Reinventing the accelerator for the high-energy frontier

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Particle physics and particle accelerators have a shared history, destiny

- Key discoveries associated with innovations in accelerator and beam capabilities,
  - Lawrence (cyclotron, radioactive elements)
  - Rubbia and van der Meer (antiproton cooling, W/Z)
  - Tevatron...

- Consensus in the field emphasize the centrality of accelerator-based HEP
  - Large Hadron Collider (LHC)
  - International Linear Collider (ILC)
**Now mature (read: aging) ideas have driven HEP accelerators forward...**

- Induction acceleration (betatron)
- Resonant electromagnetic acceleration (cyclotron)
- Normal and superconducting RF cavities (linac, synchrotron)
- Alternating gradient magnetic focusing (synchrotron)
- Fixed targetry, exotic particle sources (synchrotron, linac)
- Colliding beams in synchrotrons (circular collider)
- Colliding beams in linear accelerators (linear collider)
- Cooling of particle beam phase space (colliders)
- Particle polarization (fixed targets/colliders)

**Are these enough for the future?**
**Do we need to re-invent the accelerator?**
Colliders and the energy frontier

- Fixed target energy for particle creation
  \[ U_{PC} \approx \sqrt{2U_b m_i c^2} \]

- Colliding beams (e.g. e^+e^-) makes lab frame into COM...
  \[ U_{PC} = 2U_b \]

- Exp’l growth in equivalent beam energy w/time
  - Livingston plot: “Moore’s Law” for accelerators
  - We are now falling off plot!

- Challenge in energy, but not only... luminosity as well
Present limitations of collider energy

- **Synchrotron radiation power loss**
  - Forces future $e^+e^-$ colliders to be *linear*
  - LEP (<207 GeV COM) is last of breed
  - Consider muons?
- **Large (!) circular machines for hadrons**
- **Scaling in size/cost**
  - Approaching unitary limits
    - Few $10^4$ m in dimension
    - Few $10^9$

$$P_s \propto \frac{\gamma^4}{R^2}$$

27 km circumference
Meeting the energy challenge

- **Avoid giantism**
  - Cost above all
- **Higher fields** give physics challenges
  - Circular machines: magnets
  - Linacs: accelerating fields
- **Enter new world of high energy density (HED) physics**
  - Impacts luminosity challenge...
**HED in future colliders I: the accelerator**

- **High fields in violent accelerating systems**
  - \( \frac{eE_z}{mc\omega} \sim 1 \)
  - Relativistic oscillations...

- **Diseases**
  - Breakdown, dark current
  - Peak power, heating

- **Approaches**
  - High frequency, normal cond.
  - Superconducting
  - Lasers and/or plasma waves!

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The Luminosity Challenge

Event rate = $L \sigma_c$

Luminosity: $L = \frac{N_{e+}N_{e-f_c}}{4\pi\sigma_x\sigma_y} = \frac{\gamma N_{e+}N_{e-f_c}}{4\pi\sqrt{\beta_x^*\beta_y^*} \cdot \sqrt{\epsilon_{x,n}\epsilon_{y,n}}}$

- Circular colliders provide high repetition rate
- Linear colliders have much lower repetition rate
  - Use large $N$, small $\sigma$; very large collective beam fields
  - Inherent scaling for higher energy not enough:
    $\sigma_c \propto \gamma^{-2}$
  - Must have very small phase space, focus well...
  - “Moore’s law” also for luminosity; precision beams
**HED in future colliders II: collective effects**

- **Wakefields** in linacs; limit on beam current and stability
- **Huge collective fields in collision; luminosity limit**
- **Linear colliders:**
  - Disruption (cold beams meet HED)
  - "Beamstrahlung"; energy loss/spread, nuisance particles
  - Classical electrodynamics and quantum processes
  - LC initial state not so "clean"

\[ F_{\perp,max} \approx \frac{N_b e^2}{\sigma_z \sigma_z} \approx 4 \text{ TeV/m in LC collision!} \]
Approaches to new collider paradigms

- Advancement of existing techniques
  - Higher gradient RF cavities (X-band LC)
  - Superconducting RF cavities (TESLA LC)
- Revolutionary new approaches (high gradient frontier)
  - New sources: i.e., lasers
  - New structures and/or media: i.e., plasmas
    - Truly immersed in high energy density physics

Another Talk

Muon collider schematic
(R. Johnson, 2005)
The road to the next accelerator

First fork in the road: Snowmass 2001
- Consensus that ILC is next machine post-LHC
- VLHC and muons deferred...

Second fork: ITRP Selection of Linear Collider Technology
- Barish committee evaluates “warm” v. “cold” accelerator technology

Superconducting option chosen

The crystal ball clears due to ITRP decision, 2004

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The LC technology selection

- Superconducting option provides most robust path to ILC
- Approach mitigates collective issues... try to avoid high energy density...
Are we on the road to a 3 TeV LC?

- Surprise? SC LC option does not scale well
  - Intrinsic low gradient
    - 24 MV/m TESLA 500 GeV
    - 35 MV/m TESLA 800 GeV
  - Theoretical limit close
- X-band still difficult
  - Power sources, efficiencies
- The linear accelerator paradigm is stressed to limit
Paths to higher acceleration fields

- High field means high frequency
  - Where is power source?
- Look to *wakefields*
  - Coherent radiation from bunched, relativistic e⁻ beam
  - Also powers more exotic schemes
  - Intense beams needed by other fields (e.g. X-ray FEL)
- What about lasers? Many TW of peak power
- Need to reinvent accelerator “structure”
  - Operate at small length scales
  - Tolerate *(or embrace)* high energy density
High gradients, high frequency, EM power from wakefields: CLIC @ CERN

CLIC 30 GHz,
150 MV/m structures
The optical accelerator

- Scale the linac from 1-10 cm \( \mu \)wave to 1-10 \( \mu \)m laser!
- Resonant structure (like linac)
- Slab symmetry (unlike linac)
  - Have copious power
  - Allows high beam charge
  - Suppresses wakefields
- Limit on gradient?
  - 1-2 GV/m, avalanche ionization
- Experiments
  - SLAC (1 \( \mu \)m)
  - 10 \( \mu \)m active media at BNL (PASER!)

Resonant dielectric structure schematic

Simulated field profile (OOPIC); half structure
**Evading material breakdown: The inverse FEL accelerator**

- Run FEL backwards with high power laser
- No nearby material; laser field very high
  - Magnetic field $\leftrightarrow$ synchrotron radiation
- Acceleration dynamics like ion linac
- Experiment at UCLA Neptune Lab 15 MeV beam accelerated to over 35 MeV
  - Higher harmonic interaction observed
  - Beam captured into "beamlets"
- IFEL is now workhorse microbuncher
Coherent Cerenkov wakes can be extremely strong
- Short beam, small aperture
- SLAC FFTB, \(N_b = 3E10\), \(\sigma_z = 20 \mu m\), \(a = 50 \mu m\), > 11 GV/m!
- Not optical — THz (unique source)

\[
e E_{\text{dec}} \approx -\frac{2N_b r_m e^2 \sqrt{\varepsilon - 1}}{\sqrt{2\pi} \sigma_z a \varepsilon}
\]

Simulated GV/m Cerenkov wakes for typical FFTB parameters (OOPIC -)

Contour plot showing \(E_z\) for \(a = 50 \mu m\)

Line out of \(E_z\) at \(r = 10 \mu m\) with \(a = 50 \mu m\)
UCLA/SLAC/LLNL expt. (2005)

Quartz fibers
- 350 µm OD, 100-200 µm ID,
- 1 cm length
- Observed breakdown threshold
  - 4 GV/m surface field
  - 2 GV/m acceleration field!
- Vaporization of Al cladding...
dielectric more robust
Past the breakdown limit: Plasma Accelerators

- Very high energy density laser or electron beam excites plasma waves as it propagates.
- Excitation by ponderomotive forces (laser) or space-charge (beam).
- Extremely high fields possible:

\[ E(\text{V/cm}) \propto \sqrt{n_e(\text{cm}^{-3})} \]

Ex: tenous gas density \( E \propto 100 \text{ GV/m}, \text{ for } n_e = 10^{18} \text{ cm}^{-3} \)
**Plasma Wakefield Acceleration (PWFA)**

- **Electron beam** shock-excites plasma
- Same scaling as Cerenkov wakes
- Beam denser than plasma; nonlinear plasma waves
- **Linear** wakefield response
  - $E_z$ constant in $r$, Focusing linear in $r$
  - Familiar: like linac + quadrupoles

\[
E \propto N_b k_p^2 \propto N_b \sigma_z^{-2}
\]
Ultra-high gradient PWFA: E164 experiment at SLAC FFTB

- Uses ultra-short beam (20 µm)
- Beam causes field ionization to create dense plasma (HED)
- Over 4 GeV(!) energy gain over 10 cm: >40 GV/m fields
- Self-injection of plasma e-
- On to energy doubling...
- New experiments: >40 GeV in 90 cm plasma (E167)
Plasma wave excitation with laser: creation of very high quality beam

- Trapped plasma electrons in LWFA give $\varepsilon_{n} \approx 1$ mm-mrad at $N_b > 10^{10}$
- Narrow energy spreads produced
  - accelerating in plasma channels

- Not every shot (yet)
- Looks like a beam. Now $> 1$ GeV!
- Other applications (FEL)
- Very popular
  - Lasers cost few $M$
Application: energy doubling of LC beams — the PWFA Afterburner Concept
Addressing the luminosity problem:

Final focus plasma lenses

Magnetic Quadrupoles

Uses magnetic forces to focus electron beam in one dimension at a time.

Underdense Plasma Lens

Uses electrostatic forces to focus electron beam in both dimensions.

\[ B' \approx 250 \text{ T/m} \]

\[ B'_{\text{equiv.}} = 3 \times 10^{-11} n_p \text{ (T/m)} \]

Linear collider densities give \( >10^7 \text{ T/m} \)

Low aberrations and short focal length

Ex: superconducting quad strength

Plasma lens strength
UCLA/FNAL Underdense Plasma Lens Expt.

Beam Spot Before:
- x FWHM = 1200 µm
- y FWHM = 1100 µm
- $n_b = 5 \times 10^{12}$ cm$^{-3}$

Beam Spot After (Ave.):
- x FWHM = 200 µm
- y FWHM = 300 µm
- $n_b = 1 \times 10^{14}$ cm$^{-3}$

The beam area is reduced by a factor of 22. Equivalent to luminosity enhancement.
Prospects for advanced accelerators in HEP

- Optical/plasma accelerators challenging
  - Very large fields
  - Very small dimensions and time scales
  - Multidisciplinary in the extreme
- Many collective effects to worry about
  - Can we achieve precision HEP beams in presence of HED?
- Still orders of magnitude in learning curve
  - Breath-taking recent progress
  - More people needed; students eager/welcome
Marx HEPAP Subpanel Support

- Increased in investment in accelerator science
- Special concern for long-range research

A major challenge for the accelerator science community is to identify and develop new concepts for future energy frontier accelerators that will be able to provide the exploration tools needed for HEP within a feasible cost to society. *The future of accelerator-based HEP will be limited unless new ideas and new accelerator directions are developed* to address the demands of beam energy and luminosity …