The Making of ADONE

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Introduction

►High-energy electron and positron beams have been playing, for over half a century, an 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, 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 work on electron beams collective instabilities, self-organization phenomena, and the operation of electron-positron linear colliders helped 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.

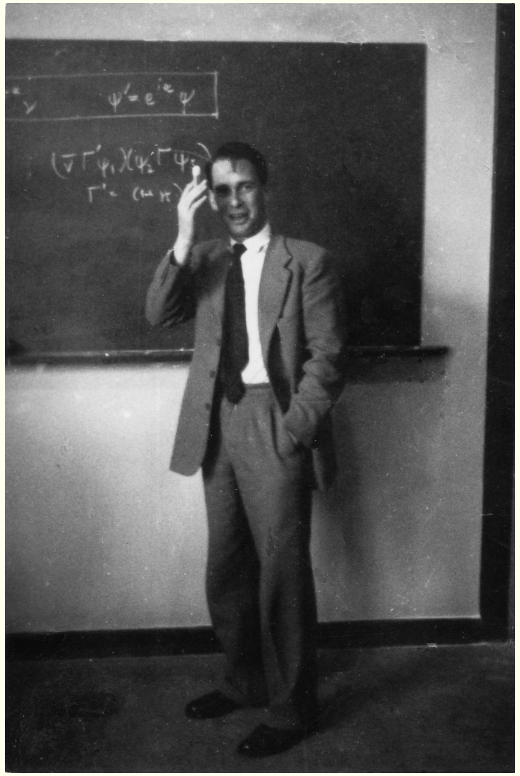
A person stands at the beginning of this remarkable progress in physics: Bruno Touschek.

In this talk I will review the main events that Touschek put in motion at the Frascati National Laboratory in the 1960s, making ADONE a reality and changing the way we do science.

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. He also discussed the kinematic advantage of colliding electron and positron beams head–on 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 received by many of the other physicist at Frascati.



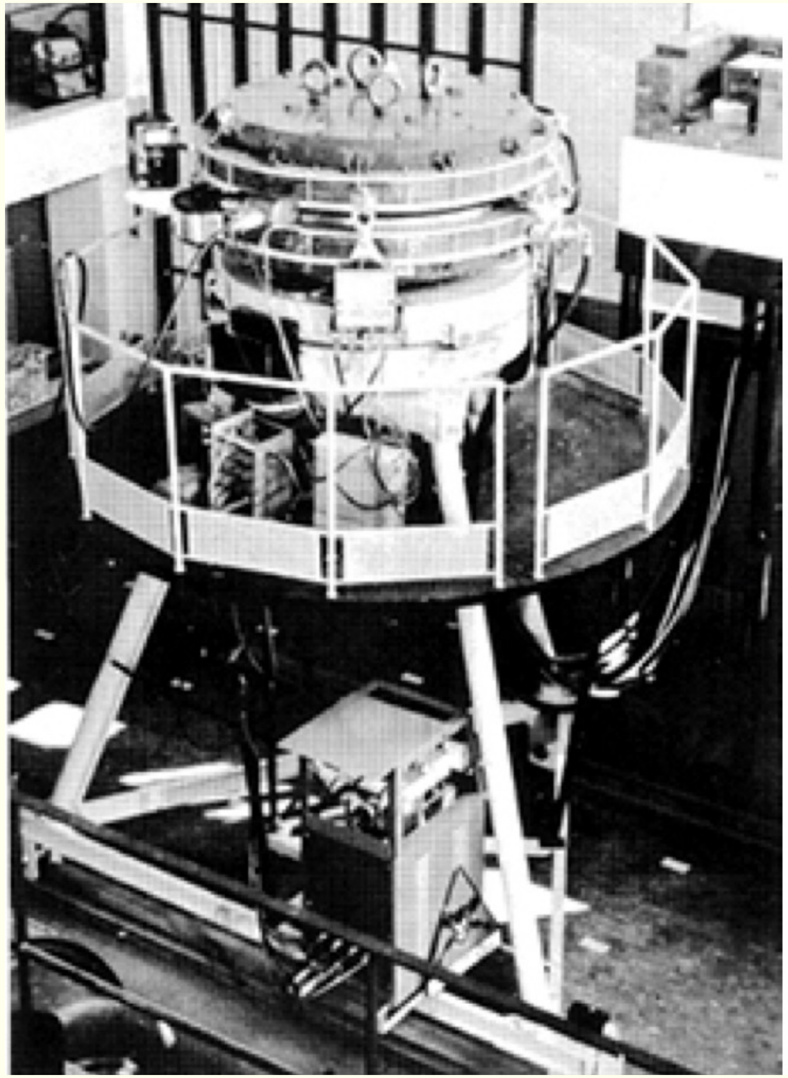
Bruno Touschek 1921-1978

“The Legacy of Bruno Touschek”
Edoardo Amaldi, CERN Rep. 1-19, 1981

- In his paper Amaldi 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.”

The Rise of Colliding Beams, B. Richter SLAC-Pub-6023,1992.

“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.”



AdA, the first electron-positron collider: 2 m diameter, 250 MeV.

ADONE draft proposal, 11/1960

Bruno Touschek and AdA: from Frascati to Orsay, In memory of Bruno Touschek, who passed away 40 years ago, on May 25th, 1978, Luisa Bonolis, Giulia Pancheri arXiv:1805.09434v2, INFN 18-05/LNF (2018)

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 ~~xxxx~~ 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 10^{-31} cm^2.

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

The Adone Project

During the same year, 1960, a start was made at Frascati, under the direction of Fernando Amman, on the design of ADONE (great AdA). The idea was to extend the study of the processes generated in e^+-e^- collisions up to centre-of-mass energies W = 3 GeV. The initial proposal was written in January 1961:

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 (27.1.61)

The paper starts with a discussion of the physics goals of the device, 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 is assumed to be 1.5 GeV, 3 GeV total in the center of mass system: “Disponendo di 3 GeV nel baricentro si puo’ pensare di ottenere dall’annichilamento e^+ - e^- la produzione, in coppia, di tutte le masse consosciute.” [“Having 3 GeV in the center of mass system it is possible to obtain the production, in pairs, of all known masses”]

TABELLA 1

DATI PRELIMINARI PER UN ANELLO DI ACCUMULAZIONE PER ELETTRONI E POSITRONI A FOCHEGGIAMENTO

	FORTE		DEBOLE	
Energia	1500 MeV		1500 MeV	
Raggio	700 cm		500 cm	
Coefficiente di allungamento	1,6		1,4	
Lunghezza sezioni diritte	(290+140)x6 cm		160x8 cm	
Peso magnete	~150 ton		~ 150 ton	
Peso bobina	~ 15 ton		~ 15 ton	
Numero settori	12(1/2F,D,1/2F+AD)		8	
Indice del campo	n = 40		n = 0,6	
Potenza alimentazione	~ 200 kW		~ 200 kW	
Vuoto	10^{-9} mmHg	t = 30 h	10^{-9} mmHg	t = 30 h
Armonica RF	k = 6		k = 2	
Tensione di picco RF	120 KV		290 KV	
Positroni per impulso	2×10^{7} a 15 MeV		10^{7} a 15 MeV	
Elettroni per impulso	2×10^{11} a 30 MeV		10^{11} a 30 MeV	
Limite carica spaziale e^{+} x e^{-}	10^{22} – 10^{23}		10^{22} – 10^{23}	
Dimensione orizzontale del fascio	0,2 cm		2,4 cm	
Dimensione verticale del fascio	?		10^{-3} cm	

From Amman et al., Anello di Accumulazione per elettroni e positroni (ADONE) Laboratori Nazionali di Frascati, LNF-61/5 (27.1.61)

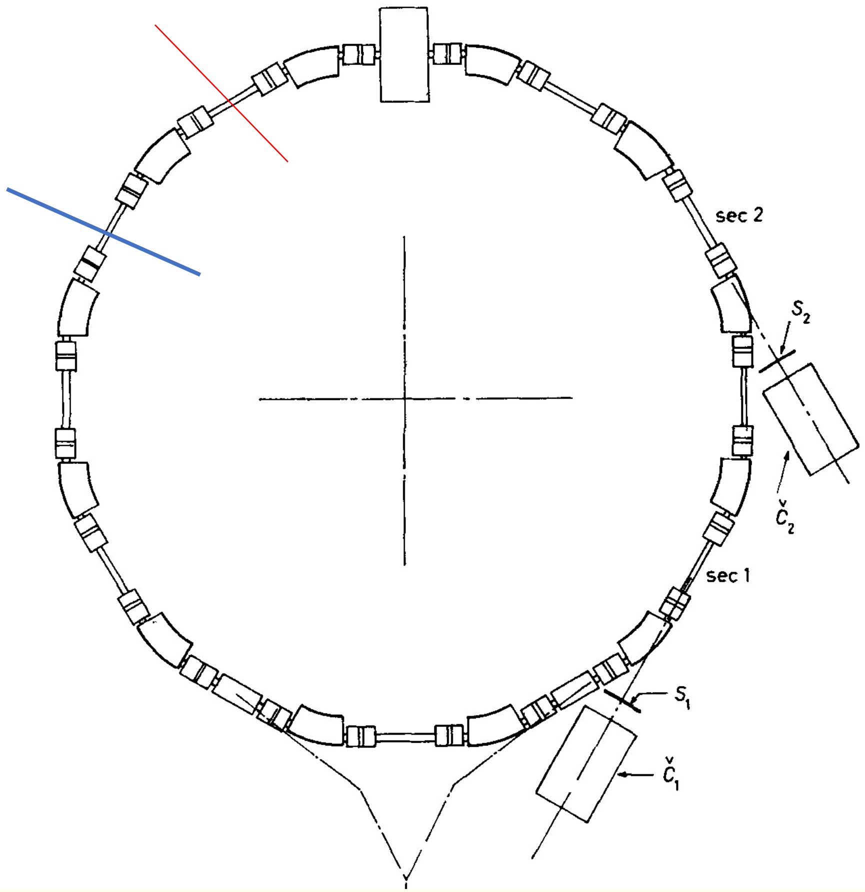
The paper continues discussing the important elements of ADONE's design, including the choice of **weak vs strong focusing**, RF system, injection system, desired luminosity and corresponding beam current, effect of beam-beam interaction.
It is important at this point to remember that Touschek had previously worked on the construction of a betatron in Germany, in 1943-44, during the war, with Widerøe, who was also the first proponent of colliding particle beams and of linear accelerators. In 1946 at the University of Gōttingen Touschek obtained the title of Diplomphysiker with a thesis on the theory of the betatron. When discussing AdA and ADONE he could use his previous theoretical and practical knowledge of particle accelerators.

ADONE magnetic structure.

The final choices for ADONE were not very different from those outlined in this first paper. The energy remained the same. The magnetic structure was the main new element introduced.

To obtain a large luminosity it was convenient to have strong focusing magnets and a smaller beam transverse cross-section respect to the weak focusing case. 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. A simple weak focusing system could not give the desired luminosity. The solution was a separated function system, where the trajectory bending is done by weak focusing magnets and the focusing by quadrupole pairs, as shown in the figure.

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



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-podsitron plus gammas.

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, synchrotron radiation and radiation reaction effects. I worked mostly with Carlo Bernardini and Mario Bassetti. We also evaluated the beam lifetime and here it became obvious that the recent discovery on AdA of the Touscheck effect required consideration of high intensity phenomena. The beam properties could change dramatically when the beam current was raised, scaling with the number of particles in the beam might be nonlinear, and thresholds for new phenomena might appear.

Another high intensity effect requiring attention was the resistive wall instability, observed in the electron storage ring at Stanford.

Touschek had discovered the first and in 1965 devoted his attention to the second.

Intensity dependence of beam lifetime in AdA

AdA at LNF today

VOLUME 10, NUMBER 9 PHYSICAL REVIEW LETTERS 1 MAY 1963

If the lines became narrower by a factor of ten (i.e., if the width was reduced from several cm^{-1} to several tenths of a cm^{-1}), as might reasonably be expected in a 10% solution of $PrCl_3$ in $LaCl_3$, then no increase in path length or exposure time would be necessary to obtain lines of the same strength on the plate as those obtained by us for the pure material.

We wish to thank Dr. B. P. Stoicheff for his help throughout the course of this work.

*On leave of absence from Atomic Energy Establishment, Bombay, India.

[1]R. J. Elliott and R. Loudon, Phys. Letters 3, 189 (1963).
[2]E. V. Sayre, K. M. Sancier, and S. Freed, J. Chem. Phys. 23, 2060 (1955); 29, 242 (1958).
[3]G. H. Dieke and R. Sarup, J. Chem. Phys. 29, 741 (1958).

LIFETIME AND BEAM SIZE IN A STORAGE RING

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(Received 1 April 1963)

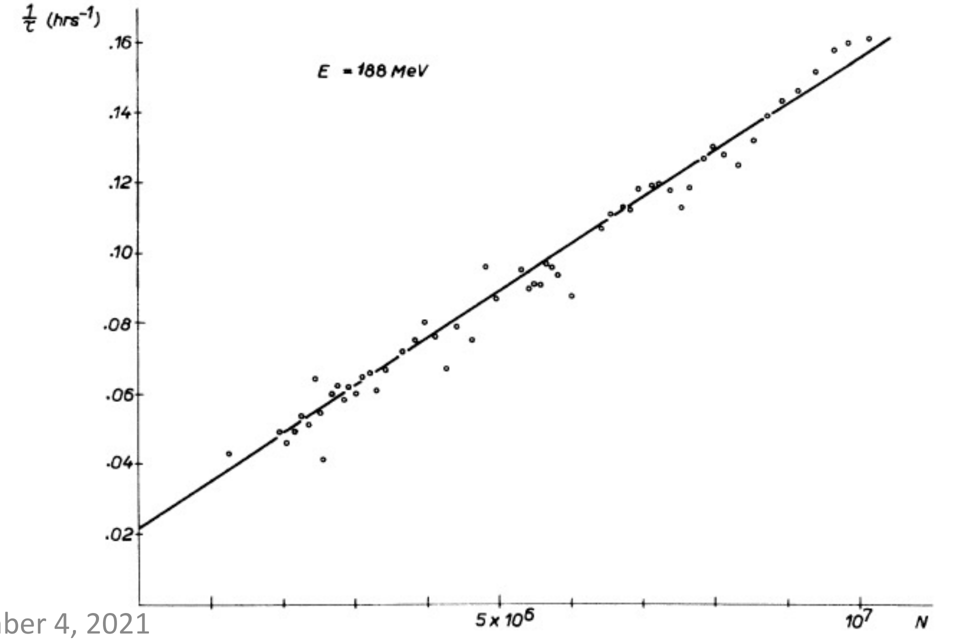


FIG. 1. Lifetime τ versus N, the number of stored particles in a beam, at the energy of 188 MeV.

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 [V. K. Neil and A.M. Sessler, Rev. Sci, Instr. 36,429 (1965), L.J. Laslett, V. K, Neil and A. M. Sessler, Rev. Sci. Instr.36, 436 (1965)]. At Frascati we generalized the theory to the case of interest to us, two counter rotating bunched beams.

IL NUOVO CIMENTO Vol. XLIV B, N. 2 11 Agosto 1966

The Transverse Resistive-Wall Instability of Extremely Relativistic Beams of Electrons and Positrons.

E. Ferlenghi, C. Pellegrini and B. Touschek

Laboratori Nazionali di Frascati, C.N.E.N. - Frascati
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto l'11 Novembre 1965)

Working with Bruno Touschek on this problem was, for a young person like me, 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, on the lake, working on the physics and the mathematics of the problem.

We analyzed the effect, its dependence on the betatron frequency and what we could expect for ADONE, including possible luminosity limitations. 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.

Commissioning ADONE

Commissioning of ADONE started in 1967 with the active participation of Bruno Touschek. He was very often present in the ADONE control room, always ready to give advice and to discuss any problem. He was a point of reference 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 luminosity of 100 mA, we encountered many unexpected effects generating sudden beam losses, limiting the current and the luminosity to values well below the design values, what was expected from the resistive wall instability and what was needed to do meaningful high energy physics experiments.

ADONE in its building during assembly. The circumference is 100 m, the 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

High Intensity, collective instabilities effects in ADONE

Amman discussed the situation in a paper he presented at 1969 Particle Accelerator Conference [IEEE Transaction in Nuclear Science, Vol. 16, p. 1073-1081. **DOI:**10.1109/TNS.1969.4325443].

Amman, PAC 69: "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 e^-e^- (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 non linearities in the focusing forces give a frequency distribution of the particles large enough to compete with the instabilities."

High Intensity and collective instabilities effects in ADONE

Amman, PAC 1969 paper.
“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 instability 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 worrying 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 $10^{30}/cm^{-2}/s$ and start doing high energy physics.

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, to understand and control the instabilities soon led to progress.
Quoting from a later paper by the ADONE group [Amman et al., Lett. al Nuovo Cimento, 15,729 (1969)]:

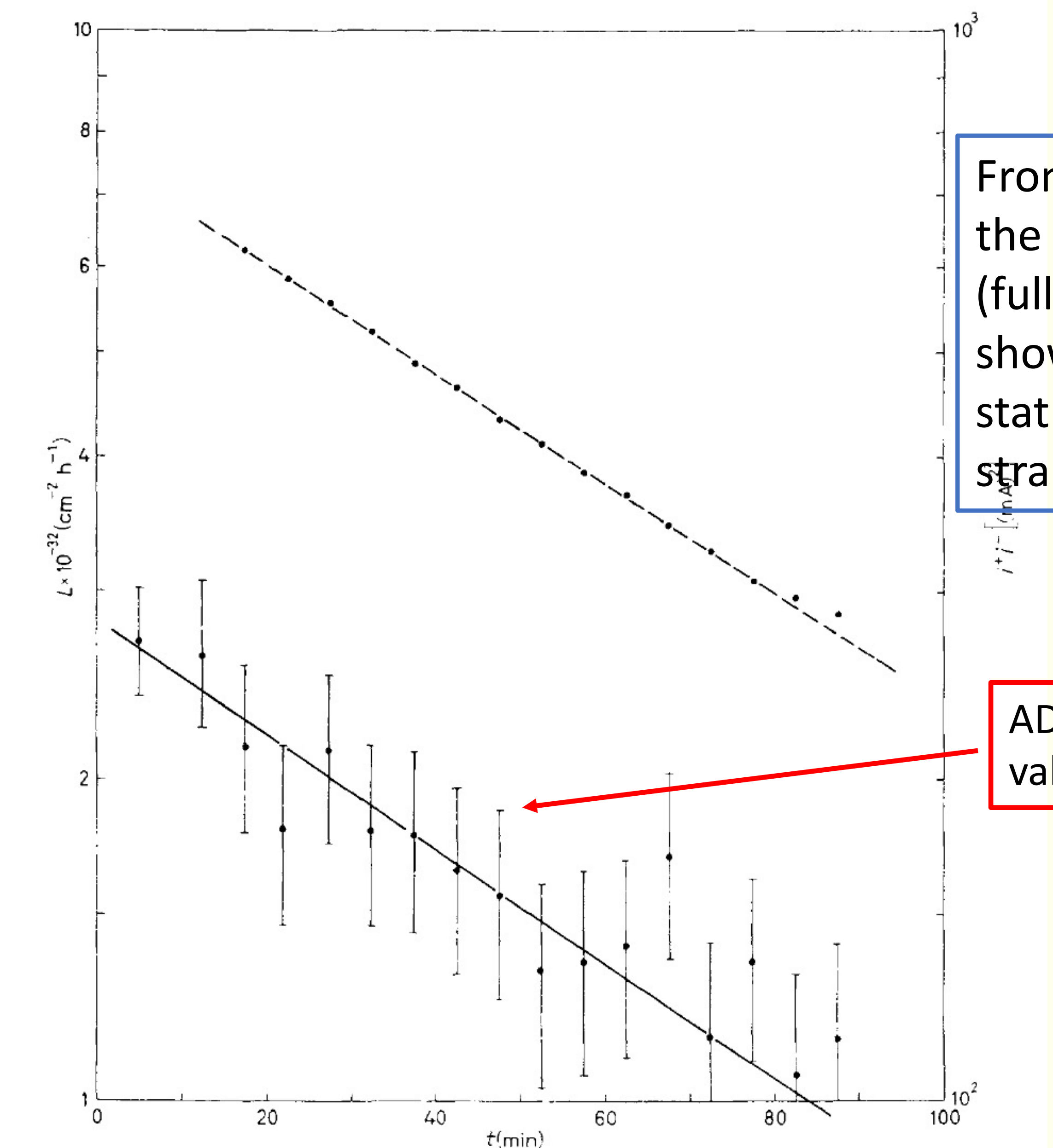
"The first electron beam was stored in ADONE in December 1967; parts of the ring still missing at that time have been installed during 1968, and the machine was completed in its present form by mid-1968. The experimental study of the single-beam instabilities has taken the major part of the ring operation 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. [M. BASSETTI, R. LITTAUER, C. PELLEGRINI, M. SANDS and B. TOUSCHEk, Adone Int. Memoranda (1968) (un-published)]."

Reaching ADONE design luminosity

Transverse betatron instabilities with very low current threshold (about 150 μ 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 paper appeared later in the same year: C. PELLEGRINI, On a New Instability in Electron-Positron Storage Rings (The Head-Tail Effect). IL NUOV0 CIMENT0, LXIV A, 2 21 (Nov. 1969).

Reaching ADONE design luminosity



From the same paper: 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.

ADONE Luminosity in 1969, after control of the instabilities: reached a value near the design value, which was later exceeded.

LETTERE
AL
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A CURA DELLA SOCIETÀ ITALIANA DI FISICA

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Two-Beam Operation of the 1.5 GeV Electron-Positron Storage Ring Adone.

F. AMMAN, R. ANDREANI, M. BASSETTI, M. BERNARDINI, A. CATTONI, V. CHIMENTI, G. F. CORAZZA, D. FABIANI, E. FERLENGHI (*), A. MASSAROTTI, C. PELLEGRINI, M. PLACIDI, M. PUGLISI, F. SOSO, S. TAZZARI, F. TAZZIOLI and G. VIGNOLA

Laboratori Nazionali di Frascati del CNEN - Frascati

(ricevuto il 12 Maggio 1969)

The paper announcing the operation of ADONE at 1 GeV and near design luminosity with the names of the ADONE Group members and the final acknowledgements.

Paper acknowledgements: “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.”

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 to be privileged to have been one of them.