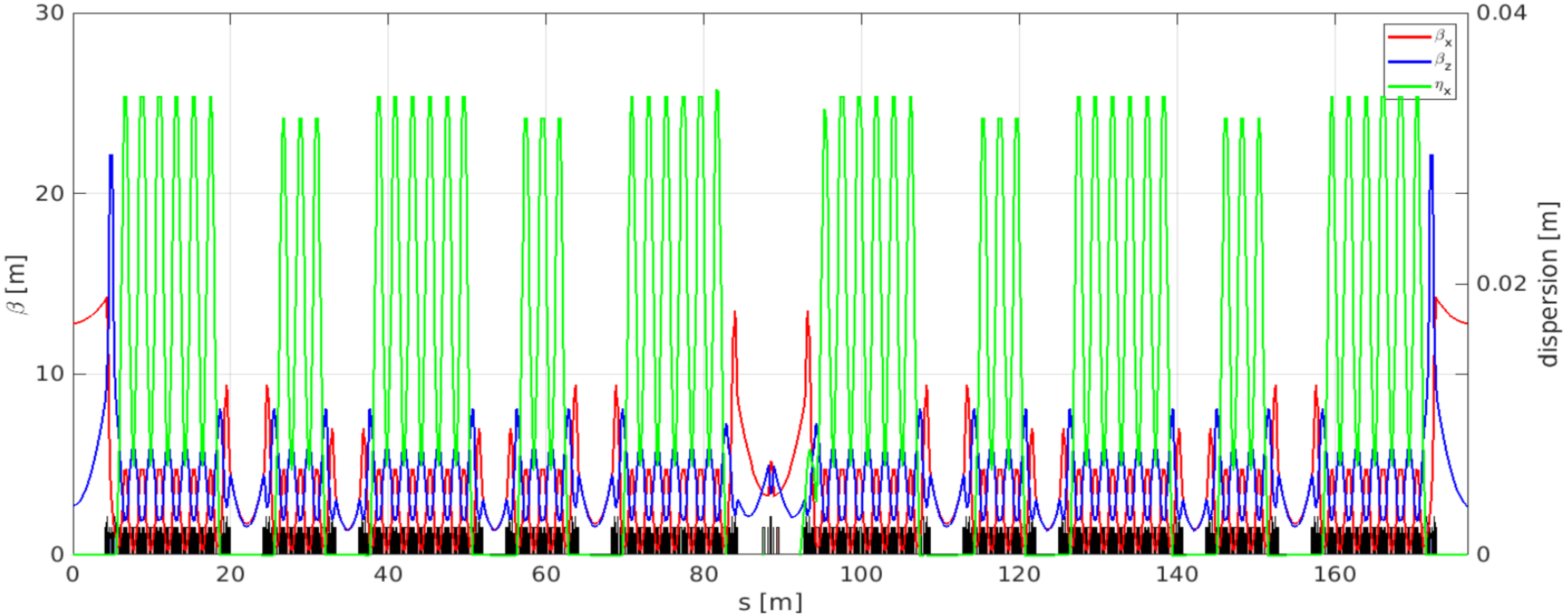


Measured beam loss at 500 mA
White: Beam, Red: TFB kick

feedback saturation

Transverse collective beam instability is anticipated to be serious for future DLSRs due to reduced vacuum chamber aperture. Many theoretical/numerical studies are being made around the world

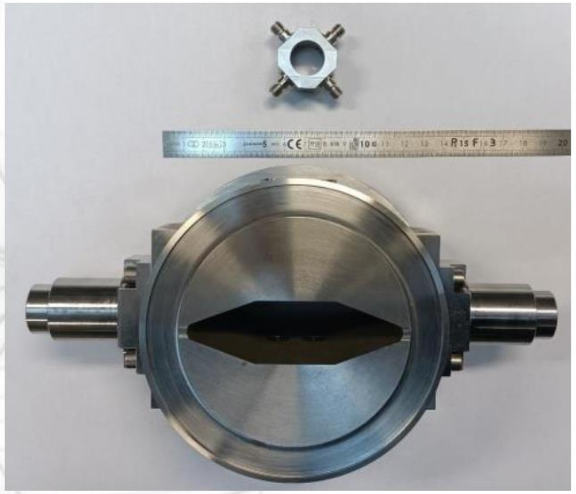
Solutions developed at SOLEIL (1/2)



Super cell optical functions of the 7BA-4BA SOLEIL upgrade lattice producing an emittance of 84 pm.mrad.

Solutions developed at SOLEIL (2/2)

Miniaturization



BPM prototypes for SOLEIL (bottom) and SOLEIL Upgrade (top)

Upgrade Permanent magnet quadrupole prototype (top)
Present Electromagnet quadrupole (bottom)

Part IV

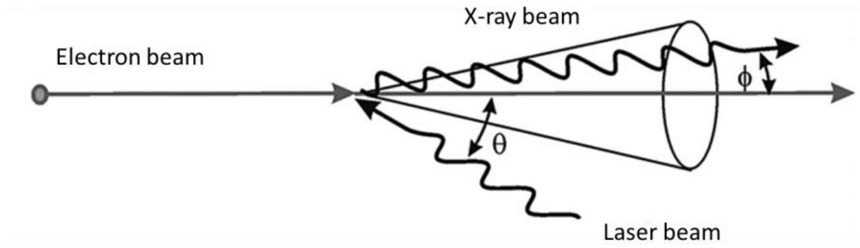
What are the "Ring-based Inverse Compton Scattering Light Sources"?

Subjects Treated:

- **Characteristics of Inverse Compton Scattering**
- **Goals of its application to storage rings**
- **Compact rings constructed for this purpose**

Characteristics of Inverse Compton Scattering (1/3)

◊ **Mechanism of Inverse Compton Scattering**



taken from: R. Kuroda et al., "Development of Laser Inverse Compton Scattering X-ray Source and Its Application", Optics Vol.43 No.9 (2014);
K. Dupraz, "Projet Thomx: nouvelle source de rayon-X", presentation given at Synchrotron SOLEIL, March 2023

- A low energy photon (typically emitted by a laser) collides with a relativistic high energy electron and scatters elastically backwards as a high energy photon (in an X-ray beam).
- Due to the relativistic electron, the scattered photons shall be confined in a cone with its opening angle *f* of the order of $1/\gamma$
- The energy $h\nu$ of an inversely scattered photon is given by

$$h\nu = \frac{(1+\beta\cos\theta)\cdot h\nu_0}{1-\beta\cos\phi+[1+\cos(\theta+\phi)]\cdot\frac{h\nu_0}{\gamma m_0 c^2}}$$

$$\xrightarrow[\text{(if } \gamma m_0 c^2 \;>>\; h\nu_0 \text{ and } \phi = 0)]{} \quad (h\nu)_{\max} \approx 2\gamma^2(1+\beta\cos\theta)\cdot h\nu_0 \underset{\theta = 0}{\approx} 4\gamma^2 h\nu_0$$

β, γ : Relativistic factors
m_0 : Electron rest mass
c : Velocity of light
$\gamma m_0 c^2$: Electron energy
θ_0 : Collision angle between the laser beam and the electron
ϕ : Scattering angle

Characteristics of Inverse Compton Scattering (2/3)

- Namely, the energy of the inversely scattered photon can be increased with the proportionality of γ^2
- The ϕ-dependence of the photon energy indicates that photons in the range $\frac{1}{2}(h\nu)_{\max} < h\nu < (h\nu)_{\max}$ are emitted within the cone of the opening $1/\gamma$

Characteristics of the inverse scattered photons:

- By varying the parameters involved above in the inverse scatting, the (peak) energy of the photons can be varied continuously
- The generated beam of photons is well oriented in a cone-like distribution
- If the beam is collimated with a small aperture, the transmitted photons could be confined in energy with a spread in the range of a few percent
- The transverse beam size of the scattered photons follows those of the electron and laser beams and could be made small, typically in the range of a few tens of microns
- The scattered photons inherit the polarization properties of the laser beam and thus could be well polarized
- The time structure of the scattered beam follows those of the electron and laser beams and thus could be made to be very short, in the range of femto seconds

Goals of its application to storage rings (1/2)

- Today there is a widespread use of X-ray imaging in many different areas of science, including physics, chemistry, biology and medicines
- Many of them use the X-ray tube technology as sources, which however are limited in their performance in terms of flux intensity and monochromaticity.
- Undulator spectra in light source rings are excellent sources for this purpose in producing intense monochromatic X-rays in the tens of keV range. However, this requires an electron beam in the GeV range with a big synchrotron ring.
- As regards the scale of a light source, the Inverse Compton Scattering technique allows reducing by **two orders of magnitude in the electron beam energy** as compared to ring-based X-ray sources using the undulator spectra

  ➔ A dramatic reduction of the accelerator dimension is possible

- Average photon production rate $\langle dN/dt \rangle$ is a product of Thomson scattering cross section σ_T and the luminosity L defined by the electron-laser beam system:

$$\langle dN/dt \rangle = \sigma_T * L \approx \sigma_T * f_{rep} \cdot N_e \cdot N_L / [2\pi * (\sigma_e^2 + \sigma_L^2)]$$

σ_T : Thomson scattering cross section ≈ 6.6×10^{-25} cm^2
f_{rep} : Compton scattering repetition rate
N_e : Number of electrons in an electron bunch
N_L : Number of photons in a laser bunch
σ_e : Transverse electron bunch size
σ_L : Transverse laser beam size

Goals of its application to storage rings (2/2)

Inverse Compton Scattering sources occupy today an important area in the "Photon intensity versus photon energy diagram" …

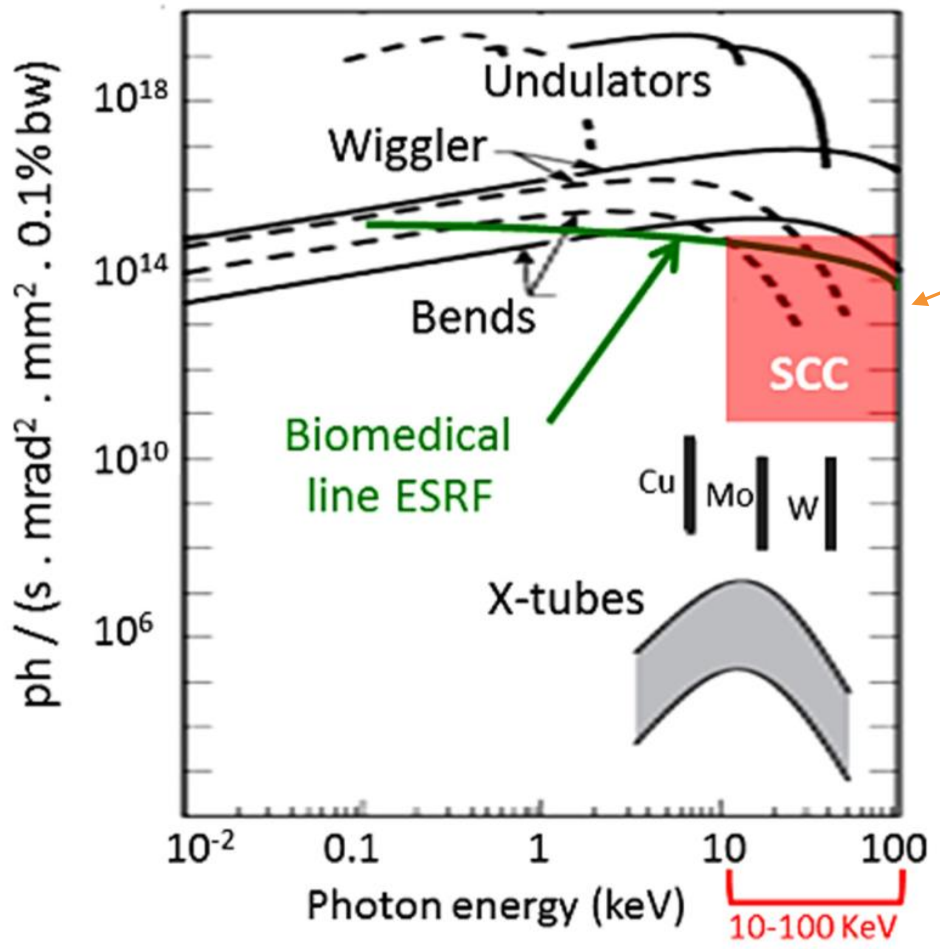


Figure 4. Typical brightnesses of synchrotrons, of conventional lab sources and of CCS projects (pink square). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Compact **C**ompton **S**ources

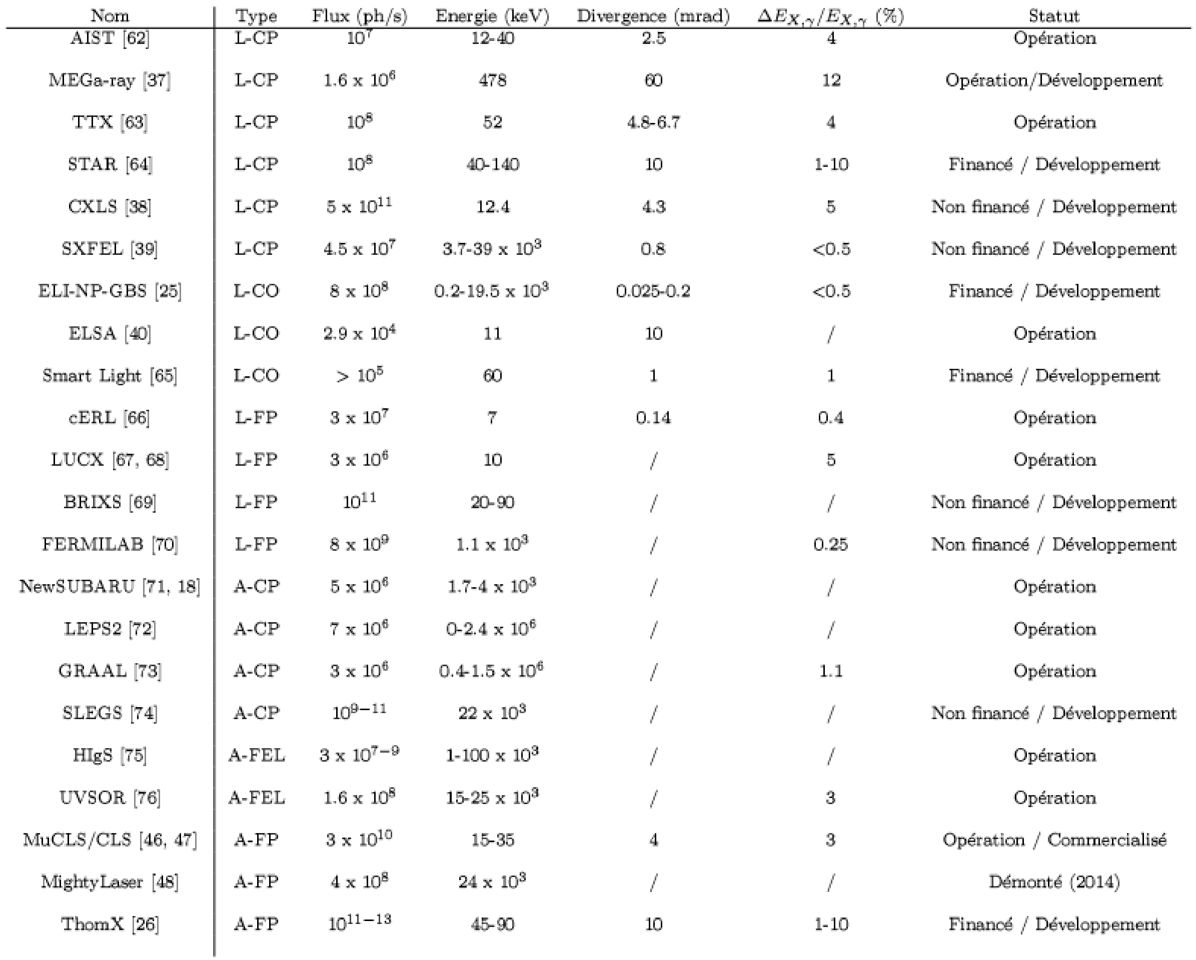
taken from M. Jaquet, "Potential of compact Compton sources in the medical field", Physica Medica 32 (2016) 1790–1794

Goals of its application to storage rings (1/3)

List of Inverse Compton Scattering Sources either existing or under development in the world:

A : Storage ring
L : Linear accelerator
FP : Fabry-Perot cavity
FEL : Free electron laser
CP : Contra-Propagating laser
CO : Circular Optics

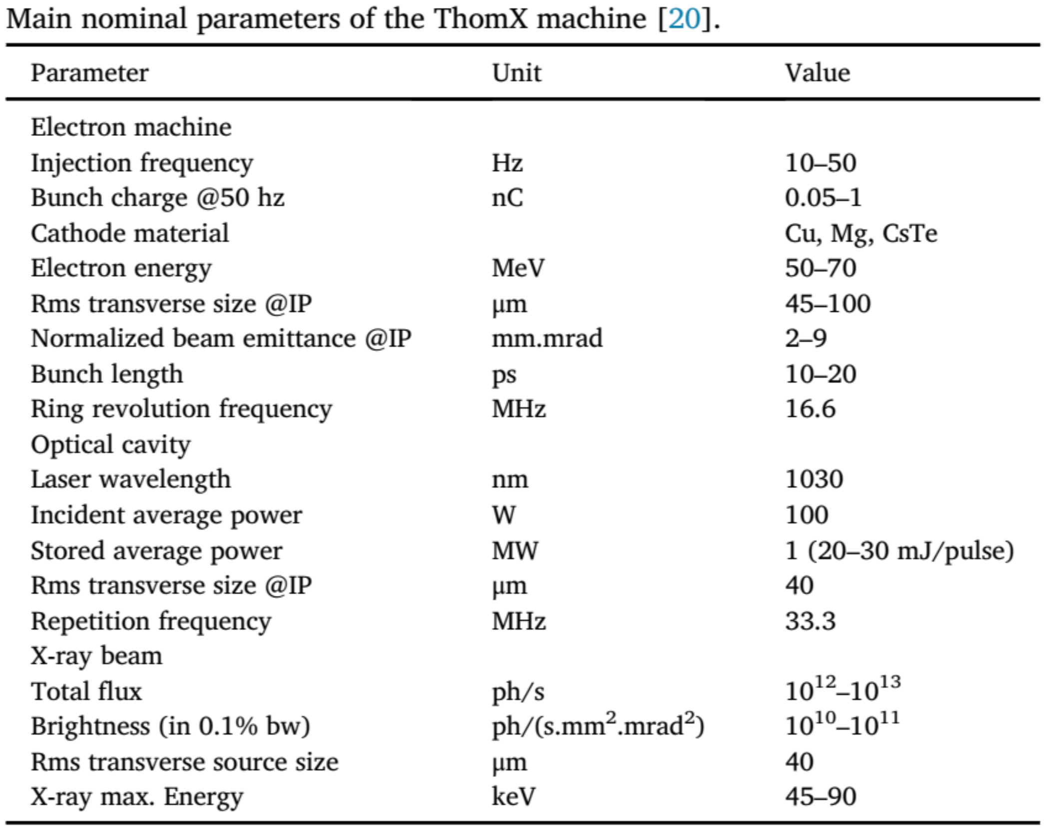
taken from Pierre Favier, “Etude et conception d’une cavité Fabry-Perot de haute finesse pour la source compacte de rayons X ThomX, Université Paris-Saclay, 2017



Nom	Type	Flux (ph/s)	Energie (keV)	Divergence (mrad)	$\Delta E_{X,\gamma}/E_{X,\gamma}$ (%)	Statut
AIST [62]	L-CP	10^7	12-40	2.5	4	Opération
MEGa-ray [37]	L-CP	1.6×10^6	478	60	12	Opération/Développement
TTX [63]	L-CP	10^8	52	4.8-6.7	4	Opération
STAR [64]	L-CP	10^8	40-140	10	1-10	Financé / Développement
CXLS [38]	L-CP	5×10^{11}	12.4	4.3	5	Non financé / Développement
SXFEL [39]	L-CP	4.5×10^7	$3.7\text{-}39 \times 10^3$	0.8	<0.5	Non financé / Développement
ELI-NP-GBS [25]	L-CO	8×10^8	$0.2\text{-}19.5 \times 10^3$	0.025-0.2	<0.5	Financé / Développement
ELSA [40]	L-CO	2.9×10^4	11	10	/	Opération
Smart Light [65]	L-CO	$> 10^5$	60	1	1	Financé / Développement
cERL [66]	L-FP	3×10^7	7	0.14	0.4	Opération
LUCX [67, 68]	L-FP	3×10^6	10	/	5	Opération
BRIXS [69]	L-FP	10^{11}	20-90	/	/	Non financé / Développement
FERMILAB [70]	L-FP	8×10^9	1.1×10^3	/	0.25	Non financé / Développement
NewSUBARU [71, 18]	A-CP	5×10^6	$1.7\text{-}4 \times 10^3$	/	/	Opération
LEPS2 [72]	A-CP	7×10^6	$0\text{-}2.4 \times 10^6$	/	/	Opération
GRAAL [73]	A-CP	3×10^6	$0.4\text{-}1.5 \times 10^6$	/	1.1	Opération
SLEGS [74]	A-CP	10^{9-11}	22×10^3	/	/	Non financé / Développement
HIgS [75]	A-FEL	$3 \times 10^{7-9}$	$1\text{-}100 \times 10^3$	/	/	Opération
UVSOR [76]	A-FEL	1.6×10^8	$15\text{-}25 \times 10^3$	/	3	Opération
MuCLS/CLS [46, 47]	A-FP	3×10^{10}	15-35	4	3	Opération / Commercialisé
MightyLaser [48]	A-FP	4×10^8	24×10^3	/	/	Démonté (2014)
ThomX [26]	A-FP	10^{11-13}	45-90	10	1-10	Financé / Développement

Table 1.5: Machines Compton existantes ou en développement. Les grandeurs flux, énergie,... sont données pour le faisceau de rayons X/γ produit. A : Anneau de stockage; L : accélérateur Linéaire; FP : cavité Fabry-Perot; FEL : Laser à Electrons Libres; CP : faisceau laser Contre-Propagatif; CO : Circulateur Optique. La divergence est donnée avant le collimateur.

Goals of its application to storage rings (2/3)



Main nominal parameters of the ThomX machine [20].

Parameter	Unit	Value
Electron machine		
Injection frequency	Hz	10–50
Bunch charge @50 hz	nC	0.05–1
Cathode material		Cu, Mg, CsTe
Electron energy	MeV	50–70
Rms transverse size @IP	µm	45–100
Normalized beam emittance @IP	mm.mrad	2–9
Bunch length	ps	10–20
Ring revolution frequency	MHz	16.6
Optical cavity		
Laser wavelength	nm	1030
Incident average power	W	100
Stored average power	MW	1 (20–30 mJ/pulse)
Rms transverse size @IP	µm	40
Repetition frequency	MHz	33.3
X-ray beam		
Total flux	ph/s	10^{12}–10^{13}
Brightness (in 0.1% bw)	ph/(s.mm^2.mrad^2)	10^{10}–10^{11}
Rms transverse source size	µm	40
X-ray max. Energy	keV	45–90

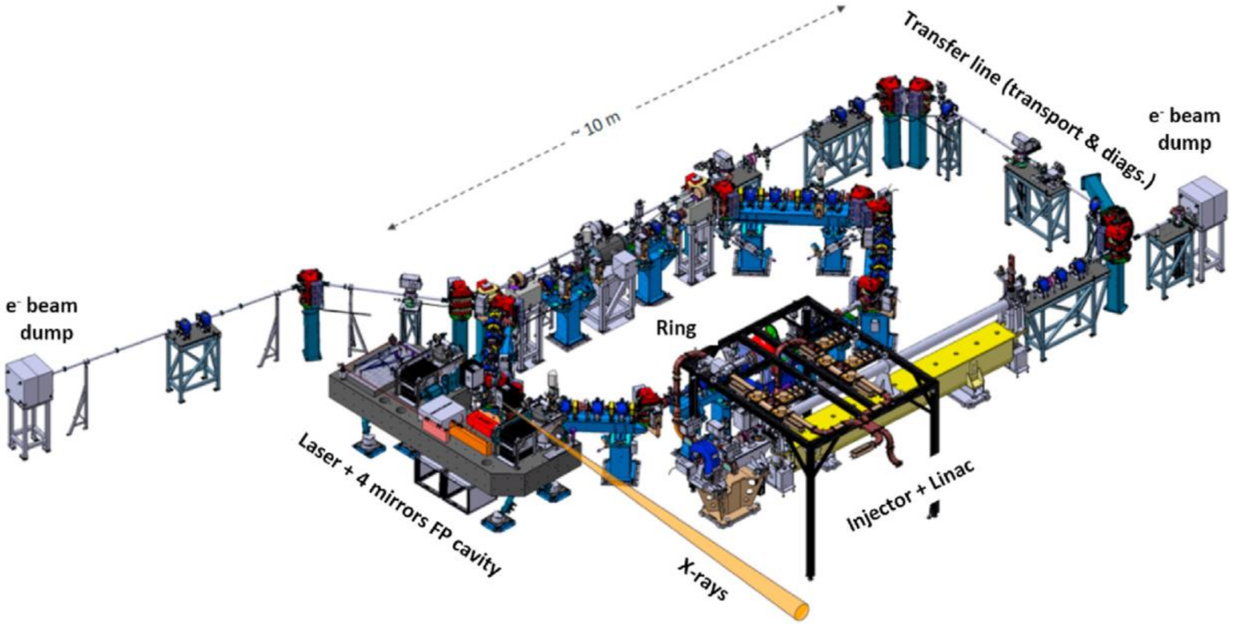


Fig. 1. ThomX layout.

An Inverse Compton Scattering Souce ThomX

taken from K. Dupraz et al., “The ThomX ICS source”, Physics Open 5 (2020) 100051

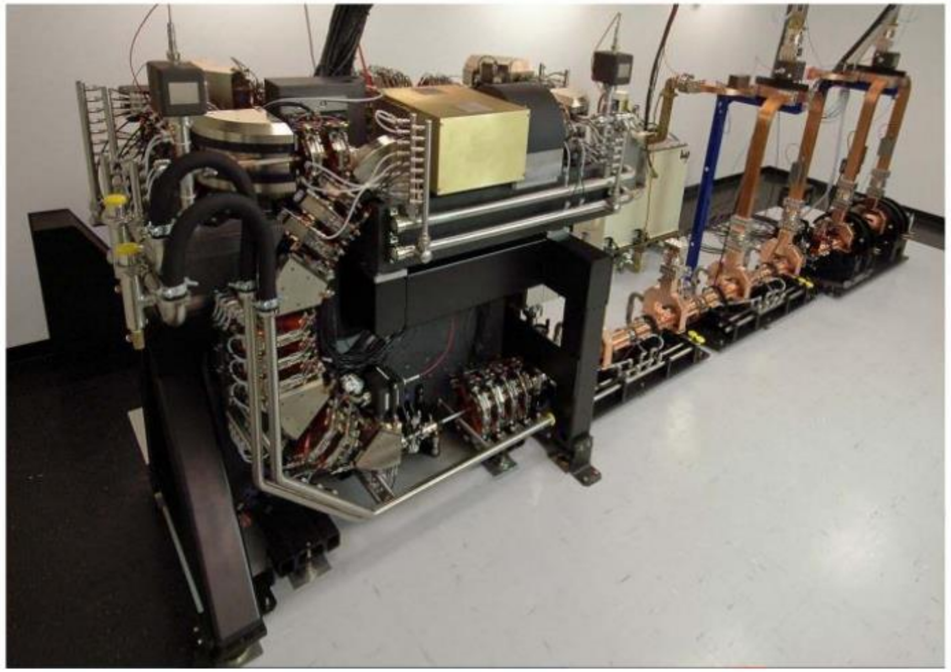
Goals of its application to storage rings (3/3)

There are also commercial Inverse Compton Scattering sources available today …

lyncean TECHNOLOGIES, INC.

ICS sources: Lyncean

first commercial ICS source



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Hard X-ray phase-contrast imaging with the Compact Light Source based on inverse Compton X-rays

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V. Summary and Perspectives

◊ Since the 1960s when Synchrotron Radiation started to be utilized parasitically in synchrotrons constructed for high energy physics experiments, the ring-based light sources emerged explosively and gave significant contributions to the material science. They evolved to what are called the 3GLSs and SOLEIL can be considered to be the state-of-the-art 3rd Generation Light Source.

◊ The ideas for the so-called DLSRs started to emerge since the early 2010s on the basis of MBA lattices along with noteworthy progress in key technologies, creating today, an outburst of a global wave of upgrading existing LSs and/or newly constructing DLSRs. Several orders of magnitude of performance upgrade expected for DLSRs as compared to 3GLSs may justify calling them 4GLSs.

◊ There are, nonetheless, a number of challenging accelerator physics and technology issues yet to overcome. The community is working intensively to tackle them including recent efforts to make the future light source accelerators more "Green".

◊ In view of the rapid evolution up till this point, the future of the ring-based, or more generally the accelerator-based Light Sources (LSs) appears to be very bright.