Low Emittance Rings
Workshop

CERN, January 12-15, 2010

Impedance evolution and collective effects at Elettra

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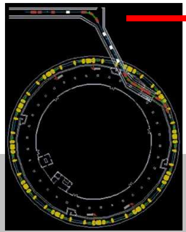
Elettra: what and where

Elettra is a 3rd generation Synchrotron light source at Trieste, Italy

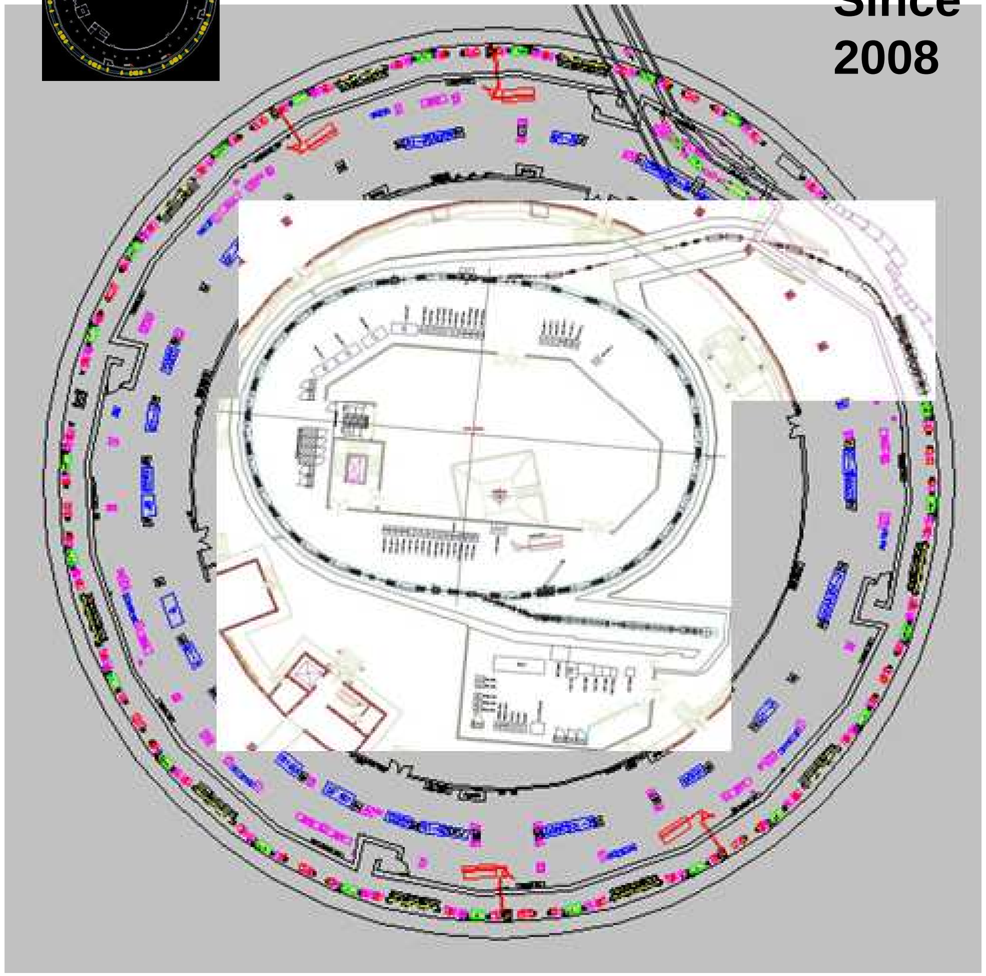
In operation for users since 1994

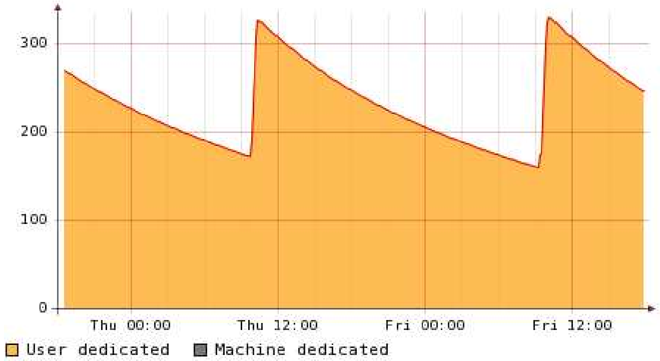
Configuration and Operational summary



Up to 2007

Since 2008





2009		
Injection energy	At any operating energy	
Final energy	2.0 GeV	2.4 GeV
Starting current	330 mA (τ ~ 22 hrs)	150 mA (τ ~ 35 hrs)
Filling pattern	multibunch, ~ 95 % contiguous	

0.9 GeV (accelerator physics time) for SR-FEL single bunch

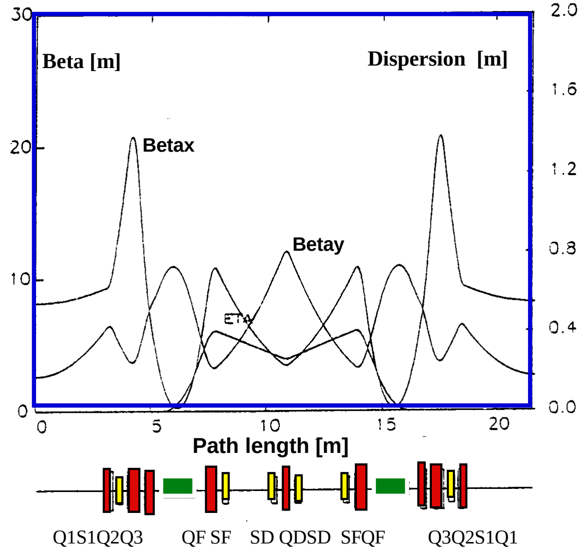
operational developments

For general diagnostic "SynchRobot" in collaboration with R. Pugliese and the scientific calculus for the programming

Programmable and autonomous can perform measurements and other actions in hazardous (radiation) environments

Machine Parameters

Beam energy [GeV]		2	2.4
Storage ring circumference [m]	259.2		
Beam height in experimental area [m]	1.3		
Number of achromats	12		
Length of Insertion Device (ID) straight sections [m]	6(4.8 utilizabile per ID's)		
Number of straight sections of use for ID's	11		
Number of bending magnet source points	12		
Beam revolution frequency [MHz]	1.157		
Number of circulating electron bunches	1 - 432		
Time between bunches [ns]	864 - 2		
Tunes: horizontal/vertical	14.3/8.2		
Natural emittance [nm-rad]		7	9.7
Energy lost per turn without ID's [keV]		255.7	533
Maximum energy lost per turn with ID's [keV] (all)		315	618.5
Critical energy [keV]		3.2	5.5
Bending magnet field [T]		1.2	1.45
Geometrical emittance coupling %	≤ 1%		
Spurious dispersion (at the centre of IDs): horizontal (rms max/min) [cm]	6/2.		
Spurious dispersion (at the centre of IDs): vertical (rms max/min) [cm]	2/0.5		
Operation mode	multibunch		
One refill per day (09:30) of duration (incl. ramping etc.) [min]	30		
Injection energy [GeV]	0.75 / 0.9 / 1		
Injected current [mA]		320	140
Machine dominated by the Touschek effect			
Energy spread (rms) %		0.08	0.12
Lifetime [hours]		8.5	26
Bunch length (1σ) [mm] &		5.4	7
Beam dimensions (1σ) &			
ID source point - horizontal/vertical [µm]		241/15	283/16
Bending magnet source point - horizontal/vertical [µm]		139/28	197/30
Beam divergence (1σ) &			
ID source point - horizontal/vertical [µrad]		29/6.	35/8.
Bending magnet source point - horizontal/vertical [µrad]		263/9	370/13
&: The values shown (taking into account the energy spread) are averages, obtained from a consideration of different angle and position values of the spurious dispersion and can very by ±10%			



Introduction

❑ Understanding wake fields and impedances is of great importance for the design and performance of accelerators since instabilities driven by the beam wakes can very much limit the performance in both beam intensity and quality.

❑ At Elettra there has always been a strong activity concerning wake fields, including also many measurements and observation on the storage ring like the impedance evolution with the addition of many low vertical gap vacuum chambers or the impedance increase due NEG coated chambers.

❑ To this extend we also have collaborated with other labs (ESRF, SOLEIL) and remote measurements using grid technologies have been also performed!

❑ Lately much work was again up for the FERMI@Elettra FEL, connected to resistive wall/geometric/ surface roughness effects at very short bunches that can deteriorate the laser efficiency via instabilities like the micro-bunching instability

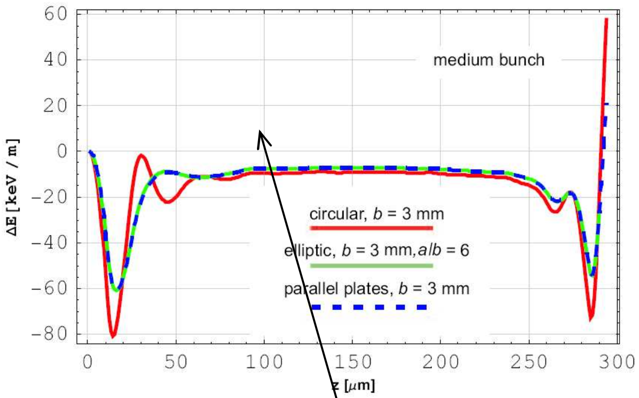
1mA at Elettra

corresponds to

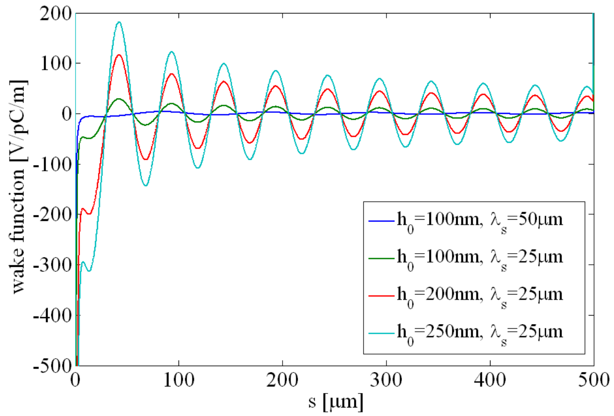
APS	0.23
ESRF	0.3
SOLEIL	0.73
SLS	0.91
BESY II	1.08
ALS	1.32
ANKA	2.33

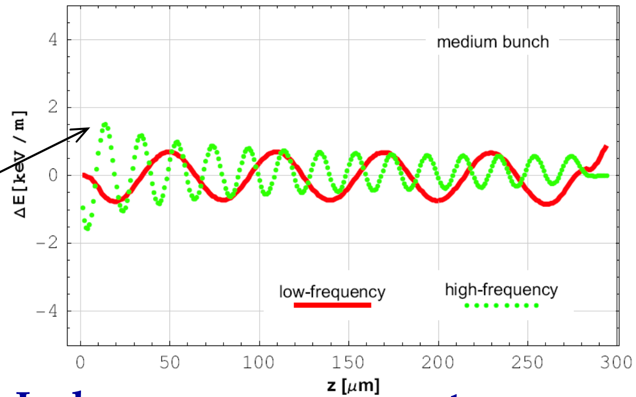
Wakefields Induced Energy Spread in the FERMI Undulator

→ **Resistive wall Wakefields (circular, rectangular and elliptic vacuum chamber)**



→ **Surface Roughness Wakefields**





0.8 nC

Estimated energy spread for the FERMI FEL undulator

Source	
Resistive wall	11.71 keV/m
Surface roughness	1.73 keV/m
Total	13.44 keV/m

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In-house measurements

→ aluminum samples were cut from an elliptical vacuum chamber

→ Atomic Force Microscope (AFM) was used

References

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L. Tosi,V. Smaluk, and E. Karantzoulis,” Landau damping via the harmonic sextupole”, Phys. Rev. ST-AB, Vol. 6, 054401 (2003);

Early Situation

- Single bunch was tried in 1994 and more than 60 mA @ 1GeV were stored on May 7th whereas at the same day were obtained 530 mA in 80% multibunch filling; the maximum reached was 700 mA (3 years later) and no injection saturation effects were observed!
- These results show that special care was taken to have the impedance of the machine as low as possible. With the exception of the rf-cavities, the vacuum chamber (shape and material) with its connections, holes, steps etc. is the other important contributor of impedance. The vacuum chamber was made of stainless steel with dimensions 81x56 mm while at insertions had initially 76x20 mm (full horizontal x vertical). The cavities are four copper single cells of a smooth bell shape.
- Impedance budget calculations using mostly analytic formulae estimated that the broad band longitudinal impedance should be < 0.7 ohm while the transverse effective < 20 kohm /m Those predictions were in agreement with single bunch measurements shown that the longitudinal broad band impedance was ~ 0.2-0.5 ohm and the transverse effective ≤ 10 kohm /m. These values confirm also the theoretically predicted high current thresholds of ELETTRA.

Instability situation in 1994

Mutibunch instabilities: existed as predicted, generated by the HOMs of the rf cavities. Four Elettra type single cell cavities are used and as usually are the biggest contributors to the machine impedance. Careful tuning of the cavity volume (via temperature control) shifts the HOMs from the beam harmonics. A complete instability free condition at 150 mA was achieved while above the 150 mA it is still possible but more difficult. Nowadays MT(L)FB systems and a 3rd harmonic cavity help to eliminate all modes.

Resistive wall: was not observed up to 330 mA and assuming that it was Landau damped due to the (measured) incoherent betatron frequency spread f of about 160 Hz confirms again the low value of the impedance.

Head tail and mode coupling : Simple threshold estimations with the measured impedance set the threshold at 58 mA (1 GeV) but 65 mA were injected without saturation, however above 50 mA the beam was blown up and throbbing clearly indicating a threshold. The m=0 mode for small positive chromaticity was stable. At much higher currents ≥35 mA the m = -1,1 were also seen but no mode merging occurred. With slightly negative chromaticity the m = 0 threshold was found at ~22 mA above which the beam blew up vertically and oscillated again confirming the measurements

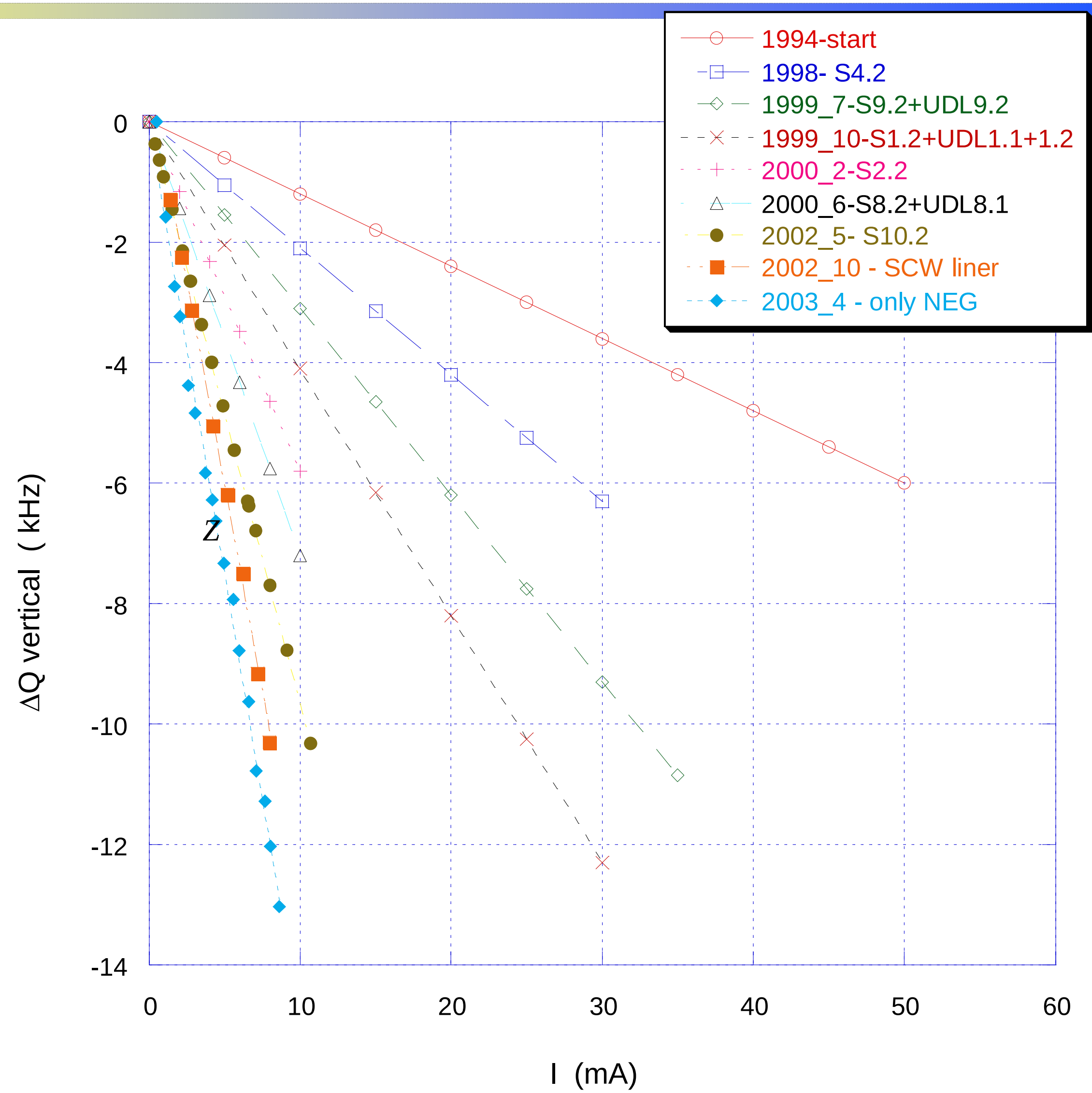
Impedance evolution

Measurements of tune shift with sb current.

The Im($Z_T$eff) can then be extracted from the known formula:

$$\mathrm{Im}\left(Z_T^{eff}\right) = -\frac{(2\pi)^2 \sigma_\tau E}{\beta_v} \frac{\Delta f}{\Delta I}$$

giving 10 kohm/m for the starting value and 10-15 koh/m for each low gap chamber



	Installed type / length m	replacing	Slope kHz /mA ($\pm$0.02)
1994	Initial measurement		-0.12
1998	ID 4 stainless steel / 4.0	S steel rhomboidal 82x53	-0.21
1999	ID 9 extruded Alu / 4.8	S steel rhomboidal 82x53	-0.31
1999	ID1 extruded Alu / 4.8	S steel rhomboidal 82x53	-0.41
2000	ID2 extruded Alu+Low gap bpm / 4.8	S steel rectangular 75x20	-0.58
2000	ID8 extruded Alu /4.8	S steel rhomboidal 82x53	-0.72
2002	S10 extruded Alu +NEG / 4.8	S steel rhomboidal 82x53	-0.96
2002	S11 copper liner / 1.5	S steel rhomboidal 82x53	-1.1
2003	S9 extruded Alu +NEG /4.8	S9 extruded Alu installed in 1998	-1.258
2003	S7 extruded Alu +NEG /3. + L G bpm	S. Steel rectangular 75x20	-1.49
2003	Copper liner replacement in S11	Previous copper liner –same dimensions	-1.425
2004	S2 extruded Alu +NEG / replacement of damaged low gap bpms	S2 extruded Alu	-1.413

Low gap chamber contribution include resistive wall, tapers and the NEG (T, Zr, V)

It appeared as if every low gap chamber contributed as much as the whole 1994 machine and furthermore the NEG was adding as much!

Further developments

During 2003/4 series of measurements in collaboration with ESRF and SOLEIL based on the bump method (T. Perron et. al.) tried understand the NEG puzzle but without a clear answer since theory predicts ~ 10 - 15Kohm/m the rest could be attributed to bad rf-fingers / surface roughness / thicker NEG

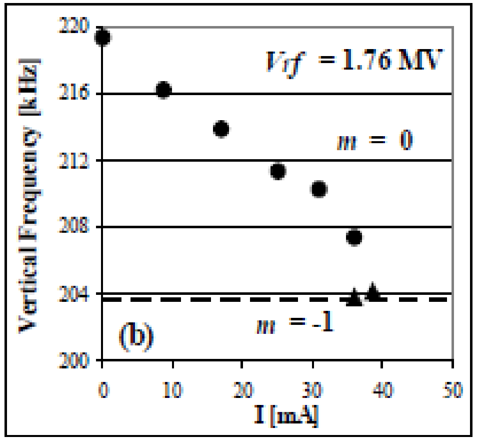
Cell	**material**	**Length**	**Vertical inner gap**	**Low gap bpm**	**Current**	**Blength**	**Zeff measured 1**	**Zeff measured 2**
		(m)	**(mm)**		**(mA)**	**(ps)**	**(kOhm/m)**	**(kOhm/m)**
2	Al NEG	4,8	14	yes	21,5/*24,5*	25,5/*27*	51±6	*44,1±6*
2	**Al**	**4,8**	**14**	**yes**	**17**	**24,5**	**47±5,5**	
1	Al	4,8	14	no	20/*25*	25/*27*	43,5±5,5	*38,1±5,5*
8	Al	4,8	14	no	21/*22,2*	25,5/*26*	36,5±5	*23,1±5*
5	SS	4,8	15	no	19/*23,2*	25/*26,5*	29±5	*24,1±5*
6	SS	4,8	20	no	20	25	10±3,5	
7	**Al NEG**	**3**	**14**	**yes**	**28**/22	**28**/*26*	**34,5±7**	*30±5*
9	**Al NEG**	**4,8**	**14**	**no**	**28**/25	**28**/*27*	**14,5±5**	*12±5*
11					*23*	*26,5*		*11±5*

$$\theta_{Kick} = \frac{I \times Y_{Bump}}{2\sqrt{\pi} \times f_0 \times \sigma_t \times \left(E/e\right)} \times \Im\left(Z_{\perp eff}\right)$$

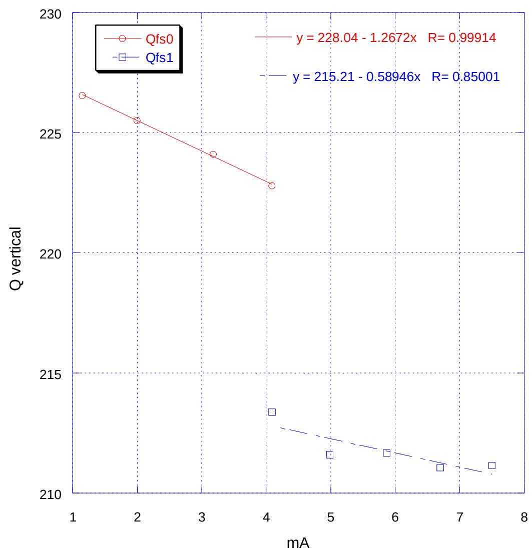
Mode coupling

Mode coupling. The mode m = 0 and m = -1 merging at 40 mA/bunch was seen with nearly zero chromaticity.

(ESRF - ELETTRA collaboration 2000).



The situation after some more Neg chambers in 2003 was as follows:



Y_0=228-1.26x

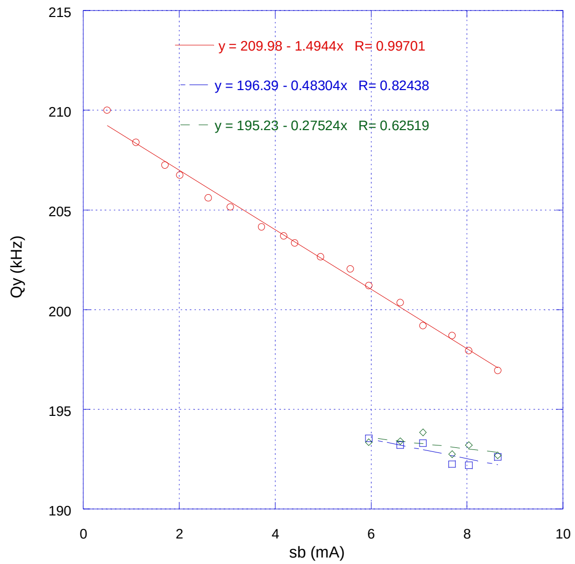
Y_{-1}=215-0.56x

~ 18 mA

Y_0=210-1.49x

Y_{-1}=196-0.48x

~ 14 mA



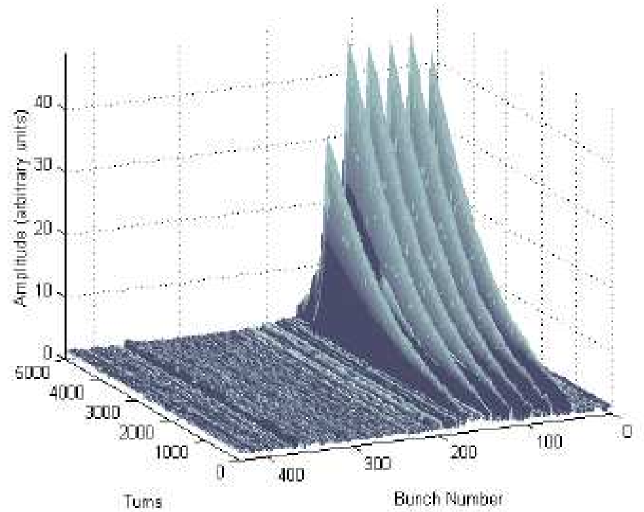
Resistive part - 2003

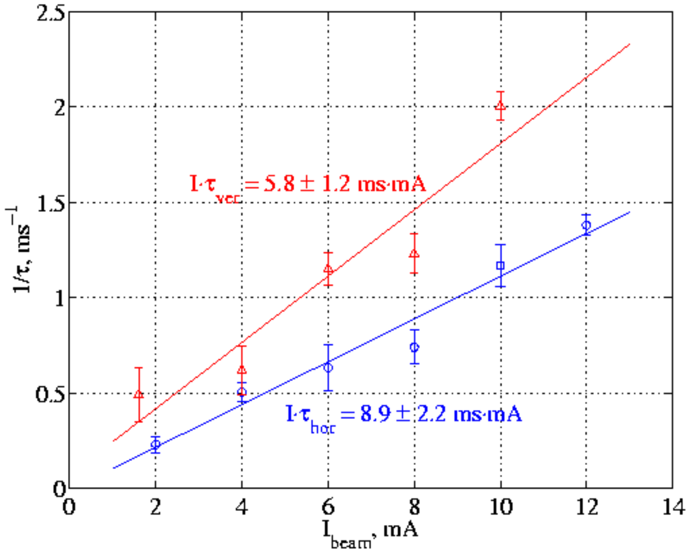
Beam interaction with a resistive transverse impedance results in the well - known head-tail instability characterized by the head-tail phase. For various beam currents, the damping rates were estimated by an analysis of the turn-by-turn beam positions whereas coherent betatron oscillations were excited by the TMFB system. On the basis of these measurements, the resistive part of the transverse impedance resulted to be

$$\mathrm{Re}Z_\perp = 0.16 \pm 0.05\ \mathrm{M\Omega/m}.$$

$$\tau_\pm^{-1} = \mp \frac{I_b c^2 \Im f(2\chi)}{32\pi^2 (E/e)\nu f_0 b} \Re Z_\perp, \quad \chi = \frac{2\pi\nu f_0 \xi \sigma_z}{c\alpha}$$

$$f(u) = \int_0^\pi e^{iu\sin x} dx$$





Coherent head-tail damping

Longitudinal Impedance 2003

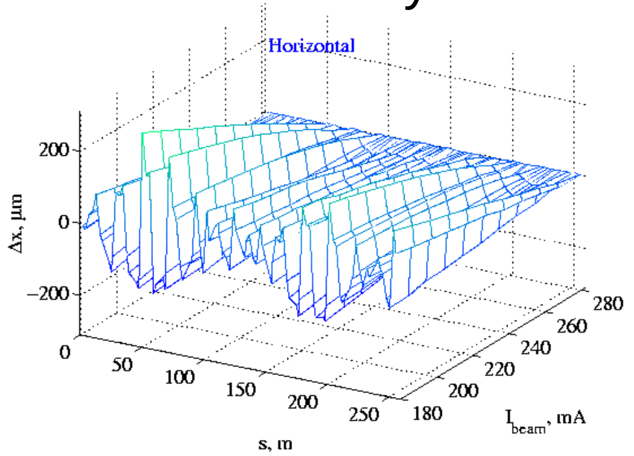
An electron beam passing through irregularities of the vacuum chamber loses energy. The total energy loss *DE* is proportional to the square of the beam charge *q*

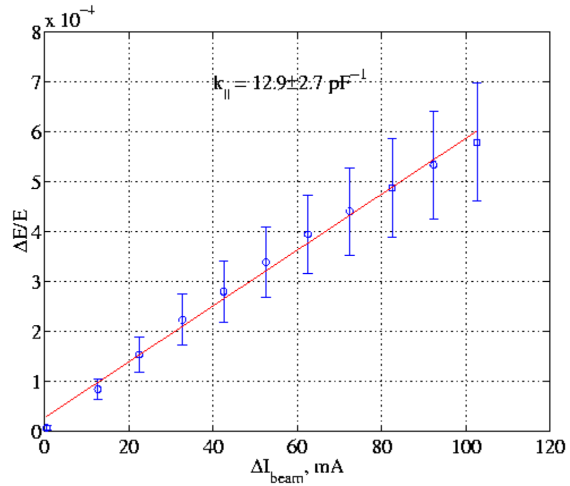
$$\Delta E = -k_{\parallel} q^2$$

$$k_{\parallel} = \frac{1}{\pi}\int_0^{\infty} \mathrm{Re}\, Z_{\parallel}(\omega)\left|\tilde{\rho}(\omega)\right|^2 d\omega$$

The measurement was based on the indirect measurement of the beam energy loss using the standard BPM system (with multiplexing), the longitudinal loss factor *k*|| can be estimated by measuring the horizontal closed orbit deviation with the beam intensity

$$\Delta x(s) = \eta(s)\frac{\Delta E}{E}$$





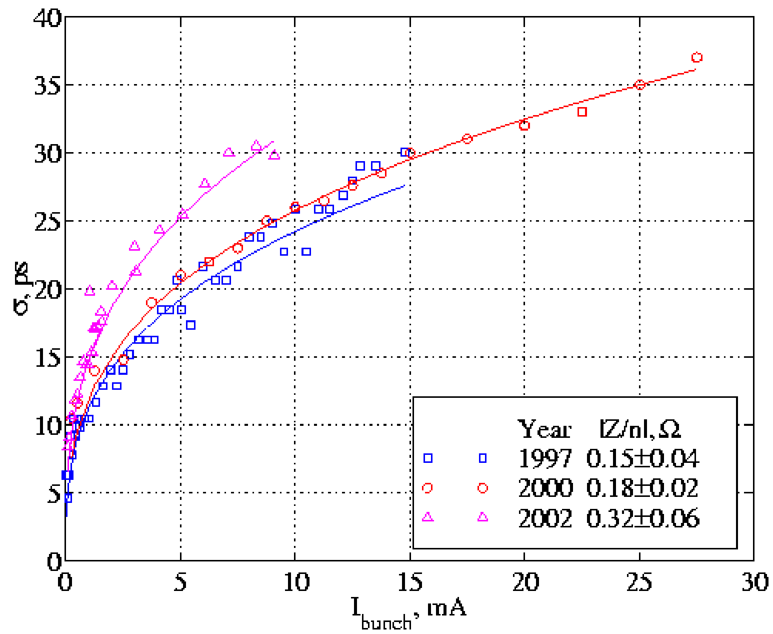
Re(Z/n)=0.21±0.04 Ohm

Microwave limit

Bunch length measurements have been performed since the beginning using fast oscilloscopes, photodiodes and finally a streak camera to monitor also the effective longitudinal broad band impedance which can be obtained directly from measurements of the bunch lengthening using the microwave limit

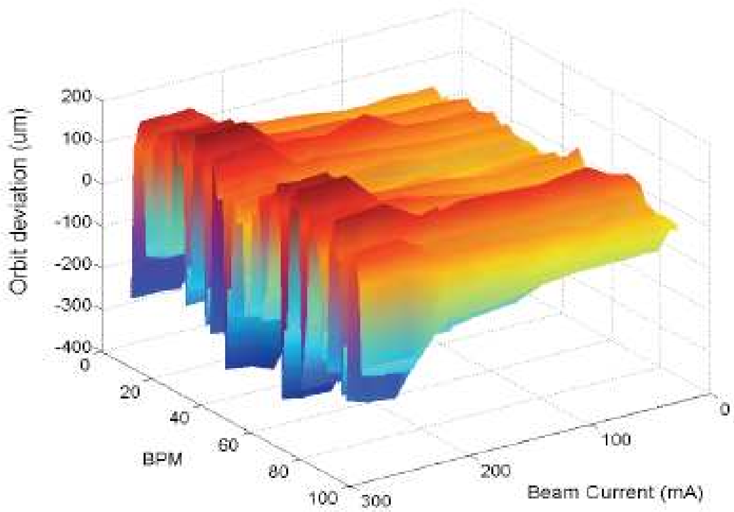
$$\left|\frac{Z_{\parallel}}{n}\right|_{BBR}^{eff} \leq \frac{8\ln 2}{2\pi}\frac{hV_{RF}\cos\varphi_s}{\sqrt{2\pi}I_b}\left(\frac{\sigma_s}{R}\right)^3$$

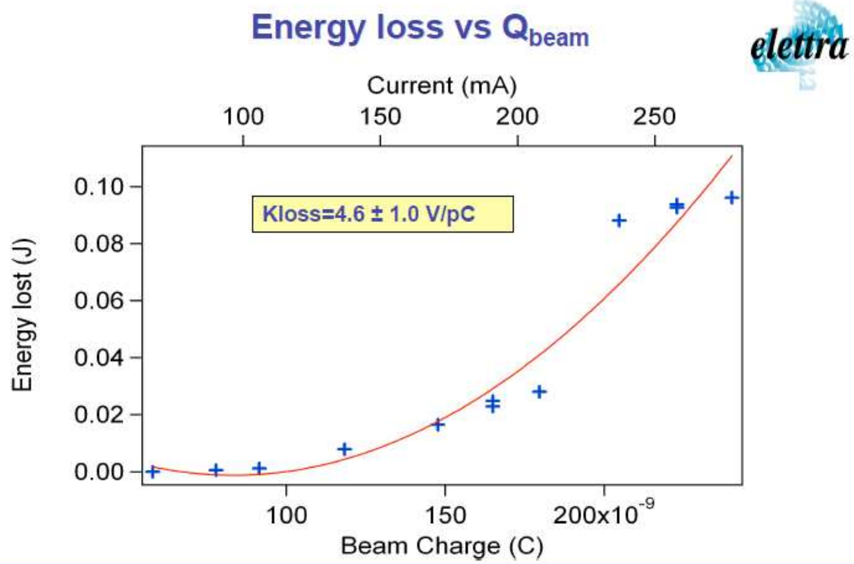
$|Z/n|^{eff}$=0.32 ±0.06 ohm



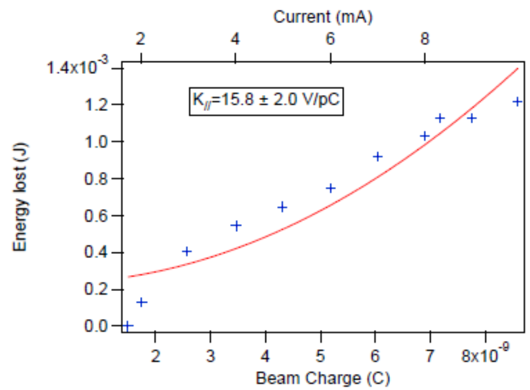
2007

New measurements with standard bpms and libera electronics were performed in 2007



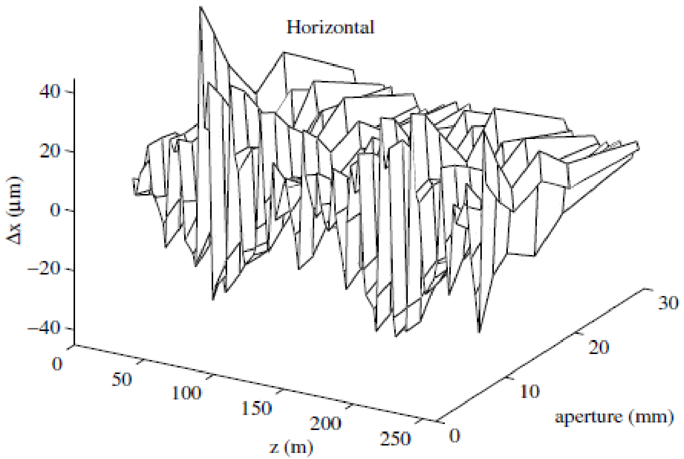


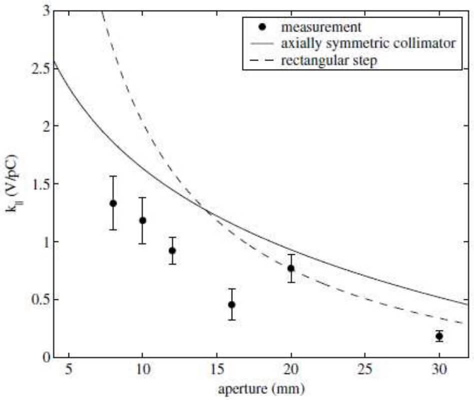
In 4-bunch mode K|| is higher showing the dominance of localized narrow band structures like rf-cavities

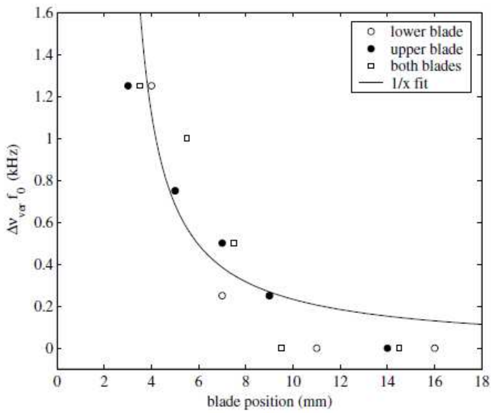


Scraper impedance

In ELETTRA the vertical scraper is discontinuous and is composed of two 1 cm in diameter rods positioned at 25 mm when it is open. Analytical formulas for the impedance of such a geometry do not exist and evaluation of its behavior has been performed using the electron beam.

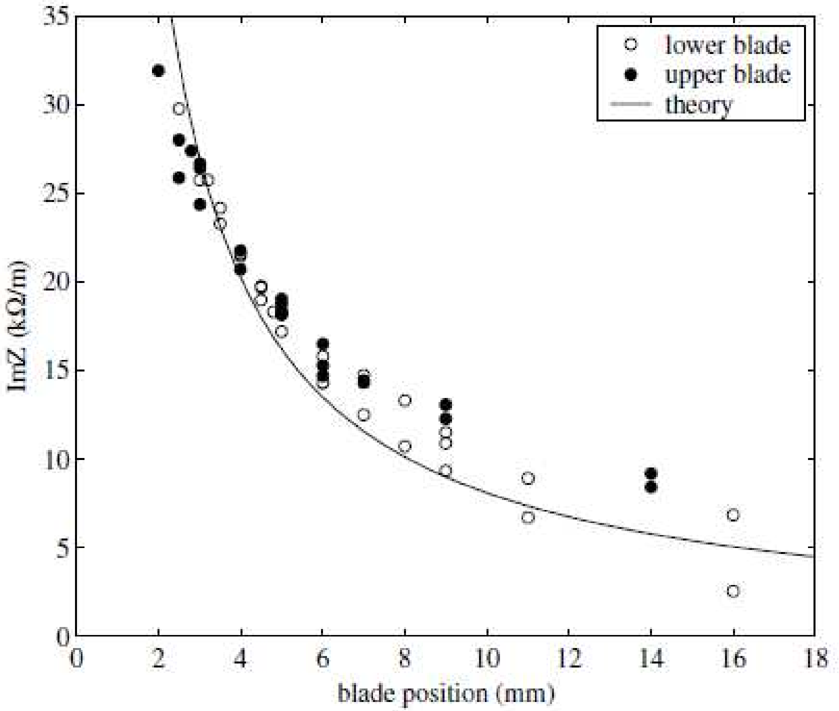






To increase the accuracy, a variant of the bump method was used with the scraper slit vertically shifted instead of the orbit bump. The method with some limitations can be used for such an asymmetrical structure as the scraper. The closed orbit deviation proportional to the impedance and to the scraper blade position was measured using the BPM system

Scraper Impedance fitting

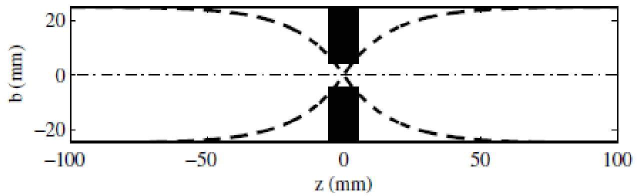


$$Z_{\perp} = -\frac{iZ_0 h}{2}\int \frac{(b')^2}{b^3}$$

h rod diameter

d= max. half gap (25 mm)

$$b(z) = de^{-(3z/2d)}$$



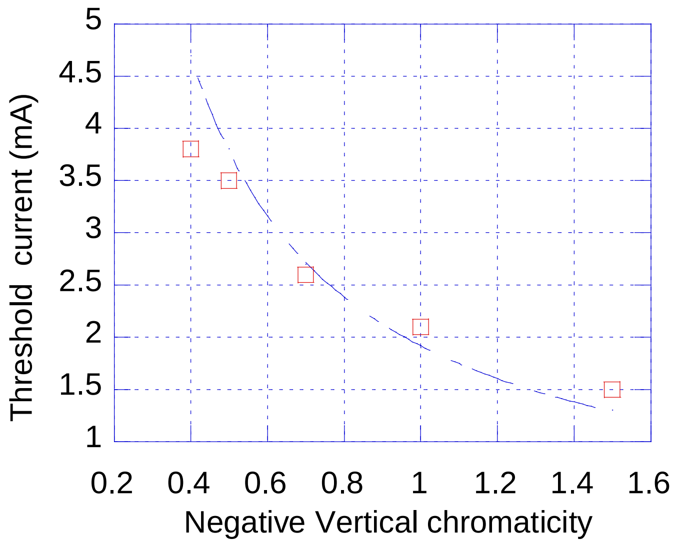
$$Z_{\perp} = \frac{3}{4}\frac{Z_0 h}{d}\left(\frac{1}{b} - \frac{1}{d}\right)$$

One sees that the rods behave more like a tapered device (1/x) instead of a step scraper ($1/x^2$)

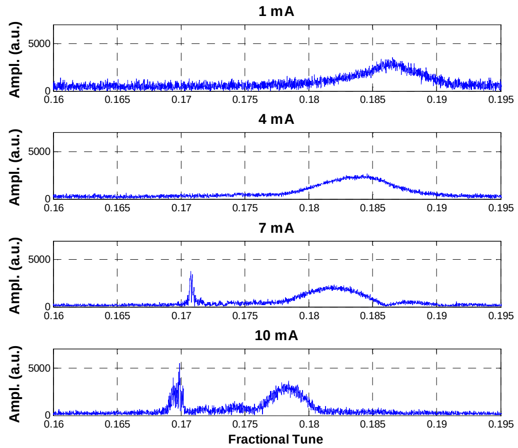
At 5 mm gap the reactive impedance is about 30 kohm/m

Negative chromaticity

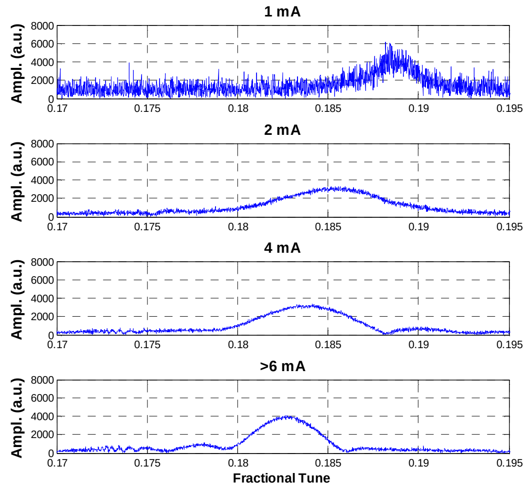
Nowadays single bunch current is mode coupling limited at most 10 mA by m=0,-1 head tail modes. TFB cannot be used since can not detect/correct them. So the idea is to go to negative chromaticity where m=-1 mode is stable and cure with the TFB the m=0 mode



$$I_{th} = \frac{q_s}{(\Delta q_v / \Delta I)} \frac{q_y}{\xi}$$



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



The m=0 mode shift with vertical negative chromaticity (0,-2)

feedback on and kickers on

An accumulated current of 15 mA was achieved but not systematically. Much depends upon the machine and feedback fine settings. Nevertheless operating with negative chromaticity in the single or 4 bunch mode, even when higher thresholds could not be reached, the beam was very stable at all reached currents whereas when at positive chromaticity the beam started becoming sometimes unstable after 7 mA.

Conclusions

Experimentalists requests compromise the machine!

Muti-bunch instabilities did not change behavior. In fact for many years almost the same cavity temperature settings are used. Using TMFB and the 3rd harmonic cavity result in efficient elimination of any multibunch instabilities. A LMFB also exists but not in use.

Mode coupling. The mode m = 0 and m = -1 merging at 12 mA/bunch with nearly zero chromaticities.

Head-tail instabilities: with slightly positive chromaticity no more than 5 mA can be stored. Increasing the chromaticity some 8 mA/bunch can be reached at 1 GeV. At 2 Gev however things are better, 10 mA/bunch are stable at near zero chromaticity.

Thus only the few bunch operations at low energies were affected but this is critical since at 1 GeV operates the SR-FEL However since it is using seeding 5mA/bunch are more that enough, usually operates at 1mA/bunch!

For 2010 two low gap (9 mm vertical) NEG chambers are to be installed replacing NEG 14 mm ones!-> life continues being interesting