Observations and Analysis of Fast Beam-Ion Instabilities at SOLEIL

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R. Nagaoka , on behalf of the instability and transverse feedback team,
Synchrotron SOLEIL, Gif-sur-Yvette, France

Content:

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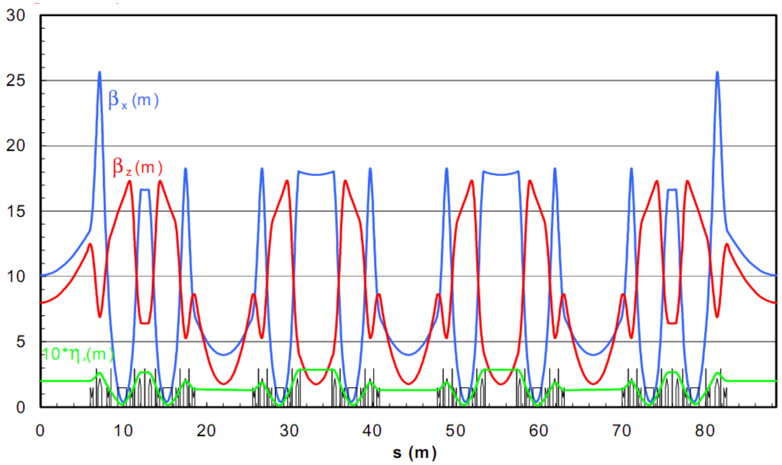
C. Herbeaux, A. Bence, J.M. Filhol, L. Cassinari, M. Diop, M.P. Level, C. Mariette, R. Sreedharan, A. Loulergue, N. Béchu, M. Labat, M.E. Couprie, A. Nadji and other Machine Physics group colleagues, A. Rodriguez (student), V. Krakowski (student), Ph. Martinez and the SOLEIL Operation group members, …

1. Introduction

- SOLEIL is the French third generation light source ring commissioned in 2006 and running its user operation since 2007.

- SOLEIL can be characterized by its small emittance, high beam current, accommodation of many insertion devices and excellent stability.

Energy [GeV]	2.75
Circumference [m]	354.097
(Operating current)*present* [mA]	400, 8 10, 1×12
RF frequency [MHz]	352.2
Harmonic number *h*	416
Betatron tunes Q_H/Q_V	18.2/10.3
Momentum compaction α	4.38×10^{-4}
Emittance $\varepsilon_H/\varepsilon_V$	3.74 nm/38 pm
(Transverse beam size)*typical* σ_H/σ_V	200 μm/17 μm
(Bunch length)*2.8MV* σ_τ [ps]	17.0
Radiation damping times [ms] $\tau_H/\tau_V/\tau_L$	6.56/6.56/3.27



Some other machine characteristics:

- Aims to achieve high average (500 mA)/bunch current (1×15 mA, 8×12.5 mA)
- Choice of relatively small vertical aperture (b = 12.5 mm) for the standard chamber
- About half of the ring NEG coated (Al vessels)
- Presence of many in-vacuum IDs [presently 7, (full gap)$_{min}$ = 5.5 mm]

Basic ion effects expected for SOLEIL:

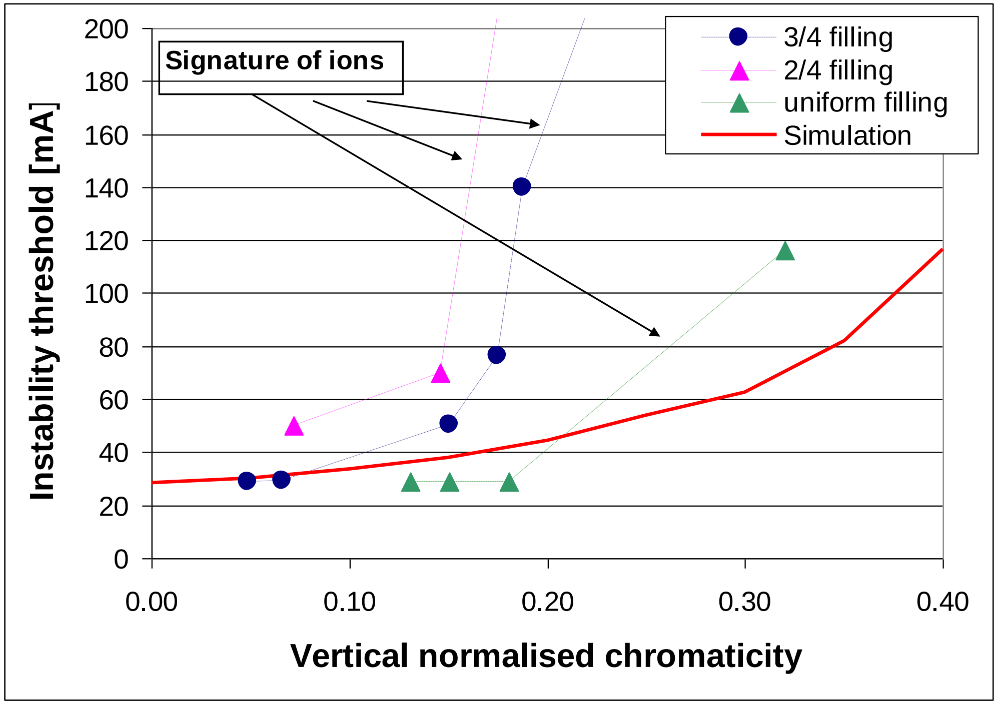
- Ion trapping: Critical mass $$A_c = \frac{N_b r_p \pi R}{n_b \sigma_y (\sigma_x + \sigma_y)}$$ = 1.3 at 500 mA

- Fast Beam Ion Instability (FBII)

$$\tau^{-1}_{aymp,e^-}(s^{-1}) \approx \frac{N_b^{3/2} n_b^2}{\gamma} \times \left[5 p_{gas}(\mathrm{Torr}) \frac{\beta_y r_e r_p^{1/2} L_{sep}^{1/2} c}{\sigma_y^{3/2} (\sigma_x + \sigma_y)^{3/2} A^{1/2}} \right]$$ = several μs at 500 mA

◊ Ion instability is being an important issue at SOLEIL, as it apparently prevents us from running the machine at 500 mA with zero chromaticity and a high RF voltage (i.e. the general conditions to improve the beam lifetime).

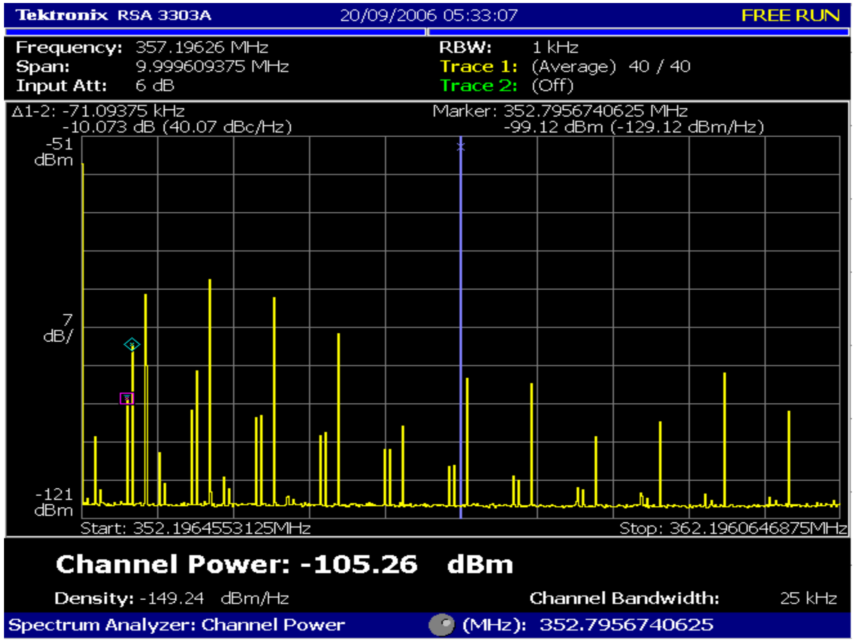
2. Early Observations

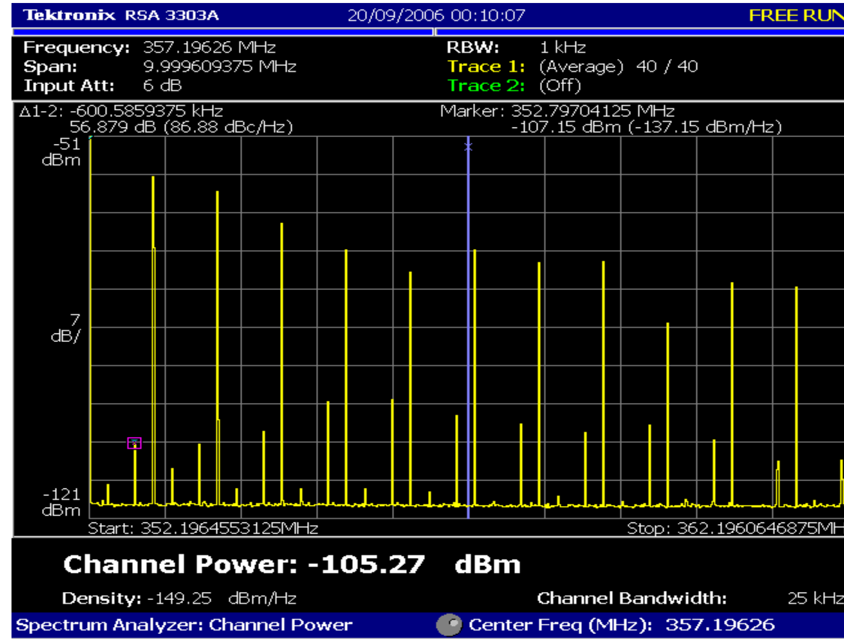


(*Measured when the beam dose was ~20 A·h*)

- Mixture of RW and ions induced instabilities in both V & H planes
- Large dependence of ion-induced instability on the beam filling
- Appearance of instability at current much lower than expected (& non-reproducible)

- Characterization of instability in terms of beam spectra





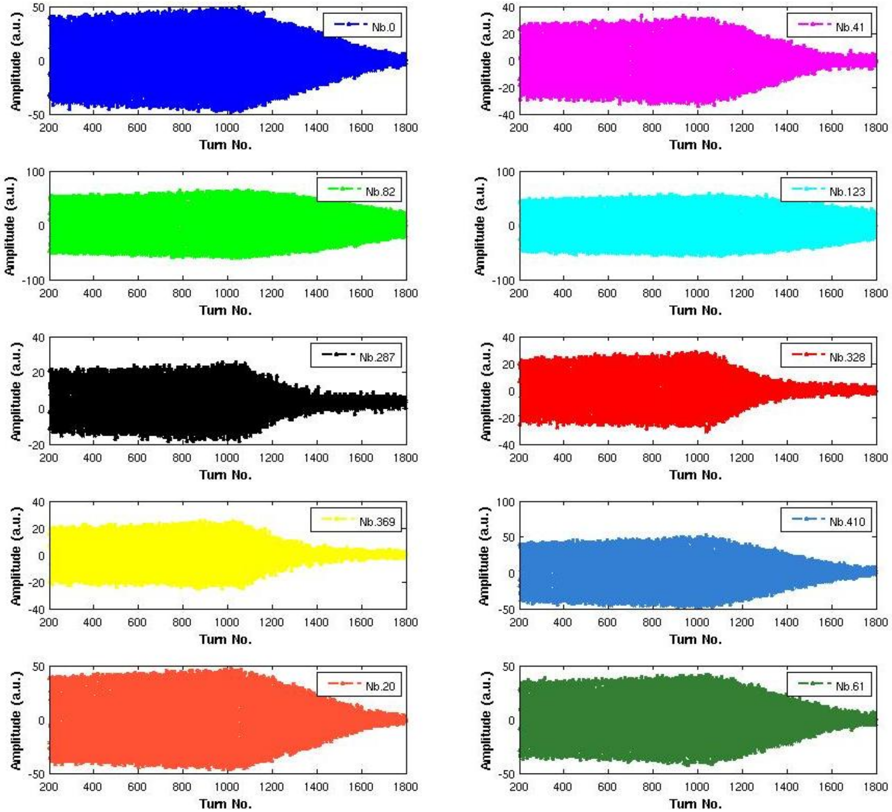
"Resistive-wall (RW) dominated"

"Ion-induced dominated"

(Observations in ¾ filling)

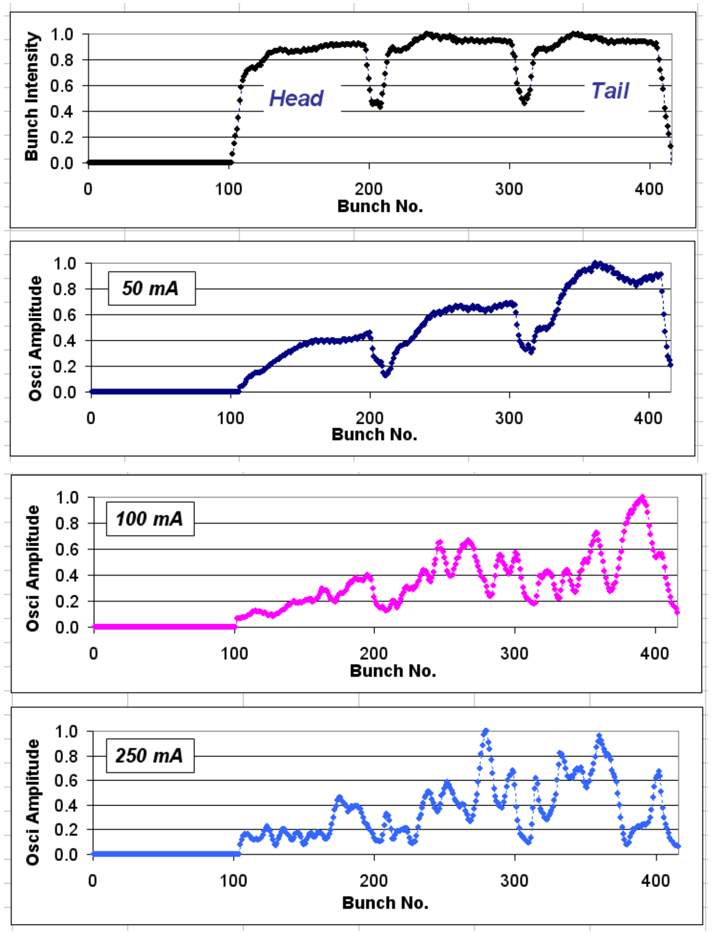
◊ Analysis using the Transverse Feedback (TFB) and its ADC data:

- TFB is switched off temporarily over *several milliseconds* to let the beam blow up naturally and follow the instability, bunch by bunch.



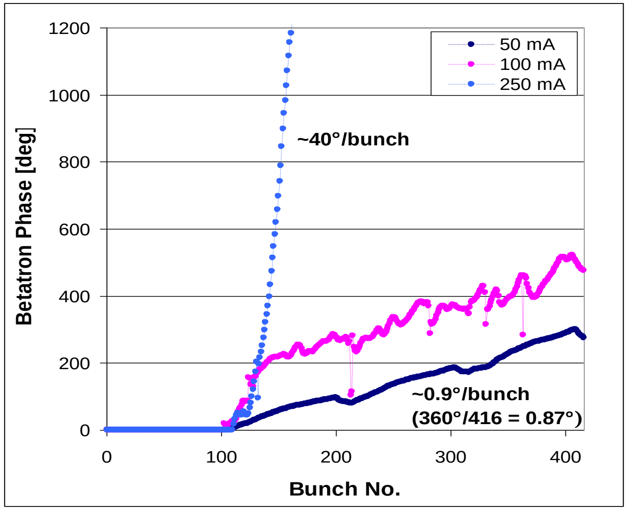
Observed evolution of oscillation amplitudes of different bunches

- Example of ADC data analysis in 3/4th filling: (June 2007)

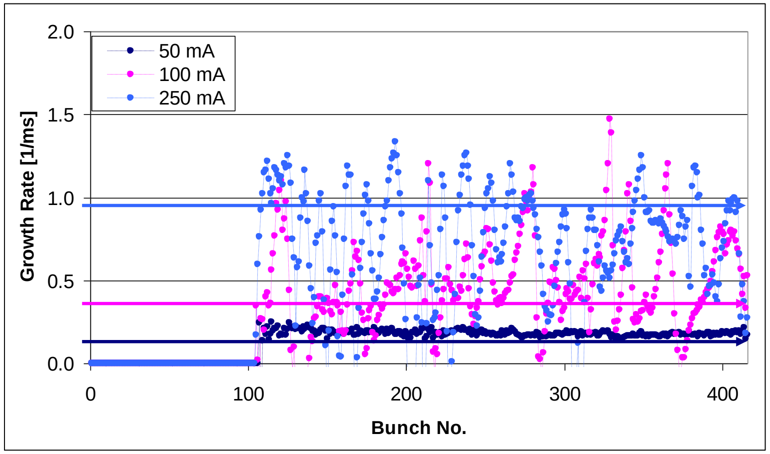


Top: Bunch intensity distribution

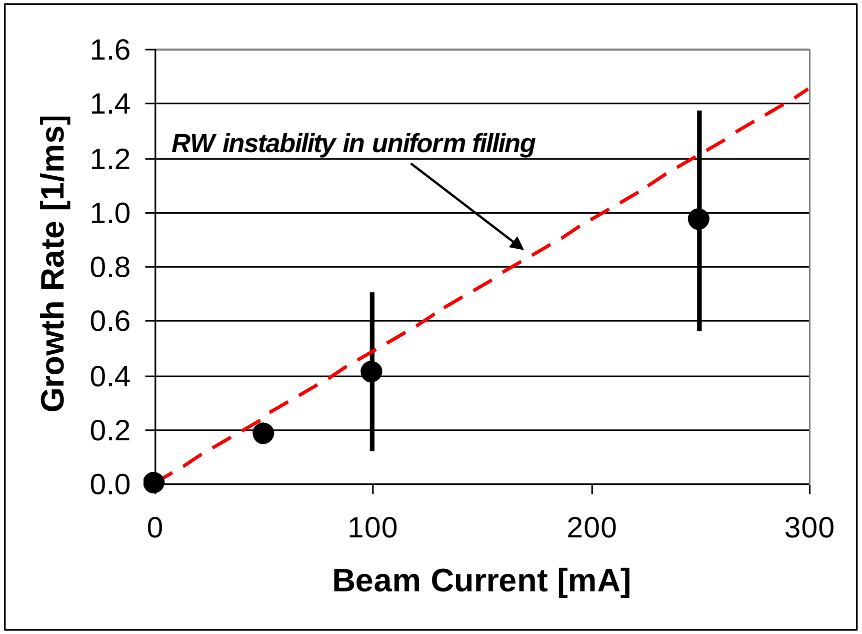
Lower 3: Oscillation amplitude distribution



Evolution of the betatron phase along the bunch train



Fitted growth rate along the bunch train



- The « turn by turn » nature observed clearly indicates that the ion instabilities are of the type « ***Fast Beam Ion Instability*** (*FBII*) ».

- A transition of instability from « *RW* » to « *FBII* » is observed at around 100 mA both in the amplitude distribution and the betatron phase advance.

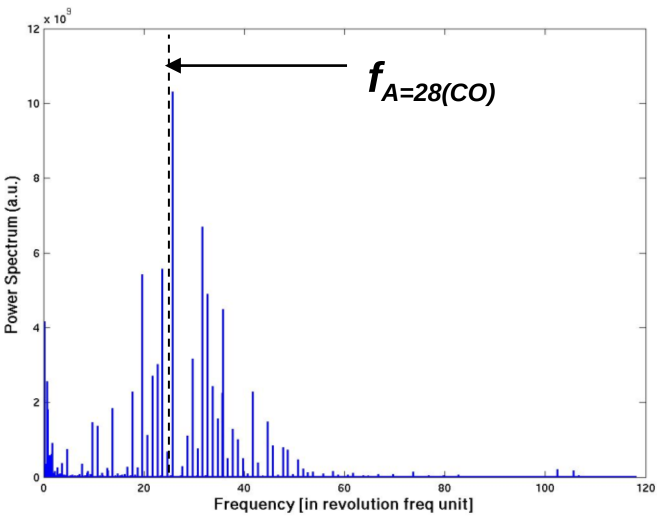
- The growth rate averaged over the beam nevertheless follows that predicted for « RW ».

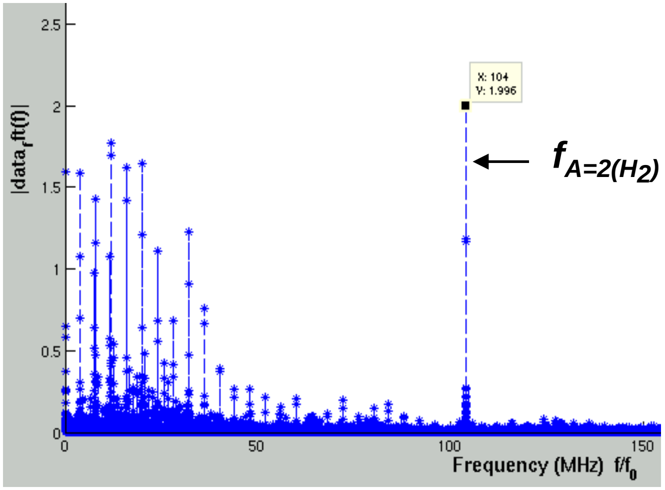
◊ Observation of ion frequencies on the beam spectra (from the ADC data)

An electron beam interacting with ions having an oscillation frequency f_i would exhibit in its spectrum, an envelope proportional to

$$\left|\frac{\sin 2\pi(f \pm f_i)T_0}{2\pi(f \pm f_i)T_0}\right| \qquad \text{with } f_i \text{ given by} \qquad f_i = \frac{c}{2\pi}\left[\frac{2N_b r_p}{A s_b \sigma_x \sigma_y}\right]^{1/2}$$

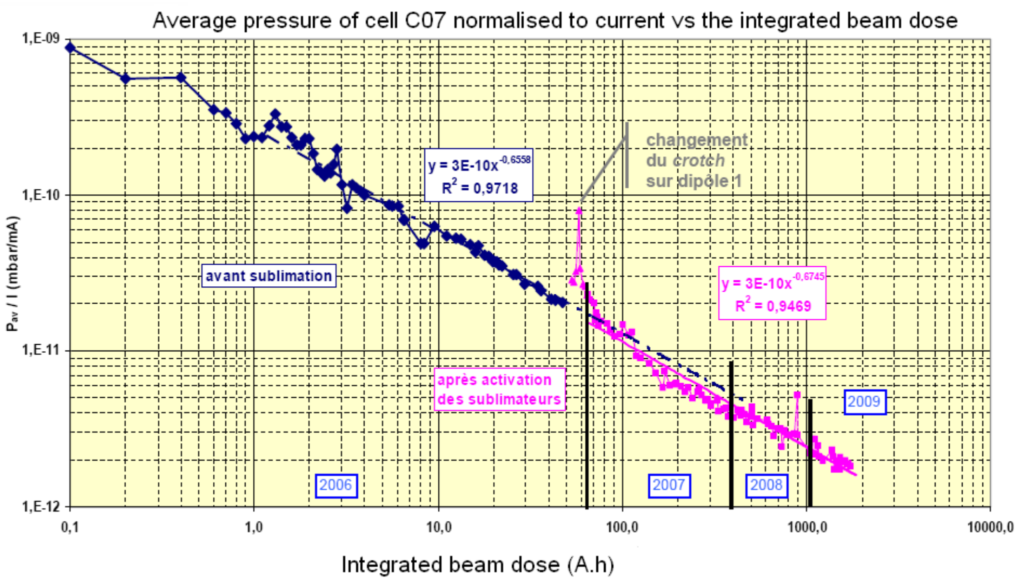
(*G. Stupakov and S. Heifets*)

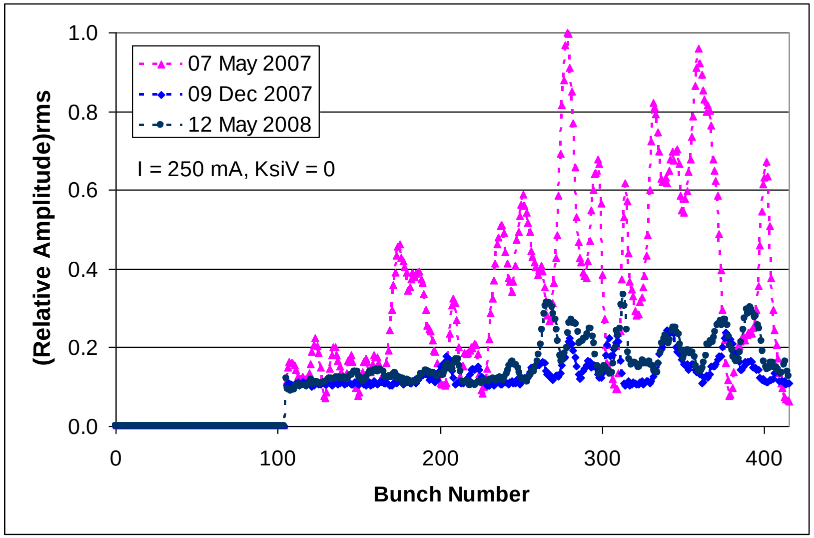




Ion frequencies observed in the ADC data

◊ Evolution of ion-induced instabilities with the improvement of the vacuum level





Courtesy C. Herbeaux

- Instability growth measurement under the same condition shows much less ion-induced beam blow up as compared to earlier times.

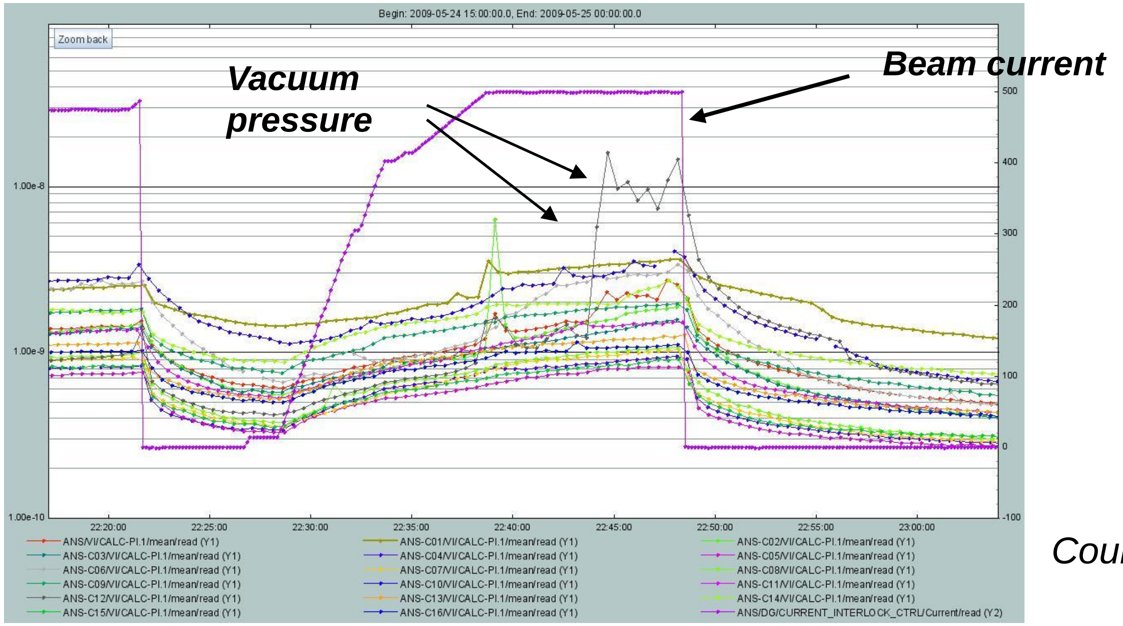
- Beam began to behave more « *monochromatically* » against feedback interruptions. (i.e. Difficult to keep the beam blown up without losing it)

3. Up to Achieving the Final Goal of a Stable 500 mA Beam

- In reaching high beam current (> 400 mA), TFB manages to keep the beam stable at its nominal size, but frequently the beam gets lost completely after ~10 minutes.

- In many of such cases, we saw local vacuum pressure bursts prior to beam losses.

- Pinhole images and Post-mortem data indicated that the beam gets lost vertically with signature of ions.



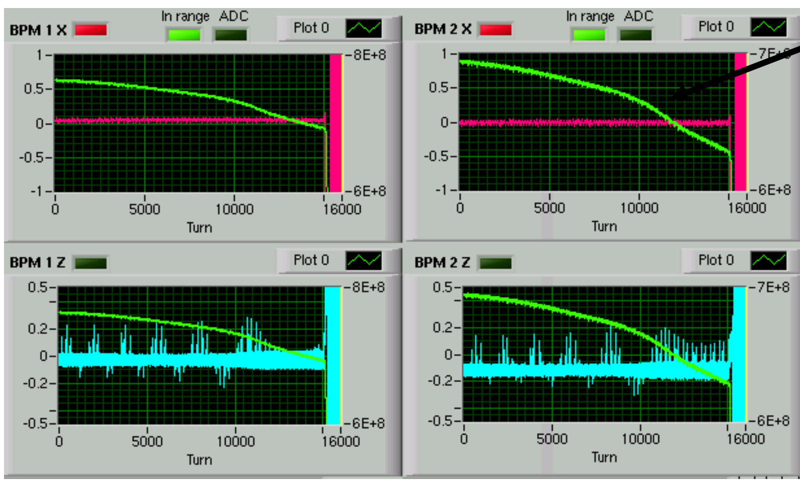
Courtesy C. Herbeaux

A local vacuum pressure rise followed by a beam loss encountered at 500 mA (24 May 2009).

- Empirically, we called this ~10 minutes the « *charging time of the ions* », which was interpreted as the time required for the locally heated vacuum components (due to longitudinal wakes) to surpass a threshold of « *outgassing* ».

(*discussions with C. Herbeaux*).

- The big question remained: Why the complete beam losses, while the theory of FBII only predicts a vertical blow up of $1\sigma \sim 2\sigma$ (phenomenon of saturation)



Beam current

BPM post-mortem data during a vertical beam loss

(*Courtesy L. Cassinari*)

⇨ A closer look into the BPM post-mortem data indicated that the beam was scraped on the chamber wall and was interlocked by the RF system.

- Why the beam blows up to several <u>mm</u> instead of several <u>tens of µm</u> is yet to be seen.

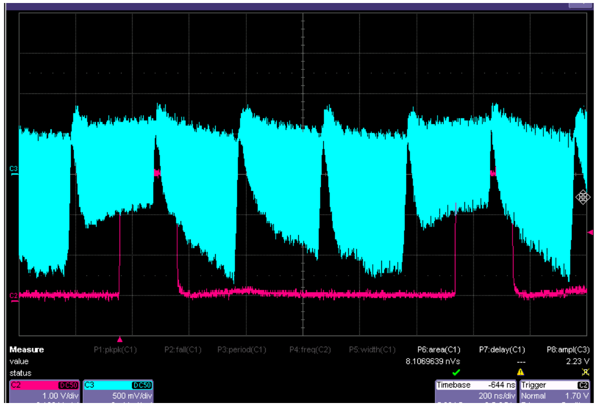
- To alleviate the effect of FBII, different beam fillings were tried:

There are 2 opposing effects:

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

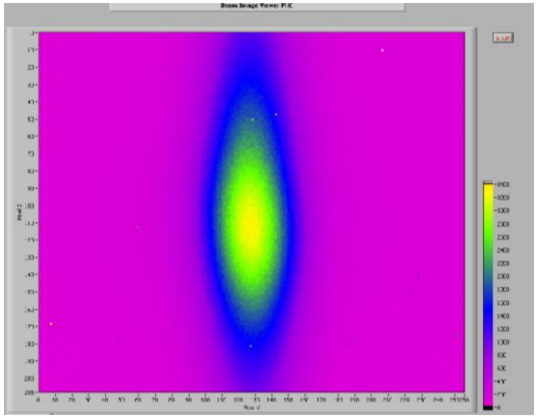
	Filling modes	Uniform	13*(25 bunches+7 empty)	3/4th	8*(32 bunches+21 empty)
Number of bunches	nb	416	325	312	256
Number of empty buckets	h - nb	0	91	104	160
Bunch current [mA]	ib	1.20	1.54	1.60	1.95
Beam induced power	nb*(ib)^2	**601.0**	769.2	801.3	**976.6**
(tau-1)FBII	(nb)^2*(ib)^1.5	**2.28E+05**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

- Tests of different fillings showed that the one with smaller current per bunch tends to give better stability ⇨ « Modulated » 4/4 filling was chosen.



« Modulated » 4/4 filling employed at 500 mA

- In parallel, we saw that an increase of chromaticity from ξ_z = 2.6 to 3.5 allows us to keep the beam at 500 mA without being lost (thanks to Landau damping).



Vertically blown up beam (ε_V > 100 pm) at 500 mA with ξ_z = 3.5

- The blown up beam was completely stable and TFB could even be switched off!

- Finally, by pushing further the idea of minimising the beam-induced heating by lowering the RF voltage (4 → 3 MV), 500 mA could be stored (*6 April 2010*) without any blow up and all the in-vacuum undulator gaps could be closed to minimum values.

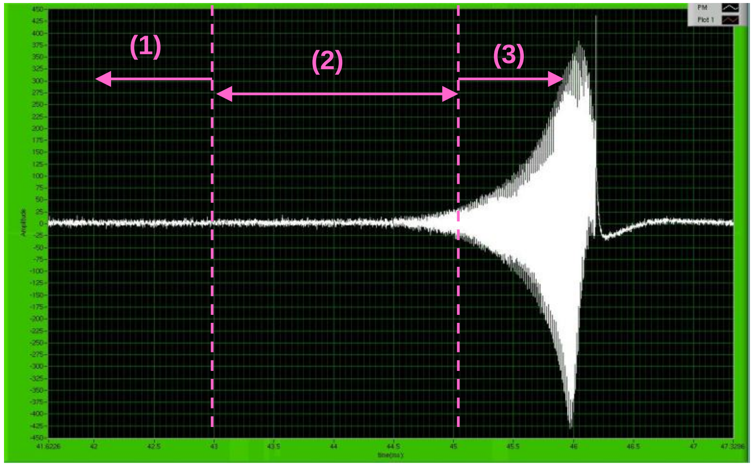
- The bunch lengthening introduced may in addition alleviate directly the FBII (to be pursued).

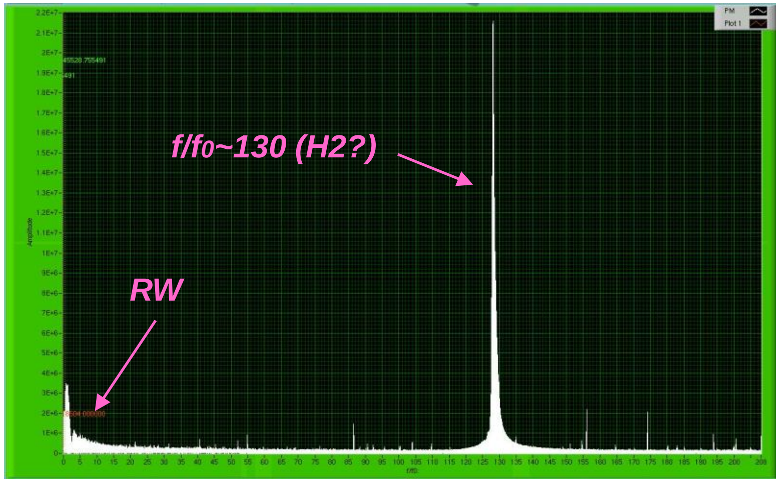
4. Recent Experimental Results

◊ Features at 500 mA

- V_{rf} = 4.2 MV and $(\xi_H, \xi_V) = (0, 0)$

(Measured on 11 October 2010)





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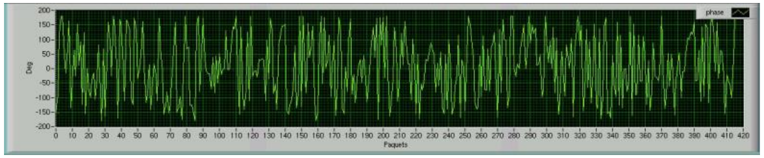
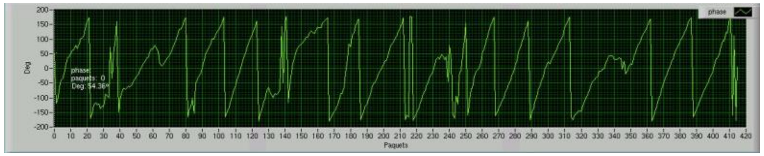


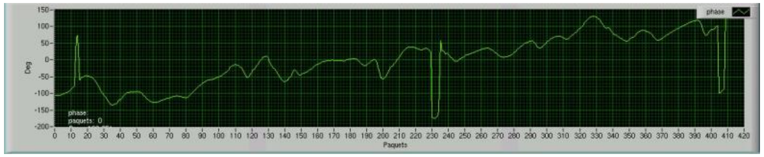
No phase correlation: Stable regime

(2)



FBII like regime

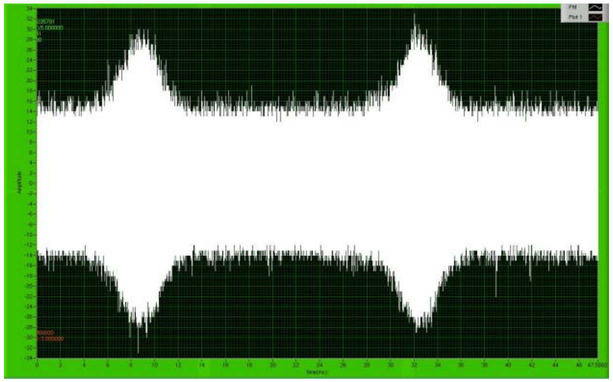
(3)

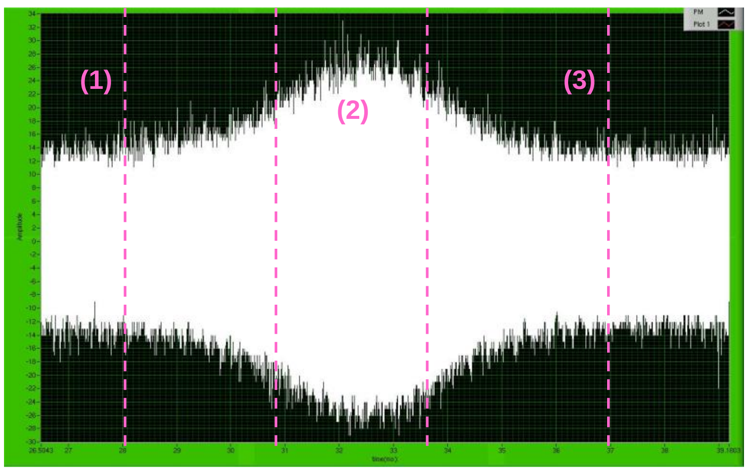


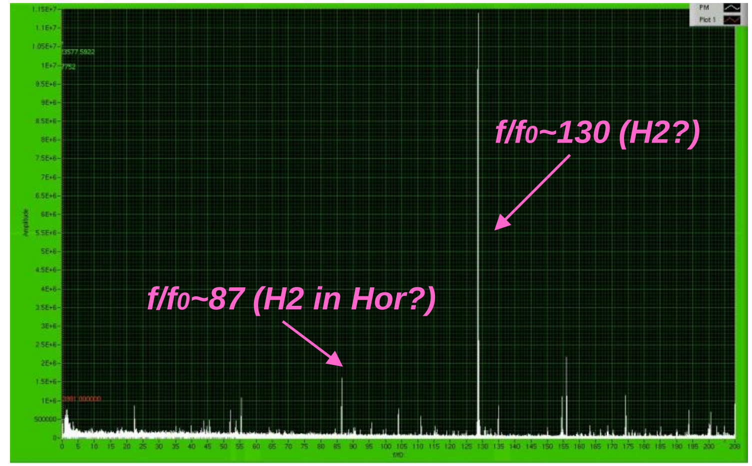
Resistive-wall (RW) like regime
(the observed exponential growth time of ~0.27 ms is close to expected from RW instability)

- V_{rf} = 4.2 MV and (ξ_H, ξ_V) = (0, **4**) (*Measured on 11 October 2010*)

  … No beam loss, but periodic vertical explosions







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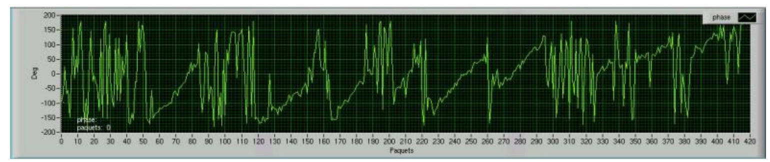
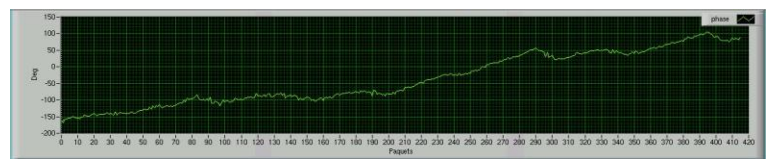


FBII-like

(2)



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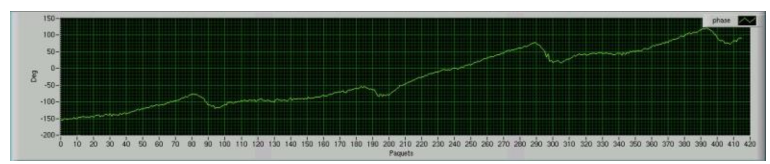
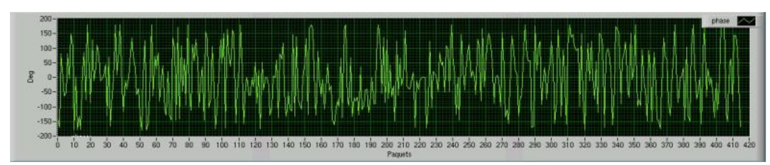


RW-like

(3)

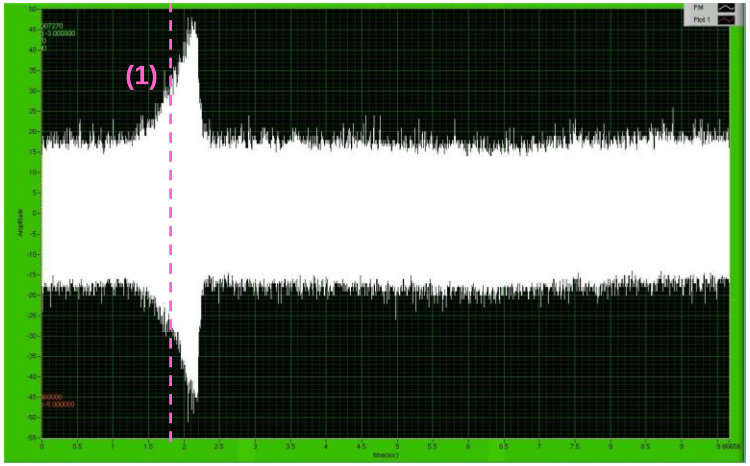


Stable

◊ Features at 400 mA (*present operation current*)

- V_{rf} = 4.2 MV and (ξ_H, ξ_V) = (0, 0) and switch off of TFB over 1 ms

(*Measured on 11 October 2010*)



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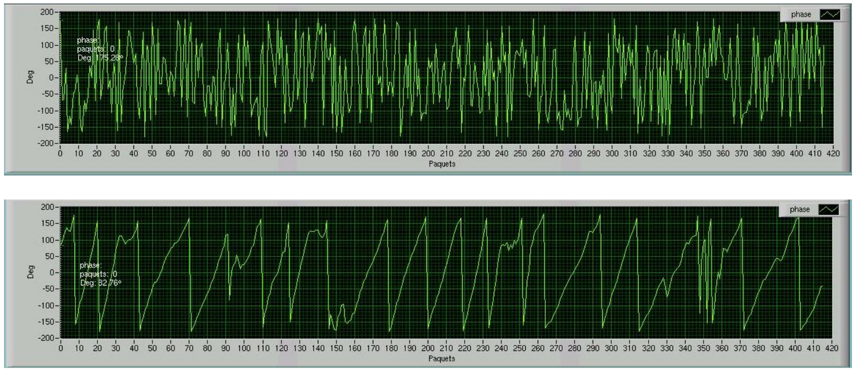
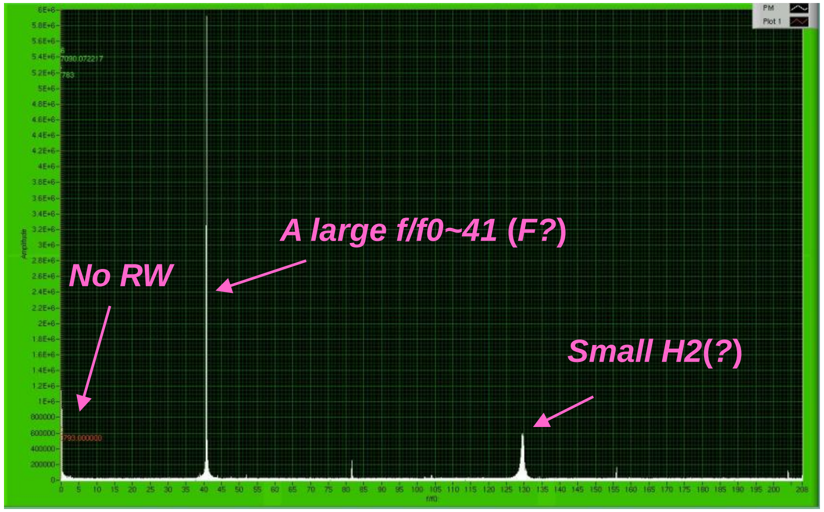


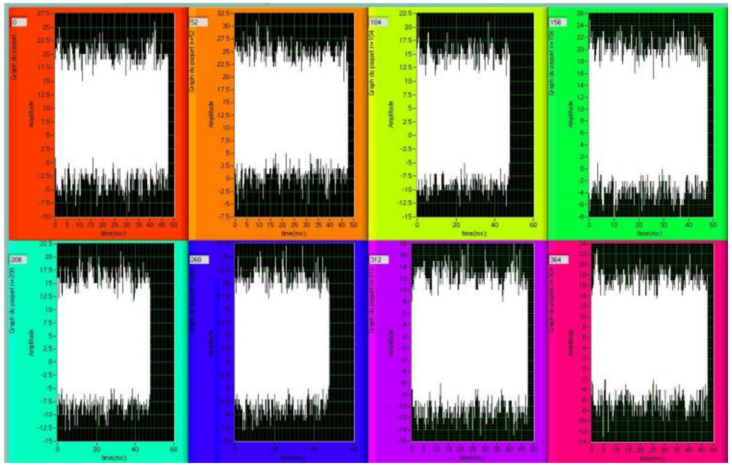
FBII-like



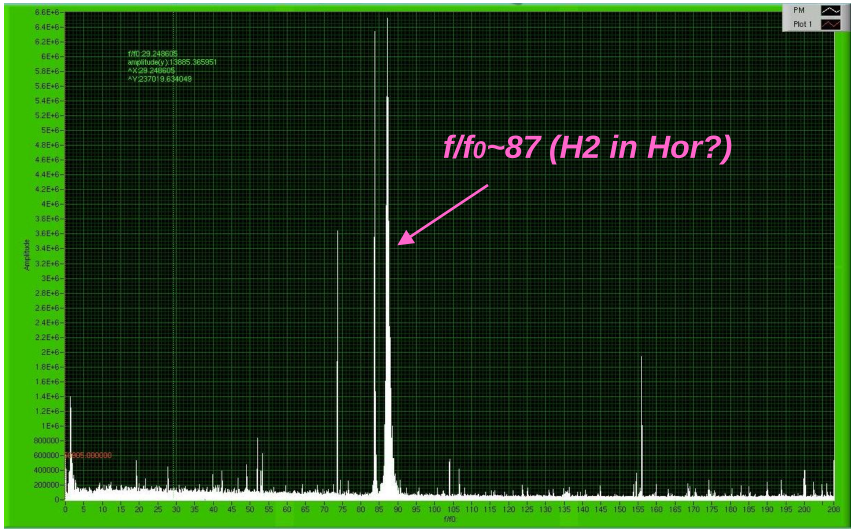
- During ~40 min of the time followed, no beam blow up or loss occurred
- Switching off of TFB reveals influence of ions (but not of H2 as at 500 mA)

- V_{rf} = 2.8 MV and (ξ_H, ξ_V) = (2, 2.6) and at an event of outgassing in an in-vacuum ID

(*Measured on 04 October 2010 triggered by an ion pump pressure threshold*)



Quasi-steady beam blow up



- Beam blow ups/losses occasionally occur during user operation associated with outgassing in in-vacuum ID sections

- In many cases, the beam becomes unstable horizontally

5. Discussions

- Answers must be found to the following questions raised:

  - At 500 mA and Vrf = 4.2 MV and zero chromaticity, are we already above the FBII threshold even with good vacuum?
  - Origin of beam blow up at ~8 min after beam ramp
  - Reason for the horizontal FBII beam blow ups in the in-vacuum IDs
  - Large amplitude growth (to be scraped on the wall) and the limit of transverse feedback

- Tracking simulation studies and some development required

  - Simulation of FBII without beam gaps
  - Simultaneous treatment of short range beam-ion and long range RW forces
  - Inclusion of tune spreads (optics nonlinearity) and TFB

6. Summary

- The ion effects strongly seen since the commissioning times at SOLEIL on top of the classical impedance originated instabilities were identified to be the Fast Beam Ion Instability (FBII).

- Although with improvement of the vacuum, the relative contribution of FBII diminished, beam losses due to FBII persist at high multibunch current.

- To achieve a stable beam at 500 mA, lowering of the RF voltage turned out to be effective, most likely due to suppression of ions by reducing the beam-induced heating of vacuum chambers.

- However, the mechanism of beam blow ups leading the beam to be scraped against the chamber walls remains to be understood, in particular the reason of transverse feedback remaining ineffective.

- Analytical and simulation studies should be made to answer the open questions.