BEAM LOSS, EMITTANCE GROWTH AND HALO FORMATION DUE TO THE PINCHED ELECTRON CLOUD

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Abstract

Electron cloud can cause beam losses and emittance growth in proton or positron storage rings. If the electron density exceeds a certain threshold value, a strong head-tail instability manifests itself, characterized by a rapid beam-size blow-up with a rise time comparable to the synchrotron period. However, even for densities below the coherent-instability threshold, the electron-cloud can give rise to a significant emittance growth. We identified the mechanism for this incoherent growth as one caused by the combined effect of the beam particles synchrotron motion and the longitudinal variation of the tune shift, which is proportional to the pinched electron-cloud distribution along the bunch. This can give rise to the periodic crossing of a resonance, in analogy to halo formation in space-charge dominated beams, or eventually, if the tune shift is sufficiently large, to the crossing of bunch regions where the single-particle motion is linearly unstable.

INTRODUCTION

Beam losses, transverse emittance growth and single-bunch instabilities induced by electron cloud have been observed in several existing proton and positron rings. In addition to the fast head-tail instability, occurring above a certain electron-cloud density threshold and inducing a beam blow-up with a rise time comparable to the synchrotron period, there is evidence of another regime for which an incoherent emittance growth is present even at moderate cloud densities. This effect, which for a long time has been neglected and confused with noise in the simulations or in the measurements, may be relevant over long term storage. In particular, it may explain observations of poor beam lifetime of the LHC proton beam in the CERN SPS and can be a concern for proton machines with long store times, like the CERN LHC, where synchrotron radiation damping is not very effective.

Two mechanisms are identified as possible causes of incoherent emittance growth [1], namely the periodic crossing of resonances and the crossing of linearly unstable regions, both driven by the combined effect of the synchrotron motion and the electron-cloud induced tune shift, which strongly depends on the longitudinal (and transverse) position inside the bunch. The following section presents the electron cloud evolution during the passage of a positively charged bunch and describes the two proposed mechanisms for emittance growth.

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We have investigated the diffusion processes [2] with the HEADTAIL code [3], used at CERN for electron-cloud effects studies, and MICROMAP [4], developed at GSI for space-charge simulations and recently modified to take into account incoherent electron-cloud effects. HEADTAIL computes the interaction between a single bunch and the electron cloud via a 2D PIC module, in a finite number (1–100) of locations ("kicks") around the ring, using the smooth focusing approximation to transport the beam between the points of interaction. This model, which is valid for studies of electron cloud induced instabilities [5], does not resolve the actual betatron motion and, if a small number of kicks is used, it leads to an artificial excitation of resonances. The MICROMAP code, instead, can include a more realistic machine lattice and an arbitrarily large number of cloud kicks, but it models the electron cloud field through a very simplified analytical model. Both codes are run considering a weak-strong approximation for the cloud-beam interaction, to speed up the simulations. The electron cloud potential, which is z-dependent, is computed only at the first bunch passage and then used for the successive interactions. As discussed in [1, 2], this model is valid for the study of incoherent effects which do not involve a very strong modification of the beam transverse shape.

Results of the benchmark between HEADTAIL and MICROMAP are presented in the following. The short-term agreement between the two codes, gives us confidence to use MICROMAP for a first study of long term emittance growth and beam losses, using a realistic model for the SPS and larger number of cloud kicks. Preliminary results will be discussed and compared with experimental observations in the SPS with LHC type beam.

RESONANCE CROSSING AND DIFFUSION PROCESSES

During the passage of a proton (or positron) bunch through an electron cloud, the cloud electrons are attracted by the beam electric field and their density strongly increases near the beam center ("pinch" effect) [6] by up to 2 order of magnitudes. This gives rise to an incoherent particle tune shift, which depends on the longitudinal and radial position within the bunch.

Figure 1 shows the electron-cloud density evolution during a bunch passage in a field-free region of LHC, at injection energy, for an initially uniform electron distribution, simulated with HEADTAIL code. Electrons located within the beam rms size perform linear oscillations in the transverse bunch potential, yielding a high local elec-

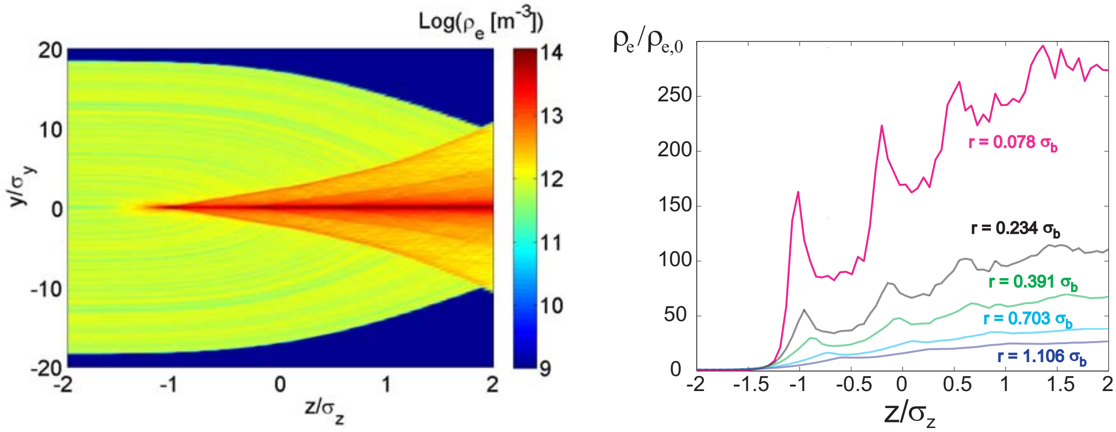

Figure 1: Simulated electron cloud density evolution during the passage of a bunch in LHC as a function of position z. The bunch tail is for $z < 0$. Left: Evolution on the vertical axis in a logarithmic scale (color code), Right: Cloud density at the beam center, averaged inside a circle of variable radius. Coordinates are normalized by the transverse and longitudinal beam size (respectively σ_b and σ_z, and by the initial density at the bunch center $\rho_{e,0}$.

tron density peak after their first quarter of oscillation, which then repeats every half electron oscillation period. Superimposed on these periodic peaks, there is a gradual increase of the central electron density due to electrons which start further away from the beam and perform nonlinear oscillations under the influence of the nonlinear beam field. In the second half of the bunch passage, the potential of the beam decreases and some of the trapped electrons may be released toward larger amplitudes. Because of the the high peaks in the electron density ρ_e, the beam particles experience a large incoherent tune shift $\Delta Q(\mathbf{r}, z) = \rho_e(\mathbf{r}, z)\pi r_p R^2/\gamma/Q_0$, where r_p is the classical proton radius, R is the machine circumference radius, γ is the relativistic factor and Q_0 is the unperturbed tune, which strongly depends on their longitudinal and transverse position. As a consequence, resonance islands change their size and location as a function of z [7].

The combined effect of synchrotron motion and the variation of the transverse tune shift with longitudinal position, can induce the periodic crossing of resonances [1]. Particles can get trapped inside an island and, as the island position changes along the bunch, they can be transported to larger (smaller) amplitudes [8]. A “scattering” mechanism similar to the one discussed for space charge dominated beam [9], applies in the electron cloud case, leading to halo formation and beam emittance increase. Compared with space charge, the electron cloud tune shift is positive, there is no front-back symmetry and the transverse distribution is highly non-uniform. Moreover, in addition to possible lattice errors and non linearities, the electron cloud itself can excite resonances because of its non-linear beam components. Resonances can also be excited by the the electron cloud density variation along the ring or between beamline elements (i.e. it is mainly localized in special elements like dipoles) and, in simulations, by the finite number of kicks used in the model.

In Fig. 2 the Courant-Snyder invariant (action) of a test

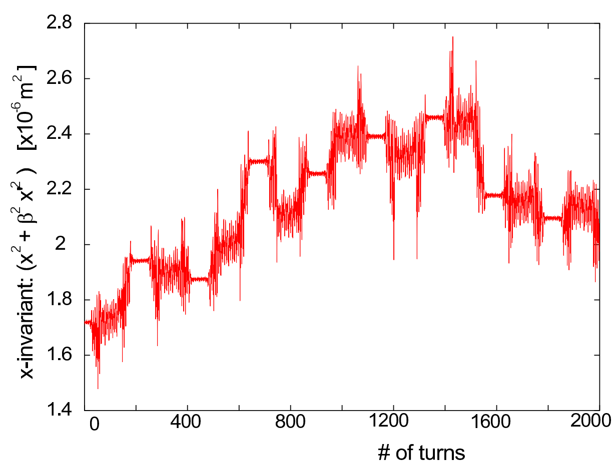

Figure 2: Horizontal Courant-Snyder invariant of a proton at a large synchrotron amplitude as a function of number of turns, from a HEADTAIL simulation. The synchrotron period is about 170 turns.

beam particle is plotted, as obtained from HEADTAIL simulations. The periodic jumps in the action, at twice the synchrotron frequency, are a clear signature of the “scattering” regime. An evidence of the key role played by the synchrotron motion is given in Fig. 3, which illustrates how the emittance growth quickly stops after a small initial blow up, when the synchrotron motion is frozen. Figure 3 also shows the growth dependence on the number of kicks used in the simulations. In particular, by changing the number of cloud-beam interaction points from 1 to 10, a reduction in the emittance growth is observed, since different (less) resonance lines are excited. Figure 4 illustrates the resonances (up to 5th order) excited by applying 1 or 10 electron-cloud kicks per turn.

Also a second effect may arise, namely the crossing of linearly unstable regions [1]. This may happen in case the

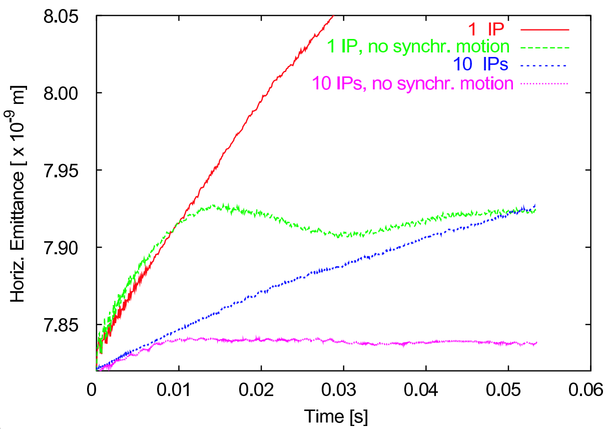

Figure 3: Simulated emittance growth for 1 and 10 electron-cloud kicks per turn, with and without synchrotron motion, for an electron density of 2×10^{11} m^{-3} in the LHC.

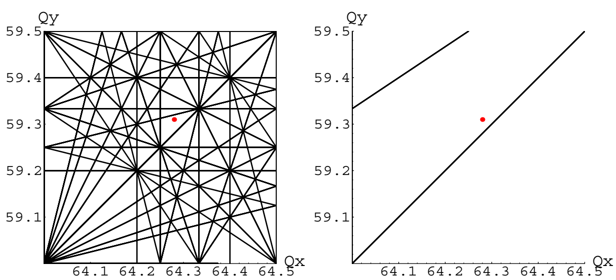

Figure 4: Tune diagram with the resonance lines excited by applying 1 (left) and 10 (right) electron-cloud kicks per turn. In red is plotted LHC working point.

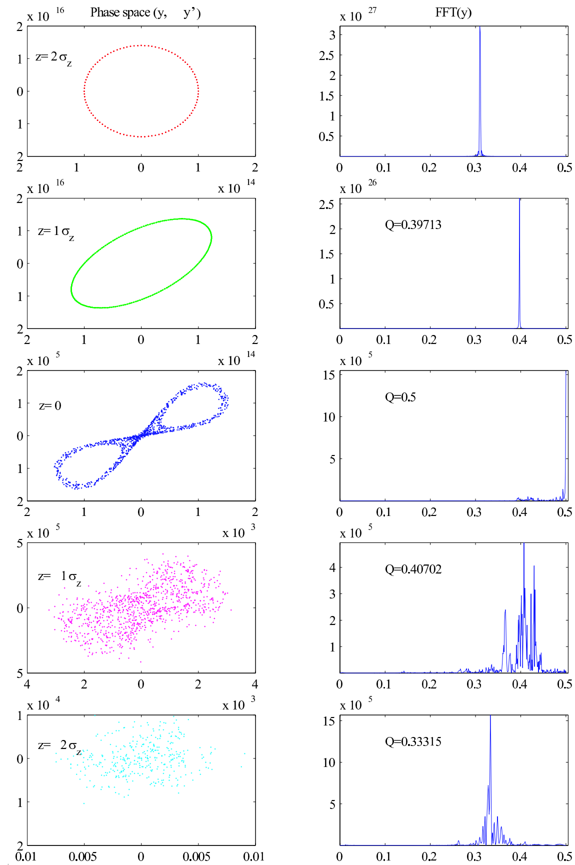

Figure 5: Vertical phase space trajectory and frequency spectrum of particles at different z positions, from HEADTAIL simulation without synchrotron motion. The initial average electron density is $\rho_e = 10^{14}$ m^{-3} and only 1 cloud kick per turn is assumed.

incoherent tune spread overlaps the half-integer stopband. Figure 5 shows the phase-space trajectory for particles at different positions z along the bunch (i.e. experiencing a different electron-cloud tune shift) and the corresponding frequency spectra, obtained form simulations without synchrotron motion. In this example, only one cloud kick per turn is assumed and the electron cloud density is 2 orders of magnitude higher than the expected value. The linear instability leads to the emergence of a hyperbolic fix point near the bunch center. The longitudinal position where it occurs depends on the tune shift induced by the electron cloud and, for a fixed tune shift and distribution, can be obtained analytically from the eigenvalues of the transfer matrix M computed by taking into account the lattice focusing and the electron cloud effect. In particular the particle motion becomes unstable when $Tr(M) \geq 2$. As shown in Fig. 5, for particles in the tail of the bunch, which experience a larger tune shift, the motion appears to be chaotic. In the following, it will be presented another example, from MICROMAP simulations with a realistic SPS lattice, in which the half-integer resonance is approached.

CODE BENCHMARK

HEADTAIL and MICROMAP have been benchmarked, with the purpose of justifying the use of the latter and of quantifying the effect of the PIC noise on the emittance growth. We considered an artificial simple model of a round beam and a transverse Gaussian electron distribution of constant rms size σ_e equal to a fraction of the beam size σ_b. The electron density increases linearly along the bunch, giving zero tune shift at the bunch head ($z = -2\sigma_z$) and a maximum tune shift ΔQ_{max} at the tail of the bunch ($z = 2\sigma_z$). Only one interaction point is assumed, the synchrotron motion is linearized. Both codes always use the weak-strong approximation to model the interaction between the cloud and the bunch. The parameters of the simulations here presented refer to the LHC at injection energy [2]. The horizontal and vertical tunes are respectively 64.28 and 59.31, while the synchrotron period is about 170 turns. Assuming an initial average cloud density of 2.8×10^{11} m^{-3}, the estimated peak maximum tune shift is $\Delta Q_{max} \approx 0.13$.

Figures 6 (a), (b) and (c) show results of the benchmark, for different values of maximum tune shift ΔQ_{max} and

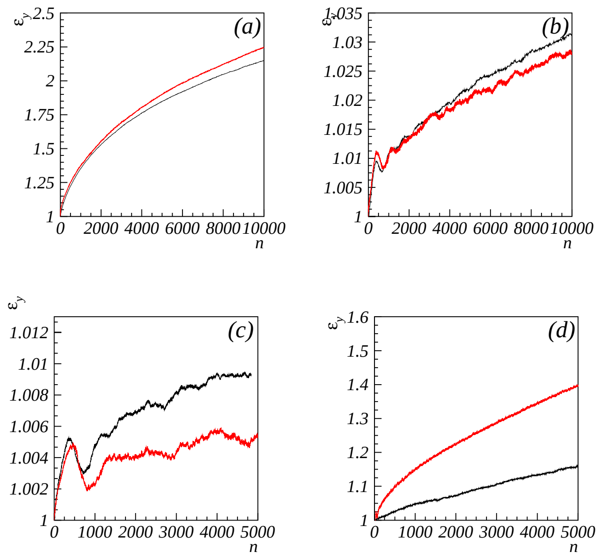

Figure 6: Simulations with HEADTAIL (red) and MICROMAP (black), of vertical emittance vs. number of turns in LHC. A Gaussian electron cloud, a linearly increasing density and one interaction point are assumed in (a), (b) and (c). In (a) the cloud rms size is $\sigma_e = 0.1\sigma_b$ and the maximum tune shift is $\Delta Q = 0.1$, in (b) $\sigma_e = 0.5\sigma_b$ and $\Delta Q = 0.04$, in (c) $\sigma_e = 0.25\sigma_b$ and $\Delta Q = 0.04$. Figure (d): Vertical emittance vs. number of turns in LHC, for the HEADTAIL pinched distribution (red) and for the analytical approximation (black). Charge conservation is assumed and the initial cloud rms size is set to $\sigma_{e,0} = 0.65\sigma_b$ (fit in the horizontal plane).

cloud rms size σ_e. For large electron-cloud sizes, the emittance evolution curves from the two codes are nearly identical (Fig. 6 (a) and (b)). If the cloud size is four times smaller than the beam (Fig. 6 (c)) - which is closer to the real case, with a highly spiked electron distribution - there are some differences in the slope, but the behavior stays qualitatively the same. The small differences are due to the roughness of the transverse PIC grid, which does not accurately resolve but smoothers the electron density, therefore generating a lower tune shift than expected.

Figure 6 (d), instead, shows the the emittance growth computed with HEADTAIL, using the electron potential from the PIC simulation of a pinching electron cloud, and with MICROMAP, using an approximated model. Namely, in MICROMAP the actual longitudinal electron cloud distribution, taken from the PIC, is implemented at the transverse center of the beam, while in the transverse plane the cloud is approximated by a bi-Gaussian distribution whose rms size at each z-location is computed assuming $\rho_e \sigma_e^2 = const$. Result of the comparison shows that the emittance growth is qualitatively the same, but differ in absolute rates by up to a factor of 2 or 3. We explain this discrepancy observing that in the analytical case the assumption of charge conservation leads to an underestimation of the electron cloud pinch and associated tune shift, since it does not take into account the increasing of the total number of electrons within $1\sigma_b$, due to the arrival of electrons from the outer regions. A more accurate modeling needs to be developed to account for this feature.

SPS SIMULATIONS WITH REAL LATTICE

Since it allows a more accurate model of the accelerator structure, the code MICROMAP is used to simulate electron cloud incoherent effects in CERN SPS. The purpose of these simulation is to compare with observation in the machine. In autumn 2004 the SPS working point has been changed for the operation with LHC type beam. In particular horizontal and vertical tunes have been switched from $(26.185, 26.13)$ to $(26.13, 26.185)$. Figure 7 shows the beam loss reduction when running with a higher vertical tune.

We tracked with MICROMAP 1000 proton macroparticles through the full SPS optics (as from a MAD-X file), including 744 beam-electrons interaction points (one per dipole magnet). A maximum tune shift of $\Delta Q_{max} = 0.13$ is assumed, which is the value corresponding to the estimated electron cloud density in the SPS. In these preliminary simulations space charge is not included and a large chromaticity $\xi \approx 1$ is used. Figure 8 shows a larger emittance growth, beam losses and bunch shortening if the vertical tune is lower, in qualitative agreement with the observation in SPS [10]. The diffusion mechanisms associated with the electron cloud pinch may thus explain the reduced beam lifetime, which concerns in particular the bunches in the last part of the train.

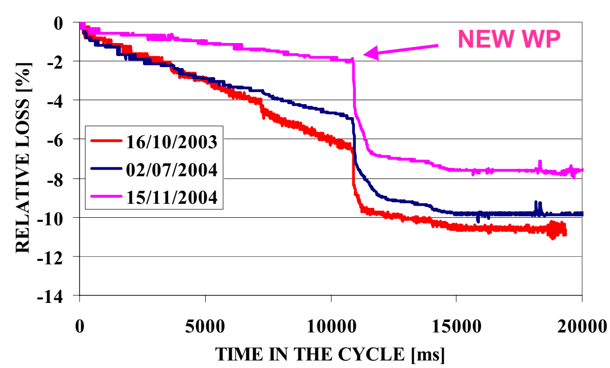

Figure 7: Relative beam losses vs. time for different run in SPS. The purple curve is for working point $(26.13, 26.185)$. Courtesy G.Arduini, [10]

Other simulations with MICROMAP, assuming a full lattice model for SPS with LHC beam and 744 electron kicks per turn, have been performed by further changing the working point. The case presented in Fig. 9, which shows the phase space trajectory of a particle which experience the maximum electron cloud density, the nominal

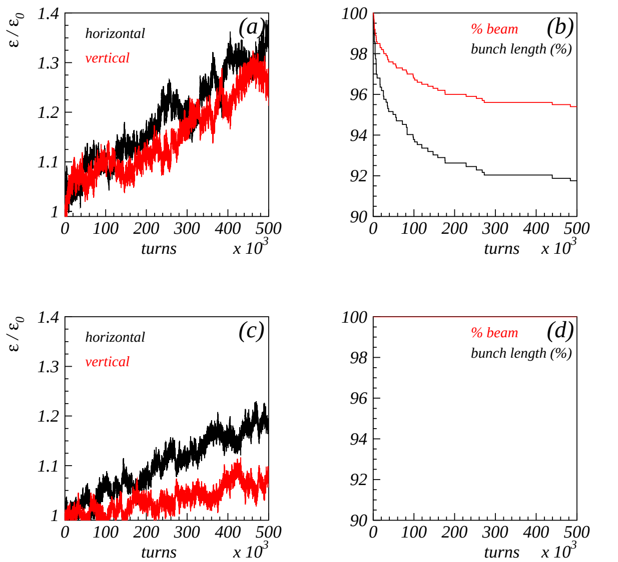

Figure 8: Simulations for SPS with different working point. Top: $(26.18, 26.15)$, Bottom: $(26.15, 26.18)$

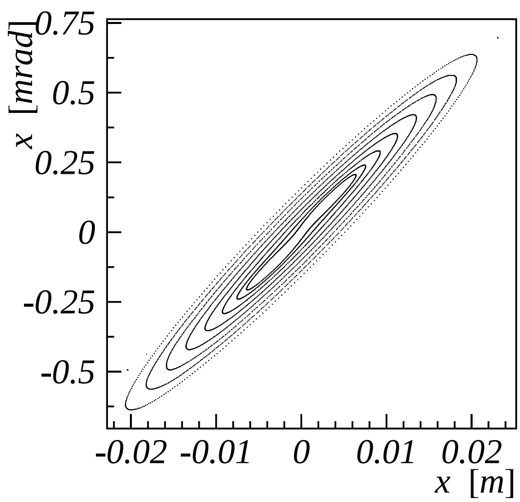

Figure 9: Horizontal phase space of a particle which experience a maximum tune shift of $\Delta Q = 0.13$. The simulations with MICROMAP, full lattice, 744 kicks per turn, are for LHC type beam in SPS at injection energy. Synchrotron motion is frozen.

horizontal tune has been increased to $Q_x = 26.38$, so that the maximum tune shift of $\Delta Q = 0.13$ leads the particles to the half integer.

Also here, as for Fig. 5, the presence of the two islands which illustrates the rise of a linear instability is visible.

SUMMARY

The electron cloud, which "pinches" toward the beam center during the passage of a bunch, causes incoherent emittance growth by two mechanisms. As for the space-charge dominated beams, the tune shift variation along the bunch and the particles' synchrotron motion causes phenomena of resonance crossing and scattering. Moreover, if the tune shift is such as to reach the half-integer stopband, there may also be crossing of linearly unstable regions. These mechanisms are likely to also happen in other two-stream problems, e.g. beam-beam or beam-plasma instabilities.

We started a benchmark of the HEADTAIL code, used for electron-cloud studies, with MICROMAP, originally written for space-charge problems and adapted to model the electron cloud, finding very good agreement in the simplified case. MICROMAP was then used to study electron-cloud effects in SPS with LHC beam, assuming a realistic model of the accelerator structure and an analytical simplified electron cloud density evolution. Results are consistent with the observed improvement of the SPS beam lifetime, if the machine is operated with higher vertical tune. A measurement campaign in SPS is planned for summer 2006, in order to carefully compare simulation predictions with the observed beam emittance, intensity and bunch length evolution.

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REFERENCES

[1] E. Benedetto, G. Franchetti, F. Zimmermann, PRL 97, 3, 034801 (2006)

[2] E. Benedetto et al., Proc. PAC'05, Knoxville (2005)

[3] G. Rumolo, F. Zimmermann, CERN-SL-Note-2002-036

[4] G. Franchetti, et al., Proc. AIP, New York, (1998)

[5] G. Rumolo, F. Zimmermann, PRST-AB 5, 121002 (2002).

[6] E. Benedetto, F. Zimmermann, Proc. EPAC'04, (2004)

[7] K. Ohmi, these proceedings (2006)

[8] A.W. Chao, M. Month, NIM 121, 129 (1974)

[9] G. Franchetti, I. Hoffmann, NIM A 561, 195-202, (2006)

[10] G. Arduini, Proc. CARE-HHH workshop, GSI, (2006)