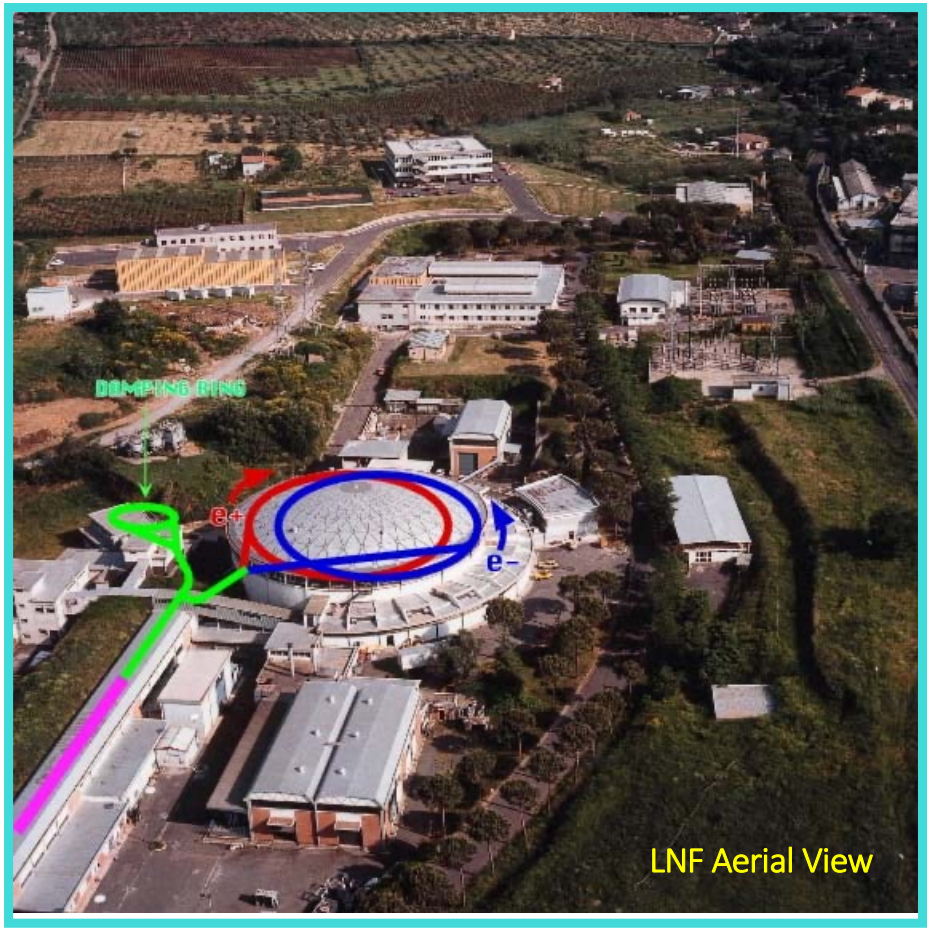
Historical Review of the DAΦNE Collider

Catia Milardi
on behalf of the DAΦNE Team



DAΦNE in the International Context

- **DAΦNE** is an electron-positron collider designed in the mid '90s, it came into stable operation in 2001.
- In the 20th century DAΦNE, together with PEP-II, KEKB, BEPC-II, introduced a new collider category: ***THE FACTORIES***.
- Relevant advances in accelerator physics and technology concerning:
  - magnets, vacuum systems, diagnostics, feedback, control systems etc. ,
  - understanding the impact of collective effects (wake-field, intra-beam scattering, e-cloud etc.),

  led to a new class of colliders that store multi bunch, high intensity beam currents in independent rings which share only the interaction region.
- The Factories had to face new challenges:
  - preserve the "single beam" parameters: 3D emittance
  - maintain stable beams;
  - Interaction Region design, especially low-β;
  - synchrotron radiation and beam losses handling;
  - beam power, and RF power;
  - Luminosity degradation due to collision with horizontal crossing angle and beam-beam interaction.

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  - synchrotron radiation and beam losses handling;
  - beam power, and RF power;
  - Luminosity degradation due to collision with horizontal crossing angle and beam-beam interaction;
  - Interplay between beam-beam and other collective effect.

At the beginning of the 21st century **DAFNE**, developing and implementing a new approach to collisions the **Crab-Waist collision scheme**, became protagonist of a new transition in the field of colliders, the advent of the ***Super Factories.***

First Beam Stored at DAΦNE



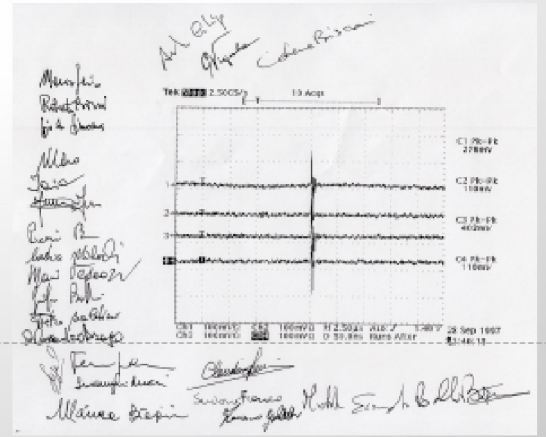


Table IV: *DAΦNE Commissioning Milestones*

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 was built in 5 years

1993

DAΦNE Design and Construction Team

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DAΦNE, The Frascati Φ-factory

The DAΦNE Project Team*
presented by G.Vignola
INFN Laboratori Nazionali di Frascati - C.P. 13 - 00044 Frascati (Roma) - Italy

Abstract

The e^+e^- Φ-factory DAΦNE is presently under construction in Frascati. It is designed as a double ring system with a maximum number of 120 bunches/beam. The short term luminosity goal is L=1.3 10^{32} cm^{-2} sec^{-1} with 30 bunches. The strategy, adopted to achieve such a luminosity, is common to many factory designs : high current, many bunches and separate rings. The technical problems are complicated by the relatively low energy of the beams. A general overview of the project and the most significant technical solutions adopted for DAΦNE are presented.

I. INTRODUCTION

The construction of DAΦNE in the Frascati National Laboratories (LNF), has been approved and fully funded by the National Institute of Nuclear Physics (INFN) in June 1990, while the engineering design phase has started in January 1991.

The layout of the new accelerator complex (housed in the buildings where ADONE and its injector Linac have been running until the last April) is shown in Fig. 1.

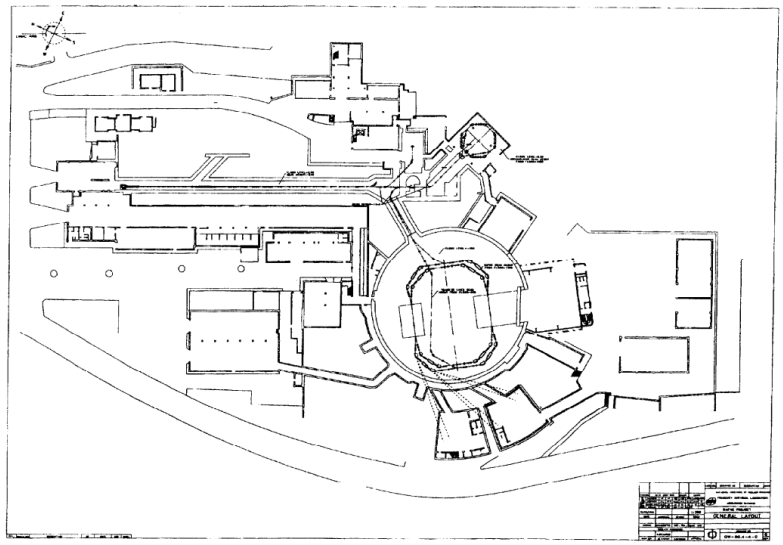


Figure 1. DAΦNE complex layout.

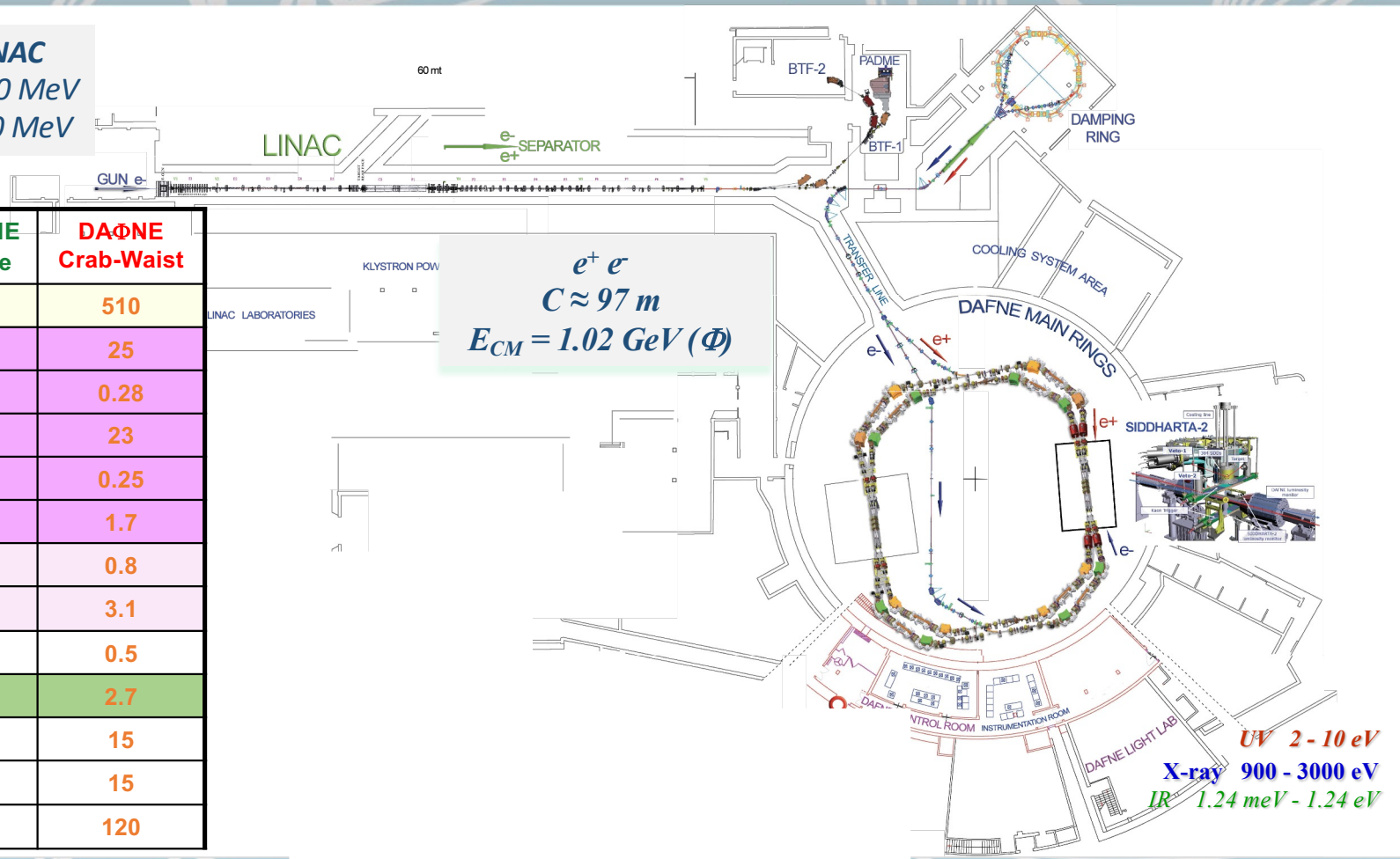
* G. Vignola, S. Bartalucci, M. Bassetti, M.E. Biagini, C. Biscari, R. Boni, A. Cattoni, V. Chimenti, A. Clozza, S. De Simone, A. Drago, G. Di Pirro, A. Esposito, S. Faini, A. Gallo, A. Ghigo, S. Guiducci, Y. He, H. Hsieh, J. Lü, C. Marchetti, M.R. Masullo, M. Migliorati, C. Milardi, M. Modena, L. Palumbo, R. Parodi, L. Pellegrino, M. Pelliccioni, M. Preger, G. Raffone, C. Sanelli, F. Sannibale, M. Serio, F. Sgamma, B. Spataro, A. Stecchi, L. Trasatti, C. Vaccarezza, M. Vescovi, S. Vescovi, J. Wang, M. Zobov.

0-7803-1203-1/93$03.00 © 1993 IEEE

The DAΦNE Accelerator Complex

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

LINAC
e^+ 550 MeV
e^- 800 MeV



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

	DAΦNE native	DAΦNE Crab-Waist
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)	0.70	0.25
$\Phi_{Piwinski}$	0.6	1.7
β_y^* (cm)	1.80	0.8
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	15
σ_z (mm)	25	15
N_h	120	120

UV 2 - 10 eV
X-ray 900 - 3000 eV
IR 1.24 meV - 1.24 eV

Machine and Beams Main Features

Collider

- Rings have no periodicity
- *Large aperture short magnets have long fringe fields*
- *Strong non-linearities coming from:*
  Wigglers, ***mitigated***
  C-type correctors,
  large high strength Quadrupoles used in the native IRs based on a triplet configuration. ***removed***
- *Low-β design based on permanent magnet quadrupoles whose design has been improved several times.*
- *Reduced spaces cause cross talk among elements in the same ring, between the two rings and among rings and TLs.*
- *Very complex Al beam pipe that must withstand a high thermal load. The arch chambers are manufactured in a single block. Al has high SEY.* ***mitigated***

Beams

Colliding beams have:

- low energy,
- high intensity beam currents, obtained filling about 110 buckets out of the 120 available,
- Beams experience bunch lengthening,
- short bunch spacing 2.7 nsec,
- long damping time.

DAΦNE Performances Optimization Strategy

Optimizing DAΦNE performances imposed to address, and study the ***complex Interplay*** *between beam-beam interaction and a large ensamble of other effects including: linear and non-linear beam dynamics, collective effects, vacuum effects, RF and FBK systems …*

These studies provided original insight, and allowed to mitigate and in many case avoid negative interferences.

DAΦNE Activity

- DAΦNE came into stable operation in 2001.
- Till 2007 it was providing data, in independent data-taking periods, to:
  KLOE, **DEAR** and **FINUDA** experiments until 2007

SIDDHARTA in 2008 ÷ 2009

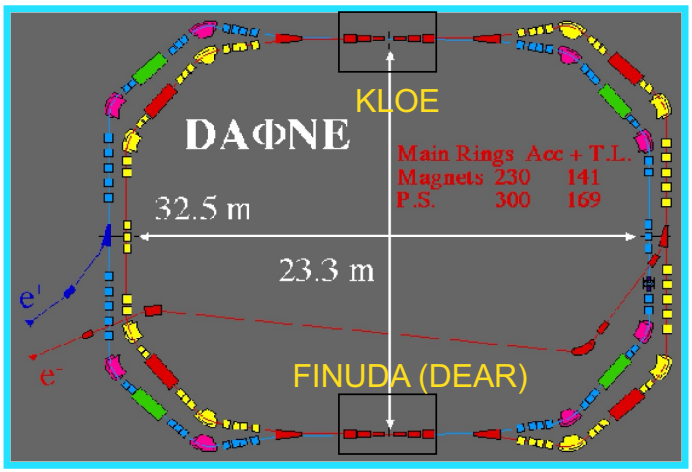
Crab-Waist Collisions Scheme successfully implemented and tested

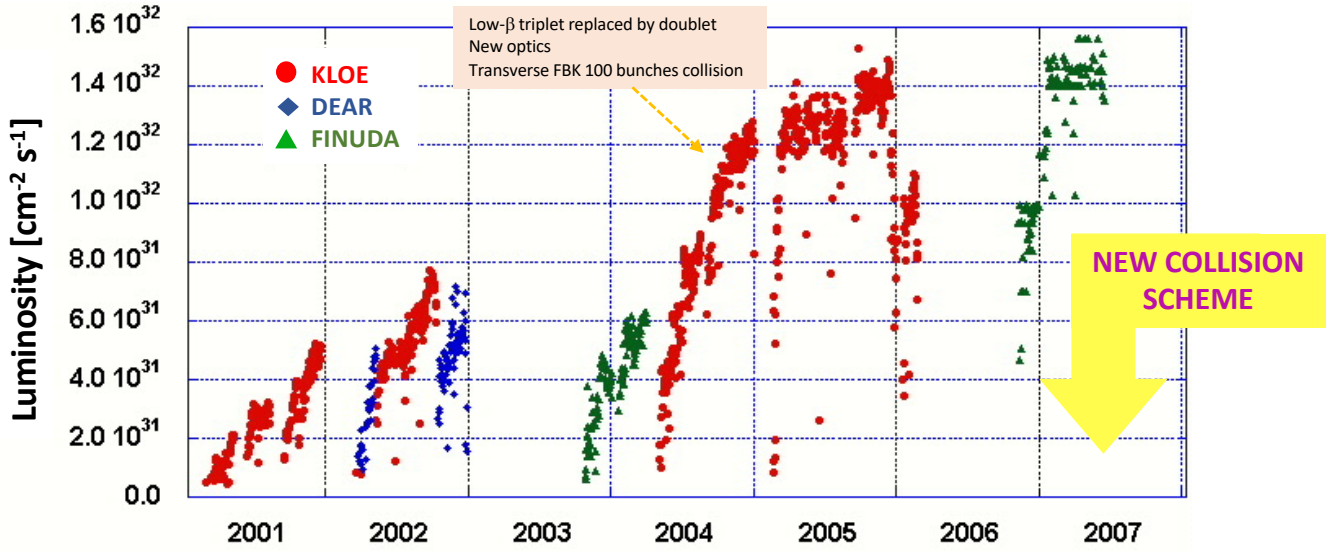
DAΦNE & KLOE-2 refurbishment**,** upgrade and preparation for the run with a large upgrated detector.
KLOE-2 run November 2014 and March 2018.

SIDDHARTA-2 experiment in 20019 ÷ 2024**,**
DAFNE-light Facility,
DAΦNE LINAC is securing data to two **BTF lines,** and the **PADME** experiment.

Presently DAΦNE LINAC is providing physics for BTF and PADME experiment,
DAΦNE collider is in standby.

DAΦNE Operations 2001 ÷ 2007



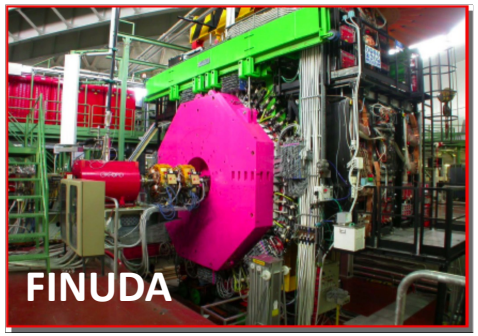


L_{peak} had a remarkable evolution mainly due to several machine upgrades

Experiments took data one at the time.

By 2007 native configuration reached its limits due to, hourglass, LRBB, fast horizontal e+ instability





L_{logged} (fb^{-1}) 2001 ÷ 2007

KLOE	3.0
FINUDA	1.2
DEAR	0.2

Large Piwinski angle

Horizontal crossing angle θ

Large Piwinski angle $\Phi >> 1$

$$\Phi \approx \frac{\sigma_z}{\sigma^*_x}\frac{\theta}{2}$$

large θ
small σ_x

Larger θ, lower ε
New IR layout
Shorter common beam pipe

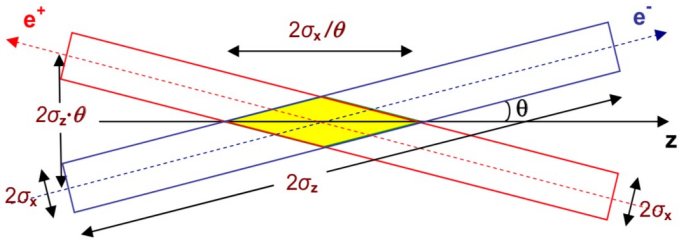
$$\zeta_y \propto \frac{N\sqrt{\beta^*_y}}{\sigma_z\theta} \qquad \zeta_x \propto \frac{N}{(\sigma_z\theta)^2} \qquad L \propto \frac{N\zeta_y}{\beta^*_y}$$

Increasing N
- L increase with N
- low ζ_x
- ζ_y constant

β^*_y can be reduced to the limit of the two beams overlap region Σ

$$\Sigma \propto \frac{\sigma_x}{\theta} \qquad \beta_y \propto \frac{\sigma_x}{\theta} << \sigma_z$$

New low-β section
Ad hoc low-β optics



P. Raimondi et al., LNF-07/003 (IR) 29 Gennaio 2007

Crab-Waist Transformation

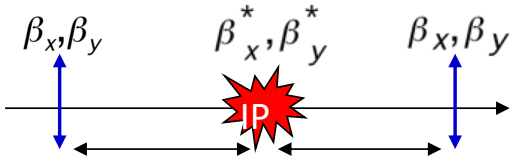
Collisions with large θ is not a new idea

Crab-Waist transformation is

$$y = \frac{xy'}{2\theta}$$

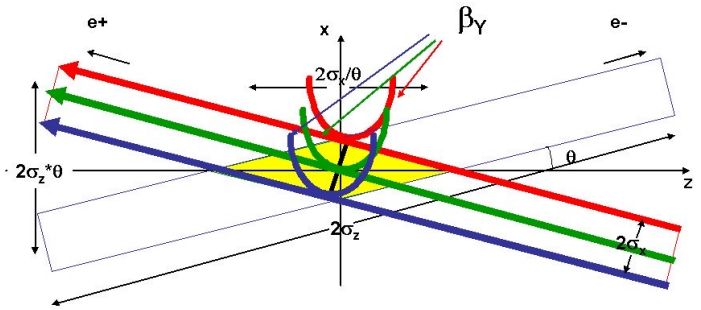
High Strenght Sextupoles
Proper IR optics

sextupole (anti)sextupole



$$\Delta\nu_x = \pi$$
$$\Delta\nu_y = \frac{\pi}{2}$$

- $L_{geometric}$ gain
- X-Y synchro-betatron and betatron resonance suppressed



CW Sextupoles OFF

P. Raimondi , *2° SuperB Workshop, March 2006,*
P.Raimondi, D.Shatilov, M.Zobov, physics/0702033,
C. Milardi et al., Int.J.Mod.Phys.A24, 2009.

Crab-Waist Transformation

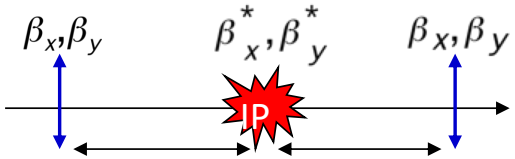
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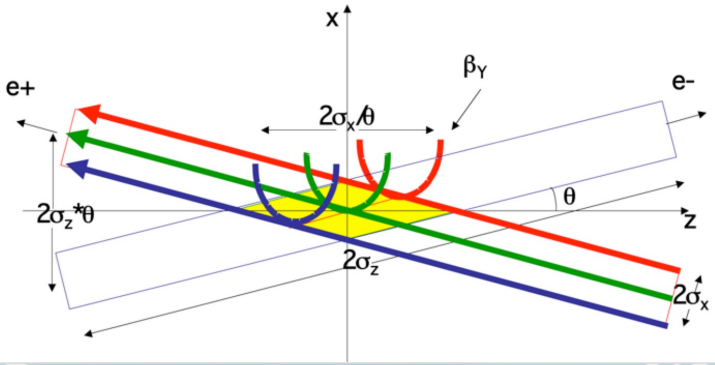
Powerful Sextupoles
Proper IR optics

sextupole (anti)sextupole



$$\Delta\nu_x = \pi$$
$$\Delta\nu_y = \frac{\pi}{2}$$

- $L_{geometric}$ gain
- X-Y synchro-betatron and betatron resonance suppressed

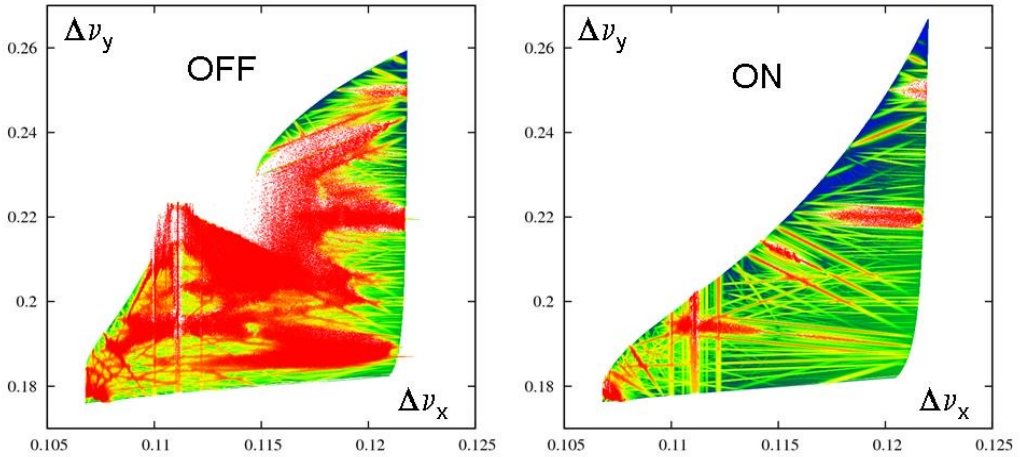


CW Sextupoles ON

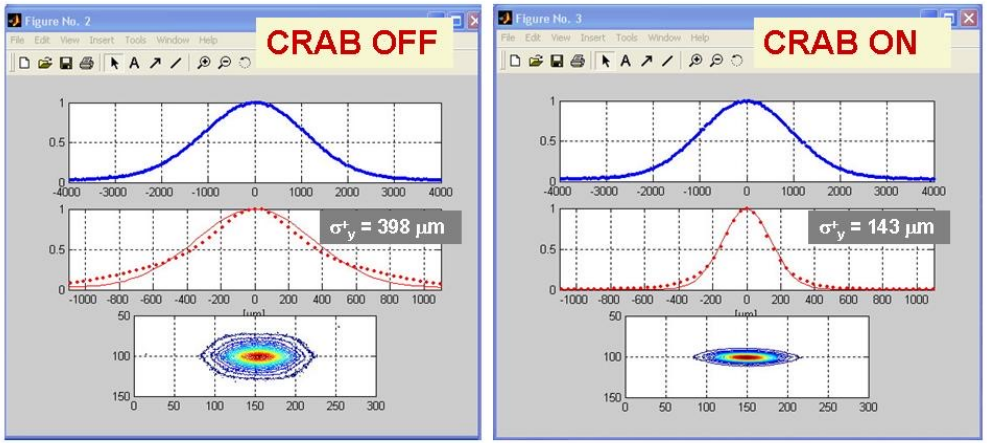
P. Raimondi , *2° SuperB Workshop, March 2006,*
P.Raimondi, D.Shatilov, M.Zobov, physics/0702033,
C. Milardi et al., Int.J.Mod.Phys.A24, 2009.

Suppression of Beam-Beam Resonances

DAΦNE case



← ***Frequency map analysis***



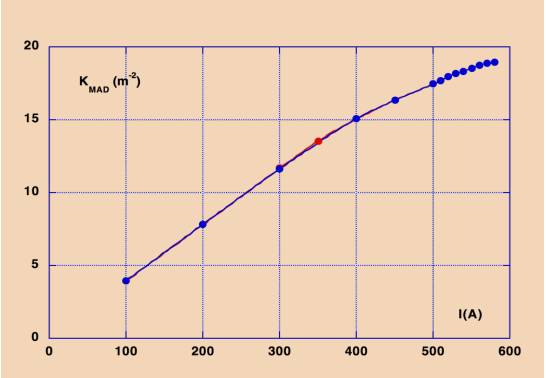
← **Measurements from synchrotron light monitor**

- Beam sizes shrink
- Beam-beam tails disappear
- Luminosity and Lifetime are improved
- Detector background gets lower

D.Shatilov et al., Phys.Rev.Lett. 14 (2011) 014001
M.Zobov, IPAC2010, pp. 3639-3643

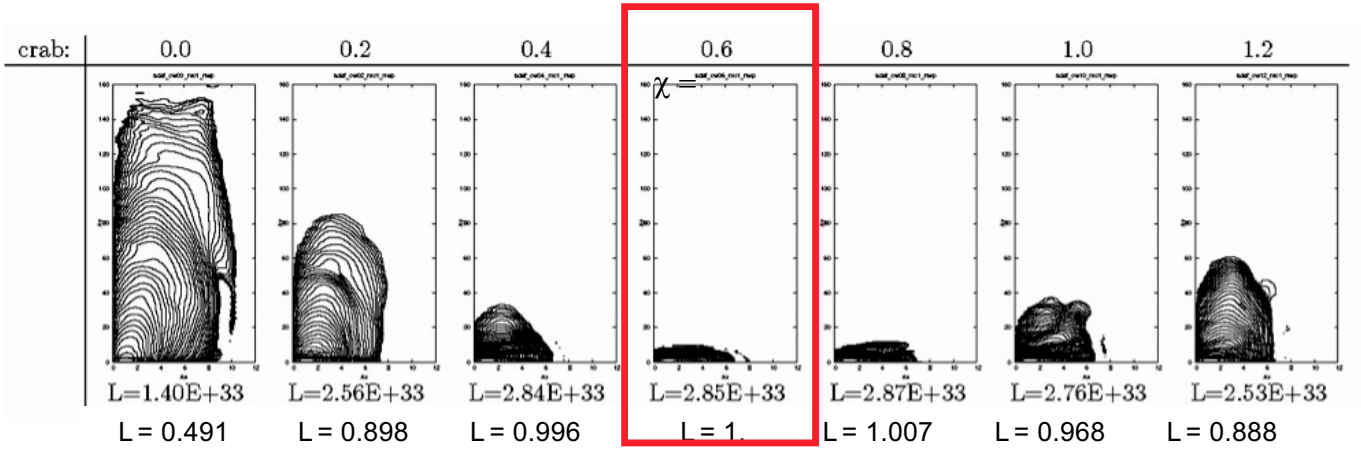
Crab-Waist Sextupoles Strenght

$$k_s = \frac{\chi}{2\theta}\frac{1}{\beta_y^* \beta_y^{sext}}\sqrt{\frac{\beta_x^*}{\beta_x^{sext}}}$$



χ nominal 0.6

χ **present value 0.5**



Luminosity (arbitrary unit) *and* ***Beam tails versus waist rotation*** χ

Catia Milardi, PAC09, May 2009, Vancouver.

Crab-Waist Collisions Test Run Results

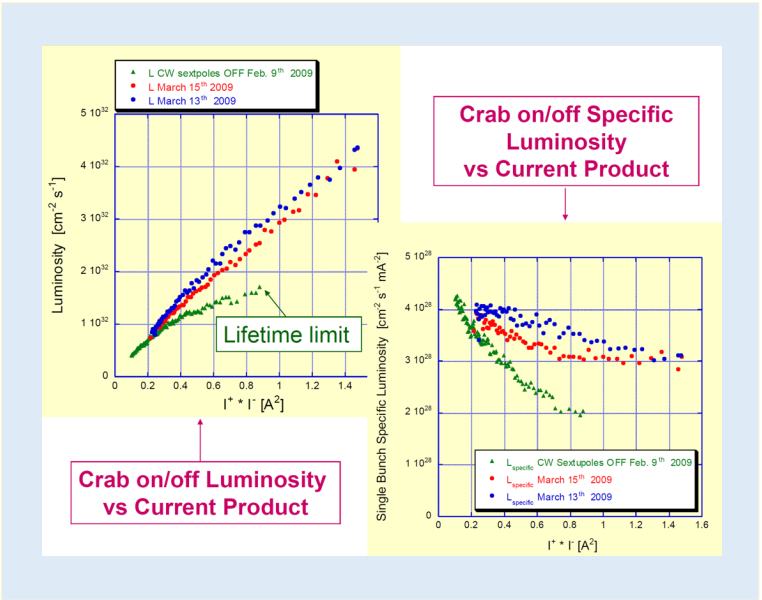
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

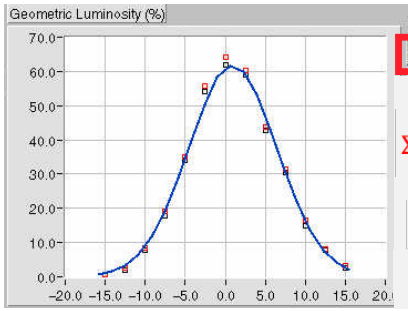
SIDDHARTA Run
(2007 – 2009)

- Large crossing angle and *Crab-Waist* collisions proved to be effective in ***increasing luminosity by a factor 3***
- The DAΦNE collider, based on the new collision scheme including Large Piwinski angle and *Crab-Waist*, was successfully commissioned achieving record performances.



$L_{peak} = 4.5*10^{32}\ cm^{-2}\ s^{-1}$
$L_{\int 1\ day} = 15.0\ pb^{-1}$
$L_{\int 1\ hour} = 1.033\ pb^{-1}$
$L_{\int run} \sim 2.8\ fb^{-1}$ (delivered in 18 months)

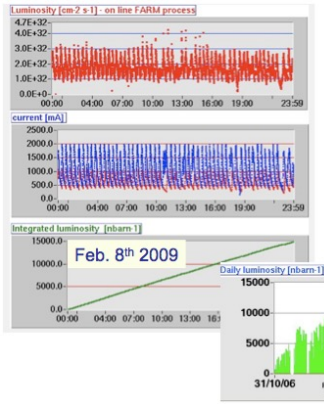




$$\Sigma_y = 0.88\sqrt{\sigma_{Ypos}^2 + \sigma_{Yele}^2}$$

$\sigma_y \approx 3.5\mu m$

Design value 3.1 μm



$L_{\int day} = 15.\ pb^{-1}$

- *moderate injection rate regime*
- *105 colliding bunches*
- $L_{\int hour} = 0.62\ pb^{-1}$

M. Zobov et al., Phys.Rev.Lett.104:174801, 2010.
C. Milardi et al., "Experience with DAFNE upgrade including crab waist", PAC09.

DAΦNE Crab- Waist Test Commissioning Team

D.Alesini, M.E. Biagini, C.Biscari, A. Bocci, R.Boni, M.Boscolo, F.Bossi, B. Buonomo, A.Clozza, G.Delle Monache, T. Demma, E.Di Pasquale, G.Di Pirro, A.Drago, A.Gallo, A.Ghigo, S.Guiducci, C.Ligi, F.Marcellini, G.Mazzitelli, C.Milardi, F.Murtas, L.Pellegrino, M.A.Preger, L.Quintieri, **P.Raimondi**, R.Ricci, U. Rotundo, C.Sanelli, M.Serio, F.Sgamma, B.Spataro, A.Stecchi, A.Stella, S.Tomassini, C.Vaccarezza, M.Zobov

(INFN/LNF, Frascati (Roma)),

I.Koop, E.Levichev, S.Nikitin, P.Piminov, D.Shatilov, V.Smaluk

(BINP, Novosibirsk),

S.Bettoni (CERN, Geneva),

Paolo Valente (INFN-Roma, Roma),

Kazuhito Ohmi (KEK, Ibaraki),

D. Teytelman, (SLAC),

Nicolas Arnaud, Dominique Breton, Leonid Burmistrov, Achille Stocchi, Alessandro Variola, Benoit Viaud(LAL, Orsay),

Marco Esposito (Rome University La Sapienza, Roma),

Eugenio Paoloni (University of Pisa and INFN, Pisa),

Paolo Branchini (University Roma3, Rome)

CW-Collisions for the KLOE-2 detector

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

First Test of the Crab-Waist collision scheme with a large experimental detector including a solenoid with an intense magnetic field

Integrating the **CW** collision scheme with a large experimental detector introduced new ***technological*** and ***accelerator physics challenges in terms of*** mechanic setup, IR layout, optics, beam acceptance, coupling correction, cooling, …

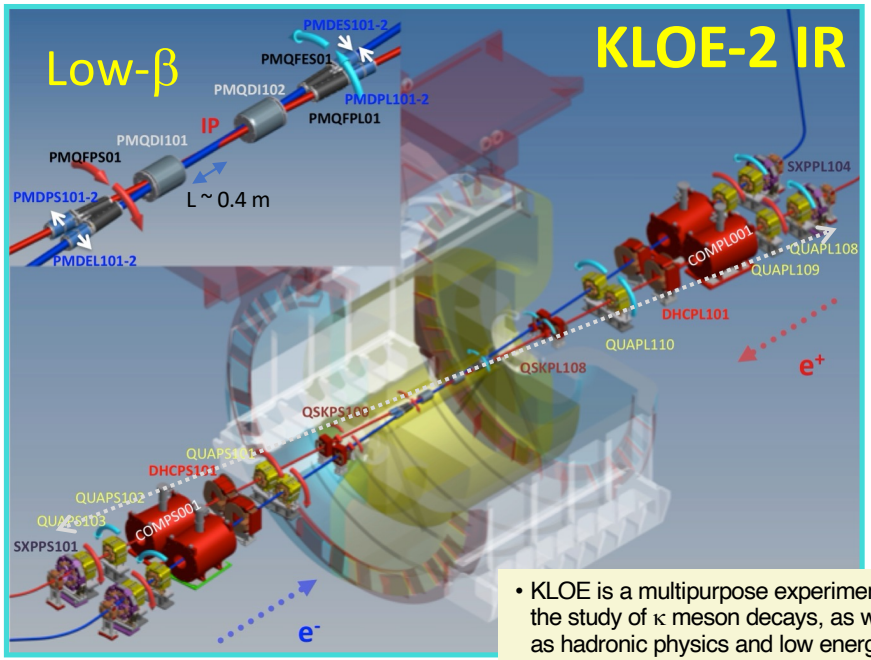
Crucial Points:

IR optics had to provide the best solution for:

- low-β,
- beam trajectory control,
- stay clear aperture,
- ***Crab-Waist*** collision scheme,
- coupling compensation.

IR mechanical design allowing:

- large crossing angle,
- early vacuum pipe separation after IP,
- mechanical stability of the low-β doublet.



- KLOE is a multipurpose experiment for the study of κ meson decays, as well as hadronic physics and low energy QCD,
- Detector includes a superconducting solenoid, 2.3 Tm field.
- Machine magnetic rigidity 1.7 Tm
- Detector is 6 m long included endcaps.

C. Milardi et al, 2012 JINST 7 T03002.
C. Milardi et al. WEOCA03, IPAC14
C. Milardi et al., IPAC'18

Betatron Coupling correction

In half detector solenoid the beam transverse oscillation plane is rotated by an angle ~39°, in module.

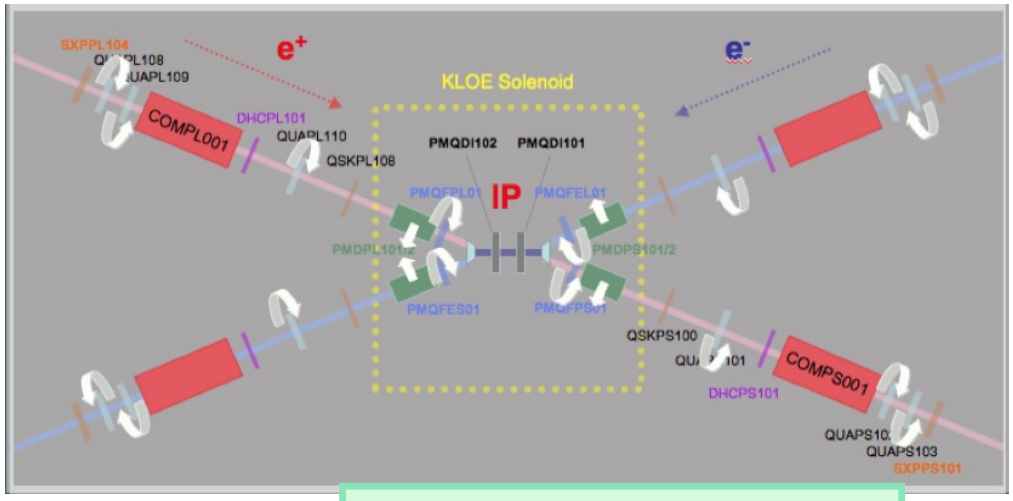
	Z from the IP [m]	Quadrupole rotation angles [deg] *Anti-solenoid current [A]*
PMQDI101	0.415	0.0
PMQFPS01	0.963	-4.48
QSKPS100	2.634	used for fine tuning
QUAPS101	4.438	-13.73
QUAPS102	8.219	0.906
QUAPS103	8.981	-0.906
COMPS001	*6.963*	*72.48 (optimal value 86.7)*

$\int_{KLOE} B \cdot dl$ *canceled by 2 anti-solenoids for each beam*

$$\int_{KLOE} B \cdot dl = 2.048 \quad [Tm] \quad \rightarrow \quad I_{KLOE} = 2300.[A]$$

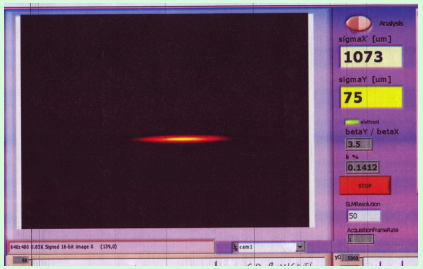
$$\int_{comp} B \cdot dl = \pm 1.024 \quad [Tm] \quad \rightarrow \quad I_{comp} = 86.7[A]$$

to have coupling compensation also for off-energy particles



PMQF rotations were used for transverse betatron coupling fine tuning

e- beam aspect ratio at the SLM

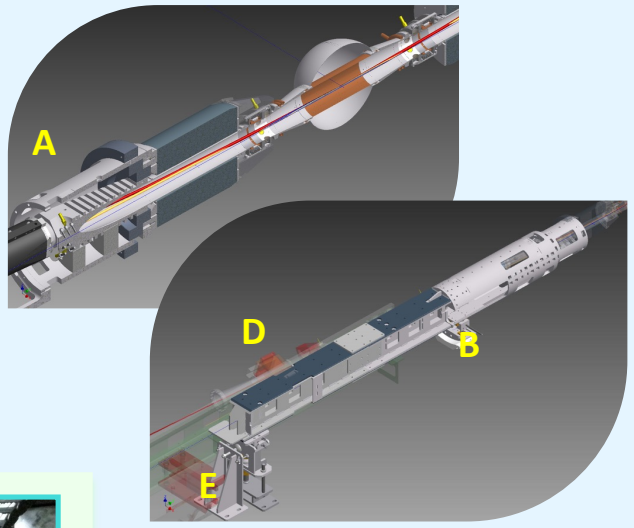


$\kappa \sim 0.14\ \%$

New IR Design

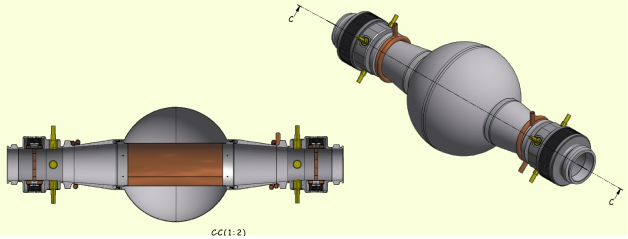
Mechanical design

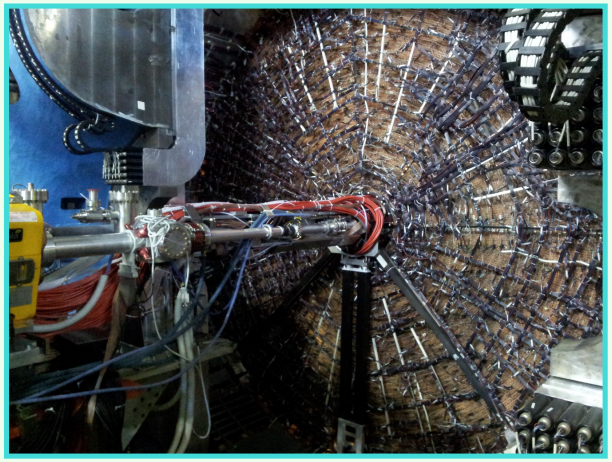
A. Additional toroidal lead shielding
B. New cylindrical vacuum chamber support
C. Alignment tools improvement
D. H-shaped supports reinforced with plates
E. Modification of tail support of the girder
F. Temperature probes added
G. Carbon fiber composite supports added



Spherical Vacuum Chamber

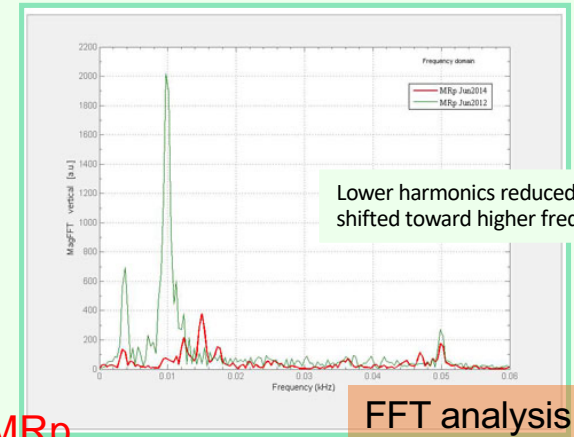
- Single vacuum chamber tapered
- New beryllium screens halved thickness 35 μm
- New bellows with improved design
- 2 BPMs around the IP
- water cooling added





Mechanical Vibration suppression

- A pair of carbon fiber composite legs have been added to the existing supports.
- some rubber pads previously inserted below the cradle support have been removed, thus strengthening the structure and increasing its rigidity.



Lower harmonics reduced in amplitudes and shifted toward higher frequencies wrt 2012

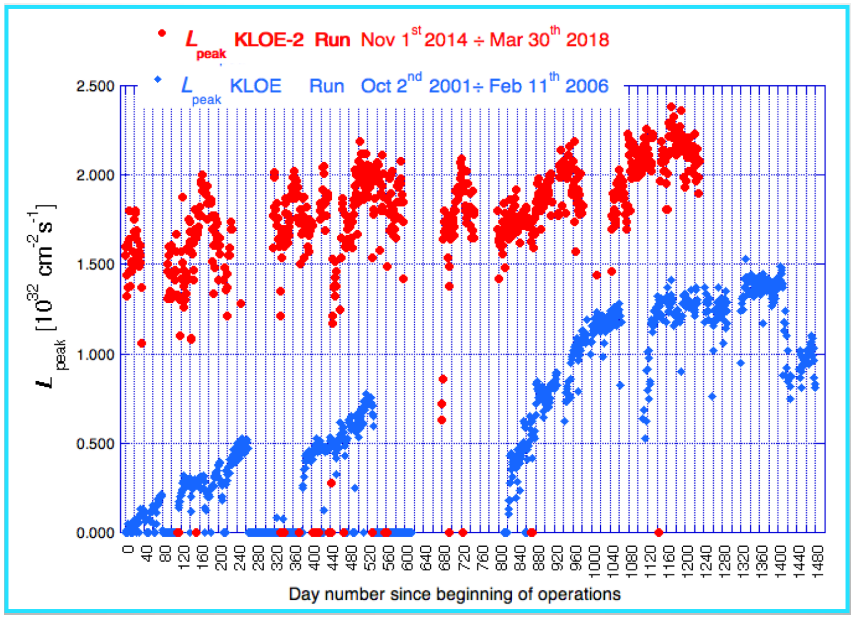
MRp

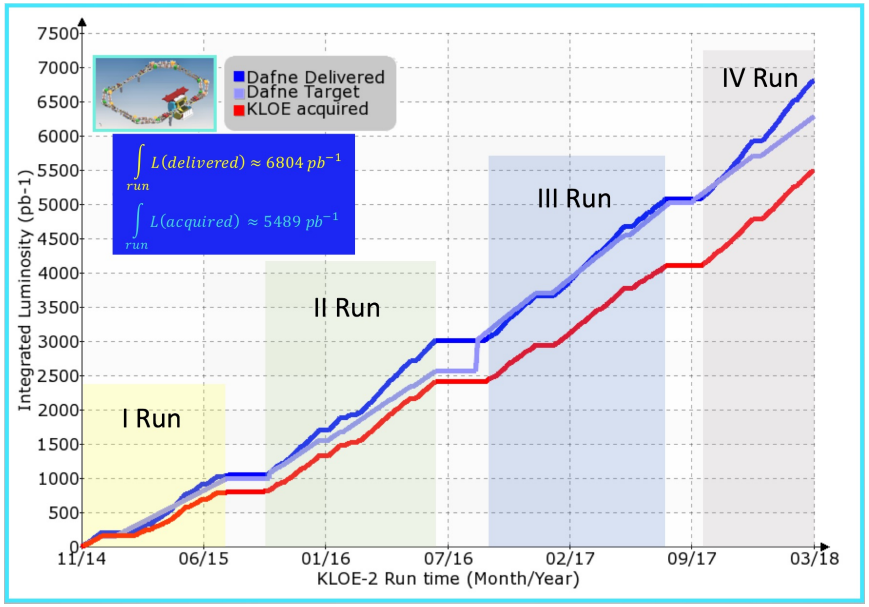
FFT analysis

Crab-Waist Collision with KLOE-2

Crab-Waist collision scheme *implemented for the first time with a large detector* including a high intensity axial magnetic field.

The new approach to collision provided a **~60% improvement** in terms of L_{peak}





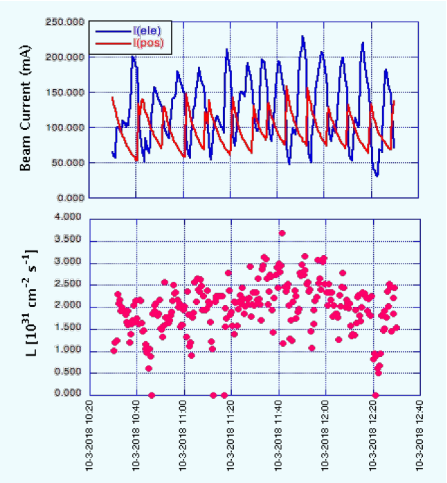
C. Milardi et al., A Review of DAΦNE Performances during the KLOE-2 Run, TUYGBD2, IPAC'18.

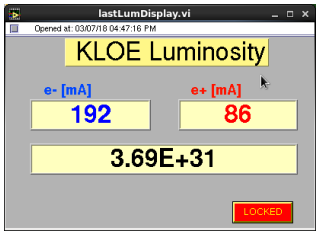
Limiting Factors analysis for KLOE-2 Run

10 Bunches Collisions aiming at minimizing the impact of multi-bunch effects and e-cloud instabilities on *Luminosity*

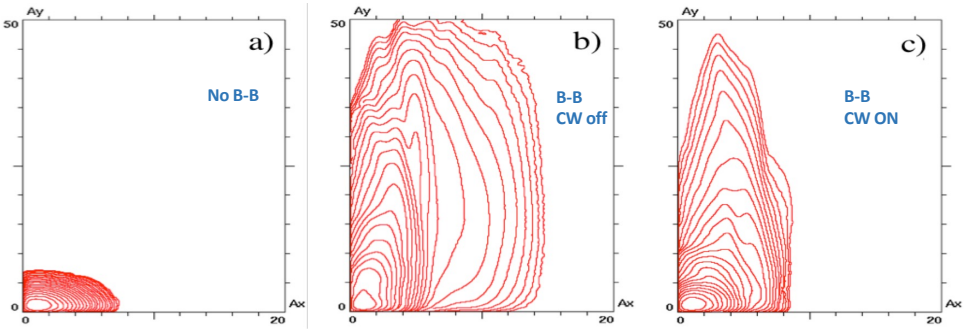
- $L_{peak} \sim 3 \cdot 10^{32}\ cm^{-2}\ s^{-1}$ *might be achieved by colliding 100 bunches*
- *Beam-beam is not a limiting factor*
- *Crab-Waist Sextupoles work as expected.*

C. Milardi et al., *IPAC'18*, pp. 1111-1114, doi:10.18429/JACoW-IPAC2018-TUYGBD2.





Numerical weak strong simulations using nonlinear collider lattice, including a strong detector Solenoid in the IR, have shown that for the given bunch currents in collision, the powering of the **Crab-Waist Sextupoles should decrease the beam core blow up by a factor of 2 indicating that even higher luminosity would have been achieved even in presence of the KLOE-2 solenoid.**



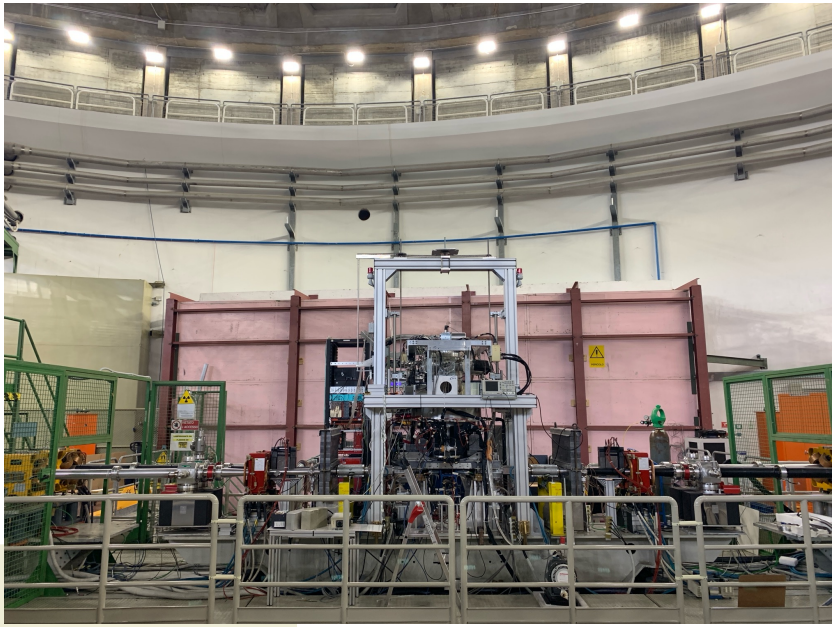
Equilibrium density contour plots in the betatron amplitude space for e^- beam in the w.p. ν_x=0.130, ν_y=0.170. Left – beam-beam off; middle – with beam-beam, CW off; right – with beam-beam, CW on

M. Zobov, A. Valishev, D. Shatilov, C. Milardi, et al., Simulation of Crab Waist collisions in DAΦNE with KLOE-2 interaction region, *IEEE Trans. Nucl. Sci.*, Apr. 2016.

SIDDHARTA-2 Run

DAΦNE operations aimed at delivering a statistically significant data sample ***to perform the first-ever measurement of kaonic deuterium X-ray transitions to the fundamental level***.

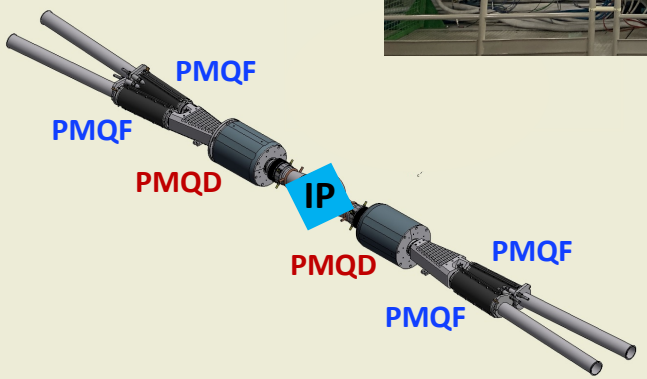
To achieve this goal collision data had to considerably reduce the signal to noise ratio wrt the previous SIDDHARTA run.



Low-β section

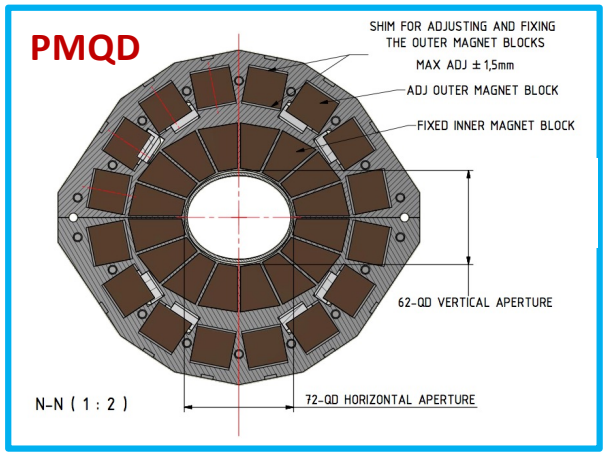
New vacuum chamber
Additional diagnostics
Permanent magnet quadrupoles have been rebuilt to:

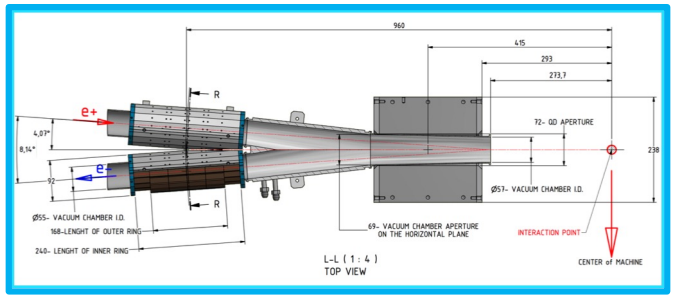
- speed up the installation procedure
- improving design issues such as:
  - ❖ *good field region*
  - ❖ *gradient uniformity*
  - ❖ ***aperture*** *for PMQD aiming at improving:*
    - stay clear aperture
    - background
    - luminosity monitor efficiency



New PMQs specifications

New PMQs are Halbach type magnets made of SmCo2:17
PMQs have been designed in collaboration with the ESRF magnet group.





	PMQD	PMQF
Beam Pipe Aperture H-V (mm) at IP (I row) and at Y (II row) side	57 69 - 55	54
Inner Apert. With Case H-V (mm)	72 - 62	58
Outer Diameter H-V (mm)	238 - 220	95.6
Mech. Length Inner-Outer (mm)	220	168 - 240
Nominal Gradient (T/m)	29.2	12.6
Integrated Gradient (T)	6.7	3.0
Good Field Region (mm)	±20	±20
Integrated Field Quality |dB/B|	5.00E-4	5.00E-4
Magnet Assembly	2 halves	2 halves

Table 2. Multipoles of the QD0 magnets, expressed at 20 mm radius and normalized to the quadrupole component

	QD0-1				QD0-2		
n	Component	Normal	Skew	n	Component	Normal	Skew
1	Dipole	–	–	1	Dipole	–	–
2	Quadrupole	10000	–	2	Quadrupole	10000	–
3	Sextupole	0.4	3.4	3	Sextupole	1.2	−1.5
4	Octupole	−1.8	−2.4	4	Octupole	−0.3	−1.4
5	Decapole	3.9	−5.1	5	Decapole	−2.2	2.1
6	Dodecapole	0.3	4.4	6	Dodecapole	1.0	4.8
7	14-pole	0.2	−0.4	7	14-pole	−2.2	−0.7
8	16-pole	0.7	1.7	8	16-pole	−1.1	0.2
9	18-pole	−0.6	0.3	9	18-pole	0.4	0.9
10	20-pole	−0.7	0	10	20-pole	1.3	0.2

New PMQDs

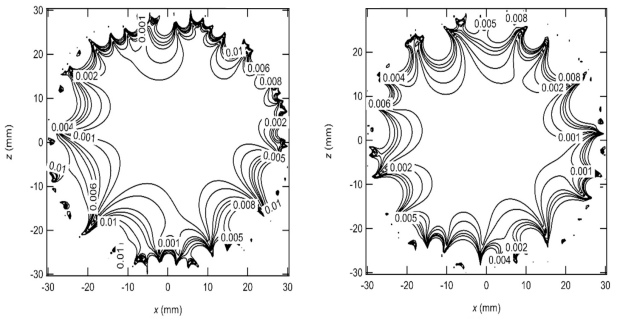
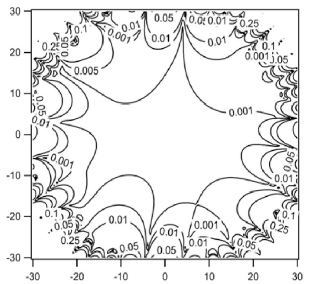


Figure 3. Gradient homogeneity contour plots for the QD0-1 (a) and QD0-2(b) magnets. The inner contour corresponds to gradient inhomogeneities below 0.001.

Old PMQD



Background Control

Injection Background optimized by:

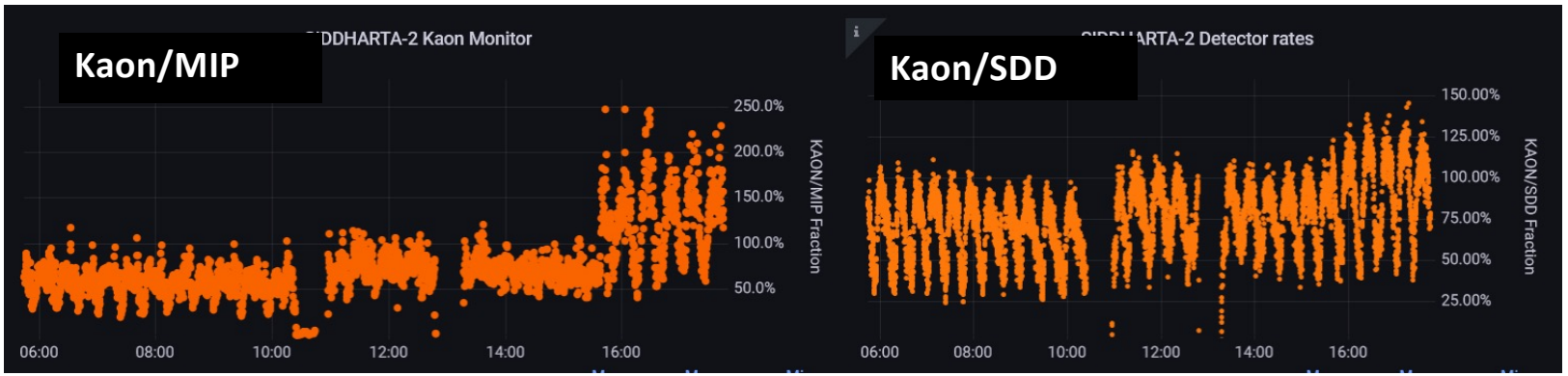
- tuning injection rate (LINAC at 25 Hz, e- injection at 2Hz, e+ injection at 1Hz);
- optimizing injection efficiency, and by properly steering the stored beam orbit in the injection sections:
  this reduced the background down to acceptable levels for the e^- beam, but it did not work as well for e^+ one;
  vertical dimension of the e^- beam are artificially increased during injection, by using a calibrated skew quadrupoles bump, thus reducing the beam-beam kick on the weak e^+ beam, thus avoiding rapid lifetime drops and sudden background bursts.

Costing Background reduced to level compatible with detector operation by:

Tuning non-linear optics which allowed to increase energy acceptance, and dynamic aperture, leading to gain almost a factor of 2, and 1.45 gain in terms of Kaon/MIP, and Kaon/SDD rate respectively.

Kaon/Mip and Kaon/SDD increased by a factor of 1.4 and 3, respectively.

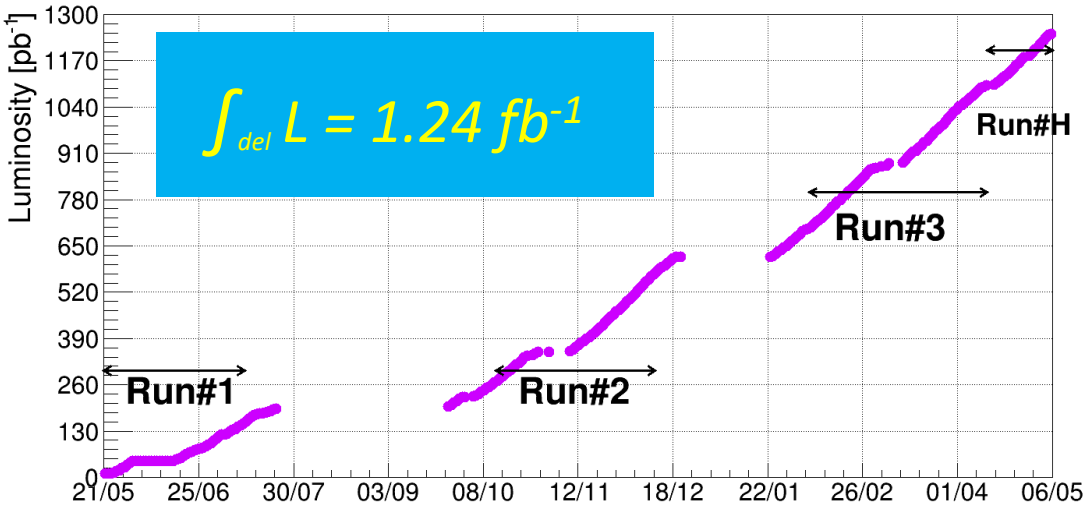
A signal to noise ratio 3 time higher w.r.t. the 2009 run was achieved.



SIDDHARTA-2 Total Integrated Luminosity

DATE	L_{acq} [pb^{-1}]	L_{acq} [pb^{-1}] $L_{HQ}\geq 0.6$	Good Data %
Run-1 (21/05/23 ÷ 21/07/23)	196	164	84
Run-2 (13/10/23 ÷ 11/12/23)	344	276	80
Run-3 (06/02/24 ÷ 12/04/24)	435	375	86
Run-H for calibration (12/4/24 ÷ 6/5/24)	153	140	91,5
Total	1128	955	85

The fraction of high-quality data increased significantly along the time thank to collider adiabatic tuning, and machine studies.



Kaonic deuterium X-ray transition was observed for the first time, results are under pubblication

DAΦNE Performances Summary

Instantaneous peak Luminosity achieved at DAΦNE is about an order of magnitude higher than the one obtained at other colliders operating in the low energy range.

	DAΦNE KLOE native (2005)	DAΦNE CW upgrade tested with SIDDHARTA (2009)	DAΦNE (CW) KLOE-2 (2014)	DAΦNE (CW) SIDDHARTA-2 (2024)
L_{peak} [$cm^{-2}s^{-1}$]	$1.50 \cdot 10^{32}$	**$4.53 \cdot 10^{32}$**	**$2.38 \cdot 10^{32}$**	**$2.4 \cdot 10^{32}$**
I^- [A]	1.4	**1.52**	**1.18**	**1.29**
I^+ [A]	1.2	**1.0**	**0.87**	**0.887**
ε_x [mm mrad]	0.34	**0.28**	**0.28**	**0.28**
$N_{bunches}$	111	**105**	**106**	**110**
$\int_{1h} L$ [pb^{-1}]	0.4	**0.79**	**0.67**	**0.41**
$\int_{day} L$ [pb^{-1}]	9.8 (seldom)	**14.98**	**14.3**	**9.37**
$\int_{1h} L$ [fb^{-1}]	3.0		**6.8**	1.24
ξ_y	0.0245	0.0443 (0.09 w.s.)	--	--

Advanced Accelerator Physics Studies

R&D

- Low impedance vacuum chamber components;
- Sophisticated feedback systems, in constant evolution;
- Improved Wigglers magnetic field quality by shimming poles then implementing in «wiggling» poles;
- Parasitic crossings compensation by wires, used for FINUDA, KLOE in the native configuration (*C. Milardi et al.,* physics/0607129.
  Conf.Proc. C060626 (2006) 2808-2810.

- e-Cloud clearing electrodes, installed for the KLOE-2 run
- Crab Waist collision scheme

Tests

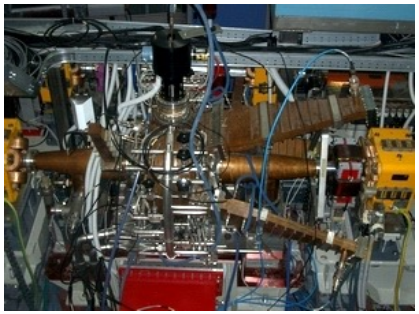
- Collisions with a very high crossing angle
- Collisions with negative momentum compaction factor *(M. Zobov, C. Milardi et al., physics/0607036)*

Proposals

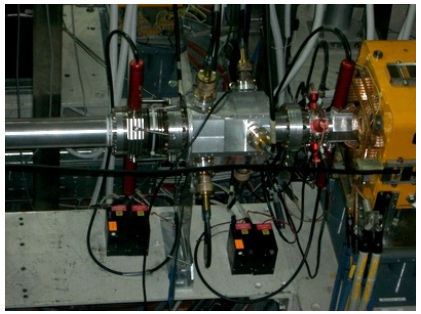
- Strong RF focusing (*A. Gallo et al., EPAC 2004, Lucerne*)
- Variable Energy collider

Vacuum Components

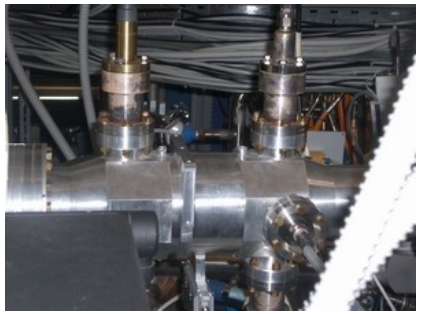
Optimized to avoid heating, reduce impedance, and damp HOM



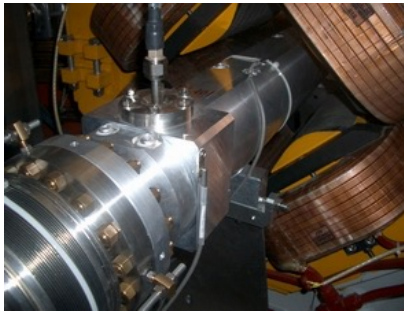
RF CAVITY



LONGITUDINAL KICKER



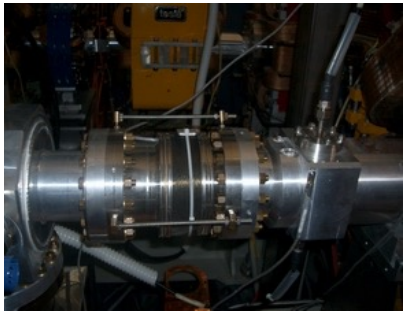
TRANSVERSE KICKER



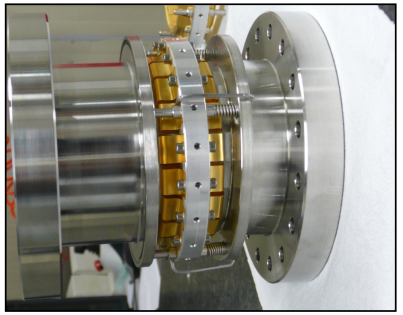
INJECTION KICKER



WALL CURRENT & DCCT MONITOR



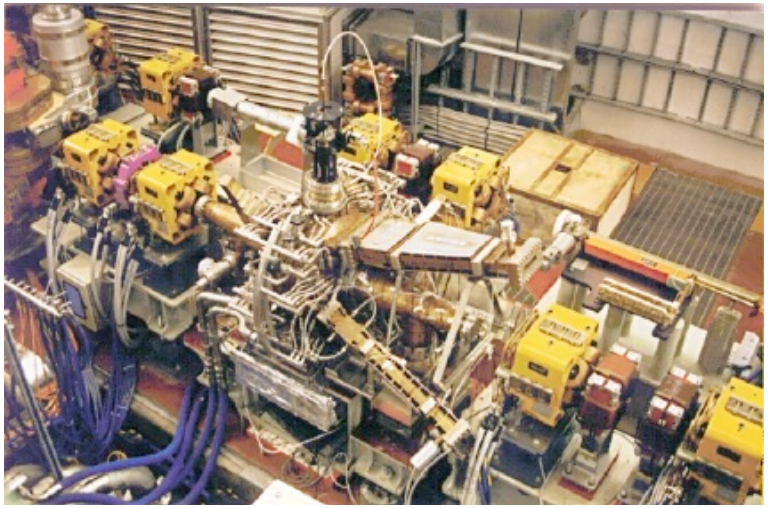
SHIELDEDBELLOWS

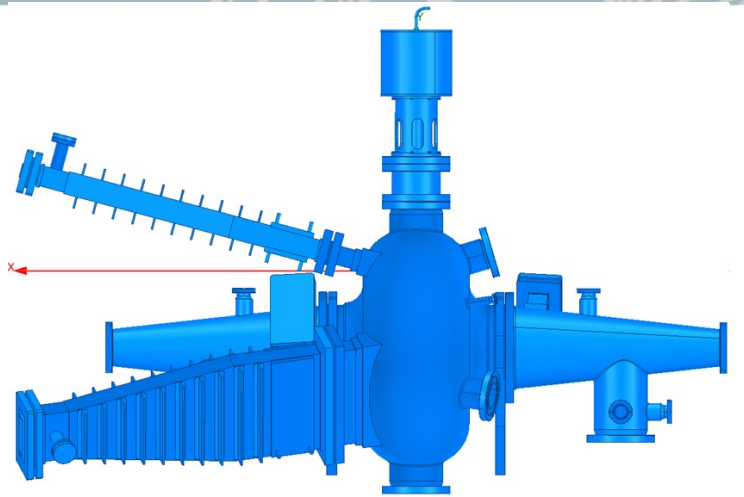


Ω SHIELDEDBELLOWS

DAΦNE Impedance budget is a factor 80 lower than in a similar storage ring (EPA at CERN).

DAΦNE RF Cavity



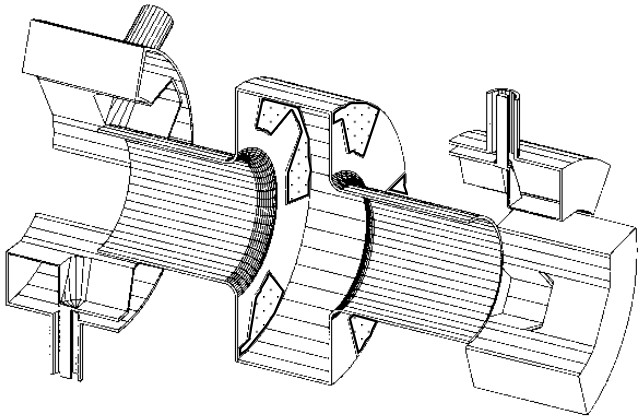


Main Design Features

- 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

R. Boni et al., *EPAC 96* Sitges, Spagna.

Longitudinal Feedback Kickers





Purpose:

used to provide correction 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

Successful Experience in:

DAFNE, KEKB, BESSYII, PLS, SLS, HLS, ELETTRA, KEK Photon Factory, Duke storage ring..
PEP-II (upgrade, December 2003)
SPEAR-3, CESR (considered)

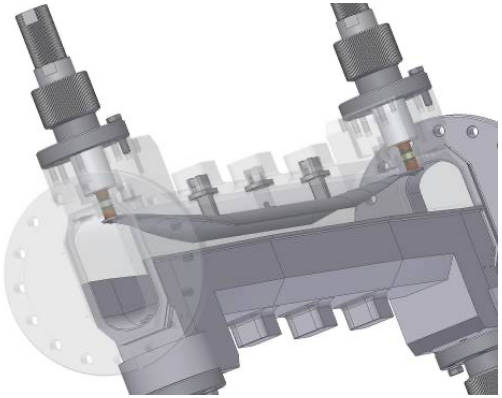
A. Drago et al., Part. Accel. 52: 95-113, 1996
(80 citations in HEP)

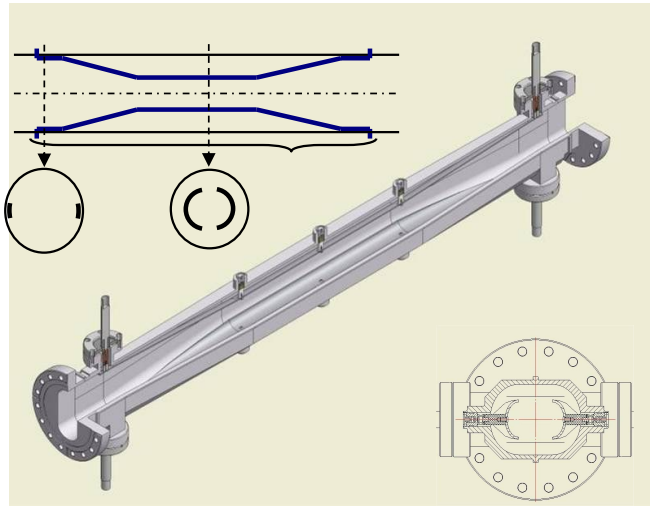
DAΦNE New Injection Kickers

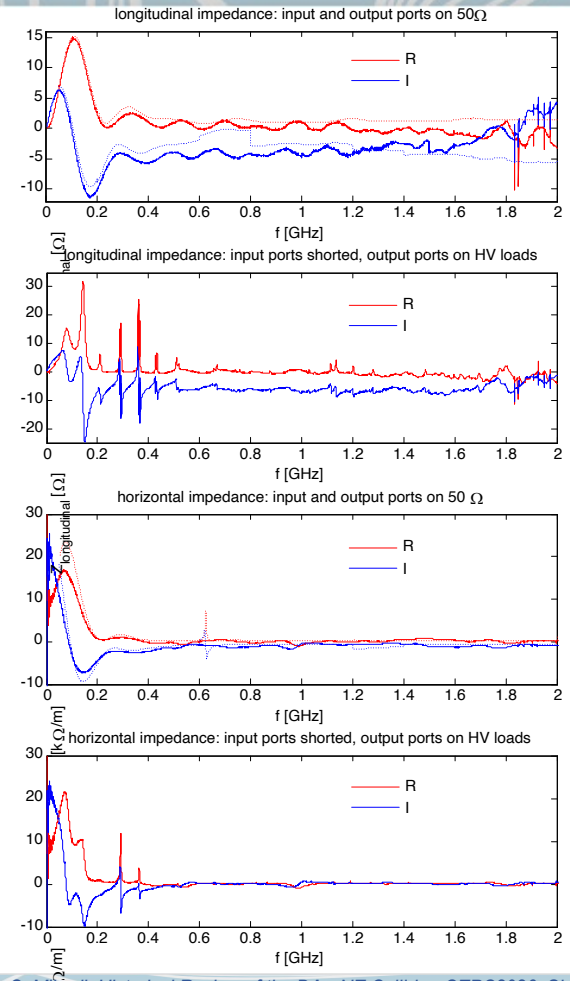
In 2010 Injection kickers have been replaced with new designed device in order to:

- overcome heating,
- reduce impedance,
- Improve colliding beams stability during injection,
- Reduce injection background to reduce acquisition veto.

Same kickers used also for transverse Feedback







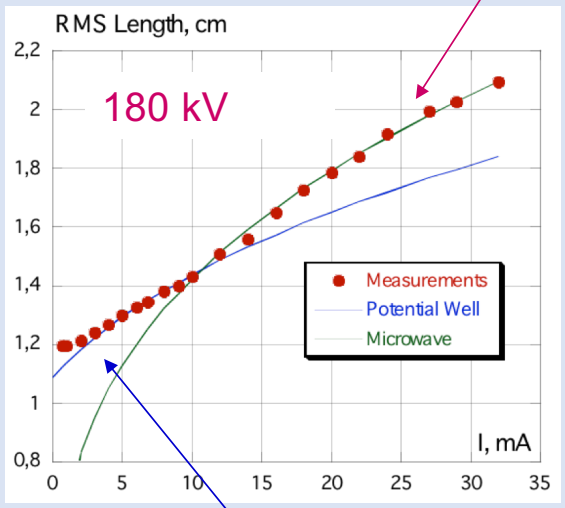
D. Alesini et al., Phys.Rev.ST Accel.Beams 13 (2010) 111002
DOI: 10.1103/PhysRevSTAB.13.111002

Bunch Length Measurements

*Numerical fits for both the microwave regime and the potential well regime give the same value of the **coupling impedance of 0.3 Ω** in the e⁻ ring and **0.34 Ω** in the e⁺ ring.*

Microwave Regime →

$$\sigma_z = R\left(\frac{2}{\pi}\right)^{1/6}\left(\frac{2\pi I}{hV_{RF}\cos\phi_s}\right)^{1/3}\left|\frac{Z}{n}\right|^{1/3}$$



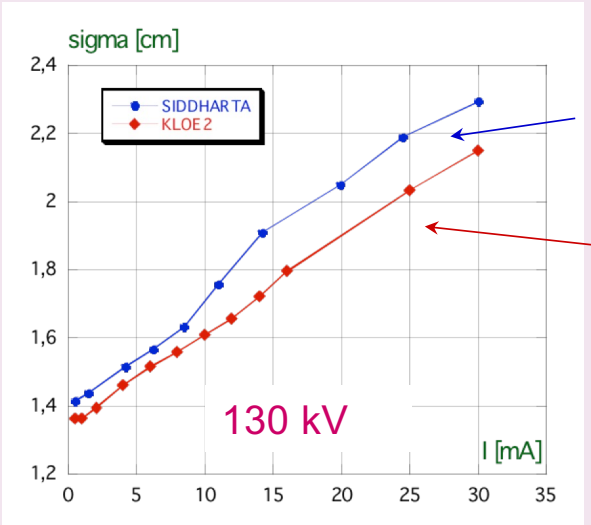
$$\left|\frac{Z}{n}\right| \approx 0.3\Omega$$

e⁻

$$\left(\frac{\sigma_z}{\sigma_{z0}}\right)^3 - \left(\frac{\sigma_z}{\sigma_{z0}}\right) - \frac{\alpha_c I}{\sqrt{2\pi}Q_{so}^2(E/e)}\left(\frac{R}{\sigma_{z0}}\right)^3\left|\frac{Z}{n}\right| = 0$$

← Potential Well

e⁺



SIDDHARTA

KLOE-2

The coupling impedance of the positron ring is also lower now despite the ECE

e^+ Beam Dynamics

Positron beam dynamics are dominated by the e-cloud effects, causing:

- vertical beam size increase,
- tune shift along the batch,
- anomalous vacuum pressure rise,
- occasionally quadrupole instability.

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
Multi-bunch 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	$2 \cdot 10^{10}$

e-cloud mitigation techniques

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

Devices

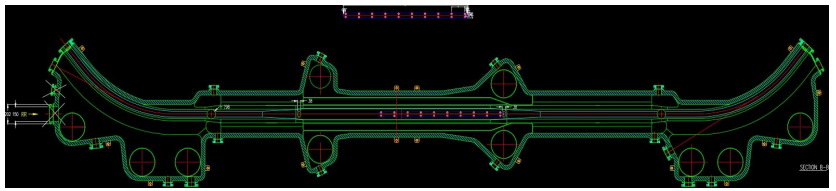
- solenoid windings
- powerful feedback system
- electrodes (**developed for KLOE-2 run**)

Tuning ring and beam parameters

- moving ξ_x ξ_y to higher positive values
- lengthening the bunch by reducing the RF voltage
- Providing Landau damping by octupole magnets

Maintaining optimal dynamic vacuum

- more frequent sublimations

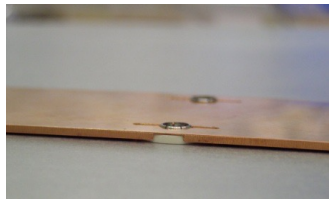


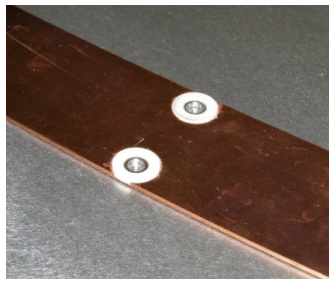
E-Cloud Clearing Electrodes

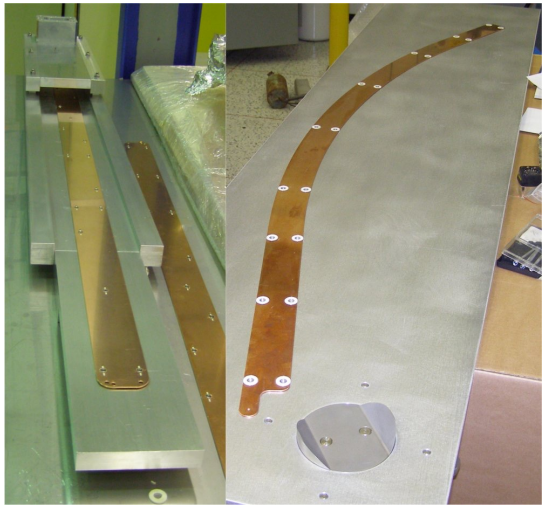
Installed for the KLOE-2 run

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.



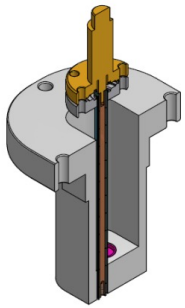


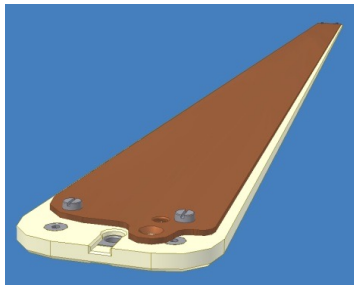


(M. Zobov et al., arXiv:1306.5944 [physics.acc-ph])









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.

Clearing electrodes for *e-cloud* suppression

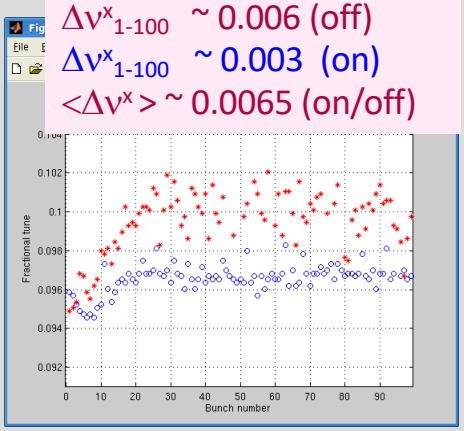
DAΦNE was the first collider operating routinely with long electrodes, for e-cloud mitigation.

Electrodes let more stable operation with the positron beam and allowed unique measurements such: *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.

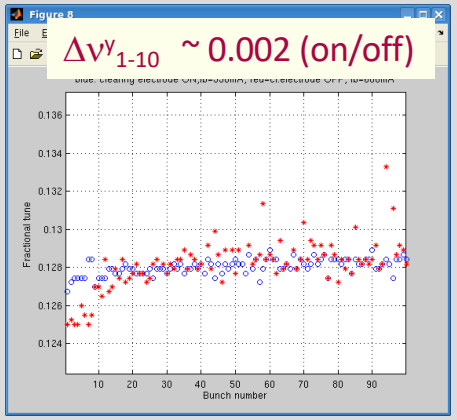
(D. Alesini et al, Phys. Rev. Lett. 110, 124801 (2013)

Tune Shift measurements

$\Delta\nu^{x}_{1\text{-}100}$ ~ 0.006 (off)
$\Delta\nu^{x}_{1\text{-}100}$ ~ 0.003 (on)
$\langle\Delta\nu^{x}\rangle$ ~ 0.0065 (on/off)

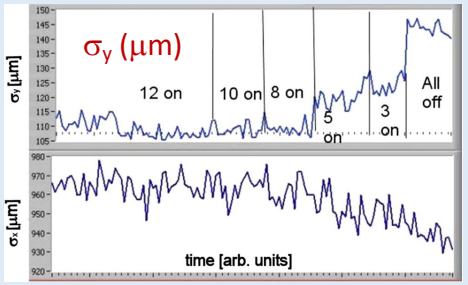


$\Delta\nu^{y}_{1\text{-}10}$ ~ 0.002 (on/off)



At the end of the KLOE-2 run only 2 out of the 12 devices were working properly, none of them was in the wigglers.
High current operations have still been possible thanks to the scrubbing process

Vertical Beam Size



e^- Beam Dynamics

At regime the maximum e^- beam currents stored in collision was mainly limited by:

- ion in the residual gas,
- impedance induced effects (TMCI),
- sporadic vacuum activity in the IR,
- occasionally by quadrupole instability.

Ions are neutralized introducing a suitable gap in the batch,
transverse V feedbacks helps in keeping under control ions related instability.

As dynamical vacuum was improving filled bunches have been progressively increased the range of 90 ÷ 111 with the same total current, thus reducing:

- Touschek contribution to the background,
- the impact of the microwave instability threshold.

Best machine performances have been achieved through collisions of 105 -111 consecutive bunches.

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

Beam current limits observed

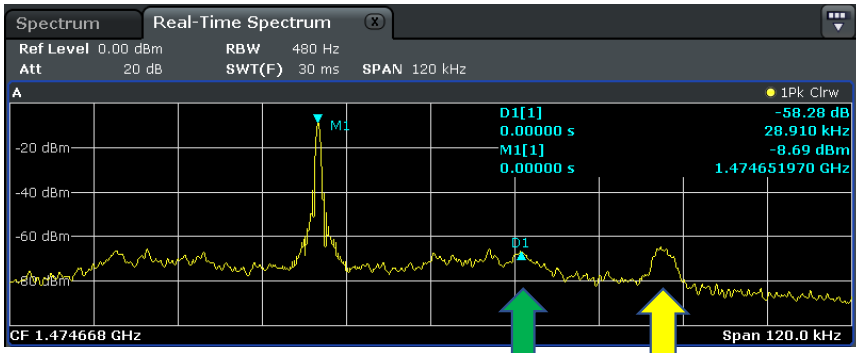
- noise coming from pickups (harmful for vertical sizes)
- Interplay between longitudinal FBK and LLRF FBK.

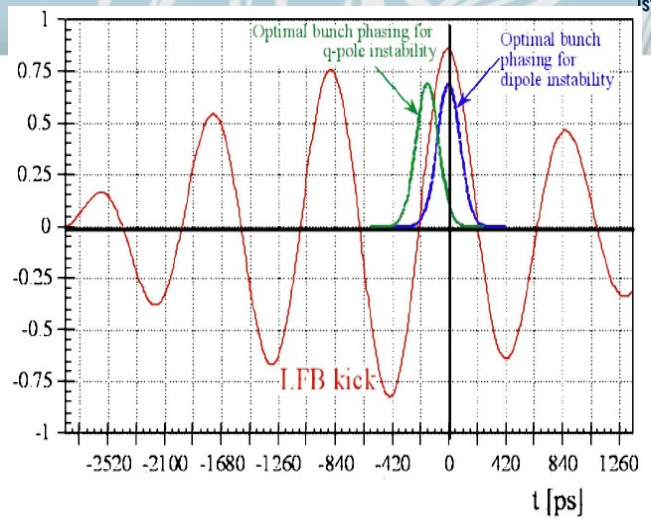
Solutions:

- transverse low noise front-end development,
- iterative fine tuning of the FBK and RF FBK systems in single bunch and in collision.
- longitudinal quadrupole control by a special technique implemented at DAFNE in the dipole feedback system.

Longitudinal Quadrupole Oscillations

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

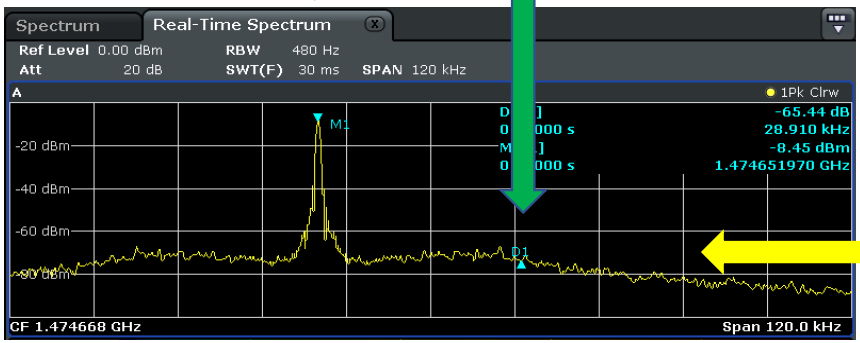




Revolution harmonic

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)

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	1.354 (e^-), 1.8 (e^+)	0.7, 0.5	7	6	
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	

Conclusions

The DAΦNE collider powered physics at the Frascati INFN laboratories for almost 30 years.

In this period DAΦNE continued to give relevant contributions to the field of circular storage rings, and assured high quality data samples to high energy, and nuclear physics experiments.
The experiments realized at DAFNE achieved unique results in the relative field of interest.

The Crab-Waist Collision Scheme implemented and tested and successfully tested at *DAΦNE*, with detectors of different complexity proved to be able to increase the luminosity up to a factor 3.
The peak luminosity measured at DAFNE is still today an order of magnitude higher than the one measured in colliders operating at comparable energy.

***The Crab-Waist Collision Scheme was* implemented, and tested in about two years**

The Crab-Waist Collision Scheme became a reference design concept for any future lepton collider.

Let me thank all the colleagues who have been, part of this fantastic ad challenging adventure.

Presently the collider is in stand by.

The Crab-Waist Colliders

Colliders	Location	Status
DAΦNE	Φ-Factory Frascati, Italy	In operation (SIDDHARTA, KLOE-2, **SIDDHARTA-2**)
SuperKEKB	B-Factory Tsukuba, Japan	Adopted CW collision in 2020 *World Luminosity record*
SuperC-Tau	C-Tau-Factory Sarov, Russia	Russian mega-science project
SuperTauCharm	Tau-Charm Factory Hefei, China	Proposed, significant R&D funding
FCC-ee	Z,W,H,tt-Factory CERN,Switzerland	91 km, CDR
CEPC	Z,W,H,tt-Factory China	100 km, CDR released in September 2018
Z-Factory	Novosibirsk, Russia	Under study

Thank You



Spare Slides

DAΦNE Stored currents in collision

	DAΦNE KLOE (2005)	DAΦNE FINUDA (2006)	DAΦNE CW SIDDHARTA (2009)	DAΦNE CW KLOE-2 (2014)
L_{peak} [$cm^{-2}s^{-1}$]	$1.5 \cdot 10^{32}$	$1.6 \cdot 10^{32}$	**$4.36 \cdot 10^{32}$**	**$2.38 \cdot 10^{32}$**
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

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 instability threshold above I_b~10 mA •
- maximum intensity was lower wrt the past •

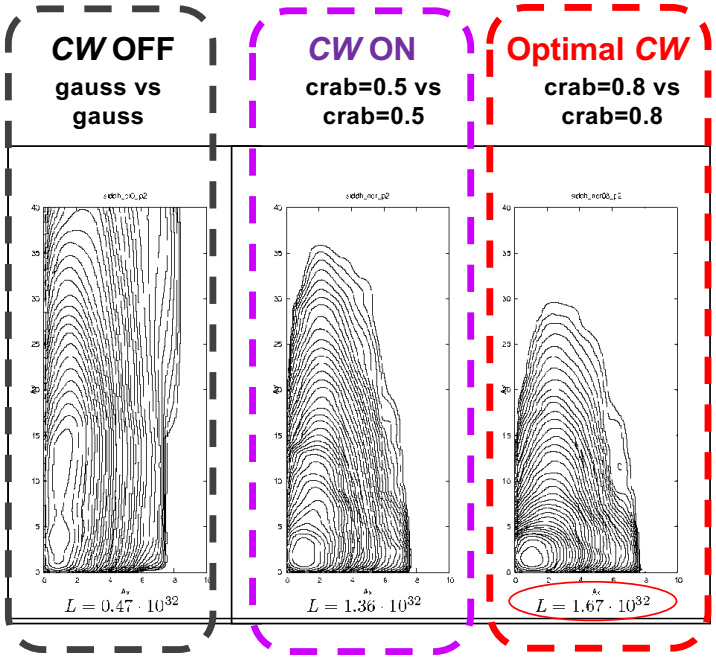
These experimental findings are likely due to:
- new FBK and damp KCKs
- new tapered transition in the IP beam pipe
- modified collimator vacuum chamber
- limited power for the RF klystron
- modified wigglers

Weak-Strong Simulations

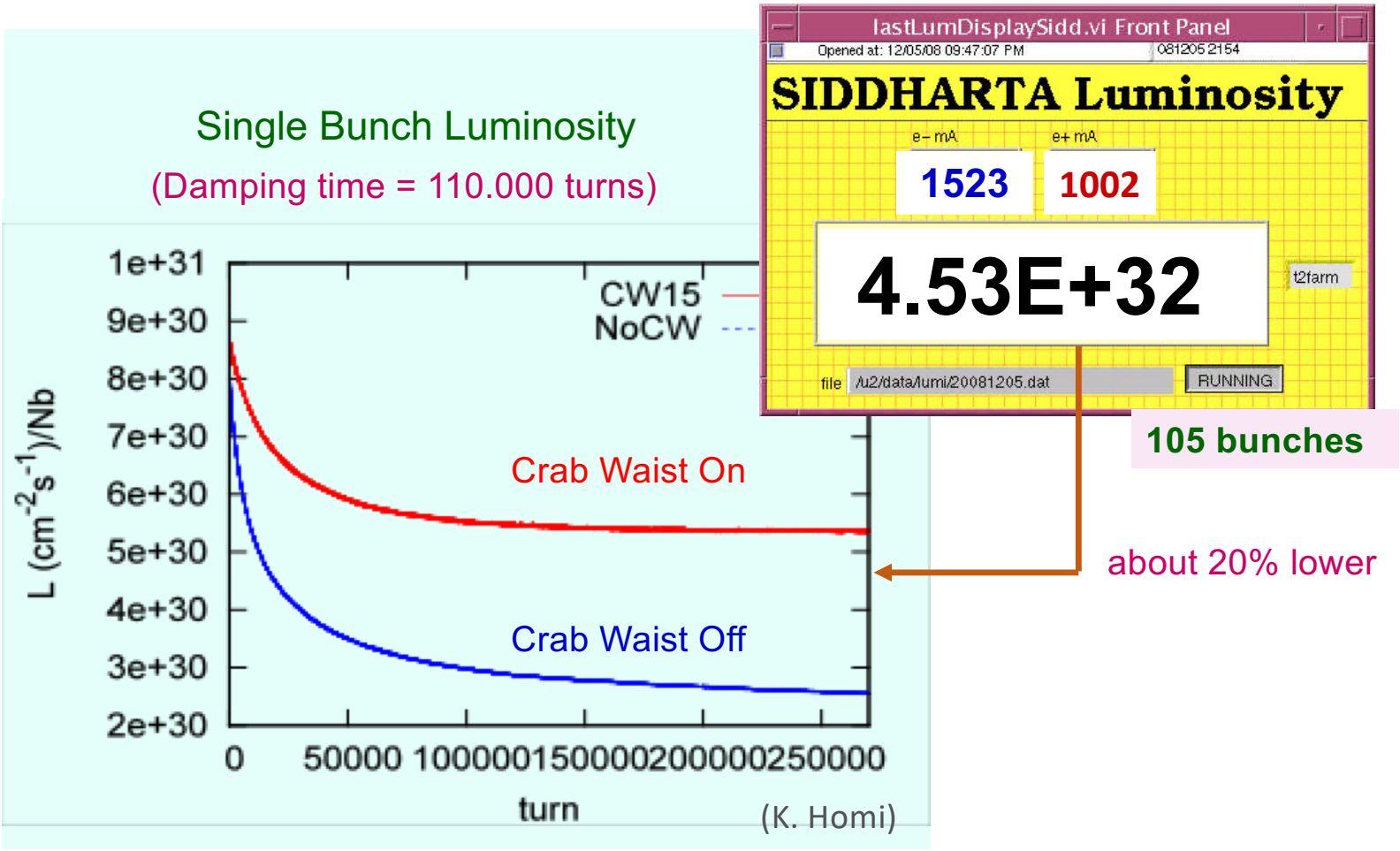
Crab-Waist compensation works in weak-strong regime also, and measured luminosity is in good agreement with *Lifetrack* code (D. Shatilov) predictions.
Electron beam is strong beam, and the crabbed one.



$\xi_y = 0.09$



Strong-Strong Beam-Beam Simulations



Limiting Factors during KLOE-2 Run

Maximum currents in collision were considerably lower than the ones used during the previous DAΦNE runs. Such current reduction can be estimated to be of the order of 30% and 20% for the electron and the positron beam respectively.

Concerning the **e^+ current, it was strongly dominated by the e-cloud effects** mitigated by using solenoidal winding around the beam pipe, clearing electrodes and feedback systems. DAΦNE was the first collider to operate with and thanks to the ECE.
It would have been necessary to do longer dedicated scrubbing runs.

In general e-/e+ beam dynamics was affected by the several new components installed on the two rings during the preparatory phase for the KLOE-2 run:

- new e-cloud electrodes were added in the e^+ ring;
- the new kicker developed for the transverse horizontal positron feedback was also used for the horizontal electron feedback, and for beam dumpers, thus adding a new kicker per ring;
- the IP vacuum chamber was replaced with a new section having a slightly different mechanical design;
- the rectangular vacuum chambers of the collimators close to the IP, the most effective ones, was replaced with chambers of reduced volume, in order to increase the blade insertion length;
- the four wigglers installed in each ring were modified to reduce the higher order multipoles of the magnetic field, and by removing a purpose built-in sextupole component, which was efficiently used to implement a smooth and distributed chromaticity control;
- low level and high-power sections of the main rings RF cavities were modified to reduce power consumption.

C. Milardi et al., A Review of DAΦNE Performances during the KLOE-2 Run, TUYGBD2, IPAC'18, Vancouver, Canada.

DAΦNE Beam Pipe Composition

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

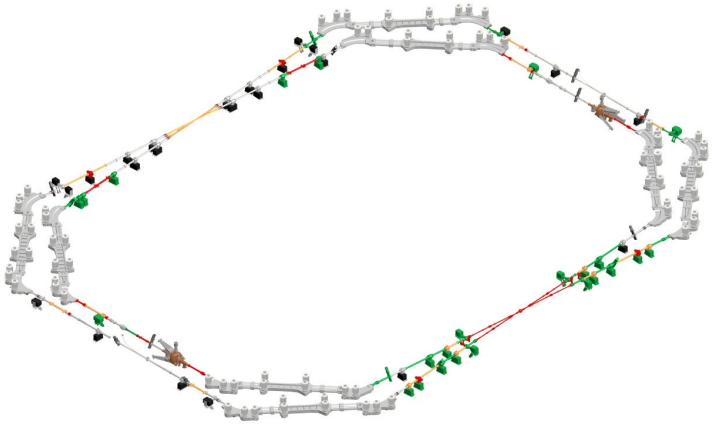
The 8 large vacuum chamber of the arcs are in **AL 5083 H321** (Al - Mg)

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

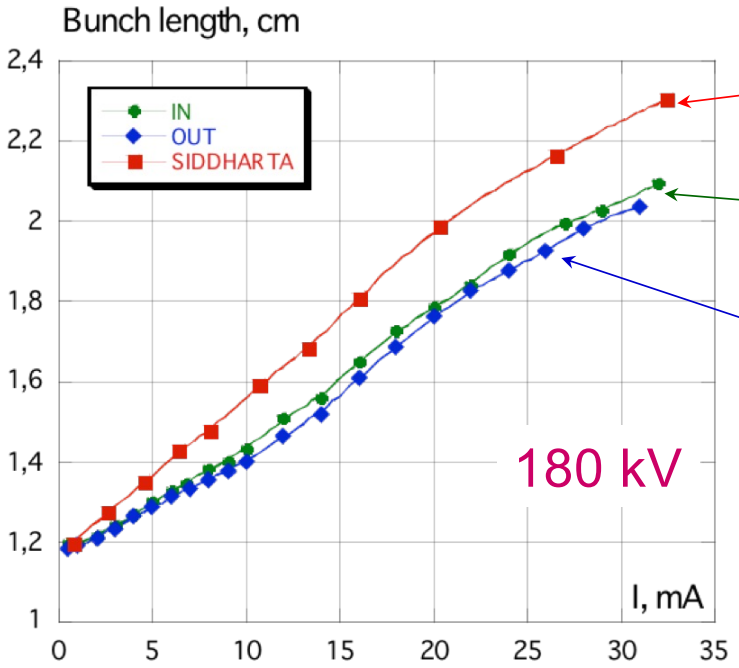
Straight section beam pipes are made by **AL 6082 T6** (Al - SI)



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

Bunch Lengthening in the Electron Ring

Electron bunches now are shorter due to lower coupling impedance.
The impedance contribution of the scrapers is relatively small.



SIDDHARTA run (2007)

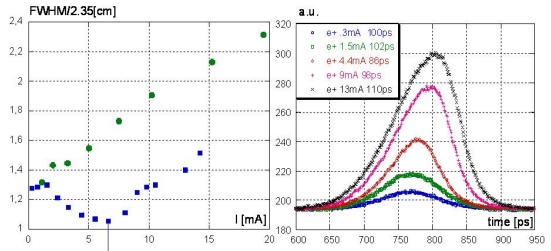
KLOE-2, all scrapers in

(2014)

KLOE-2, all scrapers out

Experience with $\alpha_c < 0$ at DAΦNE

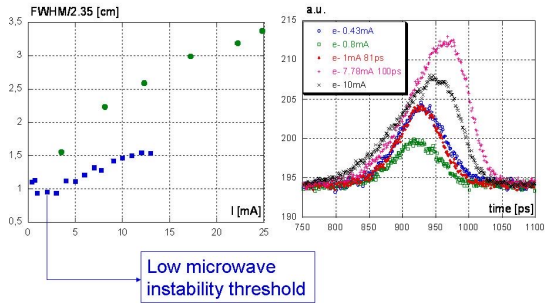
Bunch Shortening in the Positron Ring



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

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

Bunch Shortening in the Electron Ring



Low microwave instability threshold

Experimental Results

- DAΦNE flexible optics

  $-0.036 \leq \alpha_c \leq +0.034$

- Bunches shorten as predicted by numerical simulations.
- It was possible to store high bunch current with large negative chromaticity

  I_b ~40 mA

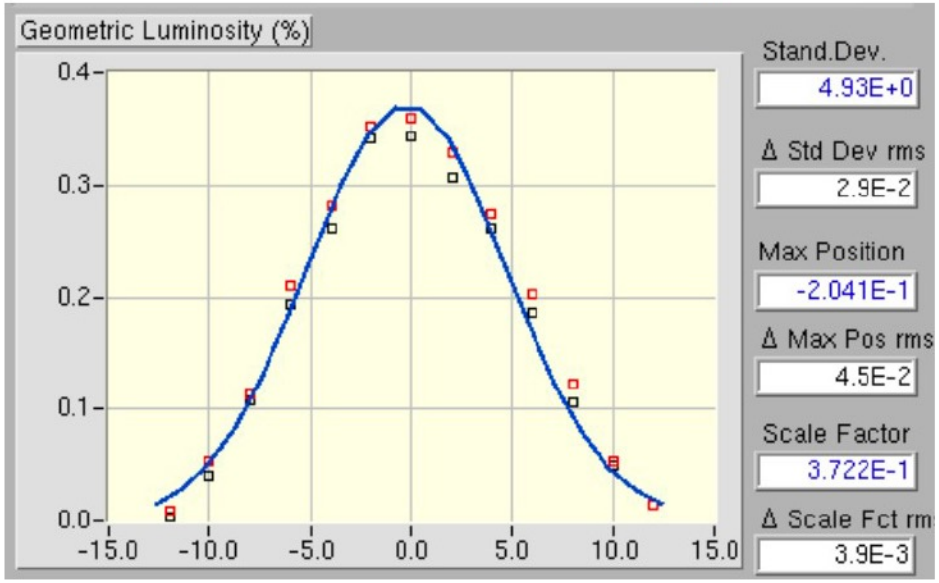
- Stable multibunch beams with ***I > 1 A***
- **Specific luminosity gain of about 25%** till 300 mA per beam without SXTs
- Higher current beam-beam collisions failed due to s_y^- above the microwave instability threshold

Collisions with $\alpha_c < 0$ have tested for the first time at DAΦNE

(M. Zobov, C. Milardi et al.. physics/0607036)

Beam-Beam Scan

Beam-Beam scan with calibrated bump



80 bunches

$I^- = 73$ mA

$I^+ = 75$ mA

$$\Sigma_y^{meas} = \sqrt{\sigma_{y+}^2 + \sigma_{y-}^2}$$

$$\Sigma_y = \Sigma_y^{meas} * 0.88$$

$\Sigma^{meas}_y = 5.0\ \mu m$

$\sigma_y = 3.1\ \mu m$

Scan provides a clear evidence of optimal beam-beam interaction