# Damping Ring Design and Technical Issues


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for

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# Outline

- Introduction
- Design Issues
- Design Status
- Low Emittance Issues
- R&D Program
- Summary

# Introduction

- DR group currently focuses on two major activities
  - conceptual design of DR and ancillary systems for RDR
    - along with the corresponding cost estimate
  - organization and execution of R&D program in support of DR design
    - focused on RDR issues to date
    - planning and organizational effort under way for TDR stage to follow

- RDR design meets specifications of baseline configuration
  - RDR lattice has evolved somewhat in response to conventional facilities requests

# Design Issues

- Damping ring is challenging
  - requirement for low emittance
    - DR must reduce positron emittance by factor of $\approx 10^6$
  - requirement for adequate dynamic aperture
    - in wiggler-dominated low-emittance lattice
  - requirement for good acceptance for injected positron beam
    - positrons have large emittance (10 mm-rad) and energy spread ($\leq$1%)
  - requirement for acceptably low instability thresholds
    - must provide highly stable beams for downstream systems
      - with high beam current and many bunches

# EDR Baseline Parameters

| | |
|---|---|
| $C$ (km) | 6.6 |
| E (GeV) | 5 |
| $N_b$ | 2700–5400 |
| $I_{avg.}$ (mA) | 400 |
| $\tau_x$ (ms) | ≈25 |
| $\varepsilon_{x,y}$ (nm) | 0.5/0.002 |
| $\sigma_\ell$ (mm) | 6 |

NOTE: Beam current halved for 2 PDR baseline

Design value; specification ≤ 0.8 nm

# RDR Planning

- Plan for RDR was established by DR ASLs in consultation with DR collaboration
  - **DR contact persons identified to help with preparation of component specifications and parts counts**
    - specifications recorded on Component Specification Sheets
      - includes references to information sources and contact info for person responsible
    - *https://wiki.lepp.cornell.edu/ilc/bin/view/Public/DampingRings/ReferenceDesignReport* set up by M. Palmer *et al.*
    - these serve as primary reference for technical and global groups responsible for DR component design
  - **A. Wolski serves as DR Specifications and Costs Coordinator**
    - collects specifications and maintains current cost roll-up
    - acts as DR interface with DCB

# RDR Contact Responsibilities

- Responsibilities shared among DR ASLs

| Technical or Global Group | DR AS Contact | TG or GG Contact |
|---|---|---|
| Magnets | Mike Zisman | John Tompkins |
| Cryogenics – wiggler | Mike Zisman | Laurent Tavian |
| Cryogenics – RF | Susanna Guiducci | Laurent Tavian |
| RF Power | Susanna Guiducci | Shigeki Fukuda |
| Instrumentation | Susanna Guiducci | Mark Ross |
| Controls | Susanna Guiducci | John Carwardine |
| Vacuum | Andy Wolski | John Noonan |
| Conventional Facilities/Siting | Andy Wolski | Tom Lackowski |
| Design Cost Board | Andy Wolski | Jean-Pierre Delahaye |
| Dumps and Collimators | Mike Zisman | Tom Markiewicz |
| Installation | Mike Zisman | Fred Asiri |
| Commissioning, Ops, Reliability | Mike Zisman | Tom Himel |

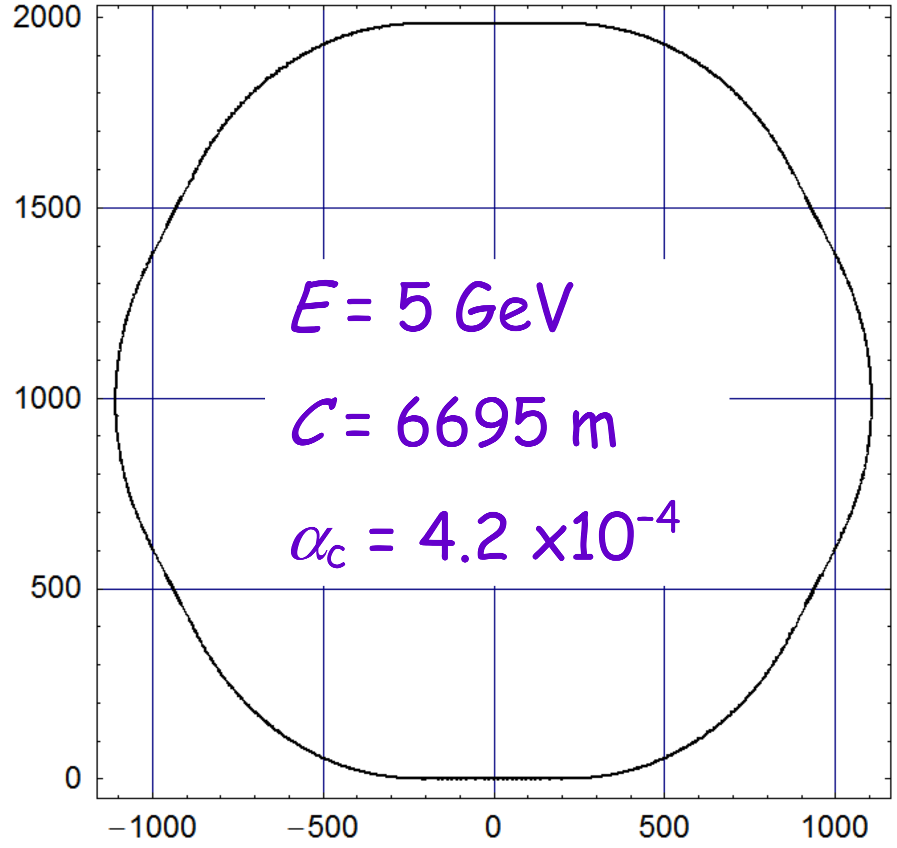
# Design Status

- Lattice ("OCS2") (Xiao) satisfying basic DR requirements presented (Gao) at Bangalore
  - interactions with CFS group identified desirability of minimizing number of RF/wiggler sections
    - reduces required number of access shafts (cost issue)
  - official RDR version of lattice ("OCS6") posted
    https://wiki.lepp.cornell.edu/ilc/bin/view/Public/DampingRings/WebHome
    - alternative FODO configuration being studied at IHEP (Sun)
      - potential for improved dynamic aperture

- Technical subsystem specifications set by lattice
  - having "stable" baseline lattice essential for developing a consistent cost estimate
    - our specifications based on OCS6

# RDR Lattice

- ≈sixfold symmetry; six straight sections
  - 4 short straights for RF and wigglers (249 m)
    - was 6 straights
  - 2 long straights (400 m)
    - injection and extraction
    - beam abort and misc.
  - 6 arcs (818 m)
    - each has 18 TME cells + dispersion suppressor



# Lattice Parameters

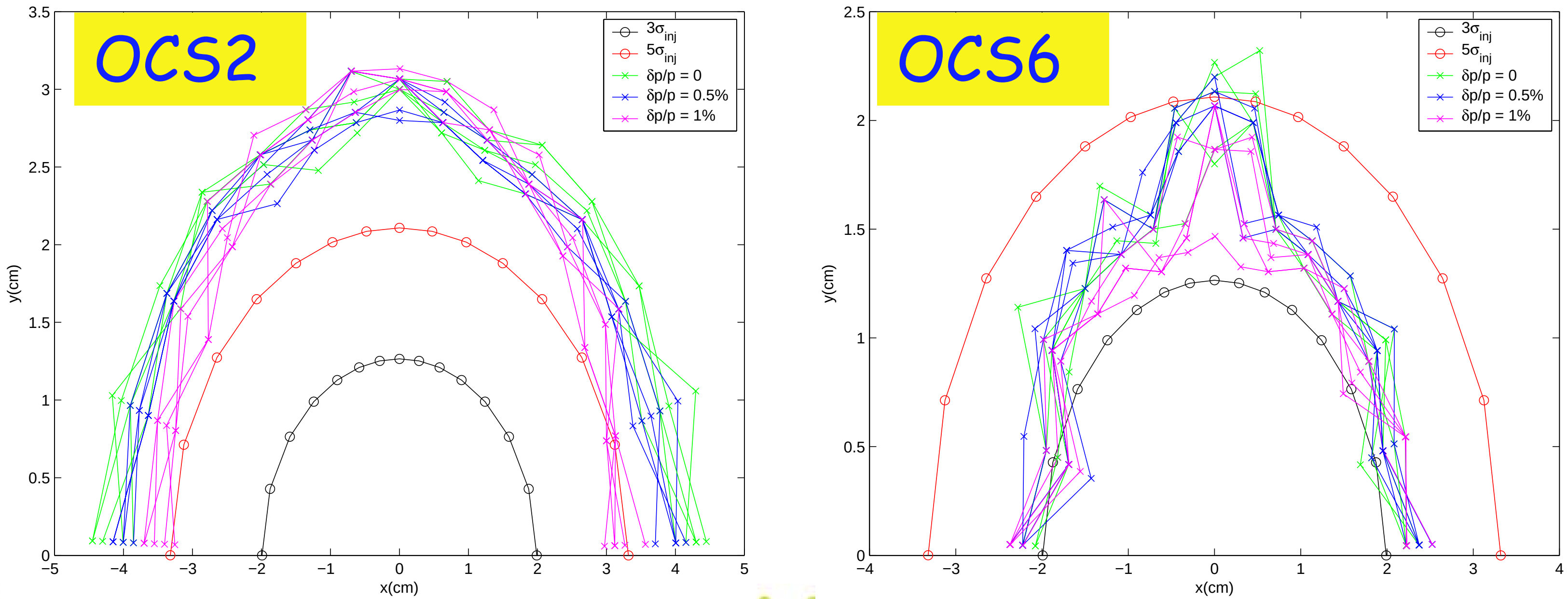
- General parameters for the OCS6 lattice

| | |
|---|---|
| Circumference [m] | 6695.057 |
| Energy [GeV] | 5.0 |
| Harmonic number | 14516 |
| Arc cell type | TME |
| Horizontal tune | 52.397 |
| Vertical tune | 49.305 |
| Natural chromaticity $(x, y)$ | -63,-62 |
| Momentum compaction $[10^{-4}]$ | 4.20 |
| Energy loss/turn [MeV] | 8.69 |
| Transverse damping time [ms] | 25.7 |
| Longitudinal damping time [ms] | 12.9 |
| Natural emittance [nm] | 0.515 |
| Norm. natural emittance [$\mu$m] | 5.04 |
| RF voltage [MV] | 48.1 |

| | |
|---|---|
| RF frequency [MHz] | 650 |
| Synchrotron tune | 0.0958 |
| Synchronous phase [deg] | 169 |
| RF acceptance [%] | 2.7 |
| Natural bunch length [mm] | 6.00 |
| Natural energy spread $[10^{-3}]$ | 1.28 |
| Average current [mA] | 402 |
| Mean horizontal beta function [m] | 13.1 |
| Mean vertical beta function [m] | 12.5 |
| Synch. radn. integral $I_1$ [m] | 2.8116 |
| Synch. radn. integral $I_2$ $[\mathrm{m}^{-1}]$ | 0.9872 |
| Synch. radn. integral $I_3$ $[\mathrm{m}^{-2}]$ | 0.08876 |
| Synch. radn. integral $I_4$ $[10^{-4}\mathrm{m}^{-1}]$ | 1.8888 |
| Synch. radn. integral $I_5$ $[10^{-5}\mathrm{m}^{-1}]$ | 1.3870 |

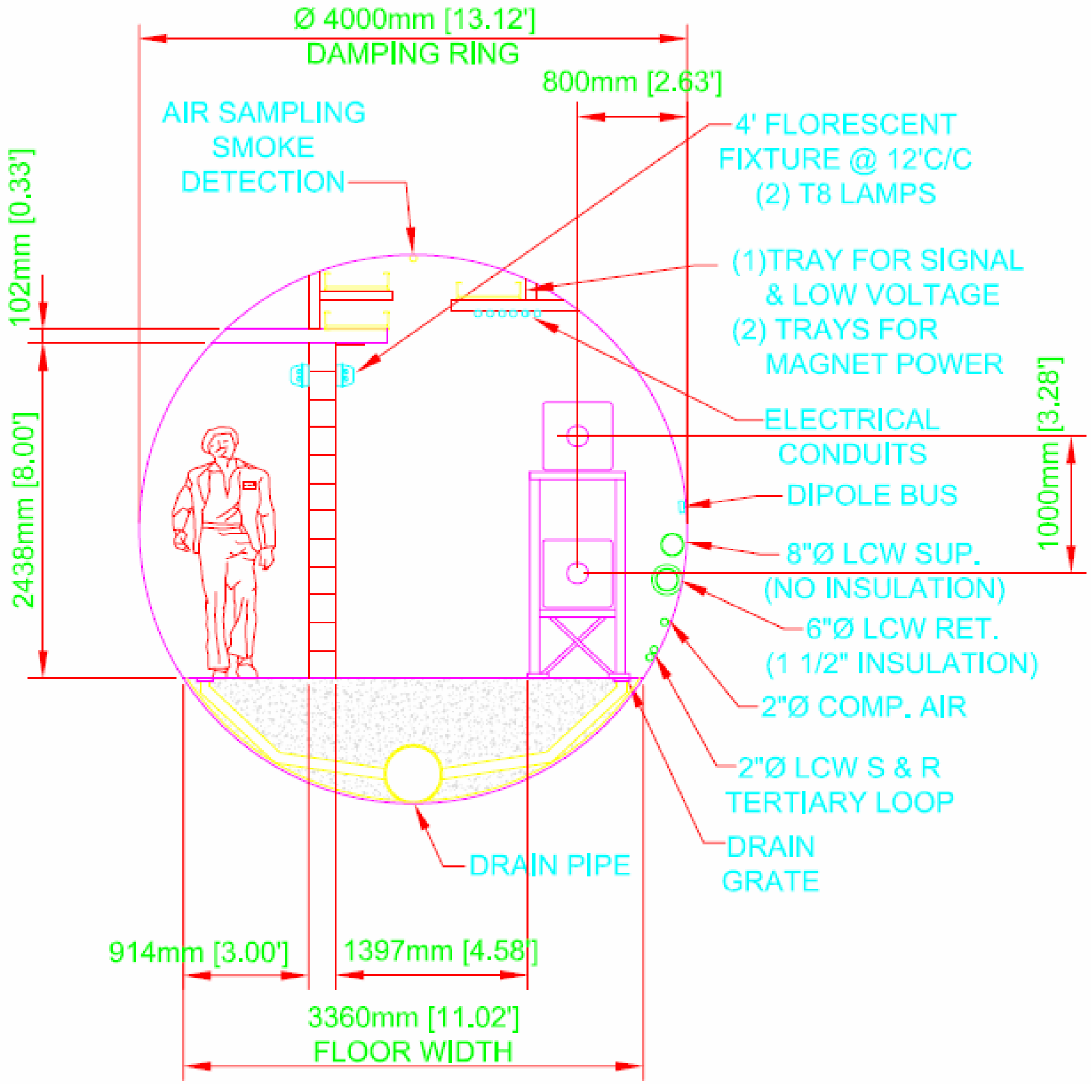
# OSC6 Lattice Issues

- Large $\alpha_c$ good for beam stability
  - but substantial RF (48 MV) needed for 6 mm bunches
- Reduction in lattice periodicity has markedly decreased dynamic aperture
  - under investigation now



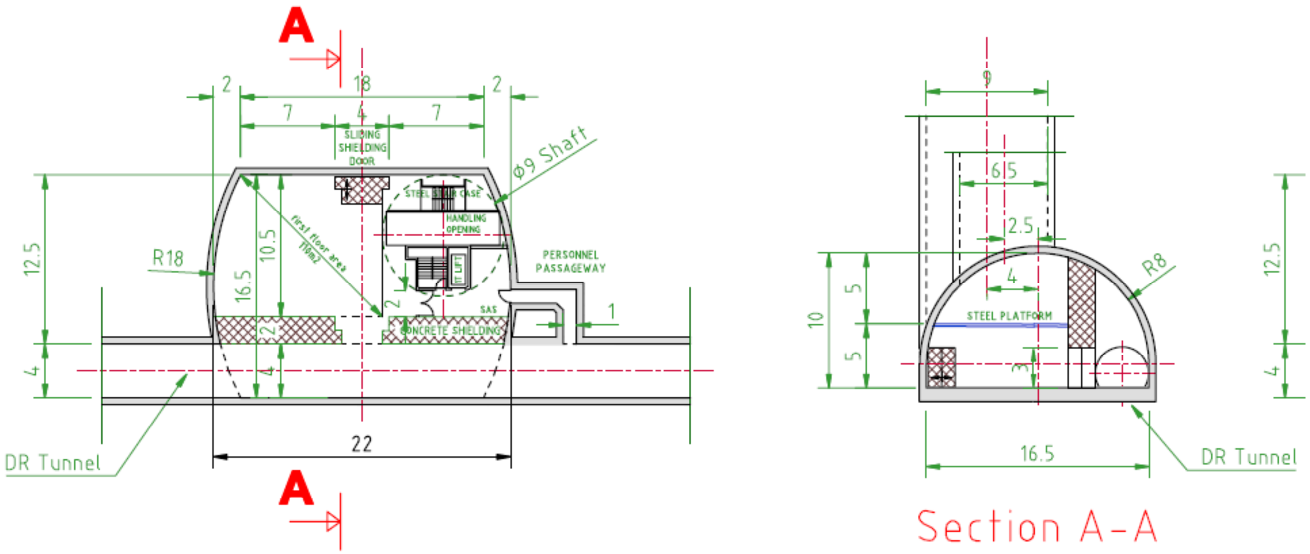
# Tunnel Layout

- Representative layout for baseline case (2 PDRs)
  - indicated vertical spacing too small unless we can "stagger" RF locations of upper and lower rings



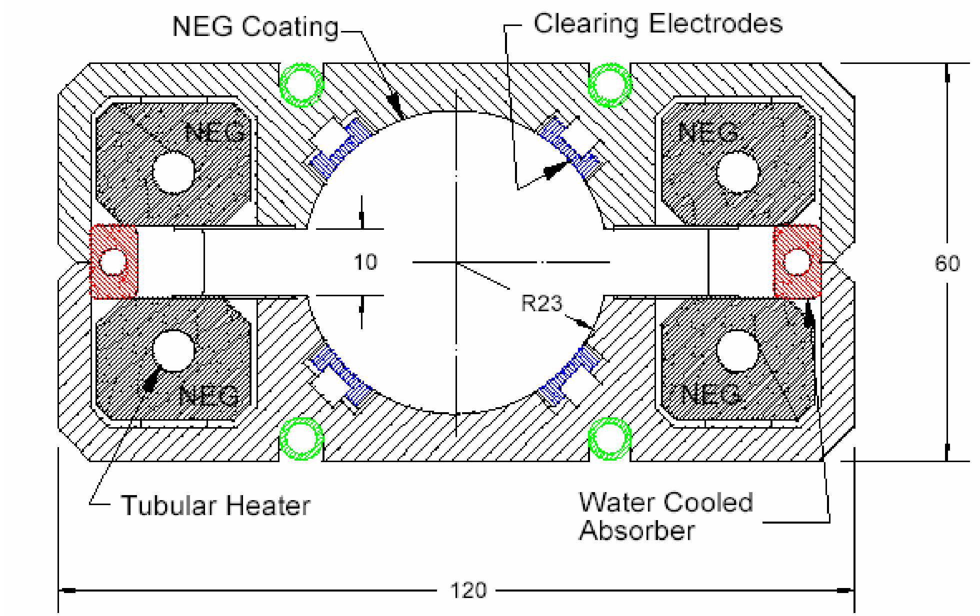
# Alcove Layout

- Four major alcoves (18 x 10.5 x 10 $m^3$)
  - **each with 9 m shaft**
- Wiggler, RF equipment located here
  - **also power supplies, controls equipment, etc.**



# Wiggler Design

- Baseline design based on Cornell SC wiggler (Urban)
  - **permits high field with large aperture**
    - alternative designs still being examined (PM or resistive)
  - **vacuum chamber concept to handle heat load and provide adequate pumping developed (Marks, Plate)**




Material: welded Al, NEG coated

$P_{CO}$ = 0.7 nTorr

Power density: 3 W/mm$^2$

Power: 26 kW/wiggler (13 kW each absorber)

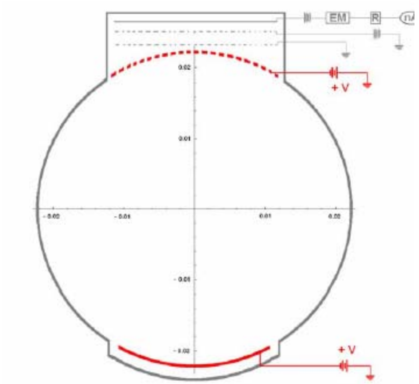
# e-Cloud Suppression (1)

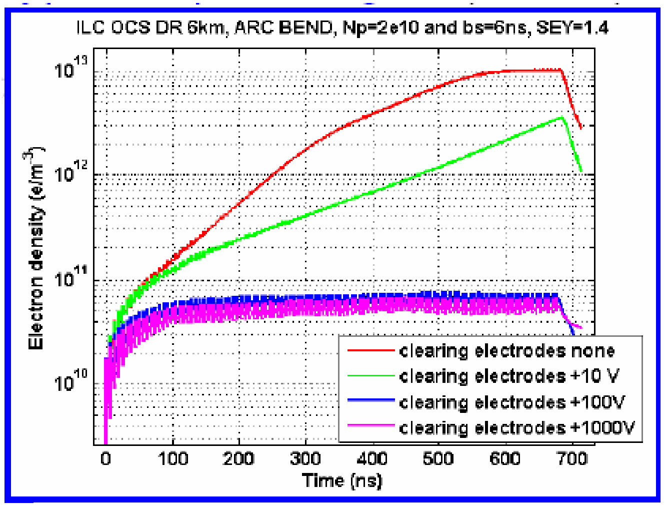
- Baseline design called for 2 PDRs
  - driven by concerns about ECI
- Recent work on mitigation techniques gives good hope of handling ECI in single PDR
  - weak solenoids for drifts
  - clearing electrodes and/or grooved chambers in magnets (+ NEG coating)
- CCR submitted after Vancouver meeting
  - asked that ECI R&D have high priority to validate efficacy of proposed cures
    - until then, design should preserve option to return to 2 PDRs

# e-Cloud Suppression (2)

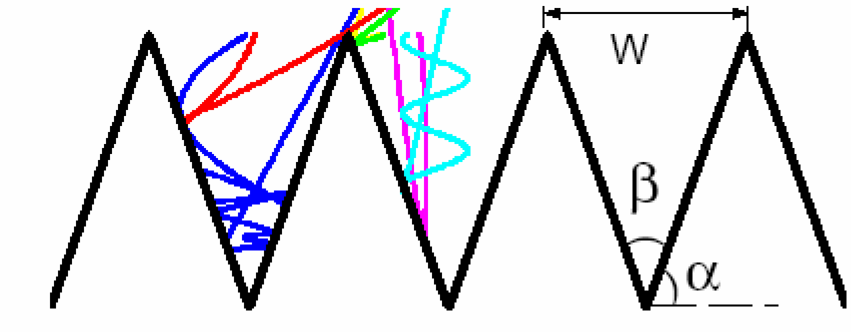
- Possible "cures"

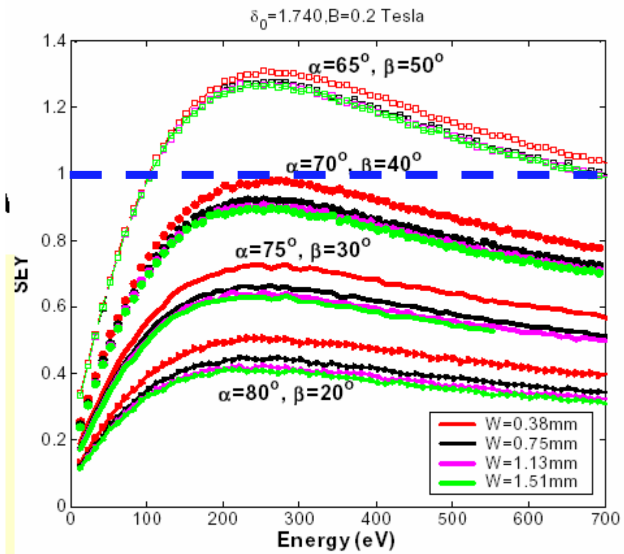
Pivi, Raimondi






Wang, Raubenheimer




B=0.2 Tesla (dipole magnet of ILC)

# RF System

- Adopted 650 MHz system
  - gives flexibility for gaps in bunch train
  - provides short bunches with lower voltage
  - convenient subharmonic of ML RF system
- Klystron will be scaled from existing designs to minimize development costs
  - klystron approach discussed with industry; incremental costs for development expected to be minor
    - consistent with klystron experience from PEP-II (500 $\rightarrow$ 476 MHz)
  - no present plans to build prototype
    - RDB or MAC may wish to weigh in on this question

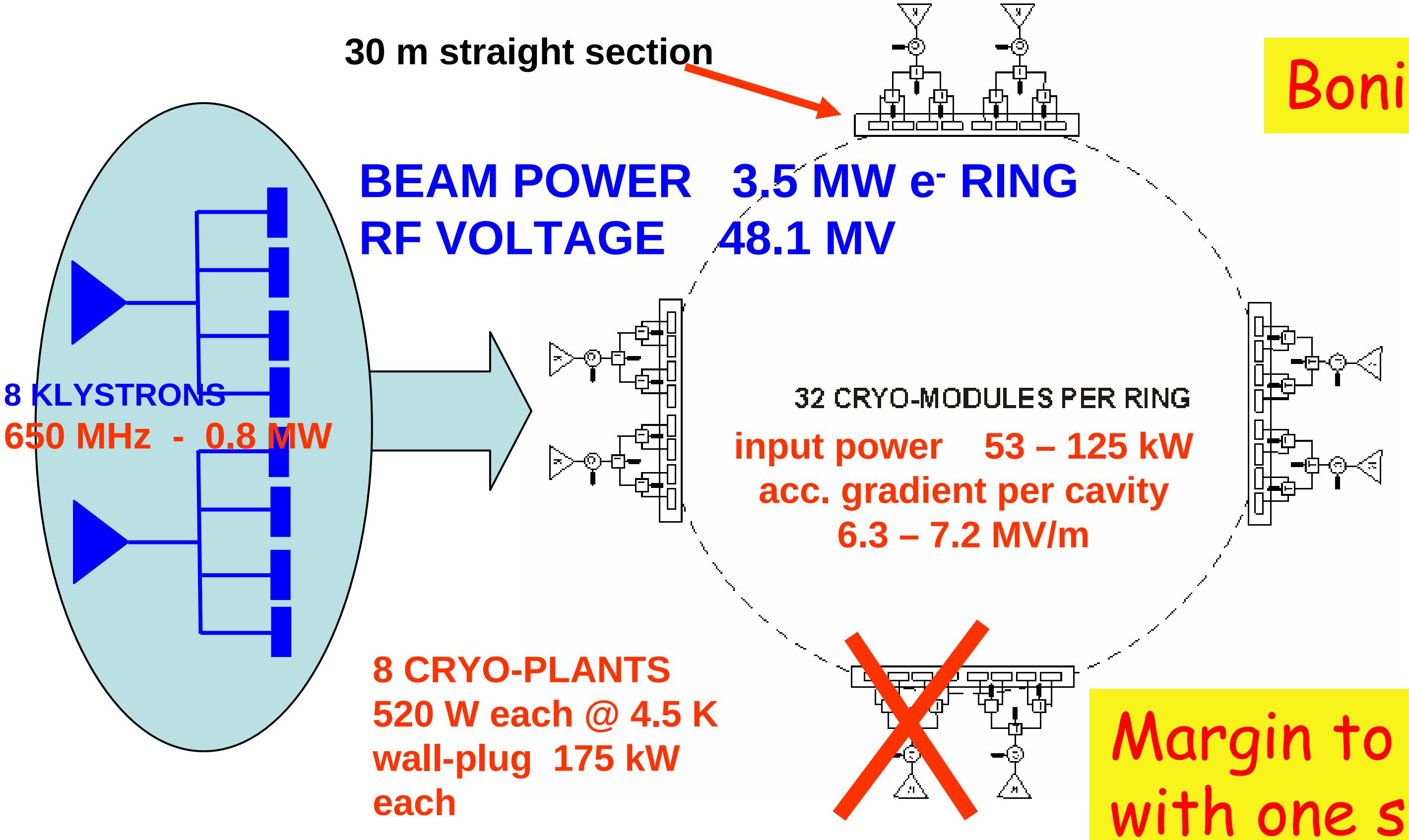
# RF Parameters

- Main RF parameters

| Damping rings parameters | | |
|---|---|---|
| | $e^-$ ring | $e^+$ rings |
| Energy (GeV) | 5 | 5 |
| Number of bunches per train | 2767 | 1384 |
| Number of particles per bunch | $2\times10^{10}$ | $2\times10^{10}$ |
| Average current (A) | 0.4 | 0.2 |
| Energy loss per turn (MeV) | 8.7 | 8.7 |
| Beam power (MW) | 3.5 | 1.75 |
| Bunch current (mA) | 0.14 | 0.14 |
| Total RF voltage (MV) | 48.1 | 48.1 |
| Circumference (km) | 6.695 | 6.695 |

# RF Layout (schematic)

- RF located in 4 straight sections
  - station comprises 1 klystron powering 4 cavities
    - 2 stations per straight section

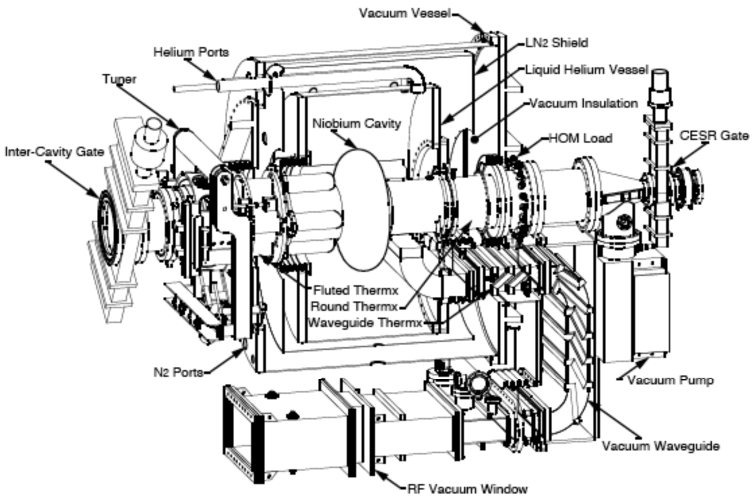



Boni

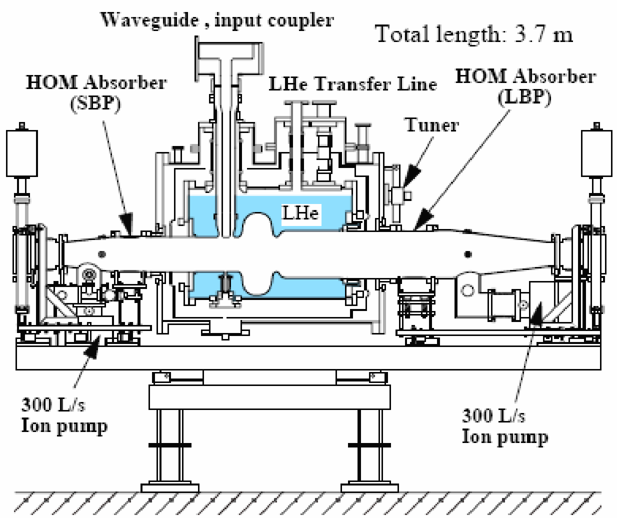
Margin to operate with one station down

# Cryomodules

- Cryomodule will be scaled from either CESR or KEK-B design (both 500 MHz)
  - **some redesign of cryostat and coupler needed**
    - this will require prototyping




[CESR Cryomodule]




[KEK-B Cryomodule]

# Emittance Requirements

- Nominal values
  - Normalized horizontal emittance $\gamma\varepsilon_x$ = $\leq$8 $\mu$m
  - Normalized vertical emittance $\gamma\varepsilon_y$ = 20 nm
  - Natural horizontal emittance $\varepsilon_x$ = $\leq$0.8 nm
  - Natural vertical emittance $\varepsilon_y$ = 2 pm
- Minimum vertical emittance achieved at KEK-ATF was $\varepsilon_y$ = 4.5 pm

  $\Rightarrow$ DR requirement will not be easy!

# Vertical Emittance Growth

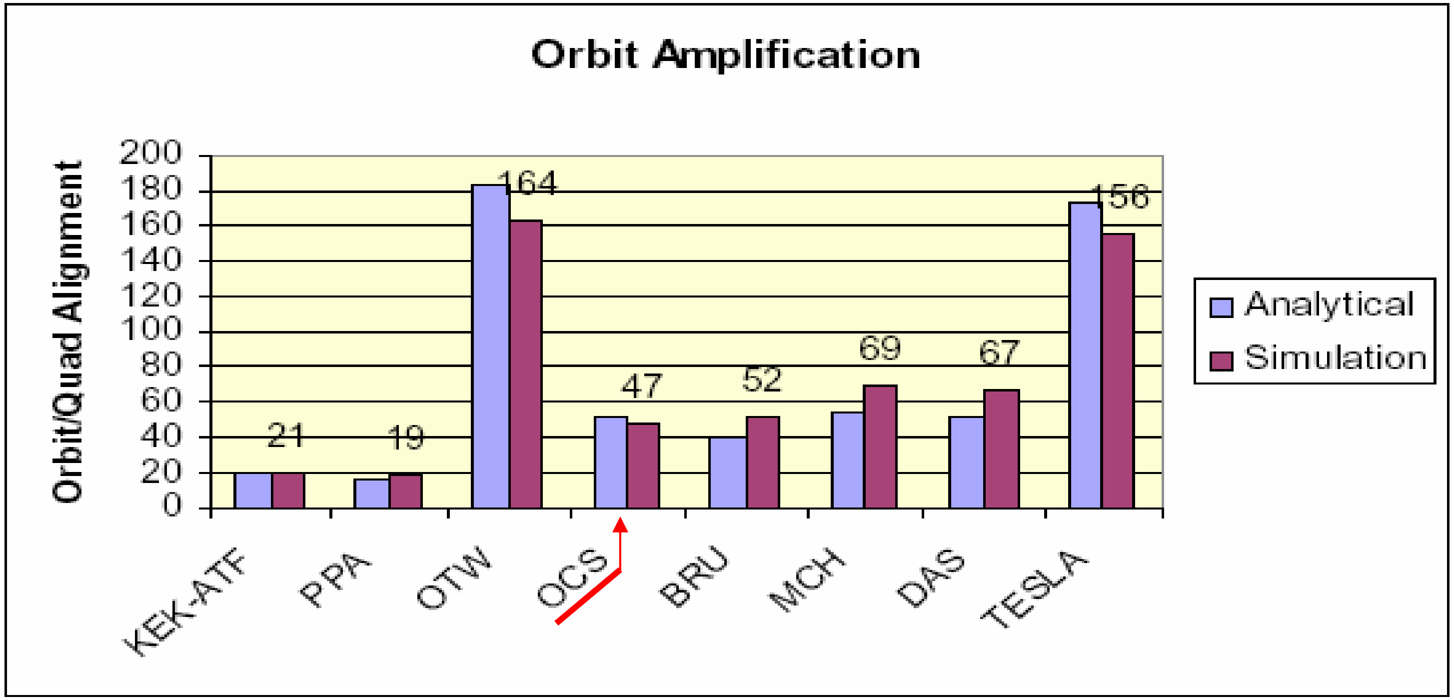
- Vertical emittance arises from:
  - synchrotron radiation opening angle
  - vertical dispersion
    - same mechanism as horizontal emittance
      - quadrupole misalignment
      - sextupole misalignment
      - dipole roll
  - coupling
    - transfers some horizontal emittance into vertical plane
      - sextupole misalignment
      - quadrupole rotation

# Emittance Studies To Date

- Low emittance tuning studies performed for Baseline Configuration (BC) lattice (LBNL-59449)
  - OCS (not quite the RDR lattice)
    - calculations will be repeated for new lattice
- Several studies were done on alignment sensitivity
  - Merlin simulations (Wolski)
    - in agreement with analytical formulae
  - SAD low-emittance-tuning studies (Kubo)
- The two programs gave identical results

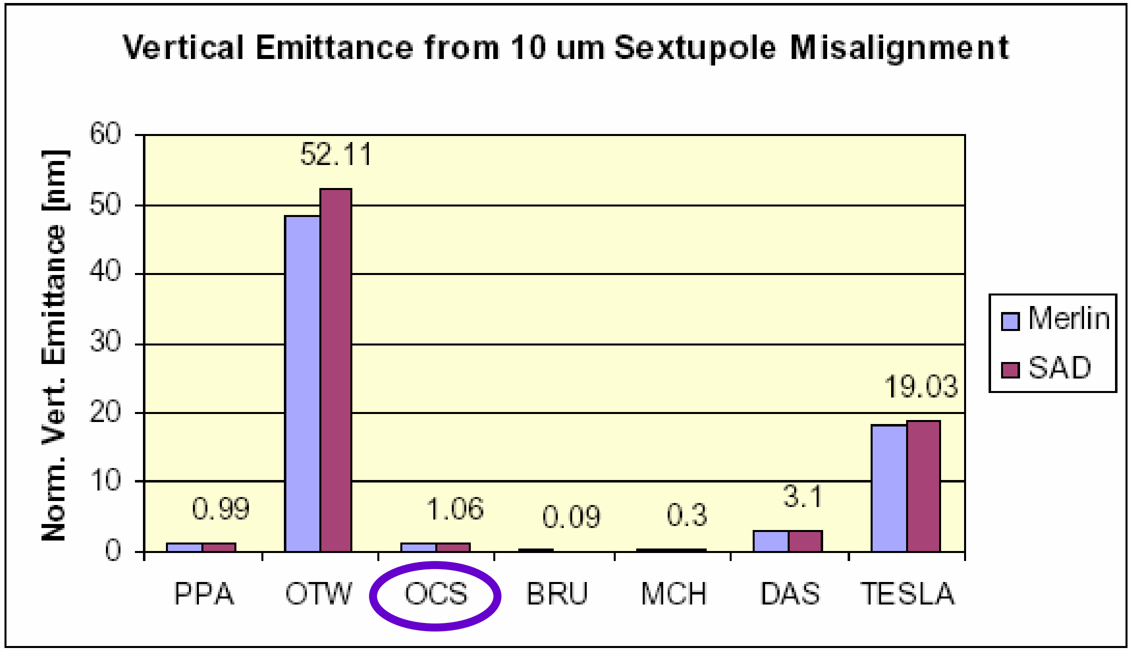
# Quadrupole Misalignment

- Orbit amplification factor is ratio of rms closed orbit deviation to rms quadrupole displacement
  - example from OCS lattice, orbit amplification = 47



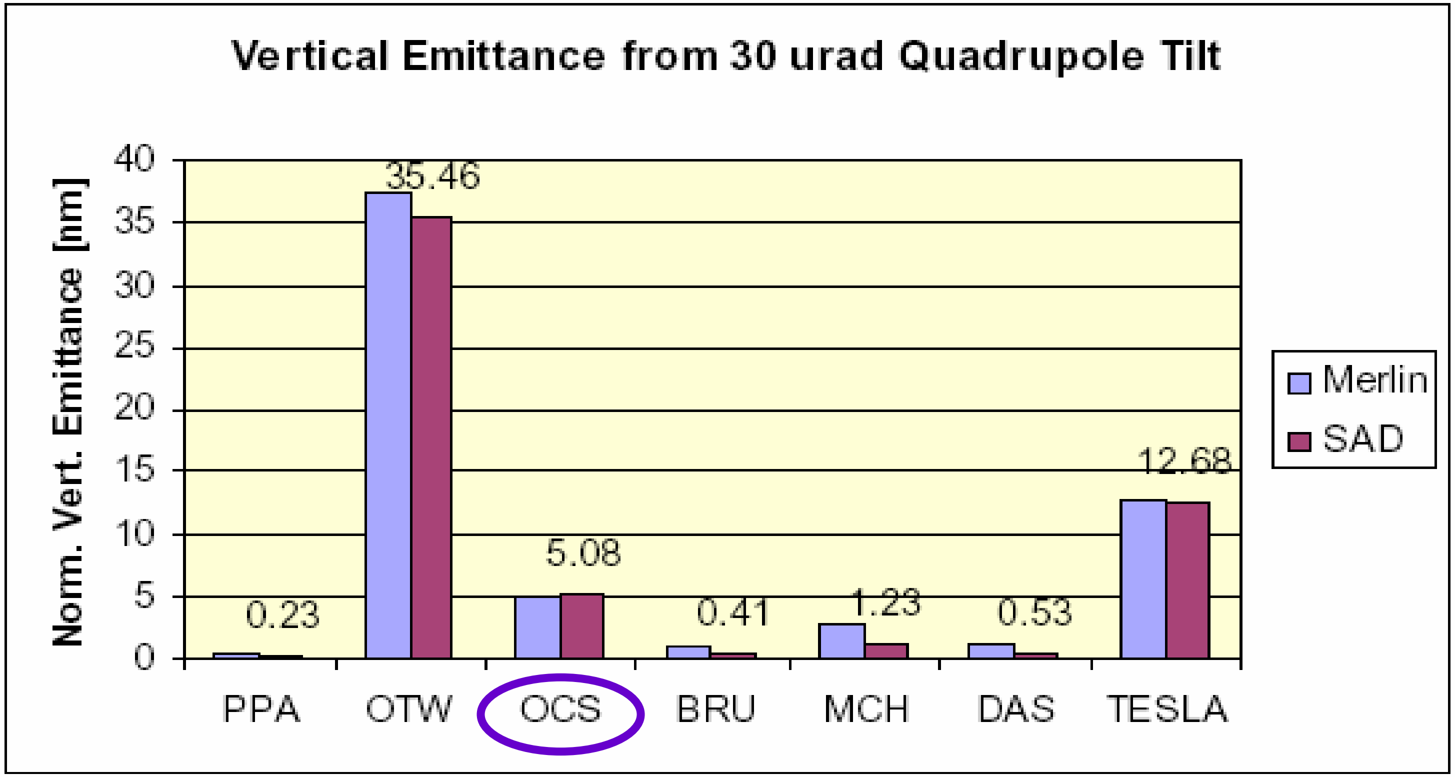
# Sextupole Misalignment

- Sextupole misalignment gives rise to significant emittance increase
  - **10 μm results in 1.06 nm emittance**
    - still one of the better lattices studied



# Quadrupole Roll

- Quadrupole roll also causes significant vertical emittance growth
  - for OCS lattice, 30 μrad ⇒ 5.08 nm



# Tuning Simulations (1)

**Using SAD (K. Kubo)**

Initial offsets and tilts:

- Magnets 30 µm, 0.3 mrad
- BPMs 100 µm, 20 mrad

Tuning was applied in three stages:

1. correction of closed orbit distortion (COD);
2. combined correction of closed orbit distortion and dispersion (by steering);
3. correction of coupling (minimizing cross-plane orbit response) using skew quads.

Normalized vertical emittance in nm (target: < 20 nm), averaged over 200 seeds

| Lattice | No correction | COD only | COD & dispersion | COD, dispersion & coupling |
|---|---|---|---|---|
| PPA | 879 | 67.4 | 4.12 | 1.74 |
| OTW | 101,000 | 60,400 | 2,680 | 1,820 |
| OCS | 667 | 526 | 106 | 22.7 |
| BRU | 1,630 | 80.4 | 2.09 | 5.05 |
| MCH | 4,700 | 189 | 6.88 | 9.27 |
| DAS | 10,000 | 266 | 22.5 | 6.12 |
| TESLA | 88,100 | 1,670 | 29.6 | 12.6 |

# Tuning Simulations (2)

- Conclusions from this study
  - **OCS has low sensitivity to alignment errors compared with other lattices**
    - emittance increase from alignment errors, before correction, is small
  - **efficacy of correction scheme for OCS was relatively poor**
    - expect that a better choice of dipole and skew quadrupole correctors will fix this
      - already confirmed (next slide)
  - **30 μm alignment tolerance is unrealistically tight***
    - but not really needed

*in my personal opinion

# Tuning Simulations (3)

- More optimized correction scheme studied for EPAC06 (Jones, MOPLS140)
  - results confirm (on paper) adequacy of RDR lattice
    - control room experience could be different
    - "None" ⇒ no correction
    - "CO" ⇒ 2 iterations of dipole orbit correction
    - "Full" ⇒ 2 iterations of dipole orbit correction and 2 iterations of coupling + dispersion correction using skew quadrupoles

Table 2 Magnet Tolerances

| Error | Quadrupoles | | | Sextupoles | | |
|---|---|---|---|---|---|---|
| | *None* | *CO* | *Full* | *None* | *CO* | *Full* |
| ΔY (μm) | 9.1 | 108 | 380 | 81 | 100 | 3548 |
| ΔΨ (mrad) | 0.084 | 0.085 | 2.81 | – | | |

# Next Steps (Tuning)

- Optimize the number and position of dipole and skew correctors
- Compare different correction algorithms and find optimum for this lattice
  - **minimum vertical emittance at lowest corrector strengths**
- Study sensitivity of correction scheme to magnet and BPM alignment errors
- Continue machine studies (ATF, ALS, CESR-TF,...)

# Intensity Dependent Effects

- Collective effects can potentially spoil the emittance at high single-bunch current
  - e-cloud instability (ECI)
  - intrabeam scattering (IBS)
  - fast ion instability
  - space-charge effects
  - microwave instability

- We are studying all these issues
  - using simulations, hardware tests, beam measurements
    - experiments at high-current, low-emittance test ring, e.g., ATF, CESR-TF or HERA-DR, likely needed to resolve these matters
  - ECI and ion effects accorded very high R&D priority

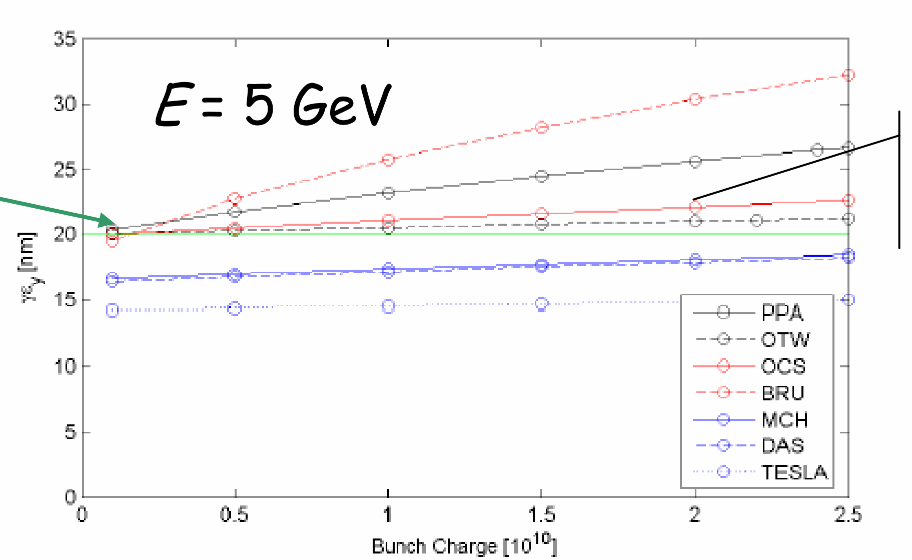
# Intrabeam Scattering (1)

- DR may have sensitivity to IBS despite high energy
  - **ultra-low emittance + high bunch charge is bad combination**
- Equilibrium emittance (transverse and longitudinal) results from balance among radiation damping, quantum excitation, and IBS
  - **IBS growth depends on phase space density of bunch**
  - **faster damping mitigates IBS emittance growth**
- Calculations of equilibrium emittance in good agreement with experimental results from ATF
  - **we know how to estimate the effect of IBS**

# Intrabeam Scattering (2)

- Equilibrium emittances calculated for candidate DR lattices (see LBNL-59499)
  - EDR assumed to have same damping time as PDR
    - could be slower, due to smaller injected emittance
      - but, IBS sets limit on EDR damping time
    - vertical growth calculated assuming vertical dispersion and betatron coupling contribute equally to $\varepsilon_y$

Design 20 nm




OCS
21 nm @2 x $10^{10}$

# Fast Ion Instability

- Fast ion instability could be an issue for the EDR
  - short bunch spacing and high bunch density
- Gaps between bunch trains mitigate effect
  - can reduce ion density by factor of 100
- Must verify experimentally that feedback system can mitigate growth
  - digital feedback system, as used at B factories or DAΦNE, can achieve 20-turn damping time
    - should be enough with appropriate gaps in bunch train
  - also need R&D to see if feedback system noise excites vertical emittance

# Other Collective Effects

- Space-charge effects have been examined for candidate DR designs
  - simulations show **no vertical emittance blowup** for OCS ring
- Microwave instability
  - could affect vertical emittance, especially in "bursting mode"
  - high $\alpha_c$ for RDR lattice means beam should be below threshold
    - would prefer to lower $\alpha_c$, or add higher harmonic, to save RF
    - need to pay attention to minimizing vacuum chamber impedance

# DR R&D Program

- Global DR R&D priorities are purview of the RDB
  - they have prepared overall list of ILC R&D activities proposed by the collaborating institutions
    - and assigned priorities
- Newly formed "S3" task force will revise and update DR R&D list and priorities on ongoing basis
  - comprises DR ASLs + other knowledgeable persons
    - led by A. Wolski
  - they will also monitor progress!

# R&D Objectives and Priorities

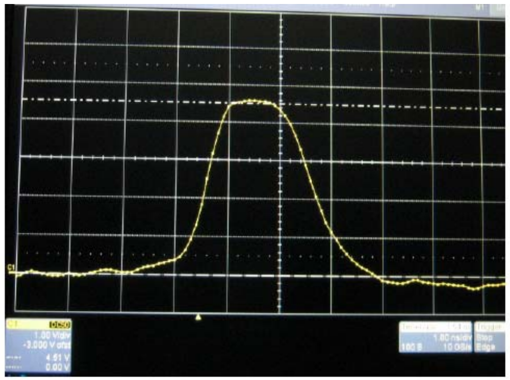
- Information being collated in R&D WBS structure
  1. Parameter optimization
  2. Beam dynamics (theory and experiment)
  3. Technical subsystem or component development
  4. Test facilities
- RDB prioritizes as Very High, High, Medium, Low
- RDB Very High priority items include
  - low-emittance tuning
  - single-bunch impedance
  - electron cloud studies
  - ion effects
  - injection/extraction kickers

# R&D Status (1)

- Low-emittance tuning
  - still 2x higher than goal of 2 pm
    - ATF results difficult to reproduce
- Single-bunch impedance
  - present lattice has high $\alpha_c$
    - would like to reduce it to reduce RF voltage requirement (cost)
- e Cloud
  - promising mitigation techniques need to be validated
    - otherwise, we may be back to 2 PDRs ☹
- Ion effects
  - need to understand impact, e.g., growth time
    - confirm feedback as cure

# R&D Status (2)

- Injection/extraction kickers (very high priority)
  - low-*Q* parameters imply 3 ns kicker rise/fall time
    - need to demonstrate technical solution
  - high-*Q* parameters relax the timing to 6 ns
  - need to evaluate and choose technology
    - need fast rise/fall time plus ~2 ns flat top
    - consider stability and reliability also



A_out = 4.5 x 600 = 2,700 V

Horizontal scale: 1 ns / div

Waveform: by the LeCroy osc., 10GS/s

Output from Drift Step Recovery Diode

1 ns/div

Kardo-Sysoev and Krasnykh

July 2006

# Planning and Coordination

- Need more proactive approach to R&D management
  - presently, just ask institutions for proposals
  - must combine overlapping proposals into coherent plan
    - S3 task force was created to do this (hopefully, by year's end)
  - global R&D coordination is high priority for GDE
- Need to consider role of test facilities
  - ATF, CESR-TF, maybe HERA-DR
    - need for these must be driven by R&D program, not vice versa
- Guiding principles
  - cooperation better than competition
  - flexibility essential (changing priorities and resources)

# Baseline Changes

- Change request has been submitted to CCB to redefine baseline as 1 EDR and 1 PDR
  - possibility of second PDR will be maintained pending R&D on ECI mitigation
    - CCB recommended that EC approve request (awaiting EC okay)
- Second CCR, for central DR complex, in preparation
  - EDR and PDR co-located in one tunnel
    - makes it harder to preserve second-PDR option
  - requires coordination (crosses area system boundaries)
- Changes assessed in terms of cost vs. performance
  - not just cost

# Summary

- DR technical design and costing progressing well
  - we understand what the technical questions are
    - now we need to get the remaining answers
  - making progress at cost-performance-risk optimization
    - single PDR, central DRs
- Confident that we can reach $\varepsilon$ goal
  - with continued studies (simulations and experiment)
- R&D plans moving ahead, coordinated by DR ASLs
- Thanks to DR co-ASLs for help with preparing talk
  - especially Susanna Guiducci