High Intensity Beams Issues in the CERN Proton Synchrotron

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Context-Introduction

- Intensity increase limited by **aperture restriction, collective effects (instabilities, space charge)**

- Here, studies of two intensity limitations on high intensity beams

  - at injection **(aperture restriction + space charge)**, more than 3% of the beam is lost, causing high radiation doses outside the ring
  - at transition energy, **fast vertical instability** causing large losses or large transverse emittance blow up, even with gamma transition jump (good method to cure the instability).

- Transition Studies
  - **Extensive measurements** of the dynamics of the instability, with and without gamma transition jump.
  - **Benchmark of the measurements** with macro-particle simulations with HEADTAIL.
  - Deduce **a effective impedance model** (Estimate the real part of the broad-band impedance).
  - Find possible **cures**.

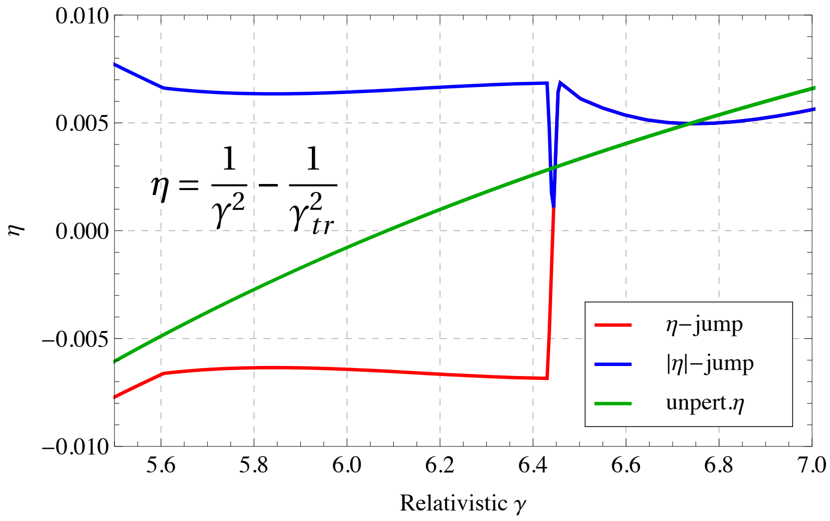
- Injection Studies
  - **Measurements of proton losses** with Beam Loss Monitors (BLMs) to identify when the losses occur
  - Losses when the beam goes through the injection septum (exactly at injection) AND then turn by turn at the minimum and maximum of the bump (orbit distortion at during 1/2ms)
  - **Space charge is making worth the losses.**
  - Tune shift measurements with intensity : deduce the **imaginary part of the effective broad-band impedance**.
- **Studies important in the framework of the PS Upgrade for LHC Injector Upgrade (High Luminosity LHC beam)**

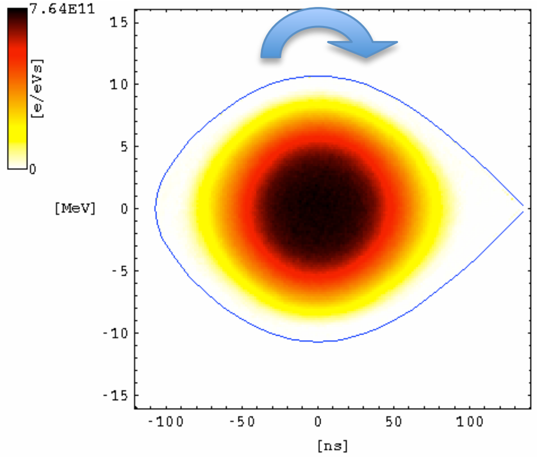
Transition Energy

- Particle oscillate around (ΔΦ,δ) in the bucket, the equation of motion for small angle is the one of a spring. Particle oscillate with a angular synchrotron frequency ω_s

$$\frac{d^2\Delta\phi}{dt^2} + \omega_s^2\Delta\phi = 0$$

- Close to transition energy, the longitudinal motion is frozen, $\omega_s \rightarrow 0$, **non-adiabatic regime**
- η defines the distance in energy from transition energy
- Stable phase shift to keep the longitudinal focusing on both side of transition energy
- In the PS, the use of a gamma transition jump is necessary to cross faster transition energy

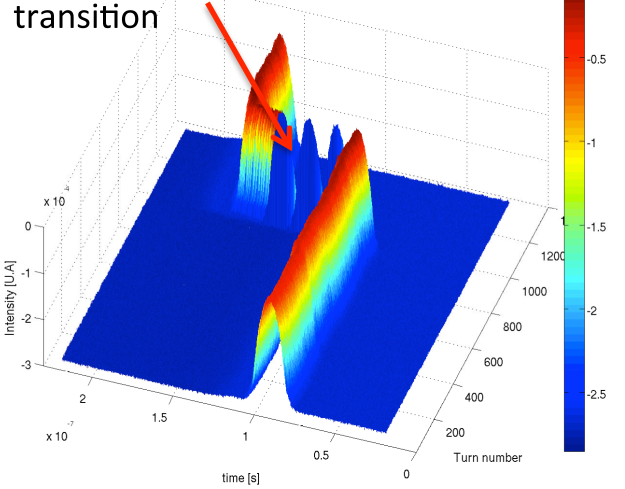




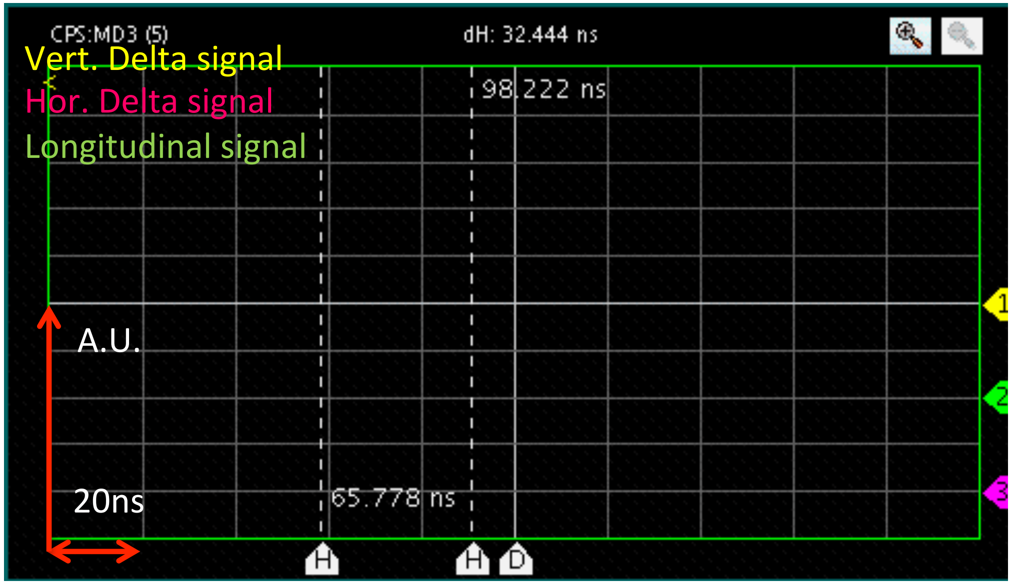
Tc non-adiabatic time~2.2ms
|t|>Tc adiabatic regime
|t|<Tc non-adiabatic regime

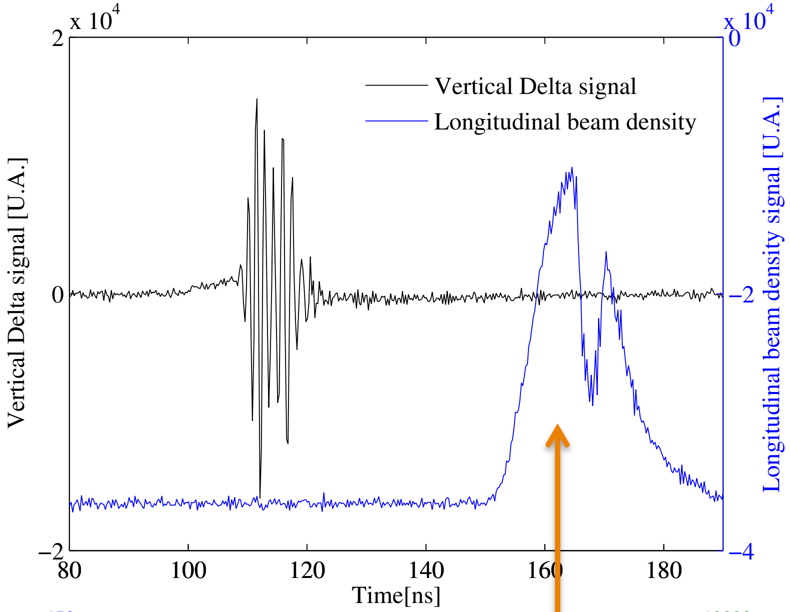
Particle are turning round in the RF bucket

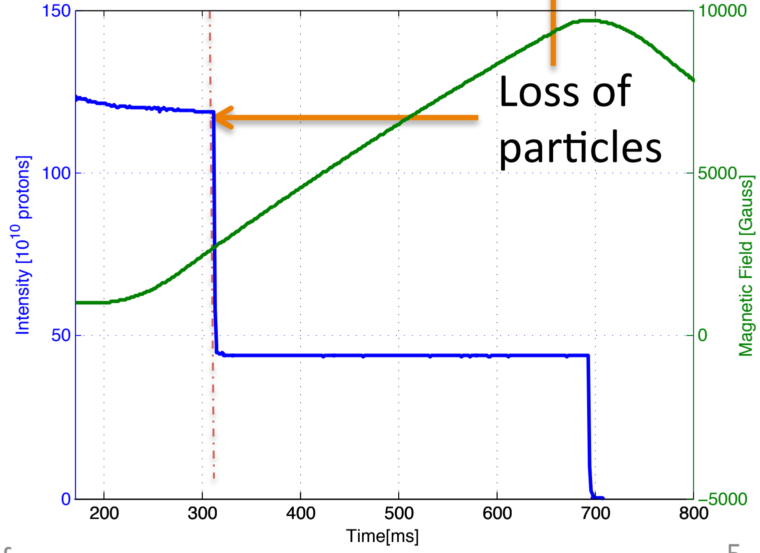
Stable phase shift at transition



Fast Vertical Instability Observation







Loss of particles

- Instrumentation: Wide band pickup, bandwidth 1GHz
- **Travelling wave** along the bunch with a frequency 700MHz.
- Oscillation close to peak density**, short range wake field.**
- Strong losses in few 100 turns, less than a synchrotron period.

Instability behavior similar to Beam Breakup (Linac), Transverse Microwave (coasting beam), TMCI (bunched beam)

Favorable conditions to develop the instability:

- Slow synchrotron motion: no exchange of particles between head and tail stabilizing instabilities
- No chromaticity: no tune spread.
- Lose of longitudinal and transverse Landau damping

Goals of Measurements

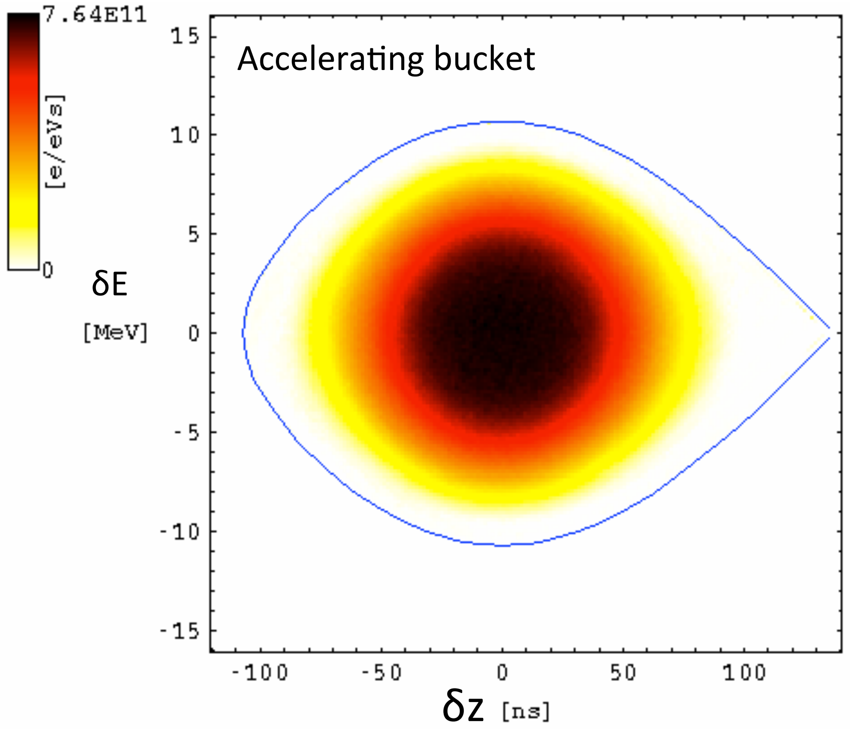
- **Characterize the mechanisms of the instability** by varying chromaticity, intensity, longitudinal emittance (ε_l) etc.
- Study behavior of instability versus intensity to compute rise time
- Measurement of intensity threshold

Defines BB model

- Momentum compaction factor threshold (η_{th}) to identify the longitudinal regime: **adiabatic/ non-adiabatic** and define η_{th} as done for the longitudinal microwave instability (1)
- First mechanism is the **beam interaction with transverse impedance**, for the PS, unknown, here assumed to be (BB) **broad-band** (resonator).
- Find an **effective transverse impedance model** with the support of macro-particle simulations.
- Identify **mechanisms** able to damp the instability: chromaticity, longitudinal emittance, use of the gamma jump

Beam Conditions

Beam parameters	
Transition Energy	~ 6.1 GeV
Number of bunches	1
Harmonic	h=8
Transverse tunes (Qx-Qy)	~ 6.22-6.28 (Set by PFWs)
Vertical Chromaticity (2 different sets) around transition ξ_y	0 and ~ -0.1 (Set by PFWs)
RF cavity voltage around transition	145 kV
Full bunch length around transition	20-30 ns
Longitudinal emittance (ε_l) at 2σ(1)	1.3 -2.5 eVs
Beam intensity	50e10 to 160e10 protons
Transverse Emittance ($\varepsilon^{x,y}_{norm}$ 1σ)	1.17 to 2.33 mm.mrad

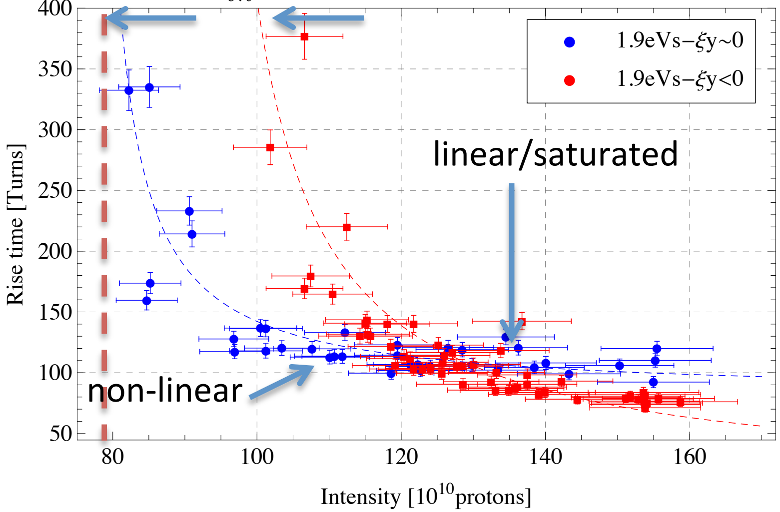


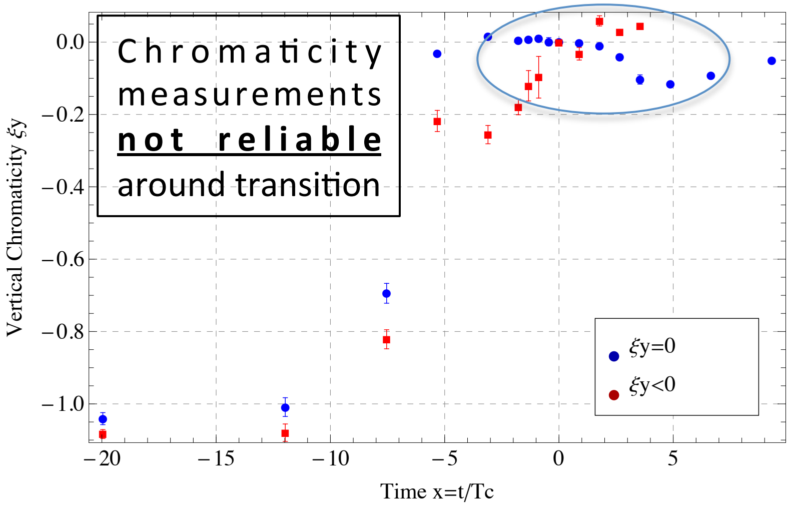
Reconstruction of the longitudinal phase space for **longitudinal emittance measurements**

(1) Measured at the beginning of the acceleration

Rise time

$$\lim_{I \to I_{th}} \tau = +\infty$$





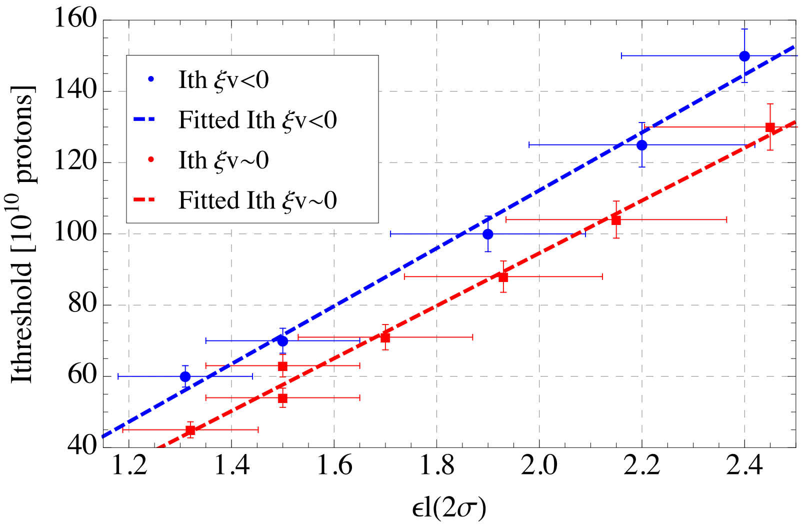
Chromaticity measurements **not reliable** around transition

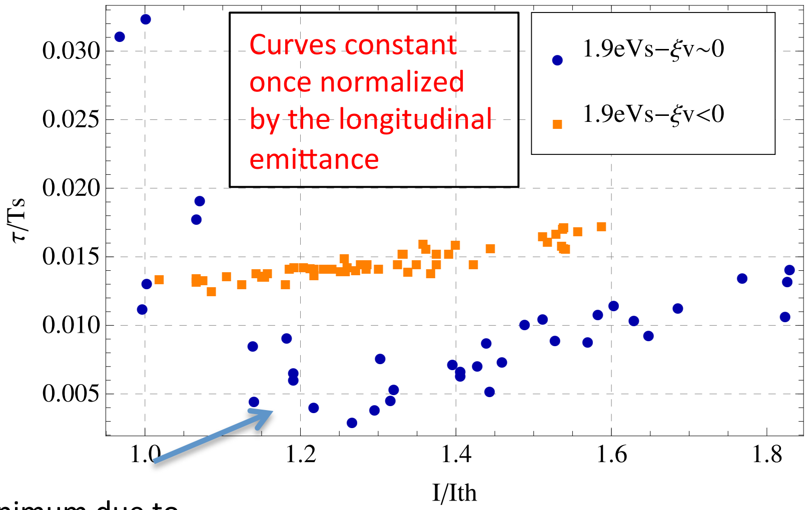
Tc: non-adiabatic time 2.2ms in the PS

- Rise time measurements performed for different longitudinal emittance and for 2 different sets in vertical chromaticity.
- Closer the beam is from transition energy, **less reliable is the measurement of the chromaticity**
- Weak reproducibility of the machine in terms of longitudinal emittance (20%)
- Surprisingly, rise time faster in linear part for the case with chromaticity.

$$I_{linear}/I_{th} \simeq 1.3$$

Threshold in Intensity I_{th}





Curves constant once normalized by the longitudinal emittance

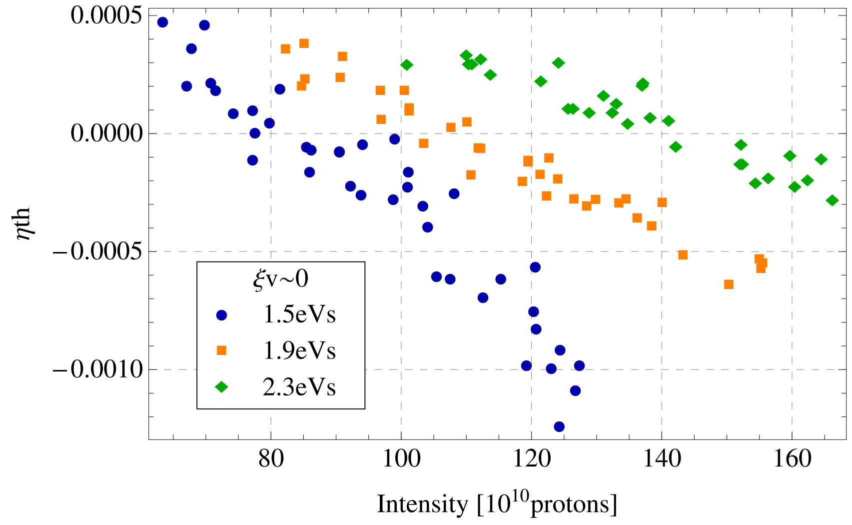
Minimum due to synchrotron period Ts

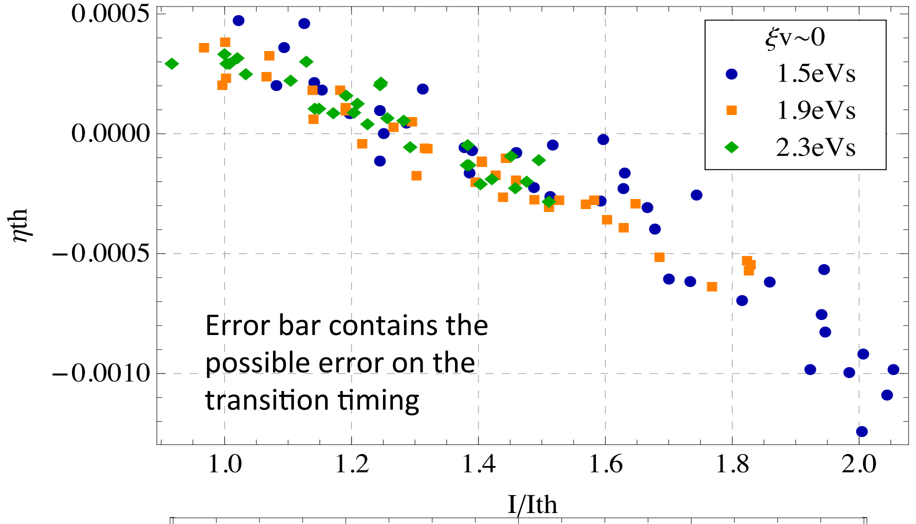
- Instability with threshold in intensity
- I_{th} increases linearly with the longitudinal emittance (here peak density), predicted by the coasting beam theory by E. Metral for zero chromaticity

$$I_{th} = \frac{32\sqrt{2}}{3}\,\frac{Q_{y0}|\eta|\epsilon_l}{e\beta^2 c} \times \frac{f_r}{|Z_y^{BB}|}$$

- Chromaticity (or the working point) increases the instability threshold: changing chromaticity in the PS means a change of tune and non linear chromaticity
- Non-linear chromaticity components in measurements are nevertheless small
- Rise time are faster than synchrotron period **(no headtail instability)**
- According to the coasting theory (microwave-TMCI), a beam crossing transition is always unstable, because η→ 0

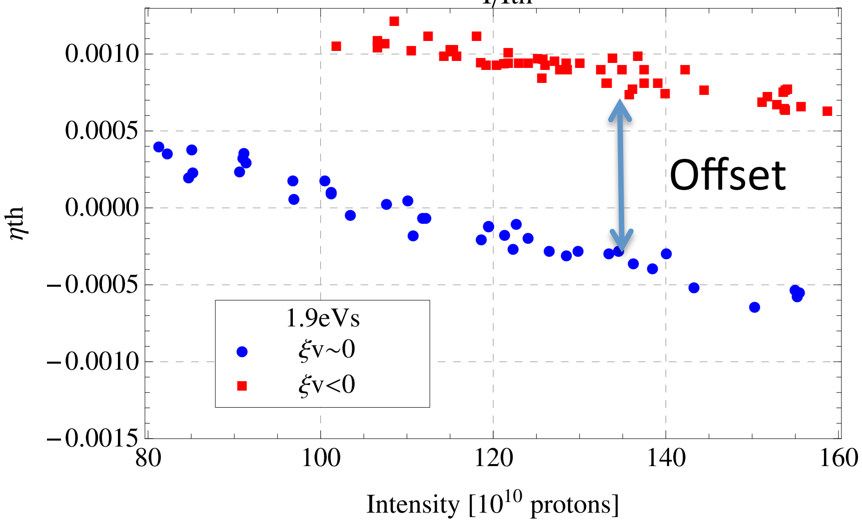
Eta threshold



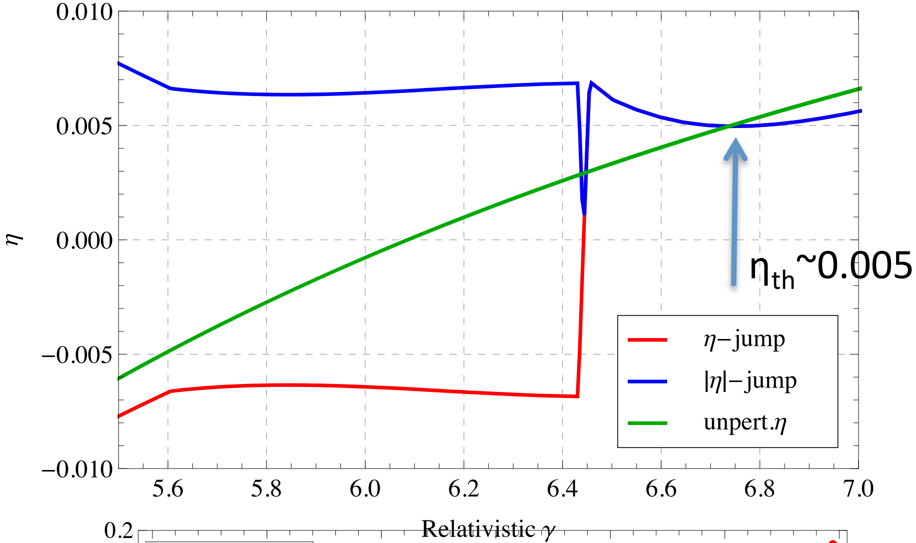


Error bar contains the possible error on the transition timing

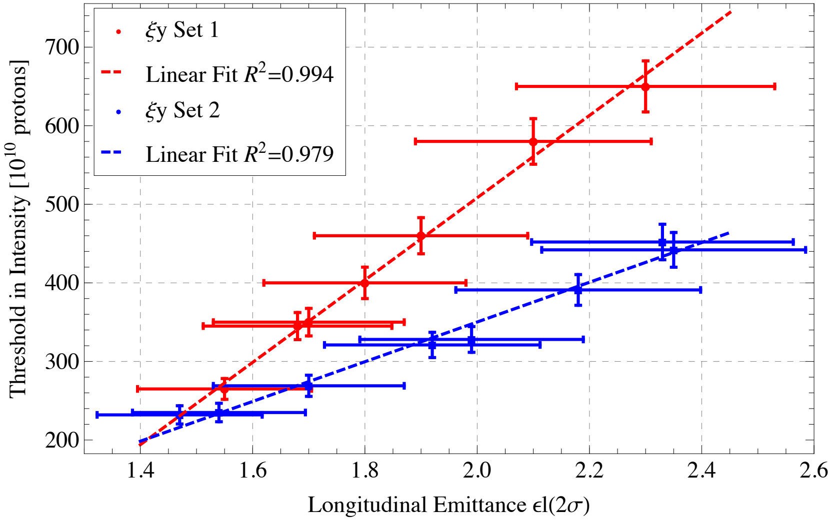
- Instability is triggered at different η, namely η_{th} for each intensity.
- η_{th} linear with beam intensity.
- Minimum η_{th} :
  - Meas. 0.0004 , zero chromaticity
  - Meas. 0.001, negative chromaticity
- **Resulting η is right only if the estimation of transition time is good.**
- With chromaticity, possibility to accelerate more intensity for the same η_{th}

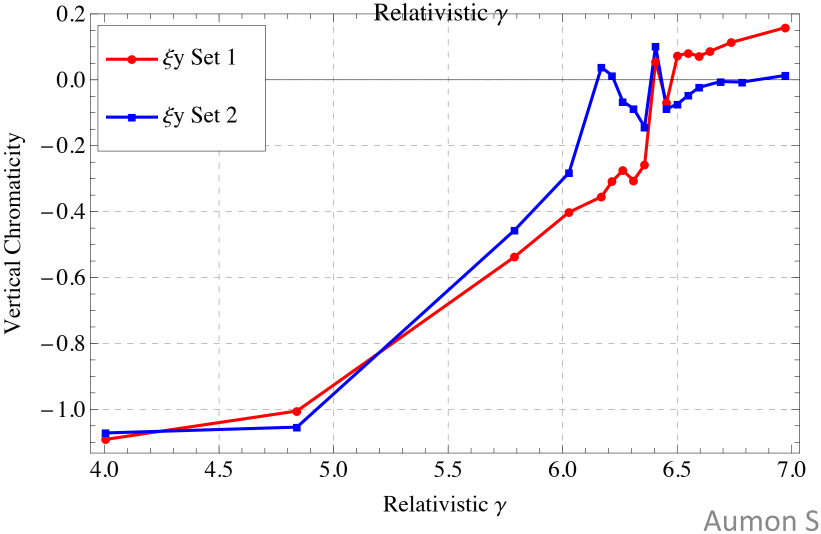


Threshold in Intensity with gamma jump



η_{th}~0.005





- Use of a gamma jump allows to increase considerably I_{th}
- Instability appears around η_{th}~0.005
- Frozen synchrotron motion for a shorter time allows to increase by a factor 3 and up to 10, I_{th} according to the working point.
- Negative large chromaticity before and positive chromaticity after transition helps to increase intensity threshold.
- Threshold in η are also increased by a factor 10.

Conclusions of Experiments

- **First time** that extensive measurements are done for this instability: instability measurements for zero and small negative vertical chromaticity varying the longitudinal emittance (peak density) and the beam intensity.
- Instability is easily developed for **zero (small) chromaticity** (not a head-tail kind) and for **slow synchrotron motion** (BBU or coasting beam), and **high peak density** (coasting beam).
- **Chromaticity** is a way to increase threshold in intensity and in η.
- **Increase synchrotron motion** (η) with the gamma jump, here close to a factor 10 with a good set in working point.
- η_{th} ≠0 for the set zero-chromaticity, could be due to an error in estimation of the transition time (~300 turns is definitively possible), need to be check with macro-particle simulations.
- It appears that fast synchrotron motion (large η) + jump in chromaticity from large negative value to large positive value is a way to cure the instability.
- Need of macro-particle simulations to benchmark the measurements and understand better the dynamics of the instability.
  - Check the ratio $I_{linear}/I_{th} \simeq 1.3$
  - threshold in η and in intensity.
  - Possibility to have a predictive model

Macro-particle Simulations (HEADTAIL)

- Use of a transverse **broad-band impedance model (resonator)**
- I modified the code to adapt it as close as possible as the measurement conditions

$$Z_{\perp} = \frac{\omega_r}{\omega} \frac{R_s}{1 + iQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)}$$

Useful outputs to consider through transition

- Turn by turn Δ_y signal
- Vertical normalized emittance
- Vertical centroid

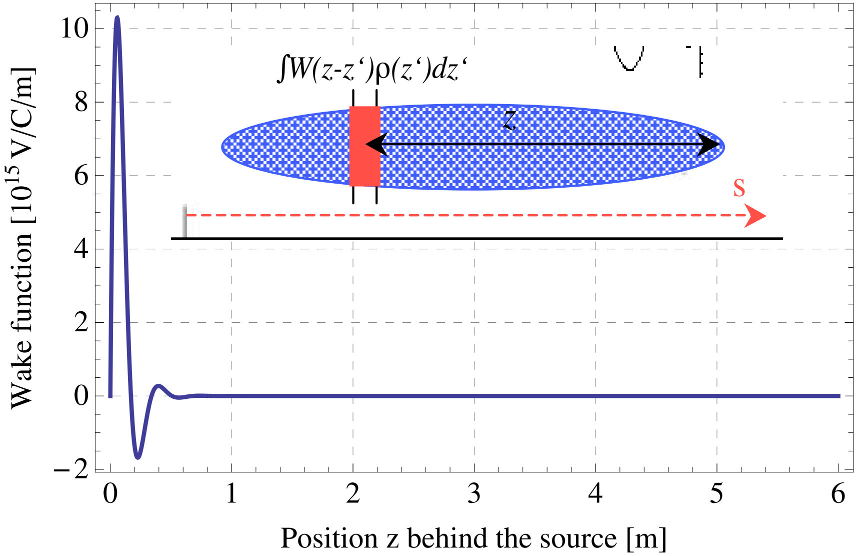
ω angular revolution frequency

ωr resonator frequency

Rs shunt impedance (MΩ/m)

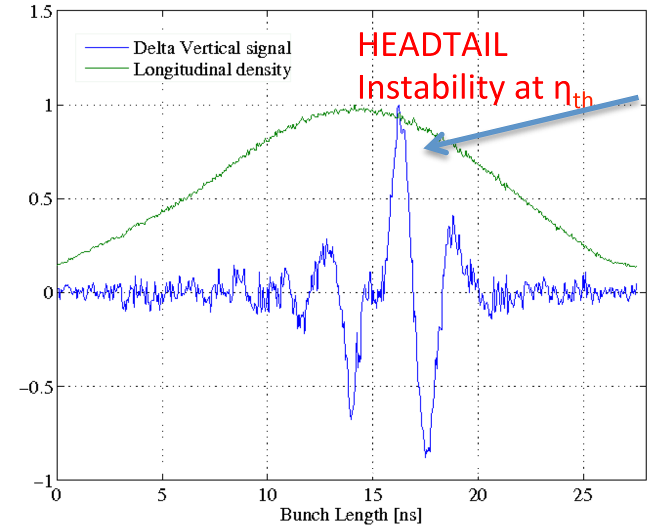
Q quality factor

Simulation parameters	
RF bucket	accelerating
Momentum rate	46 GeV/c/s
Twiss <βx,y>	16/16 m
Qx,y	6.22/6.28
Gamma transition	~ 6.1
Vacuum chamber	flat
Impedance model	broad-band
Quality factor Q	1
Resonator frequency	1 GHz
Shunt impedance Rs	To be matched



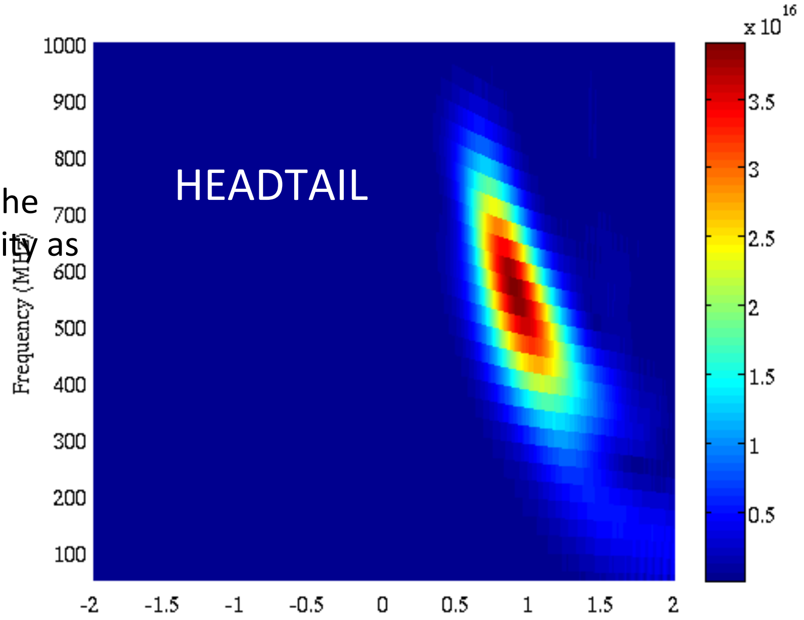
Simulation with HEADTAIL

$\xi v = 0$

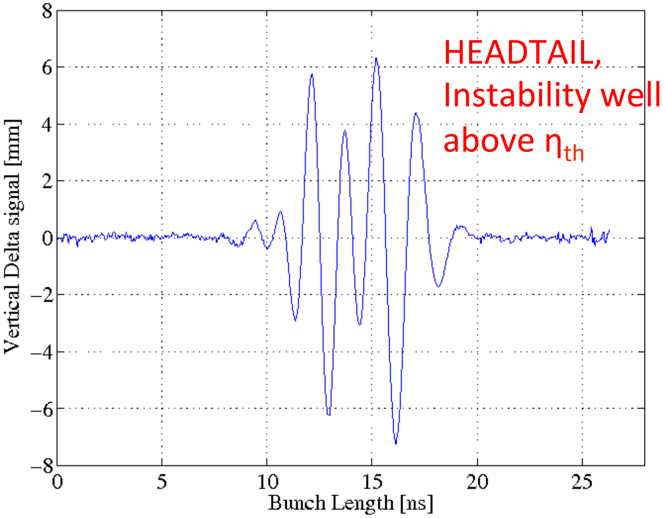


HEADTAIL Instability at η_{th}

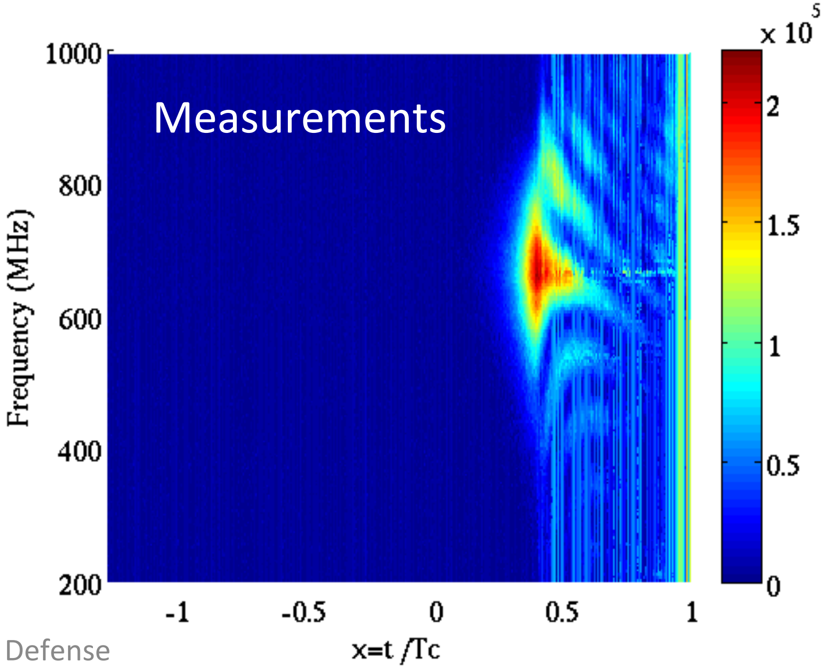
Oscillation Starts at the maximum peak density as the measurements



Tc: nonadiabatic time ~2.2ms



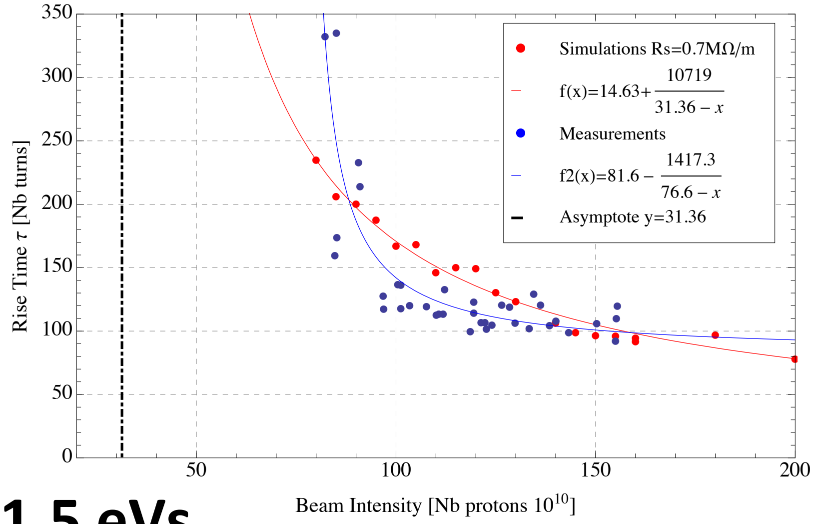
HEADTAIL, Instability well above η_{th}



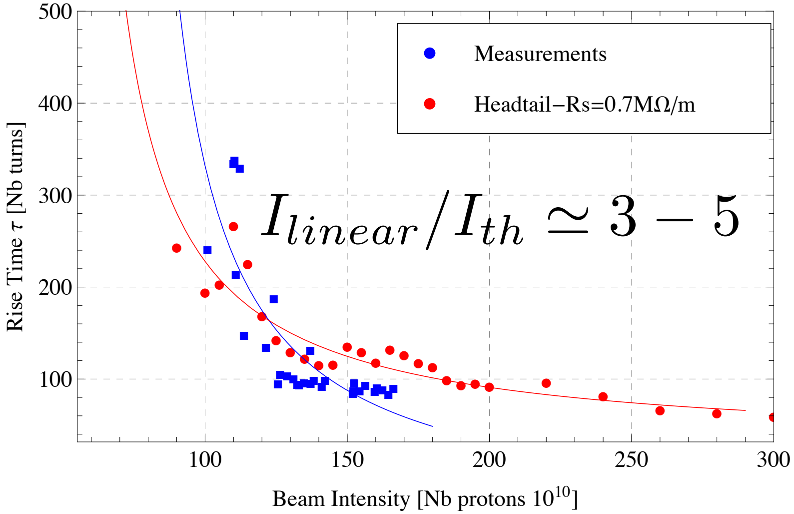
fr=1GHz
Rs=0.7MΩ/m
Q=1

Simulated Rise time

1.9 eVs

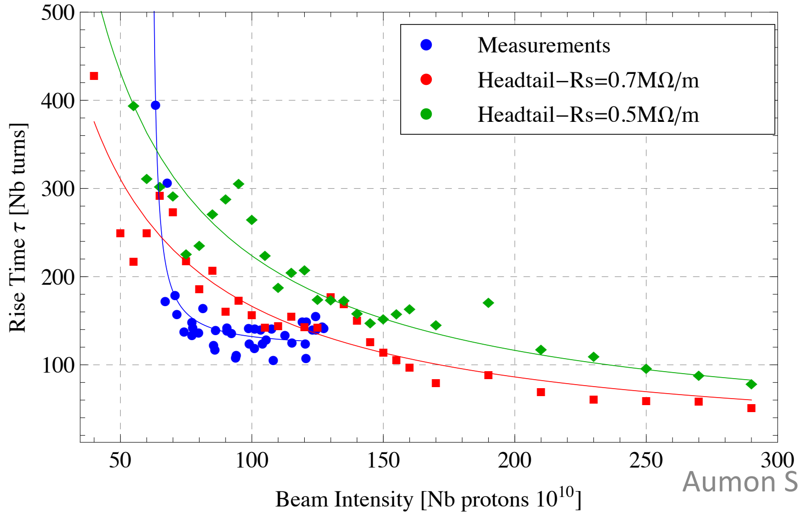


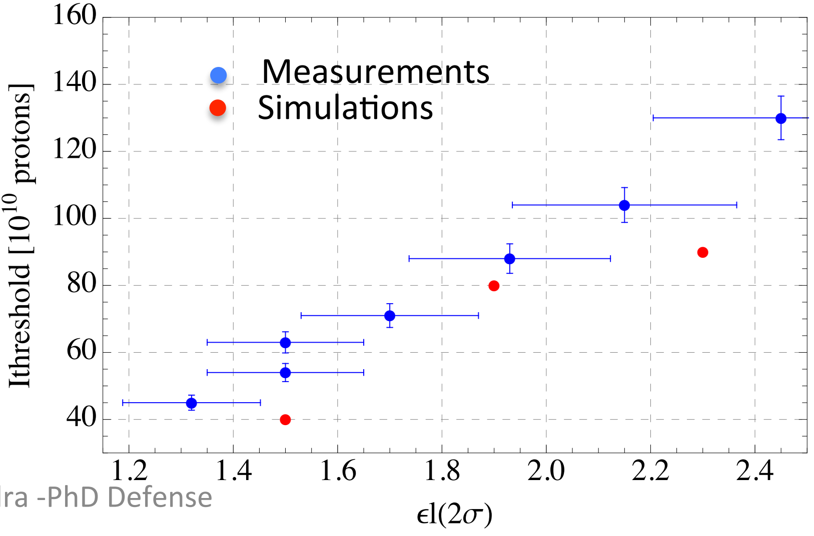
2.3 eVs



$$I_{linear}/I_{th} \simeq 3-5$$

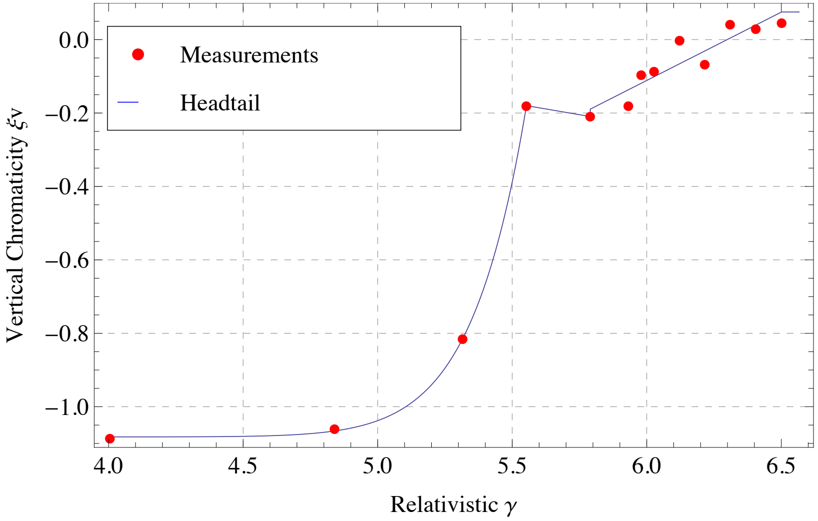
1.5 eVs

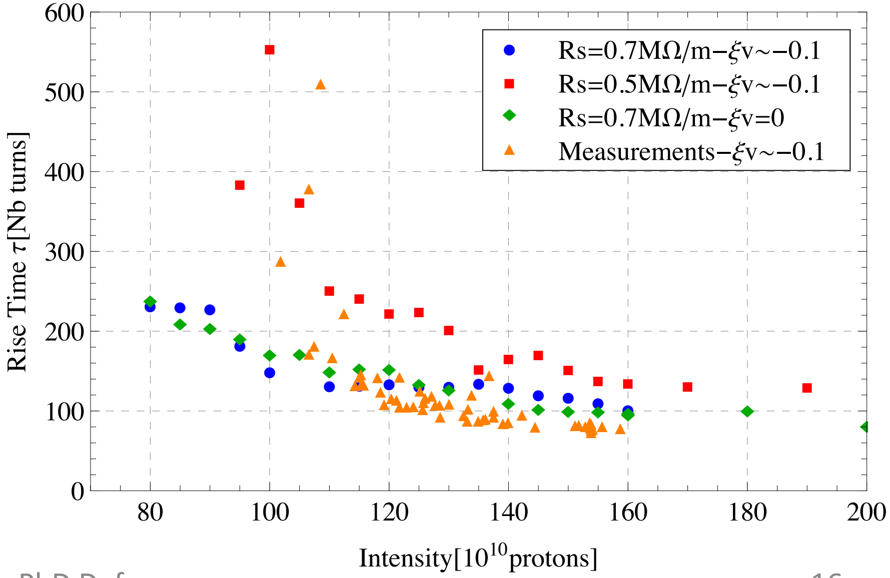




Dynamics with chromaticity

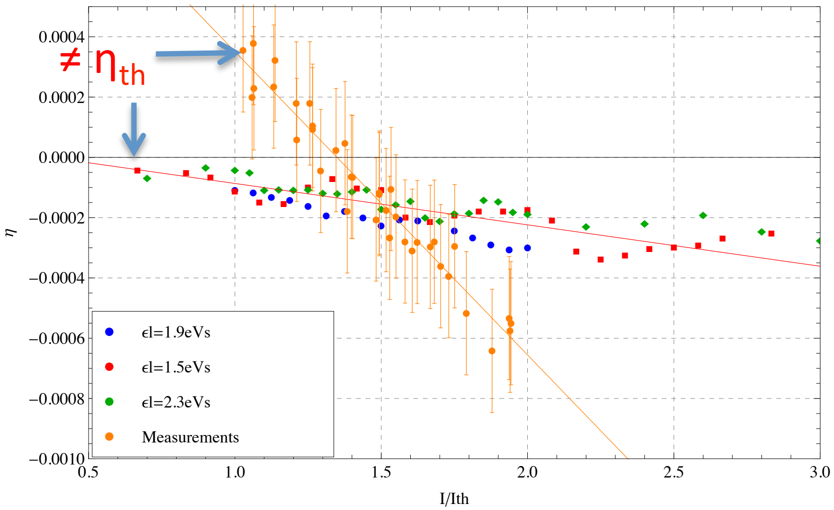
- Implementation in the code of a chromaticity change with acceleration
- Delta vertical signal shows that the oscillation of the instability is dumped with chromaticity compared to the same profile with the same energy with zero chromaticity.
- Not the same dumping at the intensity threshold as in the measurements for the same chromaticity .
- Effective impedance between 0.5 and 0.7 MOhm/m





Threshold in Eta

No Chromaticity



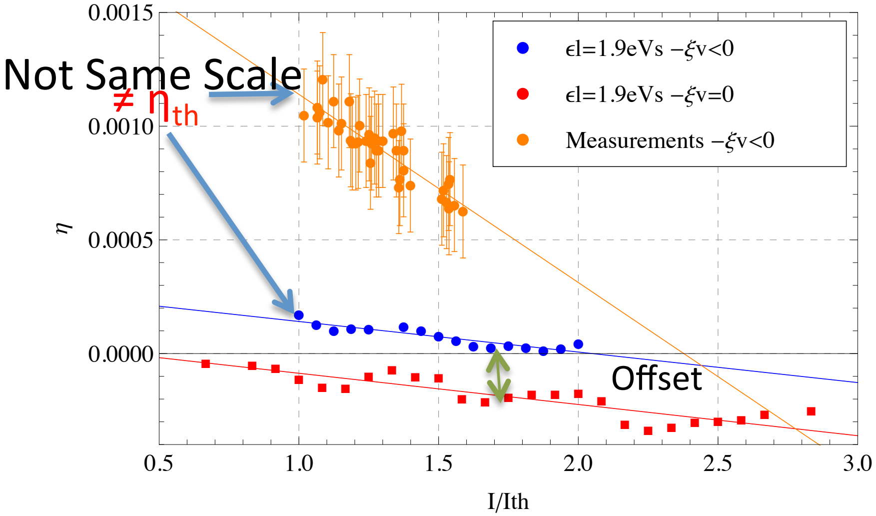
Agreement with measurements:

- η_{th} increases with chromaticity, **allows to accelerate more intensity with non zero ξ_y**
- Offset between $\eta_{th}(\xi_y=0)$ and $\eta_{th}(\xi_y<0)$
- Linear behavior eta th with intensity

Disagreement with measurement and simulations:

- Not the same η_{th} close to the intensity threshold
- Not the same linear behavior about the slope
- **Offset in η of 0.0002 in simulations , 0.0006 in measurements**

Small Negative Chromaticity



Best impedance model found

Rs=0.7MΩ/m

Q=1, short range wake field

Fr=1GHz

Conclusions

a) Conclusions of the study

- Equivalent broad-band impedance found Rs=0.7MΩ/m, fr=1GHz, Q=1
- Intensity threshold predictable at 50%
- Possible cure of the instability: adequate chromaticity (working point) + gamma jump.

Limitations

- Impedance model is the biggest unknown of the study.
- I_{linear}/I_{th} ~ 1.3-1.5 (Measurements) versus I_{linear}/I_{th} ~ 3-5 (HEADTAIL)
- η_{th} close to the threshold in intensity are very different, partly explained the setting of the transition timing in measurements.
- Different offset in η_{th}, but behavior comparable to coasting beam theory
- The effect of chromaticity is less important in the simulations than in the measurements (strong effect !)
- Not presented here, but the simulations with gamma jump show travelling wave frequency higher than in the measurements.

- Influence of space charge not included in simulations.
- Non-linearities generated by PFWs.
- linear and non-linear coupling not included in simulations.

Outlooks – Future works

- Complete impedance model
- Studies of Chromaticity jump
- Collaboration with GSI: similar studies are carried out at GSI and measurements at the CERN PSBooster and PS will be made in June.
- Octupoles

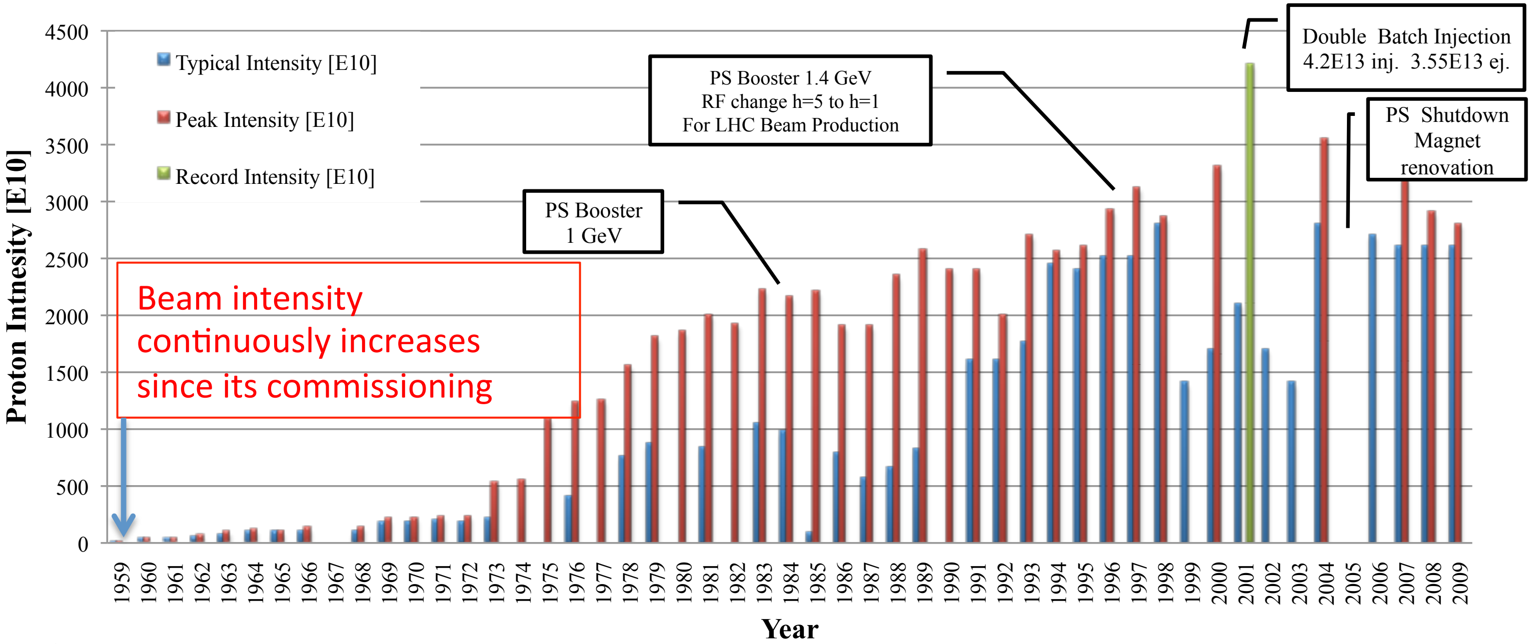
Studies of losses at Injection

Facts

- **Large losses of proton while the beam is injected into the PS.**
- Strongly dependent of the beam intensity, therefore high intensity beams most concerned (ToF, CNGS), at least **3-4% of losses**.
- High radiation dose outside the ring (the so-called Route Goward)
- Later motivation**, injection energy upgrade from 1.4 to 2 GeV kinetic**, the radiation dose will be increased by a factor ? (1) with the same scenario of losses.

Aims: find the mechanisms of the protons beam losses.

PS Proton Intensity Evolution Over 50 Years



Beam intensity continuously increases since its commissioning

PS Booster
1 GeV

PS Booster 1.4 GeV
RF change h=5 to h=1
For LHC Beam Production

Double Batch Injection
4.2E13 inj. 3.55E13 ej.

PS Shutdown
Magnet
renovation

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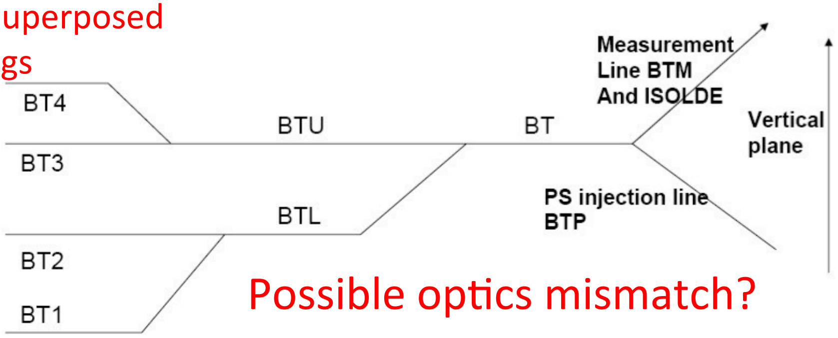
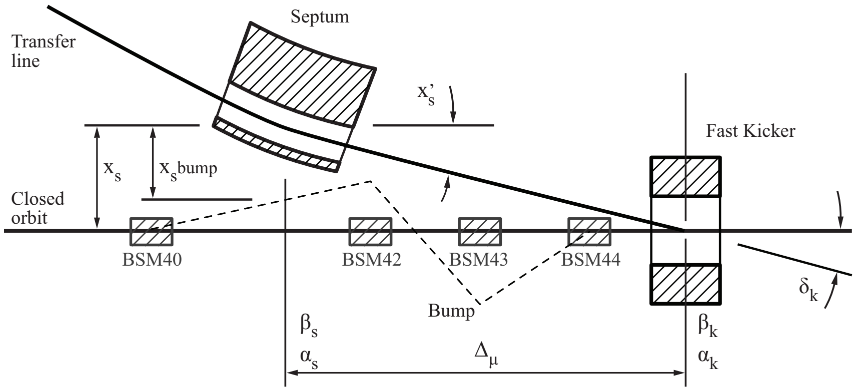
(1) Work of S. Damjanovic

Single Turn Injection System

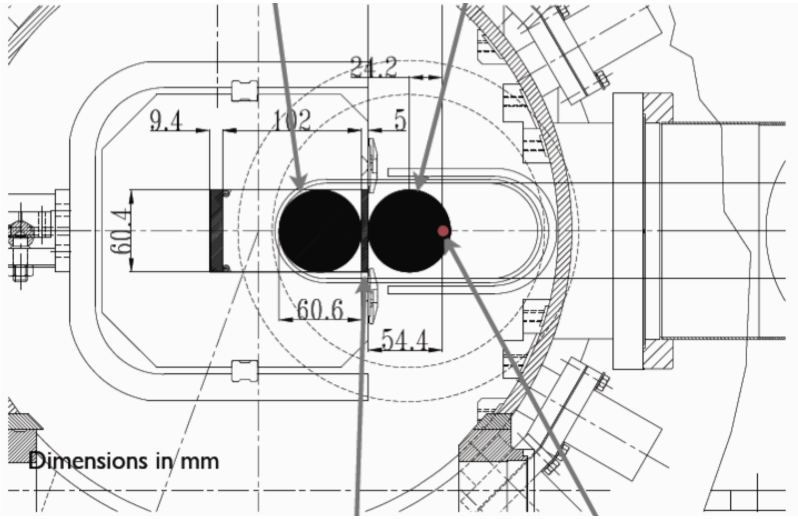
Booster
4 superposed
rings

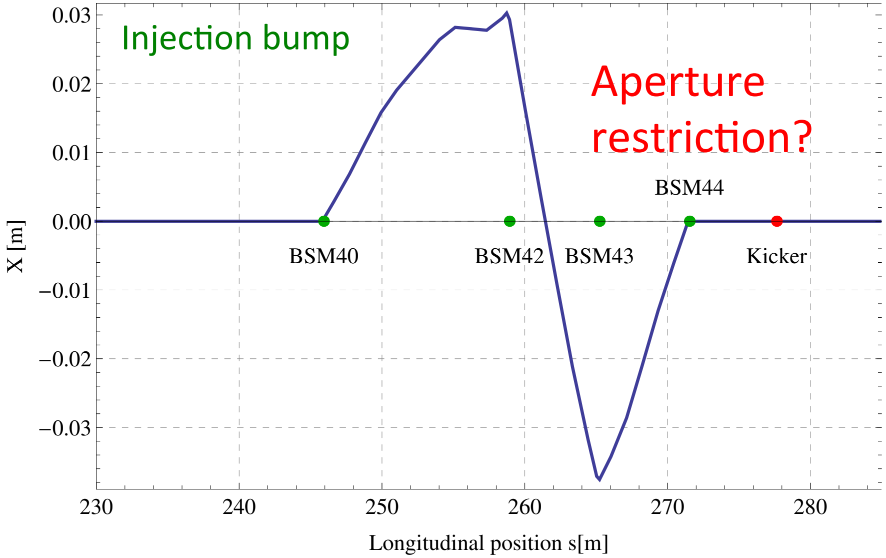


Possible optics mismatch?



Cross Section Injection Septum



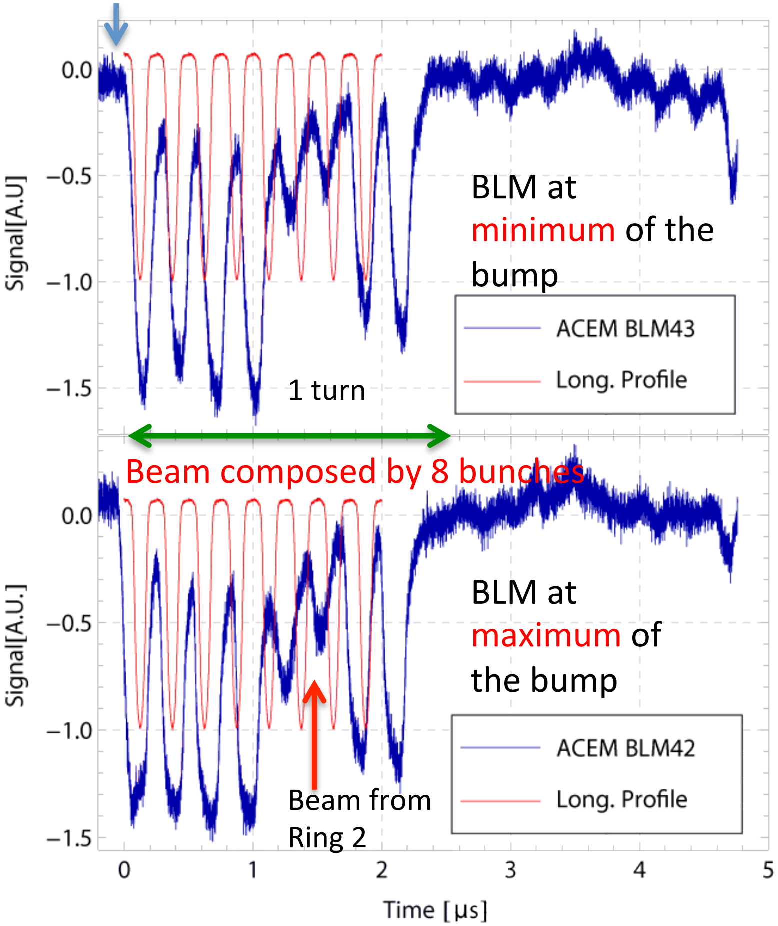


Injection bump

Aperture restriction?

Loss Experiments

Injection, transit through the septum



BLM at minimum of the bump

1 turn

Beam composed by 8 bunches

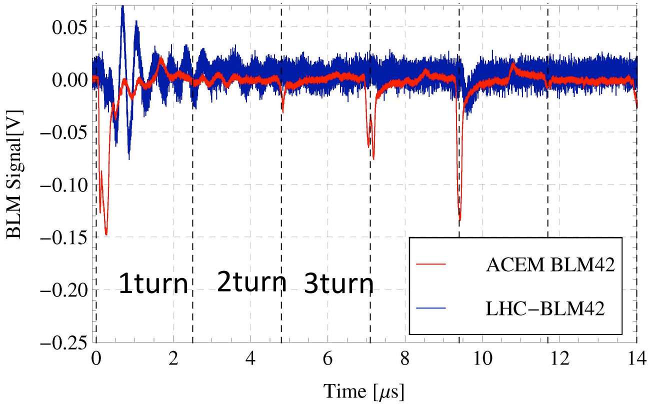
BLM at maximum of the bump

Beam from Ring 2

- BLMs located at the maximum (SS42) and minimum (SS43) of the bump, i.e. where the available aperture is minimum.
- Measurements done while the beam is injected (first turn) on single bunch ToF and multi-bunch CNGS beam.
- Losses while the beam is going through the injection septum, the beam is injected at the maximum of the bump.
- The BLM are able to distinguish the losses bunch to bunch.

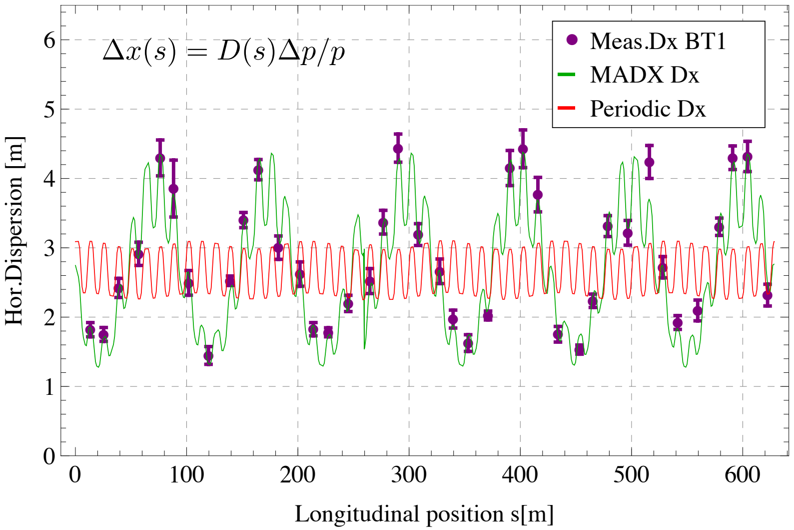
Conclusions:

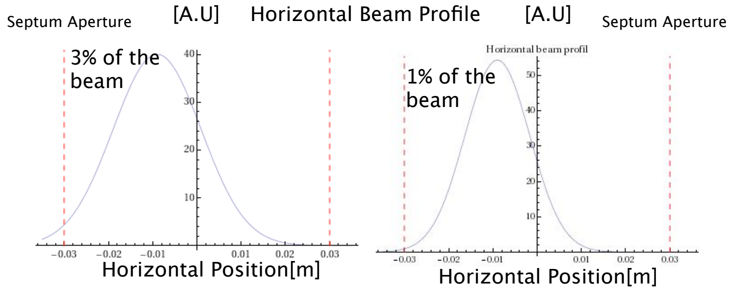
Losses occur while the beam is going through the septum and then turn by turn



Septum losses

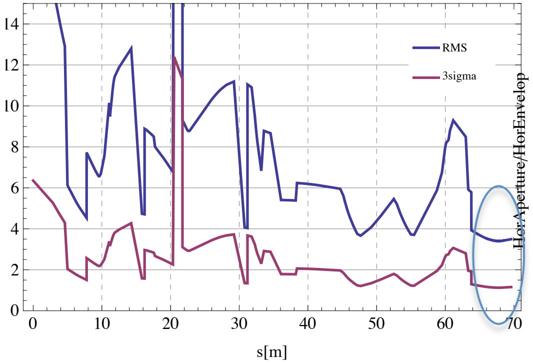
- Betatron and dispersion matching measurements in order to identify a possible mismatch between the injection line and the PS: determination of initial conditions, in particular for the horizontal dispersion.
- Good agreement with the optics model computed with PTC-MADX:
  - No large mismatch was found expect on dispersion for Ring 3.
  - Beam size measurements right at injection: tail of the beam are cut on the septum blade (~1%)
- It was found that the beam is pushed as close as possible of the septum blade to decrease the angle given to the beam by the injection kicker: **compromise between losses and kicker strength.**

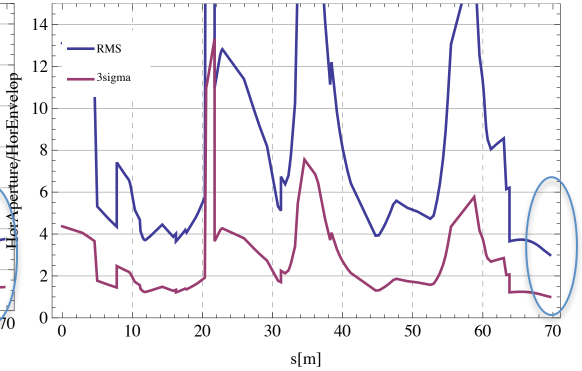




ToF beam full intensity
800e10
eHor(RMS)=12mm.mrad

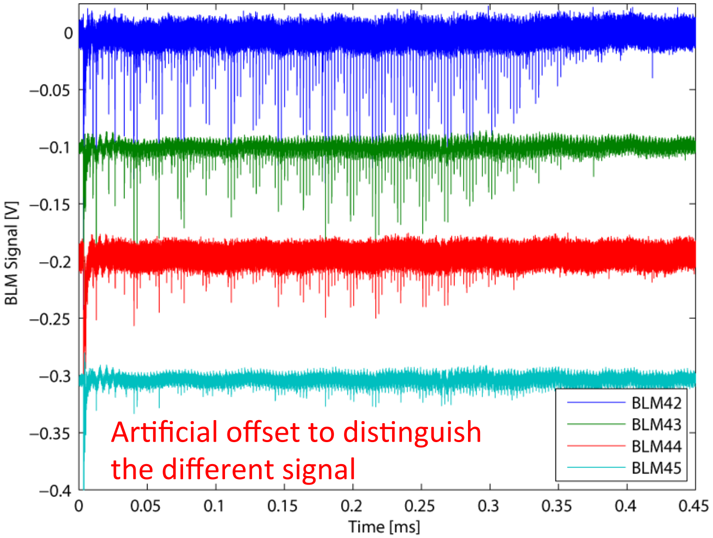
MD beam
100e10
eHor(RMS)=5mm.mrad



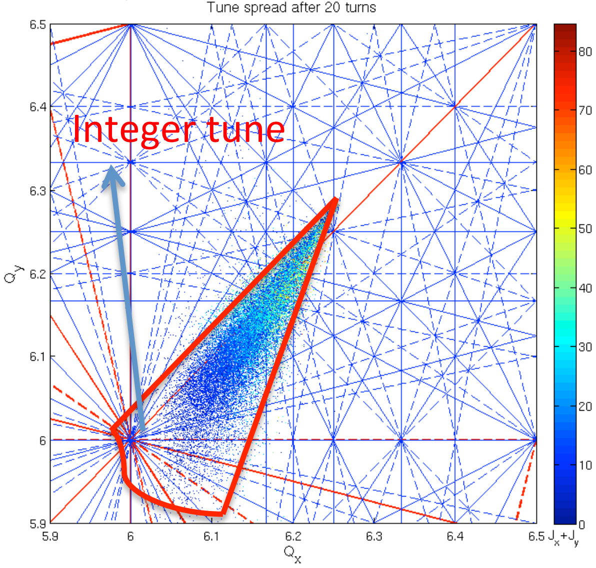


Turn by Turn losses

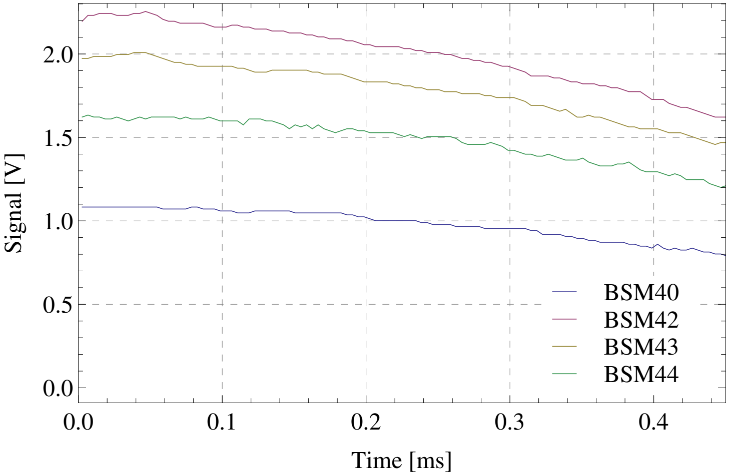
- Turn by turn losses while the injection bump is decreasing.
- The losses occurs at the maximum and at the minimum of the bump: tails of the horizontal distribution are cut around 3 sigma.
- Presence of direct space charge at injection
- Preliminary tune footprint simulation with PTC-Orbit show the possibility that particles cross the integer resonance
- It can cause emittance blow up and high amplitude oscillation which hit the vacuum chamber at the first aperture restriction



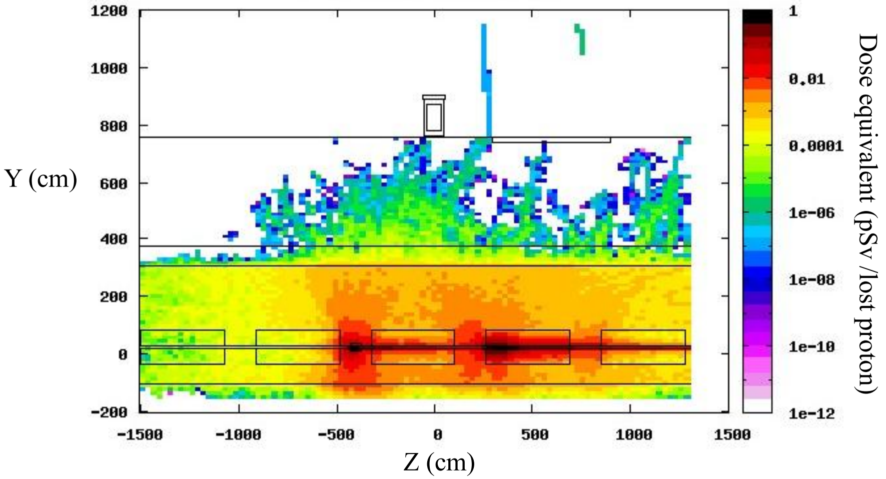
Artificial offset to distinguish the different signal

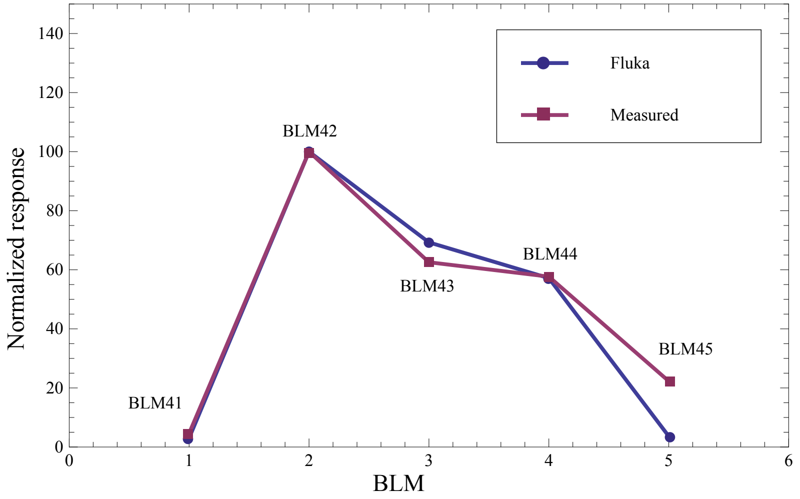


Integer tune



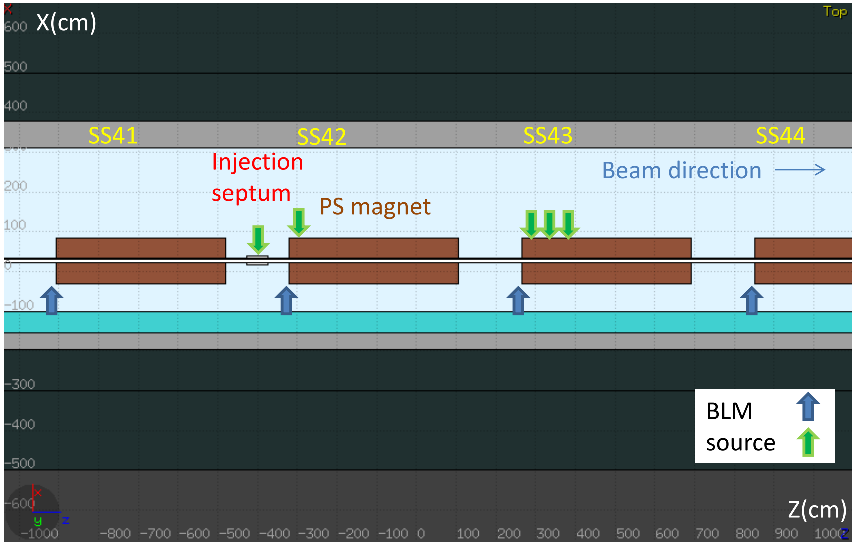
Fluka Simulations



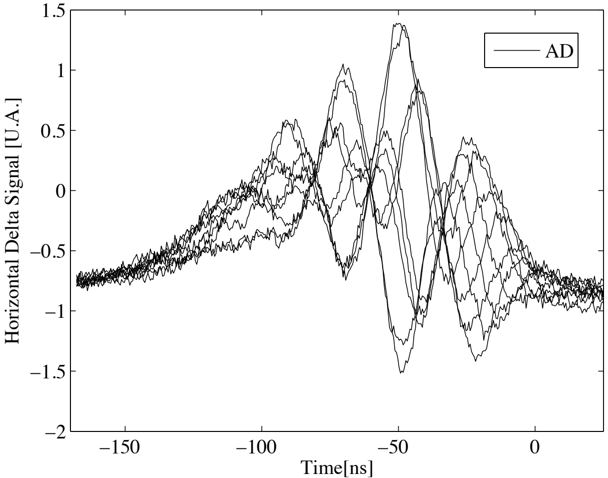


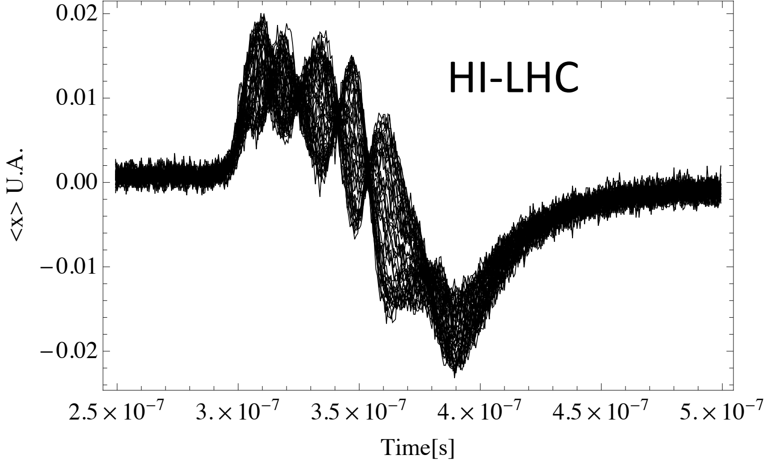
Goal: Reproduce the signal of the BLM at injection (Supervision of a student)

Injection	30%	At Septum 42, an electrostatic dipole in the straight section 42 to deflect the incoming beam form the PSB into the PS. The tail of the beam is hitting on the inside at the end of the septum
Maximum of the bump	10%	At the beginning on the outside of Septum 42, the tail of the beam is cut at the blade
Minimum of the bump	60%	On the inside on the first metre of Magnet 43. Spread on three equally spaced spots (30%,20%,10%)



Coherent tune shift measurements



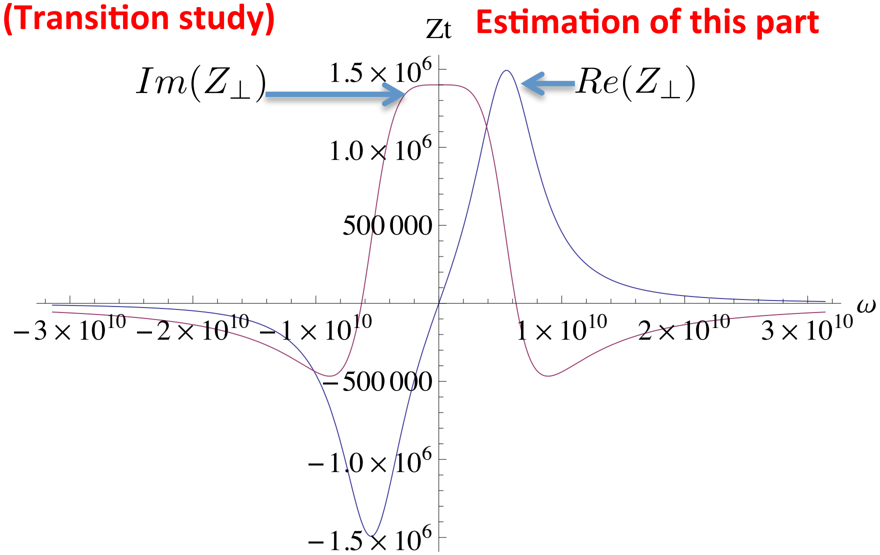


Motivation

- **Impedance effects** (wall, space charge) are important issues at injection
- First step toward a more complete PS impedance model

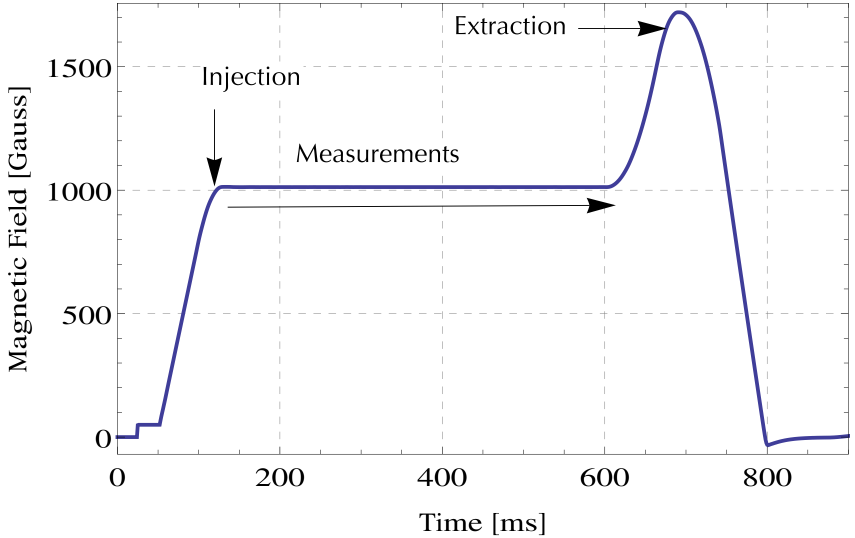
Instability rise time measurements (Transition study)

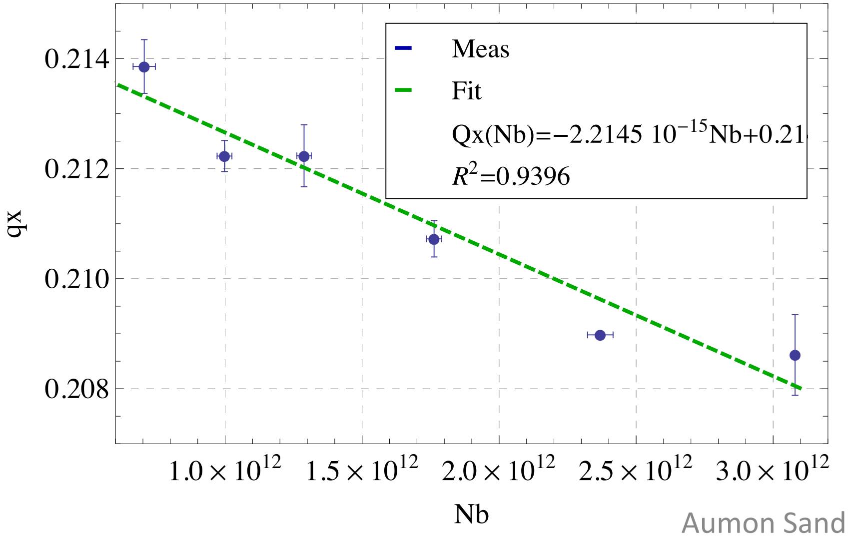
Real Tune shift measurements Estimation of this part

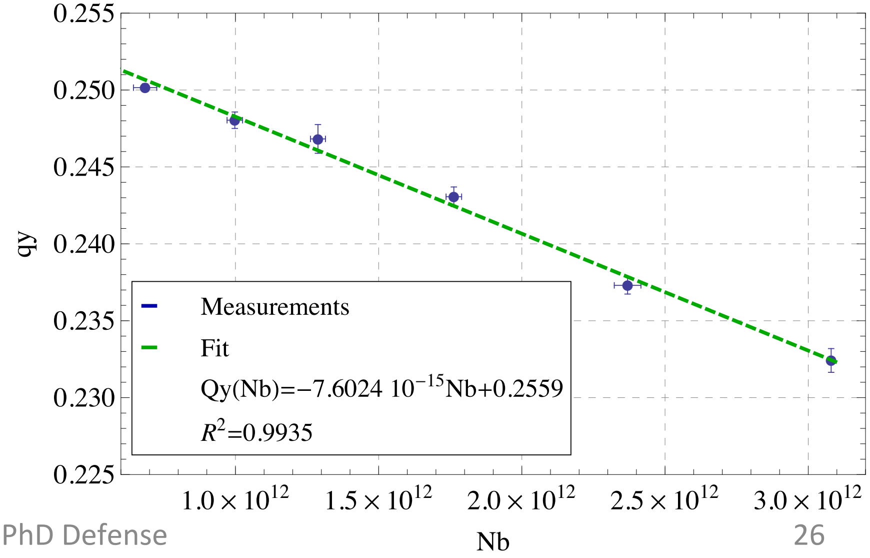


Coherent tune shift at injection

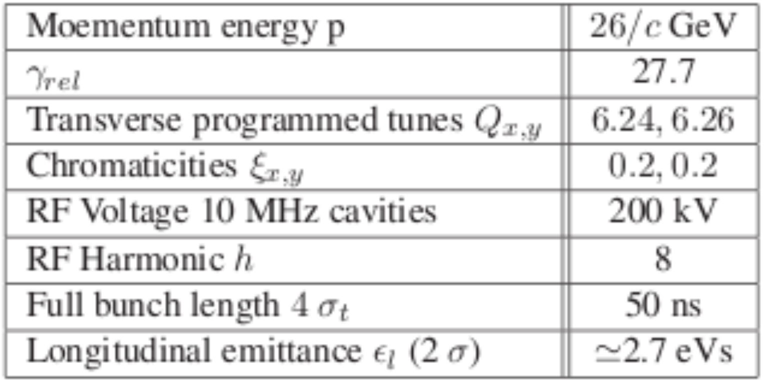
- Kinetic energy 1.4GeV
- Tune measurements all along the energy plateau



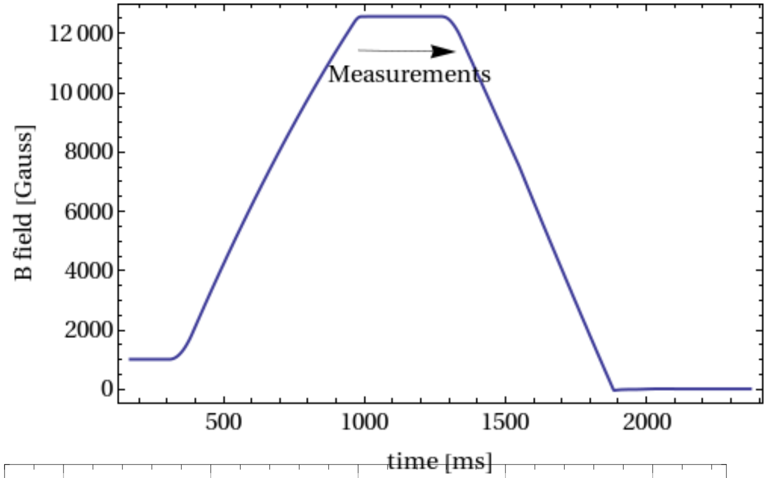


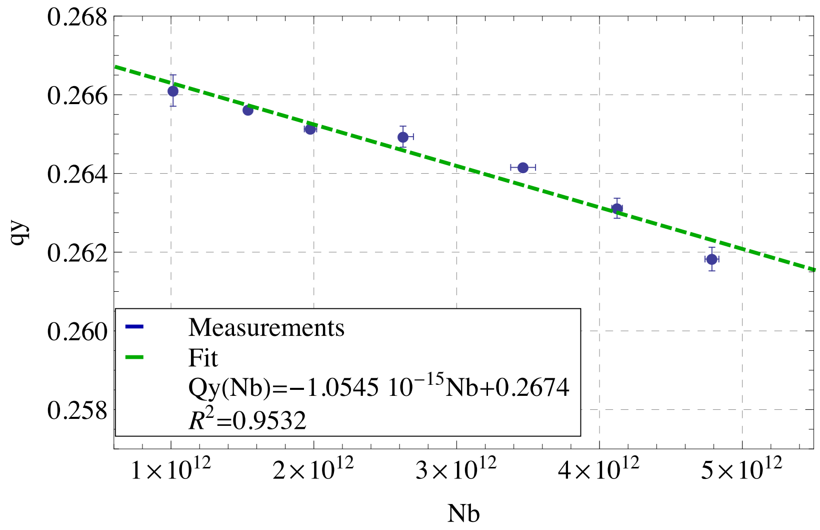


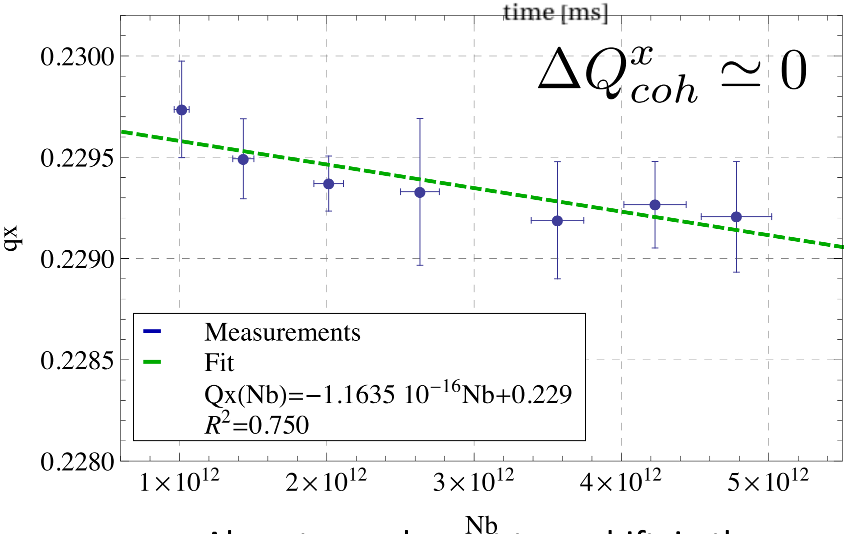
Beam parameters at LHC extraction energy



Moementum energy p	$26/c$ GeV
γ_{rel}	27.7
Transverse programmed tunes $Q_{x,y}$	6.24, 6.26
Chromaticities $\xi_{x,y}$	0.2, 0.2
RF Voltage 10 MHz cavities	200 kV
RF Harmonic h	8
Full bunch length 4 σ_t	50 ns
Longitudinal emittance ϵ_l (2 σ)	$\simeq$2.7 eVs







- Almost no coherent tune shift in the horizontal plane.

Effective Impedance

From the measured tune shift with intensity, the effective impedance can be deduced from the Sacherer formula of the interaction of the bunch spectrum in frequency with a broad-band impedance:

Zeff

$$\Delta Q_m = -\frac{1}{1+m}\frac{j}{2Q_0\omega_0^2}\frac{e\beta I}{\gamma m_0\tau_b} Im\left(\frac{\sum\limits_{p=-\infty}^{\infty} Z(\omega')h(\omega'-\omega_\xi)}{\sum\limits_{p=-\infty}^{\infty} h(\omega'-\omega\xi)}\right) \quad (1)$$

Zeff depends of bunch length

$$Z_{eff} = \frac{\sum\limits_{p=-\infty}^{\infty} Z(\omega')h(\omega'-\omega_\xi)}{\sum\limits_{p=-\infty}^{\infty} h(\omega'-\omega\xi)} \quad \begin{cases} \omega' &= \omega_0 p + \omega_\beta \\ \omega_\xi &= \xi\omega_\beta/\eta \\ h(\omega) &= e^{-\omega^2\sigma^2/c^2} \end{cases}$$

Important Conclusions

$$\Delta Q^x_{coh} \simeq 0$$

$$\Delta Q^x_{coh} \simeq \Delta Q^x_{dip} + \Delta Q^x_{quad}$$

$$\boxed{\Delta Q^x_{coh} \simeq 0 \rightarrow Z^x_{dip} + Z^x_{quad} = 0}$$

Kinetic Energy K	1.4 GeV
Bunch length	**~ 180 ns**
β_{rel}	0.91
γ_{rel}	2.47
ω_0	2728 e3 rad.s-1
Horizontal Z_{eff}	3.5 MΩ/m
Vertical Z_{eff}	12.5 MΩ/m

Momentum p	26GeV/c
Bunch length	**~ 50 ns**
β_{rel}	0.9993
γ_{rel}	27.729
ω_0	2996 e3 rad.s-1
Horizontal Z_{eff}	< 1 MΩ/m
Vertical Z_{eff}	6.1 MΩ/m

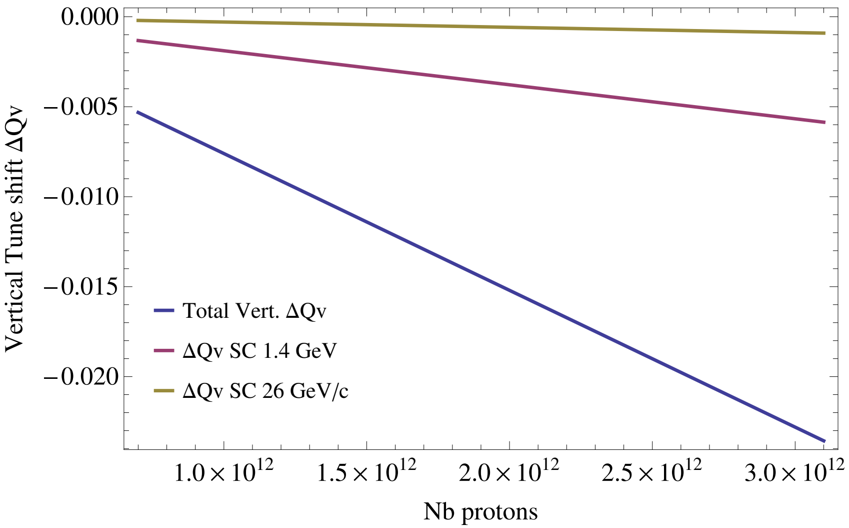
Increase by a factor 2 with respect to measurements done in 1990 and 2000

(1) From Sacherer formula (CERN/PS/BR 76-21)

Space Charge Tune Shift Estimation

$$\Delta Q^{y}_{coh} = \Delta Q^{sc}_{coh} + (\Delta Q^{Z_y}_{dip} + \Delta Q^{Z_y}_{quad})$$

$$\Delta Q_{coh} = -\frac{N_b R r_0}{\pi Q_y \gamma \beta^2}\left(\frac{\epsilon_1}{h^2} + \frac{\epsilon_2}{g^2} + \frac{\xi_1}{h^2}\frac{1-\beta^2}{B^2}\right)$$



- “Non penetrating field”
- Laslett coefficients for elliptical chamber
  a centered beam in the vacuum chamber
  valid for h/w < 0.7
  (B. Zotter CERN ISR-TH/72-8)

$$\epsilon^V_1 = -0.156\left(\frac{h}{w}\right)^2 + 0.21$$

$$\epsilon^V_2 = 0.41\left(\frac{\rho}{R}\right)$$

$$\xi^V_1 = -0.10\left(\frac{h}{w}\right)^2 + 0.617$$

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Estimation:

ΔQ-Space charge ~ ¼ Total measured ΔQ at injection. Space charge for beam used for measurement

Conclusions Injection Studies

- Large beam losses were measured on high intensity beams (more than 3%), which induce also high radiation outside of the ring. The goal of this study was to identify the loss process, limited an intensity increase.
- BLM experiments measuring the proton losses while the beam is going through the injection septum+ matching measurements:
  - combination of large beam size for high intensity beam, aperture restriction.
  - the beam is placed close to the septum blade to save some strength of the injection kicker.
  - tails of transverse distribution are cut at least at 3 sigma, explaining 1-2% of losses.
- Turn by turn losses while the injection bump is decreasing: measured losses at the maximum and minimum of the bump (minimum of available aperture).
- Direct space charge repopulated the transverse phase space extending the duration of the losses.
- Tune shift measurements with intensity in order to evaluate the imaginary part of the impedance and estimate the Laslett tune shift due to space charge (about ¼ of the total tune shift)

- Possible cures

  - For space charge: increasing the injection energy to 2GeV is a gain of 63% in the tune spread (PS-LIU Project)
  - 2GeV injection energy is a gain in beam size due the shrinking of the transverse emittance.
  - New optics in the transfer line to make a small beam size at the injection point in both x,y planes-(2 different optics for LHC and for high intensity beams)
  - The PS optics has to adapted (QKE optics) to avoid optical mismatch
  - Impedance model also needed to predict instabilities at injection, mostly head-tail kind