# Francesco Ruggiero 1957–2007

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## *Abstract*

Francesco Ruggiero (1957–2007) was a brilliant accelerator physicist, an inventive researcher, a great collaborator, an excellent mentor, and a true gentleman. We here take a look at Francesco's scientific work, and highlight some of his contributions to accelerator physics. More details can be found in the slides presented by the speakers of the Francesco Ruggiero Memorial Symposium held at CERN on 3 October 2007 [2].

Figure 1: Francesco Ruggiero, 6. December 2003

## 1 BEFORE CERN

Francesco Ruggiero was of Neapolitan origin. Interestingly, he received his first diploma from the "Instituto Nautica di Piano di Sorrento" (a nautical school), which was later followed by a diploma thesis in physics on gravitational wave detection for the title of "Laurea" at the University of Pisa in 1980 [1]. After obtaining his diploma, he spent a few months at the University of Stuttgart with Prof. H. Haken, who had written several books on synergetic models in natural science. Emilio Picasso, the LEP Project Director who at the same time also was an expert of gravitational waves, had been much impressed with the thesis work which Francesco had performed for the title of Laurea [1], and he introduced him to Steve Myers to find a topic for a doctoral thesis. By then Francesco had moved on to the prestigious Scuola Normale in Pisa, where Prof. Luigi Radicati agreed to supervise a second (doctoral) thesis "di perfezionamento" on which he wanted work at CERN, where he became a thesis student in the ISR (later LEP) division. Prof. Francesco Pegoraro was a second thesis supervisor in Pisa. In 1985, Francesco received his PhD in accelerator physics from the the Scuola Normale Superiore.

## 2 CAREER AT CERN

Francesco first came to CERN as a summer student, from July to September 1981.

At the time he contributed to beam-beam studies for LEP under the supervision of Steve Myers. He was 24 years young. Intrigued by this experience, he soon started a doctoral thesis on collective instabilities in high energy particle storage rings, about which we will say more in the following section.

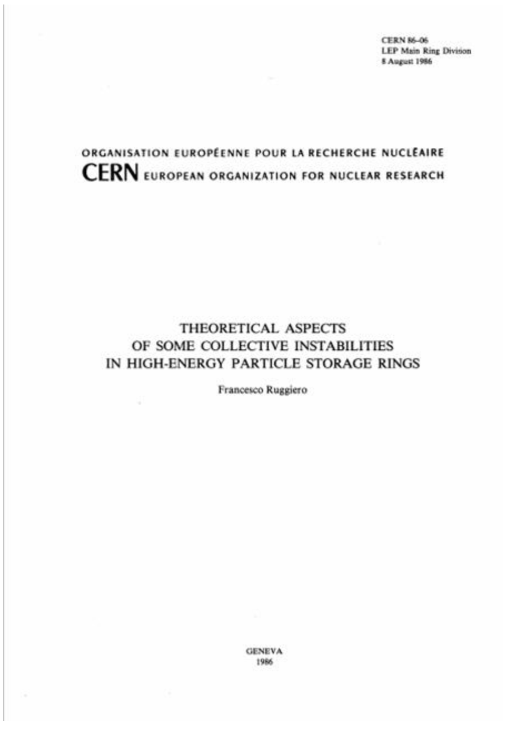
From January 1984 to July 1986 Francesco worked at CERN as a fellow, in the LEP Theory Group, at the same time as Luigi Palumbo. Luigi and Francesco were both from Naples, albeit from different parts of the city, and they shared the habits of people coming from south: late start in the morning, and late stop in the evening, often in the night. Francesco next became staff member in the LEP Theory Group from July 1986 to the end of 1989, during which time he participated in the commissioning of LEP. In 1990 he joined the accelerator physics group in the former SL division (SL-AP). In the SL-AP group Francesco made numerous invaluable contributions to the design of the LHC, in particular on collective effects, machine impedance, and beam-beam interaction. In 1997 Francesco recognized the potential danger from an electron cloud in the LHC and he launched an important remedial crash program. In 2000 he became SL-AP group leader. From 2000 onwards Francesco was the driving force behind the LHC accelerator upgrade studies, e.g., as coordinator of the CARE-HHH network. His final position was one as a section leader and deputy group leader in the newly formed AB/ABP group.

Under Francesco's wonderful and caring guidance many bright young accelerator physicists were trained or recruited at CERN, including Giulia Bellodi, Scott Berg, Oliver Brüning, Alex Koschik, Andrea Mostacci, Yannis Papaphilippou, Giovanni Rumolo, Rogelio Tomas, Hiroshi Tsutsui, Xiaolong Zhang, Frank Zimmermann, and Mari-Paz Zorzano.

## 3 PHD THESIS

The first part of Francesco's PhD thesis concerned the Transverse Mode Coupling (TMC) instability due to localized impedances, studied under supervision by Bruno Zotter, while the second topic was the beam-beam effect in electron-positron colliders, supervised by Emilio Picasso, who was the LEP Project Director from 1981 to 1989.

Francesco's thesis or "tesi di perfezionamento" on "Theoretical Aspects of Some Collective Instabilities in High-Energy Particle Storage Rings" was published as a CERN Yellow Report [3] (see Fig. 2). In the extensive introduction of his thesis Francesco first gave a short and concise Hamiltonian formulation of single particle dynamics in storage rings, followed by a clear definition of the "smooth approximation" which had often been used by other authors without much further justification.



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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THEORETICAL ASPECTS
OF SOME COLLECTIVE INSTABILITIES
IN HIGH-ENERGY PARTICLE STORAGE RINGS

Francesco Ruggiero

GENEVA
1986

Figure 2: The cover page of Francesco's PhD thesis.

He also investigated the effects of noise in electron storage rings, using a renormalized Fokker-Planck equation which he solved with the techniques of stochastic differential equations. He later applied the same approach to analyze the beam-beam effect in colliders. Here he treated the beam-beam encounters as periodic kicks which can be considered to constitute an additional source of noise and thus lead to an increase of beam size above a threshold usually called beam beam limit.

The Transverse Mode Coupling Instability (TMC), sometimes called the fast-head-tail effect in the USA, was originally observed by R. Kohaupt at DESY when he tried to identify the cause of rapid beam loss which had occurred in the DESY electron storage ring PETRA in 1980, which he had originally called "Transverse Turbulence".

However, it soon became clear that this type of instability was actually caused by coupling of neighboring head tail modes, and its threshold current was found to be inversely proportional to the total transverse impedance around the machine circumference. Hence it would be especially dangerous for very large storage rings such as LEP which was then just being designed at CERN. A good understanding of beam stability in the presence of the rather large number of unavoidable structures surrounding the beam – such as RF cavities, kickers, bellows, pick-ups etc. – was therefore important in order to choose the best design parameters and to optimize future machine performance. In all previous analytic work distributed impedances had been assumed, mainly due to a large number of small cross section variations of the vacuum chamber, and often globally described by "broad-band impedances". In addition to analytical work, computer simulation codes in time domain were then being developed both at CERN (e.g. SIMTRAC by D. Brandt) and in other accelerator laboratories (SLAC, DESY) to include the effects of large, localized structures. Their impedances or wake fields could be measured or computed with numerical codes. This was in particular important for LEP where the major contribution to the impedance was expected to come from numerous large copper and superconducting RF cavities required to compensate the large synchrotron radiation losses.

To compare the results of the two methods, it was necessary to perform an analysis also using impedances of localized structures as assumed in the simulations. Francesco was able to develop a new and original approach leading to an integral equation for the dipole moment of the bunch oscillations. From this he obtained an eigenvalue problem which then allowed calculation of threshold currents and also led to a dispersion relation [4].

For Gaussian bunches, the usual shape of electron beams, explicit solutions in terms of Hermitian polynomials were found. The resulting expressions for the threshold current were in general agreement with those for distributed impedances, but the latter were shown to be valid only for tunes far from synchro-betatron resonances, while they could become drastically lower near those resonances. Francesco made numerical predictions for LEP which agreed quite well with results from computer simulation and were later verified by measurements on the machine (Fig. 3).

We now consider in some detail the effect of a localized impedance discussed in Francesco's thesis. Take a beam which passes through a localized object (at location $s$), and which induces a charge distribution on the object's walls, that depends on the beam distribution at $s$. The charge dis-

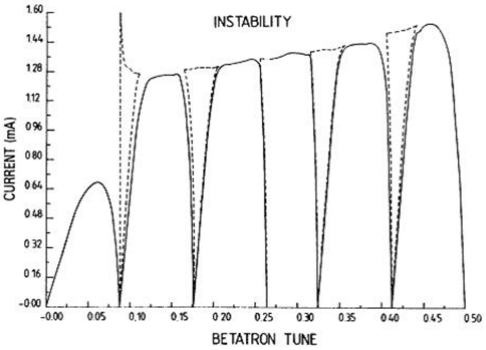

Figure 3: TMC threshold current vs. betatron tune with localized impedances, from Francesco's PhD thesis.

tribution affects the subsequent beam arriving at location $s$ The effect arises from the wall charges at $s$. The distribution at $s$ versus the turn number is to be analyzed. To this end one finds the eigenvalues of the Vlasov equation, and looks for instabilities. A Fourier transform is applied in $s$, with corresponding integer index $k$. The observation location chosen for the distribution can be taken to equal an impedance location. The Vlasov equation couples mode $k$ to another mode $\bar{k}$, resulting in the impedance mode $k - \bar{k}$.

Normally accelerator physicists apply a smooth approximation and assume a uniform effective impedance. Francesco noticed that there would be no coupling between different modes $k$ in such a case, i.e. for an effective impedance independent of $s$, while there would still be coupling between internal bunch modes and multibunch modes. Francesco looked at a different limit, namely the limit where all the ring impedance is concentrated at a single location. In this case only the fractional tunes can be relevant, and all modes $k$ defined above are strongly coupled. Instead one can use a different mode basis, localized at a point $s$. The result then is a mode coupling between non-adjacent azimuthal mode numbers $m$, e.g. between $m = 0$ and $m = 4$. Fortunately, this coupling is typically weak. After a rather narrow stop band for higher intensity the motion is stable again. And the final strong instability can arise from the coupling between the modes $m = 0$ and $m = -1$, in a standard fashion. Mode parity explains why the approach of some of the modes does not result in a stop band.

## 4 LEP & TRISTAN

Francesco actively participated in "LEP-MDs" (machine development sessions), which was particularly valuable as he had been sent for a few weeks to KEK in Japan to participate in the commissioning of the world's second largest electron-positron collider "TRISTAN". During his stay in Japan, Francesco discussed many issues related to TRISTAN and to beam-beam effects with Kohji Hirata, whom he knew from an earlier correspondence on the correct treatment of a local impedance. Francesco's experiences at KEK are summarized in a LEP note [5], which he also sent to his friends and colleagues at KEK, where it was much appreciated. Shortly after his return to Geneva, Francesco invited Kohji Hirata to visit CERN and to profit from its exciting environment during the start up of LEP, in a letter dated 7 July 1987. At that time, TRISTAN had stopped using the electrostatic separators during injection and acceleration because of discharge problems and because they appeared to be unnecessary. Francesco wanted to know more details about the separator-free operation. Following Francesco's advice, Kohji Hirata decided to go to CERN as a scientific associate. His office was next to that of Francesco in building 30 and the two discussed and talked a lot in the offices and in the cafeteria of the 7th floor, leading in particular to the development of the "synchrobeam mapping", which we will recall in a later section on the "beam-beam" interaction.

## 5 CLIC AND BEAMSTRAHLUNG

In addition to his work on LEP Francesco also took an interest in the linear collider project CLIC, which was then proposing collisions of extremely small and dense bunches in order to achieve the very high luminosities desired by the experimenters. As classical physics seemed to predict that the energy loss in to the collision could become higher than the particle energies, it was then suspected that a quantum mechanical description would be required for these extreme particle densities. Several leading quantum physicists had already started to work on this problem.

With Claudio Pellegrini, who was then visiting CERN for several months, Francesco could show that this paradox was avoided when the "radiation reaction" was properly taken into account [6]; see Fig. 4. Following this study he further proposed the use of opposing bunches as focusing elements which could form an achromatic system without sextupole correction elements as required by conventional quadrupole channels [7].


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RADIATION REACTION EFFECTS IN HIGH ENERGY ELECTRON-POSITRON LINEAR COLLIDERS

C. Pellegrini*) and F. Ruggiero

ABSTRACT

We discuss the electromagnetic interaction of electron and positron bunches at the focal point of a linear collider. Using classical electrodynamics and including the effect of the radiation reaction force, which plays a dominant role in the energy loss of the particles and influences their trajectories, we derive an expression for the beamstrahlung parameter which is consistent with energy conservation. In the limit of small losses, our results coincide with those obtained previously. We also discuss the conditions for which the classical description is no more valid and a quantum mechanical calculation is needed.

Figure 4: Paper with Claudio Pellegrini on "radiation-reaction effects" in linear colliders.

## 6 SYNCHROTRON RADIATION

In 1988 Kohji Hirata and Francesco studied the treatment of synchrotron radiation in electron storage rings, starting from basic principles [8].

Together with his former professors E. Picasso and L. Radicati Francesco also published a profound paper on the kinetic description of electron beam behavior in the presence of incoherent synchrotron radiation [9], as well as a lecture note on a statistical description of nonlinear phenomena in a charged-beam plasma [10]. With Emilio Picasso, Francesco also published an encyclopaedic article on particle accelerators [11] and some considerations on LEP [12]. Francesco also analyzed the effects of the discontinuous replacement of energy losses by RF cavities in LEP [13], and studied the proper inclusion of this radiation in simulation programs [14].

Later, for LEP, Francesco also derived a "correct" formula for the longitudinal quantum lifetime in electron storage rings [15], which differs from the classical formula of Matt Sands [16]. Francesco obtained his revised expression by applying a formalism developed much earlier by S. Chandrasekhar for problems involving diffusion across potential barriers in astrophysics [17]. After publishing his report Francesco received a phone call from Matt Sands in California. It is not clear whether that conversation came to a conclusion about the right expression.

## 7 OPTICS

Francesco published novel fundamental papers on many subjects of accelerator physics. Not quite as well known as his work on collective effects are his ingenious contributions to optics.

Together with Bob Gluckstern, Francesco derived the equation for the betatron function, the betatron phase advance, and the dispersion from variational principles [18]. These were recognized to be special cases of a general principle concerning the eigenvalues of a symplectic matrix.

For LEP Francesco also studied the subtle implications of a novel method to measure the dispersion dynamically via exciting longitudinal oscillations in the presence of spurious dispersion at the rf cavities [19], as well as, together with Alexander Zholents, a way to correct the residual dispersion in LEP resonantly [20].

Francesco wrote several novel and important modules of the accelerator design code MAD [21]. For a while Francesco's extended version of the code was called "rgo-mad", prior to its integration into the standard MAD code. The features introduced by Francesco were documented in [22]. They include an automatic search for the dynamic aperture "DYNAP", the calculation of early indicators of instability, like Lyapunov exponent or frequency detuning, and a global matching command "global" that could minimize any user-defined function. These tools were, and are still being, widely used, all over the world, for example in the design of BEPC-II at IHEP in China.

All his optics studies exhibited original approaches, novel methods, and a deep understanding of accelerator physics, which were, and remained, a key trademark of Francesco's work through his entire career in physics.

## 8 BEAM ECHOES

For many years Francesco was intrigued by beam echoes, which he considered a potentially highly efficient tool for measuring diffusion rates inside the beam. Early echo studies under his guidance were performed by Oliver Brüning [23], who joined Francesco's "collective effects" section in the SL-AP group as a fellow in 1995. Francesco's first assignment for Oliver was to study a paper by Pat Colestock, Francois Ostiguy and Linda Spentzouris on Beam Echo measurements in the Tevatron [24] and to explore the potential application of measuring small diffusion processes in an accelerator. Related echo phenomena had been studied earlier since the 1950's, for example spin echoes by E. Hahn in 1950 [25], plasma wave echoes by O. Neil in 1965 [26], or echo effects in hadron colliders by G. Stupakov and K. Kauffmann in 1992 [27], involving a dipole kick followed by a quadrupole kick. The beam echo studies at the CERN SPS in 1995 continued this type of research.

The longitudinal echo response in the beam current is of the form [23]

$$I(t) = A_{\rm form}(\rho) A_{rmenv}(t_1, t_2) A_{\rm diffusion}(D, t) \ , \qquad (1)$$

where the last term depends on the diffusion coefficient $D$. Francesco and Oliver realized that the echo response can be used for measuring small diffusion coefficients in relatively short time scales. The work at CERN clarified the correct interpretation of the diffusion term and provided the prerequisite for using this technique in a storage ring. The echo studies of the mid-90's proceeded via a strong collaboration within CERN between the accelerator physics (AP), RF and operation (OP) groups, as well as through a strong international collaboration performing and comparing measurements in several hadron machines: AGS, RHIC, HERA, Tevatron and SPS.

In 2000, a discussion of Francesco with Walter Scandale gave rise to the idea that it should be possible to generate transverse echoes in an unconventional way, namely by successively applying two dipole kicks of different magnitude rather than a single dipole kick followed by a quadrupole kick (transverse quadrupolar kickers are not available in most, if not all, machines). Francesco performed first simulations, and guided the parameter optimization for an SPS machine experiment in this new approach. The SPS study was immediately successful and led to the first ever observation of transverse beam echoes in good agreement with more advanced simulations [28]; see Fig. 5.

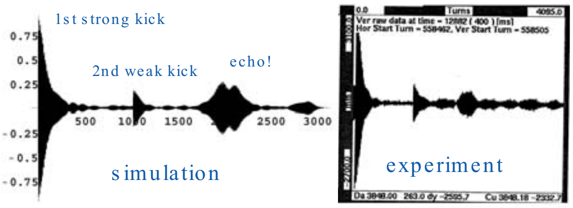


Figure 5: First observation of transverse beam echo induced by two successive dipole kicks at the SPS (right) compared with the corresponding simulation (left) [28].

## 9 LEP IMPEDANCE AND ZBASE

When Oliver Brüning joined the collective effects team Francesco also asked him to evaluate the LEP impedance as the Cu cavities were replaced by SC cavities and to estimate the TMCI threshold as a function of the installation progress. This task implied collecting the impedance data for different items from various groups, e.g. radiofrequency (RF), vacuum (VAC) etc., and to re-evaluate the wake fields and loss factors for shorter bunch length (requiring access to various computer tools: MAFIA, ABCI, etc.). The data was not always easy to get (e.g. geometry and wake potentials) and was generally not in a consistent format. This triggered the idea of building a data base "ZBASE" that ensured:

- a common data format (e.g. for measured data and for data from simulation or theoretical formulas);
- links to the programs that were used for calculating the impedance or wake potentials;
- the provision of tools for summing impedance and wake potential data of different items and converting from one to the other;
- including information of the relevant beam and optics data;
- the provision of tools for evaluation some of the key threshold values (e.g. TMCI and multi-bunch instability thresholds)

For this task to become a success, the work had to be done in the framework of a broad collaboration at CERN (e.g. including the RF and VAC groups), and in a close collaboration with external colleagues from other laboratories (e.g. Scott Berg and M. Dyatchkov); the data base had to be accessible from anywhere at CERN and in the world (leading to the choice of implementation on 'afs'); the data base had to be accessible from any platform (therefore the choice of an interpreted language: TclTk); and ZBASE had to be expandable to machines other than LEP, e.g. it included the LHC from the start.

It was not an easy task. A strong collaboration at CERN (e.g. between AP and RF) and beyond deserves credit for the successful outcome of the LEP ZBASE programme. Presently, we are at the 3rd generation of ZBASE (and there is no end in sight), which is being filled with updated data for the LHC and the SPS. The fact that the data base is still being developed demonstrates that there is a clear need for such a data base, which in turn shows that Francesco had the right vision when he asked Oliver to start this work.

## 10 LHC IMPEDANCE

### *10.1 LHC Beam Screen*

After completion of his thesis Francesco remained in the LEP division of CERN as a fellow and later became a full staff member. One of his first tasks was the calculation of the impedance of the extremely large number of holes in the "liner" for the LHC. Such an inner vacuum chamber, held at an intermediate temperature, had been proposed for the LHC in order to reduce the cryogenic power required to keep the outer vacuum chamber near the very low magnet temperature of 2 degrees Kelvin by shielding it from the powerful synchrotron radiation of the beam. A similar idea had also been developed for the SSC which was then still planned to be built in Texas. Francesco started a collaboration with that laboratory, which was later extended to include accelerator physicists from the Budker Institute in Novosibirsk.

Francesco had found that the basic formulae for the electro-magnetic fields induced by a charged particle beam in a hole of a surrounding wall had already been derived many years earlier by the Nobel Laureate Hans Bethe. He extended this technique to estimate the impedance of the very large number of holes in a liner required to permit good pumping. He varied the hole shape, size, and number, and proposed random arrangements to reduce resonant effects on the beam occurring due to periodicities in regular arrangements. Over the next years the proposed shape of the liner was changed many times for mechanical reasons and many papers were written on this subject.

By 1995 the LHC pipe design had assumed the following features: rounded corners (manufacturing limitations), stainless steel pipe (pure Cu would not sustain the quenching forces due to magnetic field penetration & parasitic currents), copper-coated surface (uncoated SS would give excessive parasitic losses; the coating was restricted to flat faces, where fields and loss would be largest), and pumping holes (removal of desorbed gas molecules by synchrotron radiation). Beam-coupling impedances for this liner were computed by invoking a reciprocity theorem which can be applied if an unperturbed potential is known and using Leontòvich boundary conditions for the perturbed potential [29]. Stefania Petracca, closely collaborating with Francesco, used this reciprocity theorem for computing the longitudinal and transverse coupling impedances of a square liner with rounded corners [29].

The Leontovinch boundary condition [30]

$$\vec{n} \times \left(\vec{n} \times \vec{H}\right) = \sqrt{\frac{j\sigma}{\omega\mu_0}} \vec{n} \times \vec{E} \,, \qquad (2)$$

was originally formulated for a planar surface, bounding some highly reflecting transversely homogeneous lossy half-space. But in fact it is much more versatile than this, and it can also be applied to (1) lossy stratified media, e.g., by repeated use of the transmission-line impedance transport formula, (2) curved surfaces, and (3) inhomogeneous media, etc [31, 32].

The coupling impedance of perforated walls was computed starting from this boundary condition [29], and the impedance expressed through hole polarizabilities. The formulae obtained were consistent with earlier findings of Kurennoy [33] and Gluckstern et al [34]. Hole polarizabilities are available for a variety of hole shapes [35]. Corrections for hole-hole coupling were worked out [36] in the quasi-static approximation [37]. Corrections to Bethe's formula for polarizabilities beyond the underlying quasi-static ($kD \ll 1$) assumption (very short bunches) can be found in Ref. [38]. Stefania Petracca calculated the LHC parasitic losses on the beam screen analytically, adding the Ohmic and hole contributions. The final numbers were in good agreement with measurements by Fritz Caspers, Michele Morville, and Francesco.

Several calculations of beam-screen impedance were done in collaboration with Weiren Chou from the SSC, in particular, on how to minimize it in the slot design. Weiren and Francesco compared different lengths, shapes and distributions of slots and concluded that the short, racetrack-shaped, randomly distributed slots would be the best choice. This design was eventually adopted by the LHC. Figure 6 compares impedances for periodic and random slots produced in the course of a similar study for the SSC. Weiren Chou had extensive discussions with Francesco on this topic during his visit to CERN in 1995 because of the similarity between the SSC liner and LHC liner.

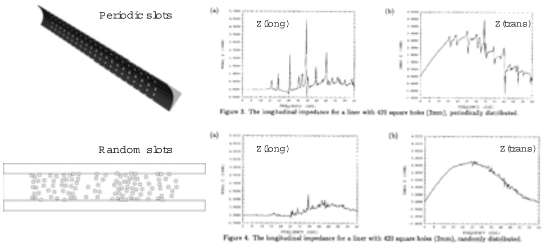


Figure 6: Longitudinal and transverse impedance of a beam screen with periodic (top) or random pumping slots (bottom) [39, 40] [Courtesy W. Chou].

In 1995 Weiren Chou tried to offer an alternative to the copper coated stainless steel pipe by an extruded aluminum pipe [41], which would have avoided the slots in the screen that might potentially generate TEM wave coupling between the beam and pipe. But Francesco refused to promote this proposal. And he was definitely right, especially in view of the later found electron cloud effect.

Detailed and advanced calculations on the beam pipe impedance were performed in the PhD thesis of Andrea Mostacci under the supervision of Francesco [42]. Andrea's thesis covered several aspects: (1) refined impedance calculations for the pumping slots, involving an analysis of the electromagnetic coupling through holes between a cylindrical and a coaxial waveguide; (2) the impedance effects of an artificial sawtooth roughness that had been added in 1997/98 to reduce the heat load from electron cloud, which required a study of the interaction between the beam and a surface (synchronous) wave in a (rectangular) beam pipe with "small" periodic corrugations; and (3) the effect of weldings, i.e. an investigation of the current distribution in a (metallic) beam pipe whose conductivity varies with the azimuth (for an ultrarelativistic beam).

With guidance from Francesco, Andrea Mostacci showed that randomizing the position of the holes does not affect the loss factor, and he calculated this (geometric) loss factor for $N$ equispaced holes at distance $D$, in the limit of negligible Ohmic losses to be [42]

$$k(\sigma) = \frac{Z_0 \sqrt{\pi} c (\alpha_m + \alpha_e)^2}{128 \pi^4 b^4 \ln(d/b) \sigma^3} \left[ N^2 + \left( \frac{\sigma}{D} \right)^2 \frac{(\alpha_m - \alpha_e)^2}{(\alpha_m + \alpha_e)^2} \right] , \tag{3}$$

with $\alpha_m$ and $\alpha_e$ denoting the magnetic and electric polarizability of the holes, respectively. Andrea also derived analytical expressions for the Ohmic losses in the coaxial region.

Depending on the length of the beam screen under consideration, one transits from a region where the losses per unit length increase linearly with the length of the beam screen to an asymptotic regime of constant loss per unit length. For LHC parameters, the transition occurs around a length of 100 m (roughly one arc FODO cell). Andrea Mostacci, Luigi Palumbo and Francesco together derived the exact formula which connects the two limiting regimes [43]. Around the nominal LHC values the (asymptotic) losses are described as [44]

$$P_\infty \approx P_0 \exp\left(-1.75 \pi T / W\right) , \tag{4}$$

with

$$P_0 \approx 42 \frac{\mathrm{mW}}{\mathrm{m}} \left( \frac{\mathrm{W}}{1.5\mathrm{mm}} \right)^4 , \tag{5}$$

where $W$ denotes the slot width and $T$ the wall thickness. A primary result of these investigations was that the power loss per unit length is negligible for holes of the nominal dimensions.

## 10.2 Resistive Wall Impedance

In addition to the impedance due to holes and other geometric obstacles, also the impedance arising from the resistivity of the liner should be included in the calculations. Francesco found a novel method to calculate the resistive wall impedance for pipes of arbitrary cross section, which he could express as derivative of their electric capacitance [45]. More specifically, Francesco showed that the longitudinal impedance is proportional to the "normal derivative" of the electrostatic energy stored in the region between the beam and the surrounding beam pipe:

$$\frac{Z_L}{L} = Z_w \frac{\delta}{\delta n} \left( \frac{\epsilon_0}{\mathcal{C}} \right) \ , \tag{6}$$

where $\mathcal{C}$ denotes the "specific capacitance," and $Z_w$ the surface impedance. He applied this new method of impedance computation to the LHC liner. From his equation he also deduced that for a centered beam pipe and for a given wall resistivity, a square pipe has the same longitudinal impedance as the inscribed circular pipe.

In the summer of 1995, while Weiren Chou visited CERN, he worked with Francesco not only on alternative beam screens, but foremost on the resistive wall heating of the LHC beam screen. Their joint study discussed for the first time the combined effect of wall resistance under three extreme conditions:

- at low temperature (a few $^\circ$K);
- in a strong magnetic field (several Tesla); and
- for high frequency (fraction of GHz or above).

The result was published in the LHC Project Note no. 2 [46]. It led to a revision of the LHC cryogenic heat load budget, since the surface resistance of copper at cryogenic temperatures was found to be about a factor two larger than previously estimated. Further experimental and theoretical studies on this subject followed, under the leadership of Francesco [47, 48, 49]. Weiren Chou and Francesco had the chance to continue their discussions during Snowmass 1996 (Fig. 7).

Figure 7: Steve Holmes, Francesco Ruggiero, Hajime Ishimaru, Weiren Chou, Eberhard Keil, and Dave Finley at Snowmasss 1996 [Courtesy W. Chou].

Andrea Mostacci studied a beam pipe with azimuthally varying conductivity, using the calculation approach that had been described by Francesco in Ref. [45]. The current distribution and resulting azimuthal magnetic fields were obtained as a function of the azimuth for room temperature and cryogenic conditions at different frequencies. The main conclusions for LHC were that the surface currents are constant over the azimuth at all relevant frequencies. The losses in the welding equal 5% of the ones in the copper at room temperature or 50% of the copper losses at cryogenic temperatures.

An interesting exploration in this same context concerned the validity of the Leontovich boundary condition (2), which is a "first order" condition, or surface impedance boundary condition. A higher frequency limit arises from the requirement that the wave length be much larger than the skin depth. For stainless steel this gives a limit at 200 THz. At low frequencies two different effects limit the applicability of the Leontovich boundary condition at room temperature and at cryogenic temperature: the variation of the material properties should be small on the scale of the skin depth, and the beam pipe curvature should be much-larger than the skin depth. For LHC the resulting lower-frequency limits are 20 kHz and 5 kHz, respectively.

Both simulations by HFSS and laboratory $Q$ measurements on a coaxial resonator comparing steel and brass bars [50] were used to corroborate the analytical results.

## *10.3 IR Y Chamber*

For the LHC IR recombination chamber, or "Y chamber", MAFIA simulations demonstrated the importance of smooth transitions between the chambers to avoid unacceptable power deposition due to modes trapped in the structure [51].

For the LHC Y-chamber design, the trapped modes were not eliminated, but only damped, and further study was needed to see whether these modes could be either completely removed or damped to even lower values. Simulations by MAFIA and HFSS were benchmarked by measurements on a rectangular scaled model. These studies were performed in a collaboration which Francesco organized between CERN, LBNL, INFN, and the University La Sapienza. The joint studies demonstrated that tapering the transition, as in the actual geometry, strongly reduces the effect of the trapped modes [52, 53].

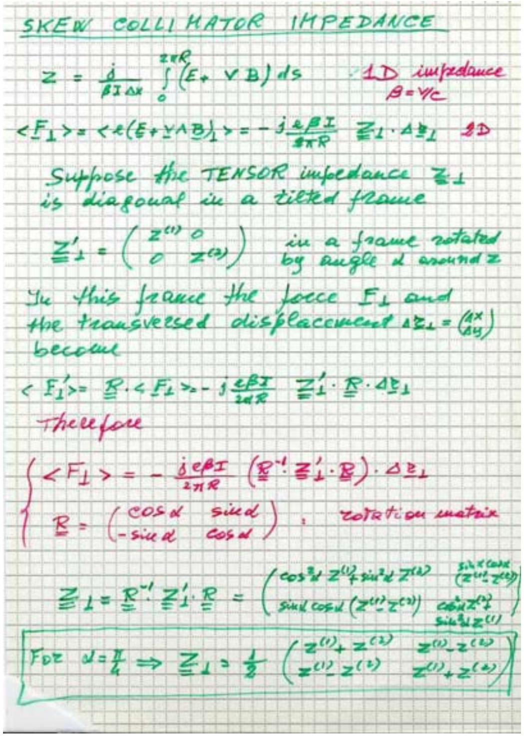
## *10.4 COLDEX*

The COLD bore EXperiment (COLDEX) in the SPS machine uses an LHC-like cryogenic vacuum chamber to study the interaction with proton beams, with particular attention to the electron cloud effect. Its impedance was calculated in a collaborative effort [54]. For the upgraded COLDEX vacuum chamber studies with MAFIA indicated that the chamber heating due to the beam coupling impedance was reduced by two orders compared with an earlier version of COLDEX, and that, as a consequence, this heating should represent a negligible part of the measured total dissipated power [55], a large part of which could instead be attributed to the electron cloud.

## *10.5 Collimators*

Invoking simple scaling arguments for the dependence of the resistive-wall impedance on length, resistivity, and aperture, Francesco was the first to point out that the LHC collimators had an impedance problem [56].

Some of the collimators in the LHC are not horizontal or vertical ones, but tilted in the transverse plane. Francesco readily showed how to deal with such cases using a tensor transformation [57], as sketched in Fig. 8.



SKEW COLLIMATOR IMPEDANCE

$$Z = \frac{j}{\beta I \Delta x}\int_0^{2\pi R} (E + v B)\, ds$$ 1D impedance $\beta = v/c$

$$\langle \underline{F}_\perp \rangle = \langle e(\underline{E} + \underline{v} \wedge \underline{B})_\perp \rangle = -j\frac{e\beta I}{2\pi R}\, \underline{\underline{Z}}_\perp \cdot \Delta\underline{z}_\perp$$ 2D

Suppose the TENSOR impedance $\underline{\underline{Z}}_\perp$ is diagonal in a tilted frame

$$\underline{\underline{Z}}'_\perp = \begin{pmatrix} Z^{(1)} & 0 \\ 0 & Z^{(2)} \end{pmatrix}$$ in a frame rotated by angle $\alpha$ around z

In this frame the force $\underline{F}_\perp$ and the transversed displacement $\Delta\underline{z}_\perp = \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix}$ become

$$\langle \underline{F}'_\perp \rangle = \underline{\underline{R}} \cdot \langle \underline{F}_\perp \rangle = -j\frac{e\beta I}{2\pi R}\, \underline{\underline{Z}}'_\perp \cdot \underline{\underline{R}} \cdot \Delta\underline{z}_\perp$$

Therefore

$$\begin{cases} \langle F_\perp \rangle = -\dfrac{je\beta I}{2\pi R}\left(\underline{\underline{R}}^{-1} \cdot \underline{\underline{Z}}'_\perp \cdot \underline{\underline{R}}\right) \cdot \Delta\underline{z}_\perp \\ \underline{\underline{R}} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \end{cases}$$ rotation matrix

$$\underline{\underline{Z}}_\perp = \underline{\underline{R}}^{-1} \cdot \underline{\underline{Z}}'_\perp \cdot \underline{\underline{R}} = \begin{pmatrix} \cos^2\alpha\, Z^{(1)} + \sin^2\alpha\, Z^{(2)} & \sin\alpha\cos\alpha\,(Z^{(1)} - Z^{(2)}) \\ \sin\alpha\cos\alpha\,(Z^{(1)} - Z^{(2)}) & \cos^2\alpha\, Z^{(2)} + \sin^2\alpha\, Z^{(1)} \end{pmatrix}$$

$$\boxed{\text{For } \alpha = \frac{\pi}{4} \Rightarrow \underline{\underline{Z}}_\perp = \frac{1}{2}\begin{pmatrix} Z^{(1)} + Z^{(2)} & Z^{(1)} - Z^{(2)} \\ Z^{(1)} - Z^{(2)} & Z^{(1)} + Z^{(2)} \end{pmatrix}}$$

Figure 8: First slide from Francesco's presentation on the tensor impedance of tilted collimators [57].

For a skew collimator titled at $\pi/4$ the expression for the resulting tune shift is particularly simple. Noting that the impedance in the non-collimating direction $Z^{(2)}$ is equal to one half that in the collimating direction $Z^{(1)}$ (so-called Yokoya coefficient), the tune shifts induced by a skew collimator in either plane are [57]

$$\Delta Q_x = j\frac{N_b r_p}{2\pi\gamma}\frac{\beta_x}{Z_0 R}\frac{3}{4}Z_{(1)} , \quad (7)$$

$$\Delta Q_y = j\frac{N_b r_p}{2\pi\gamma}\frac{\beta_y}{Z_0 R}\frac{3}{4}Z_{(1)} , \quad (8)$$

Where $Z_0$ denotes the vacuum impedance, $r_p$ the classical proton radius, and the beta functions are taken at the location of the collimator. In addition to these tune shifts the skew collimator also induced a cross term, i.e., a coherent horizontal motion will change the vertical focusing and vice versa, of strength [57]

$$\Delta Q_{xy} = j\frac{N_b r_p}{2\pi\gamma}\frac{\beta_x}{Z_0 R}\frac{1}{4}Z_{(1)} . \quad (9)$$

## 10.6 Analytic Approximations of Tune Shifts and Beam Coupling Impedances

Together with Stefania Petracca, Francesco worked towards an analytical description of tune shifts and beam coupling impedances for the LHC.

The general tune shifts of the two transverse betatron modes are described by a tensor which is related to the tensor of Laslett coefficients. Both coherent and incoherent normal modes can be derived for square and circular pipes or liners. For a twin-beam toy model of an LHC dipole (Fig. 9) Stefania considered different regimes: incoherent-incoherent, coherent-coherent, and mixed. Both high-frequency non-penetrating modes and low-frequency penetrating modes were included. Different coherent and mixed dynamics were obtained [58]. The Al collars holding the beam pipes in the LHC design considered at the time would prevent the dynamic magnetic field from coupling the two beams, even at the lowest frequency associated with collective beam oscillations. As a result, the two beams are dynamically uncoupled. Neglecting space-charge effects, all regimes (incoherent, coherent, & mixed) merge in the limit $\beta \rightarrow 1$, yielding for both pipes the same general expression for the Laslett tensor.

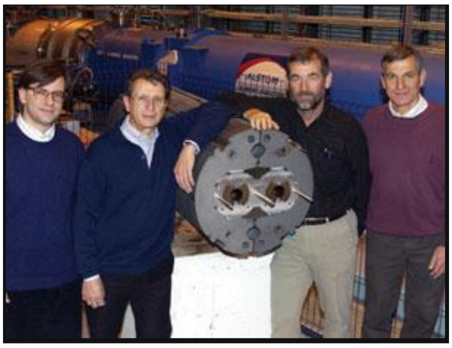


Figure 9: Francesco Ruggiero, Massimo Placidi, Flemming Pedersen, and Karl-Heinz Schindl with an LHC dipole cold bore.

For analyzing real-world geometries, various numerical approaches were explored.

One of them is the *Method of Moments*. Using this method, rounded corners and shape variations were treated based on an efficient representation of the (exact) Green's function for rectangular and circular domains, allowing one to shrink the unknown charge density support (and related number of unknown charge expansion coeffecients) to a minimum [59]. This technique was used to compute the Laslett coefficients as a function of round-corner radius, and for a hard-cut circle model of the LHC beam screen, as in the final shape.

In the *random path* approach one computes the (complex) potential only on a circle, using stochastic calculus, and then uses the Cauchy integral formula for computing the Laslett coefficients without the need of approximating derivatives with finite differences [60]. Random paths were employed to compute the higher-order modes extending to the cold bore.

### *10.7 LHC Impedance Budget*

The basic approach used for LHC impedances was to first identify the devices mostly affecting the machine impedance, and to make an impedance budget estimation for these devices: strip-line monitors, kickers, beam screen, Following the teaching of Bruno Zotter, Francesco and Luigi Palumbo perfected the impedance-wise design of LHC components. The fundamental guiding principle set up by Francesco was that the coupling impedance of each device must be estimated by means of at least two out of three methods: (1) theoretical estimation, (2) numerical simulation, and (3) bench measurements. Similar work was done for the impedance of DAFNE at LNF.

Examples of LHC impedance-wise designs, many of which were done in collaboration with Luigi Palumbo plus his students at the University La Sapienza in Rome, include (1) the LHC beam screen (vacuum pumping slots, artificial roughness, welding) [42]; (2) the anomalous skin effect [46, 47, 48, 49]; (3) the LHC IR [Y chamber] [51], and (4) the COLDEX chamber.

## 11 COLLECTIVE EFFECTS

Francesco had a deep understanding of collective phenomenona, which he demonstrated in his treatments of (1) the effect of a localized impedance treated in his thesis, (2) the two-dimensional transverse Landau damping, (3) electron cloud instability, and (4) space charge at high energy.

The effect of a localized impedance was discussed above. “Landau damping” can arise if the single-particle tune depends on the oscillation amplitude, together with a finite beam size. Due to the spread in frequencies an oscillation involving the entire beam will decohere, if the frequency of the oscillation lies within the beam frequency spread. Stability diagrams can be drawn so that any complex oscillation frequency within the boundary described by the diagram is stabilized. The boundary is a measure of the tune spread in the beam.

The LHC will have little radiation damping, but Landau damping is an important damping mechanism. When investigating the Landau damping caused by tune spread with amplitude one must take into account the betatron tune spreads in two directions. The calculation had only been done in one direction until Francesco looked at this problem. So he and Scott Berg computed it for two dimensions, with the tune shift as a function of the two transverse amplitudes pointing either into the same or in opposite directions [61]. Francesco found that if the tune shifts are in the same direction larger instabilities can be damped, but for tune shifts in opposite direction real mode shifts in both directions are allowed, which could be interesting in the presence of a modest space charge. The expected Gaussian tails must be truncated. Francesco worked out a model with cuts at $3\sigma$; later Scott and Francecsco derived the solution for arbitrary cuts [61]. Afterwards, together with Elias Métral, Francesco extended the two-dimensional Landau damping formalism to explicitly include the combined effect of octupoles and nonlinear space charge, and the two applied this to the LHC at injection [62].

On many occasions, Francesco questioned whether space charge should be treated just as an impedance. He highlighted the difference that in case of space charge the beam itself, not a wall, mediates the force. The question was important for the LHC, where a large coherent space-charge tune shift might be favorable for Landau damping (it opposes the inductance). It induces a large incoherent tune spread, but does or can the space-charge tune shift with amplitude provide the naively expected Landau damping?

Based on work by himself, Luigi Palumbo, and other collaborators, Francesco wrote a comprehensive assessment of collective effects and the resulting impedance budget in the LHC, covering a large number of possible instabilities and space-charge effects, including fundamental questions about the role of space charge and particularities related to the large circumference of the LHC [63]. This report has become the “bible” of collective effects in the LHC.

Francesco also worked with K. Hirata and S. Petracca on bunch lengthening, using mathematical catastrophe theory [64].

## 12 ELECTRON CLOUD

A new type of collective effect is the electron cloud. In 1995-96 some concerns about the effect of “beam-induced multipacting” on the LHC vacuum were expressed by Oswald Gröbner, based on the ISR experience [65]. In response to instability observations at the KEK Photon Factory [66], and their interpretation as due to photoelectrons, the so-called “Ohmi effect” [67], a decision to add an antechamber to the arc vacuum chambers of the PEP-II Low Energy Ring (LER) was taken by Mike Zisman, and a last minute TiN coating effort for the final PEP-II LER arc chambers was launched by both John Seeman and Mike Zisman at the end of 1996. Following an invitation by Francesco after Snowmass 1996 (Fig. 10), Frank Zimmermann, who was involved in the PEP-II enterprise, visited CERN for two weeks in February 1997.

Frank realized that the number of synchrotron-radiation photons emitted per turn per proton in the LHC is the same as in the PEP-II positron ring. Therefore, in the LHC, photoemission, with a critical photon energy of 44 eV, would provide a formidable source of photoelectrons that could further be amplified by secondary emission via a “multipacting” process. During his stay at CERN Frank wrote a simulation code “ECLOUD” to model the electron-cloud generation in the LHC, including both photoemission and secondary emission. The simulations showed a run-away build up of electrons over a wide range of realistic surface parameters. Inspired by discussions with Francesco he added the electron space charge to limit the build up and obtained an equilibrium at rather high electron levels which could give rise to significant multibunch instabilities. Francesco also proposed to treat electrons spiraling in

Figure 10: Francesco Ruggiero and Frank Zimmermann during Snowmasss 1996.

a magnetic field as permanent magnetic dipoles. The result of Frank's study was published as an LHC Project Report [68].

Frank's work indicated various possible limitations for the beam intensities in the LHC due to the electron cloud. Francesco soon drew a schematic which nicely illustrated and summarized the process by which an electron cloud builds up in the LHC. It is shown in Fig. 11. The label "reflected" electrons was added by Francesco a couple of years later after the importance of elastic reflection had become clear [69]. Following Frank's visit, in 1997 and 1998, Francesco encouraged simulations at CERN by Oliver Brüning [70] and at LBNL by Miguel Furman [71], respectively, which highlighted that a main concern for the LHC is the energy deposition by the electrons given the limited cooling capacity of the LHC beam screens. LHC is the first storage ring ever in which this is a potential problem. The initial estimates for the resulting heat load were of order of several W/m, which would exceed the available cooling capacity of the LHC cryogenic system. The cryogenic system had been designed before the effect was discovered. At face value, one would have had to cut the bunch intensity or increase the bunch spacing by factors of a few to stay within the available cooling capacity of the cryogenic system.

Francesco recognized the importance of this potential threat and initiated a crash program at CERN that studied the implications of this effect for the LHC operation and looked at possible remedies for the LHC before all hardware designs were frozen. The crash programme was executed via a strong collaboration between different groups and departments at CERN (e.g. AB, AT and TS) and with the help of several other laboratories world wide

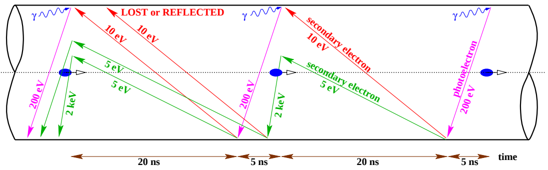


Figure 11: Schematic of electron-cloud build up due to photemission and secondary emission in the LHC, drawn by Francesco Ruggiero around 1997.

(e.g. LBNL, SLAC and BNL as part of US-LARP). Further studies and experimental evidence over the following years showed that the electron cloud effect is not only a problem for the LHC, but may also be one for the LHC injectors, SPS and PS, when operated with LHC beams.

At times there was skepticism about the electron cloud effect. Francesco looked at the calculations of others, saw its potential importance for LHC, and he vigorously started and led the crash program to address it. People involved in the LHC electron-cloud crash programme included Gianluigi Arduini, Vincent Baglin, Scott Berg, Christofore Benvenuti, Oliver Brüning, Fritz Caspers, Roberto Cimino, Ian Collins, Miguel Furman, Oswald Gröbner, Noel Hilleret, Ubaldo Iriso, Miguel Jimènez, Tom Kroyer, Mauro Pivi, Giovanni Rumolo, Daniel Schulte, Gennady Stupakov, Xiaolong Zhang, Frank Zimmermann, further colleagues of the LHC vacuum group, and many others.

The first simulation studies by Oliver Brüning aimed at a consolidation of Frank's code and an estimate of the parameter dependence of the expected heat-load [70]. Indeed the heat load in the magnets from the electron cloud was found to be a crucial issue. The heat arises via an energy transfer from the beam to the electron cloud. Francesco guessed that this could be approximated analytically assuming a known initial distribution. The analytical and approximate calculations of the electron energy gain for several longitudinal bunch profiles was accomplished by Scott Berg [72]. As a by-product, Scott's analytic computation also determined the minimum number of build-up simulation steps during a beam passage needed, so that the simulated electrons would correctly be trapped in the beam field.

Further studies looked at surface properties (secondary emission yield, energy spectrum of emitted electrons and surface conditioning due to synchrotron light and electron bombardment) and the impact of the low temperatures in the LHC with the help of laboratory setups (e.g. COLDEX installed in the EPA, and a dedicated coaxial resonator). Later studies used the SPS as a test bed and employed measurements with a real LHC-type proton beam (e.g. in-situ secondary electron yield measurements as a function of exposure time; spatial distribution of multipacting, and multipacting signals as a function of filling pattern).

Accomplishments either directly from the LHC crash programme or strongly inspired by it include: careful measurements of quantum efficiency and SEY in technical materials; the identification of TiZrV as a novel low-SEY coating for suppressing elecron-cloud effects; the development and deployment of several types of in-situ electron detectors; the measurement of electron flux and energy spectrum at SPS and RHIC with these detectors; the measurement of correlation of vacuum pressure with electron activity; the development of new mitigation mechanisms (e.g., grooved surfaces, high chromaticity mode, multibunch feedback for SPS in x-plane); the first observations of the electron cloud with LHC beam in SPS (1999) and in the PS (2001); the practical demonstration of self-conditioning of the electron-cloud effect at the SPS (within a few days); the development of careful secondary emission models; the understanding via analytical models; great developments in simulation codes, their validation, and benchmarking; the prediction of electron-cloud density and power deposition for LHC; the investigation of electron-cloud effects in other types of machines (eg., heavy-ion linacs); the investigation of the severity of the electron-cloud effect against fill pattern, bunch intensity, etc.

As a result of Francesco's concerted crash effort for the LHC, baffles were added behind the beam-screen pumping slots to prevent any direct impact of electrons on the cold magnet bore, and a sawtooth pattern was imprinted on the beam screen in the horizontal plane to minimize the photon reflectivity. In addition, LHC scrubbing and commissioning scenarios were developed, and other countermeasures, e.g. satellite bunches, were proposed [73] and tested in the SPS.

A further set of activities around the electron cloud concerned the single- and multi-bunch instabilities driven by the electron cloud. Francesco encouraged and guided the pertinent work of Elena Benedetto, Giuliano Franchetti, Giovanni Rumolo, Daniel Schulte, and Frank Zimmermann plus external collaborators like Kazuhito Ohmi and Eugene Perevedentsev [74, 75, 76, 77, 78, 79, 80], and in particular helped to establish a collaboration with Tom Katsouleas' group at USC [81].

Another outcome of the LHC electron-cloud effort is the CERN electron-cloud web site [82], which links to a simulation code repository [83, 84], code comparisons (e.g., for electron cloud [85]), experimental data, news, summaries of CERN meetings, workshop announcements and proceedings, links to related activities elsewhere, and, most importantly, an electron-cloud publications archive with about 200 articles at last count.

Much of the progress in electron-cloud R&D world-wide for the past ∼10 years is owed to, or has significantly benefited from, the LHC "Electron-Cloud Crash Program". Francesco Ruggiero deserves much of the credit for his strong and steady leadership.

The electron-cloud effect has meanwhile been recognized as an important limitation in all accelerators operating with positively charged intense particle beams. Electron-cloud effects have been observed at PEP-II, KEKB, BEPC, PS, SPS, APS, RHIC, Tevatron, MI, SNS, DAFNE, etc. They often diminish the accelerator performance. In some instances electron-cloud phenomena were generated in dedicated experiments. For the two B factories, PEP-II and KEKB, controlling the electron cloud proved essential to achieve and exceed the luminosity goals. At the Los Alamos PSR an electron cloud leads to high-current instability, and beam losses. At RHIC, fast vacuum pressure rise and instability at high current forces beam dump (in some fill patterns). Electron cloud is a major concern for future machines (LHC, LHC upgrade, LHC injector upgrades, CLIC and ILC damping rings, FNAL Main Injector upgrade,...).

For the LHC, the current consensus is that the electron-cloud heat load will cease to be a problem for the LHC when the peak secondary emission yield falls below ∼1.2–1.3. Probably this will be achieved after a relatively brief conditioning time. But, there is no clear experimental demonstration yet of this conditioning effect for a long, closed, cold Cu chamber. Concerning the effect of the electron cloud on the beam, difficult simulations are required, both below and above the threshold of strong electron-driven instability, and work is continuing. Much of the present R&D effort focuses on the proposed upgrades of both the LHC and its injectors.

## 13 BEAM-BEAM

A very important and fundamental contribution to the modeling of the beam-beam interaction is the "synchro-beam mapping", developed with Kohji Hirata, Herbert Walter Moshammer and Mario Bassetti [86, 87]. Work started at around the end of November 1989 (see the sketch from Francesco's discussion with K. Hirata dated 22 November in Fig. 12) and was completed basically at the end of January 1990. The main ingredients were: floating collision point, electric field due to focusing bunch, and an energy change due to a trajectory slope $x$; see the original slide in Fig. 13. The map was expressed by a product of several non-symplectic mappings. Symplecticity was the problem. H. Moshammer finally found that the map is symplectic using the code REDUCE. The map could be expressed in Lie algebraic form as $\exp(-H_{bb})x \rightarrow (\tilde{x} \equiv x - x'z/2))$. The result was first presented at a Workshop in Berkeley held 12–16, February 1990. It was later used, combined with Lorentz transformation, to verify the crossing angle option for the B factories.

In the early days of the US-CERN collaboration on the LHC, Weiren Chou worked with Francesco on dynamic aperture in the presence of the beam-beam effect. When Weiren presented him tracking results of the LHC dynamic aperture including the effect of long-range beam-beam collisions, Francesco immediately realized the seriousness of the problem and launched a simulation study at CERN. As a result, it was proposed to change the crossing angle in the baseline design from 200 to 300 $\mu$rad, which was later approved.

In 2001 Francesco and Frank Zimmermann recognized that the luminosity of a hadron collider can be pushed in an

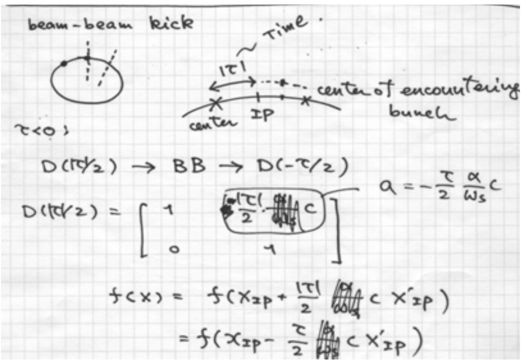
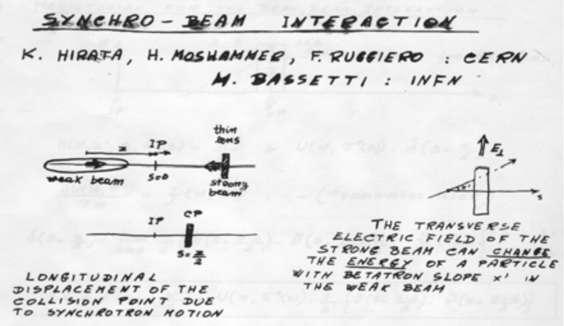


Figure 12: Initial work on the synchrobeam mapping; original sketch by Francesco during discussions with Kohji Hirata on 22/11/1989.


SYNCHRO - BEAM INTERACTION

K. HIRATA, H. MOSHAMMER, F. RUGGIERO : CERN
M. BASSETTI : INFN

LONGITUDINAL DISPLACEMENT OF THE COLLISION POINT DUE TO SYNCHROTRON MOTION

THE TRANSVERSE ELECTRIC FIELD OF THE STRONG BEAM CAN CHANGE THE ENERGY OF A PARTICLE WITH BETATRON SLOPE x' IN THE WEAK BEAM

Figure 13: Slides from Francesco's first presentation on the synchro-beam interaction.

unconventional way by operating in a regime of large Piwinski angle and alternating planes of crossing at two collision points, which introduces the same geometric reduction factor both for the peak luminosity and, importantly, for the beam-beam tune shift [88]. At the beam-beam limit the luminosity can be re-expressed in the following form [88]:

$$L \approx \gamma \Delta Q_{\rm tot}^2 \frac{\pi \epsilon_N f_{\rm rep}}{r_p^2 \beta^*} \sqrt{1 + \left( \frac{\theta_c \sigma_z}{2\sigma^*} \right)^2} \ , \qquad (10)$$

where $\Delta Q_{\rm tot}$ signifies the total beam-beam tune shift, and $\epsilon_N$ the normalized emittance. The luminosity is proportional to the collision energy and to the normalized emittance which could be increased by a higher injection energy (accompanied with higher bunch intensity and constant beam brightness).

This approach to optimizing the collider luminosity has led to one of today's LHC upgrade scenarios which comprises intense bunches with 25-ns spacing and large Piwinski angle [89].

## 14 LHC UPGRADE

Francesco was the driving force behind the LHC upgrade studies. In 2001—2002 he chaired the first feasibility study for an LHC accelerator upgrade, which, on the request of the large physics experiments, aimed at an increase of the LHC luminosity by a factor 10, and he also edited its seminal summary report [90]. Later Francesco prepared, organized and led the European Network for high-energy high-intensity hadron beams, whose principal objective was to boost the luminosity performance of the LHC via a multipronged approach, including (1) an increase in beam intensity to ultimate or beyond, (2) an upgrade of the interaction regions in IP1 and 5, allowing for a reduced $\beta^*$, (3) the tailoring of LHC beam parameters for optimum luminosity at the beam-beam limit, (4) a possible installation of auxiliary components, e.g. long-range beam-beam wire compensators or crab cavities, and (5) an upgrade of the entire LHC injector complex, in order to raise the LHC beam intensity and brightness, as well as to reduce the LHC turnaround time.

Most, if not all, of Francesco's ideas have later been adopted by the CERN top management. They have meanwhile become the objects of several official projects, numerous working groups (PAF, SPL, PS2, SPSU, LIUWG, etc), the CERN DG White Papers, etc.

Francesco's efforts on the LHC luminosity upgrade have paved the way towards a brilliant future for CERN and for high-energy physics in general.

## 15 DAFNE UPGRADE

Around 2002–03 the Frascati laboratory started to discuss numerous intriguing ideas for an upgrade of DAFNE with at least 100 times higher luminosity, in which Francesco took an active interest. One of the new ideas for the DAFNE upgrade, proposed by Alessandro Gallo, Francesco Raimondi and Mikhail Zobov, was to arrange for a varying bunch length along the ring by providing for a large longitudinal phase advance so that the bunch would be short at the collision point, allowing for a small $\beta^*$, and large over most of the rest of the storage ring, — a scheme which was soon called "strong rf focusing" [91]. Initially a monotonic increase of the "momentum compaction" integral around the ring,

$$R_1(s) \equiv \int_s^{s_{rf}} \frac{D(s')}{\rho(s')} ds' \ , \qquad (11)$$

with $s_{rf}$ the longitudinal location of the ring rf cavity, was considered for the strong rf focusing, which led to a large synchrotron tune that was not necessarily desirable. Later it was found that with a non-monotonic integral $R_1(s)$ around the ring a synchroton tune could be obtained while still retaining the strong focusing character of the longitudinal bunch evolution over one turn. The phase-space evolutions for the monotonic and non-monotonic $R_1$ integrals are compared in Fig. 14.

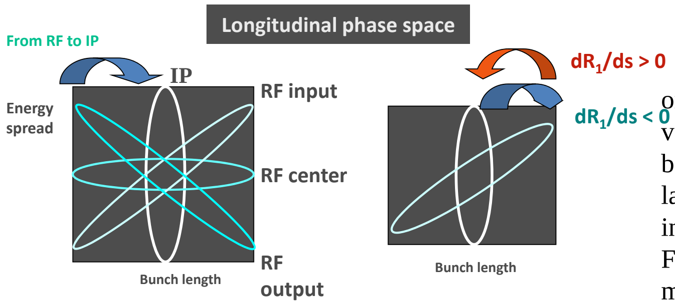


Figure 14: Schematic beam evolution in phase space for strong RF focusing with monotonic $R_1$ plushigh synchrotron tune (left) and non-monotonic $R_1$ plus low synchrotron tune (right) [92]

In September 2003 a workshop on the DAFNE upgrade was held in Alghero, Sardinia. Francesco took a vacation from CERN in order to participate in this event with his own money. Together with Mikhail Zobov, he chaired the session on "High Luminosity Issues". He reviewed the beam-beam scaling laws, plus luminosity constraints, and derived a strategy for optimizing the luminosity of the DAFNE upgrade, consisting of six ingredients. In parallel he collected other (alternative) new ideas for high luminosity, for example the collision of beams with much higher energy at a large crossing angle proposed by Pantaleo Raimondi, neutralized four-beam collisions with feedback, and ring-linac colliders, etc. Francesco's main conclusion from this workshop was that reaching a luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$, about 1000 times higher than what DAFNE had so far achieved, required combining many new ideas and technologies, implying a higher risk and longer time scale than a more moderate upgrade target of $10^{34}$ cm$^{-2}$s$^{-1}$.

## 16 NUCLEAR FUSION IN LHC

The last scientific paper of Francesco, written together with Hans Braun and Frank Zimmermann, concerned the possibility and rate of nuclear fusion events occurring inside LHC proton or ion bunches and the resulting limit on the beam lifetime [93]. Quoting his own words, "... my original motivation was to understand whether "clean" nuclear fusion can be achieved in a high energy hadron machine, thus overcoming difficult problems of confinement in plasma fusion. It would be interesting to push the LHC ion beam intensity, for oxygen or other ions species (deuterium?), and set limits on the residual vacuum density and other machine parameters (e.g. space charge) such that nuclear fusion and the associated energy production becomes the dominant process" [94].

## 17 SEMINARS AND CULTIVATION

From 1982 to 1985, as a fellow at CERN, Francesco organized seminars for and from young scientists on diverse topics like particle detectors, RFQ design, TMCI and beam-beam interaction, gravitational waves, etc. Much later, in both the SL-AP and the AB-ABP group, Francesco initiated and scheduled the regular "Accelerator Physics Forum," which again covered a wide range of topics, mostly related to accelerator physics. He also created an informal series of accelerator physics publications meant to trigger and foster discussions, which could be rapidly published without any management approval, called the "Beam Physics Notes".

Francesco was always looking for the physical insight of results, the first condition for them to be correct. His initial step to assess a result was to always look for a counter-example. By way of his example he taught students and colleagues the need (and the pleasure) to understand in depth the issues that we were dealing with.

Francesco believed in the need of the SL-AP group of preserving and transmitting AP know-how. When he became group leader, training of students was explicitly declared in the SL-AP group mandate.

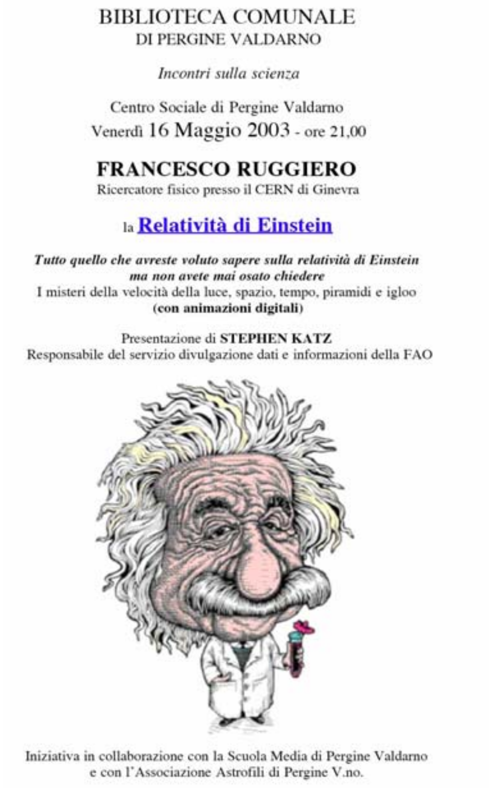
## 18 INTERNATIONAL COMMITMENTS

A member of the EPS Accelerator Group, Francesco helped in preparing the scientific programmes for several European Particle Accelerator Conferences (EPACs). He coordinated the sessions on "Beam Dynamics and Electro-Magnetic Fields" for the EPAC in Paris 2002, and for the EPAC in Lucerne 2004, as well as the session on "Circular Colliders" for the EPAC in Edinburgh 2006.

He contributed to PRST-AB, the refereed journal for accelerator physics and technology, as Associate Editor for Europe, and he belonged to the editorial board of the Springer series on *Particle Acceleration and Detection*. Since 2004 he was the coordinator of the European CARE-HHH (high energy high brightness hadron beams) accelerator network, as well as of its work package on "Accelerator Physics and synchrotron Design" (CARE-HHH-APD). It was thanks to his initiative that CARE-HHH created an accelerator-physics simulation codes web repository [83, 84] featuring programmes from many areas of beam physics, like beam-beam interaction, collimation, optics, instabilities, space charge, intrabeam scattering, cooling, nonlinear dynamics, vacuum, ions, electron cloud, etc.

## 19 BEYOND ACCELERATOR PHYSICS

Francesco loved the sea and its contemplation, animals as well as women loving animals, technological gadgets, and books about history, classical music and jazz. He was particularly fascinated by Einstein, the paradoxes of quantum mechanics, and by Pythagoras' vision of the world as a numeric harmony. In 2003 he gave two public lectures in the Comune di Pergine Valdarno on “the relativity of Einstein” and “Einstein, Bohr, and the paradoxes of quantum theory”. His 2005 article in “La Gazzetta dello Sport” explained to a general audience why boat weights measured in Valencia and Malmo differ by some 35 kg, addressing a mystery that arose during the weighing of boats between different races of the America’s Cup.



BIBLIOTECA COMUNALE
DI PERGINE VALDARNO

*Incontri sulla scienza*

Centro Sociale di Pergine Valdarno
Venerdì 16 Maggio 2003 - ore 21,00

**FRANCESCO RUGGIERO**
Ricercatore fisico presso il CERN di Ginevra

la **Relatività di Einstein**

***Tutto quello che avreste voluto sapere sulla relatività di Einstein***
***ma non avete mai osato chiedere***
I misteri della velocità della luce, spazio, tempo, piramidi e igloo
**(con animazioni digitali)**

Presentazione di **STEPHEN KATZ**
Responsabile del servizio divulgazione dati e informazioni della FAO

Iniziativa in collaborazione con la Scuola Media di Pergine Valdarno
e con l’Associazione Astrofili di Pergine V.no.

Figure 15: Announcement of Francesco’s public lecture on “the relativity of Einstein” in Pergine 2003.

## 20 EPILOGUE

Francesco Ruggiero has contributed to many more scientific studies than mentioned in this paper. The examples above represent a set of projects where we had the chance and privilege to work together with him. All examples presented in this article underline Francesco’s remarkable ability to bring people together and to work with a team for a common goal. Thereby Francesco contributed much more to our community than with his direct scientific studies alone.

But of course, Francesco’s studies, publications, and seminars, have also greatly advanced accelerator physics. Francesco deeply understood collective phenomena. He always went far beyond simple repetition of previous work, and he encouraged those around him to do so too. He gave us many great ideas, and produced a multitude of interesting results.

**COMUNE DI PERGINE VALDARNO**
(Provincia di Arezzo)

***La Biblioteca Comunale di Pergine Valdarno***
in collaborazione con la **Scuola Media di Pergine Valdarno**

organizzano per

**Venerdi 21 Maggio alle ore 21,00**

presso il Centro Sociale di Pergine Valdarno il **secondo incontro sulla scienza**

**FRANCESCO RUGGIERO**
Ricercatore fisico presso il CERN di Ginevra illustra

***"EINSTEIN, BOHR, E I PARADOSSI DELLA TEORIA DEI QUANTI"***

***"Dal principio di indeterminazione al teletrasporto"***

Figure 16: Announcement of Francesco’s public lecture on “Einstein, Bohr, and the paradoxes of quantum theory” in Pergine 2003.

ULTIMA

La Gazzetta dello Sport

VELA — VUITTON IN SVEZIA

**Malmoe, giallo sulla bilancia**

*Nessuna modifica ma barche più pesanti che a Valencia: colpa della gravit*

Sorpresa durante le operazioni di stazzatura, scafi fuori norma di circa 50 kg: questioni di latitudine

LA GUIDA

DOMANI ACT 6 COI MATCH RACE

LO SCIENZIATO

Perché ai poli pesiamo di più

di FRANCESCO RUGGIERO*

Figure 17: Francesco’s article on boat weights at the America’s cup in the Gazzetta dello Sport, August 2005

His papers and reports remain extremely useful for the design and optimization of future particle accelerators and colliders.

Francesco was humble and rigorous in the research work, open minded, ready to listen to any other’s opinion, an excellent mentor for young bright physicists, and a true gentleman. He respected and promoted the work of young people. He had the rare ability to make meaningful comments or suggestions on many technical aspects of any accelerator physics problem. He loved physics, and he was full of passion and energy, often working in his office until dawn.

During his long fight with cancer, he never gave up hope to fully recover and return to work. We are deeply saddened by his much too early death. Francesco will not only be missed as a knowledgeable scientist but also as a great colleague and friend, by us and by the worldwide accelerator community.

We take some comfort in Hirata's thought that the memory of the creative moments enjoyed together with him will not damp nor diffuse, just like a constant of motion.

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