

damping of injection oscillations and transverse stability in the PBR

Ozgur Etisken & Frank Zimmermann
Brussels, 26 June 2019

help and input from **Adrian Oeftiger**, Nicolas Mounet,
Lotta Mether, Salim Ogur, Yannis Papaphilippou, and
Benoit Salvant

also see Ozgur Etisken, “Collective effect estimates for the
FCC-ee pre-booster ring,” poster presentation

proposed PBR baseline injects small beam with large transverse offset and deploys strong wigglers to enhance radiation – look for alternative

model

use PyHEADTAIL to track 25k particles over 20k turns

SPS “Q40” optics, $\alpha_C=8 \times 10^{-4}$, 400 MHz RF, $V_{RF}=20$ MV, energy 6 GeV, 2×10^{10} ppb, $Q_x' = +1$, $Q_x'' = +60$, $Q_x''' = -1.2 \times 10^5$, $Q_y' = +1$, $Q_y'' = +300$, $Q_y''' = +4 \times 10^4$, “KOF” = +2, “KOD” = -1 (modeling the natural detuning with amplitude)

Impedance: circular broadband resonator $10 \text{ M}\Omega/\text{m}$, $f_{res}=1.3 \text{ GHz}$, $Q=1$

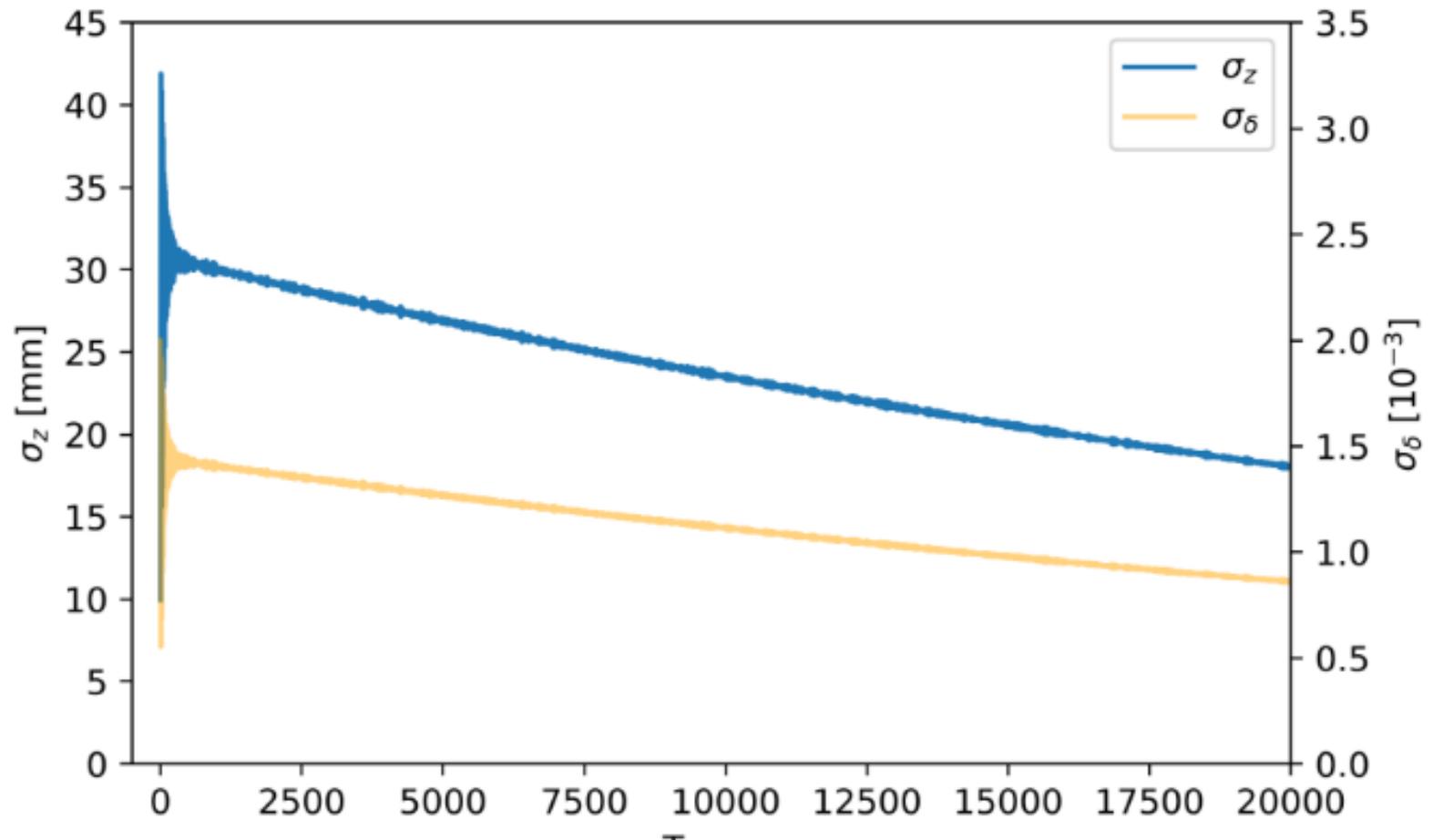
Beam parameters at injection into the SPS.

Parameters at 6 GeV without and with wigglers.

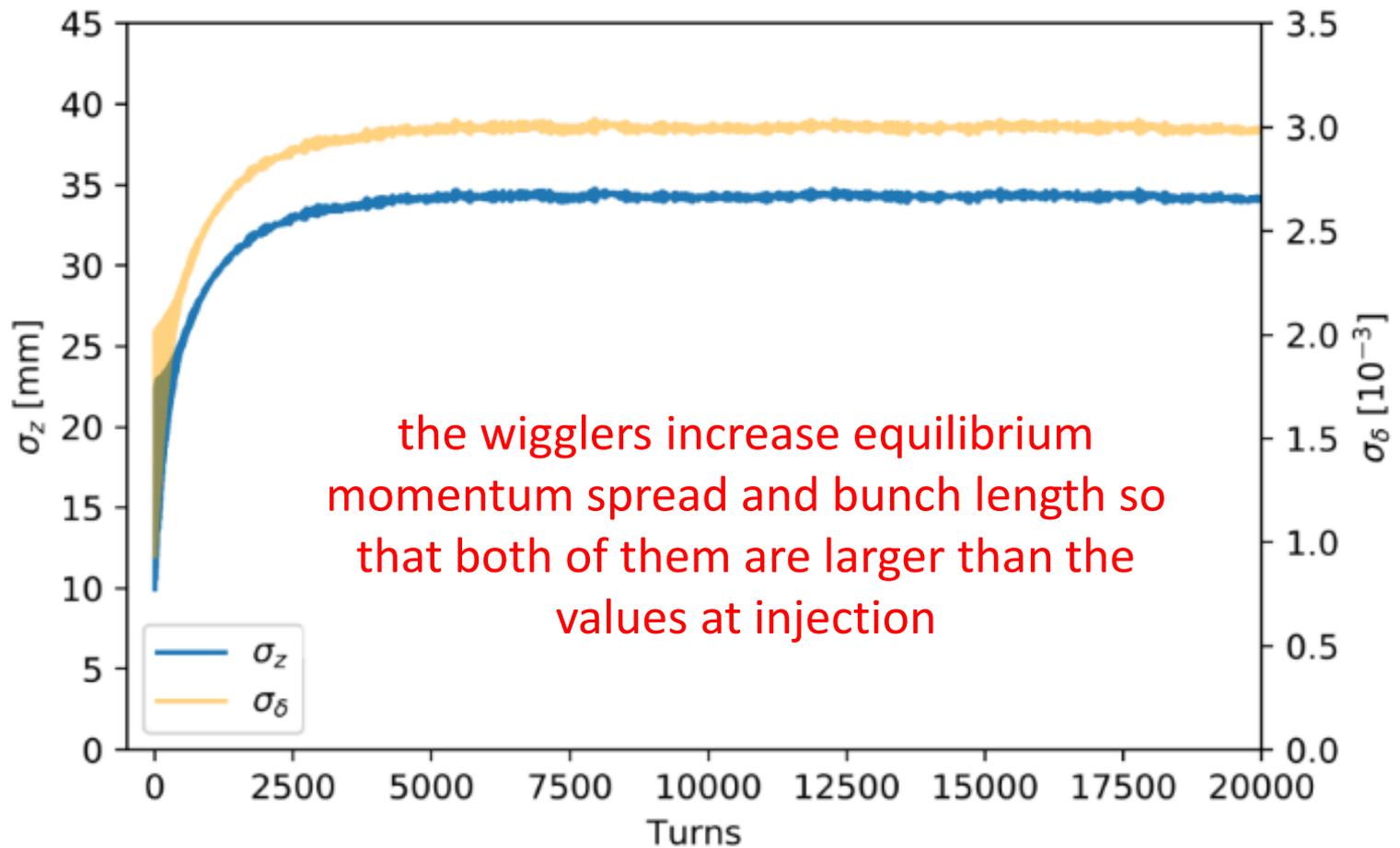
Variable	value
Energy E_b	6 GeV
Geometric emittance $\varepsilon_{x,y}$	2.5 nm
Initial injection offset	$12 \sigma_y$
Rms momentum spread σ_δ	0.2%
Rms bunch length σ_z	10 mm
Betatron tunes $Q_{x,y}$	40.13, 40.18
Momentum compaction α_C	0.0008

Variable	bare SPS	w. wigglers
Eq. emittance ε_{eq} [nm]	2.43	0.13
Eq. energy spread σ_δ , [%]	0.018	0.30
Hor. damping time [s]	1.8	0.1
Hor. damping time [turns]	80,000	4,400
Energy loss / turn U_0 [MeV]	0.15	2.7
RF voltage [MV]	20	30
Eq. bunch length $\sigma_{z,eq}$ [mm]	3	33
Synchrotron tune Q_s	6×10^{-5}	8×10^{-5}

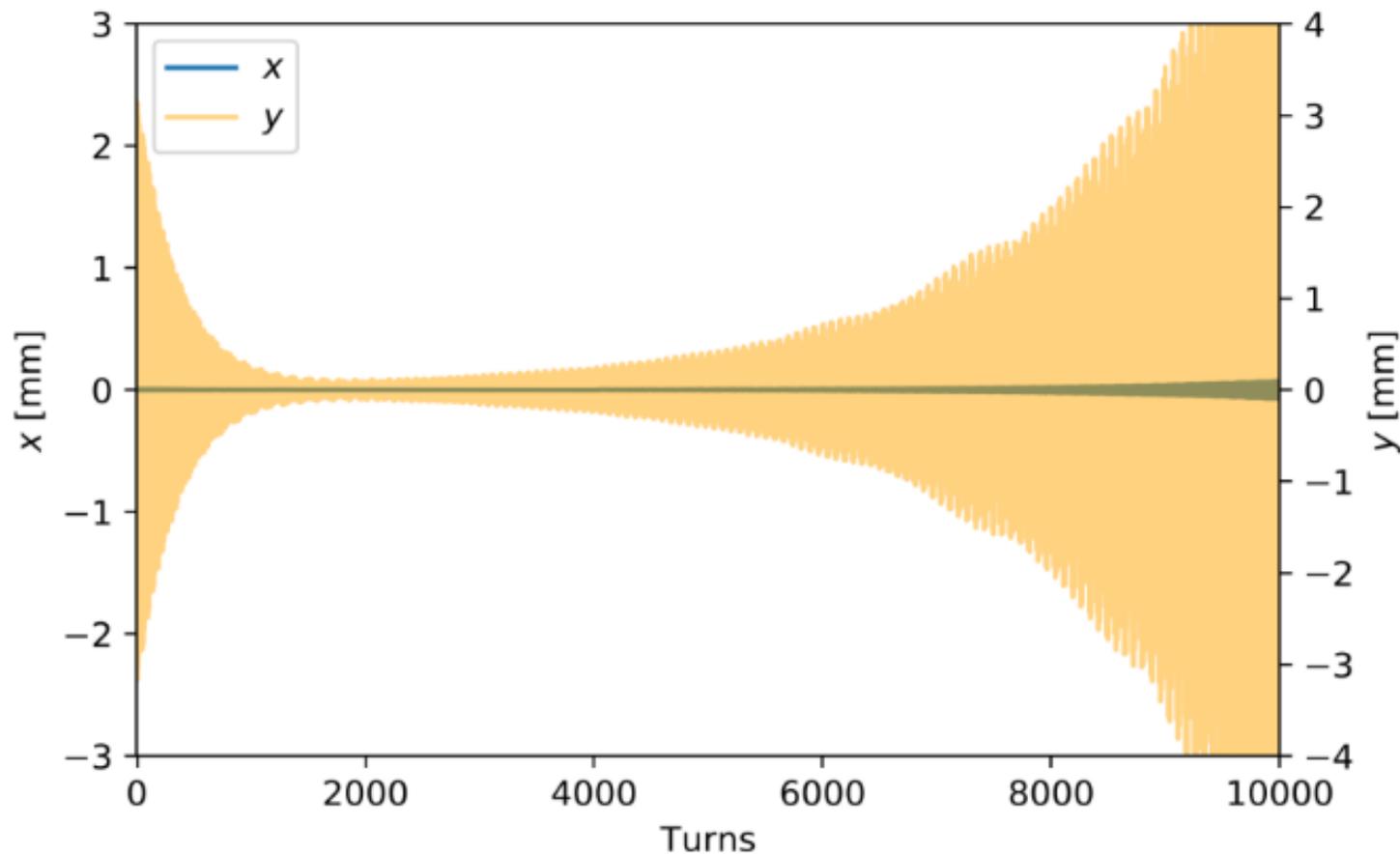
e^- rms bunch length and energy spread vs. turn number after 6 GeV injection for the bare Q40 optics, no wigglers



e^- rms bunch length and energy spread vs. turn number after injection at 6 GeV for the Q40 optics with additional wigglers

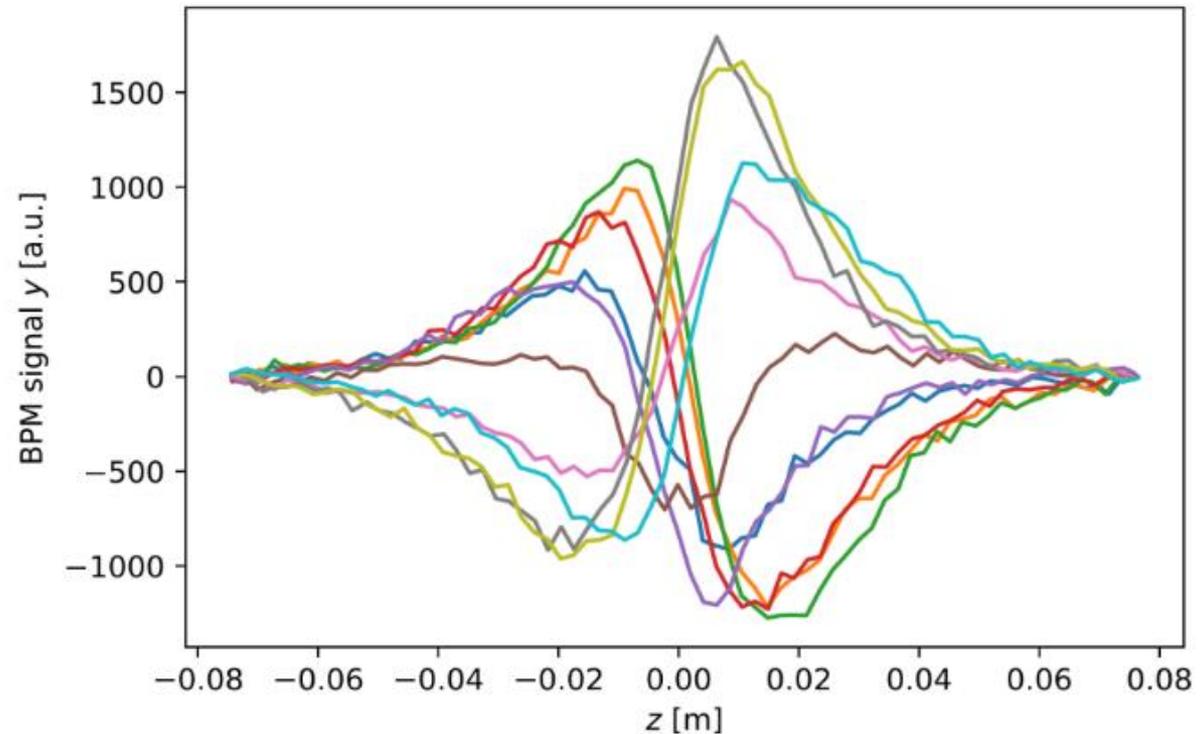


x & y bunch centroid position versus turn for bare Q40 optics, $Q'_{x,y} = +1$ without damper, at $N_b = 2 \times 10^{10}$



vertical charge-weighted slice position along the bunch on the last ten turns of the simulation for bare Q40 optics, $Q'_{x,y} = +1$ at the nominal bunch population $N_b = 2 \times 10^{10}$

signal from a simulated head-tail monitor
→ instability dominated by $l = -1$ head-tail mode; analytical model of DELPHI, based on Sacherer theory, predicts instability rise time of ~ 1500 turns for this mode, in good agreement



this transverse instability persists even when the wigglers are added, and it gets worse with higher positive chromaticity

recalling the past: when SPS was used as a LEP injector, e^+ and e^- beams were unstable at intensities above $N_b \sim 1.5 \times 10^{10}$ due to TMCI

Y.H. Chin, prediction 1985



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TRANSVERSE MODE COUPLING INSTABILITIES
IN THE SPS

Yong-Ho Chin

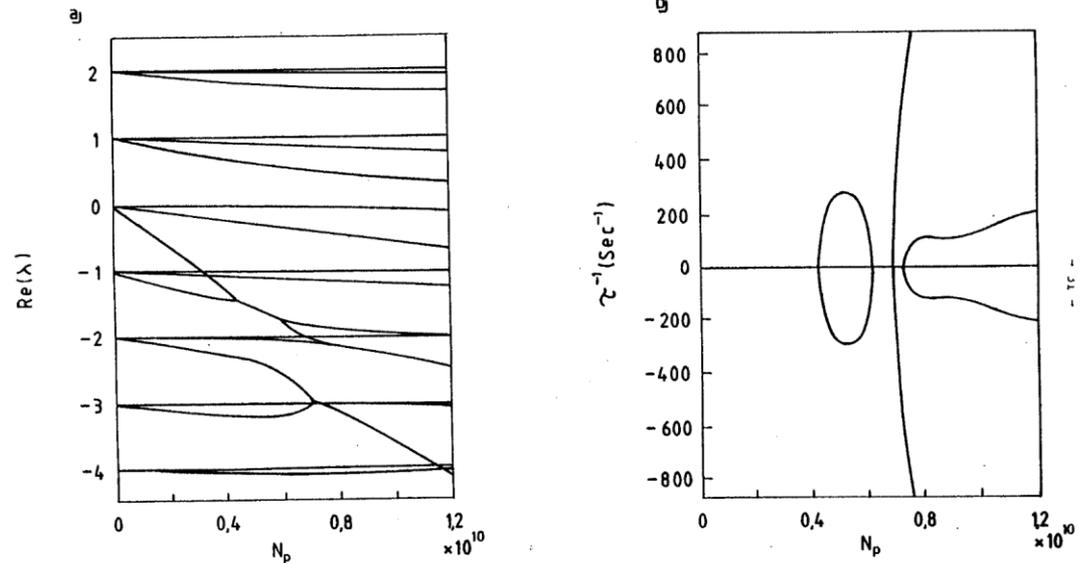


Fig. 8. Mode frequencies versus the number of particles in a bunch when operated as LEP injector at 3.5 GeV ($\sigma_x = 16$ cm)
(a) Real part (b) Growth rate

threshold for Q26 at 3.5 GeV with $47 \text{ M}\Omega/\text{m}$
 ~ 0.4 or 0.7×10^{10}

FAST INSTABILITY OF POSITRON BUNCHES IN THE CERN SPS

D. Brandt, J. Gareyte
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Abstract

LEP will be filled by repetitive injection of electron and positron bunches accelerated in the SPS from 3.5 GeV, the energy at which they are injected from the CPS, up to 20 GeV¹⁾. The nominal intensity per bunch has been chosen to be just below the predicted threshold for the transverse mode coupling instability, which corresponds to a peak current of about 1A. Above this value fast beam losses are indeed observed after only 10 to 40 turns in the machine. Fast growing signals are detected in the high frequency region above 1 GHz both on longitudinal and transverse monitors. A description of the phenomenon is given in terms of both the mode coupling and the Beam Break Up theory. Computer simulations which reproduce well the observed features, are used to refine previous estimates of the SPS transverse coupling impedance.

Introduction

The transverse mode coupling instability has been observed in many e⁺e⁻ storage rings^{2),3)}. These machines are filled by repetitive injection and accumulation of low intensity particle bunches; when the accumulated current reaches the threshold for instability a fast, usually vertical increase in the beam size is noticed, leading to partial beam loss and thereby limiting the intensity which can be accumulated in the machine. The explanation of this phenomenon, which had remained mysterious for a number of years, was given in 1980 by Kohaupt⁴⁾ in terms of coupling of head-tail modes. This was an extension to the transverse motion of a theory proposed by Sacherer⁵⁾ to explain the longitudinal microwave instability through coupling of the longitudinal coherent bunch modes. At low intensity the head-tail modes of order $\pm m$ are standing-wave patterns which oscillate at frequencies $\omega_0 \pm m\omega_s$, where ω_0 is the betatron and ω_s the synchrotron frequency. The signal induced by mode m in a transverse monitor presents m nodes, so that its Fourier spectrum can be approximated by the spectrum of the bunch line density but displaced towards higher and higher frequencies as $|m|$ increases. At higher bunch intensities the wake fields change the oscillation frequency of the different head-tail modes by different amounts, so that adjacent modes m and $m+1$ can merge and become coupled. Instead of two independent stable standing waves, the oscillation is then described by a travelling wave running along the bunch, and the amplitude of this travelling wave can grow exponentially under the influence of the wake fields.

In the SPS, when this machine is used as LEP injector, bunches of electrons and positrons are injected in one shot at 3.5 GeV/c from the CPS. While in e⁺e⁻ storage rings the threshold for the mode coupling instability can only be approached from below, in the SPS it is possible to inject directly bunches with intensities up to four times the threshold value. In this case a fast beam loss occurs after 10 to 40 revolutions, that is within a fraction of a synchrotron period. Under these circumstances the concept of head-tail modes loses its meaning; instead of using the mode coupling model which is adequate when the threshold is approached from below, it seems more appropriate in this case to describe the interaction of the bunch

with the accelerator structure in terms of the Beam-Break-Up theory, which has been developed to calculate similar effects in linear accelerators. In the following both approaches are used in a complementary way to explain the observed threshold value. In addition the detailed features of the phenomenon are rather faithfully described by a computer simulation using multiparticle tracking.

Experimental observations

Fig.1 shows the evolution in time of the intensity of a single bunch after its injection into the SPS. One observes a sharp loss after 11 revolutions, while after about 30 revolutions only one third of the beam remains in the machine. The relevant beam parameters are shown in table I. The synchrotron tune is $Q_s = .015$, and therefore one expects a negligible influence of the longitudinal RF focusing on this fast phenomenon. Indeed switching the RF voltage on or off does not change the loss pattern. Fig. 1 has been recorded with RF off. The chromaticity was close to zero and slightly positive. Fig.2 shows the signal from a wide band vertical position monitor. The signal from the exponential directional coupler (band width 0 to 2 GHz) is fed to a battery of band-pass microwave filters, amplified and peak-detected. The bunch length is $\Delta z_b = 64$ cm, and therefore the spectrum of the bunch line density extends to about 500 MHz. Indeed with filters tuned to [500 - 600] MHz one observes, starting from injection, a constant signal with small oscillations superimposed (the signature of residual injection oscillations). In contrast with this situation, when filters are tuned to [1.4 - 1.7] GHz one observes no signal on the first turn (there is no component of the bunch spectrum in this frequency range) but the signal grows on succeeding turns to reach a maximum at turn 11, which is where the first loss occurs in Fig.1.

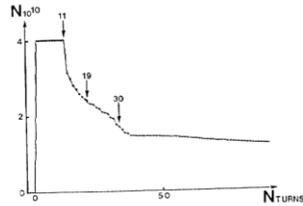
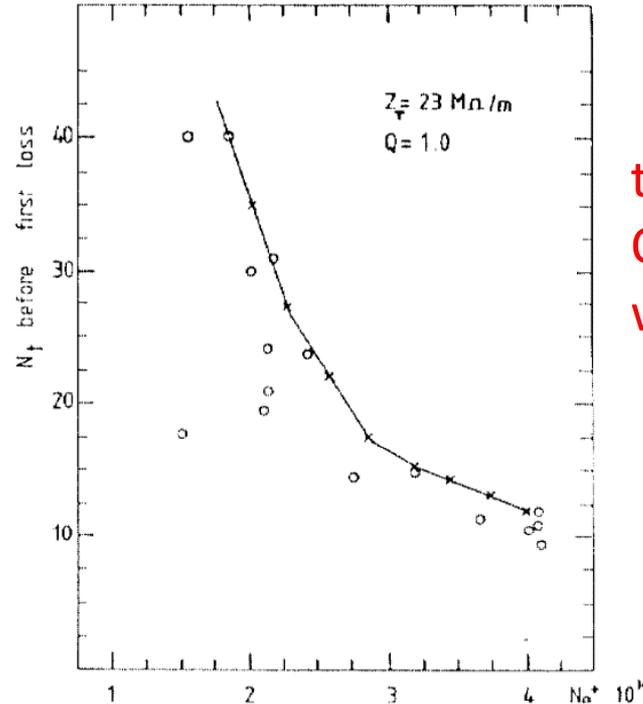


Fig. 1 : Beam loss after injection as a function of the number of turns

Such signals can be observed between 1 and 2 GHz (which is the upper limit of our monitoring system) with a broad maximum around 1.5 GHz. From this we infer that after entering the machine the bunch

Brandt & Gareyte EPAC 1988 – observations and theory



threshold for
Q26 at 3.5 GeV
with 23 MΩ/m
~1.4x10¹⁰

Fig. 3 : Number of turns before beam loss as a function of bunch intensity

CERN SPS/89-6 (AMS)

CERN LIBRARIES, GENEVA



CM-P00061451

BEAM DYNAMICS EFFECTS IN THE CERN SPS USED AS A
LEPTON INJECTOR

D. Brandt, E. Brouzet, K. Cornelis, J. Gareyte,
W. Herr, R. Lauckner, T. Linnekar, R. Schmidt

Brandt et al PAC 1989 – measurements & simulations

Paper presented at the 1989 Particle Accelerator Conference,
Chicago, Ill. U.S.A. March 20-23 1989

Prévessin - 13th March, 1989

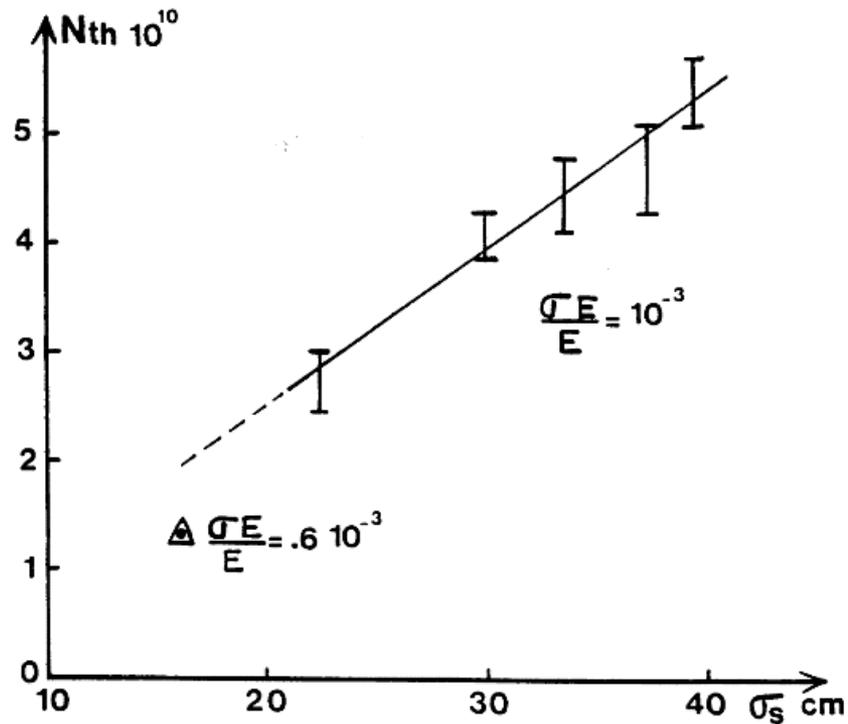
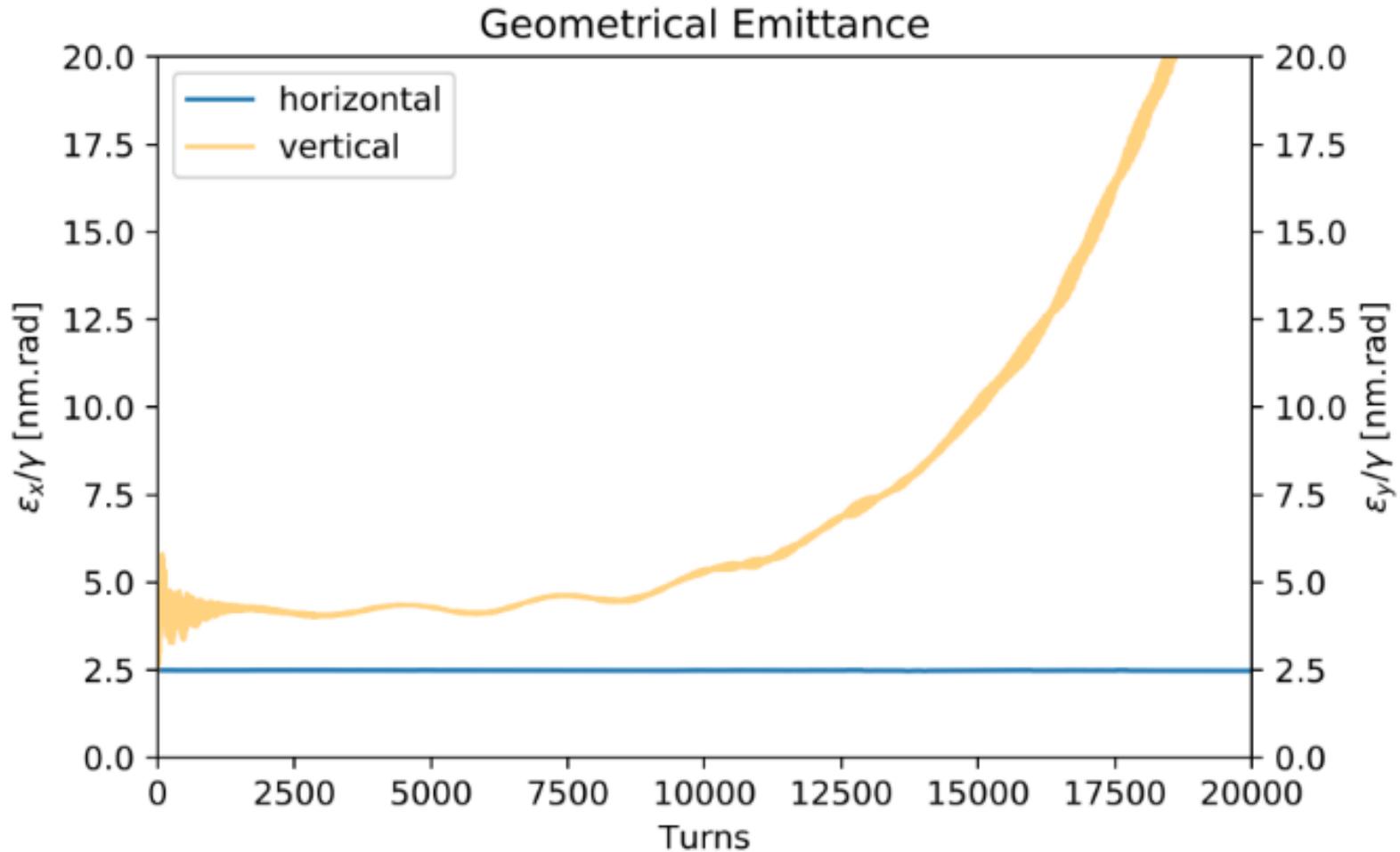


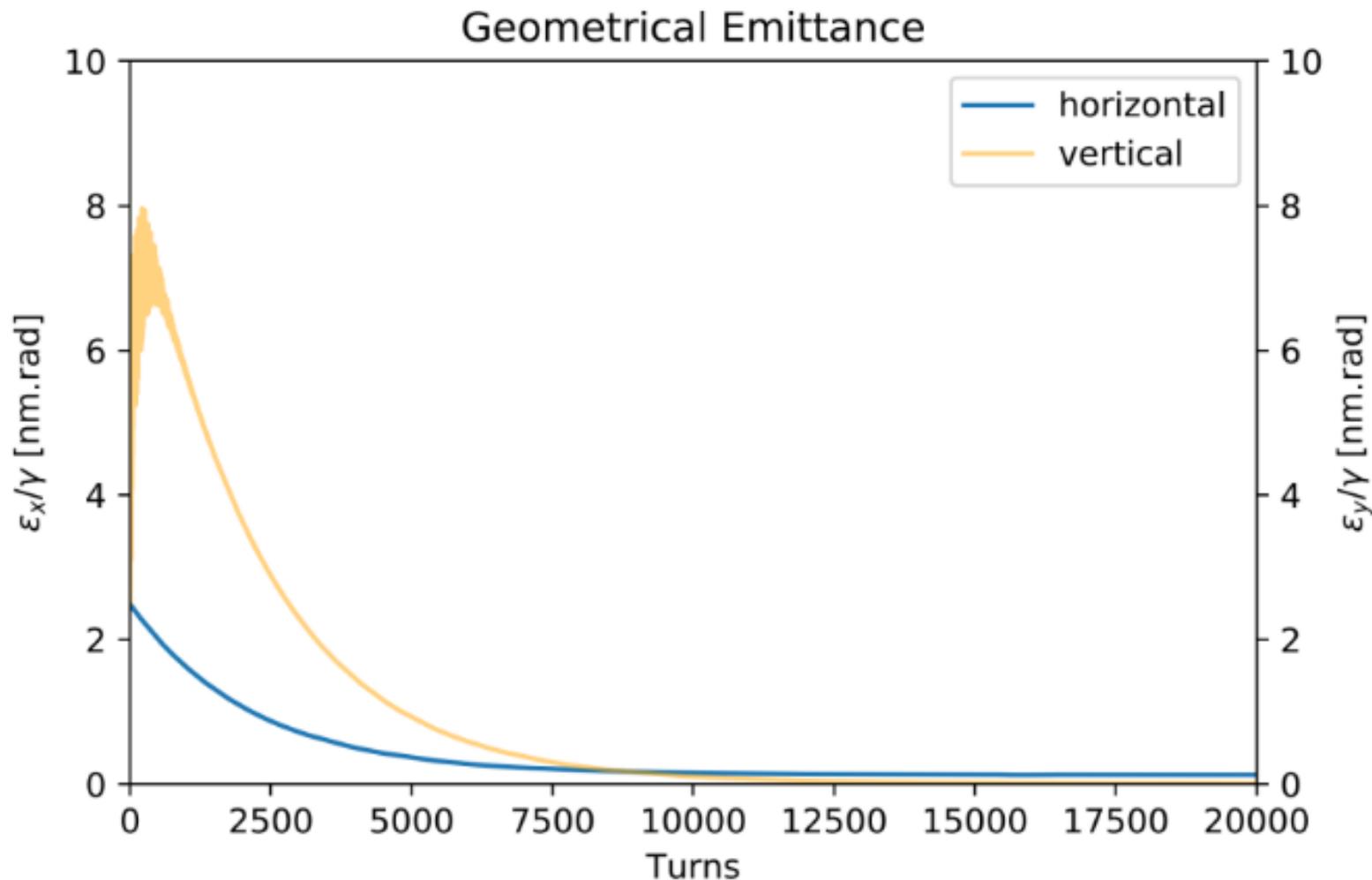
Fig. 3 Transverse mode coupling instability
threshold variation with bunch length

lowering intensity to $N_b \approx 5 \times 10^9$ the centroid motion almost stable; however, w/o wigglers, a weak residual $l = -1$ mode instability still drives significant vertical emittance growth



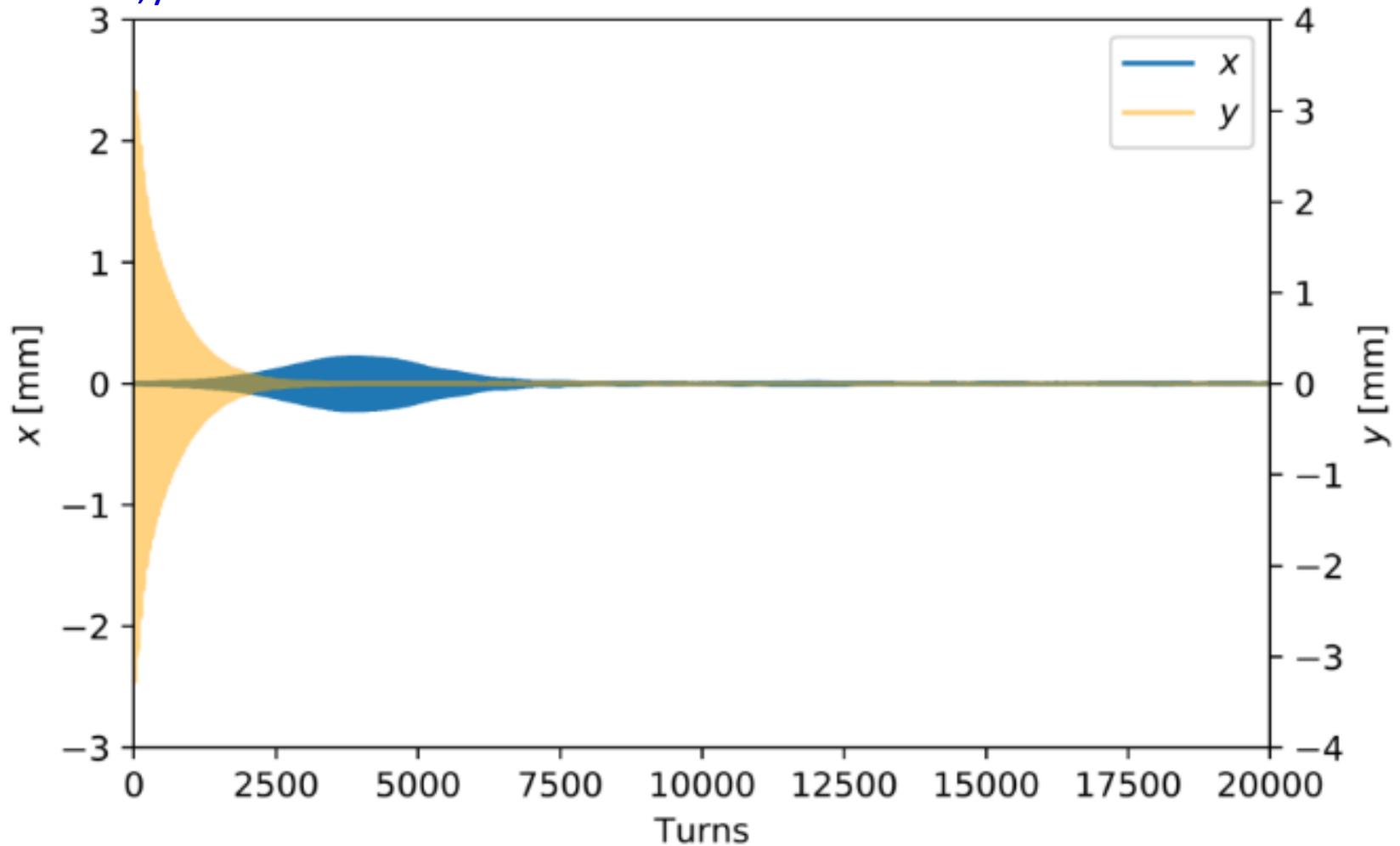
x & y bunch emittance versus turn for bare Q40 optics, $Q'_{x,y} = +1$ at a reduced bunch population $N_b = 5 \times 10^9$

x & y emittance versus turn for bare Q40 optics **with wigglers**,
 $Q'_{x,y} = +1$ at a **reduced bunch population** $N_b = 10^{10}$



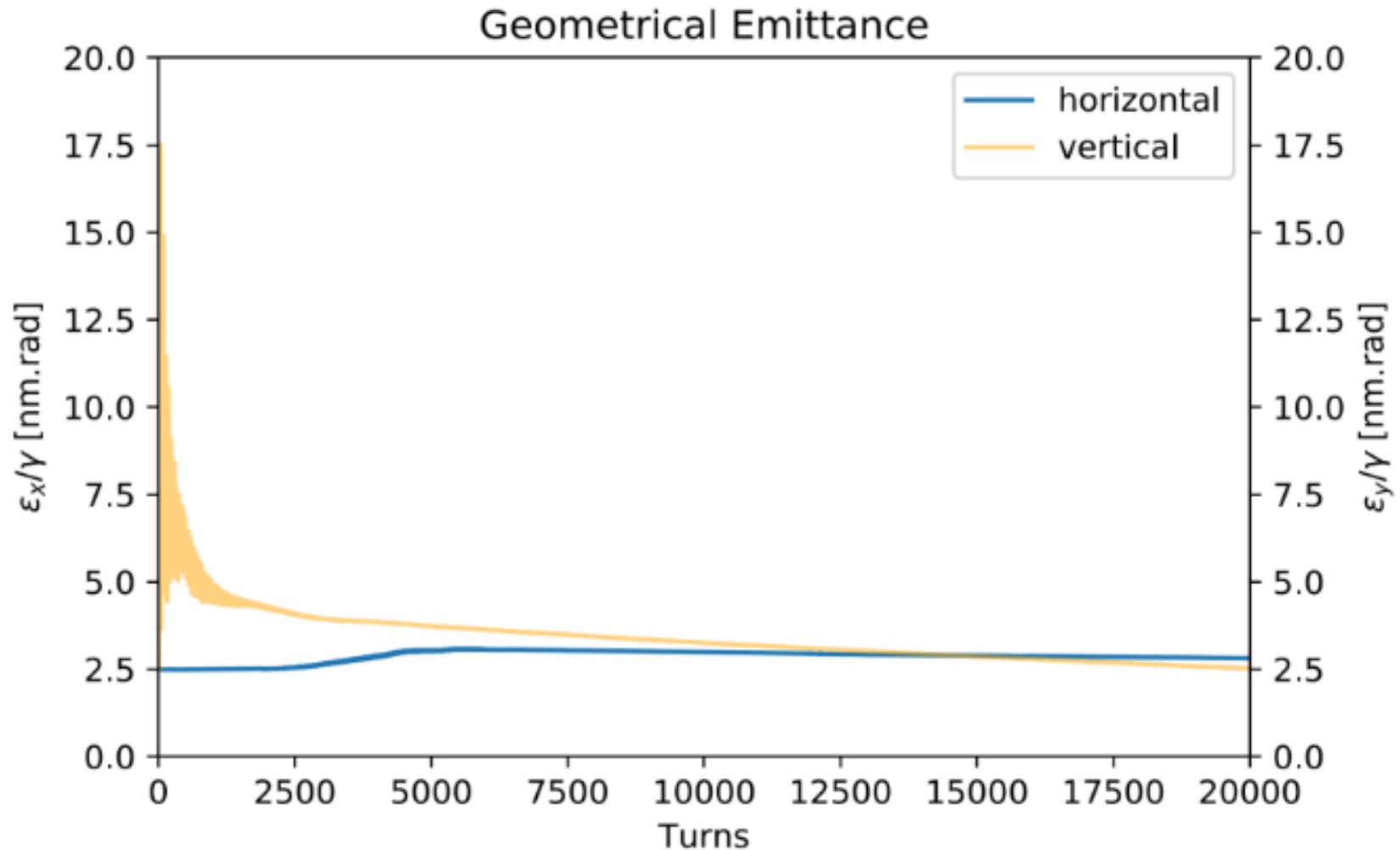
**at a reduced bunch population,
wigglers can render the beam stable**

x & y bunch centroid position versus turn for bare Q40 optics, $Q'_{x,y} = -5$ with transverse damper, at $N_b = 2 \times 10^{10}$



w/o wigglers, but **with negative Q' & damper, beam is rapidly damped and stable!**

x & y emittance versus turn for bare Q40 optics, $Q'_{x,y} = -5$ with transverse damper, at $N_b = 2 \times 10^{10}$



w/o wigglers, but with negative Q' & damper, also the emittance is quickly restored!

stabilisation with negative Q' and damper was proposed for LEP

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Comparison of Theory and Experiment on Beam Impedances: The Case of LEP

Bruno Zotter, CERN, Geneva, Switzerland

Zotter, EPAC'92

Abstract

The performance of LEP is presently limited by collective effects which restrict the amount of current which can be stored in a single bunch. These effects are due to the interaction of the particles in the beams with wake fields induced in the vacuum chamber. They can be calculated in the frequency domain if the impedances are known. Predictions and measurements of the impedances in LEP are discussed, as well as effects which bear on the machine performance.

1 INTRODUCTION

LEP is now in operation for over 2 years, and a number of machine development (MD) shifts have been spent to study the collective beam behaviour. In addition, many parasitic observations were made during physics runs in order to obtain the required data. Comparison with predicted behaviour[1] is generally quite good.

2 TRANSVERSE MODE COUPLING

TMC has been observed in most large electron storage rings: PETRA[2], PEP[3], TRISTAN[4]. It is driven by the transverse impedance which is proportional to the machine radius, and inversely to the cube of the chamber radius (the larger the machine, the smaller the chamber

*with contributions by D. Brandt, K. Cornelis, J. Haged, A. Hofmann, R. Pfitzner, L. Rivkin (PSI), E. Rossi and many EIC's.

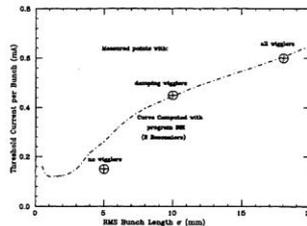


Figure 2: TMC Threshold versus Bunch Length

needs to be kept magnet cost down). TMC was thus expected to be a dominant current limitation in LEP, by far the biggest electron storage ring ever built.

For short bunches in LEP, coupling of modes $m = 1$ and $m = -1$ has the lowest threshold. It is expected to occur first in the vertical plane, due to the larger vertical impedance of flat vacuum chambers (Fig.1). However, the threshold for horizontal TMC is only slightly higher[5].

For a transverse resonator with resonant frequency f and impedance $Z_{\perp} = R/Q$, the threshold current is given approximately by

$$I_{thr} \approx \frac{2\pi f_s E/c}{\langle \beta \rangle_f Z_{\perp}} F(\sigma_x) \approx \frac{8f_s E/c}{\sum \langle \beta \rangle_i k_{\perp i}(\sigma_x)} \quad (1)$$

The form factor F increases with bunch length σ_x , but is also large for extremely short bunches. If several impedances play a role, the second expression[6] with the transverse loss factor k_{\perp} is more convenient. More reliable answers come from the computer program BBI[7] - which includes the TMC code MOSES[8] as subroutine. Fig. 1 shows the TMC thresholds computed with BBI as well as three measured points with the 90-degree lattice.

The current thresholds are strongly tune dependent which might be explained by synchro-betatron resonance (SBR) due to wake fields induced in the cavities[9]. They are proportional to energy (E), with a minimum at injection (20 GeV), and to the synchrotron frequency (f_s) which is limited at injection by the available RF voltage if f_s is kept constant during ramping to high energy. f_s

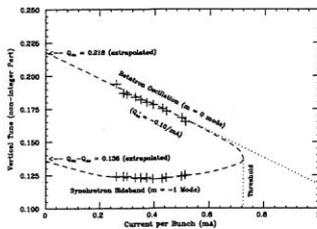


Figure 1: Vertical Tune Shift versus Current



CM-P00062664

The growth rate depends almost linearly on current and - for small ξ - on chromaticity (Fig.4), but in a more complicated manner on bunch length. Stability is lost when it exceeds the damping rate. At injection energy, radiation damping in LEP is rather weak ($\tau = 0.4s$), and Landau damping by tune spread is dominant. A value of $\Delta Q/Q \approx 5 \cdot 10^{-4}$ is compatible with the growth rate of the $m = 0$ mode at negative chromaticities.

The stable chromaticity range $0 < \xi < \xi_{thr}$ is thus quite limited, and reduces inversely with current. In order to avoid frequent adjustment during accumulation, it may actually be preferable to work with a slightly negative chromaticity and stabilize with feedback.

but LEP practical experience was not so positive

Karantzoulis & Lonza, EPAC2006

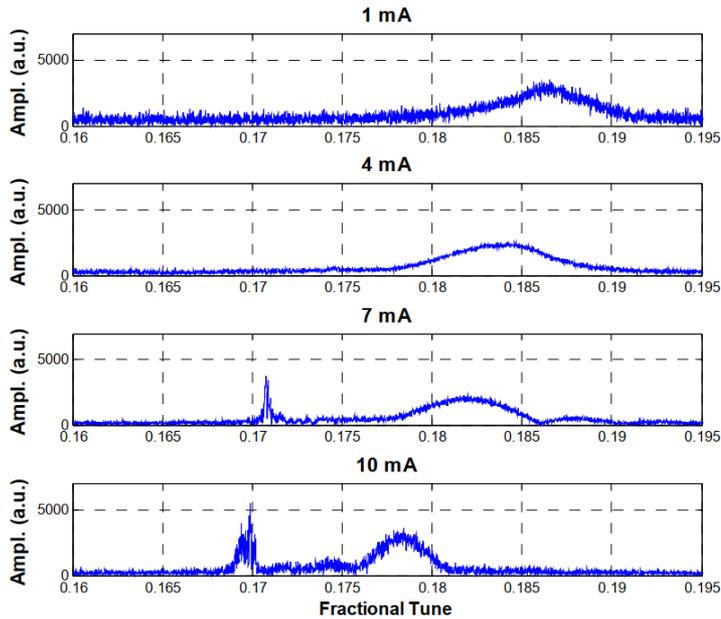


Figure 2: The $m=0$ and $m=-1$ mode merging with positive chromaticity (0.4, 0.1), feedback on and kickers on, vertical plane.

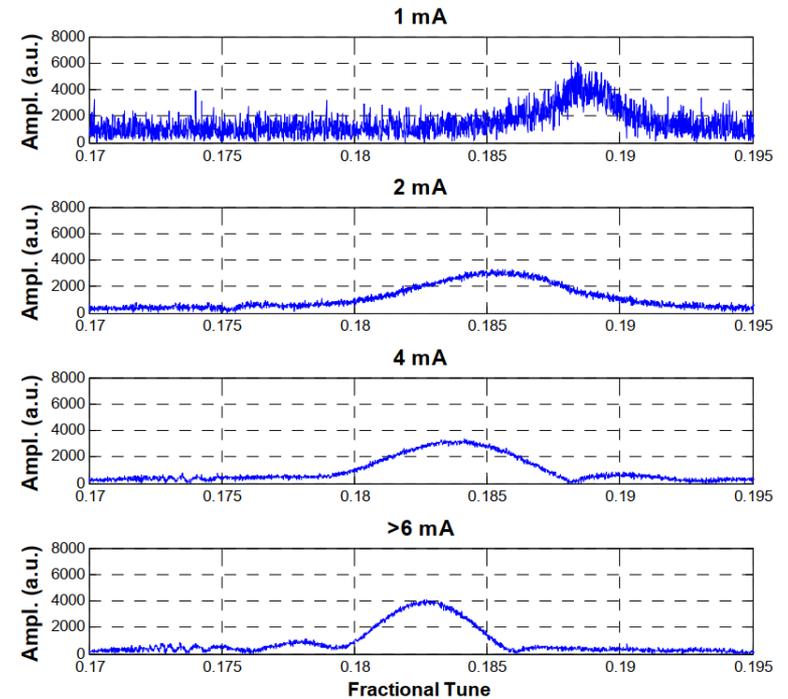


Figure 4: The $m=0$ mode shift with vertical negative chromaticity (0,-2), feedback on and kickers on.

later ESRF experience rather successful and promising

transverse and longitudinal thresholds at LEP

Brandt et al.,
 PAC 1989 –
 measurements
 & simulations

Table I

t ms	E GeV	τ_E s	$(\sigma_s)_0$ cm	Simulation		calculated longitudinal threshold 10^{10}
				σ_s cm	transverse threshold 10^{10}	
200	3.57	4.24	1.48	22.5	1.6	1.73
216	3.59	4.17	1.44	19.5	1.6	1.85
250	3.83	3.44	1.46	18.6	1.6	1.70
283	4.49	2.13	1.55	17.1	1.5	1.53
316	5.80	0.99	1.74	15.0	1.73	1.79
350	7.60	0.44	2.04	12.3	1.73	2.00
383	10.0	0.19	2.59	9.9	1.73	2.18
416	12.8	0.092	3.22	8.1	1.73	2.14
450	15.9	0.048	3.73	6.9	1.73	1.95
483	18.0	0.033	4.30	5.0	1.90	1.85

a few conclusions:

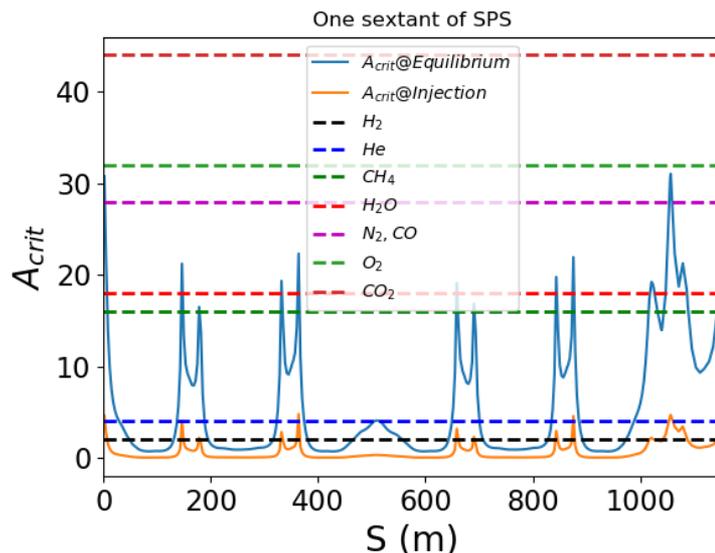
- **negative Q' & damper can stabilize the beam even better than additional wigglers**; in fact this scheme is more efficient than wigglers and allows for nominal intensity
- studies should/could be repeated with a **more precise SPS impedance model** (C. Zannini, H. Bartosik, G. Iadarola, G. Rumolo, and B. Salvant, IPAC'15)
- longitudinal μ -wave threshold and other collective effects being checked

Other collective effects in SPS PBR or new PBR (O. Etisken)

- Space charge - **benign**
- Longitudinal μ -wave instability– **OK? benchmark with LEP data**
- Transverse mode coupling instability (TMCI) by resistive wall
- **critical**
- μ -wave instability driven by coherent synchrotron radiation (CSR)
- **OK?**
- Ion effects – **OK**

$$A_{critx,y} \cong \frac{N_b \Delta T_b c r_p}{2\sigma_{x,y}(\sigma_x + \sigma_y)}$$

FBII growth time
~70 turns



ions are trapped
along bunch train

- e-cloud – **critical?** neutralisation density > blow up threshold
- coupled bunched instability by resistive wall – **benign?**