# LHC impedance model:
# Experience with high intensity operation in the LHC


Benoit Salvant (CERN), on behalf of a very large team:

**Collimation team**: Oliver Aberle, Ralph Assmann , Roderik Bruce, Alessandro Bertarelli, Federico Carra, Marco Garlasche, Luca Gentini, Luisella Lari, Stefano Redaelli, Belen Salvachua, Marc Timmins, Daniel Wollman,

**Cryogenics team**: Serge Claudet, Laurent Tavian

**Injection team:** Chiara Bracco , Mike Barnes, Brennan Goddard, Jan Uythoven

**Instability team:** Gianluigi Arduini, Xavier Buffat, Alexey Burov (LARP), Stephane Fartoukh, Werner Herr, Elias Métral, Nicolas Mounet, Tatiana Pieloni, Simon White (LARP)

**RF team**: Philippe Baudrenghien, Wolfgang Hofle, Themistoklis Mastoridis, Juan Esteban Mueller, Elena Shaposhnikova, Daniel Valuch,

**Impedance team**: Fritz Caspers, Hugo Day, Alexey Grudiev, Elias Métral, Nicolas Mounet, Jean-Luc Nougaret, Serena Persichelli, Giovanni Rumolo,

**Instrumentation team**: Rhodri Jones, Mariusz Sapinski, Andriy Nosych, Federico Roncarolo

**Operation team:** all operators, engineers and coordinators

**Vacuum team**: Vincent Baglin, Alexis Vidal, Giulia Lanza, Bernard Henrist, Gregory Cattenoz

**And the TIMBER database team!**



**HB workshop 2012**

**19 September 2012, Beijing, China**

# Main messages of this talk

- Transverse LHC impedance model is well advanced
  - New theories and simulations of more complicated devices
  - Still a discrepancy of a factor ~2 with LHC beam measurements

- Longitudinal impedance model should be improved

- Two current harmful limitations to LHC due to machine impedance
  - **Beam induced heating** of individual equipment
    - → leads to **loss of integrated luminosity** and even **damage**
    - → seems in general **well understood** from theories and simulations so far
    - → **question: what will happen after the restart in 2014 ?** (shorter bunch spacing and bunch length)

  - **Transverse beam instabilities** at collision energy
    - → lead to **loss of integrated luminosity**
    - → seems to be the result of the interplay of many ingredients (transverse impedance, beam-beam, chromaticity, octupoles and transverse damper)
    - → **question: can we understand what is happening and find solutions?**

- CERN impedance and collective effects team is very grateful for the help from its collaborators around the world
  - **GSI/ TU Darmstadt**, Germany (O. Boine-Frankenheim, G. Franchetti, L. Haenichen, U. Niedermayer)
  - **IHEP Beijing**, China (N. Wang)
  - **LARP program** with US labs (A. Burov, R. Calaga, S. Paret, J. Qiang , S. White)
  - **RRCAT, Indore**, India (P. Shrivastava)
  - **University of Naples** and **INFN** (V. Vaccaro)
  - **University of Rome**, La Sapienza and **INFN**, Italy (M. Migliorati, A. Mostacci, B. Spataro)

# Agenda

- Context:
  - LHC impedance and beam brightness increase since startup
- LHC impedance model:
- Beam brightness limitations since startup
- Summary and Expectations for the restart in 2014

# Context

- LHC beam brightness was continuously increased
  - Bunch and beam intensity reached 1374 bunches with ~1.6e11 p/b in 2012
  - Beta function at collision points ($\beta^*$) squeezed to 0.6 m in 2012 instead of 1 m in 2011
  - Lower emittances in collision (~2.4 instead of 3.75 mm.mrad rms normalized)

- Beam impedance at collision energy was increased since 2012
  - Collimators are now closer to the beam during the ramp and at collision energy (4TeV) to allow for lower $\beta^*$ in 2012.

→ As a consequence, impedance effects were predicted to be more critical in 2012 than 2011

# Agenda

- Context:
- LHC impedance model:
  - Tools at our disposal
  - Longitudinal and transverse impedance models
  - Comparisons with beam measurements
  - Ongoing issues
- Beam brightness limitations since startup
- Summary and Expectations for the restart in 2014

# Tools at our disposal for impedance assessment

- Electromagnetic theories
  - NEW Formulae for **circular beam pipes** (Zotter/Métral with Mounet implementation, Burov/Lebedev, Ivanyan, Hahn etc.)
  - NEW Formulae for **flat beam pipes** with generalized form factors (Mounet)
  - NEW Mode matching formulae for **kickers** and various inserts (Biancacci/Vaccaro) [WEO1A01]
  - NEW Formulae for **kickers** (Tsutsui/Wang/Biancacci)
  - Formulae for **inserts** (Chin/Shobuda)
  - Formulae for **bellows** (Bane and Ng)
  - Fomulae for **tapers** (Stupakov, Podobedov)
  - Formulae for **laminations** (Burov)

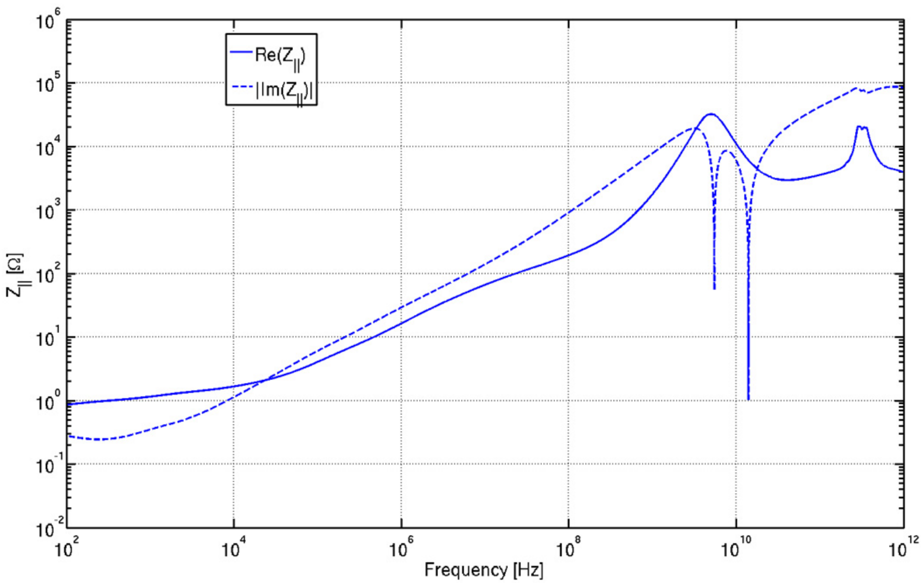
- Electromagnetic Simulations
  - Ansys HFSS
  - CST Studio
  - ABCI
  - Ace3P and Omega3P

- Bench measurements
  - Wire measurements
  - Probe measurements

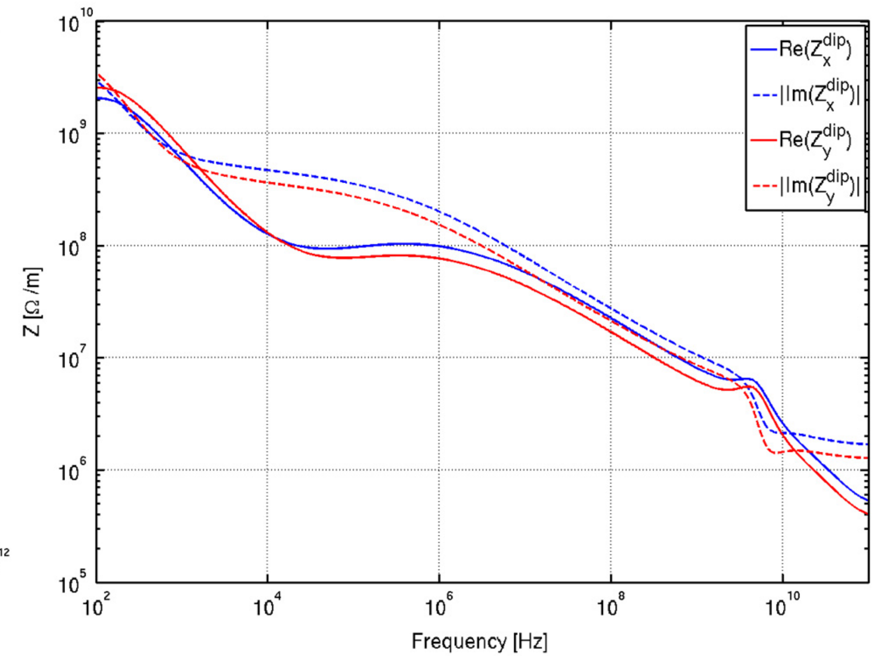
# Current LHC impedance model

The impedance model contains contributions from collimators, beam screens, warm beam pipe and a broadband impedance model (from design report).

Longitudinal impedance model at 450 GeV




Transverse impedance model at 4 TeV




Other impedance contributions will be added (in particular from 3D simulations).

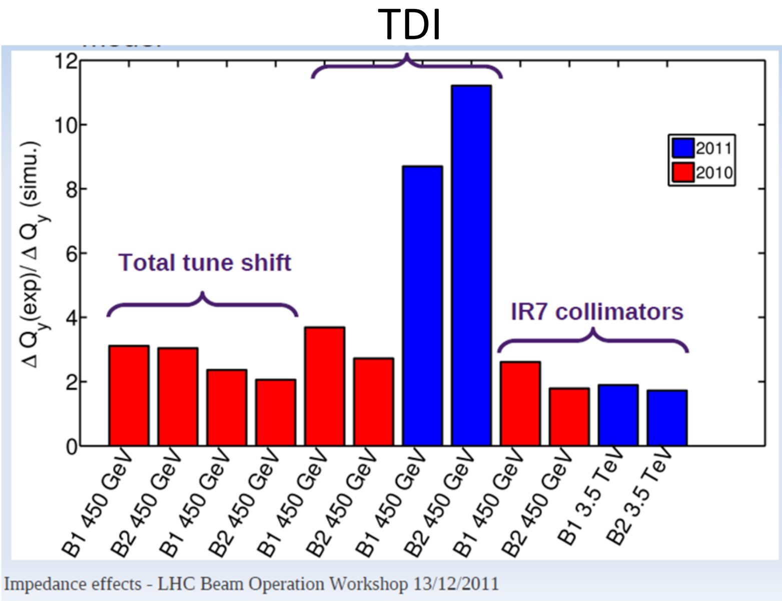
*PhD thesis N. Mounet, EPFL 2012*

# Comparison between impedance model and beam measurements

- Transverse impedance

**There is still a discrepancy of a factor 2 at top energy between the tune shift measurements and the impedance model predictions.**

N. Mounet et al, Evian LHC beam operation workshop, Dec. 2011



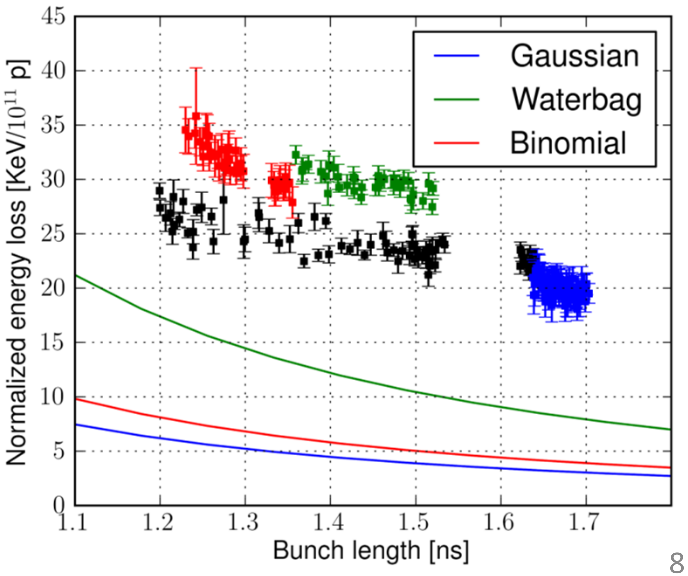

- Longitudinal impedance

**Significant discrepancy (factor 2 to 6) observed between model and synchrotron phase shift measurements**

→ Not surprising as we focused on the main contributors to the transverse impedance (beam screens and collimators)

→ need to improve the longitudinal model

J. Esteban Mueller et al, [MOP252]



# Ongoing work

- Assess the properties of materials at high frequencies

  (as they are usually not a specification by manufacturer of dielectrics and ferrites)

  → ongoing with several methods (F. Caspers, C. Vollinger, C. Zannini , E. Kournikova, G de Michele)

- Understand where the heat load is deposited in the presence of ferrite

  (as it is important to assess whether ferrite will reach the Curie point)

  → done (with H. Day and S. Persichelli)

  → collaboration started with thermal simulations experts to predict temperature

# Agenda

- Context:
- LHC impedance model:
- Beam brightness limitations since startup
  - History
  - Beam induced heating
  - Transverse stability
- Summary and Expectations for the restart in 2014

# History of impedance related limitations in LHC

- **2010: the year of the single bunch instabilities (cured)**
  - **Loss of landau damping** (longitudinal emittance was too small)
  - **Single bunch instability** during the ramp (cured with octupoles)

- **2011: the year of the beam induced heating**
  - **Beam induced heating** leading to:
    - Suspected **damage** (bellows, injection collimator)
    - Increasing **turn around time** (injection kickers)
    - **Dumps** due to temperature interlocks (2 collimators)
    - **Worry** for the future (synchrotron light monitor, ALFA detector, 1 cryomodule)

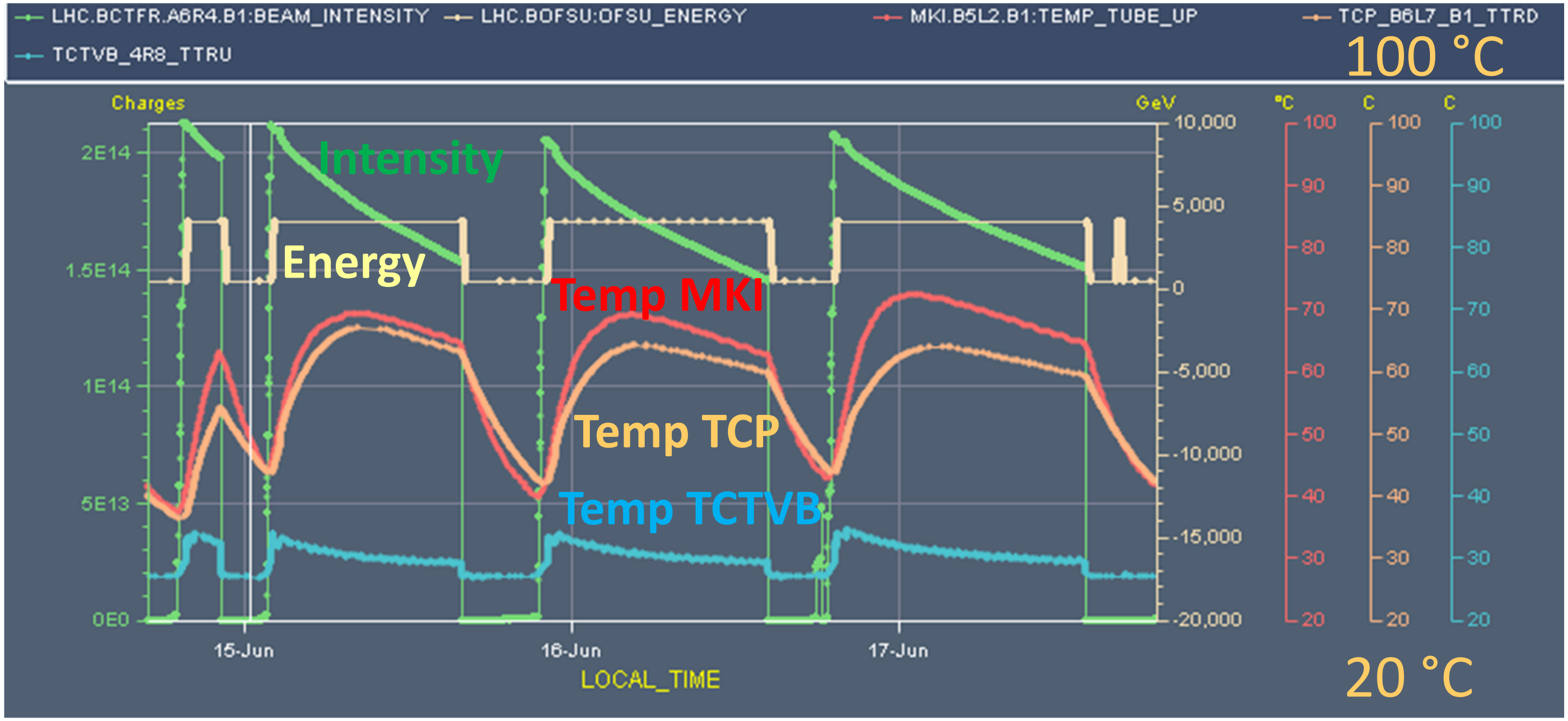
- **2012: the year of the transverse beam instabilities (not fully cured yet)**
  - **Beam induced heating** leading to:
    - Suspected **damage** (synchrotron light monitor)
    - Increasing **turn around time** (injection kicker)
    - **Dumps** due to temperature interlocks (1 primary collimator)
    - **Worry** for the future (1 tertiary collimator, ALFA detector, 1cryomodule)
  - **Transverse instabilities** during the squeeze, collision beam process and collision

    → **beam dumps, severe losses and/or emittance blow up**

# Agenda

- Context:
- LHC impedance model:
- Beam brightness limitations since startup
  - History
  - Beam induced heating
  - Transverse stability
- Summary and Expectations for the restart in 2014

# Beam induced heating?




- → Example of temperature of certain LHC devices during physics fills
  - → MKI: injection kicker (interlock for injection at ~61 degrees C)
  - → TCP: primary collimator
  - → TCTVB: 2-beam tertiary collimator
- → Temperature increase due to the interaction of beam induced wake fields with the surrounding
- → Need to compute power loss from impedance: What will happen with shorter bunch spacing and bunch length ? (25 ns spacing and 1 ns after the shutdown instead of 50 ns and 1.25 ns currently)

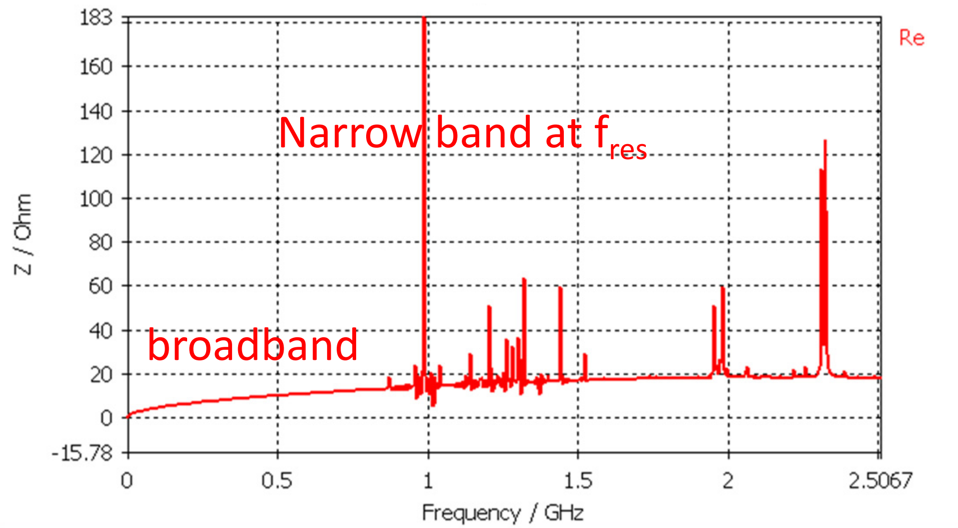
# Computing power loss

- Power lost by the beam in a device of impedance $Z_{long}$ (see E. Métral at Chamonix 2012):

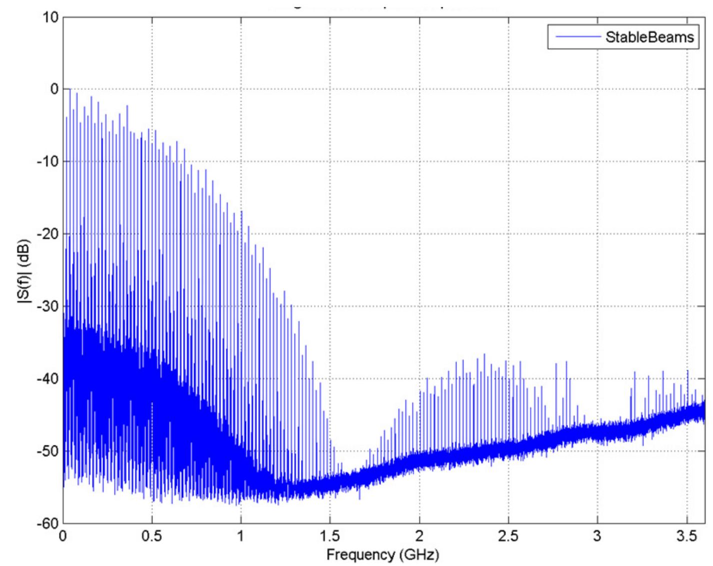
$$P_{loss} = 2\left(eMN_b f_{rev}\right)^2 \left( \sum_{p=1}^{\infty} \mathrm{Re}\left[Z_{long}\left(2\pi p M f_{rev}\right)\right] \times Powerspectrum\left(2\pi p M f_{rev}\right) \right)$$

*M*= number of bunches
$N_b$=intensity per bunch

Impedance Re($Z_{long}$) of simulated primary collimator




Power spectrum measured on 50 ns beam by P. Baudrenghien and T. Mastoridis




Broadband contribution: sum can be replaced by an integral

$$P_{loss} = 2\left(eMN_b f_{rev}\right)^2 \left( \frac{1}{Mf_{rev}} \int_0^{+\infty} \mathrm{Re}\left[Z_{long}\left(2\pi f\right)\right] \times Powerspectrum\left(2\pi f\right) df \right) \Rightarrow \boxed{P_{loss} \propto MN_b^{\,2}}$$

Narrow band contribution: sum can be replaced by a single term

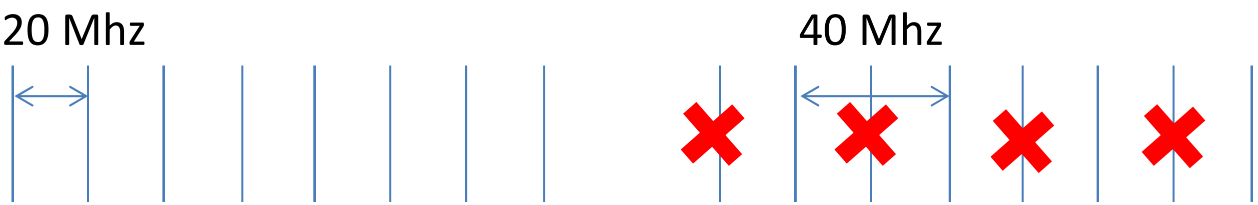
$$P_{loss} = 2\left(eMN_b f_{rev}\right)^2 \mathrm{Re}\left[Z_{long}\left(2\pi M f_{resonator}\right)\right] \times Powerspectrum\left(2\pi p M f_{resonator}\right) \Rightarrow \boxed{P_{loss} \propto M^2 N_b^{\,2}}$$

# Effect of **25 ns** on RF heating?

***Current beam: 50 ns spacing***
*M*=1374 bunches
$N_b$=1.6 $10^{11}$ p/b

***After the long shutdown 1: 25 ns spacing***
*M*=2808 bunches
$N_b$=1.15 $10^{11}$ p/b

Power spectrum:




Assuming the same bunch distribution and bunch length for both spacings

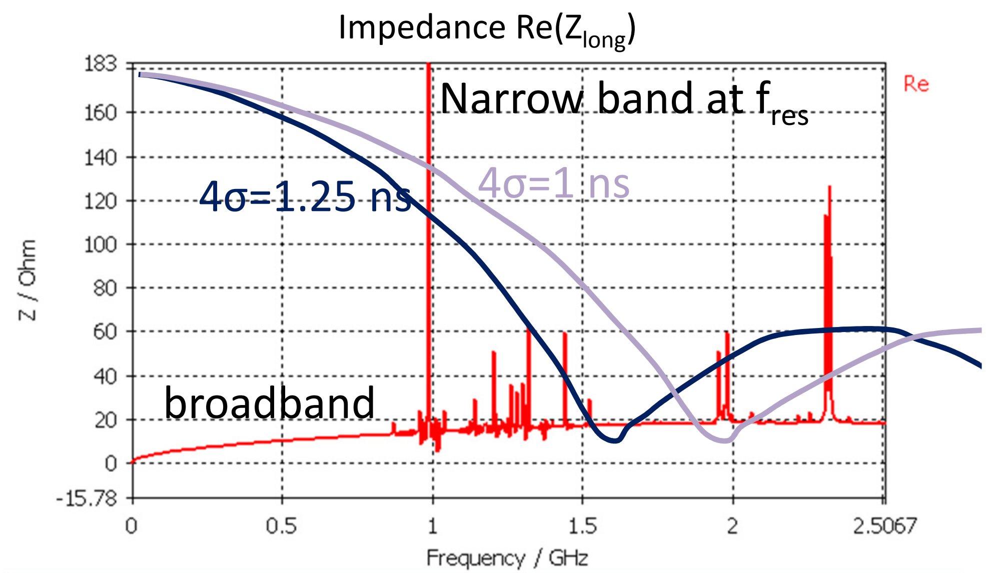
→ switching to 25 ns for broadband:

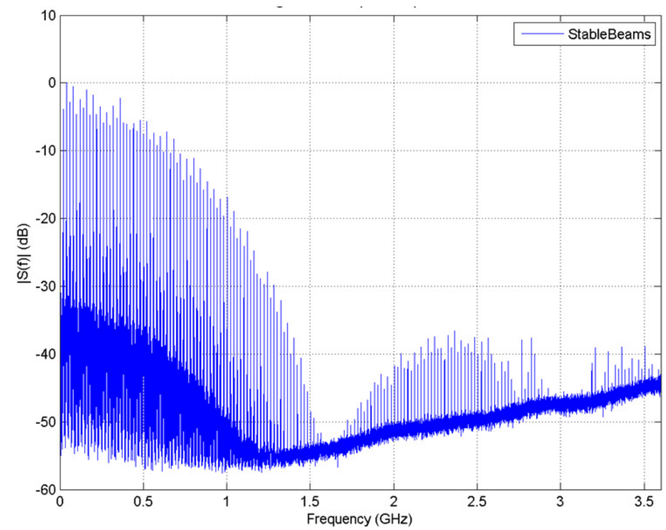
increase by factor $\frac{M^{25} *(Nb^{25})\hat{}2}{M^{50} *(Nb^{50})\hat{}2} = 1.05$

→ switching to 25 ns for narrow band falling on a beam harmonic line ($f_{res}$= k*20 MHz):

increase by factor $\frac{(M^{25} *Nb^{25})\hat{}2}{(M^{50} *Nb^{50})\hat{}2} = 2$ (if $f_{res}$=2*k*20 MHz) or 0 (if $f_{res}$=(2*k+1)*20 MHz)

# Effect of **bunch length** on RF heating?



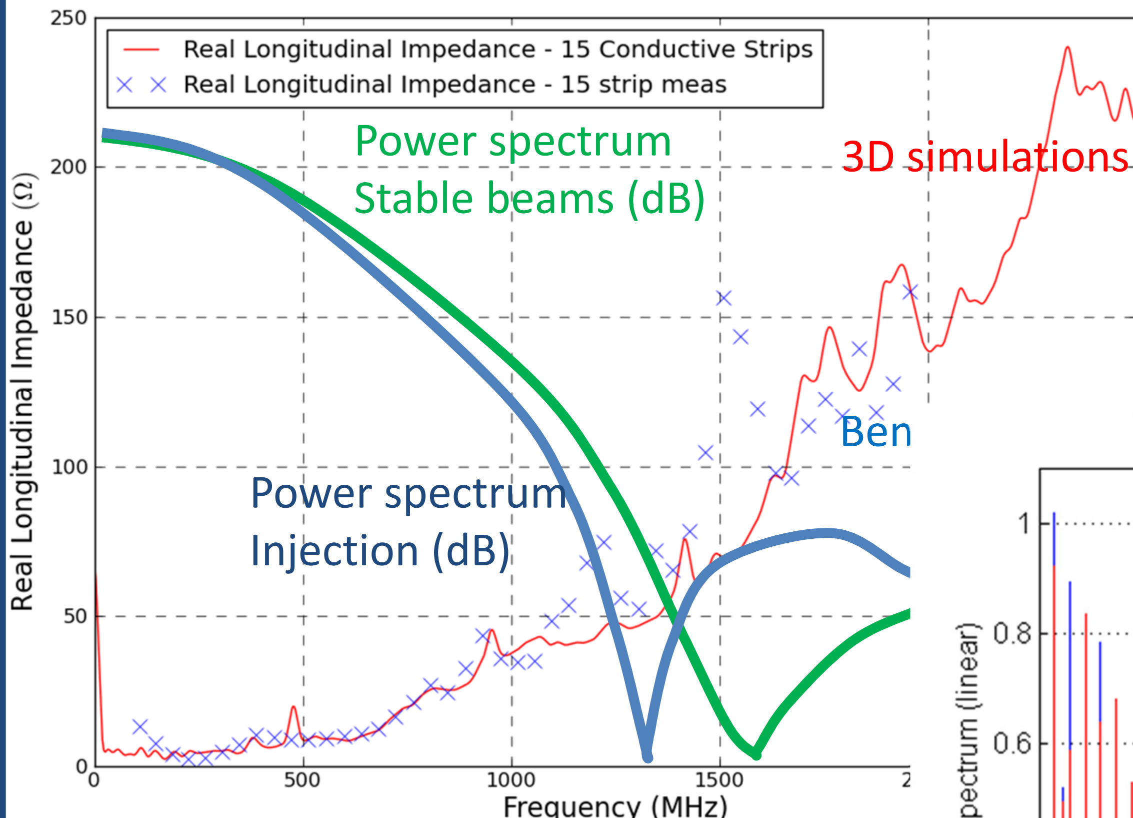

- Assumption: same bunch distribution for both bunch lengths
  → **beam spectrum is extended to higher frequencies with an homothetic envelope**

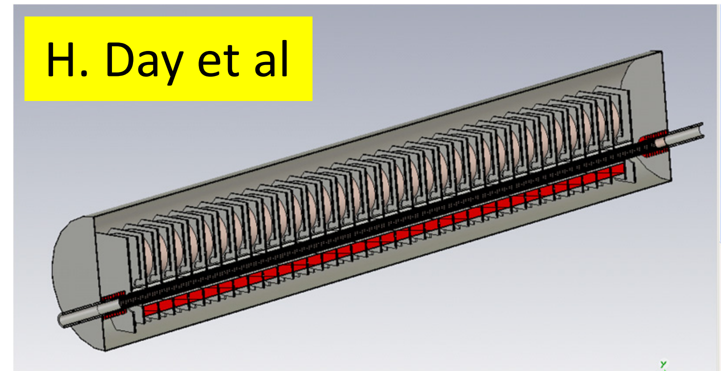
→ switching to lower bunch length for broadband:
in general regularly increases (depends on broadband resonant frequency)

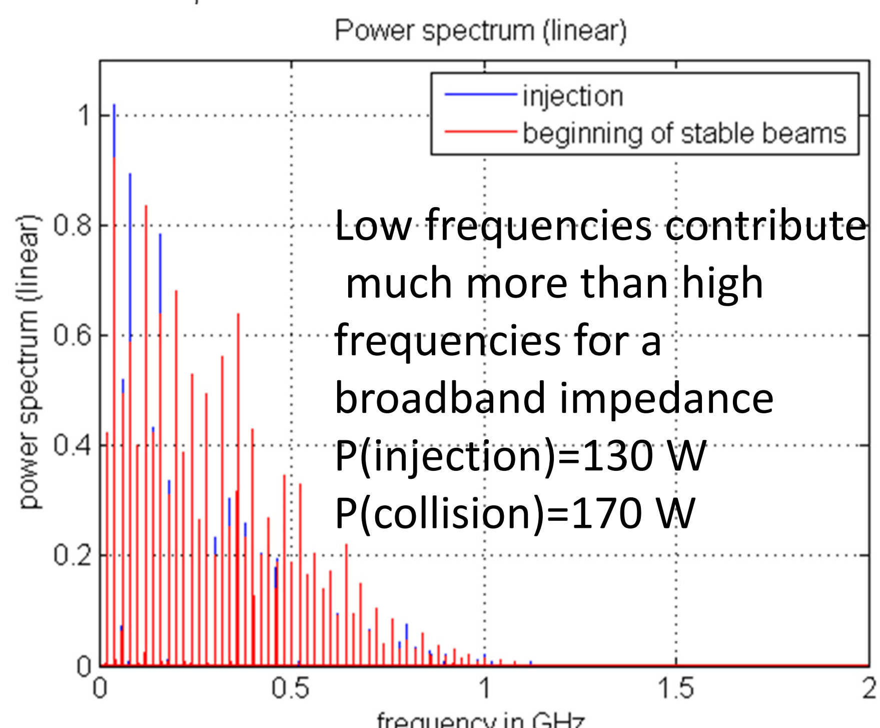
→ switching to lower bunch length for narrow band:
enhances some resonances and damps others → we could have some surprises!!!

# Example: simulations and bench measurements of the impedance of the LHC injection kicker (MKI)

This injection kicker heats too much and one needs to wait hours that it cools down to reinject



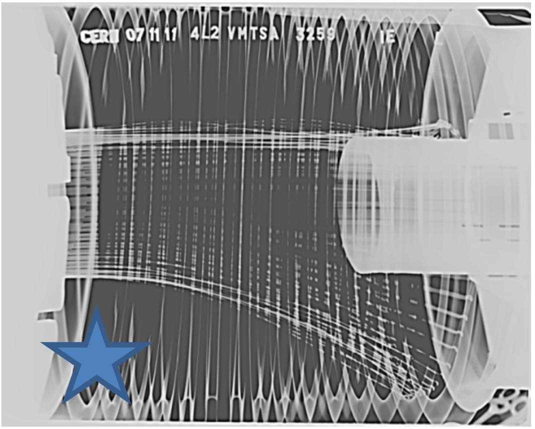

Low frequencies contribute much more than high frequencies for a broadband impedance
P(injection)=130 W
P(collision)=170 W

Very complicated 3D model (4 m long ferrite kicker with shielding done with ceramic and conducting strips)

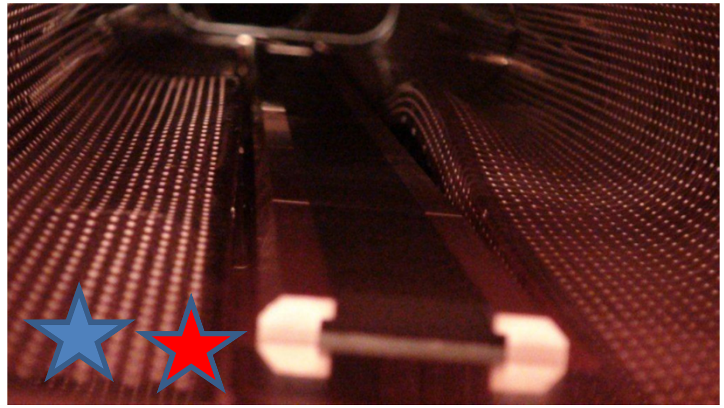
good agreement between simulations and bench measurement!

# Other heating issues

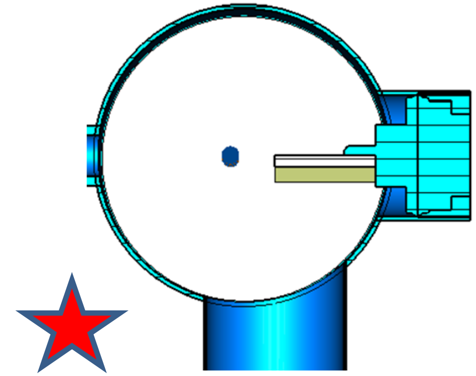
Damaged vacuum module in 2011
→ Repaired and reinforced



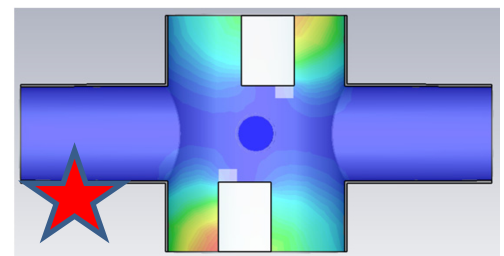
Damaged injection collimator
→ will be be reinforced
→ New design underway



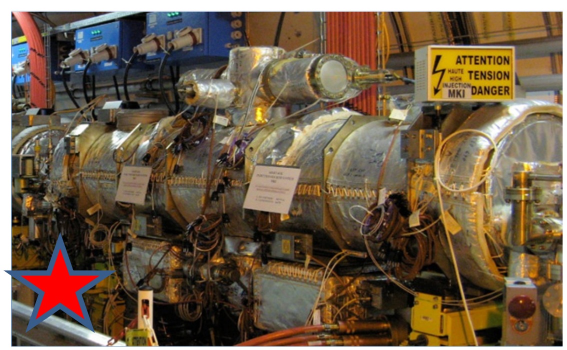
Damaged synchrotron light monitor
→ Temporary replacement
→ New design



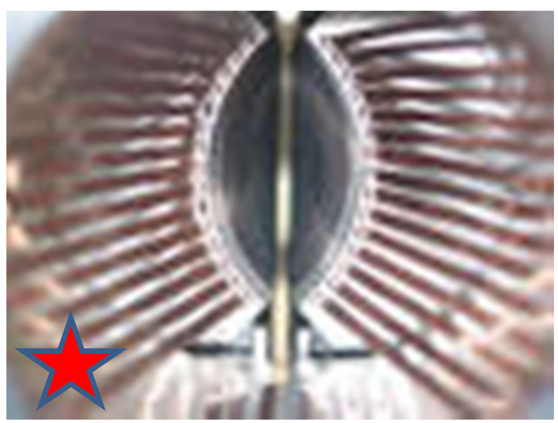
ALFA detector could be damaged
→ Cooling will be added



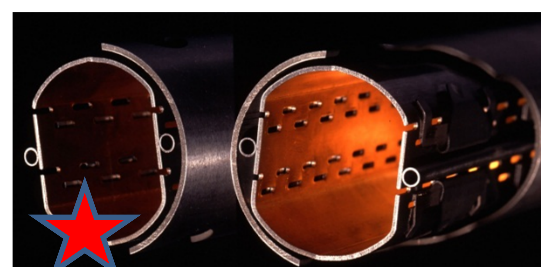
Injection kicker delays injection
→ Bakeout jackets removed
→ screen conductors optimized




Primary collimator is heating (1/6)
→ Cooling will be fully checked



one single cryogenic module (Q6R5) has no margin for cooling.



Broadband Narrow band (supposed)

# Agenda

- Context:
- LHC impedance model:
- Beam brightness limitations since startup
  - History
  - Beam induced heating
  - Transverse stability
- Summary and Expectations for the restart in 2014

Since it was not detailed in other talks at this workshop, Elias and I decided on Monday to also discuss the hottest issue of 2012 for LHC :

“the LHC transverse instabilities at collision energy”,

*already briefly mentioned by Rüdiger Schmidt on Monday and Laurette Ponce on Tuesday*

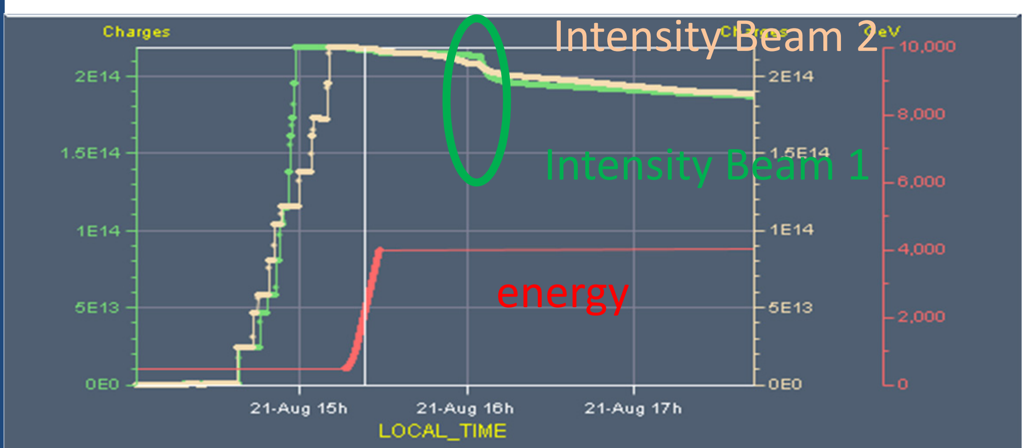
We hope to trigger discussions, comments and advice on this puzzling problem!

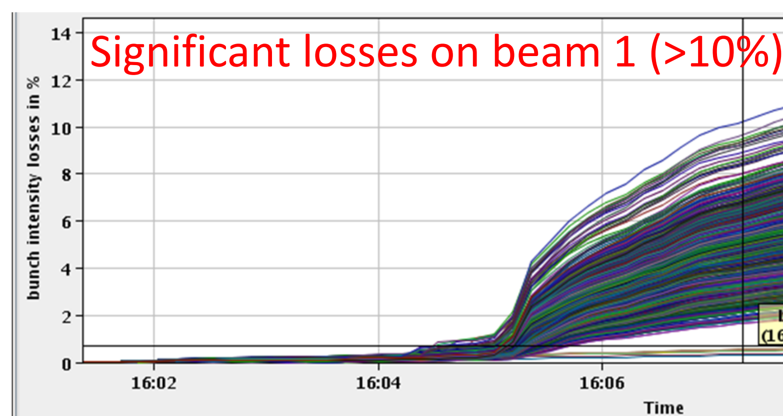
# Transverse instabilities:

- Since 2012, transverse instabilities during the *"Squeeze"*, *"Adjust" and "Stable Beam"* beam processes limit the bunch intensity and affect performance

- These losses have affected most physics fills since May 2012 and were discussed at length in most LHC meetings and heavily studied by the CERN beam-beam and instability teams.
- Several beam tests showed that:
  - Landau octupoles are needed for single bunch stability
  - Transverse damper is needed for single batch stability at 3.5 TeV
  - If only one beam circulates, it is stable with Landau octupole current as low as ~ 100 A

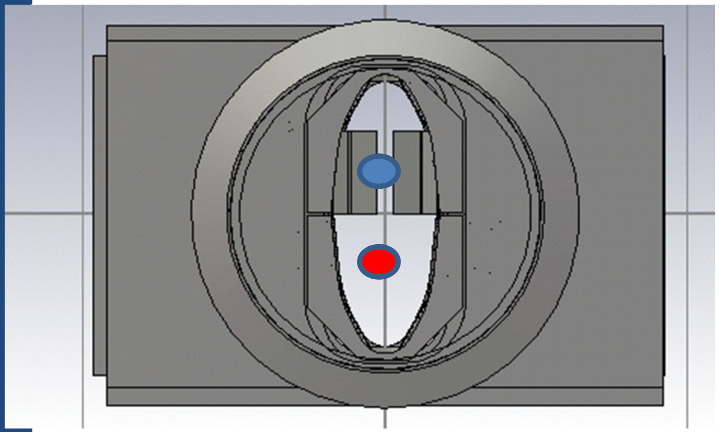
  → It looks like one beam is stable, but two beams are not stable… Instability due to presence of two beams?
- Possible explanations?
  - Beam-beam coherent excitation? But one beam is much more affected than the other. To be discussed.
  - Reduction of the incoherent tune spread due to beam-beam long range interactions? Is being checked.
  - Excitation of wake fields in a 2 beam device? Will be checked with simulations (T. Pieloni ) and a cogging MD.
  - increase of non linearities in the triplets during the squeeze → is being checked.

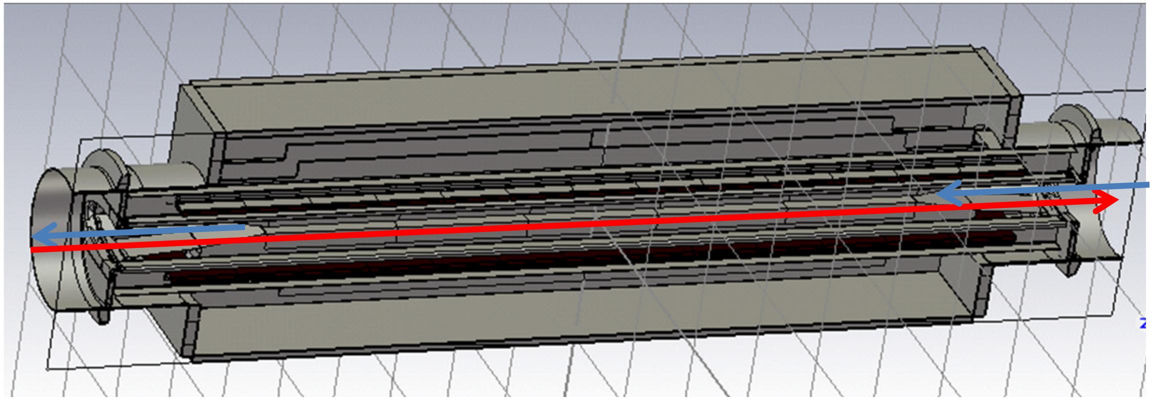


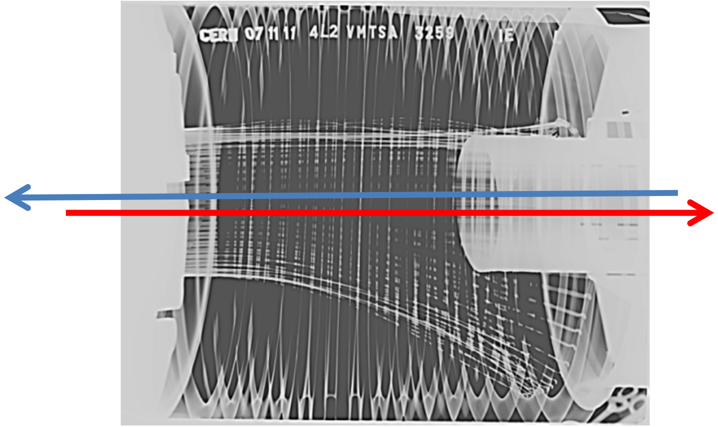
# 2-beam impedances contributions: several suspects

TCTVB – tertiary 2-beam collimators (are moving during the squeeze and adjust)

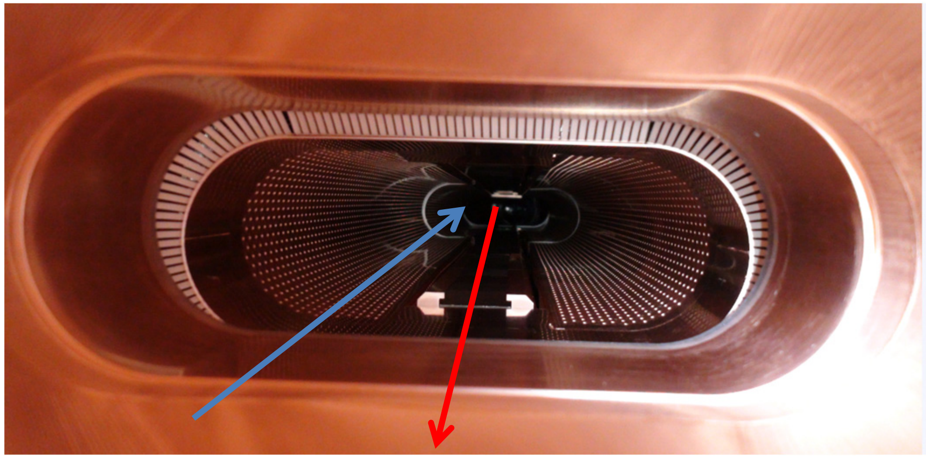




Vacuum bellow (now repaired!)

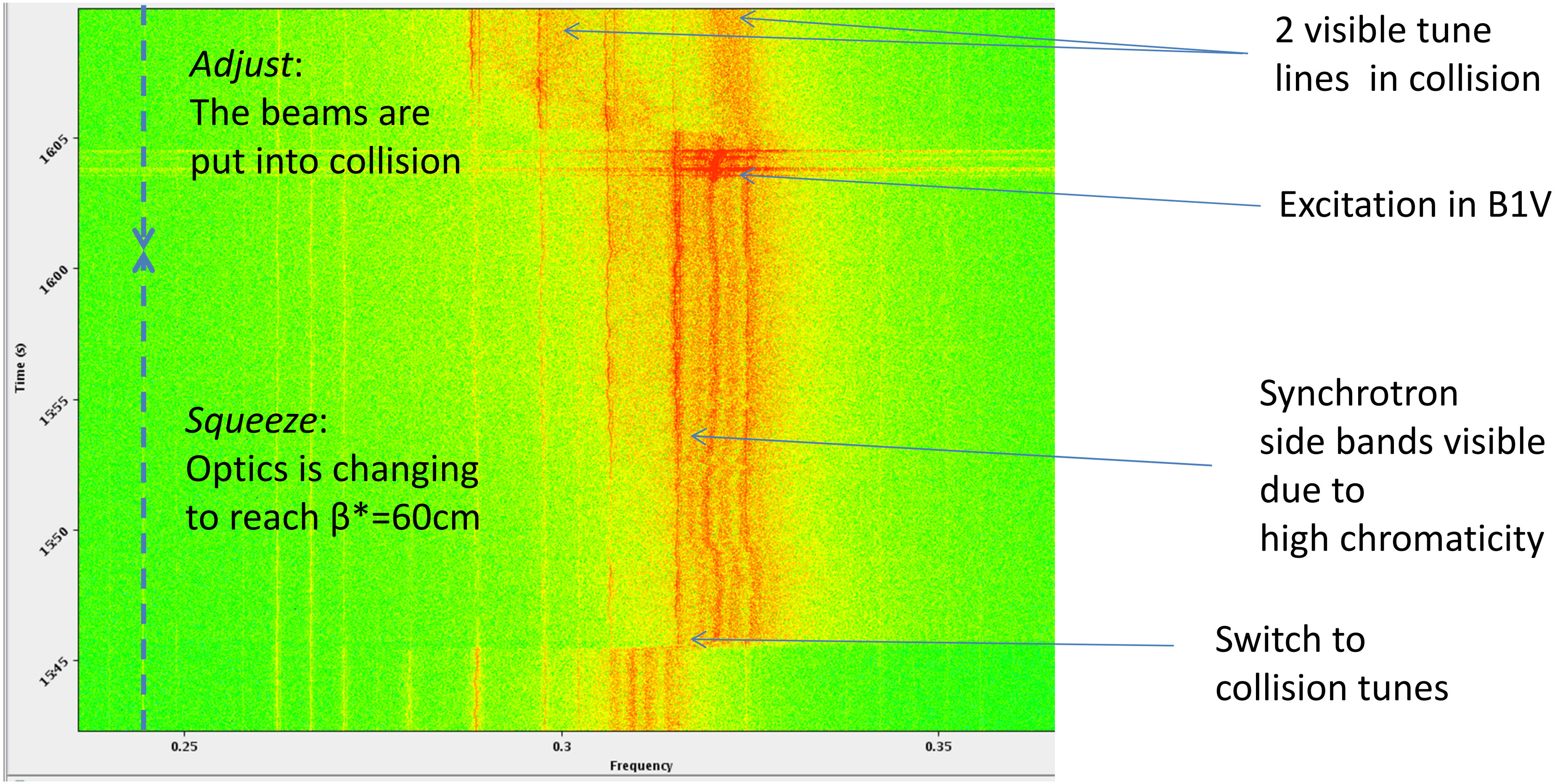



Injection protection collimator (retracted at collision energy)



# Tune spectrum for Beam 1V for Fill 2992

(start of adjust at 16:01 on 21/08/2012)




Many noise lines in the tune spectrum! Difficult to assess where the tune is.

In fact, four main types of instabilities:

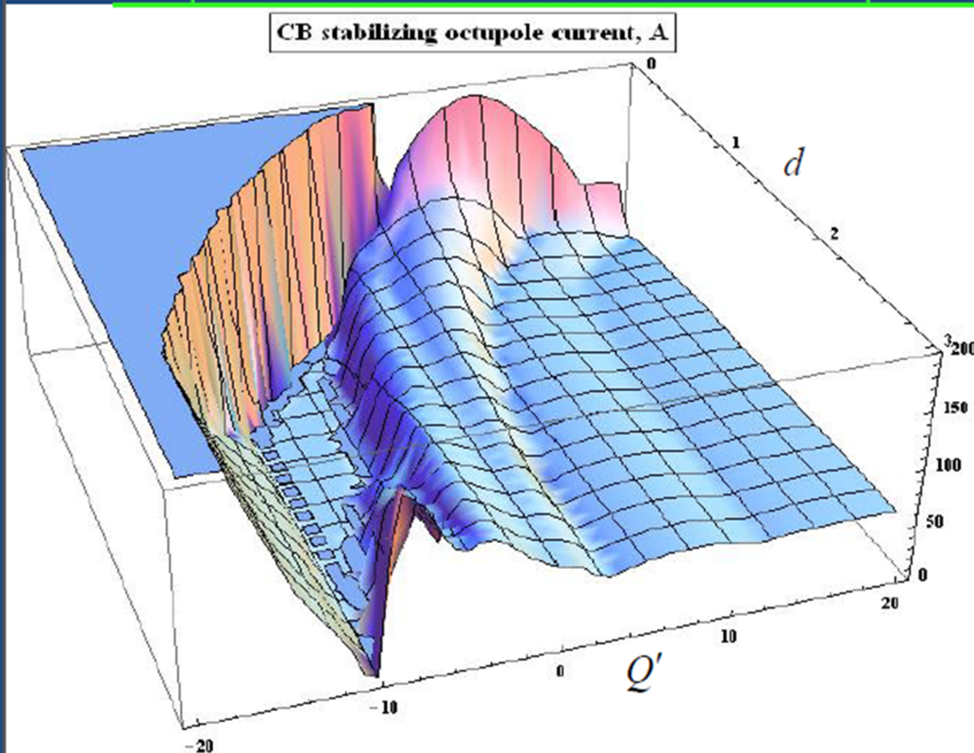
- before the squeeze (appeared since the octupole sign change)
- at the end of the squeeze
- in adjust (the case displayed)
- in collision on selected bunches

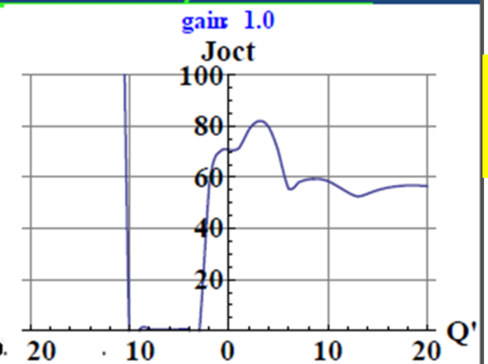
# Transverse instabilities: ongoing studies

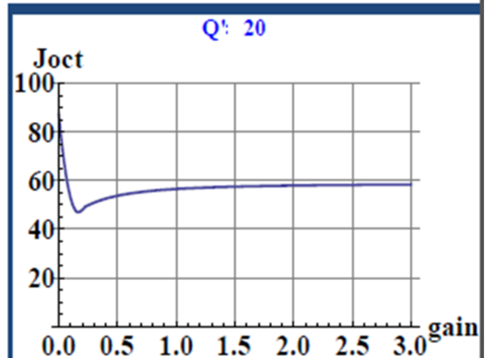
- A lot of effort at CERN has been invested to analyze and understand the reasons and possible cures for these instabilities:
  - New theories and simulations to understand
    - The interplay of beam-beam and octupoles (X. Buffat, W. Herr, T. Pieloni as well as S. Fartoukh)
    - The interplay of impedance, chromaticity, octupoles and transverse damper (A. Burov, N. Mounet, X. Buffat and S. White)
  - These studies resulted in many tests with beam
    - Stability measurements with only 1 beam
    - Stability measurements with several octupole, chromaticity, damper gain settings
    - Switched the sign of the octupole current (to avoid compensation of the long range beam-beam and octupole tune spreads)
      →implemented together with higher chromaticity, seemed to help reducing the extent of instabilities
      → lead to change the most affected plane from B2H to B1V
  - Possible cures:
    - Increase Landau octupole current (almost at the limit)
    - Increase chromaticity temporarily and reduce it after collisions (predictions do not expect benefits to increase it further)
    - Increase damper gain (now at the limit)
    - Collide beams quicker to limit the time spent with critical parameters (is being implemented)
  - Problems to move forward (besides limited machine time…):
    - Noisy tune and chromaticity measurements
    - Schottky installed but not usable yet
    - Intrabunch diagnostics are not dimensioned to cope with this instability (data rate issue).
    - Instability behaviour changes from fill to fill , often affecting the ends of batches but not systematically

# Understanding analytically the interplay of impedance, octupoles, damper and chromaticity with coupled bunch modes (A. Burov and N. Mounet)

## Coupled Bunches: Threshold octupole current, Ioct<0




NHT method
A. Burov (LARP) et al,

Note area of zero-octupole stability.

$N_b = 1.5 \cdot 10^{11};\ \tau_{bb} = 50\text{ns};\ \varepsilon = 2\mu\text{m};\ E = 4\text{TeV}.$

It is not a strip, as for a single-bunch, but a triangle.
Note the steepness. Note damper is not needed at chroma>15.

9

- → Agrees with tracking simulations (S. White, LARP) and another code without radial modes (N. Mounet)
- → Recommendation to strongly increase chromaticity (Q'/Q>15), and ADT gain, as well as flatten the ADT gain at high frequencies

# Agenda

- Context:
- LHC impedance model:
- Beam brightness limitations since startup
- Summary and Expectations for the restart in 2014

# Summary

- Transverse LHC impedance model is well advanced

- Longitudinal impedance model should be improved

- Two harmful limitations due to machine impedance with current parameters
  - **Beam induced heating** of individual equipment

  - **Transverse beam instabilities** at collision energy

    → seems to be the result of the interplay of many ingredients

    (transverse impedance, beam-beam, chromaticity, octupoles and transverse damper)

    → this interplay is **very complicated** to predict, however there is hope (and new theories)

- What will happen with nominal parameters (7 TeV, 25 ns spacing and shorter bunch length)?
  - **Beam induced heating** is expected to be globally slightly worse, but we should watch out for surprises

  - **Transverse beam instabilities** are difficult to scale to nominal parameters until we understand what is going on.

Many thanks for your attention!