

Chapter 16

The Making of ADONE



Claudio Pellegrini

Abstract We review the history, physics challenges and final success of the electron–positron 1.5 GeV collider ADONE, from its inception as Bruno Touschek’s brainchild to the beginning of elementary particle physics experiments. Many new problems were met along the road to the successful operation of ADONE, like the collective instability effects. These novel phenomena had to be understood and means to control them had to be found to reach ADONE design goals. Bruno contributed in many critical ways to a successful solution of these issues, leading the effort to make colliding beams the important particle physics instruments of discovery that they are today.

16.1 Introduction

High-energy electron and positron beams have been playing, for over half a century, a very important role in the exploration of the properties of matter at the molecular, atomic and subatomic levels. ADONE, and the following e^+e^- colliders, explored the structure of subatomic matter starting in the 1960s, helping to establish the standard model of elementary particles. The development of electron storage rings spurred by e^+e^- colliders, led to the many synchrotron radiation sources now in existence worldwide, exploring matter at the atomic/molecular level, giving critical contributions to biology, chemistry and physics. The theoretical and experimental study of electron beams collective instabilities, self-organization phenomena, necessary to bring the colliders luminosity to values useful for high energy physics experiments, together with the operation of electron–positron linear colliders, has been critically important to make free-electron lasers a reality, generating coherent X-ray beams that have opened, for the first time, the exploration of atomic/molecular processes at their characteristic length and time scales of 1 Ångstrom-1 femtosecond.

C. Pellegrini (✉)
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
e-mail: claudiop@slac.stanford.edu

© The Author(s) 2023
L. Bonolis et al. (eds.), *Bruno Touschek 100 Years*,
Springer Proceedings in Physics 287,
https://doi.org/10.1007/978-3-031-23042-4_16

ADONE was an important first step in these developments, that are continuing even today. ADONE was the brainchild of Bruno Touschek. He developed the initial concept and, together with a group of physicists and engineers at the Frascati National Laboratory, transformed his idea into a wonderful instrument to study high energy physics. In this paper I will reconstruct some of the early history of the ADONE project.

16.2 The Beginning of Electron–Positron Colliders

The starting point in the history of ADONE is the famous seminar given by Bruno Touschek at Frascati on March 7, 1960. He made a strong case for the scientific potential of electron–positron interaction and their annihilation in particle–antiparticle pairs for the study of elementary particle physics. He also discussed the kinematic advantage of colliding head–on electron and positron beams so that all their energy would be available for the creation of new particle pairs.

The fact that an accelerator system to collide electrons and their antiparticle, the positron, had never been built, did not decrease Touschek’s enthusiasm for the physics to be explored and his enthusiasm was communicated to many of the other physicists at Frascati.

The impact of the seminar cannot be over emphasized. I like to use the words of Edoardo Amaldi and Burton Richter to describe it. Edoardo Amaldi in his paper “The Legacy of Bruno Touschek”, [1] wrote:

“All of the arguments discussed by Touschek and their brilliant exposition [in the Frascati seminar], made a considerable impression on everyone present, including the then Director of the Laboratory Nazionali di Frascati, Giorgio Salvini, and Carlo Bernardini, Gianfranco Corazza and Giorgio Ghigo. During the same day, the three last mentioned persons began to work with Touschek on a project for the first e^+e^- storage ring, essentially designed as a prototype for checking the feasibility of accelerators based on the ideas set forth by Touschek during the seminar.”

Burton Richter in his paper “The Rise of Colliding Beams” [2] wrote: “The first step in the electron–positron direction was taken in Italy, and the key personality was Bruno Touschek. There is a seminal moment in this story that occurred at a seminar by Touschek at Frascati on March 7, 1960, in which Touschek outlined the scientific potential of electron–positron annihilation studies. Giorgio Salvini, then director of the Frascati laboratory, and the high-energy physics community in Italy were immediately convinced by Touschek’s arguments and began to work to bring e^+e^- colliders to life. The first machine was called AdA, and it was brought into operation less than a year after Touschek’s seminar.”

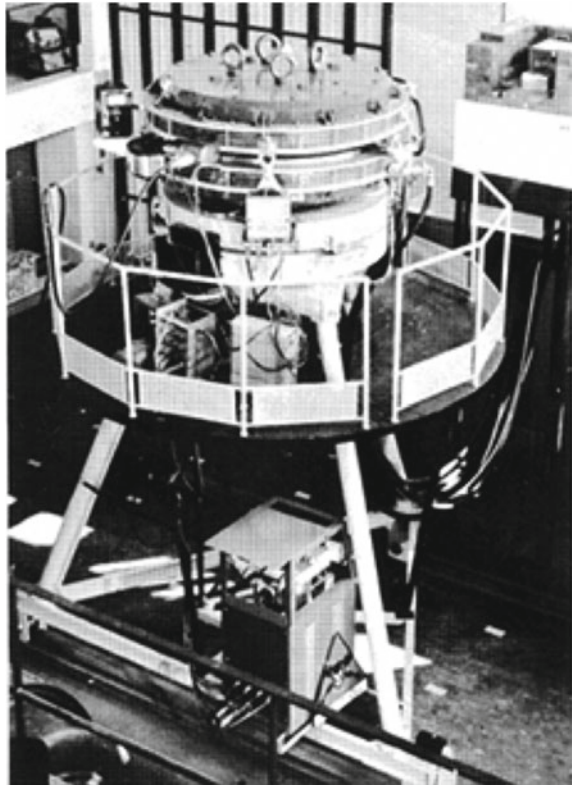
16.3 The ADONE Project

During the same year, 1960, a two prongs approach was started at Frascati. One was the construction and commissioning of AdA, to establish the feasibility of a collider. AdA (Anello di Accumulazione), shown in Fig. 16.1, was built in about one year. It had a 2 m diameter and a beam energy of 250 meV. The initial injector was the Frascati 1 GeV electron synchrotron. It was later moved to Orsay to use a linear accelerator as a more powerful injector.

The other, under the direction of Fernando Amman, was the design of ADONE (great AdA), conceived as a collider to investigate particle physics, extending the study of the processes generated in e^+e^- collisions up to center-of-mass energies $W = 3$ GeV. A draft proposal for ADONE was already written by Touschek in November 1960 and served as the basis for the design that started in 1961. The proposal discussed in some details the physics that could be done with collider, as can be seen from Fig. 16.2.

The two prongs approach is well described by Touschek in a paper presented at a CERN conference in 1961 [3]. In the paper Touschek writes:

Fig. 16.1 AdA, the first electron-positron collider, with 2 m diameter, 250 meV beam energy, at the Laboratori Nazionali di Frascati



**A D O N E - a Draft Proposal for a
Colliding Beam Experiment.**

B. Touschek,
Rome, 9. Nov. 60.

It is proposed to construct a synchrotron like machine capable of accelerating simultaneously electrons and positrons in identical orbits. The suggested maximum energy is 1.5 Gev for the electrons as well as the positrons. This energy allows one to produce pairs of all the so called 'elementary particles' so far known, with the exception of the neutrino, which only becomes accessible via a weak interaction channel.

It is assumed that experiments in which there are only two particles in the final state are most easy to interpret. There are 16 such reactions, namely:

(1) 2γ . This is the only reaction in which the ~~weak~~ intermediate state is 'quasi real' and in which therefore there should be no 'radiative corrections'. This reaction should serve as a 'monitor'. The cross-section is $2.6 \cdot 10^{-31} \text{ cm}^2$.

(2) e^+, e^- . This reaction will show strong angular variations and may require 'good geometry'. It would give information on the breakdown of electrodynamics at distances corresponding to about 1/3 the Comptonwavelength of the proton.

(3) μ^+, μ^- . Test of electrodynamics in 'bad geometry'. May also serve as an indication of the fundamental difference between electrons and muons.

(4) $\pi^+ \pi^-$ reveals the interaction between pions in odd parity states.

(5) $2\pi^0$: charge exchange interaction for pion-pion scattering.

(6) $K^+ K^-$: interaction of K-mesons in odd parity states.

(7) \bar{K}^0, K^0 : Charge exchange interaction between K-mesons.

(8) p, \bar{p} : interaction of proton and antiproton in even parity odd charge parity states.

(9) n, \bar{n} : same as (8) but for the charge exchange reaction.

(10) through (15). Interactions simple or with charge exchange of hyperons.

Fig. 16.2 The first page of Touschek's draft proposal for an electron positron collider

“Frascati is developing two storage rings. The first (code name AdA = anello di accumulazione = storage ring) designed for storing electrons and positrons of up to 250 meV is actually undergoing the first tests, the second (code name Adone) a storage ring for electrons and positrons of up to 1.5 GeV, is still being planned.

The AdA team consists of C. Bernardini, G.F. Corazza, G. Ghigo, R. Querzoli and myself. The magnet was planned by Dr. Sacerdoti and built in Terni, the radiofrequency by Dr. Puglisi.

Adone is a national effort. A design team headed by Dr. Amman has the task of arriving at a specific design proposal by the beginning of 1962. Simultaneously a committee is preparing the experiments to be carried out with the machine. If, by the beginning of 1962 it is found that the project has a reasonable chance of success from a technical point of view; it is expected that the machine should be working late in 1964.”

The initial technical proposal for ADONE was written in January 1961 [4]. The paper starts with a discussion of the physics goals of the collider, establishes the beam energy needed to reach them and discusses the various technical options to design the accelerator/storage ring. The electron and positron beam energy was chosen to be 1.5 GeV, 3 GeV total in the center of mass system, large enough to produce pairs of all known particles from electron–positron annihilation. As written in ref. [4]: “Disponendo di 3 GeV nel baricentro si può pensare di ottenere dall’annichilamento e^+e^- la produzione, in coppia, di tutte le masse conosciute.” [“Having 3 GeV in the center of mass system it is possible to obtain the production, in pairs, of all known masses”].

The paper continues discussing all important elements of ADONE’s design, including the choice of weak versus strong focusing of betatron oscillations, RF system, injection system, desired luminosity and corresponding beam current, effect of beam-beam interaction.

Most of the final choices for ADONE were not very different from those outlined in this first paper. The energy remained the same as well as many other parameters. One choice, however, remained still open at the time, what kind of magnetic focusing should be used in the ring, weak or strong focusing.

To obtain a large luminosity for a given current it was convenient to have strong focusing magnets and a smaller beam transverse cross-section area, instead of weak focusing and a larger area. However, in a strong focusing ring the emission of synchrotron radiation leads to exponential growth (anti-damping) of the betatron oscillation amplitude on a millisecond time scale, clearly too short for a storage ring [5]. A simple weak focusing system, that avoids this problem, could not give the desired luminosity. The solution was a new, never used until that time, separated function focusing system, where the trajectory bending is done by weak focusing magnets and the focusing by pairs of quadrupole magnets, as shown in Fig. 16.3.

Following ADONE, this has become the basic structure for e^+e^- colliders and all synchrotron radiation storage rings.

It is important at this point to remember that Touschek, who was an active participant in all these choices, had previously worked on the construction of a betatron in Germany, in 1943–44, during the war, with Rolf Widerøe, who was also the first

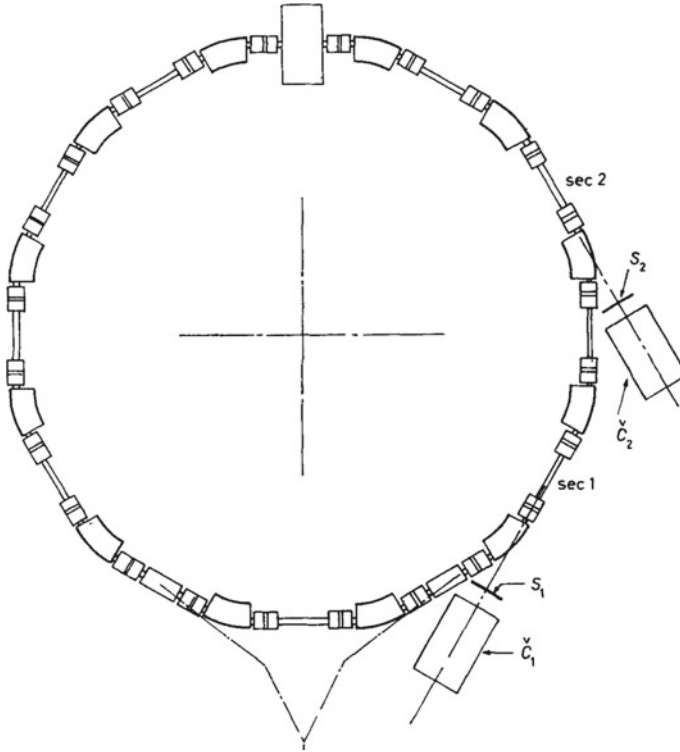


Fig. 16.3 ADONE magnetic structure. Twelve equal periods, each consisting of a long straight section, two quadrupole pairs and one weak focusing bending magnet. The boxes tangent to the ring are instruments to measure the luminosity, using small angle scattering or electron-positron going into electron-positron plus gammas

proponent of colliding particle beams and of linear accelerators. In 1946 at the University of Göttingen Touschek obtained the title of Diplomphysiker with a thesis on the theory of the betatron. When discussing AdA and ADONE he could and did use his previous theoretical and practical knowledge of particle accelerators to contribute to all aspects of their design. A more detailed biography of his life and work can be found in [1, 6].

16.4 High Intensity Effects in ADONE

I joined the ADONE group at the beginning of 1963. My initial task was to study single particle trajectories in the novel, separated functions, magnetic structure, including synchrotron radiation and radiation reaction effects in a strong, weak or separated functions accelerator. I worked mostly with Carlo Bernardini and Mario

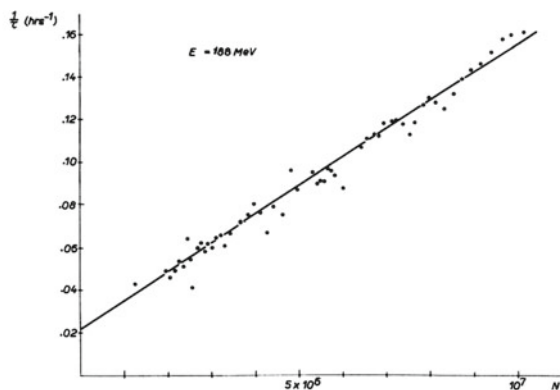


FIG. 1. Lifetime τ versus N , the number of stored particles in a beam, at the energy of 188 MeV.

Fig. 16.4 The plot showing the dependence of lifetime on the number of electrons in a bunch, from ref. [7]. The effect was observed on AdA and explained by Touschek in 1963

Bassetti. We also evaluated the beam lifetime and here it became obvious that the recent discovery on AdA of the Touschek effect [7] required consideration of high intensity phenomena. The effect showed that some beam properties, in particular lifetime and transverse area, could change substantially when the beam current was raised. It also showed that scaling of these properties with the number of particles in the beam might be nonlinear and that thresholds for new phenomena might appear. The Touschek effect, a decrease in the beam lifetime when increasing the number of electrons in a bunch, as shown in Fig. 16.4, was discovered on AdA. Touschek explained the effect as due to the Coulomb scattering of electrons within the same bunch, generating a momentum transfer from the transverse to the longitudinal oscillation and leading to particle losses.

Another high intensity effect requiring attention was the resistive wall instability. In the period 1965–66 it was realized that the finite conductivity of the vacuum chamber, within which the beam or beams are moving, can be the source of a longitudinal and a transverse collective instability, limiting the maximum beam current. The theory was first developed for the case of a coasting beam [8, 9]. At Frascati the results were generalized to the case of interest to ADONE, two counter rotating bunched beams, by Touschek, Ferlenghi and Pellegrini [10]. The effect was analyzed, its dependence on the betatron frequency and other parameters was studied, what could be expected for ADONE, including possible luminosity limitations, was evaluated. The conclusion was that it should not be an obstacle to reaching the design goals. With the consideration and analysis of the Touschek effect and of the resistive wall instability we hoped to be ready for the start of the machine.

Here I would like to add a personal note. Working with Bruno Touschek on the resistive wall instability problem was, for a young person like me at that time, quite a learning experience, that influenced my work for the rest of my career. I have very clear memories of the time we spent together at Frascati, or sometime on a place near

Castel Gandolfo lake, working on the physics and the mathematics of the problem. What I learned from Bruno Touschek followed me through the rest of my career and helped me solve many other problems.

16.5 Commissioning ADONE

The collider, shown during assembly in Fig. 16.5, was completed in 1967–68 and its commissioning, with the active participation of Bruno Touschek, started at that time. He was very much present in the ADONE control room, always ready to give advice, discuss any problem, ready to help in any emergency. He was a reference point for all of us.

The first part of the commissioning, at low current, in the tens of μA range, was pretty good. ADONE behaved exactly as calculated, as far as orbits, synchrotron radiation effects, lifetime, beam size were concerned. But when we tried to increase the current to achieve the design current of 100 mA/beam, we encountered many unexpected effects generating sudden beam losses, limiting the current and the luminosity to values well below the design values and what was needed to do meaningful high energy physics experiments.

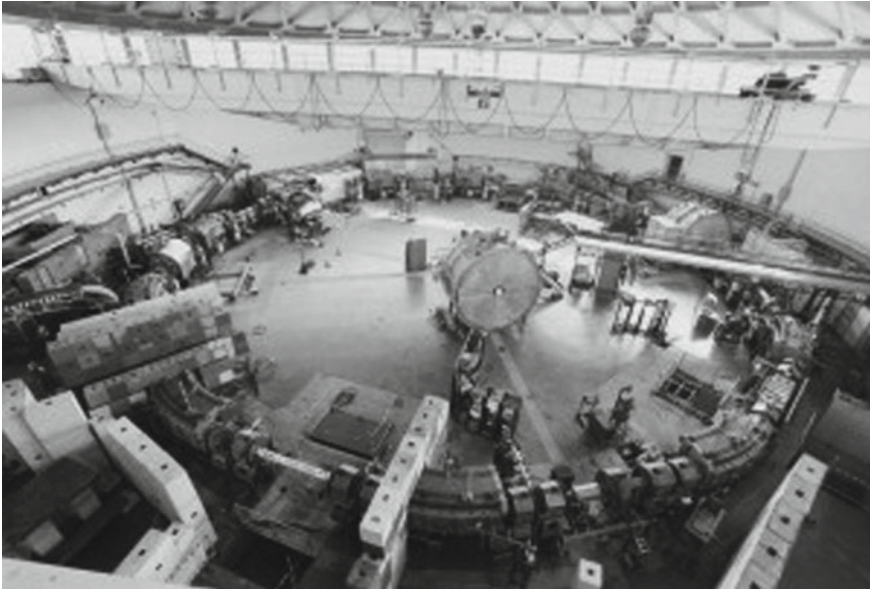


Fig. 16.5 ADONE in its building during assembly. The circumference is 100 m, the magnet bending radius 5 m and the energy 1.5 GeV. The injector is a 300 MeV electron linac built by Varian, with the capability of positron injection rate of 10 mA/minute. The design required 100 mA per beam to reach the design luminosity of about $3 \times 10^{32} \text{ cm}^{-2} \text{ h}^{-1}$

Amman discussed the situation in a paper he presented at 1969 Particle Accelerator Conference [11]. In this paper he summarized our experience with ADONE initial commissioning: “ADONE, after the first year of troubleshooting (talking of a storage ring it would be better to say instability-shooting), should start high energy physics experiments during 1969. It may seem strange that eight years after the initial operation of a storage ring, only one electron-electron (the Princeton-Stanford 550 MeV) and two e^+e^- rings, VEPP-II and ACO, have produced high energy physics results, and these are limited to experiments with very high cross section. I would like to remark that the first beam instabilities observed on the Princeton-Stanford ring, and interpreted as being due to the resistance of the walls, opened a new era in the accelerator field: it has been realized for the first time that the interaction of the beam with its environment makes a circular accelerator an essentially unstable system, that can become stable, in virtue of the Landau damping, when the beam density is not too high and the nonlinearities in the focusing forces give a frequency distribution of the particles large enough to compete with the instabilities. While a conventional accelerator operates usually at very low particle density, in an electron storage ring the radiation damping brings the density to very high values also when the current is in the mA range; a new set of theoretical and technical problems have therefore to be solved.”

Longitudinal and transverse instabilities were observed in ADONE. The longitudinal instabilities were interpreted as due to the interaction with the RF cavity and were cured by separating the synchrotron frequency of the bunches and other techniques.

Particularly worrisome were the transverse instabilities. They could not be explained by the resistive wall effect and had a very low threshold current. In ADONE, at 300 MeV, the injection energy, with the natural beam dimensions, the threshold positron current was about 0.150 mA per bunch, to be compared with the value of 30 mA per bunch, 0.1 A per beam needed to reach the design luminosity of $10^{29}/\text{cm}^2/\text{s}$ and start doing high energy physics.

16.6 Reaching ADONE Design Luminosity

Fortunately, the work done by the ADONE group, with the collaboration of Touschek and visitors like Matthew Sands from SLAC and Ralph Littauer from Cornell University, to understand and control the instabilities soon led to progress.

Quoting from a later paper by the ADONE group [12]: “The first electron beam was stored in ADONE in December 1967; parts of the ring still missing at that time have been installed during 1968, and the machine was completed in its present form by mid-1968. The experimental study of the single-beam instabilities has taken the major part of the ring operation until the beginning of 1969; the interpretation of the phenomena has allowed the development of suitable means of suppressing the instabilities. The multiple-bunch coherent-phase, longitudinal, oscillations have been cured by separating the synchrotron oscillation frequency of the bunches by means

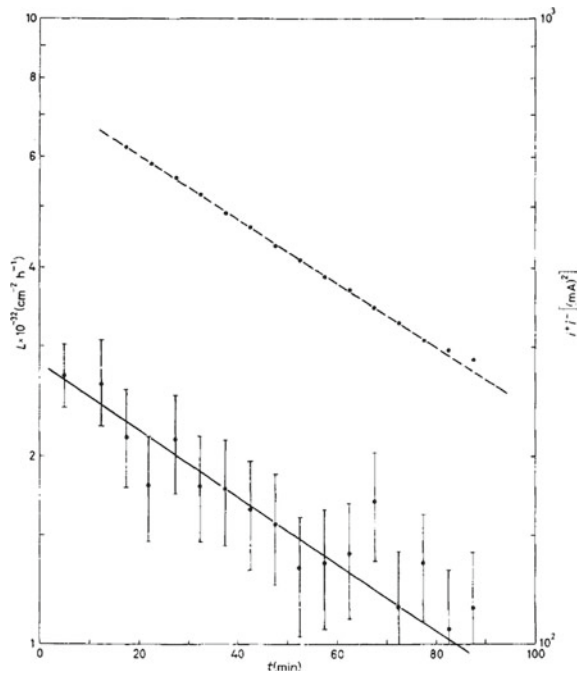
of a low-power radiofrequency cavity operating on a harmonic of the revolution frequency, but not of the main radio-frequency system [13].

Transverse betatron instabilities with very low current threshold (about 150μ A/bunch at the injection energy, 300 MeV) were observed with a positron beam, or with an electron beam when the positive ions were swept out using transverse electric fields; these thresholds were much lower than those expected on the basis of current theories, and the dependence on the machine parameters indicated that the dynamics was not that of the resistive wall instability. It has been interpreted as being due to an interaction between the beam and rapidly decaying electromagnetic fields with frequencies extending in the GHz range induced by the beam in its environment; the theory has been found correct. [The interpretation of the effect has been first proposed by C. PELLEGRINI, M. SANDS and B. TOUSCHEK; a paper by C. PELLEGRINI on the subject is in course of publication*. Therefore, all the elements in the vacuum chamber should have been suitably terminated for frequencies in the GHz range, in order to reduce the forces acting on the beam, and to increase the rise time of the instability, while previous theories on beam instabilities were concerned with frequencies in the 10 MHz range and the machine was built accordingly.”

The work done to control the beam instabilities led to an increase of the electron and positron beams currents and a corresponding increase in luminosity. In 1969 the luminosity reached a value near the design value, as shown in Fig. 16.6, and the high energy physics experiment could start. The paper reporting these results, [11], ended recognizing in the acknowledgements Touschek’s contributions to ADONE

Fig. 16.6 ADONE

Luminosity measurements with the scattering apparatus and three bunches per beam (full curve) at 1 GeV. The product of beam currents is also shown as a function of time (dashed curve). Errors are statistical, luminosity, left scale; i^+i^- , right scale. The straight lines through the data are only indicative [11]



success: “We are grateful for helpful discussions with many physicists of the Frascati Laboratories and of other laboratories; we are especially grateful to Prof. C. BERNARDINI, whose contribution has been very important in the design stage, and to Prof. B. TOUSCHEK for his brilliant ideas and for suffering with us through the instability problems.”

16.7 Conclusions

Bruno Touschek conceived the idea of electron–positron collider as a new way to explore high energy physics. He was a very active participant in the design of AdA and ADONE, in their commissioning and interpreting the many new physical effects and technical problems that had to be understood and solved before the colliders could contribute to elementary particle physics and the establishment of the standard model. He was also a mentor of young scientists in theoretical physics and in accelerator physics. I consider myself privileged to have been one of them.

References

1. E. Amaldi, The Bruno Touschek legacy. CERN Rep. 1–19 (1981)
2. B. Richter, The rise of colliding beams. SLAC-Pub-6023 (1992)
3. B. Touschek, The Frascati Storage Ring, LNF Report 61/45 (1961). Also presented at the Intern. Conf. of Theoretical Aspects of Very High Energy Phenomena, CERN, 61-22 (1961), p. 67
4. F. Amman, C. Bernardini, R. Gatto, G. Ghigo and B. Touschek, Anello di Accumulazione per elettroni e positroni (ADONE), Laboratori Nazionali di Frascati, LNF-61/5 (27.1.1961)
5. C. Pellegrini, Nuovo Cimento. Suppl. **22**, 603 (1962)
6. C. Bernardini, G. Pancheri, C. Pellegrini, Bruno Touschek: from betatrons to electron-positron colliders. Rev. Accel. Sci. Technol. **8**, 269 (2015)
7. C. Bernardini et al., Lifetime and beam size in a storage ring. Phys. Rev. Lett. **10**, 407 (1963)
8. V.K. Neil, A.M. Sessler, Longitudinal resistive instabilities of intense coasting beams in particle accelerators. Rev. Sci. Instr. **36**(429) (1965)
9. L.J. Laslett, V.K. Neil, A.M. Sessler, Transverse resistive instabilities of intense coasting beams in particle accelerators. Rev. Sci. Instr. **36**, 436 (1965)
10. E. Ferlenghi, C. Pellegrini, B. Touschek, The transverse resistive-wall instability of extremely relativistic beams of electrons and positrons. Il Nuovo Cimento, **XLIV**, 253 (1966)
11. F. Amman, Electron positron storage rings: status and present limitations. IEEE Trans. Nucl. Sci. **16**, 1073–1081 (1969)
12. F. Amman et al., Two-beam operation of the 1.5 Gev electron-positron storage ring ADONE. Lett. al Nuovo Cimento **15**, 729 (1969)
13. M. Bassetti, R. Littauer, C. Pellegrini, M. Sands, B. Touschek, ADONE longitudinal instabilities. Adone Int. Memoranda (1968) (un-published)

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

