Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

The DAΦNE lepton Collider

Catia Milardi
Scientific Head of the DAΦNE Accelerator Complex
On behalf of the DAΦNE Team

Outline

- DAΦNE *overview.*
- DAΦNE *experience with the Crab-Waist collision scheme.*
- DAΦNE *activity for High Energy and Nuclear Physics.*
- DAΦNE *achievements and contributions to the physics of particle accelerators.*
- *Conclusions.*

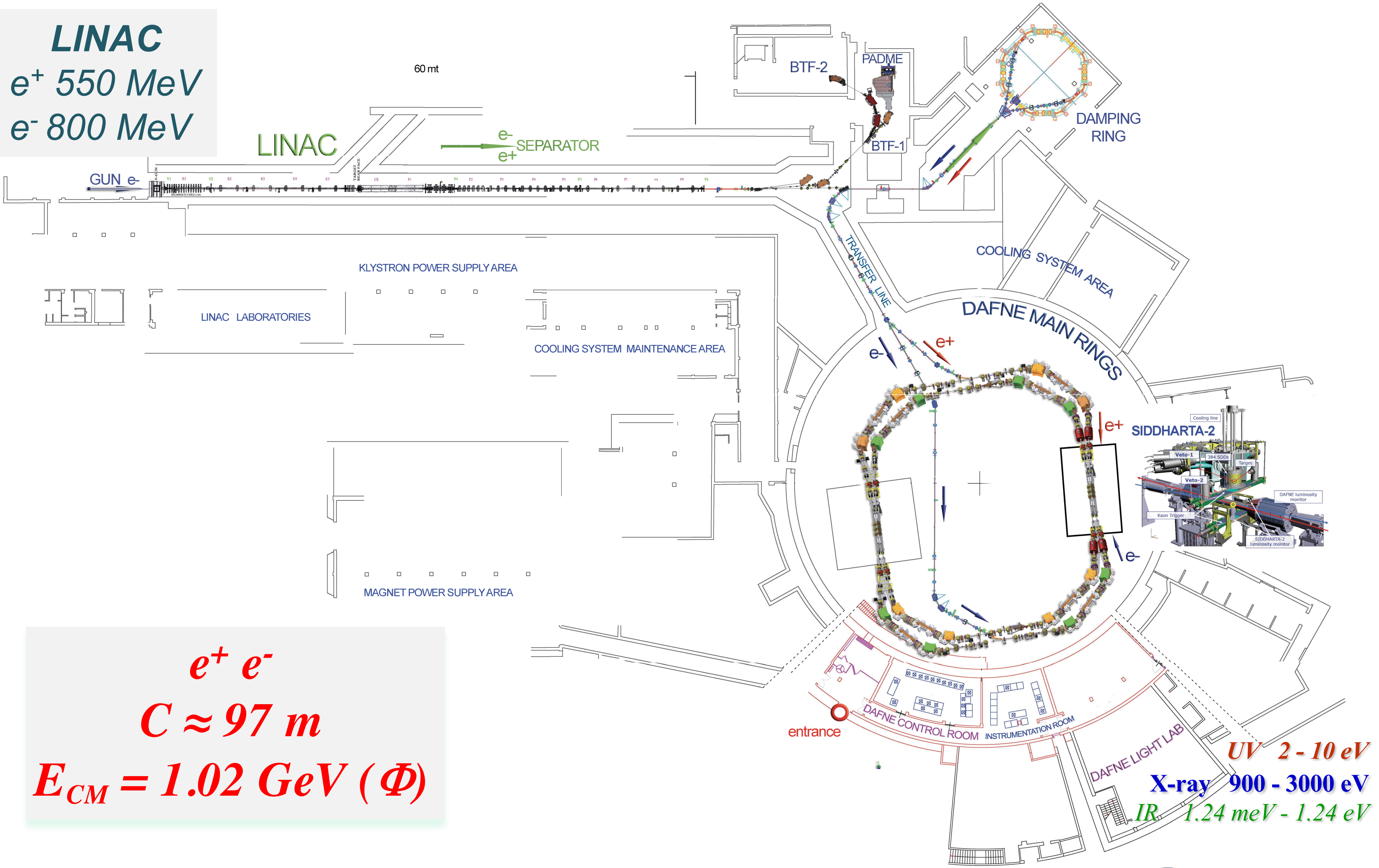
The DAΦNE Accelerator Complex

DAΦNE

LINAC

e^+ 550 MeV

e^- 800 MeV

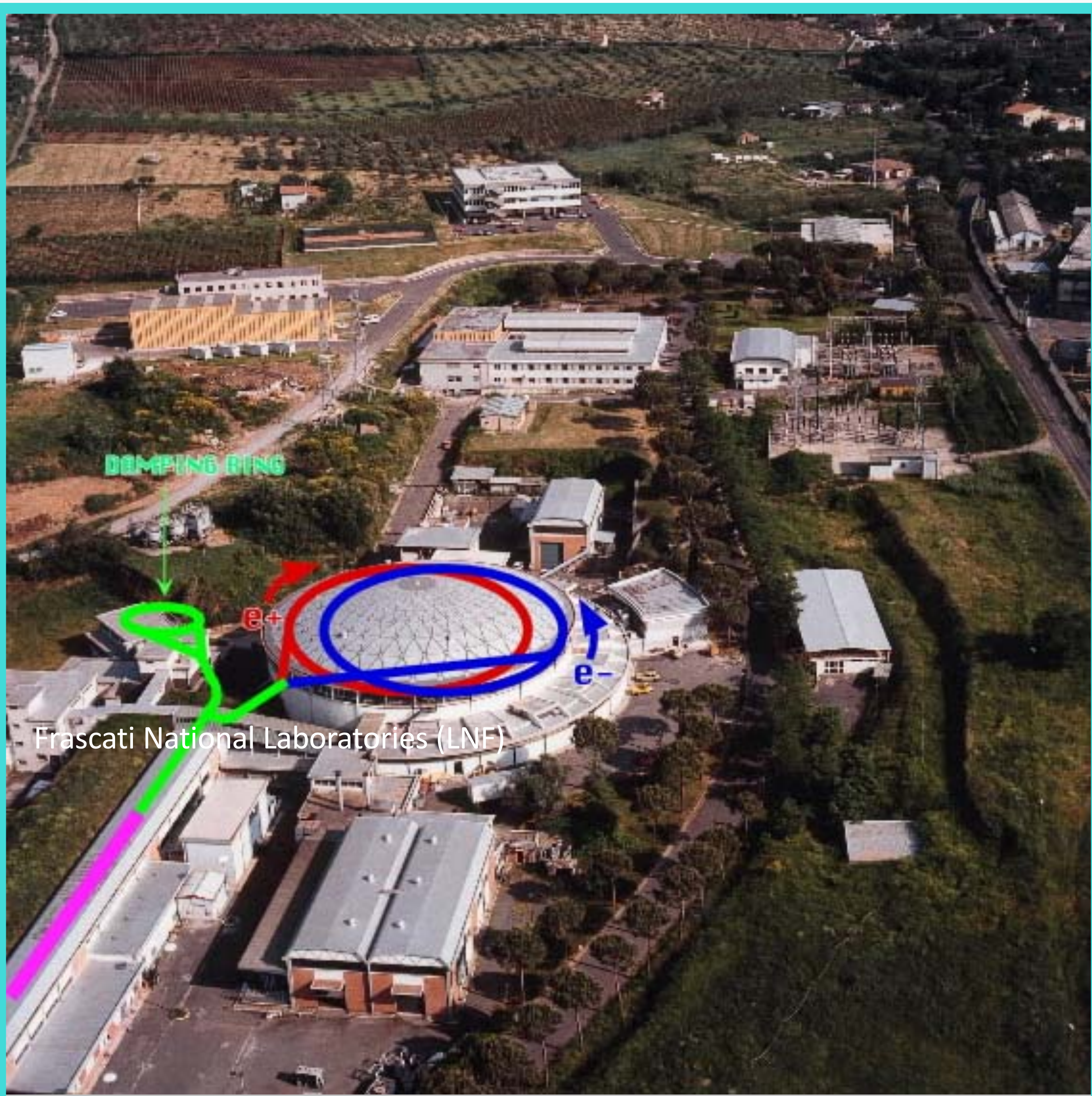


$$e^+ \; e^-$$

$$C \approx 97 \; m$$

$$E_{CM} = 1.02 \; GeV \; (\Phi)$$

LNF Aerial View



DAΦNE History & Plans

- DAΦNE is an electron-positron collider designed in the mid '90s, it came into stable operation in 2001.

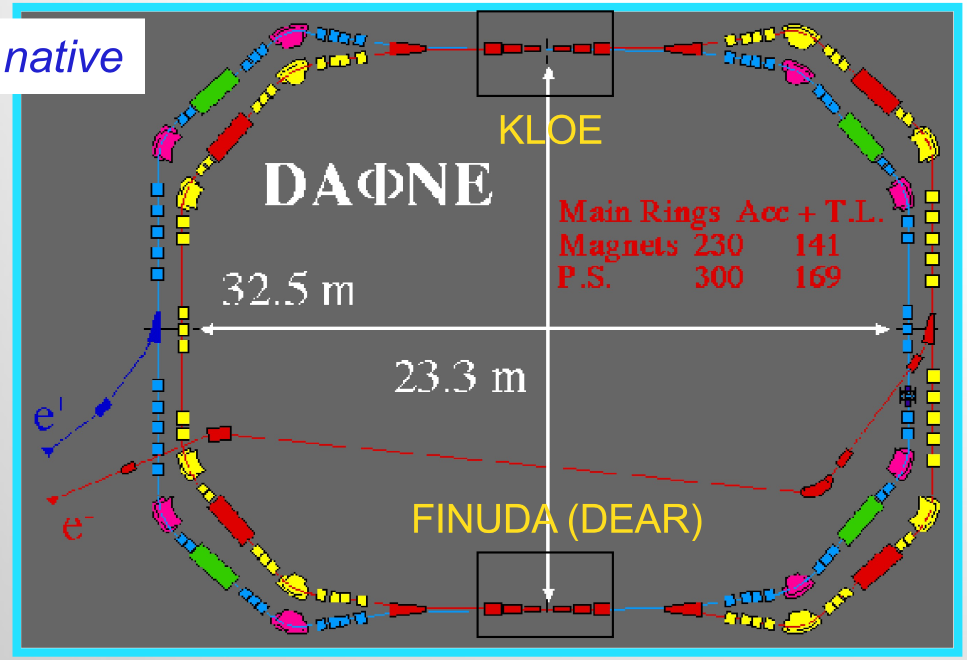
- It has been providing data in independent data-taking periods to:
  KLOE, **DEAR** and **FINUDA** experiments until 2007

  SIDDHARTA in 2008 ÷ 2009 → ***Crab-Waist Collisions Scheme successfully implemented and tested***
  again for the upgraded **KLOE-2** detector between November 2014 and March 2018.

- Present DAΦNE activities:
  as a collider for the SIDDHARTA-2 **experiment,**
  DAFNE-light Facility,
  DAΦNE LINAC is securing data to two **BTF lines,** and the **PADME** experiment.

DAΦNE Main Ring Layout and Parameters

native



"Proposal for a Φ-factory", LNF-90/031 (IR),1990.

DAΦNE Crab-Waist

	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	1.5
β_y^* (cm)	1.80	0.85
σ_y^* (μm) low current	5.4	3.1
Coupling, %	0.5	0.5
Bunch spacing (ns)	2.7	2.7
I_{bunch} (mA)	13	13
σ_z (mm)	25	15
N_b	120	120

Native layout had two IRs based on quadrupole triplet configuration.

Collisions were provided alternatively to each one of the two IRs.

Colliding Rings Main Features

- 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. *partially mitigated*
- *Main IR 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 Main Features

Colliding beams have:

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

Conventional Approach to High Luminosity

$$L = N_b f_0 \frac{N^2}{4\pi\sigma_x^*\sigma_y^*} \qquad \xi_{x,y} = \frac{N r_e}{2\pi\gamma}\frac{\beta_{x,y}^*}{\sigma_{x,y}^*\left(\sigma_x^* + \sigma_y^*\right)} \qquad L = N_b f_0 \frac{\pi\gamma^2\xi_x\xi_y\varepsilon_x}{r_e^2\beta_y^*}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)^2$$

Small $\boldsymbol{\beta_y^*}$

Higher number of particle per bunch $\boldsymbol{N}$

More bunches $\boldsymbol{N_b}$

Higher tune shift $\boldsymbol{\xi_{x,y}}$

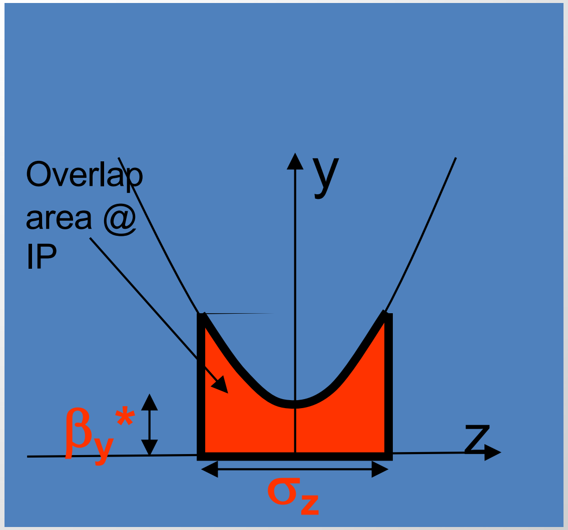
Greater horizontal rms beam size $\boldsymbol{\sigma_x}$

Small crossing angle $\boldsymbol{\theta_x}$

Small Piwinsky angle $\boldsymbol{\Phi = \frac{\sigma_z}{\sigma_x}\tan\frac{\theta_x}{2} < 1}$

Conventional Approach Limitations

$\boldsymbol{\beta_y^* \sim \sigma_z}$ to avoid hourglass effect



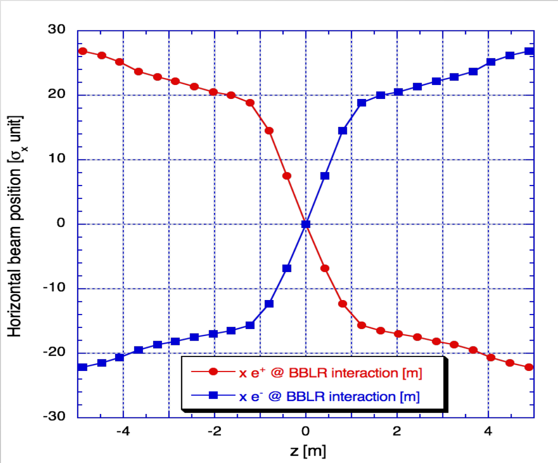
$\boldsymbol{\sigma_z}$ reduction led to:

- single bunch instability
- bunch lengthening and microwave instabilities
- CSR production

Higher $\boldsymbol{N}$ and $\boldsymbol{N_b}$

- led to enhanced power losses
- increase wall plug power requirements
- causes coupled bunch instabilities

Tune shifts $\boldsymbol{\xi_{x,y}}$ are constrained by beam-beam limit



Larger $\boldsymbol{\sigma_x}$ conflicts with

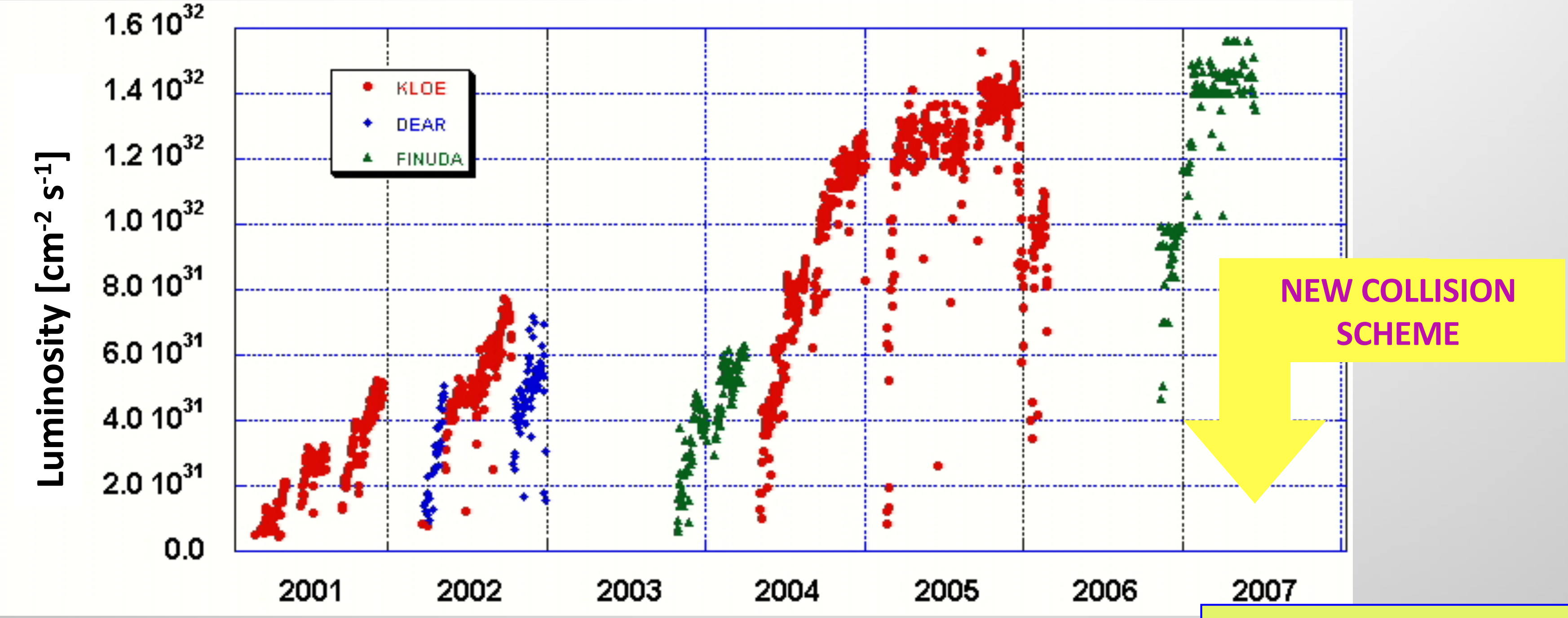
- beam stay clear and dynamical aperture requirements

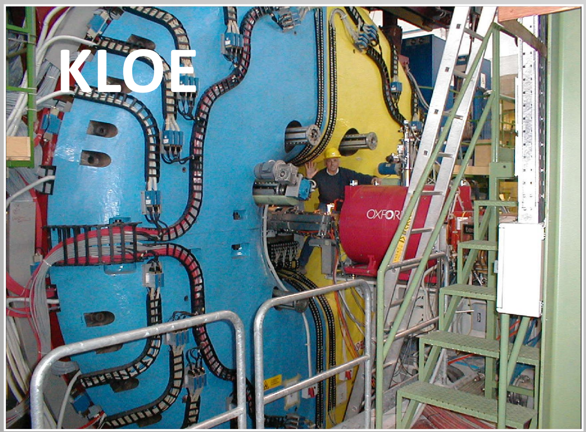
Long-range beam-beam interactions causing τ^+ τ^- reduction limiting I^+_{MAX} I^-_{MAX} and -> L_{peak} and $L_\int$

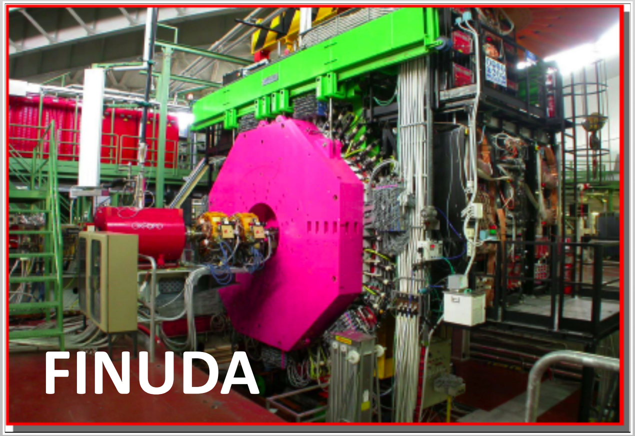
L_{peak} at DAΦNE 2001 ÷ 2007

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

Experiments took data one at the time, although DAΦNE had been originally conceived as collider with two IRs







L_{logged} (fb^{-1}) 2001÷2007

KLOE	3.0
FINUDA	1.2
DEAR	0.2

Crab-Waist Collision Scheme

Large Piwinski angle

Horizontal crossing angle θ

Large Piwinski angle Φ

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

large θ
small σ_x

New IR layout
Lower beam ε

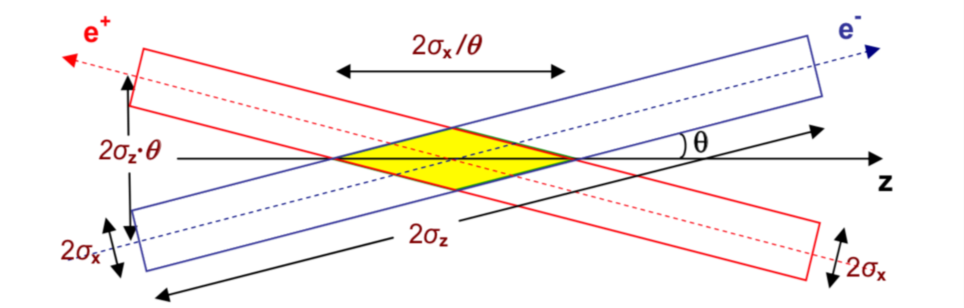
$$\xi_y \propto \frac{N\sqrt{\beta_y^*}}{\sigma_z \theta} \qquad \xi_x \propto \frac{N}{(\sigma_z \theta)^2} \qquad L \propto \frac{N \xi_y}{\beta_y^*}$$

- lower ξ_x (tune shift)
- $L_{geometric}$ gain

β_y^* can be reduced down 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

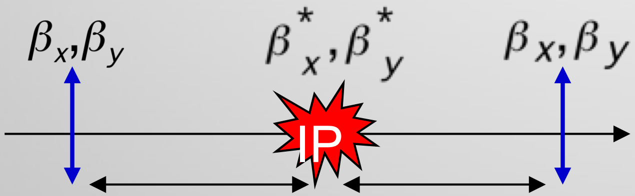
Crab-Waist transformation is

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.

Powerful Sextupoles
Proper IR optics

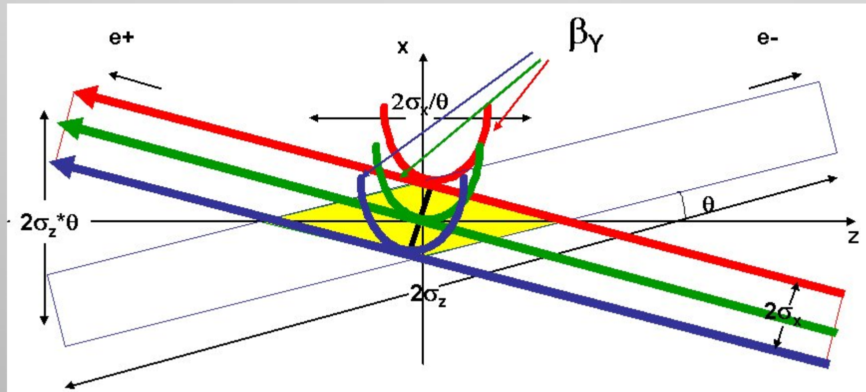
$$y = \frac{xy'}{2\theta}$$

sextupole (anti)sextupole



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

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



without CW Sextupoles

Large Piwinski angle

Collisions with large θ is not a new idea

Crab-Waist transformation it is

P. Raimondi , 2° *SuperB Workshop, March 2006,*
P.Raimondi, D.Shatilov, M.Zobov, physics/0702033,
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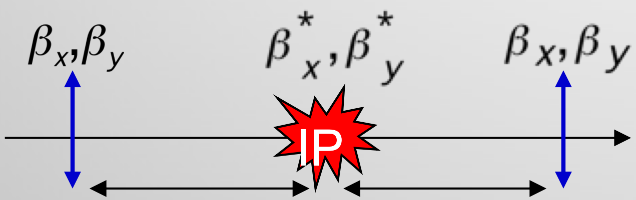
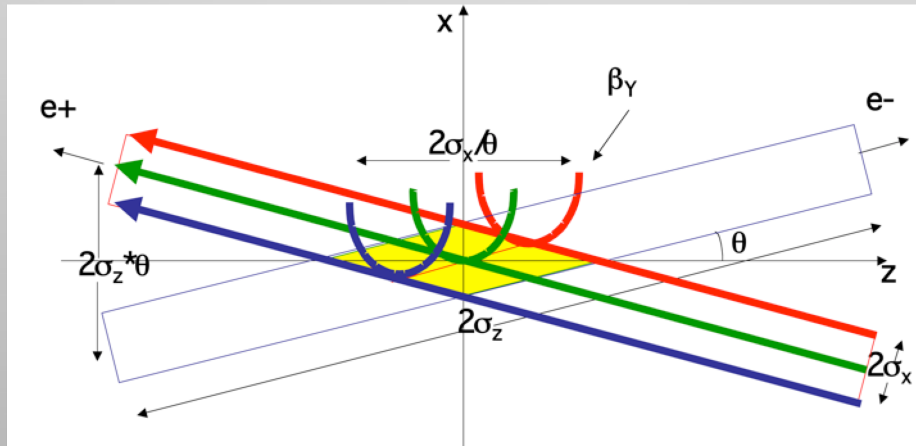


$$\Delta\nu_x = \pi$$
$$\Delta\nu_y = \frac{\pi}{2}$$

- $L_{geometric}$ gain
- X-Y and synchro-betatron resonances suppression

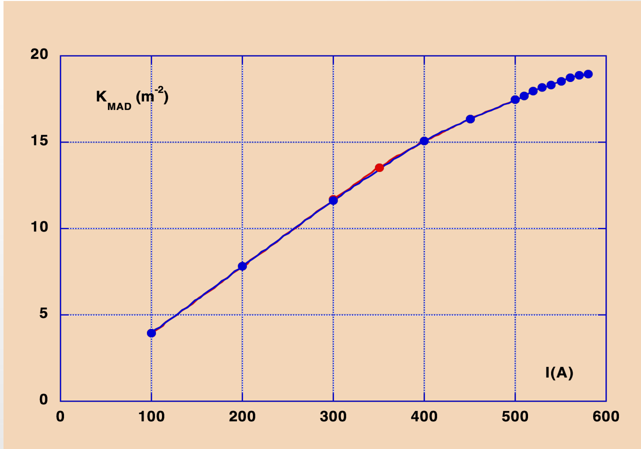


with CW Sextupoles

Crab-Waist Sextupole Parameters at DAΦNE

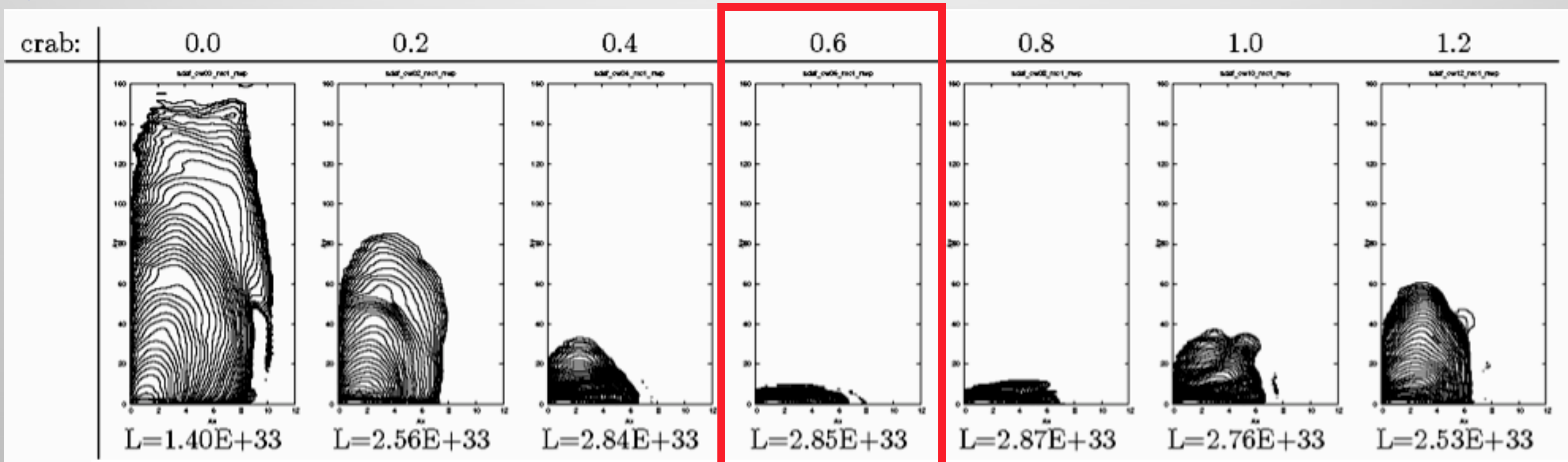
CW-Sextupoles are high strength magnets

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



χ nominal 0.6

χ used value 0.5



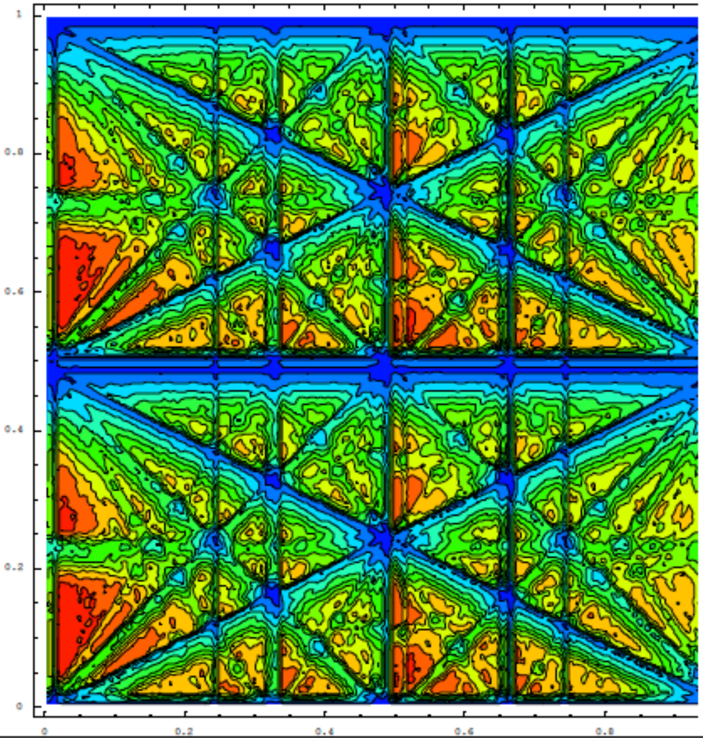
L = 0.491	L = 0.898	L = 0.996	L = 1.	L = 1.007	L = 0.968	L = 0.888

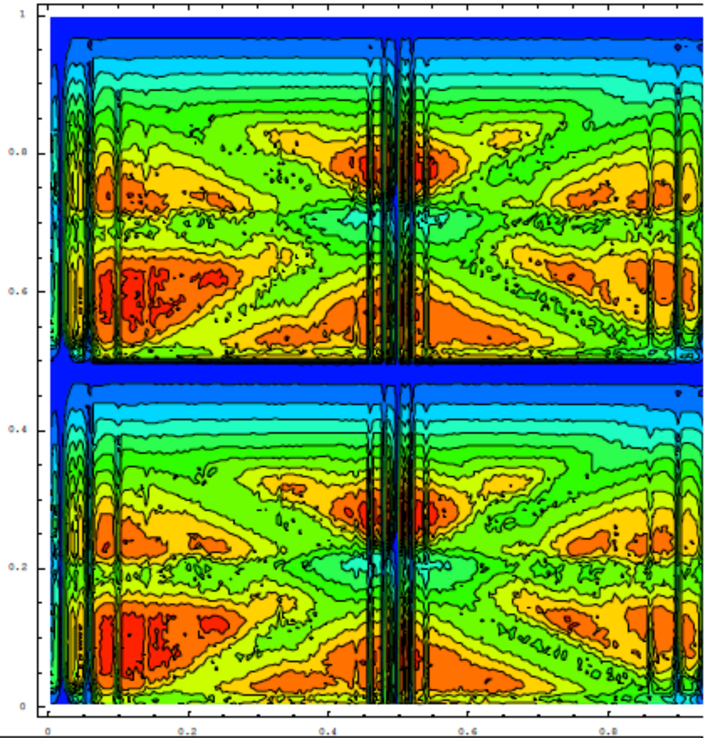
Lifetrack D. Shatilov

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

Suppression of X-Y Resonances

Much higher luminosity!





Typical case (KEKB, DAΦNE etc.):	Crab Waist On:
1. low Piwinski angle $\Phi < 1$	1. large Piwinski angle $\Phi >> 1$
2. β_y comparable with σ_z	2. β_y comparable with σ_x/θ

Crab-Waist IR for SIDDHARTA

Large Piwinski angle Φ **obtained by:**

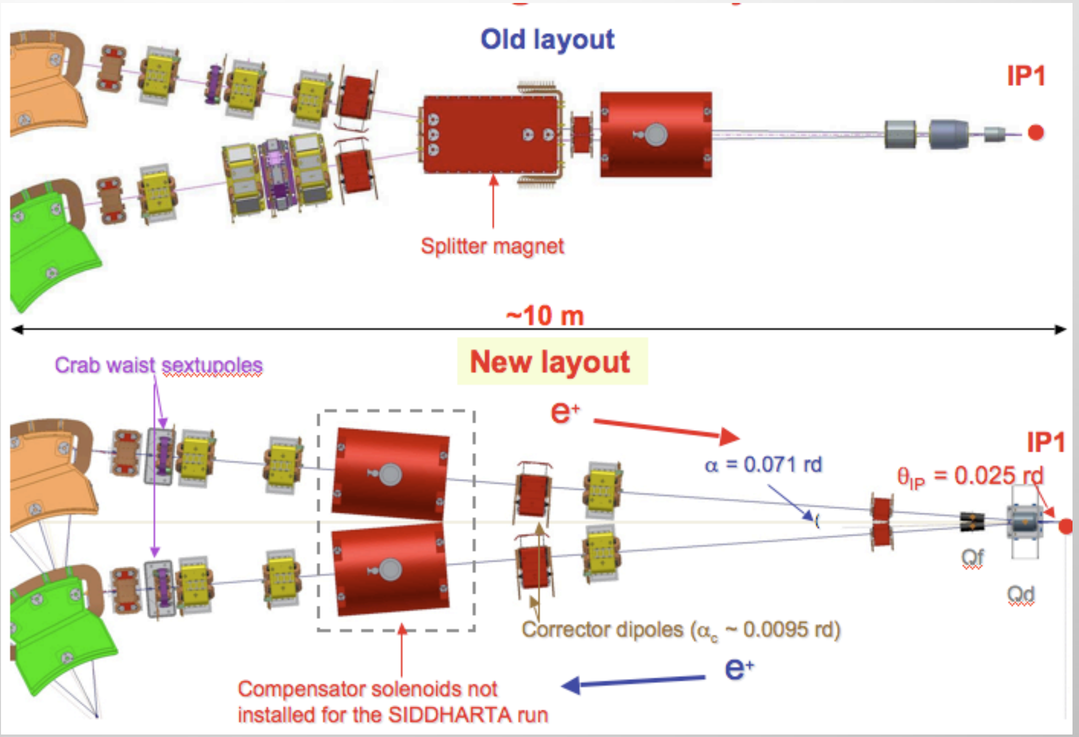
$$\Phi \approx \frac{\sigma_z}{\sigma^*_x}\frac{\theta}{2}$$

small σ_x

large θ

New IR magnetic layout

- Splitter magnets and compensator solenoids removed
- New low-β
- Sector dipols around IP rotated
- large collision angle ~ 50 mrd
- Four C type corrector dipoles used to mach the vacuum chamber in the arc

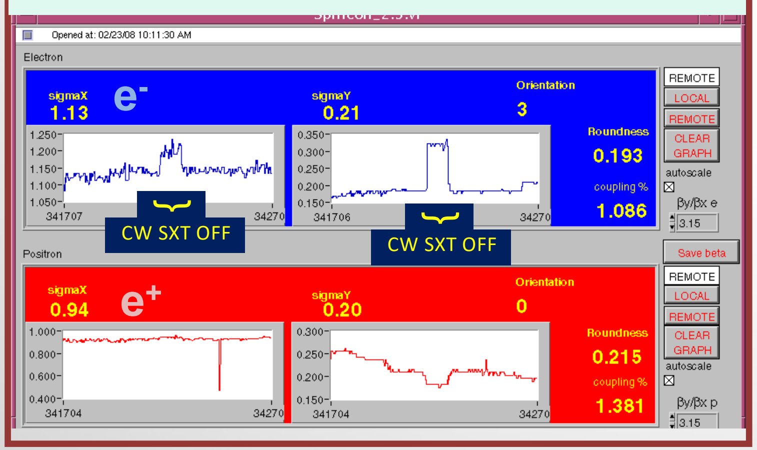


- *In 2007 the DAΦNE accelerator complex has been upgraded in order to implement a new collision scheme based on* ***large Piwinski angle, low–beta*** *and* ***Crab-Waist compensation*** *of the synchrobetatron resonances*
- *The upgrade took ~* ***five months***
- ***Since May 2008*** *DAΦNE was delivering luminosity to the SIDDHARTA experiment.*

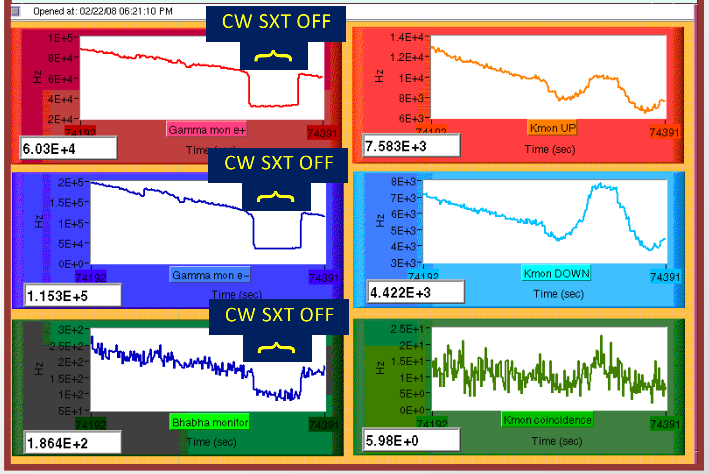
Crab-Waist Achievements during SIDDHARTA Run

Crab-Waist Compensation First Experimental Evidence

Beam transverse size measured at the SLM

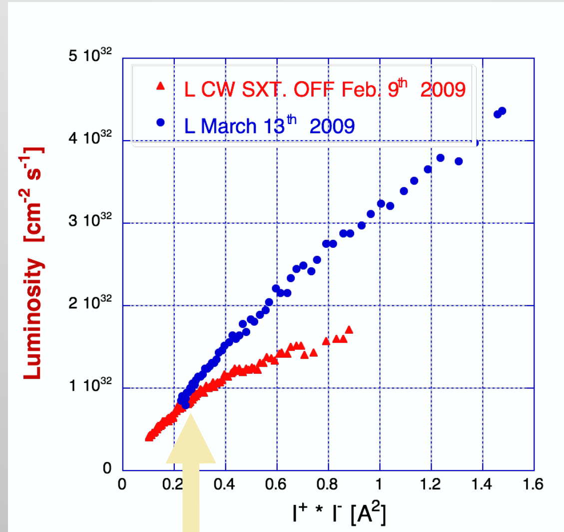


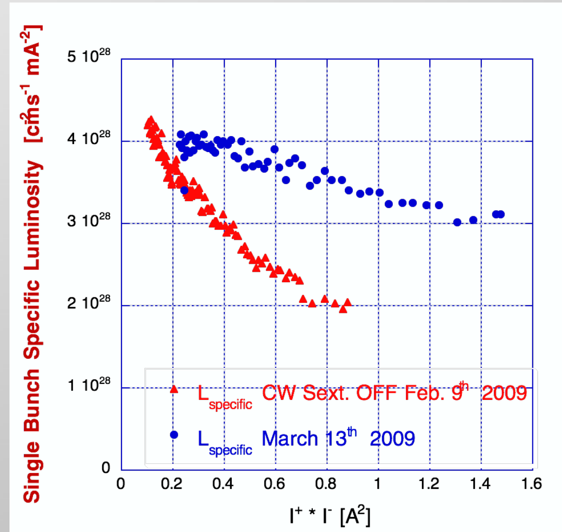
Luminosity from 2 different monitors



Transverse sizes (left) and **luminosity** (right) dependence on the ***CW-Sextupole* excitation** in the e⁻ ring

Luminosity as a function of colliding currents *CW-Sextupole* excitation



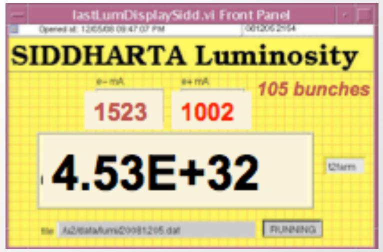


- Transverse beam blow-up
- Lifetime reduction

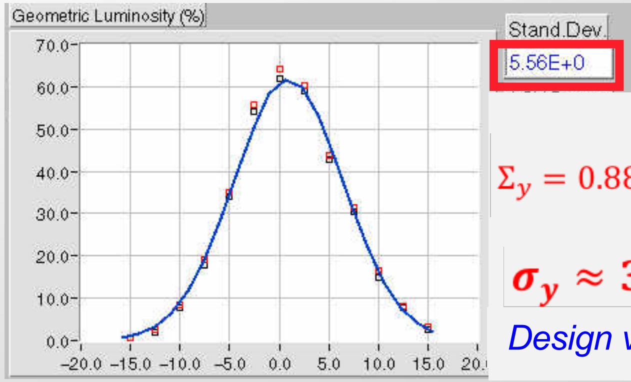
Crab-Waist collisions and SIDDHARTA

- 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*, has been successfully commissioned achieving record performances



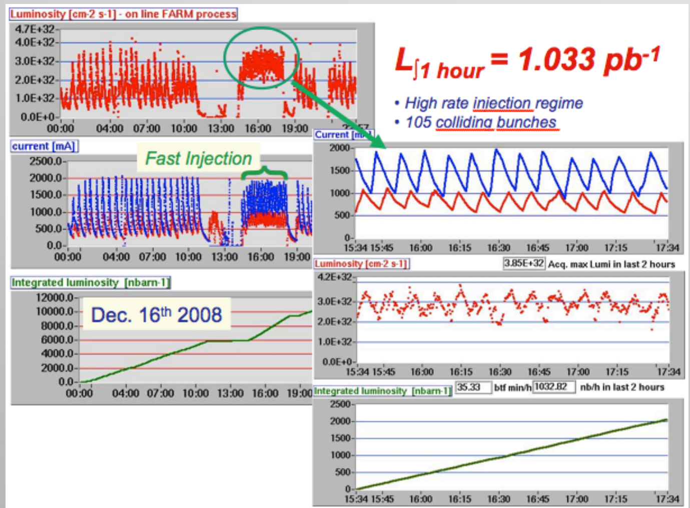
L_{peak}= 4.5*10^{32} cm^{-2} s^{-1}
$L_{\int 1\ day}$= 15.0 pb^{-1}
$L_{\int 1\ hour}$ = 1.033 pb^{-1}
$L_{\int run}$~ 2.8 fb^{-1} (delivered in 18 months)

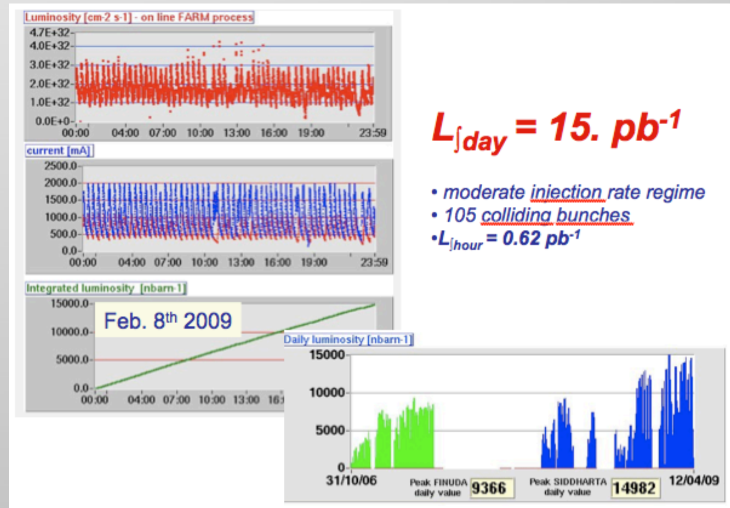


$$\Sigma_y = 0.88\sqrt{\sigma^2_{Ypos} + \sigma^2_{Yele}}$$

$$\boldsymbol{\sigma_y \approx 3.5\mu m}$$

Design value 3.1μm

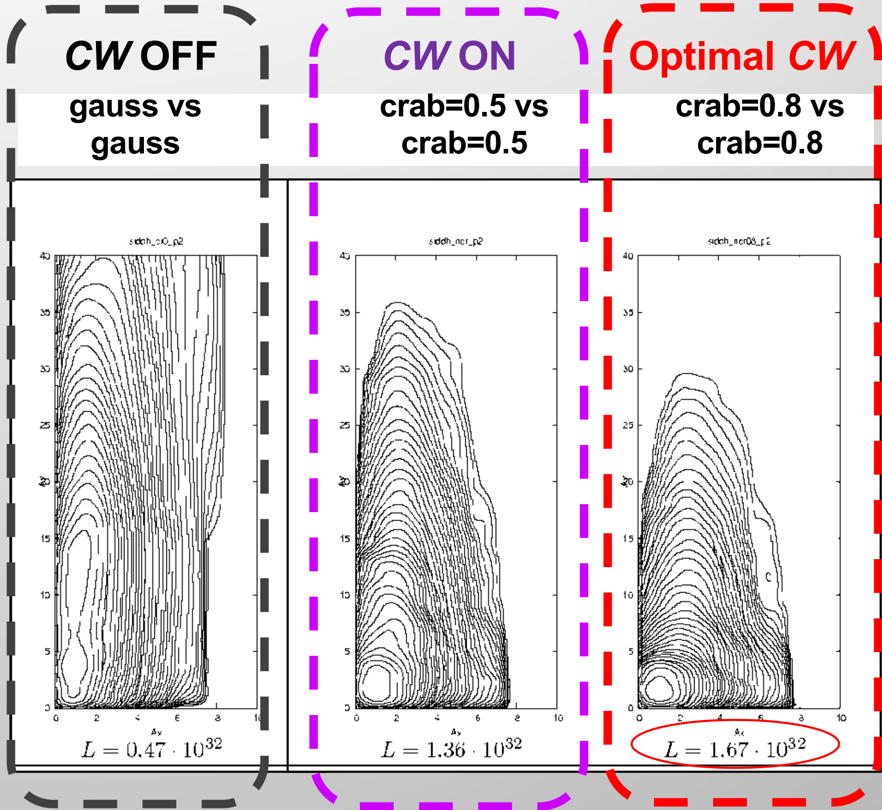




Weak-Strong Simulations

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.

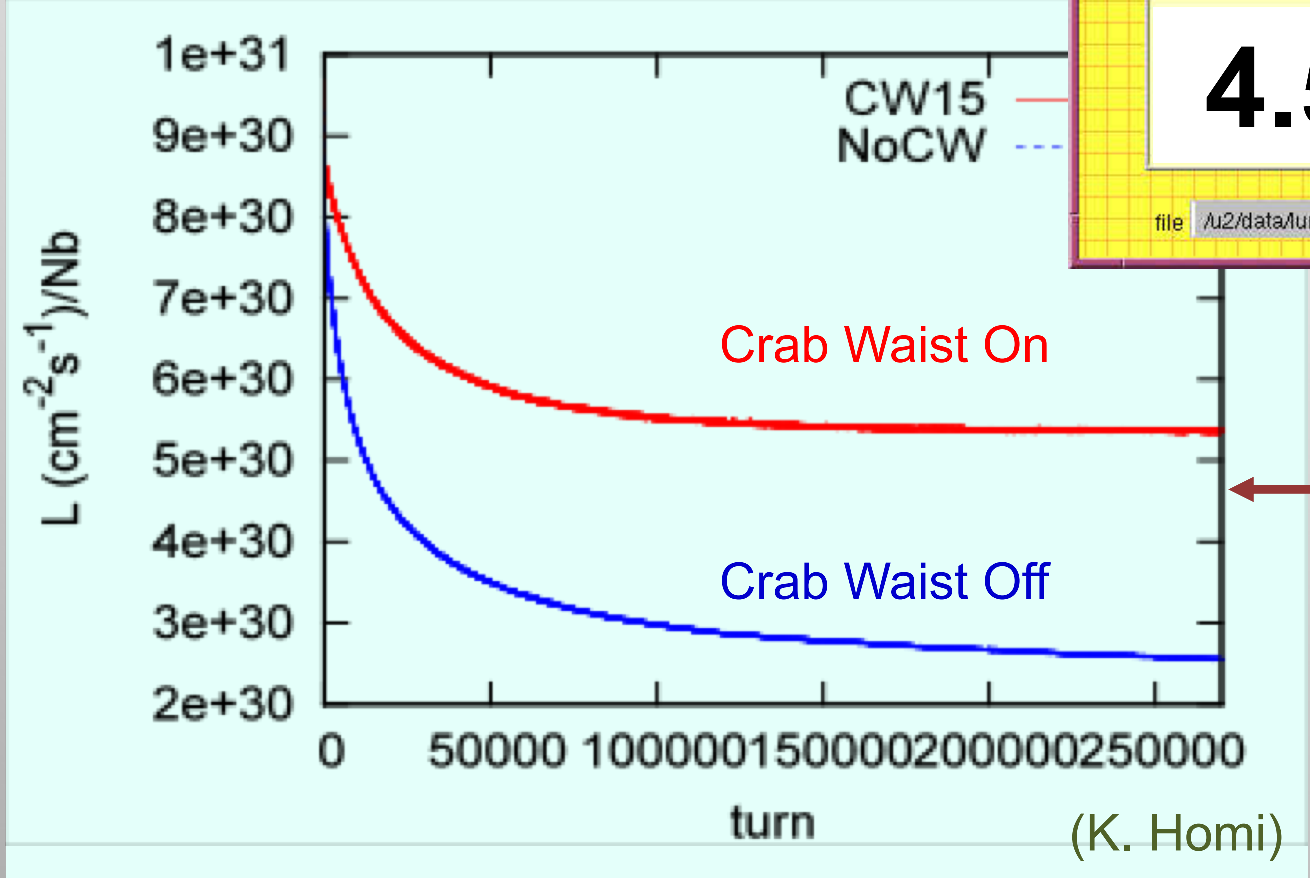
$\xi_y = 0.09$



Strong-Strong Beam-Beam Simulations

Single Bunch Luminosity

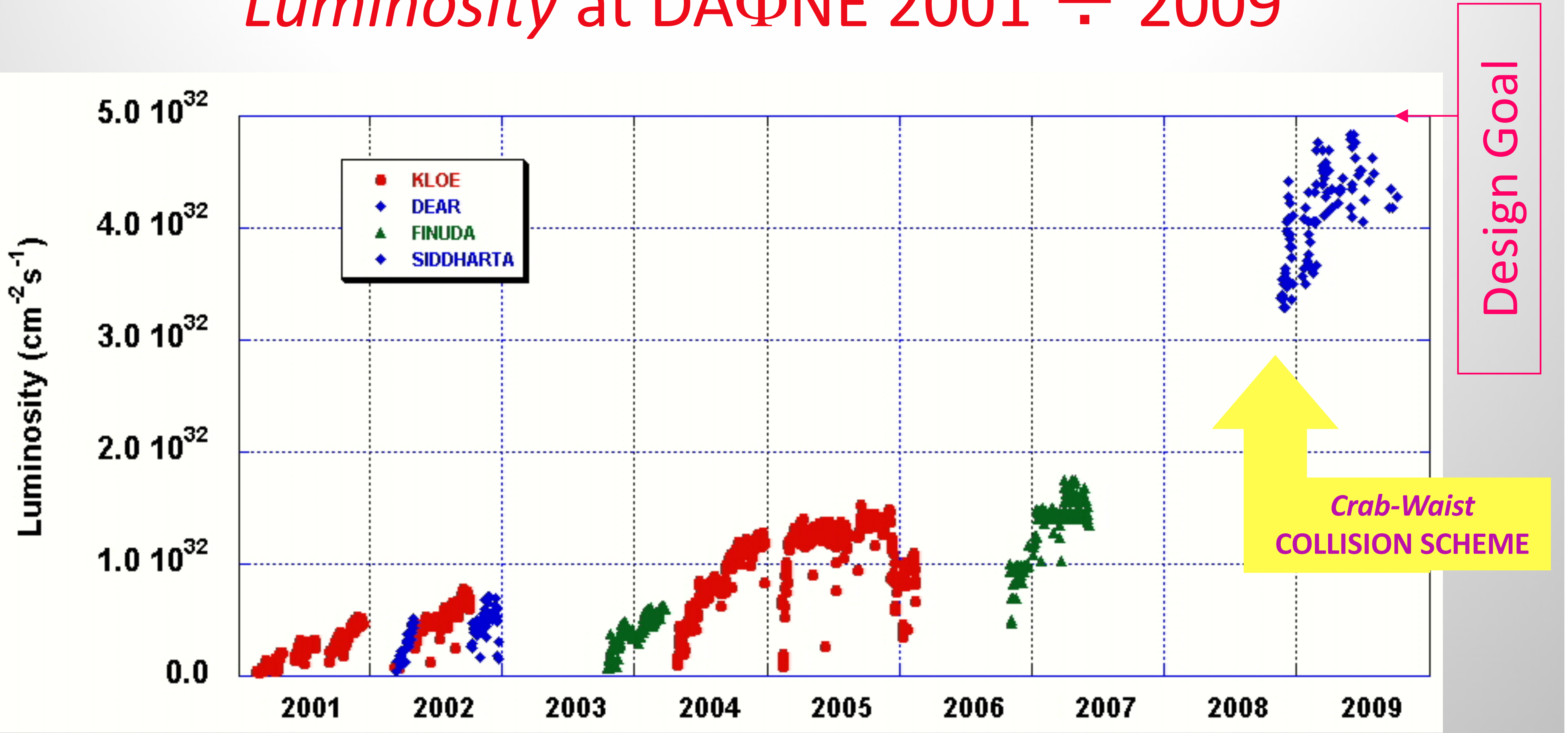
(Damping time = 110.000 turns)



105 bunches

about 20% lower

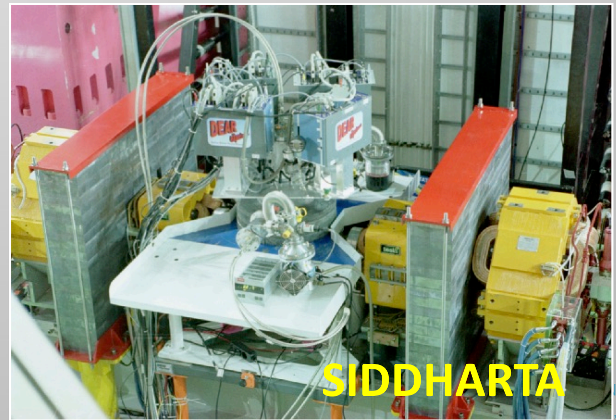
Luminosity at DAΦNE 2001 ÷ 2009



A factor 3 higher luminosity achieved without increasing beam currents

No evidence of vertical BB saturation with *CW-Sextupoles* on (ξ_y = 0.044)

LRBB interaction cancelled



Crab-Waist Achievements during KLOE-2 Run

CW-Collision scheme for the KLOE detector

Integrating the high luminosity collision scheme with a large experimental detector introduces new ***technological*** and ***accelerator physics challenges***: mechanic setup, cooling, IR layout, optics, beam acceptance, coupling correction …

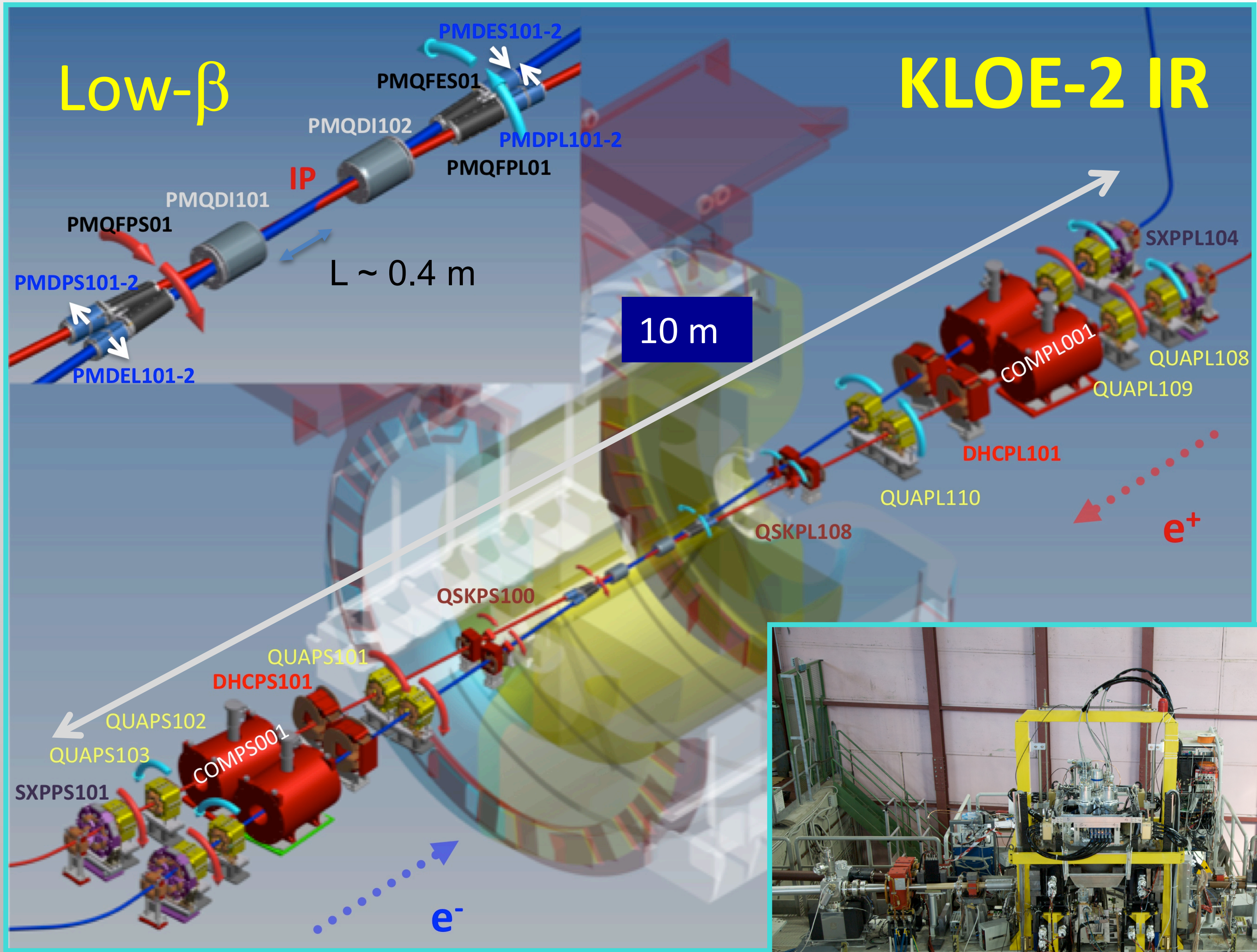
Crucial Points:

IR optics complying with:

- Low-β
- ***Crab-Waist*** collision scheme
- Coupling compensation
- Beam trajectory control

IR mechanical design allowing:

- Large crossing angle
- Early vacuum pipe separation after IP
- Mechanical stability of the low-β doublet



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

Betatron Coupling correction

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

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

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

In order to have coupling compensation also for off-energy particles

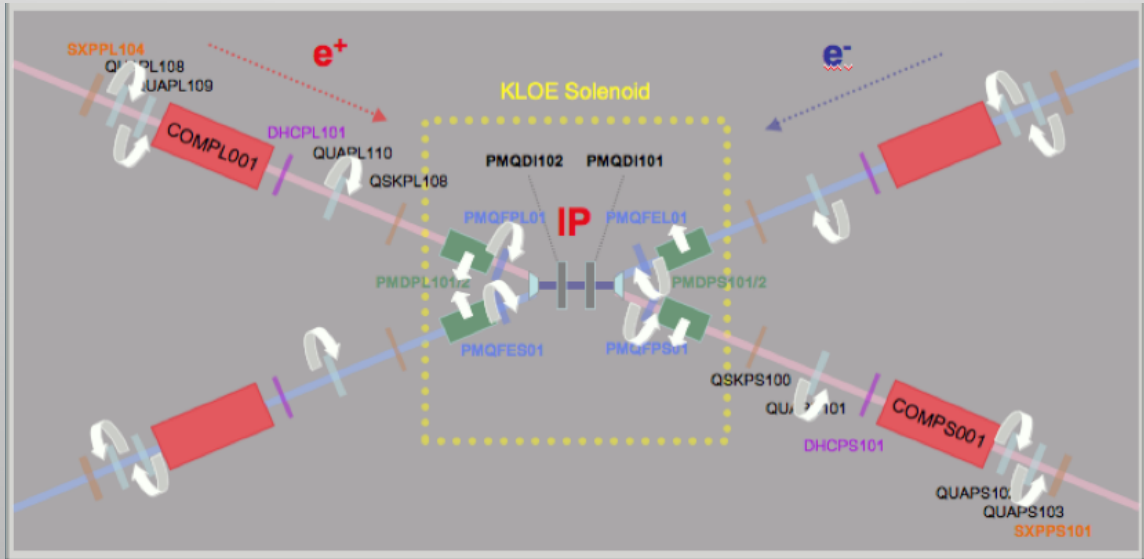
Fixed QUAD rotations

K is expected to be lower than for KLOE past

$$K_{KLOE1} = 0.2 \div 0.3 \ \%$$

	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)*

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



DAΦNE Activity Program for KLOE-2

Preliminary Test Phase *fall 2010 ÷ Dec 2012*

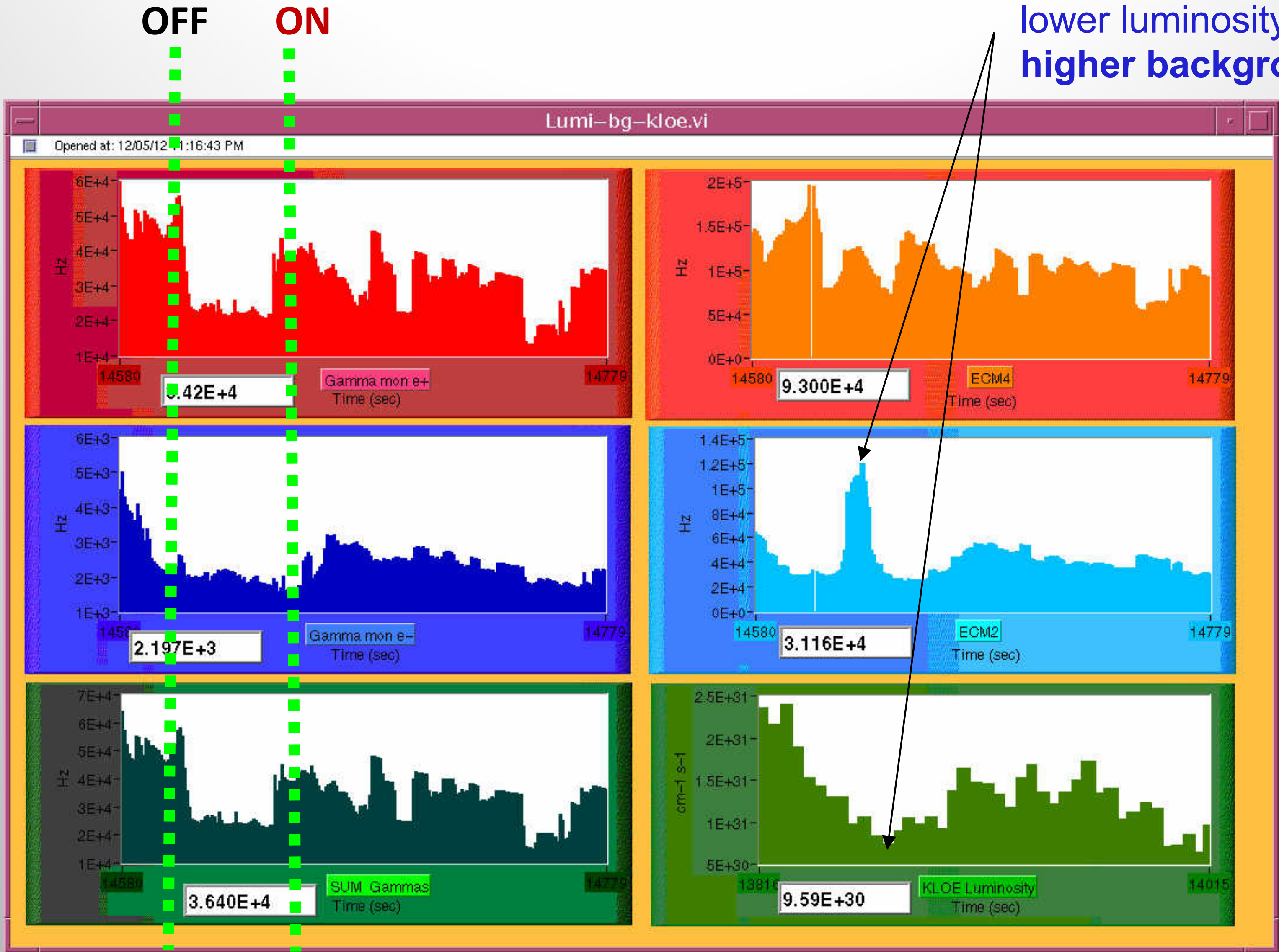
Collider Consolidation
KLOE-2 detector layers installed *Dec 2012 ÷ Jun 2013*

KLOE-2 data taking

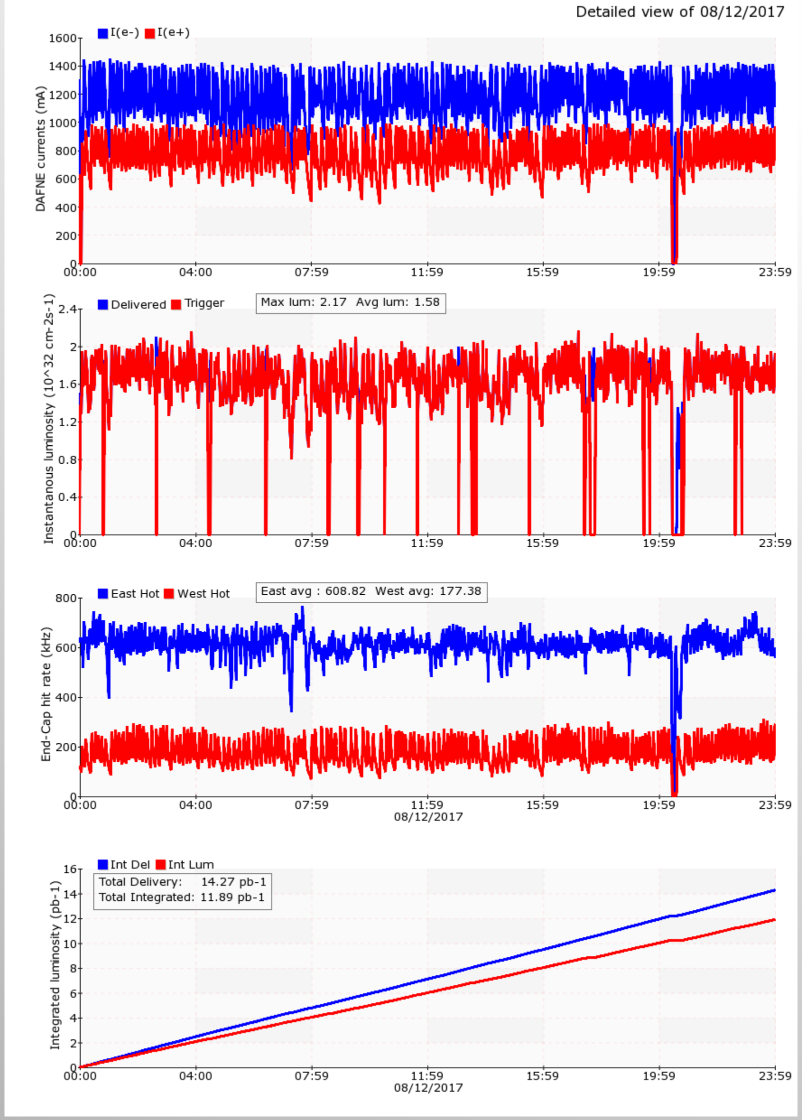
I Run *Nov 16th 2014 ÷ Jul 3rd 2015*
goal 1 fb^{-1}
II Run *Spt 28th 2015 ÷ Jun 29th 2016*
goal 1.5 fb^{-1}
III Run Spt 12nd 2016 ÷ Aug 1st 2017
goal 2 fb^{-1}
IV Run *Spt 6th 2017 ÷ Mar 31st 2018*
goal 1.5 fb^{-1}

Impact of Crab-Waist Sextupoles on Collisions

With Crab-Waist Sextupoles OFF:
lower luminosity
higher background



Highest Daily Integrated Luminosity

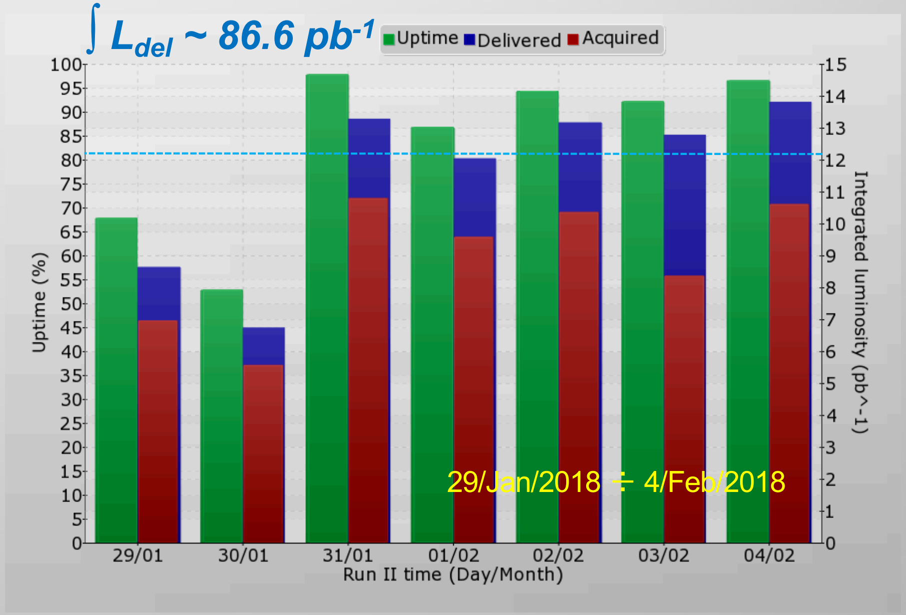


$\int L_{del} \sim 14.3\ pb^{-1}$

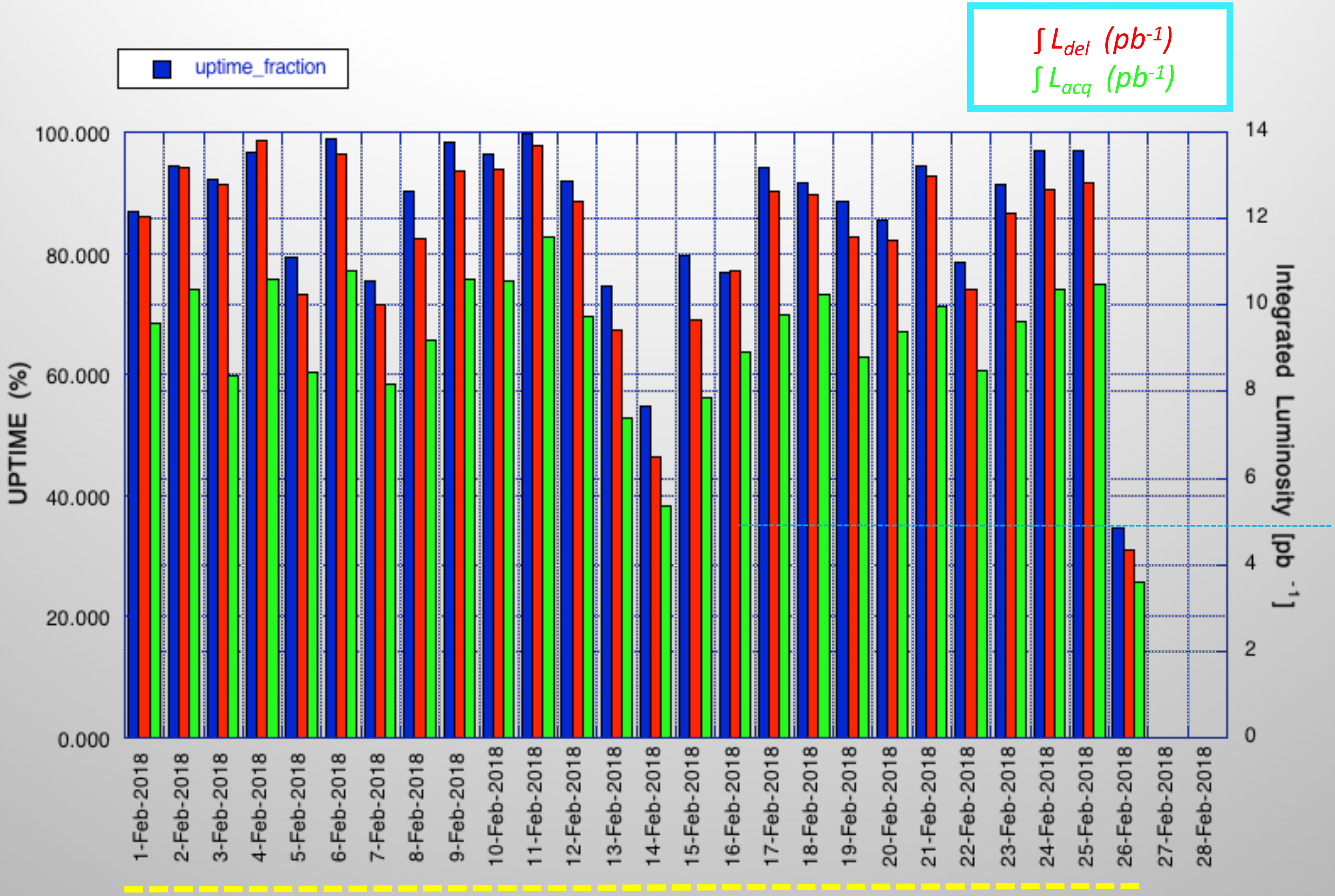
$\int L_{acq} \sim 11.9\ pb^{-1}$

Uptime ~98%

- 106 bunches
- Sustainable background

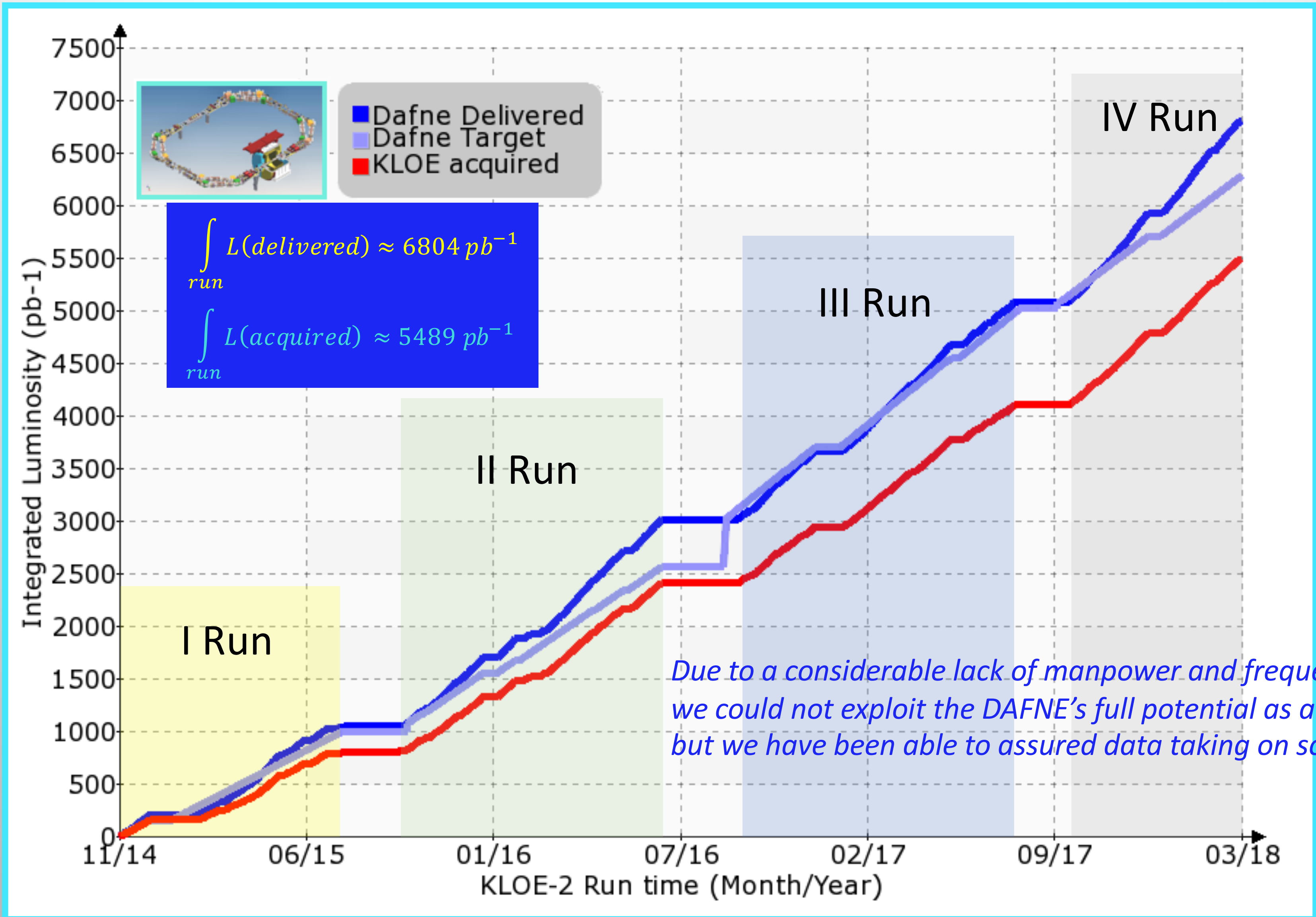


Best Operations Month



$\int L_{del}$ ~ 300 (pb^{-1}) in 26 days

KLOE-2 Run Overview

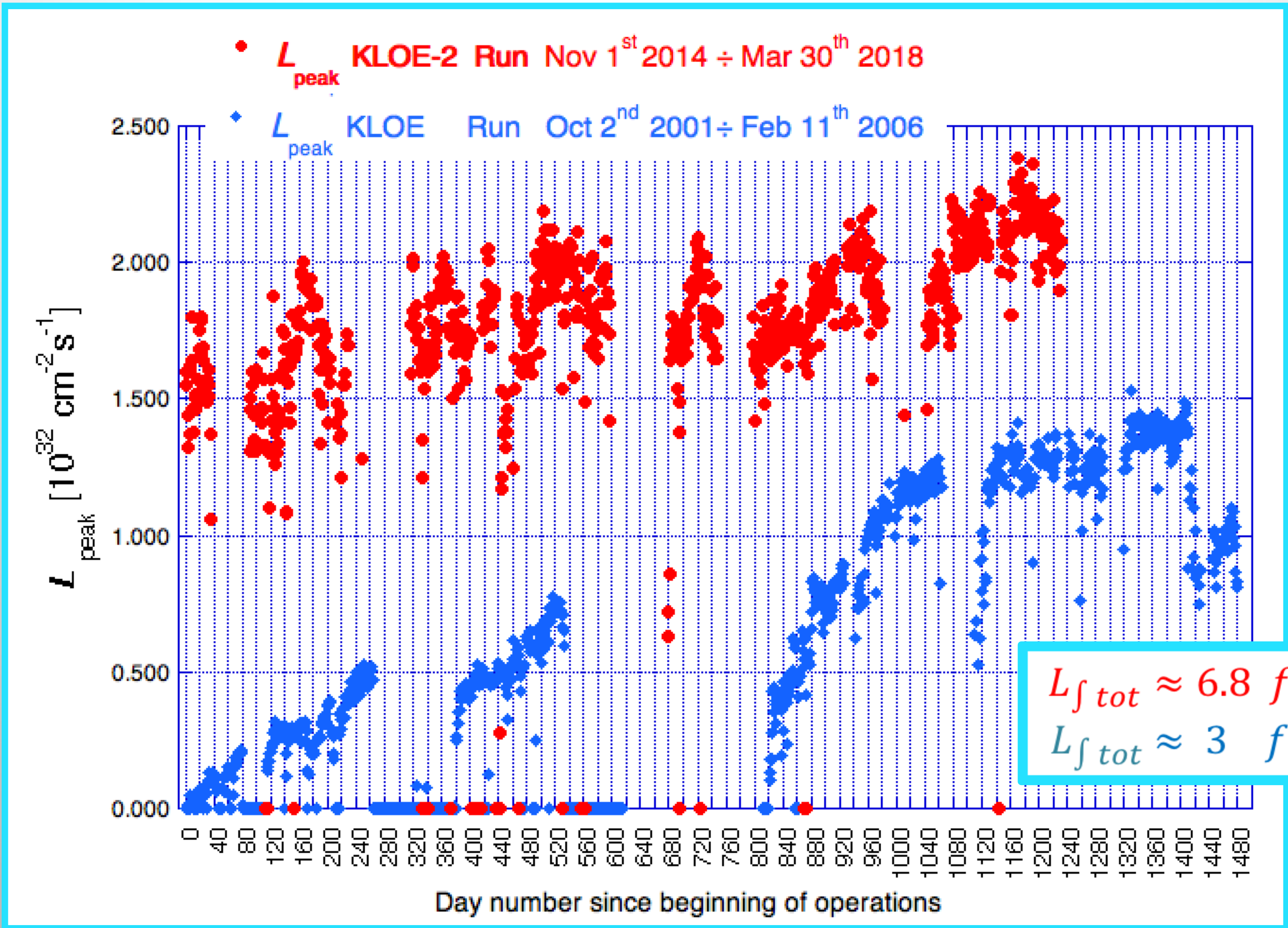


Due to a considerable lack of manpower and frequent faults we could not exploit the DAFNE's full potential as a collider, but we have been able to assured data taking on schedule.

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

Crab-Waist Luminosity Gain

Crab-Waist provides a 59% increase in terms of peak luminosity as evidenced by data taken by the same detector with the same accuracy



$L_{\int tot} \approx 6.8\ fb^{-1}$

$L_{\int tot} \approx 3\ \ fb^{-1}$

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

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

Limiting Factors

DAΦNE performance were mostly limited by collective effects, and feedback system noise.

The electron beam dynamics was affected by:

- a microwave instability (TMCI), with a threshold above a current of the order of ~10 mA per bunch, resulting in a widening of the transverse beam sizes, such effect was quite moderate in single beam operation and becomes more harmful in collision due to the beam-beam interaction;
- Ion trapping for long time it was not useful to fill more than 98 buckets.

The positron beam dynamics was mainly limited by e-cloud induced effect.

The electronic phase shifter in electron ring LLRF caused the RF phase, and consequently the beam, to shift slowly and randomly by about 10 deg.

DAΦNE performances would had profited from scrubbing runs, and further iterations about coupling correction, Crab-Waist Sextupole alignment, non-linear optics optimization …
These machine studies were not compatible with the experiment tight data taking schedule.

C. Milardi et al., "DAΦNE Operation with the upgraded KLOE-2 Detector," Proc. IPAC-2014;
C. Milardi et al., « A Review of DAΦNE Performances during the KLOE-2 Run", Proc. IPAC'18.

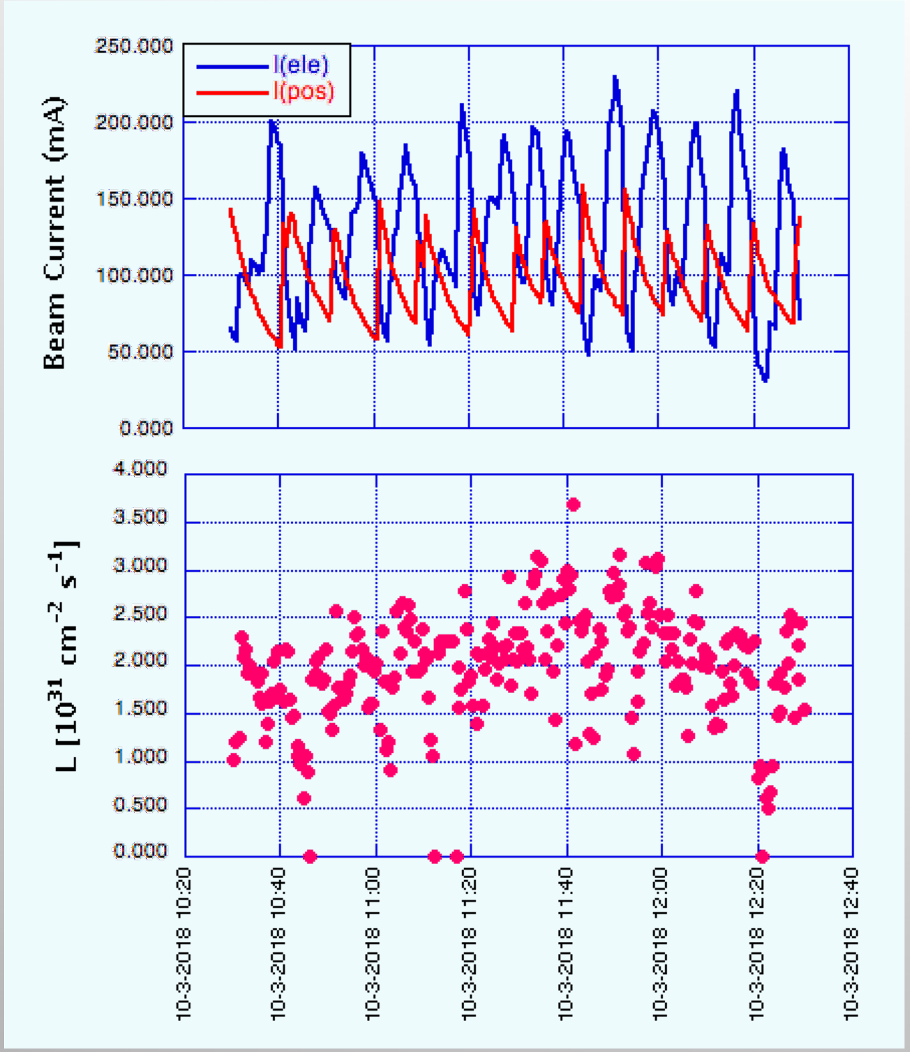
Limiting Factors and Simulations

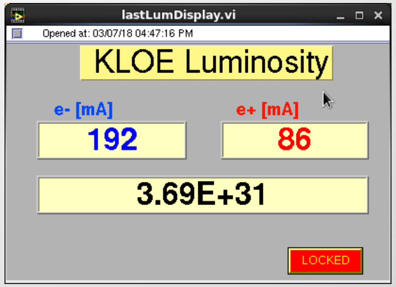
Numerical weak strong simulations using nonlinear collider lattice, including IR inside of a strong detector Solenoid, have shown that for the given bunch currents in collision, the powering of the Crab-Waist Sextupoles should decrease the beam core blow up by a factor of 2 indicating that even higher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

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

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

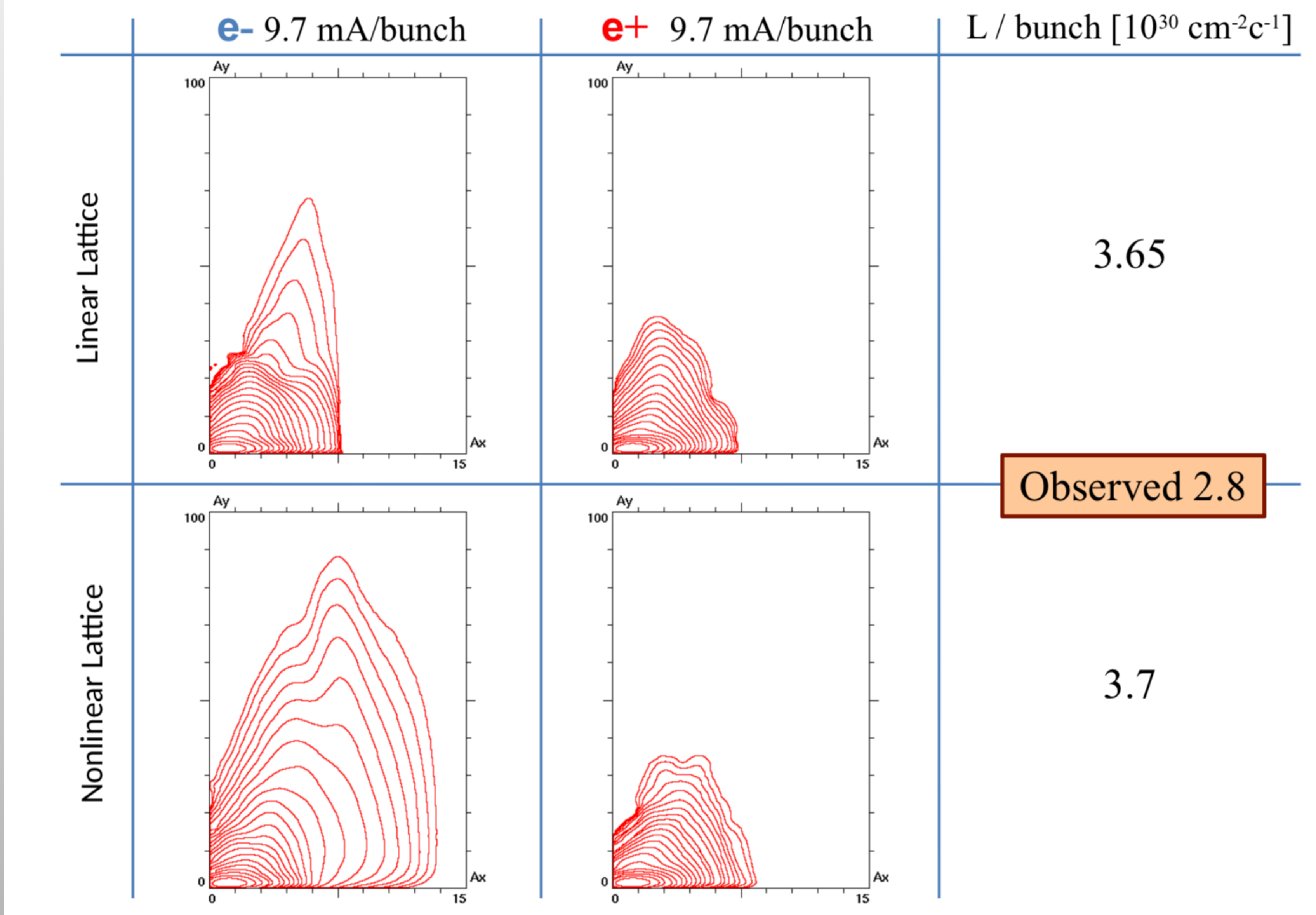




- *L_{peak} ~ 3 •10^{32} cm^{-2} s^{-1} might be achieved by colliding 100 bunches*
- *Beam-beam is not a limiting factor*
- *Crab-Waist Sextupoles work*

UNFORTUNATELY not enough time for machine studies and optimization!

Quasi-Strong-Strong Simulations CW On



D. Shatilov, private communication, 2018

DAΦNE Luminosity Achievements

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

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

SIDDHARTA-2 Run

DAFNE is a unique machine for physics studies requiring low-energy charged kaons with momenta below 140 MeV/c.

DAFNE is, therefore, ideally suited for studying particle and nuclear physics in the sector of low-energy QCD with strangeness, even more as collisions at lepton machines naturally assure the minimal possible level of background on the detector with respect to hadron beam based experiments.

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

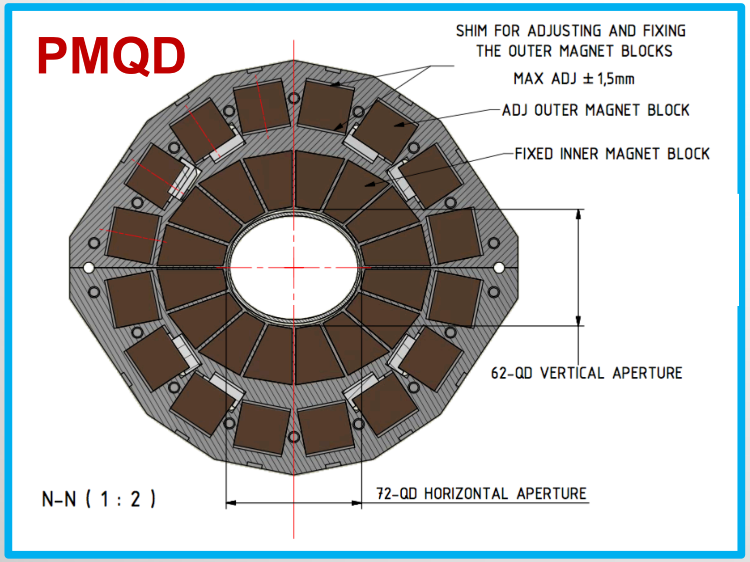
Sep 15th – Dec 19th 2023
Periodical maintenance, and winter shutdown

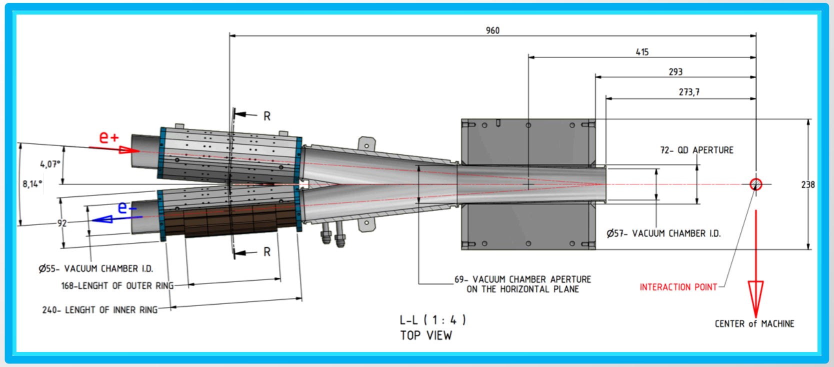
Jan 18^{h} – Jul 2024
Data taking with deuterium target

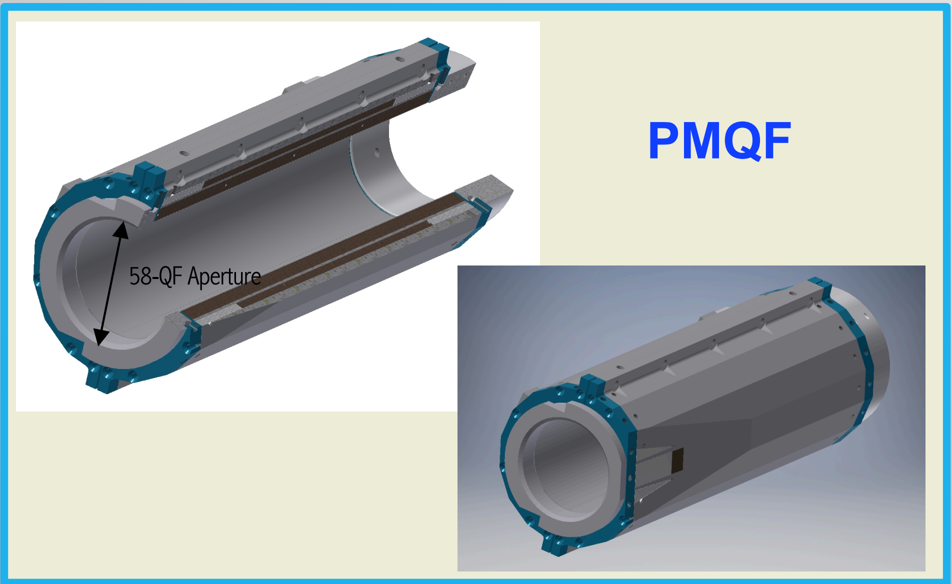
PMQs specifications

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

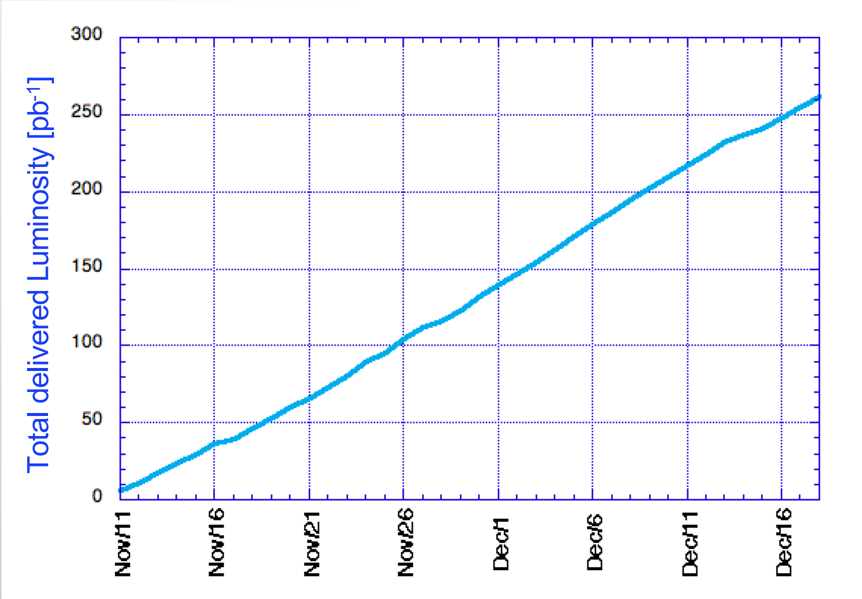
Collider Optimization

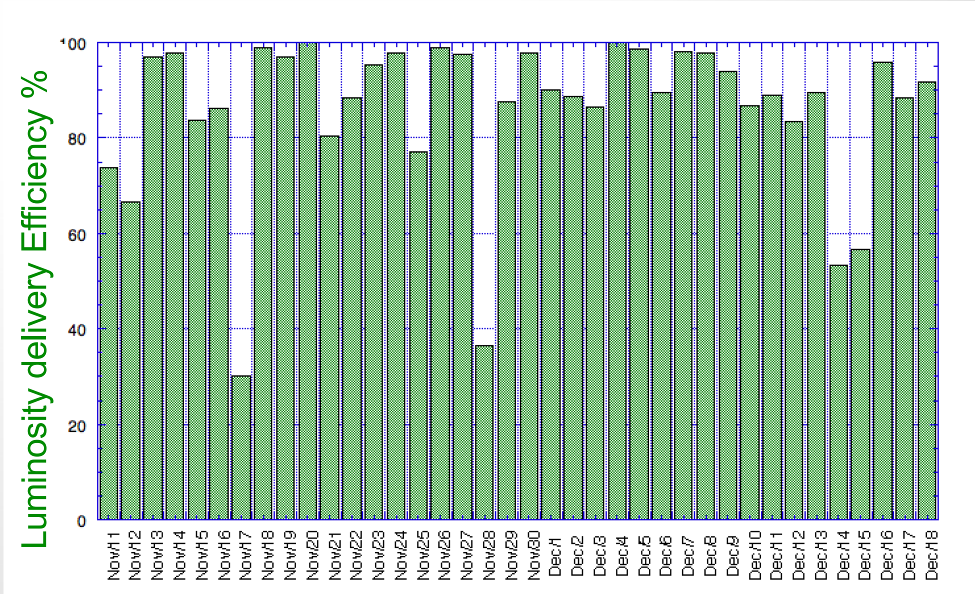
Restarting activities for SIDDHARTA-2 the collider configuration has been optimized relying on beam measurements.
Collider performances are approaching the optimal achieved in previous runs.

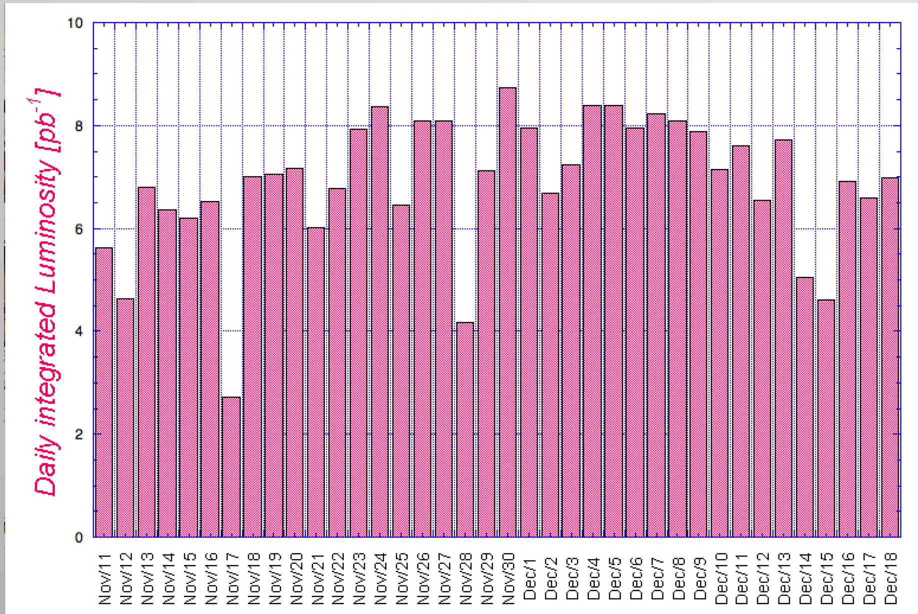
Background has been considerably reduced and is compatible with an efficient detector data taking. Kaon/Mip and Kaon/SDD increased by a factor of 1.4 and 3, respectively.

A first data sample in excess of 100 pb^{-1} has been delivered to the SIDDHARTA-2 experiment in order to **tune the detector** and realize the **first ever measurement of the kaonic-Ne atom**.

Figures from the kaonic Deuterium run





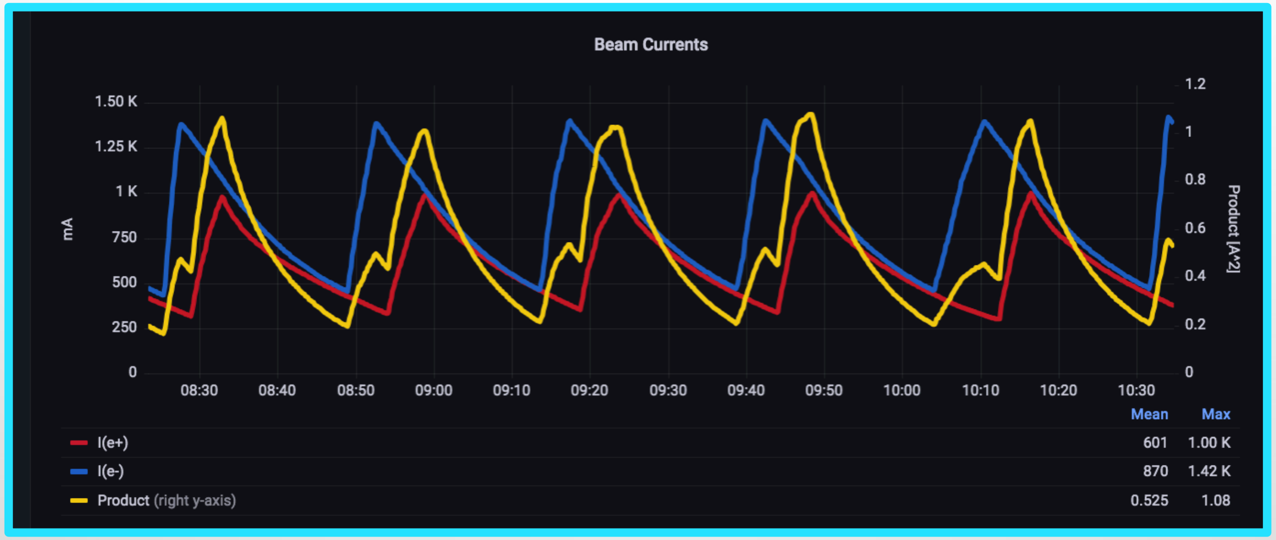


Integrated luminosity acquired so far, in costing, to the SIDDHARTA experiment taking data to detect the kaonic deuteriumX-ray transition is:

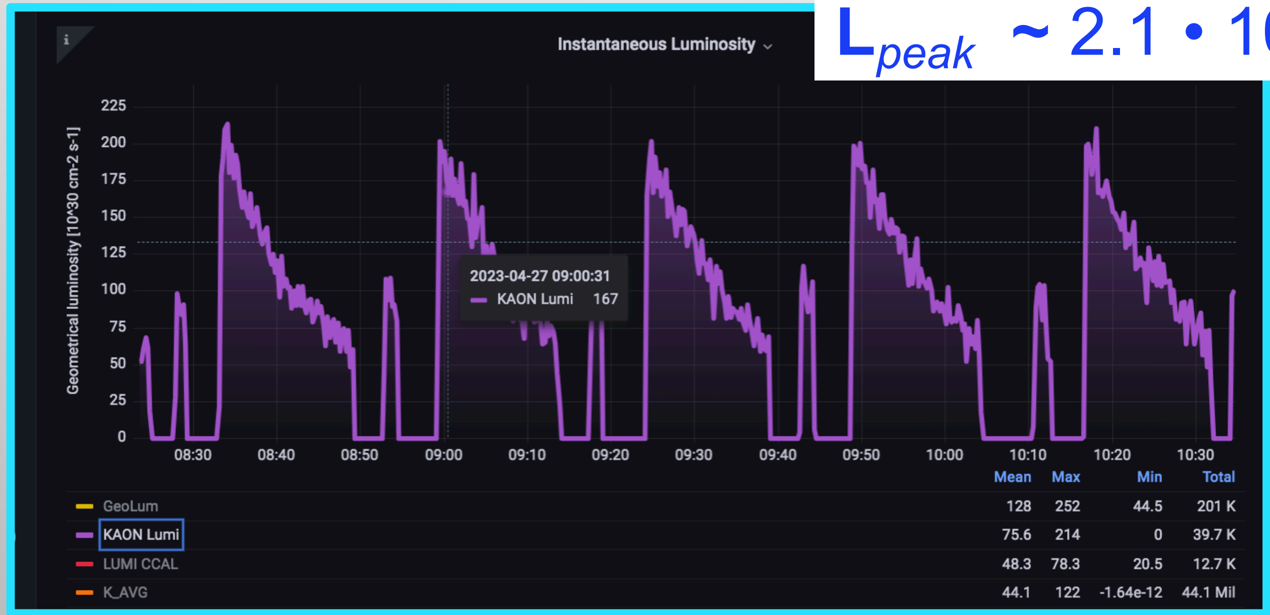
$$\int \mathbf{L} \sim 309 \text{ pb}^{-1}$$

Data range Nov 11th – Dec 18th 2023

Instantaneous Luminosity



$L_{peak} \sim 2.1 \cdot 10^{32}\ cm^{-2}\ s^{-1}$

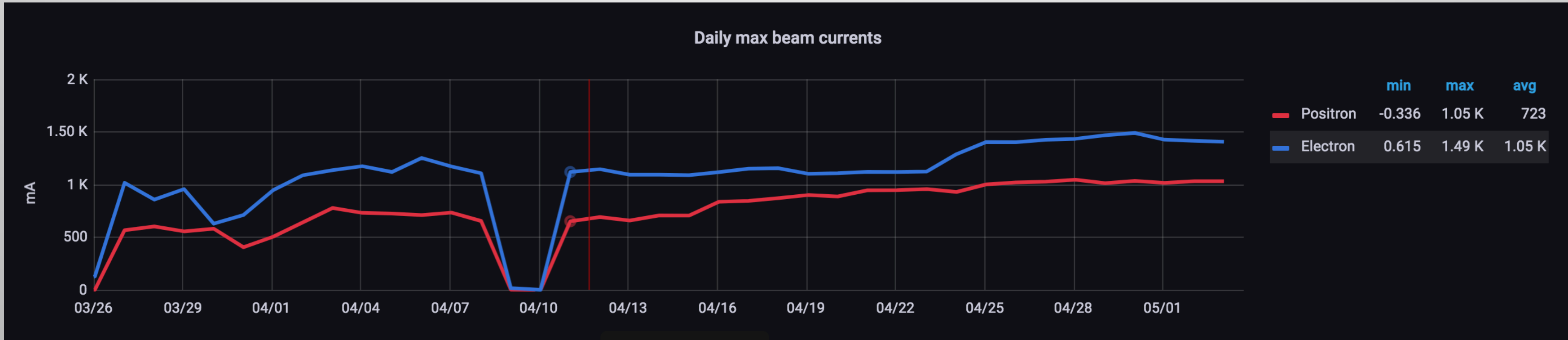


Beam Currents

Maximum **stable** beam currents stored in collision are now significantly higher if compared with the ones achieved during the previous run in 2022.

$I^{+} \simeq 1.0 \quad A$

$I^{-} \simeq 1.6 \quad A$



2023

Other DAΦNE *contributions to the physics of particle accelerators.*

DAΦNE achievements

- Impedance budget is a factor 80 lower than in a similar storage ring (EPA at CERN).
- Longitudinal feedback kicker designed for DAΦNE has been adopted at: KEKB, BESSYII, PLS, SLS, HLS, ELETTRA, KEK Photon Factory, PEP II …
- **maximum current stored in the DAFNE electron ring, 2.45 A, is the highest ever stored in particle factories and modern synchrotron radiation sources. DAΦNE also offers the highest positron current available in the world today.**
- Powerful longitudinal and transverse FBKs systems have been developed in collaboration with KEK and SLAC Labs.
  Comprehensive experimental studies have done to cure instabilities and to unveil interplay between instabilities, beam-beam and FBKs itself.
- Suppression of non linear high order terms in the Wiggler magnet magnetic field.
- DAΦNE was the first collider operating routinely with, and thanks to, electrodes for e-Cloud mitigation.
- DAΦNE tested collisions with negative momentum compaction which gave a 25% gain in terms of specific luminosity at low current without sextupoles.
- ***Crab-Waist collision scheme proved to be an effective approach to increase luminosity in circular colliders even in presence of an experimental apparatus strongly perturbing beam dynamics.***
  Luminosity achieved at DAΦNE ~ 1 order of magnitude higher than obtained at other colliders operating in a similar low energy range.

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
SuperC-Tau	C-Tau-Factory Novosibirsk, 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
HIEPA	Super Tau-Charm Factory 2 ÷ 7 GeV China	Considered option

Conclusion

DAFNE is a small machine that survived the era of giant accelerators continuing to give relevant contributions to the field, and assuring high quality data samples to high energy, and nuclear physics experiments.

Let me thank all the colleagues who have been, and still are part of this fantastic adventure.

Thank you

Spare Slides

Beam Currents stored at DAΦNE

Lepton Beam Currents achieved so far

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

R&D about *e-cloud* suppression at DAΦNE

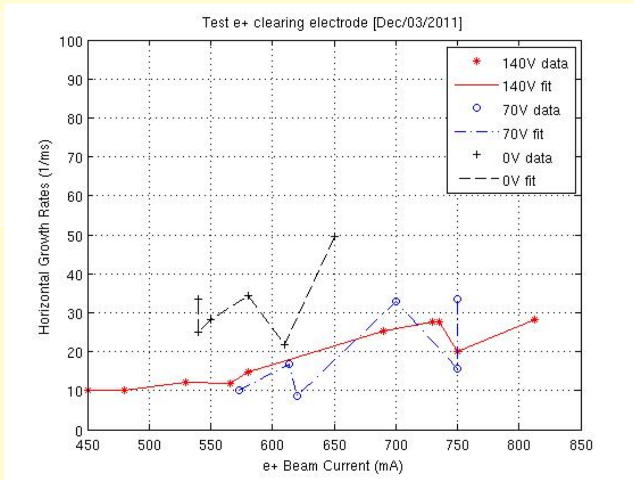
DAΦNE is the first collider operating routinely with electrodes, for e-cloud mitigation, ECE.
ECE provided stable operation with the e^+ beam, and allowed unique measurements such as:

e-cloud instabilities growth rate
transverse beam size variation
tune shifts along the bunch train

demonstrating their effectiveness in restraining e-cloud induced effects.

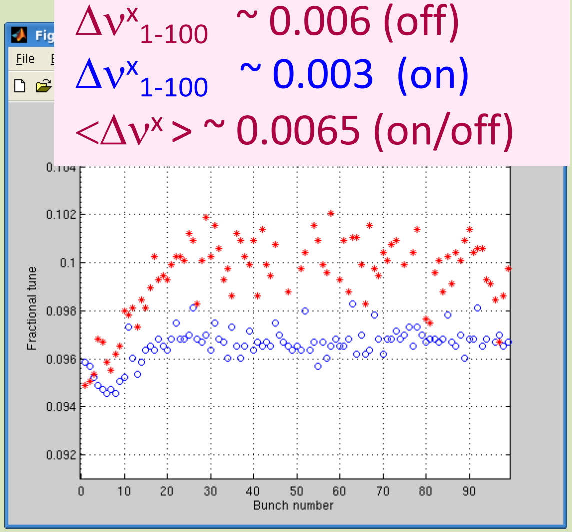
(D. Alesini et al, Phys. Rev. Lett. 110, 124801 (2013)

Horizontal Instability Growth Rate as a function of the ECE voltage measured by using bunch-by-bunch FBK frontend

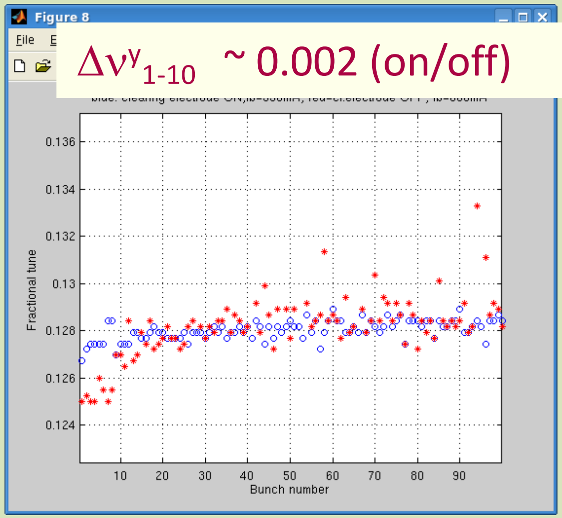


Tune Spread measurements

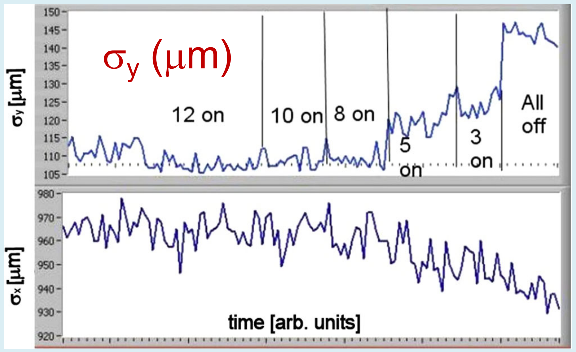
$\Delta\nu^x_{1\text{-}100}$ ~ 0.006 (off)
$\Delta\nu^x_{1\text{-}100}$ ~ 0.003 (on)
$<\Delta\nu^x>$ ~ 0.0065 (on/off)



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



Vertical Beam Size



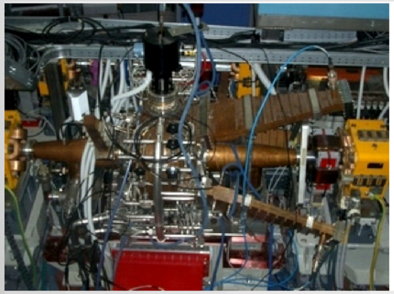
DAΦNE Vacuum Chamber Elements

Optimized to avoid heating, reduce impedance, and damp HOM

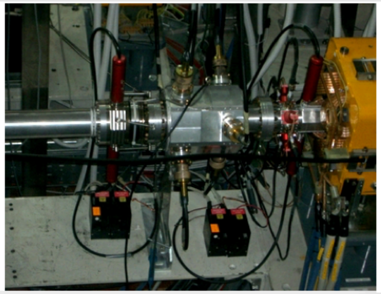
Impedance budget is a factor of 80 lower than in similar storage ring (EPA)

Longitudinal feedback kicker designed for DAFNE have been adopted at: KEKB, BESSYII, PLS, SLS, HLS, ELETTRA, KEK Photon Factory, PEP II

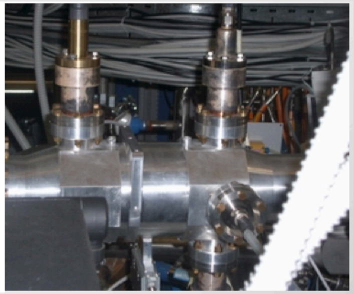
Such R&D effort largely contributed to improve beam dynamics and beam-beam performances



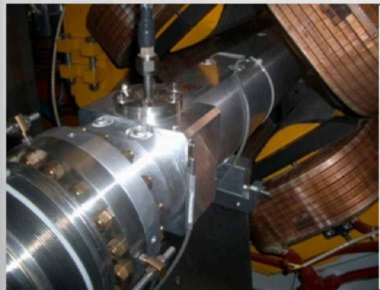
RF CAVITY



LONGITUDINAL KICKER

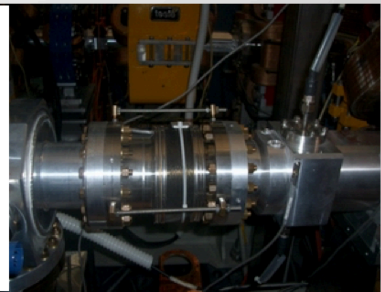


TRANSVERSE KICKER



INJECTION KICKER

WALL CURRENT & DCCT MONITOR



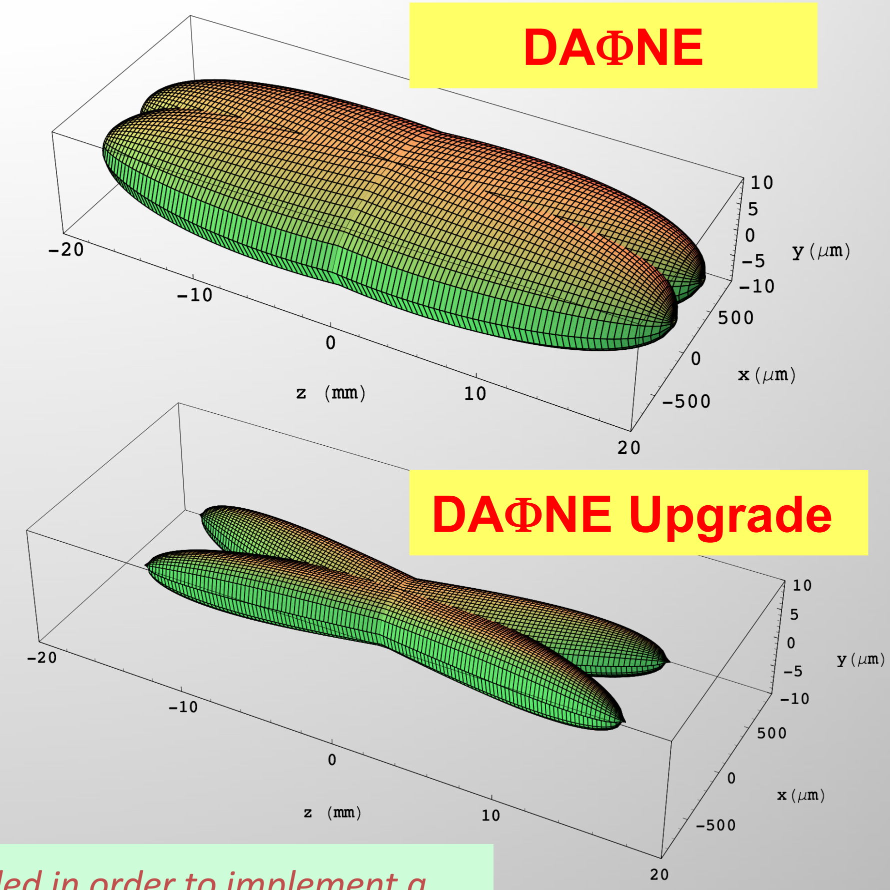
SHIELDED BELLOWS

D. Alesini, Boni, A. Drago, A. Gallo, A. Ghigo, M. Serio, A Stella, M. Zobov, F. Marcellini, P. Raimondi

DAΦNE Parameters

	DAΦNE native	DAΦNE Crab-Waist Upgrade
$\theta_{cross}/2$ (mrad)	12.5	25
ε_x (mmxmrad)	0.34	0.26
β_x^* (cm)	160	26
σ_x^* (mm)	0.70	0.26
$\Phi_{Piwinski}$	0.6	1.9
β_y^* (cm)	1.80	0.85
σ_y^* (μm) low current	5.4	3.1
Coupling, %	0.5	0.5
I_{bunch} (mA)	13	13
σ_z (mm)	25	20
N_{bunch}	110	110
L ($cm^{-2}s^{-1}$) x10^{32}	1.6	5

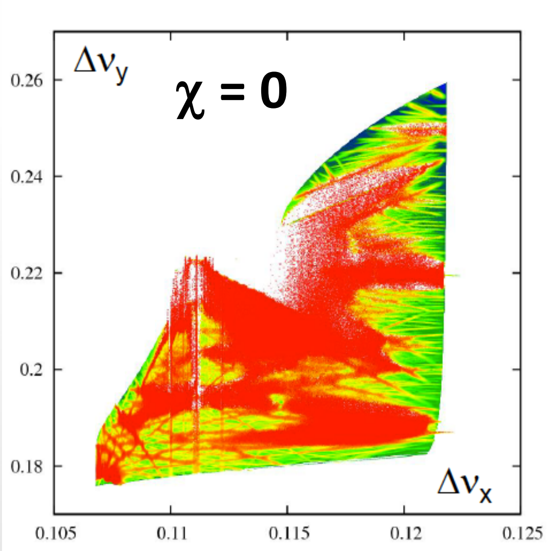
Beam distribution @ IP

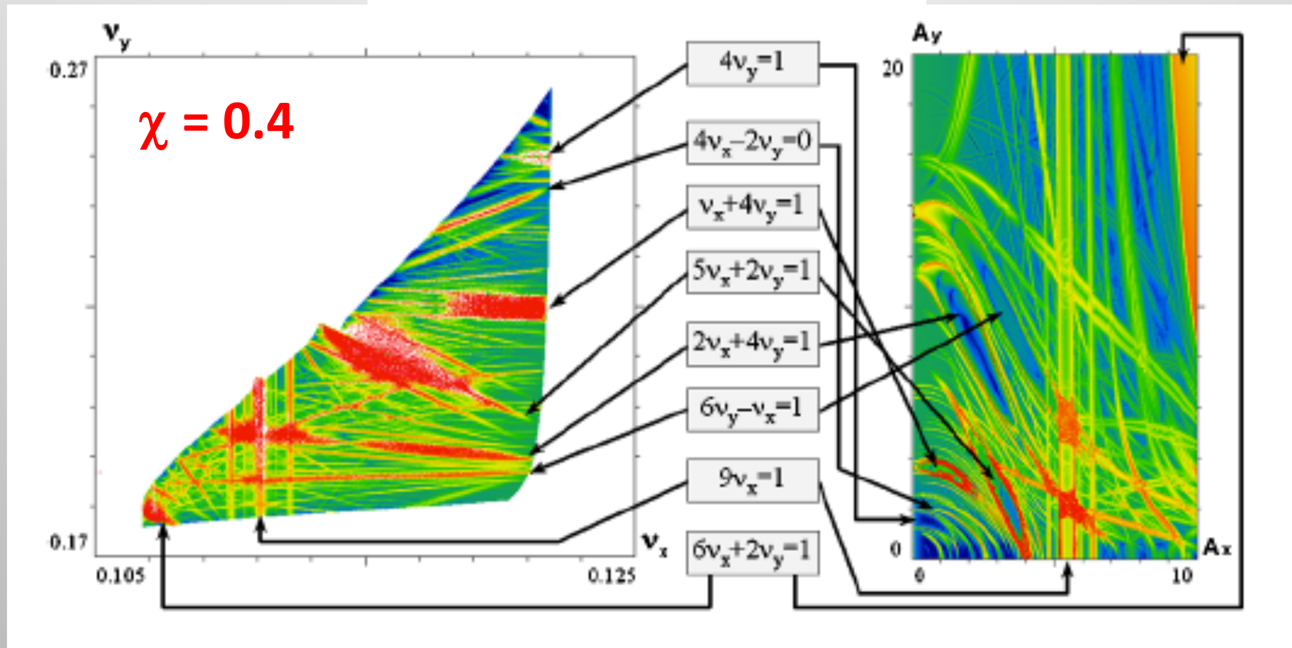


- *In 2007 the DAΦNE accelerator complex has been upgraded in order to implement a new collision scheme based on **large Piwinski angle, low–β** and **Crab-Waist compensation** of the synchrobetatron resonances*
- *The upgrade took ~ **five months***
- ***Since May 2008** DAΦNE was delivering luminosity to the SIDDHARTA experiment.*

Frequency Map Analysis of *BB* Interaction

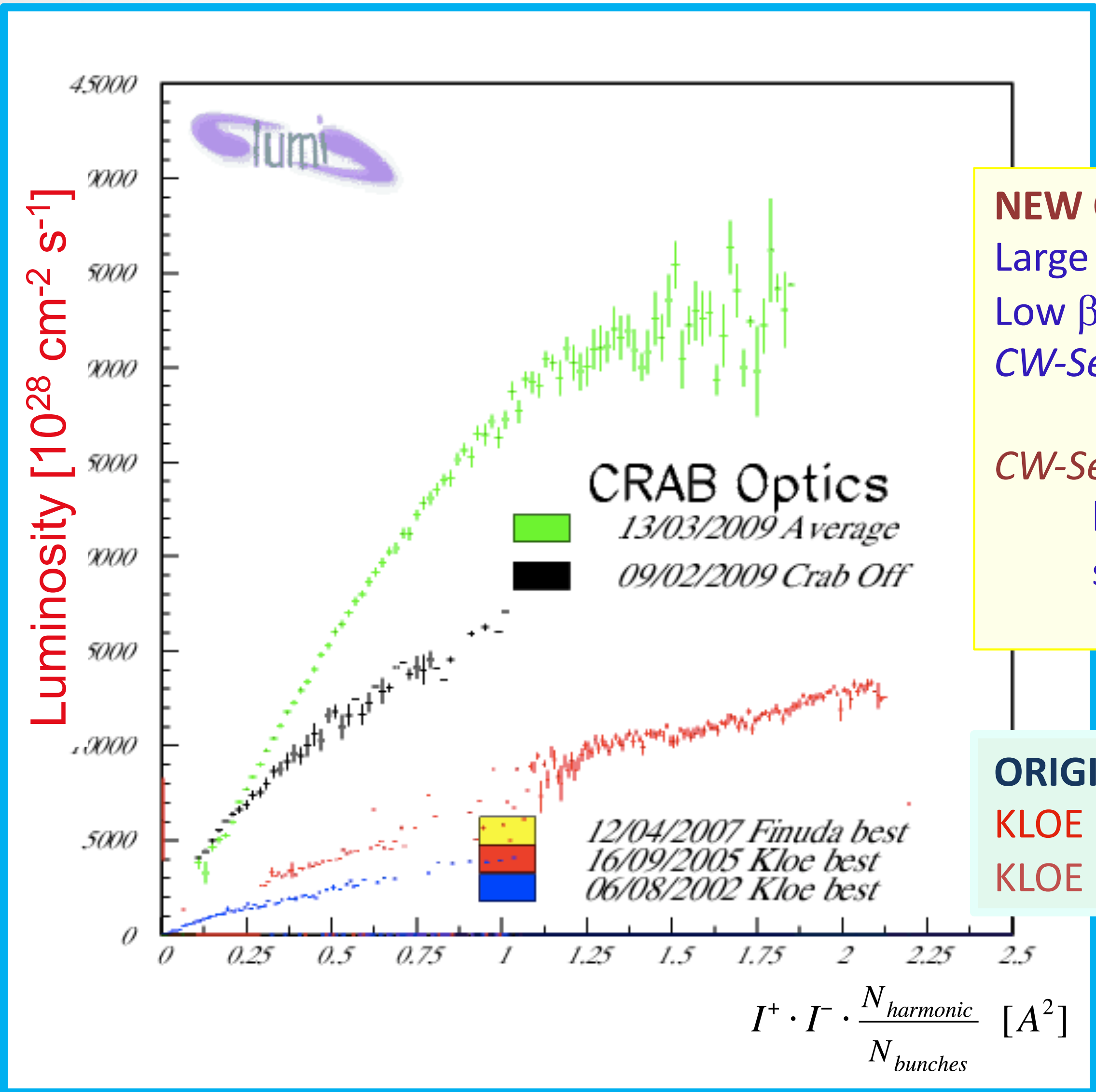
DAΦNE simulations





(D. Shatilov et al.)

Crab-Waist Collision Scheme & Luminosity



NEW COLLISION SCHEME:

Large Piwinski angle $\psi = 1.9$

Low β^*_y $\beta^*_y = 9.0$ [mm]

CW-Sextupoles $\chi = 0.6$

CW-Sextupoles off

larger transverse beam size blowup

sharp lifetime reduction

ORIGINAL COLLISION SCHEME:

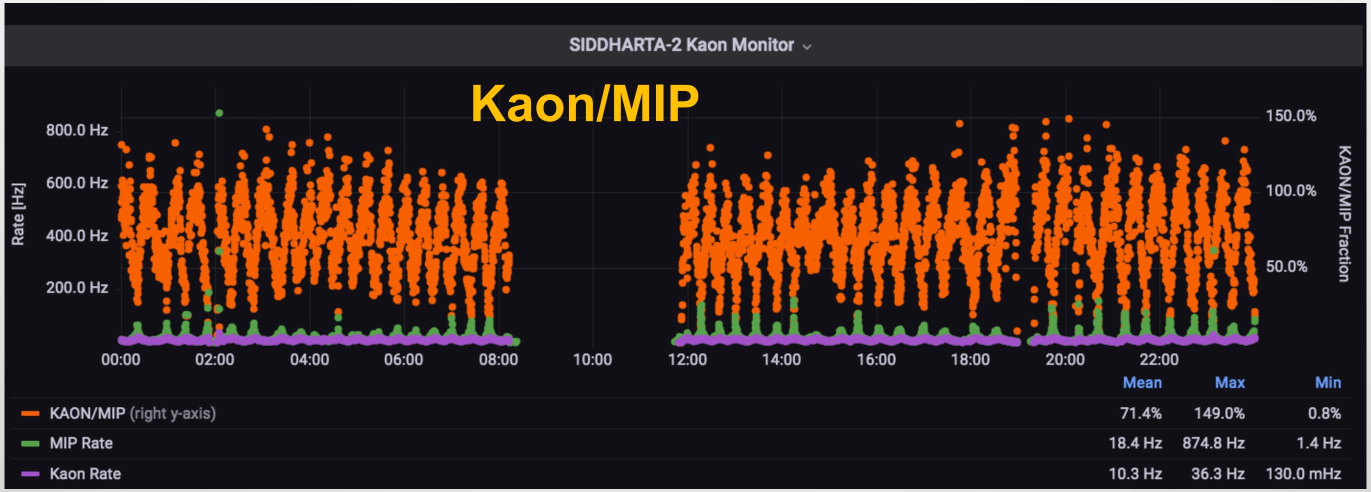
KLOE 2005 $\psi = 0.6$ $\beta^*_y = 18.$ [mm]

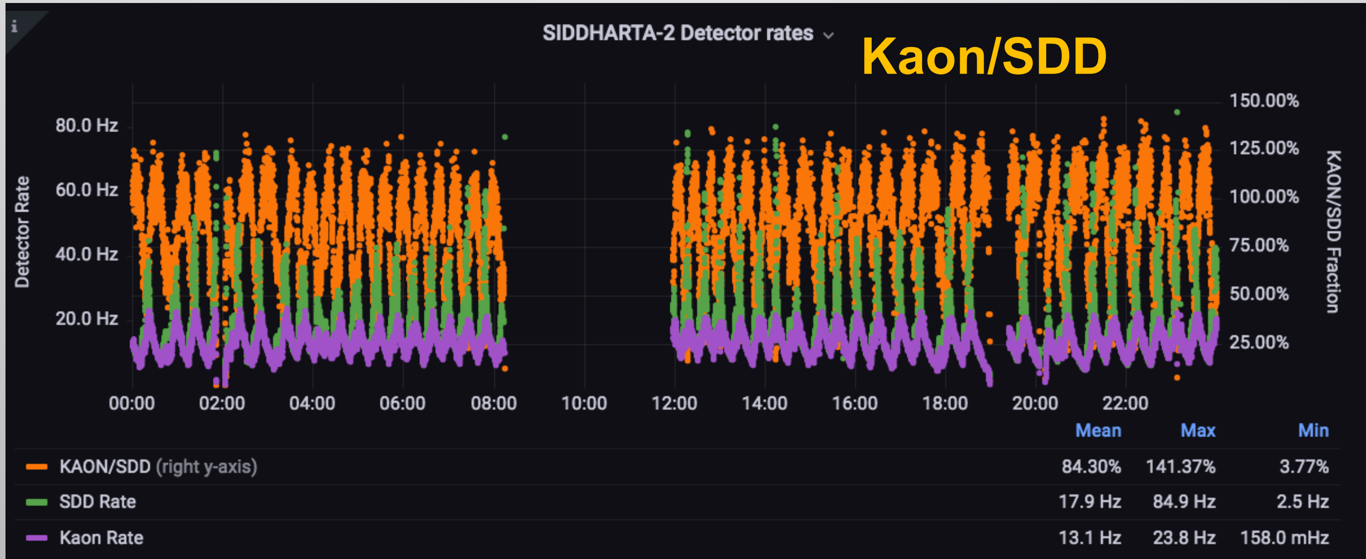
KLOE 2002 $\psi = 0.3$ $\beta^*_y = 25.$ [mm]

20% L reduction at high currents because of bunch lengthening due to the ring impedance. L $\propto 1/\sigma_z$ in Large Piwinski Angle & Crab-Waist regime.

Background Optimization

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





Background Control during KLOE-2 run

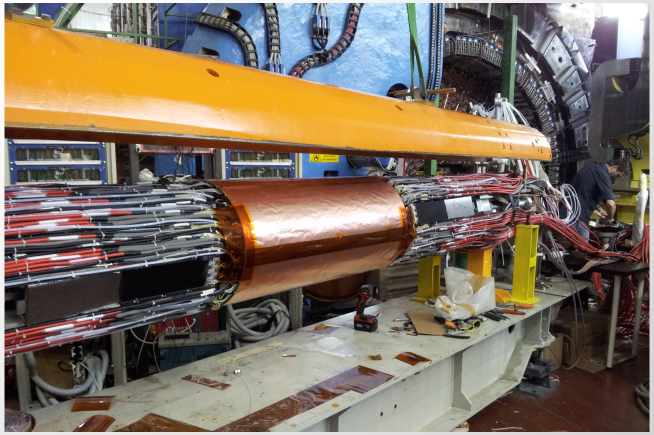
The new detector layers installed around the beam pipe posed new tight requirements on background level and control.

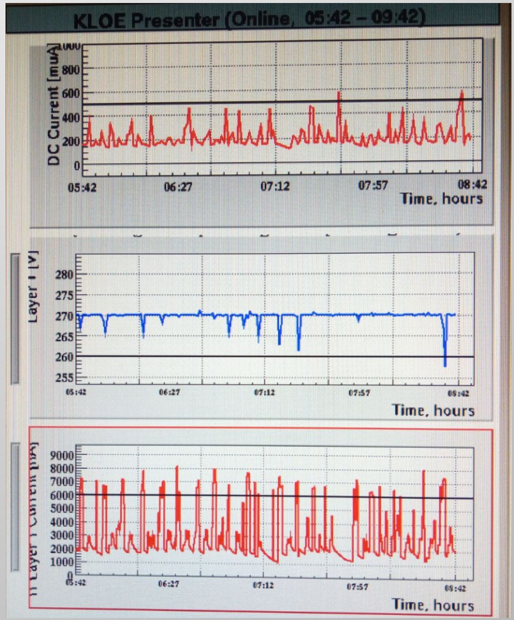
Criteria for acceptable background became:

- counting rate on the detector endcaps
- current amplitude measured by the different drift chamber sectors
- discharge threshold on the innermost IT layer

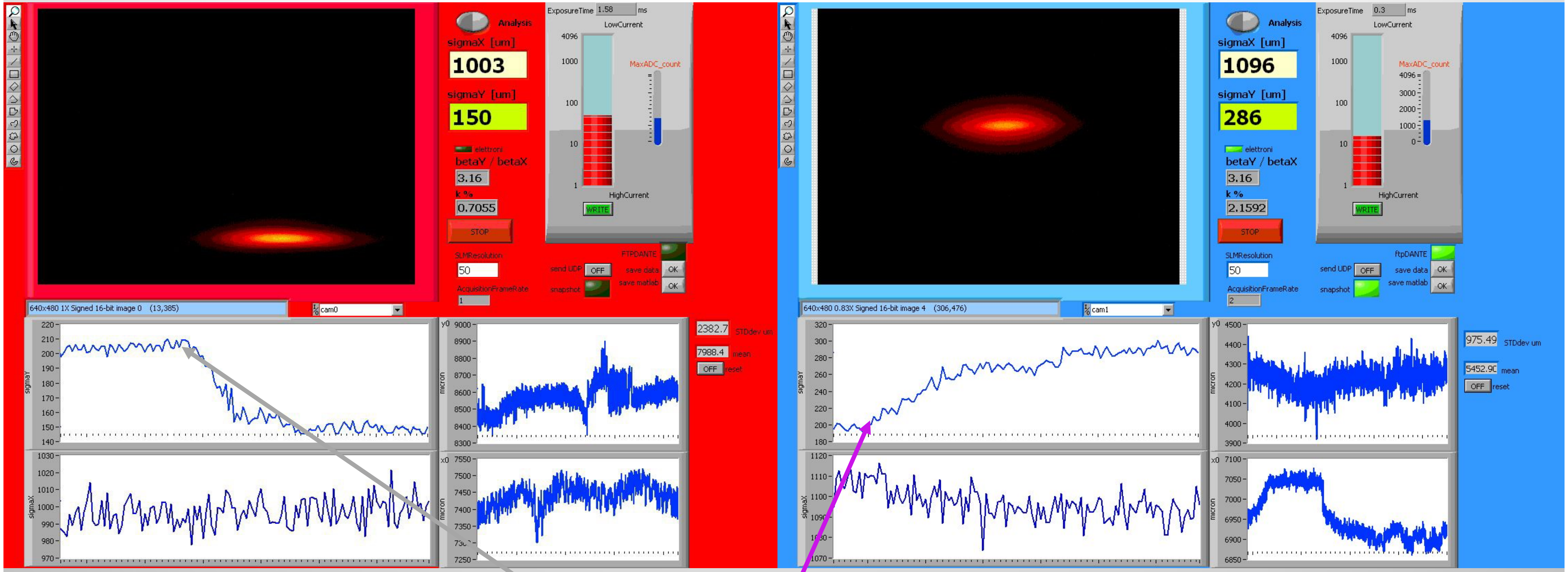
Background on the IT was heavily dependent on the injection process which had to be accurately optimized and stabilized

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





Crab Waist Sextupoles Test (during KLOE-2 run)



Reducing the CW Sextupole strenght in the electron ring : 200A →150A

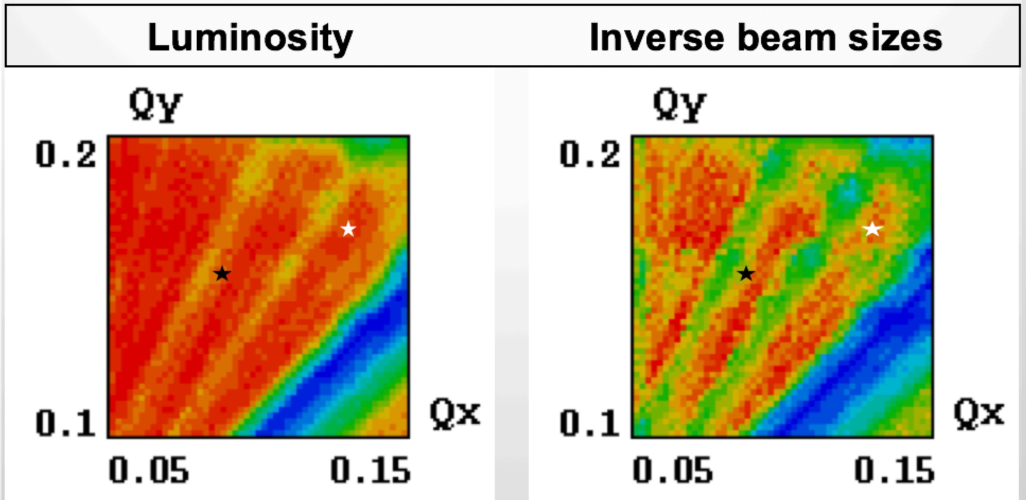
e^- Ring Working Point Scan

Numerical simulations aiming at improving:

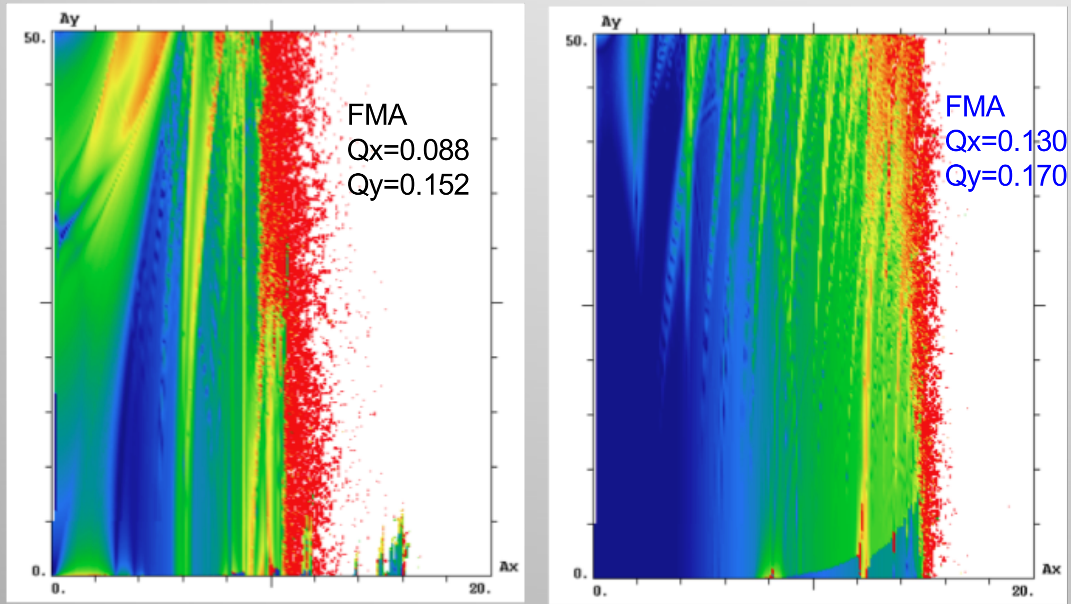
- dynamical aperture
- specific luminosity

led to define a new working point for the e^- ring

Qx=0.135 Qy=0.17 ☆



M. Zobov *et al.*, *IEEE Trans. Nucl. Sci.*, Vol. 63, no. 2, pp. 818-822,2016.

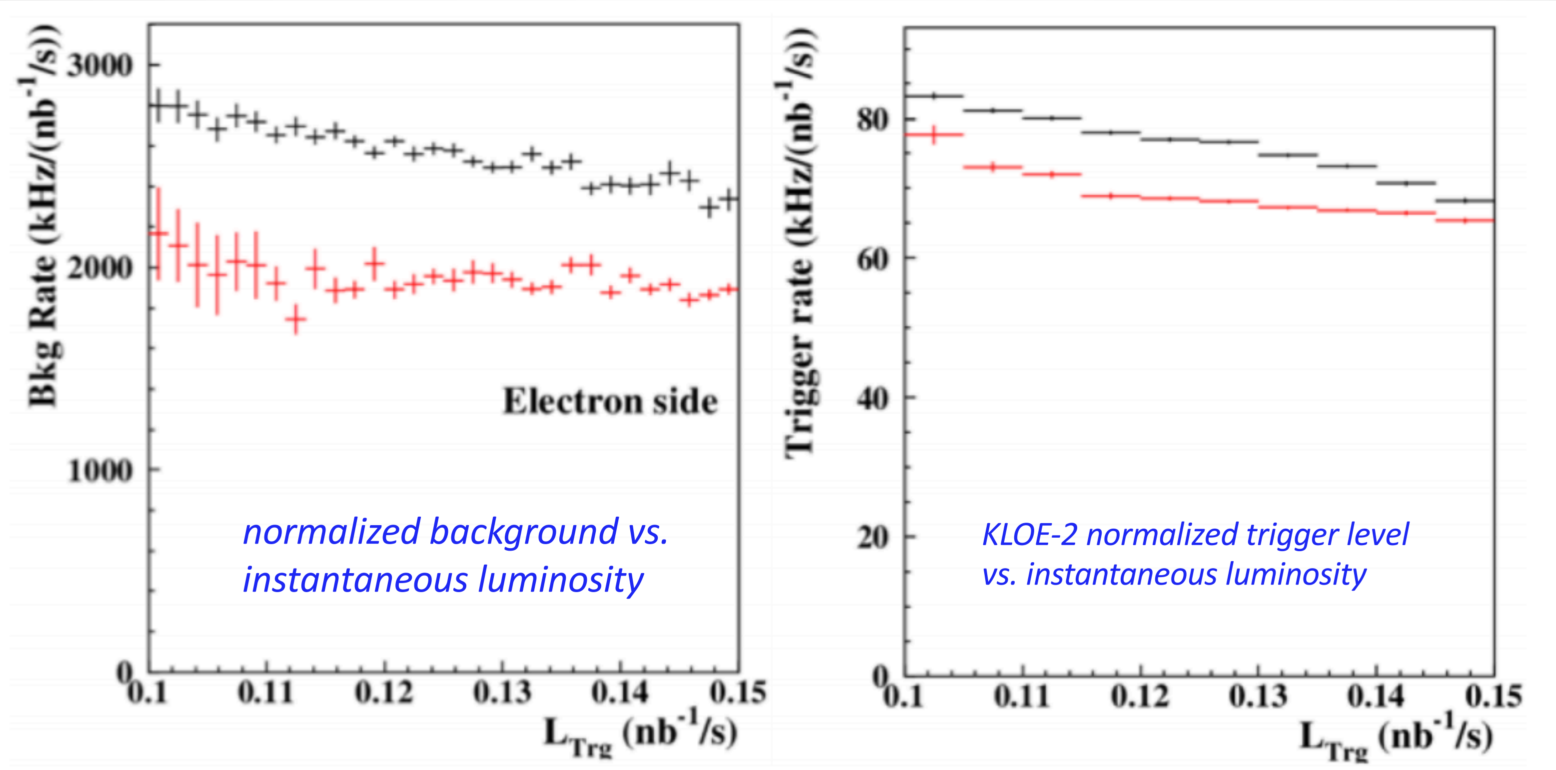


achieving:

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

Background for the New e$^-$ Ring Configuration

- old Working Point
- new Working Point

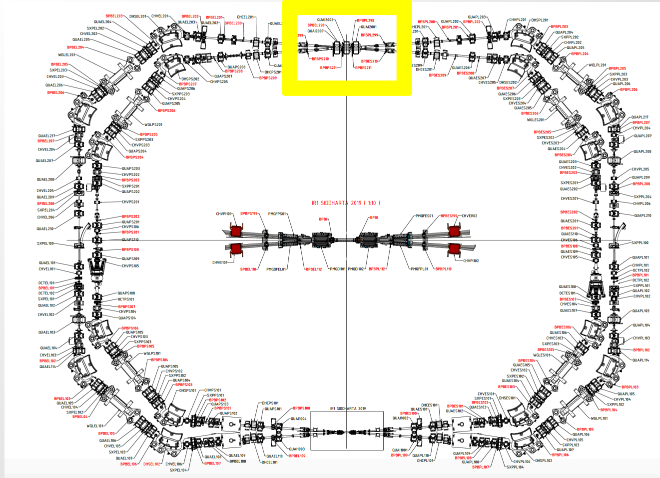


Main Rings Optics

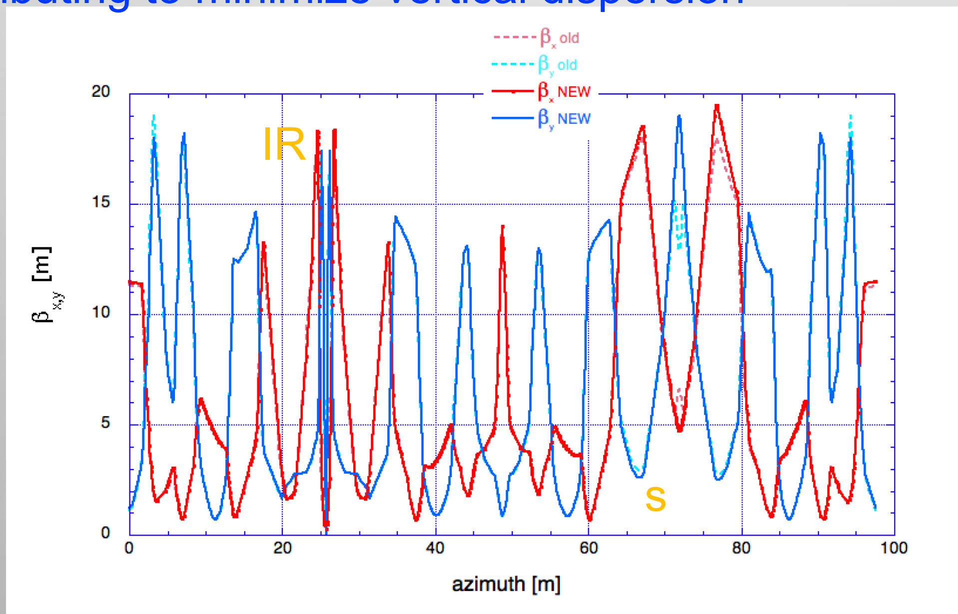
New Crab-Waist ring optics

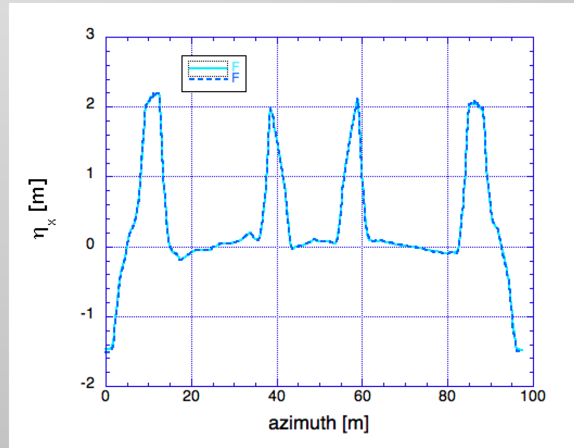
- symplified focusing structure in the RCR,
- 2 QUADs where beams pass off-axis are switched off, thus eliminating spurious component in the QUADs magnetic field,
- Same optics parameters in the IR.

RCR

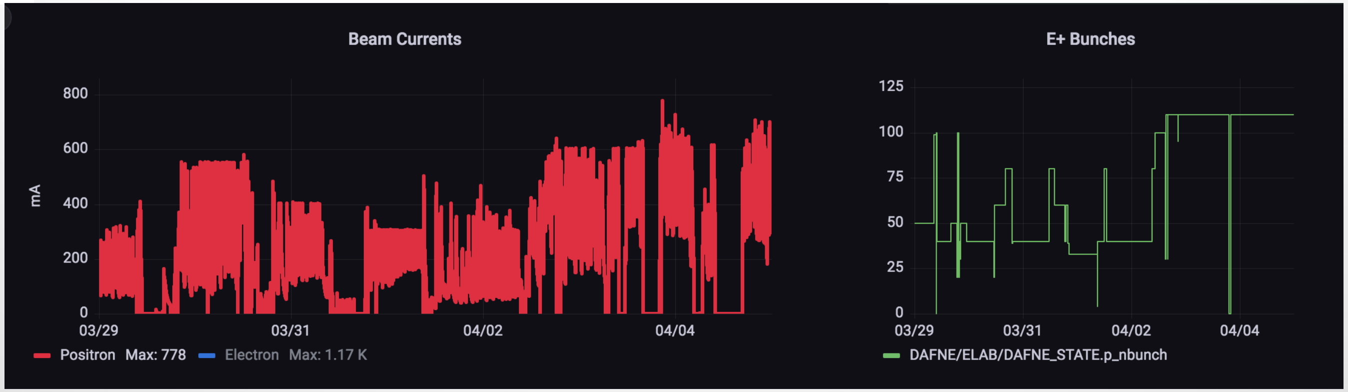


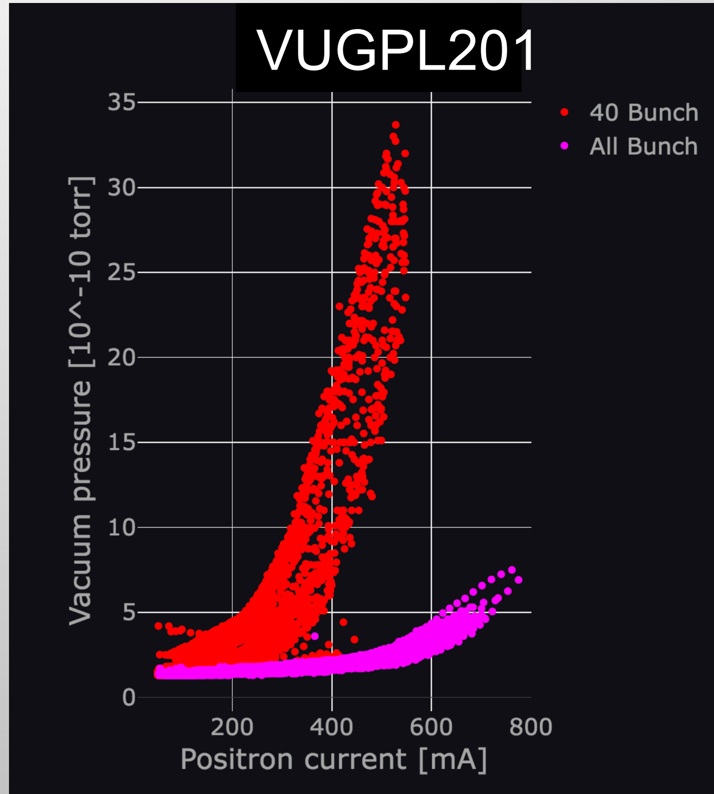
New optics improves closed orbit correction allowing to reduce the total strength of the used steering magnets, thus also contributing to minimize vertical dispersion





Scrubbing Dedicated Runs





In the first stage of the operations dedicated beam **conditioning**, and beam ***scrubbing runs.***

Scrubbing carried out using 40 bunches pattern with 2 empty buckets spacing and switching off solenoids to enhance e-cloud activity.

Non-linear Optics

Sextupole magnets:

were set to correct chromaticity to zero,

Their alignment has been checked by beam-based measurements, in a few cases small closed orbit bumps have been applied to restore optimal alignment conditions,

one of the Crab-Waist sextupole in MRp required 1 mm mechanical alignment in the horizontal plane,

then they have individually tuned in order to reduce the background shower on the detector and to improve the ring acceptance in injection,

At some point this iterative procedure required revising vertical dispersion correction, this was done by applying vertical closed orbit bumps at some of the modified magnets.

Crab-Waist Sextupoles have been progressively switched on, presently they are set at approximately 70% of their optimal strength.

Octupole magnets were used in the MRp only where they contribute to mitigate e-cloud induced effects by introducing Landau damping and to reduce background

Background Optimization

Background Diagnostics

Initially background optimization process was largely based on the counting rate out of coincidence provided by the CCAL luminometer.

At regime background level is monitored, in real-time, by counters based on Kaon/Mip rate, and Kaon/SDD rate provided by the SIDDHARTA-2 detector.

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

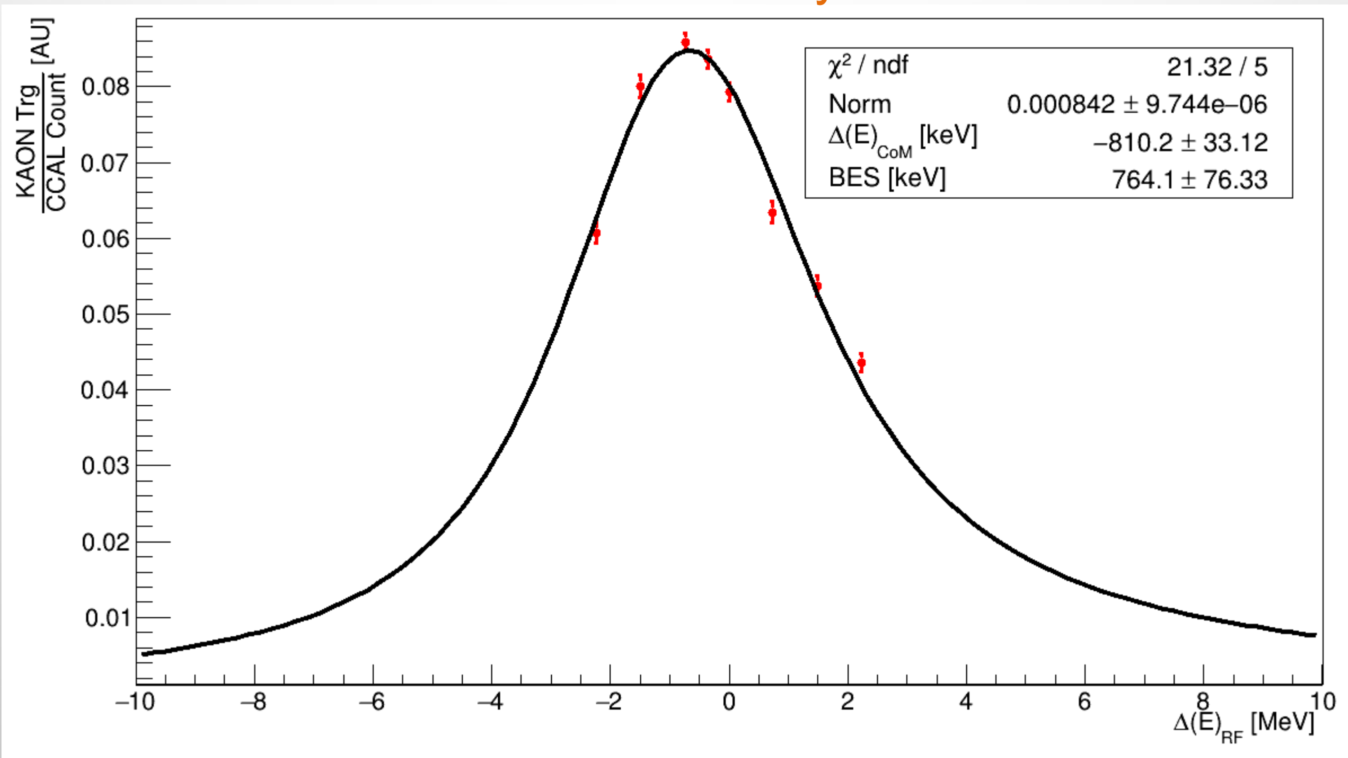
Improvements were due to:

- linear and non-linear optics fine tuning,
- RF cavity and feedback systems configuration, a strong correlation was observed between voltage of the RF cavities and background, reducing the voltage by few 10 of KV a 15% Kaon/MIP rate was measured,
- beam dynamics stability enhancement,
- collimators optimization.

Injection efficiency also played a relevant role especially as far as the background during injection is concerned.

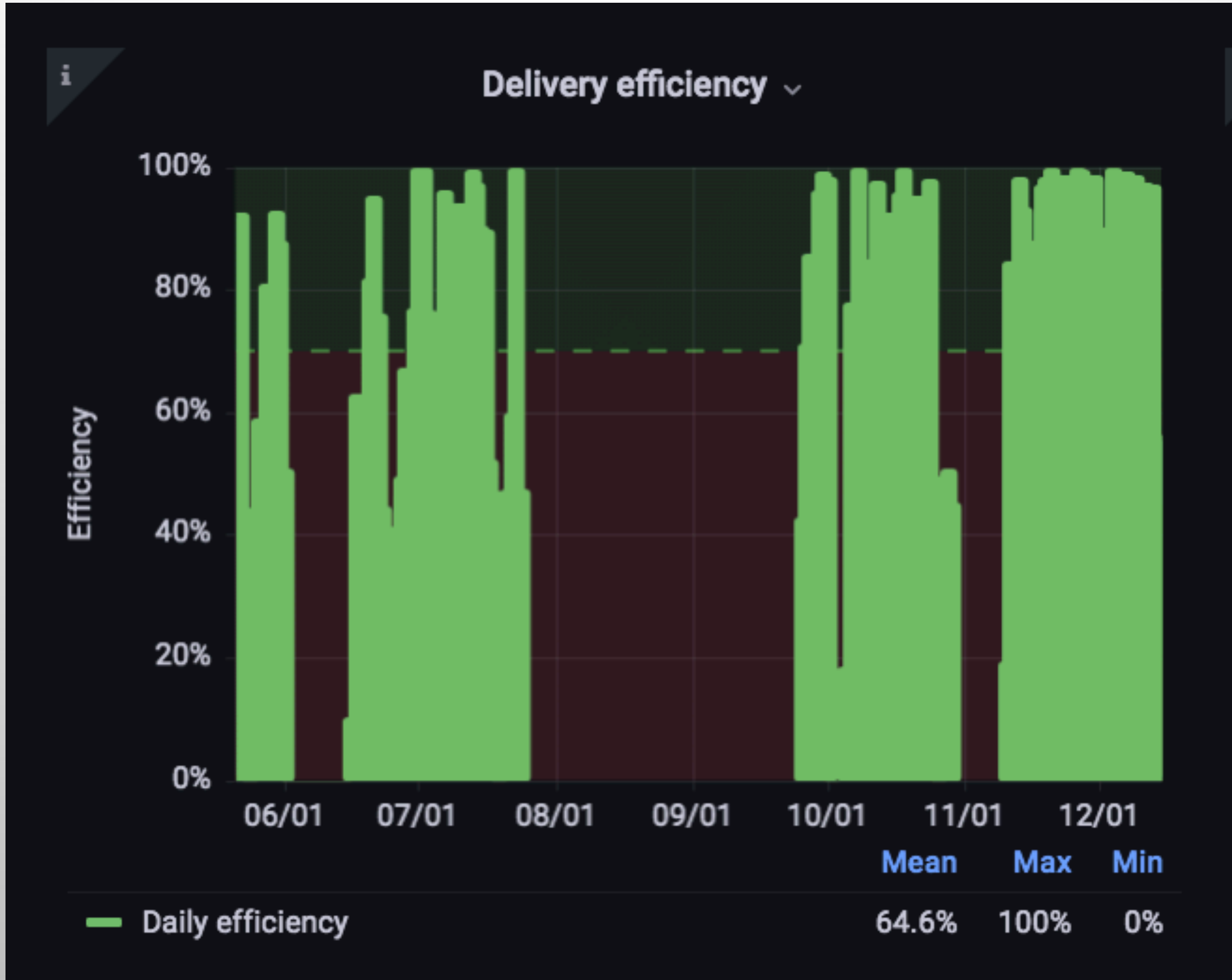
Energy Scan

ΔE_{CM} = - 760 keV → 7% gain in terms of charged kaon yield

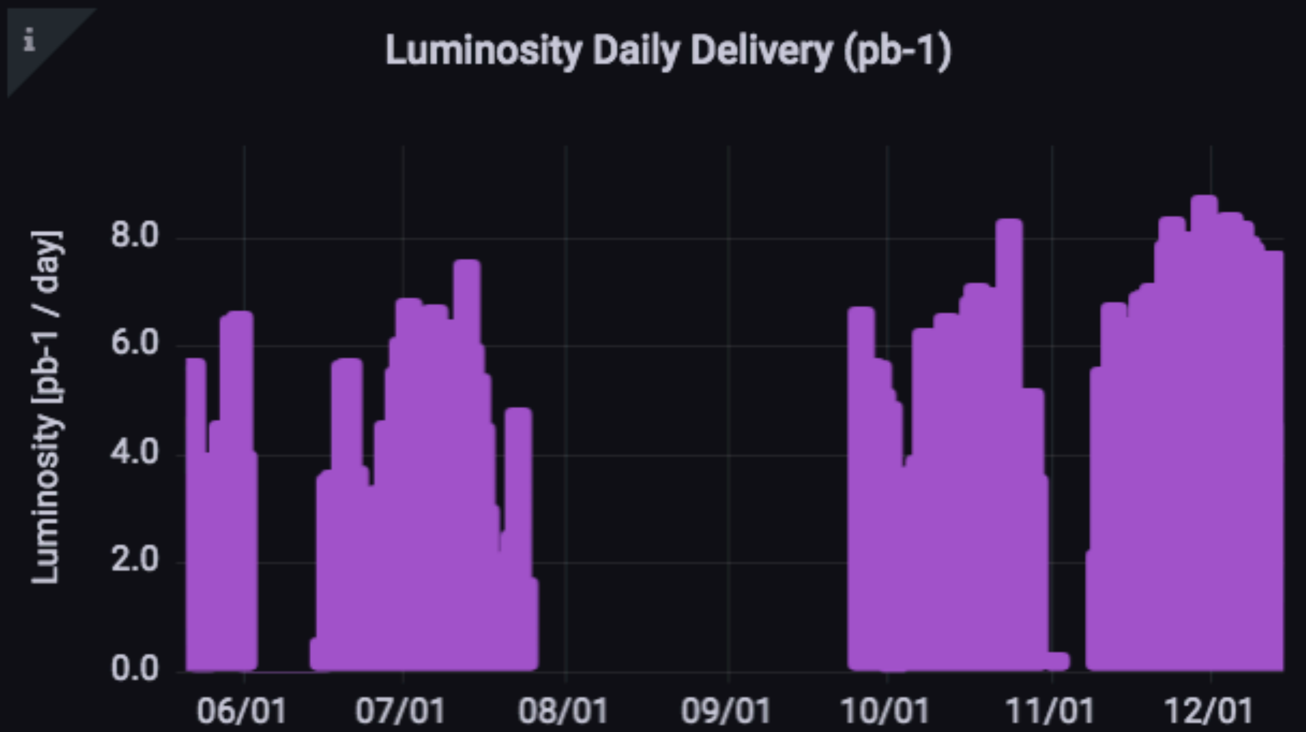


Energy scan as a function of the absolute energy deviation w.r.t. the starting point of the scan, the fitting function includes radiative corrections and the beam energy spread is left as free parameter.

Luminosity-delivery Efficiency (Uptime)



Daily integrated luminosity



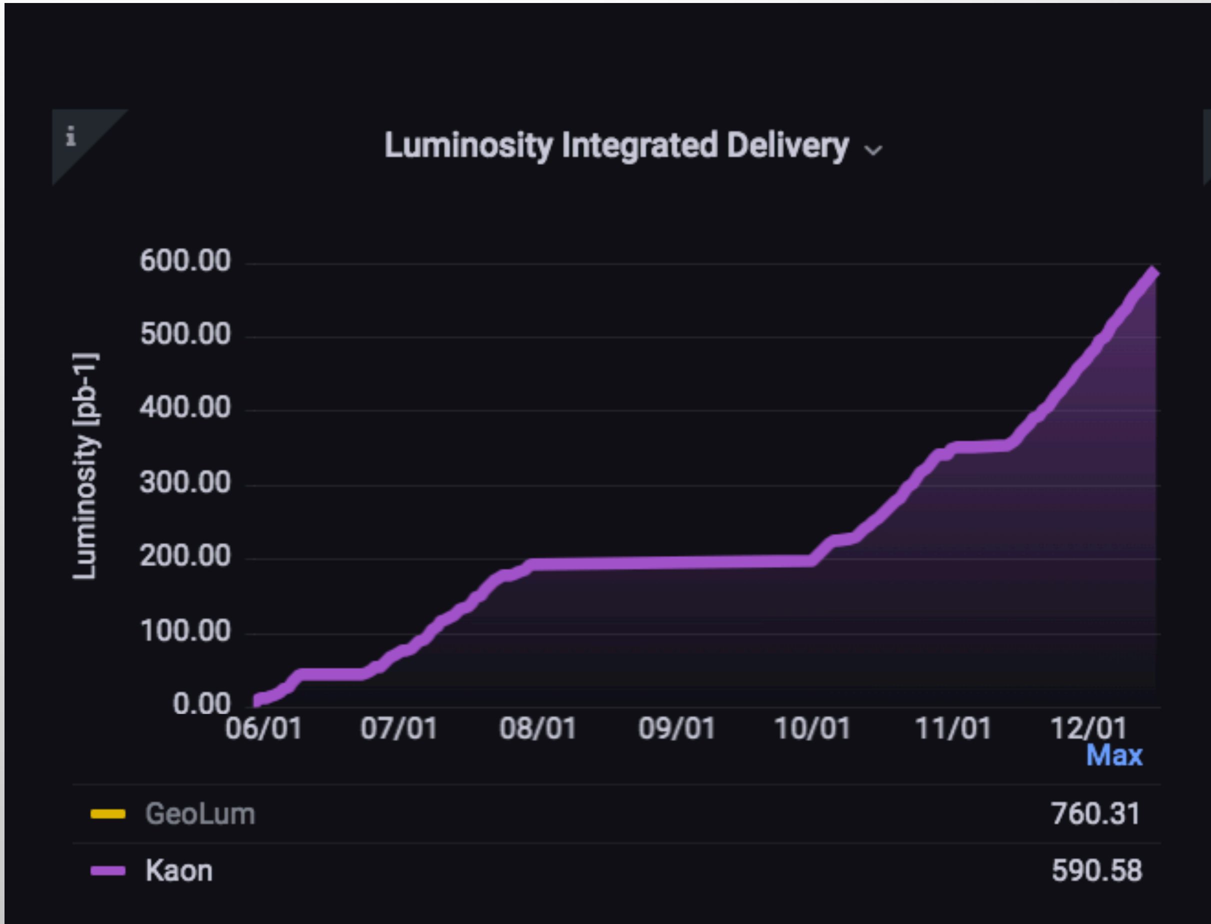
	Mean	Max	Min	Total
GeoLum	6.1	12.0	0.0	760.3
KaonLum	4.4	8.8	0.0	590.6

Delivered Integrated luminosity

After Deuterium target installation

Integrated luminosity acquired so far, in costing, from the SIDDHARTA experiment is:

$\int L \sim 309\ pb^{-1}$



May 7th – Dec 14th 2023