HarmonLIP 2024
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Double RF system for SOLEIL II

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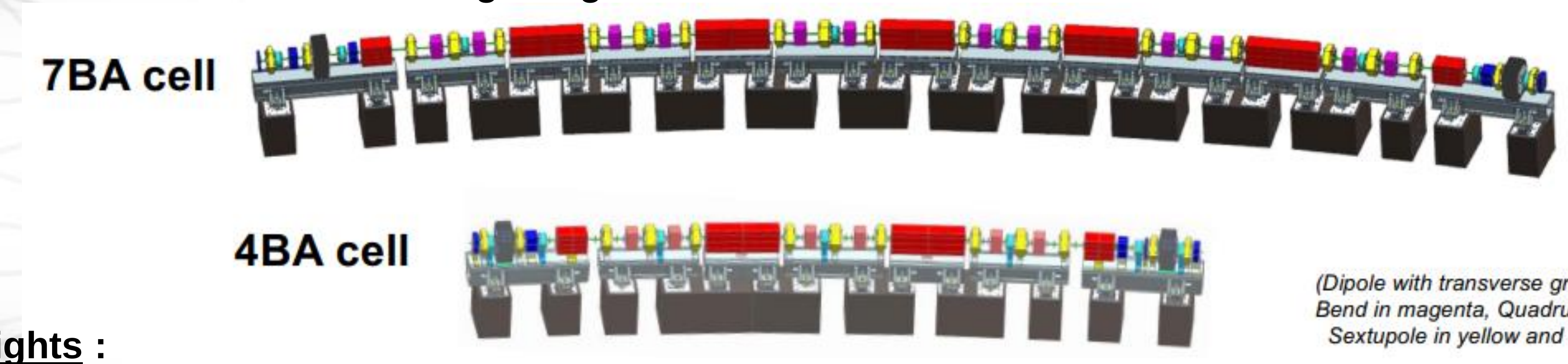
Content

SOLEIL II Overview

Objectives :

- Address present and future scientific and societal challenges through a reconstruction of the storage ring with an emittance < 100 pm.rad, 100 times brighter beams and adapted beamlines.
- Keep the broad energy range from THz to hard X-rays
- Limit beamline displacement as much as possible
- Re-use booster and storage ring tunnels

SOLEIL II storage ring non-standard MBA lattice : 12 x 7BA + 8 x 4BA

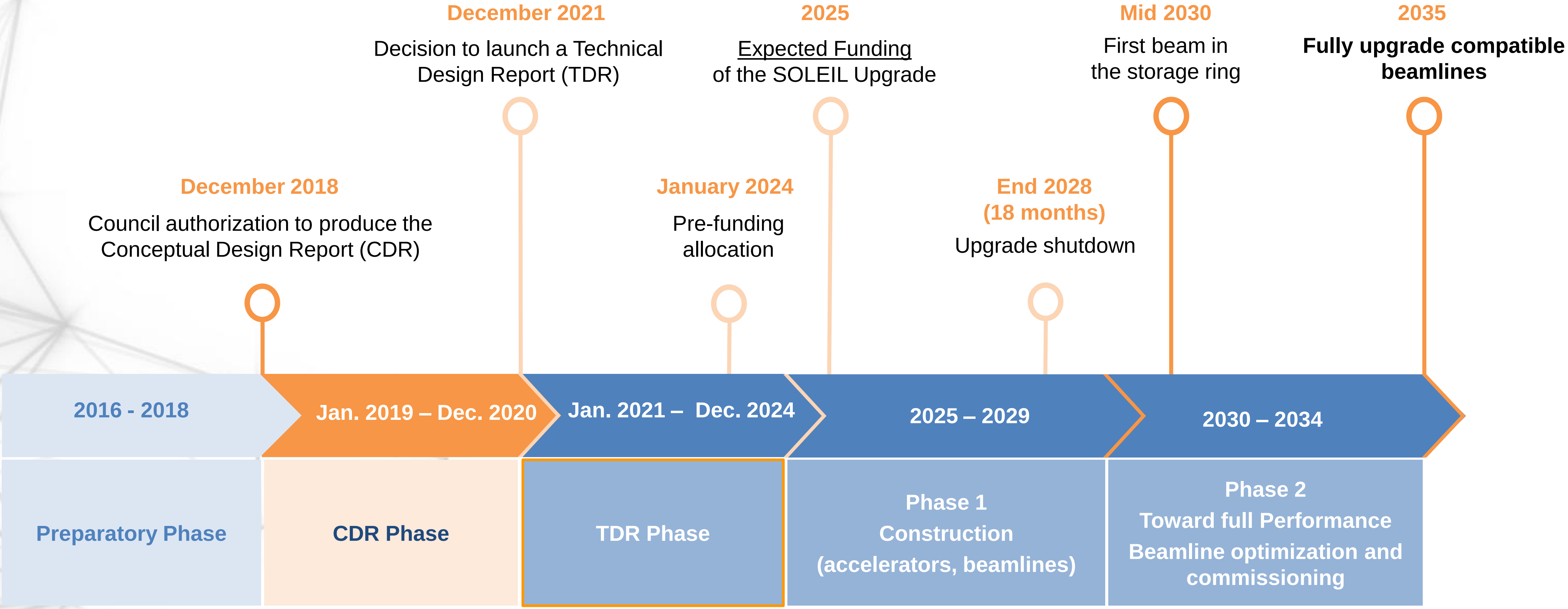


(Dipole with transverse gradient in red, Reverse Bend in magenta, Quadrupole in blue, Sextupole in yellow and Octupole in cyan)

Highlights :

- NEG coated very small vacuum chamber diameter = 12 mm
- Extensive use of permanent magnets (all dipoles, all reverse bends and all main quadrupoles)
- Off-axis injection with high performance Multipole Injection Kicker (MIK)
- Energy Savings

SOLEIL II Overview



SOLEIL II reference planning

Budget : Pre-funding of 38 M€ allocated for 2024 and 2025 ; global budget estimate : 162 M€ for Phase 1

Main SR parameters & fundamental RF specifications

PARAMETERS	SOLEIL	SOLEIL II
Circumference, L [m]	~ 354	~ 354
Energy, E_n [GeV]	2.75	2.75
RF frequency, f_{RF} [MHz]	352.097	352.331
Max beam current, I_b [mA]	500	500
Energy loss per turn, δU [keV]	1 150	484 + IDs ‡
RF power into the beam, P_b [kW]	575	242 + IDs ‡
Overall RF voltage, V_{RF} [MV]	2.8	1.7
Energy spread, σ_E / E	$1\ 10^{-3}$	$9.07\ 10^{-4}$ *
Momentum compaction factor, α	$4.2\ 10^{-4}$	$1.07\ 10^{-4}$
Horizontal emittance, ε_x [pm.rad]	$4\ 10^{3}$	84 *
RF energy acceptance, $(\Delta E / E)_{RF}$	$6\ 10^{-2}$	$7.7\ 10^{-2}$
Longitudinal damping time, τ_s [ms]	3.3	12.2 *
Transverse damping times, τ_x / τ_y [ms]	6.6 / 6.6	7.9 / 14.1 *
Synchrotron frequency, f_s [kHz]	4.5	1.79
Natural RMS bunch length, σ_s [ps]	16	8.5

* Without ID contribution

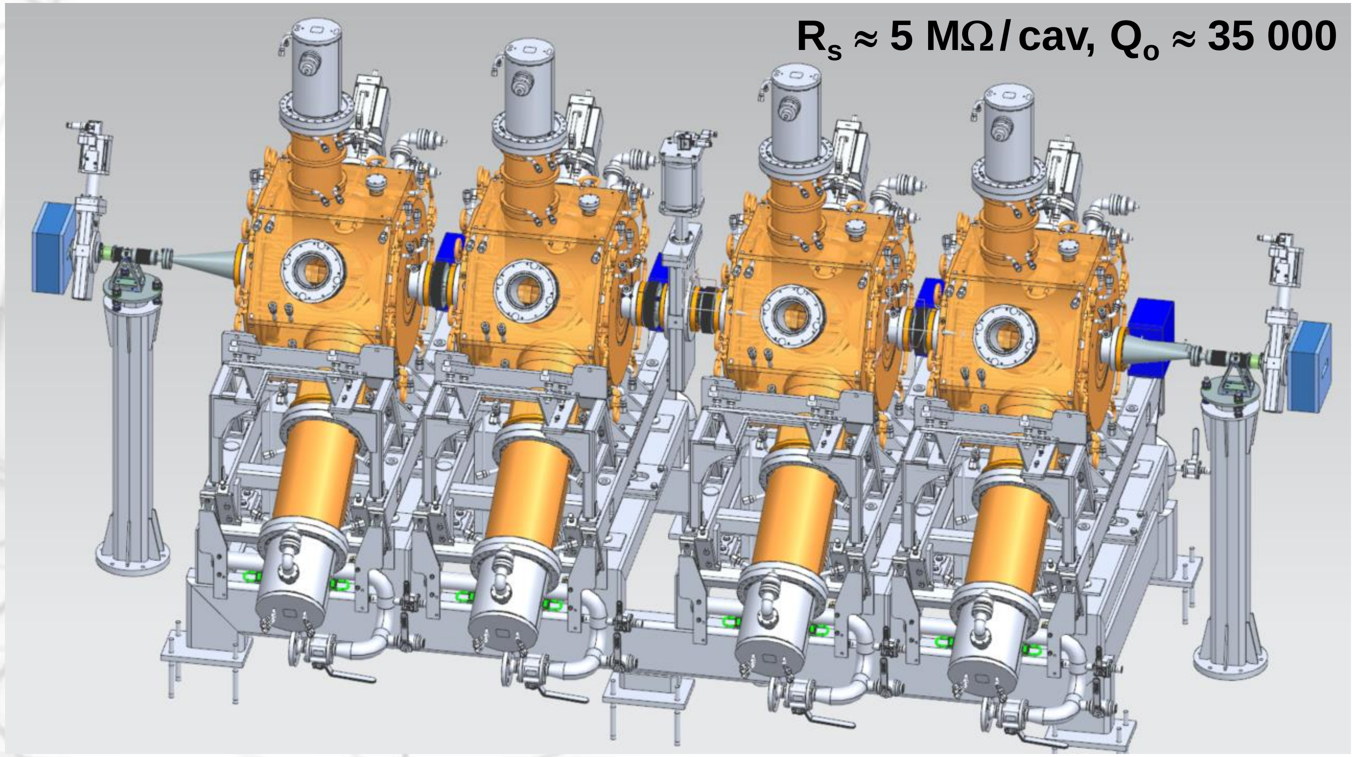
‡ w/ ID losses phase 1: 768 keV, 384 kW @ 500 mA
w/ ID losses phase 2: 854 keV, 427 kW @ 500 mA
(SOLEIL ID losses : 250 keV)

With such low RF voltage and high beam losses, reusing our SC cavities for SOLEIL II was not really justified as they would globally consume more electrical power (RF+ cryogenics) than NC ones & the present cryogenic station is thus made available for a possible SC harmonic system

Use of 4 NC ESRF-EBS cavities, each powered with a 200 kW SSPA

352 MHz Fundamental Cavities (MC)

SOLEIL SYNCHROTRON UPGRADE



	4 (3) NC cavities ESRF-EBS	
Length [m]	~ 4.20	
V_{RF} [MV]	1.7 (1.6)	
P_b [kW]	427 (w/ ID phase 2)	
V_{cav} [kV]	425 (533)	
P_{dis} [kW]	4 x 18 (3 x 29)	Passive
P_{cav} [kW]	125 (170)	← SC HC
P_{cav} [kW]	140 (190)	← NC HC
Coupling	$ß_c = 5$	

RF operating conditions (ID phase 2)

Collaboration with ESRF to benefit from their EBS-type **352 MHz HOM-damped cavities** → Specifications for the call for tender under writing → Place the order for 5 cavities (4 + 1 spare) before the end of 2024 (pre-funding)

Running 4 such cavities provides redundancy (nominal conditions achievable with 3 out of 4 cavities → P_{max} = 190 kW/cav including NC HC)

ESRF EBS fondamental power coupler limited to P_{max} ~ 160 kW → Collaboration with CERN for LHC type power coupler (P_{max} >> 200 kW)

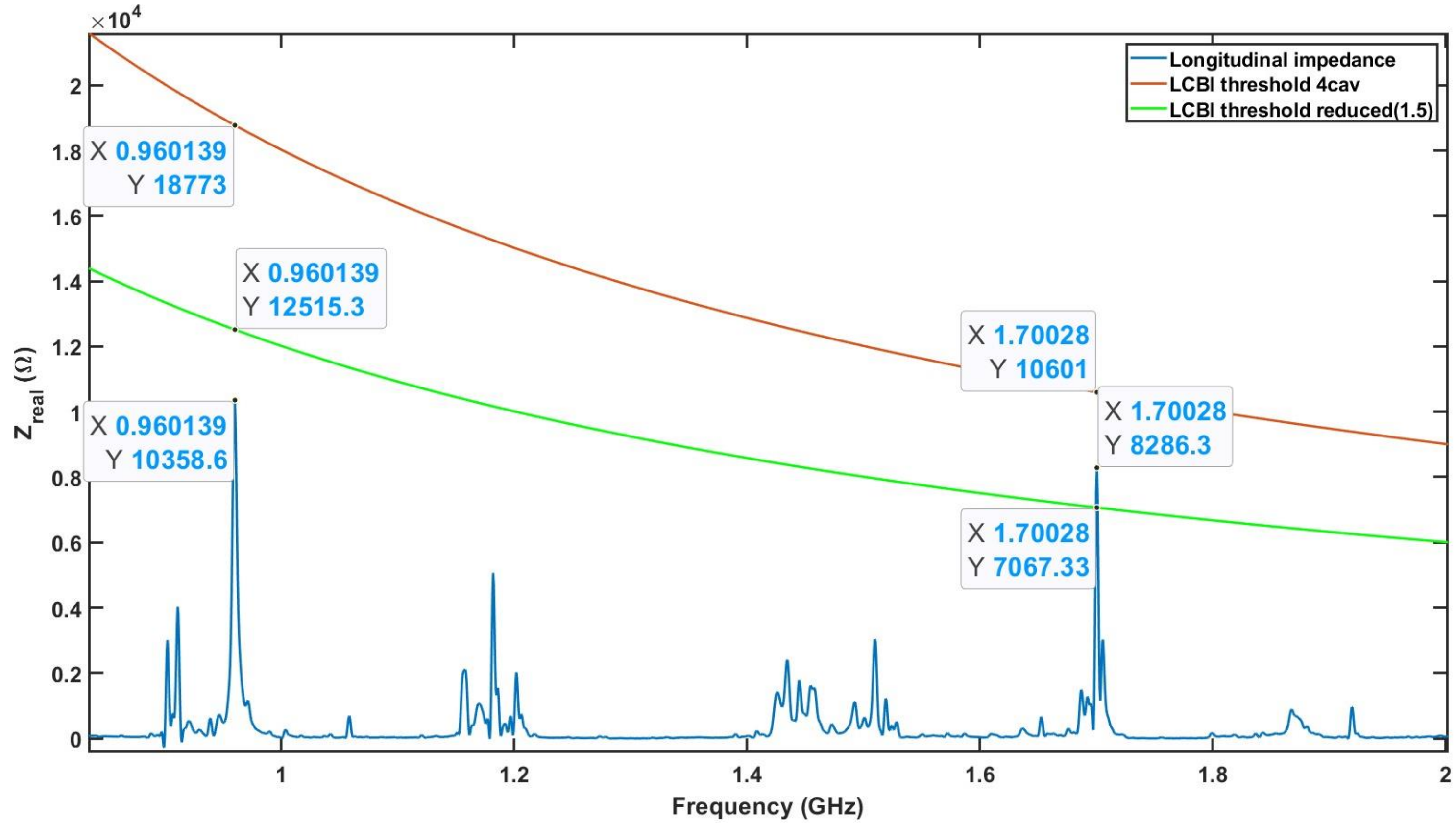
Fundamental Cavity HOMs

Coupled bunch instabilities threshold calculation:

$$Z^{th}_{long}(\omega) \simeq \frac{4\pi}{\tau_{long}\alpha_c} \cdot \frac{E_{beam}}{I_{beam}} \cdot \frac{\omega_s}{\omega_{rev}} \cdot \frac{1}{\omega}$$

Full HOM simulation with 4 cavities → *Potential "danger" mode @ 1.7 GHz*

Impedance for 4 cavities is ~ 30% smaller than the LCBI threshold (from the above approximate formula). However, it is ~ 15% higher than the anticipated reduced LCBI threshold with HC (to be confirmed by further tracking simulations).



Possible cure :

Bunch-by-Bunch Longitudinal Feedback (LFB)

Next steps :

- Launch call for tenders for cavity procurement
- Tracking simulations to confirm LCBI threshold modification in presence of harmonic cavities
- LFB study (same processing hardware that the one used presently for TFB)

352 MHz Power Sources

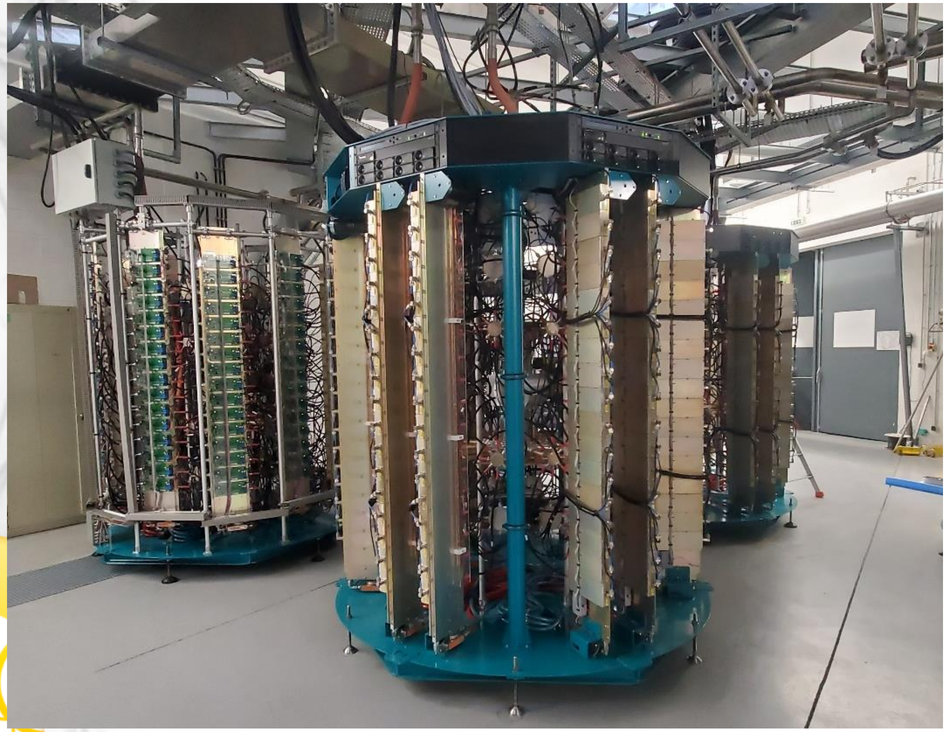
Objective: Upgrade the 4 SOLEIL SSPA's for reuse in the SOLEIL II Storage Ring (SR)

- Power supply and system supervision upgrade → redundancy and efficiency improvement (+9% with new AC/DC converters).
- Other adaptations, as for instance connecting each tower directly on the waveguide → More flexibility.

New AC/DC converters

AC/DC converter voltage remote control allows to match for maximum efficiency over the whole power range

50 kW upgraded towers for the storage ring



Status:

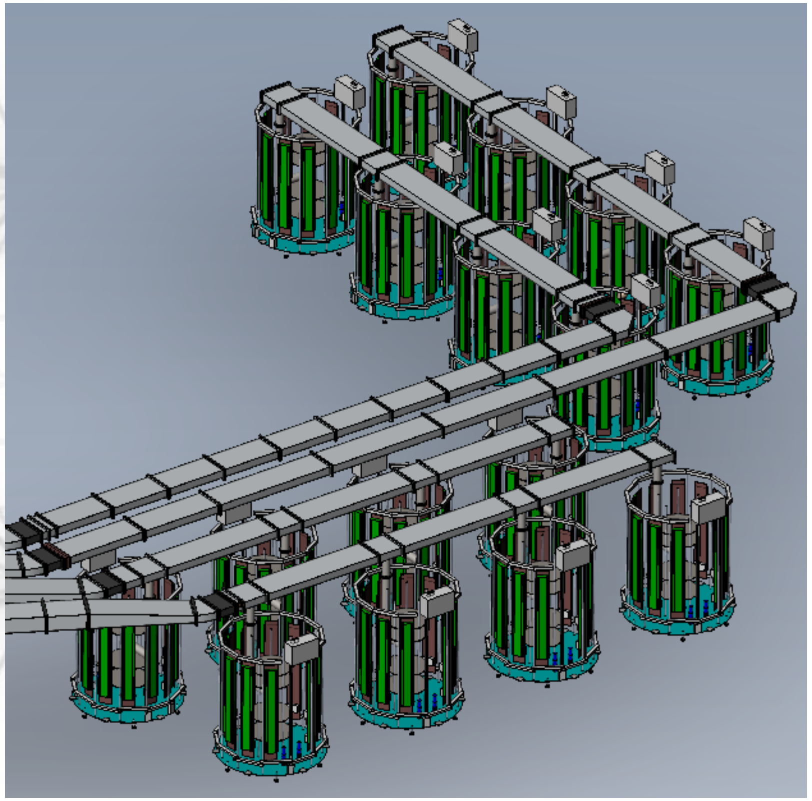
- 2 upgraded 60 kW SSPA presently in operation on the booster cavities
- 2 upgraded 50 kW SSPA towers in operation on the SR SSPA n°2

Storage Ring power supply and control upgrade plan

From beginning of 2024, 1 x 50 kW tower will be installed every 2-3 months in the SR to benefit from the **four fully upgraded 200 kW SSPA's by end 2027 for SOLEIL II.**

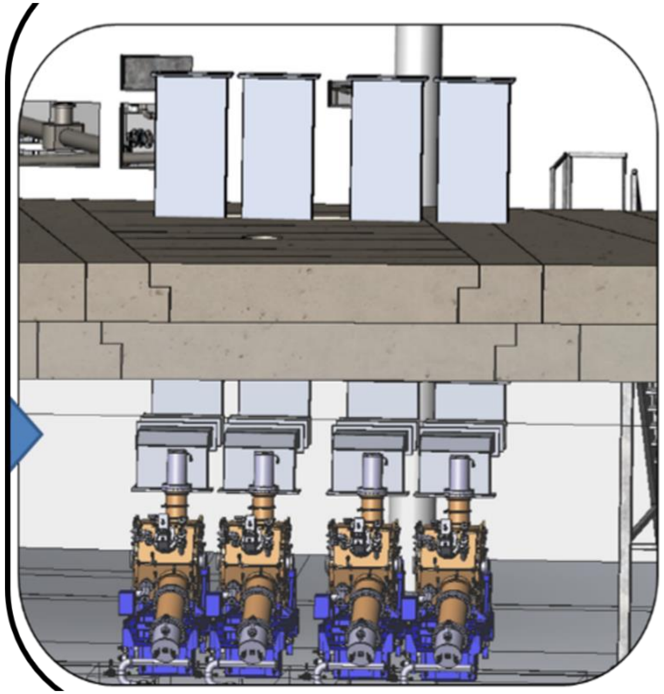
Waveguide distribution layout

- Direct SSPA tower to waveguide combination
- Possibility to match amplifier configuration depending on the number of running towers (3 - 5) thanks to adjustable waveguide antenna coupling.

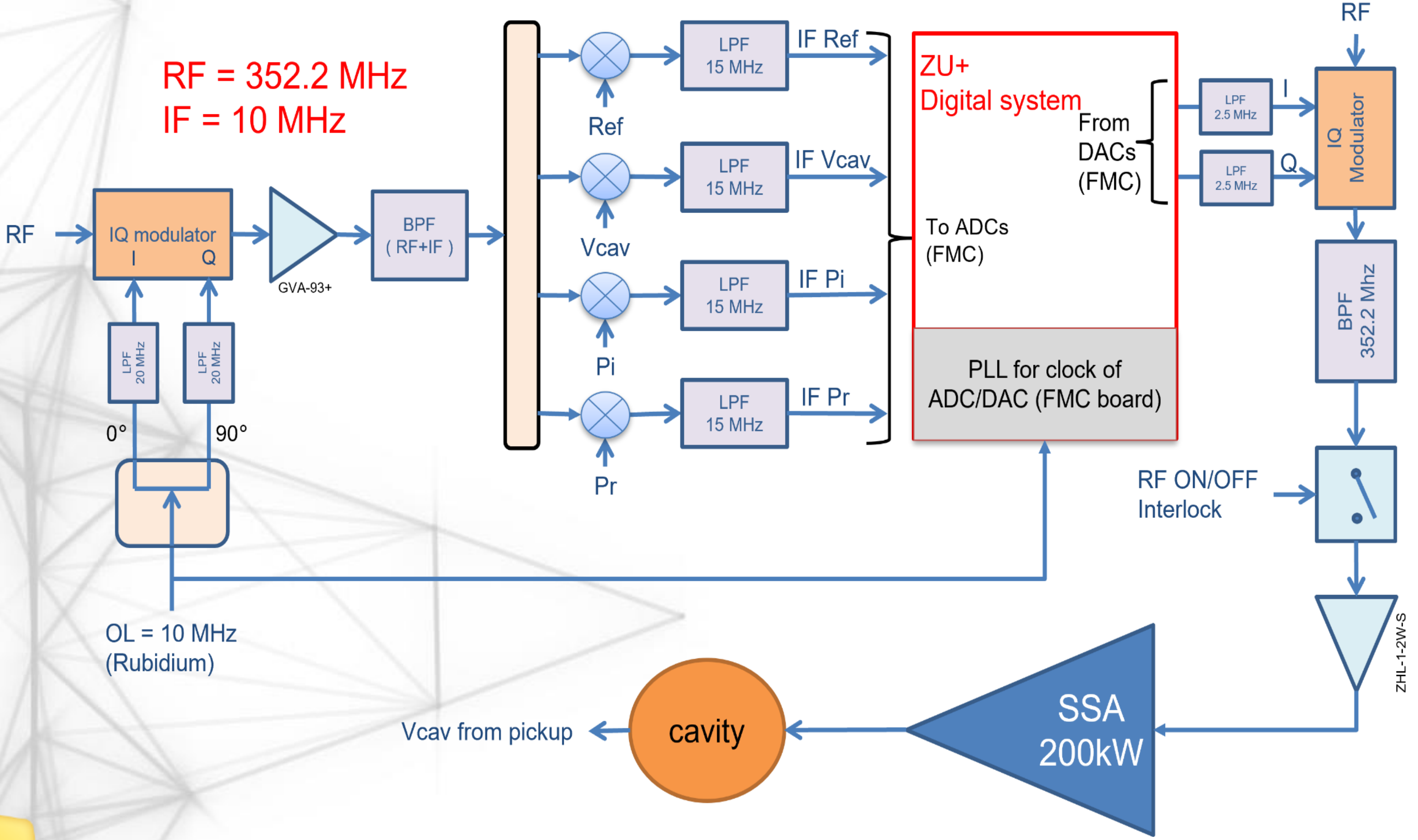


Tunnel penetrations

- Up to 200 kW power per amplifier to be transmitted
  → waveguide preference instead of coaxial line feed-through
- ✓ Positive evaluation from radiation safety (RS) for drilling two holes in the tunnel roof (one for a pair of cavities).
- − Need to have a realistic model from infrastructure for RS simulations.



352 MHz LLRF system



Experimental results:

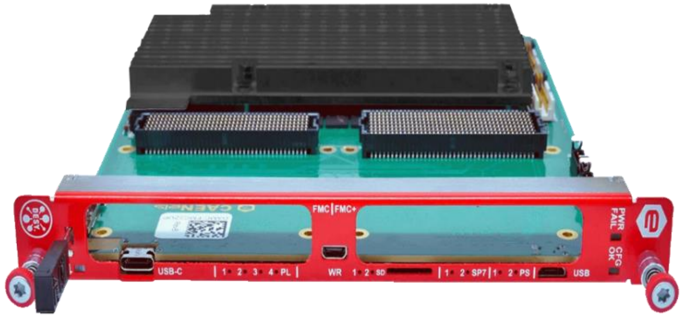
Test on one of the present SOLEIL SR cavity with stored beam fully satisfying. Closed loop accuracy :

- **3×10^{-4} in amplitude**
- **2.4×10^{-2} degrees rms in phase**

Digital LLRF tested on a SR SOLEIL cavity @ 450 mA (October 2023)

352 MHz LLRF system

Digital processor on µTCA crate



µTCA platform

ADC/DAC module + FMC

RF interface (frequency translation to 10 MHz)

Next steps

- Evaluate the possibility to increase the accuracy by optimizing the reference signal
- Tango integration for high level supervision
- Fast interlock system prototype developpement (dedicated rack based on CPLD) by mid 2024
- Followed by prototype tests on SOLEIL

Harmonic cavity (HC) story

1st SOLEIL II specification for the CDR (2020)

1) **Reproduce all the present SOLEIL operation modes** with bunches long enough to preserve the extremely low emittance while insuring a suitable lifetime: 500 mA in 416 bunches; 100 mA in 8 bunches (time structure mode); 20 mA in 1 bunch; 450 mA hybrid mode (445 mA in ¾ of the ring + 1 bunch of 5 mA in the last ¼)

2) **Additional short bunch mode** (FWHM bunch length ≤ 10 ps)
   - → **V_{1h} (352 MHz) = 1.7 MV** (from 4 ESRF-EBS NC MCs) => **V_{3h} = 2.2 MV** or **V_{4h} = 1.8 MV**
   - → Too many NC HCs (space, TBL, impedance and stability issues) & too much RF power
   - → **Selection of the passive SC HC option** using our available cryogenic plant
     - ✓ Collaboration with CERN and CEA for the technical study and evaluation of a CM based on the Super3HC design as used in SLS and ELETTRA (2 passive "HOM free" SC HCs at 1.5 GHz) → Scaling to the 3rd or 4th harmonic of 352 MHz
     - ✓ Beam dynamic simulations for 2 such cavities (R/Q = 45 Ω / cav, Qo = 10^8, h = 3 and 4) using our tracking code mbtrack2 *(the impact of the collective effects due to the global broad band impedance of the machine, was not yet included in the code at that time)*

⬇

- The simulations showed that one could achieve suitable bunch lengthening factor (BLF = σ_s / σ_{so}) of about 4 for all the specified modes in 1), excepted the hybrid one; for the latter, even with such low R/Q, the effect of the TBL due to gaps larger than a few buckets strongly limits the achievable bunch lengthening.
- TBL compensation means, like feedforward in a broad band cavity as proposed by KEK, not effective.
- A priori, no need for gap to avoid ion trapping.
  - ⇨ **Elimination of the hybrid mode and consider only modes with uniform filling.**
  - ⇨ **Then, decision from our SAC to eliminate the short bunch mode**, considering that the scientific applications and user community were too restricted.

HC story - Evolution of the specifications

2^{nd} SOLEIL II specification (2022)

500 mA in 416 bunches, 100 mA in 8 bunches (with FWHM bunch length < 100 ps), 20 mA in 1 bunch

→ V_{3h} ≈ 600 kV ; V_{4h} ≈ 450 kV

- **NC HC option back in the game but only its active version** (presented at HarmonLIP 2022) as the passive one would require too many cavities to produce the required voltage for the low average current operation in 1 or 8-bunch modes.
- After modeling the global broad band impedance in mbtrack2, the simulations showed that, for these high current per bunch modes, the strong impact of the collective effects made any version of the HC system, NC or SC, almost ineffective: only about 10 - 20% gain in lifetime brought by the HC, resulting globally in too short lifetime.

Last SOLEIL II specification (2023)

- Main operation mode: 500 mA in 416 bunches (uniform filling) with max possible length
- Time structure mode: at least 200 mA in 32 evenly spaced bunches with max possible length
- Single bunch mode**:** very little used operation; the max current of 20 mA is not a criterion anymore and the emittance can be increased as much as needed for achieving enough lifetime.

=> Bunch lengthening from HC not anymore required in 1-bunch mode and time structure mode average current increased from 100 to 200 mA => **Passive NC HC option back in the game**.

Considered HC types

	S3HC	APS-U ♦	ESRF-EBS	ALS-U	ALBA
Technology	Passive SC 1 CM with 2 cav	Passive SC 1 CM with 1 cav	Passive or active NC TM_{020} 2-cell cav	Passive NC 1-cell cav	Active NC 1-cell cav
Frequency	Scaling at 3H or 4H	4H	4H	1.5 GHz	1.5 GHz
R_s (MΩ) / cav	$4.5\ 10^3$	$1\ 10^4$	2.4	0.76	1.1
Q_0	10^8	$2\ 10^8$	36 000	38 000	13 000
R/Q (Ω) / cav	45	52	66	20	85
V_{cav} max (kV)	-	-	500	90	200
N_{cav} needed	1 CM with 2 cav	1 CM with 1 cav	1	6	3
Total R/Q [Ω]	90	52	66	120	255

♦ *APS-U passive SC HC includes 2 variable power couplers connected to external loads, allowing Q_L adjustment to maintain the flat potential (FP) condition with symmetric bunch shape for different $<I_{beam}>$ within a limited range (not relevant for low $<I_{beam}>$). It requires a significant amount of power to be compensated by the MC.*

- APS-U SC HC design : additional complexity and extra power requirement for a low gain from the bunch shape symmetry at the FP condition
- With ALS-U and ALBA NC HC designs, the relatively low achievable voltage leads to the need for too many cavities → PTBL instability due to high R/Q & requires too much space & not at our frequency.
- For SOLEIL II, $R/Q_{tot} \approx 75\ \Omega$ would be a good compromise to cope with both the PTBL instability at 500 mA and the 0 - mode instability at 200 mA

S3HC scaling and NC ESRF-EBS 4th HC selected as baseline candidates for SOLEIL

HC comparison (SC vs. NC)

Assuming our 2 retained operation modes (500 mA in 416 bunches, uniformly filled and 200 mA in 32 bunches, evenly spaced), 3 versions of HC have been evaluated :

- Passive SC HC, based on a Super-3HC type Cryomodule @ 1.41 (or 1.06 GHz) → Collaboration WP6 with CEA and CERN.
- Passive and active NC HC, based on an ESRF-EBS 1.41 GHz 2-cell cavity → Collaboration WP3 with ESRF and KEK.

Comparison resume:

- The **passive SC HC** remains the best option in terms of bunch lengthening factor (BLF = σ_s / σ_{so}) and operational « ease », but its investment cost is relatively high (~ 2 M€) → With direct RF feedback (DRFFB) on the MC, BLF ≈ 6 for h = 4
- In the same conditions, the **passive NC HC** provides slightly lower, nevertheless acceptable BLF of ≈ 5.5, but for a much lower investment cost (~ 0.6 M€) and moreover with best operational reliability (no RF power source, no cryogenics). The MC power margin is enough to compensate for the NC HC wall dissipation of about 50 kW at 500 kV.

→ Longitudinal dynamic studies to be presented by Alexis Gamelin

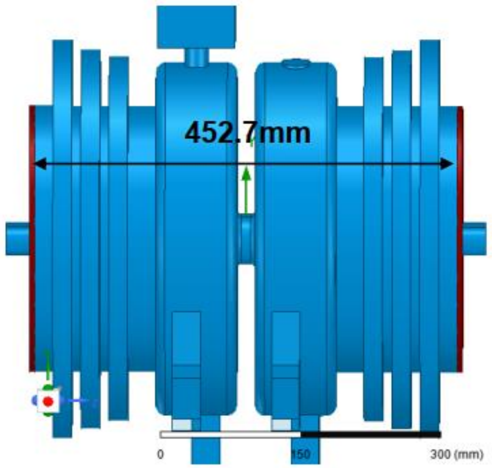
- The study of the **active NC HC** (investment cost ~ 1.2 M€) has to be completed; it should provide more flexibility than the passive HC while achieving comparable BLF; however, its operational control is much more complex and critical.

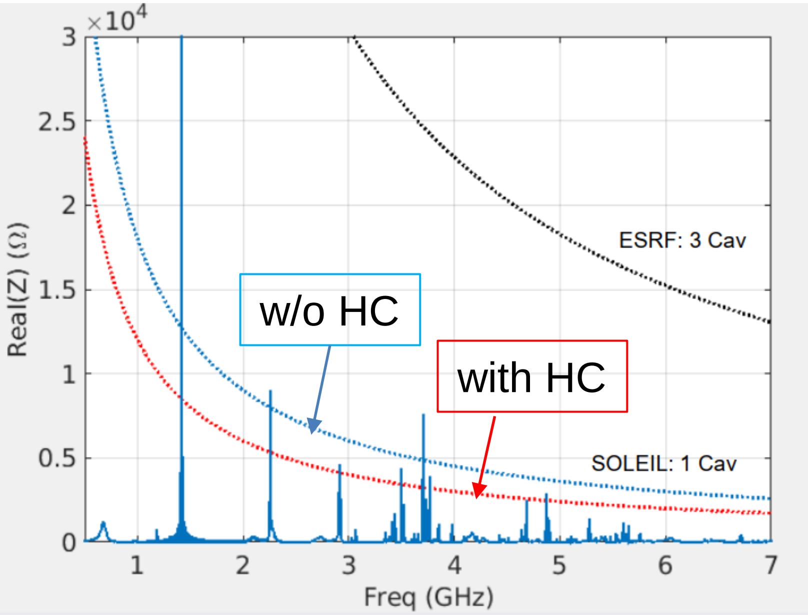
Taking into account the new operation mode specification, energy price increase and budget constraints, we now consider the passive NC HC option as the most attractive for SOLEIL II and we proposed the following strategy :

- ***Phase 1*** **: begin with passive NC HC 4H of the ESRF-EBS type (1 x 2-cell or 2 x 1-cell)**
- ***if needed after experience feedback*** **→ *Phase 2*** **: add a power source (GaN based SSA) to convert the passive HC into an active one.**

ESRF-EBS TM_{020} 4^{th} HC (2-cell design)

2-cell cavity
Rs = 2.4 $M\Omega$ / cav
Q_0 = 36 000
R/Q = 65 Ω / cav
N_{cav}= 1

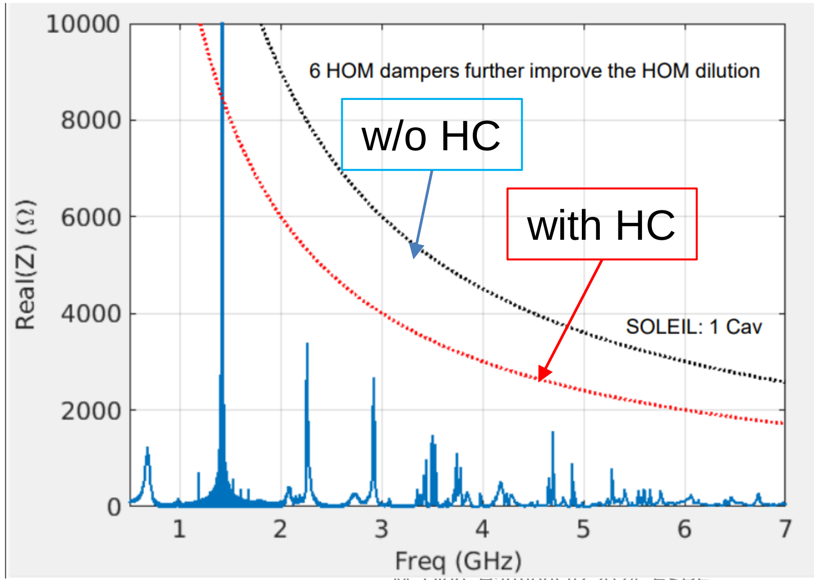




LCBI threshold for SOLEIL II case with 1 cavity is a factor of almost 8 lower than ESRF-EBS case with 3 cavities !!

→ Mitigations: HOM dampers and/or bunch by bunch longitudinal feedback

Preliminary simulations show sufficient HOM attenuations by using 2 or 3 HOM dampers per cell



ESRF simulations in the framework of WP3 collaboration among ESRF, KEK, and SOLEIL – Design and implementation of a harmonic RF system with TBL compensation

TM_{020} 4th HC (→1-cell design)

Following the decision of using the NC HC option for SOLEIL II :

- Terminate the collaboration WP6 with CEA and CERN for the design of a Super3HC cryomodule
- **Re-inforce the collaboration with ESRF for the design of a NC HC**
  - A collaboration agreement is under writing
  - As the ESRF project of HC in EBS has been postponed to 2027, first design the HC for SOLEIL II and then adapt it to the EBS needs
  - So far, the use of the 2-cell HC design was considered → Investigate the use of two 1-cell HC

    → Technical design of a 1-cell cavity, able to handle up 420 kV (P_{dis} ~ 50 kW)

    → Possibility to operate with a single one ; relaxed and flexible operation with two of them

    → Tracking simulations to determine the optimum R/Q (compromise between 200 and 500 mA operation modes)
  - Tentative planning
    - Complete the 1-cell HC design before end – 2024
    - Launch equipment procurement (cavity, SSA, DLLRF, …) before mid – 2025
    - Equipment availability before mid – 2027
    - Tests in test-stand (using the SSA) and on SOLEIL with beam (passive) before end – 2028

Conclusions

- **Four NC 352 MHz HOM-damped cavities of ESRF-EBS type for the fundamental system** (possibility to achieve nominal conditions with 1 cavity out of use) → call for tenders this year.
- Collaboration agreement to be formalized with CERN to design **power couplers >> 200 kW CW.**
- **Two 60 kW upgraded SSPAs** presently in operation on booster cavity 1 and 2.
- **Storage ring SSPA upgrade** started in January 2024 (1 x 50 kW tower installed every 2-3 months).
- **LLRF system** tested in real 450 mA operation conditions on present SOLEIL machine and shows good performance.
- **Different options of HC were considered** according to the evolution of the SOLEIL II specifications.
- **Passive NC ESRF-EBS 4H cavity** chosen as baseline for the harmonic system with possible conversion to « active », if needed in a 2nd stage.
- Collaboration with ESRF for SOLEIL II **harmonic cavity design.**

THANK YOU FOR YOUR ATTENTION