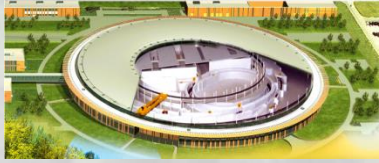


20th European Synchrotron Light Source Radio-Frequency Meeting

Paul Scherrer Institute, Villigen, Switzerland

November 16 - 17, 2016

June 2, 2016 : 10th anniversary of the 1st beam production by SOLEIL

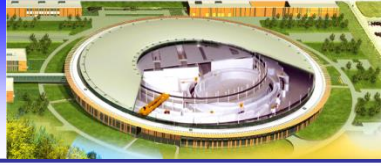
Ten years of operation with the SOLEIL RF systems (experience, upgrades, R&D) and contributions to other projects

P. MARCHAND

- ✓ **Operational experience with the SOLEIL LINAC [Jean-Pierre POLLINA]**
- ✓ **Review on the RF Solid State Power Amplifiers [Massamba DIOP]**

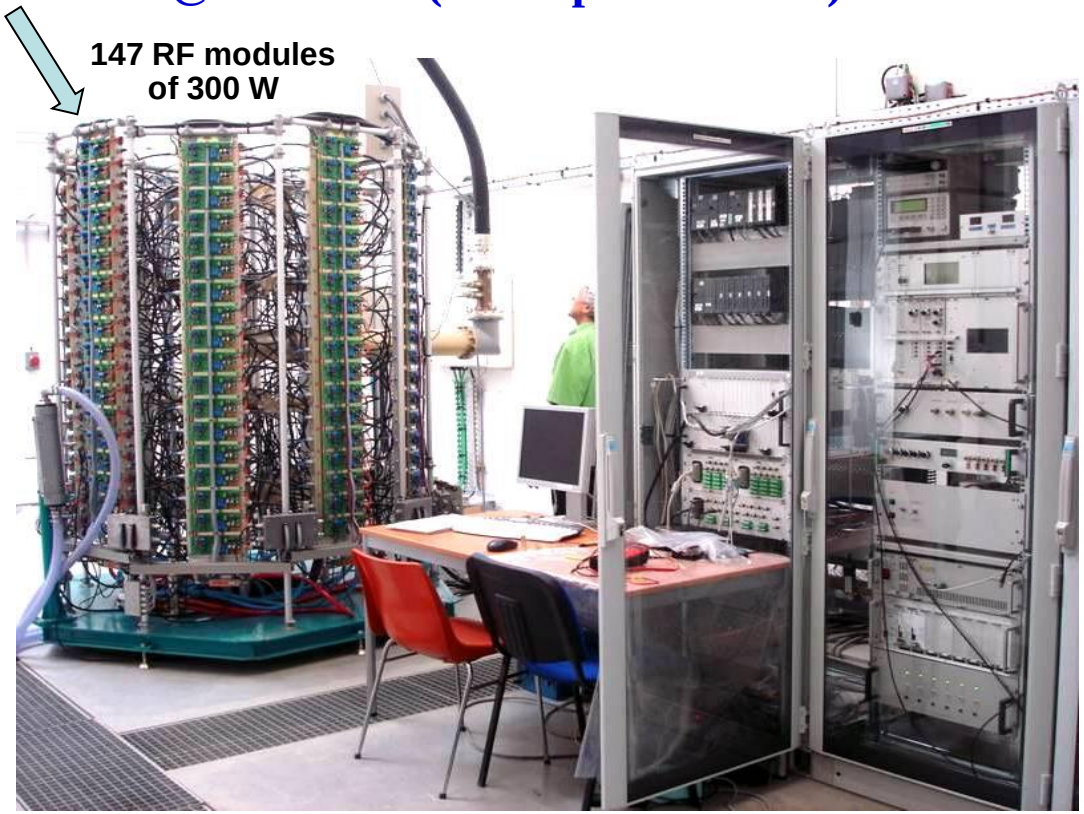
P. Marchand

SOLEIL Booster RF system



- E_n : 100 MeV → 2.75 GeV (rep. 3 Hz) ; V_{RF} : 0.2 → 1 MV @ 352 MHz
- 1 x 5-cell Cu cavity (CERN LEP) → P_{tot} : 25 kW (P_{dis} : 20 kW, P_{beam} : 5 kW)
- 1 x solid state amplifier (SSA) → 35 kW CW @ 352 MHz (developed in house)

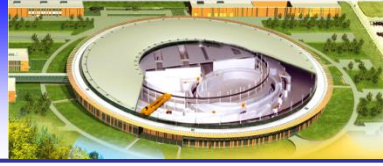
Cavity in the BO ring



BO RF room (amplifier with LLRF & control)

~ 60 000 running hours over 10 years and only 4 short downtimes in operation (< 10^{-4} overall)
First trip from the 35 kW SSA, in August 2016, due to a loose connection on a monitoring cable.
~ 1 module failure / year, without impact on the operation, thanks to the modularity and redundancy.

Booster RF upgrade plan

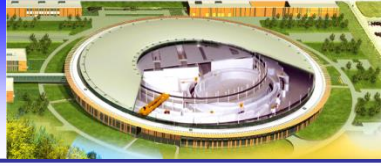


The objective is to *improve the injection efficiency in the low-α operation* mode by a factor of ~ 2 for radiation safety reasons. That requires increasing V_{RF} *from 1 MV up to 3 MV* in order to achieve the proper bunch length.

- **Install our available spare cavity in the BO ring** and power it with 60 kW (V_{RF} = 1.8 MV)
- → **Build a new 60 kW - 352 MHz SSA, identical to a standard tower of our SR amplifiers,** using the 160 RF modules of 400 W (BLF574 transistor) and their dc-dc converters, got back from the upgrade of these amplifiers
- **LLRF & Control → a replica of the actual one**
- **Increase V_{RF} of the existing plant from 1 MV up to 1.2 MV → P_{RF} ~ 30 kW (P_{beam} ~ 0)**
- There is free space for the 2nd cavity in one straight section of the ring and for the SSA with the LLRF & control inside the Booster RF room → **Infrastructure work**
- **Additional benefits** : power savings & redundancy in all the other modes of operation

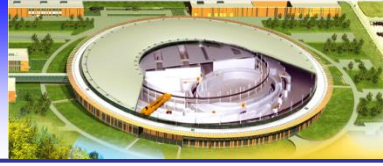
Project under way → Commissioning beginning of 2018

SOLEIL SR RF system



- **E_n = 2.75 GeV, ΔE = 1.2 MeV, I_b = 500 mA**
  → P_{RF} = 600 kW & V_{RF} : 3 - 4 MV @ 352 MHz
- 2 cryomodules (CM), each containing a pair of single-cell s.c. cavities (Nb/Cu)
- Each of the 4 cavities is powered with a 180 kW solid state amplifier (SSA)
- Both CM's are supplied with LHe (4.2 K) from a single cryogenic plant

SR RF system operational results



Beam downtime, caused by failures from the SR RF over ~ 60 000 running hours in ~ 10 years

Equipment	Downtime	Comments
a) 4 x RF amplifiers	~ $1\ 10^{-4}$	~ 5 h in 5 short events due to **preamp.** & power combiners **MTBF > 10 000 h** (cumulated by 4 ampli)
b) 4 x 500 kVA PS (230 Vac / 270 Vdc)	~ $4\ 10^{-4}$	~ 24 h in 7 faults from **the power supply control**
a) + b) = 4 x RF transmitters *	~ $5\ 10^{-4}$ *	MTBF ~ **5 000 h** (cumulated by 4 transmitters)
c) 2 x CM's (4 cavities)	~ $5\ 10^{-4}$	**Tuners**, couplers, monitoring pick-ups, vacuum gauges
d) 4 x LLRF & control systems	~ $6\ 10^{-4}$	**Wrong interlocks** from noise (→ filtering & grounding) + bad contact from a faulty solder
a) + b) + c) + d) = 4 x RF systems	~ $1.6\ 10^{-3}$	MTBF ~ 2 000 h
e) 1 x Cryo-plant	~ $1.4\ 10^{-3}$ → **$6.1\ 10^{-3}$**	~ 85 h in 6 events **(60 h a single one)** → 2nd compressor **June 2016, water contamination → 12 day shutdown** → **Implementation of a dryer and a purifier**
Complete SR RF system	$7.7\ 10^{-3}$	→ 15 % of the overall machine downtime ~ 5 %

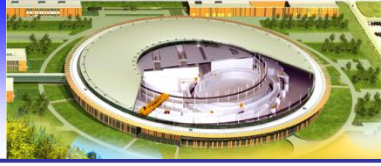
**** Much better with upgraded SSPA (6th generation transistors, modular ac-dc converters, preamp. redundancy)***

Cryogenics recovery time reduced from 6 down to 3 hours by improving the process control → it does not affect anymore machine restart time, after utility failures; gain of another fact. 2 expected from **further upgrade plans:**

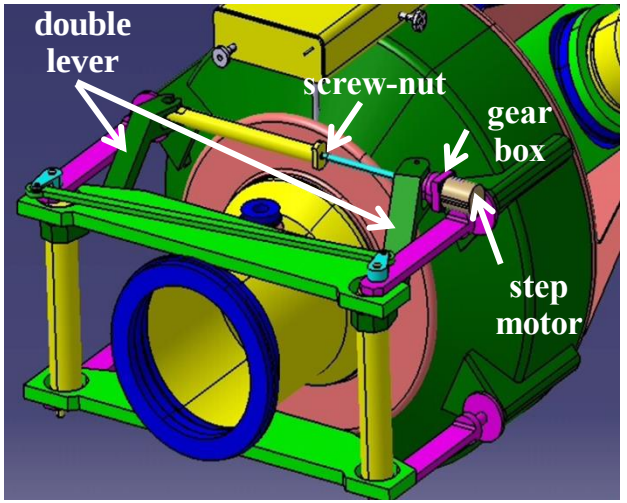
- Installation of a 3rd 50 m^3 GHe tank
- Modifications on the water cooling circuit
- Revamping of the control system and process

⇨ **Recovery time ~ 1.5 h, autonomy of ~ 5 hours with automatic restart & full compressor redundancy**

Pb with the cavity frequency tuners

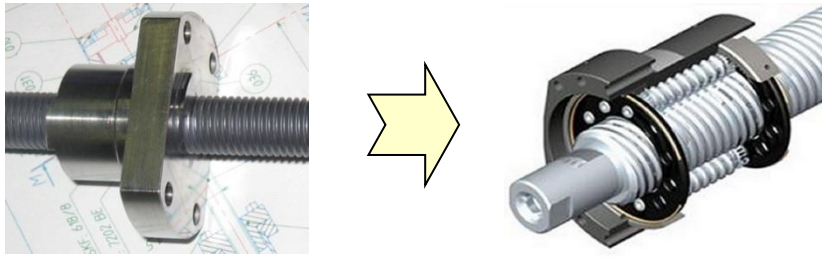


- ✓ After ~ 2 years of operation, repetitive jams of the cavity freq. tuners, fortunately with relatively small impact on the user runs
- ✓ Each cavity has its own tuner which changes its length: double lever & screw-nut assembly, driven by a step motor & a gear box
- ✓ Fully housed inside the CM, where it works under vacuum and at cryogenic temperature → hard environment for the mechanics
- ✓ Try different cures : change of the screw-nut material, threads and backlash without success → still jams and degradations !!

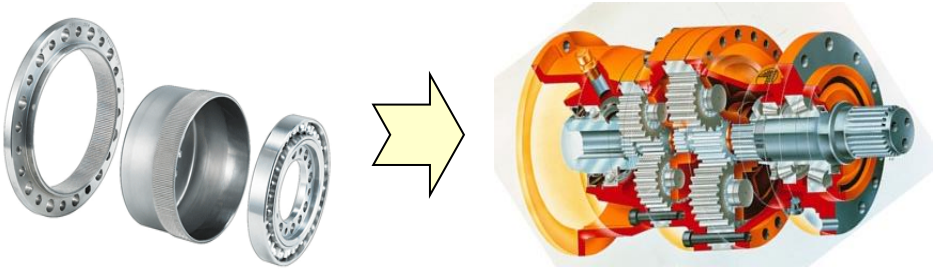


→ UPGRADED TUNER VERSION

1) Standard screw-nut assembly replaced by « planetary roller » screw

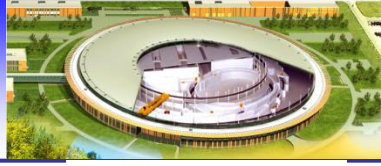


2) « Harmonic drive » gear box replaced by « planetary » gear box

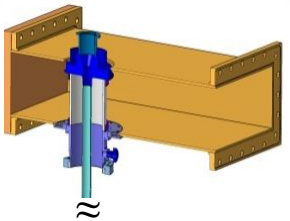


The four tuners have worked without any trouble for ~ 7 years. Recently, we detected a change in behavior on one of them ; when dismounting, we found that the cage of its screw was broken. The 3 other ones are still working well and no visible wear → Dismount one of them for a check.

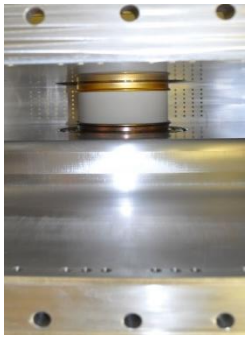
Input power coupler (IPC) upgrade

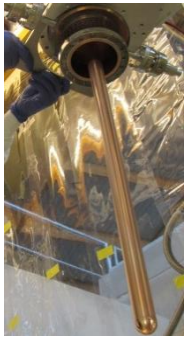


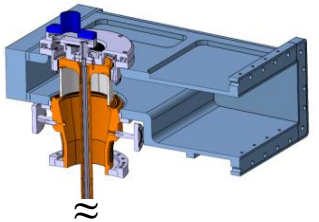
- Original SOLEIL IPC is a LEP2 type antenna → 200 kW CW @ 352 MHz
- Problems of ceramic aging with LEP type IPC's at ESRF
- *300 kW / cav* → SOLEIL can store 500 mA using a single CM → redundancy



In 2011, collaboration agreement with CERN and ESRF → develop a new 352 MHz IPC version, based on the LHC design (400 MHz), capable of handling *up to 300 kW.*



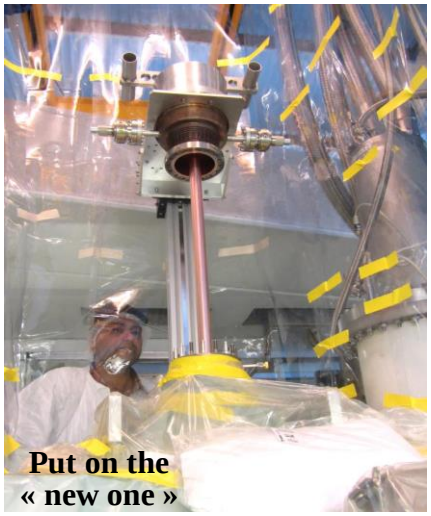




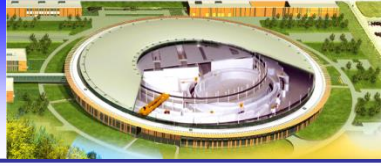
Six IPC's were built at CERN and then RF conditioned in the ESRF test-stand up to 300 kW in transmission and 200 kW in full reflection, using a copper cavity from CERN

The IPC's were mounted on the CM's, *in situ*, without removing out of the ring, using a hood with laminar air flow, enclosed within a plastic tent and with slight N_2 gas overpressure inside the cavity

→ *" Clean room " built on top of the CM !*



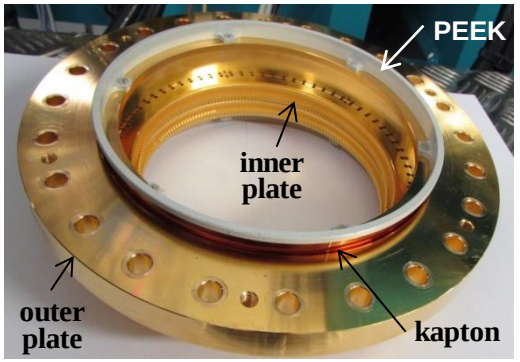
IPC multipacting (MP) cure

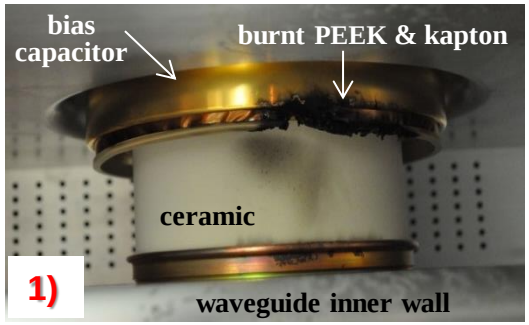


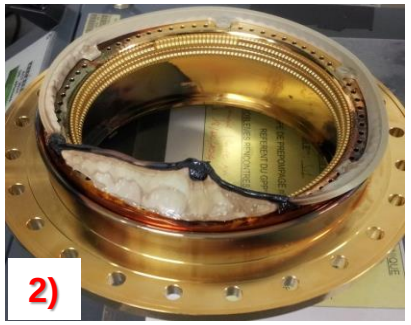
☺ Once mounted on the CM, it took only few days to recondition the IPC's up to 1.5 MV with 150 kW CW full reflection and then we could quickly store up to 500 mA without any trouble.

☹ After ~ 1 week of operation, MP activity at P ~ 110 kW → sometimes vacuum interlocks
Re-conditioning during the next shutdowns → same scenario : no pb at the beginning of the following run, then a kind of "de-conditioning" after a couple of days.
No impact on user runs → P_{coup} < 110 kW, compensating with the other cavities

Implementation of a "*bias capacitor*" generating a dc-field at the ceramic window location, aimed at destroying multipacting resonant conditions → The multipacting indeed fully disappeared when applying ~ 1 kV dc and it remained ok in operation ☺ ☺







☹ ☹

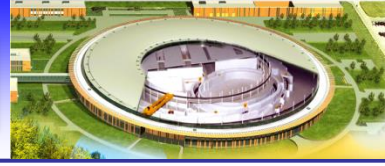
Bias capacitors damaged by overheating

1) During tests at ESRF → Arcing (air side)
2) During operation at SOLEIL
And it was still working !! 😲 → no op. impact

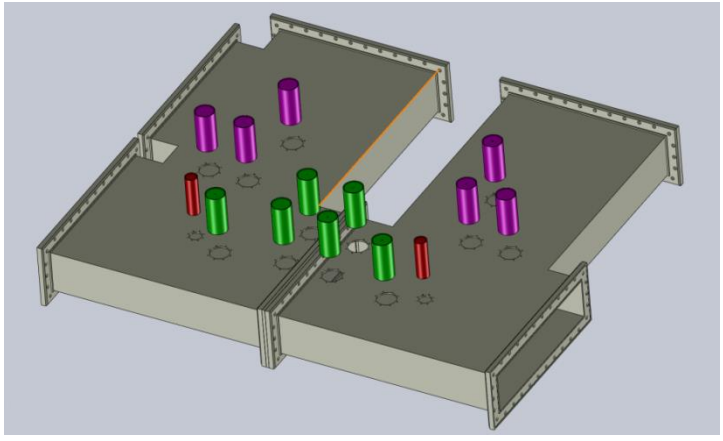
New EM simulations pointed out dimensioning errors → Beg. 2015, replaced + proper temp. controls and since then the 3 operating IPC's ok ☺ (last one to be installed beg 2017).

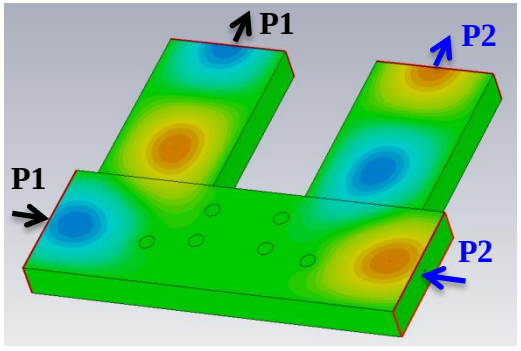
The dirty ceramics and the Cu lips with arc impacts were restored by Alumina blasting
→ Thanks to the Eric Montessinos team (CERN)

Toward storing 500 mA using a single CM

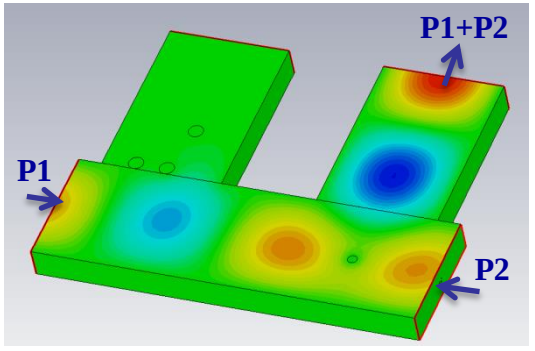


Upgrade of the cavity IPC's (300 kW / cav) → Modify the waveguide network to combine the power from 2 amplifiers into one cavity → Development of a « Magic Switch »

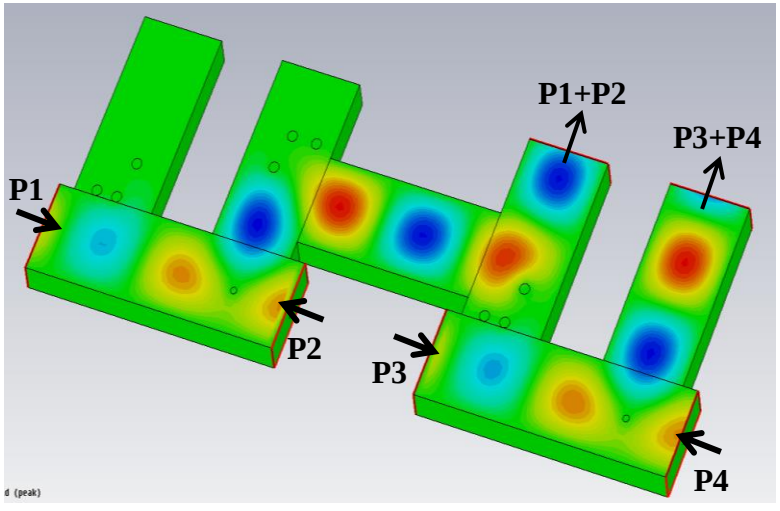




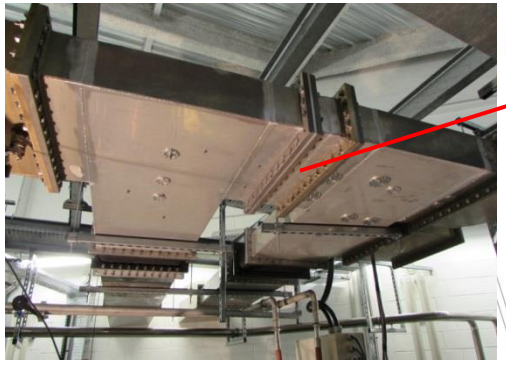
OR

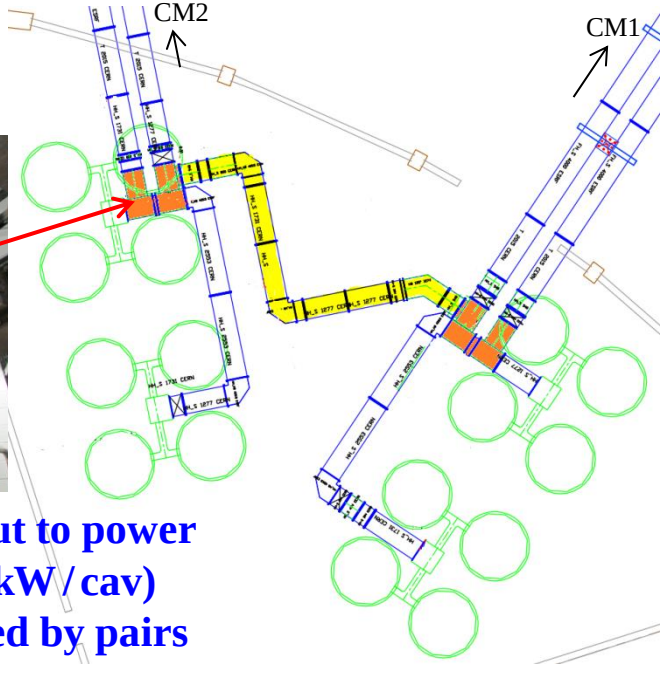


Depending on the post configuration



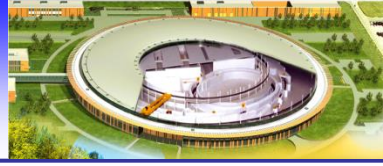
Connecting 2 Magic Switches



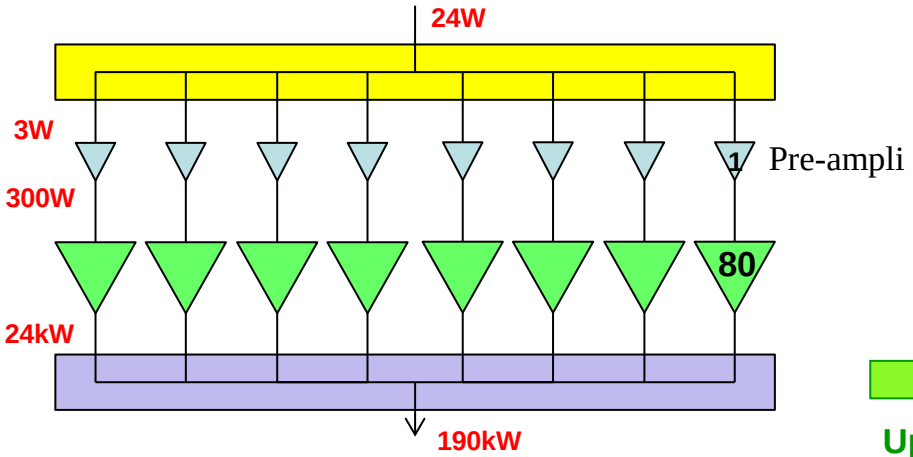


Wave guide network layout to power one or the other CM (300 kW / cav) from the 4 SSA's, combined by pairs

Refurbishment of the 180 kW SR SSA's

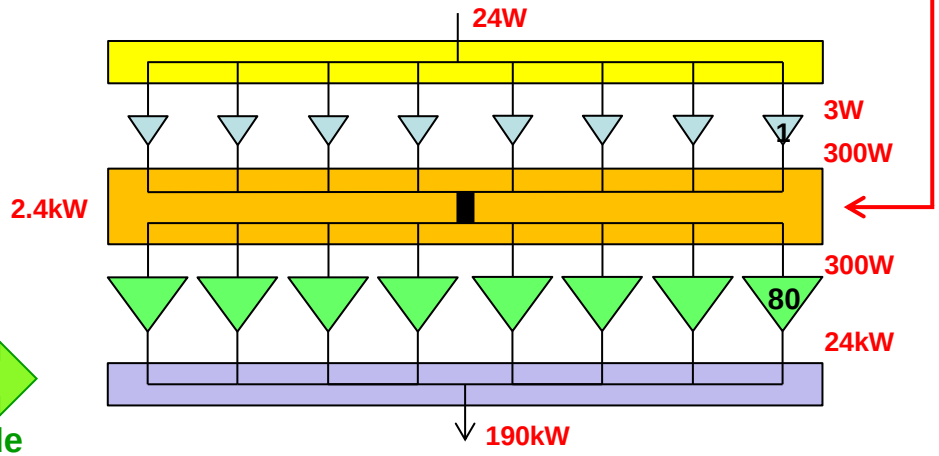


- **Excellent operational avaibility and MTBF, but still significant nb of module failures (2-3 % a year)**
  → Matter of maintenance (~ 5 k€ mat. + 3 men.week / year) ; not so bad but still perfectible
- **Low cost refurbishment : replace LR301 transistors (28 V) by BLF574XR (50 V) + « module retuning »**
  → Electrical power savings (efficiency : 50 % → 60%) compensate the investment cost in < 3 years
  + More robust transistor & lower thermal stress → much less module failures → less maintenance
  + Higher power capability (max P_{mod} : 310 W → 450 W) → 500 mA with only 3 running SSA's
  + 7 dB transistor gain → 160 pre-amp modules & their dc PS are got back for the new BO SSA
- **The four towers of Amplifier_1 have already been refurbished → go on at a rate of 2 towers a year**
- **Not a single failure of a « new » transistor until now (~ 2 years of operation)**
- **Cure the lack of redundancy in the pre-amplification stage → develop a "combiner-divider"**



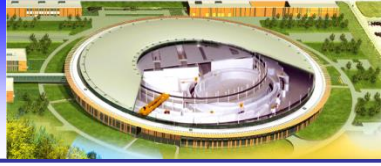
Present config : each pre-ampli drives 80 modules; if one of them fails the amplifier is stopped

Upgrade



Thanks to the **combiner-divider**, the failure of a pre-ampli does not affect the functioning anymore

Other activities on SSA's



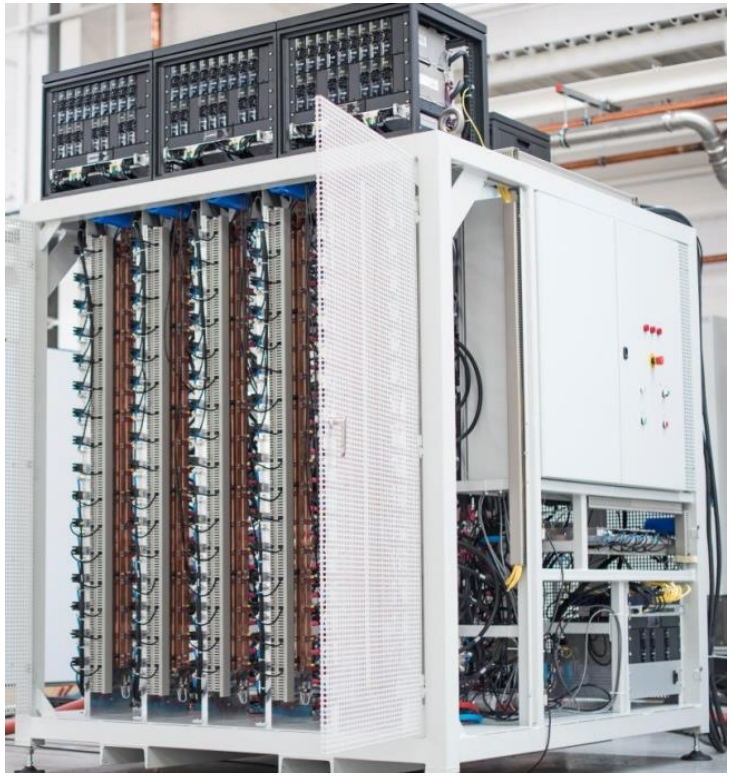
- **Collab. with LNLS (Brazil) → 2 x 50 kW SSA's @ 476 MHz** (400 W BLF574)
- **ESRF (transfer techno Elta) → 7 x 150 kW SSA's @ 352 MHz** (700 W BLF578)

} **Tower config. & dc/dc converters + rectifier**

- **500 MHz SSA's for ThomX * (50 kW) and SESAME † (80 kW)**
  - ✓ **Fully modular power supplies → redundancy & efficiency**
  - ✓ **Change from tower to cabinet configuration**
  - ✓ **Improved control → fully stand alone, self protected and more modular**

ThomX 50 kW SSA (6 x 16 modules)

SESAME 80 kW SSA (10 x 16 modules)

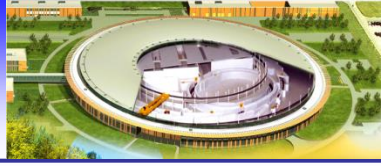


* Compton X-ray source under construction in Orsay - France

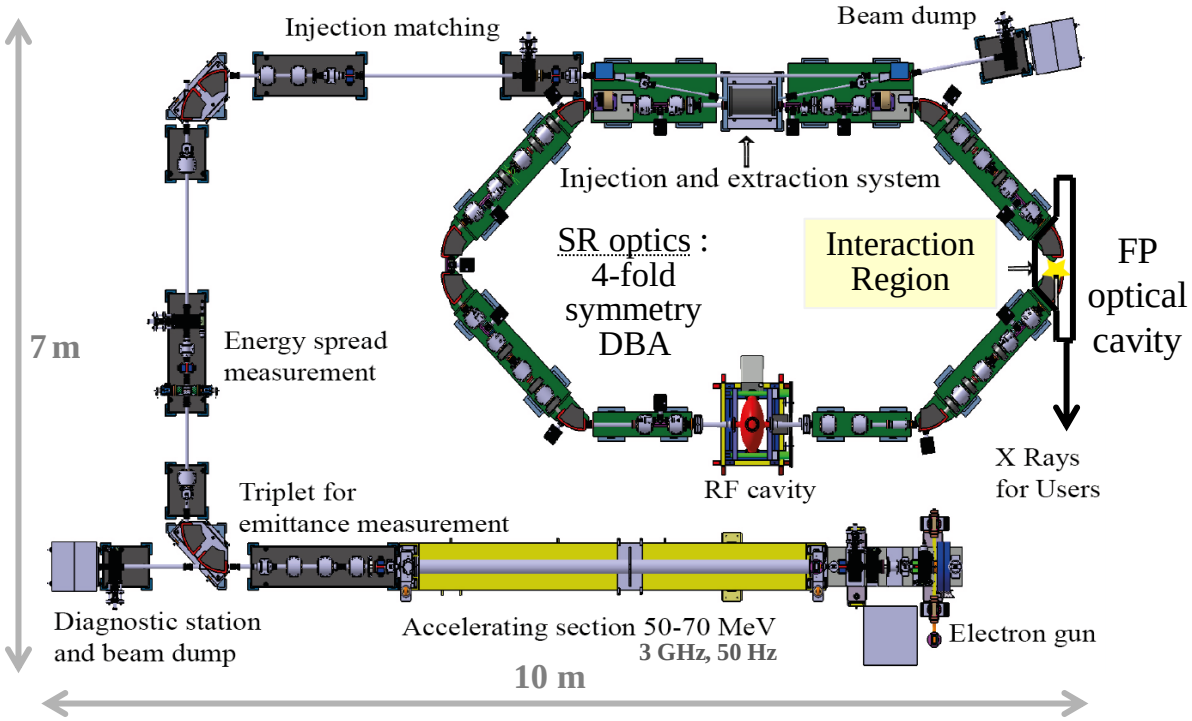
† Synchrotron light source under construction in Jordan

- **We've completed the ThomX and first SESAME SSA's**
- **3 other ones for SESAME are built by SigmaPhi Electronics (SPE), the SOLEIL licensee.**
- **Two of them are operational at SESAME, the other two will be commissioned beg. of next year**

Contribution to ThomX



Compact source of hard X-rays (40 - 90 keV), generated by Compton Back Scattering (CBS), which is under construction in Orsay - France (~ 5 km from SOLEIL)



Injection of a single e^- bunch (20 mA) at 50 Hz repetition rate, which collides at each turn with a laser pulse inside an optical cavity → X rays (10^{11}-10^{13} /s) from CBS ($\omega_{dif} \sim 4\,\gamma^2\,\omega_{laser}$)

Applications

- Medical sciences (imaging + therapy)
- Cultural heritage sciences (Louvre Museum, for instance)

→ **Compactness**

Work supported by the EQUIPEX program from the Research Ministry, Région Ile de France, CNRS-IN2P3 and University of Paris-Sud

Contributors:

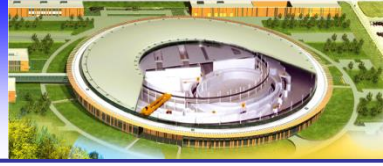
LAL-Orsay CNRS-IN2P3, SOLEIL, CELIA Bordeaux, ESRF, C2RMF-CNRS, UDIL-CNRS, INSERM Grenoble, Thales TED, Institute Neel Grenoble

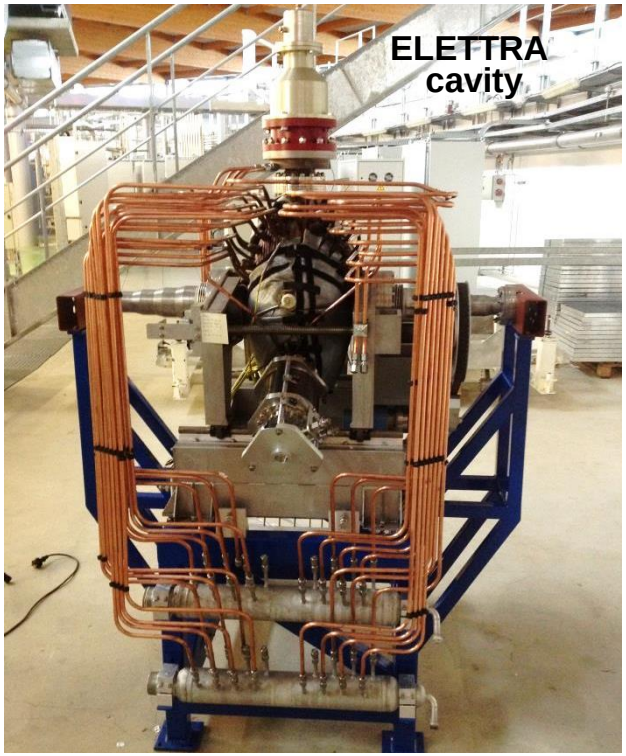
Project start : 2012

The SOLEIL RF group is in charge of :

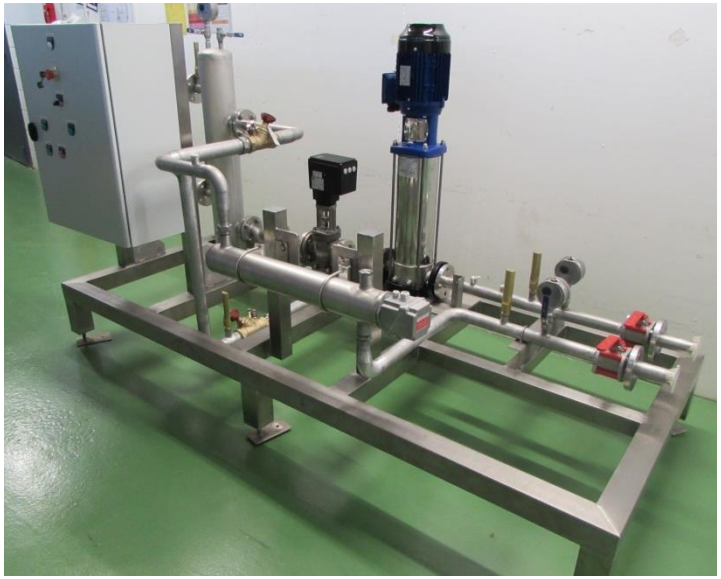
- the LINAC injector (50 - 70 MeV, 3 GHz, 50 Hz) → J.P. Pollina's talk
- the SR RF system

RF system for the ThomX SR

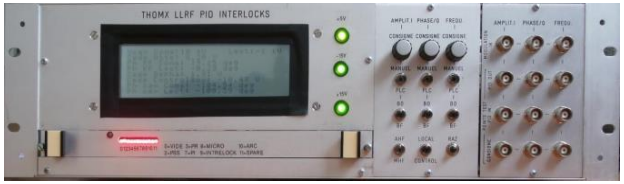




Cooling rack for HOM temperature tuning



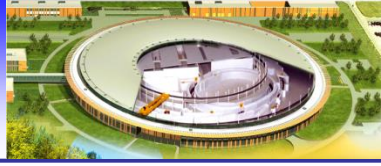
FPGA - based TFB acting on a 4 plates stripline (x, y)

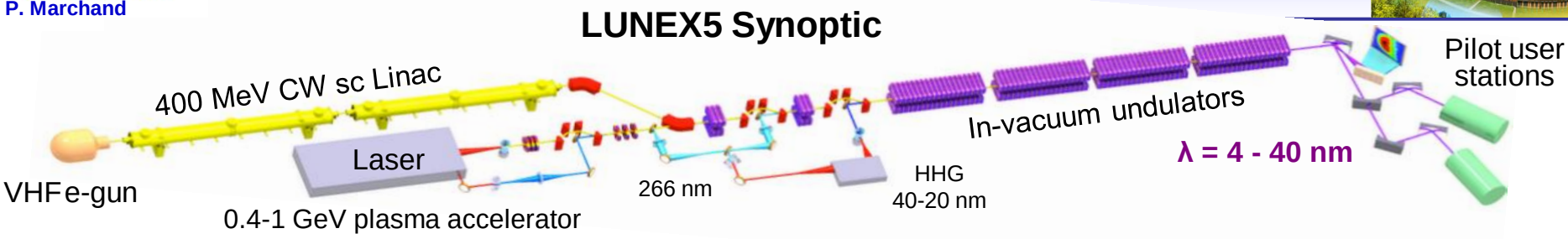


LLRF: conventional «slow» phase, amplitude and tuning loops + LFB = fast bunch phase feedback acting through the main cavity

Contribution to LUNEX5

P. Marchand





Phase 1 : based on a 400 MeV CW sc Linac → explore advanced FEL techniques and applications
Phase 2 : laser wakefield (or plasma) accelerator will be assessed in view of FEL applications

CDR end of 2011 → Green light from the SOLEIL Council for R&D program

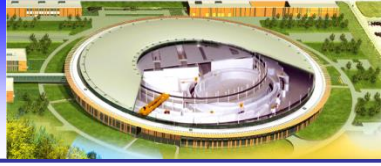
- **LUCRECE : program of R&D about RF technology for CW Linacs, with the aim to LUNEX5**

  It is coordinated by SOLEIL, involves the CEA and CNRS labs as well as industrial partners, Thales, Alsyom and SigmaPhi Electronics (SPE) ; partly financed by the Region Ile-de-France

  Objective : build an elementary (LUNEX5) RF assembly and test it in CryHoLab at CEA
  - **A 1.3 GHz - 20 kW CW SSPA, using GaN transistors *[SOLEIL, SPE]***
  - **A 1.3 GHz 9-cell sc cavity for CW operation, from the LCLS2 batch *[CEA, SOLEIL]***
  - **A TTF3 type coupler, upgraded for P > 20 kW CW *[CNRS-LAL, Thales, SOLEIL]***
  - **A digital LLRF system (10^{-4}, 0.01°), based on FPGA + CPLD + µC *[SOLEIL, CNRS-LAL]***
  - **Tests of the assembly at 2K and 1.8K in CryHoLab *[CEA, SOLEIL]***
  - **Cryomodule mechanical studies *[CEA, ALSYOM, SOLEIL]***
  - **Time schedule : 2015 → 2019**

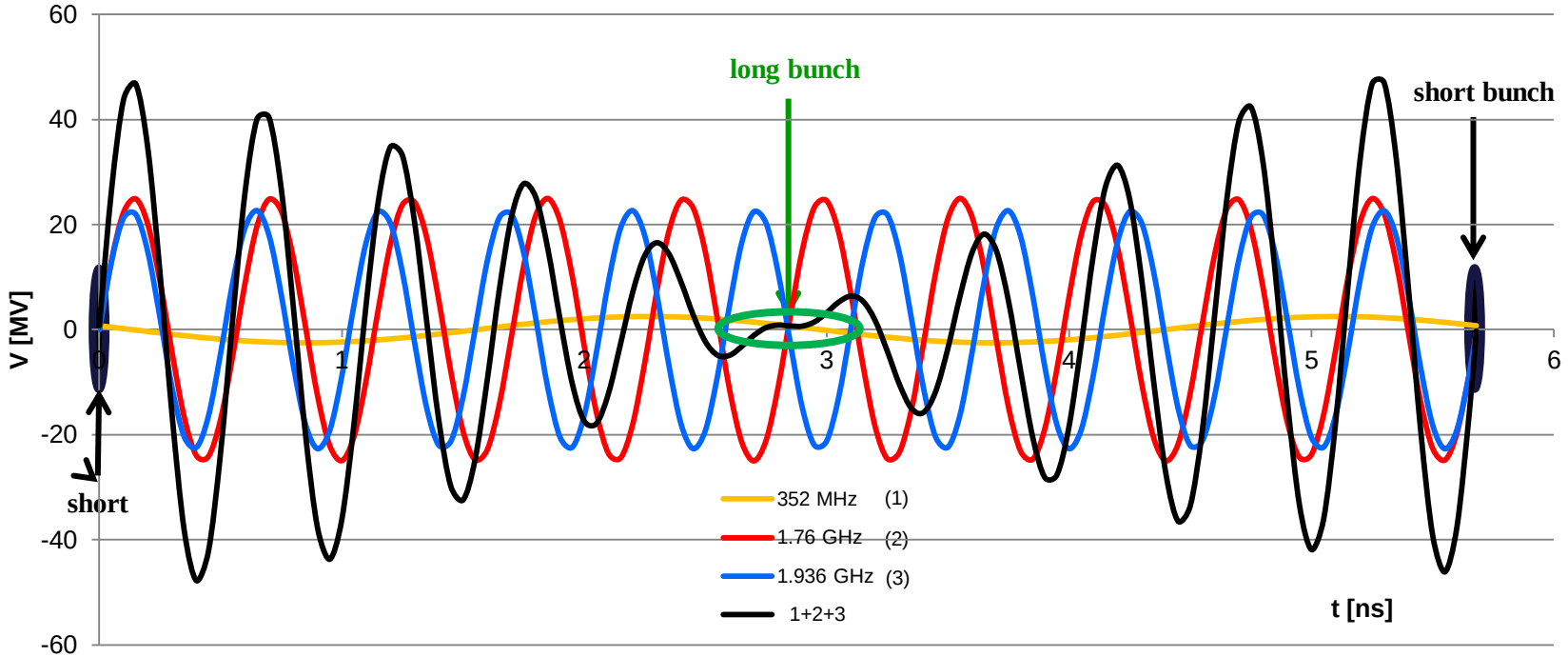
- **R&D on a VHF (186 MHz ?) photocathode e-gun for LUNEX5 → 2 x 60 kW SSPA's**
  To be launched soon

SOLEIL upgrade toward DLSR & VSR



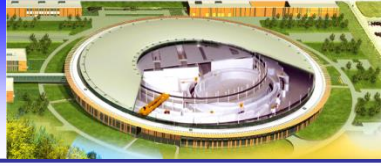
DLSR : 6 & 7 BA / cell lattice → ε ~ 200 pm

VSR : alternately long (10 ps) & short (1 ps) bunches along the train, obtained by adding 2 harmonic systems, $h_1 = 5$ and $h_2 = 5.5$



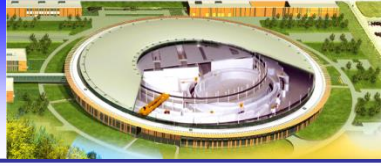
→ **Replace one of the actual 352 MHz CMs by another one containing a pair of sc cavities of each frequency, either passive or powered with 10 kW SSA's @ 1.76 and 1.94 GHz ?**

Summary - Conclusions



- The 352 MHz RF systems of SOLEIL are quite innovative with the use of HOM free sc cavities and SSA's, both developed in house. After ~ 10 years of operation they have demonstrated excellent reliability and flexibility with an overall downtime < 8 10^{-3}, in spite of a 12 day shutdown (~ 5 10^{-3}), caused by a failure of cryogenic system in 2016.
- The difficulties encountered with the sc cavity frequency tuners were quickly solved by improving the original tuning device.
- Cavity IPC's of higher power capability (300 kW) have been developed in collaboration with CERN and ESRF → 3 out of the 4 cavities are equipped with the new IPC's + bias voltage for coping with recalcitrant multipactor levels; the last one will be implemented beg. of 2017.
  Modifications of the waveguide network will give the possibility of combining 2 amplifiers and thus power each cavity of a CM with 300 kW → Storage of 500 mA using a single CM.
- A special emphasis is put on the success of the SSA's, developed by SOLEIL at 352 MHz; they have demonstrated that they can advantageously replace the vacuum tubes in such an application (extreme modularity, absence of HV, very low phase noise, …).
- R&D carried out at SOLEIL has allowed to improve the original 352 MHz design (more compact, improved reliability & efficiency) and extend it to other frequencies. It has now reached maturity, being adopted by many other facilities and taken up by the industry for applications ranging from 80 MHz up to 1.5 GHz. SigmaPhi Electronics is SOLEIL licensee since Dec. 2013.
- Contribution to other projects :
  - SSA's for other labs : LNLS, ESRF, SESAME
  - ThomX : SR RF system and LINAC injector (J.P. Pollina)
  - LUCRECE : 1.3 GHz RF technology for CW Linac → LUNEX5
  - VHF photocathode e-gun for LUNEX5
  - SOLEIL upgrade toward « DLVSR » → SC harmonic RF, 1.75 GHz & 1.94 GHz

Acknowledgements



SOLEIL RF and LINAC group


Robert LOPES


Jean-Pierre POLLINA


Massamba DIOP


Patrick MARCHAND


Rajesh SREEDHARAN


Fernand RIBEIRO


Marc LOUVET


Julien SALVIA


Cyril MONNOT


Renaud CUOQ


Helder A. DIAS


Jean-Pierre BAETE


Jocelyn LABELLE


Sylvain PETIT

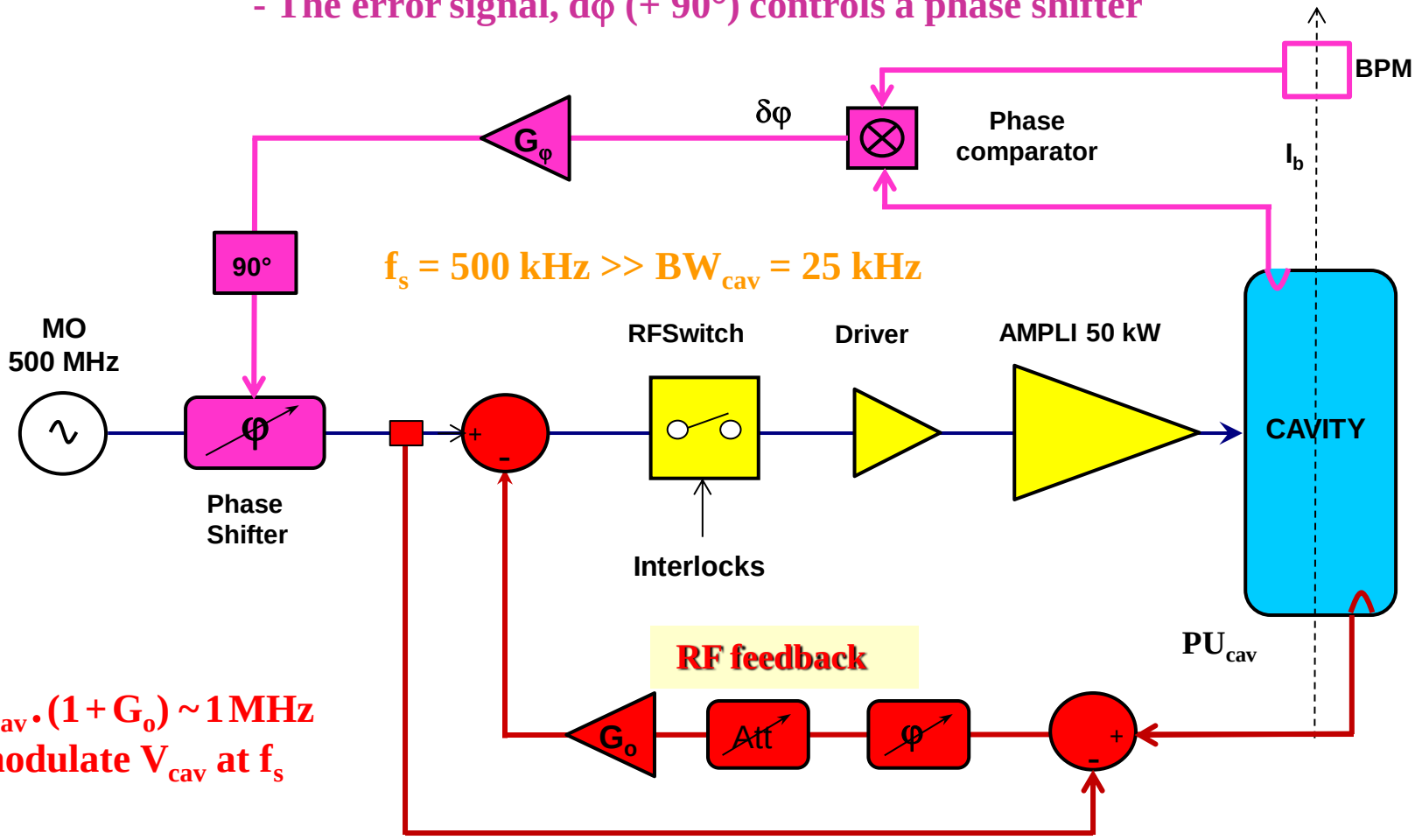
Many thanks also to all the members of CERN and ESRF who were involved in the fabrication and/or tests of the new IPC's and to SIGMAPHI ELECTRONICS, our industrial partner in the SSPA domain.

Back up - ThomX longitudinal feedback (LFB)

LFB = direct RF FB + Phase loop

Phase loop (BW > f_s) :

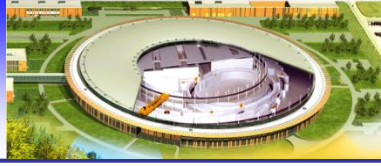
- Phase comparison between V_c (PU cav) & I_b (BPM)
- The error signal, dφ (+ 90°) controls a phase shifter



RF FB → $BW_{cav} \cdot (1 + G_o) \sim 1$MHz

→ One can modulate V_{cav} at f_s

Back up - LLRF LUCRECE / LUNEX5



MO CW

1,3 GHz

Ultra High Phase Stability Cable

Vector Modulator

I

Q

SSA

Waveguide

Forward

Reverse

1,3 GHz Cavity

1,3 GHz Field probe

Field stability
Phase : 0,01°
Amplitude : 10^{-4}

Ultra High Phase Stability Cable

1,3 GHz

Tuning

Piezo

1,3 GHz + IF

1,3 GHz + IF

1,3 GHz + IF

1,3 GHz + IF

1,3 GHz + IF

DAC

DAC

ADC

ADC

ADC

ADC

DAC

DAC

IF

Clock
F = 4 x IF

IF

Clock
F = 4 x IF

IF

Clock
F = 4 x IF

IF

Clock
F = 4 x IF

Timing

Démodulation IQ

V_I V_Q

S_I

S_Q

ε_I

ε_Q

Feedforward

H(Z)

Setpoint

LLRF

FPGA + µC + CPLD