Cornell University
Laboratory for Elementary-Particle Physics

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Damping Rings II
Part 1: Technical Systems
Part 2: Beam Dynamics Issues

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Lecture Overview

Damping Rings Lecture I

- Part 1: Introduction and DR Basics
  - Overview
  - Damping Rings Introduction
  - General Linear Beam Dynamics
- Part 2: Low Emittance Ring Design
  - Radiation Damping and Equilibrium Emittance
  - ILC Damping Ring Lattice

Damping Rings Lecture II

- Part 1: Technical Systems
  - Systems Overview and Review of Selected Systems
  - R&D Challenges
- Part 2: Beam Dynamics Issues
  - Overview of Impedance and Instability Issues
  - Review of Selected Collective Effects
  - R&D Challenges

Damping Rings Lecture II

Our objectives for today's lecture are to:

Review the technical systems and requirements for the ILC damping rings;

Review the beam dynamics issues that are expected to present the greatest challenges in the operation of the ILC damping rings;

Review key aspects of the R&D program intended to let us converge on an optimized design during the ILC Technical Design Phase.

Outline of DR Lecture II

Damping Rings Technical Systems

- Overview of selected ILC Technical Systems
- Particular focus on:
  - ILC DR Wiggler Design
  - ILC DR Kicker Design
  - ILC DR Instrumentation (selected)
- Summary of R&D Challenges

Beam Dynamics Issues

- 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 Technical Systems

The primary damping ring technical systems are:

- Vacuum System
- Magnets and Power Supplies
- Damping Wigglers
- Injection/Extraction System including Fast Kickers
- RF System
- Instrumentation
- Feedback System
- Supports and Alignment System

We will focus on the requirements and R&D on the items shown in red as part of this lecture

In addition, there are important interface issues with the ILC conventional facilities and cryogenics group. For example, temperature stability is critical to maintaining the magnet alignment requirements for stable operations. Particular engineering challenges arise in the wiggler region where the cooling system (not to mention the vacuum system) must handle the bulk of the ~3.5 MW/ring of beam radiation which is produced.

Vacuum System

The ILC DR vacuum system requirements are most closely related to the requirements for colliding beam storage rings and synchrotron light sources.

Vacuum Specifications:

- Arc Cells: <0.5 nTorr CO-equivalent
- Wiggler Cells: <2 nTorr CO-equivalent
- Straight Sections: <0.1 nTorr CO-equivalent

Recall that:
1 atm = 760 Torr
= 760 mm Hg

CO-equivalent pressure of gas species i is defined as: $P_i = P_{CO} \frac{\sigma_i}{\sigma_{CO}}$
where the σ_i are the scattering cross sections.

These requirements are driven, in particular, by the need to suppress the Fast Ion Instability in the electron DR (we will discuss the FII later in this lecture).

Special Requirements for the Vacuum System

The overall vacuum system design offers one of the most critical issues for the ILC DR. Many (*most*) critical systems interface to the vacuum system, thus presenting special challenges. Some examples are*:*

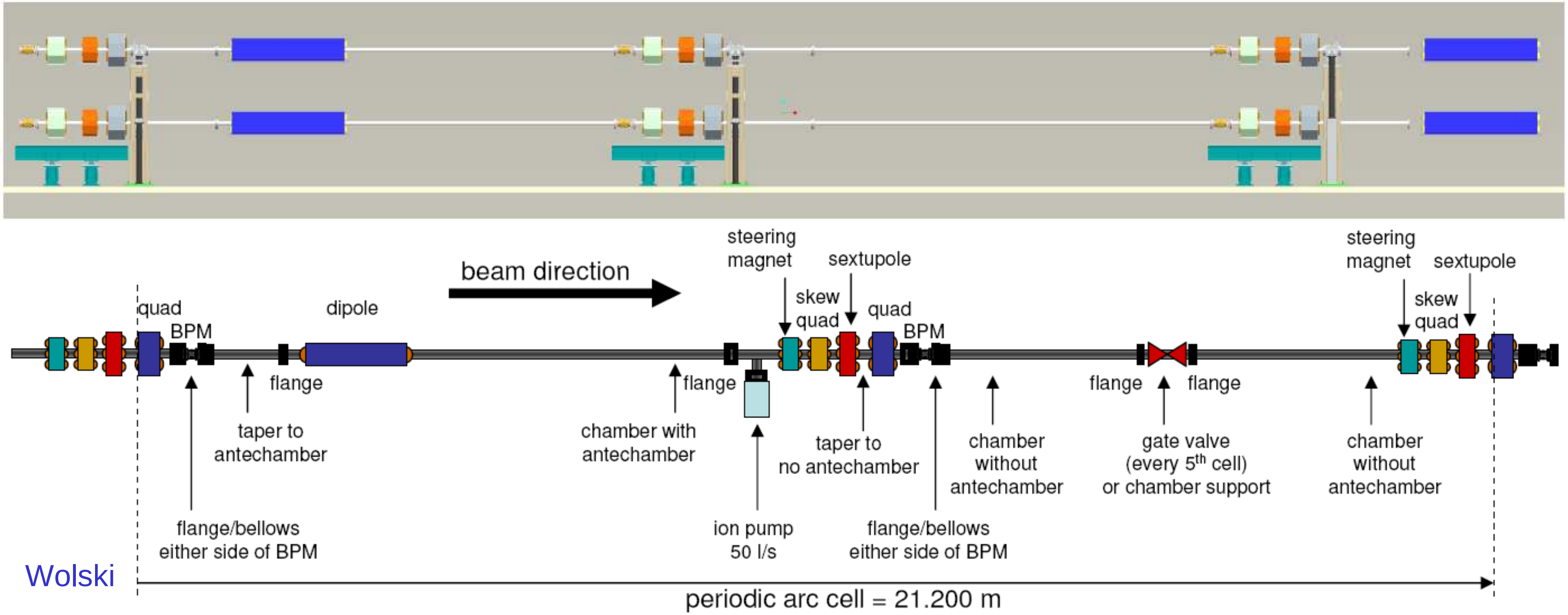
- Support for beam instrumentation and diagnostics must be incorporated. In the case of items like the beam position monitors, tight alignment tolerances to the quadrupoles must be accommodated while also dealing with potentially significant heat loads.
- Specialty hardware to mitigate specific beam dynamics effects such as the electron cloud must be added.
- Since the damping rings are a many-pass device, particular attention must be paid to developing a design that minimizes the beam impedance. The above specialty items quite often have adverse impact on the overall impedance of the vacuum system and thus require great care in their design and implementation.
- Furthermore since the key feature of damping rings is to produce large amounts of power as synchrotron radiation, the vacuum system must be able to locally handle high density power loads.
- Finally, the mechanical design must be compatible with the magnets that will be mounted around the chambers

DCO Arc Cell

In order to achieve the necessary vacuum, distributed pumping capacity via the use of Non-Evaporable Getter (NEG) coatings such as Ti.

- This requires that we be able to bake the vacuum chambers throughout the ring.
- A potential advantage of NEG coatings in the positron ring is that, in addition to providing pumping capability, these coatings also suppress secondary emission of electrons.

Vacuum chamber concept associated with the DCO lattice:

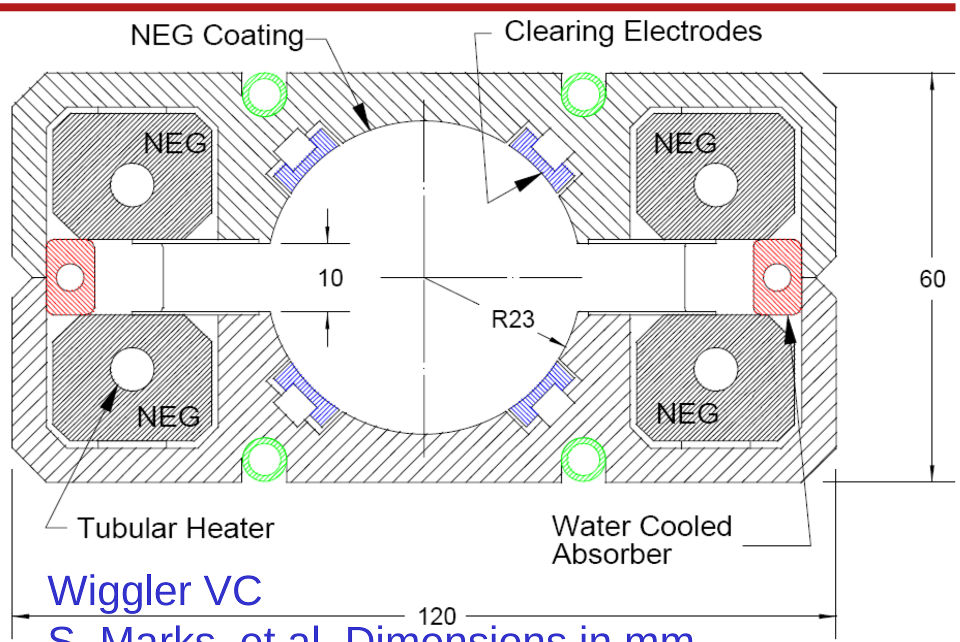


Wolski

ILC DR Vacuum System

The vacuum chambers in the wiggler regions must:

- Handle the power from the wiggler synchrotron radiation fan: ~40 kW/wiggler
- Provide pumping for photo-desorbed gases
- Suppress the electron cloud



Wiggler VC
S. Marks, et al. Dimensions in mm

Proposed vacuum chamber styles, pumping methods and EC mitigation methods:

Region	Vacuum Chamber Style	Pumping Methods	EC Mitigation
Arcs	Antechamber	NEG Coating + Sputter Ion Pumps (SIPs)	Coatings? Grooves? Electrodes?
Generic Straight Sections	Tube	NEG Coating + SIPs	Solenoids in drifts
Wiggler Straight Sections	Antechamber	NEG Strips	Coatings? Grooves? Electrodes?

ILC DR Wigglers

The damping ring wigglers are the first technical area that we will explore in somewhat greater detail.

Damping wigglers have been used in a number of rings to control the emittance of the machine. The first wiggler-dominated ring was the CESR-c ring which was used to study charm physics in conjunction with the CLEO-c detector from 2003 until early 2008.

From our discussion yesterday, the ring emittance in the presence of wigglers can be written as:

$$\varepsilon_0 = \frac{\varepsilon_{dip}}{1+F} + \frac{\varepsilon_{wig} F}{1+F} \quad \text{where} \quad F = \frac{U_{wig}}{U_{dip}}$$

In a wiggler-dominated ring, the location of the wigglers determines what that emittance may be. Clearly, if the wigglers are located in zero dispersion regions, the wiggler contribution to the emittance can be made quite small. On the other hand, by placing the wigglers in regions with dispersion, the emittance of the ring can be controlled by tailoring the dispersion function at the wiggler locations.

Emittance in a Wiggler-Dominated Ring

The emittance in a wiggler dominated ring can be written as:

$$\varepsilon_x = C_q \frac{\gamma^2 \left\langle \frac{\mathcal{H}}{\rho^3} \right\rangle}{J_x \left\langle \frac{1}{\rho^2} \right\rangle} = C_q \frac{\gamma^2 I_{5wig}}{J_x I_{2wig}}, \qquad C_q = 3.8319 \times 10^{-13} m$$

where J_x is the damping partition number and the radiation integrals are evaluated in the wiggler. If the wiggler are located in zero dispersion regions, it can be shown that the wiggler-dominated emittance is given by:

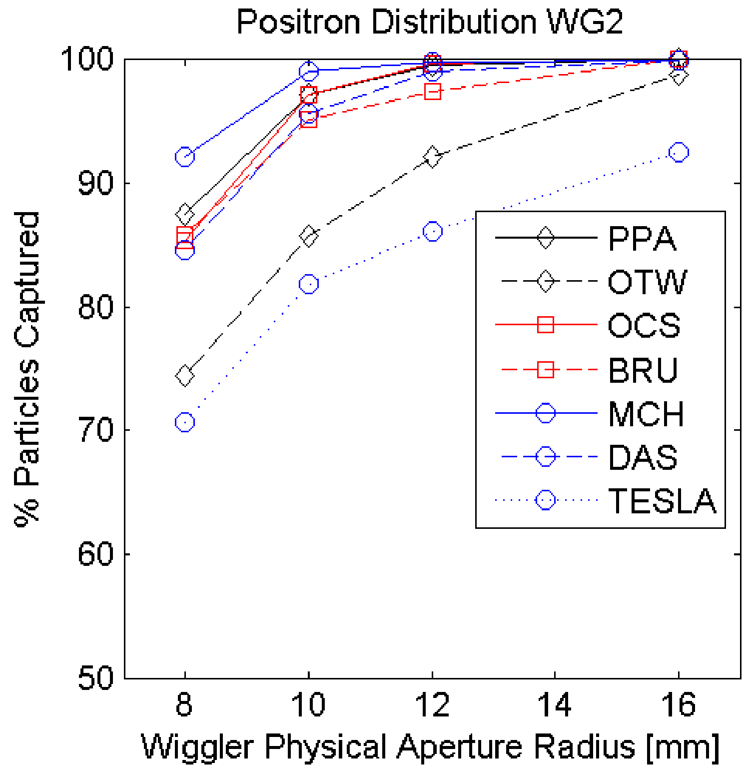
$$\varepsilon_x \approx C_q \frac{\gamma^2}{J_x} \frac{8 \langle \beta_x \rangle}{15 \pi k_p^2 \rho_w^3}$$

This will be the topic of one of today's problems.

Damping Wiggler Technical Criteria

Damping wigglers must satisfy a number of key criteria. In addition to providing the synchrotron radiation necessary to shorten the damping times and lower the emittance, they must:

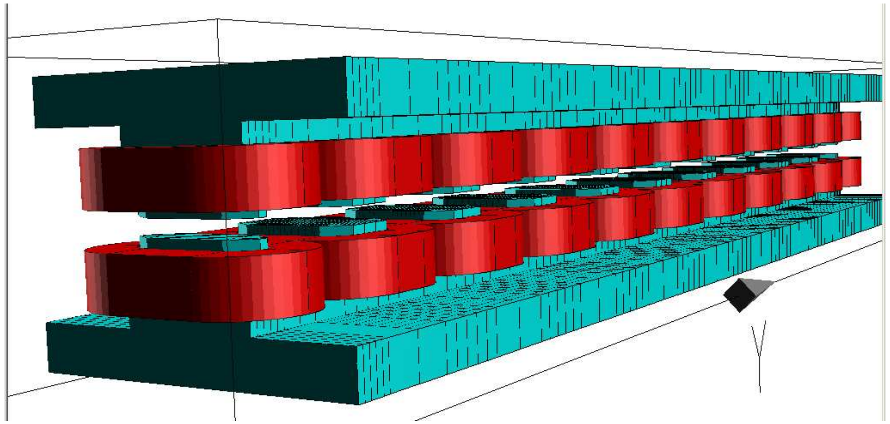
- provide sufficient aperture to allow efficient injection of positron beams which are injected with significant betatron amplitude;
- operate reliably over the long-term in an environment with large amounts of synchrotron radiation;
- have sufficient field quality such that the dynamic aperture of the ring is not compromised;
- be economical both for construction and during operation.



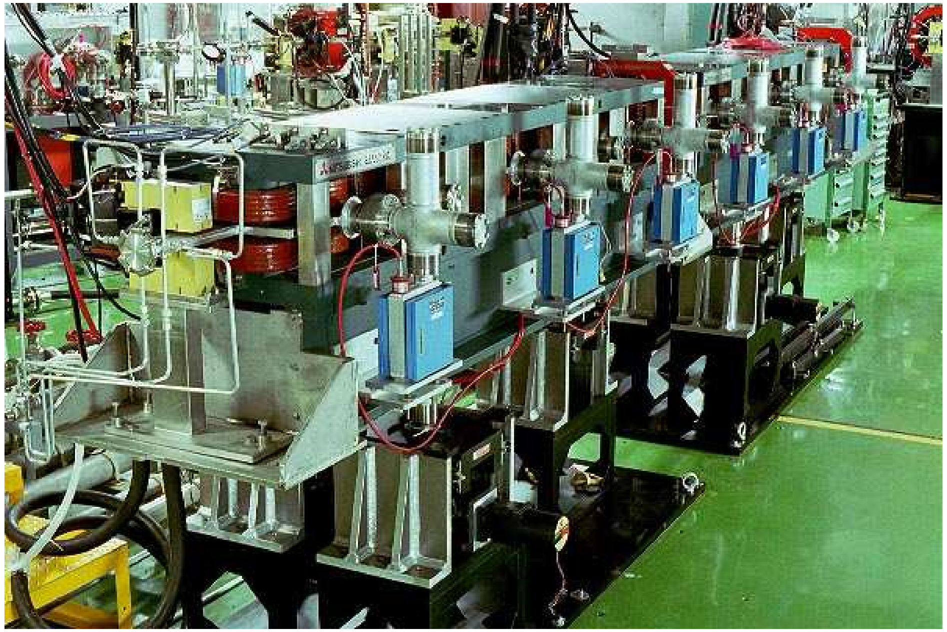
Three distinct wiggler technologies have been evaluated for use in the ILC DR: Normal conducting electromagnetic, permanent magnet hybrid, and superferric designs.

Normal Conducting Wigglers

Normal conducting wigglers have been used in a number of rings to provide additional damping. This is a proven technology with moderate construction costs, good resistance to radiation damage, and proven reliability. However, the large length of wiggler required for the damping rings means that operational costs will be quite high. It is also challenging to provide the desired vertical aperture without significantly increasing the power requirements.



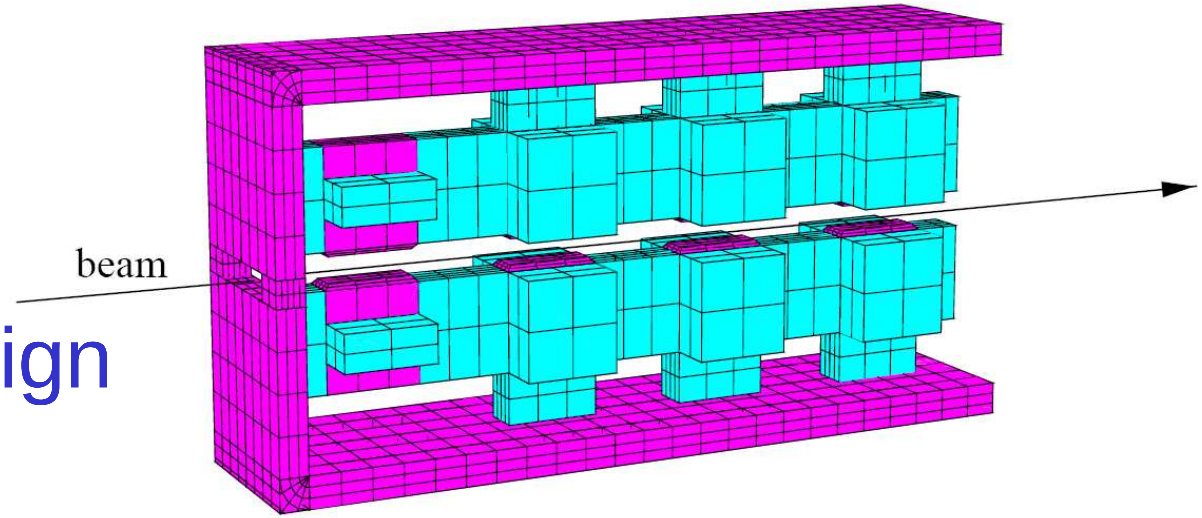
ATF Damping Wiggler



Permanent Magnet Hybrids

Permanent magnet hybrids use iron poles in conjunction with PM material to provide the field. The great advantage of a PM-based wiggler is that it is a passive device and requires no power. On the other hand, this solution requires a large amount of magnetic material in order to achieve the large physical aperture which is desired for the ILC DR wiggler. The design also requires careful pole tip shimming in order to avoid adverse impact on the DR dynamic aperture. Finally, the PM material is sensitive to radiation losses and could degrade over time.

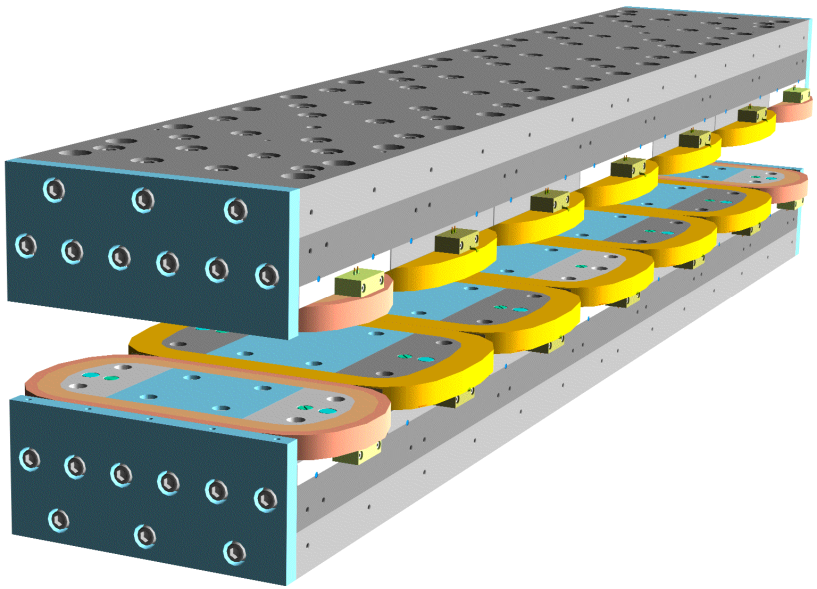
TESLA TDR Design



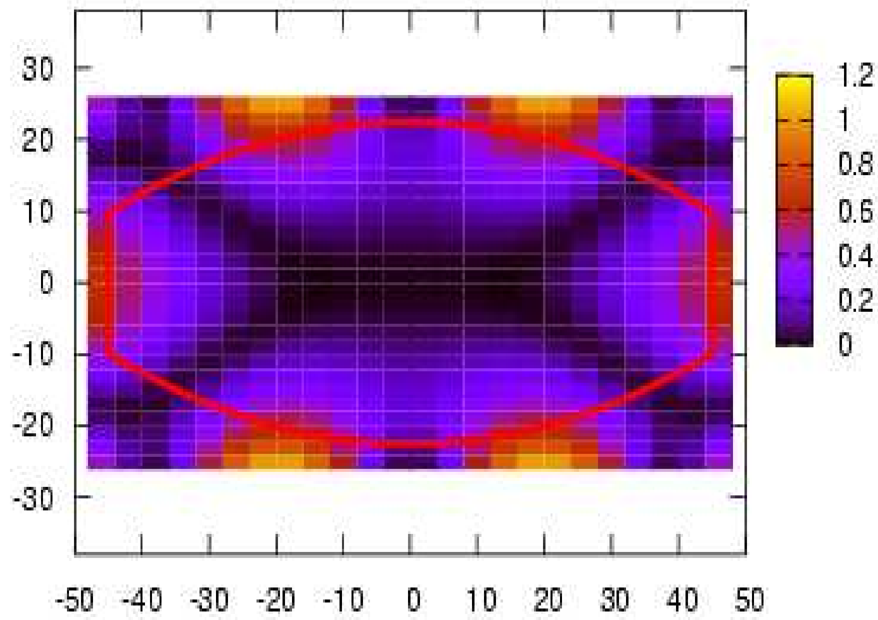
Superferric Wigglers

The CESR-c wiggler design was developed to provide damping in the CESR storage ring. They are a high field (2.1 T) design.

- Operating energy: 5.29 GeV for colliding beam operations at the ψ(4s) resonance ➪ operation in the1.8-2.5 GeV range to study charm and tau physics.
- Colliding beam operations at CESR utilized counter-rotating beams in a single vacuum chamber with electrostatic separation ➪ very good transverse field quality required



Fractional Error in B_y (%) for the CESR-c Wiggler



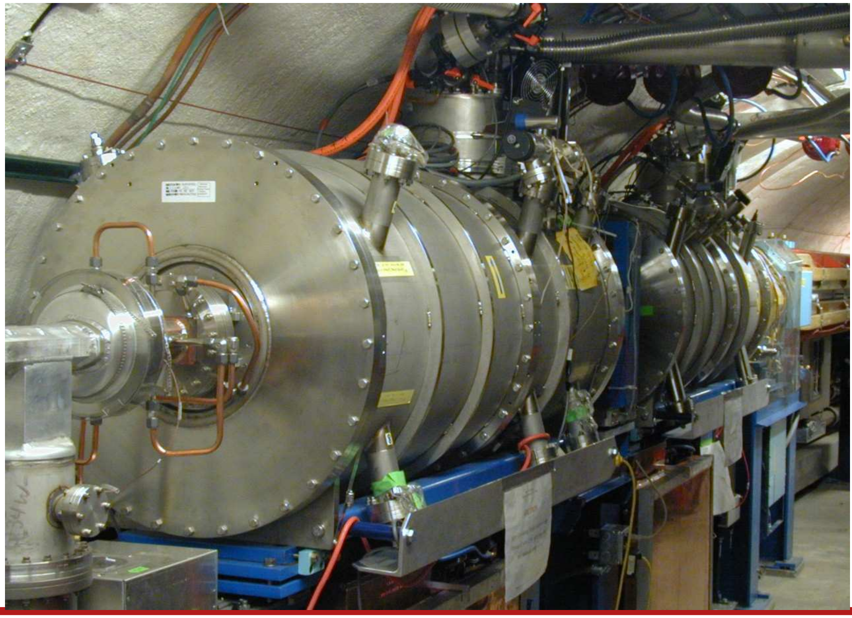
Superferric Wigglers

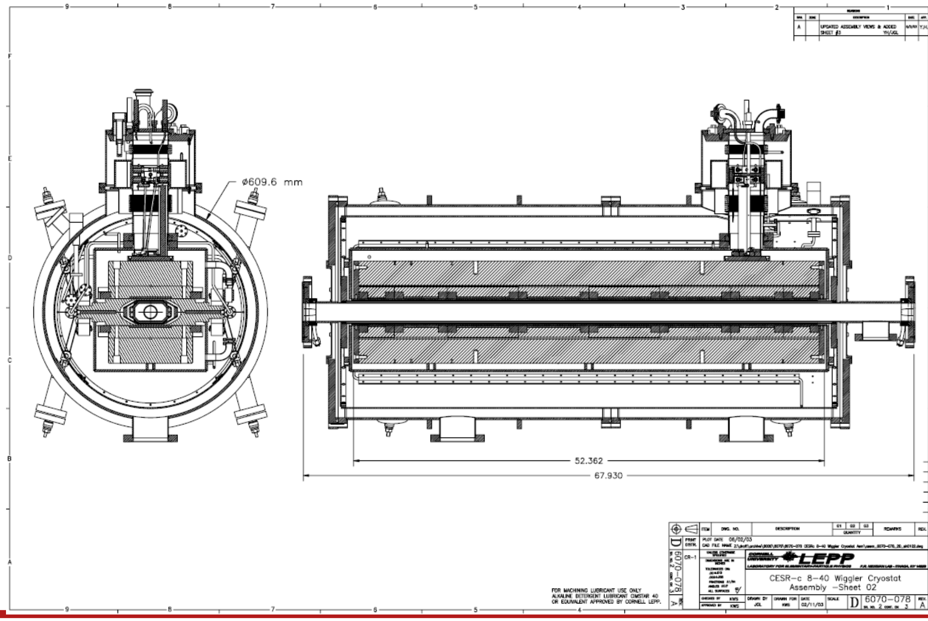
The advantages of the CESR-c design are:

- a proven high field wiggler
- extremely good field quality
- thus meets both the ILC DR field and field quality needs

Nevertheless, the superconducting design adds complexity:

- Cryogenics: cryostat adds to construction costs, cryogenics support needed for operation. Care must be taken to minimize radiation losses into cold mass.
- Vacuum chamber becomes trapped in cryostat





Wiggler Comparison

	TESLA	CESR-c	Modified CESR-c
Period	400 mm	400 mm	400 mm
$B_{y,peak}$	1.67 T	2.1 T	**1.67 T**
Gap	25 mm	76 mm	76 mm
Width	60 mm	238 mm	238 mm
Poles	14	8	**14**
Periods	7	4	**7**
Length	2.5 m	1.3 m	2.5 m

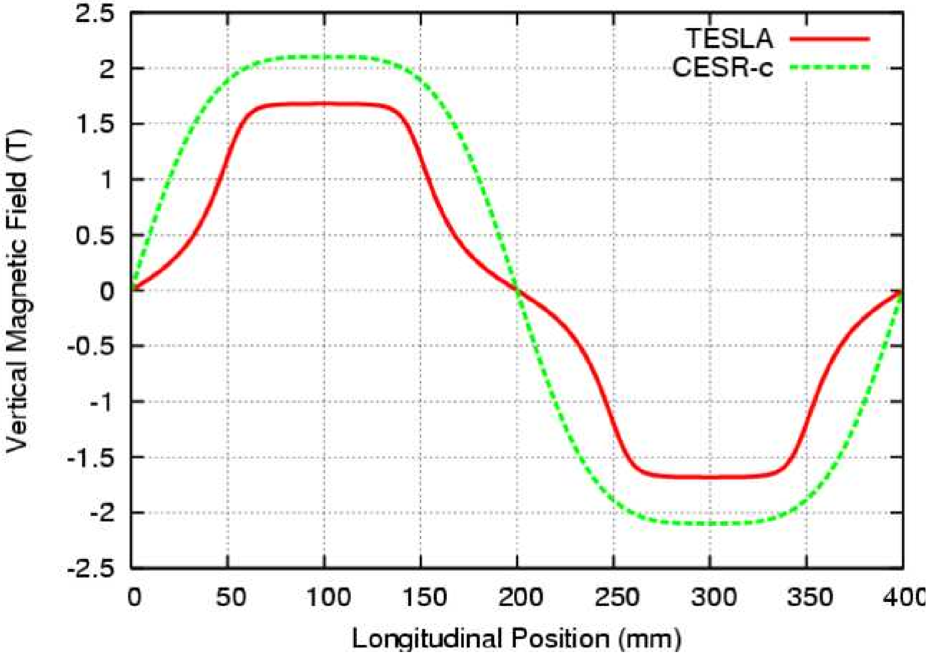
Wiggler Comparison

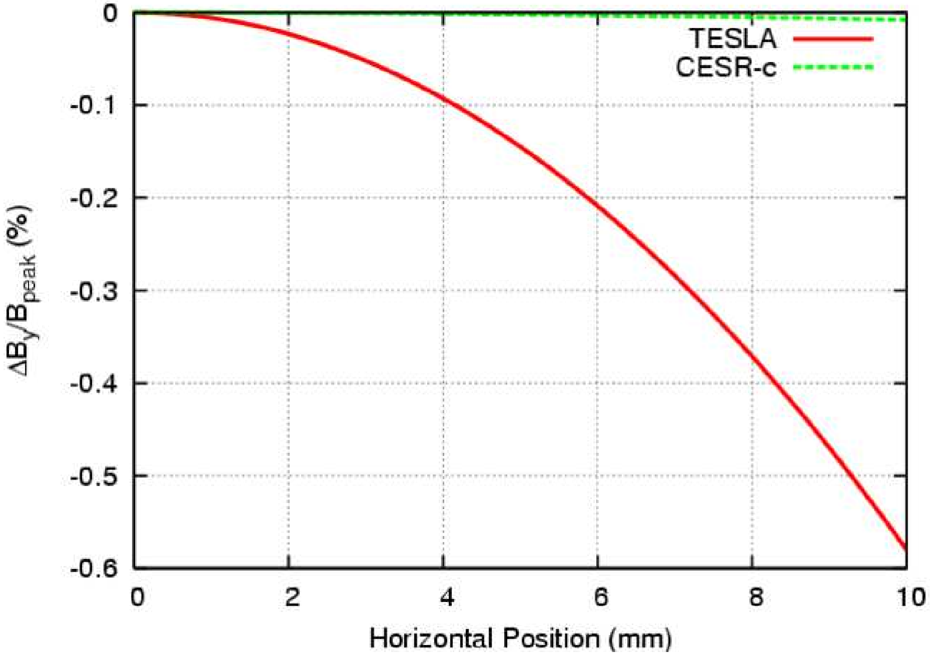
TESLA Wiggler

Hybrid permanent magnet
NdFeB with iron poles
$\Delta B_y/B_{peak}$ (x=10mm) = $5.7*10^{-3}$

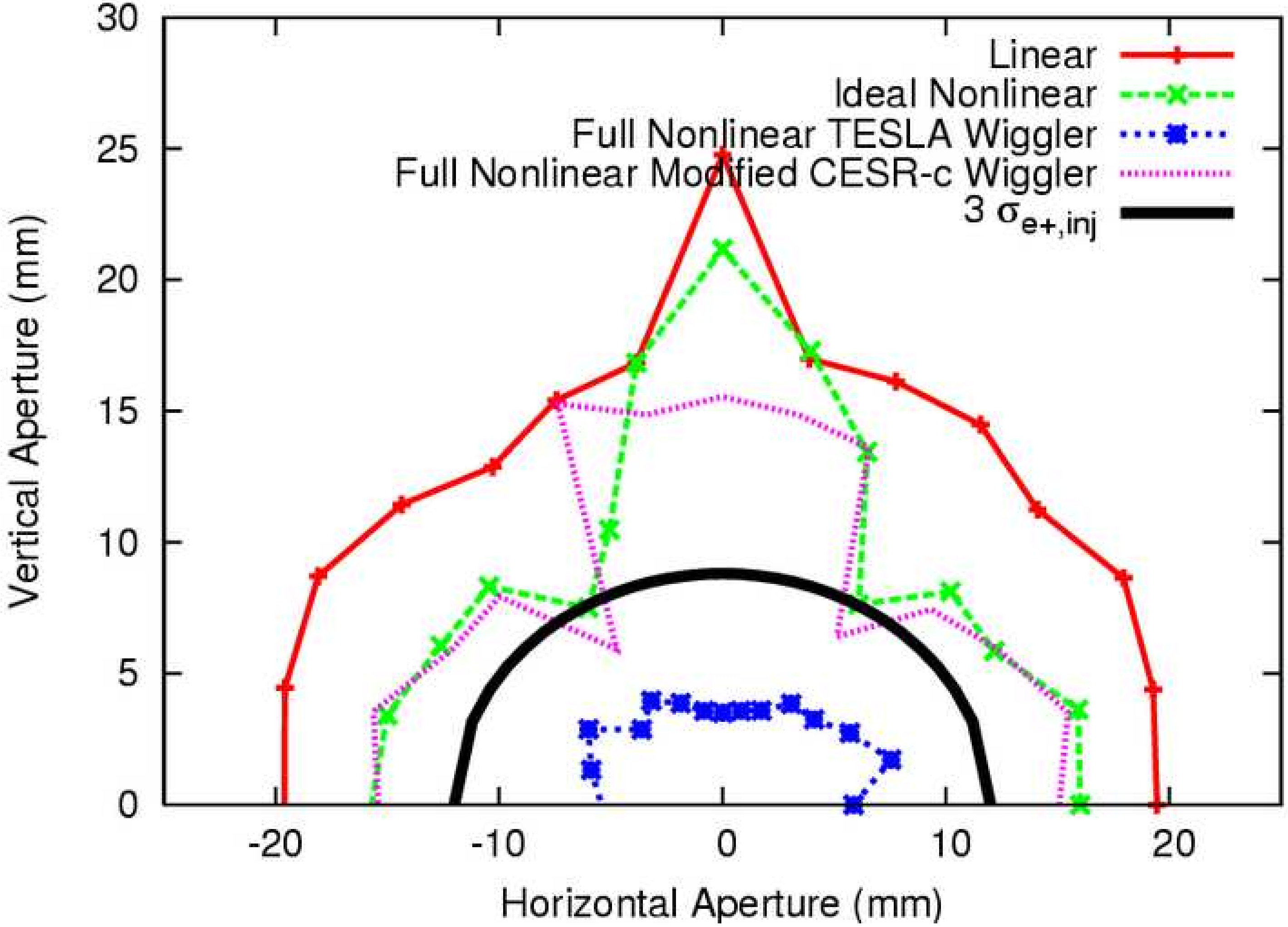
CESR-c Wiggler

Superferric magnet
NbTi coils with iron poles
$\Delta B_y/B_{peak}$ (x=10mm) = $7.7*10^{-5}$



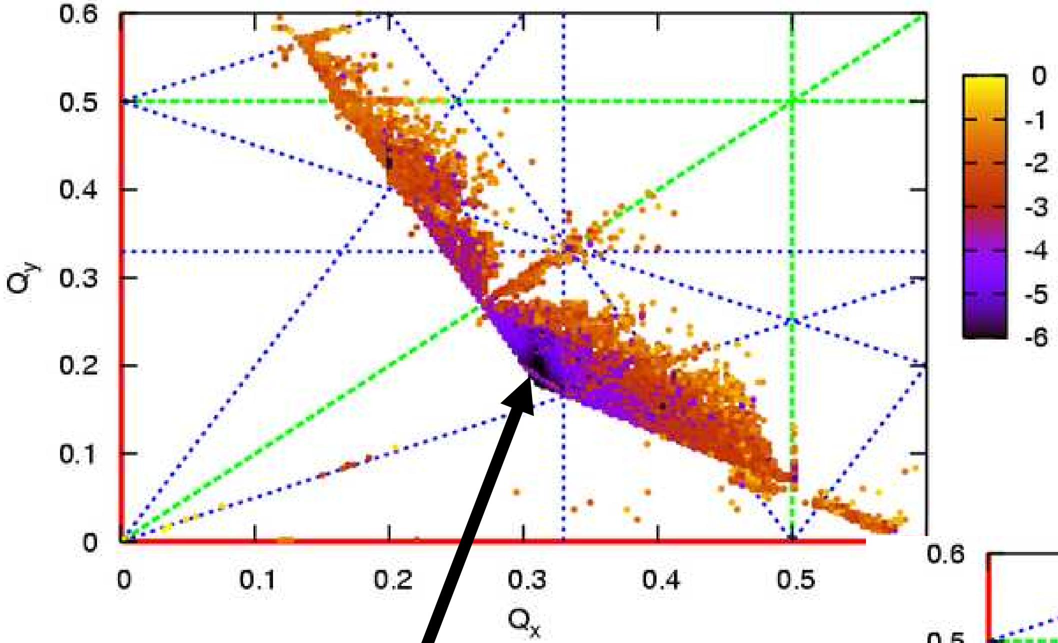


Dynamic Aperture



Frequency Map Analysis

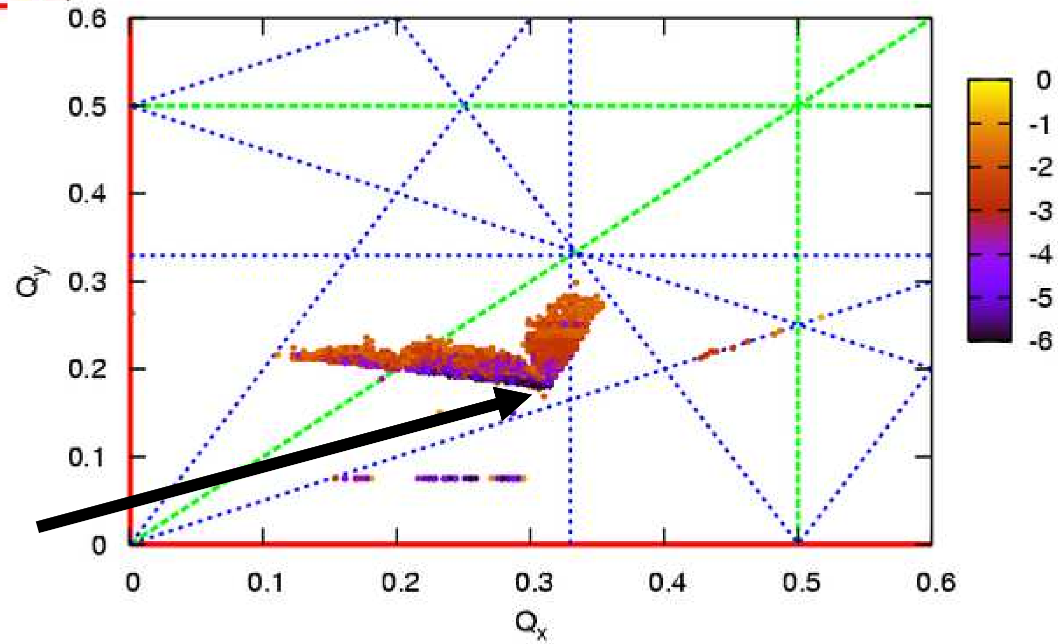
TESLA



Operating point

$$color = \log\left(\sqrt{\Delta Q_x{}^2 + \Delta Q_y{}^2}\right)$$

Modified CESR-c Wiggler



Operating point

Wiggler Optimization

Let's return to the expression for the wiggler emittance:

$$\varepsilon_x \approx C_q \frac{\gamma^2}{J_x} \frac{8\langle \beta_x \rangle}{15\pi k_p^2 \rho_w^3}$$

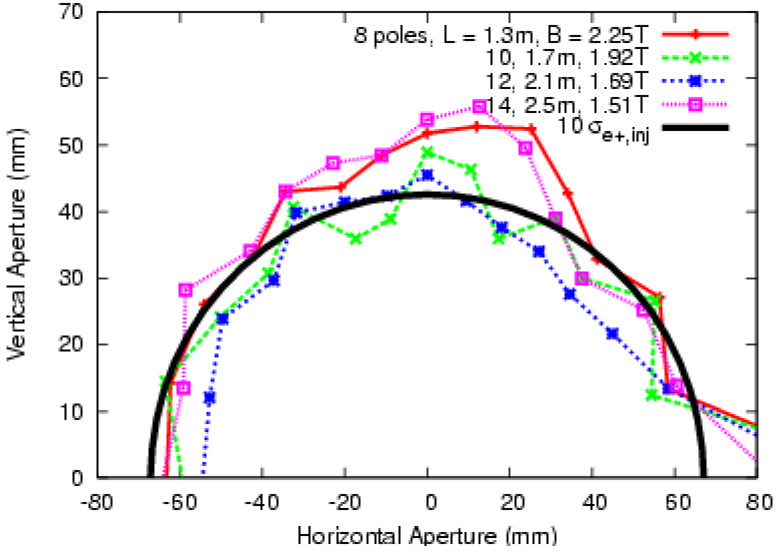
The wiggler contribution to the emittance can be lowered by:

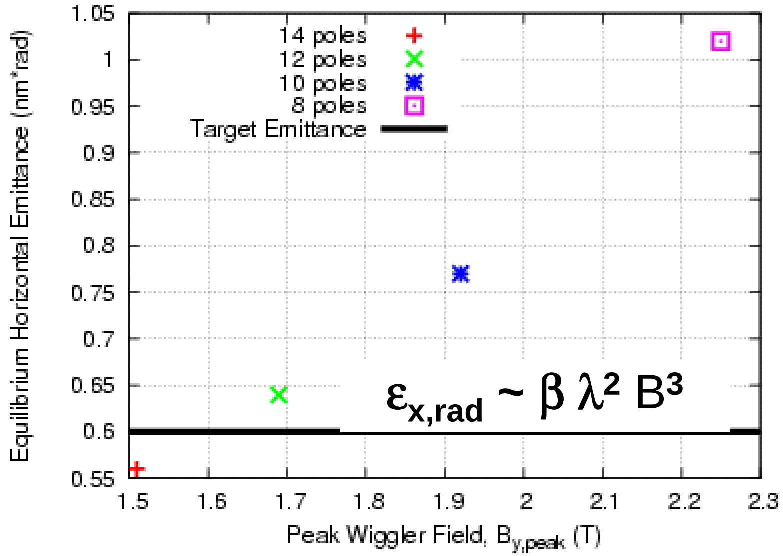
- Reducing the beta function in the wiggler
- Employing a shorter period
- Employing lower peak field

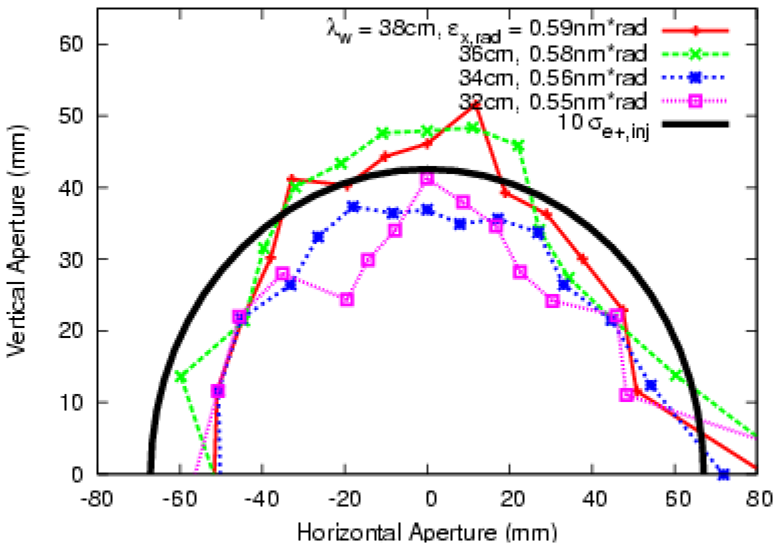
There are both positive and negative impacts:

- This will impact the energy spread – must take care to not exceed the energy acceptance of the downstream bunch compressors
- Shorter wigglers offers greater opportunity to handle synchrotron radiation outside the wiggler, hence minimizing radiation and heat load issues.
- Larger vertical gap allows more flexible access for vacuum chamber inside the cryostat in the superferric design

Optimizations







Fewer poles require higher fields which raises the emittance, a shorter period can counteract this with minimal DA degradation.

Optimize with:

12 poles and period = 32 cm

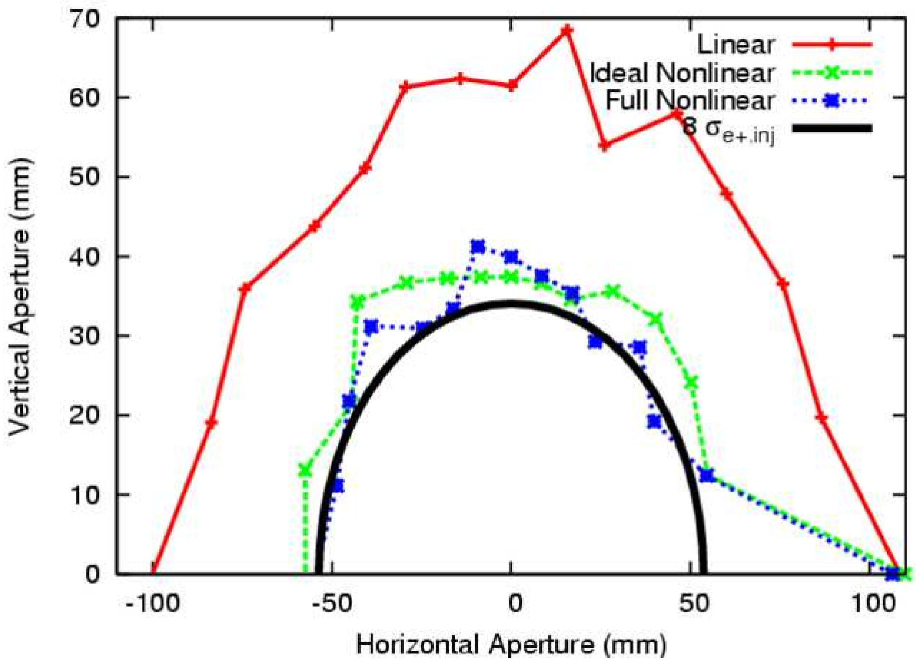
vs

14 poles and period = 40 cm

Parameters for an Optimized Wiggler

Superferric ILC-Optimized CESR-c Wiggler

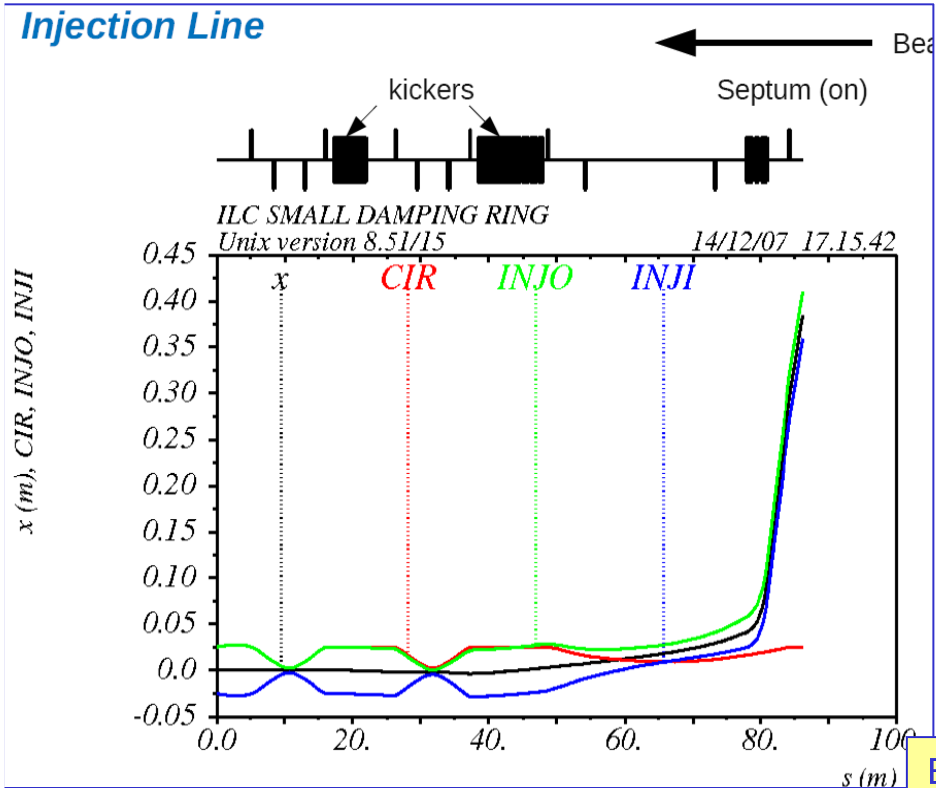
- 12 poles
- Period = 32 cm
- Length = 1.68 m
- $B_{y,peak}$ = 1.95 T
- Gap = 86 mm
- Width = 238 mm
- I = 141 A
- τ_{damp} = 26.4 ms
- $\varepsilon_{x,rad}$ = 0.56 nm·rad
- σ_δ = 0.13 %

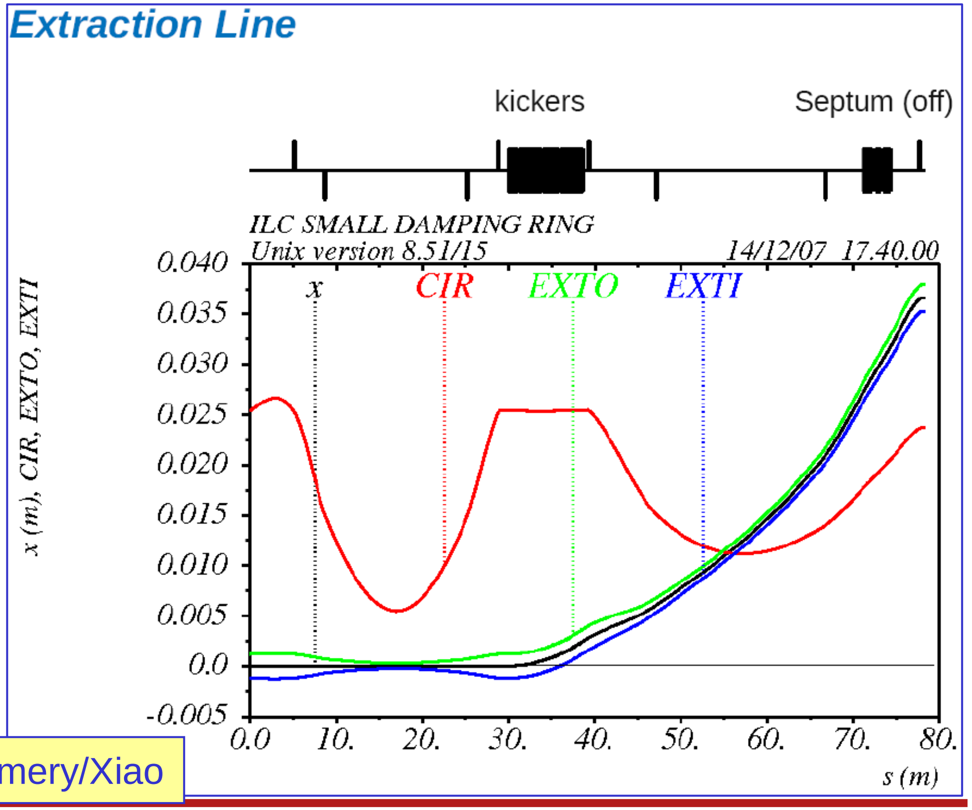


Optimized superferric design offers significant cost savings while still meeting all key design specifications

Injection and Extraction Systems

The injection and extraction scheme in the ILC damping rings is quite challenging. Bunches must be injected and extracted individually without affecting the neighboring bunches.

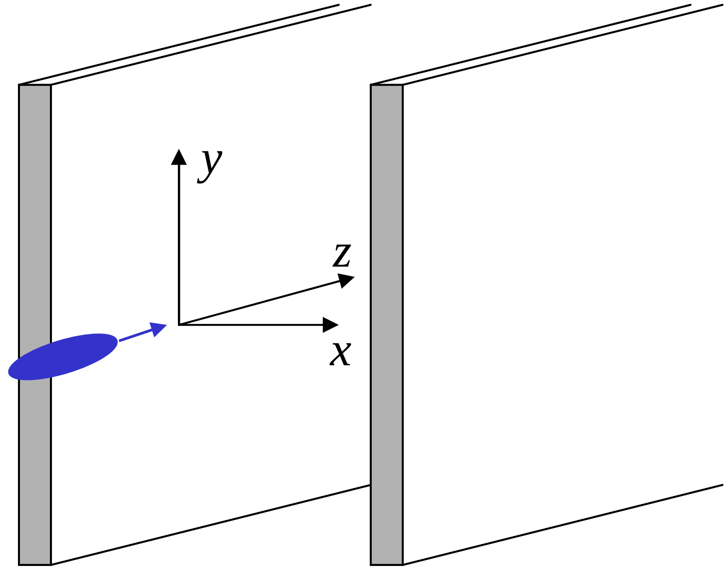




Emery/Xiao

Stripline Kickers

In order to elucidate the operation of stripline kickers, we consider the simplified geometry of 2 planar configured to provide kicks in the horizontal plane with nominally infinite extent in the vertical…



A voltage pulse applied to one end of the electrodes will produce a traveling wave with

$$E_x = E_0 e^{i(kz-\omega t)} \quad \text{and} \quad B_y = \frac{E_0}{c} e^{i(kz-\omega t)}$$

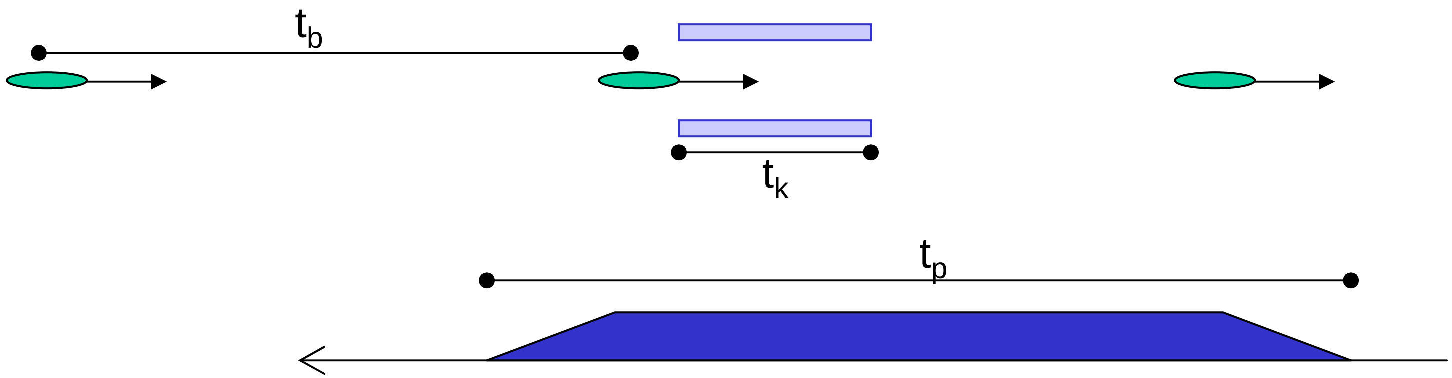
An electron moving in the $+z$ direction with velocity βc will experience a force:

$$F_x = q\left(E_x - v_z B_y\right) = q\left(1-\beta\right) E_0 e^{-(1-\beta)\omega t}$$

For $\beta \sim 1$, the forces will cancel when the particle travels with the pulse but will add when the particle travels oppositely to the pulse.

Structure Filling and Kick

Top View



We want to consider the above geometry of the kicker structure. The timing constraint on the length of the kicker structure, pulse, and bunch spacing can be written as: $t_p \leq 2(t_b - t_k)$

This condition ensures that the pulse does not affect either the bunches ahead/behind the bunch being kicked. For a bunch spacing of 3.1 ns and a kicker length of 30 cm, this corresponds to a limit on the pulse width of ~4.2 ns.

Next we will consider the impulse imparted to the bunch assuming that the bunch passes through the stripline structure when completely filled.

Stripline Kick

Assuming that:

- the stripline structure has length L
- a parallel plate model with separation d between the electrodes
- the structure is filled (ie, in the flat top of the pulse) for the duration of the bunch passage

we can write the kick that is imparted to the bunch as:

$$\Delta\theta = \frac{F_x L}{p_0 d} = 2\frac{eVL}{E_0 d}$$

where p_0 and E_0 are the nominal particle momentum and energy. This form can be generalized to:

$$\Delta\theta = 2g\,\frac{eVL}{E_0 d}$$

where g is a geometric factor representing other stripline configurations than our parallel plate case. For parallel plates with finite width, w:

$$g = \tanh\left(\frac{\pi w}{d}\right)$$

Stripline Kick

The input assumptions for the kick required to bring the bunch near enough the septum for extraction are:

- A displacement of ~30mm from center is required
- The distance between the kickers (modeled as a single unit) and septum is on the order of 10s of meters (we will use 50)

$$\Delta\theta \approx \frac{0.03}{50} = 0.6\, mrad$$

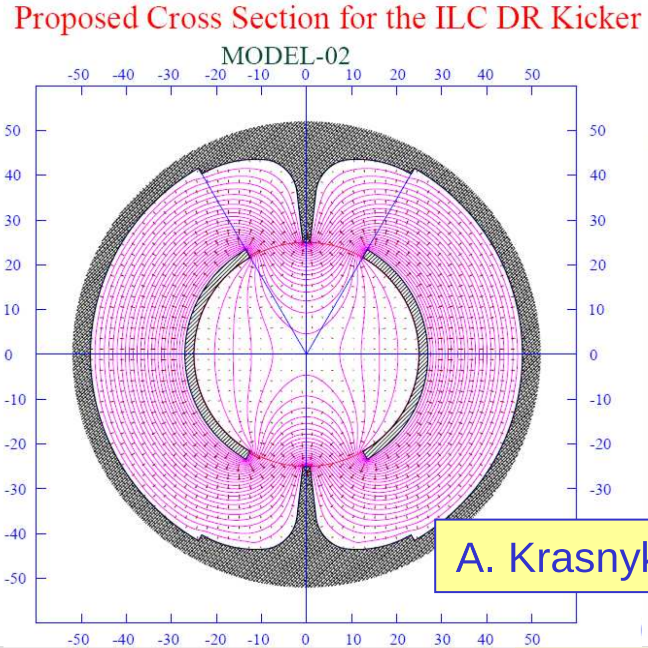
Let's take: $d = 20\, mm \qquad g = 0.7$

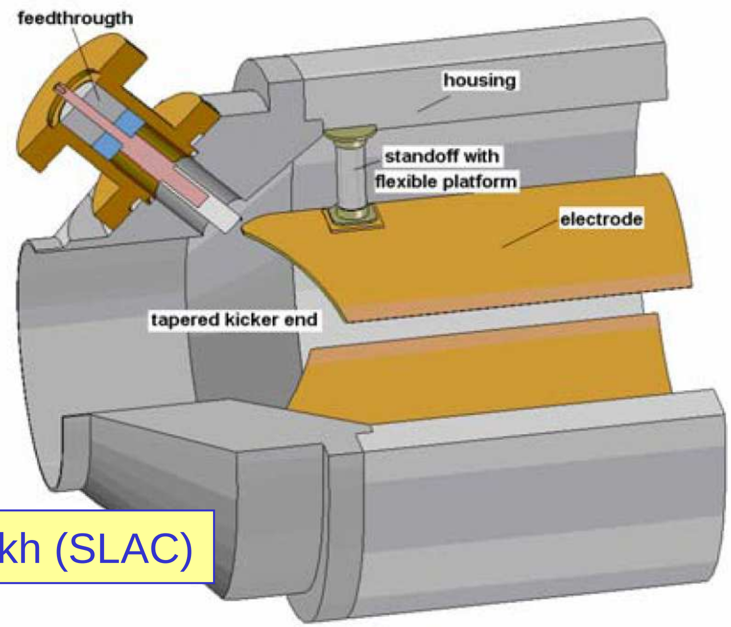
⇨ $$VL = 43\, kV - meters$$

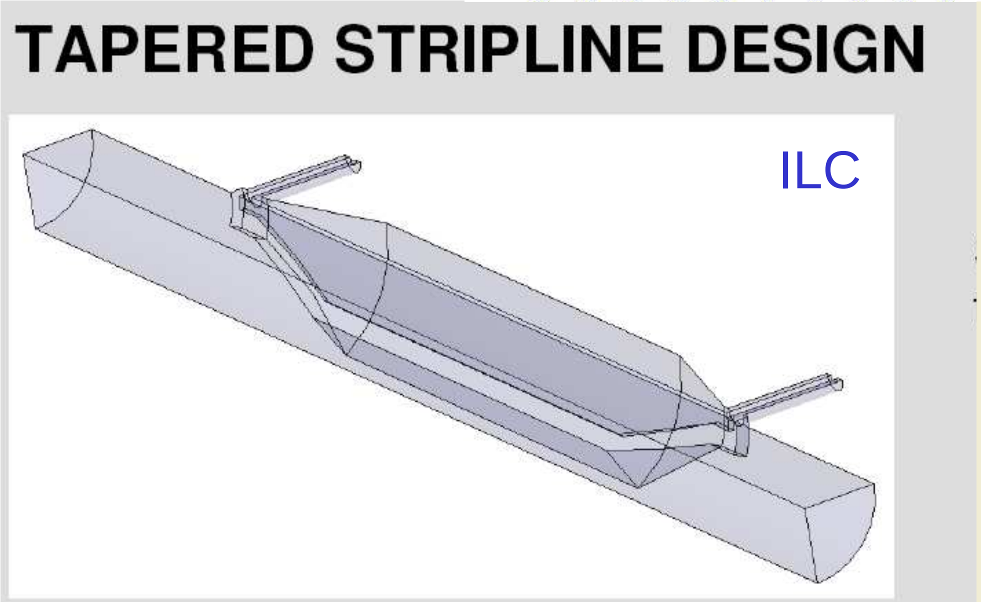
If the highest voltage pulsers available can provide 5-10 kV with the necessary rise and fall times, this immediately implies that we will need of order tens of pulsers and striplines to successfully inject or extract DR beams one bunch at a time.

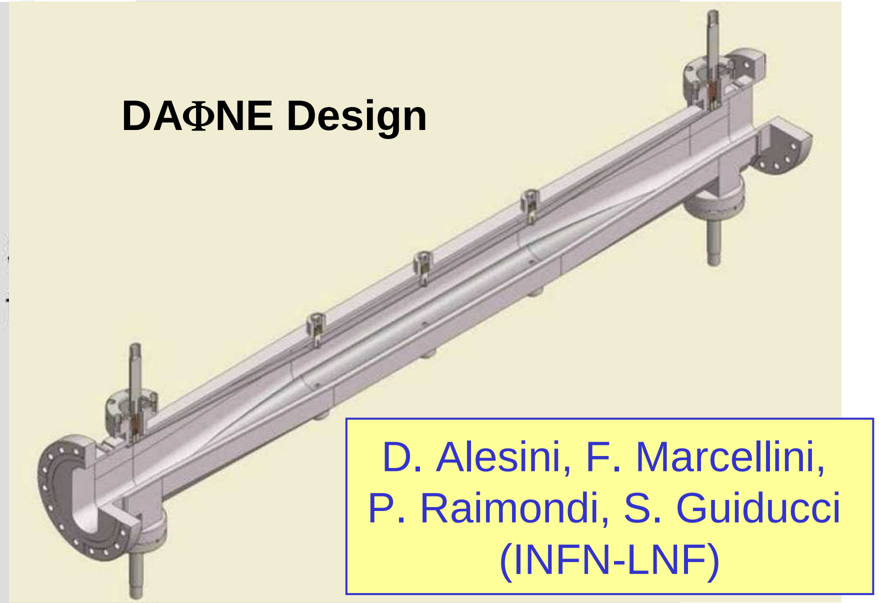
Stripline Designs

Work is underway to provide stripline kickers with the necessary field quality and suitable feedthroughs for the fast high voltage pulses required









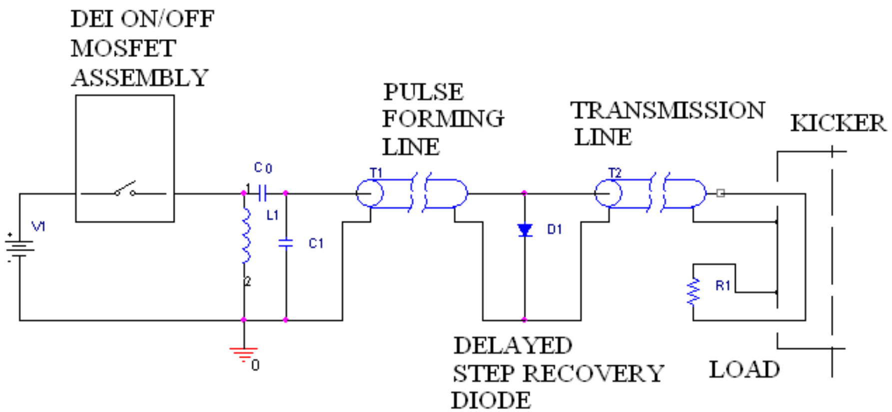
Fast Pulser Specifications

The resulting fast pulser specifications are shown in the table on the right. These parameters are somewhat beyond the current state of the art, but a major R&D effort is approaching these values.

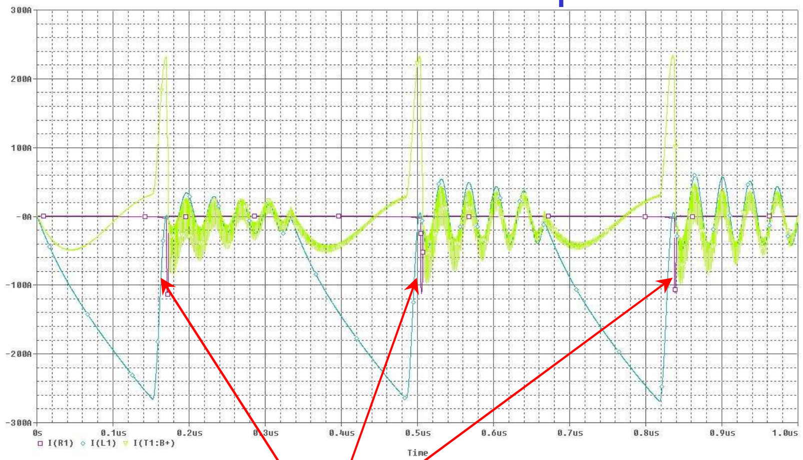
Peak Voltage	10 kV
Rise Time	~1 ns
Fall Time	~1 ns
Flat Top	~2 ns
Amplitude Stability	0.1%
Burst Rate	6 MHz
Pulse Train Length	1 ms
Average Pulse Rate	30 kHz
Pulse Train Length	1 ms

Drift Step Recovery Diode (DSRD) R&D

A. Krasnykh (SLAC)

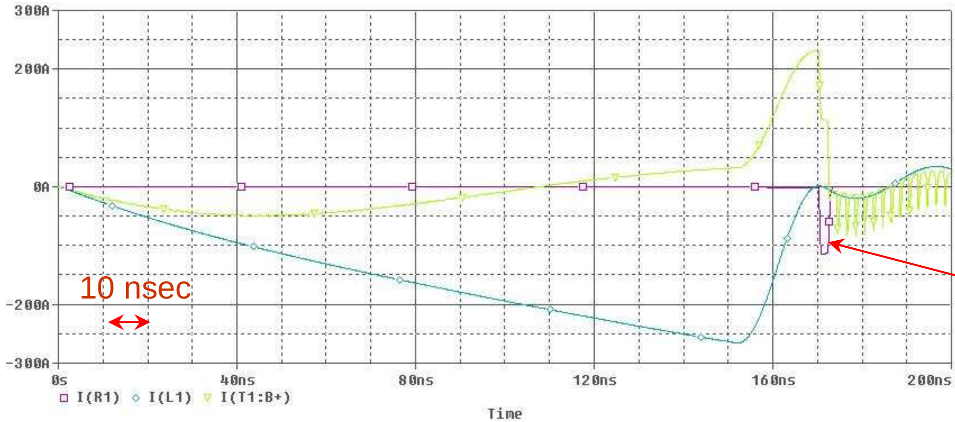


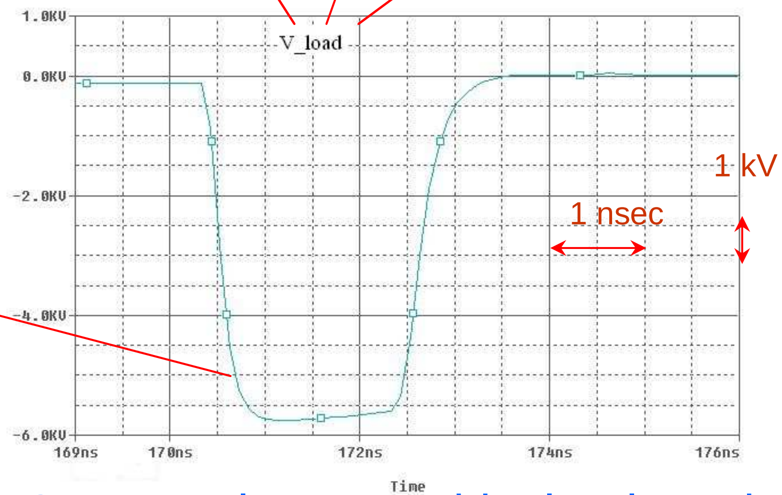
Achieved 3 MHz Rep Rate



$L=40$ nH, $C_o=30$ nF, $C_1=1.5$ nF,

$t_{on}=150$ nsec, t = 1 nsec



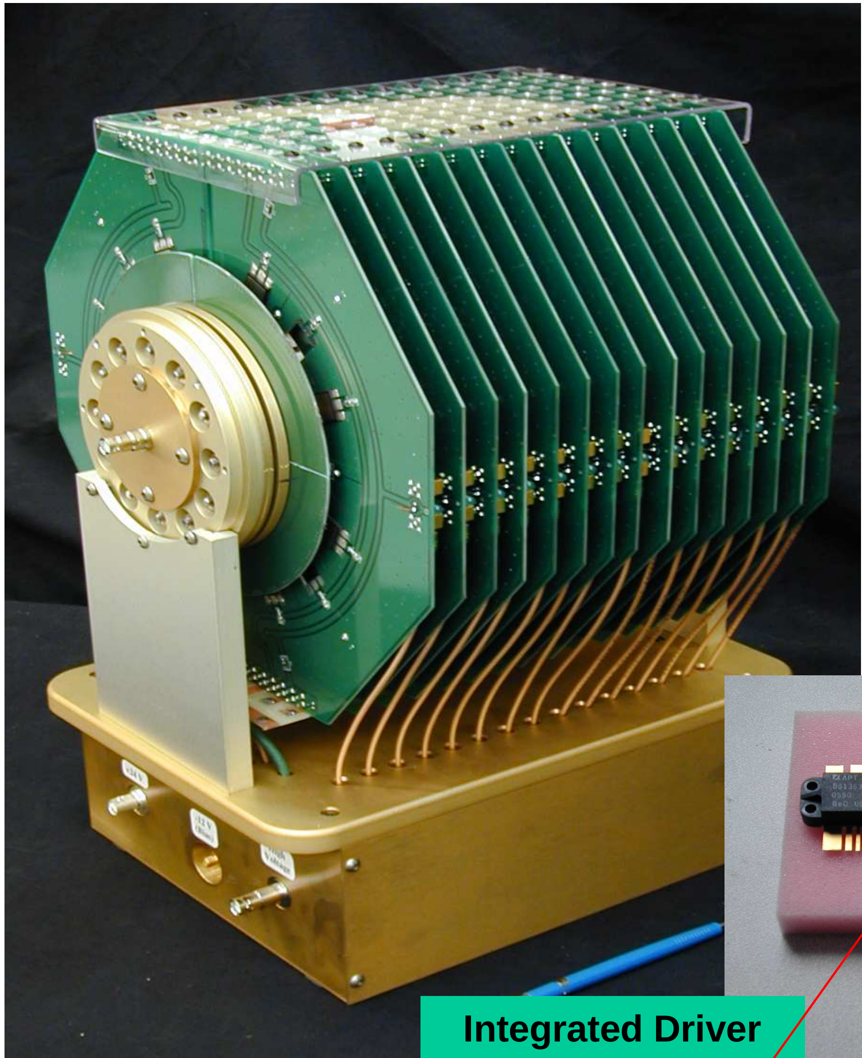


Currents vs. time for one cycle

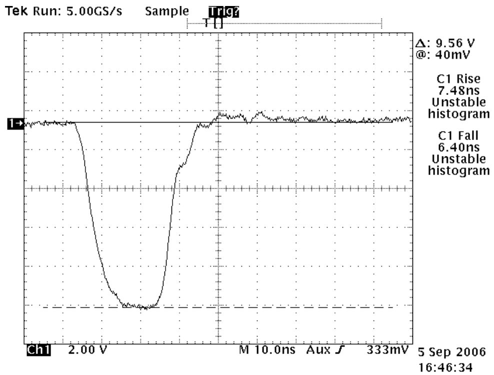
~6kV Output Voltage, Residual Voltage is ~ 2%

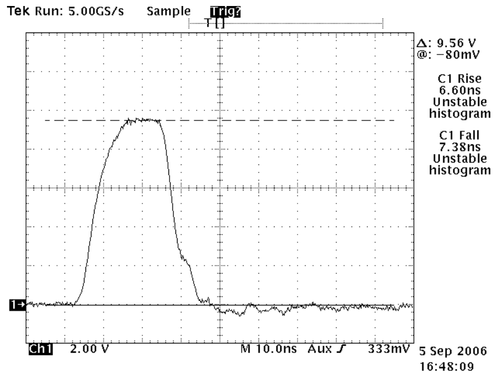
Inductive Adder (IA) Prototype

Utilizes MOSFET devices



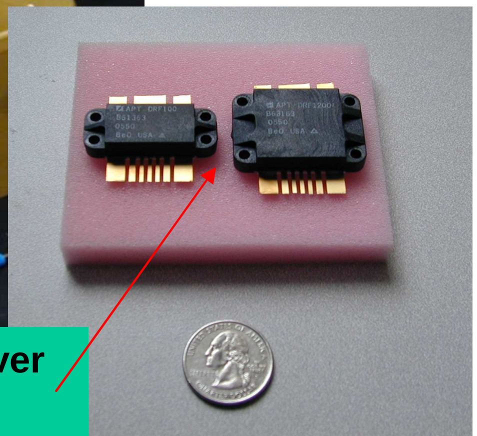
Intrinsic speed is slow for direct application to ILC DR:





±9.6 kV pulses

7 ns rise and fall times



Integrated Driver & Power MOSFET

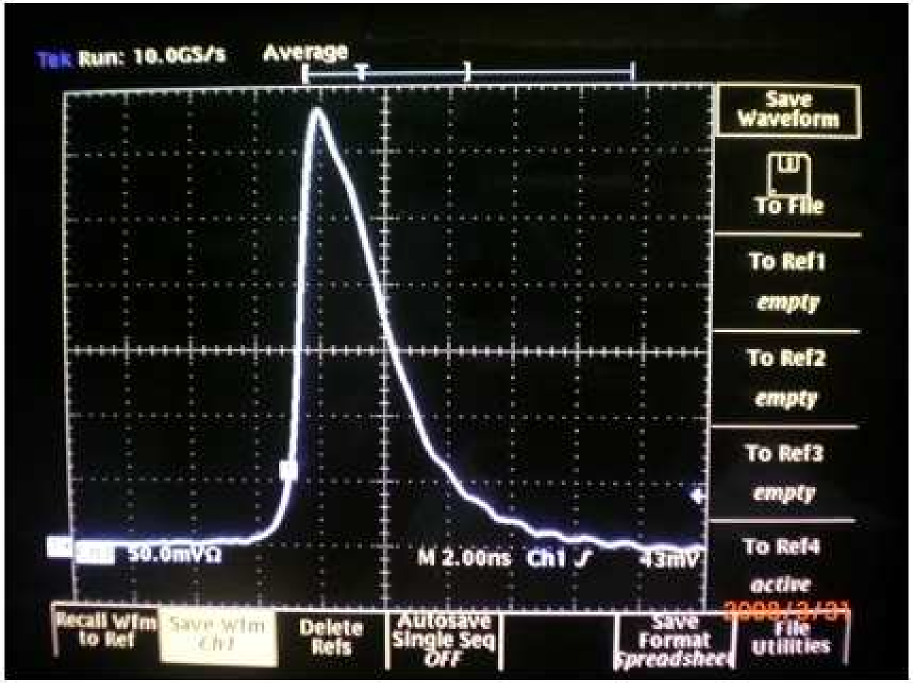
However, a hybrid Inductive Adder-DSRD device where this is the pumping stage for the DSRD is being pursued

E. Cook (LLNL)

Fast Ionization Device (FID) R&D

Tests at ATF with device targeting ±10 kV operation (T. Naito)

Pulse source(FID FPG 10-6000KN)



Specification

Maximum output voltage + 10 kV

\- 10 kV

Rise time @ 10-90% level - < 1 ns

Rise time @ 5-95% level - < 1,2 ns

Pulse duration @ 90% - 0,2-0,3 ns

Pulse duration @ 50% - 1,5-2 ns

Output pulse amplitude stability - 0,5-0,7%

Maximum PRF in burst - 6,5 MHz

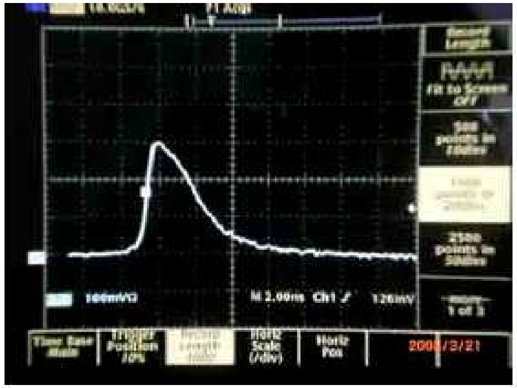
Number of pulses in burst - up to 110

PRF of bursts - up to 5 Hz

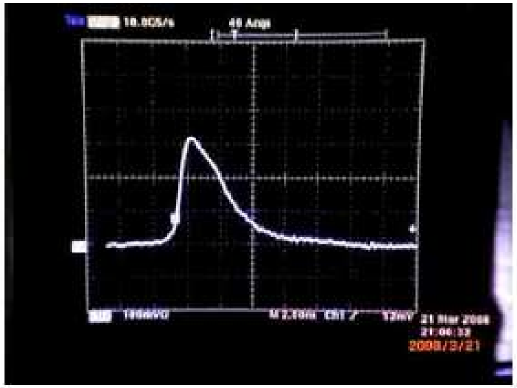
Fast Ionization Device (FID) R&D

Tests with ATF Kicker (T. Naito)

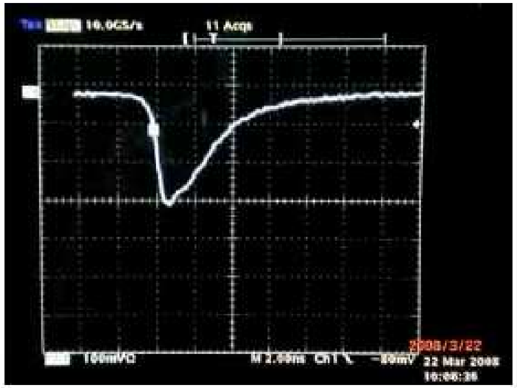
10kV pulse apply to the strip-line



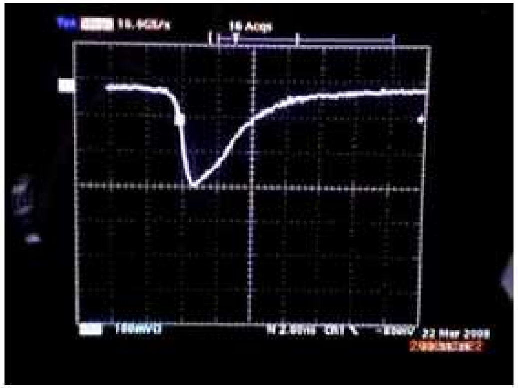
Pulser output(pos) 9.7kV peak



Strip-line output(pos)



Pulser output(neg) 8.5kV peak



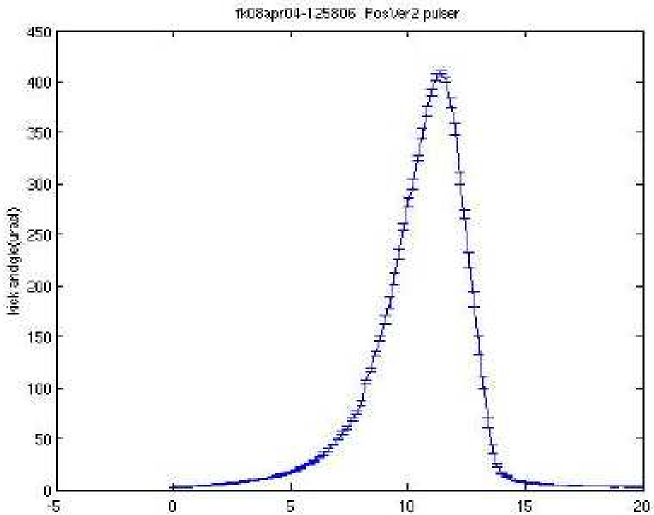
Strip-line output(neg)

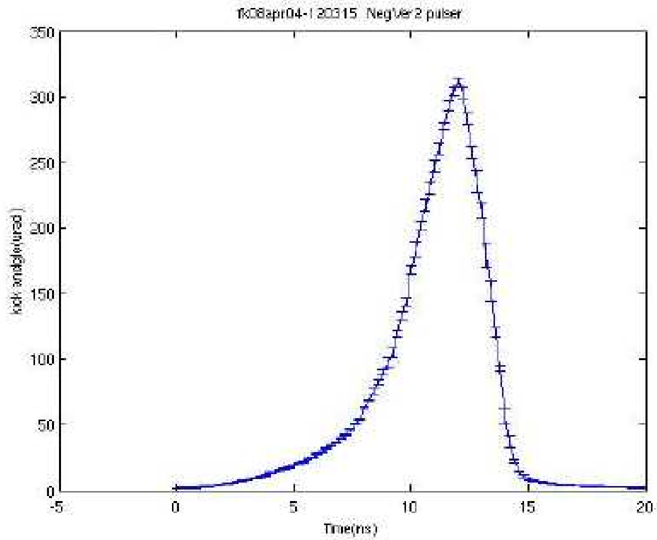
A 10kV pulse could be applied for each electrode without any deterioration to the waveform of the pulser, which means no-discharge at the connectors and the electrodes.

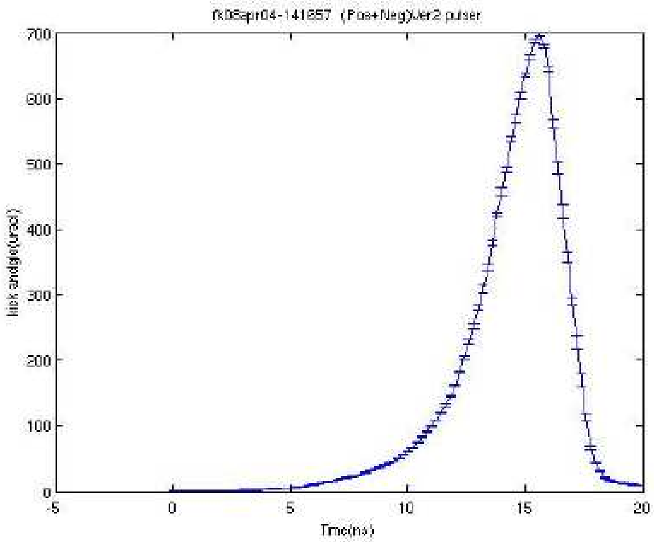
Fast Ionization Device (FID) R&D

Measured beam response (T. Naito):

Beam kick profile from the beam oscillation amplitude



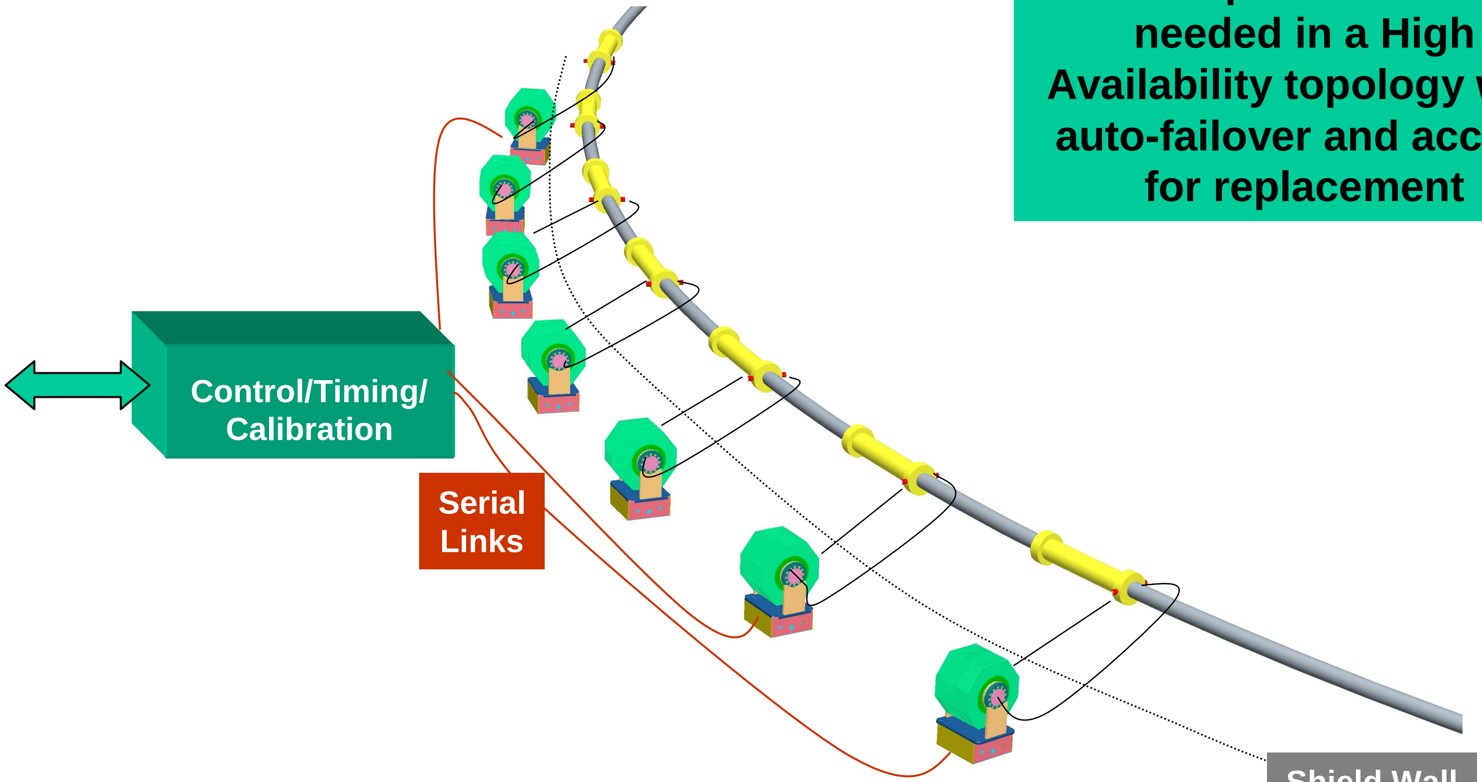




Beam kick test in the DR was carried out. The pictures show the timing scan of the kick pulses for the beam timing in the cases of the Positive, Negative and Pos+Neg pulses. The peak kick angles are 0.4, 0.3 and 0.7mrad, respectively, which agreed with the estimation from the kick voltage and the strip-line dimensions.

System Topology

10s of pulsers will be needed in a High Availability topology with auto-failover and access for replacement



C. Brooksby BN/LLNL

Instrumentation and Diagnostics

In order to provide reliable ultra-low emittance beams to the downstream portions of the ILC accelerator complex, the damping rings require high quality instrumentation and diagnostics.

- A high resolution (micron-level) beam position monitor system with turn-by-turn capability and very good stability
- Devices to characterize a range of beam instabilities

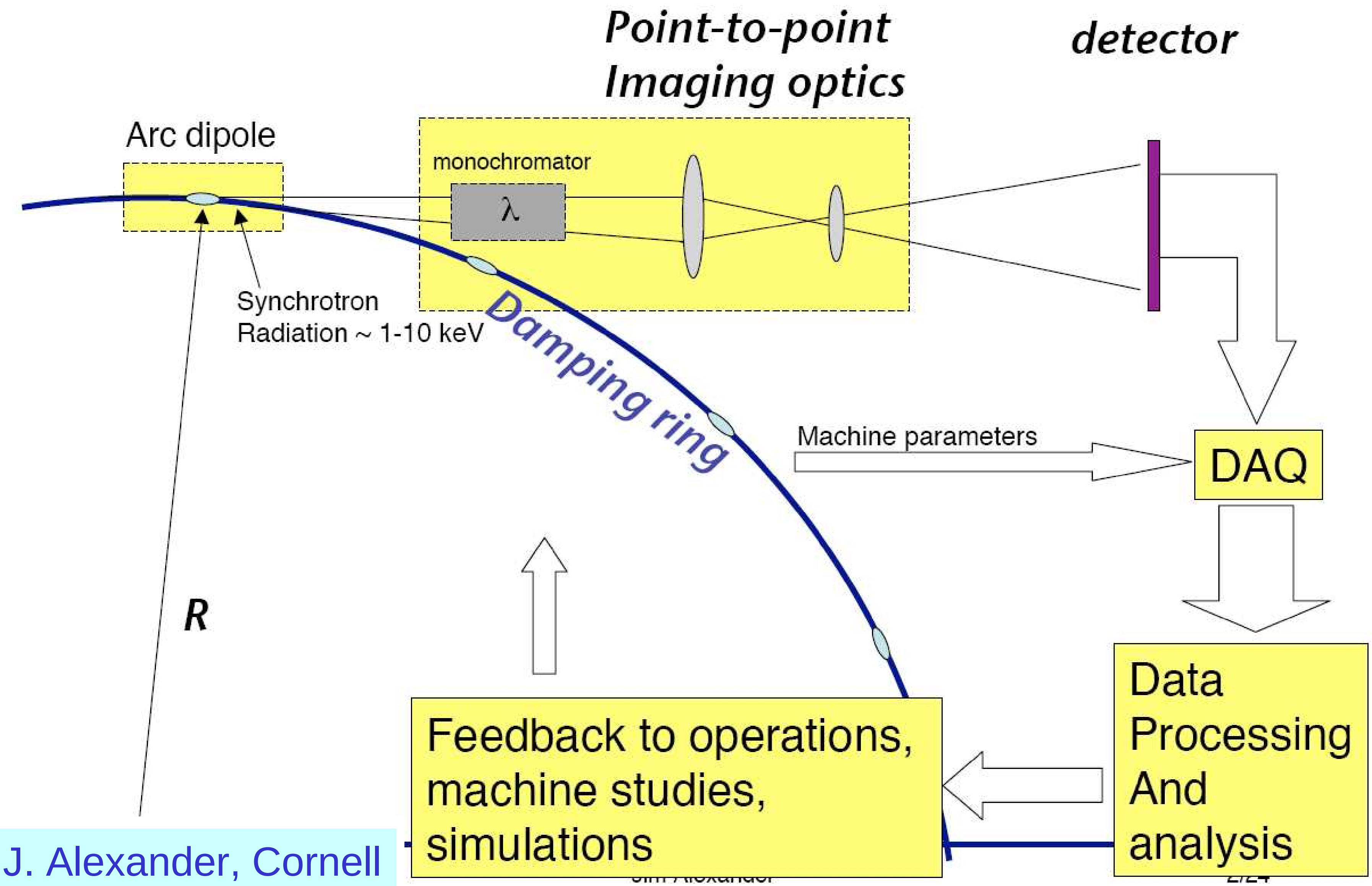
One particular device that is presently under development is a fast beam size monitor with resolution <10 μm and fast response. This device should be capable of:

- Resolving individual bunches
- An integration time scale sufficient to monitor the emittance damping process (single pass measurement capability is desirable)

Such a device will aid in:

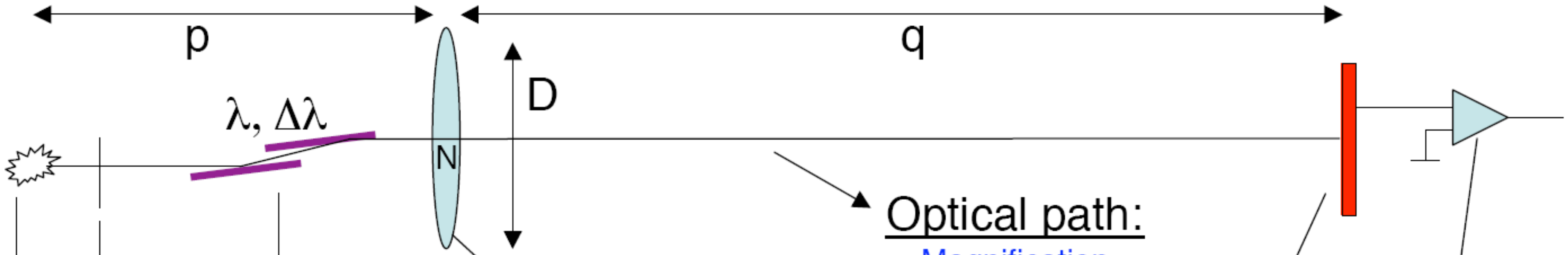
- emittance tuning
- verification the performance of the emittance damping in the ring
- understanding instability conditions during the short machine cycle

Fast X-ray Monitor Concept



J. Alexander, Cornell

System Design Issues



Optical path:
Magnification
Backgrounds

Zone Plate:
Diffraction - finite D
Chromatic aberration
Transparency

Detector:
Pixel size
Absorption
Carrier mobility

Monochromator:
Surface quality - flatness
λ, λ
Bandwidth Δλ/λ
Reflectivity

Readout:
Equivalent noise charge
Bandwidth

Vacuum window:
Absorption
Uniformity

Source:
Diffraction from source of known angular divergence
Bunch current, critical energy, etc

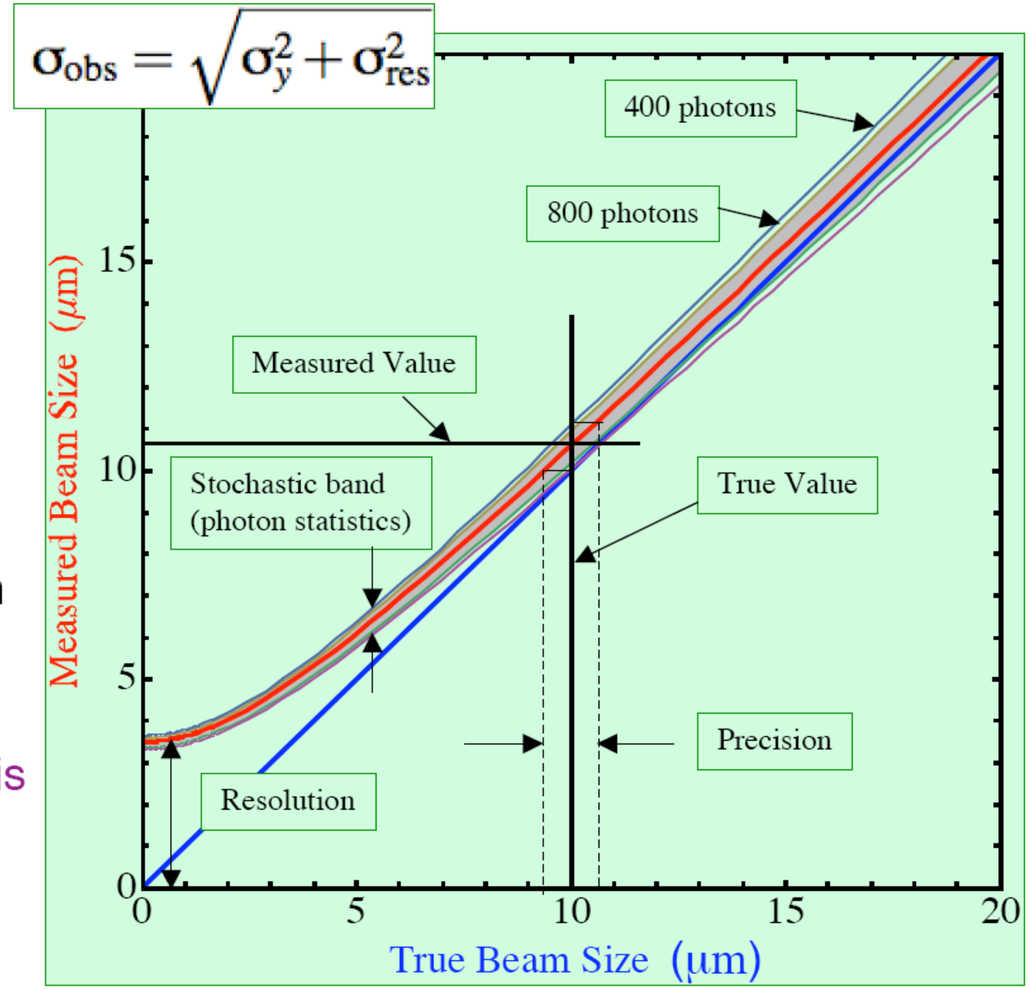
Color coding:
Photon yield
Resolution
Distortions
Speed

J. Alexander, Cornell

Resolution and Precision Issues

Sidebar: Resolution, Precision, and Photon Statistics

- Optical transfer function is characterized by a resolution (point spread function). This is a *fixed property* of the optical system.
  For CESRTA design, it is 2-3μm. (Figure at right assumes 3.5 μm)
- Photon statistics (and electronic noise, if applicable) fluctuate from snapshot to snapshot.
- The *measurement precision* of this system is determined by the stochastic element, not the fixed correction*.



J. Alexander, Cornell

* Residual uncertainty in the optical resolution will appear as a systematic error

Initial Studies

First bunch-by-bunch beam
size data in CHESS conditions ⇨
Significant CHESS support

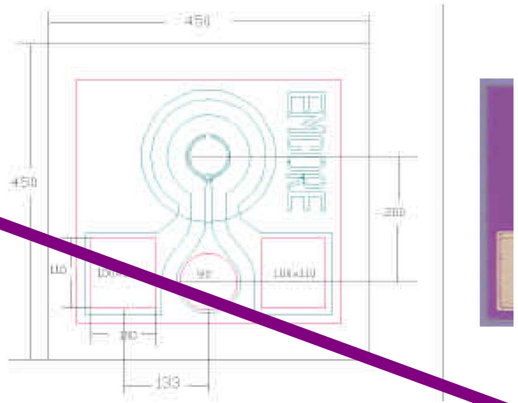
10 Gbps GaAs PIN Photodiode*

Product Description

EMCORE's 10 Gbps Gallium Arsenide (GaAs) PIN photodiode is designed for multimode fiber
EMCORE's own state-of-the-art MOCVD wafer foundry and device fabrication facility guarantees
fabrication source of package ready die to meet the growing needs of fiber optic component ma
device performance and robust operation makes this the superior device for high speed multimode
applications.

Features

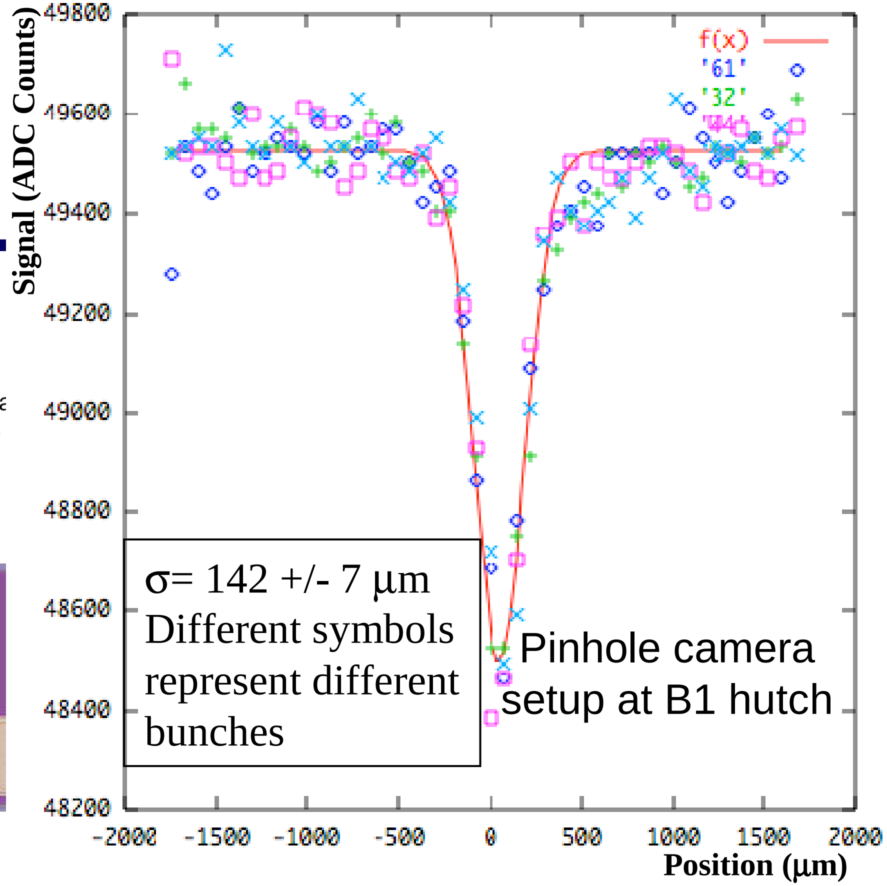
- Data rates of 10 Gb/s
- Excellent responsivity
- Large aperture size
- Low capacitance
- Low dark current



Product Specifications

Electro-Optical Characteristics (T = 30°C)

	Conditions	Min.	Typical	Max.	Unit
Speed	-1.6 V		8.5		GHz
Responsivity	3 to -26 dBm, 850 nm Epoxy coated, n=1.6		.5		A/W
Active Area (aperture)	-		60		µm
Rise/Fall Time	20% / 80%, -1.6 V bias		30/35		ps
Dark Current	-1.6 V, -70 dBm		<.2	1	nA
Capacitance	-1.6 V, 1 MHz		.28		pF
Reverse Breakdown	1 µA	20	50		V
Reflectivity	Epoxy coated, n=1.6			1	%



Fast enough for single bunch resolution

Summary of Lecture II, Part 1

In the first section of this lecture we have highlighted several technical challenges for the ILC Damping Ring design. They range from serious R&D issues such as the fast kickers to technical optimization issues that can seriously impact the cost and/or performance capability of critical systems.

During the second part of this lecture, we will look at several beam dynamics issues that affect ring design. Along with the major technical challenges, these physics issues are what drive the ongoing R&D program for the ILC damping rings. At present, the three most critical R&D challenges for the damping rings are:

- Fast pulser design
- Electron cloud instability
- Fast ion instability

Outline of DR Lecture II

Damping Rings Technical Systems

- Overview of the ILC Technical Systems
- ILC DR Wiggler Design
- ILC DR Kicker Design
- ILC DR Instrumentation (selected)
- Summary of R&D Challenges

Beam Dynamics Issues

- 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 Beam Dynamics Issues

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 wakefields 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.

Impedance and Collective Instabilities

As a charged particle beam passes through a vacuum chamber, it experiences an impedance that is very similar to the impedance of a transmission line. This impedance has both longitudinal and transverse components. The resulting wake fields that are left in the vacuum chamber due to the passage of a bunch can be short-range, where the fields can act on the bunch as it passes by, or long-range which leads to coupling between bunches and potential multi-bunch instabilities. Particular examples of interest to the damping ring design are the microwave instability, a single bunch instability, and the resistive wall instability which can couple multiple bunches together. Particular care must be taken in the design of the vacuum system and accelerator components that directly "see" the beam to insure that these impedances are kept small enough to avoid the onset of such collective instabilities.

At this point we will focus our attention strictly on the two instabilities that are of greatest concern for the damping rings:

- the fast ion instability in the electron damping ring
- the electron cloud instability in the positron damping ring

Ion Instabilities

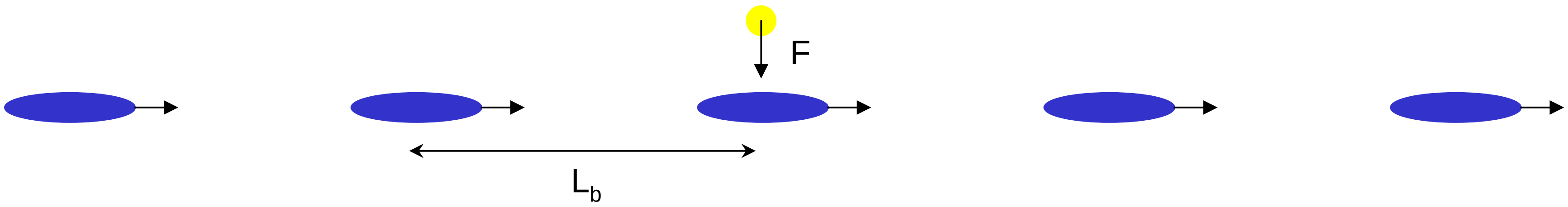
In the electron damping ring, ions that are generated by the bunches interacting with the particle beam can be trapped by the fields of the beam. This can result in high concentrations of positive ions near the beam axis. The interaction of the beam with these ions can then lead to the onset of beam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

$$Trace(\mathbf{M}) \le 2$$

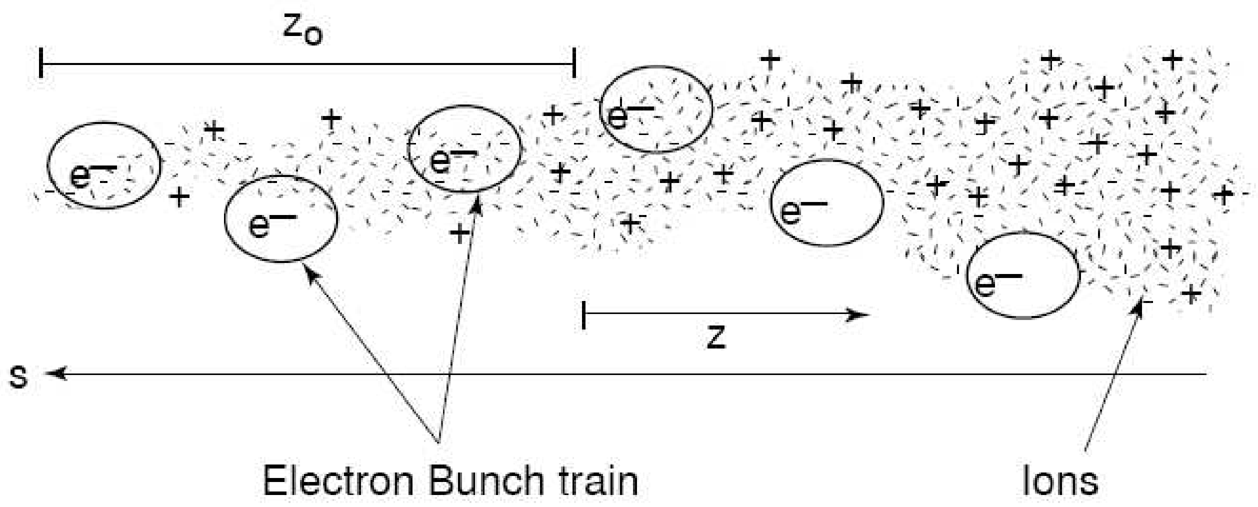
or

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

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. 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

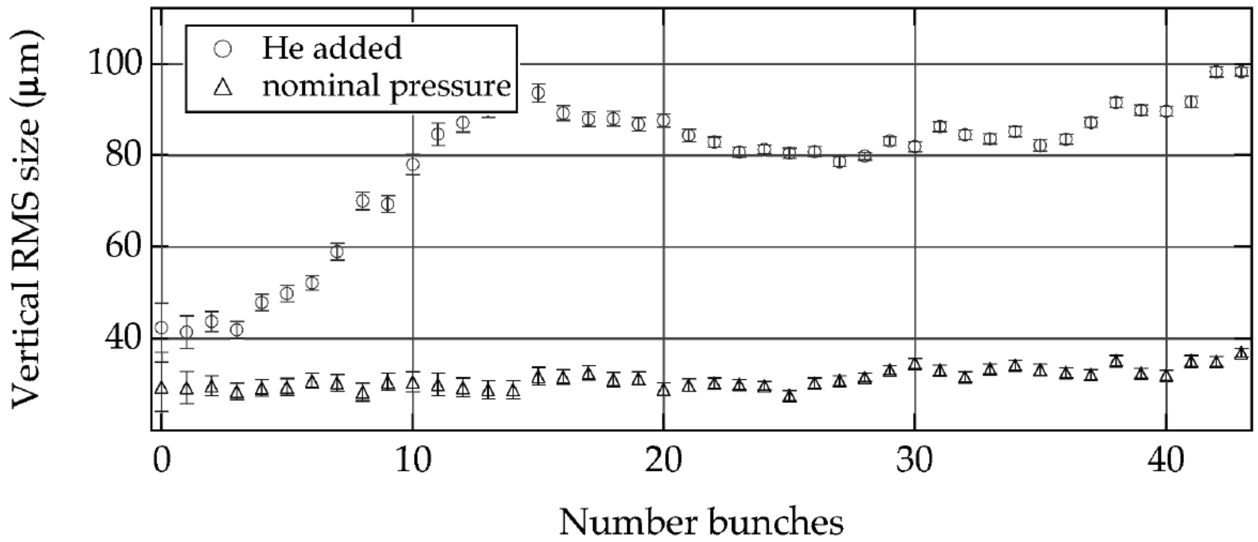


FIG. 2. rms vertical beam size vs the number of bunches for nominal and elevated pressure conditions.

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

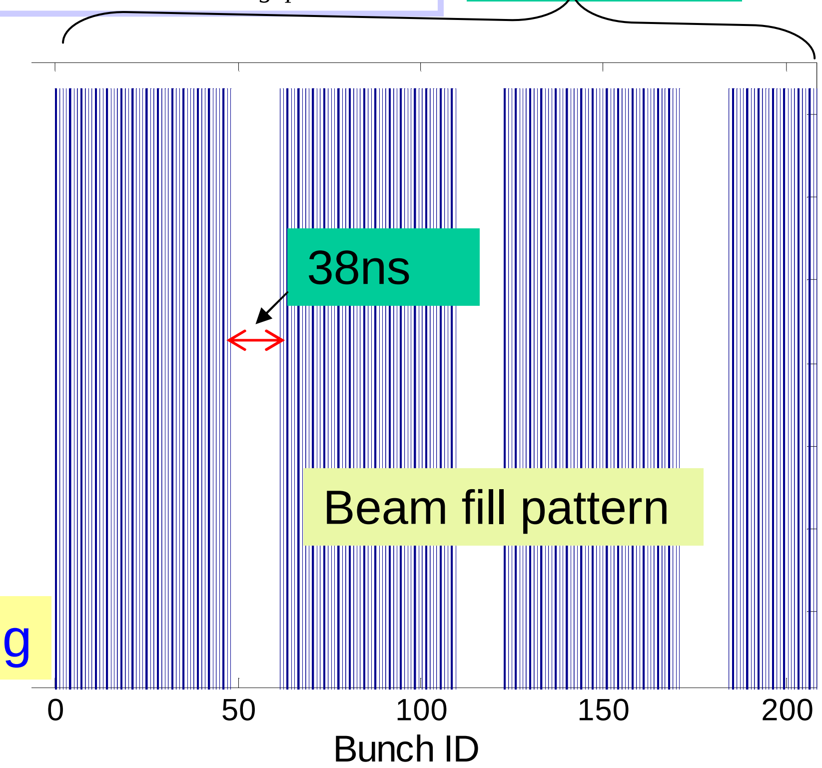
FII Modeling for the ILC DR

Growth time estimates with train gaps

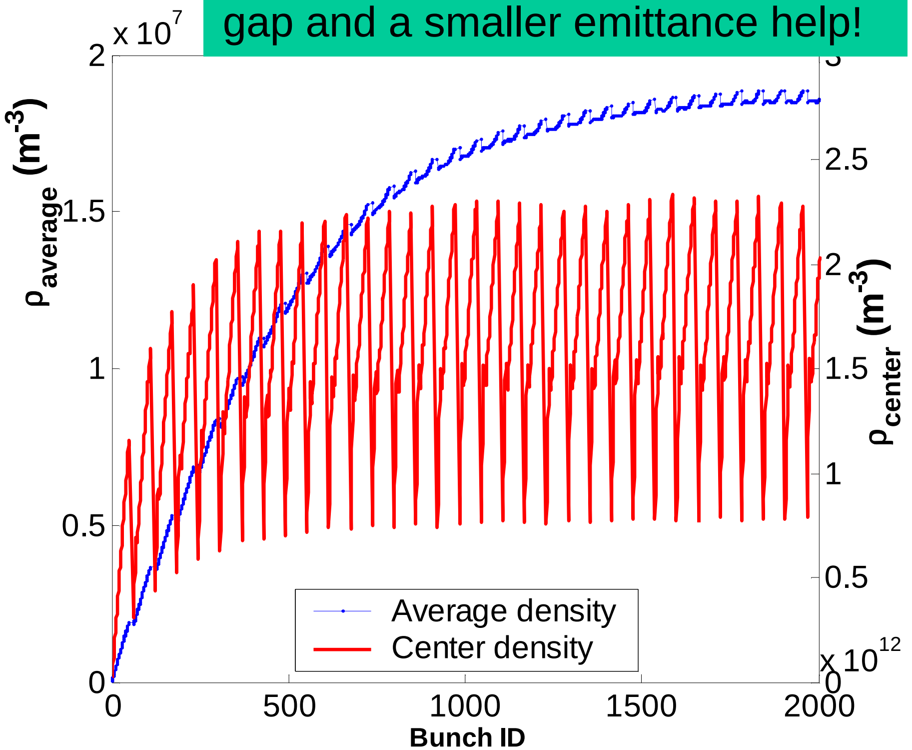
$$\mathrm{IRF} = \frac{1}{N_{train}} \frac{1}{1-\exp(-\tau_{gap}/\tau_{ions})}$$

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

118 trains



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

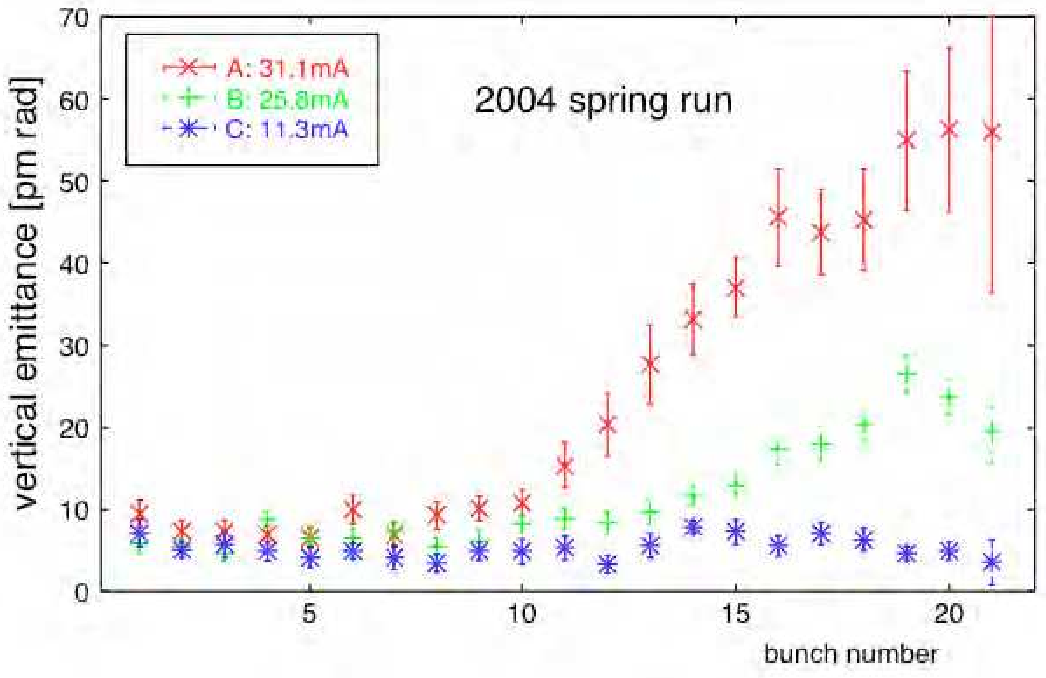


L. Wang

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 is expected to be a 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.

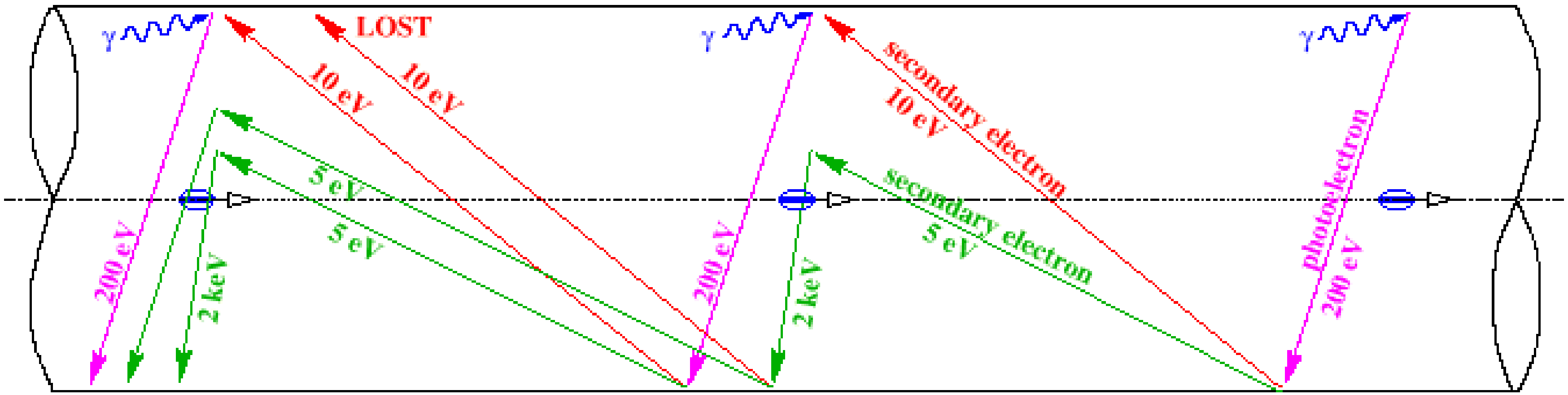
Electron Cloud Instability

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

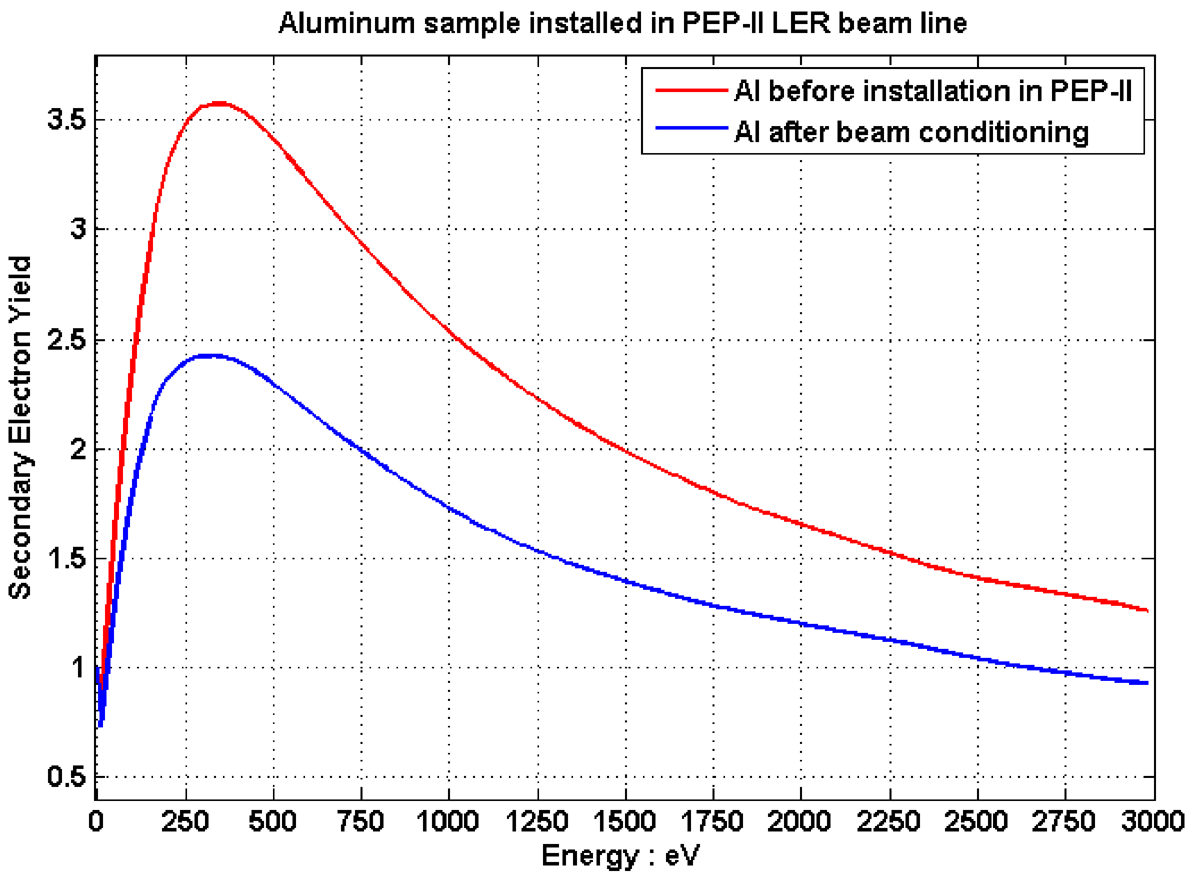
In an accelerator vacuum system the growth of the electron cloud is dependent on a wide range of parameters:

- 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.

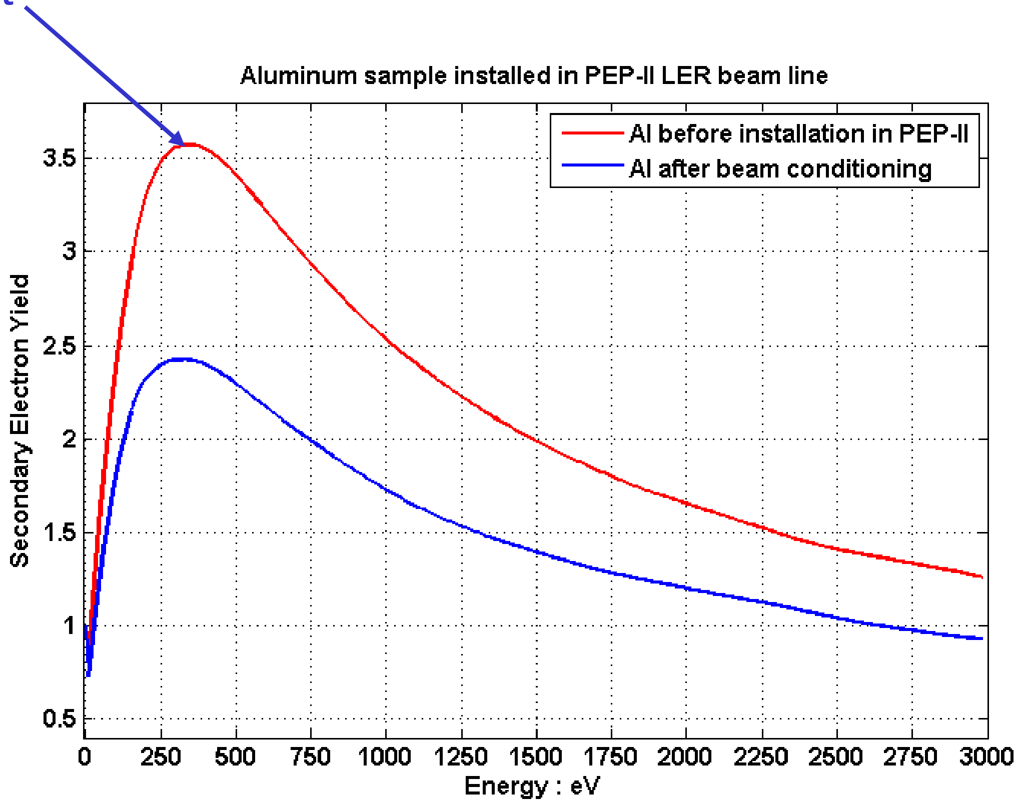


M. Pivi, SLAC Measurements of the SEY yield of an Al surface before and after beam conditioning with synchrotron radiation

The Secondary Electron Yield (SEY)

Some comments on the SEY curve:

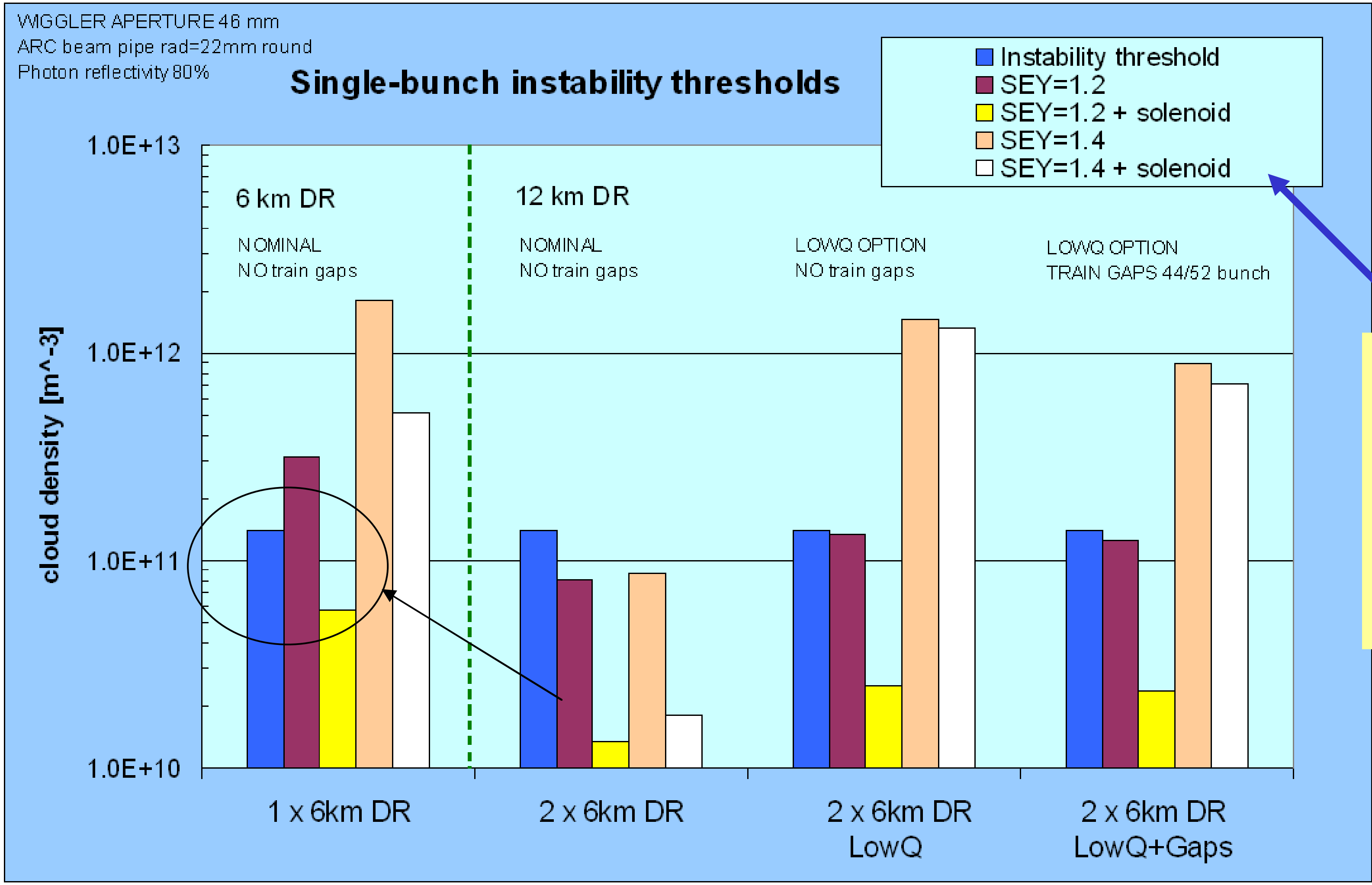
- When a single value for the SEY of a material is quoted, it is the height of the peak in the SEY curve.
- The SEY varies with the energy and angle of the incident particle.
- The SEY is dependent on the surface properties of a material. The surface properties may vary significantly depending on the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



EC Predictions for the ILC e^+ DR

How large a ring is required???

M. Pivi
ILCDR06

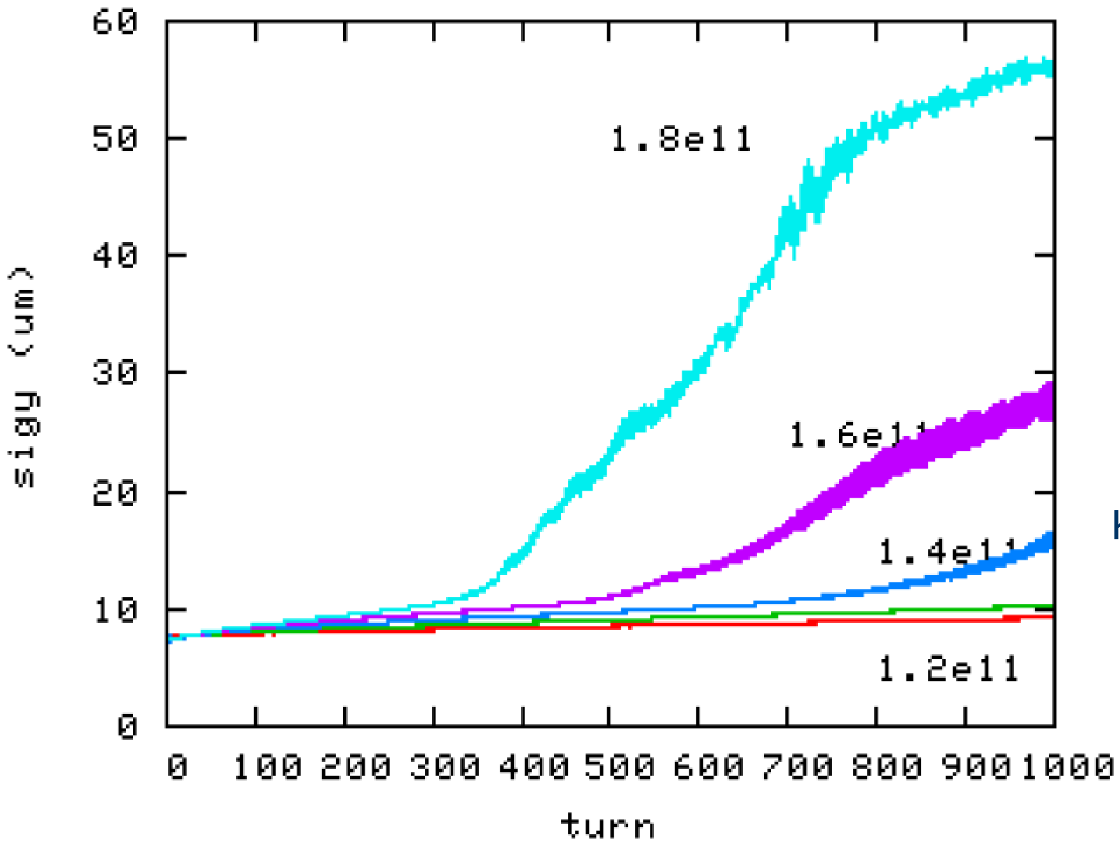


No additional suppression techniques assumed in dipoles and wigglers!

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

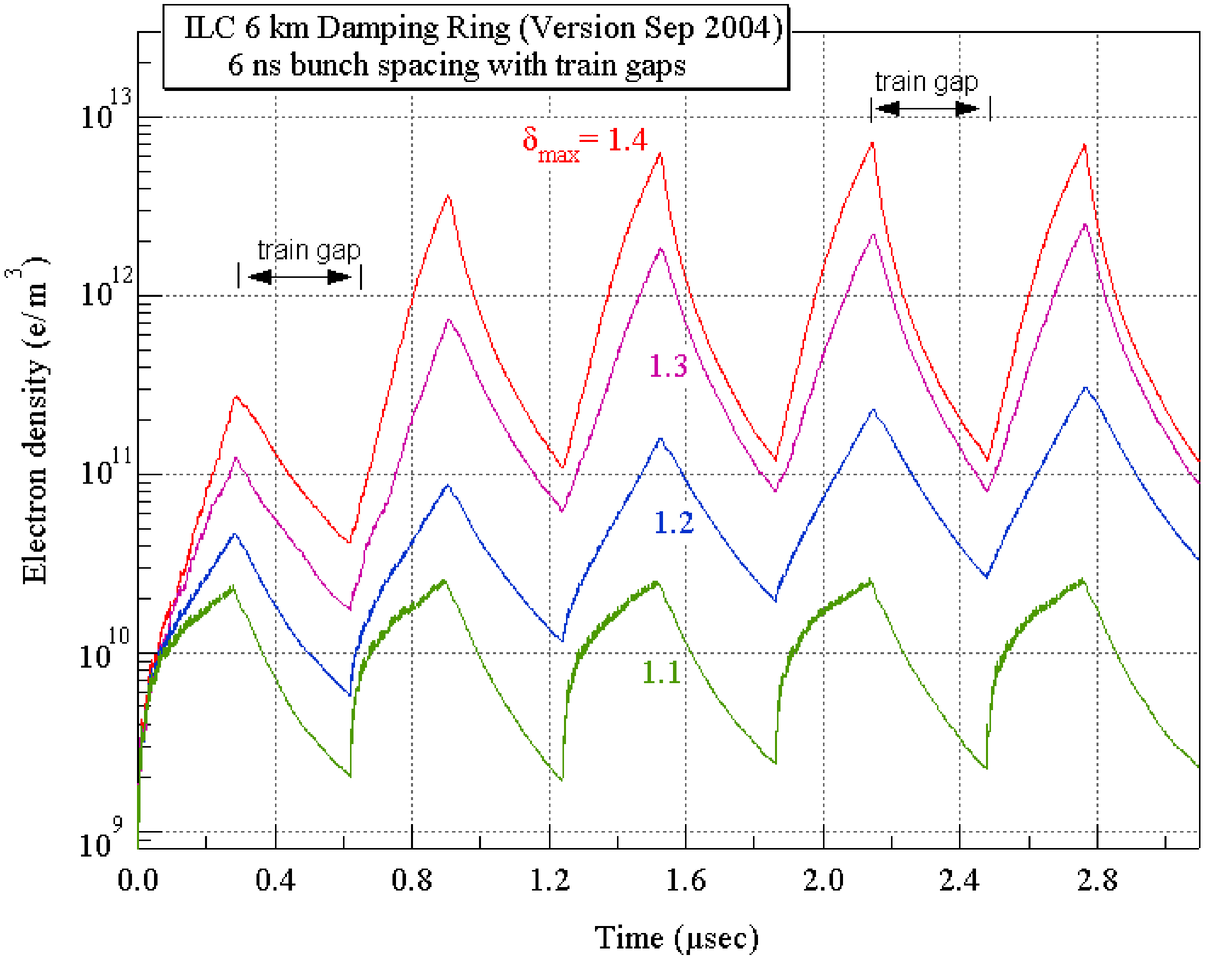
Studies of the EC interaction with the beam indicate that instabilities in the ILC DR positron beams will start at cloud densities of ~$1.4\times10^{11}m^{-3}$ (the simulation assumes that the SEY value in the vacuum chambers is ~1.2). Above this threshold, emittance growth of the beam sets in. This threshold places limits on acceptable SEY values for the damping ring vacuum chambers.



K. Ohmi KEK

Modeling the EC Growth

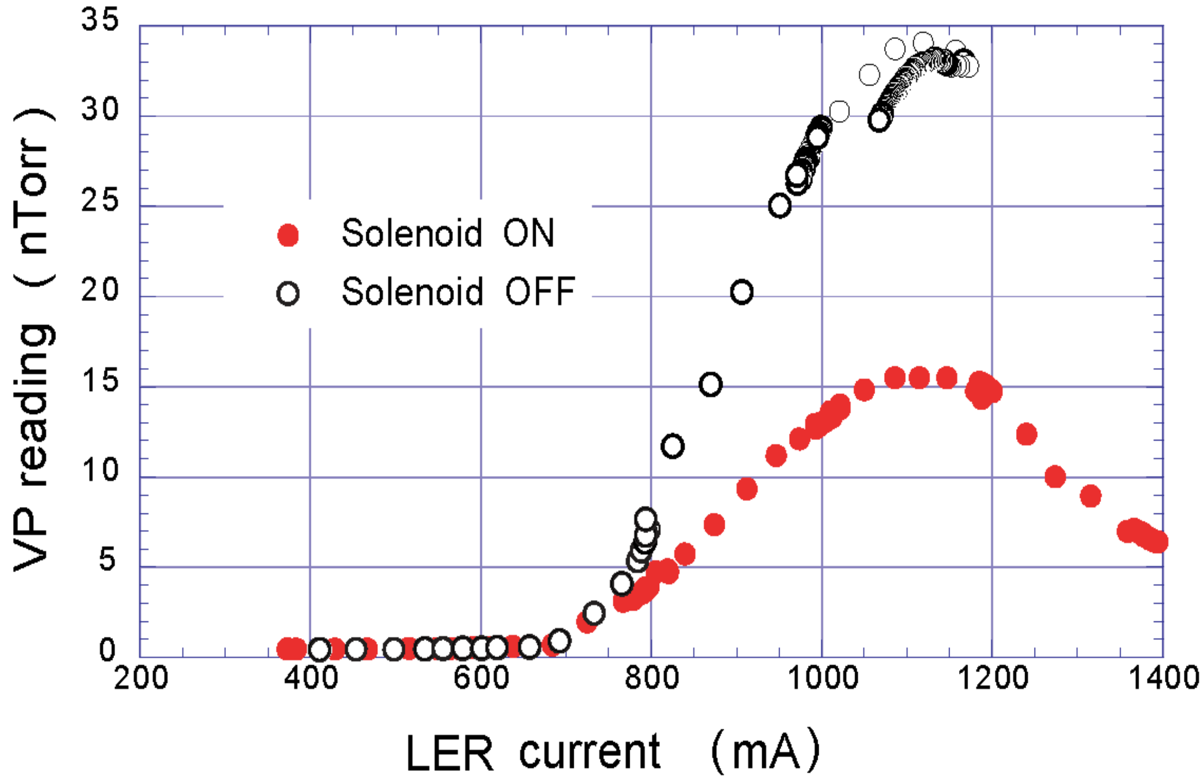
Growth of the EC in a drift space for a 6 km damping ring – simulated using POSINST



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.

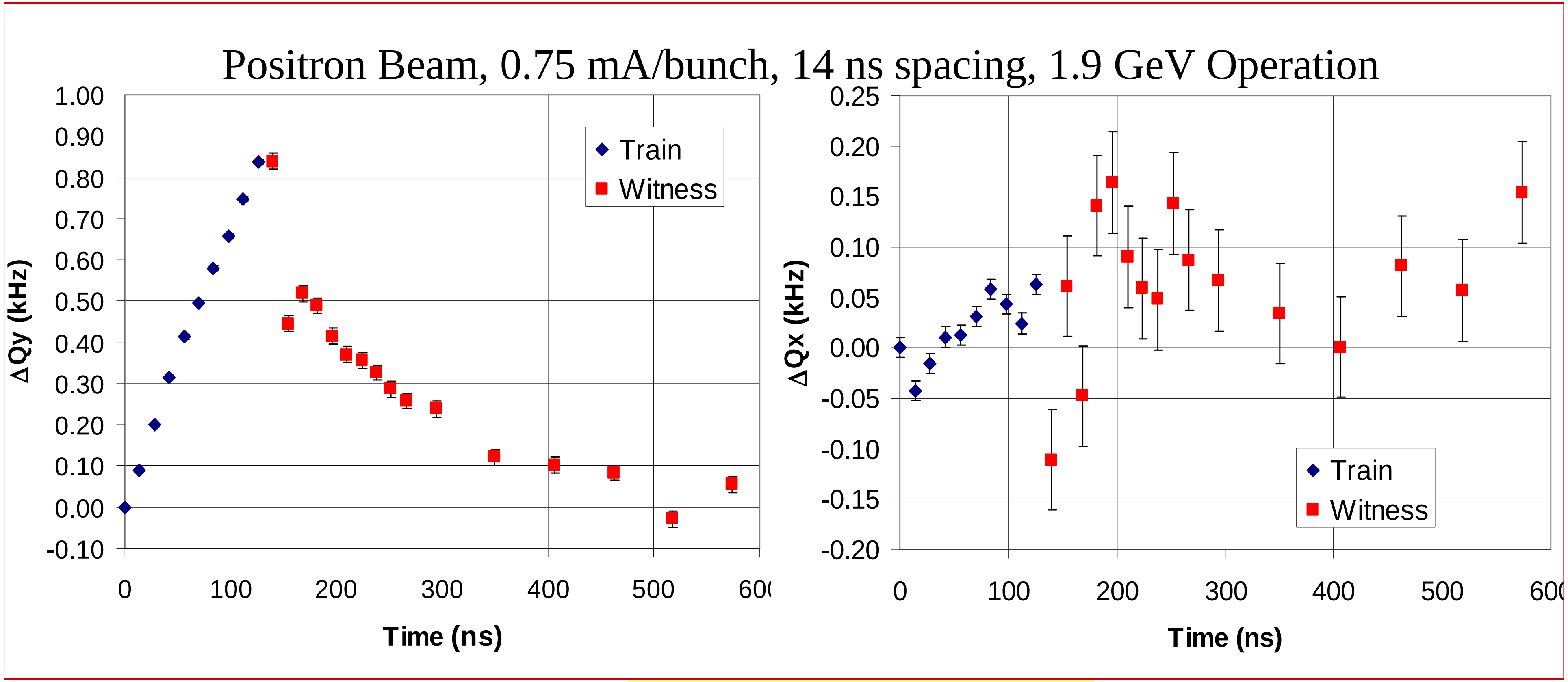


Pressure rise observed in the PEP-II LER

A. Kuliokov et al, PAC01

Measurements of the EC Tune Shift

Initial train of 10 bunches ⇨ generate EC
Measure tune shift and beamsize for witness bunches at various spacings



Error bars represent scatter observed during a sequence of measurements

1 kHz ⇨ $\Delta\nu=0.0026$
$\rho_e \sim 1.5 \times 10^{11}\ m^{-3}$
Ohmi, etal, APAC01, p.445

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:

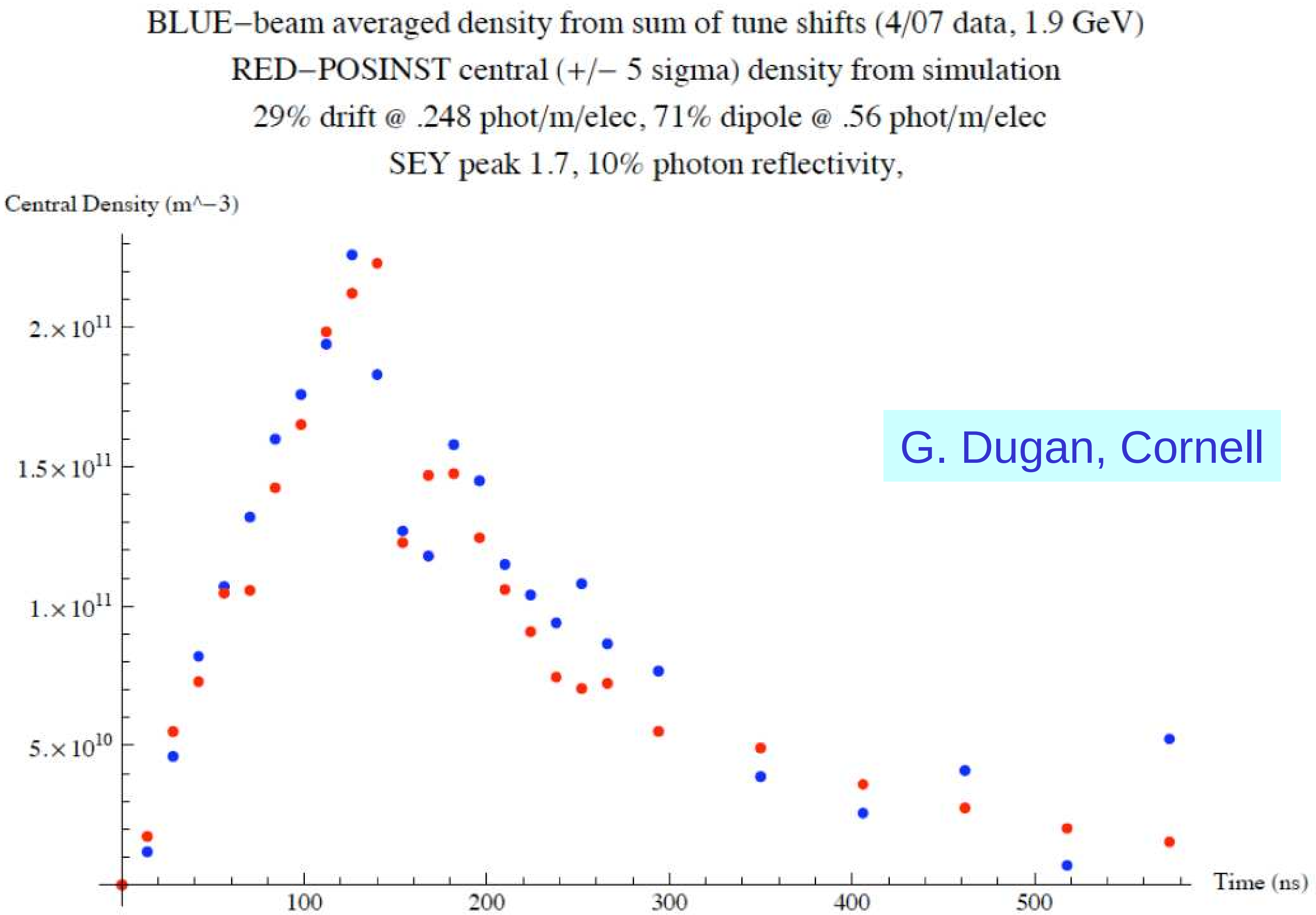
$$\Delta Q_x + \Delta Q_y = \frac{e}{4\pi E_0} \oint ds \left(\beta_x \left\langle \frac{\partial E_x}{\partial x} \right\rangle + \beta_y \left\langle \frac{\partial E_y}{\partial y} \right\rangle \right)$$

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

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…

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

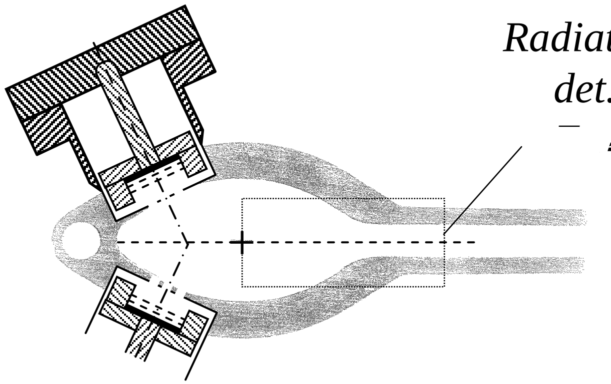
Data vs Simulation



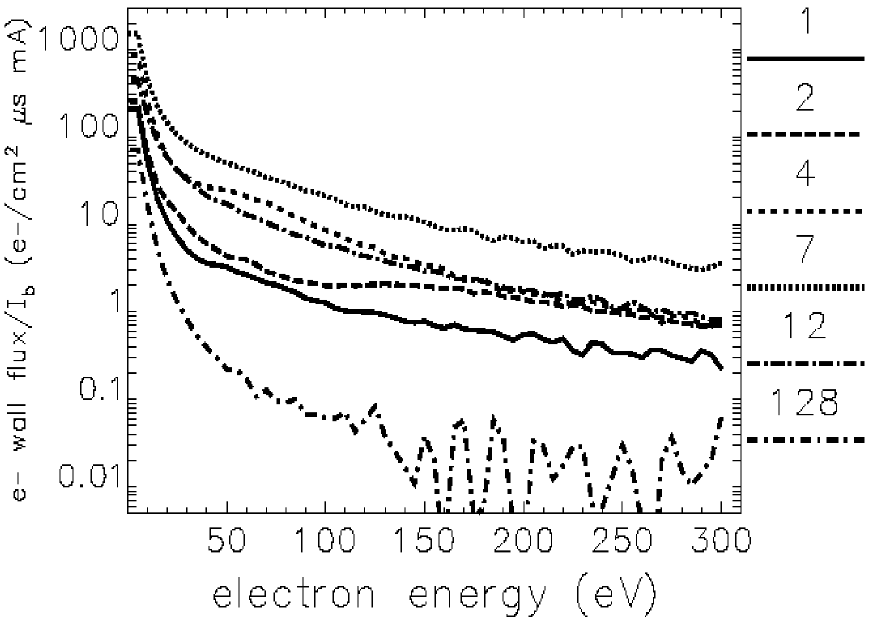
Retarding Field Analyzers

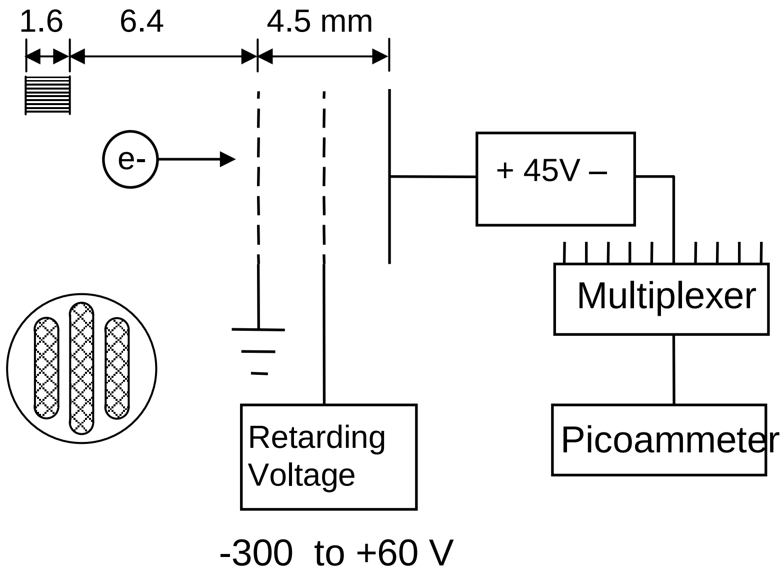
RFA measures distribution of EC colliding with walls, T~50%

Radiation fan at det. #6 for ≥ 4 eV



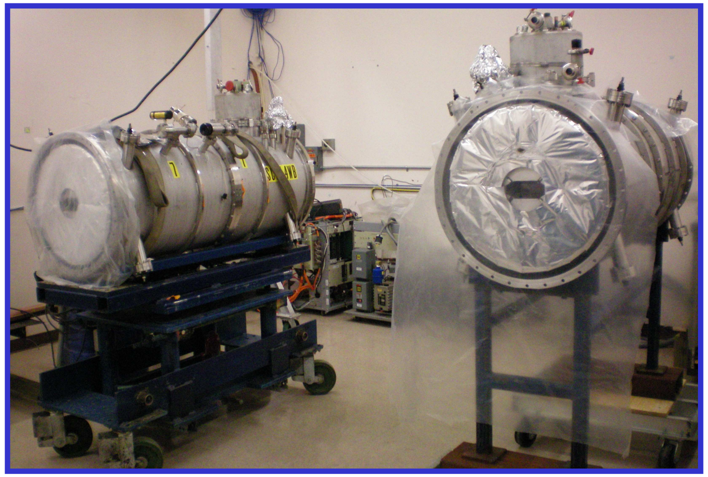
mounting on APS Al chamber ***behind vacuum penetration*** *(42 x 21 mm half-dim.)*

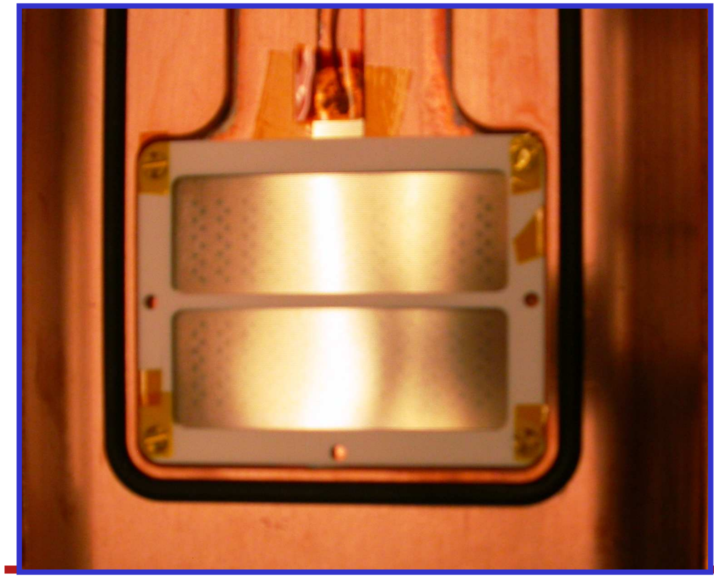


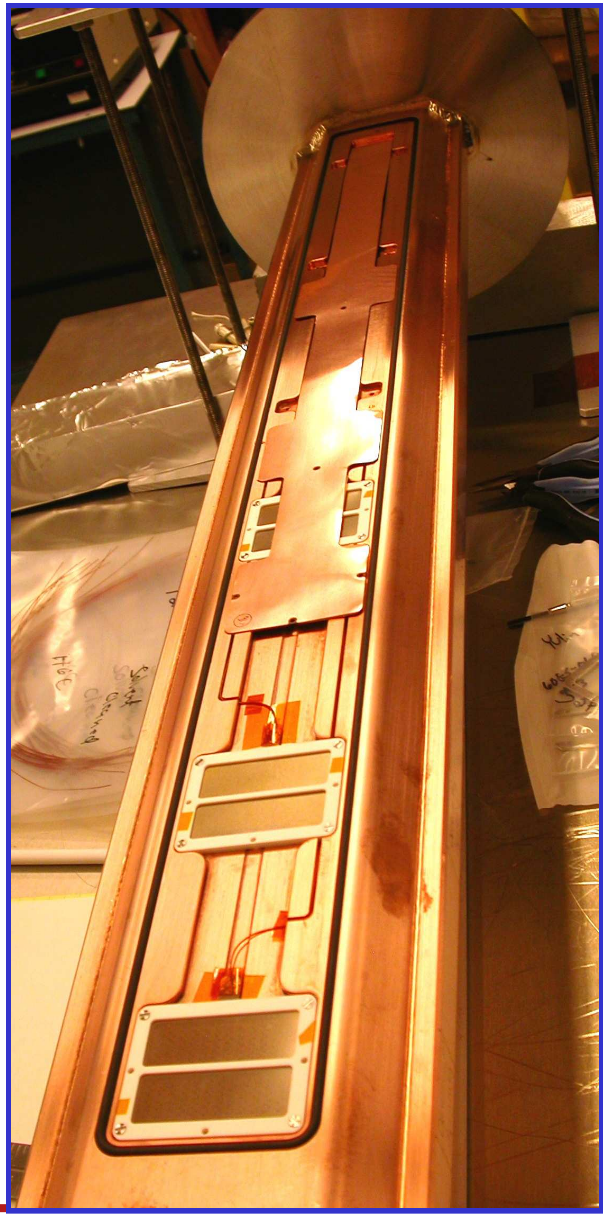


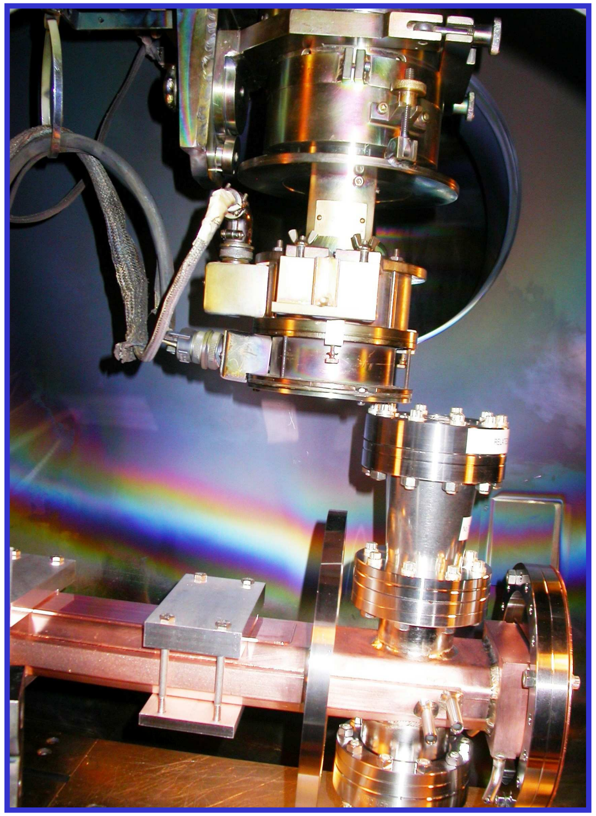
K. Harkay, APS

RFAs for CesrTA Diagnostic Wigglers



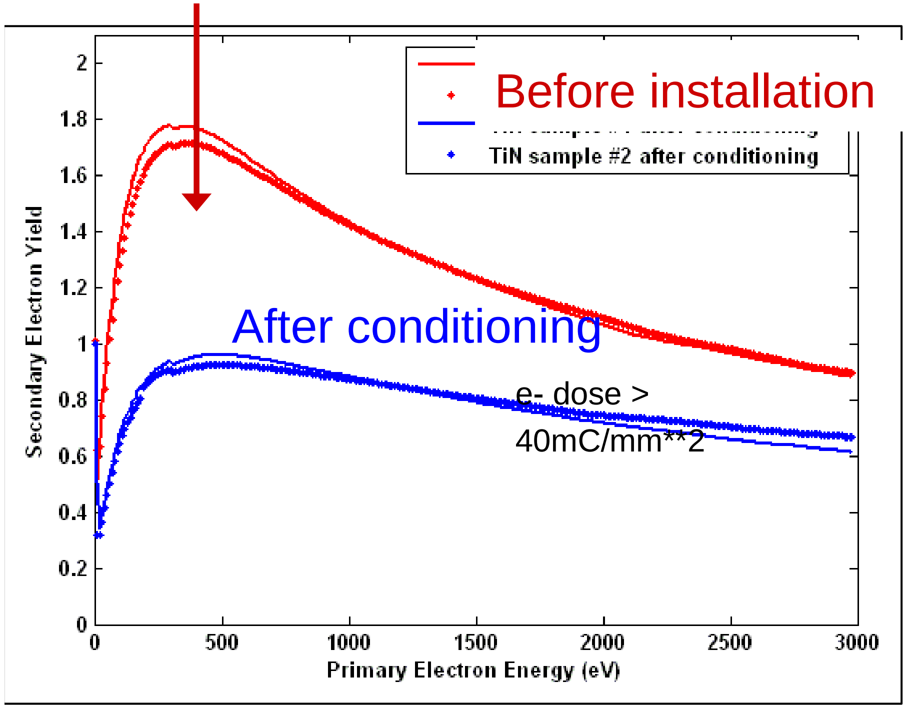


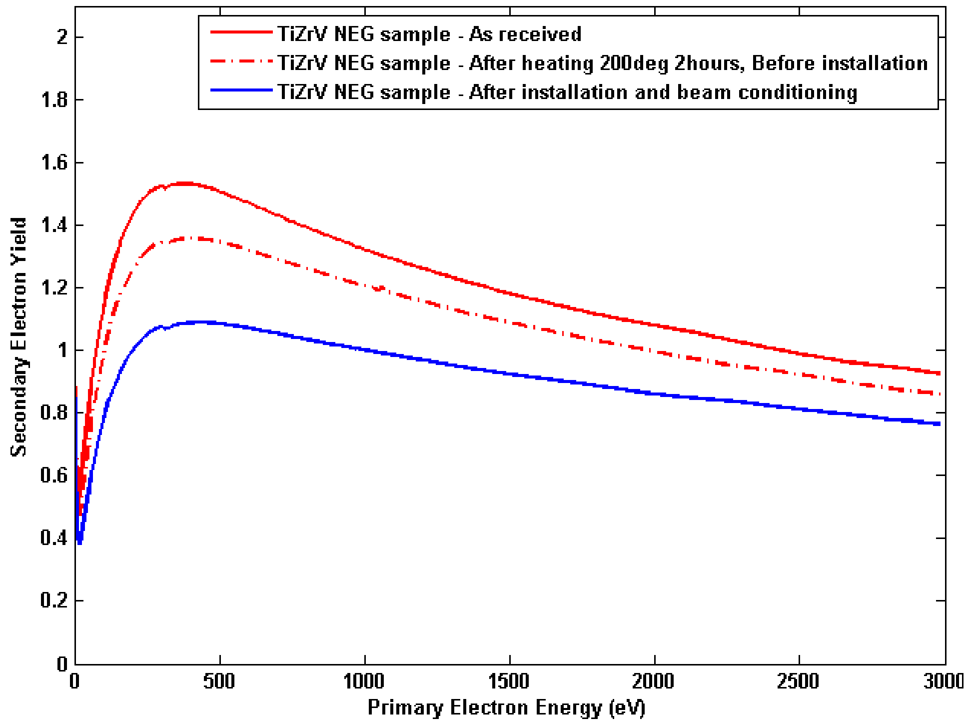




Mitigation of the EC

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.





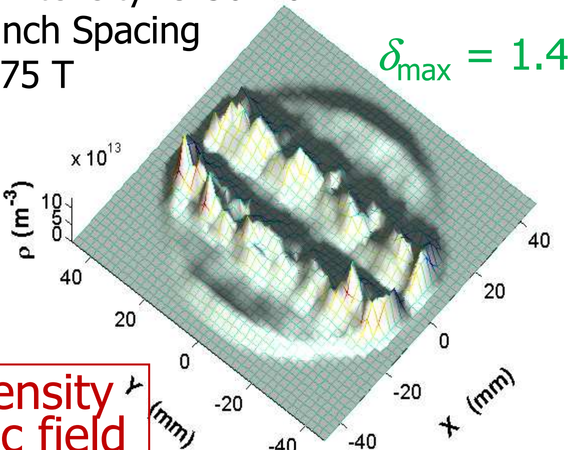
ILC tests, M. Pivi et al. – SLAC

Clearing Electrodes to Suppress Electron Cloud in Wigglers

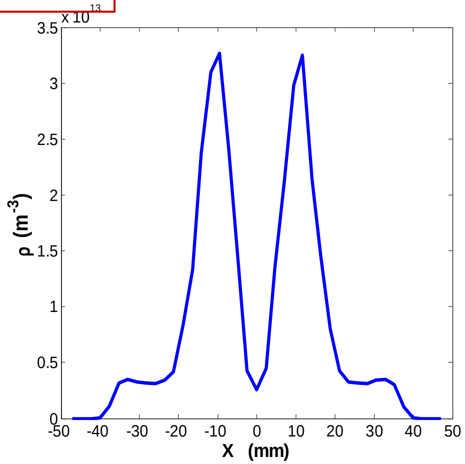
Simulations indicating the ability of an electrode to suppress the EC in an ILC DR wiggler chamber

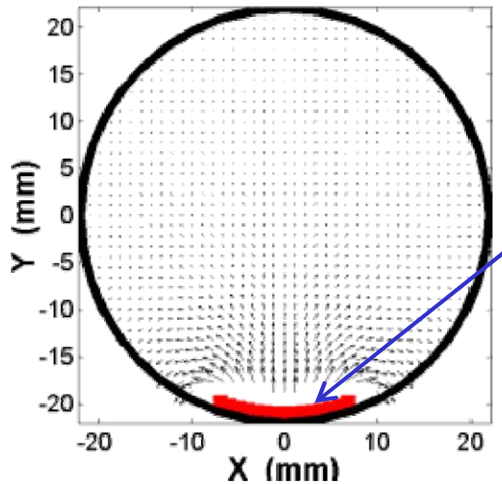
R-pipe=38mm
bunch intensity=9.36×10^{10}
3.5 Bunch Spacing
B = 0.75 T

$\delta_{max} = 1.4$

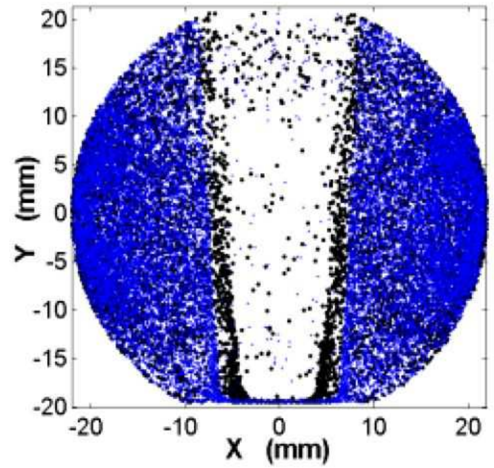


Electron density in magnetic field





Electrode (+)



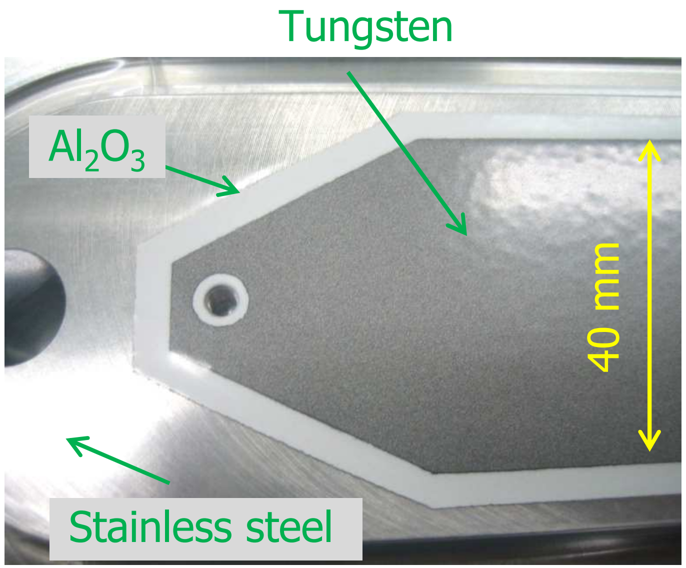
L. Wang et al, EPAC2006, p.1489

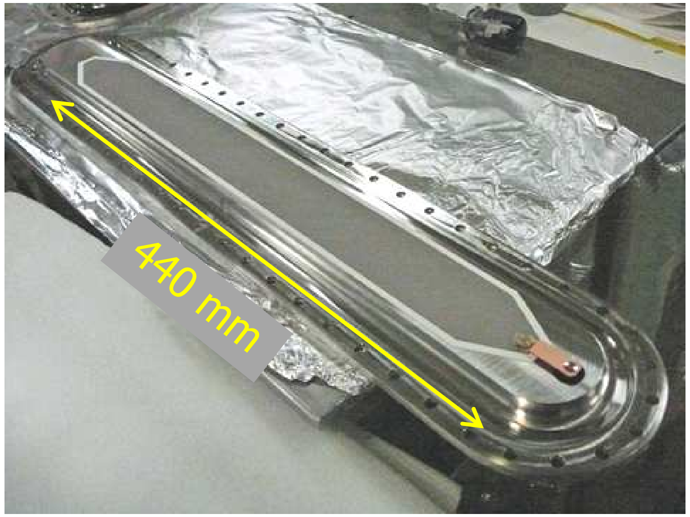
Electrode in KEKB Wiggler

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.

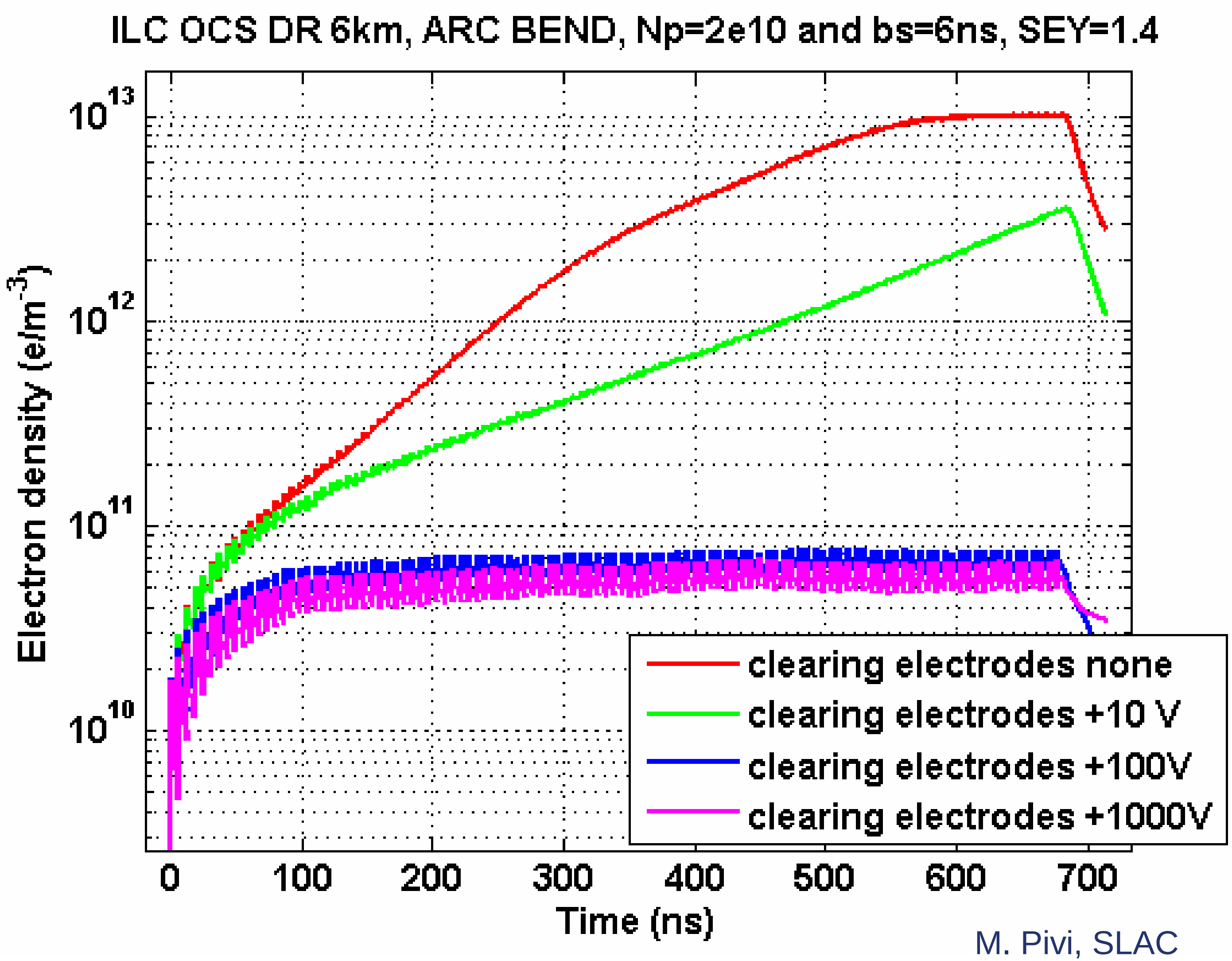




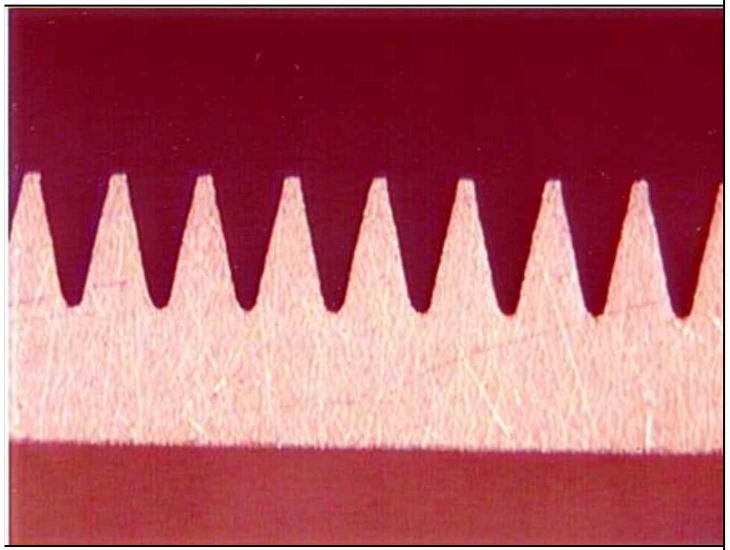
Y. Suetsugu, KEKB

Clearing Electrodes for the ILC DR Dipoles

Modeling of electrodes for use in the ILC DR dipoles



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

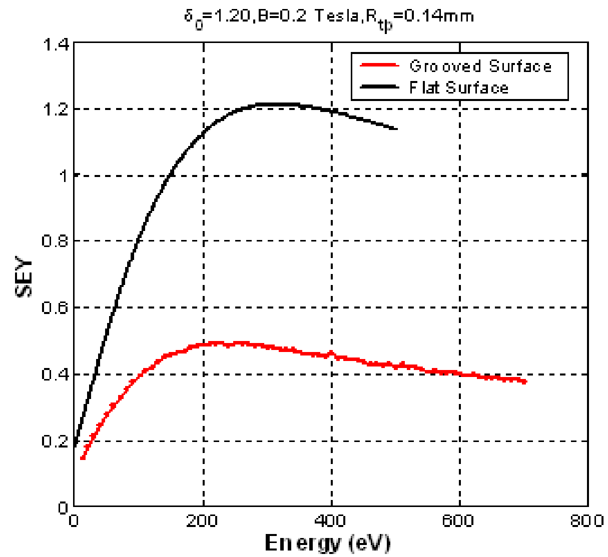
Height=3.82mm

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

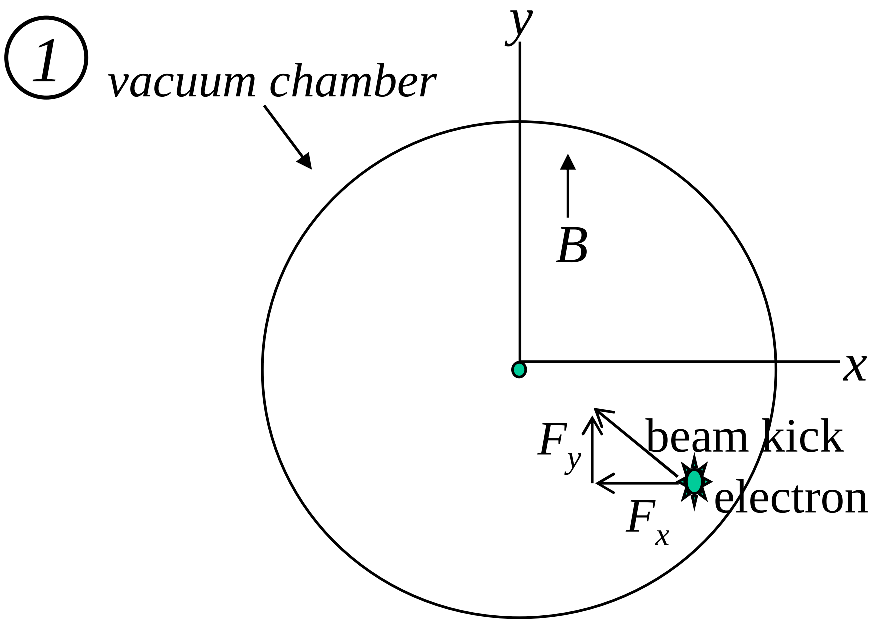


Recent estimation based on extruded groove chamber geometry

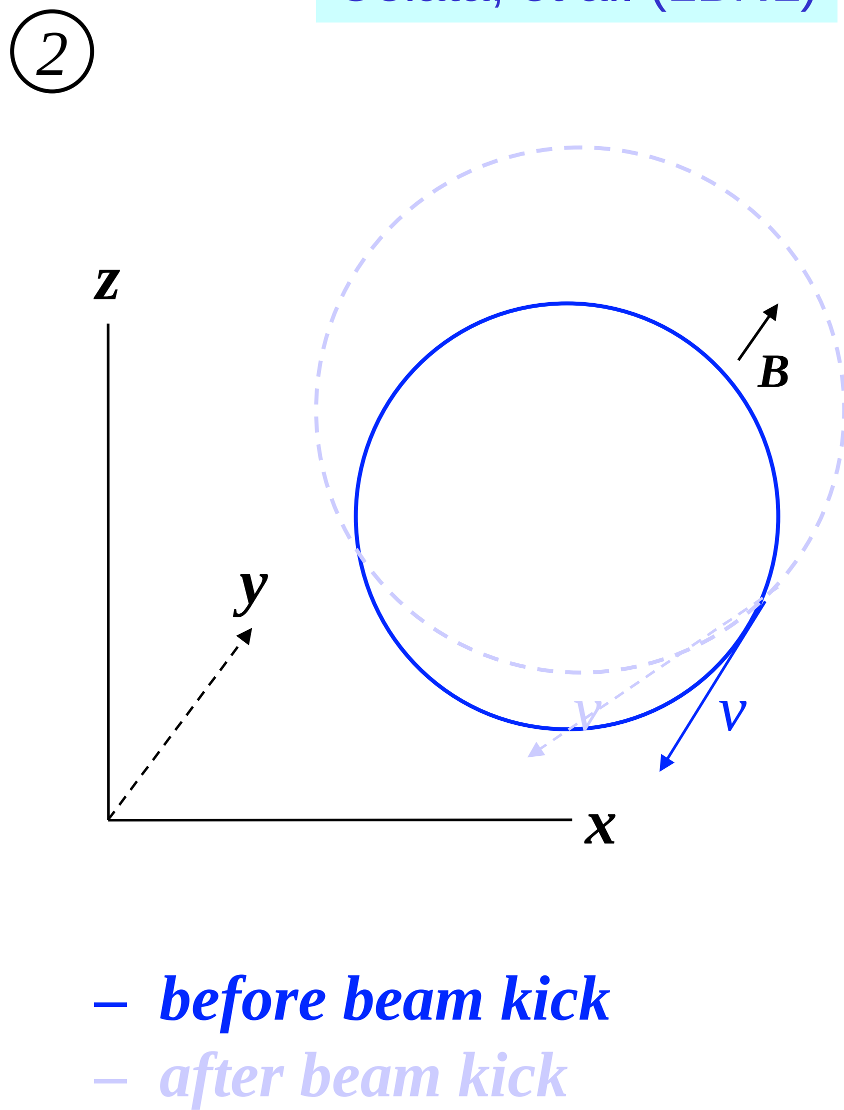
Resonant Excitation of Cloud in Magnetic Fields

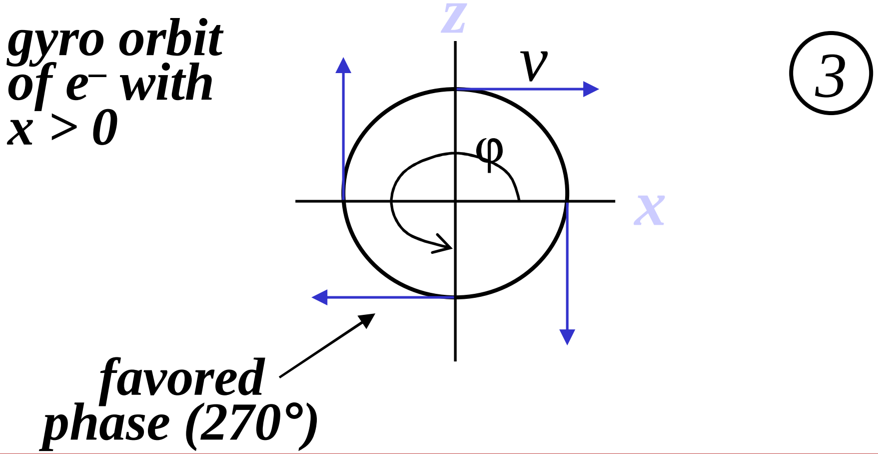
A new discovery… Observed at PEP-II

Celata, et al. (LBNL)



F_x is always toward the center

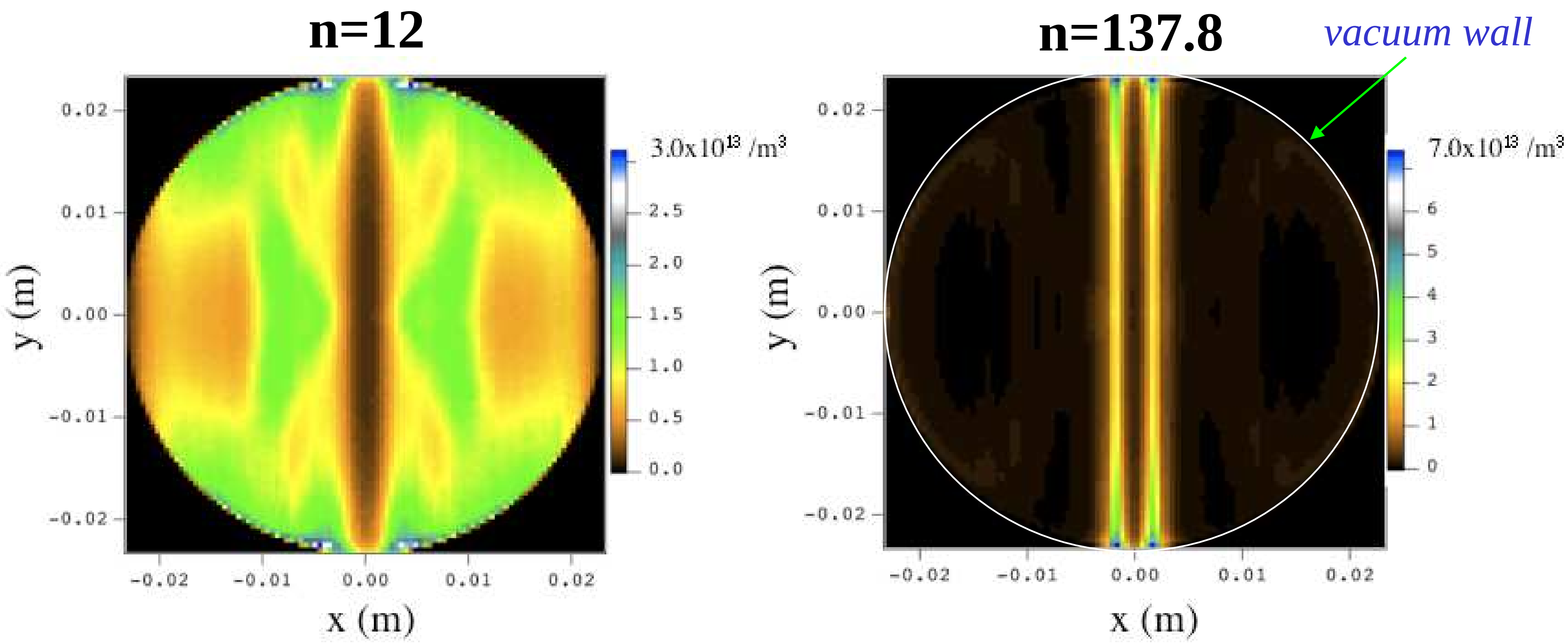




Simulation of Cyclotron Resonances in Cloud

Celata, et al. (LBNL)

Color contour plots of electron density averaged over entire simulation



The high-field(no resonance) case shows the characteristic "stripes" pattern seen in many experiments. At resonance the electrons are much more widely distributed in x.

ILD Damping Rings R&D Program

The R&D portion of the ILC DR R&D program focuses on 4 critical issues:

- Understanding the electron cloud in the ILC DR parameter regime and developing methods to suppress it
- Ensuring that the fast ion instability can be controlled in the electron damping ring
- Developing fast injection/extraction kickers
- Demonstration of ultralow vertical emittance operation ($\varepsilon_y = 2\ pm$)

Two dedicated test facilities are involved in this effort

- CesrTA
- ATF at KEK

Contributors from institutions world-wide

- Simulation and Experiment
- EC Mitigation Methods
- Low Emittance Tuning
- Design Work

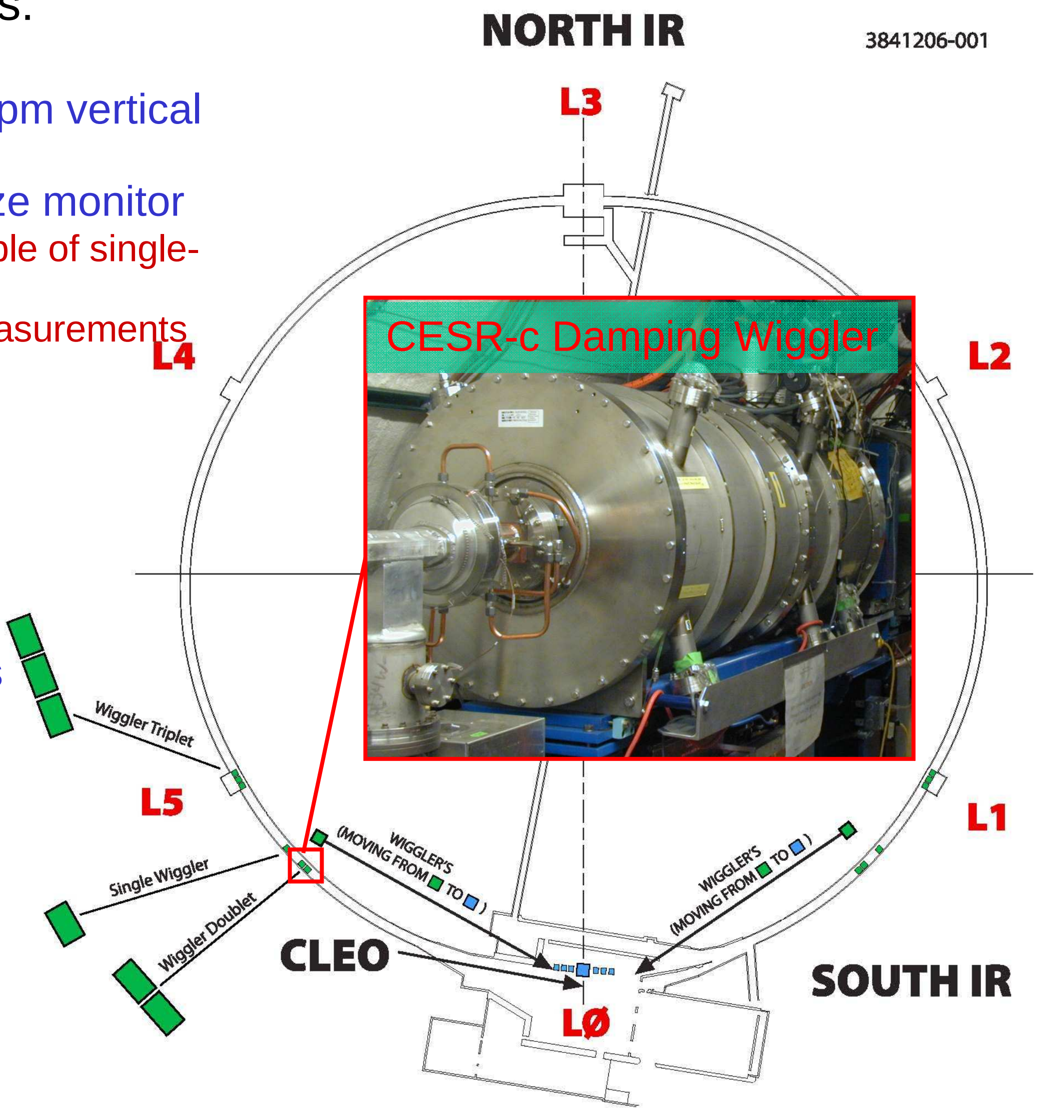
CesrTA Program

2 Year R&D Program with 3 major thrusts:

- Electron cloud studies
- Low emittance program (target of 20 pm vertical emittance)
- Development of a fast X-ray beam size monitor
  - Target bunch-by-bunch monitor capable of single-pass measurements for ILC DR
  - Resolution for ultra-low emittance measurements

CesrTA Configuration:

- 12 damping wigglers located in zero dispersion regions for ultra low emittance operation (move 6 wigglers from machine arcs to L0)
- Diagnostic vacuum chambers with EC suppression methods
- Designated sections available for installation of test devices
- Precision instrumentation
  - Multi-bunch turn-by-turn BPM system
  - Fast X-ray beam profile monitors
- 4 ns bunch train operation



CesrTA Parameters & Capabilities

Baseline Configuration

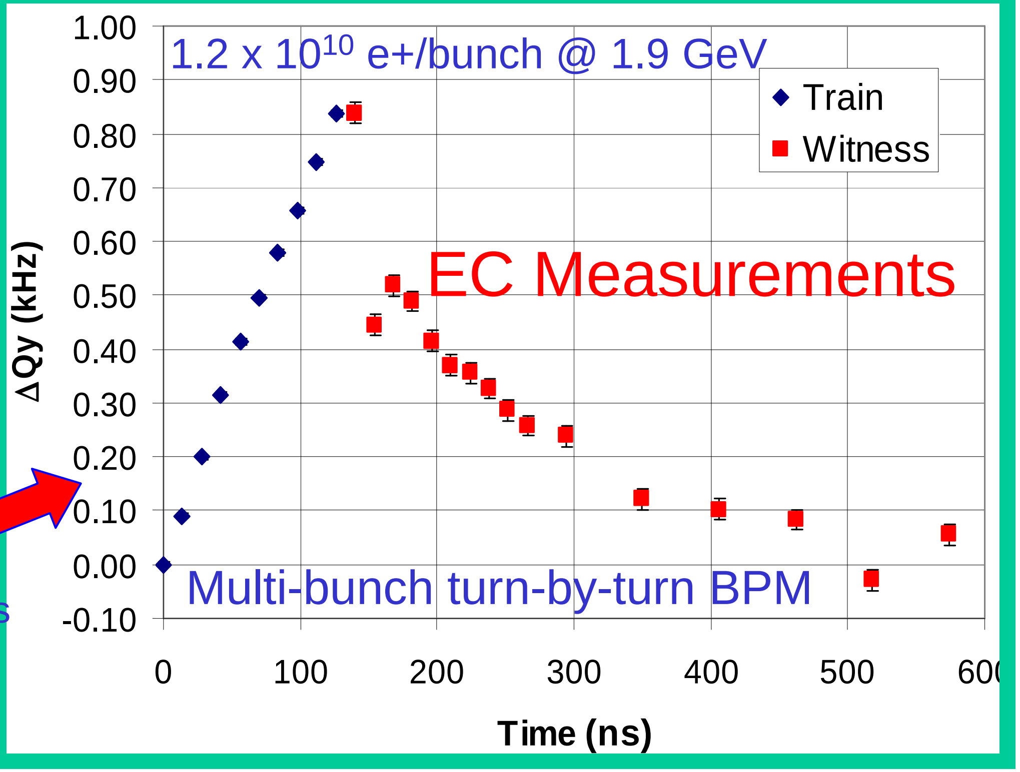
Parameter	Value
No. of Wigglers	12
Wiggler Field	2.1 T
Beam Energy	2.0 GeV
Energy Spread (ΔE/E)	8.6 x 10^{-4}
Target Vertical Emittance	<20 pm
Horizontal Emittance	2.3 nm
Damping Time	47 ms
Bunch Spacing	4 ns
Bunch Length	9 mm

Parameters:

- Baseline optics at 2 GeV for ultra low emittance studies
- Energy flexibility will allow EC growth studies at 5 GeV as specified for the ILC DR

EC Measurements:

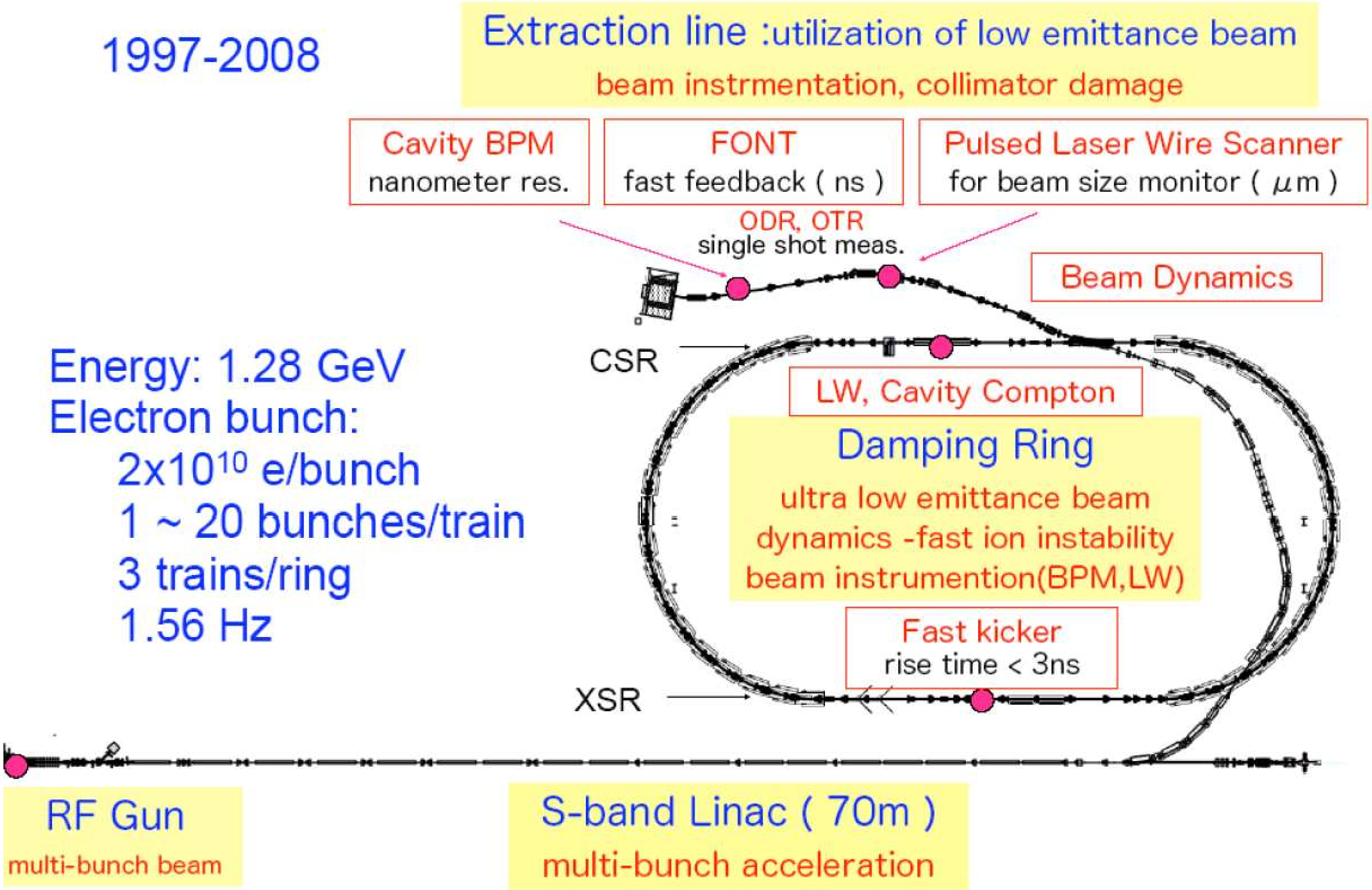
- Multi-bunch turn-by-turn instrumentation has been commissioned
- Measured vertical tune shift along a train generating the electron cloud and for witness bunches trailing the train at various intervals



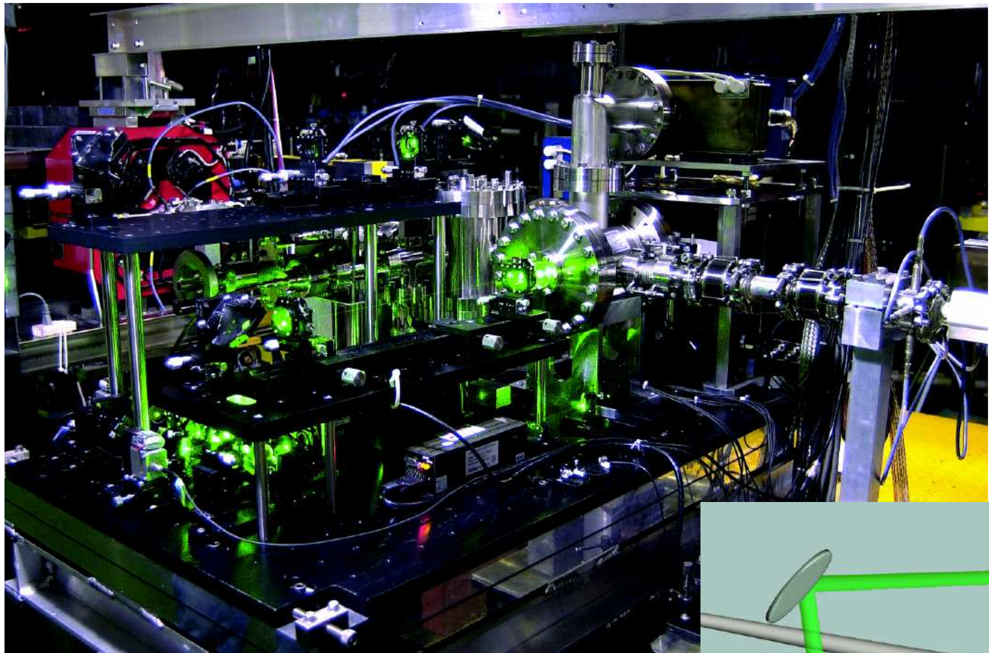
Accelerator Test Facility at KEK

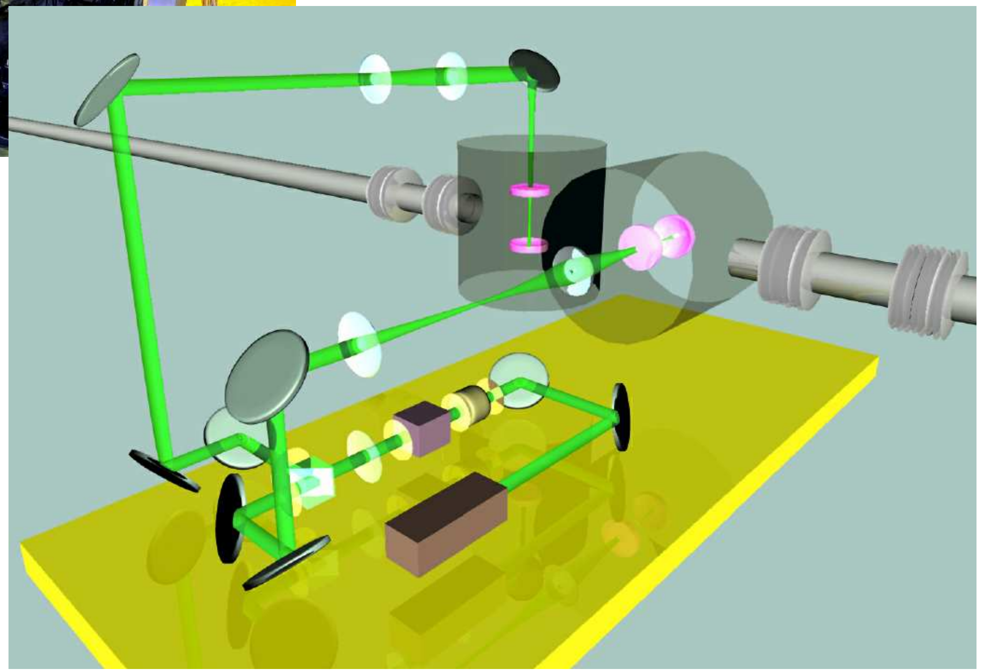
1997-2008

Energy: 1.28 GeV
Electron bunch:
- 2×10^{10} e/bunch
- 1 ~ 20 bunches/train
- 3 trains/ring
- 1.56 Hz



Laser wire beam size monitor: KEK-ATF





Conclusion to the Damping Rings Lectures

Thank you all for your attention.

I hope that I've been able to provide you all with a useful and informative overview of the issues related to the ILC damping rings.

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2. A. Wolski, J. Gao, and S. Guiducci (eds.), *Configuration Studies and Recommendations for the ILC Damping Rings,* LBNL-55449, https://wiki.lepp.cornell.edu/ilc/pub/Public/DampingRings/ConfigStudy/DRConfigRecommend.pdf
3. S. Guiducci & A. Wolski, Lectures from 1st International Accelerator School for Linear Colliders, Sokendai, Hayama, Japan, May 2006.
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5. The 3rd Mini-workshop on ILC Damping Rings R&D, December 18-20, 2007, KEK, Tsukuba, Japan.
6. ILC Damping Rings Lattice Selection Session at TILC08, March 3-6, 2008, Tohoku University, Sendai, Japan.
7. Joint CesrTA Kickoff Meeting and ILC Damping Rings R&D Workshop (ILCDR08), July 8-11, 2008, Cornell University, Ithaca, NY, USA.