Linear Collider Accelerator R&D

Andy Wolski

Lawrence Berkeley National Laboratory

DoE HEP Review

March 2005

ILC is an evolving collaboration

Our aim is to support the ILC through collaborative research and development on the damping rings and associated injector systems, to produce a design that will enable the collider to reach its performance goals.

LBNL had ownership of the NLC damping rings.

- Designs for NLC were relatively mature, and beam dynamics issues were well-explored.
- Specifications and outline designs had been set for many technical subsystems.

Decision (summer 2004) to use superconducting technology for the linacs has led to a restructuring of the international collaboration.

- Many other labs are interested in damping ring issues, including SLAC, FNAL, Cornell, KEK, DESY, LNF.
- The Global Design Effort is in the process of formation.

Tools and expertise developed for NLC damping ring studies are still applicable to ILC damping rings.

LBNL has a leading role in ILC damping ring studies.

- We have the right skills and experience (ALS, PEP-II) for this work.
- We have strong links with a large number of collaborating institutions.
- We help co-ordinate activities, e.g. by running twice-monthly DR teleconferences.

ILC Effort FY05: 3 FTE (funded through SLAC)

- Marco Venturini
- Andy Wolski

AFRD/Center for Beam Physics (Theory Group)

Lattice design and beam dynamics studies.

- Stefano de Santis
- John Byrd

AFRD/Center for Beam Physics (Beam Electrodynamics Group)

Fast injection/extraction kicker studies.

- Daniel Lee
- Kurt Kennedy

Engineering Division

Vacuum systems; low secondary electron yield coatings.

- Dan Bates

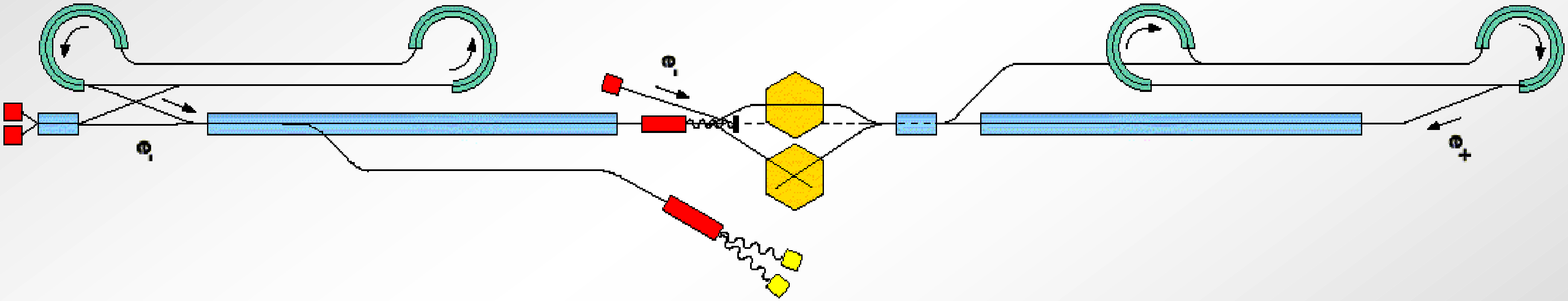
UC Berkeley (undergraduate)/Center for Beam Physics (Theory Group)

Software development for lattice and beam dynamics studies.

Damping rings are critical for luminosity production

Damping rings have three functions:

1. Reduce transverse emittances (a factor of 5×10^5 in the vertical plane).
2. Produce highly stable beams for tuning and operation of downstream systems.
3. Delay the beams for operation of feed-forward systems, e.g. to compensate variations in bunch charge.



TESLA TDR (2001) specified 17 km ‘dogbone’ damping rings to accommodate long bunch trains.

2820 bunches (with 20 ns bunch spacing) are stored for 200 ms.

Bunches are extracted individually to give ~ 300 ns spacing in the linac.

Circumference is set by the shortest kicker rise/fall time that can be achieved.

ILC damping rings have challenging specifications

Large dynamic acceptance (DA) is needed for the injected beams.

- Beam from positron source has normalized transverse emittance of 0.01 m, and full width energy spread ~ 2%.
- Average injected beam power is 226 kW: even small beam losses will cause large radiation loads.

Rapid damping rate is needed to reduce emittances in the 200 ms interval between machine pulses.

- Damping time must be <27 ms, in a 17 km ring, and…
- …beam energy must be ~ 5 GeV, to meet longitudinal emittance specifications.
- Therefore, we need a *long* (400 m) damping wiggler.

Very low vertical emittance is needed for luminosity production.

- Present specification is 2 pm, a factor of 2 lower than present world record.

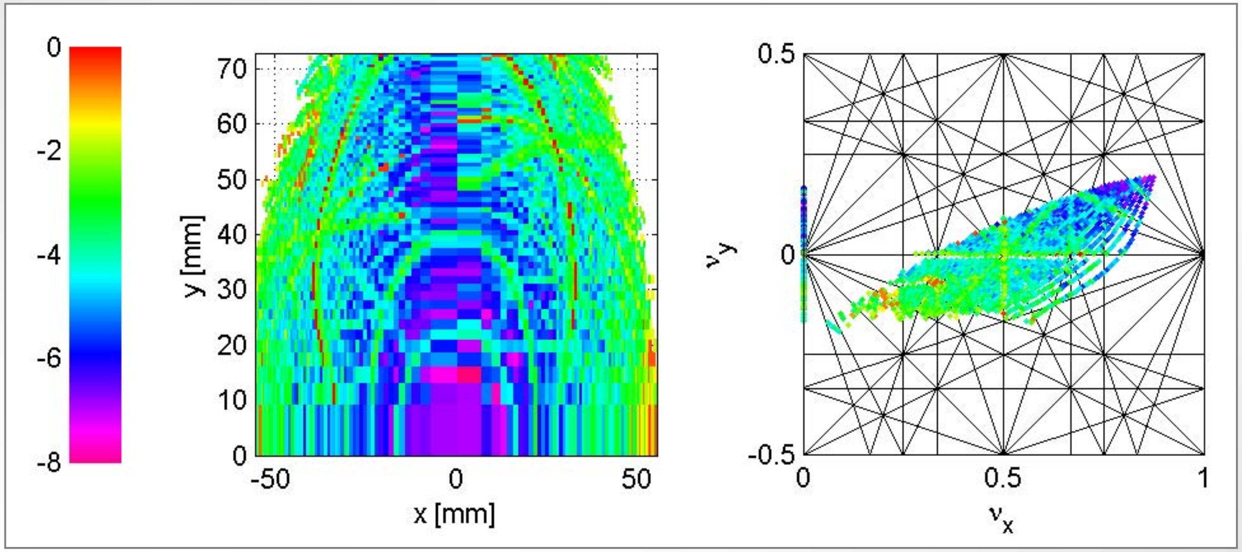
Extracted beam must meet demanding stability specifications and must preserve polarization.

Large DA is needed for good injection efficiency

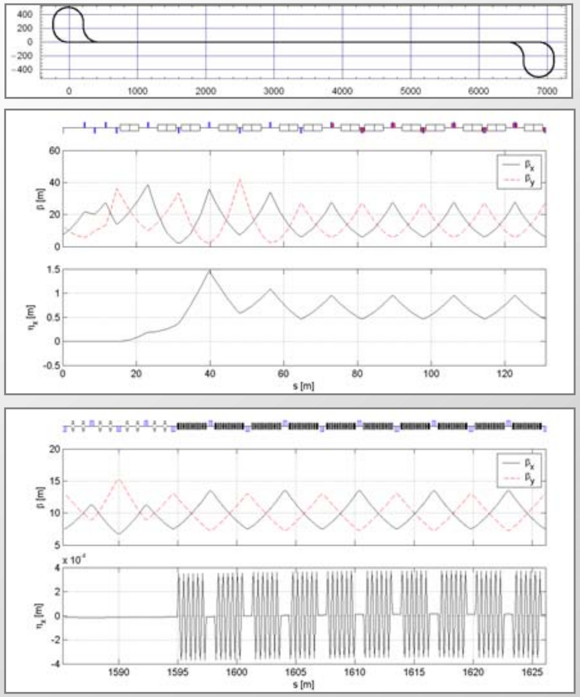
LBNL has skills in designing storage ring lattices with excellent dynamic aperture.

- Tools for advanced analysis of nonlinear dynamics have been developed and applied at the ALS.

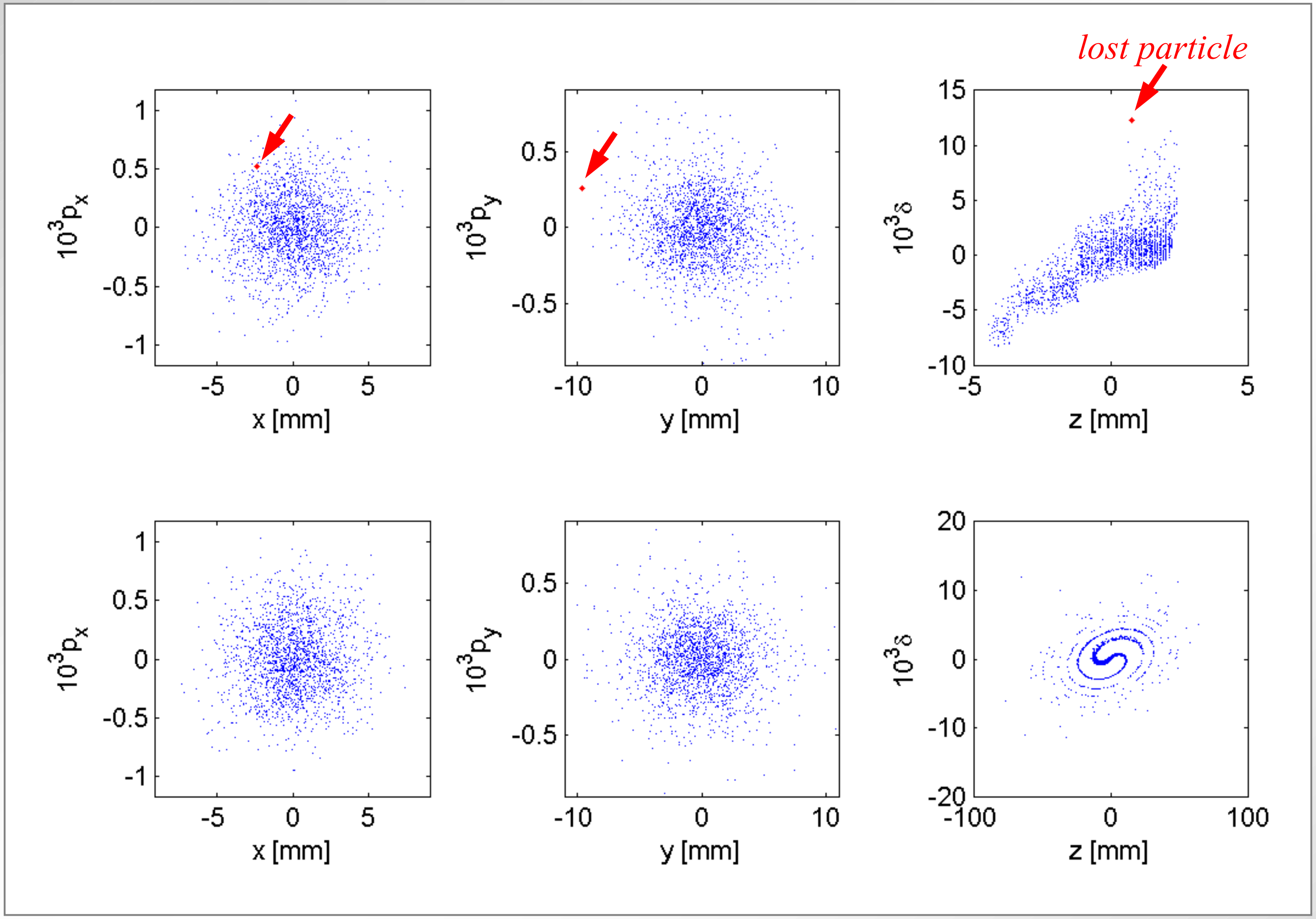
We have produced lattice designs based on simple arc FODO cells that achieve a large dynamic acceptance.



Dynamic aperture in co-ordinate space and in tune space. The colors indicate rate of change of betatron tune over successive turns through the lattice, on a logarithmic scale. The axes limits are 20× the injected positron rms beam size. (A. Wolski, LBNL)



Tracking a 'realistic' beam shows very small losses



Injected beam phase space.

Simulated distribution of 1960 particles from positron source. (Y. Batygin, SLAC)

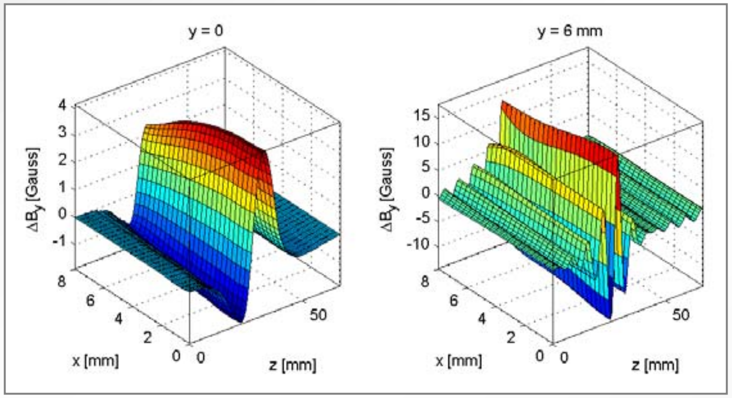
Phase space after 500 turns.

500 turns is approximately 1 damping time. 1959 particles survived. (A. Wolski, LBNL)

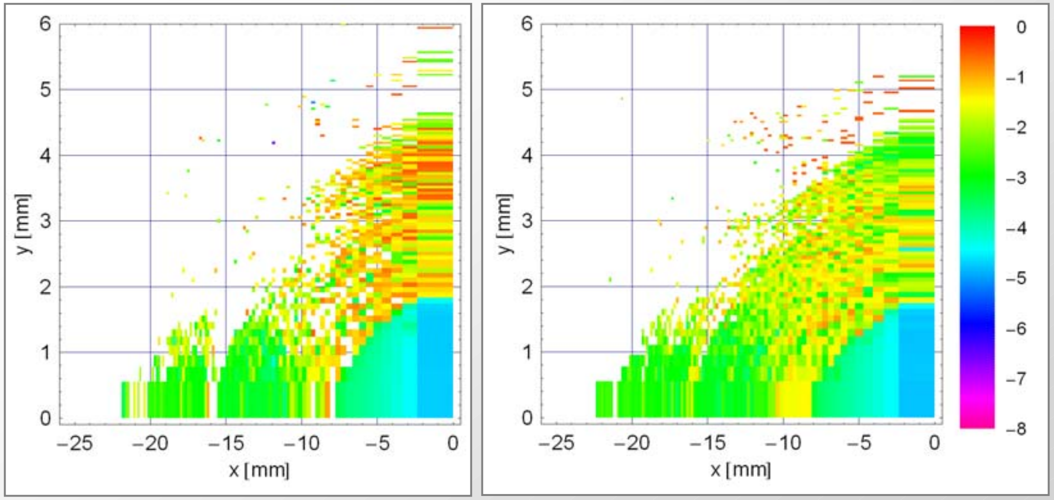
Nonlinear wiggler fields can affect the acceptance

We have developed techniques for precise modeling of nonlinear beam dynamics in wigglers.

1. Use a magnetic modeling code to calculate the magnetic field on a mesh within one periodic section of the wiggler.
2. Fit the numerical field data with an analytical series (set of cylindrical modes).
3. Use the mode expansion in a differential algebra or Lie algebra code to generate a Taylor or Lie (symplectic) map for the dynamics in the wiggler.
4. Use the dynamical map in a tracking code to estimate the impact of the wiggler on the dynamic aperture.



Residuals of a fit to 2.1T NLC damping wiggler.
Left: on mid-plane; right: 6 mm above mid-plane.
(A. Wolski, LBNL)



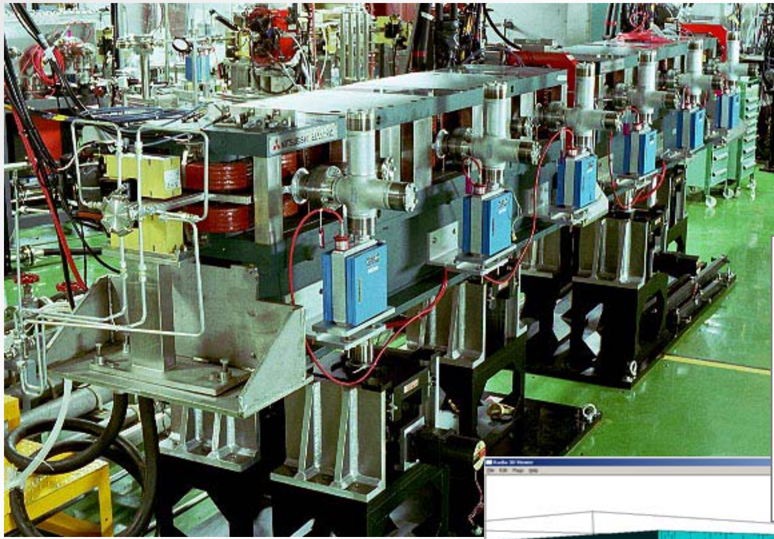
Dynamic aperture in NLC Main Damping Rings. Left: linear wiggler model; right: wiggler model using fifth-order dynamical Taylor map.(A. Wolski, LBNL)

Wiggler analysis tools are being applied at KEK-ATF

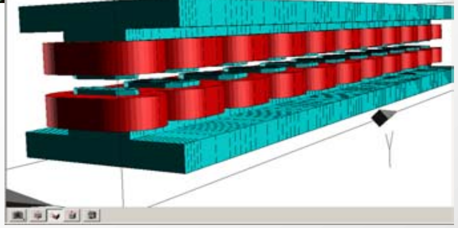
KEK-ATF is a prototype damping ring, and the world's largest linear collider test facility.

- Four electromagnetic wigglers have recently been commissioned, and their effects on the beam dynamics are being studied closely.

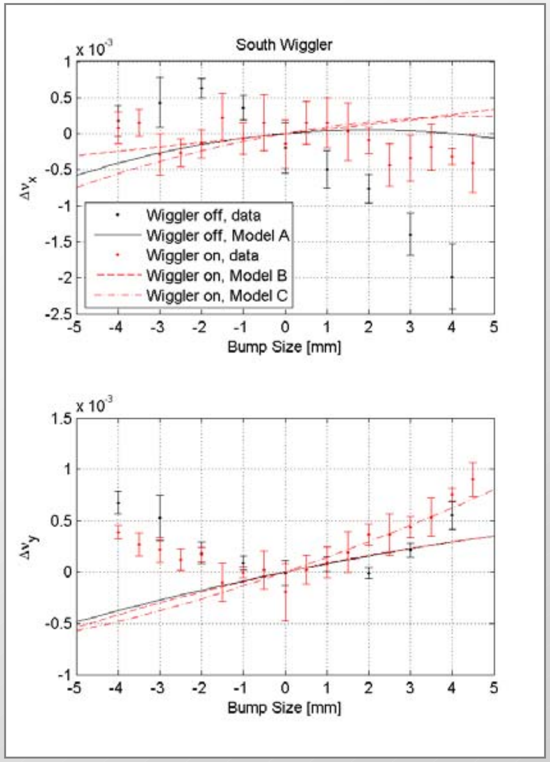
LBNL contributes strongly to beam dynamics studies at the ATF.



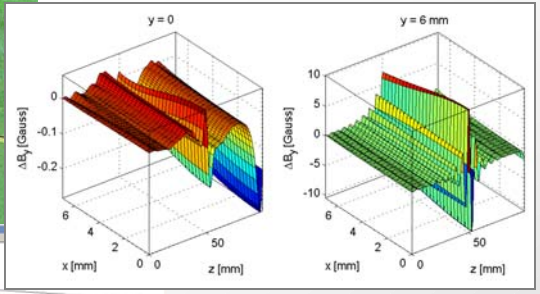
Top: wiggler in KEK-ATF.



Right: RADIA model of KEK-ATF wiggler.



Right: tune shifts with orbit bumps in one wiggler (model and machine data).



Below: residuals of fit of mode expansion to wiggler field.

(A. Wolski, LBNL)

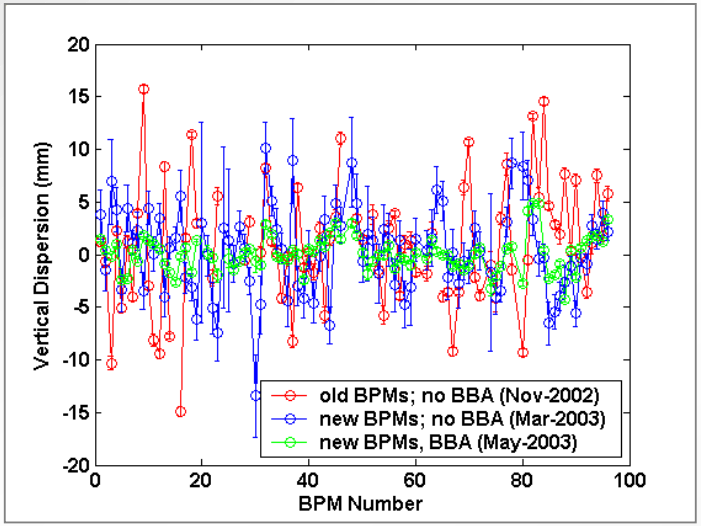
KEK-ATF has the world’s lowest vertical emittance

Smallest vertical emittance achieved to date is 4.5 pm.

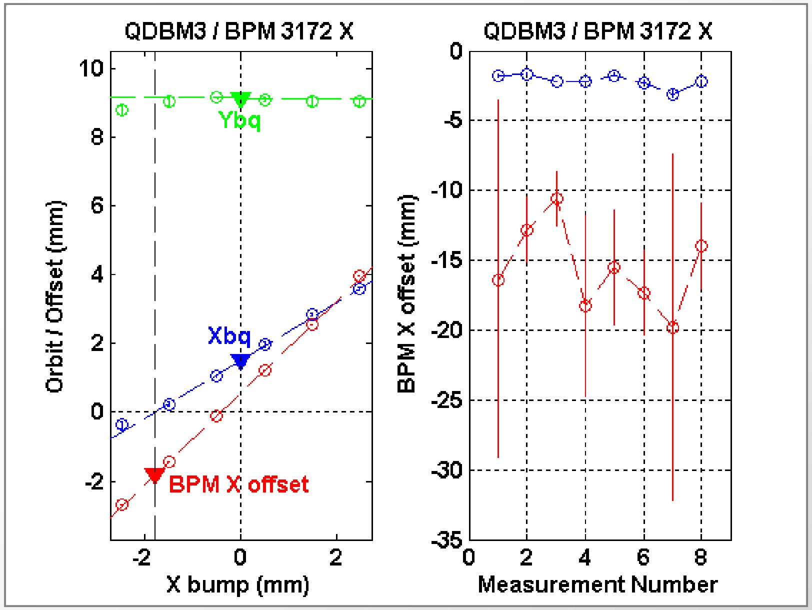
- ILC damping ring specification is 2 pm.

SLAC/LBNL contributed through development and application of beam-based alignment and coupling-correction techniques.

- New BBA techniques developed by LBNL (taking full account of coupling) are now being applied to PEP-II.



Reduction in vertical dispersion in the KEK-ATF, resulting from application of beam-based alignment. (M. Woodley, SLAC).



Results of BBA on one quadrupole in PEP-II LER. The right-hand plot compares results from the old technique (red points/line) with the new technique developed by LBNL (blue points/line) which takes full account of coupling. (M. Woodley, SLAC).

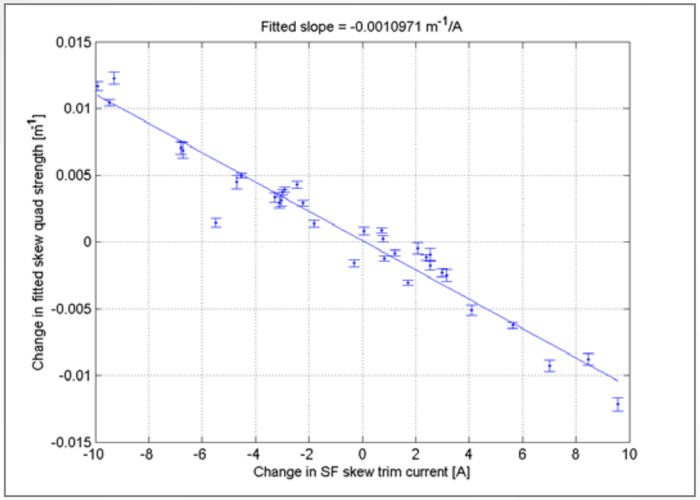
Goal is to achieve 2 pm emittance in the KEK-ATF

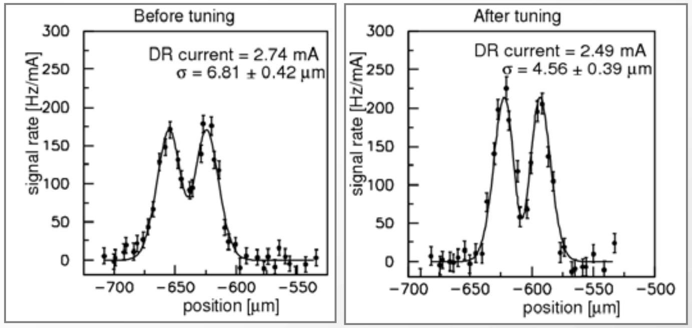
Orbit Response Matrix (ORM) analysis is a promising tool for achieving the necessary coupling correction.

- Normal and skew quadrupole strengths, BPM gains and rotations etc. can be determined from fitting a lattice model to a measured ORM.

SLAC/LBNL team demonstrated emittance reduction from 12 pm to 5 pm using ORM-based coupling correction in KEK-ATF in January 2005.

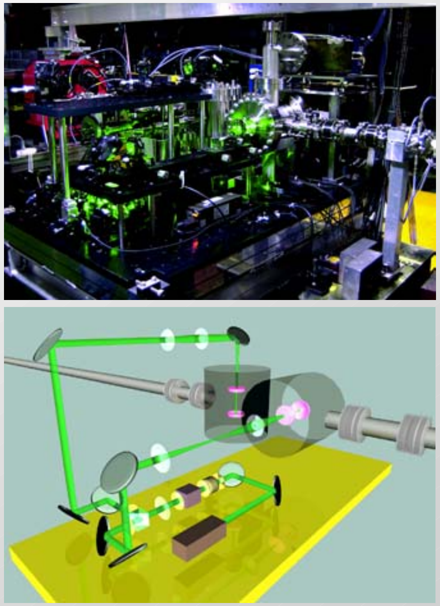
- Procedure is much quicker and more straightforward than previous methods.
- Further improvements should be possible by combining with BBA correction.
- Significant help and support provided by ALS Accelerator Physics Group.





Above: Laser-wire measurements of vertical beam size in KEK-ATF before and after tuning with ORM analysis. (Courtesy of Y. Honda, KEK)

Left: Calibration of skew quadrupole strengths using ORM analysis. (A. Wolski, LBNL)



Right: Laser wire in KEK-ATF.

Many collective effects need careful evaluation

Achieving high beam quality and stability in the damping rings will be critical for producing luminosity in ILC.

Stability problems in SLC damping rings made tuning and operation of all downstream systems very difficult – damping rings were the ‘source of all evil’.

Lattice and beam parameters make a wide range of collective effects of potential concern, including:

- Microwave instability
- Space-charge tune shift
- Coherent synchrotron radiation
- Resistive-wall instability
- Fast ion instability
- Electron cloud instability
- Intrabeam scattering

Circumference	17 km
Beam energy	5 GeV
Bunch charge	2×10^{10}
Average current	160 mA
Vertical emittance	2 pm
Bunch length	6 mm
Damping time	27 ms

Initial evaluations have been made for latest lattice designs, and more detailed studies are in progress.

Space-charge tune shifts are large…

Linear theory predicts vertical tune shift of -0.26 with 2 pm emittance.

- Potential problems are emittance growth and particle loss.

Fast simulation tools have been developed for in-depth studies.

- Marylie/Impact code (R. Ryne) has been extended to include space-charge.
- A bunch of particles (in 3 d.o.f.) is tracked through a detailed lattice model.
- Transverse space-charge kicks for each particle are calculated assuming a gaussian distribution for particles in the bunch.
  - Weak-strong: distribution used for calculating kicks is constant.
  - Quasi strong-strong: gaussian distribution, rms = 2nd order moments of bunch.
- Work has been supported by AMAC Group within Center for Beam Physics.

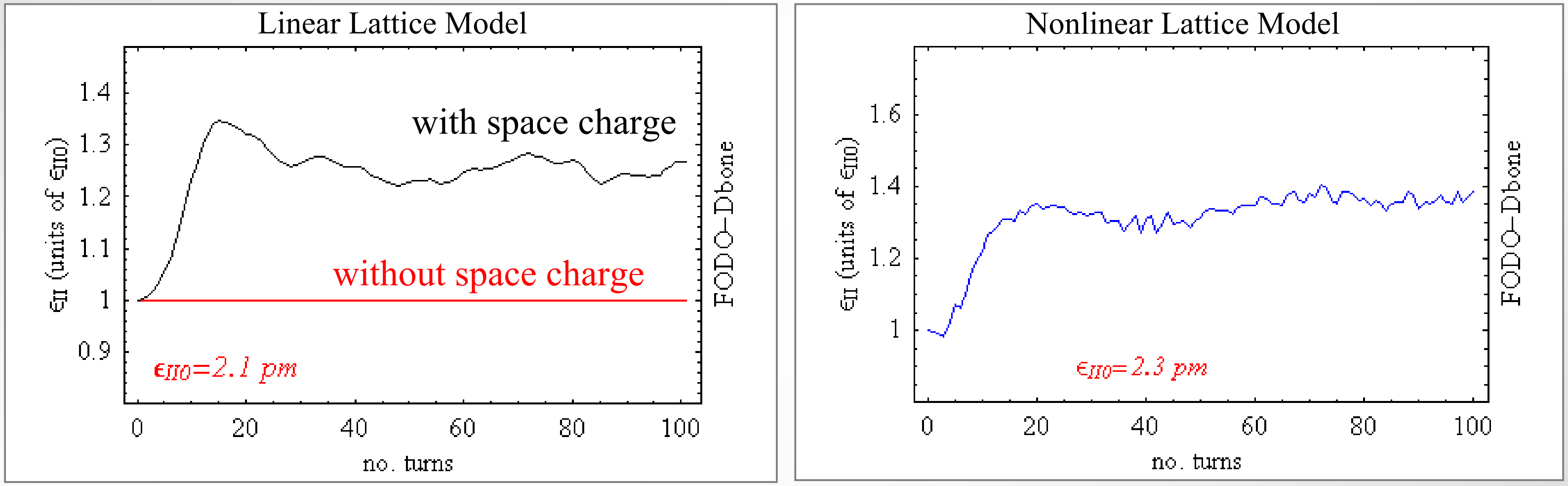
Code is parallel: can run using 6000 processors at NERSC.

- Some code development still needed before large-scale simulations are performed, but initial results have already been obtained.

…but space-charge emittance growth may be modest

Preliminary results show vertical emittance growth of ~ 40%.

- Fast initial rise is possibly the result of a mismatch between the initial distribution, and the lattice optics perturbed by space-charge.
- Longer term emittance growth is slow compared to radiation damping.



Tracking with space-charge using weak-strong model with 1000 particles in Marylie/Impact. (M. Venturini, LBNL)

It may still be desirable to take countermeasures against space-charge.

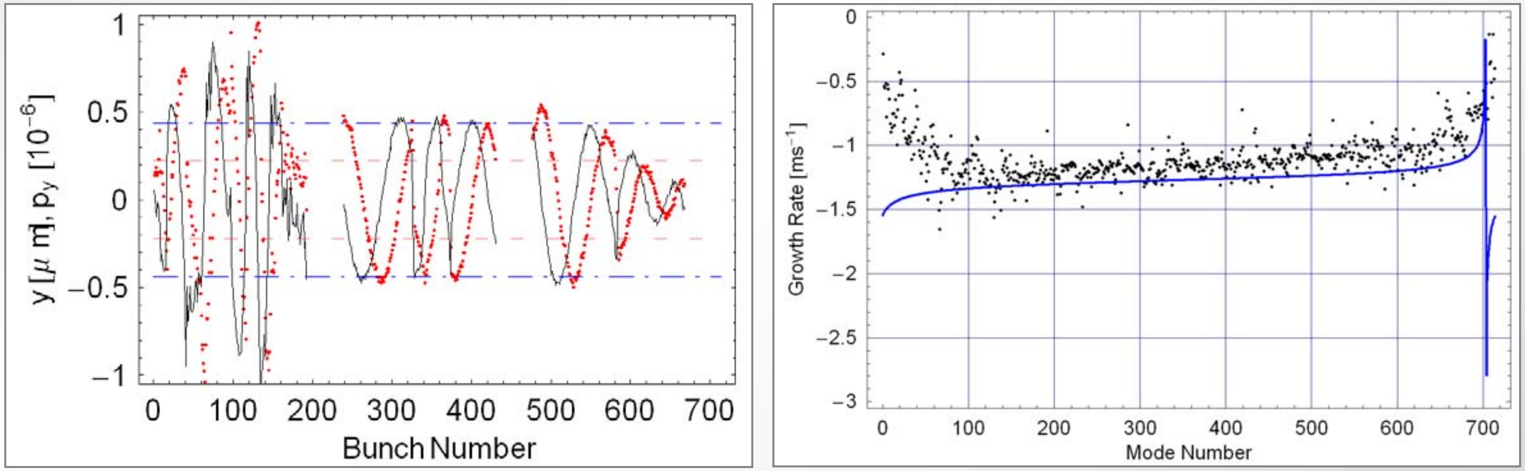
- Coupling bumps (proposed by DESY) are included in latest lattice designs.

Resistive-wall instability causes bunch-to-bunch jitter

Growth of coupled-bunch modes can be suppressed using a bunch-by-bunch feedback system…

…but the feedback system itself can induce jitter, because of the limited resolution of the pickup.

Simulation tools were developed for NLC, and will be applied to ILC.



Simulations of resistive-wall instability with bunch-by-bunch feedback system in the NLC Main Damping Rings.

Left: vertical bunch positions and angles immediately before extraction of a damped bunch train.

Right: simulated growth rates of coupled-bunch modes (black points) with feedback, compared to a simple theoretical model (blue line).

(A. Wolski and D. Bates, LBNL).

Electron cloud instabilities are a serious concern

Electron cloud is observed in many proton and positron rings.

Secondaries are released when electrons, accelerated by the beam, hit the chamber walls.

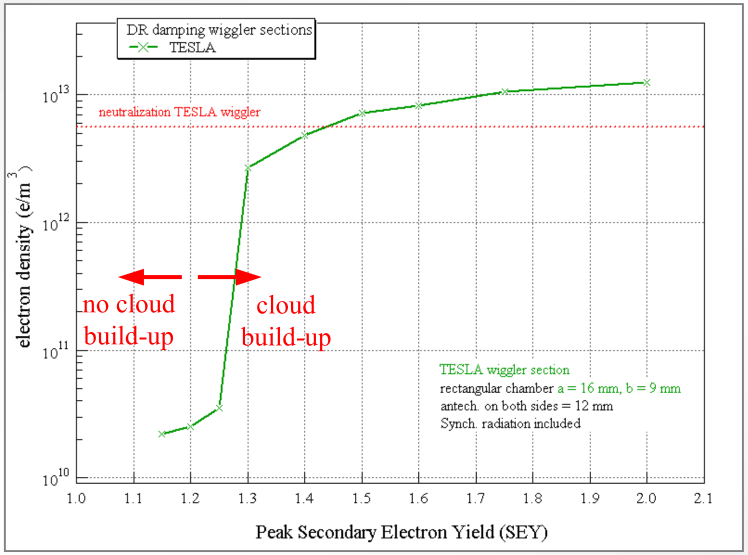
A build-up of electrons (electron cloud) drives beam instabilities.

Treating the chamber surface reduces the number of secondaries, and prevents build-up of the electron cloud.

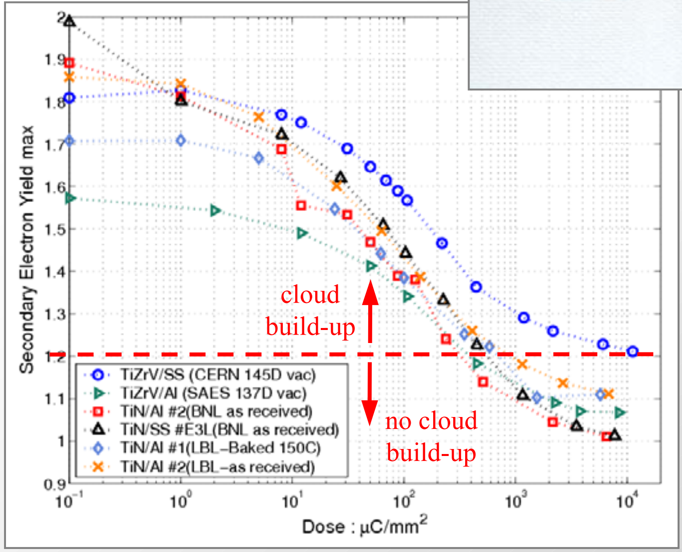
LBNL and SLAC are investigating a number of possible treatments:

- TiN coating
- TiZrV coating (NEG – can also improve vacuum)
- Grooved chamber surface

Above: TiN coatings prepared at LBNL.



Far left: Simulation of electron-cloud build-up in the ILC damping wiggler, as a function of peak SEY. (M. Pivi, SLAC.)



Left: Measurements of peak SEY of various coatings. (F. le Pimpec and R. Kirby, SLAC.)

Faster extraction kickers could provide benefits

Ring circumference is presently limited by rise/fall time of injection and extraction kickers.

20 ns rise/fall time kicker leads to 17 km ring circumference.

4 ns kicker would allow 3.5 km ring circumference, with cost and operational benefits.

Bunch-to-bunch kicker stability is the most demanding requirement.

TDR/TRC specifications are:

- kick angle 0.6 mrad (using a stripline kicker, $\int V\,dl = 3\times10^6$ Vm)
- kick angle stability 0.07%

A number of laboratories are collaborating in kicker R&D:

Cornell/FNAL: fast pulser/stripline kicker to be tested on the A0 beamline at FNAL

DESY: fast pulser R&D

KEK: low power, fast kicker to be tested in ATF

SLAC/LLNL/LBNL: high power, fast kicker to be used in ATF for single bunch extraction

LBNL is working on fast kicker for tests in ATF

ATF can operate with trains of 20 bunches, 2.8 ns separation.

- Bunch separation of 5.6 ns easily achieved by filling alternate RF buckets.

ATF2 will extend the present extraction line, for final focus R&D.

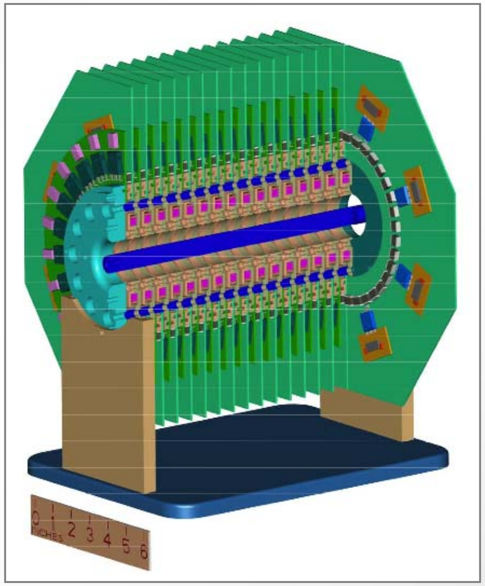
- Bunch spacing ~ 300 ns required, to replicate ILC parameters.
- Bunches must be extracted individually from the ATF damping ring.

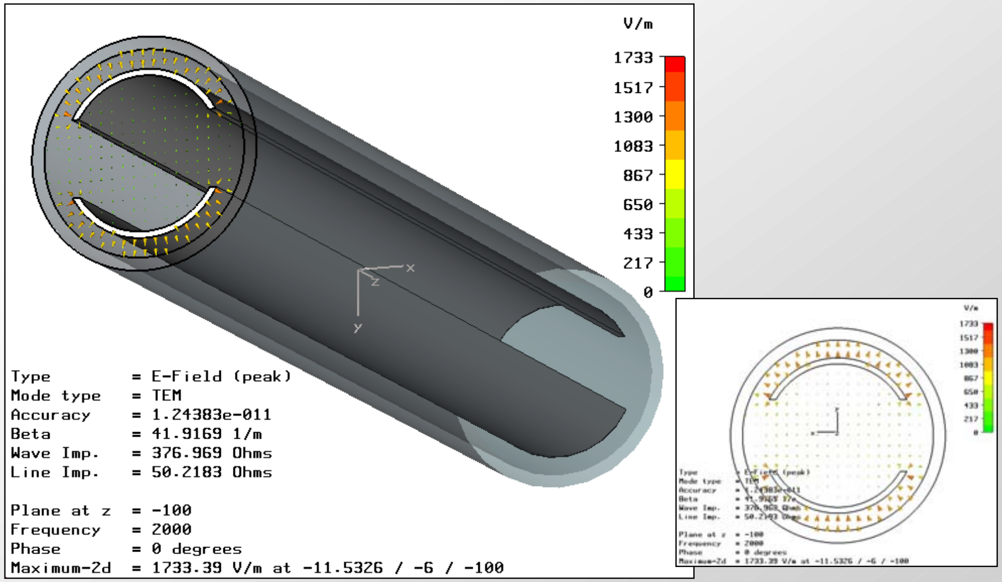
SLAC/LLNL/LBNL will develop and build an extraction kicker with <5.6 ns rise/fall time for extraction of individual bunches from ATF (to be installed in late 2006).

- SLAC/LLNL will develop and provide a fast, high-power pulser.
- LBNL will develop and build a stripline kicker.

Right: High-power fast pulser using inductive adders based on design for DARHT-II, being developed by LLNL. (E. Cook, LLNL)

Far right: Model of stripline kicker being developed at LBNL. (S. de Santis, LBNL)





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Type         = E-Field (peak)
Mode type    = TEM
Accuracy     = 1.24383e-011
Beta         = 41.9169 1/m
Wave Imp.    = 376.969 Ohms
Line Imp.    = 50.2183 Ohms

Plane at z   = -100
Frequency    = 2000
Phase        = 0 degrees
Maximum-2d   = 1733.39 V/m at -11.5326 / -6 / -100
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We are starting to look at the ILC bunch compressors

ILC bunch compressors must reduce the 6 mm bunch from the damping rings to 0.3 mm in the linac.

Our motivation for studying the bunch compressors is to design a system that will allow longer bunches (up to 9 mm) in damping rings.

- RF voltage (presently >100 MV for 6 mm bunches) can be reduced for longer bunches.
- Reduced charge density in longer bunches eases several collective effects, including microwave instability and space-charge tune shift.

TESLA TDR specified a single-stage bunch compressor.

- Simple design, but led to a large final energy spread (>2.5%) before the main linac.
- No room to increase damping ring bunch length: final energy spread would be nearly 4% for a 9 mm bunch from the damping rings.

Multi-stage designs offer the advantage of a reduced energy spread (by accelerating between stages) at the cost of a longer, more complex system.

- Final energy must not be too high, because of radiation effects in final BC chicane.
- Phase-space rotation through 90º preferred, to convert phase errors in damping rings into energy errors in the main linac.

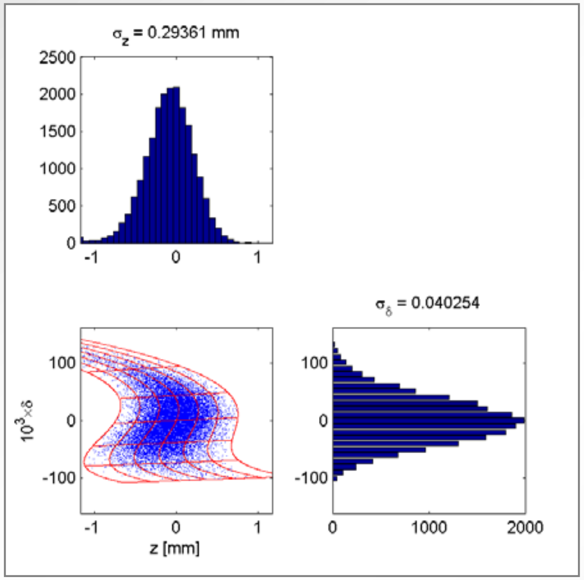
We have produced outline designs for multi-stage BCs

We are working in close collaboration with SLAC.

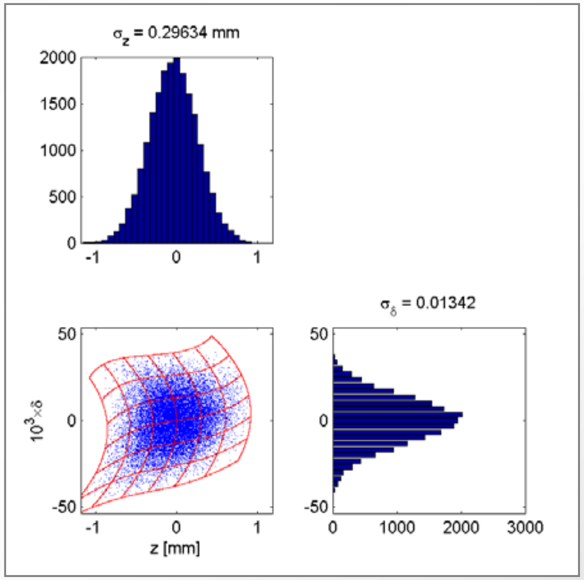
Three-stage design provides some advantages:

- Greater flexibility in operation than single-stage or two-stage systems.
- Converts phase errors from damping rings into energy errors in linac.
- Provides ample overhead for larger bunch length and energy spread in DRs.

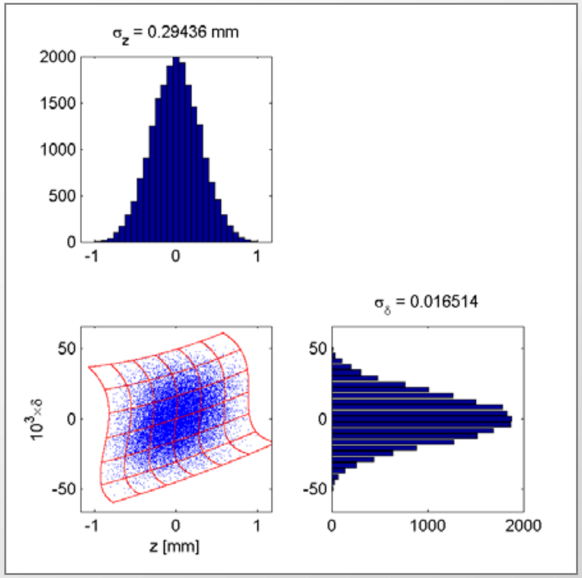
Main drawbacks of three-stage design are the greater size and cost.



Single-stage ILC Bunch Compressor.
Final energy 4.37 GeV
Phase-space rotation through 90°



Two-stage ILC Bunch Compressor.
Final energy 11.5 GeV
Phase-space rotation through 180°



Three-stage ILC Bunch Compressor.
Final energy 10.0 GeV
Phase-space rotation through 270°
(A. Wolski, LBNL)

Principal Recent Accomplishments

Development of damping rings for NLC (through to 2004)

- The quality of our work and contribution to the collaboration was repeatedly recognized by the NLC MAC
- Lattice designs for Main Damping Rings and Positron Predamping Ring
- Detailed studies of beam dynamics issues, notably nonlinear effects from damping wigglers
- Specification and development of technical subsystems and components (RF system, wigglers…)
- Contribution to beam dynamics program at KEK-ATF
- Development of software tools for detailed studies of beam dynamics in damping rings

International LC Technical Review Committee, 2nd Report (2003)

- Contributed to assessment of luminosity performance of principal LC proposals

US Linear Collider Technology Options Study (2004)

- Contributed to assessment of damping ring performance and costs

ILC Damping Rings R&D (2004-2005)

- Produced lattice designs for 17 km and 6 km rings meeting acceptance specifications
- Estimates of beam dynamics performance (single particle and collective effects)
- Presented invited WG3 DR overview talks at US ILC Workshop (SLAC, 10/2004) and 1st ILC Workshop (KEK, 11/2004)
- Co-ordination of US damping ring studies through regular US ILC DR Teleconference
- Continued contribution to beam dynamics program at KEK-ATF

ILC Bunch Compressors (2005)

- Development of schemes to ease emittance preservation, and improve overall performance

Present and Future Work Program

Damping rings: lattices and beam dynamics

- Continued optimization of lattice designs
- Detailed studies of acceptance limitations (e.g. from wiggler)
- Detailed studies of collective effects (including space-charge, and coupled-bunch instabilities)
- Continued development of software tools for beam dynamics studies in DRs

Damping rings: technical components and subsystems

- Continued investigation of low SEY preparations for preventing electron cloud
- Development of fast stripline kicker for ATF2 extraction
- Specification of vacuum system components to achieve 0.1 ntorr
- Cost estimates of different DR options, to inform selection of design for CDR

Bunch compressors

- Continued development of multi-stage designs
- Detailed performance evaluation of different BC options

Reports and Publications, 2003-2004

Journal Publications

- *Achievement of Ultralow Emittance Beam in the Accelerator Test Facility Damping Ring*, Y. Honda et al., Phys. Rev. Lett. **92**, 054802 (2004).
- *Intrabeam Scattering Formulae for High Energy Beams*, S. K. Mtingwa, K. Kubo, A. Wolski, submitted to Phys. Rev. ST AB.

Conference Papers

- *Analysis of KEK-ATF Optics and Coupling Using LOCO*, A. Wolski, M. Woodley, J. Nelson, M. Ross (EPAC 2004).
- *Beam-Based Alignment at the KEK-ATF Damping Ring*, M. Woodley, J. Nelson, J. Turner, A. Wolski, K. Kubo (EPAC 2004).
- *A Reduced-Emittance Lattice for the NLC Positron Predamping Ring*, I. Reichel, A. Wolski (EPAC 2004).
- *Dynamic Aperture Study for the NLC Main Damping Rings*, A. Wolski, M. Venturini, S. Marks (EPAC 2004).
- *Normal Form Analysis of Linear Beam Dynamics in a Coupled Storage Ring*, A. Wolski, M. Woodley (EPAC 2004).
- *Damping Ring to Interaction Point Beam Transport Issues*, N. Walker, D. Schulte, A. Wolski, P. Tenenbaum, A. Seryi, M. Woodley (PAC 2003).
- *Damping Ring Designs and Issues*, A. Wolski, W. Decking (PAC 2003).
- *A Lattice with Larger Momentum Compaction for the NLC Main Damping Rings*, A. Wolski, T. Raubenheimer, M. Woodley, J. Wu (PAC 2003).
- *Wigglers and Single-Particle Dynamics in the NLC Damping Rings*, M. Venturini, A. Wolski, A. Dragt (PAC 2003).
- *Harmonic Cavities for the NLC Damping Rings*, S. de Santis, A. Wolski (PAC 2003).
- *Coupling Correction and Beam Dynamics at Ultralow Vertical Emittance in the ALS*, C. Steier, D. Robin, A. Wolski, G. Portmann, J. Safranek (PAC 2003).
- *A Model of ATL Ground Motion for Storage Rings*, N. Walker, A. Wolski (PAC 2003).
- *Evolving Bunch and Retardation in the Impedance Formalism*, R. Warnock, M. Venturini (PAC 2003).
- *A Model for Producing Stable, Broadband Terahertz Coherent Synchrotron Radiation in Storage Rings*, F. Sannibale, J. Byrd, A. Loftsdottir, M. Martin, M. Venturini (PAC 2003).

Reports and Publications, 2003-2004

LBNL Reports

http://www-library.lbl.gov/lbnl_reports/sf

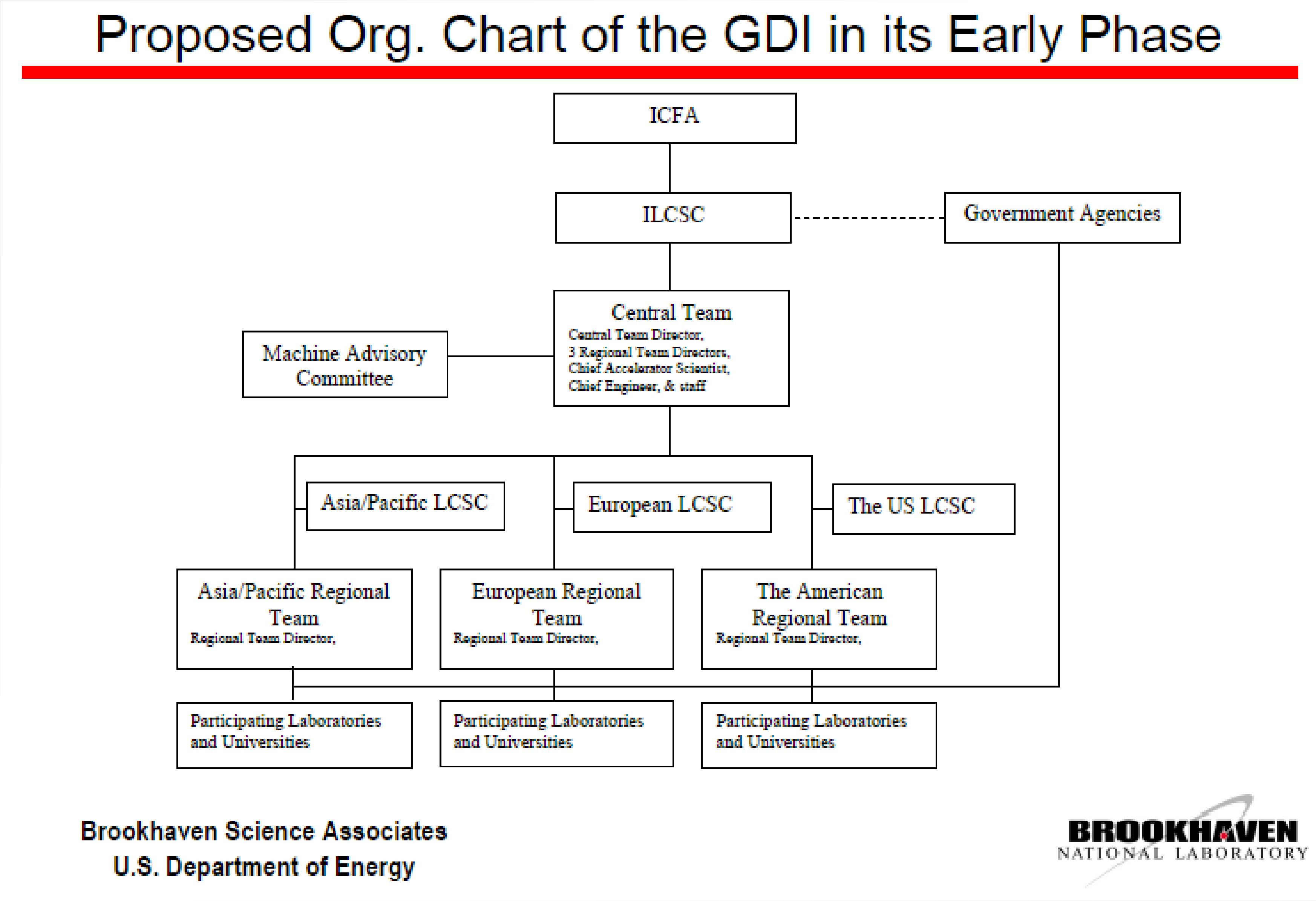
- *Initial Studies of Nonlinear Dynamics in the KEK-ATF Wigglers*, A. Wolski, J. Nelson, M. Ross, M. Woodley (LBNL-57047, Feb 2005).
- *Coupling Correction in the KEK-ATF Using Orbit Response Matrix Analysis*, A. Wolski, J. Nelson, M. Ross, M. Woodley, Y. Honda (LBNL-57046, Feb 2005).
- *Lattices with Large Dynamic Aperture for the ILC Damping Rings*, A. Wolski (LBNL-57045, Feb 2005).
- *Lattice Design for an ILC Damping Ring with 3 km Circumference*, A. Wolski (LBNL-56506, Oct 2004).
- *Frequency Map Analysis of Nonlinear Dynamics in the NLC Main Damping Rings*, A. Wolski, M. Venturini, S. Marks, W. Wan (LBNL-56505, Oct 2004).
- *Closed-Orbit Response to Quadrupole Strength Variation*, A. Wolski, F. Zimmermann (LBNL-54360, Jan 2004).

NLC Collaboration Reports

http://www-project.slac.stanford.edu/lc/ilc/TechNotes/LCCNotes/lcc_notes_index.htm

- *Spin-Tracking Studies for Beam Polarization Preservation in the NLC Main Damping Rings*, A. Wolski, D. Bates (LCC-0155, Jul 2004).
- *R&D Issues for NLC Damping Rings 2004-2005*, A. Wolski (LCC-0150, Jun 2004).
- *Resistive-Wall Instability in the NLC Main Damping Rings*, A. Wolski (LCC-0149, Jun 2004).
- *Intrabeam Scattering in the NLC Main Damping Rings*, A. Wolski (LCC-0147, Jun 2004).

From S. Ozaki, 1st ILC Workshop, KEK, 11/2004



Proposed Org. Chart of the GDI in its Early Phase

ICFA

ILCSC

Government Agencies

Central Team
Central Team Director,
3 Regional Team Directors,
Chief Accelerator Scientist,
Chief Engineer, & staff

Machine Advisory Committee

Asia/Pacific LCSC

European LCSC

The US LCSC

Asia/Pacific Regional Team
Regional Team Director,

European Regional Team
Regional Team Director,

The American Regional Team
Regional Team Director,

Participating Laboratories and Universities

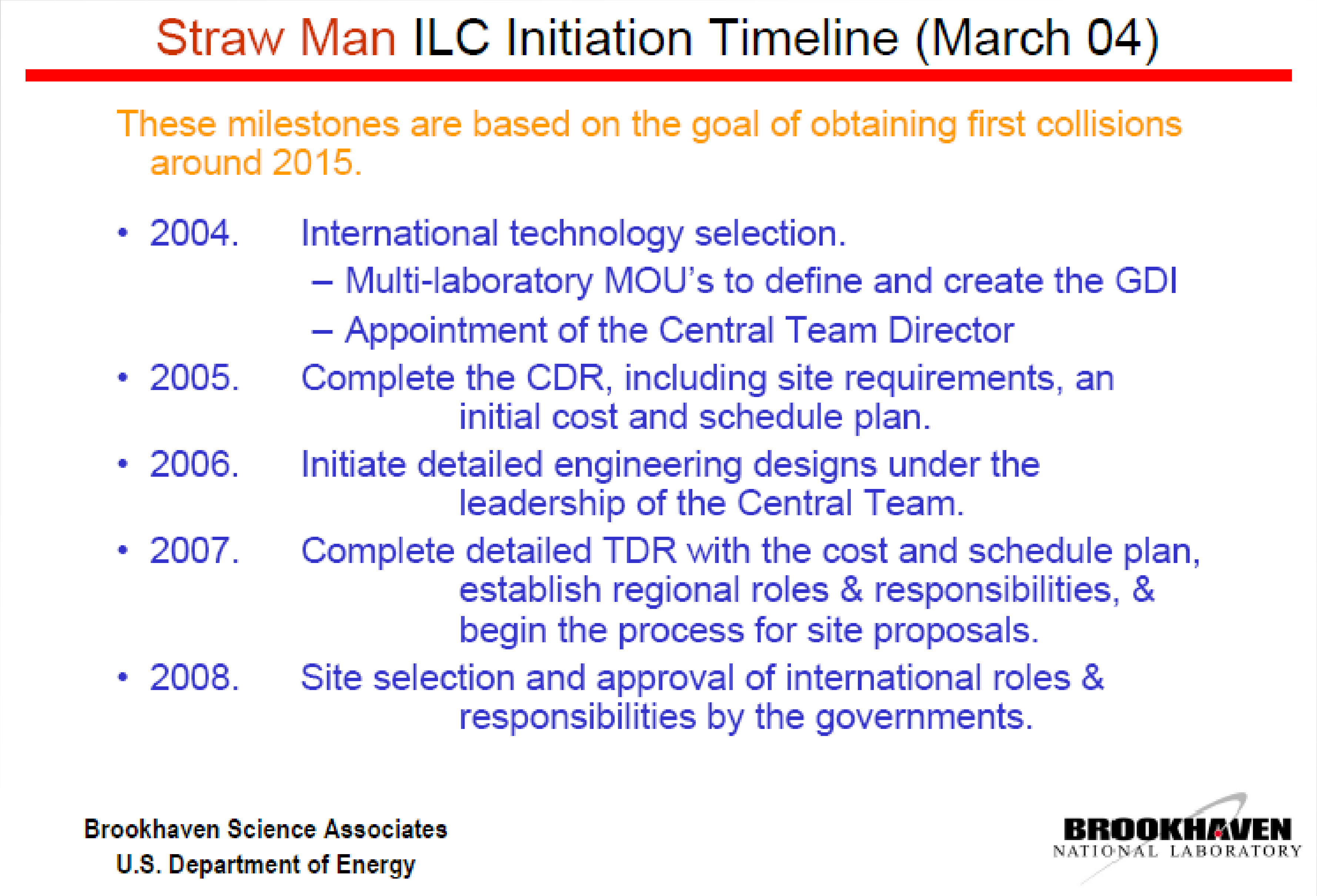
Participating Laboratories and Universities

Participating Laboratories and Universities

Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN
NATIONAL LABORATORY

From S. Ozaki, 1st ILC Workshop, KEK, 11/2004



Straw Man ILC Initiation Timeline (March 04)

These milestones are based on the goal of obtaining first collisions around 2015.

- 2004. International technology selection.
  - Multi-laboratory MOU's to define and create the GDI
  - Appointment of the Central Team Director
- 2005. Complete the CDR, including site requirements, an initial cost and schedule plan.
- 2006. Initiate detailed engineering designs under the leadership of the Central Team.
- 2007. Complete detailed TDR with the cost and schedule plan, establish regional roles & responsibilities, & begin the process for site proposals.
- 2008. Site selection and approval of international roles & responsibilities by the governments.