Accelerator Research at SLAC for Future HEP Programs

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Introduction

* Strong accelerator R&D program aimed at LHC and future HEP accelerators
  – LHC and upgrades
  – Super B-factory
  – Project-X (synergistic with ILC and LHC)
  – Linear Collider R&D
    • ILC
    • High gradient (X-band and CLIC)
    • Advanced acceleration concepts

* Important time to engage community to help set directions for future program
  – Accelerator R&D is critical to enable future HEP accelerators but it is also costly and must be chosen with care
LHC / LARP Activities

* Participate in the LHC accelerator physics program:
  – Contributing in areas where SLAC has expertise & experience
  – Enhance SLAC’s areas of core excellence:
    • Collective effects, RF cavity design, collimation systems, …

* Collimation
  – Rotatable Collimator and crystal collimation

* Instrumentation and LLRF diagnostics
  – Long-term instrumentation visitor and ongoing work on LLRF system

* Accelerator Physics and Design
  – E-cloud; Beam-Beam Studies; Crab Cavity; PS2 Studies

* Program is synergistic with other SLAC activities
  – Project-X; Super B-factory; ILC / Linear collider design
LHC Upgrade Collimators

- Errant LHC beams will destroy most materials except Carbon
- Carbon has a large resistance and impacts the beam
Super B-Factory

* Italian Super B-Factory would aim for luminosity of $10^{36}$

* Many possible SLAC contributions ranging from R&D to direct hardware contributions
Super B-Factory R&D

* PEP-ii expertise will be critical for SuperB project
  – Colliding beam ring design
  – Machine detector interface
  – Vacuum chamber design
  – High current beam collective effects, feedback, and beam instrumentation
  – Spin dynamics and transport

* PEP-ii hardware provides a low-cost route for DOE to contribute to project

* Engagement can vary from advisory to real international collaborator
Many areas for SLAC to contribute

- **Rf power sources and distribution**
  - Uses much of the ILC technology but with different optimizations
  - Utilizes L-band R&D facilities

- **Collimation**
  - Apply combined ILC and LHC collimation experience

- **Electron cloud**
  - Apply solution for linear collider damping rings
  - Verify with experimental testing apparatus from PEP-ii

- **Collective effects and feedback**
  - High current operation of rings → instabilities and feedback
  - Experience from PEP-ii and LHC
  - Electromagnetic simulations and instability calculations
  - Feedback system design
SLAC ILC R&D Effort

Only near-term option for a TeV-scale lepton collider

* RF power source R&D
  - Modulators
  - Klystrons
  - RF distribution and couplers

* Electron source R&D
  - Photocathode development
  - Laser R&D

* Beam delivery system R&D
  - FFS optics and tuning design
  - Collimation and beam dump design
  - MDI design with FD and crab cavity
  - ATF / ATF2 Test facility

* Damping ring & e-cloud R&D

Synergistic with Project-X R&D and future LC R&D

Synergistic with future LC R&D and with Super B-factory R&D
Beyond ILC: Linear Collider Cost Reduction

* Goal: need optimization all subsystems – tough!
  - New acceleration systems
  - Improved focusing concepts
  - Improved beam generation concepts

* Facility costs scale roughly with AC power and size
  - High gradient can reduce site length – are components cheaper?
  - Improved efficiency, better sources, or improved focusing can reduce power consumption
Linear Collider Cost Reduction

* Largest cost driver for a linear collider is the acceleration
  – ILC geometric gradient is \( \sim 20 \text{ MV/m} \) \( \rightarrow \) 50km for 1 TeV

* Size of facility is costly \( \rightarrow \) higher acceleration gradients
  – High gradient acceleration requires high peak power and structures that can sustain high fields
    • Beams and lasers can be generated with high peak power
    • Dielectrics and plasmas can withstand high fields

* Many paths towards high gradient acceleration
  – RF source driven microwave structures \( \sim 100 \text{ MV/m} \)
  – Beam-driven microwave structures
  – Laser-driven dielectric structures \( \sim 1 \text{ GV/m} \)
  – Beam-driven dielectric structures
  – Laser-driven plasmas \( \sim 10 \text{ GV/m} \)
  – Beam-driven plasmas
High Gradient RF Acceleration

* US Technology Options Study (2004) compared normal and superconducting collider designs (50 vs 28 MV/m)
  – Cost comparison helps set R&D directions

- Superconducting design has low gradient $\rightarrow$ $$
  \rightarrow$ R&D on high gradient acc

- Normal conducting design has high peak rf power and distribution requirements $\rightarrow$ $$
  \rightarrow$ R&D on low-cost rf power configurations
High Gradient RF Acceleration

* Extensive R&D on breakdown limitations in microwave structures
  - US High Gradient Collaboration
  - CERN and KEK

* Since 2004 ITRP decision:
  - X-band gradients have gone from ~50 MV/m loaded to demonstrations of ~150 MV/m loaded with ~100 MV/m expected
  - CERN has redesigned CLIC from 30 GHz to 12 GHz
GLC/NLC RF Power Sources (2004)

* Good success with modulator, pulse compression and rf distribution development. Klystrons achieved peak power and pulse length specs but breakdown rate was too high.
SLAC RF Power Source R&D

* Developing novel rf power sources for ILC / Project-X:
  – Marx solid state modulator – broad applicability of technology
  – Sheet beam klystron – broad applicability of SBK concept

* Developed rf power source for GLC/NLC:
  – SLED-II system delivered >500 MW
  – Two-Pac modulator fabricated but not fully tested – halted in 2004
  – X-band klystrons worked at 75 MW / 1.5 us but many breakdowns
    → Consider new output structures or reduced power levels using knowledge from high gradient studies

* Propose to complete X-band rf source development
  – Could provide a conservative option for an X-band design
  – Broad applicability: power sources for compact radiation sources and other compact linacs (complements High Gradient Program)
**Power Sources: Beam-Driven Acceleration**

* Hard to generate high peak power with rf sources
  - Long bunch trains can be efficiently generated in rf linacs
    - Microwave sources are cost effective for high average power
  - Beams can directly power rf, dielectric or plasma structures
    - Manipulate bunches to drive individual acc. sections synchronously

Example: beam-driven plasma acc
Single train for e+ and e- sides
Separation by RF deflectors

animation of beam drive distribution:

with 600 kJ per pulse at 100 Hz
Drive Beam Concept

* Drive beam concept combines best of SC, efficient low-cost rf power, with high gradient technology

- In a drive beam, rf power is converted to beam power in heavily-loaded structures
  → Efficient low-cost rf sources
- Rf distribution is minimal and accelerator structures are simple L- or S-band structures
- Drive beam can be manipulated in many ways to optimally couple to main accelerator
  → High AC→beam efficiency
SLAC Drive-Beam Experimental Facility: FACET

* Progress in beam-driven plasma and dielectric requires new facility to demonstrate single-stage e- and e+ acceleration
  - New FACET facility will provide high quality e+ & e- beams for studies of drive-witness studies of e-/e-, e+/e+ & e-/e+ acceleration
  - Plasma R&D will be discussed extensively in subsequent talk
    • Believe PWFA-LC concept could reduce cost/GeV significantly
    - FACET will also be used to develop beam-driven dielectric acceleration concepts as well as other beam physics studies
SLAC Next Generation DB Test Facility

* Generate a 80 GW drive beam using SLAC linac
  – Could be systems test for CLIC-like linear collider

The systems have been separated for clarity
The linacs are in the same tunnel
The rings are stacked vertically

Drive Beam Decelerator
1 GeV => 0.1 GeV 80 A

Sectors 2, 3, 4
High Gradient Linac
100 MeV/m, 300m, 30 GeV
Power Sources: Laser Systems

* Chirped Pulse Amplification allows a similar process
  – Generate a long pulse (ns timescale), amplify it, re-compress

A second pair of gratings reverses the dispersion of the first pair, and recompresses the pulse.
Power Systems: Lasers

* Present high power laser systems are too inefficient and too expensive
  – Billion $ industrial effort working on both issues
* Two approaches:
  – Laser wakefield (plasma) acceleration (10 GV/m)
  – Direct laser (dielectric) acceleration (1 GV/m)
* Very different laser requirements
  – Both require high average power → must generate beam power
  – Lasers are most efficient and cost effective near CW operation
    • Best use of expensive amplification medium
→ Pursuing direct laser acceleration with ~10,000 times lower peak power requirements than laser-driven plasma acceleration and more favorable cost scaling
Laser Acceleration R&D

* High gradient (~GV/m) and high efficiency are possible
* Capitalize on large diode-pumped solid state laser industry and on semiconductor fabrication technology
* Structures for High-Gradient Laser Accelerators
  - Photonic Crystal Fiber (Silica)
  - Photonic Crystal Woodpile (Silicon)
  - Transmission Grating (Silica)

* Possible to generate a reasonable set of parameters for a TeV-scale linear collider

**Luminosity** from a laser-driven linear collider must come from **high bunch repetition rate** and **smaller spot sizes**, which naturally follow from the small emittances required

<table>
<thead>
<tr>
<th>$E_{CM} = 1000$ GeV</th>
<th>Laser</th>
<th>JLC/NLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>$4 \times 10^4$</td>
<td>$7 \times 10^9$</td>
</tr>
<tr>
<td>$f_c$ (GHz)</td>
<td>3</td>
<td>11 kHz</td>
</tr>
<tr>
<td>$P_L$ (MW)</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>$\sigma_x/\sigma_y$ (nm)</td>
<td>0.5/0.5</td>
<td>330/5</td>
</tr>
<tr>
<td>$N_\gamma$</td>
<td>0.22</td>
<td>1.1</td>
</tr>
<tr>
<td>$\sigma_z$ (μm)</td>
<td>120</td>
<td>300</td>
</tr>
<tr>
<td>$\sigma_z/c$ (psec)</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>$\xi_1$</td>
<td>0.045</td>
<td>0.11</td>
</tr>
<tr>
<td>$L$</td>
<td>$2 \times 10^{34}$</td>
<td>$2 \times 10^{34}$</td>
</tr>
</tbody>
</table>
## Examples of TeV Collider Parameters

<table>
<thead>
<tr>
<th></th>
<th>Laser</th>
<th>Plasma</th>
<th>CLIC</th>
<th>&quot;ILC&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS Energy (GeV)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Luminosity (10^{34} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>2.4</td>
<td>3.5</td>
<td>2.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Luminosity in 1% of (E_{\text{cms}})</td>
<td>(\sim 2)</td>
<td>1.3</td>
<td>1.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Bunch charge (10^{10})</td>
<td>3.80E-06</td>
<td>1</td>
<td>0.37</td>
<td>2</td>
</tr>
<tr>
<td>Bunches / train</td>
<td>193</td>
<td>125</td>
<td>312</td>
<td>2820</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>1.50E+07</td>
<td>100</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>Beam Power (MW)</td>
<td>17.6</td>
<td>20</td>
<td>9.2</td>
<td>36.2</td>
</tr>
<tr>
<td>Emittances (\varepsilon_{n,x} / \varepsilon_{n,y}) (mm-mrad)</td>
<td>1e-4 / 1e-4</td>
<td>2 / 0.05</td>
<td>0.7 / 0.02</td>
<td>10 / 0.04</td>
</tr>
<tr>
<td>IP Spot sizes sx/sy (nm)</td>
<td>1.0 / 1.0</td>
<td>140 / 3.2</td>
<td>140 / 2</td>
<td>554 / 3.5</td>
</tr>
<tr>
<td>IP bunch length sz ((\mu\text{m}))</td>
<td>0.1 -&gt; 300</td>
<td>10</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>Drive beam / Laser / RF Power (MW)</td>
<td>88</td>
<td>58</td>
<td>36.8</td>
<td>80</td>
</tr>
<tr>
<td>Gradient (MV/m)</td>
<td>400</td>
<td>25000</td>
<td>100</td>
<td>31.5</td>
</tr>
<tr>
<td>Two linac length (km)</td>
<td>(\sim 4)</td>
<td>(\sim 6)</td>
<td>14</td>
<td>47</td>
</tr>
<tr>
<td>Drive beam / Laser / RF generation eff.</td>
<td>60%</td>
<td>45%</td>
<td>49%</td>
<td>53.95%</td>
</tr>
<tr>
<td>Drive beam / Laser / RF coupling eff.</td>
<td>20%</td>
<td>35%</td>
<td>25%</td>
<td>49.01%</td>
</tr>
<tr>
<td>Overall efficiency</td>
<td>12%</td>
<td>15.70%</td>
<td>12.10%</td>
<td>17.90%</td>
</tr>
<tr>
<td>Site Power (MW)</td>
<td>(\sim 180)</td>
<td>(\sim 170)</td>
<td>(\sim 150)</td>
<td>(\sim 300)</td>
</tr>
</tbody>
</table>
Summary

* SLAC is engaged in LHC, Super B, and Project-X R&D
  – Solid programs with significant effort
* P5 noted that a future lepton collider will be a necessary complement to the LHC
  – A linear collider can provide this capability
* Many options for the next-generation collider with different levels of development, risk and costs
  – ILC: most developed, lowest risk but high cost
  – X-band klystron: medium risk but significant cost savings
  – X-band Two-beam: higher risk but probably greater savings
  – Dielectric or Plasma acceleration: much higher risk but potential for much lower costs
* SLAC infrastructure can support critical HEP accelerator R&D