Overview of Beam Physics
Department

Yunhai Cai

ARD Meeting
October 26, 2010
Core Competencies

• Lattice design and single-particle beam dynamics
  – Optics for LCLS-II, FACET, ATF2, SuperB, and PEP-X
  – Accelerator modeling and improvement, LCLS, ATF2
  – Nonlinear dynamics and resonances
• Wakefield and impedance, collective effects and instabilities of intensely charged beam
  – Impedance at very high frequency
  – Coherent synchrotron radiation and its dynamical effects
  – Physics related to ultra-short bunches
  – Beam-beam effects in the colliders
• Simulation, parallel computing, and computational science
  – Suite of electromagnetic software: ACE3P (Omega3P, T3P, …)
  – Lie-algebra-based linear and nonlinear analysis codes: LEGO and Zlib
  – PIC simulation of beam-beam interaction and luminosity: BBI
  – Nonlinear Vlasov solver for microwave instability: VFP
• Theory of free-electron laser
  – LCLS upgrades, seeding, polarization, partial lasing in storage ring
• Teach at Stanford University and US Particle Accelerator School
  – Single-particle dynamics, FEL physics, impedance and instabilities
Funding Profile in FY2011

• HEP projects: ILC, LARP, SciDAC
• Others: Spear3, Echo-7, PEP-X, …
Research in Accelerator Science

Mission
- Charged particle optics and accelerator design
- Analytical calculation of impedance and collective instabilities
- Electromagnetic computation and RF design
- FEL physics and seeding schemes

Highlights (in this year)
- Published 55 papers (12 on peer-reviewed journals)
- Taught two courses at USPAS
- Served on review committees, reviewed proposals, refereed journal papers
Wakefield due to CSR is given

\[ W(z) = \frac{4\pi \rho^{1/3}}{3^{1/3}} \frac{\partial}{\partial z} z^{-1/3} = -\frac{4\pi \rho^{1/3}}{3^{4/3} \sigma_z^{4/3}} q^{-4/3} \]

For \( z > 0 \). It vanishes when \( z < 0 \) (force is on the particle ahead).

The Impedance is derived by Falten and Laslett

\[ Z_{CSR}(\omega) = \left(\frac{4\pi}{c}\right) \frac{\Gamma\left(\frac{2}{3}\right)(\sqrt{3} + i)}{2} \left(\frac{\rho \omega}{c}\right)^{1/3} \]

where \( \rho \) is the bending radius.
Short bunch length in Sector-20 (60 to 20 µm) results in strong CSR effects leading to growth of horizontal beam size at IP.

ELEGANT simulations:
- $\sigma_x = 11.6 \ \mu m$ with ISR,
- $\sigma_x = 15.0 \ \mu m$ with ISR and CSR,
- $E = 23 \ \text{GeV}, \ N = 2 \cdot 10^{10} \ \text{part/bunch}$

Beam profile and beam size at IP

Gaussian fit X-Y size:
- $\sigma_x = 15.0 \ \mu m$
- $\sigma_y = 7.1 \ \mu m$

Gaussian fit bunch length:
- $\sigma_z = 18.6 \ \mu m$
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.

K. Bane, et al. PRSTAB 12 (2009) 030704
CSR Wakefields in Bend Magnets

Theory: Stupakov, Kotelnikov, PRSTAB 12 (2009) 104401

A computer code was written which calculates the CSR wakefields for a bend of finite length with account of the transients at the entrance to and the exit from the magnet. The code was used for simulations of the CSR wake in PEP-X and SuperKEK-B.

The CSR threshold as a function of the wavelength for SuperKEK-B. The blue solid, red dashed and green dashed-dotted lines are results of CSR impedances by A & Y formulae, our code, and free space model, respectively.

A simple scaling law based on the shielding parameter and normalized current was found. The dimensionless parameters are $S_{\text{csr}} = I_n \rho^{1/3}/\sigma_z^{4/3}$ and $\Pi = \rho^{1/2}\sigma_z/h^{3/2}$, where $I_n = r_c N_b/2\pi v_s \gamma \sigma_\delta$.

Laser Heater Improves FEL Power & Gain Length

Heater OFF

Heater ON

Heater is effective, and μ-bunching is under some control

Z. Huang, FEL2009

Gain Length (m)

Laser–Heater Energy spread (keV)

0.4-μm emit

0.5-μm emit

Heater OFF

Heater ON
Measurements and Simulations for 20-pC bunch

MEASURED SLICE EMITTANCE

20 pC  
135 MeV

Extremely short electron & x-ray pulses possible...

γεₓ = 0.14 µm

time-slicing at 20 pC

Y. Ding et al., PRL 102 254801, June 2009

SIMULATED FEL PULSES

1.5 Å,  
3.6 × 10¹¹ photons  
I pk = 4.8 kA  
γε ≈ 0.4 µm

Simulation at 1.5 Å based on measured injector & linac beam & Elegant tracking, with CSR, at 20 pC.

15 Å,  
2.4 × 10¹¹ photons,  
I pk = 2.6 kA,  
γε ≈ 0.4 µm

Simulation at 15 Å based on measured injector & linac beam & Elegant tracking, with CSR & 20 pC.
Single-Shot Method for Measuring fs Bunches

- Diagnostic chicane can be part of BC2
- Final energy spread/profile corresponds to short bunch length/profile
- Wakefield of long linac must be taken into account

\[
\begin{bmatrix}
    z_3 \\
    \delta_3
\end{bmatrix} = \begin{bmatrix}
    1 & 0 \\
    h_3 & 1
\end{bmatrix} \begin{bmatrix}
    1 & R'_{56} \\
    0 & 1
\end{bmatrix} \begin{bmatrix}
    z_2 \\
    \delta_2
\end{bmatrix} = \begin{bmatrix}
    1 & R'_{56} \\
    h_3 & 1 + h_3 R'_{56}
\end{bmatrix} \begin{bmatrix}
    z_2 \\
    \delta_2
\end{bmatrix}
\]

\[z_2 = \delta_3 / h_3\]

Z. Huang, K. Bane, Y. Ding, P. Emma, PRST-AB, 2010
Preliminary Results of Ultrashort LCLS bunch measured with A-line spectrometer

- Use A-line high-dispersion screen (PR18) as spectrometer
- Use LCLS low-charge (10-40 pC), highly compressed electron bunches
- Preliminary measurements show the technique can measure bunch length down to ~1 µm and observe double-horn current profile
- Improvement to PR18 resolution is planned
Parallel Electromagnetic Code Suite ACE3P

Meshing - **CUBIT** for building CAD models and generating finite-element meshes.

Modeling and Simulation – SLAC’s suite of conformal, higher-order, C++/MPI based parallel finite-element electromagnetic codes

**ACE3P (Advanced Computational Electromagnetics 3P)**

<table>
<thead>
<tr>
<th>Frequency Domain:</th>
<th>Omega3P</th>
<th>– Eigensolver (damping)</th>
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<tbody>
<tr>
<td></td>
<td>S3P</td>
<td>– S-Parameter</td>
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<tr>
<td>Time Domain:</td>
<td>T3P</td>
<td>– Wakefields and Transients</td>
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<td>Particle Tracking:</td>
<td>Track3P</td>
<td>– Multipacting and Dark Current</td>
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<td>EM Particle-in-cell:</td>
<td>Pic3P</td>
<td>– RF gun (self-consistent)</td>
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<tr>
<td>Multiphysics:</td>
<td>TEM3P</td>
<td>– Thermal, RF and Structural</td>
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Postprocessing - **ParaView** to visualize unstructured meshes & particle/field data.
http://www.paraview.org/

Goal is the Virtual Prototyping of accelerator structures
T3P - Short Bunch Wakefields in ERL

**Energy Recovery Linac**

*Bunch length = 0.6 mm*

**Vacuum chamber transition model**

**Beam direction**

**Scalability on jaguar**

**Longitudinal wakefield**

Loss factor = 0.413 V/pC
CEBAF BBU - Solving the Inverse Problem

CEBAF 12-GeV upgrade –

- Beam breakup (BBU) observed at beam currents well below design threshold.
  - Used measured RF parameters such as $f$, $Q_{ext}$, and field profile as inputs

- **Solutions to the inverse problem** identified the main cause of the BBU instability: **Cavity is 8 mm shorter** – predicted and confirmed later from measurements

- The fields of the **3 abnormally high Q modes** are shifted away from the coupler

- Showed that experimental diagnosis, advanced computing and applied math worked together to solve a real world problem as intended by SciDAC
T3P - CLIC Two-Beam Accelerator

Compact Linear Collider
two-beam accelerator unit

10 hours, 12000 cores on jaguar

PETS + TD24
EEHG concept

The Echo-7 experiment at NLCTA

- EEHG is proposed in late 2008 at SLAC and first demonstrated in 2010 at SLAC
- Echo-7 is collaborated among BP, TF, AARD within ARD
- About one year from inception to execution & demonstration
First Demonstration of the EEHG Principle

The experiment confirms the feasibility of preservation of the phase space correlations.