1. Changing the Paradigm of Particle Acceleration: Laser-driven Particle Beams

- laser-plasma interaction
- electron acceleration
- ion acceleration
Modern High-Energy Accelerators

CERN Geneva
LHC:
Energy: 14 TeV
27 km

Internat. Linear Collider (ILC)
250 GeV (e) + 250 GeV (e+)
Length: 31 km

FCC (Future Circular Collider)
80 – 100 km, 100 TeV

modern high-energy accelerators reach the limits of technical feasibility → novel concepts needed
Development of high-power lasers

G. Mourou, T. Tajima, Science 331, 41 (2011)
TW-PW Power Lasers

decrease the pulse duration or increase the pulse energy:

- 5-30J, 5-30fs $\Rightarrow$ 1 PW
  - high rep-rate: 1-5 Hz
  - compact
  - low energy content
  - other: Dresden, JAERI, KAERI, Hercules, Paris, ....

- 500J, 500fs $\Rightarrow$ 1 PW
  - med. rep-rate:
    - $\sim$ 1 shot per hour
  - large
  - medium energy content
  - other: PHELIX (GSI), Trident (Los Alamos), Texas-PW (Austin) ...

- 4MJ, 4ns $\Rightarrow$ 1 PW
  - low rep-rate:
    - <3 shots per day
  - very large
  - high energy content
  - other: LMJ (Bordeaux), Omega (Rochester), ....
High-Power Laser Facilities

- total peak power of all CPA systems operating (2011): ~25 PW
- by the end of 2015 planned CPA projects will bring the total to ~127 PW
- these CPA projects represent ~$4.3B of effort by ~1600 people
  (no NIF or LMJ)

source: ICUIL/C.P.J. Barty
Amplification of Ultra-Short Laser Pulses

- **Chirped Puls Amplification (CPA):**
  - very short laser pulse → large bandwidth (30 fs: ca. 30 nm)
  - direct amplification: would lead to destruction of amplifier medium
  → peak pulse intensity needs to be reduced

- pulse is stretched in time by dispersive delays (gratings)
- amplification
- compression by reversed delay

G. Mourou, D. Strickland, Optics Comm. 56, (1985) 219
- focussed laser intensities > $10^{19}$ W/cm$^2$:
  - target material ionizes, turns into plasma
  - $I > 10^{18}$ W/cm$^2$ : laser accelerates target electrons

\[ m' = m_e \cdot \gamma ; \quad \gamma = (1 - \frac{v^2}{c^2})^{-1/2} \]

- induced transparency:

laser light propagates in plasma:

- dispersion relation

\[ \omega^2 = \omega_p^2 + c^2 k^2 \]

- plasma frequency

\[ \omega_p^2 = 4\pi e^2 n_e / m \langle \gamma \rangle \]

\[ n_e : \text{electron density} \]

- dense plasma ($\omega < \omega_p$) : light cannot propagate, is reflected from the surface
- relativistic intensities: $\langle \gamma \rangle$ can be large
  $\rightarrow$ plasma becomes transparent
**Relativistic Self-Focusing**

- **index of refraction** $n_R$:
  
  \[ n_R = (1 - \left( \frac{\omega_p^2}{\langle \gamma \rangle} / \omega^2 \right)^{1/2} \]

  \[ n_R = (1 - \left( \frac{n_e}{n_c} / \langle \gamma \rangle \right)^{1/2} \]

- **relativistic self-focusing**:
  - transverse laser intensity profile:
    - relativistic effects: strongest on axis
    - $n_R$ will be modulated:
      - lower $\omega_p^\prime$ → higher $n_R$
    - phase velocity: $v_{ph} = c / n_R$
      - lower $v_{ph}$ in central region of pulse
  - plasma acts as focussing lens

  ... if critical power is exceeded: $P_{crit} = 17.4$ GW $\cdot n_c / n_e$
  - relativistic self-focusing depends on power, not intensity

- **critical electron density**:
  \[ n_c = n_e \left( \frac{\omega = \omega_p}{\omega} \right) \]
Relativistic Self-Focusing

Laser pulse

Electrons are dragged by laser pulse:
- enormous currents: ~ kA
- quasi-static B-field: ~ $10^4$ T

Electrons are pushed aside by light pressure:
- macroscopic charge separation
- quasi-static E-field: ~ TV/m

Free electrons:
- pushed aside by light pressure
- macroscopic charge separation
- quasi-static E-field: ~ TV/m

Laser pulse $10^{19}$ W/cm²

Plasma box ($n_e/n_c=0.6$)

B ~ mcω₀/ε ~ $10^8$ Gauss

Relativistic electron beam

j ~ en₀c ~ $10^{12}$ A/cm²

10 kA of 1-20 MeV electrons

Laser-Acceleration of Electrons

Pioneering work:

3 groups report on laser acceleration of (low-emittance) electron beams with (quasi-monochromatic) 70-200 MeV

Nature 431 (Sept. 2004):

rapidly expanding field:
since 2000: >156 x PRL
> 11 x Nature

P.G. Thirolf, LMU Munich

Carpathian Summer School, Sinaia (Romania), July 18, 2014
Wake field: radiation pressure of intense laser pulse excites plasma wave with high amplitude behind laser pulse

Invention: T. Tajima, J.M. Dawson
PRL 43 (1979)

- Electron acceleration by ‘surfing’ on the plasma wave
- Efficient for laser pulses shorter than plasma wavelength
- Well-known mechanism, but: how to inject electrons into wake field?
**Laser-‘Bubble-Acceleration’**

**electron injector:**
- wave breaking already after first plasma period
- creation of a soliton-like wakefield ‘bubble’
  (depleted from electrons)
- electrons continuously trapped into bubble
  $\rightarrow$ acceleration

---

**best for short laser pulses (<30 fs):**
$\rightarrow$ pulse length $< \lambda_p$

Laser-Accelerated Electron Beams

- plasma channel pre-formation in gas-discharge capillary:

Capillary discharge plasma waveguides

- Plasma fully ionized for $t > 50$ ns
- After $t \sim 80$ ns plasma is in quasi-equilibrium: Ohmic heating is balanced by conduction of heat to wall
- Ablation rate small: cap. lasts for $>10^6$ shots
- $n_p \approx 10^{17} - 10^{19}$ cm$^{-3}$
results from Berkeley group:

- acceleration in capillary:
  - d= 225μm/310 μm, l=33mm
  - laser: 12- 40 TW


E_e = 1.00(5) GeV  (in 3 cm !)
Laser-Accelerated Electron Beams

(published) world record: ≥3 GeV electrons: Gwangyu (Korea)
laser: 1PW, 30 J, 30 fs → 3\times10^{19} \text{ W/cm}^2
25 \mu\text{m} focal diameter: in center gap (2 mm) between gas jets
dual-stage laser wakefield acceleration: electron injection - acceleration

H.T. Kim et al., PRL 111,165002 (2013)
P.G. Thirolf, LMU Munich
Laser-Accelerated Electron Beams

- injected (seed) beam: 400 MeV
- $E_e > 3$ GeV for $n_e = 0.8 \cdot 10^{18}$ /cm$^3$
  (bubble radius $R \approx 1/\sqrt{n_e}$)
- beam divergence: 4 mrad
- charge: total $\sim 80$ pC, $> 2$ GeV: $\sim 10$ pC
- $\Delta E/E (> 1.5$ GeV) $\sim 50\%$ (spectrometer)

yet unpublished: 4 GeV from Berkeley group
perspective: 10 GeV achievable with existing lasers
Perspective: ‘Staging’ – Cascaded Electron Acceleration

- ‘staging’:
  - adapt the concept of cascaded acceleration cavities
  - requires: controlled, periodic, rapid plasma formation via discharge laser-pulse injection into each stage
  - refocusing of electron beams is inevitable to efficiently suppress beam-quality degeneration due to betatron-phase decoherence

- vision of a (cascaded) laser-driven electron-positron collider:

W. Leemans et al., Physics Today (March 2009): BELLA project (Berkeley)
Laser-Ion Acceleration

‘Traditional’ mechanism: Target Normal Sheath Acceleration (TNSA)

- electron acceleration
- hot (MeV) electrons penetrate the (μm) foil
- quasi-static field forms normal to target surface
- source size > laser spot

- use thick (metallic) foil targets (~μm)

proton source: CH contamination on foil surfaces (typically ~50Å)
ion source: foil bulk material/
proton removal by heating.

- space charge field:
  \[ E \sim \frac{T_{hot}}{\lambda_{Debye}} \sim \text{MeV/μm} = 10^{12} \text{ V/m} \]

- conversion efficiency:
  \[ E_{ion} \propto \sqrt{I_{Laser}} \]

first publications: E.L. Clark et al., PRL 84 (2000) 670
R. Snavely et al., PRL 85 (2000) 2945
**TNSA: Typical Results**

- exponential (thermal) energy spectra:

  ![Graph showing exponential energy spectra](image)

  - **Typical conventional accelerator**:
    - Target: 10μm Al
    - Temperature
      - ~ 1.8 MeV for 12 J
      - ~ 5 MeV for 85 J
    - Energy conversion
      - η~2 10^-3 for 12 J
      - η~5 10^-2 for 85 J
      - η~1 10^-1 for 400 J
    - Efficiency at 30-35 MeV
      - η_{hot}~10^{-5}-10^{-4}

- **Typical conventional accelerator**: ΔE/E = 10^-4 @ 20 MeV:
  - ΔEΔt ~ 2keV * 10ns = 2 * 10^{-5} eV s

- **Laser accelerator**:
  - ΔEΔt ~ 10 MeV * 1ps = 1 * 10^{-5} eV s
  - Comparable to conventional accelerator
Summary TNSA

- ultra compact proton/ion accelerator
  - high acceleration gradient $>10^{12}$V/m
- excellent beam emittance
- ps pulse duration at source
- perfect for probing ultrafast fields
- good efficiency (1-10%)
- exponential energy distribution
  - inefficient to highest energies near cut-off
- slow scaling to high beam energies
  - 100's of MeV protons requires very large lasers
  - could be overcome with micro-targets to limit lateral spreading
Novel Approach: Radiation Pressure Acceleration (RPA)

- thin targets (~ nm thick diamond-like carbon foils)

- light pressure ($\propto I$) scales more rapidly than fast-electron driven processes ($\sim I^{1/2}$)
- for $I \sim 10^{21}$ W/cm$^2$ thin foils can be accelerated to $\sim c$ in $<1$ ps
Hole-Boring vs. Light Sail Regime

- **light sail regime:**
  - the target is sufficiently thin for the laser pulse to punch through the target and accelerate a slab of plasma as a single object

  ultra thin foil (d~5-10 nm)  electrons leave the foil
  circularly polarized laser pulse: focused on an ultra-thin foil
  → fully ionizing the foil.

- **hole boring regime:**
  - laser pulse interacts with semi-infinite target (overdense plasma: opaque)
  → driving material ahead of it as a piston
  → no interaction with the target rear surface
RPA vs TNSA

- 5 \times 10^{20} \text{ W/cm}^2:
  - RPA becomes comparable to TNSA
  - can \( E_{\text{max}} \sim I \) - scaling be exploited?


- \( I > 10^{23} \text{ W/cm}^2 \):
  - RPA dominates over TNSA
  \rightarrow \text{quasi-monoenergetic GeV protons (for } E_{\text{laser}} = 10 \text{ kJ)}

Comparison: TNSA vs RPA @ $10^{21}$ W/cm$^2$

- RPA dominates for realistic intensities using *circular polarization*
- excellent longitudinal emittance possible: $\Delta E\Delta t \sim 10$ MeV * 5 fs $\sim 5 \cdot 10^{-8}$ eV s
- extremely short pulse duration: foil thickness/c $\sim 100$ attoseconds

almost all protons in small phase-space volume

note: beam is quasi-neutral

courtesy: M. Zepf
- thin foils can be accelerated to high energies
- linear scaling – until relativistic effects become important

- 200 MeV predicted in quasi-monoenergetic beam for \(7 \cdot 10^{20} \text{ W/cm}^2\)
  → feasible with current generation of lasers (e.g. 33 J in 64 fs - Astra Gemini, Oxford)
  → ELI-NP 10PW will reach GeV/u (300J in 30 fs)
First Experiments with Circular Polarization

- **laser:** $5 \cdot 10^{19} \text{ W/cm}^2$, 5 nm DLC target foil

- **protons:** > 160 MeV (DLC target: 50 nm)

- **carbon ions:** > 400 MeV (DLC: 200 nm)


D. Jung et al., N. Jour. Phys. 15 (2013) 023007

P.G. Thirolf, LMU Munich

Carpathian Summer School, Sinaia (Romania), July 18, 2014
**RPA Summary**

- highly desirable beam qualities predicted with circular polarization
  - low divergence
  - high efficiency
  - quasi-monoenergetic distribution
  - little other radiation (γ’s, fast electrons)
  - sub-fs pulse duration

- limitations:
  - denting: no longer normal incidence, hot electrons produced
  - radial mass loss: foil becomes transparent (RPA stops)
  - growth of instabilities

- laser requirements at the high end
  - short pulse (< 100 fs)
  - high contrast (≥ 10^{12})
  - laser focal spot shaping required

- optimum laser: 10's of J, <100fs, >1Hz rep. rate
  - standard Ti:Sapphire with diode pumped final stage
  - mid-IR (≈3-10 μm) OPCPA diode-pumped systems
Laser-driven Ion Beam Divergence

5-20 nm thin DLC foils:
much improved beam quality compared to μm targets

Proton beam: half-angle 2°
Summary: Laser Particle Acceleration

- high-power (100 TW – PW), short-pulse (few fs) lasers
- focused intensity on target: $10^{20} – 10^{24} \text{ W/cm}^2$

Electron acceleration (gas jet)

LWFA
(laser wake-field acceleration)

- field $\sim TV/m$
- $E_e \leq \text{GeV}$
- $E_{\text{ion}} \leq 150 \text{ MeV/u}$
- charge $\sim 10$’s of pC
- $\Delta E/E \sim 1$-$2\%$ (e$^-$)
- $\epsilon \sim 10^{-5}$ mm mrad

Ion acceleration (thin foil)

RPA
(radiation-pressure acceleration)

- $E_e \leq 10^2 \text{ mm mrad}$

E. Esarey et al., Rev. Mod. Phys. 81 (2009) 1229

Summary

- laser-accelerated ions: more than a niche technology?
  - unrivalled for time resolved probing
  - excellent emittance
  - compared to conventional accelerators: what is needed to be competitive?
    - higher average flux ✓
    - narrow angular distribution ✓
    - narrow energy distribution (not simply slicing): RPA
    - higher endpoint energy: 200 MeV protons for 200 mm range in H₂O (e.g. for hadron therapy)
  - prerequisite for novel nuclear reaction schemes
  - exploit unprecedented ion bunch density

- realization of these schemes:
  - (increasingly) large number of TW-PW laser facilities worldwide
  - ELI-NP laser research infrastructure in Bucharest (10 PW)