Beam Physics at SLAC

Yunhai Cai
Beam Physics Department Head

Members in the ABP Department

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  - Gennady Stupakov
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  - Yiton Yan
  - Yuri Nosochkov
  - Min-Huey Wang
* Associates:
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  - John Irwin
* Professors:
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  - Ron Ruth
* Post-doctor:
  - Yuantao Ding
  - Dao Xiang
* Students:
  - Daniel Ratner
  - Huiping Geng

Recent Activities in the ABP Department

* **Lattice design and single-particle beam dynamics in storage rings**
  - **Optics improvements for PEP-II**
  - **Lattice design, beam dynamics, and optimization of beam parameters for FACET**
  - **Lattice design and beam dynamics for PEP-X**
* **Wakefield and impedance, collective effects and instabilities of intensely charged beam**
  - **Analytical calculation of Impedance and wakefield due vacuum chambers**
  - **Coherent synchrotron radiation (CSR) and its dynamical effects**
  - **Instabilities driven by electron cloud and ions**
  - **Beam-beam effects in colliders, for example, crossing angle and crab cavity**
  - **Estimate of thresholds of collective instabilities for PEP-X**
* **Simulation and parallel computing**
  - **Lie-algebra-based linear and nonlinear analysis codes: LEGO and Zlib**
  - **PIC simulation of beam-beam interaction and luminosity: BBI**
  - **High resolution nonlinear Vlasov solver for microwave instability**

PEP-II Improvement of Optics

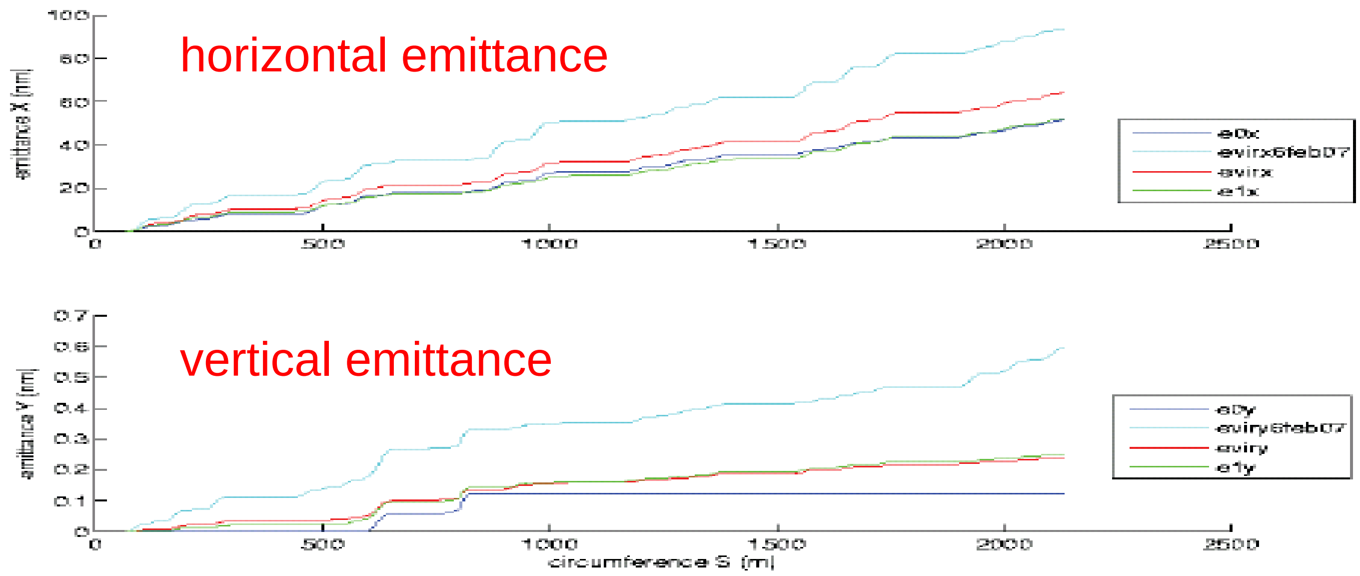
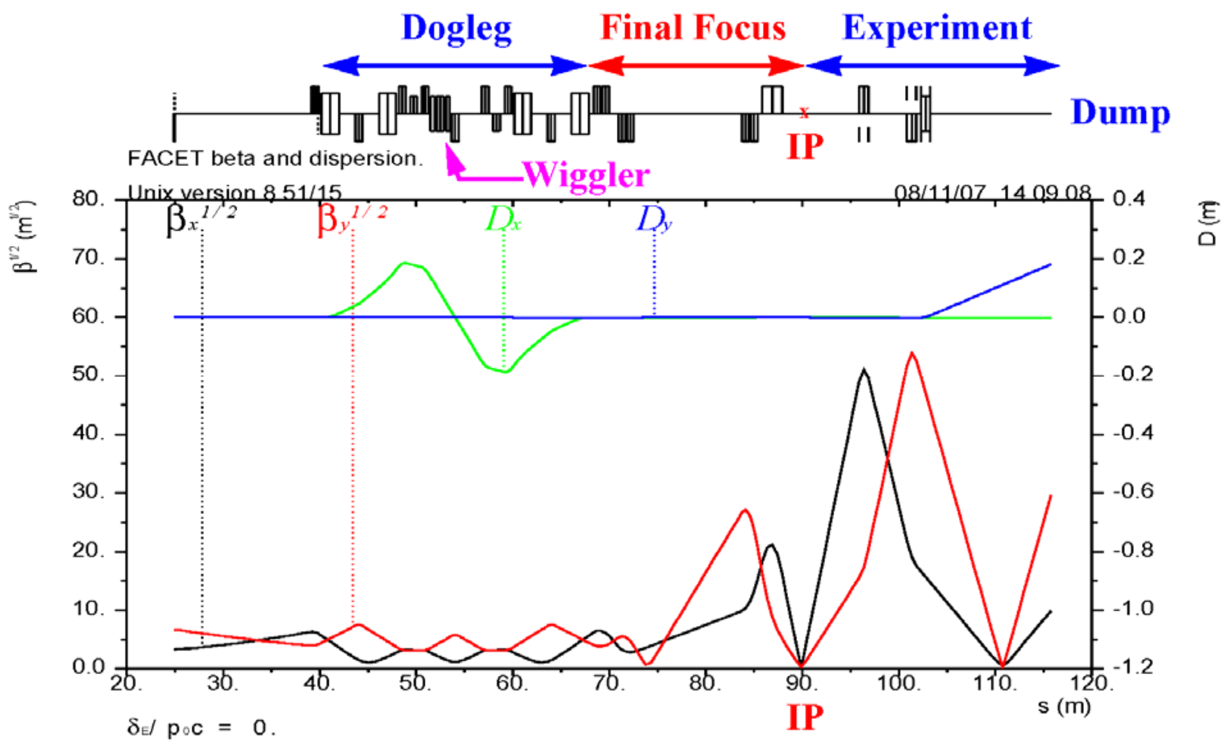


Figure 13: Comparison of PEP-II HER X emittance (top plot) and Y emittance (bottom plot) contribution through circumference for the virtual machine on Feb 6, 2007 (evirx6feb07, eviry6feb07), the virtual machine on Feb 8, 2007 (evirx, eviry), the wanted model for the new half solution derived from the virtual HER on Feb 8, 2007 (e1x, e1y), and the ideal lattice of HER (e0x, e0y).

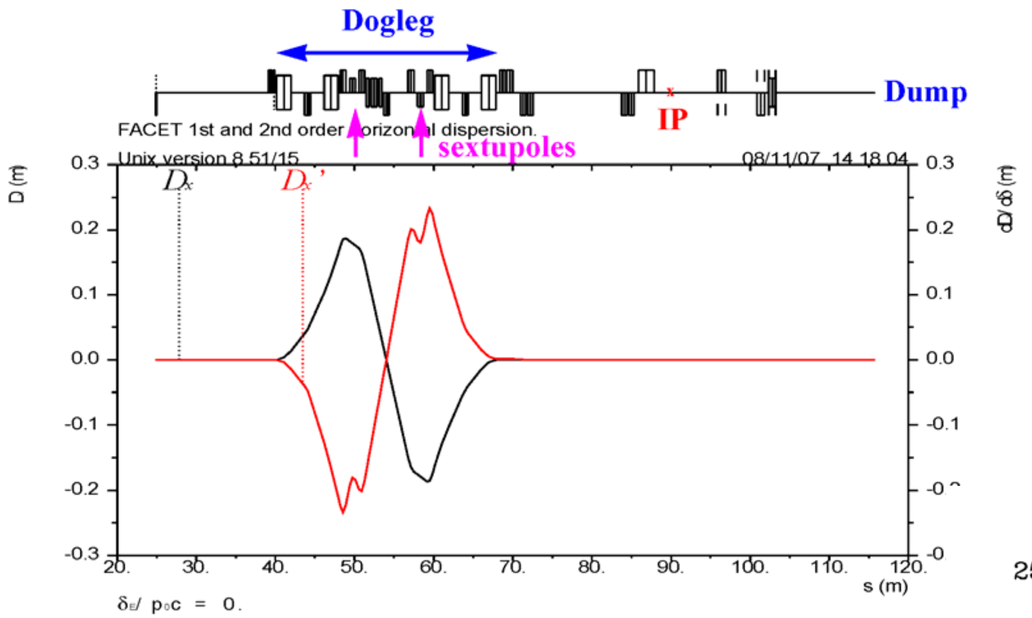
- Led PEP-II optics improvement in the past three years
- Provided beam-based and online machine optics model for PEP-II
- Corrected optics errors: beta beating, dispersion, and coupling
- To apply the method in the ILC damping ring test facility at Cornell

FACET Optics Design



FACET final focus optics is designed for a round beam spot at the IP where $\beta_x^* = 1.5$ cm, $\beta_y^* = 15$ cm. For beam emittance of $\gamma\varepsilon_x$ = 50e-6 m-rad and $\gamma\varepsilon_y$ = 5e-6 m-rad, the IP beam sizes are $\sigma_x^* = \sigma_y^* = 3.9$ μm (at 25 GeV without errors).

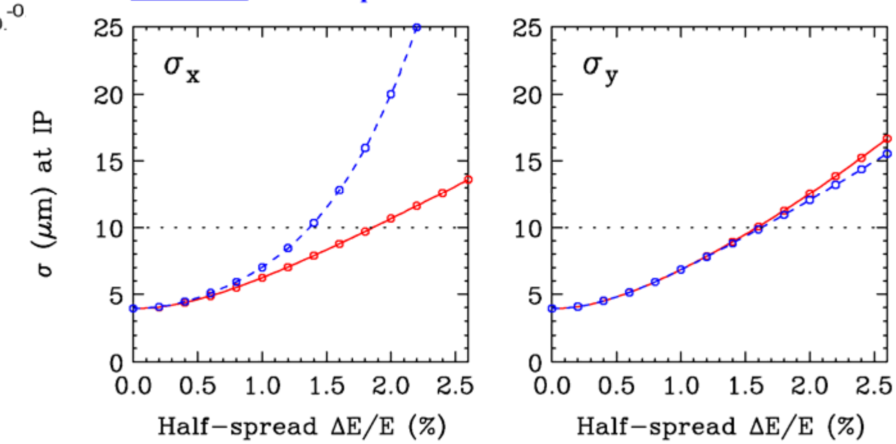
Correct the second-order dispersion inside bunch compressor in FACET



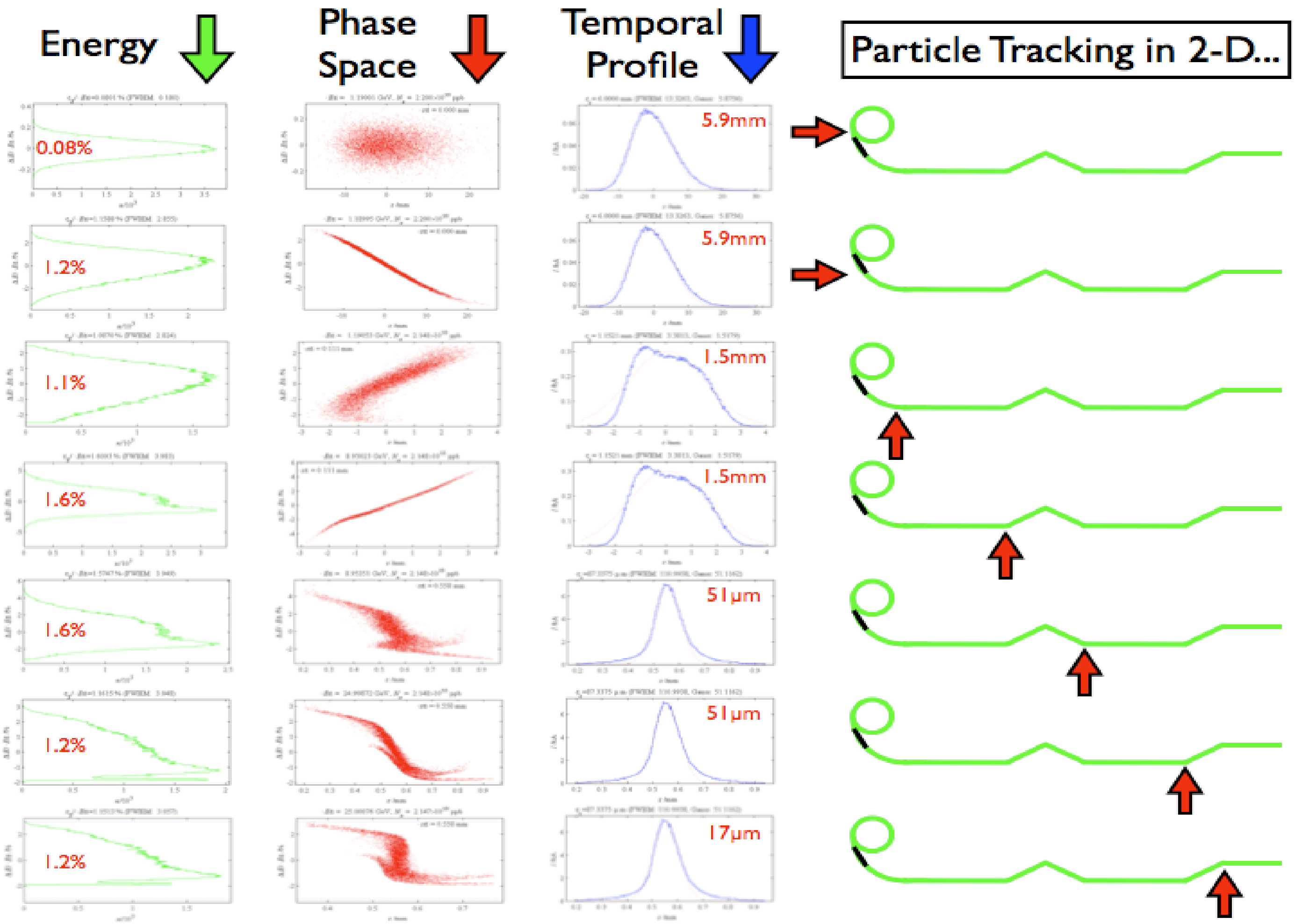
Two sextupoles cancel the 2nd order dispersion

The sextupoles reduce chromatic beam size growth at the IP (shown for flat energy spread)

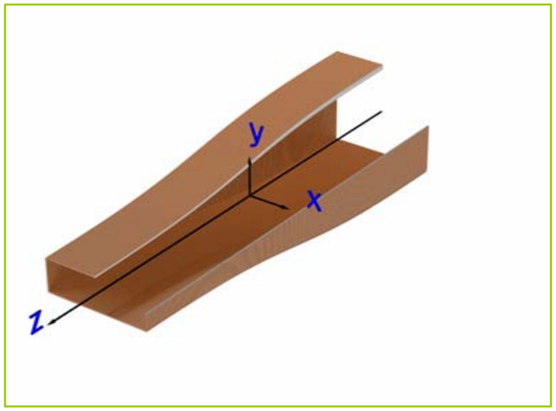
red: with sextupoles and SR
blue dash: w/o sextupoles and with SR



Simulation of Longitudinal Beam Dynamics in FACET using LiTrack (include wakefield in structure)



Analytical Calculation of Wakefield and Impedance
for tapered collimators or chamber of insertion devices

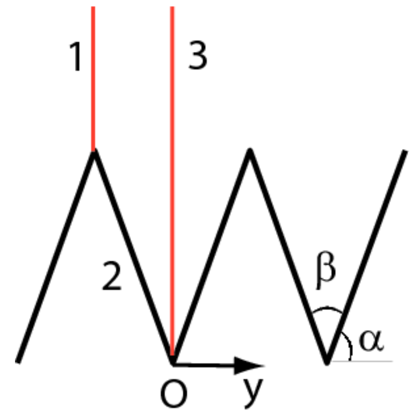


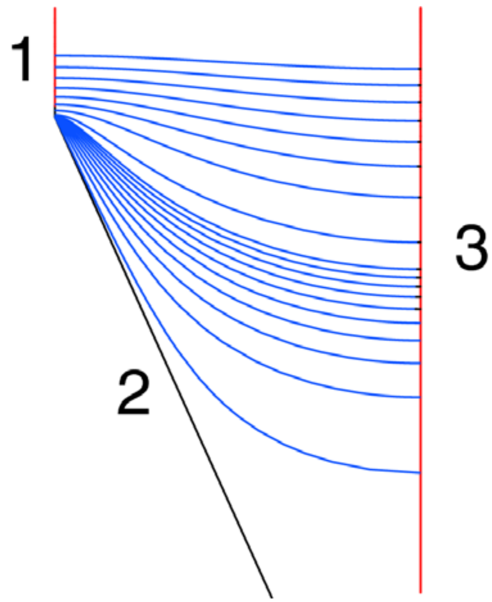
The method reduces the calculation of the 3D impedance to solving a 2D Poisson equations with Dirichlet boundary conditions. In simple cases such solutions can be obtained analytically; for more complicated geometries they can easily be found numerically. For the axisymmetric and rectangular geometries the method reproduces results known from the literature.

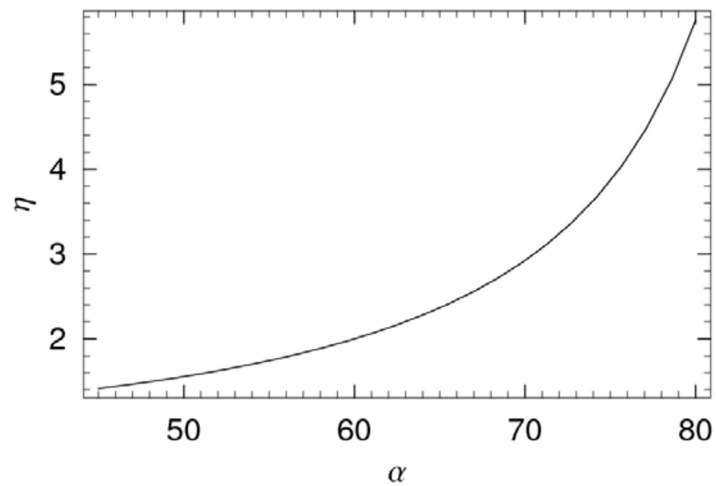
- * The beam current in many storage rings are limited by this kind of transitions
  - – LHC phase-I collimators limit the current at a half of its design value
  - – A dominate source of impedance in modern light source
- * Recently, the theory is extended to arbitrary cross section
  - – Work was published in PRSTAB 094401 (2007)
  - – Resolved a factor of two discrepancy between the results of the previous calculation and measurements at SLAC for rectangular collimators
- * The theory could be used to study impedance in Project X, LHC phase-II collimators, and PEP-X

RESISTIVE WALL IMPEDANCE OF A SURFACE WITH TRIANGULAR GROOVES

A surface with triangular grooves can significantly reduce the secondary emission yield below the multipacting threshold with weak dependence on the size of surface and magnetic field.



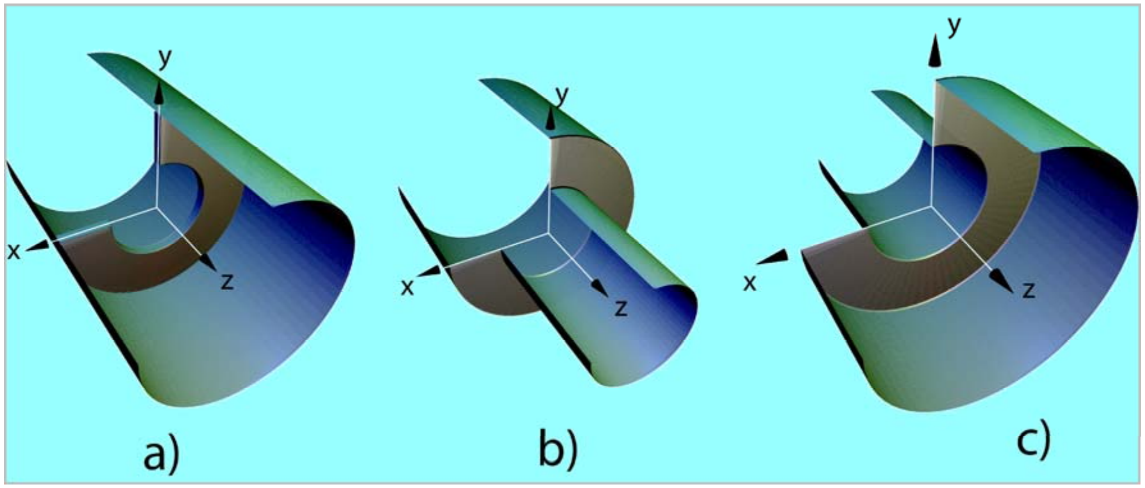




Electric field lines in the groove.

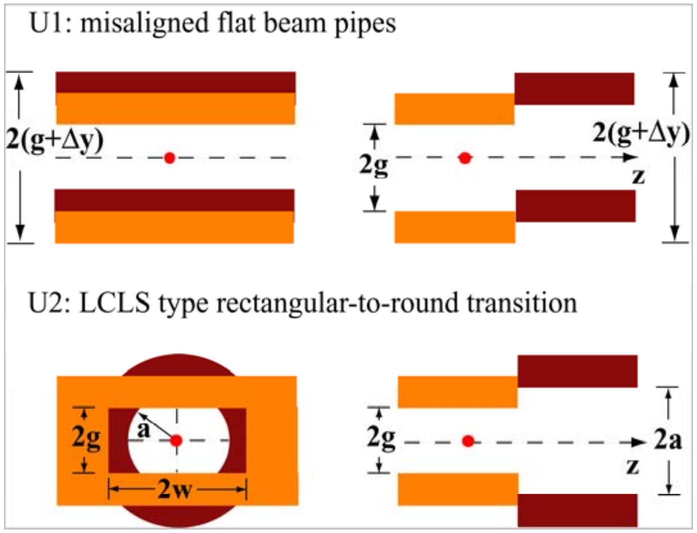
Impedance amplification factor as a function of the angle.

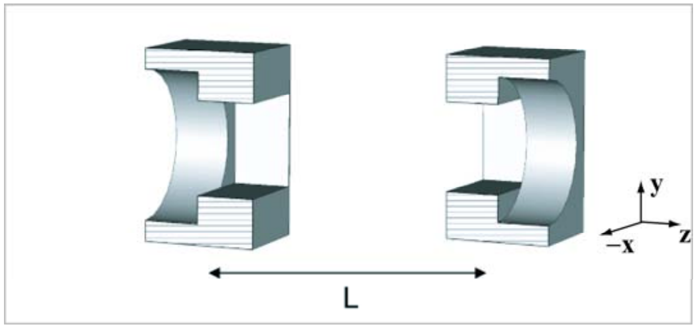
Optical approximation in the theory of geometric impedance

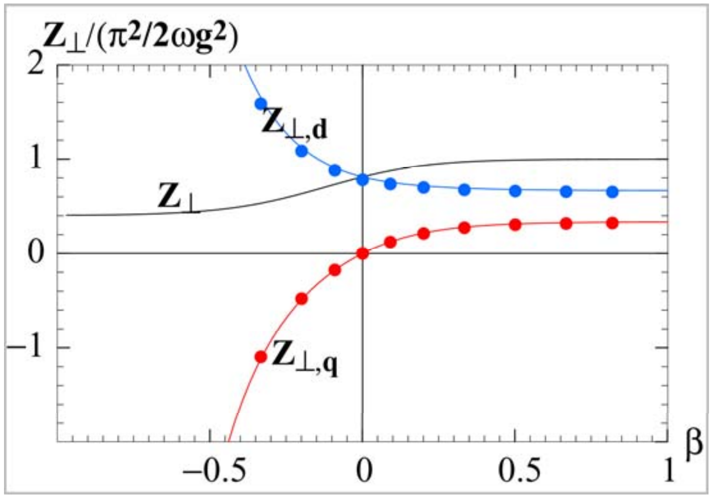


A optical approximation in the theory of impedance calculation is developed, valid in the limit of high frequencies and short bunches (PRSTAB, 054401 (2007); PRSTAB, 074401 (2007)). Using this approximation, both equations for the longitudinal impedance and the transverse impedance are obtained (valid for arbitrary offsets). The final expressions for the impedance, in the general case, involve two dimensional integrals over various cross-sections of the transition. The analytical results agree well with the numerical simulations.

Optical approximation in the theory of geometric impedance



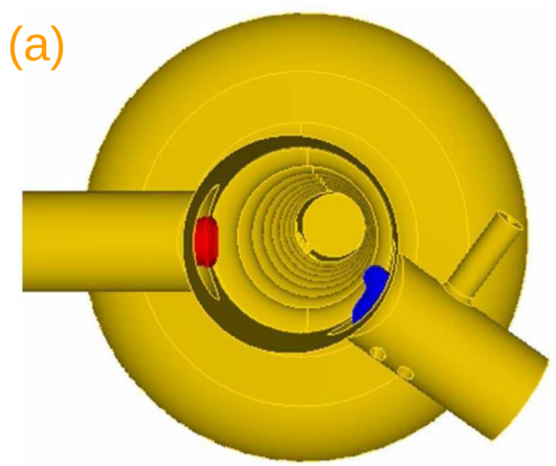


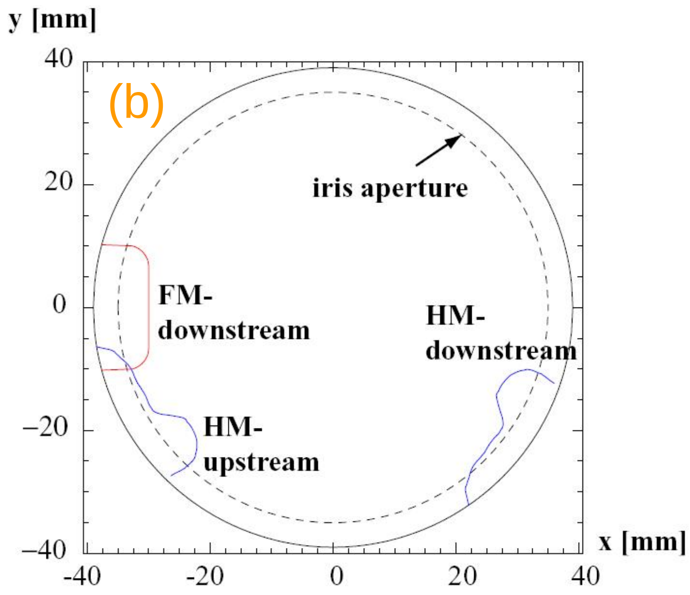


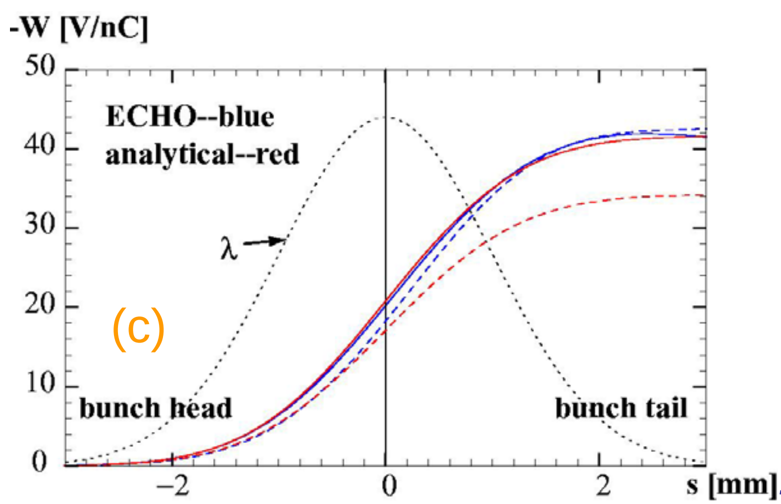
Comparison of the optical theory with numerical simulations using the ECHO computer code for a small elliptical iris in a beam pipe.

Examples of various 3D transitions

On-axis wake kicks due to coupler asymmetry in ILC cavity



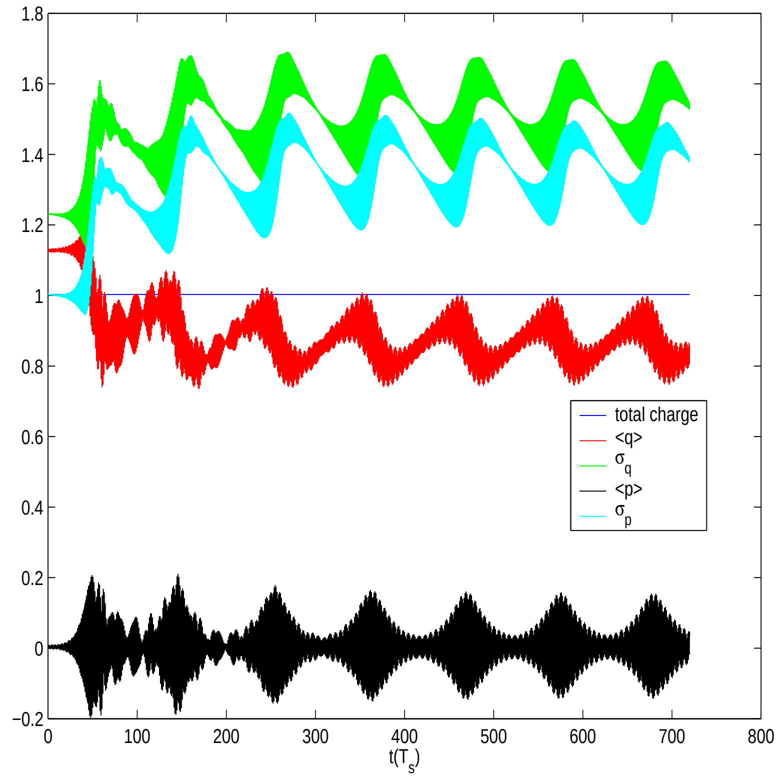




(a) Fundamental mode (fm) and higher mode (hm) couplers as seen from downstream end of ILC cavity. (b) profiles of the 3 couplers in a cavity. (c) wake of σ_z= 1 mm bunch due to couplers in their beam pipes, as obtained by (3D finite-difference program) ECHO (blue) and by optical approximation (red) [*x* is solid, *y* is dashed].

Single-Bunch Longitudinal Instability

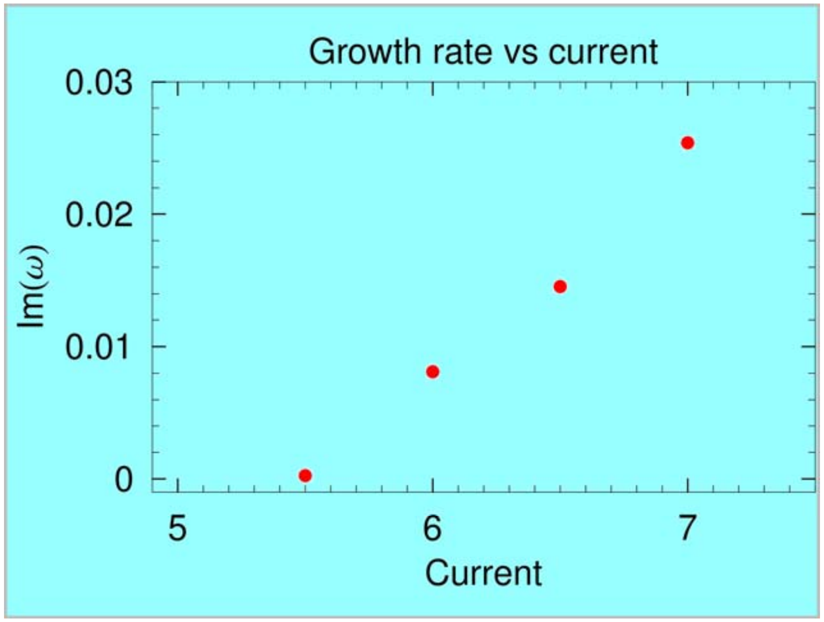
* Developed a high-resolution Vlasov-Fokker-Planck solver for longitudinal instability and calibrated it against the measurements in the SLC damping ring. It produced the saw-tooth oscillation with accurate period.
* Extending it to include the coherent synchrotron radiation with shielding.
* Study the possibility to use it in proton storage ring.
* Improve the theory to understand the underline physics of microwave instability.

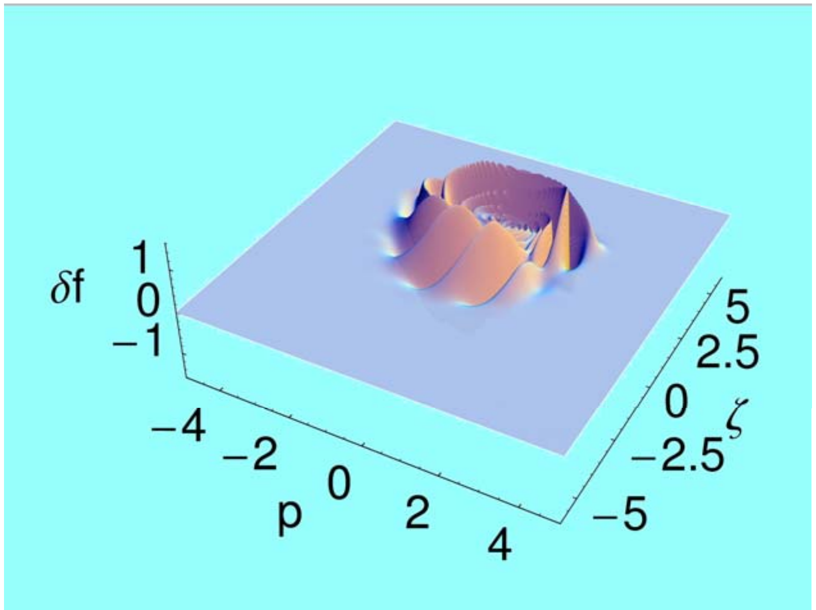


Simulation of SLC damping ring with a realistic and accurate impedance model.

MICROWAVE 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.

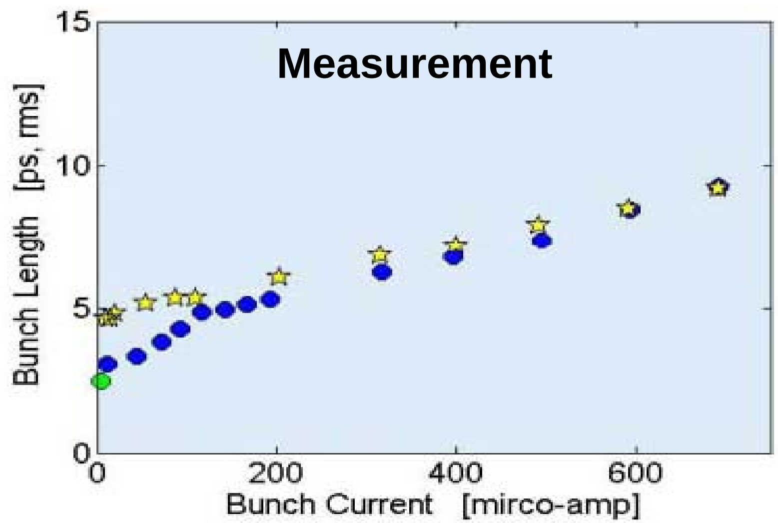


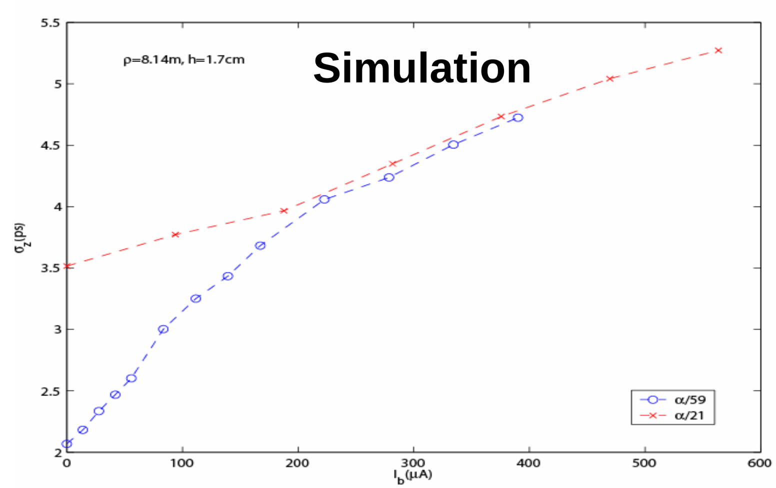


Growth rate for the CSR induced microwave instability as a function of current.

Phase space of the microwave instability.

Comparison to Measurement at SPEAR3





* Streak camera measurement was carried out by J. Corbett, A. Fisher, X. Huang, J. Safranek, J. Sebek, A. Lumpkin, F. Sannibale, W. Mok at SPEAR. The result was published in Proceedings of PAC07.
* Parameters in the simulation are based on the design lattices provided by Y. Nosochkov.
* Averaged longitudinal beam sizes were plotted both in the measurement and the simulation. There is no fitting parameters in the simulation.
* Momentum compaction factor: α was lower by a factor of 21 and 59 respectively.

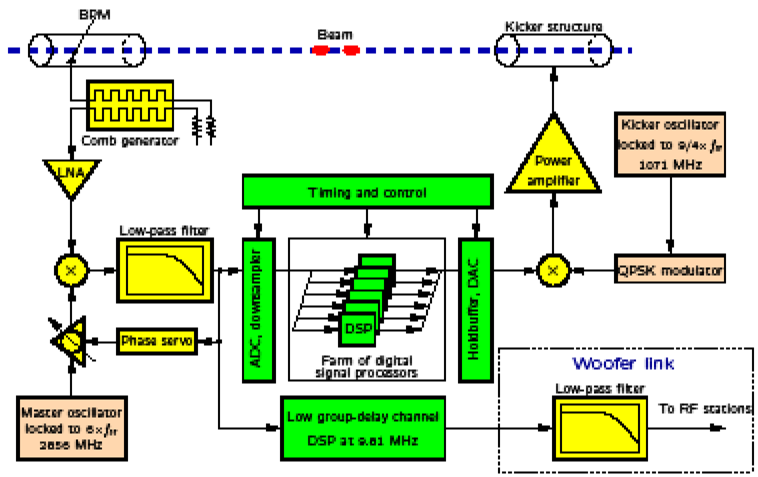
Advanced Electronics – Dynamics and Instability Control

Recent Achievements - Our efforts were central in achieving PEP-II record 1.2e34 luminosity via control of coupled-bunch instabilities and RF system dynamics

Group - 3 SLAC Staff, 2 Ph.D. Students

Central expertise in particle dynamics, instability control via feedback techniques. Technology experts (RF processing, DSP)

Active feedback technology development and measurements at PEP-II, KEKB, DAFNE



RF- Beam Dynamics, RF system stability modelling, high current instability control.

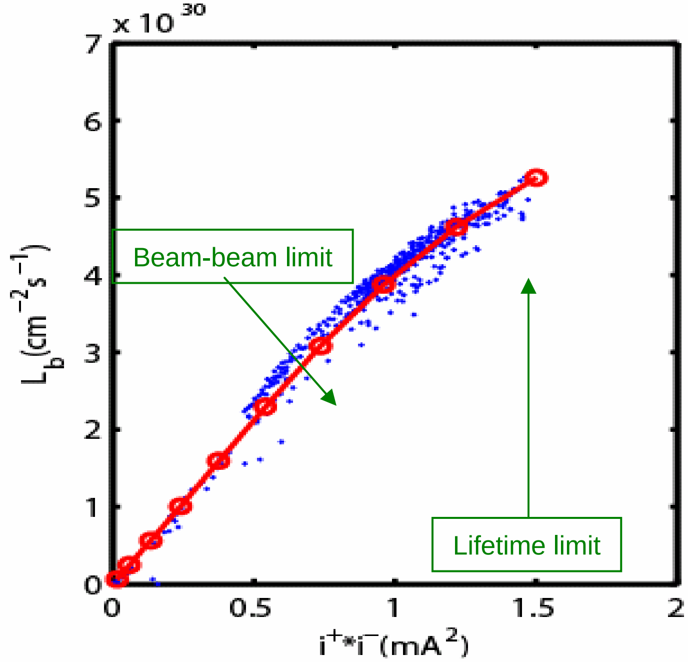
Contributions

- Beam instability measurement and dynamics control, LLRF system stability and impedance control
- Technology Development - 13 instability control systems built/commissioned for US, European and Asian Labs
- Training of Ph.D. students, M.S. Engineering students (7 group alumni at national labs and industry)
- International and US Particle Accelerator School courses on RF Signal processing and Optimal Control

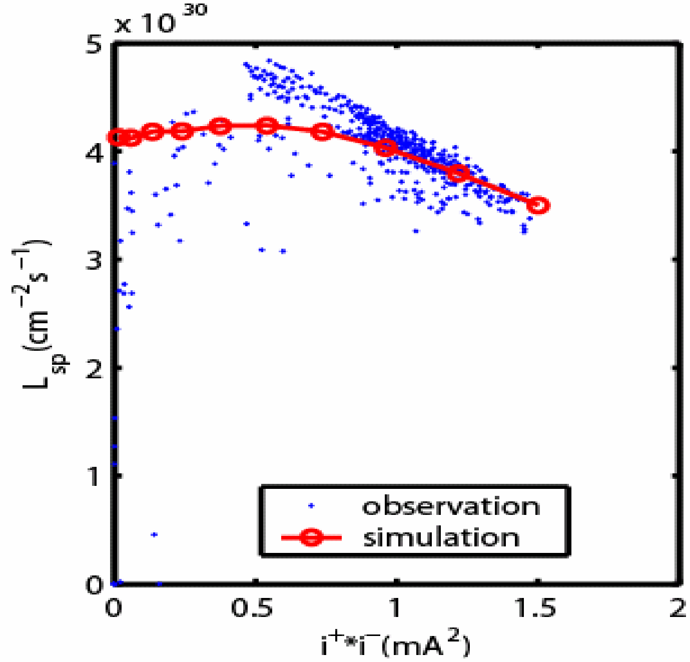
Research Focus - Leadership role in beam instability dynamics and control. Development of wideband electronic and optoelectronic technology for ultrafast applications. Reconfigurable high-speed signal processing systems for accelerators and light sources.

Beam-Beam Simulation at PEP-II

Bunch Luminosity



Specific Luminosity

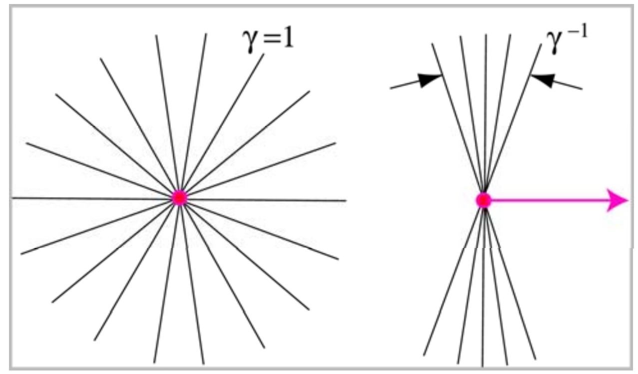


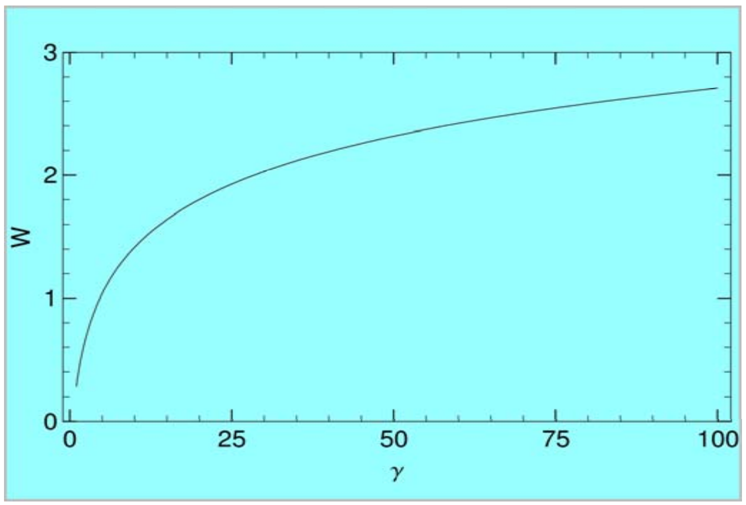
Topic of interests:

- **To study the crossing angle and compensation with a crab cavity**
  - **why KEK-B did not get a factor of two as expected at high currents**
- **Super-B with crab waist and “long-range beam-beam”**

Space charge effect in an accelerated beam

The electromagnetic field of a moving bunch is compressed in the transverse direction. The moving field carries more electro-magnetic energy then the field at rest.





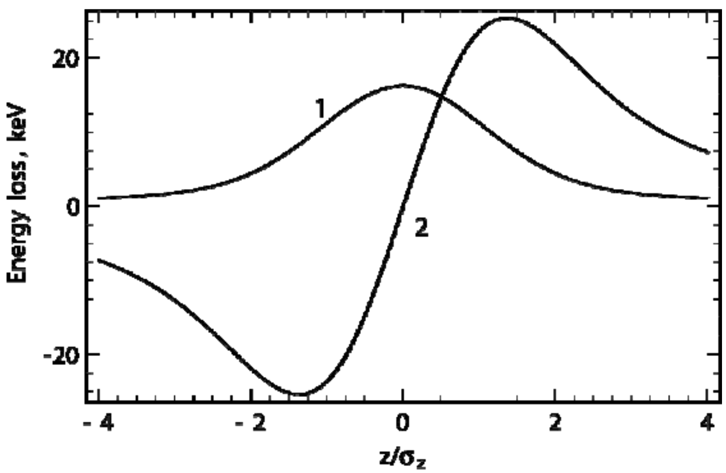
The increasing energy of the EM field is taken from the kinetic energy of the particles via longitudinal electric field that is generated inside the beam. This field is caused by acceleration, but it is NOT due to radiation! The effect is referred to in textbooks as ``the electro-magnetic mass of electron''. In is usually neglected in simulation codes.

Plot of electromagnetic energy of a spherical Gaussian bunch in units Q^2/σ

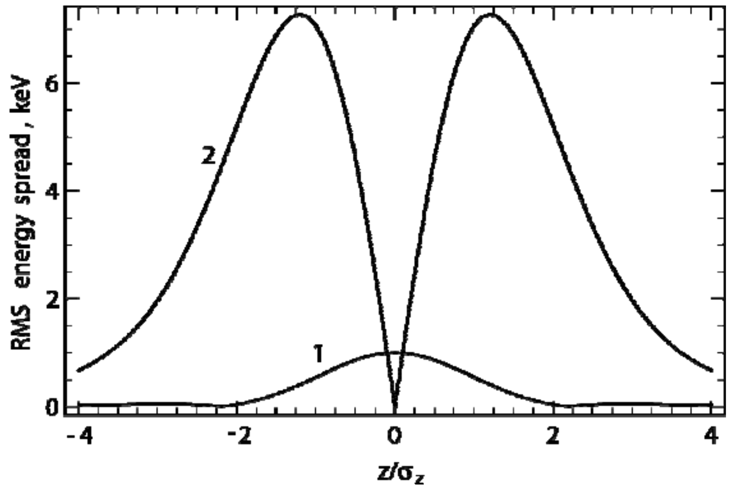
$$(\sigma_\perp = \sigma_z = \sigma).$$

Longitudinal Space-Charge Effect Due to Acceleration

The energy spread in the beam of the LCLS bunch compressor introduced by this effect was computed (PRSTAB 2008). LCLS rf-gun parameters: σ_z = 0.86 mm, σ_x = 0.6 mm, and Q = 0.72 nC (corresponding to the peak current of I = 100 A).



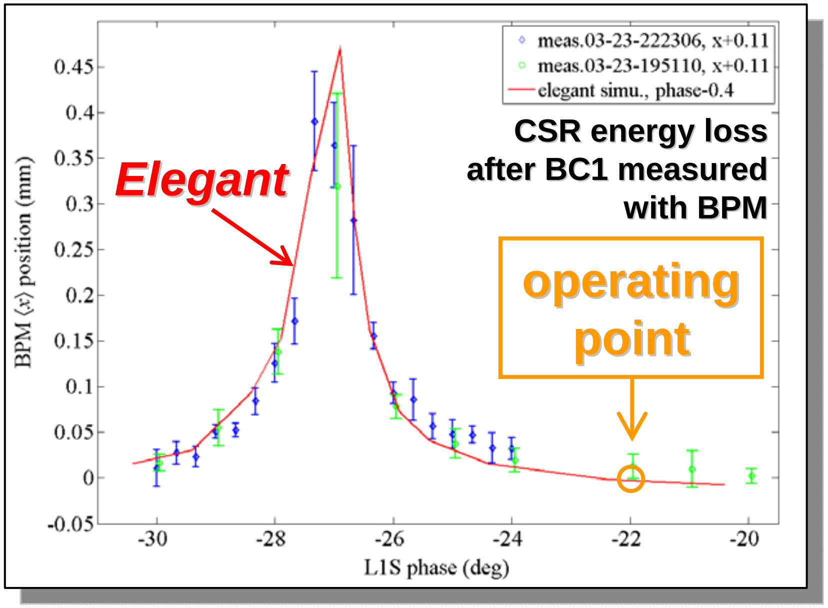
The energy loss averaged over the transverse coordinate as a function of the position z, (curve 1) (for comparison, the energy loss introduced by the space charge effect, (curve 2) is also shown).

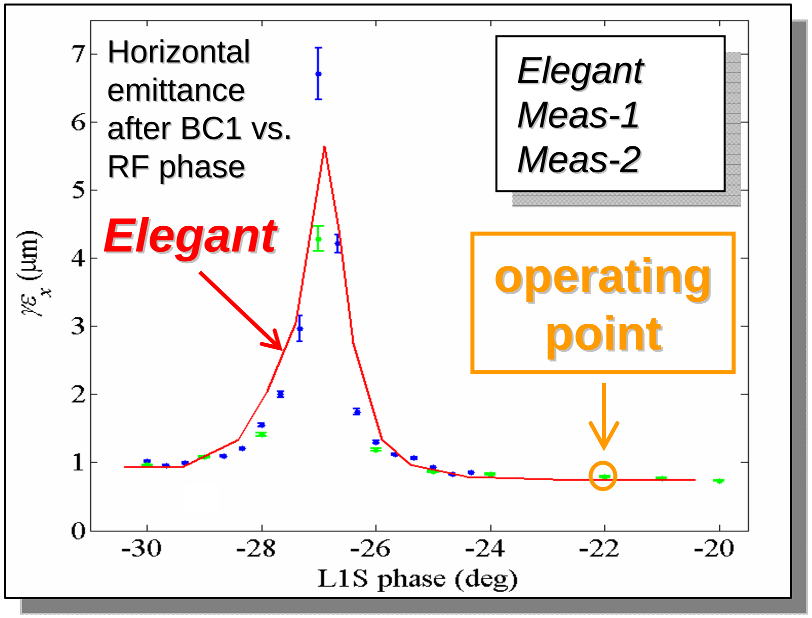


The rms energy spread in slices as a function of z, (curve 1) (the rms energy spread introduced by the space charge forces, (curve 2) is also shown).

CSR Studies at LCLS

- Studied CSR effects on beam quality at BC1 and BC2;
- measured energy loss and emittance growth due to CSR, compared with 1D and 3D model;
- 1D model results are in good agreement with data, as shown in the following BC1 examples.





Main Parameters of PEP-X

Parameter	Value
Energy [Gev]	4.5
Circumference [m]	2199.32
Horizontal emittnace [nm-rad]	0.094 (0.14 including IBS)
Minimum vertical emittance [nm-rad]	0.008 (including IBS)
Beam current [A]	1.5
Number of bunch	3154 (83x38)
Bunch length [mm]	5.0 (High harmonic cavities)
Minimum Touschek lifetime [minute]	41
Number of insertion devices	30
Harmonic number	3492
Betatron tunes	86.23/36.14 (x/y)
Energy loss per turn [Mev]	3.27
Momentum compaction factor	4.72×10^{-5}

Possible Contributions to Project X Workshop, Nov. 2007

* Quantify instability thresholds due to electron cloud in the Main Injector and Recycler using the simulation codes being benchmarked against the experiments at PEP-II.

* Suggest modifications to the vacuum chamber design to mitigate the effects of electron cloud, if necessary.

* Develop an accurate impedance budget for the rings and estimate the threshold of impedance driven instabilities, in particular, simulating the microwave instabilities with a Vlasov solver.

* Study beam dynamics and beam losses including full machine nonlinearity, space charge, and realistic collimators.

Conclusion

* Historically, we designed the PEP-II lattice, supported PEP-II operation, and helped to improve its peak luminosity. We are continuing to support the onsite accelerator projects: LCLS, SPEAR3, and FACET.
* We continue to make many contributions to accelerator science. Many are published in peer-reviewed journals.
* We have made significant contributions to the preliminary design of PEP-X, which could become an integral part of SLAC's long-term future.
* We also plan to contribute toward Project-X, LHC upgrades, ILC, and super-B.