Damping Rings and Ring Colliders

Damping Ring Beam dynamics

S. Guiducci, INFN-LNF

Seventh International Accelerator School for Linear Colliders

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Outline

- A3.1 - DR Basics: Introduction to Damping Rings
- A3.2 - DR Basics: General Linear Beam Dynamics
- A3.3 - LER Design: Radiation Damping and Equilibrium Emittance
- A3.4 - LER Design: Damping Ring Lattices
- A3.5 – DR Technical systems
- A3.6 – Beam Dynamics
  - Overview of Beam Impedance and Classical Instabilities
  - Critical Beam Dynamics Issues
    - Fast Ion Instability
    - Electron Cloud
- A3.7 – R&D Challenges and Test Facilities
- A3.8 – Circular Colliders

These slides have been presented at the 2010 LC school by Mark Palmer

Outline of DR Lecture – Part 4

Beam Dynamics Issues

- Brief Overview of Beam Impedance and Classical Instabilities
- Critical Beam Dynamics Issues
  - Fast Ion Instability
  - Electron Cloud
- ILC R&D Program
  - Dedicated Test Facilities
    - ATF
    - CESRTA
  - Other R&D Efforts
- Summary of R&D Challenges

Conclusion

ILC DR Impedance and Instability Issues

I will approach this lecture primarily from the point of view of the ILC Damping Rings.

The ILC damping rings will operate in a parameter regime that has not yet been explored by any operating machine. For the remainder of this lecture we will explore (*briefly*) several of the key physics issues that will determine how well the damping rings, and hence how well the ILC, will perform.

There are a number of effects that are important for the DR design. Existing machines have demonstrated the need to carefully control the impedance in machine components to minimize the impact of wake fields which can lead to single- and multi-bunch instabilities. In addition, effects like the fast ion instability and the electron cloud instability are expected to play a more dominant role in the ILC DR than they have in previous machines. We will review these effects and briefly look at the role that test facilities have to play in characterizing and learning to mitigate them.

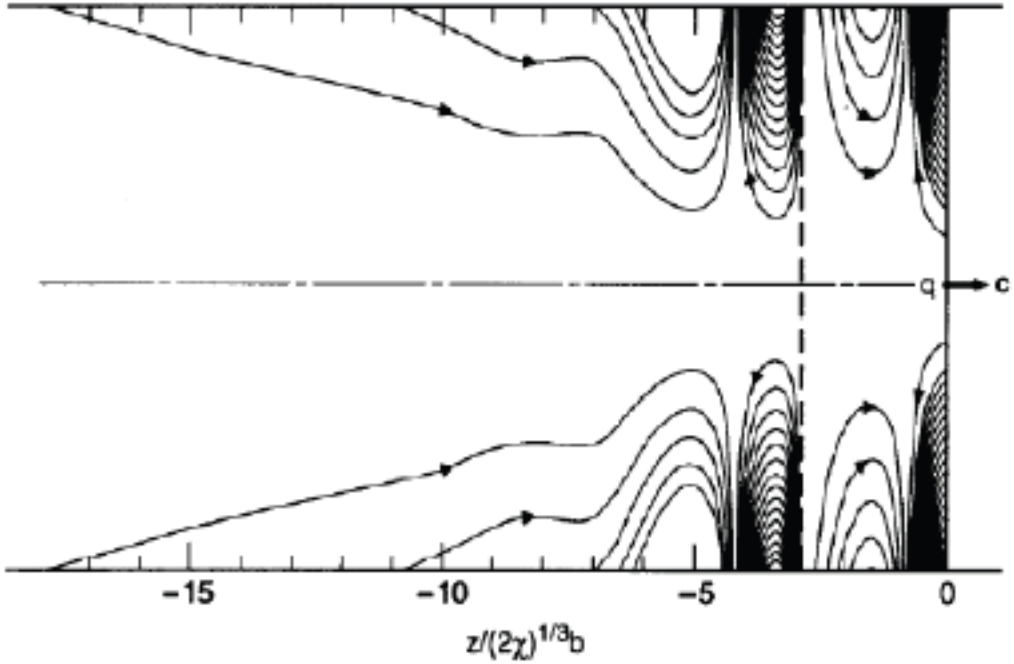
Wake Fields I

For a bunch travelling in a vacuum chamber:

- The EM fields must satisfy Maxwell's equations
- The vacuum chamber imposes boundary conditions that modify those fields from their free space values
- The interaction can result in having fields generated by the head of a bunch act on trailing particles, thus changing their motion
- If the impact on the trailing particles is sufficiently large, this can potentially cause an instability to develop

The EM fields generated by a particle or bunch during its passage are called ***wake fields***

Illustration: Wake fields following a point charge in a cylindrical beam pipe with resistive walls (K. Bane)



Wake Fields II

The wake fields generated by a bunch passage may be

- short range wakes which can impact particles in the tail of the bunch that generated them
- long range wakes which impact other bunches later in the bunch train

The formalism used to calculate the impact of the wakes left by charges on trailing charges is that of *wake functions and impedances*.

In designing a vacuum system that must include:

- RF cavities
- Beam diagnostics
- Sliding joints to handle thermal expansion issues
- Kickers
- Etc.

particular care must be taken to minimize the wake fields that will be generated as bunches move past these structures.

Collective Effects and Instabilities

A number of “classical” instabilities can result if these wakefields grow too large. Some examples are the

- Microwave instability (short range wake)
- Transverse mode coupling instability (short range wake)
- Resistive wall coupled bunch instability (long range wake)
- etc

Other collective effects that must be considered include:

- Intrabeam scattering
- Space charge effects
- Electron cloud effects in the positron ring
- Ion effects in the electron ring
- Touschek lifetime

A broad study of potential effects was undertaken during the initial ILC DR lattice selection process.

Unfortunately we won’t have time to discuss them all here.

The ILC DR Configuration Choice

The potential instability issues were reviewed as part of the ILC DR configuration choice that took place at a meeting in November 2005 at CERN. Various lattices were studied, and while some were found to have specific problems (eg, see the next slide), viable candidates appeared to be present. One of the most difficult decisions was the choice of circumference. At the time, it was unclear what circumference would be required to ensure that the positron damping ring would not be adversely affected by the electron cloud. At that time the choice was made to pursue a
~6 km ring design with plans to use 2 positron rings, as needed.

Since that time, confidence has grown in the ability to meet the ILC DR specifications with a single 6.4 km ring and that has been the baseline.

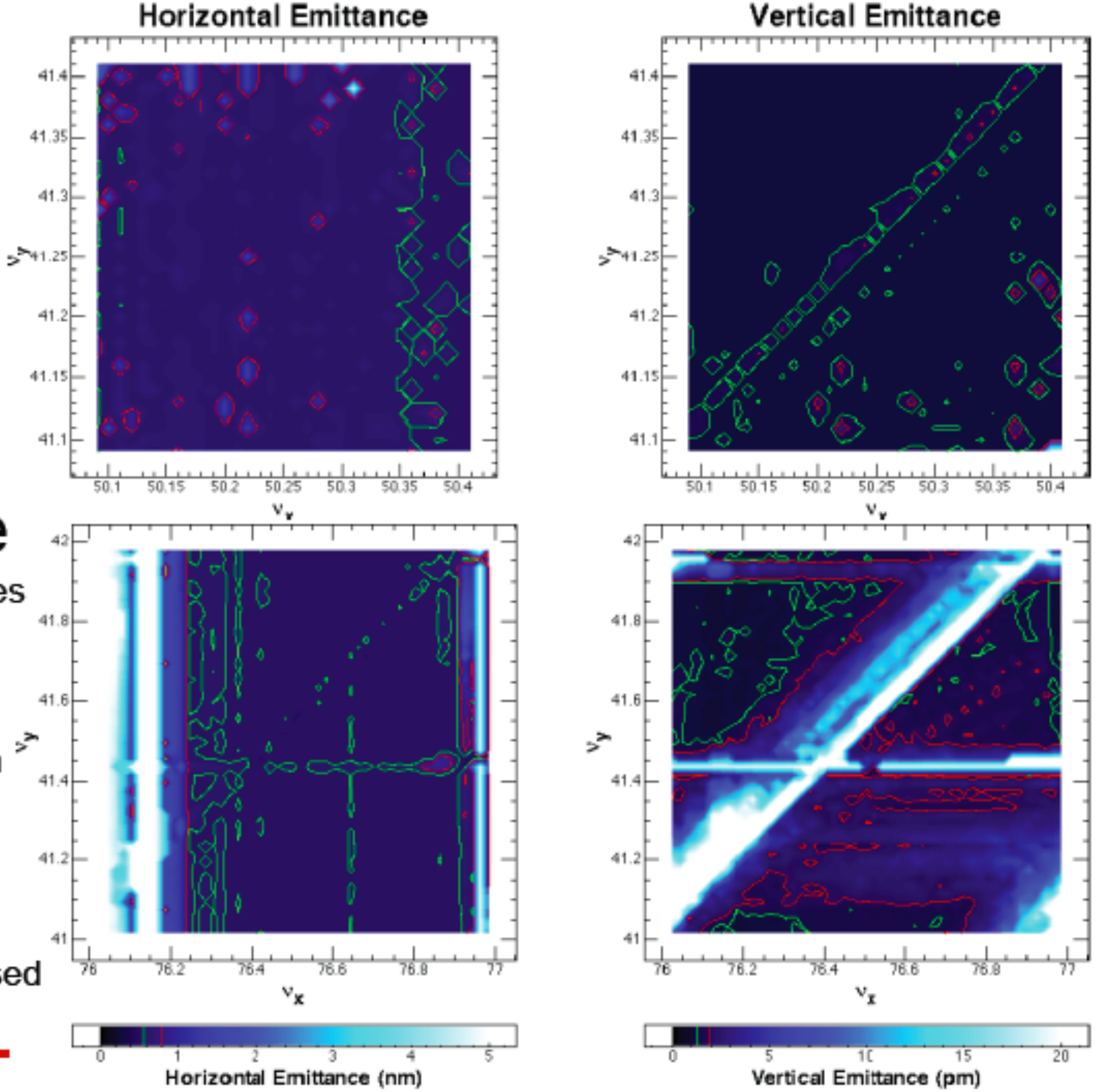
Space-Charge Comparison (OCS2 vs TESLA)

Emittance growth vs working point:

OCS Lattice

TESLA Lattice

For the TESLA lattice, studies were sensitive to the space-charge tune shift in the long straights. The incoherent tune shift grows linearly with circumference. The use of coupling bumps to mitigate the space-charge issue tended to drive coupling resonances which also caused vertical emittance growth.



Principal Instability Concerns

At the time of the configuration choice, two instabilities were identified as being of the greatest concern for the damping rings:

- The Fast Ion Instability in the electron damping ring
- The Electron Cloud Instability in the positron damping ring

We will focus on these for the remainder of the discussion on instabilities.

Ion Instabilities

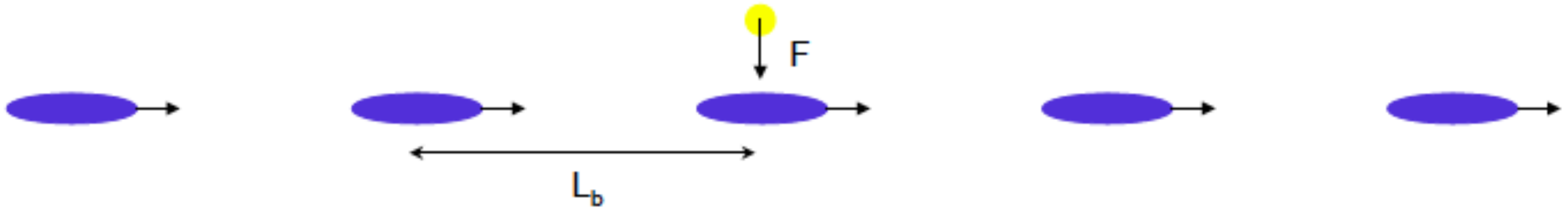
In the electron damping ring, ions that are generated by the bunches interacting with the particle beam can be trapped by the fields of the beam. This can result in high concentrations of positive ions near the beam axis. The interaction of the beam with these ions can then lead to the onset of beam instabilities.

There are generally 2 classes of ion effects that are discussed in the context of an electron storage ring:

- For rings that are uniformly filled with electron bunches, the ions can build up over many turns
  - This effect is know as ion trapping
  - It can be mitigated by placing large “clearing” gaps in the bunch train during which the ions can drift away from the beam axis and escape the potential well formed by the beam
  - Clearing electrodes have also been used to help mitigate the ion build-up
- A more serious effect for the damping rings is the rapid build-up of the ion density along the bunch train during a single passage
  - This is known as the fast ion instability
  - This is expected to be a significant issue for the electron damping ring

Ion-Beam Interaction

For an ion in the proximity of the beam, the electric fields of the bunches create a focusing force which acts on the ion and serves trap it near the beam axis.



The effective k-value of this focusing force is given by:

$$k = \frac{2 r_p N_0}{A \sigma_y (\sigma_x + \sigma_y)}$$

where A is the atomic mass of the ion, r_p is the classical radius of the proton, and N_0, σ_x and σ_y are the bunch charge and transverse sizes of the electron beam.

Ion-Beam Interaction

The motion of the of the ion during the passage of one bunch can be expressed in terms of transfer matrices as we developed yesterday:

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

The stability criteria is then: $Trace(\mathbf{M}) \leq 2$

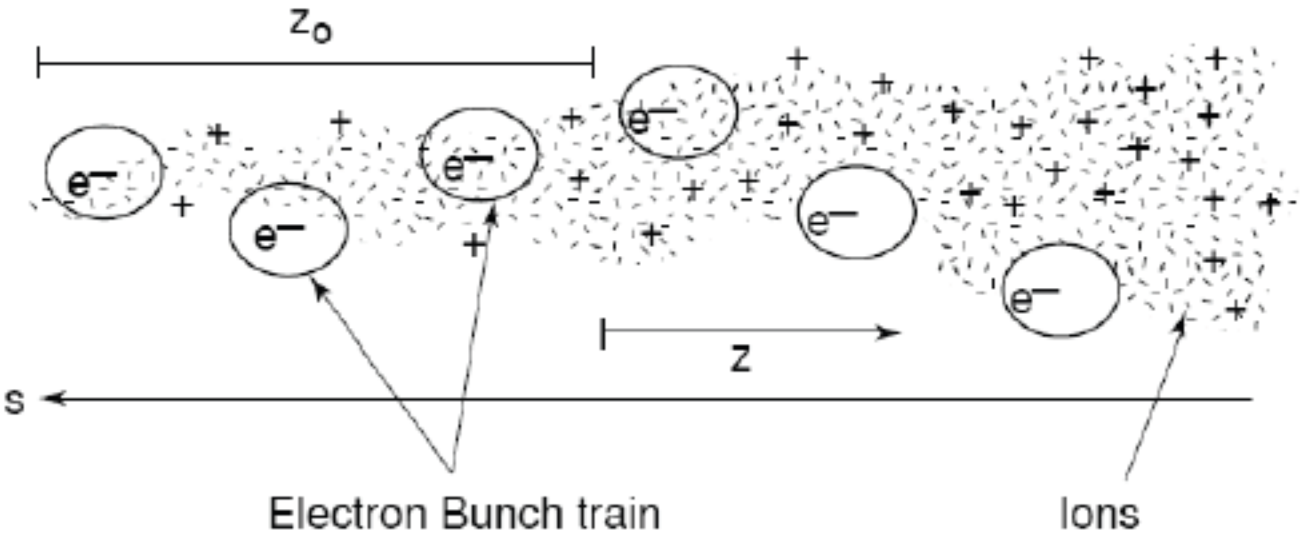
or

$$A \geq \frac{r_p N_0 s_b}{2\sigma_y \left(\sigma_x + \sigma_y\right)}$$

Thus, having high bunch charges or very small beam sizes increases the mass for which ion trapping will take place. For the damping rings, where the beam sizes change dramatically through the course of the damping cycle, this means that the mass of ions that can be trapped will change continuously throughout the machine's injection/extraction cycle. As already noted, this effect can be mitigated by having large gaps in the electron bunch train.

Fast ion instability

Even with large gaps in the electron bunch train, however, there can still be rapid build-up of ions along the train in a single passage. This effect was first discussed by Raubenheimer and Zimmerman and was subsequently observe in the ALS by Byrd, et al. as a blow-up in beam size along the ALS bunch-train when the pressure was artificially increased in one section of the ring by the addition of a He pressure bump.



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

Observation of FII at the LBNL-ALS

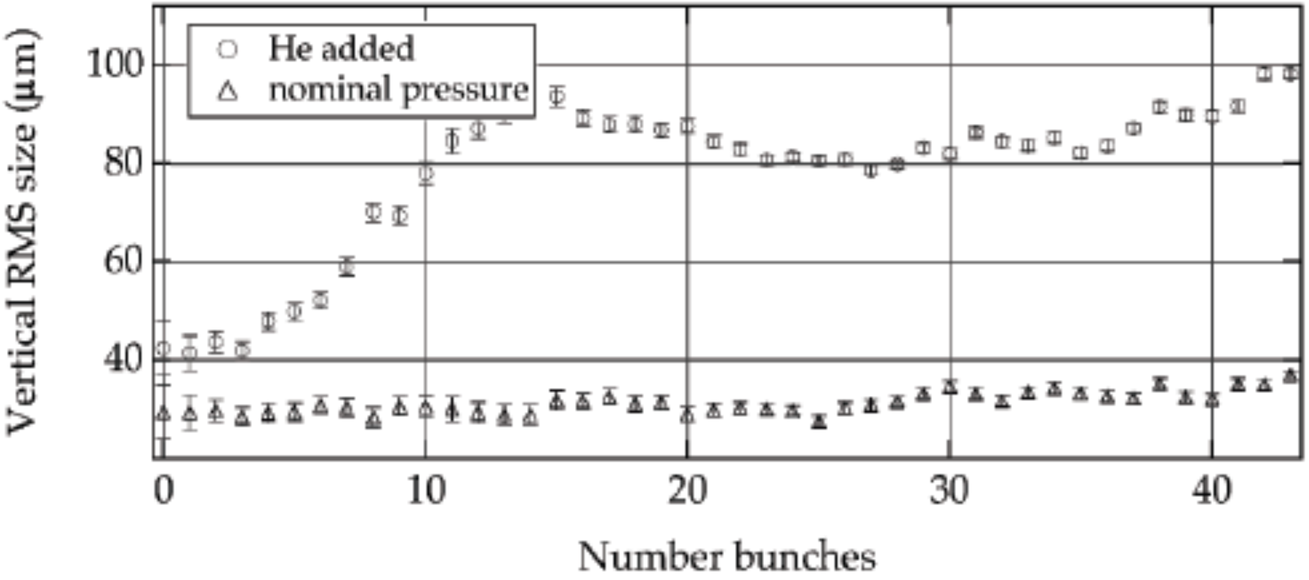


FIG. 2. rms vertical beam size vs the number of bunches for nominal and elevated pressure conditions.

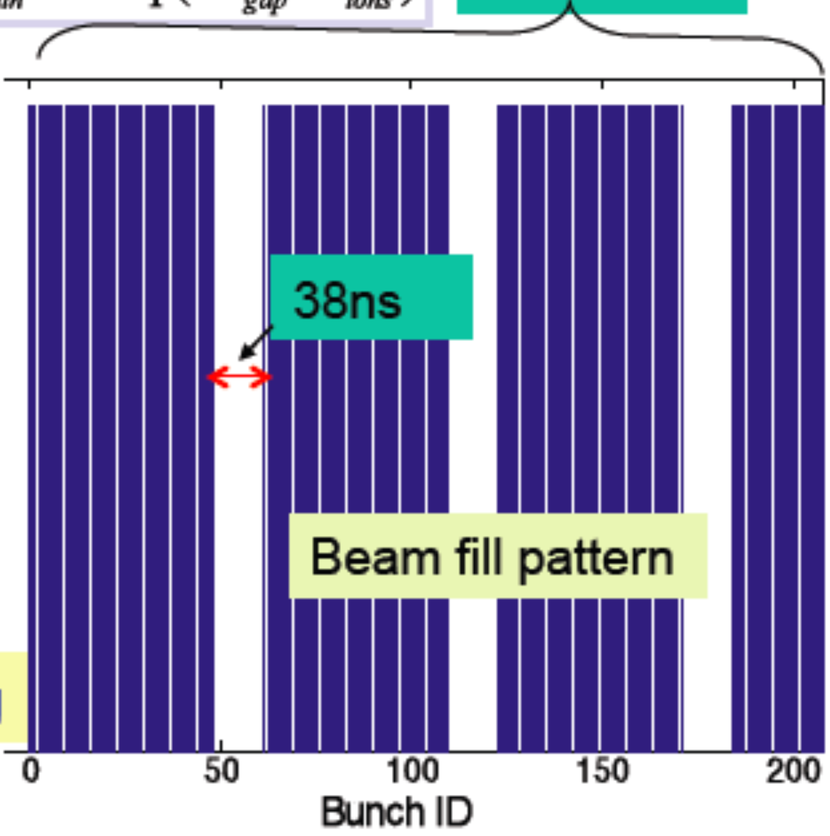
J. Byrd et al, Phys. Rev. Lett. **79**, 79-82 (1997).

FII Modeling for the ILC DR

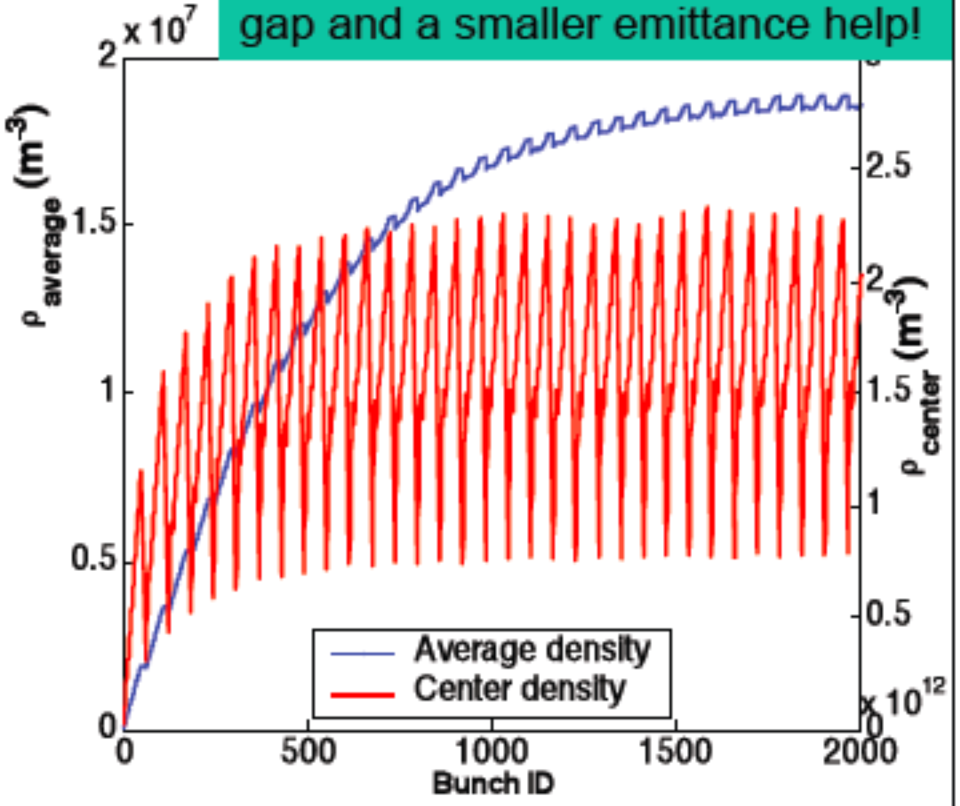
Growth time estimates with train gaps

$$\mathrm{IRF} = \frac{1}{N_{train}} \frac{1}{1-\exp(-\tau_{gap}/\tau_{ions})}$$

The central ion density, and hence the instability rate, is reduced by a factor of 60 compared with a fill consisting of a single long train



Larger number of trains, longer gap and a smaller emittance help!

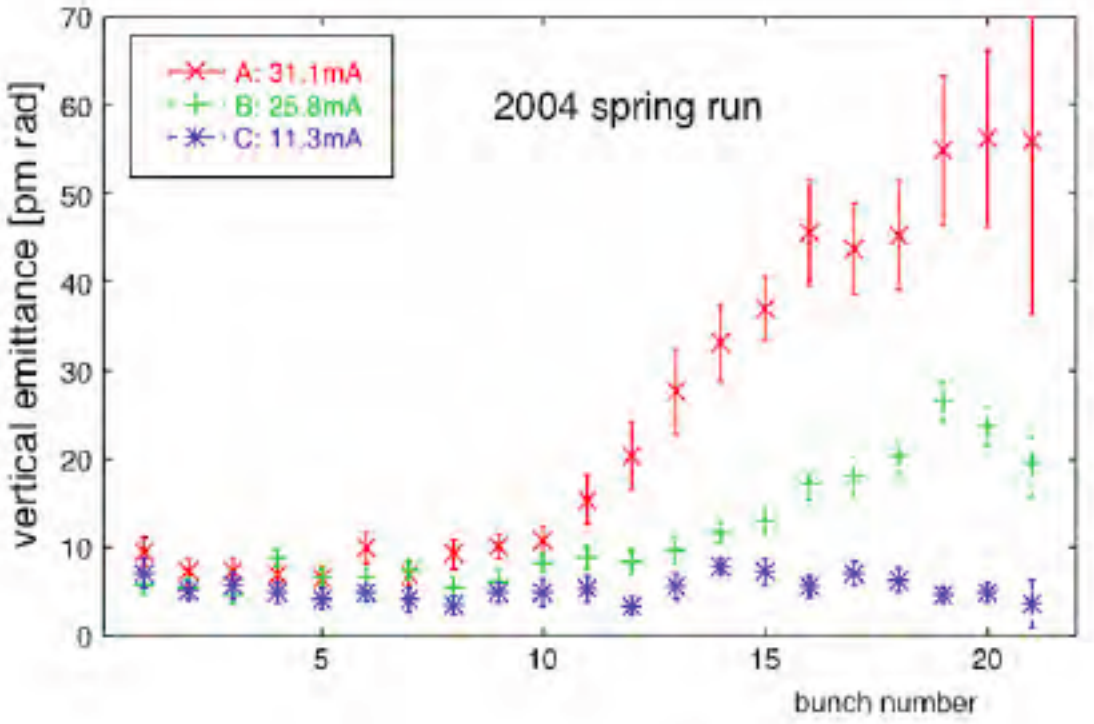


L. Wang

Build-up of CO+ ion cloud at extraction (with equilibrium emittance). The total number of bunches is 5782, P=1 nTorr. Growth time>10 turns. Can be handled with a fast feedback system.

FII R&D

The FII has also been observed at the KEK-ATF:



Vertical emittances along a bunch train as measured during 2004 ATF run

Further measurements are planned in order to characterize the FII with the ultra-low emittance beams that ATF can provide. A critical deliverable is whether suitable specifications for the vacuum system, bunch train configuration, and bunch-by-bunch feedback system can be achieved to suppress this instability.

Electron Cloud Instability

The electron cloud instability has become the dominant issue for the operation of the ILC positron damping ring. A key component of the ILC Technical Design Phase is an ongoing R&D program into mitigation techniques to ensure that the build-up of the electron cloud can be reduced to levels that will not impact the emittance performance of the positron DR. In addition, beam dynamics studies with ultralow emittance beams are planned to characterize the cloud-induced dynamics in this regime and to provide data which can benchmark the modeling tools in a regime much closer to that of the ILC DR.

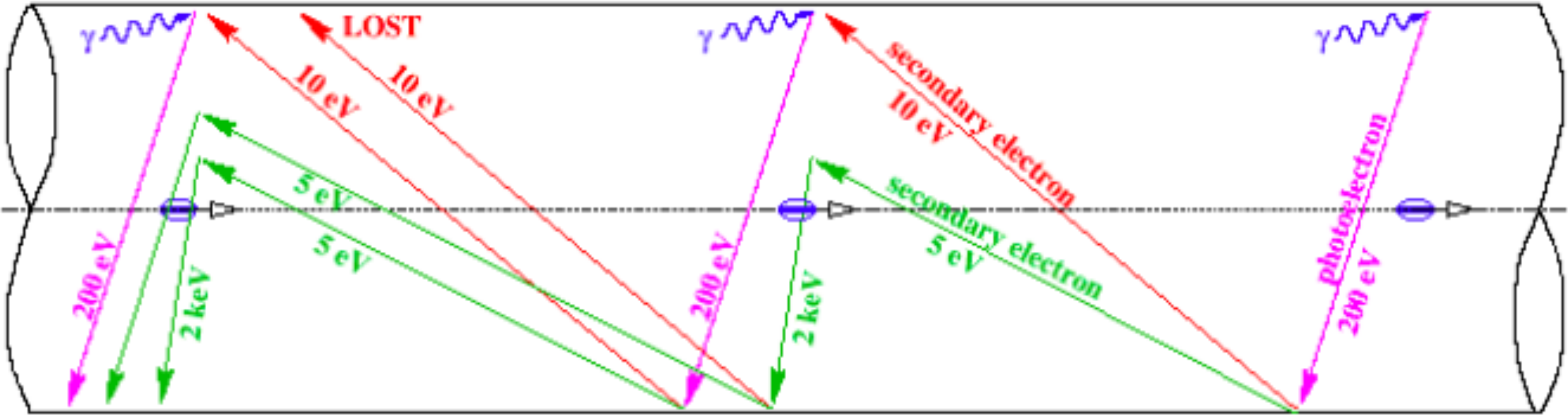
Electron Cloud Instability

Our discussion of the electron cloud (EC) instability will focus on several issues. We will:

1. Take a qualitative look at how the cloud is formed and interacts with a particle beam
2. Look at the predictions of how significant EC effects are expected to be for the operation of the ILC positron damping ring
3. Review of some of the existing observations of the cloud
4. Look at some of the methods that have been employed to measure the electron cloud
5. Look at ways to mitigate the electron cloud
6. Review the key components of the R&D plan for the ILC damping rings that are needed to give us confidence that we can successfully build and commission these challenging machines

Electron Cloud Instability

The following picture illustrates the build-up of the electron cloud in a vacuum chamber and how it can interact with a positron beam



Key features of this picture are:

- Synchrotron photons striking the chamber walls produce primary photoelectrons
- The photoelectrons can strike the vacuum chamber wall and produce secondary electrons which typically have energies of a few eV
- When a cloud electron passes near a bunch, it receives a kick and can be accelerated to much higher energies before striking the wall
- Rapid multiplication of the number of electrons in the chamber along a bunch train can lead to cloud densities of sufficient magnitude to cause beam instabilities and emittance growth

Features of the EC Build-up

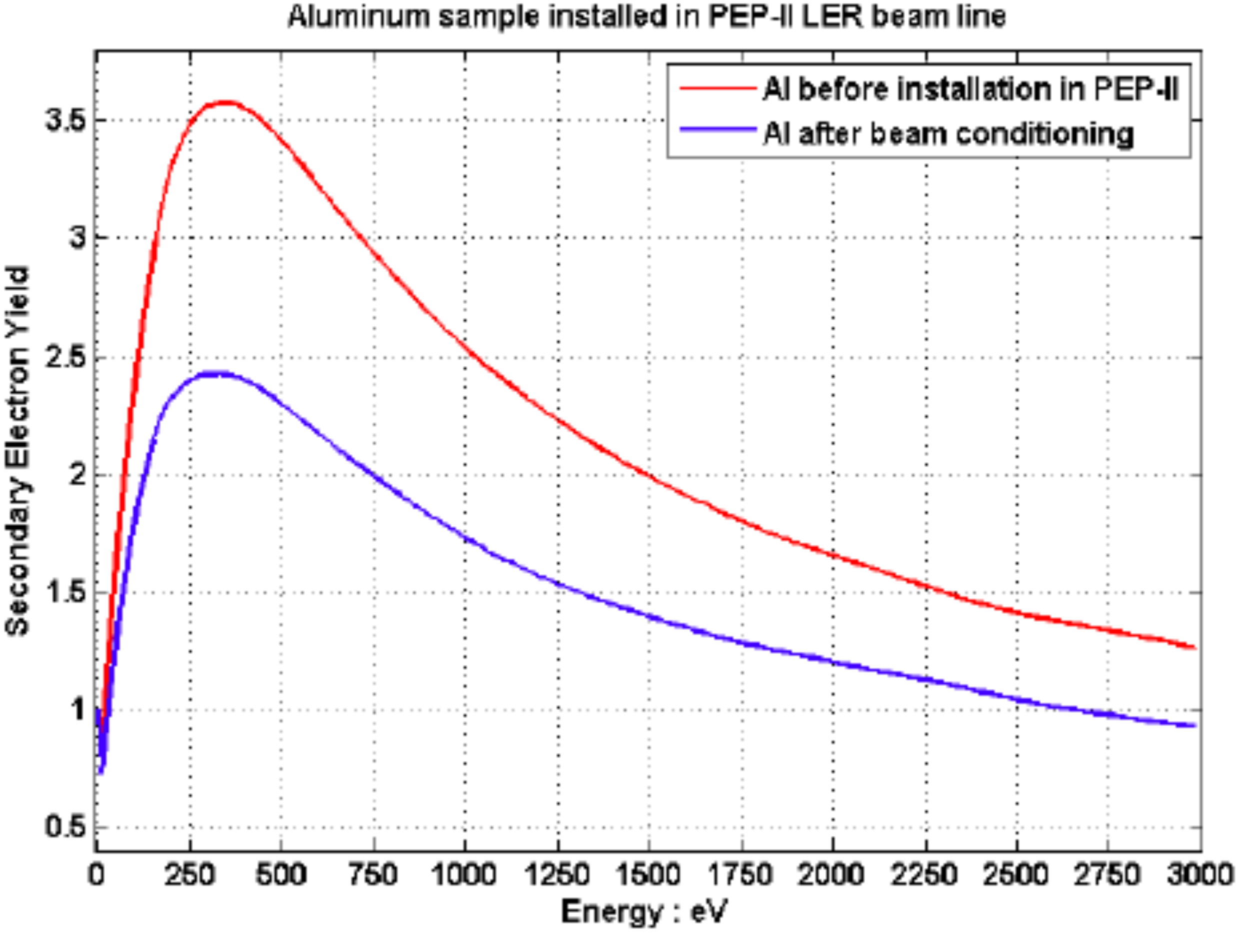
In an accelerator vacuum system the growth of the electron cloud is dependent on a wide range of parameters:

- The bunch structure of the beam, both intensity and bunch spacing
- The surface properties of the vacuum chamber
- The geometry of the vacuum chamber
- The presence and geometry of electric and magnetic fields in the vacuum chamber
- Various sources for electrons including primary photoelectrons, secondary electrons, and electrons from the ionization process
- The properties of electrons which are produced in the chamber (typical energy, angular spread)

All of these issues have been incorporated into a number of EC simulation codes which are used to model the growth of the cloud and its interaction with the beam.

The Secondary Electron Yield (SEY)

A key parameter for understanding the development of the electron cloud is the secondary electron yield. This parameter describes the number of secondary electrons produced when an incident electron strikes the surface of the vacuum chamber.

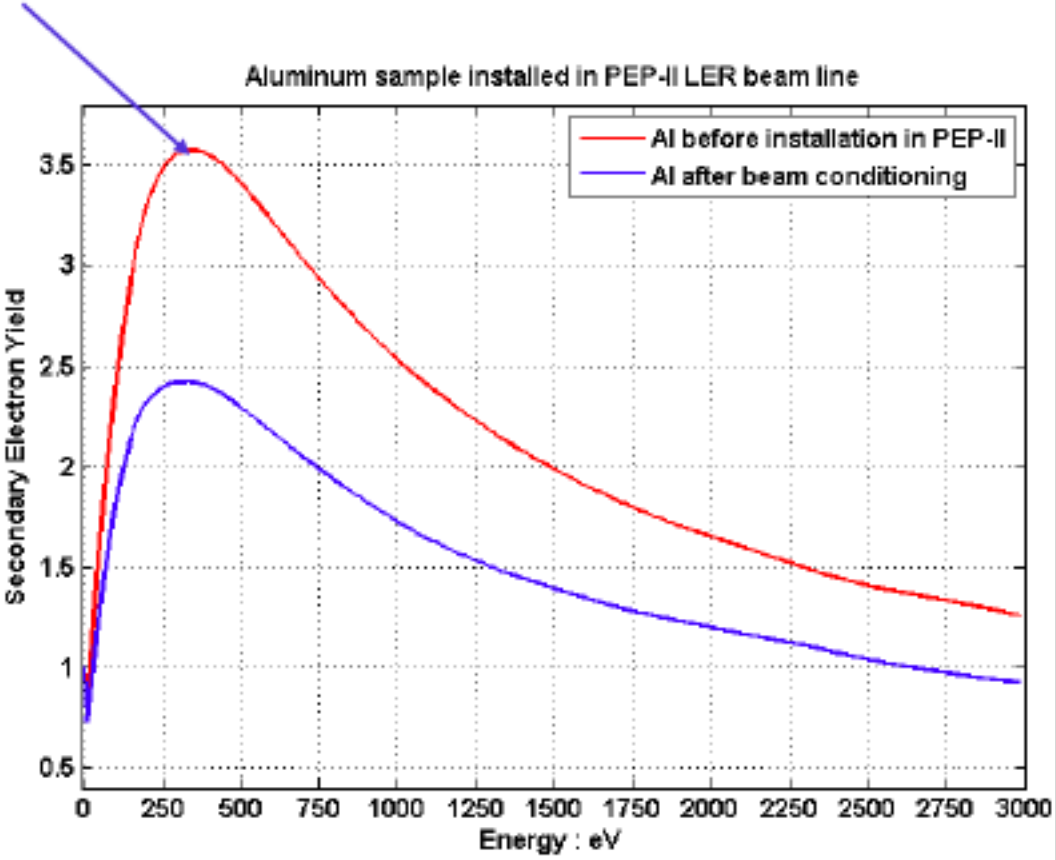


M. Pivi, SLAC
Measurements of the SEY yield of an Al surface before and after beam conditioning with synchrotron radiation

The Secondary Electron Yield (SEY)

Some comments on the SEY curve:

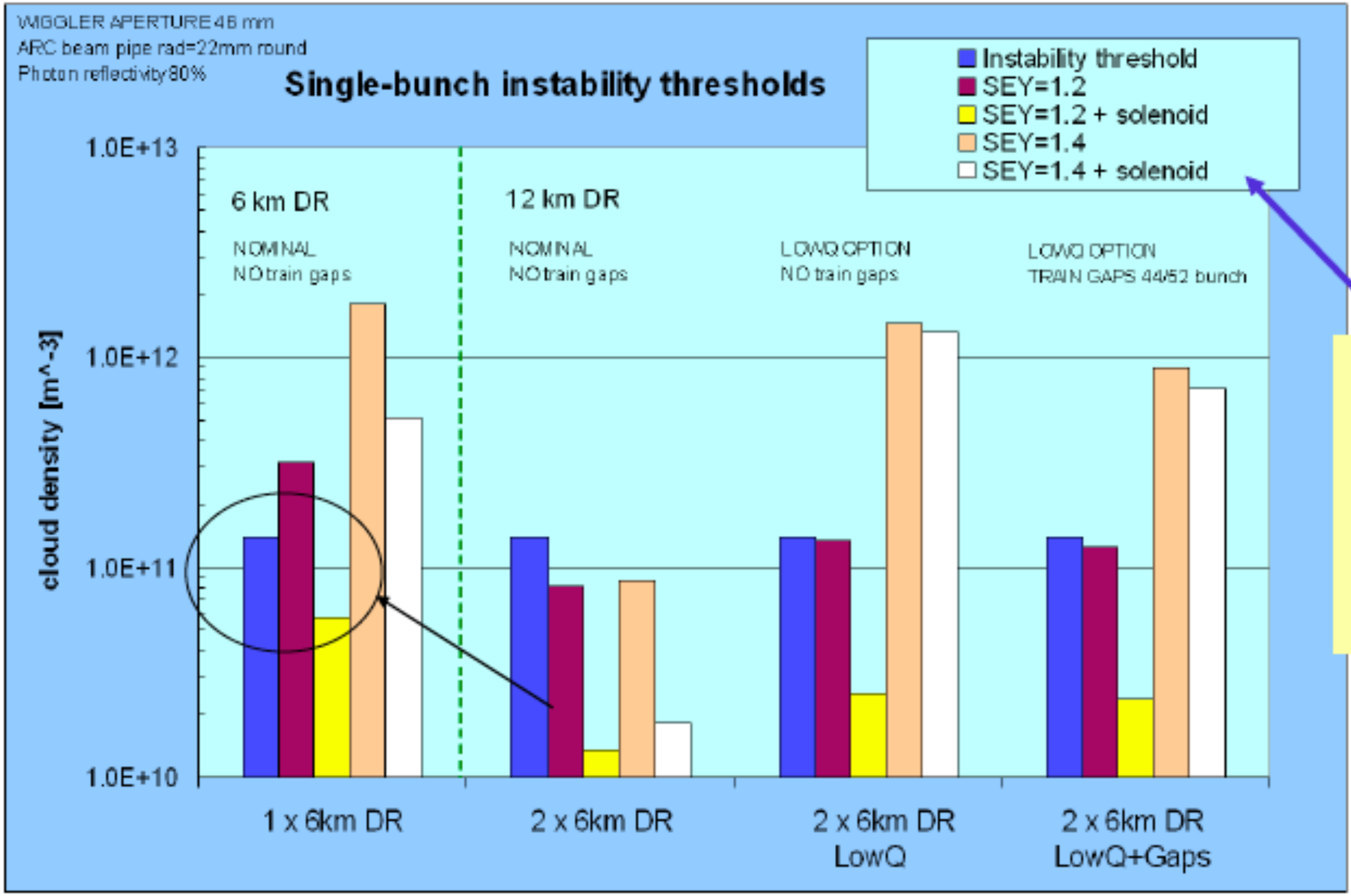
- When a single value for the SEY of a material is quoted, it is the height of the peak in the SEY curve.
- The SEY varies with the energy and angle of the incident particle.
- The SEY is dependent on the surface properties of a material. The surface properties may vary significantly depending on the history of the sample.



EC Predictions for the ILC e^+ DR

How large a ring is required???

M. Pivi
ILCDR06

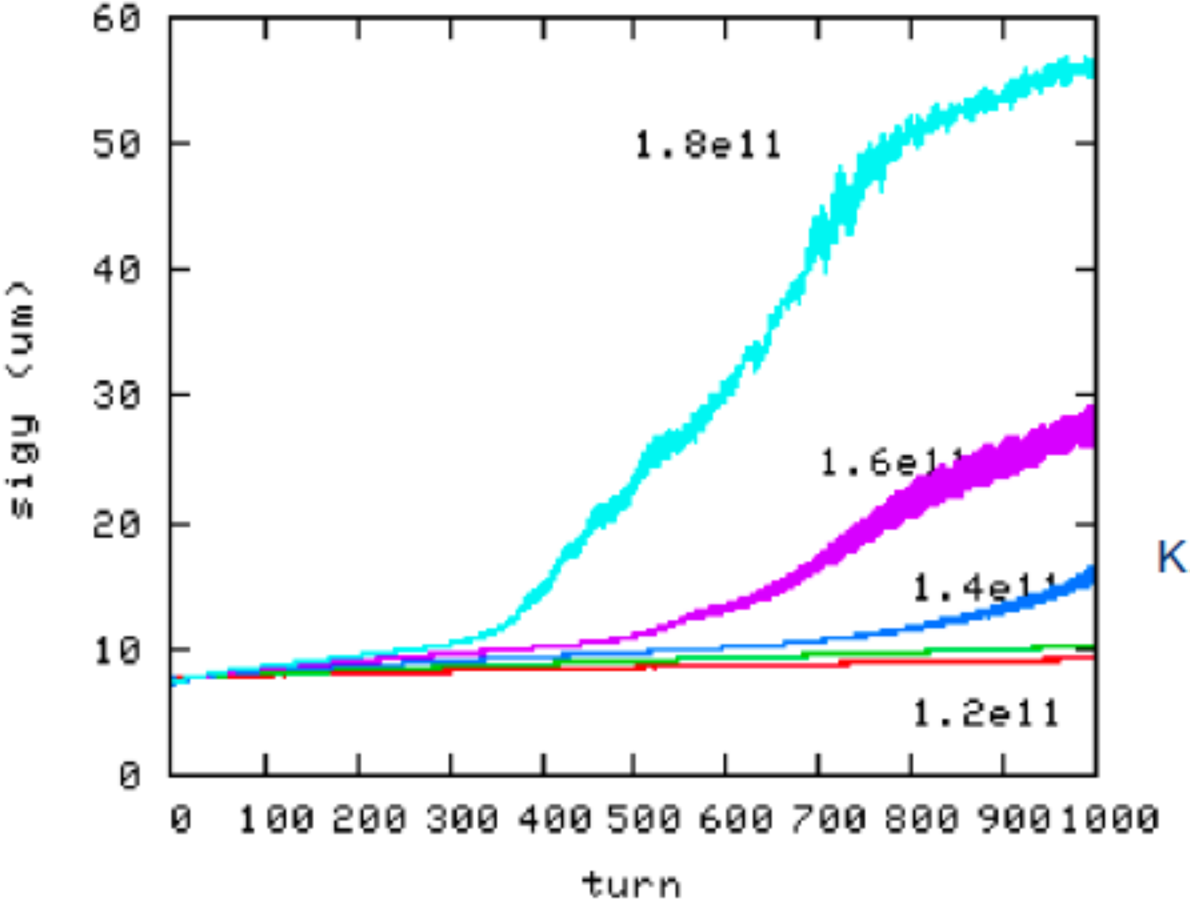


No additional suppression techniques assumed in dipoles and wigglers!

Cloud density near (r=1mm) beam (m^{-3}) before bunch passage, values are taken at a cloud equilibrium density. Solenoids decrease the cloud density in DRIFT regions, where they are only effective. Compare options LowQ and LowQ+train gaps. All cases wiggler aperture 46mm.

Emittance Growth Studies

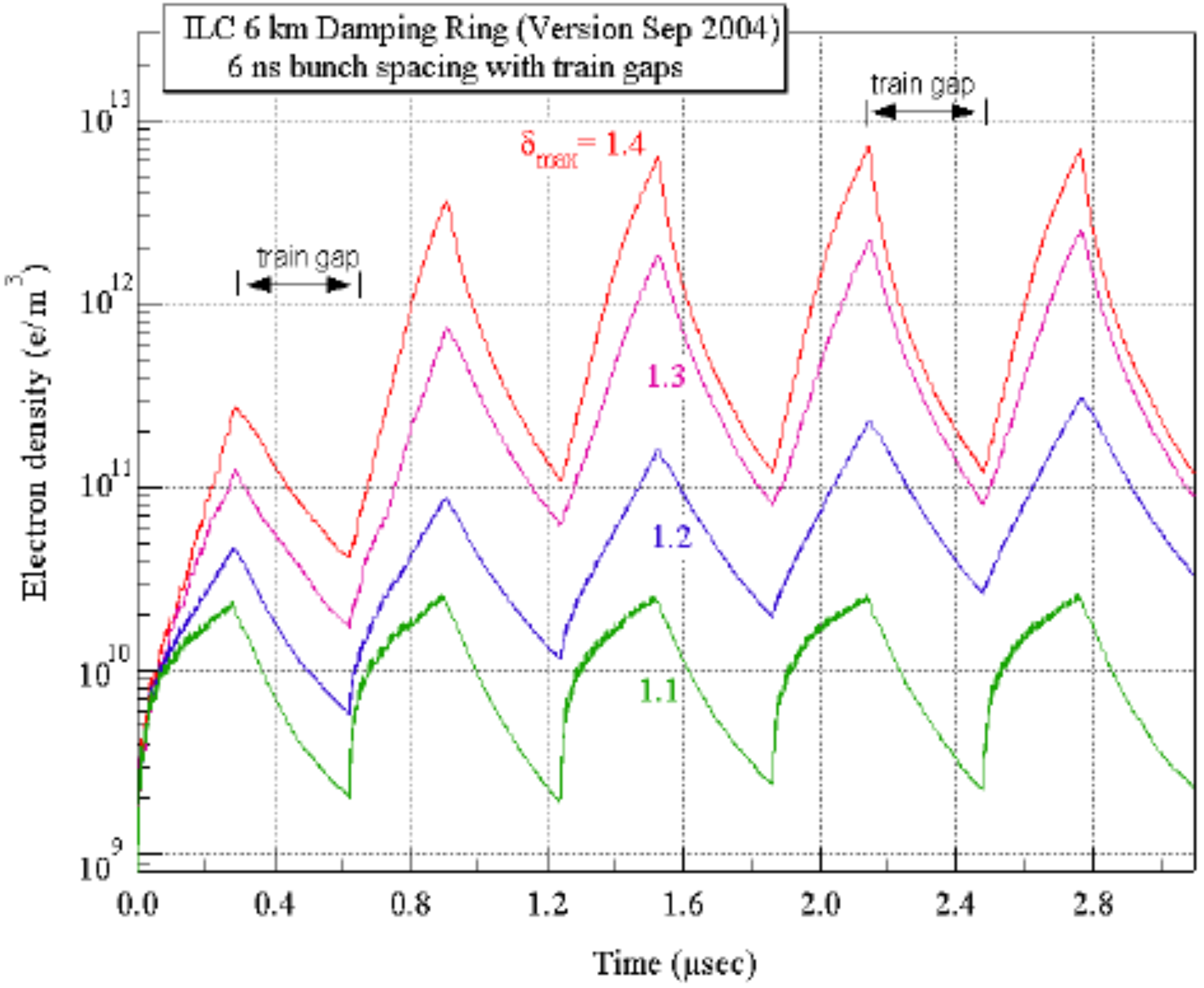
Studies of the EC interaction with the beam indicate that instabilities in the ILC DR positron beams will start at cloud densities of ~1.4×10^{11}m^{-3} (the simulation assumes that the SEY value in the vacuum chambers is ~1.2). Above this threshold, emittance growth of the beam sets in. This threshold places limits on acceptable SEY values for the damping ring vacuum chambers.



K. Ohmi KEK

Modeling the EC Growth

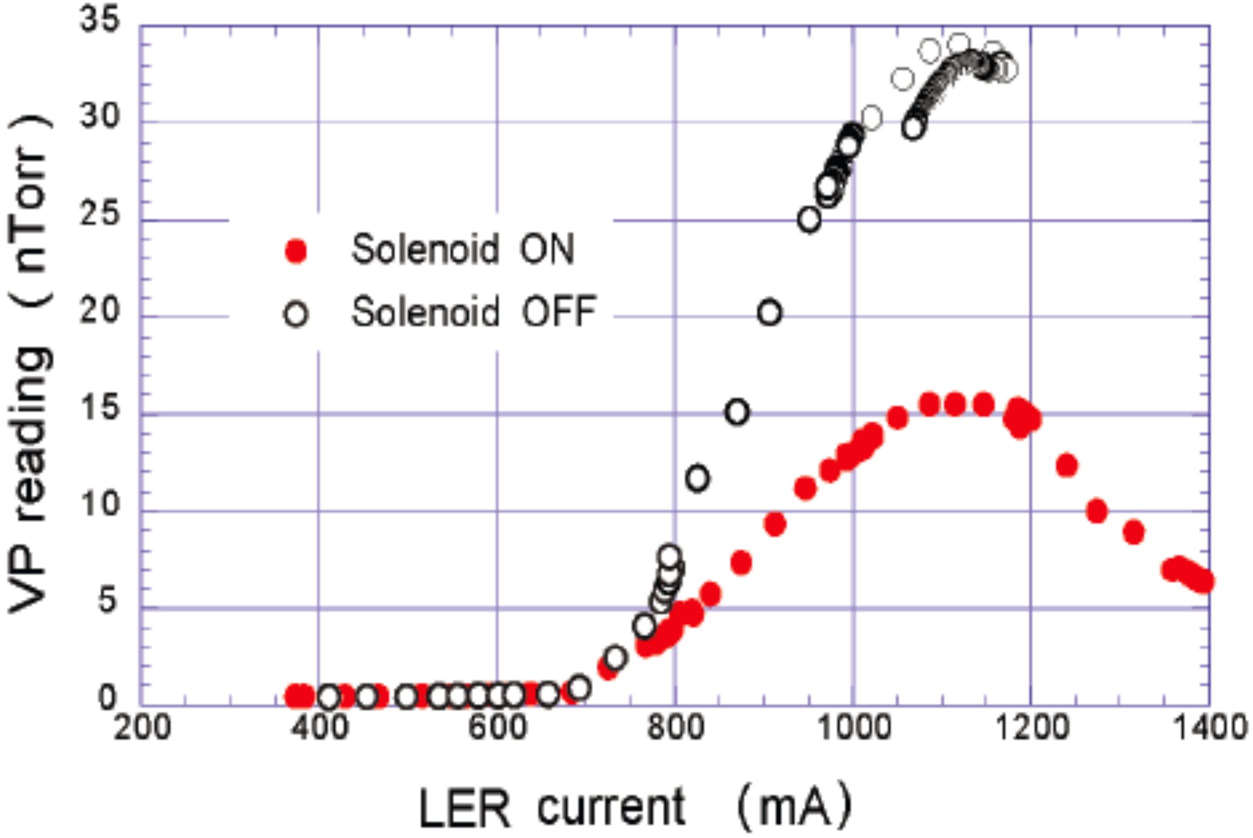
Growth of the EC in a drift space for a 6 km damping ring – simulated using POSINST



M. Pivi

Observations of the Electron Cloud

The electron cloud can be observed by looking at its impact on the vacuum in storage ring, by using local detectors mounted on the surface of vacuum chambers, and through its interaction with the beam.



Pressure rise observed in the PEP-II LER

A. Kuliokov et al, PAC01

The EC Tune Shift

In order to understand the observed tune shifts, consider Poisson's equation which gives:

$$\frac{\partial E_x}{\partial x}+\frac{\partial E_y}{\partial y}=\frac{e\rho(x,y))}{\varepsilon_0}$$

We can then write:

$$\Delta Q_{x(y)}=\frac{e}{4\pi E_0}\oint ds\beta_{x(y)}\left\langle\frac{\partial E_{x(y)}}{\partial x(y)}\right\rangle_{beam\ distribution}$$

If we assume $\beta_x \sim \beta_y \sim \beta$, we can then write a very simple expression for the sum of the horizontal and vertical tune shifts:

$$\Delta Q_x+\Delta Q_y=\frac{e}{4\pi E_0}\oint ds\left(\beta_x\left\langle\frac{\partial E_x}{\partial x}\right\rangle+\beta_y\left\langle\frac{\partial E_y}{\partial y}\right\rangle\right)$$

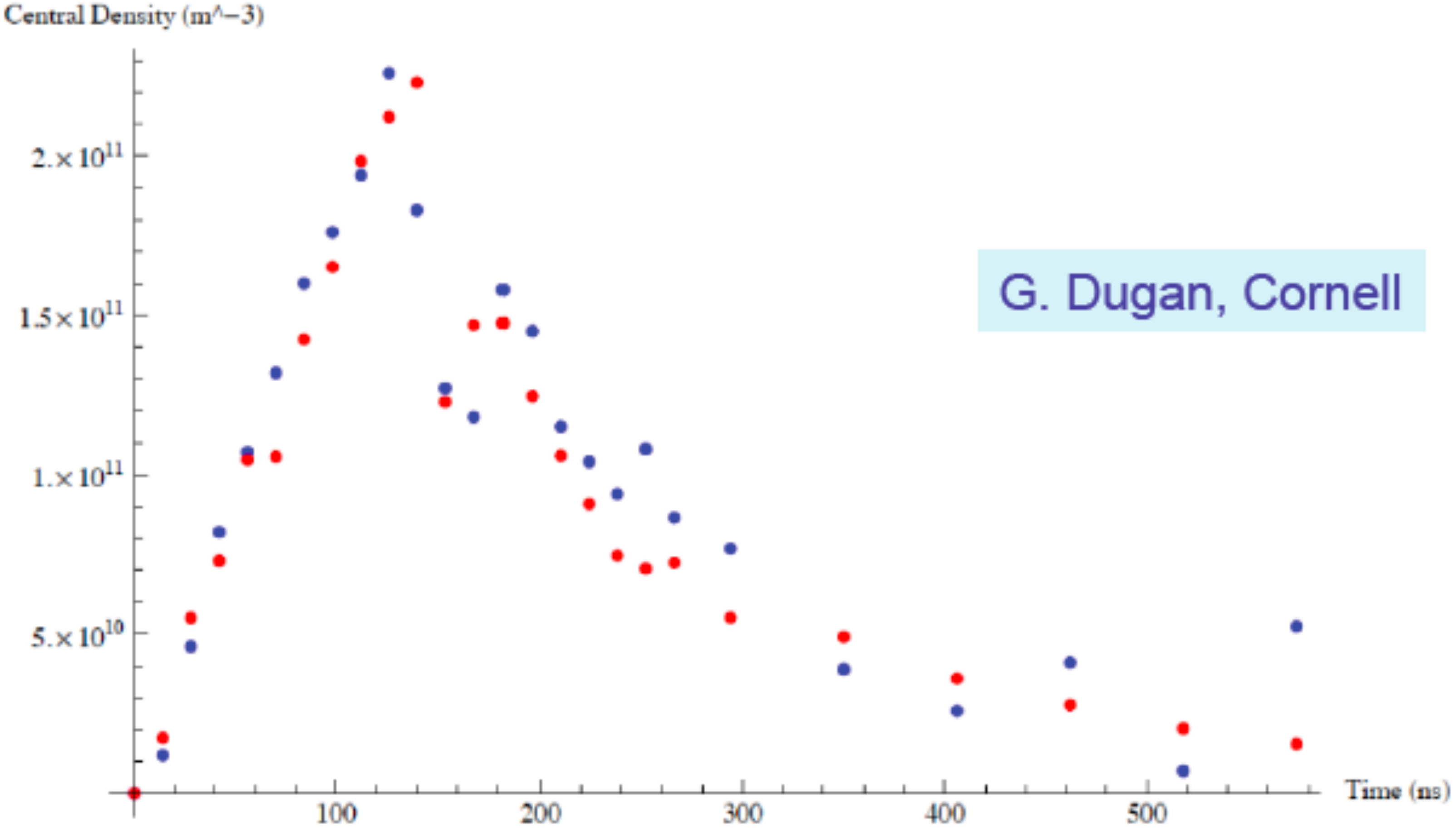
$$\approx\frac{e}{4\pi E_0}\oint ds\beta\left(\left\langle\frac{\partial E_x}{\partial x}\right\rangle+\left\langle\frac{\partial E_y}{\partial y}\right\rangle\right)$$

NOTE: This effectively assumes the EC distribution stays static during the bunch passage – not quite true ⇨ modifies the result somewhat. But this is quite close…

$$\boxed{\Delta Q_x+\Delta Q_y\approx\frac{e^2}{4\pi\varepsilon_0 E_0}\oint ds\beta\langle\rho\rangle_{beam\ distribution}}$$

Data vs Simulation

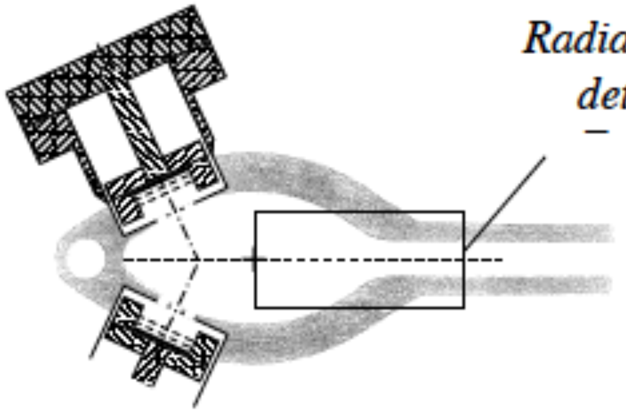
BLUE–beam averaged density from sum of tune shifts (4/07 data, 1.9 GeV)
RED–POSINST central (+/– 5 sigma) density from simulation
29% drift @ .248 phot/m/elec, 71% dipole @ .56 phot/m/elec
SEY peak 1.7, 10% photon reflectivity,



G. Dugan, Cornell

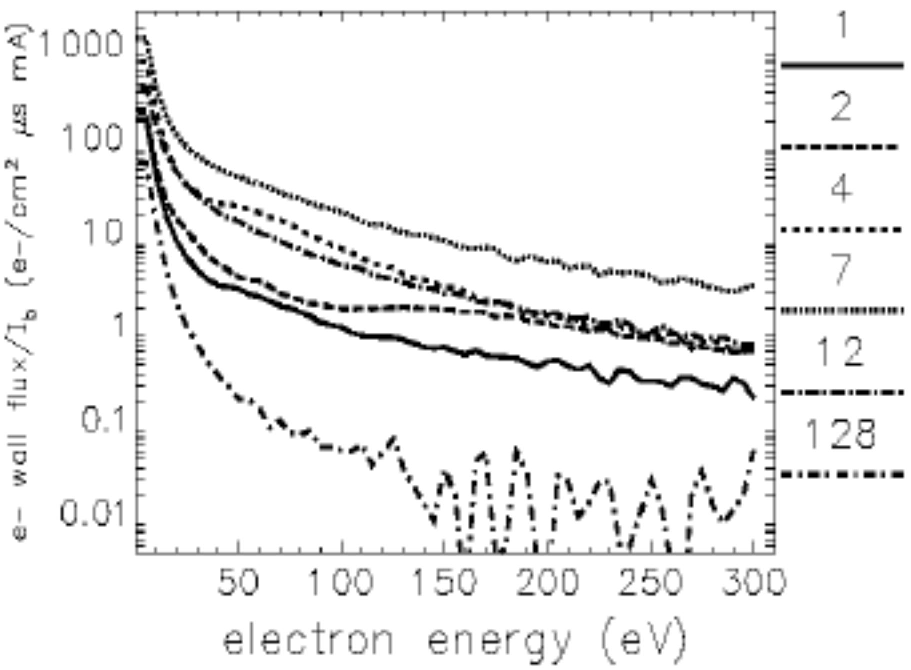
Retarding Field Analyzers

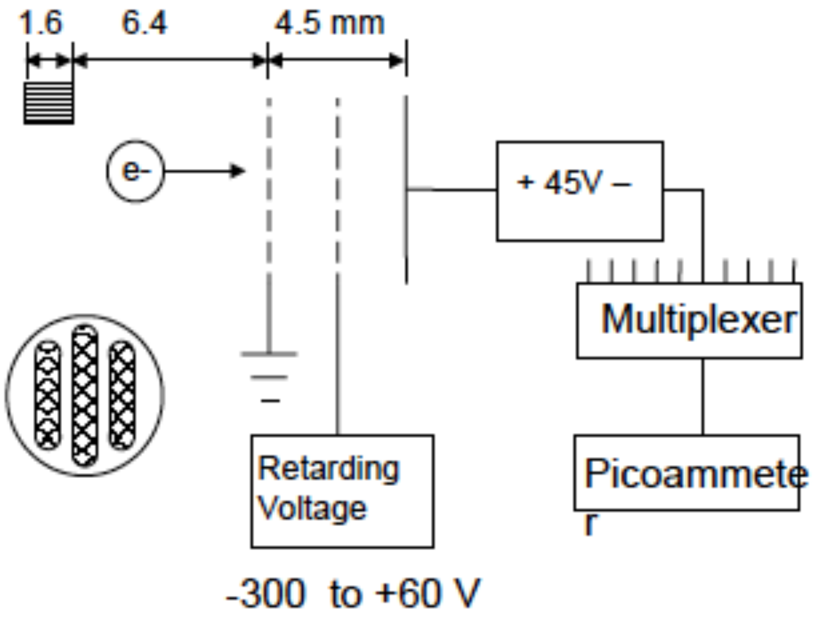
RFA measures distribution of EC colliding with walls, T~50%



Radiation fan at det.#6 for ¯ ≥ 4 eV

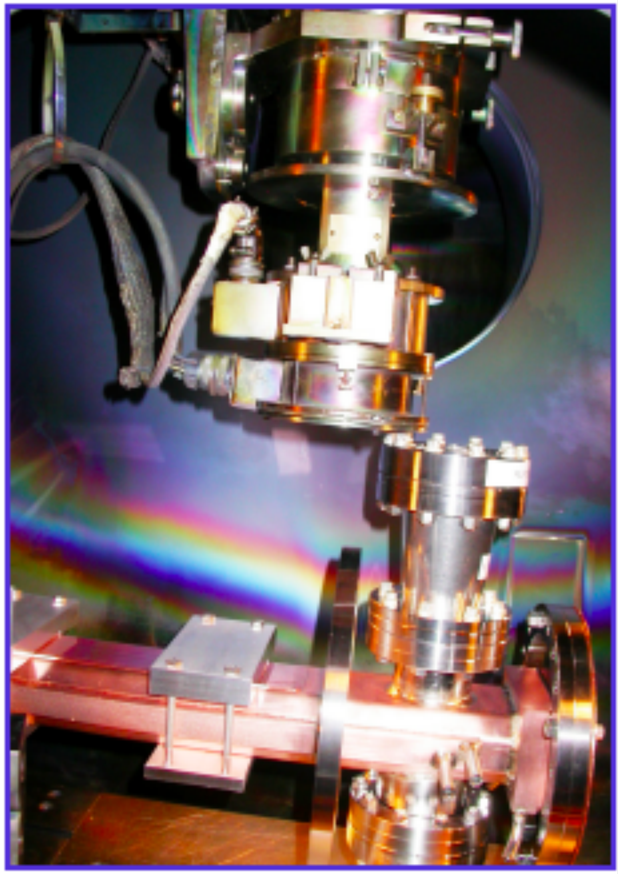
mounting on APS Al chamber behind vacuum penetration (42 x 21 mm half-dim.)

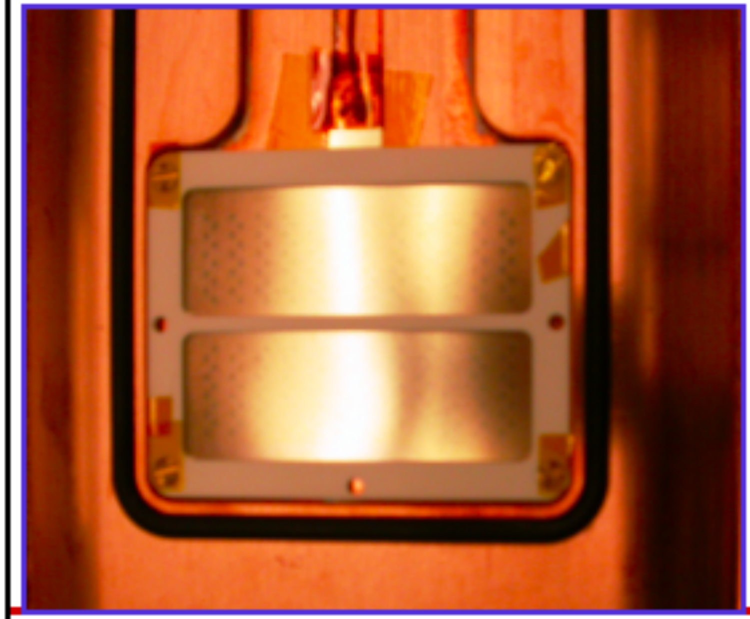




K. Harkay, APS

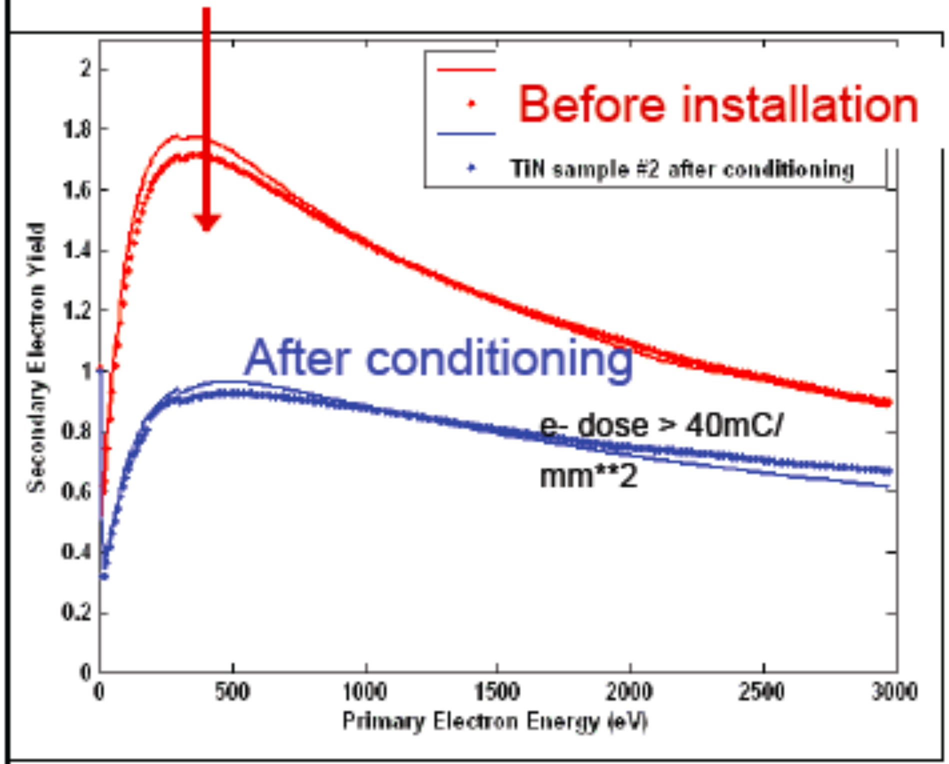
RFAs for CesrTA Diagnostic Wigglers

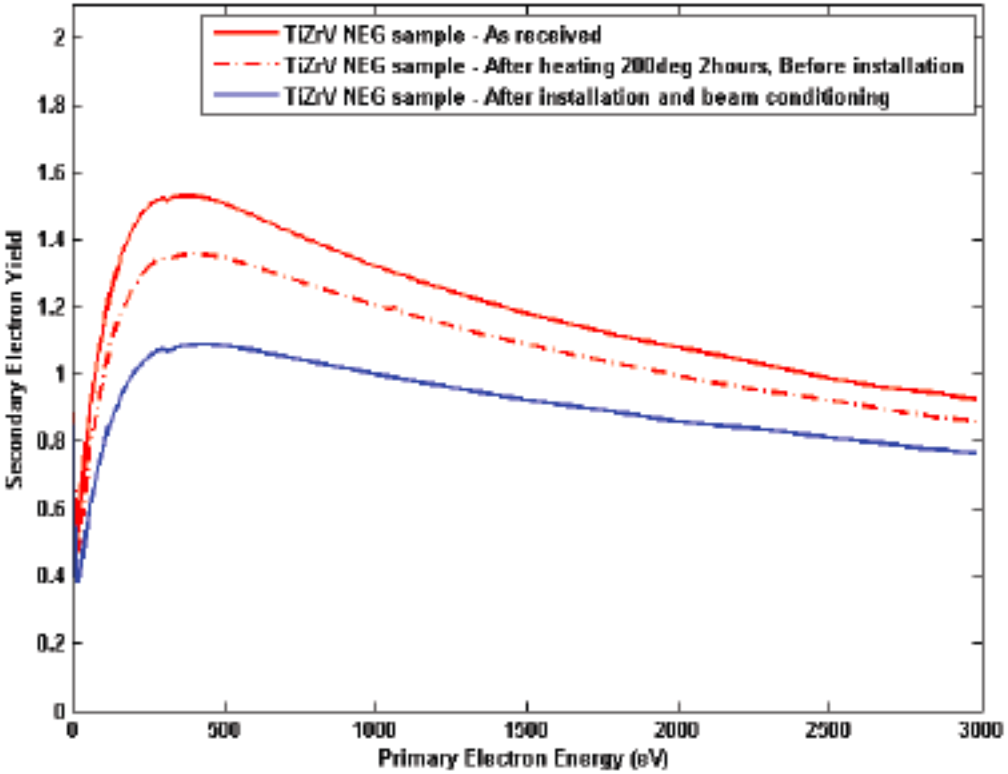




Mitigation of the EC

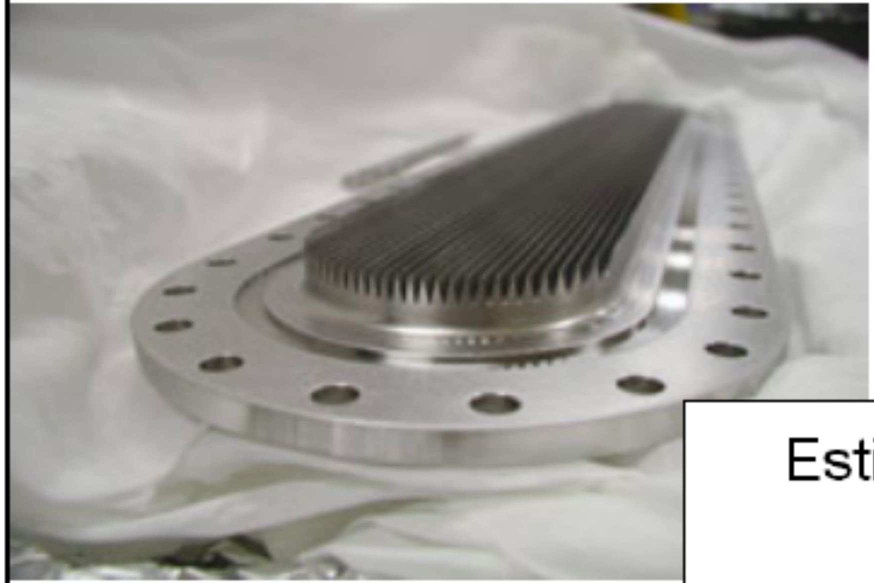
One method is to coat the surface of vacuum chambers with low SEY materials. TiN is an excellent candidate and shows SEY peak values that drop below unity after suitable processing. NEG coatings are also promising.



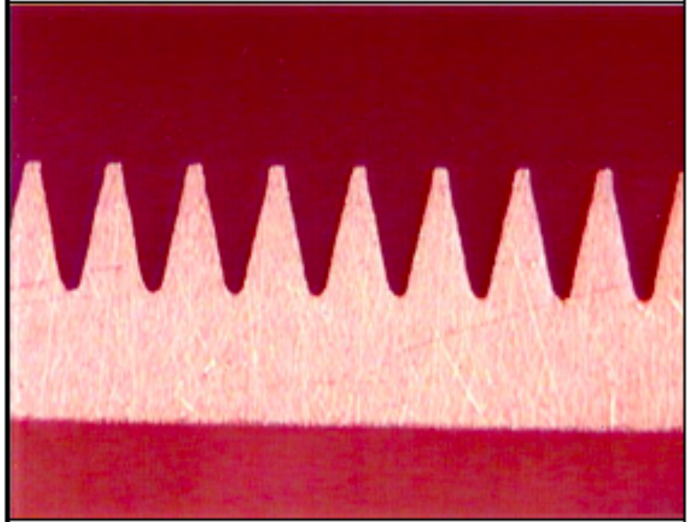


ILC tests, M. Pivi et al. – SLAC

Grooved Surfaces



Grooved surfaces can also suppress the cloud (but increase the vacuum chamber impedance)



Estimation of SEY of the triangular groove

Simulation Parameters

Peak SEY δ_0=1.2

Width =2mm

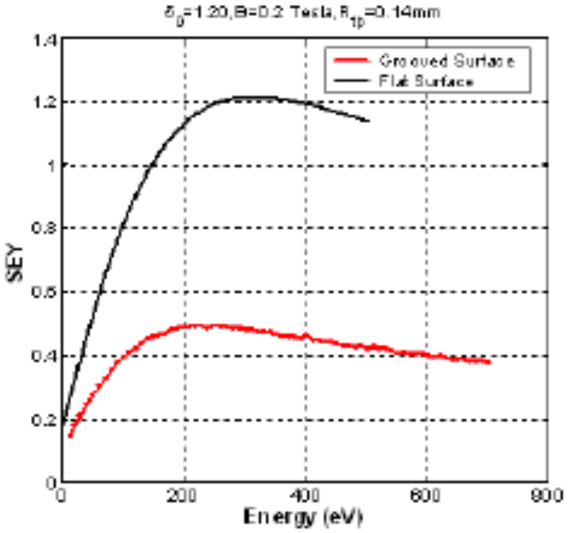
Height=3.82mm

Radius of tip=0.14mm

α=78.6º

Dipole field=0.2Tesla

1. Use the same radius for both tip and bottom
2. Slope angle is adjusted to keep the height same as the measured one



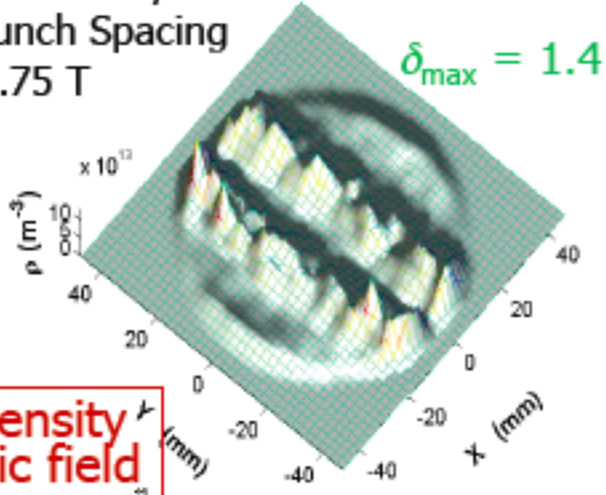
Recent estimation based on extruded groove chamber geometry

Clearing Electrodes to Suppress Electron Cloud in Wigglers

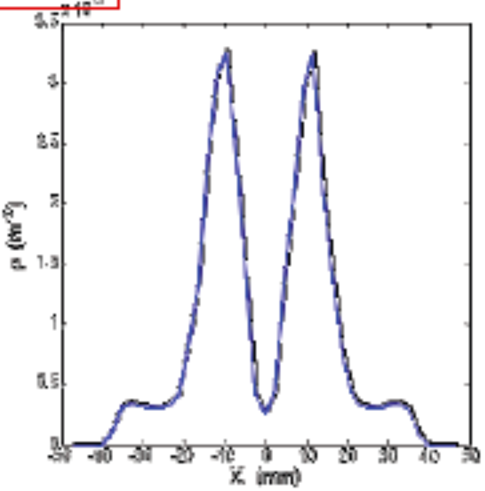
Simulations indicating the ability of an electrode to suppress the EC in an ILC DR wiggler chamber

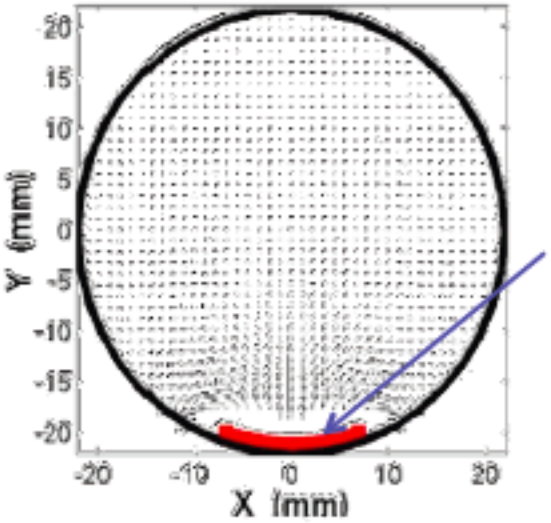
R-pipe=38mm
bunch intensity=9.36×10^{10}
3.5 Bunch Spacing
B = 0.75 T

$\delta_{max} = 1.4$

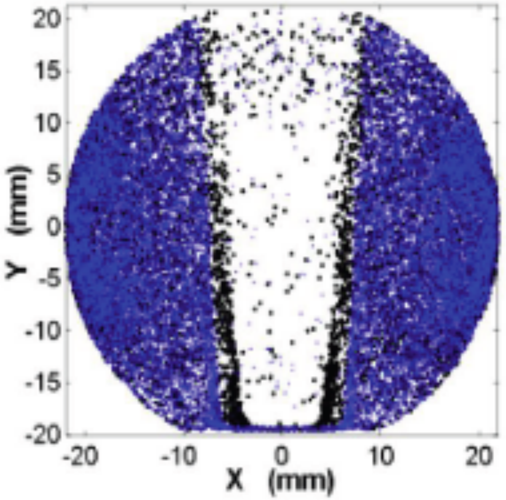


Electron density in magnetic field





Electrode (+)



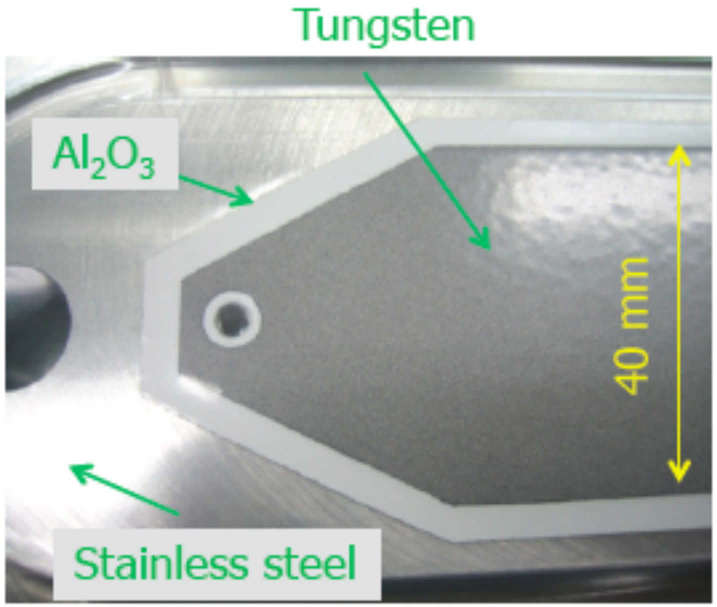
L. Wang et al, EPAC2006, p.1489

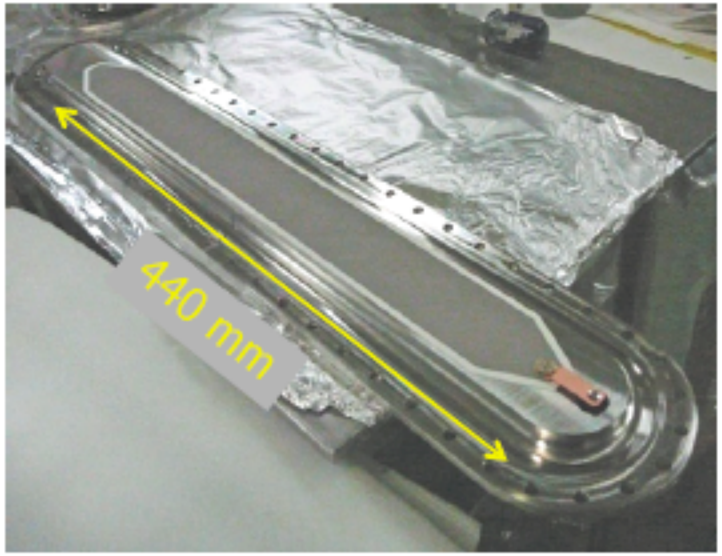
Electrode in KEKB Wiggler

New strip type electrode technology was developed.

Employs a very thin electrode and insulator;

- Electrode: ~0.1 mm, Tungsten, by thermal spray.
- Insulator: ~0.2 mm, Al_2O_3, by thermal spray.



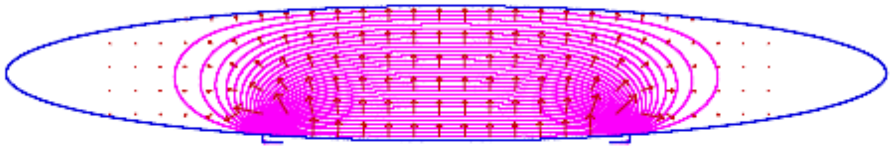


Y. Suetsugu,
KEKB

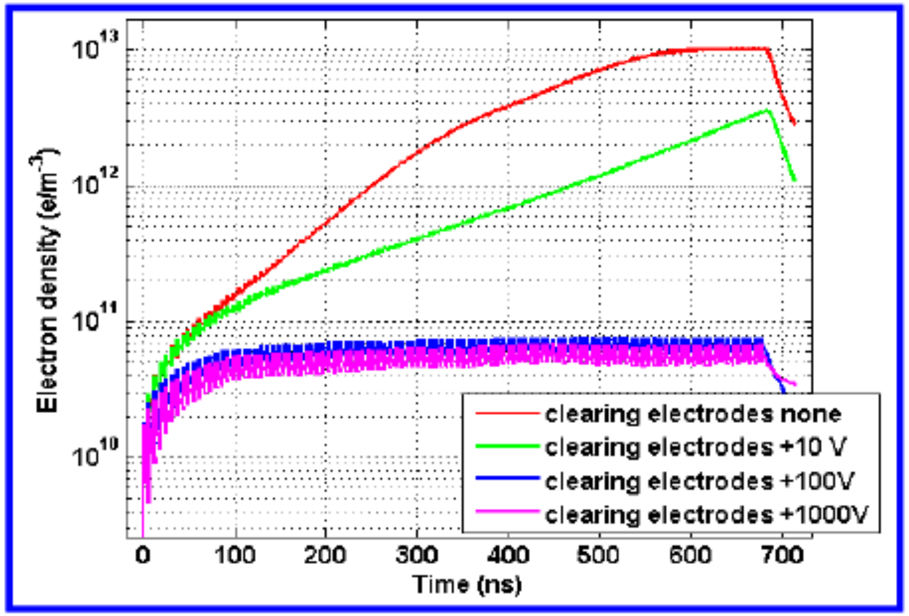
DAΦNE

Clearing electrodes design

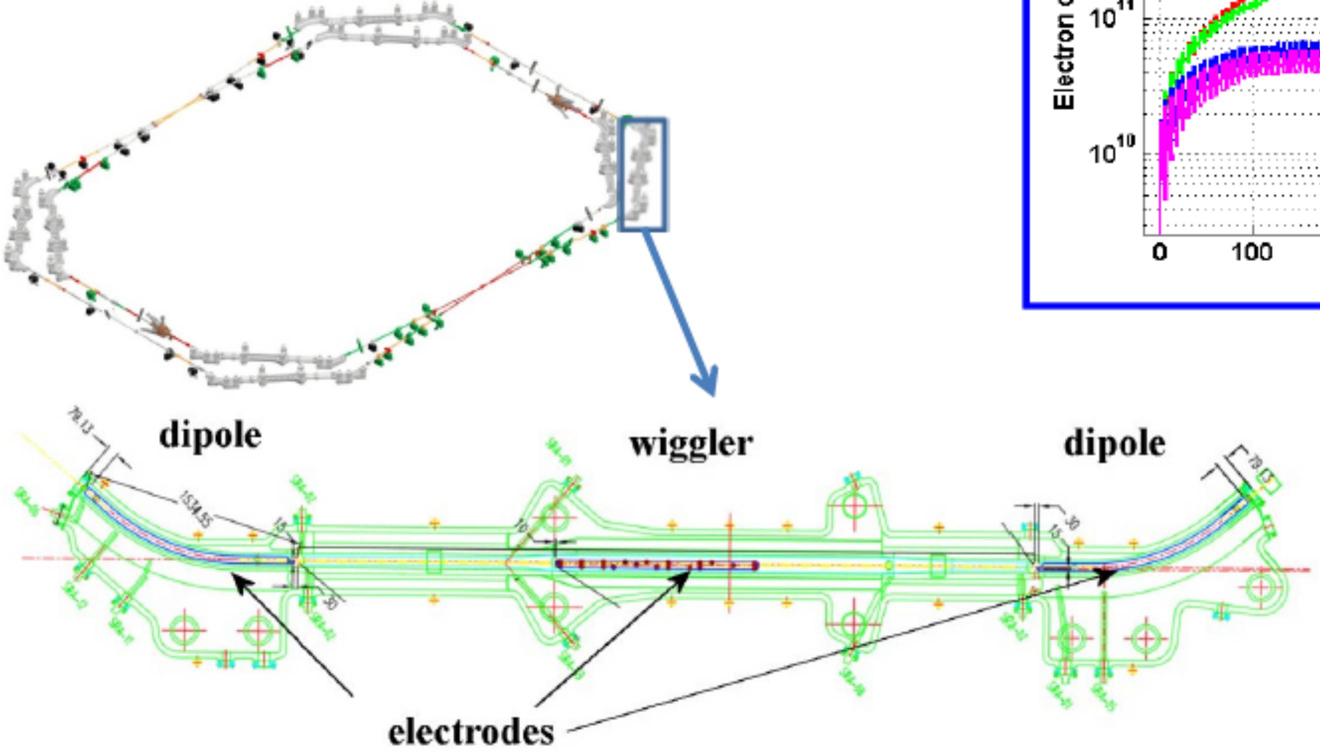
To mitigate the e-cloud instability **copper electrodes have been inserted in all dipole and wiggler chambers** of the machine and have been connected to external dc voltage generators in order to absorb the photo-electrons. The dipole electrodes have a length of 1.4 or 1.6 m depending on the considered arc, while the wiggler ones are 1.4 m long . Simulations of the e^- cloud density and instability threshold with and without the voltage applied to the electrodes have been done. **With a dc voltage of 100-500 V applied to each electrode we expected a reduction of such density** by two orders of magnitude that will contribute to reduce substantially the source of the instability.



Simulation using ECLOUD code of electron cloud build-up and suppression with clearing electrodes.



Bunch population	2.1×10^{10}
Bunch spacing L[ns]	2.7
Bunch length σ_z [mm]	18



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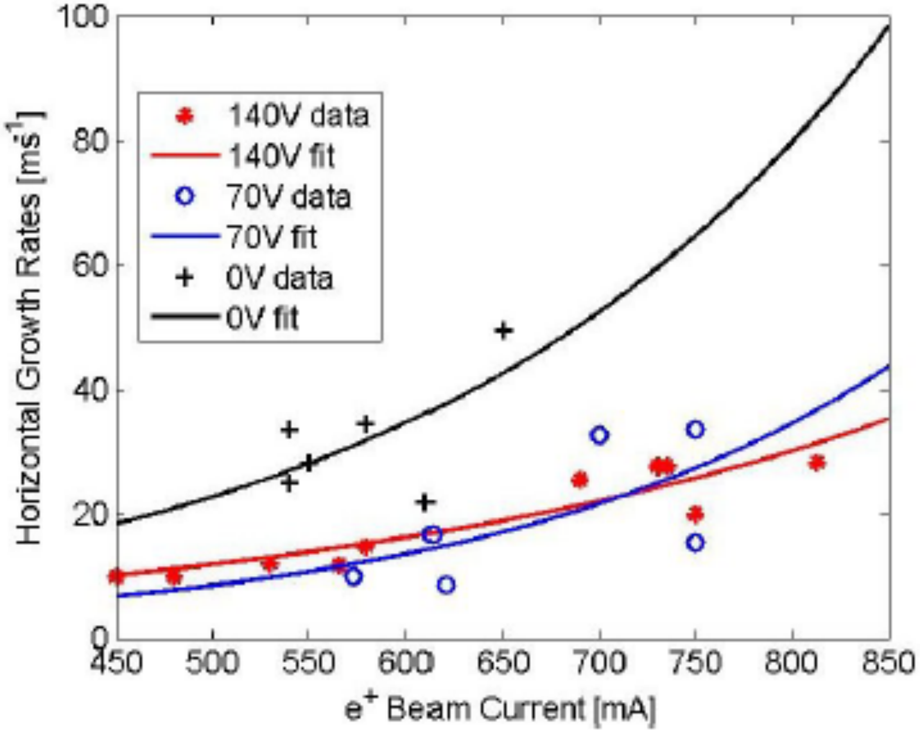
DAΦNE Growth rate of the horizontal instability

Growth rates measurements of the coupled bunch instabilities can be performed by means of the bunch by bunch transverse feedbacks. With ***electrodes OFF,*** the growth rate of the horizontal instability at 650 mA exceed 50 ms^{-1} and the measurements above this current becomes quite difficult since the beam is strongly unstable. With ***electrodes ON***, these growth rates are strongly reduced and it is possible to store a higher stable current.



Total length of the electrodes
L_{CE} = 15.5 m

Circumference
C = 97 m

L_{CE}/C = 16%

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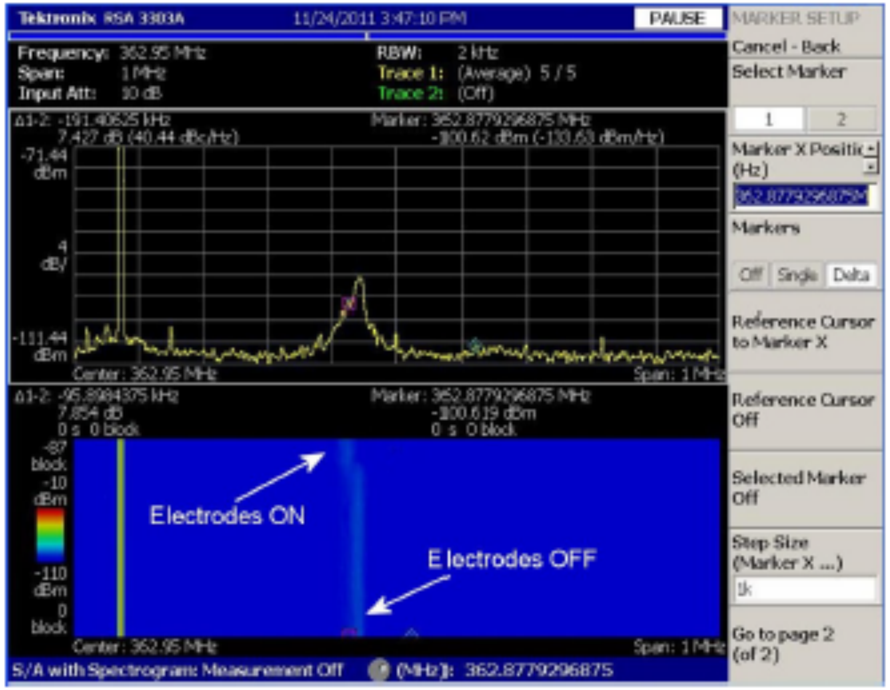
DAΦNE - Tune shift and beam size measurements

Horizontal tune shift measurements with electrodes on and off (in figure the case of 550 mA). The frequency shift of the horizontal tune line switching off all electrodes is ≈20 kHz which correspond to a difference in the **horizontal tune of ≈0.0065.**


Tektronix RSA 3303A 11/24/2011 3:47:10 PM

Frequency: 362.95 MHz
Span: 1 MHz
Input Att: 10 dB
RBW: 2 kHz
Trace 1: (Average) 5 / 5
Trace 2: (Off)

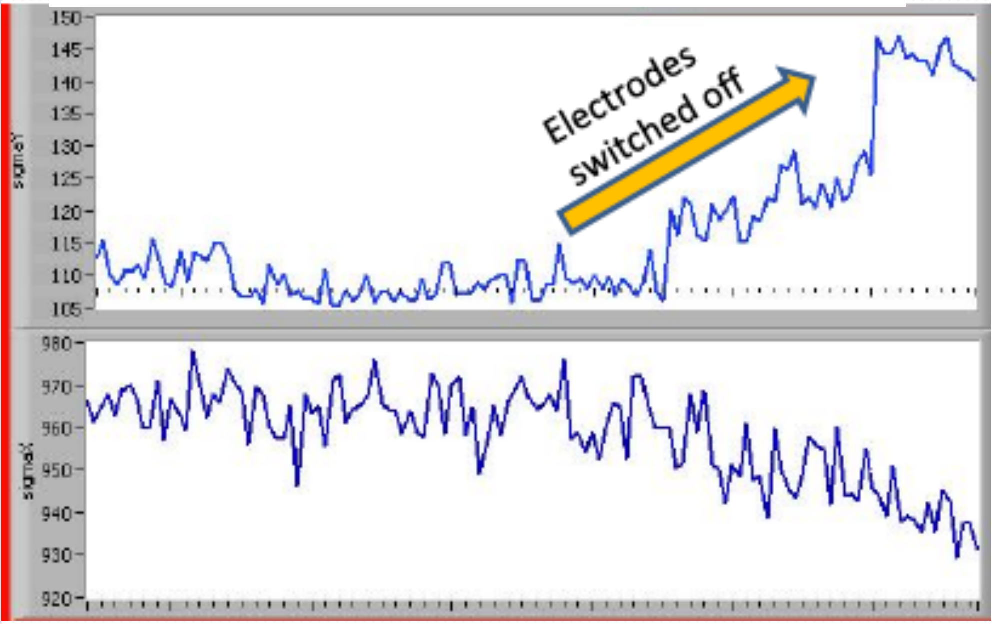
Δ1-2: -191.40625 kHz 7.427 dB (40.44 dBc/Hz)
Marker: 362.8779296875 MHz -100.62 dBm (-133.63 dBm/Hz)

Δ1-2: -95.8984375 kHz 7.854 dB 0 s 0 block
Marker: 362.8779296875 MHz -100.619 dBm 0 s 0 block

Marker X Position (Hz): 362.8779296875M
Step Size (Marker X ...): 1k

S/A with Spectrogram: Measurement Off (MHz]: 362.8779296875

The transverse beam dimensions (in µm) measured at the synchrotron light monitor (SLM) **turning off, progressively, all electrodes** are given in the figure. The beam vertical size goes from less than 110 µm with electrodes on to more than 145 µm with electrodes off.

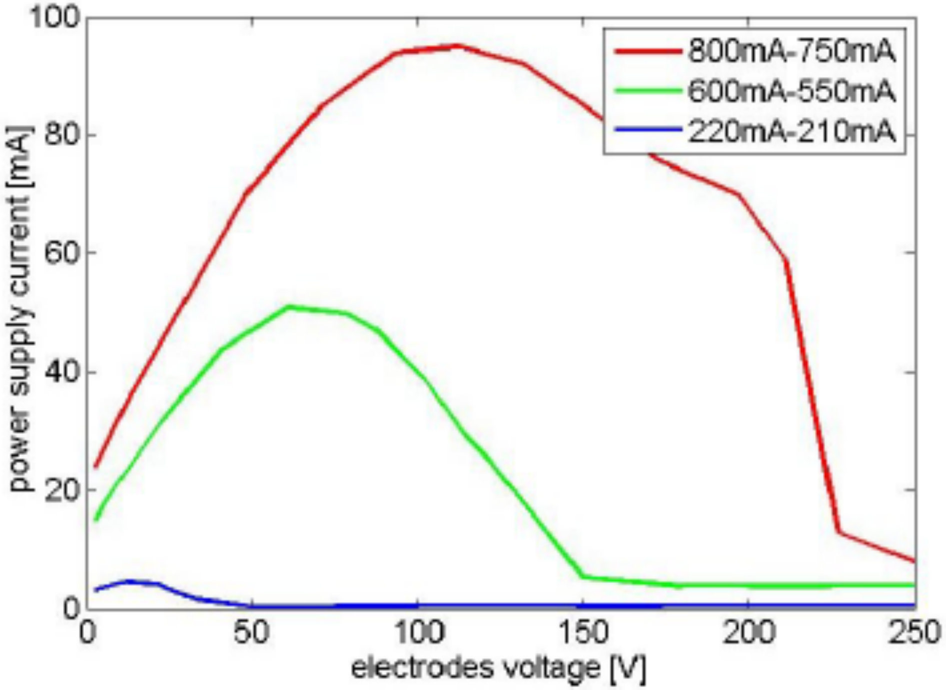


Current delivered by voltage generators

The voltage generators connected to the electrodes absorbs the photo-electrons.

In the present layout one voltage generator is connected to three electrodes of one arc (i.e. one wiggler and two dipoles).

The ***current delivered by the generator has been measured as a function of the generator voltage and for different beam currents.***



Possible explanation

Recent simulations show the same behavior

Current supplied by the generator $I \propto V_{DC} \cdot n_{e-}$

e-cloud density $n_{e-} \propto I_B - \beta V_{DC}$.

Combining the two previous relations we obtain that $I \propto V_{DC} \cdot I_B - \beta V^2_{DC}$,

The e-cloud is completely absorbed when $I \approx 0$. In all other situations there is still an e-cloud density. Fitting these curves and scaling their behaviour up to currents >1A, one discover that a voltage of the order of 250 V is no longer adequate to completely absorb the e-cloud when I_B>1A. ***So the applied voltage has to be increased.***