Title
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Abstract

We summarize Session F of the ECLOUD'04 workshop. This session was dedicated to beam instabilities driven by electron cloud. Specifically, we discuss the principal observations of electron-cloud instabilities, analytical models, simulation codes and the next steps that need to be taken to arrive at a predictive theory.

Disclaimer

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SUMMARY OF WORKSHOP SESSION F ON ELECTRON-CLOUD INSTABILITIES

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Abstract

We summarize Session F of the ECLOUD'04 workshop. This session was dedicated to beam instabilities driven by electron cloud. Specifically, we discuss the principal observations of electron-cloud instabilities, analytical models, simulation codes and the next steps that need to be taken to arrive at a predictive theory.

1. INTRODUCTION

In Section 2 we describe the principal observations of electron-cloud instabilities, considering both single-bunch and multi-bunch effects. This is followed, in Section 3, by a review of analytical models, most of which assume some pre-existing electron distribution and are based on impedance or wake-field approximations. In Sections 4 and 5 we discuss various simulation codes and their results, for single-bunch and multi-bunch instabilities, respectively. This summary concludes with a number of comments in Section 6, and a perspective on future work in Section 7.

2. PRINCIPAL OBSERVATIONS OF ELECTRON-CLOUD INSTABILITIES

Revealing the Electron-cloud as Culprit

How can one identify the electron-cloud as the source of an observed instability? Some clues are given by:

- direct observation of electrons using special detectors or circumstantial detection;
- effects are observed with positron beams and not with electron beams;
- positive effect of electron-specific suppression techniques, e.g., turning solenoids on/off;
- correlation of vacuum pressure with bunch pattern and beam time structure;
- correlation of instabilities with vacuum pressure;
- tune shift or beam size along bunch trains (KEKB, SPS, PEP-II).

Observations of Single Bunch Effects

A characteristic of the single-bunch effect - especially with positron beams, but also for the LHC beam in the SPS - is a beam-size blow up or instability growth rate that depends on the charge of a bunch. Different types of blow up can occur on fast or slow time scales. Often the blow up is predominantly in the (smaller) vertical direction, which also coincides with the direction of the bending magnetic field, but sometimes the blow up is seen primarily in the horizontal plane. Horizontal blow up was observed, for example, at PEP-II, which also demonstrated a strong dependence on the betatron tune. High chromaticity is sometimes effective in suppressing the blow up, such as in the CERN SPS, but this is not always the case. Recent studies at BEPC have shown that octupoles and a BPM bias voltage can both be efficient countermeasures as well. For long proton bunches, like those in the PSR and SNS, the instability mechanism appears to be slightly different from that for short bunches in long bunch trains. For the long bunches, electrons produced during the passage of the bunch itself (via 'trailing-edge multipacting' [1,2]) strongly contribute to the onset of instability, which explains why in long bunches, as in the PSR, the tail becomes unstable first. If the instability is a single-bunch phenomenon, the centroid motion of successive bunches should be uncorrelated. This is clearly the case in the CERN SPS.

Zimmermann showed measurements by Fukuma at KEKB that not only reveal the efficiency of solenoids in suppressing a fast blow up, but also suggest the existence of a different, less violent, emittance-growth mechanism below the threshold.

The head-tail motion inside a bunch was directly observed at the CERN SPS using a wideband pick-up to follow the difference in betatron phase between the head and tail of a bunch over a few synchrotron periods after kicking the bunch vertically. Comparing the evolution of this phase difference for a bunch at the start or end of the train, Cornelis was able to extract the frequency and amplitude of the electron-cloud wake, which was found to be consistent with analytical estimates.

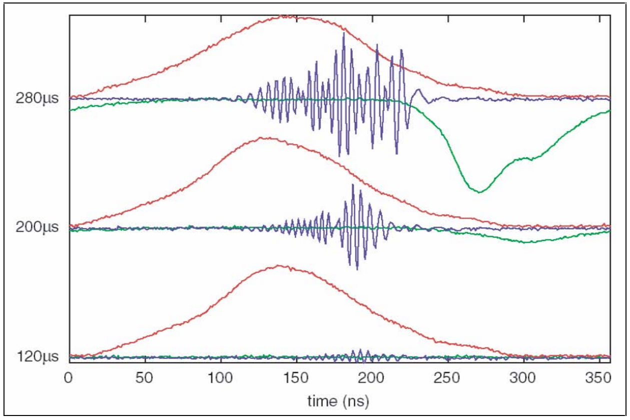

Figure 1: Beam current (red), stripline position signal (blue), and electron flux at the wall (green) recorded during three different bunch passages in the PSR. The instability progresses from the bottom to the top picture. Presented by M. Blaskiewicz (BNL).

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Various attempts were also made at KEKB to observe the head-tail motion inside a bunch, in this case using a streak camera. The measurements show that bunches towards the tail of the bunch train are blown up, but the resolution is too limited to discern clearly a head-tail tilt. Zimmermann gives further details and several figures in a review of single-bunch instabilities [3].

Figure 1 shows various signals recorded during the passage of an unstable bunch at the Los Alamos PSR, from the talk by M. Blaskiewicz. The instability first develops at the end of the bunch. Larger beam amplitudes coincide with enhanced electron flux at the wall.

Ng discussed observations of a fast emittance blow up in the Fermilab recycler ring, which could be caused by ions. The recycler and its beam-ion interaction look like a scaled version of the single-bunch electron-cloud instability, and might open a path for controlled experiments. Figure 2 illustrates the sudden emittance jump that has been observed in this machine.

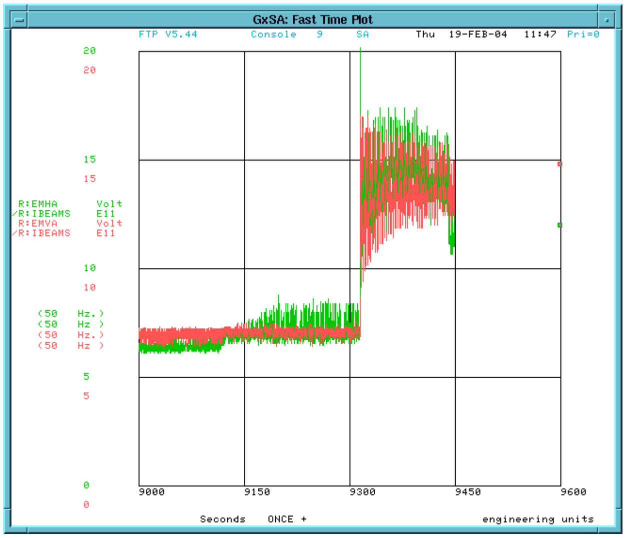

Figure 2: Sudden increase of horizontal and vertical emittance by about 100%, observed in the FNAL recycler ring. The jump in emittance coincides with a beam loss of about 1%. Presented by K.Y. Ng (FNAL).

Observations of Coupled-Bunch Effects

Coupled bunch instabilities can be identified by a growth in oscillation amplitude along the bunch train*; by a phase correlation between the centroid positions of successive bunches; and by a variation of the unstable mode frequencies with the beam current. Again, as for the single-bunch blow up, significant differences are observed between the horizontal and vertical planes.

Figures 3 and 4 show the first observation of coupled-bunch positron-beam instability in the KEK Photon Factory [4]. About half the modes are unstable, which indicates a short-range wake field. The unstable mode pattern varies with beam current, which hints at electrons as the source. By contrast, the spectrum for the electron beam exhibits only 1 or 2 singular modes.

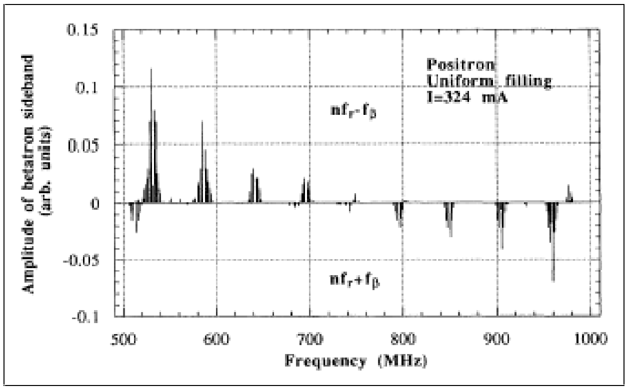

Figure 3: Distribution of the betatron sidebands during positron multibunch operation with uniform filling at 324 mA current in the KEK Photon Factory observed by Izawa et al. [4]. Presented by K. Ohmi (KEK).

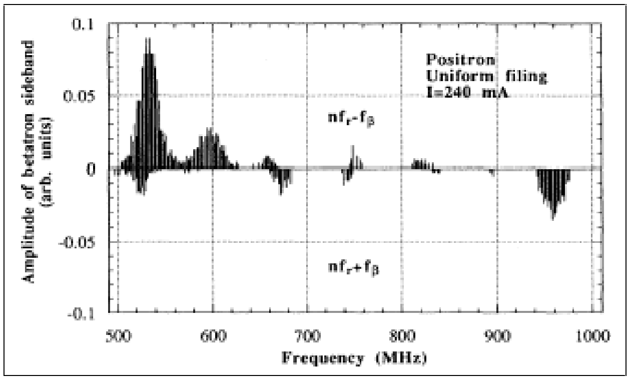

Figure 4: Distribution of the betatron sidebands during positron multibunch operation with uniform filling at 240 mA current in the KEK Photon Factory observed by Izawa et al. [4]. Presented by K. Ohmi (KEK).

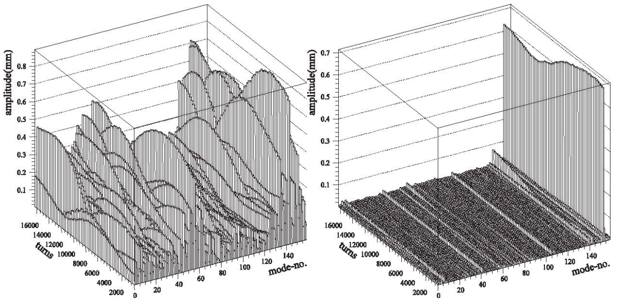

Figure 5: BEPC mode spectra measured by single path beam position monitor for a positron beam (left) and electron beam (right). Presented by K. Ohmi (KEK).

Similar observations were made at several other machines. Figure 5 illustrates the difference in the mode evolution for positrons and electrons measured using a multi-turn BPM at BEPC.

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[*] Note, however, that a growth in oscillation amplitude along the bunch train could also be present for the single-bunch effects because of the build up of the electron-cloud along the train. Time scales and bunch-by-bunch tune shifts need to be compared to give a clearer indication of the cause of the growth in oscillation amplitude.

3. ANALYTICAL MODELS

The analytical models generally assume the existence of an electron cloud with a particular density distribution in phase space. In some of the models the pinch effect, i.e., the increase of the electron density at the center of the beam during a bunch passage (Figure 6), is not included, though this likely affects thresholds and growth rates - it is not evident, a priori, in which direction. The pinch effect also increases the tune spread of the beam (see Figure 7). Also, nonlinear forces are often ignored in analytical treatments. Most models are based on linear perturbation theories and assume that the superposition principle applies. In reality, this is not strictly true.

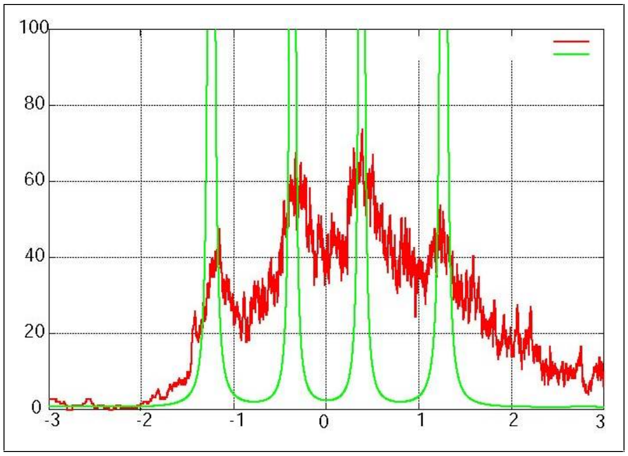

Figure 6: Density enhancement (pinch effect) during the passage of a Gaussian bunch in the CERN SPS. The red curve shows results of a simulation that includes the nonlinear force; the green curve shows the results of an analytical calculation for a linearized force. The bunch head is on the left. The peaks reflect half periods of linear electron oscillations in the beam potential. Inside the bunch the density enhancement is about a factor of 50. Presented by E. Benedetto (Politecnico Torino & CERN).

Different types of instabilities are described by different models. If the single-bunch instability growth time is much faster than the synchrotron period, a natural model is the beam break up. If there is a threshold and the growth rate above threshold is comparable to the synchrotron frequency, we are in the regime of the strong head-tail or transverse mode coupling instability (TMCI). A model proposed in [5] approximates the wake field of the electron cloud by that of a broadband resonator, with appropriately defined values for shunt impedance, quality factor and resonator frequency. For the broadband resonator the standard instability theory can be applied. If there are many electron (or resonator) oscillations along the bunch length, the TMCI calculation smoothly merges into the coasting beam instability theory [6]. The mechanism for slow and apparently 'incoherent' single-bunch emittance growth, observed in simulations and some experiments, is presently not understood. Thus, it has not yet been modeled analytically.

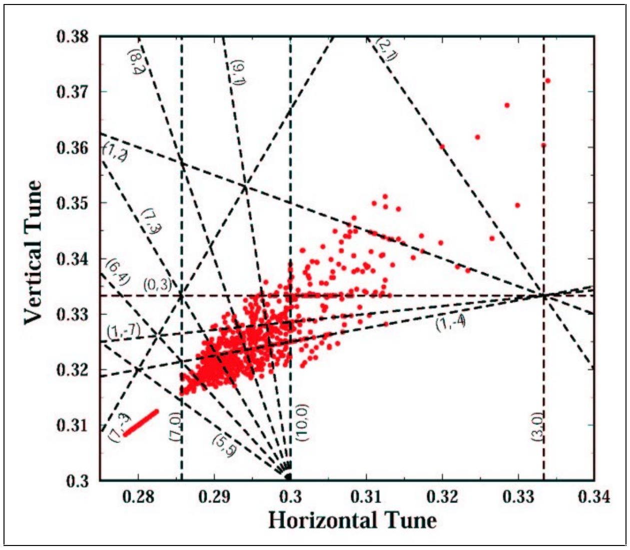

Figure 7: Tune footprint determined by a frequency map analysis for single-particle trajectories tracked through a frozen pinched electron potential using the HEADTAIL code, computed by Y. Papaphilippou and E. Benedetto [7]. The tune spread is about several 10 times larger than expected from the unperturbed cloud. Presented by E. Benedetto (Politecnico Torino & CERN).

The approach adopted for the coupled-bunch instabilities is rather similar to that taken for the single-bunch TMCI. Namely, an expression for the wake field is derived, usually from electron-cloud build up simulations with displaced bunches, and then the standard theory is used. Simulations presented by K. Ohmi indicate that it is reasonable to apply the superposition principle, and that the wake is linear for the first few bunches behind a displaced bunch. Solenoid fields covering much of the circumference (as in the two B factories) introduce a second characteristic frequency in the coupled-bunch wake, which is related to the cyclotron frequency of electrons in the solenoid field. Examples were presented by L. Wang in another session.

One flaw in the approach based on the conventional wake field, is that the electron pinch, and thus the time dependence of the electron-cloud density inside the beam volume, is ignored. This can at least partially be taken into account by generalizing the notion of the wake field from one that depends only on the distance between the driving and the test particle, $W_1(z-z')$, to one that independently depends on the positions of these two particles, $W_1(z,z')$. The mathematical framework for this generalization has been worked out in great detail by Perevedentsev [8]. The generalized wake is related to a generalized impedance by a two-dimensional Fourier transform:

$$W_1(z,z') = \iint \frac{d\omega}{2\pi}\frac{d\omega}{2\pi}\frac{1}{i}\hat{Z}_1(\omega,\omega')e^{i(\omega z-\omega' z')/c} \ .$$

The wake $W_1(z,z')$ can be obtained from simulations (see for example, Figure 8) and the inverse Fourier transform then yields the two-dimensional impedance.

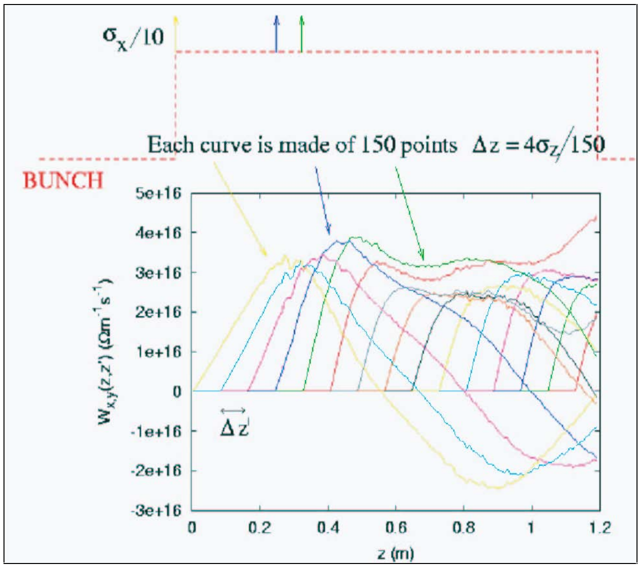

Figure 8: Two-dimensional wake field simulated by G. Rumolo [9] using the HEADTAIL code. Displacing different bunch slices gives rise to non-identical wake fields that enter into the Fourier transform for the two-dimensional impedance. The bunch head is on the left. Presented by F. Zimmermann.

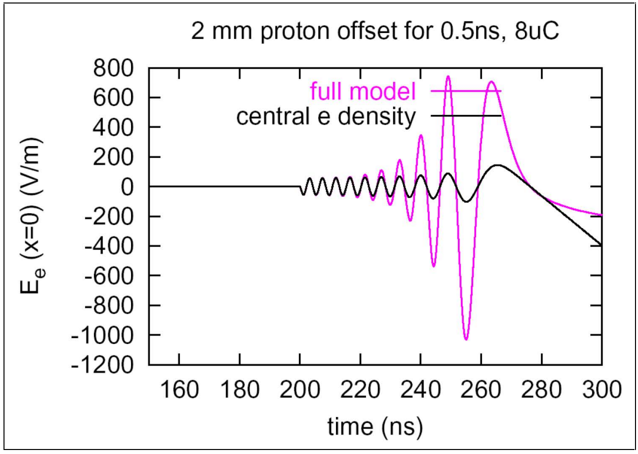

Figure 9: PSR wake fields calculated by M. Blaskiewicz for a 'full model' including the electron density variation inside the beam and for a simplified model in which the electron density is assumed to be constant equal to the central value.

It is important to note that, when making estimates and wake approximations, the transverse distribution of electrons affects the magnitude of the wake field. In the PSR for example, assuming a uniform density for the cloud distribution based on the electron density at the beam center can lead to an underestimate of the wake field (Figure 9).

There is yet another complication: unlike a conventional wake, the electron-cloud wake is not constant as a function of test-particle amplitude. Figure 10 compares the wake computed by averaging the force resulting from a displaced preceding bunch slice over the transverse beam size with the force experienced on axis. Both amplitudes and shapes of the wake fields differ greatly depending on the calculation recipe, while for a classical wake field the result would be the same.

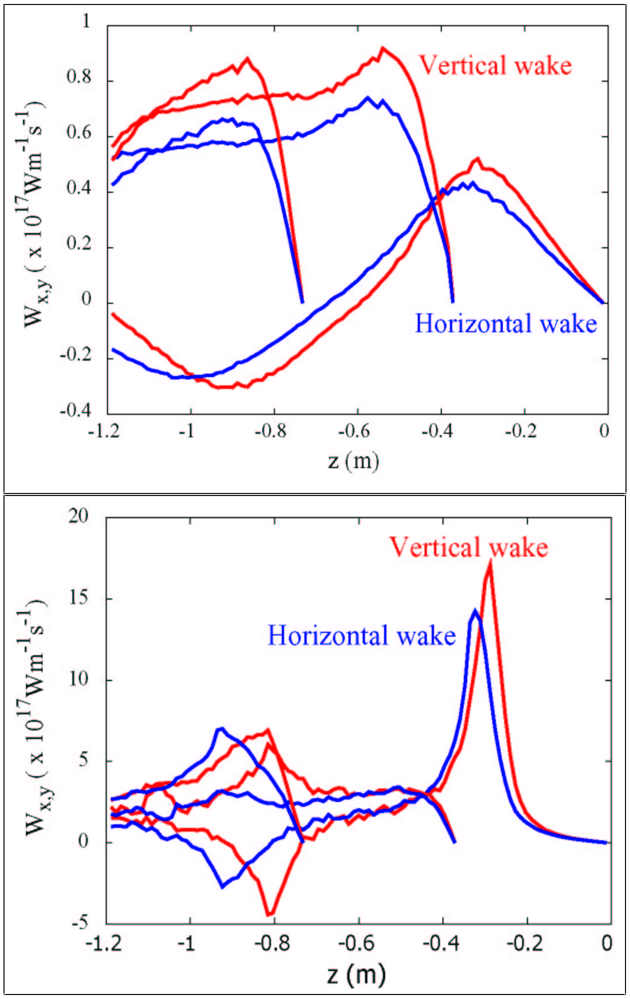

Figure 10: Wake fields obtained by displacing several slices and either computing the average force over the transverse beam size (top) or inferring the wake from the force on the axis (bottom). Computed by G. Rumolo [10] and here presented by F. Zimmermann.

Elegantly extending the classical TMCI theory to the case of the generalized two-dimensional wake and impedance, it was demonstrated by Perevedentsev [8] that the pinch effect can greatly increase the threshold of the TMC instability. For example, if the electron pinch leads to a betatron tune shift of ±2.5 times the synchrotron tune at $\pm\sigma_z$ from the bunch center, the TMCI threshold increases by more than a factor of 4, in line with an earlier similar analysis for an rf quadrupole suppressing the instability caused by a classical wake field [11]. The predicted stabilizing effect of the electron pinch is illustrated in Figures 11 and 12.

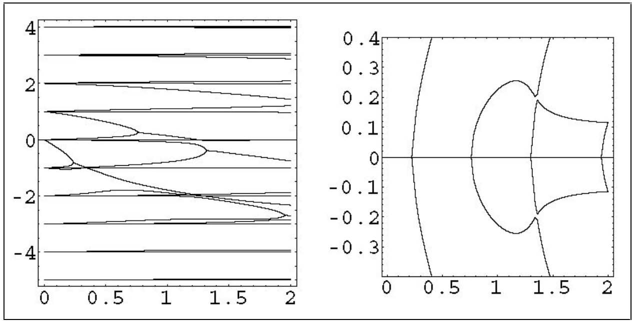

Figure 11: Real and imaginary part of the coherent tune shift in units of the synchrotron tune without incoherent tune shift vs. the electron density in units of 10^{12} m^{-3} for a bunch of $N_b=10^{11}$ protons in the SPS. Computed by E. Perevedentsev [8]; presented by F. Zimmermann.

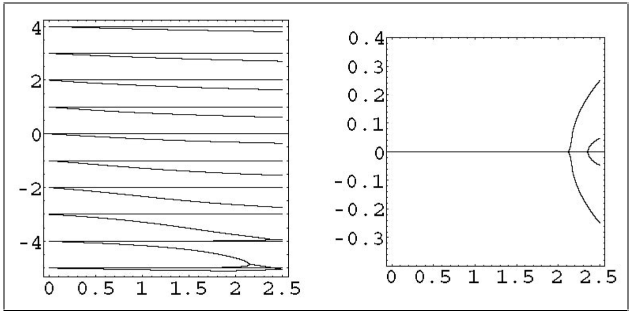

Figure 12: Real and imaginary part of the coherent tune shift in units of the synchrotron tune with an incoherent tune shift of $\pm 2.5\nu_s$ at $\pm\sigma_z$ vs. the electron density in units of 10^{12} m^{-3} for a bunch of $N_b=10^{11}$ protons in the SPS. Computed by E. Perevedentsev [8]; presented by F. Zimmermann.

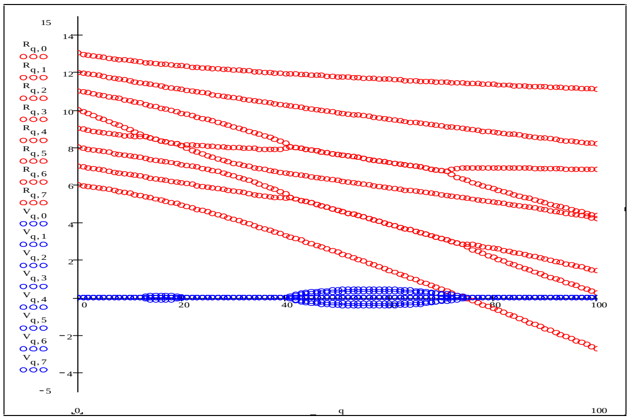

Figure 13: Real and imaginary vertical head-tail mode frequencies for a flat chamber without electron-cloud. Strong instabilities are prevented by the incoherent wake of the chamber. Presented by K. Cornelis (CERN).

The presentation by K. Cornelis clarified the interplay between the electron cloud and the impedance of a flat chamber. The TMC instability is often suppressed by the incoherent wake component of a flat chamber. Cornelis pointed out that the incoherent component of the electron-cloud wake is opposite in sign to the incoherent chamber wake. As a result the TMCI threshold decreases and the coupling of head-tail modes for the flat chamber with electron cloud looks similar to that for a round chamber without electron-cloud. Figures 13 and 14 illustrate this point, showing results from a few-particle model.

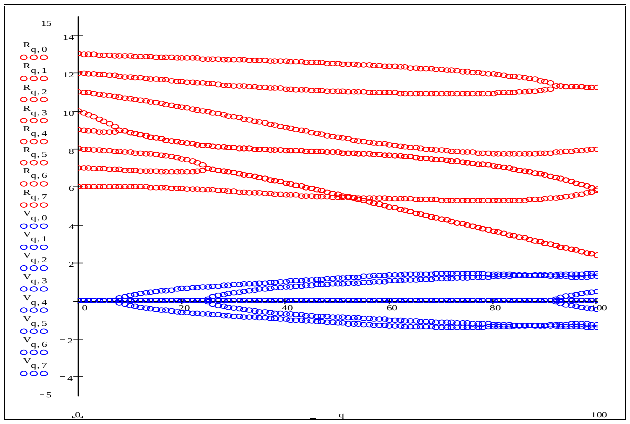

Figure 14: Real and imaginary vertical head-tail mode frequencies for the same flat chamber as in Figure 13 when an electron-cloud is present. The instability threshold is reduced and the growth rates are much higher than in the case without electron cloud. Presented by K. Cornelis (CERN).

4. SIMULATION CODES FOR SINGLE-BUNCH INSTABILITIES

A number of codes are being used to study the development of single-bunch instabilities in the presence of electron-cloud. These include:

- PEHTS (K. Ohmi, KEK), a PIC code based on the BBSS program [12] developed to simulate strong-strong beam-beam interactions; the code shows the occurrence of a TMC instability; it has been benchmarked against threshold observations at KEKB and an agreement better than 30% has been achieved with some assumption on the cloud density that is supported by tune shift data; results from PEHTS for KEKB and SPS were benchmarked with the code HEADTAIL (see next);
- HEADTAIL (G. Rumolo, GSI, E. Benedetto, D. Schulte, and F. Zimmermann, CERN), in which the bunch is sliced longitudinally, and interacts at a number of discrete points around the ring with an electron cloud modeled by macroparticles; the simulation shows an ‘incoherent’ slow emittance growth in addition to the TMCI threshold; it was benchmarked with QuickPIC (in discrete interaction mode), with PEHTS, and against the resonator model; agreement of simulations with observed thresholds at KEKB and SPS are also within 30%; the efficiency of a high chromaticity in suppressing the SPS instability is well reproduced if the broadband machine impedance is also included;

- QuickPIC (T. Katsouleas, USC), a plasma code, adapted for electron-cloud studies; this code models the continuous interaction of electrons and beam around the ring; it employs a quasi-static approximation, assuming that the beam dynamics is slow compared with the electron motion; the simulation yields both coherent and incoherent tune shifts in addition to the emittance growth;
- BEST (Y. Qin, PPPL), a Maxwell-Vlasov solver that evolves a perturbation to the stationary bunch distribution; the code predicts unstable modes and growth rates of density perturbations;
- NCSEC, an extension of the code CSEC to cases without circular cylindrical symmetry (M. Blaskiewicz, BNL); it numerically solves an analytical description of the coupled beam-electron system including electron generation at the wall.

Work is still in progress to benchmark the codes against one another, and against machine data; however, some of the codes have already been applied to estimate instability modes and thresholds for present and future machines, such as KEKB or the LHC, respectively.

K. Ohmi has used PEHTS to study single-bunch instabilities in the damping rings of the Global Linear Collider (GLC). In the simulation, the bunch is divided into 50 longitudinal slices, and makes one interaction per turn with the electron cloud. The cloud density is projected from the full circumference onto a single position in the ring. The vertical size of the bunch is evolved over many turns, with different values for the cloud density and the synchrotron tune. Above a certain threshold, a fast blow-up is observed, with a growth rate increasing with higher cloud densities, and decreasing with higher synchrotron tunes. This is the behavior that might be expected from a strong head-tail instability. For cloud densities below 5x10^{11} m^{-3}, the growth rate scaled by the electron density appears to be roughly independent of the ratio of the cloud density to the synchrotron tune, consistent with the theory of the strong head-tail effect. For a cloud density of 10^{12} m^{-3}, the scaling appears no longer to hold, suggesting that some other mode of instability is present (see Figure 15).

The simulations suggest that the threshold for the fast head-tail instability in the GLC damping rings is near $\rho_e/\nu_s = 10^{12}/0.01$ m^{-3}. The nominal synchrotron tune is a little above 0.01. The threshold estimated from the simulations is a factor of 2-3 lower than that obtained from an analytical estimate based on a linear wake model; however, the analytical wake model does not include effects such as the force nonlinearity and the “pinch” enhancement of the cloud density inside the beam during a bunch passage. Assuming that 99.5% of the synchrotron radiation photons are absorbed by an antechamber, which translates to about 3.3x10^{-4} residual photoelectrons produced per meter and per passing positron, the electron-cloud density in the GLC damping rings is estimated to be of the order 10^{12} m^{-3}. Therefore, although it is possible that the damping rings could operate below threshold for a fast beam blow-up instability, there are no real safety margins, and it seems appropriate to design measures for preventing build up of the electron cloud in the beam pipe proper.

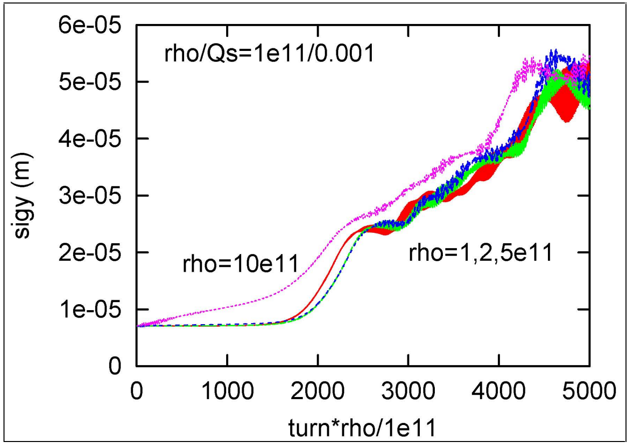

Figure 15: Simulated vertical beam size as a function of normalized turn number for the GLC damping ring, presented by K. Ohmi (KEK). The various curves refer to different electron densities and synchrotron tunes, keeping the ratio of these two quantities constant. The nominal synchrotron tune is near 0.01, which, in the figure, would correspond to a density of 10^{12} m^{-3}. This case no longer obeys the scaling behavior observed at lower density.

Ohmi has also studied a possible coasting beam instability in JPARC. It is expected that electrons will be trapped by the beam potential, and not be able to reach the wall; thus, the principal source of electrons will be from ionization of residual gas in the chamber rather than from secondary emission. The Landau damping introduced by the nonlinearity of the electron oscillation is much stronger than the Landau damping due to the beam frequency spread. If the density of the cloud reaches the level where a small instability develops in the beam, this can drive diffusion of electrons from the cloud into the wall at low energy. As a result, the density of electrons reaches equilibrium (even when there is a production of secondary electrons), and a strong instability is avoided, unless the vacuum pressure is extremely poor or there are huge beam losses at the wall. Ohmi’s simulations suggest that a strong instability could occur above a pressure of 10^{-4} Pa (750 ntorr), but below a “normal” vacuum pressure of 10^{-6} Pa, there should be no instability.

E. Benedetto has used HEADTAIL to study growth of vertical emittance in the LHC driven by electron cloud. Depending on the parameters in the simulation, the emittance growth can be ‘apparently’ incoherent, or coherent (that is, with some correlation between the vertical and longitudinal motion, as may be expected from a fast head-tail instability). The important simulation parameters are not just the physical parameters of the machine, but also the number of interaction points between the beam and the electron cloud, and their locations around the ring. It is found that a large number (between 20 and 50) interaction points are needed for the characteristics of the instability to converge.

The transition point from incoherent emittance growth to a fast instability is found to depend on the chromaticity: the larger the chromaticity, the higher the density of the cloud needed to produce a fast blow up (Figure 16). At a chromaticity of 40, the threshold electron-cloud density for the fast instability is around 10^{12} m^{-3}. Below threshold for the fast instability, the chromaticity has little (if any) effect on the growth rate of the emittance. Work is being pursued to benchmark simulations of electron-cloud instabilities against experiments at the SPS, in order to possibly explain short beam lifetimes which were occasionally observed in the presence of electron cloud, and to resolve the rate of long-term emittance growth. If the LHC can be operated below the fast blow-up threshold, then the simulations suggest that for cloud densities below about 10^{10} m^{-3}, the slow beam size growth from electron cloud should be acceptable. The initial density of electron cloud in the LHC is expected to be around 10^{11} m^{-3}. It is not clear yet, whether the slow growth is real or an artifact of the simulation.

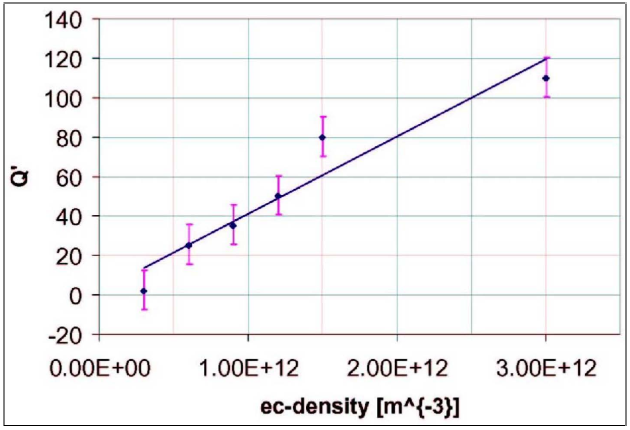

Figure 16: Minimum chromaticity needed to suppress the fast emittance blow up as a function of electron density at injection into the LHC, simulated by E. Benedetto using the code HEADTAIL. The dependence is roughly linear as expected on analytical grounds.

A linear wake model for the fast instability gives good agreement with the HEADTAIL simulations for the initial growth rate in the LHC, over a wide range of cloud densities (Figure 17). However, the simulations show a saturation of the beam size that is not a feature of the analytical model; this is likely due to nonlinear effects and/or due to the finite size of the grid on which the fields of beam and electron cloud are calculated. Initial comparisons have been made with QuickPIC, with mixed results (growth rates agree within a factor of two).

A. Ghalam has confirmed with QuickPIC that the instability characteristics seen in a simulation can vary with the number of interaction points between the beam and the electron cloud in a single turn. QuickPIC is able to avoid possible convergence issues associated with this effect by modeling the interaction continuously around the ring.

QuickPIC has been used to study the tune shift caused by electron cloud for the SPS. It is found that the simulated measured coherent tune shift is close to the value expected from an “unperturbed” cloud, i.e., the one computed by assuming that the cloud distribution in the chamber remains uniform during the passage of a bunch. This result is consistent with earlier studies by Ohmi and colleagues [13], which did not include image charges. Simulations of the SPS have also emphasized the importance of accounting for the effect of magnetic fields in the model; the dipole fields, for example, are found to affect significantly the dynamics of the electron cloud during the passage of a bunch (Figure 18), with a result that instabilities in both the centroid motion of the bunch and the bunch size are reduced.

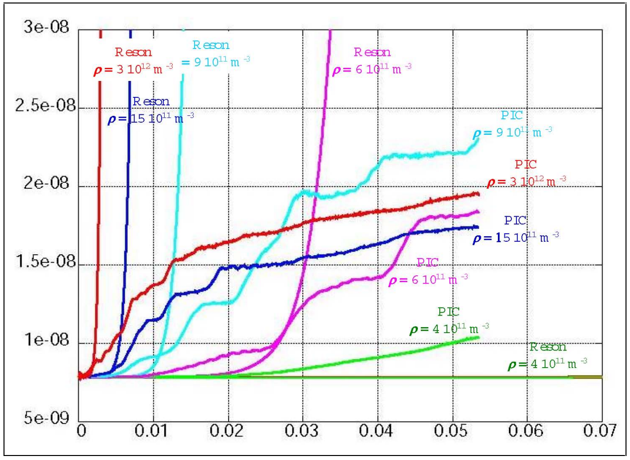

Figure 17: Emittance (in meters) as a function of time (in seconds) simulated by E. Benedetto using HEADTAIL, at different electron densities (the various colors) in the LHC at injection. Results from the PIC model are compared with those from an equivalent broadband resonator model [4].

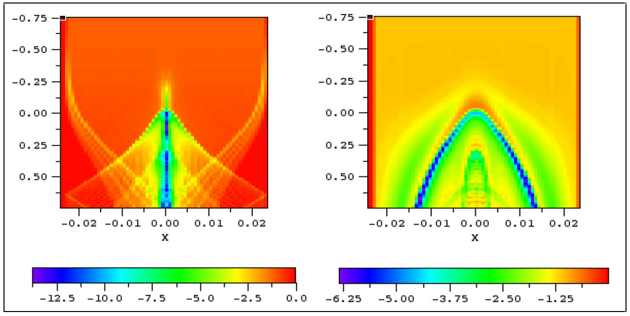

Figure 18: Cloud density during the bunch passage in the horizontal plane, as simulated by A. Ghalam (USC) using QuickPIC without external magnetic field (left) and with a field of 0.117 T (right). The severe cloud compression on the left becomes shallower due to the magnetic field. Beam parameters are those of the CERN SPS at injection.

H. Qin has applied the Vlasov-Maxwell solver BEST [14] to study electron-cloud in the PSR and in a proposed accelerator for Heavy Ion Fusion (HIF). The HIF accelerator will need to handle intense beams of heavy ions in a strongly space-charge dominated regime. Electron cloud is a potential problem because of the beam intensity. In common with other electron-cloud instability simulation codes, BEST assumes an initial density and distribution for the cloud. Like in QuickPIC, the beam is treated in the smooth focusing approximation (i.e., there is no variation of the lattice functions). BEST also assumes that the wavelength of any instable mode is short compared to the bunch length, so that a coasting beam model can be used. Space-charge forces are modeled self-consistently. Rather than evolve the complete bunch distribution, BEST solves the dynamics for a perturbation to a known stationary solution to the Vlasov-Maxwell equations: this reduces computation time, since fewer simulation particles are needed to achieve similar accuracy to that obtained using a conventional PIC code.

Results of simulations using BEST are in good agreement with theoretical predictions, e.g., for the structures of the unstable modes, and the damping resulting from space-charge induced tune spread. Simulations of the PSR are in agreement with the mode structure, frequency, and possibly also growth rate of the observed instability. The BEST simulations reveal a late-time nonlinear growth for system parameters above marginal stability. A second interesting effect observed in the simulations is the behavior of the electrons in the presence of beam instability: regular orbits of low-energetic electrons in the potential of a stable beam can become chaotic when the beam is unstable. This is reminiscent of the electron diffusion observed by Ohmi in the simulation of electron-cloud effects in JPARC.

Blaskiewicz has used the code NCSEC/CSEC [15] to study electron-cloud instabilities in long bunches. The code allows calculation of a transverse wake field, which may be compared with analytical models. Simulations for the PSR show that at large bunch charges, it is important to use a detailed model for the electron-cloud distribution. Simulations also for the PSR have shown that the instability can be strongly dependent on the cloud density: in some cases, a small reduction in the electron-cloud density can more than compensate a reduction in bunch length an increase in bunch charge, leading to a weaker instability. This could explain the observed insensitivity of the instability threshold to the bunch length, a long-standing puzzle.

CSEC is now being used to predict electron-cloud effects in the SNS. With a uniform beam density, it appears that the beam will be stable, although new simulations may need to be performed, without the debuncher cavity that was recently removed from the SNS baseline.

5. SIMULATIONS OF COUPLED-BUNCH INSTABILITIES

Coupled-bunch instabilities caused by electron cloud have been observed at a number of machines, including the B-factories, the Photon Factory, and BEPC. Ohmi has simulated the long-range wake from the electron-cloud in KEKB, and obtained results that suggest that the strength of the wake is linear in the displacement of the leading bunch only for a small number of following bunches. However, by the time the assumption of linearity breaks down, the wake is already quite weak, and models of the instability based on a linear wake model should still be appropriate. The results of simulations of coupled-bunch instabilities in KEKB have been published previously [16]. These are in good agreement with the observations, provided certain assumptions are made about the density and distribution of the electron cloud.

Ohmi has computed the longitudinal wake from the electron cloud (earlier studies of longitudinal single-bunch and multi-bunch wakes can be found in [17,18] and [19], respectively), and he has carried out calculations for the resulting longitudinal coupled-bunch growth rates in Super KEKB based on the strength of the simulated wake when a bunch is displaced longitudinally (Figure 19). It appears that the growth times are long enough (more than 10 ms) that the instability can be dealt with by an appropriate feedback system.

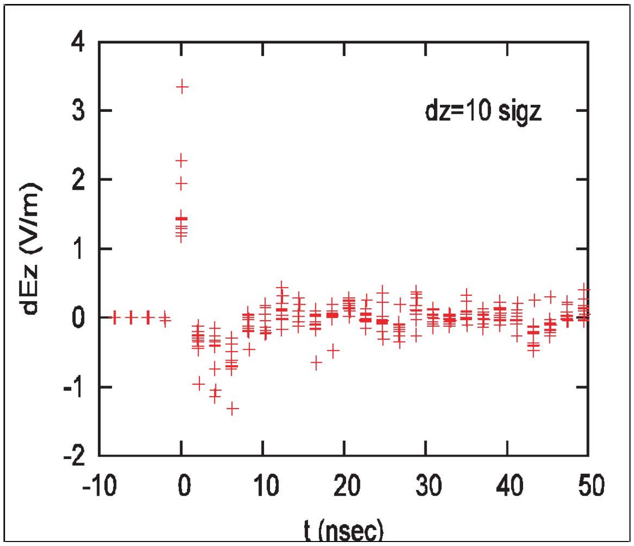

Figure 19: Change in the longitudinal electric field for subsequent bunches, if one bunch at *t*=0 is displaced longitudinally by $10\sigma_z$, as simulated by K. Ohmi for Super KEKB.

6. COMMENTS

Most of the simulation efforts presently focus on single-bunch instabilities. The variety of different machines and parameter regimes being studied makes it difficult to compare the results from the codes. Where electron-cloud instabilities have been observed in operating machines, the experimental challenges involved in obtaining detailed data on the instability modes often make it difficult to benchmark the codes in a rigorous way. A significant uncertainty is the density and distribution of the electron-cloud; although the simulation codes generally include the dynamics of the electrons in the positron or proton beam, most do not include build-up of the electron-cloud as part of the simulation. Ohmi and Qin have observed in their separate simulations of different machines, with long proton bunches, that beam instability can have an effect on the electron dynamics in a way that potentially affects the build up of electron cloud, by releasing electrons from the potential of the beam to impact the chamber wall. The likely necessity of combining build-up and instability simulations to get sound results was also emphasized by Heifets. Similarly, Blaskiewicz has observed that the results of simulations of instability in long bunches can depend strongly on the density distribution of the cloud that is present. Taken together, this work provides a strong argument for the need to include electron-cloud build up, dynamics and beam instability in a self-consistent way in the simulations, though the computational challenge appears formidable. The previous successes in using simulations to understand the single-bunch instability thresholds [20,21] and the coupled-bunch instability mode patterns [16,22] in machines such as KEKB, the KEK photon factory and the CERN SPS provide strong encouragement for achieving a similar model accuracy for all electron-driven instabilities, if the build up of the electron cloud, and its resulting density and distribution, can be predicted with confidence.

There are several different techniques employed by the simulation codes to model electron-cloud instabilities. This makes it interesting and useful to compare the results from the different codes, even though the physics of the interaction between the cloud and the beam should be the same in each case. Progress is being made to include all effects likely to be important. For example, magnetic fields or nonlinear space charge can have a significant impact on the dynamics of the electron cloud. However, these and various other aspects such as the vacuum chamber impedance, variation in lattice functions, detailed boundary conditions, etc., have yet to be included in many of the codes. As the simulations become more complete, they will be valuable for improving the analytical models that could enable reliable predictions of long-term behavior. However, there is still a significant amount of work needed in order to fully benchmark the simulation codes against observations in existing machines.

7. TOWARDS A PREDICTIVE THEORY

Input parameters are important but not always well known and also vary in time. An example is the change of the secondary emission yield as a function of dose deposited by beam scrubbing. We are still some distance away from a truly self-consistent model.

Observations are often difficult to interpret. An example is the instability threshold seen in DAFNE, which may or may not be related to electron cloud (although, given the striking difference in the behavior of positron and electron beam, and the similarities with observations at other storage rings, it seems likely to have some contribution from electron-cloud).

An impressive agreement between simulations and measurements has been achieved in reproducing the observed multi-bunch mode patterns at KEKB, which in turn has provided new insight into the actual distribution of electrons inside the chamber. Many more data are already available, which still need to be fully analyzed and understood, for example, from APS, PSR, PS, and SPS. The analytical models appear in relatively good shape, if linearity and superposition are approximately fulfilled.

Feedback systems have not yet been fully exploited in diagnosing and curing electron-cloud effects, though they would provide a powerful tool. Beam-transfer function measurements could also prove important; a promising first result from the PSR was presented at the workshop by R. Macek. The cloud distribution is a key ingredient, and novel local electron diagnostics may be needed to determine this distribution with sufficient accuracy.

For single bunch effects, it is possible to measure emittance growth, tune shifts, and sometimes even the head-tail modes. This has been demonstrated at KEKB and SPS, where a satisfactory agreement was achieved almost immediately between simulations and measurements, and results could be cross-checked with independent measurements of tune shifts along a bunch train, and of the local electron flux at the wall. Analytical treatments based on perturbation theories may provide reasonable estimates of instability thresholds, but cannot predict the detailed dynamics above the threshold. In particular, for large electron densities, the simulations push parameters (for example, the number of interaction points per turn, the number of bunch slices, etc.) and are computationally expensive: QuickPIC needs about a month of computing time to model a few thousand turns in the LHC.

A number of comments were made in or during the presentations and the successive discussion. R. Macek presented an erratum to a previously published centroid theory of transverse electron-proton oscillations in a long proton bunch [23]; the correction increases the frequency spread required for stability by a factor 2 compared with the result in [23]. S. Heifets pointed out that all sources of tune spread need to be included, which may help with the convergence of the simulations. He raised the question at which small number of kicks an anomalous chaotic behavior may occur, like the one studied many years ago by B. Chirikov. S. Heifets also asked if we know whether existing preventive measures like solenoid fields will be effective in higher-current B factories. A fundamental question is whether we should spend a lot of time simulating future machines before we understand the existing ones. This question seems to reflect a generic dilemma, not limited to the electron-cloud effects.

To make further progress in the electron instability simulations, a number of steps can be envisioned, as outlined by T. Katsouleas. In the simulation codes, various additional effects should be included (if not already done), such as the real magnetic field profile around the ring, the variation of the beta functions, the beam-pipe impedance, and the boundary conditions. Since some of the simulations take a prohibitive amount of time, it would be advantageous to develop 'useful' reduced models, which could foster the ability to make fast simulations of long-term behavior, for example, by using parameters found in a more detailed simulation over a few turns. Several promising ideas were discussed how one might accomplish this, but clearly more studies are needed. Scaling laws could play a vital role for accessing the long time scales. Examples are the scaling of instability behavior with the ratio of density over synchrotron tune presented by Ohmi, and the idea to apply many kicks per turn distributed over a single synchrotron period, which, possibly, was first proposed by A. Chao. One aim of these improvements is to reliably simulate the LHC behavior; first, over a few thousand turns, and ultimately, over 30 minutes.

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