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Proposal for a possible use of DAFNE as an open infrastructure (DAFNE-TF) for the study of physics and innovative technologies for accelerators

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The conclusion of the Siddharta-2 run will make DAFNE available to accelerator researchers and technologists by 2020 onwards. This comprises an infrastructure made of a Linac, an accumulator, two storage rings for electrons and positrons, and a synchrotron-light laboratory with seven beam lines. A complex that is almost unique in the world, could become a test facility (DAFNE-TF) open to the international community for studies of accelerator technologies, beam physics, for small experiments, and to be used as a technological test bed for enterprises in the sector. This report, prepared for the INFN management, is intended to list some of the most interesting research options and to present a preliminary assessment of the operation costs together with the necessary refurbishments.

Introduction

DAΦNE is an electron-positron collider designed in the mid '90s, becoming operational in 2000. It has been providing data in consecutive data-taking periods for the KLOE, DEAR and FINUDA experiments until 2006, for Siddharta in 2009, and again for the upgraded KLOE-2 between November 2014 and March 2018. It will continue operating for PADME (just using the upgraded Linac) and for Siddharta-2 in 2019. DAΦNE is the only existing phi-factory on which starting from 2007 the *crab-waist* scheme has been successfully implemented with and without the experiment solenoid.

Much of the hardware installed in DAΦNE, although constantly maintained and improved, dates from mid '90s. A refurbishment focused on the most relevant aspects was realized in 2013, and continued in the following years, while a significant upgrade of the Linac is in progress, including the split of the Beam Test Facility (BTF) in order to increase the number of future users.

Despite the relatively obsolete nature of part of its components, DAΦNE and BTF were able to regularly provide beams for more than 6,000 hours per year, keeping their operational efficiency at levels above 80% for long periods. During the last decade, the Linac has powered the BTF for external users with great success, while DAΦNE was simultaneously operating in collider mode.

In the same years, the synchrotron-light laboratory operated in parasitic mode, hosting external users for about 800 hours per year, getting the financial support from the CALYPSO program, in Horizon 2020. Thanks to synchrotron-light activity, the Laboratory is included in LEAPS, the *League of European Accelerator-based Photon Sources*, which stands as one of the big communities entitled to apply for EU Horizon Europe (FP9 program) funding, for the development and operation of research facilities for synchrotron light users.

The DAΦNE complex hosts also a cryogenic plant, recently modernised, enabling to operate superconducting magnets, experimental setups, and superconducting radiofrequency systems (although the latter have never been used at DAΦNE).

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 to this purpose. If one considers just electron machines, the 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 ANKA (Karlsruhe), devoted to R&D of machines and applied research. Recently also the IOTA storage ring started its operation with electrons at FNAL, an innovative test bed dedicated to the science of particle acceleration. Generally, these infrastructures are meant to operate for a few months per year. In the case of DAΦNE-TF, users would benefit from a level of scientific and technical support, provided by the LNF personnel, built on longstanding expertise.

Furthermore, the facility 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 DAΦNE-TF for accelerator studies even more interesting.

Tests of Accelerator Physics and Technology

The lines of technological research identified so far for DAΦNE-TF consider:

- the machine operating parameters (reported in Annex 1);
- the impact that tests can have in terms of machine layout and components modification, thus excluding invasive measurements and experimental activities hardly compatible with current configuration;
- the maturity level of the experimental programmes proposed.

The list includes:

1. *Study of low SEY (Secondary Electron Yield) elements and impedances. Graphitization of chambers and other technologies.*

The reduction of SEY in the vacuum chambers allows to inhibit or reduce the resonance effect that originates the *electron cloud* and the resulting instabilities. The effect of graphitization on the SEY has already been proven, but machine tests remain central to assess its impact in terms of impedance budget. Special devices, like coldDIAG (superconducting vacuum chamber, a very preliminary version of which has been realized at ANKA), could be installed in the present interaction region of KLOE to implement measurements also as a function of temperature, both with electron and positron beams. Such apparatus could be also useful to characterize and study new technologies to construct collimators. These studies are declared to be of CERN interest in view of HL-LHC and, in future, for FCC.

2. *Components for accelerators (vacuum chambers, collimators, masks, kickers) and innovative beam diagnostic techniques*

The chance to test with beams the performance of diagnostic tools based on innovative concepts and materials is of particular importance not only for the particle accelerator community, but also for specialized companies, which would have at their disposal an exceptional test-bed.

3. *Accelerator components realized with 3D printers*

The new technologies related to 3D printing seem to be particularly suitable, especially for high-precision mono-block structures, as recently proven at BNL with the realization of the structures for the permanent magnets.

4. *High power solid state RF amplifiers*

Solid state amplifier technologies have already been implemented and successfully tested as RF power source in many circular machine (SOLEIL, ESRF, DAFNE Damping Ring, etc...). That enabled a significant increase of the accelerator up-time, avoided configurations with high-voltage gradients, and reduced costs of acquisition, operation, and maintenance. The future trends will aim at reaching frequencies near 500 MHz, with efficiencies greater than 50%, and at extending the technology to the L band structures.

5. *Wide-excursion adjustable permanent magnets*

The development of the technology to realize adjustable permanent magnets is of particular interest for synchrotron-light machines, since it would make possible to drastically reduce operation costs maintaining, at the same time, an appropriate level of flexibility for machine configuration now guaranteed only by the use of electromagnets.

6. *High-power positron sources. Peak Energy Deposition Density in the targets, wide aperture capture, accelerating sections in S Band*

One of the most advanced challenges for the future projects of linear colliders is the realization of medium-current positron sources (e.g. for ILC). The latter must be designed not only at level of production target, but also in the capture phase reducing the angle by systems transforming angles in positions (QWT or AMD systems). In terms of design, the solution that captures positrons in L band sections in 2^{nd} harmonics, or in S band sections with large iris, sounds particularly promising.

7. *Components for future SLED and pulse flatness compensation*

For multi-bunch operations, the regulation of SLED pulses is fundamental. It can be performed by the study and realization of high precision LLRF masks in the classical systems, or by developing new techniques such as the dual mode SLED ones. Developments of single cavity systems, like in BOC systems of PSI, look interesting too.

8. *Emittance manipulators*

Also if 6D emittance is an invariant under linear transformation it is possible, by means of special devices, to transfer the 2D subset emittances from one degree of freedom to another. This would provide beams with different characteristics for a variety of purposes, ranging from low emittance beams mandatory for FEL or Compton emission experiments, to beams with really small energy spread essential in order to accurately define initial states as a function of the energy.

9. *Beams interacting with amorphous materials, crystals, lasers, plasma*

Beam tests at high currents with insertion of targets, lasers or plasma are particularly relevant. Measurements of the average lifetime of the interacting beams and the characterization of sources derived from the interaction, would represent a desirable progress. In the case of targets, it is important to study how a very high-flux source can be achieved, preserving the chemical-physical characteristics of the target, and how to measure the beam dynamics in this regime. Activities related to the exploration of future use of crystals to manipulate particle beams (as focalization or acceleration) may be of interest at DAΦNE-TF, after the necessary assessment of the experimental setup required. In the field of plasma acceleration, besides the source characterization, a first test of the behaviour of high repetition rate plasma in CW could be achieved.

10. *Testing new methods to generate terahertz coherent radiation*

Recently, a new mechanism has been proposed to produce coherent radiation with high repetition rate at wavelengths from the submillimetre to extreme ultraviolet range by inducing steady-state microbunching in a storage ring. One could explore the possibility to test such new method or some of its specific aspects on one of the DAΦNE rings.

Most of the topics proposed above are of general interest for the community of accelerator physicists and synergies with the ongoing studies for the future colliders are clearly recognizable. In this list, priority was given to measurements and tests performed with a single operating ring. However, running with two beams should also be considered, since it opens to other possibilities, such as the study of fundamental parameters in the beam-beam interaction at high-current.

Some expressions of interest concerning some of the research lines presented, already arouse from informal discussions with colleagues of INFN, CERN and other foreign Laboratories:

- preliminary proposal [1] of converting the DAΦNE positron ring as a high duty cycle positron pulse stretcher and storage ring, for producing a high-intensity (up to 10^{10}), high-quality and high-energy (up to 500 MeV) positron beam for HEP experiments, mainly, but not only, motivated by light dark-particles searches. Such a facility would provide a unique source of ultra-relativistic, narrow-band and low-emittance positrons, with a high duty cycle. In this frame the option of using channelling in crystals, has been proposed to further extend pulse duration on the positron ring;
- collaboration [2] with CERN Vacuum Group to study the behaviour of vacuum pipe surfaces with DAΦNE-Light lines for HL-LHC and FCC R&D;
- proposal [3] to test high positron fluxes on thin targets at DAΦNE, in order to test new design concepts to be used for a possible future muon collider.
- possibility of tests of SRF cavities [4] at high beam currents for future machines.

[1] S. Guiducci, Preliminary Considerations on the Use of DAFNE Positron Ring as a Pulse Stretcher for the DAFNE Linac, DAFNE Technical Note, G-73;
P. Valente, POSEYDON - Converting the DAFNE Collider into a double Positron Facility: a High Duty-Cycle pulse stretcher and a storage ring, arXiv:1711.06877;

[2] KE3724/TE/HL-LHC, INFN-CERN Collaboration in synchrotron radiation studies in the framework of the High Luminosity upgrade for the LHC at CERN;

[3] M. Boscolo et al., Low emittance muon accelerator studies with production from positrons on target, Phys. Rev. Accel. and Beams, vol. 21, p. 061005, 2018;

[4] M. Benedikt, F. Zimmerman, private communications

Experimental physics measurements

We intend to propose DAΦNE-TF also as a machine where small physics experiments, both of fundamental and applied research, can be developed and carried out within a short time-scale. A qualifying element of every possible proposal in this field is its time-scale. Experiments needing very long data-taking, with high efficiency and high luminosity, can be hardly included in the operational scheme described above.

Therefore, among the possible proposals still to be assessed, there are the measurement of processes with high effective cross sections, which are feasible with small experimental set-ups. These comprise tests for the 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 opportunities

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

There are very few accelerators available for academic training programs. DAΦNE-TF could develop programmes connected to the PhD theses in Accelerators at Roma Sapienza and in related areas in other Universities. In the field of advanced training, LNF could participate, together with other European laboratories, to specific calls in Horizon 2020, like for instance, the *Innovative Training Networks.*

Resources necessary for consolidation and operation

The accelerators are operated 24/7 by a team of technicians (in 3 daily shifts of 4 people each) and by a group of accelerator researchers and technologists. The operation in collider mode, having to maximize luminosity for the experiments, is very demanding for the Accelerator and Technical Division teams, since it requires rapid intervention. This effort will be reduced at DAΦNE-TF and the manpower will be shared with the one operating BTF.

A significant factor to assess the operational costs of DAΦNE-TF is the energy consumption. A year of functioning (about 10 months) in collider mode has a cost of 3.4 ME, at the current average price of 160 E/MWh, distributed as follows: 0.4 ME for the consumption of BTF, 0.4 ME for KLOE2 and the cryogenic plant, 0.7 ME for the 8 wigglers, and 1.9 ME for the accumulator and the two rings.

Assuming the operation of BTF will continue all the year round, and that, typically, in DAΦNE-TF it will be necessary to operate just one ring, the run for a few months a year (for example four) would have an additional economic impact compared to the BTF – in terms of electricity – of about 500-600 kE/year. Specific cooperation agreements with the users could include a financial contribution from the participating institutes to that expenditure, and even to the costs of supporting staff. A very preliminary evaluation of minimal consolidation costs can be summed up in about 2.7 ME. A qualifying aspect of the interventions lies in the upgrade of the diagnostic components of the machine, which could initially be focused to a single ring. The refurbishment plan presented here is based on the following assumptions: the BTF will not require relevant interventions after the on-going upgrade; the service facilities (electricity, cooling, various plants) will continue to operate with the current maintenance programme, with no structural overhauls. These assumptions, which are entirely reasonable, should in any case be supported by further studies, considering any issues emerging from the future runs.

Conclusions

The possible use of DAΦNE-TF at the end of its operation as a collider is believed of great interest and useful for the international community of accelerator physicists. Maintaining the experimentation on electron machines would be an asset for LNF and INFN. The functioning, including a partial one, from 2020 onwards, would allow to preserve the expertise of the community of LNF and INFN physicists, technologists, and technicians in electron-based machines, which would represent a resource for the future EuPRAXIA project as well.

Without conducting a systematic investigation, a range of technological problems that could be studied at DAΦNE-TF, and which are of great interest to the community, have been identified. Moreover the availability of this machine would certainly lead to other ideas, whose feasibility should be assessed. There is also space for small fundamental and applied physics experiments, besides the measurements with synchrotron light, which further justifies the operation of the machine for a few months a year, without overburdening on costs and personnel engagement.

In order to take full advantage of such opportunities, a plan of consolidation of some of the most obsolete hardware components, together with the installation of a more advanced diagnostics must be scheduled. In this framework, cooperation agreements with other European laboratories can include the use of equipment provided by the users.

To launch the initiative, a mini-workshop will be organized in the coming months, to discuss some of the most promising proposals. Then, a standard call procedure would allocate the beam on the basis of scientific interest, feasibility, complexity, and machine availability.

Preserving a big facility as DAΦNE-TF is crucial to maintain and develop the LNF human, technical and scientific resources. The access of international users, the new challenges, the young people in training, the dissemination, the technological transfer, the small and big projects to be performed, and the new ideas, represent the lifeblood that enlivens, day-to-day, the acquisition of knowledge in our field and the cultural atmosphere of the largest and oldest INFN Laboratory.

Annex 1

The DAΦNE collider Parameters

	DAΦNE 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 (μ s)	0.0027
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 (τ_E/τ_x), ms	17.8 / 36.0

- **Linac**

Based on S-band technology

PARAMETERS

repetition rate 50 Hz
e^+ beam with E ≤ 550 [MeV]
I^+(pulse) ~ 100 mA
e^- beam with E ≤ 800 [MeV]
I^-(pulse) ~ 250 mA
ε_- ~ 1 mm mrad   Dp/p ~ 1%
ε_+ ~ 5 mm mrad   Dp/p ~ 5%
pulse width: 1 ns ≤ $I^\pm$ < 200 ns

A possible upgrade plan for the Linac by adding a fifth accelerating section which should provide:

e^+ beam with E ≤ 700 [MeV]
e^- beam with E ≤ 1000 [MeV]

DIAGNOSTICS

14 Beam Position Monitors
4 fluorescent screens
4 Wall Current Monitors
1 spectrometer for energy and energy spread measurement
emittance measurement

- **Damping Ring**

Dipoles and Quadrupoles can work and have been characterized up to E ≤ 560 [MeV]
All magnets are based on laminated yoke technology.

DIAGNOSTICS

Removable fluorescent screens equipped with cameras and accessible by a triggered Frame Grabber unit.
8 four buttons BPMs acquired by LIBERA modules
1 total current monitor
1 synchrotron radiation monitor
1 beam loss monitor
Network analyser + white noise generator for transverse betatron oscillation frequency measurements.
Oscilloscope to monitor and setup the injection/extraction timing

- **Transfer Lines**

Dipoles can work up to E ≤ 800 [MeV]
All magnets are based on laminated-yoke technology.

DIAGNOSTICS

Removable fluorescent screens equipped with cameras and accessible by a triggered Frame Grabber unit:

7 Tle injection
12 Tle extraction
5 Tlp injection
12 Tle extraction

16 Stripline Tle extraction
10 Stripline Tlp extraction
3 current monitors (ICT) in injection
5 current monitors (ICT) iin extraction

- **Main Rings**

Magnets

Dipoles can work and have been characterized up to E ≤ 530 [MeV]
Large quadrupoles |Kq|E ≤ 2224 [MeV m^{-2}]
Small quadrupoles |Kq|E ≤ 3200 [MeV m^{-2}]
Large Sextupoles |Ks| Ls E ≤ 7500 [MeV m^{-2}]
Small Sextupoles |Ks| Ls E ≤ 6666 [MeV m^{-2}]

All magnets are based on laminated-yoke technology.
All quadrupoles and sextupoles in the Main Rings are independently powered
Wiggler are powered in series in each Main Ring
Wigglers can be switched off accepting to have longer damping times
MRs RF systems

250 – 300 KV
120 harmonic number

DIAGNOSTICS in each ring

46 BPMs (4 buttons each) acquired by Bergoz modules working at 6 Hz
rms resolution for orbit measurement 5 ÷ 10 μm
6 BPMs (8 buttons each) used for diagnostics and FBKs
4 Libera (Brilliance) modules available on the purpose for commissioning and diagnostics
resolution few microns
1 DCCT total current monitor
1 synchrotron radiation monitor
1 triggerable (RF/4) streak Camera
resolution ~ 10 ps
1 gated camera used for transverse beam size measurements (gate time 20 μs)
resolution ~ 20 μm
FFT spectrum analyser + white noise generator for measuring transverse betatron oscillation frequency.
Front end of the transverse and longitudinal FBKs can be used as bunch by bunch diagnostics tools
Oscilloscope to measure bunch by bunch current
Oscilloscope to monitor and setup the injection timing

Feedbacks, 3 in each ring