

# *Damping Rings and Ring Colliders*

## *Damping Ring Technical Systems*

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**Seventh International Accelerator School for Linear Colliders**

**Hosted by Raja Ramanna Centre for Advanced Technology**

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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
  - Review technical challenges of ILC and CLIC DR
  - Vacuum system and e-cloud mitigations
  - Damping wigglers
  - Injection/extraction kickers
- A3.6 – Beam Dynamics
- 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

# Damping Ring 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

For the ILC DR, there are important interface issues with the conventional facilities and cryogenics groups. 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  $\sim 3.5$  MW/ring of beam radiation which is produced.

## Technical Challenges

Technical Area	CLIC DR	ILC DR
Vacuum	EC Mitigations, FII, photon absorbers	EC Mitigations, FII, photon absorbers
Magnets and PS	-	-
Damping Wigglers	High Field	Aperture and Field Quality
Injection/Extraction	Stable Kickers	Fast Kickers
RF System	2 GHz	
Instrumentation	General	Bunch-by-bunch issues
Feedback	-	-
Supports and Alignment	-	-

- indicates that issues are probably within the current state-of-the-art capabilities

# 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  $\sigma_i$  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 series).

## 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

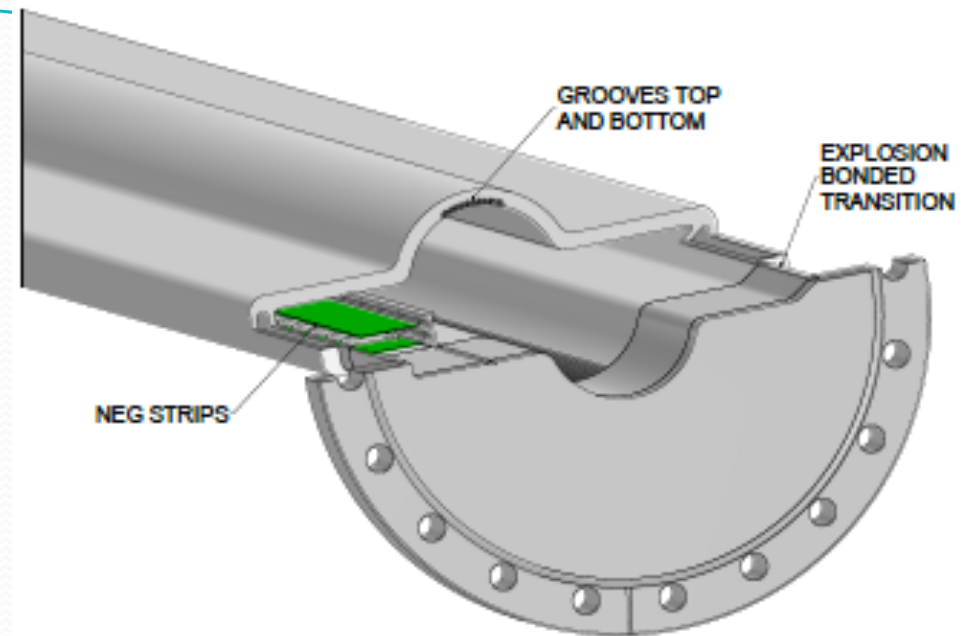
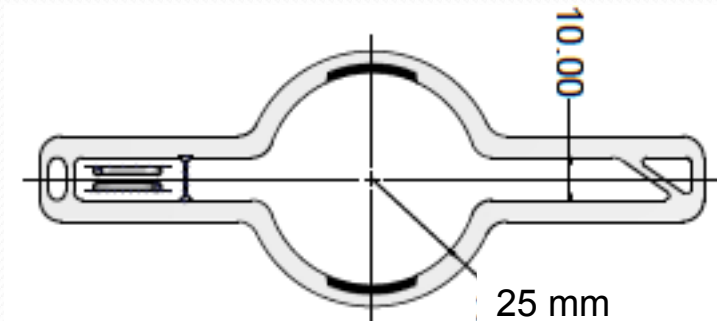
# Vacuum System

- The vacuum system conceptual design draws on previous design work and incorporates Electron Cloud (EC) mitigation techniques (we will discuss Electron Cloud later in these lessons)

EC Mitigations specified for the positron ring

<b>Magnetic Region</b>	<b>Primary Mitigation</b>	<b>Secondary Mitigation</b>
Drift	TiN Coating	Solenoid Windings
Dipole	Grooves with TiN Coating	Antechamber
Wiggler	Clearing Electrodes	Antechamber
Quadrupole	TiN Coating	-

# Dipole Vacuum Chamber

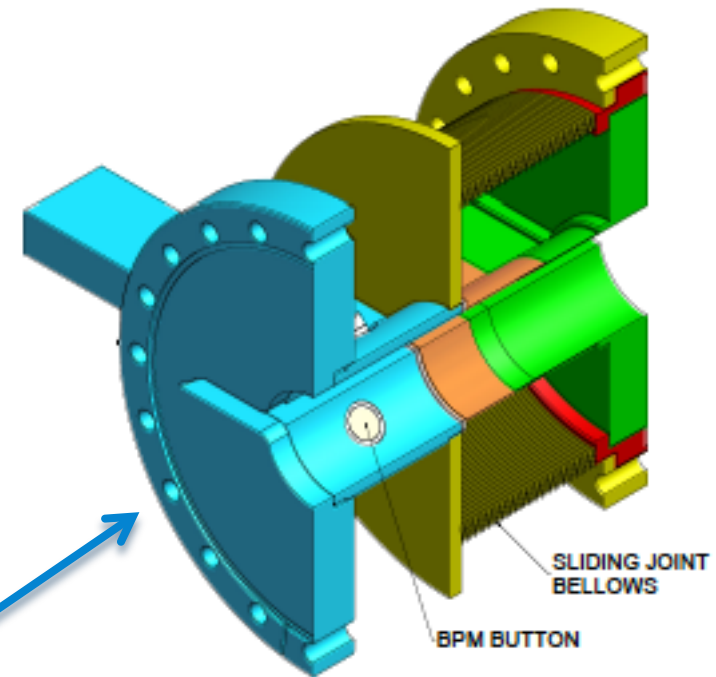


- EC mitigations:
  - titanium nitride (TiN) coating of the chamber to reduce secondary electron yield (SEY)
  - grooved top and bottom surfaces further reduce the number of secondary electrons in the central region near the beam
  - radially inside antechamber with NEG strips to provide distributed pumping
  - radially outside antechamber with sloped wall to minimize scattered photons

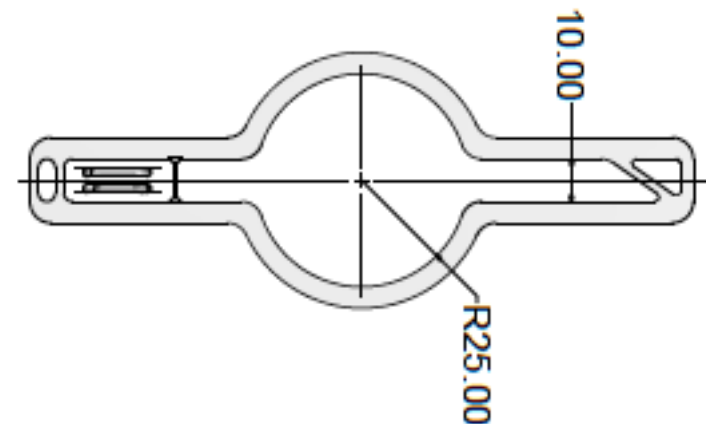


# Arc Vacuum Chamber

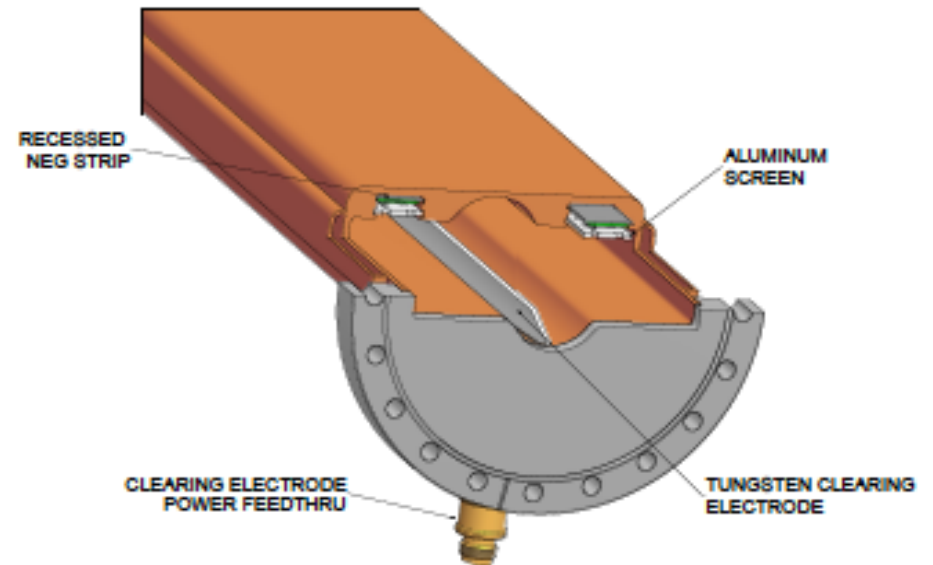
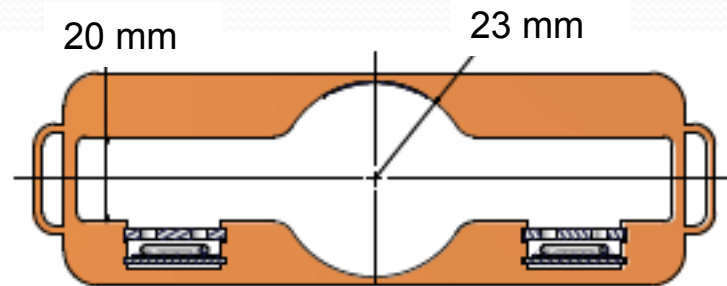
- One chamber extends through 3 quadrupoles, 4 sextupoles, and 3 corrector magnets
- TiN coating to reduce SEY
- BPM assemblies are located at each end of the chamber



(b) ARC CHAMBER



# Wiggler Vacuum Chamber



- Copper for high conductivity
- Titanium nitride (TiN) coating to reduce (SEY)
- Clearing electrode deposited via thermal spray is the primary EC mitigation
- NEG strips for distributed pumping are recessed into the upper wall of the antechambers
- A single chamber goes through 2 wigglers and 1 quadrupole
- Most synchrotron radiation (SR) passes through the antechambers and is trapped in the photon stops at the end of each cell

# 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:

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

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:

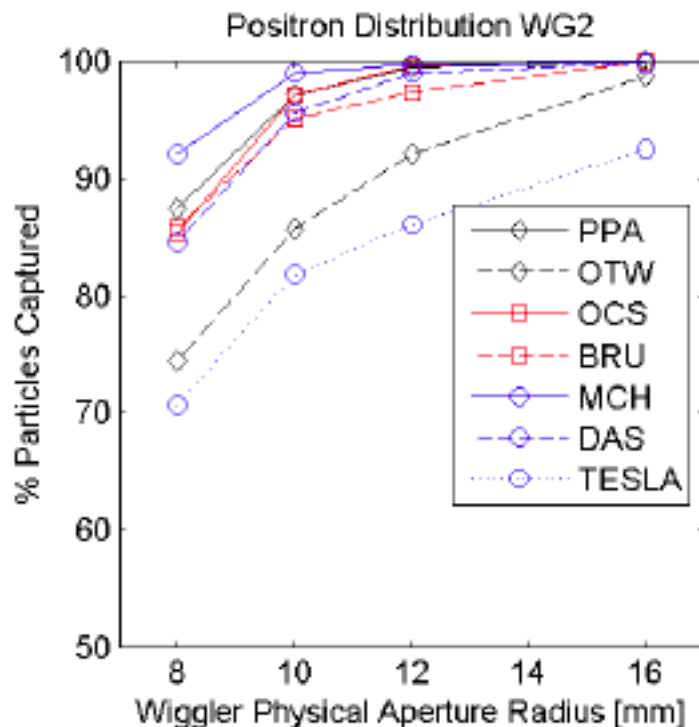
$$\varepsilon_x \approx C_q \frac{\gamma^2}{J_x} \frac{8 \langle \beta_x \rangle}{15 \pi k_p^2 \rho_w^3}$$

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:

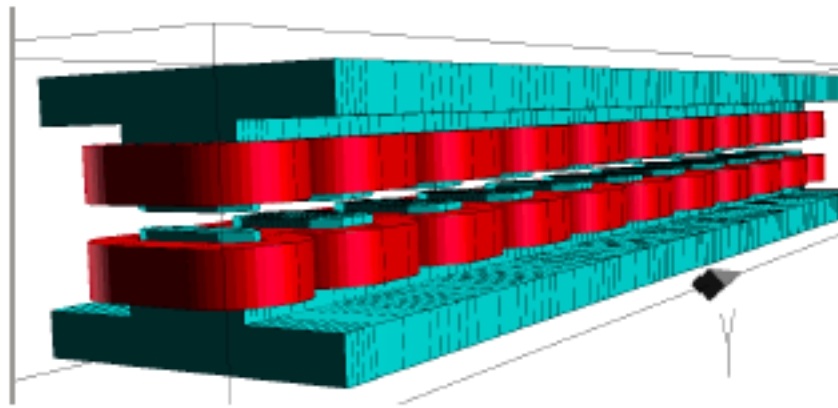
- provide sufficient aperture to allow efficient injection of positron beams which are injected with significant betatron amplitude;
- operate reliably over the long-term in an environment with large amounts of synchrotron radiation;
- have sufficient field quality such that the dynamic aperture of the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



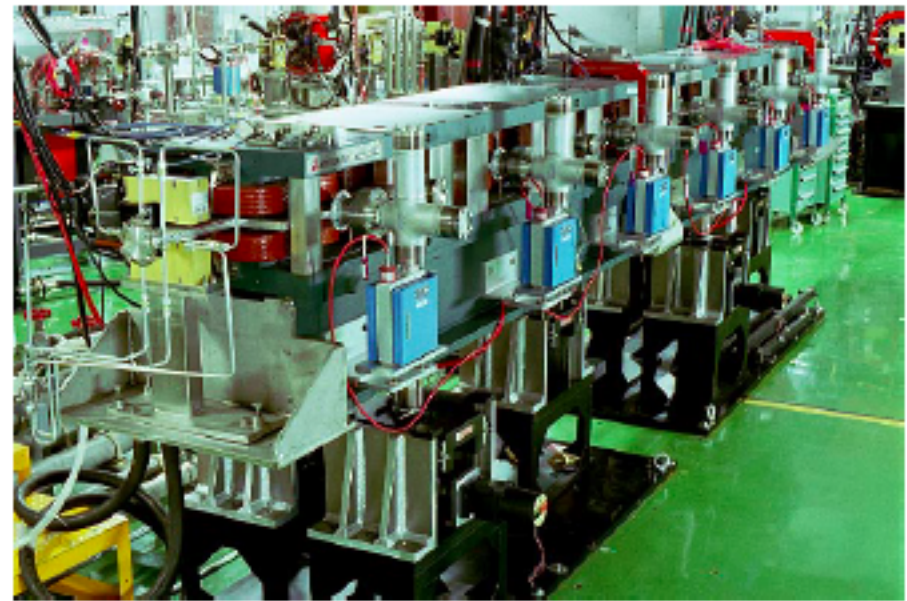
Three distinct wiggler technologies have been evaluated for use in the ILC DR: Normal conducting electromagnetic, permanent magnet hybrid, and superferric designs.

## 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.

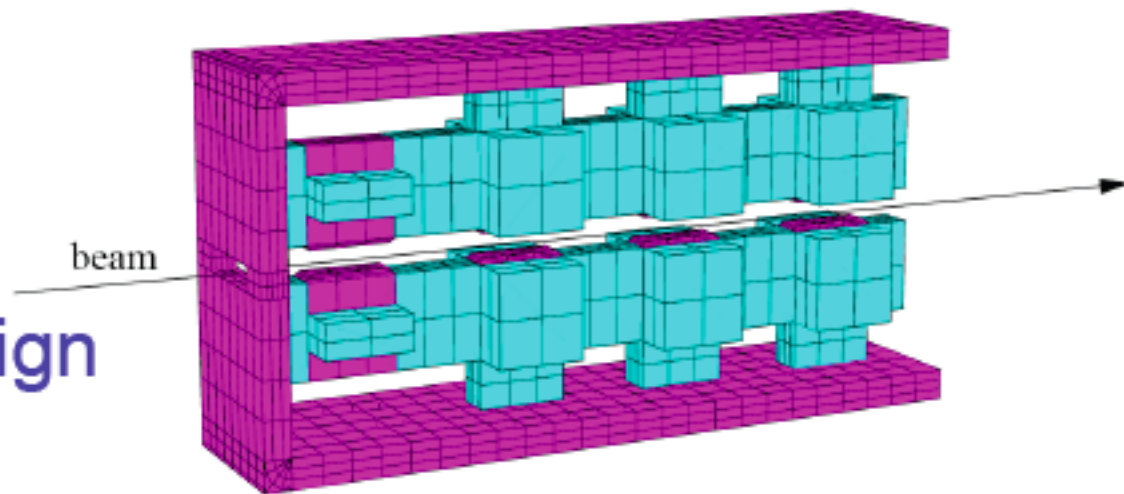


## ATF Damping Wiggler



## 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.

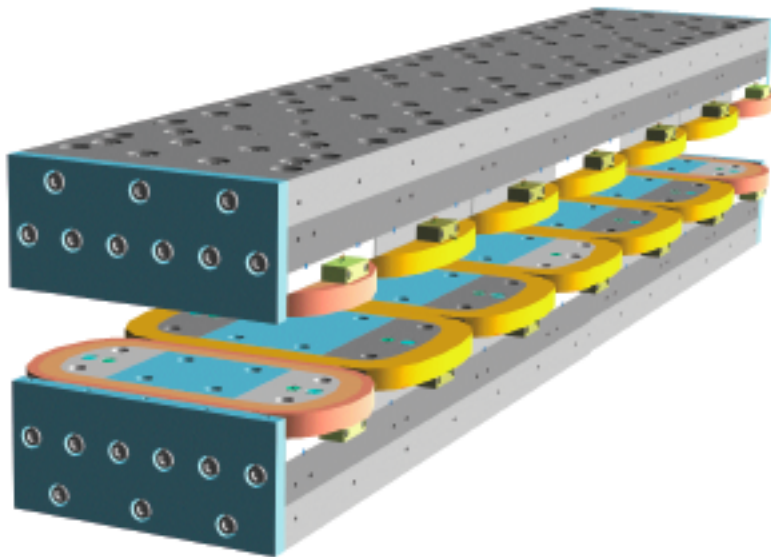


TESLA TDR Design

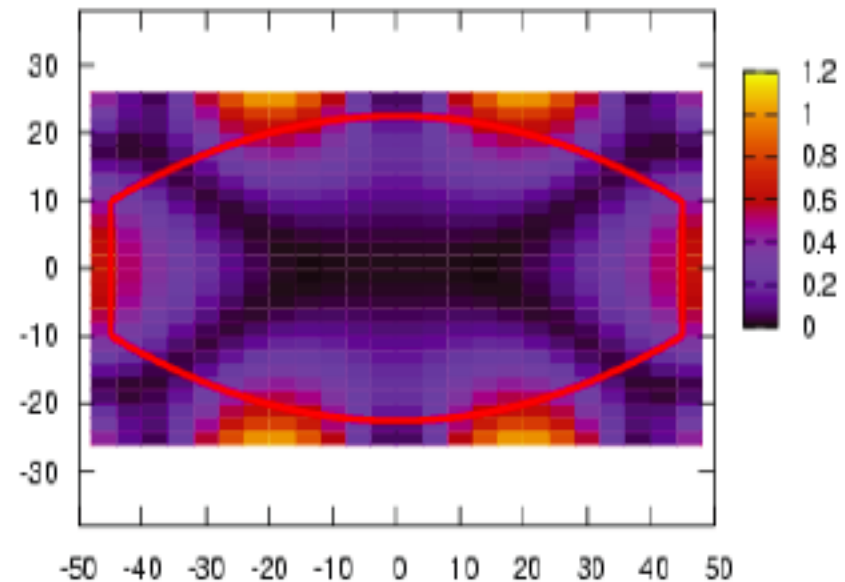
# Superferric Wigglers

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  $\psi(4s)$  resonance  $\Rightarrow$  operation in the 1.8-2.5 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  $\Rightarrow$  very good transverse field quality required



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





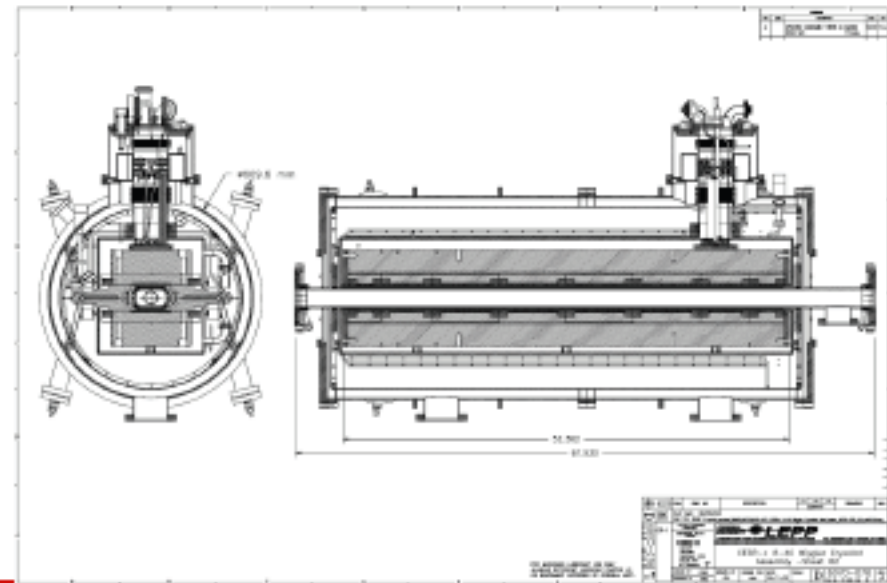
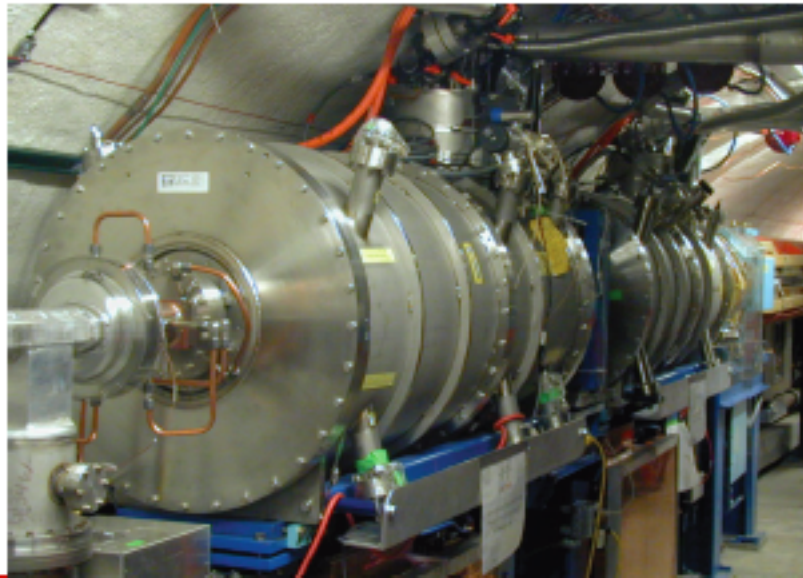
# Superferric Wigglers

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

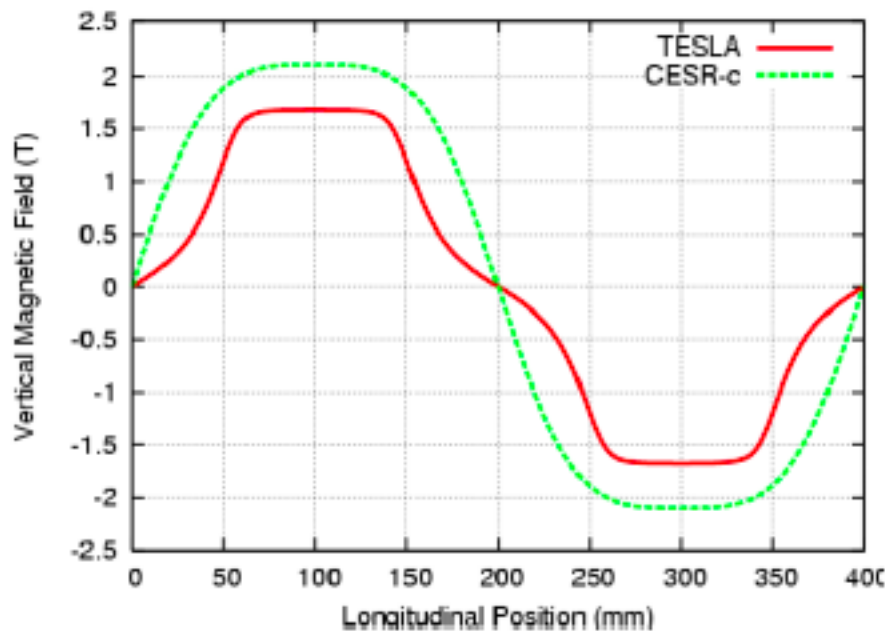


# Wiggler Comparison

## TESLA Wiggler

Hybrid permanent magnet  
NdFeB with iron poles

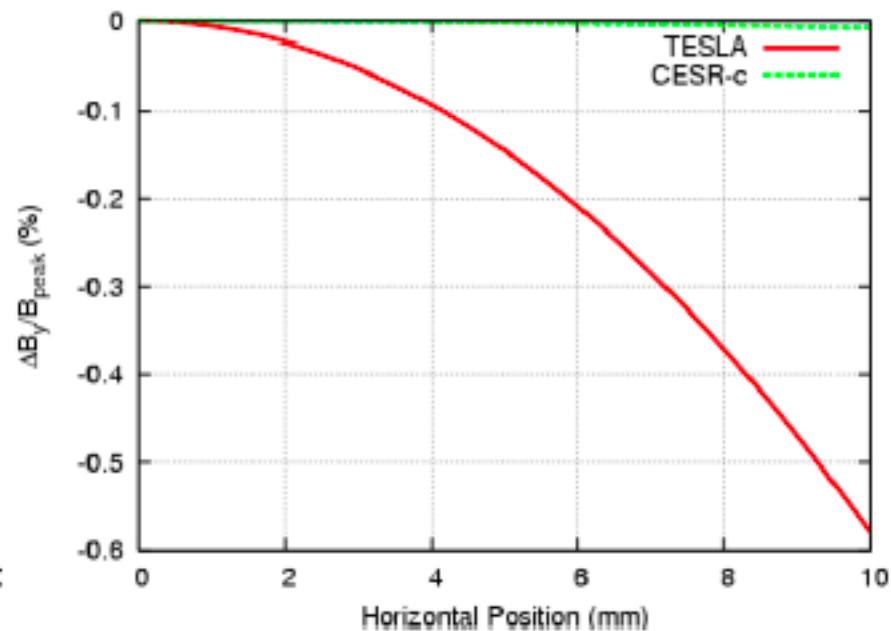
$$\Delta B_y / B_{\text{peak}} (x=10\text{mm}) = 5.7 \times 10^{-3}$$



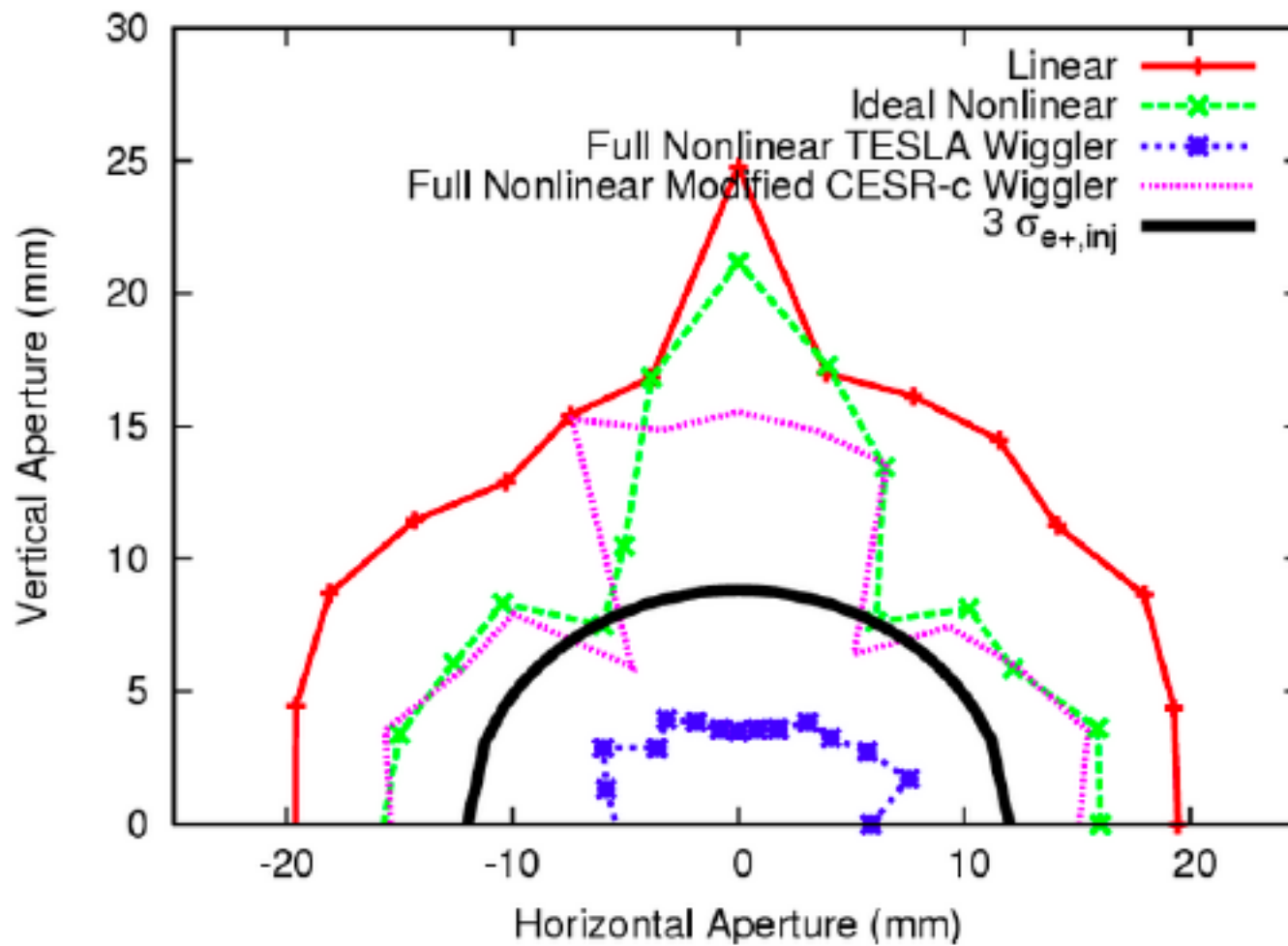
## CESR-c Wiggler

Superferric magnet  
NbTi coils with iron poles

$$\Delta B_y / B_{\text{peak}} (x=10\text{mm}) = 7.7 \times 10^{-5}$$

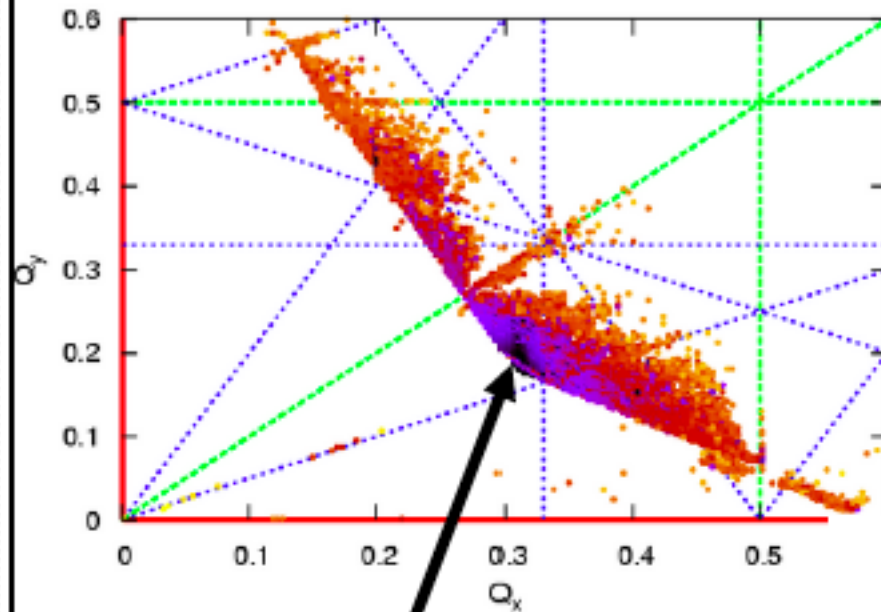


# Dynamic Aperture



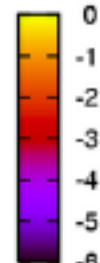
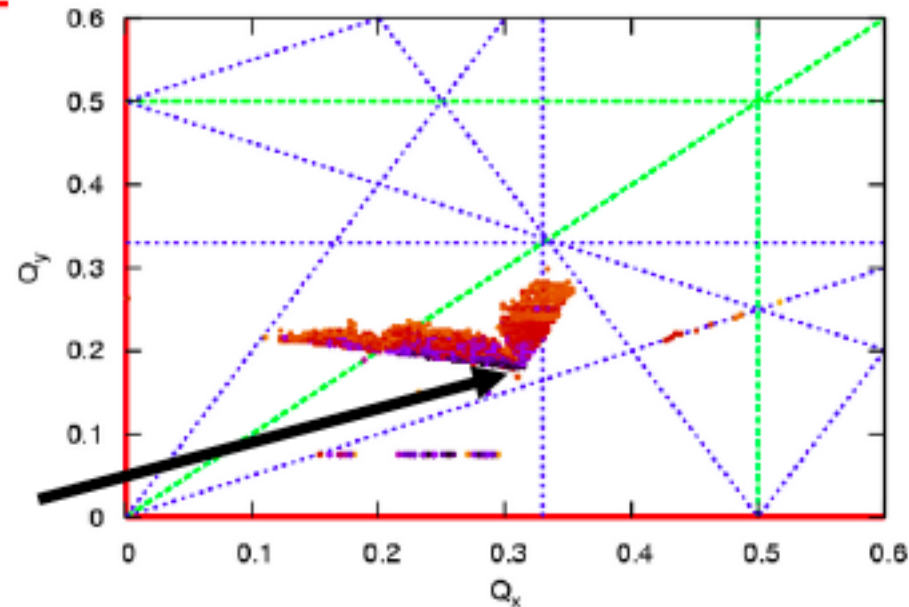
# Frequency Map Analysis

TESLA



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

Modified CESR-c  
Wiggler



Operating  
point

Operating  
point

## Wiggler Optimization

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

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

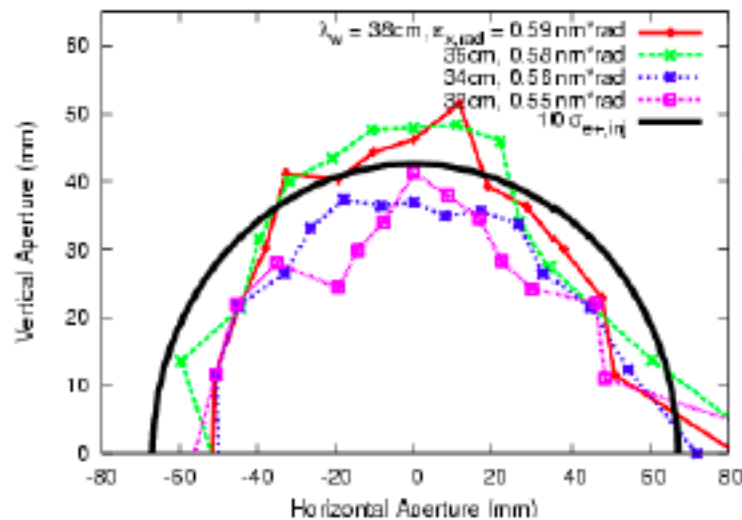
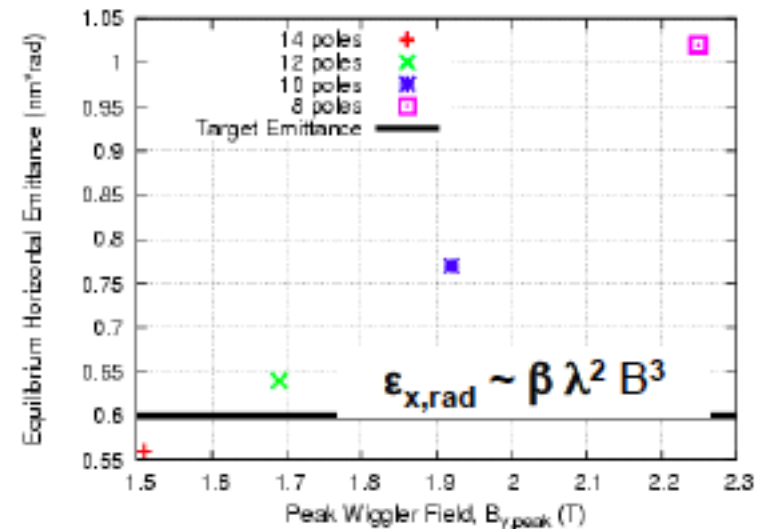
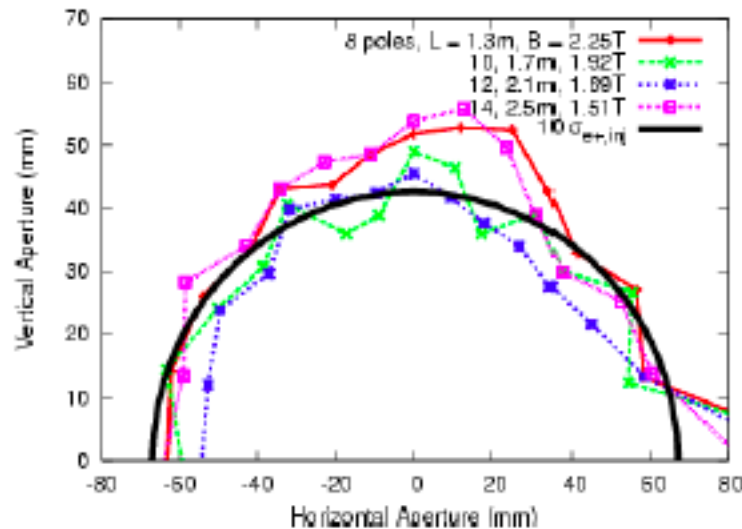
The wiggler contribution to the emittance can be lowered by:

- 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.

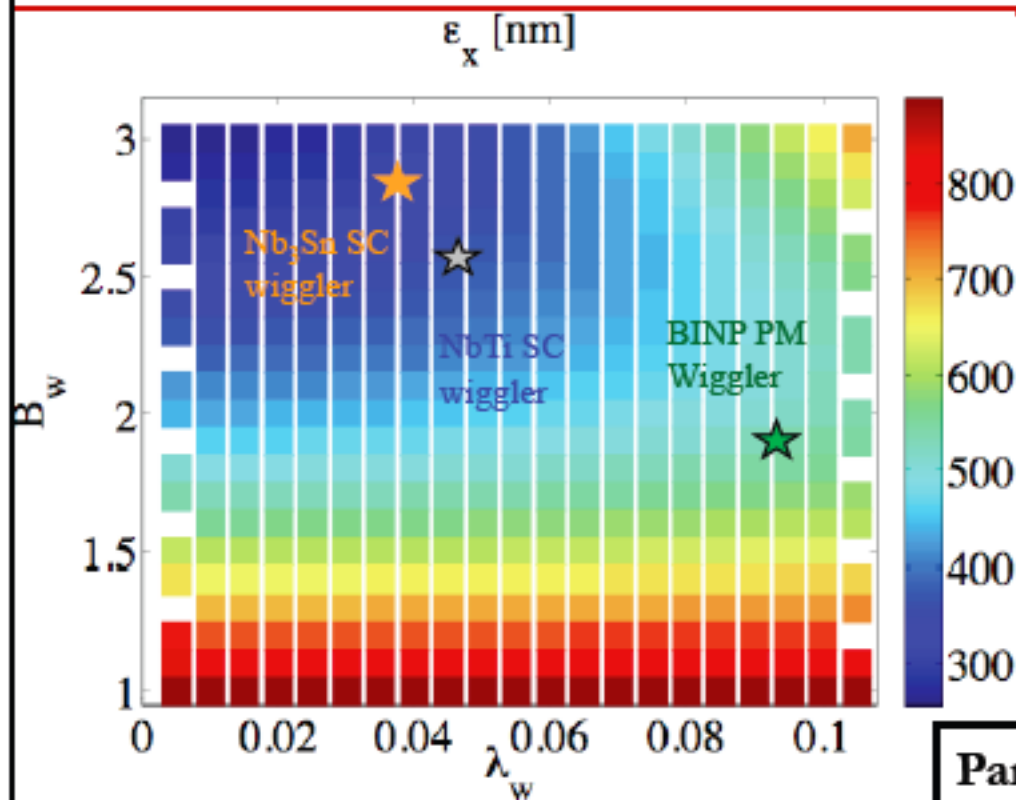
**Optimize with:**

12 poles and period = 32 cm

VS

14 poles and period = 40 cm

# Emittance with Wigglers and IBS



Stronger wiggler fields and shorter wavelengths necessary to reach target emittance due to strong IBS effect

Current density can be increased by switch to Nb<sub>3</sub>Sn

Nb<sub>3</sub>Sn can sustain higher heat load (potentially 10 times higher than NbTi)

Y. Papaphilippou

Parameters	BINP	CERN
$B_{\text{peak}}$ [T]	2.5	2.8
$\lambda_w$ [mm]	50	40
Beam aperture full gap [mm]	13	
Conductor type	NbTi	Nb <sub>3</sub> Sn
Operating temperature [K]	4.2	

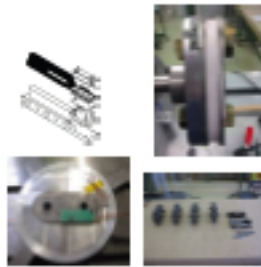
D. Schoerling,  
S. Russenchuck, et al.

## Nb<sub>3</sub>Sn Technology

## Nb-Ti Technology

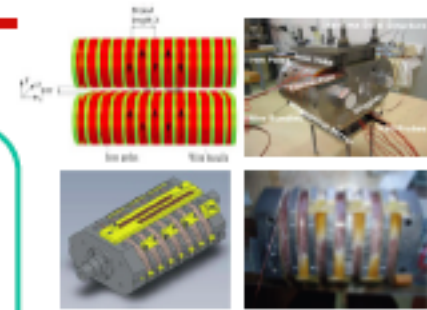
### First Tests Short Model

- Conceptual Design for Short Model (Design Office Support needed!)
- 5 Test Coils for Insulation and Heat Treatment tests
- One Vertical Racetrack Coil ready to be tested
- Horizontal racetrack coil planned to wind
- 2-period wiggler in mirror and full configuration (planned)



### First Tests Short Model

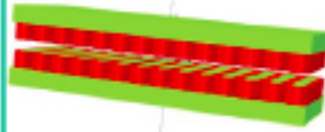
- Conceptual Design for Short Model
- 2-Period Short Model, successful tested at CERN in mirror configuration
- Short Model at BINP successful tested



CDR

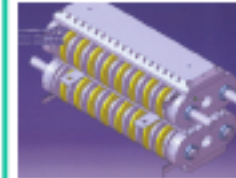
### Small Prototype

- Modules, Design and Test
- Joint Testing
- Field Quality Measurements at CASPER at ANKA



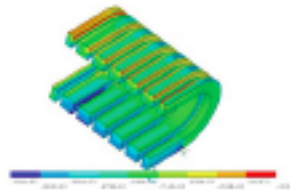
### Small Prototype

- Modules, Design and Test
- Joint Testing
- Field Quality Measurements at CASPER at ANKA



### Full-Scale Prototype

- Full Scale Nb<sub>3</sub>Sn Prototype with cryogenics to be tested at ANKA
- Design and manufacturing at CERN but with synergies from Nb-Ti wiggler!



### Full-Scale Prototype

- Full Scale Nb-Ti Prototype with cryogenics to be tested within the collaboration framework with ANKA, Karlsruhe, Germany
- Design: Collaboration of ANKA, BINP and CERN.
- Manufacturing at BINP

SCU14 in ANKA



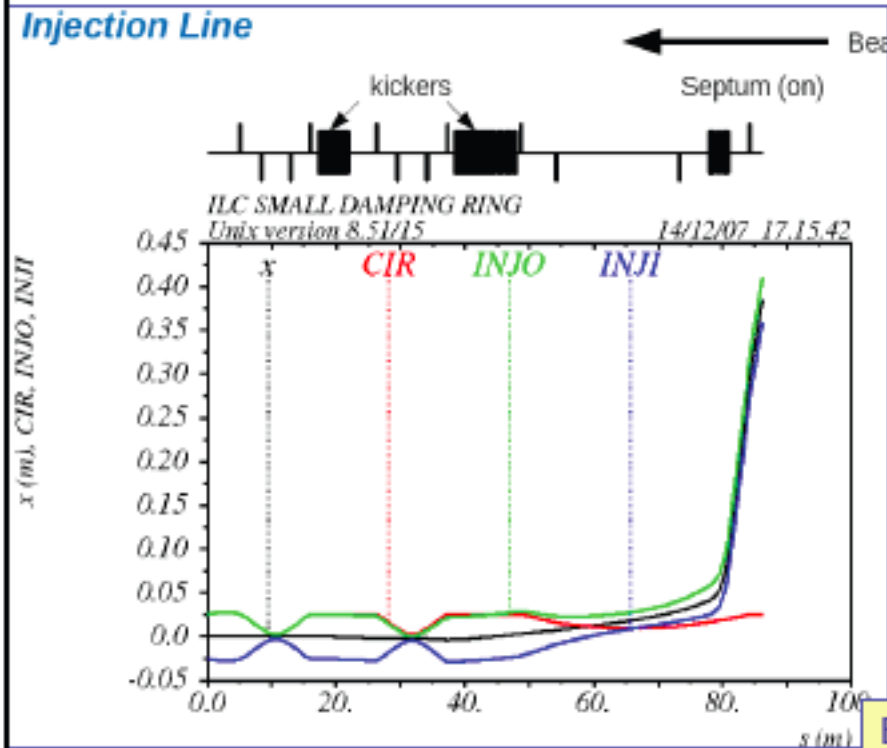
TDR



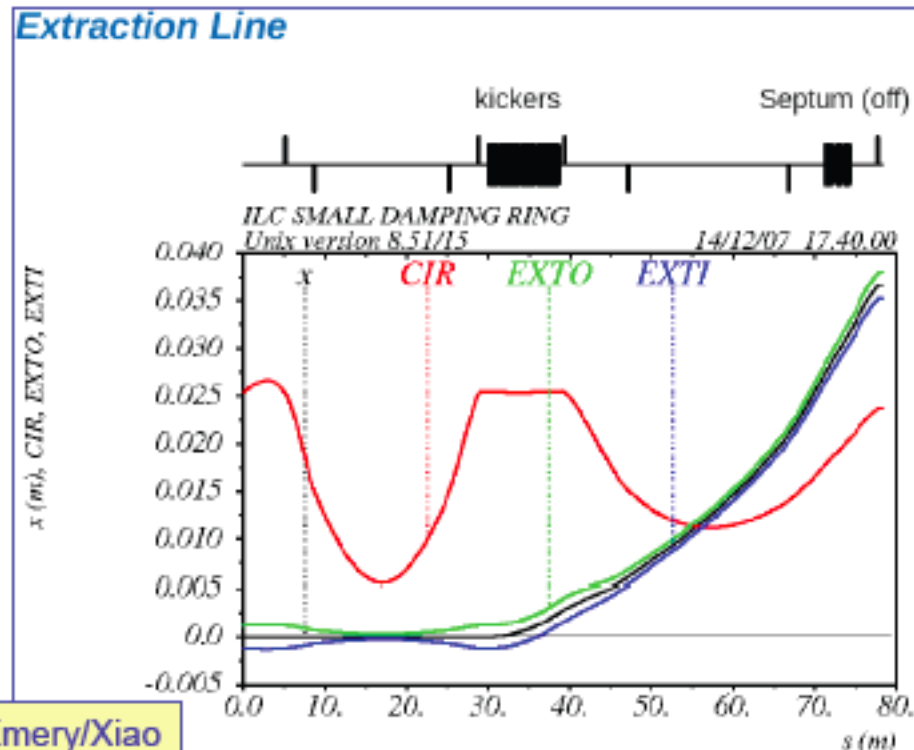
# Injection and Extraction Systems

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.

Injection Line



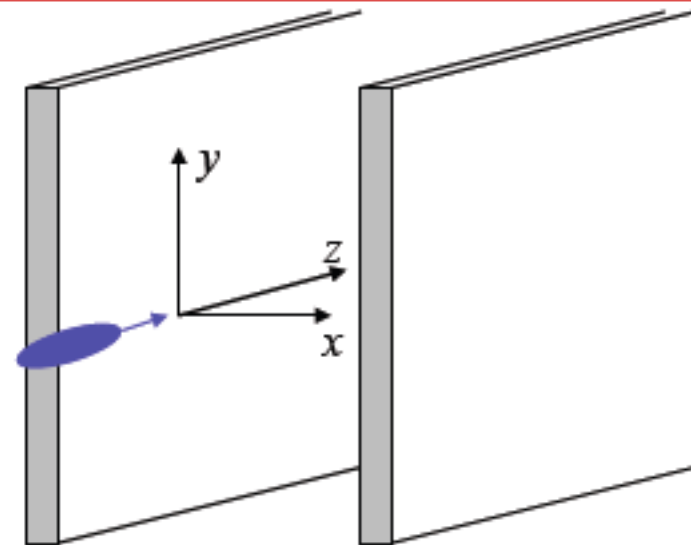
Extraction Line



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

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

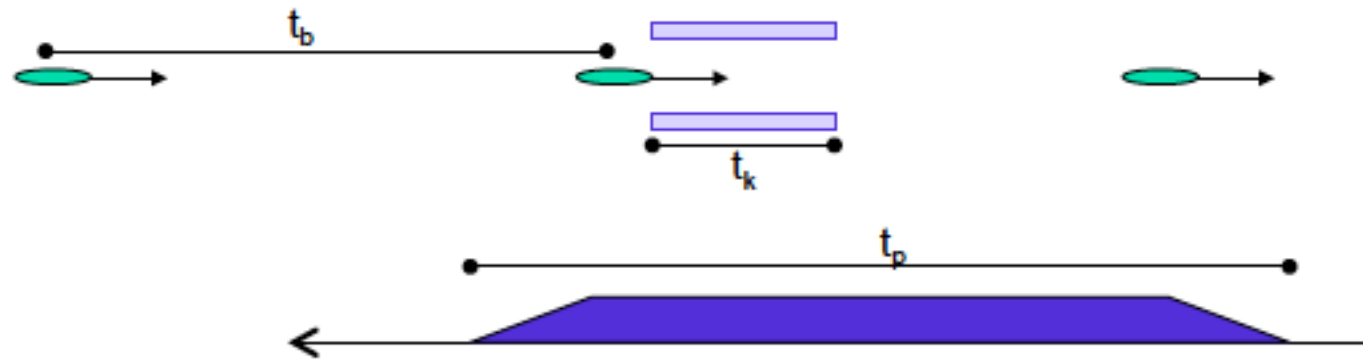
An electron moving in the  $+z$  direction with velocity  $\beta c$  will experience a force:

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

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  $\sim 4.2$  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  $\sim 30\text{mm}$  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)

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

Let's take:

$$d = 20 \text{ mm} \quad g = 0.7$$

⇒

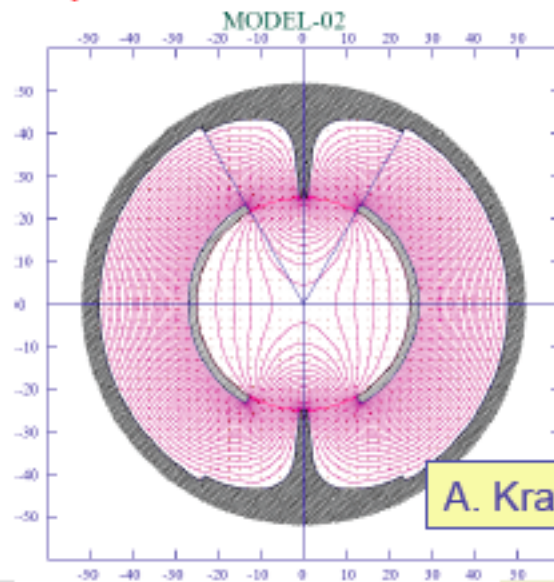
$$VL = 43 \text{ kV} - \text{meters}$$

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.

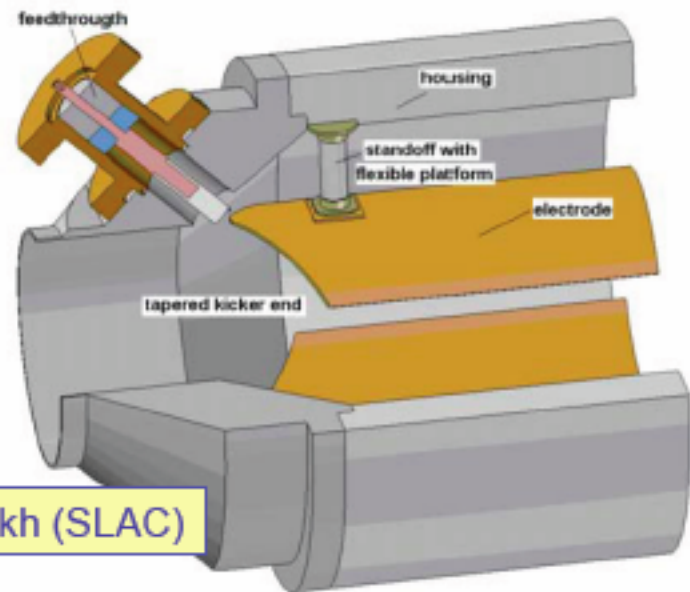
# Stripline Designs

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

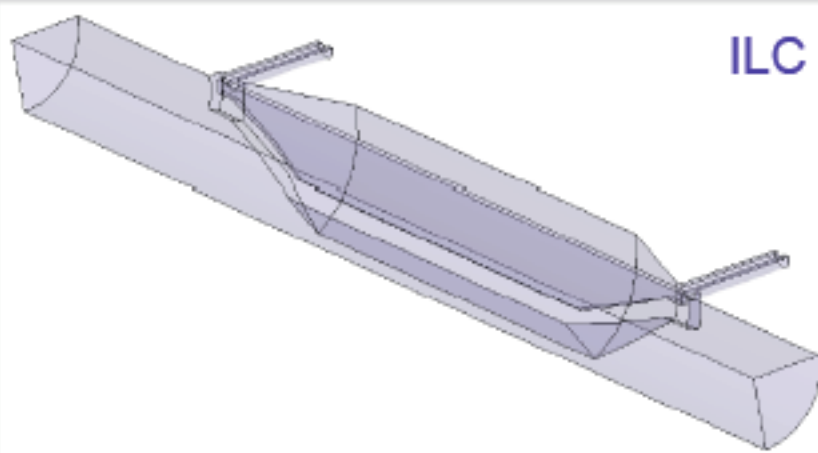
Proposed Cross Section for the ILC DR Kicker



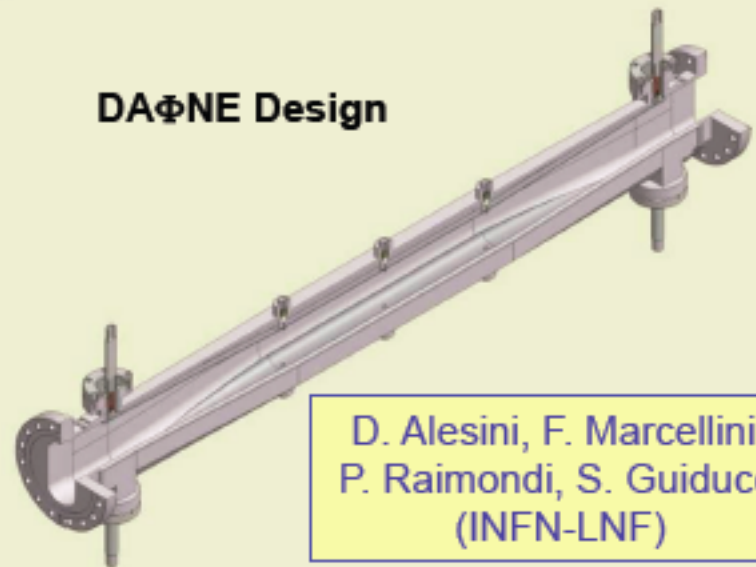
A. Krasnykh (SLAC)



## TAPERED STRIPLINE DESIGN



## DAΦNE Design



D. Alesini, F. Marcellini,  
P. Raimondi, S. Guiducci  
(INFN-LNF)

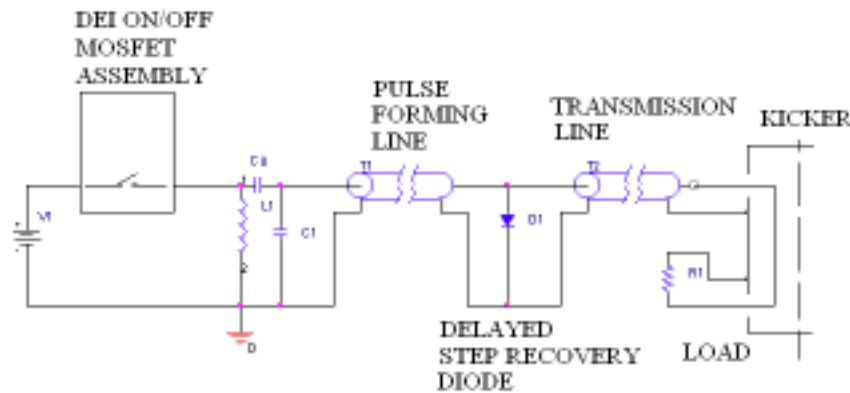
## Fast Pulser Specifications

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

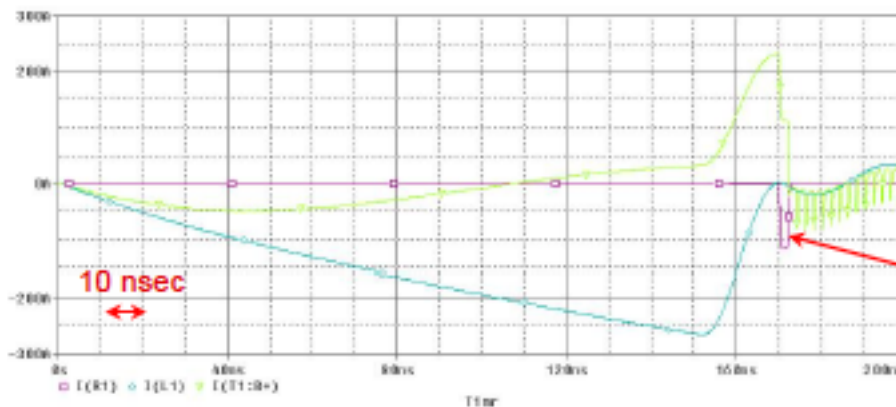
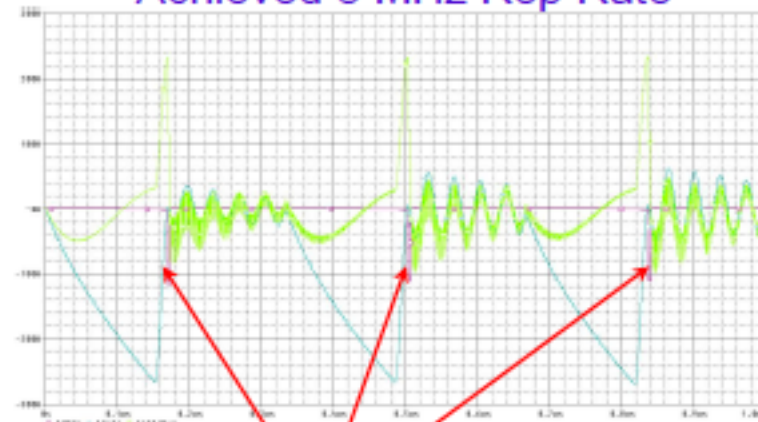
# Drift Step Recovery Diode (DSRD) R&D

A. Krasnykh (SLAC)

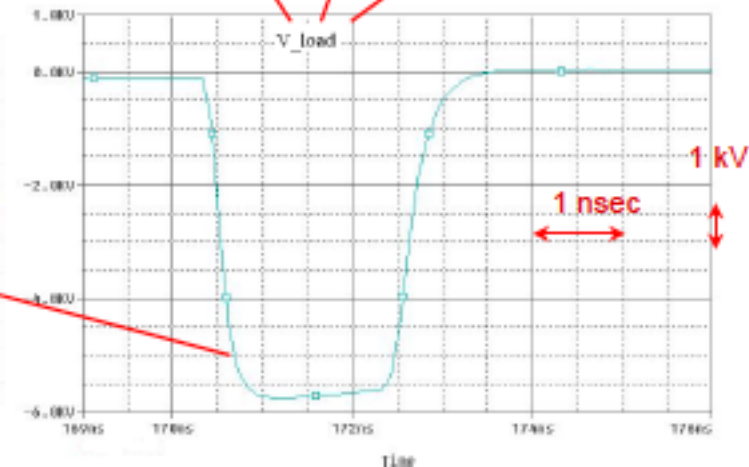


$L=40 \text{ nH}$ ,  $C_0=30 \text{ nF}$ ,  $C_1=1.5 \text{ nF}$ ,  
 $t_{on}=150 \text{ nsec}$ ,  $t = 1 \text{ nsec}$

Achieved 3 MHz Rep Rate



Currents vs. time for one cycle



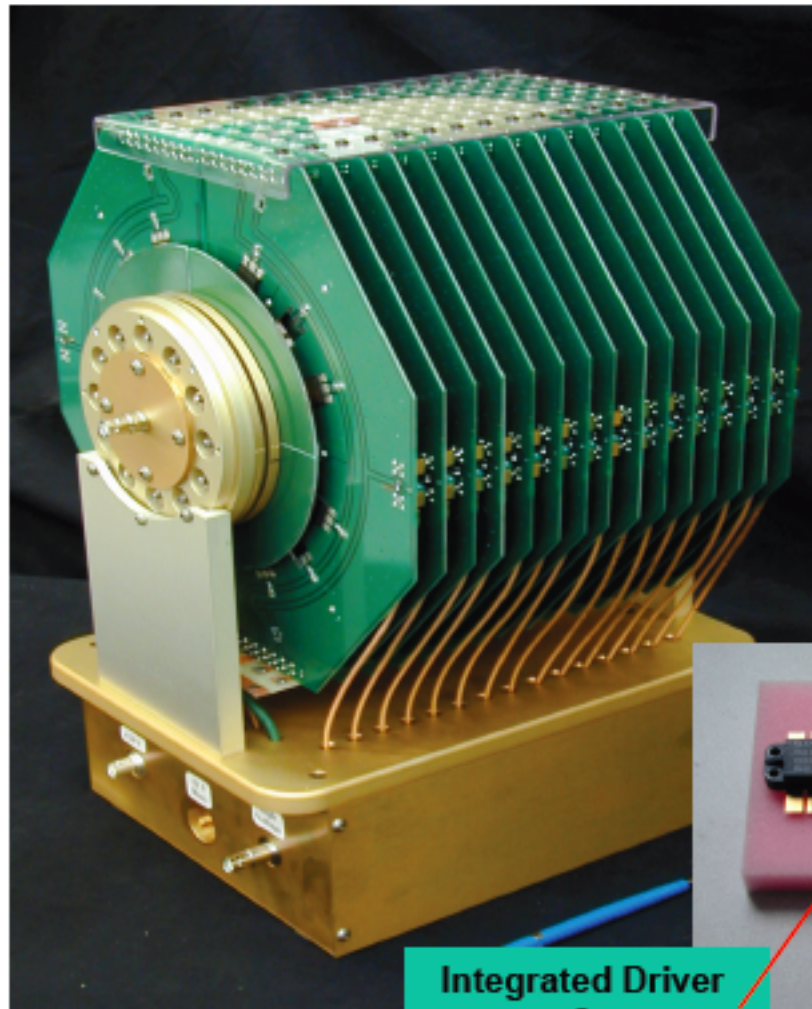
~6kV Output Voltage, Residual Voltage is ~2%



# Inductive Adder (IA) Prototype

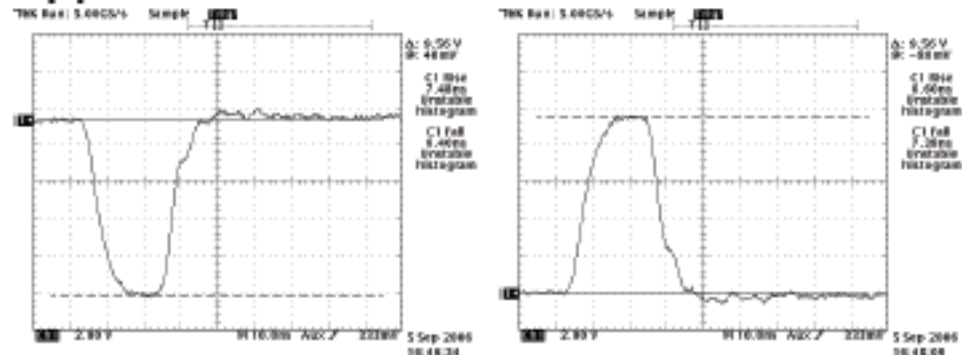
Utilizes MOSFET devices

Intrinsic speed is too slow for direct application to ILC DR:



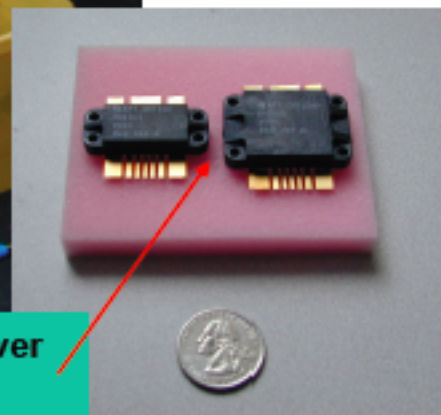
E. Cook (LLNL)

Integrated Driver  
&  
Power MOSFET



$\pm 9.6$  kV pulses

7 ns rise and fall times

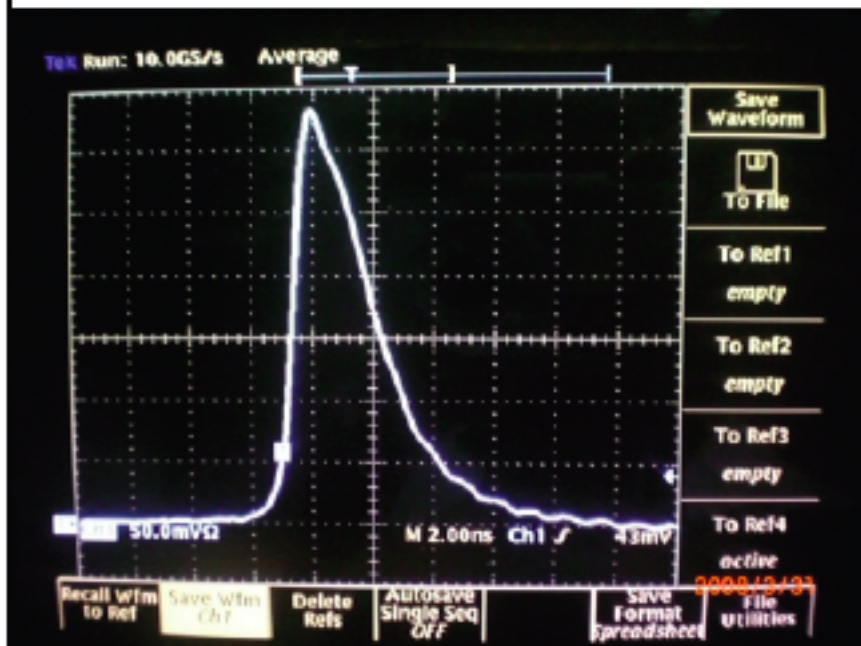


However, a hybrid Inductive Adder-DSRD device where this is the pumping stage for the DSRD is being pursued

# Fast Ionization Device (FID) R&D

Tests at ATF with device targeting  $\pm 10$  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 Kicker Tests at ATF

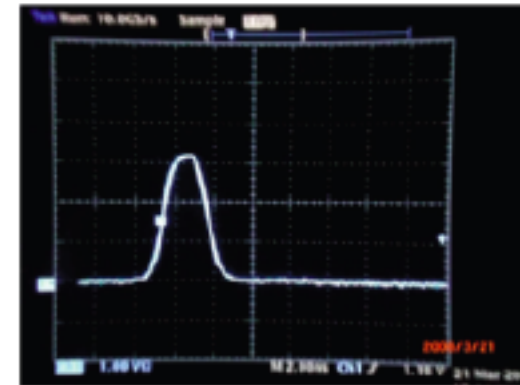
T. Naito  
IWLC2010

## Single unit test

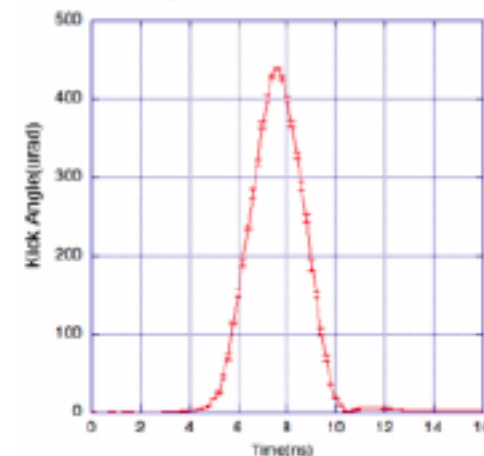
(To confirm 3ns of the rise time of the strip-line kicker)



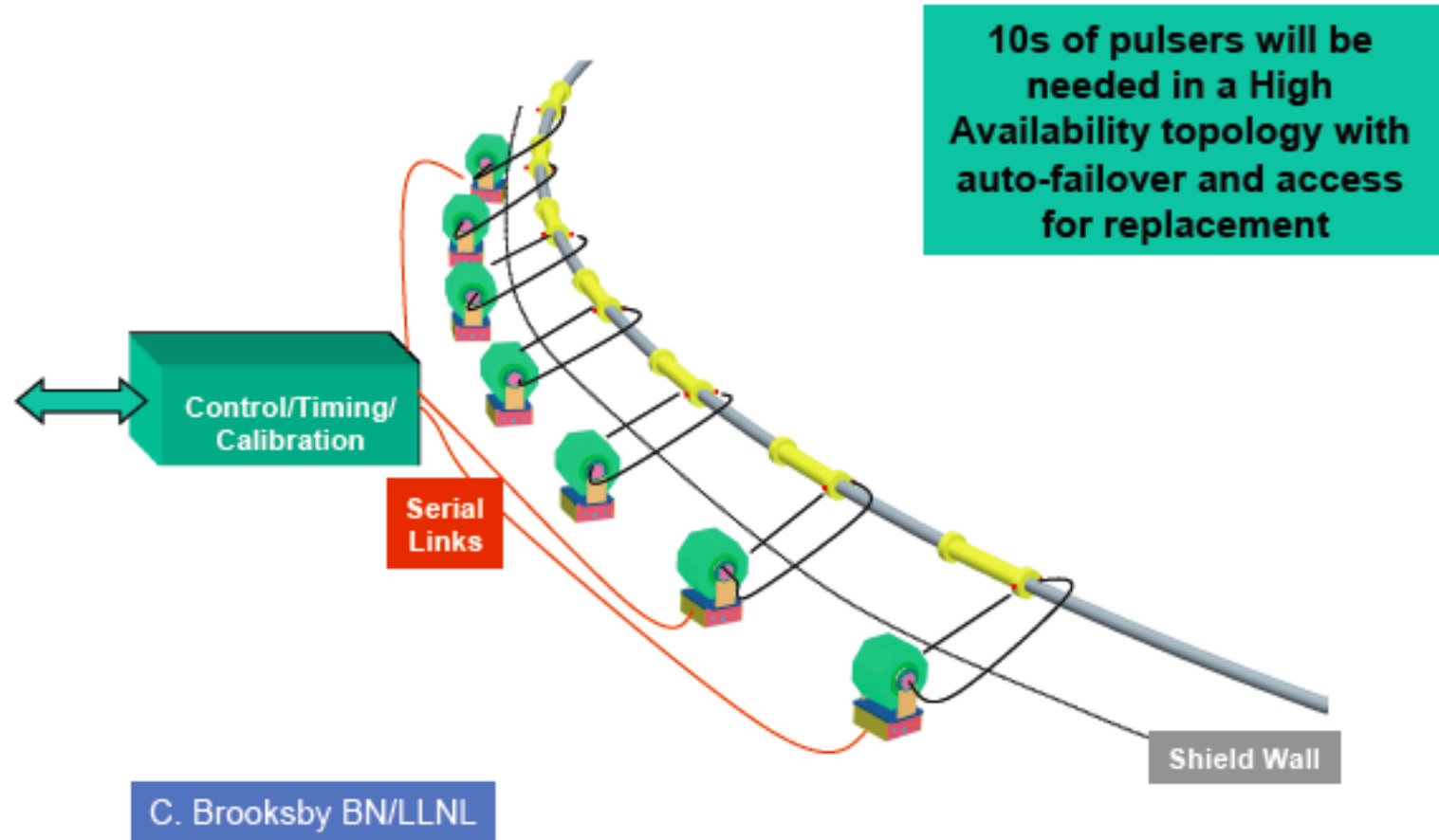
- *The time response of the kick field is strongly depends on the waveform of the drive pulse and the length of the strip-line electrode.*
- *FID pulser have 1.5ns rise time, 5kV peak voltage, 3MHz and 3000 burst pulse.*
- *The time response was tested when the drive pulse was applied to the 30 cm long strip-line electrode.*
- *The time response of the strip-line kicker was measured by measuring the betatron amplitude in ATF-DR. The measured rise time was 3ns, which meets the ILC requirement.*



Waveform of FID pulser  
5kv peak, 1.5ns rise time



# System Topology



## Fast Kicker Summary

At present, the fast kicker R&D program appears to be converging towards viable solutions for bunch trains with spacings as small as 3ns. The overall system stability requirements for the ILC and CLIC kicker systems are very similar. Both groups plan to collaborate on further R&D in this area.

# 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  $<10 \mu\text{m}$  and fast response.

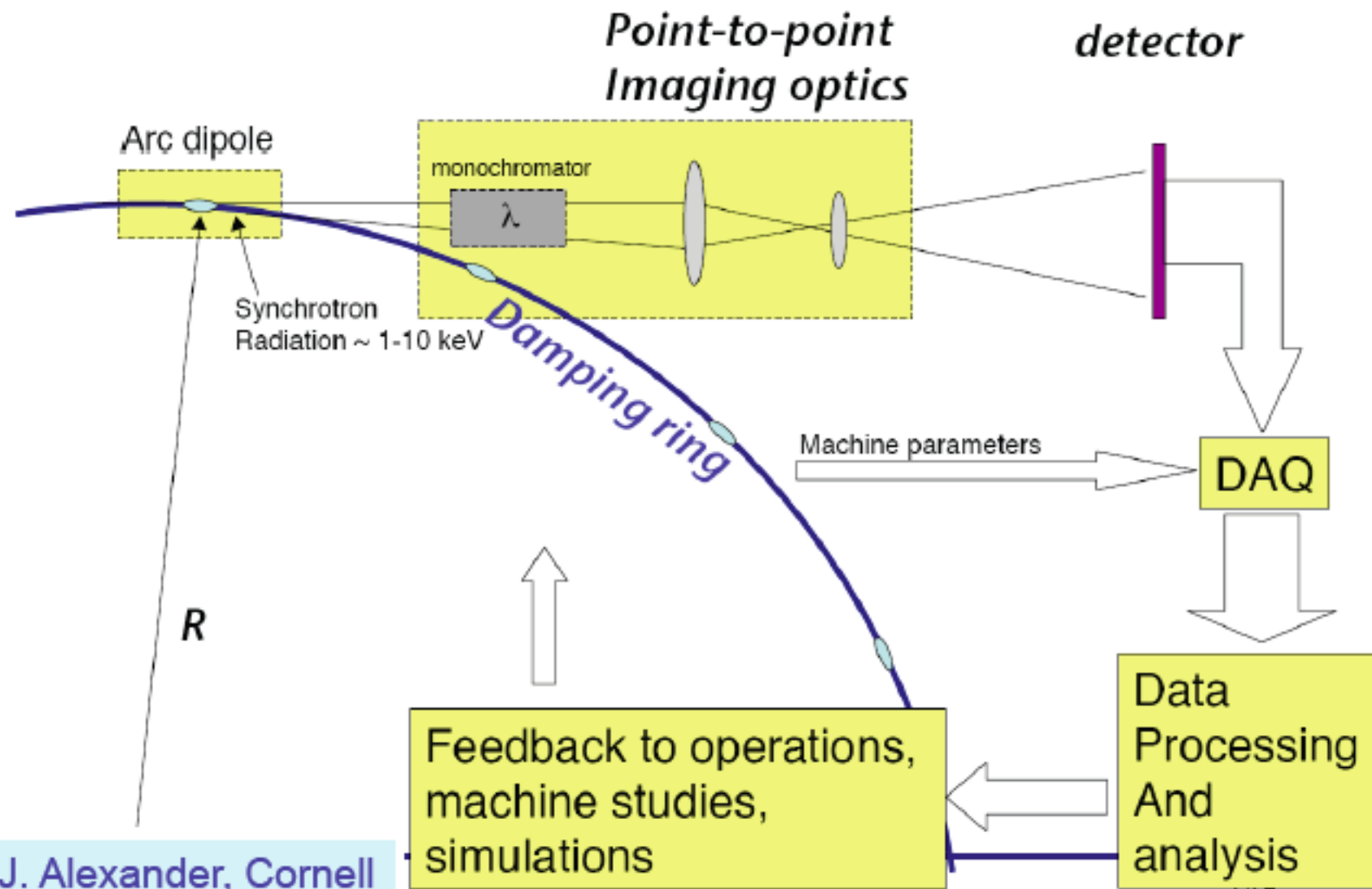
This device should be capable of:

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

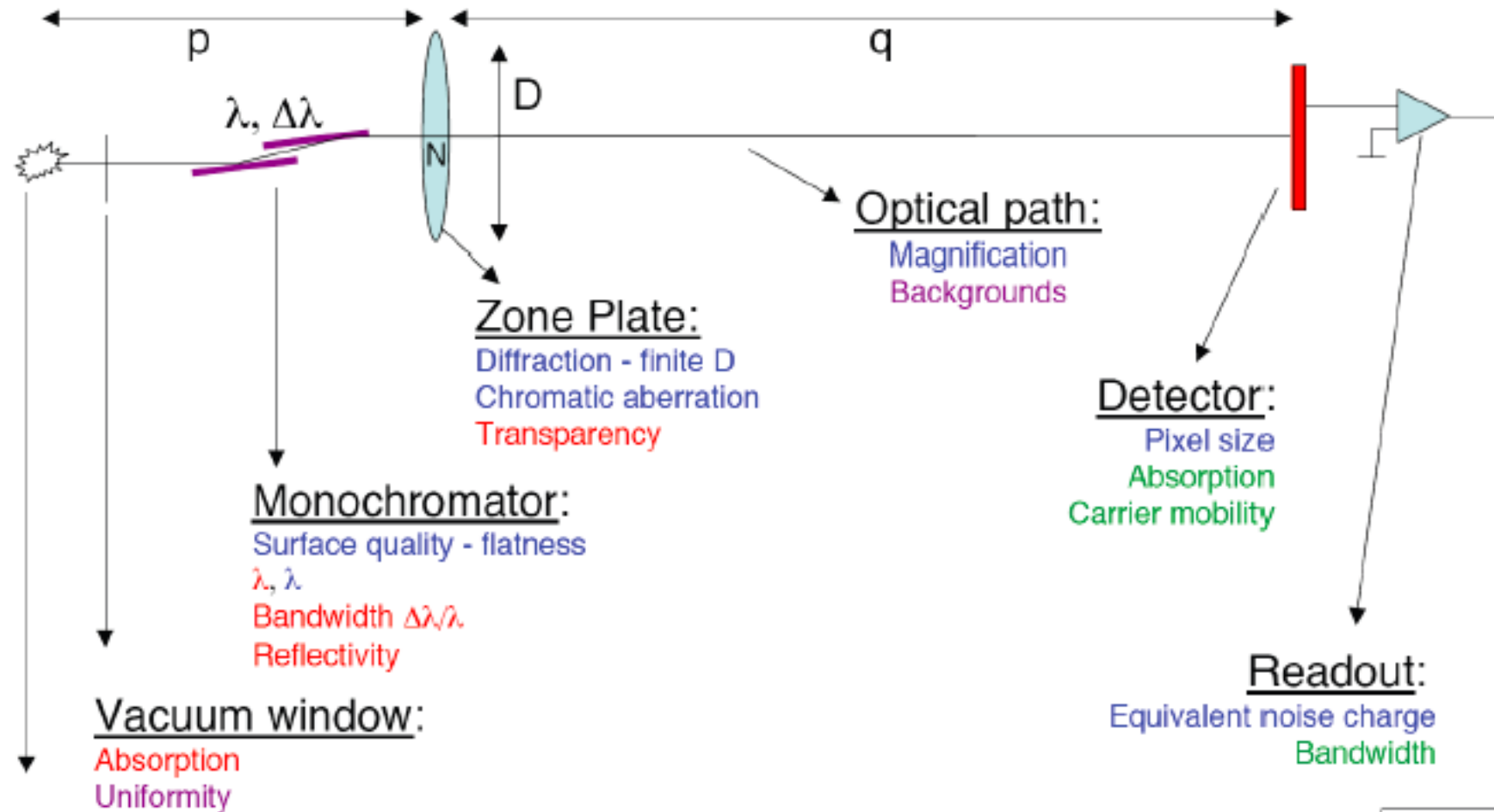
Such a device will aid in:

- 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



# System Design Issues



## Source:

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

## Vacuum window:

Absorption  
 Uniformity

## Monochromator:

Surface quality - flatness  
 $\lambda, \lambda$   
 Bandwidth  $\Delta\lambda/\lambda$   
 Reflectivity

## Zone Plate:

Diffraction - finite  $D$   
 Chromatic aberration  
 Transparency

## Optical path:

Magnification  
 Backgrounds

## Detector:

Pixel size  
 Absorption  
 Carrier mobility

## Readout:

Equivalent noise charge  
 Bandwidth

Color coding:  
 Photon yield  
 Resolution  
 Distortions  
 Speed

J. Alexander, Cornell

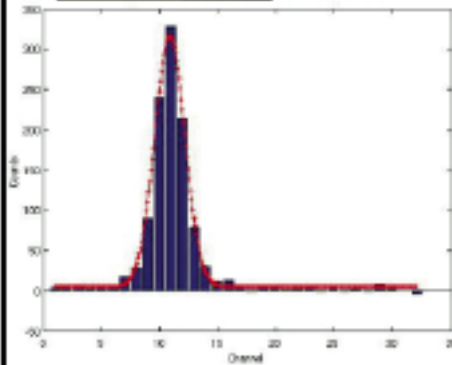
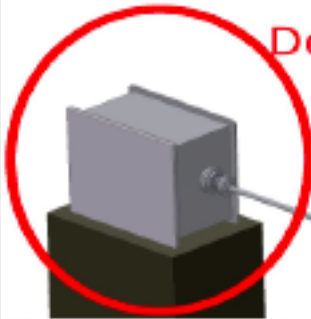


# CESR Reconfiguration: X-Ray Lines

Detector: InGaAs Array  
Single-pass readout  
Few micron resolution

Helium or Vacuum

Detector box



Source to Optics Box = 4.29 m,  
Optics box to detector = 10.5m  
 $m = 2.45$

New all-vacuum optics lines  
installed in collaboration with  
CHESS:

- Positron line (shown) deployed summer 2008
- Electron line completed summer 2009

High Vac

UHV

Optics  
Box

Source

Coded Aperture

Fresnel Zone Plate

Upstream



# Application of Turn-by-Turn Imaging

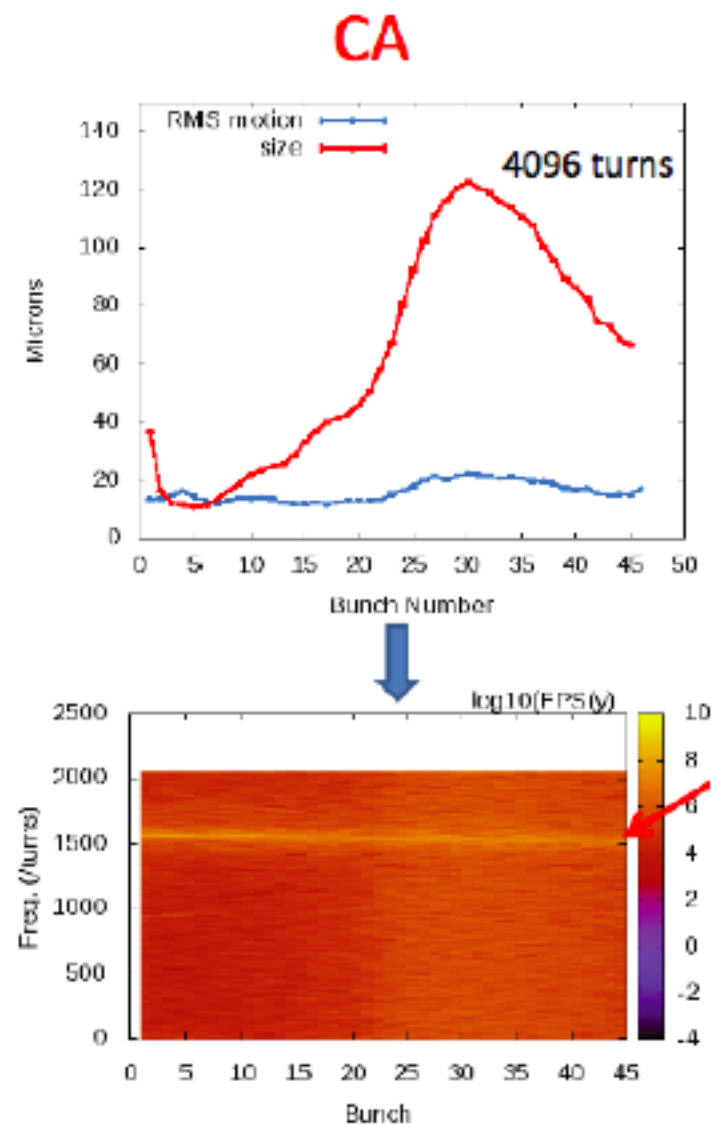
Results of turn-by-turn imaging of a 45 bunch train of positrons in CEsR-TA.  $\sim 2 \times 10^{10}$  particles/bunch with 14ns bunch-spacing

Data was acquired for each bunch on the same set of 4096 turns

Bunches in the train show the onset of a head-tail instability shortly after bunch 20.

Bottom plot shows the bunch-by-bunch vertical tune

If this can be developed into a “production” device, it will be of great use in monitoring the interleaved bunches in the ILC DR



## Summary

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 next 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 ILC damping rings are:

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