New Acceleration Techniques

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ICHEP 2010
Paris, France
July 28th, 2010
Introduction

• Context
  – Why new accelerator techniques?
  – Challenges in accelerator research?
  – Energy frontier concepts: Lepton Colliders and LEHC
  – Intensity frontier concepts: neutrinos and flavor factories

• Advances in accelerator techniques
  – High beam power
  – High beams brightness
  – High beam energy

• Issues for the future
Why New Acceleration Techniques?

• Accelerator have been primary tool to advance HEP frontiers
  – But accelerators have continued to increase in size and cost and appear to be approaching the limit that can be supported

• Need new technologies that are aimed at cost effective solutions

• Accelerator research very broad from materials to rf to nonlinear dynamics
  • Advances come from both fundamental research and directed R&D aimed at applications
Primary Challenges for Accelerator R&D

1. Beam power → average luminosity or brightness
   - Power (average current times energy) is frequently measured in megawatts and has both technical and physical limitations

2. Beam brightness and control → peak luminosity and radiation source brightness
   - Brightness is flux divided by 6-D phase space volume (emittance) which should be conserved after beam creation

3. Beam energy → energy reach or radiation wavelength
   - Critical problem for HEP requiring new cost-effective concepts
   - Novel concepts will enable new applications elsewhere as well

• Cost-effective approaches are needed across the field
• Paths to educate and attract more people to field
1. Beam Power Challenge

- Many critical technologies
  - Targets, collimators and dumps, materials, MPS, SCRF, …

Barry Barish, Saturday session

- LHC beam will be ~350 MJ
  - Beam collimation challenge!

Metallic collimator to reduce $Z_\perp$

- SCRF $\rightarrow$ high power proton beams for a number of new applications:
  - Neutrino beams
  - Neutrino factory & Muon Collider
  - Accelerator Driven Systems (sub-critical reactors) and transmutation of waste
2. Beam Brightness Challenge

• Beam brightness most tightly tied to ‘beam physics’
  – Some of the hot topics over the years:
    • Rf guns, final focus systems, emittance preservation, electron cloud, long-range wakefields, emittance exchange, …
  
• New e- guns 1000 x brighter than best storage/damping rings
  – Development pushed by FEL community
  – How can HEP benefit?

• High luminosity B-factories

Nano-beam scheme

Overlap region ~L

Hourglass condition: $\beta_y^* > \sim L$

Super B-factories described in Sat. afternoon session
2. Muon Cooling

- Ionization cooling is the critical technology for muon collider
  - Requires $10^6$ reduction of 6-dimensional emittance
  - Multiple concepts being studied

Stages of Muon cooling

See Gail Hansen, Saturday pm session
3. Beam Energy Challenge

- Size of a facility is a large cost driver
  - Recirculating systems, e.g. Muon Collider vs. Linear Collider
  - High gradient acceleration and high field magnets

- High field magnets
  - Examples abound: LHC, LEHC, MC
    - 20T for LEHC and 50T for MC
  - Continuous improvement in fields relies on fundamental research and directed magnet R&D

From Gail Hansen – Saturday
Superconducting Wire

From Palmer, AAC’2010

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High Gradient Acceleration

• 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 metallic structures \(~100 \text{ MV/m}\)
  – Beam-driven metallic structures \(~1 \text{ GV/m}\)
  – Laser-driven dielectric structures \(~10 \text{ GV/m}\)
  – Beam-driven dielectric structures
  – Laser-driven plasmas
  – Beam-driven plasmas
Beam-Driven vs Discrete Source

- Beam-driven accelerators could be cost effective for large installations
  - Electron beams couple better to structures than lasers or rf
  - Use highly efficient rf→beam transfer to generate drive beam
  - Electron beams easier to manipulate than rf
  - Consolidate main power sources

- Not appropriate for compact installations
- Complicated power handling
- Little experience with large systems and difficult to demonstrate in advance

CLIC Scheme
Schulte, Saturday
High Gradient RF Acceleration

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

- In the last few years:
  - X-band gradients have gone from ~50 MV/m loaded to demonstrations of ~150 MV/m loaded with ~100 MV/m expected
  - C-band rf unit is operating at 35 MV/m; 8 GeV XFEL almost finished
Accelerator Materials

Investigating Cu and Cu-alloys Mo, Ti, ...

New Acceleration Techniques

Intergranular fractures 500X
Understanding Cu Breakdown Limits

- Combination of analytic modeling, simulation and experiments have made great progress in understanding.
  - Still not at ‘Standard Model’ status but many advances since 2000’s

Doebert & Adolphsen

Tantawi & Dolgashev
Dielectric Structures

- Unlike Cu, dielectric structures have higher breakdown limits approaching 1 GV/m at THz frequencies
  - Extensive damage measurements to characterize materials
  - Structures can be either laser driven or beam driven (wakefield)

- Beam-driven structures
  - Frequencies are in GHz regime and dimensions are cm-level
  - Higher gradients than metallic structures but more difficult wakes

- Laser-driven structures
  - Use lasers to excite structures similar to microwave accelerators but with 10,000x smaller wavelengths

See Colby, Saturday am session
Concept of Beam-Driven Dielectric Linac

3GeV module (15m)
(38 DWPE & 38 DLA → fill factor=76%)  

1.33 GW output/Dielectric PETS;  
5% rf transportation loss;  
$E_{load} = 267$ MV/m ($I_b=6.5A$);  
Drive beam becomes 80MeV, main beam gain 3GeV

W. Gai, Argonne National Lab

Competitive rf-beam efficiency for the short pulse TBA

$$\eta_{bRF} = \frac{I_{beam}E_{load}L_s}{P_{rf}} \times \frac{T_{beam}}{T_{rf}} = 26\%$$

$T_{beam} = 16$ ns = 416 rf cycles (26 GHz)  
1 bunch / 2 rf periods, 0.5nC / bunch

<table>
<thead>
<tr>
<th>AWA Short Pulse (1.5TeV,e+)</th>
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<tbody>
<tr>
<td>Average drive beam current</td>
<td>80 mA</td>
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<tr>
<td>Average drive beam power</td>
<td>68.8 MW</td>
</tr>
<tr>
<td>Average rf power to main linac</td>
<td>60MW</td>
</tr>
<tr>
<td>Average main beam current</td>
<td>10.4 uA</td>
</tr>
<tr>
<td>Average main beam power</td>
<td>15.6 MW</td>
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</table>
Laser-Driven Dielectric Accelerator
(Accelerator-on-a-chip)

32 MeV Energy Gain

Input waveguide

Fiber coupled input
\( \lambda = 2 \, \mu m \)
20 \( \mu J/pulse \)
1 ps laser pulse

Cutaway sketch of coupler region

Image courtesy of B. Cowan, Tech-X.

Image courtesy of C. McGuinness, Stanford.

4-layer Structure Fabrication (completed at SNF)
Concept of Laser-Driven Dielectric Linac

**CW Injector**
- Warm rf gun
- Cold Preaccelerator
- Optical Buncher

433 MHz x 6E03 e⁻/macropulse (145 μpulse/macropulse)
εₙ~10⁻¹⁰ m (but note Q/εₙ << 1 nC/μm)

**Laser Accelerator**
- λ=2-4 μ, G~1 GeV/m
- Photonic Band Gap Fiber structures embedded in optical resonant rings
- Permanent Magnet Quads (B’~2.5 kT/m)

- DLA concept benefits from commercial laser and semiconductor industries
  - 100 MHz lasers with μJ per pulse
  - Potential cost break using lithographic techniques
  - Challenge is nm-level tolerances
Plasma Acceleration
(Beam-driven or Laser-driven)

- 50 GV/m demonstrated
  - Potential use for linear colliders and radiation sources

Simulation of 25 GeV PWFA stage

Laser pulse or electron beam
World-Wide Interest in Plasma Acc.

Plasma Acceleration on the Globe, T. Katsuoleas

D. H. Froula
2010 Advanced Accelerator Conference

Laser Wake Expts  Electron Wake Expts  e-/e+ Wake Expts
Compact Plasma Accelerators

- Plasma accelerators have many potential applications
  - Experiments at MPQ, Oxford Univ., Univ. of Edinburgh, JAERI aimed at generating a compact laser plasma-based FEL
    - Working on beam quality, stability, etc
  - Many other labs around the world have similar goals

Laser-driven soft-X-ray undulator source
Fuchs et al, Nature Physics (2009)
Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module’s 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module’s plasma channel. The collider’s positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm’s string of modules and accelerated just like the electrons.
Concept of Beam-Driven Plasma Linac

- Concept for a 1 TeV plasma wakefield-based linear collider
  - Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
    - Makes good use of PWFA R&D and 30 years of conventional rf R&D
  - Concept illustrates focus of PWFA R&D program
    - High efficiency
    - Emittance pres.
    - Positrons
  - Allows study of cost-scales for further optimization of R&D
Challenges for Plasma-based Colliders

• Luminosity drives many issues:
  – High beam power (20 MW) → efficient ac-to-beam conversion
  – Well defined cms energy → small energy spread
  – Small IP spot sizes → small energy spread and small $\Delta \epsilon$

• These translate into requirements on the plasma acc.
  – High beam loading of e+ and e- (for efficiency)
  – Acceleration with small energy spread
  – Preservation of small transverse emittances – maybe flat beams
  – Bunch repetition rates of 10’s of kHz
  – Highly efficient power sources
  – Acceleration of positrons
Plasma-based Linear Colliders

- DOE OHEP has funded two new plasma accelerator test facilities: FACET and BELLA
  - Both are aimed at linear collider relevant parameters:
    - ~1nC per bunch, many GeV energy gain, small emittance beams
    - Will address next generation challenges: emittance preservation, small energy spreads, stability and efficiency

### FACET Test Facility

#### Nominal FACET Beam Parameters

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Energy</td>
<td>23 GeV</td>
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<tr>
<td>Charge</td>
<td>3 nC</td>
</tr>
<tr>
<td>Sigma z</td>
<td>14 μm</td>
</tr>
<tr>
<td>Sigma r</td>
<td>10 μm</td>
</tr>
<tr>
<td>Peak Current</td>
<td>22 kAmps</td>
</tr>
<tr>
<td>Species</td>
<td>e⁻ &amp; e⁺</td>
</tr>
</tbody>
</table>

#### Beam Parameters Driven by Science Needs

Delivered to 100m area with three distinct functions:
1. Chicane for final stage of bunch compression
2. Final Focus for small spots at the IP
3. Experimental Area(s)

Advantageous location:
- Preserves e+ capability
- No bypass lines or interference with LCLS
- Linac setup virtually identical to SPPS/FFTB

### BELLA Test Facility

- BELLA Laser
- Gowning Room
- Final focus
- Plasma
- ~10 GeV e⁻ beam
- < 100 cm
Accelerator Research & Development

• Timescales for accelerator development are long
  – Need to maintain pipeline of new ideas
  – Test facilities and infrastructure are critical to enable R&D
  – Requires support for both fundamental and directed (project) R&D

• Large-scale projects tend to be conservative
  – Likely will require many systems-level demonstrations
  – Important to understand timescales and costs both for the R&D as well as the demonstrations

• Important to consider early applications
  – Provides funding while allowing consideration of operational issues while demonstrating technology
Success: C-band rf Technology

- C-band technology development began in mid-1990’s
  - Motivated by linear collider application
- Proceeded as independent research until 2002
  - Started development for Spring-8 XFEL
  - Industrialization proceeded rapidly
- Now installed 8 GeV C-band 35 MV/m linac
  - Commissioning fall of 2010