Advanced Accelerator Concepts

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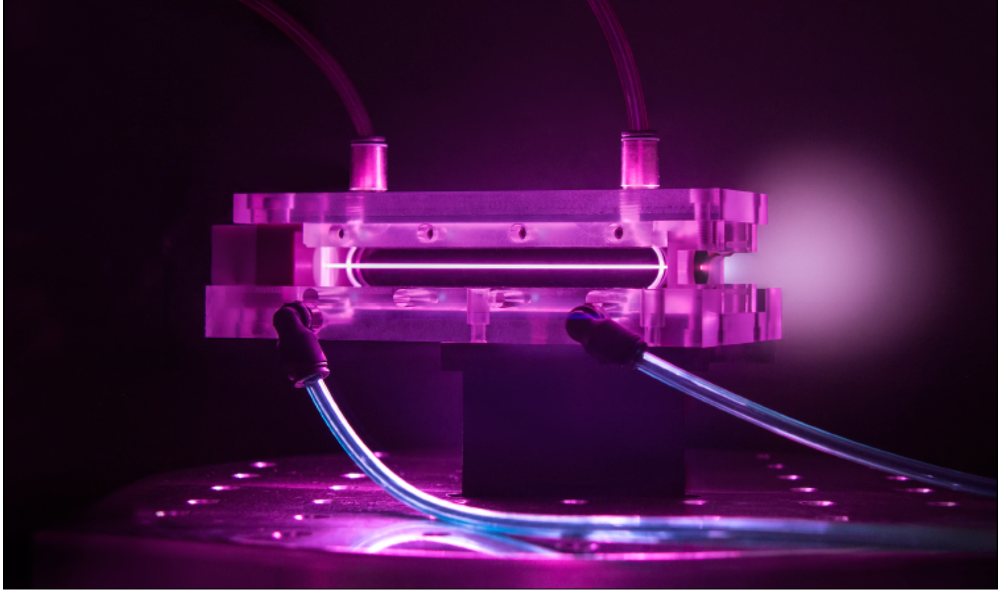
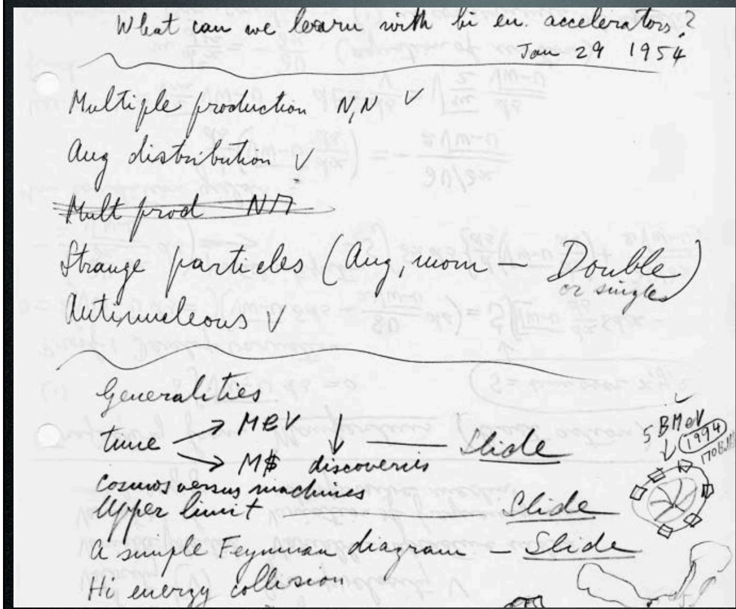


Globatron: 5000 TeV, 170 B$, fixed target 3 TeV c.m.

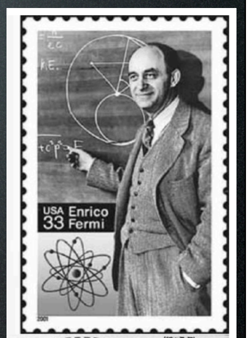


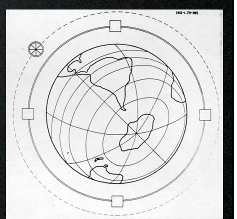
What can we learn with hi en. accelerators?
Jan 29 1954

Multiple production N,N ✓
Ang distribution ✓
~~Mult prod NΠ~~
Strange particles (Ang, mom — Double or single)
Antinucleons ✓

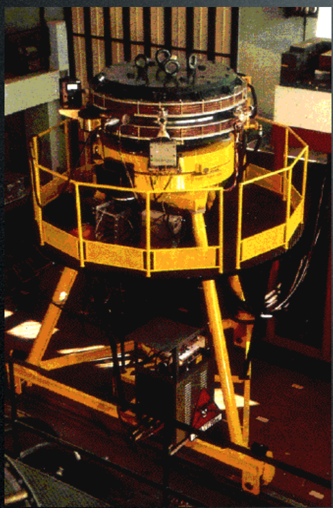
Generalities
time → MeV ↓ — Slide
→ M$ discoveries
Cosmos versus machines
Upper limit — Slide
A simple Feynman diagram — Slide
Hi energy collision

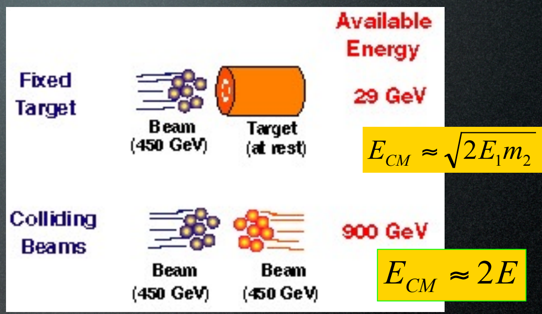
5 BMeV (1994) 170B$





ADA: (Anello Di Accumulazione), 1961-1964
the first e+e- Collider





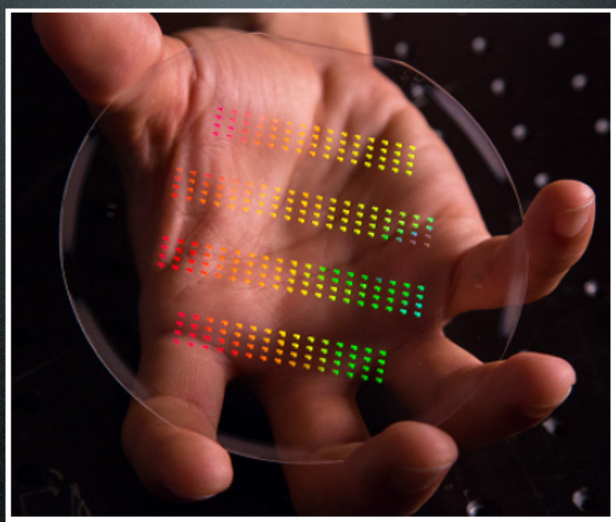
LHC	HE-LHC	VHE-LHC	VHE-LHC
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

Hawking: the Solartron

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

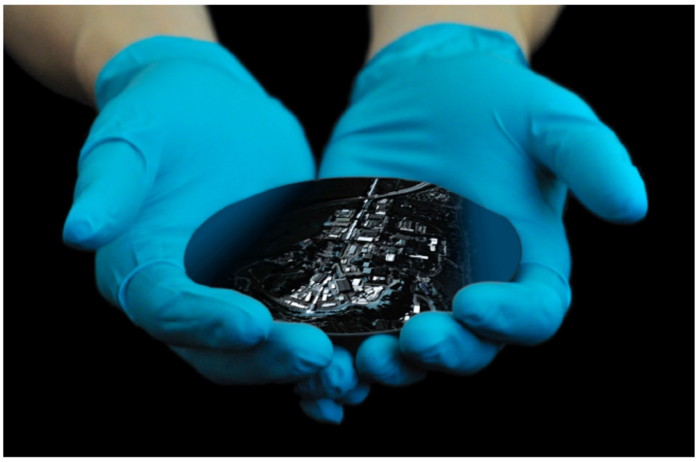
"The Universe in a Nutshell", by Stephen William Hawking, Bantam, 2001

Accelerator on a Chip?

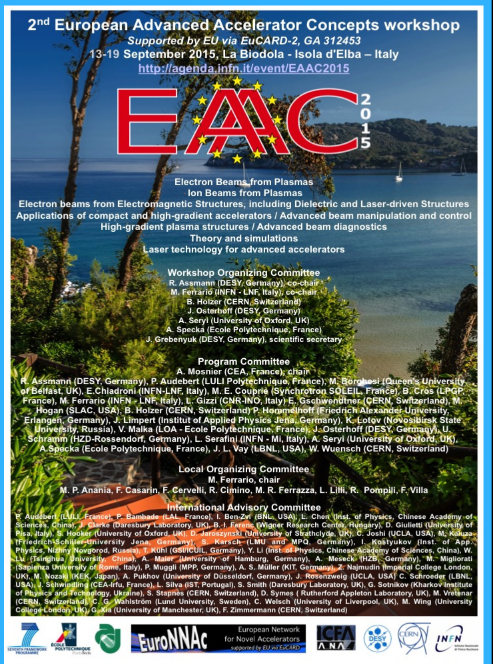


Laser?

Stanford ~~Linear~~ Accelerator Center



photoshop rendering of SLAC on a wafer by K. Soong



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

Modern accelerators require high quality beams: ==> High Luminosity & High Brightness

==> High Energy & Low Energy Spread

$$\uparrow \quad L = \frac{N_{e+} N_{e-} f_r}{4\pi \sigma_x \sigma_y}$$

- –N of particles per pulse => 10^9
- –High rep. rate f_r=> bunch trains
- –Small spot size => low emittance

$$\uparrow \quad B_n \approx \frac{2I}{\varepsilon_n^2}$$

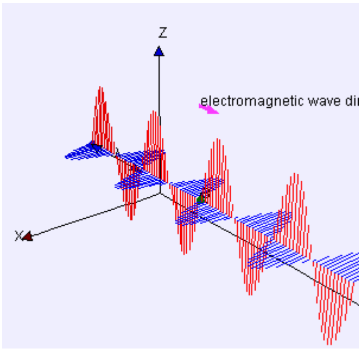
- –Short pulse (ps to fs)
- –Little spread in transverse momentum and angle => low emittance

Lawson-Woodward Theorem

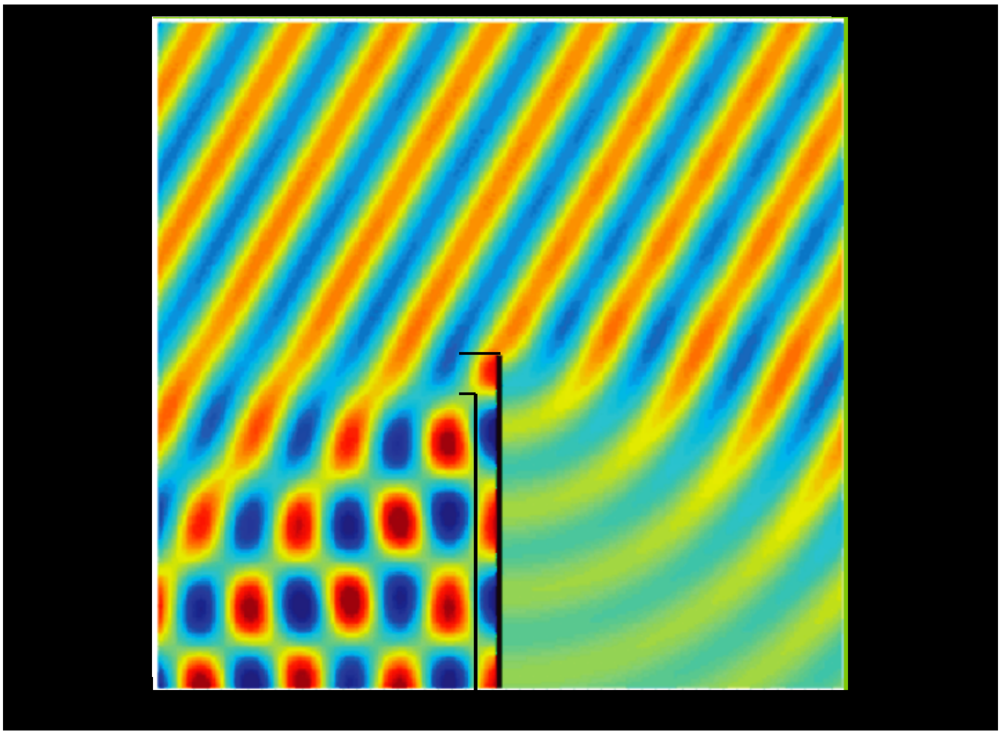
(J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979)

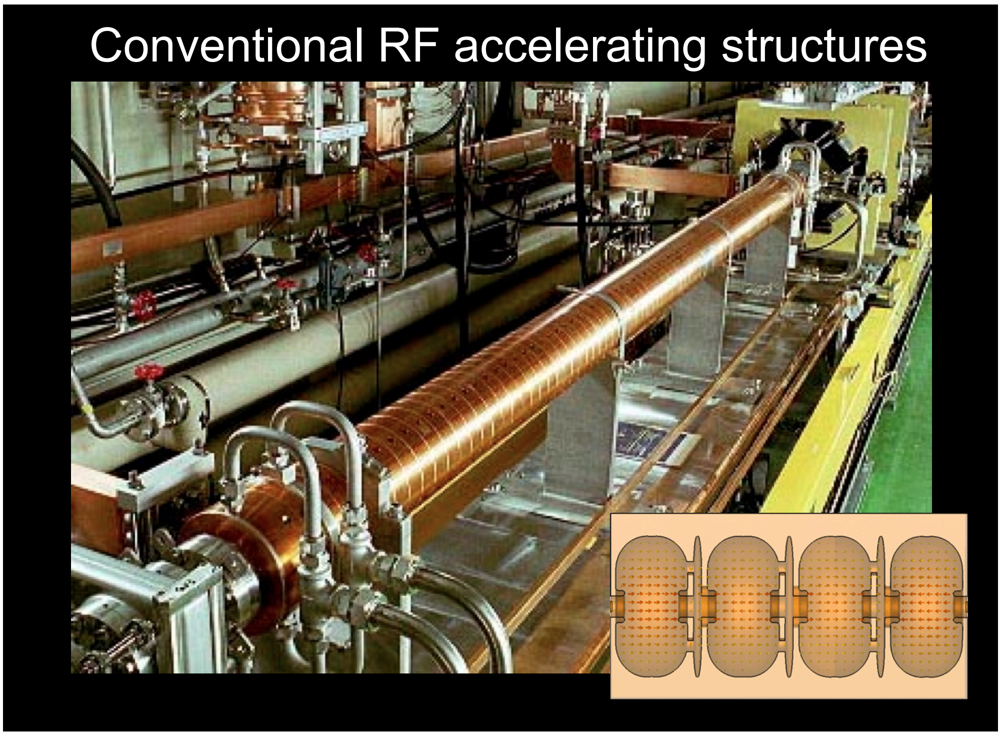
The net energy gain of a relativistic electron interacting with an electromagnetic field **in vacuum** is zero.

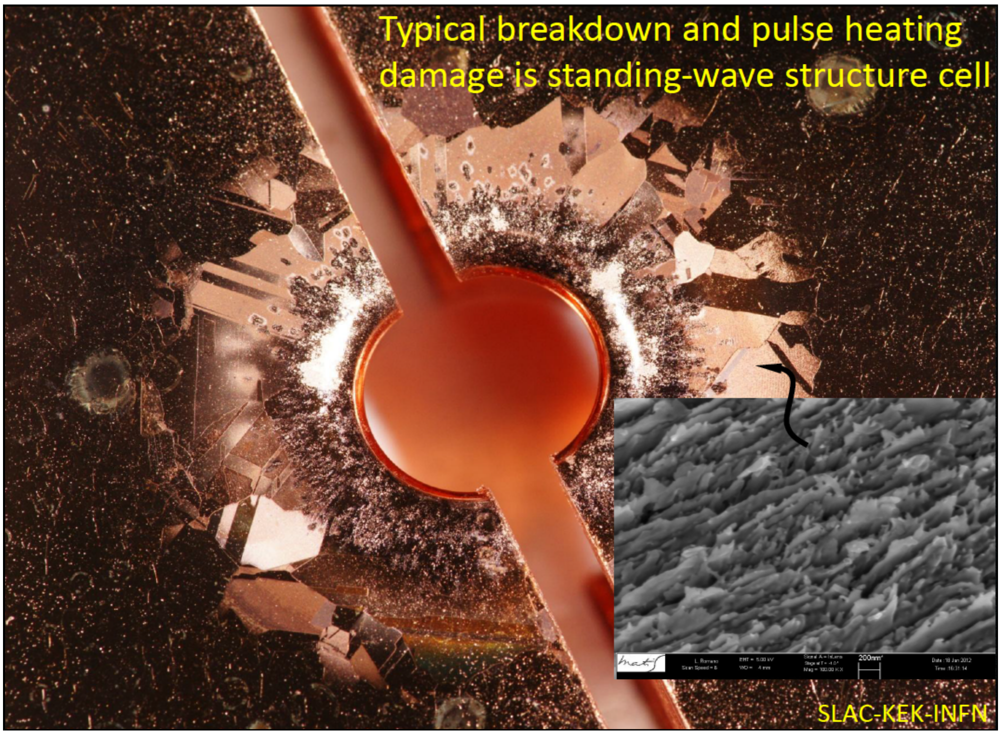
The theorem assumes that
(i) field is in vacuum with no walls or boundaries present,
(ii) the electron is highly relativistic (v ≈ c) along the acceleration path,
(iii) no static electric or magnetic fields are present,
(iv) the region of interaction is infinite,

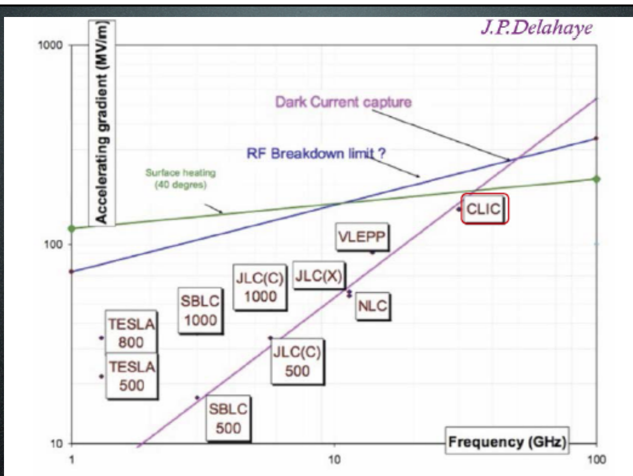


$$F_\perp \cong \frac{eE_x}{2\gamma^2}\cos\left(\frac{\omega t}{2\gamma^2}\right)$$




Conventional RF accelerating structures


Typical breakdown and pulse heating damage is standing-wave structure cell
200nm
SLAC-KEK-INFN



Breakdown limits metal:

$$E_s = 220(f[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

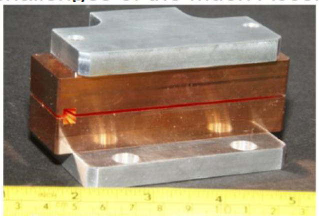
High field ->Short wavelength->ultra-short bunches-> low charge

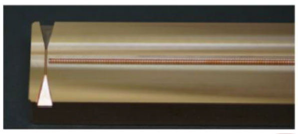
Miniaturization of the accelerating structures

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)

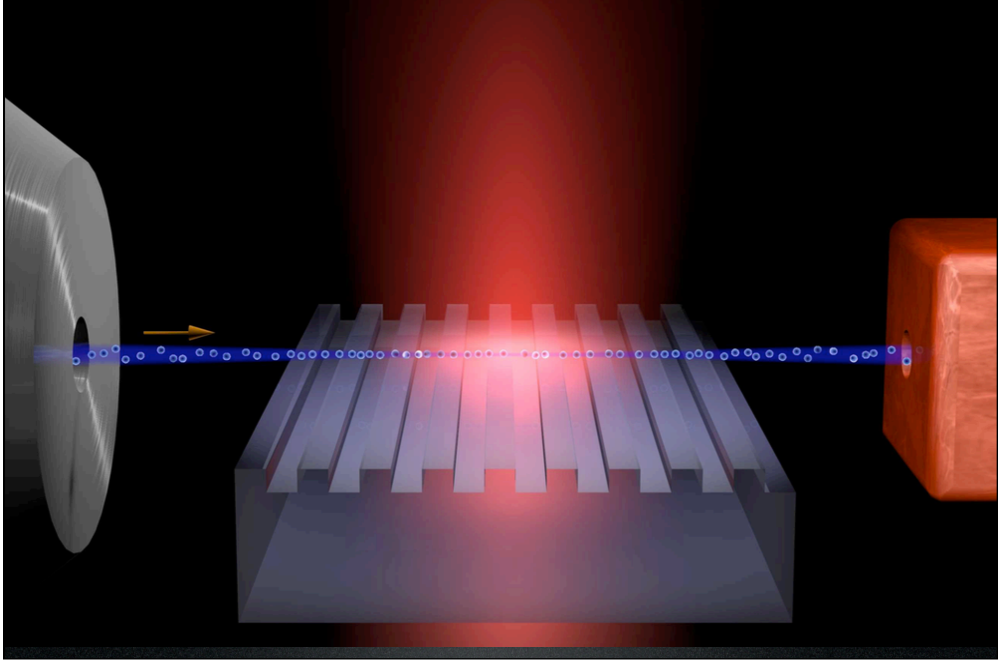
mm-Wave structure to be tested at FACET



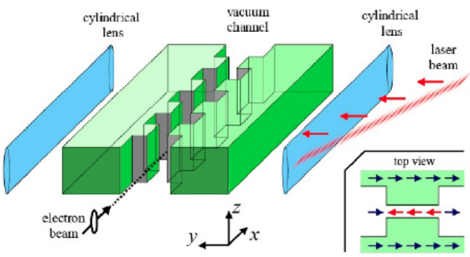


SLAC NATIONAL ACCELERATOR LABORATORY

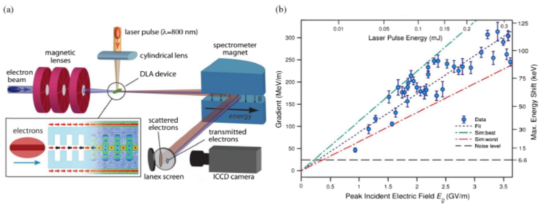
Laser based dielectric accelerator



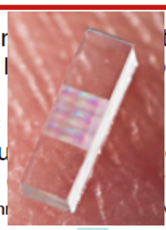
Grating-Based Planar Structure



T. Plettner, et al. PRST-AB **9**, 111301 (2006).

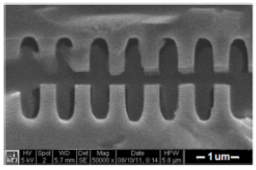


SiO$_2$ plar   th side-
coupled l   eam.

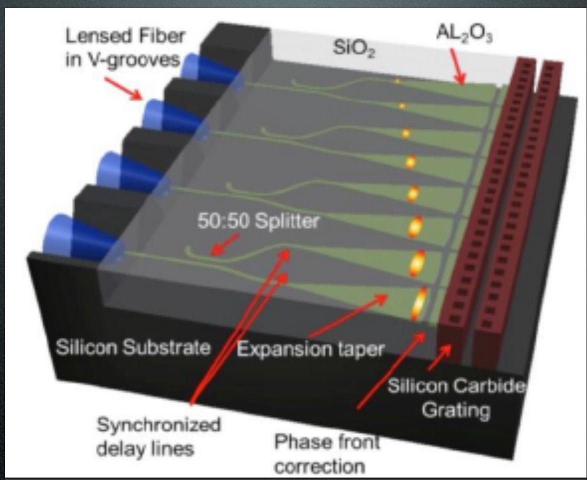


Periodic   the EM
field resu   ccelerating
gradient   iods.
damage thr   V/m @ 1ps

$G_{0,max}$ ~ 1GV/m



E. Peralta, recently fabricated prototype structure



Light Source on a Chip

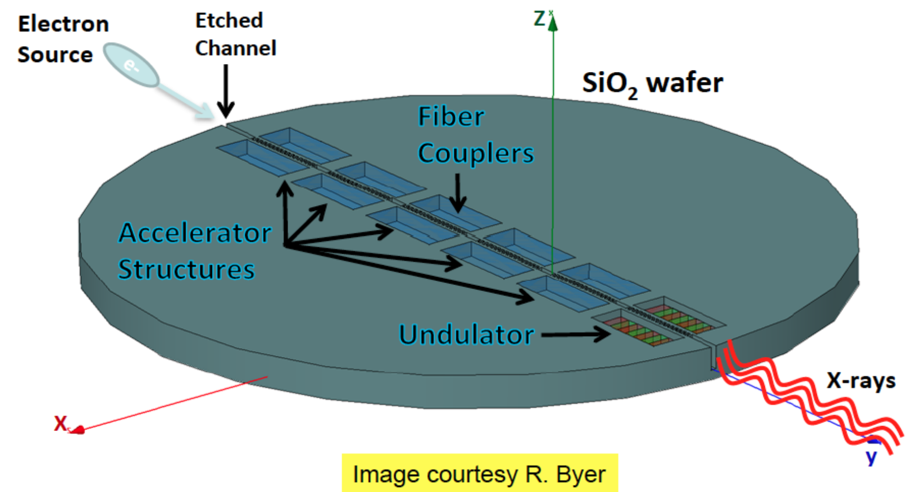
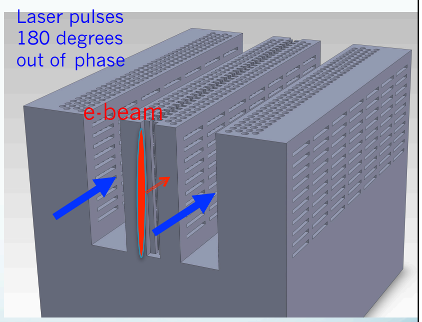


Image courtesy R. Byer

Dielectric Photonic Structure

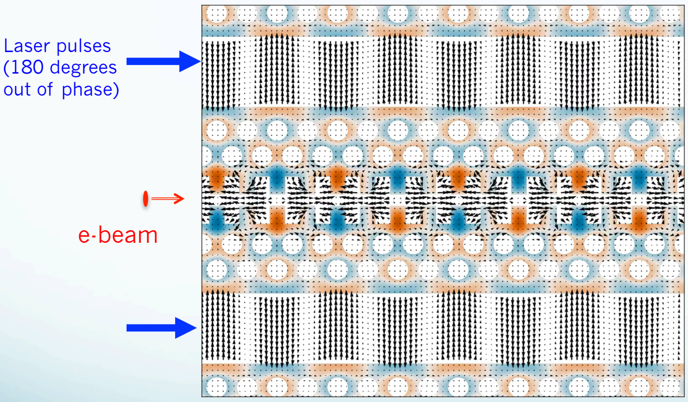
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes



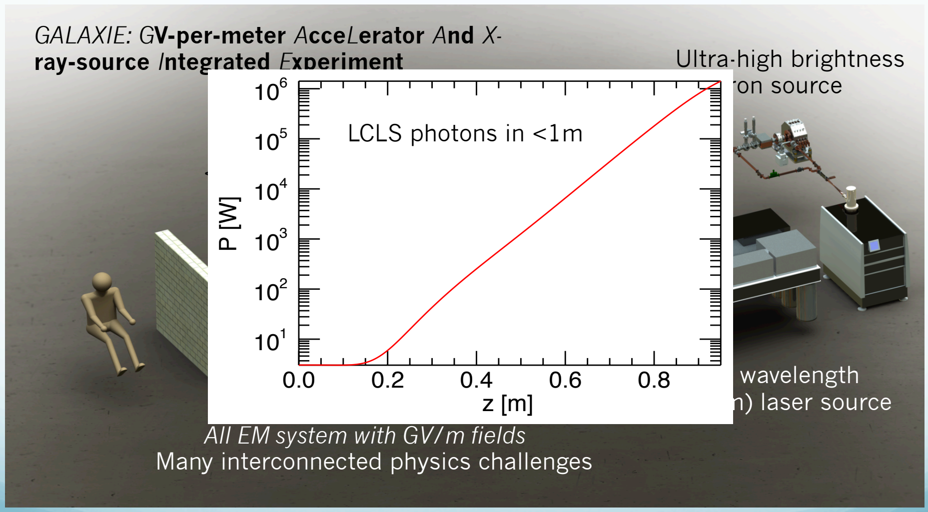
Schematic of GALAXIE
monolithic photonic DLA

Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles



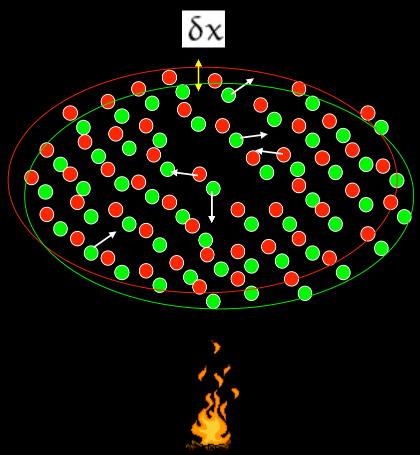
5th Gen Light Source: A Table-top X-ray FEL



Wake Field Acceleration 1
Laser Driven
LWFA

Surface charge density

$$\sigma = e\,n\,\delta x$$



Surface electric field

$$E_x = -\sigma/\epsilon_0 = -e\,n\,\delta x/\epsilon_0$$

Restoring force

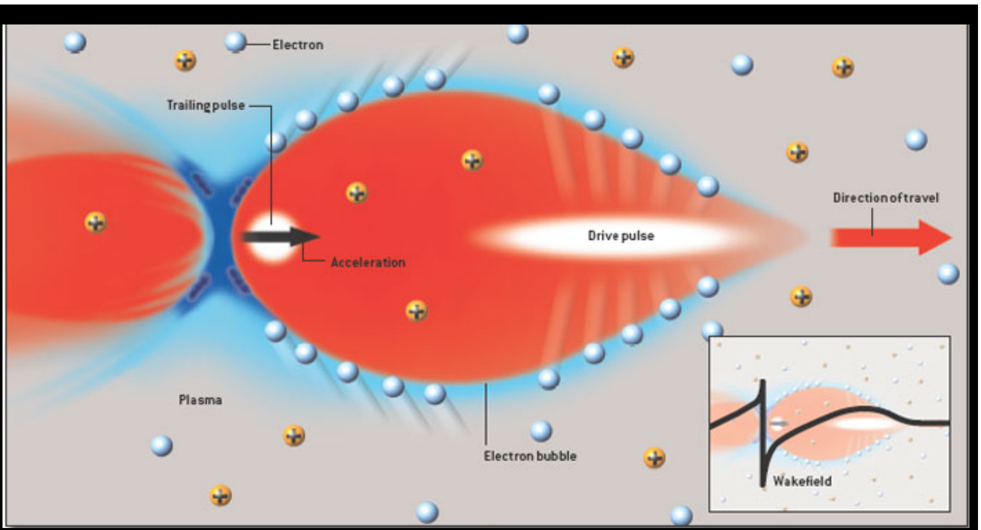
$$m\,\frac{d^2\delta x}{dt^2} = e\,E_x = -m\,\omega_p^{\,2}\,\delta x$$

Plasma frequency

$$\omega_p^{\,2} = \frac{n\,e^2}{\epsilon_0\,m}$$

Plasma oscillations

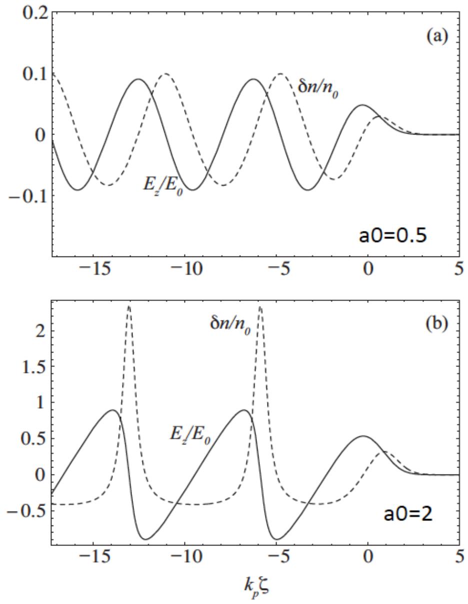
$$\delta x = (\delta x)_0 \cos(\omega_p\,t)$$



Breakdown limit?

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Regimes: Linear & Non-Linear

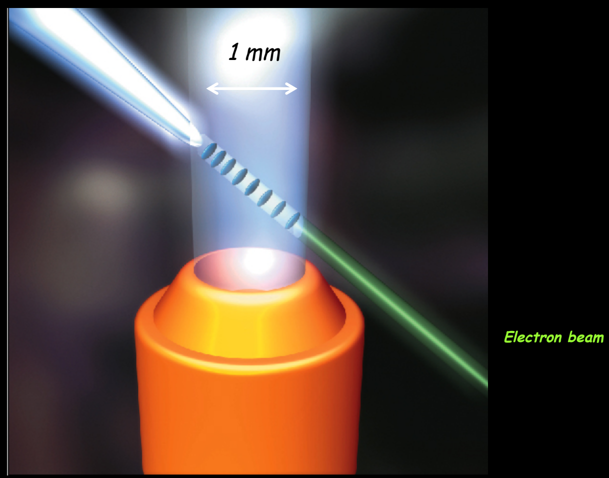


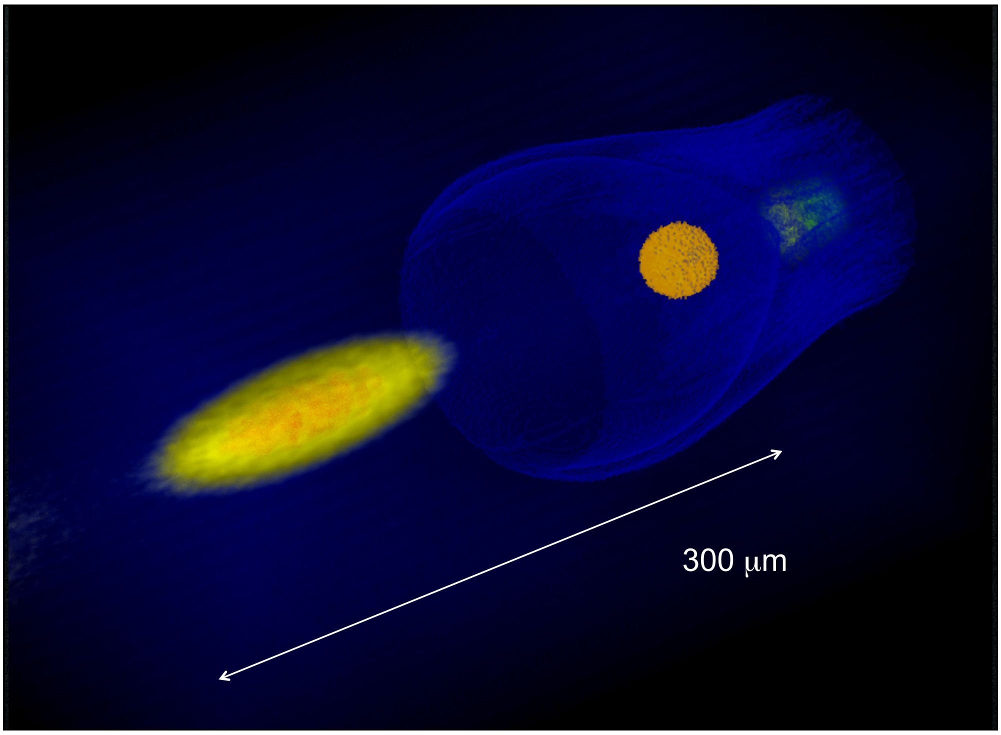
Linear

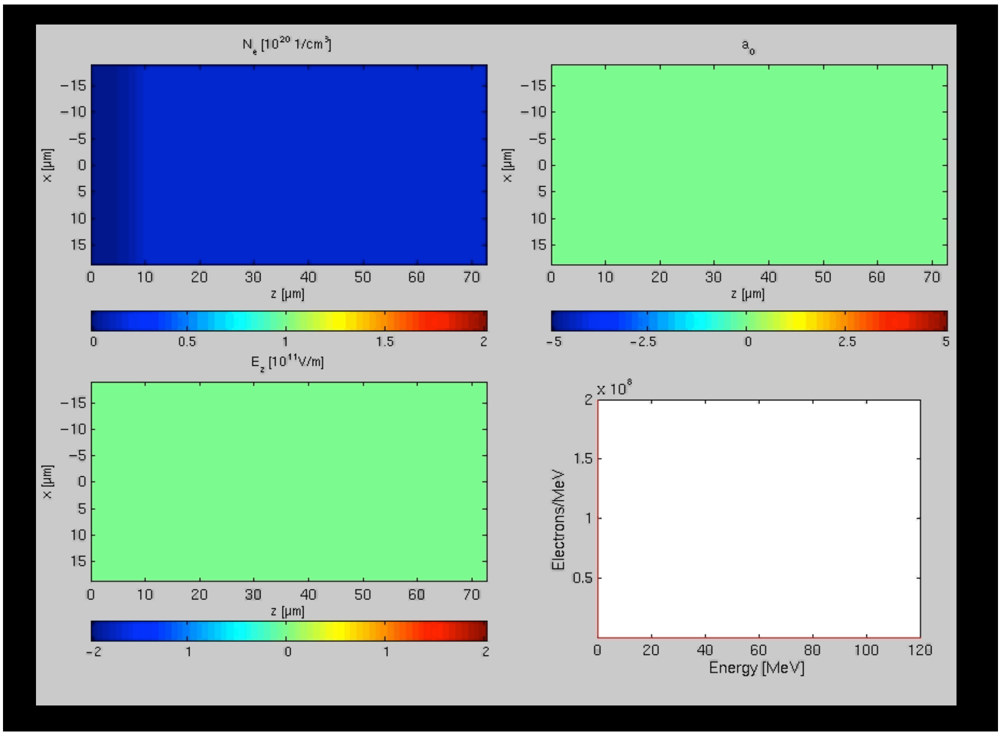
FIG. 8. Time-averaged density variation $\delta n/n_0$ (dashed curve) and axial electric field E_z/E_0 (solid curve) in an LWFA driven by a Gaussian laser pulse (pulse is moving to the right, centered at $k_p\zeta=0$ with rms intensity length $L_{rms}=k_p^{-1}$) for (a) $a_0=0.5$ and (b) $a_0=2.0$.

Non-Linear

Direct production of e-beam







2005 The Dream Beam

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

[1]The Blackett Laboratory, Imperial College London, London SW7 2AZ, UK
[2]Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK
[3]Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
[4]Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2]University of California, Berkeley, California 94720, USA
[3]Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands
[4]Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, Colorado 80303, USA
[5]University of Colorado, Boulder, Colorado 80309, USA

A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

[1]Laboratoire d'Optique Appliquée, Ecole Polytechnique, ENSTA, CNRS, UMR 7639, 91761 Palaiseau, France
[2]Institut fur Theoretische Physik, 1, Heinrich-Heine-Universitat Duesseldorf, 40225 Duesseldorf, Germany
[3]Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, 91680 Bruyères-le-Châtel, France

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

http://loa.ensta.fr/ UMR 7639

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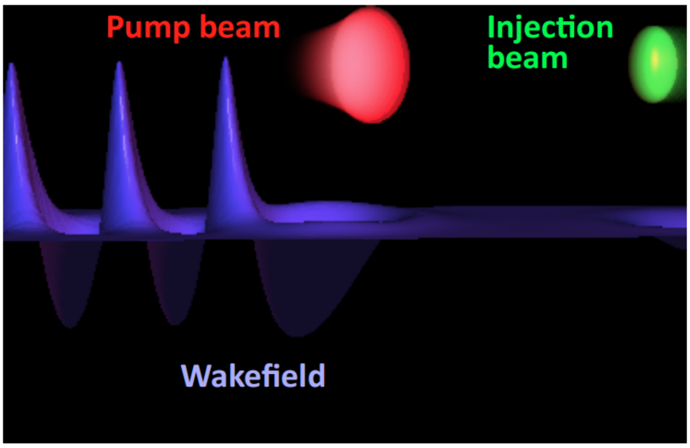
Colliding Laser Pulses Scheme

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



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

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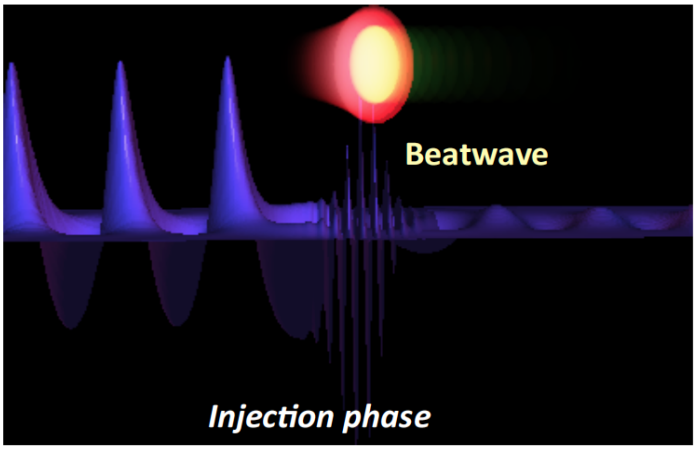

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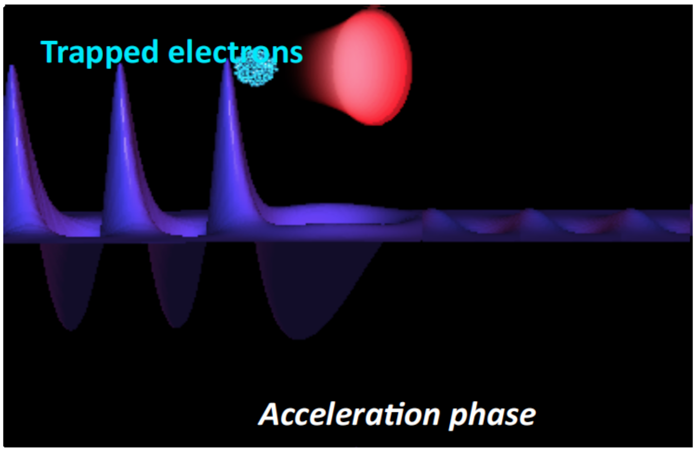

Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
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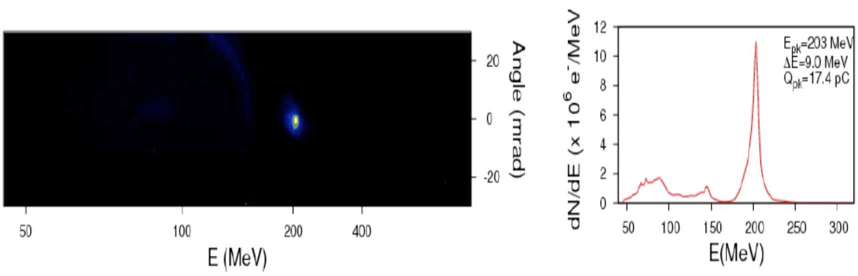
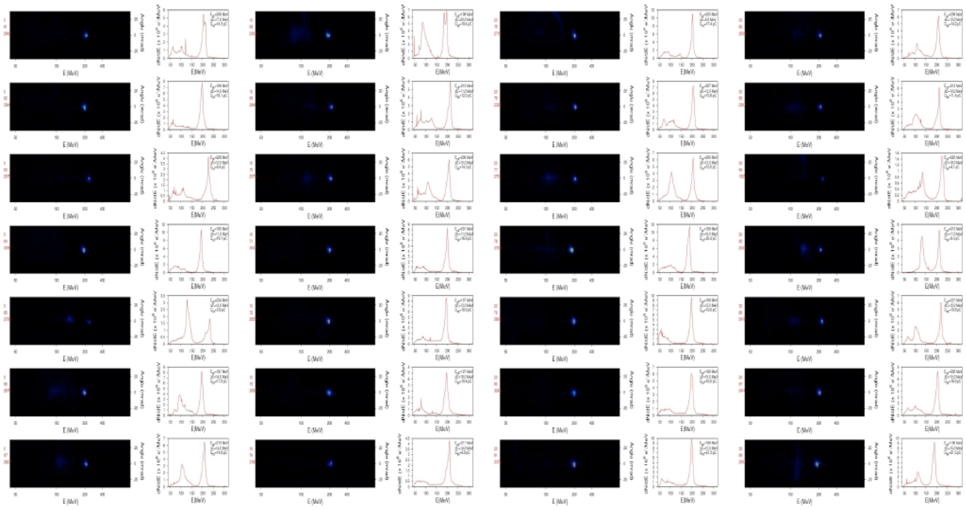
Stable Laser Plasma Accelerators

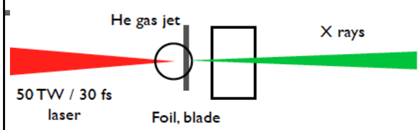


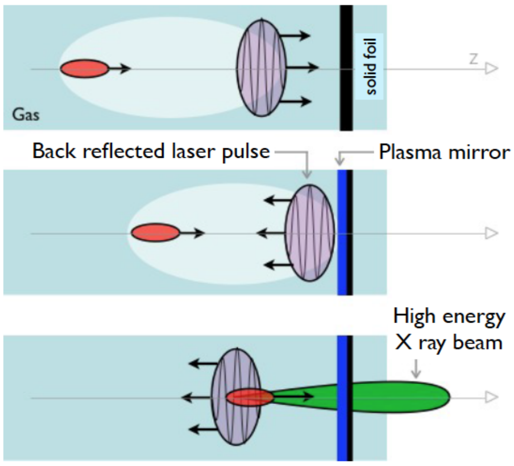
Stable Laser Plasma Accelerators

Series of 28 consecutive shots with : $a_0=1.5$, $a_1=0.4$, $n_e=5.7\times10^{18}cm^{-3}$



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 !

Accelerators point of view :

- Good beam quality & Monoenergetic dE/E down to 1 % √
- Beam is very stable √
- Energy is tunable: up to 400 MeV √
- Charge is tunable: 1 to tens of pC √
- Energy spread is tunable: 1 to 10 % √
- Ultra short e-bunch : 1,5 fs rms √
- Low divergence : 2 mrad √
- Low emittance[1-3] : < π.mm.mrad √

With PW class laser : peak energy at 3 GeV √

[1]S. Fritzler *et al.*, Phys. Rev. Lett. **92**, 165006 (2004), [2]C. M. S. Sears *et al.*, PRSTAB **13**, 092803 (2010)
[3]E. Brunetti *et al.*, Phys. Rev. Lett. **105**, 215007 (2010)

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

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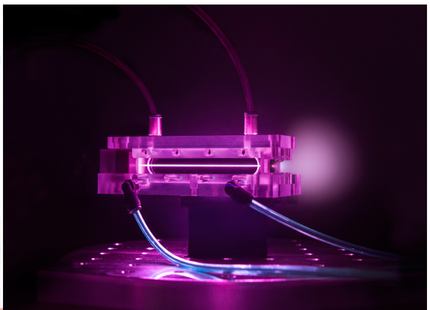
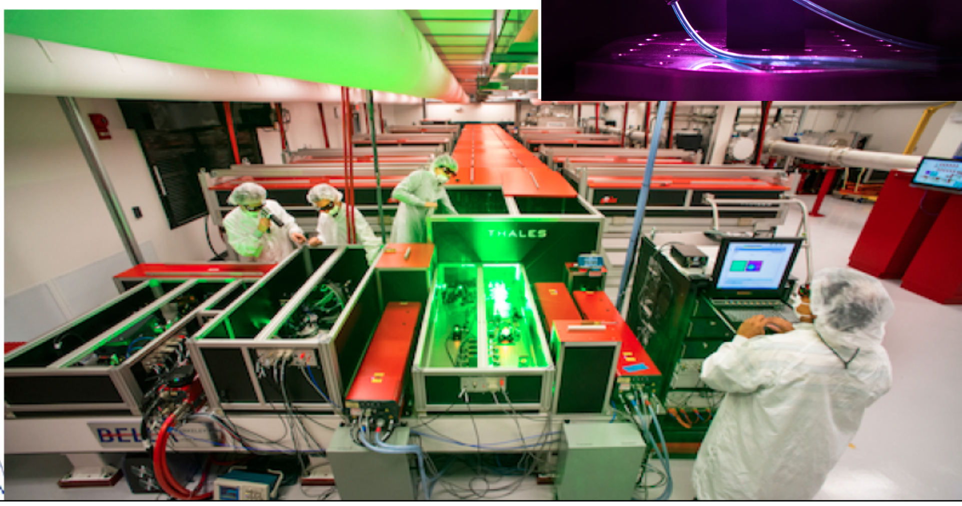
World Leader

BELLA LPWA facility:

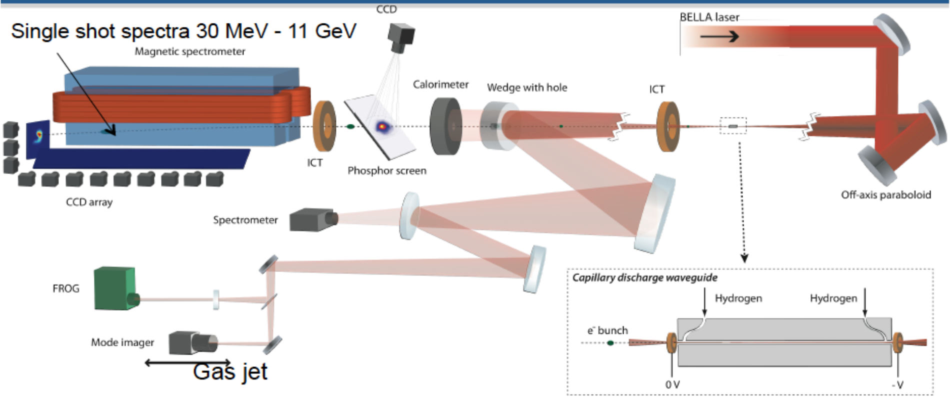
3 cm 1 GeV 40 TW laser ~1Hz

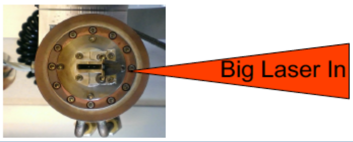
10-30 cm 5-10 GeV PW laser, ~1 Hz





Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets

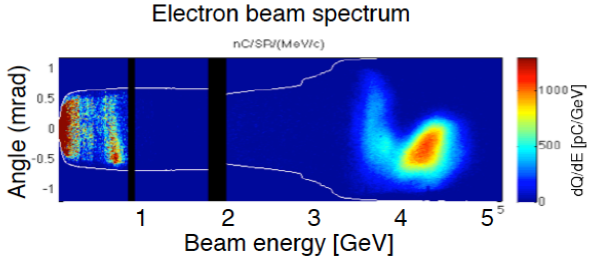


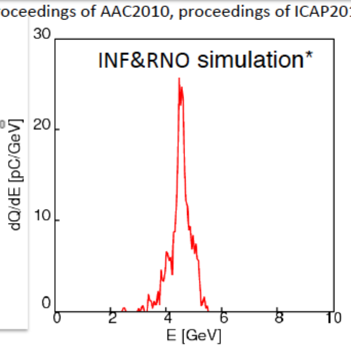


Capillary discharge

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





- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 μm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

W.P. Leemans et al.,PRL 2014

PRL 113, 245002 (2014) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 12 DECEMBER 2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

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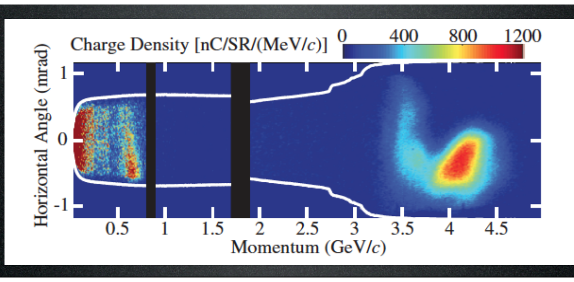
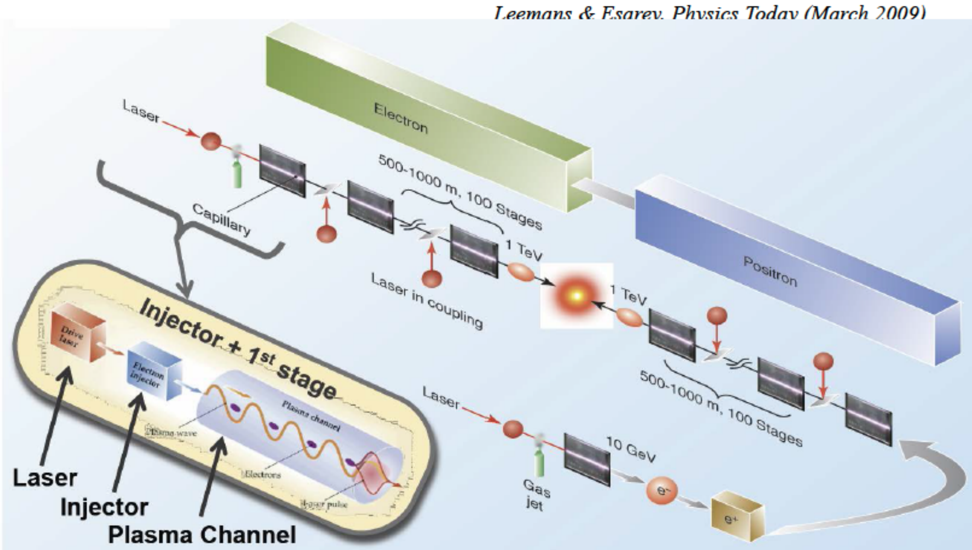
(Received 3 July 2014; revised manuscript received 11 September 2014; published 8 December 2014)

Multi-GeV electron beams with energy up to 4.2 GeV, 6% rms energy spread, 6 pC charge, and 0.3 mrad rms divergence have been produced from a 9-cm-long capillary discharge waveguide with a plasma density of $\approx 7 \times 10^{17}$ cm^{-3}, powered by laser pulses with peak power up to 0.3 PW. Preformed plasma waveguides allow the use of lower laser power compared to unguided plasma structures to achieve the same electron beam energy. A detailed comparison between experiment and simulation indicates the sensitivity in this regime of the guiding and acceleration in the plasma structure to input intensity, density, and near-field laser mode profile.



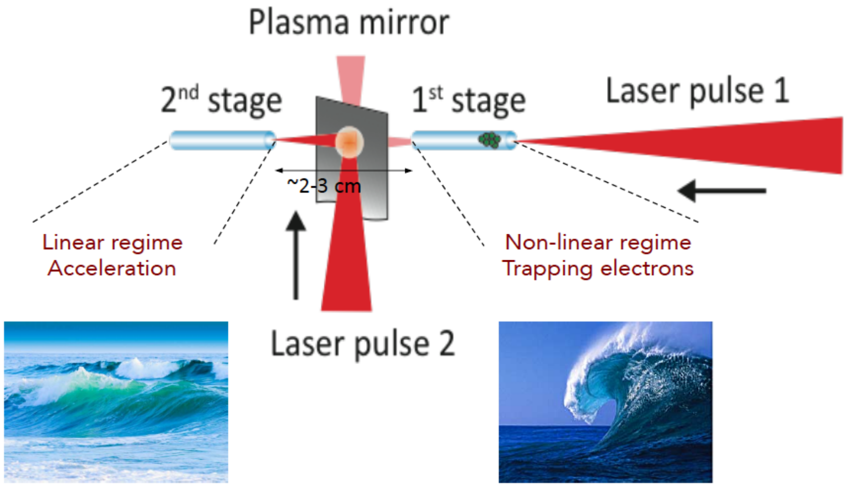
Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)



Staging Experiment Aims at Demonstrating Key Element of Collider Concept

W. P. Leemans and E. Esarey, Physics Today (2009).



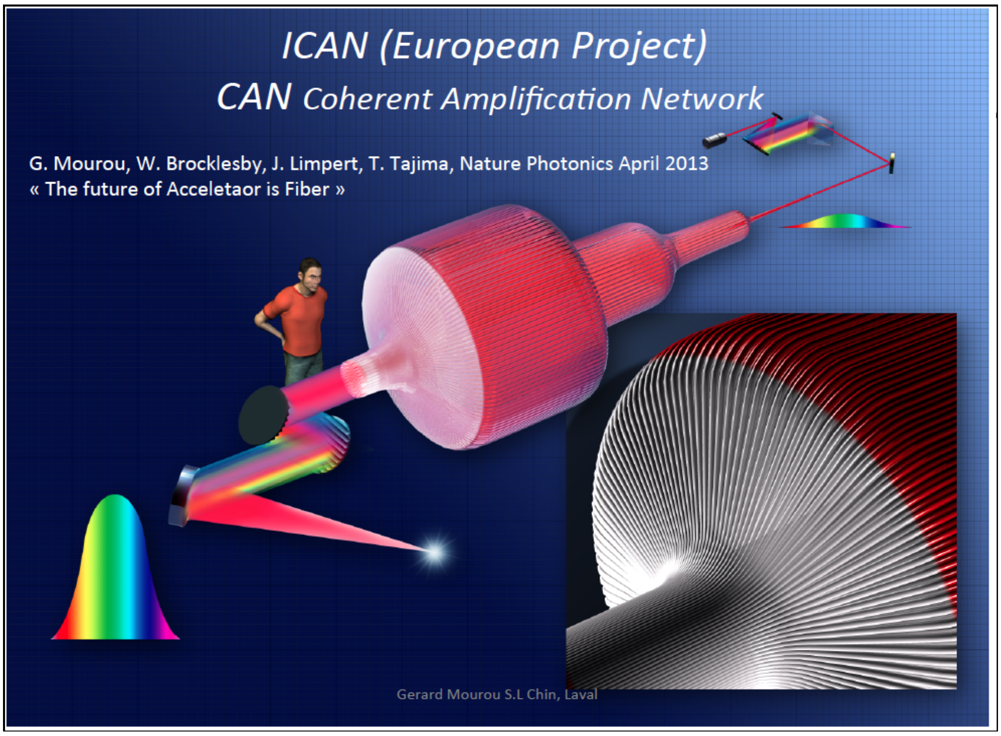
Ph.D. thesis S. Shiraishi, B. Shaw, K. Swanson

Talk by Sven Steinke

Parameter Set for LPWA LC

Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15	0.3	15	0.3
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	100	100	50	50
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	100	100	50	50
β* (mm)	1	1	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	10	10	1	1
Vertical beam size at IP σ^*_y (nm)	10	10	1	1
Disruption parameter	0.12	5.6	1.2	56
Bunch length σ_z (μm)	1	7	1	7
Beamstrahlung parameter ϒ	180	180	18,000	18,000
Beamstrahlung photons per e, n_γ	1.4	10	3.2	22
Beamstrahlung energy loss δ_E (%)	42	100	95	100
Accelerating gradient (GV/m)	10	1.4	10	1.4
Average beam power (MW)	5	0.7	50	7
Wall plug to beam efficiency (%)	6	6	10	10
One linac length (km)	0.1	0.5	1.0	5

×2+FF



Protons and Ions?

Protons and ions are too slow to catch the wave - only indirect acceleration via electrons

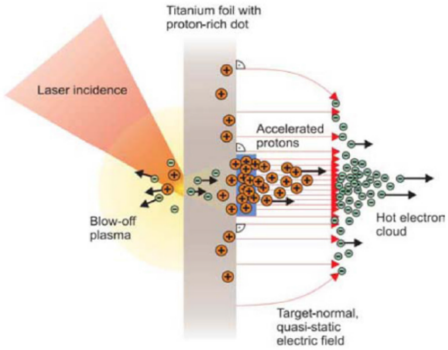
Laser Driven Acceleration of Protons

- 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

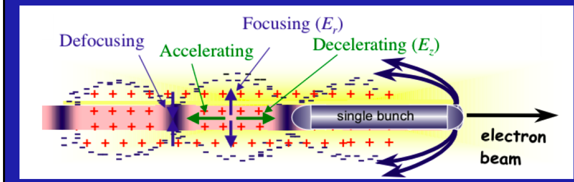
Need typically:
50 J 500 fs → 100 TW
30 μm radius → 10^{19} W/cm²

Target Normal Sheath Acceleration
"best understood" candidate:

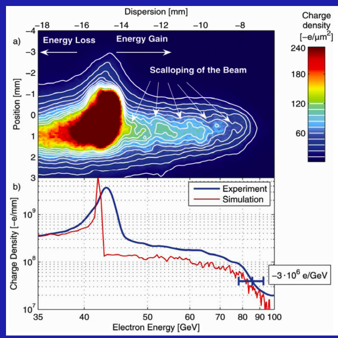
- laser creates blow-off plasma on front surface
- backside expansion accelerated electrons ionize hydrogen
- hot electrons create electric field (by space charge)
- causes acceleration of protons (electrons slowing down – end of acceleration)
- neutralized bunch of comoving p and e generated

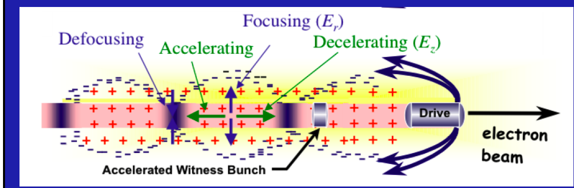


Wake Field Acceleration 2
Beam Driven
PWFA

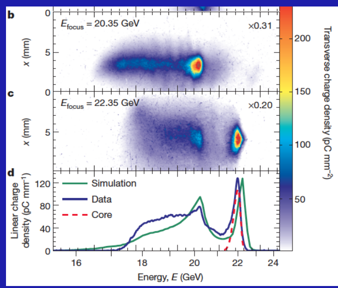


Blumenfeld, I. et al. *Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator*. **Nature** 445, 741–744 (2007).





Litos, M. et al. *High-efficiency acceleration of an electron beam in a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

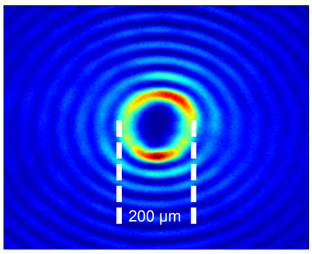


Positrons and Hollow Channel Plasma

SLAC

- The physics of accelerating positrons in a plasma is different than that of electrons!
- Hollow channel plasmas might be a viable method for accelerating positrons in a plasma.
- A special optic called a kinoform is used to create a hollow channel plasma.

Laser Profile for J_5 Bessel Focus



Positrons plasma acceleration is a crucial step towards a plasma based linear collider. FACET hosts the only active research on positron PWFA.

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doi:10.1038/nature14890

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

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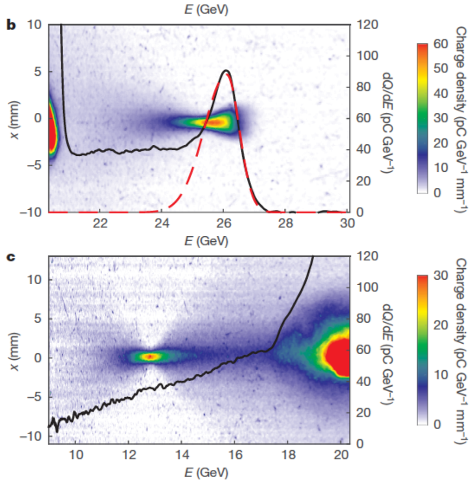


CONCEPTUAL DESIGN OF THE DRIVE BEAM FOR A PWFA-LC*

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

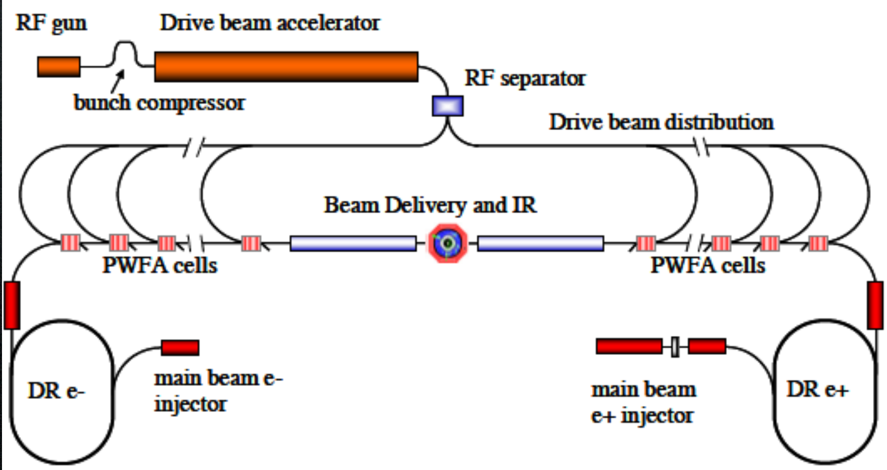


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

Table 1: Key Parameters of the Conceptual Multi-Stage PWFA-based Linear Collider

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

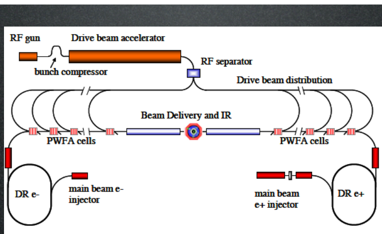


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

ILC – International Linear Collider

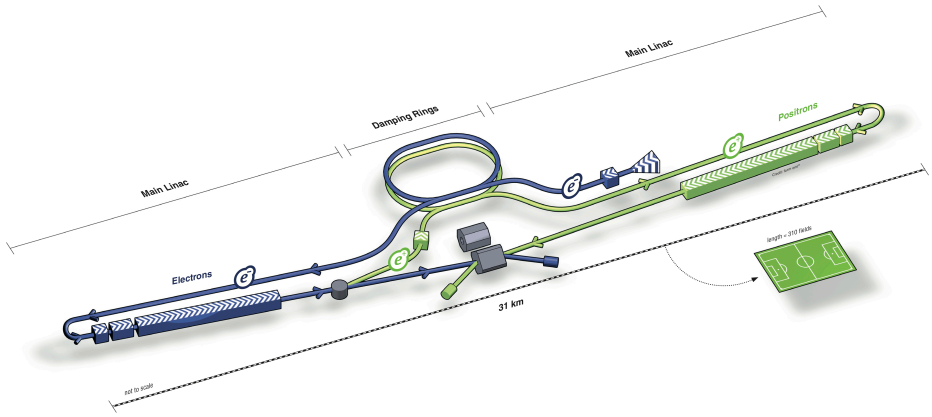


Table 2: ILC energy upgrade by PWFA after-burner

Parameter	Unit	ILC	ILC	ILC + PWFA
Energy (cm)	GeV	500	1000	PFWA = 500 to 1000
Luminosity (per IP)	$10^{34}cm^{-2}s^{-1}$	1.5	4.9	2.6
Peak (1%)Lum(/IP)	$10^{34}cm^{-2}s^{-1}$	0.88	2.2	1.3
# IP	-	1	1	1
Length	km	30	52	30
Power (wall plug)	MW	128	300	175
Lin. Acc. grad.(p/eff)	MV/m	31.5/25	36/30	7600/1000
# particles/bunch	10^{10}	2	1.74	0.66
# bunches/pulse	-	1312	2450	2450
Bunch interval	ns	554	366	366
Pulse repetition rate	Hz	5	4	15
Beam power/beam	MW	5.2	13.8	13.8
Norm Emitt (X/Y)	$10^{-6}/10^{-9}$radm	10/35	10/30	10/30
Sx, Sy, Sz at IP	nm,nm,µm	474/5.9/300	335/2.7/225	286/2.7/20
Crossing angle	mrad	14	14	14
Av # photons	-	1.70	2.0	0.7
δb beam-beam	%	3.89	9.1	9.3
Upsilon	-	0.03	0.09	0.52

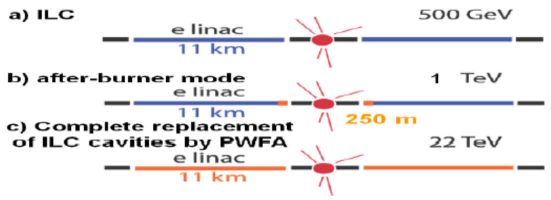
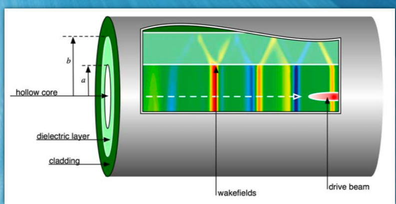
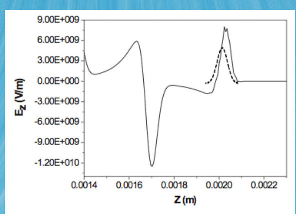


Figure 3: ILC energy upgrade by PWFA technology in the 500 GeV ILC tunnel (a), in after-burner mode (b), in the extreme case of PWFA technology use only (c).

Dielectric Wakefield Accelerator



- Design Parameters a,b σ_z ε



Ez on-axis, OOPIC

- Electron bunch (β ≈ 1) drives wake in cylindrical dielectric structure
  - Dependent on structure properties
  - Generally multi-mode excitation
- Wakefields accelerate trailing bunch
  - Mode wavelengths (quasi-optical

$$\lambda_n \approx \frac{4(b-a)}{n}\sqrt{\varepsilon-1}$$

  - Peak decelerating field

$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\,\varepsilon\sigma_z + a\right]}$$

Extremely good beam needed

  - Transformer ratio (unshaped beam)

$$R = \frac{E_{z,acc}}{E_{z,dec}} \leq 2$$

European Network

AWAKE

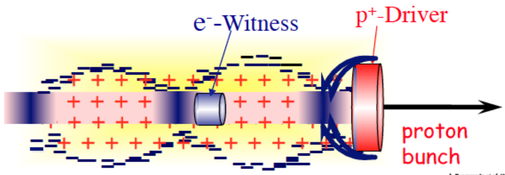
Proton-driven Plasma Wakefield Acceleration Collaboration: Accelerating e⁻ on the wake of a p⁺ bunch

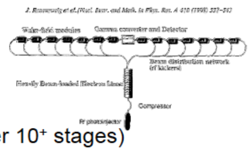
P. Muggli, 06/04/2013, EAAC 2103

European Network

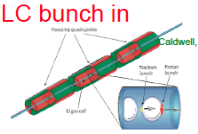
AWAKE

WHY p⁺-DRIVEN PWFA?





- ✧ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ
- ✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~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)



Caldwell, Nat. Phys. 5, 363, (2009)

P. Muggli, 06/04/2013, EAAC 2103

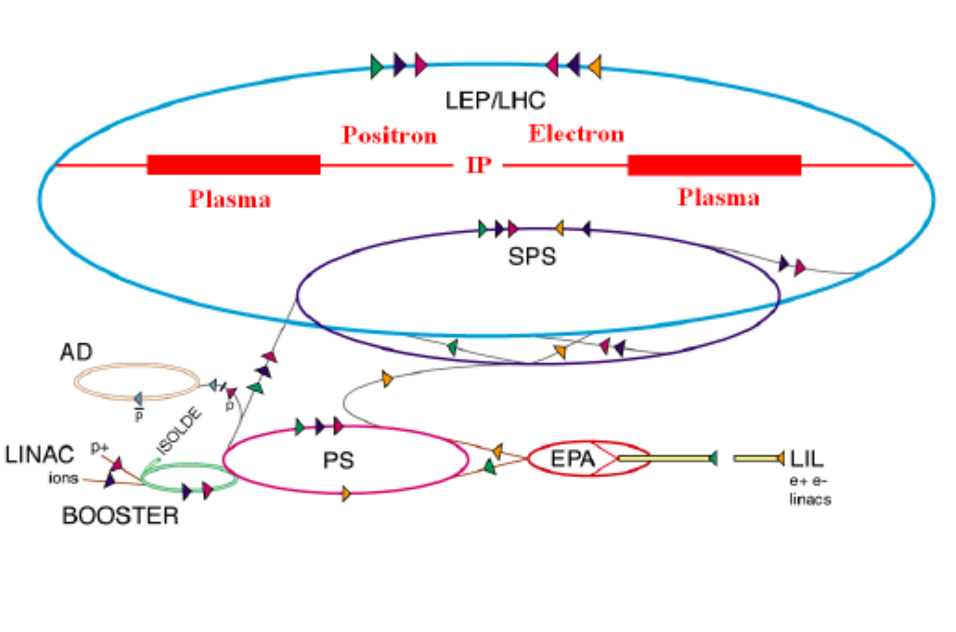


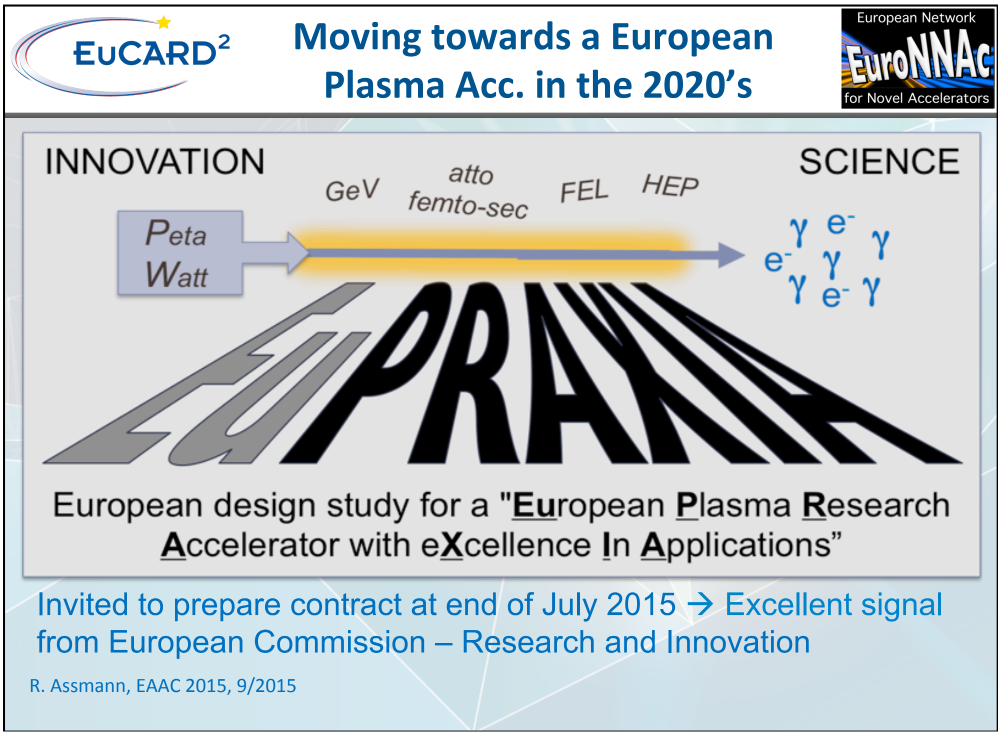
Figure 1: Schematic layout of a 2 TeV CoM electron-positron linear collider based on a modulated proton-driven plasma wakefield acceleration.

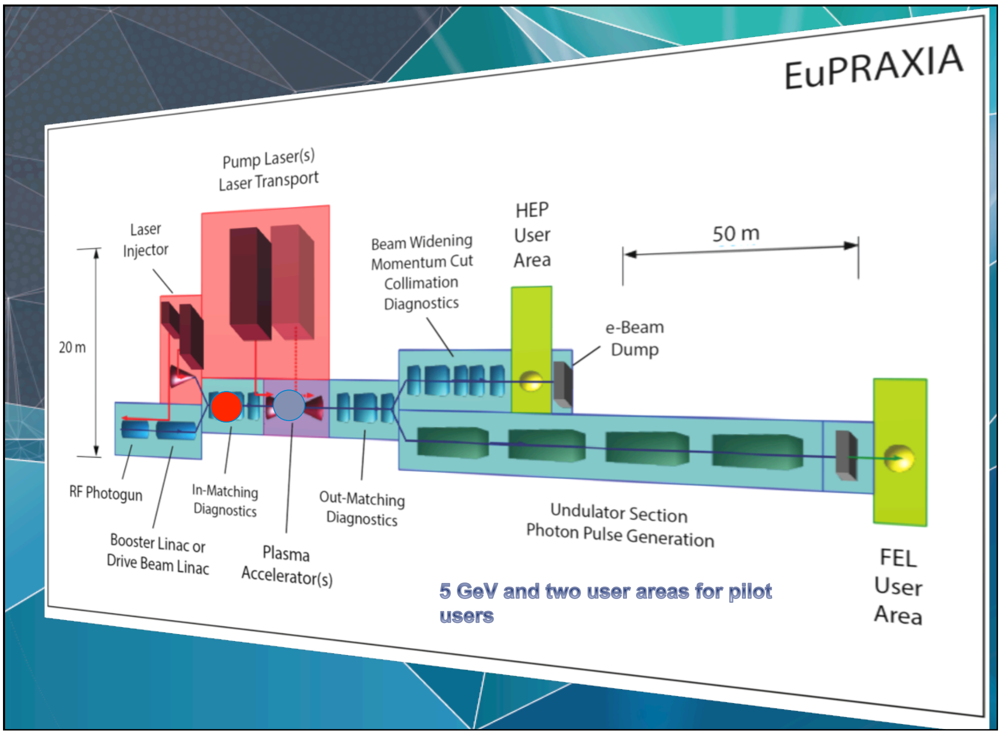
3 Steps towards a reliable PWA

① High Gradient – Low e- Beam Quality

② High e+e- Beam Quality – Low Gradient

③ High e+e- Beam Quality - High Gradient


EuCARD²
Moving towards a European
Plasma Acc. in the 2020's
European Network
EuroNNAc
for Novel Accelerators
INNOVATION
SCIENCE
GeV
atto
femto-sec
FEL
HEP
Peta
Watt
EuPRAXIA
European design study for a "European Plasma Research
Accelerator with eXcellence In Applications"
Invited to prepare contract at end of July 2015 → Excellent signal
from European Commission – Research and Innovation
R. Assmann, EAAC 2015, 9/2015


EuPRAXIA
Pump Laser(s)
Laser Transport
Laser
Injector
20 m
Beam Widening
Momentum Cut
Collimation
Diagnostics
HEP
User
Area
50 m
e-Beam
Dump
RF Photogun
In-Matching
Diagnostics
Out-Matching
Diagnostics
Undulator Section
Photon Pulse Generation
Booster Linac or
Drive Beam Linac
Plasma
Accelerator(s)
5 GeV and two user areas for pilot
users
FEL
User
Area

EuPRAXIA Research Infrastructure Goal Parameters

Beam Parameter	Unit	Value
Particle type	-	Electrons
Energy	GeV	1 – 5
Charge per bunch	pC	1 – 50
Repetition rate	Hz	10
Bunch duration	fs	0.01 - 10
Peak current	kA	1 – 100
Energy spread	%	0.1 – 5
Norm. emittance	mm	0.01 – 1

R. Assmann, EAAC 2015, 9/2015

Conclusions

Short term perspective (< 10 years):

Relevant applications in medicine, radiobology, material science
Compact FEL with moderate average power (10 Hz system)
Designing future accelerators
Compact X ray source (Thomson, Compton, Betatron, or FEL)
mJ-kHz laser plasma accelerators for fs electron diffraction (J. Faure' talk)

Long term possible applications

High energy physics that will depend on the laser technology evolution, on laser to electron transfer efficiency, on progress of multistage design, guiding over logn distance (energy dissipation, robustness), acceleration of positron, etc...