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Laboratori Nazionali di Frascati

25 Years of DAΦNE Operation

Catia Milardi

Scientific Head of the DAΦNE Accelerator Complex,

on behalf all the colleagues, protagonist of the DAΦNE endeavor

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First Beam Stored at DAΦNE

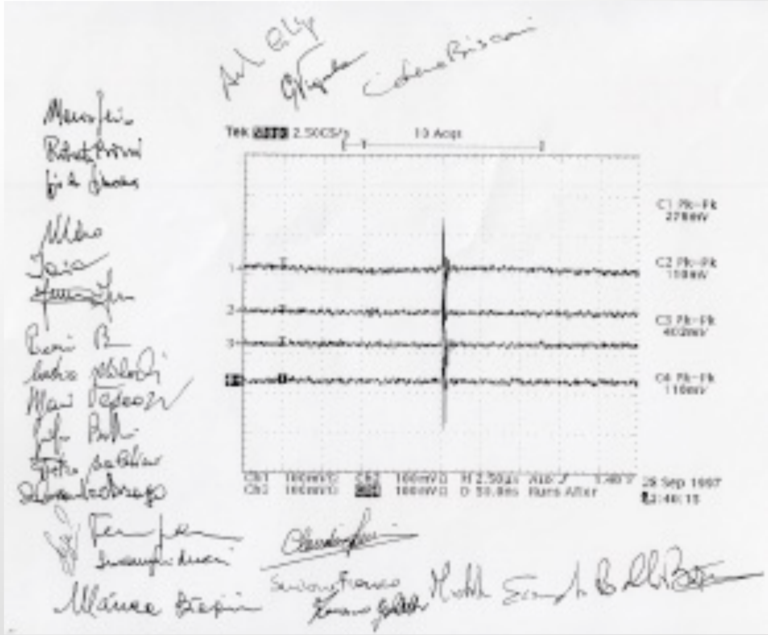

Table IV: *DAΦNE Commissioning Milestones*

Accumulator Ring Installation	December 95
First e- beam through the Tr. Line	27 May 96
First Turn in the Accumulator	1 June 96
Multiturn in the Accumulator	6-7 June 96
First Stored Beam in the Accumulator	21 June 96
120 mA in the Accumulator	30 January 97
LINAC e^+ beam to specifications	March 97
Main Rings Vacuum Connected	July 97
Extraction from the Accumulator	20 September 97
First e^- Beam in the Main Ring	28 September 97
Multiturn in the Main Ring	4 October 97
First Stored Beam in the Main Ring	25 October 97

ICFA Advanced Beam Dynamics Workshop on Beam Dynamics Issues for e+e- Factories,
Frascati, October 20-25, 1997

DAΦNE was built in 5 years

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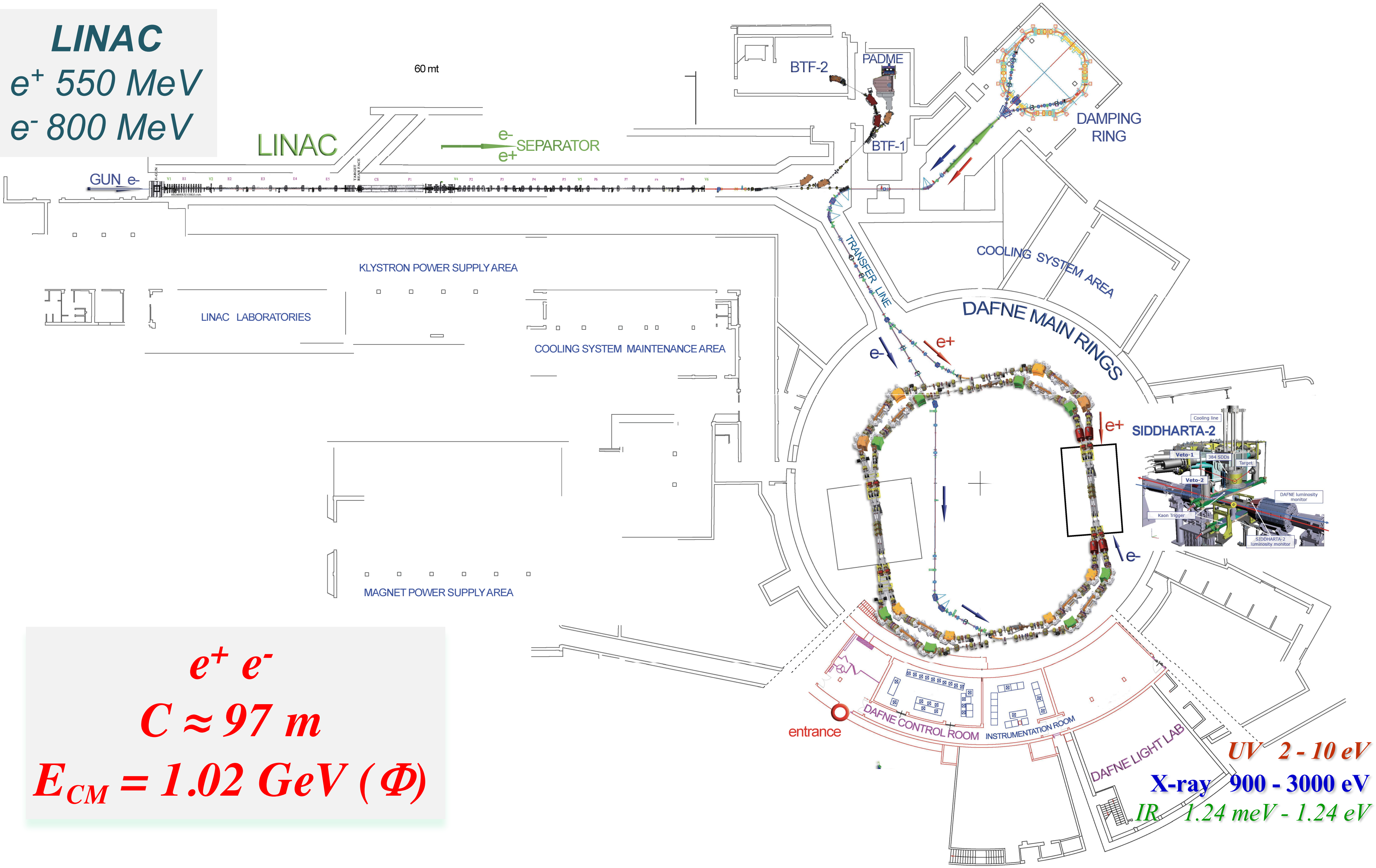
Outline

- DAΦNE *history and overview.*
- DAΦNE *performances optimization.*
- DAΦNE *experience with the Crab-Waist collision scheme.*
- DAΦNE *achievements and contributions to the physics of particle accelerators.*
- *Physics activities at DAΦNE.*
- *Conclusions.*

The DAΦNE Accelerator Complex

DAΦNE

LINAC
e^+ 550 MeV
e^- 800 MeV



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

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DAΦNE History

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

- In the 20th century DAΦNE, together with PEP-II, KEKB, BEPC-II, introduced a new collider category: ***THE FACTORIES***.

- Advances in accelerator physics concerning:
  - magnets, vacuum systems, diagnostics, feedback, control systems etc. ,
  - understanding the impact of collective effects (wakefield, intrabeam scattering, e-cloud etc.),

  led to a new class of colliders that store multi bunch high intensity beam currents in independent rings which share only the interaction region.

- The Factories had to face new challenges:
  - preserve the "single beam" "low charge" parameters: 3D emittance
  - maintain stable beams;
  - Interaction Region design, especially low-beta;
  - synchrotron radiation and beam losses handling;
  - beam power, and RF power;
  - Luminosity degradation due to collision with horizontal crossing angle and beam-beam interaction.

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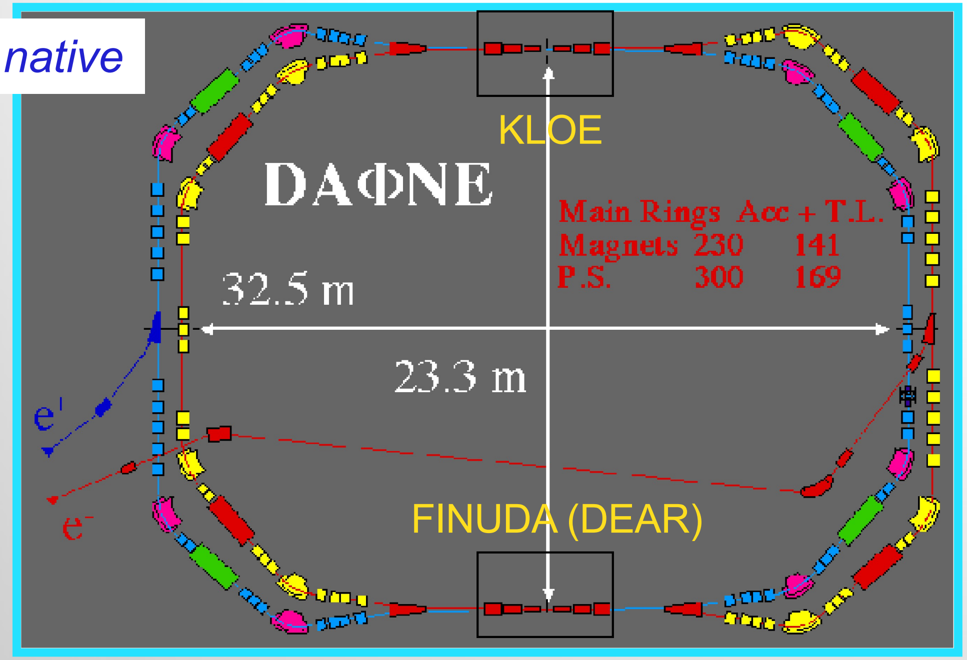
  - beam power, and RF power;
  - Luminosity degradation due to collision with horizontal crossing angle, and beam-beam interaction.

At the beginning of the 21st century DAFNE, developing and implementing a new approach to collisions the Crab-Waist collision scheme, became protagonist of a new transition in the field of colliders, the advent of the ***Super Factories.***

DAΦNE Main Ring 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	1.7
β_y^* (cm)	1.80	0.8
σ_y^* (μm) low current	5.4	3.1
Coupling, %	0.5	0.5
Bunch spacing (ns)	2.7	2.7
I_{bunch} (mA)	13	15
σ_z (mm)	25	15
N_b	120	120

Native layout included 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 with long fringe fields*
- *Strong non-linearities coming from:*
  Wigglers,
  C-type correctors,
  large high strength Quadrupoles used in the native IRs based on a triplet configuration.
- *Main IR based on permanent magnet quadrupoles whose design has been revised and 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

Colliding Rings Main Features

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- 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 revised and 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*

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Beams Main Features

Colliding beams have:

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

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Bringing DAΦNE to achieve design performances imposed to address and study, the complex Interplay between beam-beam interaction and a large ensamble of other effects including: collective effects, vacuum effects, RF and FBK systems, non-linear beam dynamics …

These studies provided original insight, and allowed to mitigate, and in many case avoid negative interferences.

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Conventional Approach to High Luminosity

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

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

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

σ_z reduction led to:

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

Higher N and N_b

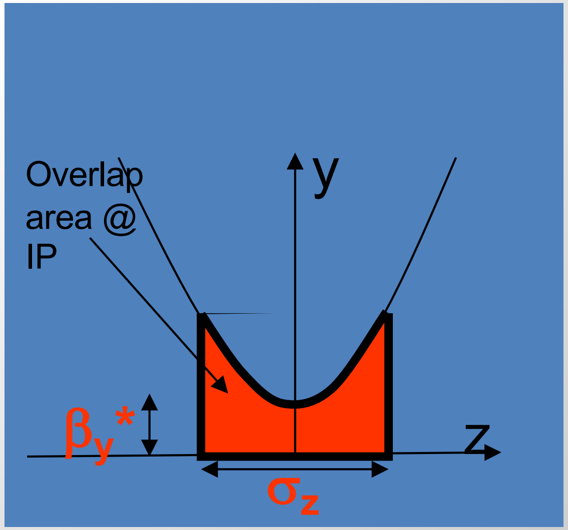
- led to enhanced power losses
- increase wall plug power requirements
- causes coupled bunch instabilities

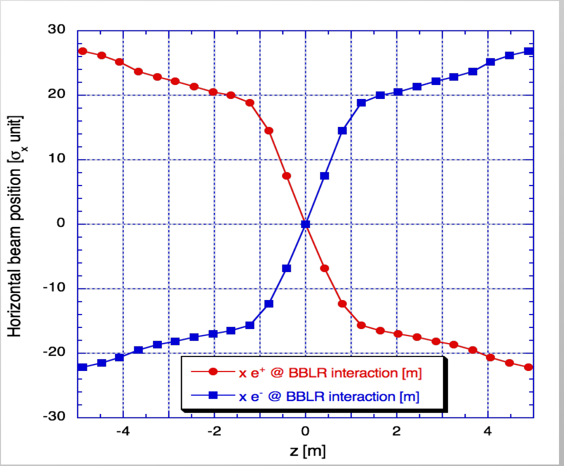
Tune shifts $\xi_{x,y}$ are constrained by beam-beam limit

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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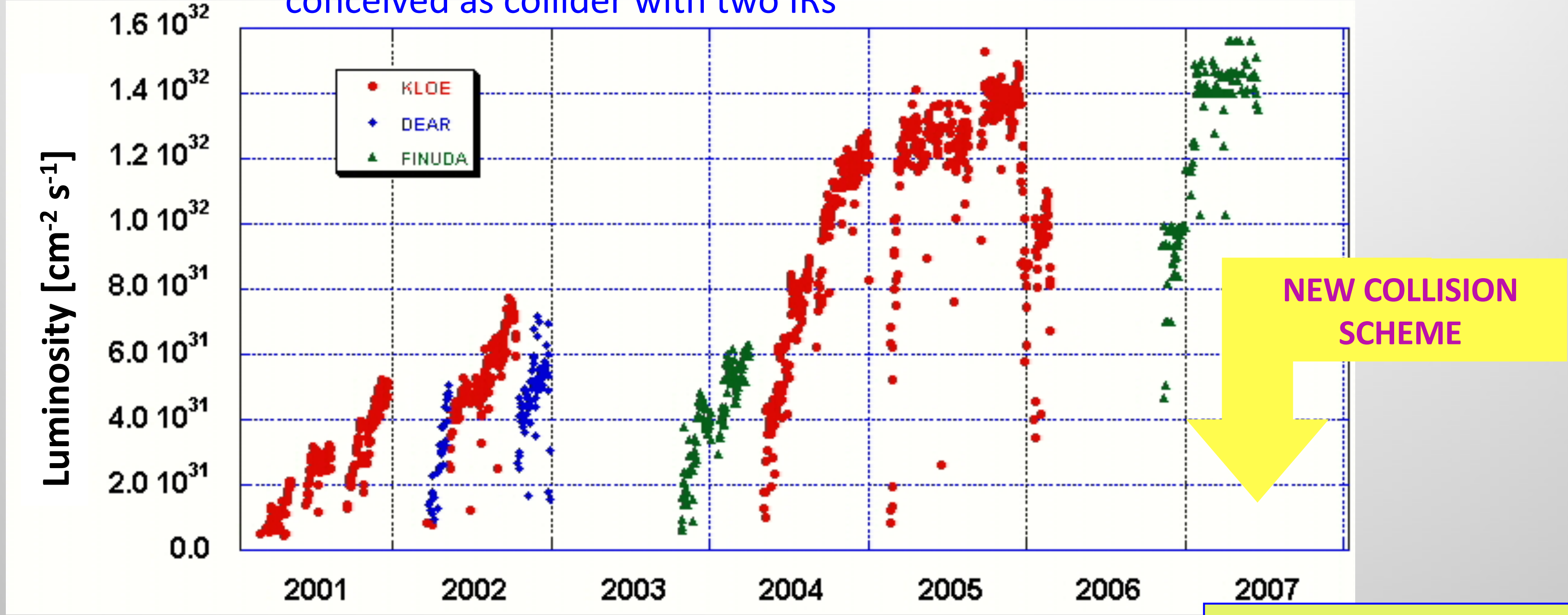
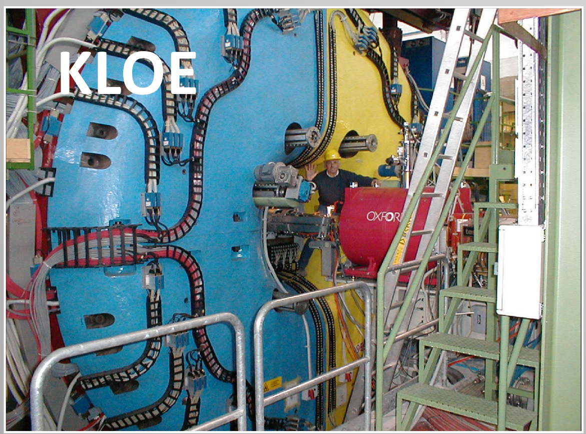
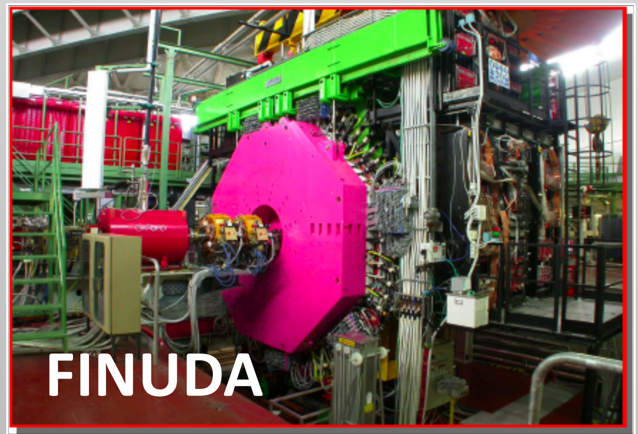
L_{peak} at DAΦNE 2001 ÷ 2007

L_{peak} had a remarkable evolution mainly due to several machine upgrades
Experiments took data one at 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

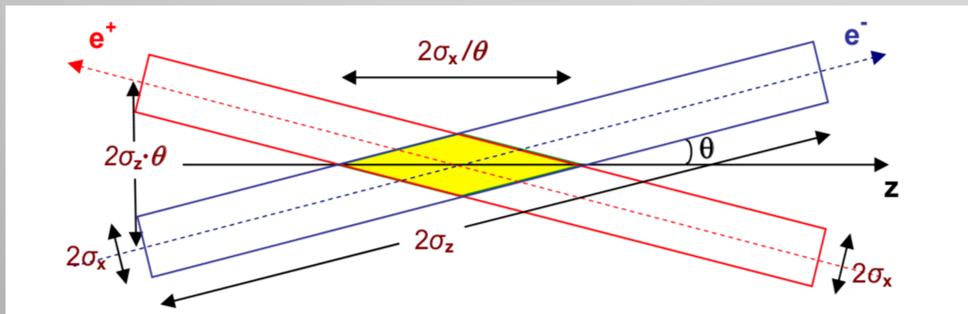
$$\xi_y \propto \frac{N\sqrt{\beta_y^*}}{\sigma_z \theta} \qquad \xi_x \propto \frac{N}{(\sigma_z \theta)^2} \qquad L \propto \frac{N\xi_y}{\beta_y^*}$$

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

$\boldsymbol{\beta_y^*}$ 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

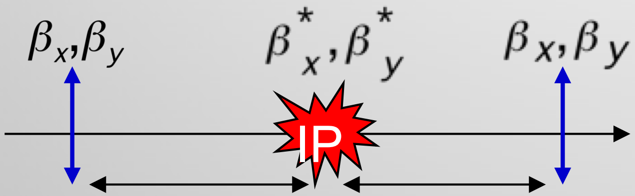
Crab-Waist transformation is

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

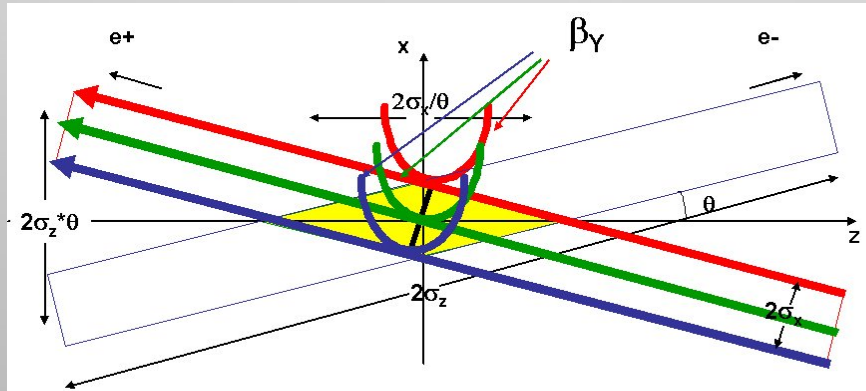
$$y = \frac{xy'}{2\theta}$$

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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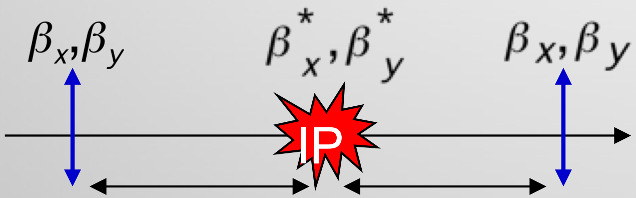

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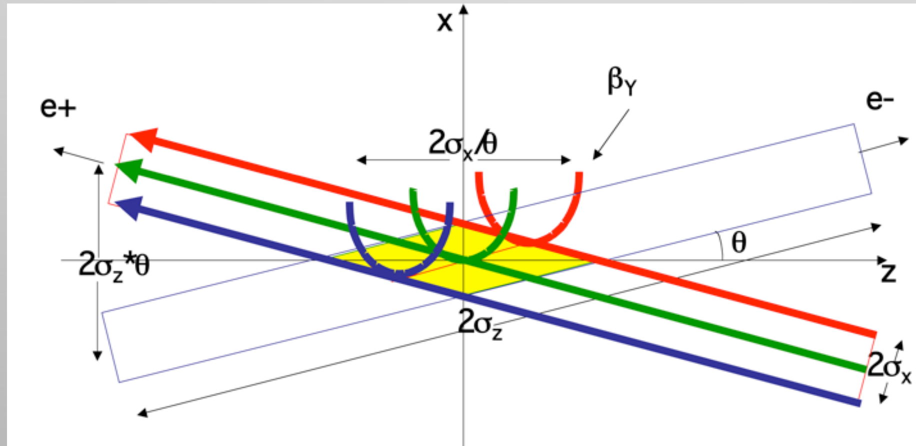


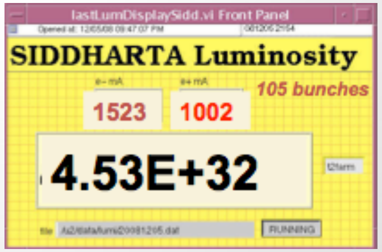
with CW Sextupoles

Crab-Waist Test during SIDDHARTA Run

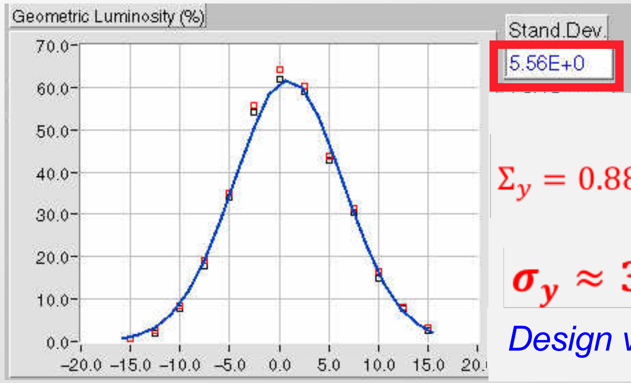
Crab-Waist collisions and SIDDHARTA

- 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



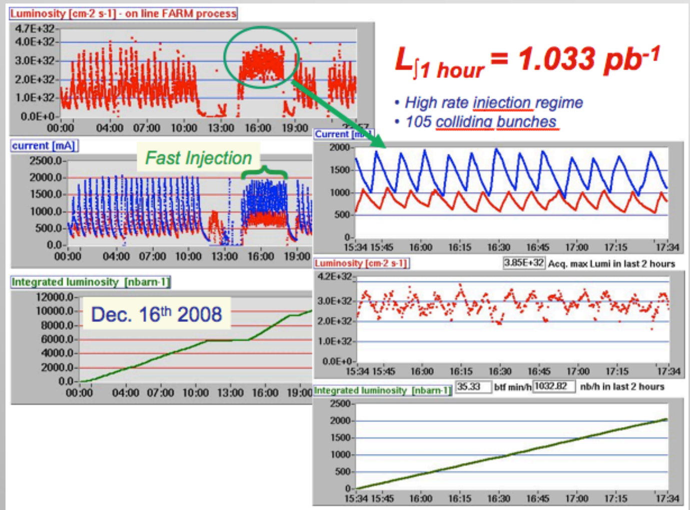
L_{peak}= 4.5*10^{32} cm^{-2} s^{-1}
$L_{\int 1\ day}$= 15.0 pb^{-1}
$L_{\int 1\ hour}$ = 1.033 pb^{-1}
$L_{\int run}$~ 2.8 fb^{-1} (delivered in 18 months)

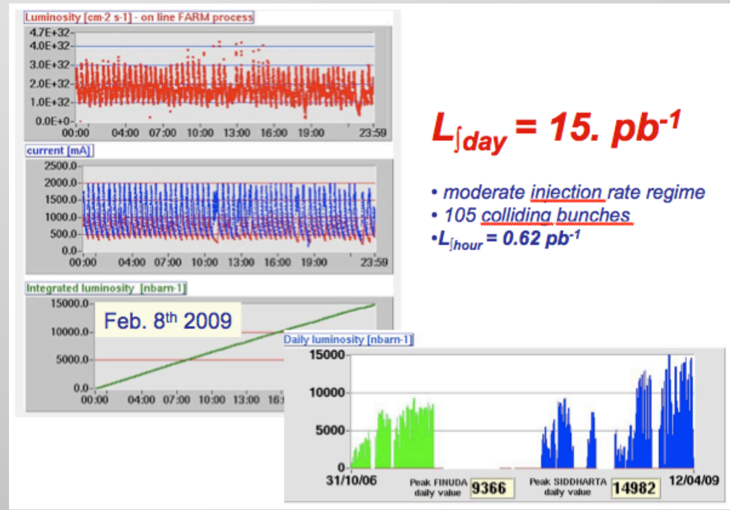


$$\Sigma_y = 0.88\sqrt{\sigma^2_{Ypos} + \sigma^2_{Yele}}$$

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

Design value 3.1μm





(C. Milardi et al., "Experience with DAFNE upgrade including crab waist", PAC09)

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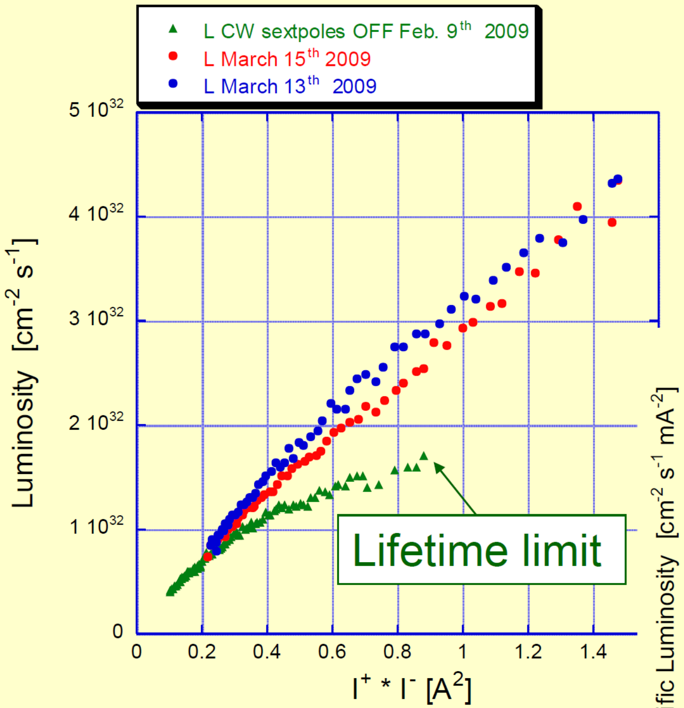
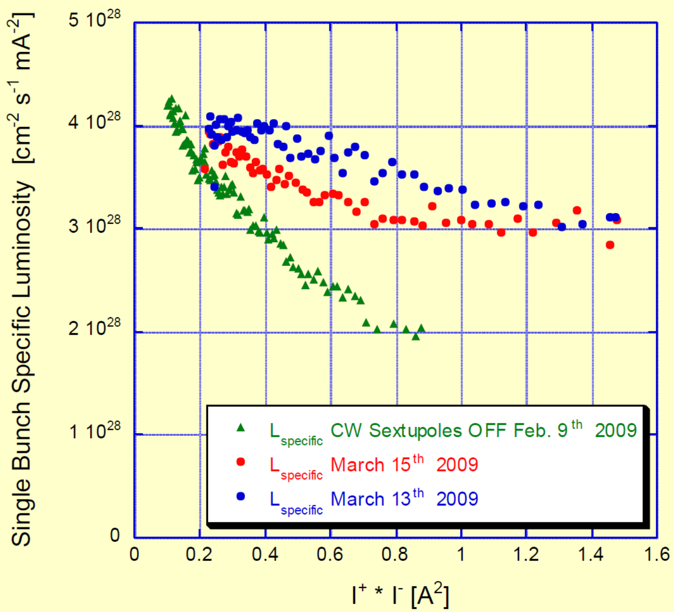
Crab-Waist Compensation, First Experimental Evidence

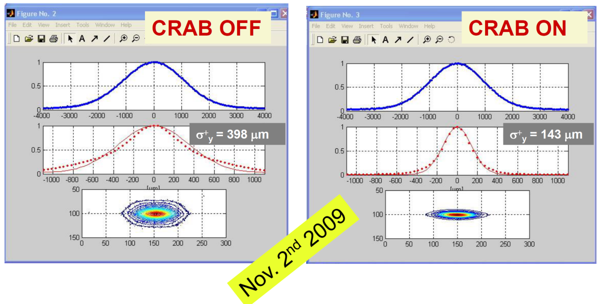


Crab on/off Luminosity vs Current Product

Crab on/off Specific Luminosity vs Current Product



Transverse Beam Profile Measurements

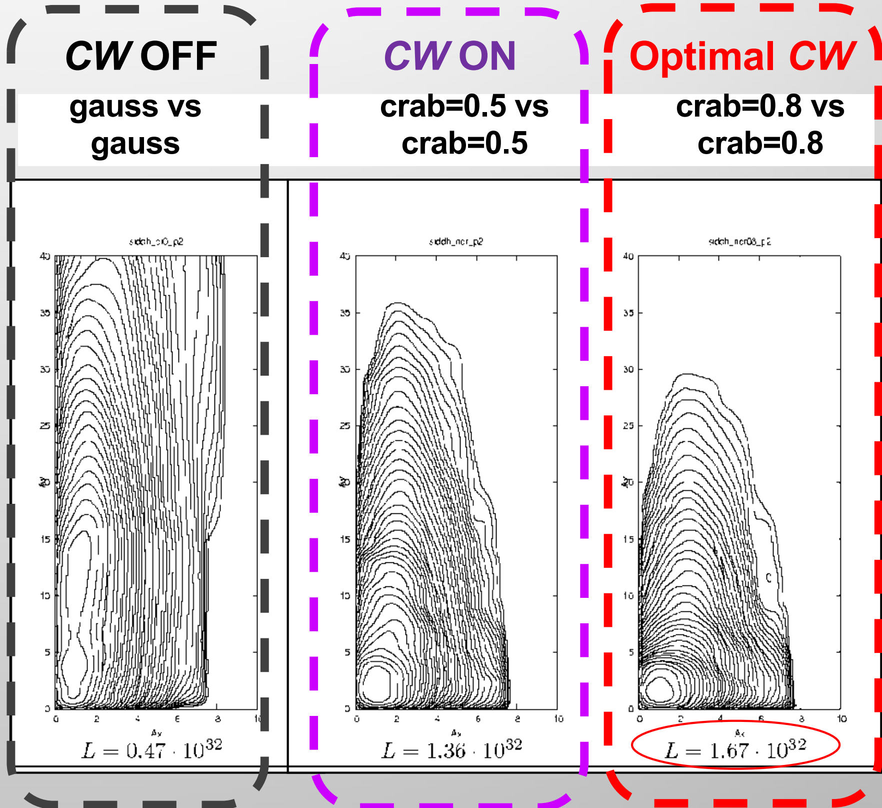


Specific luminosity drop consistent with single beam collective effects

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.

$\xi_y = 0.09$



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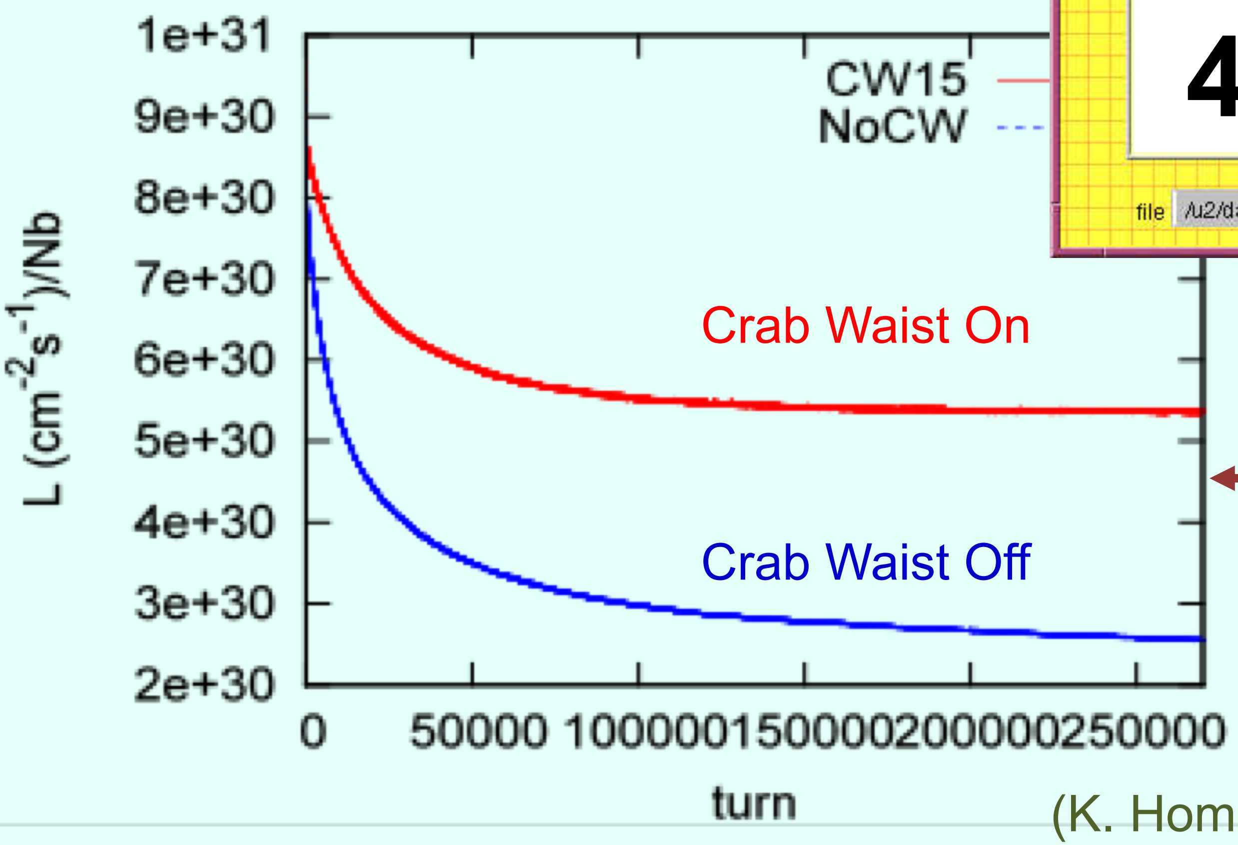
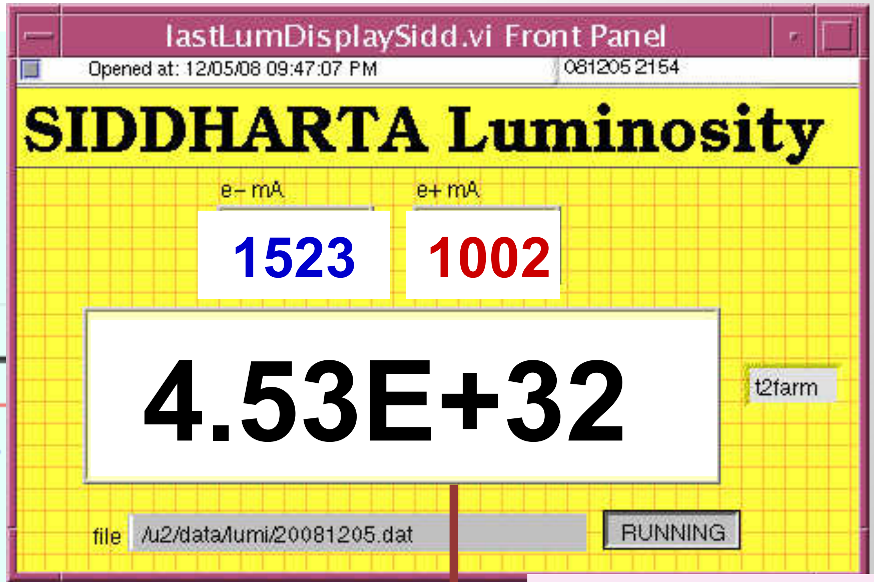
Strong-Strong Beam-Beam Simulations

Single Bunch Luminosity
(Damping time = 110.000 turns)



(K. Homi)



105 bunches

about 20% lower

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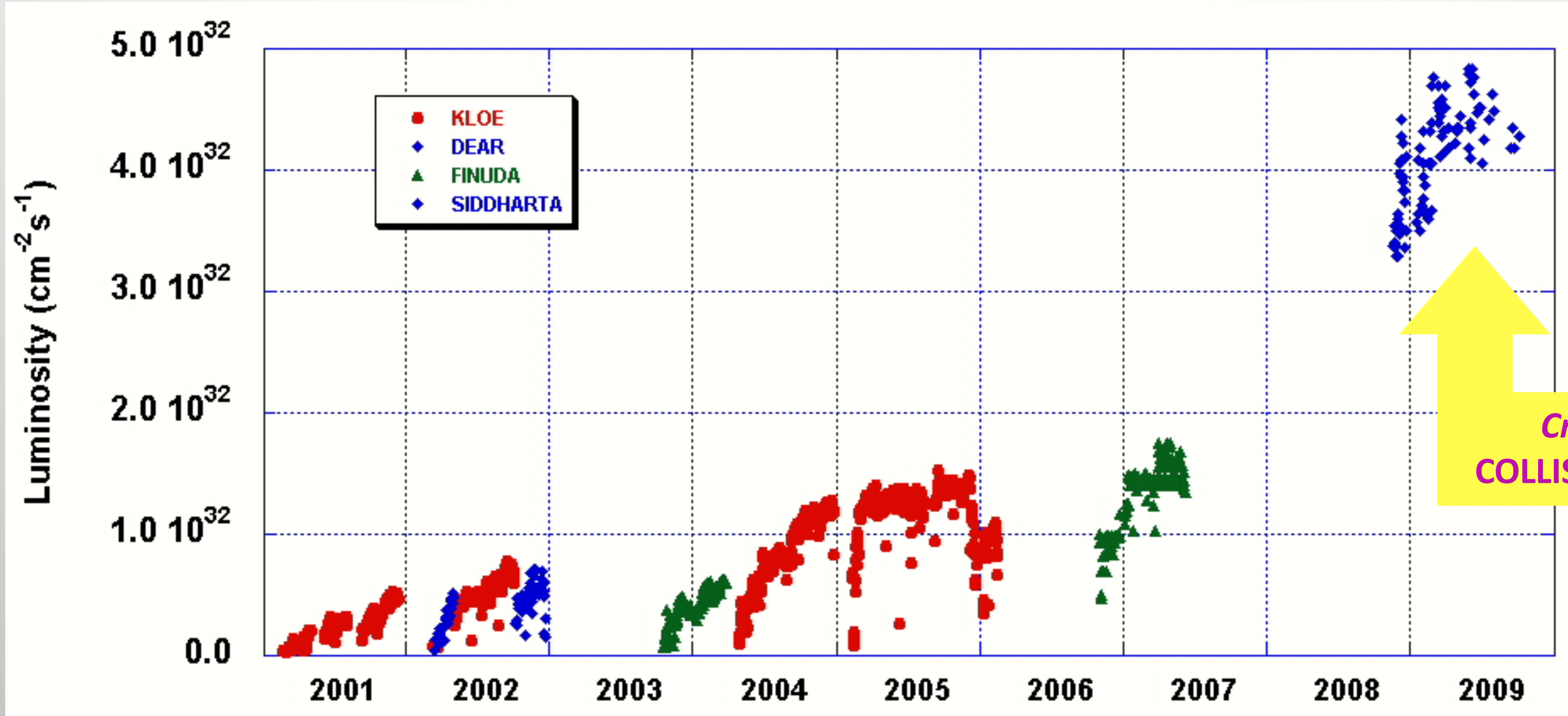
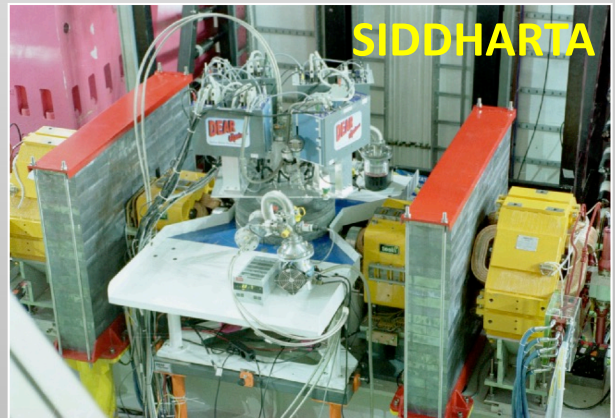
Luminosity at DAΦNE 2001 ÷ 2009

DAΦNE



Design Goal

Crab-Waist
COLLISION SCHEME



- 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

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DAΦNE

MAY 2008

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 SIDDHARTA 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.

KLOE-2 Run with *Crab-Waist*

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 …

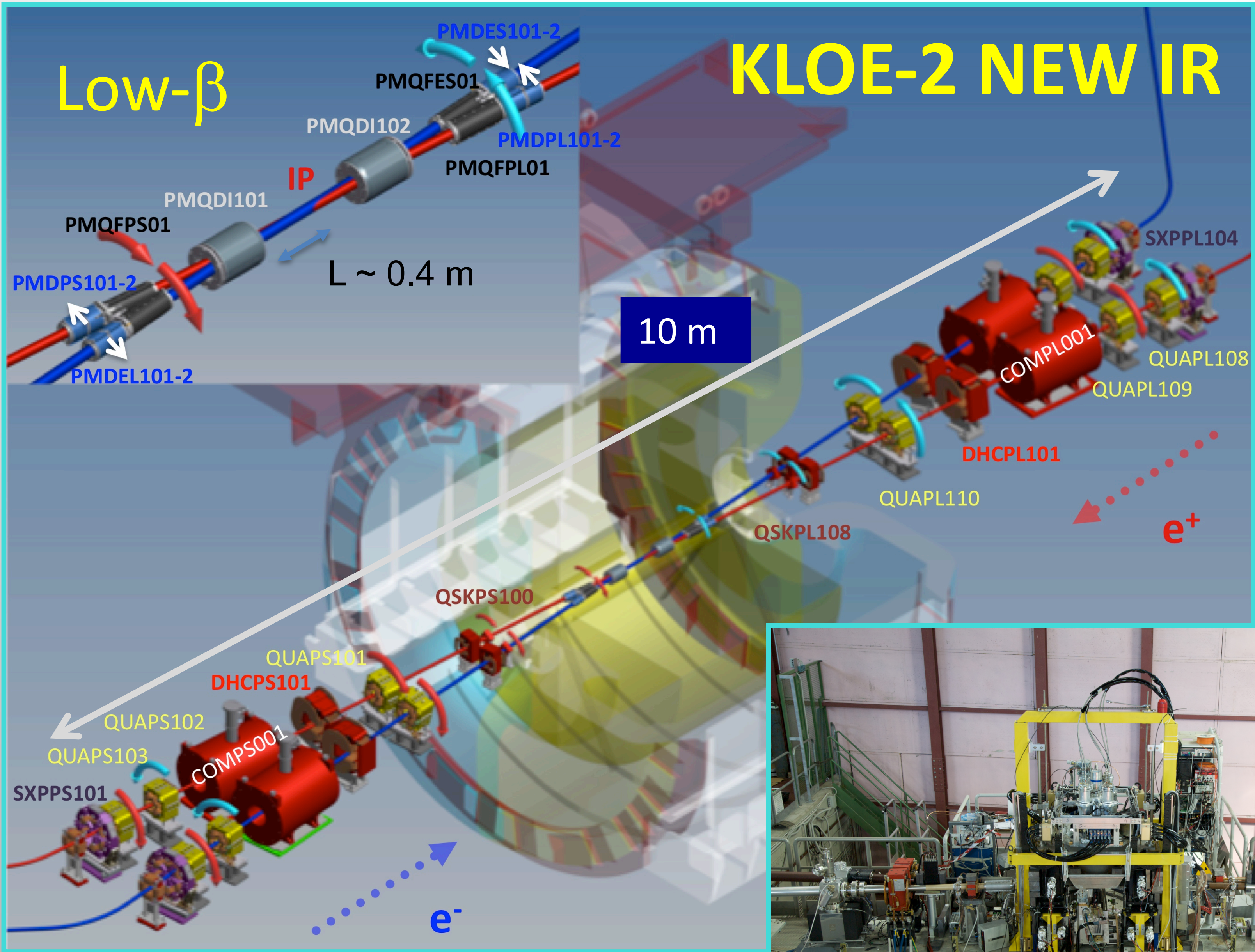
Crucial Points:

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.*

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DAΦNE Activity Program for KLOE-2

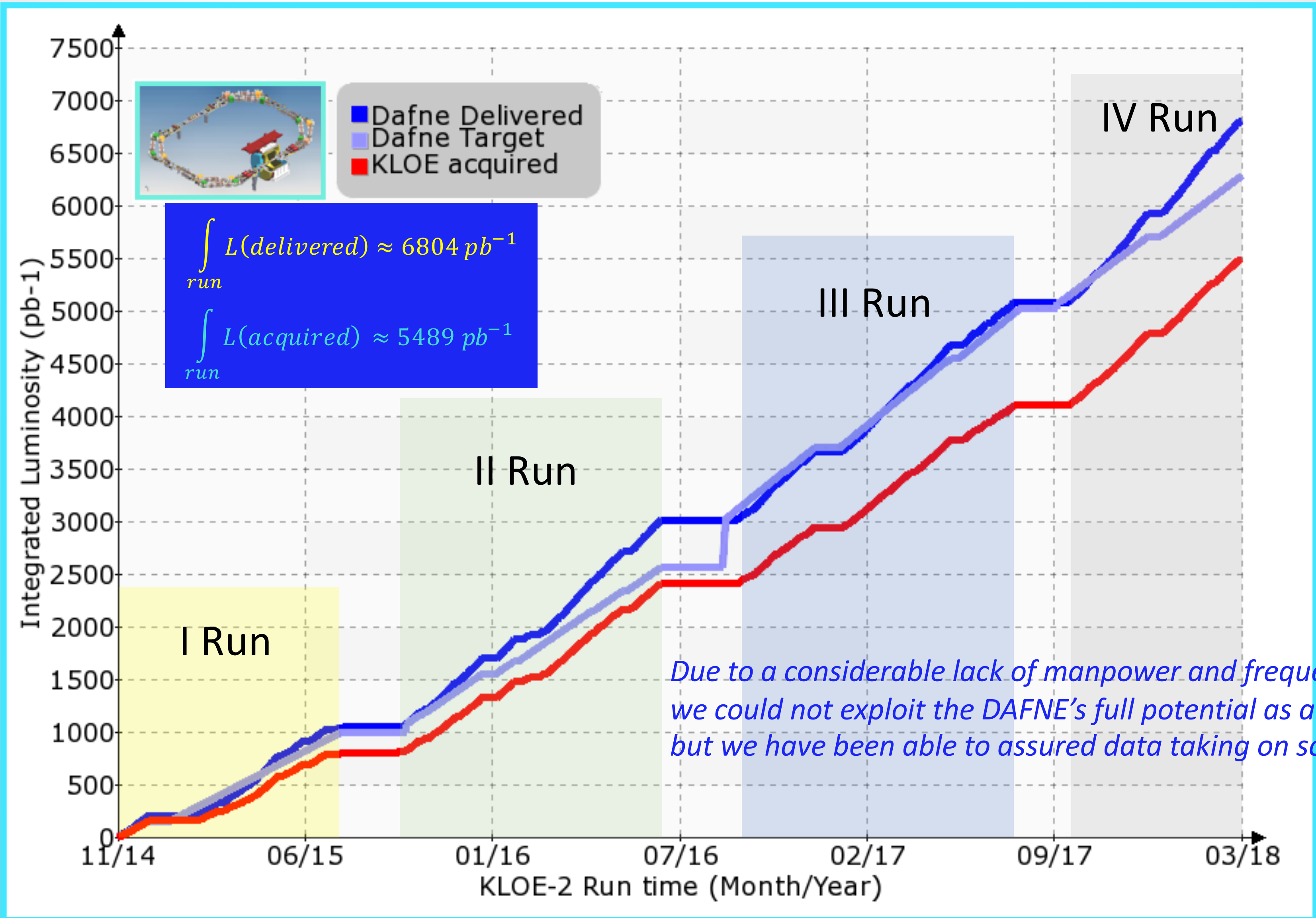
Preliminary Test Phase *fall 2010 ÷ Dec 2012*

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



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

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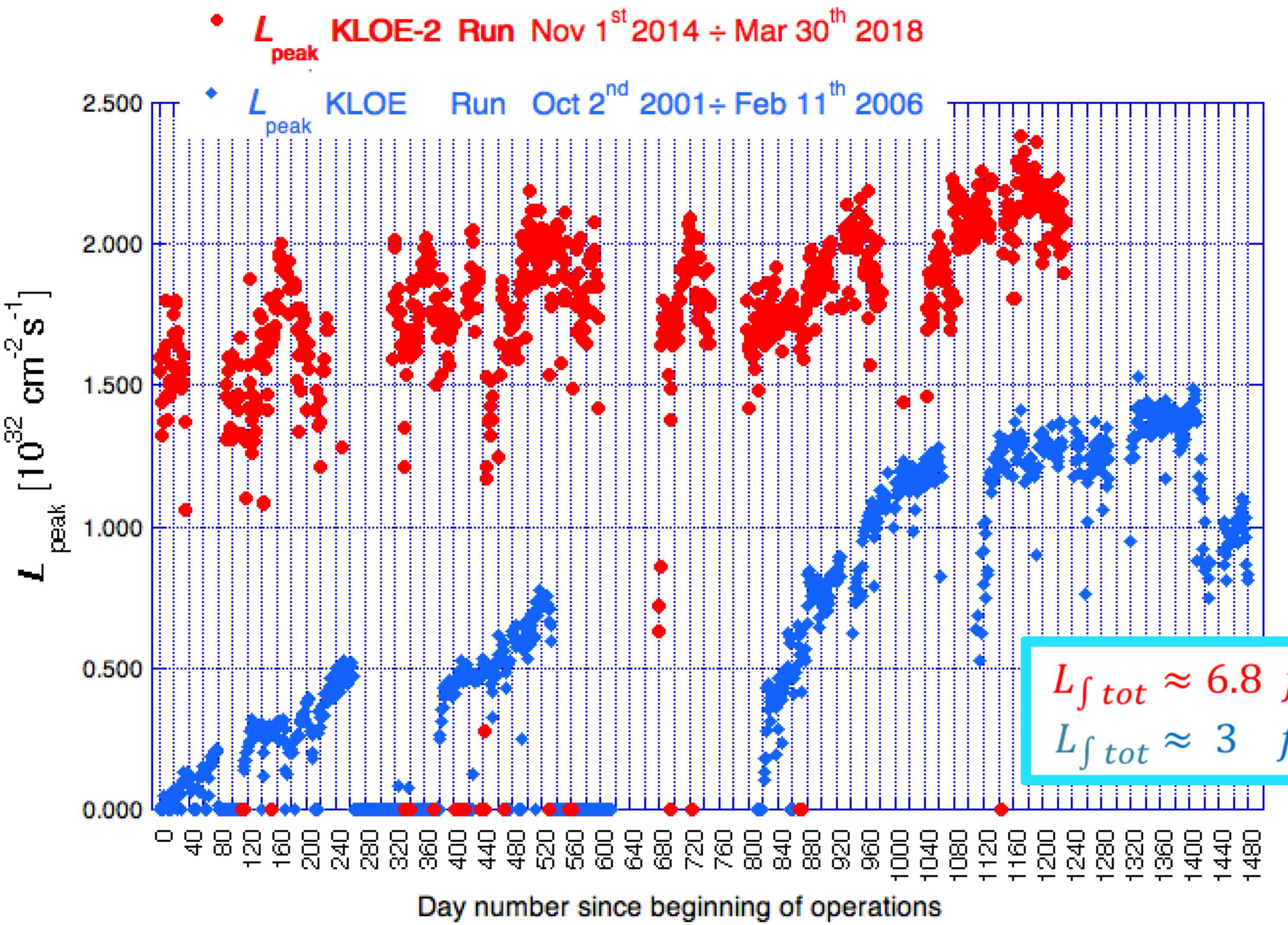
Crab-Waist provides a 59% increase in terms of peak luminosity as evidenced by data taken by the same detector with the same accuracy



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

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

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

SIDDHARTA-2 Run with *Crab-Waist*

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SIDDHARTA-2 Run

Aimed at performing the first-ever measurement of kaonic deuterium X-ray transitions to the fundamental level.

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.

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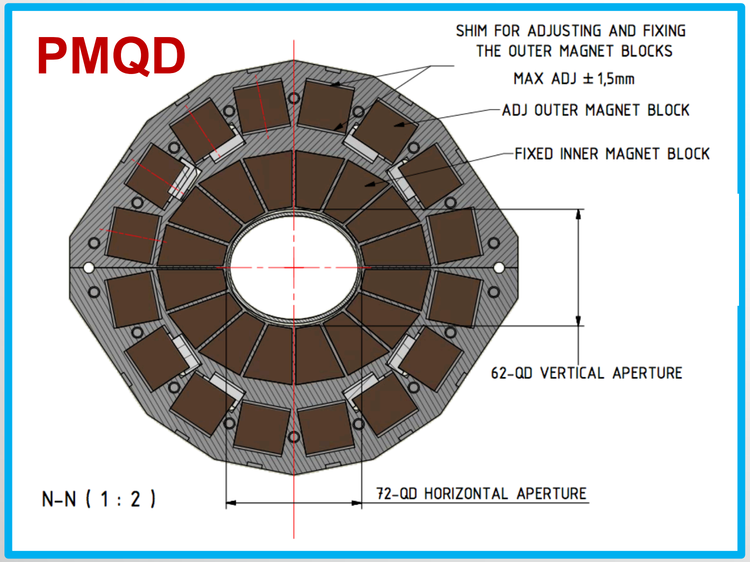
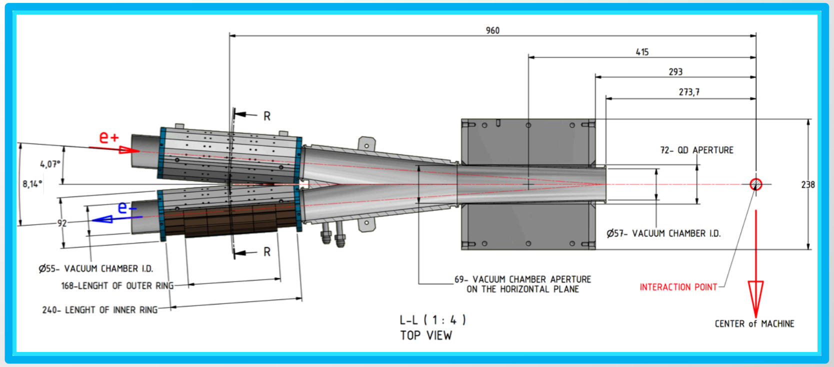
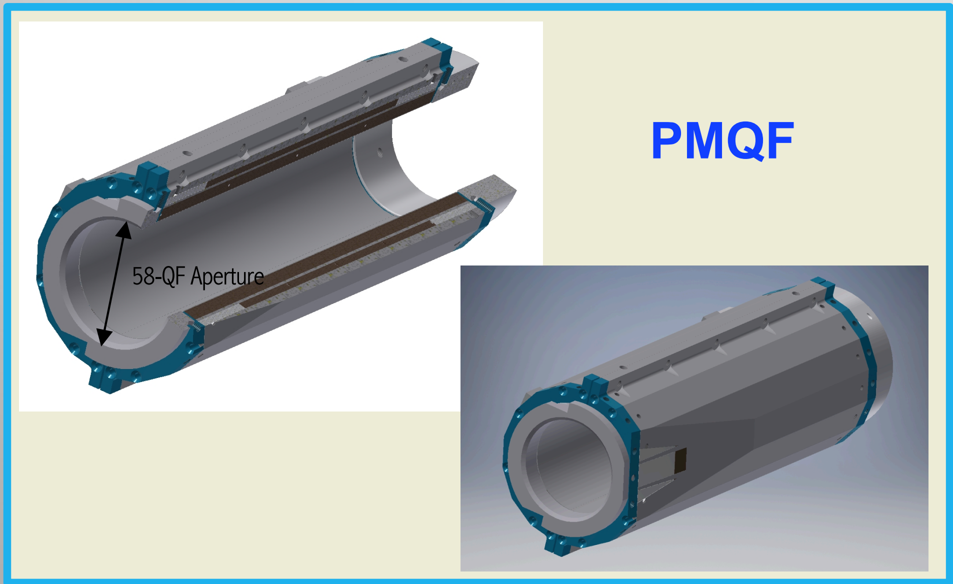
PMQs specifications

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

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SIDDHARTA Run Timeline

Spt – Dec 2019 collider commissioning for SIDDHARTA-2

Mid Jan – March 2020

February – Jul 2021

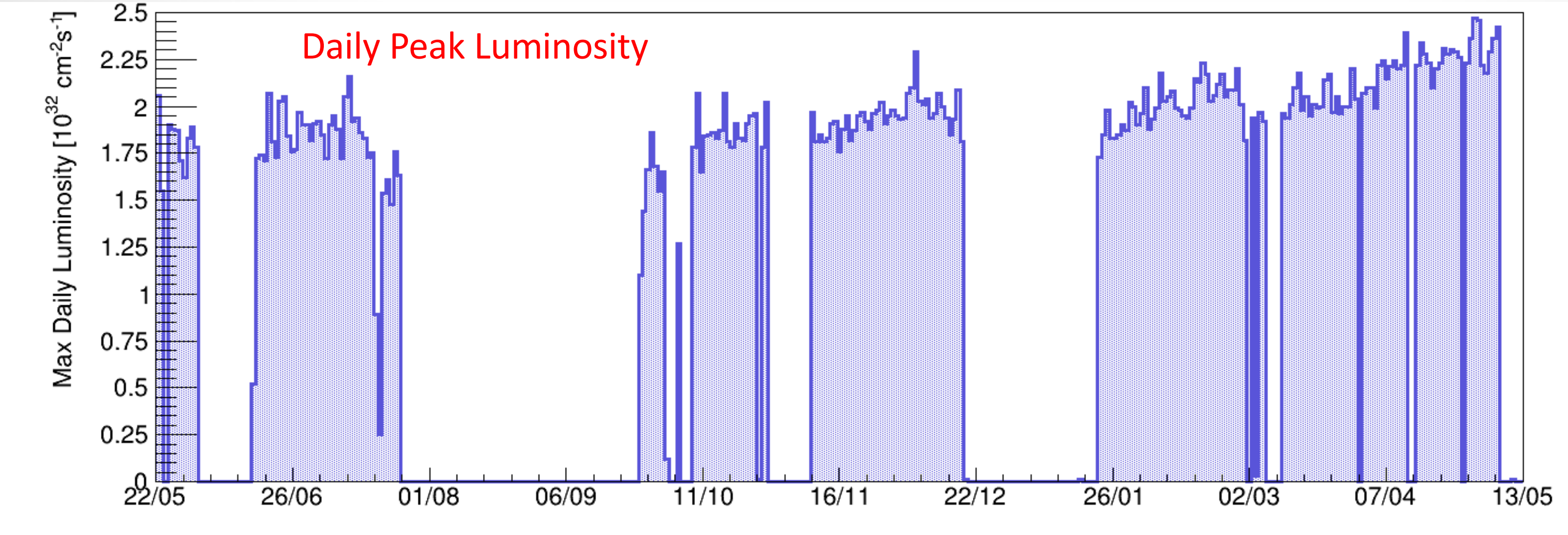
***Apr – Jul 2022 SIDDHARTINO run completed** and preliminary run with Deuterium target*

Apr – Jul 2023

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

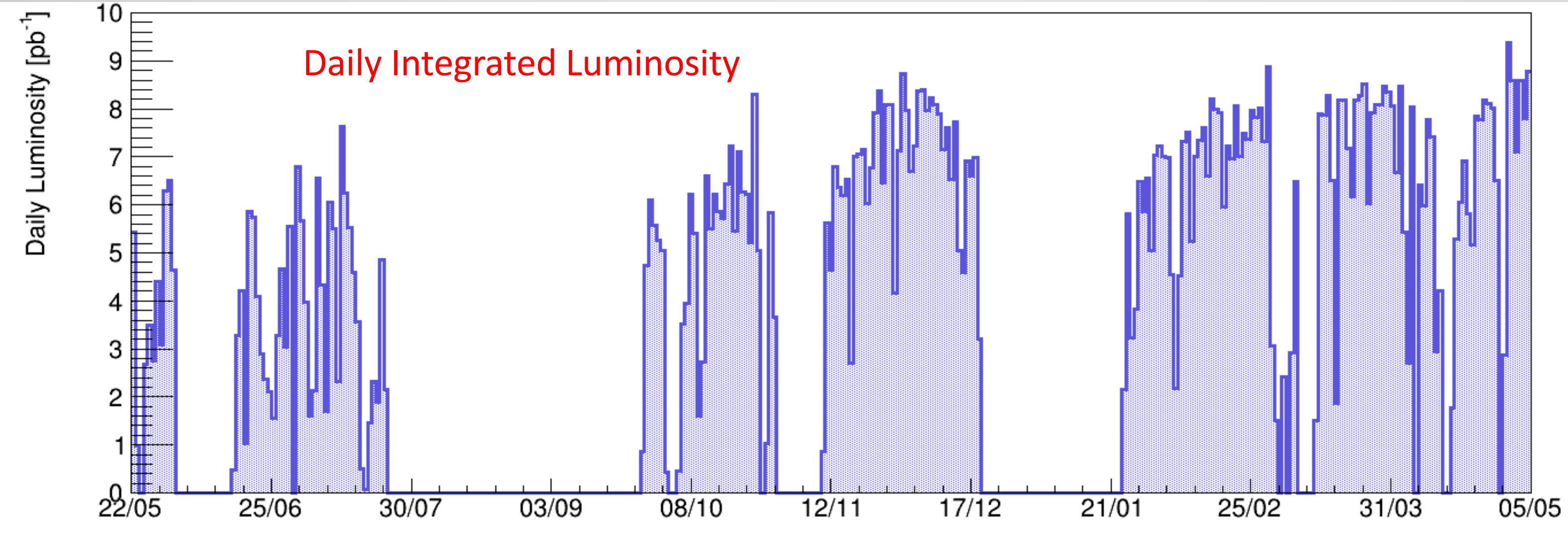
Jan 18h – Jul 2024
Data taking with deuterium target

Luminosity trends



2023

2024

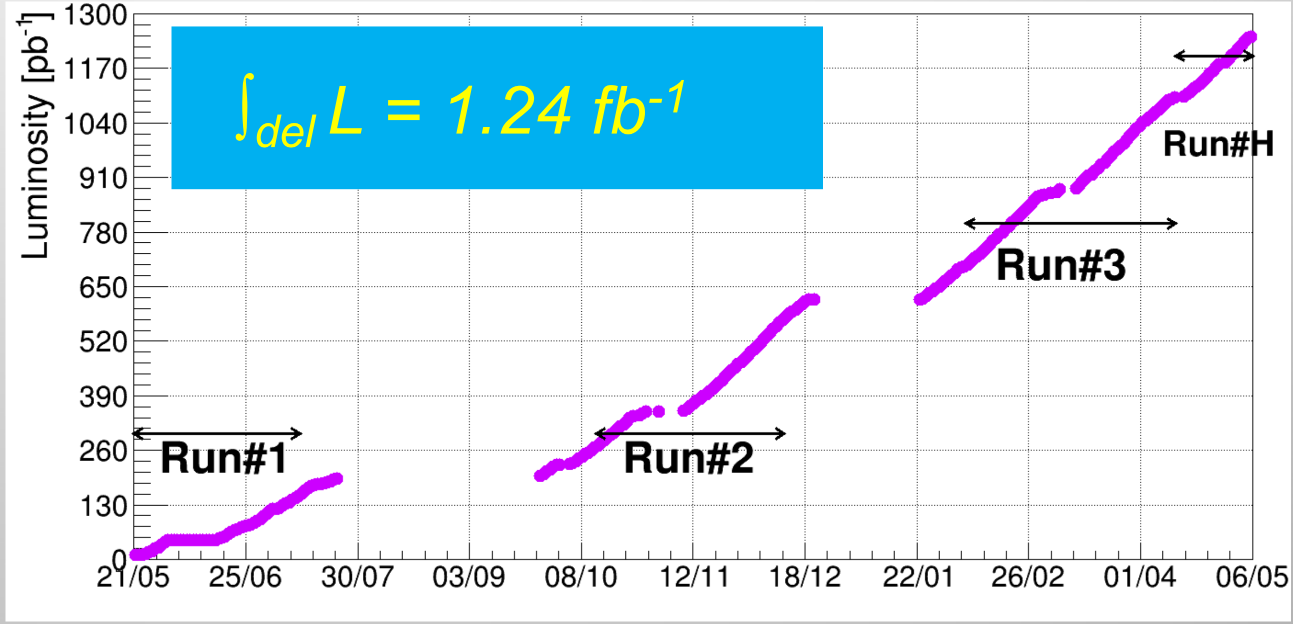


Total Integrated Luminosity

DATE	L_{acq} [pb^{-1}]	L_{acq} [pb^{-1}] $L_{HQ} \geq 0.6$	Good Data %
Run-1 (21/05/23 ÷ 21/07/23)	196	164	84
Run-2 (13/10/23 ÷ 11/12/23)	344	276	80
Run-3 (06/02/24 ÷ 12/04/24)	435	375	86
Run-H for calibration (12/4/24 ÷ 6/5/24)	153	140	91,5
Total	1128	955	85

The fraction of high-quality data increased significantly along the time thank to collider adiabatic tuning, and machine studies.

Signal to noise ratio was 3 times higher wrt the one measured in 2009.
It was evaluated taking into account the acceptance of the new detector components: kaon, trigger, and SDD.



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

DAΦNE Key achievements

- **Impedance budg**et 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.

Beam Currents stored at DAΦNE

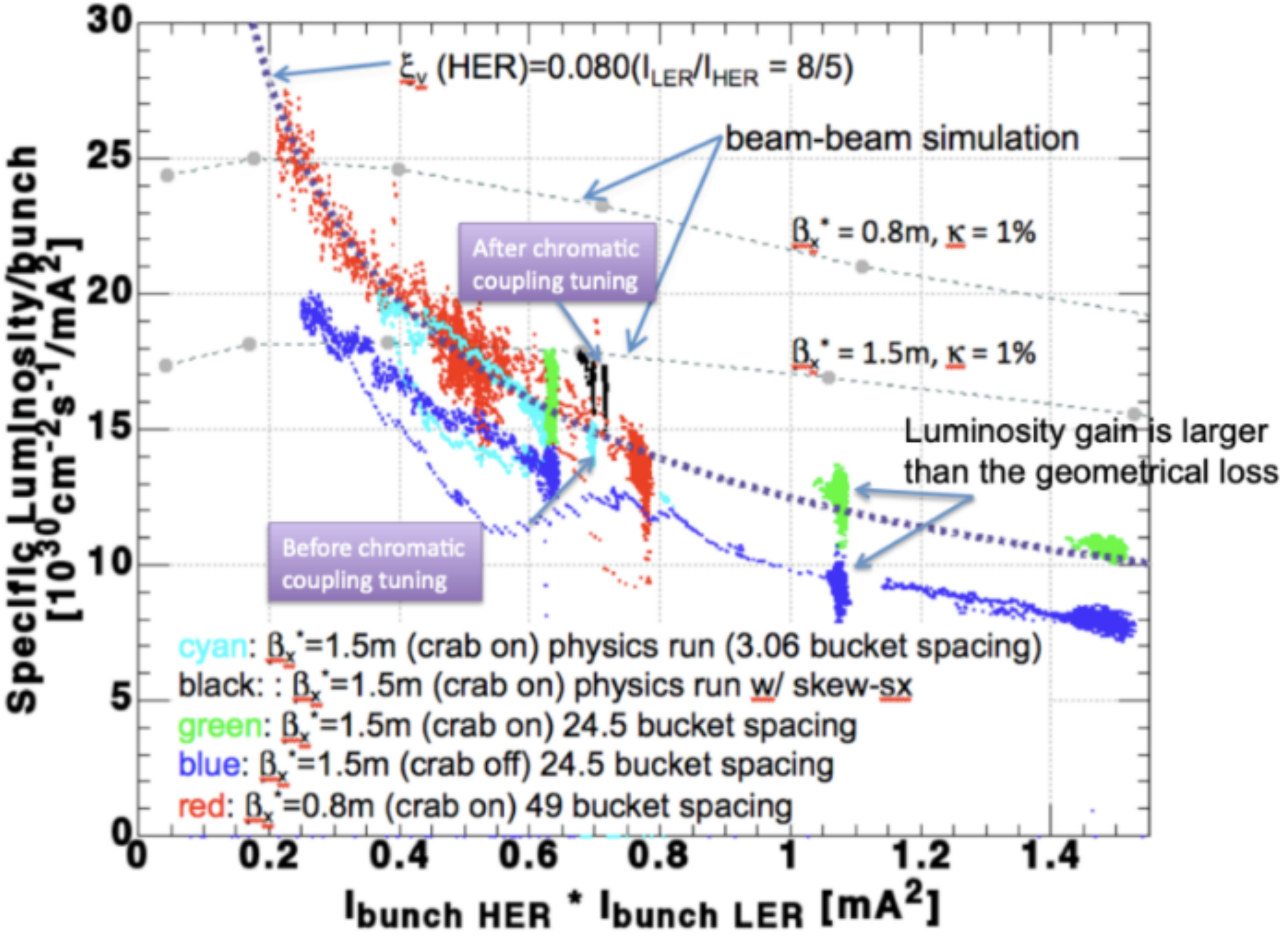
Lepton Beam Currents achieved so far

	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	Super Factory
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	

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

Crab-Waist at SuperKEKB

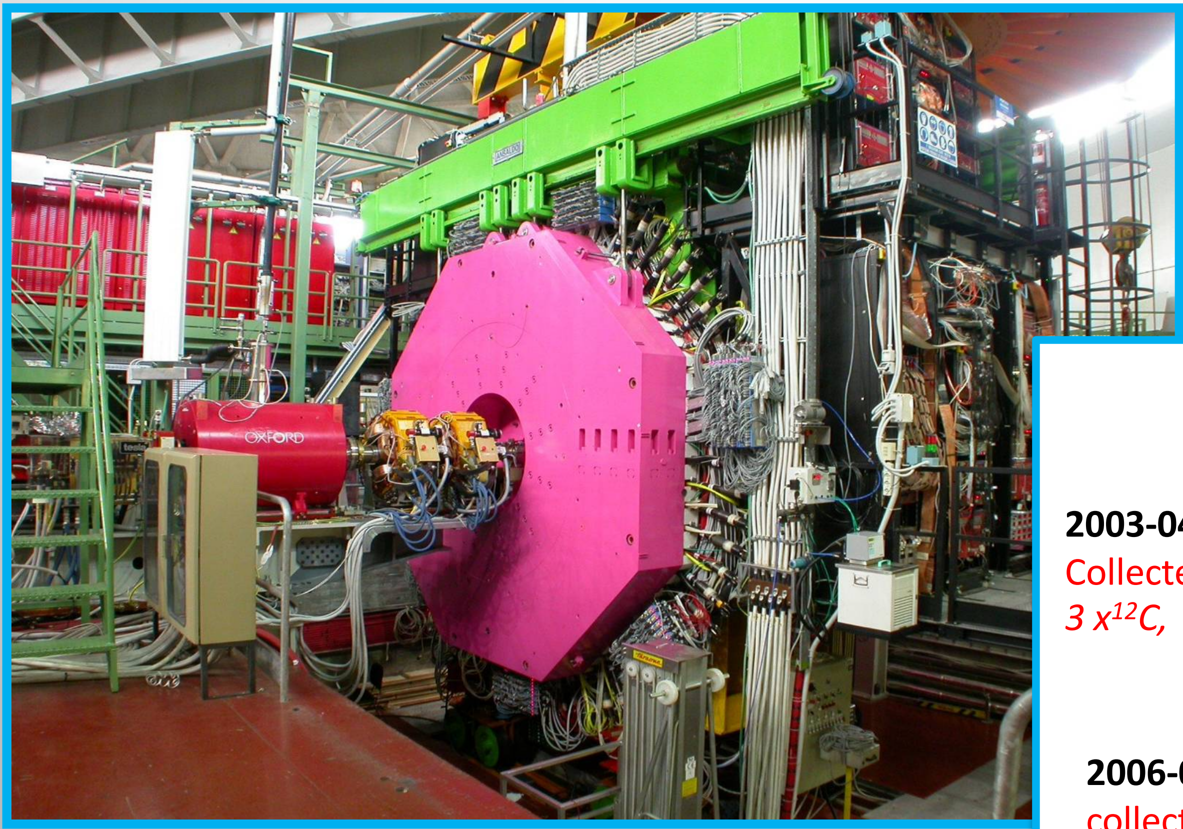


Blue data refer to Crab-Waist OFF

The FINUDA experiment

FINUDA at DAΦNE

FINUDA is a large acceptance, high resolution magnetic spectrometer dedicated to **hypernuclear physics**.



FINDUA data-taking

2003-04 first run

Collected *Luminosity ≈ 220* pb^{-1}

3 x^{12}C*, 2 x*^{6}Li*, 1 x*^{7}Li*, 1 x*^{27}Al*, 1 x*^{51}V *nuclear targets.*

2006-07 second run,

collected *Luminosity of ≈ 966* pb^{-1}

2 x^{6}Li*, 2 x*^{7}Li*, 2 x*^{9}Be*, 1 x*$^{1}3C$*, 1x*D_2O *nuclear targets.*

(Courtesy of P. Gianotti)

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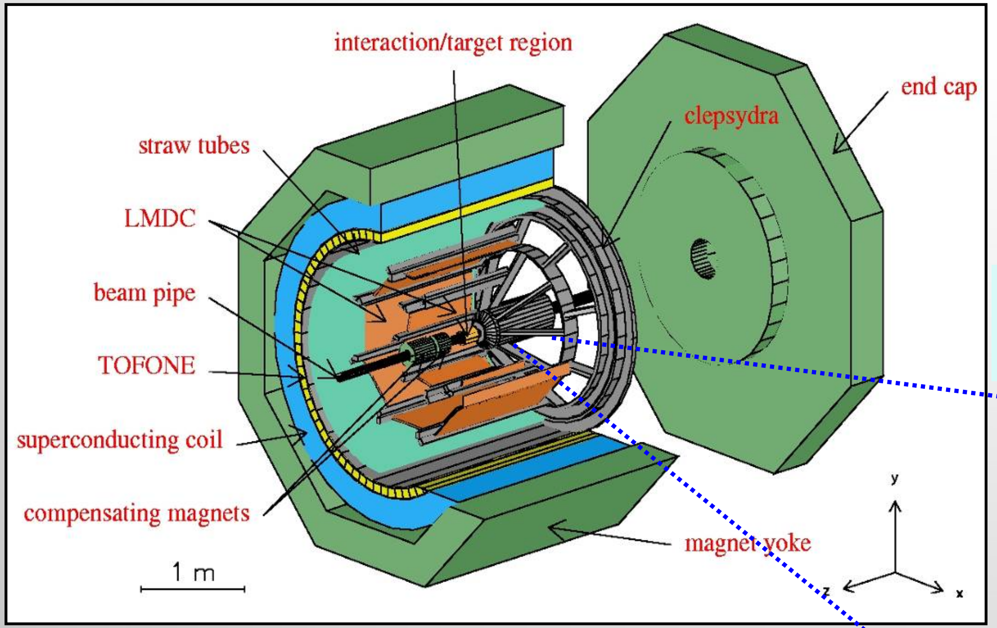
The FINUDA Collaboration

- Bari University and I.N.F.N. Bari
- Brescia University and I.N.F.N. Pavia
- KEK
- L.N.F. / I.N.F.N. Frascati
- Pavia University and I.N.F.N. Pavia
- RIKEN
- Seoul National University
- Teheran Shahid Beheshty University
- Torino University and I.N.F.N. Torino
- Torino Polytechnic and I.N.F.N. Torino
- Trieste University and I.N.F.N. Trieste
- TRIUMF

(Courtesy of P. Gianotti)

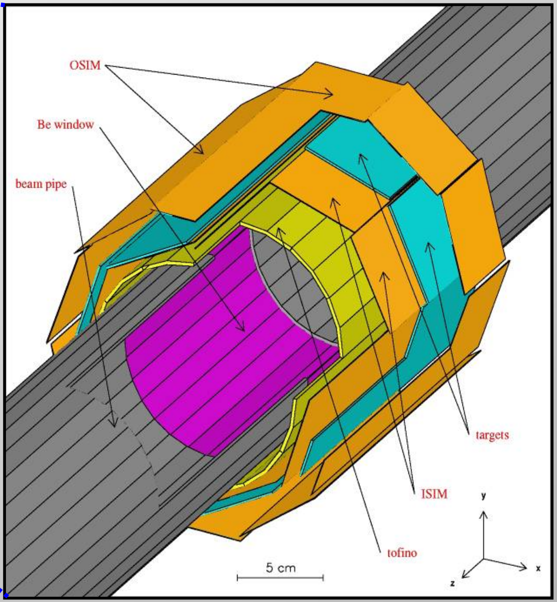
FINUDA Spectrometer



$$e^- + e^+ \rightarrow \phi \rightarrow K^- K^+$$

$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$

Measuring precisely the momentum of this pion you can infer on the hypernuclear level.

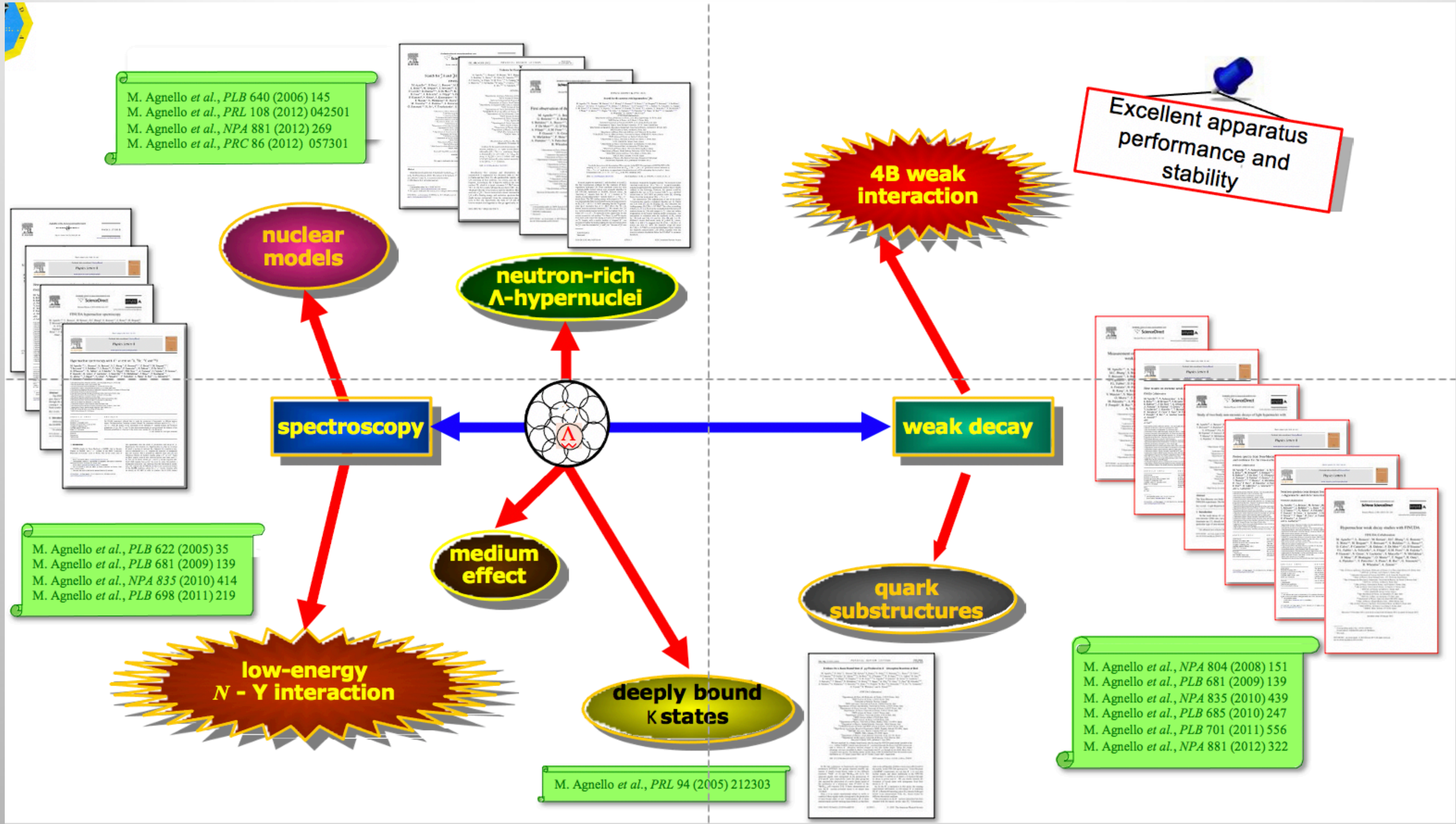


$$ {}^{A}_{\Lambda}Z \rightarrow \begin{cases} {}^{A}(Z+1) + \pi^- \\ {}^{(A-2)}(Z-1) + p + n \\ {}^{(A-2)}Z + n + n \end{cases} $$

Measuring precisely the hypernuclear decay products you can study weak-interaction in the medium.

(Courtesy of P. Gianotti)

FINUDA Physics outcome



(Courtesy of P. Gianotti)

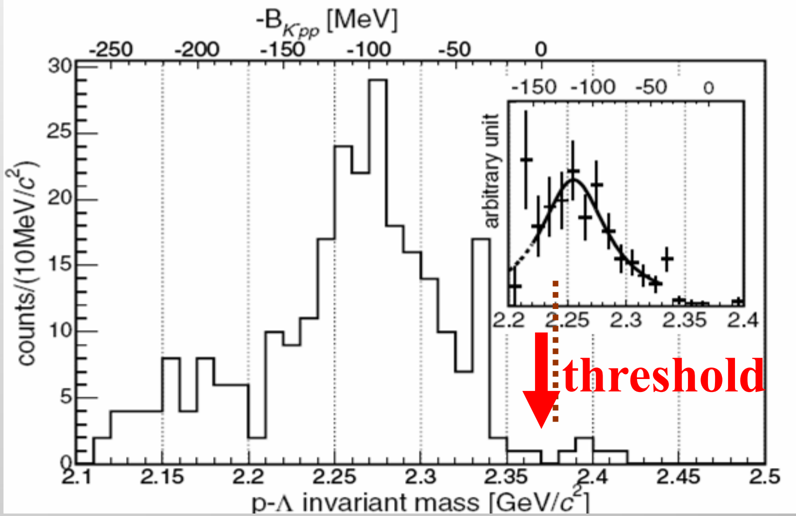
FINUDA Physics outcome

First application of Invariant mass spectroscopy (K^-_{stop}, $pp\pi^-$)

$$K^- \text{"pp"} \rightarrow \Lambda + p$$
$$\Lambda \rightarrow p\,\pi^-$$

$\Rightarrow \Lambda\, p$ inv. Mass.

Step 2: inv. Mass of back-to-back Λ-p events



Invariant mass of a Λ and a proton in back-to-back correlation from light targets before the acceptance correction.
The inset shows the result after the acceptance correction for the events which have two protons with well-defined good tracks.

$$B = 115\,^{+6}_{-5}\,^{+3}_{-4}\ \text{MeV}$$
$$\Gamma = 67\,^{+14}_{-11}\,^{+2}_{-3}\ \text{MeV}$$

M = (2255 ± 9) MeV
Yield ≈ 1%/stopped K-

6 light nuclear targets used: 6Li,7Li,12C

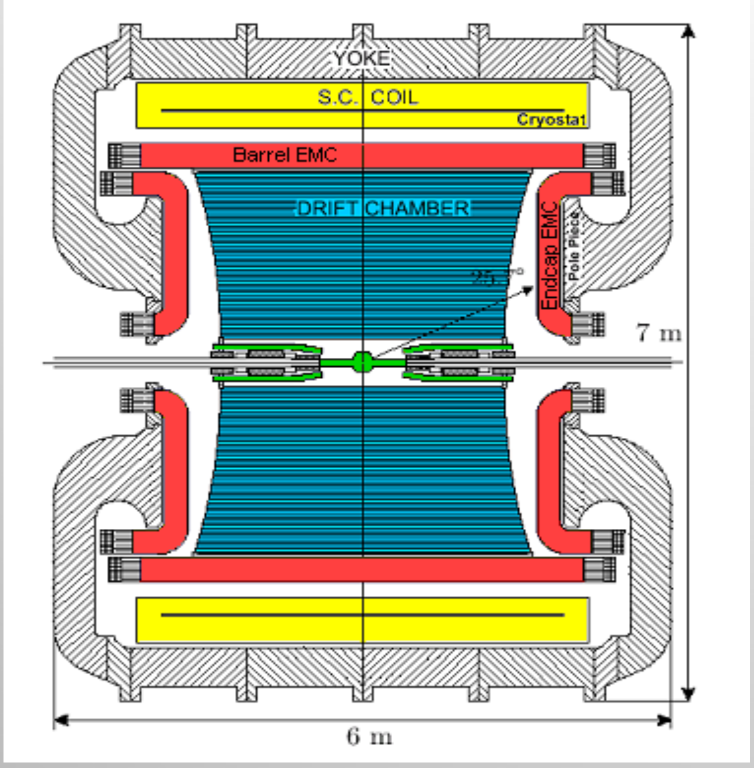
Phys. Rev. Lett. **94** 212303 (3 June 2005)

(Courtesy of P. Gianotti)

The KLOE-KLOE2 experiment

The KLOE detector

The research program of KLOE was aimed at studying discrete symmetries in the production of entangled kaon-pair final states, the spectroscopy of light mesons, the total e+e- annihilation cross section at low energy and the search for phenomena beyond the Standard Model mediated by new interactions.



- **Superconducting coil** $B = 0.52$ T
- **AlBeMet beam pipe** (0.5 mm thick), spherical 10 cm radius
- **ECM calorimeter** Lead/scintillating fibers (1 mm ∅) 4880 PMT's, 15 X_0
- **Drift chamber** (4 m ∅ × 3.3 m) 90% He + 10% IsoB, CF frame, 12582 stereo, single sense wire, "almost squared" cells
- **Quadrupole calorimeter**

	Data Taking period	Int. Luminosity (pb^{-1})
KLOE	2000-2006	2500
KLOE-2	2014-2018	5500

(Courtesy of F. Bossi)

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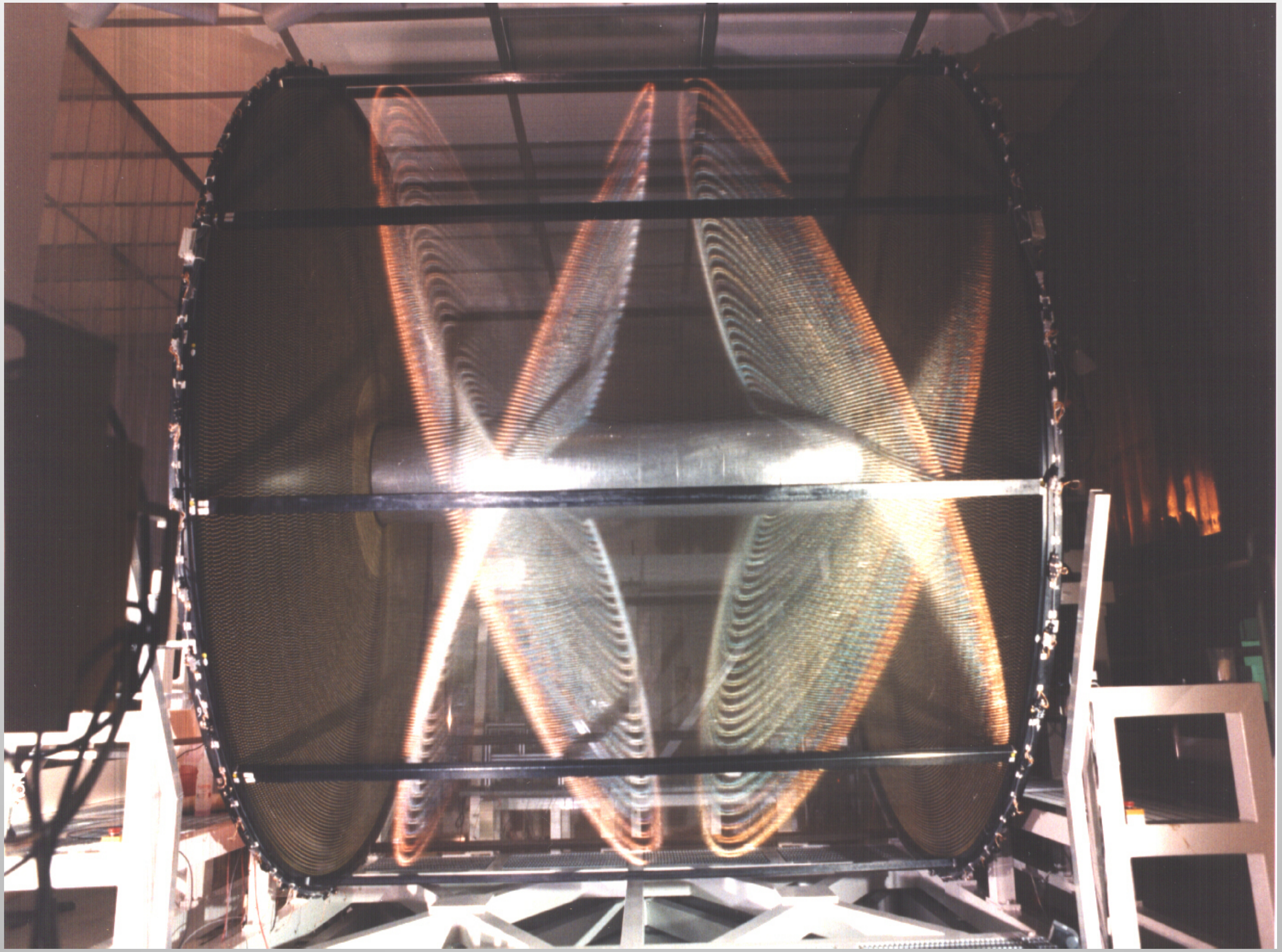
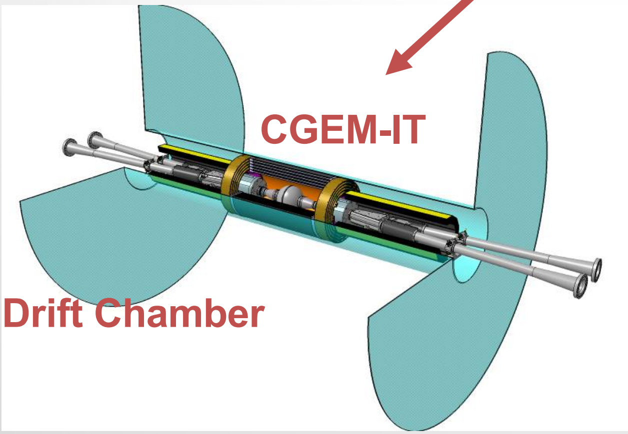
The KLOE Drift Chamber

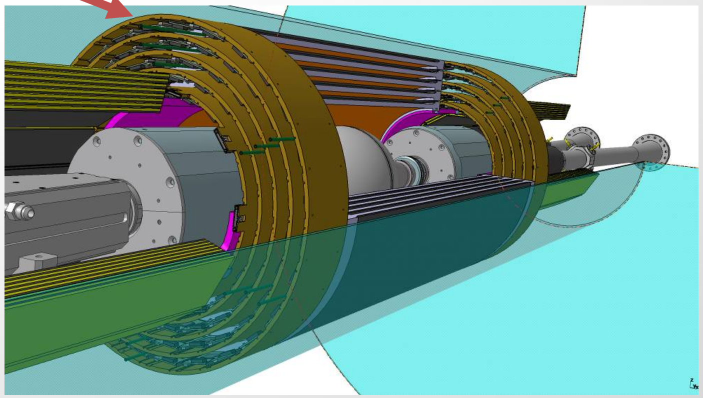


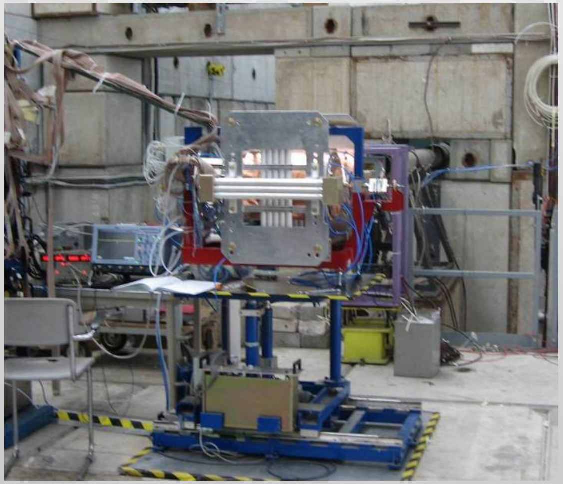
(Courtesy of F. Bossi)

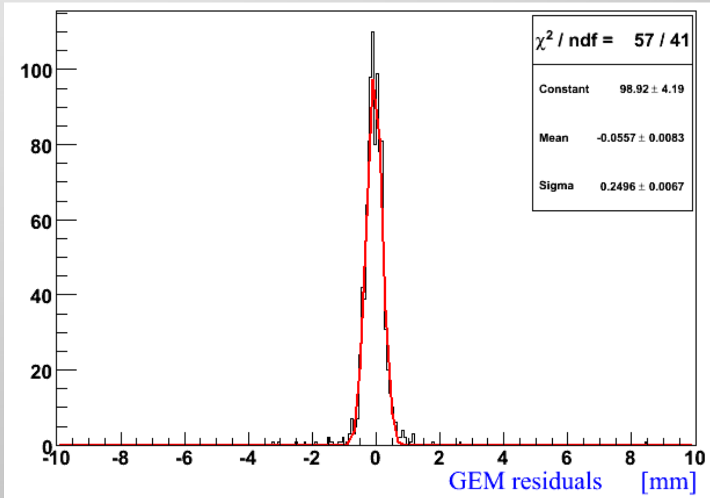
The KLOE-2 Inner Tracker

Four layer detector based on Cylindrical GEM technology









$\sigma(\text{global})^2 = \sigma(\text{GEM})^2 + \sigma(\text{tracker})^2$

$\sigma(\text{GEM}) = \sqrt{(250\mu m)^2 - (140\mu m)^2} \sim 200\mu m$

(Courtesy of F. Bossi)

The KLOE detector

(Courtesy of F. Bossi)

KLOE Physics Achievements

Despite the c.m. energy of DAFNE is low as compared to the present day frontier accelerators (LHC), still the KLOE physics program was very rich, it was in fact at the very core of some *fundamental physics* issues.

KLOE contributed to the progress in the field with several outstanding achievements:

- **high precision measurement of V_{us}** setting the best unitarity limit on the CKM matrix;
- a very precise determination of the **hadronic contribution to the g-2 of the muon**;
- set the best limit on **LFV in K_{e2} decays**;
- set some of the best limits on **discrete symmetries violation** in particle physics;
- measured some of the **rarest branching ratios** of the K_s and η mesons;
- provided a suitable environment for experimental studies about **neutral kaon entanglement**

(Courtesy of F. Bossi)

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KLOE / KLOE-2 publications

(March 2018)

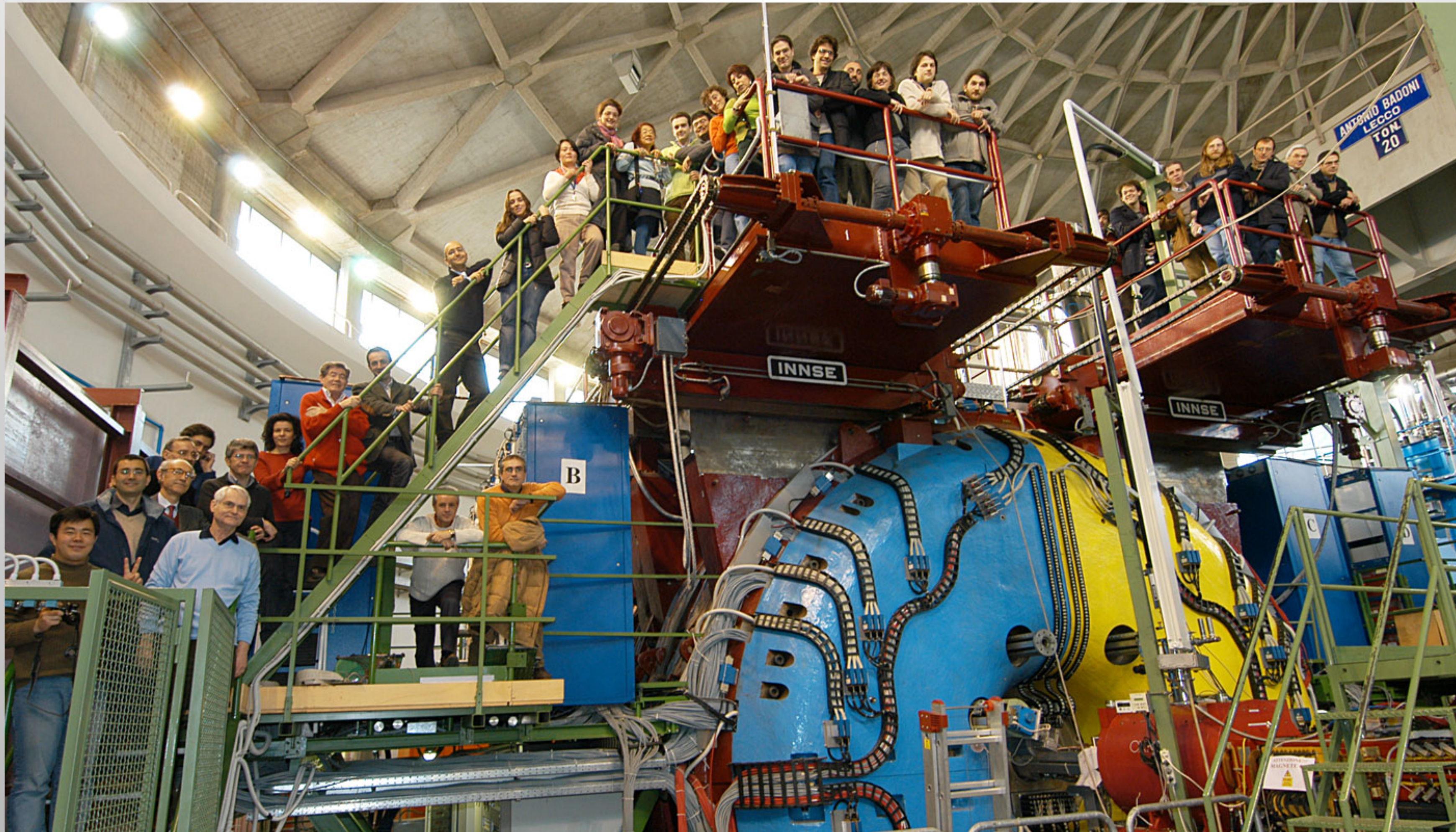
KLOE-KLOE-2 have published about 100 papers in international journals, some of the most cited ones are listed below:

- *A. Aloisio et al., Phys.Lett.B 537 (2002) 21-27 hep-ex 020413*
- *A. Aloisio et al., Phys.Lett.B 606 (2005) 12-24 hep-ex 0407048*
- *F. Ambrosino et al. Phys.Lett.B 632 (2006) 43-50 hep-ex 0508027*
- *F. Amrosino et al., Phys.Lett.B 636 (2006) 173-182 hep-ex 0601026*
- *F. Ambrosino et al., Phys.Lett.B 670 (2009) 285-291 hep-ex 0809.3950*
- *F. Ambrosino et al., JHEP 07 (2009) 105 hep-ex 0906.3819*
- *D. Babusci et al., Phys.Lett.B 720 (2013) 336-343 hep-ex 1210-3927*
- *A. Anastasi et al., JHEP 03 (2018) 173 hep-ex 1711.03085*

(Courtesy of F. Bossi)

KLOE-2 end run

(March 2018)

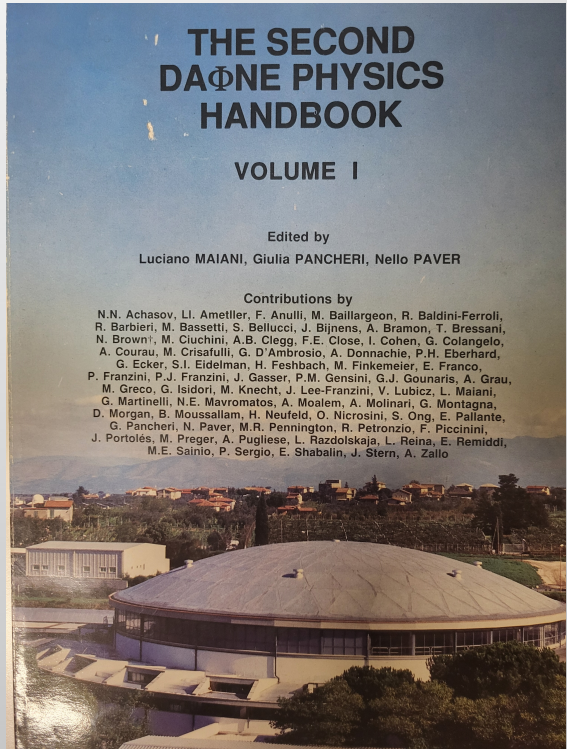


(Courtesy of F. Bossi)

Theoretical Activity

DAΦNE has also promoted an intense theoretical activity, focused on the main topics of interest for the various experiments, and organized in large pan-european networks like **EuroDAFNE** and **Euridice.**

Among the many products of this activity it is worth mentioning the release of the first and the second **DAΦNE Physics Handbook**, a real «bible» for the experimentalists along the years.



(Courtesy of F. Bossi)

Kaonic Atoms

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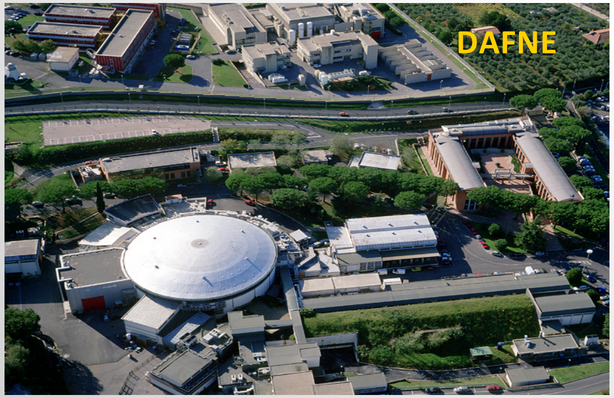
Laboratori Nazionali di Frascati

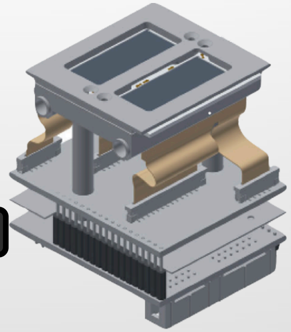
Kaonic Atoms at DAΦNE



The modern era of light kaonic atom experiments
Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

Rev. Mod. Phys. **91**, 025006 – Published 20 June 2019

1 cm² x 144 SDDs

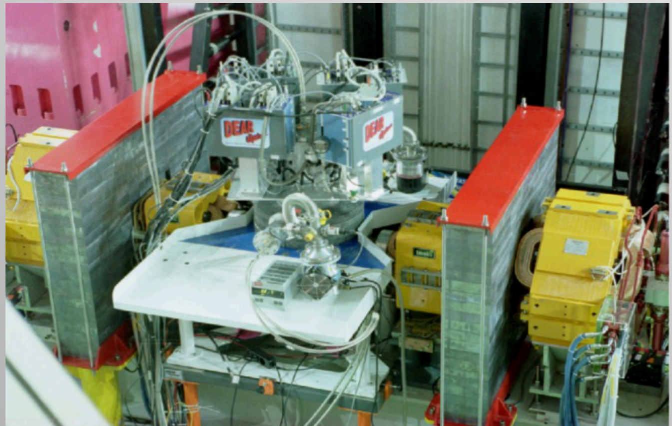


SDD detectors used for the first time for spectroscopy in a collider experimental setup

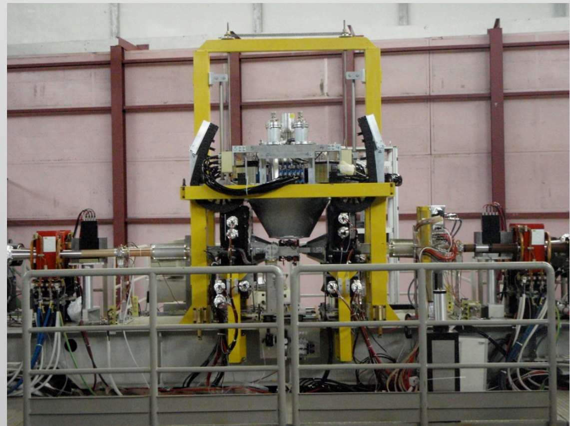
HadronPhysics I3 — Study of Strongly Interacting Matter

HadronPhysics2 — Study of Strongly Interacting Matter

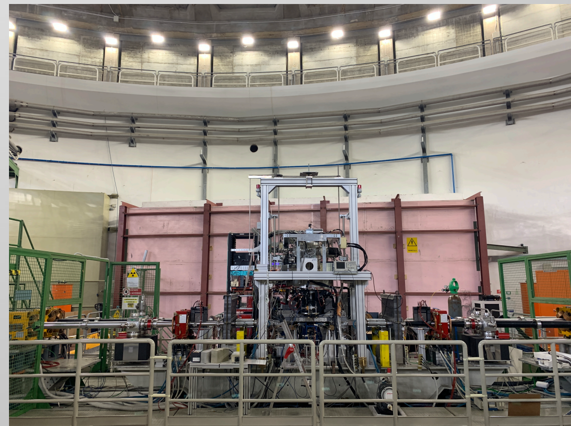
DEAR 2002



SIDDHARTA 2009



SIDDHARTA-2 2022



(Courtesy of C. Curceanu)

Kaonic Atoms X-ray Spectroscopy

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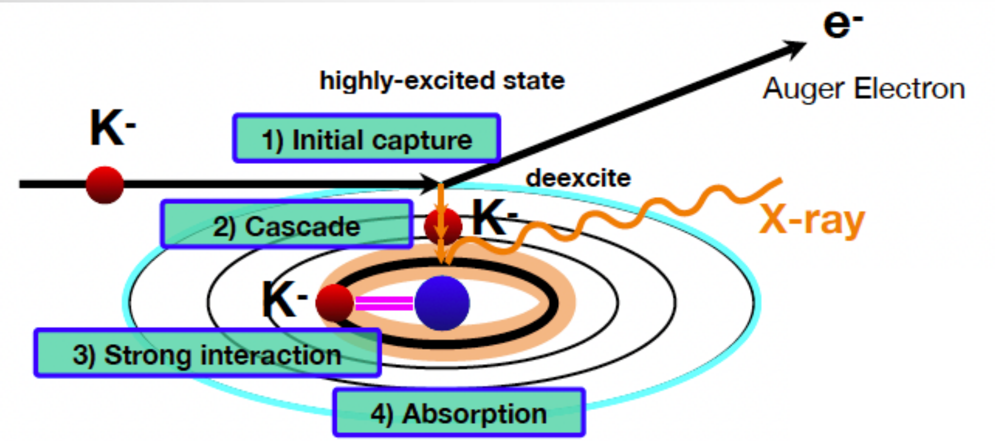
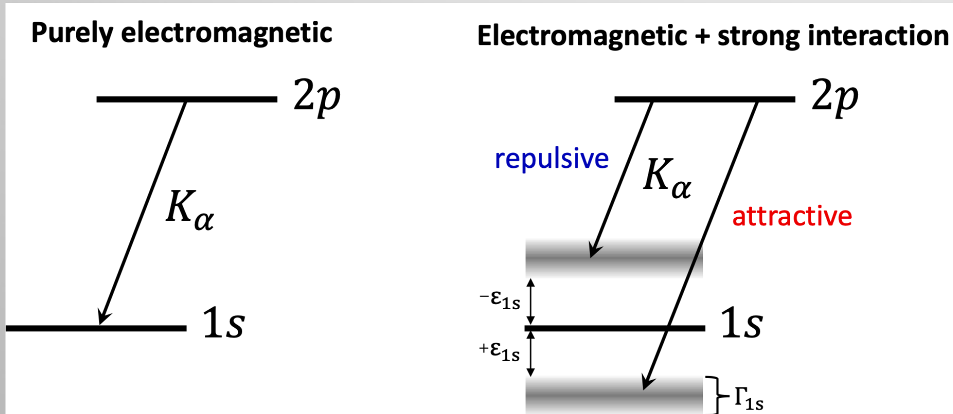
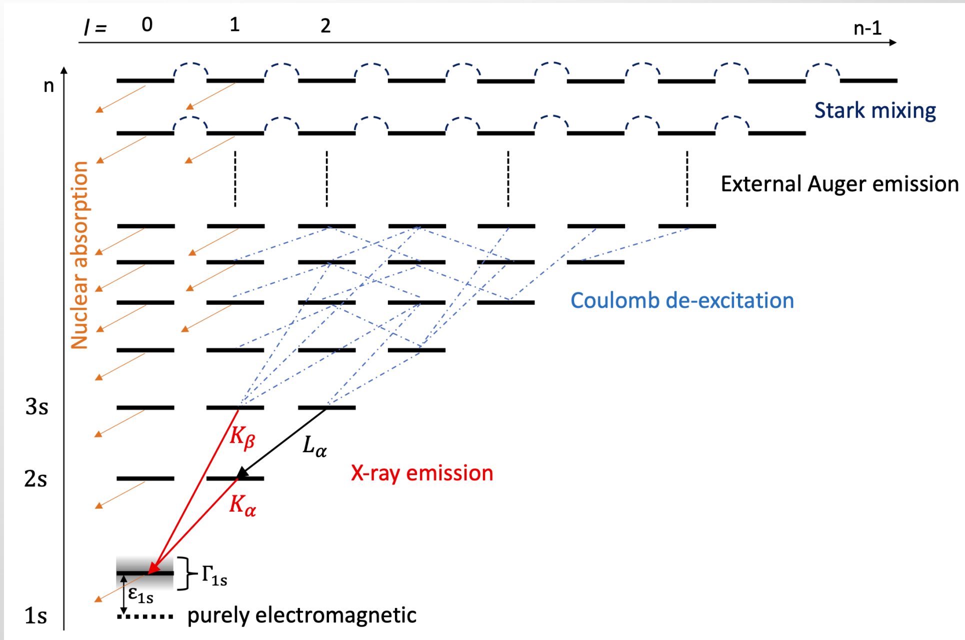
n ~ sqrt(M/me) n' ~ 25 (for K-p)*
(*M** : K-p reduced mass)





$$\varepsilon_{1s} = E^{2p-1s}_{\text{meas}} - E^{2p-1s}_{e.m.}$$



Key observables:
Shift (ε), **Width** (Γ)
and **X-ray Yield**

(Courtesy of C. Curceanu)

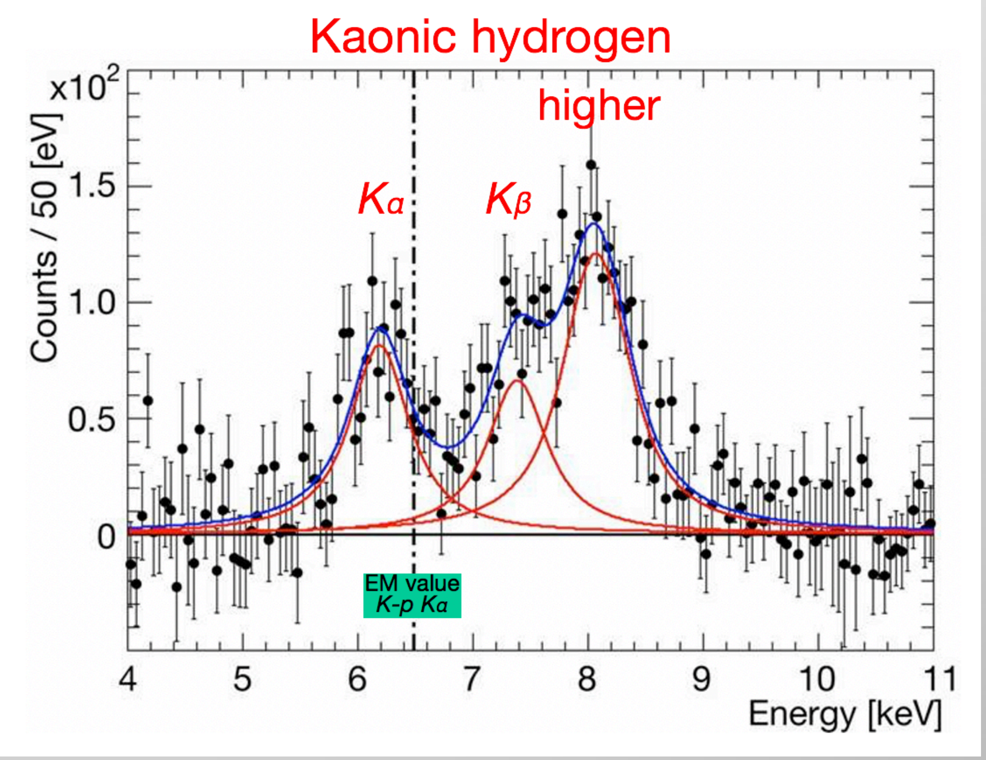
SIDDHARTA Physics outcome

SIDDHARTA measurement of the **Kaonic hydrogen spectrum** is the **most precise in the world**

ε_{1S}= −283 ± 36(stat) ± 6(syst) eV

Γ_{1S}= 541 ± 89(stat) ± 22(syst) eV

>400 citations



Phys. Lett. B 704 (2011) 113

(Courtesy of C. Curceanu)

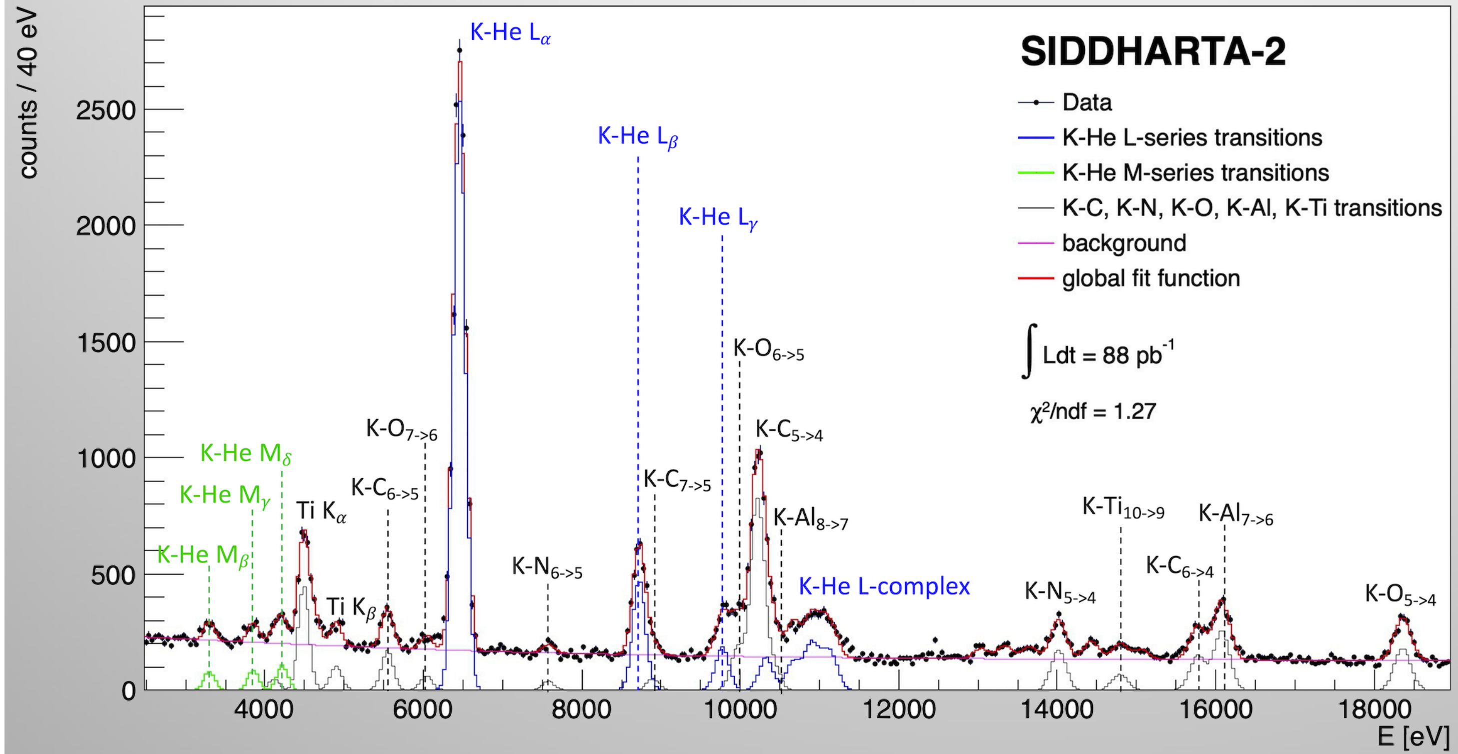
SIDDHARTA Physics outcome

The Kaonic ^{4}He measurement (2021-2022)

- Most precise measurement of kaonic helium-4 Lα in gas: 2p level energy shift and width
- First observation of kaonic helium-4 M-series transition (n→3d)
- First Measurement of high-n transition in kaonic carbon – nitrogen – oxygen and aluminium

$$\varepsilon_{2p} = E^{exp}_{3d\to 2p} - E^{e.m}_{3d\to 2p} = -1.9 \pm 0.8\,(\text{stat}) \pm 2.0\,(\text{sys})\ \text{eV}$$
$$\Gamma_{2p} = 0.01 \pm 1.60\,(\text{stat}) \pm 0.36\,(\text{sys})\ \text{eV}$$

→ no sharp effect of the strong interaction on the 2p level



new data to enrich the kaonic atoms transitions database

Transition	Energy [eV]
K^-C (6→5)	5546.0 ± 5.4 (stat) ± 2.0 (syst)
K^-C (7→5)	8890.0 ± 13.0 (stat) ± 2.0 (syst)
K^-C (5→4)	10216.6 ± 1.8 (stat) ± 3.0 (syst)
K^-C (6→4)	15760.3 ± 4.7 (stat) ± 12.0 (syst)
K^-O (7→6)	6014.8 ± 8.4 (stat) ± 2.0 (syst)
K^-O (6→5)	9965.1 ± 6.9 (stat) ± 2.0 (syst)
K^-O (5→4)	18361.1 ± 5.4 (stat) ± 12.0 (syst)
K^-N (6→5)	7581.1 ± 16.0 (stat) ± 2.0 (syst)
K^-N (5→4)	14008.0 ± 6.0 (stat) ± 9.0 (syst)
K^-Al (8→7)	10441.0 ± 8.5 (stat) ± 3.0 (syst)
K^-Al (7→6)	16083.4 ± 3.8 (stat) ± 12.0 (syst)
K^-Ti (10→9)	14790.3 ± 16.6 (stat) ± 9.0 (syst)

Sgaramella F., et al., 2023, Eur. Phys. J. A, 59 (3) 56

(Courtesy of C. Curceanu)

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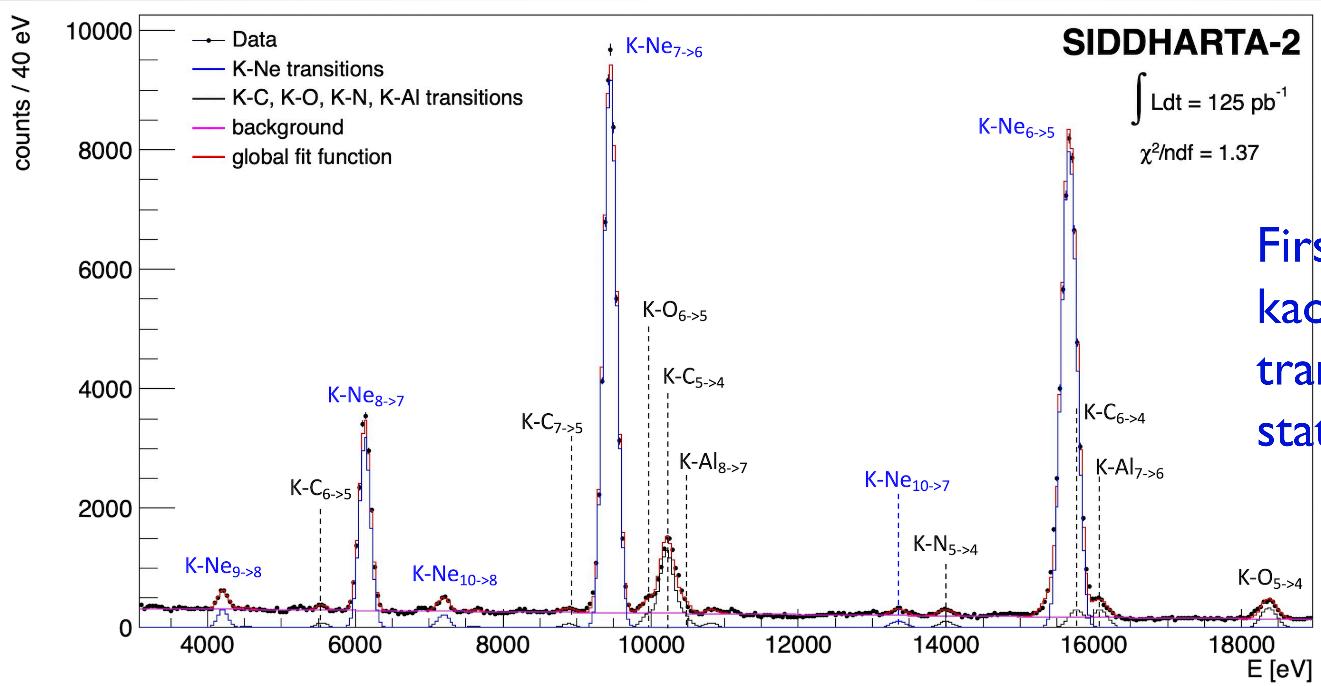
SIDDHARTA-2 Physics outcome

The Kaonic Neon measurement (2023)



First measurement of kaonic neon X-ray transitions (sub eV statistical accuracy)

Transition	Energy [eV]
K-Ne $(9 \to 8)$	4206.35 ± 3.75 (stat) ± 2.00 (syst) eV
K-Ne $(8 \to 7)$	6130.86 ± 0.71 (stat) ± 1.50 (syst) eV
K-Ne $(10 \to 8)$	7191.21 ± 4.91 (stat) ± 2.00 (syst) eV
K-Ne $(7 \to 6)$	9450.08 ± 0.41 (stat) ± 1.50 (syst) eV
K-Ne $(10 \to 7)$	13352.20 ± 10.07 (stat) ± 3.00 (syst) eV
K-Ne $(6 \to 5)$	15673.30 ± 0.52 (stat) ± 9.00 (syst) eV

Article in preparation

(Courtesy of C. Curceanu)

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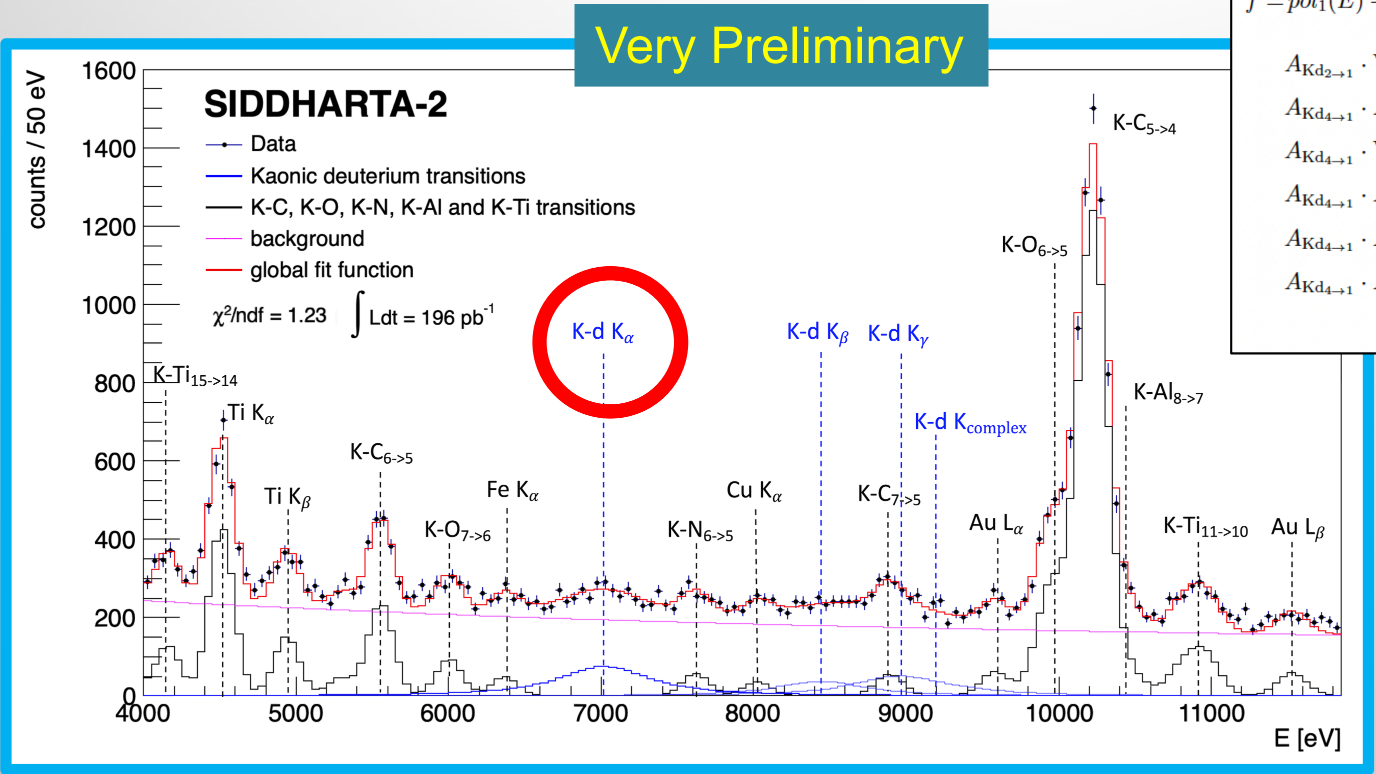
SIDDHARTA-2 latest result

The first kaonic deuterium measurement



$$f = pol_1(E) + \exp(E) + \sum_i \mathrm{Gauss}(A_{Gi}, E_i, \sigma) + \mathrm{Tail}(A_{Ti}, E_i, \beta, \sigma) +$$
$$A_{\mathrm{Kd}_{2\to1}} \cdot \mathrm{Voigt}(E_{2\to1}, \sigma, \Gamma_{1s}) +$$
$$A_{\mathrm{Kd}_{4\to1}} \cdot A_{rel_{3\to1}} \cdot \mathrm{Voigt}(E^{e.m.}_{3\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\mathrm{Kd}_{4\to1}} \cdot \mathrm{Voigt}(E^{e.m.}_{4\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\mathrm{Kd}_{4\to1}} \cdot A_{rel_{5\to1}} \cdot \mathrm{Voigt}(E^{e.m.}_{5\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\mathrm{Kd}_{4\to1}} \cdot A_{rel_{6\to1}} \cdot \mathrm{Voigt}(E^{e.m.}_{6\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\mathrm{Kd}_{4\to1}} \cdot A_{rel_{7\to1}} \cdot \mathrm{Voigt}(E^{e.m.}_{7\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s})$$

"The **most important experiment to be carried out in low energy K-meson physics today** is the **definitive determination of the energy level shifts in the K−p and K−d atoms**, because of their direct connection with the physics of $\overline{K}N$ interaction and their complete independence from all other kinds of measurements which bear on this interaction".

R.H. Dalitz (1982)

$$\varepsilon_{1s} = E^{meas}_{2p\to1s} - E^{e.m.}_{2p\to1s} = -816 \pm 53\ (\mathrm{stat}) \pm 2\ (\mathrm{syst})\ \mathrm{eV}$$
$$\Gamma_{1s} = 756 \pm 271\ (\mathrm{stat})\ \mathrm{eV}$$

(Courtesy of C. Curceanu)

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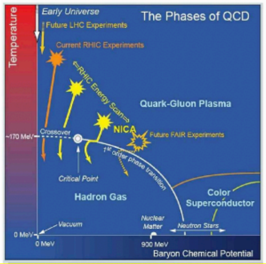
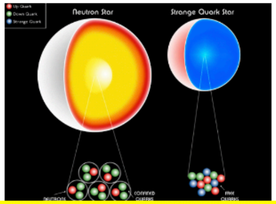
SIDDHARTA Physics

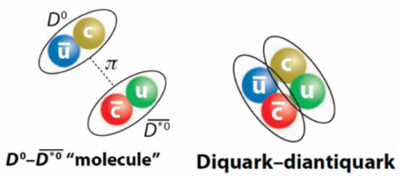
About 100 papers published



Cold Dense matter

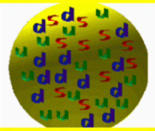


Neutron star EOS



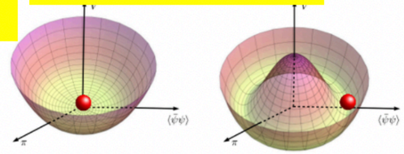
Particles structure

Strangeness Fundamental Physics

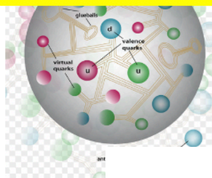


Strangelets & Dark Matter

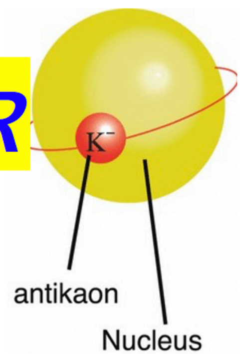
QCD
Chiral symm.



Mass generation, visible Universe



EXKALIBUR



EXtensive Kaonic Atoms research:
from LIthium and Beryllium to Uranium

(Courtesy of C. Curceanu)

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DAΦNE-Light

DAΦNE-Light is a **Material Science Laboratory** using **synchrotron radiation** but also **conventional sources.**

Beamlines @ DAΦNE

Building 12

1) **SINBAD - IR beamline (1.24 MeV - 1.24 eV)**

2) **DXR1- Soft X-ray beamline (900-3000 eV)**

3) **DXR2 - UV-VIS beamline (2-10 eV)**

Building 13

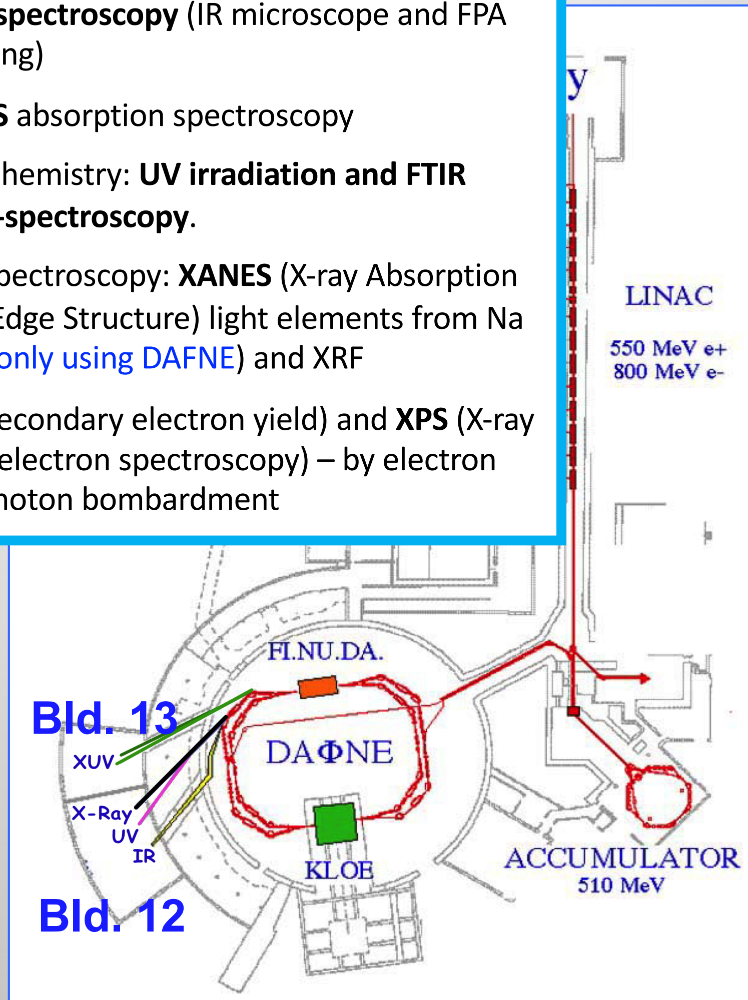
4) **XUV1 - Low Energy Beamline (30-200 eV)**

5) **XUV2 - High Energy Beamline (60-1000 eV)**

6) **WINDY - White beam XUV2 branch line**

Available techniques

- **FTIR spectroscopy** (IR microscope and FPA imaging)
- **UV-VIS** absorption spectroscopy
- Photochemistry: **UV irradiation and FTIR micro-spectroscopy**.
- X-ray spectroscopy: **XANES** (X-ray Absorption Near Edge Structure) light elements from Na to Cl (only using DAFNE) and XRF
- **SEY** (secondary electron yield) and **XPS** (X-ray photoelectron spectroscopy) – by electron and photon bombardment



(Courtesy of A. Balerna)

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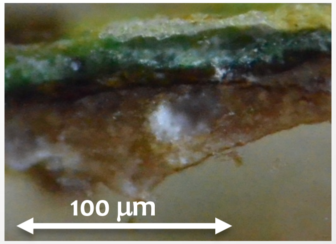
DAΦNE-Light

Every year about **30 experimental teams** get access to the **DAFNE-Light Laboratory** coming from **Italian Universities and Research Institutions, from EU/not EU Countries** and **third parties.**

Users receive beamtime submitting **proposals** and **quick requests**. Many **collaborations, projects** (**CHANGES, ET ITALIA**), **R&D for accelerators** and **third-parties' activities** (**CHNet, EIC**) are ongoing using the available beamlines equipments.

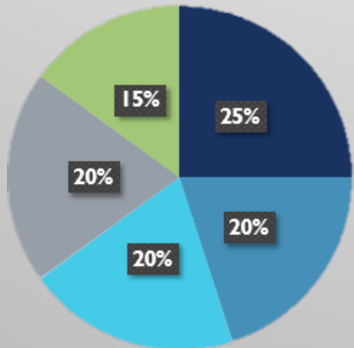


Dated 1846 (3.13 m x 2.29 m)

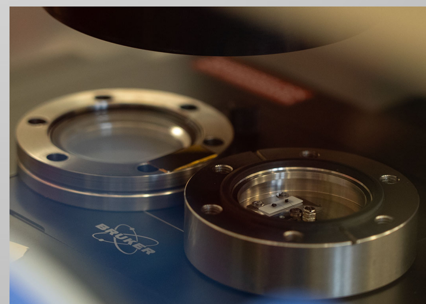
Thin section of a **copy of a Raffaello's painting (Spasimo di Palermo) hosted at DAFNE-Light** to achieve information on its **complex multi-layered structure** using the **IR** beam.

IR proposals application fields

- Physics
- Geology/mineralogy
- Life science
- Cultural Heritage
- R&D



Discovering the primordial universe: very small fragments of the Ryugu asteroid studied at SINBAD-IR



Information, highlights and publications at: **https://dafne-light.lnf.infn.it/**

(Courtesy of A. Balerna)

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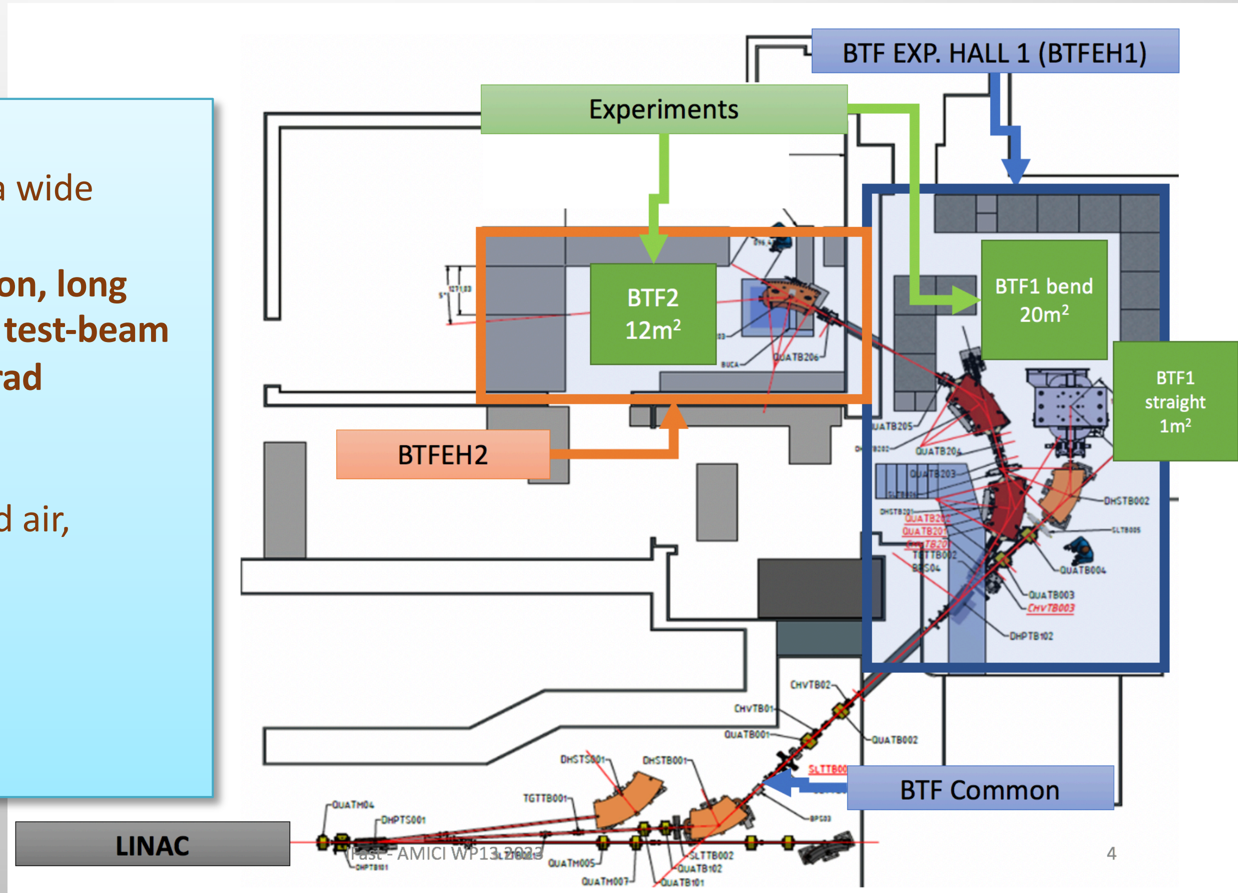
LNF – BTF Facility

The Beam Test Facility (BTF) is part of the DAΦNE accelerator complex in LNF (Frascati, Italy).
It can extract and manipulate the high intensity LINAC e+/e- beam, in dedicated or beam spare-pulse mode when DAΦNE collider is operative since 20 years.

BTF features:

- **pulsed** electron or positron beam, in a wide range of parameters
- Beam optimized for detector **calibration, long time-based experiments and weekly test-beam**
- possibility of **device e+/e- high flux irrad**
- services available for users:
  - DAQ and DCS data,
  - Gas pipelines, dried compressed air,
  - HV,
  - Networking,
  - Detectors,
  - Dedicated Staff, Logistics,
  - 24/7 operations.



(Courtesy of L. Foggetta)

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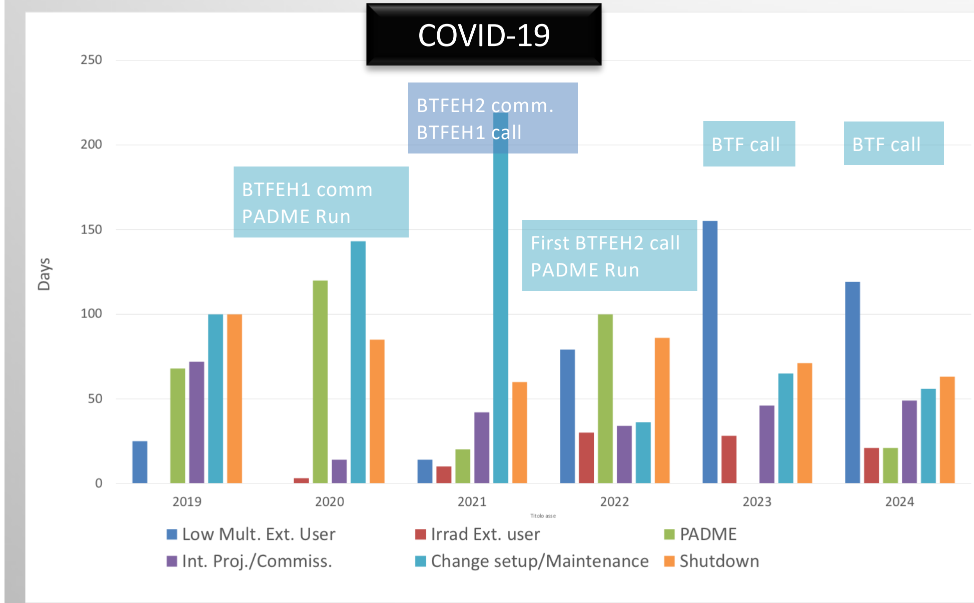
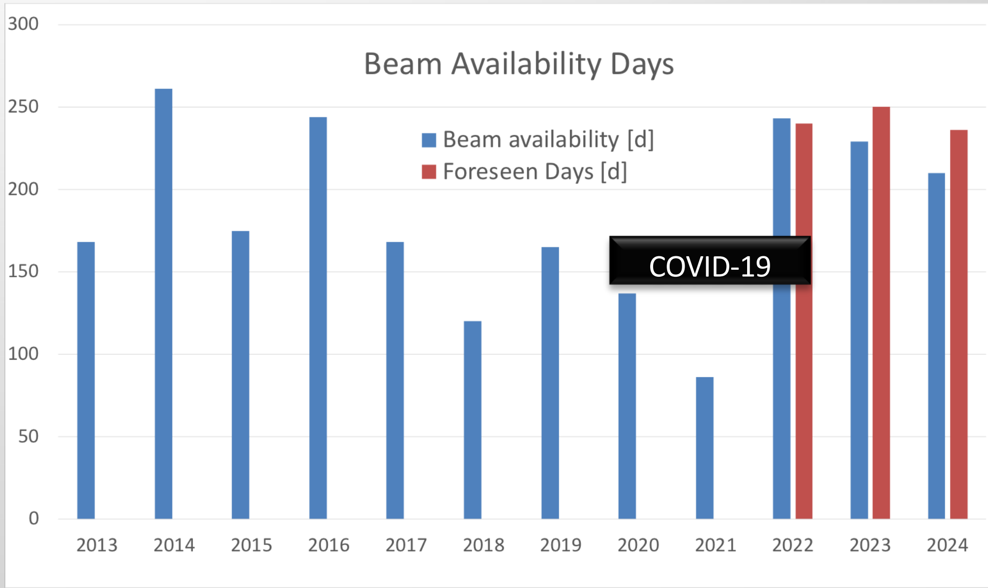
2019-2024 Activities



Beam Availability Days (up today)



BTF web page: https://mediawall.infn.it/v/1030

In 2024 Expected Beam availability days ~240 almost used
Shift average time = 6,5 days
Average team member number = 7

(Courtesy of L. Foggetta)

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Conclusions

The DAΦNE lepton collider has been powering physics research at the LNF in the last 25 years.

This has been possible thanks to the continuous developments and to the successful implementation of a new approach to keep under control the beam beam interaction: the ***Crab-Waist Collision Scheme***.

The *Crab-Waist* concept, conceived, implemented, and tested in about two years, allowed to increase the DAΦNE luminosity by about a factor three, reducing at the same time the background on the detector.
The peak luminosity measured at DAFNE is still today an order of magnitude higher than the one measured in colliders operating at comparable energy.

The experiments implemented at DAFNE achieved unique results in the relative field of interest.

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

Thank you

Spare Slides

Istituto Nazionale di Fisica Nucleare
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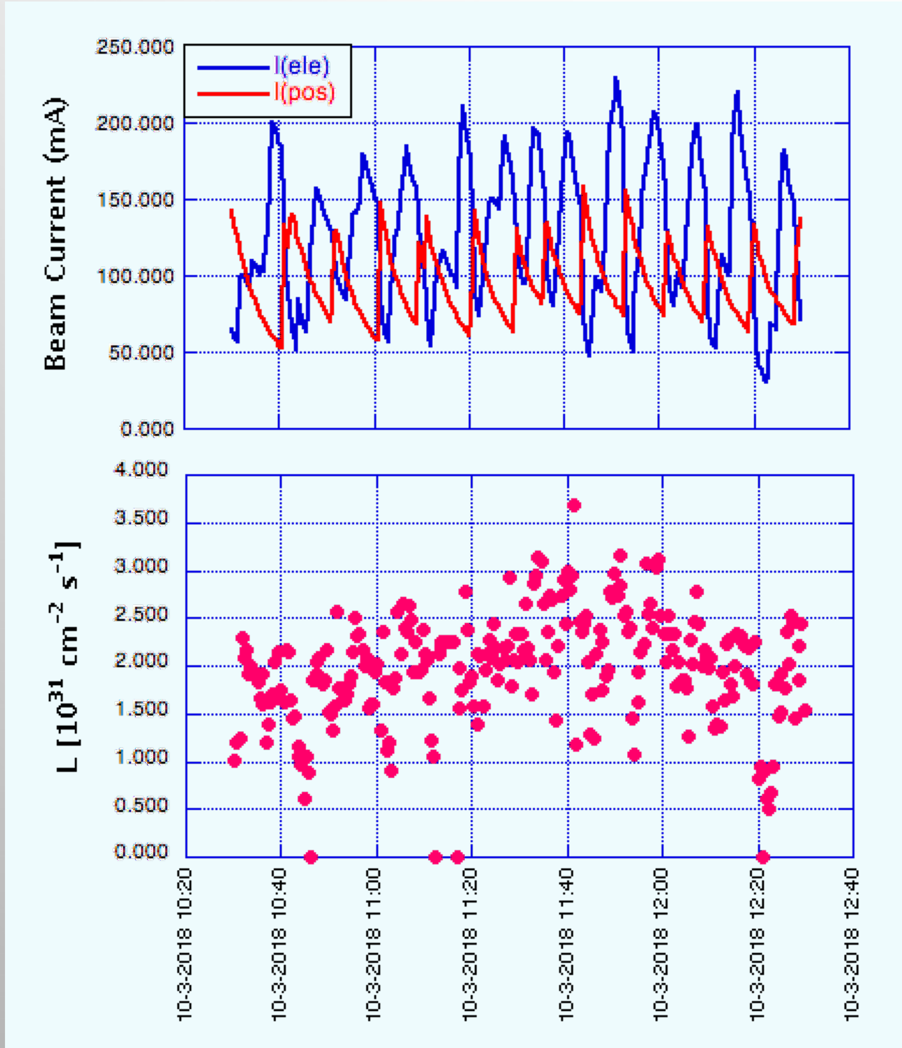
DAΦNE Luminosity Achievements

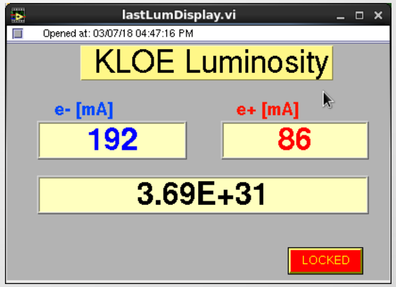
Luminosity achieved at DAΦNE is almost an order of magnitude higher than the one obtained at other colliders operating in the low energy range

	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	--

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!

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

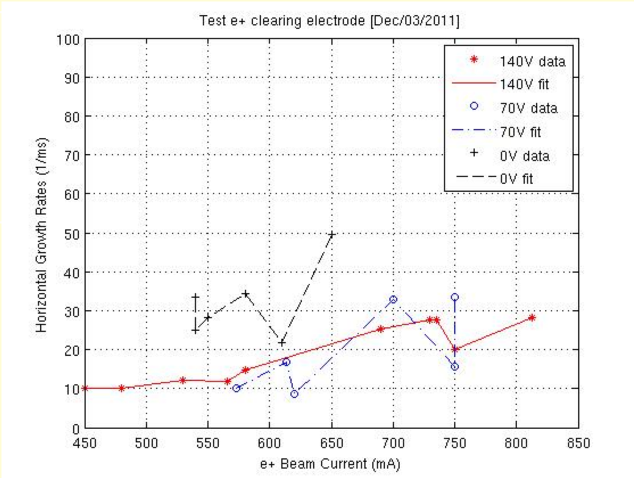
DAΦNE is the first collider operating routinely with electrodes, for e-cloud mitigation, ECE.
ECE provided stable operation with the e^+ beam, and allowed unique measurements such as:

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

demonstrating their effectiveness in restraining e-cloud induced effects.

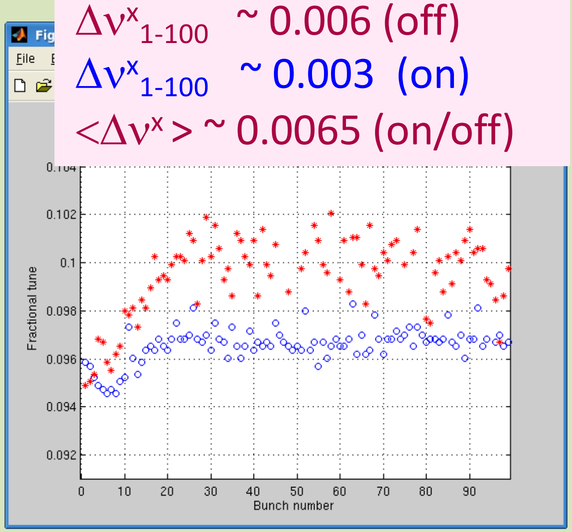
(D. Alesini et al, Phys. Rev. Lett. 110, 124801 (2013)

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

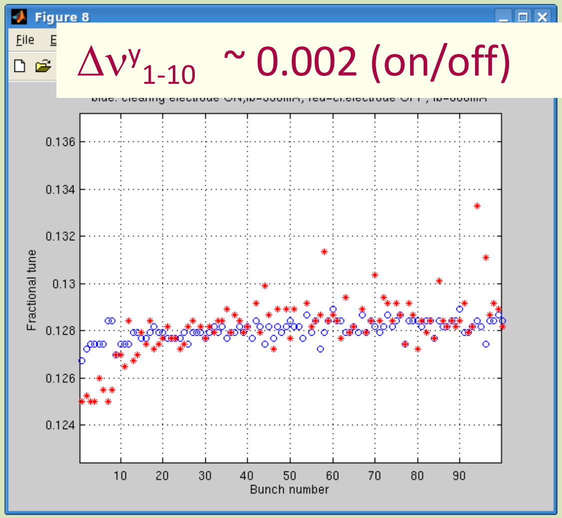


Tune Spread measurements

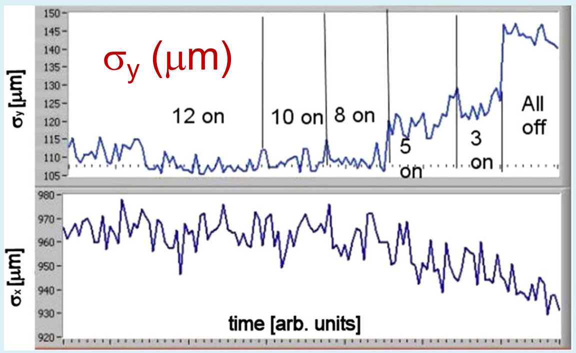
$\Delta\nu^x_{1-100}$ ~ 0.006 (off)
$\Delta\nu^x_{1-100}$ ~ 0.003 (on)
$<\Delta\nu^x>$ ~ 0.0065 (on/off)



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



Vertical Beam Size



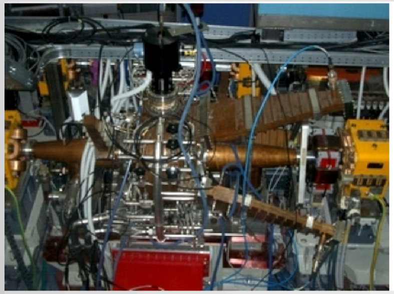
DAΦNE Vacuum Chamber Elements

Optimized to avoid heating, reduce impedance, and damp HOM

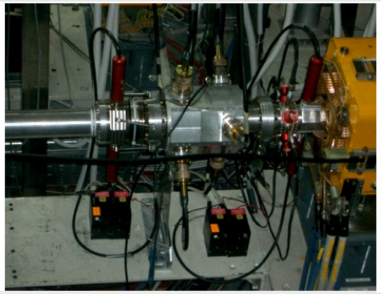
Impedance budget is a factor of 80 lower than in similar storage ring (EPA)

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

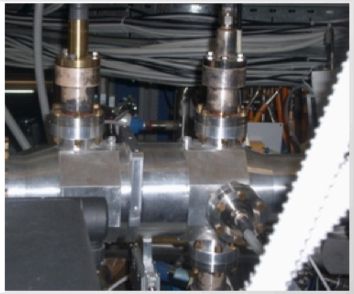
Such R&D effort largely contributed to improve beam dynamics and beam-beam performances



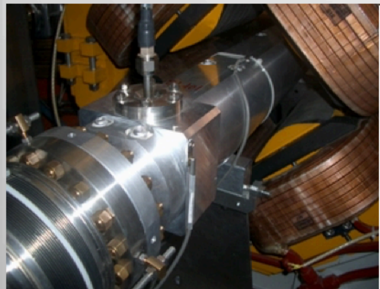
RF CAVITY



LONGITUDINAL KICKER

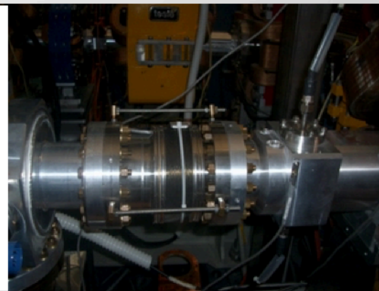


TRANSVERSE KICKER



INJECTION KICKER

WALL CURRENT & DCCT MONITOR

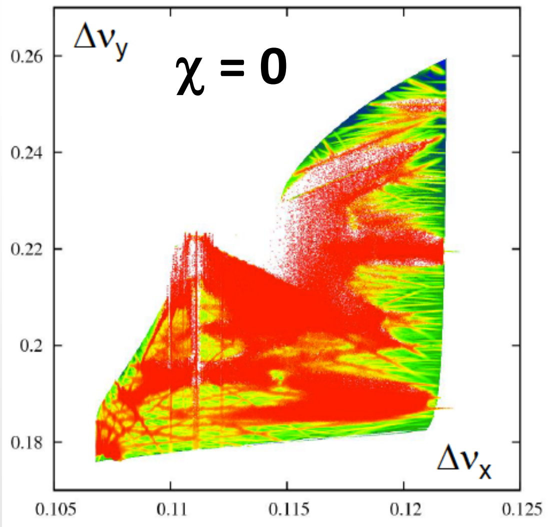


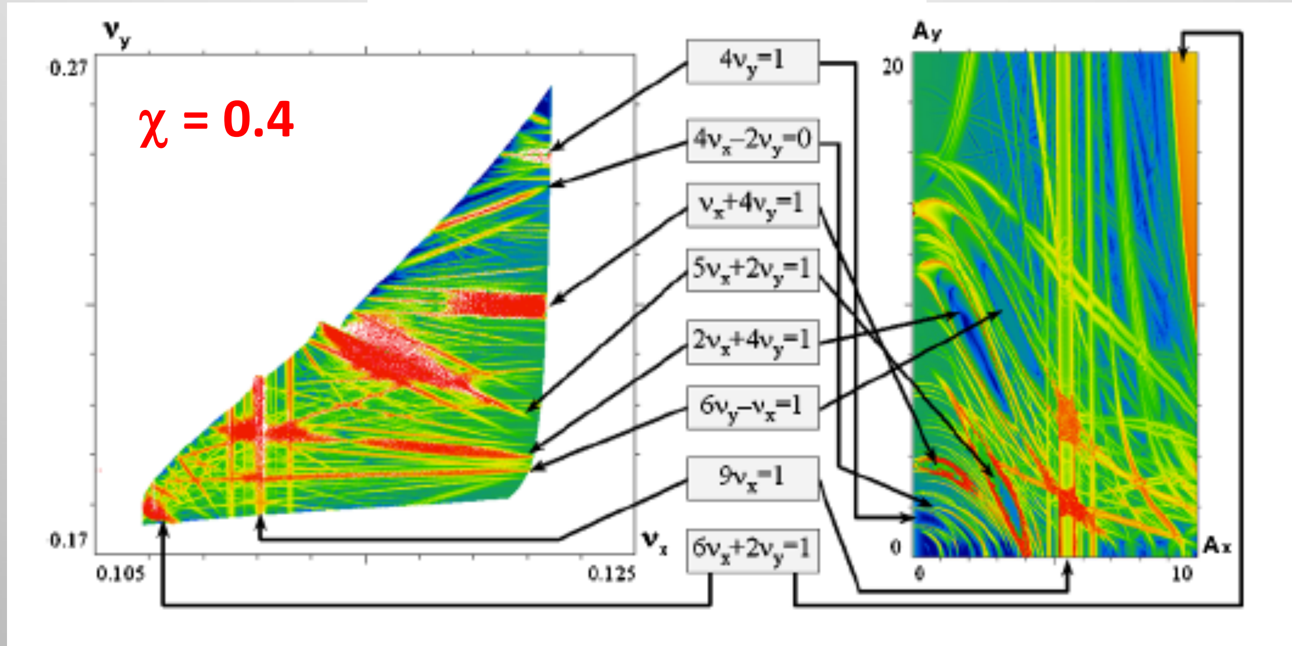
SHIELDED BELLOWS

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

Frequency Map Analysis of *BB* Interaction

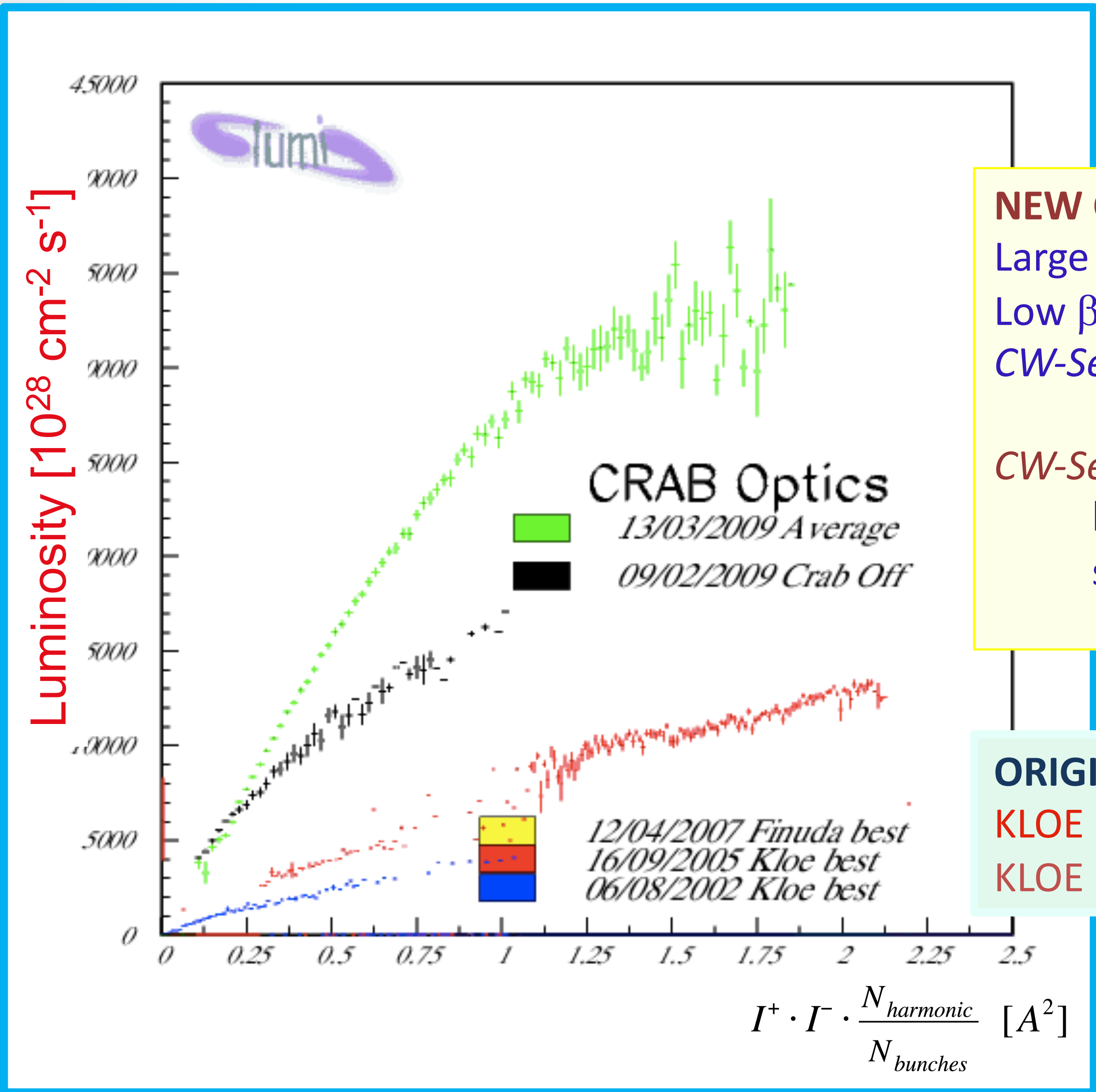
DAΦNE simulations





(D. Shatilov et al.)

Crab-Waist Collision Scheme & Luminosity



NEW COLLISION SCHEME:

Large Piwinski angle ψ = 1.9

Low β^*_y β^*_y = 9.0 [mm]

CW-Sextupoles χ = 0. 6

CW-Sextupoles off

larger transverse beam size blowup

sharp lifetime reduction

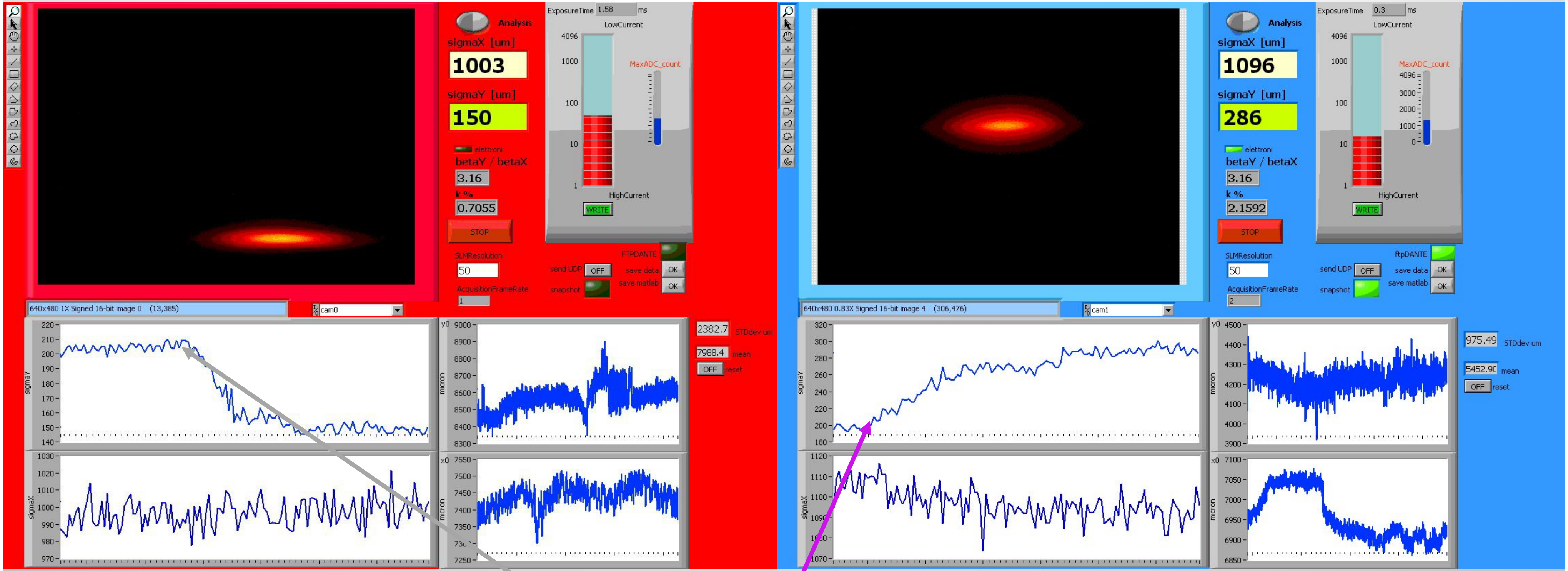
ORIGINAL COLLISION SCHEME:

KLOE 2005 ψ = 0.6 β^*_y = 18. [mm]

KLOE 2002 ψ = 0.3 β^*_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.

Crab Waist Sextupoles Test (during KLOE-2 run)



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