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Damping Ring Design and Physics Issues

Lecture 9
Electron Cloud and Ion Effects

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An International Centre for Research in
Accelerator Science and Technology

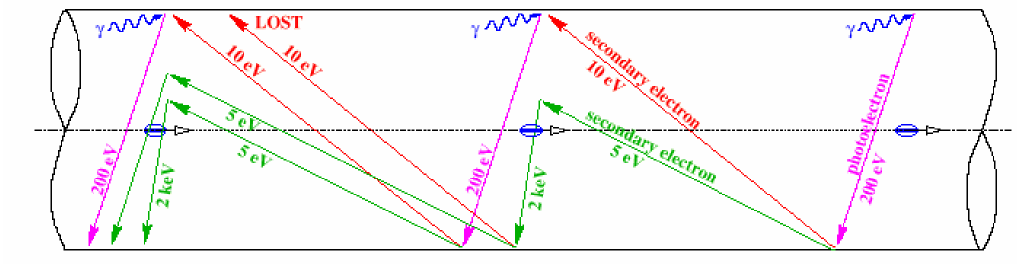
Electron cloud and ion effects

In this lecture, we shall discuss:

- Electron cloud effects
- Techniques for suppressing electron cloud
- Ion effects

Electron cloud effects

In a positron (or proton) storage ring, electrons are generated by a variety of processes, and can be accelerated by the beam to hit the vacuum chamber with sufficient energy to generate multiple "secondary" electrons.



Under the right conditions, the density of electrons in the chamber can reach high levels, and can drive instabilities in the beam.

Important parameters determining the electron cloud density include:

- the bunch charge and bunch spacing;
- the geometry of the vacuum chamber;
- the properties of the vacuum chamber surface (the "secondary electron yield").

The secondary electron yield (SEY) of a surface is a key parameter

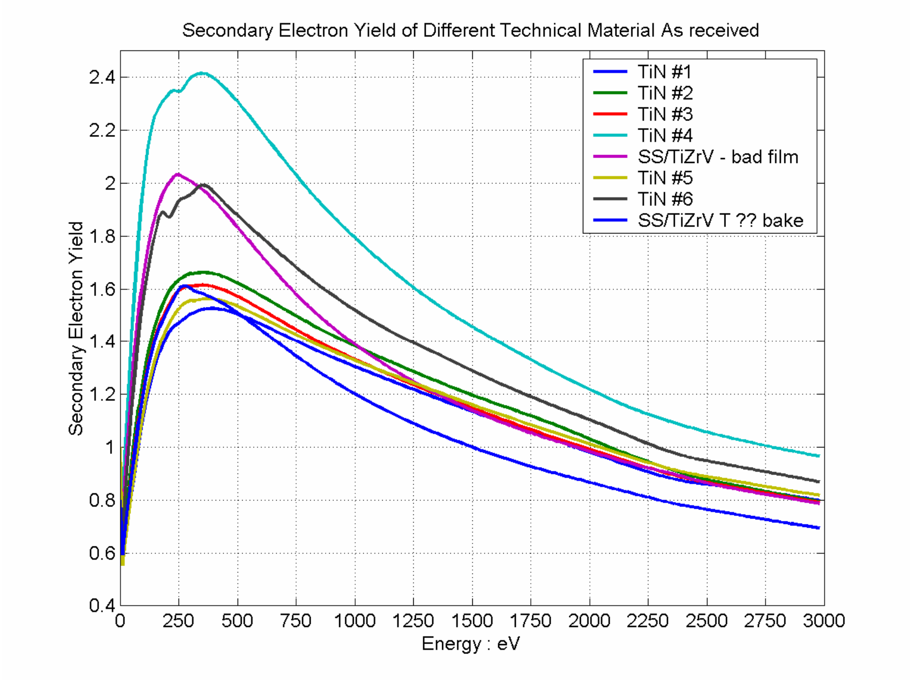
The secondary electron yield specifies the number of electrons emitted from a surface per primary incident electron.

The number of secondary electrons emitted in any particular event depends on the energy and angle of incidence of the primary electron, as well as the properties of the surface.

Surfaces of nominally the same material can show very different properties, depending on the history of the material.

For convenience, we often quote a single number for the SEY, which gives the maximum number of electrons emitted per incident electron under any conditions.

SEY as a function of primary electron energy (normal incidence)



From Bob Kirby and Frederic le Pimpec.

Determining the density of the electron cloud in an accelerator

The development of an electron cloud in an accelerator environment is a complicated process, depending on details of the beam distribution and on the chamber geometry and surface properties.

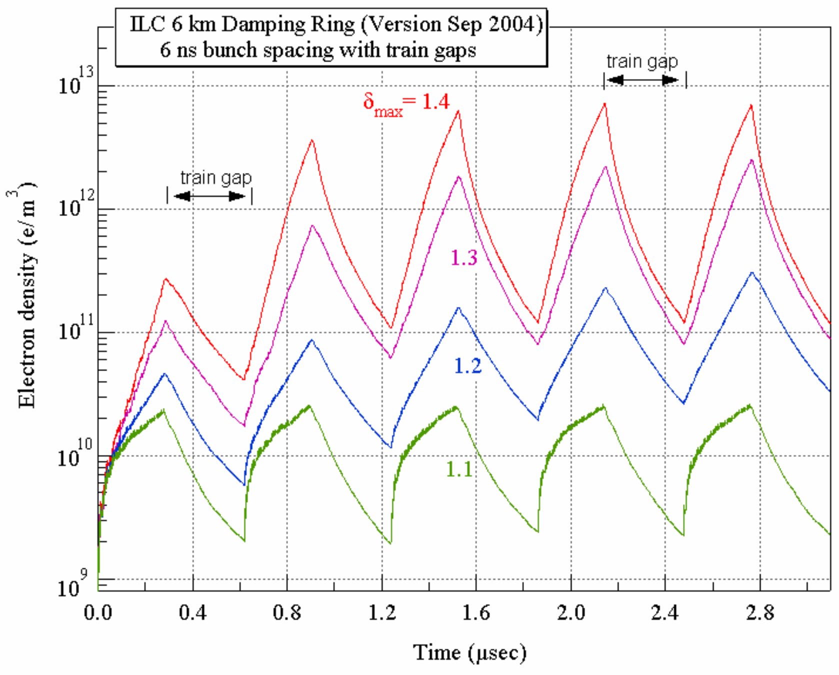
Significant effort has been devoted to developing accurate computer simulations of the build-up process, which allow specification of:

- beam charge and time structure;
- chamber geometry (including antechamber);
- chamber surface properties;
- various sources of electrons (including secondary emission, photoelectrons, gas ionisation);
- properties of secondary electrons (energy and angular distribution);
- external electromagnetic fields.

Codes are available that make detailed simulations of the electron-cloud build-up and dynamics, including such effects as the space-charge of the cloud itself.

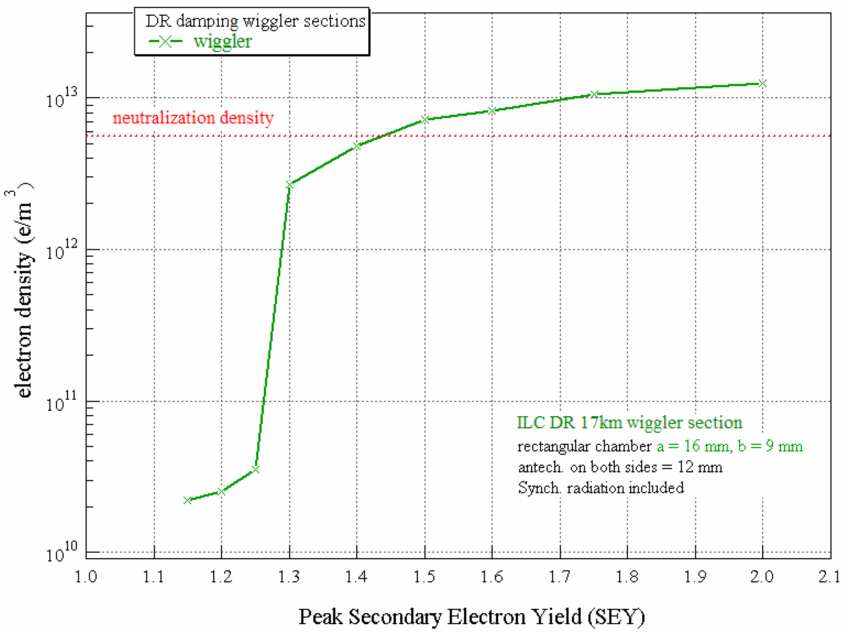
The output of the simulation codes includes the density distribution of the cloud in the vacuum chamber, and its time evolution.

Determining the density of the electron cloud in an accelerator



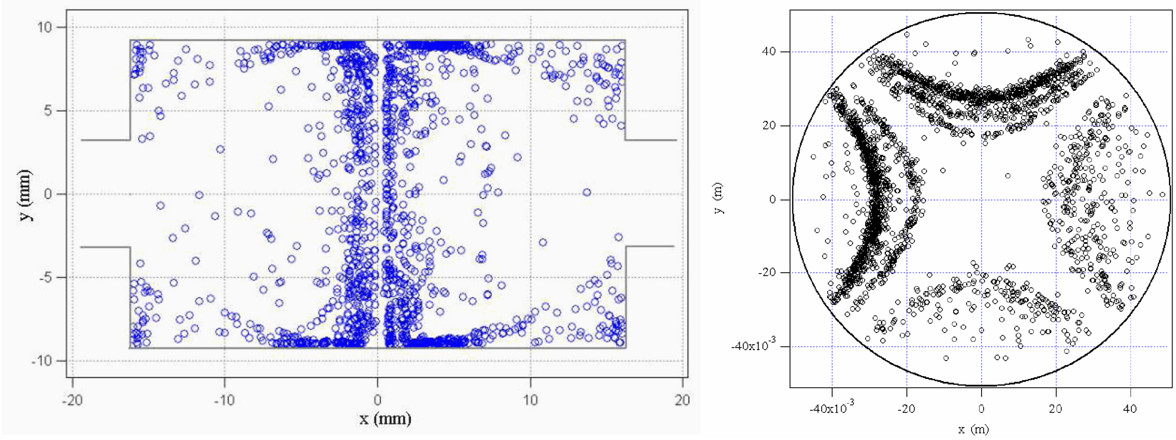
Posinst simulation of average electron cloud density in a drift space in a 6 km design for the ILC positron damping ring, by Mauro Pivi.

The electron cloud density can reach the neutralisation density



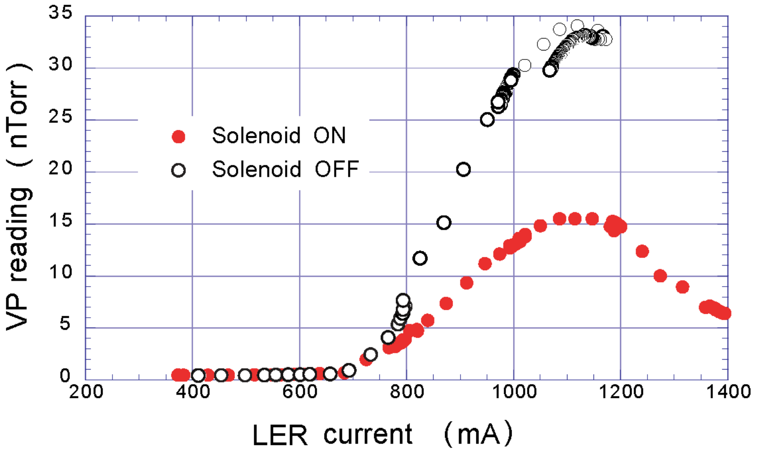
The neutralisation density is the point where there are as many electrons inside the vacuum chamber as there are positrons.

External magnetic fields can "trap" low-energy electrons



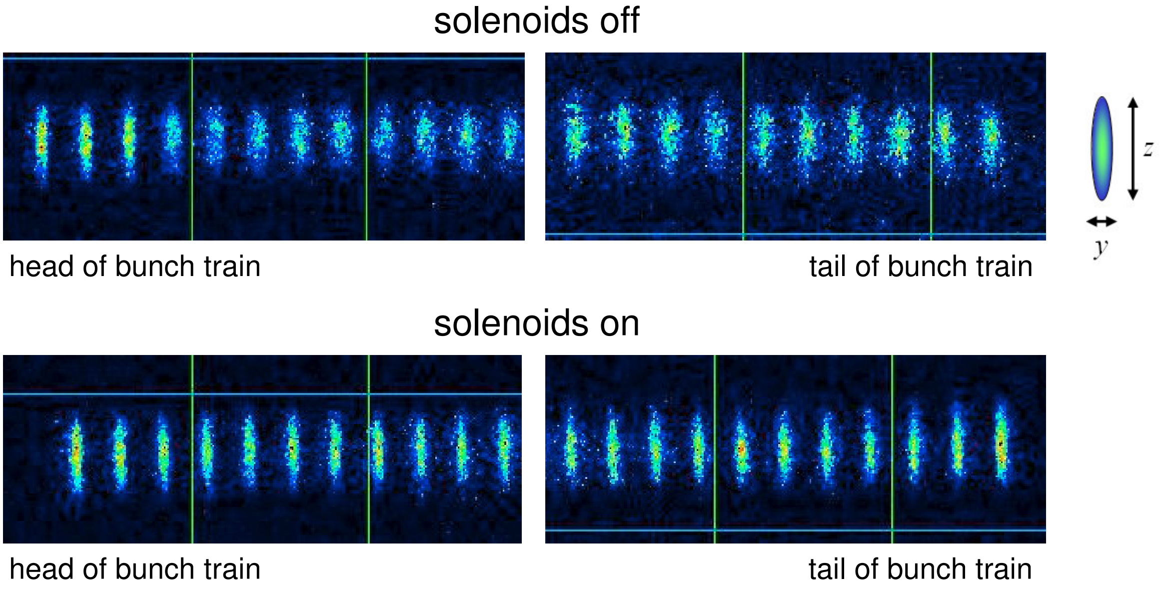
Simulations of electron cloud in the wiggler of the TESLA damping ring (left), and in a quadrupole in the PSR (right), by Mauro Pivi.

Observations of electron cloud: increase in residual gas pressure



Observations of pressure rise in the PEP II LER.
A. Kuliokov et al, Proceedings of PAC01.

Observations of electron cloud: increase in beam size



solenoids off

head of bunch train

tail of bunch train

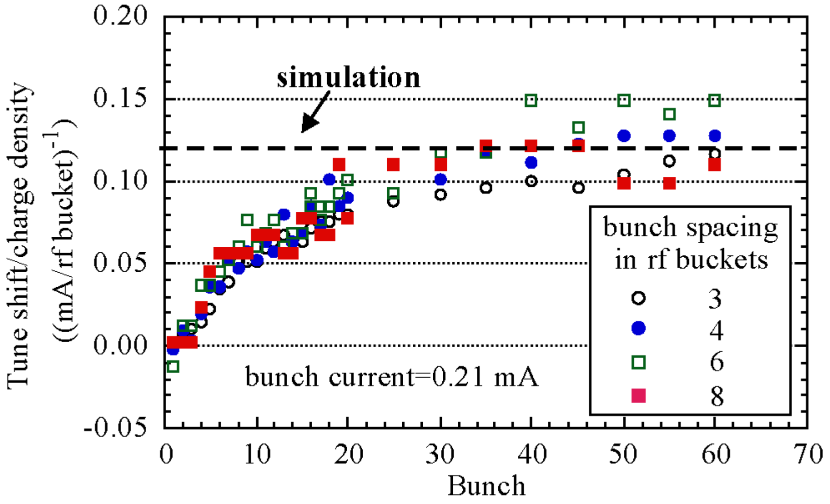
solenoids on

head of bunch train

tail of bunch train

Observations of beam-size increase in KEKB.
H. Fukuma, Proceedings of ECLOUD04.

Observations of electron cloud: tune shifts



Measurements of vertical tune shift as a function of bunch number in a bunch train in KEKB.
H. Fukuma, Proceedings of ECLOUD02.

Simulations and predictions of electron cloud effects

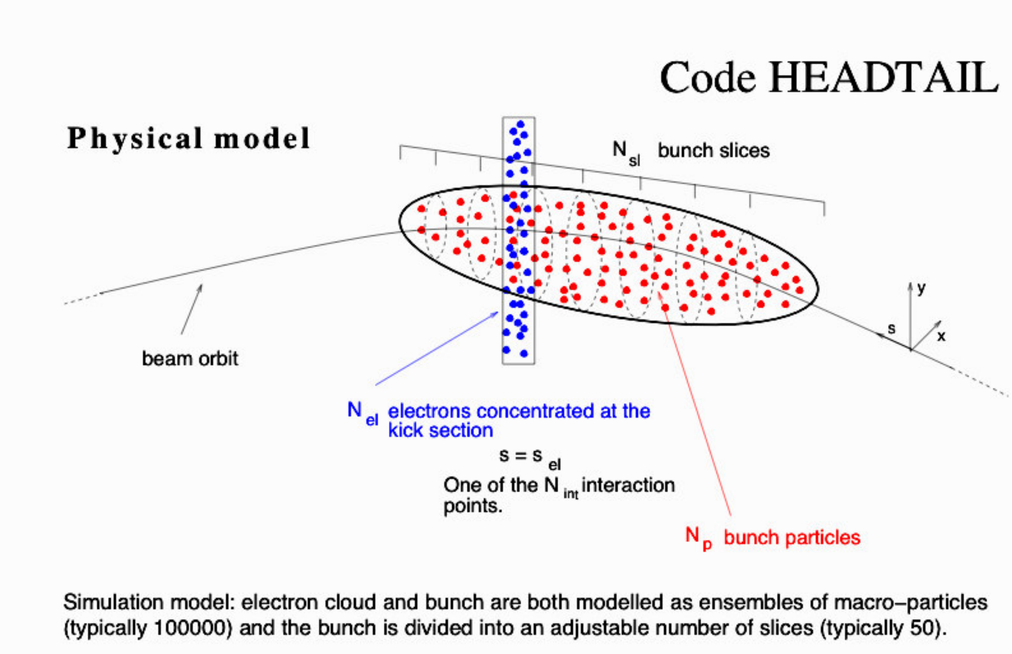
The interaction between the beam and any electrons in the chamber is complicated. Ideally, we would use a fully self-consistent model, in which we solve simultaneously the equations of motion of the beam in the cloud, and the equations of motion of the cloud in the beam, and include also the build-up of the cloud.

Self-consistent simulations tend to be computationally very expensive. Nonetheless, several codes have been developed, generally using some simplifications; for example, considering a reduced number of degrees of freedom for particles in the beam.

The instability simulations generally use a fixed cloud density, which is determined from a separate simulation of the cloud build-up.

The goal of the instability simulations is to find the cloud density at which beam instability starts to occur.

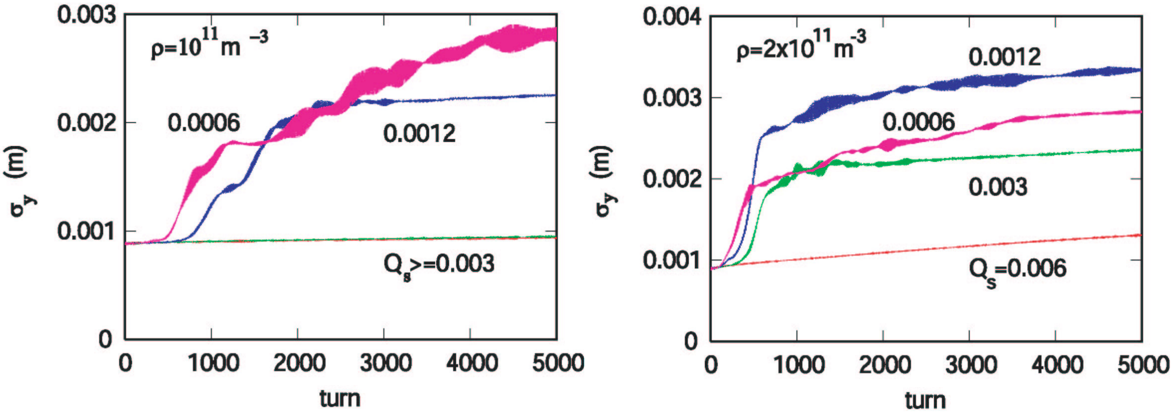
Simulations and predictions of electron cloud effects



Simulation model: electron cloud and bunch are both modelled as ensembles of macro–particles (typically 100000) and the bunch is divided into an adjustable number of slices (typically 50).

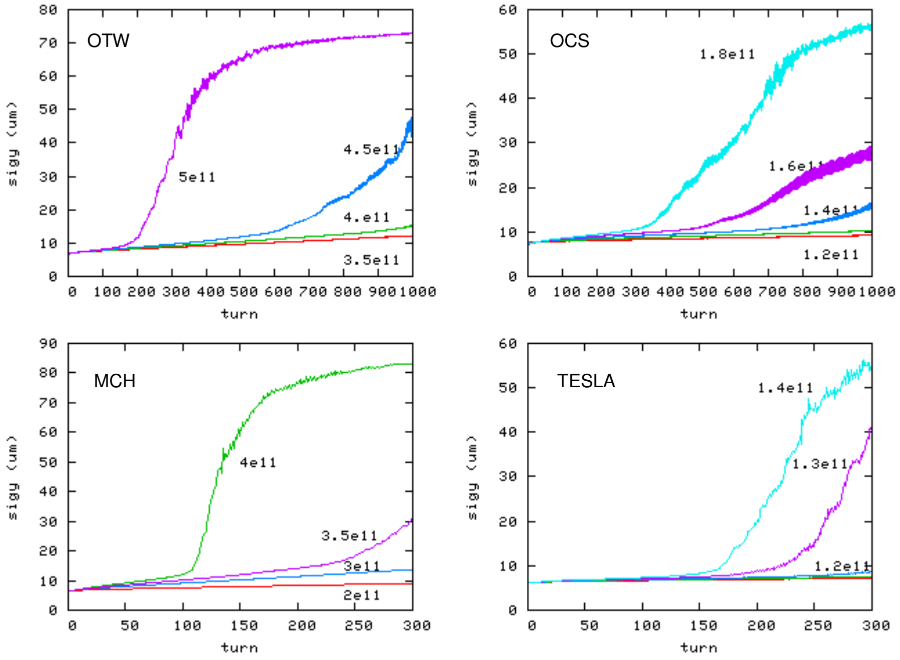
Example of a model used in an electron cloud instability simulation code: HEADTAIL by Giovanni Rumolo.

Simulations and predictions of electron cloud effects



Simulation of evolution of vertical beam size in the LHC, showing dependence on electron cloud density and the synchrotron tune. Simulation by Kazuhito Ohmi, using PEHTS.
(E. Benedetto et al, Proceedings of PAC03).

Simulations and predictions of electron cloud effects

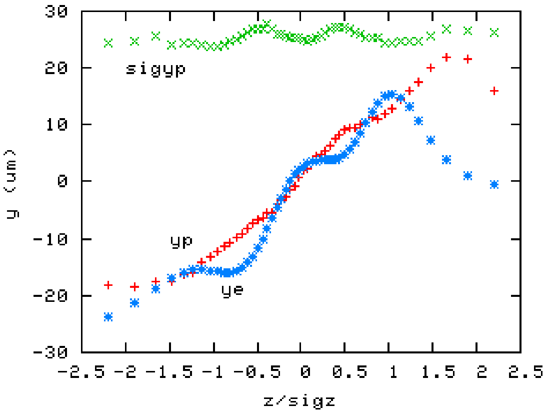


Simulations of electron cloud build-up in different designs for the ILC damping rings. (Kazuhito Ohmi).

Simulations and predictions of electron cloud effects

Simulation results can guide us in developing analytical models of the dynamical effects of electron cloud.

There are two important effects that must be included in any model. The first is that the electron cloud responds to variations in the transverse position of the centroid in a bunch. This suggests that it may be possible to model the effect of the electron cloud as a transverse wake field.

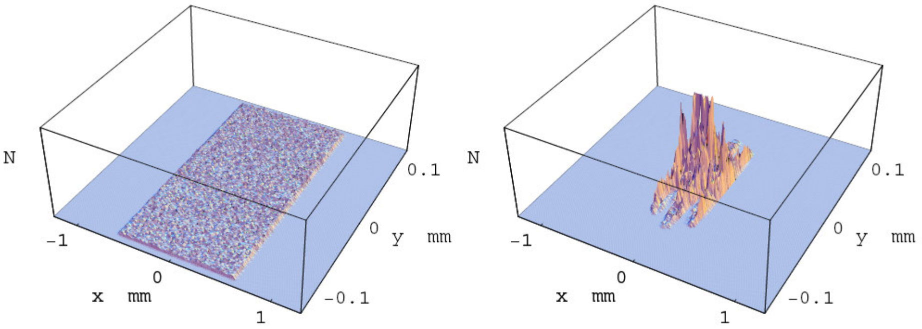


Positron transverse beam size (green), positron beam centroid (red) and electron cloud centroid (blue) as functions of longitudinal position in a bunch.

Simulations and predictions of electron cloud effects

The second important effect to include in models of electron cloud is the "focusing" effect of the beam. As a bunch passes through the cloud, the density distribution of the cloud changes, and peaks sharply at the location of the bunch.

The significant cloud density for calculating the instability threshold is not the average density of the cloud across the vacuum chamber (which is often quoted from the build-up simulations), but the peak density at the position of the bunch.



Electron cloud density as a function of transverse position in a section of vacuum chamber before (left) and during (right) a bunch passage.

Estimating the instability threshold

Let us consider a simple analytical model of the electron cloud instability, in which the effect of the electron cloud is represented by a transverse wake field.

Our goal is not to derive an accurate and reliable formula; but rather to see how well a formula based on a resonator wake field model for the electron cloud describes the instability.

We expect the electrons in the cloud to perform transverse oscillations around the beam, so the wake field corresponds to that of a low-Q resonator. We can estimate the characteristic frequency ω_e of the "resonator" from a linear model of the field around the positron bunch. Assuming that the electrons have negligible longitudinal velocity, only the electric field is significant.

The characteristic frequency is then:

$$\omega_e^2 = \frac{e}{m}\frac{\partial E_y}{\partial y} = \frac{2r_e c^2 \lambda_p}{\sigma_y\left(\sigma_x + \sigma_y\right)}$$

where λ_p is the longitudinal density of positrons in the bunch (positrons per meter).

Estimating the instability threshold

For the ILC damping ring parameters, the oscillation frequency is large compared to the length of a bunch; i.e. a typical electron completes many transverse oscillations in the time taken for the bunch to pass. This suggests we should treat any instability as a "transverse microwave" instability rather than TMCI.

The impedance threshold can be written as:

$$\left|\frac{cZ_\perp}{\omega}\right|_{\max} = Z_0 \frac{\gamma \alpha_p \sigma_z \sigma_\delta \nu_y}{r_e N_0}$$

We assume that the impedance of the electron cloud can be estimated from:

$$\left|\frac{cZ_\perp}{\omega}\right| \approx \frac{Z_0 c}{4\pi}\frac{r_e C}{\omega_e}\bar{\rho}_e \frac{b^2}{\sigma_x \sigma_y}$$

where $\bar{\rho}_e$ is the average electron cloud density in the chamber, of radius b, and the factor $b^2/\sigma_x\sigma_y$ accounts for the increase in cloud density at the location of the bunch during the bunch passage.

Estimating the instability threshold

Combining the expressions for the instability impedance threshold and the electron cloud impedance, we find an estimate for the average cloud density at which we expect to see an instability:

$$\bar{\rho}_e = \frac{2}{r_e^2} \frac{\gamma \alpha_p \sigma_\delta}{N_0 \langle \beta_y \rangle} \frac{\sigma_x \sigma_y}{b^2} \frac{\omega_e \sigma_z}{c}$$

Applying this formula (with parameters consistent with those used in the simulations) and comparing with the simulation results, we find that the threshold density predicted by this model is roughly a factor of two below that expected from simulations:

	Threshold density from simulation	Threshold density from formula
OTW	4.0×10^{11} m^{-3}	1.1×10^{11} m^{-3}
OCS	1.4×10^{11} m^{-3}	0.67×10^{11} m^{-3}
MCH	3.0×10^{11} m^{-3}	1.7×10^{11} m^{-3}
TESLA	1.2×10^{11} m^{-3}	0.67×10^{11} m^{-3}

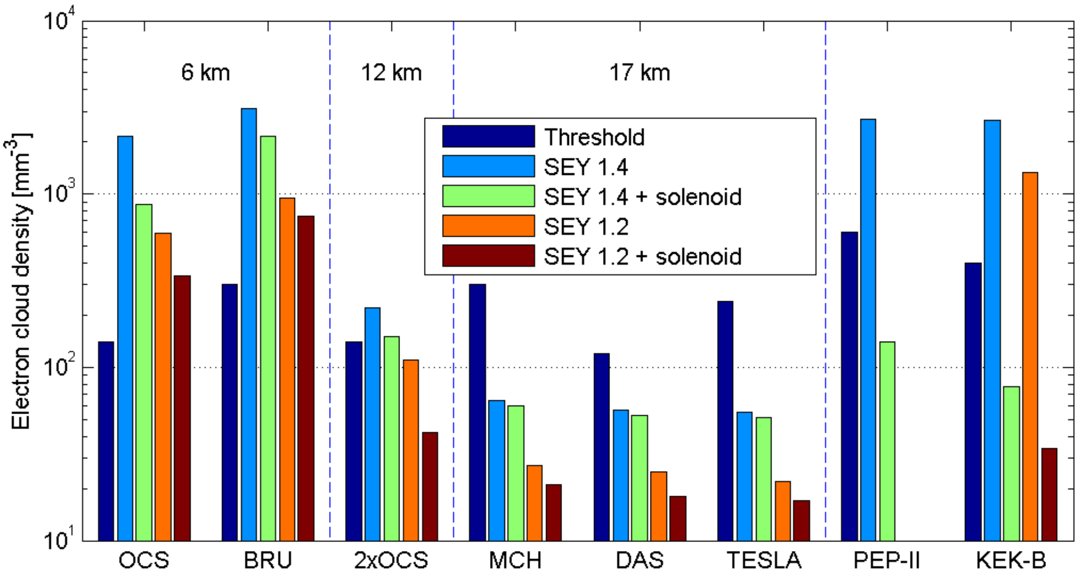
Estimating the instability threshold

More careful models to estimate the threshold of electron-cloud instability have been developed. See for example:

K. Ohmi, F. Zimmermann and E. Perevedentsev, Phys. Rev. E 65, 16502 (2002).

The electron cloud can also drive coupled-bunch instabilities. However, we expect that in the parameter regime of the damping rings, single-bunch instabilities will be the primary limitation.

Predictions of electron cloud in the ILC damping rings



Summary of electron cloud instability thresholds and equilibrium density levels in different lattices proposed for the ILC damping rings. LBNL-59449 (2006).

Suppressing the build-up of electron cloud

Electron cloud could limit the operational performance of the damping rings.

Without implementing some measures to suppress the build-up of electron cloud, we expect that the cloud density will approach the neutralisation density, and that beam instabilities will occur.

There are a number of techniques that can be used to suppress the build-up of electron cloud in an accelerator.

- Adjusting the beam parameters.

  Higher energy, lower current, larger momentum compaction all help to reduce the rate of build-up of electron cloud or mitigate its impact on the beam. Actions in this category may be difficult to implement after construction.

- Treating or conditioning the vacuum chamber surface.

  The chamber surface can be coated with a material having low SEY.

  Grooves can be cut into the chamber surface.

- Applying external fields.

  Solenoids trap electrons near the wall of the vacuum chamber.

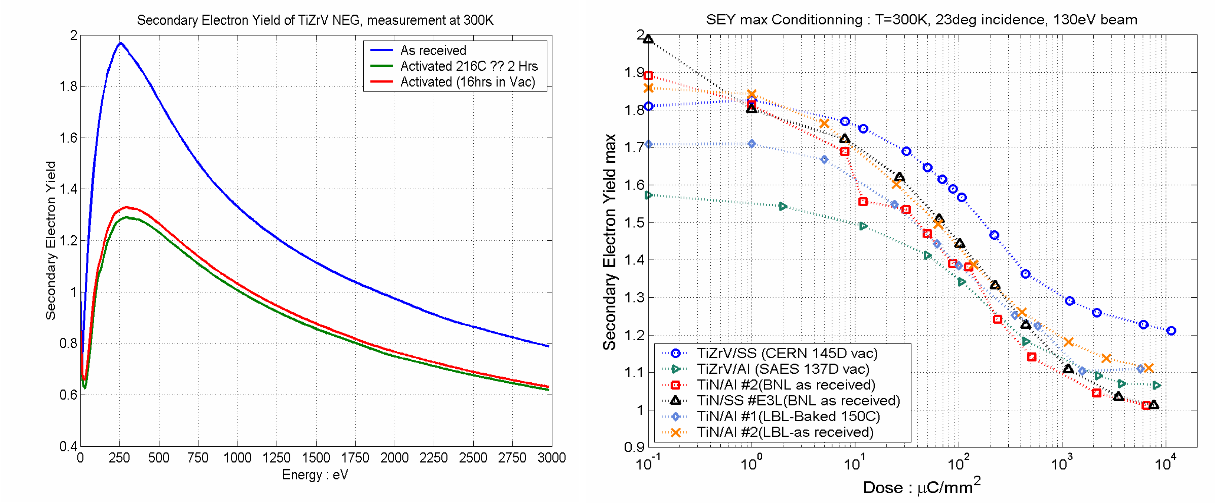
  Clearing electrodes can similarly prevent build-up of electron cloud in the vicinity of the beam.

Suppressing electron cloud with low-SEY coatings

Coatings that have been investigated include TiN and TiZrV.

Achieving a peak SEY below 1.2 seems possible after *conditioning*.

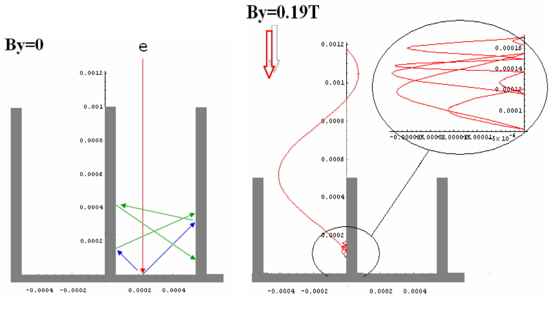
Reliability/reproducibility and durability are concerns.

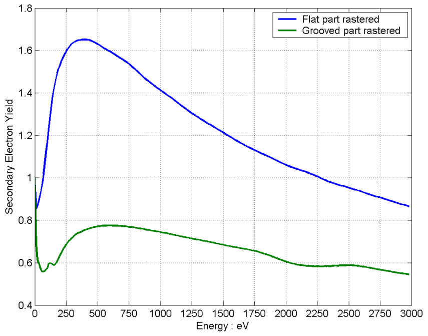


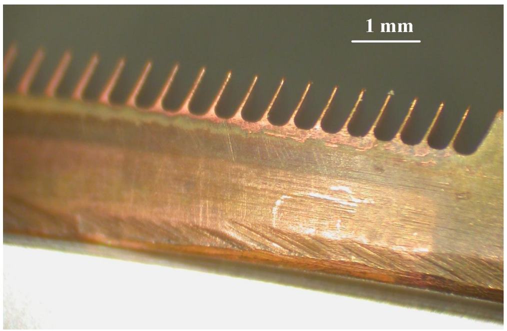
Measurements of SEY of TiZrV (NEG) coating. (F. le Pimpec, M. Pivi, R. Kirby)

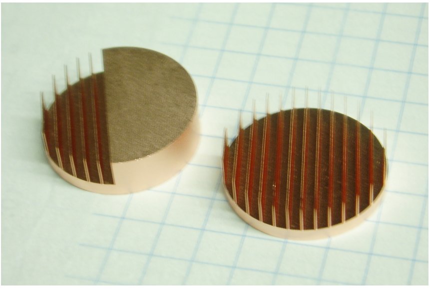
Suppressing electron cloud with a grooved vacuum chamber

Electrons entering the grooves release secondaries which are reabsorbed at low energy (and hence without releasing further secondaries) before they can be accelerated in the vicinity of the beam.



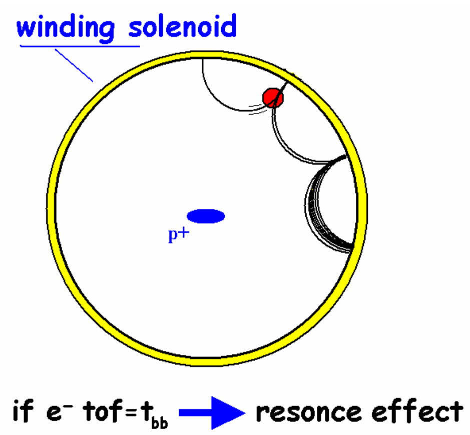


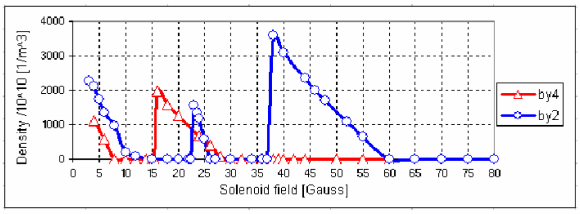




Suppressing electron cloud with solenoids

A solenoid field keeps secondary electrons close to the wall, where they can be re-absorbed without gaining enough energy to release further secondaries. However, there is evidence for a "resonance" effect, which occurs when the field strength leads to a time of flight for the electrons equal to the bunch spacing.



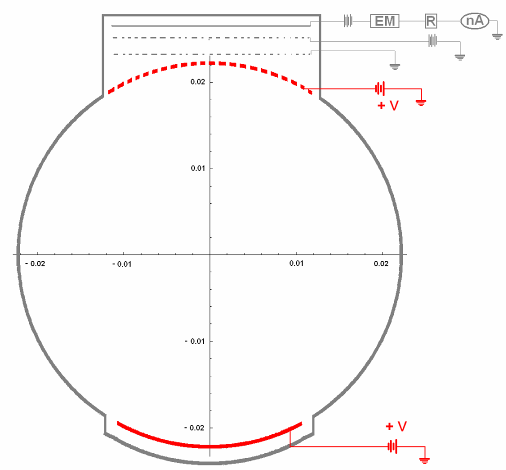


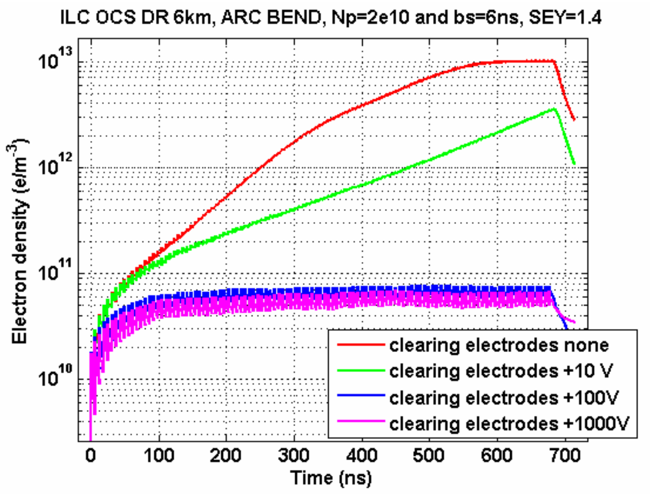
e$^-$ density at by-2 and 4 RF buckets spacing in PEP II LER.
A. Novokhatski and J. Seeman (PAC03)

e$^-$ density at by-2 RF buckets spacing in PEP II LER.
Y. Cai and M. Pivi (PAC03)

Suppressing electron cloud with clearing electrodes

Low-energy secondary electrons emitted from the electrode surface are prevented from reaching the beam by the electric field at the surface of the electrode. This also appears to be an effective technique for suppressing build-up of electron cloud.





Ion effects

While electron cloud effects are a concern for the positron rings, ion effects are a concern for the electron rings.

In electron storage rings, residual gas molecules can be ionised by the beam. The resulting positive ions may then be trapped in the electric field of the beam, and accumulate to high density. The fields of the ions can then drive beam instabilities.

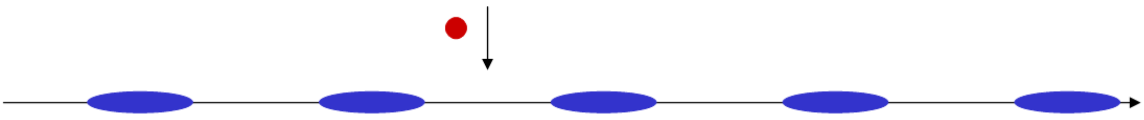
The differences between electron cloud and ion effects arise principally from the difference in mass between electrons and ions. While electrons move rapidly on the time scale of a single bunch passage, ions move relatively slowly. The dynamical behaviour is then somewhat different.

If a storage ring is uniformly filled with electron bunches, then ions accumulate over many turns. This leads to the well-known phenomenon of ion trapping, which is usually solved by including one or more "gaps" in the fill pattern.

However, under certain conditions, sufficient ions can accumulate in the passage of a small number of bunches to drive an instability, known in this case as the "fast ion instability".

Ion trapping

Consider an ion of relative molecular mass A moving in the electric fields of a sequence of electron bunches:

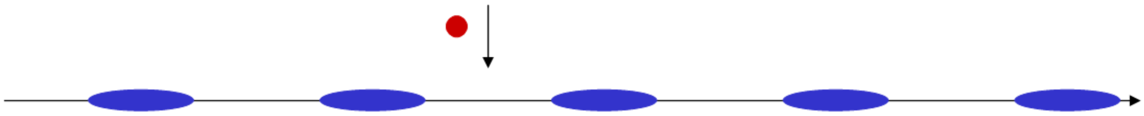


Making a linear approximation to the electric field around a bunch, the force on the ion as the bunch goes past can be represented by a focusing force k:

$$k = \frac{r_p N_0}{A\sigma_y(\sigma_x + \sigma_y)}$$

where r_p is the classical radius of the proton, N_0 is the number of electrons in a bunch, and σ_x and σ_y are the rms bunch sizes.

Ion trapping



The motion of the ion over a period represented by one bunch and the following gap before the next bunch arrives, can be represented by a transfer matrix:

$$\begin{pmatrix} 1 & s_b \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -k & 1 \end{pmatrix} = \begin{pmatrix} 1 - s_b k & sb \\ -k & 1 \end{pmatrix}$$

As we know from linear beam dynamics, the motion is only stable if the absolute value of the trace of the periodic transfer matrix is less than 2. Hence, for the motion of the ion to be stable, we require:

$$s_b k < 2$$

which means that:

$$A > \frac{r_p N_0 s_b}{2\sigma_y (\sigma_x + \sigma_y)}$$

Ion trapping

The ion trapping condition is:

$$A > \frac{r_p N_0 s_b}{2\sigma_y (\sigma_x + \sigma_y)}$$

This tells us that for large bunch charges, or bunches with very small transverse dimensions, only very heavy ions will be trapped.

In the damping rings, the beam sizes are large at injection, and all ions can be trapped. But during damping, the beam sizes decrease and the minimum mass of trapped ions steadily increases.

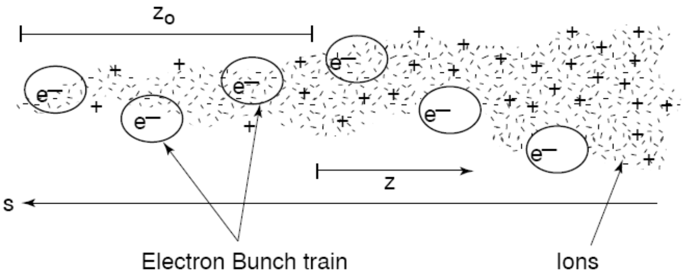
We can compare the minimum mass of trapped ions at injection and at equilibrium, assuming normalised injected emittances of 45 μm:

	Injection	Equilibrium
N_0	2×10^{10}	2×10^{10}
s_b	1.8 m	1.8 m
σ_x	600 μm	250 μm
σ_y	300 μm	6 μm
A_{min}	0.10	18

Fast ion instability

We can prevent multi-turn ion trapping by including gaps in the fill, i.e. by periodically having a very large separation between two bunches (ten or twenty times larger than normal).

However, ions accumulating during the passage of a small number of bunches can still drive instabilities.



The theory of "fast ion instability" has been developed by Raubenheimer and Zimmermann:

T. Raubenheimer and F. Zimmermann, Phys. Rev. E **52**, 5, 5487 (1995).

Fast ion instability

The fast ion instability can be treated as a coupled-bunch instability, with a growth rate $1/\tau_e$ given by:

$$\frac{1}{\tau_e} \approx \frac{1}{3}\sqrt{\frac{2}{3}}\frac{c}{\Delta\omega_i/\omega_i}\beta_y k_y$$

where k_y is the focusing force on the beam from the ions, β_y is the beta function, and $\Delta\omega_i/\omega_i$ is the relative spread of oscillation frequencies of ions in the beam. Normally, we can assume that:

$$\Delta\omega_i/\omega_i \approx 0.3$$

The focusing force of ions on the beam is given by:

$$k_y = \frac{\lambda_i r_e}{\gamma\sigma_y\left(\sigma_x + \sigma_y\right)}$$

where we assume that the transverse distribution of the ions is comparable to that of the particles in the beam, and the longitudinal ion density is:

$$\lambda_i = \sigma_i \frac{p}{kT} N_0 n_b$$

The longitudinal ion density depends on the ionisation cross section σ_i, on the residual gas pressure p, on the number of particles in each electron bunch N_0 and on the number of bunches n_b that have passed.

Observation of fast ion instability in the LBNL-ALS

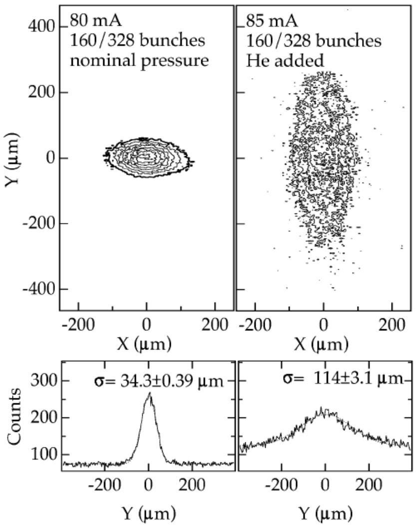


FIG. 1. Transverse profile images (shown as contour plots) of the beam for nominal pressure and with He added; the vertical profile for each image is also shown, along with a fit to a Gaussian distribution.

J. Byrd et al, "First observations of a fast beam-ion instability", Phys. Rev. Lett. **79**, 79-82 (1997).

Observation of fast ion instability in the LBNL-ALS

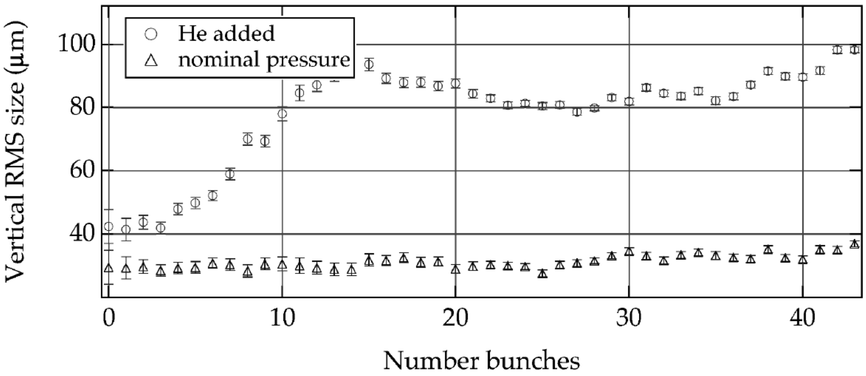
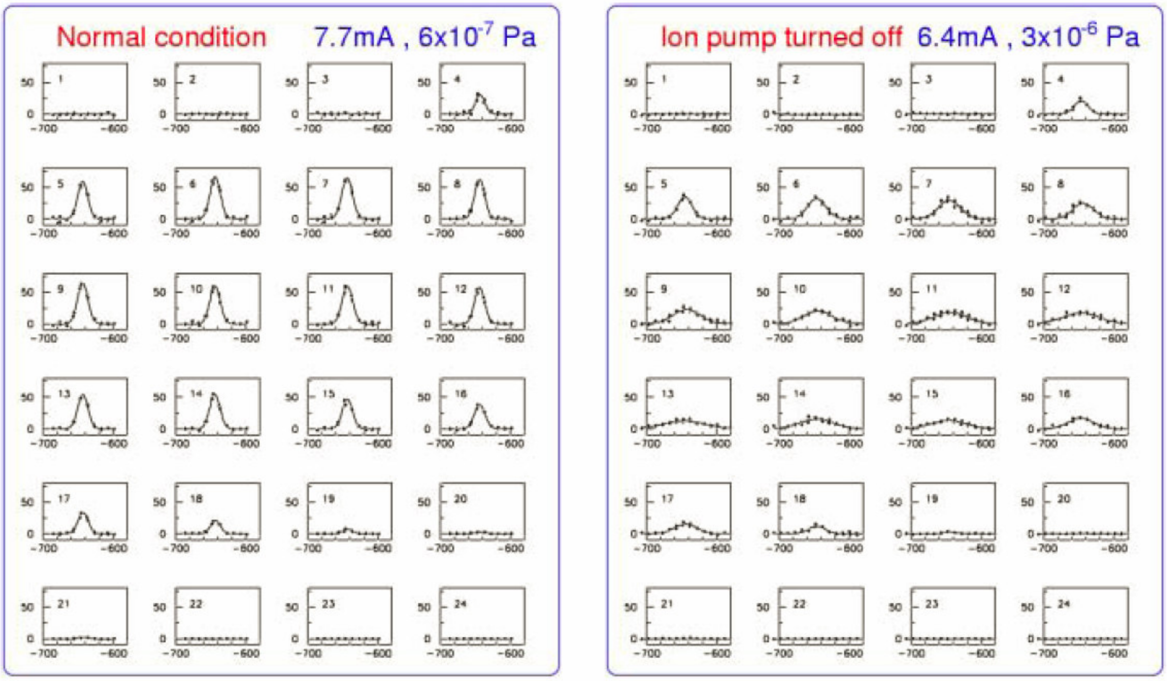


FIG. 2. rms vertical beam size vs the number of bunches for nominal and elevated pressure conditions.

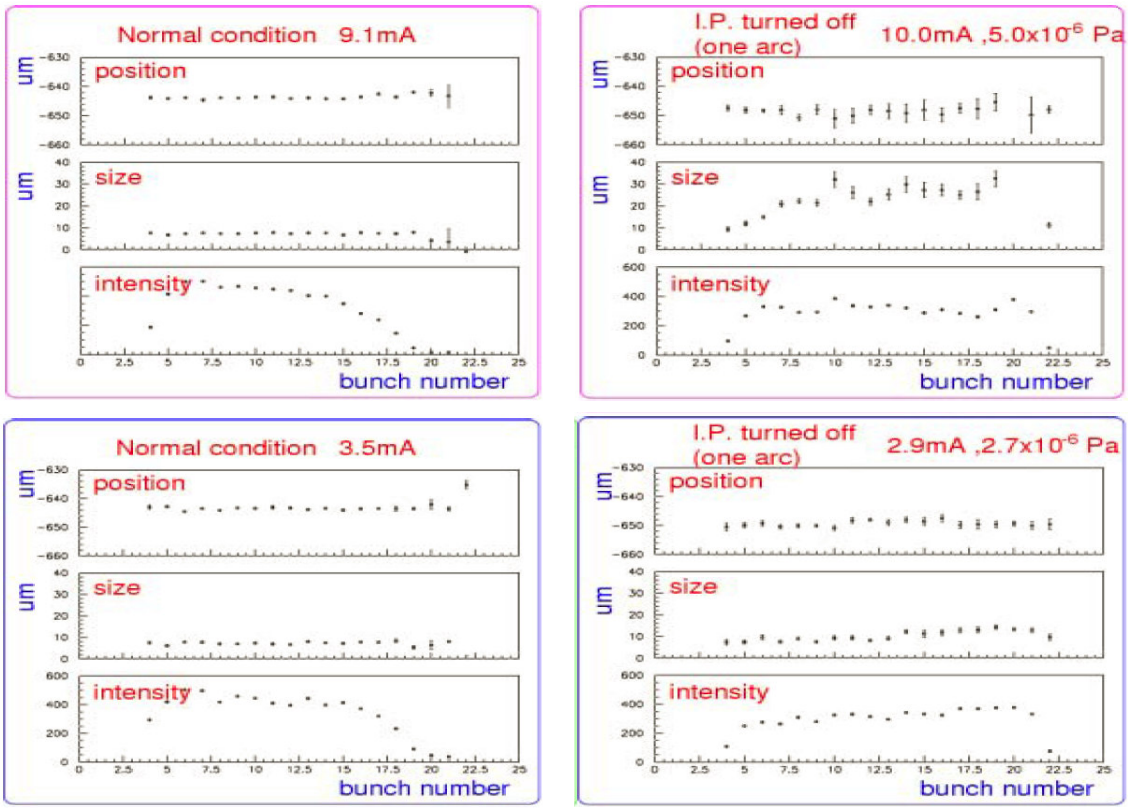
J. Byrd et al, "First observations of a fast beam-ion instability", Phys. Rev. Lett. **79**, 79-82 (1997).

Measurements of fast ion instability in KEK-ATF



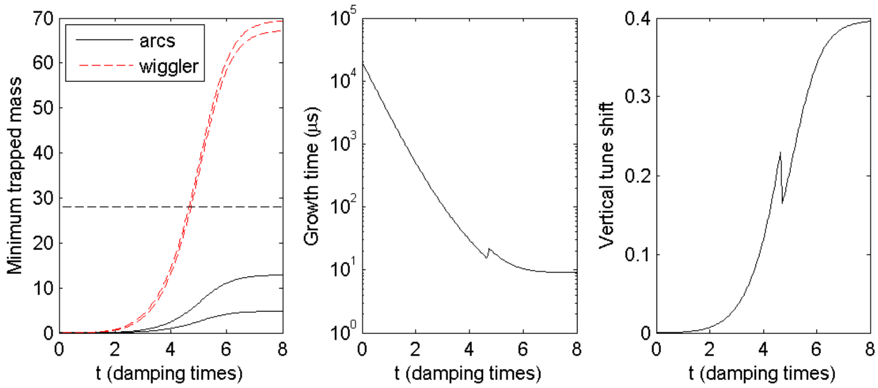
Bunch profile measurements made using laser wire in ATF damping ring, by Yosuke Honda (presented at ISG XI, KEK, 2003).

Measurements of fast ion instability in KEK-ATF



Fast ion instability in the ILC damping rings

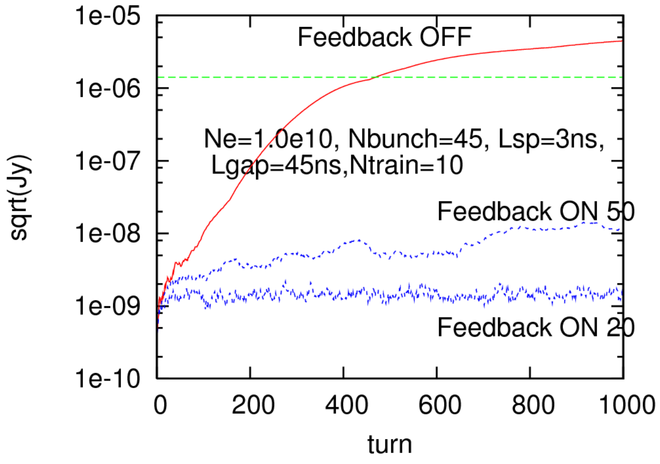
The fast ion instability is expected to be a significant effect in the ILC damping rings.



Calculations of ion growth times and tune shift in the OCS lattice (6 km) for the ILC damping rings. Note that one revolution period is 20 μs. The growth times and tune shifts are calculated assuming an average pressure of 2 ntorr of CO in the wiggler, and 0.5 ntorr of CO in the arcs.

Fast ion instability in the ILC damping rings

Simulations suggest that the growth rates might be somewhat slower than suggested by the analytical formulae. Also, there is some evidence that the effects of the ions are mitigated by decoherence of the ions, and that the effect may saturate at low levels.



Simulation of fast ion instability in a recent 6.7 km lattice for the ILC damping rings, by Kazuhito Ohmi.

Studies are ongoing to develop a reliable model for the ion effects in the damping rings. At present, it is regarded as prudent to specify the vacuum system to achieve quite demanding residual gas pressures.

Summary of electron cloud and ion effects

Electron cloud is one of the main concerns for the ILC damping rings. Studies suggest that without taking preventative measures, electron cloud in the positron damping ring could reach densities (close to the neutralisation density) sufficient to drive instabilities in the positron beam.

Some simple analytical models can be used to describe the dynamics of a positron beam with electron cloud; but more reliable estimates can be obtained using simulation codes.

A variety of methods for suppressing the build-up of electron cloud are available, and some look promising for the ILC damping rings. Research and development are ongoing to develop a sufficiently effective means of suppressing build-up of electron cloud in the damping rings.

Ion effects are a concern for the electron damping ring. Instability growth rates for the fast ion instability appear fast when estimated from simple analytical formulae. However, more detailed simulations suggest that the effects may be less severe, and could be mitigated using bunch-by-bunch feedback systems.

Studies of ion effects are continuing.