DAΦNE Experience with the *Crab-Waist* Collision Scheme

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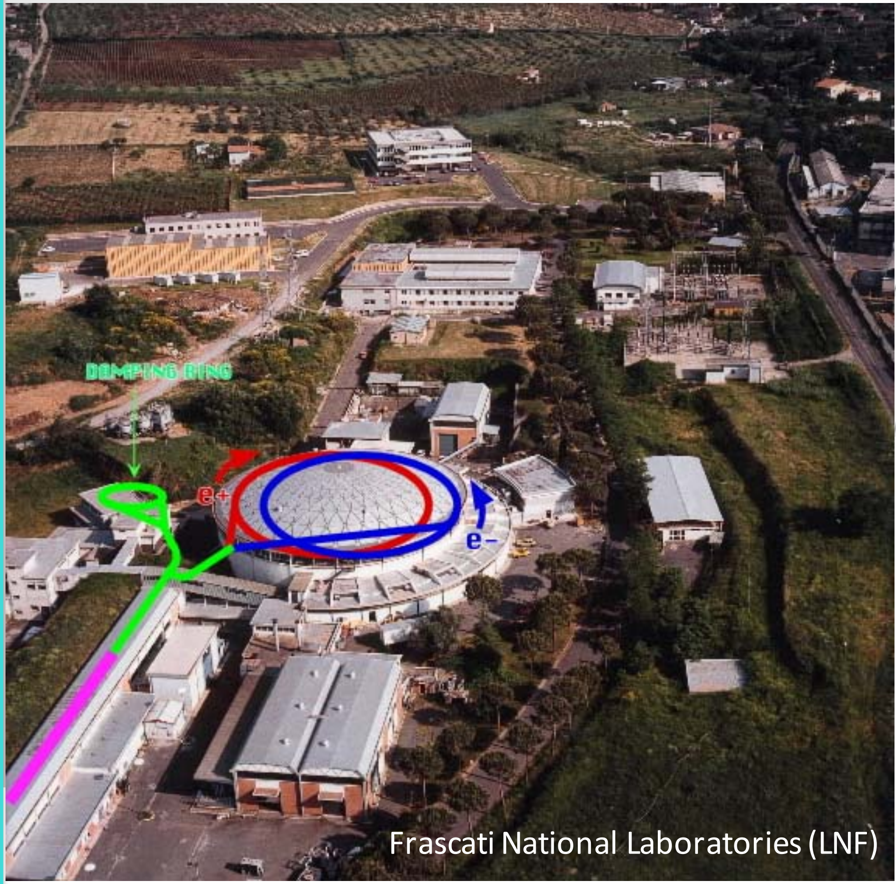
on behalf of the DAΦNE Team

IAS Program on High Energy Physics (4-29 Jan 2016), Hong Kong

Outline

- *Overview on DAΦNE*
- *Crab-Waist Collision Scheme*
- *Testing the new approach to collisions with the SIDDHARTA experiment*
- *The new KLOE IR including CW*
- *CW collisions for the KLOE-2 detector*
- *Conclusions*

The DAΦNE Accelerator Complex

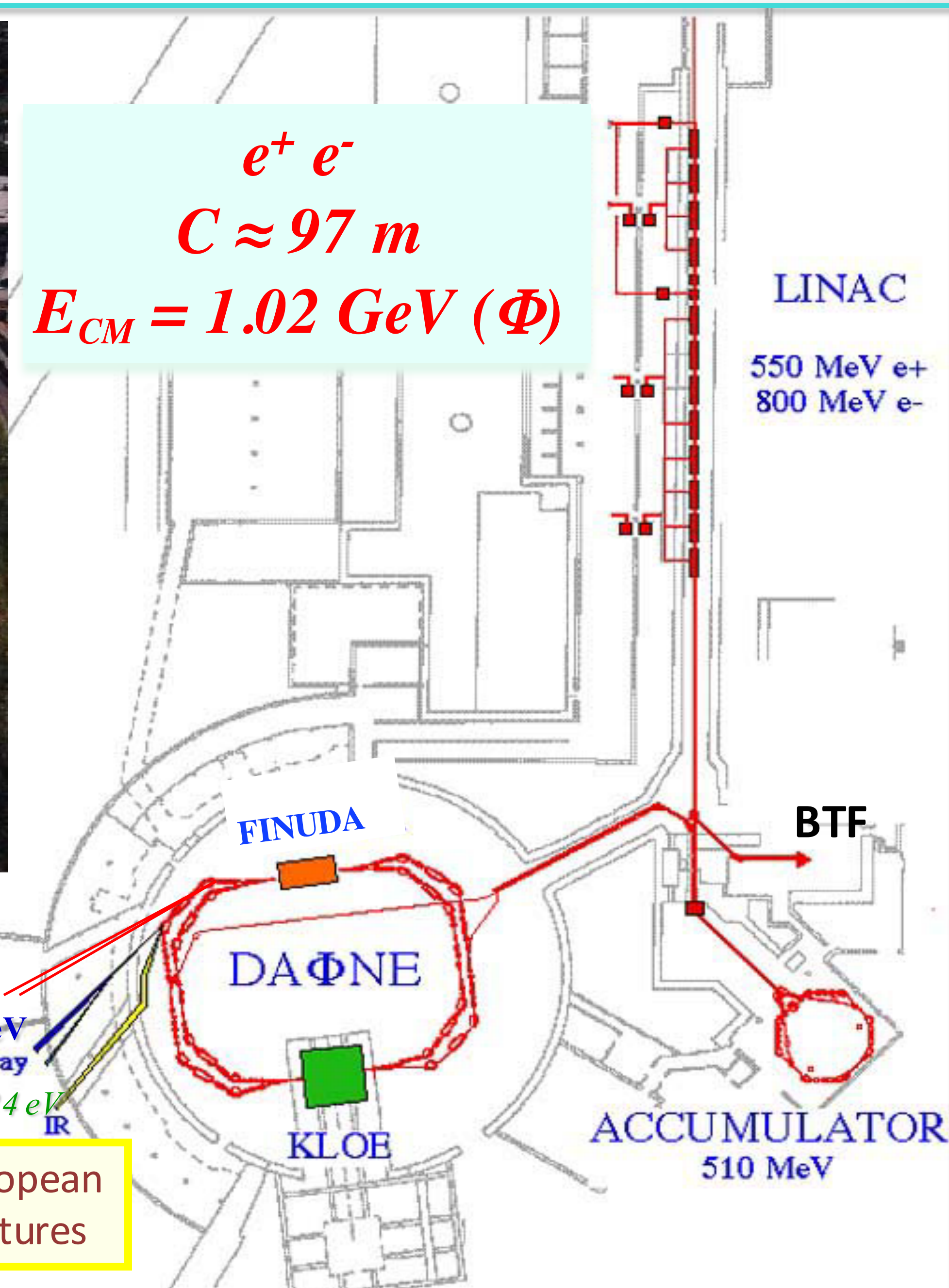


Frascati National Laboratories (LNF)

$e^+ e^-$

$C \approx 97\ m$

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

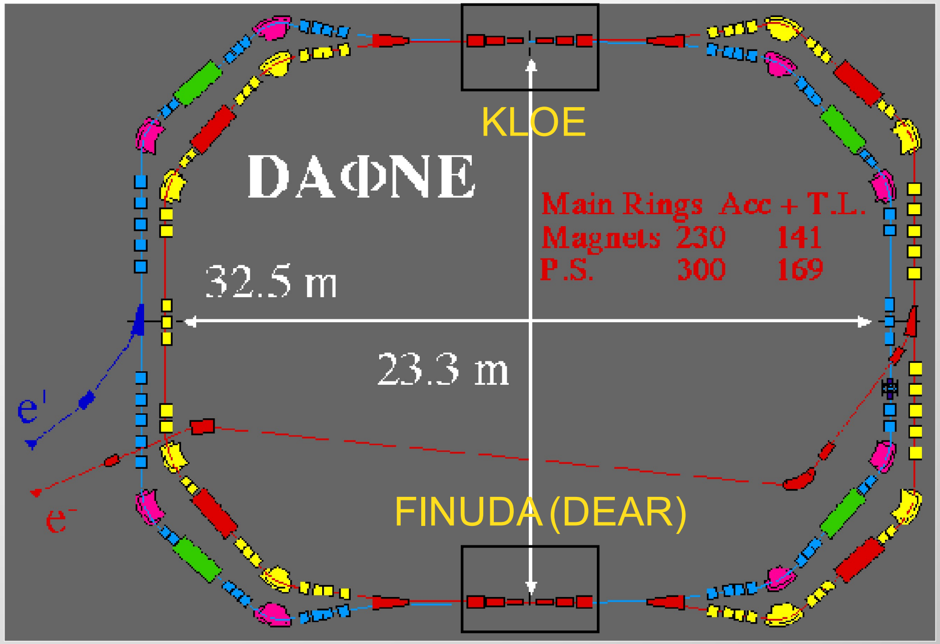


LNF are also part of the European synchrotron light Infrastructures

DAΦNE Parameters

(original configuration)

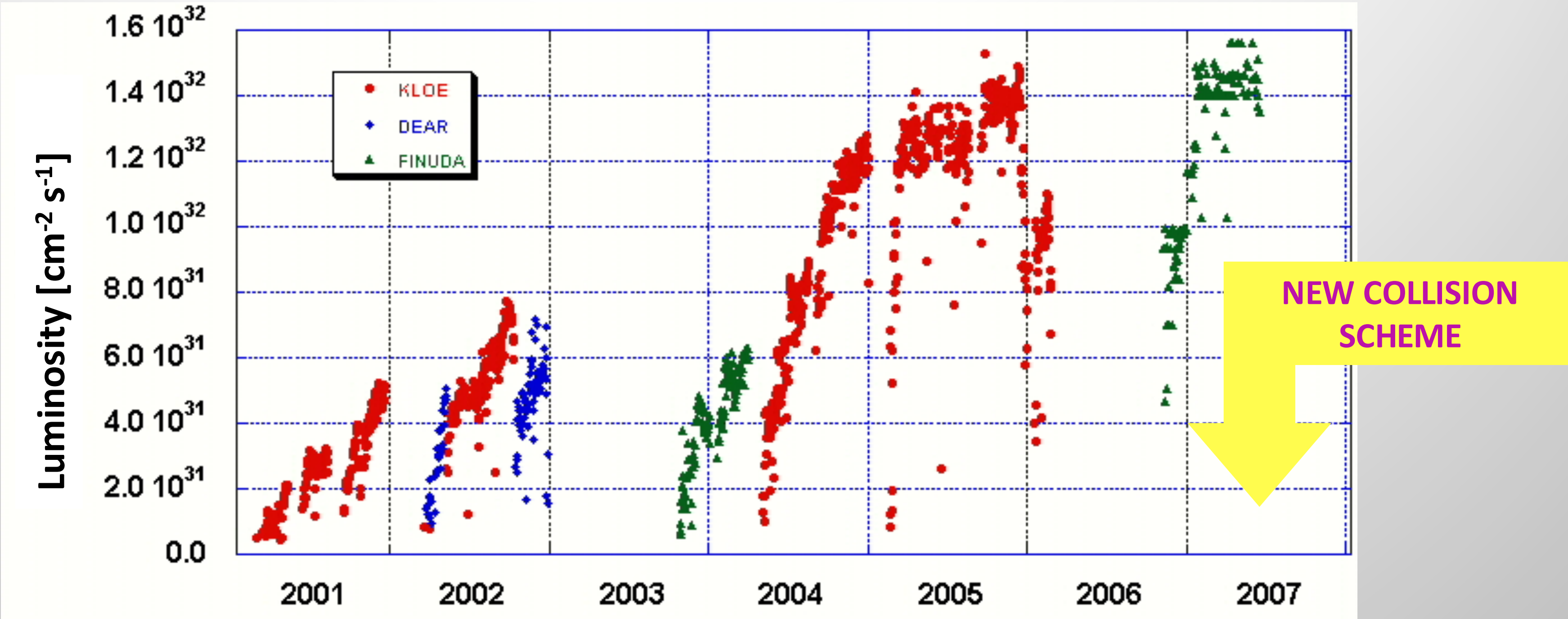
Energy, GeV	0.51
Circumference, m	97.69
RF Frequency, MHz	368.26
Harmonic Number	120
Damping Time, ms	17.8/36.0
Bunch Length, cm	1-3
Emittance, mmxmrad	0.34
Coupling, %	0.2-0.3
Beta Function at IP, m	1.7/0.017
Max. Tune Shifts	.03-.04
Number of Bunches	111
Max.Beam Currents, A	2.4/1.4

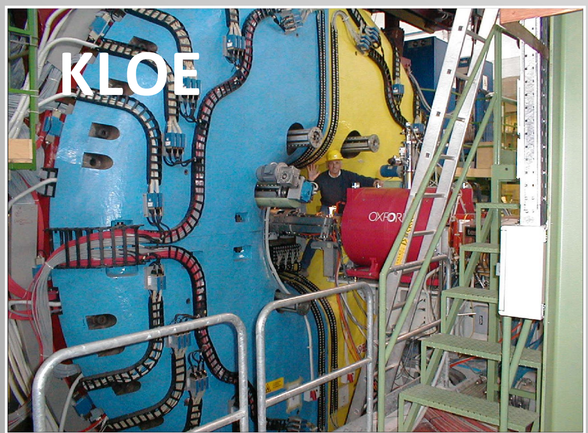


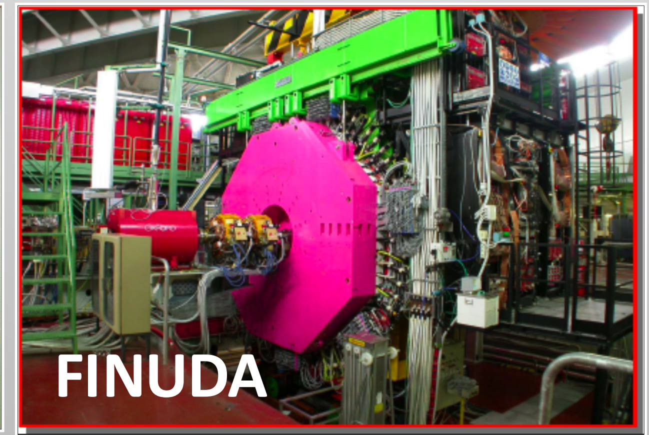
"Proposal for a Φ-factory", LNF-90/031 (IR), 1990.

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







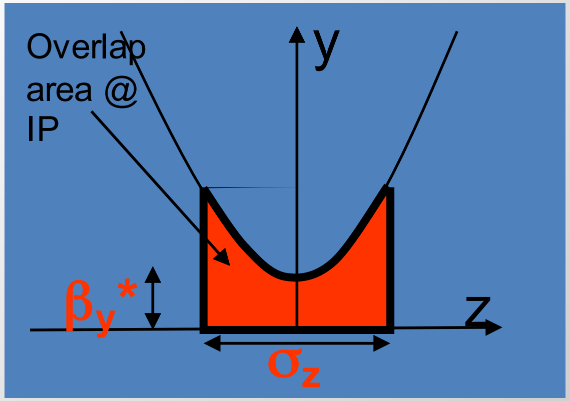
L_{logged} (fb^{-1}) 2001÷2007

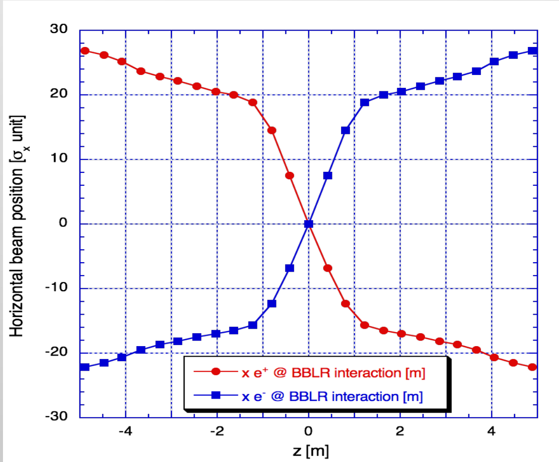
KLOE	3.0
FINUDA	1.2
DEAR	0.2

Rationale for the Upgrade

L_{peak} ~ 1.6 10^{32} cm^{-2} s^{-1} was the maximum luminosity achievable in the original DAΦNE configuration due to:

- $\beta^*_y \sim \sigma_z$ to avoid hourglass effect
- Long-range beam-beam interactions causing τ^+ τ^- reduction limiting I^+_{MAX} I^-_{MAX} and consequently L_{peak} and $L_\int$
- Transverse size enlargements due to the beam-beam interaction





A new conceptual approach was necessary to reach L~10^{33}
Collision scheme based on **Large Piwinski** angle and **Crab-Waist**

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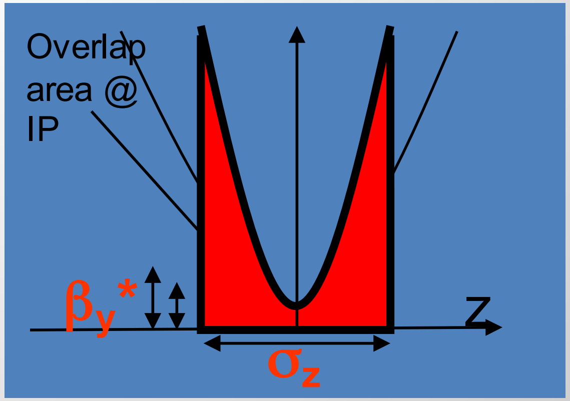
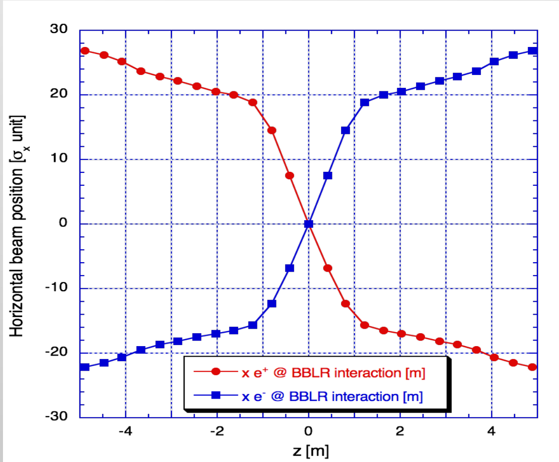




A new conceptual approach was necessary to reach L~10^{33}
Collision scheme based on **Large Piwinski** angle and **Crab-Waist**

Large Piwinski angle

Large Piwinski angle Φ obtained by:

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

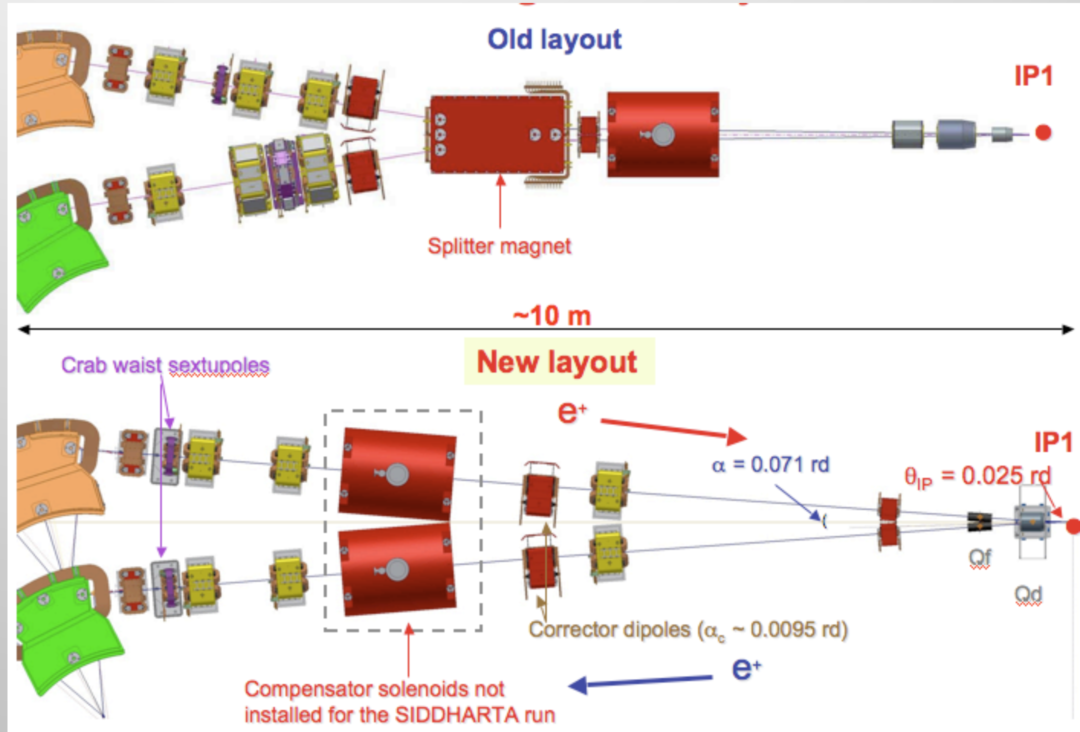
small σ_x

large θ

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

- low ξ_x
- $L_{geometric}$ gain
- no parasitic crossing

New IR magnetic layout



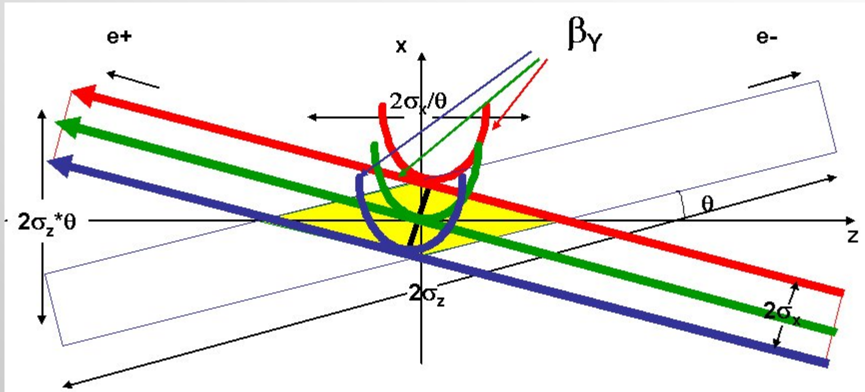
- Splitter magnets and compensator solenoids removed
- New low-β
- Sector dipols around IP rotated
- large collision angle ~ 50 mrd
- Four C type corrector dipoles used to mach the vacuum chamber in the arc

Lower β^*_y possible

Small β_y^* in fact the bunch overlap lenght Σ is:

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

- $L_{geometric}$ gain
- low ζ_y
- Vertical synchro-betatron resonances suppression



New low-β section

- *low-beta* section based on PM QUADs:

  K_{QD} = -29.2 [T/m]

  K_{QF} = 12.6 [T/m]

- e^+ e^- vacuum chambers separate after Q_D

Crab-Waist compensation

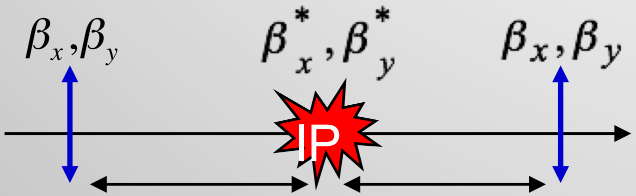
Collision with large Φ is not a new idea .....

Crab-Waist transformation is !
(P.Raimondi et al., 2006)

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

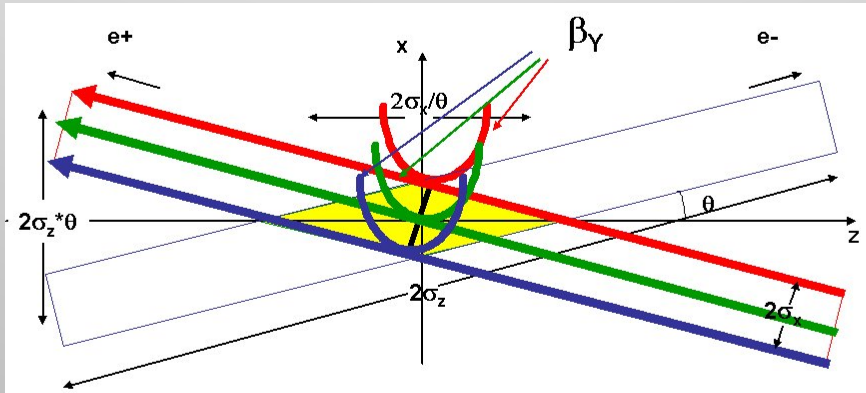
- $L_{geometric}$ gain
- x-y synchro-betatron and betatron resonance suppression

sextupole (anti)sextupole



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

P. Raimondi et al., arXiV:physics/0702033
C. Milardi et al., Int.J.Mod.Phys.A24, 2009
M. Zobov et al., Phys. Rev. Lett. 104, 2010



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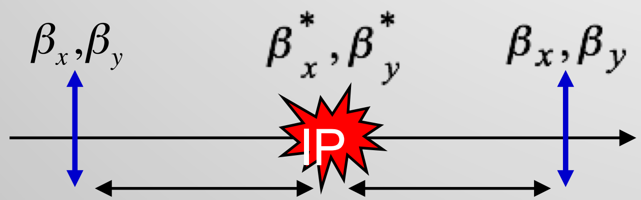

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P. Raimondi , 2° *SuperB Workshop, March 2006*
P.Raimondi, D.Shatilov, M.Zobov, physics/0702033
C. Milardi et al., Int.J.Mod.Phys.A24, 2009
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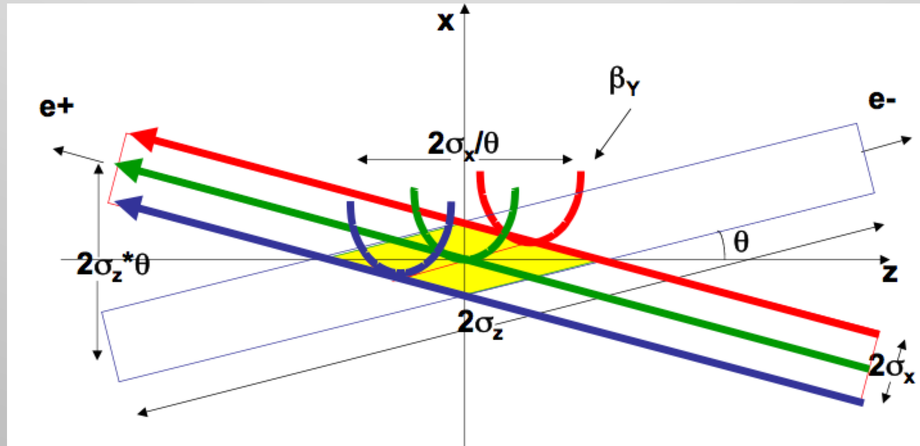
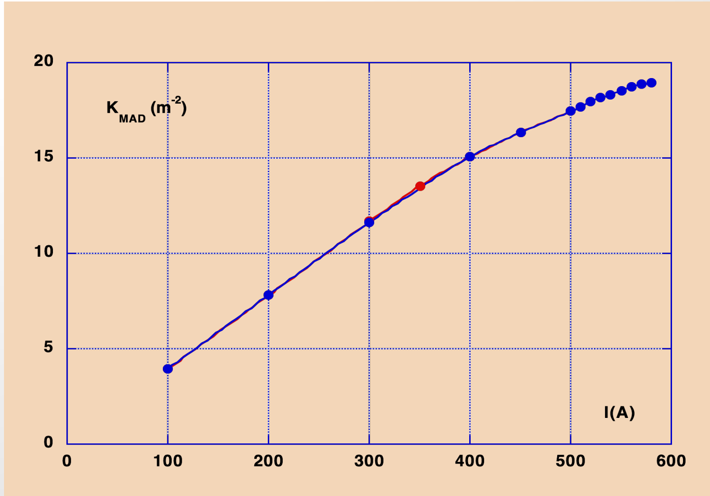


Crab-Waist Sextupole Parameters

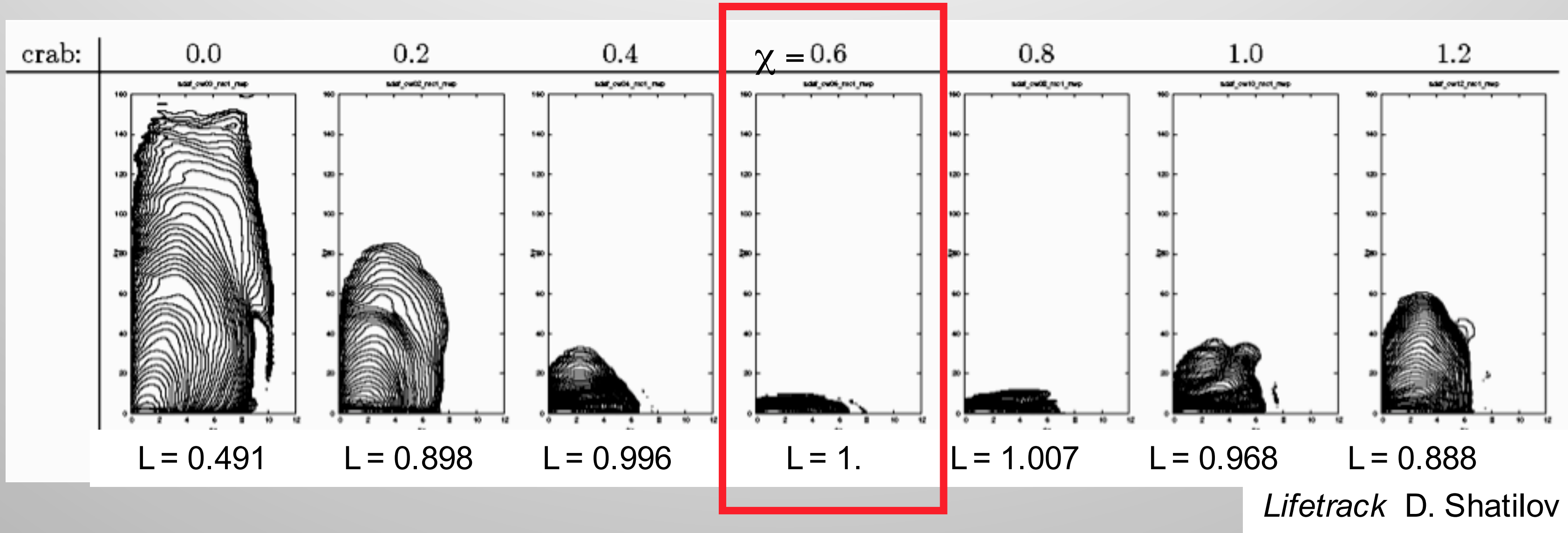
CW-Sextupoles are high strength magnets

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



χ nominal 0.6

χ used value 0.5

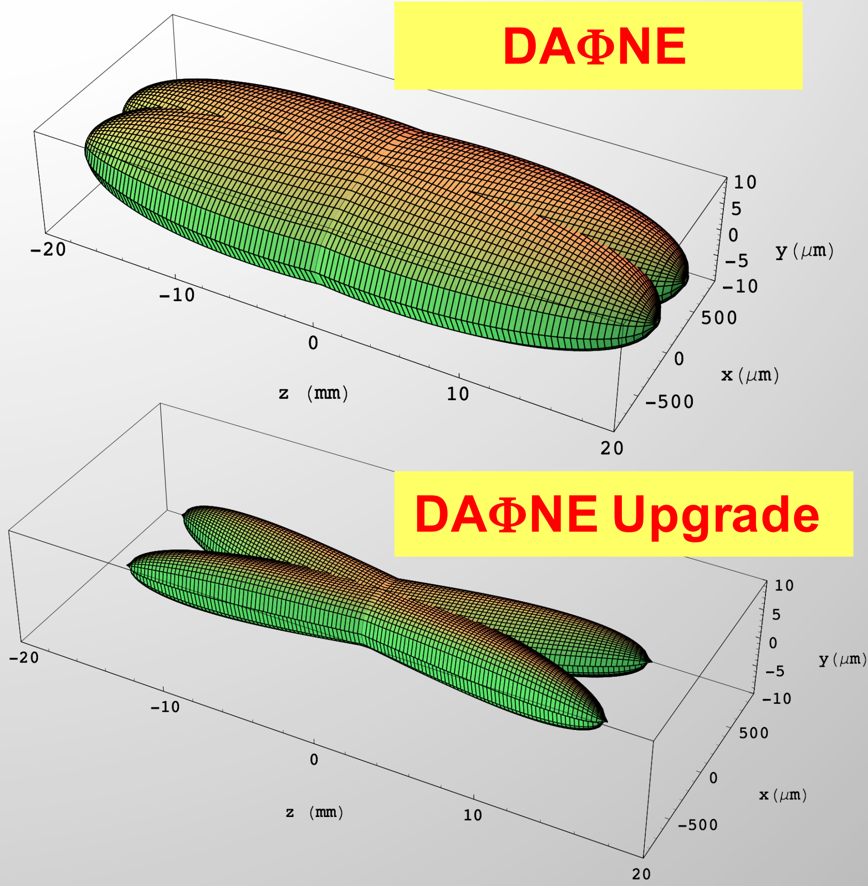


Luminosity (arbitrary unit) *and **Beam tails versus waist rotation** χ*

$DA\Phi NE$ Upgrade Parameters

	DAΦNE KOE	DAΦNE 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 ($cm^{-2}s^{-1}$) $\times 10^{32}$	1.6	5

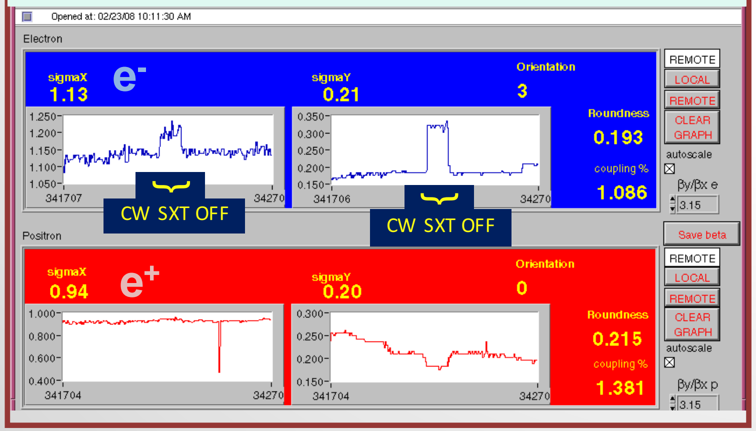
Beam distribution @ IP



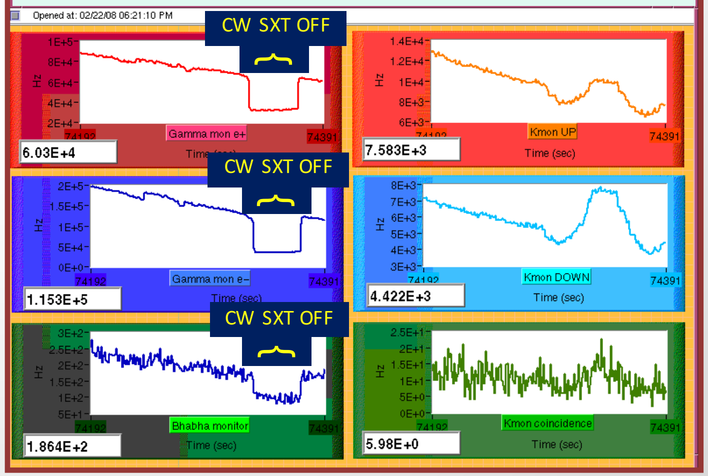
- *In 2007 the DAΦNE accelerator complex has been upgraded in order to implement a new collision scheme based on **large Piwinski angle**, **low–β** and **Crab-Waist compensation** of the synchrobetatron resonances*
- *The upgrade took ~ **five months***
- ***Since May 2008** DAΦNE is delivering luminosity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

Crab-Waist Compensation First Experimental Evidence

Beam transverse size measured at the SLM

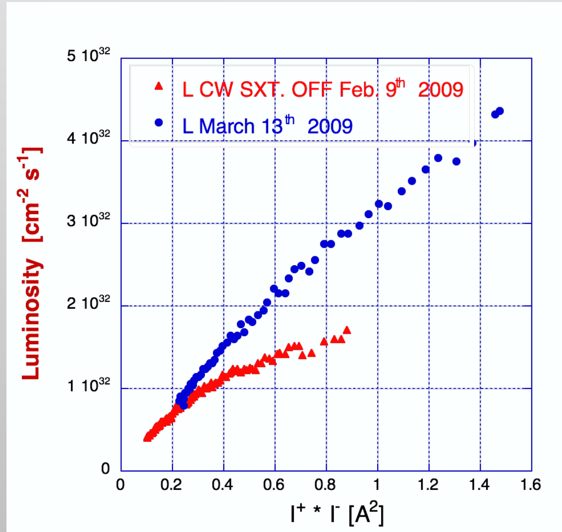


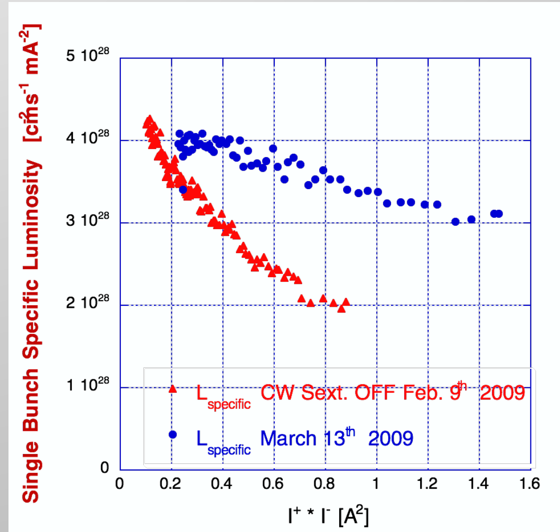
Luminosity from 2 different monitors



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



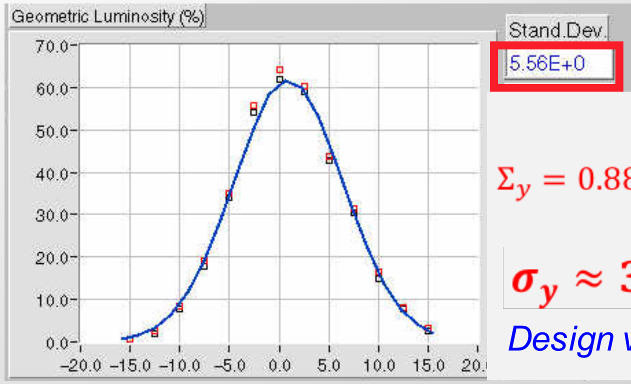


Crab-Waist collisions and SIDDHARTA

- 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

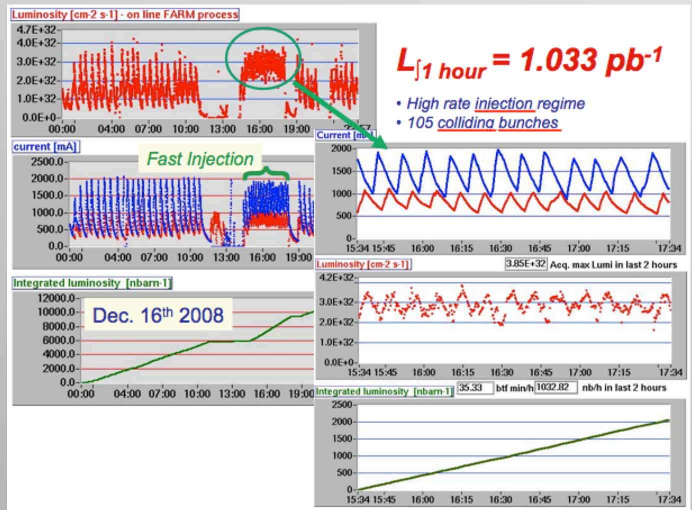
L_{peak}= 4.5*10^{32} cm^{-2} s^{-1}
$L_{\int 1\ day}$= 15.0 pb^{-1}
$L_{\int 1\ hour}$ = 1.033 pb^{-1}
$L_{\int run}$~ 2.8 fb^{-1} (delivered in 18 months)

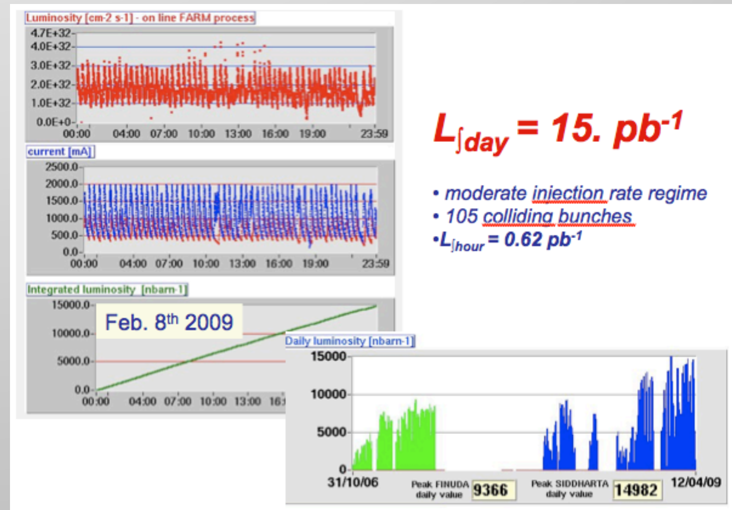


$$\Sigma_y = 0.88\sqrt{\sigma^2_{Ypos} + \sigma^2_{Yele}}$$

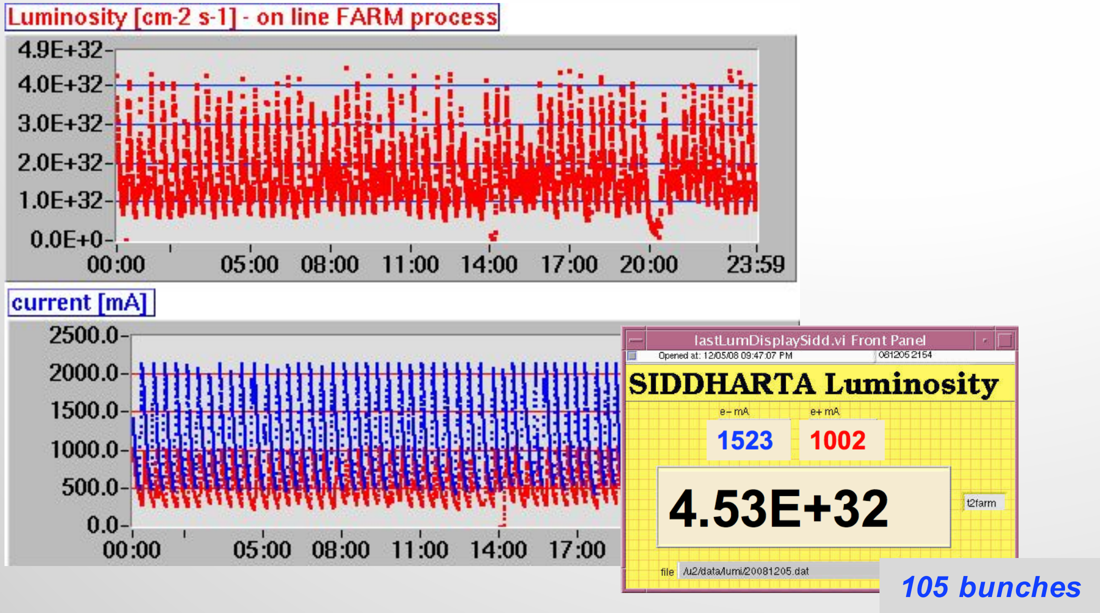
$$\sigma_y \approx 3.5\mu m$$

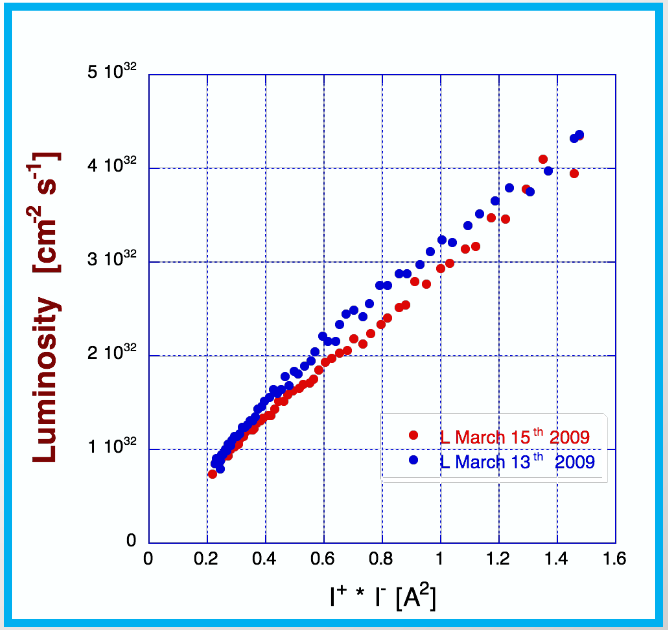
Design value 3.1μm



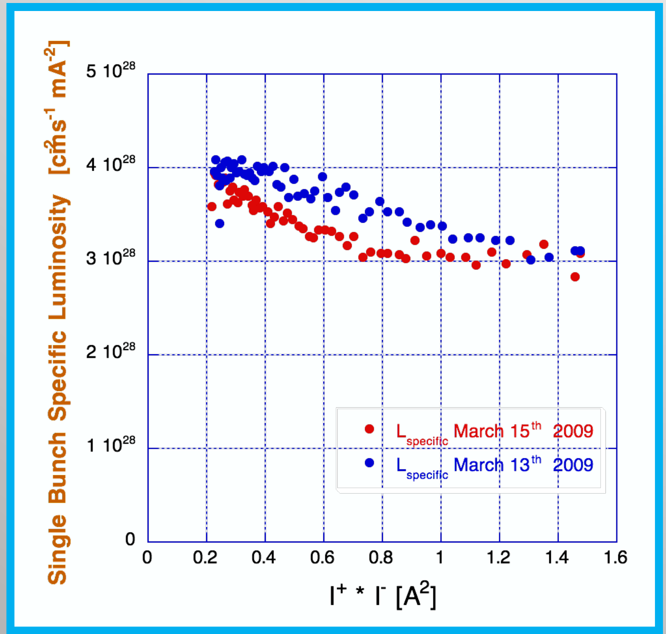


Peak Luminosity





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 in the original configuration without *Crab-Waist*
- improvement is underestimated since collisions are optimized mainly at high ***I***

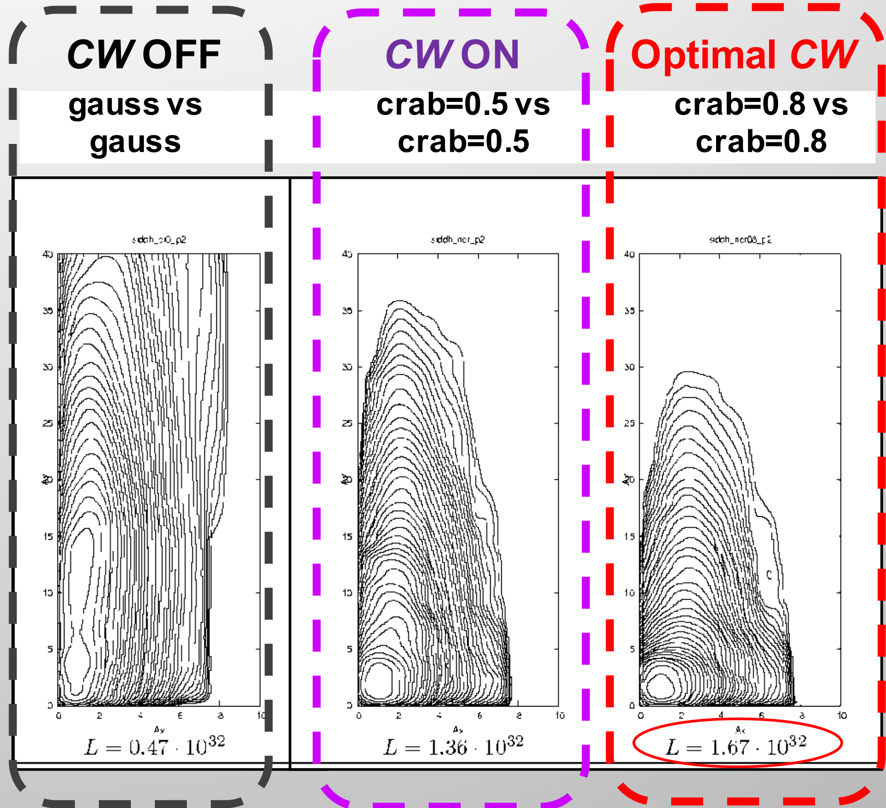
DAΦNE Luminosity and Tune Shift

	KLOE (Spt 2005)	FINUDA (Apr 2007)	SIDDHARTA *CW* (Jun 2009)
Luminosity $[10^{32}\ cm^{-2}s^{-1}]$	1.53	1.6	**4.53**
I(ele) [A]	1.38	1.50	1.52
I(pos) [A]	1.18	1.1	1
n_b	111	106	105
ε_x [mm mrad]	0.34	0.34	0.28
β_x [m]	1.5	2.	0.25
β_y [cm]	1.8	1.9	0.9
ξ	0.0245	0.0291	**0.0443 (0.074)**

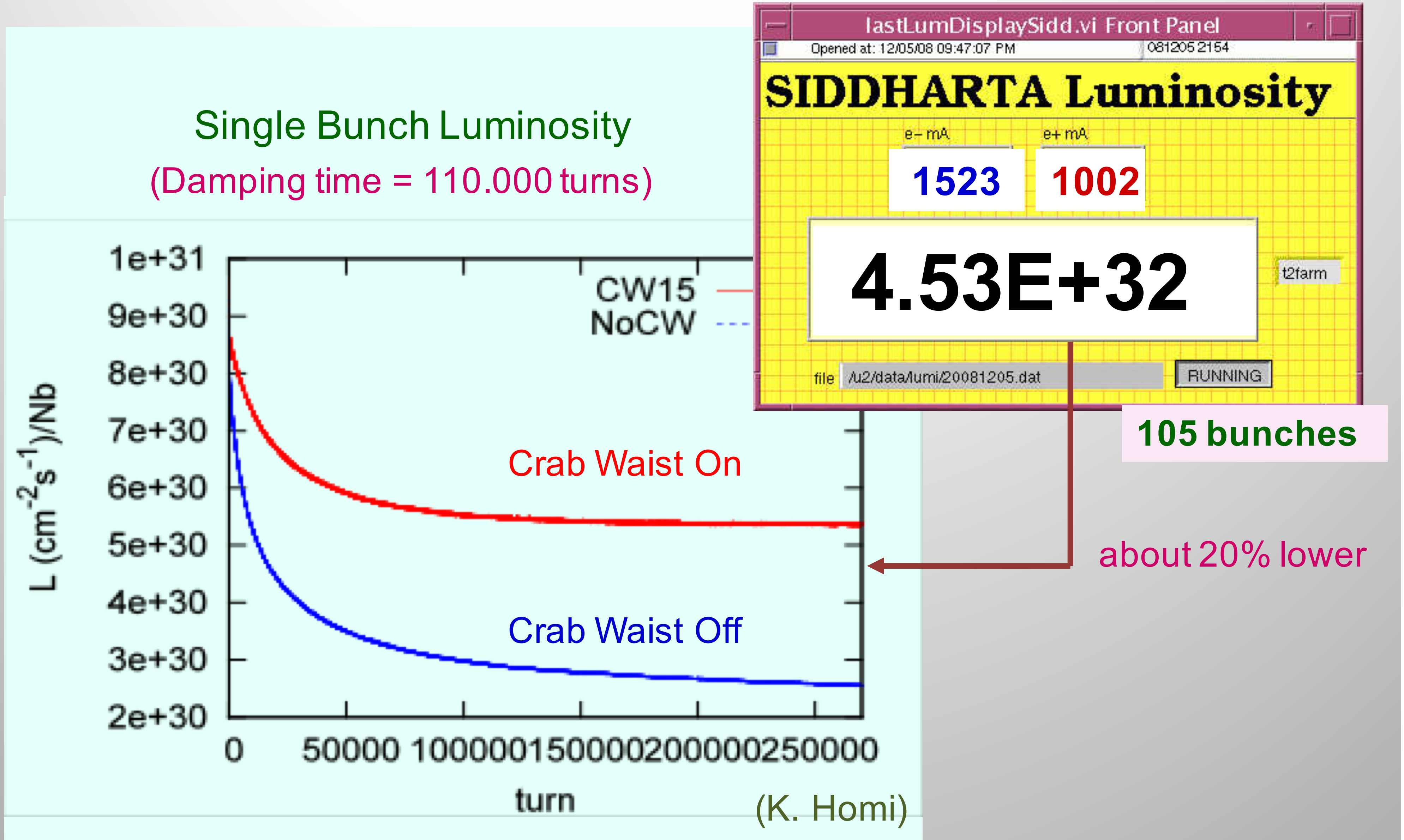
Weak-Strong Tune Shift

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

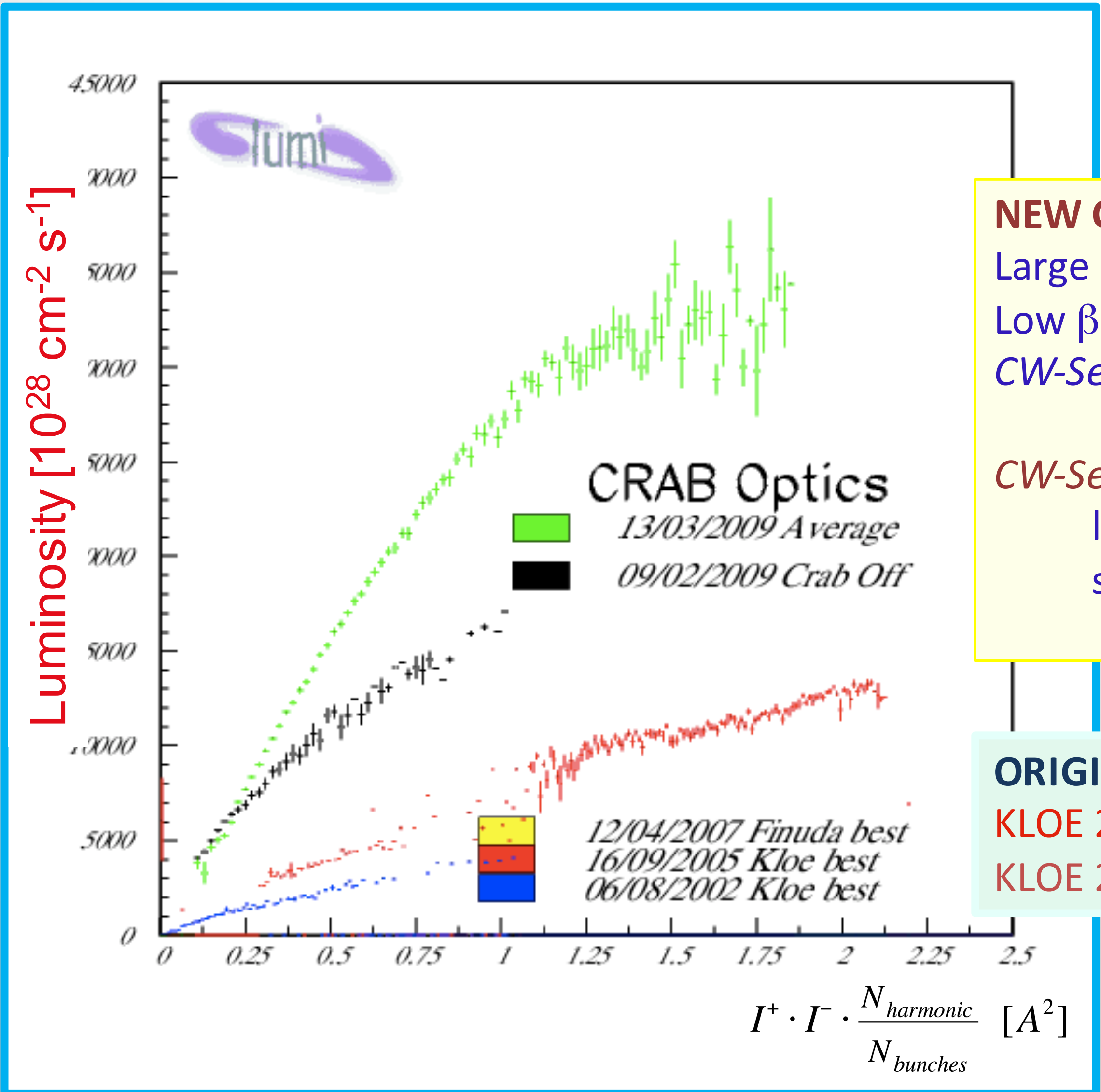
$\xi_y = 0.074$



Strong-Strong Beam-Beam Simulations



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

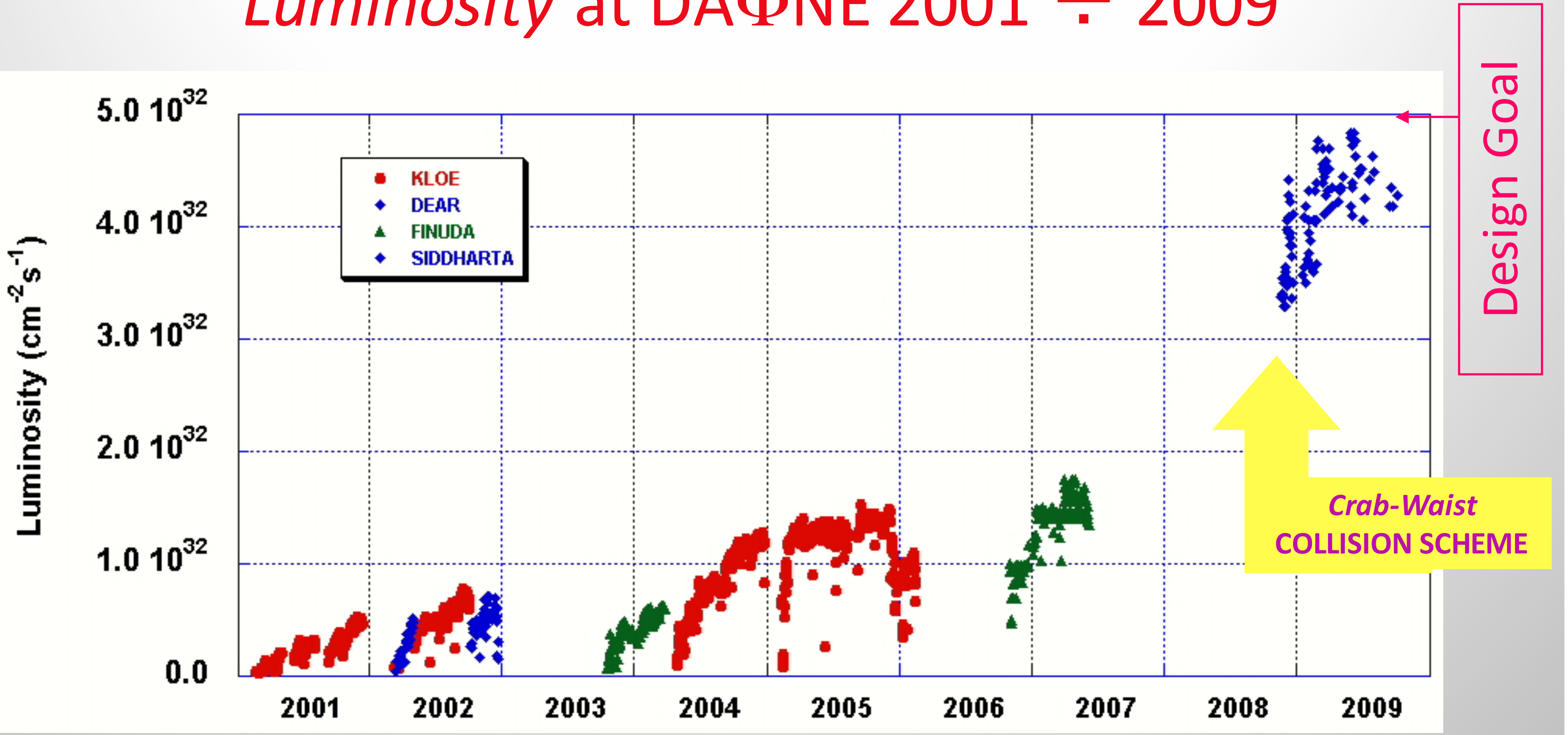
ORIGINAL COLLISION SCHEME:

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.

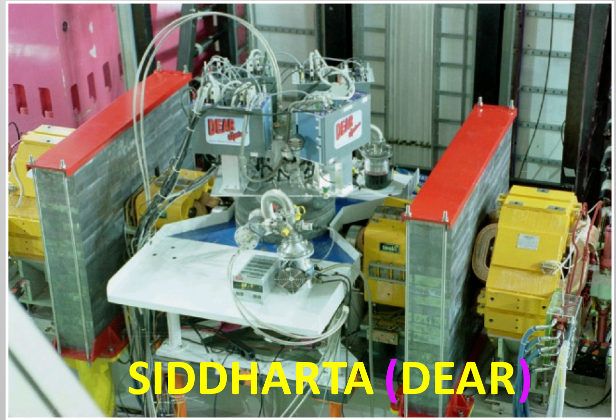
Luminosity at DAΦNE 2001 ÷ 2009



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



KLOE-2 run

Integrating the high luminosity collision scheme with a large experimental detector introduces new challenges in terms of:

- IR layout
- optics
- beam acceptance
- coupling correction

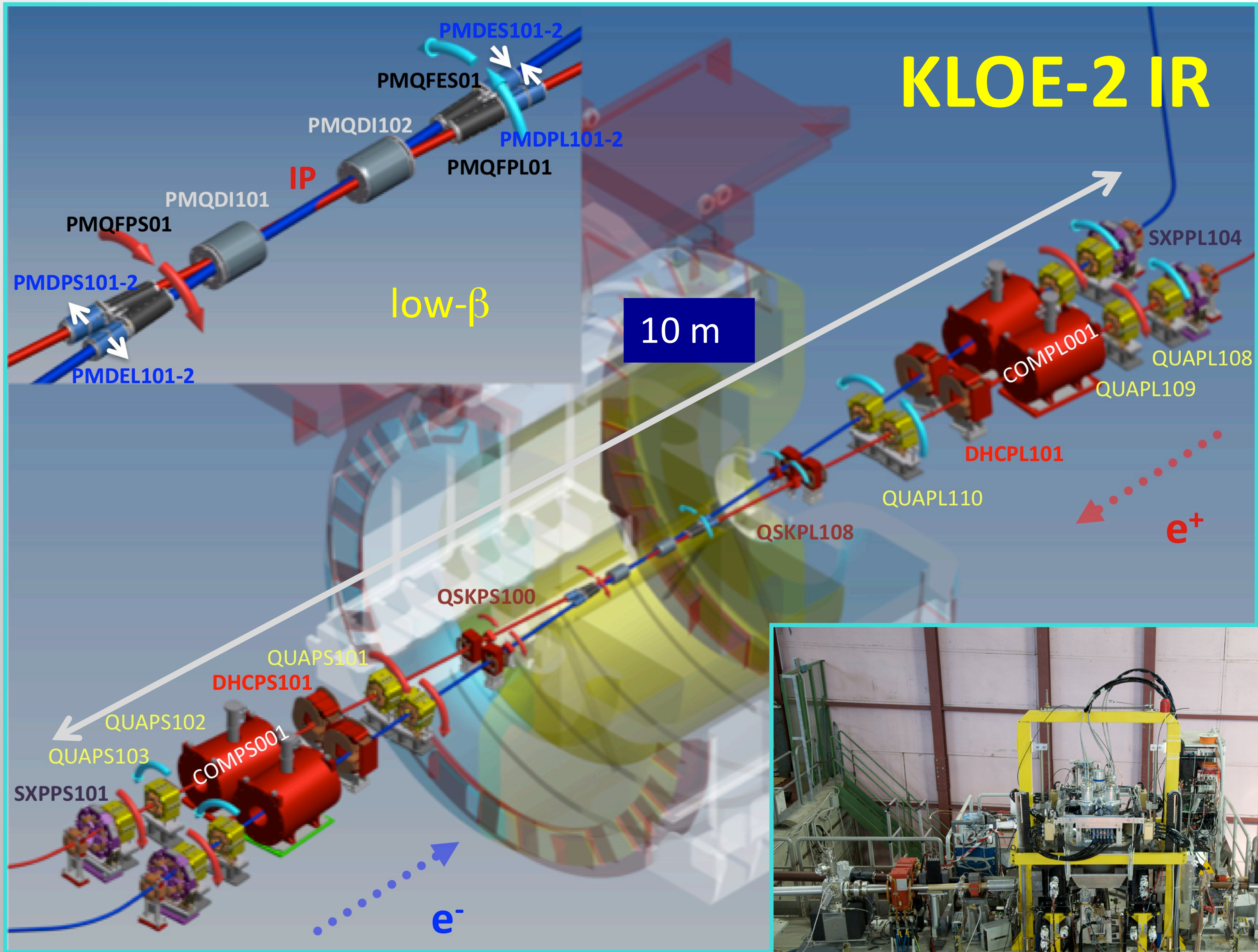
Crucial Points:

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 inside the detector

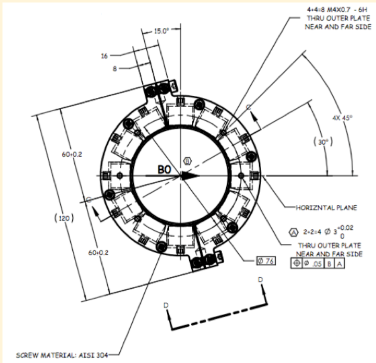


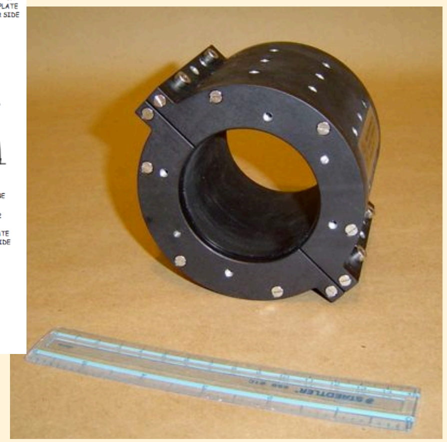
C. Milardi *et al 2012 JINST 7 T03002.*

Beam Trajectory in the new IR

- *The beam trajectory in the IR is an order of magnitude larger than in the past KLOE run due to:*
  - *larger crossing angle*
  - *stronger first low-β quadrupole (PMQD)*
  - *experimental solenoidal field*

- *A **Permanent Magnet Dipole** is used to keep under control the vertical beam trajectory.*



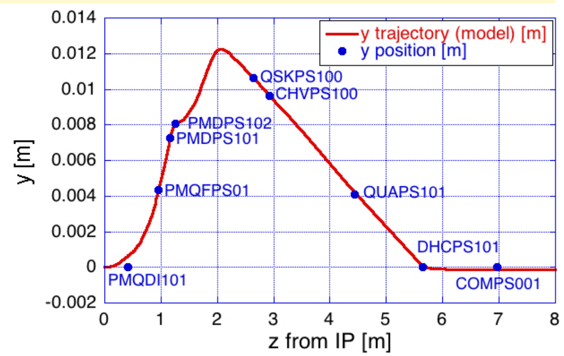


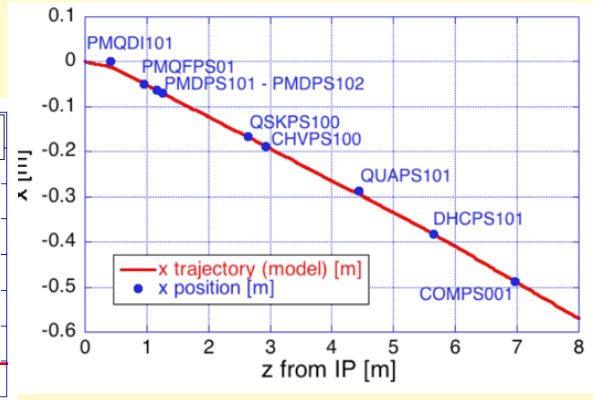
Magnetic length (mm) 75
field (T) 0,22933
Good field region radius (mm) 15
Magnet material type SmCo

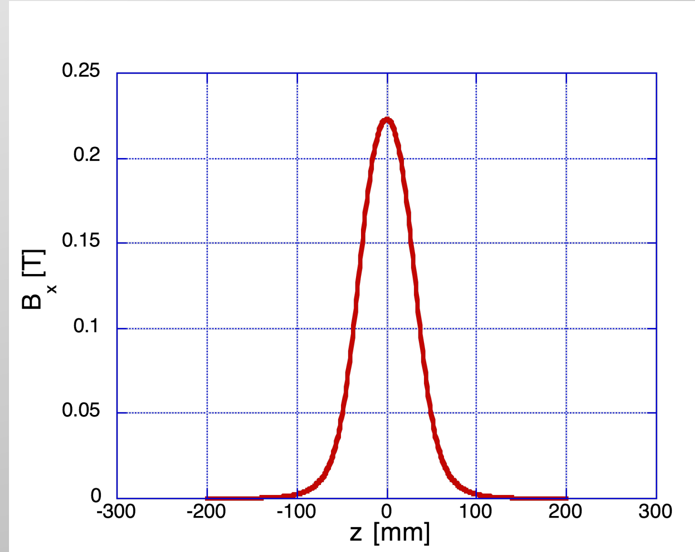
PMD consists of two halves each of them:

- Magnetic length 75.0 mm
- BL = 0.0168 Tm
- Bx is directed inward and outward in the e+ and e- rings respectively
- α_y ~ 10.0 mrad

QUADs are centered as much as possible on the beam trajectory to improve beam acceptance.
Vacuum chamber design is very much simplified: straight sections and few bellows







Betatron Coupling correction

$\int_{KLOE} B \bullet dl$ 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

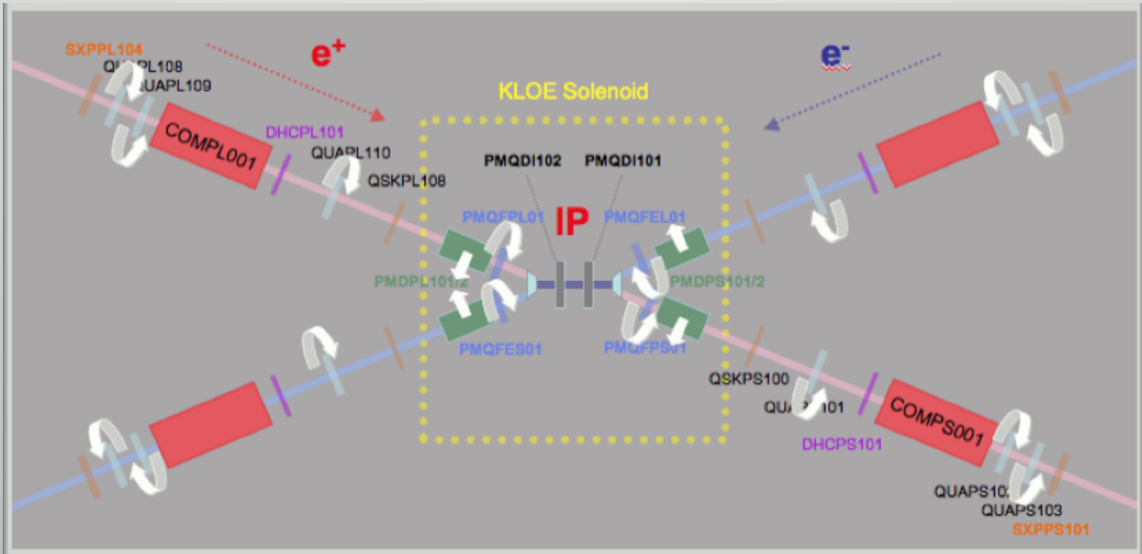
Fixed QUAD rotations

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.*



Crab-Waist Collisions for KLOE-2

Operations with the Crab-Waist collision scheme and the KLOE detector have been organized in four stages:

July 2010 - Dec 2012

- KLOE rolled in and the new IR based on *CW Collision Scheme* installed
- Collision tested despite high fault incidence
- Physics run with a pure C target (100 pb^{-1})
- Peak instantaneous luminosity $1.52 \bullet 10^{32}\ cm^{-2}s^{-1}$

Dec 2012 - Jul 2013

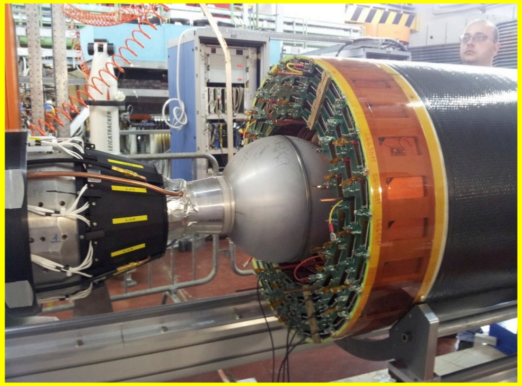
- IR extracted mended and modified
- Detector upgrade KLOE -> KLOE-2
- Several component and subsystems replaced, maintained and upgraded

Jul 2013 - Nov 2014

- Infrastructural problems affecting the whole Lab
- Commissioning

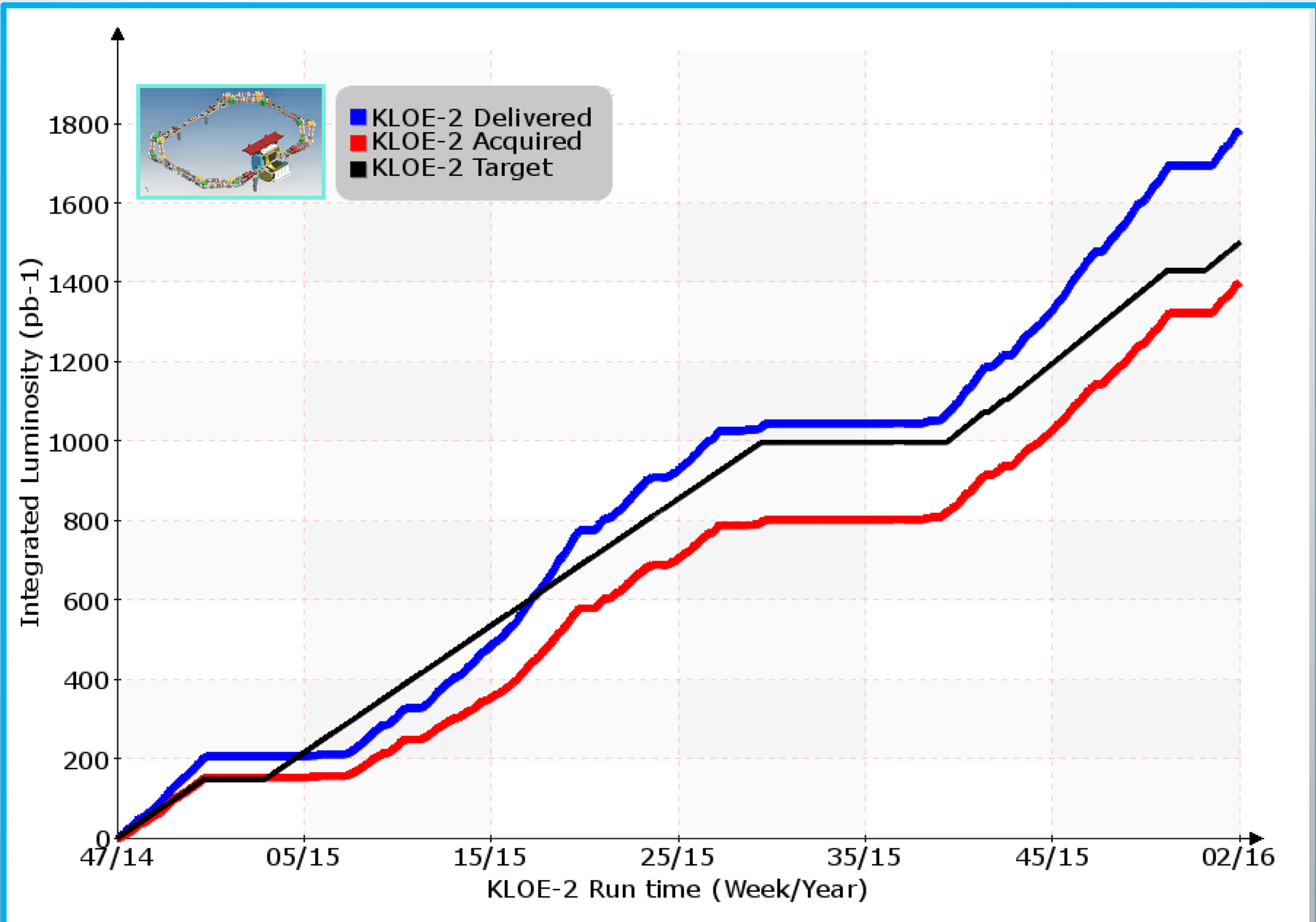
Mid Nov 2014

- KLOE-2 systematic data taking

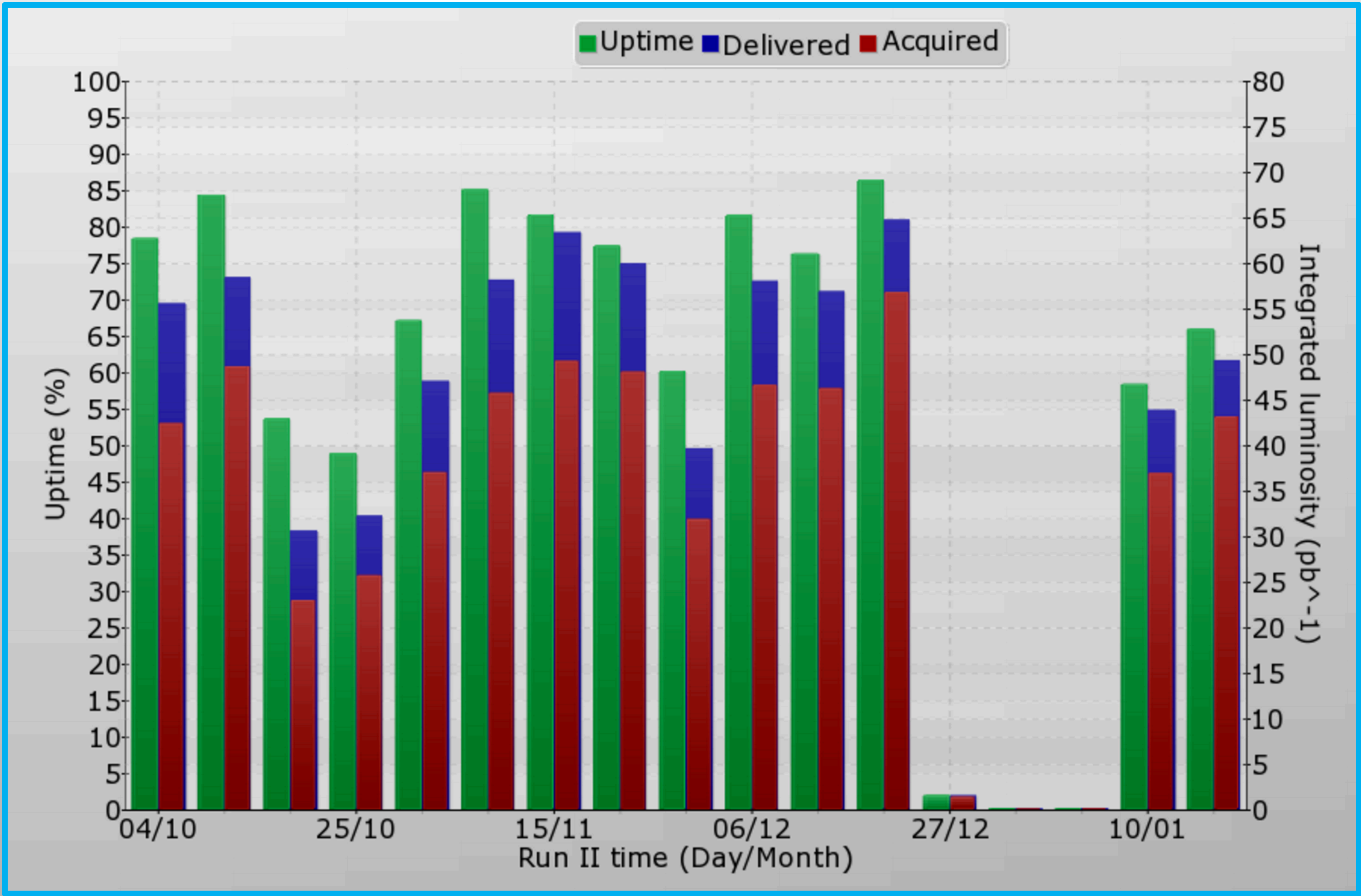


C. Milardi *et al ICFA Beam Dynamics No.67*

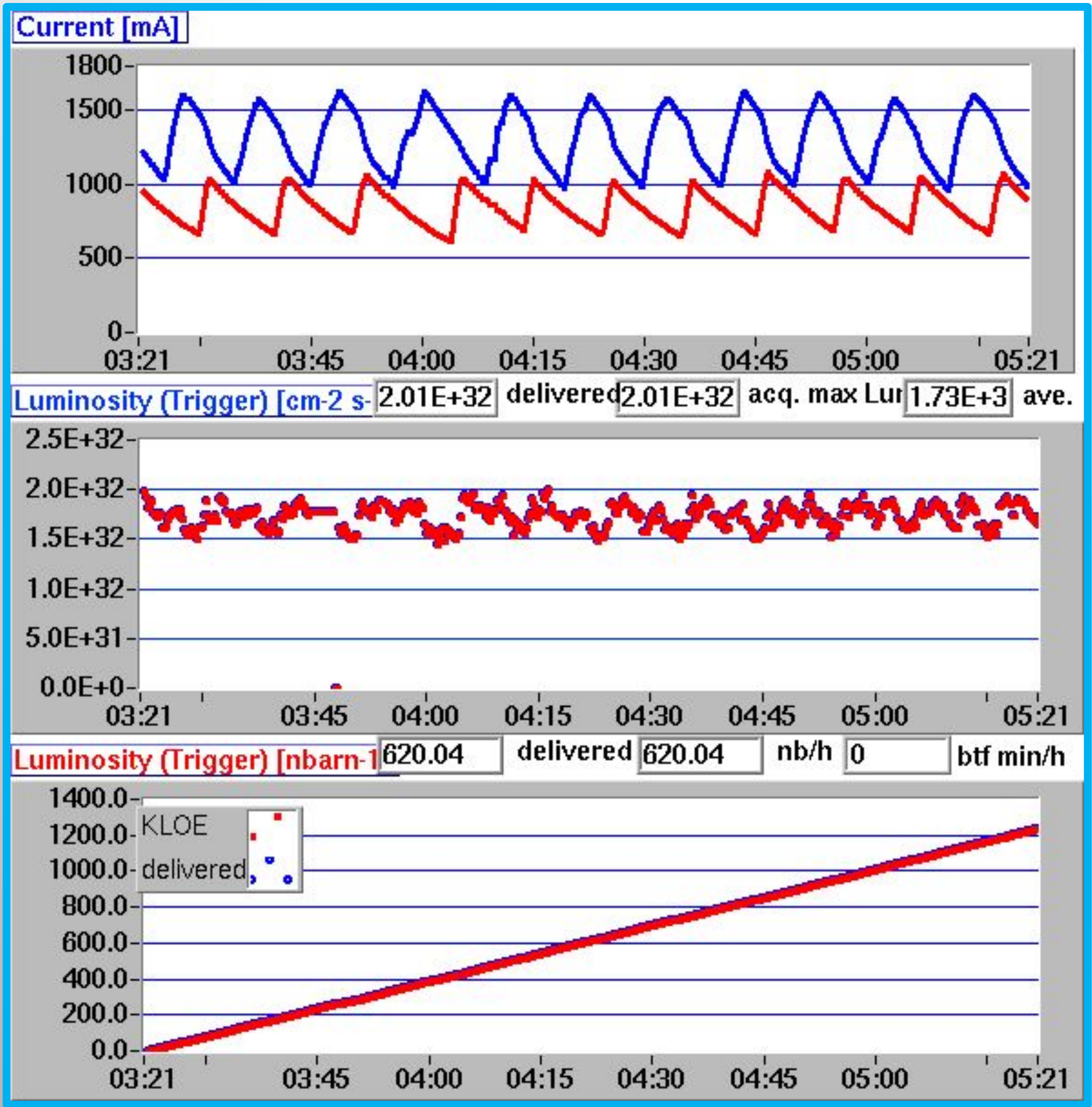
Integrated Luminosity



Weekly Integrated Luminosity



Hourly Integrated luminosity

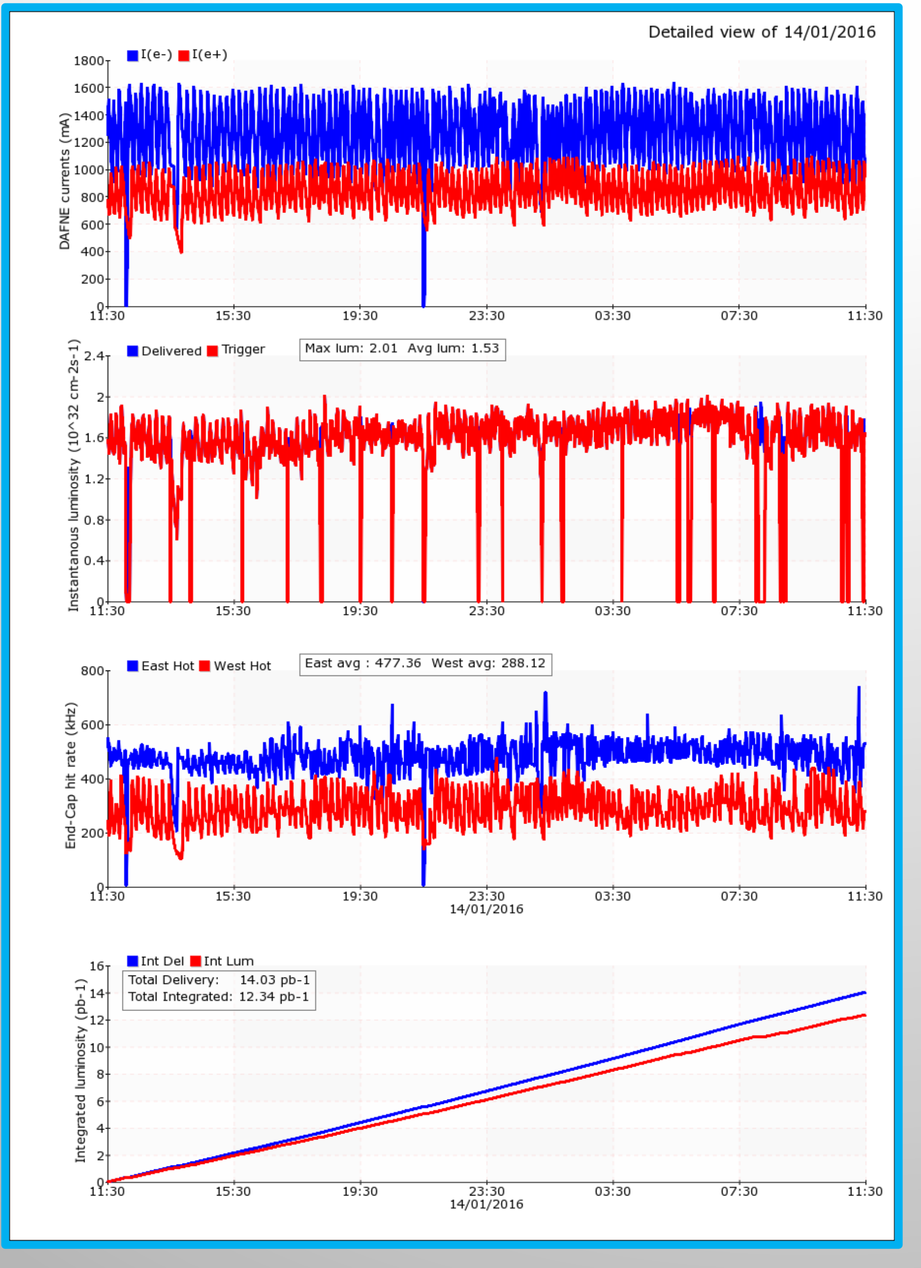


$L_{\int 1\ hour} = 0.620\ pb^{-1}$

$L_{\int day} \approx 14.8\ pb^{-1}$

- *Collisions suitable for KLOE-2 data taking*
- *Background compatible with an efficient acquisition*
- *$L_{\int 1\ hour}$ is the highest ever measured with the KLOE detector*

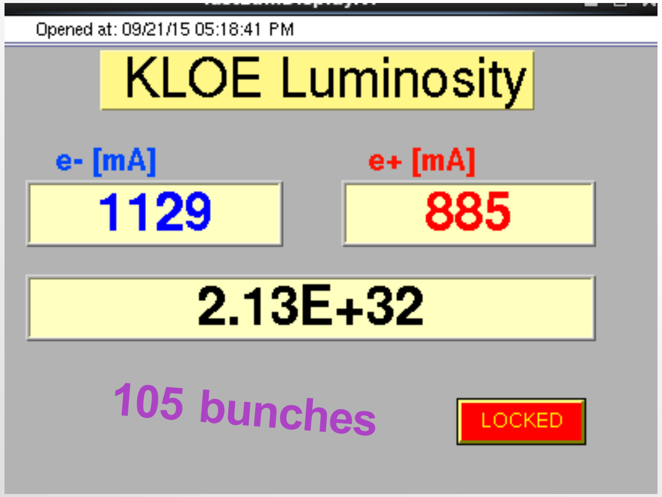
24 Hours Integrated luminosity



$L_{\int 24\, hous} \approx 14.03\ pb^{-1}$ *delivered*

$L_{\int 24\, hous} \approx 12.35\ pb^{-1}$ *acquired*

Maximum Peak Luminosity so far



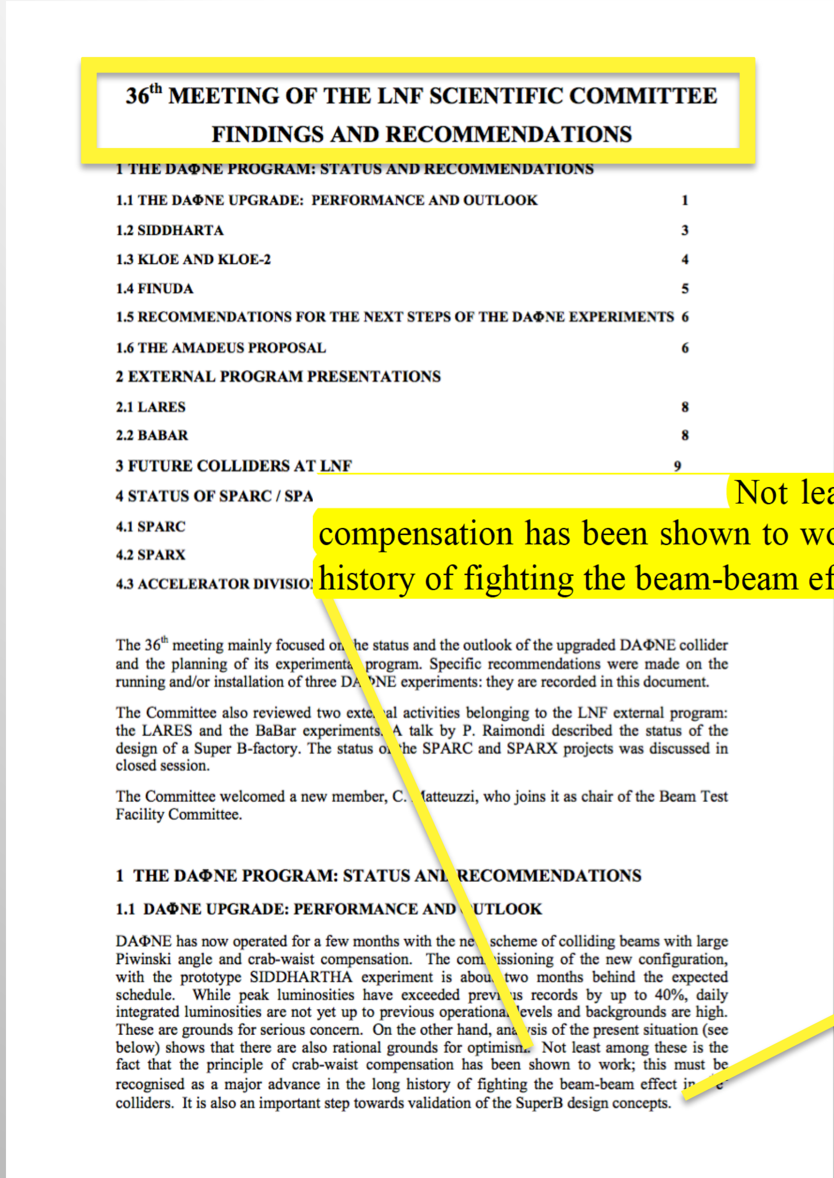
Still the full potential of the new *CW* collision scheme has not been completely exploited

	DAΦNE CW upgrade SIDDHARTA (2009)	DAΦNE CW KLOE-2 (2015)
L_{peak} $[10^{32}\ cm^{-2}s^{-1}]$	4.53 **(5.0)**	**2.1**
$L_{\int day}$ $[pb^{-1}]$	14.98	**14.03**
$L_{\int 1\ hour}$ $[pb^{-1}]$	1.033	**0.62**
I^{-}_{MAX} in collision [A]	1.52	**1.129**
I^{+}_{MAX} in collision [A]	1.0	**0.885**
$N_{bunches}$	105	**105**

Conclusions

The new collision scheme including Large Piwinski angle and Crab-Waist compensation of the beam-beam interactions has proved to be a viable approach to increase the luminosity of the DAΦNE collider

- *It has been succesfully tested and routinelly used during the SIDDHARTA run when a factor 2.7 higher instantaneous luminosity has been measured*
- *Crab-Waist collision scheme has also been the leading concept in designing the new IR for the KLOE-2 experiment.. KLOE-2 is currently taking data profiting from a daily integrated luminosity comparable with the best ever measured at DAΦNE, despite the instantaneous luminosity gain is still a factor 2 lower wrt the one measured with the SIDDHARTA optics.*
- *The KLOE-2 run has also clearly assessed the Crab-Waist* collision scheme effectiveness even in presence of a large detector including high intensity solenoidal field
- *The Crab-Waist collision scheme has been considered to upgrade one of the LHC interaction regions*
- *The design study of several new circular colliders includes the CW collision scheme as a main design concept.*



36th MEETING OF THE LNF SCIENTIFIC COMMITTEE

FINDINGS AND RECOMMENDATIONS

The 36th meeting mainly focused on the status and the outlook of the upgraded DAΦNE collider and the planning of its experimental program. Specific recommendations were made on the running and/or installation of three DAΦNE experiments: they are recorded in this document.

The Committee also reviewed two external activities belonging to the LNF external program: the LARES and the BaBar experiments. A talk by P. Raimondi described the status of the design of a Super B-factory. The status of the SPARC and SPARX projects was discussed in closed session.

The Committee welcomed a new member, C. Matteuzzi, who joins it as chair of the Beam Test Facility Committee.

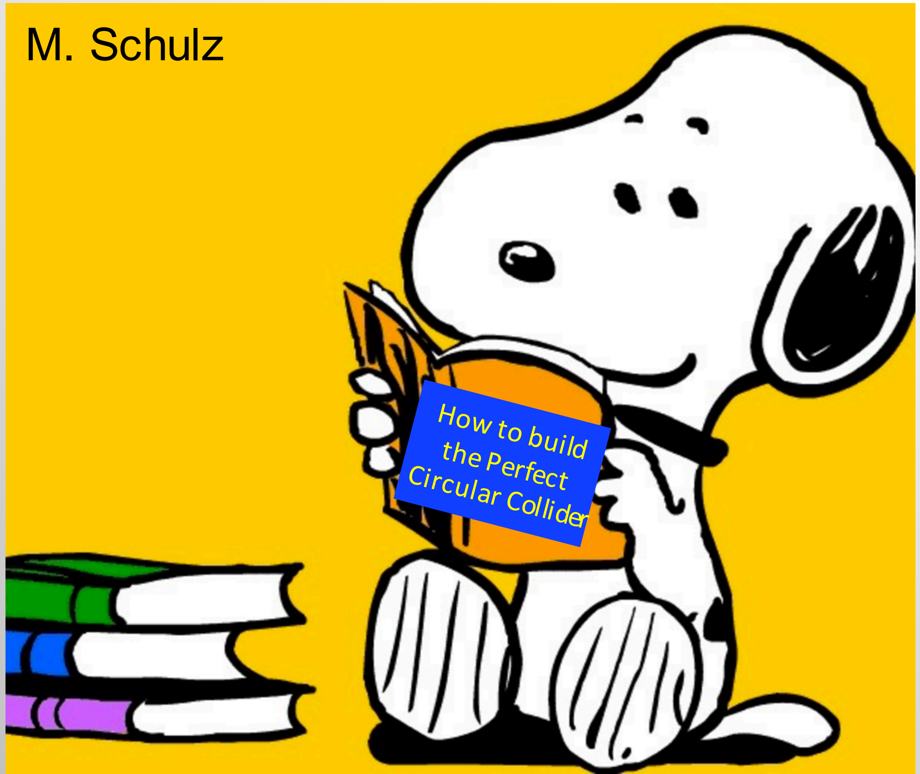
1 THE DAΦNE PROGRAM: STATUS AND RECOMMENDATIONS

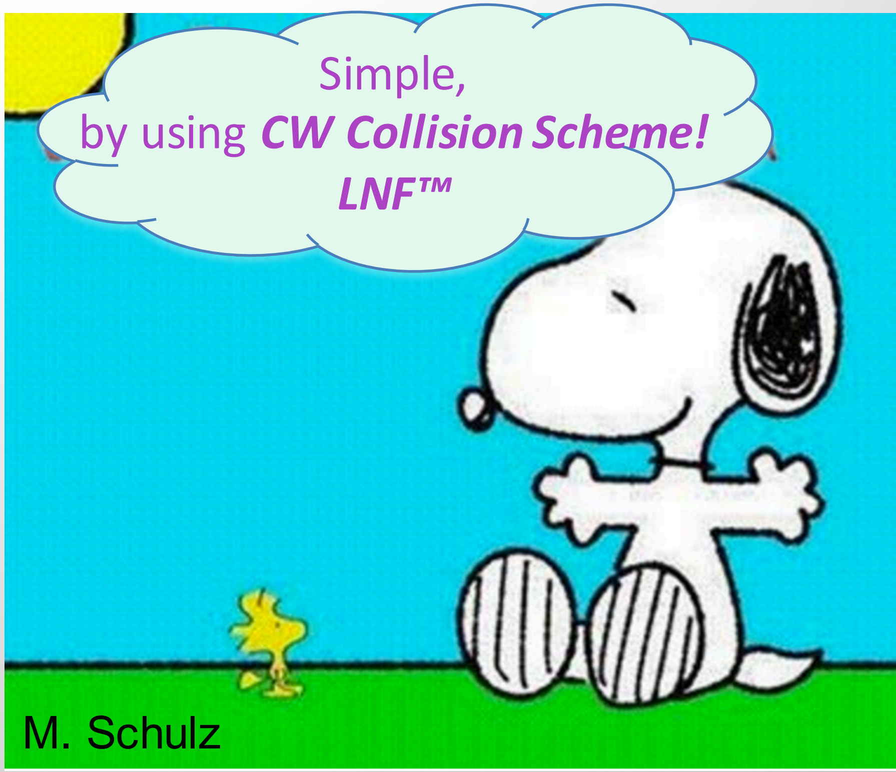
1.1 DAΦNE UPGRADE: PERFORMANCE AND OUTLOOK

DAΦNE has now operated for a few months with the new scheme of colliding beams with large Piwinski angle and crab-waist compensation. The commissioning of the new configuration, with the prototype SIDDHARTHA experiment is about two months behind the expected schedule. While peak luminosities have exceeded previous records by up to 40%, daily integrated luminosities are not yet up to previous operational levels and backgrounds are high. These are grounds for serious concern. On the other hand, analysis of the present situation (see below) shows that there are also rational grounds for optimism. Not least among these is the fact that the principle of crab-waist compensation has been shown to work; this must be recognised as a major advance in the long history of fighting the beam-beam effect in e^+e^- colliders. It is also an important step towards validation of the SuperB design concepts.

Not least among these is the fact that the principle of crab-waist compensation has been shown to work; this must be recognised as a major advance in the long history of fighting the beam-beam effect in e^+e^- colliders.

…. let me joke





Thank you for your attention