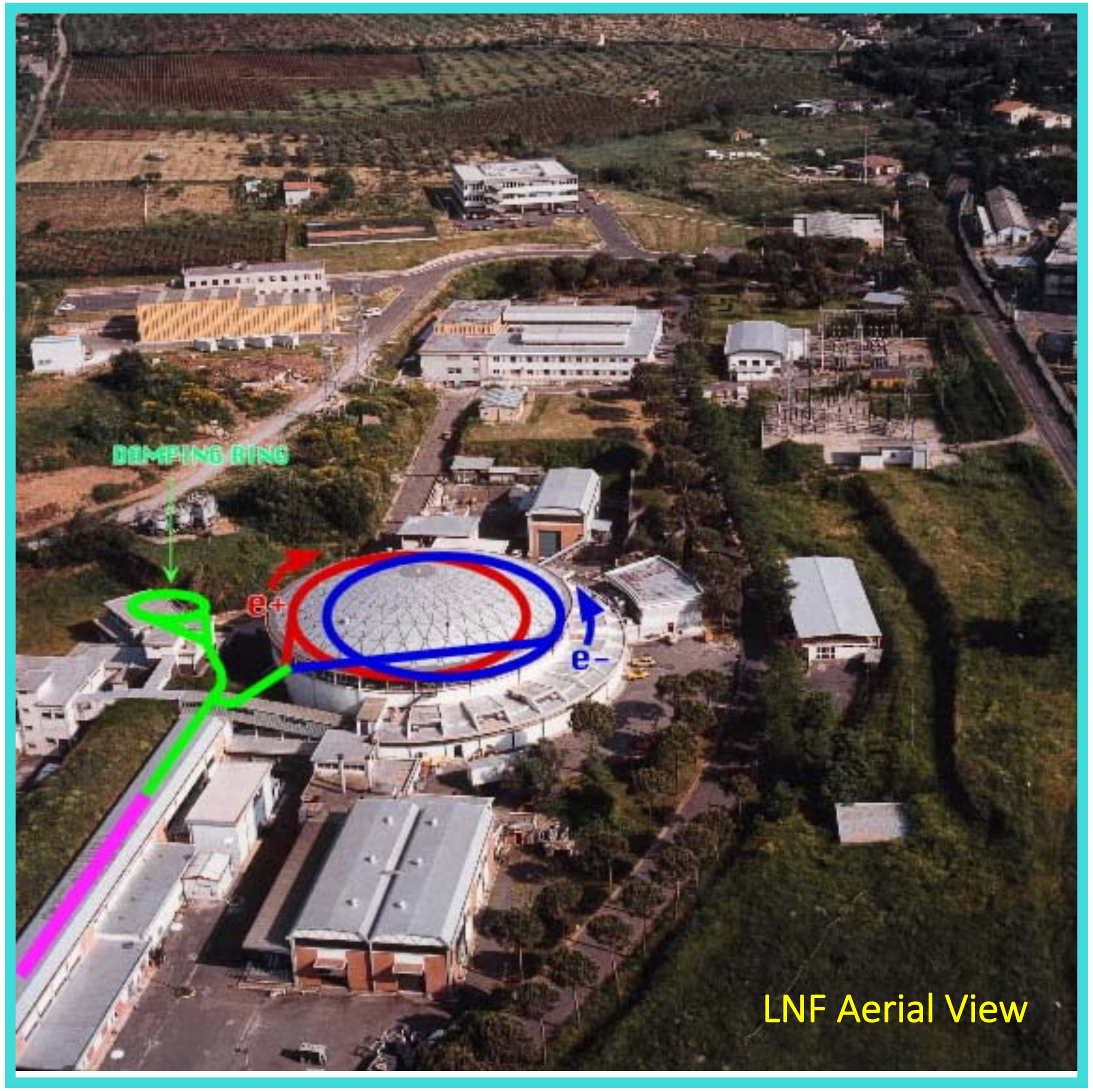
DAΦNE collider,
Operational Experience during KLOE-2 and SIDDHARTA-2 runs

Catia Milardi
on behalf of the DAΦNE Team



Outlines

Summarizing more than 10 years of activity in a short time is rather difficoult.

Concerning KLOE-2 and SIDDHARTA-2 operation experience it's probably more useful to highlight:

- design solution adopted during the different run preparatory phases,
- the upgrade interventions aimed at removing and/or mitigating limiting factors,
- the more relevant unexpected problems encountered during commissioning and operation the different setups,
- concluding revising the machine performances in terms of luminosity and data taking efficiency.

DAΦNE History

- DAΦNE is an electron-positron collider designed in the mid ‘90s, it came into stable operation in 2001.
- It was providing data in independent data-taking periods to:

KLOE, **DEAR** and **FINUDA** experiments until 2007, delivering ~

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.

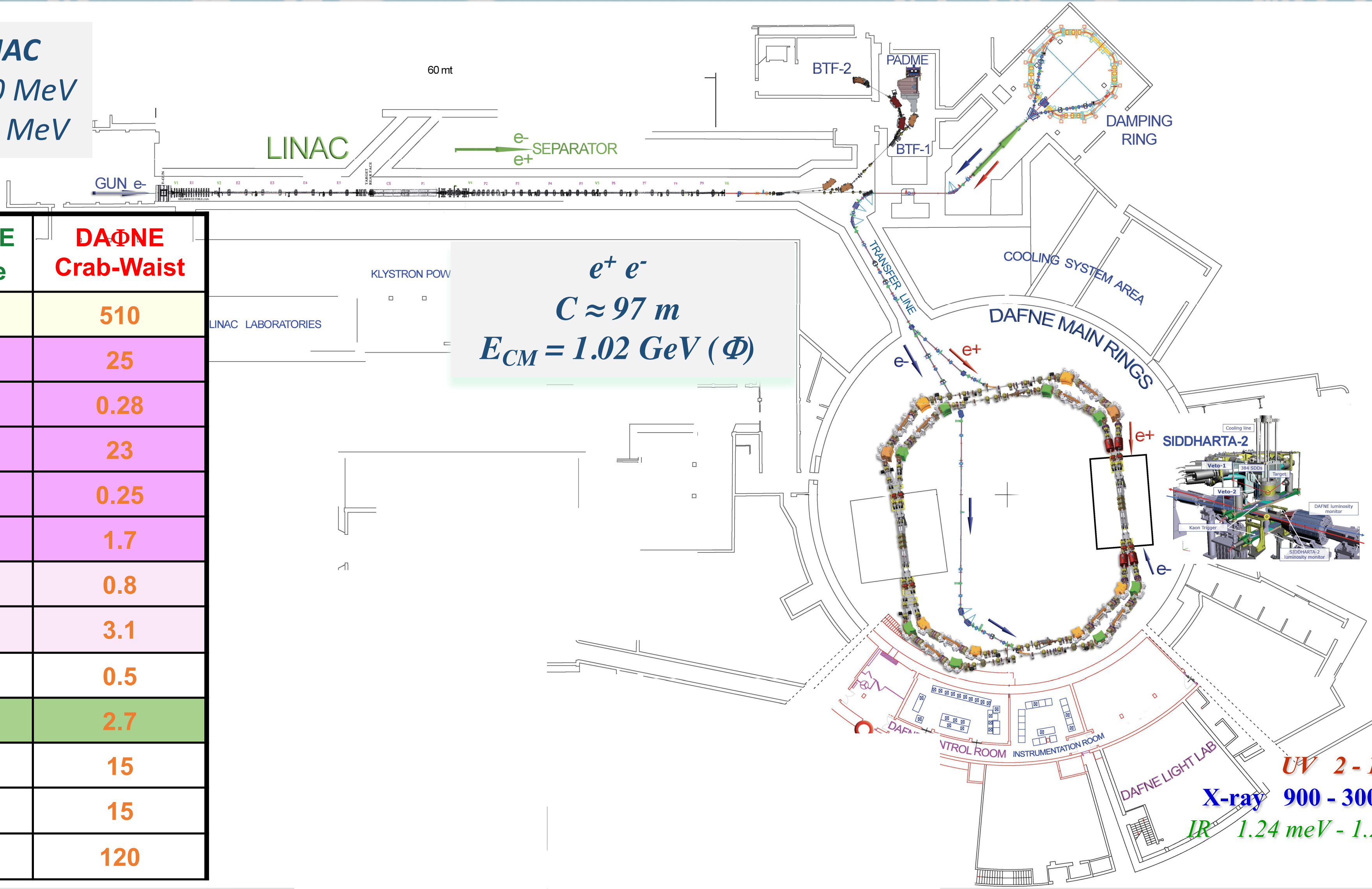
SIDDHARTA-2 **experiment** in 20019 ÷ 2024**,**
DAFNE-light Facility,
DAΦNE LINAC is securing data to two **BTF lines,** and the **PADME** experiment.

Presently DAΦNE LINAC is providing physics for PADME only.

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. ***mitigated in the IR***
- *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.

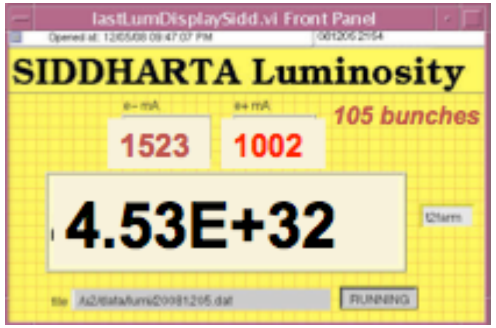
DAΦNE Performances Optimization Strategy

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.

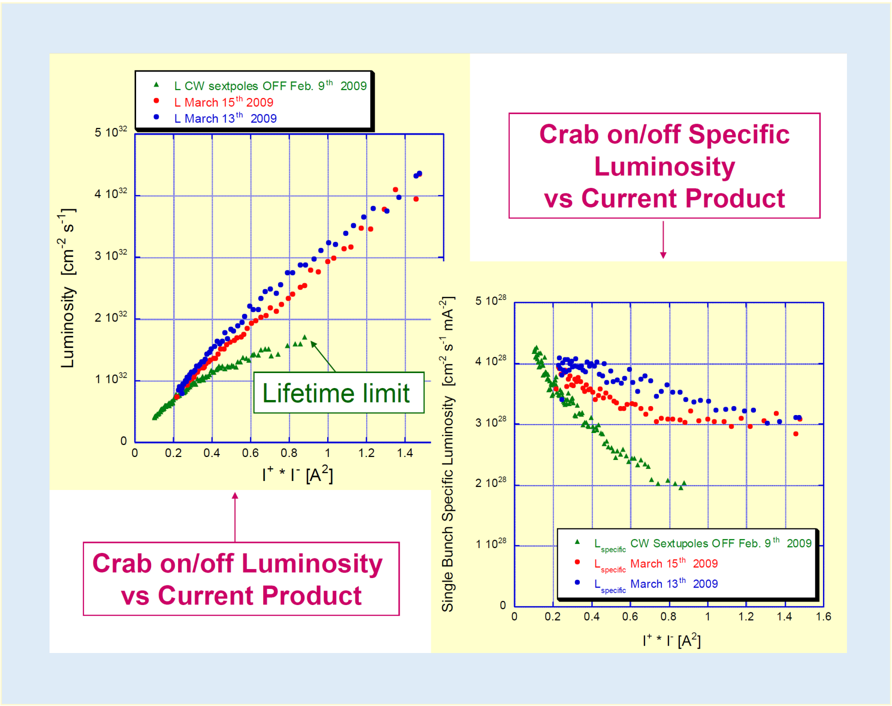
Crab-Waist Collisions Test Run Results

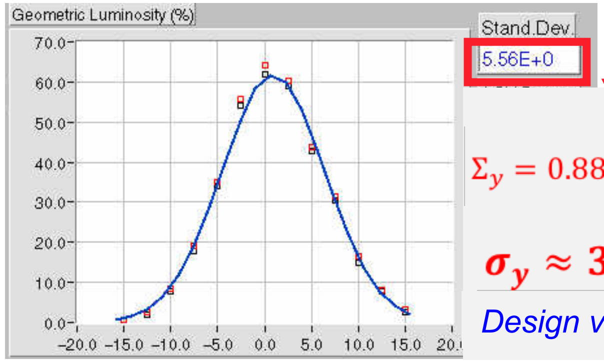
SIDDHARTA Run
(2007 – 2009)



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}
$L_{\int run}$~ 2.8 fb^{-1} (delivered in 18 months)

- 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.

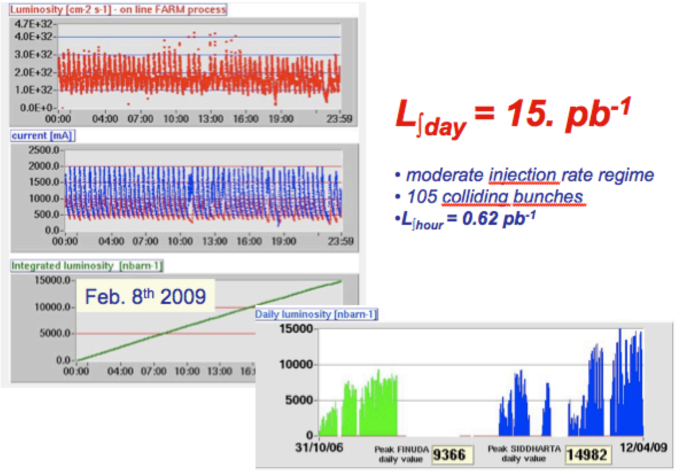




$$\Sigma_y = 0.88\sqrt{\sigma^2_{Ypos} + \sigma^2_{Yele}}$$

$$\sigma_y \approx 3.5\mu m$$

Design value 3.1μm



$L_{\int day}$ = 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.

KLOE-2 run with the *Crab-Waist*
Collision Scheme

CW-Collision for the KLOE-2 detector

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 for***: mechanic setup, cooling, IR layout, optics, beam acceptance, coupling correction …

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.

DAΦNE Activity Program for KLOE-2

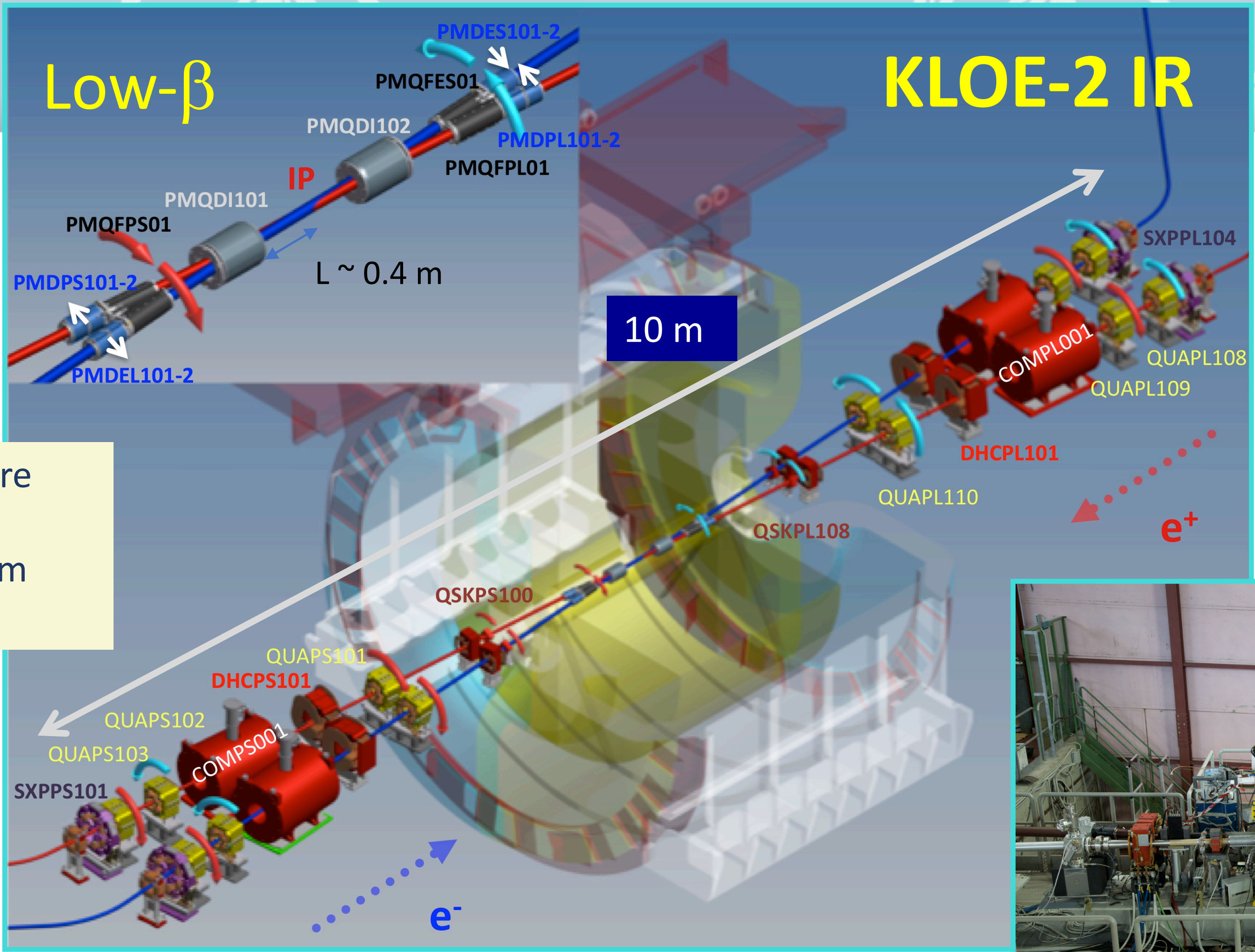
Preliminary Test Phase *fall 2010 ÷ Dec 2012*

Collider Consolidation
KLOE-2 detector layers installed *Dec 2012 ÷ Jun 2013*

(C. Milardi et al. WEOCA03, IPAC14)

KLOE-2 data taking
- I Run *Nov 16th 2014 ÷ Jul 3rd 2015*
- II Run *Spt 28th 2015 ÷ Jun 29th 2016*
- III Run Spt 12nd 2016 ÷ Aug 1st 2017
- IV Run *Spt 6th 2017 ÷ Mar 31st 2018*

(C. Milardi et al., IPAC'18)

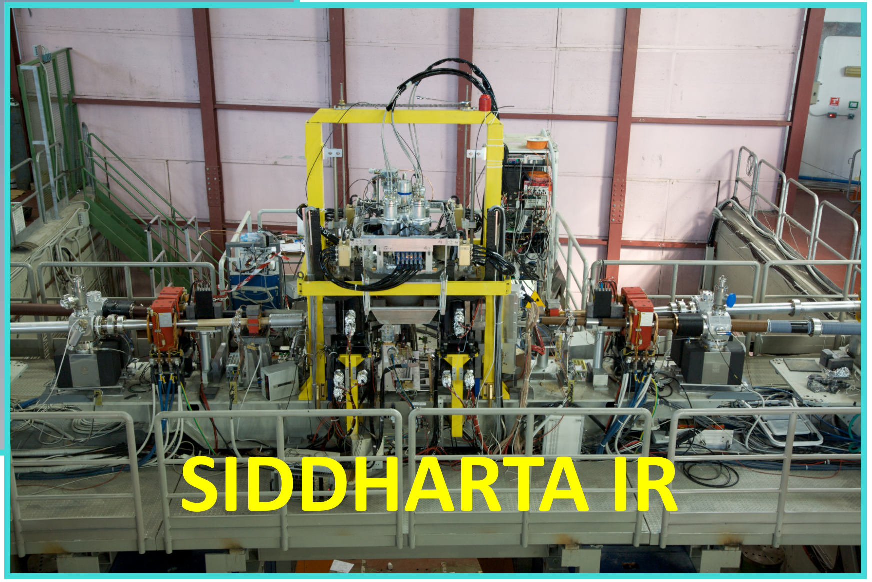


Low-b quadrupoles are made of SmCo alloy:

PMQD = 29.2 T/m

PMQF12.6 T/m

C. Milardi *et al 2012 JINST 7 T03002.*



Beam Trajectory Control in the IR

Doubling crossing angle, and increasing low-β quadrupole strength determined very efficient beam separation, ~ 40 σ_x separation in the ~1.6 m long common IR part.

LRBB were cancelled.

100 contiguous bunch operation became possible.

Due to the detector solenoid field the beam trajectory was strongly perturbed.

To keep under control the beam vertical trajectory a permanent magnet dipole, PMD, was added just after PMQF, inside the detector, in each one of the four IR branches.

Beam pipe of the IR branches was properly shaped to provide stay clear aperture:

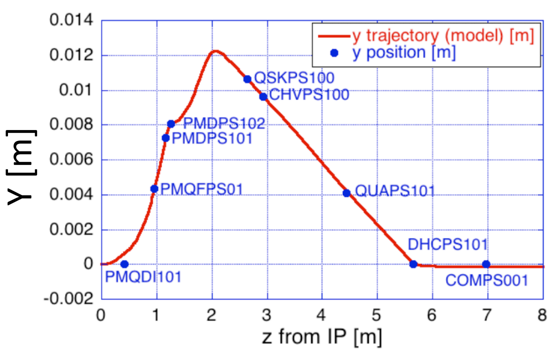
$$X_{SC} = x_{trj} \pm 10\sigma_x \qquad Y_{SC} = y_{trj} \pm 10\sigma_y$$

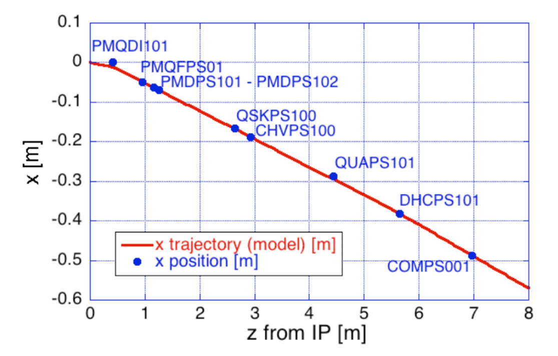
The new beam pipe radius was almost halved (2.75 cm) reducing contribution to ring impedance budget:

- *simplified design and less bellows*
- *less intense trapped HOM,*
- *HOM with frequencies farer from beam spectral lines.*

More space for the new detector layers.

(F. Marcellini et al., IPAC 2007)





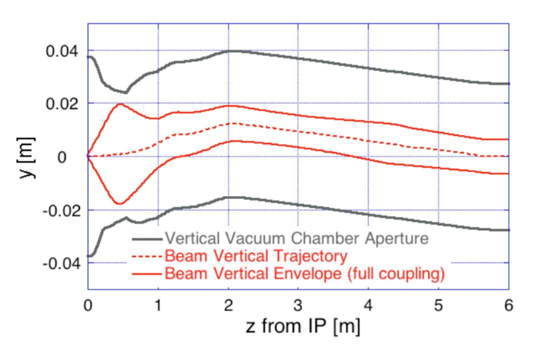


Figure 6. Vertical beam stay-clear aperture in the KLOE-2 IR.

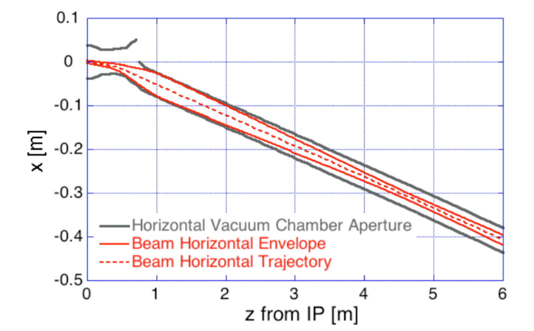
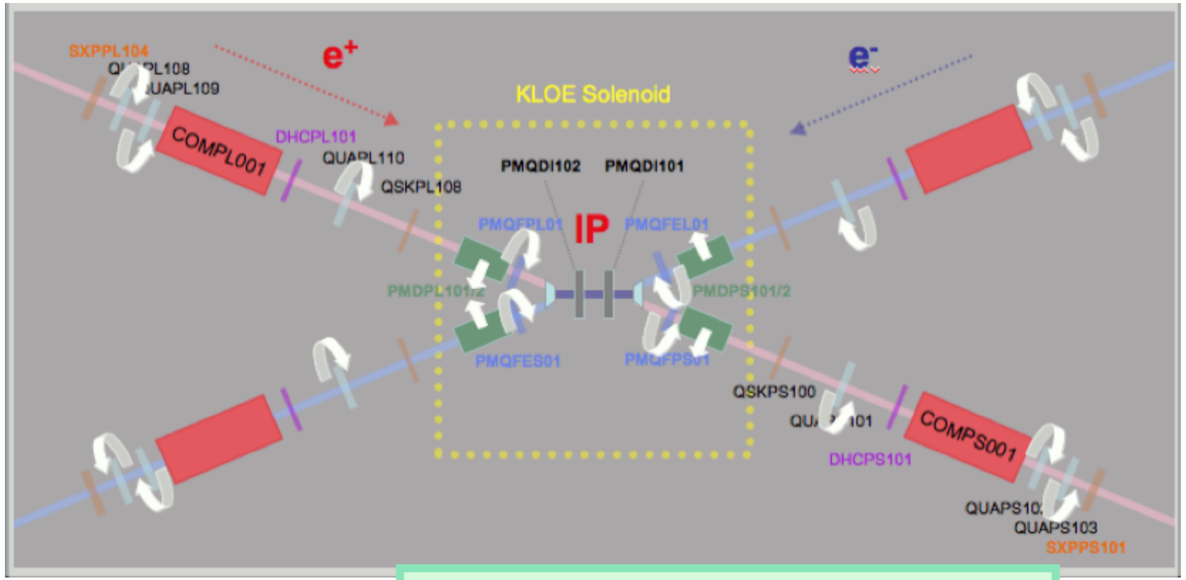


Figure 5. Horizontal beam stay-clear aperture in the KLOE-2 IR.

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•dl canceled by 2 anti-solenoids for each beam

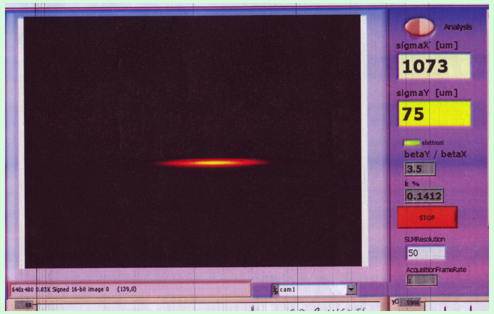
$$\int_{KLOE} B \cdot dl = 2.048 \quad [Tm] \quad \rightarrow \quad I_{KLOE} = 2300.[A]$$

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

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



$\kappa \sim 0.14$ %

Collider modifications in 2009÷2013

Vacuum Components

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

Damping Wiggler Magnets modifications

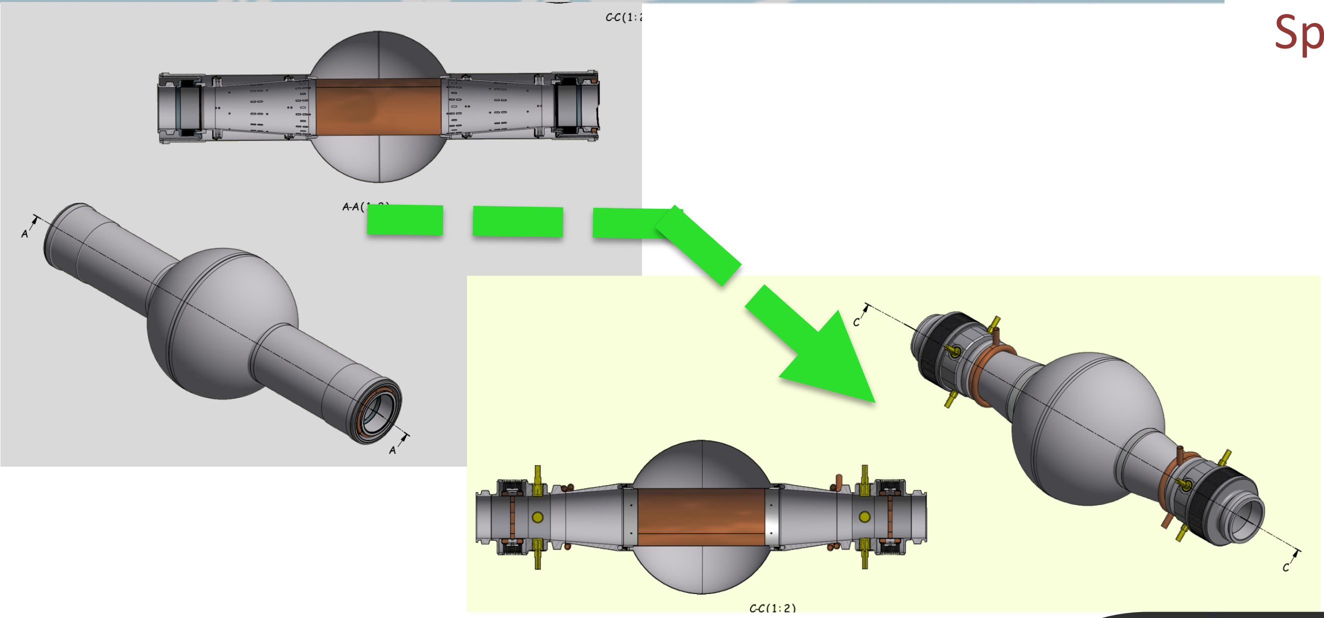
The four wigglers installed in each ring have been modified to reduce the higher order multipoles of the magnetic field, and by removing a purpose built sextupole component, which was efficiently used to implement a smooth and distributed chromaticity control.

RF

Low level and high-power sections of the main rings RF cavities were modified to reduce power consumption.

IP Chamber Consolidation

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

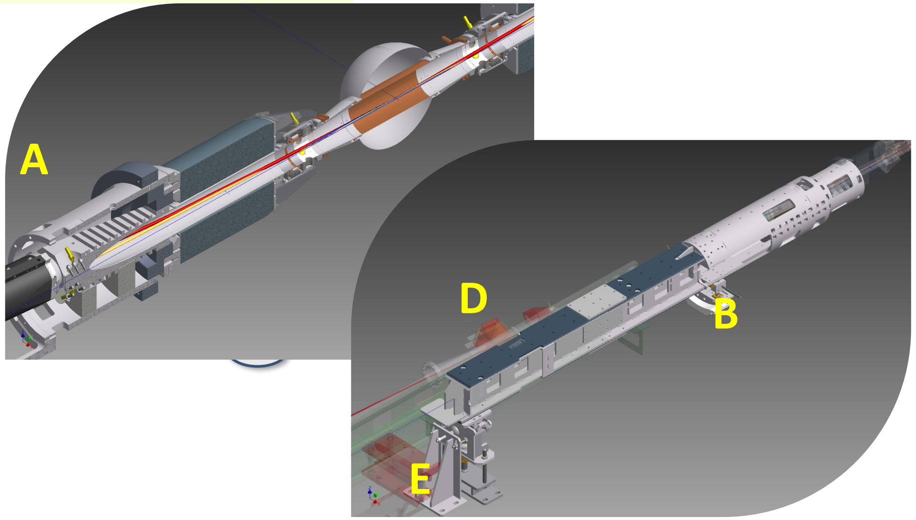


Spherical vacuum chamber evolution

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

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

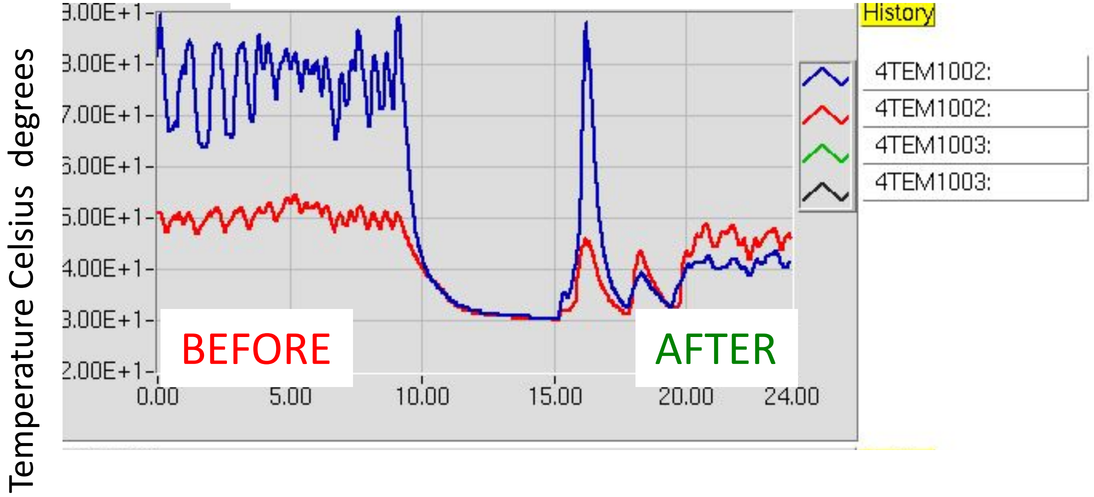


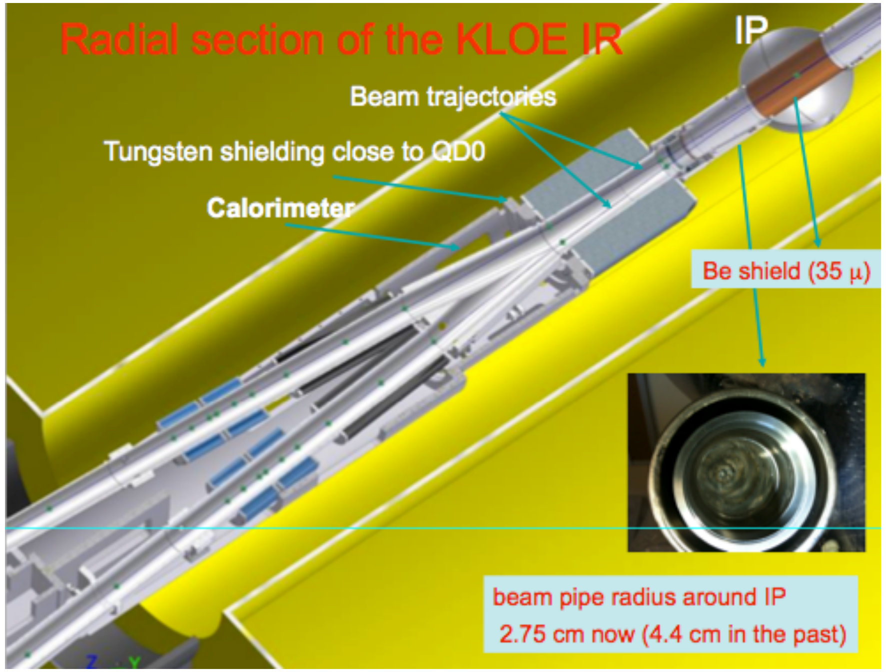
Fault in the IP beam Pipe

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 (Δq_2 ~ 0.04)

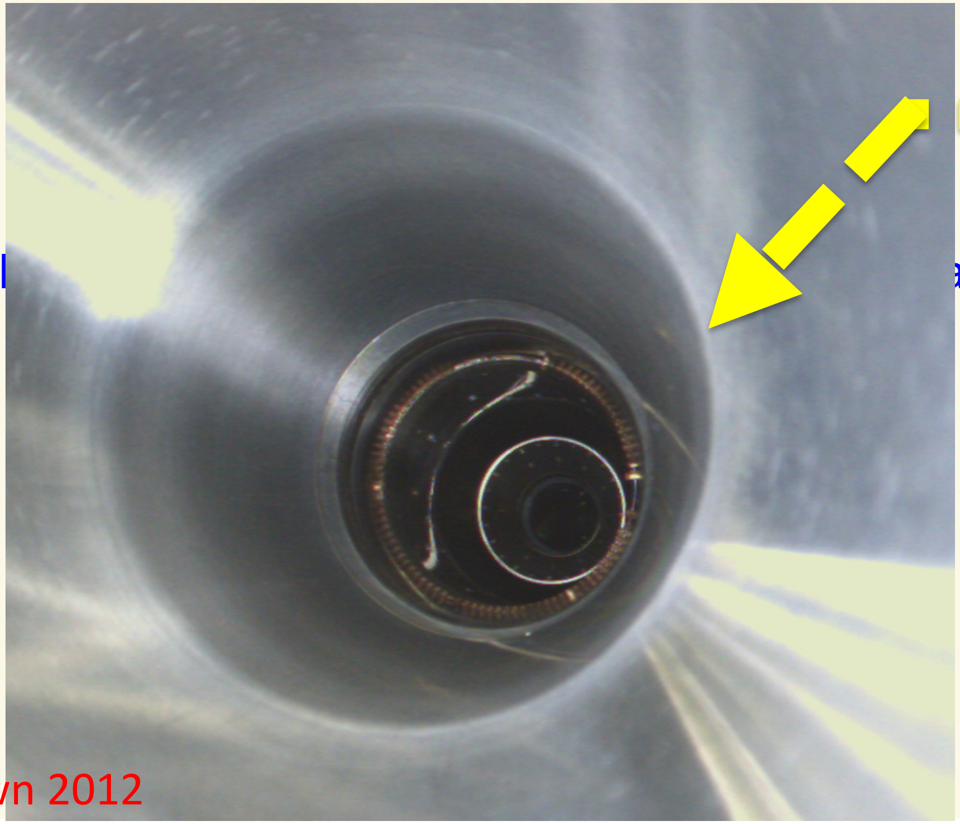
Restoring electrical continuity

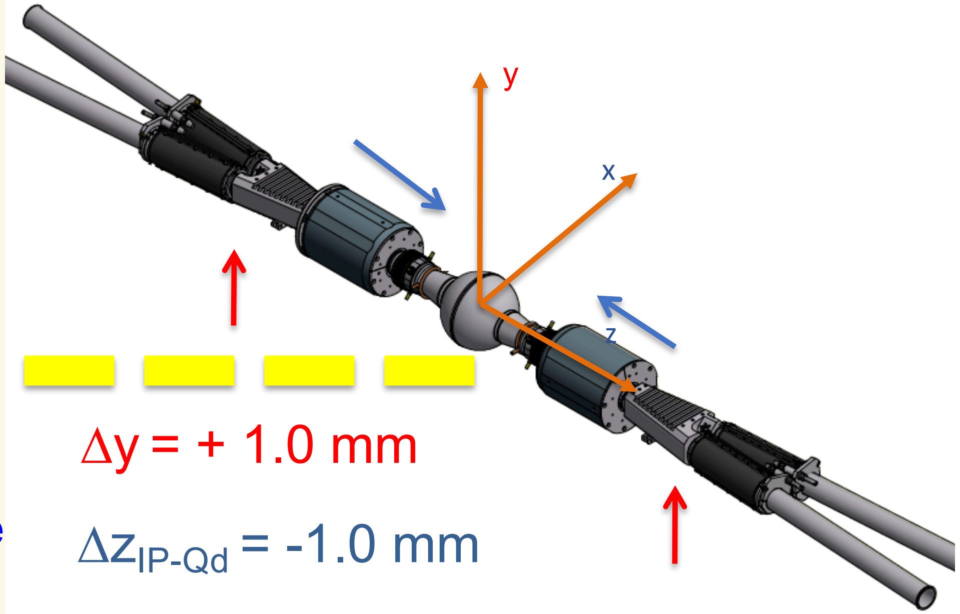




IR Bellows Replacement

IR measurement and alignment





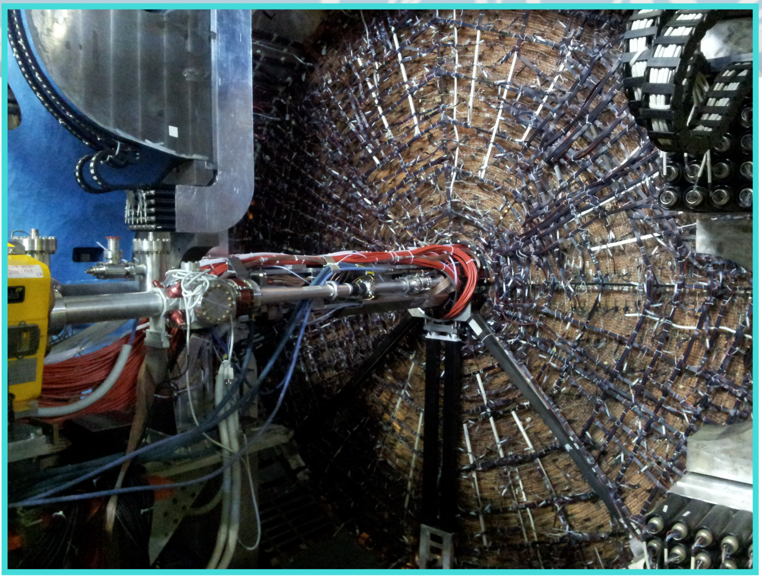
Endoscopic inspection of the low-β vacuum chamber

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

Summer shutdown 2012

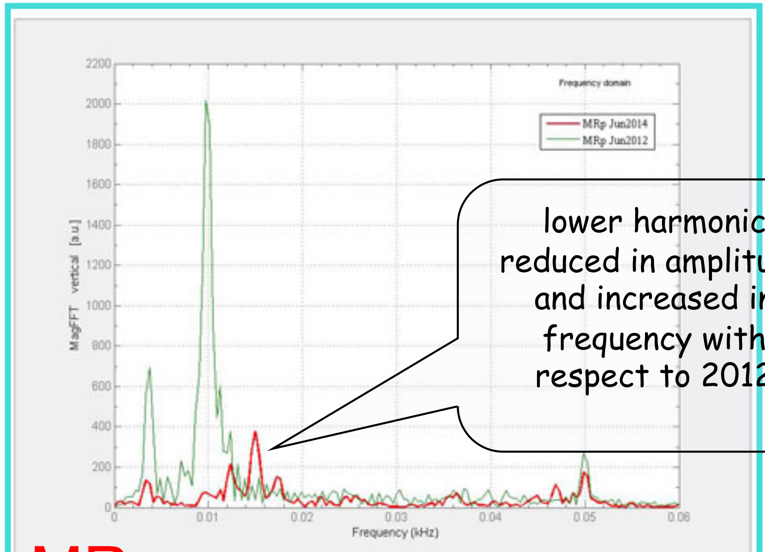
IR Structural Modifications

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



The spectrum of the vertical beam oscillation before and after the intervention.

The main harmonic was shifted toward higher frequencies, ~15 HZ, and its amplitude reduced by a factor five.



lower harmonic reduced in amplitude and increased in frequency with respect to 2012

MRp

FFT analysis

e^+ Beam Dynamics

During the KLOE-2 run the maximum current stored in the e^+ beam has been of the order of $I^+ \sim 1.2$ A.

- 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
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	$2 \cdot 10^{10}$

e-cloud mitigation techniques

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

Devices

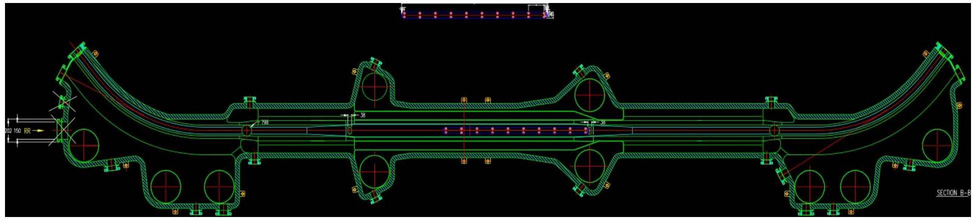
- solenoid windings
- powerful feedback system
- electrodes (**developed for KLOE-2 run**)

Tuning ring and beam parameters

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

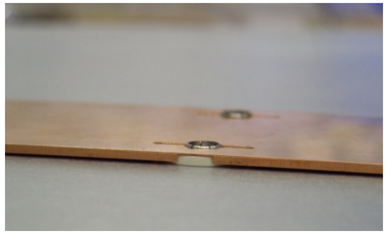
Maintaining optimal dynamic vacuum

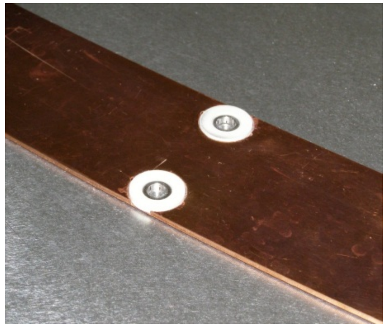
- more frequent sublimations

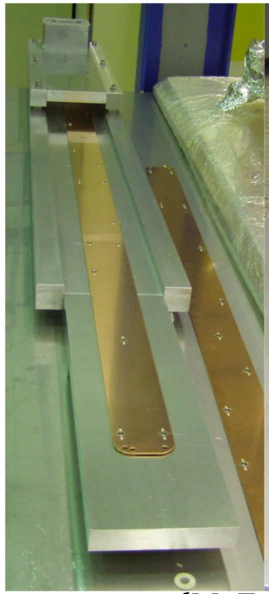


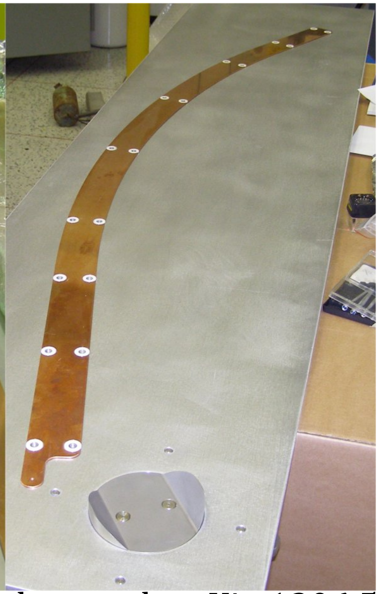
E-Cloud Clearing Electrodes
Installed for the KLOE-2 run

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.

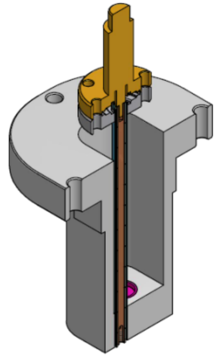


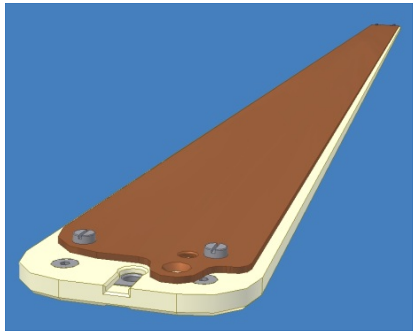






(M. Zobov et al., arXiv:1306.5944 [physics.acc-ph])





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.

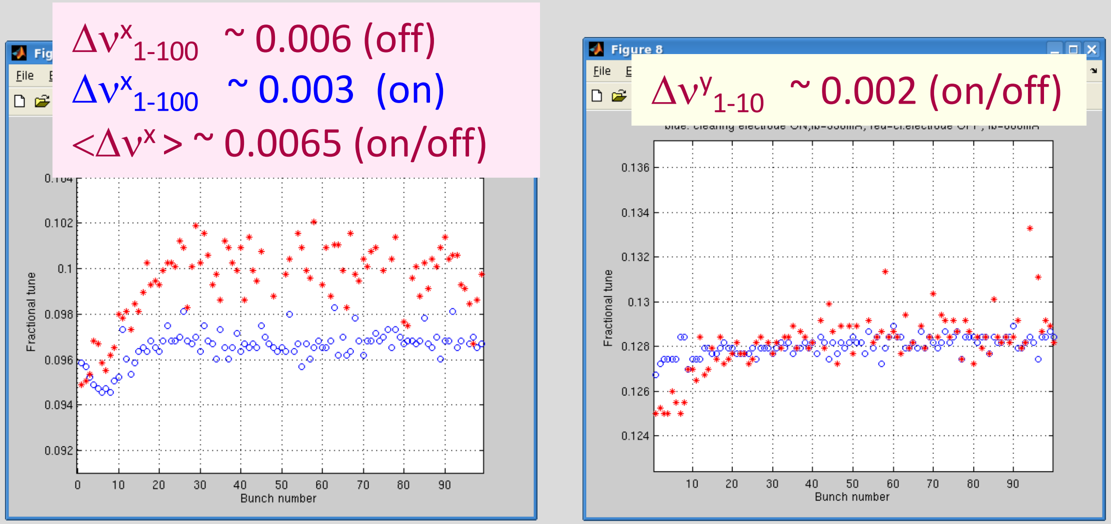
Clearing electrodes for *e-cloud* suppression

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 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.

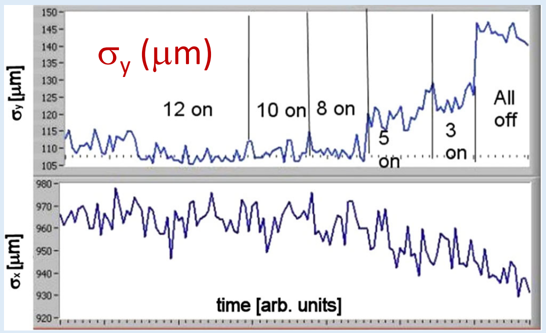
(D. Alesini et al, Phys. Rev. Lett. 110, 124801 (2013))

Tune Spread measurements



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

During the KLOE-2 run the maximum e^- currents stored at regime in collision has been in the range

$$1.3 \div 1.5\ \text{A}$$

It 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

As dynamical vacuum was improving filled bunches have been progressively increased the range of $93 \div 108$ 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 106 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

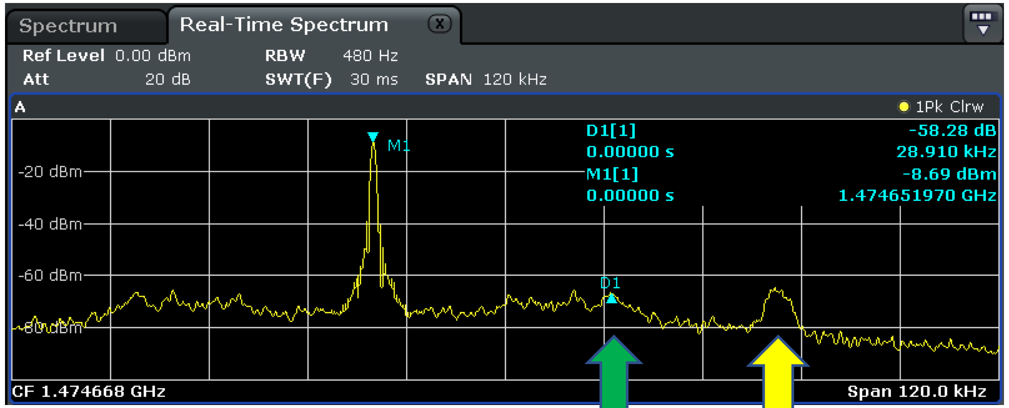
- noise coming from pickups (harmful for vertical sizes)
- Interplay between longitudinal FBK and LLRF FBK.

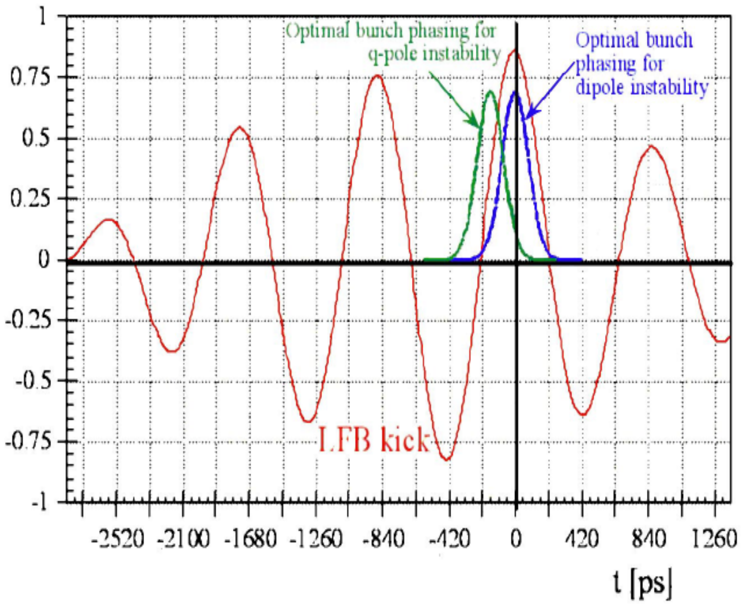
Solutions:

- 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

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

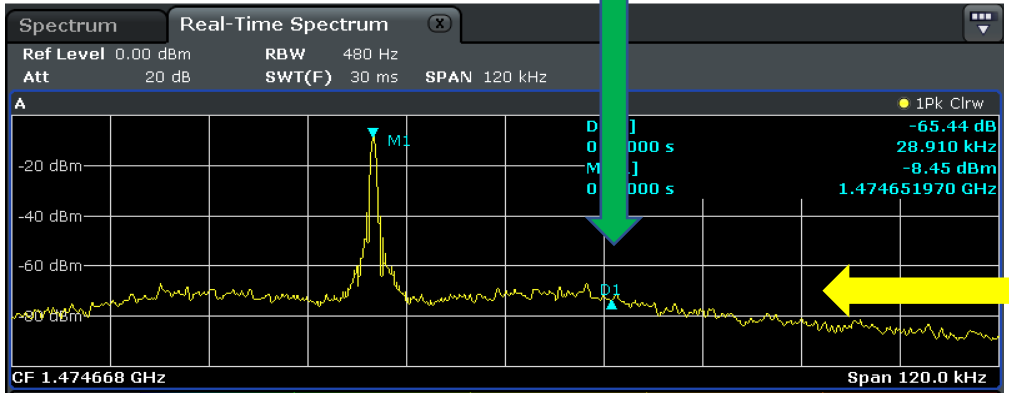




Revolution harmonic

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)

Background Control

The new detector layers installed around the beam pipe posed new tight requirements on background level and control.

Criteria for acceptable background became:

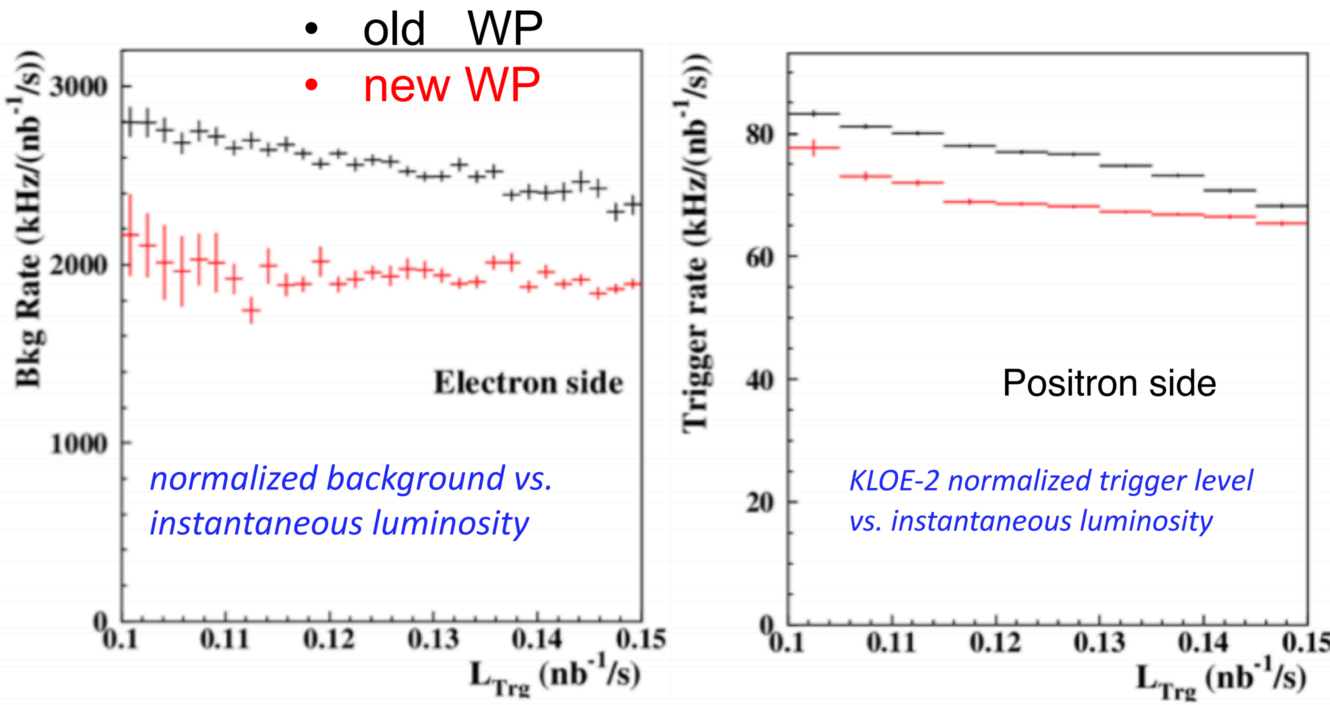
- counting rate on the detector endcaps
- current amplitude measured by the different drift chamber sectors
- discharge threshold on the innermost IT layer installed at a distance of 15 cm from the Interaction Point.

Background on the IT was heavily dependent on the injection process which had to be accurately optimized and stabilized

Even small drifts in the energy of the incoming beam, 0.01 ÷ 0.02 %, were causing unaffordable background level.

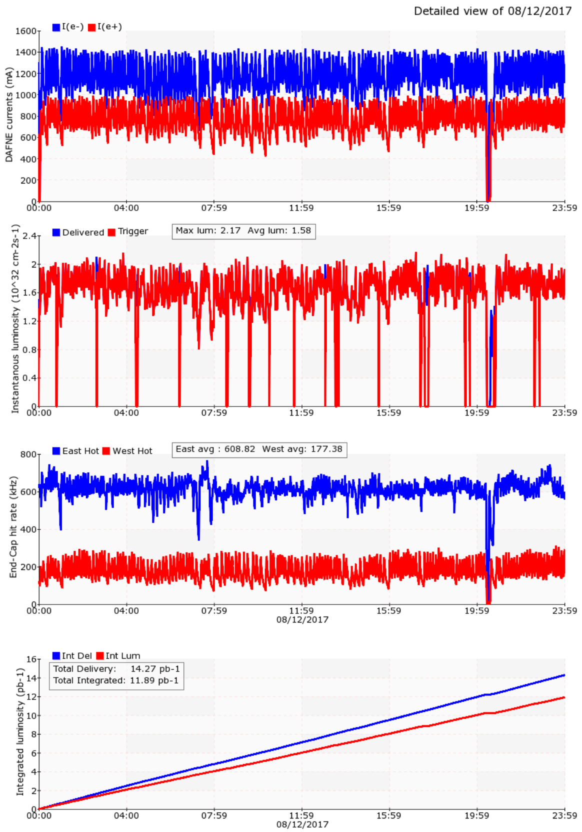
Relevant background control was achieved by optimizing the colliding ring working points by using Lifetrack code achieving:

- larger DA 2 – 3 σ
- Improved injection efficiency
- higher beam lifetime
- reduced background ~ 20%
- higher luminosity ~ 7%



Luminosity Trends during Operations

Best Daily integrated Luminosity



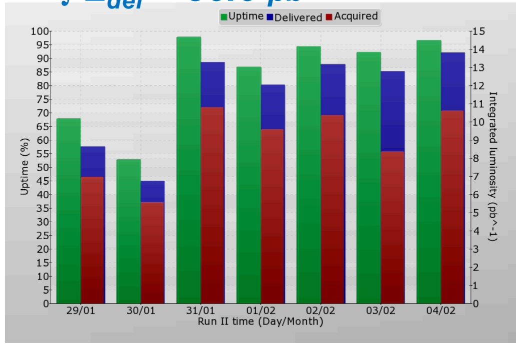
$\int L_{del} \sim 14.3\ pb^{-1}$

$\int L_{acq} \sim 11.9\ pb^{-1}$

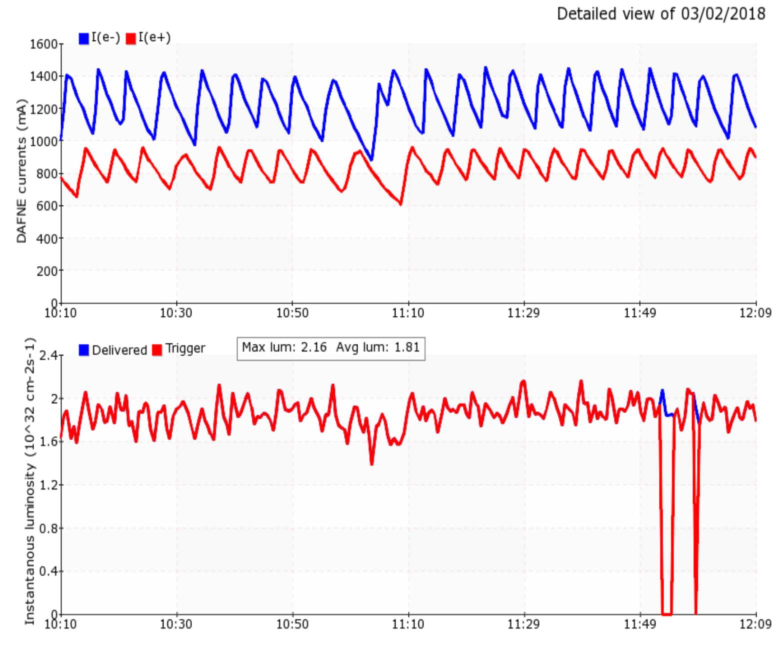
Uptime ~98%

- 106 bunches
- Sustainable background

$\int L_{del} \sim 86.6\ pb^{-1}$



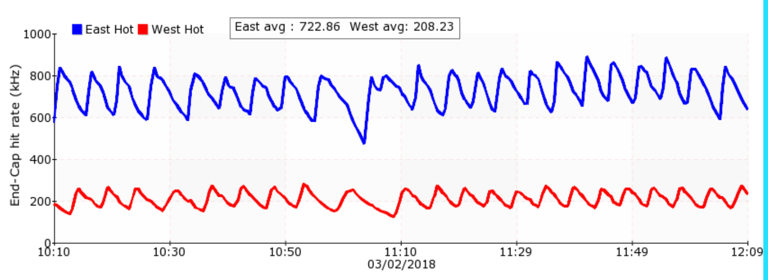
Best Hourly integrated Luminosity



$\int_{1h} L \sim 0.67\ pb^{-1}$

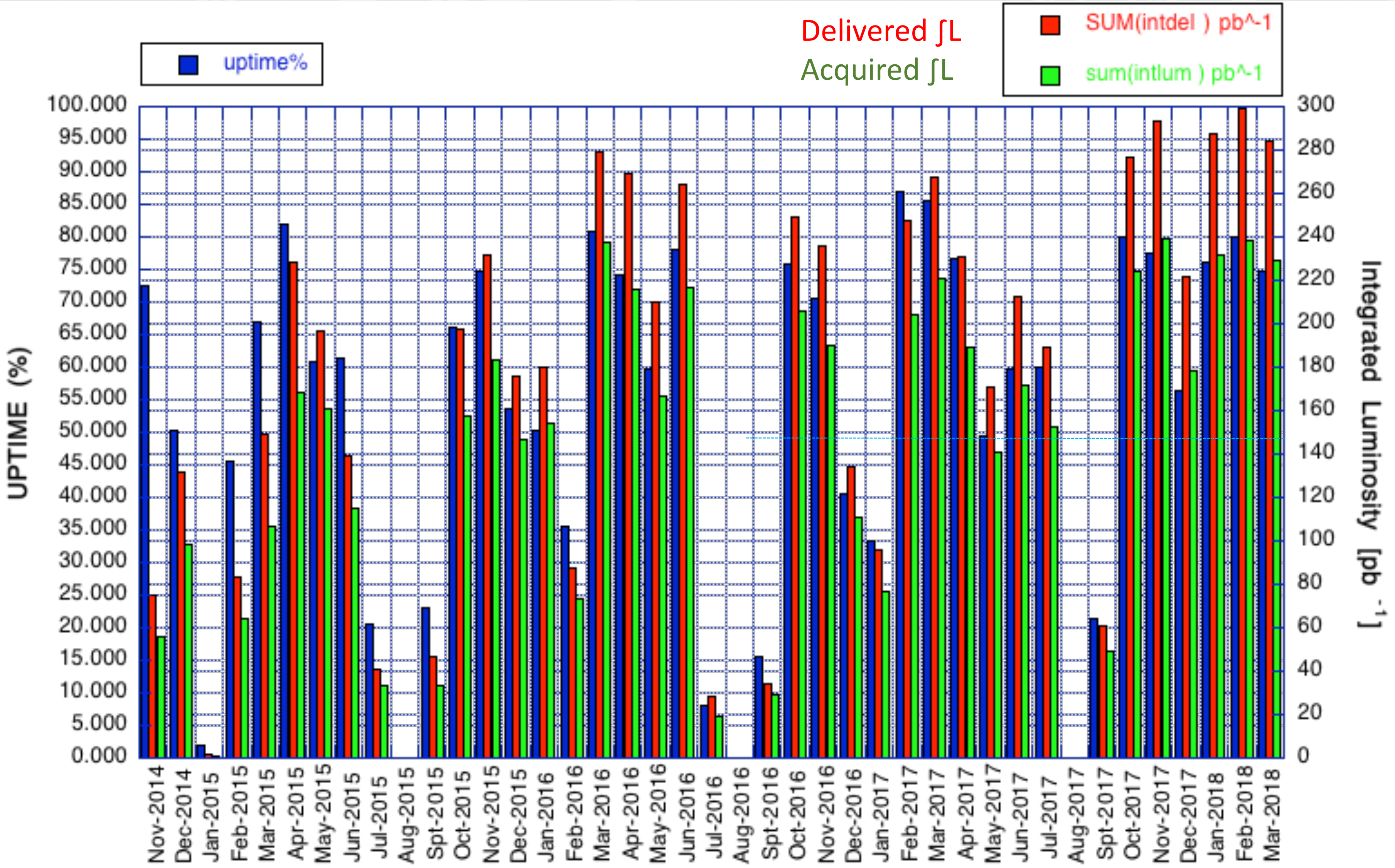
$N_b = 107$

$\int_{1\ day} L \sim 16\ pb^{-1}$



Background

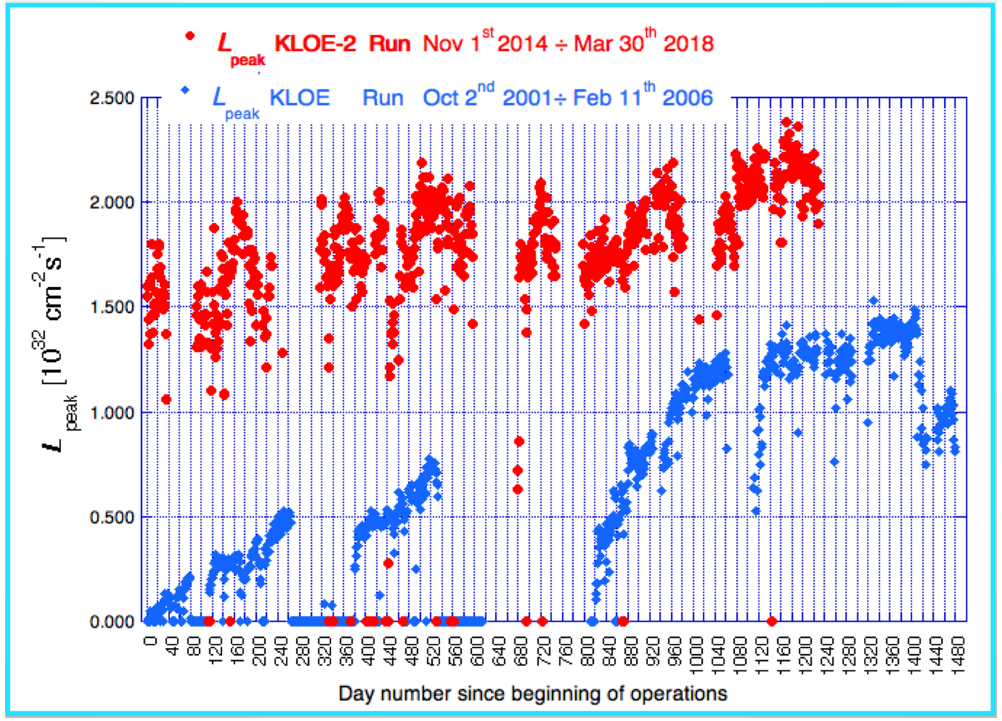
Monthly integrated Luminosity trend

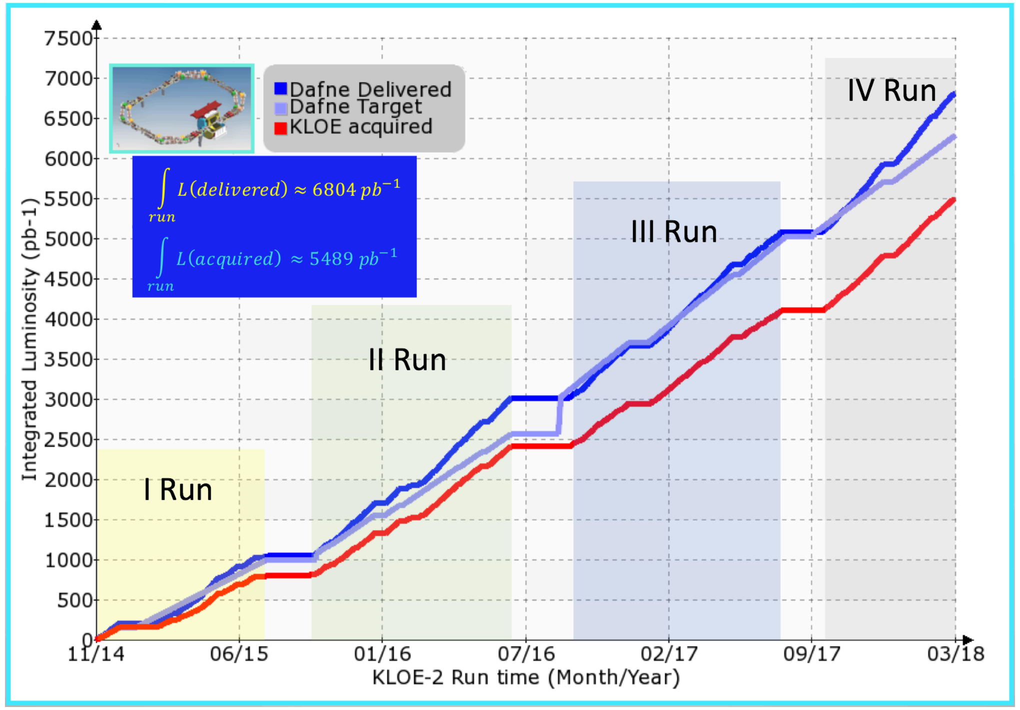


Crab-Waist Collision with KLOE-2

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 $\boldsymbol{L_{peak}}$

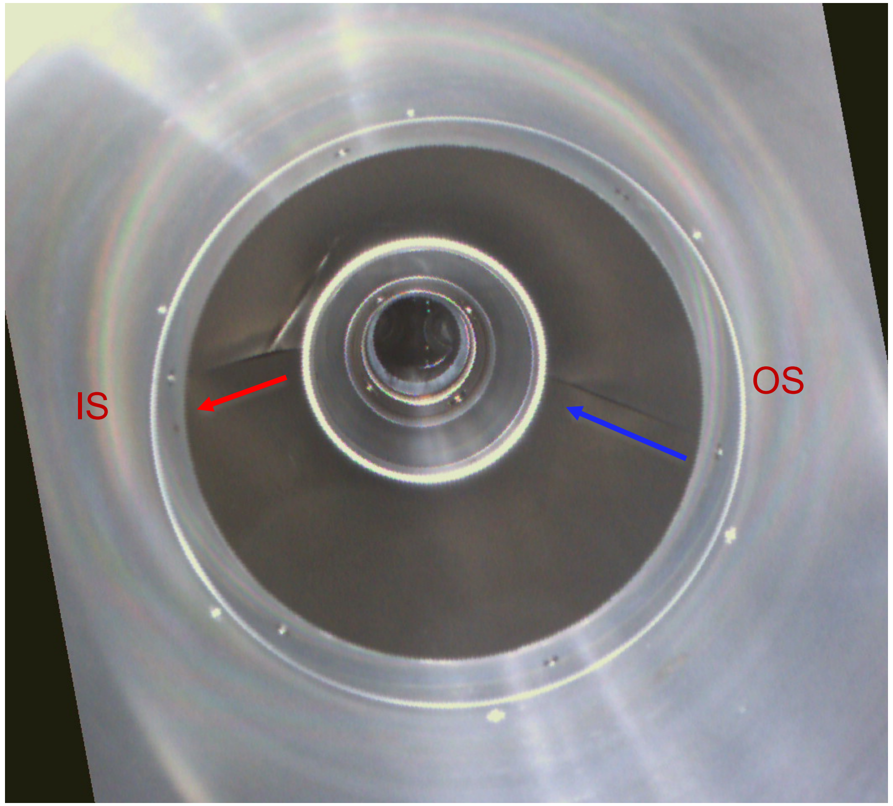




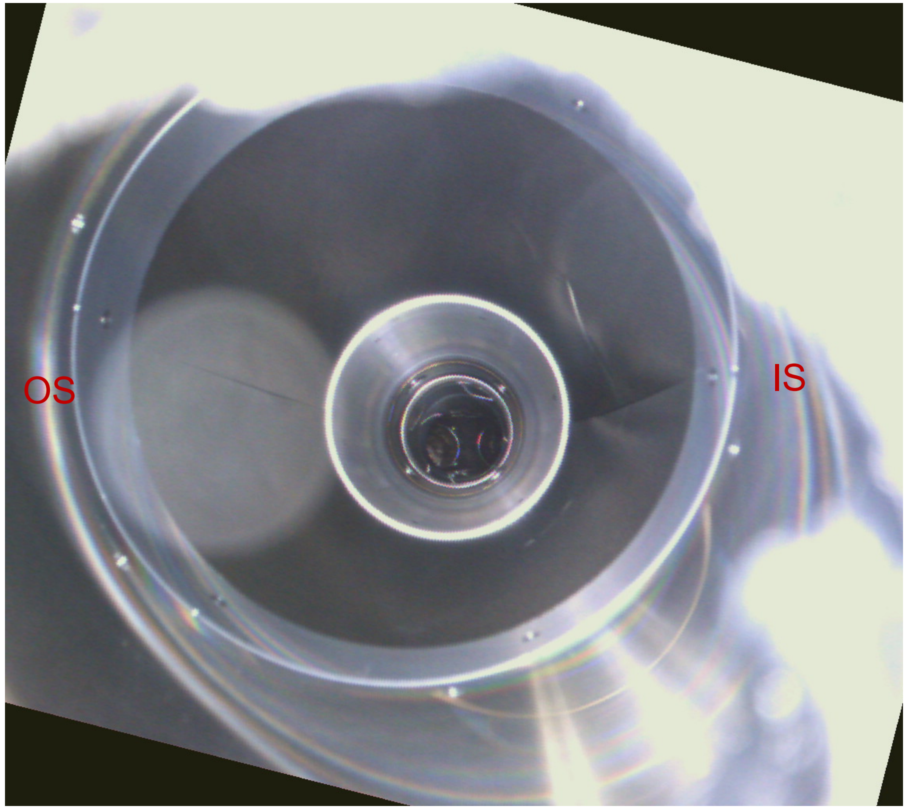
C. Milardi et al., A Review of DAΦNE Performances during the KLOE-2 Run, TUYGBD2, IPAC'18.

Post Hoc Analysis of the IP Vacuum Chamber

View from the IR branch side downstream the positron beam



View from the IR branch side downstream the electron beam



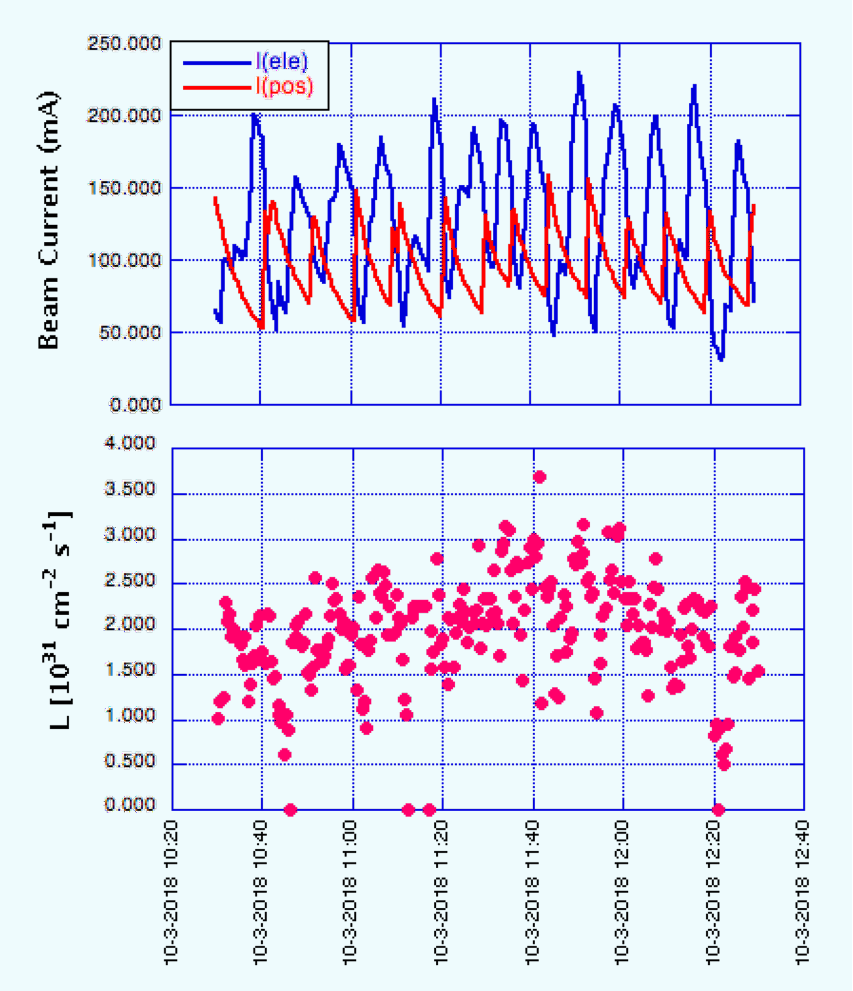
Limiting Factors and Simulations during KLOE-2 Run

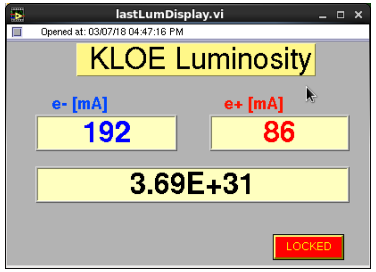
Numerical weak strong **simulations** using nonlinear collider lattice, including a strong detector Solenoid in the IR, have shown that for the given bunch currents in collision, the powering of the **Crab-Waist Sextupoles should decrease the beam core blow up by a factor of 2 indicating that even higher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

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.

10 Bunches Collisions (KLOE-2 run)

Aiming at minimizing the impact of multi-bunch effects and e-cloud instabilities on *Luminosity*





- *L_{peak} ~ 3 •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.*

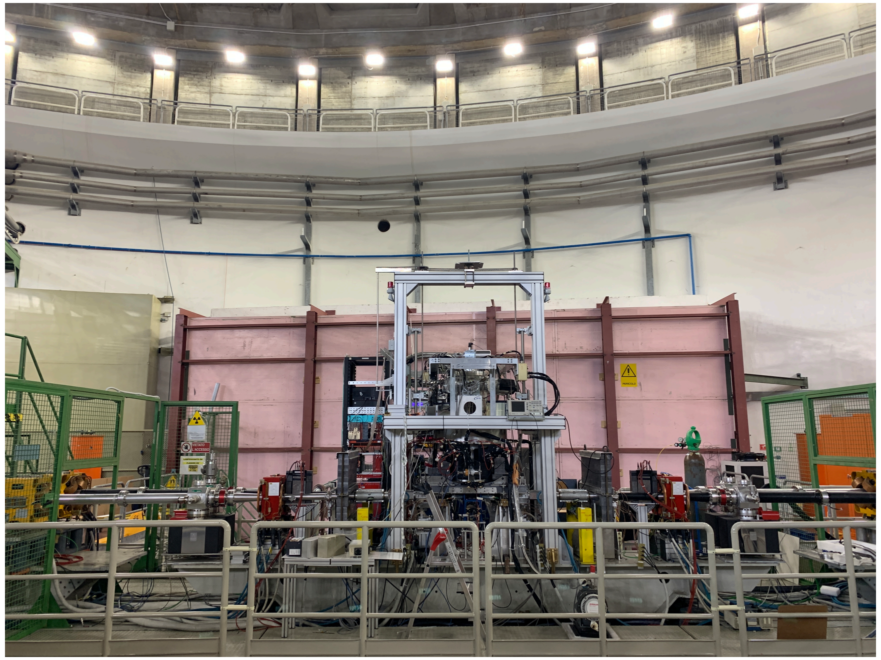
UNFORTUNATELY, not enough time for machine studies and optimization!

SIDDHARTA-2 Run

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.



SIDDHARTA Run Timeline

Spt – Dec 2019 collider commissioning for SIDDHARTA-2

Mid Jan – March 2020

February – Jul 2021

Apr – Jul 2022 SIDDHARTINO run completed *and preliminary run with Deuterium target*

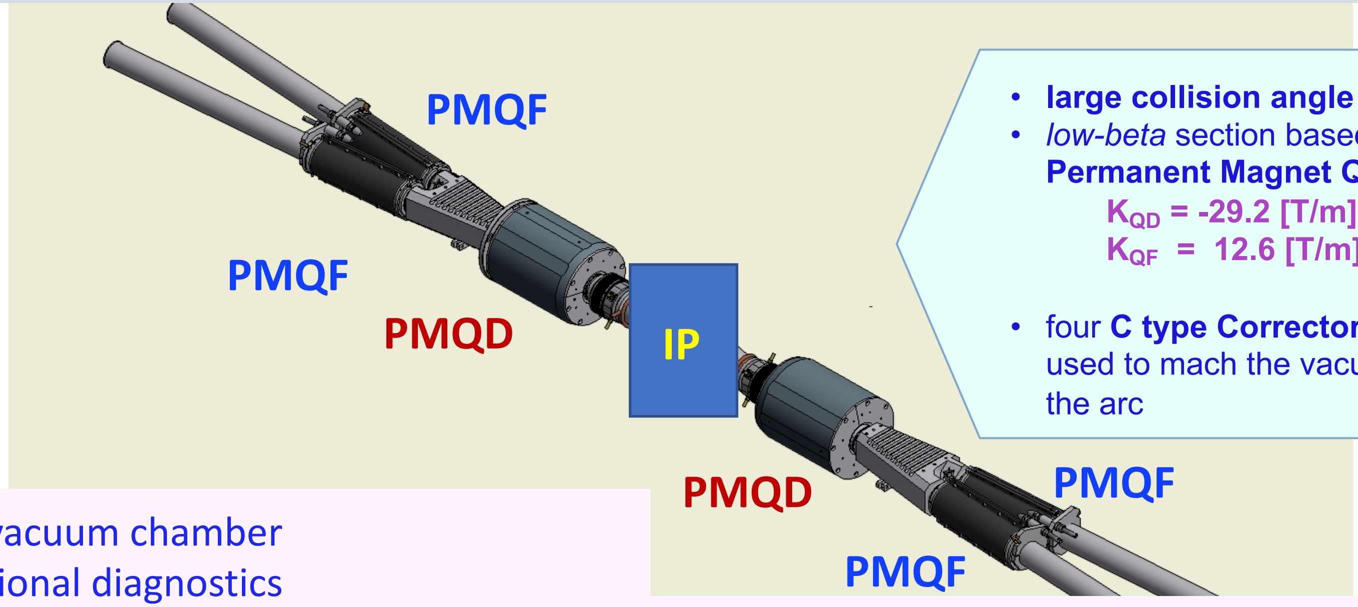
Apr – Jul 2023

Sep 15th – Dec 19th 2023
Periodical maintenance, and winter shutdown

Jan 18h – Jul 2024
Data taking with deuterium target

SIDDHARTA-2 low-β section

It is essentially based on the same design concepts used for the SIDDHARTA one



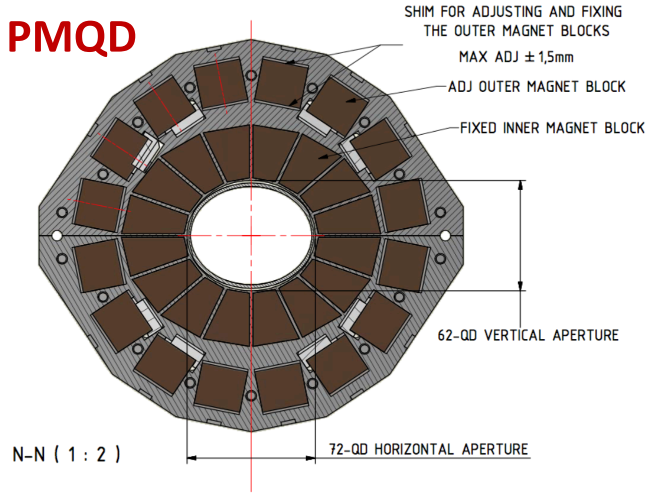
- **large collision angle ~ 50 mrd**
- *low-beta* section based on **Permanent Magnet QUADs**:
  K_{QD} = -29.2 [T/m]
  K_{QF} = 12.6 [T/m]
- four **C type Corrector** dipole are used to mach the vacuum chamber in the arc

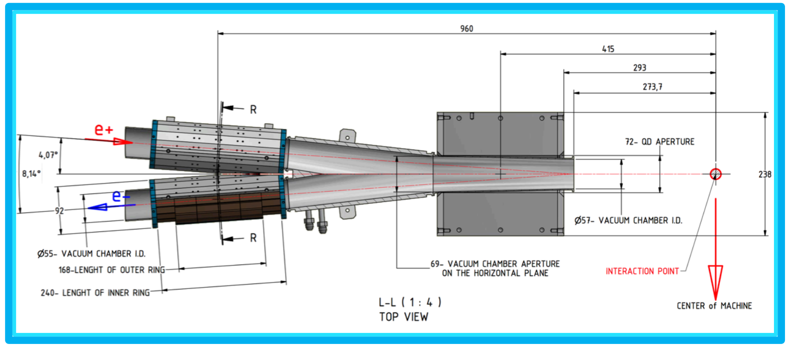
New vacuum chamber
Addidional diagnostics
The permanent magnet quadrupoles, that have been rebuilt aiming at:

- speeding 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 $SmCo_2:17$
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

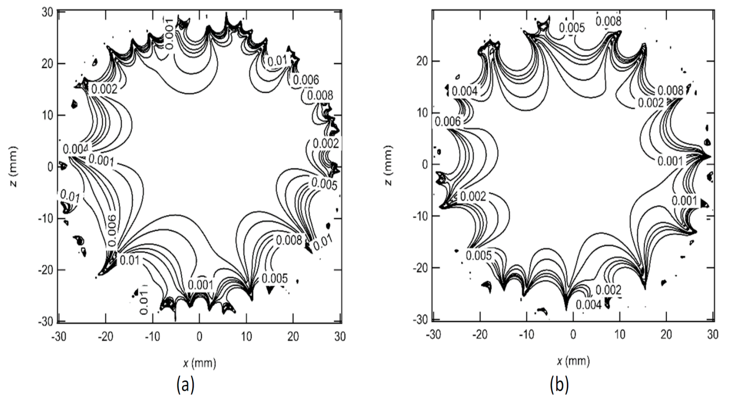
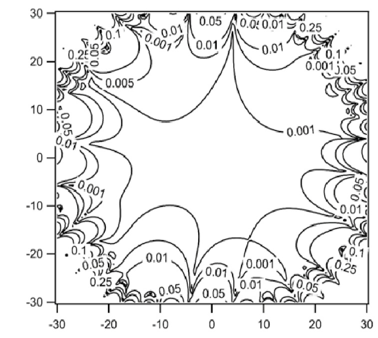


Figure 3. Gradient homogeneity contour plots for the QD0-1 (a) and QD0-2(b) magnets. The inner contour corresponds to gradient inhomogeneities below 0.001.

Old PMQD

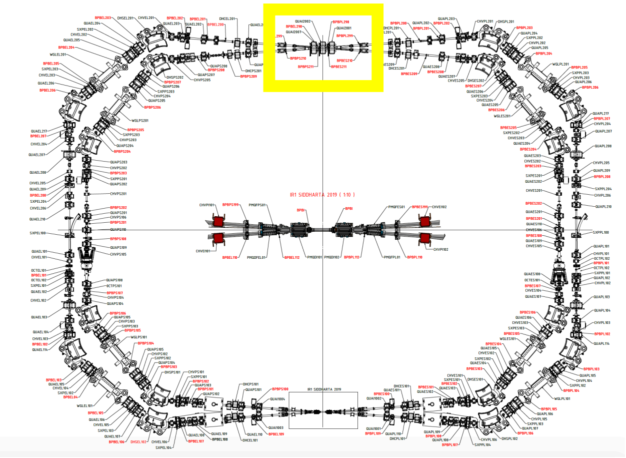


Main Rings Optics

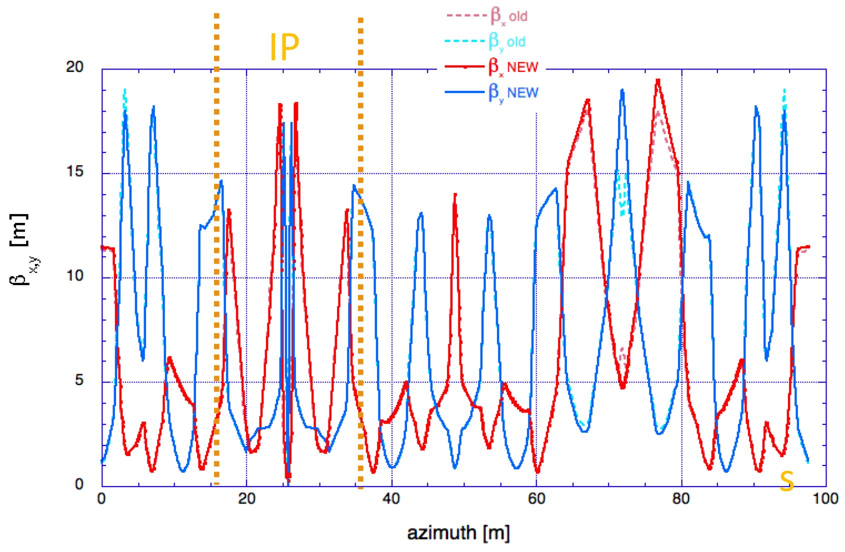
New **Crab-Waist ring optics**
- symplified focusing structure in the RCR,
- 2 QUADs where beams pass off-axis are switched off, thus eliminating spurious component in the QUADs magnetic field,
- Same optics parameters in the IR.

New optics improves closed orbit correction allowing to reduce the total strength of the used steering magnets, thus also contributing to minimize vertical dispersion

RCR



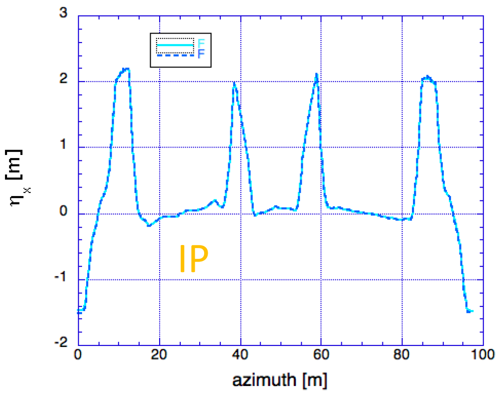
CW SXTs



$\beta_y^* = 0.008$ m
$\beta_x^* = 0.26$ m

MRs working point:
$Q_x^- = 0.103$
$Q_y^- = 0.162$

$Q_x^+ = 0.114$
$Q_y^+ = 0.180$



Non-linear Optics

The strengths of ***Crab-Waist Sextupoles*** have been progressively increased, up to **77% of their nominal value**. This allowed to improve instantaneous luminosity and background level control.

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

Chromatic sextupole and octupole set-points have been **refined** according a comprehensive iterative optimization process, implemented experimentally, during data delivery, increasing:

- injection efficiency,
- beam lifetime,
- dynamic aperture,
- energy acceptance.

Energy aperture A_E

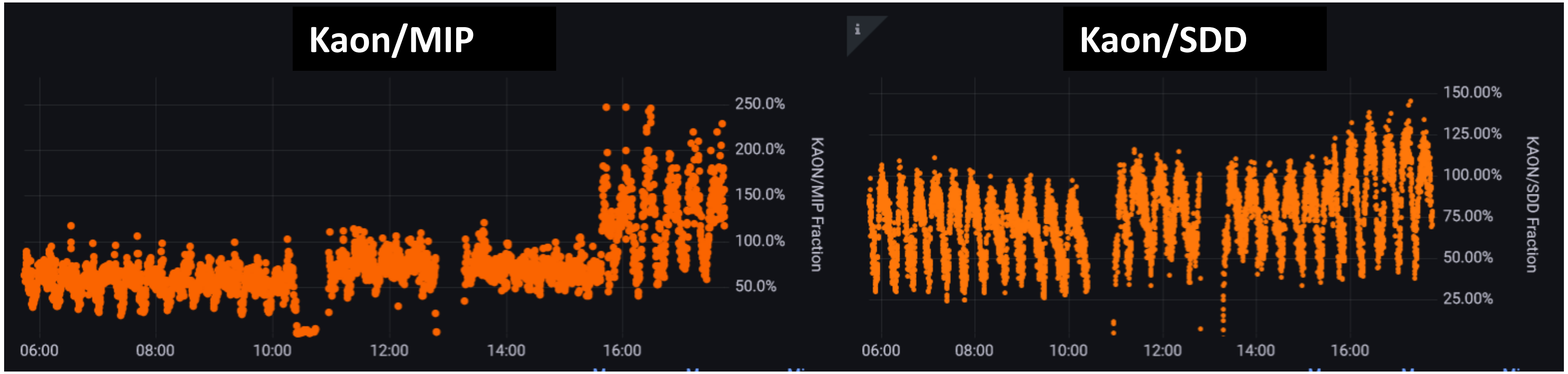
$$-3.8 \text{ MeV } (-0.8\%) \leq A_E \leq 3.1 \text{ MeV } (0.6\%)$$

This procedure led to a remarkable reduction of the background affecting the measurements, how it will be shown in the following.

DAΦNE

Background Improvement

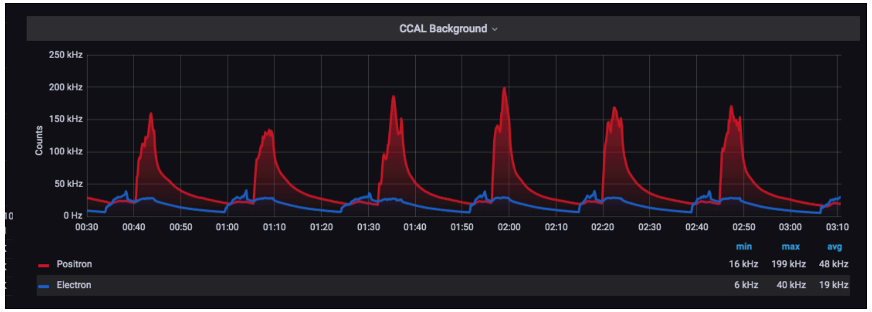
Non-linear optics tuning allowed to increase energy acceptance, and dynamic aperture, leading to gain almost a factor of 2, and 1.45 in terms of Kaon/MIP, and Kaon/SDD rates respectively.



Restarting activities for SIDDHARTA-2 the collider configuration has been optimized relying on beam measurements.
Collider performances are approaching the optimal achieved in previous runs.

MRs Injection

LINAC works at 25 Hz
Injection in MRs:
- 2 Hz for e-
- 1 Hz for e+



In a collider there are two different kinds of backgrounds produced during the injection and costing phase respectively.

They require completely different analysis and mitigation approaches.

Injection background has been considerably reduced by 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.

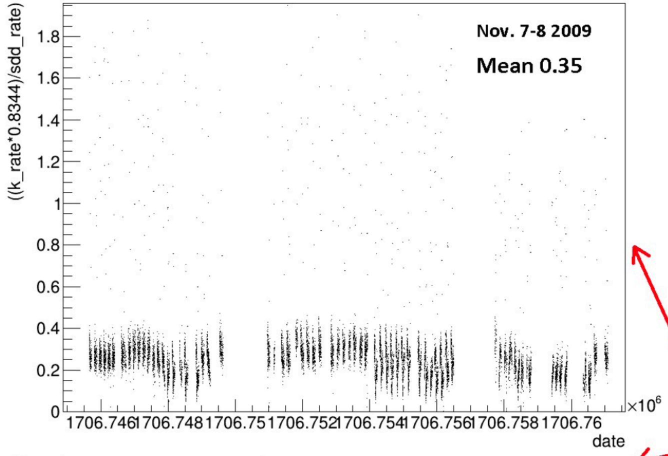
For this reason, **vertical dimension of the e^- beam are artificially increased** during injection, by using a calibrated skew quadrupoles bump. In order to reduce the beam-beam kick on the weak e^+ beam, thus avoiding rapid lifetime drops and sudden background bursts.

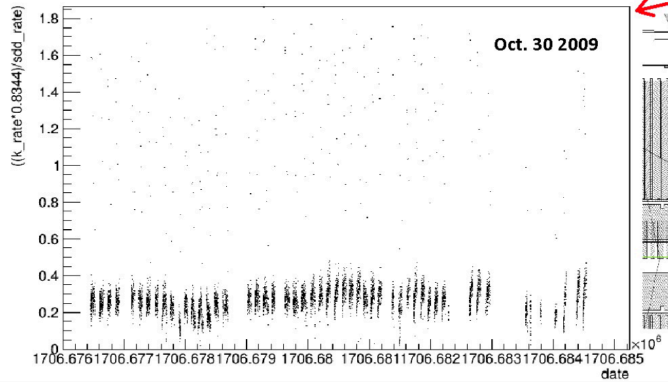
Background Improvement

Physics events delivered to SIDDHARTA-2 experiment exhibit now **a signal to noise ratio 3 time higher w.r.t. the 2009 run.** This was evaluated taking into account the acceptance of the new detector components: kaon trigger, and SDD. Other analysis parameters such as trigger efficiency, and veto system have not been included.

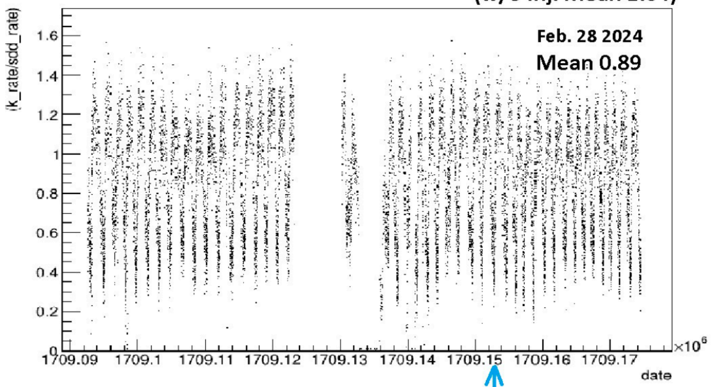
Preliminary analysis indicates this improvement is in large part due improvements is in large part due to the collider configuration, and to the new design of the PMQD installed in the low-beta of the interaction region.

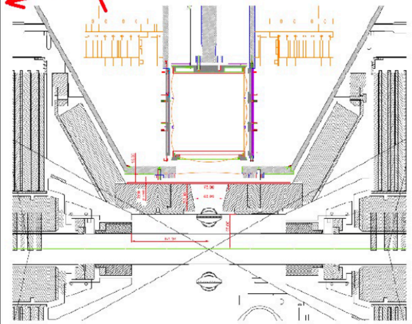
SIDDHARTA Data quality (r)evolution 2009-2024



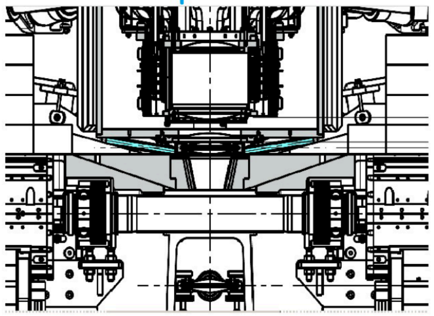


(w/o inj. Mean 1.04)





SIDDHARTA



SIDDHARTA-2

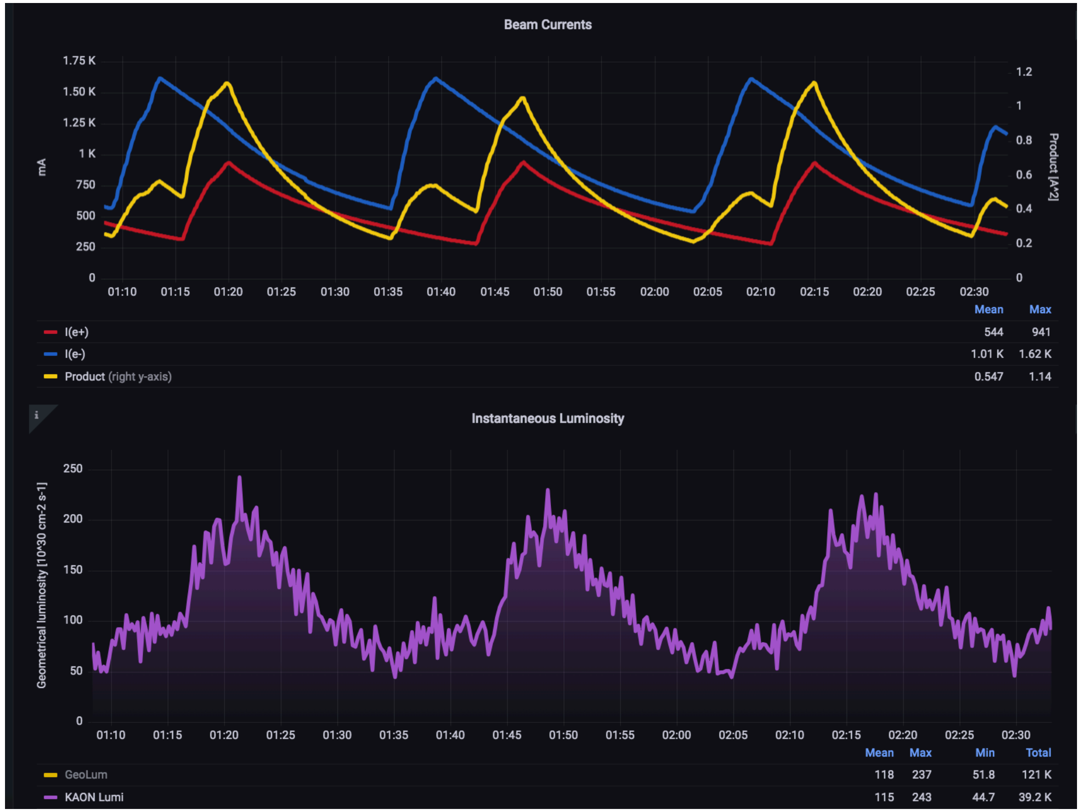
(*Analysis from M. Iliescu*)

Luminosity Achievements

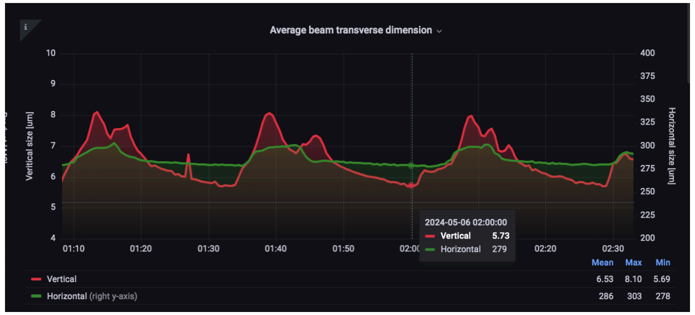
$L_{peak} = 2.4 \bullet 10^{32}\ cm^{-2}s^{-1}$

$I^{-}_{peak} = 1.14$ A

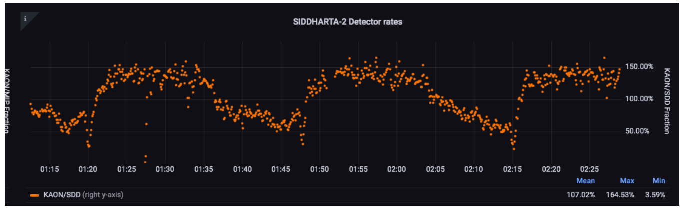
$I^{+}_{peak} = 0.89$ A



Average value of the convoluted transverse beam dimensions

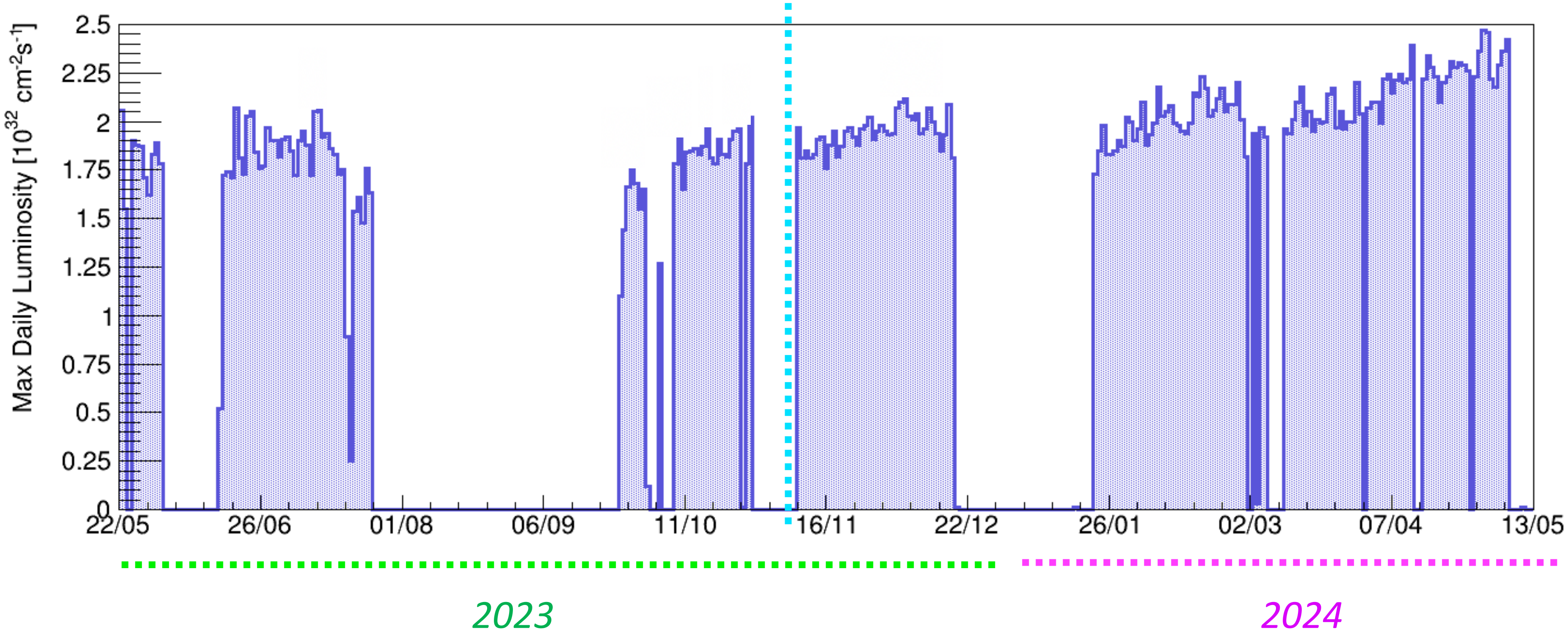


Kaon/SDD

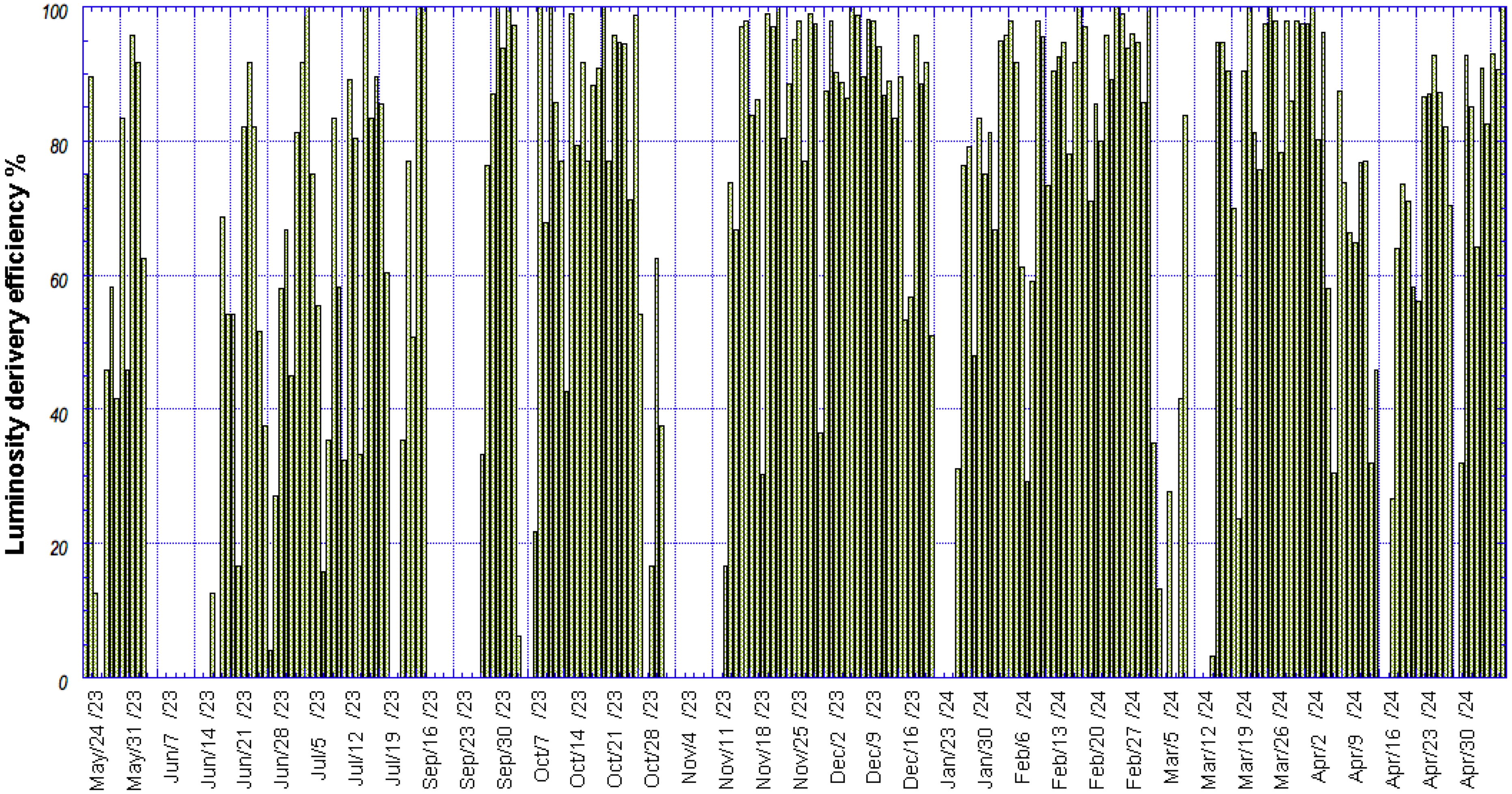


$L_{HQ} \sim 97\%$

Daily Peak Luminosity trend



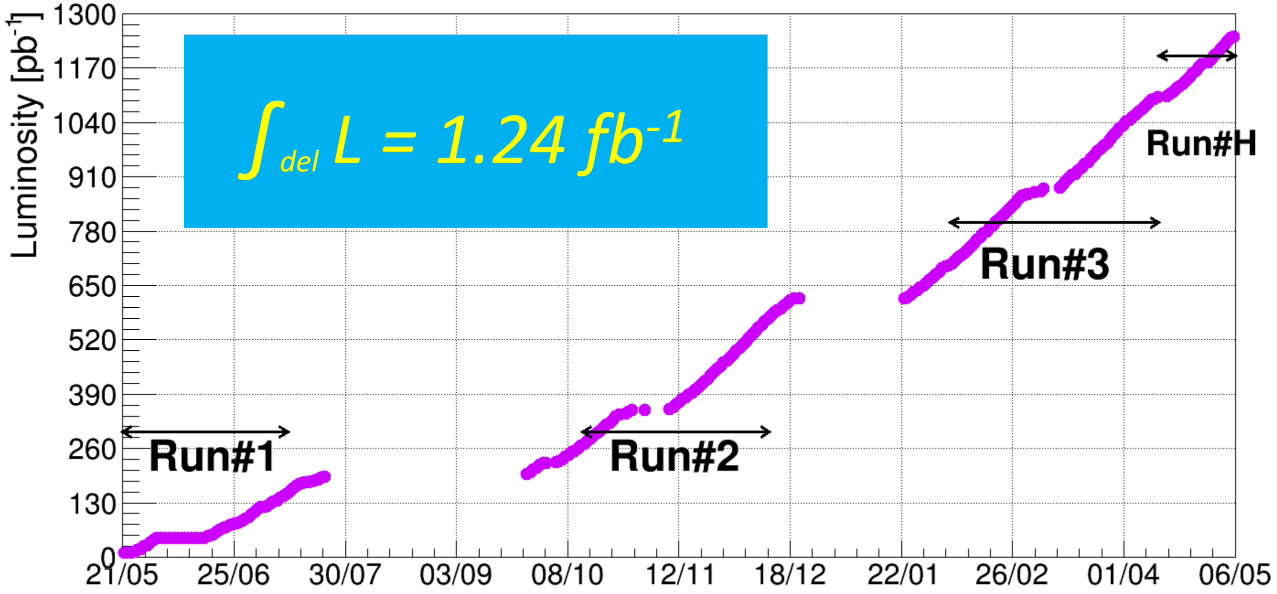
Luminosity-delivery Efficiency (Uptime)



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.



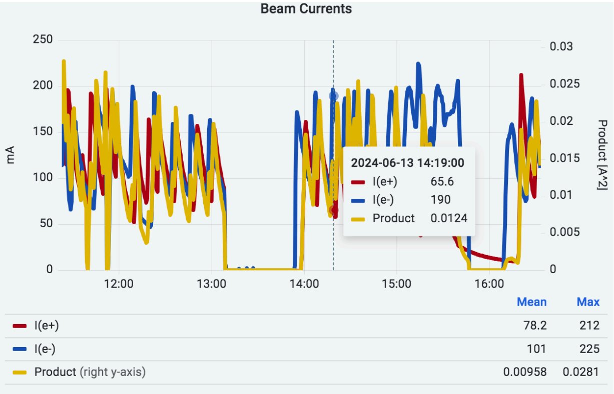
Preliminary data analisys show a clear evidence of the kaonic deuterium X-ray transition.

10 Bunches Collisions (SIDDHARTA-2)

DAΦNE

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

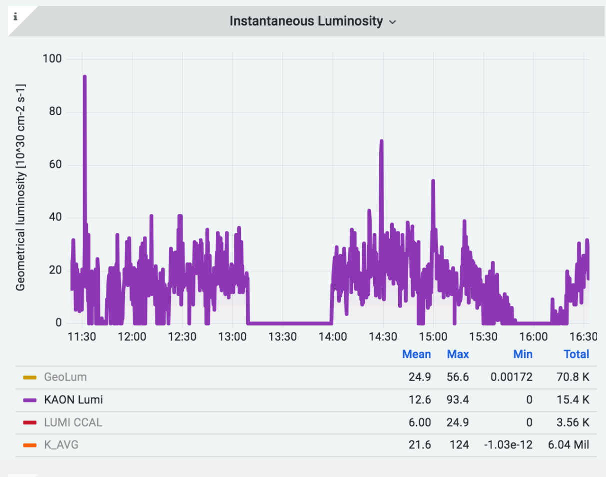
Aiming at minimizing the impact of multi-bunches effects and e-cloud instabilities on *Luminosity.*



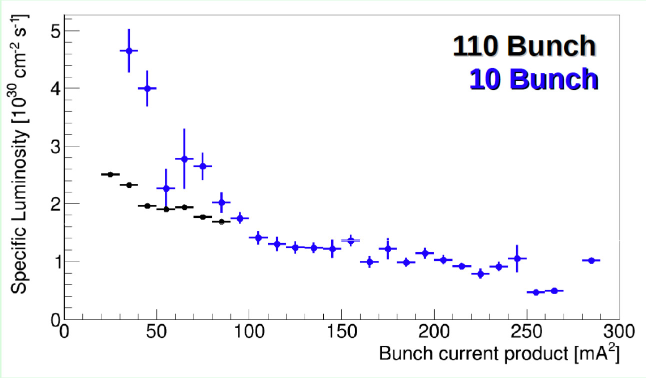
$L_{peak} \sim 4 \bullet 10^{31} cm^{-2}\ s^{-1}$

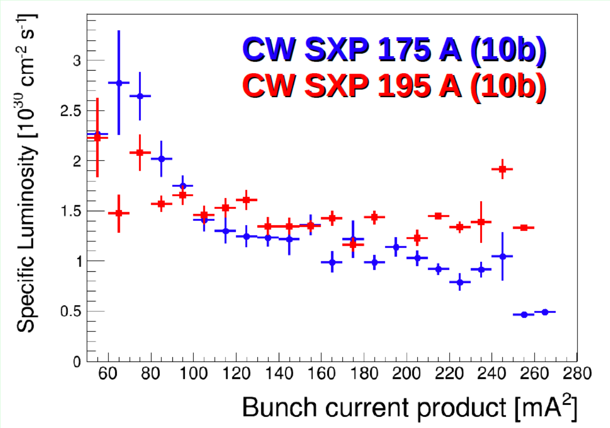
- *Beam-beam is not a limiting factor*
- *Crab-Waist Sextupoles work*

Time for machine studies and measurements was very limited



Specific Luminosity

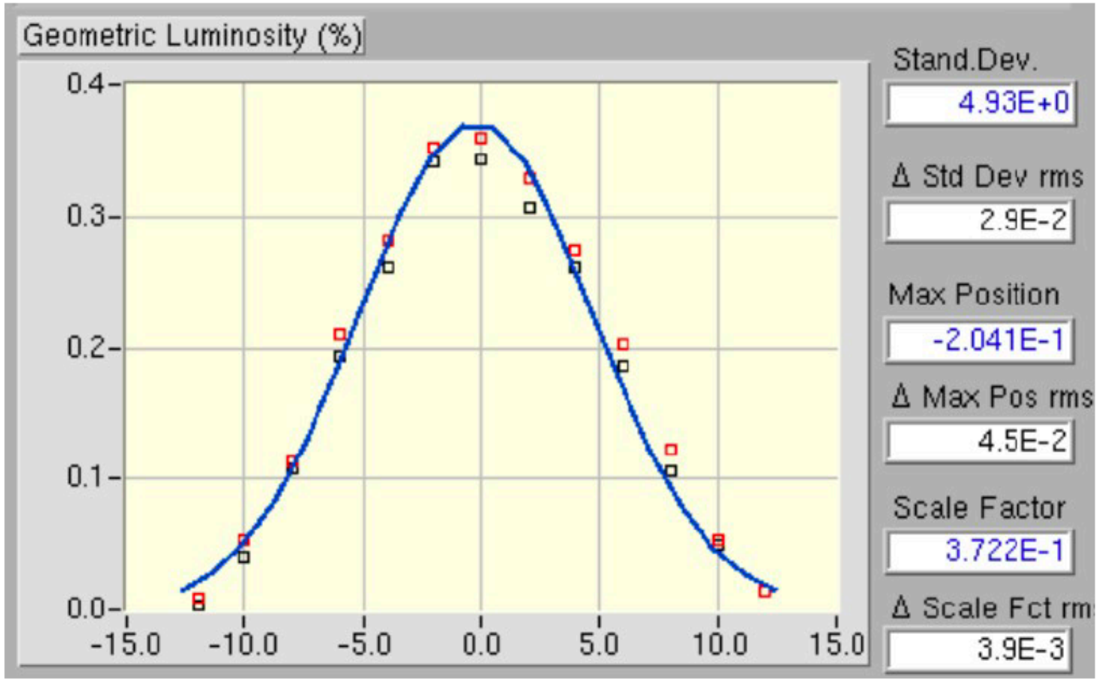




Specific luminosity is almost twice the one with 110 bunches al low current, and higher single bunch currents can be stored in collision. Increasing Crab-Waist SXTs it is possible to reach even higher specific luminosity at high bunch current.

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

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 (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.)	--	--

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 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.

Talk “DAΦNE as possible test facility for future circular colliders” from A. De Santis

Thank You

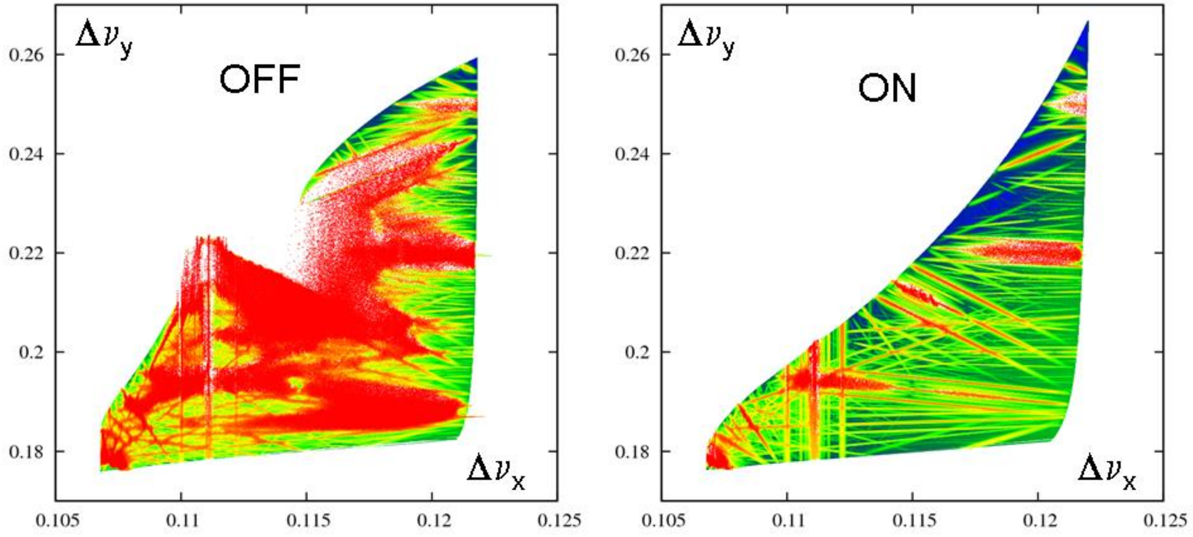
Spare Slides

The Crab-Waist Colliders

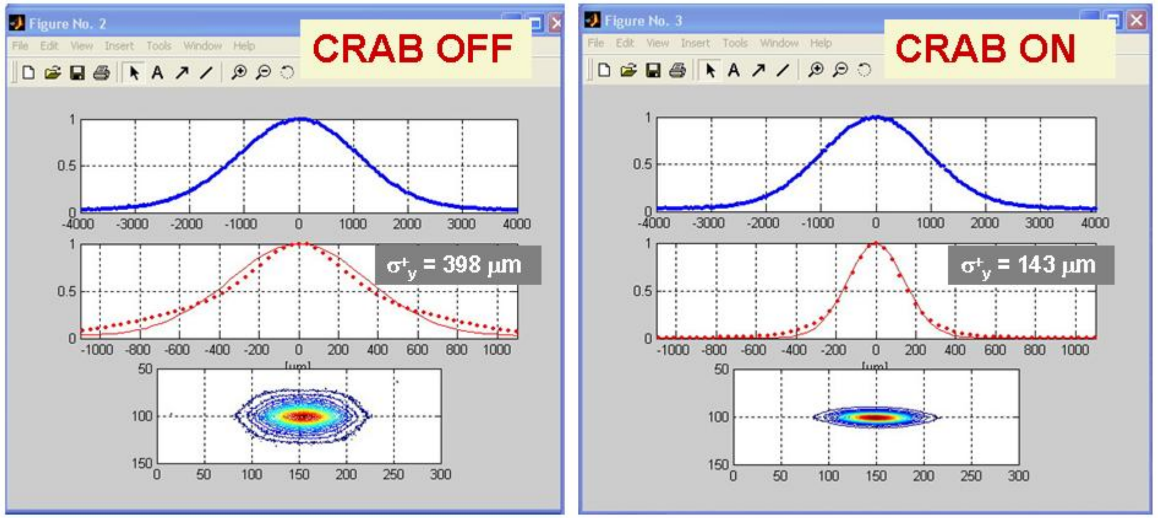
Colliders	Location	Status
DAΦNE	Φ-Factory Frascati, Italy	In operation (SIDDHARTA, KLOE-2, **SIDDHARTA-2**)
SuperKEKB	B-Factory Tsukuba, Japan	Adoped CW collision in 2020 *World Luminosity record*
SuperC-Tau	C-Tau-Factory Sarov, Russia	Russian mega-science project
SuperTauCharm	Tau-Charm Factory Hefei, China	TDR published, waiting for project 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	It will be presented in this WRK

Suppression of Beam-Beam Resonances

DAΦNE case



← ***Frequency map analysis***



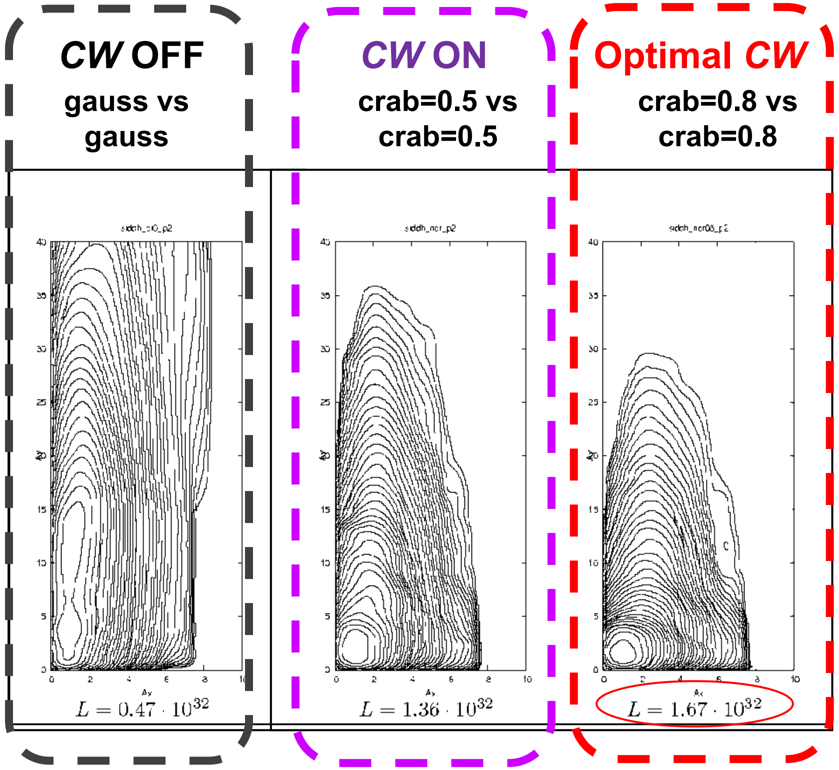
← **Measurements from synchrotron light monitor**

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

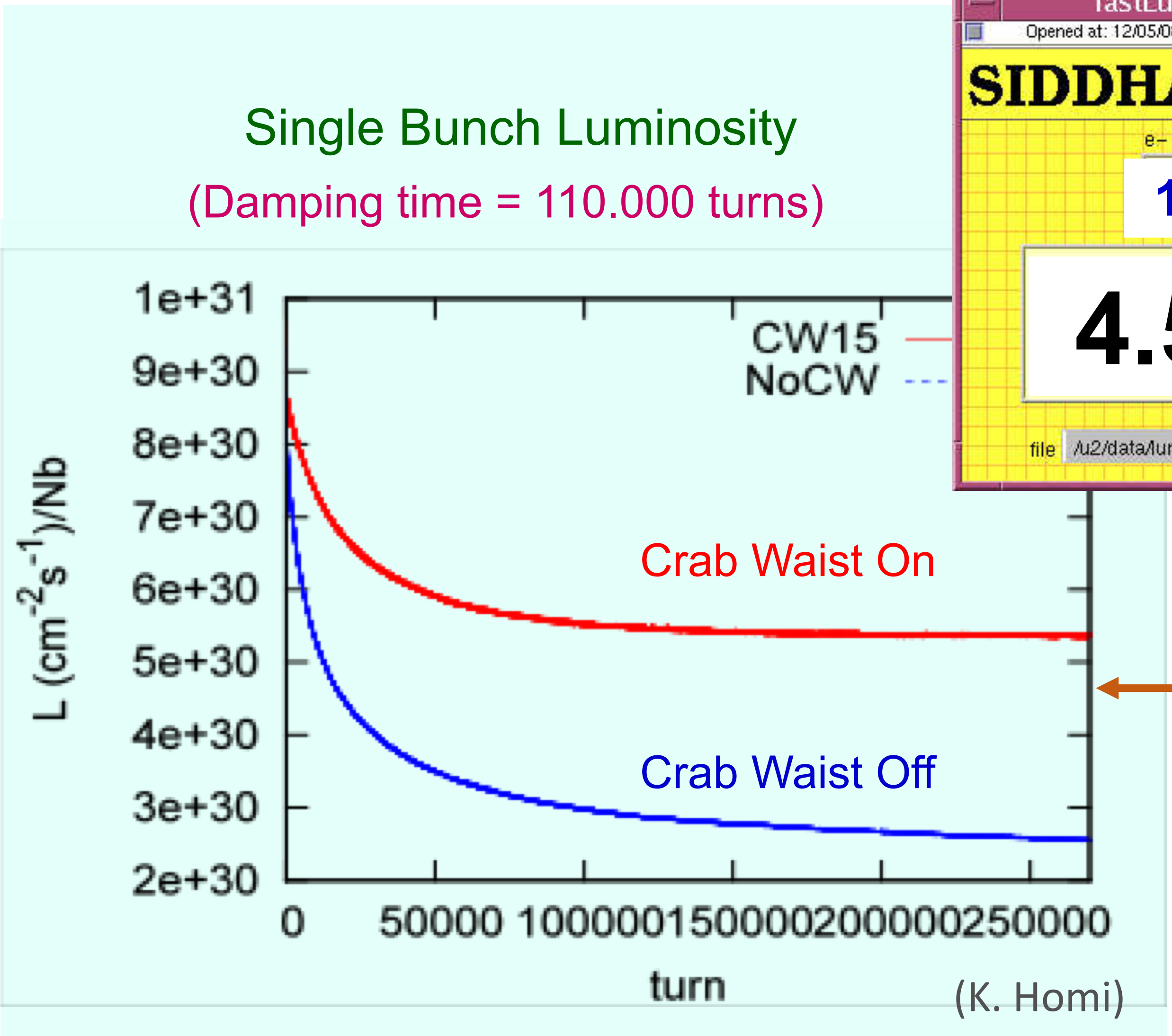
Weak-Strong Simulations

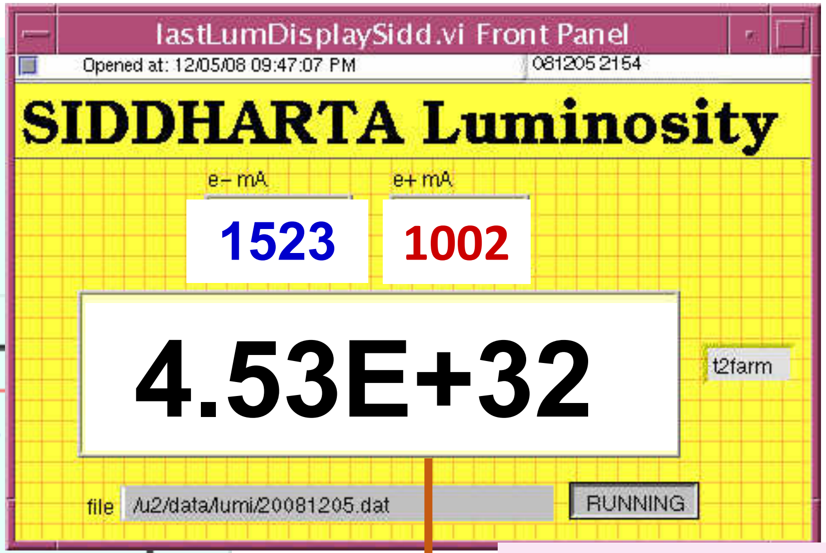
Crab-Waist compensation works in weak-strong regime also, and measured luminosity is in good agreement with *Lifetrack* code (D. Shatilov) predictions.
Electron beam is strong beam, and the crabbed one.

$\xi_y = 0.09$



Strong-Strong Beam-Beam Simulations





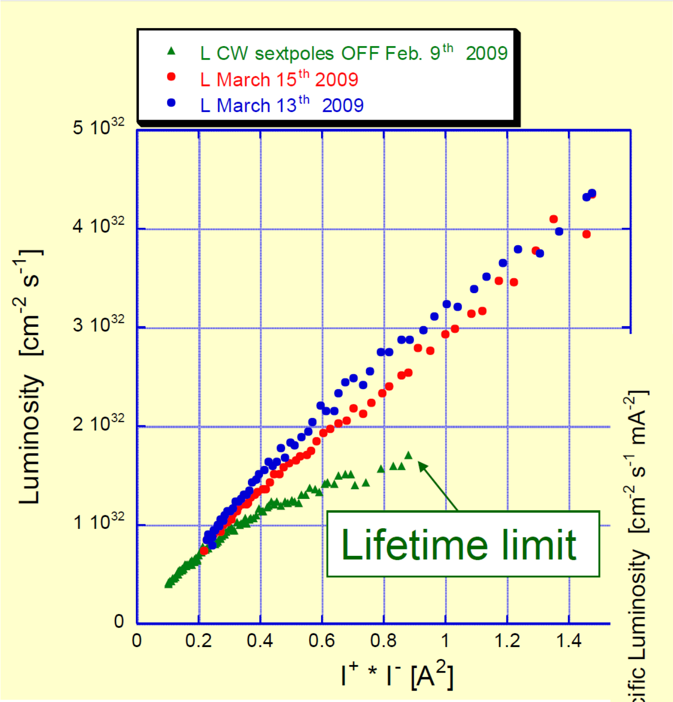
105 bunches

about 20% lower

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

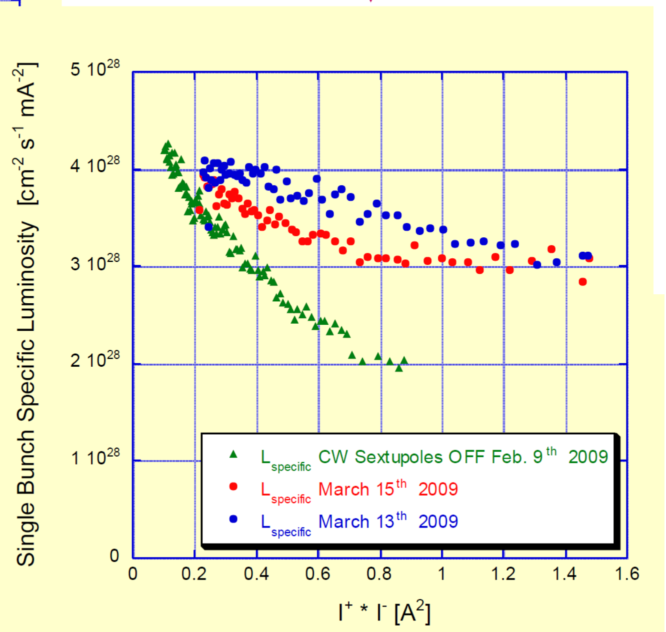
Crab-Waist Compensation, First Experimental Evidence

DAΦNE

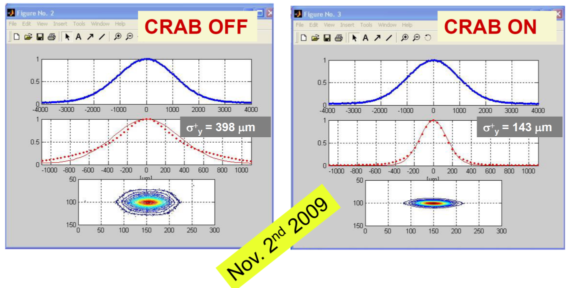


Crab on/off Luminosity vs Current Product

Crab on/off Specific Luminosity vs Current Product

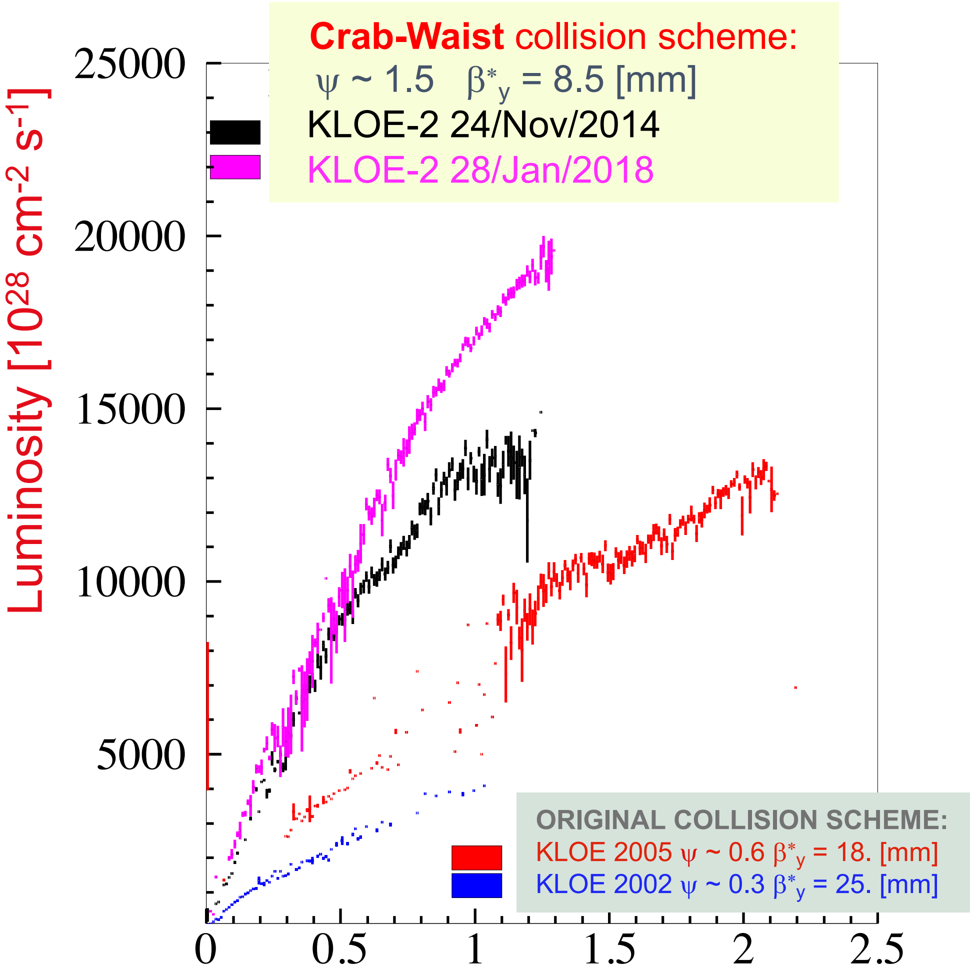


Transverse Beam Profile Measurements



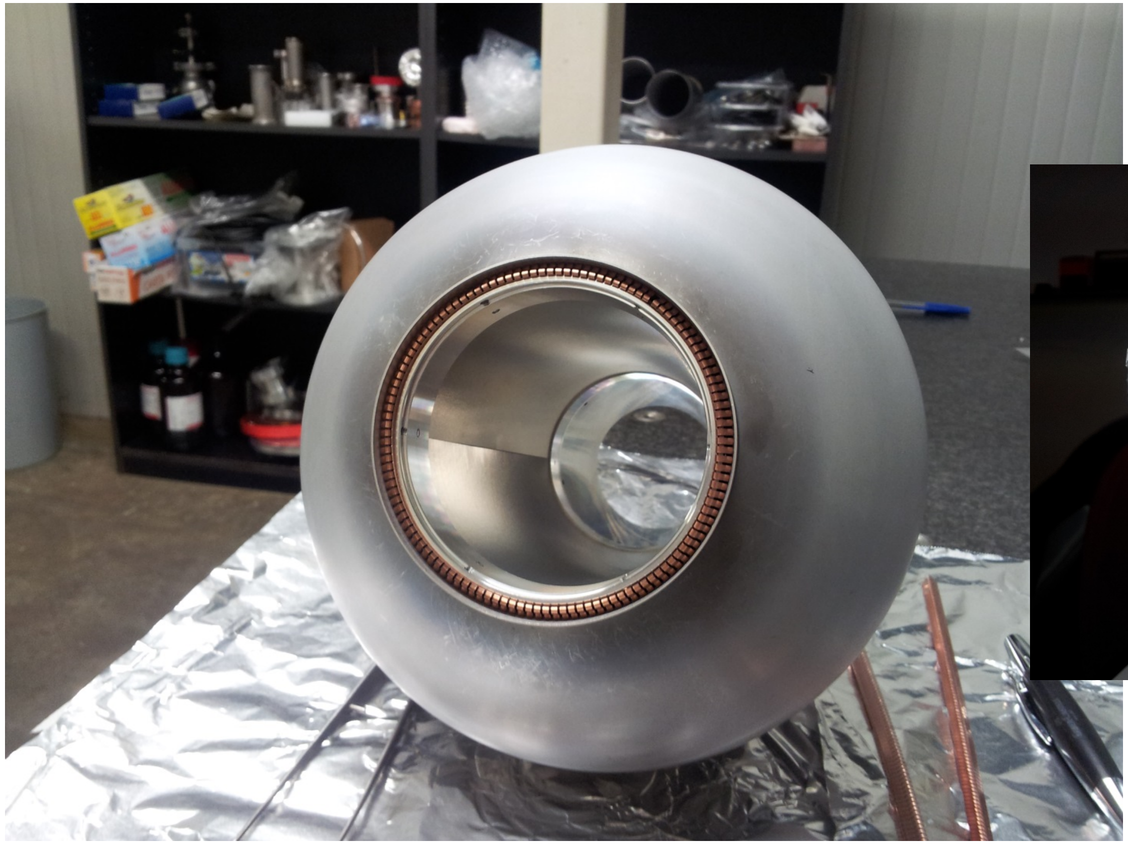
Specific luminosity drop consistent with single beam collective effects

Crab-Waist Luminosity Gain



$$I^+ I^- \frac{N_{harmonic}}{N_{bunches}} \quad [A^2]$$

Spherical Vacuum chamber



- Heating problem affecting the low-β defocusing quadrupole downstream the e-beam has been fixed
- working point stability in operations
- New BPMs allow more accurate beams overlap and transverse betatron coupling studies

Time Managment

Regardless the major upgrade done before starting the run, many relevant measures had to be done during data taking as for instance:

replacement of the Cryo plant compressor

revision of the cooling system serving low-β section and detector electronic equipment

revision of the wiggler magnet cooling system

Linac gun pulser replaced + several mendings

Time originally allocated for machine studies and measurements has been often spent for:

planning interventions suggested by anomalous fault rates in specific subsystems

outlining failures resulting in subtle effects on beam optics and beam dynamics.

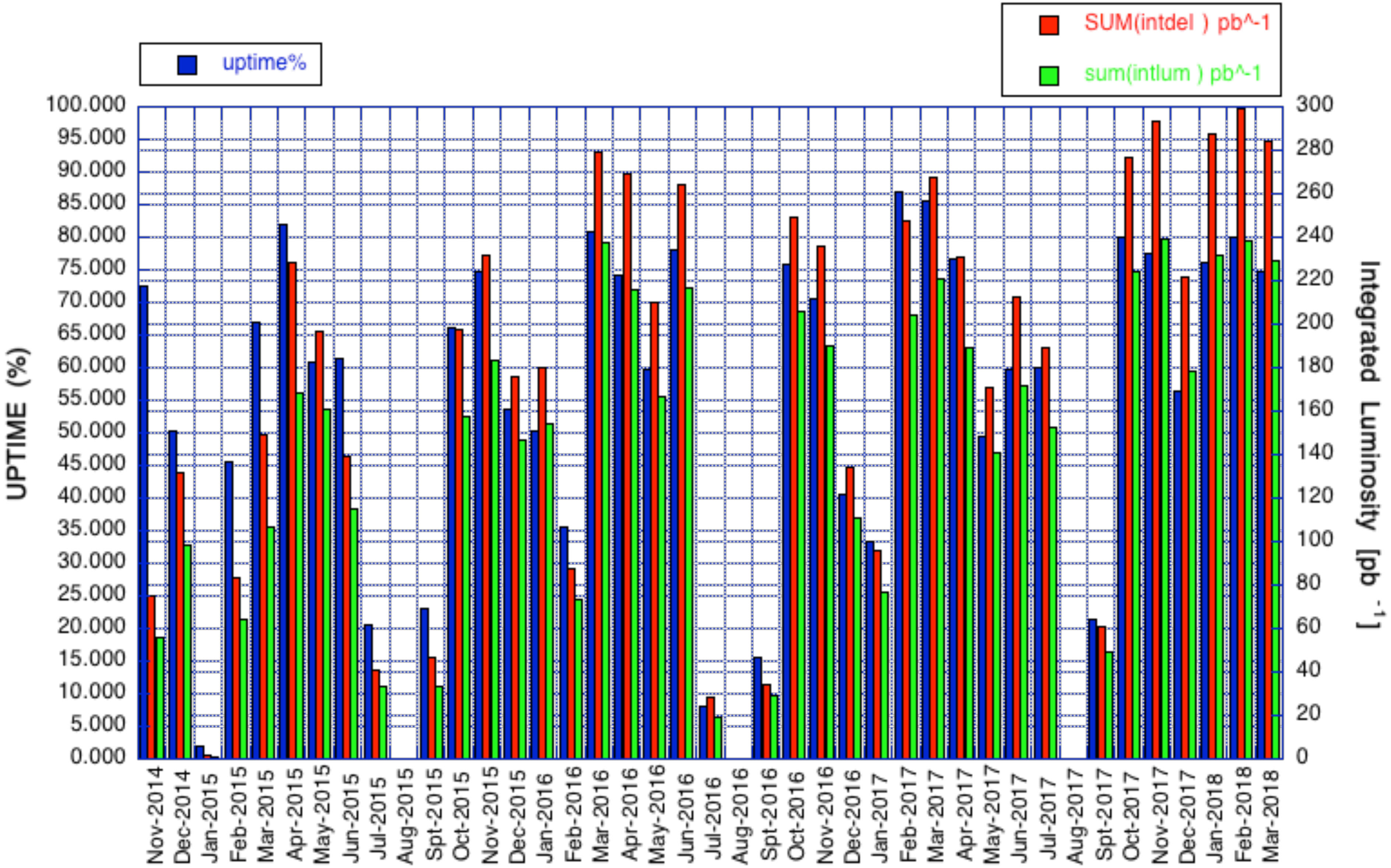
As in the case of the failure affecting the electronic phase shifter in the e^- ring LLRF, which caused the RF phase and consequently the beam, to shift slowly and randomly by about 10 deg

This approach and a considerable lack of manpower did not allow to exploit the DAFNE's full potential as a collider, but assured:

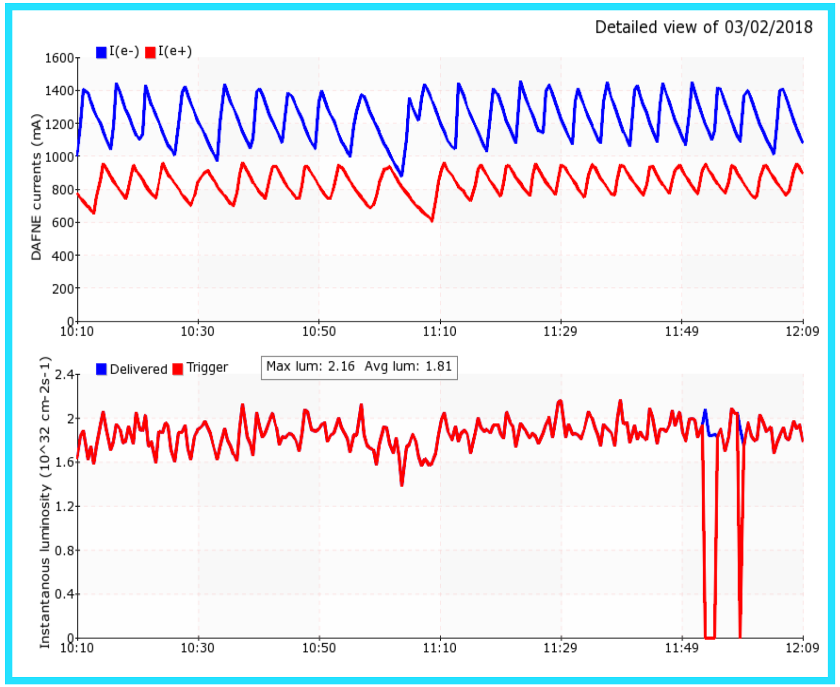
successful data taking

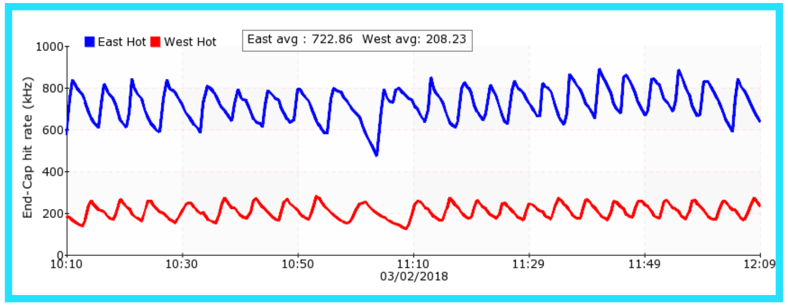
collision uptime of the order of 75%

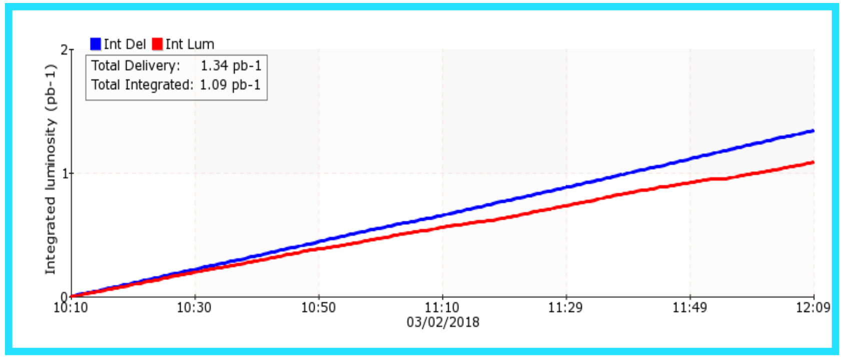
Month by Month Luminosity Trend



Highest Hourly Integrated Luminosity





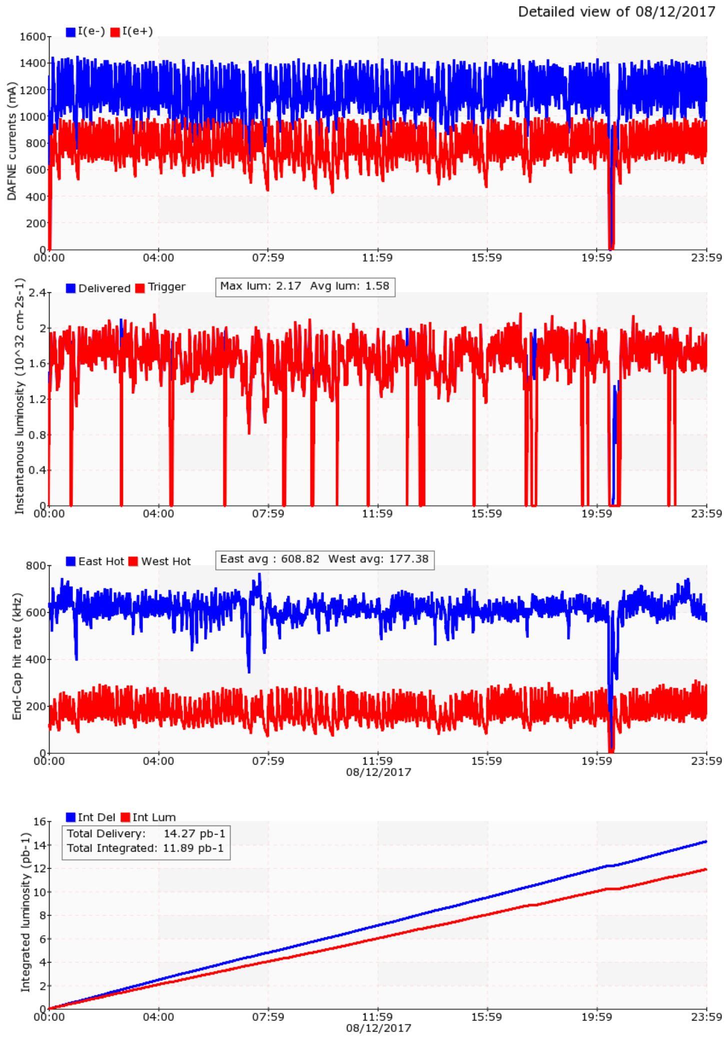


$\int_{1h} L \sim 0.67\ pb^{-1}$

$N_b = 107$

$\int_{1\ day} L \sim 16\ pb^{-1}$

Highest Daily Integrated Luminosity

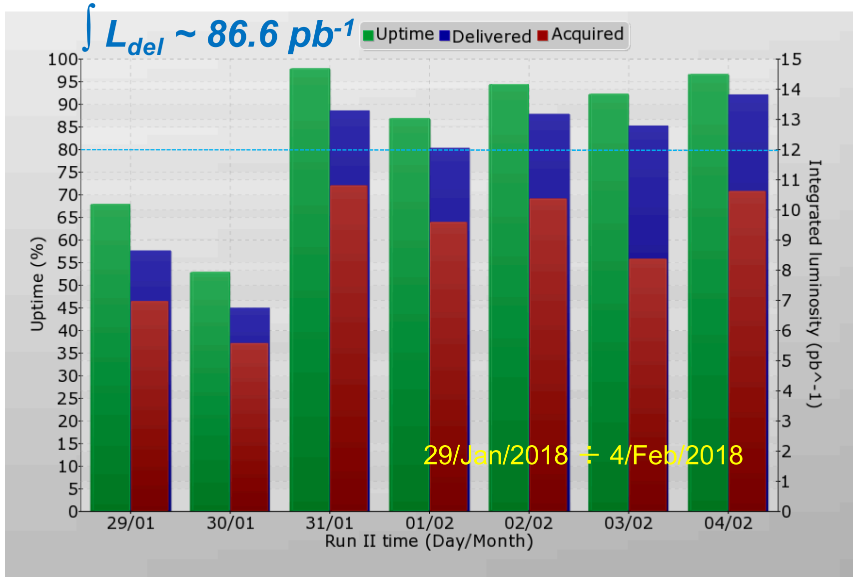


$\int L_{del} \sim 14.3\ pb^{-1}$

$\int L_{acq} \sim 11.9\ pb^{-1}$

Uptime ~98%

- 106 bunches
- Sustainable background



Beam Current Figures

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

* 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 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

Luminosity Achievements

Best $\int_{3h} L = 1.33\ pb^{-1}$

Optimal BCK levels, and L_{HQ} factor.