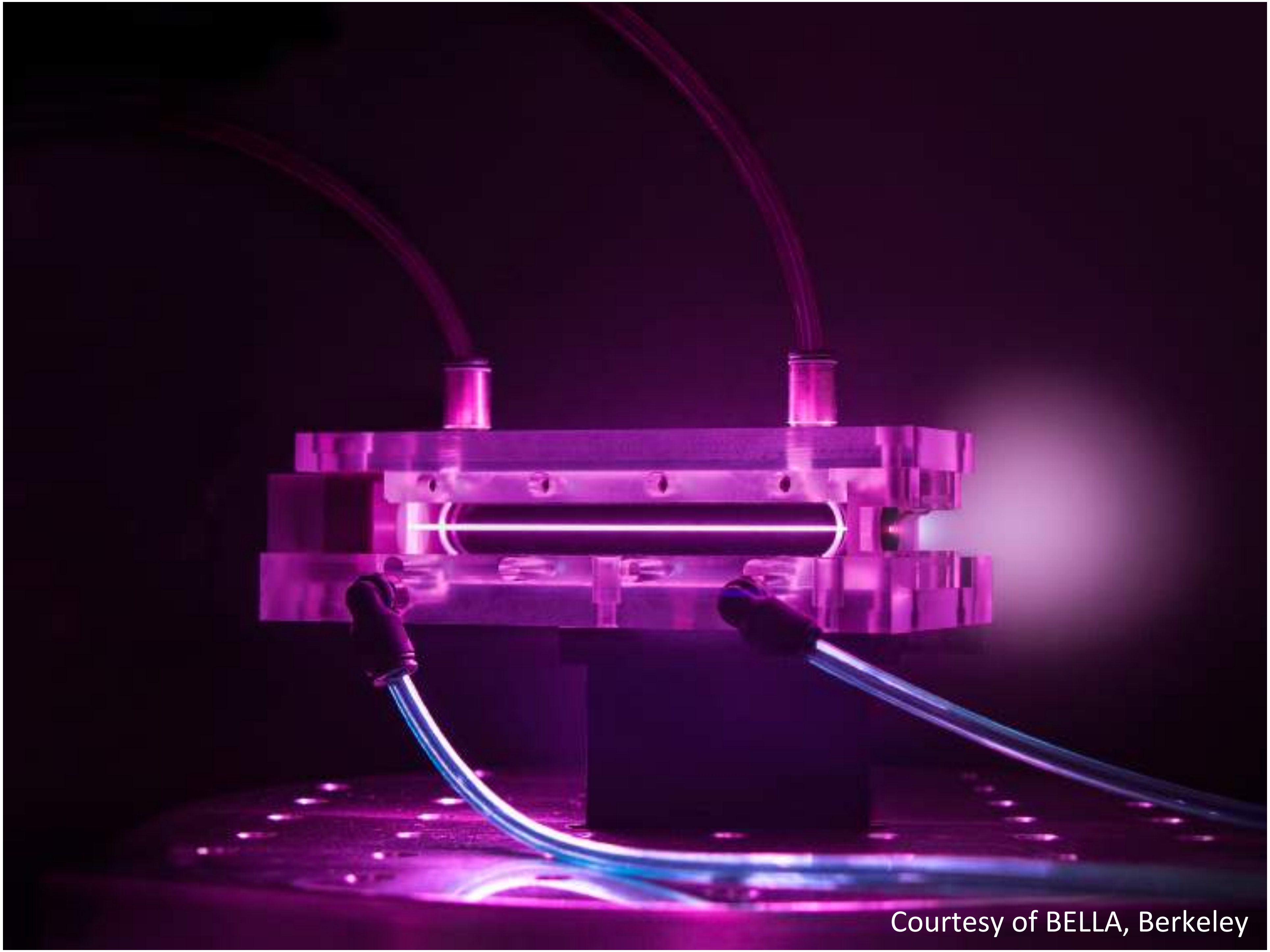
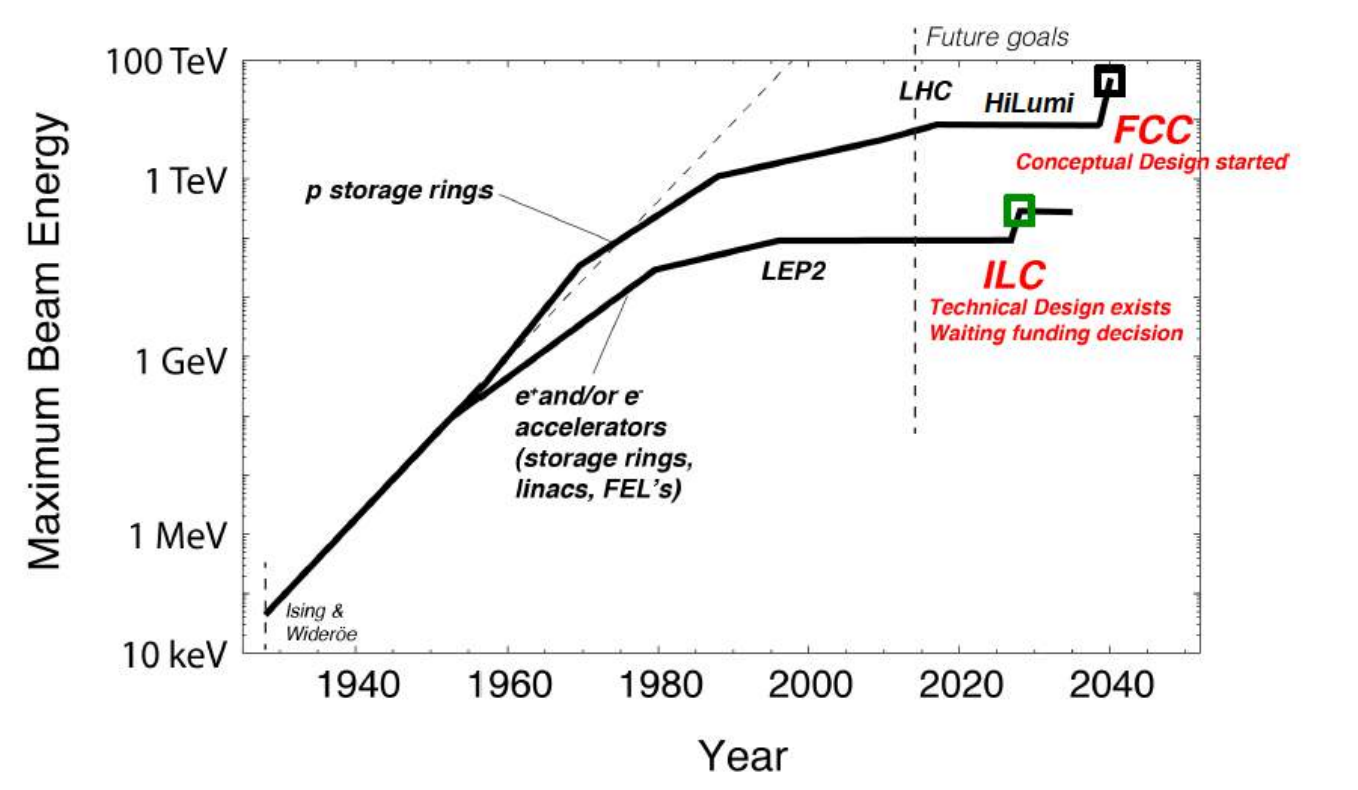

Courtesy of BELLA, Berkeley

New Acceleration Techniques

Massimo.Ferrario@lnf.infn.it



"How to advance?"

Hadron (p) circular collider

$$p = e \cdot R \cdot B_y$$

Increase bending field
SC bend magnet work (FCC-hh)

Increase radius = size (FCC-hh)

Lepton (e-,e+) circular collider

$$p \propto E_0 \cdot \sqrt[4]{\rho \cdot U_0}$$

Increase supplied RF voltage
(FCC-ee)

Increase mass of acc. particle (muon)

Increase radius = size (FCC-ee)

Lepton (e-,e+) linear collider

$$p = L \cdot G_{acc}$$

Increase accelerating gradient
(a) Pushing existing technology (ILC, CLIC)
(b) New regime of ultra-high gradients (plasma, dielectric accelerators)

Increase length (ILC, CLIC)

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

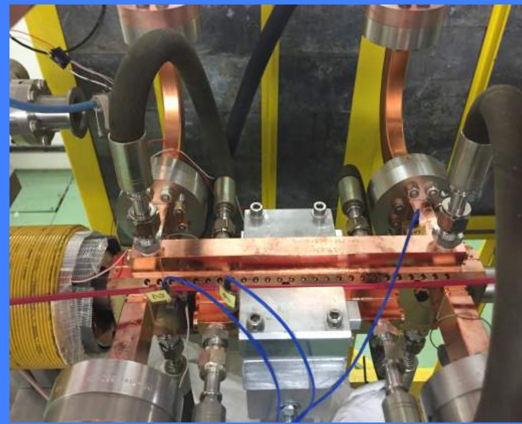
$$\uparrow \quad B_n \approx \frac{2I}{\varepsilon_n^2}$$

- Short pulse (ps to fs)

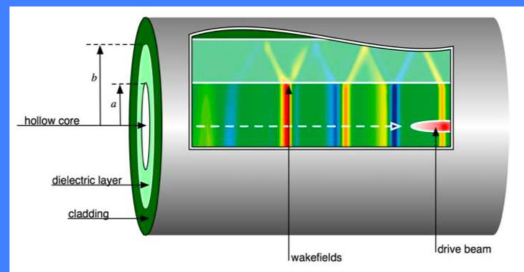
- Little spread in transverse momentum and angle => low emittance

High Gradient Options

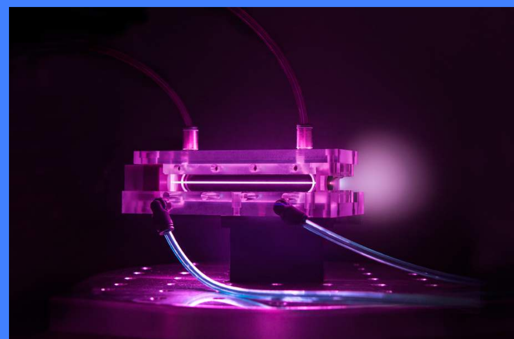
- RF accelerating structures, from X-band to K-band => 100 MV/m < E_{acc} < 1 GV/m



- Dielectrict structures, laser or particle driven => 1 GV/m < E_{acc} < 5 GV/m



- Plasma accelerator, laser or particle driven => 1 GV/m < E_{acc} < 100 GV/m

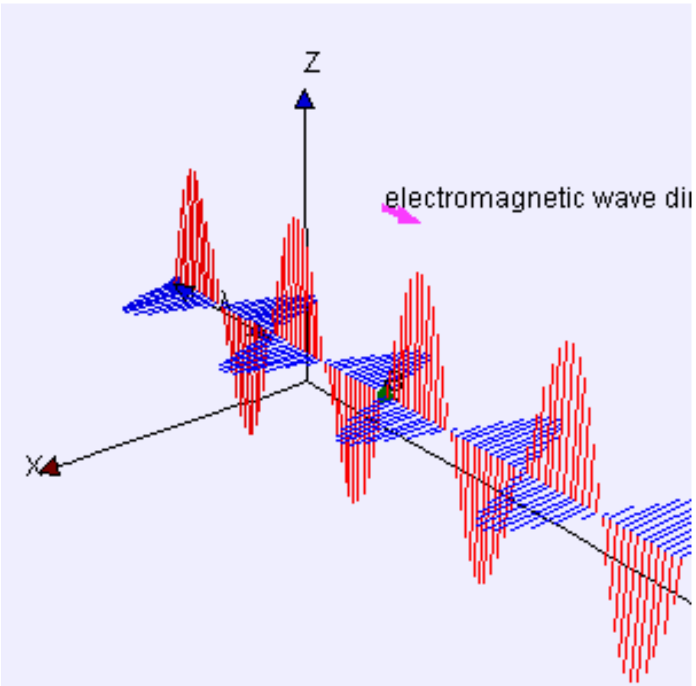


Lawson-Woodward Theorem

(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 ($v \approx c$) along the acceleration path,
(iii) no static electric or magnetic fields are present,
(iv) the region of interaction is infinite,



$$\Delta\mathcal{E} = e\int_{-\infty}^{\infty} \boldsymbol{v}\cdot\boldsymbol{E}(\boldsymbol{r}(t),t)dt, \qquad \boldsymbol{r}(t) = \boldsymbol{r}_0 + \boldsymbol{v}t,$$

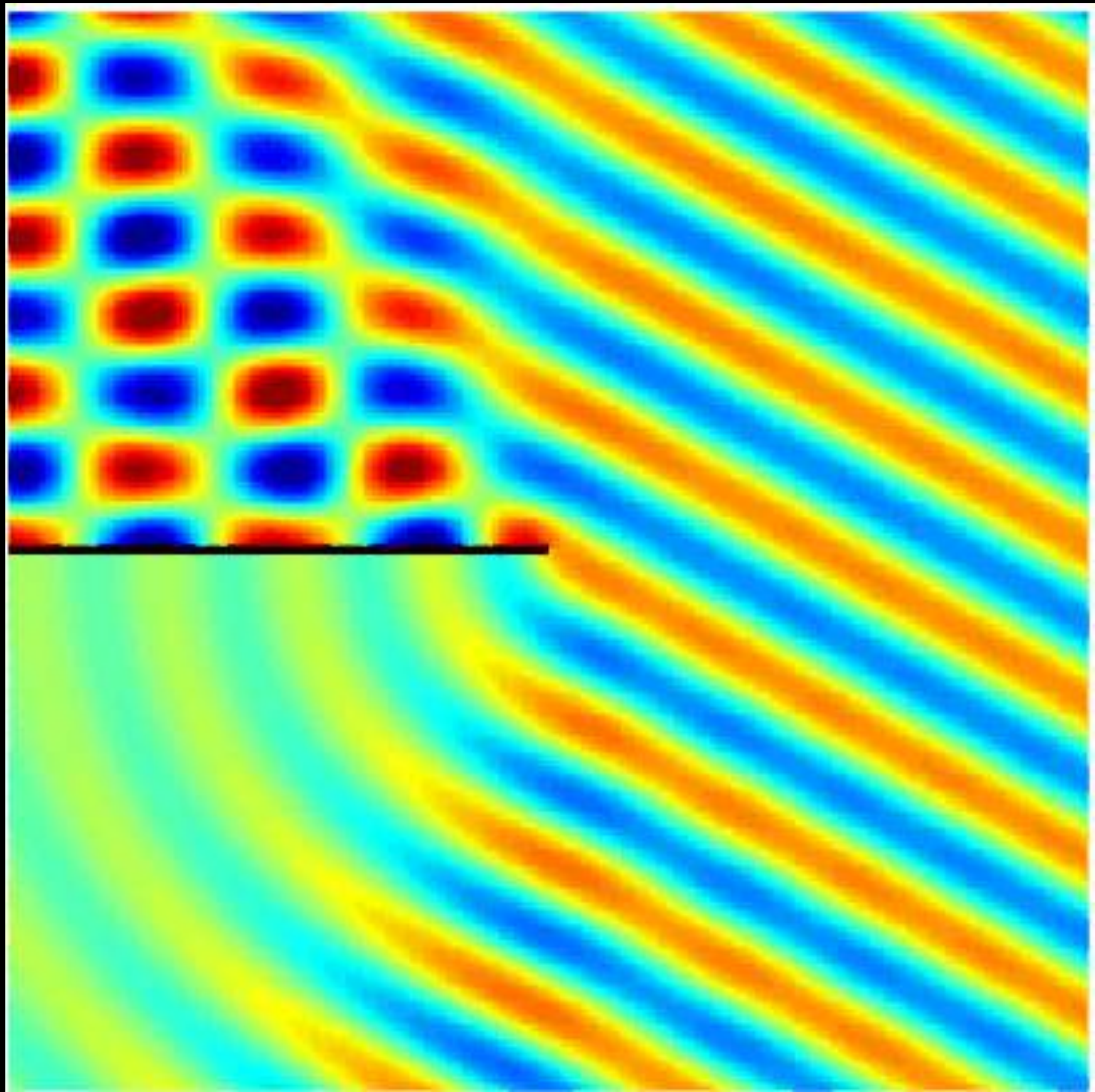
$$\boldsymbol{E}(\boldsymbol{r},t) = \int d^3k\tilde{\boldsymbol{E}}(\boldsymbol{k})e^{i\boldsymbol{k}\cdot\boldsymbol{r}-i\omega t}, \qquad \omega = ck.$$

$$\Delta\mathcal{E} = e\boldsymbol{v}\cdot\int_{-\infty}^{\infty} dt\int d^3k\tilde{\boldsymbol{E}}(\boldsymbol{k})e^{i\boldsymbol{k}\cdot(\boldsymbol{r}_0+\boldsymbol{v}t)-i\omega t}$$

$$= 2\pi e\int d^3k\boldsymbol{v}\cdot\tilde{\boldsymbol{E}}(\boldsymbol{k})e^{i\boldsymbol{k}\cdot\boldsymbol{r}_0}\delta(\omega-\boldsymbol{k}\cdot\boldsymbol{v}) \equiv 0$$

$$\omega - \boldsymbol{k}\cdot\boldsymbol{v} = ck(1-\beta\cos\alpha) > 0, \quad \Rightarrow \delta \equiv 0$$

RF Acceleration



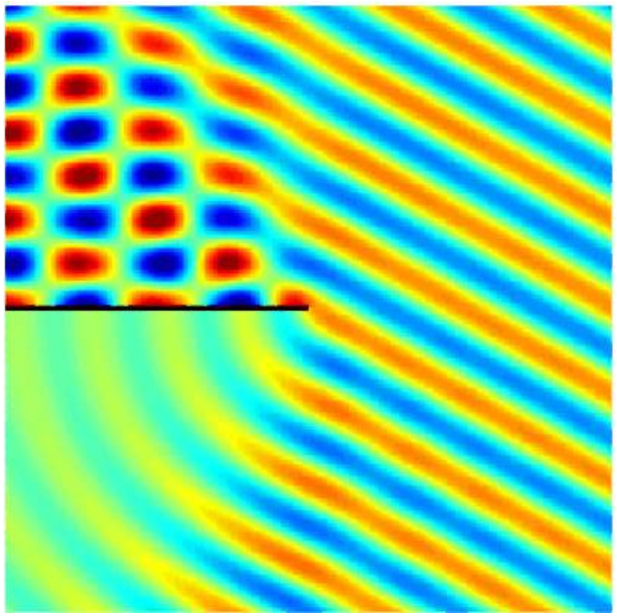
Taking into account the boundary conditions the accelerating component of the field becomes:

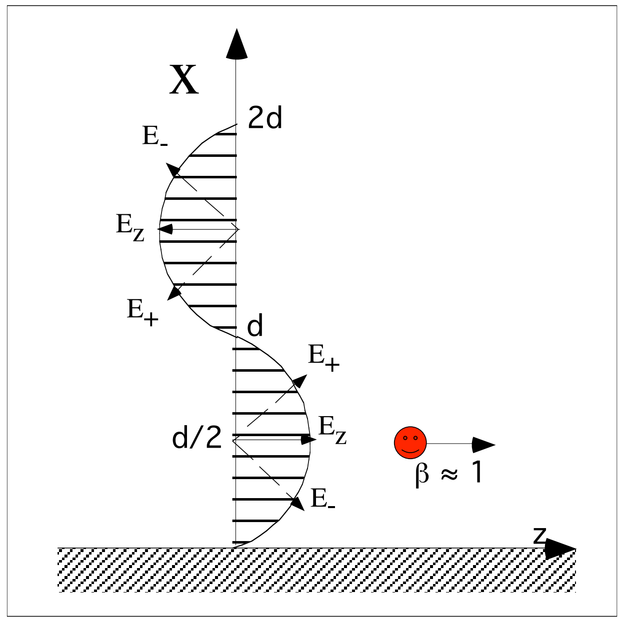
$$E_z(x,z,t) = (E_+ \sin\theta)e^{i\omega t - ik(z\cos\theta - x\sin\theta)} - (E_+ \sin\theta)e^{i\omega t - ik(z\cos\theta + x\sin\theta)}$$

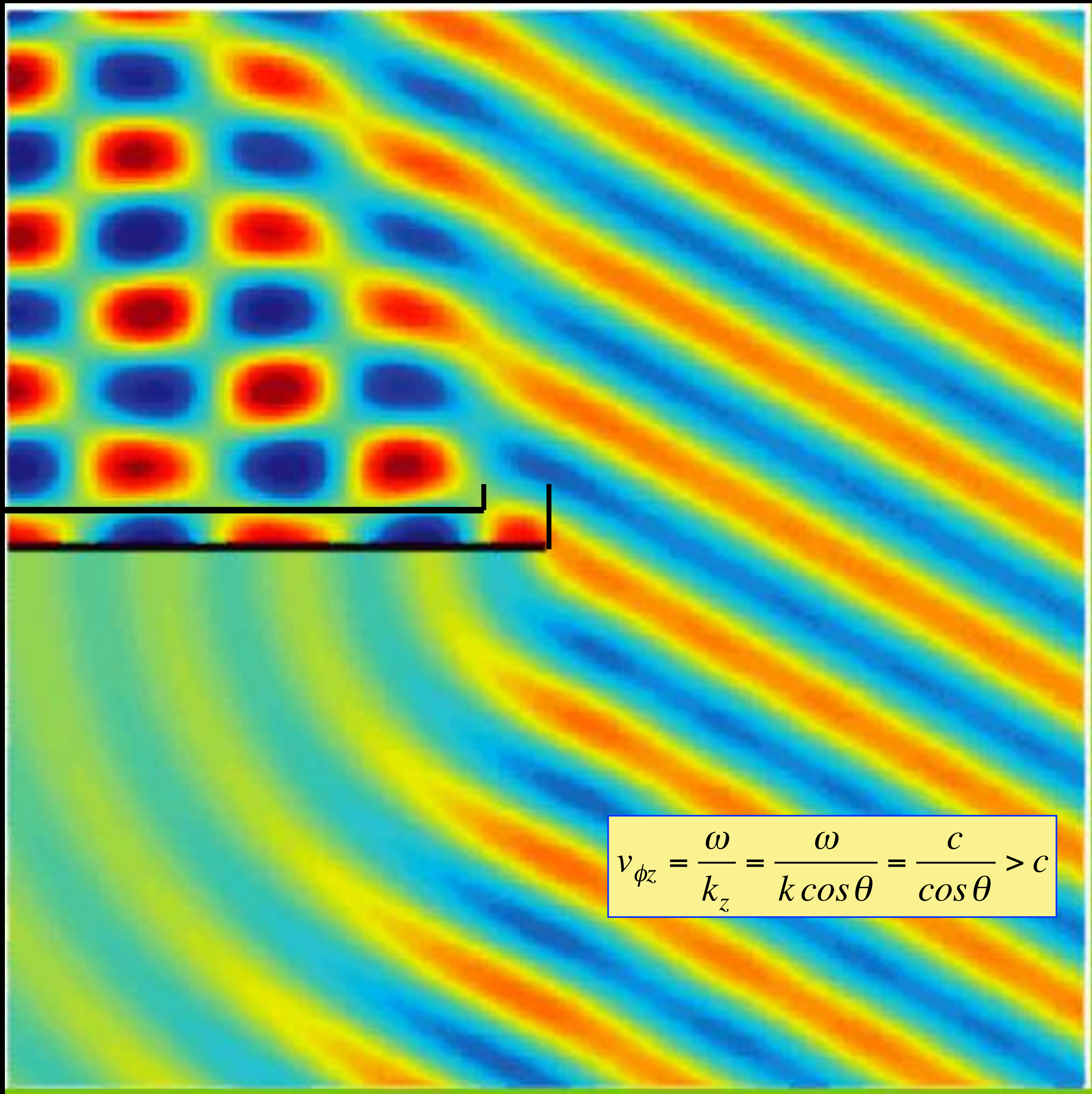
$$= 2iE_+ \sin\theta \sin(kx\sin\theta)e^{i\omega t - ikz\cos\theta}$$

z-TW pattern

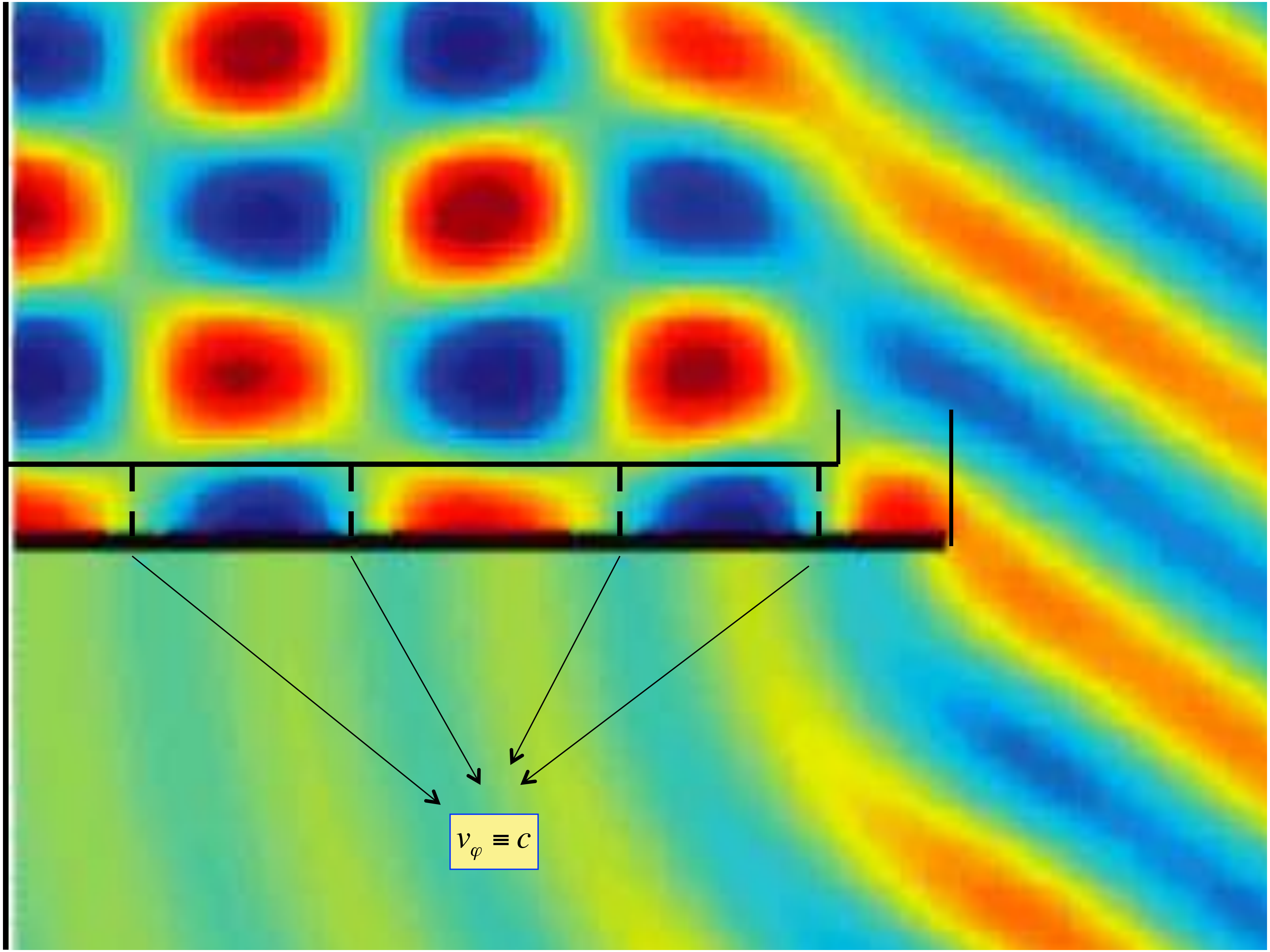
x-SW pattern



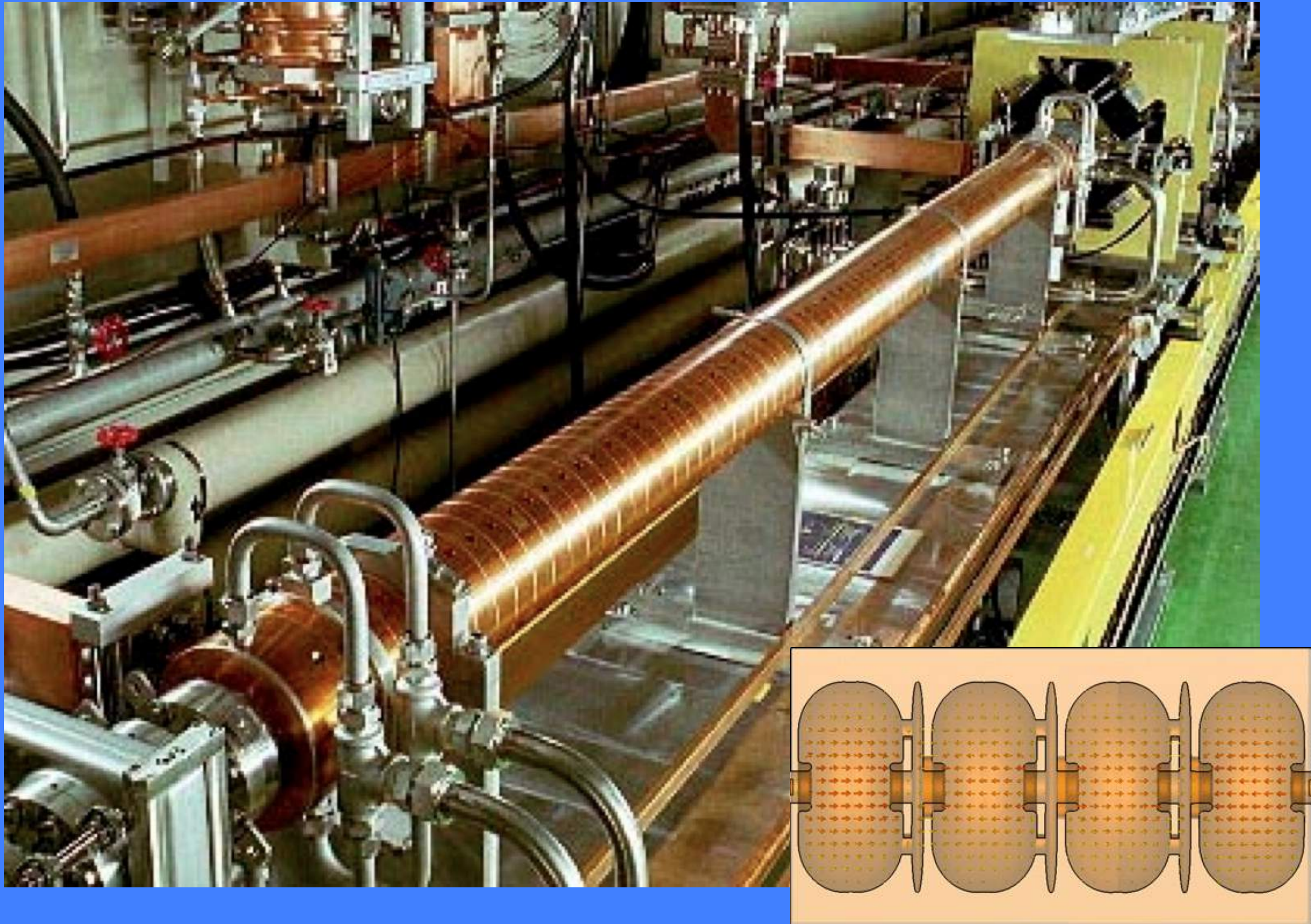


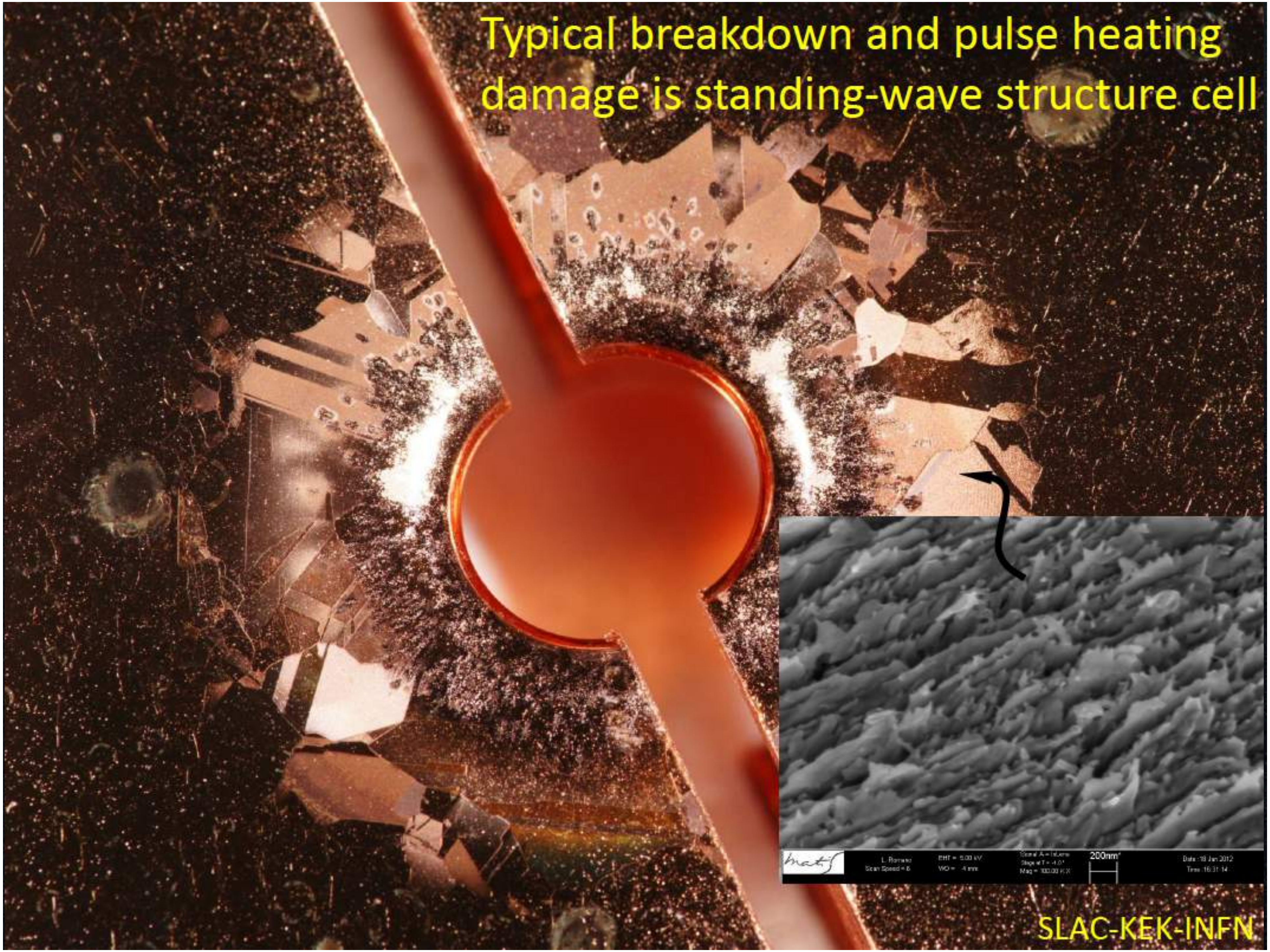


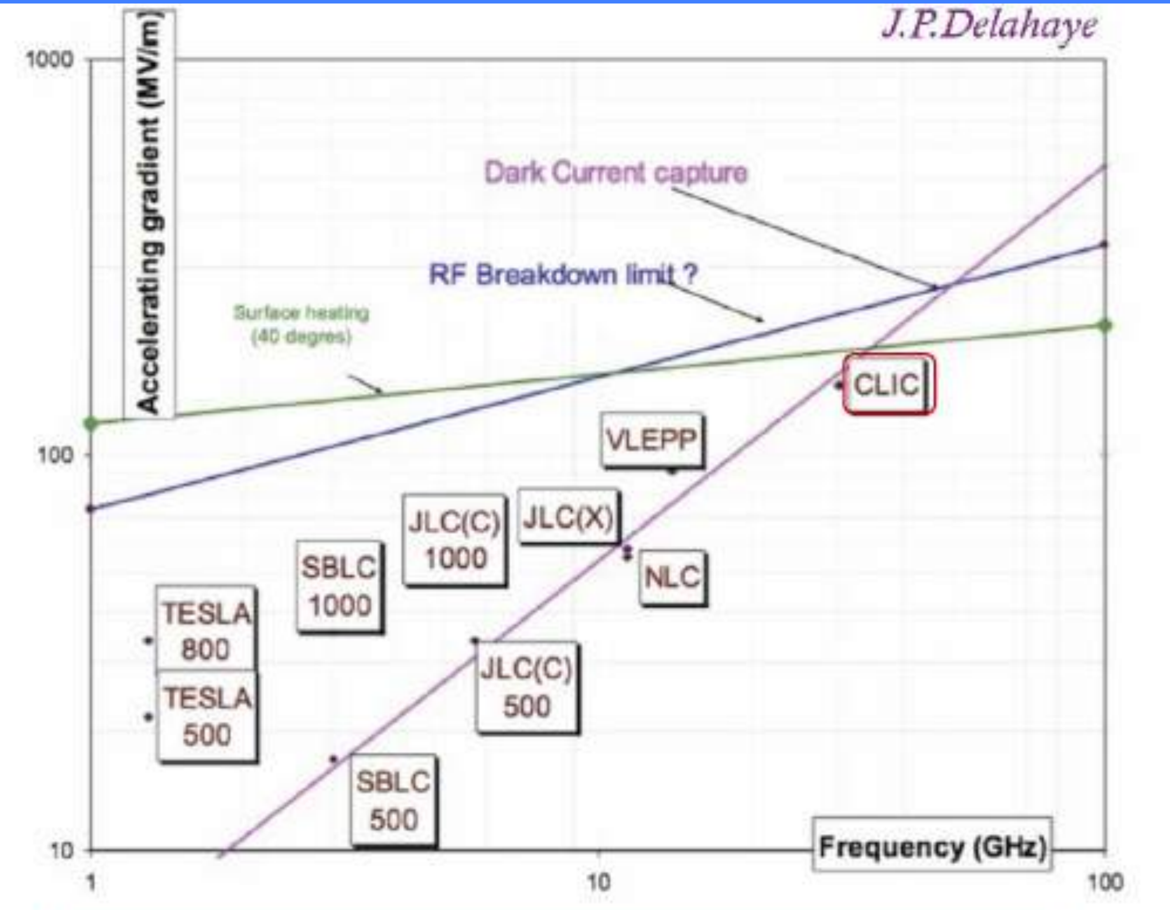
$$v_{\phi z} = \frac{\omega}{k_z} = \frac{\omega}{k\cos\theta} = \frac{c}{\cos\theta} > c$$


$v_\varphi \equiv c$

Conventional RF accelerating structures




Typical breakdown and pulse heating
damage is standing-wave structure cell
200nm
Date :18 Jan 2012
SLAC-KEK-INFN

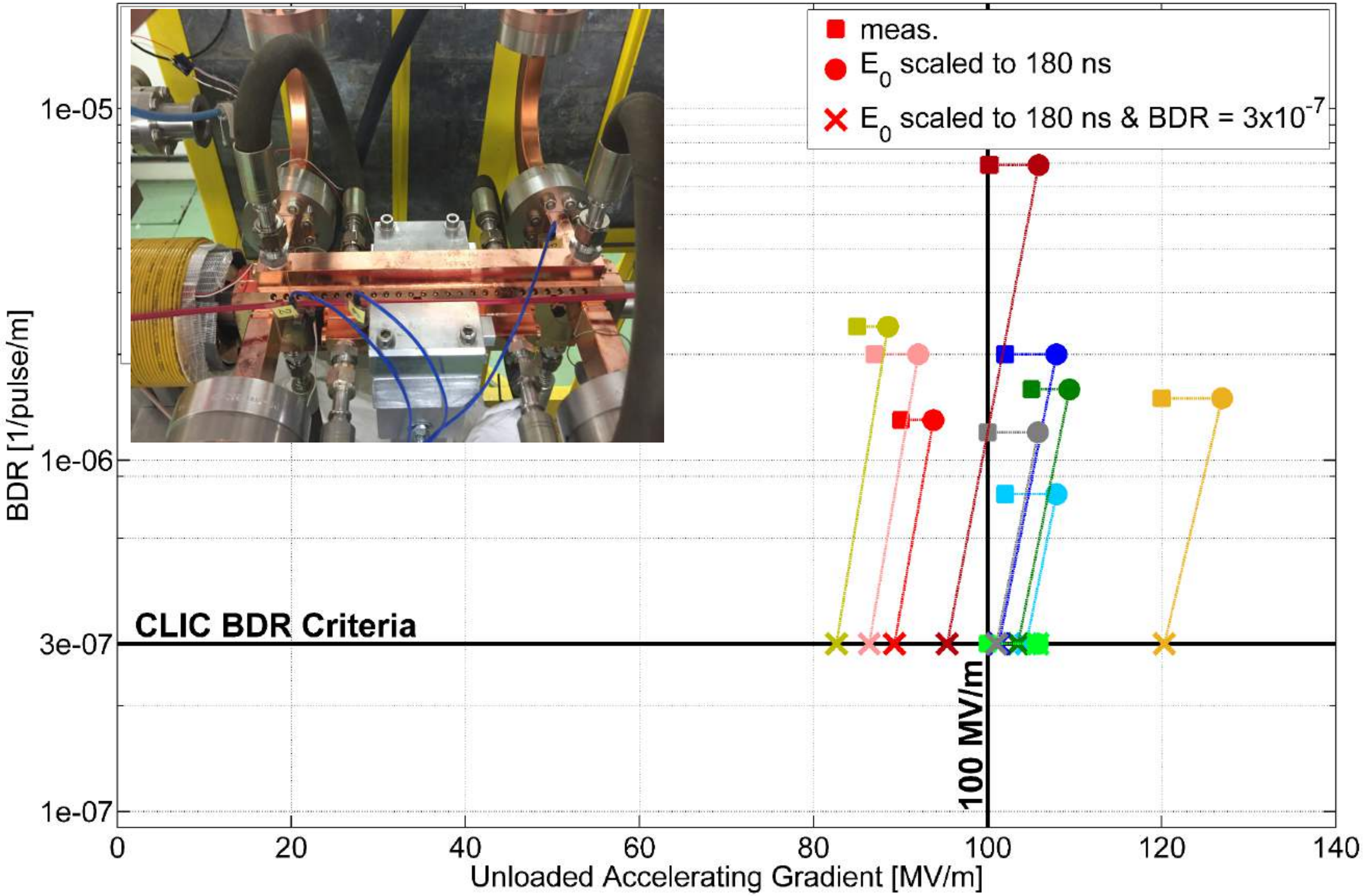


Breakdown limits metal:

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

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

X-band RF structures best performances



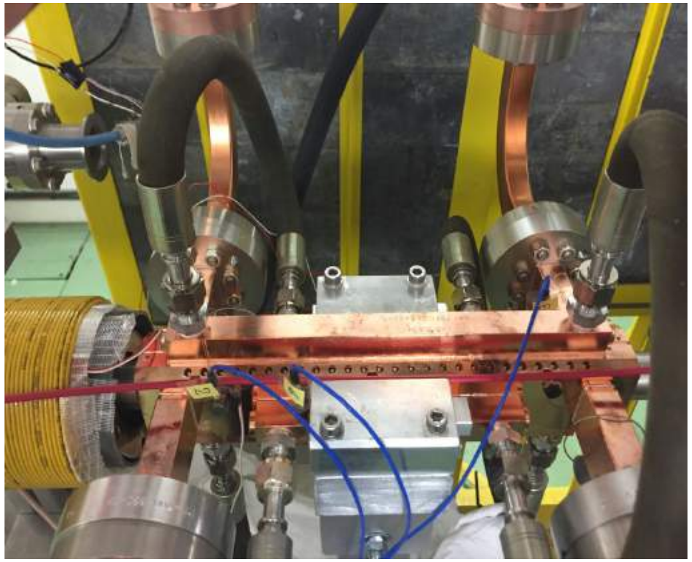
Compact

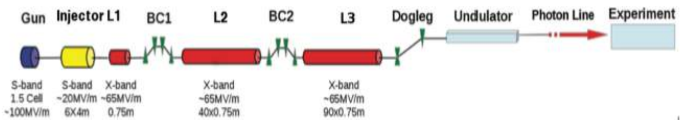
EU Design Study Approved

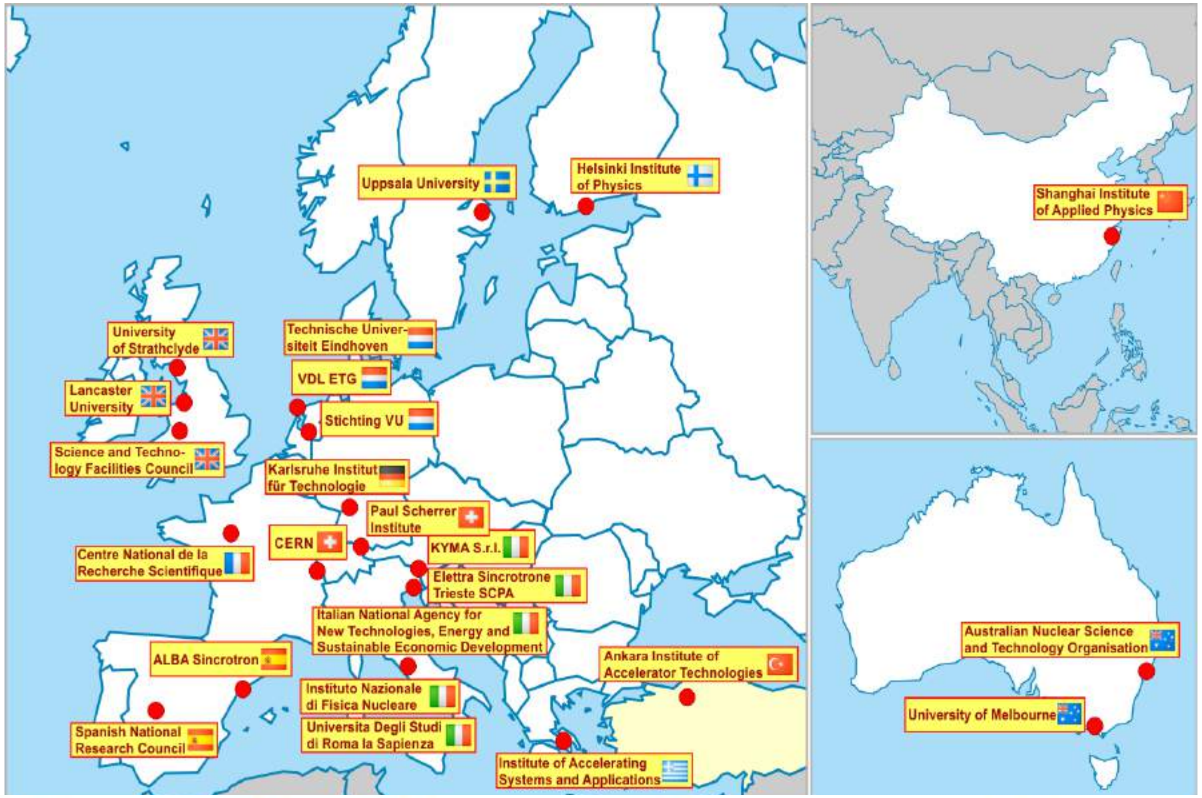
3 years – 3 MEuro

Coordinator: G. D'Auria (Elettra)

Focus on X-band technology







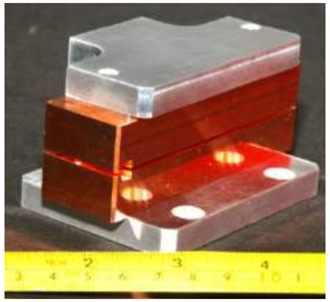
The key objective of the CompactLight Design Study is to demonstrate, through a conceptual design, the feasibility of an innovative, compact and cost effective FEL facility suited for user demands identified in the science case.

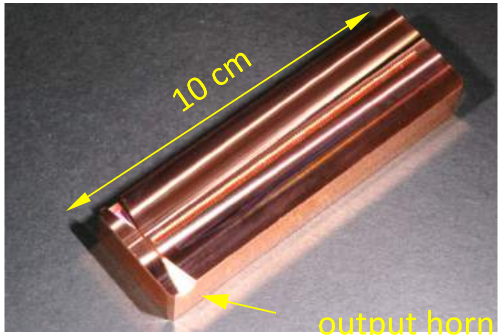
First 110 GHz Open Structure

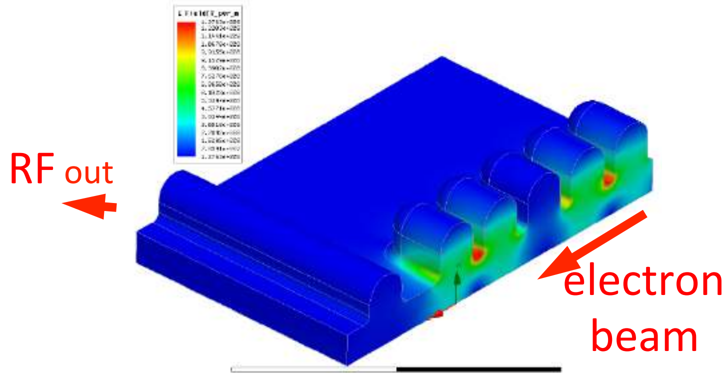
PRST – AB (4 papers)

M. Dal Forno, V- Dolgashev et al. (SLAC) – INFN/LNF

Eacc = 300 MV/m   Esup = 1.5 GV/m



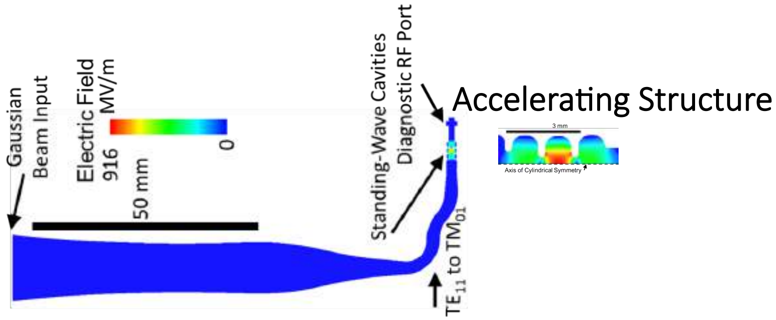


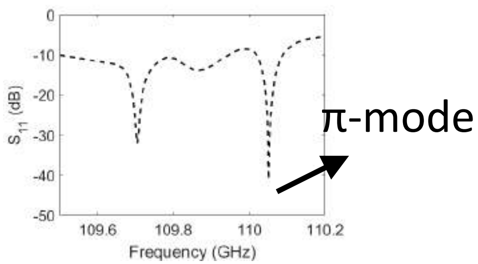


High- Gradient Acceleration structure at 110 GHz at MIT

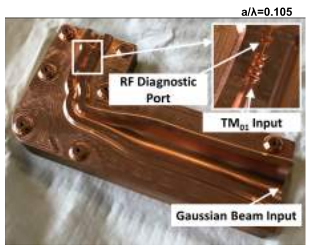
E. Nanni – V Dolgachev et al. (SLAC) – INFN/LNF

Moving Forward to Test @ MIT, Target 1 MW
Eacc > 400 MeV/m



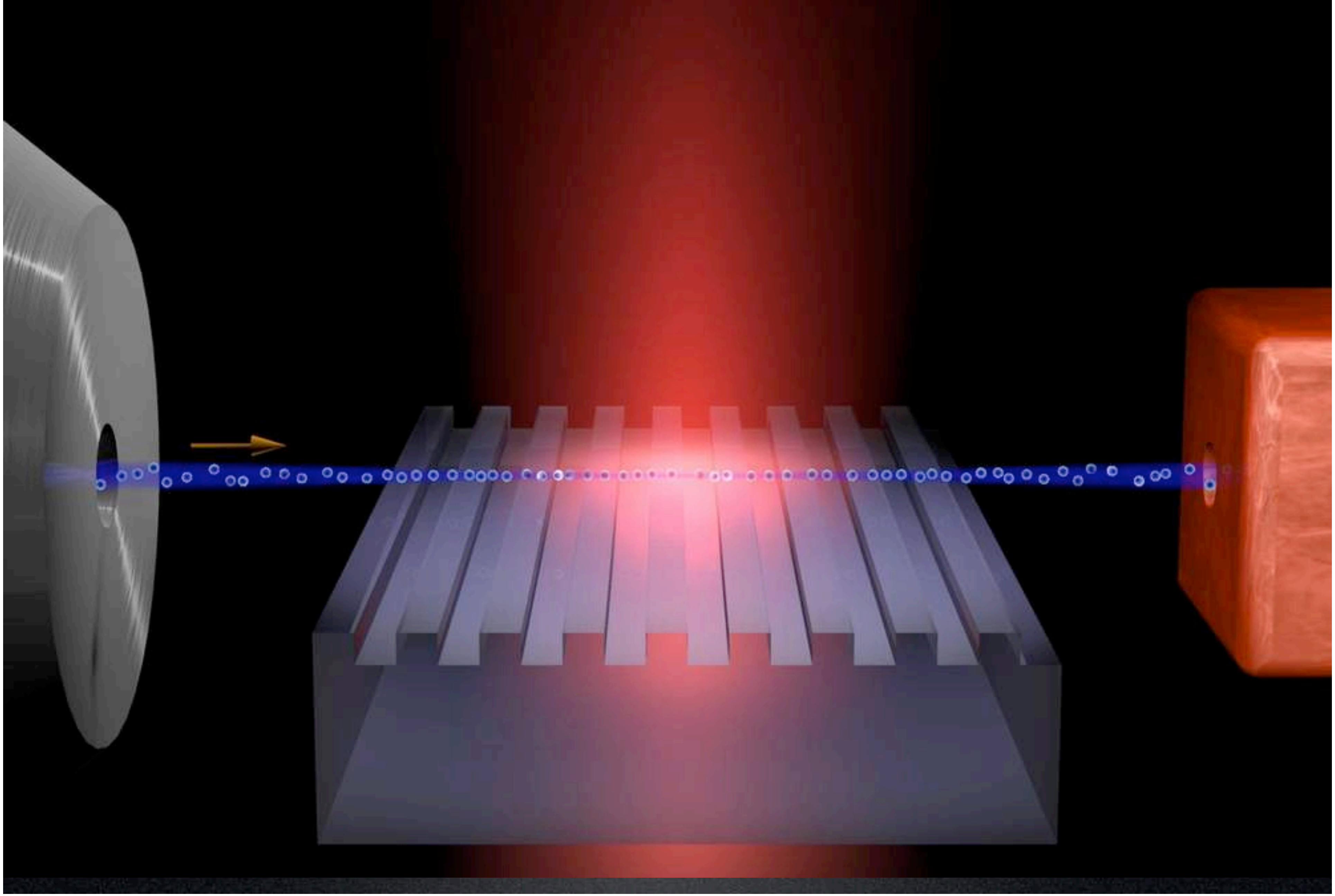


Split-Cell Structure with Mode Converter and Cavities



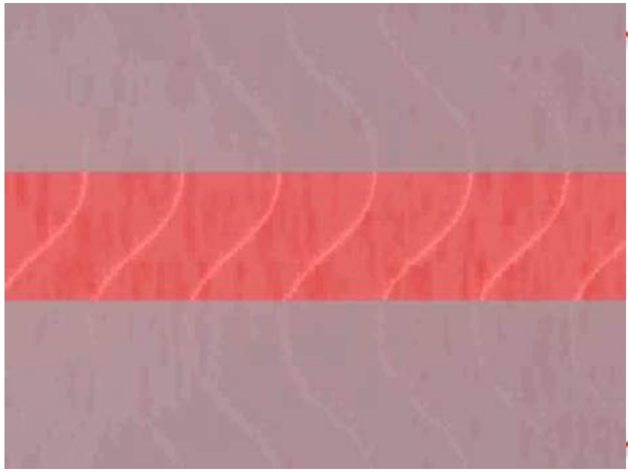
Direct Laser Acceleration
DLA

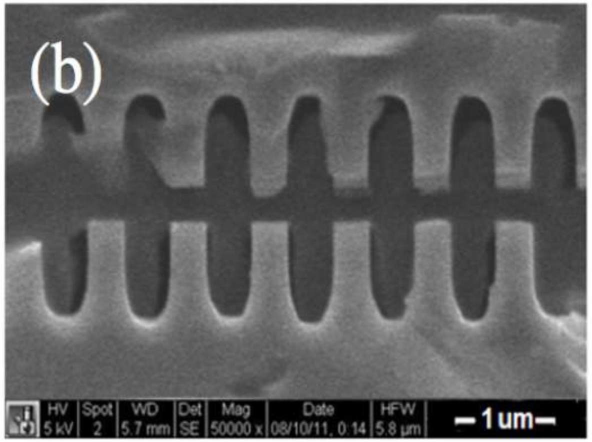
Laser based dielectric accelerator

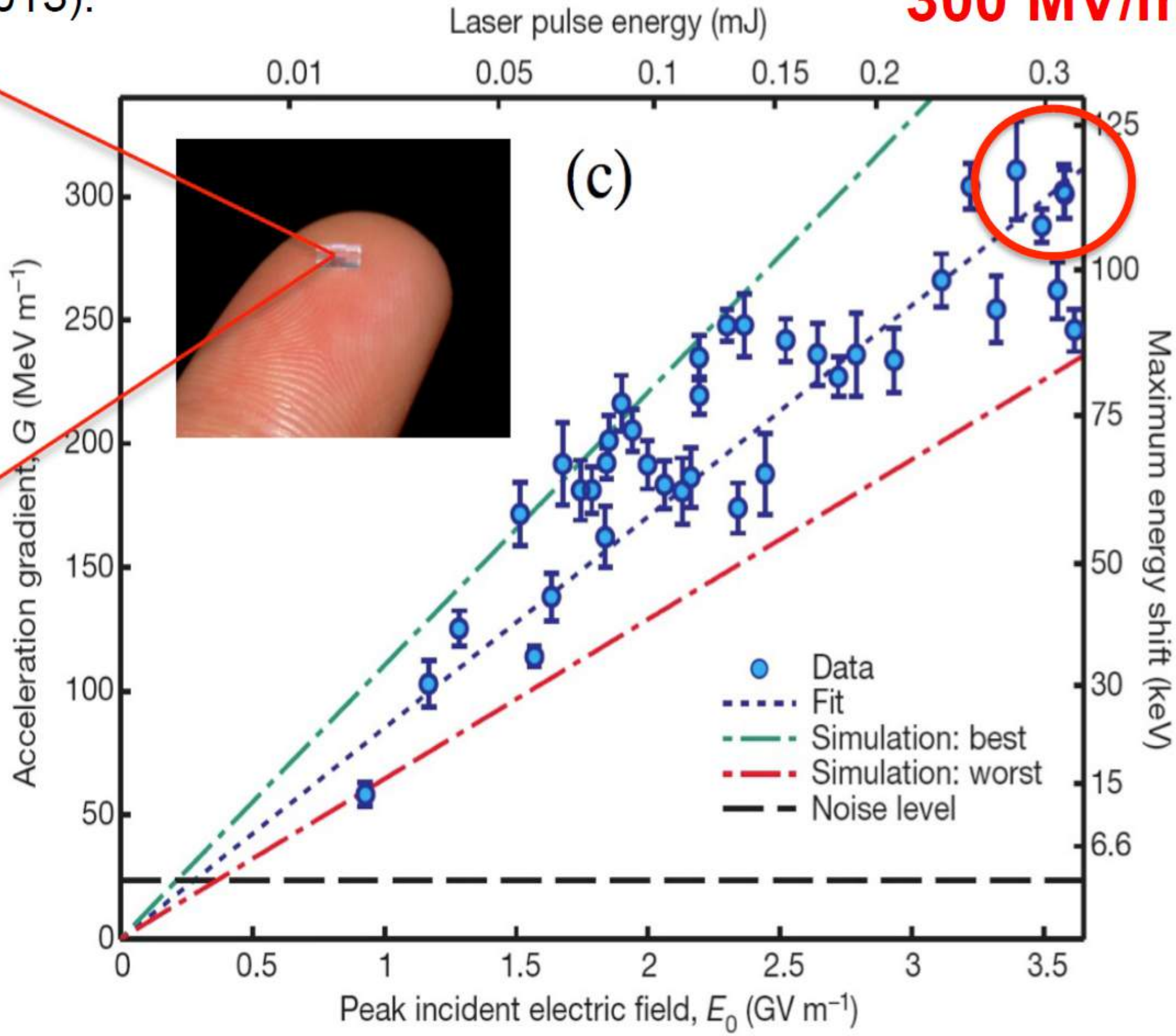


Nature **503**, 91-94 (2013).

300 MV/m

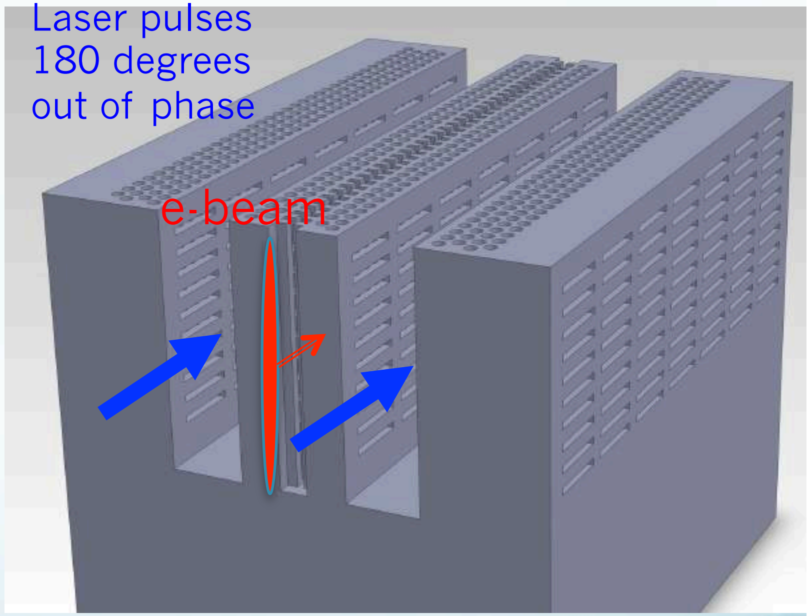






Dielectric Photonic Structure

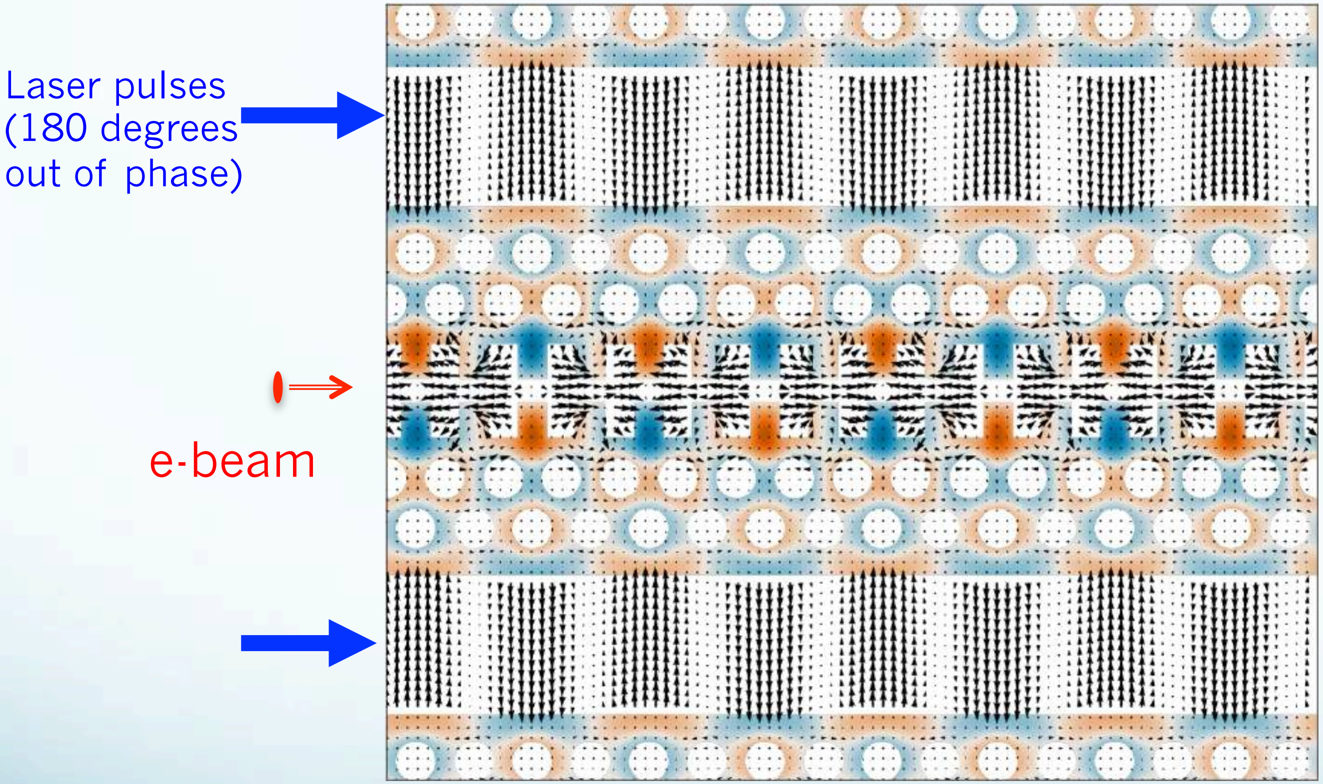
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes



Schematic of GALAXIE
monolithic photonic DLA

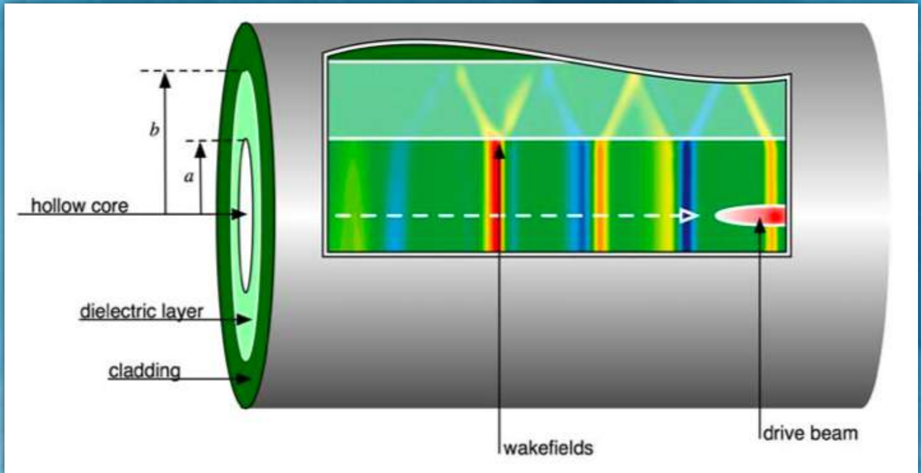
Laser-Structure Coupling: TW

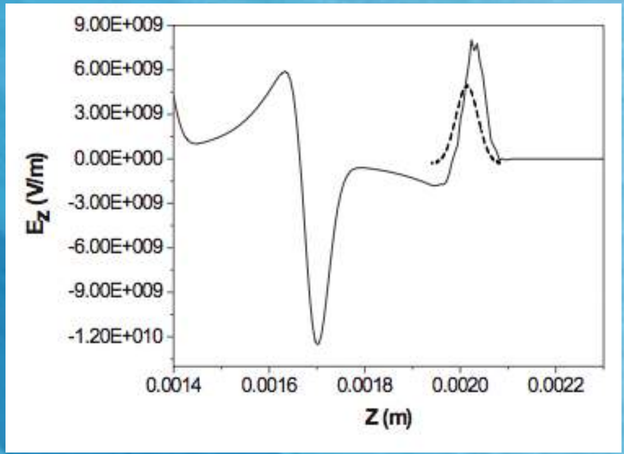
GALAXIE Dual laser drive structure, large reservoir of power recycles

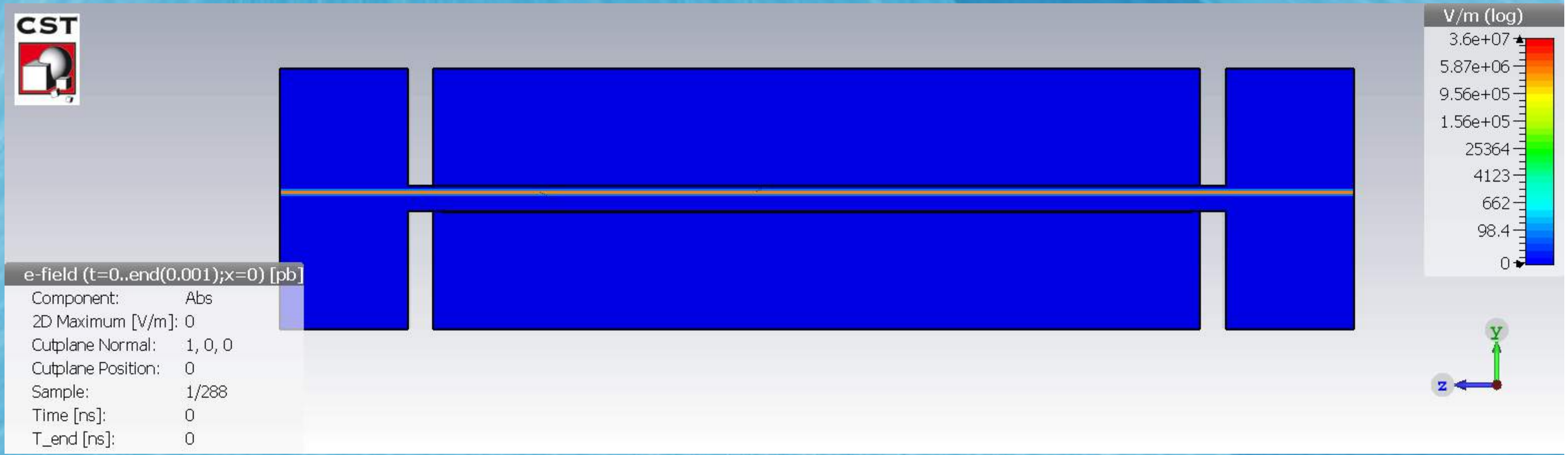


Dielectric Wakefield Acceleration
DWA

Dielectric Wakefield Accelerator

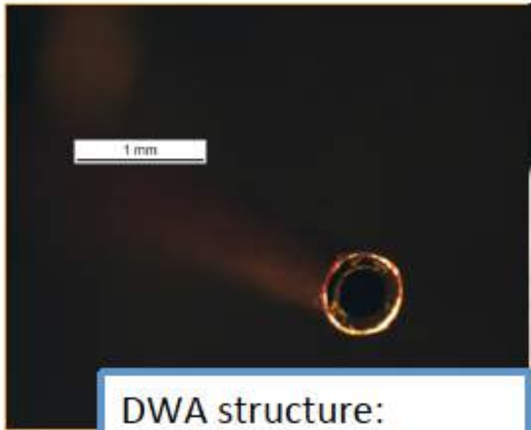




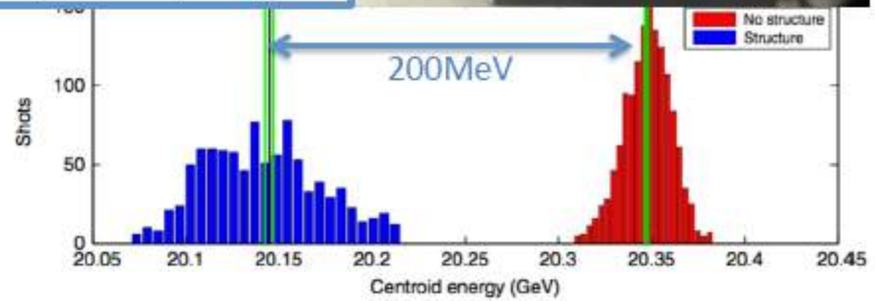


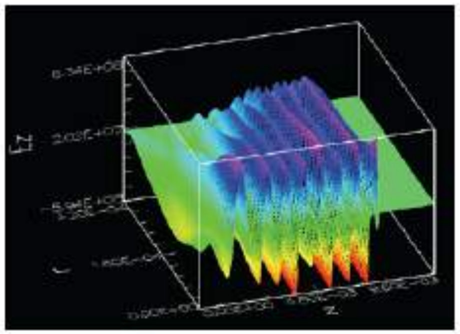
GV/m fields in DWA

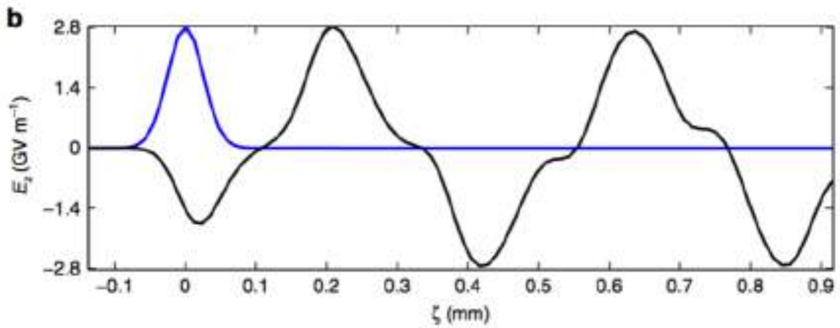
- High-fields with small ID structures
  - Compressed beam (<25μm)
  - High charge (3nC)
- Beam centroid data
  - Measured Energy loss of 200 MeV
  - 1.3 GeV/m deceleration
  - 2.6 GeV/m peak field
  - Strong agreement with PIC simulations
- Continuous operation of >28hours (>100k shots at 10 Hz rep)
- No signs of damage or performance deterioration



DWA structure:
- a/b = 150/200 μm
- L = 15cm
- Cylindrical, SiO_2







Plasma Wakefield Acceleration

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[(a)]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

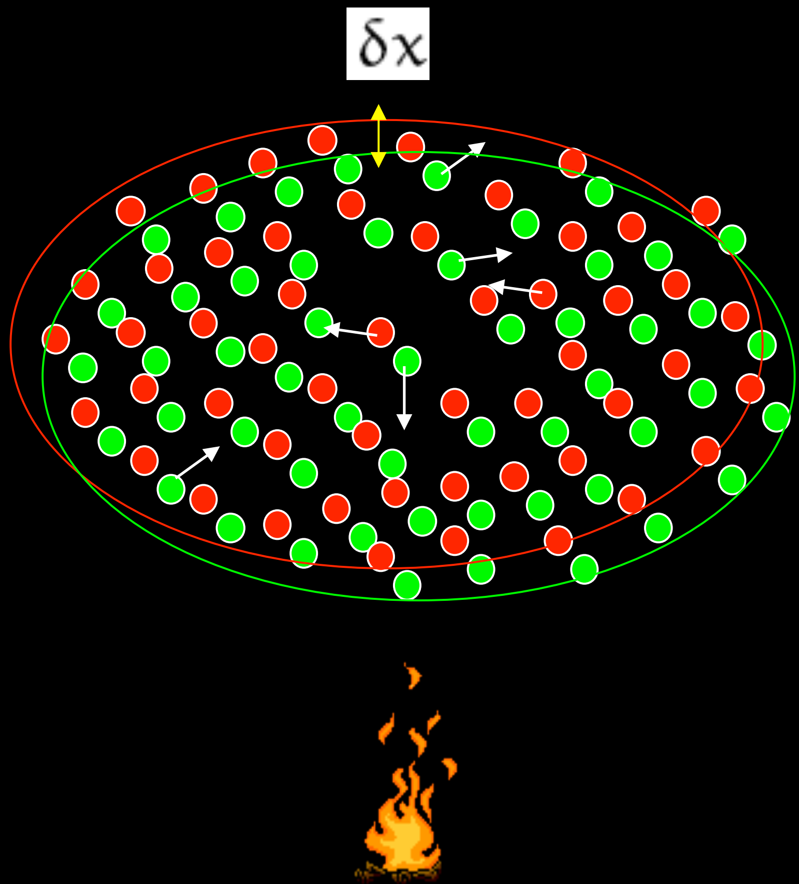
and

J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0^2 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

Surface charge density

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



Surface electric field

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

Restoring force

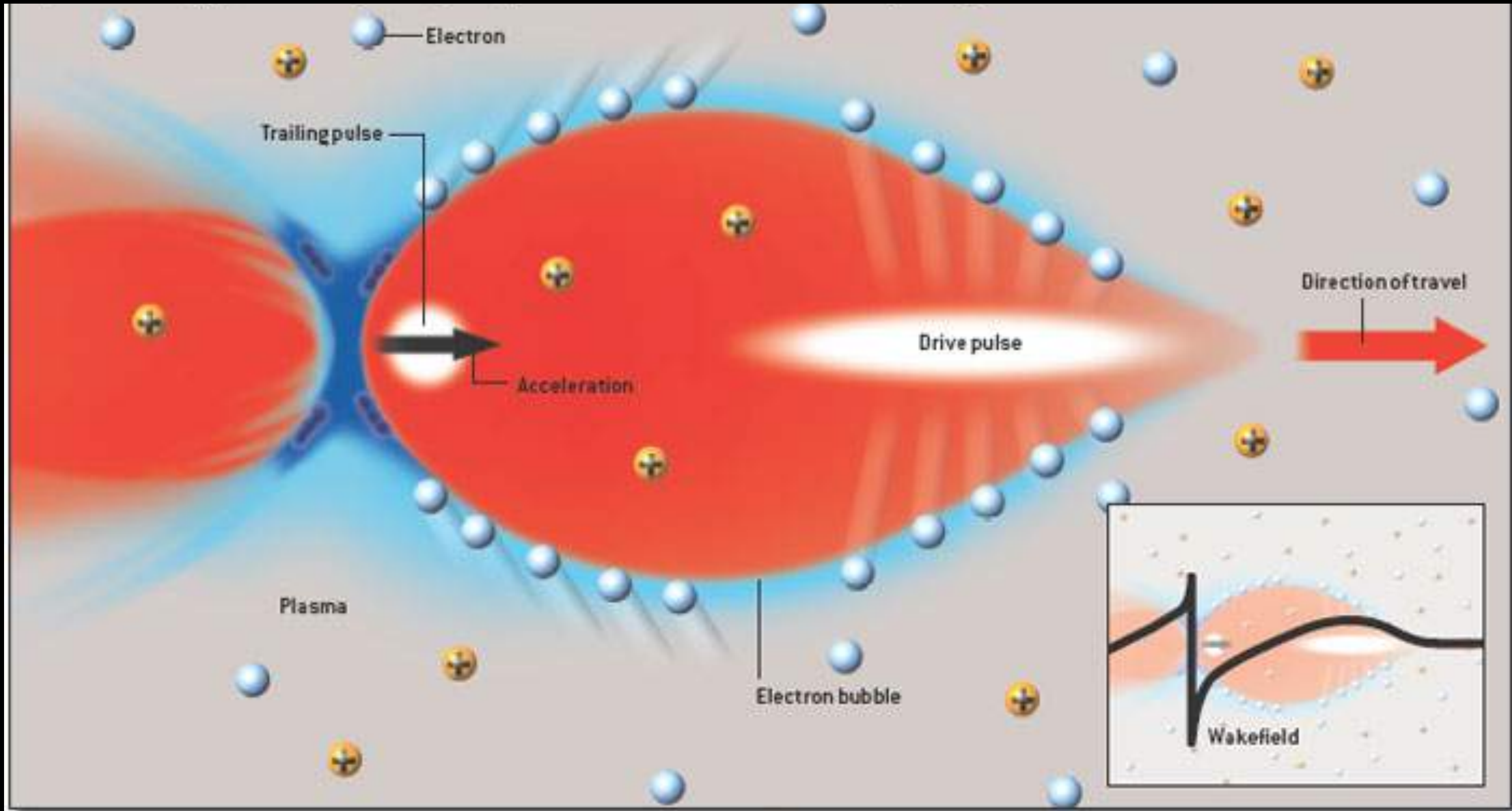
$$m\,\frac{d^2\delta x}{dt^2} = e\,E_x = -m\,\omega_p{}^2\,\delta x$$

Plasma frequency

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

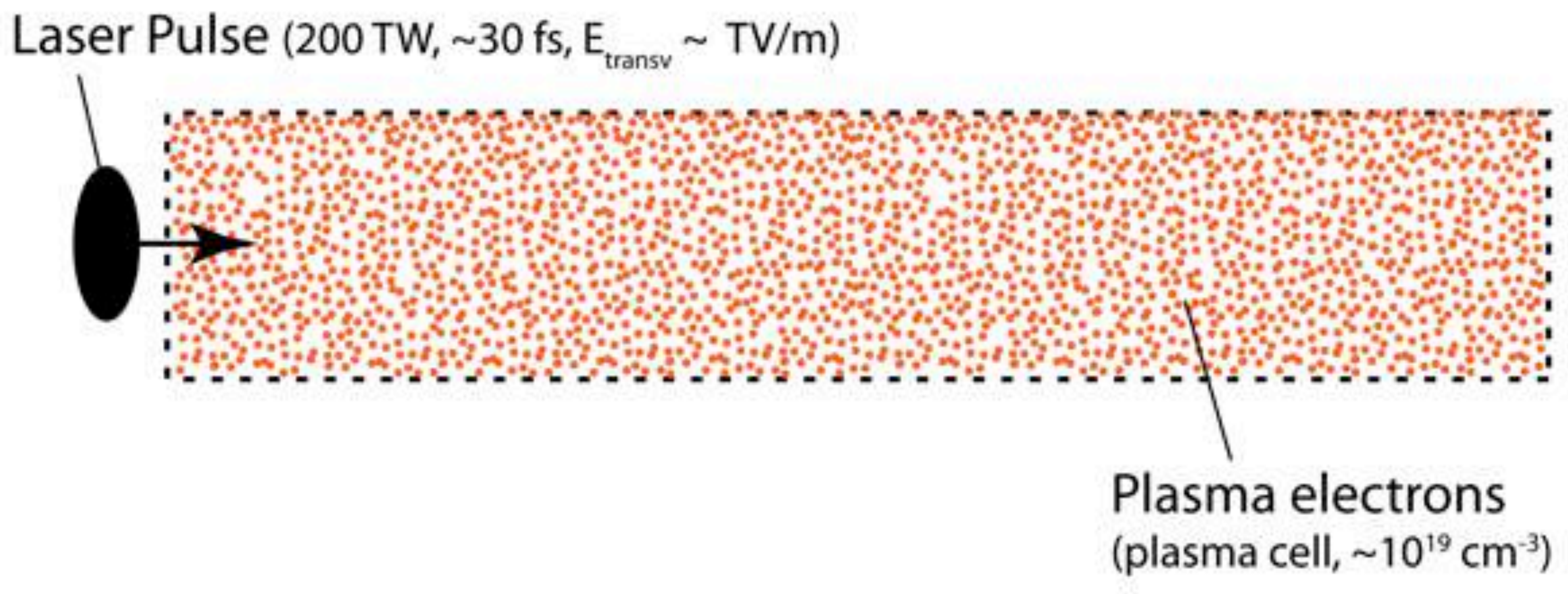
Plasma oscillations

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



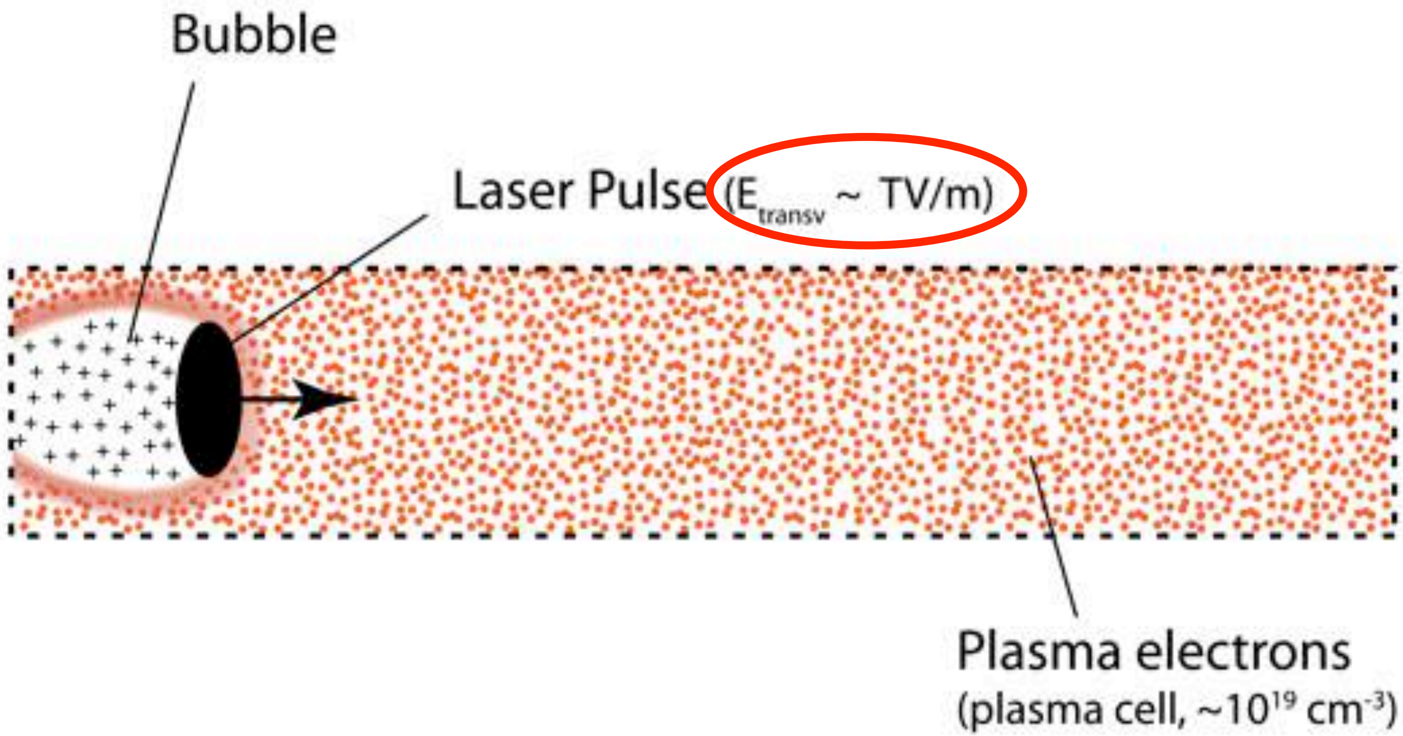
Electron
Trailing pulse
Direction of travel
Drive pulse
Acceleration
Plasma
Electron bubble
Wakefield

Plasma Wake-Acceleration

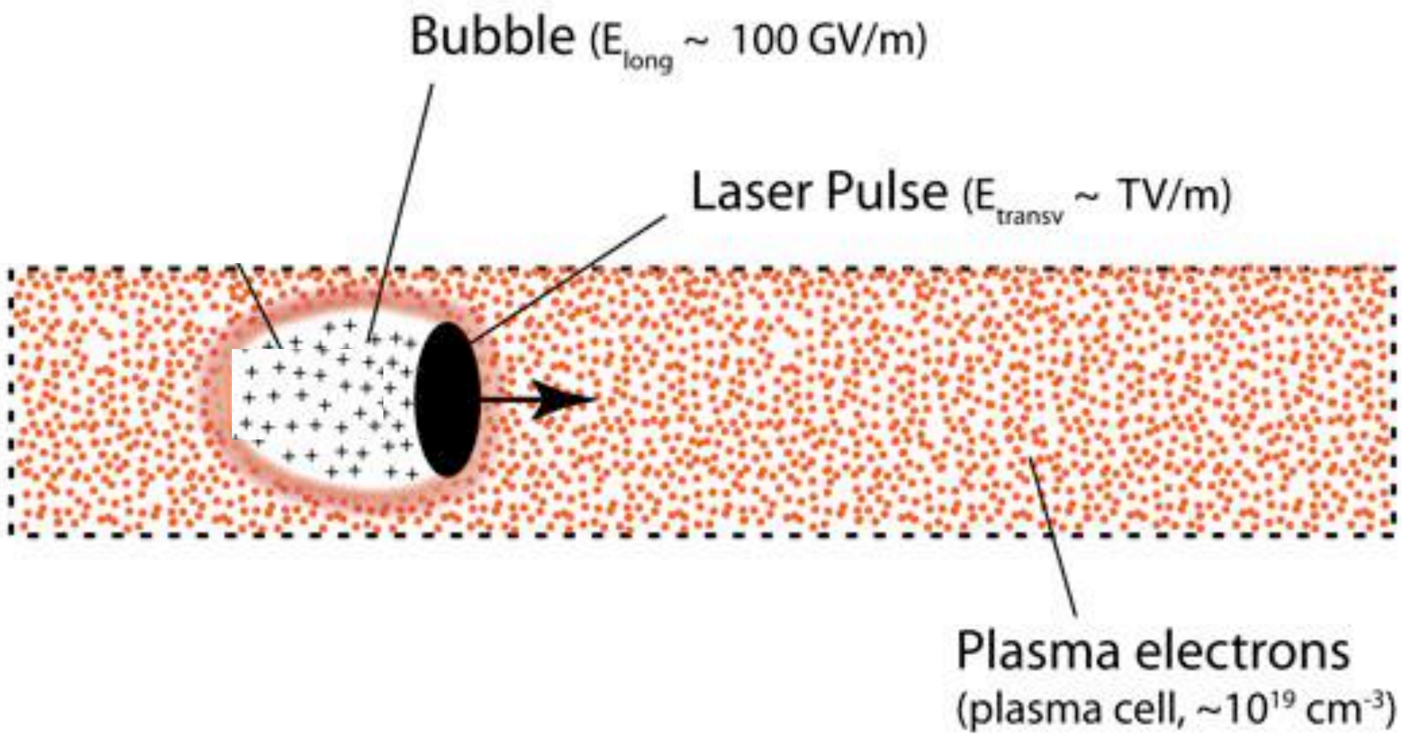


Plasma Wake-Acceleration

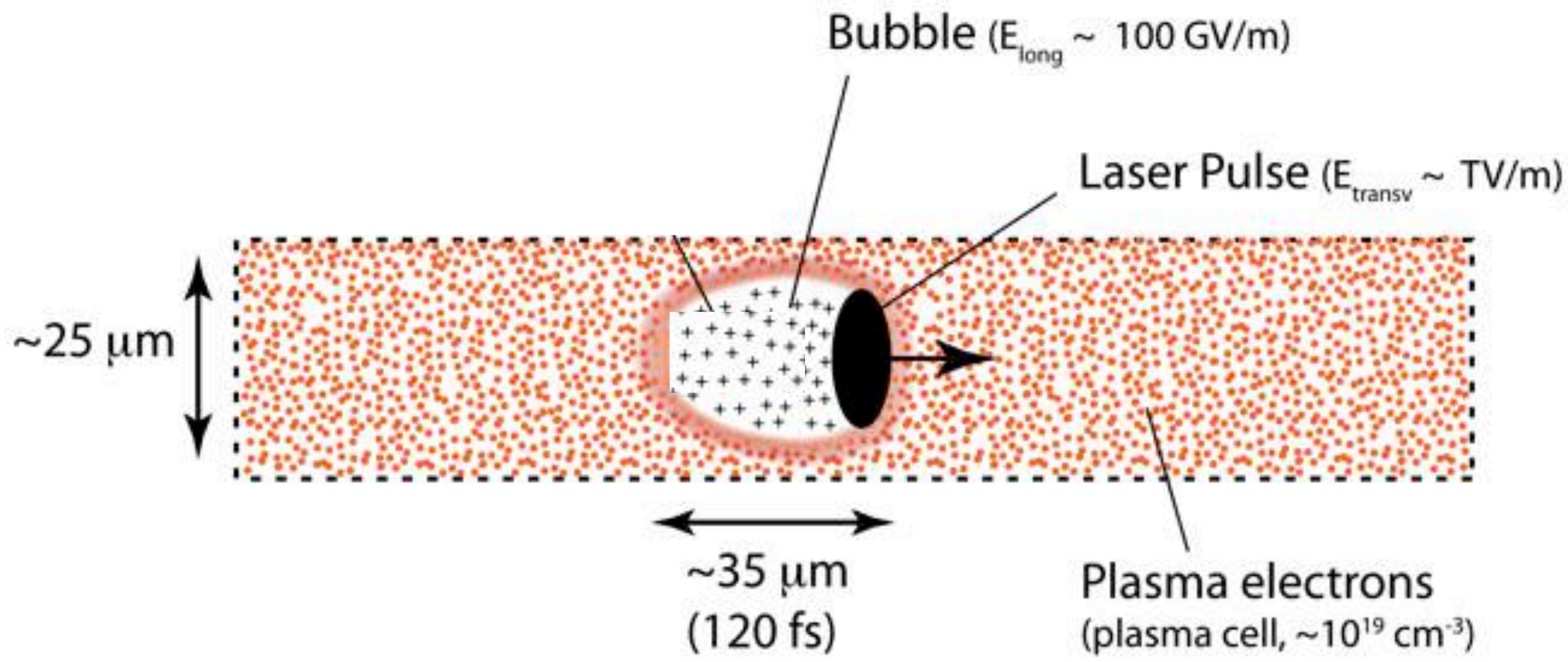
Horizon2020



Plasma Wake-Acceleration



Plasma Wake-Acceleration



This accelerator fits into a human hair!

Plasma acceleration: ultrahigh accelerating gradients

Tajima & Dawson, PRL (1979)
Chen et al., PRL (1985)

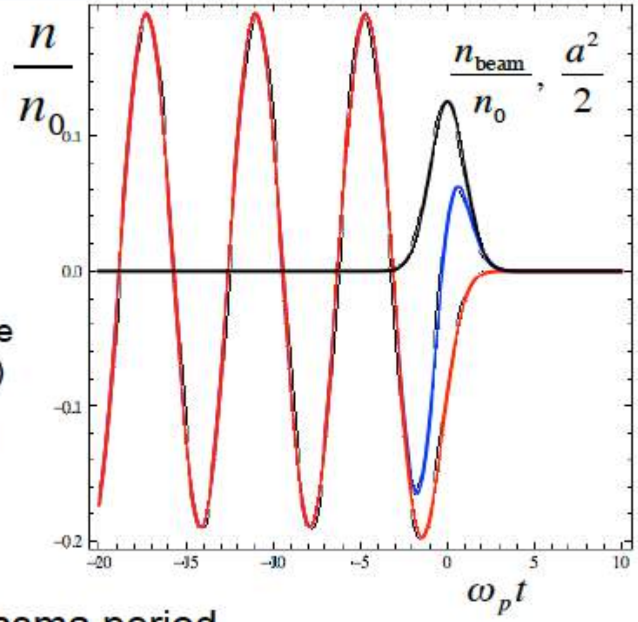
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_0}=-\omega_p^2\frac{n_{\text{beam}}}{n_0}+c^2\nabla^2\frac{a^2}{2}$$

Plasma wave: electron density perturbation

Space-charge force of particle beam

Ponderomotive force (radiation pressure)

$$a=\frac{eA}{mc^2}\propto\lambda I^{1/2}$$

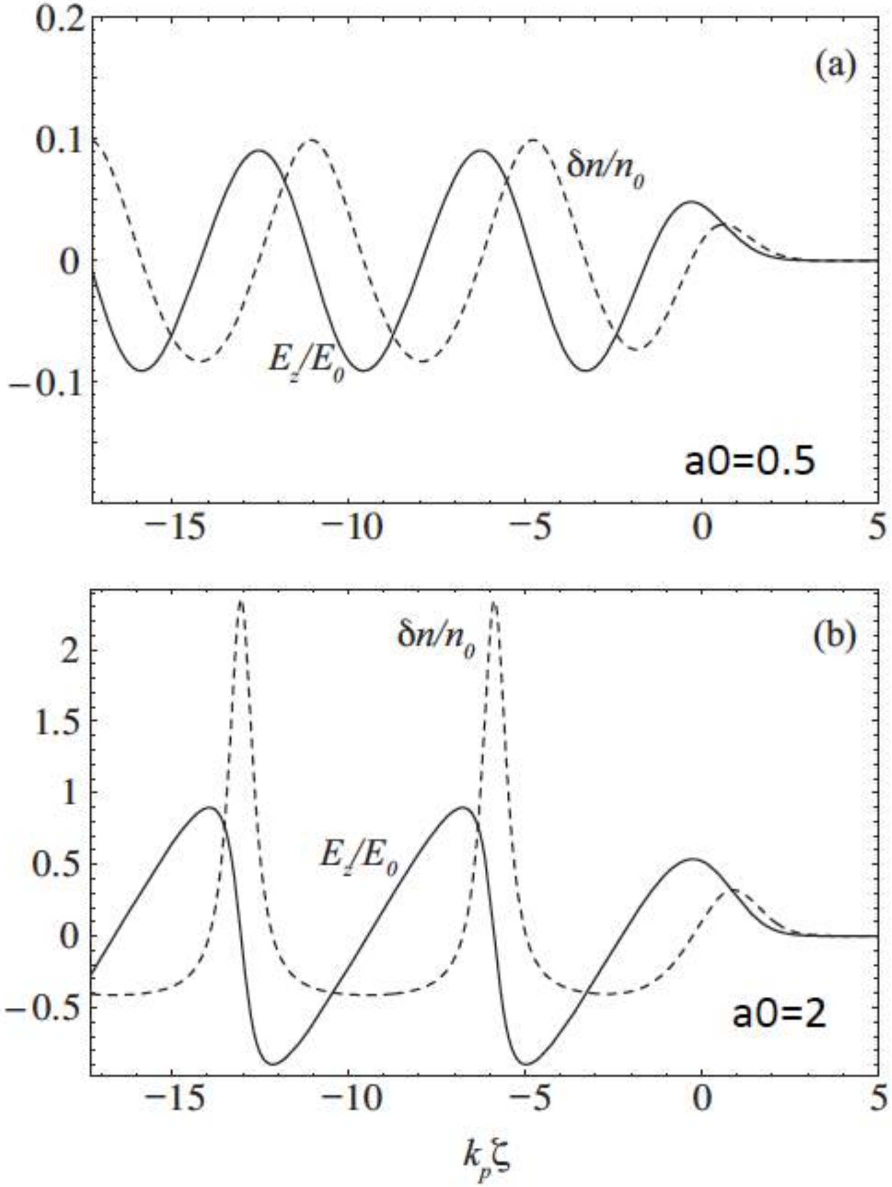


Common features:

- Wave excitation efficient for driver duration ~ plasma period
- Bucket size ~ plasma wavelength: $\lambda_p = 2\pi c/\omega_p = (\pi r_e^{-1/2})\, n_p^{-1/2}$ ~10-100 μm
- Large waves excited for $n_{beam}/n_0 \sim 1$ or $a \sim 1$
- Characteristic accelerating field: $E\sim\left(\frac{mc\omega_p}{e}\right)\approx(96\text{V/m})\sqrt{n_0[\text{cm}^{-3}]}$
- Phase velocity of wave determined by driver velocity

Courtesy C. Schroeder

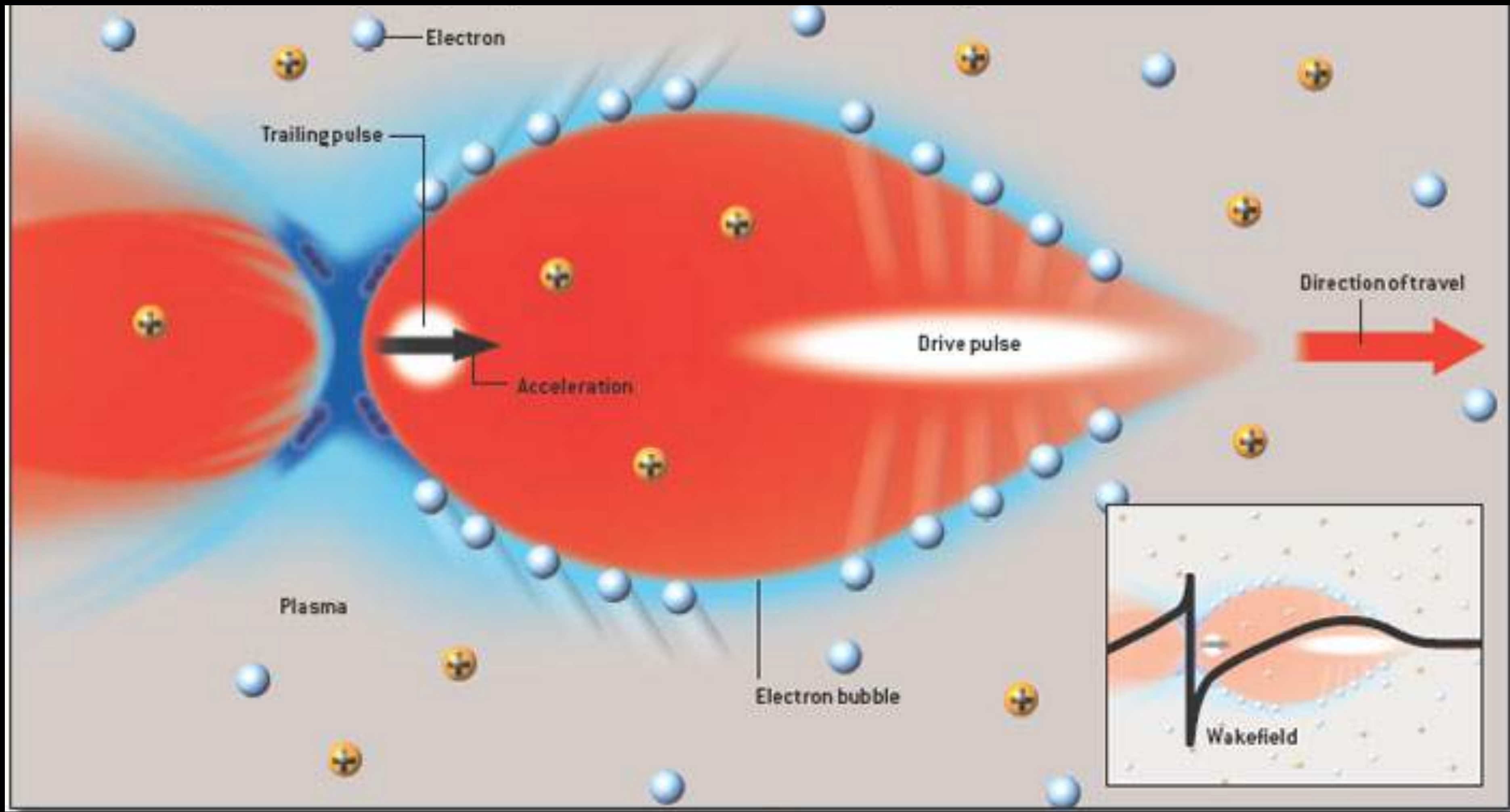
Regimes: Linear & Non-Linear



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 $L_{\mathrm{rms}}=k_p^{-1}$) for (a) $a_0=0.5$ and (b) $a_0=2.0$.

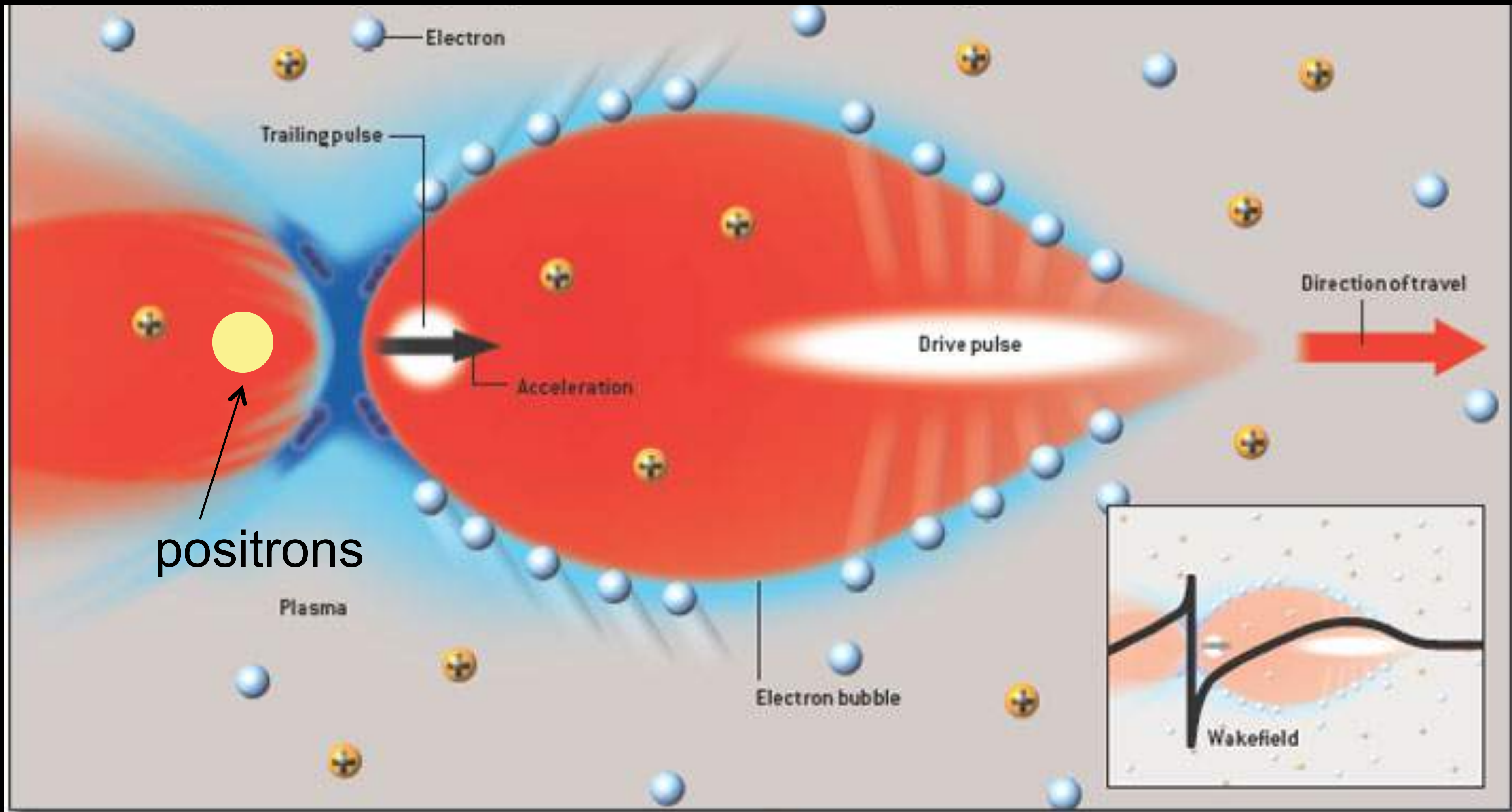
Non-Linear



Breakdown limit?

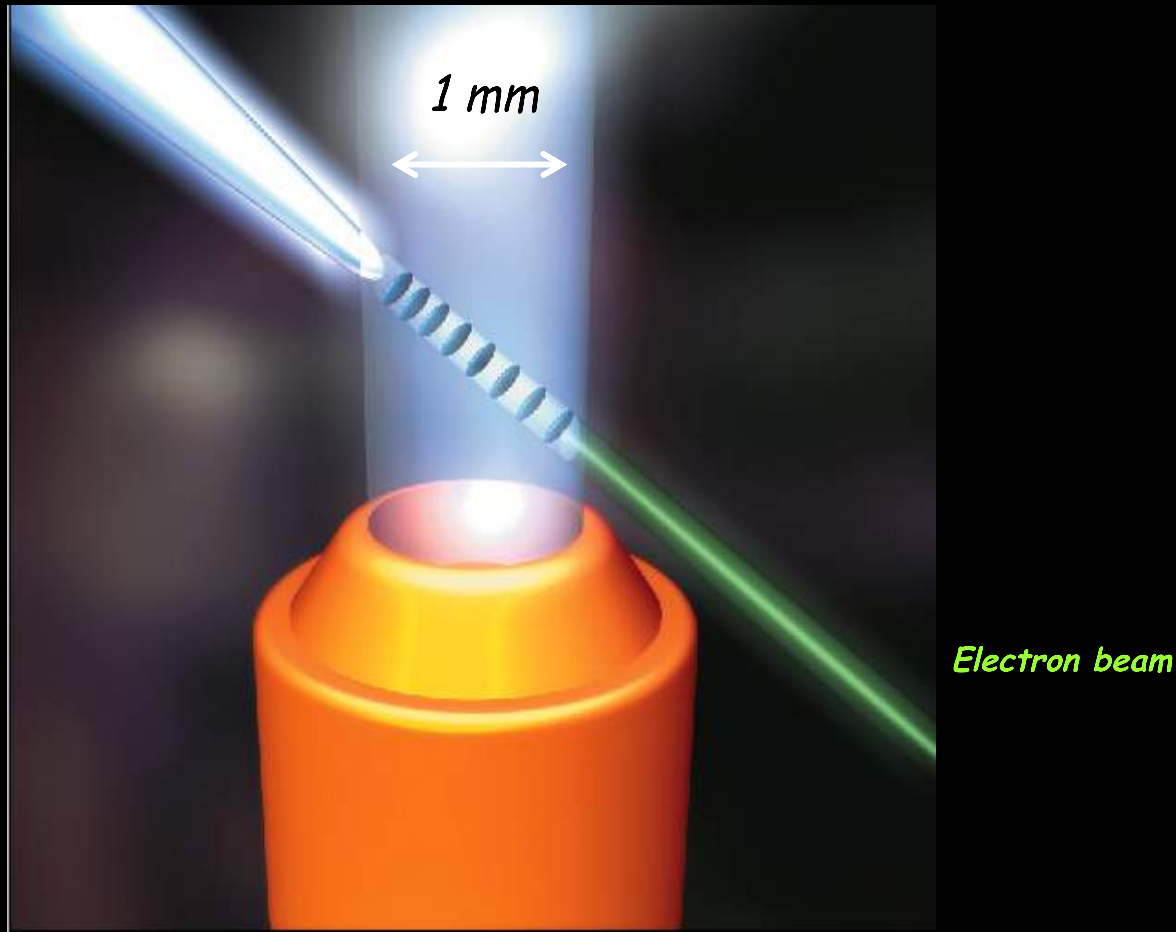
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

What about positrons?

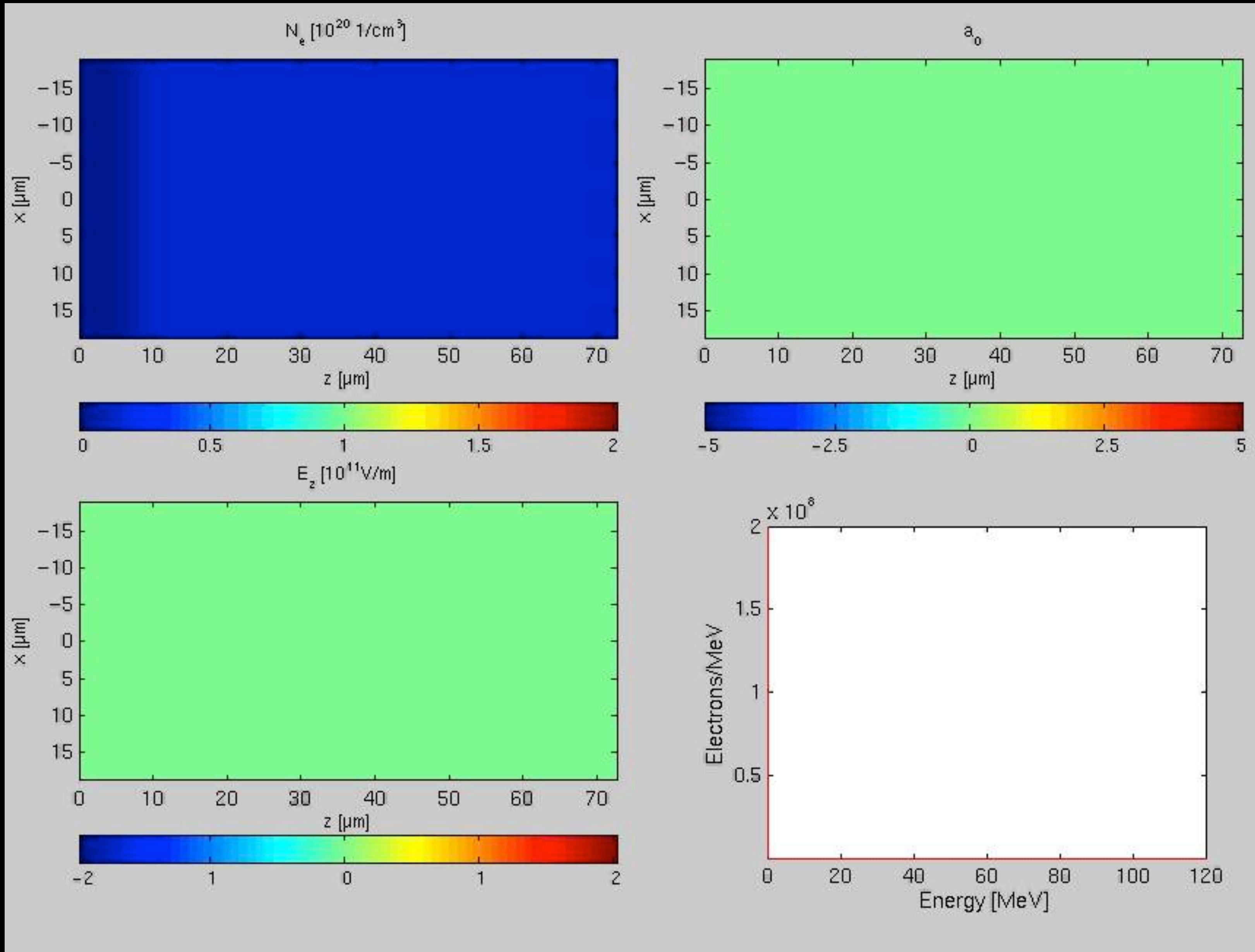


Laser Driven
LWFA

Direct production of e-beam

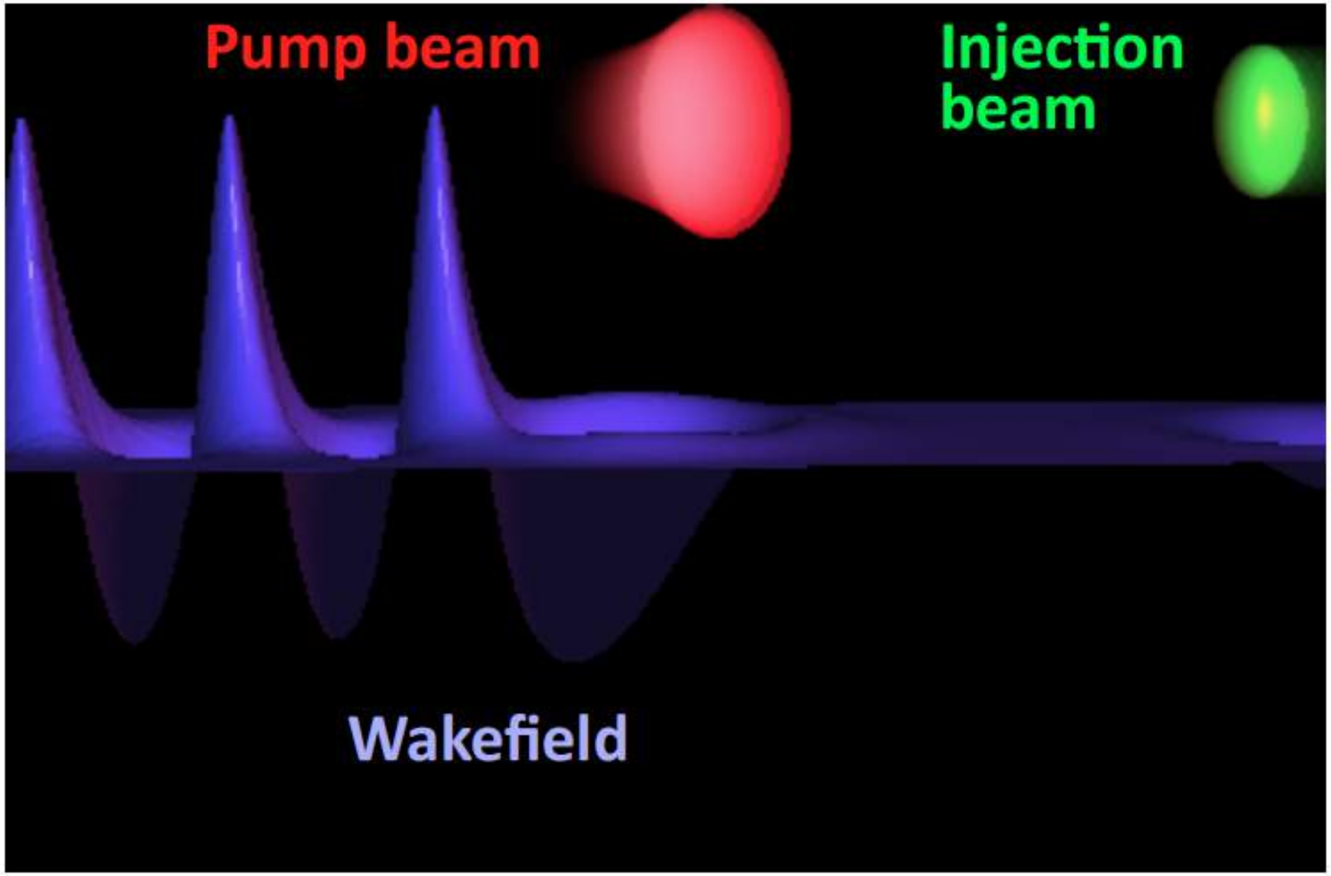


Diffraction - Self injection - Dephasing – Depletion



Colliding Laser Pulses Scheme

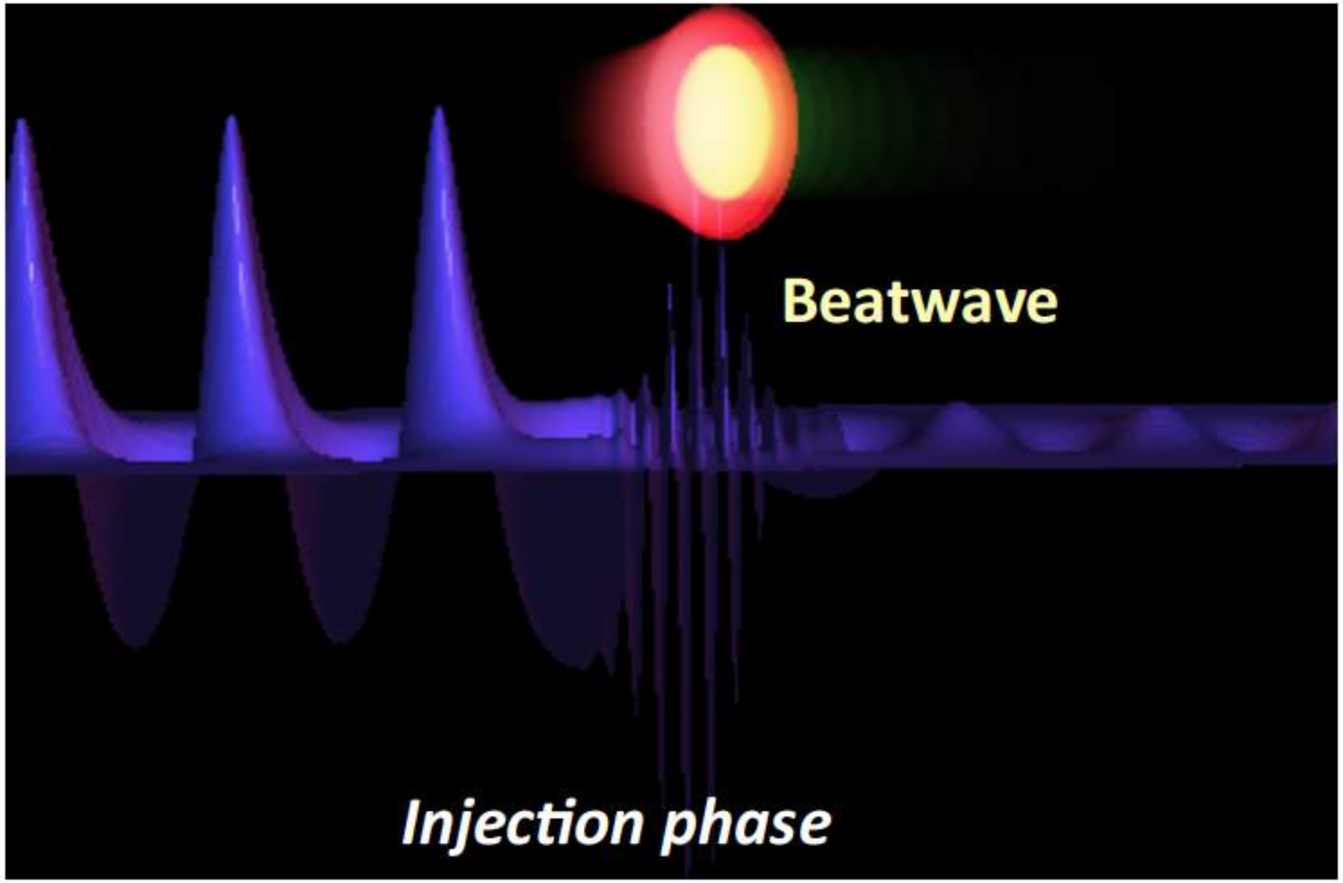
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



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)

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)

Colliding Laser Pulses Scheme

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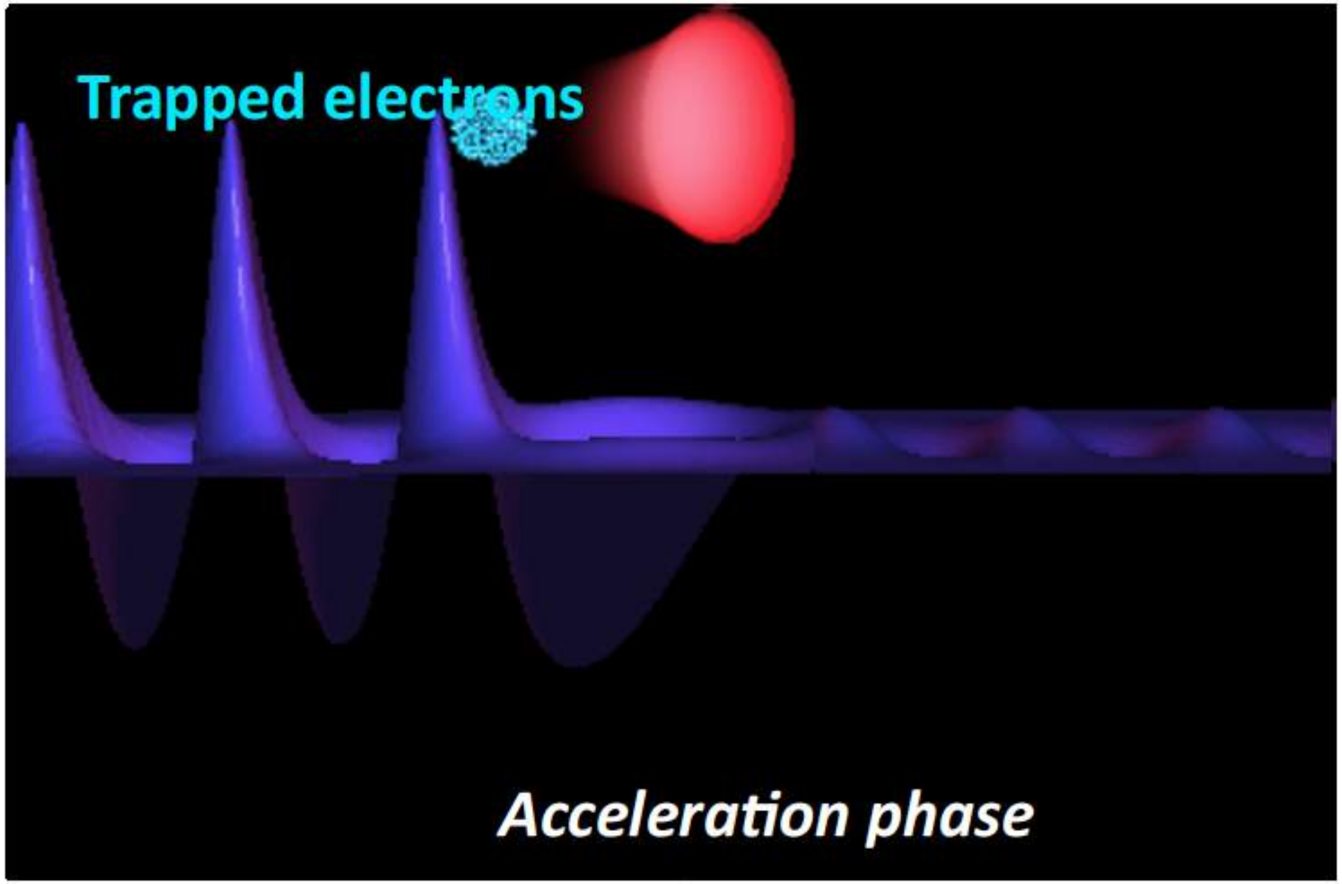
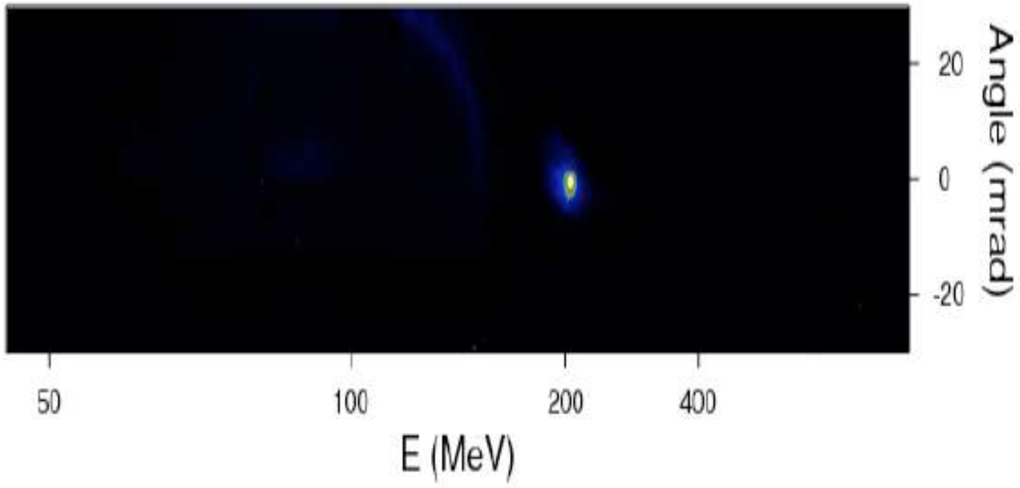
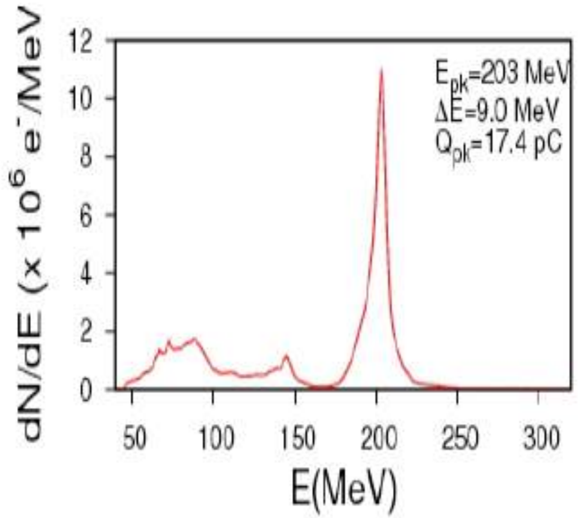


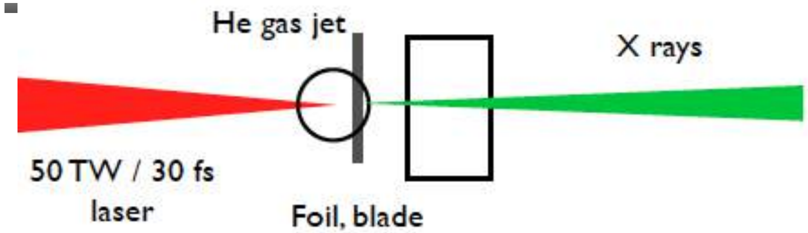
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

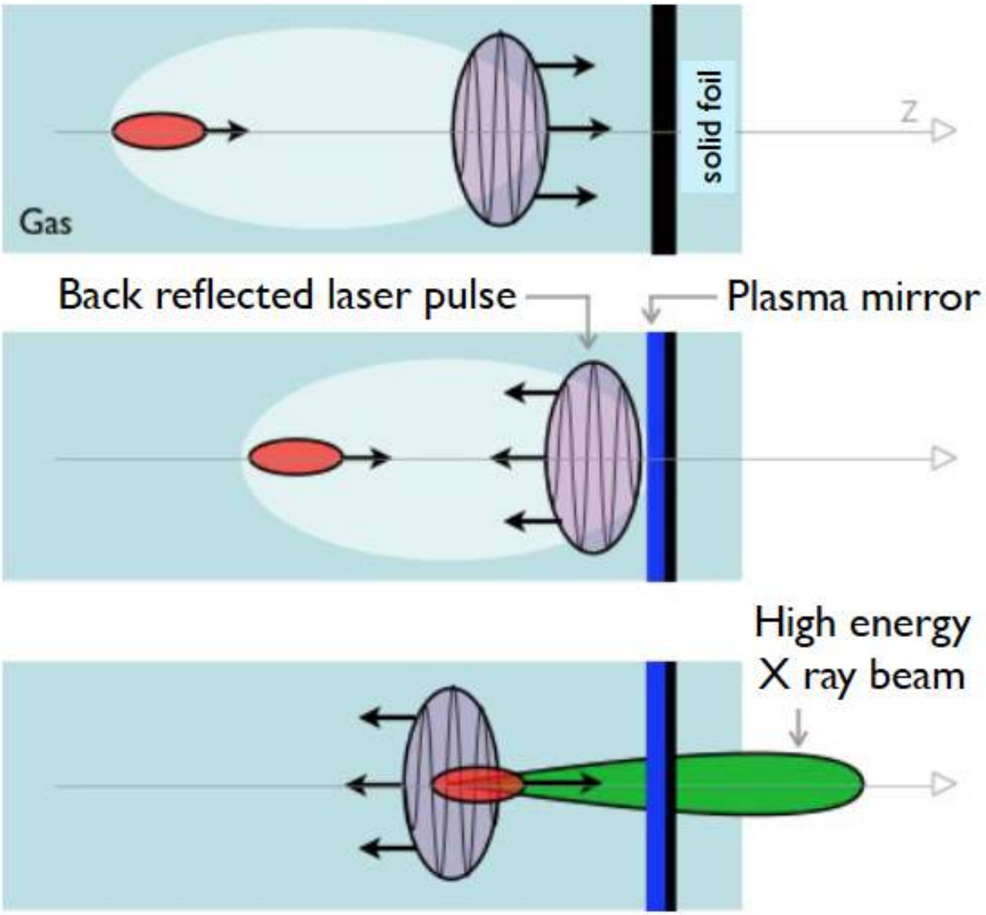
Stable Laser Plasma Accelerators





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

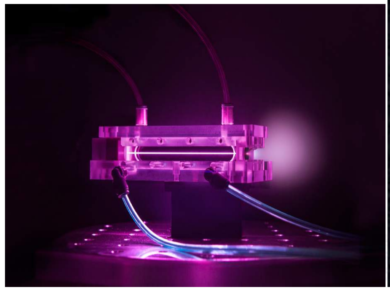
Save the laser energy !

BELLA: BErkeley Lab Laser Accelerator

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

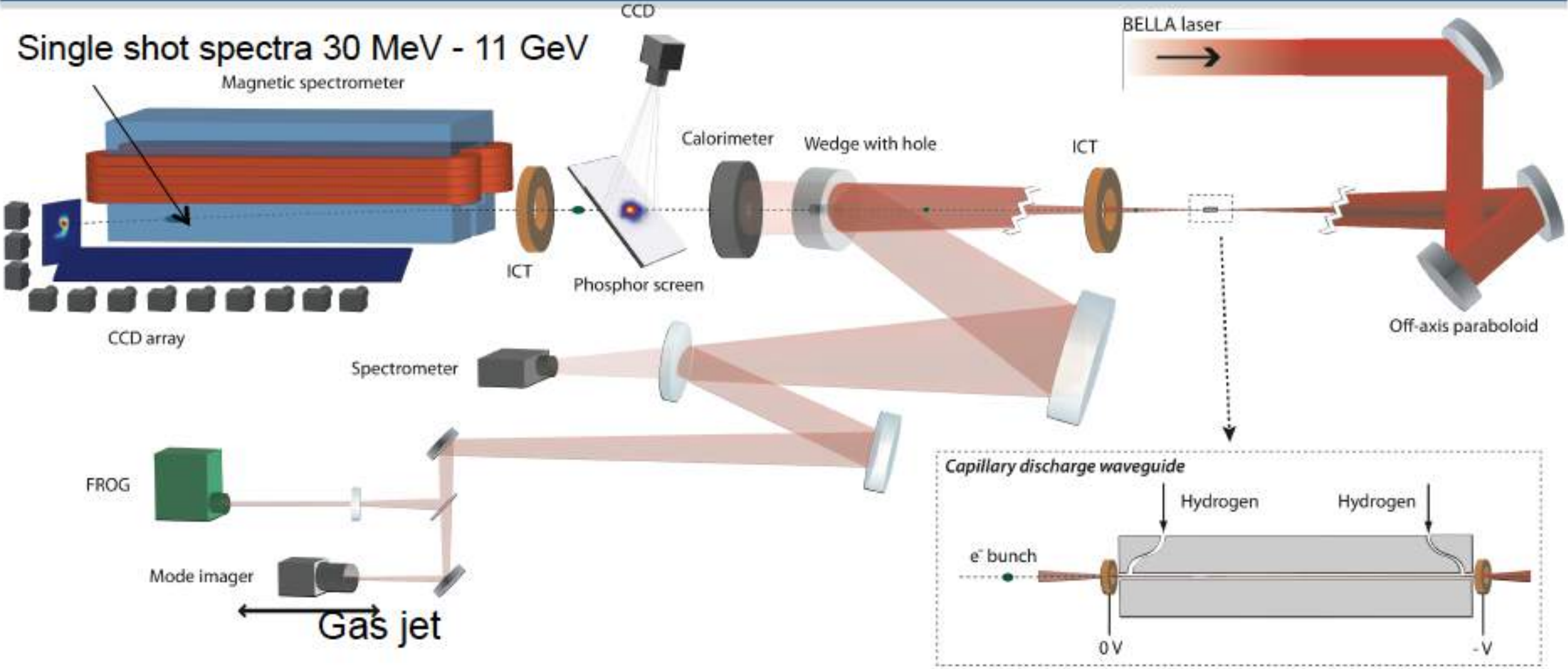
Critical HEP experiments:

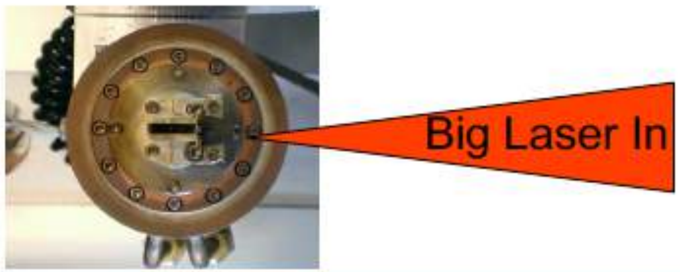
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



BELLA

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

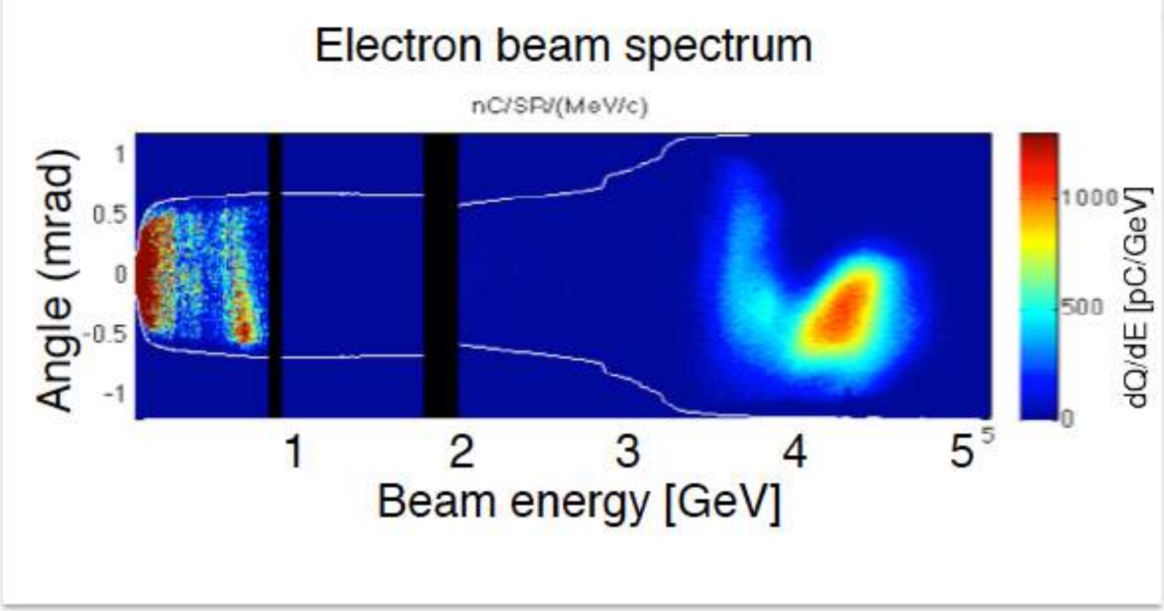


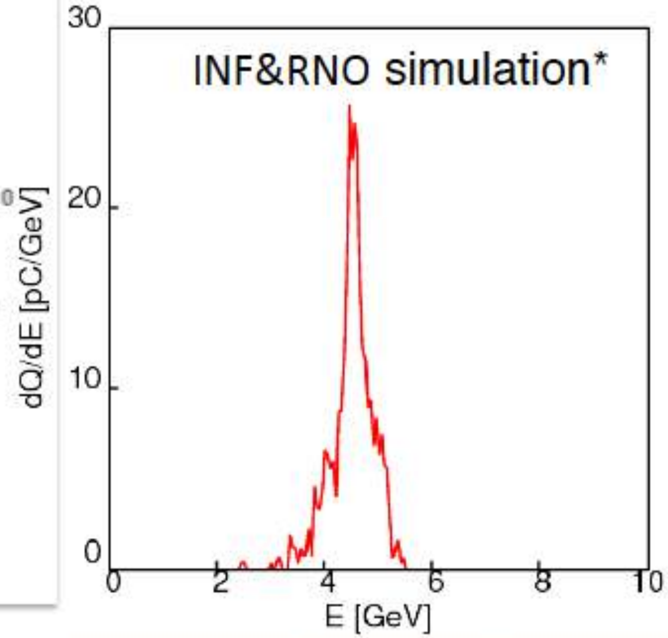


Capillary discharge

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





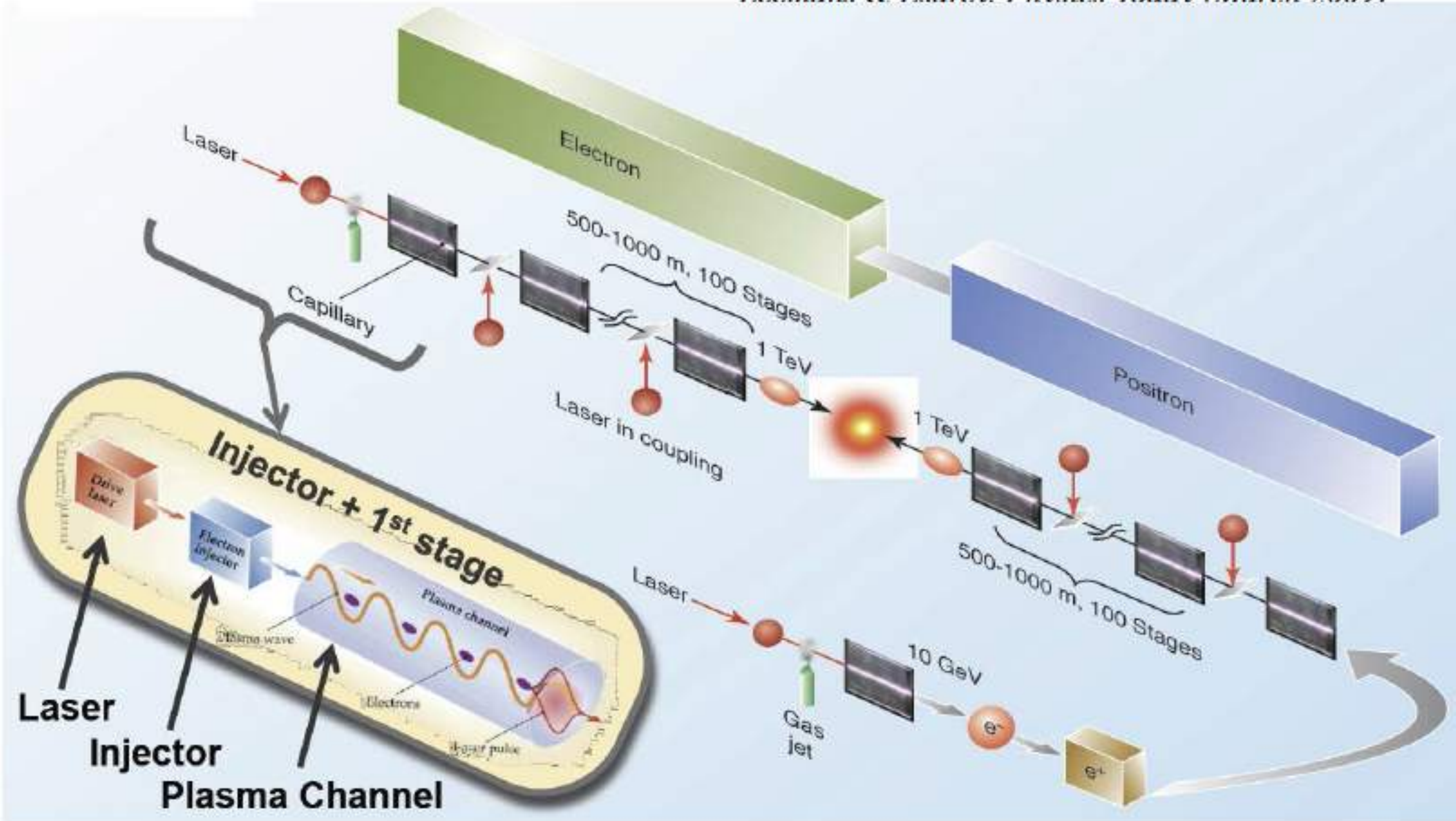
- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 µm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

	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

Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)



Parameter Set for LPWA LC

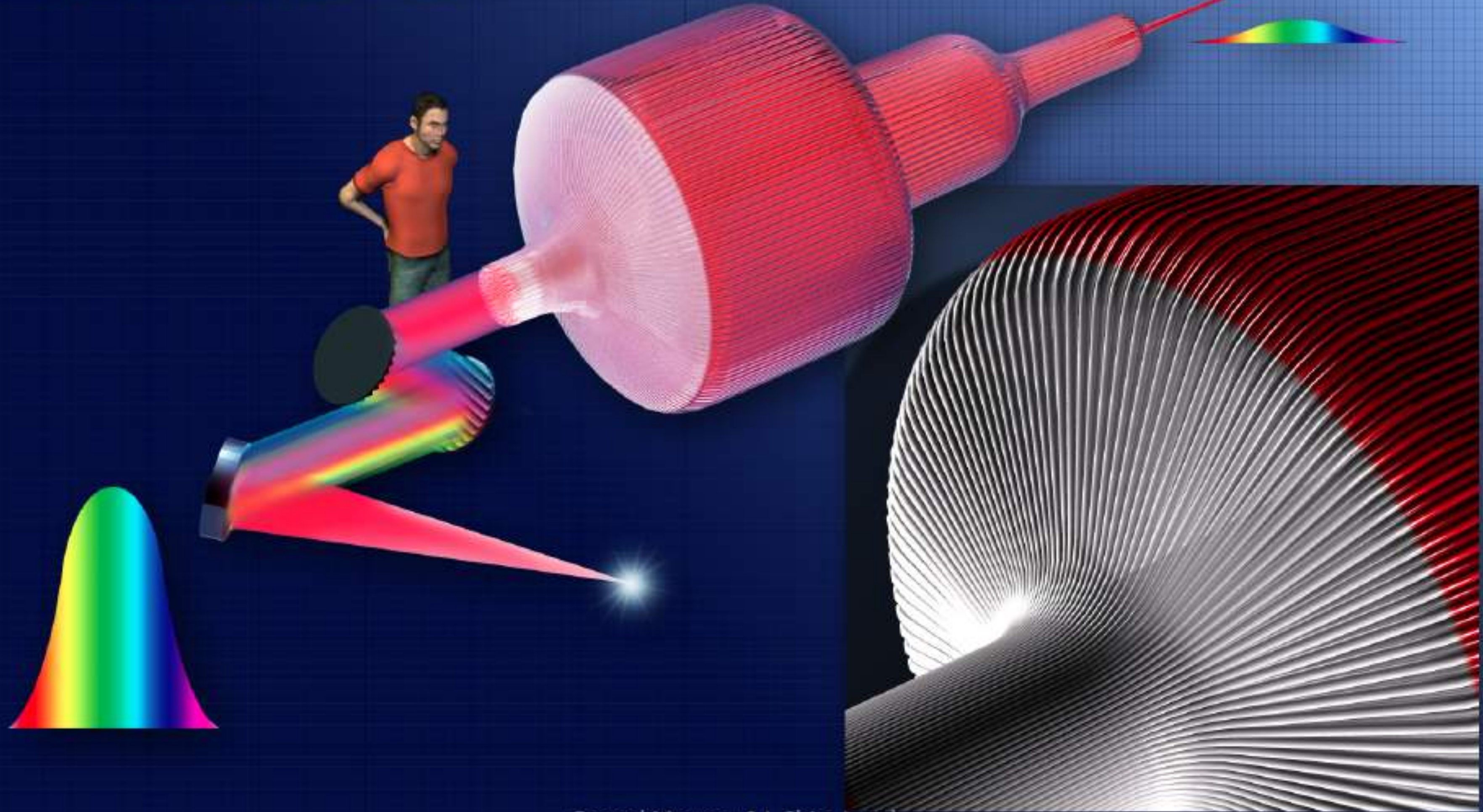
Case: CoM Energy (Plasma density)	**1 TeV** (10^{17} cm^{-3})	**1 TeV** (2×10^{15} cm^{-3})	**10 TeV** (10^{17} cm^{-3})	**10 TeV** (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} $cm^{-2}s^{-1}$)	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition 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

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 »

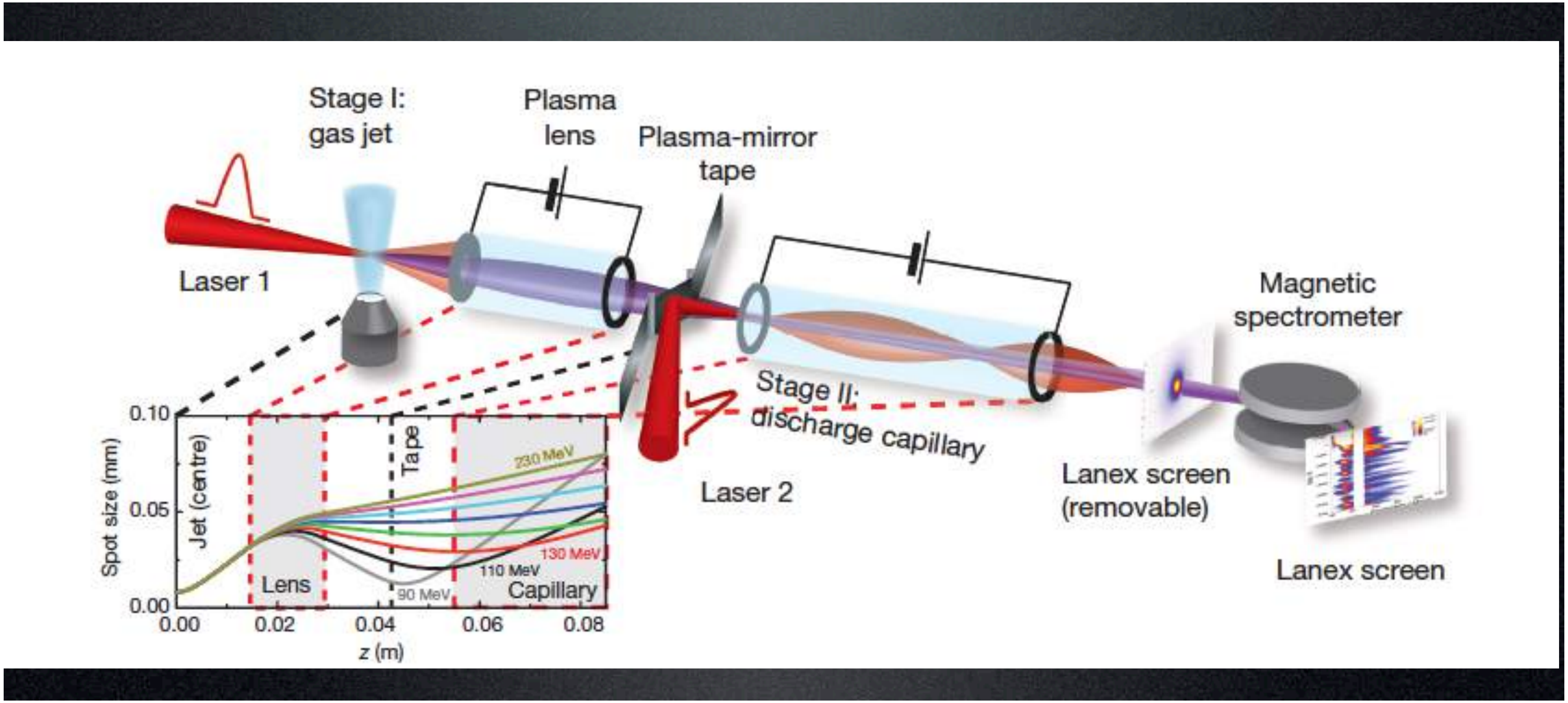


LETTER

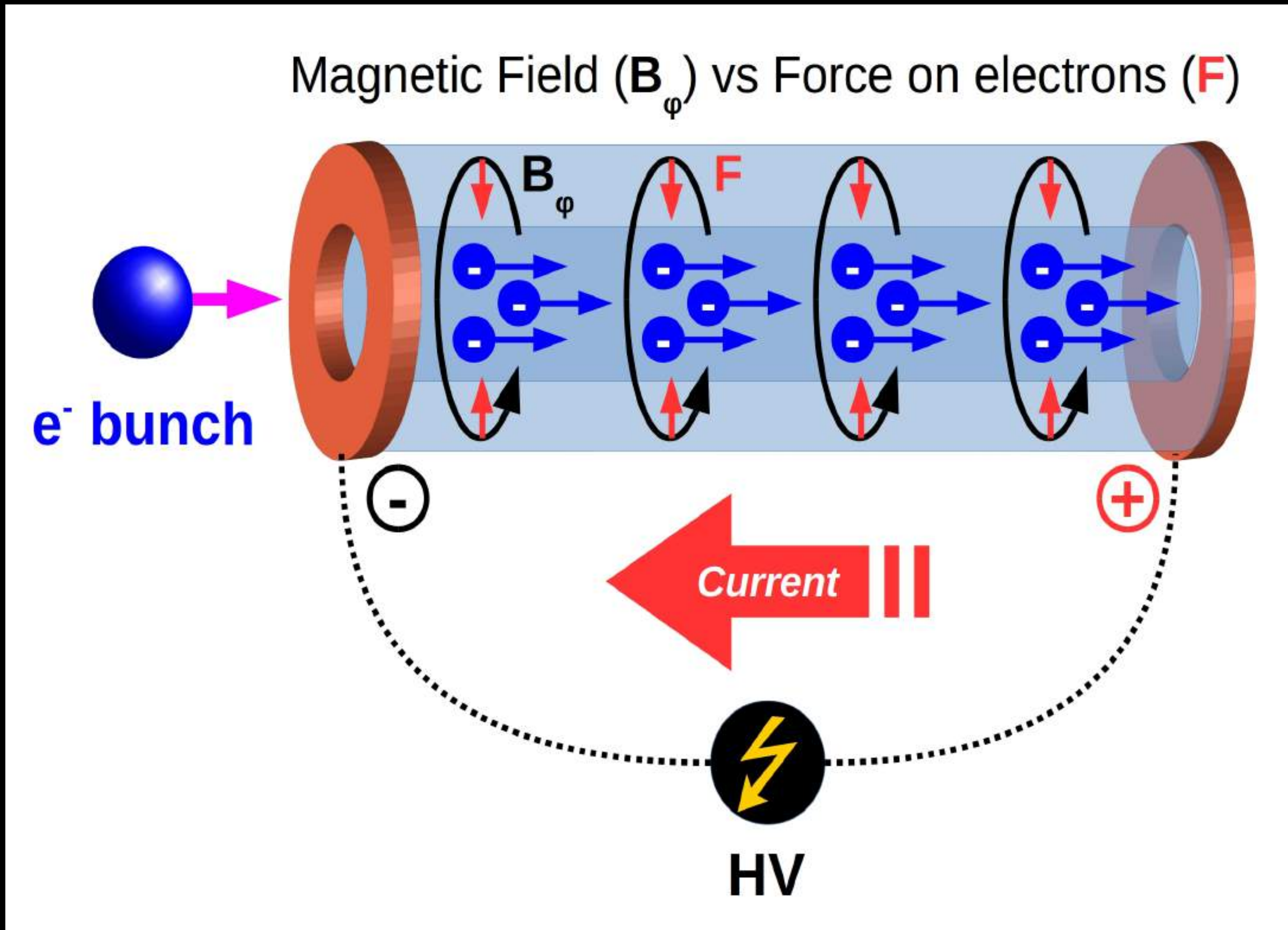
doi:10.1038/nature16525

Multistage coupling of independent laser–plasma accelerators

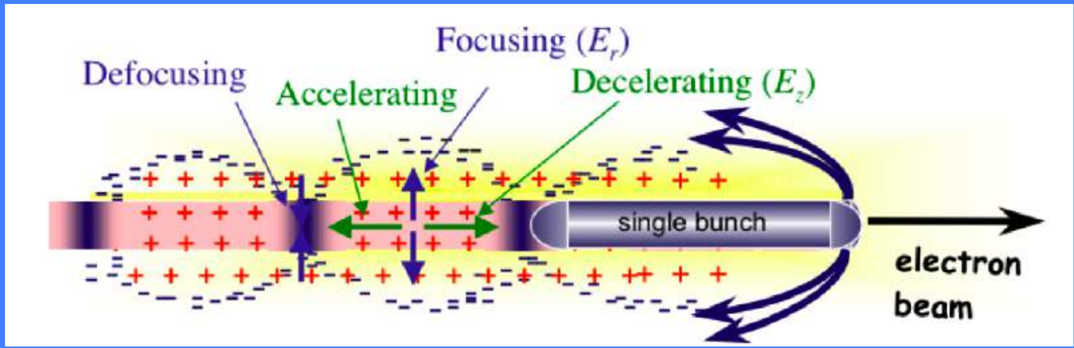
S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]

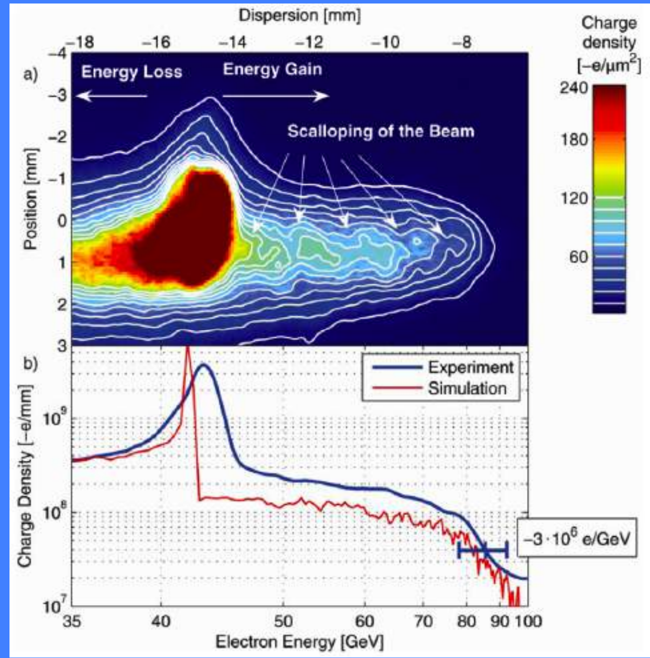


Active Plasma Lens

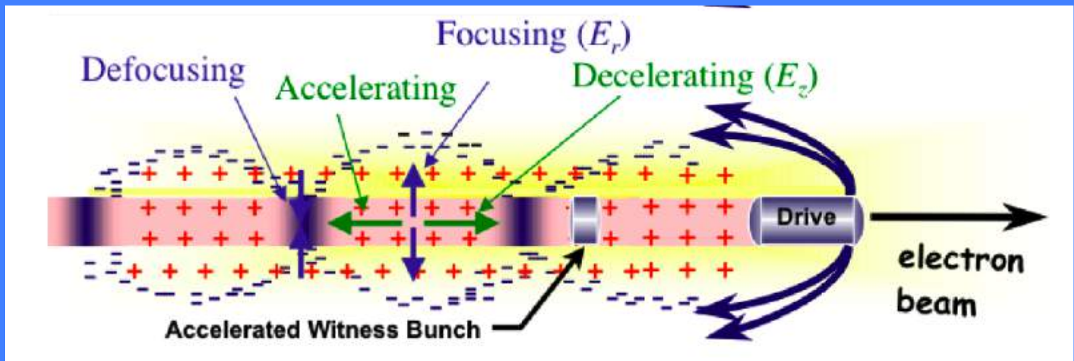


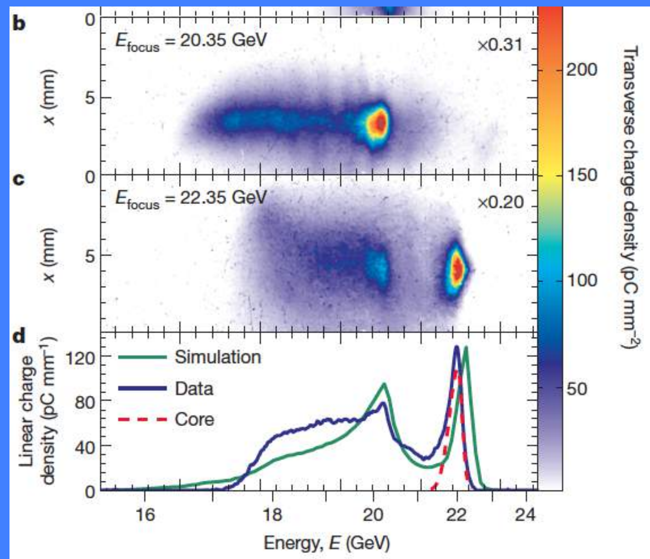
Beam Driven
PWFA





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



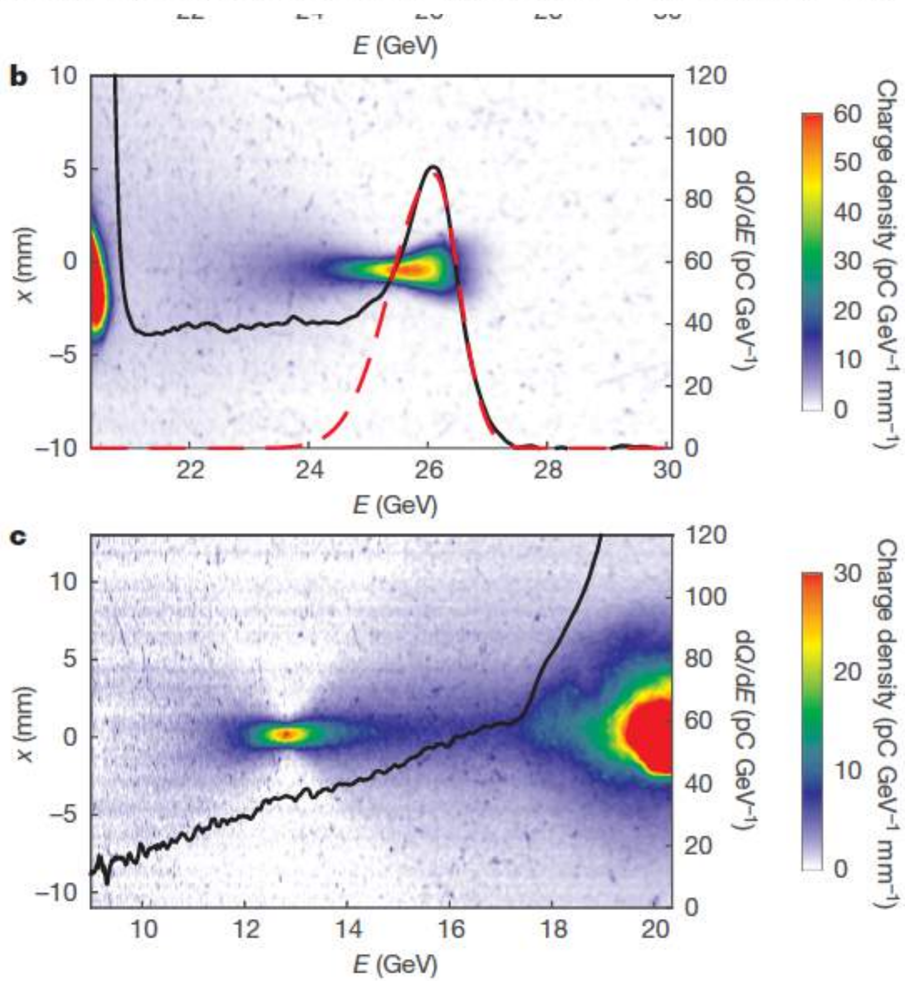


Litos, M. et al. *High-efficiency acceleration of an electron beam in a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

doi:10.1038/nature14890

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

S. Corde[1,2], E. Adli[1,3], J. M. Allen[1], W. An[4,5], C. I. Clarke[1], C. E. Clayton[4], J. P. Delahaye[1], J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], N. Lipkowitz[1], M. Litos[1], W. Lu[6], K. A. Marsh[4], W. B. Mori[4,5], M. Schmeltz[1], N. Vafaei-Najafabadi[4], D. Walz[1], V. Yakimenko[1] & G. Yocky[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

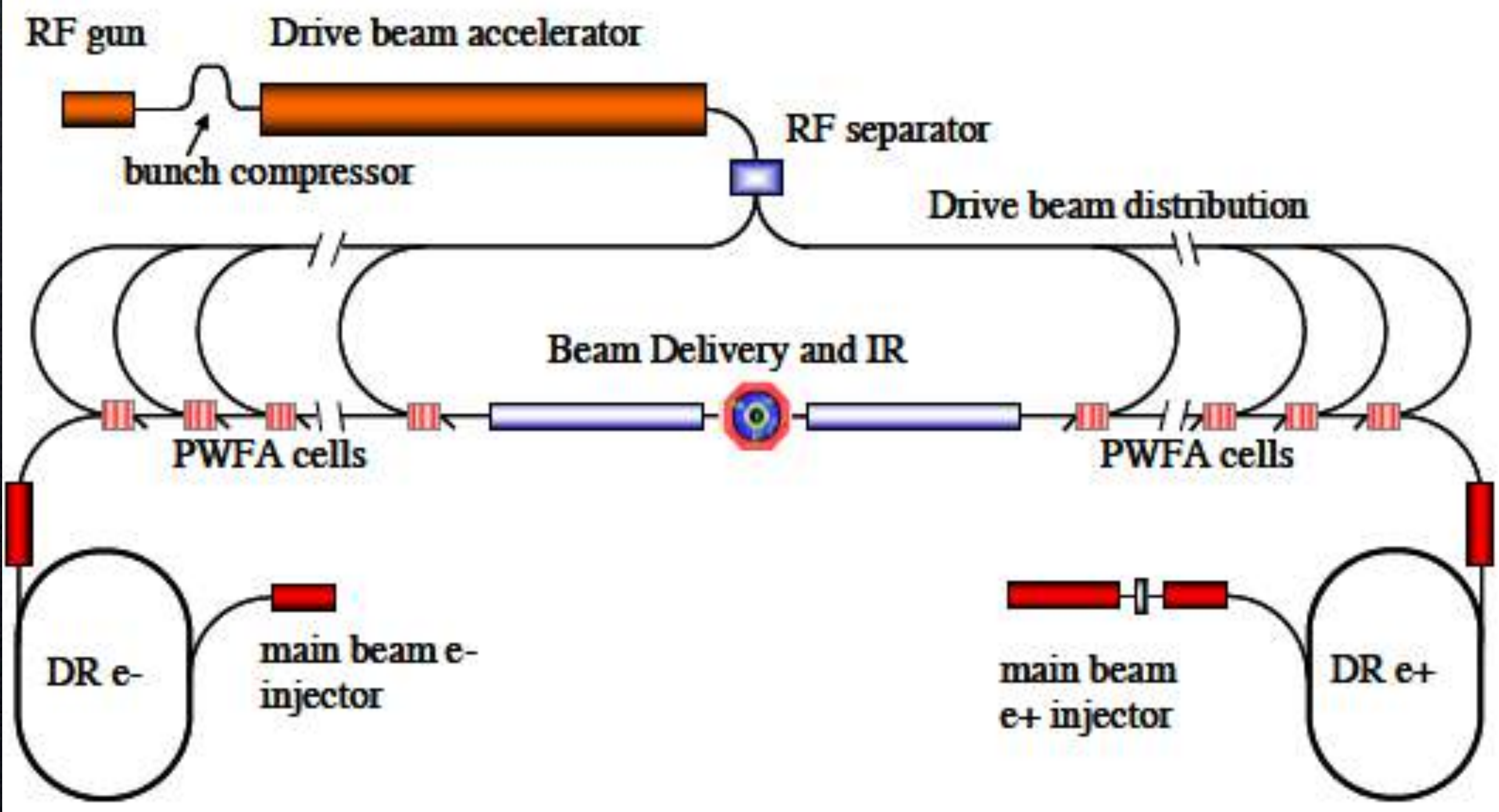


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

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

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} $cm^{-2}s^{-1}$

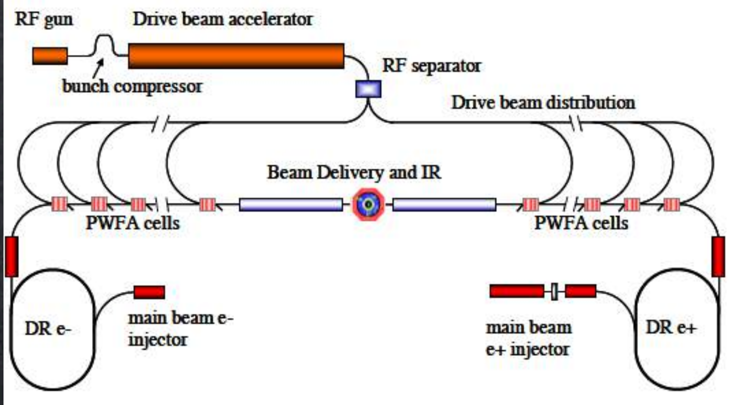


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

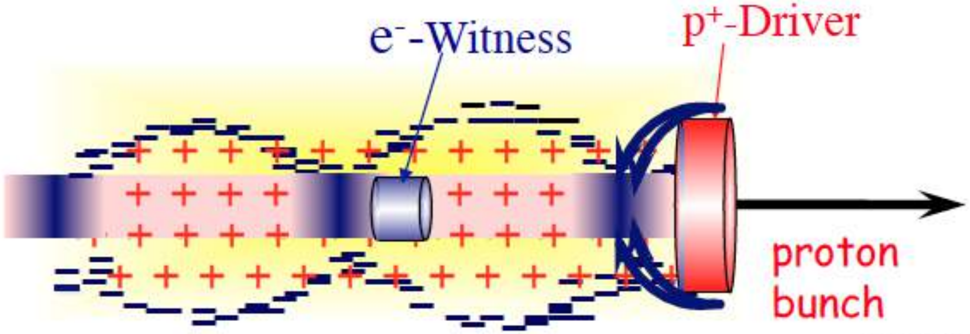
European Network

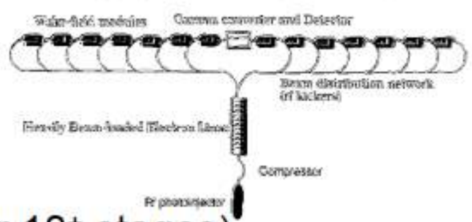
Proton-driven Plasma Wakefield Acceleration Collaboration: Accelerating e^- on the wake of a p^+ bunch

MAX-PLANCK-GESELLSCHAFT

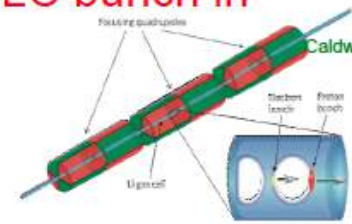
AWAKE

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)

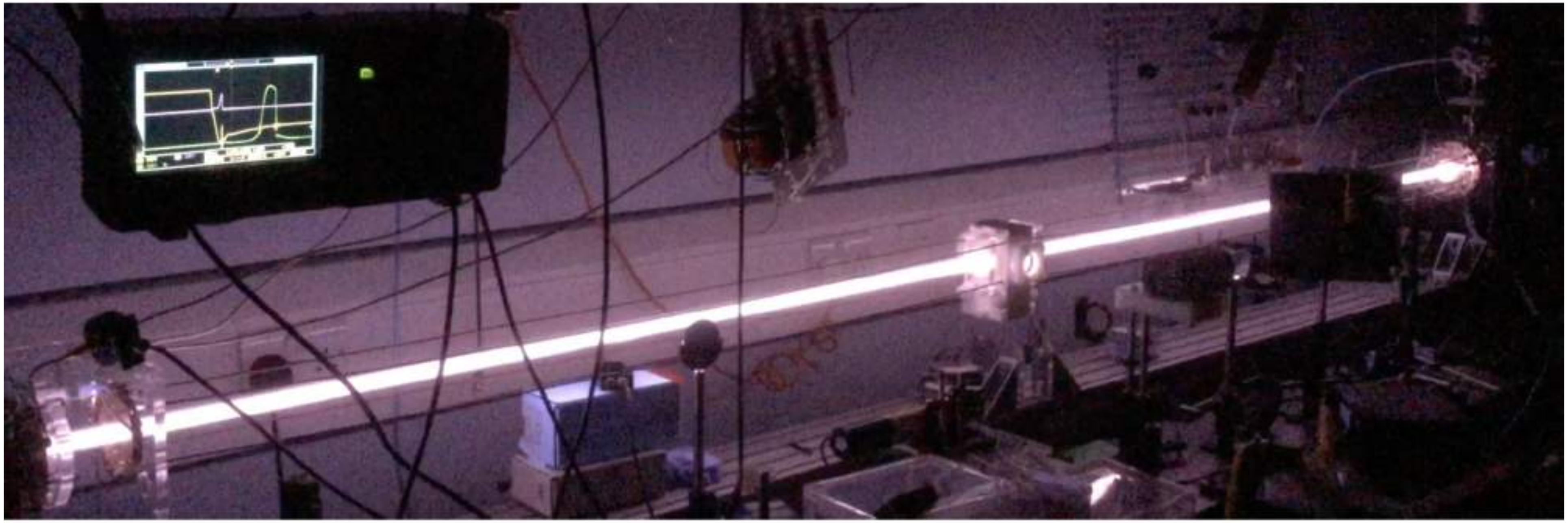


Caldwell, Nat. Phys. 5, 363, (2009)

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

Discharge configuration II

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



very promising results

… reliable, low jitter plasma formation

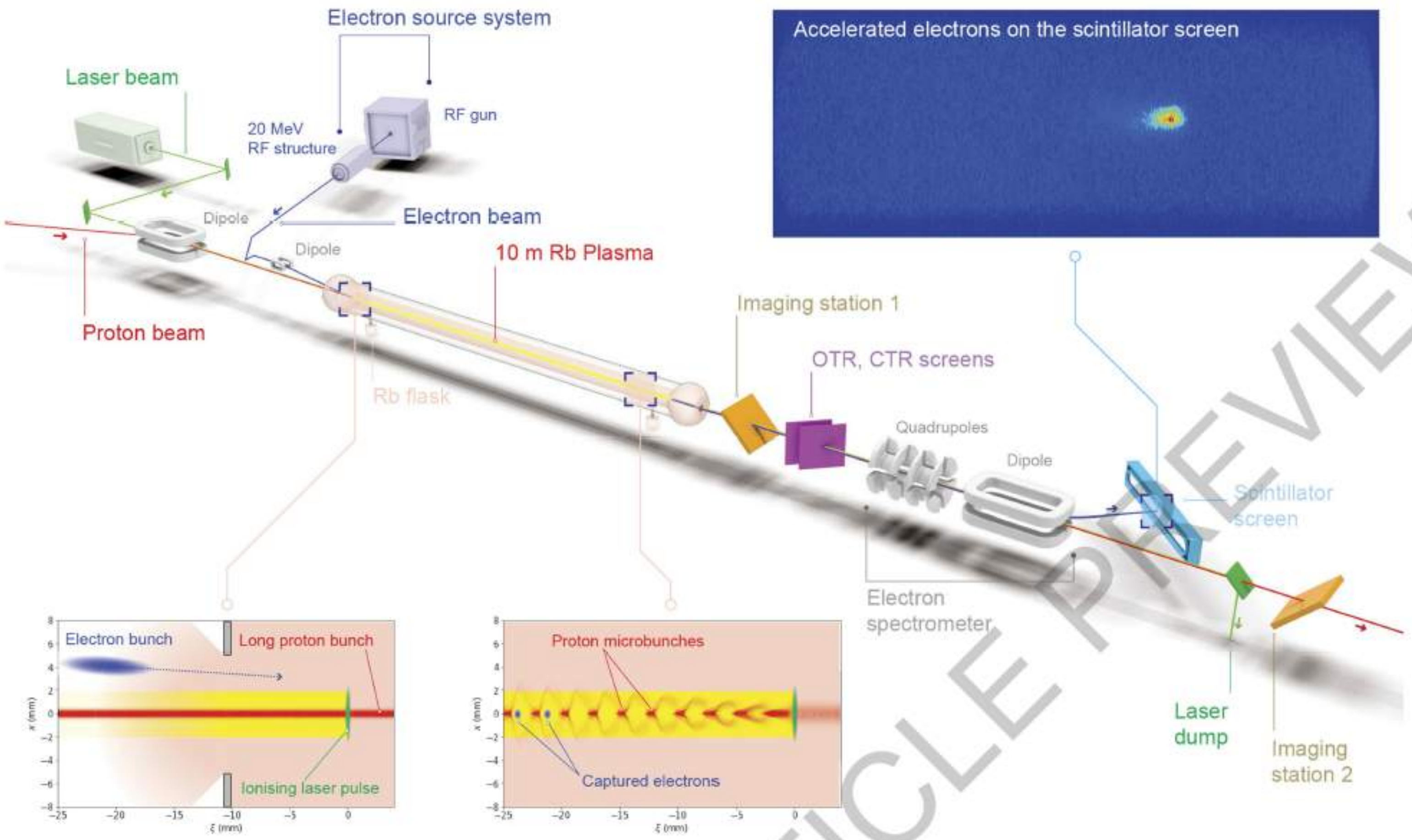
scalability of electric circuit for plasmas > 10 m seem achievable…

nature Accelerated Article Preview

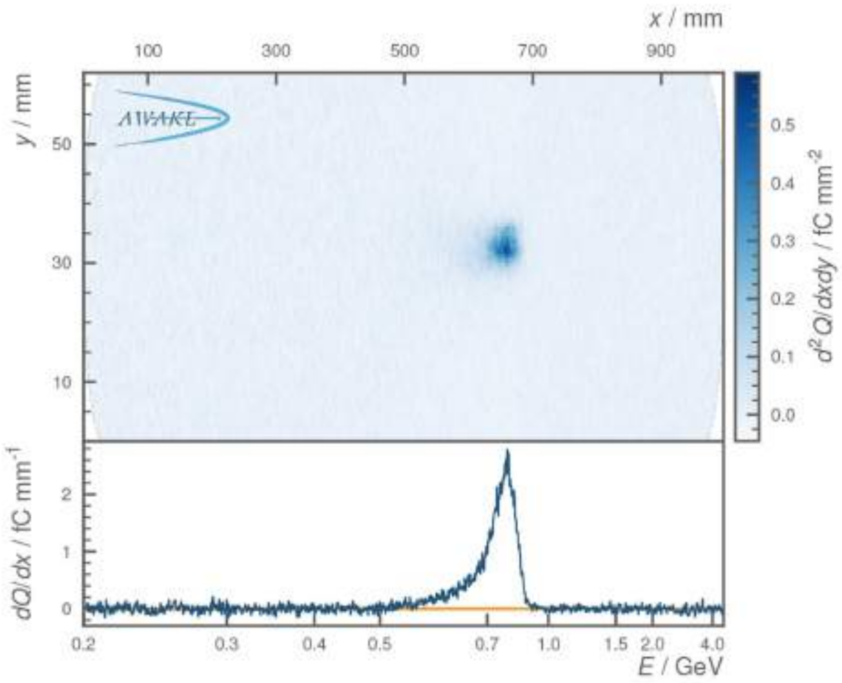
LETTER
doi:10.1038/s41586-018-0485-4

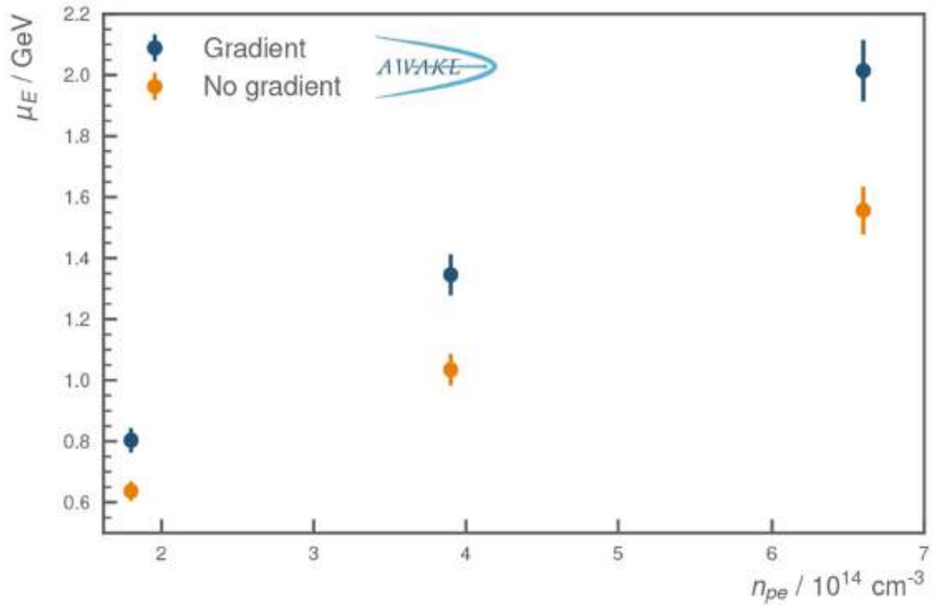
Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli, A. Ahuja, O. Apsimon, R. Apsimon, A.-M. Bachmann, D. Barrientos, F. Batsch, J. Bauche, V.K.Berglyd Olsen,



Experimental Results





- Mean energy of 800 ± 40 MeV, => E_{acc}~150 MV/m
- FWHM of 137.3 ± 13.7 MeV => Spread >10%
- Total charge of 0.249 ± 0.074 pC => Low charge transmission

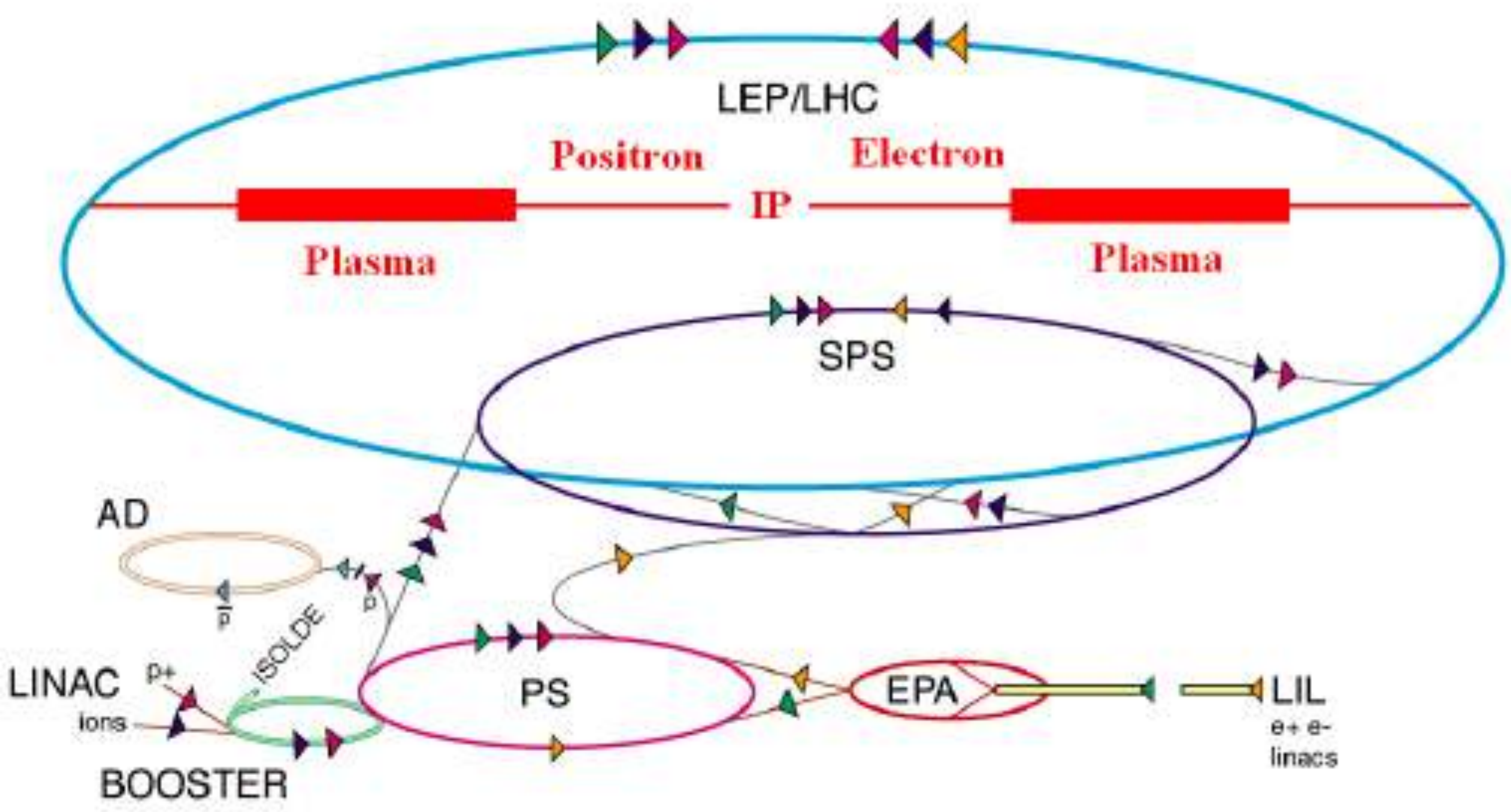


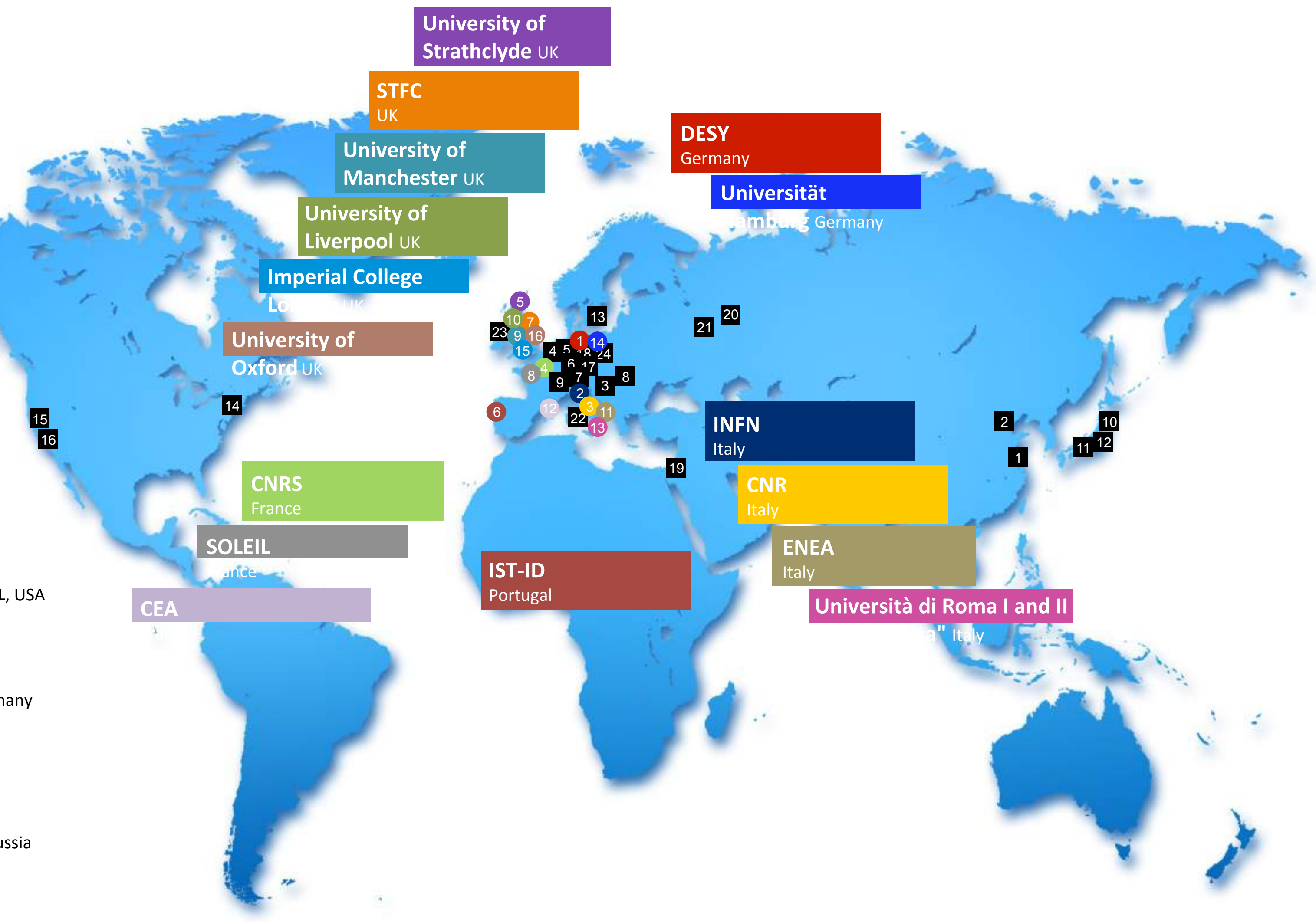
Figure 1: Schematic layout of a 2 TeV CoM electron-positron linear collider based on a modulated proton-driven plasma wakefield acceleration.

The near future

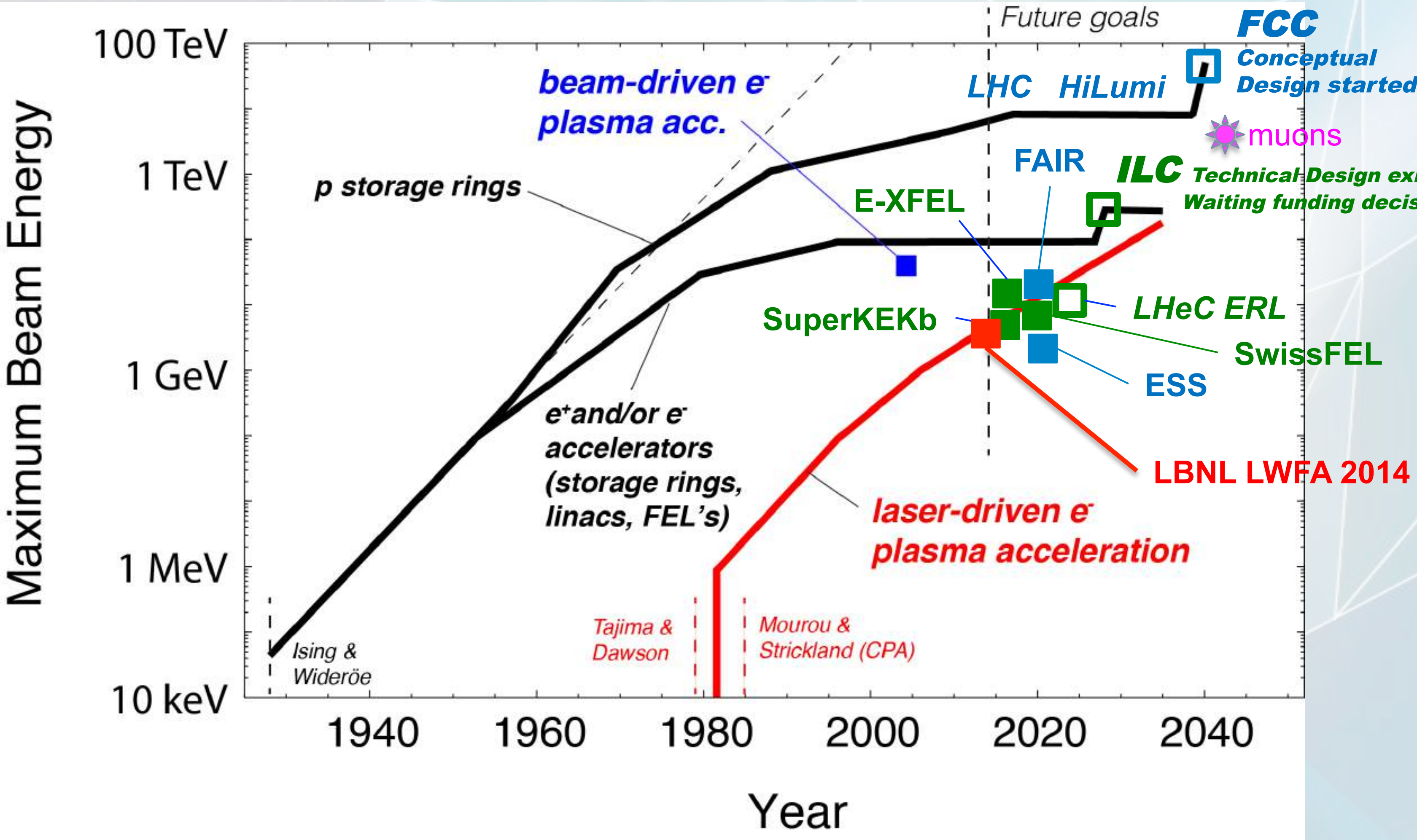
Worldwide effort towards high quality plasma beams

Associated Partners
(as of December 2017)

1. **Shanghai Jiao Tong-University**, China
2. **Tsinghua University Beijing**, China
3. **ELI Beamlines**, International
4. **PHLAM, Université de Lille,** France
5. **Helmholtz-Institut Jena**, Germany
6. **HZDR (Helmholtz)**, Germany
7. **LMU München**, Germany
8. **Wigner Fizikai Kutatóközpont**, Hungary
9. **CERN**, International
10. **Kansai Photon Science Institute**, Japan
11. **Osaka University**, Japan
12. **RIKEN SPring-8**, Japan
13. **Lunds Universitet**, Sweden
14. **Stony Brook University & Brookhaven NL**, USA
15. **LBNL**, USA
16. **UCLA**, USA
17. **Karlsruher Institut für Technologie**, Germany
18. **Forschungszentrum Jülich**, Germany
19. **Hebrew University of Jerusalem**, Israel
20. **Institute of Applied Physics**, Russia
21. **Joint Institute for High Temperatures**, Russia
22. **Università di Roma 'Tor Vergata'**, Italy
23. **Queen's University Belfast**, UK
24. **Ferdinand-Braun-Institut**, Germany



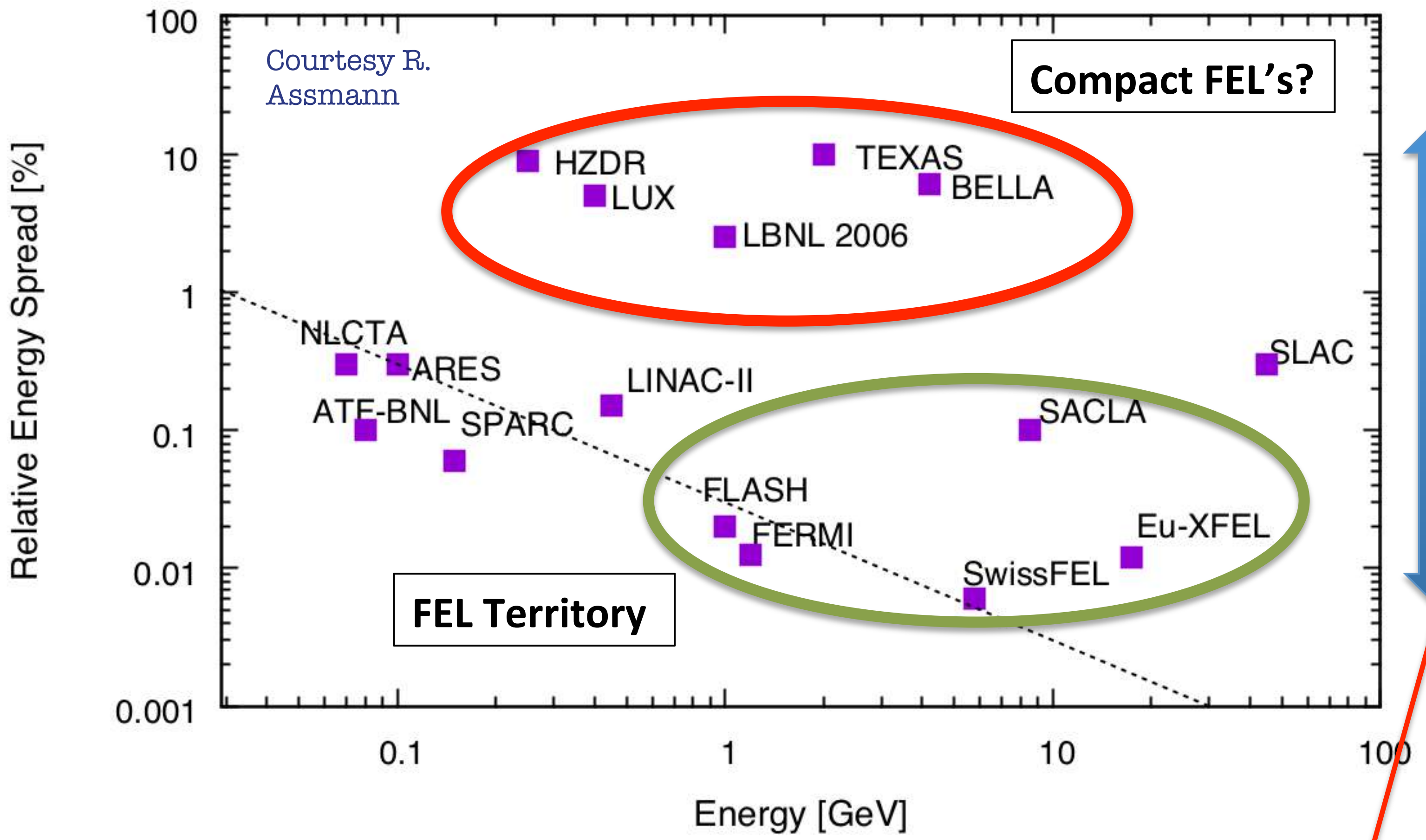
Future of Accelerators



Hadron acc. project
Lepton acc. project
Hadron acc. proposal
Lepton acc. proposal

R. Assmann, EAAC 2015, 9/2015

Quality: Example Energy Spread



Lower quality

$$\frac{\sigma_\gamma}{\gamma} = \frac{\sqrt{3}}{2} k_p^2 \sigma_z^2$$

$$\sin\varphi_w \propto \frac{q_w}{Q_d}$$

Higher quality

$$\varepsilon_{n,rms} = \sqrt{\langle\gamma^2\rangle\left(\sigma_\gamma^2\sigma_x^2\sigma_{x'}^2 + \varepsilon_{rms}^2\right)}$$

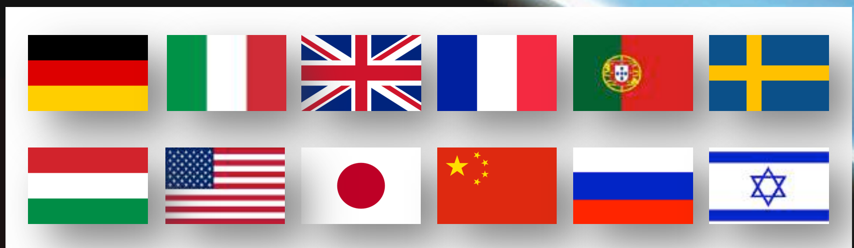
EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

EuPRAXIA Design Study started on Novemebr 2015

Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€

Coordinator: Ralph Assmann (DESY)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

http://eupraxia-project.eu

Motivations

Horizon2020

PRESENT EXPERIMENTS

Demonstrating **100 GV/m** routinely

Demonstrating **GeV** electron beams

Demonstrating basic **quality**

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator

5 GeV electron beam for the 2020's

Demonstrating user readiness

Pilot users from FEL, HEP, medicine, ...

PRODUCTION FACILITIES

Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

Medical, industrial applications soon





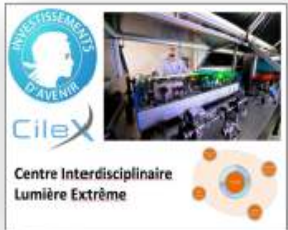
Courtesy R. Assmann

Location of possible sites within EU

Horizon 2020

EuPRAXIA site studies:

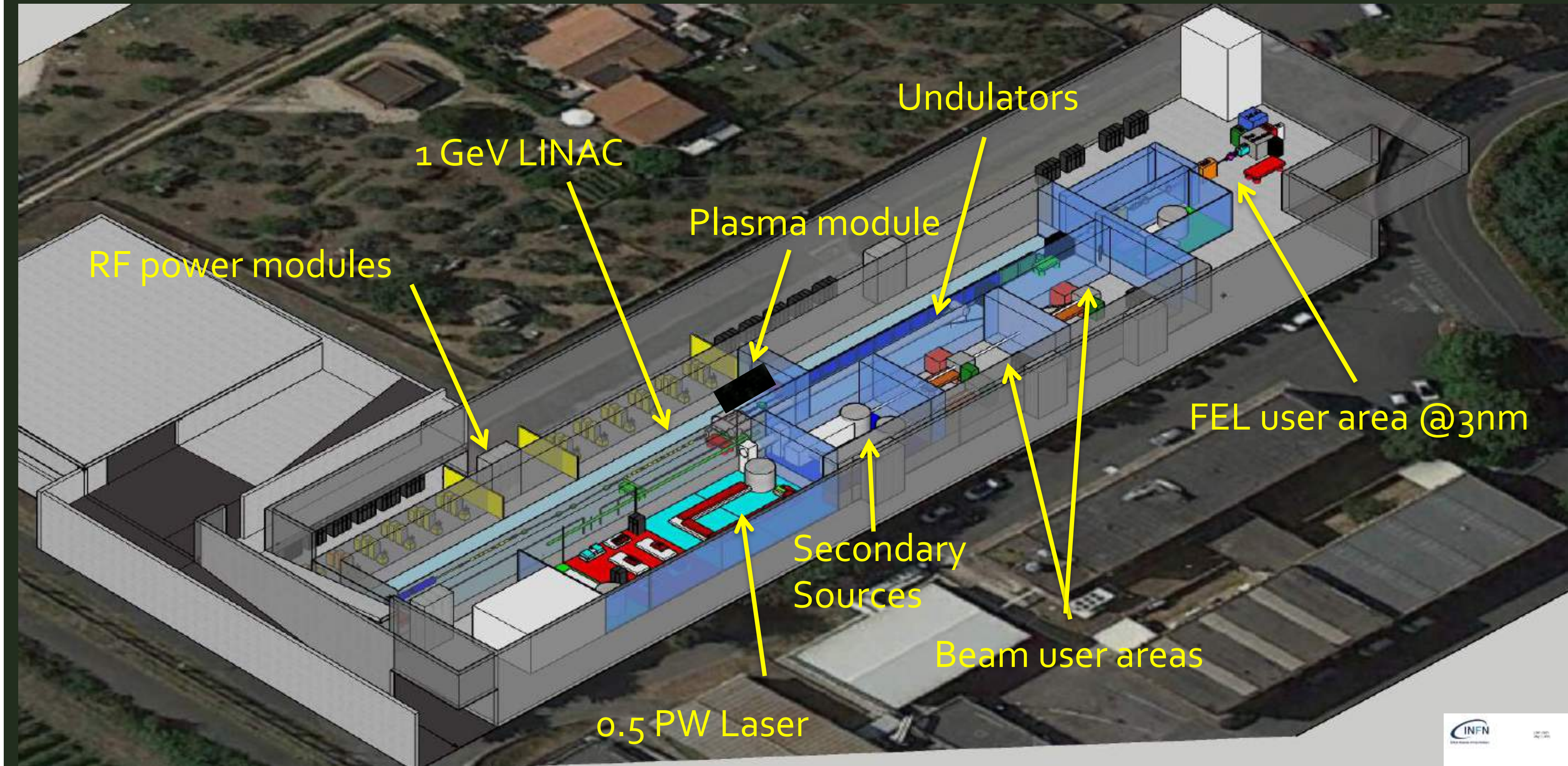
- Design study is site independent
- Five possible sites have been discussed so far
- We invite the suggestions of additional sites



Central Laser Facility
Didcot, United Kingdom

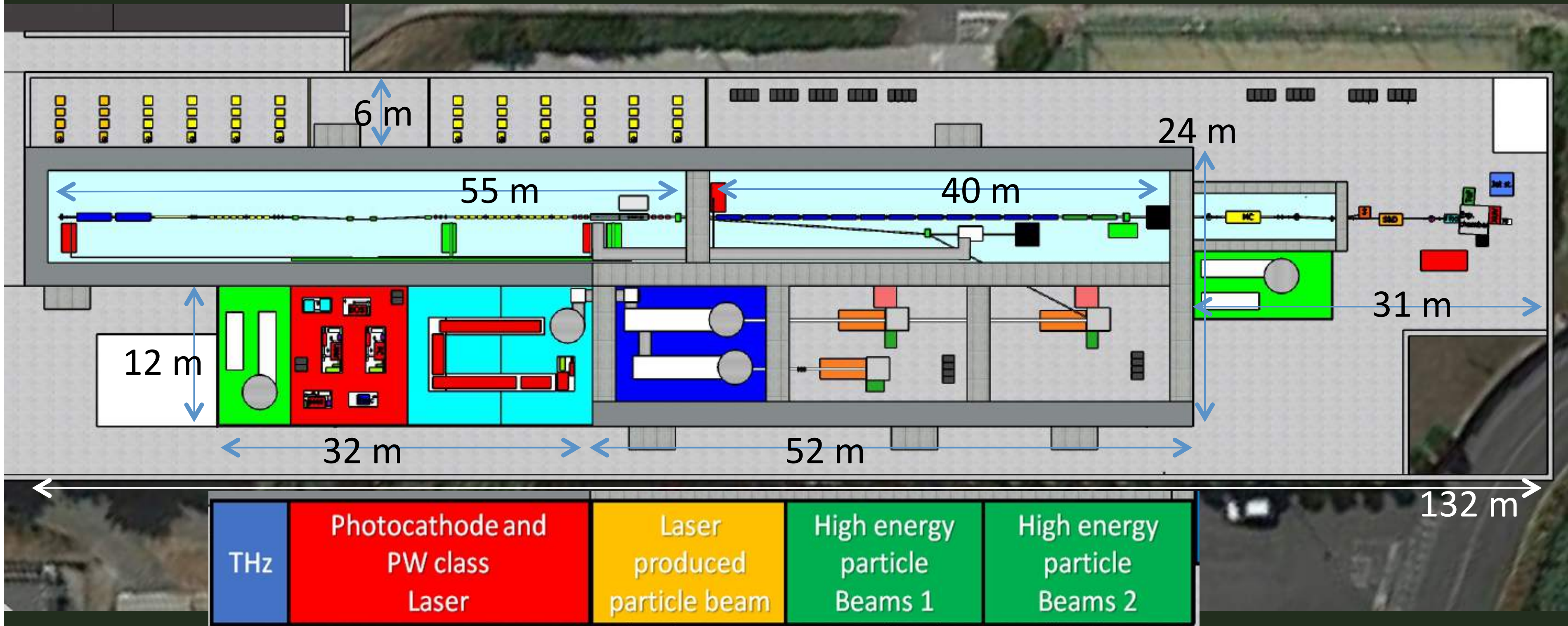
Eli Beamlines
Prague, Czech Republic

EuPRAXIA@SPARC_LAB



http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

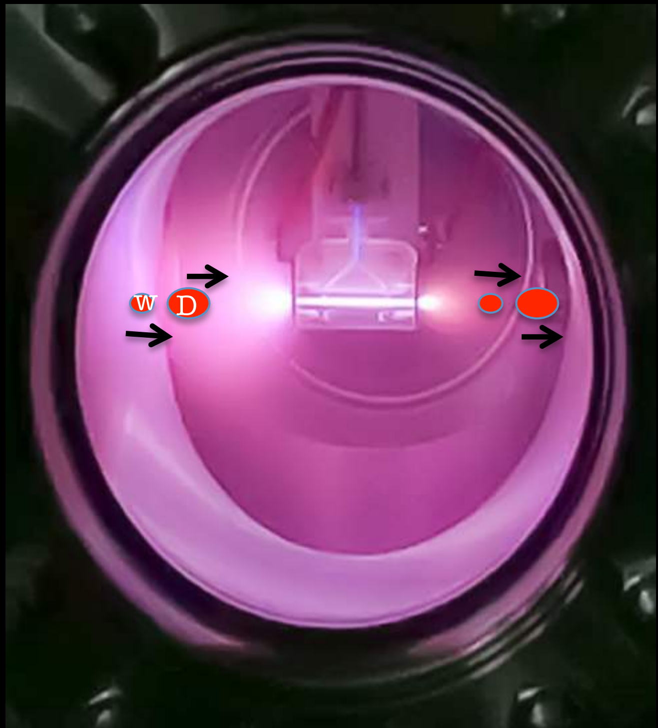
- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN



- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator

SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)

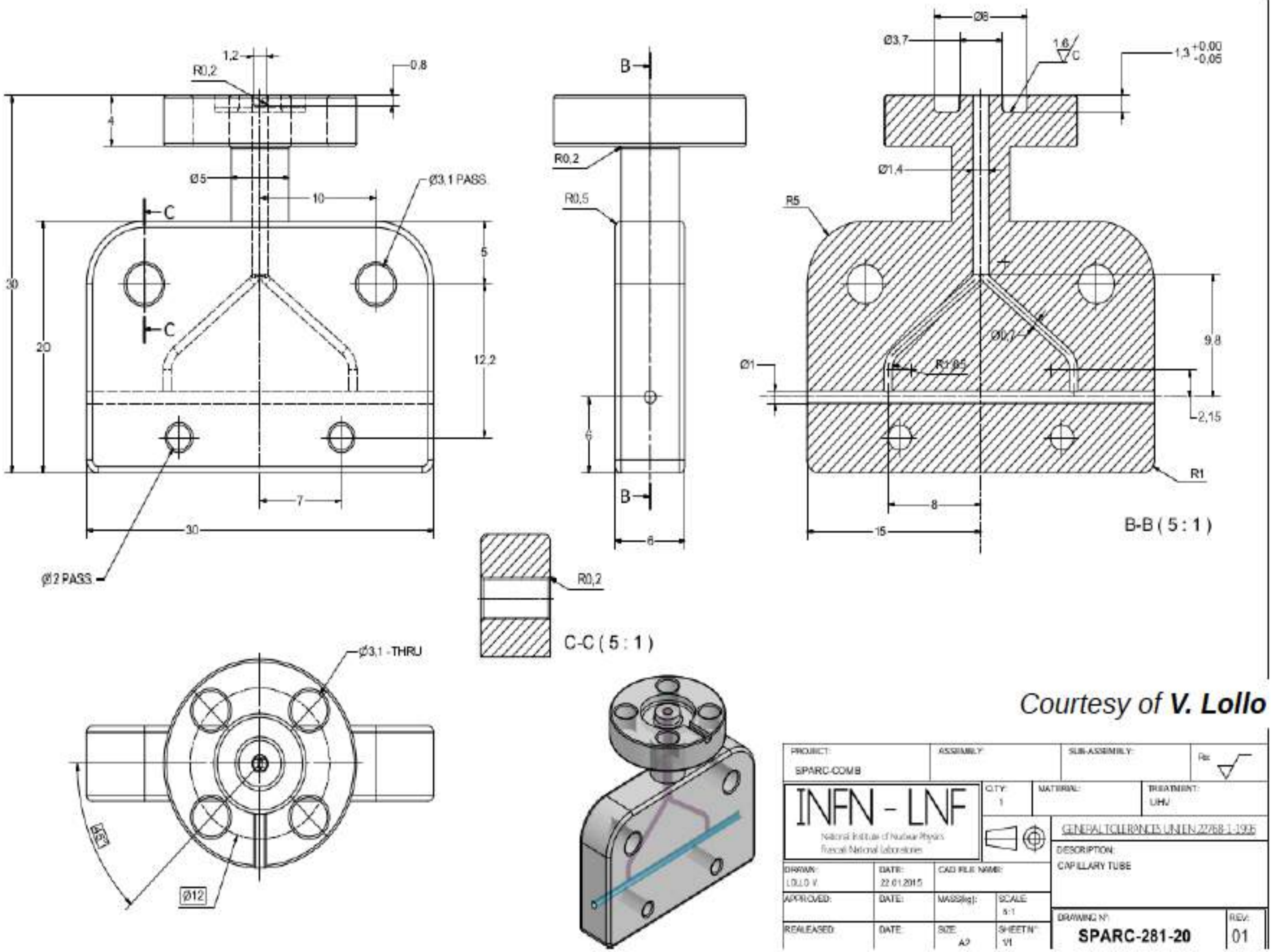
External Injection



$$\Delta T_w = \left(R - \frac{q}{Q}\right)\left|\Delta T_D\right|$$

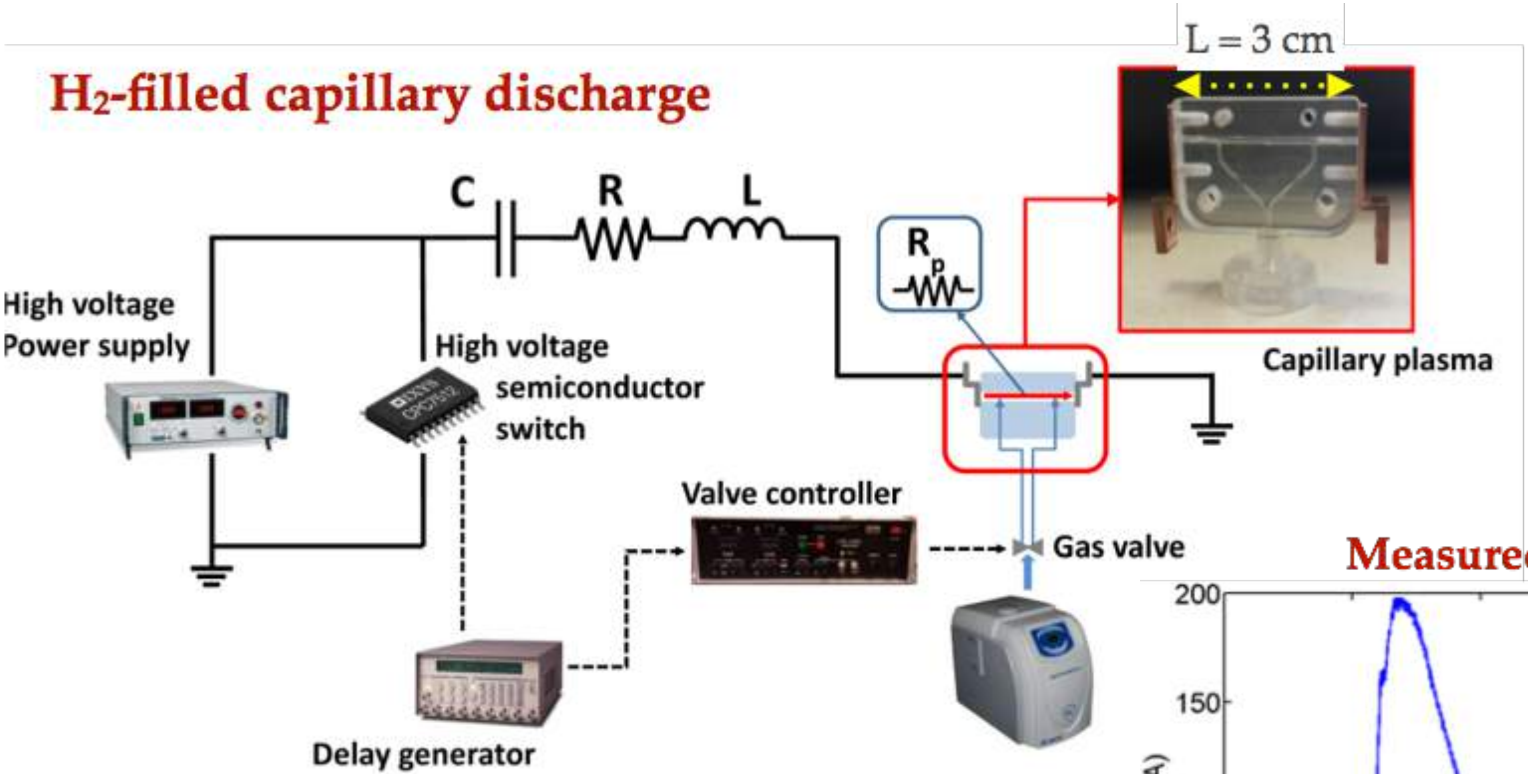
$$R \cong 2$$

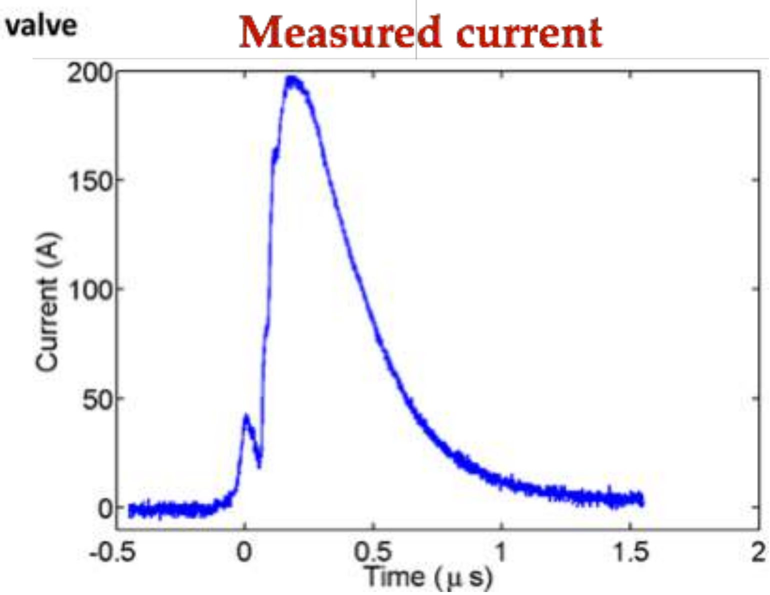
Plasma capillary



Courtesy of ***V. Lollo***

Plasma Source

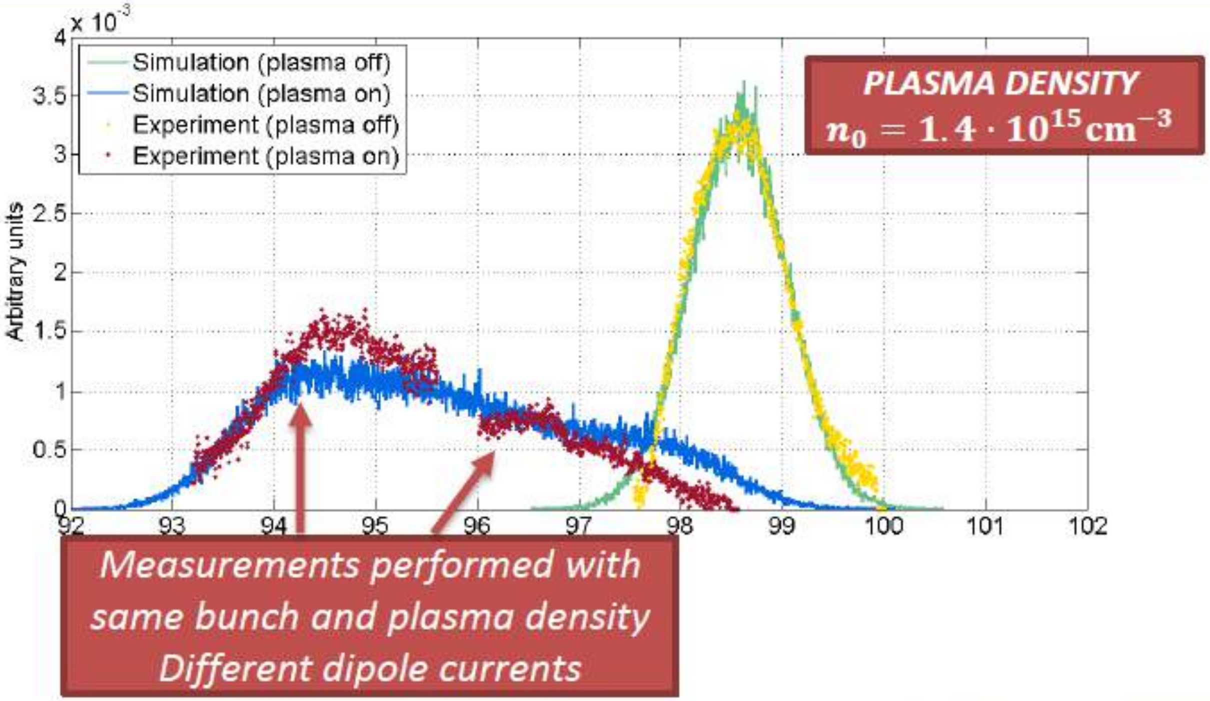




P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

Deceleration test - July 2018



Experimental data at injection

$\sigma_{x,(y)} = 24(33)\mu\mathrm{m}$

$\sigma_z = 50\mu\mathrm{m}$

$\varepsilon_{x,(y)} = 1.7(1.8)\mathrm{mm\ mrad}$

$\sigma_E = 0.5\%$

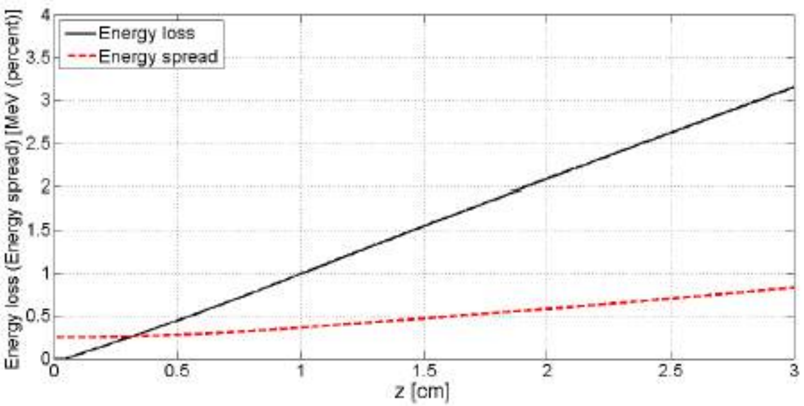
Simulation parameters

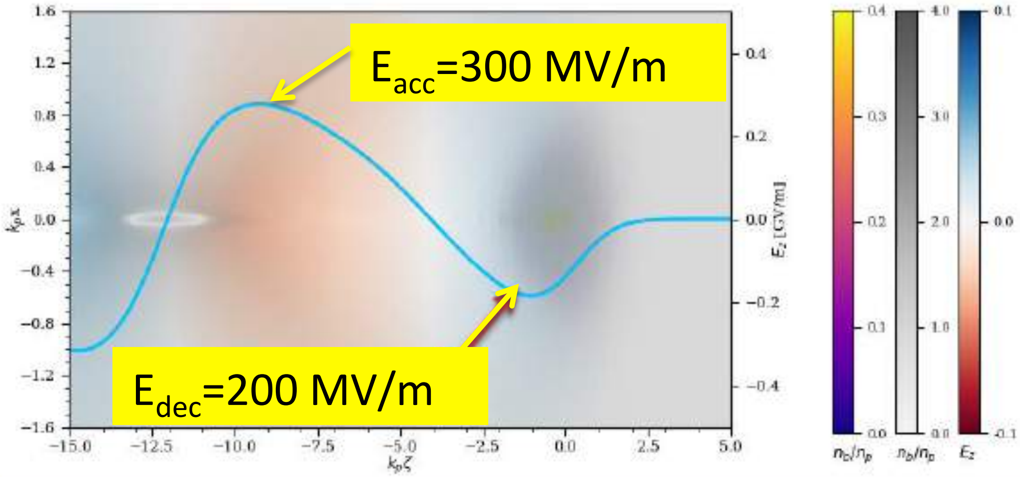
$\sigma_{x,y} = 28.3\mu\mathrm{m}$

$\sigma_z = 50\mu\mathrm{m}$

$\varepsilon_{x,y} = 1.75\mathrm{mm\ mrad}$

$\sigma_E = 0.5\%$



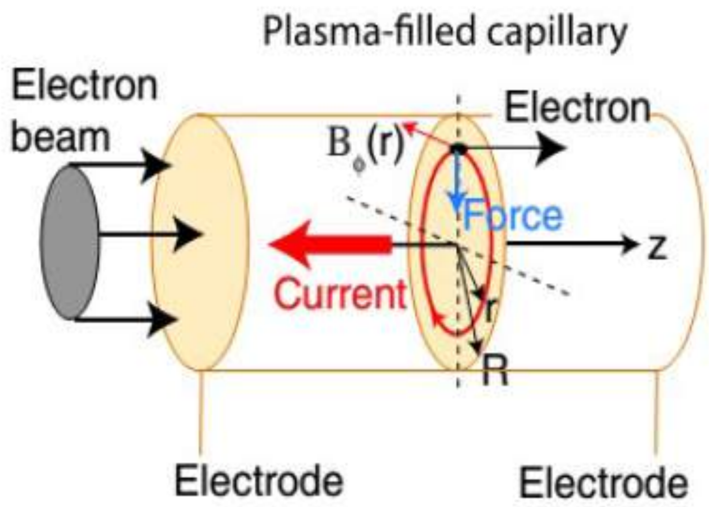


Active plasma lens

- Focusing field produced by electric discharge in a plasma-filled capillary
  - *Focusing field produced, according to Ampere's law, by the discharge current*

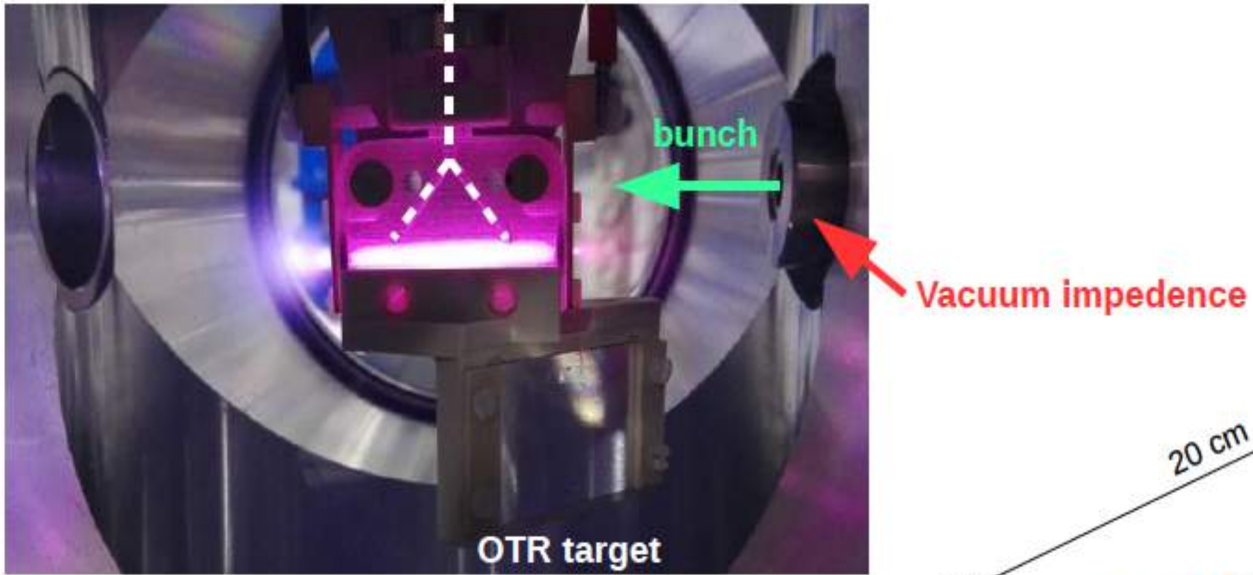
$$B_{\phi}(r)=\frac{1}{2}\int_{0}^{r}\mu_{0}J(r')\,dr'$$

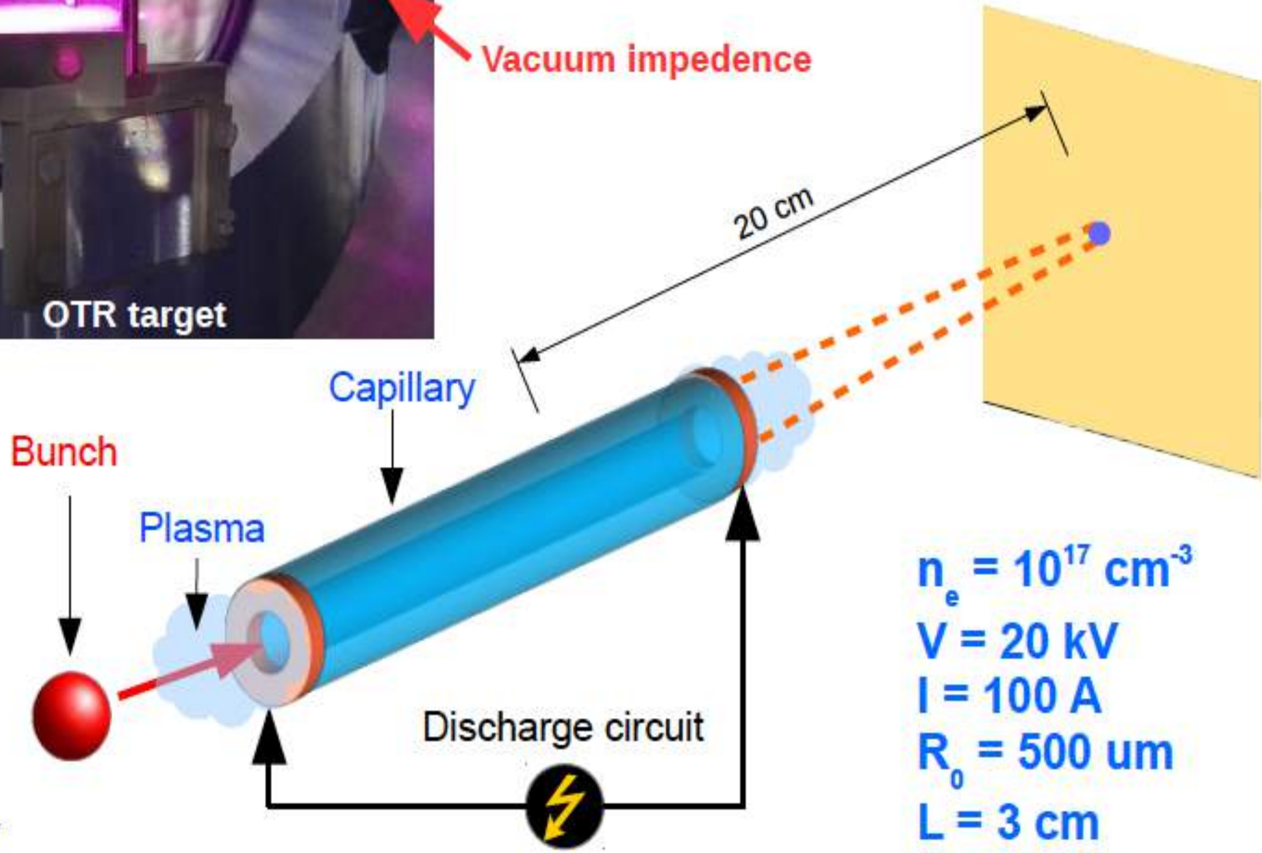
- Radial focusing
  - *X/Y planes are not dependent as in quads*
- Weak chromaticity
  - *Focusing force scales linearly with energy*
- Compactness
  - *Higher integrated field than quad triplets*
- Independent from beam distribution
  - *Not sensitive to longitudinal/transverse charge profile as in passive plasma lenses*



Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.

Experimental layout

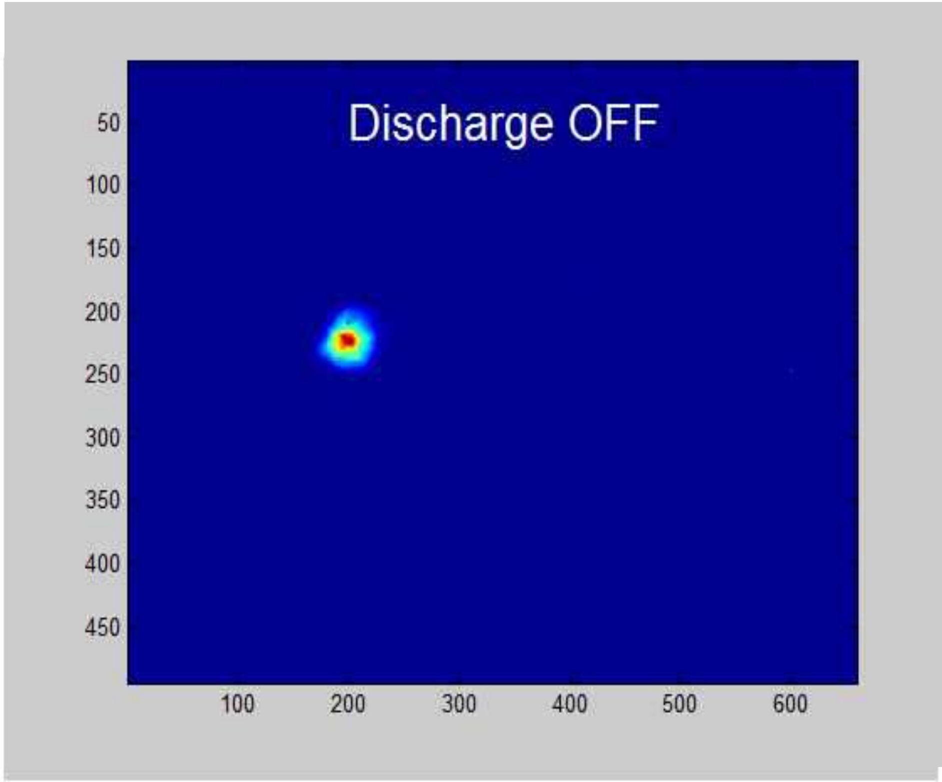


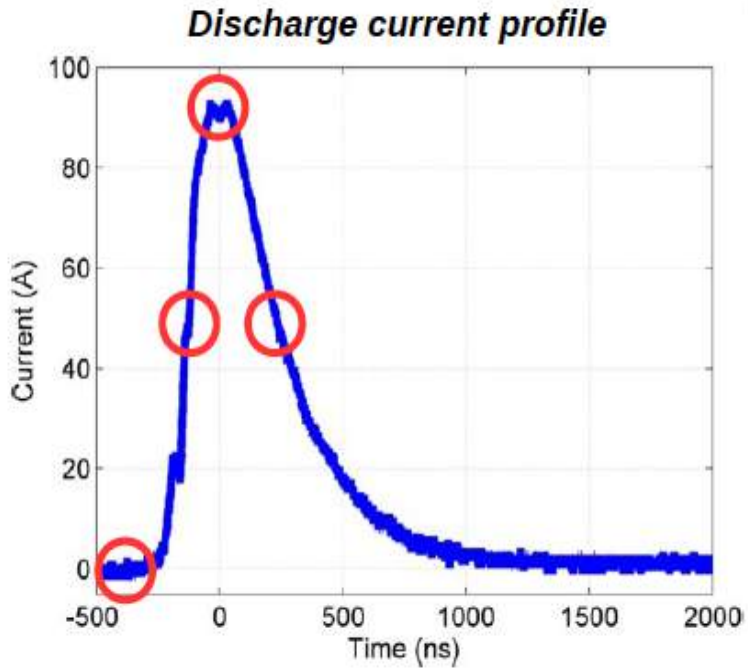


50 pC
1 ps
130 um
120 MeV
1 mm mrad

$n_e = 10^{17}$ cm^{-3}
V = 20 kV
I = 100 A
R_0 = 500 um
L = 3 cm
Sapphire

Preliminary results

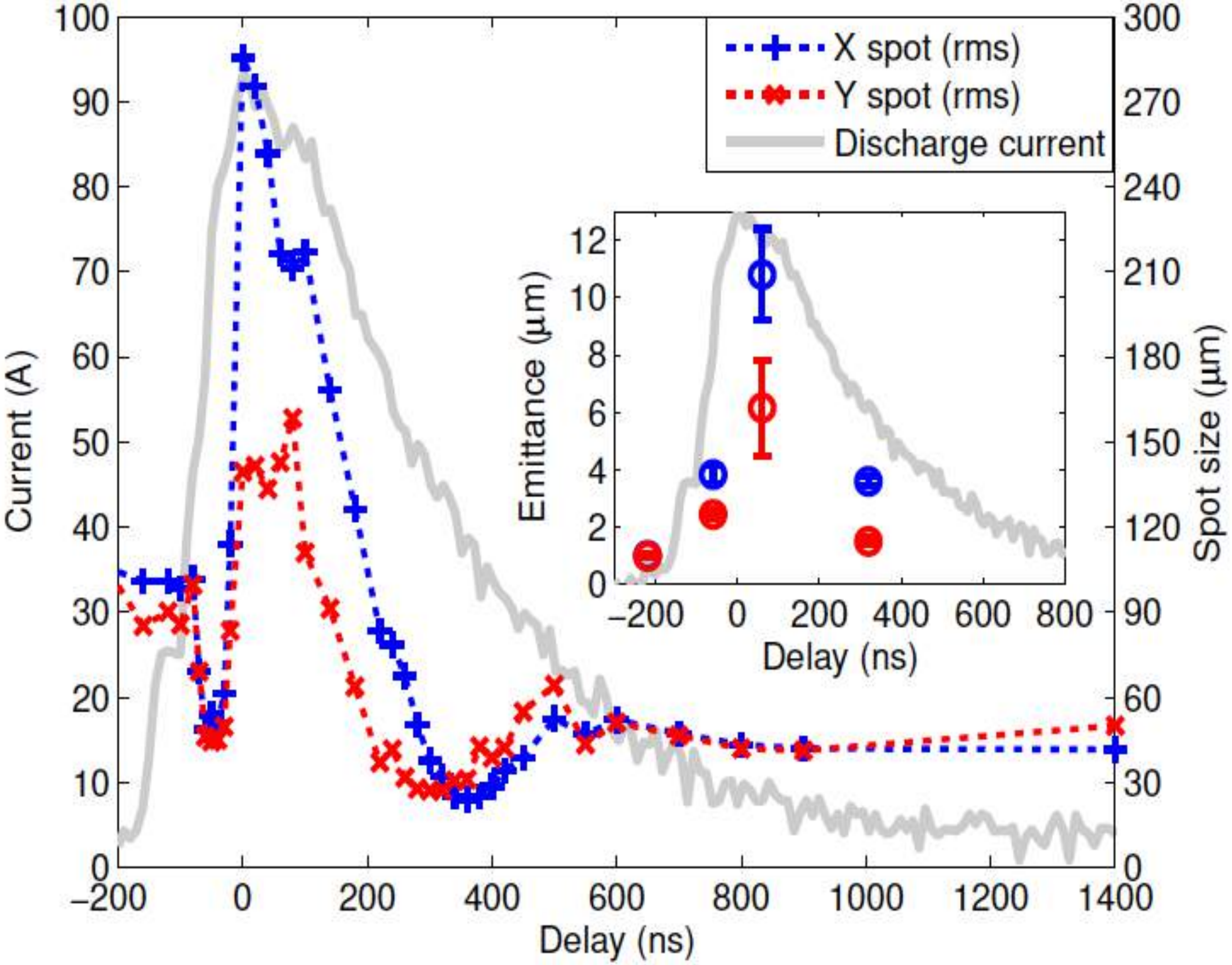




APPLIED PHYSICS LETTERS **110**, 104101 (2017)

Experimental characterization of active plasma lensing for electron beams

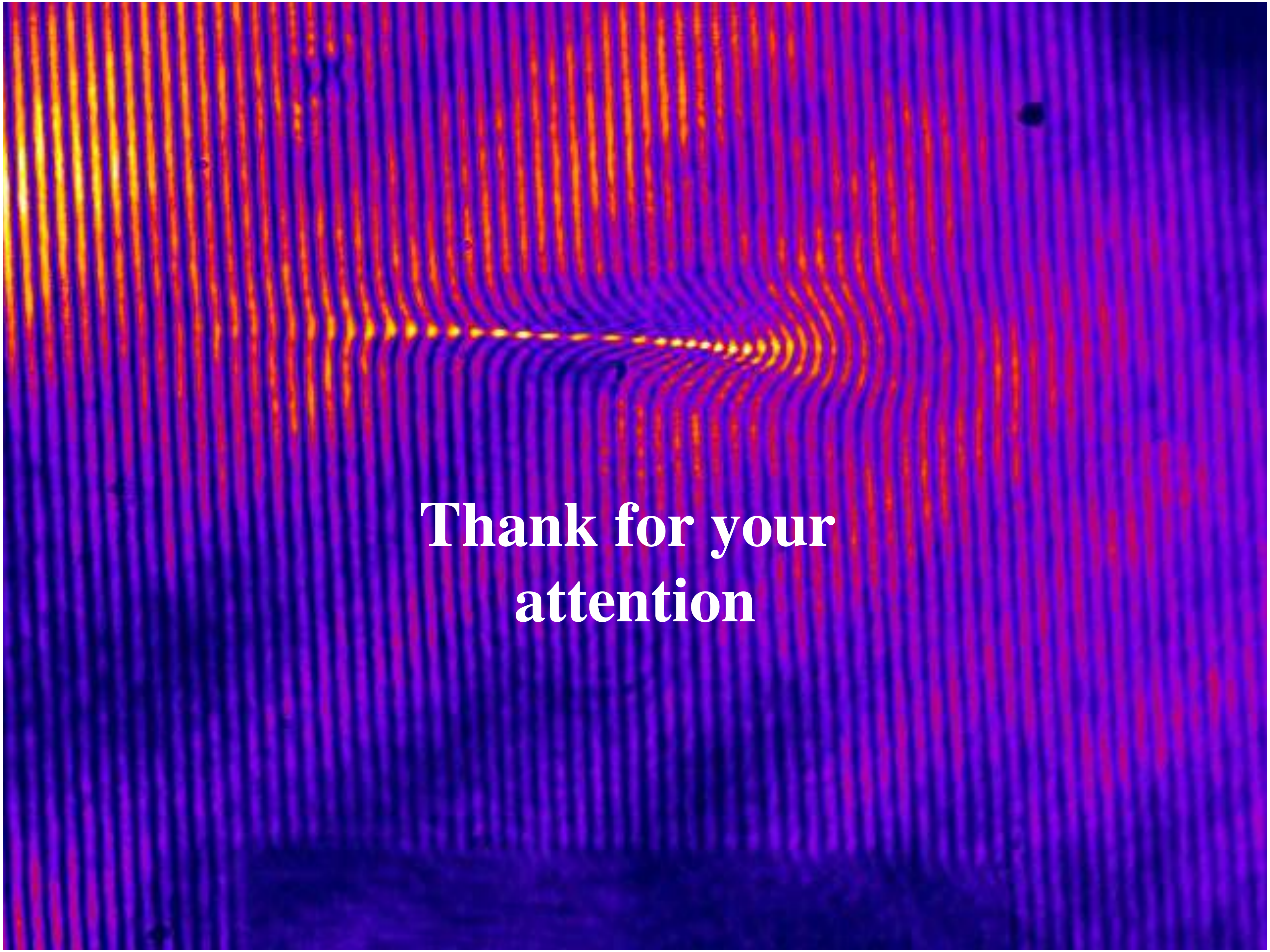
R. Pompili,[1,a)] M. P. Anania,[1] M. Bellaveglia,[1] A. Biagioni,[1] S. Bini,[1] F. Bisesto,[1] E. Brentegani,[1] G. Castorina,[1,2] E. Chiadroni,[1] A. Cianchi,[3] M. Croia,[1] D. Di Giovenale,[1] M. Ferrario,[1] F. Filippi,[1] A. Giribono,[4] V. Lollo,[1] A. Marocchino,[1] M. Marongiu,[4] A. Mostacci,[4] G. Di Pirro,[1] S. Romeo,[1] A. R. Rossi,[5] J. Scifo,[1] V. Shpakov,[1] C. Vaccarezza,[1] F. Villa,[1] and A. Zigler[6]



Conclusions

(Statement from the European Network for Novel Accelerators (EuroNNAc))

- Accelerator-based High Energy Physics will at some point become practically limited by the size and cost of the proposed e^+e^- colliders for the energy frontier.
- Plasma-based acceleration techniques have demonstrated accelerating gradients up to 3 orders of magnitudes beyond presently used RF technologies.
- **Plasma-based, ultra-high gradient accelerators therefore open the realistic vision of very compact accelerators for scientific, commercial and medical applications.**
- The R&D now concentrates on **beam quality, stability, staging and continuous operation**. These are necessary steps towards various technological applications.
- The progress in advanced accelerators benefits from strong synergy with general advances in technology, for example in the laser and/or high gradient RF structures industry.
- **A major milestone is an operational, 1 GeV compact accelerator. Challenges in repetition rate and stability must be addressed. This unit could become a stage in a high-energy accelerator..➔ PILOT FACILITY Needed**
- An increased support from Particle Physics will foster the R&D on advanced acceleration techniques and will provide important help and guidance.
- **Ultra-high gradient plasma accelerators should be recognized as essential inter-disciplinary R&D towards future e^+e^- colliders for HEP**.


Thank for your
attention

The CERN Accelerator School
is organizing a course on
PLASMA WAKE ACCELERATION
23-29 November, 2014
CERN, Geneva, Switzerland
The course will be of interest to staff and students in accelerator laboratories, university departments and companies working in or having an interest in the field of new acceleration techniques.
Following introductory lectures on plasma and laser physics, the course will cover the different components of a plasma wake accelerator and plasma beam systems. An overview of the experimental studies, diagnostic tools and state of the art wake acceleration facilities, both present and planned, will complement the theoretical part. Topical seminars and a visit of CERN will complete the programme.
11-22 March 2019
Portugal
Beatwave
Contact: Barbara Strasser
CERN Accelerator School
CH - 1211 Geneva 23
Tel.: +41 22 767 8607 / Fax: +41 22 767 5460
email: barbara.strasser@cern.ch
http://cas.web.cern.ch/cas
The CERN Accelerator School
CERN

3rd European Advanced Accelerator Concepts Workshop
Supported by EU/ARIES via EuroNNAc3
24-30 September 2017, La Biodola - Isola d'Elba – Italy
Laser technology for advanced accelerators
Dielectric structures and other novel technologies
Advanced and novel accelerators for high energy physics
High gradient and multibunch acceleration in metallic structures
(C-X-band and beyond) with innovative power generation schemes
Plasma accelerators driven by: modern lasers, electron beams, proton beams
Computations for accelerator physics advanced beam diagnostics for beams and plasma
Novel schemes using advanced technologies (table-top FEL, medical imaging ...)
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European Plasma Roadmap for HEP - ***Example, based on personal view of a few persons*** *Drafted January 2016, Plasma LC Workshop at LBNL*

As a start of discussion,not an end point of discussion. Cannot be used as an official roadmap, should trigger discssuions and thoughts. Requires input, discussion, iteration, refinement, ... To be complemented by detailed R&D roadmaps from WG's.