DAΦNE Legacy to Future Colliders

M. Zobov on behalf of the colleagues partecipated in DAΦNE design, commissioning and operation

65th ICFA Advanced Beam Dynamics Workshop
on High Luminosity e+e- Colliders,
Frascati 12 September 2022

INFN
LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Frascati

First beam in DAΦNE stored 25 years ago

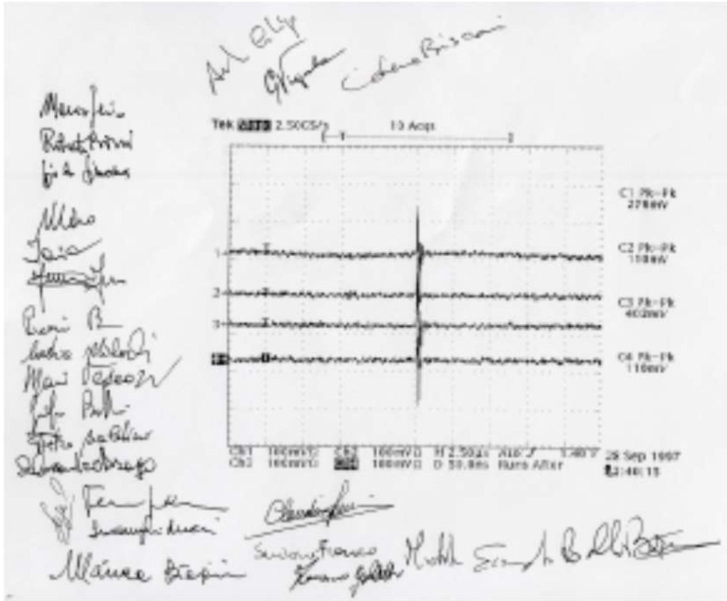
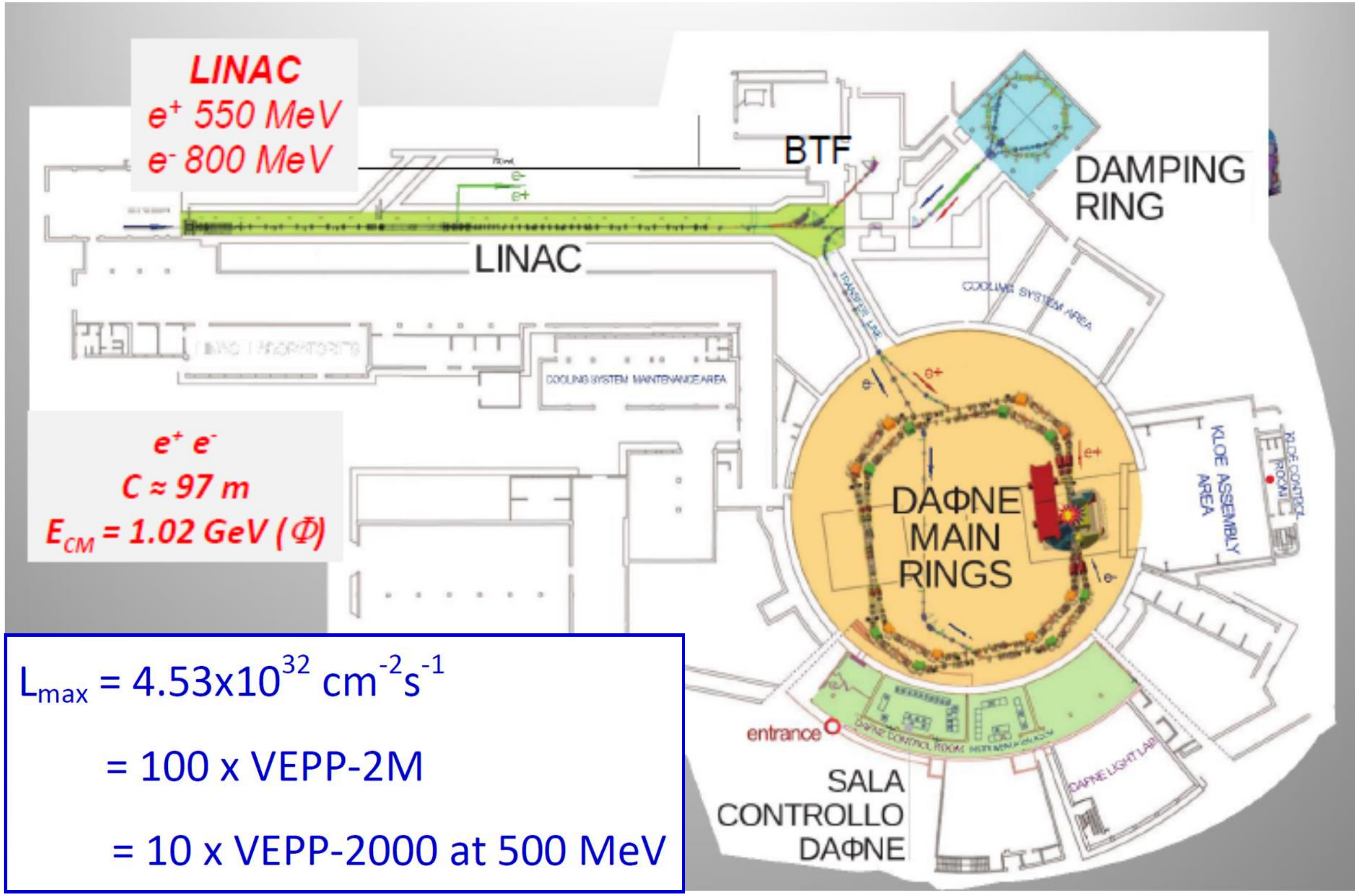


Table IV: *DAΦNE Commissioning Milestones*

Accumulator Ring Installation	December 95
First e- beam through the Tr. Line	27 May 96
First Turn in the Accumulator	1 June 96
Multiturn in the Accumulator	6-7 June 96
First Stored Beam in the Accumulator	21 June 96
120 mA in the Accumulator	30 January 97
LINAC e^+ beam to specifications	March 97
Main Rings Vacuum Connected	July 97
Extraction from the Accumulator	20 September 97
First e^- Beam in the Main Ring	28 September 97
Multiturn in the Main Ring	4 October 97
First Stored Beam in the Main Ring	25 October 97

ICFA Advanced Beam Dynamics Workshop on Beam Dynamics Issues for e+e- Factories, Frascati, October 20-25, 1997

DAΦNE Accelerator Complex



$L_{max} = 4.53 \times 10^{32}\ cm^{-2}s^{-1}$

$= 100 \times$ VEPP-2M

$= 10 \times$ VEPP-2000 at 500 MeV

“Small” does not mean “Simple”

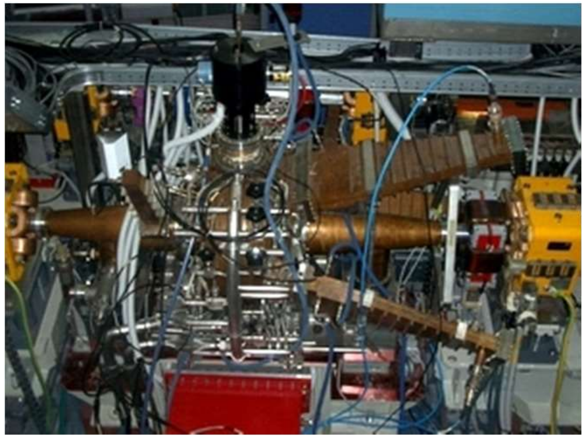
1. High intensity of colliding beams (maximum currents 2.5A e-, 1.4A e+)
2. Long damping time (110.000 turns)
3. Shortest bunch separation (2.7 ns)
4. Complicated aluminium vacuum chamber (impedance, eCloud)
5. Very nonlinear optics (short magnets with large apertures, wiggler nonlinearities, crosstalk between the two rings)
6. etc.

Advanced Accelerator Physics Studies

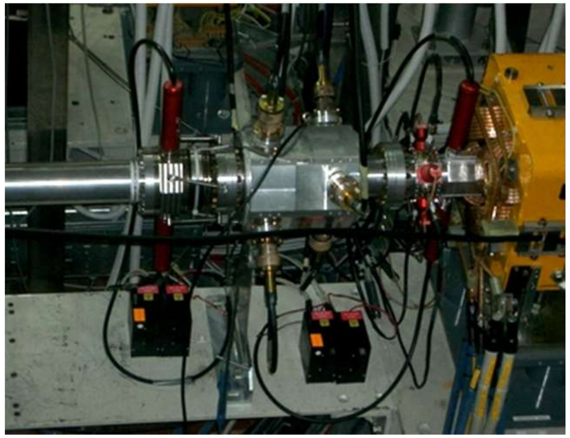
1. Low impedance vacuum chamber components (using)
2. Sofisticated feedback systems (using, in constant evolution)
3. Wigglers with «wiggling» poles (using)
4. Parasitic crossings compensation with wires (used for FINUDA, KLOE)
5. Collisions with negative momentum compaction factor (tested experimentally)
6. e-Cloud clearing electrodes (were using)
7. Collisions with a very high crossing angle (proposal)
8. Strong RF focusing (proposal)
9. Crab Waist collision scheme (in operation)
10. Others

Low Impedance Vacuum Chamber

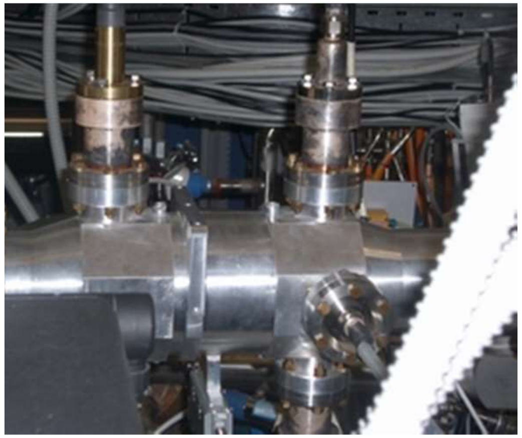
HOM Damped Vacuum Chamber Elements



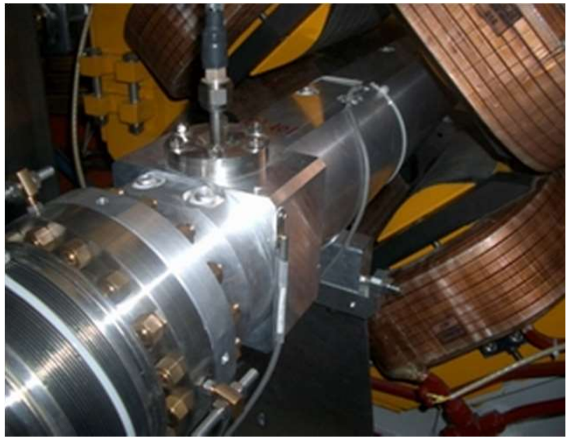
RF CAVITY



LONGITUDINAL KICKER

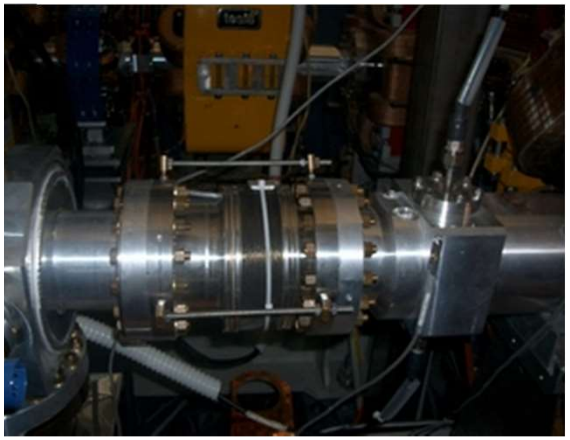


TRANSVERSE KICKER



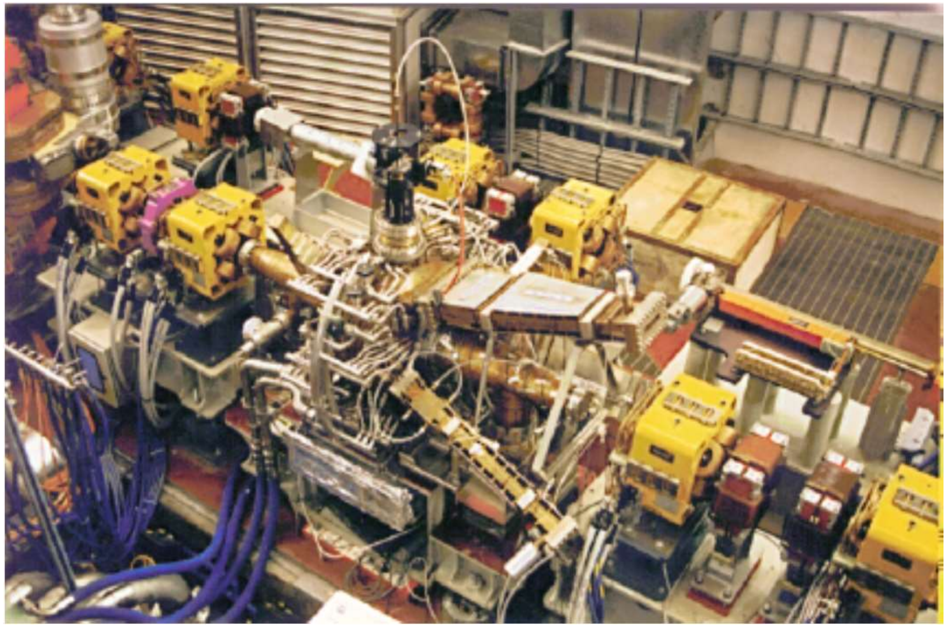
INJECTION KICKER

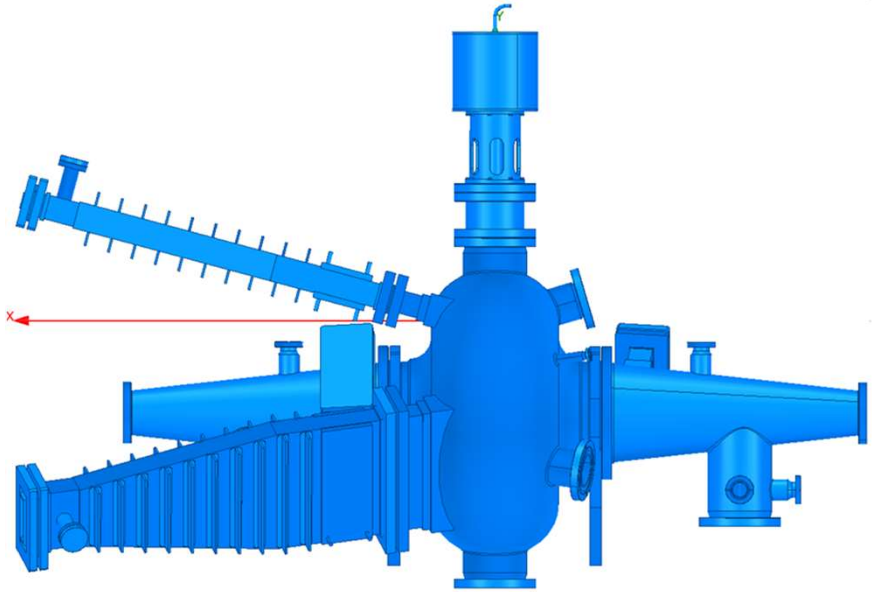
WALL CURRENT & DCCT MONITOR



SHIELDED BELLOWS

DAΦNE RF Cavity

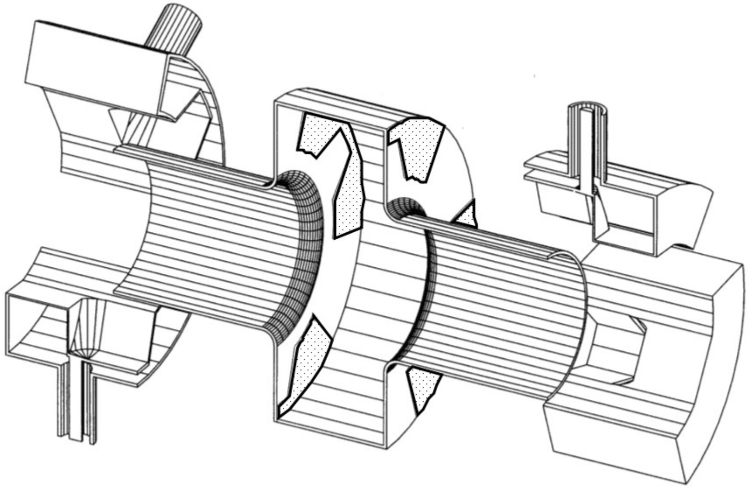




Principal Design Features

- Rounded body: simple mechanical design, no multipacting
- Long tapers: low broad-band impedance, lower RF losses
- HOM positions far from principal beam harmonics
- No dissipative materials under high vacuum
- Waveguides with broad-band transitions to external loadings

Longitudinal Feedback Kicker



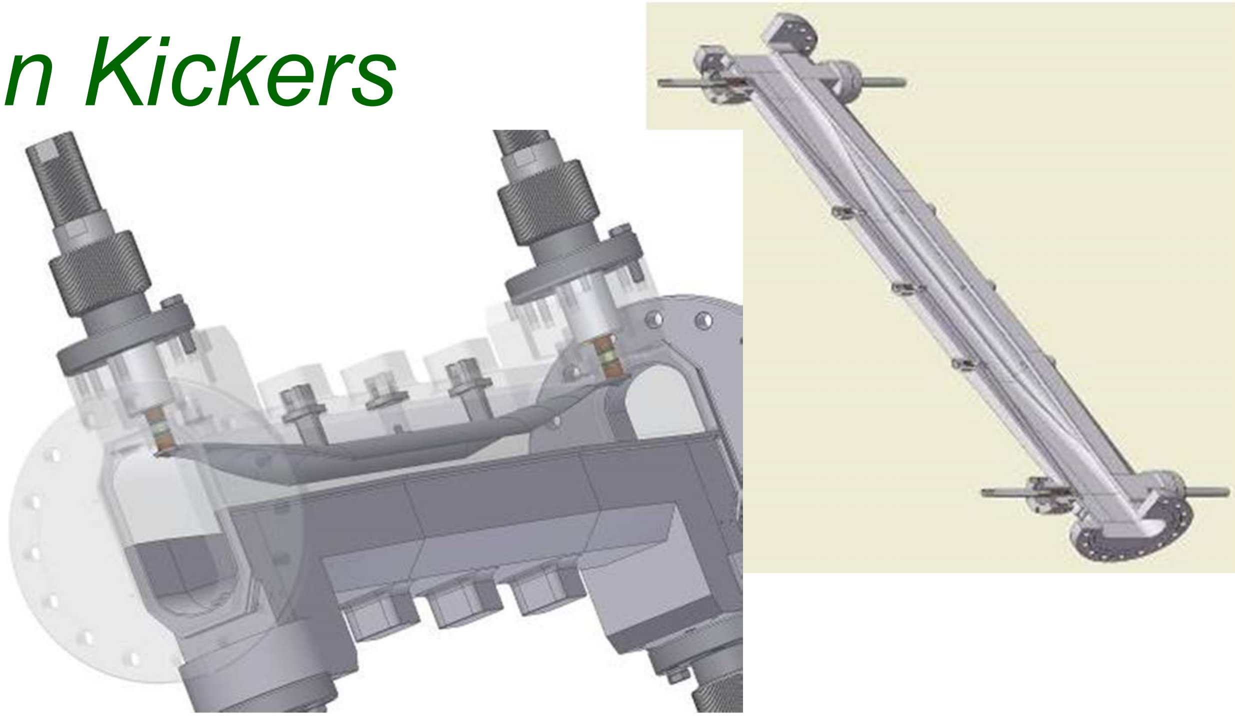
Purpose:
- used to provide correcting longitudinal kick

Design Features:
- heavily loaded pill-box cavity
- 6 ridged wave guides rounded to fit cavity shape
- special transitions to coaxial feed through

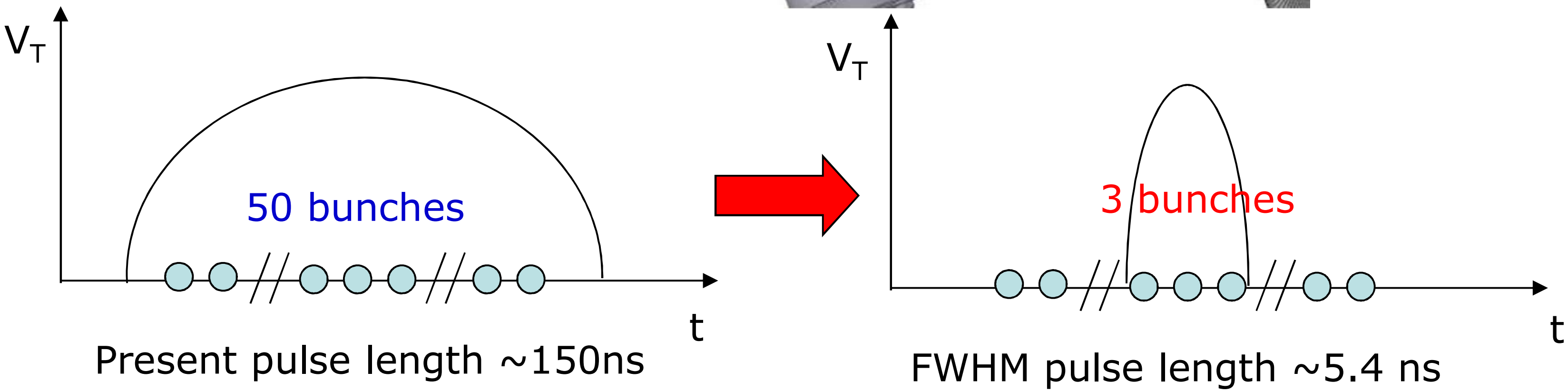
Advantages
- High broad-band shunt impedance
- All HOM are damped

- Publications
  - Part. Accel. 52: 95-113, 1996
    (80 citations in HEP)
- Successful Experience in:
  - DAΦNE, KEKB, BESSYII, PLS, SLS, HLS, ELETTRA, KEK Photon Factory, Duke storage ring..
  - PEP-II (upgrade, December 2003)
  - SPEAR-3, CESR (considered)

New Injection Kickers



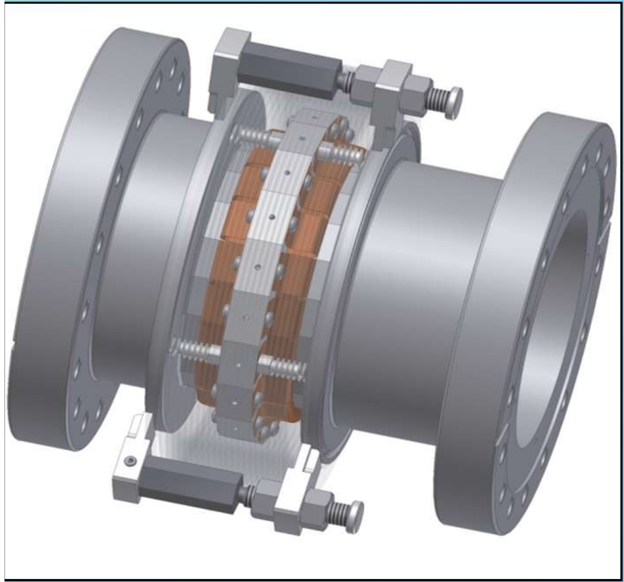
New injection kickers with
5.4 ns pulse length
to reduce perturbation on stored beam

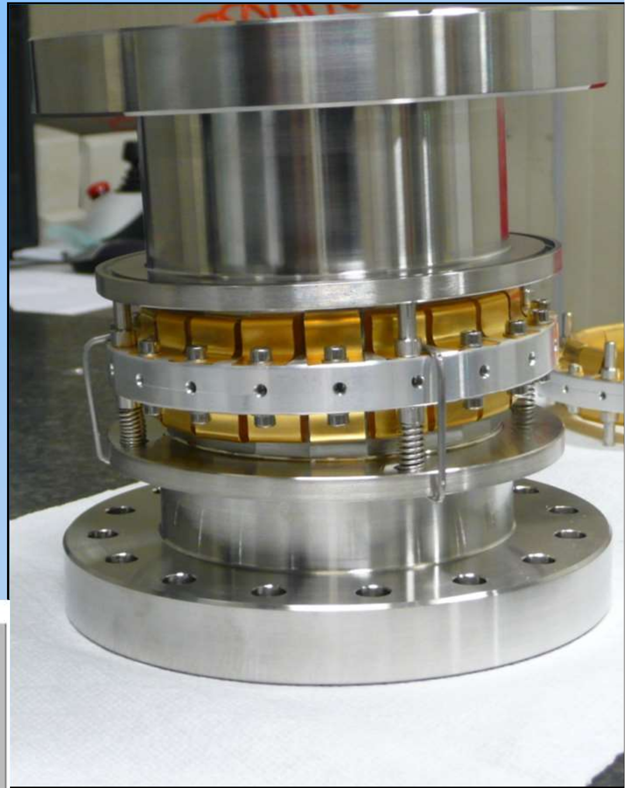


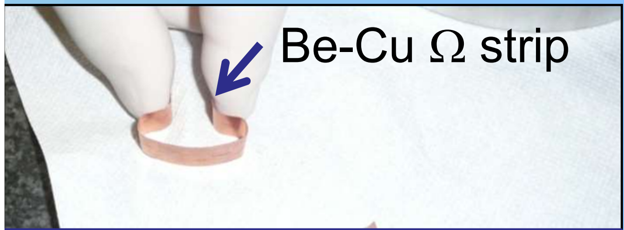
Expected benefits:

- **higher maximum stored currents**
- **Improved stability of colliding beams during injection**
- **less background allowing data acquisition during injection**

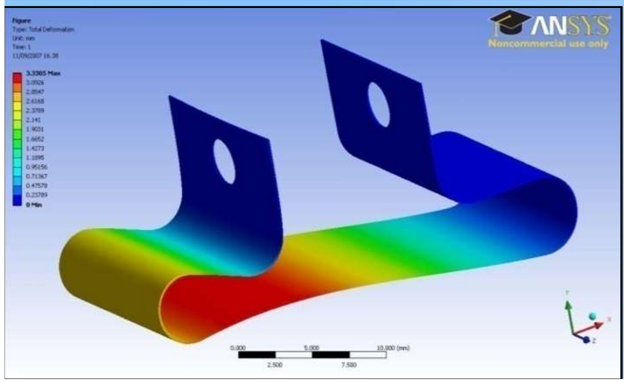
Ω Shielded Bellows

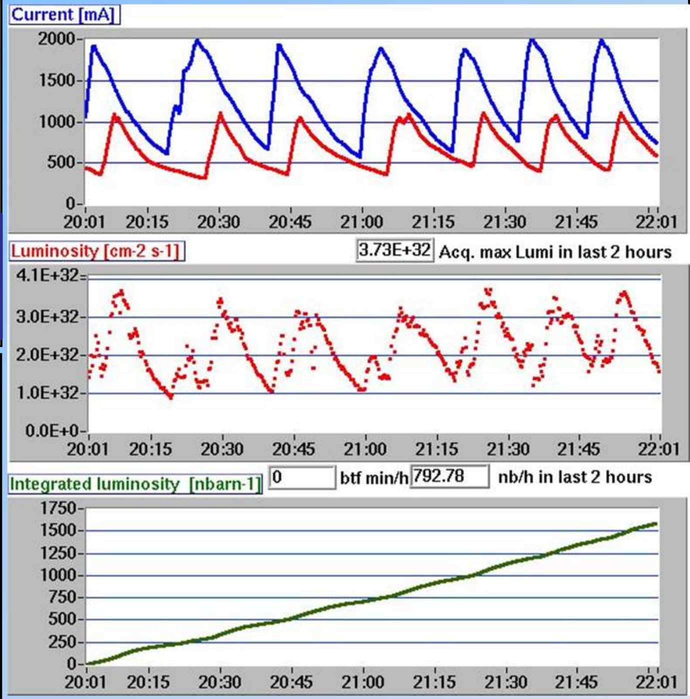






- Shielding based on Be-Cu Ω strips 0.2 mm thickness





Electron Cloud Effect Mitigation

e-Cloud in DAΦNE

Challenges

1. Aluminium vacuum chamber
2. Bunch separation of 2.7 ns
3. High beam current

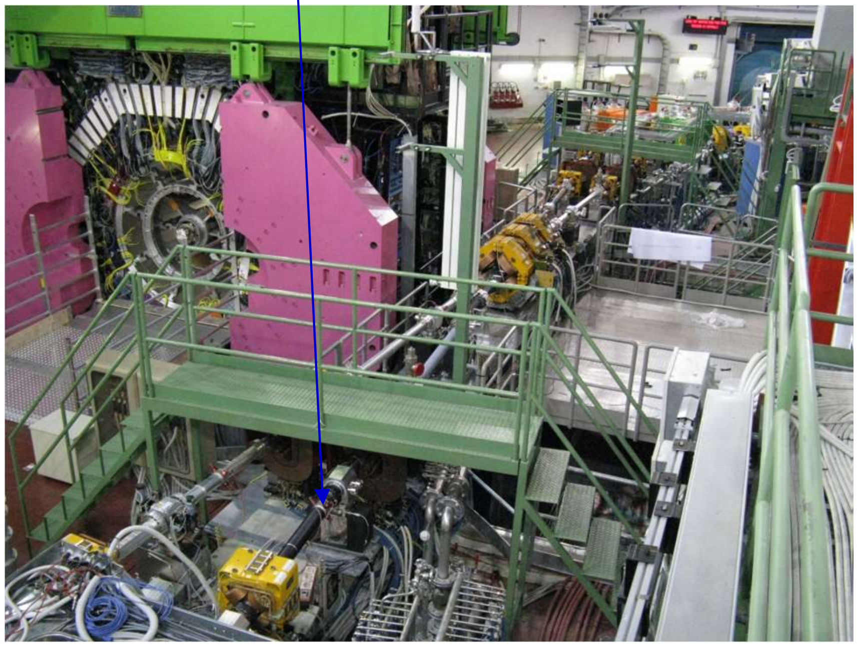
Mitigation

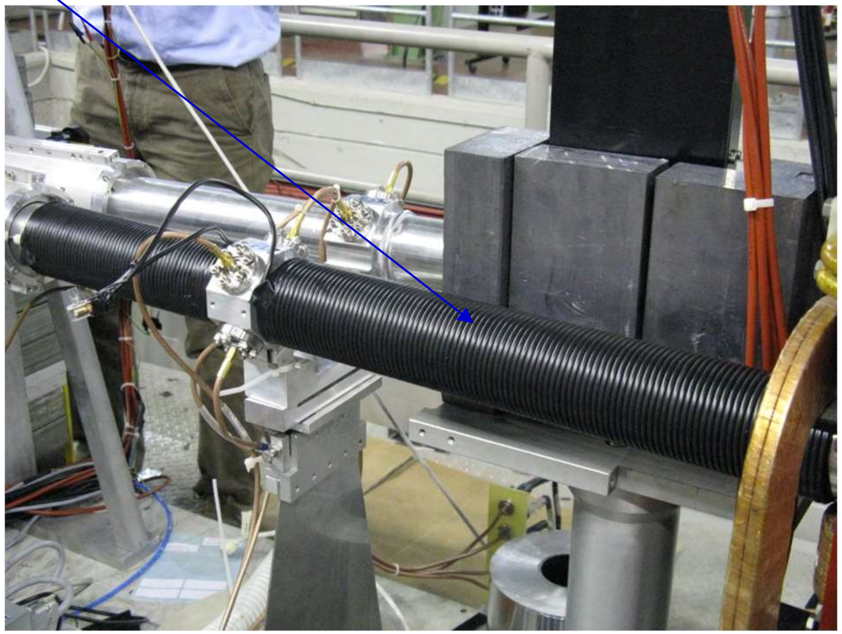
1. Feedback systems
2. Solenoids in straight sections
3. Clearing electrodes
4. Lower RF voltage
5. others

Effects

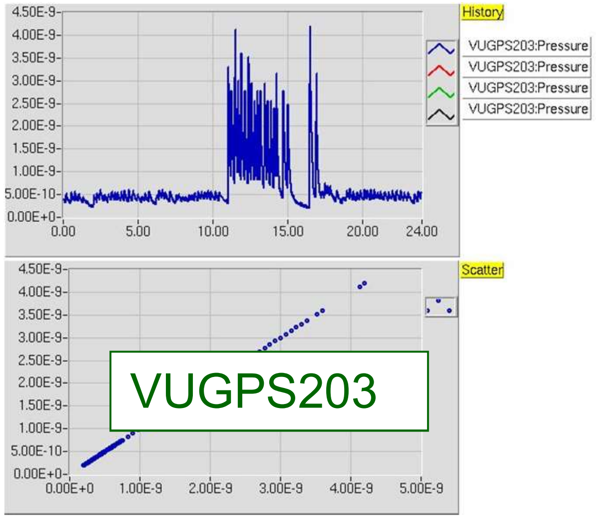
1. Anomalous pressure rise
2. Tune spread along bunch train
3. Fast horizontal multibunch instability
4. TMCI single bunch instability
5. others

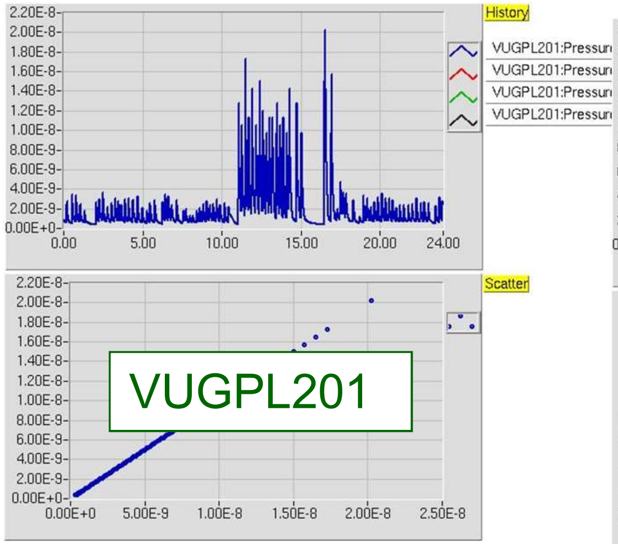
Solenoids

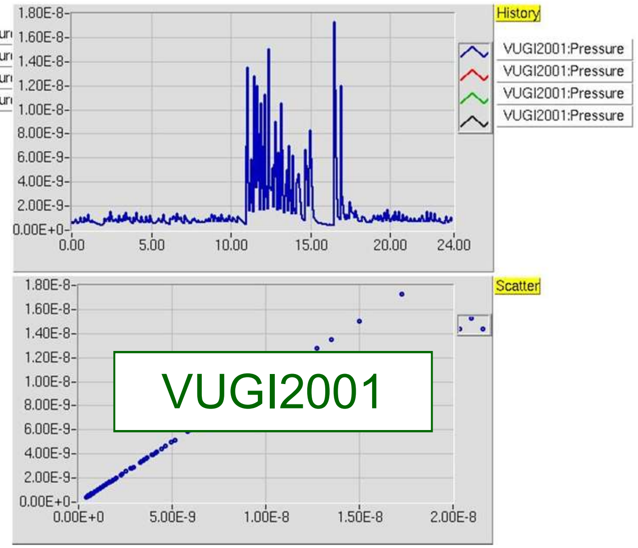


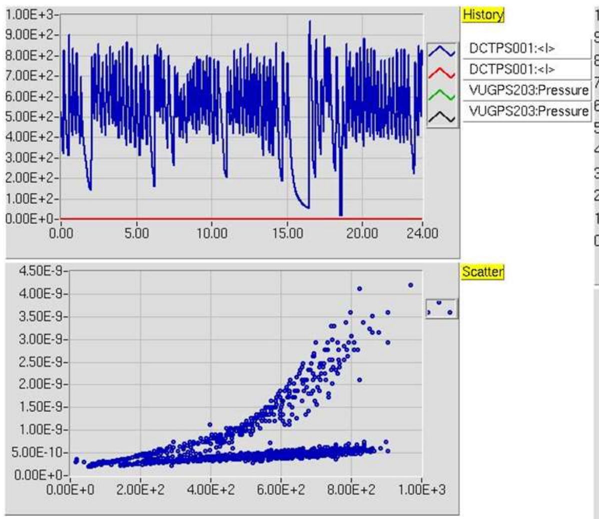


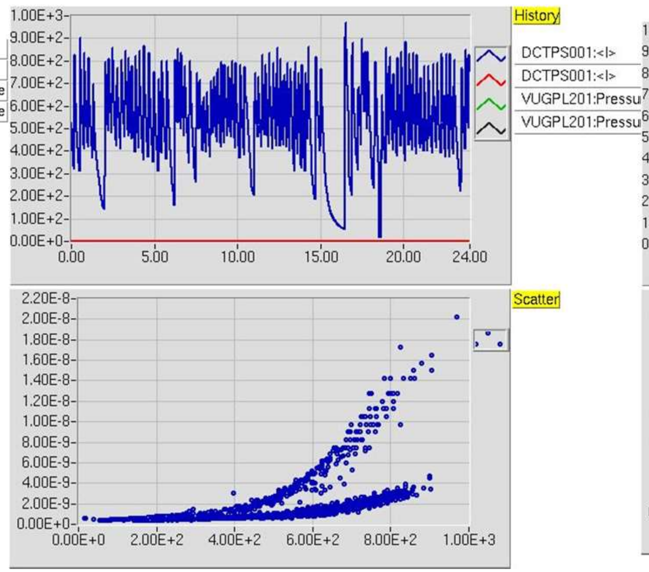
Solenoids Off 28/05/2012

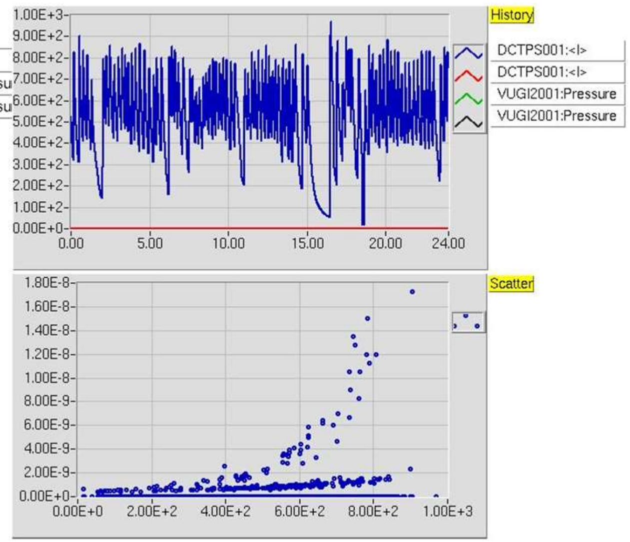








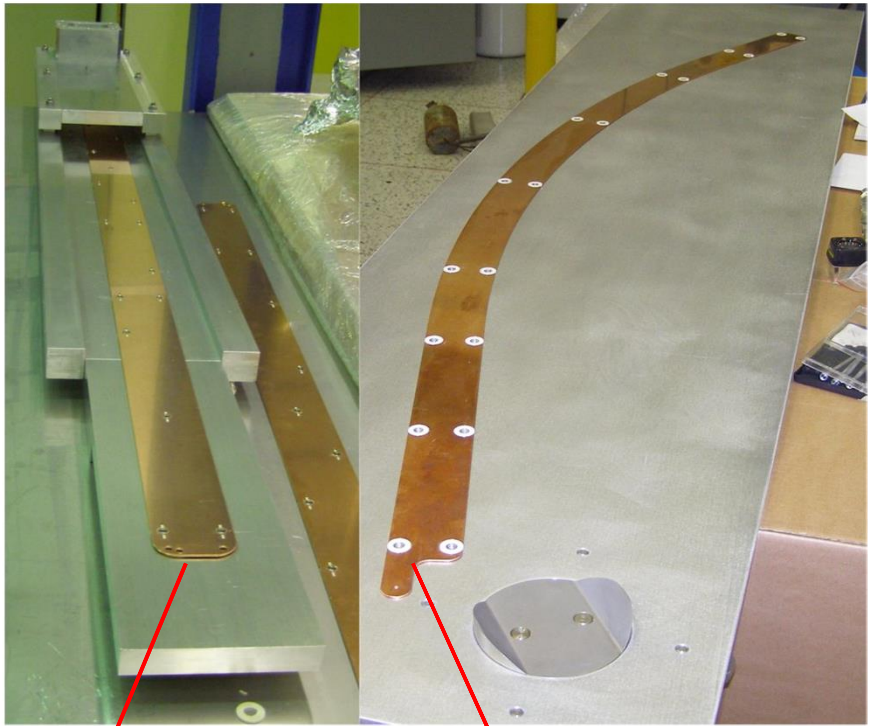


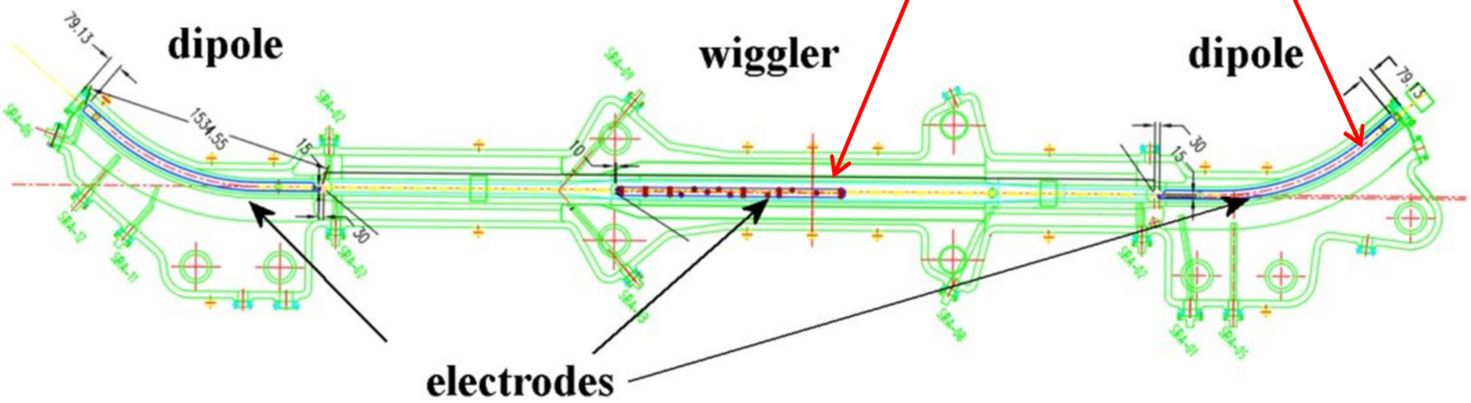


Installation of Electrodes

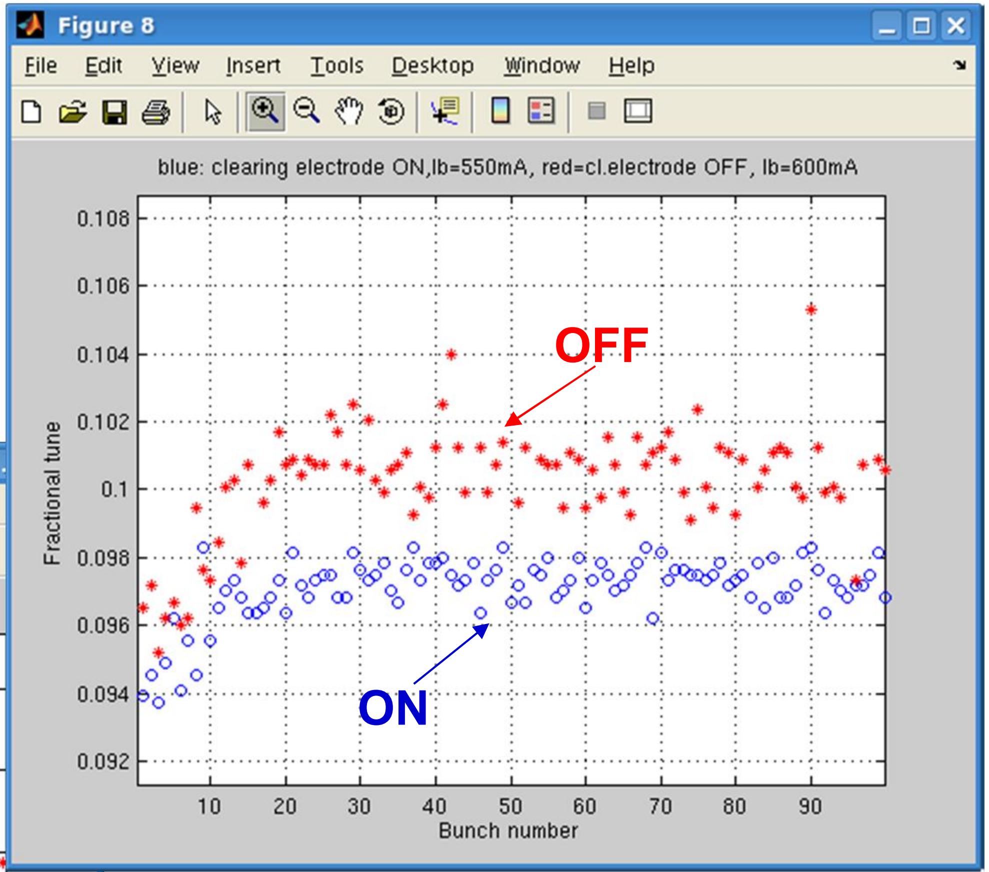
To mitigate the e-cloud instability *copper electrodes have been inserted in all dipole and wiggler chambers* of the machine and have been connected to external dc voltage generators.

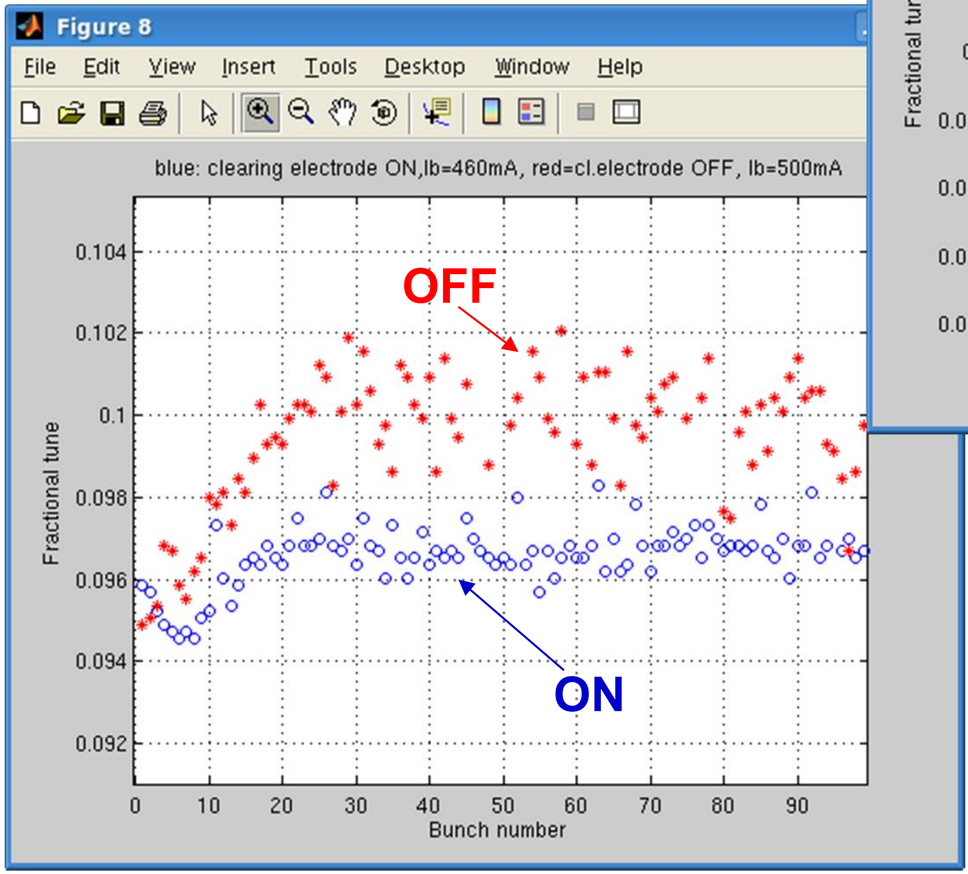
The dipole electrodes have a length of 1.4 or 1.6 m depending on the considered arc, while the wiggler ones are 1.4 m long.





Horizontal Bunch-by-Bunch Tune Spread Measured by the Feedback System





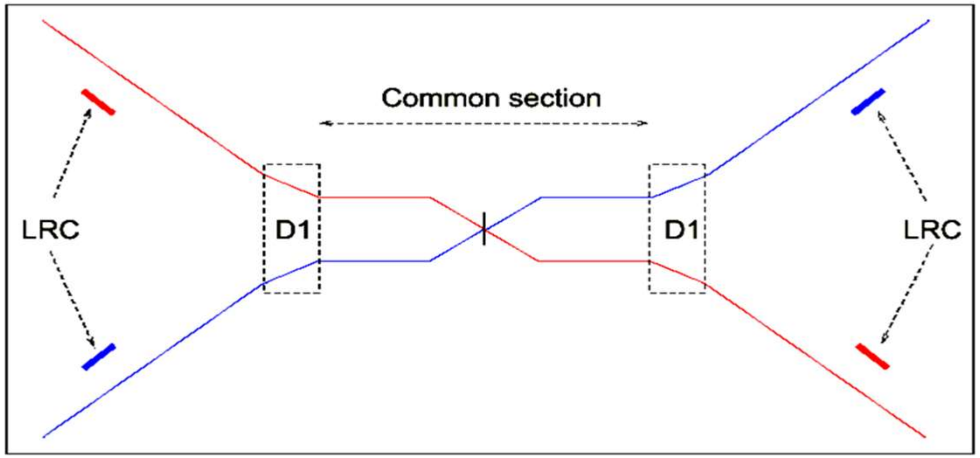
DAΦNE e+ beam:
100 bunches, spaced by 2.7ns with 20 buckets gap

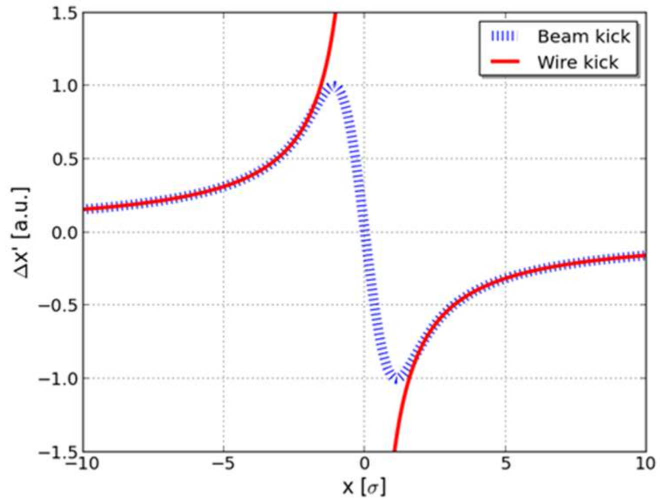
Turning on the electrodes in 4 wigglers and 2 dipoles (not all) horizontal tune spread decreases

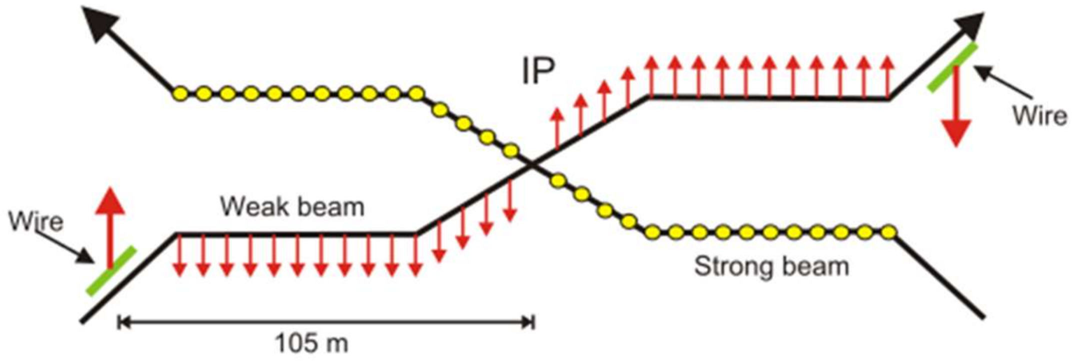
Wire Compensation of Parasitic Crossings

Correction of Long-Range Beam-Beam Interactions

J.P. Koutchouk, LHC Project Note 223 (2000)







Correction requires

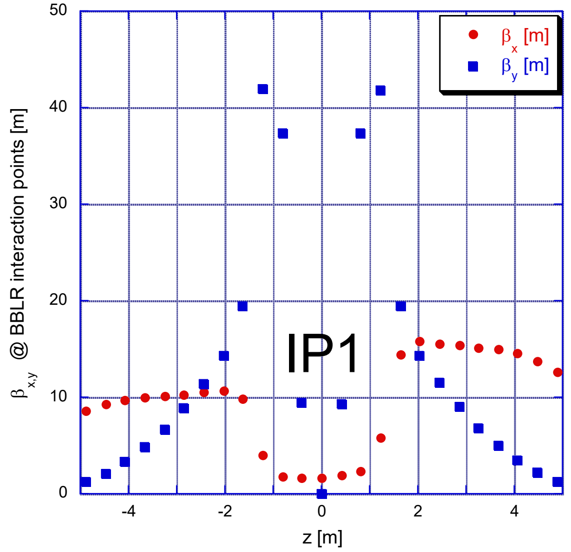
- the same integrated current
- the same transverse distance in terms of sigmas
- transverse phase advance n2π

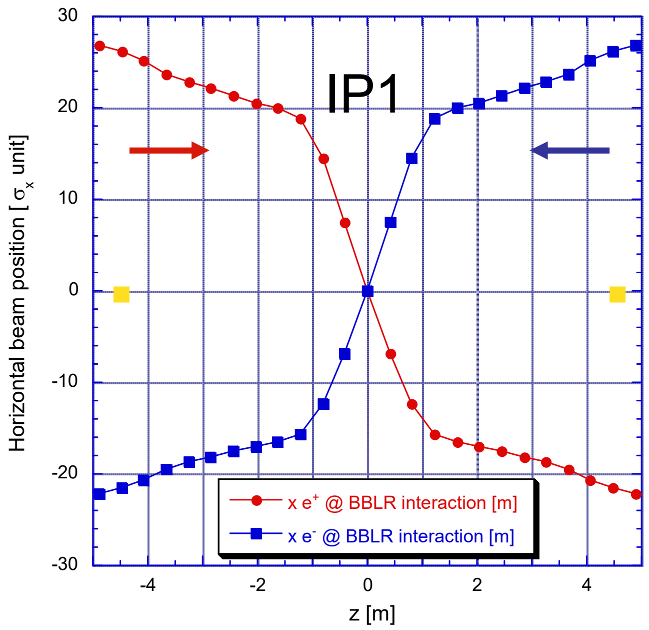
Parasitic Crossings in the DAΦNE IR1

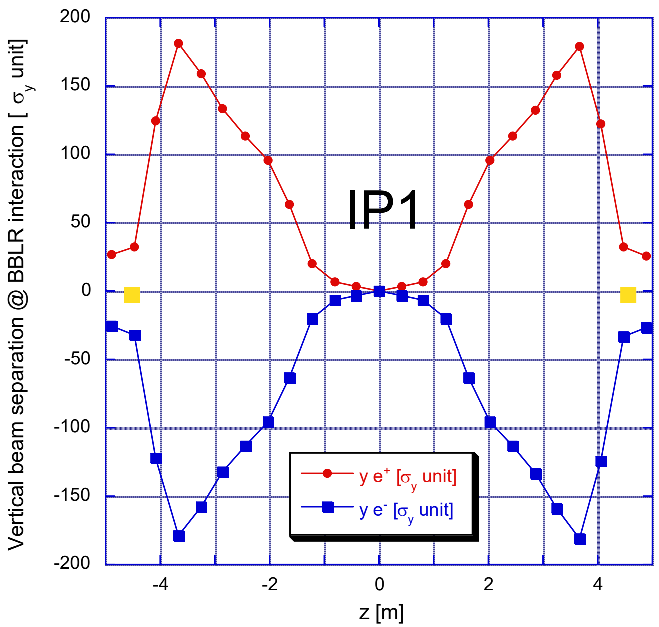
In the DAΦNE IRs the beams experience 24 Long Range Beam Beam interactions

Parameters for the Pcs, one every four, in IR1.

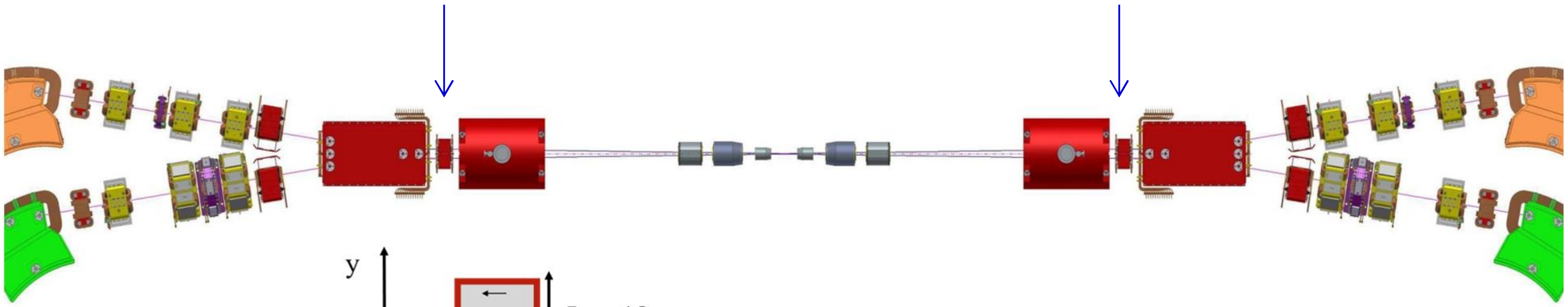
PC order	$Z-Z_{IP}$ [m]	β_x [m]	β_y [m]	$\mu_x-\mu_{IP}$	X [σ_x]	Y [σ_y]
BB12L	-4.884	8.599	1.210	0.167230	26.9050	26.238
BB8L	-3.256	10.177	6.710	0.140340	22.8540	159.05
BB4L	-1.628	9.819	19.416	0.115570	19.9720	63.176
BB1L	-0.407	1.639	9.426	0.038993	7.5209	3.5649
IP1	0.000	1.709	0.018	0.000000	0.0000	0.0000
BB1S	0.407	1.966	9.381	0.035538	-6.8666	3.5734
BB4S	1.628	14.447	19.404	0.092140	-16.4650	63.196
BB8S	3.256	15.194	6.823	0.108810	-18.7050	157.74
BB12S	4.884	12.647	1.281	0.126920	-22.1880	25.505

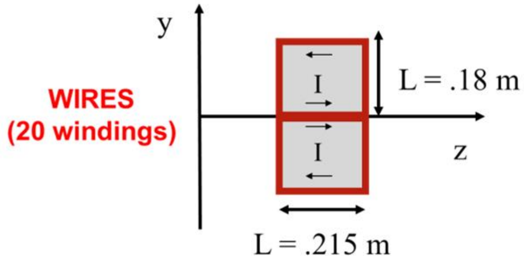


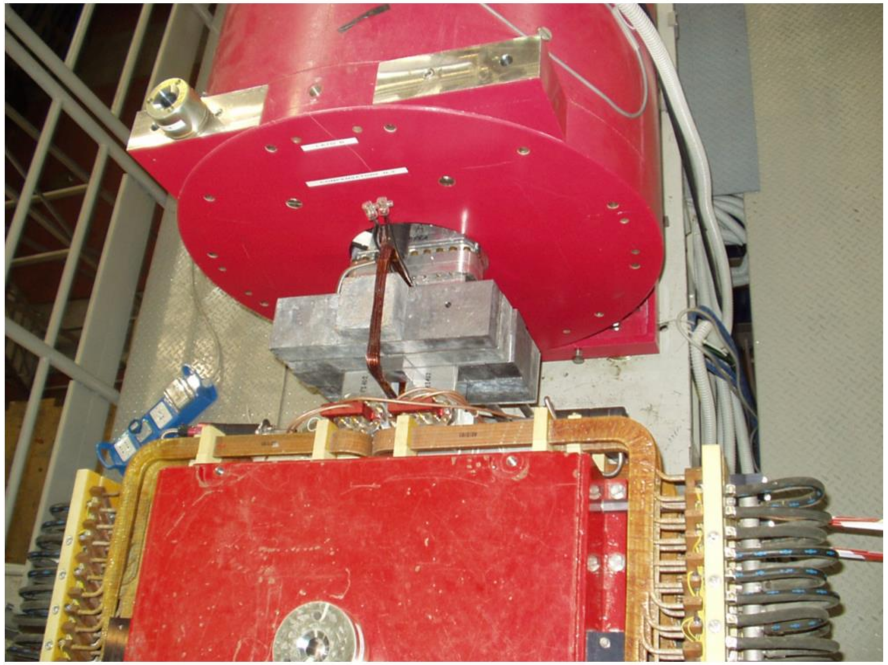




Wires in the KLOE IR

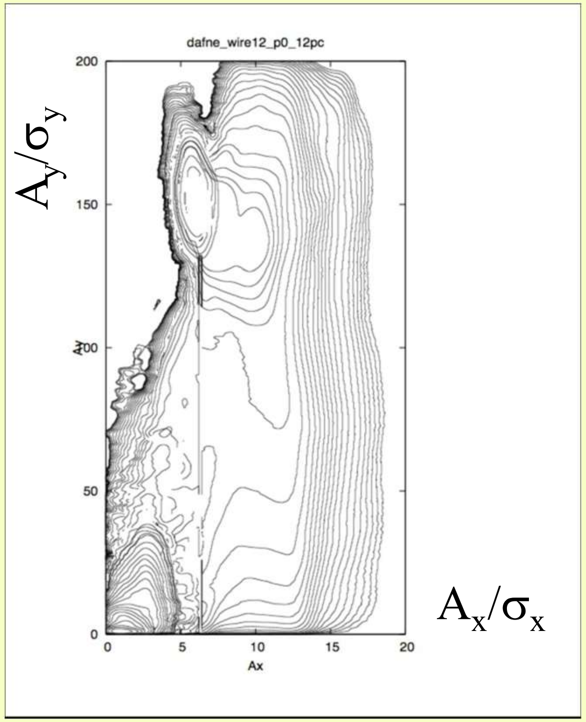




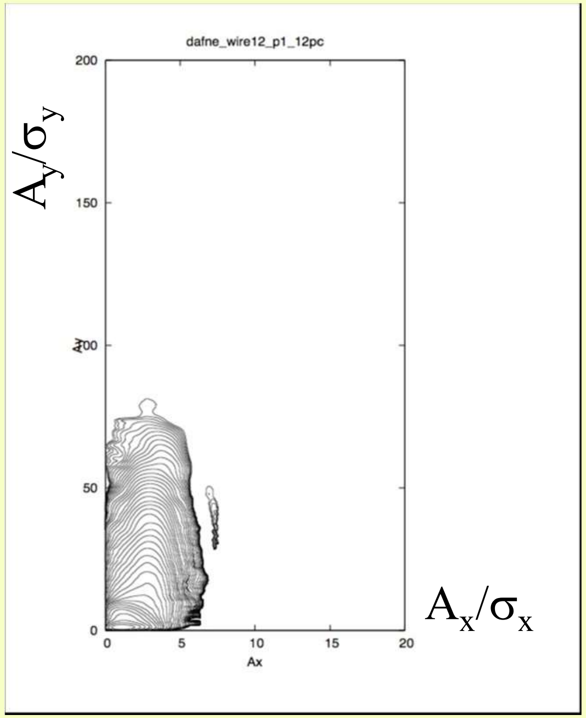


RESULTS from LIFETRACK

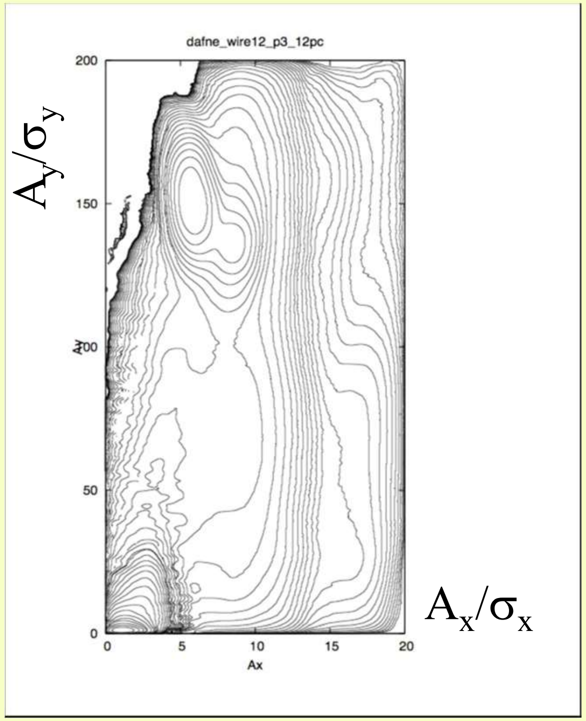
$A_{x,y}$ are the particle equilibrium density in the transverse space of normalized betatron amplitude



Wires OFF

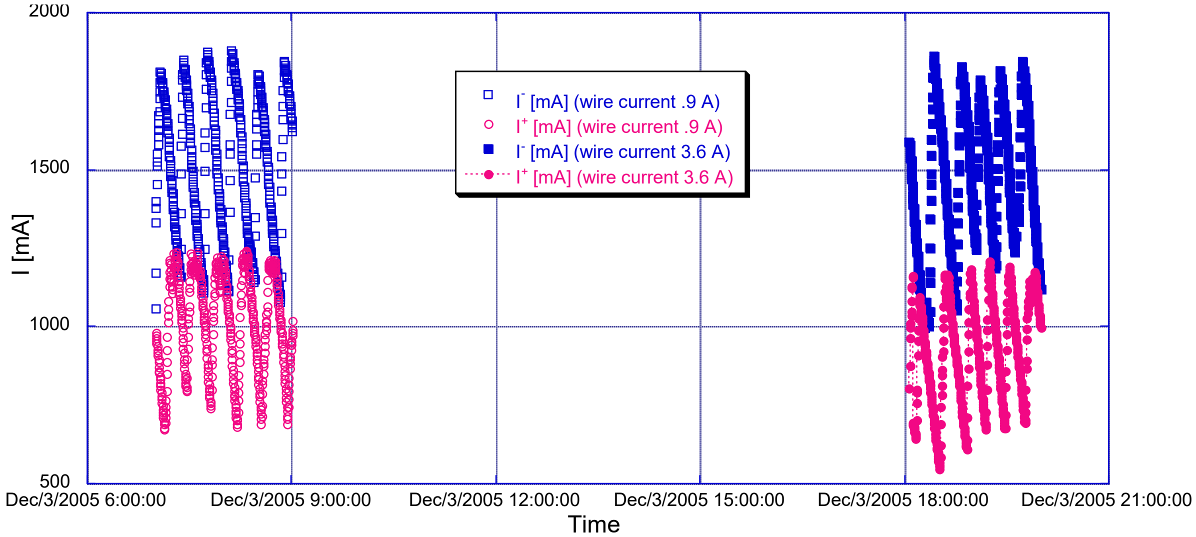


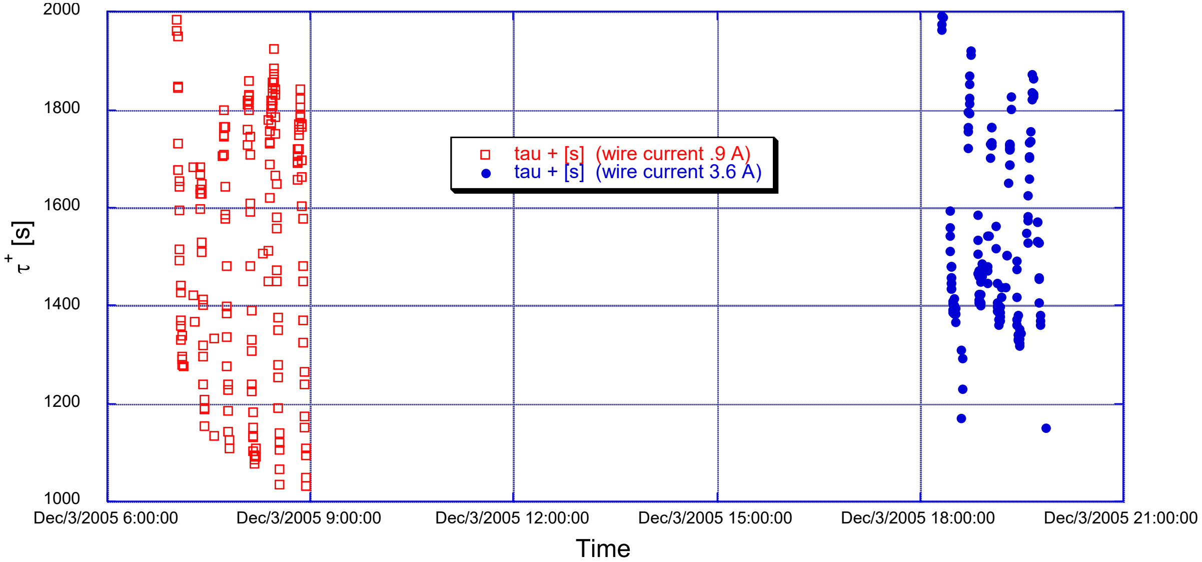
Wires ON



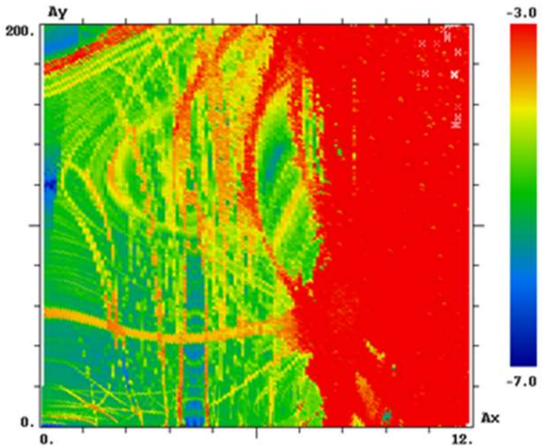
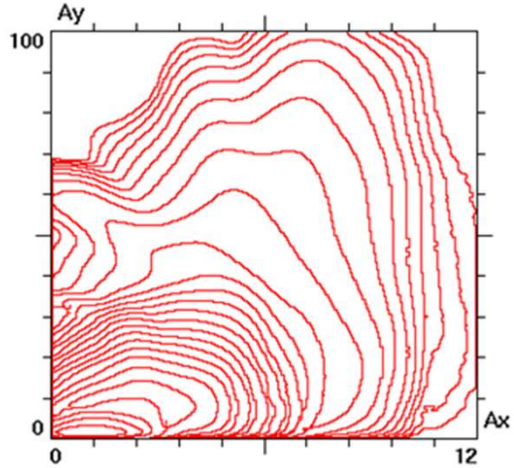
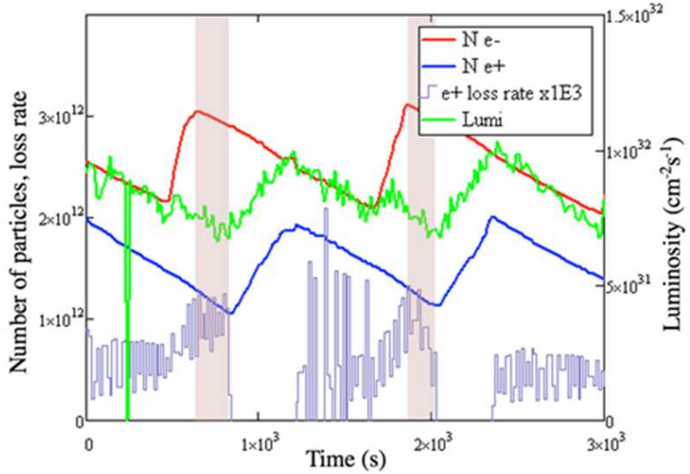
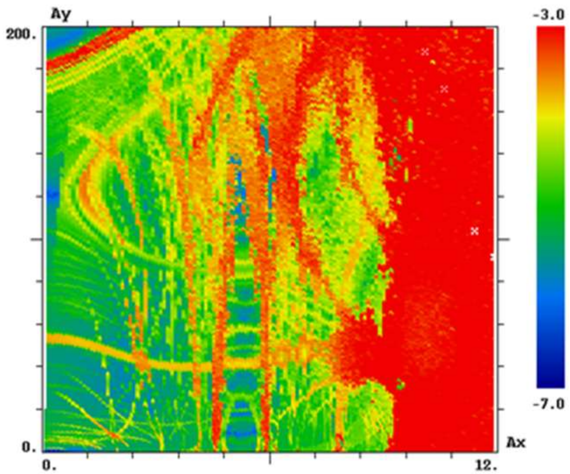
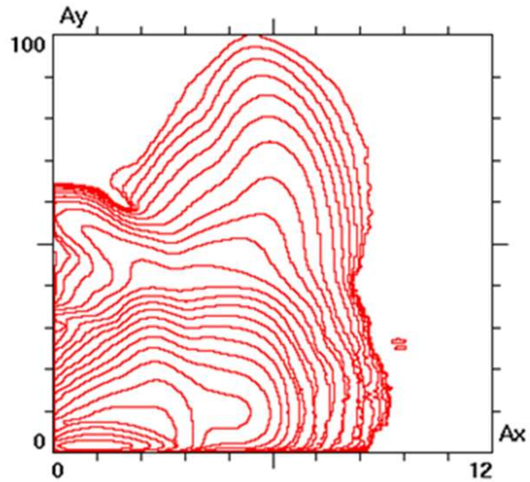
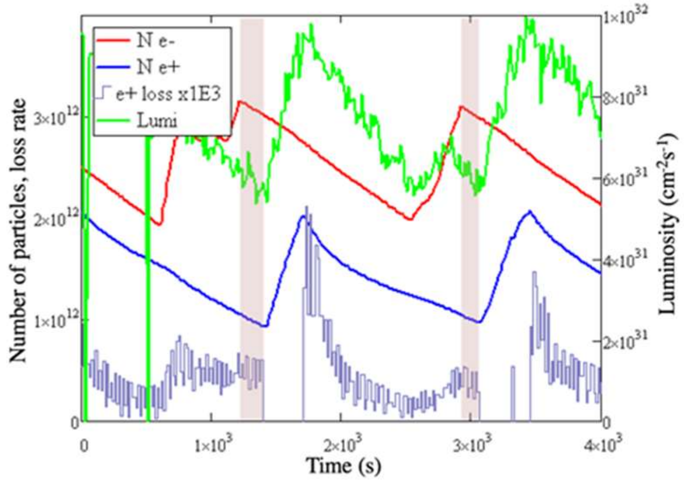
Wires ON (wrong polarity)

Observations During Electron Beam Injection





Analysis of Parasitic Crossings Compensation

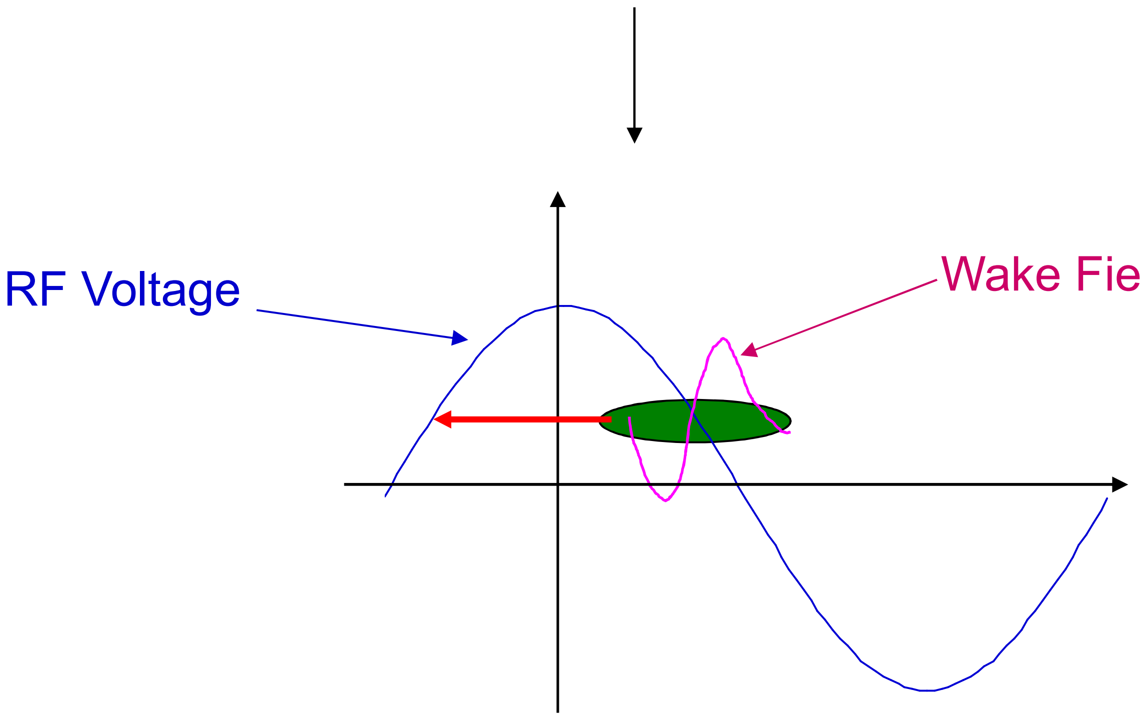
Dynamic Aperture (FMA)	Non-Gaussian Tails	Particle Losses
		
		

Twofold improvement in beam-beam induced losses!

Collisions with Negative Momentum Compaction Factor

Negative Momentum Compaction Factor

$$\alpha_c = \frac{dL/L}{dp/p} = \frac{1}{L}\oint \frac{D_x(s)}{\rho(s)} ds < 0$$

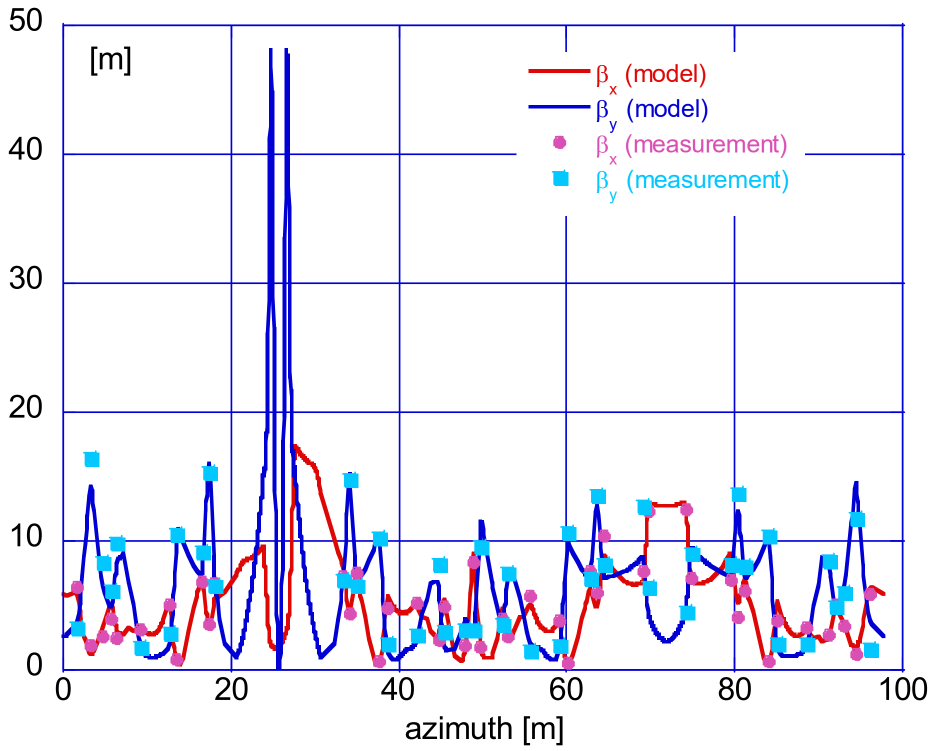


Potential Advantages for a Collider

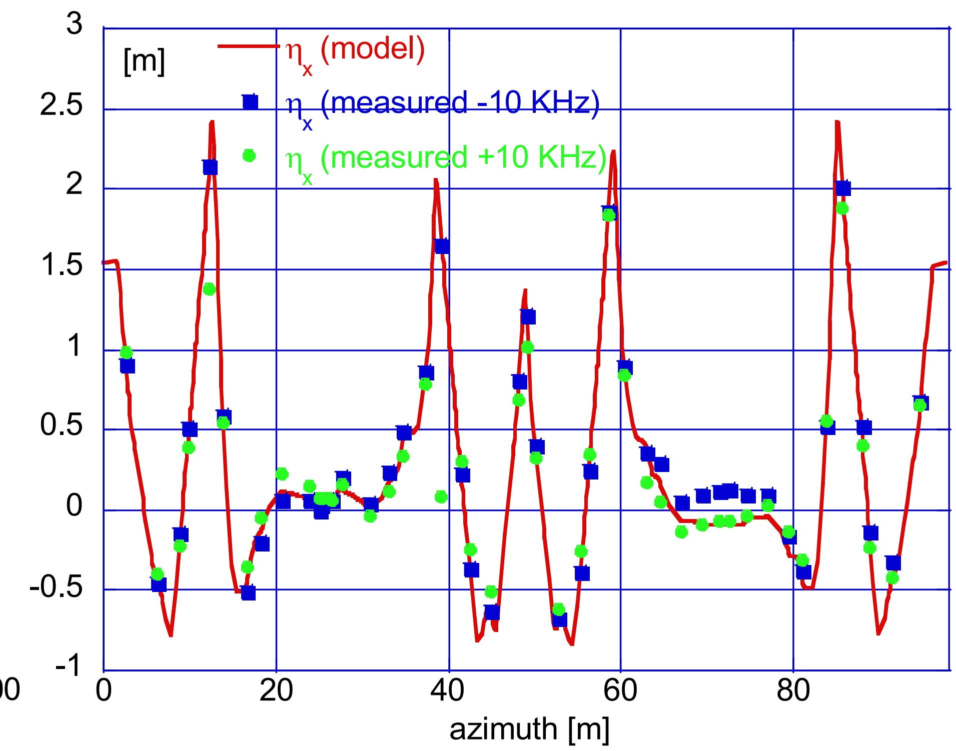
- Shorter bunch -> Higher luminosity
  - L scales with σ_z if $\beta_{x,y}$ are reduced proportionally to σ_z
  - Piwinski's angle ('badness factor') $\theta = \phi\ \sigma_z/\sigma_x$ is lower
- Longitudinal beam-beam effects are less dangerous *(V. V. Danilov et al., HEACC 1992)*
  - No coherent and incoherent instabilities
  - Synchro-betatron resonances
- Single bunch is stable with negative 'natural' chromaticity
  - Lower sextupole strenghts -> larger dynamic aperture
  - Higher instability thresholds

Electron Ring Optical Functions

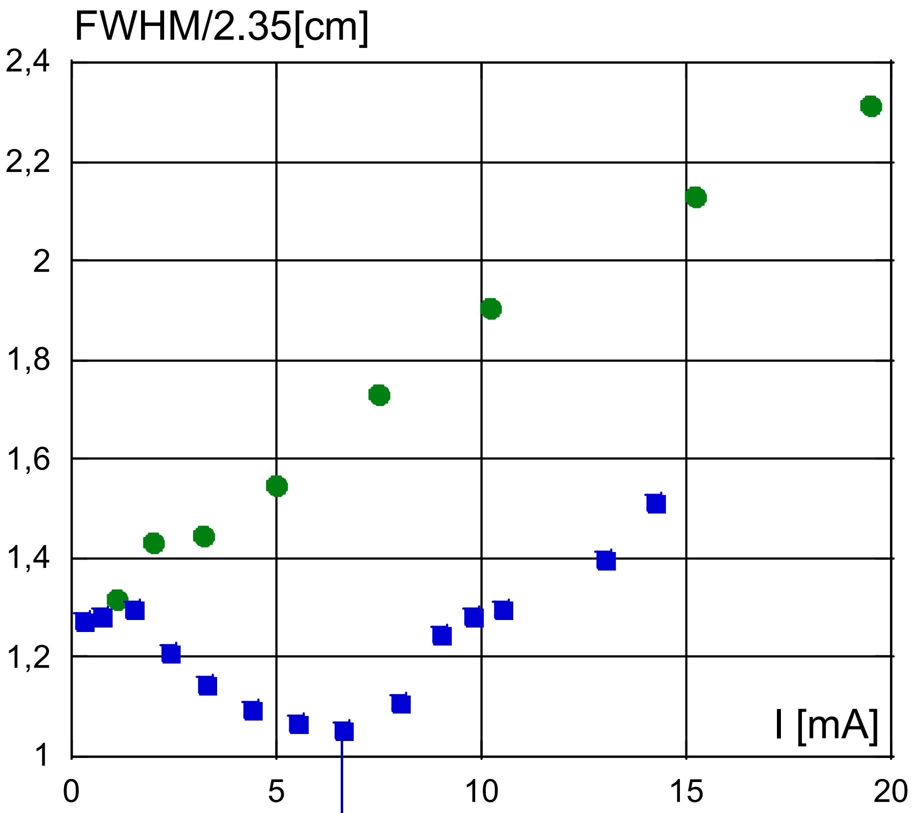
Beta Functions

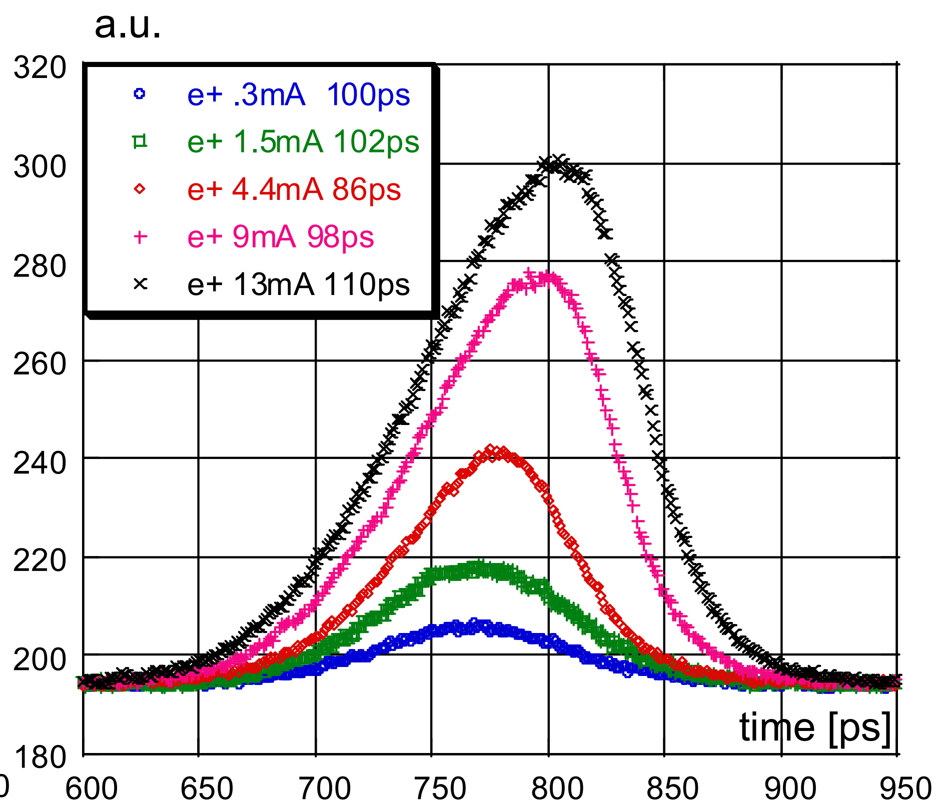


Horizontal Dispersion



Bunch Shortening in the Positron Ring





I_{th} = 7 mA at $\alpha_c < 0$

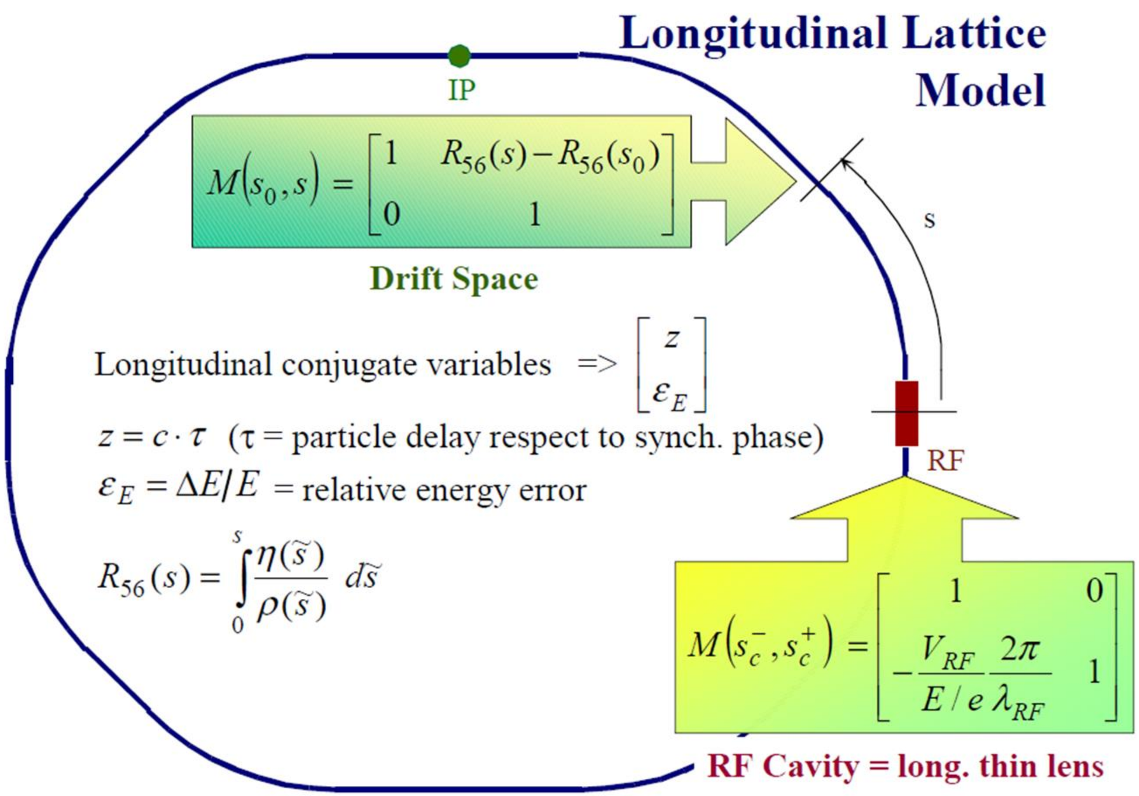
I_{th} = 9 mA at $\alpha_c > 0$

Principal Results with α_c<0

- DAΦNE optics model has proven to be reliable in providing collider operation with α_c ranging from +0.034 to –0.036
- With α_c< 0 bunches shorten as predicted by numerical simulations
- High bunch currents (>40 mA) can be stored with high negative chromaticities
- No hard limit has been seen in multibunch operation. About 1 A stable beams have been stored in both rings
- At beam currents up to 300 mA/beam a better specific luminosity (> 25%) has been obtained in beam-beam collisions

Strong RF Focusing Proposal

Longitudinal Strong RF Focusing



1. High RF Voltage
2. High RF Frequency
3. High Momentum Compaction Factor

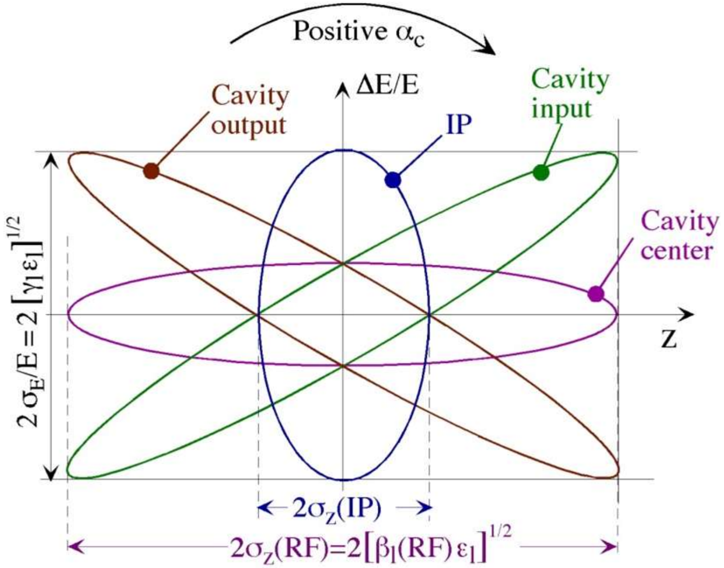
$$M(s,s+L)=\begin{bmatrix} 1-2\pi\frac{R_{56}(s)}{\lambda_{RF}}\frac{V_{RF}}{E/e} & \alpha_c L\left(1-2\pi\frac{R_{56}(s)}{\lambda_{RF}}\left(1-\frac{R_{56}(s)}{\alpha_c L}\right)\frac{V_{RF}}{E/e}\right) \\ -\frac{V_{RF}}{E/e}\frac{2\pi}{\lambda_{RF}} & 1+2\pi\frac{R_{56}(s)}{\lambda_{RF}}\left(1-\frac{\alpha_c L}{R_{56}(s)}\right)\frac{V_{RF}}{E/e} \end{bmatrix}$$

One-turn transfer matrix

$$\cos\mu = \frac{1}{2}Tr\left[M(s_0,s_0+L)\right] = 1-\pi\frac{\alpha_c L}{\lambda_{RF}}\frac{V_{RF}}{E/e}; \quad \nu_s = \frac{1}{2\pi}A\cos\left[1-\pi\frac{\alpha_c L}{\lambda_{RF}}\frac{V_{RF}}{E/e}\right]$$

Synchrotron phase advance

Longitudinal Twiss parameters



$$\alpha_l(s)=\frac{1-\cos\mu}{\sin\mu}\left[1-\frac{2R_{56}(s)}{\alpha_c L}\right]$$

$$\beta_l(s)=\frac{\alpha_c L}{\sin\mu}\left[1-(1-\cos\mu)\frac{2R_{56}(s)}{\alpha_c L}\left(1-\frac{R_{56}(s)}{\alpha_c L}\right)\right]$$

$$\gamma_l(s)=\frac{1-\cos\mu}{\sin\mu}\frac{2}{\alpha_c L}$$

$$\frac{\sigma_E}{E}=\sqrt{\varepsilon_l\gamma_l}\ \Rightarrow \varepsilon_l=(\sigma_E/E)^2\ \frac{\sin\mu}{2(1-\cos\mu)}\alpha_c L$$

Normalized energy spread

$$\sigma_z(s)=\sqrt{\varepsilon_l\beta_l(s)}=\frac{\sigma_E}{E}\alpha_c L\sqrt{\frac{1}{2(1-\cos\mu)}-\frac{R_{56}(s)}{\alpha_c L}\left(1-\frac{R_{56}(s)}{\alpha_c L}\right)}$$

Bunch length varying along the ring

..in the limiting case

$$\sigma_z(s) = \sqrt{\varepsilon_l \beta_l(s)} = \frac{\sigma_E}{E}\alpha_c L \sqrt{\frac{1}{2(1-\cos\mu)} - \frac{R_{56}(s)}{\alpha_c L}\left(1 - \frac{R_{56}(s)}{\alpha_c L}\right)} =$$

$$= \sigma_z(0)\sqrt{1 - 2(1-\cos\mu)\frac{R_{56}(s)}{\alpha_c L}\left(1 - \frac{R_{56}(s)}{\alpha_c L}\right)}$$

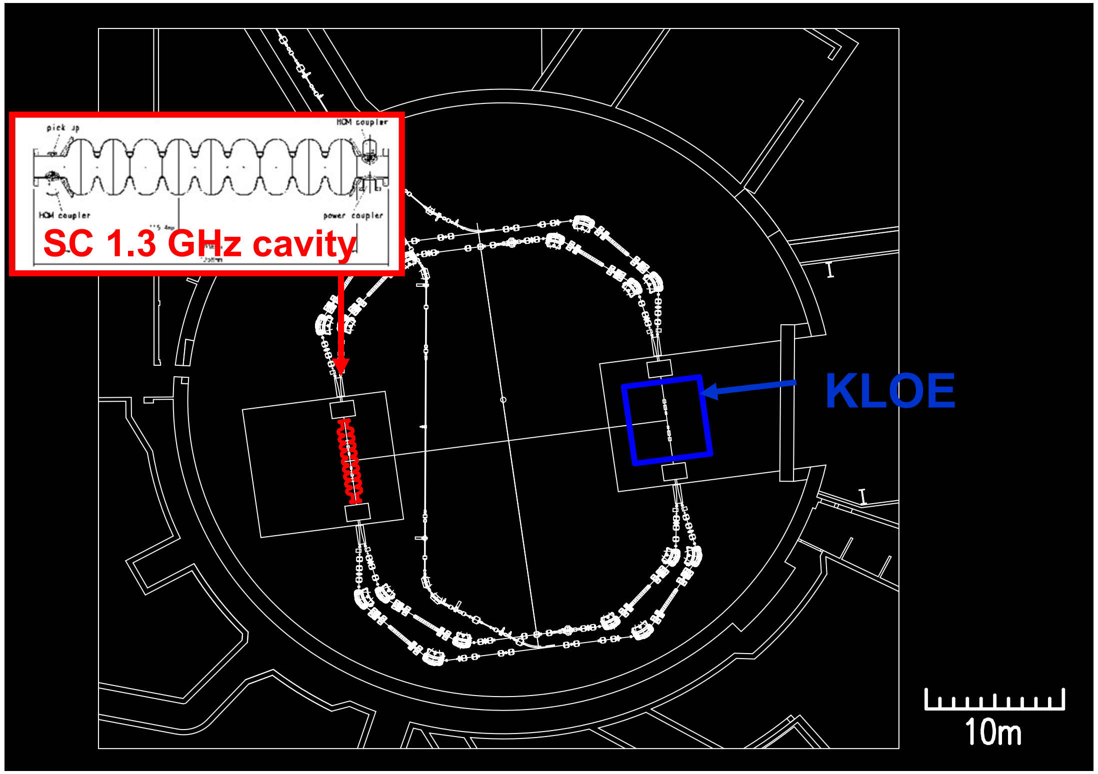
where $\boldsymbol{\sigma_z(0)}$ is the bunch length at $\boldsymbol{s=0}$ (i.e. at the cavity position). It may be noticed that $\boldsymbol{\sigma_z(0) = \sigma_{z,cav}}$ is the maximum value of the bunch length along the ring. On the other hand, there is a minimum value of $\boldsymbol{\sigma_z}$ corresponding to the $\boldsymbol{s_m}$ position where $\boldsymbol{R_{56}(s_m) = \alpha_c L/2}$. If the minimum position corresponds to the IP one gets:

$$\sigma_z(IP) = \frac{\sigma_E}{E}\frac{\alpha_c L}{2}\sqrt{\frac{1+\cos\mu}{1-\cos\mu}} = \sigma_z(Cav)\sqrt{\frac{1+\cos\mu}{2}}$$

As $\boldsymbol{\mu}$ approaches $\boldsymbol{\pi}$, the ratio $\boldsymbol{\sigma_z(IP)/\sigma_z(Cav)}$ goes to zero!

However, one has to take into account damping and quantum fluctuations due to the synchrotron radiation...

Strong RF Focusing Experiment at DAΦNE (proposal)



with a high momentum compaction factor and a high RF gradient:

$$\sigma_z(s) = \left(\frac{\sigma_E}{E}\right)\alpha_c L \sqrt{\frac{1}{2(1-\cos\mu)} - \frac{R_{56}(s)}{\alpha_c L}\left(1 - \frac{R_{56}(s)}{\alpha_c L}\right)}$$

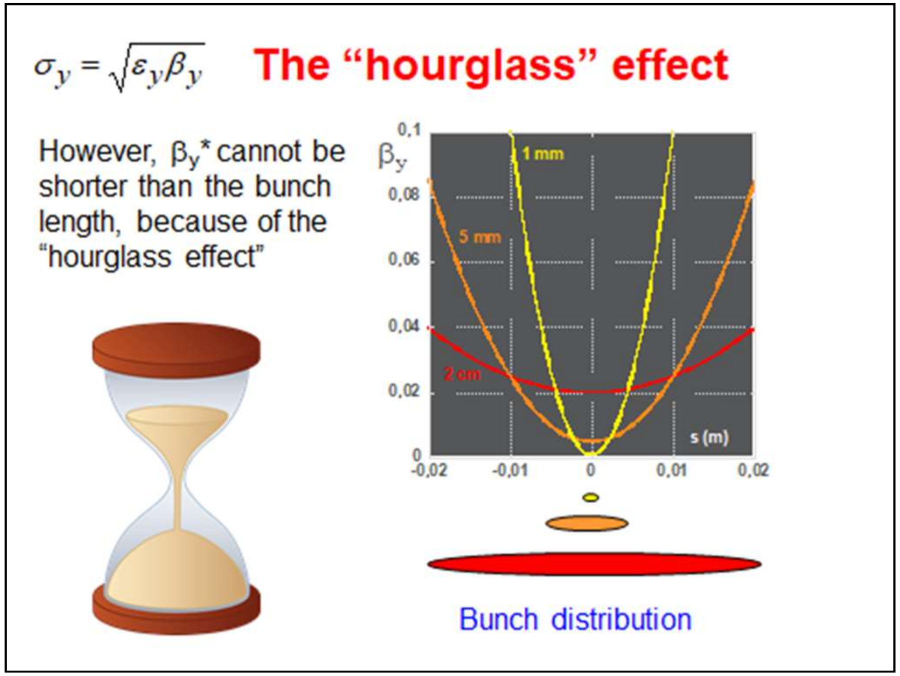
$$\left(\frac{\sigma_E}{E}\right)^2 = \frac{1}{1+\cos\mu}\frac{55}{48\sqrt{3}}\frac{r_e \hbar}{m_e}\frac{\gamma^5 \tau_d}{L}\oint\left[1-(1-\cos\mu)\frac{2R_{56}(s)}{\alpha_c L}\left(1-\frac{R_{56}(s)}{\alpha_c L}\right)\right]\frac{ds}{|\rho(s)|^3}$$

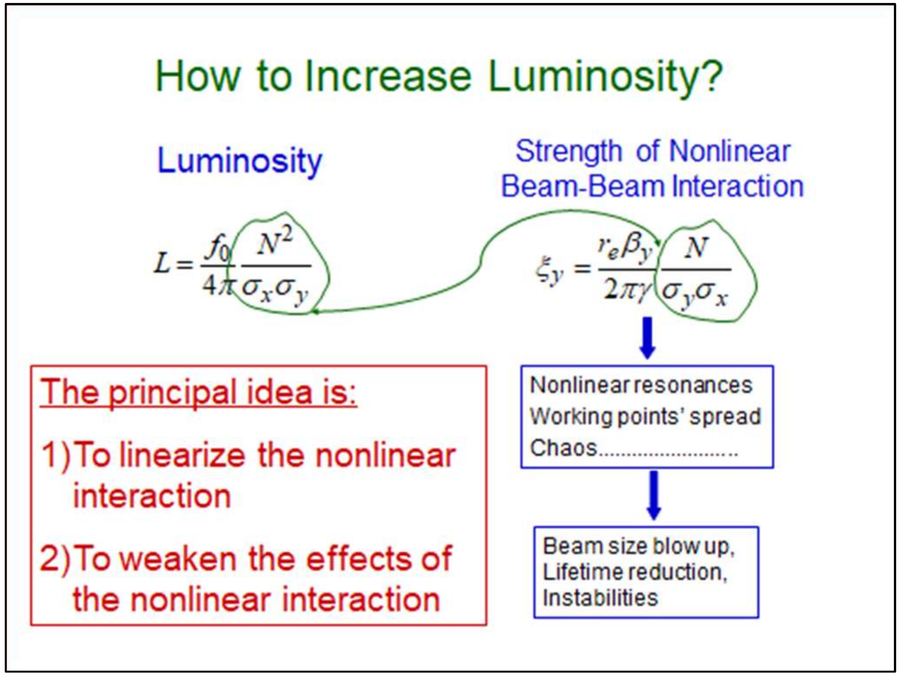
Crab Waist Collision Concept

Crab Waist helps

to overcome the hourglass effect

to alleviate the effects of the nonlinear beam-beam interaction

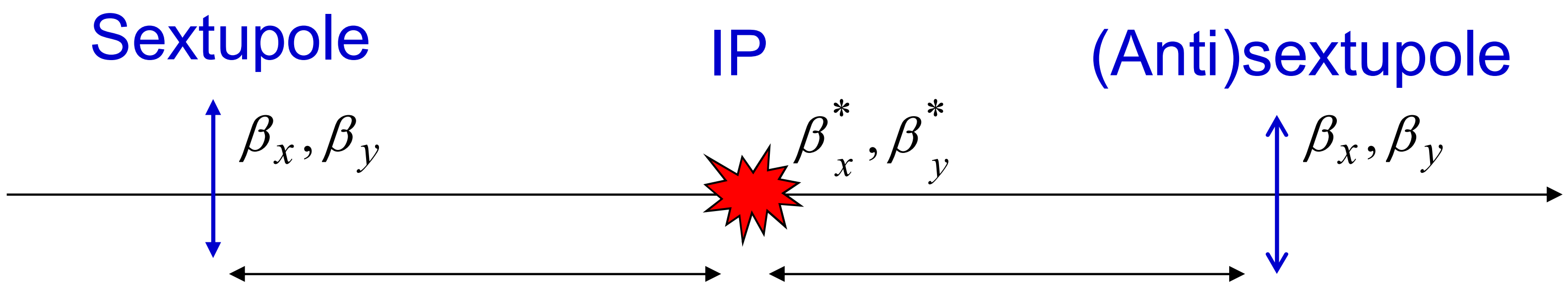




Large Piwinski angle
Small overlap area

Crab waist sextupoles

Crabbed Waist Scheme



$$\Delta\mu_y = \frac{\pi}{2} \qquad \Delta\mu_y = \frac{\pi}{2}$$

$$\Delta\mu_x = \pi \qquad \Delta\mu_x = \pi$$

Sextupole strength

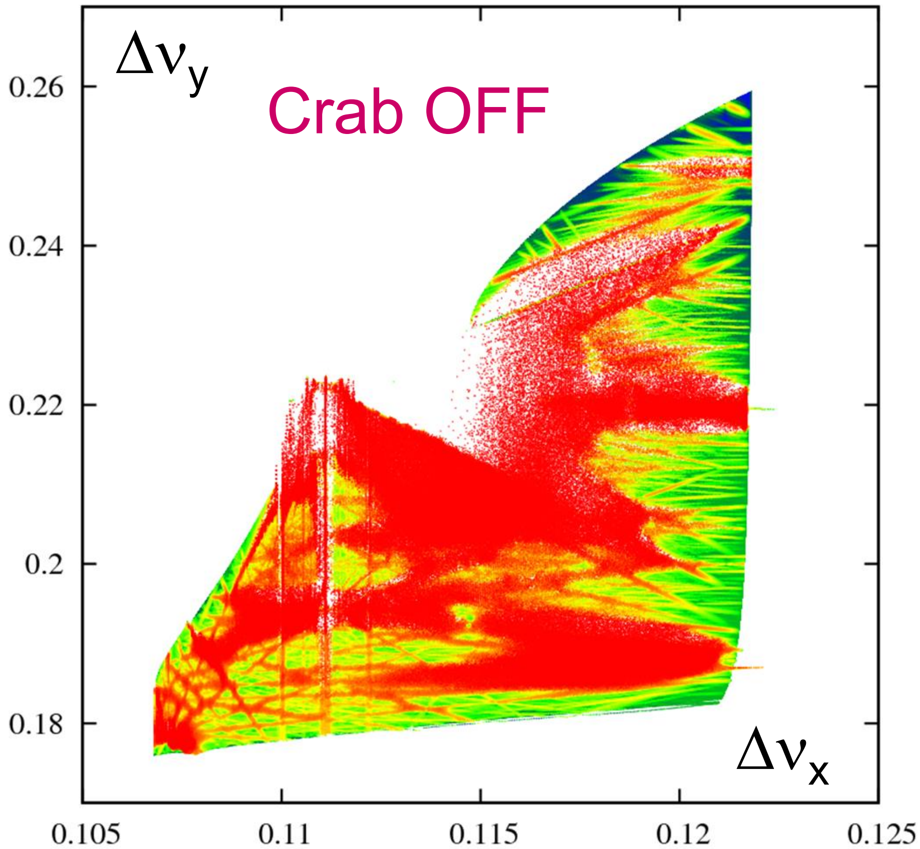
$$K = \frac{1}{2\theta}\frac{1}{\beta^*_y \beta_y}\sqrt{\frac{\beta^*_x}{\beta_x}}$$

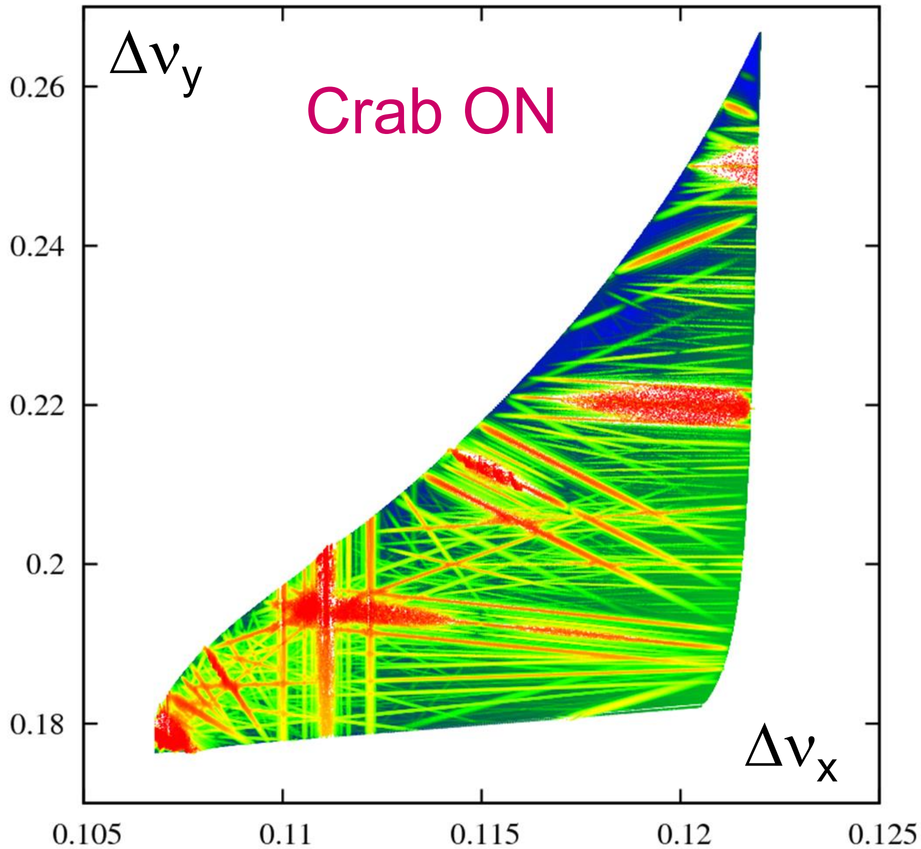
Equivalent Hamiltonian

$$H = H_0 + \frac{1}{2\theta} x p_y^2$$

$$\beta_y = \beta^*_y + \frac{(s - x/\theta)^2}{\beta^*_y}$$

Frequency Map Analysis of Beam-Beam Interaction

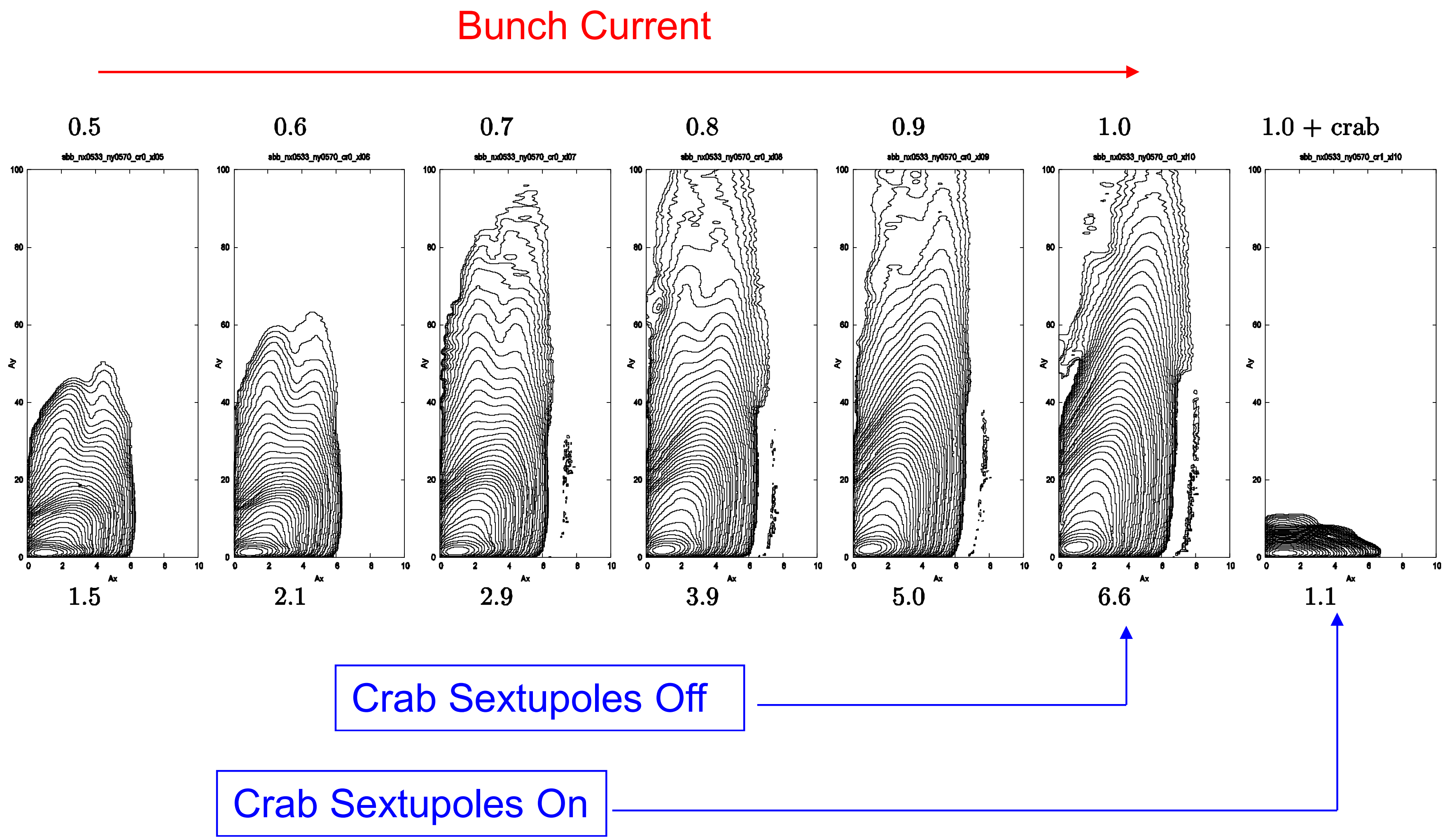




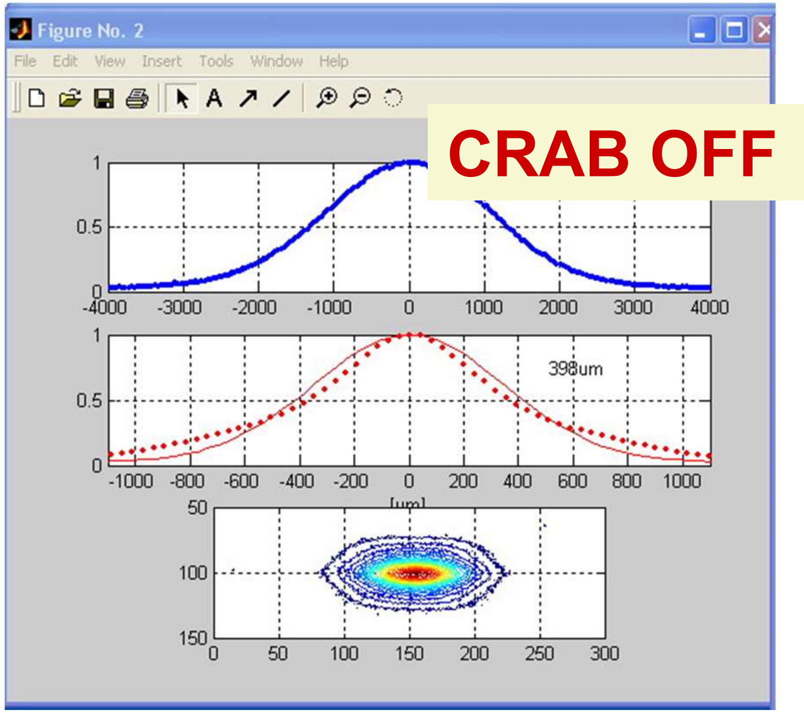
D.Shatilov, E.Levichev, E.Simonov and M.Zobov

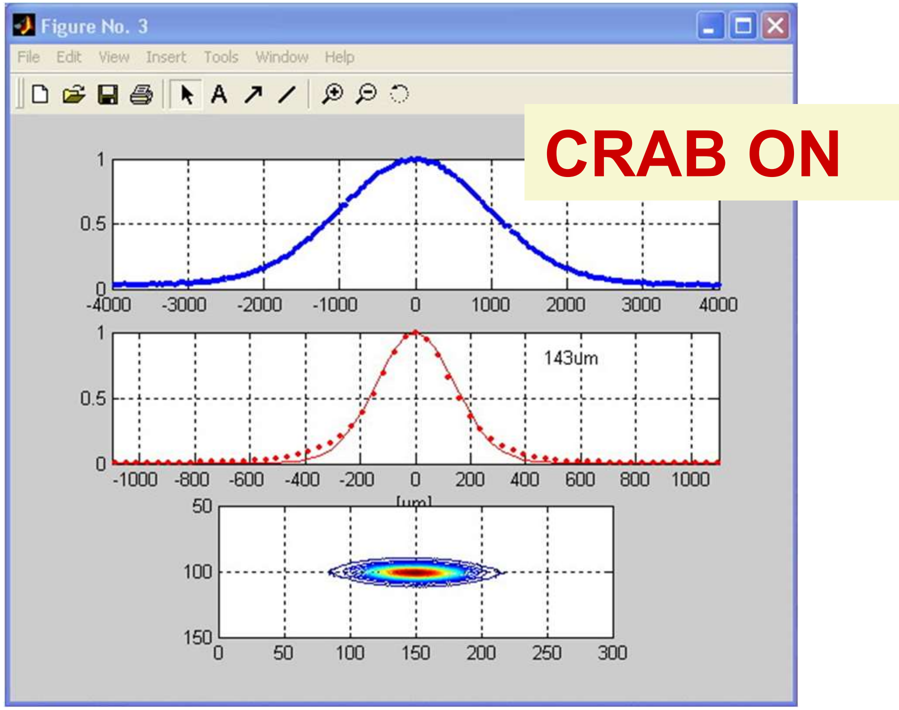
Phys.Rev.ST Accel.Beams 14 (2011) 014001

Beam Blowup and Tails in SuperB



Effect of CW Sextupoles

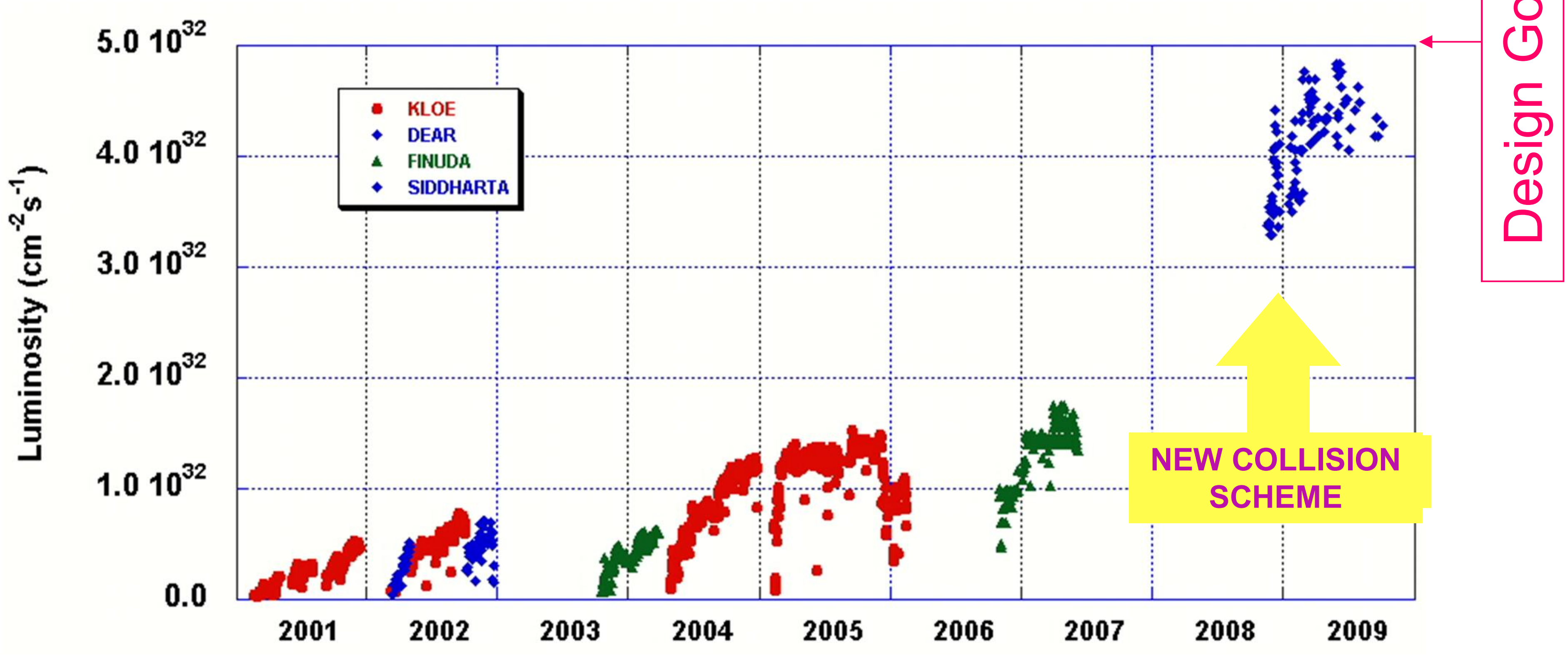


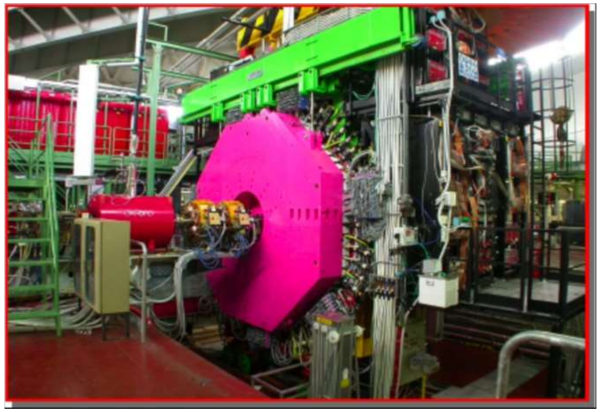


Switching on the CW sextupoles

1. Beam sizes shrink
2. Beam-beam tails disappear
3. Luminosity and Lifetime are improved
4. Detector background gets lower

DAΦNE Peak Luminosity





Colliders based on Crab Waist concept

Colliders	Location	Status
DAΦNE	Φ-Factory Frascati, Italy	In operation (SIDDHARTA, KLOE-2, SIDDHARTA-2)
SuperKEKB	B-Factory Tsukuba, Japan	In operation, the world record luminosity has been achieved
SuperC-Tau	C-Tau-Factory Sarov, Russia	Russian mega-science project
FCC-ee	Z,W,H,tt-Factory CERN,Switzerland	100 km, CDR released in December 2018
CEPC	Z,W,H,tt-Factory China	100 km, CDR released in September 2018
HIEPA	2-7 GeV China	Considered base line option

I would like to express my warmest thanks to my colleagues for many exciting years of working together at DAΦNE!