Collective Effects at SOLEIL

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1. Introduction

SOLEIL is the French synchrotron light source storage ring commissioned in 2006 and operating for users since 2007.

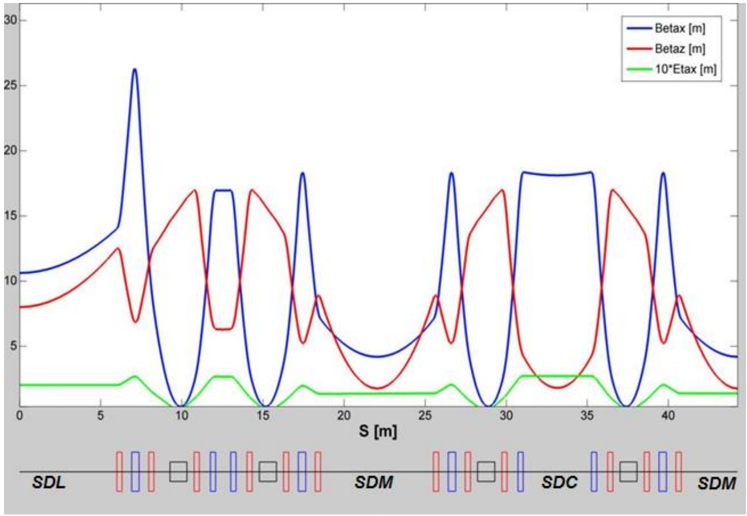
It may be characterised by its diverse modes of operation delivering high beam current in both multibunch and single bunch.

Energy [GeV]	2.75
Circumference [m]	354.1
Horizontal emittance [nm·rad]	3.9
Adjusted emittance coupling [%]	1
Betatron tunes	(18.17, 10.23)
Synchrotron tune	0.0048
Momentum compaction α	4.38×10^{-4}
Revolution frequency [kHz]	846.6
RF frequency [MHz]	352.2
RF voltage [MV]	2.4 - 4
Harmonic number	416
Radiation damping times [ms] ($\tau_x/\tau_z/\tau_s$)	(6.9/6.9/3.4)

Main machine parameters

Modes of Operation	Descriptions
Multibunch Uniform	I_{tot} = 500 mA
Multibunch Hybrid	I_{tot} = 450 mA (3/4 filling + 1×5 mA bunch)
8-bunch	Symmetric filling of 8×12.5 mA = 100 mA
1-bunch	1×16 mA bunch
Low alpha (α/25 and α/100)	2/4 filling (100 μA/bunch) + 1×60 μA
Femto-Slicing	A few μA at laser repetition of 1-5 kHz

6 modes of operation provided to users



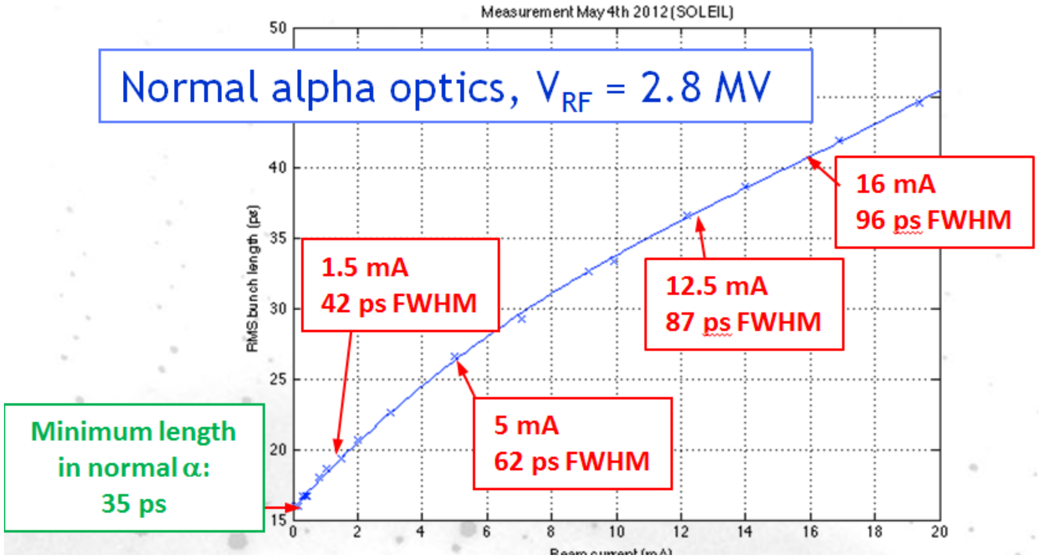
1/8th of the ring

- Ring is composed of 16 DB (Double Bend) cells
- Half of DB cells incorporate 3.8 m long short straight sections in between dipoles
- There are 24 free straight sections, consisting of 4×12 m (*SDL*), 12×7 m (*SDM*) and 8×3.8 m (*SDC*), representing ~45% of the circumference
- Two units of **HOM-free** superconducting RF cavities installed in two SDM sections

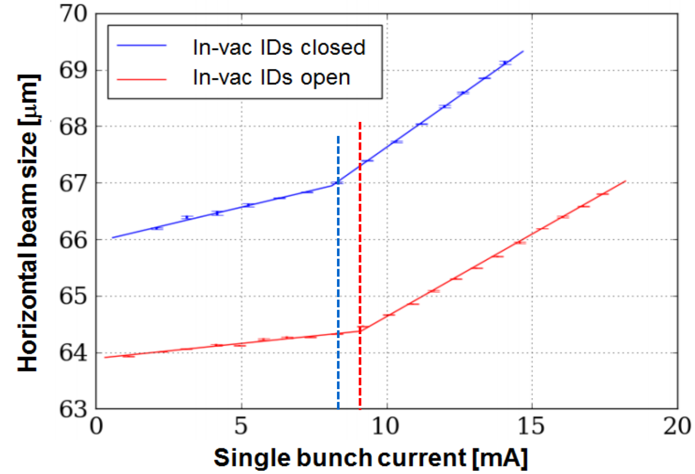
- Vacuum chambers are mostly in aluminium and **nearly half** of them **NEG coated**
- Ring is composed of flat and low gap chambers. Full apertures in [mm]: Standard chambers (70×25), SDL (56×14), SDM (46×10), and in-vacuum IDs installed in SDCs
- There are altogether **9 in-vacuum IDs** installed, whose gaps can be closed down to 5.5 mm
- There are **three** transverse bunch-by-bunch feedback (TFB) systems installed. Two are used in vertical and one in horizontal.
- Basic beam instability mitigation methods applied:
  - TFB
  - Chromaticities
  - Lowering of the RF voltage

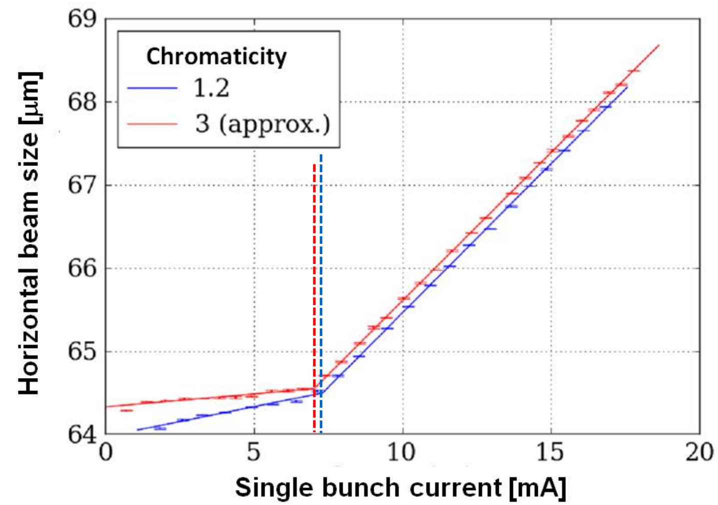
2. Longitudinal instabilities

- Standard momentum compaction α regime



Bunch length versus current
(*Courtesy M.-A. Tordeux*)

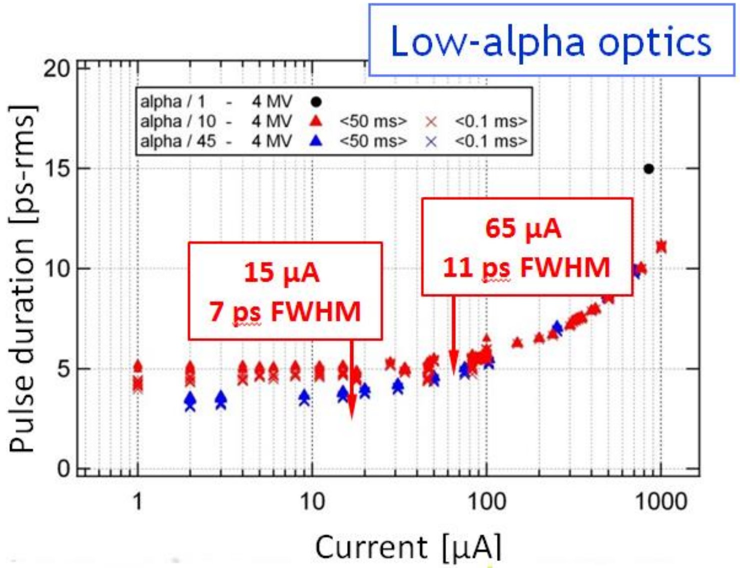




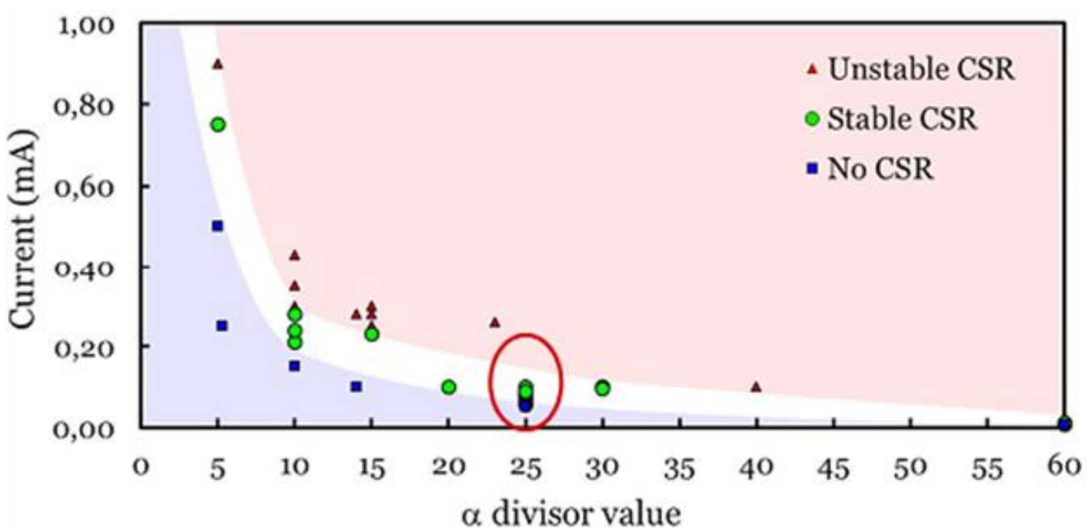
- As expected, no HOM-driven coupled-bunch instability yet observed

Detection of microwave instability threshold from horizontal beam size measurement. With machine impedance, no microwave threshold expected up to ~20 mA.

• Low momentum-compaction α regime

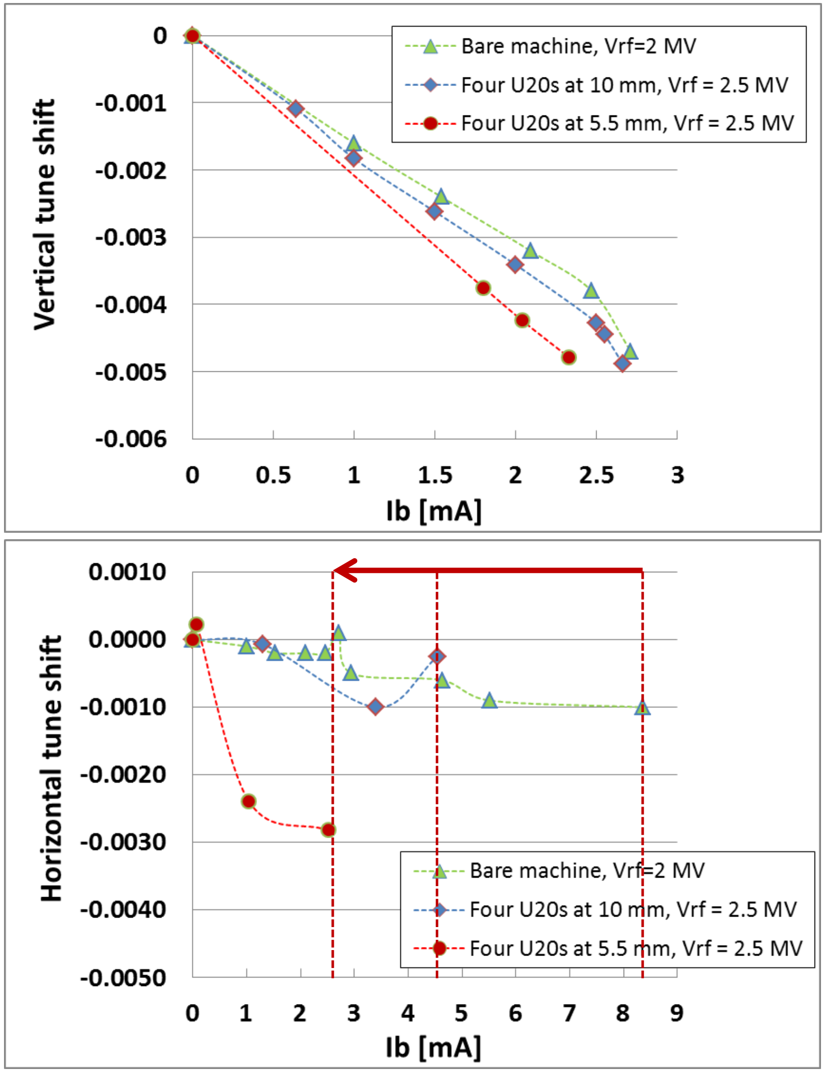


Measured bunch length versus current (above) and CSR-induced bursting threshold versus α (below) (Courtesy M.-A. Tordeux)

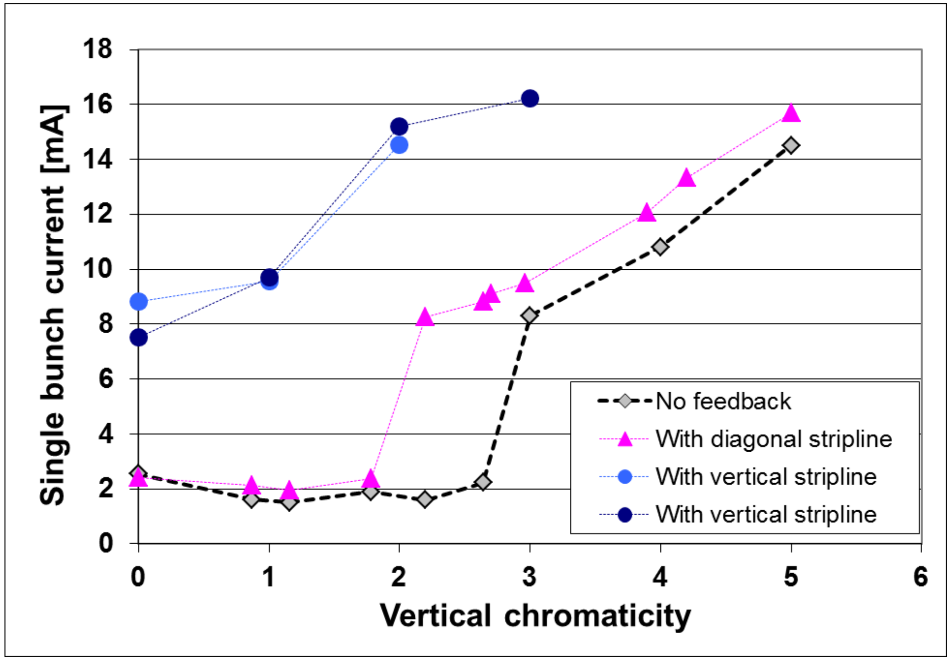


→ More detailed studies in the talk by S. Bielawski (PhLAM)

3. Transverse (impedance-induced) instabilities

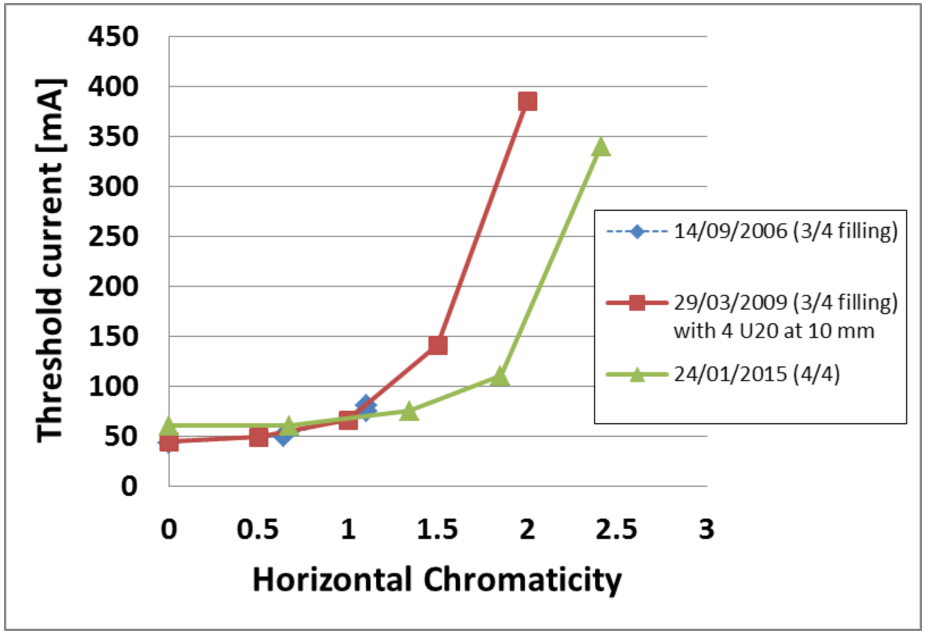


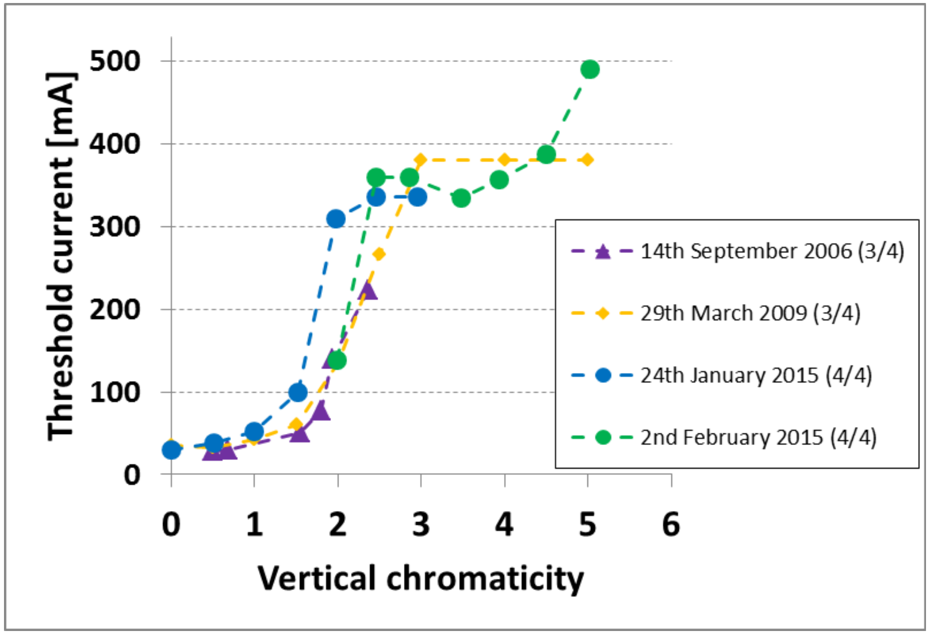
Mode 0 detuning and TMCI thresholds at zero chromaticity



Vertical single bunch threshold versus chromaticity, with and without TFB

◊ Measured resistive-wall threshold versus chromaticity in multibunch fillings





- RW thresholds measured over ~10 years tend to remain sufficiently constant
- In the V plane, the transitions from head-tail mode m=0 to m=-1 and -2 are seen, while m=0 dominates in H in the range up to 500 mA
- With chromaticity of ~1 and TFB running in both planes, the beam can be stabilised against resistive-wall instabilities without difficulties up to the maximum current of 500 mA

4. Other collective effects

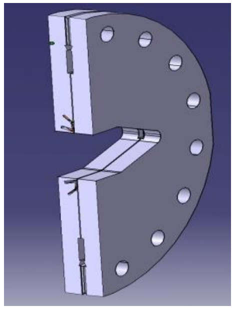
◊ **Incoherent betatron tune shifts due to flat vacuum chambers** → A dedicated talk later on

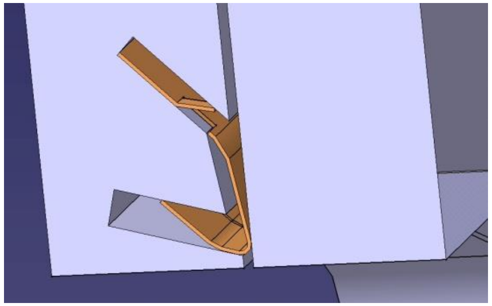
◊ **Beam-induced heating of vacuum elements**

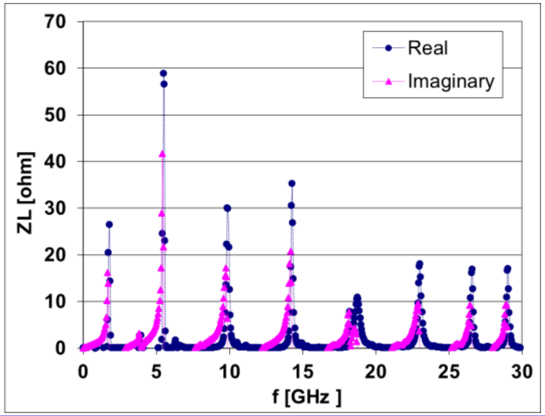
- Particularly a problem in 8-bunch (100 mA) and hybrid (450 mA) modes.
- Often resulting in damages of some specific vacuum elements, beam-induced heating is a serious issue in the daily operation.

A melted RF finger

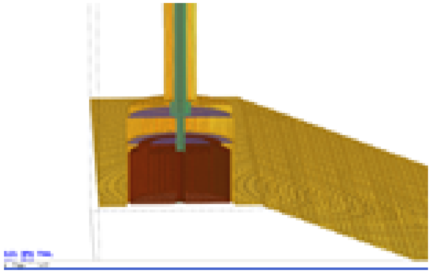
- **Flanges**

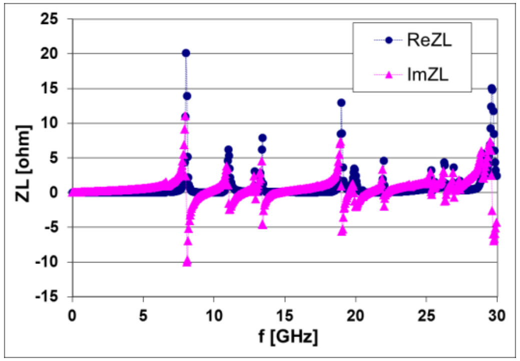






- **BPMs**

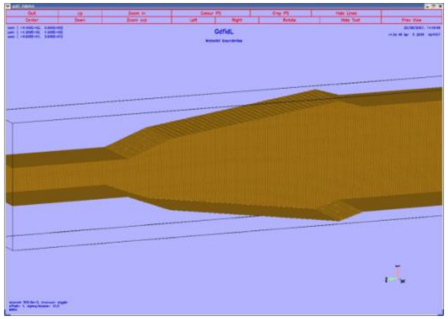


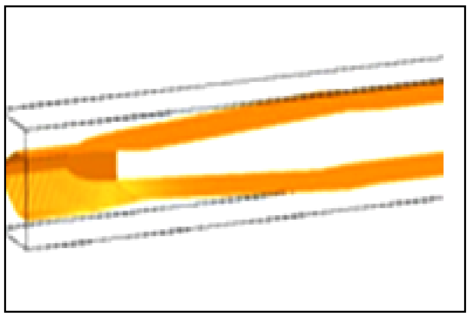


- RF Shielding foil helps drastically suppress the flange impedance, but its possible mis-positioning may induce serious heating.

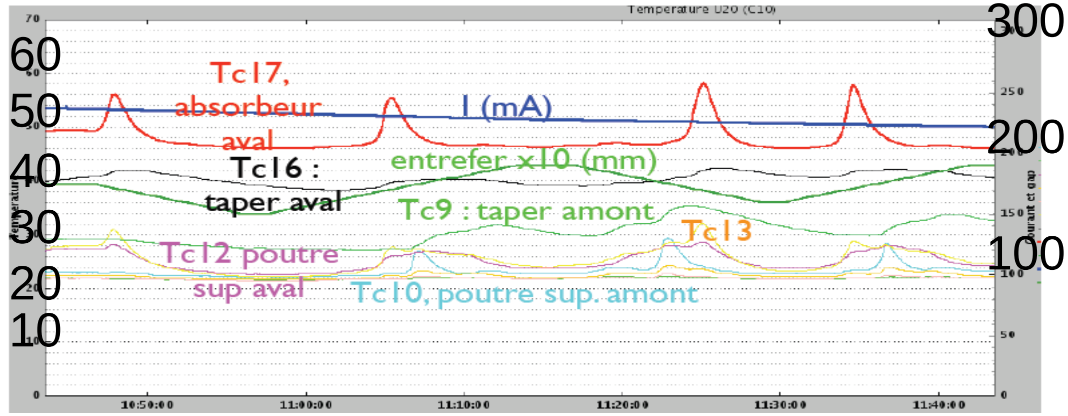
- Malfunctioning of BPM button electrodes encountered are likely due to the heating due to the trapped mode at ~8 GHz.

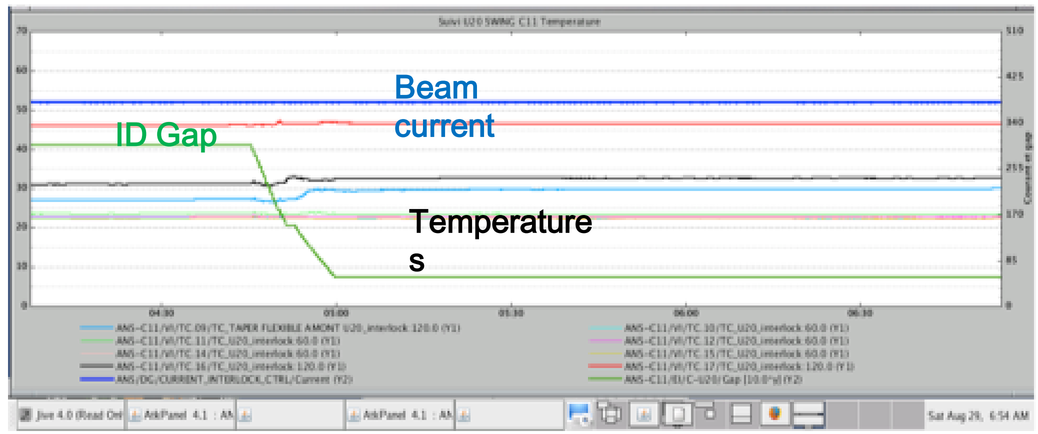
• In-vacuum ID tapers





In-vacuum taper structure: Initial (above). Improved (below)



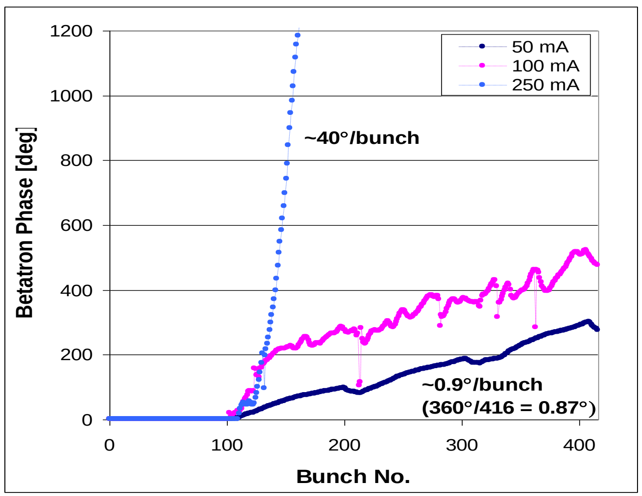


Monitoring of heating in a taper with the 1st design (above) and absence of heating with the improved design (below)

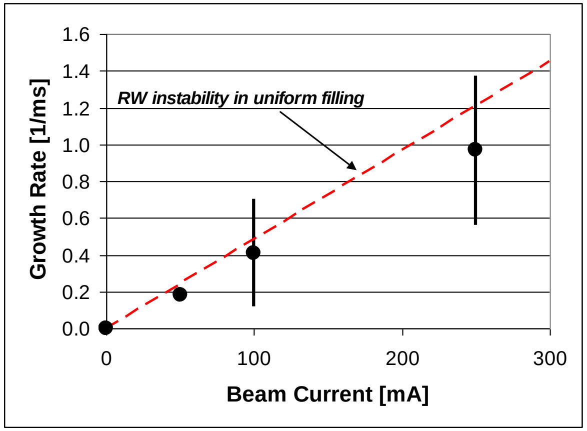
- Initial tapers creating a cavity structure when the ID gap was opened had a serious problem of beam-induced heating → Had to be taken out and be replaced.
- New tapers greatly improved the heating issues. They could still occasionally exhibit heating problems when their expected movements are affected by mechanical defects.

5. Fast Beam-Ion Instability

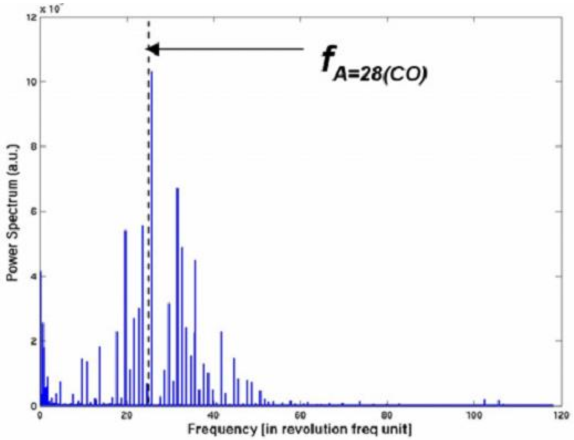
- FBII existed since the beginning of the operation at SOLEIL and yet remains to be the one that we do not manage to overcome completely today
- The common symptom of the instability: Sudden beam excitations or losses even if its intensity was kept constant (i.e. during stationary states)
- The instability is enhanced; - At high total beam current, - With relatively high RF voltage, - With low chromaticities
- We know today that TFB is one of the causes of the beam losses, which however, is indispensable in stabilising the beam against RW instability



Clear transition detected in betatron phase difference between adjacent bunches



Measured vertical growth rate averaged over all bunches versus beam current



Beam spectrum deduced from bunch-by-bunch data

- Associated with this instability, there are usually local pressure bursts. However, we cannot identify whether they were the origins or consequences.
- With vacuum conditioning, the critical beam current progressively got higher, but does not seem to exceed 500 mA in partial fillings.

To suppress FBII, different beam fillings were experimentally tried:

n_b: Number of bunches
i_b: Bunch current

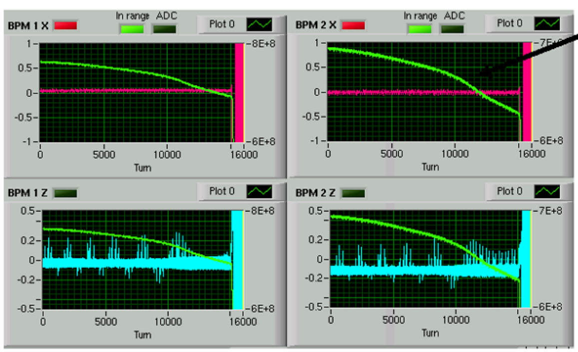
Two opposing effects:

- FBII growth rate that scales as $n_b^{\,2} \cdot i_b^{\,3/2}$
- Beam-induced heating that scales as $n_b \cdot i_b^{\,2}$

	Filling modes	Uniform	13*(25 bunches+7 empty)	3/4th	8*(32 bunches+21 empty)
Number of bunches	nb	416	325	312	256
Number of empty buckets	h - nb	0	91	104	160
Bunch current [mA]	ib	1.20	1.54	1.60	1.95
Beam induced power	nb*(ib)^2	**601.0**	769.2	801.3	**976.6**
(tau-1)FBII	(nb)^2*(ib)^1.5	**2.28E+05**	2.02E+05	1.97E+05	**1.79E+05**

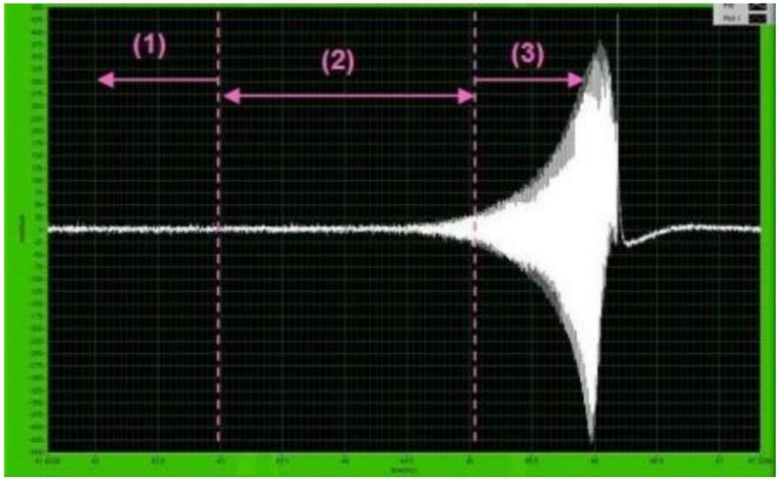
- Beam filling with lower bunch current gives better stability → Uniform filling
- In addition, lowering of V_{RF} (i.e. bunch lengthening) gave a significant stabilization effect

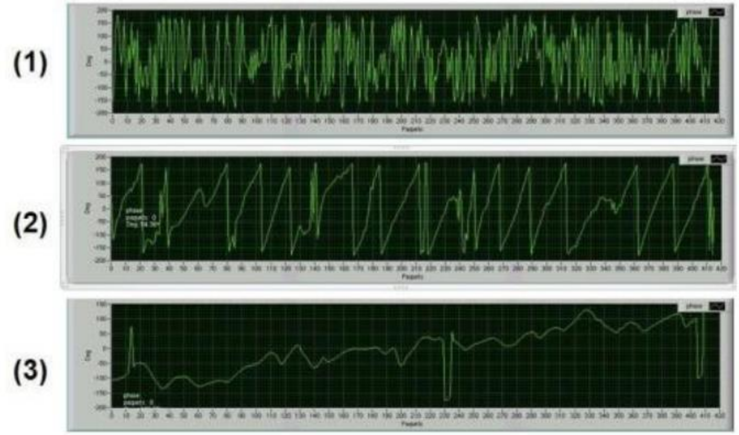
Beam current



Turn-by-turn diagnostics

- Sudden beam losses due to ions was puzzling
  ⇒ Turned out to be due to beam scraping that triggers the RF interlock (due to reflected power)





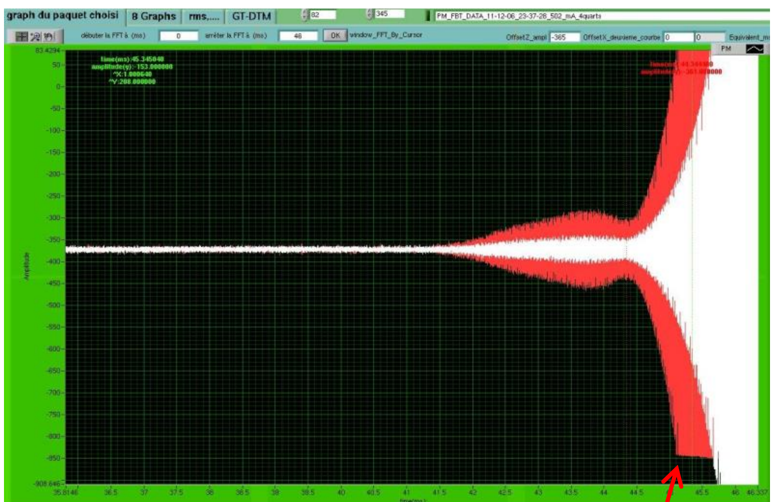
No phase correlation

Ion regime

RW regime

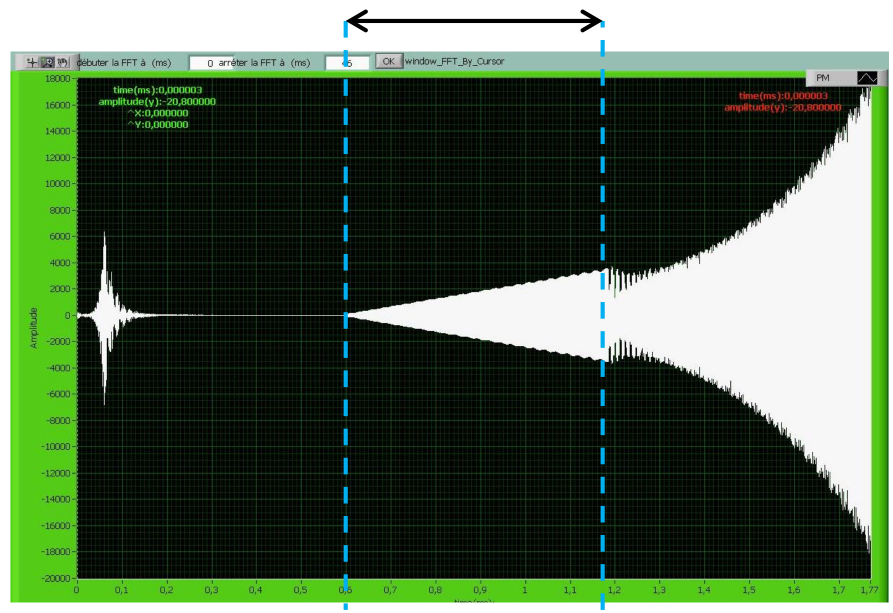
Post-mortem analysis reveals that the beam blows up finally in the resistive-wall (RW) regime

→ **Big question**: Why TFB fails to keep the beam stable in the RW regime?



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

feedback saturation



Simulation: RW with temporal "shaker" excitation at F_{ion}

6. Summary

- With low-gap chambers all around the ring and in-vacuum IDs (9), along with the modes of operation involving both high total current (500 mA) and high bunch current, SOLEIL experiences quite a few collective effects and instabilities
- However, most are well understood and controlled, especially resistive-wall and head-tail instabilities
- Microwave threshold is fortunately well above the bunch current in multibunch modes in the standard optics
- Beam-induced heating may be said to be the most critical collective effect issue impacting the daily machine operation
- FBII due to beam-induced heating prevents us from achieving the ultimate goal of 500 mA in the hybrid mode