Advanced Accelerator Concepts

Andrea.Mostacci@uniroma1.it

(special thanks to Massimo Ferrario)

Constantia – 22 September 2018
Fermi’s Globatron: ~5000 TeV Proton beam
1954 the ultimate synchrotron

$B_{\text{max}}$ 2 Tesla
$\rho$ 8000 km
fixed target
$3 \text{ TeV cm}$
170 $\text{G}$$\text{s}$
1994
Touschek’s Anello Di Accumulazione (ADA) 1961 the first e+e- Collider

\[ E_{CM} = \sqrt{2E_1 m_2} \]

\[ E_{CM} = 2E \]
Fixed Target equivalent accelerator energy versus year

GeV

Year

10^10

10^8

10^6

10^4

10^2

10^0

Without further novel technology, we will eventually need an accelerator as large as Hawking expected.

Big science machines ...

- **LHC**
  - 27 km, 8.33 T
  - 14 TeV (c.o.m.)
- **HE-LHC**
  - 27 km, **16 T**
  - 33 TeV (c.o.m.)
- **VHE-LHC**
  - 80 km, **20 T**
  - 100 TeV (c.o.m.)
- **VHE-LHC**
  - 100 km, **16 T**
  - 100 TeV (c.o.m.)
... or accelerator on a Chip?
SLAC Now and Tomorrow?
Modern accelerators require high quality beams:  
High Luminosity & High Brightness

High Energy & Low Energy Spread

\[ L = \frac{N_e + N_e^+ f_r}{4 N e x y} \]

- N of particles per pulse => 10^9
- High rep. rate f_r => bunch trains
- Small spot size => low emittance
- Short pulse (ps to fs)
- Little spread in transverse momentum and angle => low emittance
HIGH GRADIENT AAC ROAD MAP

1. Miniaturization of the accelerating structures (~resonant)

2. Wake Field Acceleration (~transient) (LWFA, PWFA, DWFA)

   - Power sources
   - Accelerating structures
   - High quality beams
The simplest solution: particle interacting with a plane wave in free space (e.g. laser)
Lawson-Woodward Theorem


The net energy gain of a relativistic electron interacting with an electromagnetic field in vacuum is zero.

The theorem assumes that
(i) field is in vacuum with no walls or boundaries present,
(ii) the electron is highly relativistic ($v \approx c$) along the acceleration path,
(iii) no static electric or magnetic fields are present,
(iv) the region of interaction is infinite,

\[
F = \frac{eE_x}{2} \cos \left( \frac{t}{2} \right)
\]
Taking into account the boundary conditions the accelerating component of the field becomes:

\[ E_z(x, z, t) = (E_+ \sin \theta) e^{i \omega t} e^{i(kz \cos \alpha - x \sin \theta)} (E_+ \sin \theta) e^{i \omega t} e^{-ikz \cos \alpha + x \sin \theta} \]

\[ = 2iE_+ \sin \theta \sin(kx \sin \theta) e^{i \omega t} e^{-ikz \cos \alpha} \]

- **z-TW pattern**
- **x-SW pattern**
$v_z = \frac{k_z}{k \cos \theta} = \frac{c}{\cos \theta} > c$
Conventional RF accelerating structures
Typical breakdown and pulse heating damage is standing-wave structure cell.
High field -> Short wavelength -> ultra-short bunches -> low charge
① Miniaturization of the accelerating structures (resonant)

② Wake Field Acceleration (transient) (LWFA, PWFA, DWFA)
Accelerating structures routinely used

S-BAND (2.856 GHz)

C-BAND (5.712 GHz)

X-BAND (12 GHz)

SLAC linac

3 m long sections
3.1 km total accelerator length
960 accelerating structures
up to 50 GeV electron energy
~20 MV/m average acc. gradient

NLC-CLIC projects
0.5-1 m long sections
up to 100 MV/m acc. gradient

Accelerating gradient (~f^{1/2})

Dipole wakefield intensity (f^3)

Complication in fabrication technology

Available commercial components

Courtesy of D. Alesini, INFN-LNF
Accelerating structures and EM spectrum

8.56MHz

3GHz

110GHz

450GHz

800MHz

1.3GHz
Future plans for the high gradient collaboration

- The collaboration during the next 5 will address 4 fundamental research efforts:
  - Continue basic physics research, materials research frequency scaling and theory efforts.
  - Put the foundations for advanced research on efficient RF sources.
  - Explore the spectrum from 90 GHz to THz
    - Sources at MIT
    - Developments of suitable sources at 90 GHz
    - Developments of THz stand alone sources
    - Utilize the FACET at SLAC and AWA at ANL
    - Address the challenges of the Muon Accelerator Project (MAP)

mm-Wave structure to be tested at FACET
THz-driven linear acceleration

THz accelerator

Segmented waveplate

Photoemitted electrons from d.c. gun

THz E-field polarization longitudinal + radial

THz mirror

Electrons to energy spectrometer

ARTICLE
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DOI: 10.1038/ncomms9486

Terahertz-driven linear electron acceleration

Emilio A. Nanni¹, Wencian R. Huang¹, Kyung-Han Hong¹, Koustuban Ravi¹, Arya Fallahi²,³, Gustavo Moriena⁴, R. Dwayne Miller³,⁴,⁵ & Franz X. Kärntner¹,²,³,⁶
Direct Laser Acceleration

DLA
Laser based dielectric accelerator
Dielectric Photonic Structure

- Why photonic structures (periodic optical nanostructures)?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication

- Dynamics concerns

- External coupling schemes

Schematic of GALAXIE monolithic photonic DLA
Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles

Laser pulses (180 degrees out of phase)

e-beam
Limitations of Direct Laser Acceleration

- Low emittance
- Low charge
- Longitudinal dynamics
- Timing issue
- Alignment issues

Inverse Free Electron Laser
Accelerator on chip option

Rasmus Ischebeck for the ACHIP Collaboration, EAAC 2017
1. Miniaturization of the accelerating structures (~resonant)

2. Wake Field Acceleration (~transient) (LWFA, PWFA, DWFA)
What about wakefields?

(Particle Driven) Wakefield Acceleration paradigm

the EM fields of the accelerating wave are created inside of the structure itself by an intense, relativistic particle beam. This drive beam may be of lower quality and energy than a trailing, accelerating beam. Further, the drive beam may be specially shaped (in, e.g. a rising triangular current profile) to give much larger acceleration in the trailing beam than deceleration in the driver.
Wakefield feeding RF structures

Courtesy of Cho Ng, SLAC
Dielectric Wakefield Acceleration

DWA
Dielectric Wakefield Accelerator
Dielectric Wakefield Accelerator
Dielectric Wakefield Accelerator

The image shows a diagram of a dielectric wakefield accelerator, including labels for the hollow core, dielectric layer, cladding, wakefields, and drive beam. A graph illustrates the electric field strength ($E_z$) as a function of position ($Z$) with two curves, possibly representing different conditions or stages of the process. Below the diagram, there are some technical details related to CST software, indicating the electrical field ($E$) at a specific time ($t$) and sample ($x$) with values such as 2D Maximum [V/m] = 2.76e+06 and Cutplane Normal: 1, 0, 0.
Dielectric Wakefield Accelerator
Plasma Acceleration
Surface charge density
\[ \sigma = e n \delta x \]

Surface electric field
\[ E_x = -\sigma/\varepsilon_0 = -e n \delta x/\varepsilon_0 \]

Restoring force
\[ m \frac{d^2 \delta x}{dt^2} = e E_x = -m \omega_p^2 \delta x \]

Plasma frequency
\[ \omega_p^2 = \frac{n e^2}{\varepsilon_0 m} \]

Plasma oscillations
\[ \delta x = (\delta x)_0 \cos(\omega_p t) \]
Breakdown limit?

\[ E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[ \frac{GeV}{m} \right] \cdot \sqrt{n_0 \left[ 10^{18} cm^{-3} \right]} \]
From linear regime ...
... to quasi linear and non linear regime
What about externally injected electrons or positrons?
Wake Field Acceleration 1
Laser Driven
LWFA
Direct production of e-beam
Diffraction - Self injection - Dephasing – Depletion
Regimes: Linear & Non-Linear

**Linear**

FIG. 8. Time-averaged density variation $\delta n/n_0$ (dashed curve) and axial electric field $E_z/E_0$ (solid curve) in an LWFA driven by a Gaussian laser pulse (pulse is moving to the right, centered at $k_p \xi = 0$ with rms intensity length $L_{\text{rms}} = k_p^{-1}$) for (a) $a_0 = 0.5$ and (b) $a_0 = 2.0$.

**Non-Linear**
Colliding Laser Pulses Scheme

The first laser creates the accelerating structure, a second laser beam is used to heat electrons.

The first laser creates the accelerating structure, a second laser beam is used to heat electrons.

Colliding Laser Pulses Scheme

The first laser creates the accelerating structure, a second laser beam is used to heat electrons.

Trapped electrons

Acceleration phase

Stable Laser Plasma Accelerators
Inverse Compton Scattering: New scheme

A single laser pulse

A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

No alignment: the laser and the electron beams naturally overlap

Save the laser energy!

50 TW / 30 fs laser

He gas jet

Foil, blade

X rays

Gas

Back reflected laser pulse

Plasma mirror

High energy X ray beam

1st European Advanced Accelerator Concepts Workshop, La Biodola, Isola d'Elba - Italy, June 2-7 (2013)

http://loa.ensta.fr/
BELLA Facility: state-of-the-art 1.3 PW-laser for laser accelerator science: >42 J in <40 fs (> 1PW) at 1 Hz laser and supporting infrastructure at LBNL

Critical HEP experiments:
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration
Capillary Discharge
Capillary in the beam line
Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets.

Single shot spectra 30 MeV - 11 GeV

Magnetic spectrometer

CCD array

Spectrometer

FROG

Mode imager

Gas jet

Calorimeter

Wedge with hole

ICT

Phosphor screen

Capillary discharge waveguide

e⁻ bunch

Hydrogen

0 V

- V

Big Laser In

Capillary discharge
4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012

Electron beam spectrum

INF&RNO simulation*

- **Laser** (E=15 J):
  - Measured) longitudinal profile (T₀ = 40 fs)
  - Measured far field mode (w₀ = 53 μm)
- **Plasma**: parabolic plasma channel (length 9 cm, n₀ ~ 6-7x10¹⁷ cm⁻³)

<table>
<thead>
<tr>
<th></th>
<th>Exp.</th>
<th>Sim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>4.25 GeV</td>
<td>4.5 GeV</td>
</tr>
<tr>
<td>ΔE/E</td>
<td>5%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Charge</td>
<td>~20 pC</td>
<td>23 pC</td>
</tr>
<tr>
<td>Divergence</td>
<td>0.3 mrad</td>
<td>0.6 mrad</td>
</tr>
</tbody>
</table>

W.P. Leemans et al., PRL 2014
Active Plasma lens

The use of plasma wakefields for creating lenses with extreme focusing strength was proposed for a linear collider final focus (5 orders stronger than conventional magnets).

- Focusing field produced by electric discharge in a plasma-filled capillary
  - $B_\phi(r) = \frac{1}{2} \int_0^r \mu_0 J(r') dr'$

- Radial focusing
  - $X/Y$ planes are not dependent as in quads

- Weak chromaticity
  - Focusing force scales linearly with energy

- Compactness
  - Higher integrated field than quad triplets

- Independent from beam distribution
  - Not sensitive to longitudinal/transverse charge profile as in passive plasma lenses

An example of active Plasma lens
Multistage coupling of independent laser–plasma accelerators

S. Steinke¹, J. van Tilborg¹, C. Benedetti¹, C. G. R. Geddes¹, C. B. Schroeder¹, J. Daniels¹,³, K. K. Swanson¹,², A. J. Gonsalves¹, K. Nakamura¹, N. H. Matlis¹, B. H. Shaw¹,², E. Esarey¹ & W. P. Leemans¹,²
## Parameter Set for LPWA LC

<table>
<thead>
<tr>
<th>Case: CoM Energy (Plasma density)</th>
<th>1 TeV ($10^{17}$ cm$^3$)</th>
<th>1 TeV ($2 \times 10^{15}$ cm$^3$)</th>
<th>10 TeV ($10^{17}$ cm$^3$)</th>
<th>10 TeV ($2 \times 10^{15}$ cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per beam (TeV)</td>
<td>0.5</td>
<td>0.5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Luminosity ($10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>2</td>
<td>2</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Electrons per bunch ($\times 10^{10}$)</td>
<td>0.4</td>
<td>2.8</td>
<td>0.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Bunch repetition rate (kHz)</td>
<td>15</td>
<td>0.3</td>
<td>15</td>
<td>0.3</td>
</tr>
<tr>
<td>Horizontal emittance $\gamma \varepsilon_x$ (nm-rad)</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Vertical emittance $\gamma \varepsilon_y$ (nm-rad)</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$\beta^*$ (mm)</td>
<td>1</td>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Horizontal beam size at IP $\sigma_x^*$ (nm)</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Vertical beam size at IP $\sigma_y^*$ (nm)</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Disruption parameter</td>
<td>0.12</td>
<td>5.6</td>
<td>1.2</td>
<td>56</td>
</tr>
<tr>
<td>Bunch length $\sigma_z$ (μm)</td>
<td>1</td>
<td>7</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Beamstrahlung parameter $\Upsilon$</td>
<td>180</td>
<td>180</td>
<td>18,000</td>
<td>18,000</td>
</tr>
<tr>
<td>Beamstrahlung photons per e, $n_\gamma$</td>
<td>1.4</td>
<td>10</td>
<td>3.2</td>
<td>22</td>
</tr>
<tr>
<td>Beamstrahlung energy loss $\delta E$ (%)</td>
<td>42</td>
<td>100</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td>Accelerating gradient (GV/m)</td>
<td>10</td>
<td>1.4</td>
<td>10</td>
<td>1.4</td>
</tr>
<tr>
<td>Average beam power (MW)</td>
<td>5</td>
<td>0.7</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td>Wall plug to beam efficiency (%)</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>One linac length (km)</td>
<td>0.1</td>
<td>0.5</td>
<td>1.0</td>
<td>5</td>
</tr>
</tbody>
</table>
ICAN (European Project)

CAN Coherent Amplification Network

« The future of Accelelaor is Fiber »
Wake Field Acceleration 2
Beam Driven
PWFA

Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield

S. Corde\textsuperscript{1,2}, E. Adli\textsuperscript{1,3}, J. M. Allen\textsuperscript{1}, W. An\textsuperscript{4,5}, C. I. Clarke\textsuperscript{1}, C. E. Clayton\textsuperscript{4}, J. P. Delahaye\textsuperscript{1}, J. Frederico\textsuperscript{1}, S. Gessner\textsuperscript{1}, S. Z. Green\textsuperscript{1}, M. J. Hogan\textsuperscript{1}, C. Joshi\textsuperscript{4}, N. Lipkowitz\textsuperscript{1}, M. Litos\textsuperscript{1}, W. Lu\textsuperscript{6}, K. A. Marsh\textsuperscript{4}, W. B. Mori\textsuperscript{4,5}, M. Schmeltz\textsuperscript{1}, N. Vafaie-Najafabadi\textsuperscript{4}, D. Walz\textsuperscript{1}, V. Yakimenko\textsuperscript{1} & G. Yocky\textsuperscript{1}
CONCEPTUAL DESIGN OF THE DRIVE BEAM FOR A PWFA-LC*

S. Pei, M. J. Hogan, T. O. Raubenheimer, A. Seryi, SLAC, CA 94025, U.S.A.
H. H. Braun, R. Corsini, J. P. Delahaye, CERN, Geneva

Fig. 1: Concept for a multi-stage PWFA Linear Collider.
Table 1: Key Parameters of the Conceptual Multi-Stage PWFA-based Linear Collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main beam: bunch population, bunches per train, rate</td>
<td>$1 \times 10^{10}$, 125, 100 Hz</td>
</tr>
<tr>
<td>Total power of two main beams</td>
<td>20 MW</td>
</tr>
<tr>
<td>Drive beam: energy, peak current and active pulse length</td>
<td>25 GeV, 2.3 A, 10 $\mu$s</td>
</tr>
<tr>
<td>Average power of the drive beam</td>
<td>58 MW</td>
</tr>
<tr>
<td>Plasma density, accelerating gradient and plasma cell length</td>
<td>$1 \times 10^{17}$ cm$^{-3}$, 25 GV/m, 1 m</td>
</tr>
<tr>
<td>Power transfer efficiency drive beam$\rightarrow$plasma$\rightarrow$main beam</td>
<td>35%</td>
</tr>
<tr>
<td>Efficiency: Wall plug$\rightarrow$RF$\rightarrow$drive beam</td>
<td>$50% \times 90% = 45%$</td>
</tr>
<tr>
<td>Overall efficiency and wall plug power for acceleration</td>
<td>15.7%, 127 MW</td>
</tr>
<tr>
<td>Site power estimate (with 40MW for other subsystems)</td>
<td>170 MW</td>
</tr>
<tr>
<td>Main beam emittances, x, y</td>
<td>2, 0.05 mm-mrad</td>
</tr>
<tr>
<td>Main beam sizes at Interaction Point, x, y, z</td>
<td>0.14, 0.0032, 10 $\mu$m</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$3.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Luminosity in 1% of energy</td>
<td>$1.3 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

Fig. 1: Concept for a multi-stage PWFA Linear Collider.
ILC – International Linear Collider
### Table 2: ILC energy upgrade by PWFA after-burner

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>ILC</th>
<th>ILC</th>
<th>ILC + PWFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (cm)</td>
<td>GeV</td>
<td>500</td>
<td>1000</td>
<td>PFWA = 500 to 1000</td>
</tr>
<tr>
<td>Luminosity (per IP)</td>
<td>$10^{34}$cm$^{-2}$s$^{-1}$</td>
<td>1.5</td>
<td>4.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Peak (1%)Lum/(IP)</td>
<td>$10^{34}$cm$^{-2}$s$^{-1}$</td>
<td>0.88</td>
<td>2.2</td>
<td>1.3</td>
</tr>
<tr>
<td># IP</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Length</td>
<td>km</td>
<td>30</td>
<td>52</td>
<td>30</td>
</tr>
<tr>
<td>Power (wall plug)</td>
<td>MW</td>
<td>128</td>
<td>300</td>
<td>175</td>
</tr>
<tr>
<td>Lin. Acc. grad.(p/eff)</td>
<td>MV/m</td>
<td>31.5/25</td>
<td>36/30</td>
<td>7600/1000</td>
</tr>
<tr>
<td># particles/bunch</td>
<td></td>
<td>10$^{10}$</td>
<td>2</td>
<td>1.74</td>
</tr>
<tr>
<td># bunches/pulse</td>
<td></td>
<td>1312</td>
<td>2450</td>
<td>2450</td>
</tr>
<tr>
<td>Bunch interval</td>
<td>ns</td>
<td>554</td>
<td>366</td>
<td>366</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>Hz</td>
<td>5</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Beam power/beam</td>
<td>MW</td>
<td>5.2</td>
<td>13.8</td>
<td>13.8</td>
</tr>
<tr>
<td>Norm Emitt (X/Y)</td>
<td>$10^{-4}$/10$^{-4}$radm</td>
<td>10/35</td>
<td>10/30</td>
<td>10/30</td>
</tr>
<tr>
<td>$S_x$, $S_y$, $S_z$ at IP</td>
<td>nm, nm, mµm</td>
<td>474/5.9/300</td>
<td>335/2.7/225</td>
<td>286/2.7/20</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>mrad</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Av # photons</td>
<td></td>
<td>1.70</td>
<td>2.0</td>
<td>0.7</td>
</tr>
<tr>
<td>δb beam-beam</td>
<td>%</td>
<td>3.89</td>
<td>9.1</td>
<td>9.3</td>
</tr>
<tr>
<td>Upsilon</td>
<td></td>
<td>0.03</td>
<td>0.09</td>
<td>0.52</td>
</tr>
</tbody>
</table>

#### Figure 3: ILC energy upgrade by PWFA technology

- **a)** ILC
  - e linac
  - 11 km
  - 500 GeV

- **b)** after-burner mode
  - e linac
  - 11 km
  - 1 TeV

- **c)** Complete replacement of ILC cavities by PWFA
  - e linac
  - 11 km
  - 250 m
  - 22 TeV

In the extreme case of PWFA technology use only (c).
Proton-driven Plasma Wakefield Acceleration Collaboration: Accelerating $e^-$ on the wake of a $p^+$ bunch
WHY p⁺-DRIVEN PWFA?

✧ ILC, 0.5TeV bunch with $2 \times 10^{10}e^-$ ~1.6kJ
✧ SLAC, 20GeV bunch with $2 \times 10^{10}e^-$ ~60J
✧ SLAC-like driver for staging (FACET= 1 stage, collider 10⁺ stages)
✧ SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
✧ LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
✧ A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
✧ Large average gradient! (≥1GeV/m, 100’s m)

© P. Muggli
Discharge configuration II

preliminary tests with the AWAKE 3 meter test tube at IC - 2016

very promising results
... reliable, low jitter plasma formation

scalability of electric circuit for plasmas > 10 m seem achievable...
Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli, A. Ahuja, O. Apsimon, R. Apsimon, A.-M. Bachmann, D. Barrientos, F. Batsch, J. Bauche, V.K. Berglyd Olsen,
Figure 1: Schematic layout of a 2 TeV CoM electron-positron linear collider based on a modulated proton-driven plasma wakefield acceleration.
Protons and Ions
Protons and ions are too slow to catch the wave - only indirect acceleration via electrons

Laser Driven Acceleration of Protons
- Direct acceleration in laser field > $10^{25}$ W/cm² far beyond current lasers
- Plasma wakefield phase velocity too fast for protons & ions
- only indirect ways

Target Normal Sheath Acceleration
"best understood" candidate:
- laser creates blow-off plasma on front surface
- backside expansion accelerated electrons ionize hydrogen
- hot electrons create electric field (by space charge)
- causes acceleration of protons (electrons slowing down – end of acceleration)
- neutralized bunch of comoving p and e generated

Need typically:
50 J 500 fs $\rightarrow$ 100 TW
30 μm radius $\rightarrow$ $10^{19}$ W/cm²
3 Steps towards a reliable PWA

① High Gradient – Low e- Beam Quality

② High e+e- Beam Quality – Low Gradient

③ High e+e- Beam Quality - High Gradient
EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

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There are several options for high gradient structures:

- **RF accelerating structures, from X-band to K-band** => $100 \text{ MV/m} < E_{\text{acc}} < 1 \text{ GV/m}$

- **Dielectric structures, laser or particle driven** => $1 \text{ GV/m} < E_{\text{acc}} < 5 \text{ GV/m}$

- **Plasma accelerator, laser or particle driven** => $1 \text{ GV/m} < E_{\text{acc}} < 100 \text{ GV/m}$
Conclusions (II)

The R&D now concentrates on **beam quality, stability, staging and continuous operation**.

The R&D is pursued in a modern way

- **Collaborative effort** (networking, both in Europe and US)
- Building a **demonstrator facility**
- Strong use of **simulation** (start-to-end, multidisciplinary)

**Compact machine** to spread the use of particle accelerators

**Application driven** accelerators (HEP, radiation sources, material science, radio-biology, ...)

Accelerator physics is opening to different fields (laser science, plasma physics, computer science, advanced technology...) ...**very interesting**!
CAS on High Gradient Wakefield Accelerator

Hotel Do Mar, Sesimbra Portugal,
11-22 March 2019
Thank you