Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

DAΦNE as Open Accelerator Test Facility

aimed at studying physics and innovative technology for particle accelerators

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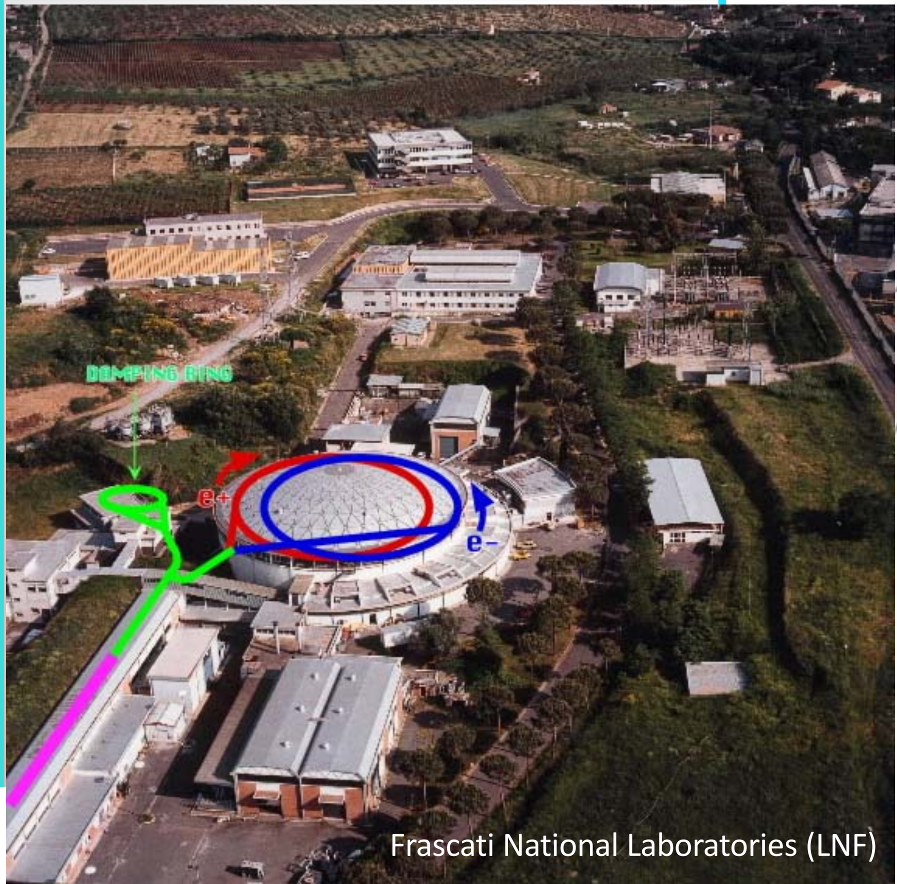
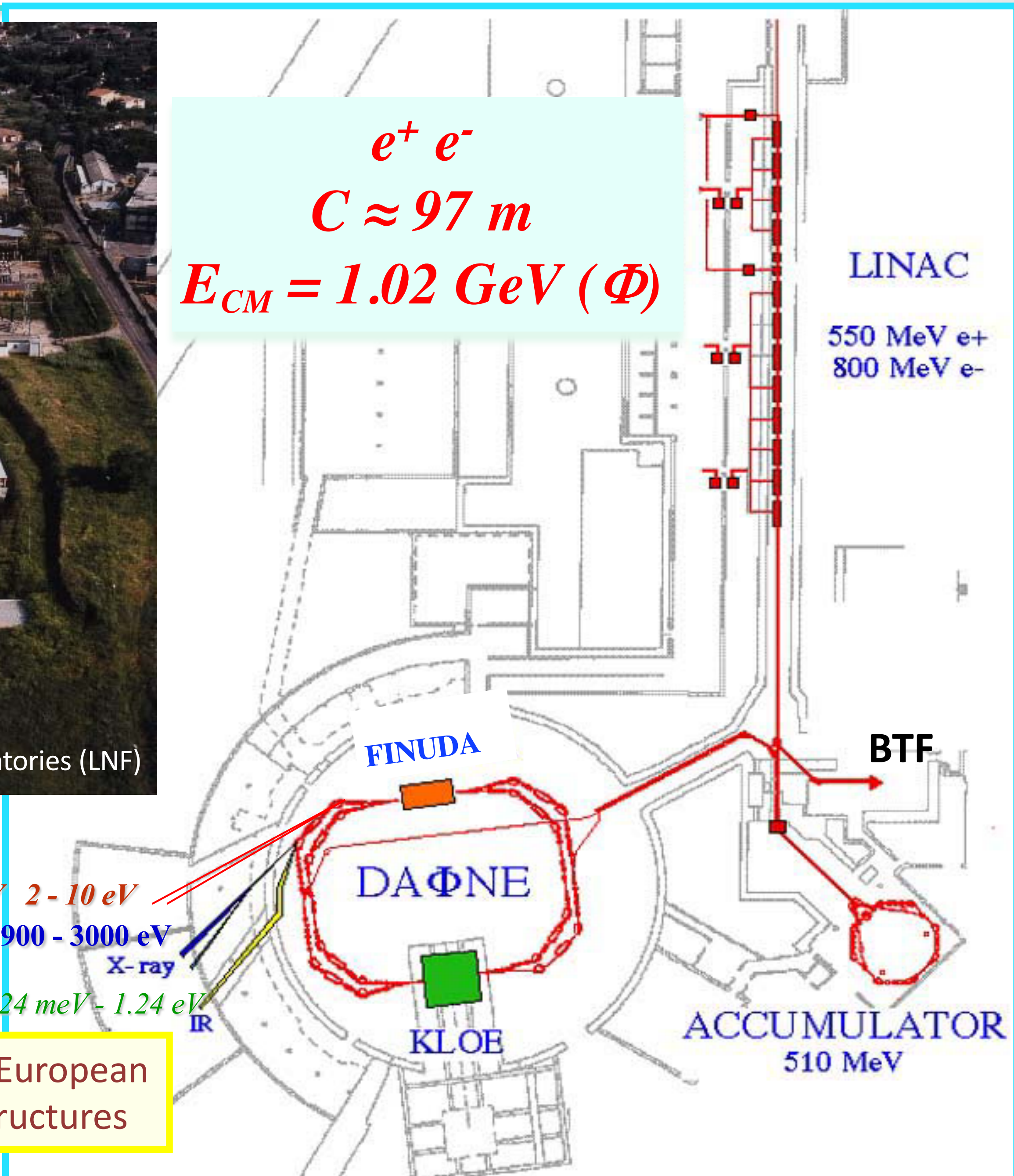
on behalf of the **DAΦNE Team** and of the **DAΦNE-TF workshop ISC**

Outline

- DAΦNE *overview*
- DAΦNE *achievements and contributions to the physics of particle accelerators*
- *The opportunity of converting the accelerator complex into a Test Facility*
- DAΦNE *technical details*
- *Conclusions*

The DAΦNE Accelerator Complex





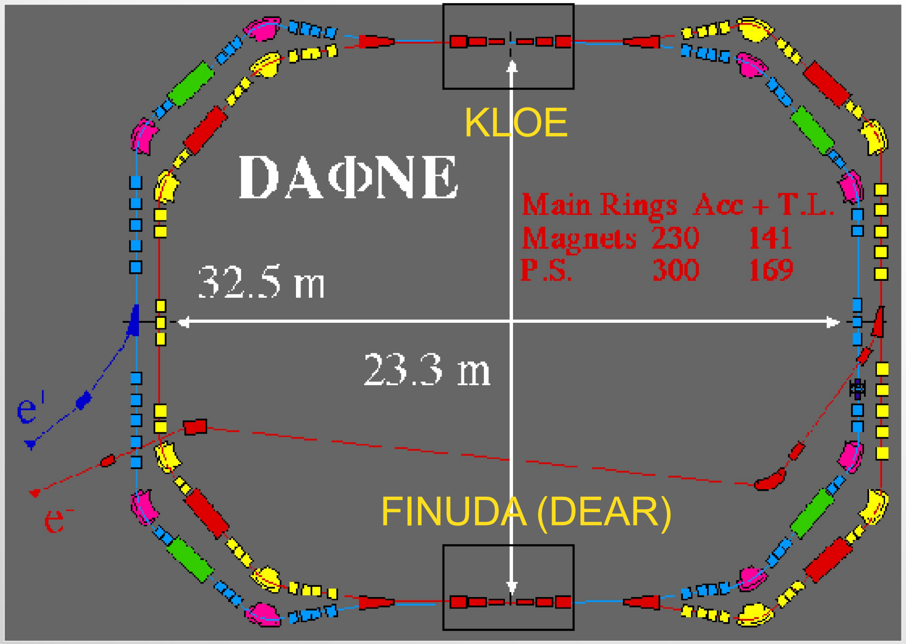
LNF are also part of the European synchrotron light Infrastructures

DAΦNE History

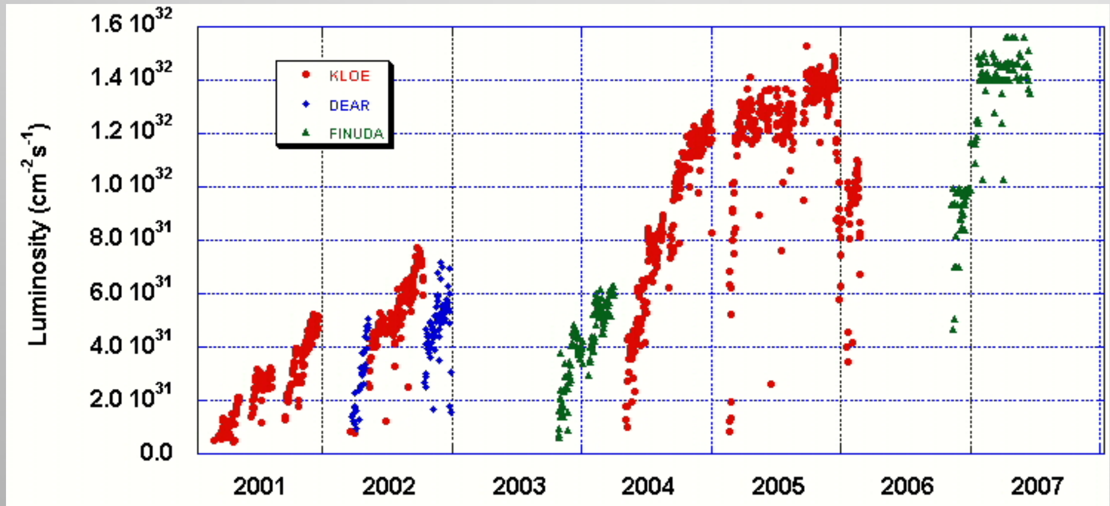
- DAΦNE is an electron-positron collider designed in the mid '90s, it came into operation in 2000
- It has been providing data in consecutive data-taking periods to:
  KLOE, **DEAR** and **FINUDA** experiments until 2007
  SIDDHARTA in 2008 ÷ 2009
  again for the upgraded **KLOE-2** between November 2014 and March 2018
- Presently the DAΦNE LINAC is operating for the **PADME** experiment
- In 2019 DAΦNE will provide physics events to the **SIDDHARTA-2** detector.

In 2020 DAΦNE *will stop running as a collider and will be most likely transformed in a open accelerator test facility.*

Luminosity Achievements (native configuration)



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



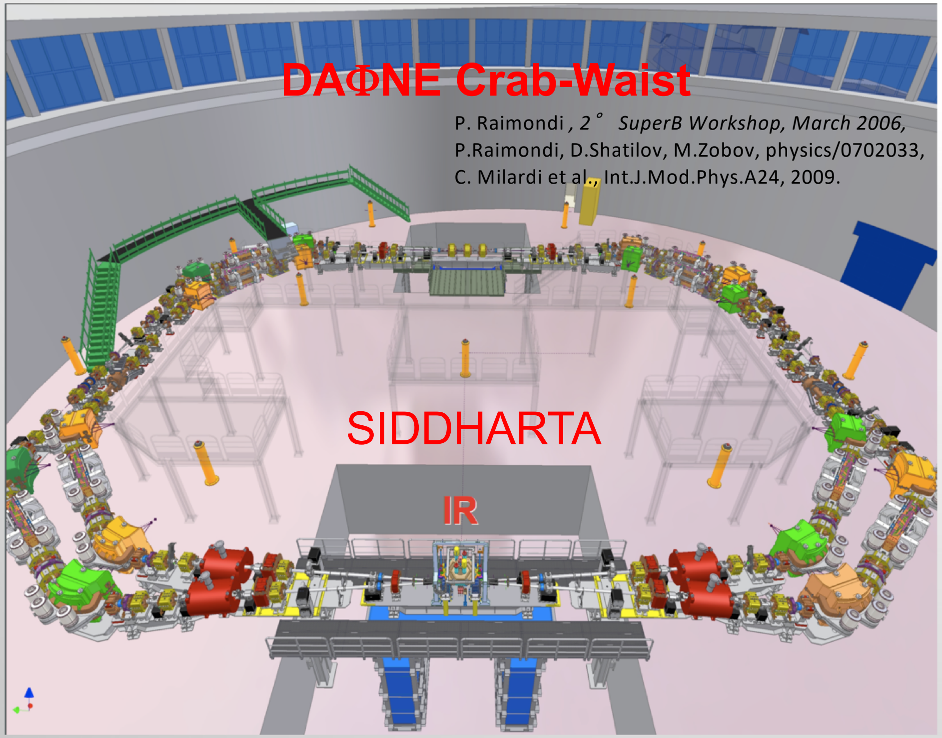
	DAΦNE native
Energy (MeV)	510
$\theta_{cross}/2$ (mrad)	12.5
ε_x (mm•mrad)	0.34
β_x^* (cm)	160
σ_x^* (mm)	0.70
$\Phi_{Piwinski}$	0.6
β_y^* (cm)	1.80
σ_y^* (μm) low current	5.4
Coupling, %	0.5
Bunch spacing (ns)	2.7
I_{bunch} (mA)	13
σ_z (mm)	25
N_b	120

L_{logged} (fb^{-1}) 2001÷2007

KLOE	3.0
FINUDA	1.2
DEAR	0.2

Crab-Waist Collision Test Run

Tested with the SIDDHARTA detector in 2008÷2009



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

- Large Piwinski angle and Crab-Waist scheme provided:
  - optimal control of the beam-beam interaction
  - a factor 3 higher L_{peak}
  - complete elimination of the LRBB

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

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

$L_{\int 1\ hour} = 1.033\ pb^{-1}$ *(test run)*

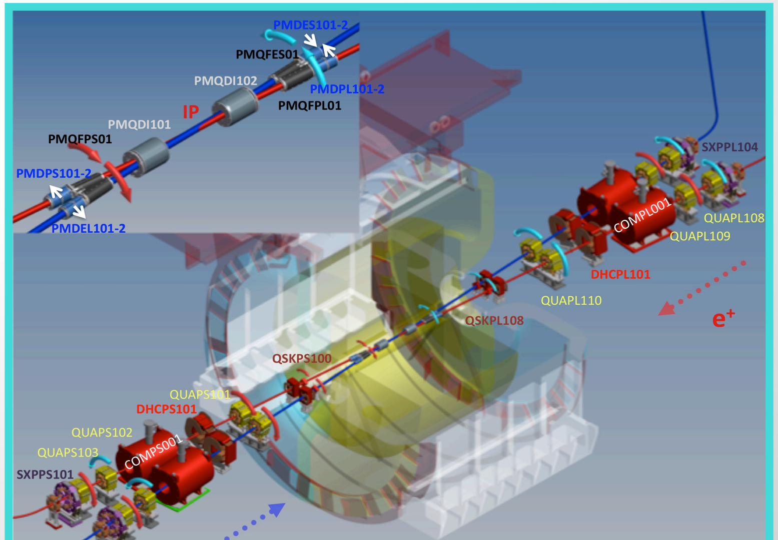
$L_{\int run} \sim 2.8\ fb^{-1}$ *(logged by the experiment)*

M. Zobov et al., Phys.Rev.Lett.104:174801, 2010.

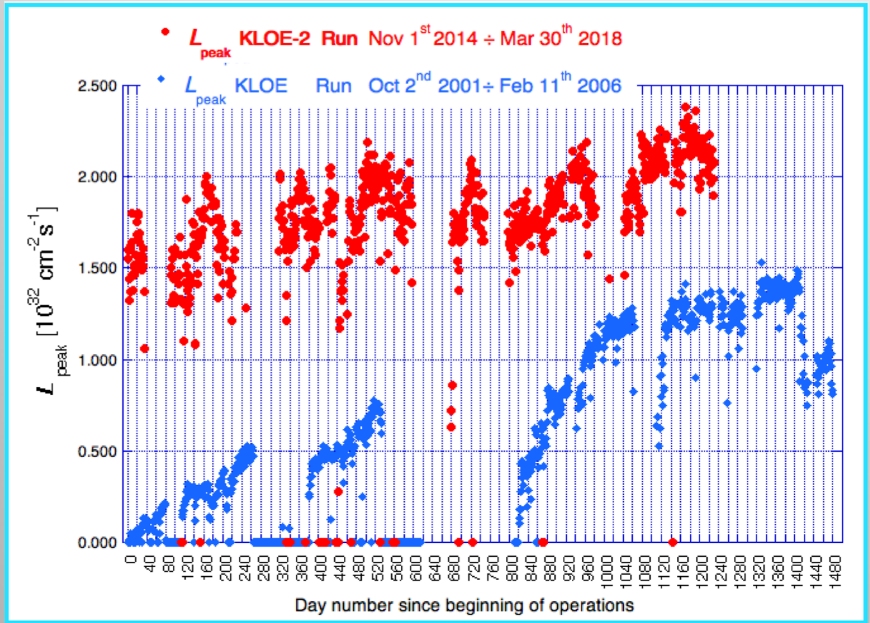
Crab-Waist Collision KLOE-2 Run

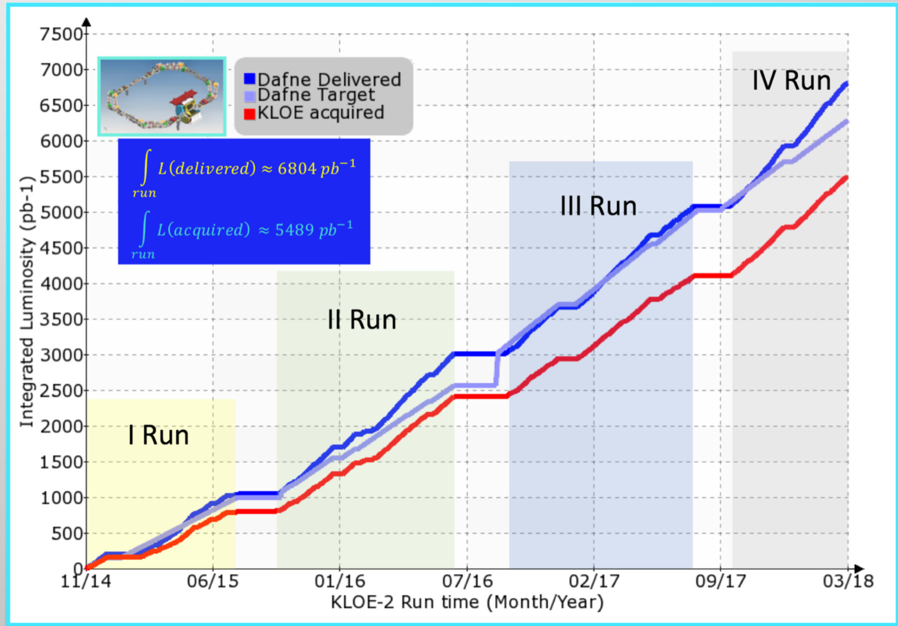
Crab-Waist collision scheme *implemented for the first time with a large detector* including a high intensity axial field

The new approach to collision provided a **~60% improvement** in terms of $\boldsymbol{L_{peak}}$



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





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**

Crab-Waist Colliders

New machines and projects around the world have adopted the *Crab-Waist collision scheme* as their main design concept

Collider	*Location*	*Status*
DAΦNE	Φ-Factory Frascati, Italy	In operation
SuperKEKB	B-Factory Tsukuba, Japan	Under commissioning
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)

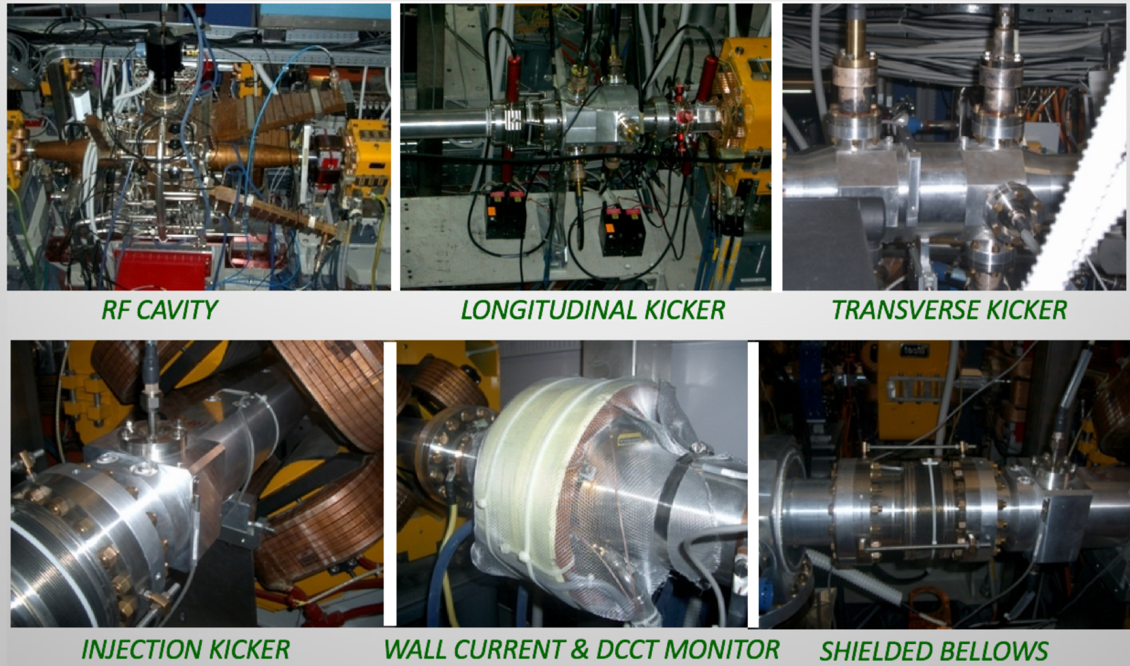
DAΦNE Vacuum Chamber Elements

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

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



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

Beam Currents stored at DAΦNE

Lepton Beam Currents achieved so far

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

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

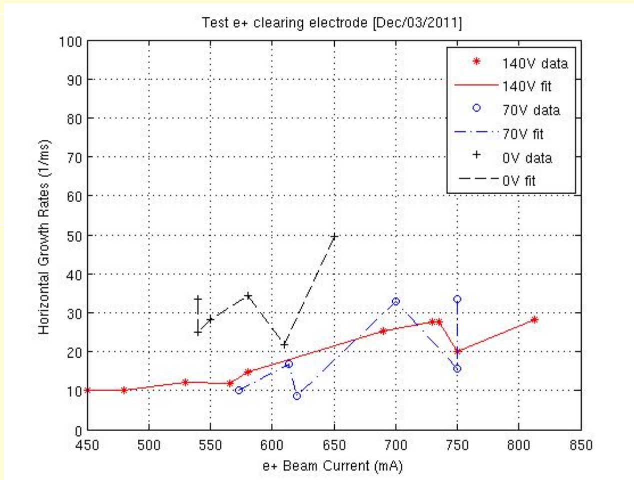
DAΦNE is the first collider operating routinely with electrodes, for e-cloud mitigation, ECE.
ECE provided stable operation with the e^+ beam, and allowed unique measurements such as:

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

demonstrating their effectiveness in restraining e-cloud induced effects.

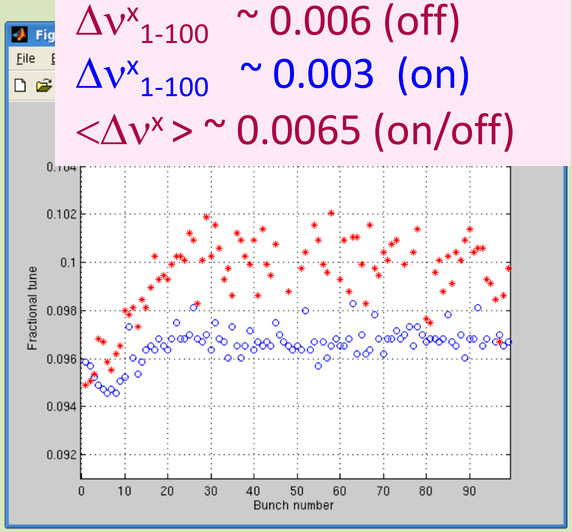
(D. Alesini et al, Phys. Rev. Lett. 110, 124801 (2013)

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

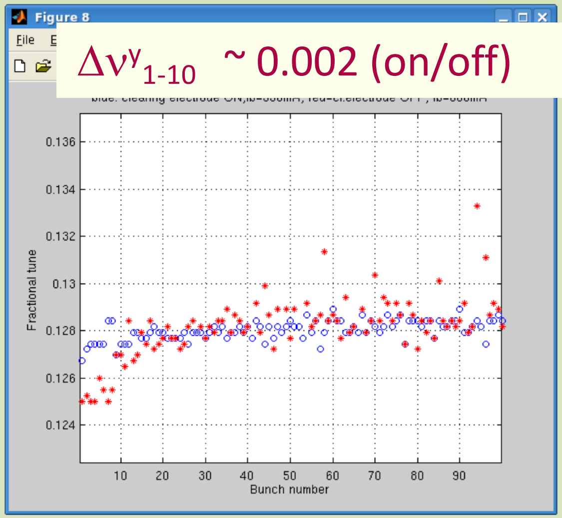


Tune Spread measurements

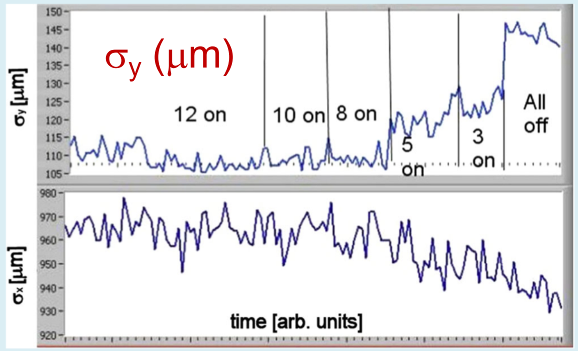
$\Delta\nu^x_{1\text{-}100}$ ~ 0.006 (off)
$\Delta\nu^x_{1\text{-}100}$ ~ 0.003 (on)
$<\Delta\nu^x>$ ~ 0.0065 (on/off)



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



Vertical Beam Size



Feedback R&D and Instability Cures at DAΦNE

High current performances in a low energy machine greatly depend on bunch by bunch feedback systems.
DAΦNE performances are assured by the **3 feedbacks installed in each ring in order** to dampen coupled-bunch instabilities both in the longitudinal and transverse plane

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

The **total pow**er available for each apparatus is of the order of **500 W** and **750 W** for transverse and longitudinal feedbacks respectively

Transverse FBKs have been equipped with **in house developed new kickers** having doubled strip-line length and providing larger shunt impedance at the low frequencies typical of the unstable modes.

Beam current limits observed

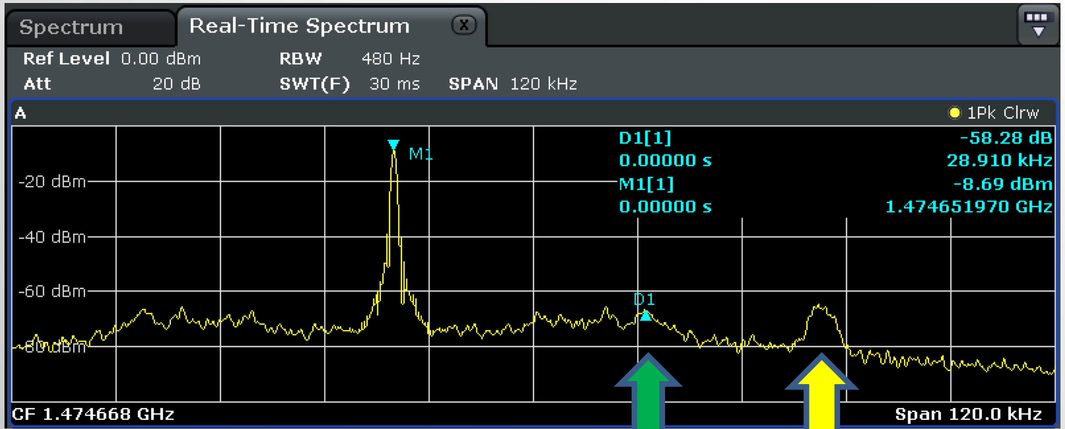
- longitudinal mode-0 & quadrupole oscillations
- noise coming from pickups (harmful for vertical sizes)
- e-cloud effects (in the e+ ring)

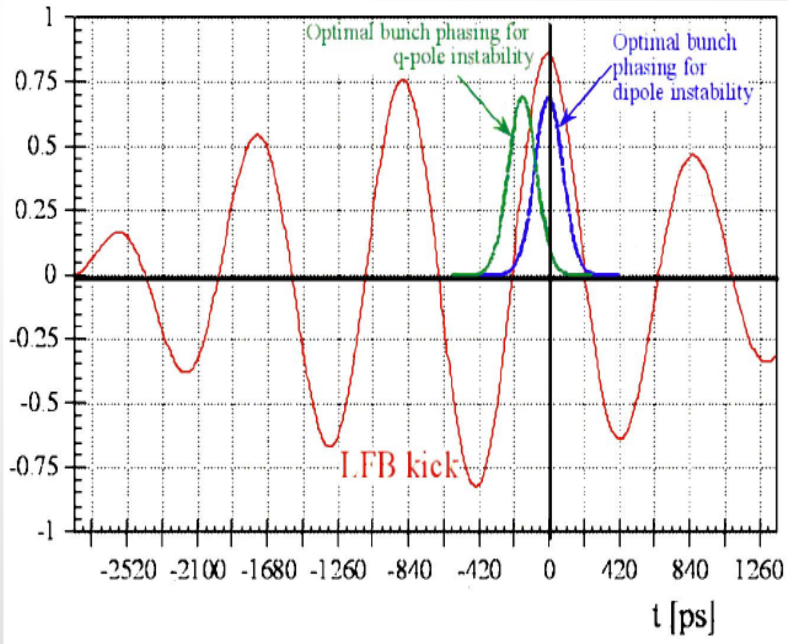
Solutions:

- Longitudinal quadrupole control by a special technique implemented at DAFNE in the dipole feedback system
- Transverse low noise front end (in collaboration with KEK)

Longitudinal Quadrupole Oscillations

@ $f \sim 2 \cdot f_{sync}$



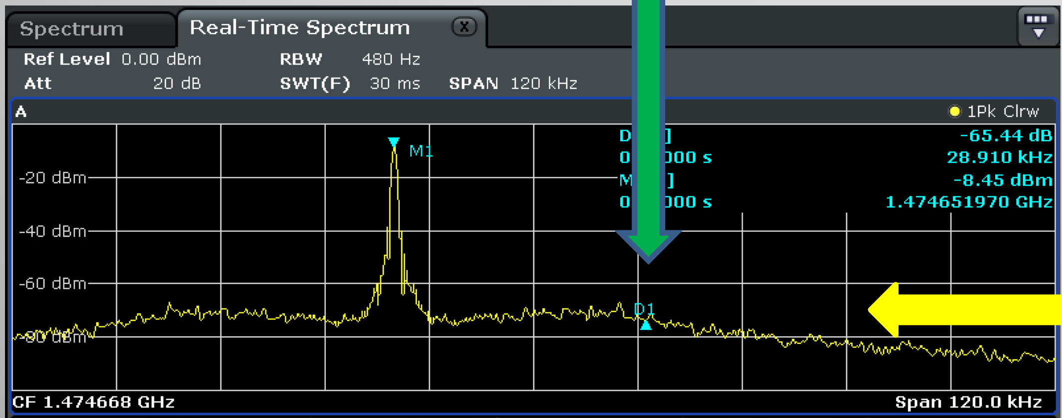


Revolution harmonic

Quadrupole oscillation

Synchrotron (dipole) oscillations damped by Long FBK

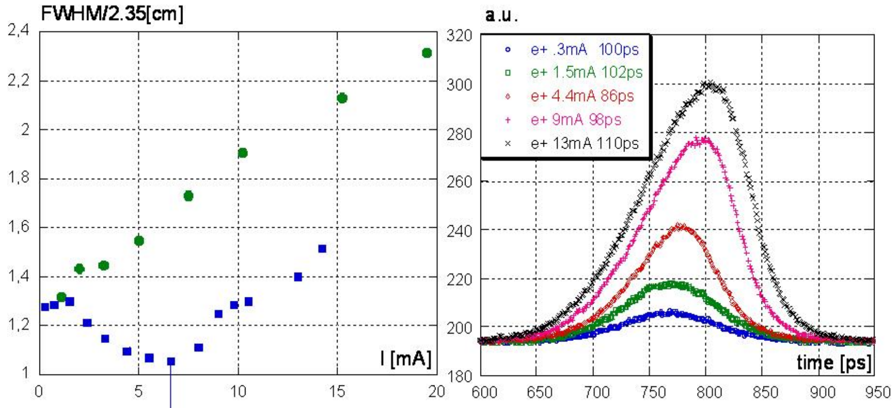
This instability, if not controlled, saturates the longitudinal feedback



(A.Drago, et al., PRST-AB, 6, 052801-1-11, 2003)

$\alpha_c < 0$ at DAΦNE

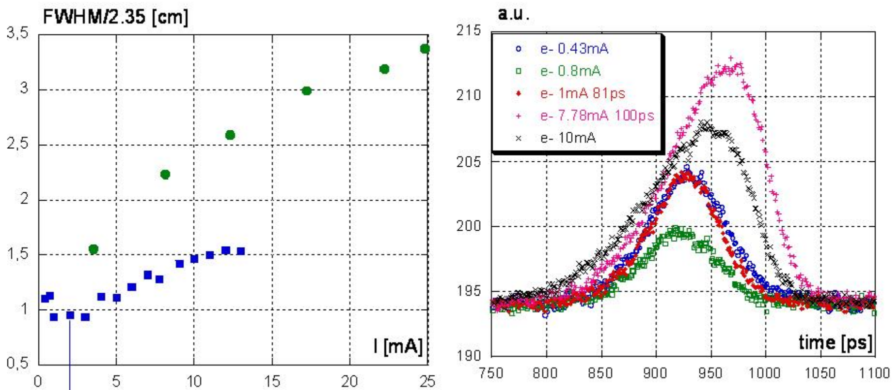
Bunch Shortening in the Positron Ring



I_{th} = 7 mA at $\alpha_c < 0$

I_{th} = 9 mA at $\alpha_c > 0$

Bunch Shortening in the Electron Ring



Low microwave instability threshold

Experimental Results

- DAΦNE flexible optics

$$-0.036 \leq \alpha_c \leq +0.034$$

- Bunches shorten as predicted by numerical simulations.
- It was possible to store high bunch current with large negative chromaticity

I_b ~40 mA

- Stable multibunch beams with ***I > 1 A***
- **Specific luminosity gain of about 25%** till 300 mA per beam without SXTs
- Higher current beam-beam collisions failed due to s_y^- above the microwave instability threshold

Collisions with $\alpha_c < 0$ have never been tested elsewhere

Other contributions to particle accelerator physics

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

- short pulse PS for injection kickers
- non-linearities mitigation in magnet fields especially in wigglers
- **parasitic crossing compensation by current carrying wires**
- collisions with very high crossing angle
- strong RF focusing

Proposals:

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

That said ....

The previous considerations, and not just those, led to conclude that DAΦNE is a unique facility to realize tests and measurements finalized to:

- study physics problems and innovative technologies which are of interest for the particle accelerator community
- test innovative concepts
- implement short term experiment about fundamental and applied physics
- train young generations of particle accelerator physicists

The Opportunity of DAΦNE-TF

It is the only existing phi-factory and, until the entry into operation of SuperKEKB, it will be the only collider on which the ***Crab-Waist*** **Collision scheme has been successfully implemented** with and without the experiment solenoid.

If converted into a facility for the study of physics and technologies for accelerators, **DAΦNE-TF** would add to the small number of accelerators available for this purpose.
If one considers just electron machines, this list includes **ATF2** (KEK), a top-class facility designed for the development of the International Linear Collider, **CLASSE** (Cornell Laboratory for Accelerator Based Science and Education), a centre of excellence in the development of accelerator technologies located in an university campus, and **KARA** (Karlsruhe), devoted to R&D of machines and applied research.
DAΦNE-TF would be the only facility in Europe to provide a positron beam.

Furthermore, **DAΦNE-TF would operate when CERN won't have beams,** i.e. over 2019-20, due to the realization of the upgrade of LHC injectors and during each of the long stops *LS3 (2024, HL-LHC installation*) and *LS4 (2030)*, which will make the availability of DAFNE-TF for accelerator studies even more interesting.

DAΦNE-TF Operation Framework

The lines of scientific and technological research should meet some basic conditions

- Compliance with the machine operating parameters
- Limited impact in terms of machine layout and components modification, invasive measurements and experimental activities hardly compatible with the actual machine configuration are unlikely to be considered
- maturity level of the experimental programmes proposed.

About the DAΦNE Infrastructure

- Much of the **hardware** installed in DAΦNE, although constantly maintained and improved, dates from the mid '90s.
- A major **refurbishment** (for an amount of about 1000 K€) was realized in 2013, and continued in the following years.
- A significant upgrade of the **LINAC** is under way, including the split of the Beam Test Facility (**BTF**) in order to increase the number of future users.
- The PSs, of the steering magnets (short and long type) both in the positrons and in the electrons rings are going to be substituted by new equipment. The new PSs have accuracy and resolution improved by more than a factor 10 with respect to the old devices.

- Despite the relatively obsolete nature of part of its components, DAΦNE and BTF are able to regularly provide beams for more than 6,000 hours per year, keeping their **operational efficiency** at levels above 80% for long periods.

- In the same years, the **synchrotron-light laboratory** has profited from the e^- beam radiation in parasitic mode, hosting external users for about 800 hours per year, and getting the CALYPSO program of Horizon 2020. The synchrotron-light activity allowed the Laboratory to be included into LEAPS, *League of European Accelerator-based Photon Sources*

- The DAΦNE complex also hosts a **cryogenic plant**, recently refurbished, which can be efficiently used to operate superconducting magnets, experimental setups, and superconducting radiofrequency systems (although the latter ones have never been used at DAFNE).

Possible activities

- ***Study of low SEY (Secondary Electron Yield) elements and impedances; Graphitization of chambers and other technologies.***
- ***Accelerator components realized with 3D printers.***
- ***High gradient tuneable permanent magnets***
- ***High power solid state RF amplifiers***
- ***High-power positron sources: peak Energy Deposition Density in the targets, wide aperture capture, accelerating sections in S Band***

Possible activities

- *Components for future SLED and pulse flatness compensation*
- *Components for accelerators (vacuum chambers, collimators, masks, kickers) and innovative beam diagnostic techniques*
- *Emittance manipulation*
- *Beams interacting with amorphous materials, crystals, lasers, plasma*

Possible activities

DAΦNE-TF might also host **small-size experiments in the field of fundamental and applied physics** requiring a small-size data sample. The qualifying element of every possible proposal in this field is the ***time scale***.

Among the possible proposals there are the measurement of processes with high effective cross sections, which are feasible with small experimental set-ups such as study of interactions K^0_L or K charged with specific materials or small-angle scattering, where interesting possibilities of testing small-angle detection systems in vacuum exist, e.g. with Roman Pot detectors highly demanding in terms of spatial and temporal resolution, high rate, radiation resistance, etc ....

Training Opportunity

DAΦNE-TF might represent an excellent training tool for physicists, technologists and technicians with skills in accelerators and related technologies, in particular in the field of lepton machines, in which LNF has always played a leading role, internationally acknowledged.

DAΦNE LINAC

Diagnostics	
Fluorescent screens	5
BPMs	14
Current monitors	4
Spectrometer	1

Based on S-band technology

LINAC Parameters

Pulse width: 1ns ≤ *Ip* < 350 ns
f = 2.865 GHz
15 accelerating sections
4 klystron 45 MW, each one followed by a SLED
repetition rate 50 Hz

LINAC Beam Parameters

$E_{e+} \leq 550$ MeV $I^{+}_{(pulse)} \sim 100$ mA
$E_{e-} \leq 780$ MeV $I^{-}_{(pulse)} \sim 250$ mA
$\varepsilon^{-} \sim 1$ mm•mrad, $\Delta p/p \sim 1\%$
$\varepsilon^{+} \sim 5$ mm•mrad, $\Delta p/p \sim 5\%$

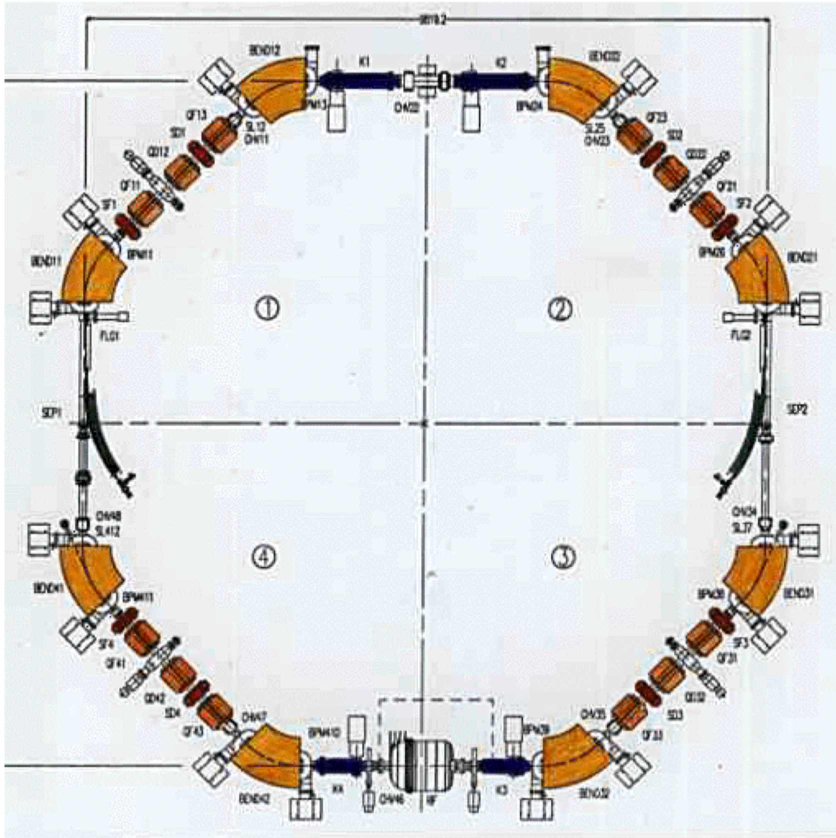
A possible LINAC upgrade aims at reaching $E_{e-} \sim 1.$ [GeV] by installing additional accelerating sessions

DAΦNE Accumulator

Energy [MeV]	510
Circumference [m]	32.56
ε_x [mm•mrad]	0.26
RF f [MHz]	73.65
RF V [KV]	200.
σ_z [cm]	3.8
SR loss [KeV]/turn	5.2
Damping time τ_E/τ_x [ms]	10.7/21.4

All Dipoles and Quadrupoles are based on laminated yoke technology
Energy operation range up to E = 560 [MeV]

8 45^0 sector dipole n = 0.5
3 independent QUAD families
2 independent SXT families



Schematic layout of the DAFNE Accumulator.

Transfer Lines

All Dipoles are based on laminated yoke technology

Dipoles can work up to E ~ 800 [MeV]

Diagnostics	Tle Acc inj	Tle Acc ext	Tlp Acc inj	Tlp Acc ext
Fluorescent screens	7	12	5	12
Striplines	9	16	9	10
Current monitors	3	5	3	5

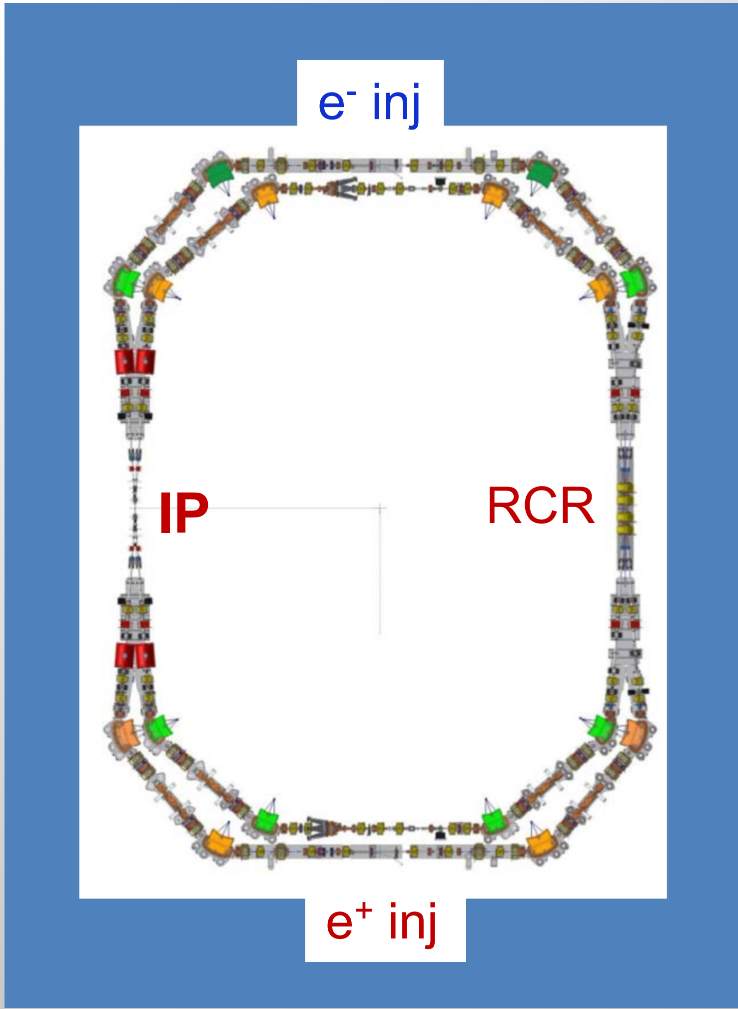
Main Rings

DAΦNE ring optics does not have any periodicity,
each ring is a cell

Ring optics is based on a modified Chasman-Green lattice
It consists of 4 achromats, each one including a 2 m long normal conducting wiggler allowing to tune over a wide range:

- beam emittance
- radiation damping
- momentum compaction

Ring optics is very flexible since all *Quadrupole* and Sextupole magnets are independently powered



Main Rings

All magnets are based on laminated yoke technology.

All Quadrupoles and Sextupoles in the Main Rings are independently powered

Wiggler are series powered in each Main Ring

Magnets:

Dipoles can work and have been characterized up to $E \leq 530$ [MeV]

Large quadrupoles $|Kq|E \leq 2224$ [MeV m^{-2}]

Small quadrupoles $|Kq|E \leq 3200$ [MeV m^{-2}]

Large Sextupoles $|Ks|$ Ls $E \leq 7500$ [MeV m^{-2}]

Small Sextupoles $|Ks|$ Ls $E \leq 6666$ [MeV m^{-2}]

RF systems:

f_{RF} = 368.667 [MHz]

V_{RF} = 250 ÷ 300 KV

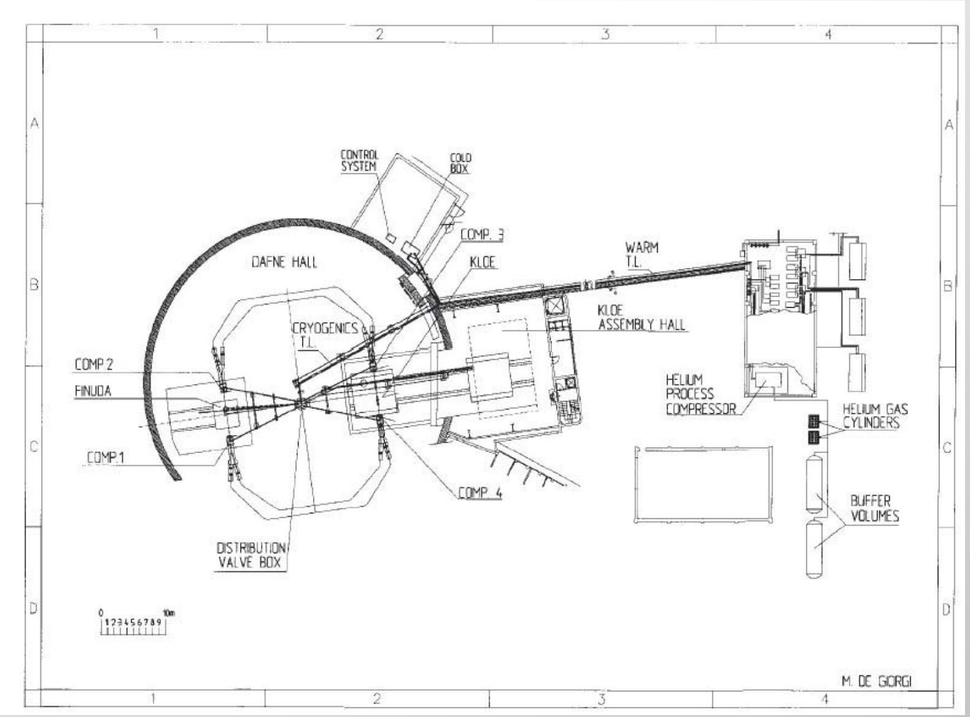
120 harmonic number

Diagnostics in each ring	Number	Details
BPMs	46	4 buttons, Bergoz acq. 6 Hz, res_{rms} = 5÷10 μ
BPMs	6	8 buttons for diag. and FBKs
Libera modules	4	res ~ μ
DCCT	1	
SRM	1	
Streak Camera	1	res ~ 10 ps
Gated Camera	1	gate time ~ 20 ms, res ~ 20 μ
FFT spectrum analyser + white noise generator	1	Tune measurements
Scope	2	
FBK systems	3	

DAΦNE Cryogenic System

LINDE TCF 50 liquid He refrigeration plant

- Users: KLOE/FINUDA/4 Antisolenoids
- Operated at DAΦNE 1998-2018
- Refrigeration capacity:
  - 100 W @ 4.4K/1.2 bar
  - 1.14 g/s LHe
  - 900 W @77 K/10 bar
- Distribution valve box for 6 users
- Control system updated on 2014
- Plant compressor replaced on 2016



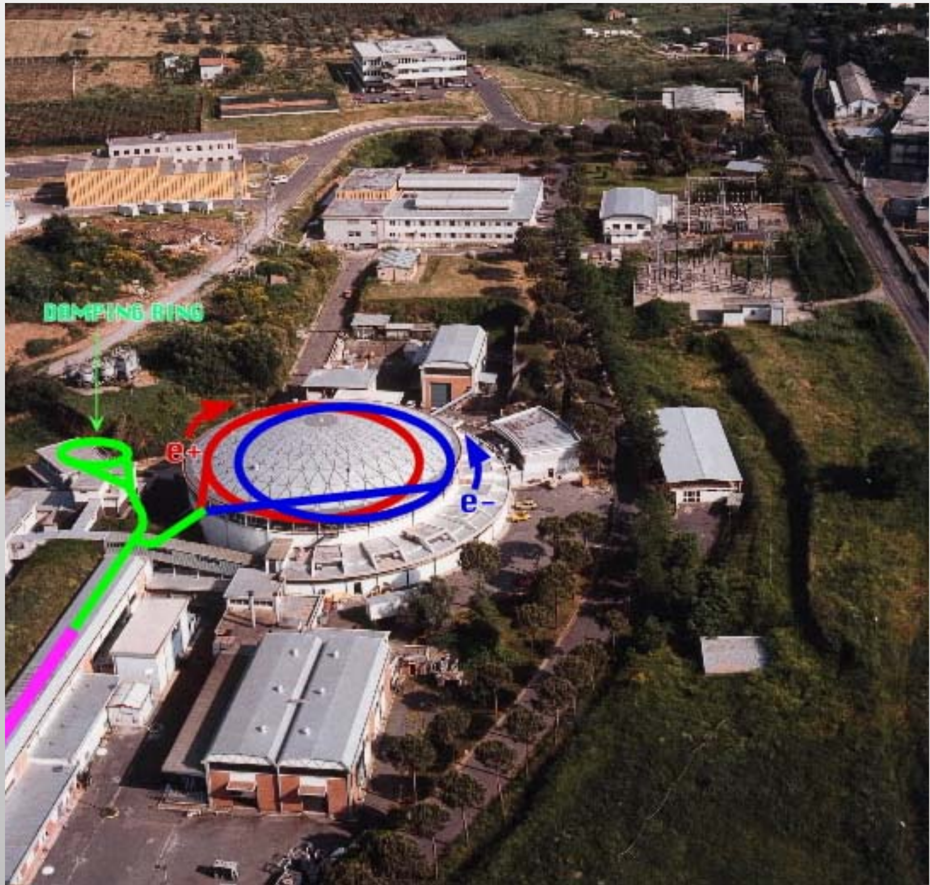
G. Delle Monache, C. Ligi

The DAΦNE Parameter List

	DAFNE Frascati
Physics start date	1999
Physics end date	---
Maximum beam energy (GeV)	0.510
Luminosity (10^{30} cm^{-2} s^{-1})	453
Time between collisions (μs)	0.0027
1. Full crossing angle (μ rad)	5.*10^4
Energy spread (units 10^{-3})	0.40
Bunch length (cm)	1.4 (at 10 mA)
Beam radius (μ)	H: 260 (at IP) V: 4.8
Free space at interaction point (m)	±0.295
Luminosity lifetime (h)	0.2
Maximum achieved current e^-/e^+ (A)	2.45 / 1.4
Turn-around time (min)	2 (topping up)
Injection energy (GeV)	on energy
Transverse emittance (10^{-9} π rad-m)	H: 260 V: 2.6
β* amplitude function at interaction point (m)	H: 0.26 V: 0.009
Beam-beam tune shift per crossing (units 10^{-4})	440 (at L_{MAX} SIDDHARTA run)
RF frequency (MHz)	368.667
Particles per bunch (units 10^{10})	e^-: 3.2 / e^+: 2.1
Bunches per ring per species	100 ÷ 105 (120 buckets)
Average beam current per species (mA)	e^-: 1500 e^+: 1000
Circumference (km)	0.098
Interaction regions	1 (a second one can be restored)
Magnetic length of dipole (m)	Outer ring: 1.2 Inner ring: 1
Length of standard cell (m)	No standard cell
Phase advance per cell (deg)	---
Dipoles in each ring	8
Quadrupoles in each ring	48
Peak magnetic field in dipoles (T)	1.2
Wigglers in each ring	4
Damping Times (t_E/t_x), ms	17.8 / 36.0

Conclusions

DAΦNE is a valuable and unique infrastructure that should still play a role in the particle accelerator community.



DAΦNE-TF Workshop

(December 17th 2018 in Frascati)

Organized under the auspices of the LNF Director Dr. Pierluigi Campana

Scientific Committee:

__L. Rivkin__ (EPFL and PSI, chair)
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A. Ghigo (INFN-LNF)
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C. Milardi (INFN-LNF),
N. Pastrone (INFN-Torino)
A. Variola (INFN-LNF)

Local Organizing Committee

__A. Drago__ (INFN-LNF, chair)
S. Caschera (INFN-LNF)
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Thank you to all the participants