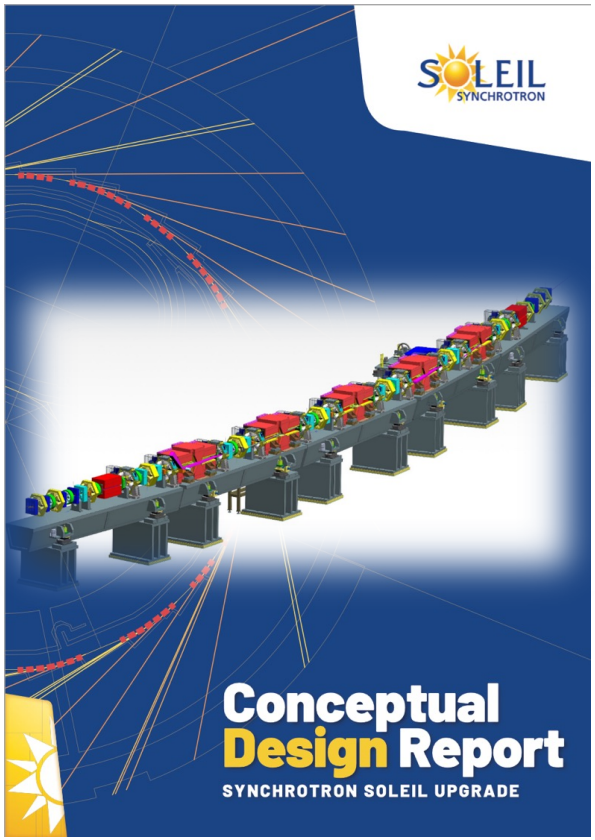


SOLEIL: Operation, Upgrade Status and Economy Plan

Laurent S. Nadolski
Accelerators Coordinator
Synchrotron SOLEIL
on behalf of the Accelerators and
Engineering Division

Presentation Layout

- SOLEIL
  - Main Performance
  - Main Achievements
  - Project Update
- Energy Saving Plan
- THOMX and COXINEL Major Results
- SOLEIL II update
  - TDR phase
  - Lattice Update
  - Protypes Overview

SOLEIL

Third Generation Light Source

Location: France, 11 km South of Paris

Circumference: **354 m**

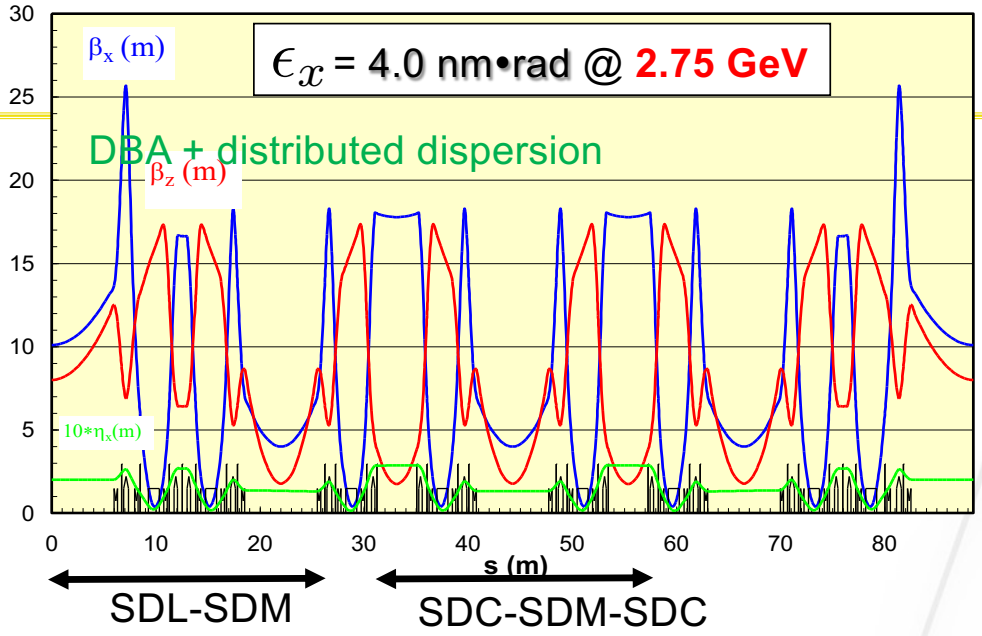
24 straight sections

(variable length)

SDL: 4 x 12 m
SDM: 12 x 7 m
SDC: 8 x 3.6 m

29 beamlines

- 2 IR
- 7 on bending magnets
- 20 on insertion devices



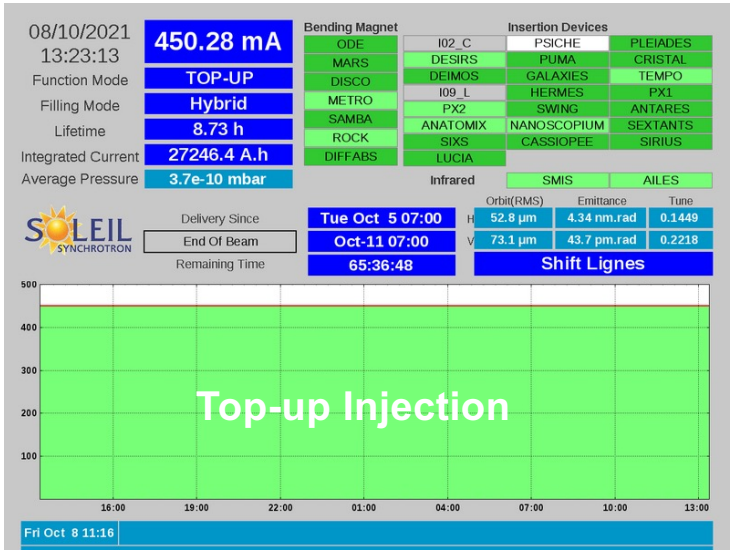
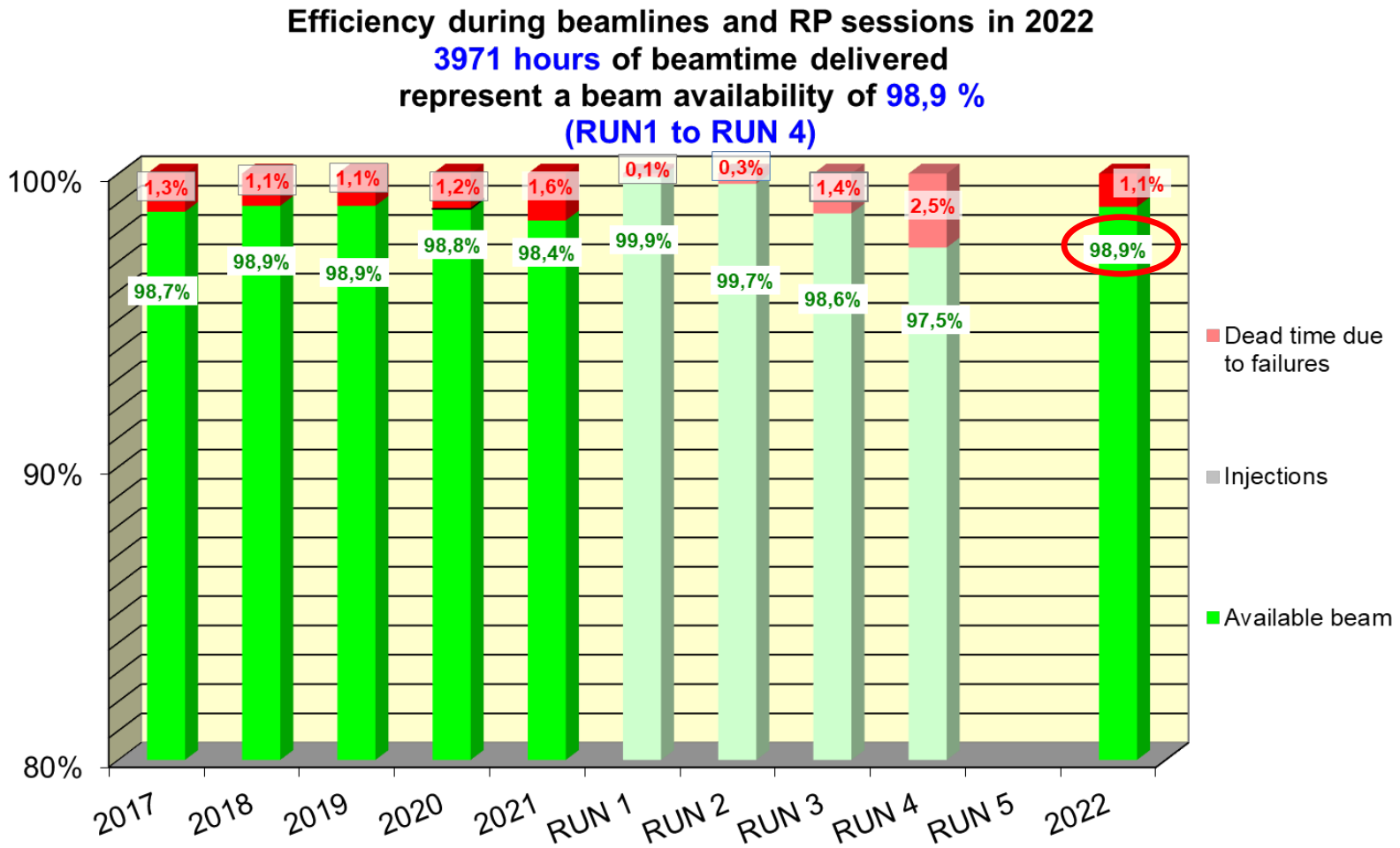


Table 1: Storage Ring Main Parameters

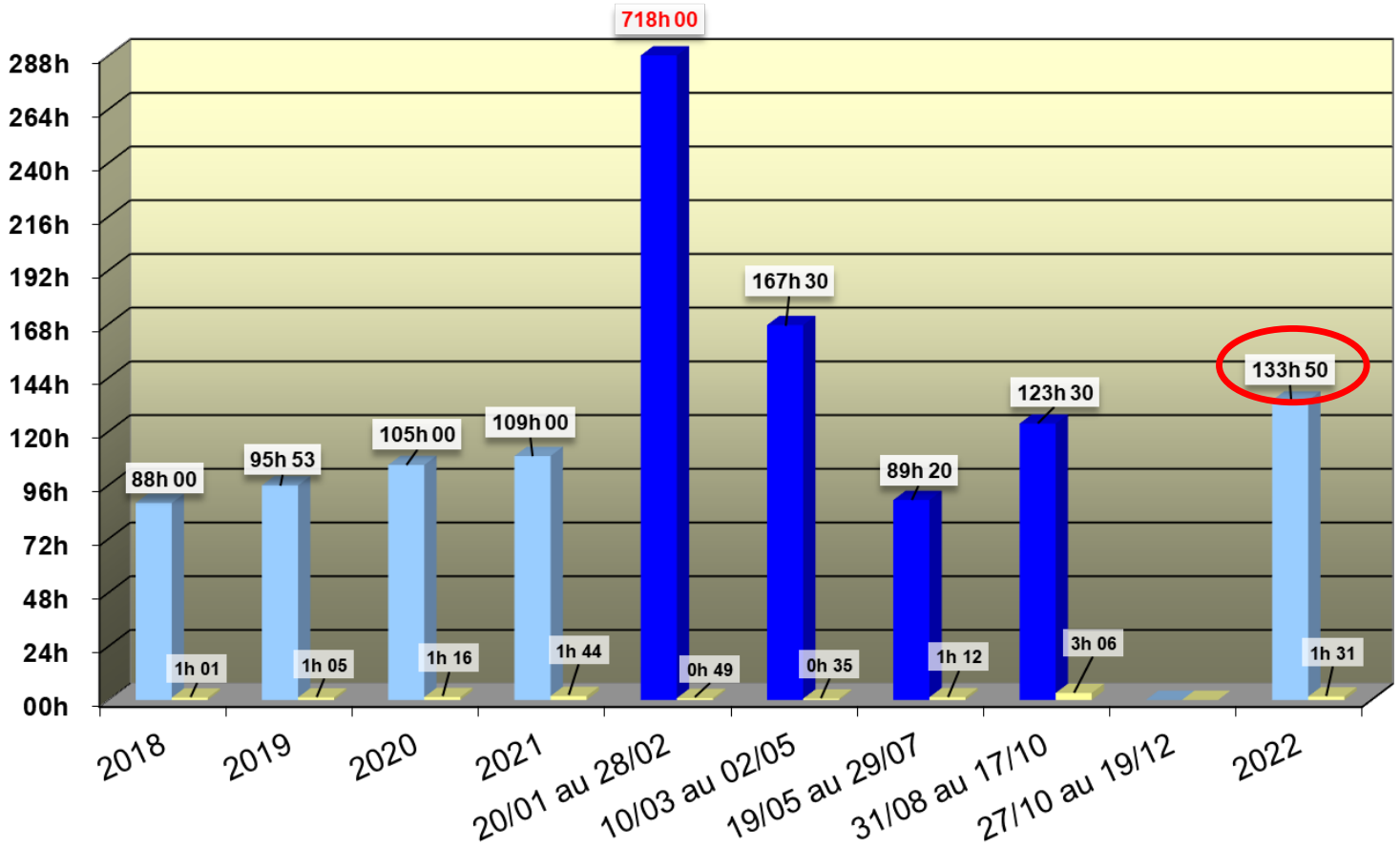
Parameters	Values
Energy	2.75 GeV
Circumference	354.097 m
Natural chromaticities (H/V)	-53/-19
Natural Emittance	4.0 nm · rad
Number of Cells/Symmetry	16/1
Tunes (H/V)	18.155 / 10.229
RF frequency (harmonic number)	352.197 MHz (416)
Total RF Voltage	2.8 MV

User Photon Beam Availability



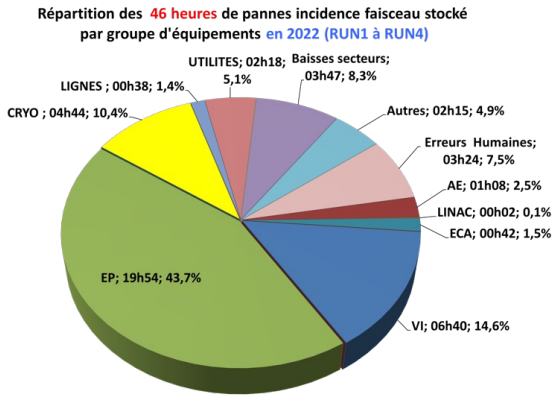
Mean Time Between Failure

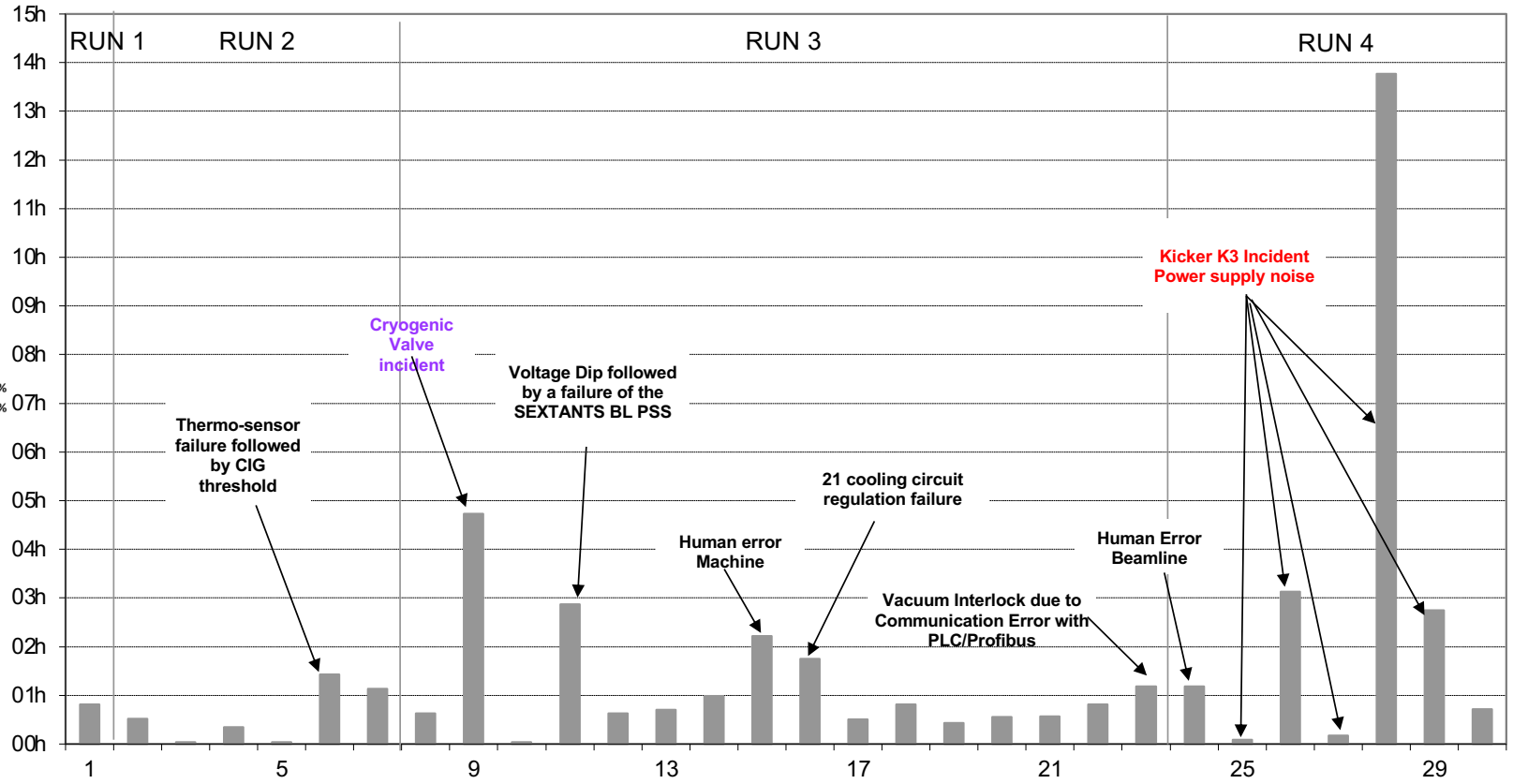
2022 (RUN1 to RUN4): 133 hours



RUN1 to RUN 4 2022
Duration of the 30 beam Interruptions

Total 45:32
Min 00:02
Max 13:46
Mean 01:31
RMS 02:33





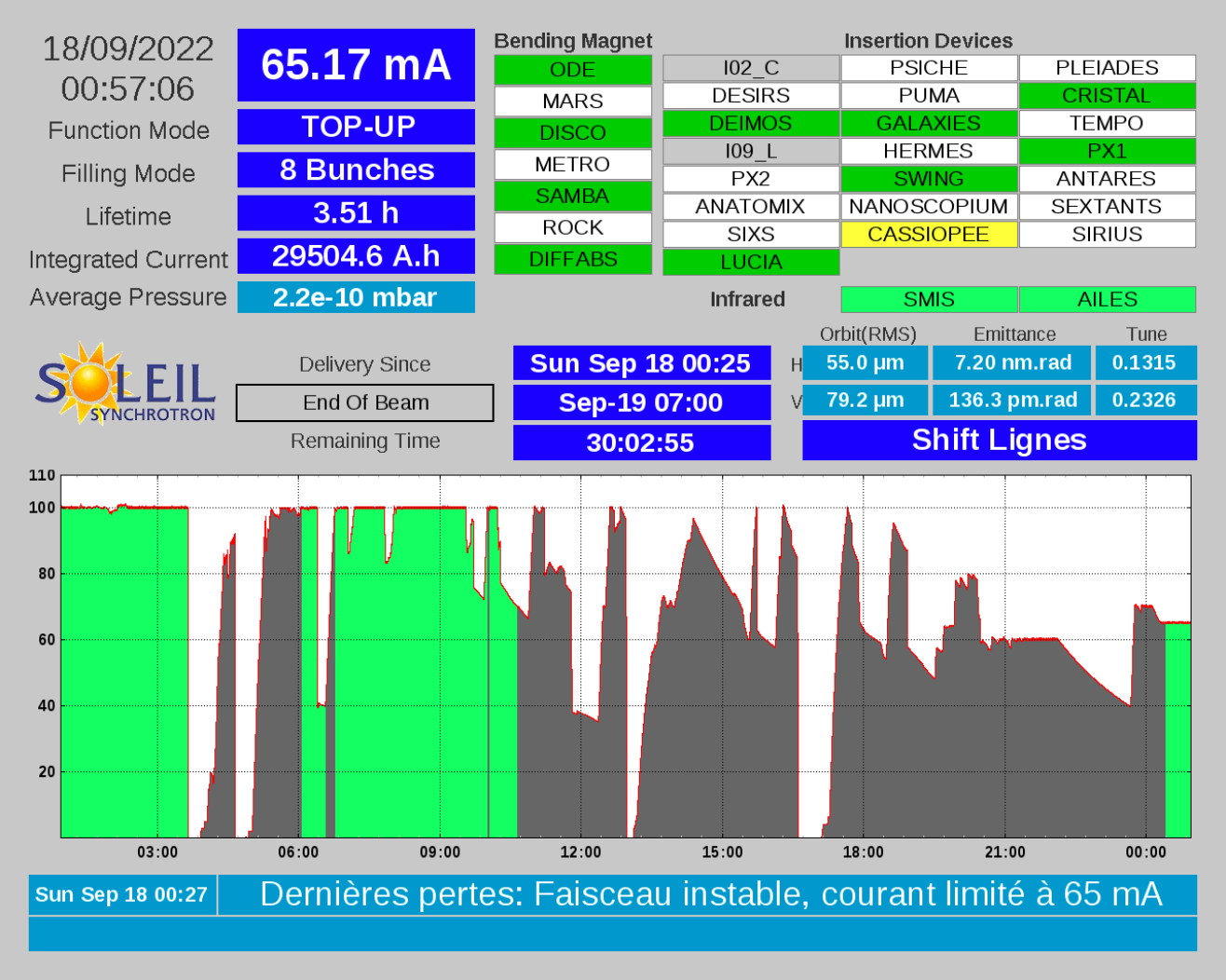
A Very Difficult Day: a Noisy (Random) Injection kicker

A long and very subtle failure on one of the injection kickers which made us lose 19 hours on Saturday 17/09 during a User session in 8 bunch filling pattern.

<u>First incident of this kind since 2006</u>

Learnt lesson

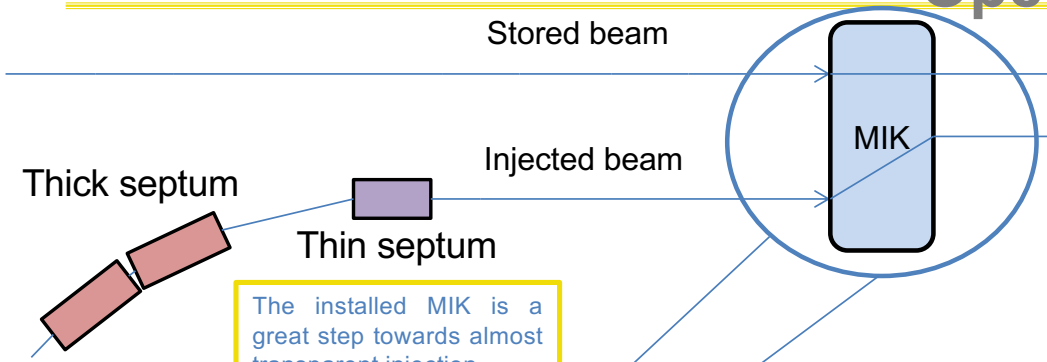
- Loss of experience
- Continuous training
- Reinforcing postmortem capability for partial beam losses



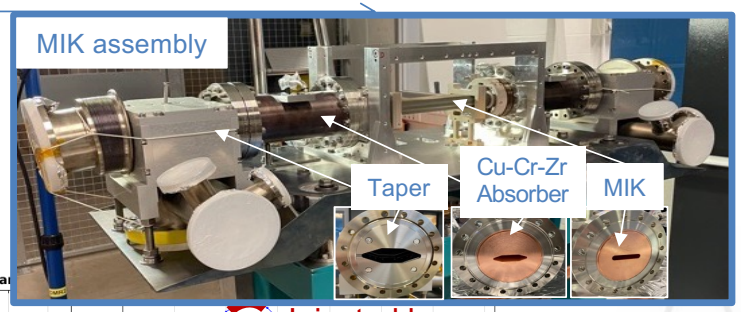
A Selection of Major Projects

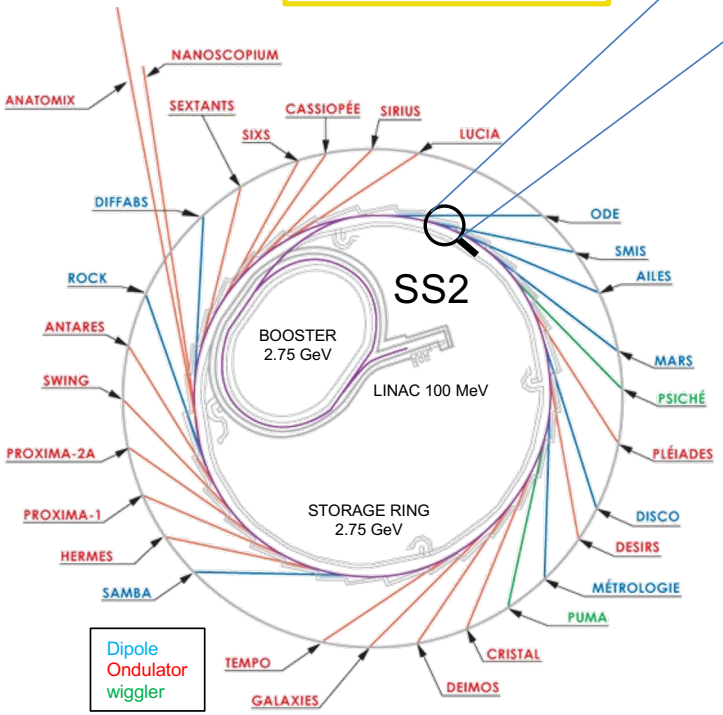
Off-axis MIK Injection Layout for Top-Up Operation at SOLEIL

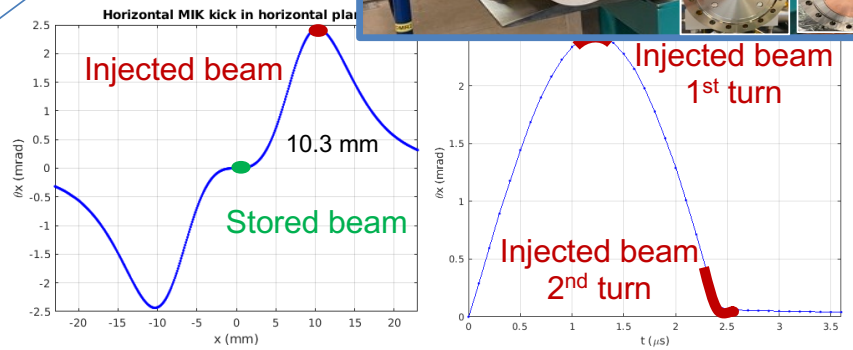
As a key element for making a **compact** injection scheme.



The installed MIK is a great step towards almost transparent injection







Main parameters	MIK
Pulse duration	2.4 μs
Magnetic length	0.304 m
Nominal kick	1.8 mrad
Target residual closed orbit distorsion (combining all devices)	Horizontally <20 μm Vertically <2 μm <10% beam size

Towards Transparent and Reliable Injection

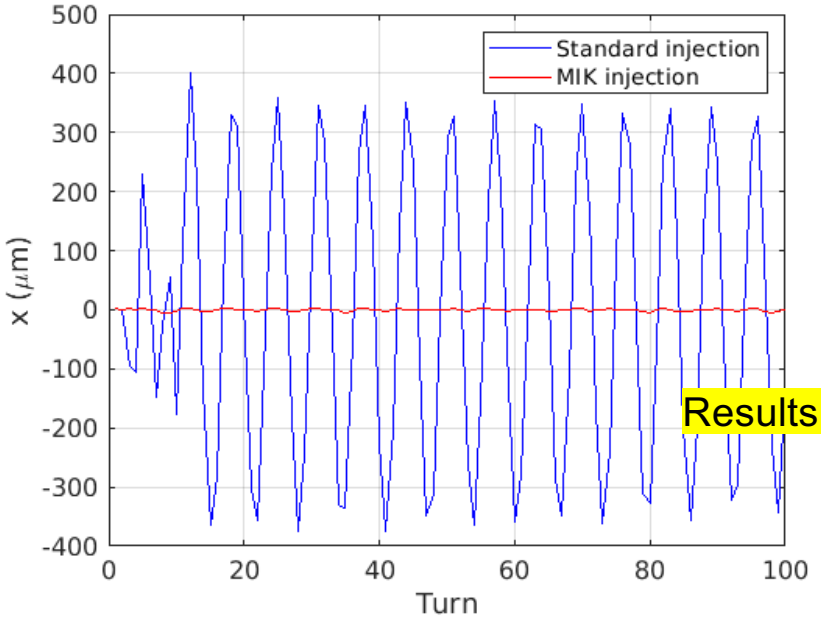
Randy Ollier PhD
December 13, 2022

Maximum injection efficiency measured 97%

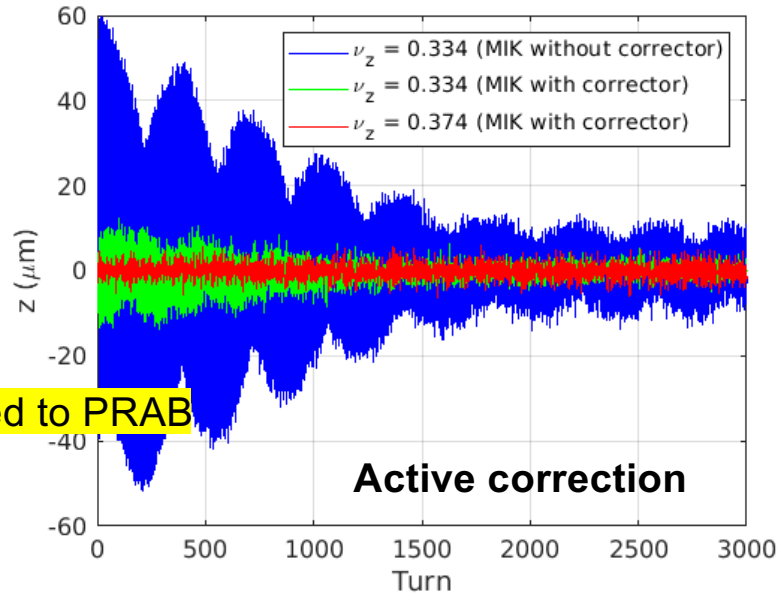
Position perturbations **< 2% $\sigma_{x,z}$** (including active correction)

$\Delta\sigma_x$ = 3.5% of σ_x

Turn-turn High performance Diagnostics
BLM, Brillance+ Libera, Kalypso Camera



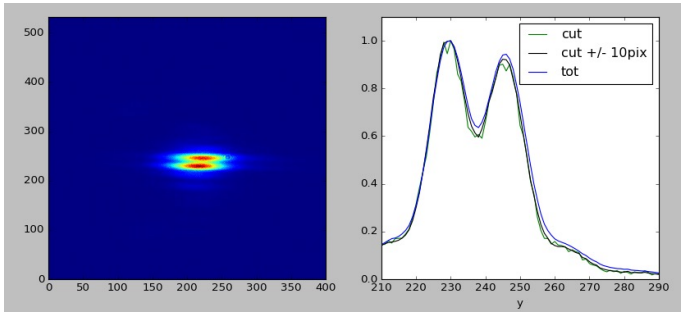
Results submitted to PRAB



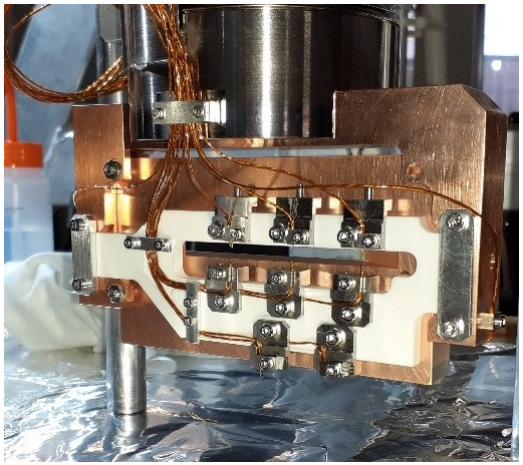
H-plane **V-plane**

Visible Mirror Upgrade for New Optical Diagnotics

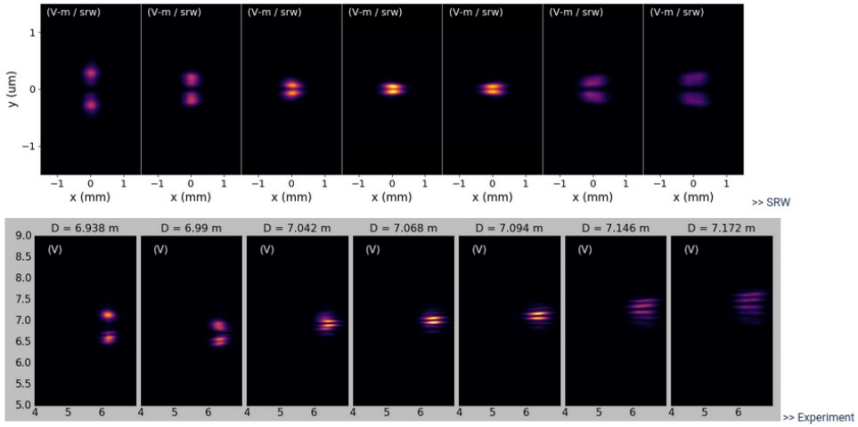
Next extraction mirror with a new extraction **slit mirror** equipment and a **more efficient cooling system**: the collected photon flux is increased by more than a factor of 2. This diagnostic beamline is now being used to commission innovative equipment like the **turn-by-turn Kalypso Camera** and **high resolution beamsize measurement** using **polarization** in preparation for the SOLEIL II



Size measurement from the vertical polarization of the photon beam from a bending magnet (λ = 400 nm)



Slit mirror for the diagnostics beamline
Test bed for new diagnostics in the frame of the upgrade

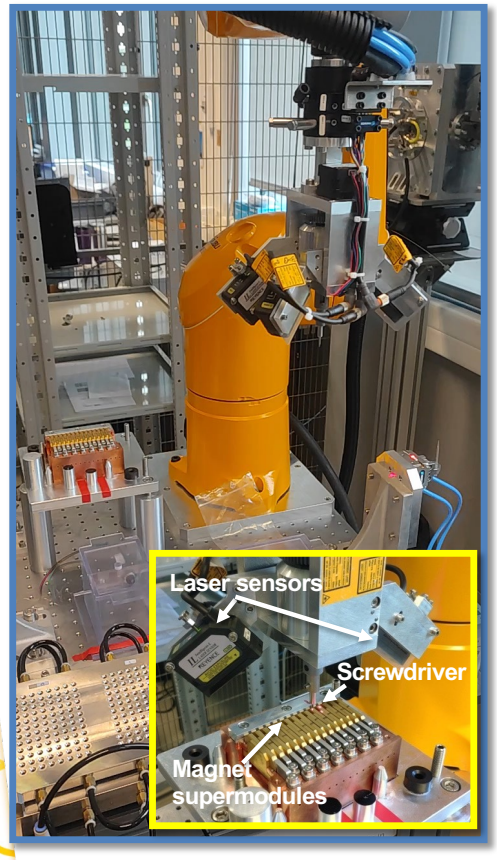


Very good agreement between simulated (top) and measured (bottom) images as a function of lens-camera distance in vertical polarization θ_x=3.5 mrad, λ = 400 nm.

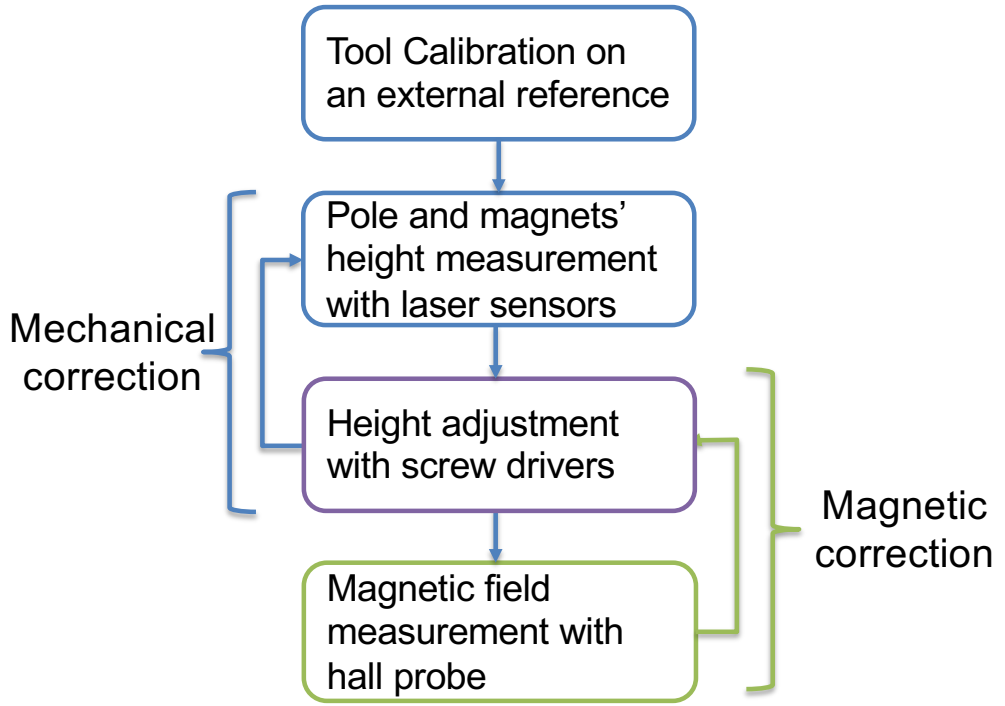
Robotizing Magnet Modules Measurement Bench for Insertion Devices

- **Robotization**: part of a roadmap for machine and beamlines. Based on STAUBLI robots standardized in 2019.
- **Included in global automation strategy** under development in IT and Data management program.
- Measurement bench complementary from the one developed in 2021.

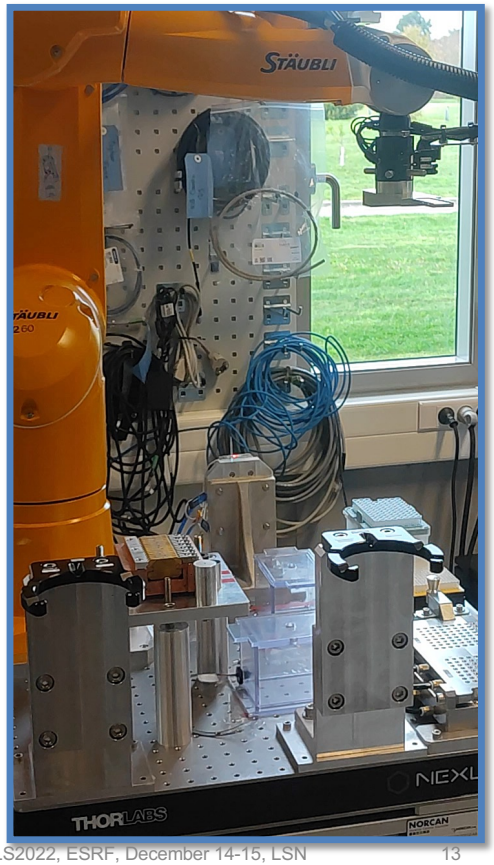
Under development !



Mechanical and magnetic correction of the super magnet modules



Include automatic tool changer between screwdriver and hall probe



Major Achievements

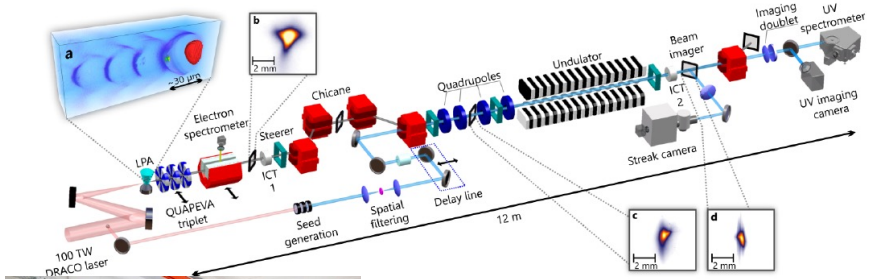
First LPA based seeded FEL: a successful French (SOLEIL) / German (HZDR) collaboration

Aim: Demonstrate the feasibility of an LPA based seeded FEL in the UV range

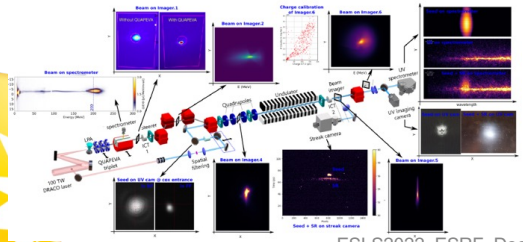
Experimental setup:

>> The high-performance Laser Plasma Accelerator of HZDR (Germany)

>> The versatile COXINEL beamline of SOLEIL (France)

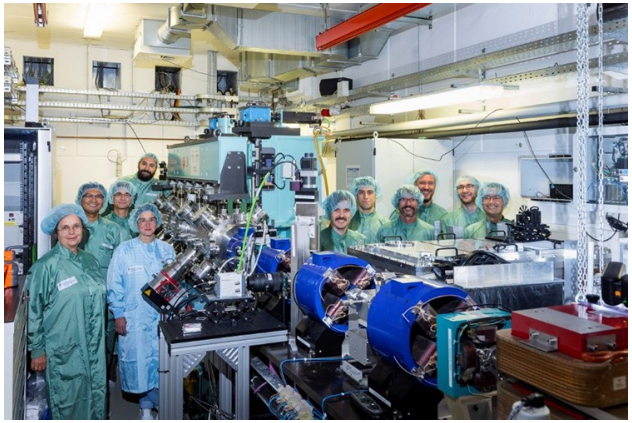


Installation of COXINEL @ HZDR: November 2021



Full commissioning of beamline : December 2021

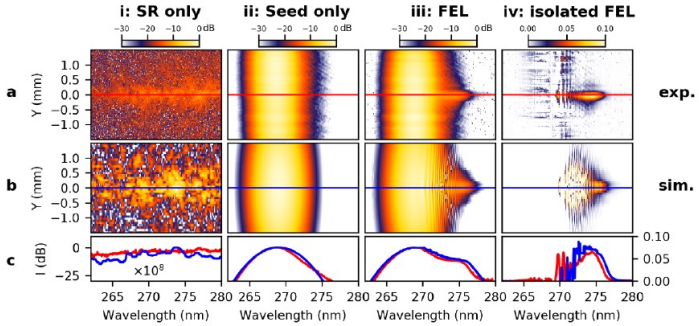
Results:



>> Demonstration of an LPA based seeded FEL @274 nm

>> Spectral control of the FEL wavelength

>> Achievement of temporal coherence



M. Labat et al., Nature Photonics (2022) https://doi.org/10.1038/s41566-022-01104-w

Perspectives:

>> Full optimization of the present configuration

>> Operation @ 1 Hz

>> Operation at shorter wavelength

A compact light source based on Compton Back Scattering

Electron beam (nominal)

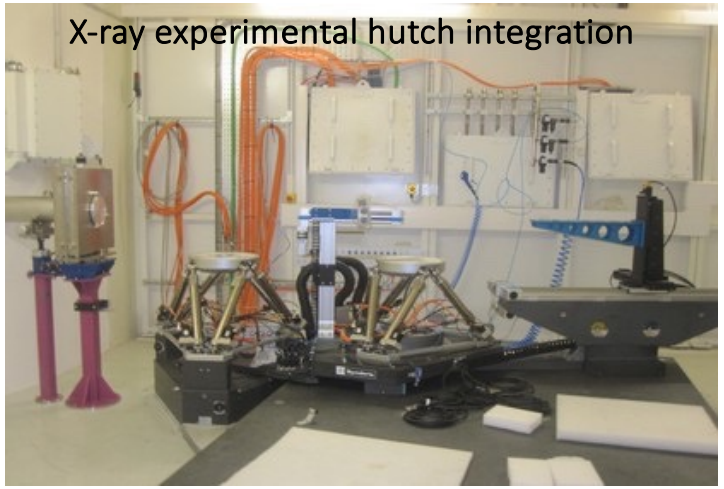
- **Energy: 50 (70) MeV**
- **Charge: 1 nC (1 bunch)**
- **Transv. emittance: 5 pi mm mrad**

✓ 19 May 2021 Phase I authorization from French Nuclear Safety Authority
Linac (E = 50 MeV, Frep = 10 Hz, Charge = 100 pC)

✓ 29 July 2022 => Phase II authorization from French Nuclear Safety Authority
Linac + Transfer Line + Ring + Extraction Line

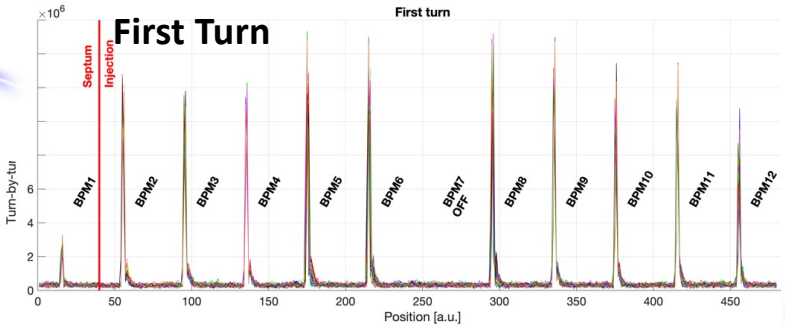
First X-rays are expected during 2023

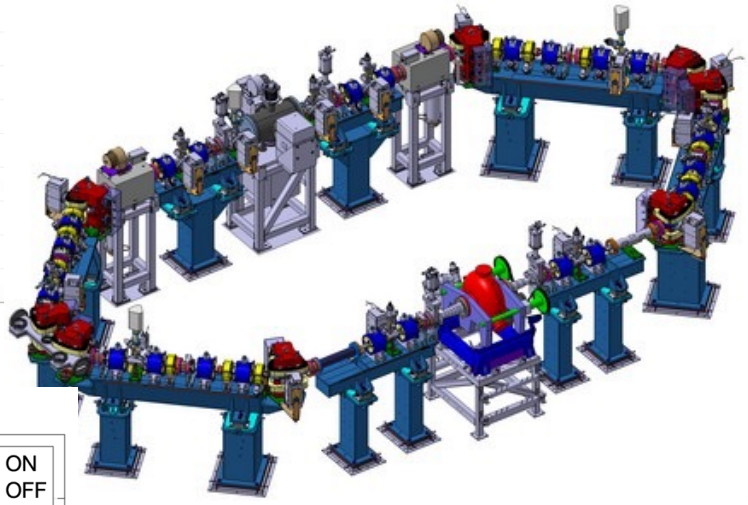
ThomX: 45-90 keV
Flux ~ 10^{12} - 10^{13} ph/s
Brill ~ 10^{10} – 10^{11} unit

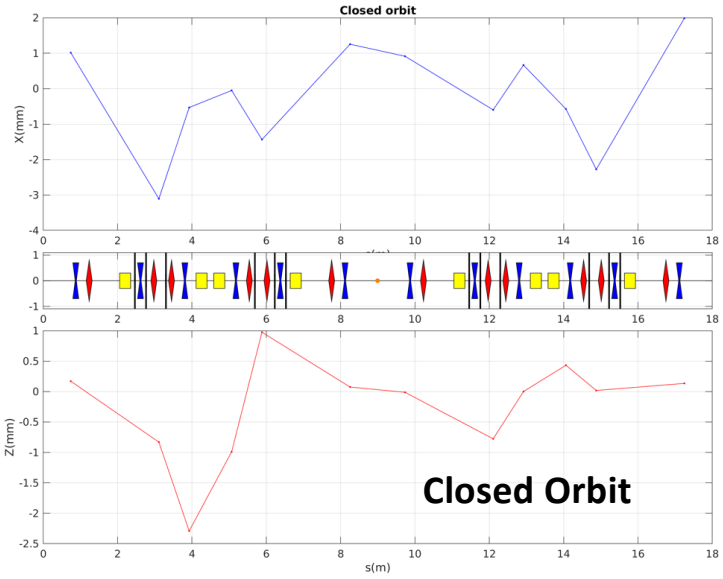


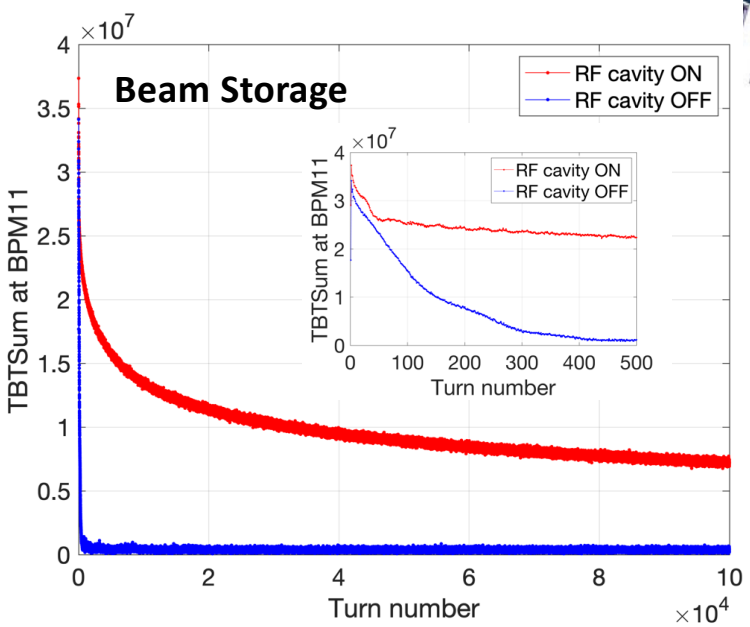
ThomX Ring: L = 18 m, T = 60 ns, Frep = 16.7 MHz

- Injection + threading (19 Sept. 2022)
- First Turns ~300 turns (3 Oct. 2022)
- Storage with RF cavity > 200k turns (8 Dec. 2022)





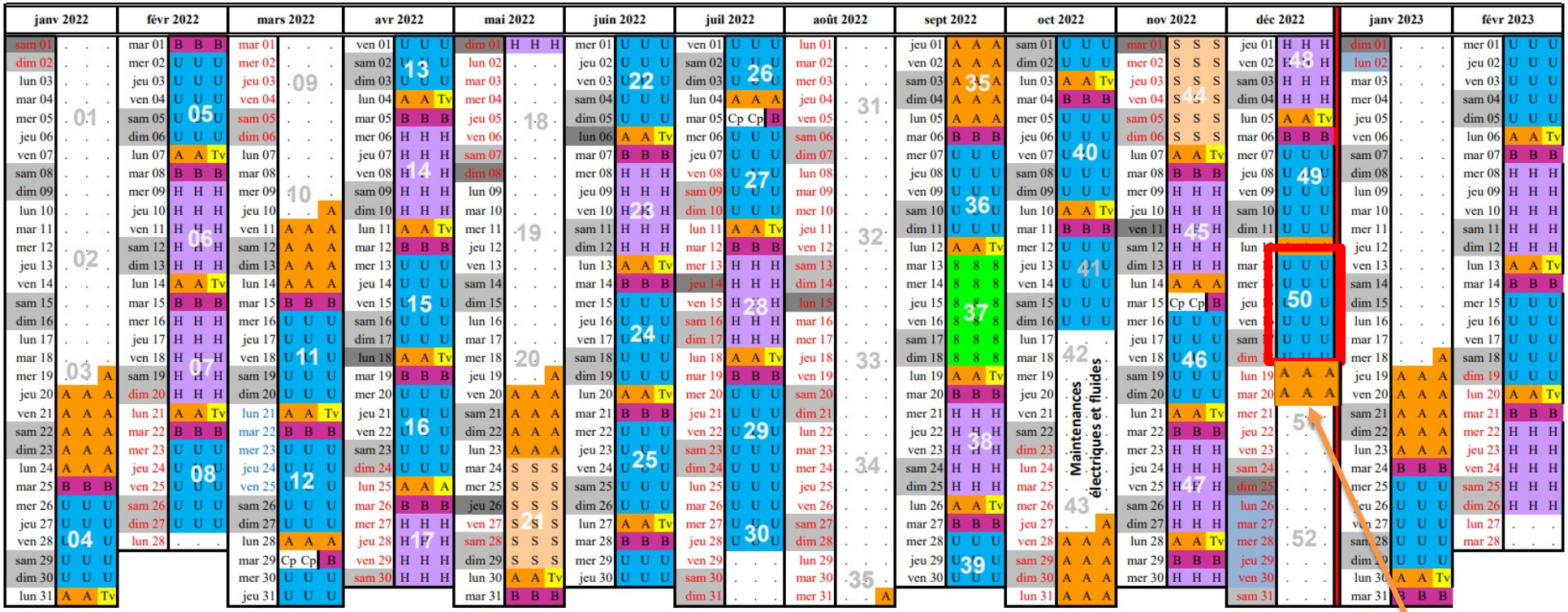




Energy Saving

2022 Beam Schedule

Modification of the mode of operation for the last week of the year (from Low Alpha to Uniform mode)



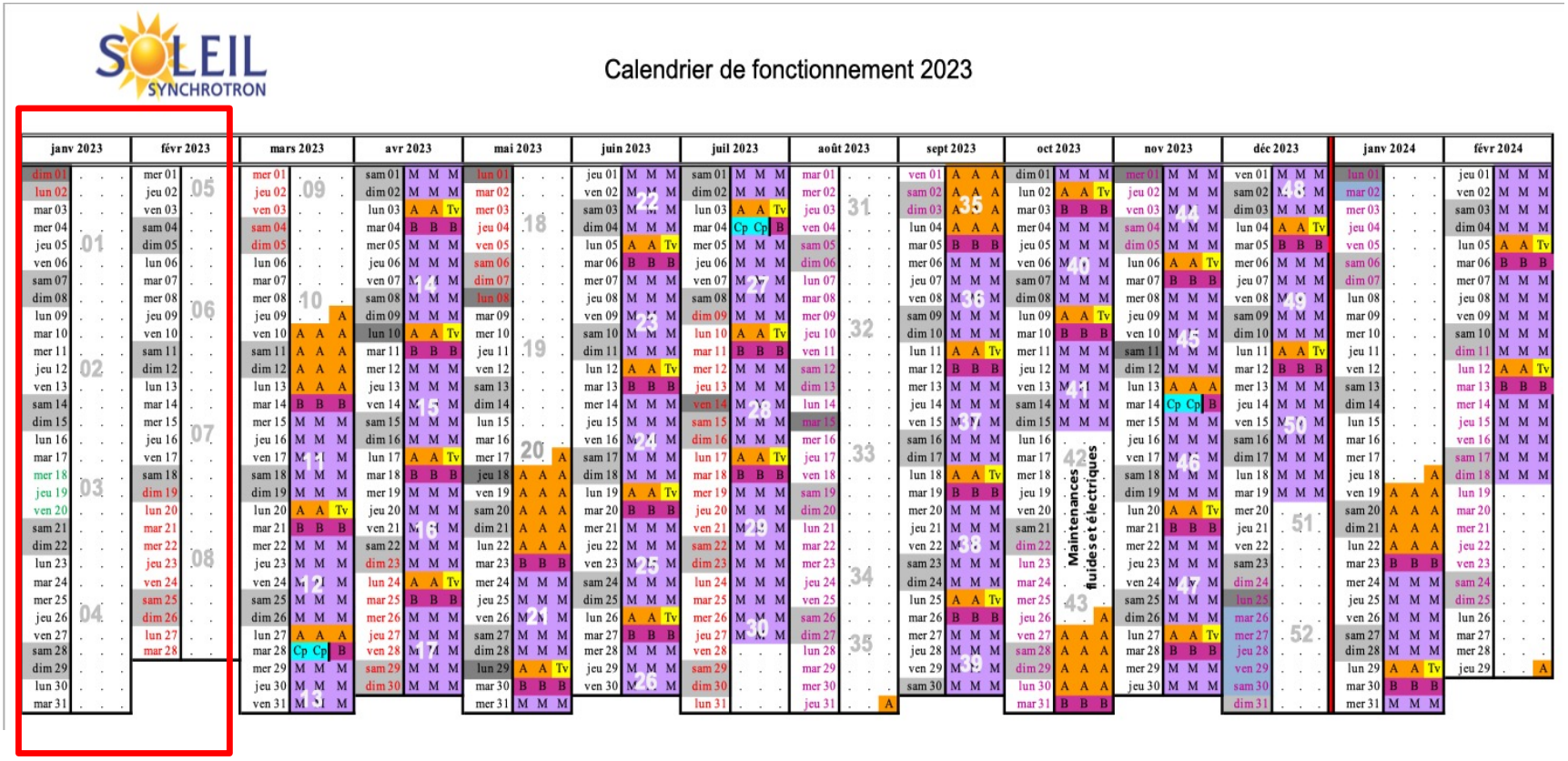
U Uniforme Top-Up - 500 mA
H Hybride Top-Up - 450 mA
8 8 paquets Top-Up - 100 mA
S 1 paquet Top-Up - 16 mA
L Low-Alpha Top-Up
B Beamlines
Cp Contrôles RP périodiques, 3 mardis de 7h à 23h
Tv Tests RP de validation possibles, faisceau Lignes redonné à 10h
A Temps Accélérateurs
. Arrêt Machine

Version validée par la RD et le CSE (28/10/2021)
MaJ du 12/05/2022 (semaine Low-Alpha en fin d'année)
Users meeting du 20 et 21 janvier 2022
Ecole HERCULES du 21-25 mars 2022
Congés scolaires zone C

2023 Beam Schedule

RUN1 supressed

10% saving requested at national level By French Government

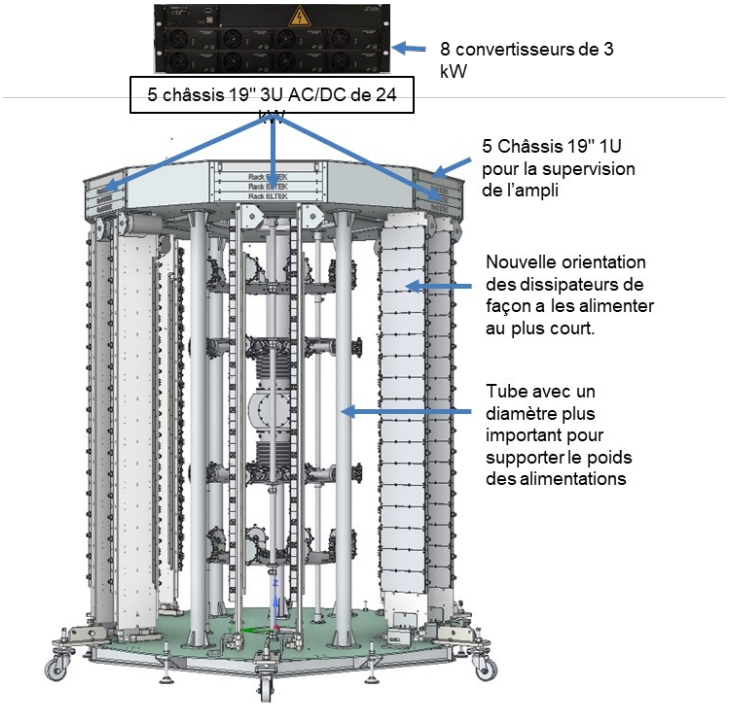


1 bunch , 8 bunch, low-alpha filling patterns converted to high current (450 hybrid or uniform) filling patterns

Refurbishment of RF amplifier power supplies

(obsolescence treatment and better energy efficiency)

The power supply upgrade consists of replacing the existing Bruker power supplies and DC/DC converters to address the obsolescence of this equipment and to achieve much higher efficiencies. The **96% efficiency** and the possibility to optimize the RF operating point by controlling the voltage allow a reduction in consumption of **over 20%.** These power supplies, provided with a 30% redundancy, have a high reliability (MTBF > 350 000 h) and are not very sensitive to "mains" failures.



Vue 3D d'une tour ampli RF avec les alimentations Eltek AC/DC

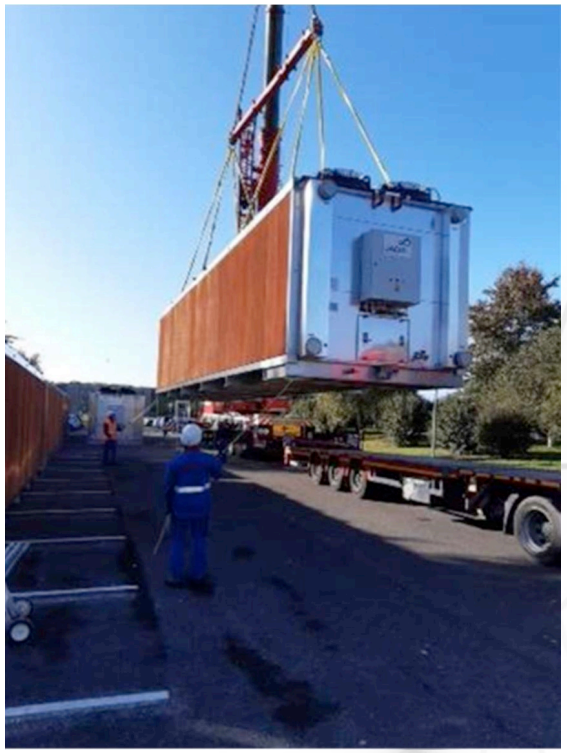
Beam current	450 mA	500 mA
Total RF Power	506 kW	562 kW
Electric Power (today: 4 amplis)	1148 kW	1278 kW
Electric Power (upgrade to 50 V amplis)	1019 kW	1081 kW
Electric Power (upgrade to 44 V amplis)	894 kW	952 kW
Expected consumption reduction	**22.1%**	**25.5%**

Annual reduction in consumption of up to 1.75 GWh
Annual savings of 240 k€
Return on investment of about 4 years

New Cooling Station

Connection to the Synchrotron building expected early 2024.

Total budget: 12.67 M€



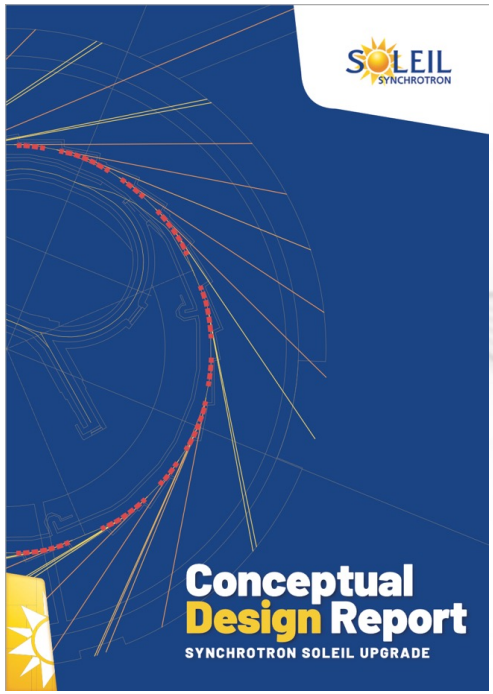
Energy Savings

SOLEIL	Electrical Power (kW)	Power Consumption (MWh)	Losses to the air (kW)		Losses to the water (kW)	
			Tunnel	Hall / PS room	Tunnel	Hall / PS room
STORAGE RING POWER SUPPLIES	830	5400	60	75	640	55
TL POWER SUPPLIES	65	420	8	7	45	5
BOOSTER POWER SUPPLIES	130	60				
ID Power SUPPLIES	175	620	10	30	115	20
RF (SR + BOOSTER + CRYO)	1450	8400				
Total	**2650**	**14900**				

SOLEIL II (projection oct 2022)	Electrical Power (kW)	Power Consumption (MWh)	Losses to the air (kW)		Losses to the water (kW)	
			Tunnel	Hall / PS room	Tunnel	Hall / PS room
STORAGE RING POWER SUPPLIES	185	1200	40	85	60	0
TL POWER SUPPLIES	65	420	8	7	45	5
BOOSTER POWER SUPPLIES	255	200				
ID Power SUPPLIES	25	80	5	8	10	2
RF (SR + BOOSTER + CRYO)	1000	5800				
Total	**1530**	**7700**				

Gain estimation cooling station (T3)	130 kW	800 MWh
Total Gain	**1250** kW	**8000** MWh

The future use of the new cooling station (T7) will save about 2 GWh.
The total gain becomes about: 10 GWh.



https://www.synchrotron-soleil.fr/fr/file/13803/download?token=OUzsp46P

Upgrade Status

TOWARDS a 4th GENERATION SYNCHROTRON LIGHT SOURCE

- While maintaining the broad spectrum of photons ranging from IR to hard X-rays, the SOLEIL upgrade project aims at **maximizing the intensity of coherent photon flux (highest brilliance and transverse coherence possible)** arriving at the beamlines especially in the soft to tender X-rays photon energy range.

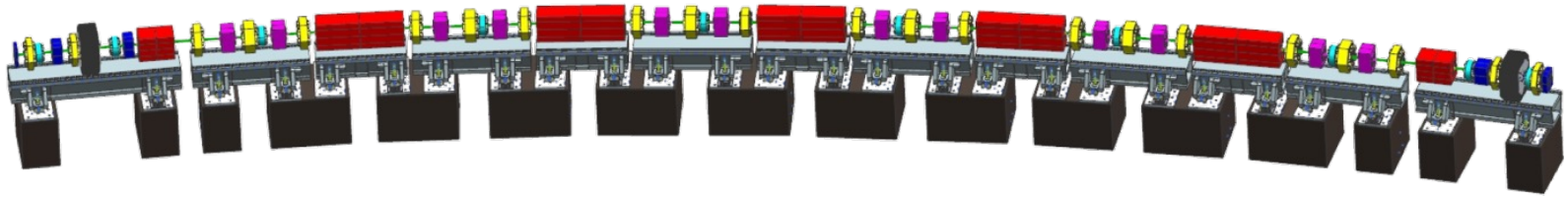
- Three objectives are the key guiding principle for the optimization of the NEW LATTICE.

1. **Electron beam emittances** in both horizontal and vertical planes must be close to the single-electron photon beam emittance in this energy range **(up to 4 keV).**
   - an electron beam emittance of at most **50 pm.rad** in both planes is needed for X-ray energies up to 4 keV.
   - obtain a natural horizontal emittance of less than **100 pm.rad** which provides the target of 50 pm.rad in each plane after full coupling.
2. **Insertion device β-functions** close to the matching value.
3. **New insertion devices** well optimized (benefit the most from the New Lattice).

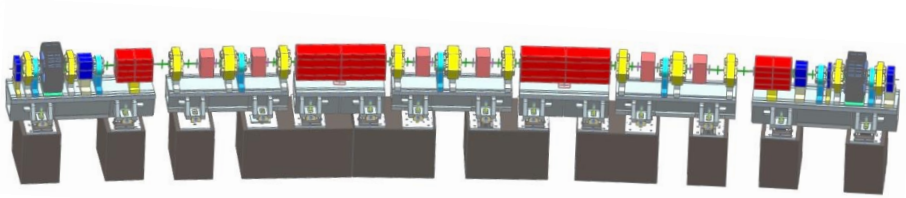
With the highest electron beam current possible (500 mA/uniform fil. pattern)

SOLEIL II Storage Ring Key Features

7BA cell



4BA cell



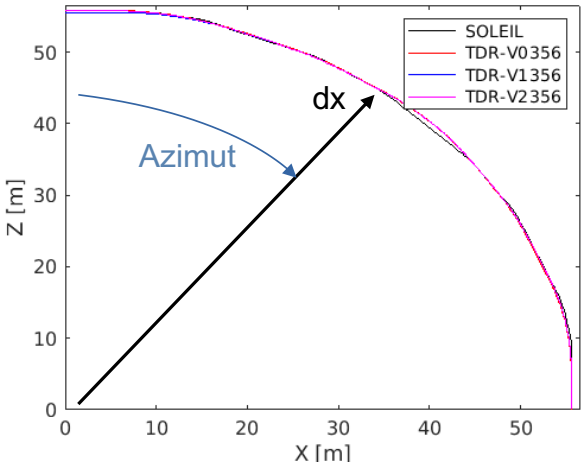
(Dipole with transverse gradient in red, Reverse Bend in magenta, Quadrupole in blue, Sextupole in yellow and Octupole in cyan)

1. Non-standard MBA lattice: 12 x 7BA + 8 x 4BA.
2. 85 pm.rad (63 pm.rad with IDs) / 2.75 GeV / 354 m.
3. 20 straight sections (4 of ~8 m; 4 of ~4.2 m ; 4 of ~3.6 m and 8 of ~3.0 m).
4. Large photon spectrum (far IR to hard X-rays).
5. NEG coated very small vacuum chamber diameter = 12 mm.
6. Extensive use of permanent magnets (All Dipoles, all RB and all main quadrupoles).
7. Miniaturization.
8. Off-axis injection.
9. High performance Multipole Injection Kicker (MIK).
10. Energy Savings.

General Update

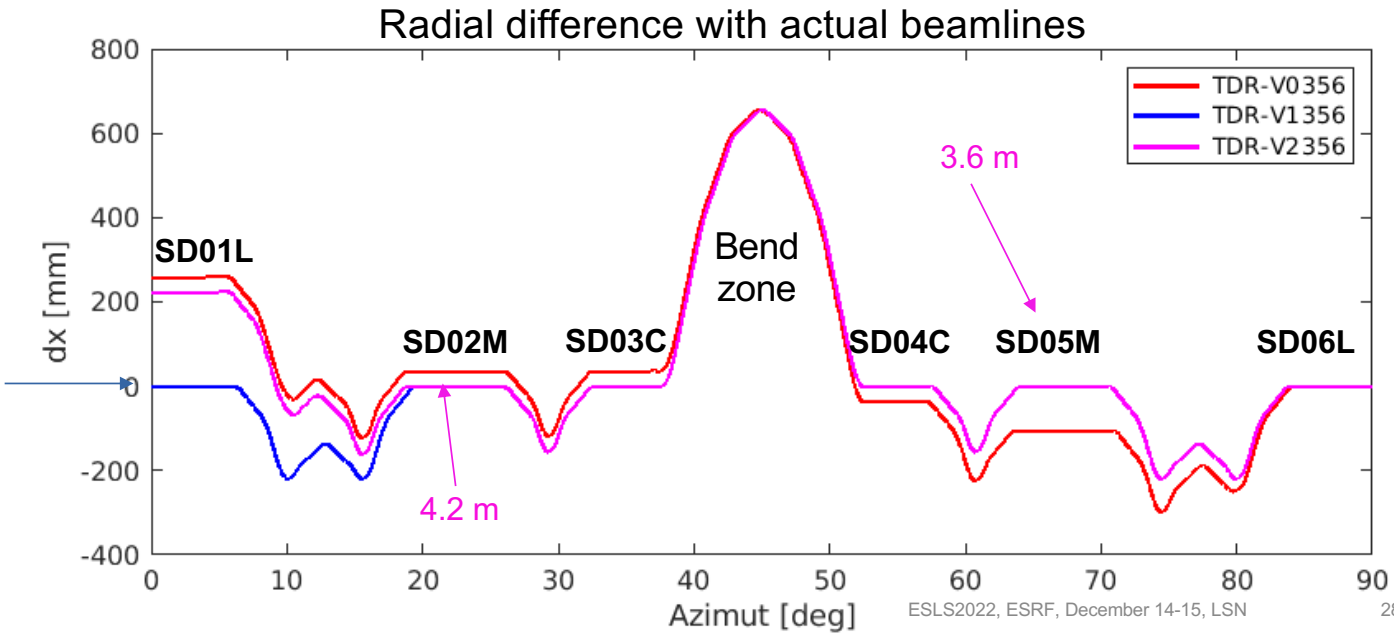
1. Modification of the lattice to perfectly align radially all the ID's Beamlines: **V0356 → V2356**
2. Towards a new version **V2366** (V2356 + better mechanical integration + BBA). **New Baseline lattice.**
3. Reduction of the number of girders from 174 to 86 and the number of plinths from 234 to 172.
4. Launching of the prototype of a "dipole" vacuum chamber to validate all the construction stages including NEG coating in such complex chamber.
5. Launching of the prototype of the sextupole with notch.
6. Launching of the second prototype of the permanent quadrupole.
7. Progress in mechanical integration and light extraction.
8. First prototypes of Insertion Devices & exchange meetings with BL^2 program.
9. Promising new results with the Multipole Injection Kicker (MIK) device.
10. Progress in infrastructure and logistics thoughts.

Modification of the Lattice to Align Radially all the ID's Beamlines



- Next step is to split the medium sections in two families : 4 at 3.6 m and 4 lengthened to 4.2 m to be able to accommodate the main RF in SD02M.
- Only the injection (SD01L) and the opposite (SD11L) presently free for a new beamline are shifted outward by 240 mm.
- **All other ID's beamlines are kept perfectly radially aligned: V1356 ➡ V2356**

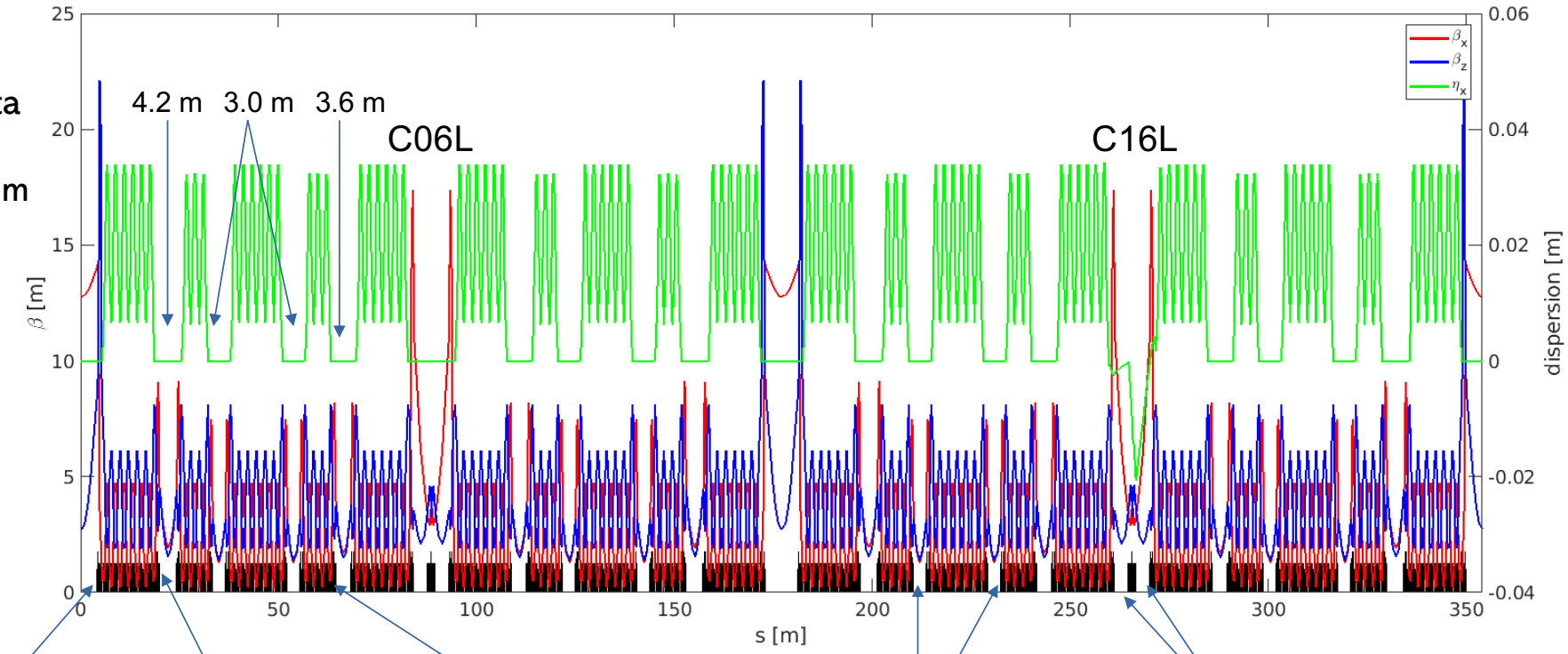
Perfect alignment



Optical functions TDR-V2356

Unchanged main data

Circ. = 353.9618 m
Ex = 82.55 pm.rad
Jx = 1.85
MCF = 1.065 10^{-4}
UO = 454 keV/tr
Tune = 54.2 18.3



$Injection\ section$
$L = 8m$
$\beta_x \sim 12.7m$

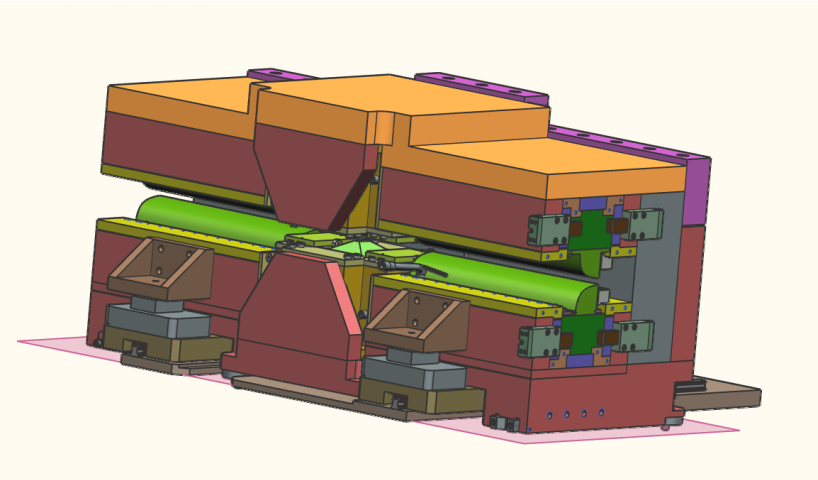
$Medium - long$
$L = 4.2m$
$\beta \sim 1.7m$

$Medium - short$
$L = 3.6m$
$\beta \sim 1.6m$

$Short$
$L = 3.0m$
$\beta \sim 1.3m$

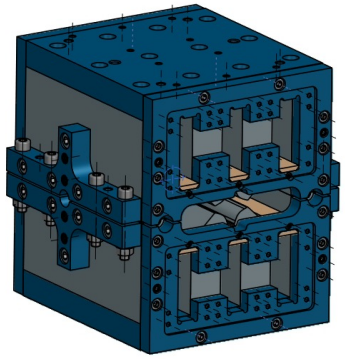
$Double\ low\ beta$
$L = 3.5m$
$\beta_z \sim 2.1m$

A Selection of Prototypes



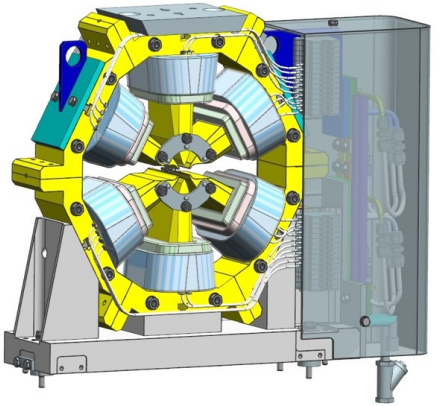
PM Long Combined Dipole (3T)
3 pieces: Sm2Co17 (PM) + Low Carbon Steel (LCS)
Gap 22 mm

100 T.m-1 Aperture Ø 21 mm



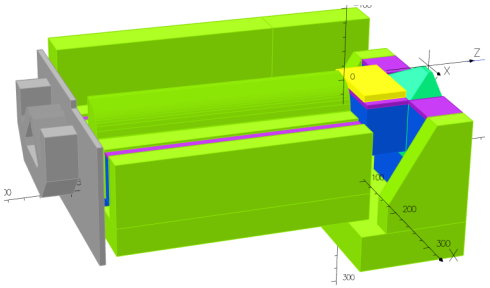
Second prototype
Permanent Magnet Quadrupoles

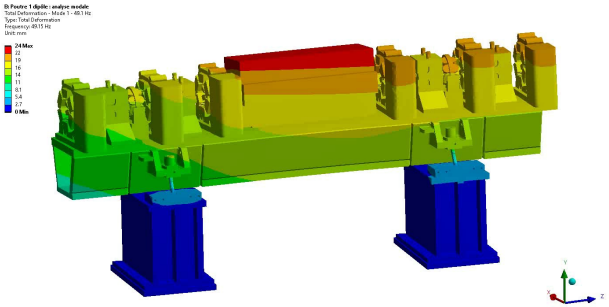
8200 T.m-2 Aperture Ø XX mm



3D view of the sextupole prototype with notch
Expected delivery but April 2023

Cross-talk between magnetz under study





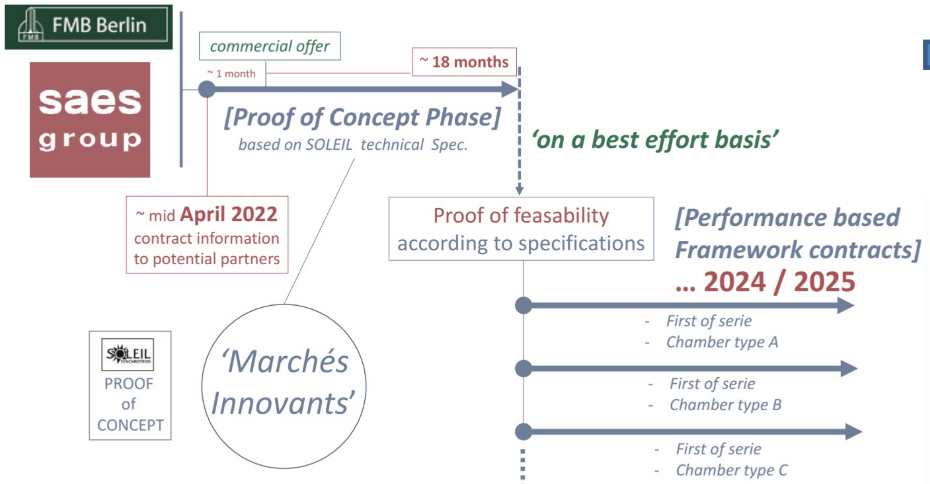
Girder Prototype expected in 2023

MIK: Prototype V1 testing: electrical testing (in-air)

- Parts for prototype V1 delivered on time (July 2022).
  - Assembled a first version with Kapton insulated copper wire (UHV compatible).
  - Second version (*same MACOR parts*) will be assembled with bare copper wire.
- Dedicated pulser assembled and commissioned.
  - Traditional short coaxial transmission (10 m) capacitive resonant discharge topology.
    - *Worst* voltage per amp ratio on the magnet (~3 kV / kA).
    - Better topologies are studied.
  - Tested up to 10 kV – 3 kA – 2.2 µs on dummy load.
- Prototype V1 electrical tests
  - **Pulsed at 6.5 kV – 2 kA without liners: no issue with arcing between conductors.**
  - **Inductance of 1.095 µH & resistance of 116 mΩ, as per calculated in FEA simulations.**
    - Value used for pulser design.
- Future tests in air then in vacuum (Q4 – 2022).
  - UHV electrical connections & magnet.
  - Uncoated liners with simulated grounding.
  - In-air additional connections as per complete magnet model.

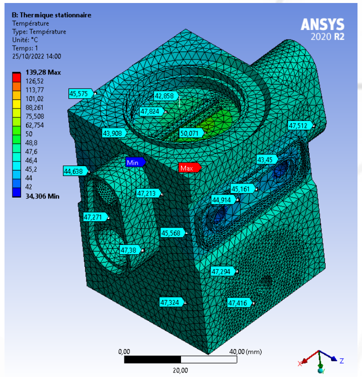
Vacuum Arc design

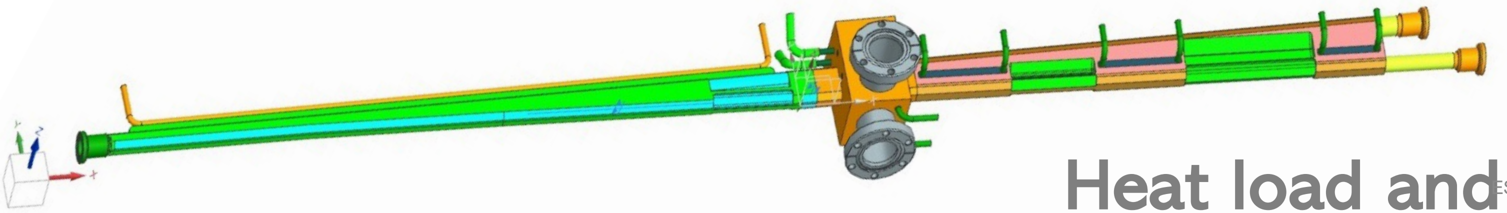
Update info for Proof-of-concept phase for high stake chambers



to evaluate the 'showstoppers' of the ***Mechanical and NEG coating deposition issues a*** *"Proof of concept" phase was initiated with FMB Berlin and SAES Group for a generic Dipole chamber*

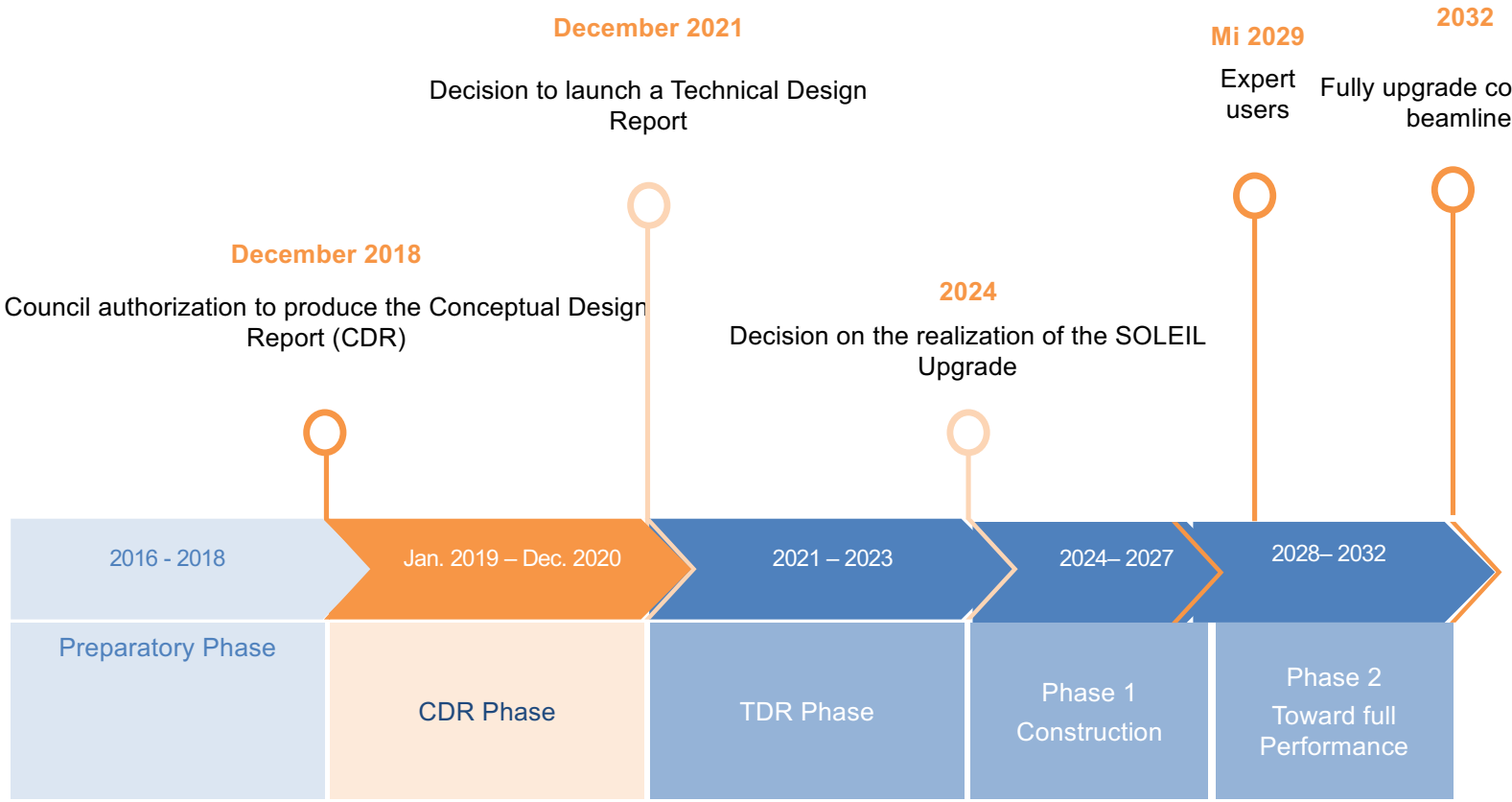
Based on that objective, Upgrade Chambers procurement will be done on "*Performance based Framework contracts"*





Heat load and power handling

Present SOLEIL II Timeline



Conclusions

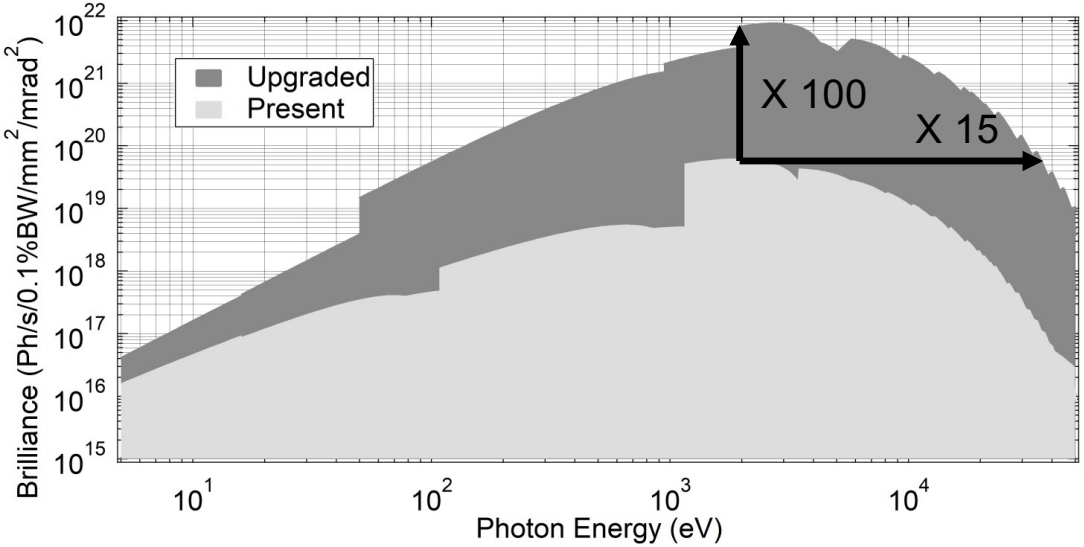
Conclusions

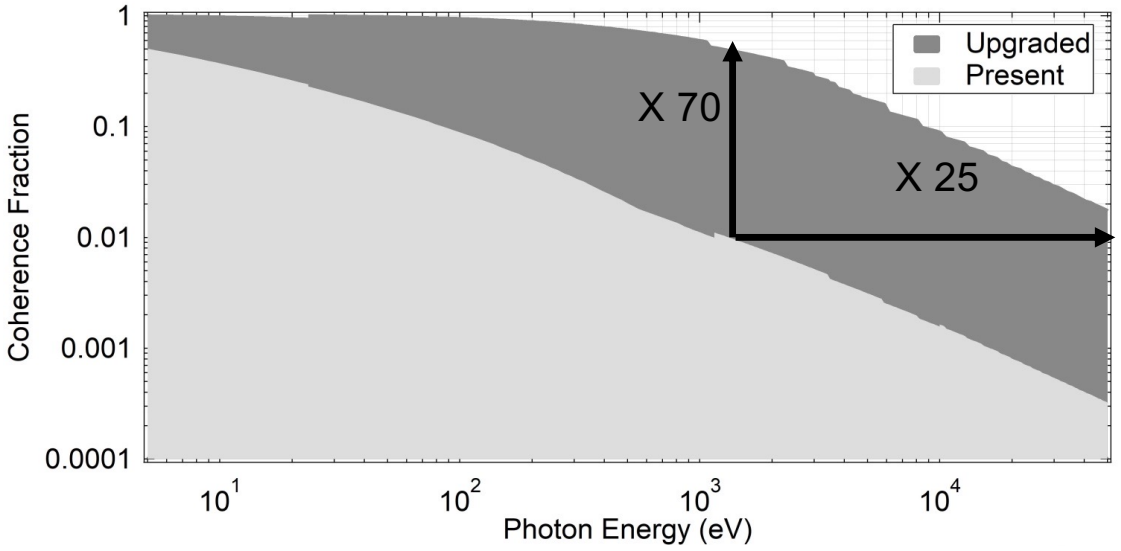
- SOLEIL:
  - Another year with high performance
  - Test bed for testing new technologies for the upgrade
  - LINAC upgrade (spare buncher under construction, increase of energy under consideration)

- SOLEIL II
  - Storage ring
    - Mechanical integration in progress
    - Heavy Prototype phase to remove all possible technical bottle necks
    - Ray tracing and Machine interlock
    - Selection of the main photon sources
    - Collimation studies
    - Logistics and Human resources
    - Reinforced Interaction with the Experimental Division
  - New Booster (150 MeV to 2.75 GeV, 3 Hz)
    - Mechanical integration
    - Modification of the transfer lines

Appendix

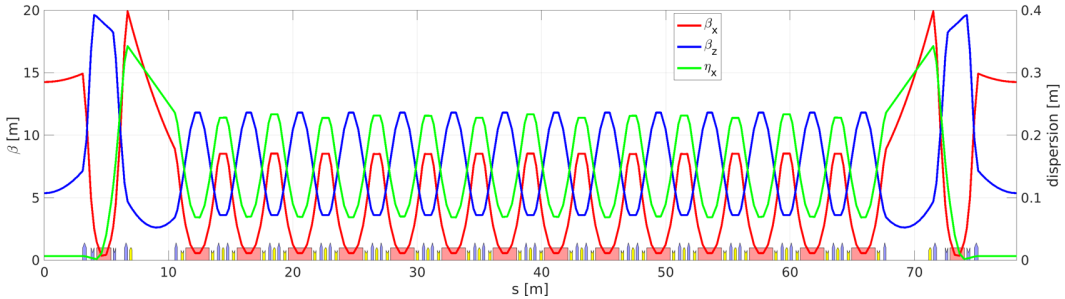
PHOTON BRILLIANCE AND TRANSVERSE COHERENCE





BOOSTER UPGRADE PROGRESS

- Two top-up injection schemes into the storage ring upgrade still being studied: betatron off-axis injection and on-axis chromatic injection, using the MIK device. Both need a drastic reduction of booster emittances in transverse and longitudinal planes at the extraction energy.



- 16BA HOA type lattice: 14 unit cells including combined function dipole (D+TG), two matching cells, a 6.2 m long straight section and two 3.44 m short straight sections.
- Reuse of the 2 RF systems at the same place in short straights (copper units each comprising 5 cells @ 352 MHz, LEP type).
- Reuse of the injection system, necessary renewal of the extraction system. Thick septum of booster extraction foreseen in permanent magnet and mutualized with the SR injection one, to minimize the angular/position jitter of the injected beam into storage ring.

Parameter	Unit	Target	Present booster	New designed booster
Energy range	**GeV**	**0.15 – 2.75**	**0.1 – 2.75**	**0.15 – 2.75**
Circumference	m	-	156.6	156.46
Natural emittance	**nm.rad**	**< 10**	**140**	**5.2**
RMS bunch length	**ps**	**< 25**	**50 @ 3 MV**	**25 @ 3 MV**
Nat. chromaticities	-		[-7.3,-5.8]	[-27, -12]
M.C. F.	-		$2.8 \cdot 10^{-2}$	$3.3 \cdot 10^{-3}$
Energy loss / turn	keV		409	554
Energy spread	-		$0.66 \cdot 10^{-3}$	$0.93 \cdot 10^{-3}$
Max. RF voltage	MV		3.6	3.6