DAΦNE as Open Accelerator or FCC-ee Test Facility

aimed at studying Physics and Innovative Technologies for Particle Accelerators
and exploring FCC-ee Key Concepts and Hardware Prototypes

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Scientific Head of the DAΦNE Accelerator Complex

Frank Zimmermann

Presenter

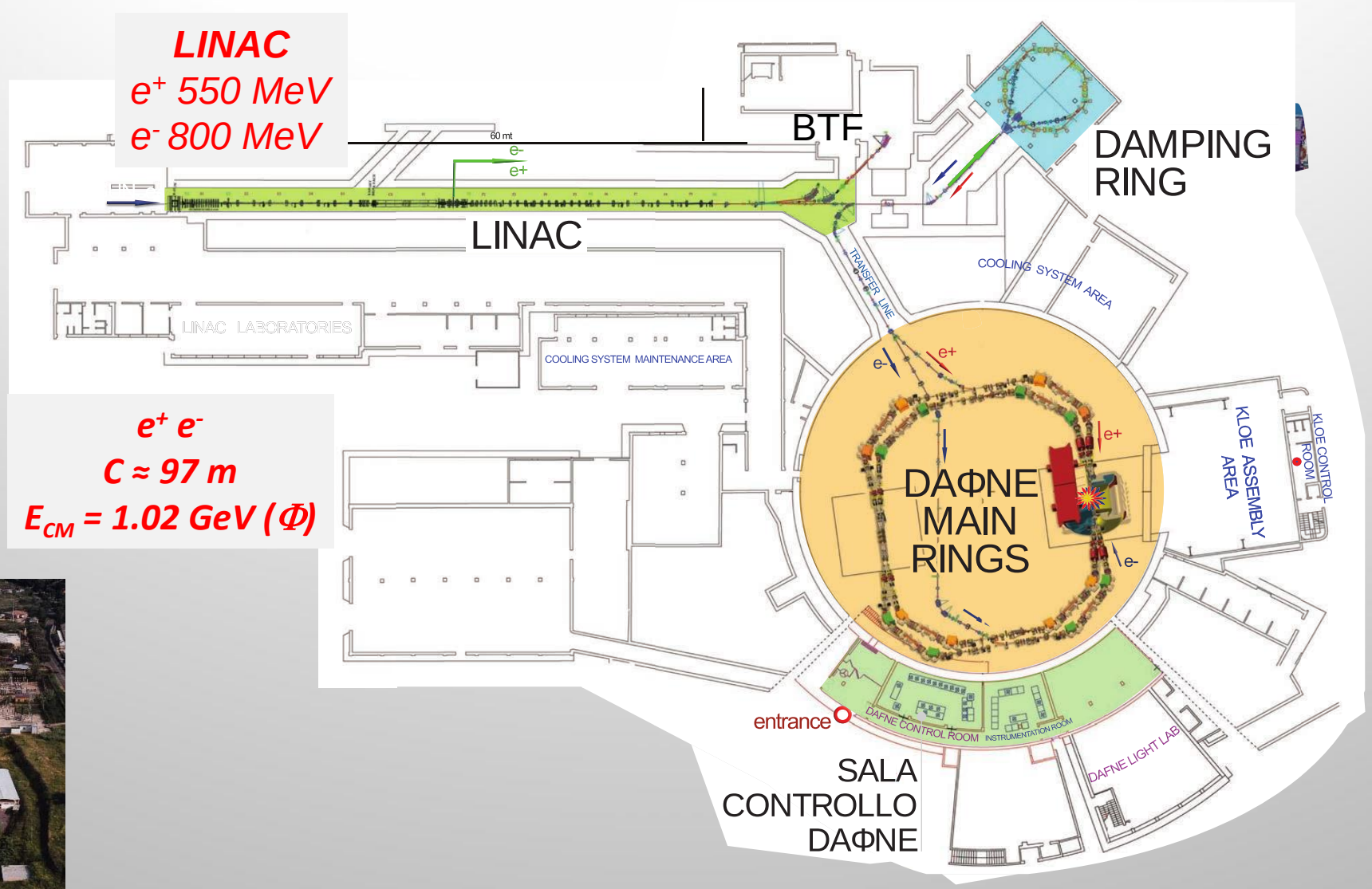
FCCIS 23 WP2 Workshop, Circular Collider Innovation Study**, Nov 13 – 15, Rome Italy.**

Outline

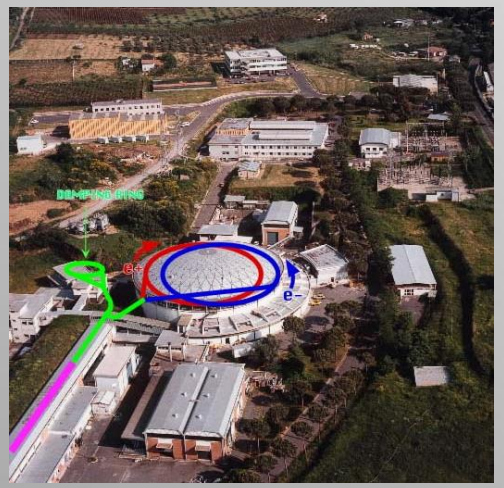
- **DAΦNE *overview***
- **DAΦNE achievements** *and contributions to the physics of particle accelerators*
- ***The opportunity*** *of converting the accelerator complex into a Test Facility*
- *Some ideas from the* **DAΦNE-TF *workshop***
- *One proposal: Converting DAFNE* ***to European/Int'l high-current beam & cw SRF Test Facility***
- **Conclusion**

The DAΦNE Accelerator Complex

LINAC
e^+ 550 MeV
e^- 800 MeV



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



DAΦNE History & Plans

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

- It has been providing data in independent 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

  Crab-Waist Collisions successfully implemented and tested

- Present DAΦNE activities
  as a collider for the **SIDDHARTA-2 experiment**
  DAFNE-light Facility
  DAΦNE LINAC is securing data to two **BTF lines,** and the **PADME** experiment.

DAΦNE achievements

- luminosity achieved at DAΦNE ~order of magnitude higher than obtained at other colliders operating in a similar low energy range.
- impedance budget is a factor 80 lower than in a 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 highest ever stored in particle factories and modern synchrotron radiation sources. DAFNE also offers the highest positron current available in the world today.**
- DAΦNE is the first collider operating routinely with, and thanks to, electrodes for e-Cloud mitigation
- ***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.***

Crab-Waist Colliders

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

Colliders	Location	Status
DAΦNE	Φ-Factory Frascati, Italy	In operation (SIDDHARTA, KLOE-2, **SIDDHARTA-2**)
SuperKEKB	B-Factory Tsukuba, Japan	Adoped CW collision Scheme few years ago
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

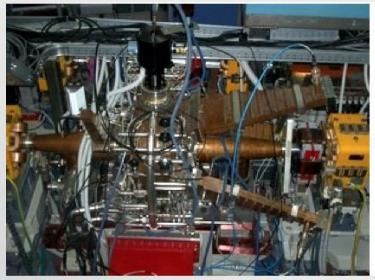
DAΦNE Vacuum Chamber Elements

Optimized to: avoid heating, reduce impedance, and damp HOM

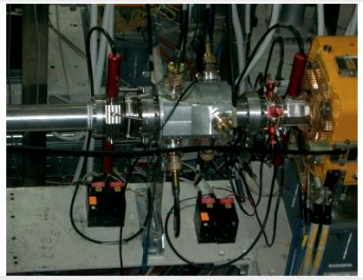
Impedance budget is a factor of 80 lower than in similar storage ring (EPA)

Longitudinal feedback kicker designed for DAFNE adopted at: KEKB, BESSYII, PLS, SLS, HLS, ELETTRA, KEK PF, PEP II

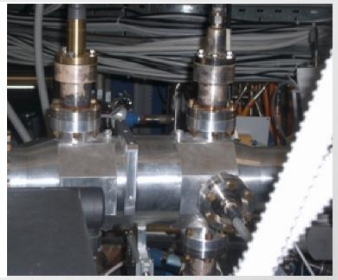
This R&D effort largely contributed to improve beam dynamics and beam-beam performances



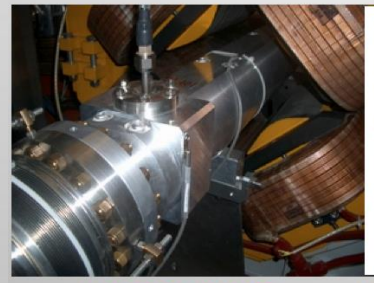
RF CAVITY



LONGITUDINAL KICKER

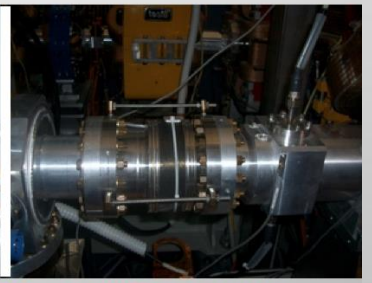


TRANSVERSE KICKER



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

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	terminated
SuperKEKB	2.62 (e^-), 3.6 (e^+) 1.1 (e^-), 1.3 (e^+)	0.7, 0.5	7	6	design values, obtained so far
DAFNE	**2.4 (e^-), 1.4 (e^+)**	**0.4, 0.3**	**16**	**2.7**	**highest in the world**
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

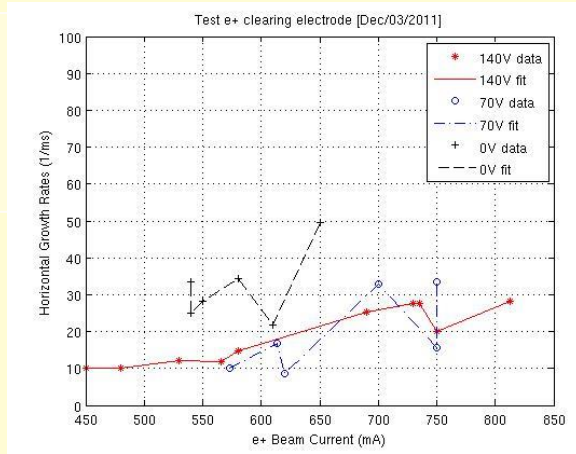
DAΦNE is the first collider operating routinely with electrodes, for e-cloud mitigation, ECE.
ECE provided stable operation with the e^+ beam, and allowed unique measurements such as:

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

demonstrating their effectiveness in restraining e-cloud induced effects

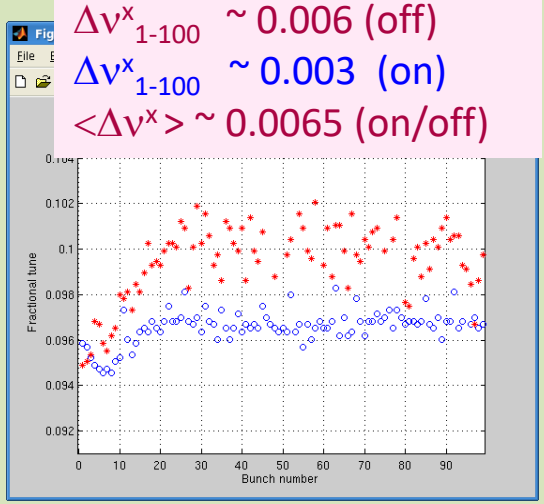
(D. Alesini et al, Phys. Rev. Lett. 110, 124801 (2013)

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

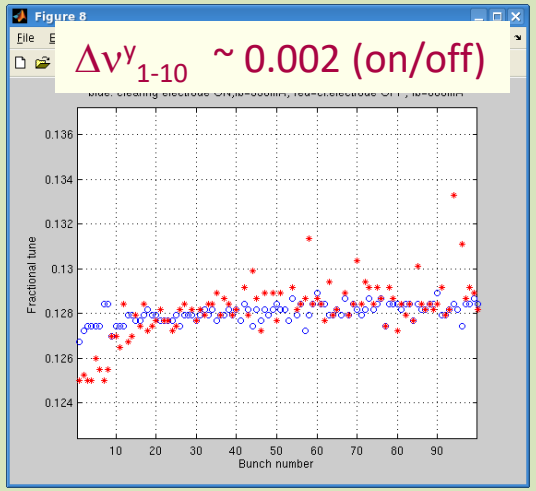


Tune Spread measurements

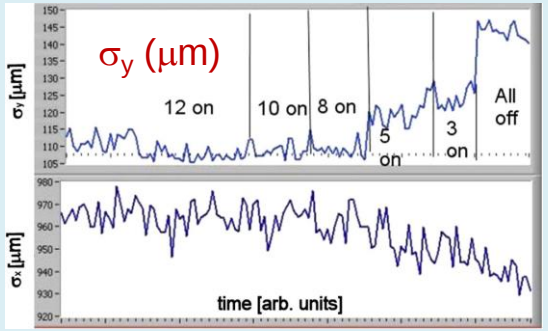
$\Delta\nu^x_{1\text{-}100}$ ~ 0.006 (off)
$\Delta\nu^x_{1\text{-}100}$ ~ 0.003 (on)
$\langle\Delta\nu^x\rangle$ ~ 0.0065 (on/off)



$\Delta\nu^y_{1\text{-}10}$ ~ 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) 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

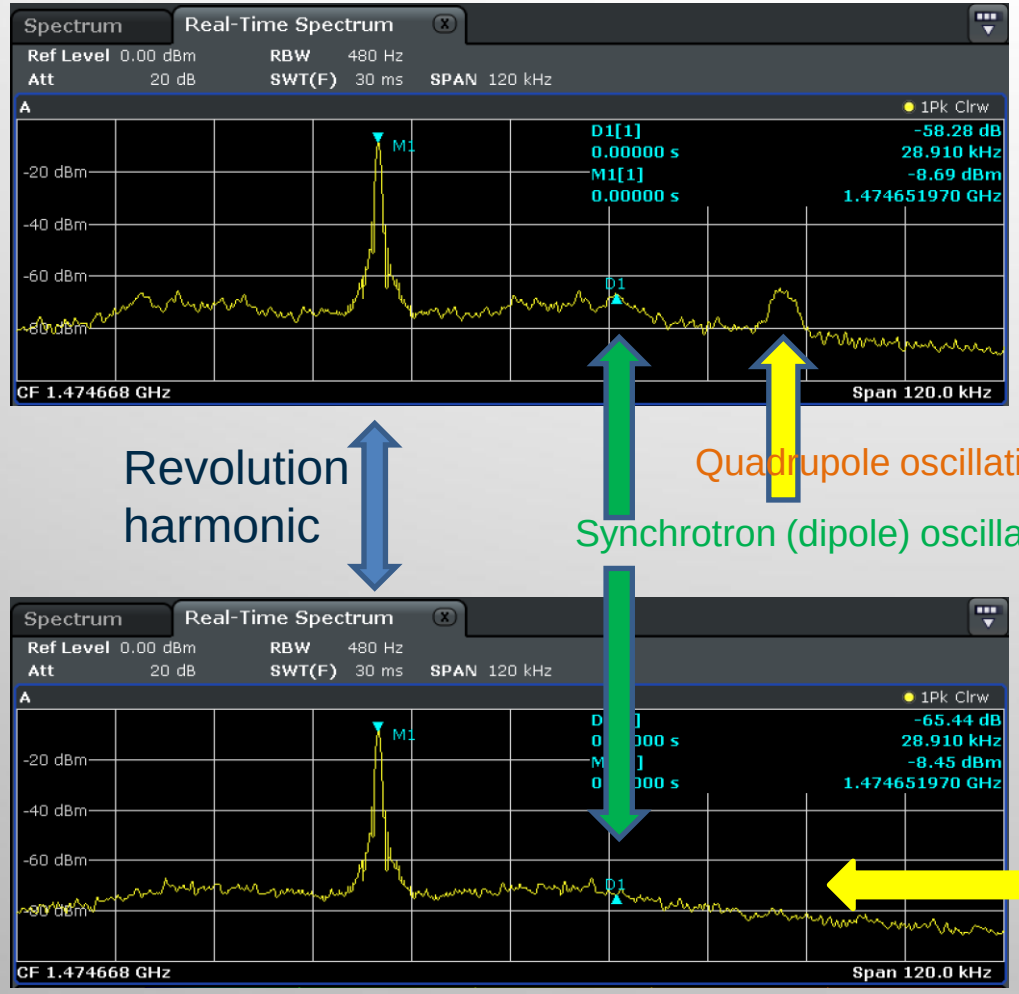
- longitudinal mode-0 & quadrupole oscillations
- noise coming from pickups (harmful for beam vertical size)
- e-cloud effects (in the e+ ring)

Solutions:

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

Longitudinal Quadrupole Oscillations

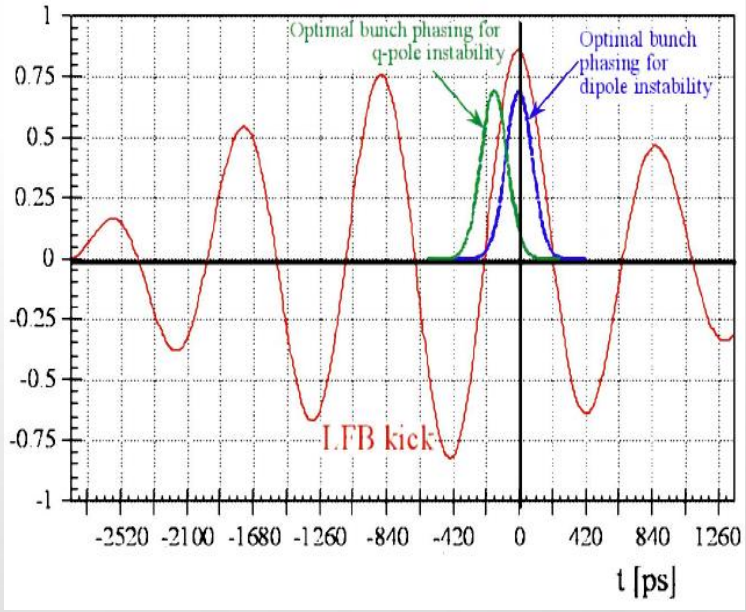
@ $f \sim 2 \cdot f_{sync}$



Revolution harmonic

Quadrupole oscillation

Synchrotron (dipole) oscillations damped by Long FBK

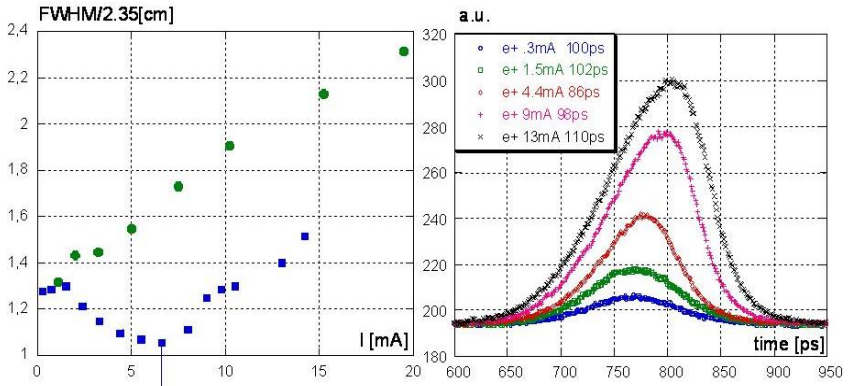


This instability, if not controlled, saturates the longitudinal feedback

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

$\alpha_c < 0$ at DAΦNE

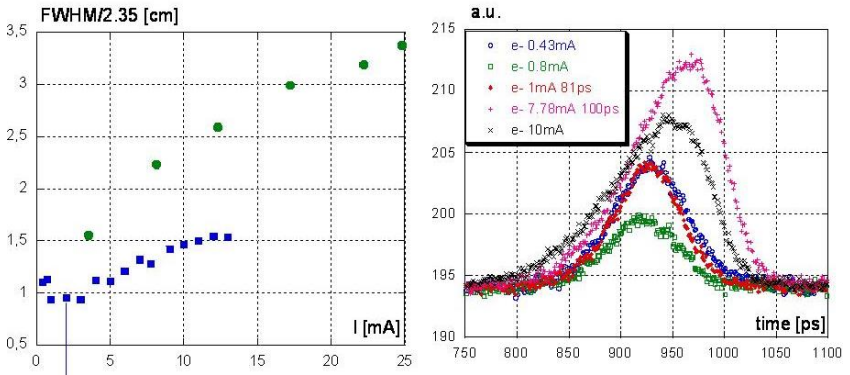
Bunch Shortening in the Positron Ring



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

$$I_b \sim 40\ mA$$

- 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 & 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 length 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 aimed at:

- studying physics problems and innovative technologies which are of interest for the particle accelerator community
- testing innovative concepts
- implementing short term experiment about fundamental and applied physics
- training young generations of particle accelerator physicists

DAΦNE Possible Plans

Beyond 2024

DAFNE might be used for 3-4 additional years (or more!);
with machine operation over 4-5 months per year

During these periods, it could still be used as a collider, and / or as an Accelerator test facility

Some specific tests would require the presence of an experimental apparatus able to evaluate collision efficiency.

DAFNE-light Facility could operate in parallel and/or in other periods

DAΦNE LINAC will continue to power two **BTF lines**

This plan requires a minimal refurbishment of the accelerator complex that can also be implemented progressively

The DAΦNE-TF Opportunity

DAFNE is the first **collider on which the Crab-Waist Collision scheme** worked and where it is still working at full regime with different kinds of experimental apparata with and without experiment solenoid.

If converted into a facility for the study of physics and technologies for accelerators, **DAFNE-TF would add to the small number of accelerators available for this purpose.** If one considers just electron machines, this list includes ATF2 (KEK, for ILC/CLIC), CLASSE (Cornell Laboratory for Accelerator Based Science and Education) for the development of accelerator technologies located on an university campus, and KARA (Karlsruhe), devoted to R&D of machines & applied research.

DAΦNE-TF would be the only facility in Europe providing a positron beam. It also is the only e^+e^- collider in Europe where key concepts of FCC-ee can be tested

DAΦNE-TF would operate when CERN won't have beams

- during each long stop

In this context the availability of DAΦNE-TF for accelerator studies could be even more interesting.

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 electron rings have been 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** close to 70%.

- 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

- ***E-cloud studies***
- ***Monochromatization test***
- *Validation of codes for luminosity, beam-lifetime and background simulation in lepton colliders (including tune scans; and controlled IP aberrations)*
- ***Study of interplay among beam-beam and collective effects, including simulation code validation.***

These activities in some extent have already started

- ***Study of low SEY (Secondary Electron Yield) elements and impedances; Graphitization of chambers and other technologies.***
- *Study of* ***Beam Ion Instabilities***
- ***Beams interacting with amorphous materials, crystals, lasers, plasma***
- *Test of* ***Emittance manipulation***
- ***Components for accelerators (vacuum chambers, collimators, masks, kickers, perhaps SRF cavities) and innovative beam diagnostic techniques***

Possible activities

- ***High gradient tuneable permanent magnets***
- ***New Architectures for Fast Low Noise Feedback***
- ***Narrowband feedback to suppress the (FCC-ee) Res. Wall instability***
- ***Novel Tune and Beam Diagnostics***
- ***Wideband Kicker structure***
- ***Components for future SLED and pulse flatness compensation***
- ***Accelerator components realized with 3D printers.***
- ***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 additional 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:

- 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
- 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 would represent an excellent and unique 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.

It may be an indispensible training ground in the run up to FCC-ee

https://agenda.infn.it/event/16334/images/2335-DAFNE2020_EN.pdf

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

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)*
C. Bloise (INFN-LNF)
Ghigo (INFN-LNF)
M. Giovannozzi (CERN)
C. Milardi (INFN-LNF),
N. Pastrone (INFN-Torino)
A. Variola (INFN-LNF)

Local Organizing Committee

A. Drago *(INFN-LNF, chair)*
S. Caschera (INFN-LNF)
A. De Santis (INFN-LNF)
O. R. Blanco Garcia (INFN-LNF)

https://agenda.infn.it/event/16334/

25 proposals

96 participants from: CERN, Switzerland, Italy, Germany, Austria, Japan, China, USA

DAFNE Test Facility

Katsunobu Oide and Frank Zimmermann

INFN Frascati, 17 December 2018

many thanks to
Michael Benedikt, Manuela Boscolo, & Catia Milardi

Work supported by the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

one proposal: Converting DAFNE to European/Int'l high-current beam & cw SRF Test Facility

(M. Benedikt)

1. qualifying multi-cell SC cavities for high current CW operation

(truly unique facility!)

- **extremely relevant for all proposed future circular colliders**, ***FCC-ee, FCC-hh***, *CepC, SppC,* ***LHeC, HL-LHC****, FCC-he, eRHIC, MEIC* [+ also for **ERLs, synchrotron light sources**, etc.]
  - potentially huge group or partners and users
- **key issues**: **trapped modes**, longitudinal & transverse impedance, fundamental power coupler, **HOM losses**,… cavity design optimization

Converting DAFNE to European/Int'l high-current beam & cw SRF Test Facility

2. demonstrating target SRF efficiency (wall plug to beam power)

- another key issue for all future facilities

3. impedance & HOM effects for RF cavity and other accelerator components

- qualification of vacuum chamber prototypes, collimators and masks, kickers, etc. for *e* and p colliders with various filling patterns
- qualifying novel beam diagnostics for *e* and *p* colliders

Converting DAFNE to European/Int'l high-current beam & cw SRF Test Facility

4. tests & demonstration of other essential, or proposed, **concepts** for future circular colliders

- **pushing the limits of the crab-waist collision scheme**
- **novel pretzel–orbit wake field effects**
- **SR effects on vacuum for *ee* and hh colliders**
- **energy calibration methods (?)**
- **mono-chromatization schemes (?)**
- **e^+ source studies, various e^+ targets, even polarised e^+?**
- **several schemes for top-up injection**

- **4-beam collisions? plasma b-b compensation? crystals?**

some of these concepts would also strengthen DAFNE physics program

big question: can we use multi-cell SC cavities with A beam current? (Ross, Yokoya)

past operation of multi (4 or 5)-cell SC cavities at KEK, CERN, and DESY

maximum beam current:
TRISTAN: ~14.5 mA
LEP: ~8.5 mA
HERA: <100 mA

more modern higher-current (*Ampere*-scale) facilities

PEP-II: only normal conducting RF.
KEKB: mostly NC storage cavities & 10 1-cell SC cavities

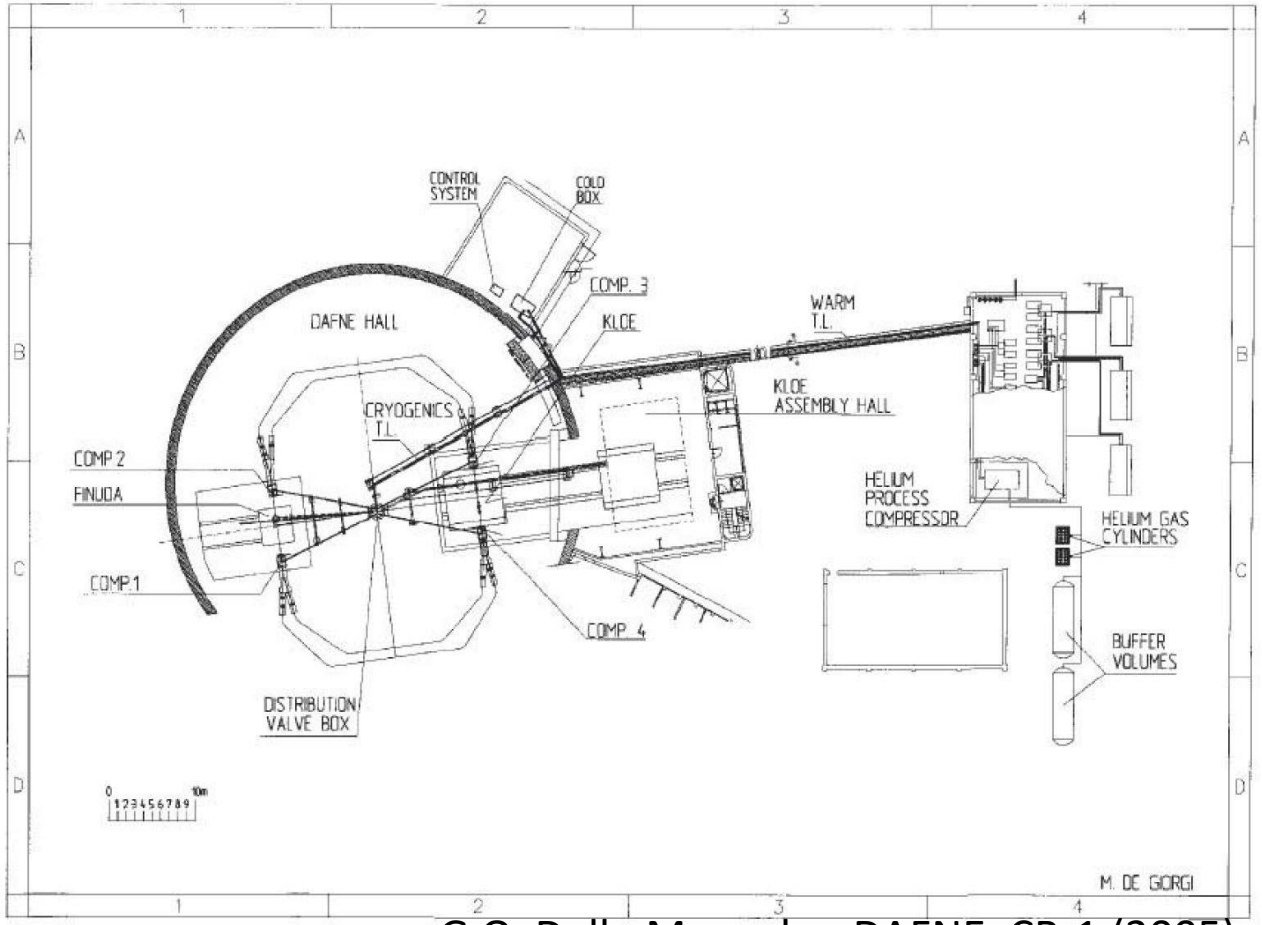
present/past designs of multi-cell cavities for high current

BNL eRHIC for 0.6 to 1 A, DAFNE for > 1 A

existing DAFNE cryogenic system

layout of DAFNE cryo system for 6 SC magnets

marginal for 4.4 K operation of 1 cavity ?



G.O. Delle Monache, DAFNE, CR-1 (2005)

refrigerator plant LINDE TCF 50

nominal compressor power of 250 kW, delivering two cold He lines:

- **4.4 K @ 3.0 bar (100 W nominal power** + 1.14 g/s LHe);
- 77 K @ 10 bar (900 W nominal power).

summary

"… an SRF and high-current test facility [in Frascati] could nicely complement CERN's SRF development program and could be also relevant for testing any high-current related effects (impedances, vacuum, beam heating, etc.) while making efficient use of an existing infrastructure and supporting in this case strongly the Italian accelerator community"

Michael Benedikt, FCC Study Leader,

in full agreement with Frédérick Bordry,
then CERN ATS Director,

10 November 2014

DAΦNE Test Facility –

an opportunity not to be missed !