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THE BIRTH AND CHILDHOOD OF A COUPLE OF TWIN BROTHERS

V. G. Vaccaro, INFN Sezione di Napoli, Naples, Italy

Abstract

The context in which the concepts of Coupling Impedance and Universal Stability Charts were born is described in this paper. The conclusion is that the simultaneous appearance of these two concepts was unavoidable.

INTRODUCTION

At beginning of 40's, the interest around proton accelerators seemed to quickly wear out: they were no longer able to respond to the demand of increasing energy and intensity for new investigations on particle physics.

Providentially important breakthrough innovations were accomplished in accelerator science, which produced leaps forward in the performances of particle accelerators.

The first breakthrough: the Phase Stability

Based on the principles stated by Vladimir Veksler and Edwin McMillan a proton synchrotron was built at Brookhaven National Laboratory, named Cosmotron. Its construction started in 1948 and it reached its full energy in 1953. It was the first particle accelerator to break into the GeV wall, accelerating protons up to 3.3 GeV. Since Brookhaven's Cosmotron went into operation in the early 1950's, scientists quickly realised that achieving even higher energies was going to be difficult. Calculations showed that, using existing technology, building a proton accelerator 10 times more powerful than the 3.3 GeV Cosmotron would require 100 times as much steel.

The second Breakthrough: the Alternating Gradient

While the cosmotron shape was strictly toroidal and the magnetic field task was to guide and to focus the beam at the same time, a second breakthrough was performed: the strong focusing. Its principle, independently discovered by Nicholas Christofilos (1949) and Ernest Courant (1952), allowed the complete separation of the accelerator into the guiding magnets and focusing magnets, shaping the path into a round-cornered polygon and drastically reducing the transverse dimensions of the beam.

Without strong focusing, a machine as powerful as the Alternating Gradient Synchrotron (AGS) would have needed apertures (the gaps between the magnet poles) between 0.5 m and 1.5 m instead of apertures of less than 0.1 m. The construction of AGS was accomplished and shortly after the one of PS.

Looking Far

Even before the successful achievements of PS and AGS, the scientific community was aware that another step forward was needed. Indeed, the impact of particles against fixed targets is very inefficient from the point of view of the energy actually available: for new experiments, much more efficient could be the head on collisions between counter-rotating high-energy particles.

With increasing energy, the energy available in the Inertial Frame (IF) with fixed targets is incomparably smaller than in the head-on collision (HC). If we want the same energy in IF using fixed targets, one should build gigantic accelerators. In the fixed target case (FT), according to relativistic dynamics, an HC-equivalent beam should have the following energy.

$$E_{FT} = 2\gamma E_{HC}$$

The challenge was to produce intense and high-collimated beams and make them collide.

Two Forerunners: Wideroe and Touschek

Bruno Touschek was born in Vienna where he attended school. Because of racial reasons, he was not allowed to finish high school. However, he tried to continue his studies in a precarious way. After Anschluss (1938), he moved to Hamburg, where nobody knew of his origins. There he met Rolf Wideroe, with whom he started cooperating in building a betatron and discussing on Wideroe's visionary thoughts. Wideroe is variously credited with the invention the betatron, the linac, the synchrotron and storage rings for colliding beams, and, certainly, he built the first pair of linac drift tube for accelerators (Sessler and Wilson). Among others, Wideroe exposed his ideas about colliding beams. In the meanwhile, Touschek was discovered and arrested by the Gestapo in 1945. Wideroe was visiting him in prison, bringing cigarettes, food and, during these meetings, they continued to talk about the betatron and accelerators in general. Incidentally, in that context Touschek conceived the idea of radiation damping for electrons. When the Allied army reached Hamburg, Wideroe, suspected of collaboration, was arrested. The situation was reversed: Touschek started to pay visit to Wideroe. Sometime after, he was found not guilty and released. After war, Touschek roamed around Europe. Finally, in 1952 he decided to stay in Rome permanently, receiving the position of researcher at the National laboratories of the Istituto Nazionale di Fisica Nucleare in Frascati, near Rome.

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THE COLLIDER AGE

Collider Contest: Frascati vs Princeton

The idea to build colliders attracted many accelerator scientists. A contest between Princeton and Frascati Laboratories started: both labs were developing collider programs. Princeton chose an eight-shaped structure: two circular rings in which electrons were circulating with the same orientation, meeting in one collision point. Frascati team, which took the field later, was even more audacious: they used a single ring with "counter-rotating" beams of electrons and positrons.

The enterprise began on March 7, 1960, when Bruno Touschek held a seminar at Frascati Laboratories. He was proposing to build an electron-positron storage ring. On March 14, a preliminary study demonstrated the feasibility of the proposal. The storage ring was named ADA (Anello Di Accumulazione = Storage Ring). Touschek pointed out the extreme scientific interest of high-energy collisions between particles and antiparticles, and the simplicity of realization of such an accelerator. The machine was conceived as a feasibility experiment to provide a sound basis for the realization of electron-positron colliders of larger centre of mass energy and luminosity. The total cost of the project (converted to the present purchasing power) was around 800.000 €.

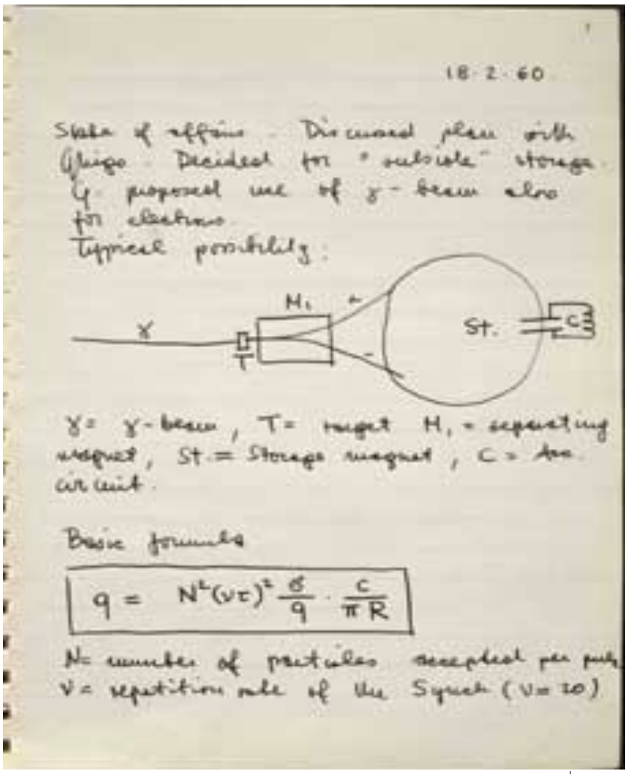


Figure 1: Sketch from Touschek notebook of e-e^+ collider

ADA was brought to operation in February 1961. A first stored beam of few electrons was obtained at the end of May 1961, using the Frascati Electron Synchrotron as an injector. On March 14, a preliminary study demonstrated the feasibility of the proposal. ADA then moved to LAL-Orsay, Paris, with a more powerful injector. Here, on February 1964 the first electron-positron collisions were detected. The success was encouraging for boost for the ISR (Intrsecting Storage Ring at CERN) designers.

Figure 2: ADA collider at INFN Laboratori Nazionali di Frascati.

Clouds are appearing

The vast impact of ADA Collider opened a new chapter of accelerator physics: it was the first particle-antiparticle collider and the first electron-positron storage ring. In addition to this grand accomplishment, the machine was also able to prove the idea that one could accelerate and make beams of particles and antiparticles collide in the same machine.

Many laboratories started programs to accelerate and store particles in order to prove the feasibility of intense beams. The most important one was the Intersecting Storage Ring at CERN. Surprisingly enough, a longitudinal instability below transition energy was discovered in 1963 in the MURA 40 MeV electron accelerator. At the same time the observation of vertical instabilities took place in the MURA 50 MeV [1]. At that time, it was a common place that above transition energy, a beam could be unstable: since it was postulated that the prevalent electromagnetic (EM) interaction with the vacuum pipe was capacitive, as we would define it nowadays with the present lexicon. Furthermore, it was not known that there could exist some stabilizing mechanism.

The Analysis of Instabilities. A Step Forward.

An interpretation of the phenomenon was given by two companion papers [2,3] appeared in 1965 on the Review of Scientific Instruments, one concerning longitudinal coherent instability and the second one transverse coherent instability.

The novelty was the use of Vlasov equation where it is assumed that the beam particles have an energy distribution function. The problem is solved by means of perturbative techniques that lead to a dispersion relation. The role of Landau damping of the instability coming from the energy spread was emphasized. The pipe is supposed circular, smooth, and lossy and with circular or rectangular cross section. In both papers it examined the case of absence of frequency spread and it was found that the rise-time depends on the conductivity of the pipe. However, allowing for a finite spread, the stability criteria obtained from the dispersion relation do not involve the pipe losses. It is worth of note that the stability criteria were derived assuming Gaussian or Lorentzian distribution functions. The stream of research born in 1965 and still lasting gave and gives results that have fundamental importance for particle accelerator.

An Intermezzo for Pedestrians

The phenomenon of beam instabilities in circular accelerator can be understood resorting to pictorial representation of Fig. 3. This follows the explanation that I gave to myself when I first tackled the beam instability problem.

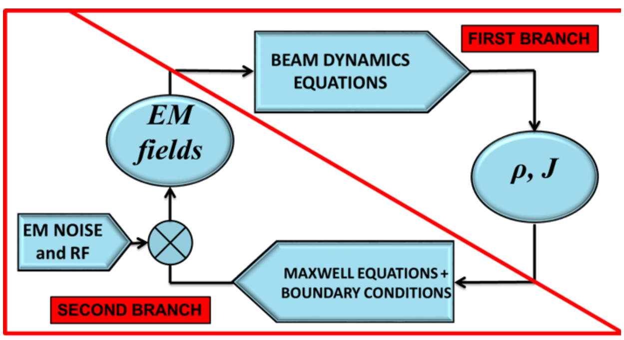


Figure 3: Block diagram of the coupling between EM equations and dynamics equation.

Like many modulational instabilities, the present one is triggered by the electric field noise. Let us take a frequency component $\Delta E_N(\omega) = \Delta E_N exp(j\omega t)$. This component will act as the initial input of the beam dynamics equation. The field noise $\Delta E_N(\omega)$ acting on the charged particles introduces a small modulation on the beam current having the same frequency as the noise; at the same time, the interaction of the perturbed current with the surrounding medium produces an additional electric field. This process is continuous, but one may represent it stepwise, turn-by-turn. Let us introduce integrated values over one turn

$$\Delta V_N(\omega) = < 2\pi R \Delta E_N(\omega) >$$

defined as input voltage. One may define the transfer function (input-output) $Y_D(\omega)$ in the frequency domain for the beam dynamics branch; this quantity relates the perturbed current to the voltage $\Delta V_N(\omega)$. Therefore, the perturbed current in the beam will be represented as:

$$\Delta I_1(\omega) = Y_D(\omega)\Delta V_N(\omega)$$

Then, the perturbed current, acting as input to Maxwell's equations (namely interacting with the surrounding medium via electromagnetic fields), will produce after one turn a perturbed electric field $\Delta E_1(\omega)$. Similarly, by taking $\Delta V_1(\omega) = < 2\pi R \Delta E_1(\omega) >$, one may define $Z_{EM}(\omega)$ for the electromagnetic branch

$$\Delta V_1(\omega) = Z_{EM}(\omega)\Delta I_1(\omega)$$

Allowing for the second turn, the **total** perturbed current will be the sum of the new one and the perturbed previous current. The latter is affected by a factor $\alpha(\omega)$, in modulus smaller than one, which takes into account its damping over one turn:

$$\begin{aligned}\Delta I_2(\omega) &= \alpha(\omega)\Delta I_1(\omega) + Y_D(\omega) Z_{EM}(\omega)\Delta I_1(\omega)\\ &= \{\alpha(\omega) + Y_D(\omega) Z_{EM}(\omega)\}\Delta I_1(\omega)\end{aligned}$$

The quantity α comes from a realistic picture of the phenomenon. In general, the particles exhibit a spread in their velocities. Therefore, any unevenness in the beam tends to dissolve over time.

After *n* turns:

$$\Delta I_n(\omega) = \{\alpha(\omega) + Y_D(\omega) Z_{EM}(\omega)\}^n \Delta I_1(\omega) \qquad (1)$$

It is apparent that the perturbed current has only two possibilities: it may diverge (instability) or converge (stability) to zero. It will certainly diverge if there is no damping ($\alpha = 1$). In all the other cases, the beam is conditionally stable. We may infer some general features of the phenomenon:

- The perturbed current is proportional not only to the perturbing field but also to the unperturbed current, namely $Y_D(\omega) \propto I_0$.
- The perturbed current is inversely proportional to the relativistic mass of the charged particle, namely $Y_D(\omega) \propto 1/\gamma m_0$.

The above analysis is only qualitative since it cannot predict under what conditions the beam will be stable or not. However, it indicates that the coupling between the EM beam interaction with the surrounding medium and the beam dynamics must be formulated in a self-consistent way.

As a conclusion, the problem will lead to two concepts: Coupling Impedance and Stability Diagrams.

An Impedance is in the Air. The First Twin is brought to Light

When I was hired by CERN on June 1966, I joined the RF group of the Intersecting Storage Ring (ISR) Department. ISR was under construction and was destined to be the world's first hadron collider. It ran from 1971 to 1984, with a maximum centre of mass energy of 62 GeV. At that time at CERN, there was big concern about stability of the beams because of large number and various kind of lumped equipment (300 pairs of clearing electrodes, pick-ups, cavities etc.), which could be "seen" by the beam. Unfortunately, the stability criteria did not apply to the situation of ISR. I was committed to work on this problem. The task was to introduce in the dispersion relation the contribution of a lumped element, e.g. cavity of impedance Z_c (eventually clearing electrodes, too)

$$I_i = const\langle 2\pi R E_\theta \rangle \int \frac{d\psi_0(W)}{dW} \frac{dW}{[\omega - n\omega_0(W)]} \qquad (2)$$

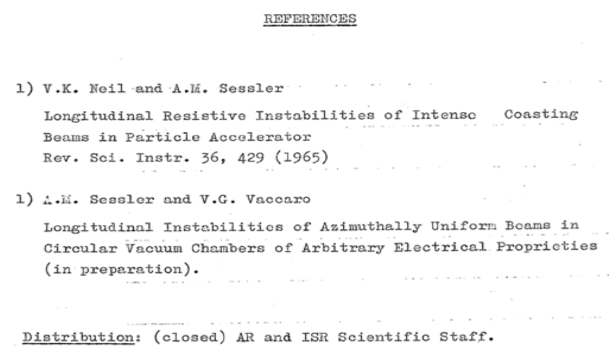
where I_i is the incipient perturbed current in the beam, ω the frequency of the instability, ω_0 is the revolution frequency, $\psi_0(W)$ is the energy dispersion function.

The procedure is described in Ref. [4]. The impressed voltage at the cavity gaps V_i is calculated assuming that the image current that loads the cavity is equal to the perturbed beam current I_i. The field distribution in the accelerator is expanded in travelling waves inside the pipe. Then, only the n-th harmonic is retained which is riding with the perturbation. Therefore, the mean integral in the above equation may be written as

$$\langle 2\pi R E_\theta \rangle = -Z_c I_i \qquad (3)$$

The concept of coupling impedance was later extended to a pipe with uniform properties. Of course, the above procedure consisted in a brute force approach. Its validity is restricted to wavelengths much larger than the cavity gap and of the pipe radius; however, this limitation does not affect the principle. It only needed a self-consistent formulation of the EM problem for the lower branch of Fig. 3. Fifty years have passed since. In the meantime, exact approaches were performed resorting to numerical codes or to analytical-numerical techniques such as the mode matching.

Few months after my arrival, Andy Sessler (2012 Fermi award), on leave of absence from LBL, joined the ISR-RF group. At that time CERN was a crossroads of the most prominent accelerator scientists. I was lucky enough to meet Ernest Courant (1986 Fermi award), Claudio Pellegrini (2014 Fermi award), with whom I was co-author of a paper on wake fields, Fernando Amman (director of Laboratori di Frascati and ADA project), John Lawson, AN Skrinsky (Director of Institute of Nuclear Physics of Novosibirsk), who were all paying visits at CERN for discussions on ISR design. I was committed to Sessler and I showed him the manuscript of my results. He reviewed it, making corrections, suggesting integrations and then he stated that the report had to appear with my name only. However, the paper was issued in closed distribution restricted to AR and ISR Scientific Staff.


REFERENCES

1) V.K. Neil and A.M. Sessler
Longitudinal Resistive Instabilities of Intense Coasting Beams in Particle Accelerator
Rev. Sci. Instr. 36, 429 (1965)

1) A.M. Sessler and V.G. Vaccaro
Longitudinal Instabilities of Azimuthally Uniform Beams in Circular Vacuum Chambers of Arbitrary Electrical Proprieties (in preparation).

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Figure 4: Last page of Ref. [4].

At the same time, he proposed a general treatment of impedance of arbitrary electrical properties [5]. However, none of us gave importance to this concept. We rather underlined that the concept of coupling impedance is a handy concept. This is very well illustrated by Sessler in one of his papers [6]: "It was emphasized — and, it was the main point of [5] -- that Z described the impedance of the wall elements and as, thus, amenable to computation--or measurement--by means of all the standard techniques employed in electrical engineering. –OMISSIS- This engineering technique was applied to a number of problems--such as helical conducting walls [7] and allowed complicated structures to be readily analysed. For example, the impedances presented in Section 1.5 of this paper may be employed to study the azimuthal stability of beams interacting with various elements such as pickup electrodes." Probably this feature was one of the factors that determined the success of the beam coupling impedance concept.

The Second Twin. The Universal Stability Charts

The introduction of the beam coupling impedance concept is tightly linked to the analysis of the dispersion relation. The first step was done: a simplification in the analysis of complicated structures (transfer function of the lower branch in Fig. 3). The second step was devoted to make an analogous simplification in manipulating the transfer function of the upper branch and is already indicated in the same paper of the first step in Ref. [4]. The success of the first one influenced the advancement of the second one. Except special cases, Eq. 2 cannot be solved analytically; namely, given the impedance, the distribution function, the harmonic number n and the function $\omega_0(W)$ it is not in general possible to find analytically for any distribution function the frequency ω of the instability, if any.

It is worth of note that in Eq. 18 in Ref. [4] (see Fig. 5) it is apparent the drift toward a new formulation but the drift is not yet accomplished. There is a reactive impedance (X/n) of the lumped element, but it is not so for the space charge; the impedance is expressed in cgs [cm/sec]; there is the classical proton radius: all aspects that nowadays are superseded. Furthermore, the stability inequality comes from the solution of the dispersion relation with a Lorentzian distribution function. As shown in Fig. 7, for a Lorentzian distribution function, this is possible and a parabola delimits the stability region.

$$\frac{X}{n} \leqslant \frac{1}{f_0} \left\{ - \frac{\gamma^{-2}}{R} \left[1 + 2 \ln \frac{b}{a} \right] + \frac{1}{r_p} \frac{\pi}{2N} \left[\gamma_T^{-2} - \gamma^{-2} \right] \gamma \beta^2 \left(\frac{\Delta p}{p} \right)^2 \right\}$$

where r_p is the proton classical radius and f the circulation frequency of the particles.

Figure 5: Eq. (18) in Ref. [4].

I felt that such a large stability region could be unphysical. An indicator of this issue is the divergence of its second order momentum. Therefore, I was intrigued on what could happen with a truncated cosine distribution. The solution of the dispersion relation was facilitated because I had to perform the integration on the imaginary axis. I had tackled the problem of the normalization of the spread in order to make a reasonable confrontation with the Lorentzian distribution.

the inequality (18) becomes, if V ≪ U

$$\frac{X}{n} \leqslant \left\{ \frac{C_f}{r_p} \frac{\pi}{2N} \left[\gamma_T^{-2} - \gamma^{-2} \right] \gamma \beta^2 \left(\frac{\Delta p}{p} \right)^2 - \frac{\gamma^{-2}}{R} \left[1 + 2 \ln \frac{b}{a} \right] \right\} \frac{1}{f_0}$$

where C_f has the value

$$C_f = \frac{4}{\pi} S_i \left[\frac{\pi}{2} \right] \simeq 0.29$$

Figure 6: Eq. (19) in Ref. [4]

The results are reported in Fig. 8. The absence of long tails and the finiteness of the second order momentum drastically reduce the stability margin. I asked Sessler what he thought of this finding. He said: “Go on!”.

Later on, the complete stability was calculated and I remarked that it was including a finite region of the impedance plane. One may notice that the formula of Fig. 6 is written with the classical radius r_p and that the impedance is still measured in cgs system dimensions. Nowadays, accelerator scientists would be horrified!

As a conclusion, I would like to stress that the two brothers are real twins. Maybe the second one had a slower growth. They are actually Siamese twins, because the existence of one is the reason of existence of the other.

I did not continue my studies because there was no interest on the subject. Afterwards, I knew that my contract would not be renewed. Therefore, I felt free to work on the subject that was sleeping since many months. A collaboration with Alessandro Ruggiero was set up, which tackled the problem by another point of view: find the coupling impedance for a given value of the complex frequency ω, assuming a linear dependence of ω_0 on W. The results are represented in Fig. 7 where the curves at constant rise-time, i.e. with a constant frequency shift, are drawn. The procedure was repeated for various distribution functions [2]. Therefore, we had to perform analytically the integral assigning the same distribution used in Ref. [8] and some others, that could seem reasonable:

$$Z(\omega) = -\frac{1}{const \int \frac{d\psi_0}{dW} \frac{dW}{[\omega - n\omega_0(W)]}}$$

This is just a conformal mapping of the complex variable ω into the complex variable Z. The interest is to explore the region where the imaginary part of ω is negative, namely where the oscillation is exponentially increasing. A particular interest was devoted to the mapping of the lines where the frequency is real with a vanishing imaginary part, namely

$$\omega = \omega_r + j_0$$

This procedure gave quite surprising results:

- The mapping of the lower, half plane covers almost entirely the Z plane.
- The mapping of the upper half plane covers the same region Z plane.
- There is a “neutral region” which is covered by none of the two mappings and is defined as the stable region
- The stable region is finite if the tails of the distribution function have a finite area.
- The stable region of a mono-energetic distribution (infinitesimal tails) is the positive imaginary axis.

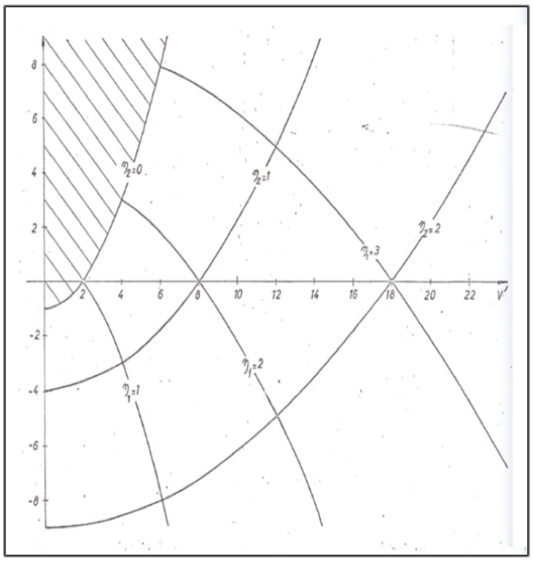

Figure 7: Longitudinal stability chart for Lorenzian distribution function with curves at constant rise-time and frequency shift

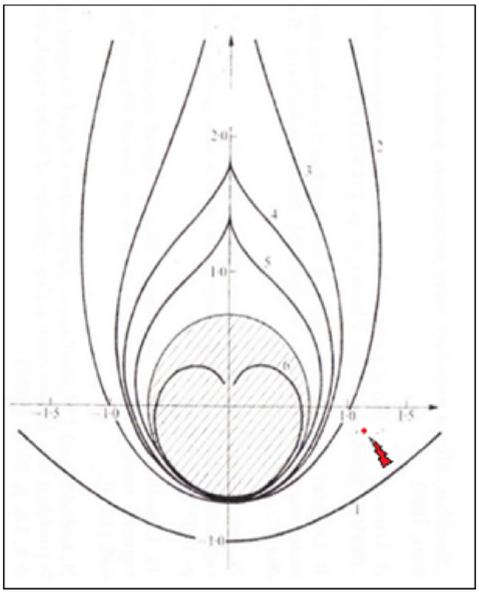

Figure 8: Stability boundaries for various distributions functions

Fig. 7 reports the result of the mapping for a Lorentzian distribution function, the same one adopted in Ref [2,.3]. The impedance is normalized in such a way to get a universal stability diagram. The dashed domain is the stability region, the contour of which is a parabola. It is apparent that the stable domain is infinite. The coupling Impedance of smooth pipe has small real part due to the pipe resistivity and a large positive imaginary (normalized) part, from the diagram of Fig. 2 one could infer that the beam should be stable, that was the same conclusion inferred by the authors. Other distribution functions were taken. The results are reported in Fig. 8 where the stability boundaries are drawn:

1- Lorentzian
2- Gaussian
3- 4th order Parabola. $\psi = (1 + x^2)^4$
4- 3rd order Parabola. $\psi = (1 + x^2)^3$
5- 2nd order Parabola. $\psi = (1 + x^2)^2$
6- Truncated cosine region.

According to the available data, the working point of MURA accelerator is very close to the imaginary axis and has a very large imaginary component. This is represented in red in Fig. 8. This means that, the detected instability is compatible the results obtained from the Vlasov equation, provided that one takes a realistic distribution function. That was an excellent result confirming that correctness of the Vlasov equation approach.

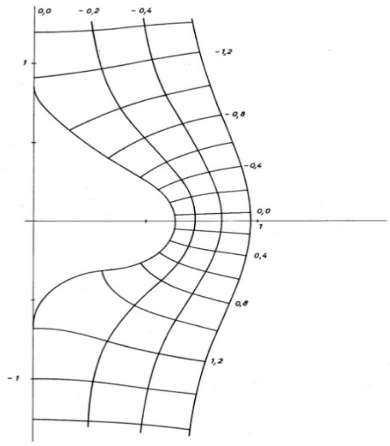

Figure 9: Transverse stability chart with curves at constant rise-time and frequency shift.

Then, when the picture of the longitudinal instability phenomenon was clear, the problem of transverse instability was tackled. The successful aftermaths stimulated the extension of the research on transverse instabilities. An example is reported in Fig. 9, in this case it is taken into account not only the frequency spread but also the distribution functions of the betatron amplitude oscillation.

This year the Coupling impedance and universal stability charts turn fifty-two, but they do not show it.

REFERENCES

[1] C.P. Curtis et al., Proc. of the International Conference on High Energy Accelerators (Atomizdat, Moscow, 19639)

[2] V.K. Neil and A.M. Sessler, Rev. Sci. Instr. 36,429 (1964)

[3] L.J. Laslett, V.K. Neil,and A.M.Sessler, Rev. Sci. Instr. 36,436 (1964)

[4] V.G. Vaccaro, Longitudinal Stability of an Intense Coasting Beam in a Circular Accelerator CERN, ISR-RF/66-35, 1966

[5] A,M. Sessler, V. G. Vaccaro, Longitudinal Instabilities of Azimuthally Uniform Beams in Circular Vacuum Chambers with Walls of Arbitrary Electrical Properties. CERN-Report ISR-RF 67-2 (1967)

[6] A.M. Sessler, Beam-Surrounding Interaction and the Stability of Relativistic Particle Beam, PAC1971-1039

[7] A.M. Sessler Passive Compensation of Longitudinal Space Charge Effects in Circular Accelerators: the Helical Insert. CERN-Report ISR-RF 68-1 (1968)

[8] A.G. Ruggiero, V. G. Vaccaro, Solution of the Dispersion Relation for Longitudinal Stability of an Intense Coasting Beam in a Circular Accelerator. CERN-Report ISR-TH 68-33 (1968).