# INCOHERENT EFFECT OF SPACE CHARGE AND ELECTRON CLOUD

G. Franchetti*, I. Hofmann, GSI; F. Zimmermann, CERN; W. Fischer, BNL

*Abstract*

Trapping in, or scattering off, resonances driven by space charge (SC) or electron cloud (EC) in conjunction with synchrotron motion can explain observations of slow beam loss and emittance growth, which are often accompanied by changes in the longitudinal beam profile. This talk will review recent progress in understanding and modeling the underlying mechanisms, highlight the differences and similarities between space charge and electron cloud, and discuss simulation results in the light of experimental observations, e.g., at GSI, CERN and BNL.

## SC & EC INCOHERENT EFFECTS

### *Space Charge Incoherent Effects*

The term "incoherent effects" of space charge in a 2D beam normally refers to the incoherent tuneshift of each particle in a beam [1]. Coherent space effects in transverse plane are more related to the collective beam response to the beam perturbations [2, 3]. The interplay of the coherent tuneshift with lattice driven resonances or structure resonances is essential for the correct identification of the tunes where the resonant effect will take place [4]. These studies are made mainly for 2D beams. The request of long term storage of high intensity bunches brought to the attention in circular accelerator the full 3D problem. The beam dynamics of a bunch is approximated by partially decoupling the dynamics of the transverse-longitudinal planes: the synchrotron motion is considered, in first approximation, independent. As the transverse-longitudinal frequency ratio is typically large, $Q_x/Q_z > 500$, parametric resonances are excluded. The only remaining effect of the synchrotron motion on the particles in a bunch is to advance them longitudinally and via space charge induce a transverse tune modulation at a frequency twice the synchrotron frequency. In the CERN benchmarking experiment [5] this mechanism was tested under controlled experimental conditions. It was found that the beam response and beam loss are consistent with the numerical modeling. The underlying mechanism for this beam response relies on the space charge transverse tune modulation for inducing a periodic resonance crossing. In this beam dynamics regime trapping/scattering of beam particles into the resonance creates a complex diffusive dynamics which becomes evident only after many synchrotron oscillations. Only the particles, which cross the resonance are subjected to trapping/scattering and this condition of "resonance crossing" depends on the initial particle invariants $\epsilon_x, \epsilon_y, \epsilon_z$, the space charge tuneshift $\Delta Q_{x,sc}$, and the working point $(Q_{x0}, Q_{y0})$. In Ref. [5] it is shown that the maximum amplitude a particle can reach depends on the distance from the resonance approximately as $\sim 1/(Q_x - Q_{x,res})$. This dependence creates two regimes: a beam loss regime for tunes located in the proximity of the resonance (above), and a neighboring emittance growth regime (no beam loss). In Ref. [6] the role of the transverse tune dependence induced by space charge is discussed for a Gaussian stationary bunched beam. The fraction of particles to be trapped/scattered is estimated as $\Delta N/N \sim (Q_x - Q_{x,res})/\Delta Q_{x,sc}$. As only particles with large synchrotron amplitude will span the full space charge tune-spread and therefore may reach a large transverse amplitude, the beam loss will shorten the bunch length [7]. Recently also the role of chromaticity in the 3D high intensity bunched beams has been explored and it is found that it enhances beam loss bringing the numerical results closer to the experimental findings [8].

### *Electron Cloud Incoherent Effects*

The presence of the electron cloud in proton machines has been always associated with the creation of instabilities [9, 10]. The interaction of localized electrons with proton beams is very complex in terms of formation and dynamics: when a proton bunch passes through a localized electron cloud it causes a pinch of the electron cloud itself [11, 12]. The idea that the pinched electron cloud is also responsible for the creation of incoherent effects on the proton beam has been around for several years. At the ICFA-HB2004 workshop, the analogy with space charge induced trapping phenomena was brought into the discussion. The essential key suggesting a similarity with space charge is the correlation of the amount of pinch with the extent of the bunch that has passed through the EC. This correlation creates a dependence of the pinch experienced by a bunch particle and its longitudinal position inside the bunch at the time of passage through the EC [13]. In this dynamics the electrons are the weak beam as it is subjected to large variations in density, which however may "resonantly" feed back on the strong main beam. For a bunch longer than the EC extension, the EC pinch occurs several times for the same electrons [11] according to the bunch charge density and sizes. The possibility of trapping/scattering induced by pinched EC is shown in [14]. There a simplified model of EC is used by assuming the EC kick modeled by an EC beam of density linearly growing from the bunch head to the tail. This model showed that a small emittance growth can be created similarly to what happens with space charge. Clearly the prediction capability of such a model is based on the modeling of the pinched EC. Simulations in fact show that the EC pinch progresses as the bunch goes through the EC and exhibits a complicated time dependent EC morphology with "rings" [12]. A previous attempt to model the effect of such rings

* g.franchetti@gsi.de

is reported in Ref. [15] where a one dimensional model is studied. We here extend the EC modeling to EC rings and compare its effect on the bunch dynamics with that induced by SC.

## SC & EC INCOHERENT EFFECTS: DIFFERENCES AND SIMILARITIES

The main difference between the SC and EC is that the SC force scales with the beam energy as $1/\gamma^2$ making the high intensity effects negligible at high energy, while EC forces still remain relevant for the beam dynamics. Another difference is in the shape of the Coulomb force much more nonlinear than for EC. Both SC and EC create a transverse amplitude dependent detuning which is a function of the beam distribution for the space charge, and of the EC pinch morphology for the electron clouds. The EC is often localized in specific regions of the ring creating a distribution of kicks on the strong beam the strength of which depends on the particle position within the bunch. The pinching of the EC causes always two effects: 1) the correlation of EC intensity of the pinch with the position along the bunch; 2) systematic resonances of even order. In the bunch reference frame the structure of the EC density assumes quite a complex form during the pinch process, which makes its effect on the main beam dynamics particularly difficult to asses in long term storage. Note that SC may create systematic resonances too of a strength consistent with the harmonics of the lattice optics. In this respect both SC and EC create structure resonances. In terms of incoherent effects, the main difference arises from the complex dependence of the amplitude dependent detuning, which characterizes the efficiency of trapping/scattering regimes [6]. In order to compare SC and EC incoherent effects we model the beam dynamics in a constant focusing lattice and for the sake of simplicity we consider two special frozen models, one for the SC, and another one for the EC as follows:

- We consider a stationary bunched beam where the particle distribution forms a 3D Gaussian distribution $\rho(x,y,z) = \exp[-(x^2+y^2)/(2\sigma) - z^2/(2\sigma_z)]$ from which the SC can be found analytically [6];

- Based on simulation results of the EC pinch [12, 16] we construct a simplified frozen model formed by 3 EC rings that are created along the bunch at the locations of the 3 pinches $z_p = -1\sigma_z, 0.3\sigma_z, 1.5\sigma_z$. Each EC ring has a radial thickness of $1\sigma$ of the beam, and its radial position is $R(z) = 3.33 \times (z - z_p)$ for $z > z_p$. As simplifying ansatz the model assumes an electron charge conservation inside each EC ring and that the EC electric field is well described by a "cylindrical sheet" approximating the EC rings allowing then a straightforward calculation of the electric field. This model extends the previously studied one dimensional sheet model presented in Ref. [15].

### *Comparison of EC & SC Incoherent Effects in Case of a Resonance Driven by a Lattice Nonlinearity*

We first consider an example with tunes as in the SPS and study the transport of a high intensity axi-symmetric bunched beam in presence of a lattice nonlinearity excited via a single octupole (similarly to what was done exper- periment [5]). The single

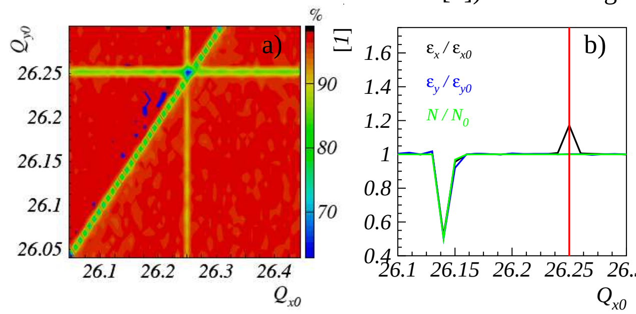


Figure 1: a) Resonance lines excited by a single octupole; b) Emittance growth and beam loss for several tunes at $Q_{y0} = 26.1$.

octupole excites all harmonics, and in order to evaluate the effective stop band we performed a scan of the beam loss over $(Q_{x0}, Q_{y0})$. For this particular simulation we assume a beam pipe of size $3.3\sigma$ and simulated the survival of $10^3$ particles after $10^3$ turns (Fig. 1a). The longitudinal beam motion is frozen here, and Coulomb forces are absent. This picture shows that the resonances $4Q_{x0} = 105, 4Q_{y0} = 105$, and $2Q_{x0} - 2Q_{y0} = 0$ are excited. We then restore the beam pipe to $10\sigma$, and simulate the beam loss for $Q_{y0} = 26.1$, and several tunes $26.1 < Q_{x0} < 26.3$: in Fig. 1b we observe that the resonance $4Q_{x0} = 105$ is weakly excited and a small emittance growth appears. At $Q_{x0} \sim 26.13$ the resonance $2Q_{x0} - 2Q_{y0} = 0$ is crossed with significant beam loss.

**Pure SC effects.** We now study the effect of space charge (in absence of EC) by applying 38 SC kicks per betatron wavelength, which are enough for this detuning, to guarantee an error in the detuning better than 0.1%. The space charge tunespread is taken as $\Delta Q_{sc} = -0.075$. The bunch is formed by applying a longitudinal linear focusing force such as to produce a longitudinal tune of $Q_{z0} = 1/300$. A partially compensated chromaticity is included creating an rms tune-spread of $\Delta Q_{chr} = \pm 0.015$. The results are shown in Fig. 2a. The beam emittances $\epsilon_{x/y}$ (black/blue) are plotted after $1.5 \times 10^5$ turns versus $Q_{x0}$; in green we plot the beam survival. This picture is characteristic of the SC effects (see Ref. [7]), it exhibits an emittance growth on the right of the resonance over a region as large as the SC tune-spread. The tiny beam loss region with a peak loss of 12% appears as consequence of the residual chromaticity and is as large as the chromatic spread.

**Pure EC effects.** In the next example we ignore SC and take an equally large maximum EC detuning at the pinch location on axis of $\Delta Q_{ec} = +0.075$. In Fig. 2b we plot the same beam quantities when the incoherent effects are EC driven. The picture is more complex: beam losses are localized on the left of the resonance as consequence of the positive detuning exerted by the pinched electrons on the strong beam. In the region $26.2 < Q_{x0} < 26.27$ beam loss is found as result of the complex detuning dependence on transverse and longitudinal amplitude. Note that on the 4th order resonance $4Q_{x0} = 105$, in spite of the beam loss, the horizontal emittance increases by a factor 2.5 due to the presence of 3 EC rings. The loss at $Q_{x0} \sim 26.1$ is the effect of the coupled 4th order resonance.

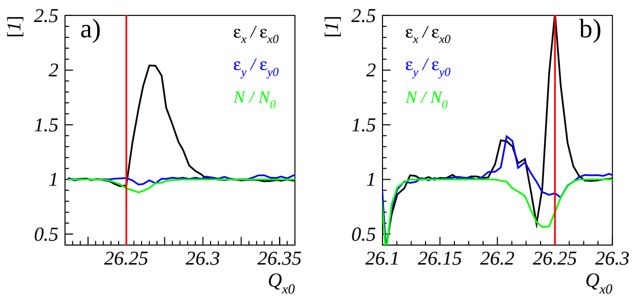


Figure 2: Octupolar resonance: a) Space charge induced emittance increase and beam loss; b) Electron cloud induced emittance increase and beam loss. (38 kicks per betatron wavelength and synchrotron. motion included).

### *Comparison of SC & EC Incoherent Effects in the Presence of a Structure Resonance*

We take the same bunch as described in the previous section, but apply the SC or EC with 105 kicks along the ring so as to excite the 4th order structure resonance. Again we set the maximum SC detuning $\Delta Q_{sc}$ or the maximum detuning of EC at pinch location $\Delta Q_{ec}$ equally large: $\Delta Q_{sc} = -\Delta Q_{ec} = -0.075$. We firstly compare the incoherent effect in the condition of a longitudinally motion frozen. In Fig. 3a is plotted the emittance growth for a purely SC driven effect from the bunched beam. We find the characteristic asymmetric beam response typical of the SC dominated 2D beams [17, 18]. The lack of self-consistency plays a minor role as the number of particles beyond $3\sigma$ is less than 8%. For comparison we plot in Fig. 3b the equivalent case of a pure EC incoherent effect. The picture is somewhat the mirrored situation of Fig. 3a with respect to the 4th order structure resonance. The difference in emittance increase stems from the EC pinch modeling, which here assumes 3 EC rings. The fraction of particles beyond $3\sigma$ of the beam is 4% justifying a frozen model approach. Clearly no periodic crossing of 4th order structure resonance happens in Fig. 3a,b as there is no synchrotron motion. The beam response to the longitudinal motion and the consequence of the tune modulation - via SC or EC tuneshift - is visible for both cases in Fig. 3c,d. The comparison with Fig. 2 reveals a significant effect which stems, in this example, from the much stronger 4th order driving term than the octupolar error given in Fig. 1: the ”octupolar” component from SC is 10 times larger than the external octupolar error assumed in Fig. 1. In Fig. 3d the large emittance increase for $Q_{x0} > 26.25$ is a consequence of the structure 4th resonance $2Q_{x0} + 2Q_{y0} = 105$ excited by the EC kicks.

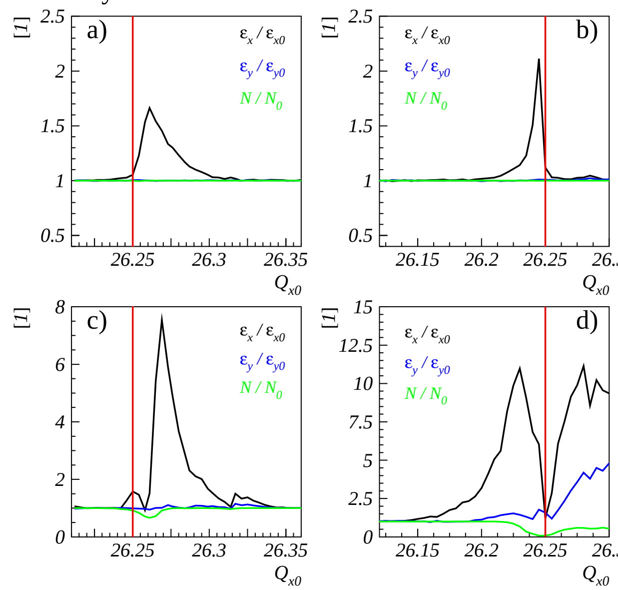


Figure 3: Beam response and survival with longitudinally frozen motion a) SC, b) EC; and including longitudinal motion c) SC, d) EC.

## EXAMPLES OF INCOHERENT EFFECTS

As pointed out, the impact of the incoherent effects generated by high intensity bunched beams or structured pinched EC requires consideration for long term beam storage. For medium energy projects like the SIS100 of the FAIR project, long term diffusion in high intensity bunches should be carefully controlled. The RCS at JPARC [19] will operate also in this regime, while the main ring (MR) exceeds the $10^4$ turns storage time and high intensity incoherent effects should be carefully assessed. In the SPS synchrotron at CERN, the presence of EC is assumed to play a role in the degradation of the bunch lifetime in bunch trains of 72 bunches. Ref. [20] reports experimental data supporting the interpretation that EC trapping related effects induces bunch shortening correlated to beam loss. This experimental evidence finds its SC counterpart in the results of the CERN-PS benchmarking experiment [7], where this effect was directly measured. The complexity of the presence of EC was experienced in RHIC, and an extensive campaign of measurements and countermeasures is described in Ref. [21]: slow emittance growth is suspected to be caused by EC incoherent effects [22]. EC incoherent effects are also of concern for LHC, where the hours of storage for collision in presence of a possible slow EC-induced diffusion might affect the collider luminosity performance.

### *Application to SC Incoherent Effects of Ion Beams in SIS100*

In the SIS100 synchrotron in the FAIR project at GSI [23] bunches of $U^{28+}$ ions are stored for a time of the order of a second. The limit imposed by radiation damage [24] and the current strategy of containment of the negative effects of beam loss - which rely on NEG coating [25] and a dedicated new halo collimation concept [26] - set a threshold of beam loss acceptance to probably much less than 10% over the total accelerator cycle. We study here the incoherent SC effect during the 1 s long injection flat-bottom for WP1 at $Q_{x/y} = 18.84/18.73$. In SIS100 the nonlinearities are given by standard multipoles in sc dipoles obtained via an elliptic coordinate transformation [27, 28] and by the multipoles for sc quadrupoles taken from [29]. No chromatic correction sextupoles are powered. The pure systematic multipoles yield a short term dynamic aperture ($10^3$ turns) of $4.8\sigma$ for a reference beam of 8.75 mm-mrad rms emittance at an injection energy of 18 Tm. Magnet random errors are assumed to have $\pm30\%$ fluctuation for all multipoles of the sc dipoles [30]. In this modeling we take into account a possible residual closed orbit distortion (COD), after correction, of 1mm vertical rms COD (1.6 mm horizontal) which, causing a feed-down, yields an average DA of $3.3\sigma$ with a variance of $0.21\sigma$. This statistical effect of COD is analyzed in a wide range of WP in Fig. 4a. For each WP is plotted $\langle \mathrm{DA} \rangle - 3\sigma_{\mathrm{DA}}$ by evaluating 10 random seeds of sc dipole errors as well as the 1mm level of vertical rms COD. We model the bunch beam with a Gaussian transverse distribution truncated at $2.5\sigma$ in amplitudes as result of a controlled beam shaping during transfer from SIS18 and SIS100. Two sets of reference emittances ($2\sigma$)

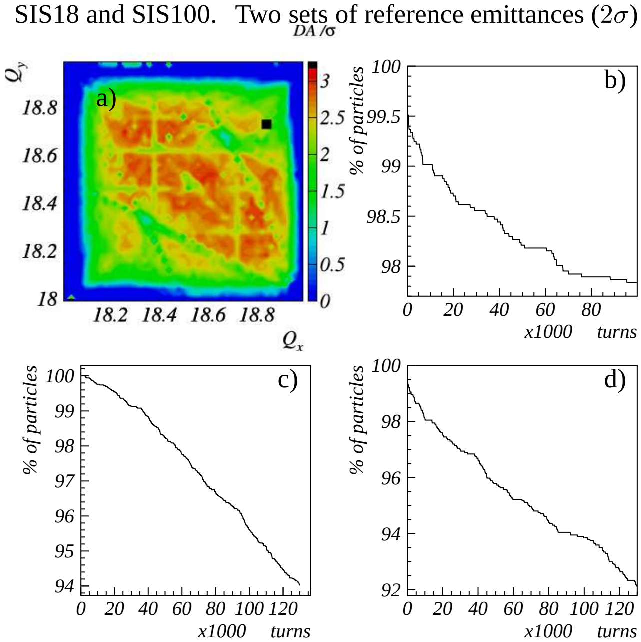


Figure 4: a) DA scans with reference random errors. Black marker: proposed working point WP1; b) Beam2 for the standard error case; Beam loss with space charge for Beam1 c) and Beam2 d) for an intensity of $3 \times 10^{11}$ ions.

are defined. Beam1: $\epsilon_{x/y} = 35/15$ mm-mrad (edge at $2.5\sigma$ < DA=$3.1\sigma$), which assume no dilution within the SIS18 acceleration cycle; Beam2: $\epsilon_{x/y} = 50/20$ mm-mrad (edge at $2.98\sigma$ < DA=$3.1\sigma$), which allows for some dilution getting closer to the dynamic aperture limitation, but reducing SC tune shift. Including all systematic and random terms so far discussed we explored, for 27 error seeds consistent with the standard 1mm vertical rms COD, the beam loss over $10^4$ turns and we single out a "standard error case" with the moderately pessimistic beam survival of 99% (Fig. 4b extends prediction till $10^5$ turns). Simulation results for the "standard error case" including chromaticity show that up to $10^5$ turns (0.6 s) the Beam1 exhibits a beam loss up to about 1%, while for Beam2 we find 6% of beam loss. We then evaluated the effect of the chromaticity in a bunched beam with rms momentum spread of $\delta p/p = 5 \times 10^{-4}$ consistent with a bunch length of $\pm 90^0$ for a bunching factor of 0.33 and linear synchrotron period of 233 turns (RF voltage of 53 kV if SC is ignored). Simulations with SC are made with MICROMAP including all previously discussed effects for the "standard error case". For the maximum nominal intensity of a total of $6 \times 10^{11}$ of $U^{28+}$ in 8 bunches the SC tune-spread is -0.31 / -0.47 for Beam1 and -0.21 / -0.34 for Beam2. In Fig. 4c,d we present results for Beam1/Beam2 at $1.2 \times 10^5$ turns (0.7 s storage) for half nominal intensity, which helps avoiding the half-integer resonance. In comparison with the case without SC the Beam1 is SC dominated as losses increase from 1% to 6%. For Beam2 the loss is more dominated by the DA and chromaticity, whereas SC only leads to an increase of the loss from 6.5% to 8%. The SC dominated loss for Beam1 at half nominal intensity can be understood as a result of the periodic crossing of the tune-footprint with the third order error resonance $2Q_x + Q_y = 56$, possibly also with $3Q_y = 56$. The nominal intensity for the same set of parameters (and the same error set) results in a more than proportional increase of the loss. At maximum intensity many more particles cross the resonance $2Q_y + Q_x = 56$ and become candidates for loss. We have therefore investigated an alternative working point for WP1: $(Q_x, Q_y) = (18.84, 18.40)$, which is exposed to the apparently weaker third order resonance $Q_x + 2Q_y = 56$. Results for beam survival (linearly) averaged over the full cycle, which is half of the first bunch, are presented in Table 1. The loss is improved for full intensity, but slightly worse for half intensity, possible because of the proximity of the line $Q_x + 2Q_y = 56$. It should be noted here that the simulation model employed in this study lacks dynamical self-consistency. This is not expected to matter, if losses are a few percent, but for larger losses inclusion of full self-consistency (e.g. updating the SC force as a consequence of losses) could easily enhance the loss rate (or diminish)

Table 1: Beam survival averaged over full SIS100 cycle.

| WP | (18.84, 18.83) | | (18.84, 18.40) | |
|---|---|---|---|---|
| $\epsilon_x/\epsilon_y$ | 35/15 | 50/20 | 35/15 | 50/20 |
| Part. $6 \times 10^{11}$ | 75% | 78% | 87% | 86% |
| Part. $3 \times 10^{11}$ | 97% | 96% | 95% | 91% |

## *Exploratory Discussion of EC Incoherent Effects in RHIC and LHC*

RHIC has experienced incoherent emittance growth likely to be caused by electron clouds [22]. We apply the model of EC rings stemming from pinched EC with 144 EC kicks located at the position of each long dipole. The structure of kicks respects the real lattice geometry (blue ring), but the tracking in between the pinched EC is made in smooth approximation. The model of RHIC has tunes $Q_x = 28.735, Q_y = 29.725$, and the integrated EC incoherent detuning is taken as $\Delta Q_{ec} = 0.03$ (Fig. 5a). In Fig. 5c the main structure resonances are found with a frequency map: $-Q_{x0} + 5Q_{y0} = 120, 2nQ_{x0} + 2nQ_{y0} = 117n, -3nQ_{x0} + 3nQ_{y0} = 3n$, with $n$ integer.

We also apply the pinched EC dynamics to LHC, again with one EC kick at each of the 1152 main dipoles taken with correct geometry structure of the real machine and tracking the beam in smooth focusing to gain in computational speed. A single bunch is composed of $10^4$ macroparticles and tracked in absence of chromatic effects in a fully linear lattice. The LHC tunes are $Q_x = 64.28, Q_y = 59.31, Q_s = 1/168$. The integrated EC detuning is arbitrarily assumed with values $\Delta Q_{ec} = 0.1, 0.3, 05, 0.7$ and the beam evolution is shown in Fig. 5b showing different average beam responses $(\epsilon_x + \epsilon_y)/(\epsilon_{x0} + \epsilon_{y0}) - 1$ function of $\Delta Q_{ec}$. In Fig. 5d a frequency map shows that the EC structure resonances $5Q_{x0} + 9Q_{y0} = 856, 4Q_{x0} + 2Q_{y0} = 376$, and $4Q_{x0} + 14Q_{y0} = 1088$, jointly with the EC induced modulational tune, are the responsible of the emittance growth in Fig. 5b.

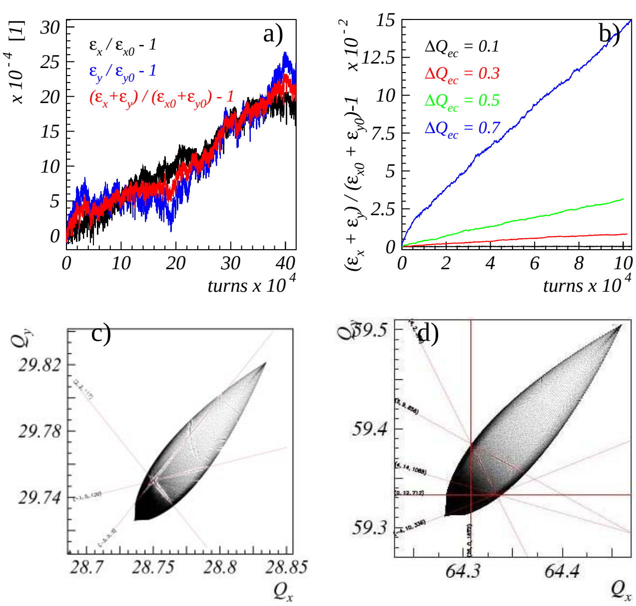


Figure 5: a) RHIC beam emittance evolution versus turns for $\Delta Q_{ec} = 0.03$; b) LHC beam emittance evolution versus turns for $\Delta Q_{ec} = 0.1$; c) Frequency map for RHIC for a beam with $\Delta Q_{ec} = 0.1$; d) Frequency map for LHC for a beam with $\Delta Q_{ec} = 0.1$.

## CONCLUSION AND OUTLOOK

We have shown that for SC & EC the long term beam response to incoherent effects is a possible source of slow emittance growth. In this respect SC & EC incoherent effects have similar features. We have evaluated the relevance of these incoherent effects for SIS100, and made an exploration study for future application to RHIC and LHC. The long term predictions for SC incoherent effects are presently better understood than those of EC and experimentally benchmarked. EC incoherent effects need further studies and dedicated experiments in order to validate models for long term beam evolution prediction.

## REFERENCES


[1] L. J. Laslettt, Proc. 1963 Summer Study on Storage Rings, Accelerators and Experimentation at Super-High Energies, p. 324.

[2] I. Hofmann, Phys. Rev. E **57**, 4713 (1998).

[3] I. Hofmann *et al.*, Phys. Rev. ST Accel. Beams **6**, 024202 (2003).

[4] R. Baartmann, Proc. of workshop on space charge physics in high intensity hadron rings, AIP **448**, 56, (1998).

[5] G. Franchetti *et al.*, Phys. Rev. ST Accel. Beams **6**, 124201 (2003); E. Metral *et al.*, NIM A, **561**,257,(2006).

[6] G. Franchetti and I. Hofmann, NIM A **561**, 195, (2006).

[7] G. Franchetti *et al.*, Proc. of 33rd ICFA worksop, AIP **773**, 137, (2004); G. Franchetti *et al.*, Proc. of 39rd ICFA worksop (2006), p. 344, THBW01.

[8] G. Franchetti, Proc. of PAC 2007, p. 794, TUZAAB02.

[9] G. Rumolo, F. Ruggiero, and F. Zimmermann, Phys. Rev. ST Accel. Beams **4**, 012801 (2001); F. Zimmermann, Phys Rev. ST Accel. Beams **7** 124801 (2004).

[10] K. Ohmi and F. Zimmermann, Phys. Rev. Lett. **85**, 3821 (2000).

[11] E. Benedetto and F. Zimmermann, Proc. of EPAC'04, Lucerne, Switzerland, WEPLT009, p. 1834 (2004).

[12] F. Zimmermann and G. Franchetti, THPC089, these proceedings.

[13] E. Benedetto and F. Zimmermann, Proceedings ECLOUD'04, Napa April 2004, CERN Report CERN-2005-001, p. 81 (2005).

[14] E. Benedetto *et al.*, Phys. Rev. Lett. **97**, 034801 (2006); K. Ohmi and K. Oide , Phys. Rev. ST Accel. Beams **10**, 014401 (2007).

[15] G. Franchetti and F. Zimmermann, Proc. of CARE-HHH-ADP BEAM07 workshop, Geneva, Switzerland (2007).

[16] E. Benedetto *et al.*, Proc. PAC 2005, p. 1344.

[17] I. Hofmann, G. Franchetti, A.V. Fedotov, Proc. of 20th ICFA worksop, AIP **642**, 248 (2002).

[18] A.V. Fedotov and I. Hofmann, Phys. Rev. ST Accel. Beams **5**, 024202 (2002).

[19] F. Noda *et al.*, Proc. of PAC 2005, p. 2759, MPPE043.

[20] G. Franchetti *et al.*, Proc. of LHC-LUMI-06 p.192 (2006).

[21] W. Fischer *et al.*, Phys. Rev. ST Accel. Beam **11**, 041002 (2008).

[22] S.Y. Zhang and V. Ptitsyn, Phys. Rev. ST Accel. Beam **11**, 051001 (2008).

[23] P. Spiller, MOPC100, these proceedings; G. Franchetti *et al.*, Proc. of EPAC 2006 p. 1882, THPCH005; SIS100 Technical report, `http://www.gsi.de/fair/reports/btr.html`.

[24] E. Mustafin *et al.*, Proc. of EPAC 2004, p. 1408, TUPLT112; E. Mustafin *et al.*, Proc. of PAC 2005, p. 3943, FPAE075.

[25] H. Kollmus *et al.*, Proc. of EPAC 2006, p. 1426, TUPCH174; A.W. Molvik *et al.*, Phys. Rev. Lett. **98** 054801 (2006).

[26] C. Omet, MOPC099, these proceedings.

[27] P. Akishin, E. Fischer and P. Schnizer, 3D field calculations for the SIS100 dipoles, November 14, 2007.

[28] F. Revuelta Peña and G. Franchetti, ACC_note-2008-001.

[29] A. Kovalenko, private communication.

[30] P. Spiller, private communication.