DAΦNE the First and Only Collider Running with the *Crab-Waist* Collision Scheme

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on behalf of the DAFNE Team

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EU edition
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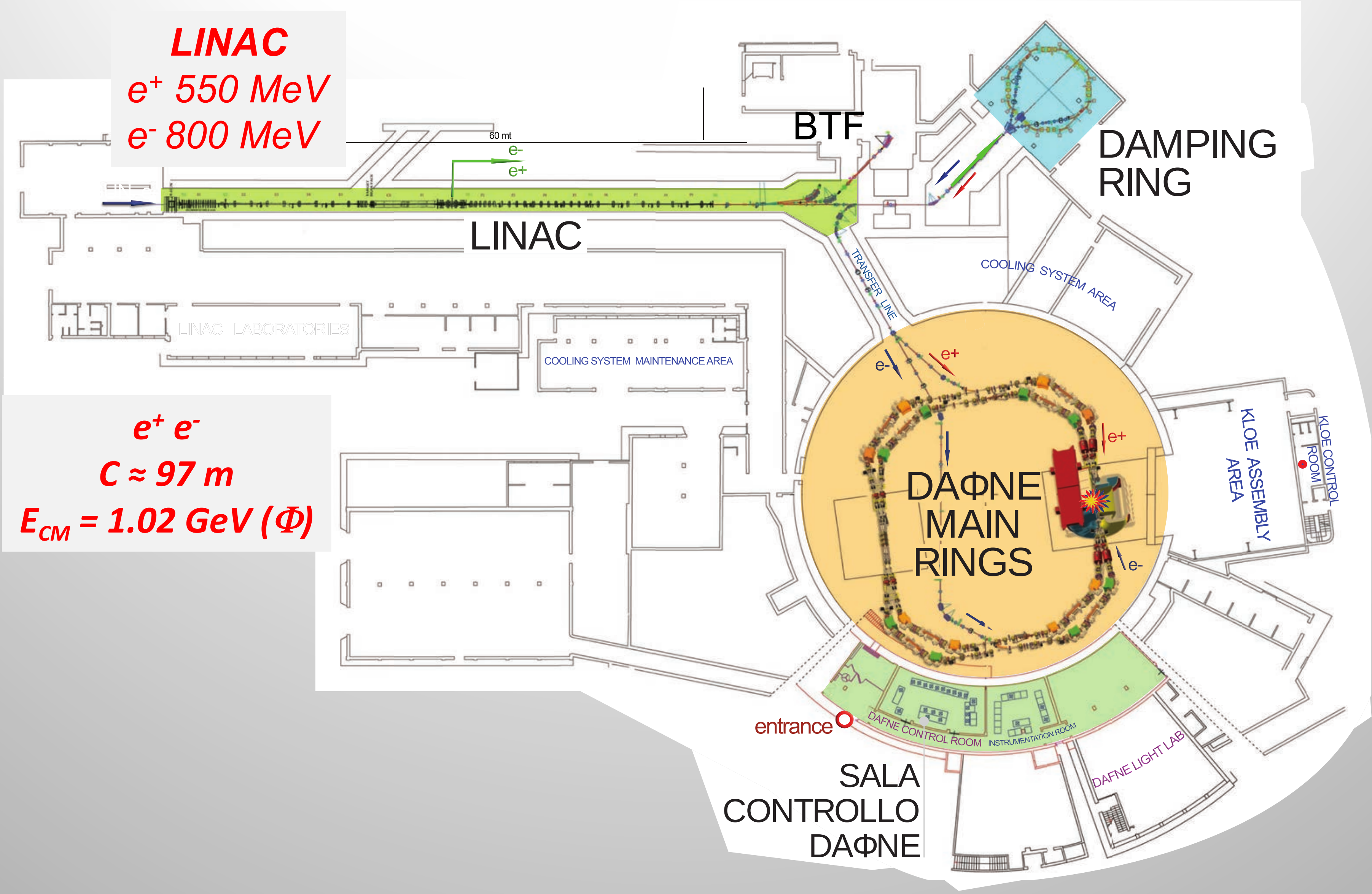
Outline

- *DAΦNE*
- *path toward high luminosity*
- *Crab-Waist Collision Scheme*
- *Performances of Crab-Waist collisions with:*
  - *SIDDHARTA*
  - *KLOE-2*
- *DAΦNE timeline*
- *Conclusions*

The DAΦNE Accelerator Complex

LINAC
e^+ 550 MeV
e^- 800 MeV



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

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 Meets Limitations

$\beta_y^* \sim \sigma_z$ to avoid hourglass effect

σ_z reduction led to:

- single bunch instability
- bunch lenghtening and microwave instabilityies
- CSR production

Higher N and N_b

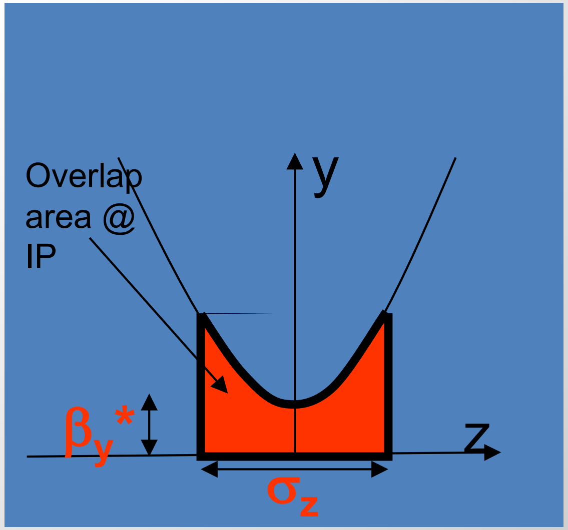
- led to enhanced power losses
- increase wall plug power requirements
- causes coupled bunch instabilityies

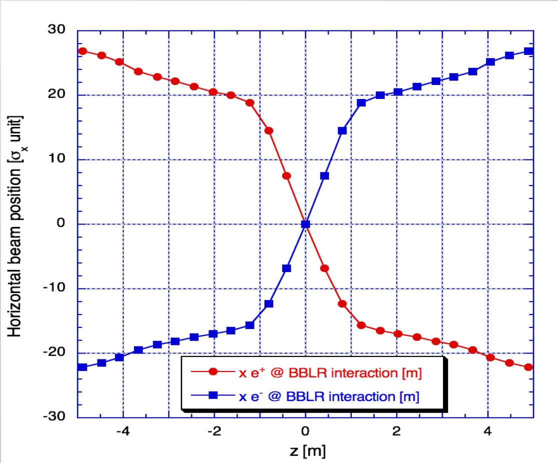
Tune shifts $\xi_{x,y}$ are restricted by the beam-beam limit

Larger σ_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 $L_\int$





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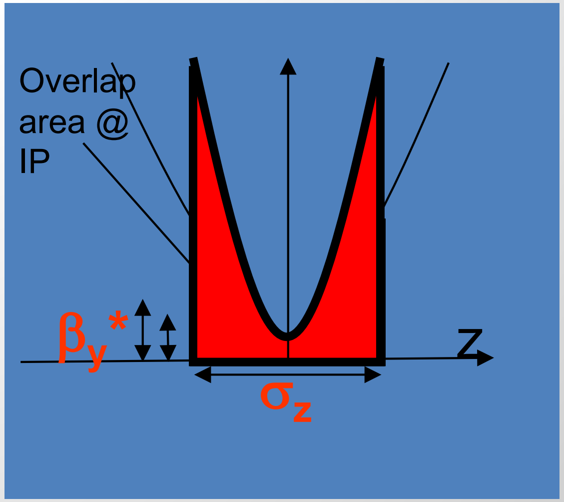
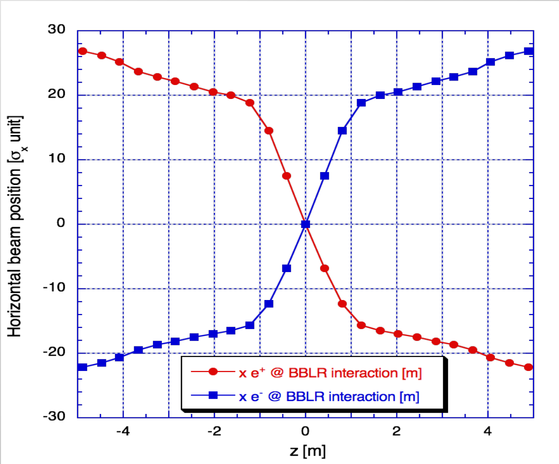


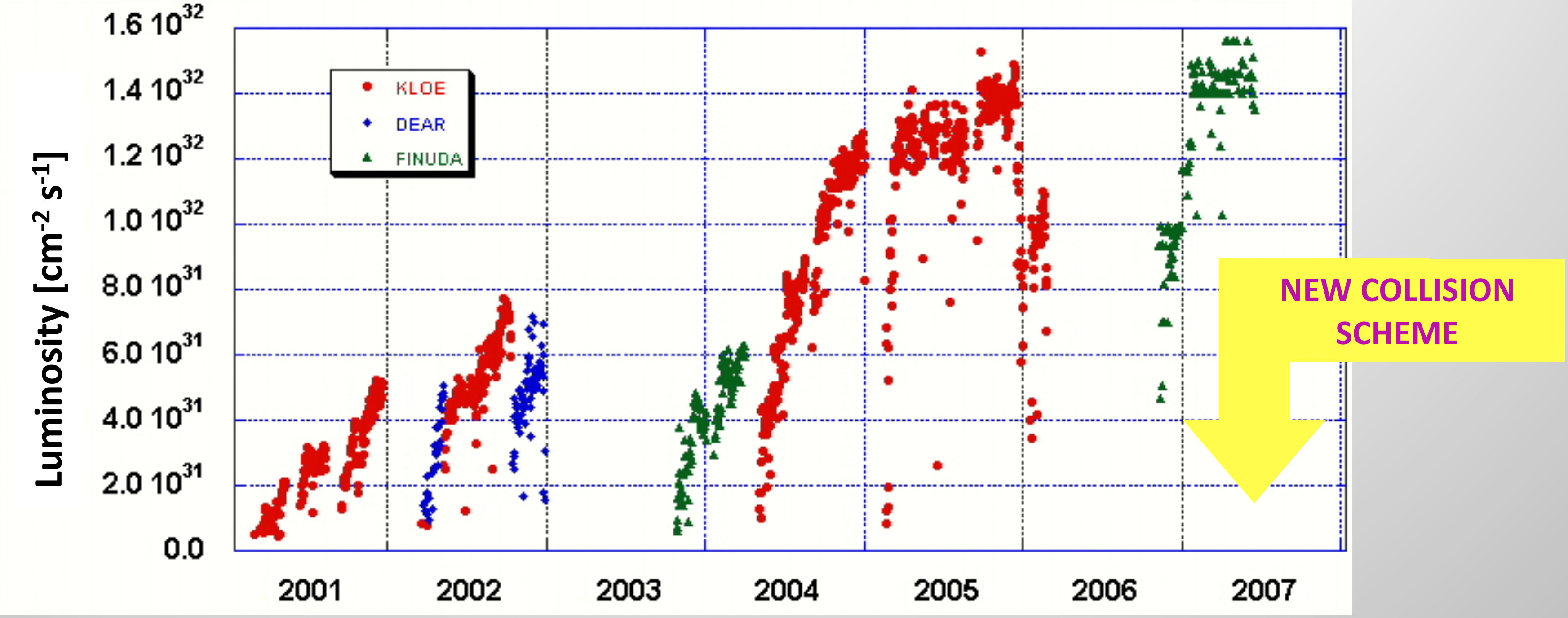


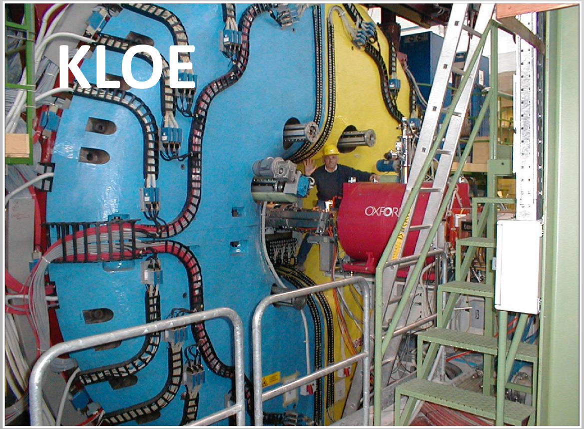
L_{peak} at DAΦNE 2001 ÷ 2007

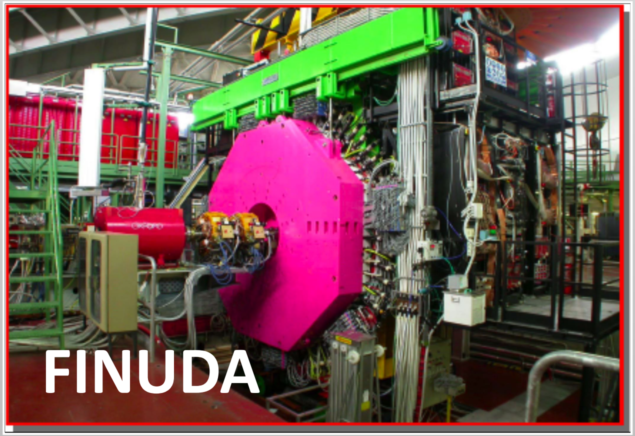
L_{peak} had a remarkable evolution mainly due to several machine upgrades

Experiments took data one at a time, although DAΦNE had been originally conceived with two Irs

In 2004 the low-β triplet of the KLOE IR has been replaced by a PMQUAD doublet -> 100 bunches operation







L_{logged} (fb^{-1}) 2001÷2007

KLOE	3.0
FINUDA	1.2
DEAR	0.2

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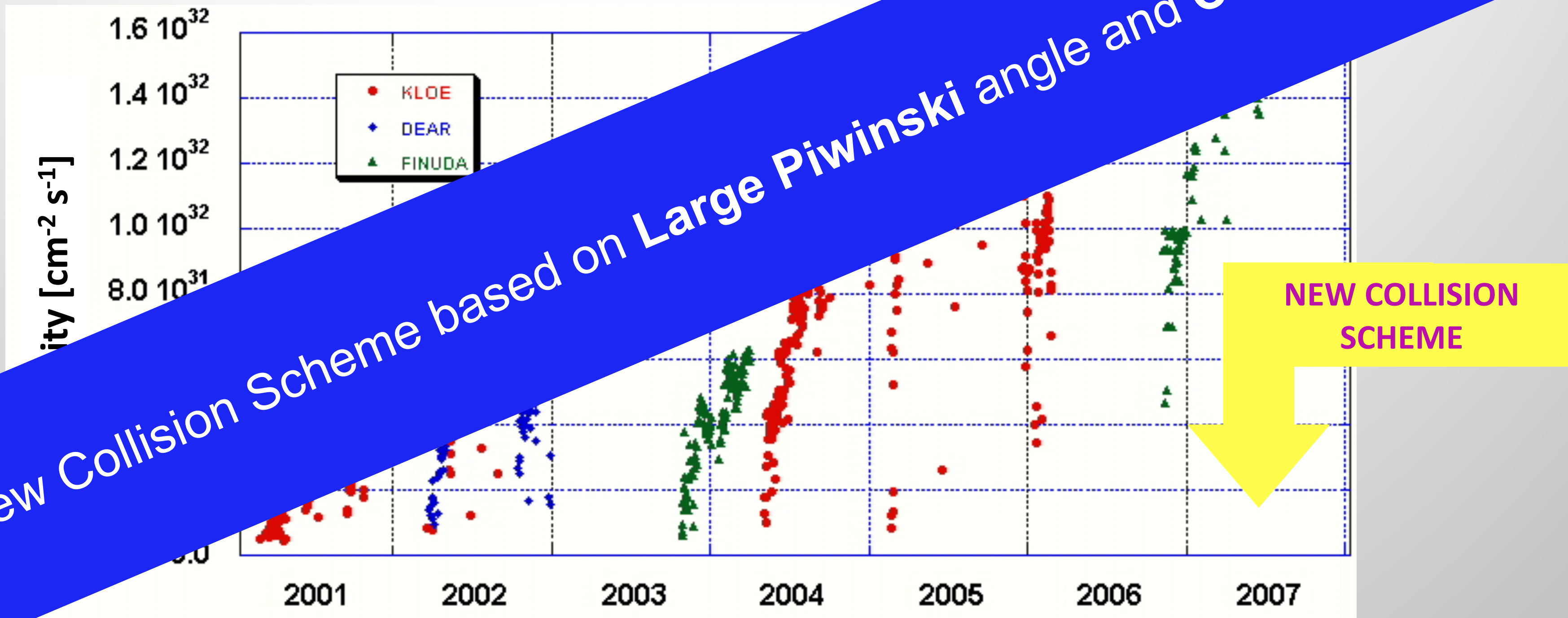
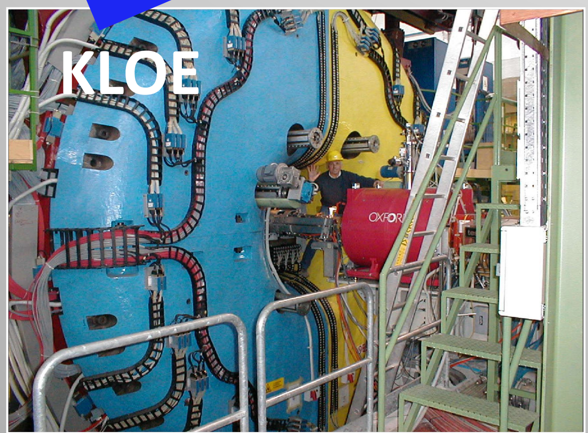
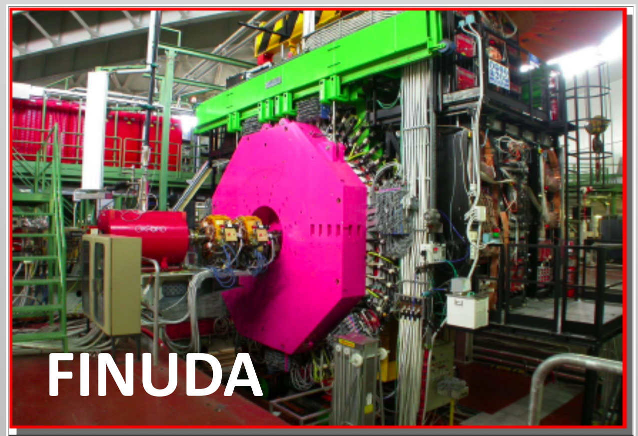
A new Collision Scheme based on Large Piwinski angle and Crab-Waist







L_{logged} (fb^{-1}) 2001÷2007

KLOE	3.0
FINUDA	1.2
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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

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

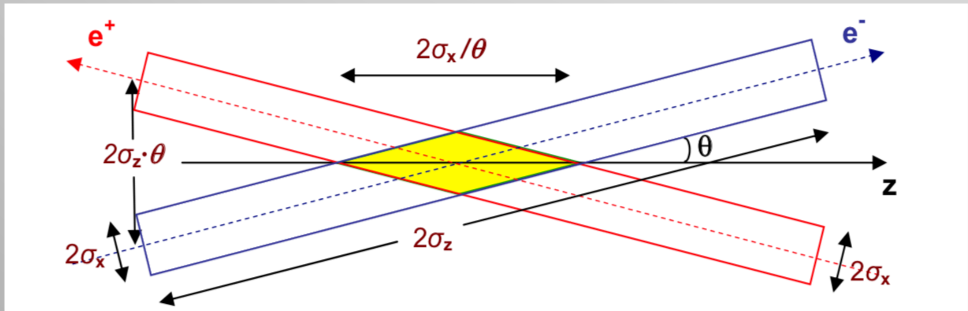
- low $\xi_{x,y}$ (tune shift)
- $L_{geometric}$ gain

β_y^* can be reduced for sake of the beams overlap region Σ

New low-β section
Ad hoc low-β optics

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

- $L_{geometric}$ gain
- lower ξ_y
- synchro-betatron resonances suppression
- ξ_y reduction with the synchrotron oscillation amplitude



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

Large Piwinski angle

Collisions with large θ is not a new idea

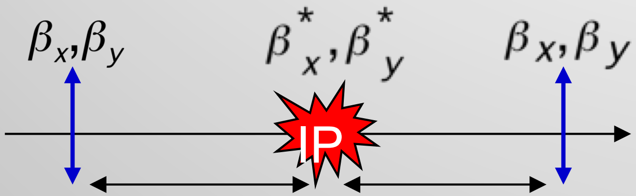
Crab-Waist transformation is

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

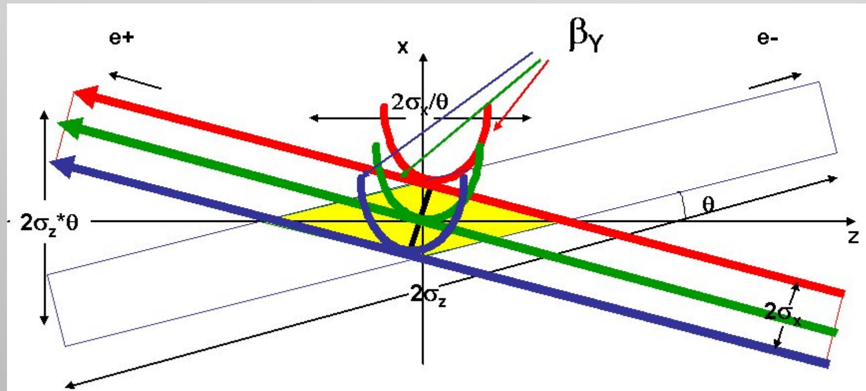
$$y = \frac{xy'}{2\theta}$$

sextupole (anti)sextupole



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

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



without CW Sextupoles

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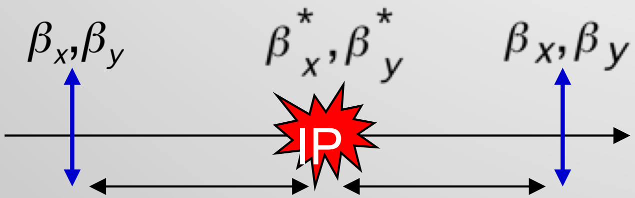

$$\Delta\nu_x = \pi$$
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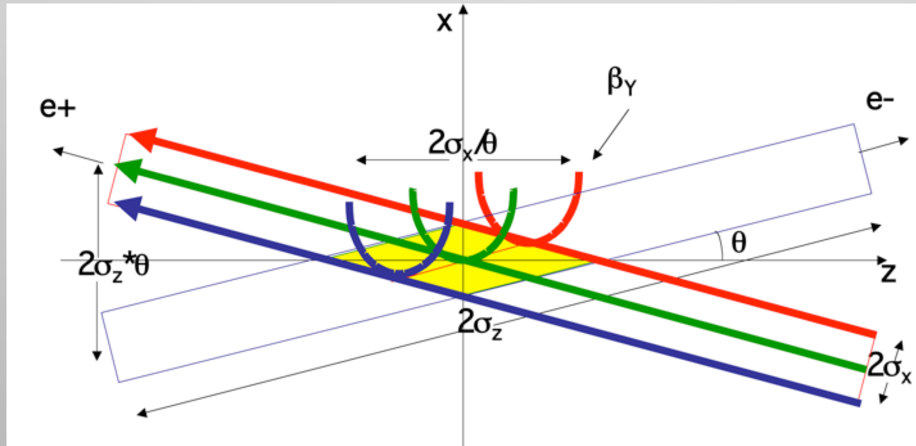
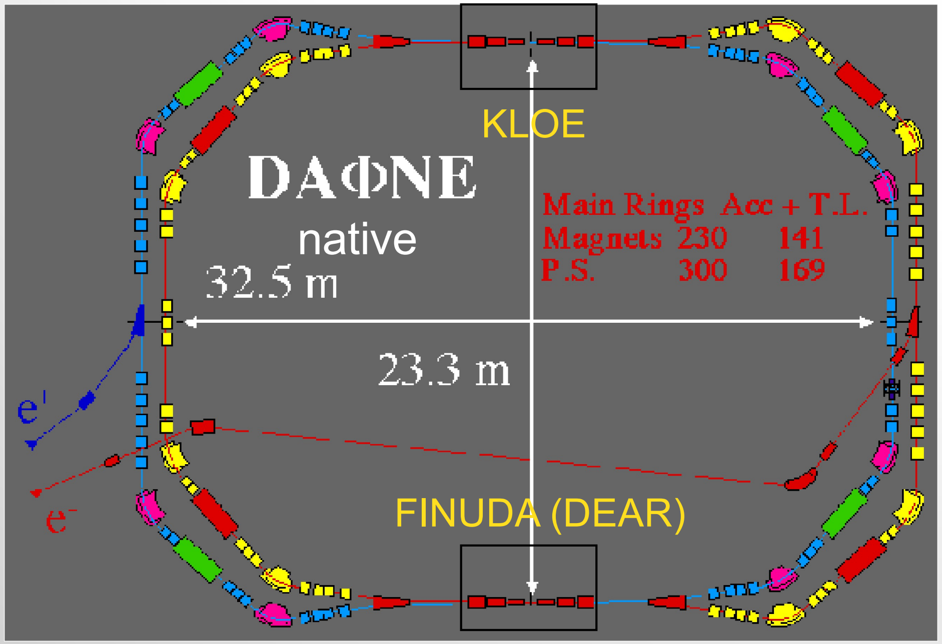
- $L_{geometric}$ gain
- X-Y and synchro-betatron resonances suppression



with CW Sextupoles

DAΦNE Layout and Parameters



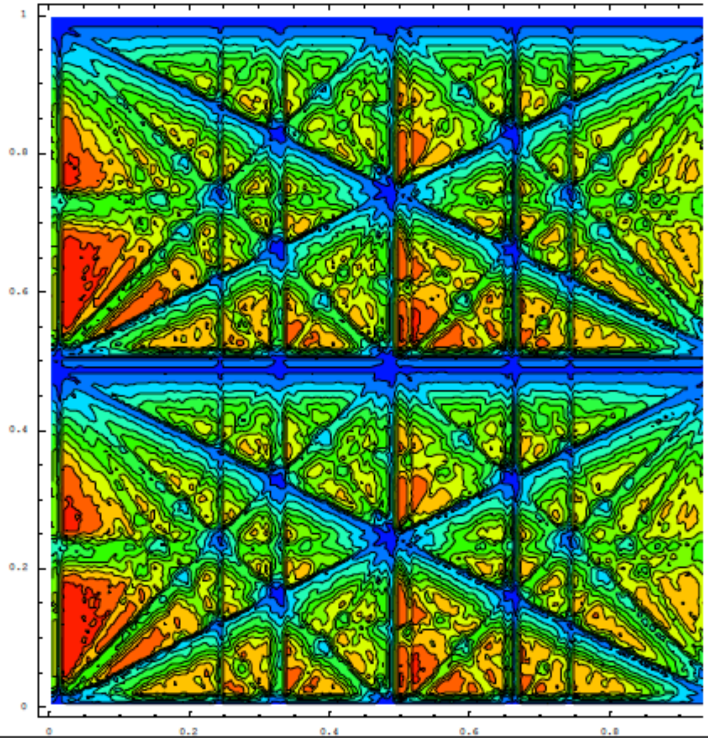
"Proposal for a Φ-factory", LNF-90/031 (IR),1990.

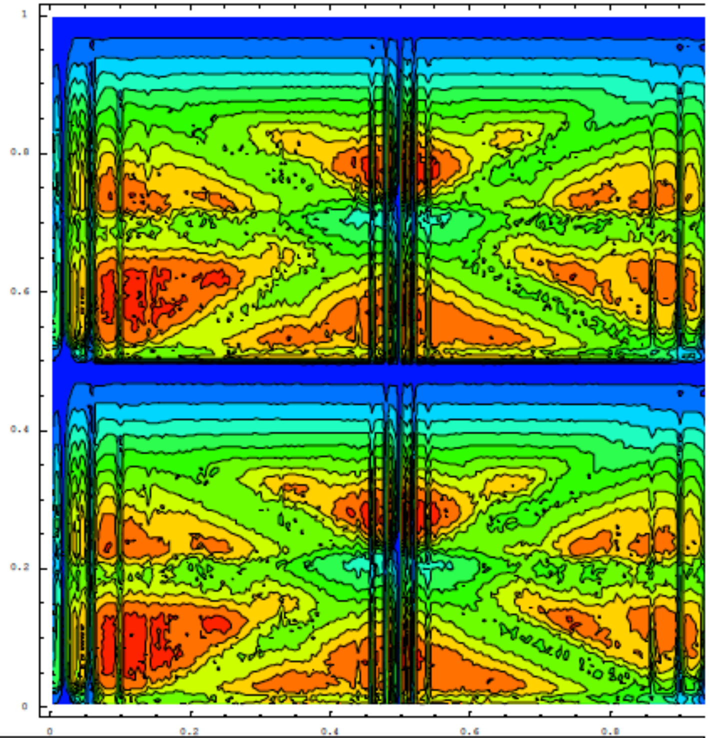
	DAΦNE native	DAΦNE Crab-Waist
Energy (MeV)	510	510
$\theta_{cross}/2$ (mrad)	12.5	25
ε_x (mm•mrad)	0.34	0.28
β_x^* (cm)	160	23
σ_x^* (mm)	0.70	0.25
$\Phi_{Piwinski}$	0.6	1.5
β_y^* (cm)	1.80	0.85
σ_y^* (μm) low current	5.4	3.1
Coupling, %	0.5	0.5
Bunch spacing (ns)	2.7	2.7
I_{bunch} (mA)	13	13
σ_z (mm)	25	15
N_b	120	120

Colliding Beams have:
- *low E*
- *high currents*
- *short bunch spacing 2.7 nsec*
- *long damping time*

Suppression of X-Y Resonances

Much higher luminosity!





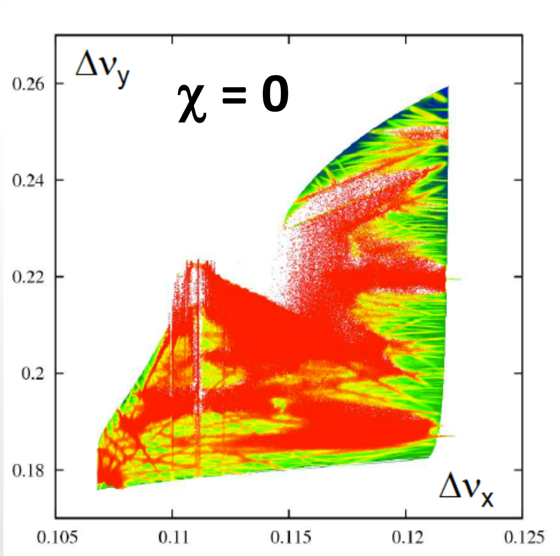
Typical case (KEKB, DAΦNE etc.):

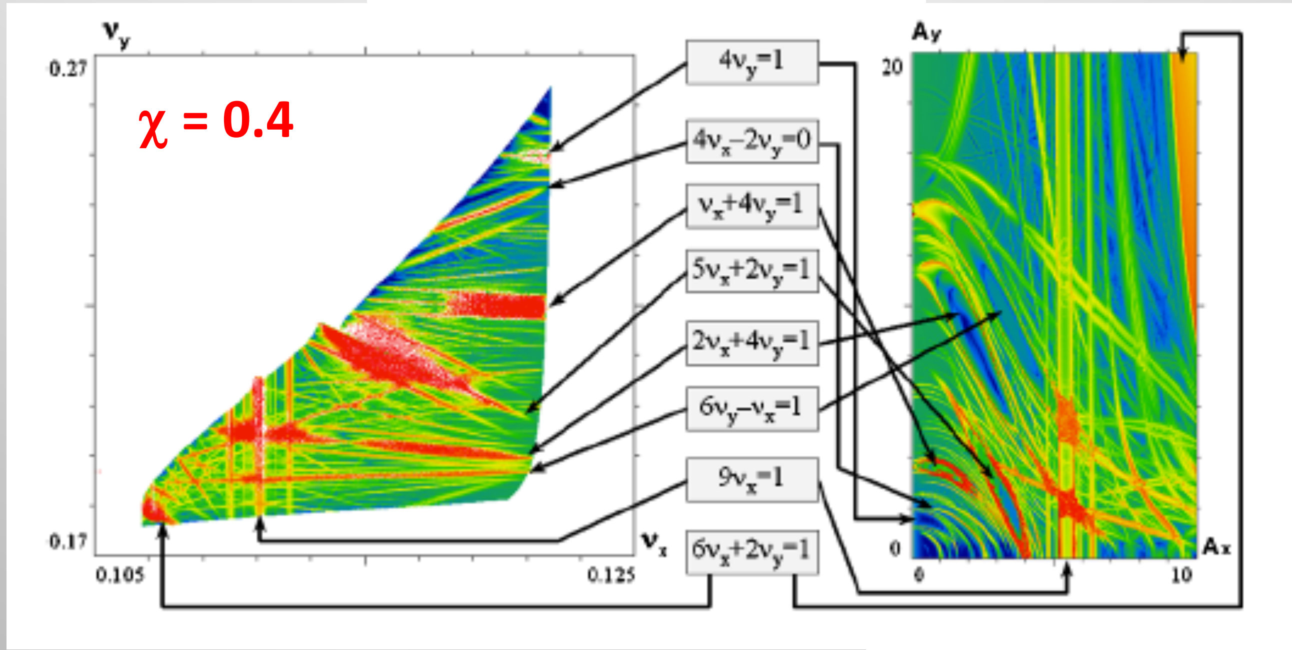
1. low Piwinski angle $\Phi < 1$
2. β_y comparable with σ_z

Crab Waist On:

1. large Piwinski angle $\Phi \gg 1$
2. β_y comparable with σ_x/θ

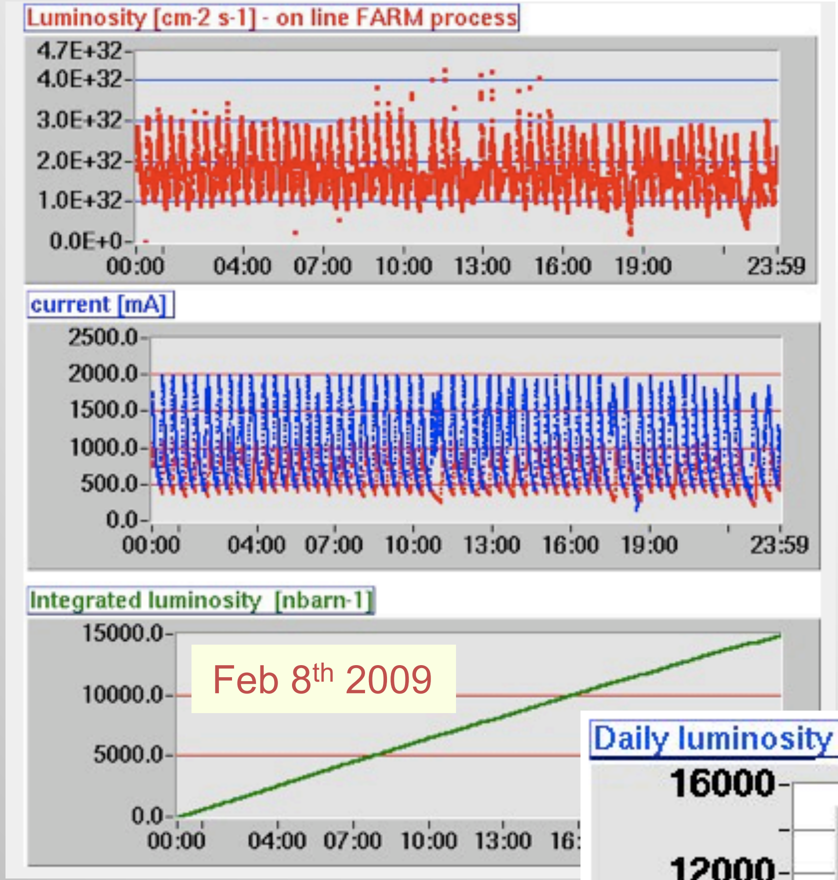
Frequency Map Analysis of *BB* Interaction

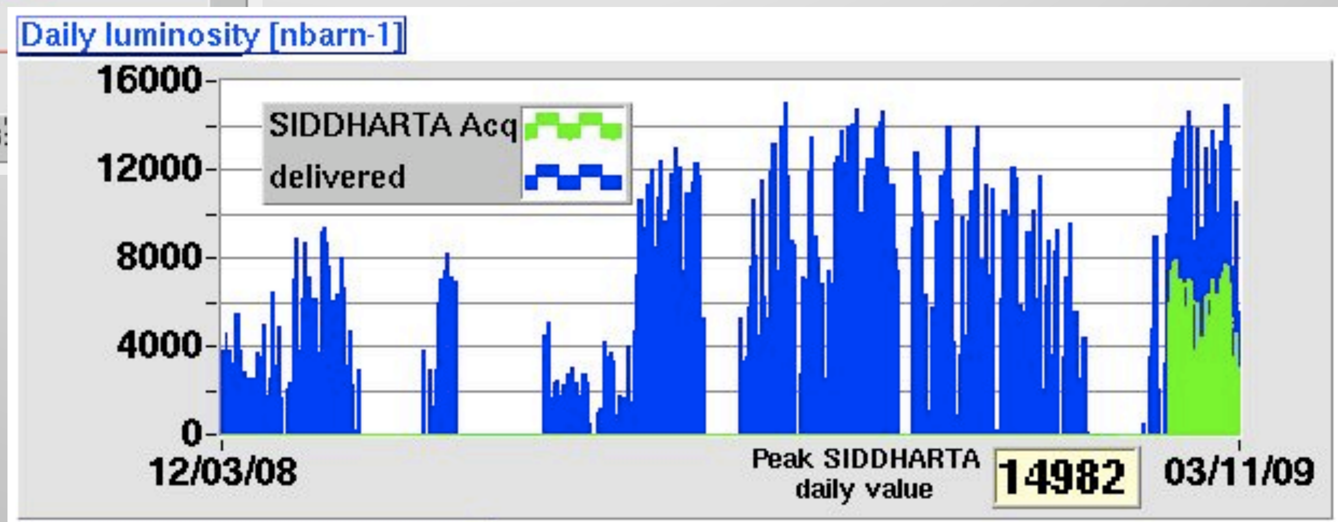




(E. Simonov, D. Shatilov et al.)

Best daily integrated luminosity

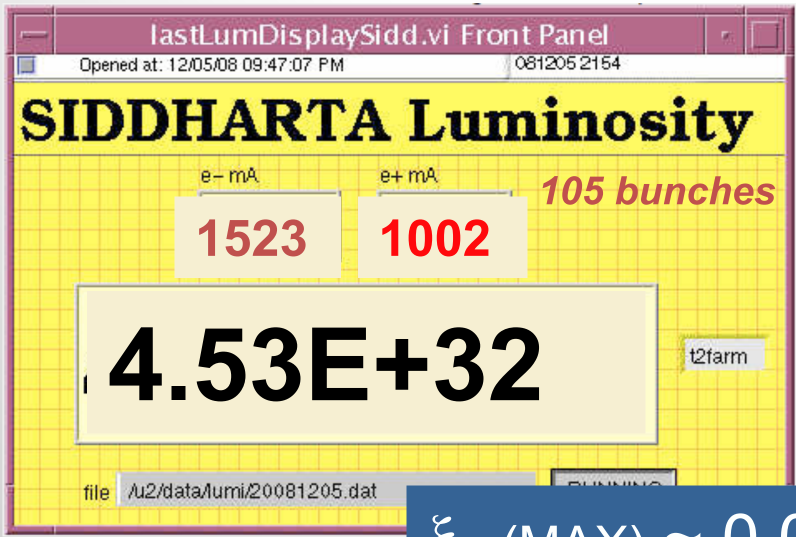




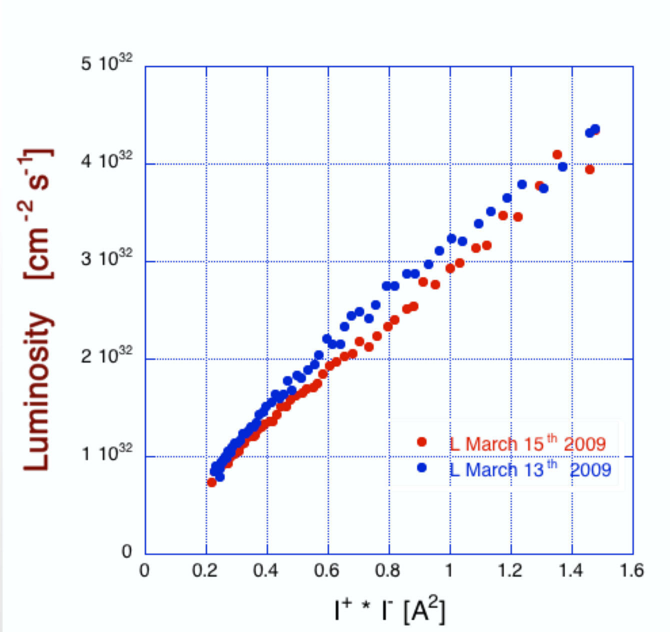
$$L_{\int day} = 15.\ pb^{-1}$$

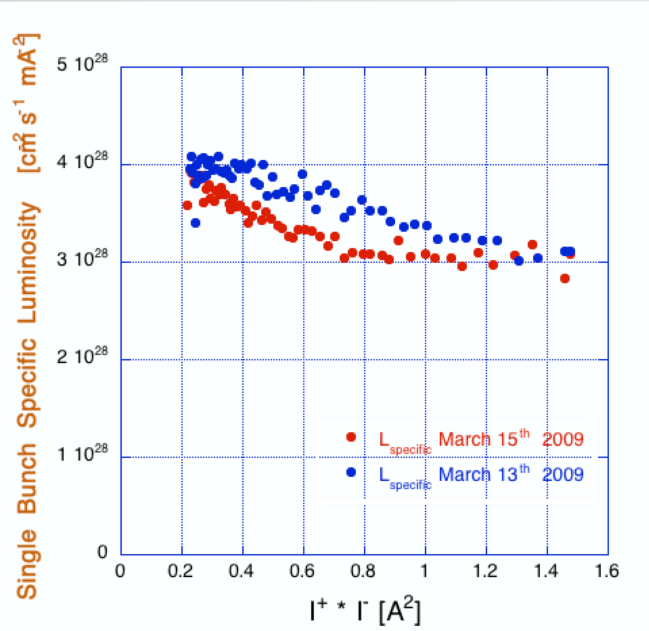
- *moderate injection rate regime*
- *105 colliding bunches*
- $\int_{1hour} L = 0.62\ pb^{-1}$

Luminosity during SIDDHARTA run



ξ_y (MAX) ~ 0.0443

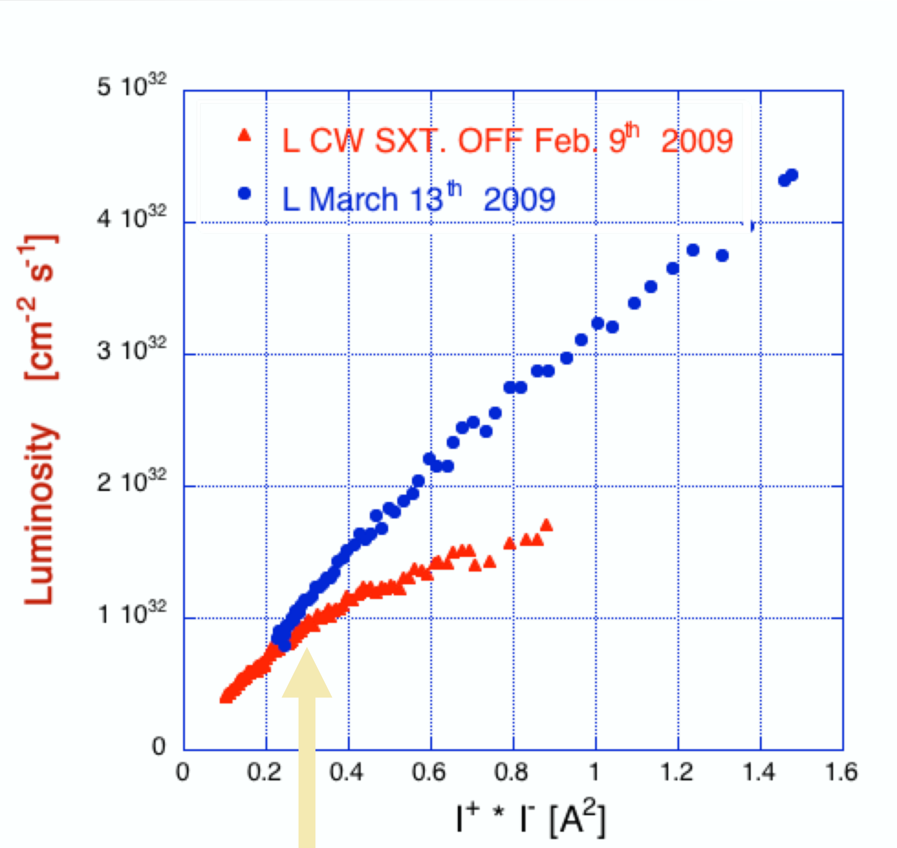


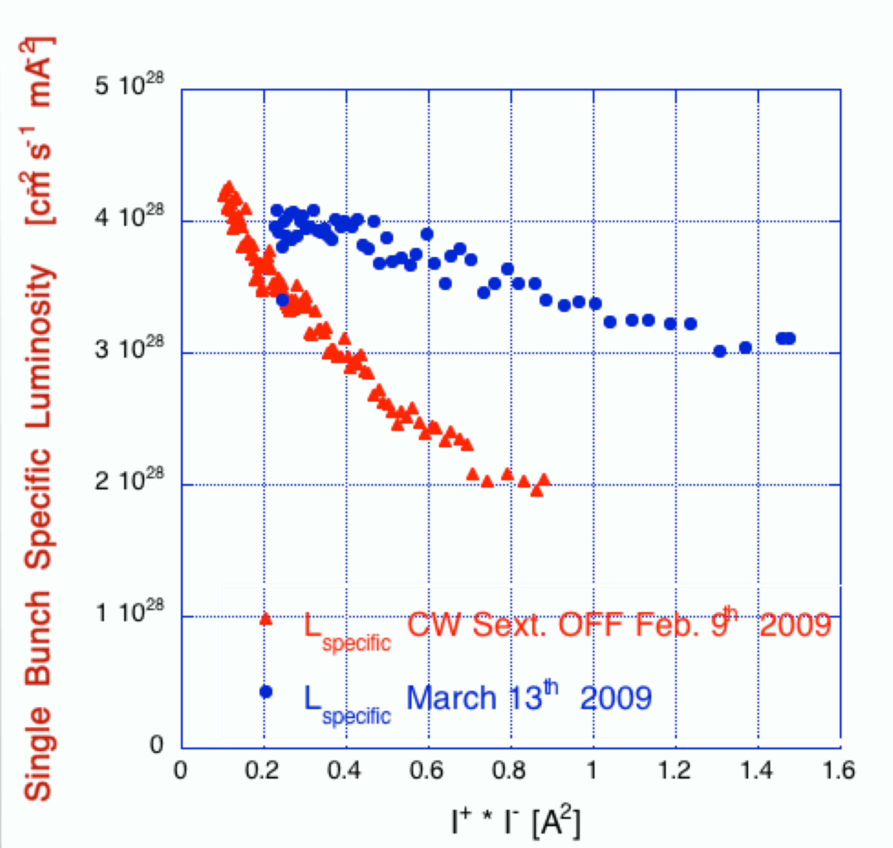


Specific Luminosity:

- Drops with the product of the colliding currents due to:
  - residual beam-beam blow up
  - bunch lengthening
- At low currents is four times higher than without *Crab-Waist*
- The reduction is underestimated since collisions are optimized mainly at high ***I***, it has been considerably reduced during the collider commissioning

Crab-waist compensation and luminosity





- Transverse beam blow-up
- Lifetime reduction

CW-Collision scheme for the KLOE detector

Integrating the high luminosity collision scheme with a large experimental detector introduces new challenges in terms of: IR layout, optics, beam acceptance, coupling correction

Crucial Points:

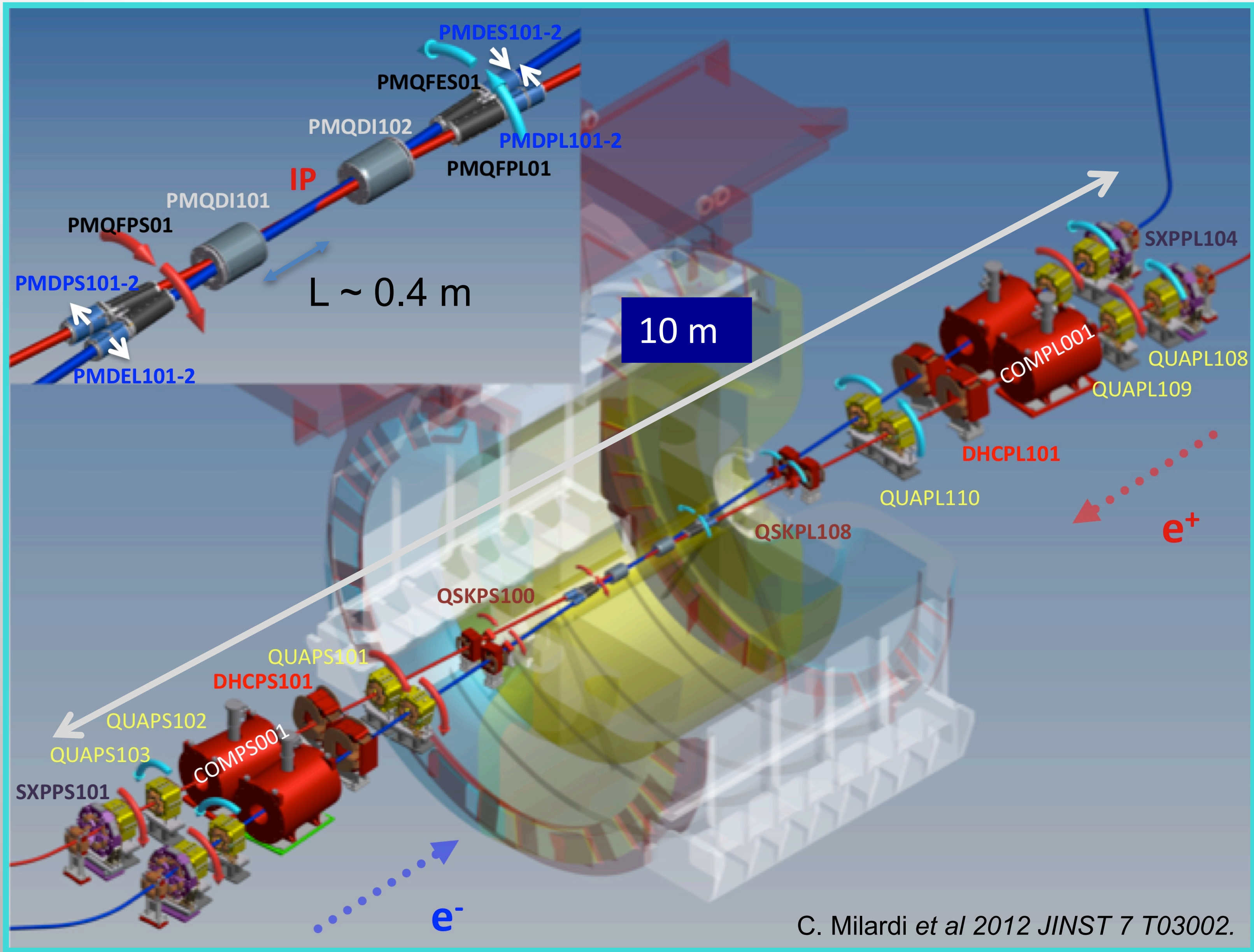
IR optics complying with:

- 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

KLOE-2 IR



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

Coupling correction

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

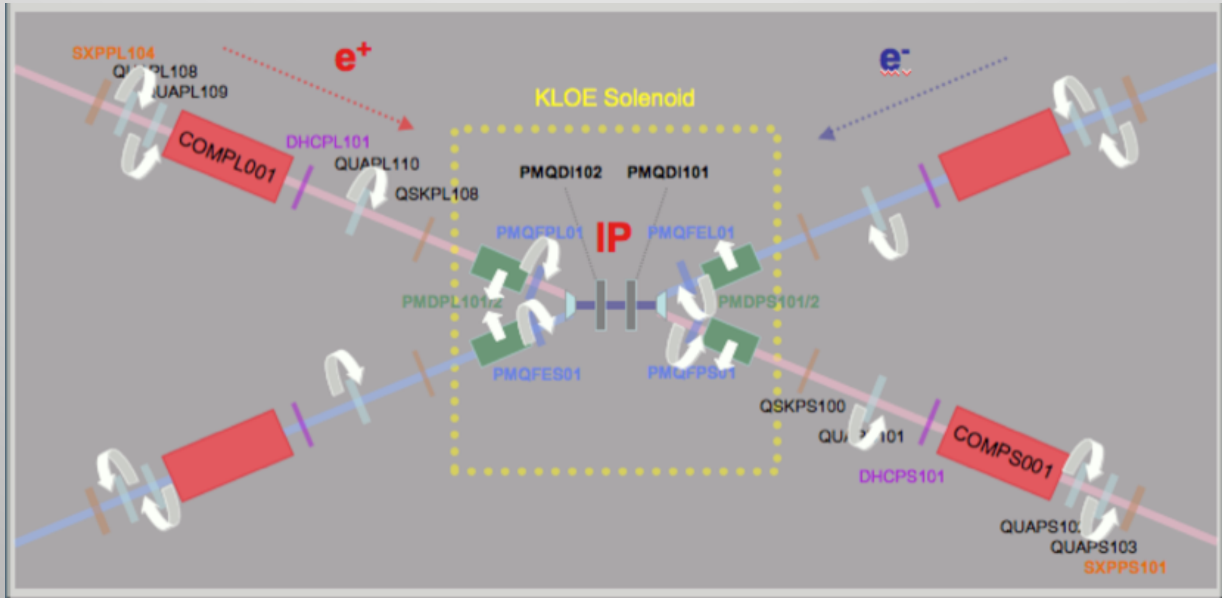
$$\int_{KLOE} B\cdot dl = 2.048 \quad [Tm] \quad \rightarrow \quad I_{KLOE} = 2300 [A]$$

$$\int_{comp} B\cdot dl = \pm 1.024 \quad [Tm] \quad \rightarrow \quad I_{comp} = 867 [A]$$

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

	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)***

Fixed QUAD rotations
K is expected to be lower than for KLOE past
K_{KLOE1} = 0.2 ÷ 0.3 %

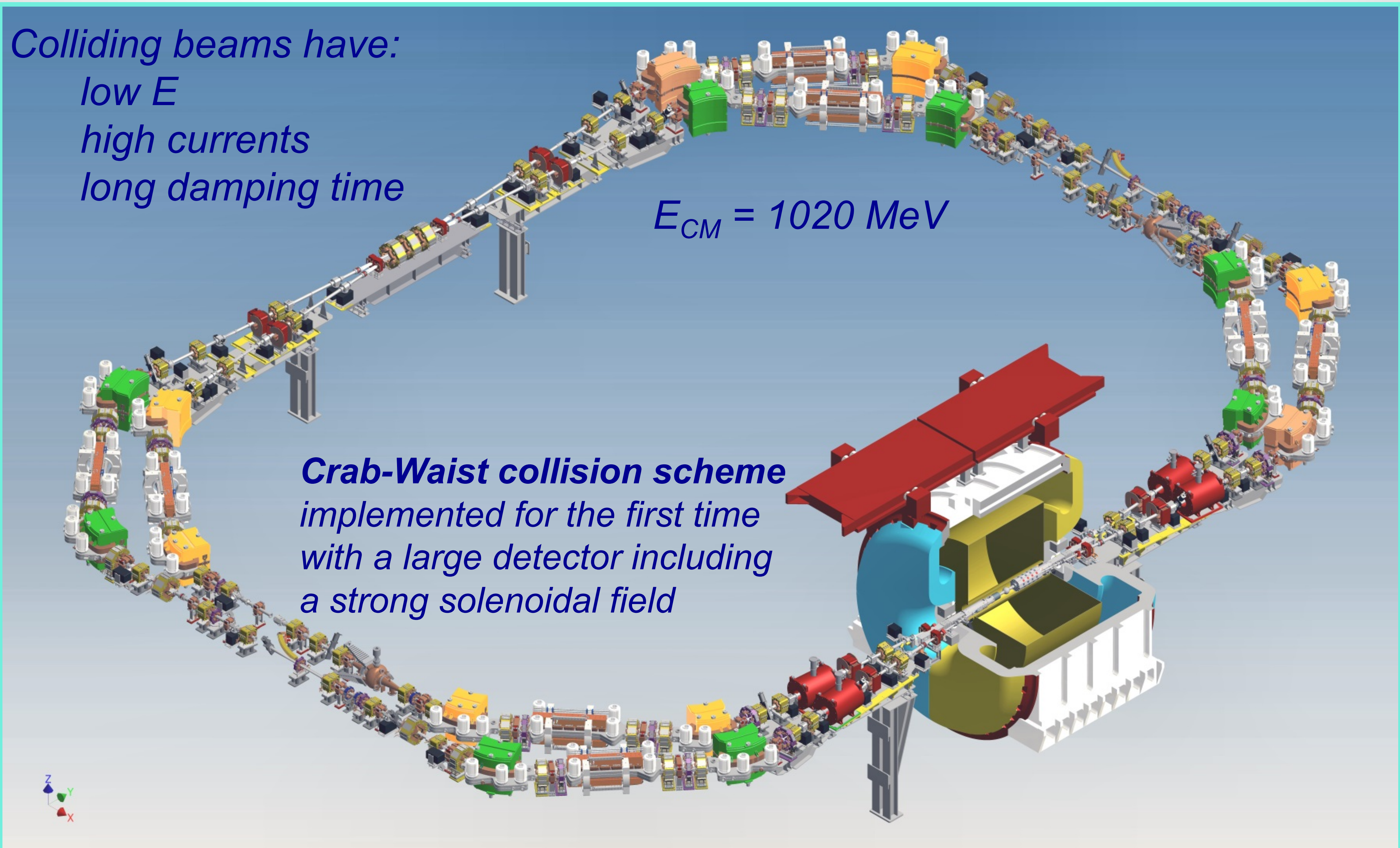


DAΦNE and KLOE-2

Colliding beams have:
low E
high currents
long damping time

E_{CM} = *1020 MeV*

Crab-Waist collision scheme *implemented for the first time with a large detector including a strong solenoidal field*



DAΦNE Activity Program for KLOE-2

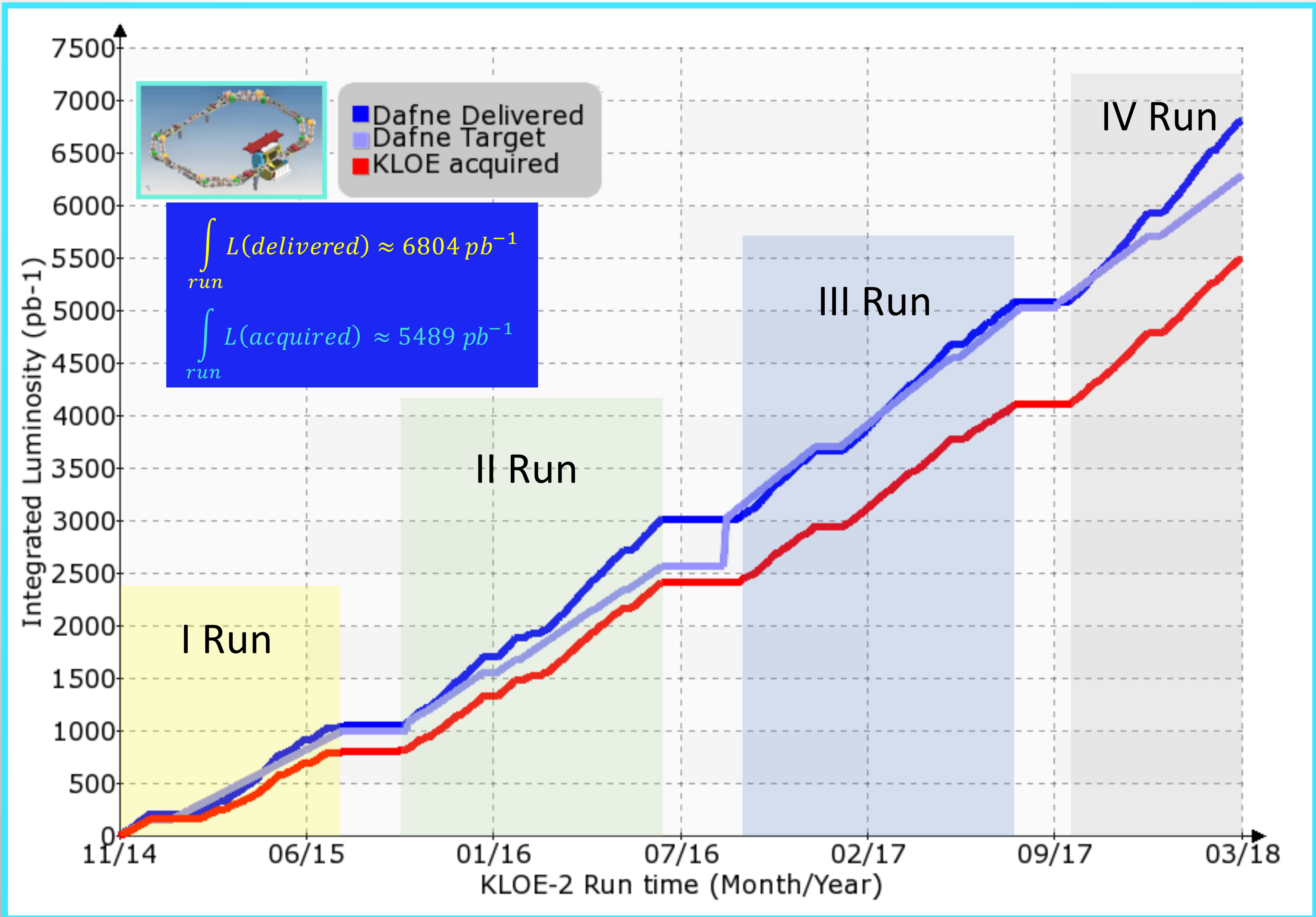
Preliminary Test Phase *fall 2010 ÷ Dec 2012*

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

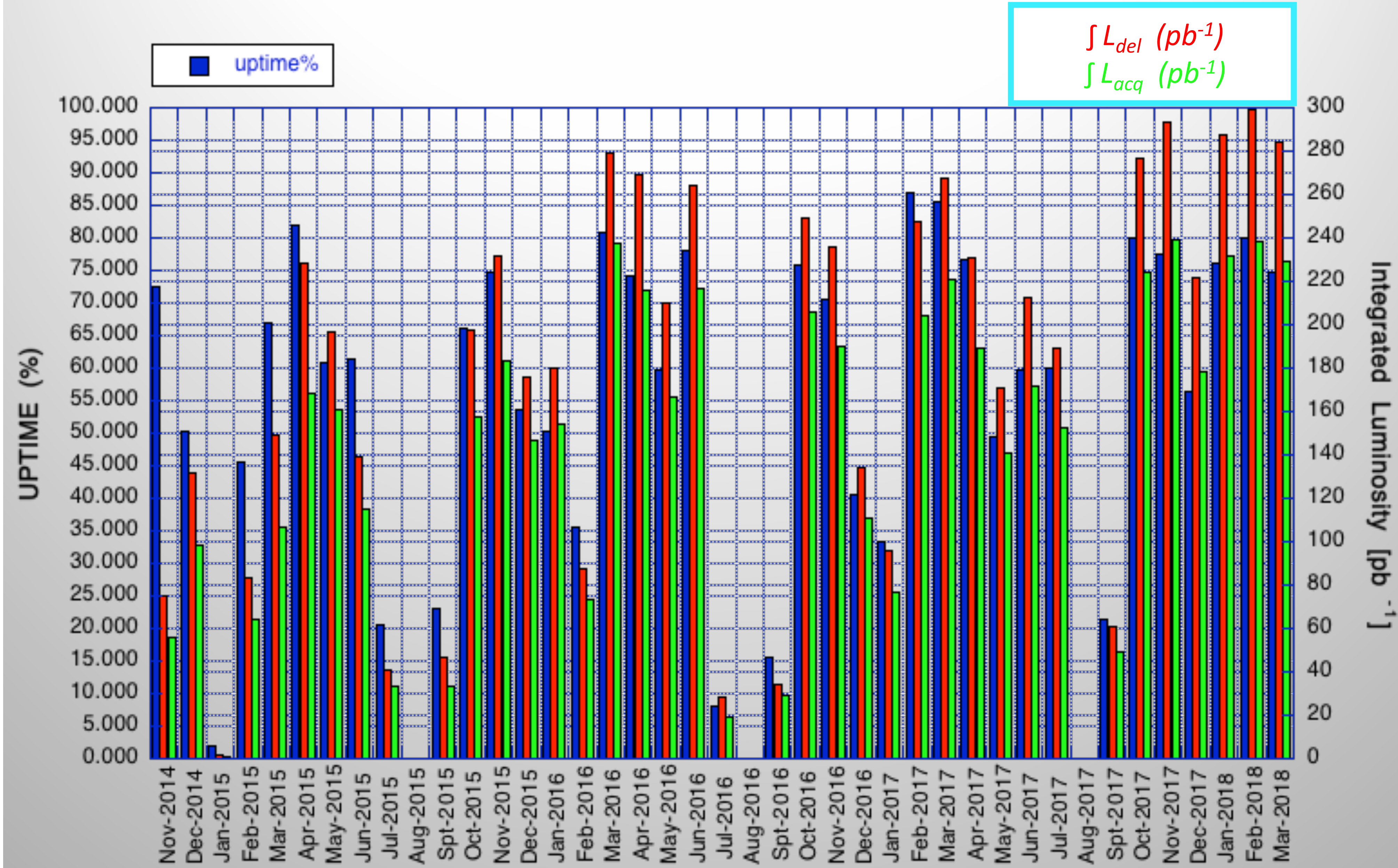
KLOE-2 data taking

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}

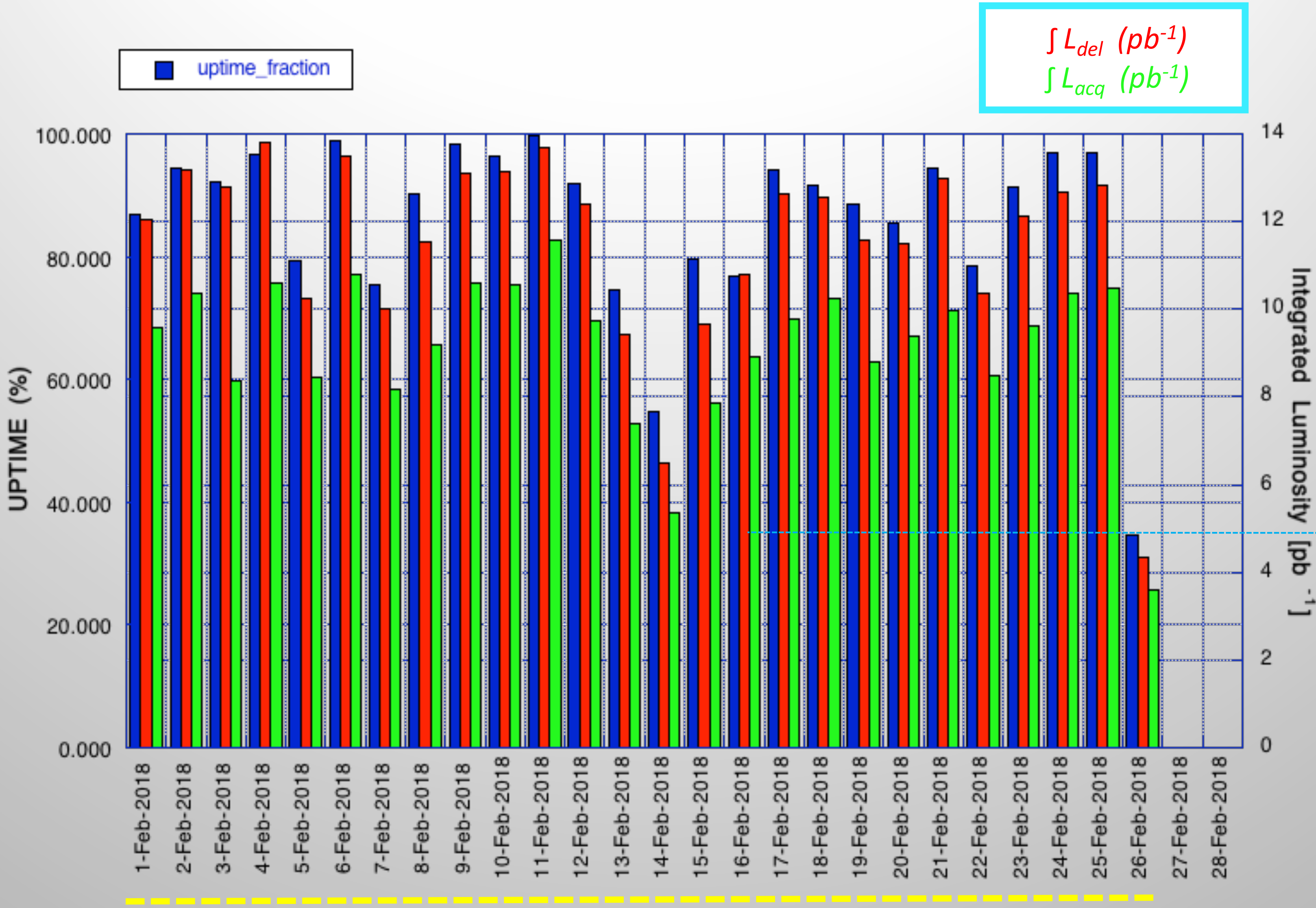
KLOE-2 Run Overview



Month by Month Luminosity Trend

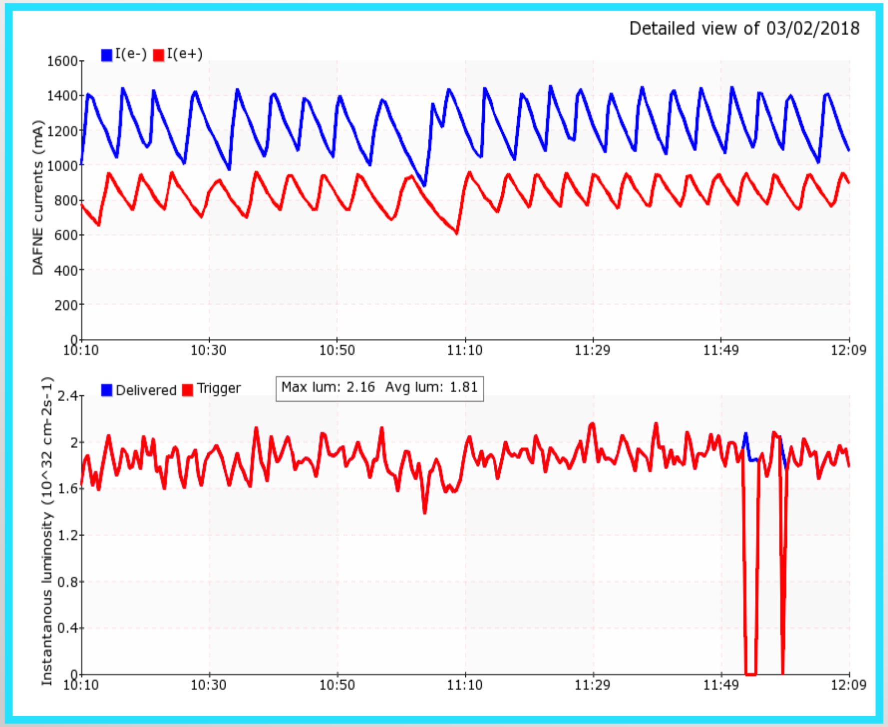


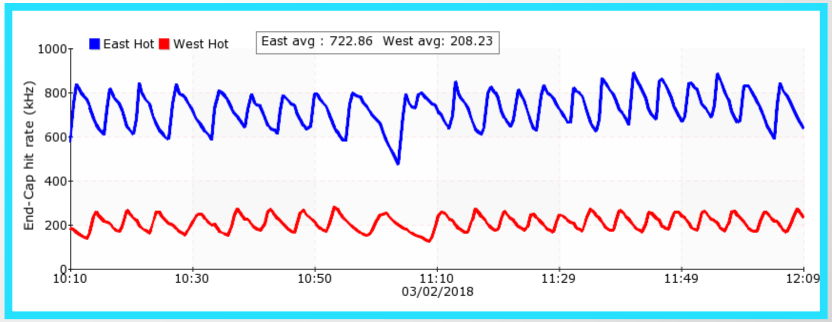
Best Operations Month

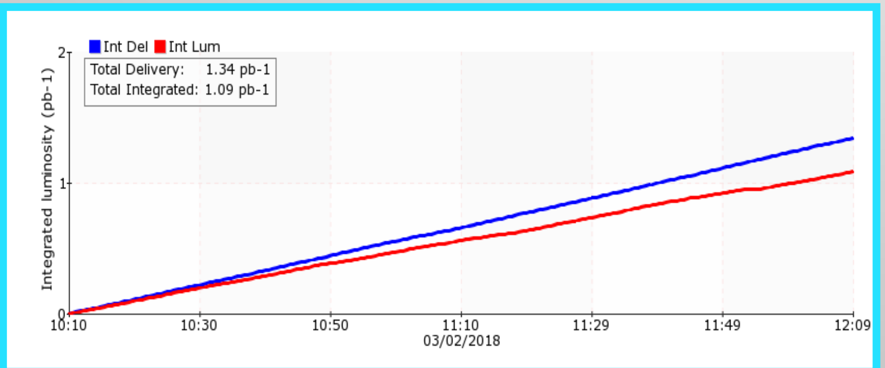


$\int L_{del}$ ~ 300 (pb^{-1}) in 26 days

Highest Hourly Integrated Luminosity





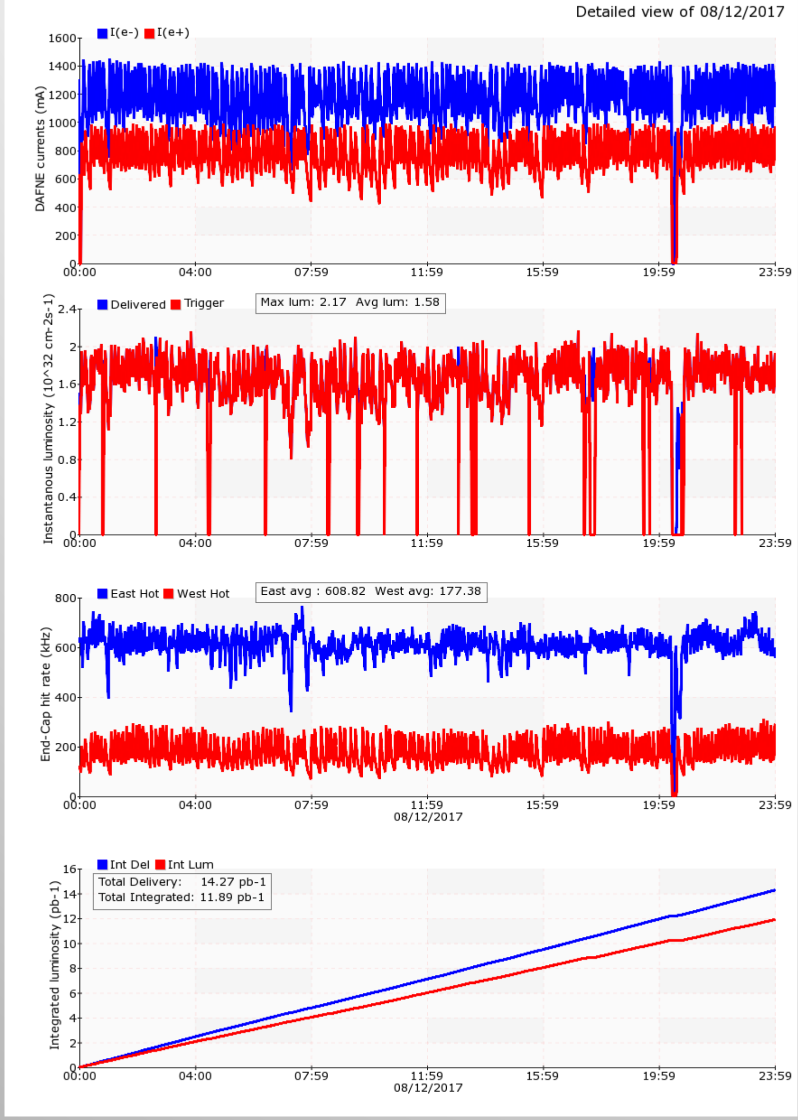


$$\int_{1h} L \sim 0.67\ pb^{-1}$$

$$N_b = 107$$

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

Highest Daily Integrated Luminosity

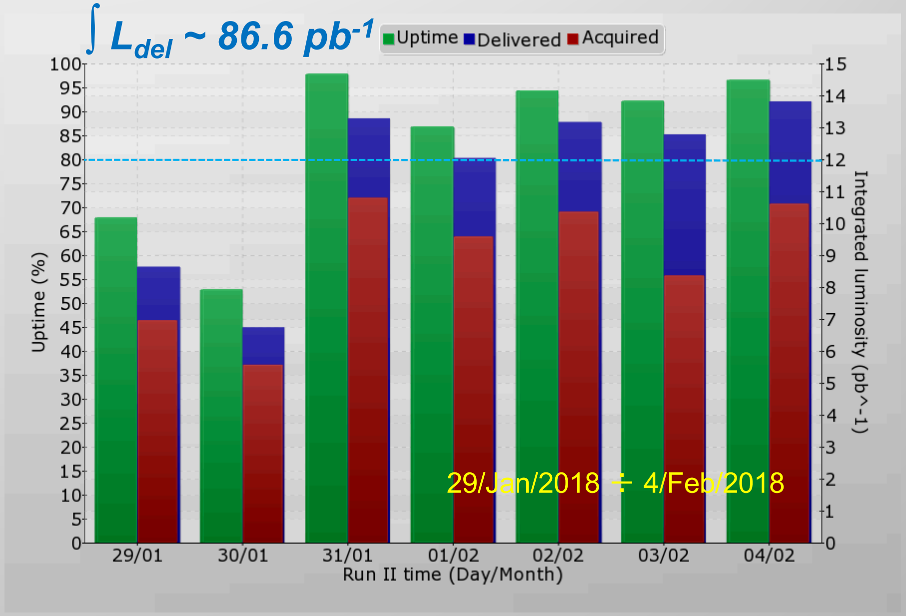


$\int L_{del} \sim 14.3\ pb^{-1}$

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

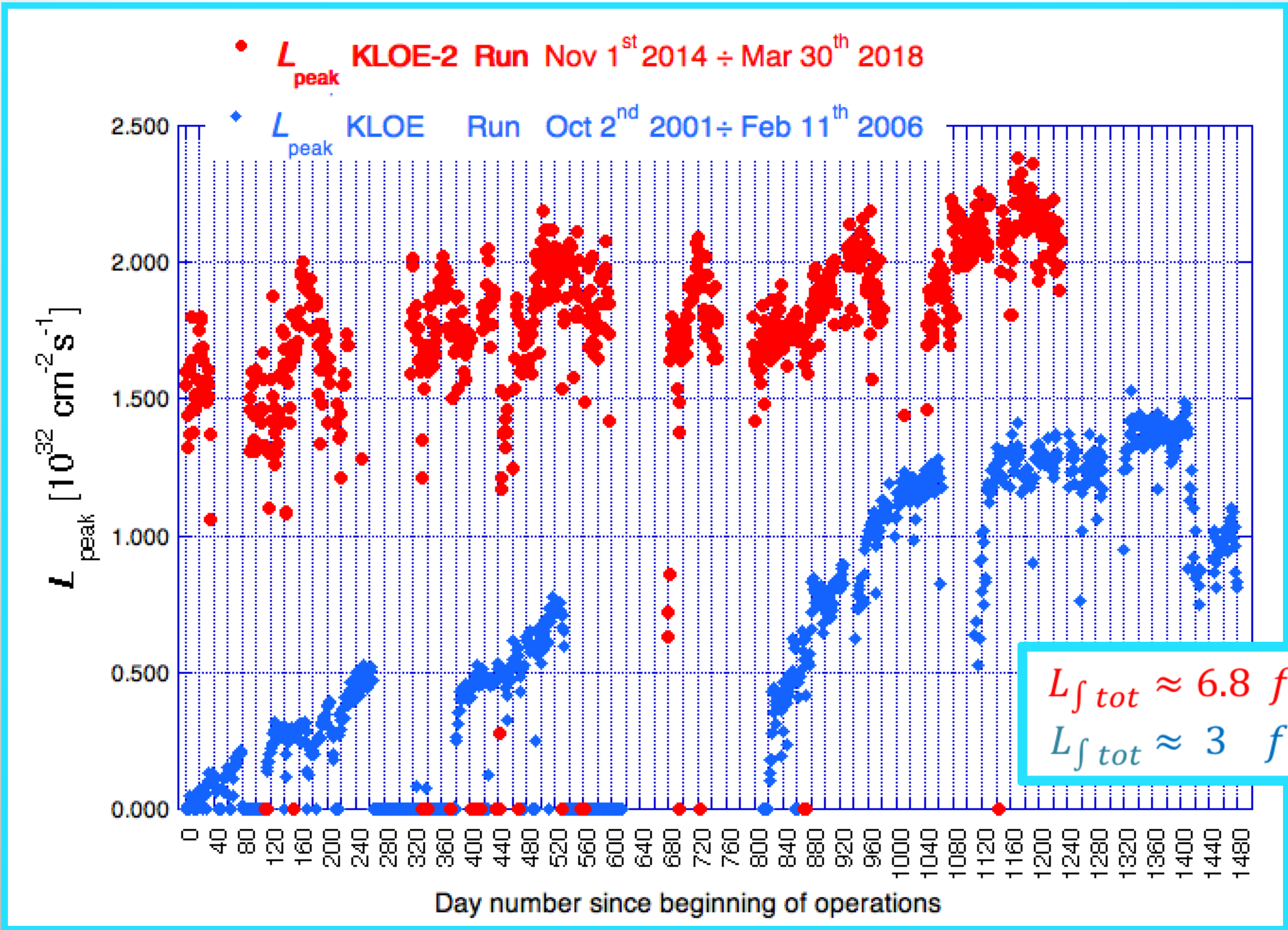
Uptime ~98%

- 106 bunches
- Sustainable background



Crab-Waist Luminosity Gain

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

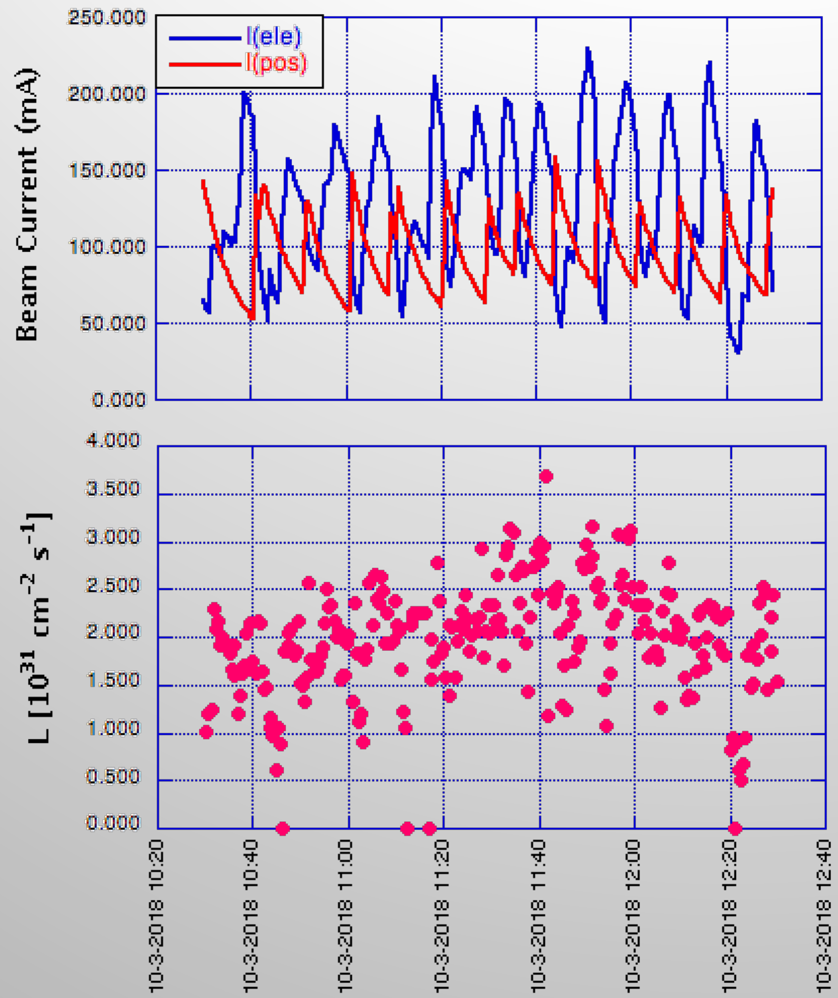


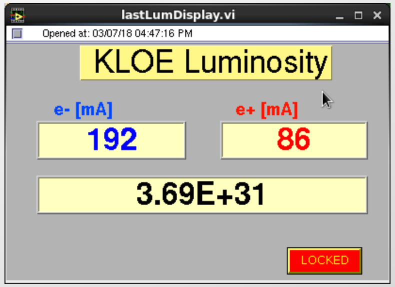
$L_{\int tot} \approx 6.8 \;\; fb^{-1}$

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

10 Bunches Collisions

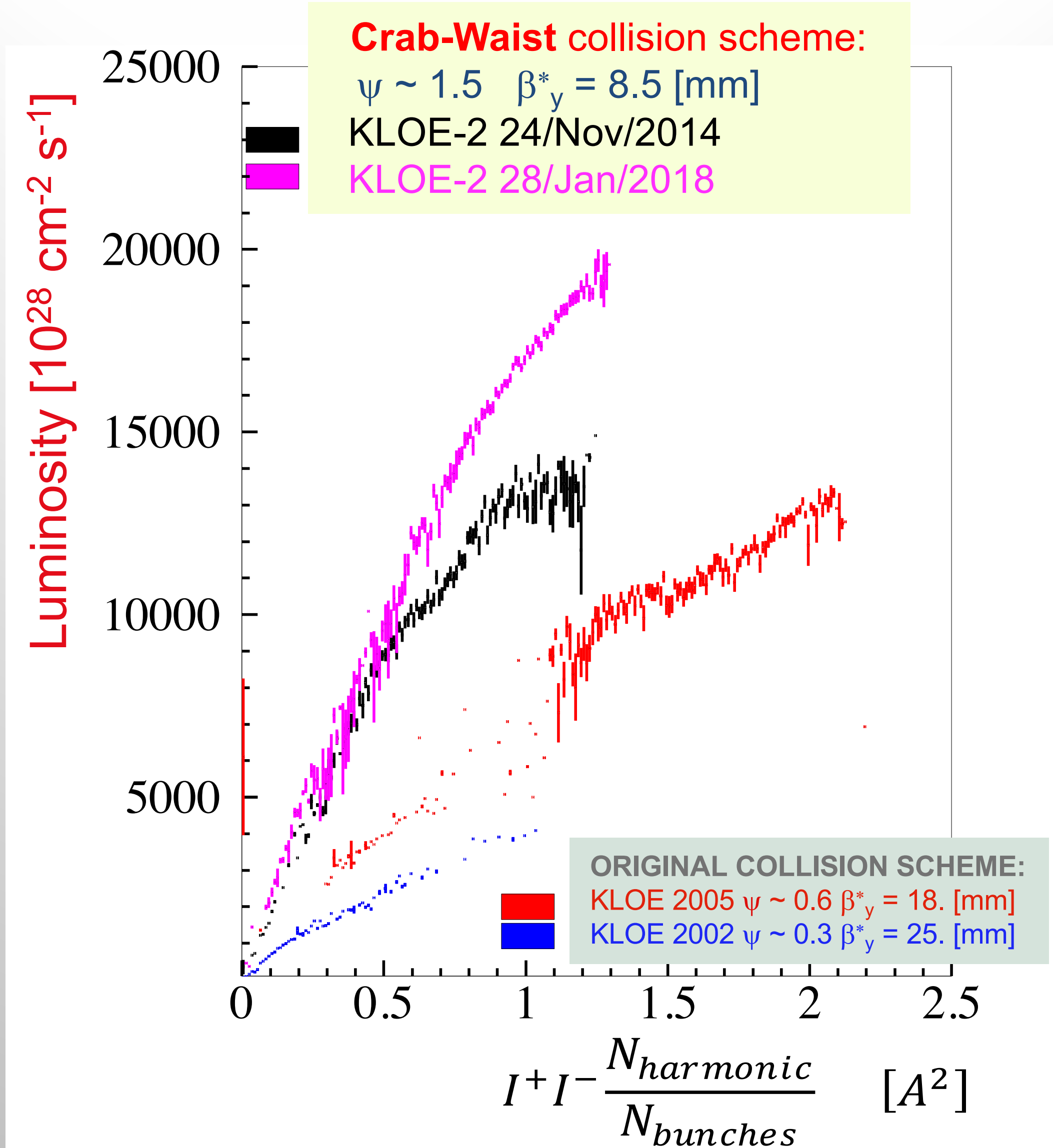
Aiming at minimizing the impact of multi-bunches effects and e-cloud instabilities on *Luminosity*





- *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*

Crab-Waist Luminosity Gain



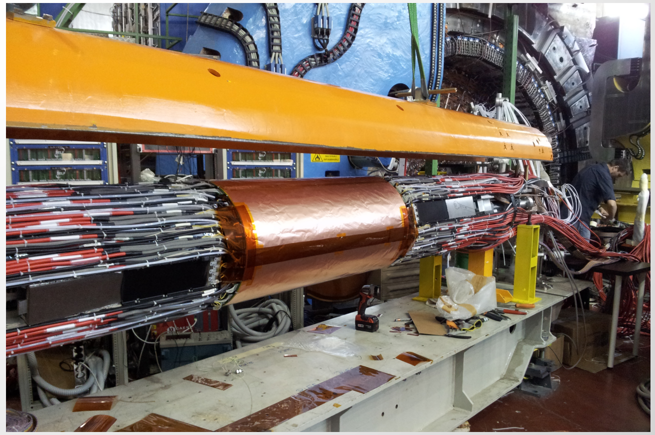
Peak Luminosity

	DAΦNE CW upgrade SIDDHARTA (2009)	DAΦNE KLOE (2005)	DAΦNE (CW) KLOE-2 (2014)
L_{peak} [$cm^{-2}s^{-1}$]	$4.53 \bullet 10^{32}$	$1.50 \bullet 10^{32}$	$2.38 \bullet 10^{32}$
I^- [A]	1.52	1.4	1.18
I^+ [A]	1.0	1.2	0.87
$N_{bunches}$	105	111	106
$\int_{day} L$ [pb^{-1}]	14.98	9.8 (seldom)	14.3

L_{peak} exceeds by a 59% the best luminosity ever achieved, at DAΦNE, during operations for an experimental apparatus including high field detector solenoid.

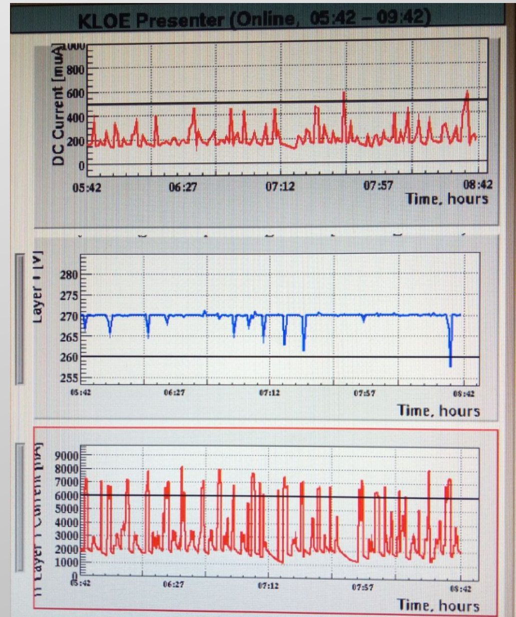
Background Control

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



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

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

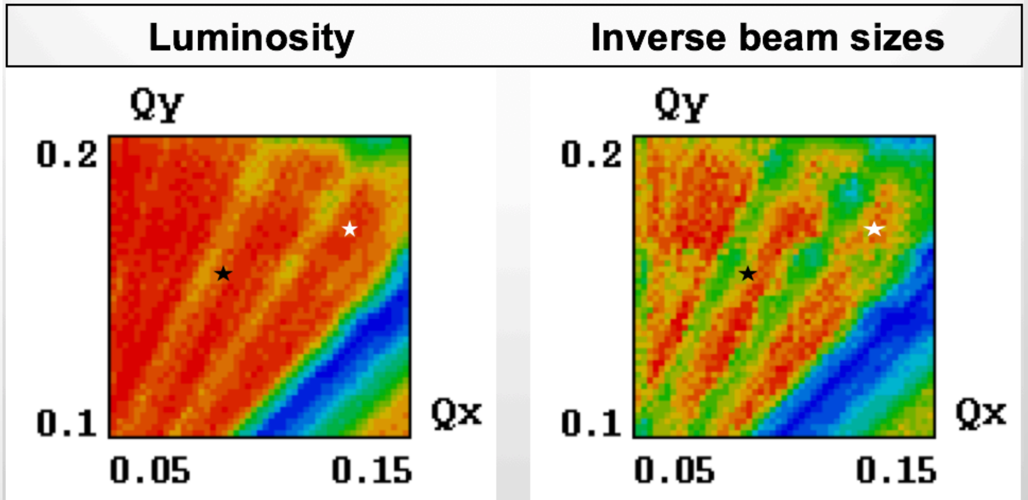
e⁻ Ring Working Point Scan

Numerical simulations aiming at improving:

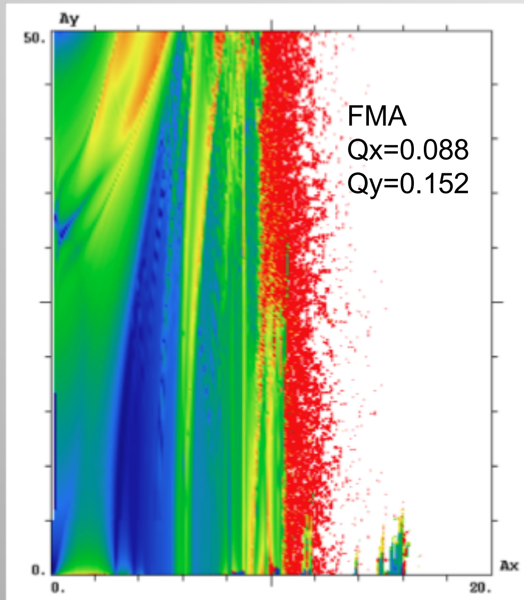
- dynamical aperture
- specific luminosity

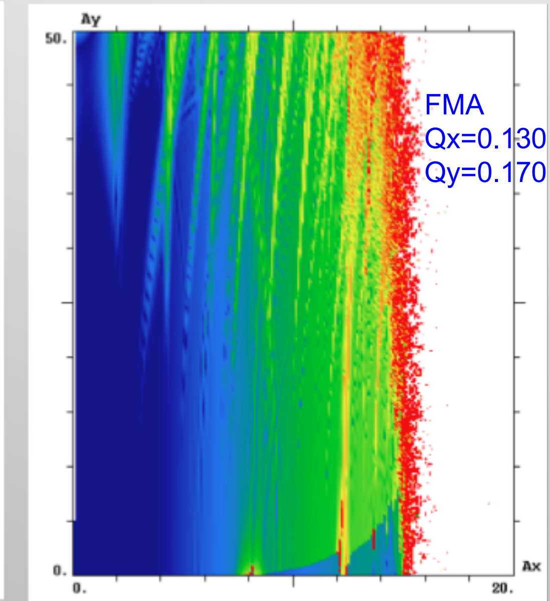
led to define a new working point for the e⁻ ring

Qx=0.135 Qy=0.17 ☆



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



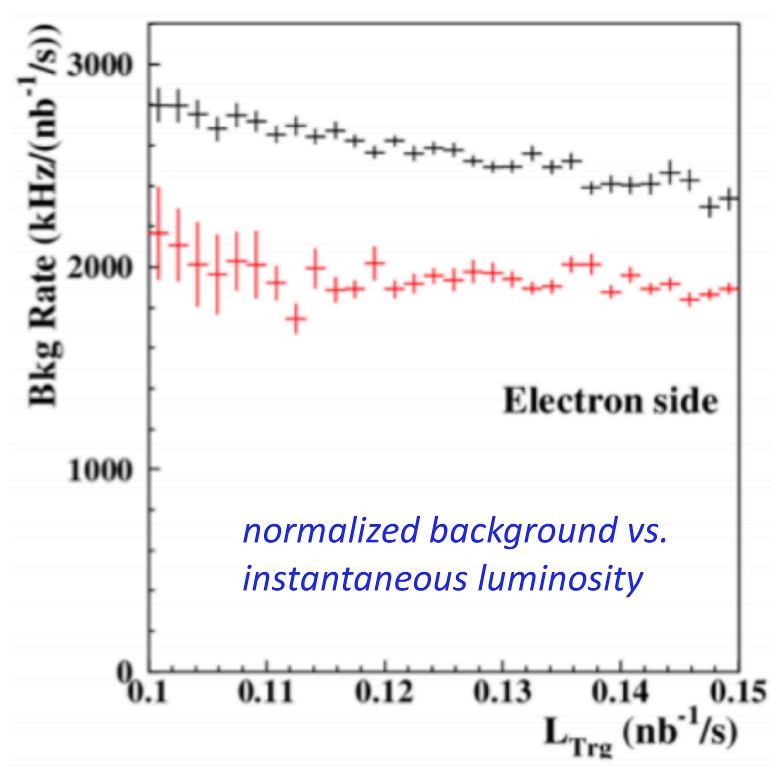


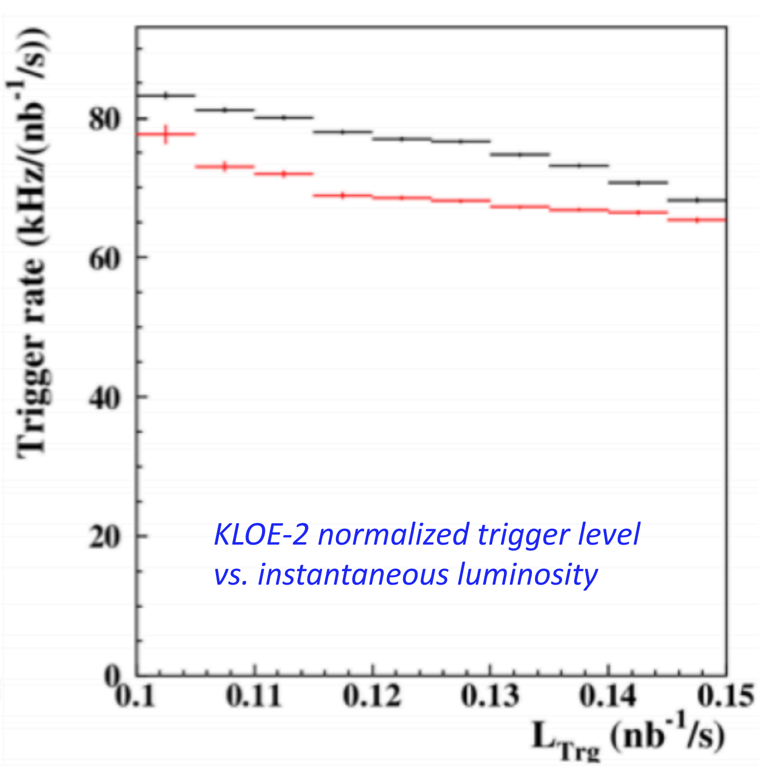
achieving:

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

Impact of the New e^- Ring Configuration

- old WP
- new WP





Electron Beam Dynamics

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

1.3 ÷ 1.5 A

It was mainly limited by:

- ion in the residual gas
- impedance induced effects (TMCI)

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 ÷ 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.

Positron 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.

Highest e^+ current stored routinely in collision rarely exceeded $I^+ > 0.95$ a value considerably lower than the one achieved during the past runs

Beam dynamics in the e^+ ring is clearly dominated by the e-cloud induced instabilities

At DAΦNE the e-cloud effects are controlled by:

- solenoid windings
- FBK systems
- electrodes ECE
- moving ξ_x ξ_y to higher positive values
- lengthening the bunch by reducing the RF cavity voltage

DAΦNE Timeline

March 31st 2018

end of the KLOE-2 Run

April ÷ September

KLOE-2 roll-out and SIDDHARTA-2 IR installation

September ÷ December 2018

DAΦNE commissioning and SIDDHARTA setup

In year 2019

SIDDHARTA-2 data taking

Starting from 2020 DAΦNE might be transformed in a test facility:

DAΦNETF

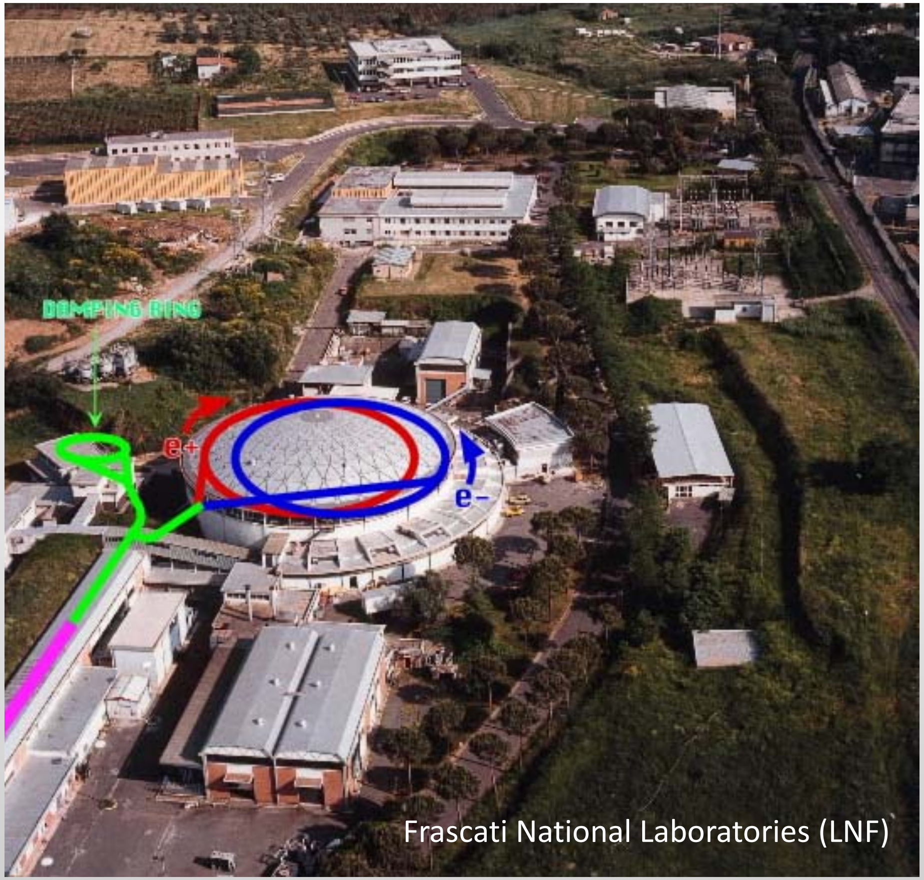
Conclusions

DAΦNE has just concluded the run for the KLOE-2 experiment achieving unprecedented results in terms of luminosity.

This has been possible thanks to an effective integration of the Crab-Waist Collision Scheme with the high field detector solenoid.

The Crab-Waist Collision Scheme has proven to be a viable approach to increase luminosity in circular colliders even in presence of an experimental apparatus strongly perturbing beam dynamics.

Good news for all the new machines and projects around the world that have adopted Crab-Waist as their main design concept.



Thank you for your attention