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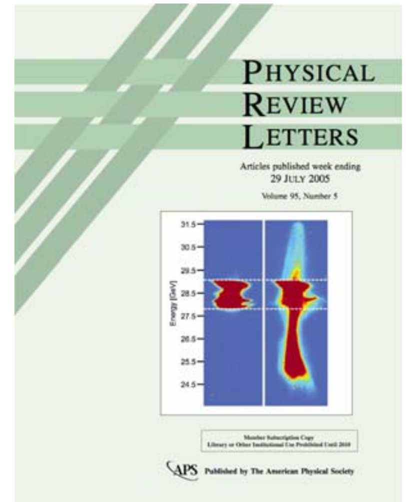
Accelerator Research

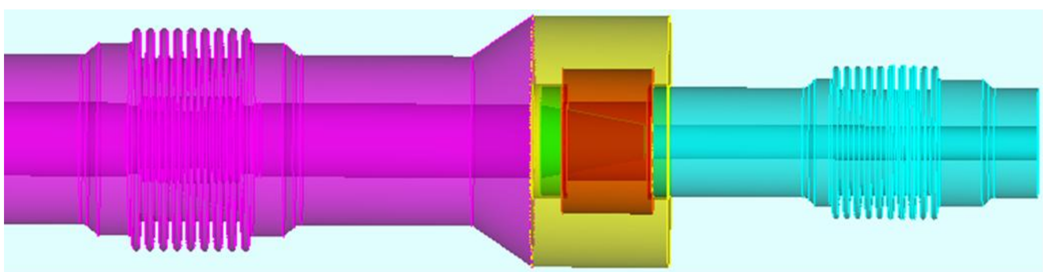
Bob Siemann
DOE Annual Review

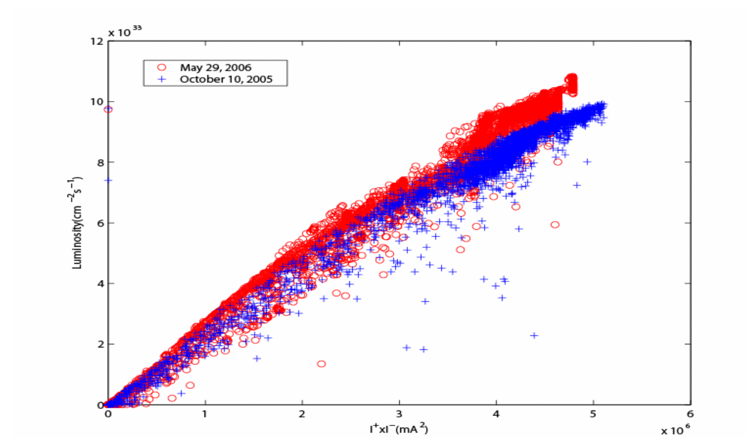
I. Introductory Remarks
II. Accelerator Research Activities at SLAC
III. Concluding Remarks

Breakout session in Redwood C&D



The combination of outstanding science using accelerators and accelerator science has made SLAC a world leader in particle physics, photon science, and accelerator science and technology





Optical Microbuncher

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Accelerator Science at SLAC

Accelerators and accelerator science permeate SLAC

- Most often SLAC accelerator science is driven by exploration at the frontier of particle physics.
- Also has significant impact on Photon Science
- Includes - Improvement of existing accelerators, development of new accelerators, and development of new accelerator science and technology
- From an organization and management perspective accelerator science is spread out widely: PEP II operations, SPEAR operations, LCLS, ILC, Klystron Dept, Surface & Material Science Dept, Accelerator Research Depts.
- From an accelerator physicist's perspective there is an intellectual commonality among these activities be they short- or long-term, specific or generic

Look in more detail at part of this - Accelerator Research, Activities that

- Support the operating accelerators
- Develop accelerator technology and physics for the future
- Explore new ways to accelerate particles

Beam Physics Department (Yunhai Cai Dept Head)

- **Accelerator support:**
  - Improve machine optics and study the beam-beam effects for PEP-II
  - Design lattices for ILC, SABER, and SPEAR3
  - Estimate impedance and analyze and mitigate instabilities for ILC
  - Calculate wake field and study CSR and FEL physics for LCLS
- **Accelerator research:**
  - Develop precision methods to measure optics in circular accelerators
  - Develop tools to calculate luminosity and beam-beam lifetime in e+e- colliders
  - Phase-space manipulations of high-brightness electron beams
  - Study coherent synchrotron radiation and its dynamical effect on the beam
  - Advance theory and calculation of the impedance beyond conventional condition, such as rough surface, grooved surface
  - Study multi-particle beam dynamics, for example, interaction of beams with ions or electron cloud in accelerators
  - Various problems related to the advancement of the Free-Electron Lasers
  - Theoretical analysis of laser acceleration in vacuum
- **Community service:**
  - Teach in Stanford University and several particle accelerator schools
  - Serve on advisory committee for many accelerator complex worldwide
  - Develop and maintain codes: LEGO, BBI, Zlib, MIA

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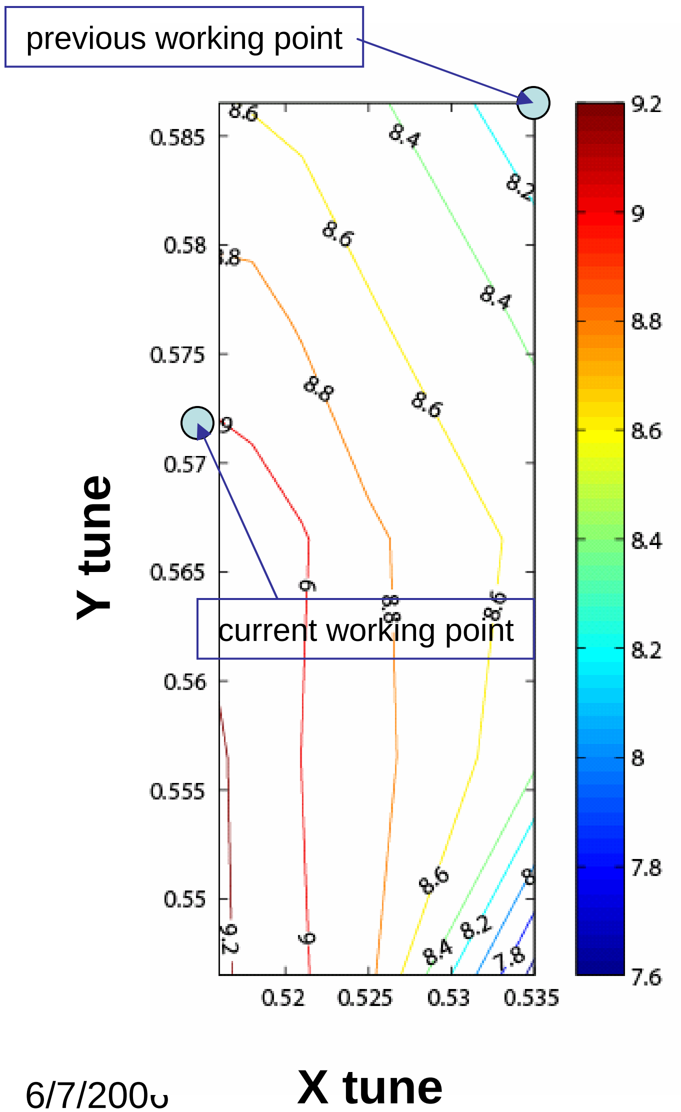
Beam-Beam Simulation and its Application to PEP-II



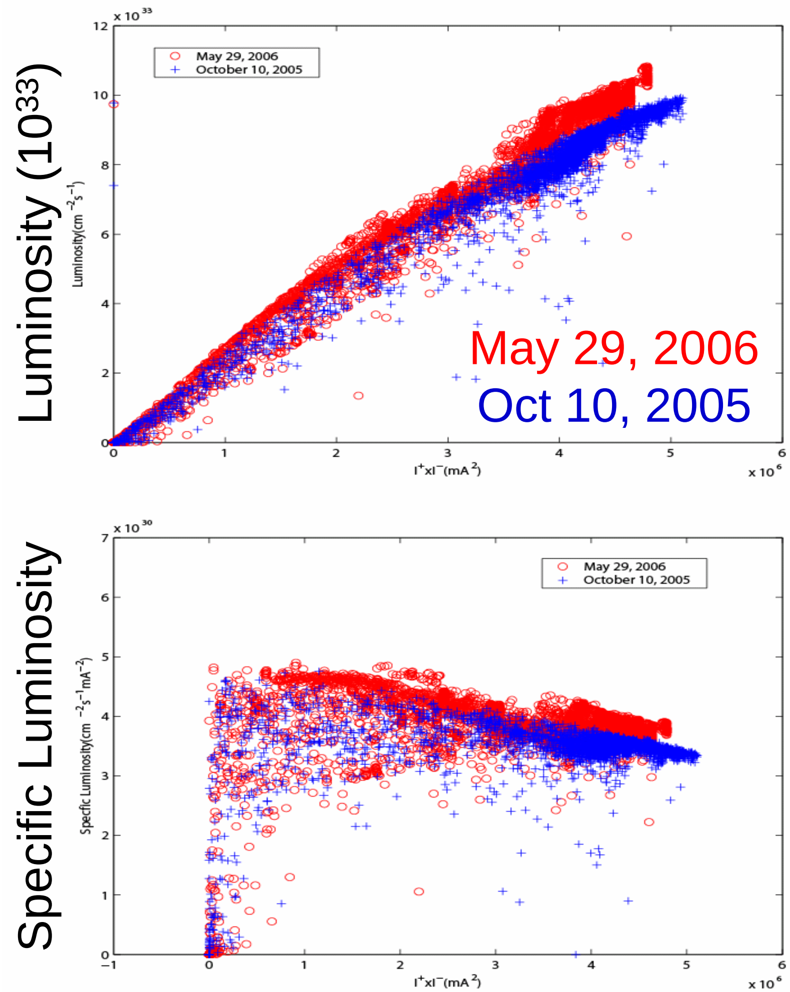
- Three-dimensional simulation code: BBI
- MIA models are used for the inputs
- Simulation is carried out at currents of 1600mA/2400mA
- Lower both x and y tunes to gain luminosity shown a contour plot in unit of 1E33 $cm^{-2}s^{-1}$

We made **a quantitative prediction** and followed by:

- MD study and identified beam-beam lifetime as the limitation
- Run x-chromaticity -1 to improve chromatic optics
- Tweaked SCY3 by 7% to gain beam-beam lifetime
- Lower the V_{RF} from 4.5 to 4.0 MV
- Actual tune change was accomplished by operators during the delivery

Luminosity Increase as a Result of Improvement of Machine Optics

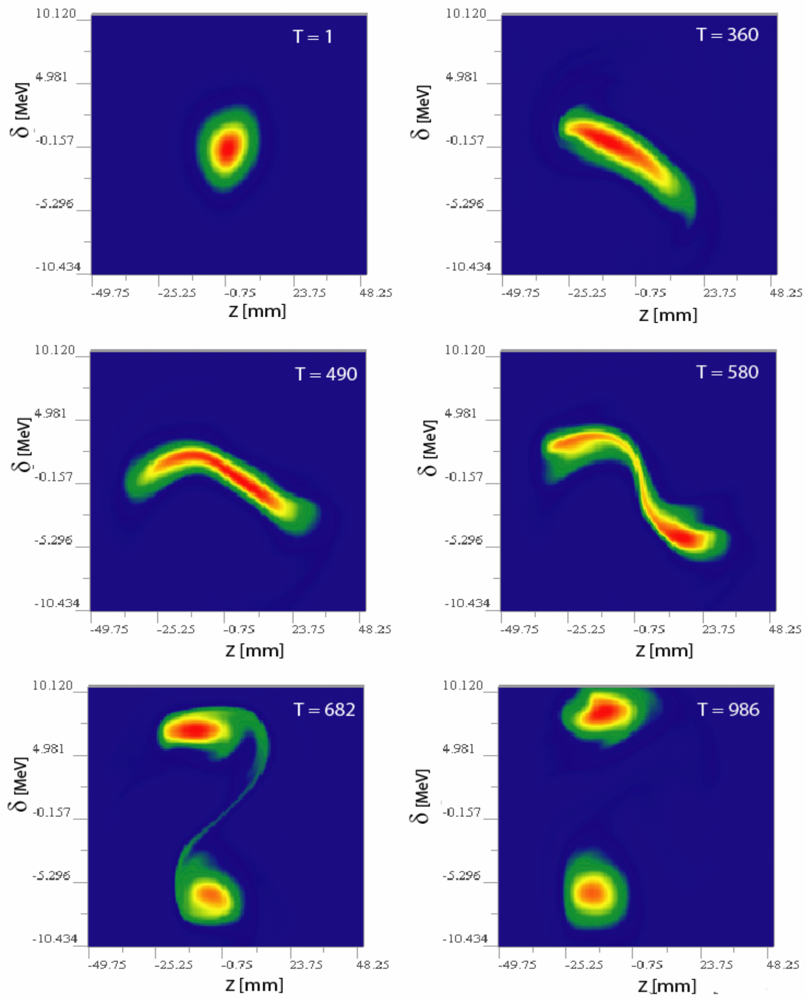
- Lead the PEP-II optics task force and closely work with many colleagues in Accelerator System Division
- Significantly improve the online optics model for PEP-II
  - **beam-based**
  - **faster and robust**
- Introduce many new correction schemes and tuning knobs
- Better understanding of the machine nonlinearity
  - **Improve chromatic optics**
  - **increase dynamic aperture**



$I^+ x I^-$

Study of Instabilities in Ultra-Low Momentum Compaction Lattice

- Bunch length less than a millimeter in storage ring
- Negative momentum compaction factor of -5.3E-4 with its nonlinear parts
- Found the head-tail instability in the longitudinal plane is a limiting factor as shown: the beam is splitting into two parts within 1000 turns
- Feedback is not so effective to control this instability
- Published by S. Heifets and A. Novokhaski, PRST-AB, April 2006.



Accelerator Technology Research (Sami Tantawi Dept. Head)

High Gradient Research:

- Breakdown in rf structures: theoretical and experimental investigations
- Material Characterization, Geometrical Effects, Frequency scaling, Wake field damping
- High Frequency RF Source Developments
- Novel Accelerator structure designs Manufacturing and characterization techniques for Accelerator Structures
- New test setup for inexpensive accurate characterization of RF properties of materials and processing techniques

Ultra High Power RF Components and Systems:

- Active pulse compression systems and ultra-high-power solid-state devices,
- Novel low field fundamental mode RF couplers
- A new concept of spatially combined devices for ultra-high power semiconductor switches and RF sources .

Novel FEL Technologies and Light Sources: RF undulators and bunch compression techniques for ultra-short pulses.

Advanced Accelerator Concepts: Practical design and implementation of a Bragg optical electron accelerating structures including couplers

Advanced Concepts for the ILC : fundamental mode couplers, RF distribution system, fast kickers.

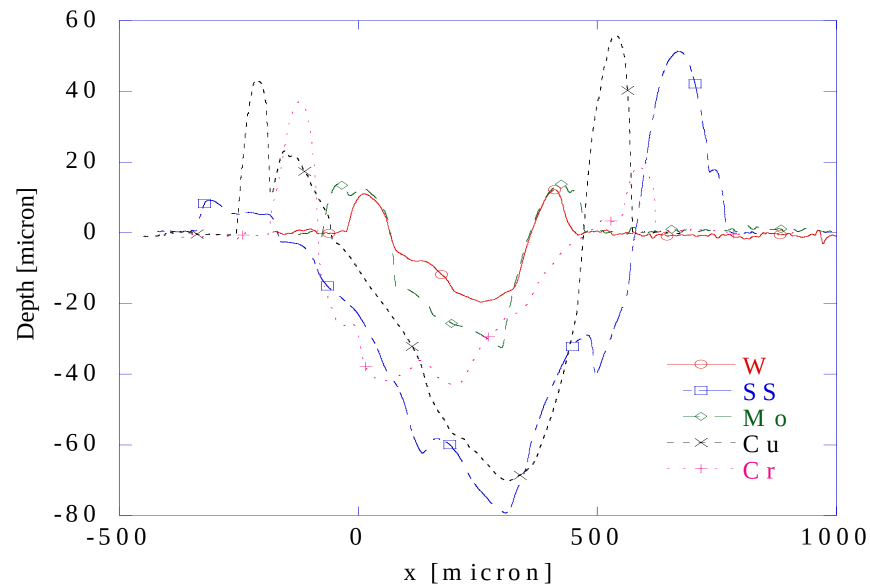
Advanced Electronics:

- Instability control formalism and machine diagnostics for accelerators and light sources .
- Next-generation reconfigurable signal processing (demonstrated at KEK, PEP-II, and Dafne)

High Gradient Research

- Breakdown in rf structures: theoretical and experimental investigations
- Material Characterization, Geometrical Effects, Frequency scaling, Wake field damping
- High Frequency RF Source Developments
- Novel Accelerator structure designs Manufacturing and characterization techniques for Accelerator Structures

Profile of craters from 150 keV electron beam on 5 different metals: Tungsten, Molybdenum, Copper, Chromium, and Stainless Steel



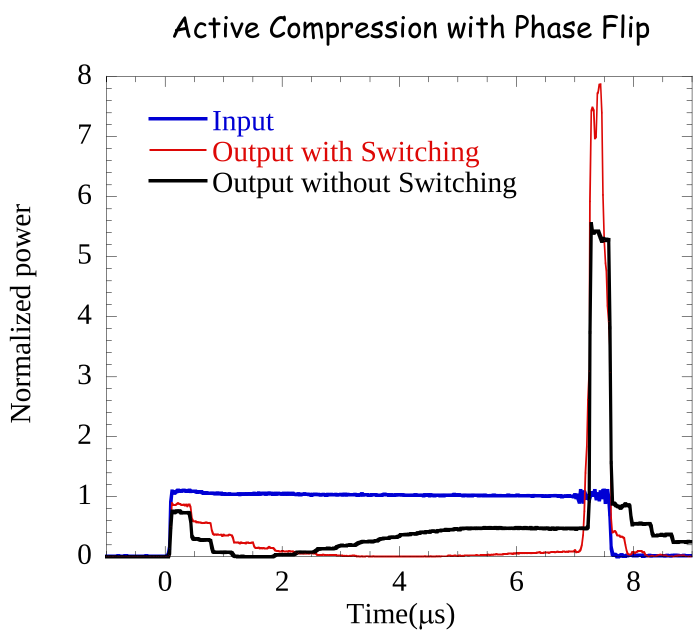
Understanding material electron bombardment interaction (Central to breakdown theory as developed by P. Wilson/V. Dolgashev)

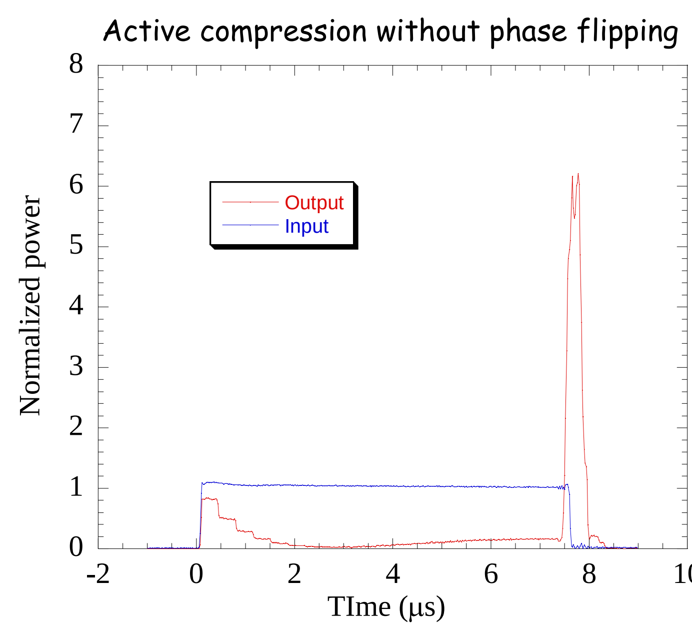
SLAC/KEK collaboration: V. Dolgashev (SLAC),Y. Higashi (KEK), T. Higo (KEK)

Ultra High Power RF Components and Systems

- Active pulse compression systems and ultra-high-power solid-state devices,
- Novel low field fundamental mode RF couplers
- A new concept of spatially combined devices for ultra-high power semiconductor switches and RF sources .

Active Window





Active Pulse compression using 960 spatially combined PIN diodes Pulsed at 700 Volts

Jiquan Guo and Sami Tantawi

Advanced Electronics & Research in Accelerator Dynamics & Instability Control

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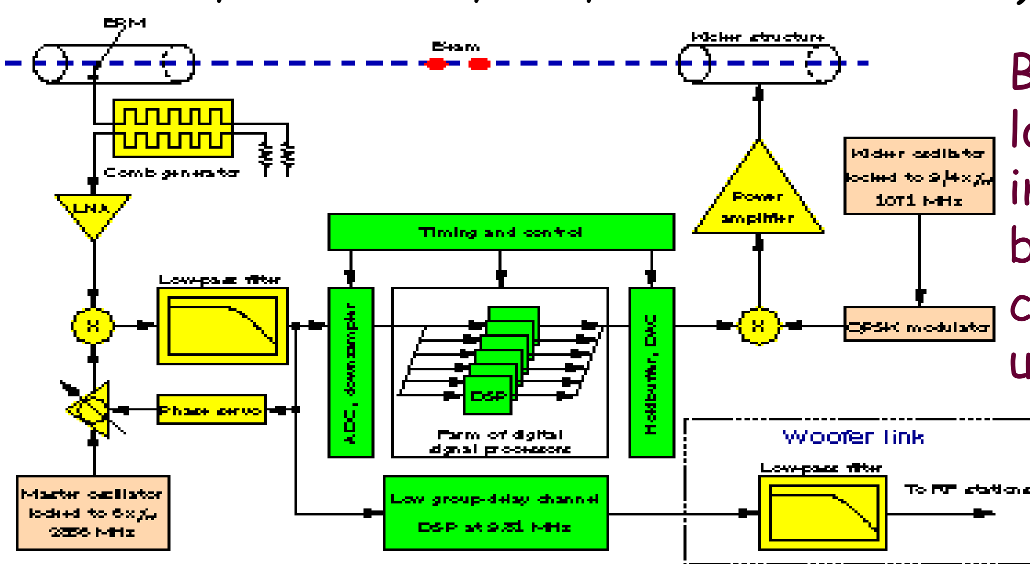
- Instability control formalism and machine diagnostics for accelerators and light sources including beam instability measurement and dynamics control, LLRF system stability and impedance control.
- Development of simulation models, techniques to model Beam- RF system interactions, studies of accelerator dynamics
- Technology Development - 13 instability control systems built/commissioned for US, European and Asian Labs
- Next-generation reconfigurable signal processing (demonstrated at KEK, PEP-II, Dafne, BESSY-II, PLS, SPEAR-3 and ALS)



Broadband (bunch by bunch) longitudinal feedback system as used in PEP-II. This system samples 1746 bunches (238 MHz sampling rate) and computes correction signals using a using a parallel processing DSP farm

Recent Achievements - Our efforts were central in achieving PEP-II record 10^{34} luminosity via control of coupled-bunch instabilities and RF system dynamics

J. Fox et. al.

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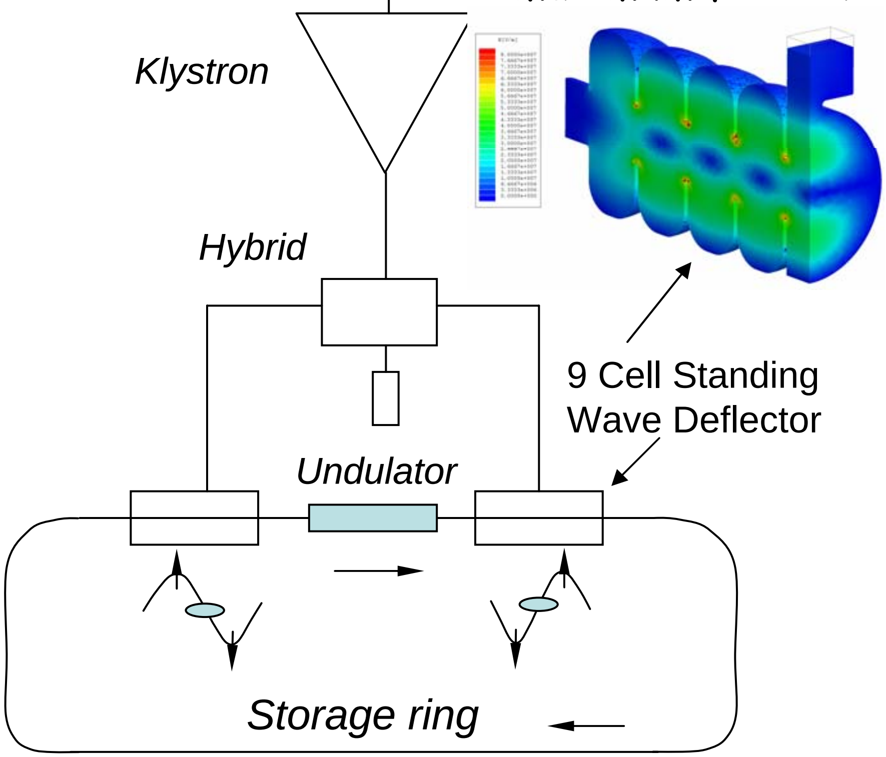
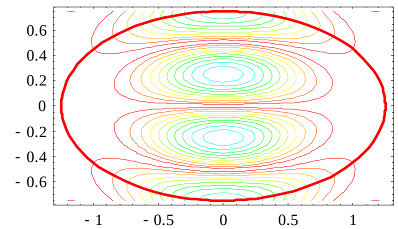
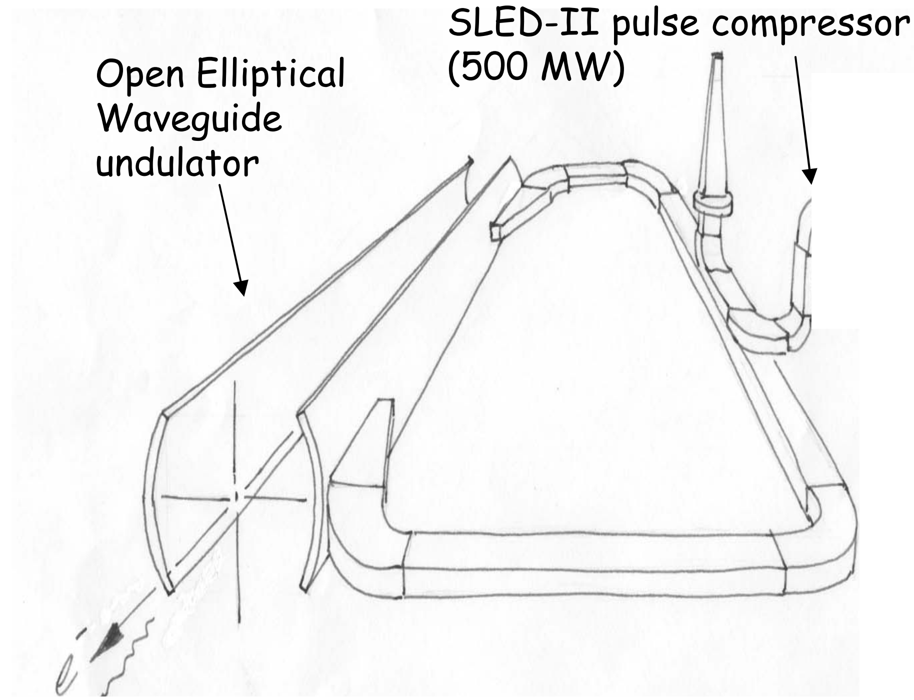
Novel FEL and Light Source Technology



Proposed bunch compression techniques for ultra-short light (x-ray) pulses from synchrotron storage rings (in collaboration with M. Borland from APS)

Surface electric field for 5 MW of input power, maximum field ~70 MV/m


Ratio between peak surface field/Field at the center is 1/5



Development of RF undulator: Because of the integration of RF pulses in a resonant ring the rf pulse in the undulator can be smoothed. Further, the ring can have a multiplication factor of more than 10, resulting in 5 GW of RF power through the undulator waveguide.

S. Tantawi and V.Dolgashev

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Advanced Computations Dept. (Kwok Ko Dept. Head)

***ACD** is a major participant in DOE's computing initiative – Scientific Discovery through Advanced Computing (SciDAC)*

FOCUSES ON:

- ***Parallel code development** in Electromagnetics and Beam Dynamics for accelerator design, optimization and analysis*
- ***Application to major DOE accelerator projects** such as the International Linear Collider (ILC) and the LCLS*
- ***Terascale to Petascale simulations** on DOE's flagship supercomputers at NERSC (LBNL) and NCCS (ORNL)*
- ***Computational science research** in algorithms, solvers, meshing, refinement, optimization, visualization and parallel computing to advance accelerator modeling*
- ***Multi-disciplinary education and training** of next generation computational scientists*

SciDAC Scientific Discovery through Advanced Computing

ACD – ILC R&D w/ SciDAC Tools (1)

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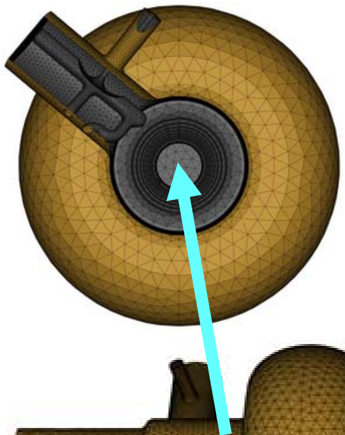
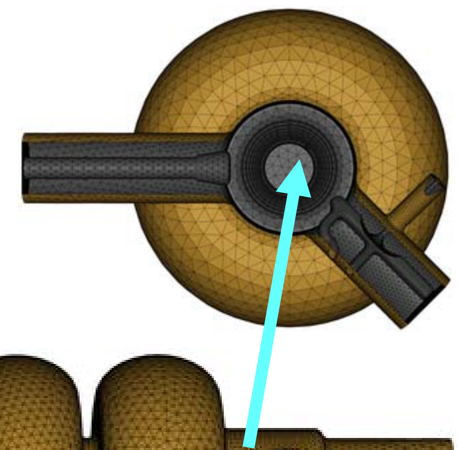
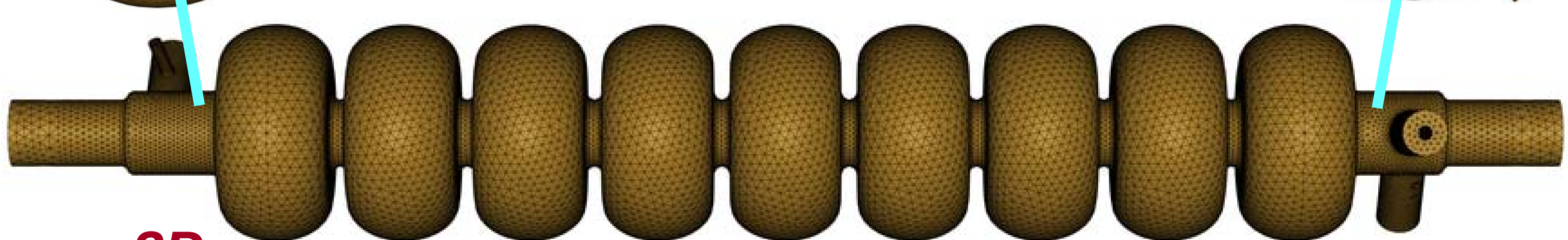
- **Low-loss Cavity Design**

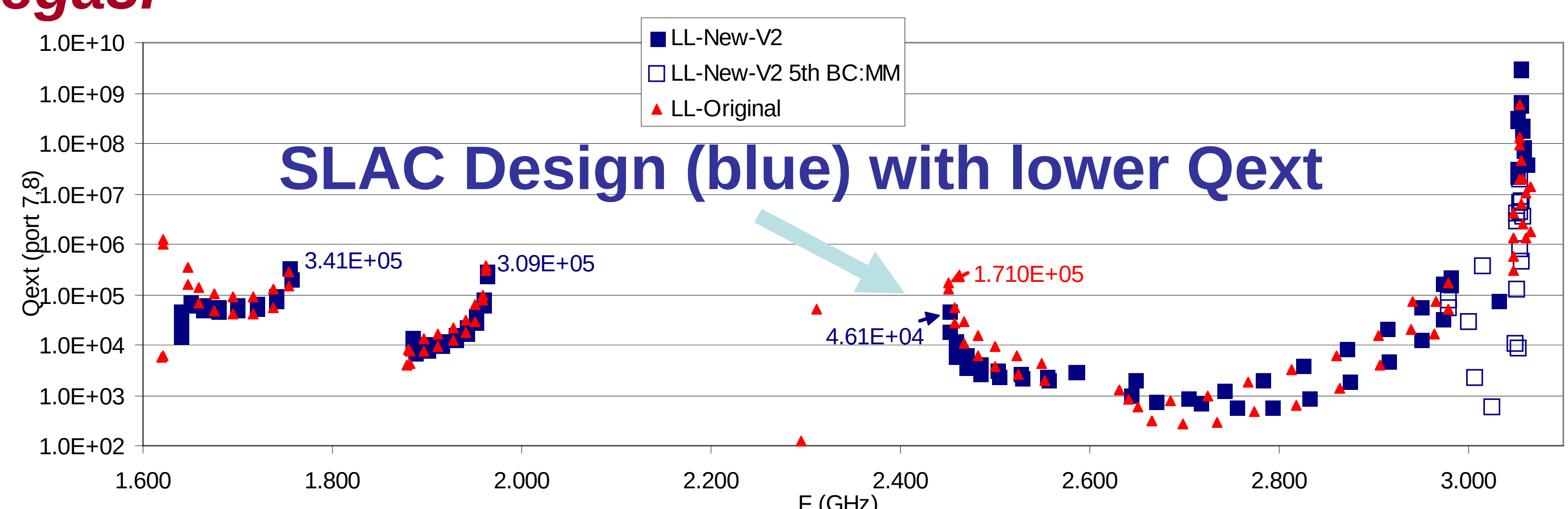
  ACD designed new end-groups with adequate HOM damping for 3rd dipole band.





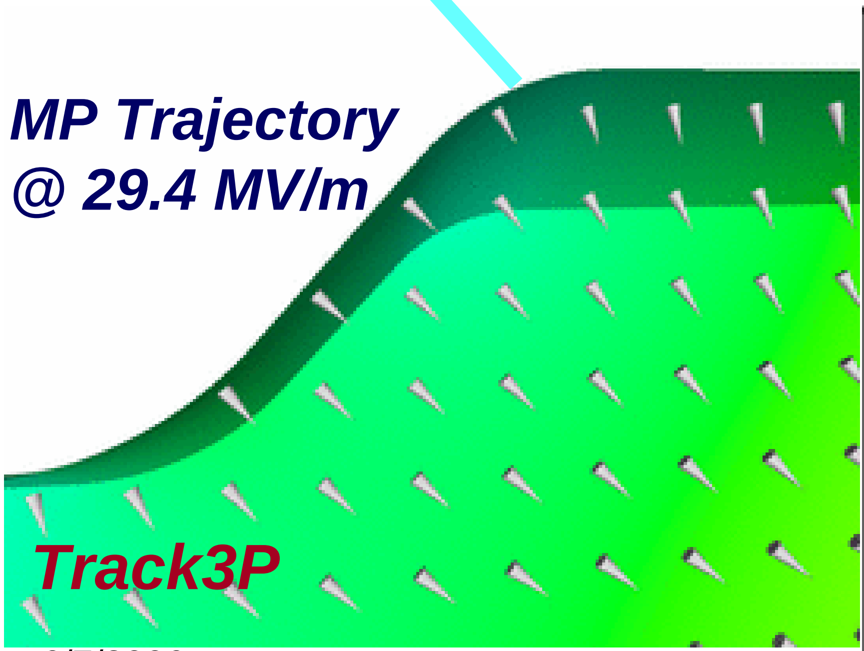


Omega3P



ACD – ILC R&D w/ SciDAC Tools (2)

- **<u>ICHIRO Cavity Design</u> (KEK) –** *ACD found Multipacting barriers in beampipe which limited cavity from higher gradients*



SLAC simulated MP levels [MV/m]	ICHIRO#0 X-ray barrier [MV/m]
	7.4, 9.0, 7-17
12.0	11-29.3, 12-18
13.9	13, 14, 14-18, 13-27, 13-27
16.8	(17, 18)
21.2	20.8
29.4	28.7, 29.0, 29.3, 29.4

K. Saito (KEK)

ACD – ILC R&D w/ SciDAC Tools (3)

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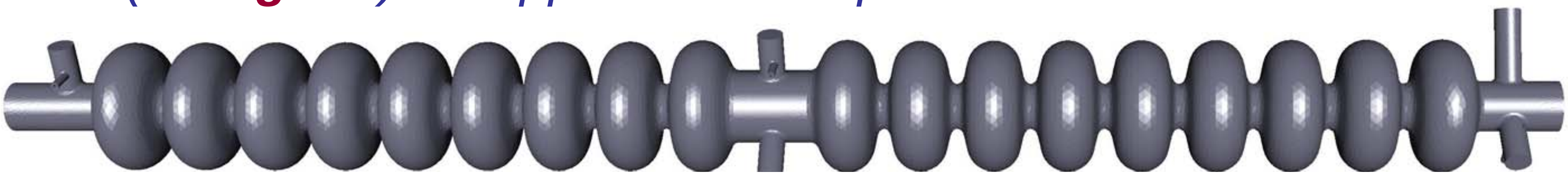
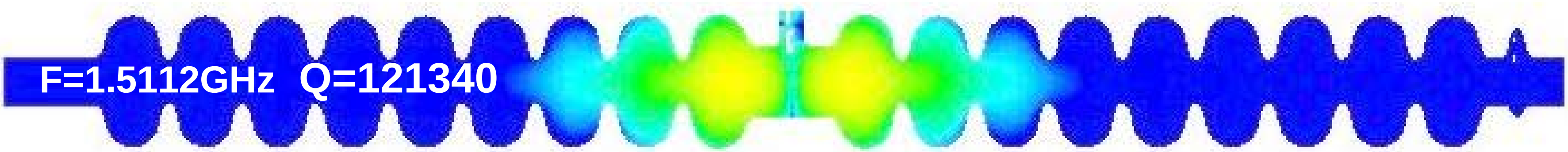
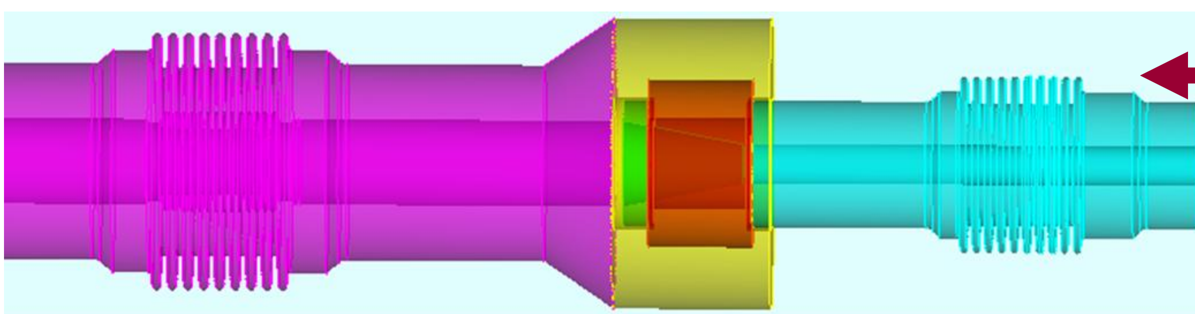
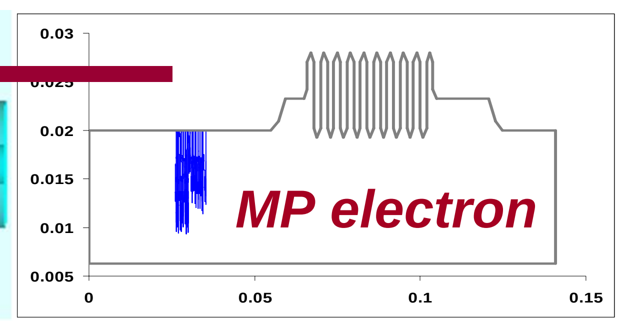
- **<u>Superstructure</u> (JLab. DESY)** - *Trapped mode analysis (**Omega3P**) in support of ILC superstructure R&D .*





- **<u>TTF III Input Coupler</u> (SLAC, LLNL) –** *Multipacting studies (**Track3P**) to support the ILC coupler test stand expt.*

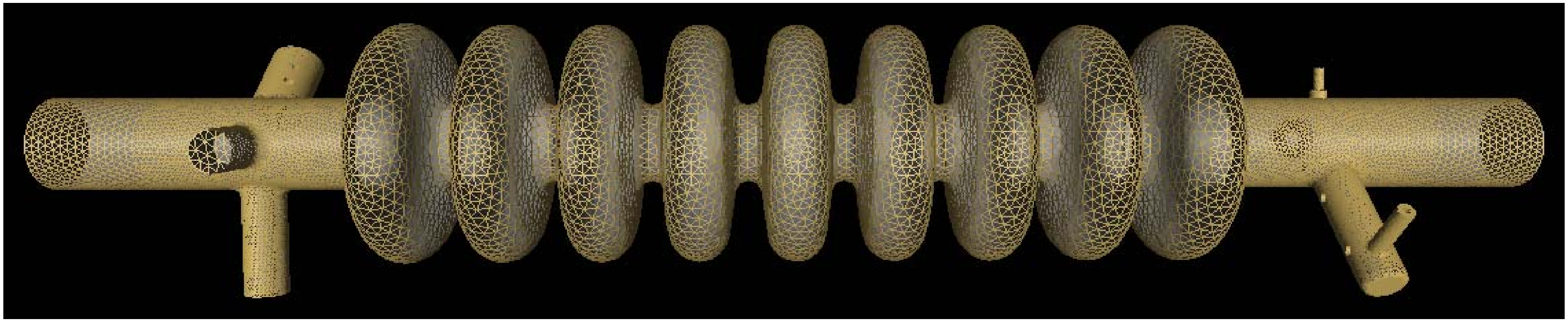




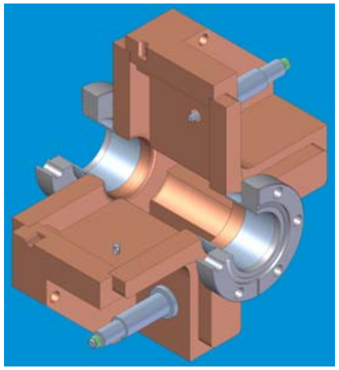
Cold bellows

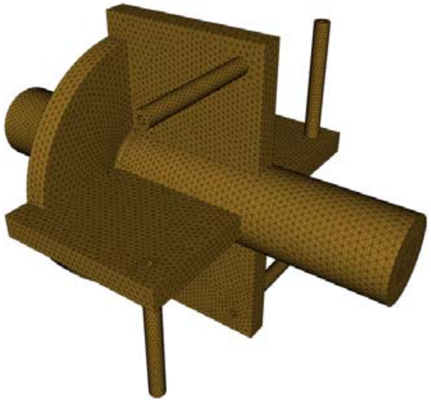
ACD – ILC R&D w/ SciDAC Tools (4)

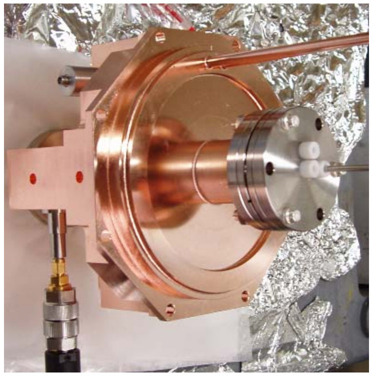
- **Defecting Cavity for Crab Crossing** – *FNAL design evaluated and redesign in progress to reduce wakefields*



- **S-Band BPM for SC Linac Quadrupole** – *Numerically designed with* ***Omega3P****, 3 prototypes built and ESA beam measurements show resolution below one micron level.*







Surface and Materials Science (Bob Kirby, Dept Head)

High Gradient Research:

- Breakdown in rf structures: first systematic autopsies on real accelerating structures, linking breakdowns in low electric field areas to high magnetic fields at sharp corners of couplers.

- Material Science: Adaptation of atomic force microscopy to ambient Fowler-Nordheim field emission measurements, enabling rapid identification of emitters on technical surfaces.

- Development of in-gun hydrogen-ion cleaning of rf copper photocathodes, eliminating downtime for contaminated cathode exchanges.

Beam Instabilities:

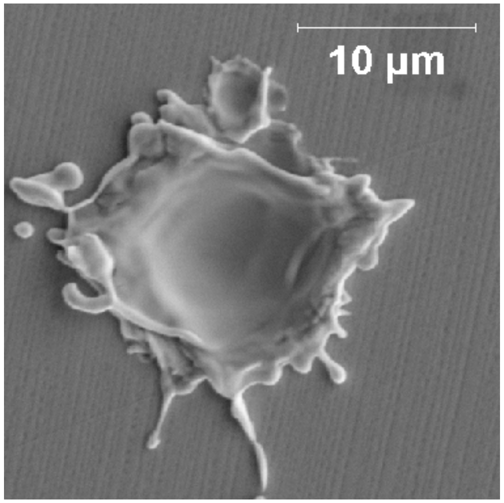
- Secondary electron yield and surface chemistry measurements on beam chamber materials, leading to coatings (TiN and NEG) that suppress the electron cloud effect.

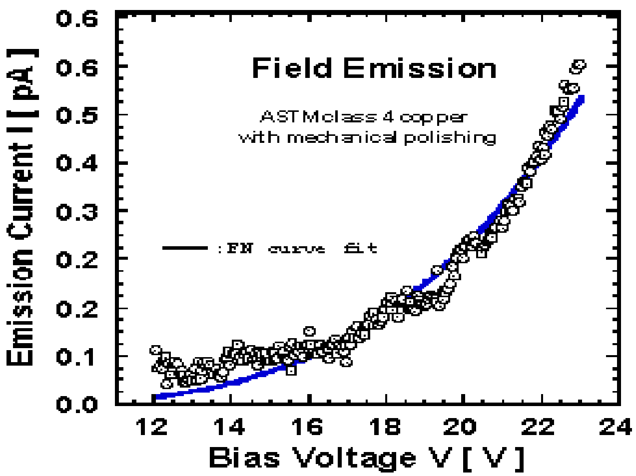
High Polarization Electron Sources:

- Development of the high-polarization, high bunch-charge semiconductor source that is now standard in many fields of polarized electron research.

High Electric-Field Atomic Force Microscopy

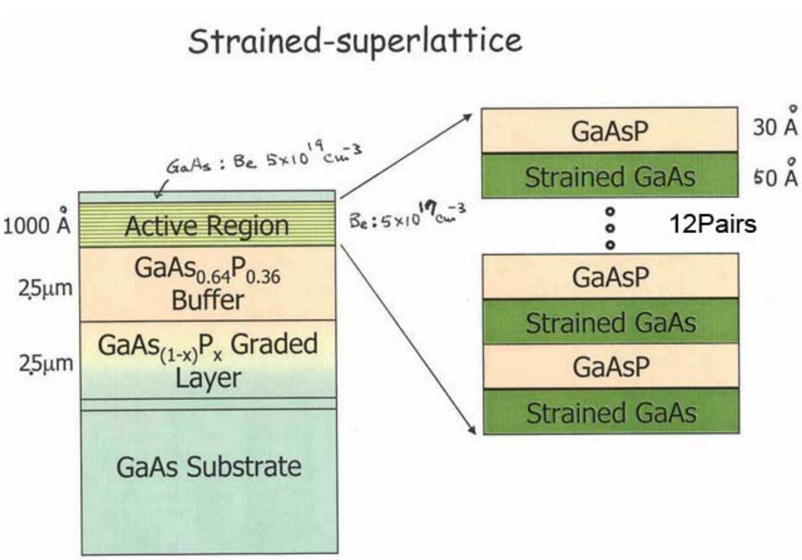
Fundamental studies at nanometer-level, using atomic force microscopy, locate the native sources of field emission (necessary for initiation of breakdown) from accelerator materials, primary copper. Field emission (“Fowler-Nordheim”) measurements under controlled dry-N_2 atmosphere show that these instrinsic sources are not identifiable by topographic methods and are apparently associated with subsurface native defects (as yet unidentified) in the material. Further work must move to UHV conditions, where searching for defects is better controlled and sensitive to surface potential.

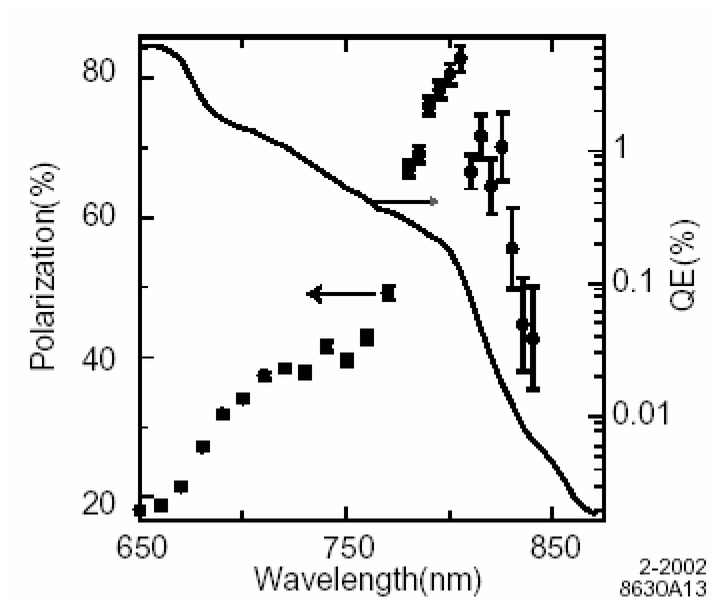




High Polarization Electron Sources (with ILC and U. of Wisconsin)

Program is aimed at producing high (> 80%) polarization, high (> 10^{12} e-) charge bunchs/bunch trains for SLAC's experimental program (E-122 through E-158) and the NLC/ILC. High polarization development has progressed from bulk GaAs (22% P at RT) photocathodes to high-gradient-doped strained-layer superlattice structures based on GaAs1-xPx compounds. Exciting laser wavelength is 780 nmeters. Both charge and polarization requirements for ILC have been demonstrated.





Advanced Accelerator Research Department (Bob Siemann, Dept Head)

Experimental research exploring new physics and technology for particle acceleration

Key aspects of this work

- Collaboration with university researchers with expertise in lasers, photonics, plasmas, simulations,…
- Graduate student education

Research Directions

Laser Acceleration – A Stanford Applied Physics/SLAC Collaboration

- LEAP (Laser Electron Acceleration Project) & E163 at the NLCTA

Plasma Acceleration – A UCLA/USC/SLAC Collaboration

- E157, E162, E164, E164X & E167 at the FFTB
- Future experiments at SABER

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Laser-Driven Acceleration: LEAP & E-163

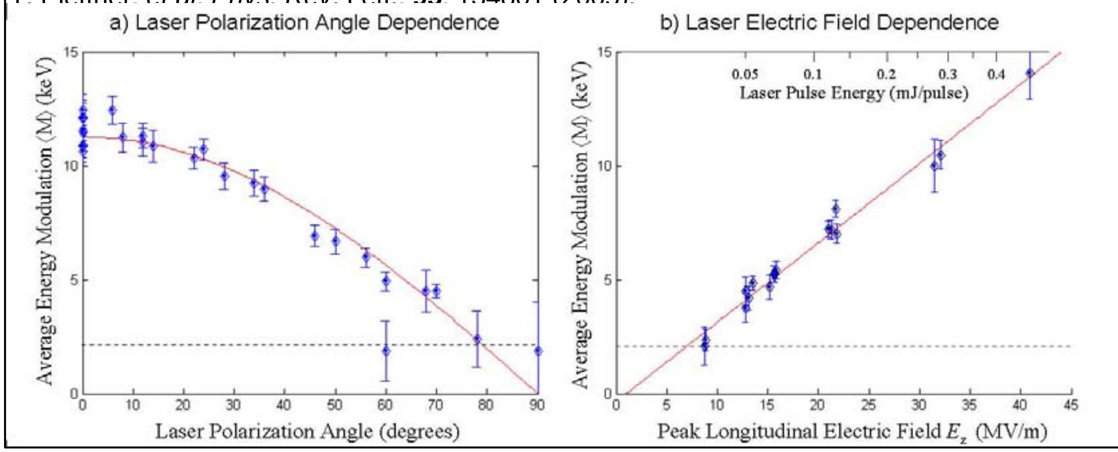
- Motivation
  - Very large electric fields (~1 GV/m) can be tolerated on dielectric surfaces
  - High-power high-efficiency power sources are becoming available
  - Short wavelength naturally leads to attosecond pulse generation
- Difficulties
  - ~~TEM nature of radiation (➔ Lawson-Woodward Theorem)~~
  - ~~Cost, complexity, and inefficiency of lasers as an accelerator power source~~
  - Very small interaction volume $\pi\sigma_t\sigma_r^2$ ~10^{-9} ns-cm^2 (cf. ~10 ns-cm^2 for CLIC)

The difficulties have outweighed the benefits in the past; however, progress in laser and semiconductor technologies has changed the situation significantly:

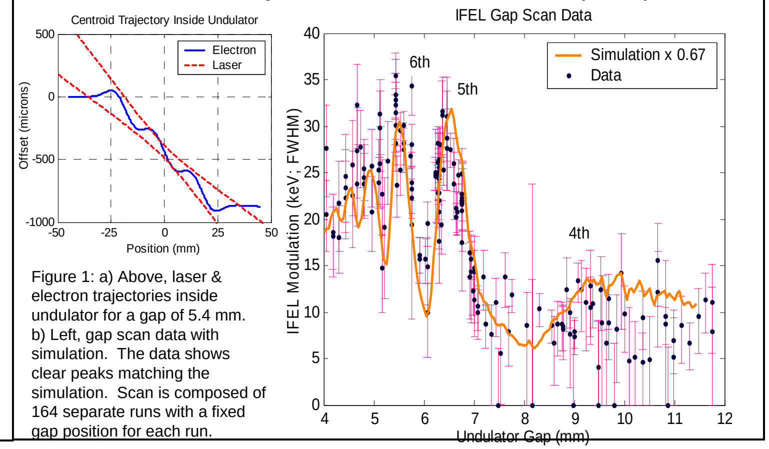
- Techniques for making micron-scale TM-mode structures have evolved rapidly in the semiconductor and telecommunications industries
- Laser technology has evolved markedly, with mode locking, phase locking, CPA, diode pumping, fiber amplifiers, and low quantum-defect laser materials all bringing significant gains in power, efficiency, and reliability
- Challenges of working with a very small interaction volume remain, but we have addressed and have begun to successfully met this challenge

LEAP - Stanford-campus based experiment conclusively demonstrated laser-driven acceleration at 0.8 μm by two fundamentally different physical mechanisms

T. Plettner, *et al*, *Phys. Rev. Lett.*, **95**, 134801 (2005).



C. M. Sears, *et al*, *Phys. Rev. Lett.*, **95**, 194801 (2005).



Inverse Transition Radiation Acceleration | **Harmonic Inverse FEL Acceleration**

E163 – Laser Acceleration at the NLCTA

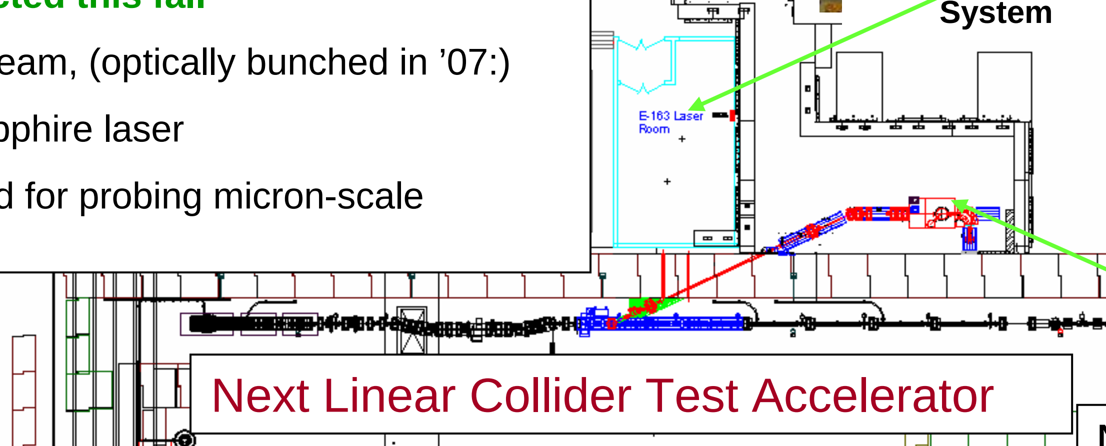
We have constructed a new user facility for advanced accelerator R&D based around the NLCTA

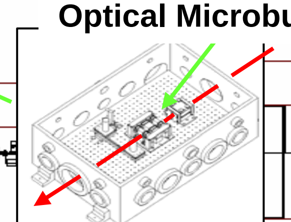
First science expected this fall

- 60 MeV Electron beam, (optically bunched in '07:)
- 10 GW-class Ti:Sapphire laser
- Beamline optimized for probing micron-scale structures

Ti:Sapphire Laser System

Optical Microbuncher





New Expt. Chamber

Next Linear Collider Test Accelerator

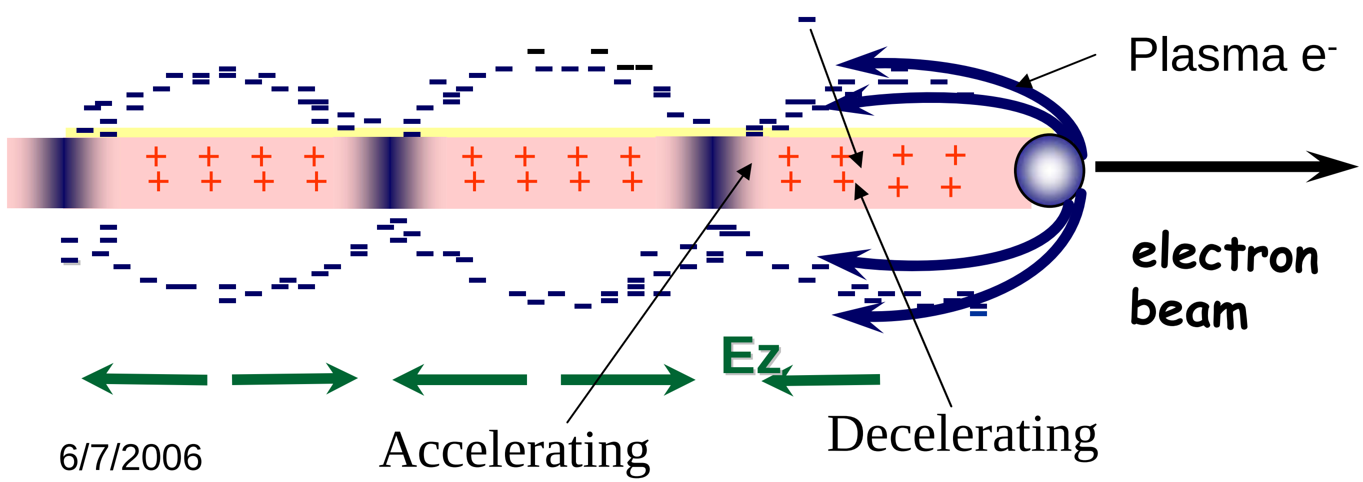
Plasma Acceleration

Motivation

- Accelerating gradients > 100 GeV/m have been measured in laser-plasma interactions
- The SLAC beams have unique properties – at various times during this experimental program we have had 30 GeV e^+ beams, 10^{20} W/cm^2 (42 GeV) e^- beams

Scientific questions

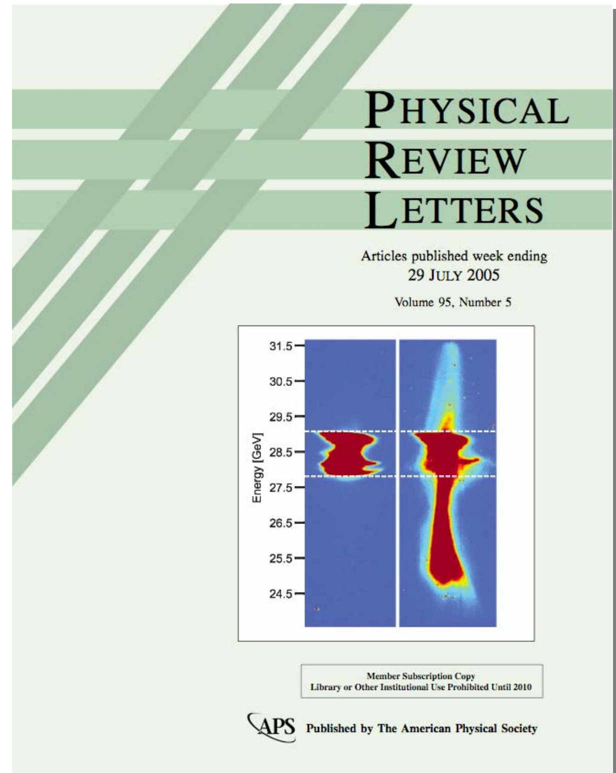
- Can one make & sustain such high gradients for lengths that give significant energy gain?
- Explore beam-plasma physics is a completely new parameter regime.



$$E_z \sim \frac{N}{\sigma_z^2}$$

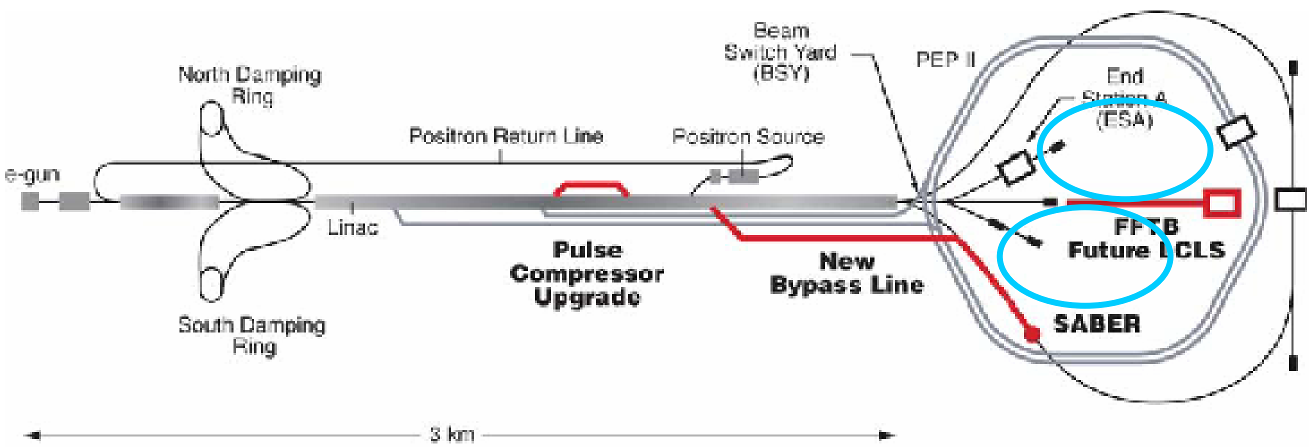
Plasma Acceleration

Recent results:
$\Delta E > 2.7$ GeV in 10 cm of plasma
$\Delta E > 10$ GeV in 30 cm of plasma
E167, April 2006: $\Delta E > 30$ GeV
in 90 cm of plasma



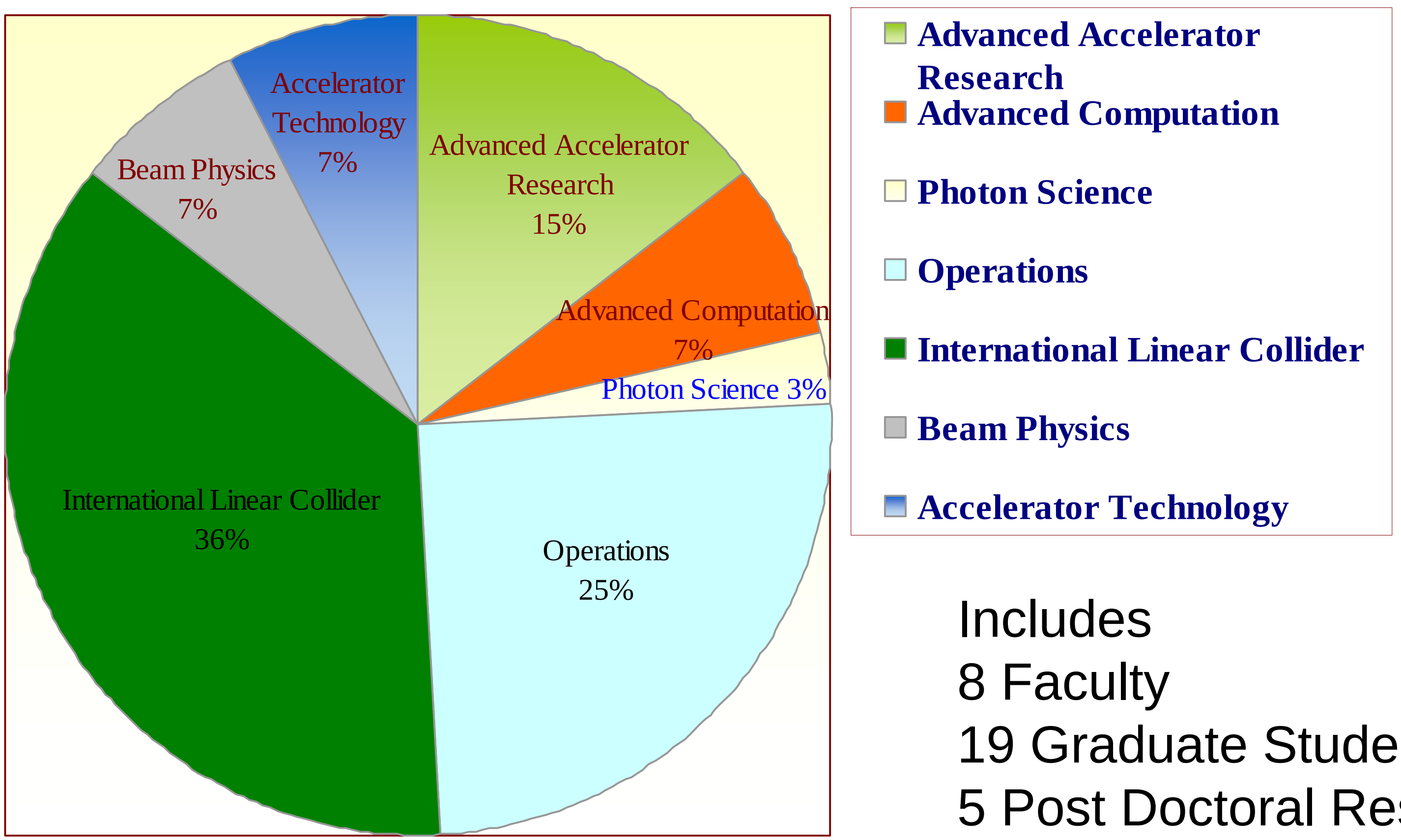
This research was performed in the FFTB, which has now been decommissioned for LCLS

- This is a frontier of advanced accelerator and beam-plasma physics
- It will continue at SABER



Accelerator Research in Context (Dec 2005 Survey)

- SLAC—1500 staff, 3000 users (HEP + Photon Science)
  - Accelerator Physics-HEP— around 100 scientists (Including



Includes
8 Faculty
19 Graduate Students
5 Post Doctoral Research Associates

Accelerator Research at SLAC

- Push the envelope of operating accelerators
  - PEP-II + flavor factories world wide—all operating facilities
- Study Beam Physics and develop Accelerator Technology and for next generation facilities.
  - ILC
  - Future Multi-TeV Linear Colliders—High Gradient Research
- Push the state of the art in computational tools
  - To bridge the gap between theory and technology
- Explore Advanced Accelerator Research
  - Laser Acceleration
  - Plasma Acceleration
- Exploit unique facilities for Accelerator Research
  - Final Focus Test Beam (FFTB & SABER)
  - NLC Test Accelerator (NLCTA)