Chapter 12
Accelerators at LNF: From AdA to EuPRAXIA

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Abstract The accelerators realized, installed and operated in the Frascati National Laboratories (LNF) from ADONE to the present day are described together with the main characteristics necessary for the experiments that were carried out. The absolutely new elements that characterized all the accelerators realized in LNF and which were then used by other accelerators in the world are described: in particular Bruno Touschek's great contribution to accelerator physics is underlined. Present and future plans are also mentioned in the development of the new generation of accelerators in LNF.

12.1 Introduction

The scientific activity of the National Laboratories of Frascati (LNF) began with the realization of the first Italian high-energy accelerator: the Synchrotron, that produced an intense electron beam at a maximum energy of 1 GeV.

Giorgio Salvini, who was entrusted with the construction of the accelerator and its infrastructure, recruited young and brilliant physicists and engineers from the best Italian universities willing to move to Frascati to participate in this challenge.

The team that built the Synchrotron, an accelerator of formidable complexity, gave an example of how a truly complex system can be realized with study, commitment and perseverance, starting from scratch. The Synchrotron was completed, starting the operations, in 1959.

Bruno Touschek, working with the Synchrotron group, had the brilliant idea of accumulating and accelerating matter and antimatter in the same accelerator and then making them collide to create new elementary particles. Touschek proposed to inject a positron beam into the newly built synchrotron but Salvini was against because many experiments using the synchrotron beam were impatient to take data,

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L. Bonolis et al. (eds.), *Bruno Touschek 100 Years*,
Springer Proceedings in Physics 287,
https://doi.org/10.1007/978-3-031-23042-4_12

then Giorgio Ghigo proposed to build a test accelerator. In only one year: AdA, Anello di Accumulazione was realized, in which electrons and positrons, produced with the Synchrotron beam, were injected and accumulated with a maximum energy of 500 meV. AdA was the world's first matter and antimatter storage ring and from AdA all the colliders built successively descend.

After the AdA great success, ADONE, an electron positron collider 100 m long with an energy up to 3 GeV, was realized in Frascati.

The story of the AdA and ADONE storage rings, the advantages of this collision scheme and the experiments in the particle physics field are presented in this book by my colleagues, showing how, starting from a brilliant intuition, a machine was born that no one thought could be made.

The example of this first generation of accelerators: Synchrotron, AdA and ADONE, has remained in the DNA of the laboratories.

12.2 ADONE Second Life

After the period of experiments on elementary particle physics, a second life was expected for ADONE. The use of storage rings for photon production gave to ADONE a new lifeblood; indeed, in the 1980s, synchrotron radiation lines were installed and ADONE was one of the first-generation synchrotron radiation sources for users.

The photon produced in bending magnet, wiggler and undulator, in the X and VUV range, have been used for many experiments in biological field and in material science.

Gamma rays were also generated in ADONE both using bremsstrahlung on gas jet and Compton backscattering of laser photons by electrons stored in the ring. These high energy photons were used in nuclear physics experiments, starting a generation of accelerators dedicated to these purposes.

At that time several accelerator projects have been proposed, without success, due to budget constraints, for the Frascati labs. INFN continued to participate in the construction of the large accelerators at CERN and of the equipment for high energy physics experiments.

12.3 LISA

While the ADONE accelerator was being used for photon experiments, the accelerator division of the laboratories continued a research and development program on new acceleration techniques. Sergio Tazzari proposed to develop new technologies for future accelerators such as superconducting accelerating cavities and low emittance beams for use in free electron lasers. A project of a low-energy, high repetition frequency linear accelerator LISA was funded, realized and installed in the Frascati Labs in the early ‘80. LISA was one of the first R&D activities in Europe that eventually gave birth to the European XFEL at DESY Hamburg.

The LISA infrastructure, consisting of an underground bunker and control room on the surface, is currently reused by the SPARC-LAB complex.

12.4 DAΦNE Φ-Factory

Touschek’s attitude of looking forward reinvigorated the Frascati Labs in the ‘90s with the creation of a new class of accelerators: the very high luminosity electron–positron collider.

The cost and the size of the high energy accelerators became prohibitive, so the laboratories that have made collider history, such as LNF in Italy, SLAC in USA and KEK in Japan, decided to change the paradigm of the particle physics research with accelerators. Instead of chasing the limits of high energy, they conceived new medium–low energy accelerators with very high luminosity, called Factories, aimed at precision measurements, whose mission was to produce large quantities of particles to study rare events with high statistics.

All three laboratories reused the existing infrastructures to install their new machines in order to save on the budget and the time needed to build the new colliders. A collaborative competition pushed the three laboratories to impressive results in a very short time.

It was therefore decided to realize a Φ-Factory in Frascati, a collider just above 1 GeV in the center of mass, to produce and study the decays of Φ particles. SLAC and KEK, where they had longer tunnels, opted for colliders at 11.5 GeV to produce B particles. The primary purpose of these accelerators was to measure the violation of the charge-parity conservation theorem.

In the early ‘90s the INFN president Nicola Cabibbo set up a working group, chaired by Luciano Maiani, to draw up the possible experiments and define the parameters that the accelerator had to have in terms of luminosity.

INFN called back to Italy Gaetano Vignola, who, together with Mario Bassetti and all the accelerator Division staff, proposed a completely new concept collider: DAΦNE.

After the approval of the project, the group was formed, under the directorate of Enzo Iarocci, also with the recruitment of young people. In less than five years, from the end of ADONE’s operations, the new collider was ready to begin testing (Fig. 12.1).

The basic idea behind the DAΦNE Project was to produce an amount of Φ-particles per year enough to measure the ratio between the direct (in the K-decay) and indirect (connected to the oscillation of K_L in K_S) components of CP violation. This ratio (ε'/ε) was expected of order 10^{-4}. On the resonance peak, 1020 MeV, the effective cross section for Φ production is approximately 2 μb. The collider goal

Fig. 12.1 DAΦNE: the Frascati Φ-Factory. Copyright INFN – LNF

was to produce 10^{10} Φs and 2×10^9 K_S per year. Therefore, a *luminosity* of 2.5×10^{32} cm^{-2} s^{-1} was initially requested.

The Luminosity formula can be written as simply as

$$L = f\, N_b \left(N_e N_p\right) / (4\pi \sigma_x \sigma_y)$$

where f is the revolution frequency of the machine and N_b the number of bunches stored in the rings (f N_b the collision frequency). N_e and N_p are the number of electrons and positrons in each bunch respectively and $\sigma_x \sigma_y$ the rms transverse dimensions at the interaction point.

The luminosity of 1×10^{30}, in single bunch, reached by the best 1 GeV collider at that time, VEPP2M, was taken as a reference for the proposal and it was decided to store up to 120 bunches in two rings 100 m long.

The max number of bunches is determined by the minimum distance between the bunches that avoid the simultaneous collision of two contiguous bunches in the detector.

Scaling all the parameters to get 10^{32}, the scary current of more than 2 A had to be stored in each ring with 10^{11} particles per bunch. In order to avoid parasitic collisions outside the interaction region proper, which contribute detrimentally to the beam-beam limit without *useful* luminosity, it was chosen to build two separate rings for electrons and positrons, intersecting at two interaction points (thus allowing the possibility of accommodating two distinct detectors, although not operating at the same time) where they collide at an angle. A frequency of the accelerating cavities of ~360 MHz has been chosen: since the revolution frequency is ~3 MHz. As many as 120 packets could be injected into 100 m long rings with a distance between them of 2.7 nsec.

In the interaction of two colliding bunches, the limit parameter was the so-called tune-shift. During the interaction of an electron bunch with its positron homologue, one beam, due to the electric charge, acts as a [de]focusing system on the other, with the consequence of producing a *tune shift*; if the tune shift is large the working point moves close to a resonance, with the consequence of widening the beam dimension, losing luminosity, or worse, making the beam completely unstable.

It was decided to make flat beams collide, i.e. they had a horizontal dimension of 2 mm and the vertical one 100 times smaller. This strong focusing had to be obtained at the center of the experimental setup with the latest magnetic lenses far enough away not to obscure the detector's field of view. The bunch length should not exceed 3 cm, otherwise the "*hour glass*" effect would have decreased the luminosity.

The first major concern in this interaction scheme was the synchro-betatron effect in the interaction angle, i.e. the longitudinal and transverse motion transfer from one plane to another with the risk of widening the beams, losing luminosity. The second was the multibunch instability in which each ring could induce longitudinal and transverse oscillations from one bunch to the subsequent ones, through the interaction with electromagnetic field due to the impedance of the components of the vacuum chamber, especially in the RF accelerating cavity, in which the particles traveled.

A great deal of attention has been paid to all other possible sources of limitation of the various parameters. Just to list a few:

- The current was so high that the desorption of the walls of the vacuum chamber required an impressive synchrotron pumping and light absorption capacity: vacuum pumps with enormous pumping capacity and mirror grade vacuum chamber (wall roughness below a micron).
- The very low impedance was obtained by designing all the components of the vacuum chamber with e.m. shielding system and tapered shape.
- The radiofrequency cavities were realized by suppressing the high order excitation modes produced by the beam field, that could act on the contiguous bunches, with innovative waveguide absorber systems.
- Clearing electrodes were installed in the rings to avoid *ion trapping* in the electron ring and to reduce the *electron cloud* effect in the positron one.
- To damp the longitudinal and transverse oscillation modes, a very effective bunch by bunch feedback system was realized, in collaboration with SLAC. This is one of the first examples of parallel data processing in which the position signals from beam detectors were sent to a digital signal processor to reach the calculation speed that allowed an immediate correction of the position of every single bunch.
- A series of wiggler magnets have been installed in order to increase synchrotron radiation emission to decrease the damping time of the injected bunches and to increase the emittance of the beam in order to store higher charge per bunch.
- A fast injection system at full energy in the ring has been realized to inject in top-up scheme. The injection system is composed by a e^+e^- linear accelerator working at 500 meV injection energy. An accumulator / damping ring has been placed between the linac and the main rings; this provides the injection of the charge per bunch with an emittance close to the main rings one, mainly for positrons.

– The *Crab Waist* collision scheme was proposed and implemented on DAΦNE from Pantaleo Raimondi to improve the luminosity.
– In the end the most important limitations of the storable and usable current in DAΦNE, and therefore of the maximum luminosity reached, were the lifetime of the particles which, due to the very high density in the individual bunches, was limited by the *Touschek effect* and the electron cloud.

Several particle physics experiments were installed on DAΦNE during 20 years of operation: first KLOE and KLOE2 which aimed to measure CP violation and make all the high statistical measurements of Kaon physics.

Subsequently the nuclear physics experiment FINUDA was installed in the other interaction region, which was proposed to produce hypernuclei with tags close to the interaction point. The Kaons produced, at the threshold energy by Φ decay, were allocated inside the nucleus, thus creating hypernuclei.

Another class of experiments: Dear, Siddhartha and Siddhartha2, aiming to study the Kaonic atoms, generated by the capture of the K, produced in the Φ decay, by light atoms of cryogenic targets, have been installed on the DAΦNE interaction region.

12.5 SPARC-Lab

A new type of accelerator was proposed in Frascati in the 2000s: a very low emittance injector.

The first experiments on Free Electron Lasers, FEL, to generate coherent synchrotron light in the ultraviolet and X region had been performed on ADONE with the strong limitation of high energy spread and emittance of the electron beam. To have a significant effect, intense beams of low-emittance electrons had to be produced.

SPARC was one of the first injectors in which the electron bunches were no longer generated by thermionic gun and static accelerating fields but by photo-emitters installed in radiofrequency cavities.

In SPARC the charges of the electron bunch and their temporal structures are generated by a laser pulse, of suitable wavelength, sent to the photocathode. The laser beam is easy to manipulate and, together with the possibility of changing amplitude and phase between the accelerating structures, different configurations of electron bunches can be experimented within the same RF bucket.

The cathode is installed in a radiofrequency cavity so that the accelerating electric field on its surface can reach values of the order of 100 MV/m. In this configuration the electrons reach ultra-relativistic speeds in a very short space, reducing the increase in emittance due to space charge. Furthermore, the laser pulse can be of short duration to generate pulses of high peak current (Fig. 12.2).

SPARC was the first radiofrequency photo injector in which the concept of emittance reduction was successfully employed by placing the first accelerating section on the maximum oscillation of the emittance at the gun exit, reducing the value

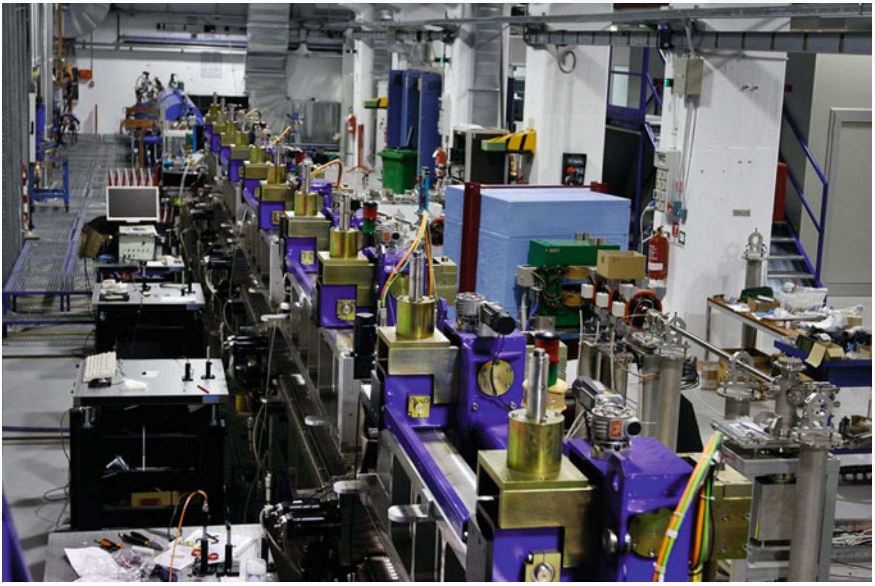

Fig. 12.2 SPARC seen from the FEL undulator side. Copyright INFN – LNF

below 1 mm·mrad. The method of compressing the length of the bunch through the *velocity bunching* technique passing the electron bunch in the off-crest radiofrequency oscillation has also been tested and verified. Different accelerating fields have been experienced between the head and the tail of the bunch to favor longitudinal compression with the achievement in the injector of the high peak current necessary to generate FEL radiation in magnetic undulators.

The SPARC scheme was subsequently adopted in all electron injectors dedicated to FEL or short electron pulse production.

With such intense beams obtained and with the possibility of generating multiple pulses with the laser in the same radiofrequency bucket, the experimentation of plasma acceleration based on the Wake Field Acceleration particle has begun. In this technique a plasma wave is formed by a driver bunch and a following bunch, witness, properly injected into the plasma wave, could be accelerated with accelerating gradients of the order of 10 GeV/m.

The SPARC injector flexibility has given rise to a series of important experiments.

- The two-color FEL was thus tested in Frascati, sending two bunches at slightly different energy to the undulator magnets. It has been successfully replicated at short wavelengths at FACET (SLAC) and in FERMI, the Trieste FEL.
- The train of pulses hundreds of fs short and spaced by 1 ps for efficient generation of THz radiation.
- The harmonics generation of the FEL radiation by injecting short wavelength photons, generated by lasers into a gas, together with the electron beam in the undulators to force their stimulated emission at shorter wavelengths.

- The X photons production by means of the backward diffusion due to the Compton effect of the pulses of the high power laser, FLAME, by the electron beam.
- Finally, the plasma acceleration of electron bunch. The production of FEL coherent radiation with an accelerated plasma beam was also measured at SPARC demonstrating that an accelerated plasma beam can maintains high quality emittance and energy spread characteristics.

On the basis of these experiments and those of the FEL, the new European user facility project EuPRAXIA was proposed and one of the project infrastructures will be built in Frascati.

12.6 EuPRAXIA

In the tradition of the Laboratories, the realization of new-concept particle accelerators, called EuPRAXIA, has been proposed to the European Commission involving the construction of a Free Electron Laser facility driven by a plasma accelerator.

The generation of the electron beam takes place with a high-brightness photoinjector followed by an innovative accelerator that uses radiofrequency in the X band. The beam thus generated is then accelerated by a pre-ionized plasma aiming to reach accelerating gradients greater than 10 GeV/m maintaining the excellent beam quality needed for FEL operations.

The EuPRAXIA project has been approved and funded by INFN and has entered the European road map of research infrastructures, ESFRI. The construction phase is starting with the civil infrastructure. INFN-LNF is also the headquarters of the European project.

The construction phase has begun with the design of the new building that will house the infrastructure and with the study of the accelerator components and the radiation beam lines for users.

12.7 Conclusion

The legacy that Touschek has left, since he first proposed to build AdA, has marked the 60 years of activity of the Frascati Laboratories. We have always projected ourselves into the realization of accelerators and experiments at the frontier of knowledge. In every accelerator that we have realized for research and development or for users there are concepts and elements of absolute novelty that have often been used by the world community of accelerators.

This is a source of pride and a sense of belonging for all those who have worked in the Labs, therefore we are grateful to Bruno Touschek for his teaching and inspiration.