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High Currents Effects in DAΦNE

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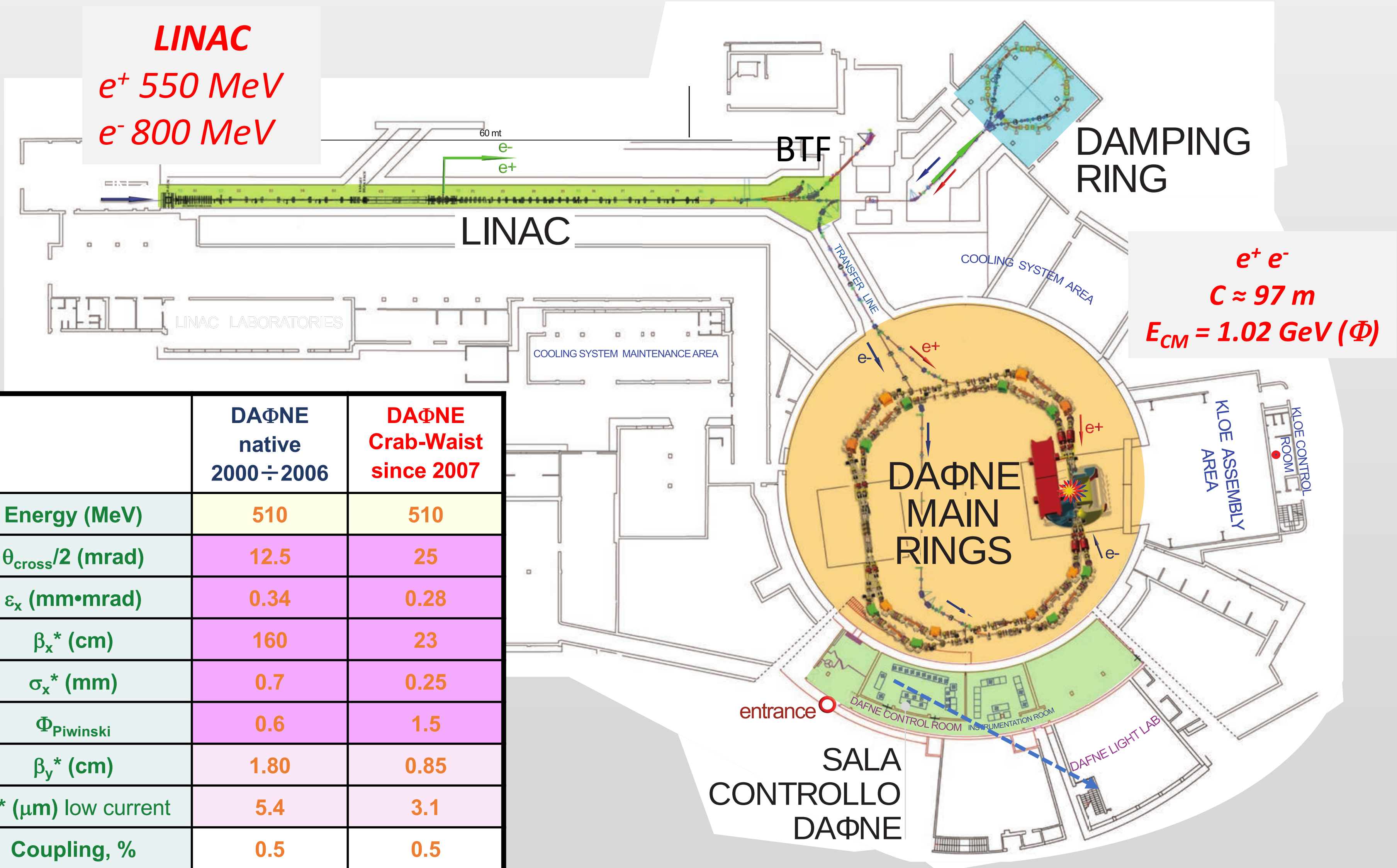
The DAΦNE Accelerator Complex

LINAC
e^+ 550 MeV
e^- 800 MeV



$e^+ e^-$
C ≈ 97 m
E_{CM} = 1.02 GeV (Φ)

	DAΦNE native 2000÷2006	DAΦNE Crab-Waist since 2007
Energy (MeV)	510	510
$\theta_{cross}/2$ (mrad)	12.5	25
ε_x (mm•mrad)	0.34	0.28
β_x^* (cm)	160	23
σ_x^* (mm)	0.7	0.25
$\Phi_{Piwinski}$	0.6	1.5
β_y^* (cm)	1.80	0.85
σ_y^* (μm) low current	5.4	3.1
Coupling, %	0.5	0.5
Bunch spacing (ns)	2.7	2.7
I_{bunch} (mA)	13	13
σ_z (mm)	25	15
N_b	120	120

DAΦNE implemented and tested succesfully a new approach to beam-beam interaction: the ***Crab-Waist* collision scheme**.

DAΦNE is a collider operating with high currents

Lepton Beam Currents achieved so far

	beam current I [A]	bunch population N_b [10^{11}]	rms bunch length [mm]	bunch spacing [ns]	comment
PEP-II	2.1 (e^-), 3.2 (e^+)	0.5, 0.9	12	4.2	closed
superKEKB	2.62 (e^-), 3.6 (e^+)	0.7, 0.5	7	6	commissioning
DAFNE	**2.4 (e^-), 1.4 (e^+)**	**0.4, 0.3**	**16**	**2.7**	
BEPC-II	0.8	0.4	<15?	8	
CesrTA	0.2	0.2	6.8	4	
VEPP-2000	0.2	1	33	80 (1 b)	
LHC (des)	0.58	1.15	75.5	25	
ESRF	0.2	0.04	6.0	2.8	
APS	0.1	0.02	6.0	2.8	
Spring8	0.1	0.01	4.0	2.0	
SLS	0.4	0.05	9.0	2.0	

DAΦNE Beam Pipe Composition

All Dipole and Wiggler vacuum chambers are equipped with **antichamber**, and **SR adsorbers**

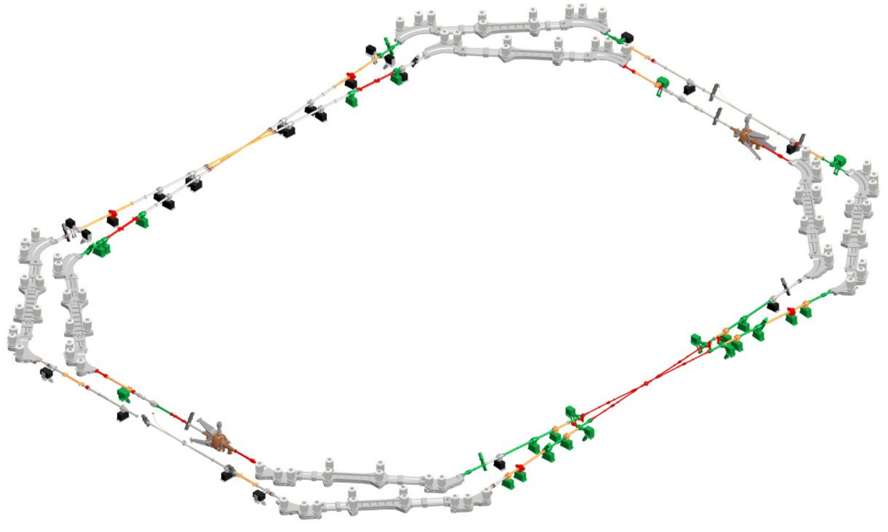
The 8 large vacuum chamber of the arcs are in **AL 5083 H321** (Al - Mg)

Property Results

Chemistry Data : [top]

Aluminum	Balance
Chromium	0.05 - 0.25
Copper	0.1 max
Iron	0.4 max
Magnesium	4 - 4.9
Manganese	0.4 - 1
Remainder Each	0.05 max
Remainder Total	0.15 max
Silicon	0.4 max
Titanium	0.15 max
Zinc	0.25 max

Straight section beam pipes are made by **AL 6082 T6** (Al - SI)



A system of long gradual transitions among different cross-sections of the arc vacuum chamber is used to minimize the coupling impedance

DAΦNE vacuum components

Due to beam pipe shape and dimensions, BPMs, vacuum ports, RF fingers, RF cavities, tapers and transitions, bellows, scrapers and collimators are main sources of impedance.

All the vacuum components of the DAΦNE rings have been carefully optimized from the **resistive wall impedance** point of view

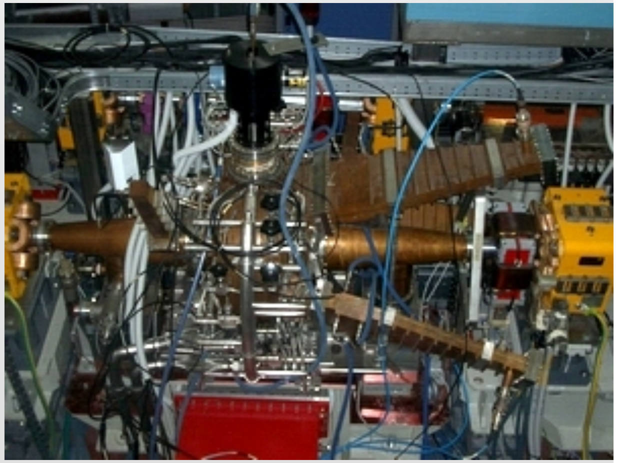
Element	Im Z_L/n [Ω]
Tapers	0.156
Transverse feedback kickers (low frequency)	0.128
Scrapers	0.062
Bellows	0.024
Resistive wall (at roll - off frequency)	0.013
BPMs	0.01
Vacuum pump screens	0.02
Injection port	0.0031
Antechamber slots	0.0005
Synchrotron radiation	< 0.015
Space charge	-0.0021
Other inductive elements	0.1
Total	**0.53 Ω**

Element	$k_l, V / pC$ at $\sigma_z = 3$ cm
RF cavity	0.129
Third harmonic cavity	0.157
Longitudinal feedback kicker	0.120
Transverse kickers	0.064
Injection kickers	0.047
IR taper system	0.0026
Scrapers	0.00007
Injection port	0.00004
Total	**0.52**

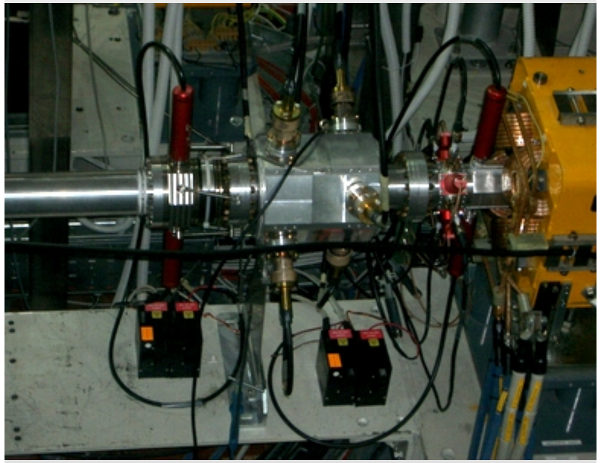
DAΦNE –. Zobov et al., LNF-95/041 (P), 1995

DAΦNE Vacuum Chamber Elements

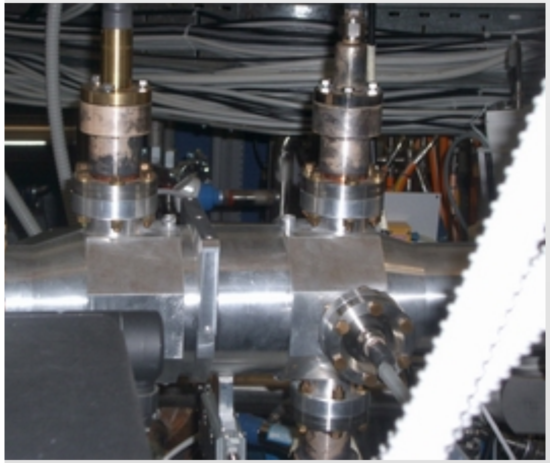
Optimized to: avoid heating, reduce impedance, and damp HOM



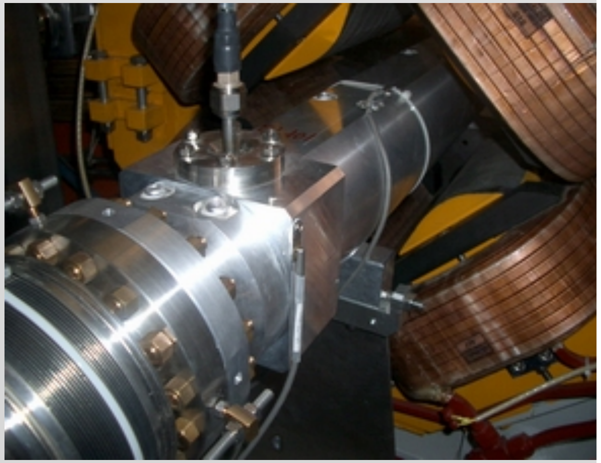
RF CAVITY



LONGITUDINAL KICKER

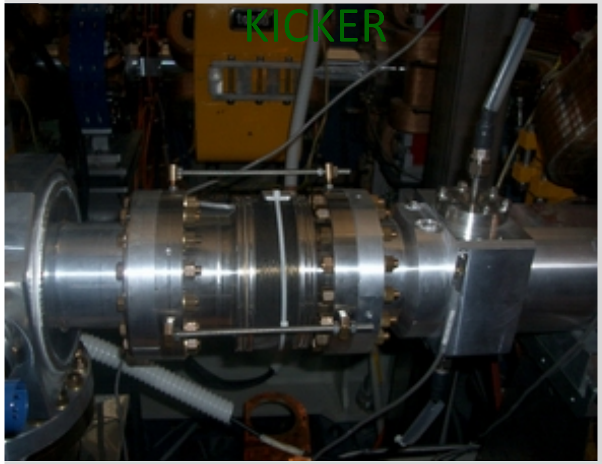


TRANSVERSE KICKER



INJECTION KICKER

WALL CURRENT & DCCT MONITOR



SHIELDED BELLOWS

Impedance budget in the DAΦNE Rings
(native configuration)

- Impedance in the DAFNE Main Rings:

$$\left(\frac{Z}{n}\right)_0 \approx 1\Omega \quad e^-$$

$$\left(\frac{Z}{n}\right)_0 \approx 0.54\Omega \quad e^+$$

difference mainly due to Ion Clearing Electrodes in the Wigglers!

- Impedance affects bunch length:

$$\left(\frac{\sigma_z}{R}\right) \approx \left(\frac{2}{\pi}\right)^{1/6} \xi^{1/3} \left(\frac{Z}{n}\right)_o^{1/3} \qquad \xi = \frac{\alpha_c I}{\nu_s^2 (E/e)} = \frac{2\pi I}{h V_{RF} \cos\phi_c}$$

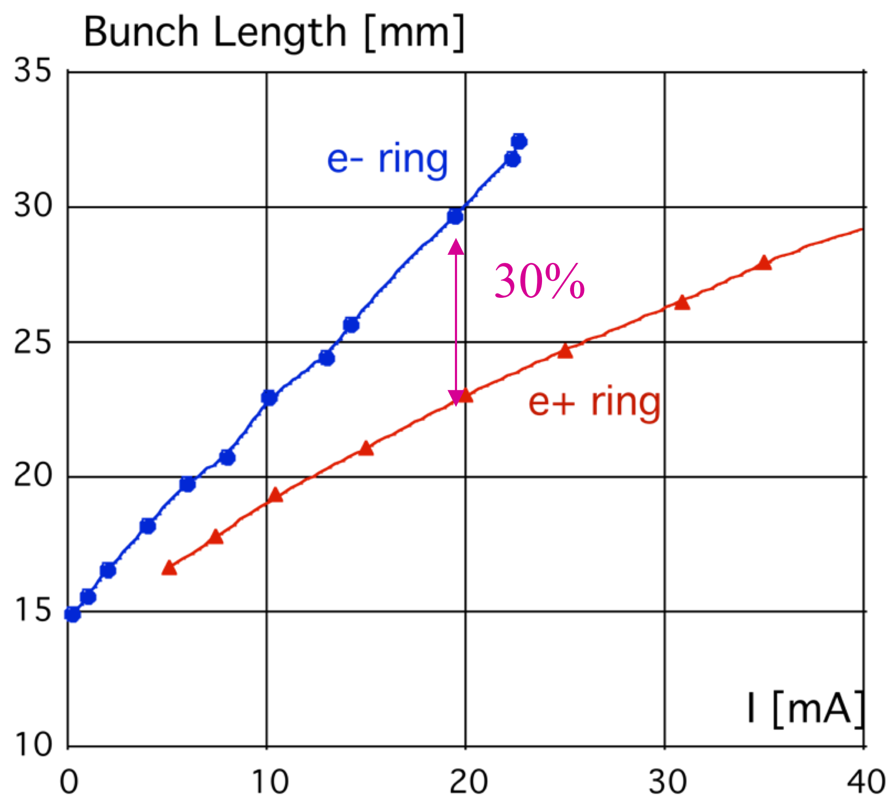
$\sigma_z^- \approx 2.7\text{cm}$

$\sigma_z^+ \approx 2\text{ cm}$ measured @ I_b ~ 15 mA

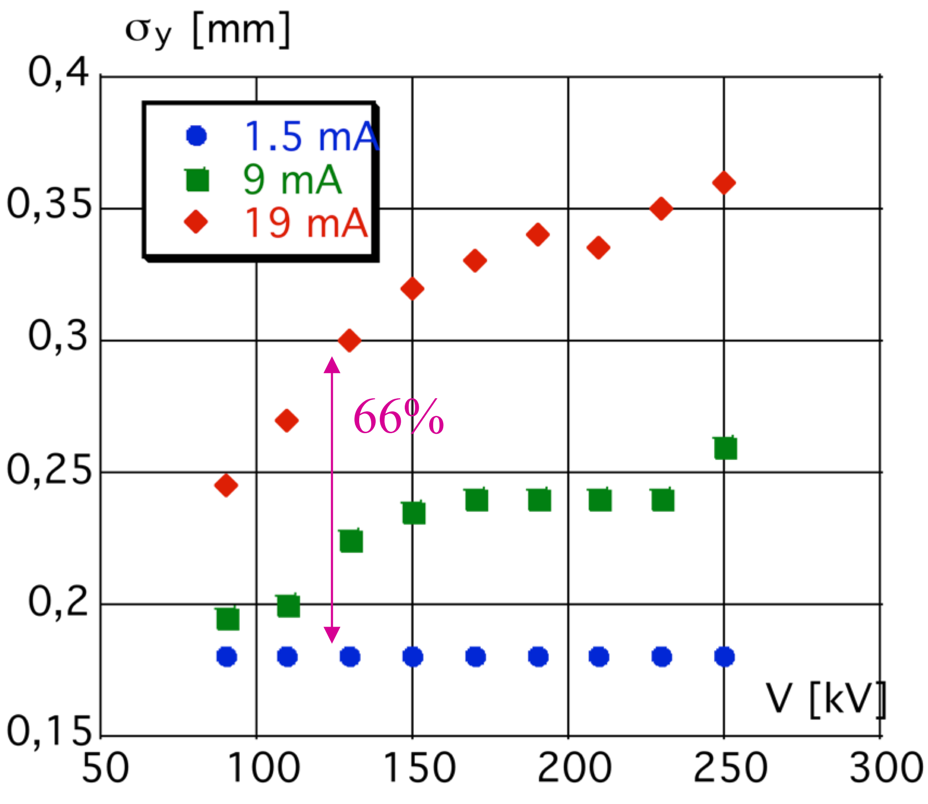
- hence the need for reducing the ring impedance especially the e^- ring one

Impedance Effects in the DAΦNE e⁻ Ring

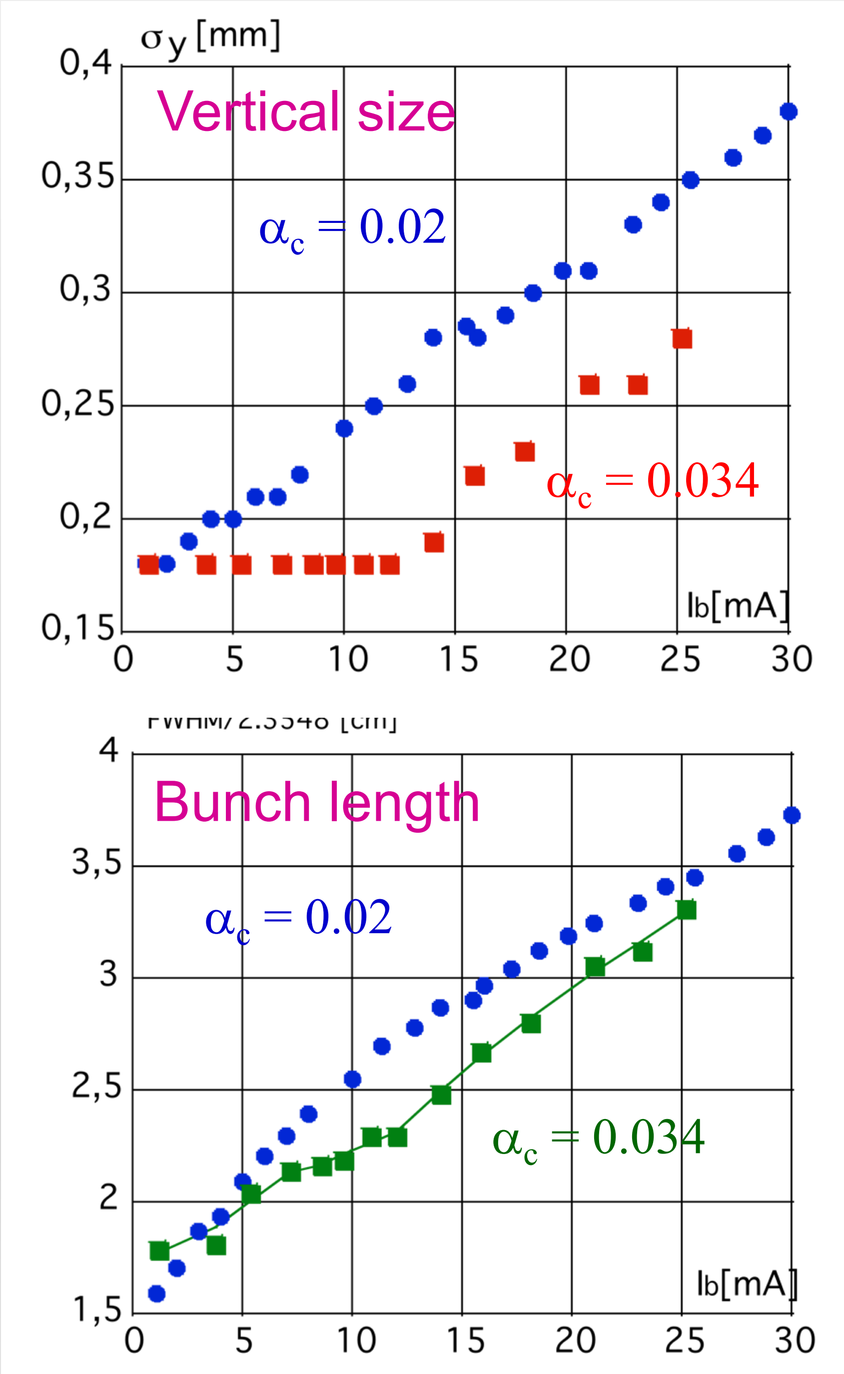
Stronger Bunch Lengthening in the e⁻ beam



e⁻ beam vertical Size Blow $f(V_{RF}, I_b)$



e⁻ Beam Vertical Size Blow Up



- **Single bunch effect**
- **It is correlated with the longitudinal microwave instability, in fact it has:**
  - the same threshold
  - the same dependence on RF voltage
  - the threshold is higher for higher momentum compaction
  - more harmful impact on the e- ring having higher coupling impedance

Instability Cures

The e^- beam was also affected by a quadrupole mode instability

Quadrupole Instability has been cured by means of the bunch by bunch longitudinal feedback meant for coupled bunch instability control

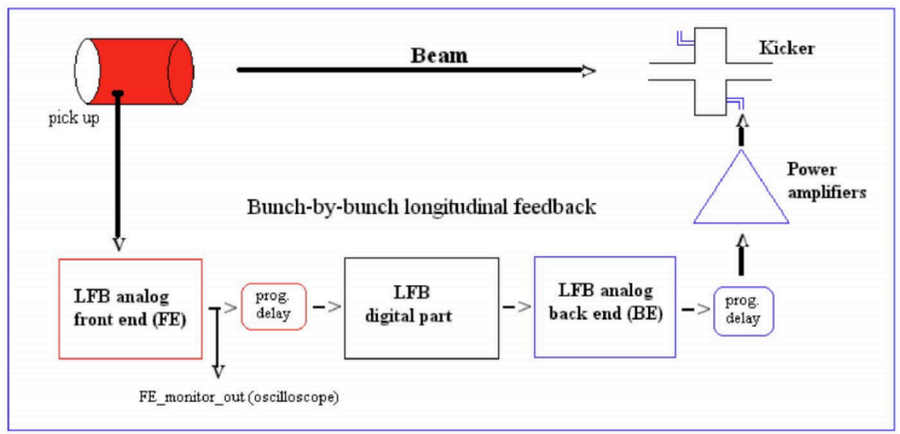
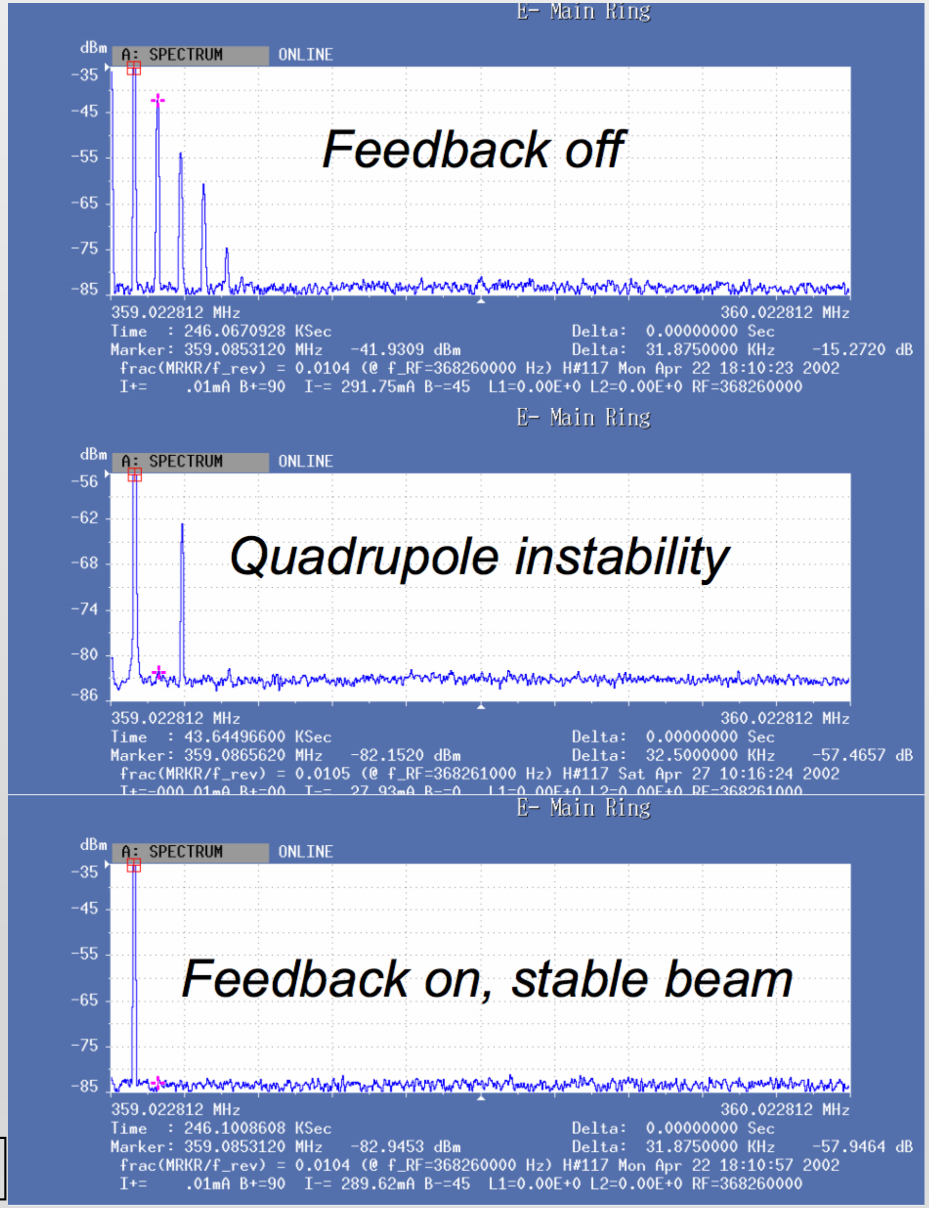


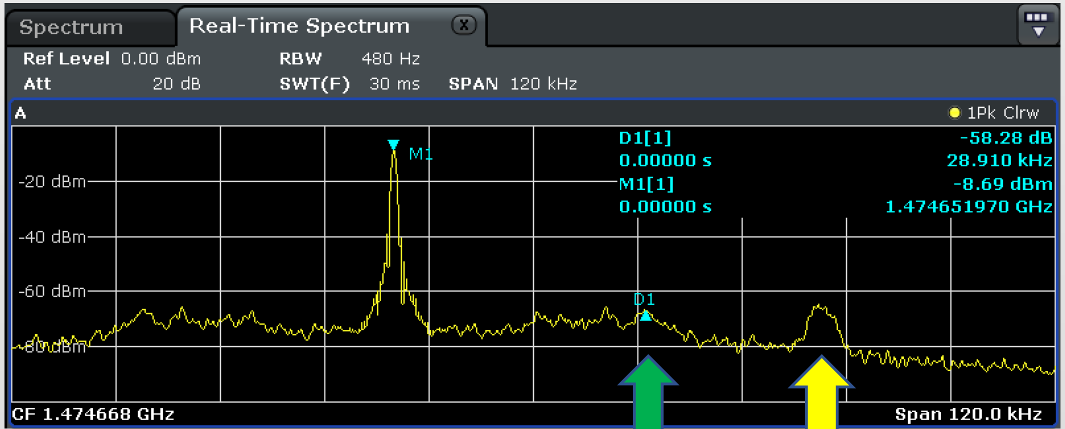
FIG. 1. (Color) Block diagram of the longitudinal feedback system.

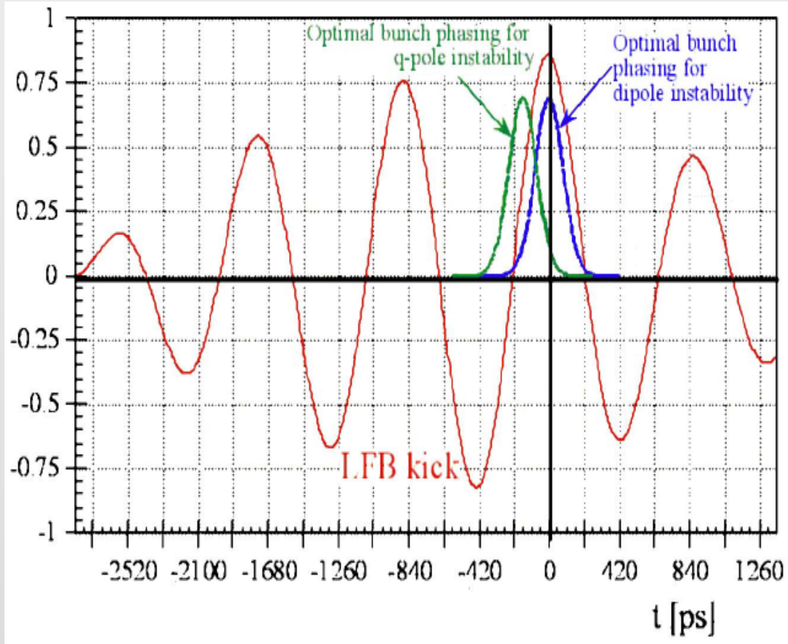


A. Drago et al., PRST-AB 6, 052801 (2003)

Longitudinal Quadrupole Oscillations

@ $f \sim 2 \cdot f_{sync}$

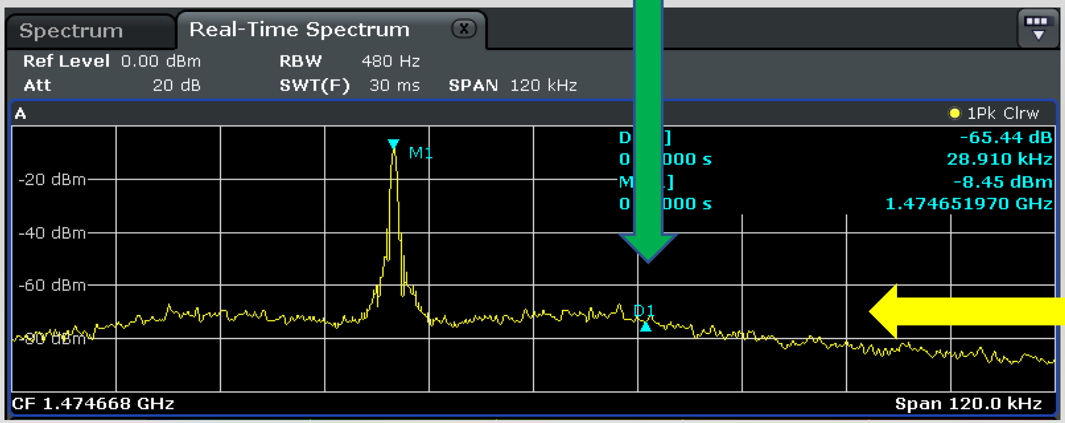




Revolution harmonic

Quadrupole oscillation

Synchrotron (dipole) oscillations damped by Long FBK

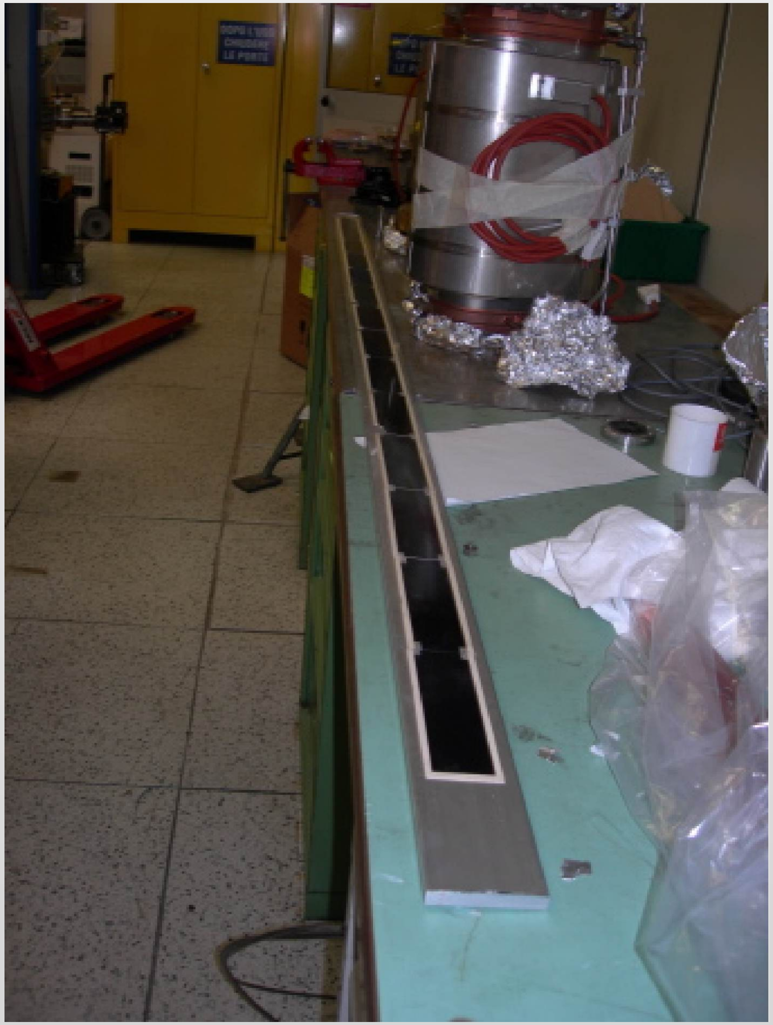


The present source of quadrupole instability is still under investigation

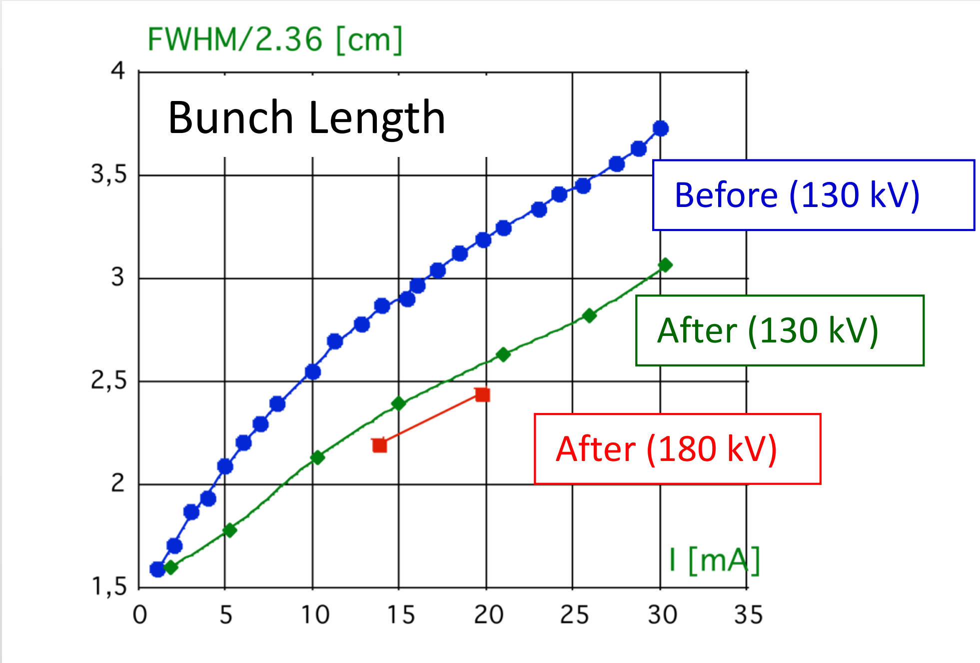
This instability, if not controlled, saturates the longitudinal feedback

(A.Drago, et al., PRST-AB, 6, 052801-1-11, 2003)

After Removing ICE



M. Zobov et al., Journal of Instrumentations 2, P.08002, 2007



- About 30% e^- bunch length reduction
- Twice higher longitudinal microwave instability threshold
- No quadrupole instability
- No single bunch vertical blow up

Geometric luminosity by 50% higher!

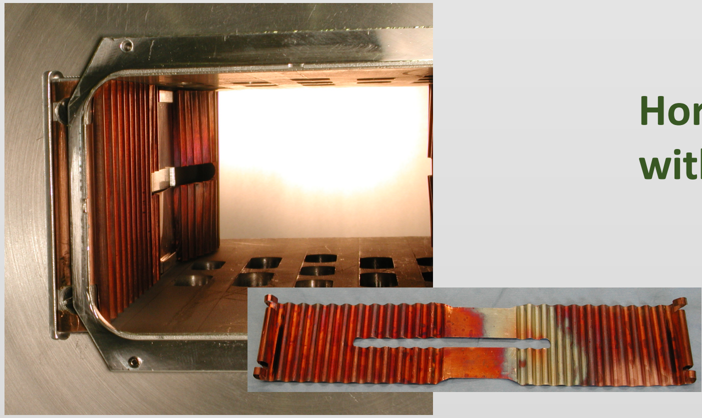
Scrapers Modifications (2003)

Few collimators were not working properly due to mechanical problems with jaw tapers

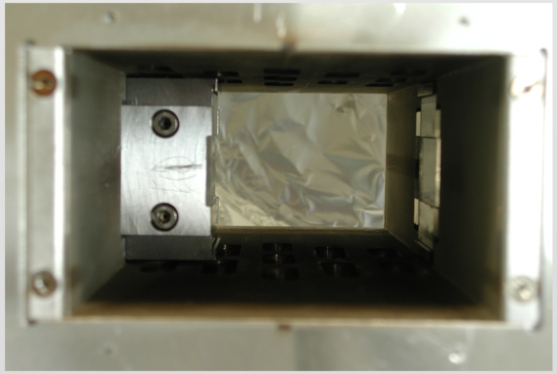
The problem has been fixed by:

- removing the horizontal tapers, which are less critical to the ring impedance
- modifying the vertical ones, that were intercepting the beam instead of the jaws

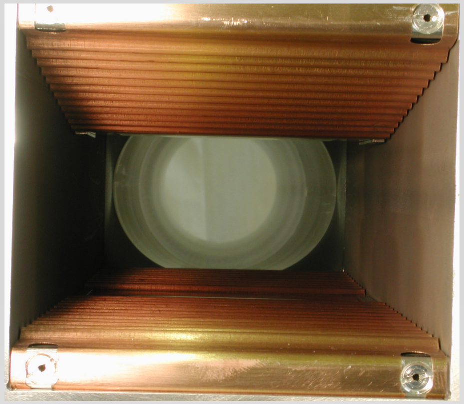
Horizontal jaw with taper



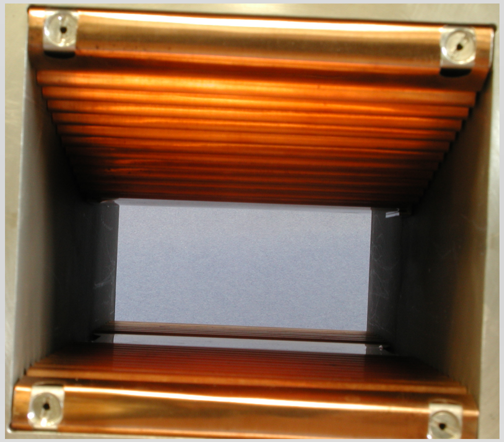
Horizontal jaw without taper



Vertical tapering sheets



Modified vertical tapering sheets



Beam Current Figures

	DAΦNE KLOE (2005)	DAΦNE FINUDA (2006)
L_{peak} [$cm^{-2}s^{-1}$]	$1.5 \cdot 10^{32}$	$1.6 \cdot 10^{32}$
I^{-}_{MAX} [A] @ L_{peak}	1.4	1.5
I^{+}_{MAX} [A] @ L_{peak}	1.2	1.1
I^{-}_{MAX} [A]	2.4	
I^{+}_{MAX} [A]	1.4	
N_b in collision	111	106

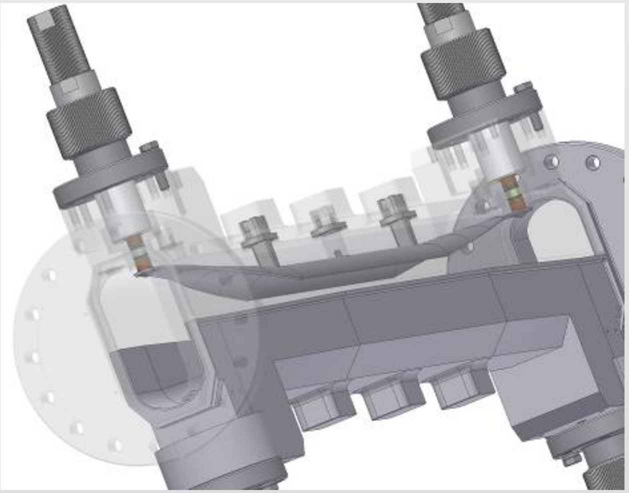
DAΦNE native configuration, no Crab-Waist

Vacuum Components Modifications in 2007
(prior to the Crab-Waist Collision Scheme test)

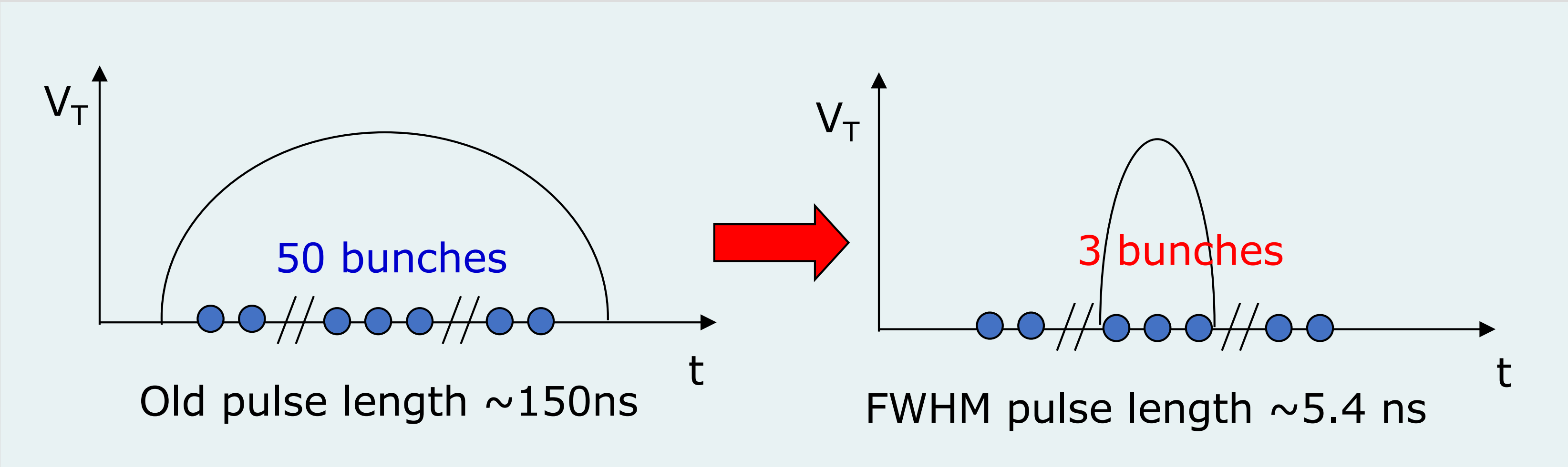
- new vacuum chambers for the main Interaction Region
- new vacuum chambers, implementing a full separation between the two beams, replaced the old second IR
- injection kickers replaced with new equipment
- old bellows replaced with devices based on a new design

DAΦNE new injection kickers

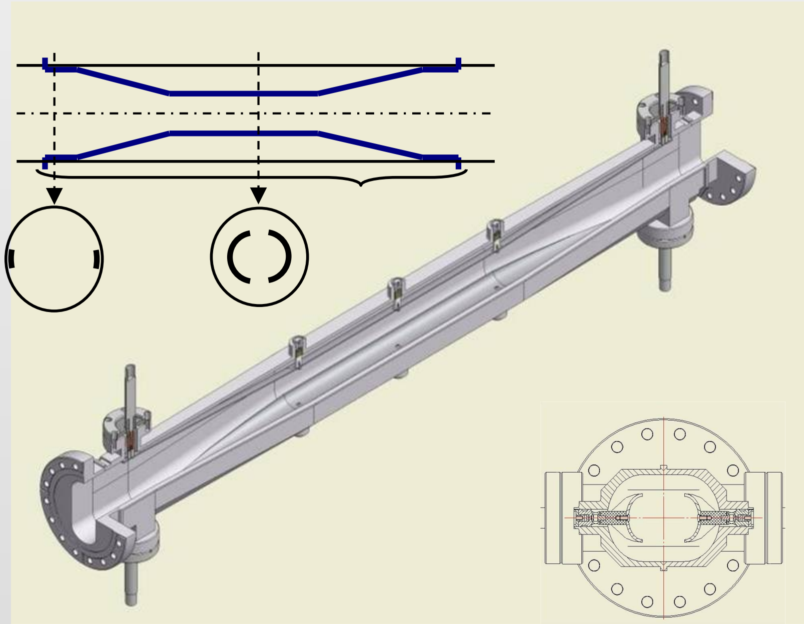
Injection kickers have been replaced with new designed device in order to overcome heating and reduce impedance.

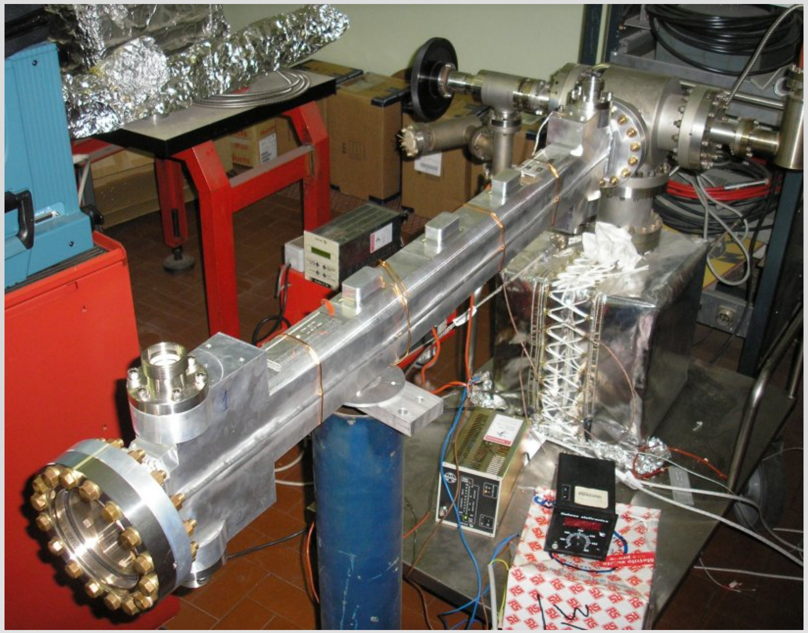


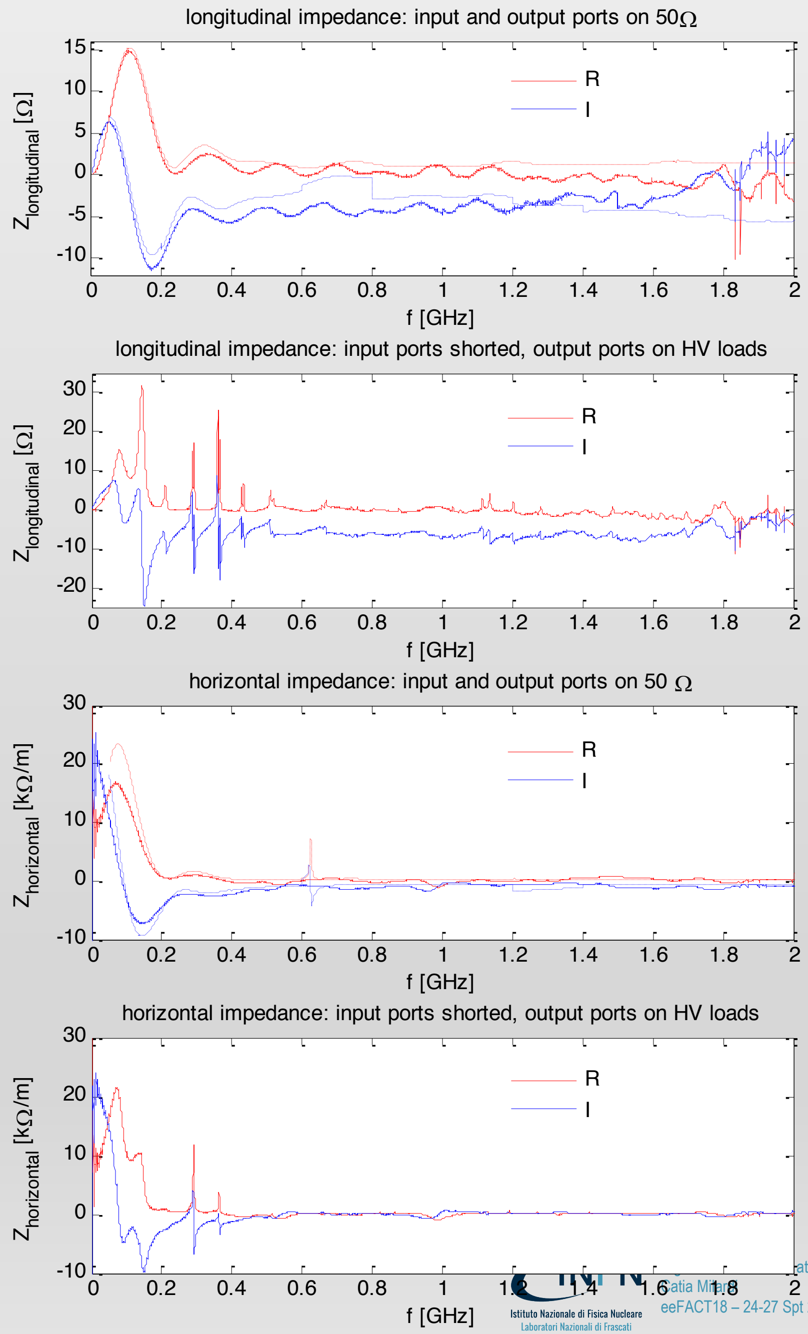
New injection kickers with 5.4 ns pulse length to reduce perturbation on stored beam



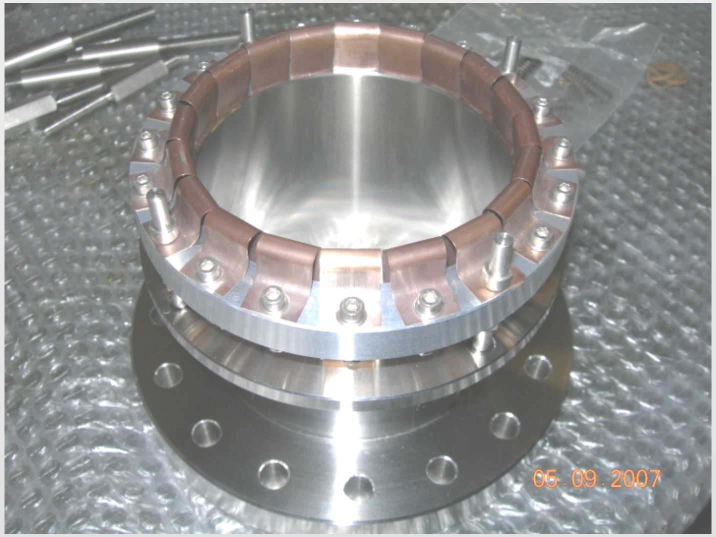
New Injection Kicker Impedance

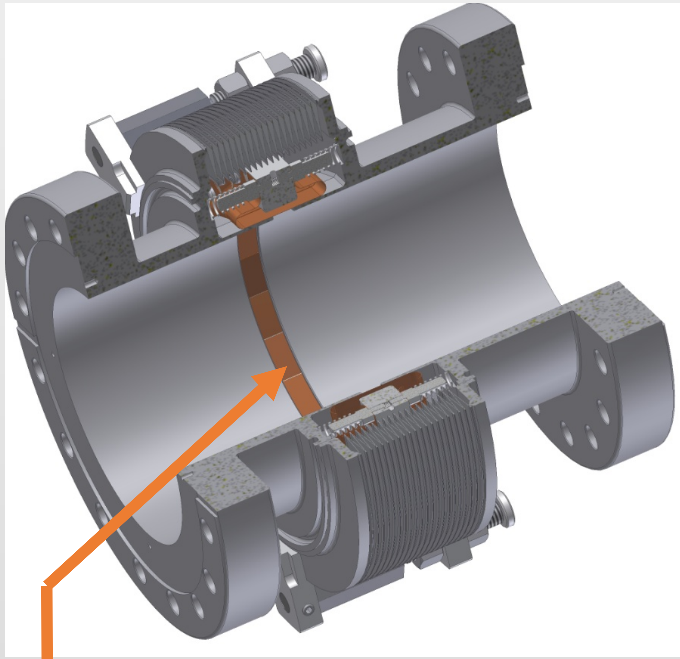




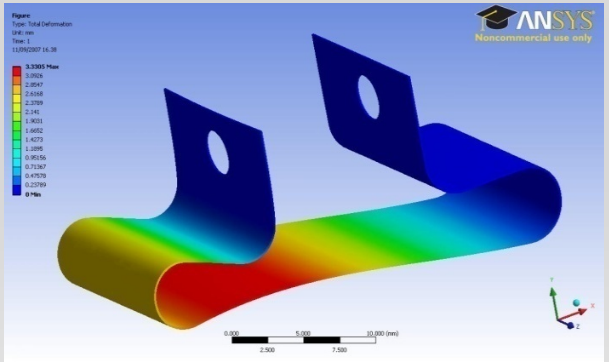


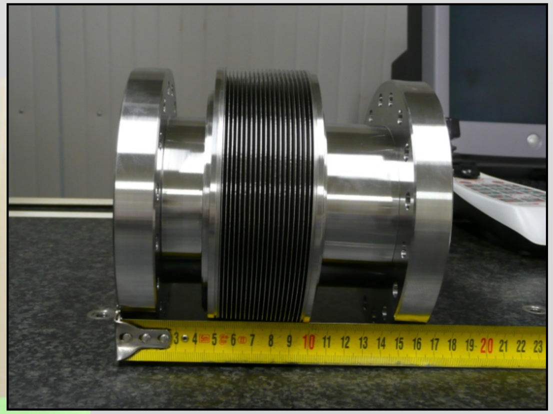
NEW BELLOWS



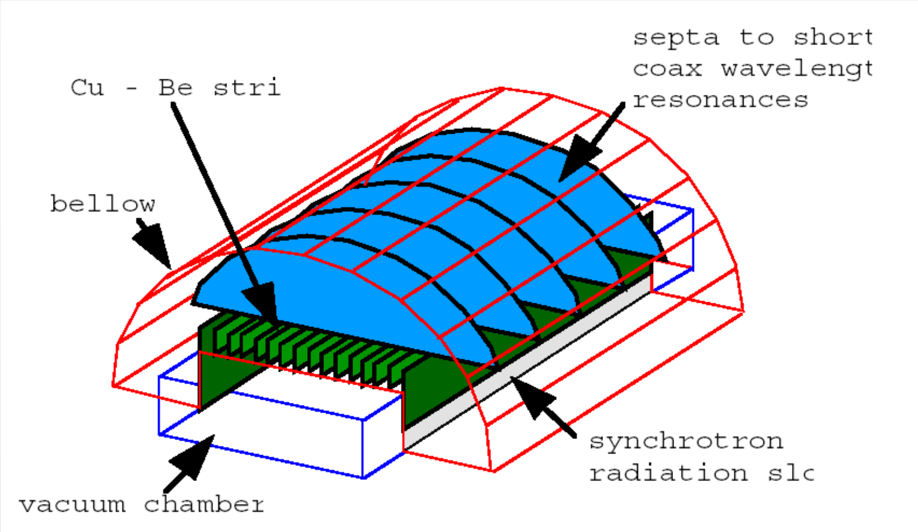


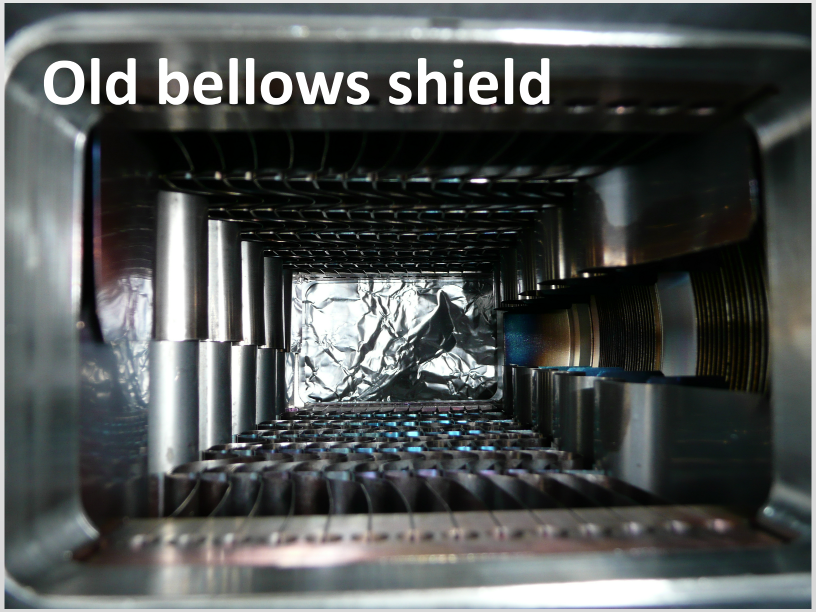
- 6 new bellows for each ring;
- Shielding based on Be-Cu Ω strips 0.2 mm thickness;
- lower impedance and improved mechanical specifications;

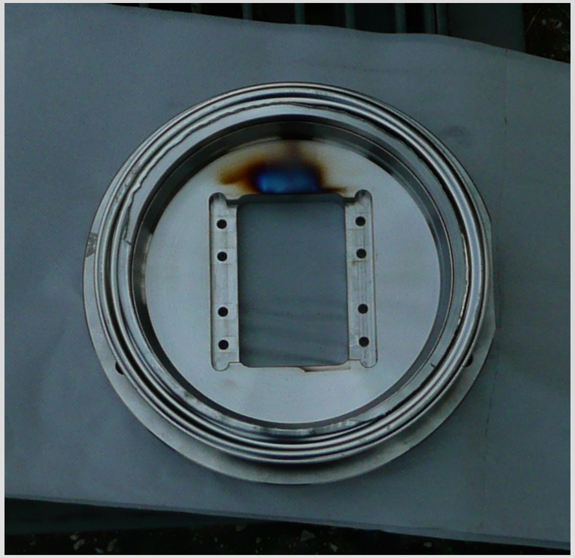




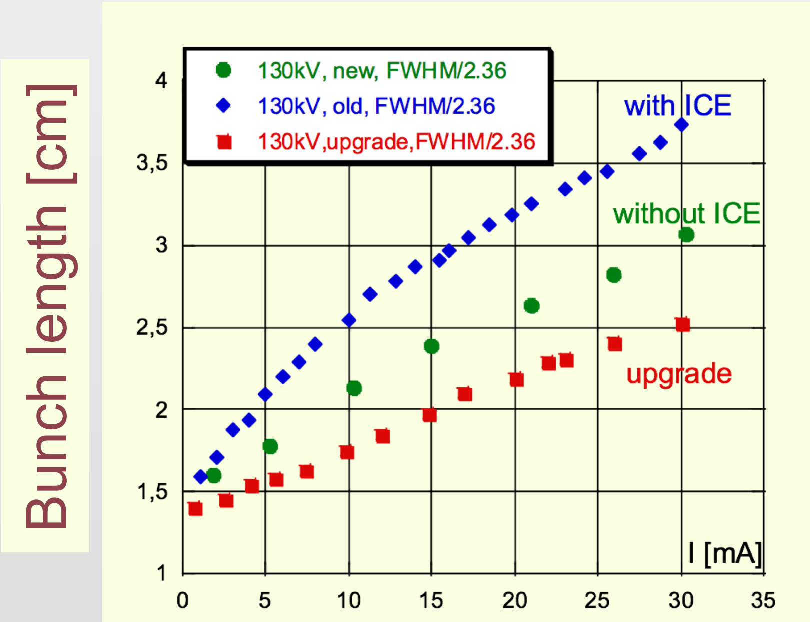
Old Bellows


septa to short
coax wavelengt
resonances
Cu - Be stri
bellow
synchrotron
radiation slc
vacuum chamber


Old bellows shield

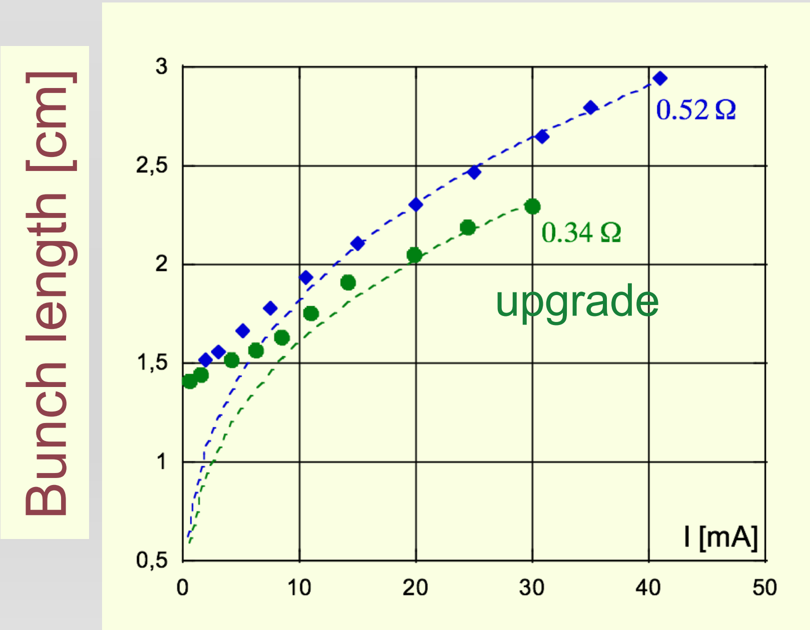


Bunch Lengthening in the Main Rings



e⁻

20% bunch length reduction @ I_{bunch} ~ 10 mA due to:
- ICE removal
- new injection kickers
- new bellows



e⁺

Few % reduction in bunch length due to:
- new injection kickers
- new bellows

Beam Current Figures

	DAΦNE KLOE (2005)	DAΦNE FINUDA (2006)	DAΦNE CW SIDDHARTA (2009)
L_{peak} [$cm^{-2}s^{-1}$]	$1.5 \cdot 10^{32}$	$1.6 \cdot 10^{32}$	**$4.36 \cdot 10^{32}$**
I^-_{MAX} [A] @ L_{peak}	1.4	1.5	1.47
I^+_{MAX} [A] @ L_{peak}	1.2	1.1	1.0
I^-_{MAX} [A]	2.4		2.2
I^+_{MAX} [A]	1.4		1.2
N_b in collision	111	106	105

Vacuum Components Evolution in 2009÷2013
(KLOE-2 run with the *Crab-Waist* Collision Scheme)

2009 (during the preparatory phase for the KLOE-2 run)

- beam scrapers in the IR branches have been modified
- new horizontal feedback kickers installed
- replacement of old style bellows has been completed
- one beam damp kicker has been installed in each ring
- E-Cloud Electrodes (ECE) installed in the e^+ ring

2013 (during the shutdown for the KLOE-2 upgrade)

- The vacuum chamber of the Interaction Point has been replaced with a pipe having modified tapered transitions

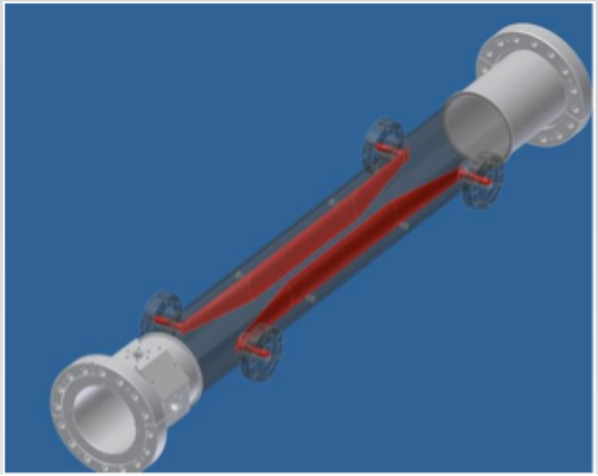
Transverse Horizontal Feedback upgrade

New horizontal kickers have been installed in the DAFNE rings having:

- double stripline length
- reduced stripline separation in the horizontal plane (88 mm -> 60 mm)
- *larger shunt impedance at the low frequencies typical of the unstable modes*
- *the kicker has been moved in a lattice position having a higher β_x value.*

Feedback power has been doubled (500 W now) providing ~40% increase in the kick strength

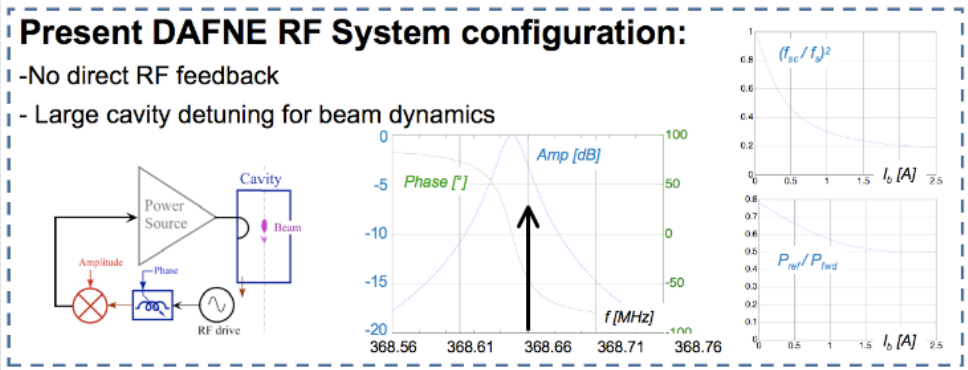
The new BPMs (EL108/PL108) installed on the MR long straight sections include also 4-button pickups dedicated to the FBK systems

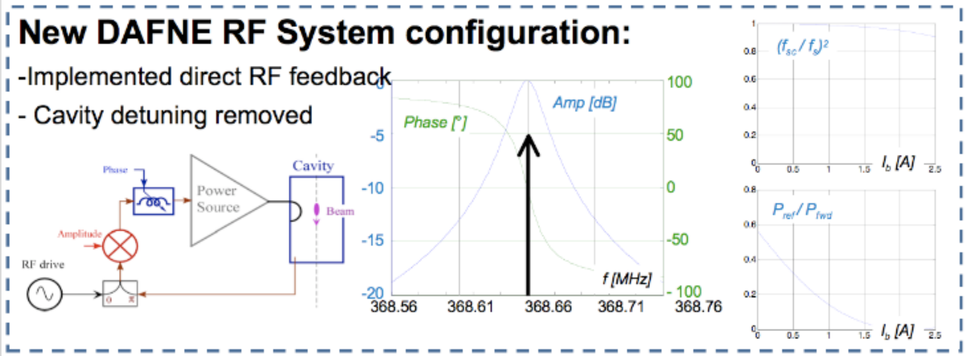


Low Level RF Feedback

A direct RF feedback system in the low level RF is being developed to:

- reduce the cavity detuning angle
- increase the overall efficiency
- limit the reduction of the coherent ‘0-mode’ synchrotron frequency with beam current



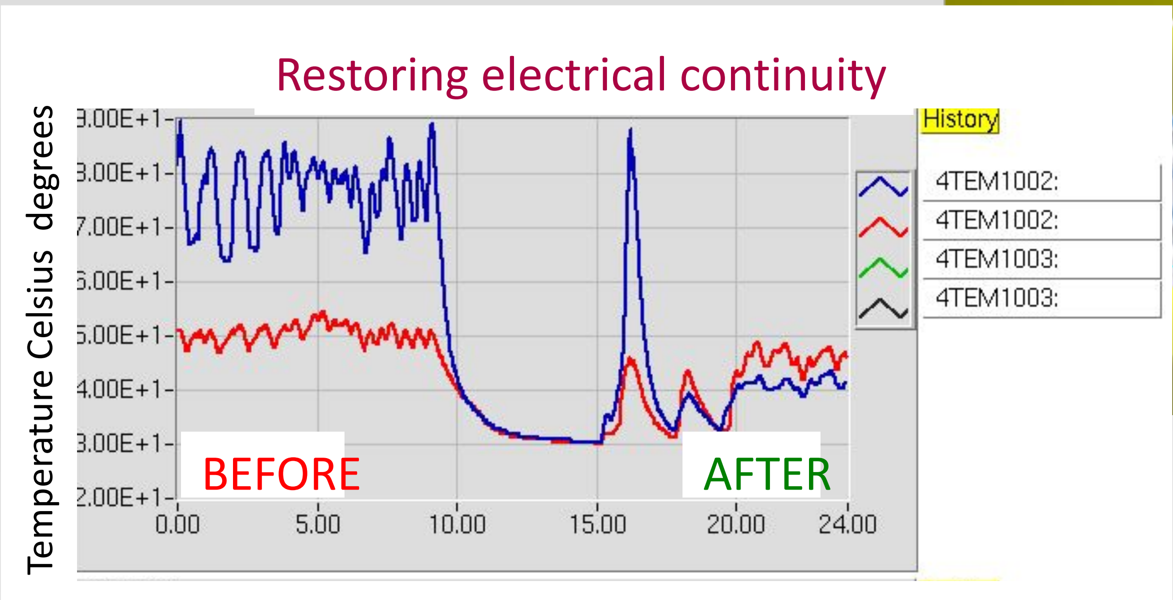


High power sections have also been modified in order to reduce power consuption

Fault in the IP beam Pipe

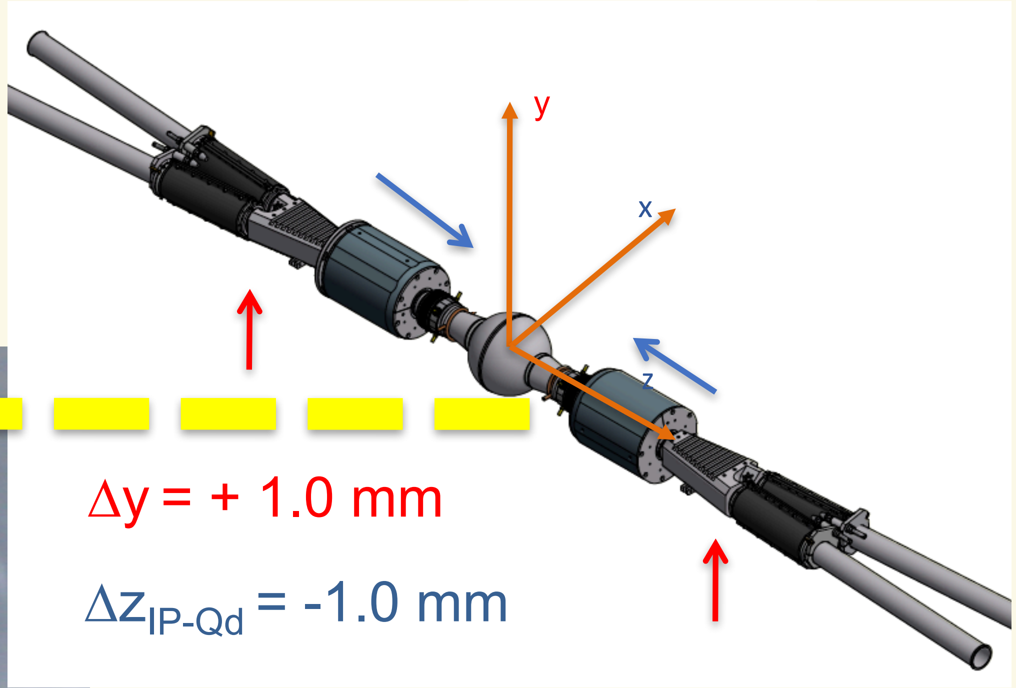
On mid January 2012 a sudden temperature rise occurred in the of the beam pipes of the IP inside the KLOE detector.
It was due to the leak of electrical continuity in the bellows at both ends of the section common to the two beams.

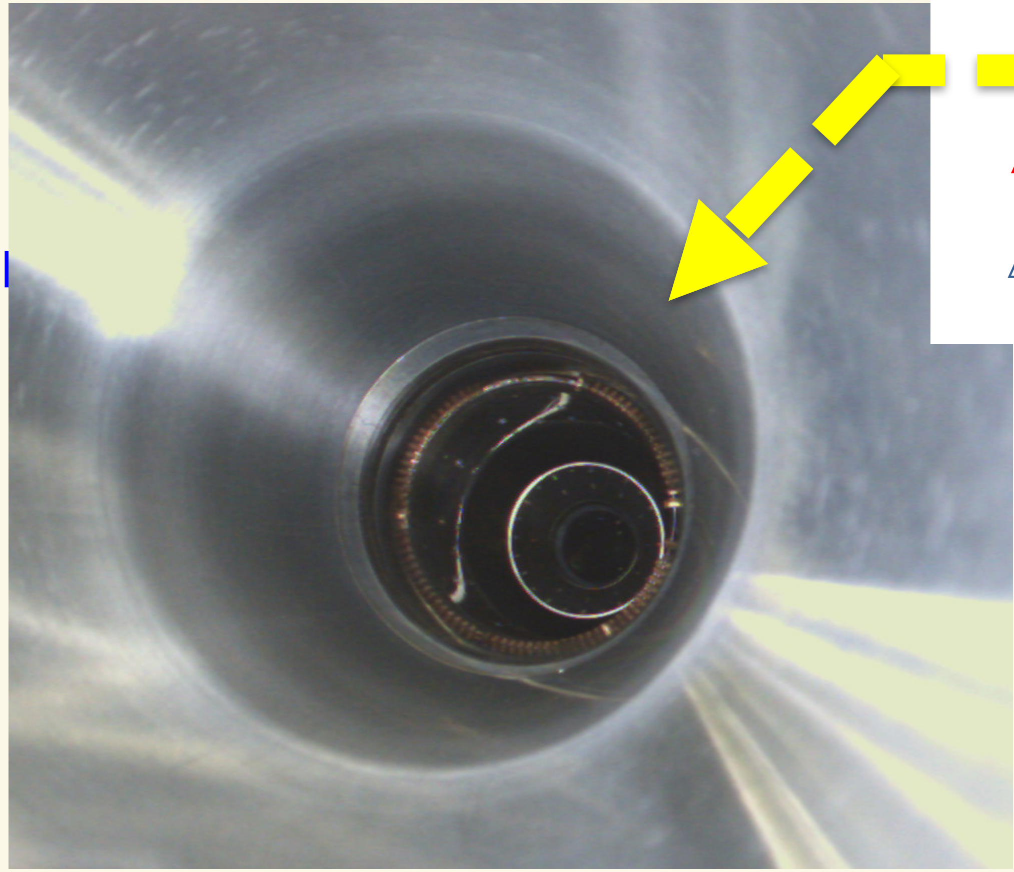
- Temperature excursion in the range 50 ÷ 60 ^{0}C with stored beams
- Drifts in the optics and the relevant vertical tune variations ($\Delta q_2 \sim 0.04$)



Summer shutdown 2012

IR measurement and alignment

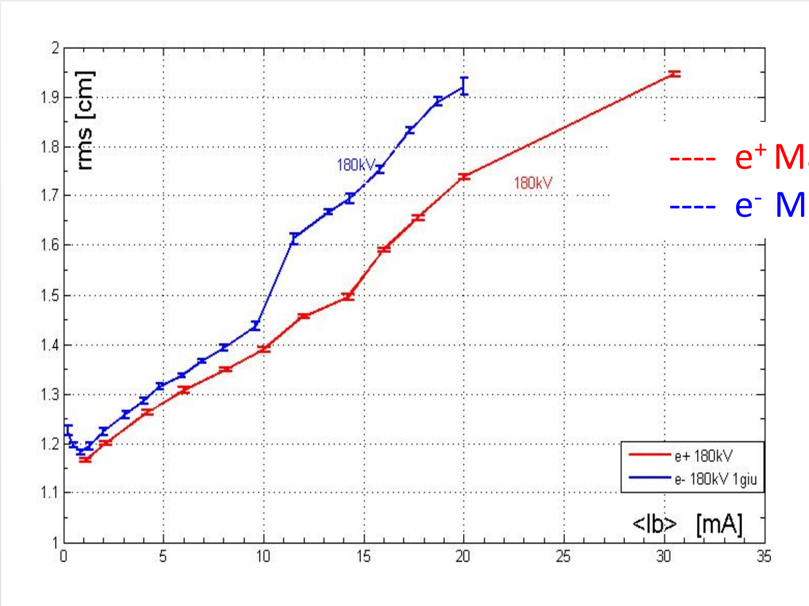




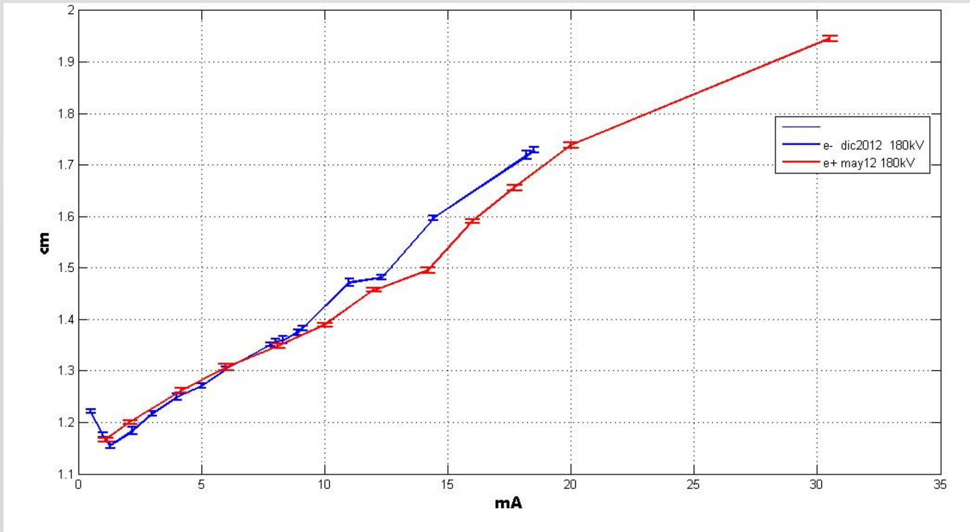
Endoscopic inspection of the low-β vacuum chamber

- 1 bellow was broken
- fingers stuck out inside the vacuum chamber

Bunch length measurements

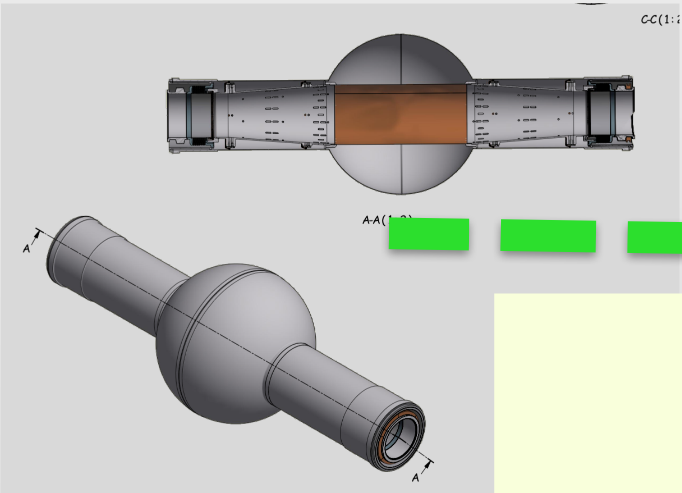


---- e^+ May 2012 (V_{RF}= 180 kV scrapers in)
---- e^- May 2012 (V_{RF}= 180 kV scrapers in)



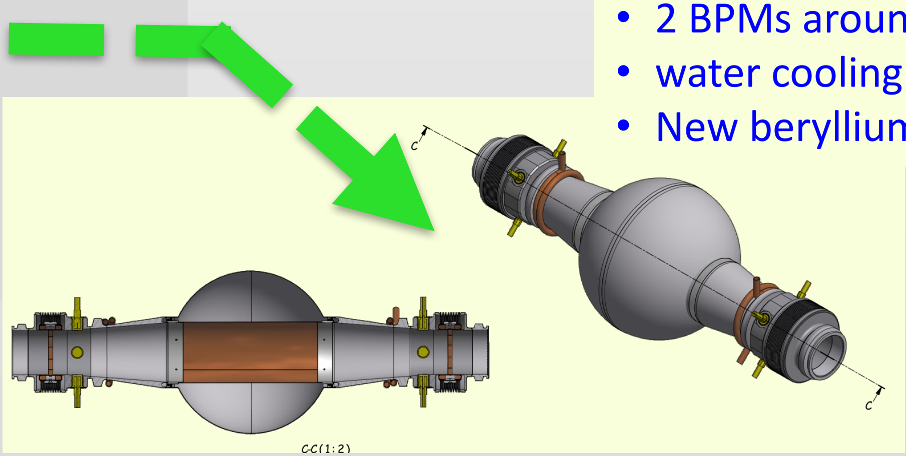
IP Chamber Consolidation

Relying on beam measurements, operation experience and profiting from the shut down planned to complete the KLOE-2 detector upgrade



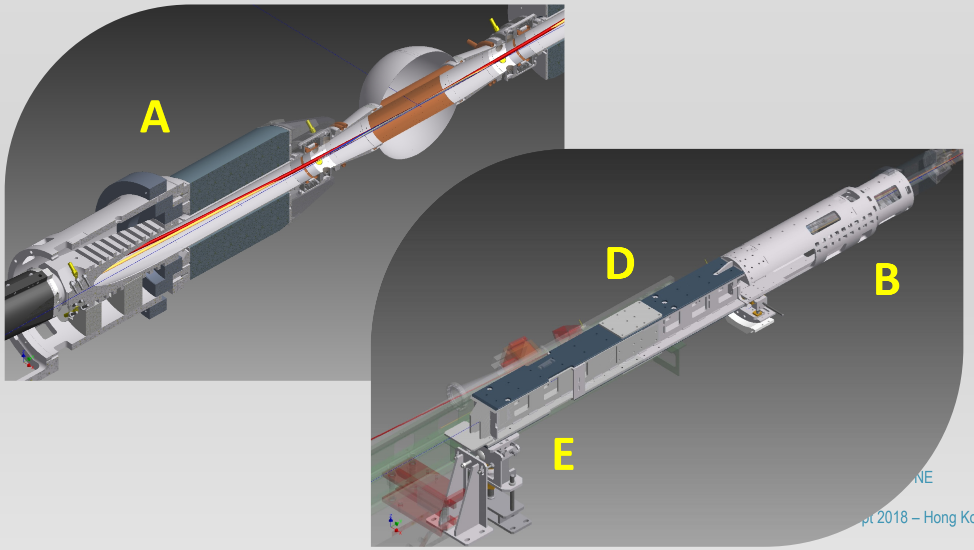
Spherical vacuum chamber evolution

- Single vacuum chamber tapered
- New bellows with improved design
- 2 BPMs around the IP
- water cooling added
- New beryllium screens



Mechanical modification

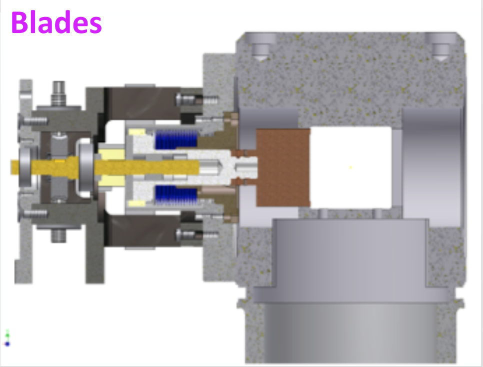
A. Lead toroidal shields added
B. New Cylindrical vacuum chamber support
C. Improvements on alignment tools
D. H supports reinforced with plates
E. Modification of tail support of the girder
F. Temperature probes added
G. Carbon fiber composite additional supports



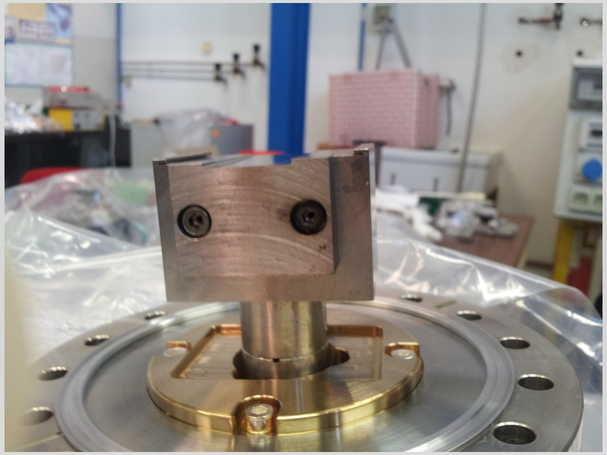
Collimators

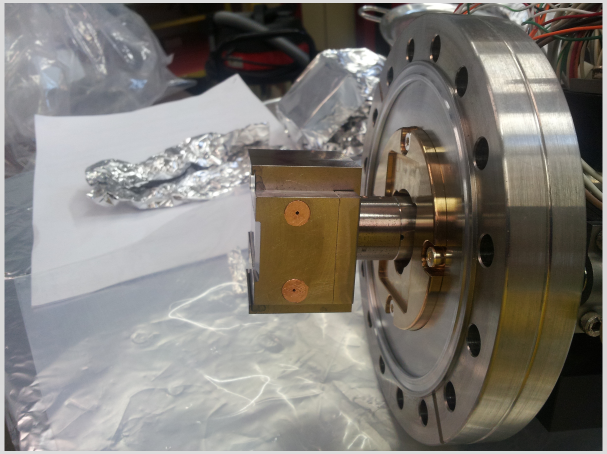
The collimators installed around the IP and the RCR have been modified as well as their vacuum chambers

*In 2009 the **Collimator** rectangular vacuum chambers, (20 mm high and 90 mm wide), have been replaced by square ones (55 mm)*



In 2013 blades have been modified once again





e^+ Beam Current Limitations

- e^+ current limit ~ 1.4 A due to a fast horizontal instability
- vertical beam size increase
- tune spread along the batch
- anomalous vacuum pressure rise

Measurements and simulations showed how horizontal instability was triggered by the *e-cloud formation* in the *DIPOLES* in the *WIGGLERS* of the DAΦNE positron ring.

Not strange considering that:

low beam energy E = 510 MeV
Al vacuum chamber with high SEY
multibunch high current operations
short bunch spacing 2.7 nsec

Beam energy	**510 [MeV]**
Ring length	**97 [m]**
Max. e+ beam current (Kloe run)	**1.4 [A]**
N filled bunches	**100**
RF frequency	**368.67 [MHz]**
RF voltage	**130 [kV]**
Harmonic number	**120**
Bunch spacing	**2.7[ns]**
SR emitted per turn	**9.7 [keV]**
n per bunch @ 10 mA	**$2 \cdot 10^{10}$**

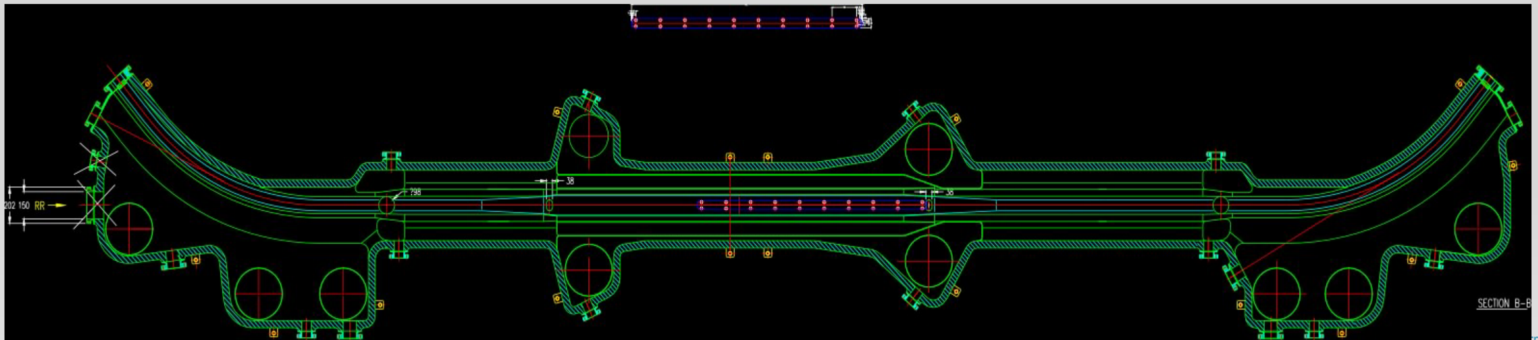
Countermeasures at DAΦNE

All Dipole and Wiggler vacuum chamber are equipped with antichamber, and SR adsorbers

Devices
- solenoid windings
- powerful feedback system
- electrodes

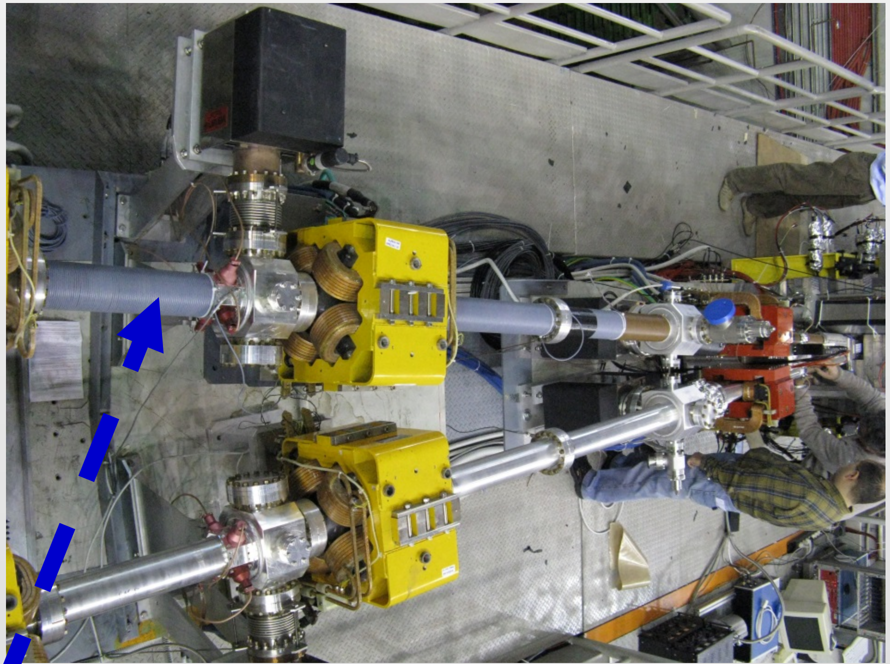
Varying ring and beam parameters
- moving ξ_x ξ_y to higher positive values
- lengthening the bunch by reducing the RF voltage
- tuning octupole magnets

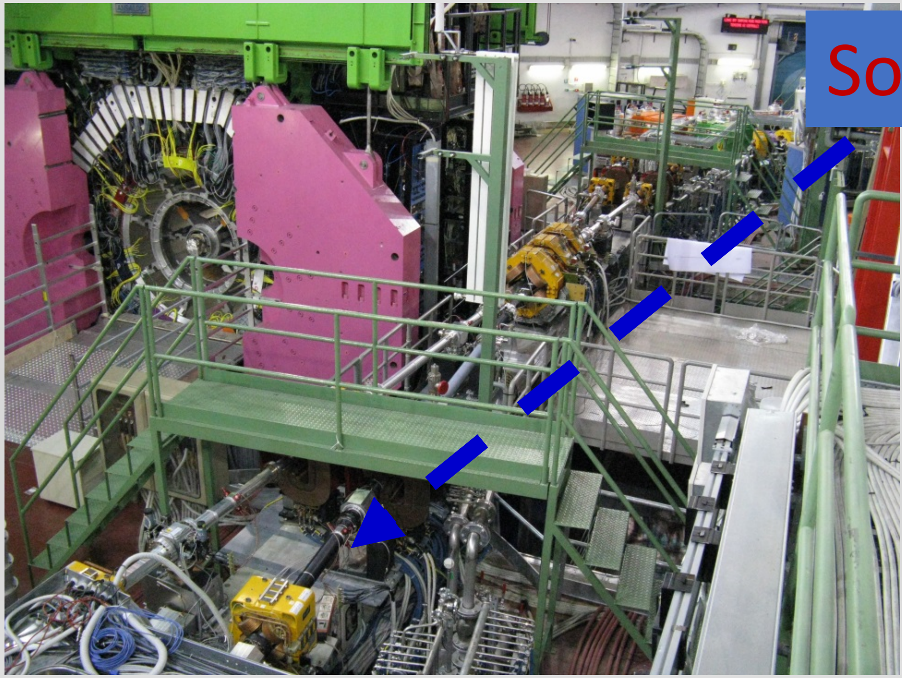
Maintaining optimal dynamic vacuum
- more frequent sublimations

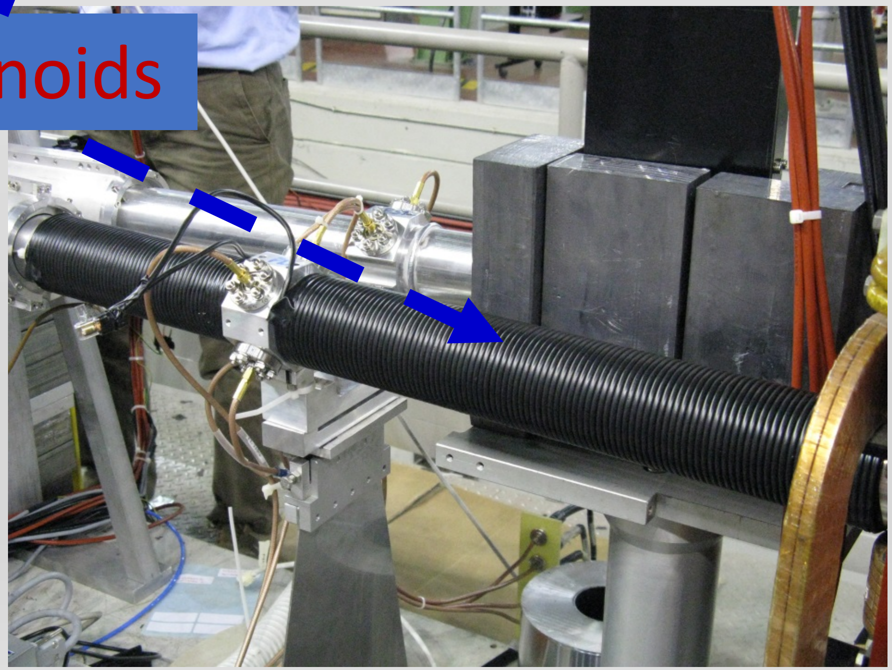


Solenoids

Solenoids have been winded around all the straight sections and connected to an external DC PS







Solenoids

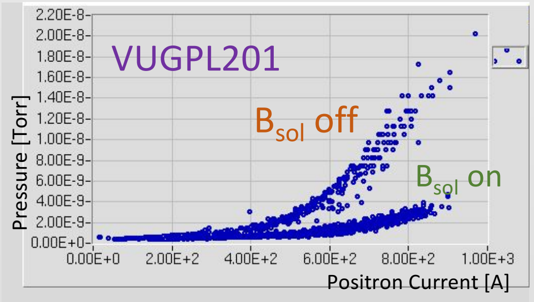
Operations with Solenoids

Solenoid currents have been initially set so to have:

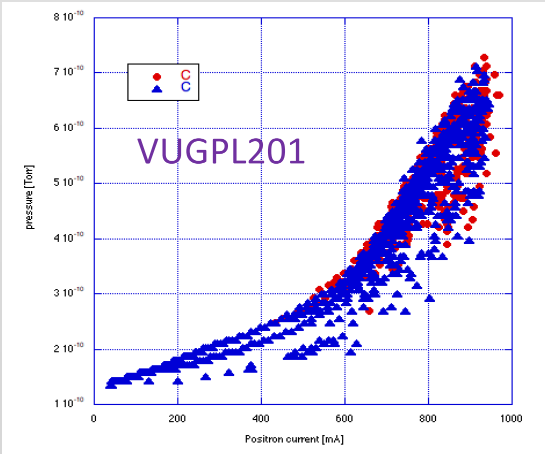
B_{sol} ~ 45 Gauss

as indicated by numerical simulations.

Such value has then been tuned experimentally



Impact of solenoid windings (May 2012)



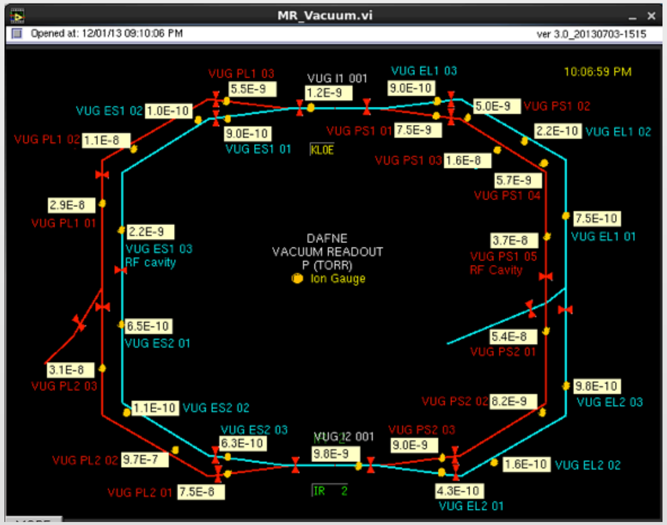
Red and blue dots refer to two different values of the B_{sol} in a given section at the end of the optimization process

Blue dots exhibit different trends corresponding to different values of the RF voltage.

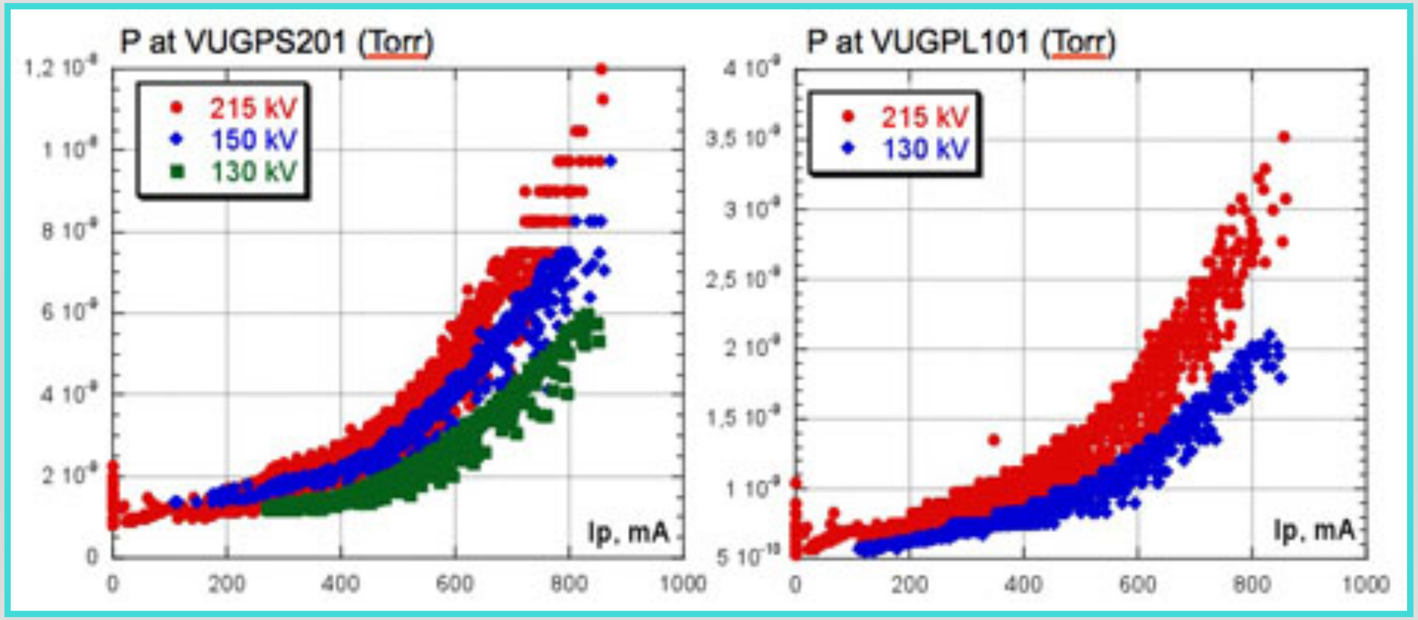
Solenoids are also effective in:

- reducing the transverse instability rise time
- boosting the action of the transverse feedbacks
- keeping under control the growth of the beam transverse size

Tuning Bunch Length



e-cloud induced effects have been mitigated also by lengthening the bunch by reducing the RF cavity voltage



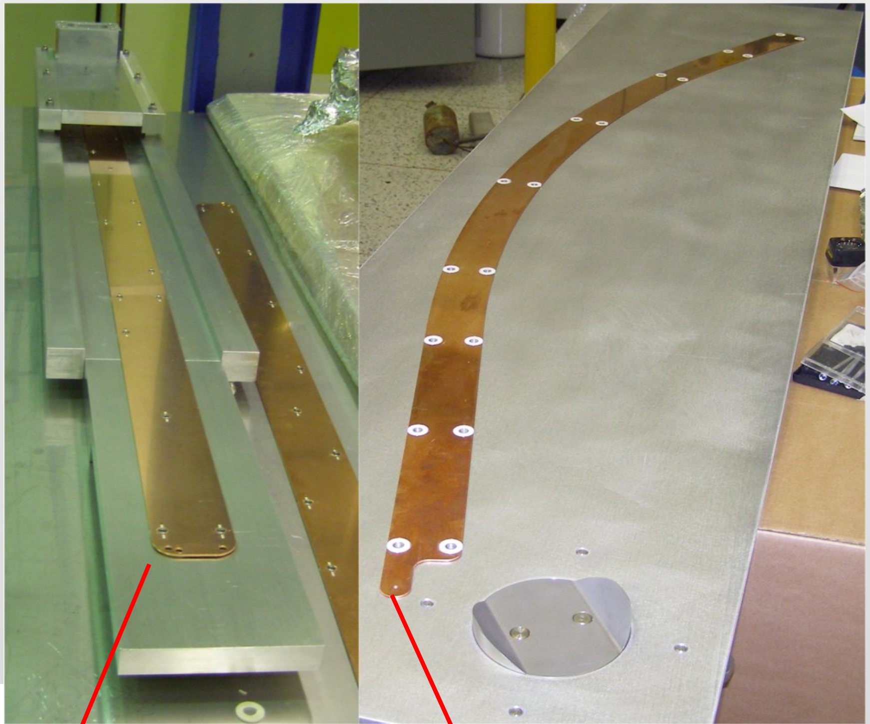
Electrodes for DAΦNE e+ ring

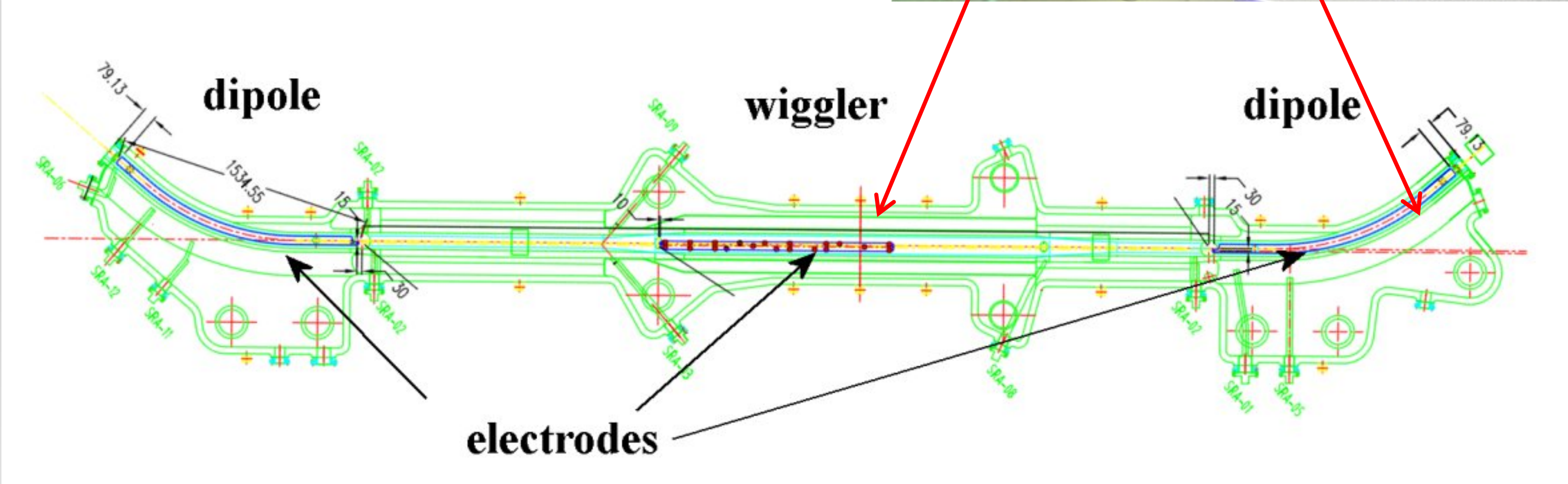
E**-cloud **C**learing **E**lectrodes **ECE

A new type of electrode never used before has been installed and tested on the DAΦNE positron ring

Copper electrodes

$L_{WGL} = 1.4\ m$
$L_{SDIP} = 1.6\ m$
$L_{RDIP} = 1.4\ m$

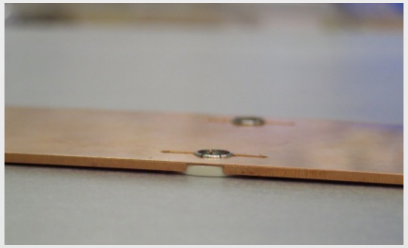
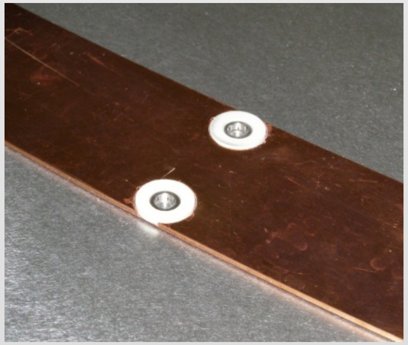
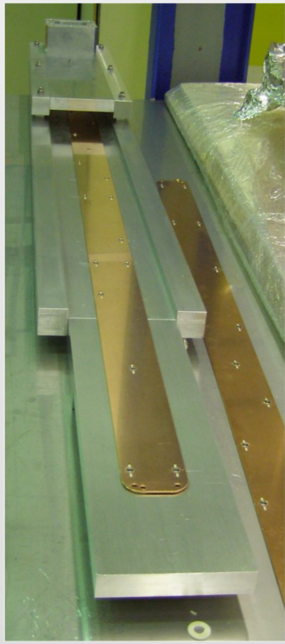
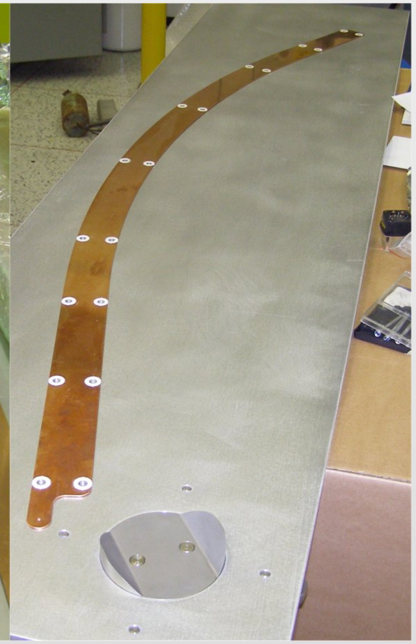


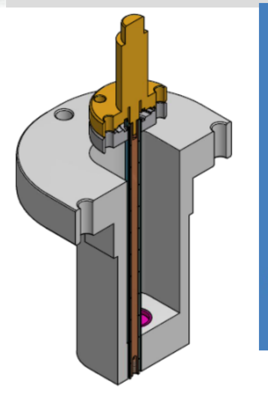
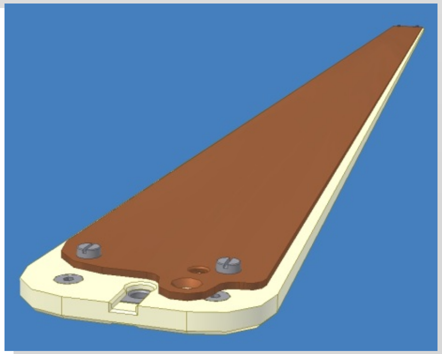


Electrodes Design & Installation

DAΦNE electrodes:

- 50 mm width
- 1.5 mm thickness
- ~ 0.5 mm *ceramic supports* (made in *SHAPAL*), optimized to minimize the beam coupling impedance
- electrode distance from the beam axis is 8 mm in the wigglers and 25 mm in the dipoles.

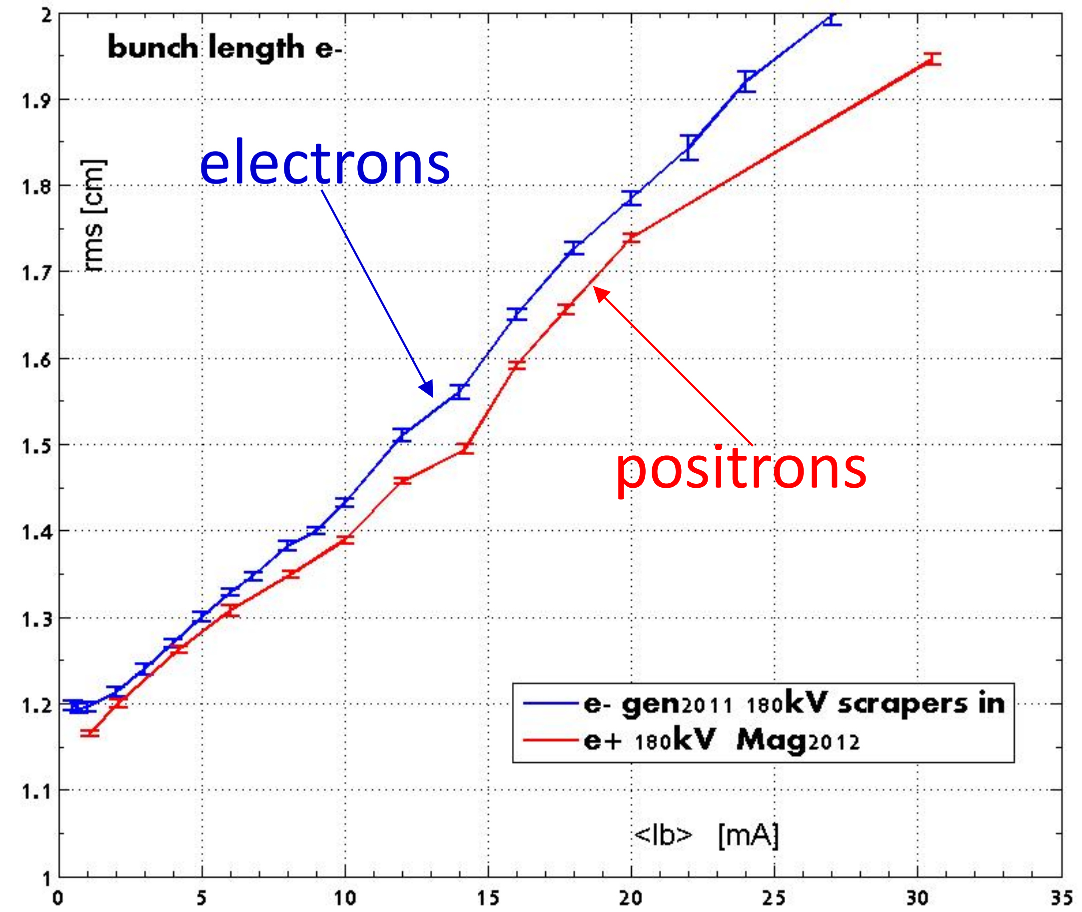




Electrodes have been inserted in the vacuum chamber using a dedicated tool

They have been connected to the external *dc voltage* modifying the existing BPM flanges.

Bunch Length Measurements

extimated Z/n ~ 0.003 Ω



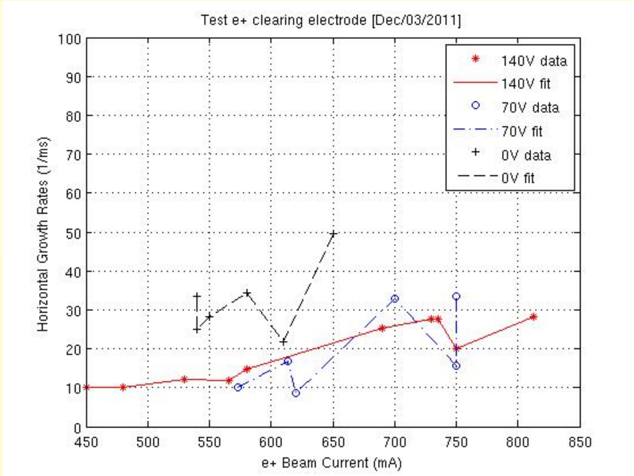
Electrode contribution to the ring impedance (inductive part) is negligible.
Bunch lengthening with current is lower in the e^+ ring than in the e^- one, where there are no electrodes.

Clearing electrodes for *e-cloud* suppression

DAΦNE is the first collider operating routinely with long electrodes, for e-cloud mitigation. Electrodes let more stable operation with the positron beam, and allowed unique measurements such as: e-cloud instabilities' growth rate, transverse beam size variation, and tune shifts along the bunch train, demonstrating their effectiveness in restraining e-cloud induced effects.

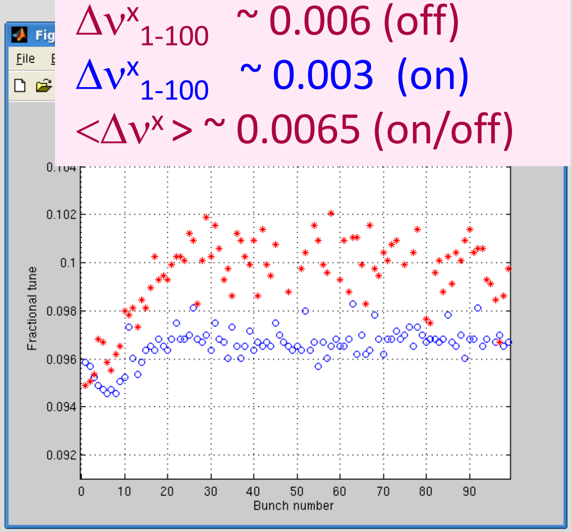
(D. Alesini et al, Phys. Rev. Lett. 110, 124801 (2013)

Horizontal Instability Growth Rate as a function of the electrode voltage measured by using bunch-by-bunch feedback

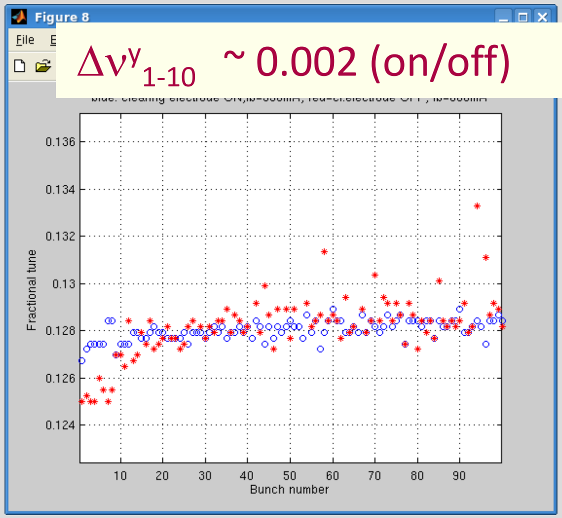


Tune Spread measurements

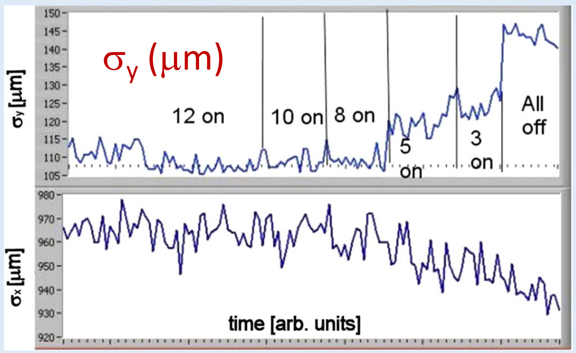
$\Delta\nu^x_{1\text{-}100}$ ~ 0.006 (off)
$\Delta\nu^x_{1\text{-}100}$ ~ 0.003 (on)
$<\Delta\nu^x>$ ~ 0.0065 (on/off)



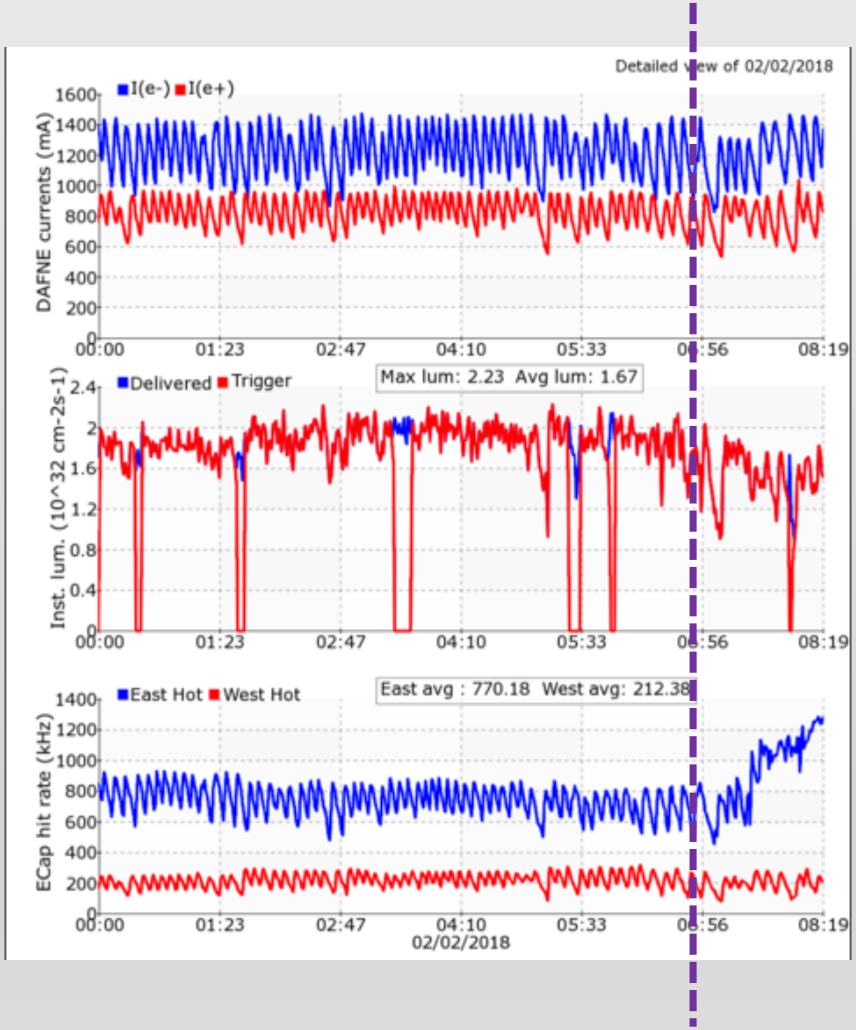
$\Delta\nu^y_{1\text{-}10}$ ~ 0.002 (on/off)



Vertical Beam Size



Operations with e-cloud Electrodes



All ECE (four) off due to a CS fault:

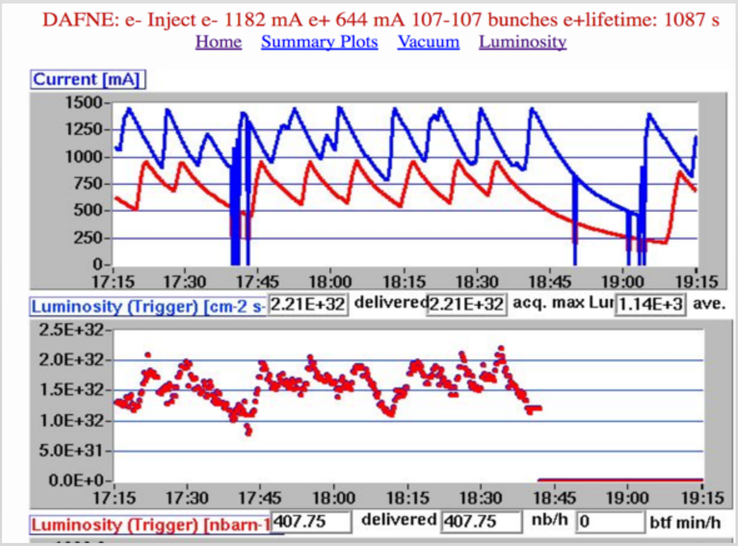
- larger σ_y -> lower ***L***
- lower injection efficiency for the e+ beam
- higher background on the detector

Operations with e-cloud Electrodes

At the end of the 40 months run only 2 out of the 12 ECE were working properly, none of them was in the wigglers

A posteriori analysis to explain the ECE behavioue is under way

However it was still possible to run the collider at peak performances

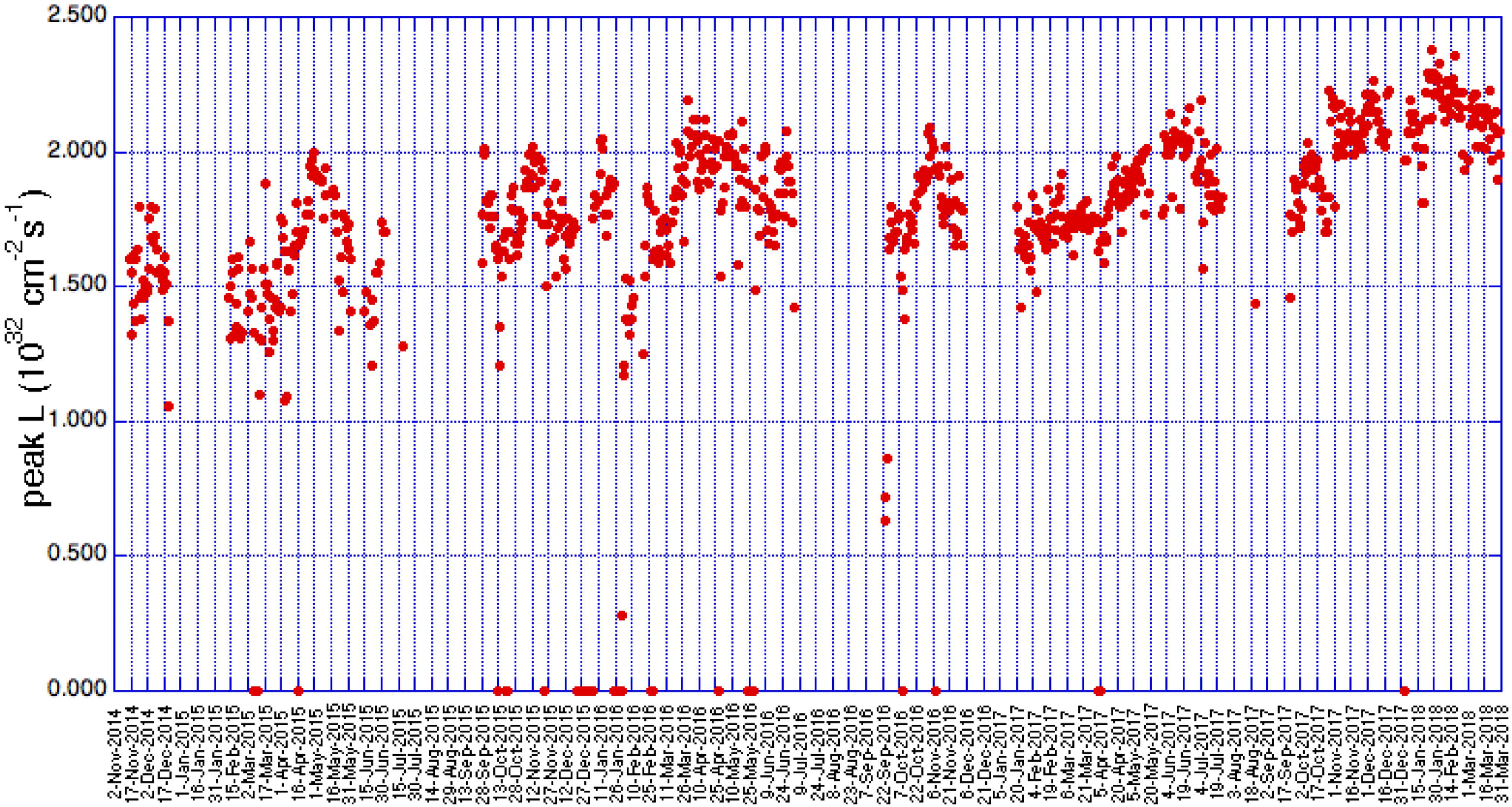


$L_{peak} = 2.21 \bullet 10^{32}$ $cm^{-2}s^{-1}$

$I^{+} \leq 1$ A

with 2 ECE only

Instantaneous peak Luminosity during the KLOE-2 run



scrubbing may be??

Beam Current Figures

	DAΦNE KLOE (2005)	DAΦNE FINUDA (2006)	DAΦNE CW SIDDHARTA (2009)	DAΦNE CW KLOE-2 (2014)
L_{peak} [$cm^{-2}s^{-1}$]	$1.5 \bullet 10^{32}$	$1.6 \bullet 10^{32}$	$4.36 \bullet 10^{32}$	$2.38 \bullet 10^{32}$
I^-_{MAX} [A] @ L_{peak}	1.4	1.5	1.47	1.18
I^+_{MAX} [A] @ L_{peak}	1.2	1.1	1.0	0.87
I^-_{MAX} [A]	2.4		2.2	1.7*
I^+_{MAX} [A]	1.4		1.2	1.1*
N_b in collision	111	106	105	106

* values achieved only sporadically

During CW run for KLOE-2:

both beams were affected by quadrupole instability • •

e^- beam current was limited (more than in the past) by:

- dependence from ions in the residual gas
- microwave instabiliy threshold above I_b~10 mA •
- maximum intensity was lower wrt the past •

These experimental findings are likely due to:

- new FBK and damp KCKs
- new tapered transition in the IP beam pipe
- modified collimator vacuum chamber
- limited power for the RF klystron
- modified wigglers

DAΦNE Feedback Systems

In a low energy machine as DAΦNE high current performances depend greatly on bunch by bunch feedback systems.

DAΦNE works routinely thanks to the 3 bunch by bunch feedbacks installed in each ring

The total power available for each apparatus is of the order of 500 W and 750 W for transverse and longitudinal feedbacks respectively

Limits observed

- noise coming from pickups (harmful for vertical sizes)

Solutions:

- transverse low noise front end (in collaboration with KEK)

Conclusions

Positron beam current at DAΦNE is clearly limited by *e-cloud induced effects* determining:

- anomalous vacuum pressure rises
- transverse beam size growth
- fast multibunch horizontal instability

Several countermeasures have been devised and successfully implemented:

- ring optics and beam dynamics optimization
- feedback
- solenoid windings
- electrodes

DAΦNE is the first and only collider to operate routinely with and thanks to the electrodes for e-cloud mitigation

E-cloud mitigating techniques have been essential in keeping under control the progressive decrease in the maximum positron beam current intensity, which has been observed when opening the vacuum in a Al beam pipe.

Electron beam current is dominated by the ions in the residual gas and by the microwave threshold instability

DAΦNE still holds the record for the highest electron beam current ever stored in particle factories and modern synchrotron radiation sources.

Thank you for your attention