Accelerator Research Program

Sami Tantawi

DoE Annual Review

June 12, 2007

Accelerator Science and Technology at SLAC

Accelerators and accelerator science permeate SLAC

- SLAC accelerator science drivers:
  - The Frontier of Particle Physics.
  - The Frontier of Photon Science
- Incorporates:
  - Improvement of existing accelerators
  - Development of new accelerators
  - Development of new accelerator science and technology
- Organization-management: accelerator science is spread out widely:
  - PEP II operations, SPEAR operations
  - LCLS and ILC
  - Accelerator Research Departments
  - Klystron Dept., Surface & Material Science Dept.
- Accelerator physics perspective:
  - Intellectual commonality
  - Technical commonality
  - Among <u>all</u> these activities: short term, long term, specific or generic

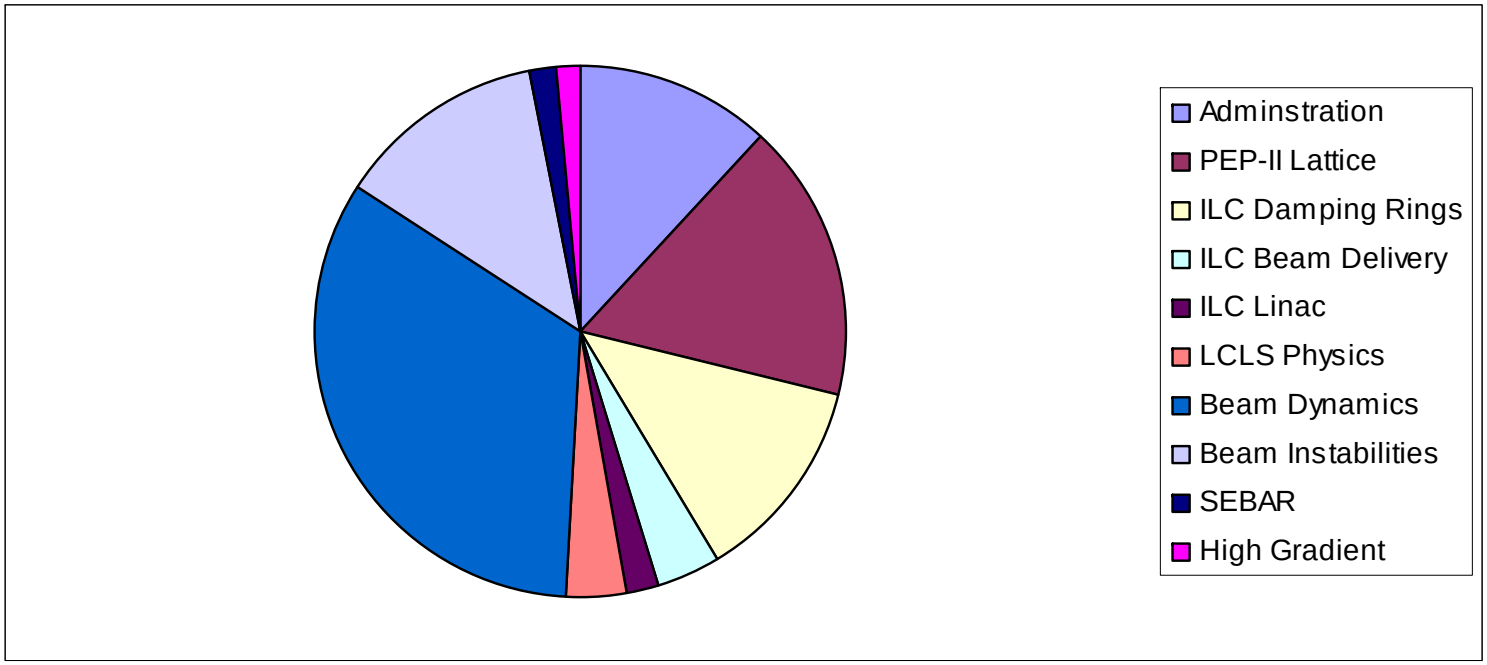
Look in more detail at part of this - Accelerator Research, Activities:

- 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)

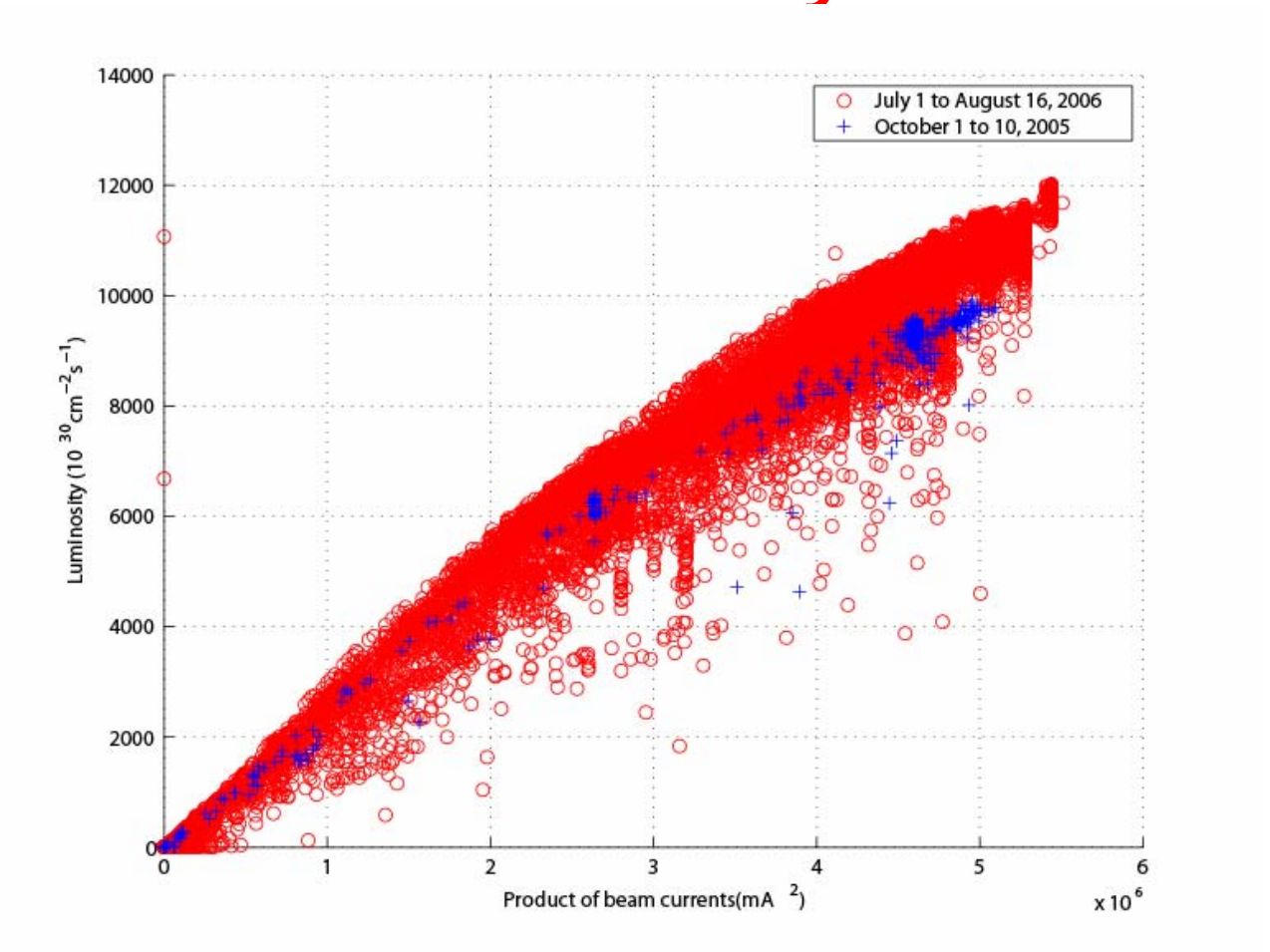
For 2007-2007 year 67 published papers among them 16 in peer-reviewed journals

Accounts Charged for the Activities



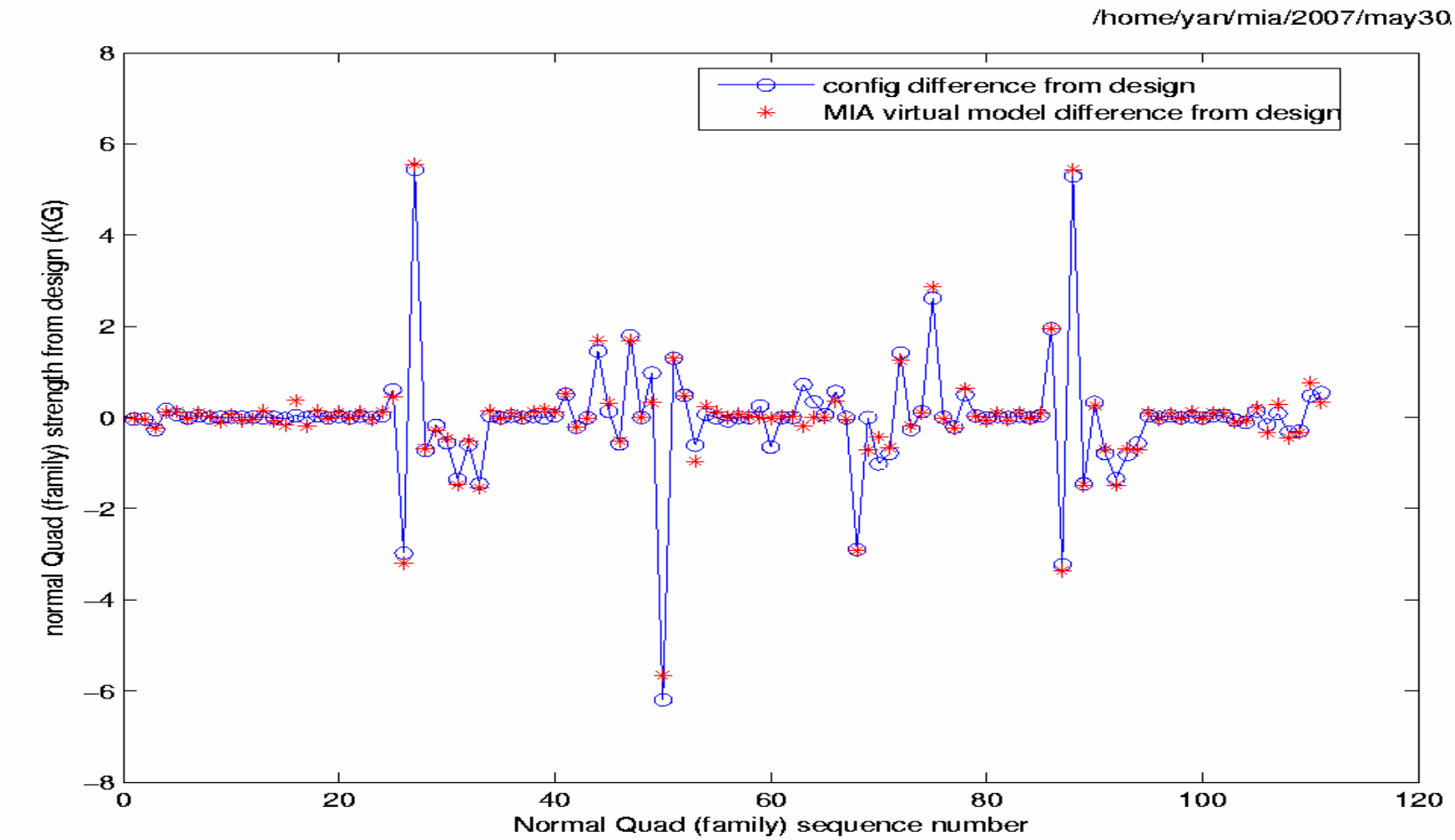
- ~50% accelerator research: beam dynamics and instabilities, FEL physics
- ~50% program support: PEP-II, ILC, LCLS, SEBAR

Improvement of Machine Optics and Luminosity for PEP-II



Achieved peak luminosity: $1.2 \times 10^{34} cm^{-2} s^{-1}$, August 15, 2006

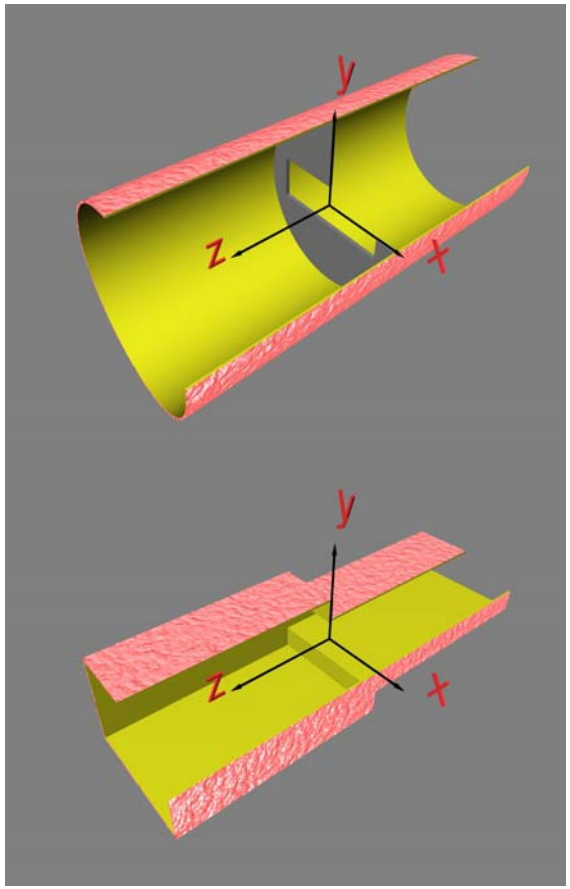
Developed Accurate Online and Offline Models

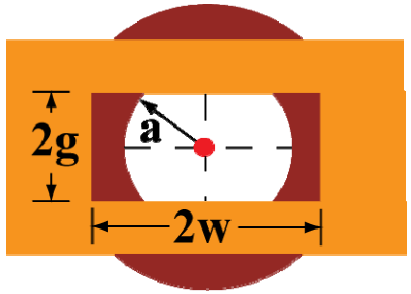


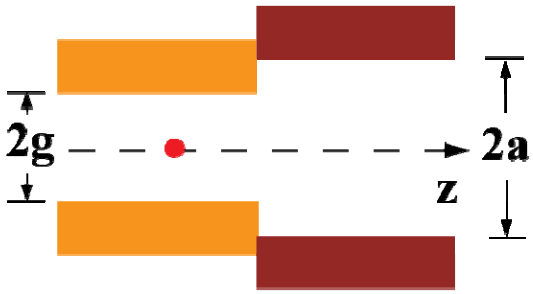
Comparison of quadrupole strength between LER model and configuration, May 30, 2007

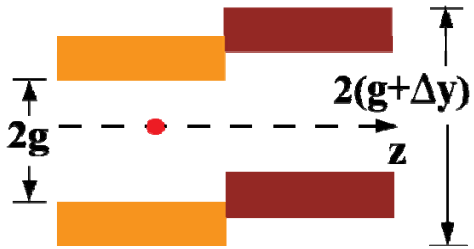
HIGH FREQUENCY IMPEDANCE CALCULATIONS

A theory of high frequency impedance is developed for various non-axisymmetric geometries such as irises/short collimators in a beam pipe, step-in transitions, step-out transitions, and more complicated transitions of practical Importance [PRSTAB 10, 054401 (2007)].

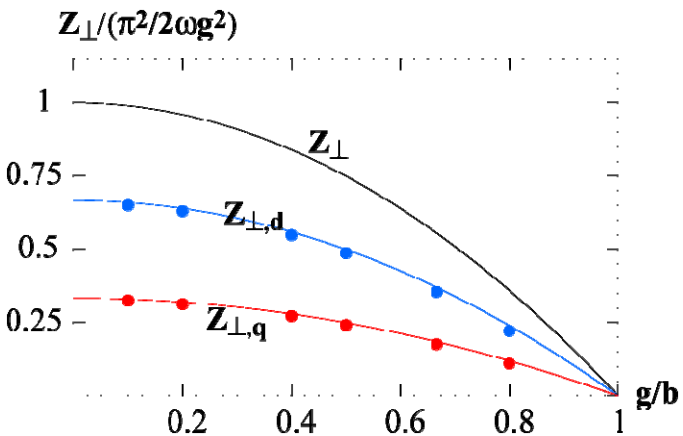




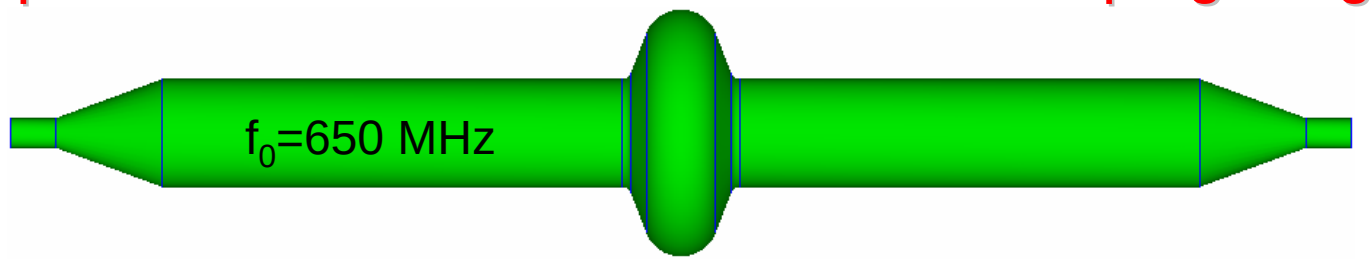




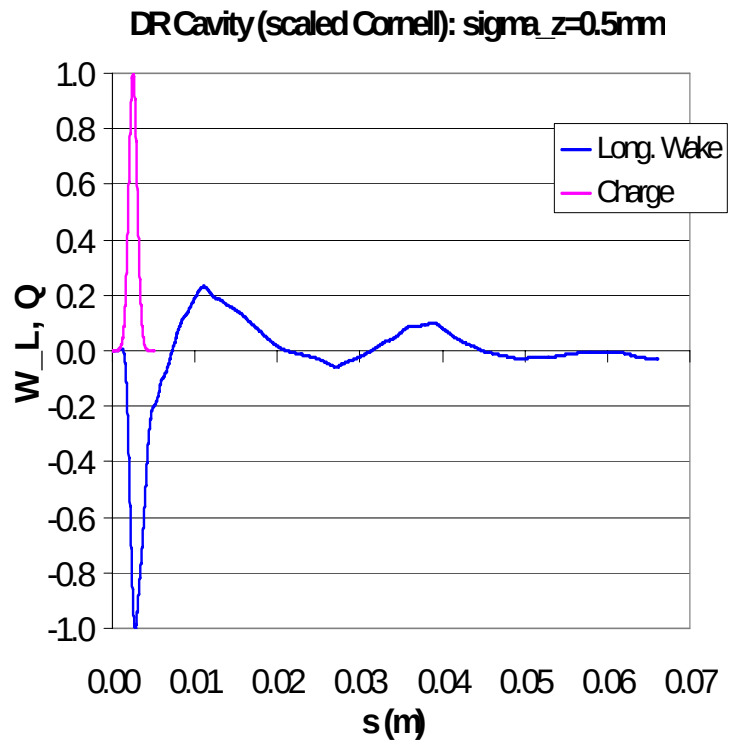
For a flat iris with aperture 2*g* in a flat beam pipe of aperture 2*b*, the transverse impedances as functions of *g/b*.



Impedance & Instabilities in the ILC Damping Rings



- A working group from several departments: PBD, ACD, ASD
- Develop an impedance model and estimate threshold of instabilities, in particular, microwave instability, which may has impact of choice of momentum compaction factor for the damping rings.

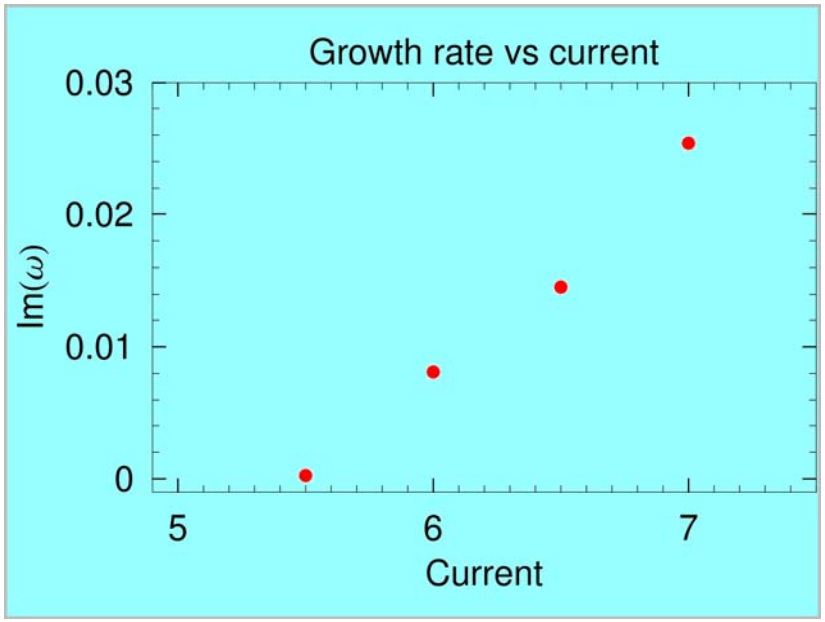


ABCI

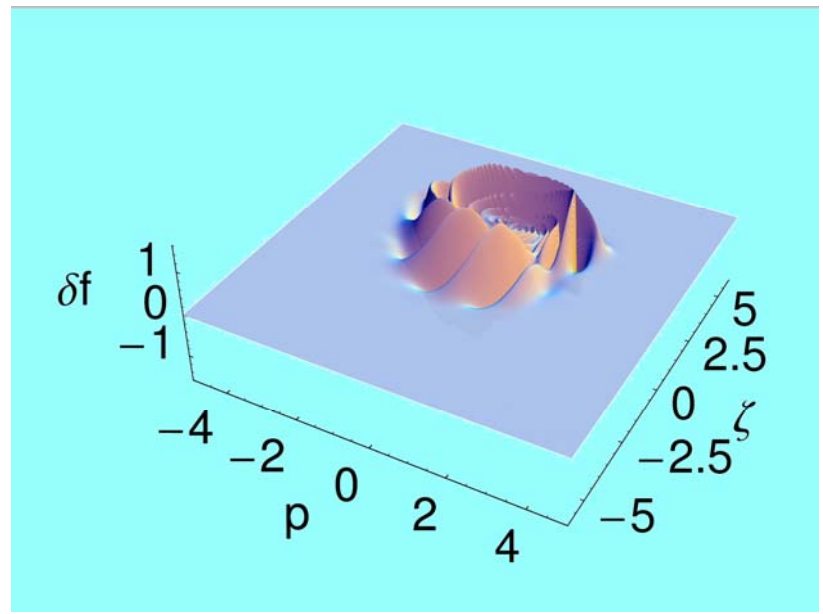
Scale = 22.05 V/pC
Loss Factor = 16.17 V/pC

MICROWAY INSTABILITY STUDIES FOR THE ILC DR

A new computer code is developed that solves a linearized Vlasov equation in the time domain. The code is implemented in Mathematica; it can be easily modified and augmented.



Growth rate for the CSR induced microwave instability as a function of current.



Phase space of the microwave instability.

Optimization of ILC Main Linac RF Distribution System

- For one overall P and individual Q adjustments, the optimized solution has $q = Q/Q_0$ (Q_0 is the matched loaded Q) mostly in the range [1, 2]

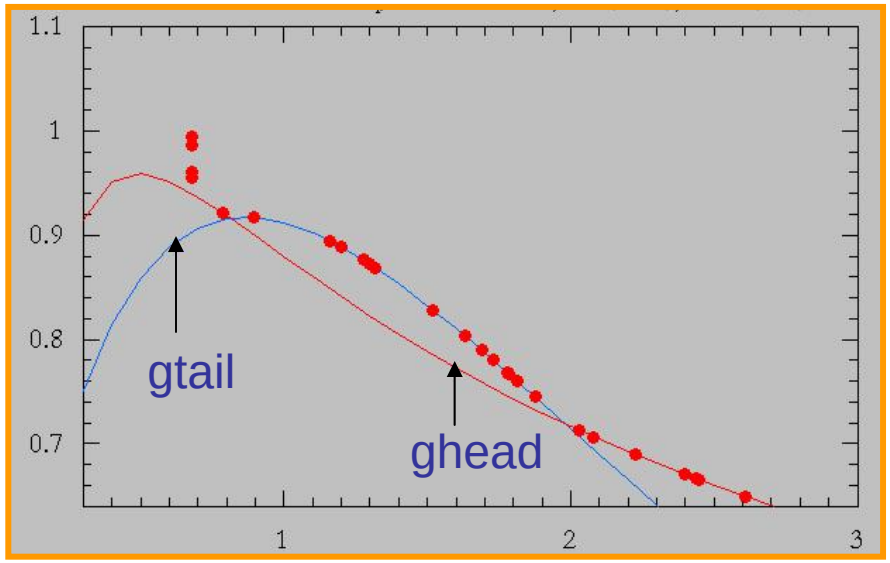
- Optimize gradient of the 26 cavities Σg_i (while keeping boundary conditions) where

$$g_i = 2\sqrt{p q_i}\left(1 - e^{-t/q_i}\right) - q_i\left(1 - e^{-(t - t_b \ln 2)/q_i}\right), \qquad [t > t_b \ln 2]$$

- 27d optimization $\{q_i, t_b\}$, can be turned into 3d optimization $\{p, t_b, q_{min}\}$:

For $p = 0.92$, $t_b = 0.89$, gradient at head and tail of train

$g = G/G_0$



$q = Q/Q_0$

- One seed

- Red dots give $(g_{lim})_i$

Advanced Accelerator Research Department At-a-glance (Bob Siemann. Dept Head)

Who We Are

1 Faculty member
4 Staff physicists
1 Postdoctoral Associate
4 Graduate students
1 administrative assistant

What we do

Experimental investigation of novel concepts for high-gradient particle acceleration:

- Beam-driven plasma acceleration
- Laser-driven dielectric accelerator structures

Publications:

40 since May 2006:
* 6 Refereed papers (3 *Phys. Rev*., 1 *Nature*, 1 *Med. Phys*., 1 *Eur. Phys. J.*)
* 34 Conference papers

Graduate Theses since May 2006

•**Ben Cowan**, Ph.D., Stanford, "PHOTONIC CRYSTAL LASER-DRIVEN ACCELERATOR STRUCTURES", March 2007.

Service since May 2006

• Editor of *Physical Review Special Topics -- AB*
• Technical review committees for Tevatron, SNS
• Reviews of LBNL, BNL, Muon Collider
• SBIR and HEP grant reviews
• Injector Test Facility Task Force Co-chair
• Panofsky Fellowship Committee
• DPB Executive and Education Committees
• Conference session conveners/group leaders for AAC, APS, and DPF
• Conference Committees for AAC, APS, DPF, PAC
• SLAC Liaison to local city government; local science fair judging…

Refereed Publications since May 2006

Published

- T. Li, *et al,* “Four-Dimensional Cone-Beam Computed Tomography Using an On-Board Imager”, Med. Phys. **33**, 3825 (2006)
- D.K. Johnson, *et al,* “Positron Production by X Rays Emitted by Betatron Motion in a Plasma Wiggler”, Physical Review Letters, **97**, 175003 (2006)
- C.L. O’Connell, *et al,* “Plasma Production via Field Ionization”, Physical Review Special Topics – Accelerators and Beams, **9**, 101301 (2006)
- I. Blumenfeld, *et al,* “Energy Doubling of 42 GeV Electrons in a Meter Scale Plasma Wakefield Accelerator”, Nature, **445**, 741 (2007)
- E. Oz, *et al,* “Ionization Induced Electron Trapping in Ultra-relativistic Plasma Wakes”, Physical Review Letters, **98,** 084801 (2007)
- V. Ayvazyan *et al,* “First operation of a free-electron laser generating GW power radiation at 32 nm wavelength”, European Physical Journal D, **vol. 37,** nb. 2, 297 (2006).

In Preparation

- C. D. Barnes, *et al*, “Measuring Ultra-Short Beams at SLAC”, Physical Review Special Topics – Accelerators and Beams, in preparation.
- B. Cowan, *et al*, "Dielectric photonic crystal accelerator structure based on a three-dimensional lattice“, Physical Review Special Topics – Accelerators and Beams, in preparation.

Community Service Since May 2006

Eric Colby

APS-DPB Executive Committee Member-at-large
2006 Advanced Accelerator Concepts Workshop Organizing Committee Member and Working Group Leader
2007 Particle Accelerator Conference Program Committee Member
2007 Director's Review of LBNL Accelerator & Fusion Research Department
DOE SBIR Proposal Reviewer, 2001 – present
DOE HENP Grant Renewal Reviewer, 2001 – present
PRST-AB, IEEE Trans. Plasma Science, PRE, and Physics of Plasmas paper referee
LCLS Gun Test Facility Task Force Co-leader, 2006 – present
Panofsky Fellowship Selection Committee Member, 2006
Member, Accelerator Research Associate Committee, PPA Division
Member, DOE Office of Independent Oversight Action Item C-2 Response Committee

Mark Hogan

2006/2007 Technical Consultant for the DOE Review of the BNL HEP Program
2008 Advanced Accelerator Concepts Workshop Organizing Committee Member
Physical Review, Physical Review Letters, and Physics of Plasma paper referee
DOE SBIR Proposal Reviewer, 2006/2007
DOE Grant Proposal Reviewer, 2006/2007
2nd SABER Workshop Organizing Committee Member

Rasmus Ischebeck

2006 Advanced Accelerator Concepts Workshop Organizing Committee Member and Working Group Leader
LCLS Design Reviewer, 2006

Robert Noble

Chair, Accelerator Research Associate Committee, PPA Division
Referee for *Physics of Plasma* Journal

Stephanie Santo

Assistant to the Editor, *Physical Review Special Topics - Accelerators and Beams*, 2003 – 2007
AARD Safety Committee Member, 2004 –

Robert Siemann

Founding Editor, *Physical Review Special Topics - Accelerators and Beams*, 1998 – 2007
Chair, Accelerator Systems Advisory Committee of the Spallation Neutron Source, 1998 – 2006
DOE Tevatron Operations Review, March 2006

James Spencer

DOE SBIR Proposal Reviewer, 2006
Physical Review and Physical Review Letters paper referee
Member, ARD Research Associate Committee
Judge, Santa Cruz County and Santa Clara Science Fairs
Member, Accelerator Research Associate Committee, PPA Division
Member, ETF Committee that assessed SLAC's commitment to education and outreach with the idea of proposing a broader, more unified program
Member, SULI selection committee

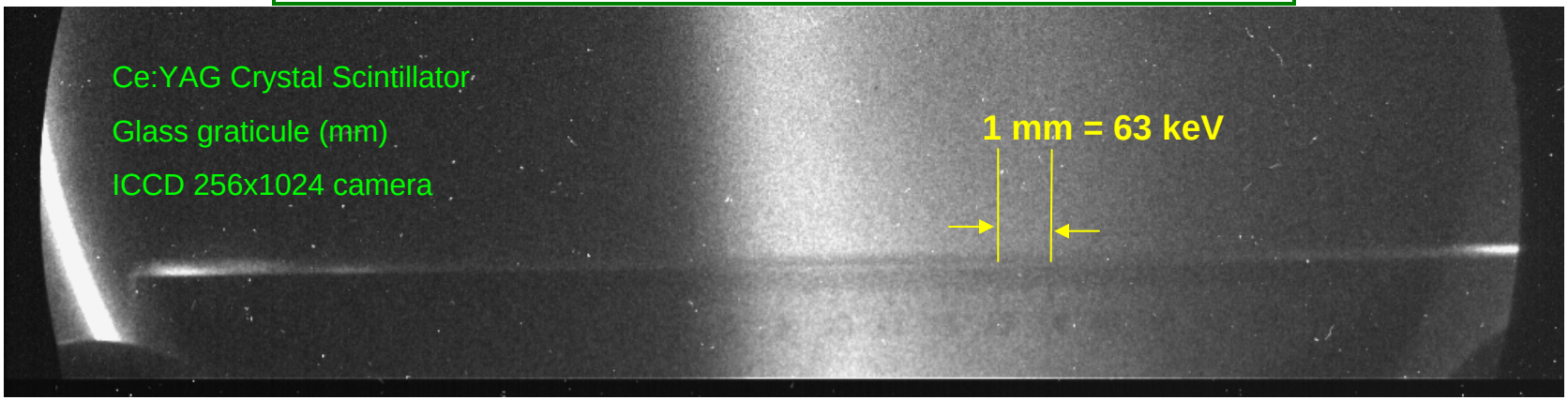
E-163: Laser Acceleration at the NLCTA

E-163 Scientific Goal: Investigate physical and technical issues of laser acceleration using dielectric structures

Build a test facility with high-quality electron and laser beams for advanced accelerator R&D

- Test facility construction completed December 2006
- Accelerator Readiness Review completed December 18th, 2006
- Director's and DOE Site Office approval to begin operations granted March 1st, 2007
- E163 Beamline commissioning begun March 8th, 2007

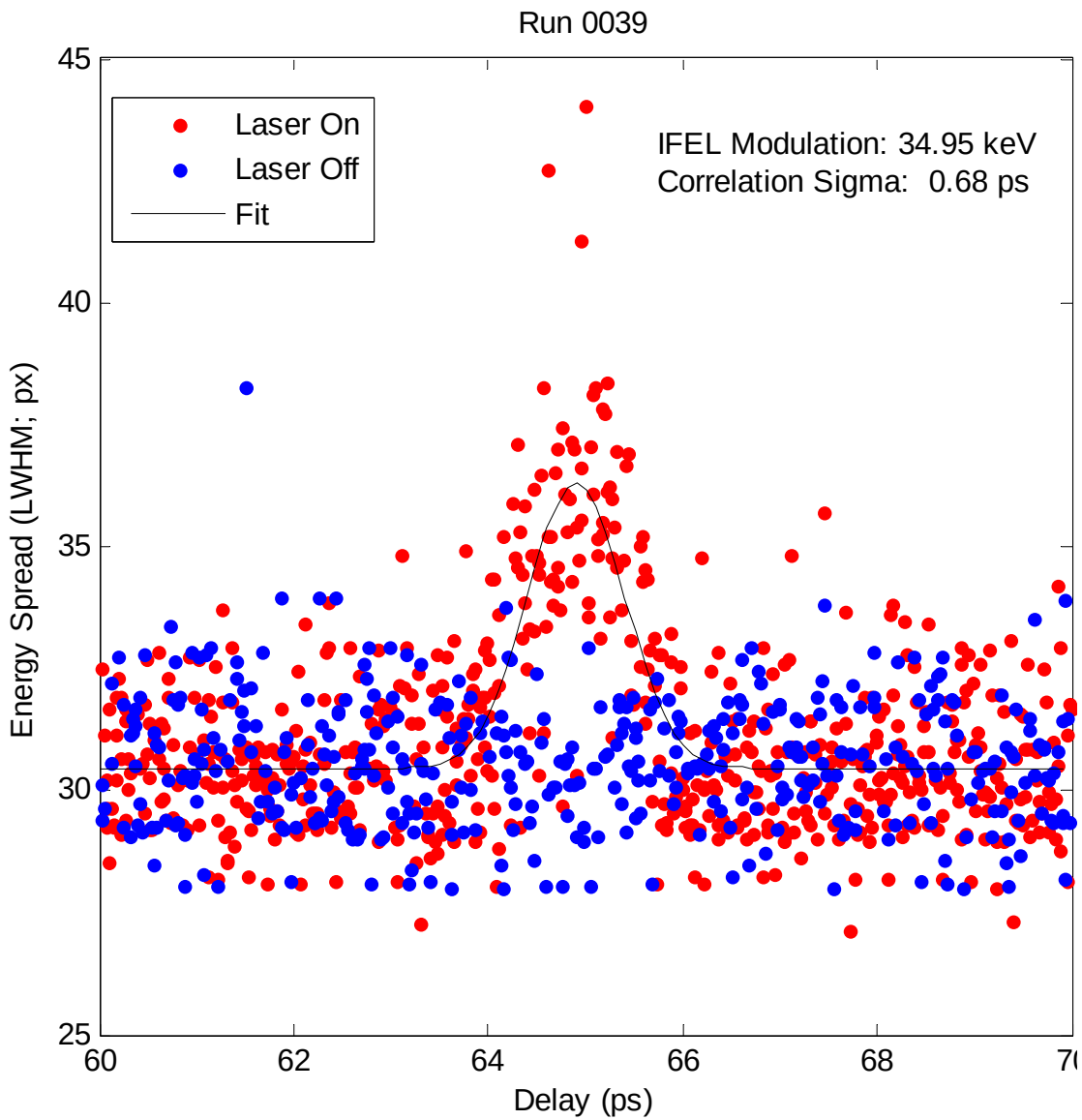
First beam to high resolution spectrometer of E163 beamline on March 16th, 2007!



Energy

Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC) and DE-FG03-97ER41043-II (LEAP).

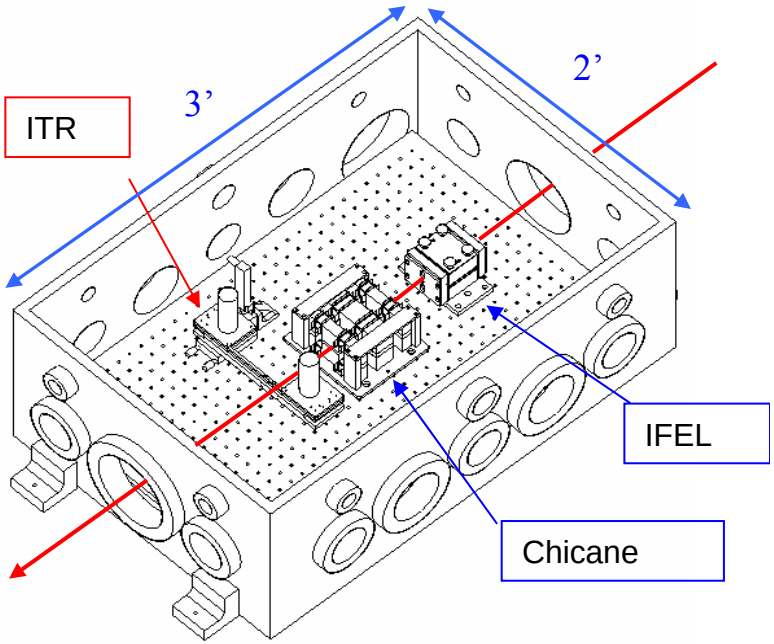
E-163: Laser Acceleration at the NLCTA



First Laser-Electron Interaction Signature observed on 5/23/07!

➔35 keV modulation from IFEL clearly visible

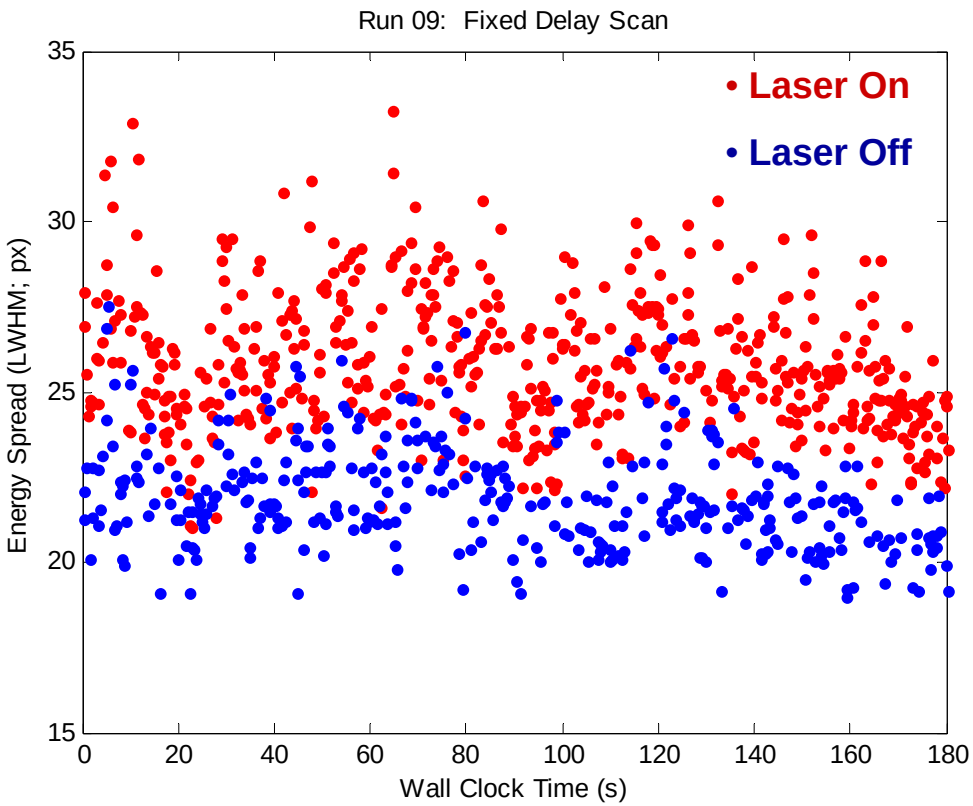
➔ Duration (Γ=1.6 ps) shows stability of electron & laser beams



Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC) and DE-FG03-97ER41043-II (LEAP).

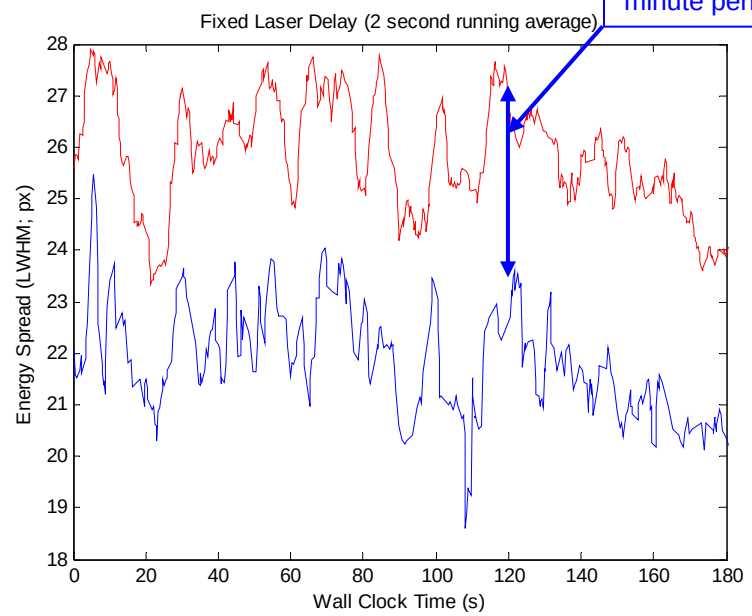
E-163: Laser Acceleration at the NLCTA

Timing Stability Demonstration



IFEL interaction, set to maximum of interaction.

Interaction Strength remains essentially constant over 3 minute period

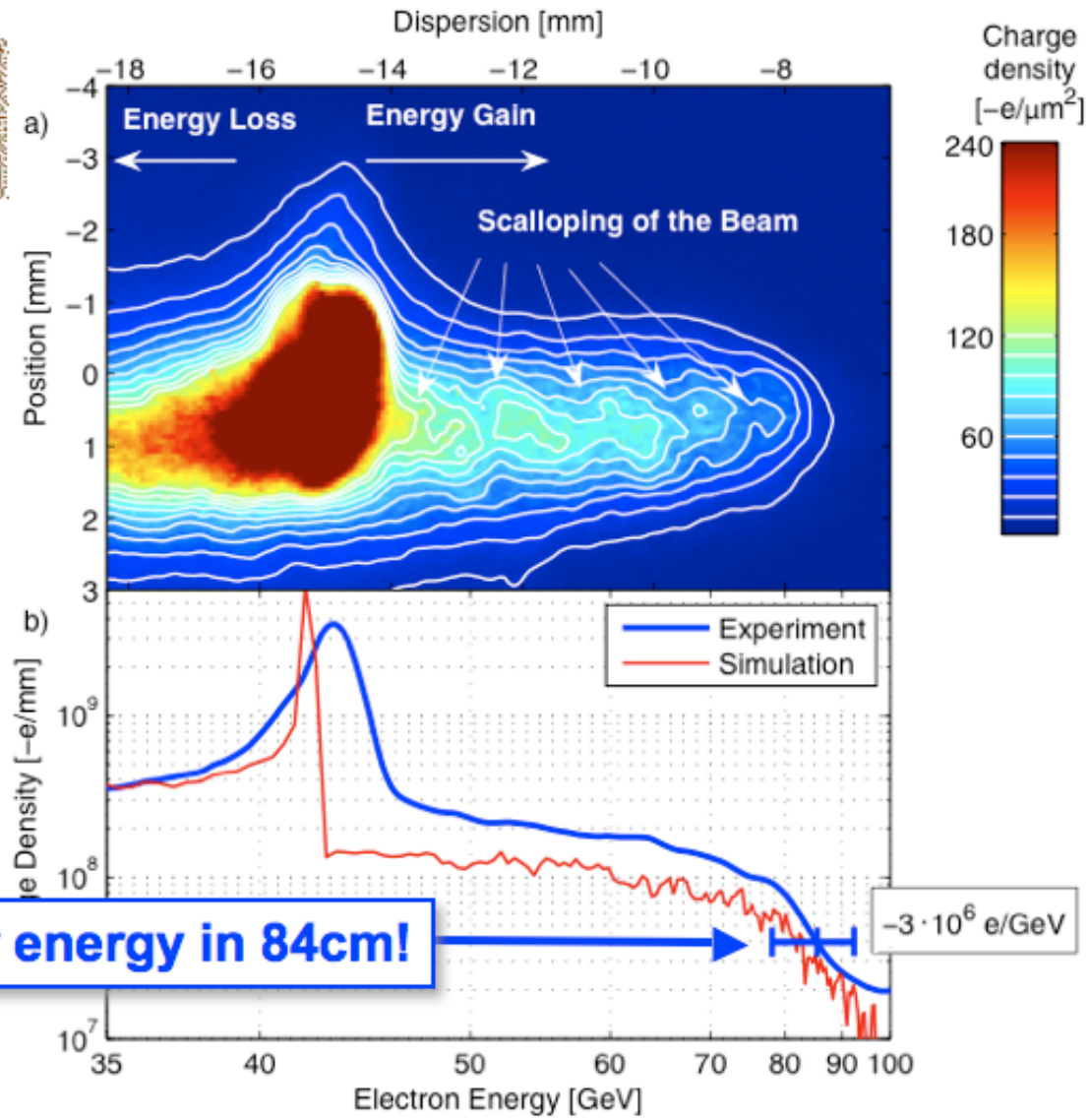


The sub-picosecond timing stability required for laser acceleration experiments has been demonstrated!

Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC) and DE-FG03-97ER41043-II (LEAP).

E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB

- Linac running all out to deliver compressed 42GeV Electron Bunches to the plasma
- Record Energy Gain
- Highest Energy Electrons Ever Produced @ SLAC
- Significant Advance in Demonstrating Potential of Plasma Accelerators



Some electrons double their energy in 84cm!

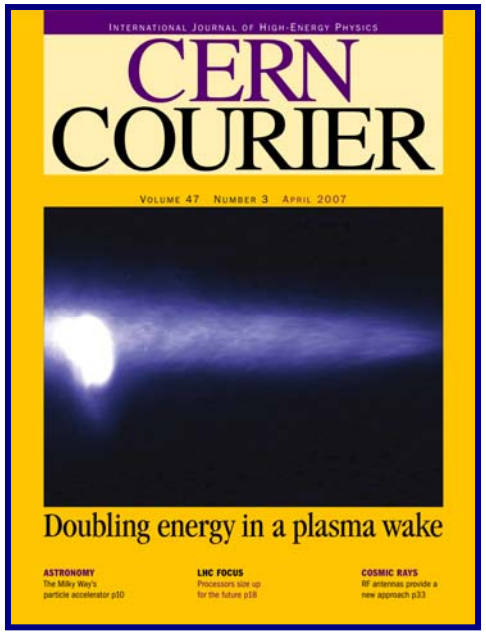
Nature 445 741 15-Feb-2007

Advanced Accelerator Research Department

We are focused on challenging technologies that offer unique capabilities as accelerators

Beam Driven-Plasma Wakes

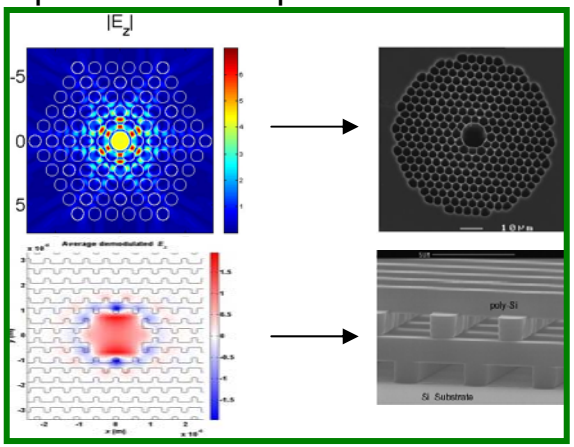
- Extraordinary gradient
- New Regimes of Beam/Matter Interaction
- THz Generation



We combine analytical, computational, and experimental skills to perform interdisciplinary, collaborative research in accelerator physics, plasma physics, and laser science. These diverse aspects make Advanced Accelerator R&D very attractive to students.

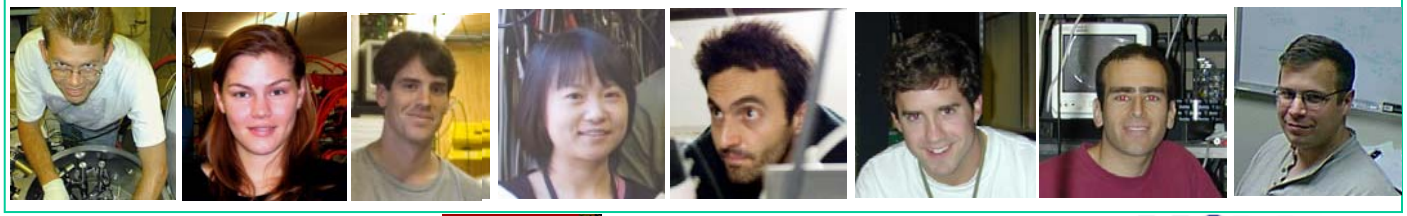
Dielectric Laser-Driven Accelerators

- High Gradient · Photonic Crystals
- Attosecond pulses
- Unparalleled compactness



Current Students

Some of the AARD Alumni since 2003



USC Stanford University UCLA

Advanced Computations Department (Cho Ng, Acting Dept Head)

ACD will continue to play a major role in DOE computing initiative Scientific Discovery through Advanced Computing ***(SciDAC)*** *new Community Petascale Project for Accelerator Science and Simulation (COMPASS) project.*

Focuses on:

- ***Parallel code development*** *in electromagnetics and beam dynamics for accelerator design, optimization and analysis*
- ***Application to HEP accelerator projects*** *such as the International Linear Collider (ILC), LHC, PEP-II, etc…*
- ***Large-scale parallel simulations*** *on DOE's supercomputers at NERSC (Seaborg, Bassi) and NCCS (Phoenix) with 3 allocation awards and* ***petascale simulations*** *in* ***SciDAC****2*
- ***Computational science research*** *through collaborations with SciDAC CET's computer scientists and applied mathematicians*
- ***Multi-disciplinary education and training*** *of next generation computational scientists (PhD and summer students, USPAS,…)*

SciDAC Tools for Accelerator Applications

ILC - *The suite of codes (*Omega3P, S3P, T3P, Track3P, GUN3P*) is being applied to the ILC R&D using flagship computers at NERSC and NCCS:*

- ***Accelerating Cavity (DESY, KEK, JLab)***
  – TDR, Low-loss, ICHIRO & Superstructure designs
- ***Input Coupler (SLAC, LLNL)*** *– TTFIII multipacting studies*
- ***Crab Crossing (FNAL/UK)*** *- Deflecting cavity design*
- ***Damping RIng (LBNL)*** *– Impedance calculations*
- ***L-band Sheet Beam Klystron*** *– Gun and window modeling*

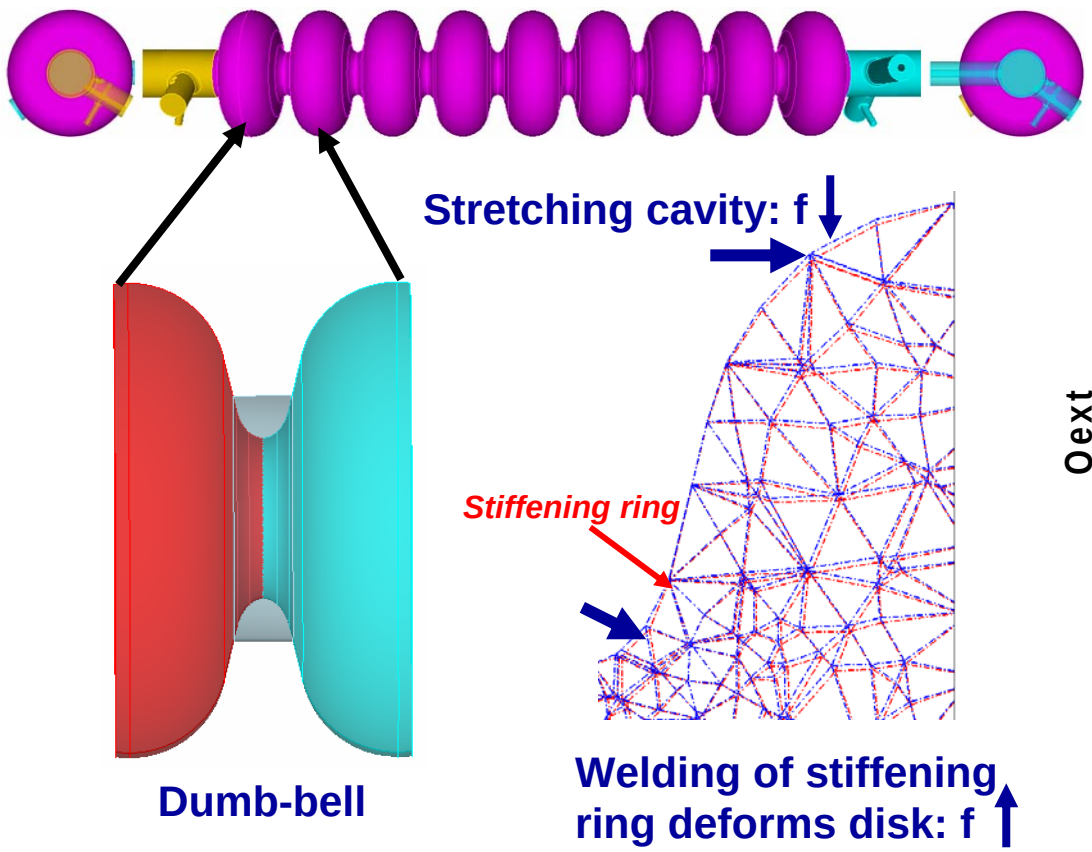
LHC – *Beam-beam effects*

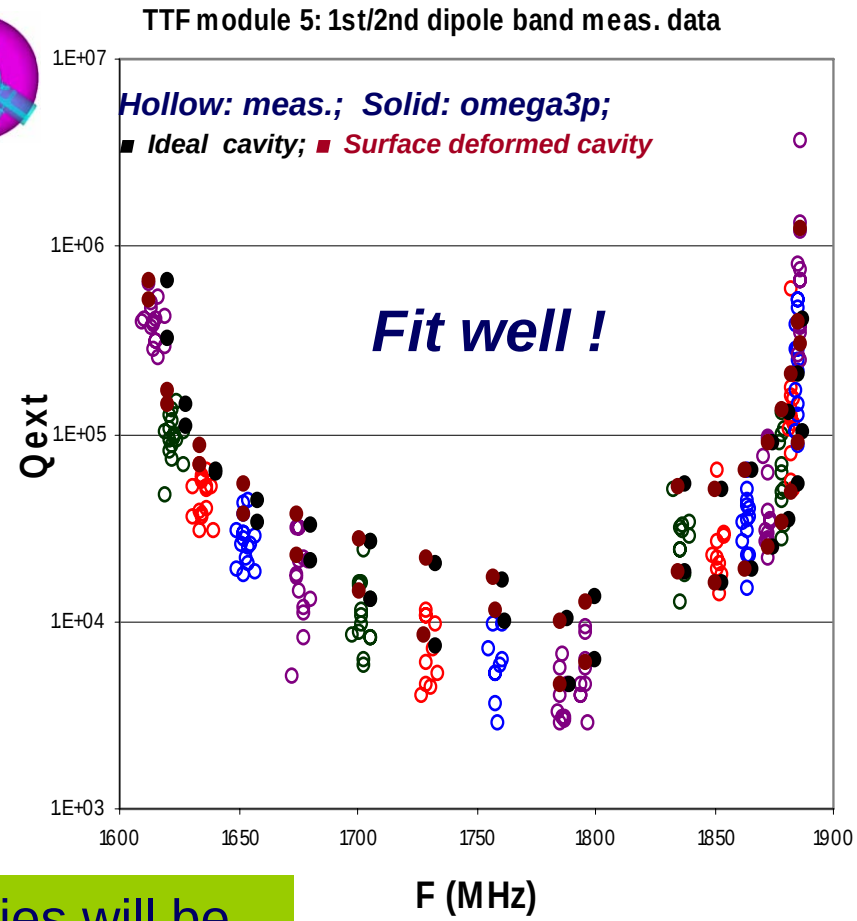
LCLS RF Gun – *Simulation using 2D FEM PIC code*

Support for other SLAC projects – *High gradient structure, photonic crystal accelerator, etc*

Imperfection Studies for TDR Cavity

- Frequency shift caused by fabrication errors and subsequent application of stiffening rings during the tuning process

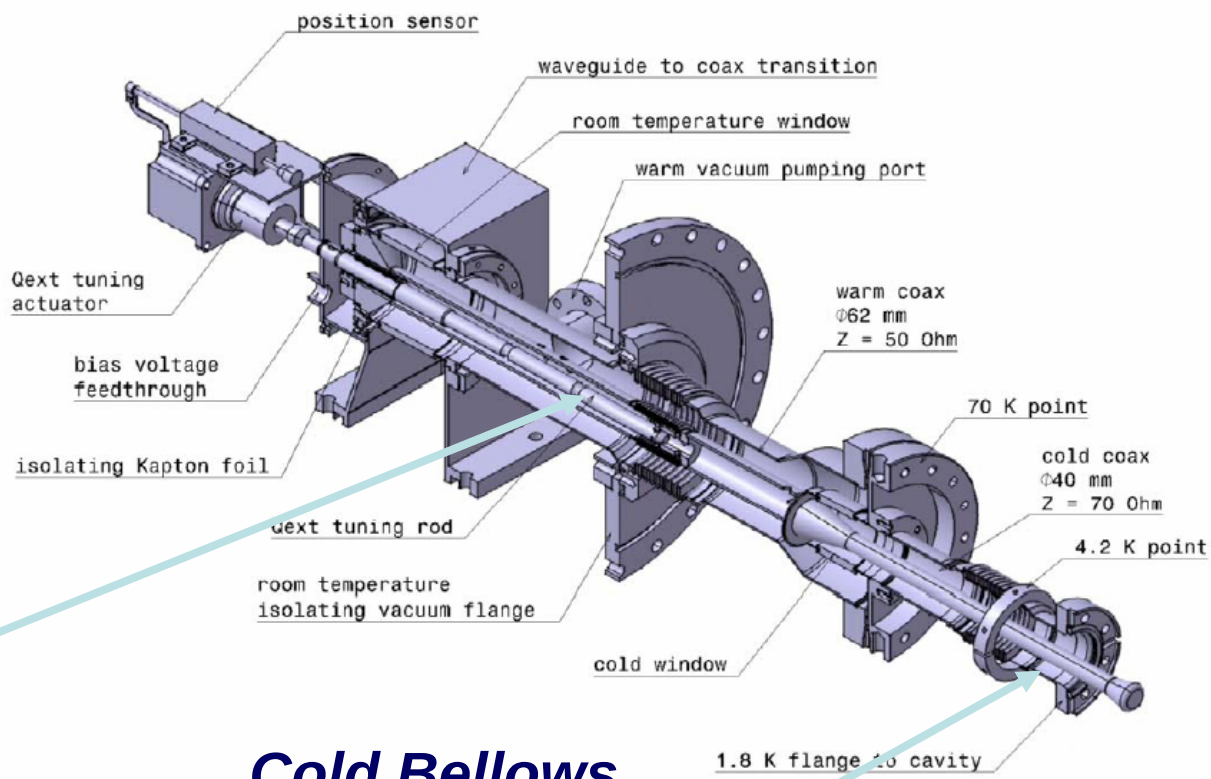




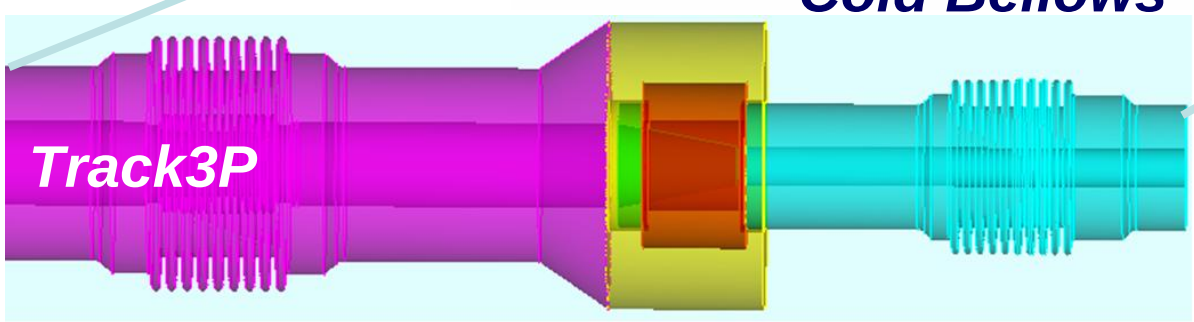
Wakefields from distorted cavities will be used for Lucretia beam dynamics studies

TTFIII Coupler – Multipacting Studies

MP simulations are carried out in support of ILC test stand at SLAC (LLNL) to study the cause of the TTFIII coupler's long processing time



Cold Bellows

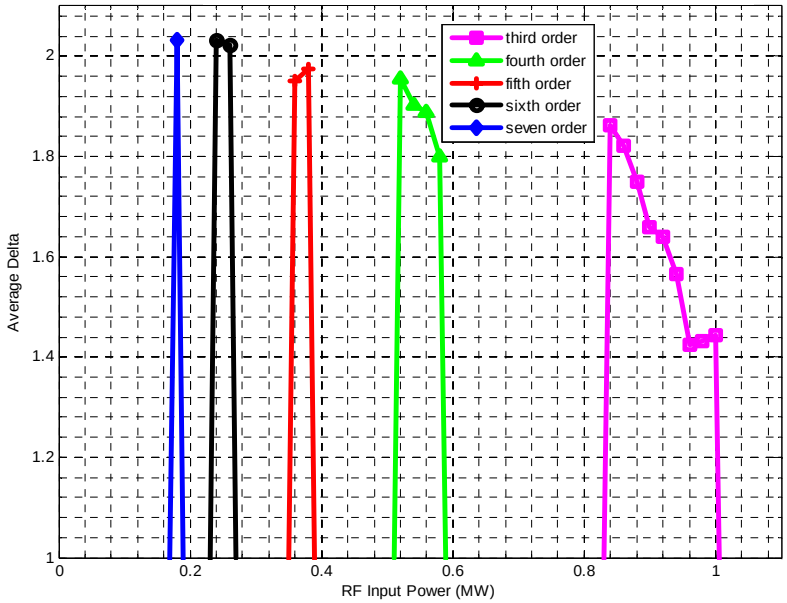


Multipacting in coax of TTFIII Coupler

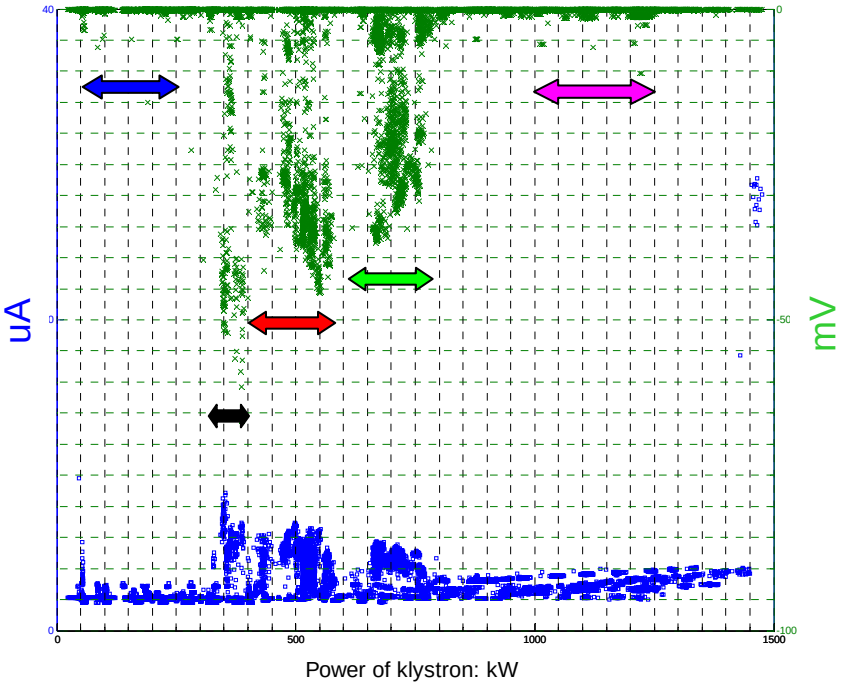
Cold coax

(F. Wang, C. Adolphsen, et. al)

Track3P Simulation



After high power processing

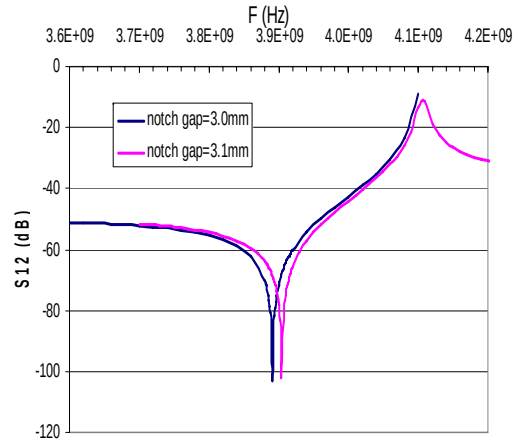


Simulation power (kW)	170~190	230~270	350~390	510~590	830~1000
Power in Coupler (kW)	43~170	280~340	340~490	530~660	850~1020
klystron power (kW)	50~200	330~400	400~580	620~780	1000~1200

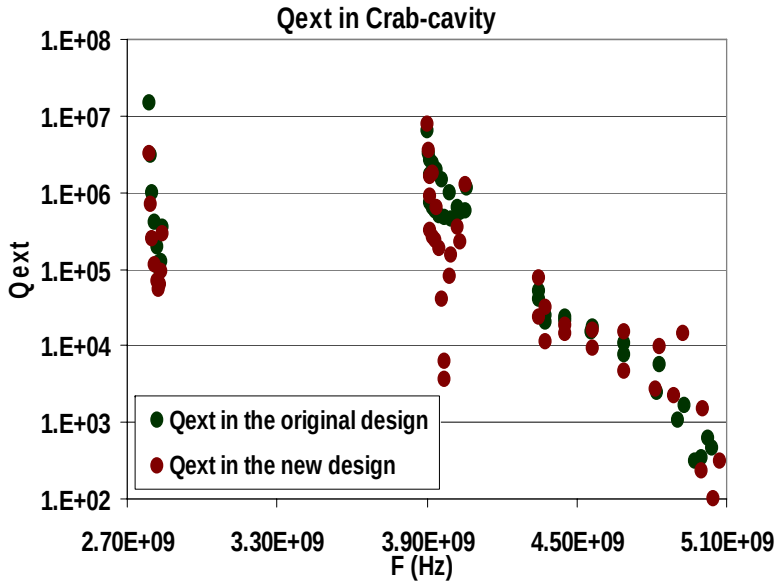
Crab Cavity Design for BDS

Improve FNAL design for:

- *Better HOM, LOM and SOM damping*
- *Reduction of HOM notch gap sensitivity (to 0.1 MHz/μm from original 1.6 MHz/μm)*
- *Elimination of LOM notch filter*
- *Elimination of SOM twist to avoid x-y coupling*

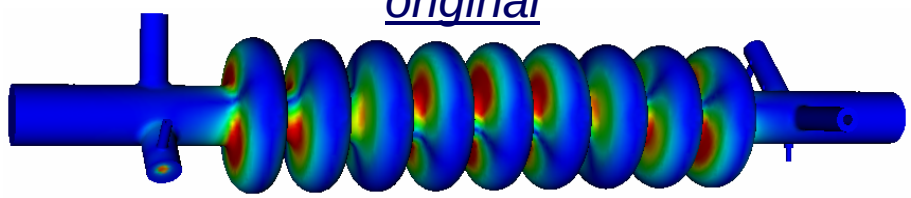


Notch gap sensitivity

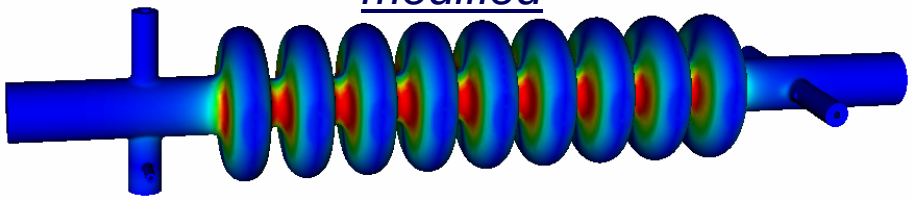


Omega3P damping calculation

original



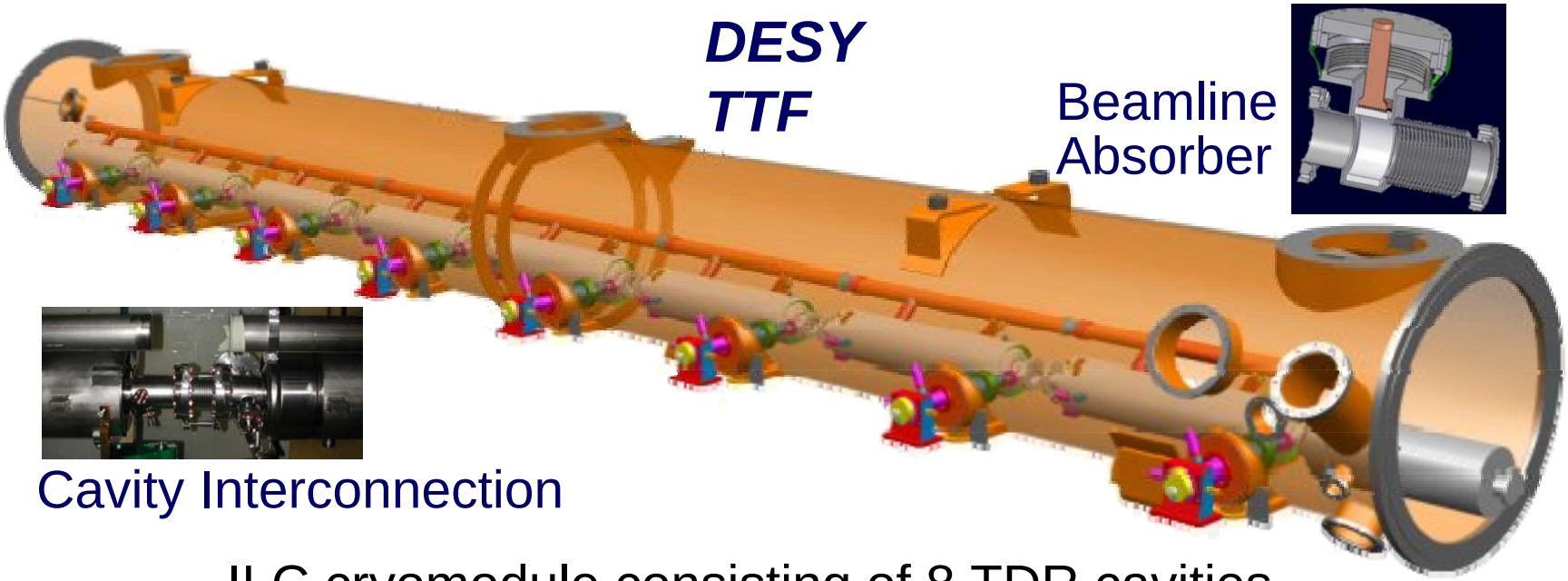
modified



Elimination of SOM twist

A copper model is being built in UK lab based on SLAC design.

Trapped modes in ILC cryomodule



ILC cryomodule consisting of 8 TDR cavities

A dipole mode from Omega3P

SciDAC2 *petascale computing required to model an entire rf unit consisting of 3 connected cryomodules*

Accelerator Technology Research (Sami Tantawi Dep. Head)

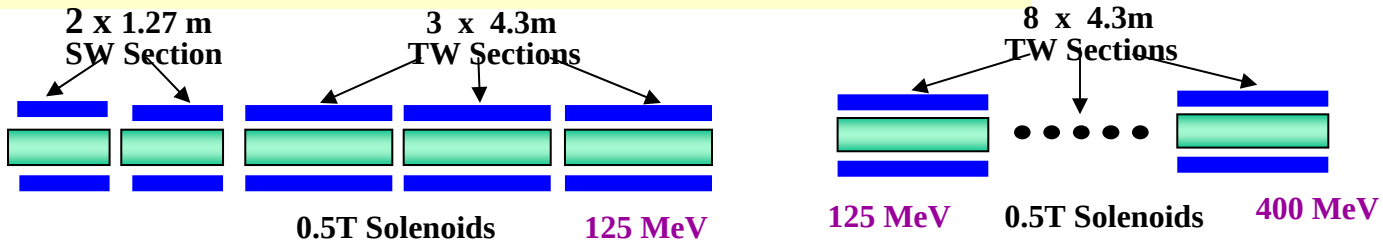
1 faculty member, 2 professor emeritus, 3 graduate students, 1 research associate, and 10 staff members. 25 publications since May 2006, 5 journal articles, 2 invited talks

- High Gradient Research:
  - *Host for the US Collaboration on High Gradient Research for Future Colliders*
  - Breakdown in rf structures: theoretical and experimental investigations.
  - Material Characterization, Geometrical Effects, Frequency scaling, Wake field damping.
  - High Frequency RF Source Developments.
  - Novel Accelerator structures, designs, manufacturing and characterization techniques.
  - New test setup for inexpensive, accurate characterization of High Power RF properties of materials.
- 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
  - 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 Bragg structures.
- Advanced Concepts for the ILC : fundamental mode couplers, RF distribution, 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)

•Studies on L-Band Normal Conducting Accelerating Structures for the ILC e^+ Source
•Tuning and Characterization of RF Gun for the Linac Coherent Light Source (LCLS)

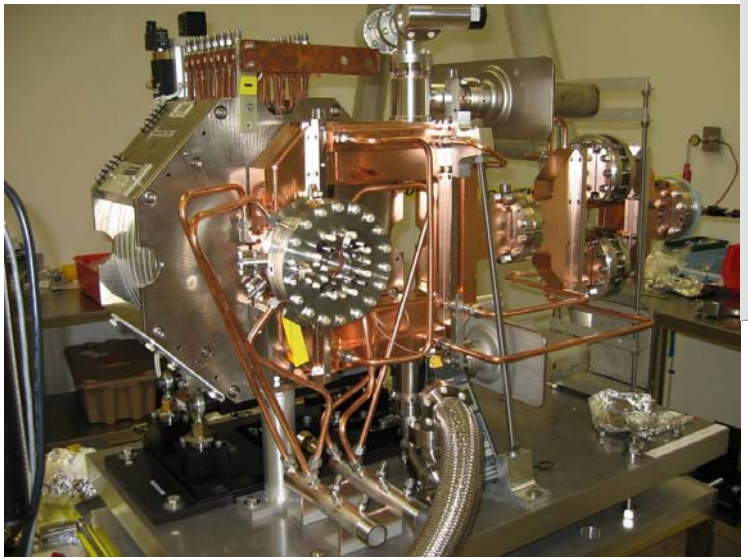
Proposed an Improved Alternative Structure Design for Positron Source with Mechanical Simplicity, Effective Cooling and Lower Pulsed Heating:

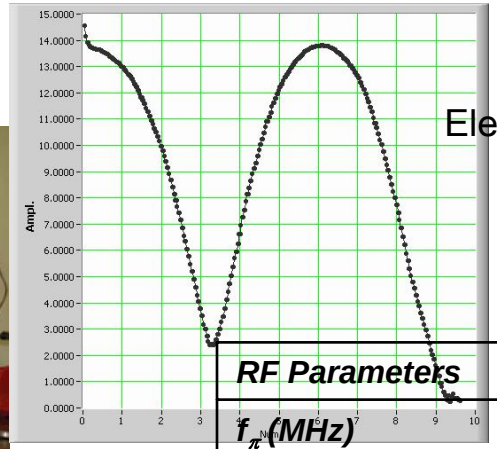
- Capture sections: Simple π mode short SW sections.
- Pre-Acceleration: High phase advance TW structures.



Welding Cooling System

LCLS Injector Gun





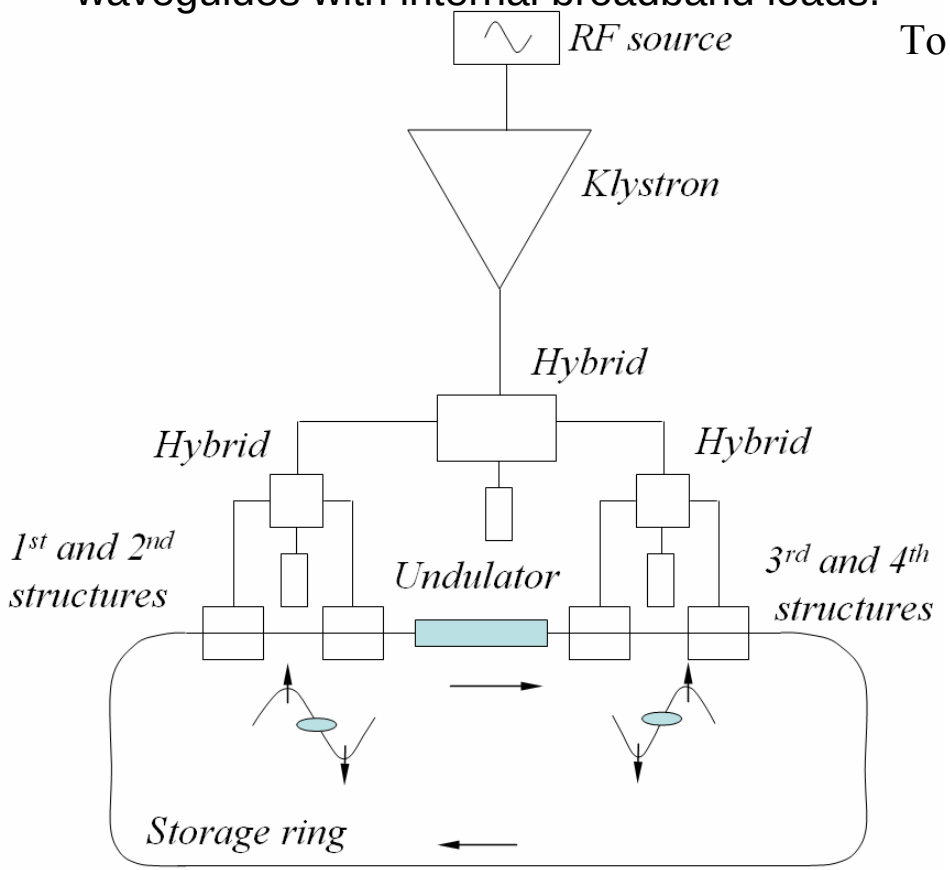
Electrical Field Distribution along Axis

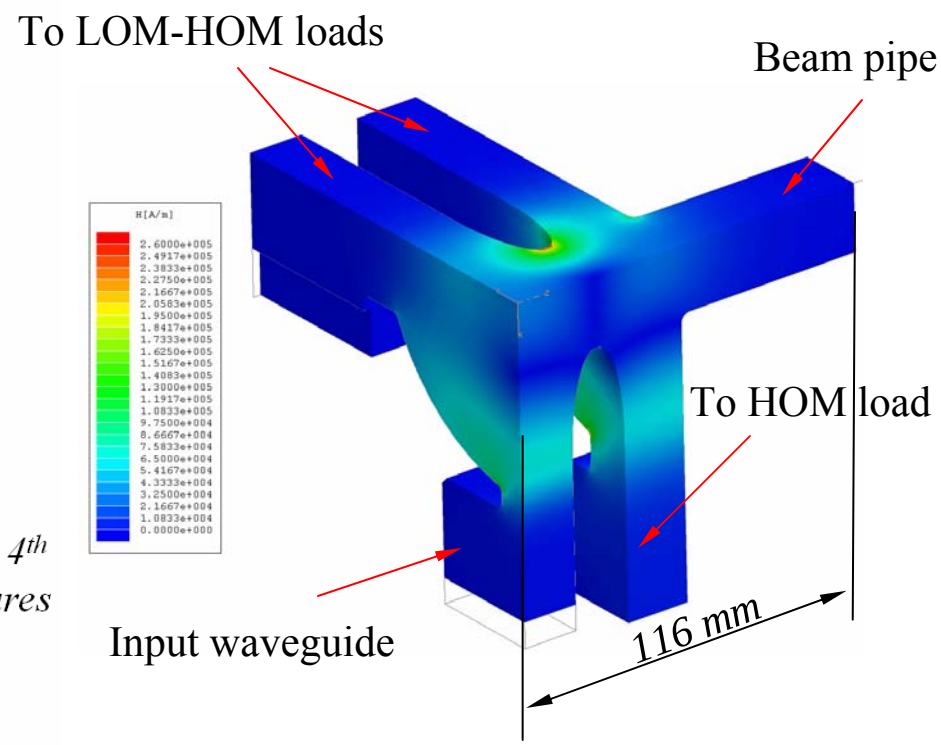
RF Parameters	Design	Measured
f_π (MHz)	2856 MHz at 35° C	2856 MHz at 36.2^O C
Q0	13960	14062
β	2.1	2.03
Mode Sep. Δf (MHz)	15	15.17
Field Balance	1	1

Design of S-band Standing Wave Deflector for Production of *ps* X-ray Pulses at Argonne APS

- Four structures will produce 4 MeV initial kick and 4 MeV recovery kick if powered by one
  20 MW klystron. Set of two structures will occupy less then 50 cm of beam space.
- Low-order- and high-order- modes are loaded by 6 ridged and 4 rectangular waveguides with internal broadband loads.

Frequency	2.815 GHz
Deflecting voltage	2 MV per structure
Available power	4 MW per structure
Repetition rate	~1000 Hz





Surface electric field for 2 MeV kick, maximum surface electric fields 60 MV/m

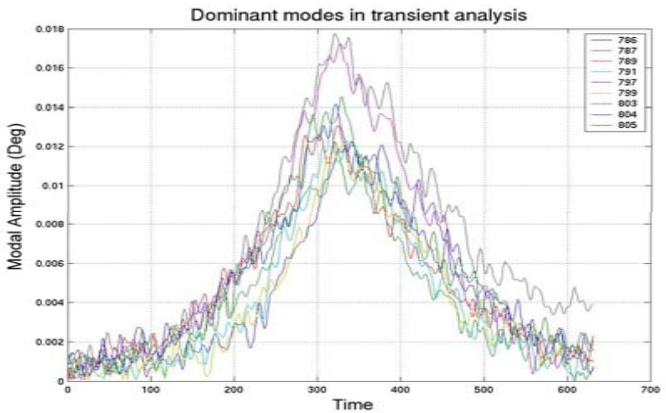
J

Electronics Research Group – Accelerator Technology Department

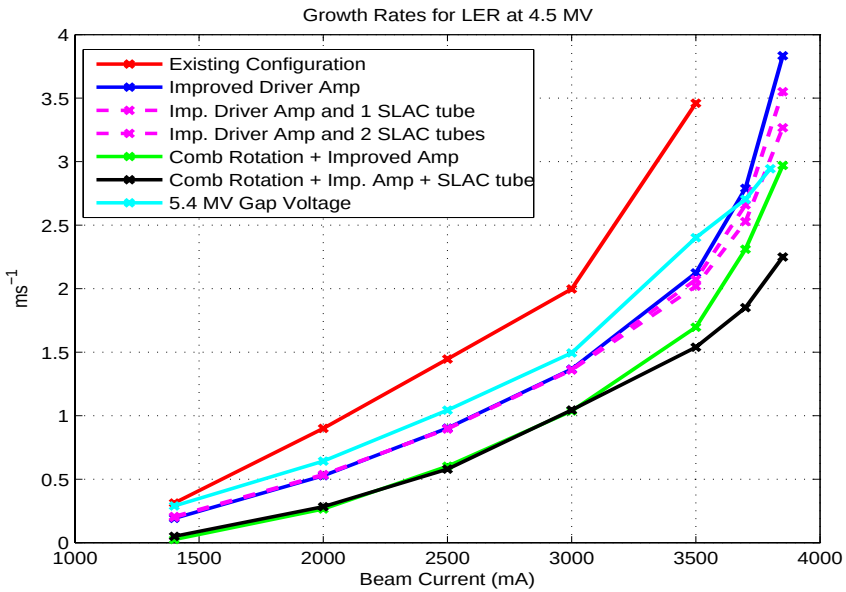
Accelerator Dynamics and Control, High Speed Instrumentation and Technology Development.

- Major Activities in 2006/2007

- **PEP-II High Current Instability Studies**
  - Coupled-bunch studies (HOM driven instabilities), tuning/configurations of LFB and LLRF systems.
  - Instability Studies at LNF-INFN, KEKB, ATF.
- **RF-Beam Dynamics, RF system stability modeling.**
  - Development of nonlinear LLRF model – Quantification of PEP-II Limits.
  - LARP contribution for 2007/2008 – LHC LLRF modeling, limits.
  - Development of new control techniques, intermodulation distortion control.



PEP-II HOM Damping rate studies

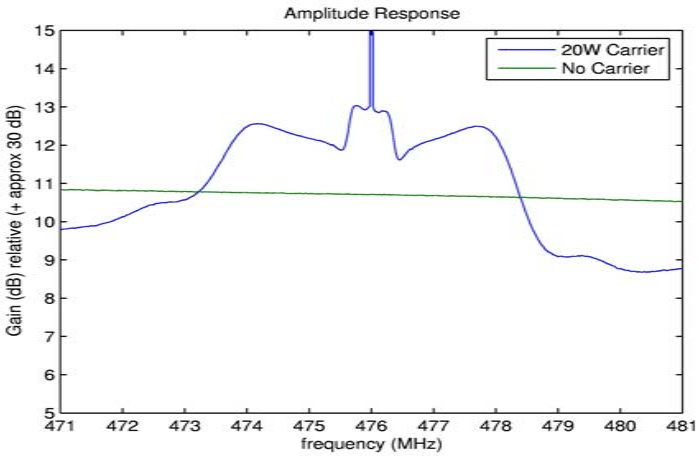


Growth rate predictions for PEP-II LER at high currents

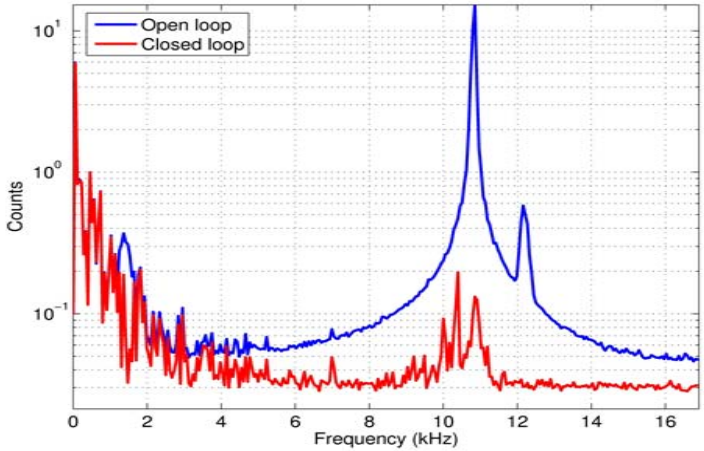
Electronics Research Group – Accelerator Technology Department

Accelerator Dynamics and Control, High Speed Instrumentation and Technology Development.

- **Technology Development**
  - iGp (500MS/sec instability control) – in use at PEP-II, KEKB, LNF-INFN.
  - Gboard Technology development – Next generation 1.5 GS/sec reconfigurable processor.
  - LCLS X-Band Instrumentation
  - LCLS RF Gun temperature control dynamics modeling.
- **Publications**
  - Conference papers (EPAC, DIPAC and PAC), Journal papers, Internal MAC reviews.
- **Teaching**
  - Applied Physics, US Particle Accelerator School.

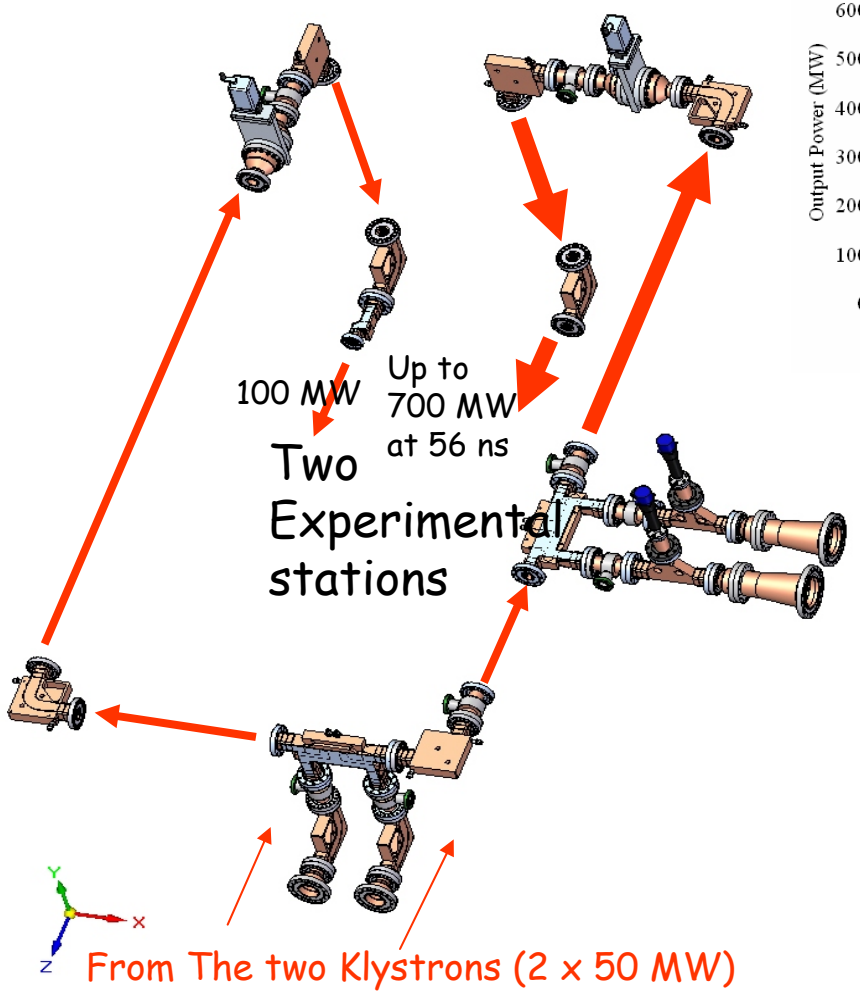


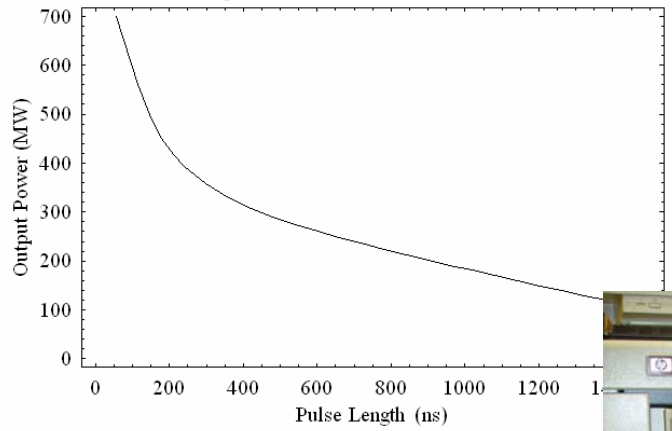
Klystron driver amplifier characteristics

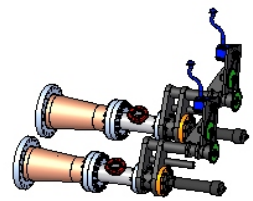


ATF longitudinal studies

Test Facilities for the High Gradient Collaboration







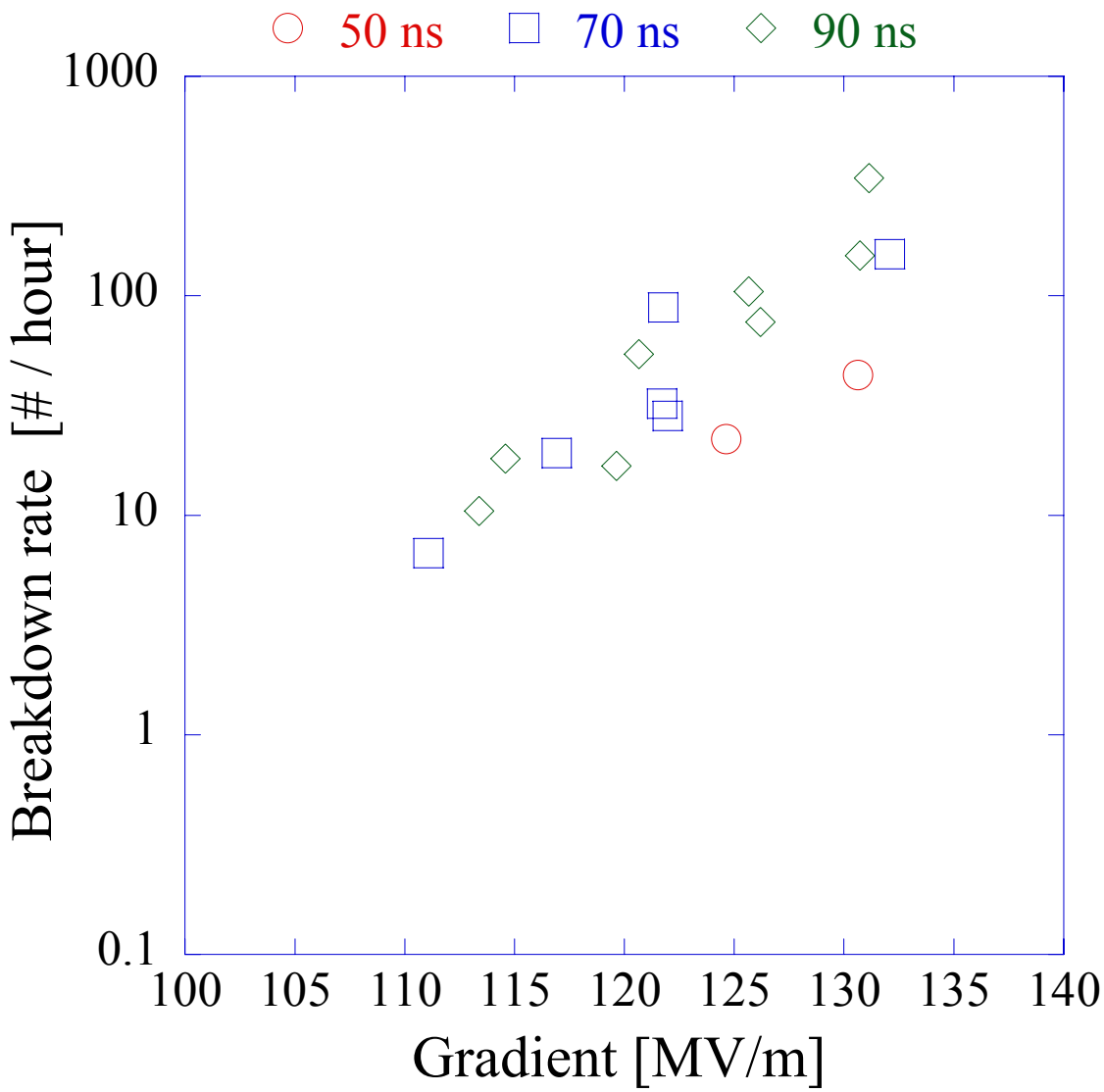
Test Cavity for material characterization

- Unique ultra-high power X-band testing facilities
- Over-moded test cavities for material characterizations: pulsed heating at room temperature and quenching fields at cryogenic temperatures

High power tests at X-band which was performed during the last few month

- Molybdenum CERN structure
- Copper CERN Structure
- Old NLC structures
- Single Cell traveling wave structures
- ANL dielectric structure
- Semiconductor (si) breakdown test
- Superconducting Material Test
- Single Cell Standing wave accelerator structure
- CERN's Pulsed heating

Standing-Wave Structure Result Summary at Repetition Rate of 60 Hz (a/l~0.21)



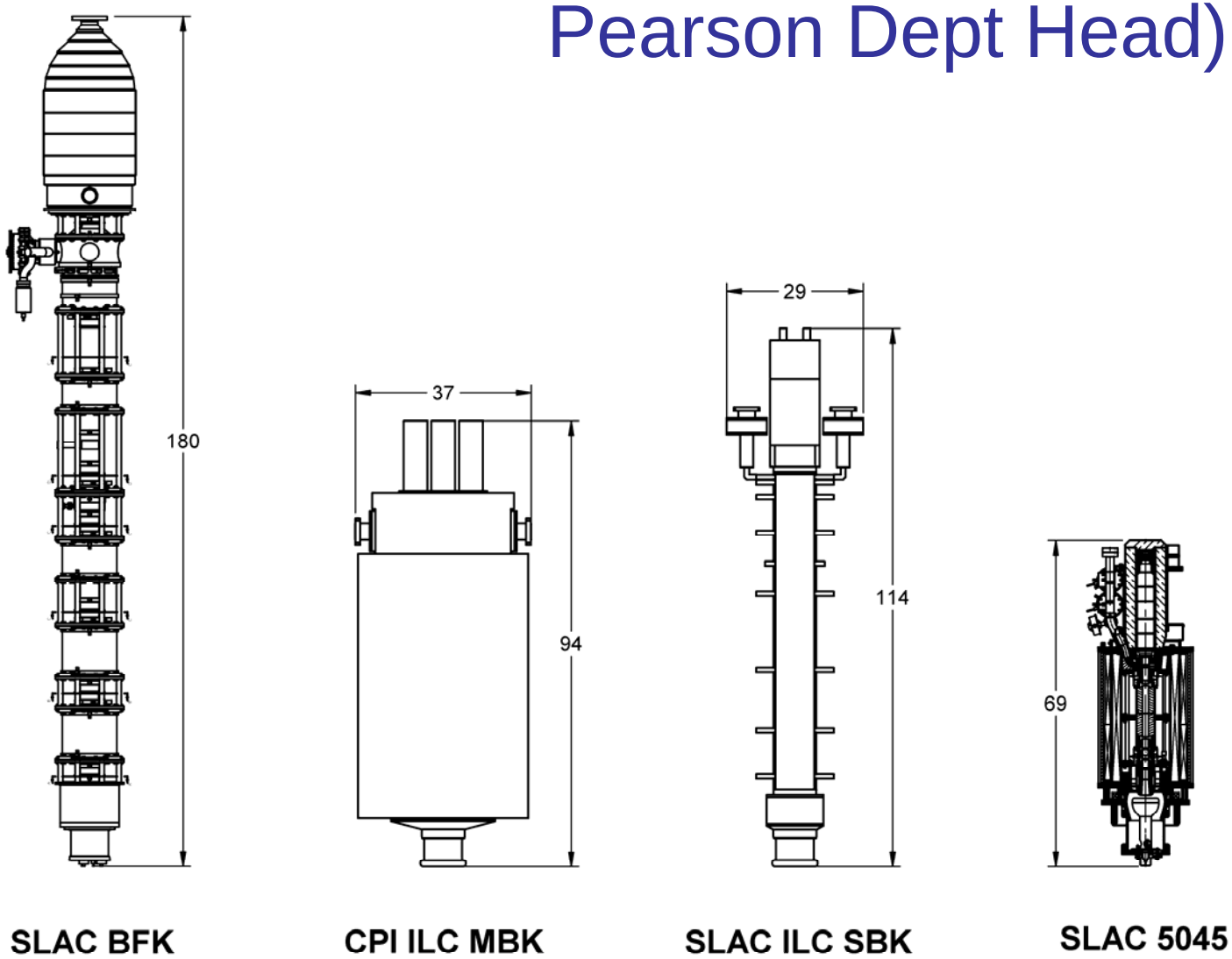
Summary of Structure Testing Results

- Standing wave structure > 100 MV/m for very low breakdown rate at 90 flat pulse width after the filling time (equivalent 180 ns for TW structures) $a/\lambda \sim 0.21$

- H75vg4S18, it is < unity at 94 MV/m with 150 ns pulses. $a/\lambda \sim 0.17$

- T53VG3MC, it is < unity at 100 MV/m with 150 ns pulses. $a/\lambda \sim 0.13$

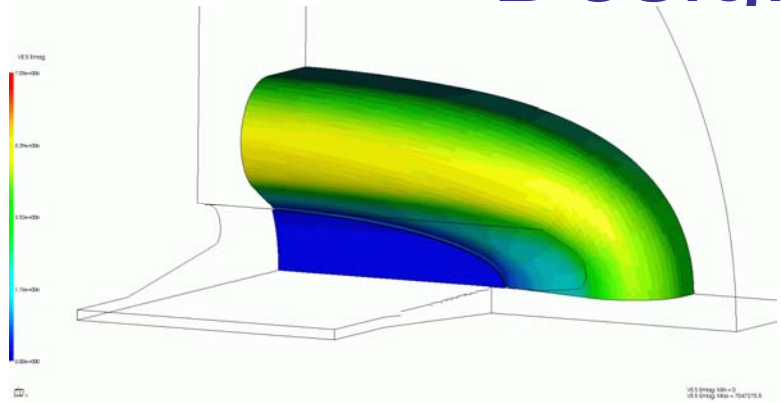
Klystron Department (Chris Pearson Dept Head)



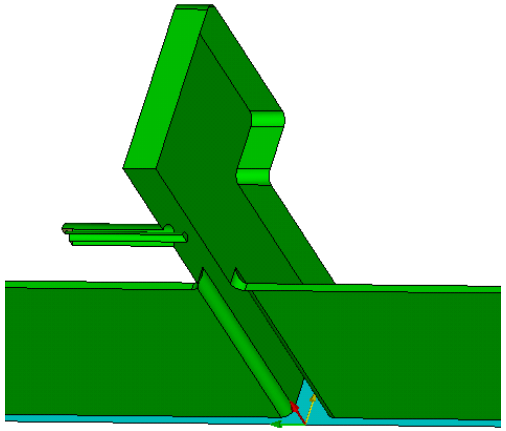
RF and Electrical Design

ILC SBK Development

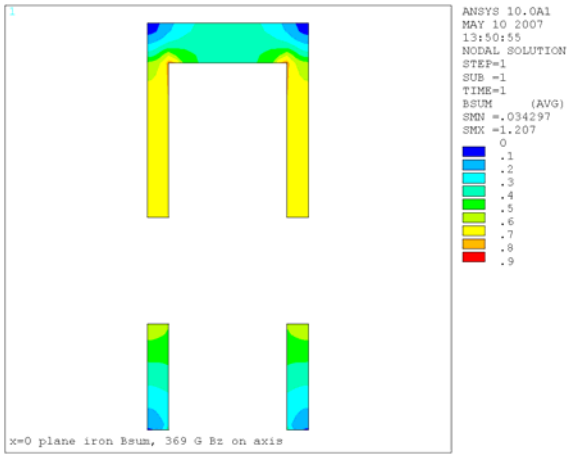
HV Seal



Focus Electrode



Cavity Coupling Antenna



Focusing PPM Structure

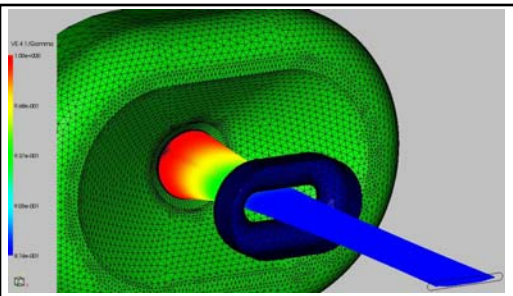
W-Band Sheet Beam Klystron

Objectives

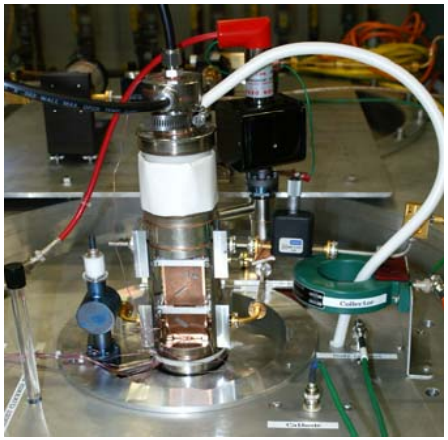
- **Develop high average power 95 GHz RF source**
- **Validate sheet beam klystron concepts (beam formation, beam transport and RF stability) in an inexpensive vehicle**
- **Validate 3-D simulation codes for sheet beam klystrons**

Fabrication and Test

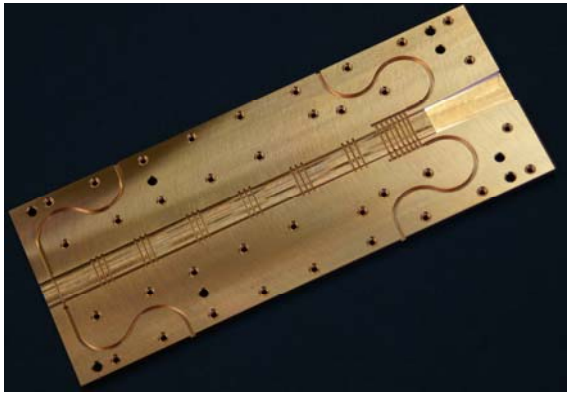
- **Prototype tube built and tested – validated beam formation, beam transport, zero-drive stability and small signal gain predictions**
- **Full power tube nearly complete – testing to begin in July 2007**
- **Specifications - 50 kW peak power, 2.5 kW average power, 74 kV, 3.6 A**
- **Beam size 6 mm x 0.5 mm**



3D electron trajectory simulation



Photograph of prototype WSBK in test.



One half of the eight cavity RF circuit for WSBK. Circuit halves are diffusion bonded Multi-gap cavities increase impedance and lower electric fields in output cavity

Surface and Materials Science Department R&D

(Bob Kirby Dept. Head)

RF Gun Photocathodes:

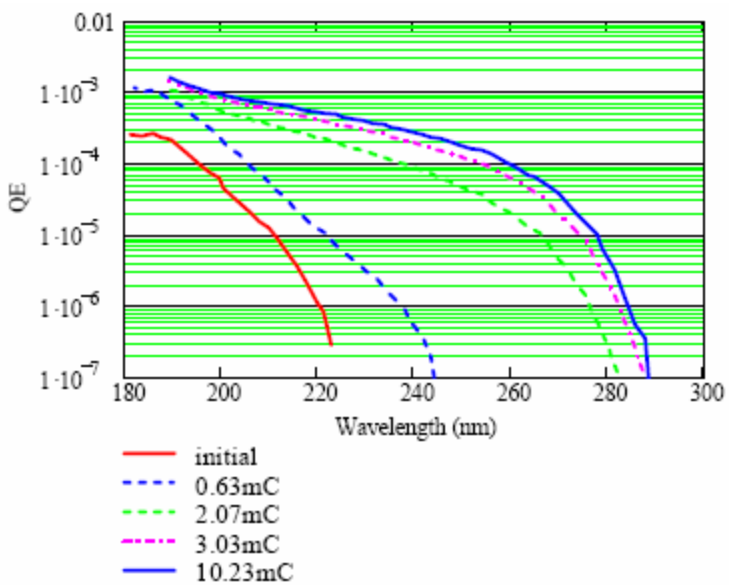
- Development of in-gun cleaning of rf copper photocathodes, using hydrogen-ion bombardment and thermal gas desorption techniques.
- Qualification for photo-quantum efficiency (QE) of copper photocathodes for LCLS injector guns.
- Deposition of oxidation-resistant higher QE, low-emittance cathode materials (e.g., CsBr) onto existing copper gun cathode surfaces.

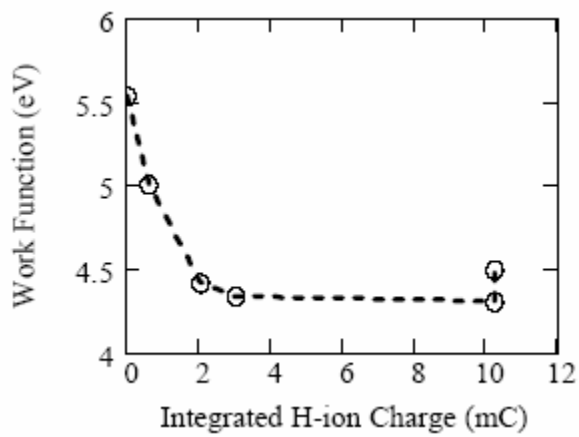
Electron Cloud Instability:

- Secondary electron yield and surface chemistry measurements on beam chamber materials, leading to coatings (TiN and NEG) that suppress the electron cloud effect.
- Suppression of secondary electron emission in LER Al beam chambers by using electron-trapping grooved surfaces. Installed extruded-grooved chambers into LER.

Copper Photo-Cathodes

- **Lab system for testing LCLS cathodes**
  - **cathode cleaning (H^+ ion bombardment)**
  - **measure QE, chemistry (XPS)**
  - **deposit higher QE overlayer (e.g.,CsBr)**





Copper cathode QE and work function change with H^+ ion-cleaning dose

Accelerator Research at SLAC

- Push the envelope of operating accelerators
  - PEP-II + flavor factories world wide—all operating facilities
- Research in Beam Physics and Development of 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 (SABER)
  - NLC Test Accelerator (NLCTA)
- SLAC provides
  - Accelerator Science leadership though its outstanding faculty and staff.
  - A unique facility infrastructure
  - A unique technical development environment.
  - Integrates of all aspects of accelerator physics and technology
  - Develops the accelerator-based foundation for particle physics and photon science