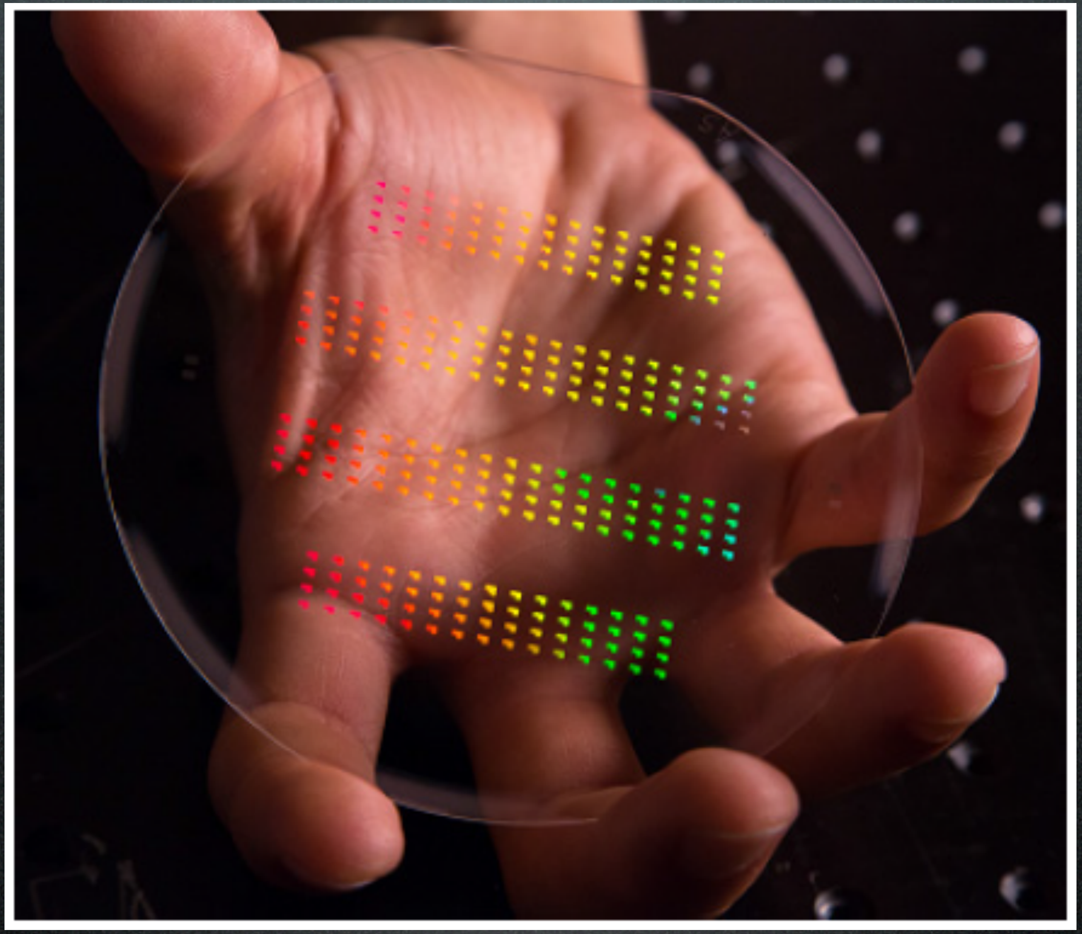
Novel acceleration techniques

Massimo Ferrario
INFN-LNF

LNF - April 2, 2015

Accelerator on a Chip?



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

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

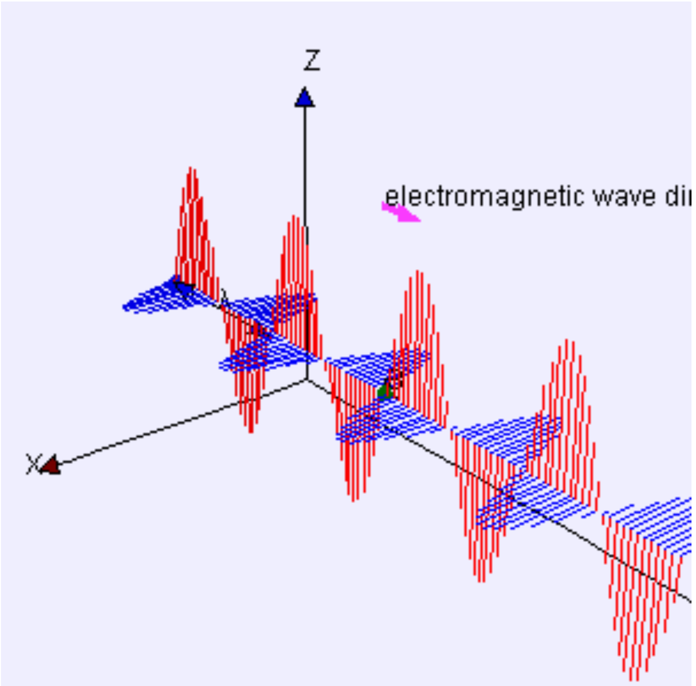
- –Short pulse (ps to fs)
- –Little spread in transverse momentum and angle => low emittance

Lawson-Woodward Theorem

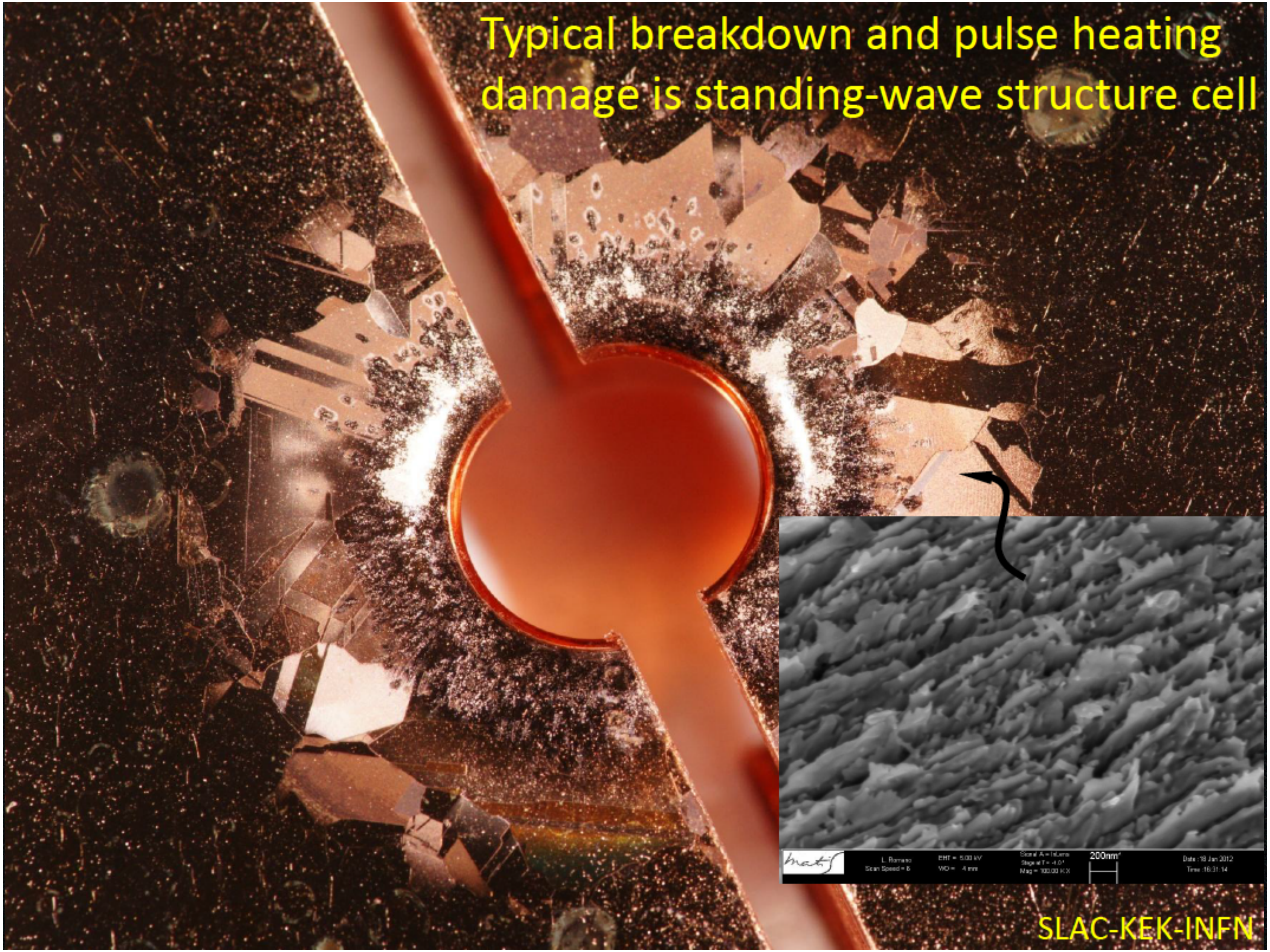
(J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979)

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

The theorem assumes that
(i) the laser 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,



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


Typical breakdown and pulse heating
damage is standing-wave structure cell
L. Romano
Scan Speed = 6
EHT = 5.00 kV
WD = 4 mm
Mag = 100.00 K X
200nm
Date :18 Jan 2012
Time :16:31:14
SLAC-KEK-INFN

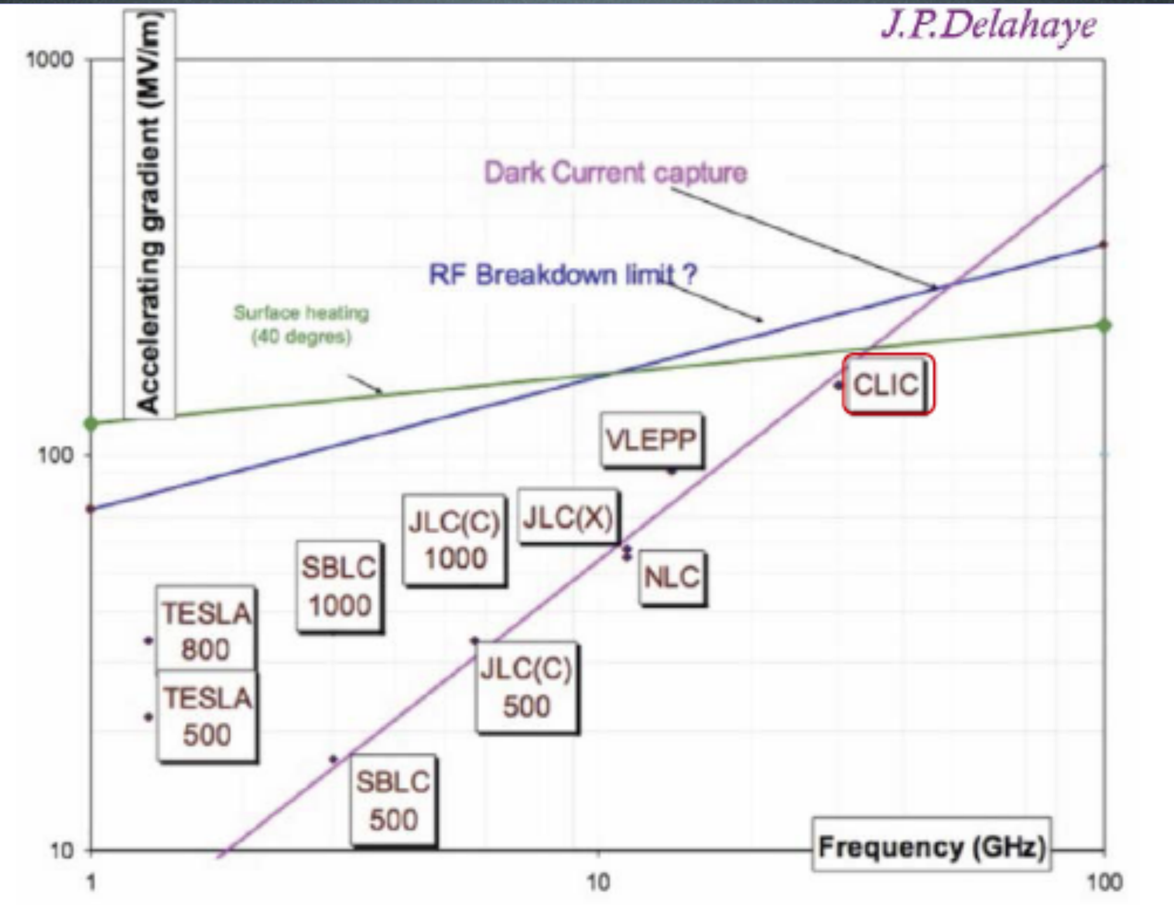
2 WAYS NTA ROAD MAP

① Miniaturization of the accelerating structures (resonant)

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

- Power sources
- Accelerating structures
- High quality beams

Miniaturization of the accelerating structures



Breakdown limits metal:

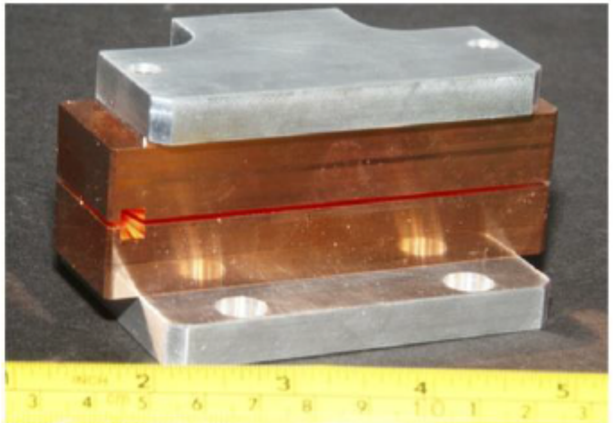
$$E_s = 220(f[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

high field ->short wavelength->ultra-short bunches-> low charge

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)

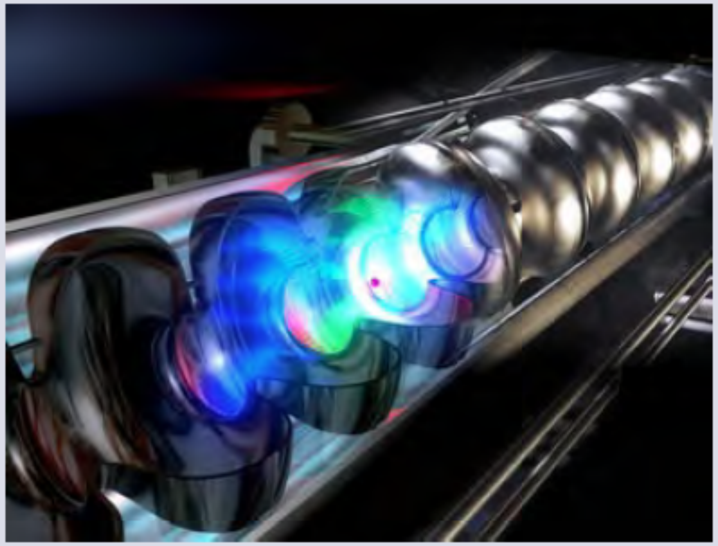
mm-Wave structure to be tested at FACET



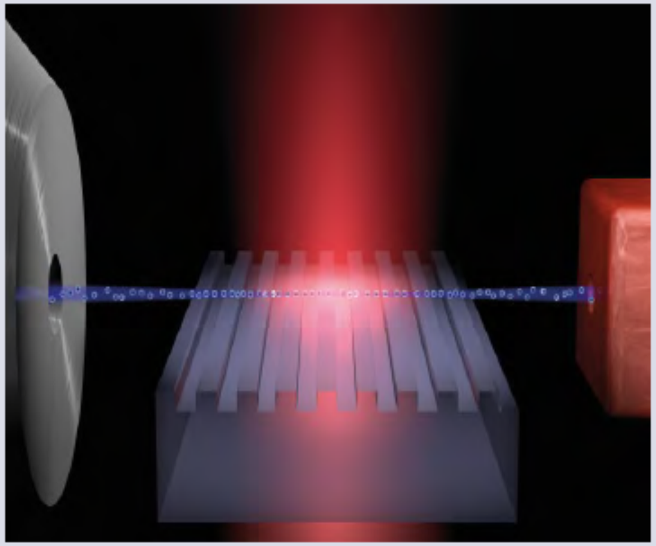
Measured so far:
@ 130 GHz
⇒ 300 MV/m acceler.
⇒ 1 GV/m peak
(NORCIA)

SLAC NATIONAL ACCELERATOR LABORATORY

Particle accelerators: from RF to optical/photonic drive?

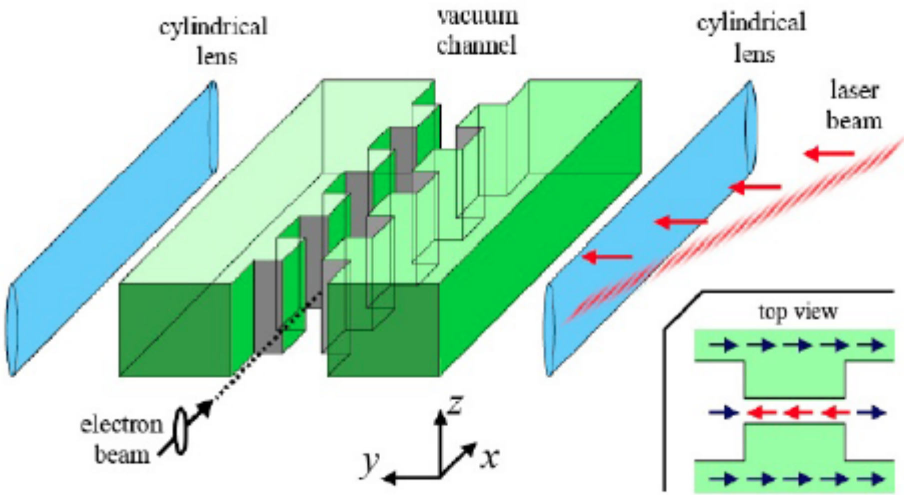


RF cavity (TESLA, DESY)

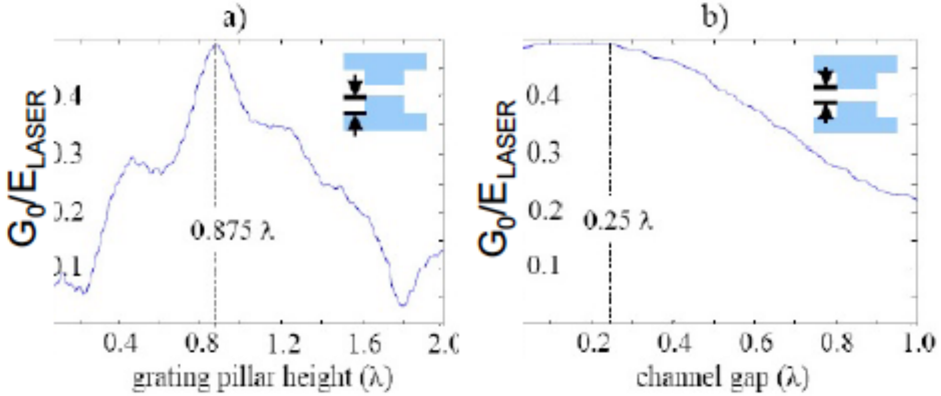


	Conventional linear accelerator (RF)	**Laser-based dielectric accelerator (optical)**
Based on	(Supercond.) RF cavities	Quartz grating structures
Peak field limited by	**Surface breakdown: 200 MV/m**	**Damage threshold: 30 GV/m**
Max. achievable gradients	**50 MeV/m**	**10 GeV/m**

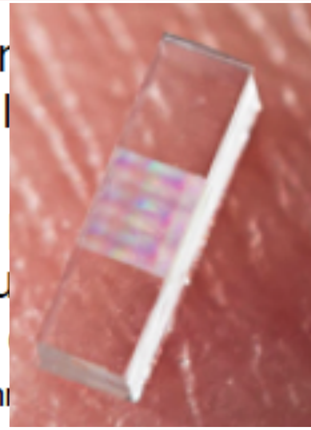
Grating-Based Planar Structure



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

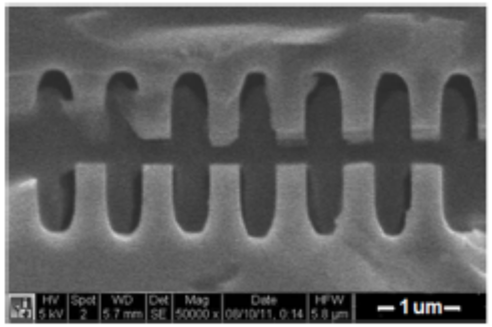


SiO_2 plar th side-
coupled l eam.



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

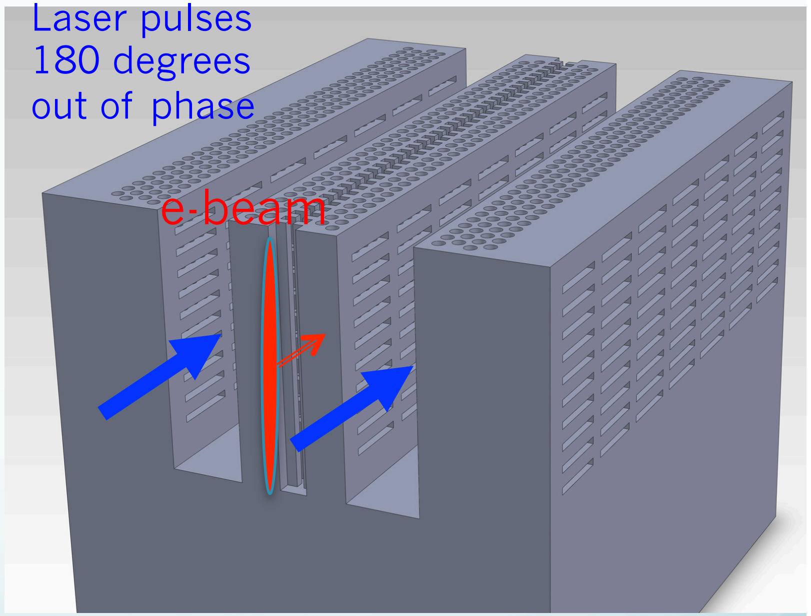
$G_{0,max}$ ~ 1GV/m



E. Peralta, recently fabricated prototype structure

Dielectric Structure Design Philosophies

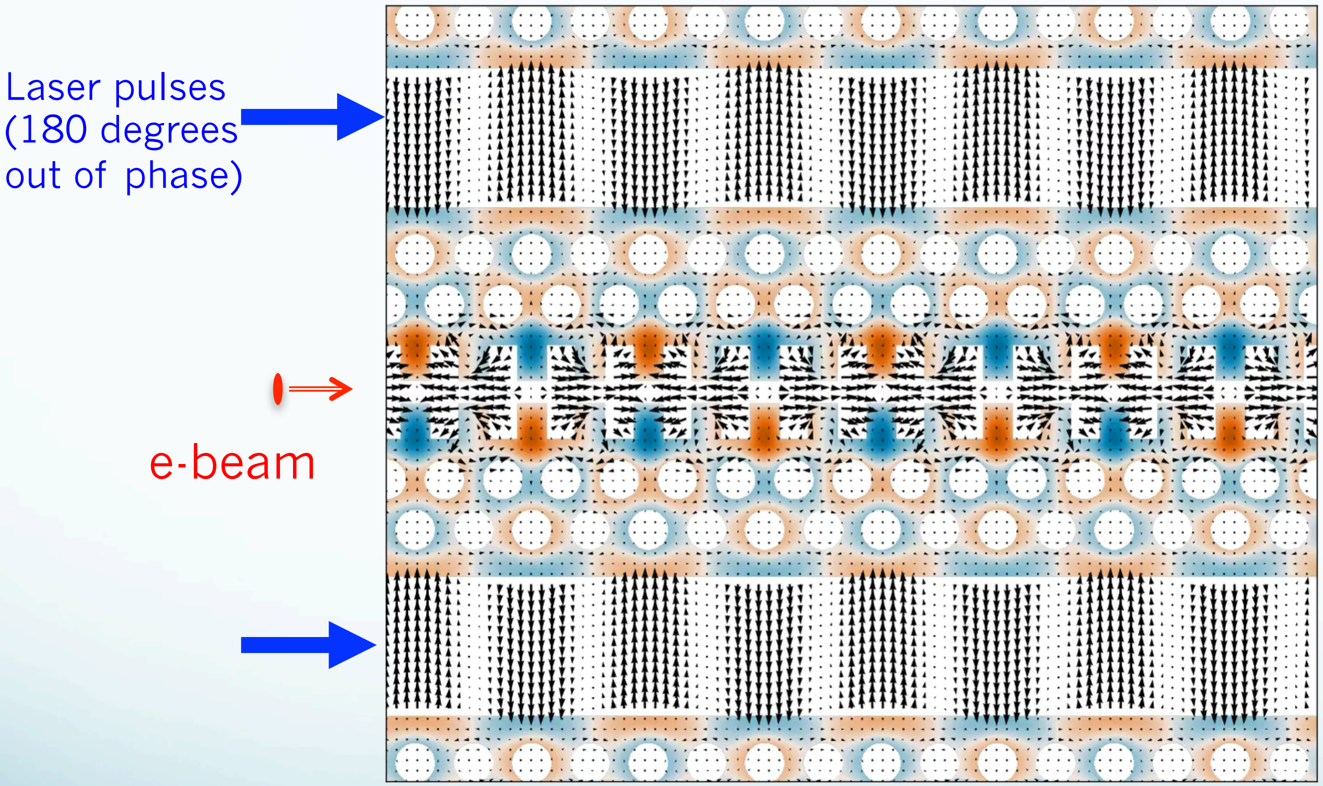
- Why dielectric?
  - *Dissipation and breakdown* in metals
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes



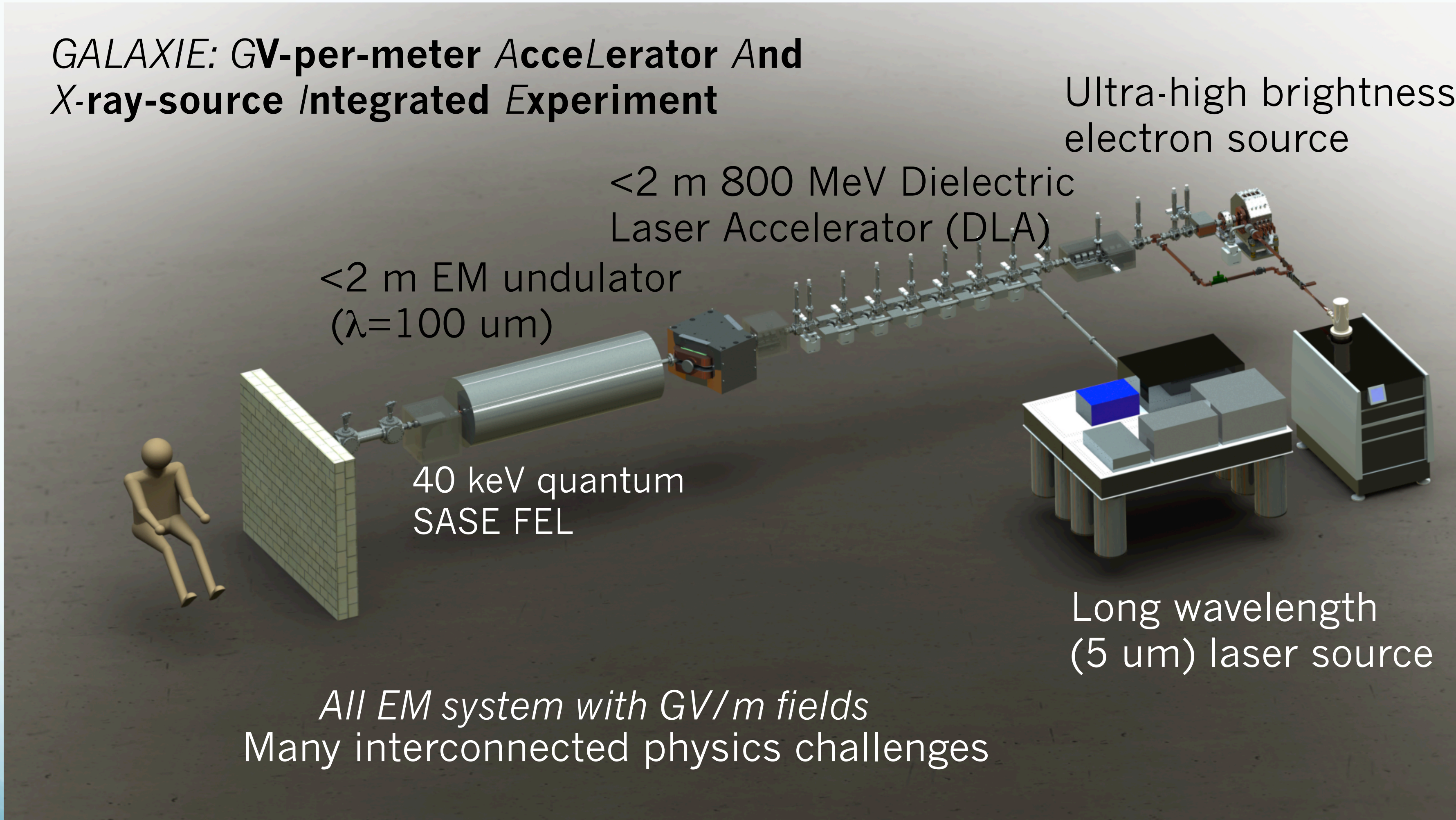
Schematic of GALAXIE
monolithic photonic DLA

Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles



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



Ambitious program supported by DARPA AXiS initiative

Dielectric laser accelerators

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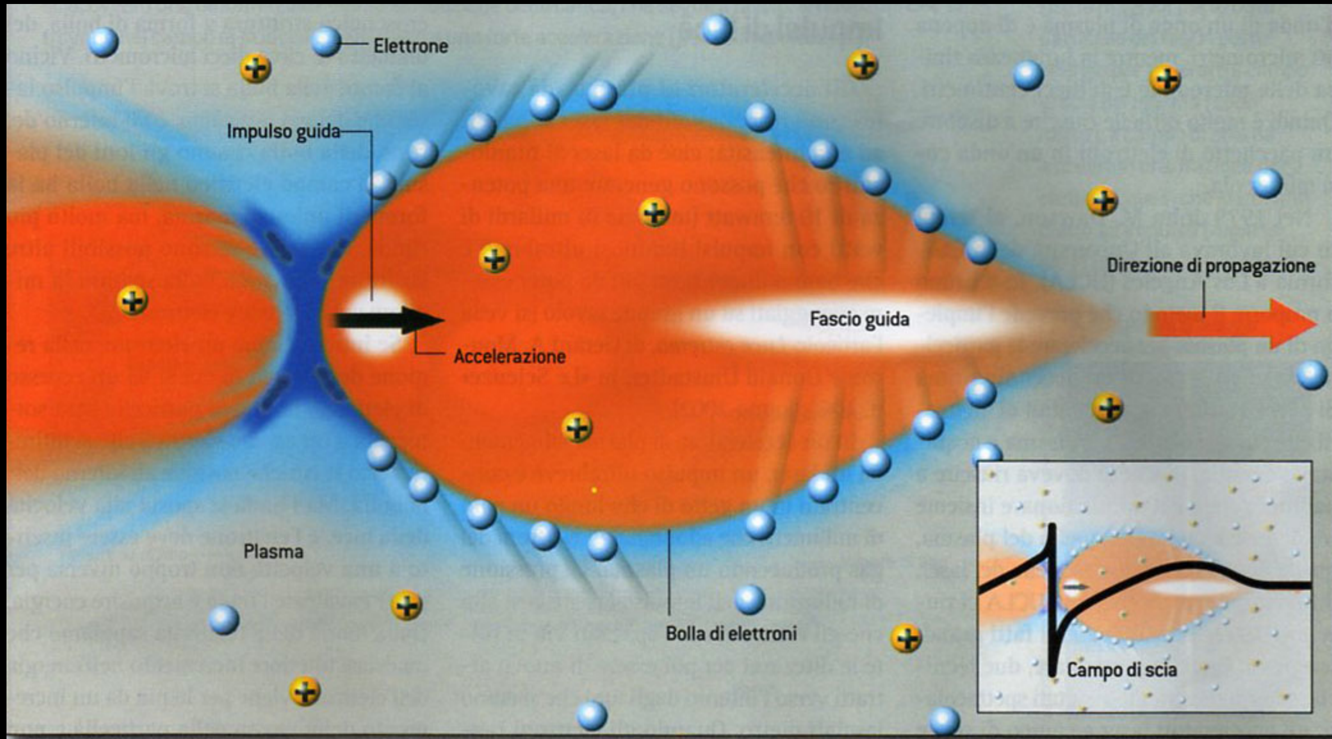
Wake Field Acceleration

High quality beam Plasma Acceleration



Breakdown limit?

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

Demonstration of electron beam focusing by a laser-plasma lens

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J.-P. Goddet,[1] A. Tafzi,[1] A. Flacco,[1] F. Tissandier,[1] S. Sebban,[1] A. Rousse,[1] and V. Malka[1]
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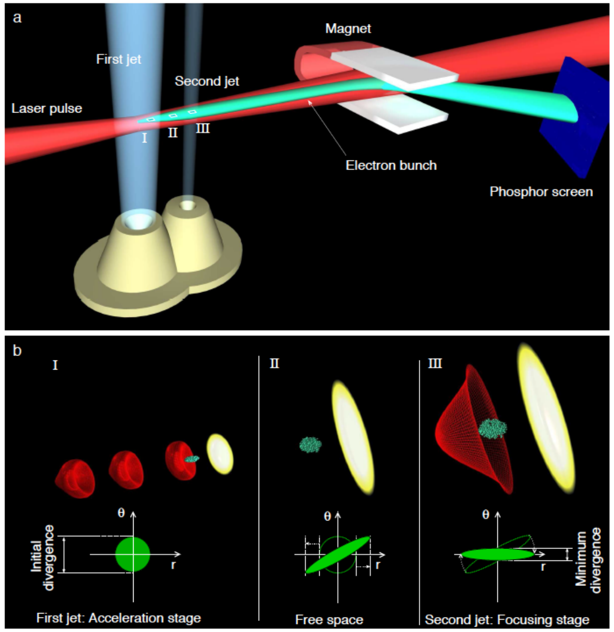
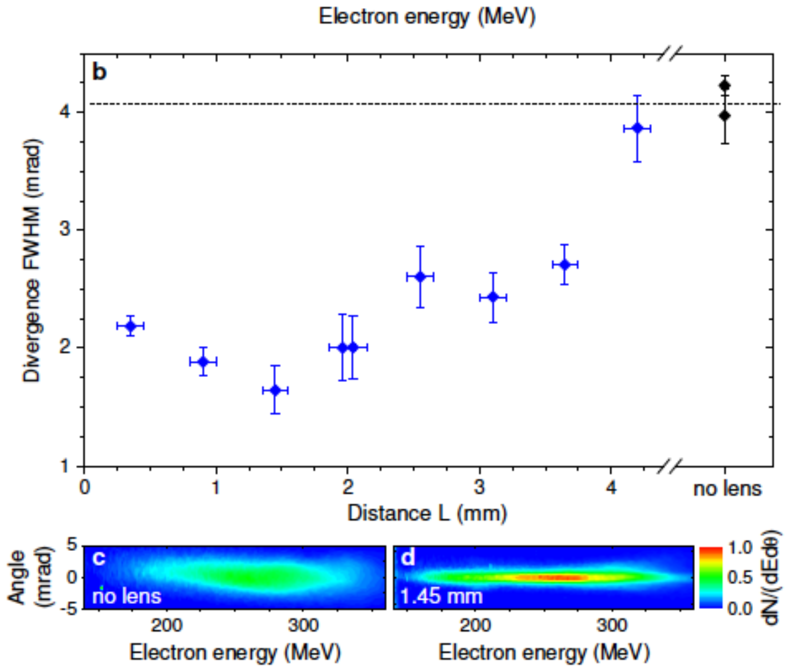


FIG. 1. Principle scheme of the laser-plasma lens. (a) An electron beam is accelerated in the first gas jet (accelerator), then it enters free space where it diverges, and is eventually focused in the second gas jet (lens). The same laser triggers a wakefield in both gas jets. Electron spectra are measured using an electron spectrometer consisting of a dipole magnet and a phosphor screen, imaged by a CCD camera. (b) Phase spaces at the end of the acceleration (I), drift (II) and focalization (III) stages.



3 Steps towards a reliable PWA

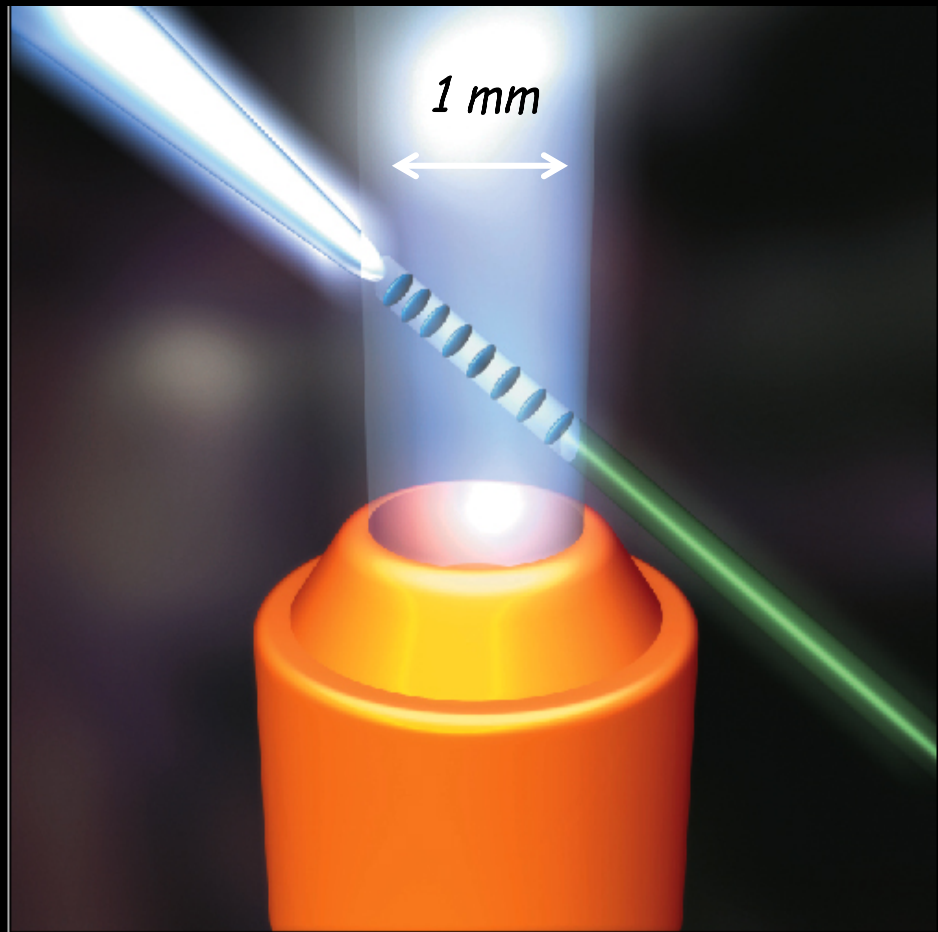
① High Gradient – Low e- Beam Quality

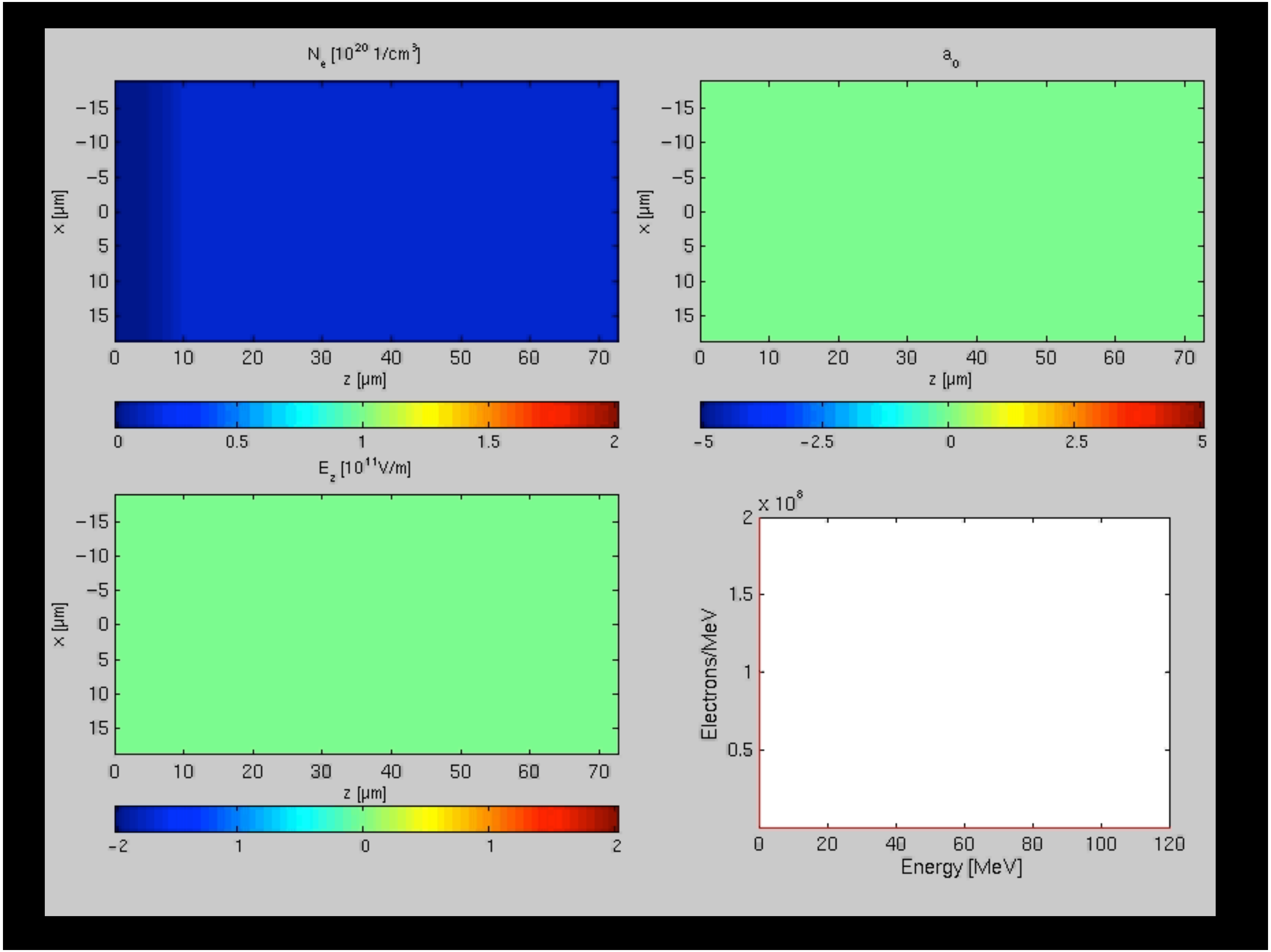
② High e+e- Beam Quality – Low Gradient

③ High e+e- Beam Quality - High Gradient

Laser Wake Field Acceleration
LWFA

Direct production of e-beam





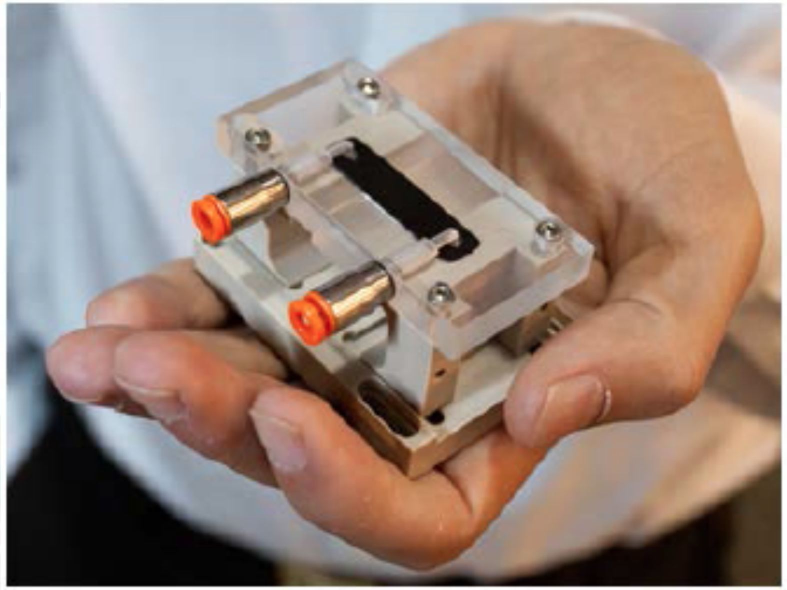
N_e [10^20 1/cm^3]
a_0
x [μm]
z [μm]
−15
−10
−5
0
5
10
15
0
10
20
30
40
50
60
70
0
0.5
1
1.5
2
−5
−2.5
0
2.5
5
E_z [10^11 V/m]
−2
1
0
1
2
x 10^8
Electrons/MeV
0.5
1
1.5
2
0
20
40
60
80
100
120
Energy [MeV]

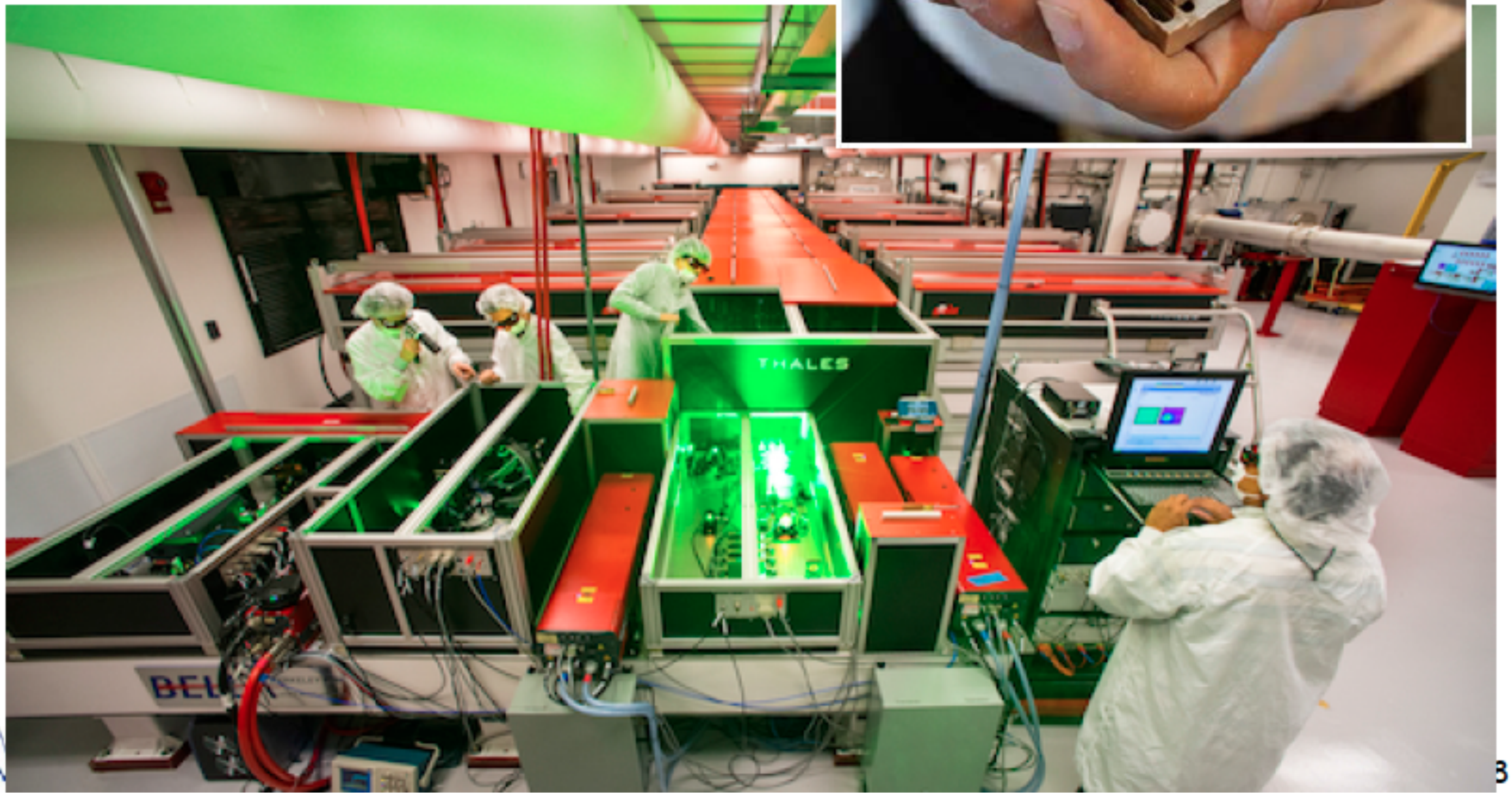
World Leader

BELLA LPWA facility:

3 cm 1 GeV 40 TW laser ~1Hz

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





Selected for a Viewpoint in *Physics*

PRL **113,** 245002 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

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

W. P. Leemans,[1,2,*] A. J. Gonsalves,[1] H.-S. Mao,[1] K. Nakamura,[1] C. Benedetti,[1] C. B. Schroeder,[1] Cs. Tóth,[1] J. Daniels,[1] D. E. Mittelberger,[2,1] S. S. Bulanov,[2,1] J.-L. Vay,[1] C. G. R. Geddes,[1] and E. Esarey[1]

[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

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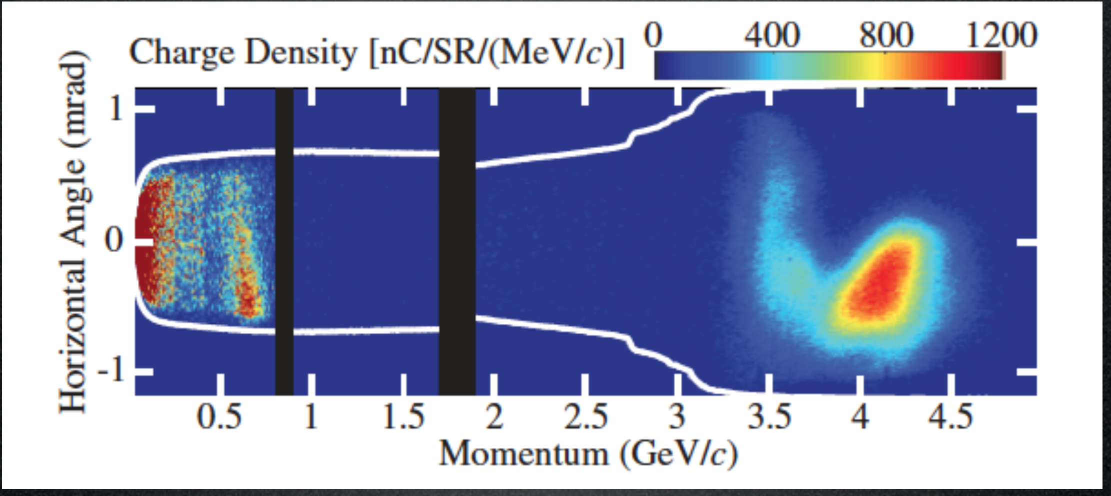
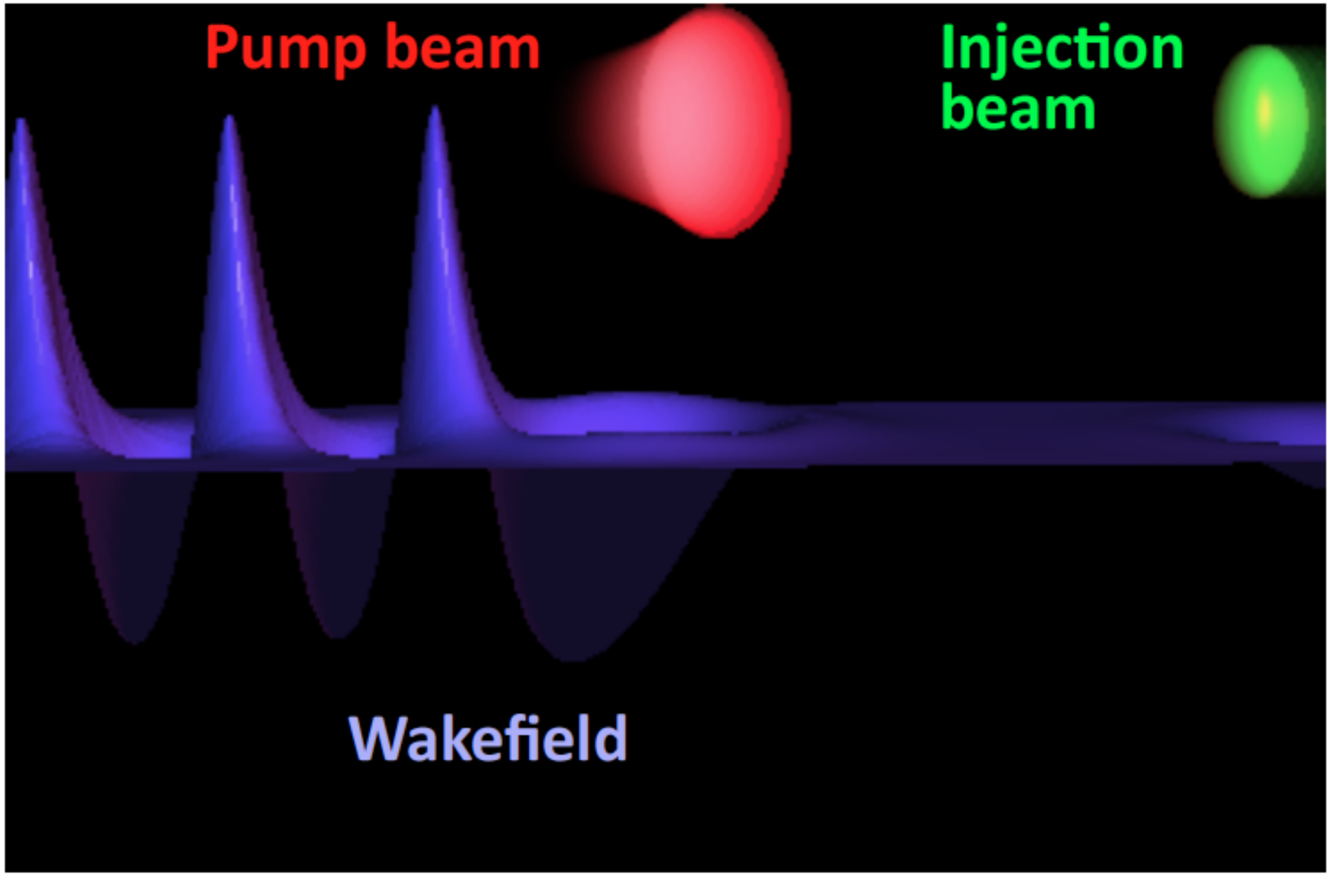
(Received 3 July 2014; revised manuscript received 11 September 2014; published 8 December 2014)

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.



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)
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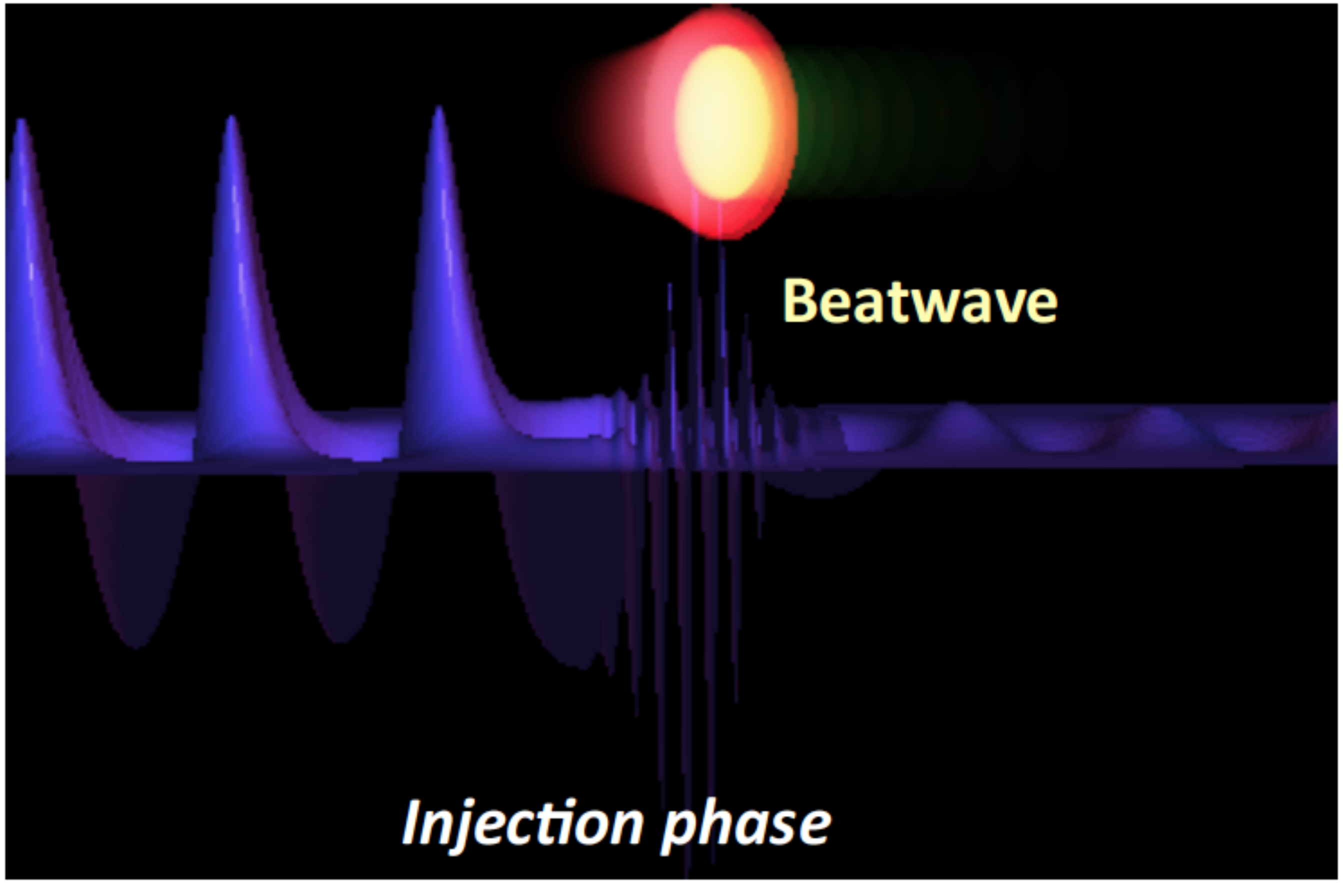

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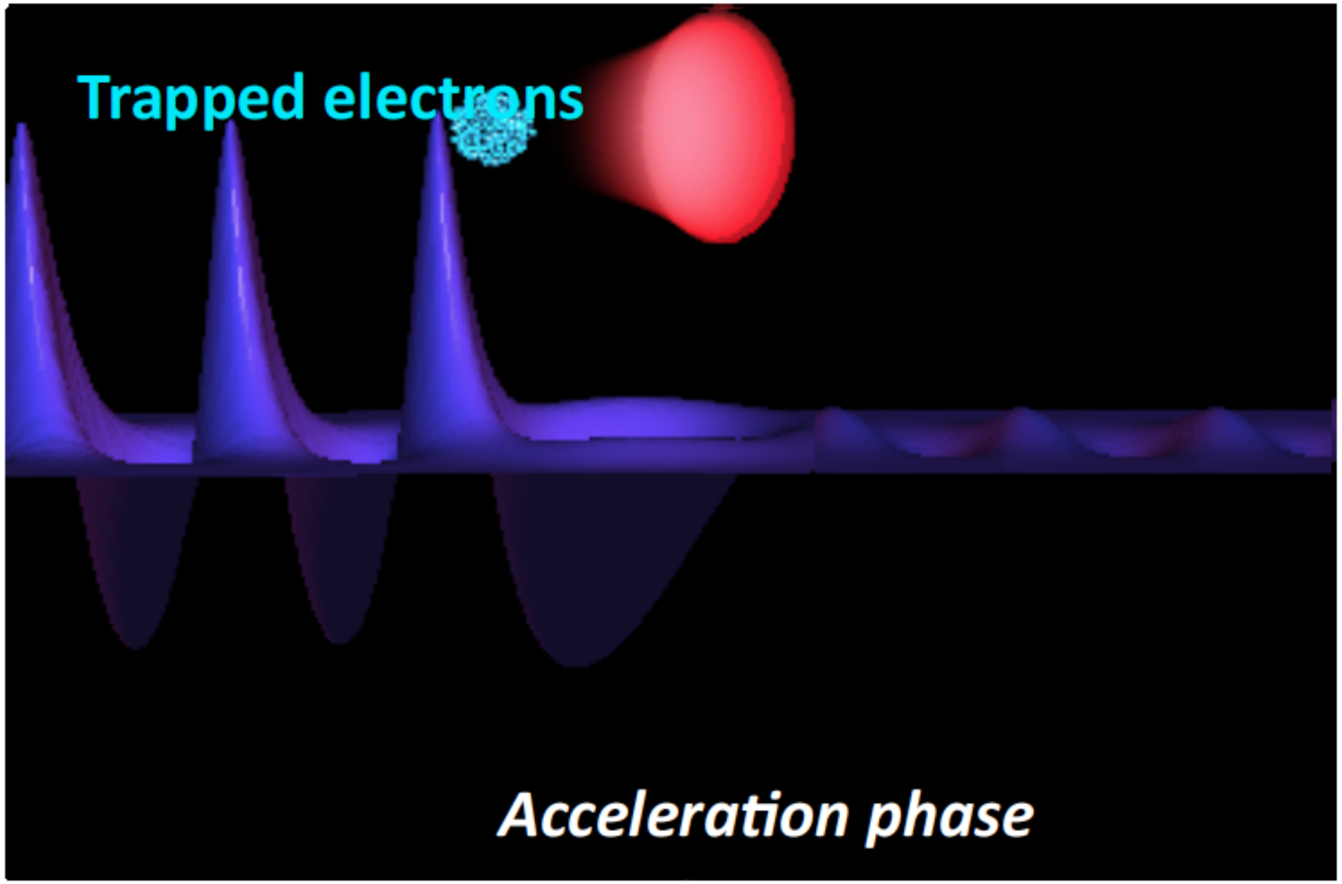

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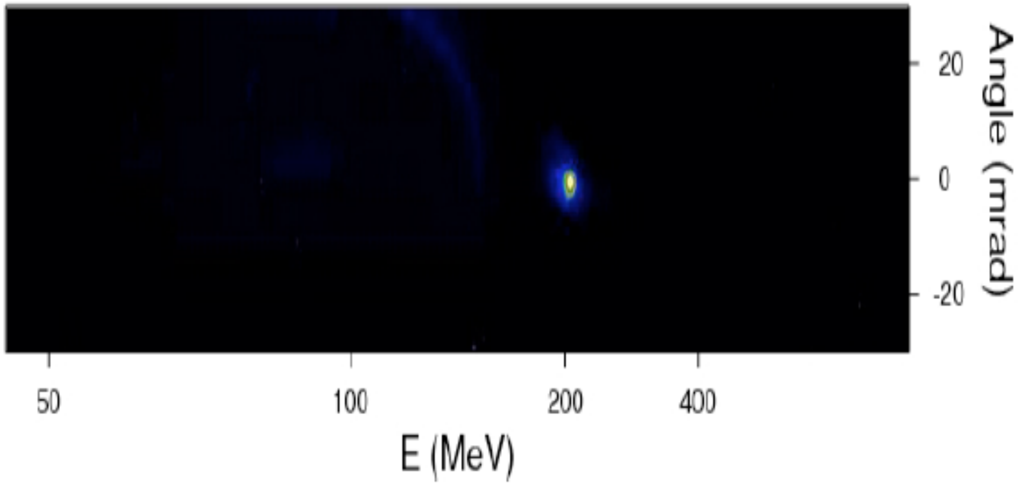
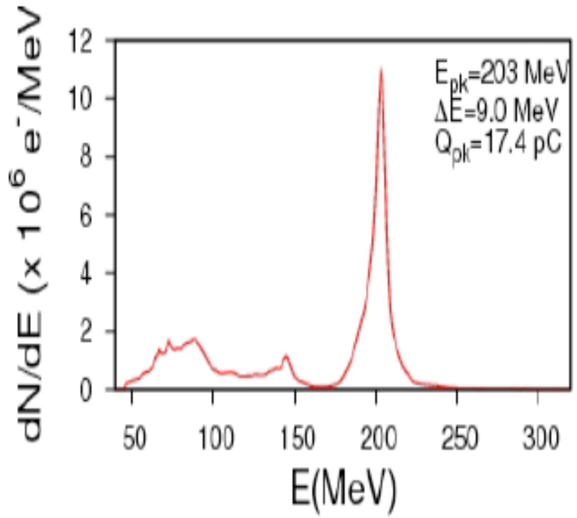
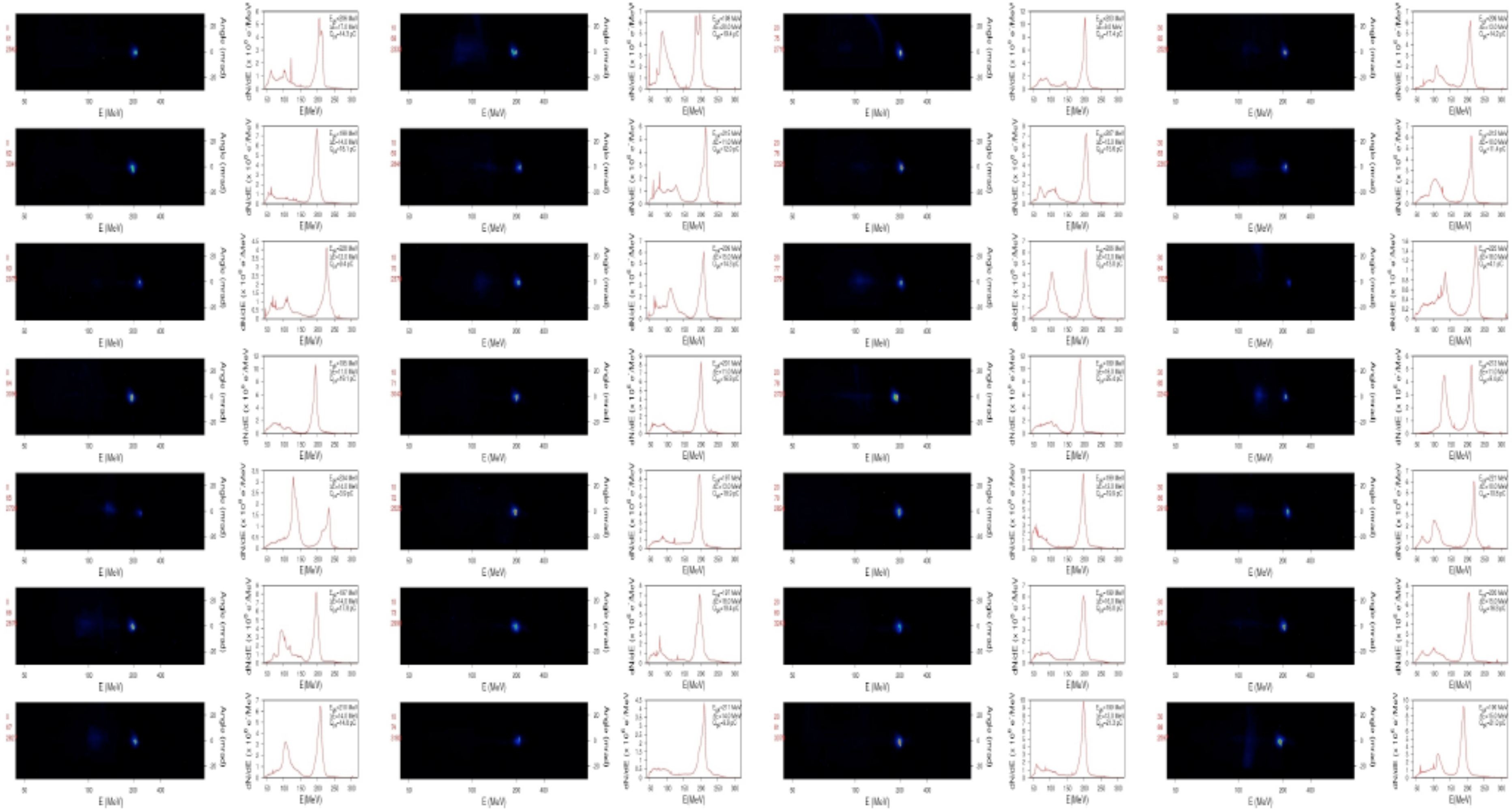
Stable Laser Plasma Accelerators





Stable Laser Plasma Accelerators

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



Conclusions

Accelerators point of view :

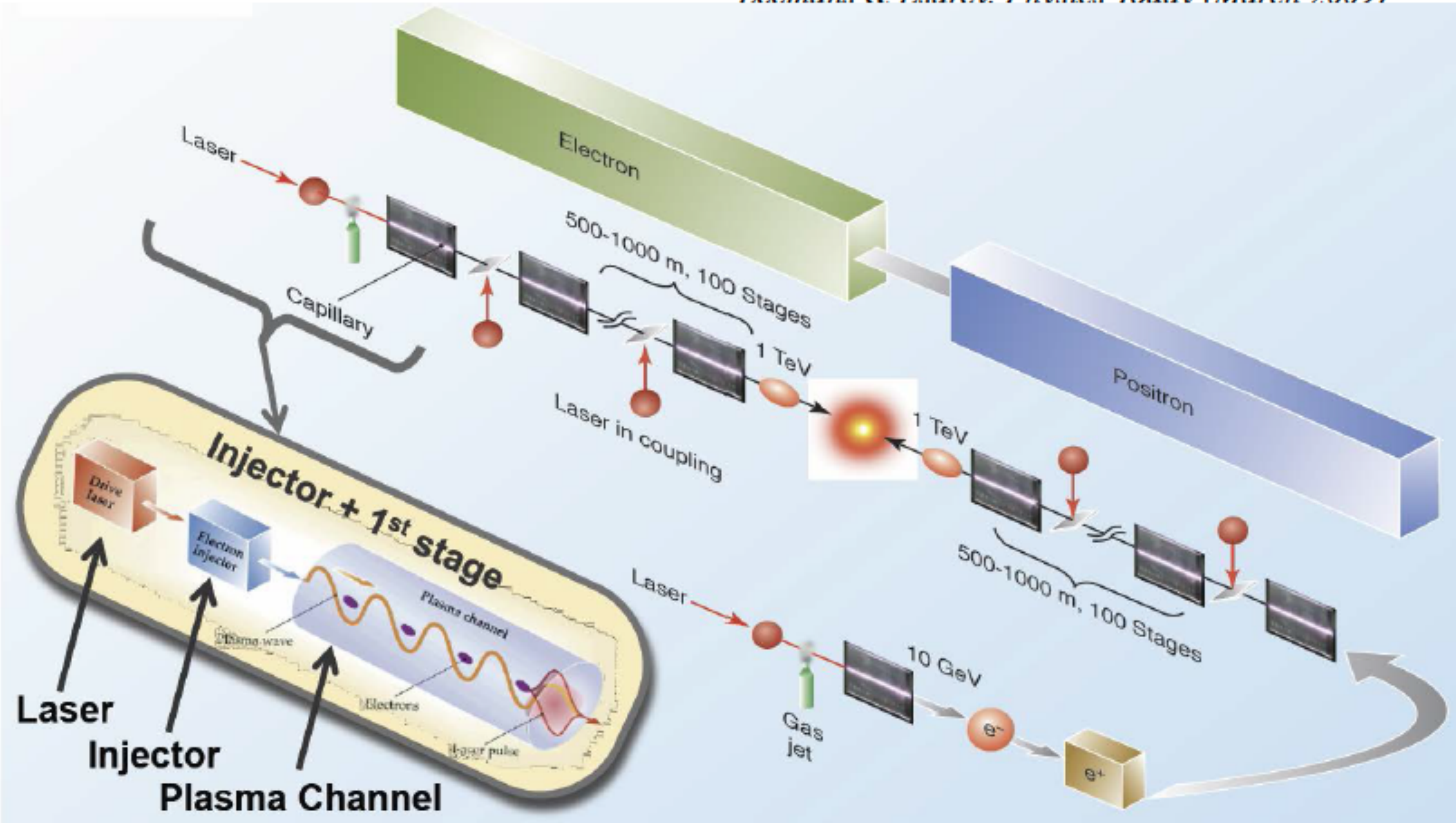
- Good beam quality & Monoenergetic dE/E down to 1 % √
- Beam is very stable √
- Energy is tunable: up to 400 MeV √
- Charge is tunable: 1 to tens of pC √
- Energy spread is tunable: 1 to 10 % √
- Ultra short e-bunch : 1,5 fs rms √
- Low divergence : 2 mrad √
- Low emittance[1-3] : < π.mm.mrad √

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)

Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)



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

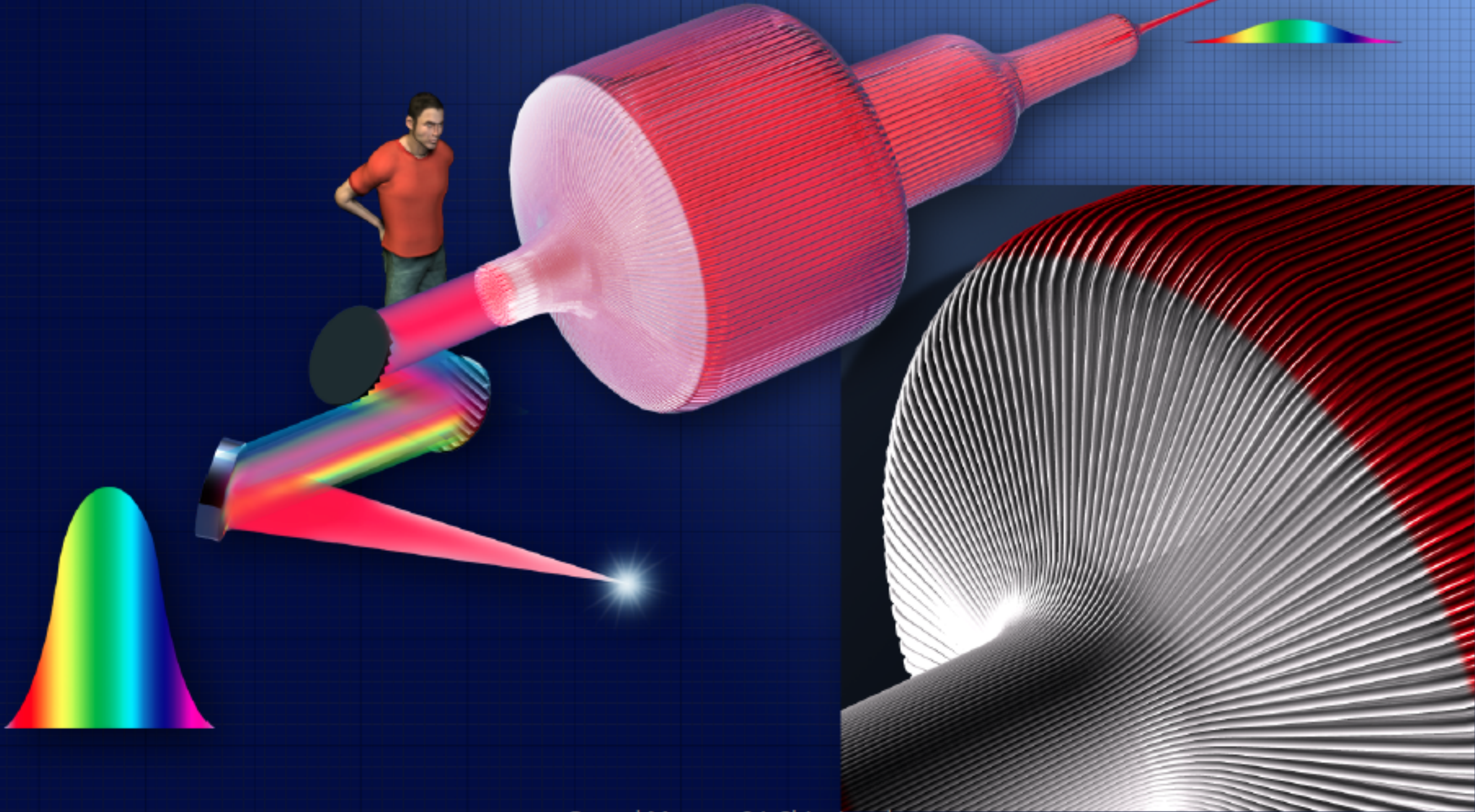
×2+FF

W.Leemans, ICFA BD Newsletter, No.56 (2011)

ICAN (European Project)

CAN Coherent Amplification Network

G. Mourou, W. Brocklesby, J. Limpert, T. Tajima, Nature Photonics April 2013
« The future of Acceletaor is Fiber »



Gerard Mourou S.L Chin, Laval

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

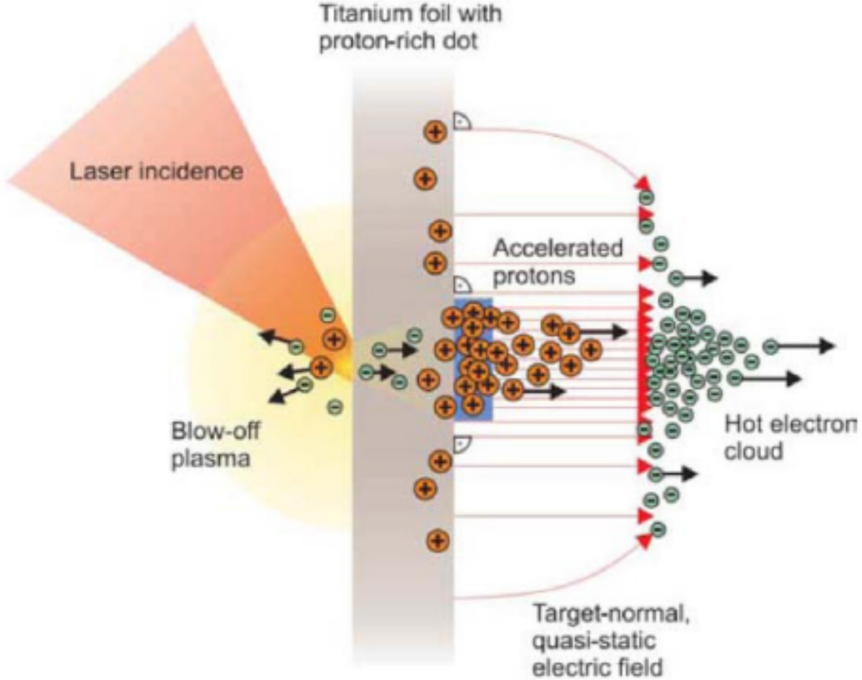
Laser Driven Acceleration of Protons

- Direct acceleration in laser field > 10^{25} W/cm^2 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/cm^2

Target Normal Sheath Acceleration
"best understood" candidate:

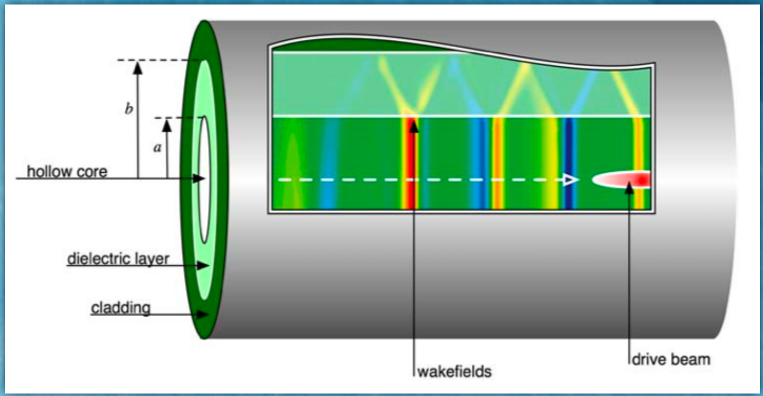
- laser creates blow-off plasma on front surface
- backside expansion accelerated electrons ionize hydrogen
- hot electrons create electric field (by space charge)
- causes acceleration of protons (electrons slowing down – end of acceleration)
- neutralized bunch of comoving p and e generated



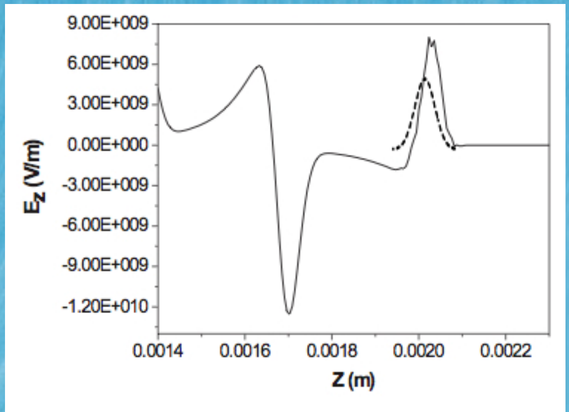
Particle Wake Field Acceleration

PWFA & DWFA

Dielectric Wakefield Accelerator



- Design Parameters $a,b \quad \sigma_z \quad \varepsilon$



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

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

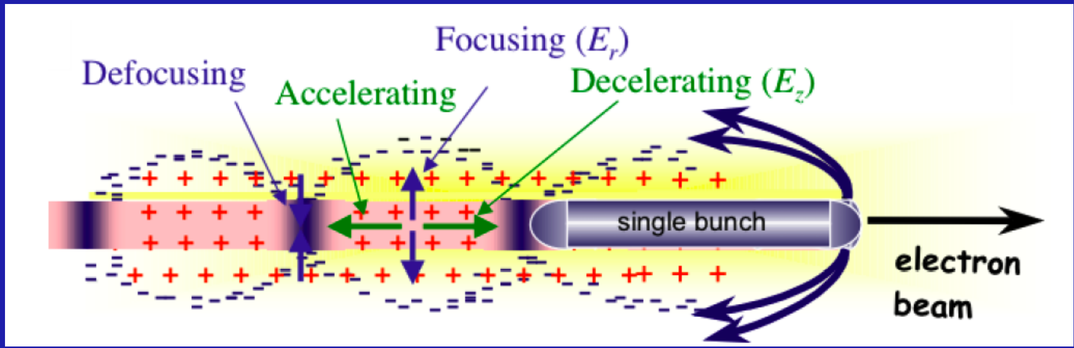
  - Peak decelerating field

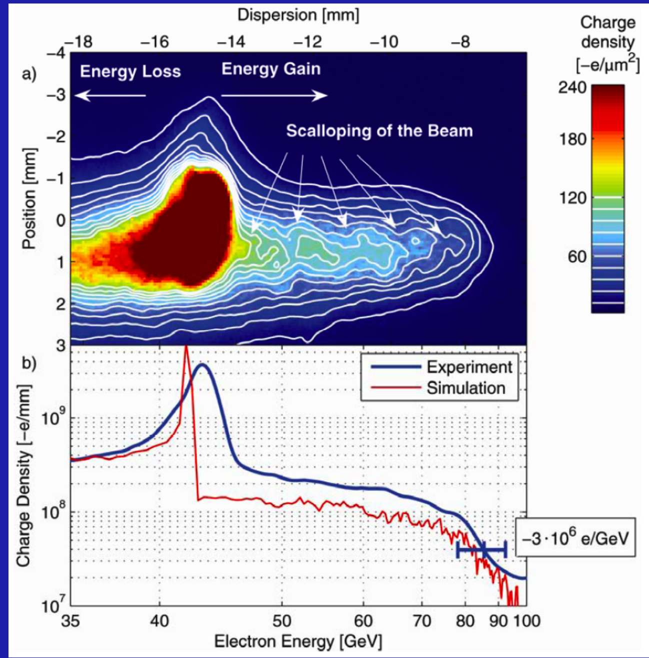
$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right]}$$

Extremely good beam needed

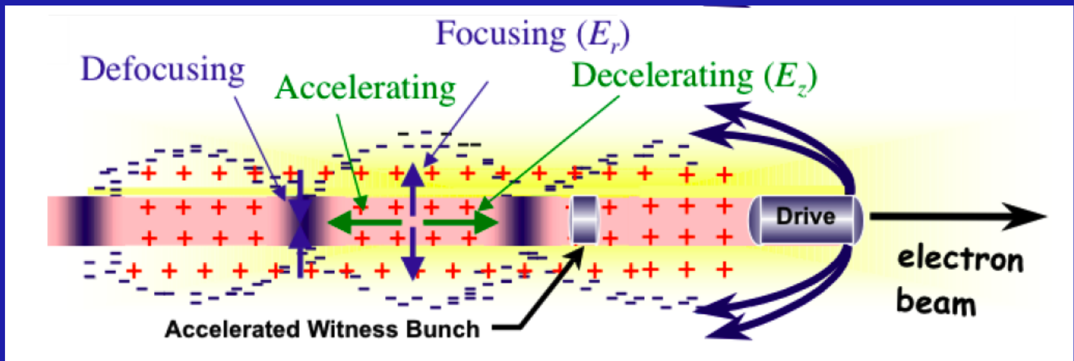
  - Transformer ratio (unshaped beam)

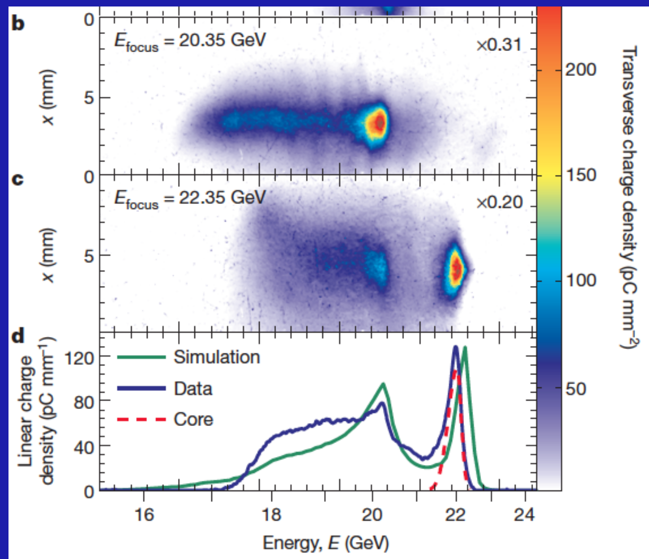
$$R = \frac{E_{z,acc}}{E_{z,dec}} \leq 2$$





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





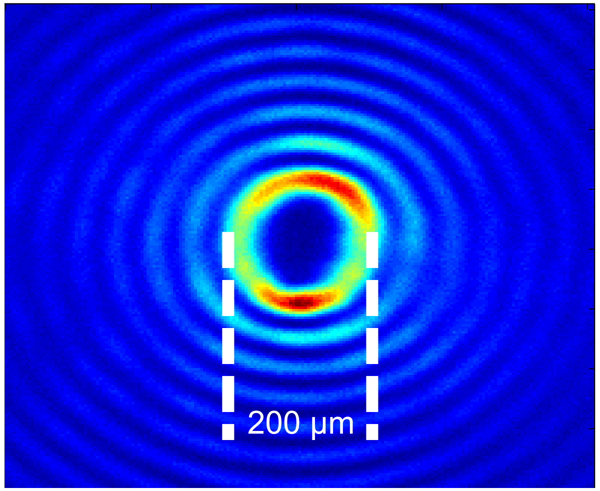
Litos, M. et al. *High-efficiency acceleration of an electron beamin a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

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.

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

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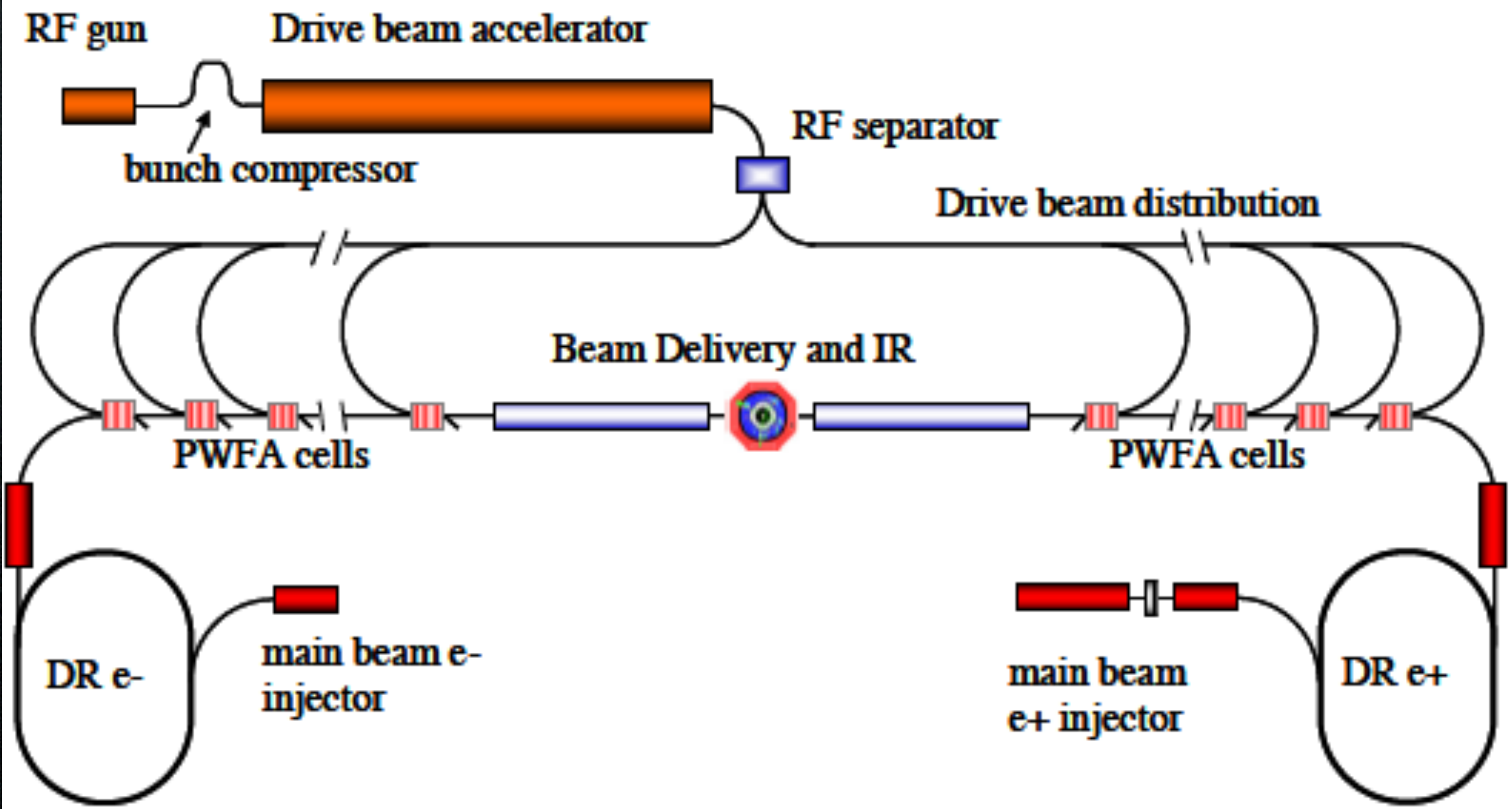

Fig. 1: Concept for a multi-stage PWFA Linear Collider.

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}

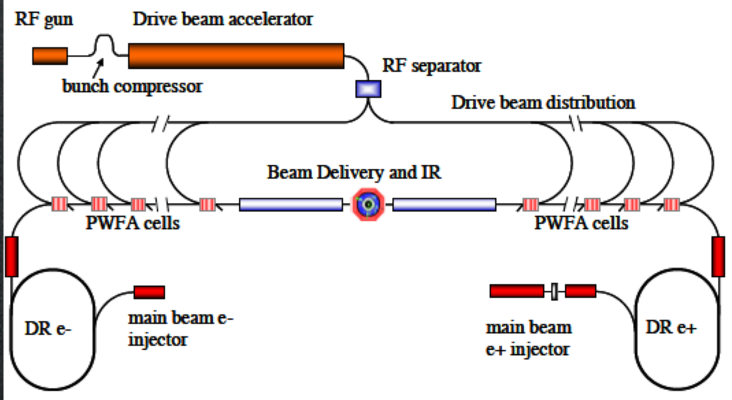

Fig. 1: Concept for a multi-stage PWFA Linear Collider.

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

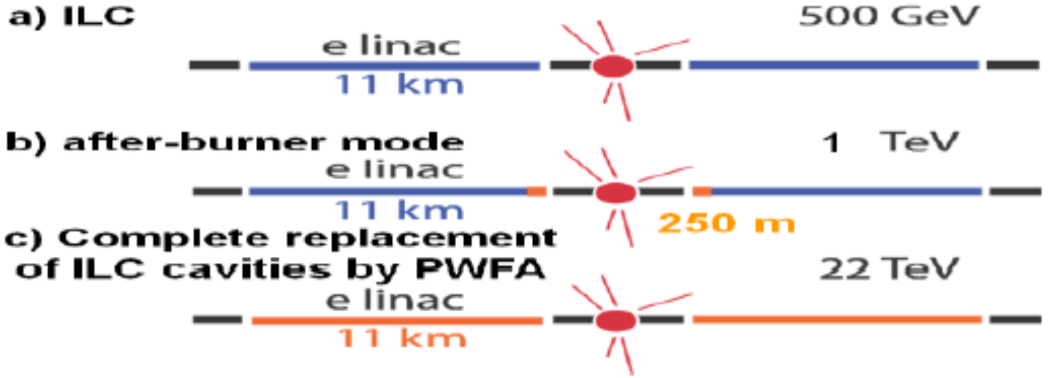

Figure 3: ILC energy upgrade by PWFA technology in the 500 GeV ILC tunnel (a), in after-burner mode (b), in the extreme case of PWFA technology use only (c).

A BEAM DRIVEN PLASMA-WAKEFIELD LINEAR COLLIDER FROM HIGGS FACTORY TO MULTI-TEV*

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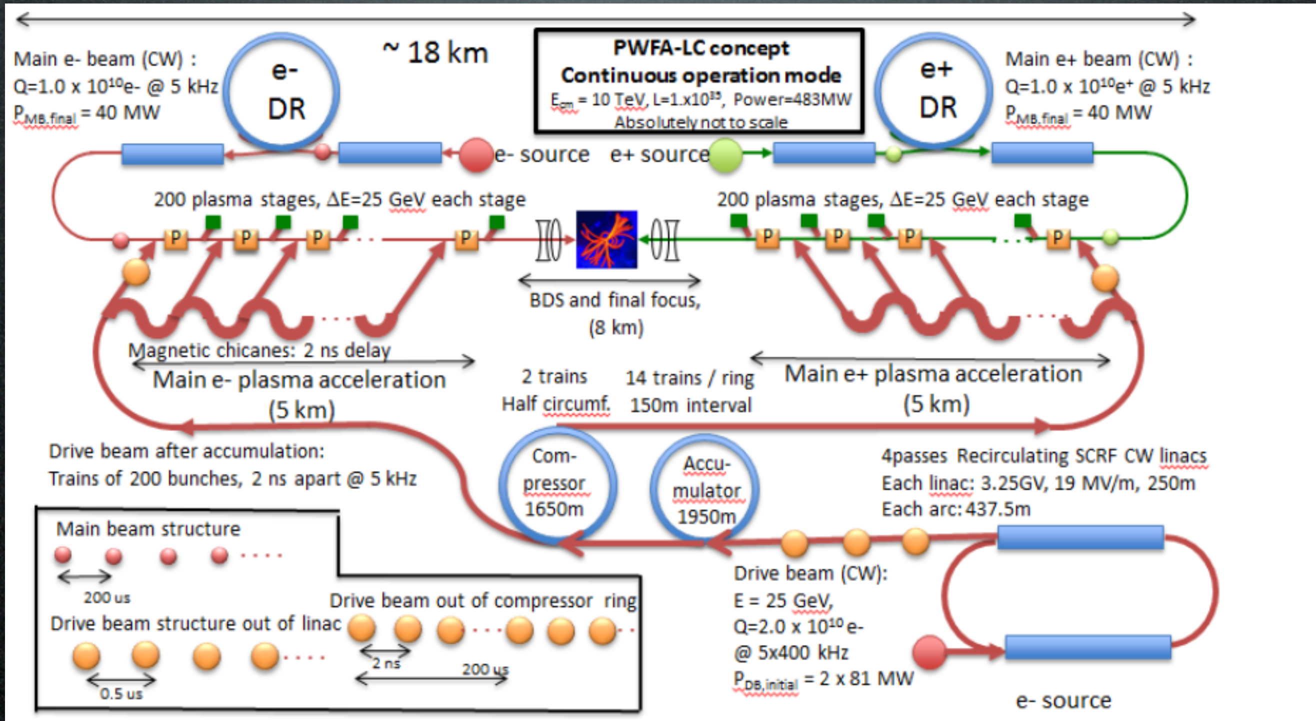
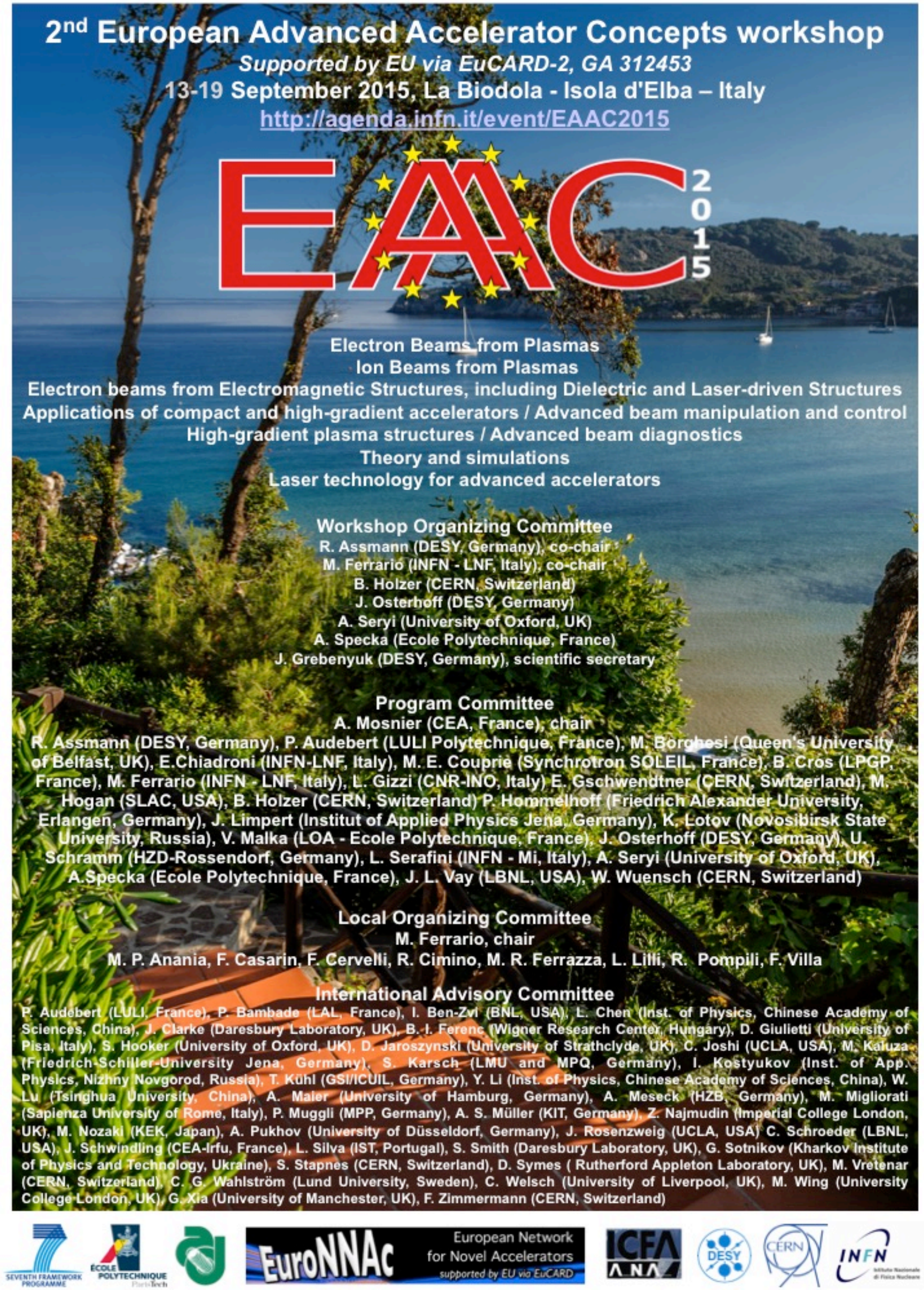


Figure 1: Layout of a PWFA-based 10 TeV Linear Collider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