Status of DAΦNE

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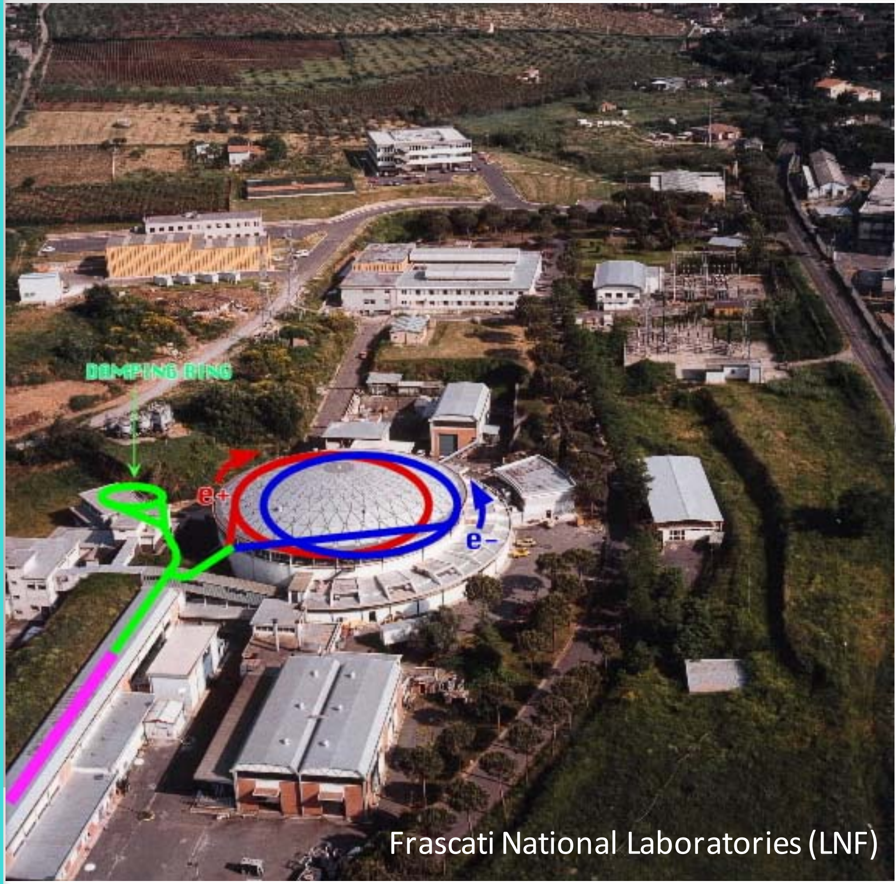
on behalf of the DAΦNE Team

KLOE-2 Workshop on e^+e^- collision physics at 1 GeV
26-28 October 2016 INFN – Laboratori Nazionali di Frascati, Italy

Outline

- *DAΦNE overview*
- *The contribution of DAΦNE to the developments in the field of Particle Accelerator Physics*
- *Crab-Waist Collision Scheme*
- *KLOE-2 run*

The DAΦNE Accelerator Complex

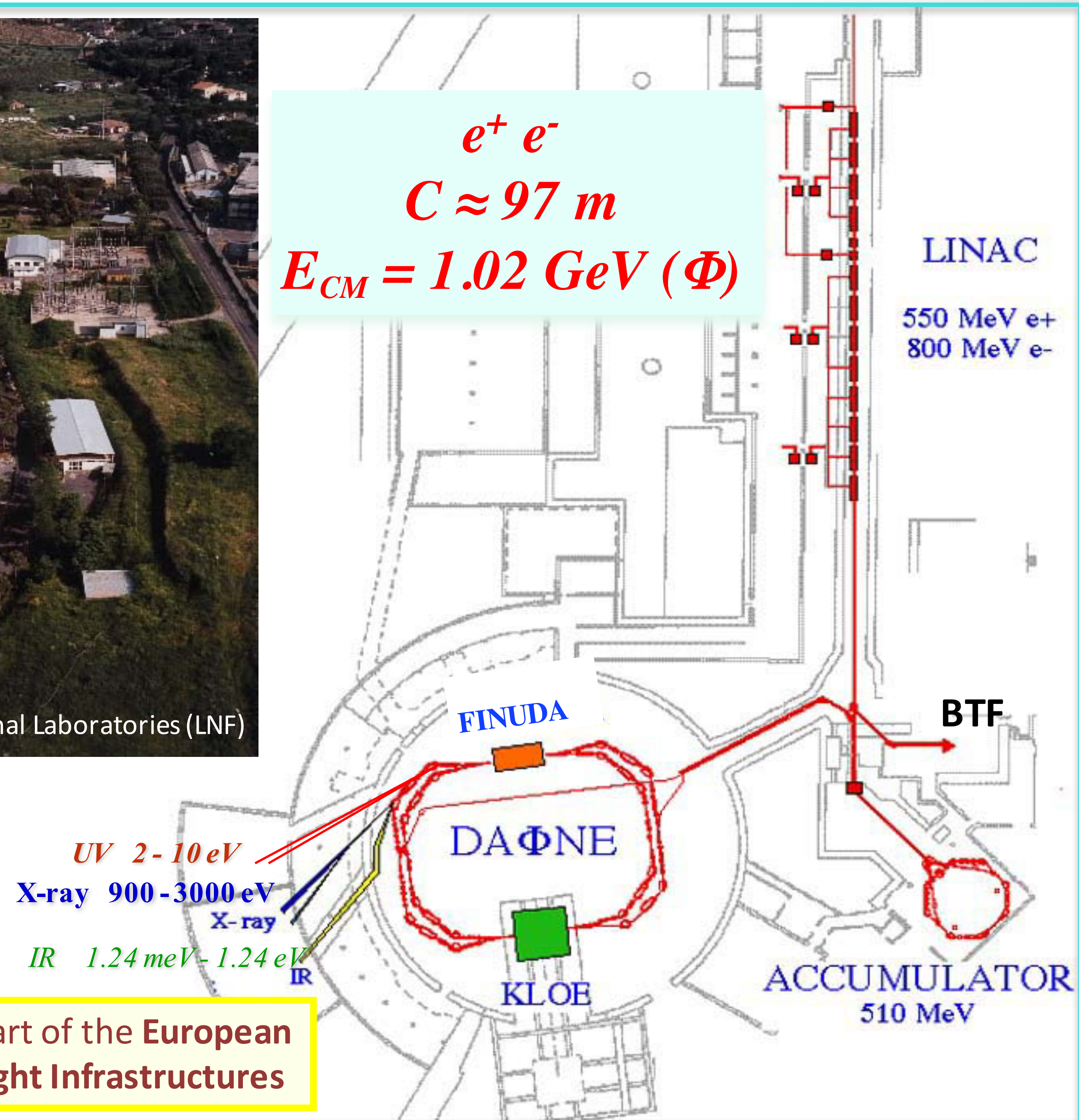


Frascati National Laboratories (LNF)

$e^+ e^-$

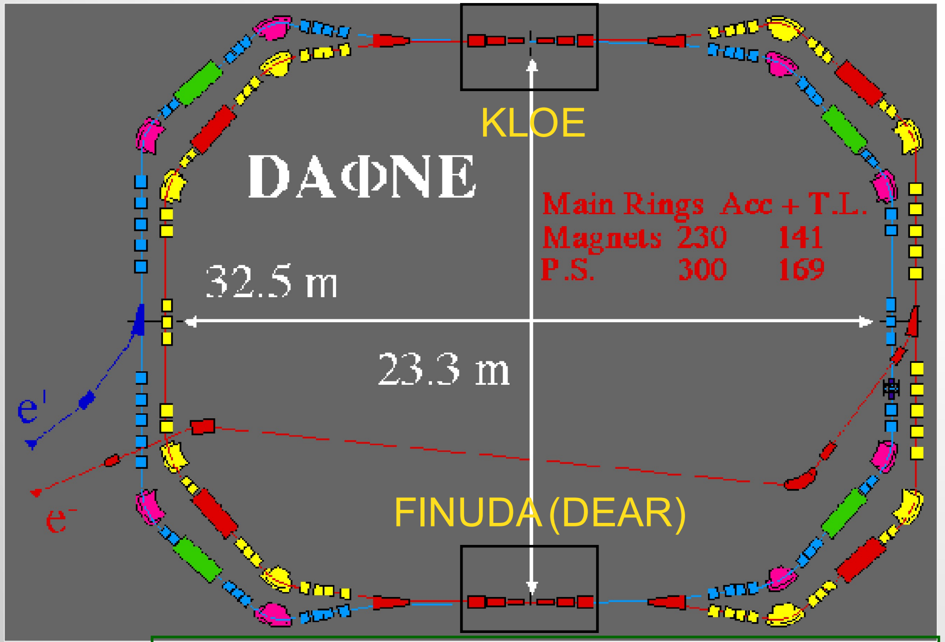
$C \approx 97\ m$

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



LNF are also part of the **European synchrotron light Infrastructures**

DAΦNE parameters

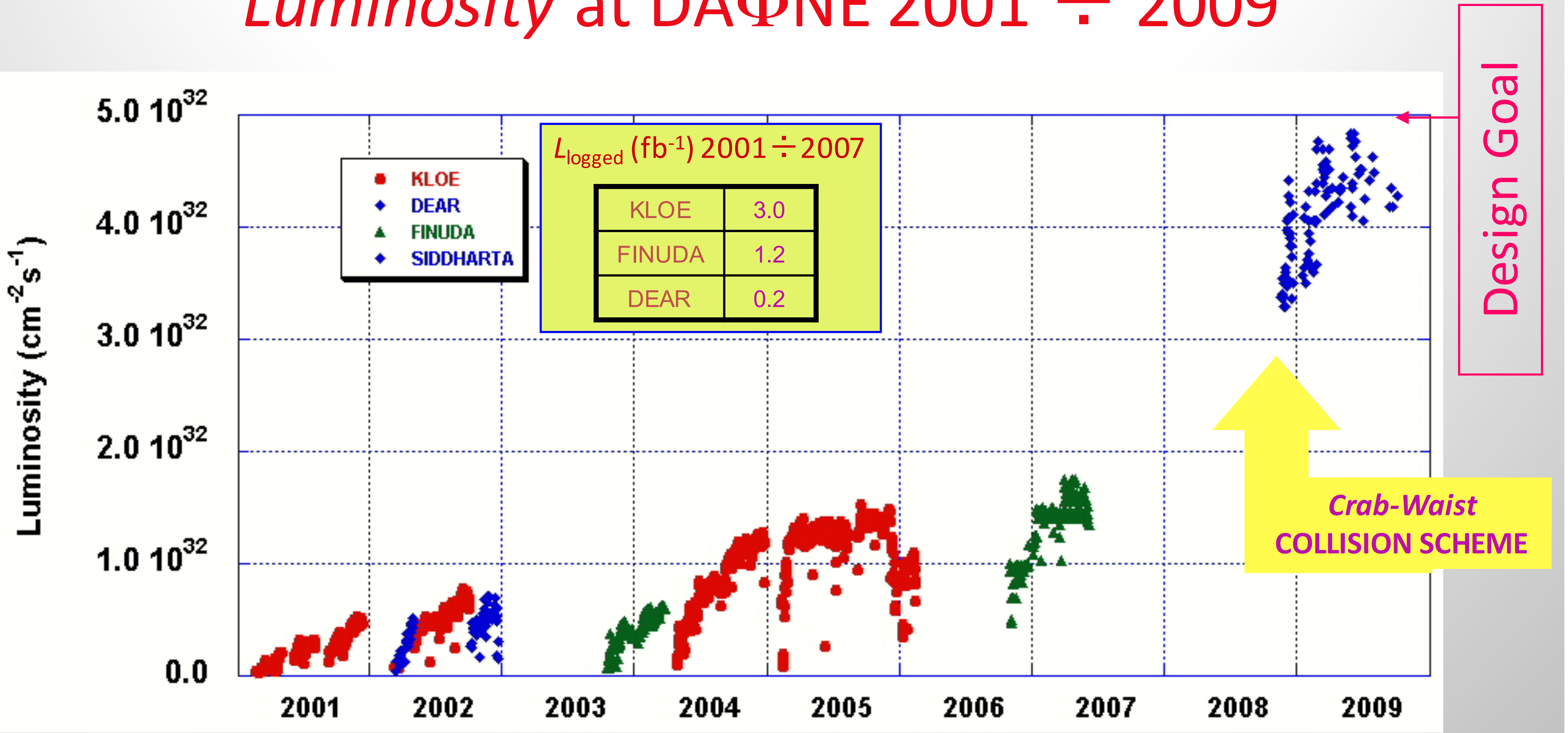


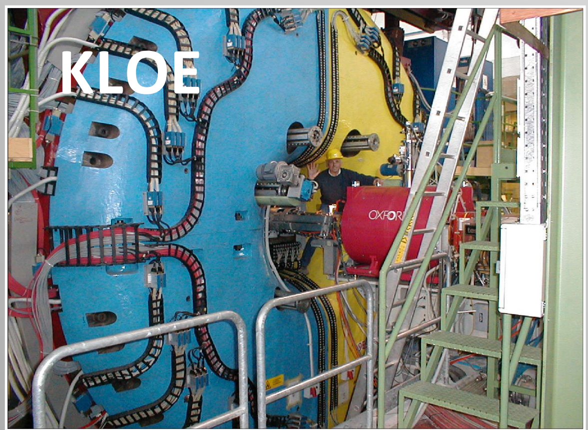
"Proposal for a Φ-factory", LNF-90/031 (IR),1990.

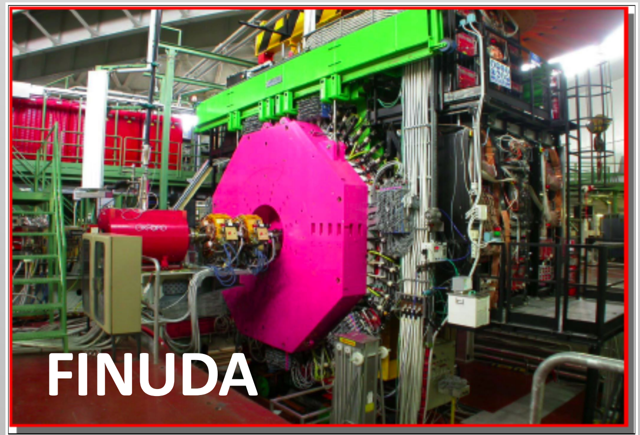
low E
high currents
short bunch spacing
long damping time

	DAΦNE native	DAΦNE Crab-Waist
Energy (MeV)	510	510
$\theta_{cross}/2$ (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
Bunch spacing (ns)	2.7	2.7
I_{bunch} (mA)	13	13
σ_z (mm)	25	20
N_{bunch}	110	111
L ($cm^{-2}s^{-1}$) $\times 10^{32}$	1.6	4.5

Luminosity at DAΦNE 2001 ÷ 2009







Contributions to particle accelerator physics

Ideas and studies aimed at improving beam dynamics and beam-beam performances:

- Low impedance vacuum chamber components
- innovative bunch by bunch feedback systems
- short pulse PS for injection kickers
- non-linearities suppression in magnet fields especially in wigglers
- collisions with negative momentum compaction
- parasitic crossing compensation by current carrying wires
- collisions with very high crossing angle
- strong RF focusing
- electrodes for *e-cloud* mitigation
- ***Crab Waist* collisions**

Proposals:

- DANAE (1.02 GeV ÷ 2.4 GeV)
- Bunch lenght modulation experiment
- DAFNE-VE (0.6 GeV ÷ 3 GeV with CW)

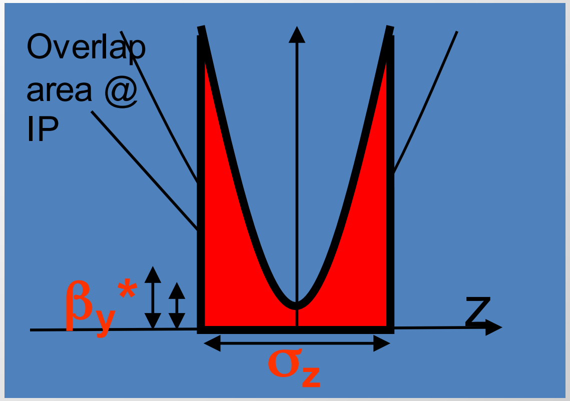
DAΦNE achievements

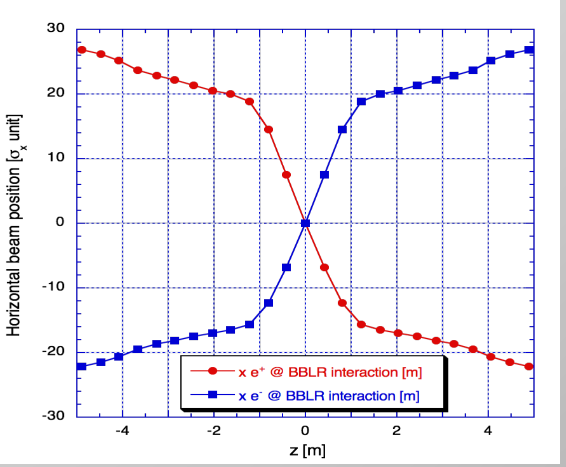
- Impedance budget is a factor 80 lower than in similar storage ring (EPA)
- Collisions with negative momentum compaction gave a 25% gain in terms of specific luminosity at low current without sextupoles
- Longitudinal feedback kicker designed for DAFNE has been adopted at: KEKB, BESSYII, PLS, SLS, HLS, ELETTRA, KEK Photon Factory, PEP II …
- Maximum current stored in the DAFNE electron ring, 2.45 A, is the higher ever achieved in the world
- DAΦNE is the only collider operating routinely with, and thanks to the electrodes for e-Cloud mitigation
- luminosity achieved at DAΦNE is by two orders of magnitude higher than the one obtained at other colliders operating in the same energy range
- *Crab-Waist* collision scheme has become a basic design concept for future new projects

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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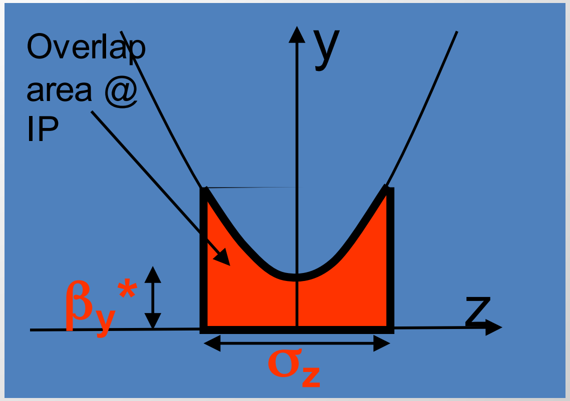
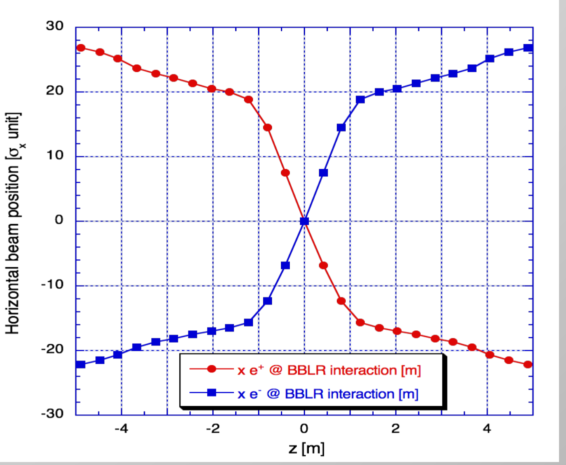




A new conceptual approach was necessary to reach L~10^{33}

Collision scheme based on **Large Piwinski** angle and **Crab-Waist**

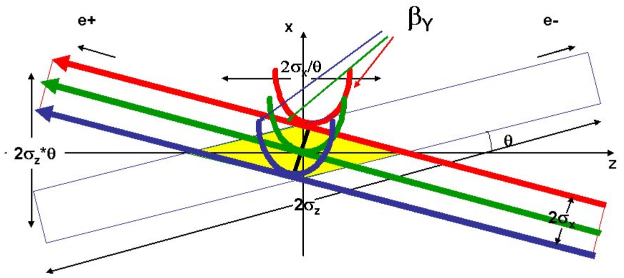
DAΦNE's Approach to *Beam-Beam* Interaction Optimization

A new collision scheme, the *Crab-Waist* collision scheme, has been devised and implemented on the DAΦNE collider in order to overcome all the limitations coming from:

- hourglass effect $\beta^*_y \sim \sigma_z$
- ***LRBB*** interactions
- beam transverse sizes enlargement due to ***BB* interaction**

and the synchro-betatron resonances due to the new configuration itself

Crab-Waist is based on:



Large Piwinski angle Φ — large θ, small σ^*_x

$$\Phi \approx \frac{\sigma_z}{\sigma^*_x} tg\left(\frac{\theta}{2}\right) >> 1$$

→ *L* gain with N
low ξ_x
ξ_y decrease with Y oscillation amplitude

β^*_y comparable with overlap area

$$\beta^*_y \approx 2\sigma^*_x/\theta$$

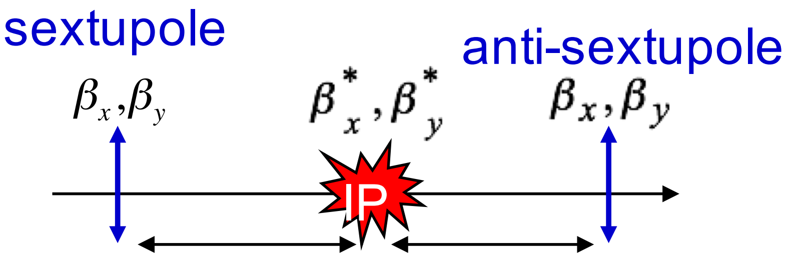
→ *L* geometrical gain
lower ξ_y
Y Synchro-betatron resonances suppression

Crab-Waist transformation by two Sextupoles

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

→ *L* geometrical gain
lower ξ_y
X-Y Synchro-betatron resonances suppression

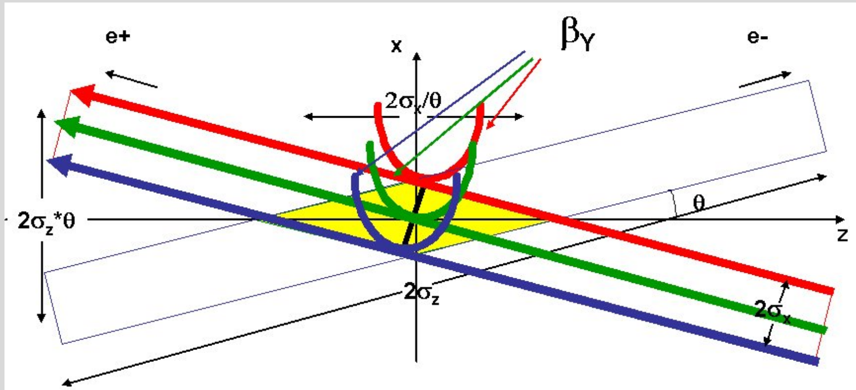
Crab-Waist Transformation



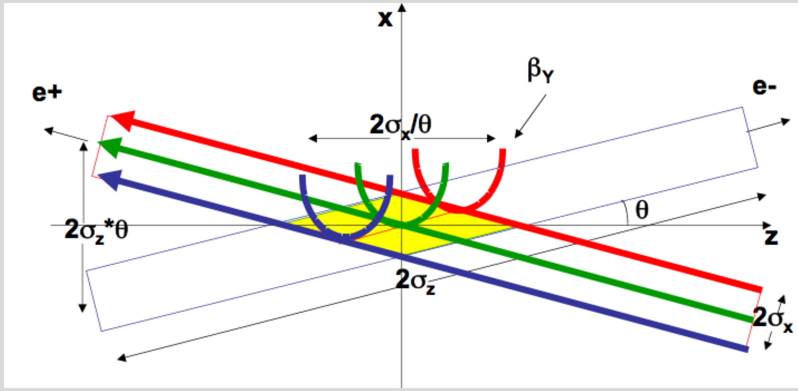
$$\Delta\nu_x = \pi$$
$$\Delta\nu_y = \frac{\pi}{2}$$

Sextupole strength

$$K_s = \frac{\chi}{2\theta} \frac{1}{\beta^*_y \beta^s_y} \sqrt{\frac{\beta^*_x}{\beta^s_x}}$$



Crab OFF



Crab ON

P. Raimondi , 2° *SuperB Workshop, March 2006*
P.Raimondi, D.Shatilov, M.Zobov, physics/0702033
C. Milardi et al., Int.J.Mod.Phys.A24, 2009
M. Zobov et al., Phys. Rev. Lett. 104, 2010

L and ξ as a function of Φ

$$L = bf_r \frac{1}{4\pi\sigma_x\sigma_y}\left[\frac{N^2}{\sqrt{1+\Phi^2}}\right]$$

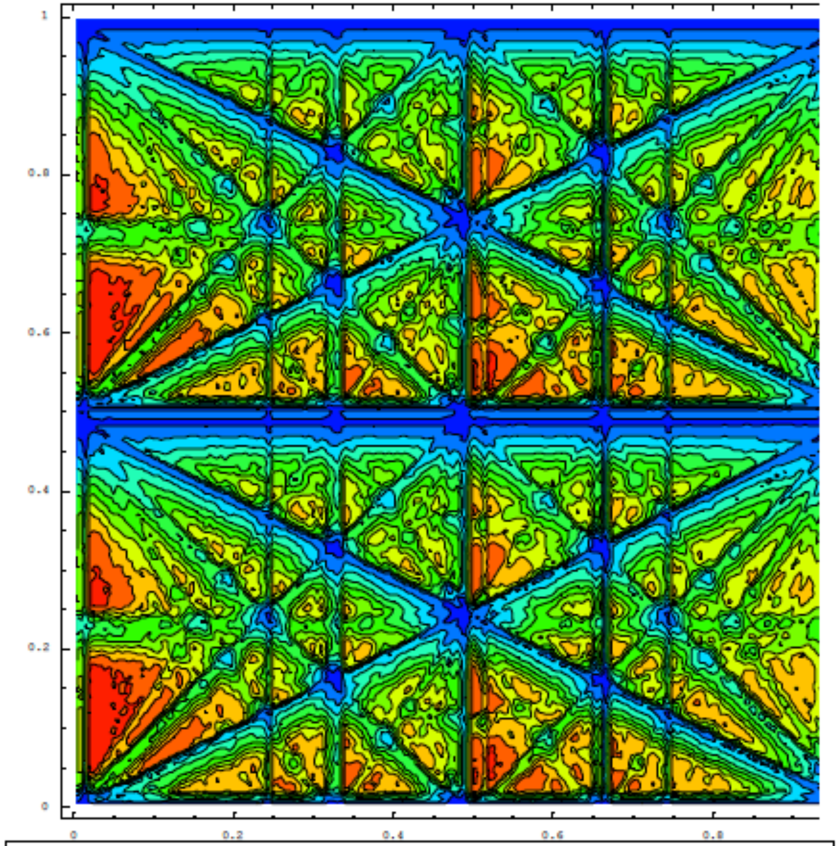
$$\xi_x = \frac{r_0\beta_x}{2\pi\gamma\sigma^2{}_x}\left[\frac{N}{1+\Phi^2}\right] \qquad \xi_y = \frac{r_0\beta_y}{2\pi\gamma\sigma_y\sigma_x}\left[\frac{N}{\sqrt{1+\Phi^2}}\right]$$

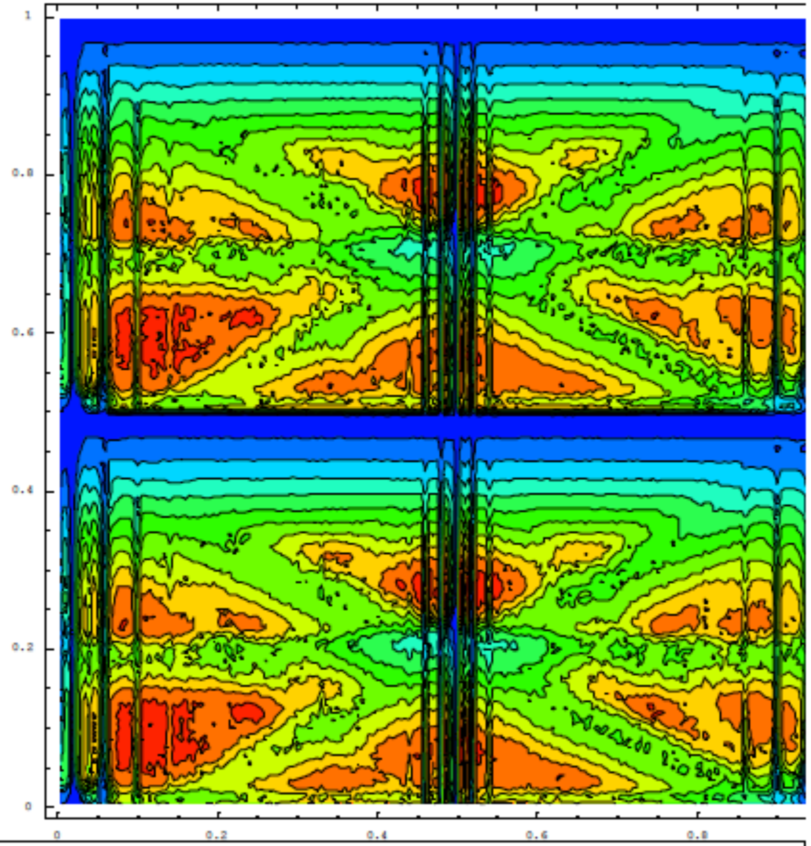
Increasing N proportionally to Φ

- L grows as Φ
- ξ_y remains constant
- ξ_x decreases as $1/\Phi$

Suppression of X-Y Resonances

Much higher luminosity!





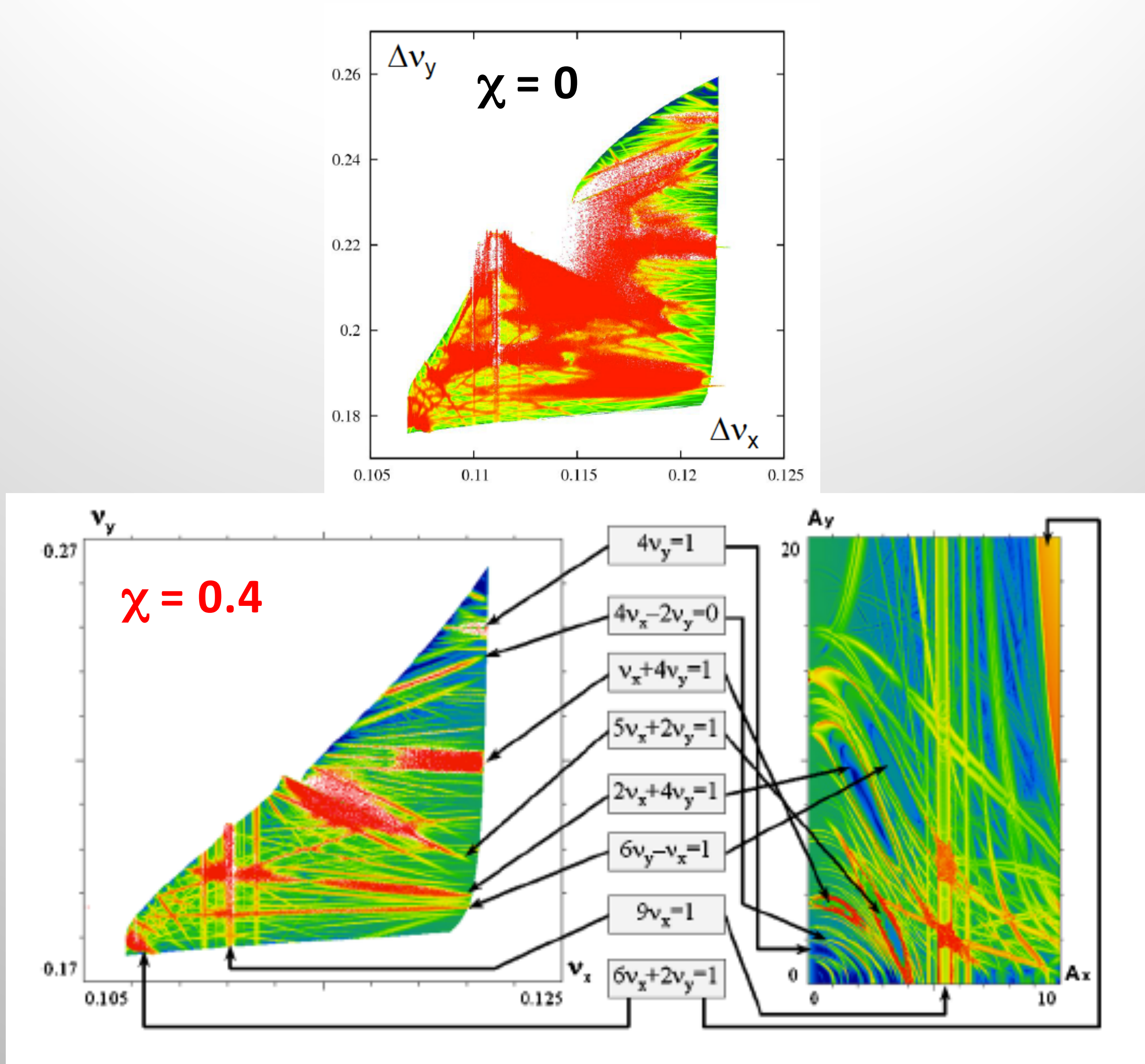
Typical case (KEKB, DAΦNE etc.):

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

Crab Waist On:

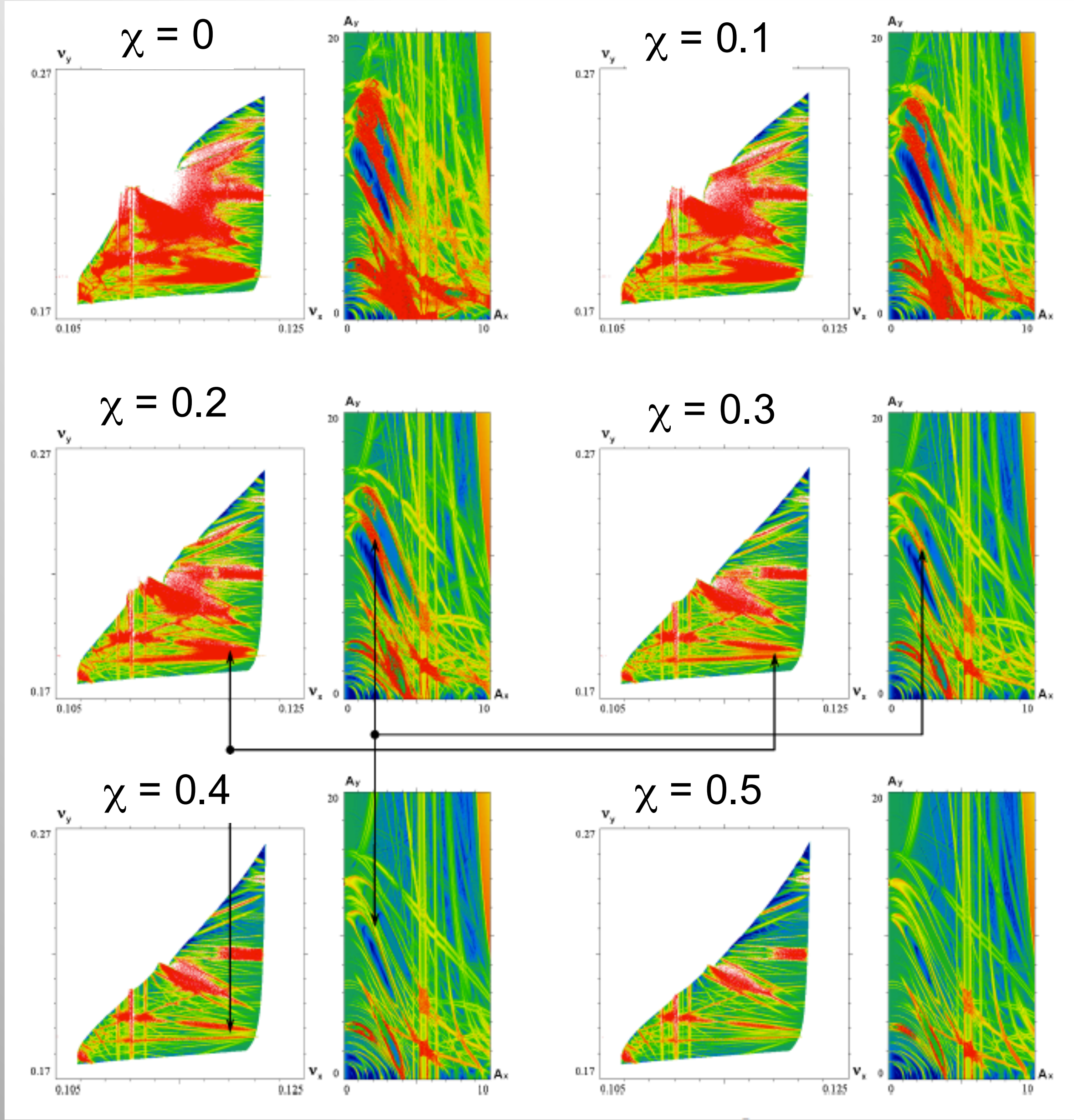
1. large Piwinski angle $\Phi >> 1$
2. β_y comparable with σ_x/θ

Frequency Map Analysis of *Beam-Beam* Interaction



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

χ Optimization by *FMA*



How resonances are suppressed by CW transformation

Tune and amplitude plane are shown

Let us consider the evolution of two specific resonances

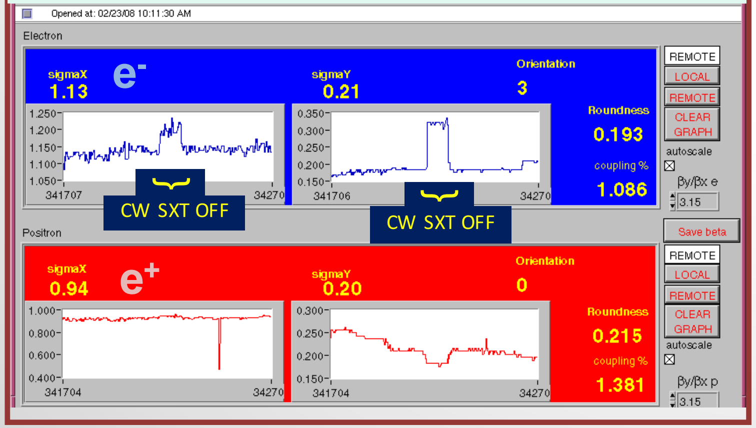
$$2\nu_x + 4\nu_y = 1$$
$$6\nu_y - \nu_x = 1$$

As χ **-> 0** the two resonances merge and form a wide forbidden area for the beam tunes

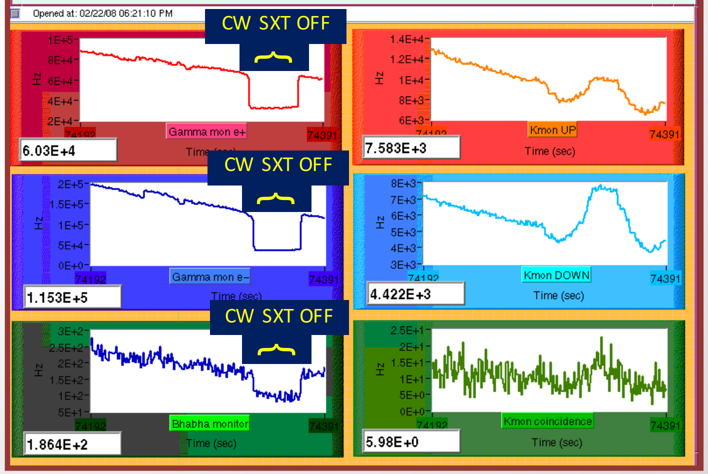
As resonances are suppressed the footprint area shrinks

Crab-Waist Compensation First Experimental Evidence

Beam transverse size measured at the SLM

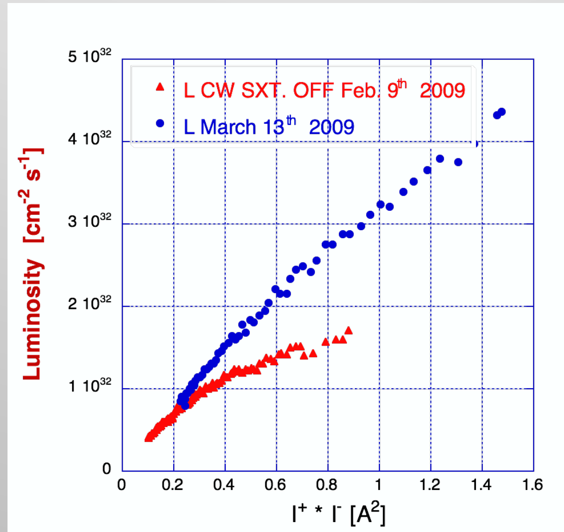


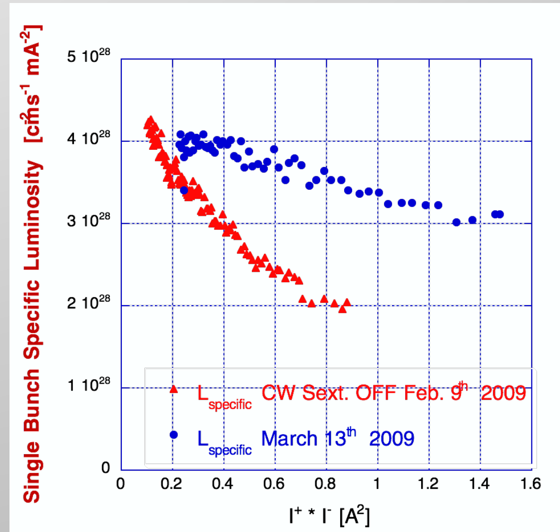
Luminosity from 2 different monitors



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 collision scheme and SIDDHARTA

- Large crossing angle and Crab-Waist scheme proved to be effective in increasing luminosity, a factor 3 higher than in the past

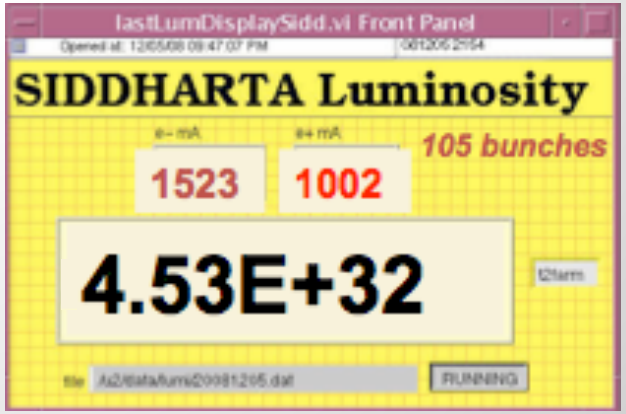
- The DAΦNE collider, based on a new collision scheme including Large Piwinski angle and Crab-Waist, has been successfully commissioned and has delivered:

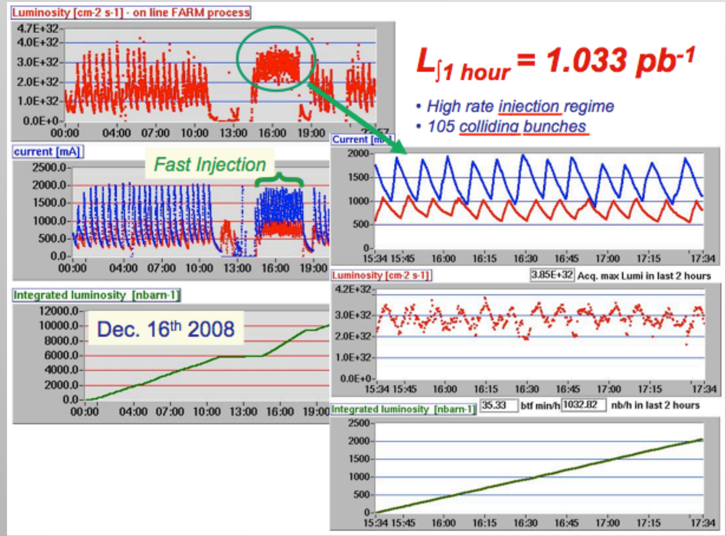
$L_{peak}= 4.5 \cdot 10^{32}\ cm^{-2}\ s^{-1}$

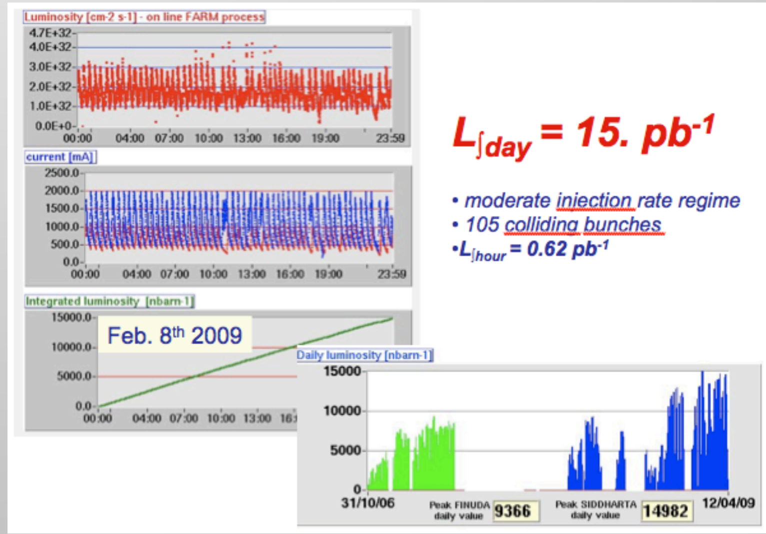
$L_{\int 1\ day}= 15.0\ pb^{-1}$

$L_{\int 1\ hour}= 1.033\ pb^{-1}$

$L_{\int run} \sim 2.8\ fb^{-1}$ (SIDDHARTA detector)







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

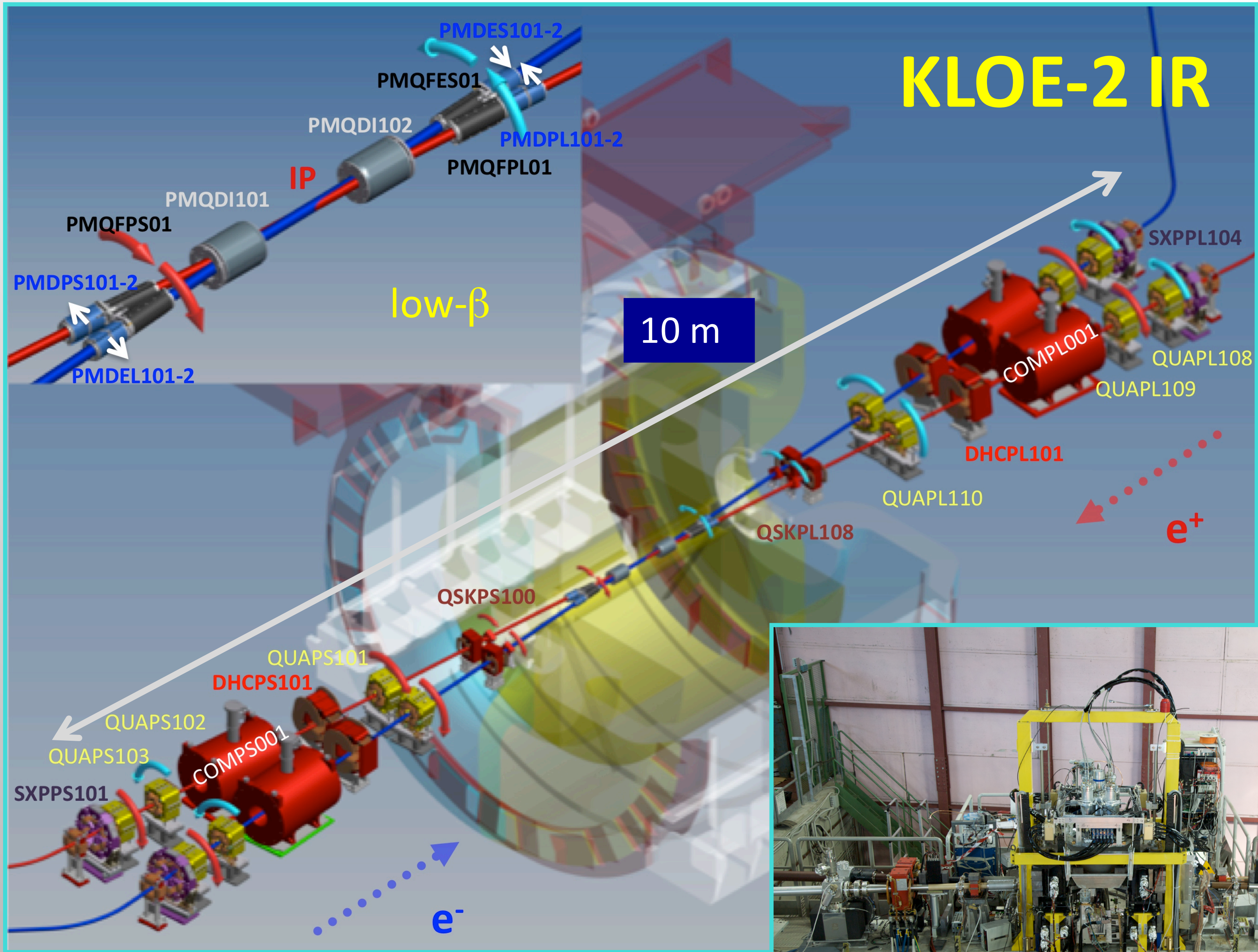
Crucial Points:

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



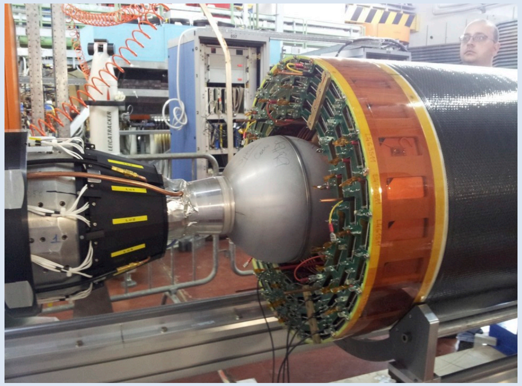
(C. Milardi *et al. 2012 JINST 7 T03002)*

Crab-Waist Collisions for KLOE

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

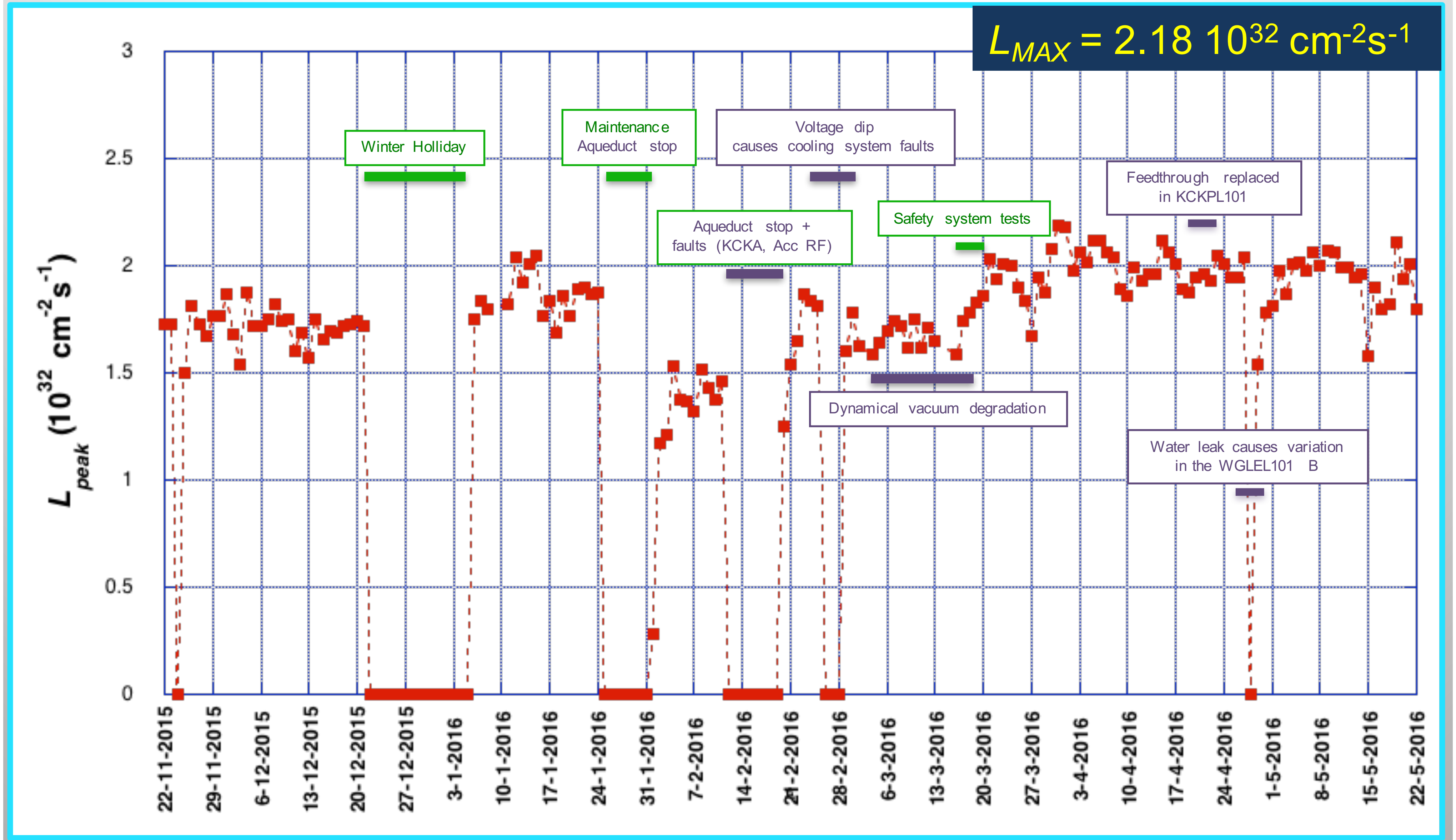
- KLOE rolled in and new IR installed (winter 2010)
- Collision tested
- Physics run with a pure C target (100 pb^{-1})
- Instantaneous luminosity $1.52 \bullet 10^{32}\ cm^{-2}s^{-1}$

- IR extracted (Jan 2013)
- Detector upgrade **KLOE -> KLOE-2**
- Several component and subsistems replaced,maintained and upgraded
- Commissioning



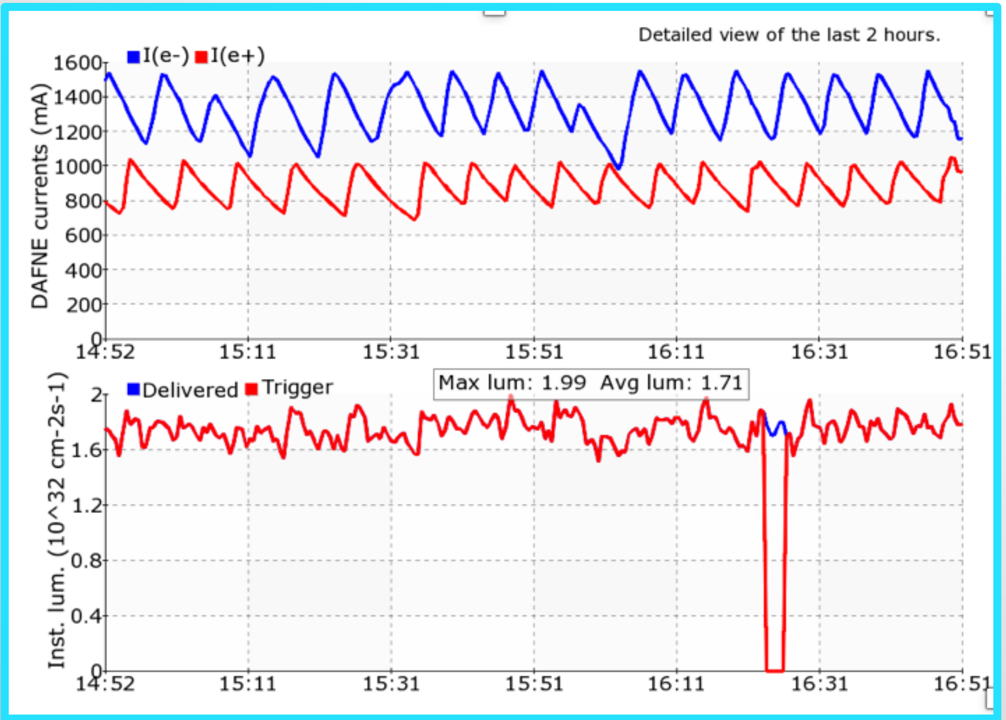
- KLOE-2 data taking started on Nov 2014
  - **I Run** (Nov 2014 – Jul 2015)
  - **II Run** (Oct 2015 – Jun 2016)
  - **III Run** started on Oct 2016 is ongoing

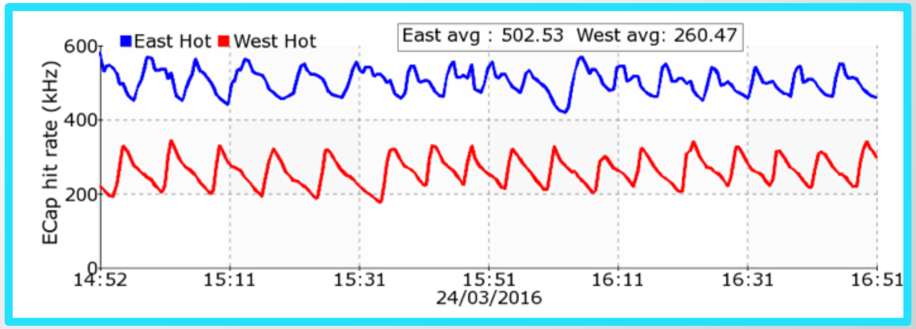
Peak Luminosity Trend

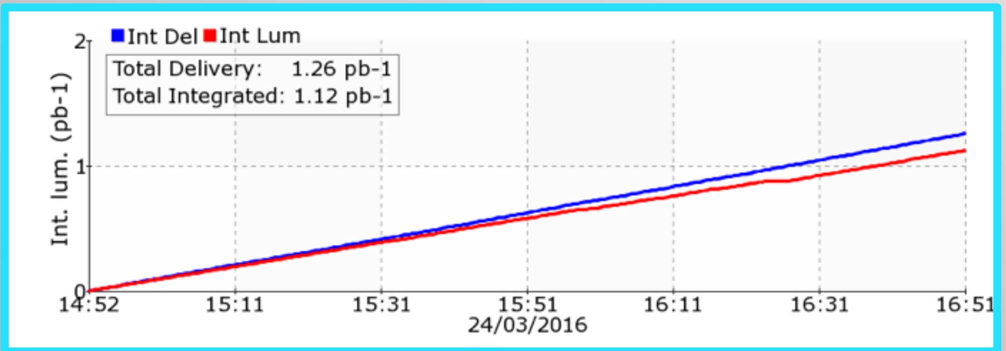


(Courtesy of Catia Milardi

Best Hourly Integrated Luminosity



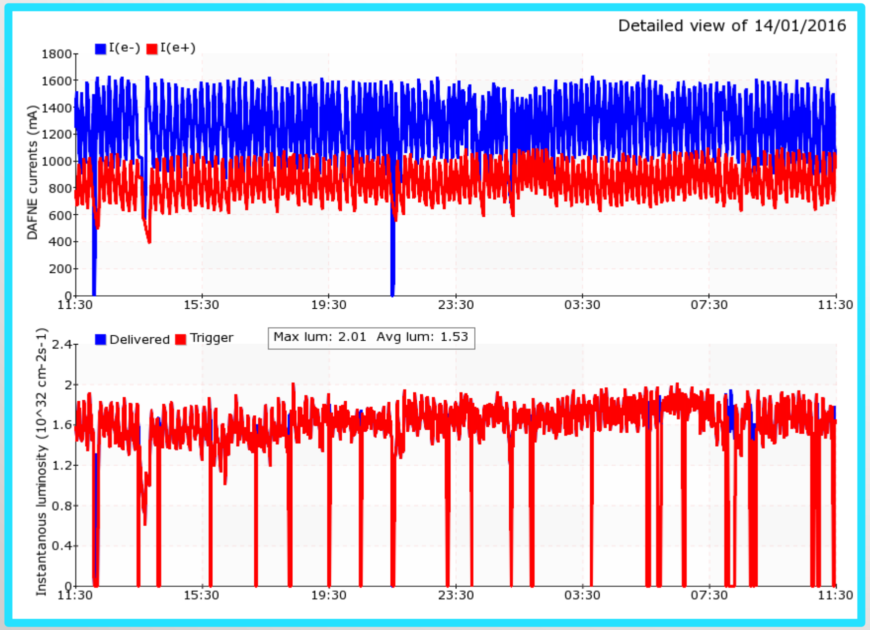


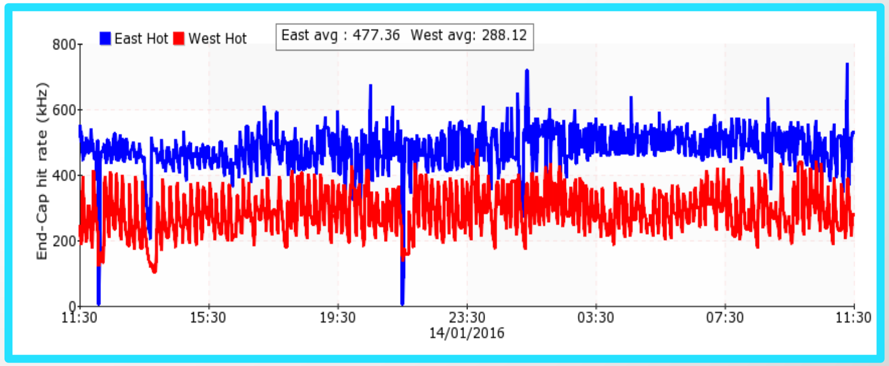


$L_{\int 1h}$ ~ $0.63\ pb^{-1}$

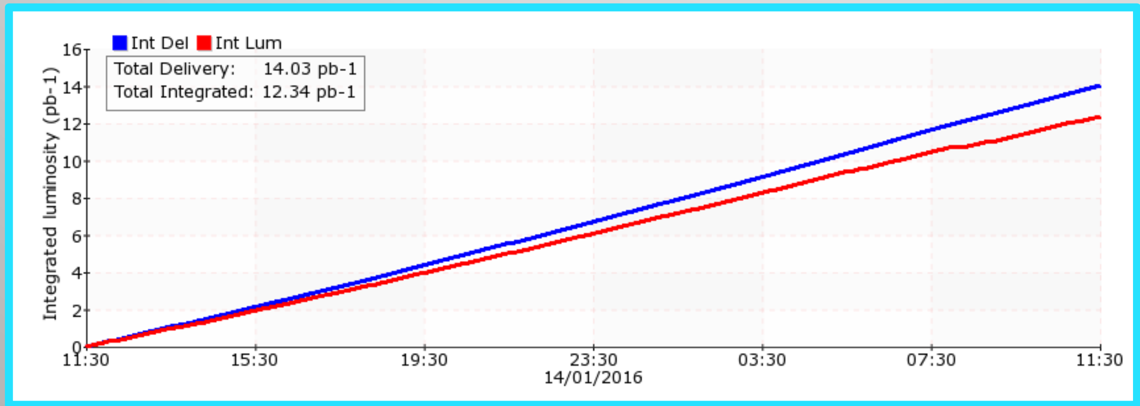
$L_{\int day}$ ~ $15.1\ pb^{-1}$

Best 24 Hours Integrated Luminosity





- 2 beam losses due to PS faults
- 105 bunches
- I^{-}_{MAX} = 1.5 ÷ 1.6 A
- I^{+}_{MAX} = 1.0 ÷ 1.16 A
- Sustainable background

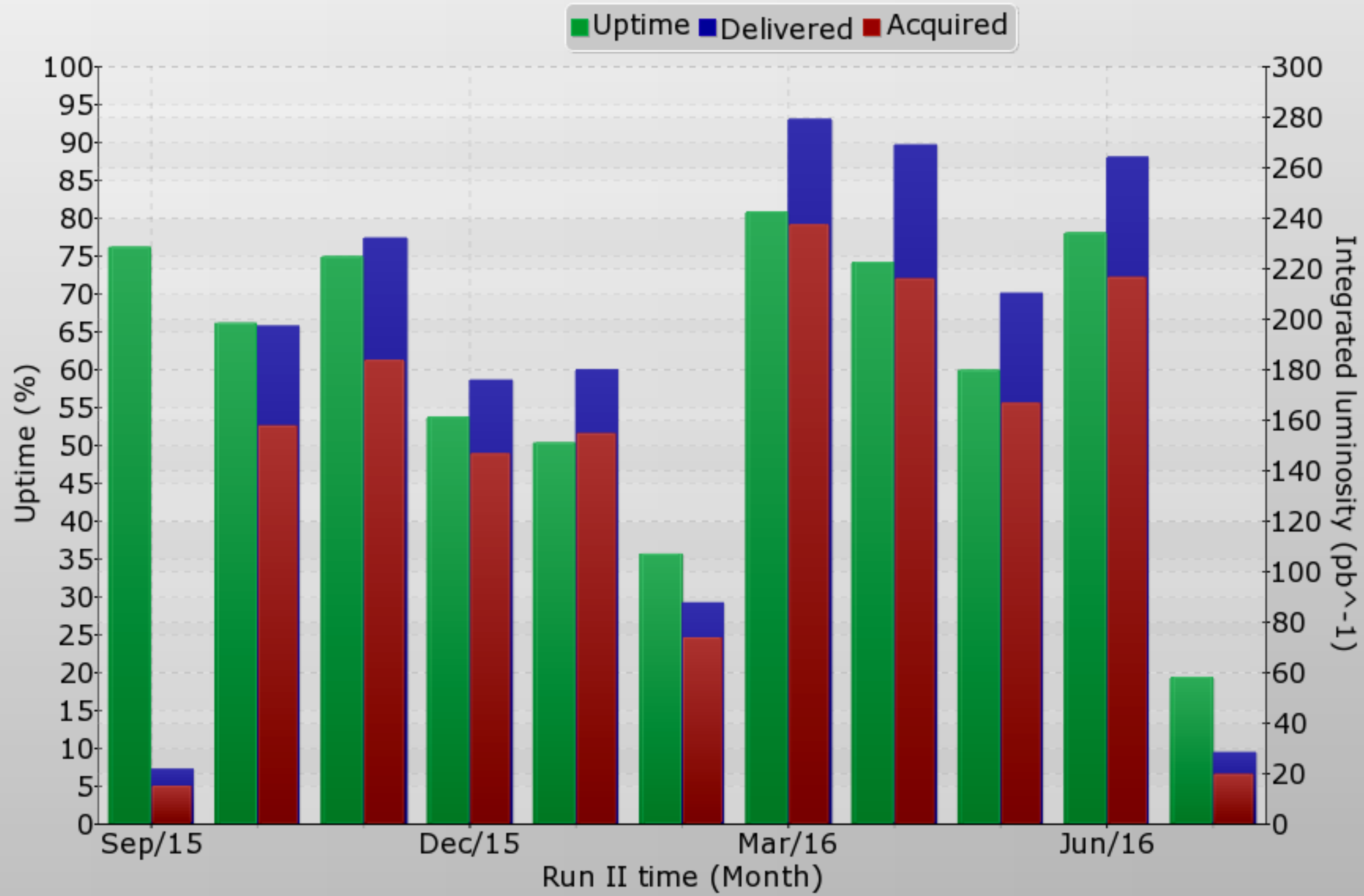


$\int_{del} L \sim 14.03\ pb^{-1}$

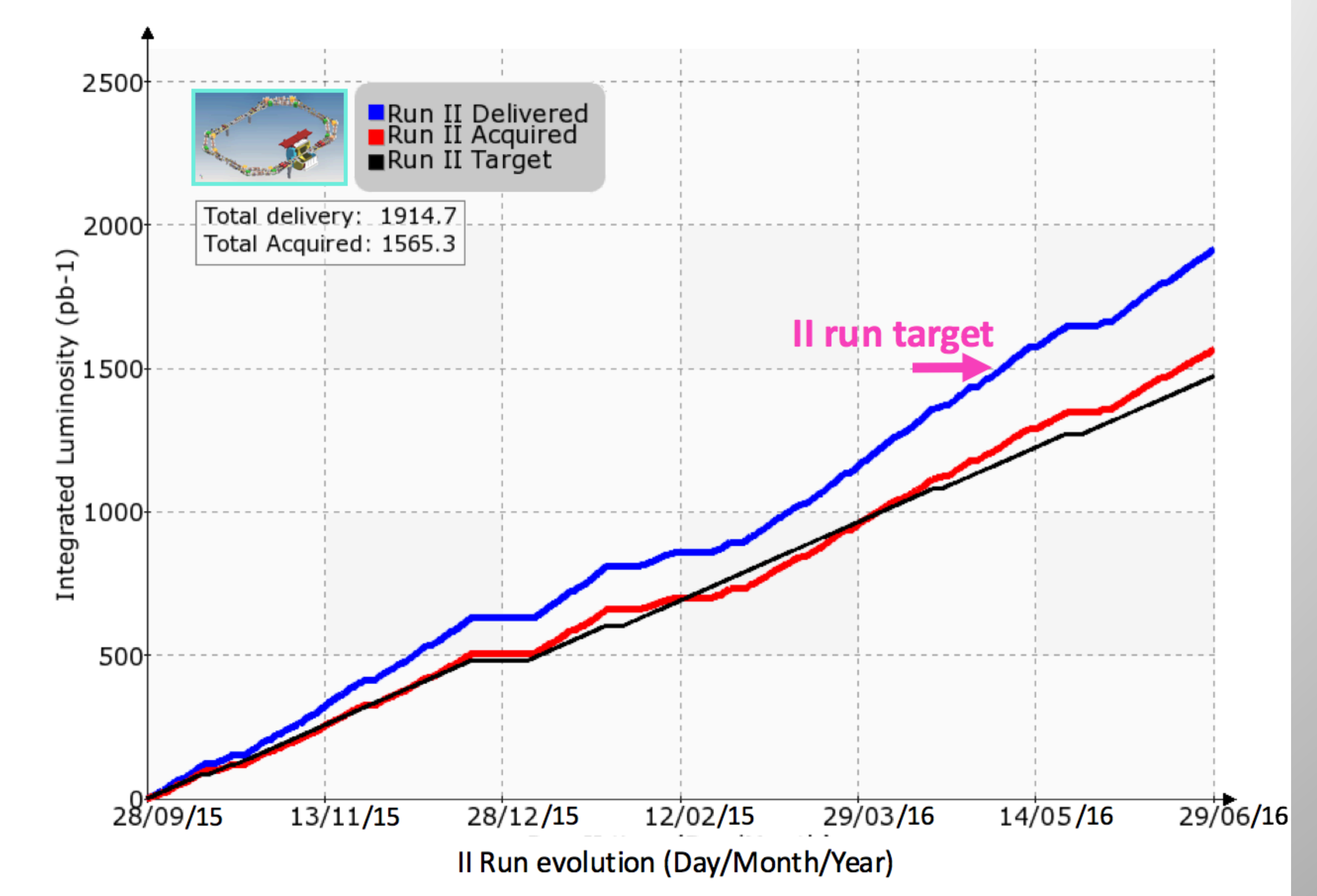
$\int_{acq} L \sim 12.34\ pb^{-1}$

Uptime ~98%

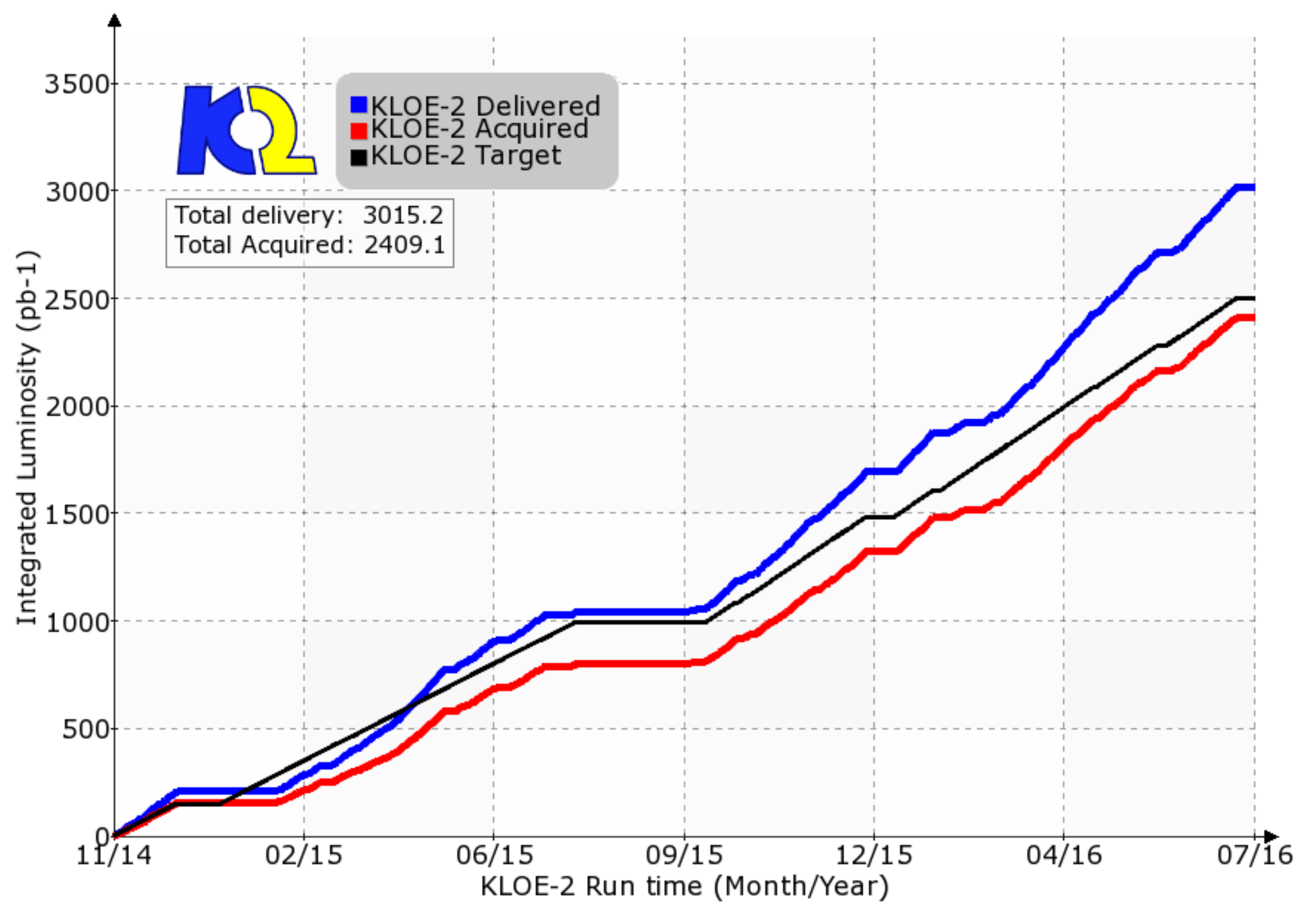
Monthly Performances



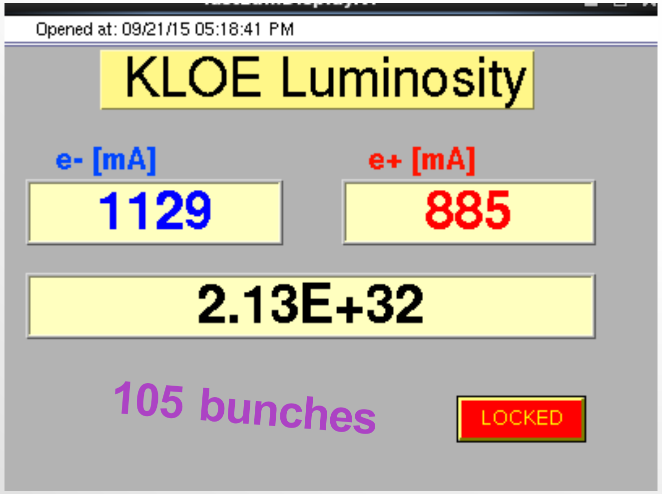
II Run Summary



Total Integrated Luminosity so far



Peak Luminosity during the KLOE-2 run



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

	DAΦNE CW upgrade SIDDHARTA (2009)	DAΦNE CW KLOE-2 (2016)
L_{peak} [10^{32} cm^{-2}s^{-1}]	4.53 (5.0)	**2.13**
$L_{\int day}$ [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**

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

Crab-Waist Colliders

Colliders	Location	Status
DAΦNE	Φ-Factory Frascati, Italy	In operation
SuperKEKB	B-Factory Tsukuba, Japan	Commissioning started in first months of 2016
SuperC-Tau	C-Tau-Factory Novosibirsk, Russia	Russian mega-science project
FCC-ee	Higgs-Factory CERN,Switzerland	100 km, CW baseline design option
CEPC	Higgs-Factory China	54 km, local double ring option with CW
LHC Upgrade	LHC CW Option CERN,Switzerland	LHC with very flat beams (low priority)

Bunch by bunch Feedback systems

Used to damp coupled bunch instabilities both in the longitudinal and transverse plane

DAFNE FBKs are based on **iGp** (Integrated Gigasample Processor) an innovative digital bunch-by-bunch hardware developed by a **KEK / SLAC / INFN-LNF joint collaboration**.

Processing unit can sample at **500 MHz** and compute the bunch-by-bunch output signal for up to ~5000 bunches.

The FBK gateware code is implemented inside just one FPGA chip, a Xilinx Virtex-II.
The FPGA implements two banks of 16-tap FIR (Finite Impulse Response) filters. Each filter is realtime programmable through the operator interface. At DAΦNE, the Frascati Φ-Factory, two iGp units have been

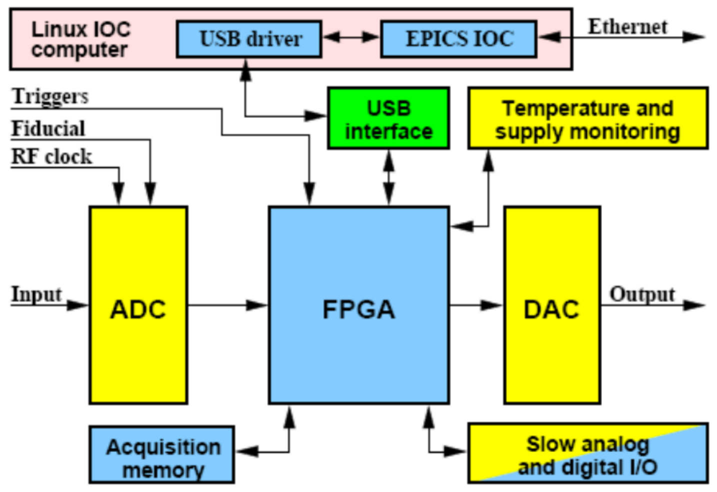


Figure 1: iGp block diagram.

(A.Drago, "Trends in Fast Feedback R&D", arXiv:0806.1864 , Jun 12, 2008)

Beam Current compared with other factories

Parameters	PEP-II		KEKB		DAΦNE	
	LER	HER	LER	HER	e+	e-
Circumference (m)	2200	2200	3016	3016	97.69	97.69
Energy (GeV)	3.1	9.0	3.5	8.0	0.51	0.51
Damping time (turns)	8.000	5.000	4.000	4.000	110.000	110.000
Beam Currents (A)	3.21	2.07	1.70*	1.25*	1.40	**2.45**

Maximum positron beam current

Maximum currents with SC cavities

Maximum electron beam current

* 2.00 A and 1.40 A without crab cavities

Pushing luminosity further

A considerably higher luminosity might be attained by:

- Improving the transverse betatron coupling correction in the main rings
- Optimizing the present rings optics and working point
- Setting the *CW*-Sextupoles to the nominal values
- Improving dynamic vacuum

- Tuning the subtle interplay between beam-beam interaction and collective effects dominating beam dynamics (ion trapping, e-cloud mitigation, microwave single bunch instability threshold, TMCI single bunch instability) in order to:
  - increase stored currents and number of colliding bunches
  - achieve a higher beam-beam parameter

Extensive beam dynamics studies, feedback systems improvements and new optics configuration with higher α_c might greatly help this process

Conclusions

DAΦNE performances:

- *operation are stable and reproducible*
- *peak and integrated luminosity are growing*
- *background is compatible with an efficient data-taking*

Instantaneous luminosity is a 45% higher than the best ever measured with the KLOE detector although beam currents are still lower than in 2005

Maximum daily integrated luminosity is comparable with the best achieved during the Crab-Waist test run with SIDDHARTA and has been measured while KLOE-2 was taking data

Limiting factors have been well understood and still many parameters can be ameliorated to further improve the collider performances

Remarks

After almost 20 years of activity DAΦNE is still able to:

- *power world-class experiments in foundamental physics*
- *give original contributions to reserch and development in the field of particle accelerators*

Luminosity measured at DAΦNE is by two orders of magnitude higher than the one achieved at other colliders operating in the same energy range

***Crab-Waist collision scheme** has become a basic design concept for future new machines and projects*

Thank you for your attention