Beam Transfer Function Measurements in the LHC: motivations, goal and possible set-up

X. Buffat, A. Florio, C. Tambasco, D. Banfi, J. Barranco, T. Pieloni

Acknowledgements:
Instability End of the Squeeze

**Bbb Losses**

- **Squeeze**
- **Losses**

**Instabilities 2012**
- Coherent oscillations single bunches
- Emittance blow-up
- Loss of intensity

**Flat-top:**
Single beam stability → Landau

**Octupoles**
Squeeze:
Long-range beam-beam detuning with amplitude → deterioration of octupoles effects

**Adjust**
- **Squeeze**
- **B1 H**
- **B2 H**
- **B1 V**
- **B2 V**
- **Losses coll**

**Amplitude [a.u.]**

**Time from end of squeeze [s] × 10³**

**Loss**

**Intensity**
Landau damping from octupoles

Detuning from octupoles
\[ q_x = q_{0x} + a^* J_x + b^* J_y \]
\[ q_y = q_{0y} + b^* J_x + c^* J_y \]
Footprint → Stability Diagram
Detuning with amplitude

Dispersion Integral:

\[ SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} d\Psi_{x,y}(J_x, J_y)}{Q_0 - q_{x,y}(J_x, J_y)} dJ_x dJ_y \]

from Tracking

- “Landau Damping by Non-Linear Space-Charge Forces and Octupoles” D. Mohl & H. Schonauer
- Berg-Ruggiero

Pyssd Code (X. Buffat) :
Numerical solver of Dispersion Integral
Landau Damping → Stability Diagram

Particle distributions

Dispersion Integral

\[ S \Delta^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y}}{Q_0 - q_{x,y}(J_x, J_y)} \frac{d\Psi_{x,y}(J_x, J_y)}{dJ_{x,y}} dJ_x dJ_y \]

Gaussian Distribution

\[ \sigma^{-1} = -\frac{1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y}}{Q_0 - q_{x,y}(J_x, J_y)} \frac{d\Psi_{x,y}(J_x, J_y)}{dJ_{x,y}} dJ_x dJ_y \]
Beam Transverse Function Measurement

BTF $R(\Omega)$: Fraction of the complex response amplitude $A(\Omega)$ of the beam per driving amplitude $D(\Omega)$ of a beam excited at the frequency $\Omega$

$$R(\Omega) = \frac{A(\Omega)}{D(\Omega)}$$

$$R_i(\Omega) = c \cdot \int_0^\infty \int_0^\infty \frac{1}{\Omega - w_i(J_x, J_y)} \frac{J_i d\psi_{x,y}(J_x, J_y)}{dJ_i} dJ_x dJ_y$$

- white noise and measure amplitude phase response
- swap frequency of excitation over range of interest
- Store Amplitude and phase response

BTF powerful diagnostic tool
Transparent to the beams

- tune measurement, spread (RHIC) operationally used
- stability diagram measurements our interest
- Coherent mode observation in Landau damping region
- Impedance measurements...

"The Use of RF-Knockout for Determination of the Characteristics of the Transverse Coherent Instability of an Intense Beam"
D. Mohl & A. M. Sessler
Landau Damping → Stability Diagram

Dispersion Integral

\[ SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} d\Psi_{x,y}(J_x, J_y)}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y \]
Stability Diagram with beam-beam effects

Dispersion Integral

\[
SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} d\Psi_{x,y}(J_x, J_y)}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} \ dJ_x dJ_y
\]

- Compute the detuning with amplitude with MADX: any configuration best knowledge of the spread
- Assume Gaussian distribution for particles
- Solve the dispersion integral

Why we would like to have BTFs?
Measurements and Analysis of the Transverse Beam Transfer Function (BTF) at the SIS 18 Synchrotron
V. Kornilov; O. Boine-Frankenheim, W. Kaufmann, P. Moritz

\[ BTF = SD^{-1} = R_i(\Omega) = c \cdot \int_0^\infty \int_0^\infty \frac{1}{\Omega - \omega_i(J_x, J_y)} \frac{J_i d\psi_{x,y}(J_x, J_y)}{dJ_i} dJ_x dJ_y \]
BB Tune Spread

- LR effects will introduce non-linear detuning with amplitude → reducing or increasing SD
- During squeeze LR becomes stronger
- Head-on contribution...
Modified distribution: Colored Noise

\[ SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_{0}^{\infty} \int_{0}^{\infty} \frac{J_{x,y}}{Q_{0} - q_{x,y}(J_{x}, J_{y})} d\Psi_{x,y}(J_{x}, J_{y}) \]

- Colored Noise source → Diffusion of resonant particles
- Modification of particle density in action space with time
- Strong effect on stability diagram at edge of variation (derivative of distribution)
Modified distribution: Colored Noise

- Effect on particle distribution very small (% level)
- Profile measurement dominated by core of beam

→ Impossible to measure the effect with profile measurement!
Modified distribution: Feedback

Similar result if feedback with sensitivity to head-tail motion is used...

- The beams perform small oscillations at finite amplitude (ADT on) + non-linearities $\rightarrow$ diffusion of particles
- Particles resonant with impedance coherent modes $\rightarrow$ diffuse faster

X. Buffat PhD Thesis
Effect of resonances are not fully taken into account

FP “smooths” the resonances and numerical integration assumes Gaussian distributions

How are particles distributed in reality along resonances?
Beam-beam driven resonances

- Particles trapped on resonances
- Areas with less particles left

D. Banfi, J. Barranco FMA analysis
Long range beam-beam driven resonances

- Long range beam-beam interactions excites resonances
- Larger amplitude particles more affected
- Particles trapped on resonance $\rightarrow$ Distribution changes

D. Banfi, J. Barranco FMA analysis
Particle densities vary depending on amplitude and resonances

$\frac{d\psi}{dJ}$ could give an important contribution to stability diagrams/BTFs
Example:

Measure BTF and stability diagrams at CERN ISR

INFORMATION FROM BEAM RESPONSE TO LONGITUDINAL AND TRANSVERSE EXCITATION J. Borer, G. Guignard, A. Hofmann, E. Peschardt, F. Sacherer and B. Zotter
Beam-Beam Exciting non linear resonances

Octupoles exciting 4\textsuperscript{th} order resonance

INFORMATION FROM BEAM RESPONSE TO LONGITUDINAL AND TRANSVERSE EXCITATION J. Borer, G. Guignard, A. Hofmann, E. Peschartd, F. Sacherer and B. Zotter
BTFs in RHIC: Octupole Scan at Injection

Curtesy of the RHIC teams W. Fischer, S. WHite

Reproduce an Octupole Scan at Injection:

- Space Charge
- Chromaticity
- OCTUPOLES
- The Beam Transfer Function (BTF) functionality option would be the only interesting functionality from the former PLL system. At the beginning the BTF would be an MD tool deployed “on demand” on the development (DEV) system.

- BTF would use the same hardware as the standard DEV FFT system. The only difference would be that the DEV FPGA would run the BTF code instead of the FFT one. The changes FFT/BTF and BTF/FFT could be done within a few minutes (providing that the appropriate software is prepared).

- Why the PLL would not be efficient for regular tune measurement and feed-back:
  - For the PLL the “natural” beam oscillations are just useless “noise”, while for the FFT systems most of the time they are sufficient for regular operation.
  - The PLL needs always an excitation, that is the required excitation level would have to be well above the “natural” oscillation amplitudes.
  - The PLL gives only one point on the beam spectra while the FFT gives the whole picture allowing to determine where the tune picks are with even quite complex algorithms.
  - The PLL would have to be accompanied by an FFT system anyway, showing the whole beam spectrum.
BTFs: summary

- Despite the spread we had in 2012 sever instabilities were always present
- We have several mechanisms which brings modification of particle distribution (colored noise, non-perfect damper, BB resonances)
- Tiny variations in distribution have important impact on Stability
- BTF depends on density variations \( \frac{d\omega}{dJ} \) → which can give a loss of Landau damping we want to observe the distributions of particles
- BTF can give also: spread, coherent modes, chroma measurements...

Set-up
We need to set-up the devise to do not perturb the beams properties (emittance)
Coherent modes could perturb the measurement: in squeeze in relaxed impedance and no head-on beam-beam
Need to explore in early stage of the collider...
On-going work:

- Multiparticle simulations to reproduce RHIC data and prepare for 2015 LHC (Claudia, Adrien): chromaticity effect, BB, Octupoles...

- Exploring also newer techniques from P. Georgen et al. for spread measurement “Beam Transfer Functions for relativistic proton bunches with beam-beam interaction”, to be published

- Multiparticle tracking to compute distribution densities with FMA weak-strong (Danilo, Javier)

- Mechanism for instabilities (Xavier, Tatiana, Claudia)

- With BI (Marek Gasior and Andrea Boccardi):
  - Set-up the BBQ system for BTF measurements (BI)
  - Provide analysis tools (Claudia, Tatiana)
  - Prepare for start-up BEST with weak Impedance to check BB...to be discussed