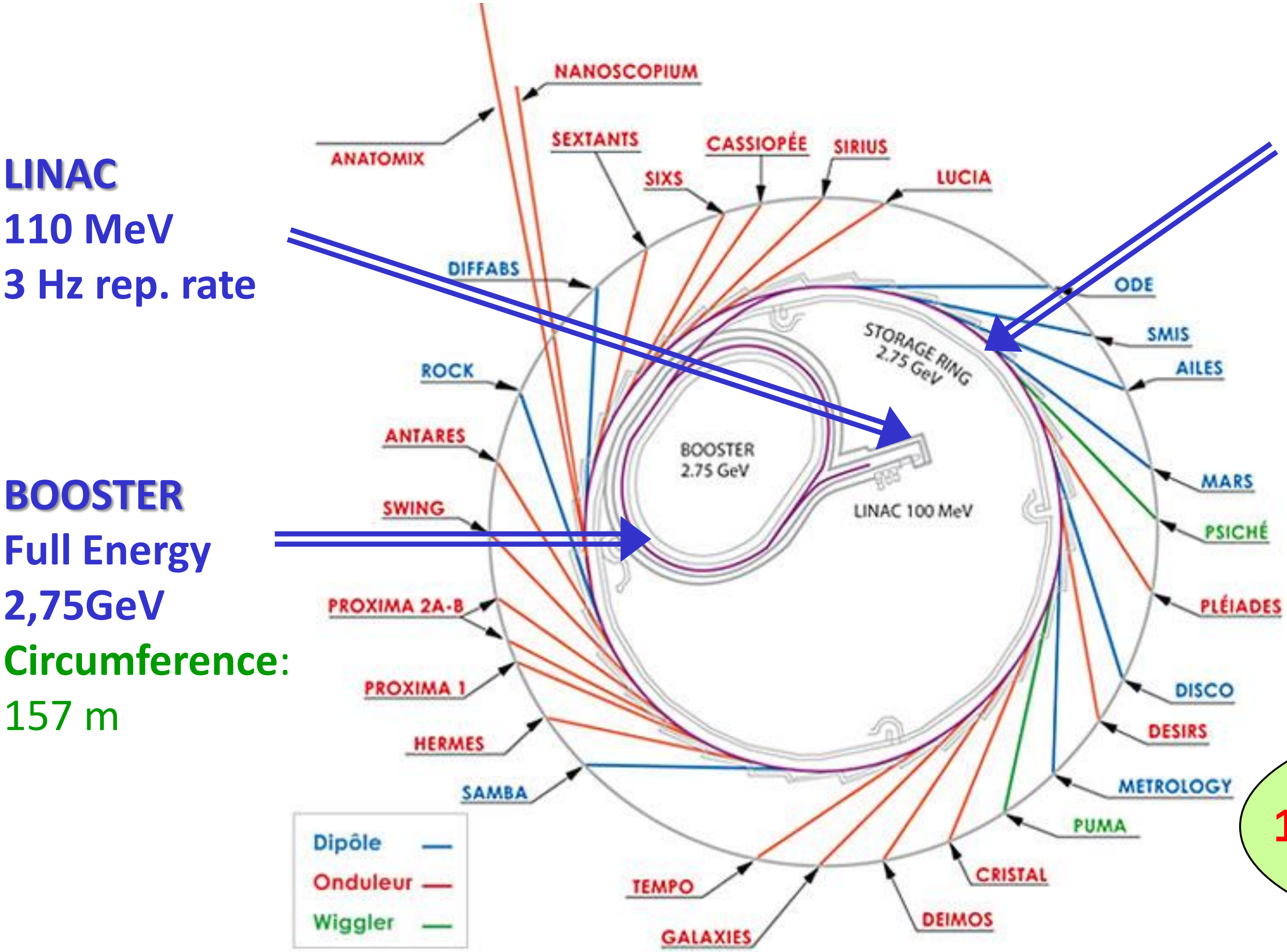
Towards an upgrade of the French synchrotron light source SOLEIL

François BOUVET

6th POCPA Workshop, 24-26 Sept 2018, LNLS

SOLEIL today



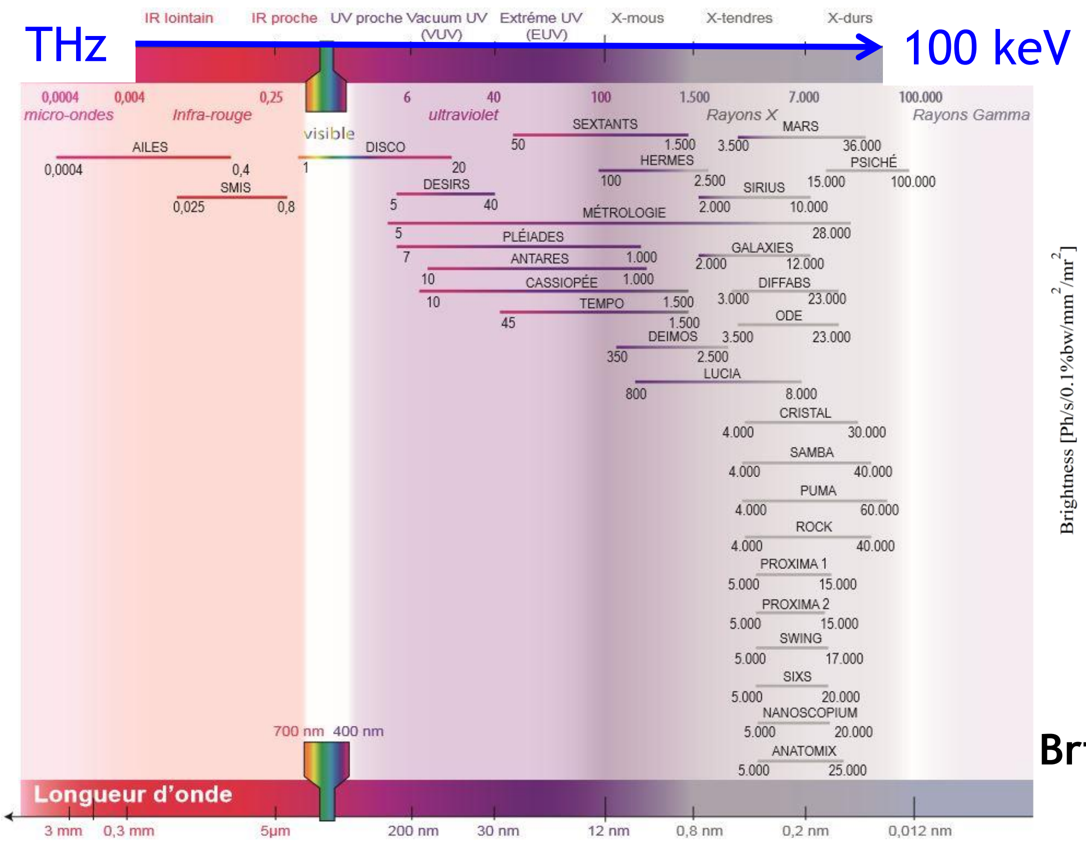
10 years of operation

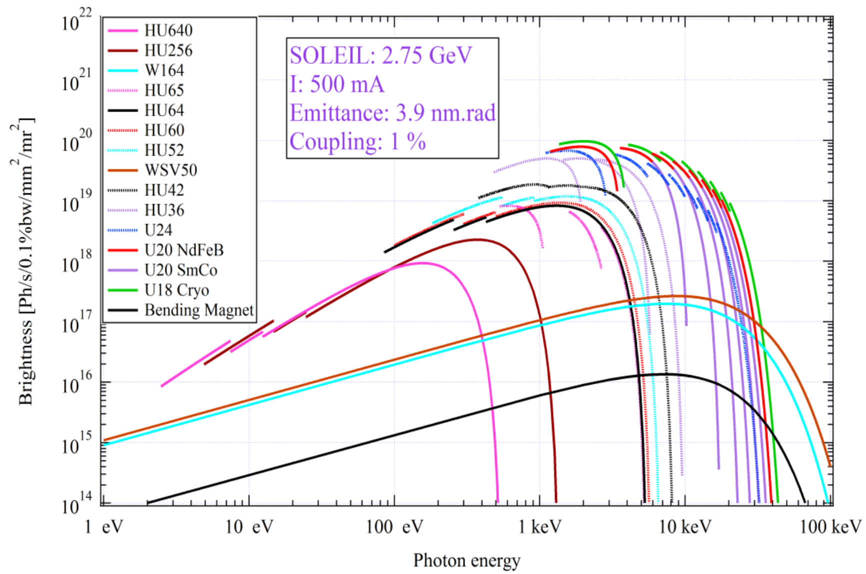
- June-December 2006: Commissioning of the Storage Ring
- 2008: Open to users
- 2009: Top-up operation
- 2018: 29 beamlines
- 10,000th user arrived in September

SOLEIL today

Present SOLEIL storage ring performance:

Wide range of photon energy





Brilliance of photon beam = 10^{20} @ few keV

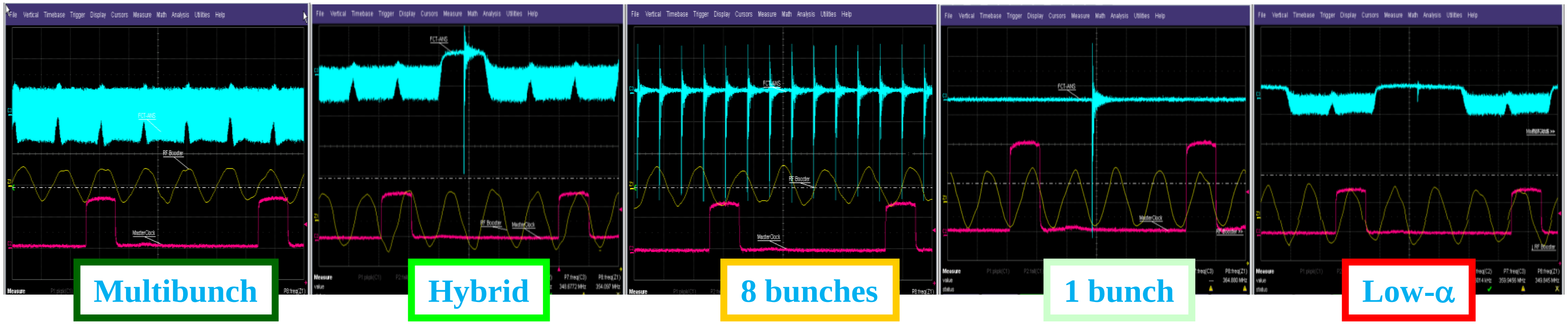
(photons/s/mm²/mrad²/0.1% b.w.)

SOLEIL today

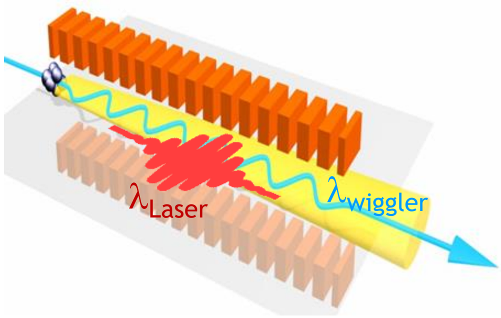
Present SOLEIL storage ring performance:

Filling patterns allowing time resolved experiments

5 modes of operation, all in Top-up mode:



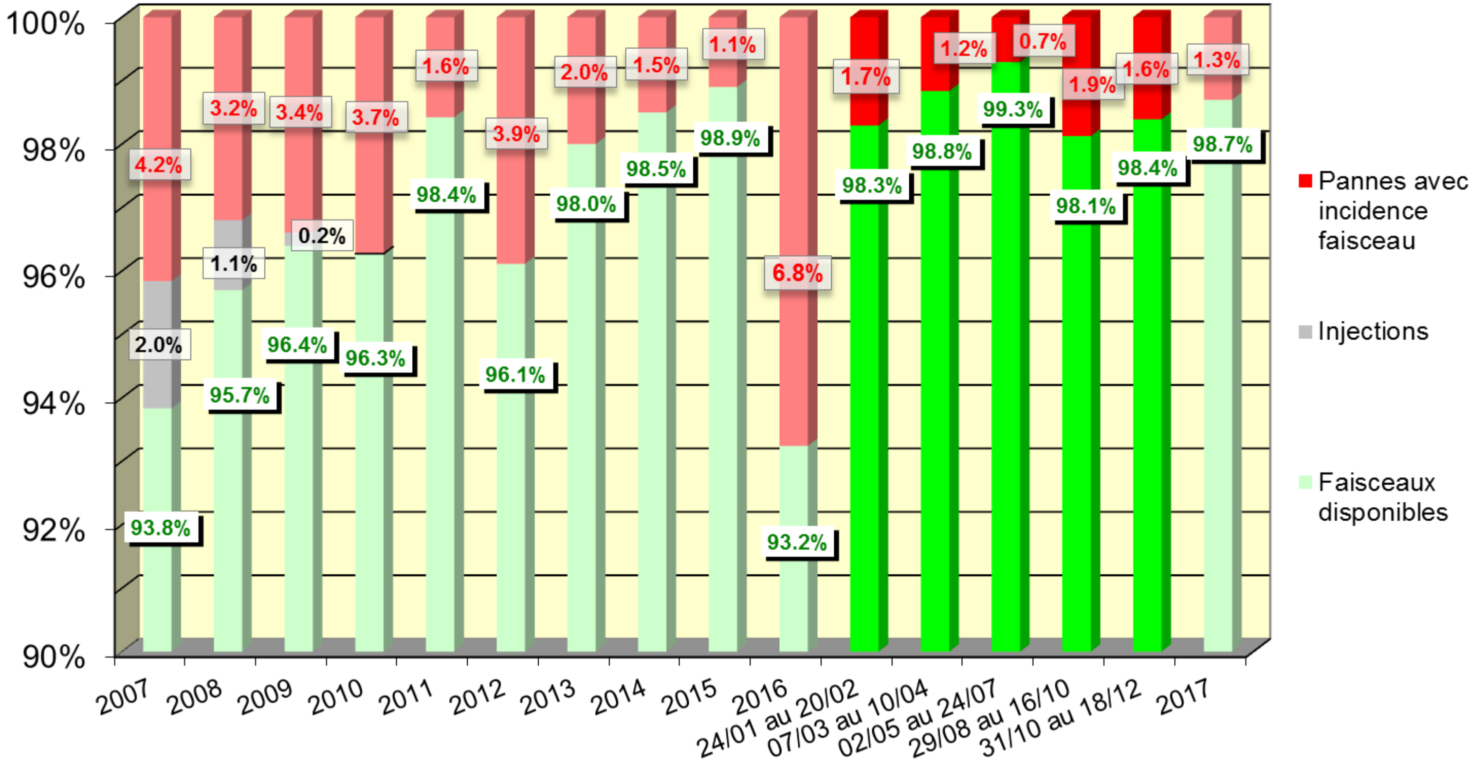
Mode of operation Bunch fill. patterns	User Operation in 2017	Ultimate performance achieved
Multibunch (M2)	500 mA	500 mA
Hybrid/camshaft mode (M)	425 mA + 5 mA	425 mA + 10 mA
	+ Slicing on high intensity bunch	Slice length < 200 fs FWHM
8 bunches (8)	100 mA	110 mA
1 bunch (S)	16 mA	20 mA
Low-α: Hybrid mode (L)	4.7 ps RMS for 65 µA	< 3.2 ps RMS for 15 µA



< 200 fs synchrotron pulses for 2 beamlines

SOLEIL today

A good beam availability:

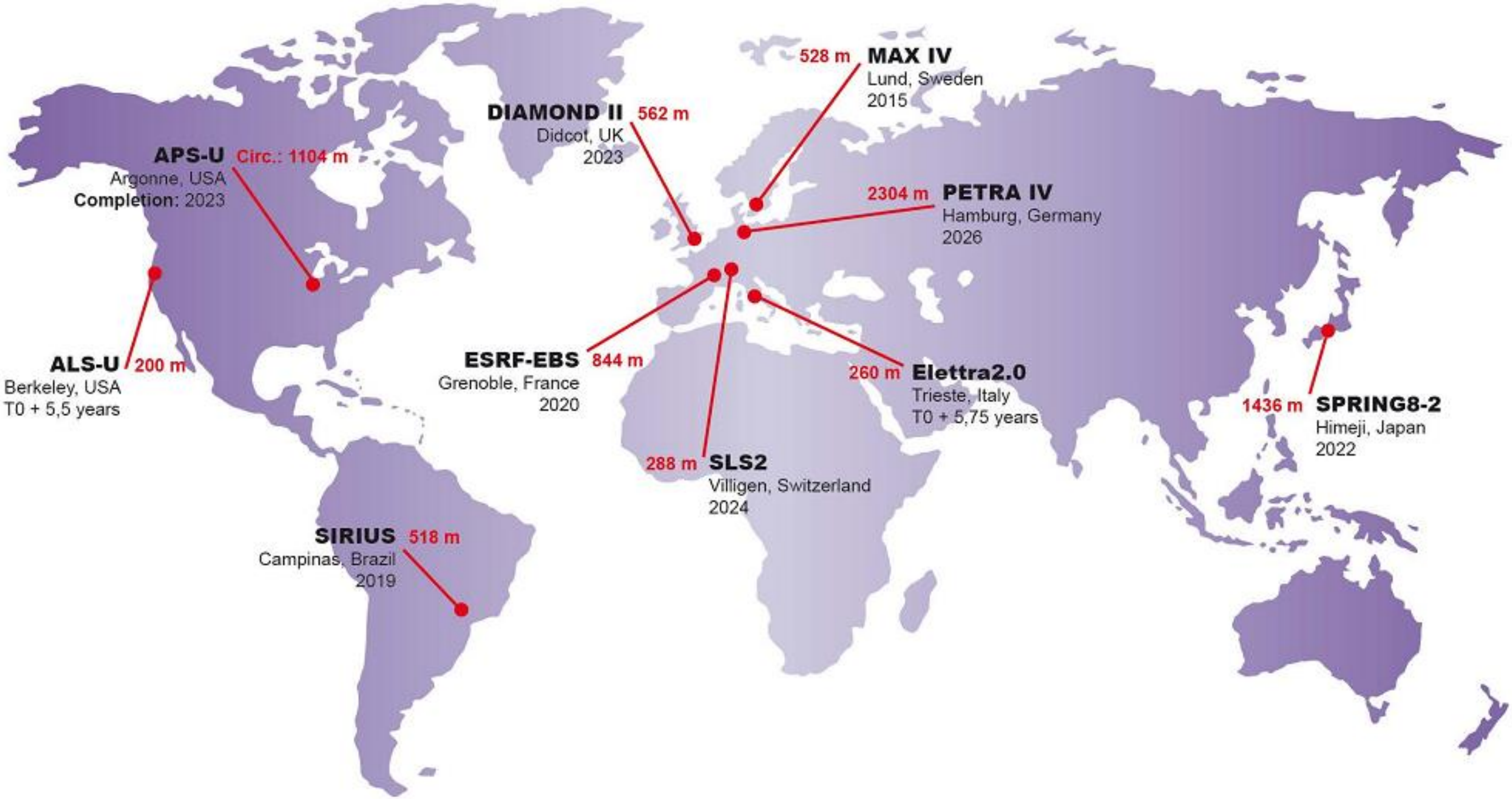


Availability in 2017: 98,7%

MTBF: 93h

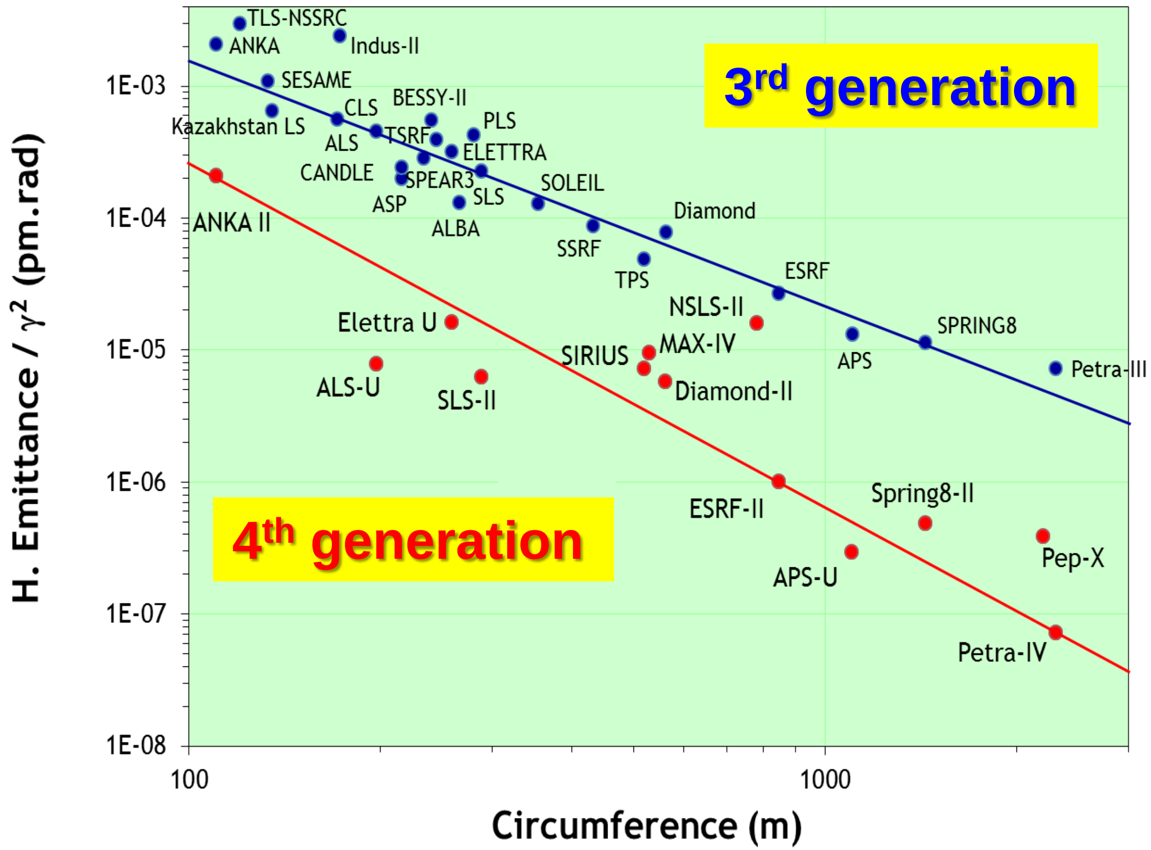
MTTR: 1h10

International context



New generation of synchrotron light sources => new class of experiments critically dependent on source brightness and coherent flux fraction

International context



Brightness and coherent fraction are proportional to stored current and scale inversely to beam emittance

=> Evolution of 3rd generation rings towards Very Low Emittance Rings

Brilliance and coherent fraction are maximized for smaller electron beam emittances until diffraction limit is reached (i.e. when electron emittance is about the same as photon emittance) => **Diffraction Limited Storage Rings (DLSR)**

International context

How to decrease horizontal emittance ?

$$\varepsilon_H \propto E^2 \times \theta^3$$

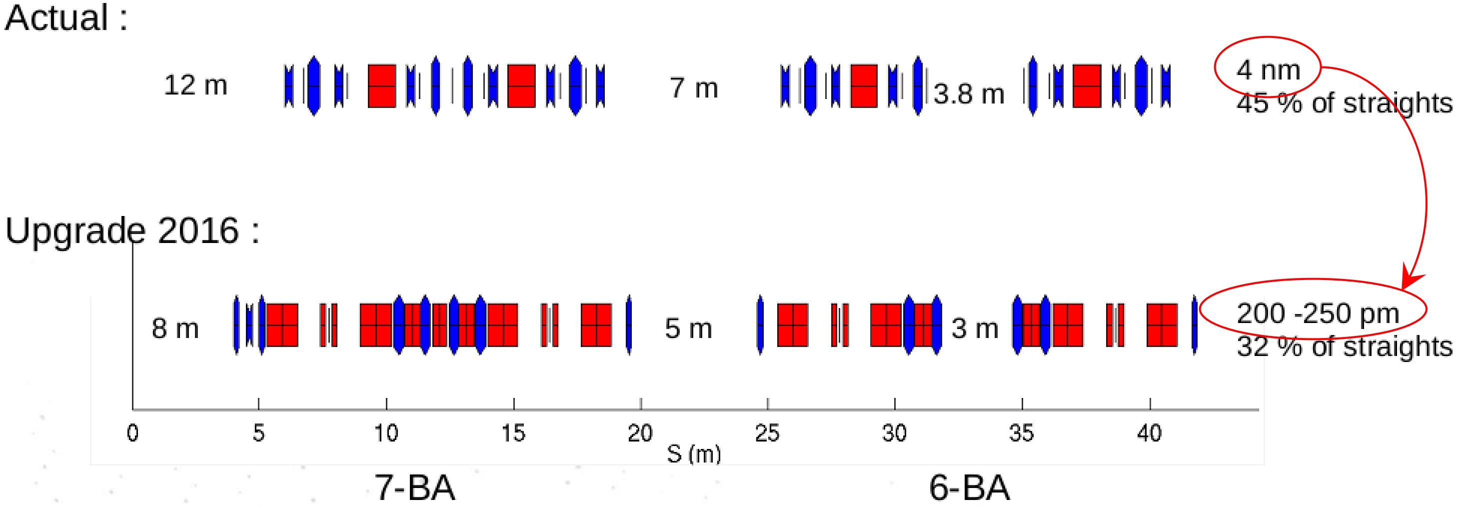
H emittance — e- beam energy — bending magnet angle

=> Divide bending magnets into small pieces !

Use of Multi Bend Achromat (MBA) structures

Example (Preliminary studies from 2016):

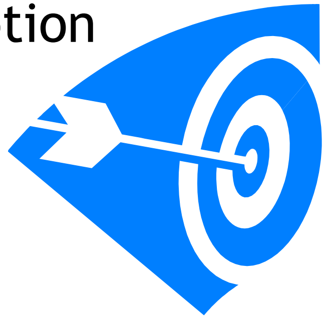
1/8 of the Storage Ring:



First steps for the upgrade of SOLEIL

Constraints and requirements:

- Reduce H emittance of the electron beam by a factor > 30
- Reuse the existing Storage Ring tunnel and the shielding walls
- Preserve the very wide range of photon energy
- Preserve the large intensity of 500 mA in the multi-bunch mode operation
- Maintain Top-up operation
- Find alternative radiation sources for dipole based beamlines
- Preserve the present filling patterns
- Examine all the possibilities to provide a short bunch operation
- Minimise running costs and especially electrical consumption
- Minimise the « dark period » (max. 2 years)



First steps for the upgrade of SOLEIL

Timeline:

Date	Phase
Dec. 2016	Council meeting, presentation of the first proposal for an upgrade.
2017 - 2019	Discussions regarding the definition of the project (beamlines and storage ring); definition of objectives. Baseline Lattice defined.
2018 - 2019	Continuation of discussions and prototyping to assess feasibility of key options.
2019	**Decision to launch a Conceptual Design Report (CDR).**
2019-2020	CDR based on preliminary studies and prototyping.
2020	**Decision to launch a Technical Design Report (TDR).**
2020-2022	Technical Design Report.
2022	**Decision to start the project.**
2022-2025	Reconstruction of storage ring and beamlines.
2026	Restart of user operation.

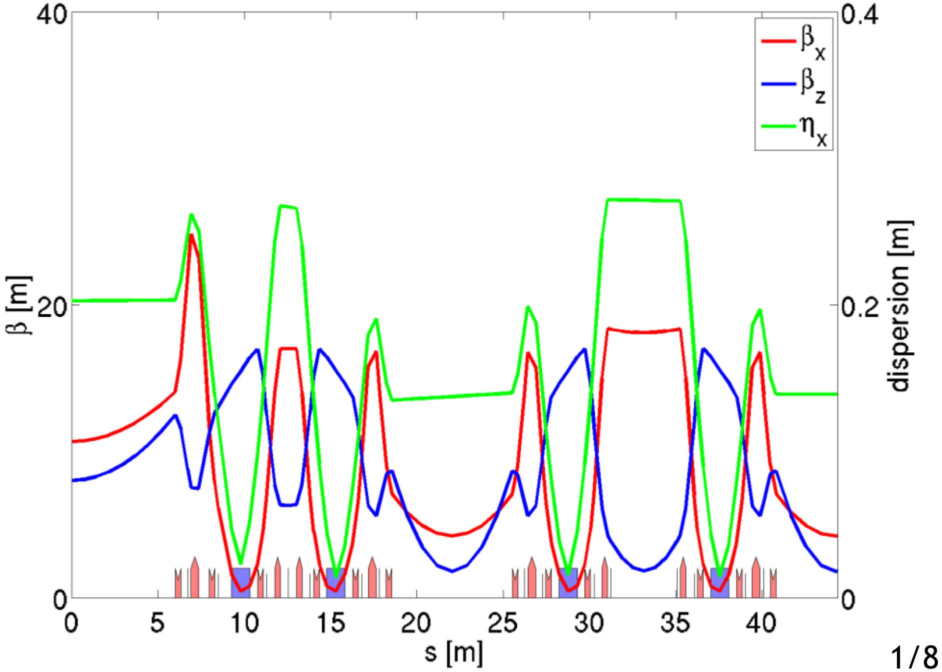
First steps for the upgrade of SOLEIL

Baseline upgrade lattice:

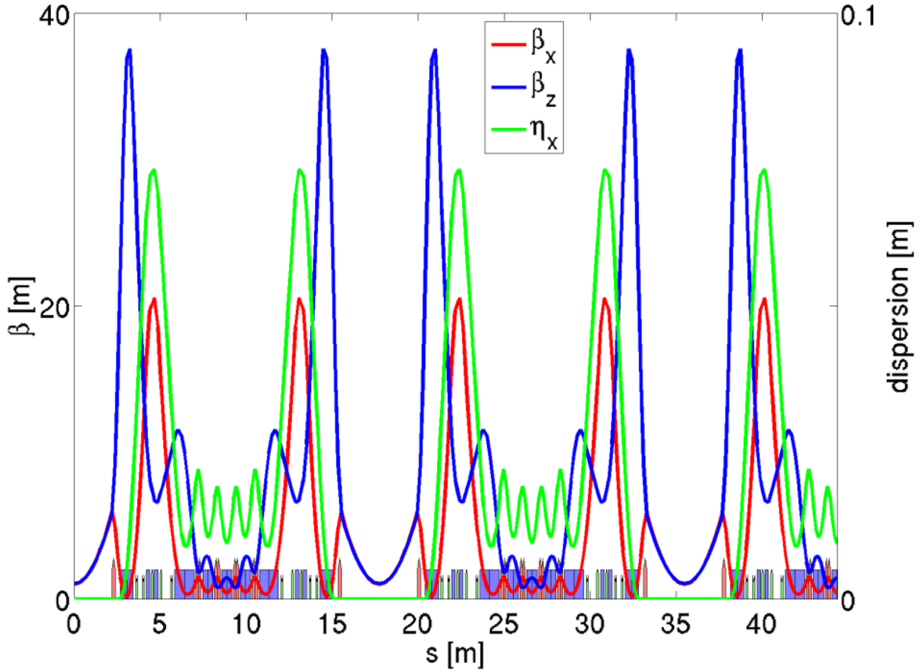
7BA

ε_x = 4 nm.rad

ε_x = 72 pm.rad



Present SOLEIL lattice



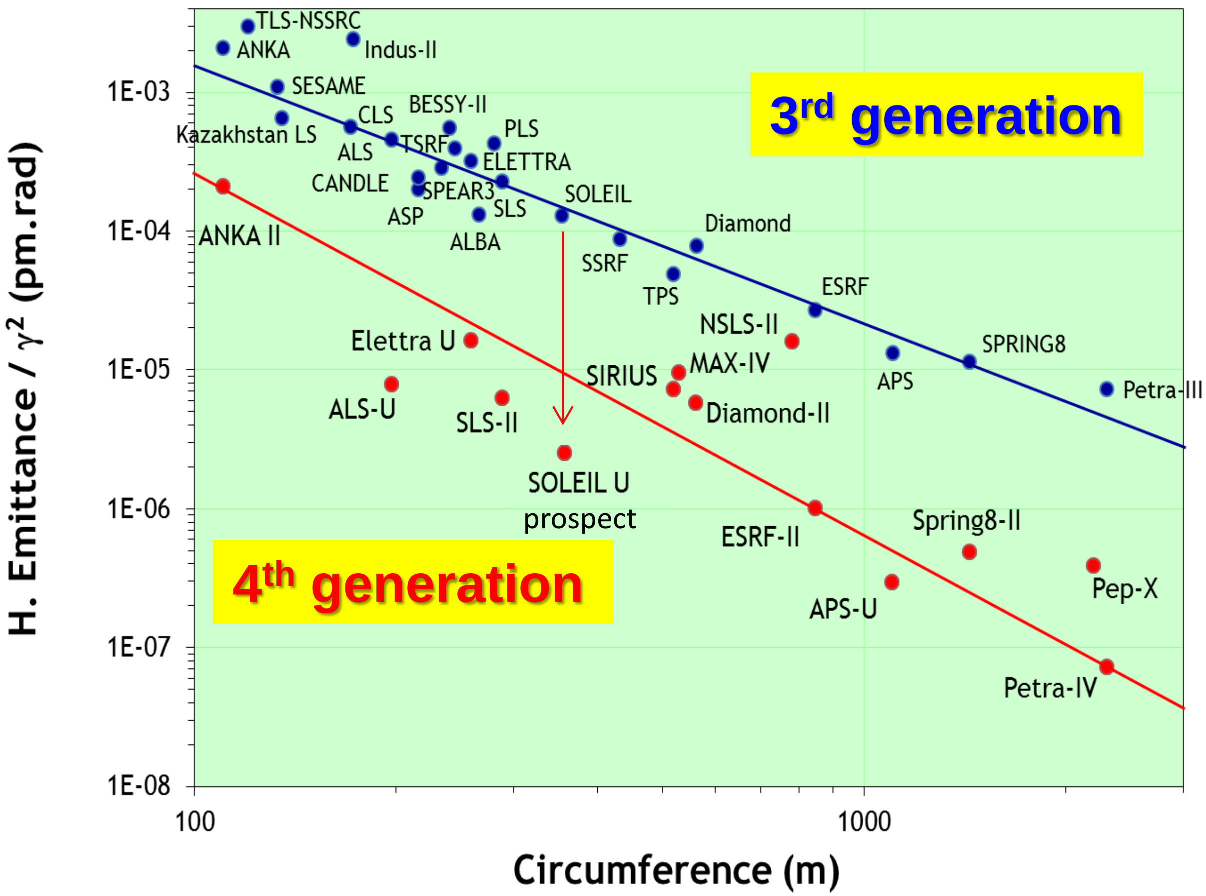
Upgrade

Beam focusing is strongly increased !

- Sext < 2000 T/m^2
- Quad < 100 T/m
- DQ ~ 0.6 T & 40 T/m

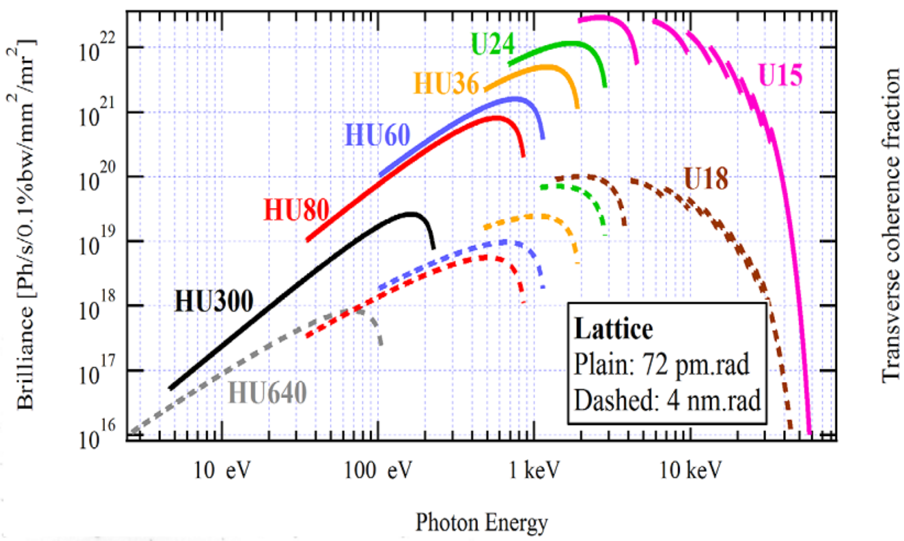
=> Many challenges: Space limitation, magnets complexity, injection, beam lifetime, vacuum systems, …

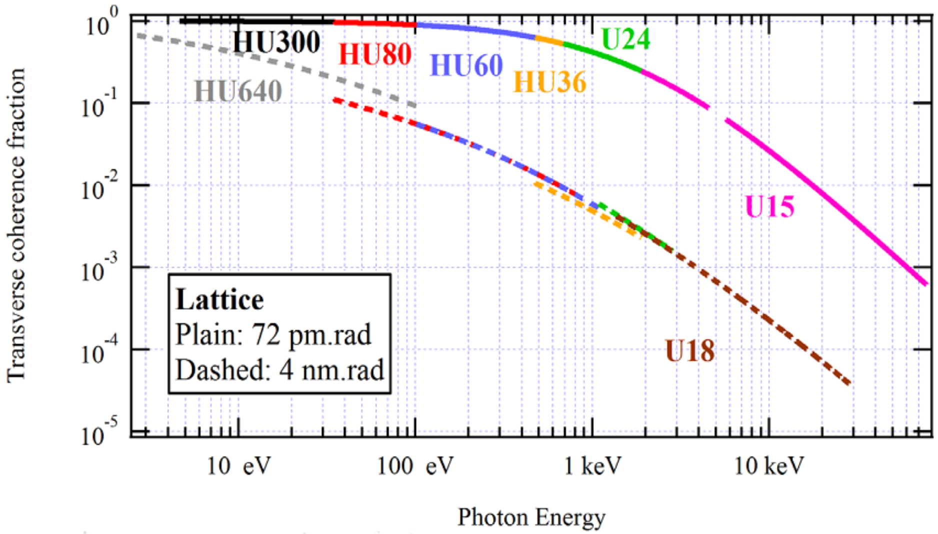
First steps for the upgrade of SOLEIL



First steps for the upgrade of SOLEIL

Brilliance and coherence comparison:





Brilliance of photon beam > 10^{22} @ few keV
(photons/s/mm²/mrad²/0.1% b.w.)

Increase by 2 orders of magnitude

Photon beam fully coherent up to 200eV, > 40% at 1keV, > 14% at 3keV

Focus on Storage Ring injection

Key feature in light sources: High stability of the photon beam

⇒ Top-up operation is requested, with **minimal perturbation** to the stored beam

MBA structure with N dipoles:

⇒ Beam focusing is strongly increased: High gradient quadrupoles required

⇒ Strong chromaticity correction sextupoles ($\propto N^3$)

⇒ Dynamic aperture reduced ($\propto 1/N^3$)

⇒ Negative impact on beam lifetime and injection efficiency

Injection is a critical point: One of the keys of the project ambition !

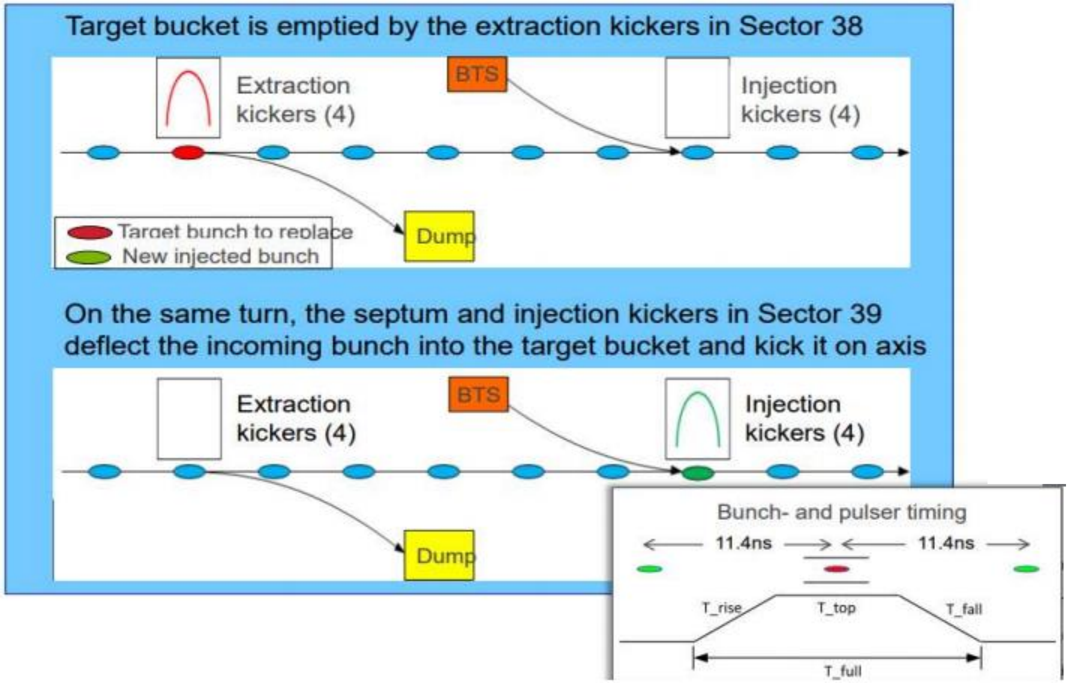
Focus on Storage Ring injection

How to deal with the small dynamic aperture ?

Solution 1:

- On-axis injection
- Individual bunch replacement using fast kickers

= Bunch swap-out scheme



Kicker constraints:

T_rise and T_fall < spacing between 2 bunches

Argonne NATIONAL LABORATORY The APS Upgrade (J. Carwardine) - EPICS Collaboration Meeting, June 2018

Focus on Storage Ring injection

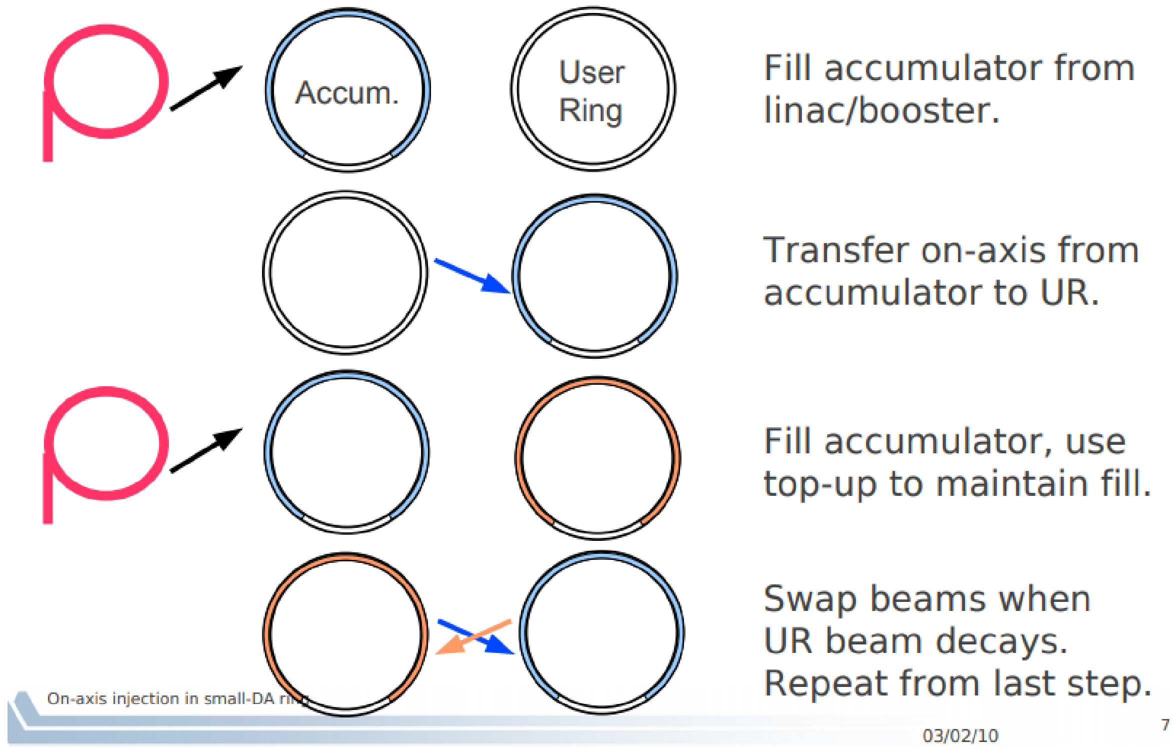
How to deal with the small dynamic aperture ?

Bunch swap-out scheme

2 solutions for the extracted beam:

- Send it on a beam dump (=> increasing radiation)
- Send it in an accumulator ring

"On-axis injection into small dynamic aperture", L. Emery, Accelerator Systems Division, Argonne National Laboratory, Future Light Source Workshop 2010



Focus on Storage Ring injection

How to deal with the small dynamic aperture ?

Bunch swap-out scheme:

Is this solution suitable for SOLEIL ?

Seems difficult…

Frequency RF system = 352MHz + 416 bunch fill pattern

⇒ T_rise = T_fall < 2,8ns

Total kicker length: 2,7m

Bend angle: 1mrad

High number of stripline modules/kickers required

With beam dump: Max. charge per bunch (Single-bunch mode !) ?

With accumulator: Difficult to reuse the existing SR tunnel, costs, …

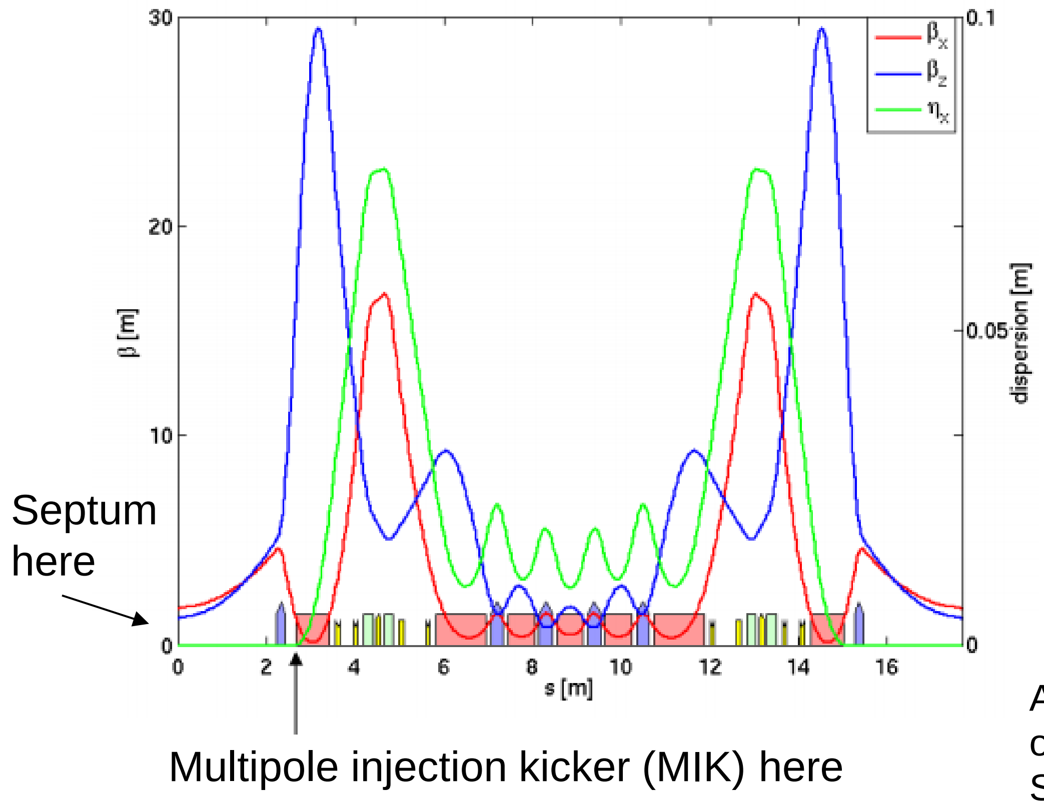
Focus on Storage Ring injection

How to deal with the small dynamic aperture ?

Solution 2:

- **Off-axis injection**
- **Vertical injection with non linear Kicker**

Actual SOLEIL-U lattice : 72 pm.rad



Off axes to accumulate

Keep the lattice symmetry

Take advantage of the large vertical beta function

Take advantage of the natural small vertical emittance of the booster

But : vertical betatron oscillation versus low gap ID …

A. Loulergue, « Baseline Lattice For the Upgrade of SOLEIL », Future Light Source, March 5-9 2018, Shanghai Institute of Applied Physics

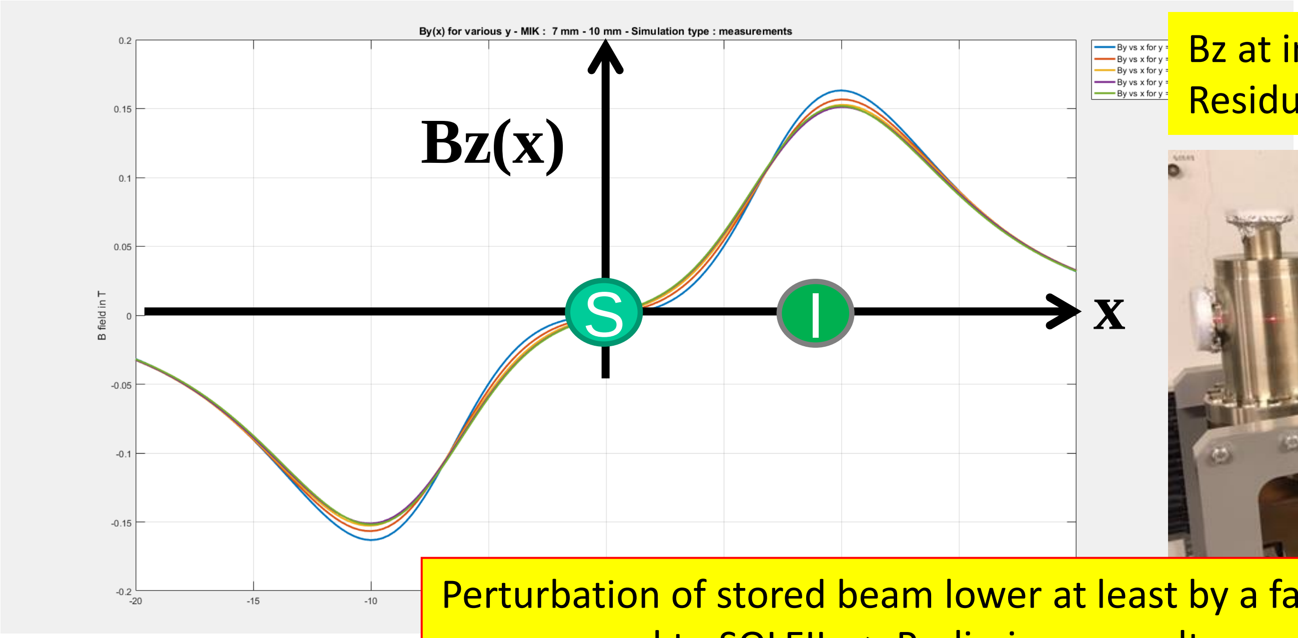
Focus on Storage Ring injection

How to deal with the small dynamic aperture ?

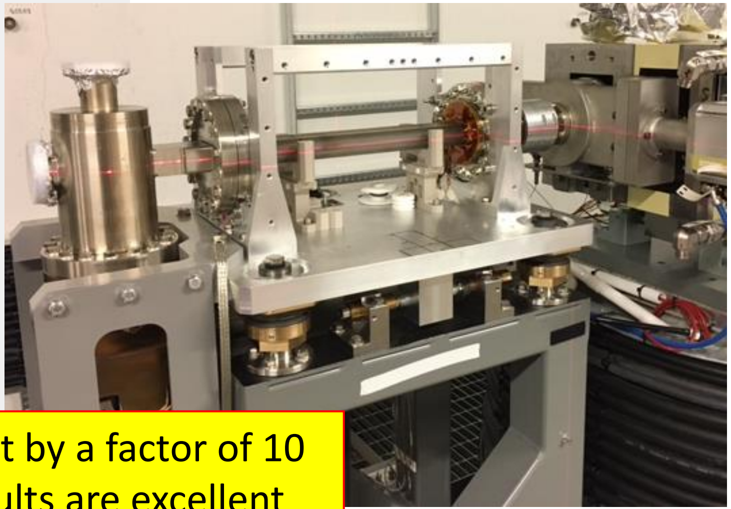
Vertical injection:

- **Thin septum:** Thickness of the septum must be as thin as possible to lower induced betatron oscillations and the kick required for the MIK
- **Transverse non linear kicker (MIK):** Enables to kick the beam injected off-axis inside the dynamic aperture, while providing minimal perturbation of the stored beam

SOLEIL has developped such kind of kicker for MAX-IV:



Bz at injected beam location: 11,7mT.m
Residual Bz in central area: < 5µT.m



Perturbation of stored beam lower at least by a factor of 10 as compared to SOLEIL => Preliminary results are excellent

Focus on Storage Ring injection

How to deal with the small dynamic aperture ?

Vertical injection:

- **Thin septum specifications:**

Active length (mm)	Kick (mrad)	Septum thickness (mm)	Leakage field
750	135	≤ 1	Few ppm of peak field

- **MIK specifications:**

Active length (mm)	Available length (mm)	Kick (mrad)	Distance from axis (mm)	Pulse duration (µs)	Beam Stay Clear inside MIK (mm)
150	250	2	3-4	< 2,4	+/-5 (V plane)

Very demanding requirements…

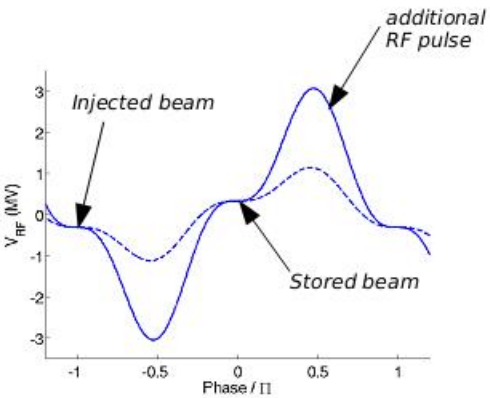
Focus on Storage Ring injection

How to deal with the small dynamic aperture ?

Solution 3:

- On-axis injection
- **Longitudinal injection** on chromatic orbit with MIK and extra RF pulse

	Main RF (MV)	Harm. 3 (MV)
Normal	0.9	0.3
+ injection	+1.4	+0.47



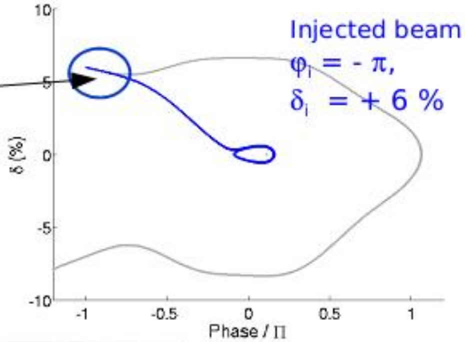
Derived from :
M. Aiba et al., Longitudinal injection scheme using short pulse kicker for small aperture electron storage rings, Phys. Rev. ST Accel. Beams 18, 020701 (2015).

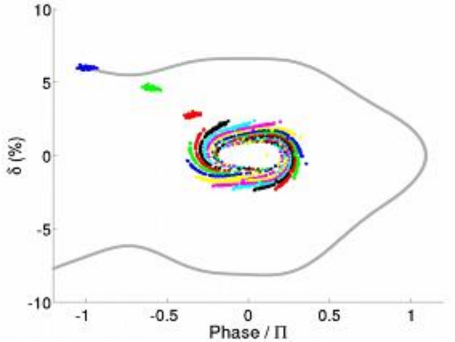
Tracking with a booster emittance of 30 nm.rad gives 100 % efficiency on a perfect baseline lattice

Beam injected on a chromatic orbit by mean of an NLK located in the dispersion bump at an energy offset of + 6%

200 turns

NLK accomodation still under investigation ...





Focus on Storage Ring injection

How to deal with the small dynamic aperture ?

Longitudinal injection:

- **Thin septum specifications:**

Active length (mm)	Kick (mrad)	Septum thickness (mm)	Leakage field
750	135	≤ 1	Few ppm of peak field

- **MIK specifications:**

Active length (mm)	Available length (mm)	Kick (mrad)	Distance from axis (mm)	Pulse duration (µs)
250	300	2,5	3,5	< 2,4

Again very challenging…

In-depth studies are underway. A viable injection scheme has to be determined by mid-2020 (Start of CDR). For the studies of the pulsed systems, we intend to ask for some help from international experts: Brainstormings, technical advices, feedbacks, design reviews, …

Focus on the DC power supplies

Preliminary magnet characteristics:

- 7BA lattice: Much higher number of magnets than today
- Very dense lattice => Compact magnets, few space between magnets
- Smaller magnet apertures (down to 16mm)
- Low dipole fields (0,6T) but combined with rather strong quadrupole components (40T/m)
- Pure quadrupole fields are strong: Close to 100T/m
- Strong sextupoles: Close to 2000T/m^2
- + Octupoles, reverse-bends, and of course dipolar and skew quadrupole correctors
- Fields and gradients adjustment: ±5% to ± 10%

Focus on the DC power supplies

Preliminary magnet characteristics:

- Magnet design should:
  - Be part of a global optimization including capital investment, cooling systems, energy consumption, equipment standardization (magnets, power supplies), etc…
  - Allow easy installation and alignment to save cost and installation time

=> Significant interactions between the groups: Teamwork !

Focus on the power supplies

Power supplies: First trends for the upgrade

- Energy saving => Use of permanent magnets seriously considered
- Correction coils to allow adjustment of fields and gradients
- Whatever the solution (permanent or electro magnet), high number of power supplies requested
- Favoured option: Individual powering of the magnets for a maximum beam optics flexibility

=> More power converters with smaller power ratings

- No information yet on current resolution and stability requirements for the power supplies

Significant concern: How to maintain a high MTBF / MTTR with a much greater number of power supplies ?

=> Some facilities have opted for very interresting solutions:

See for example Jean-François BOUTEILLE's presentation tomorrow…

Focus on the power supplies

Power supplies: First reflections for the construction phase

Several possibilities:

- In-house design (power + control) & subcontracted manufacturing according to our drawings and models: With this strategy, SOLEIL has full control over the power supply performance. Possibility to standardize the equipment, easier spare parts management
- Purchase commercial off-the-shelf power supplies (voltage sources) and implement ourselves the current control loop using our own electronics: Due to low power ratings, no need to buy (big) custom built power supplies. Possibility to use small off-the-shelf products with proven reliability. Use of our own standardized control electronics to have full control over the performance of the current loop
- Subcontract the whole design and construction of the power supplies (power + control): In this case, complete documentations (schematics, BOM, manuals, Gerber files, firmware sources) should be part of the deliverables, in view of the exploitation phase. Standardization more difficult with this strategy (different suppliers), more work for computing people, …

Focus on the power supplies

Power supplies: First reflections for the construction phase

Preferred options at this stage are the 2 first ones

Major concerns in this perspective:

- Juggle upgrade preparation and operation of the existing machine at the highest performance
- Human resources: Internal competencies and staff number will have to be preserved and even reinforced => Anticipation of upcoming retirements of employees, judicious recruitments, trainings, …

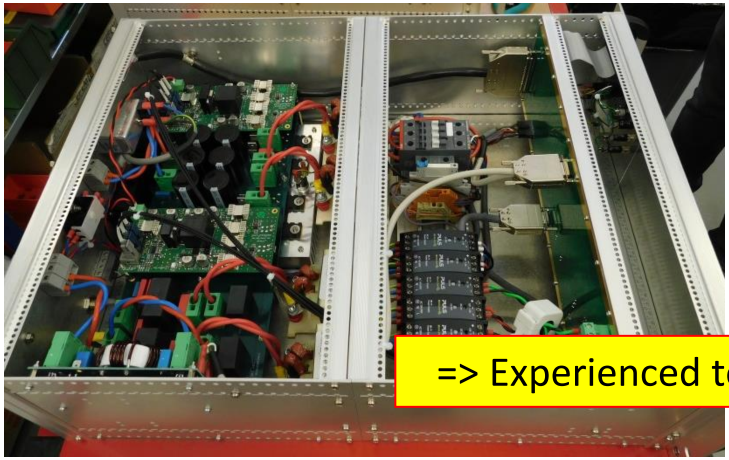
⇒ Learn from the experience of other facilities which are currently achieving their upgrade

Focus on the power supplies

Power supplies: First reflections for the construction phase

Some internal developments:

1 kW switched-mode 4-quadrant power converter



Spare SR dipole power supply 400 kW

5kW one-quadrant power converters

Spare SR sextupole & TL2 dipole power supply 50 kW

=> Experienced team in power converter construction

Focus on the power supplies

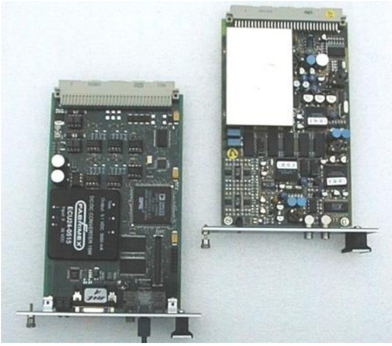
Power supplies: First reflections for the construction phase

Some internal developments:

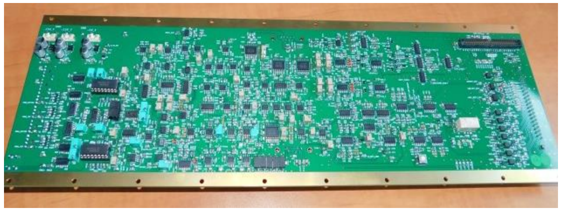
Main control & regulation platforms used for these developments:

1/ Hazemeyer control boards: Fully digital ; Current resolution: 18 bits ; Based on 2 16-bit 40 MIPS µcontrollers + 18-bit 500 kS/s ADCs

2/ PSI controllers (old generation): Fully digital ; Current resolution: 18 bits ; Based on a FPGA / DSP (32-bit 66 MIPS) architecture + 2 16-bit 2-channel ADCs with self calibrating capabilities for the current measurement



3/ Home-made control boards: Analog current regulation ; Current resolution: 16 bits ; Associated with SIEMENS PLCs



Some of the components of the first 2 platforms are now obsolete

Focus on the power supplies

Power supplies: First reflections for the construction phase

Foreseen power converter strategy:

- Power supply performance deeply linked to the performance of the control and measurement electronics
- Control electronics: Critical element for operation and maintenance because of its high complexity in a power converter
- Having a single control system is a major advantage in terms of standardization with a direct impact in system operation and maintenance

⇒ **Implementation of a standardized control electronics for all the power converters would be a major benefit**

⇒ **Need to developp a new electronics with the latests components**

Difficult due to limited resources…

⇒ **We seek to launch collaborations with (an)other institute(s) to build a new control platform**

(=> My phone number: +33 (0) 1 69 35 98 70)

Some reflections after 10 years of operation

Between 2005 and 2006: Procurement of the majority of the power supplies. Main lessons:

- **We experienced (and had to solve) many failures during the 2 first years of operation**
- **Most of them could have been avoided by means of:**

  - More detailed specifications: Design rules (semiconductors, capacitors, fans…), EMC (immunity / emissions), reparability (too complex / compact systems are difficult to repair), …

  - In-depth design reviews: Sizing of main power components (semiconductors, capacitors, etc…) should have been more closely examined

  - Extensive acceptance tests, with thermal & EMC measurements

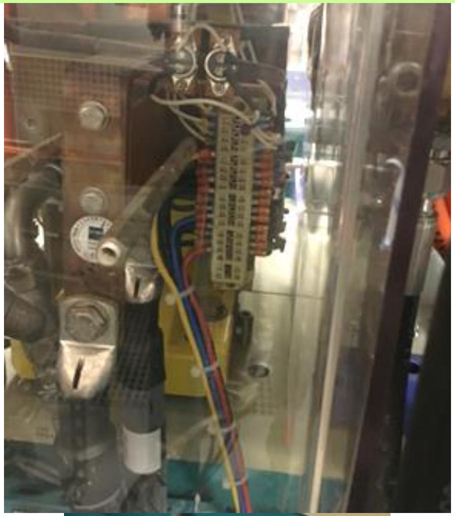
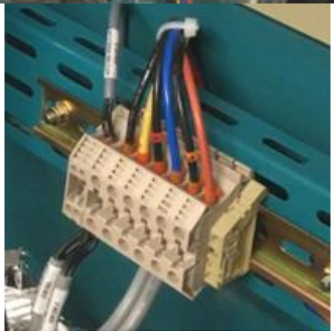
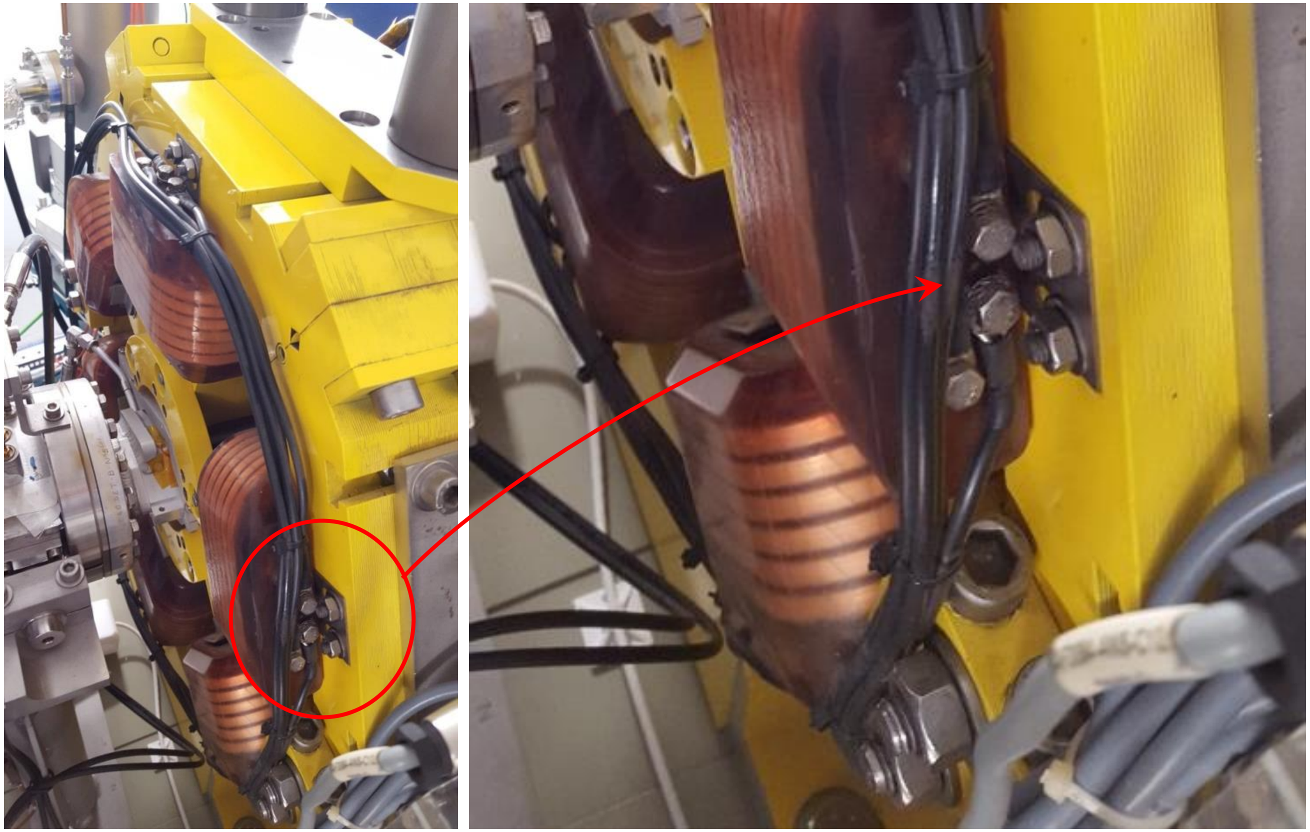
- **Some of the problems (mostly erratic => difficult to reproduce and thus to solve) were caused by firmware bugs:** In our view, it is essential to have the complete documentation of the equipement (schematics, BOM, manuals, gerber files, and firmware sources). Fortunately it was the case for us.

Some reflections after 10 years of operation

Stronger interactions with the magnet people might have prevented some problems:

Terminal blocks for DC cables fixed on the magnets not adapted to wire sections => Necessary to add intermediate teminal blocks

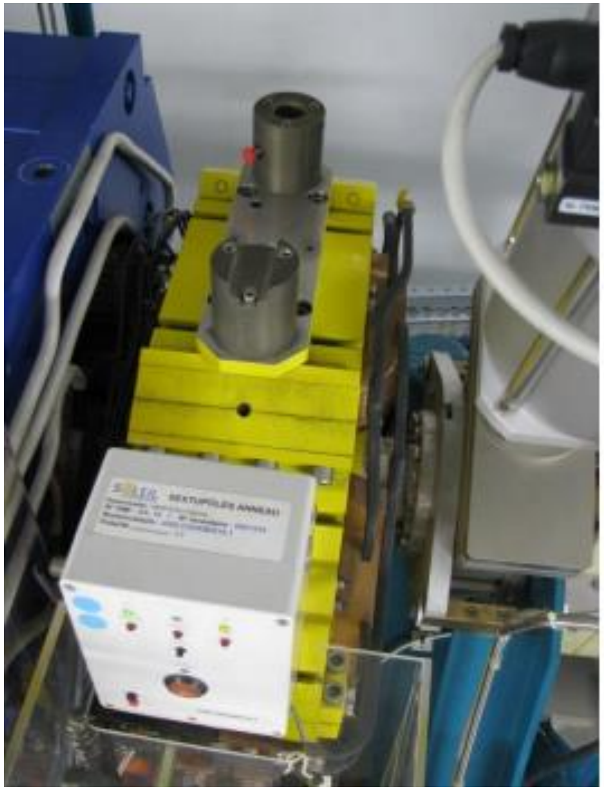
Correctors inside the sextupoles: High risk of making short-circuits during campains of electrical connections tightening

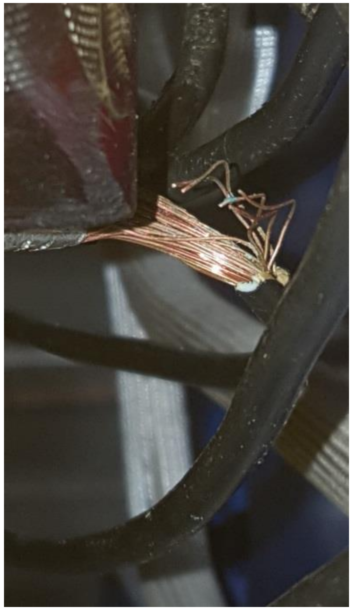
Some reflections after 10 years of operation

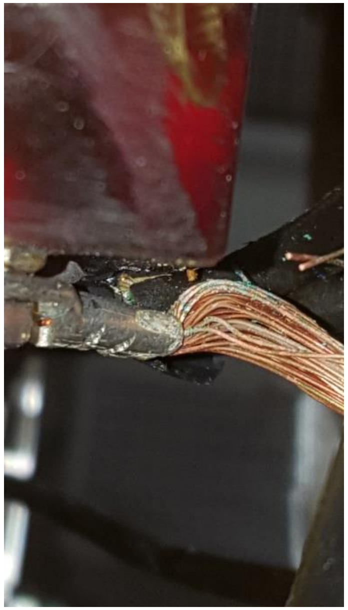
Stronger interactions with the magnet people might have prevented some problems:

Many electrical connexions not accessible…



=> To crimp new cable lugs here,
the magnets have to be removed from
the machine…

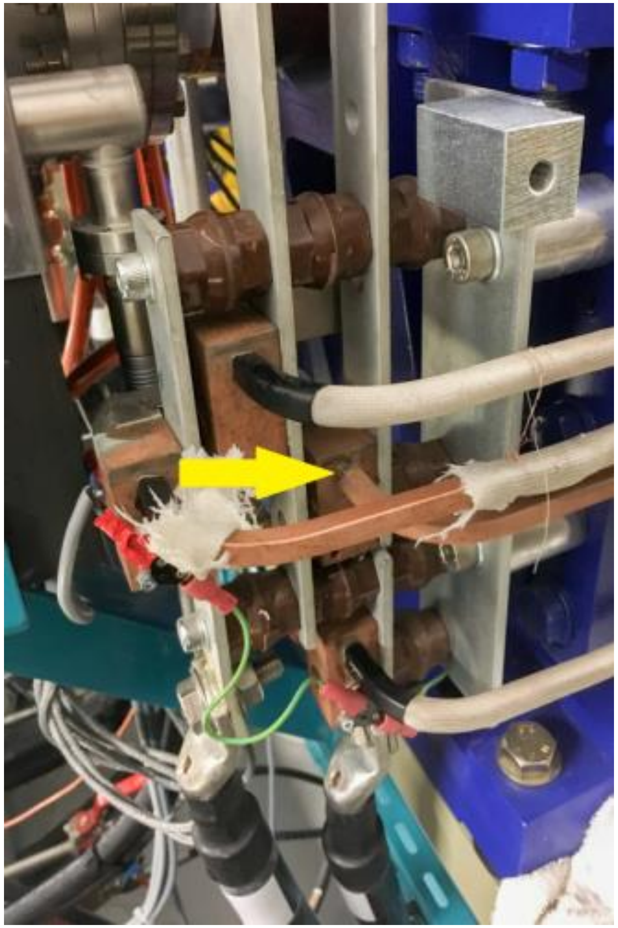


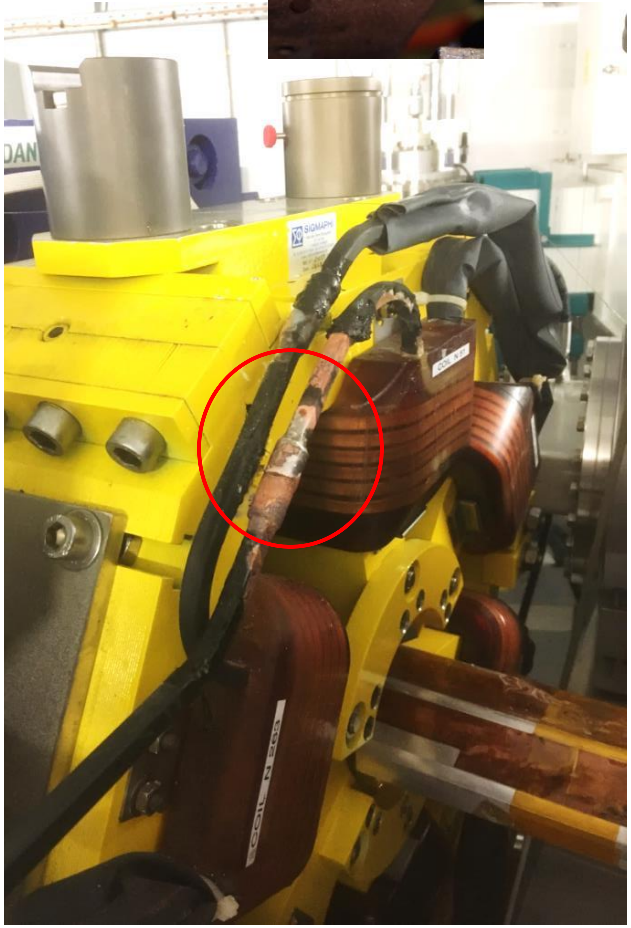


Some reflections after 10 years of operation

A serious concern at SOLEIL: Leaks at braze joints

7 failures in 10 years !



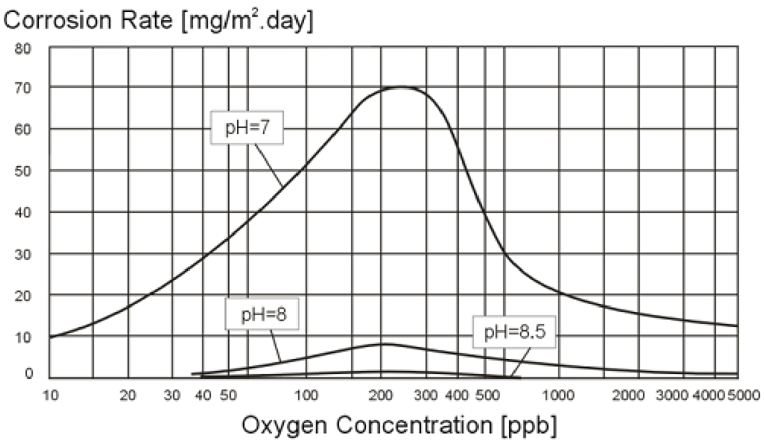


Some reflections after 10 years of operation

A serious concern at SOLEIL: Leaks at braze joints

Many things to rethink for the SOLEIL-U cooling circuits, among which:

- Dissolved O2 (DO) level: Many facilities have high extremely low DO rates (< 10 ppb). At SOLEIL, DO rate is even not monitored at the moment
- PH level (currently 7,4 at SOLEIL)
- Separation of cooling water circuits (Al / SS + Cu): At SOLEIL, vacuum chambers of straight sections are in aluminium => risk of corrosion. In some facilities, aluminium is forbidden
- Maximum water velocity to limit cavitation erosion, vibrations: 2-3 m/s



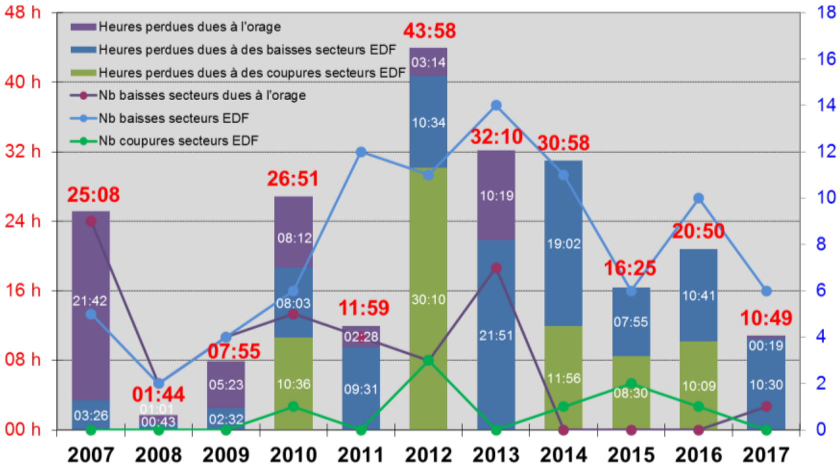
. Corrosion rate of copper in fast flowing de-ionized water as a function of dissolved O_2 concentration in the water, at 3 different pH

Some reflections after 10 years of operation

Electrical infrastructures:

- Voltage disturbances are part of the normal operation of electrical netwoks
- At SOLEIL, voltage dips are the principal cause of power quality issues (most them < 150ms with an amplitude < 25%)
- Network disturbances and power quality are issues of critical importance for particle accelerators
- Equipment must possess a certain immunity to correctly function in this environment

Nb. beam losses / hours of beam lost
due to mains voltage drops / losses



- It is essential to define immunity levels for the power supplies (extremely sensitive to network distrubances due to their high requirements for precision), in order to survive most of the disturbances without tripping the particle accelerator

Some reflections after 10 years of operation

Electrical infrastructures:

K. KAHLE (CERN):

⇒ Establish detailed statistics about these disturbances to better define the immunity levels for your equipment

⇒ All groups installing and operating electrical equipment need to be involved in power quality considerations, right from the beginning of the project

Some reflections after 10 years of operation

To remember for the future …

For the rest, let's be as creative as possible ☺

See you in 2 years for more information about this topic

A special tribute to a friend, Pierre Lebasque, team leader of the Power Supplies and Pulsed Magnets group for many years, who left us on the 7th of June 2018.

During his carrer, Pierre developped an exceptional and broad expertise on pulsed magnets and accelerator technology. His tenacity and determination have played an important role in all the projects he led.

Questions

Thank you for your attention.
Questions ?