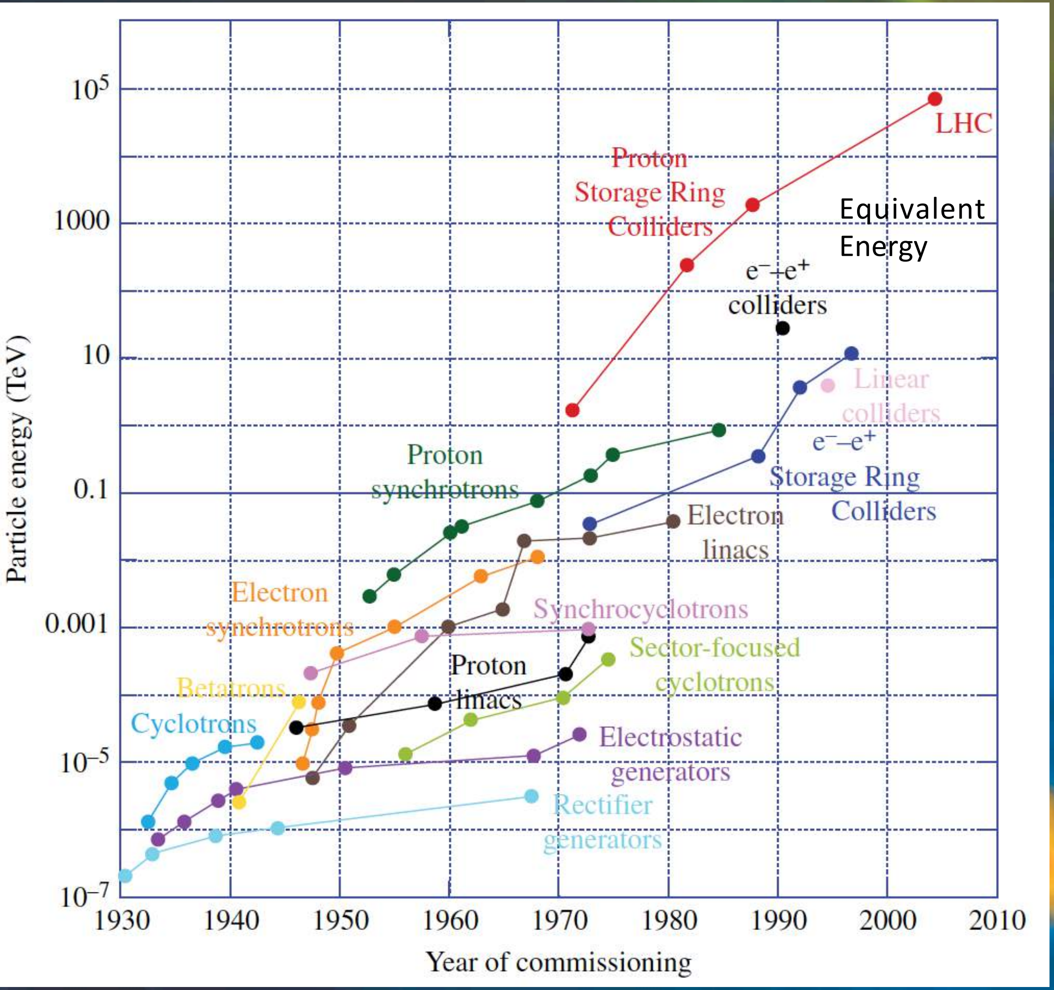
Advanced Accelerator Concepts

Massimo.Ferrario@lnf.infn.it



Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

The CERN Accelerator School

SPARC LAB

Advanced Accelerator Concepts

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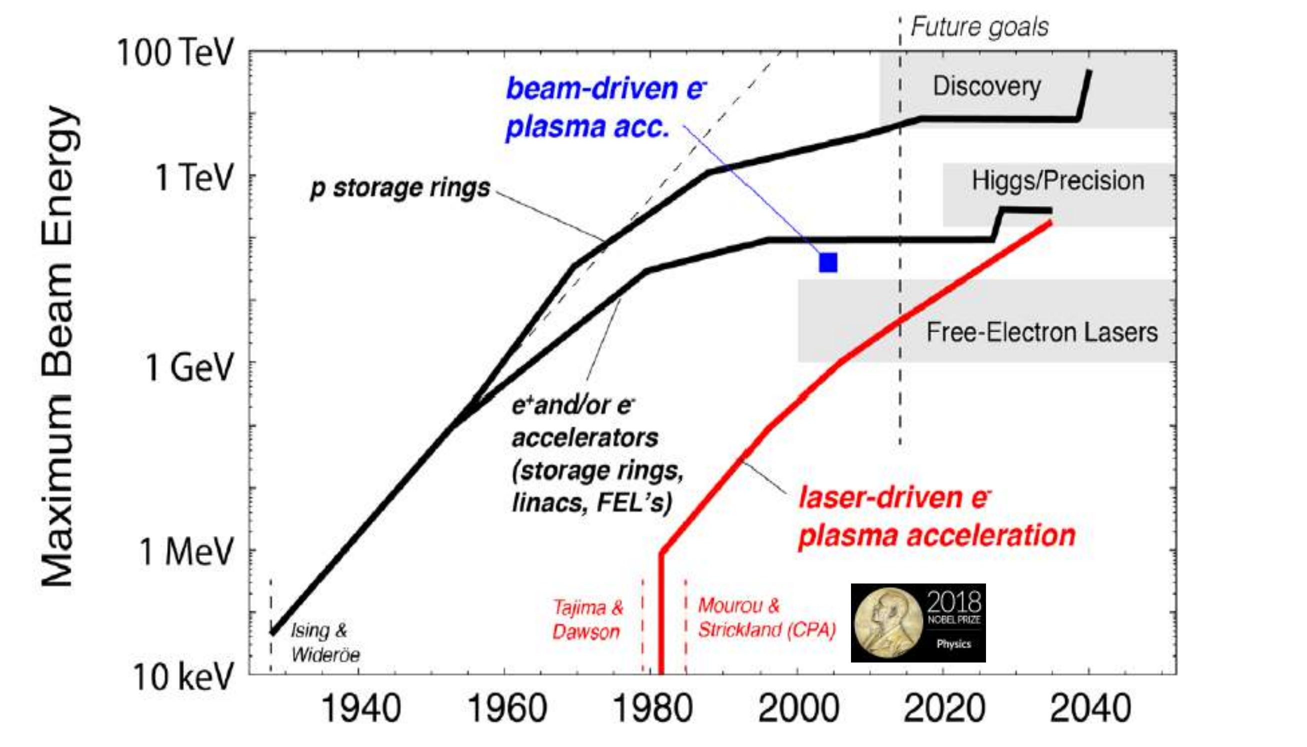

Courtesy R. Assmann

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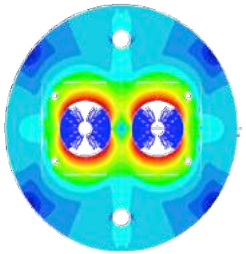
Options towards higher energies

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)



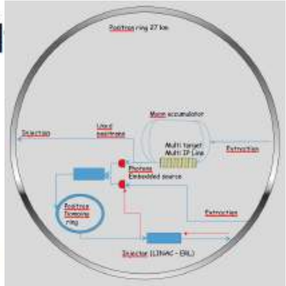
Lepton (e-,e+) circular collider

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

Increase supplied RF vol
(FCC-ee)

Increase mass of acc. particle (muon)

Increase radius = size (FCC-ee)



Lepton (e-,e+) linear collider

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

Increase length (ILC, CLIC)

Compact and Cost Effective....

Beam Quality Requirements

Future accelerators will require also high quality beams :

==> High Luminosity & High Brightness,

==> High Energy & Low Energy Spread

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

- –N of particles per pulse => 10^9
- –High rep. rate f_r => bunch trains

- –Small spot size => low emittance

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

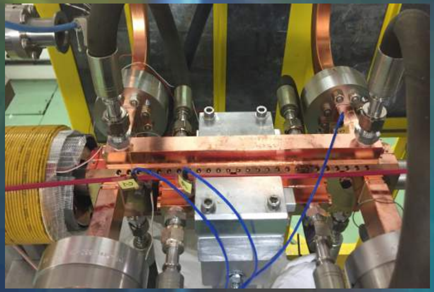
- –Short pulse (ps => fs)

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

High Gradient Options

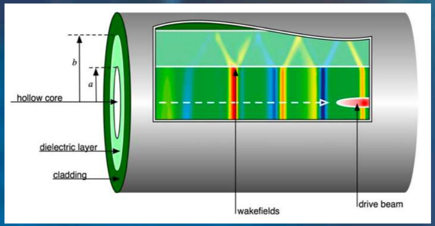
Metallic accelerating structures =>

100 MV/m < E_{acc} < 1 GV/m



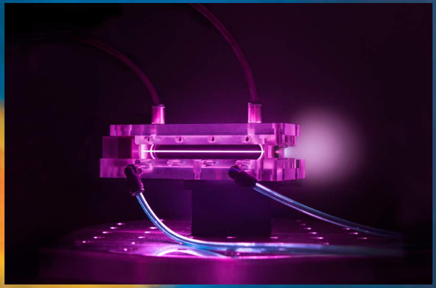
Dielectrict structures, laser or particle driven =>

E_{acc} < 10 GV/m



Plasma accelerator, laser or particle driven =>

E_{acc} < 100 GV/m



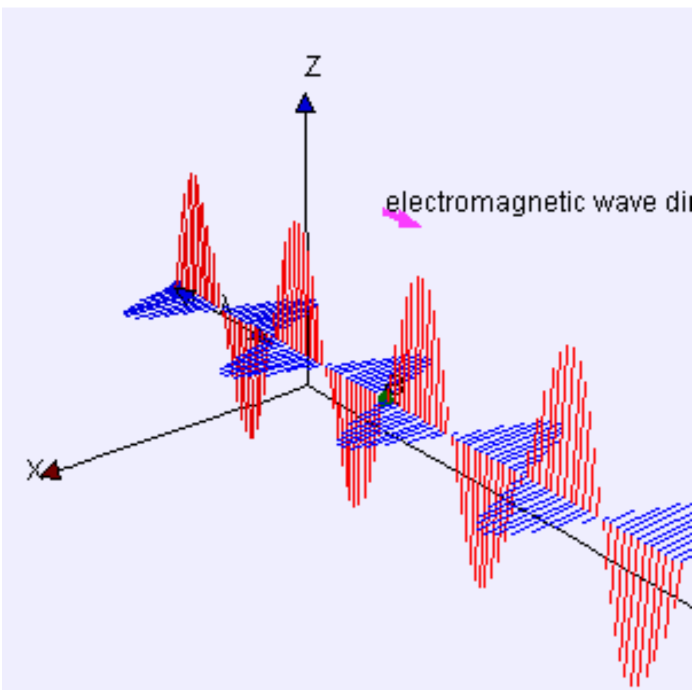
Related Issues: Power Sources and Efficiency, Stability, Reliability, Staging, Synchronization, Rep. Rate and short (fs) bunches with small (μm) spot to match high gradients

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



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

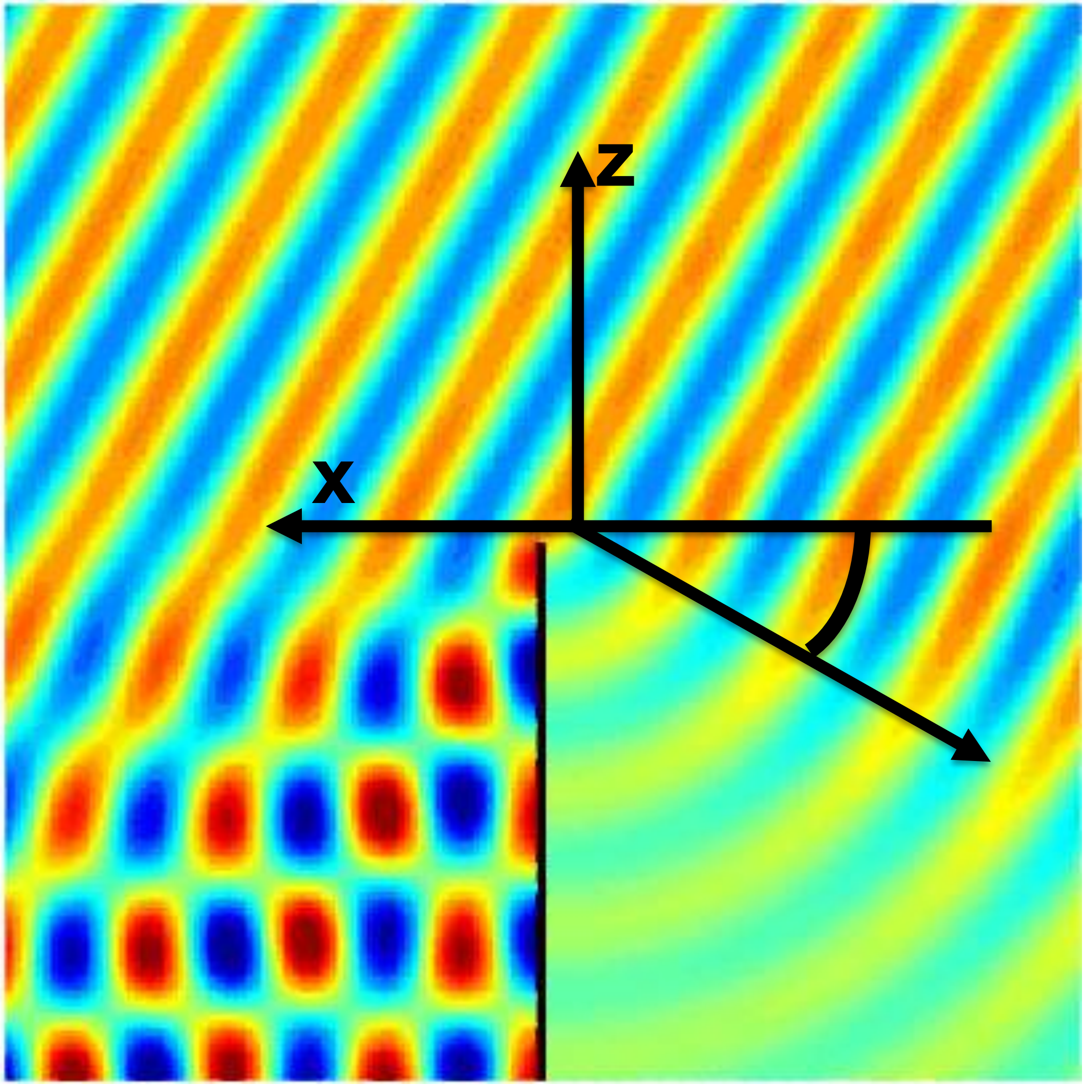
$$\boldsymbol{E}(\boldsymbol{r},t) = \int d^3k\,\tilde{\boldsymbol{E}}(\boldsymbol{k})e^{i\boldsymbol{k}\cdot\boldsymbol{r}-i\omega t}, \qquad \omega = ck.$$

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

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

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

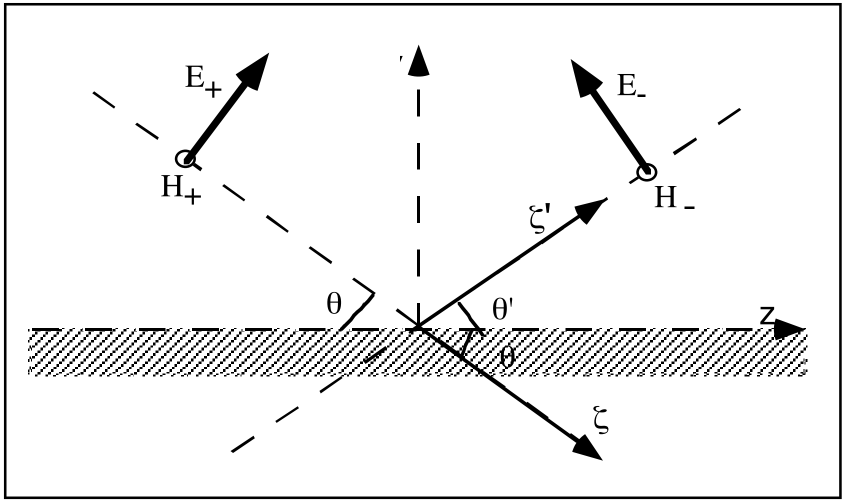
Reflection of plane waves



Reflection of plane waves

Plane wave reflected by a perfectly conducting plane

$$\sigma = \infty$$



In the plane xz the field is given by the superposition of the incident and reflected wave:

$$E(x,z,t) = E_{+}(x_o,z_o,t_o)e^{i\omega t - ik\zeta} + E_{-}(x_o,z_o,t_o)e^{i\omega t - ik\zeta'}$$

$$\zeta = z\cos\theta - x\sin\theta \qquad \zeta' = z\cos\theta' + x\sin\theta'$$

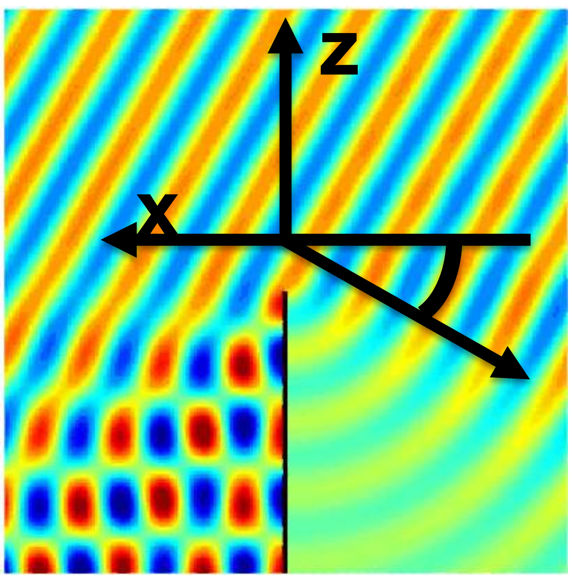
And it has to fulfill the boundary conditions (no tangential E-field)

Reflection of plane waves (a first boundary value problem)

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

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

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



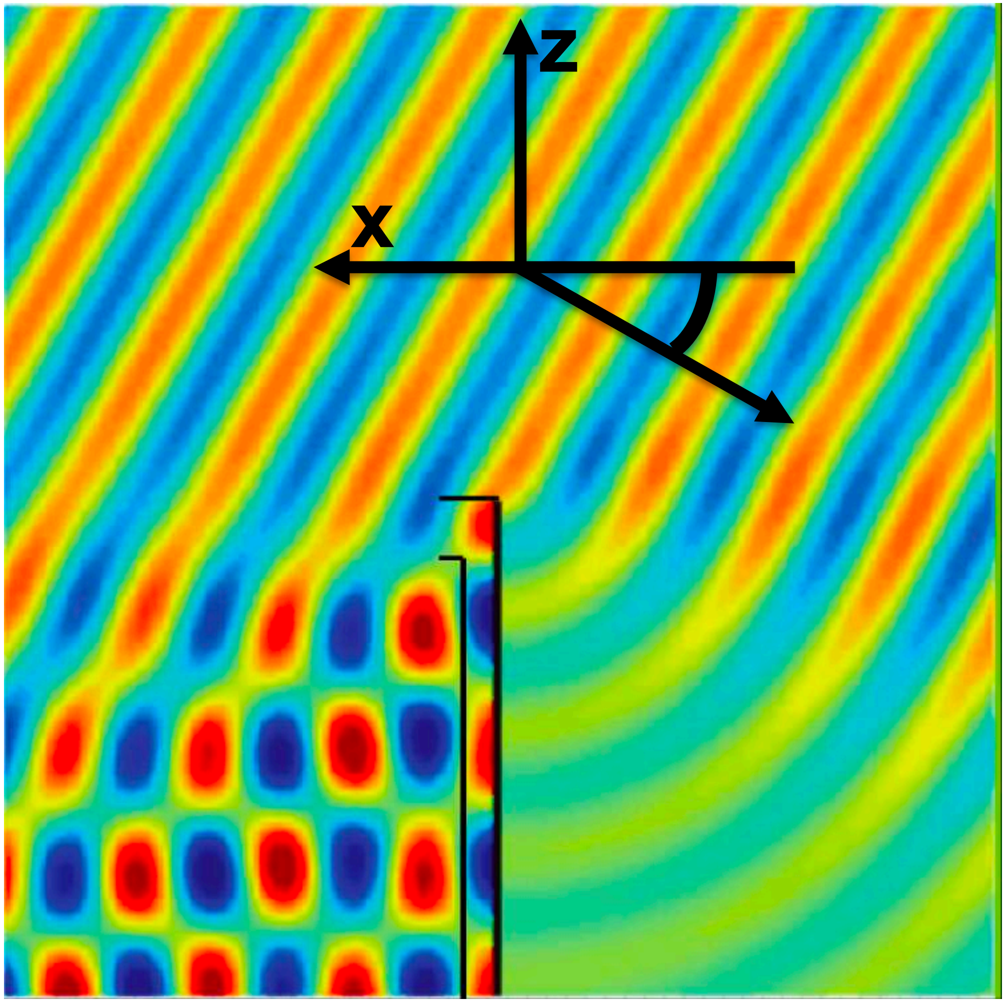
Standing Wave pattern (along x)

Guided wave pattern (along z)

The phase velocity is given by

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

From reflections to waveguides



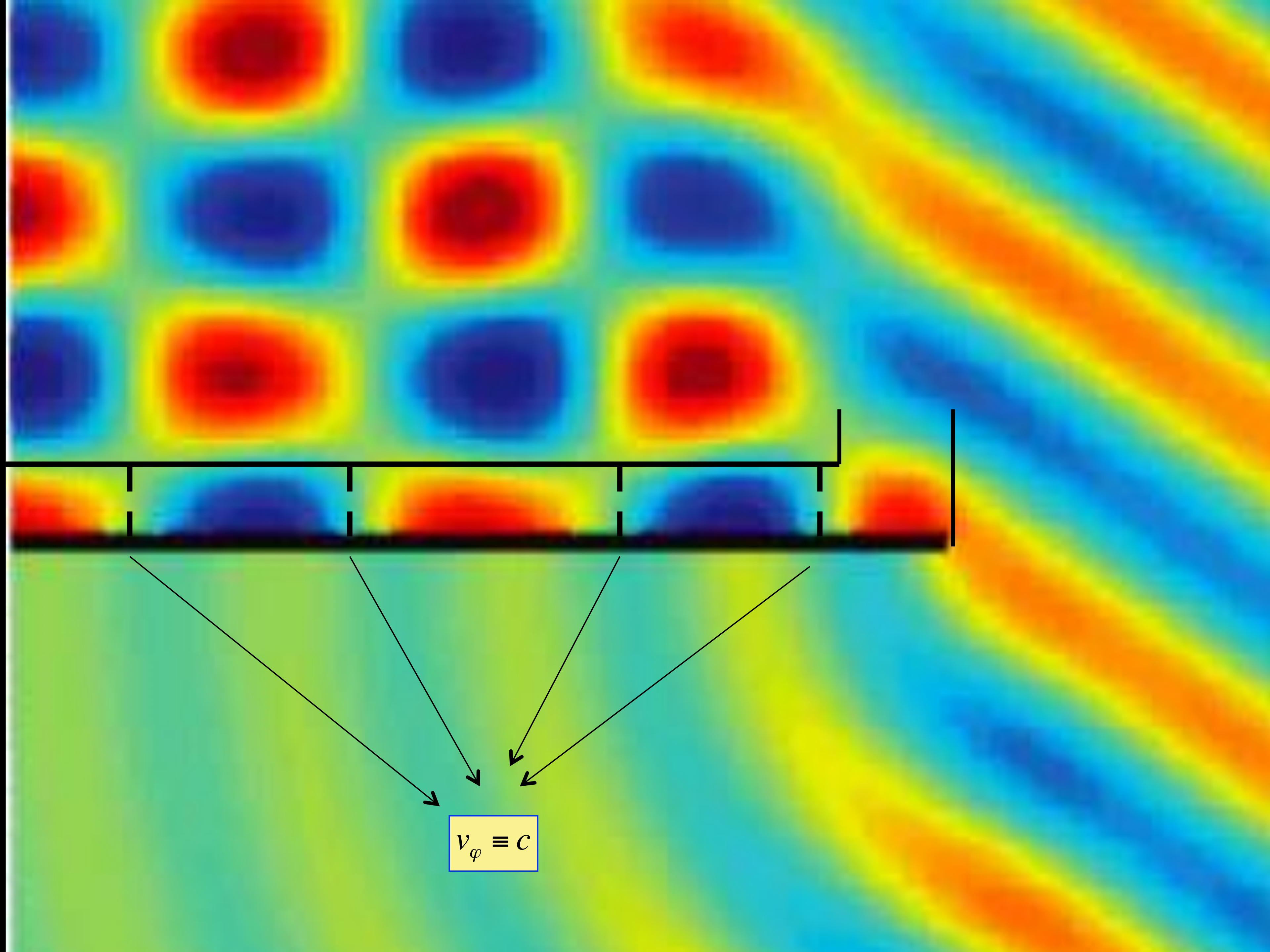
Put a metallic boundary where the field is zero at a given distance from the wall.

Between the two walls there must be an integer number of half wavelengths (at least one).

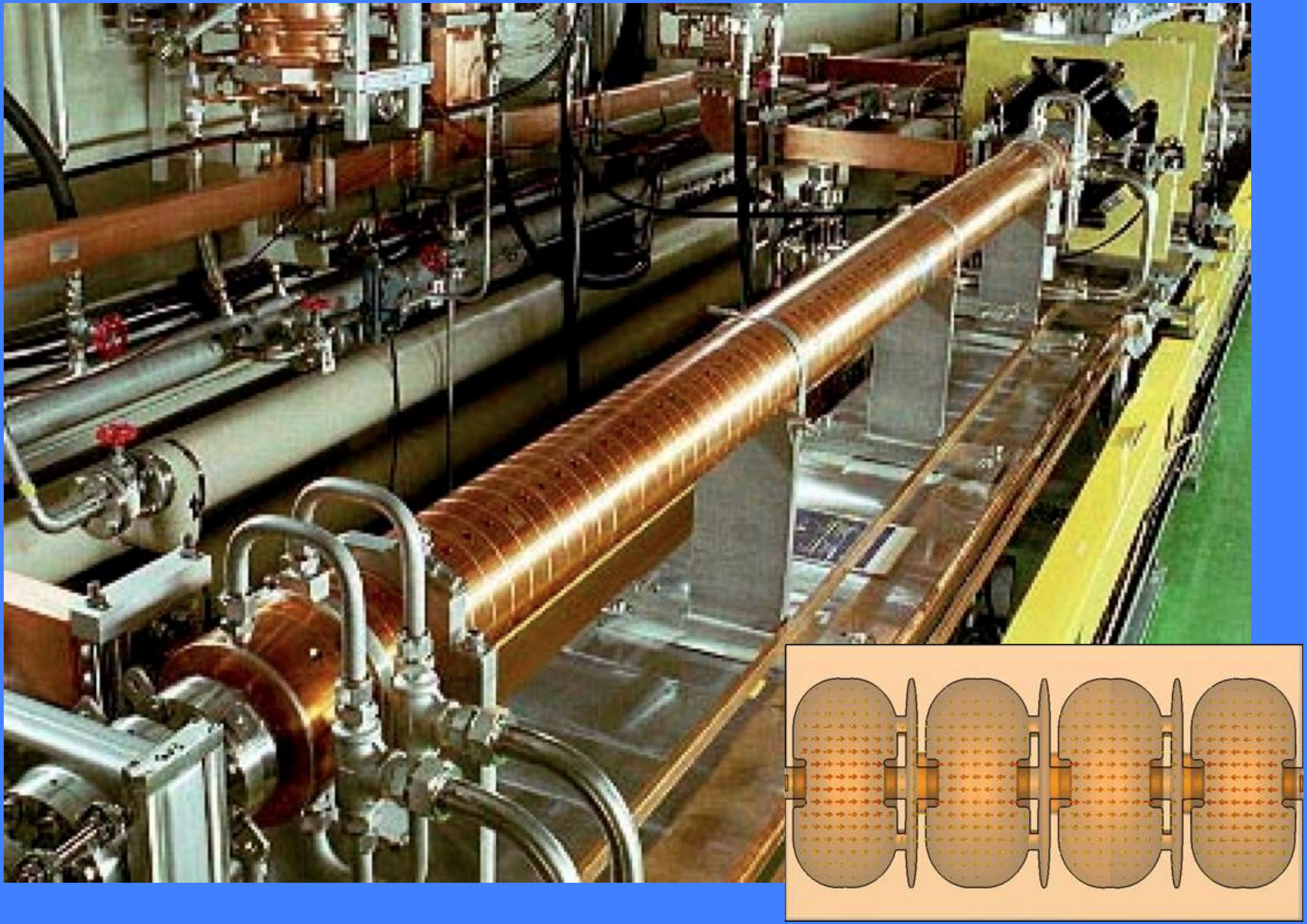
For a given distance, there is a maximum wavelength, i.e. there is **cut-off frequency**.

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

→ It can not be used as it is for particle acceleration

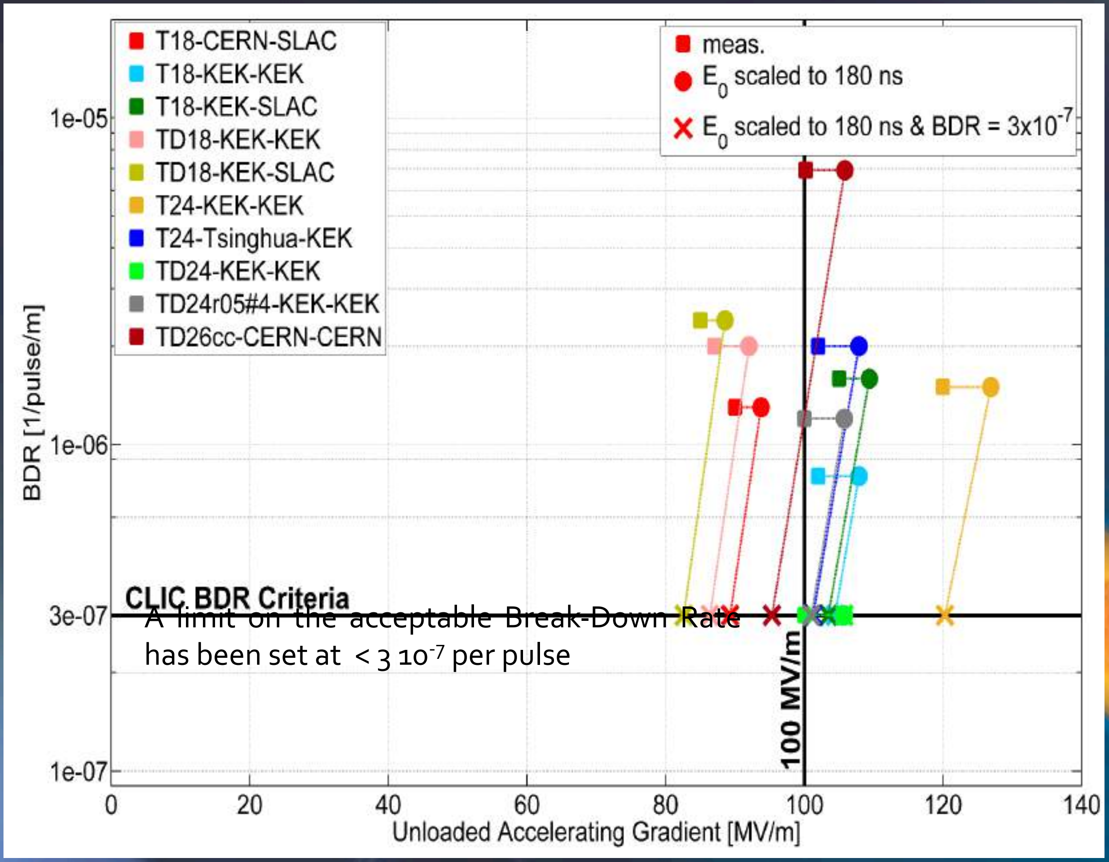

$v_\varphi \equiv c$

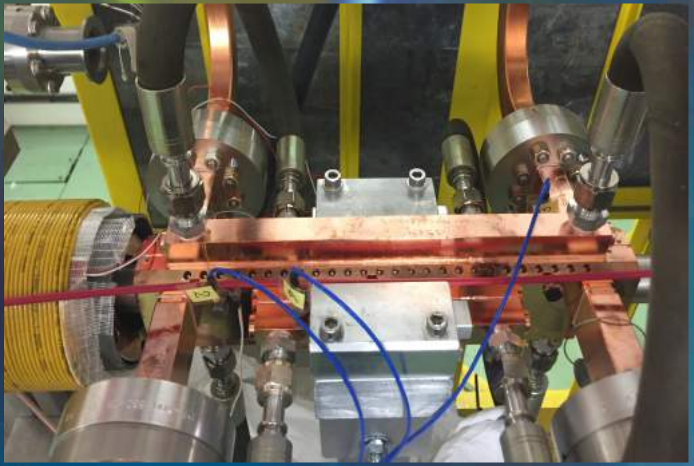
Conventional RF accelerating structures

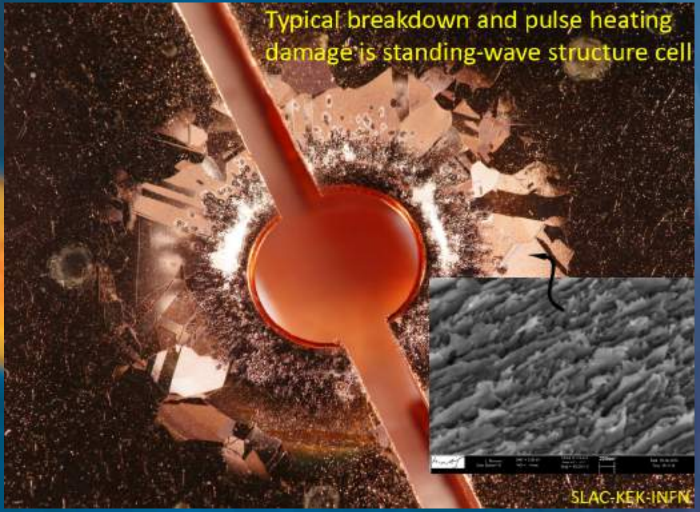


X-band RF structures – State of the Art

Max accelerating field: $\tau_{rf}^{-1/6}$
Stored energy: f^{-3}

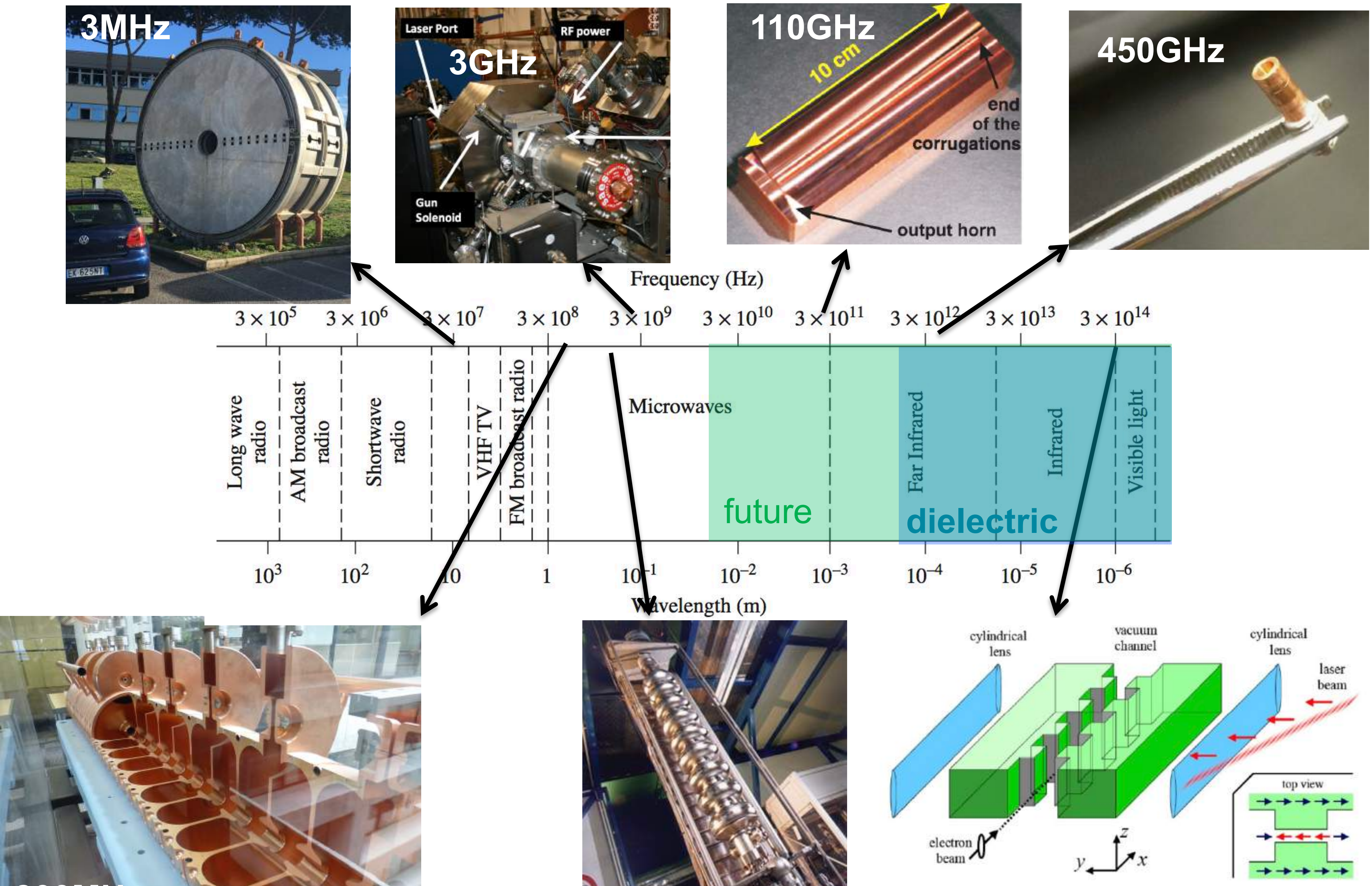






- Kilpatrick, W. D., Rev. Sci. Inst. 28, 824 (1957).
- *A. Grudiev et al, PRST-AB 12, 102001 (2009)*
- S. V. Dolgashev, et al. Appl. Phys. Lett. 97, 171501 2010.
- M. D. Forno, et al. PRAB. 19, 011301 (2016).

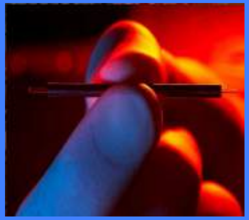
The E.M. Spectrum of Accelerating Structures



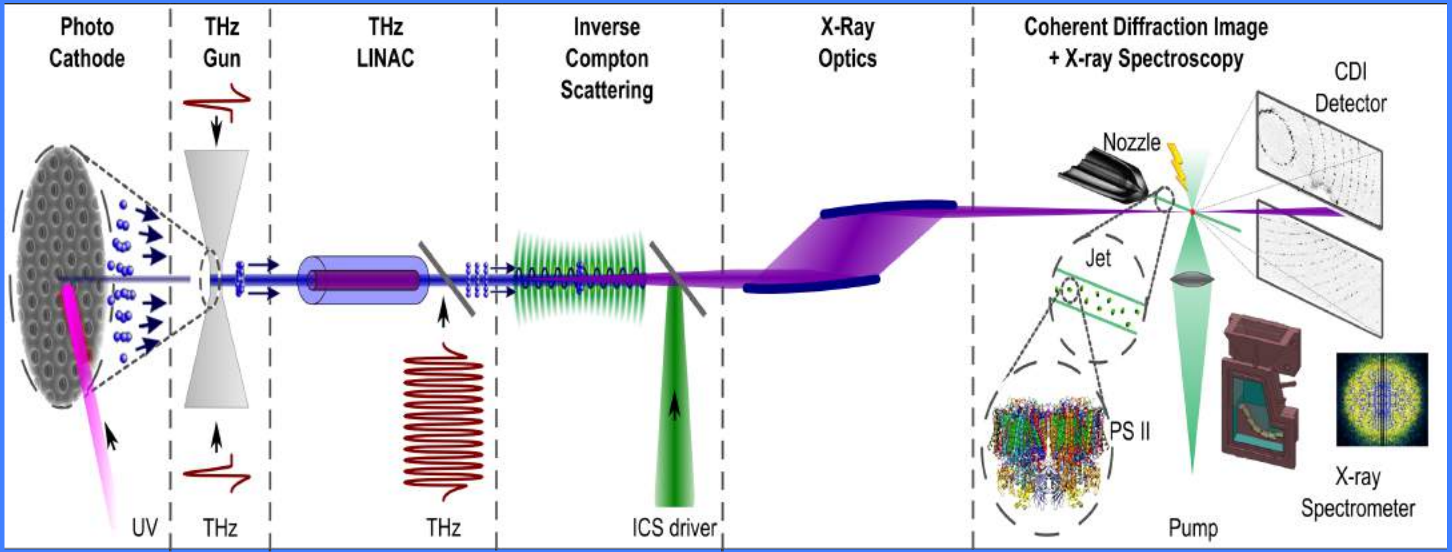
Andrea.Mostacci@uniroma1.it

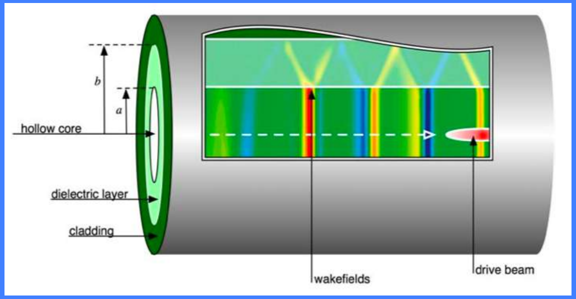
Dielectric Structures

Attoseconds X-ray Science Imaging and Spectroscopy



F.X. Kärtner et al., NIM A 829, 24 (2016)



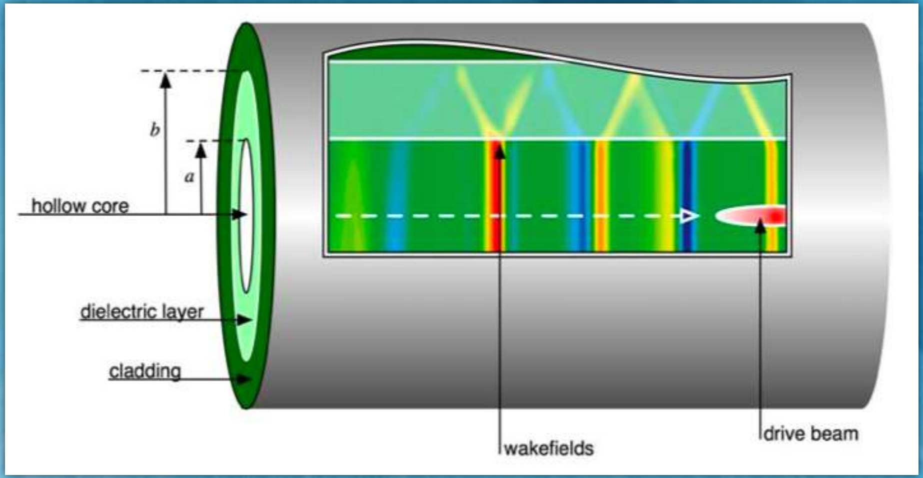


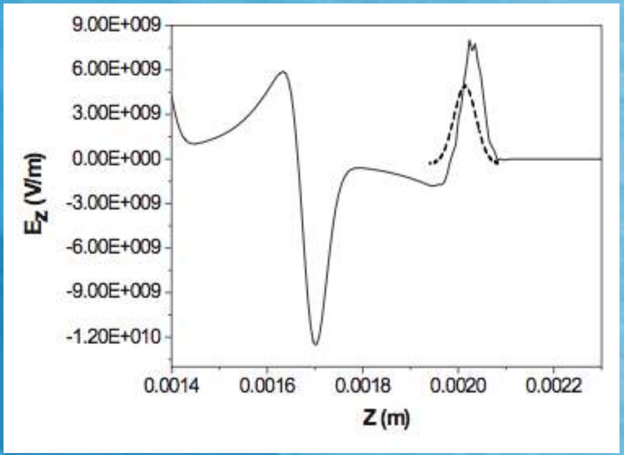
All laser driven => intrinsic attosecond synchr.,
1 Joule, 1 kHz Cryogenic Yb:YAG Laser
Laser-based THz generation
THz Linac, Optical undulator
Copper Inner Diameter = 940 µm
Fused Silica Inner Diameter = 400 µm

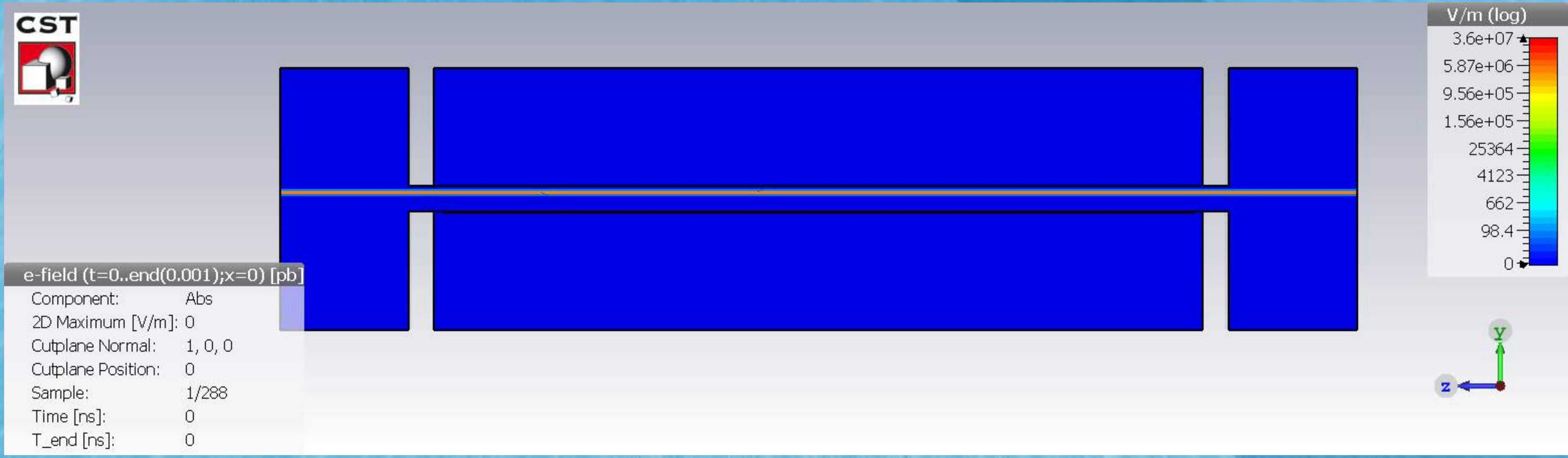
E. Nanni et al., Nat. Comm. 6, 8486 (2015)

Dielectric Wakefield Acceleration
DWA

Dielectric Wakefield Accelerator



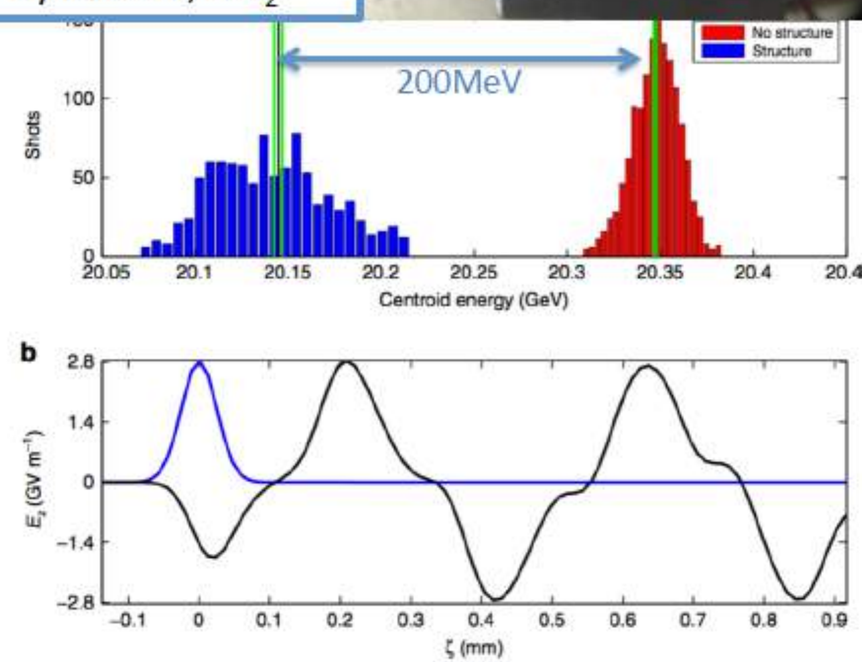


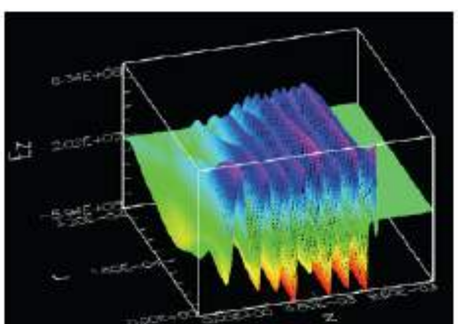


GV/m fields in DWA

- 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

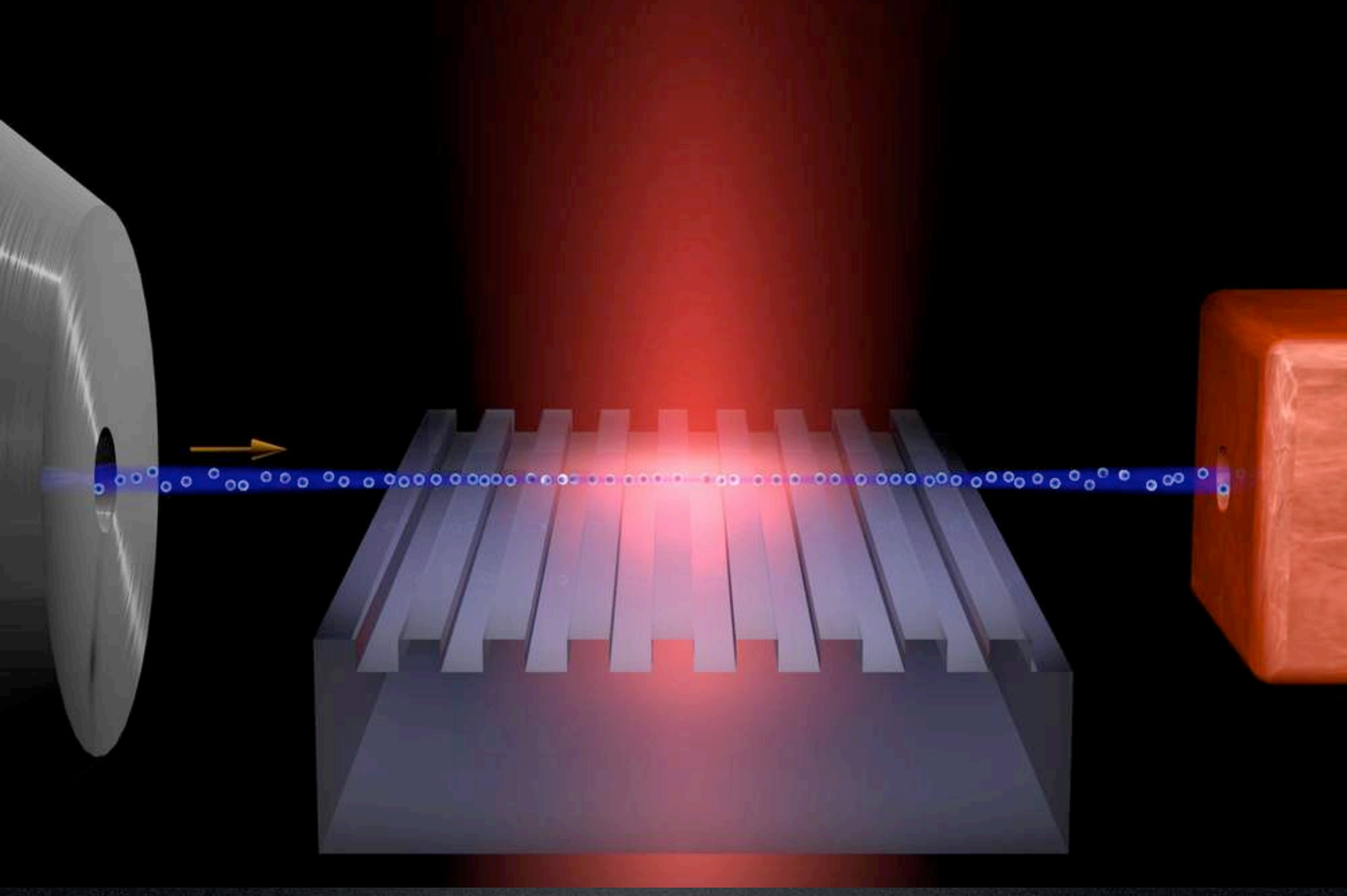
DWA structure:
- a/b = 150/200 μm
- L = 15cm
- Cylindrical, SiO_2





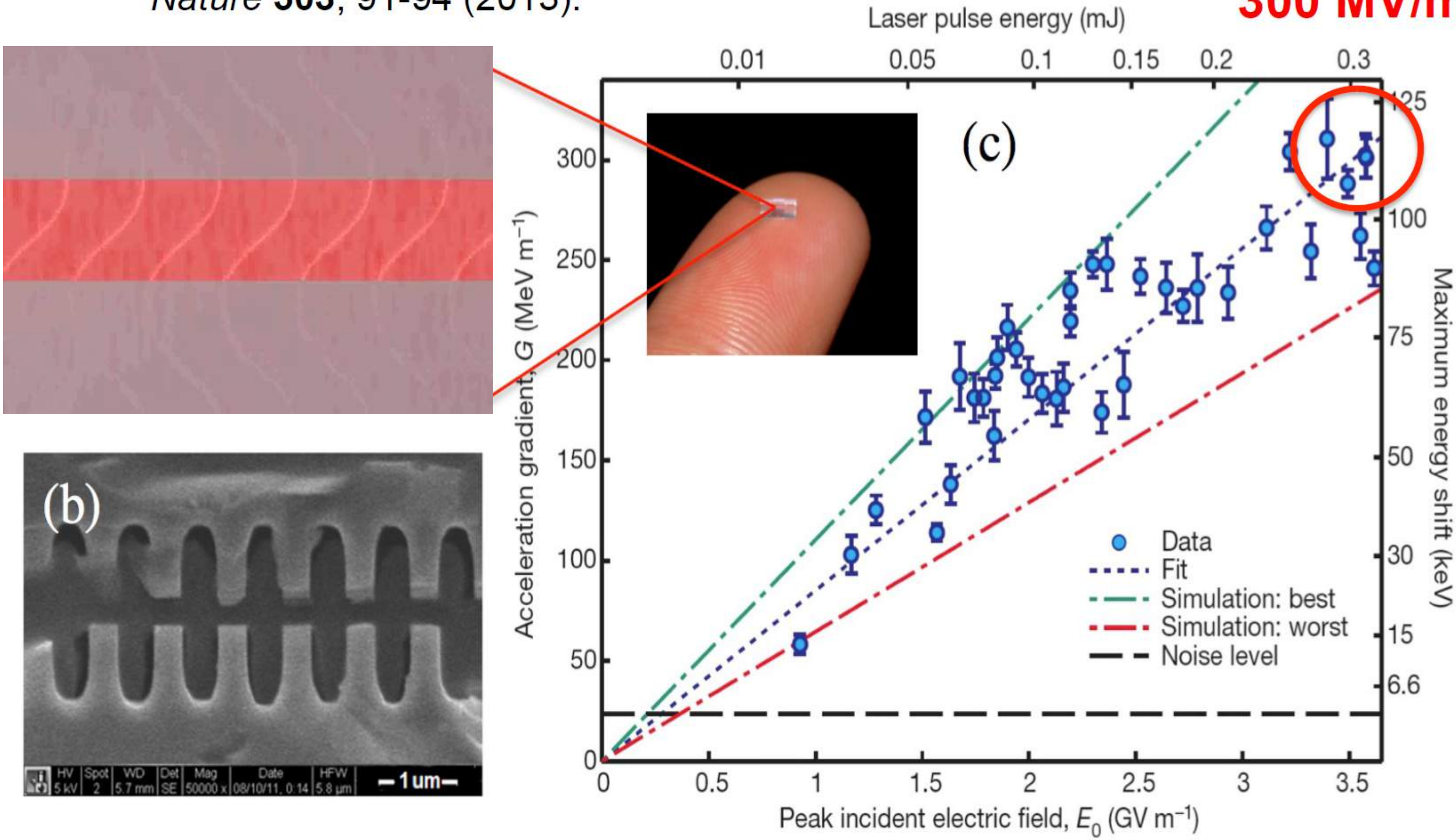
Dielectric Laser Acceleration
DLA

Laser based dielectric accelerator



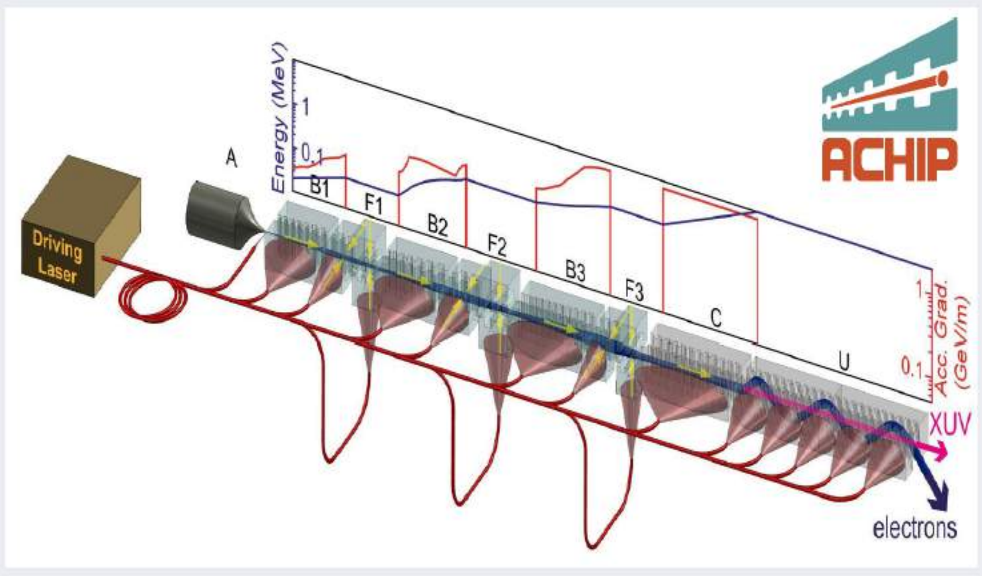
Nature **503**, 91-94 (2013).

300 MV/m

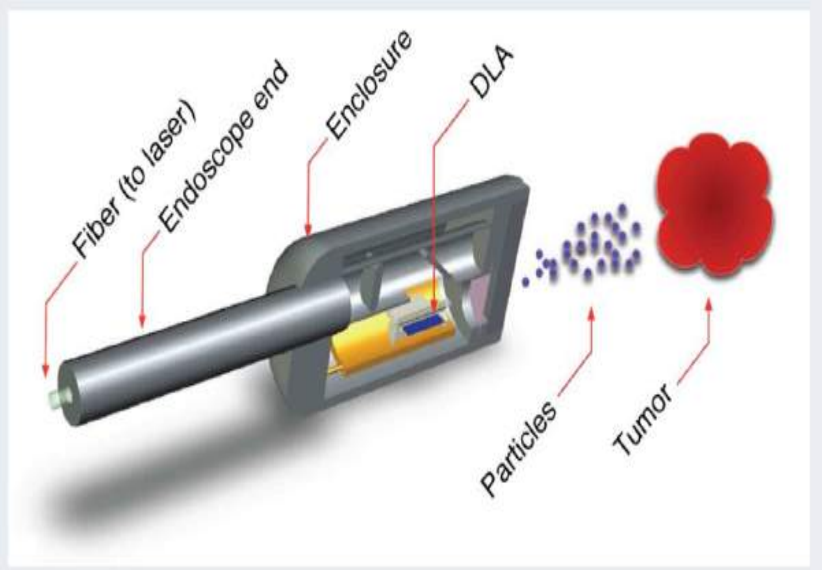


Dielectric Structures Applications

A combination of DLA modules and optical undulator allows dreaming for a compact table top FEL



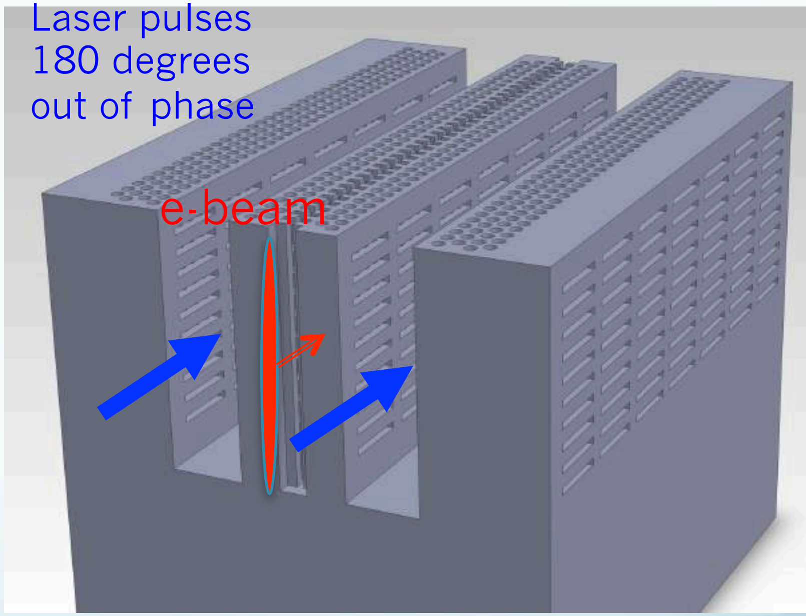
DLA module can be built onto the end of a fiber-optic catheter and attached to an endoscope, allowing to deliver controlled, high energy radiation directly to organs, tumors, or blood vessels within the body.



Electrons with 1-3MeV have a range of about a centimeter, allowing for irradiation volumes to be tightly controlled.

Dielectric Photonic Structure

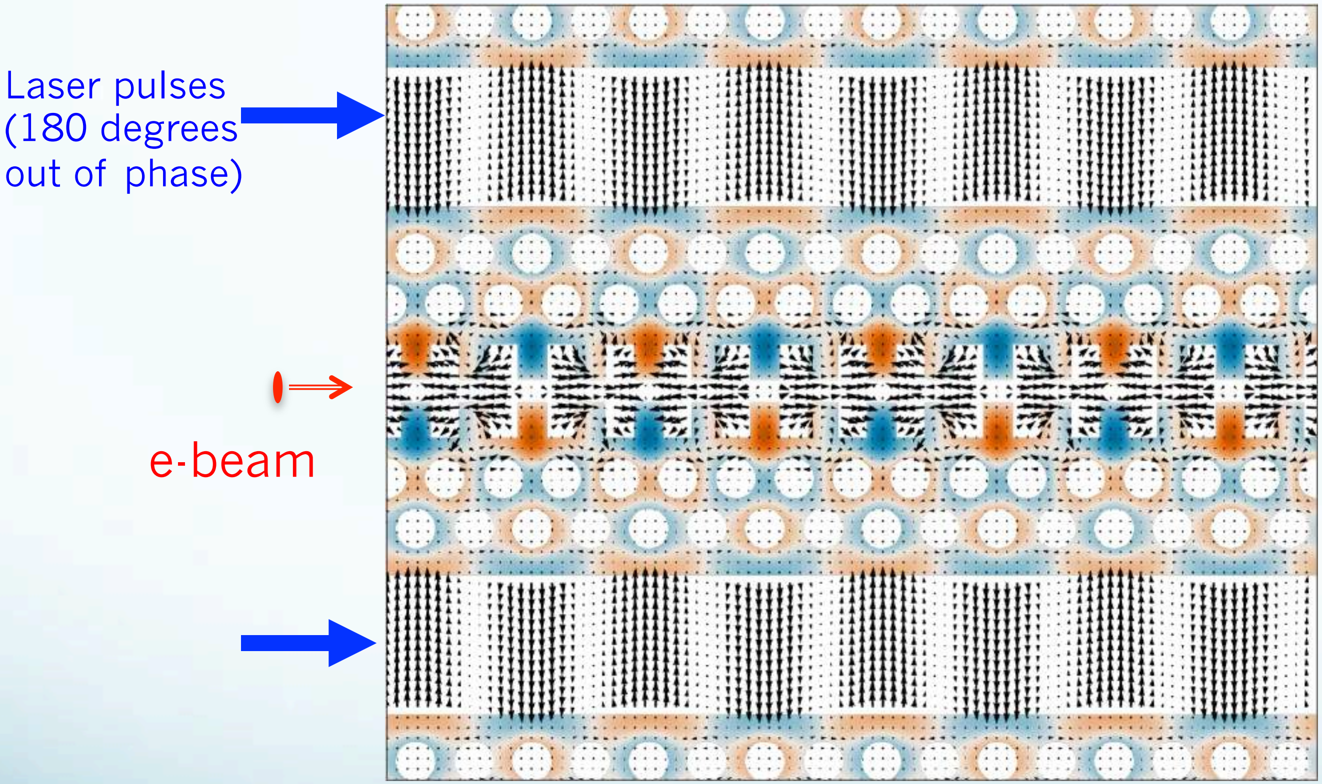
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes



Schematic of GALAXIE monolithic photonic DLA

Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles



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

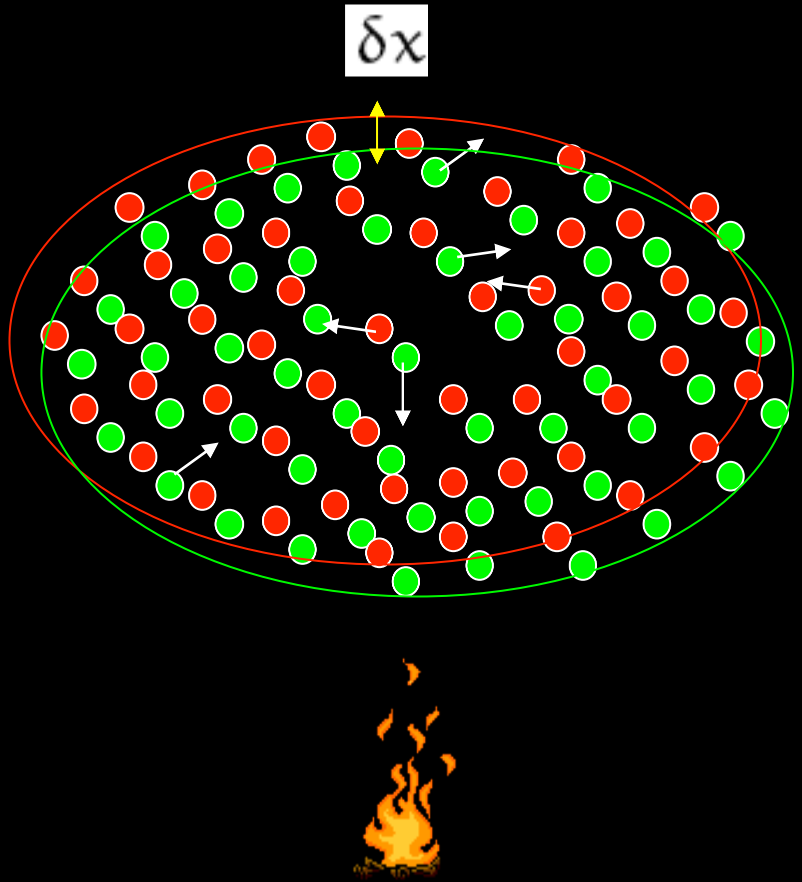
and

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 $4\gamma_0^3 mc^2$ 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

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

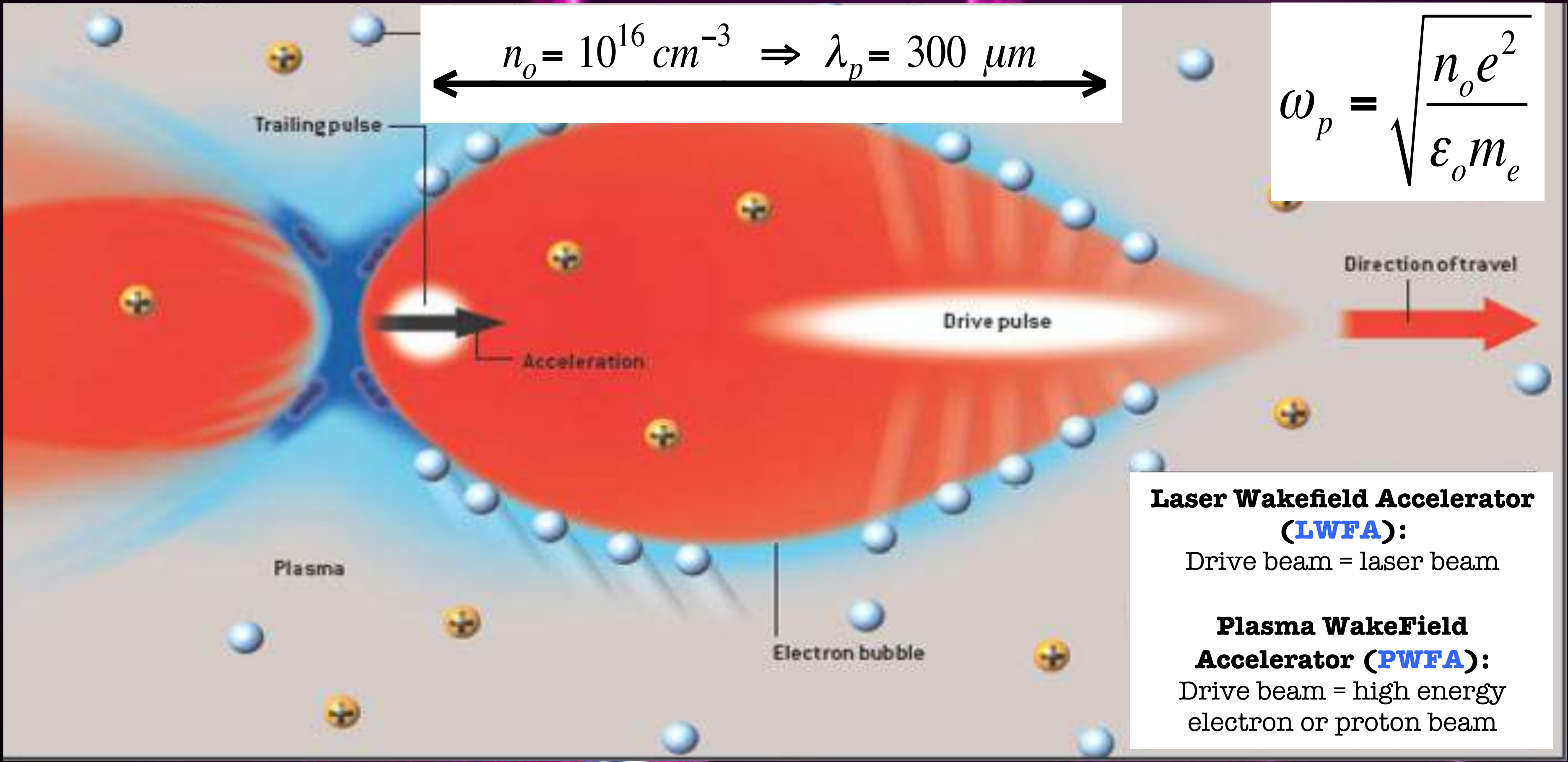
Plasma frequency

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

Plasma oscillations

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

Principle of plasma acceleration



$$n_o = 10^{16}\ cm^{-3} \Rightarrow \lambda_p = 300\ \mu m$$

$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

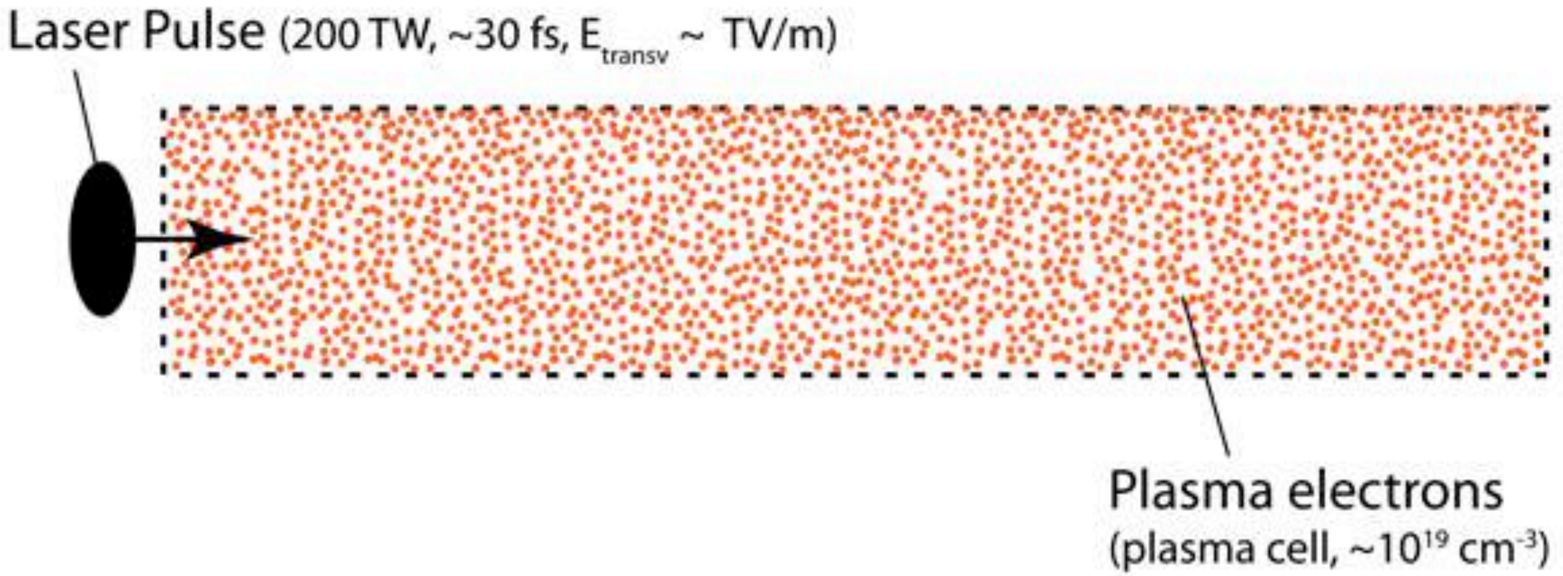
Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

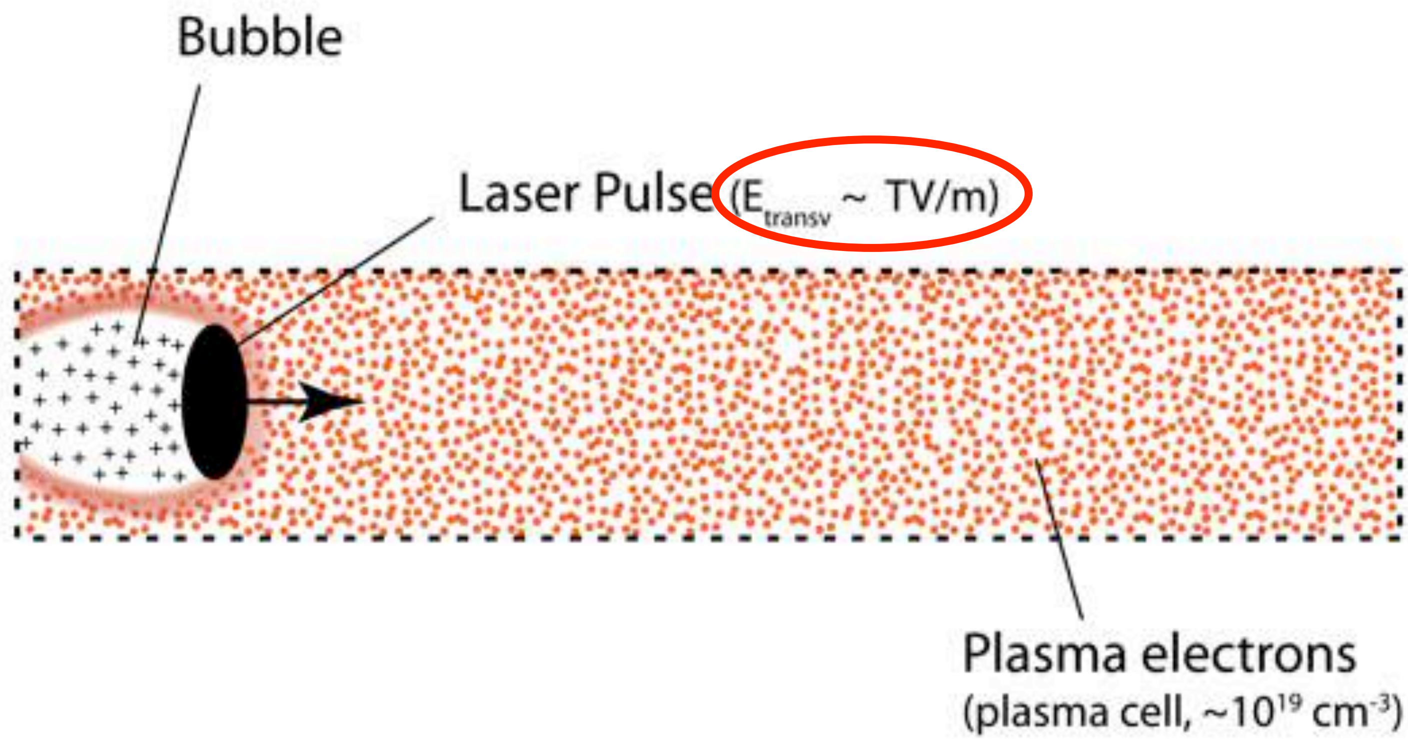
Break-Down Limit?
⇒ Wave-Breaking field:

$$E_{wb} \approx 100\left[GeV/m\right]\sqrt{n_o\left[cm^{-3}\right]}$$

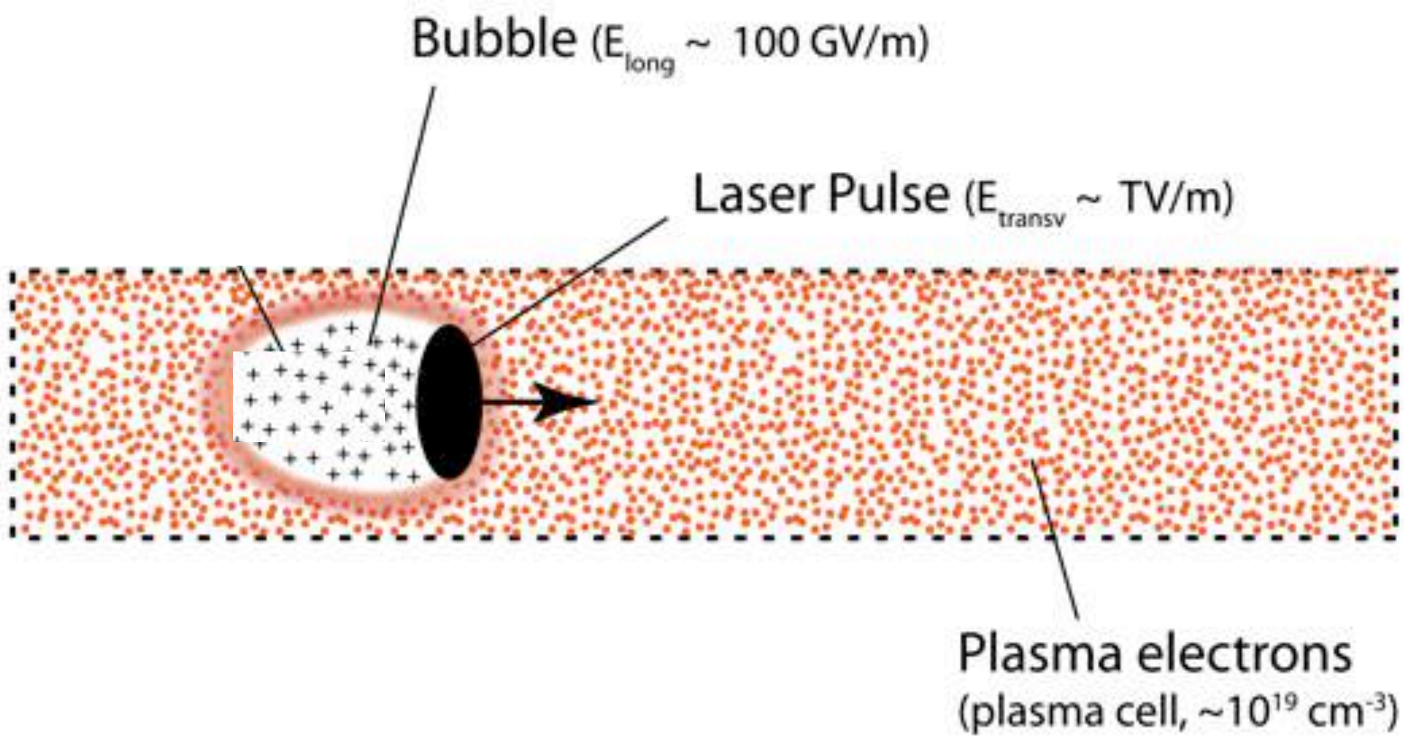
Plasma Wake-Acceleration



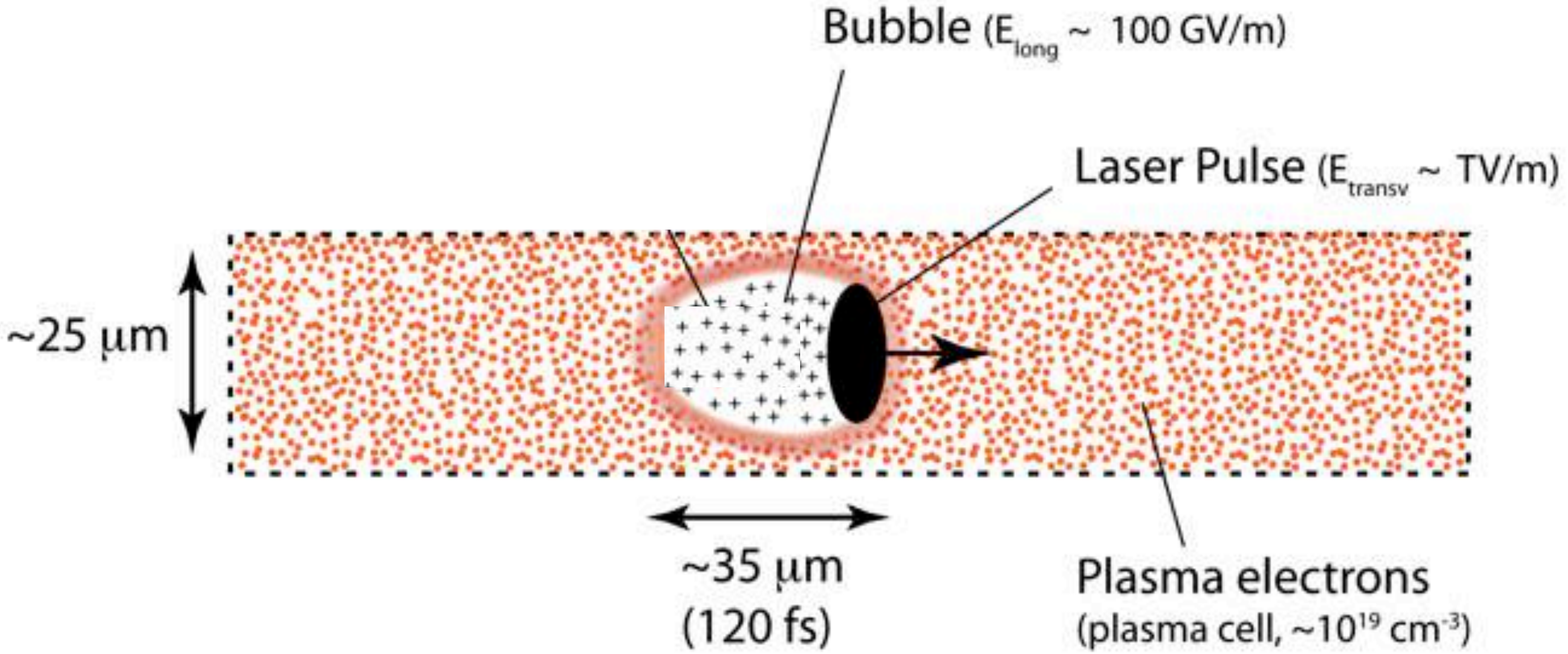
Plasma Wake-Acceleration



Plasma Wake-Acceleration



Plasma Wake-Acceleration



This accelerator fits into a human hair!

Principle of plasma acceleration

Driven by Radiation Pressure

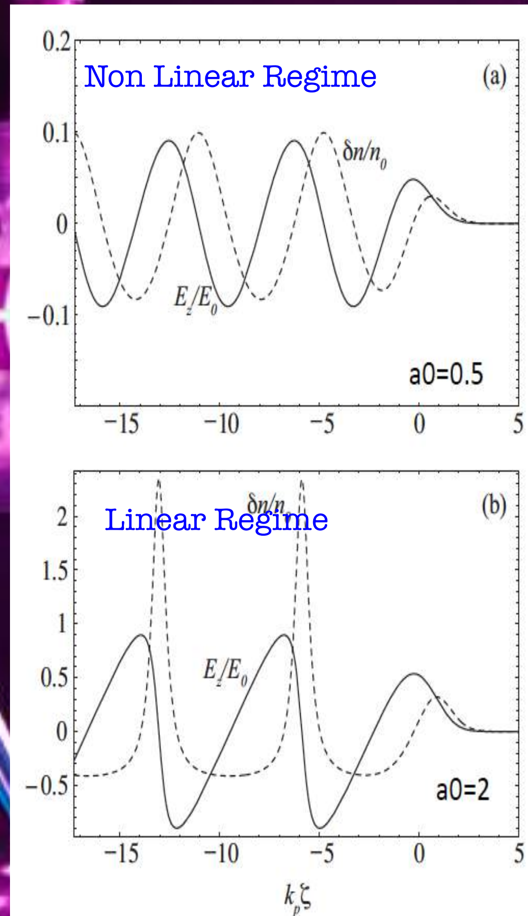
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

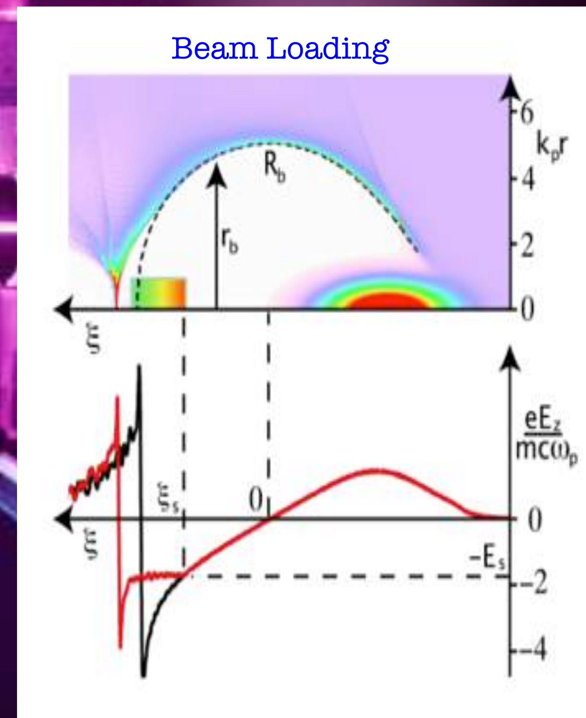
$$a=\frac{eA}{mc^2}\propto\lambda J^{1/2}$$

Driven by Space Charge

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=-\omega_p^2\frac{n_{beam}}{n_o}$$

$$n_{beam}=\frac{N}{\sqrt{(2\pi)^3}\sigma_r^2\sigma_z}$$



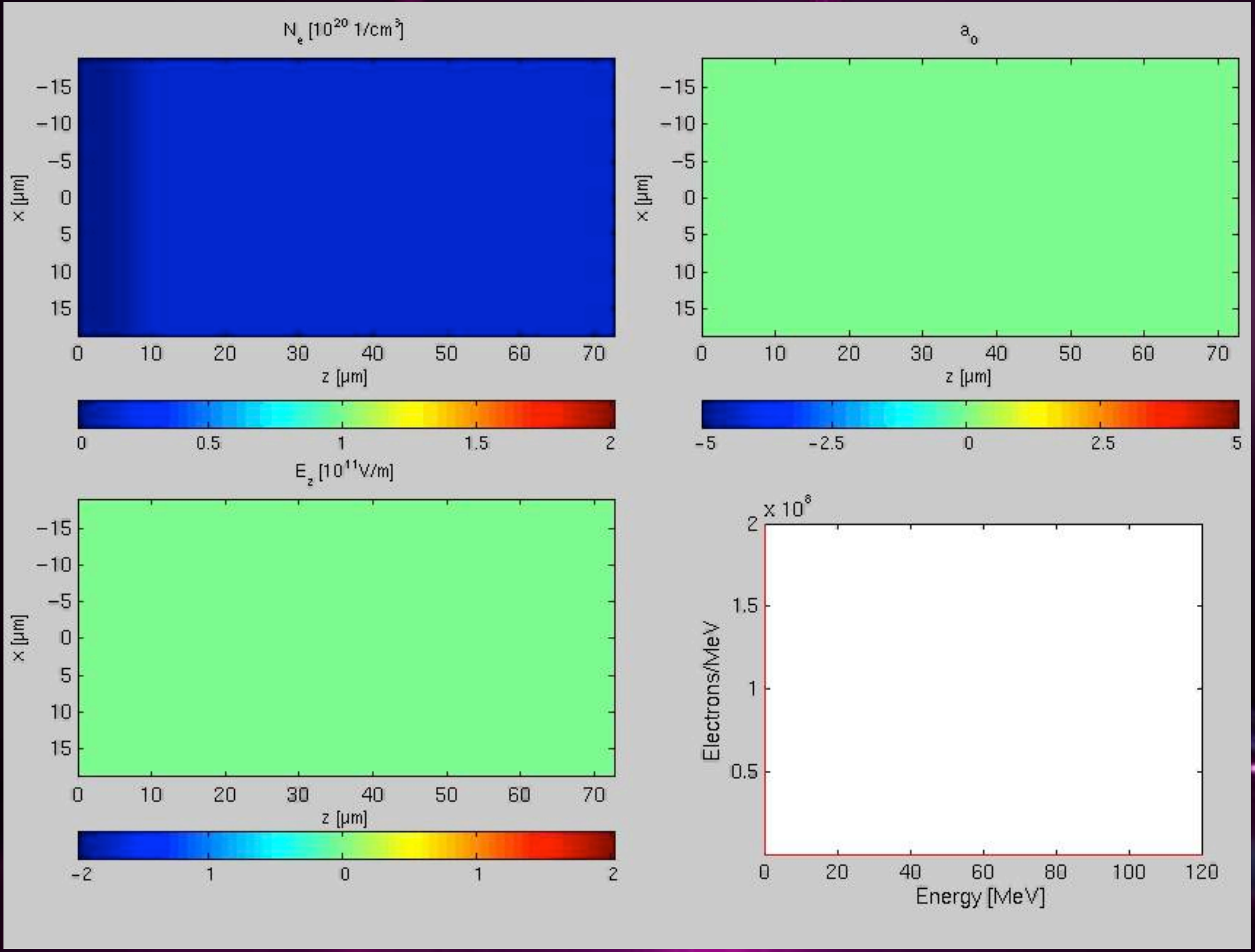


LWFA limitations: Diffraction, Dephasing, Depletion

PWFA limitations: Head Erosion, Hose Instability

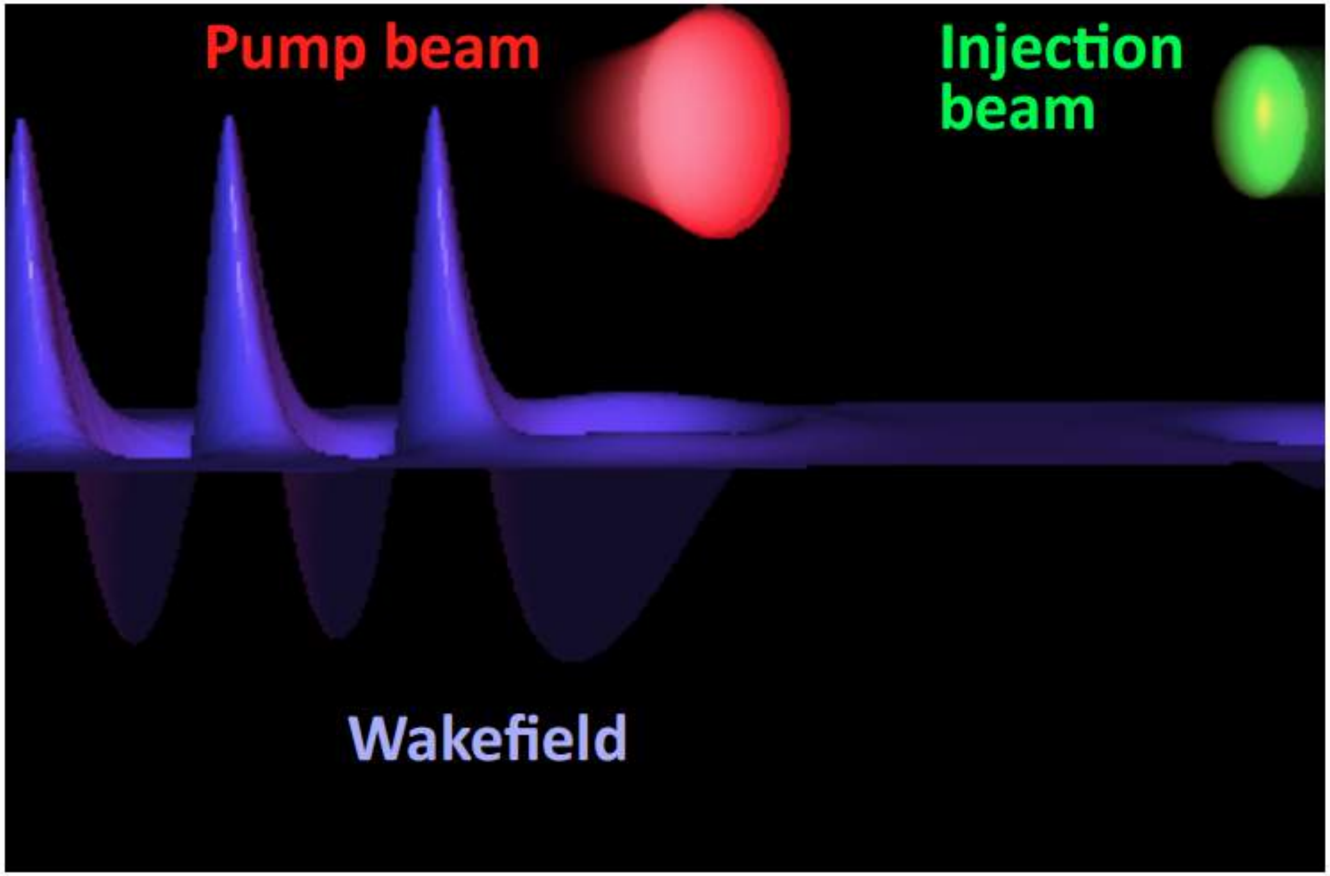
Laser Driven
LWFA

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)

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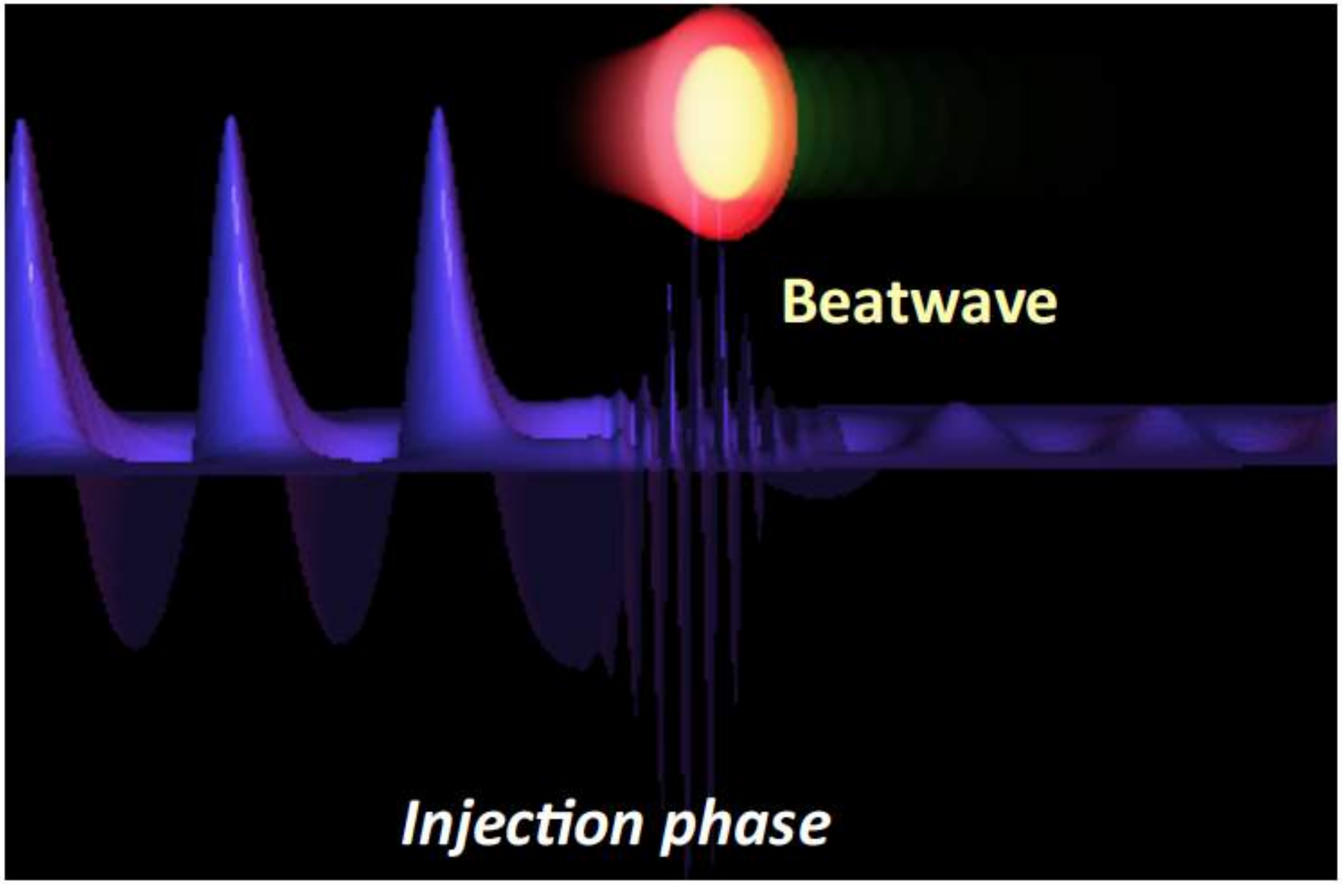

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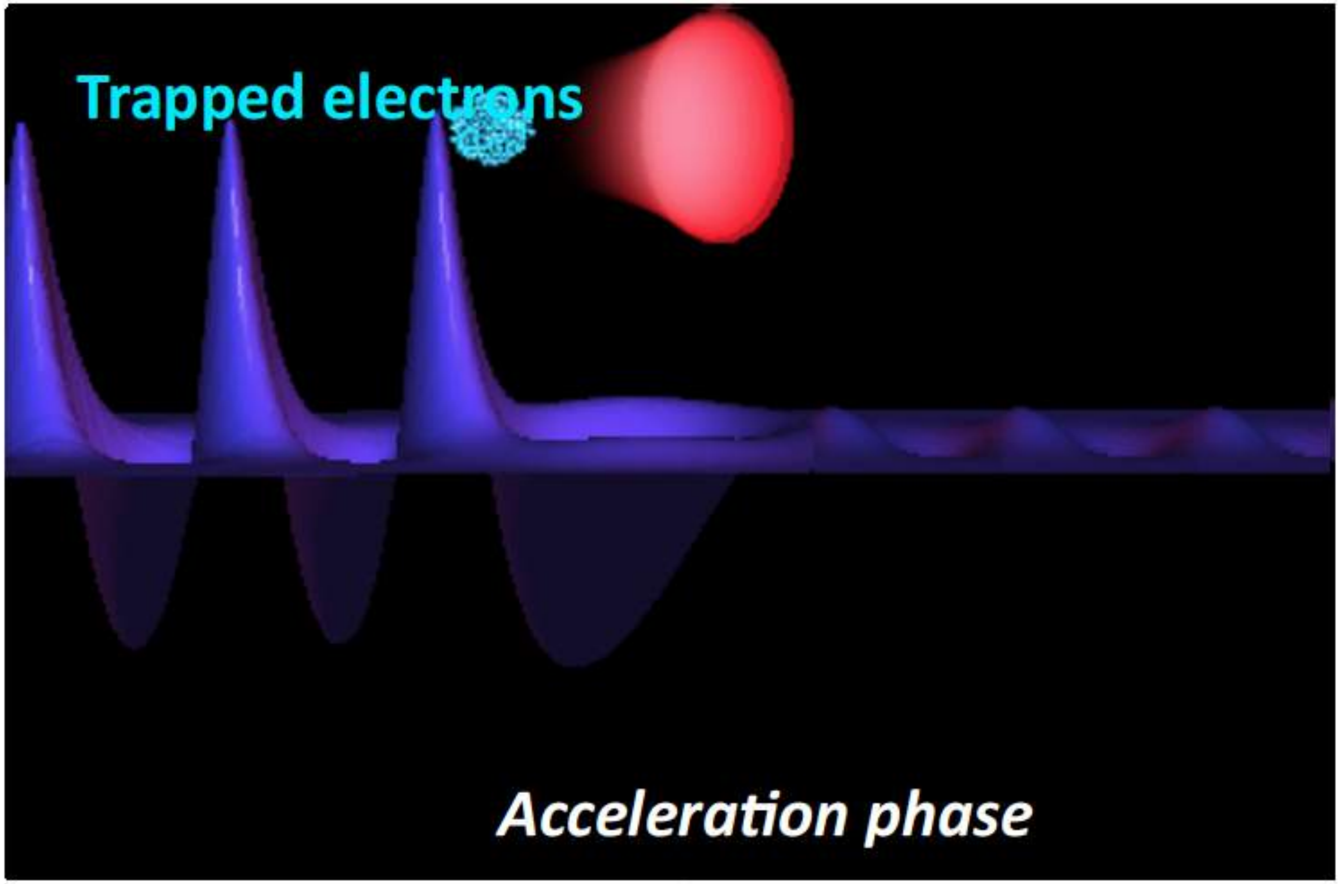

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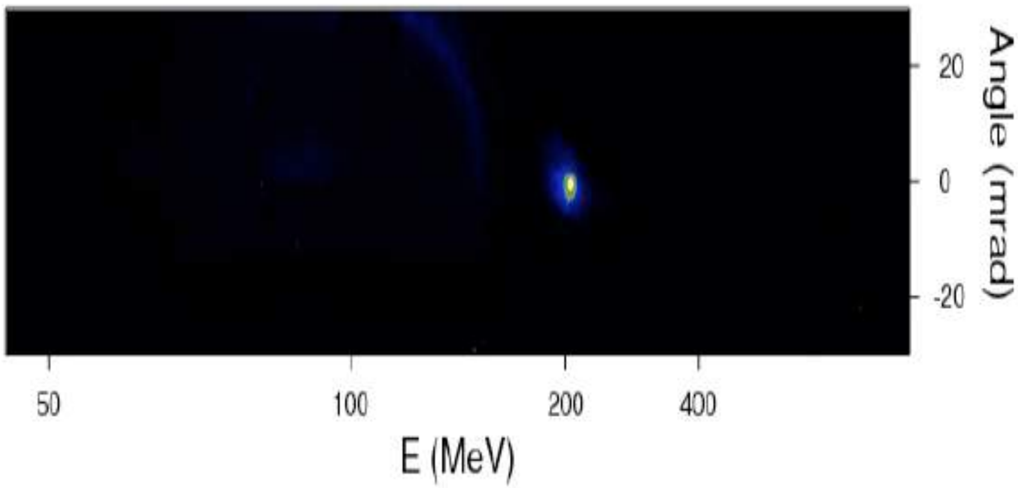
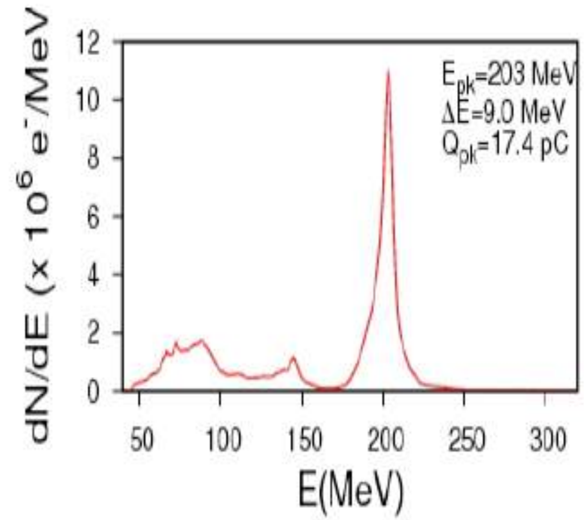
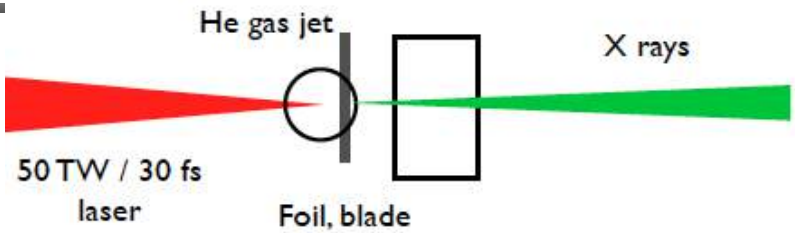
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

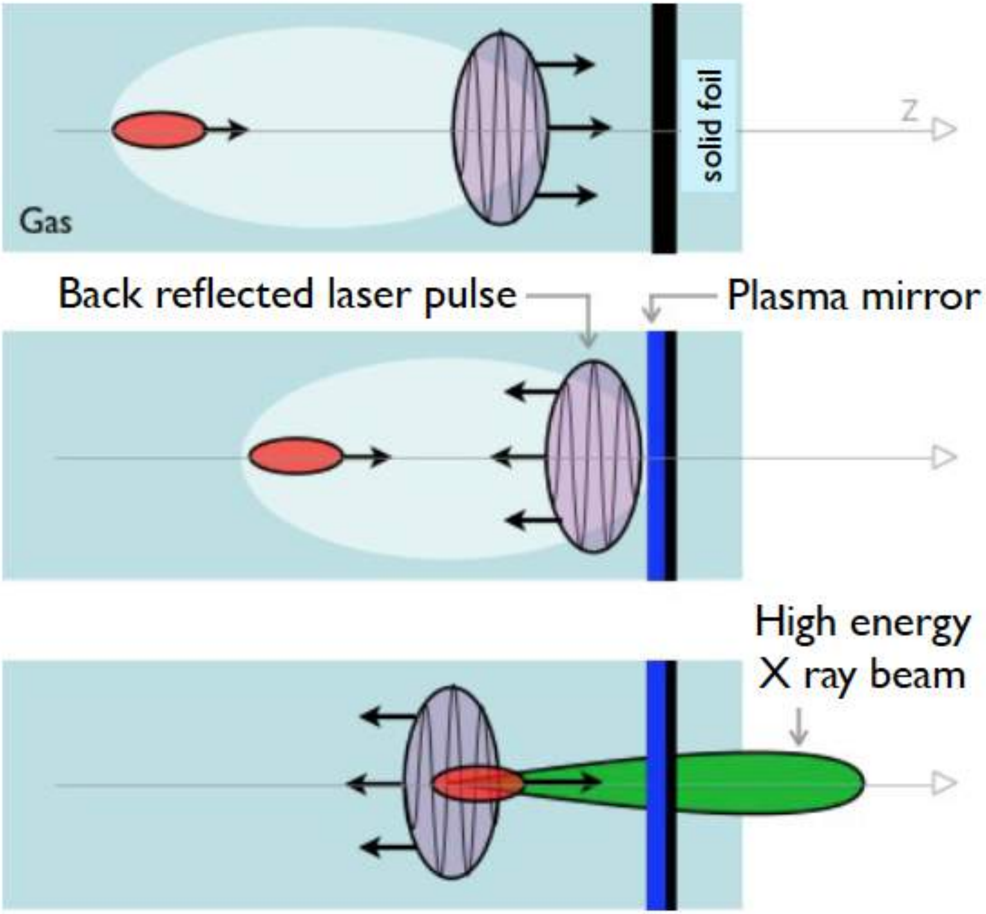
Stable Laser Plasma Accelerators





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

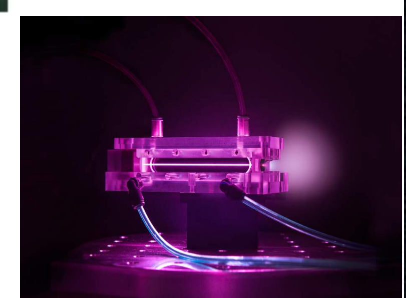
Save the laser energy !

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:

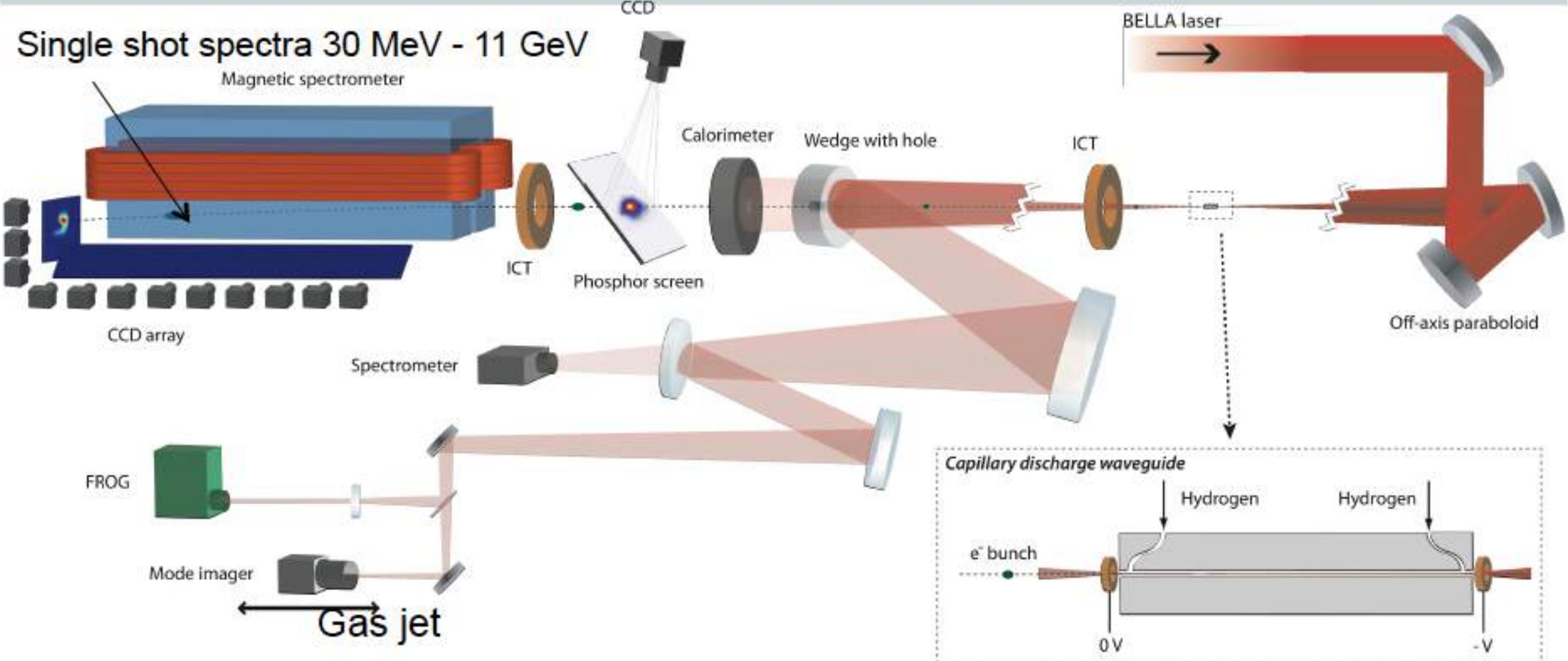
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



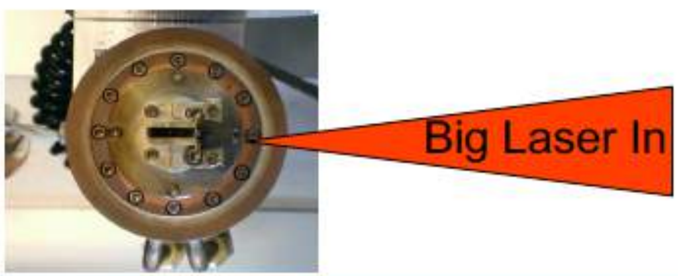
BELLA

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

Single shot spectra 30 MeV - 11 GeV



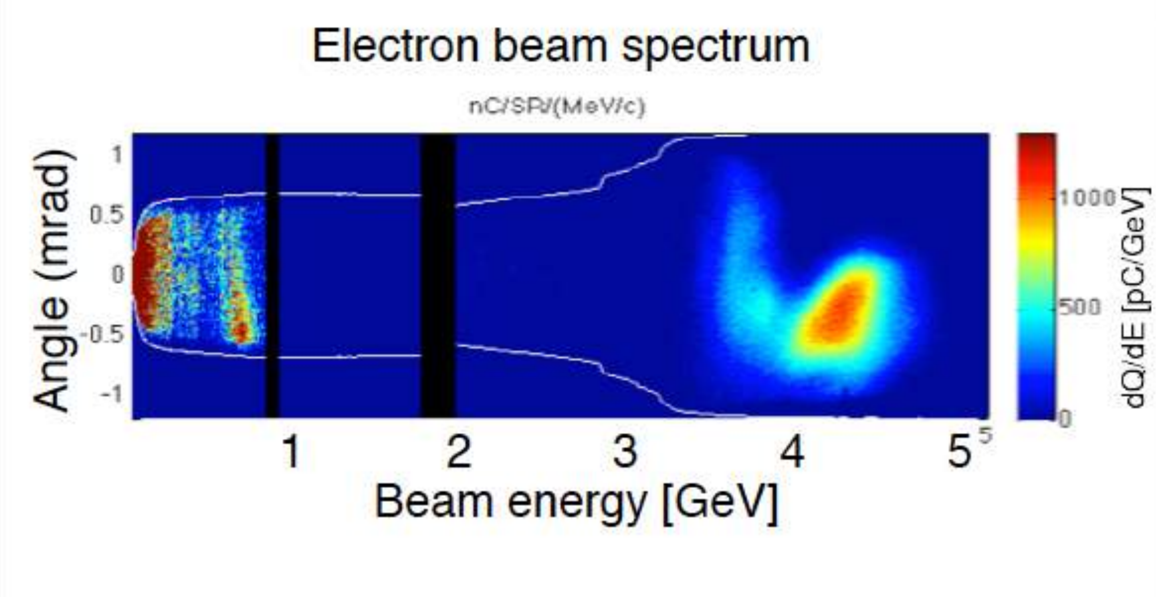
Gas jet

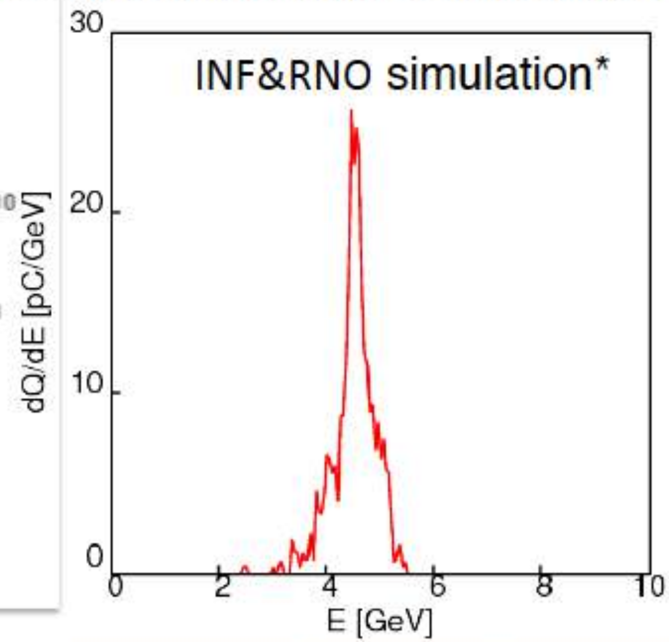


Capillary discharge

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

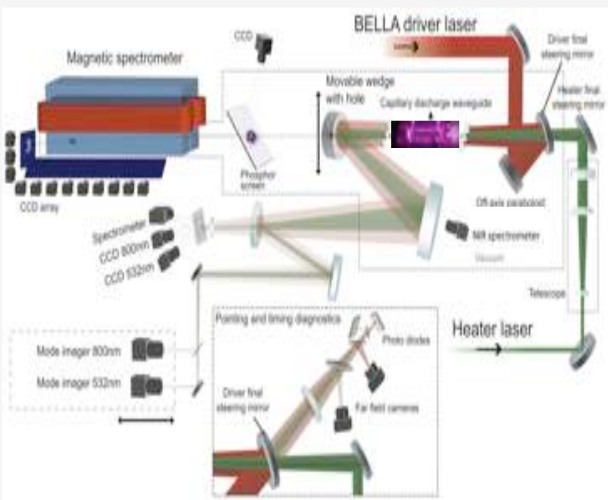
W.P. Leemans et al.,PRL 2014

BELLA, Berkeley Lab, US

Laser Driven Plasma Wakefield Acceleration Facility: Today: PW laser!

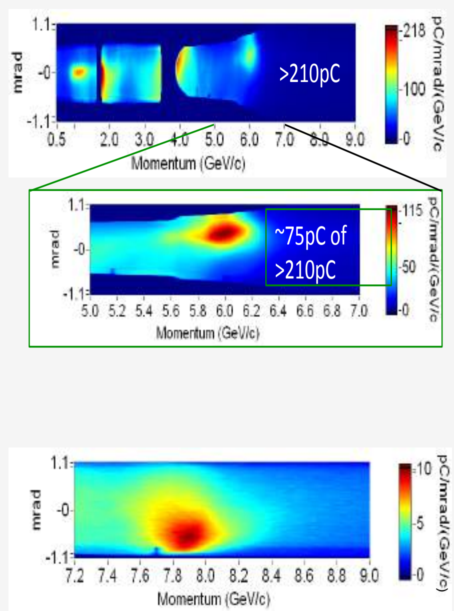
Petawatt laser guiding and electron beam **acceleration to 8 GeV** in a laser-heated capillary discharge waveguide

A.J.Gonsalves et al., Phys.Rev.Lett. ***122****, 084801 (2019)*



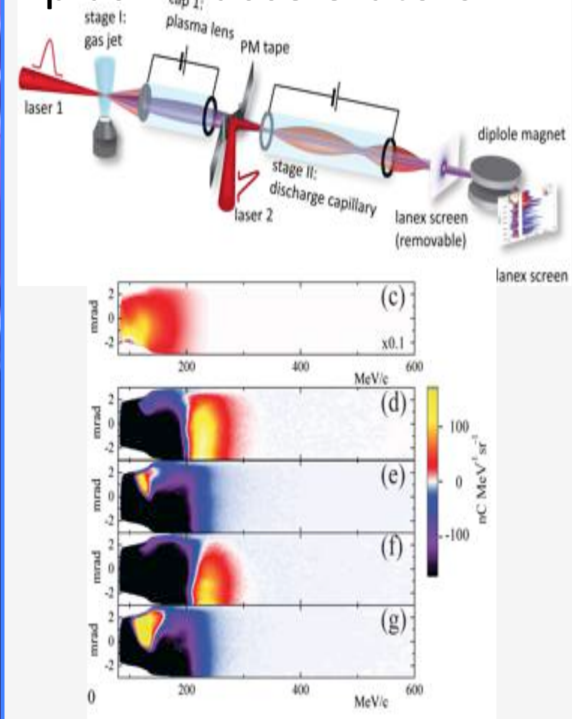
Laser heater added to capillary

Electron spectra, up to 6- 8 GeV



→ path to 10 GeV with continued improvement of guiding in progress

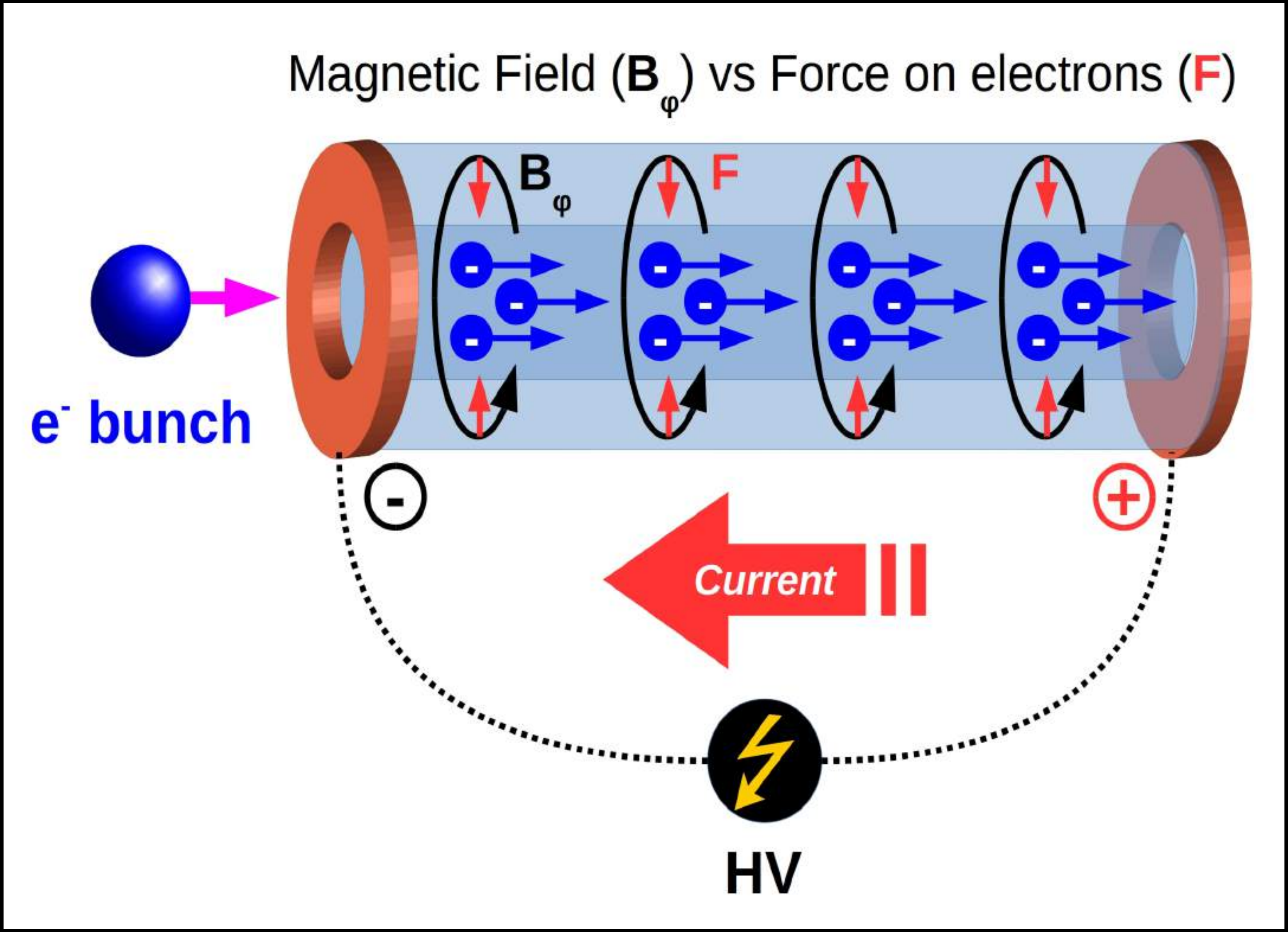
Multistage coupling of independent laser-plasma accelerators



Staging demonstrated at 100 MeVs

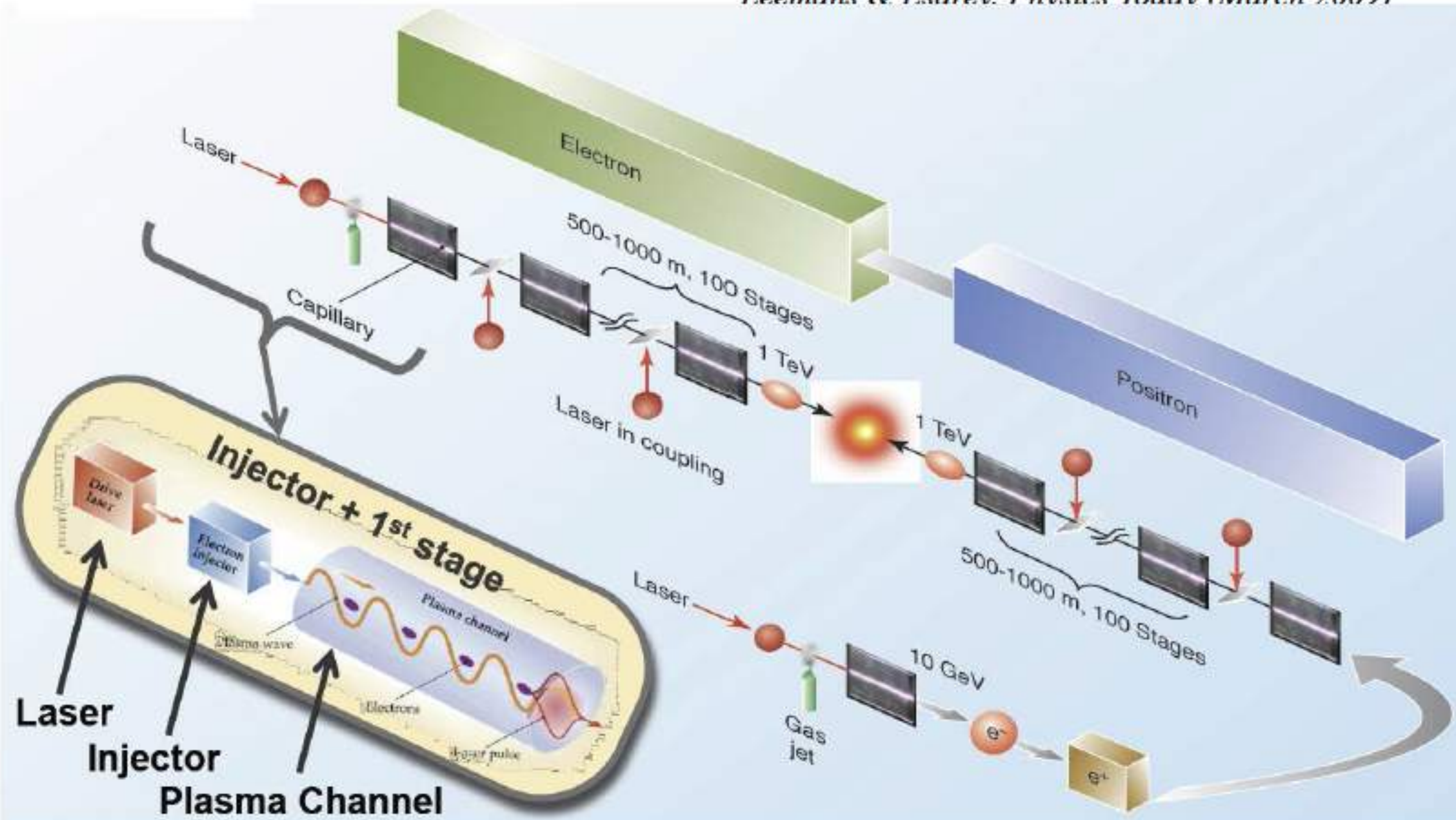
S. Steinke, Nature ***530****, 190 (2016)*

Active Plasma Lens



Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)



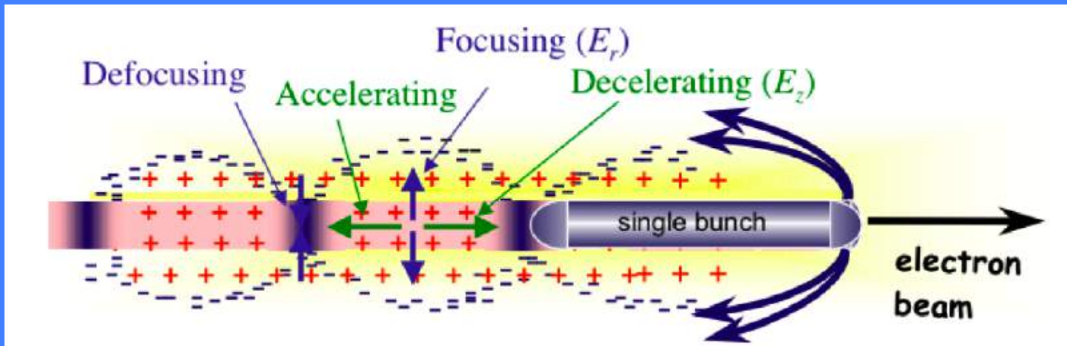
Parameter Set for LPWA LC

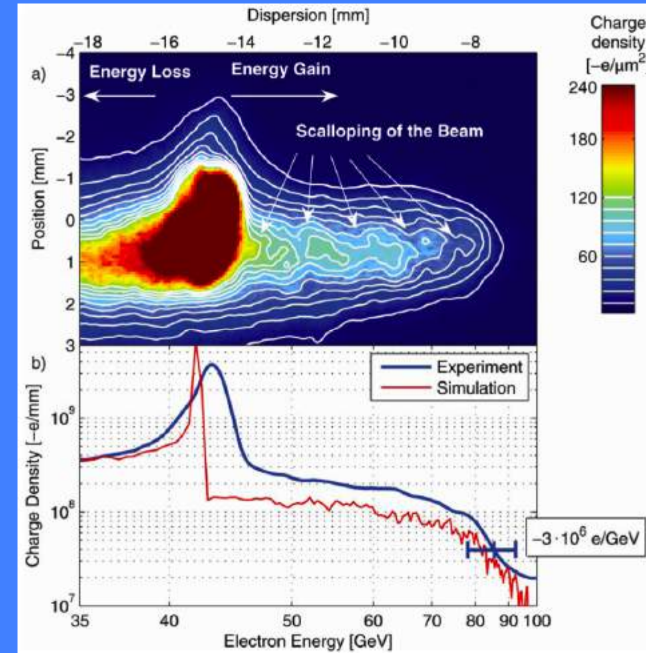
Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15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

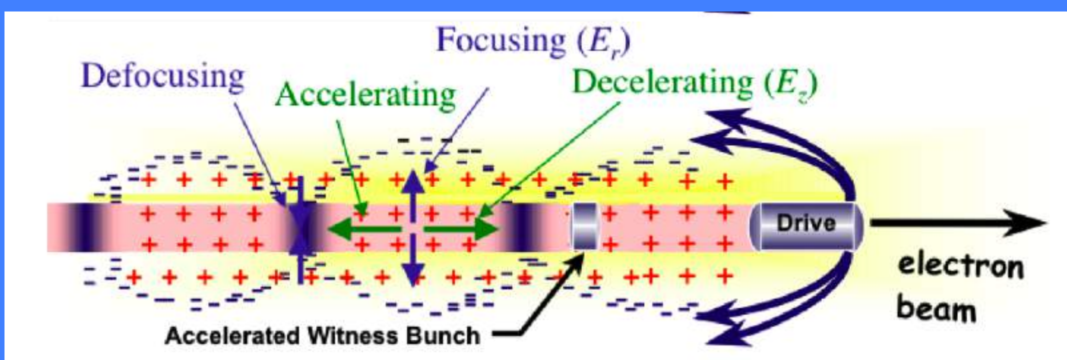
Beam Driven

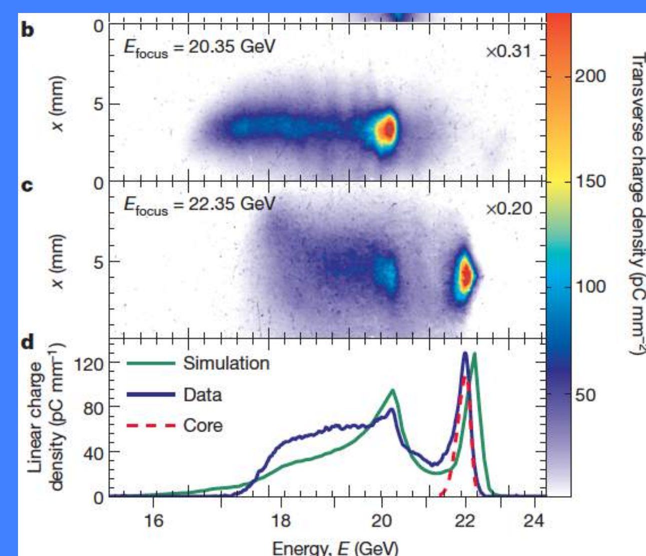
PWFA





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).

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

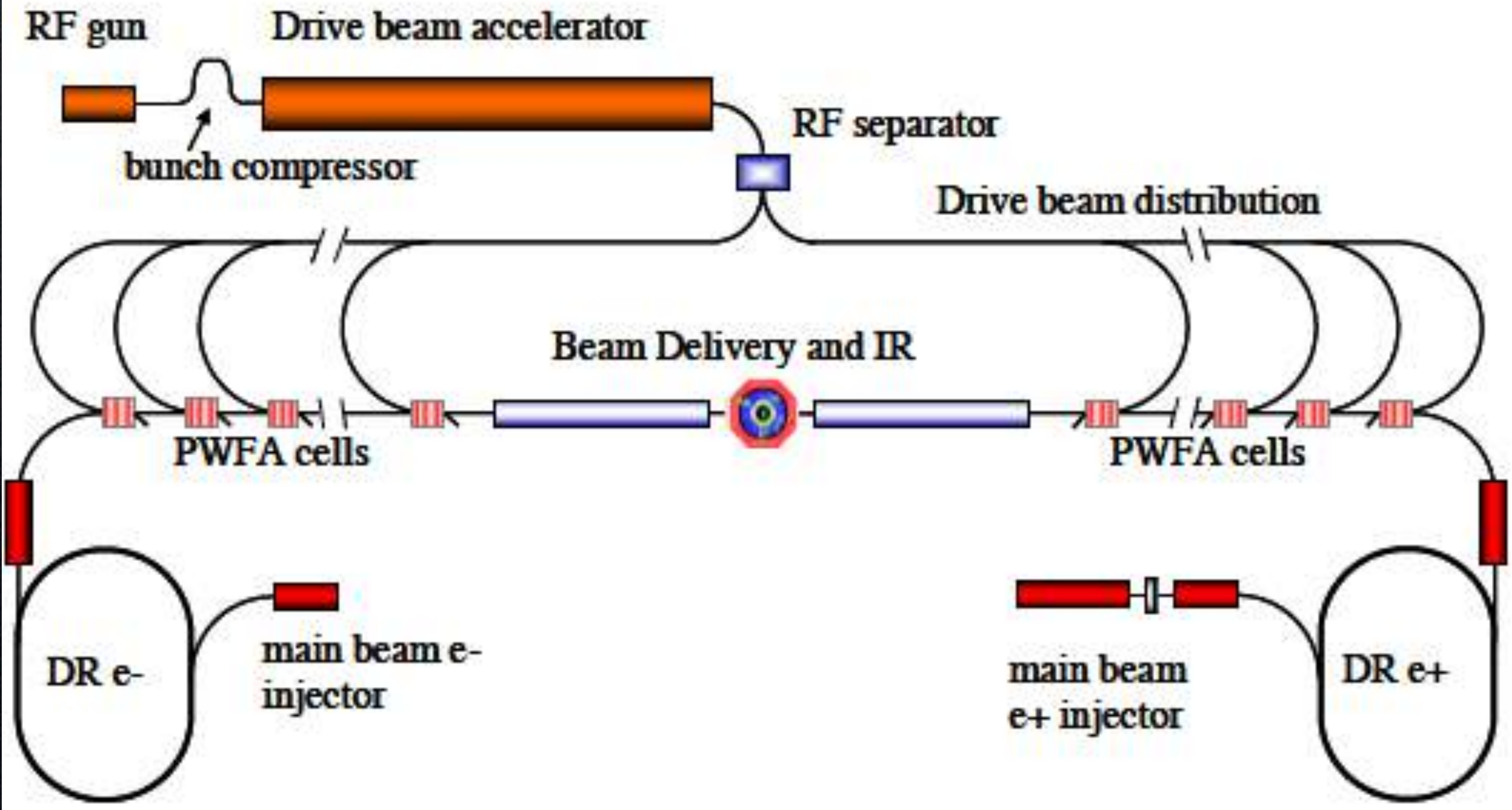


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

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}

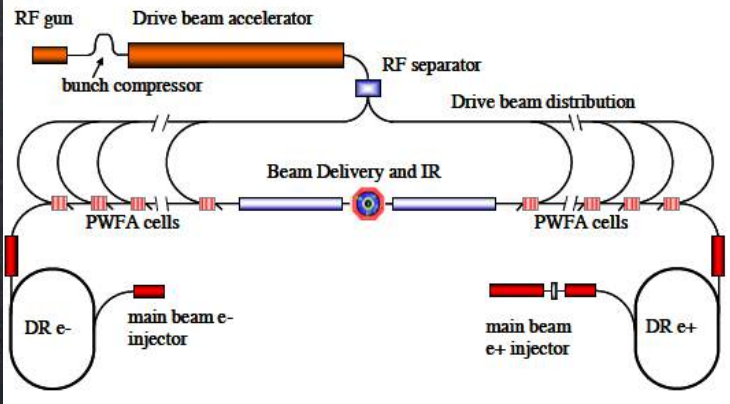


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

Positron Acceleration, FACET

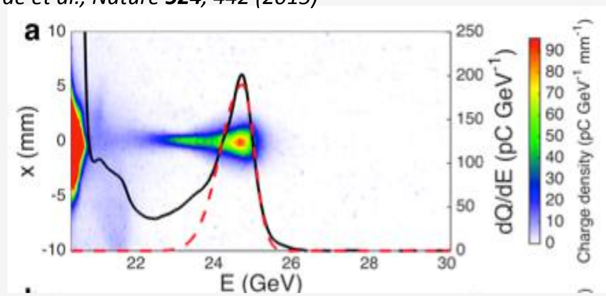
Positrons for high energy linear colliders: **high energy, high charge, low emittance**.

First demonstration of positron acceleration in plasma (FFTB)

*B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (**2003**)*
M. J. Hogan et. al. Phys. Rev. Lett. 90 205002 (2003).

Energy gain of 5 GeV. Energy spread can be as low as 1.8%

*S. Corde et al., Nature **524**, 442 (2015)*

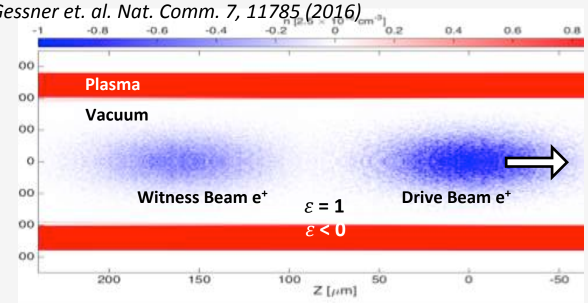


High-density, compressed positron beam for non-linear PWFA experiments. Energy transfer from the front to the back part of the bunch.

Two-bunch positron beam: **First demonstration** of controlled beam in positron-driven wake
S. Doche *et al.*, Nat. Sci. Rep. 7, 14180 (2017)

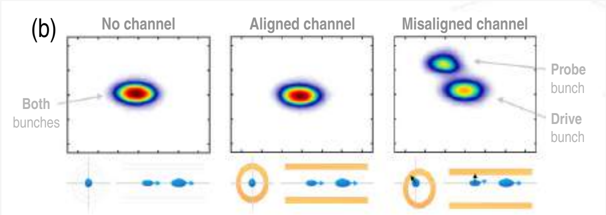
Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.

S. Gessner et. al. Nat. Comm. 7, 11785 (2016)



Measurement of **transverse wakefields in a hollow plasma** channel due to off-axis drive bunch propagation.

*C. A. Lindstrøm et. al. Phys. Rev. Lett. 120 124802 (**2018**).*

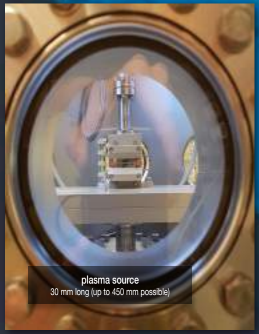


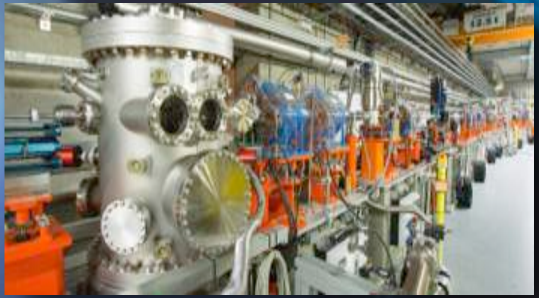
➔ **Emittance blow-up is an issue!** → Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma → but then strong transverse wakefields when beams are misaligned.

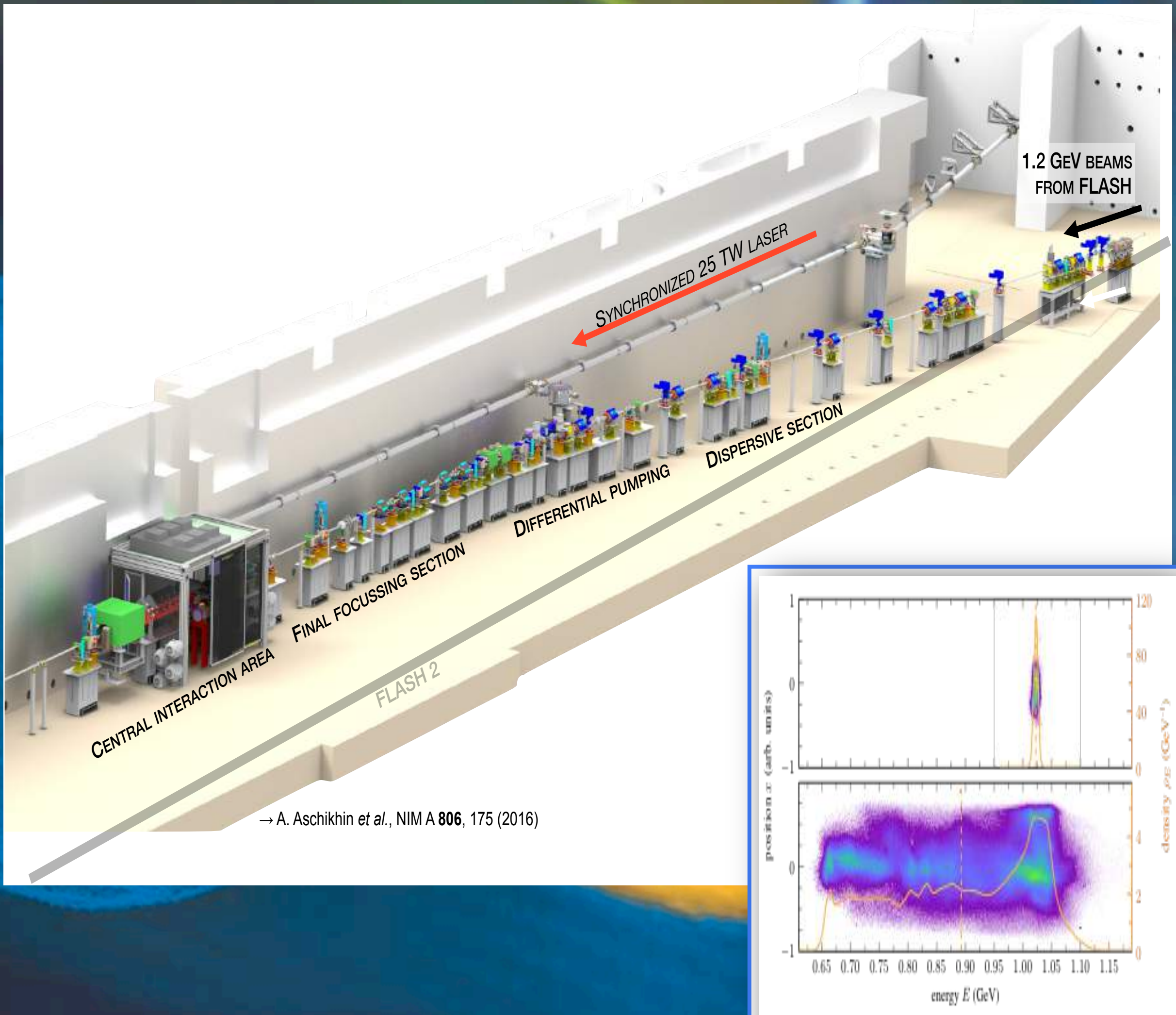
FLASHForward>>, DESY

→ unique FLASH facility features for PWFA

- FEL-quality drive and witness beams
- up to 1 MHz repetition rate
- 3rd harmonic cavity for phase-space linearization → tailoring of beam current profile
- differentially pumped, windowless plasma sources
- *2019*: X-band deflector of 1 fs resolution post-plasma (collaboration with FALSH 2, SINBAD, CERN & PSI)
- *Future:* up to 800 bunches (~MHz spacing) at 10 Hz macro-pulse rate, few 10 kW average power.



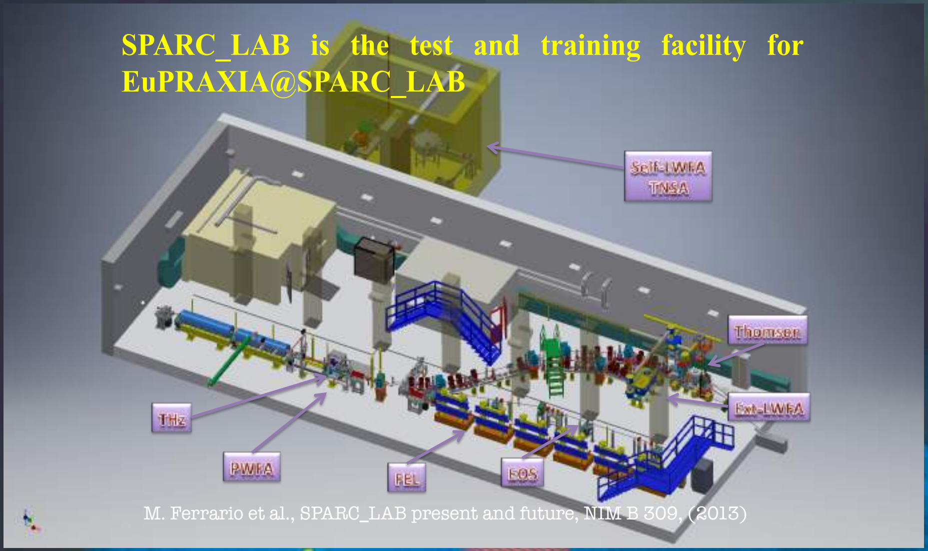




→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)

- → (12.3 ± 1.7) GV/m wakefield generated in 30 mm plasma cell
- → 12.7% total energy loss to plasma wakefield

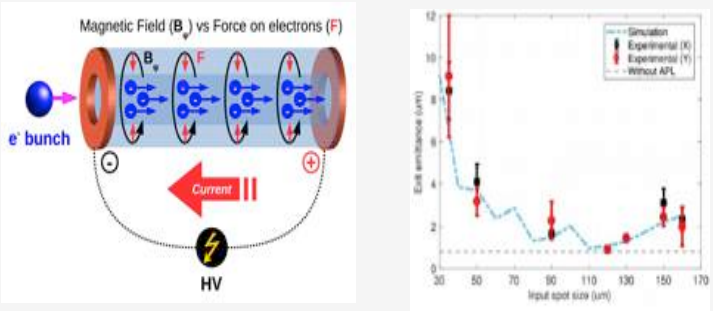
SPARC_LAB, Frascati, Italy



➔ Main challenges addressed in this facility: beam quality, beam transport

- 150 MeV drive/witness beam
- FEL experiments
- Resonant LWFA with 200 TW laser
- PWFA

Active Plasma Lens Experiments:

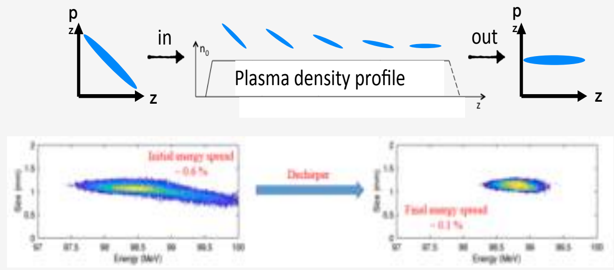


R. Pompili et al., PRL 121 (2018), 174801

BELLA, LBNL: *J. van Tilborg et al., PRL 115 (2015), 184802*
CLEAR, CERN: *C.A. Lindstrom et al., PRL 121 (2018), 194801*

Plasma dechirper:

Longitudinal phase-space manipulation with the wakefield induced in plasma by the beam itself.



From 0.6% to 0.1% energy spread

V. Shpakov et al., PRL 122 (2019), 114801

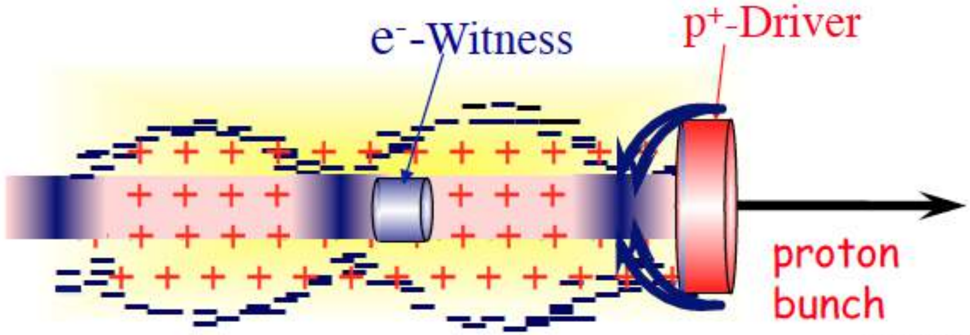
FLASHForward, DESY: *R. D'Arcy et al., PRL 122 (2019), 034801*

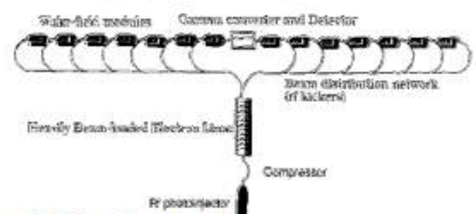
MAX-PLANCK-GESELLSCHAFT

AWAKE

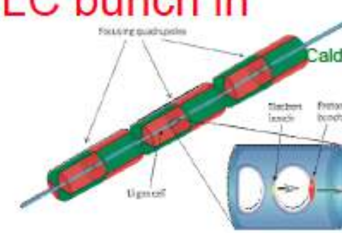
Proton-driven
Plasma Wakefield Acceleration
Collaboration:
Accelerating e⁻ on the wake of a p⁺ bunch

WHY p+-DRIVEN PWFA?





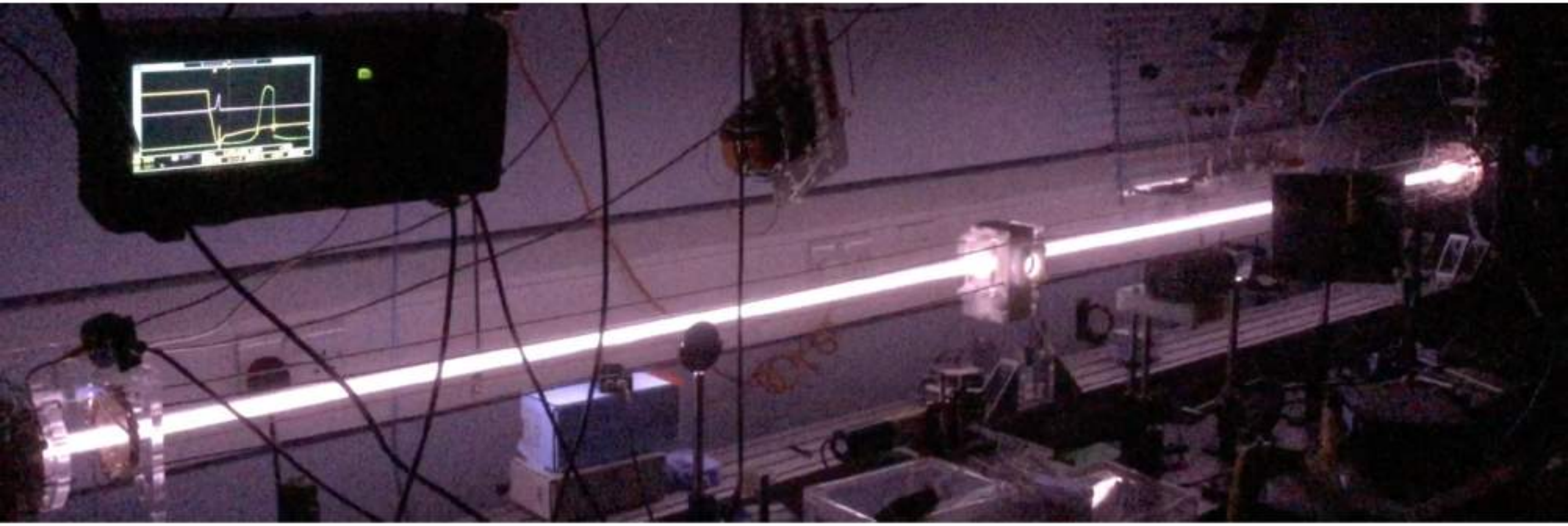
- ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ
- SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J
- SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)
- SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
  LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
- A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- Large average gradient! (≥1GeV/m, 100's m)



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

Discharge configuration II

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



very promising results

… reliable, low jitter plasma formation

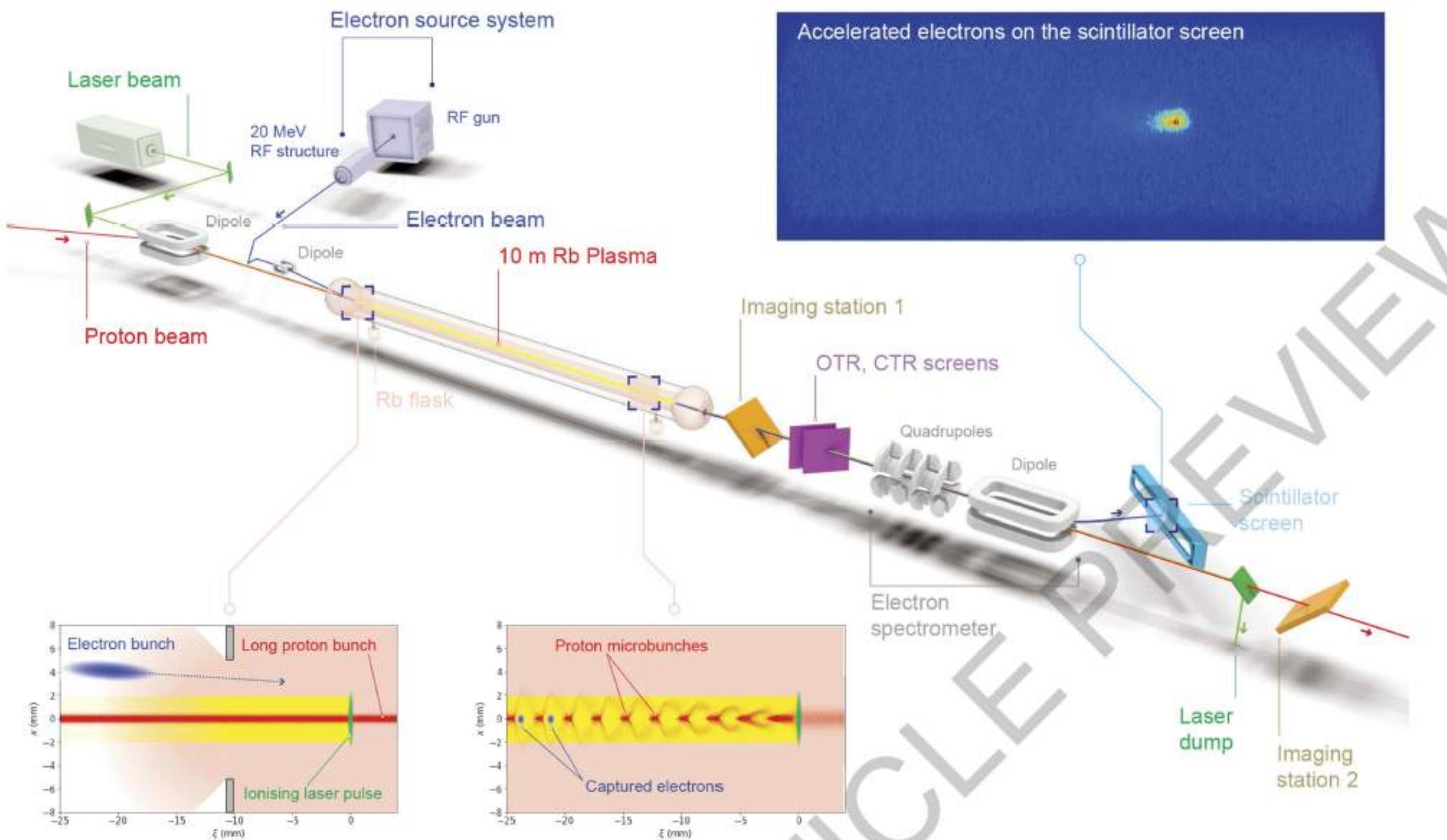
scalability of electric circuit for plasmas > 10 m seem achievable…

nature Accelerated Article Preview

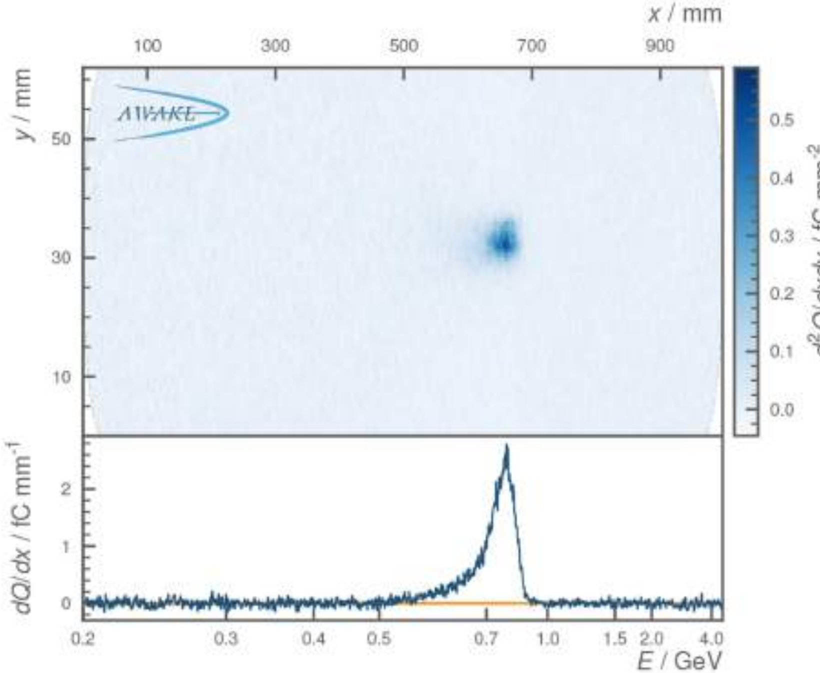
LETTER
doi:10.1038/s41586-018-0485-4

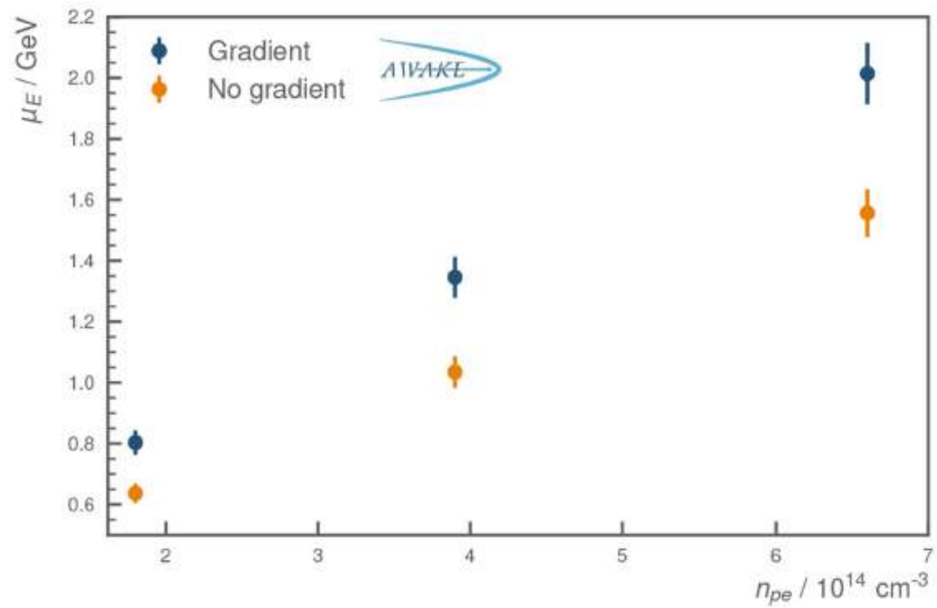
Acceleration of electrons in the plasma wakefield of a proton bunch

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

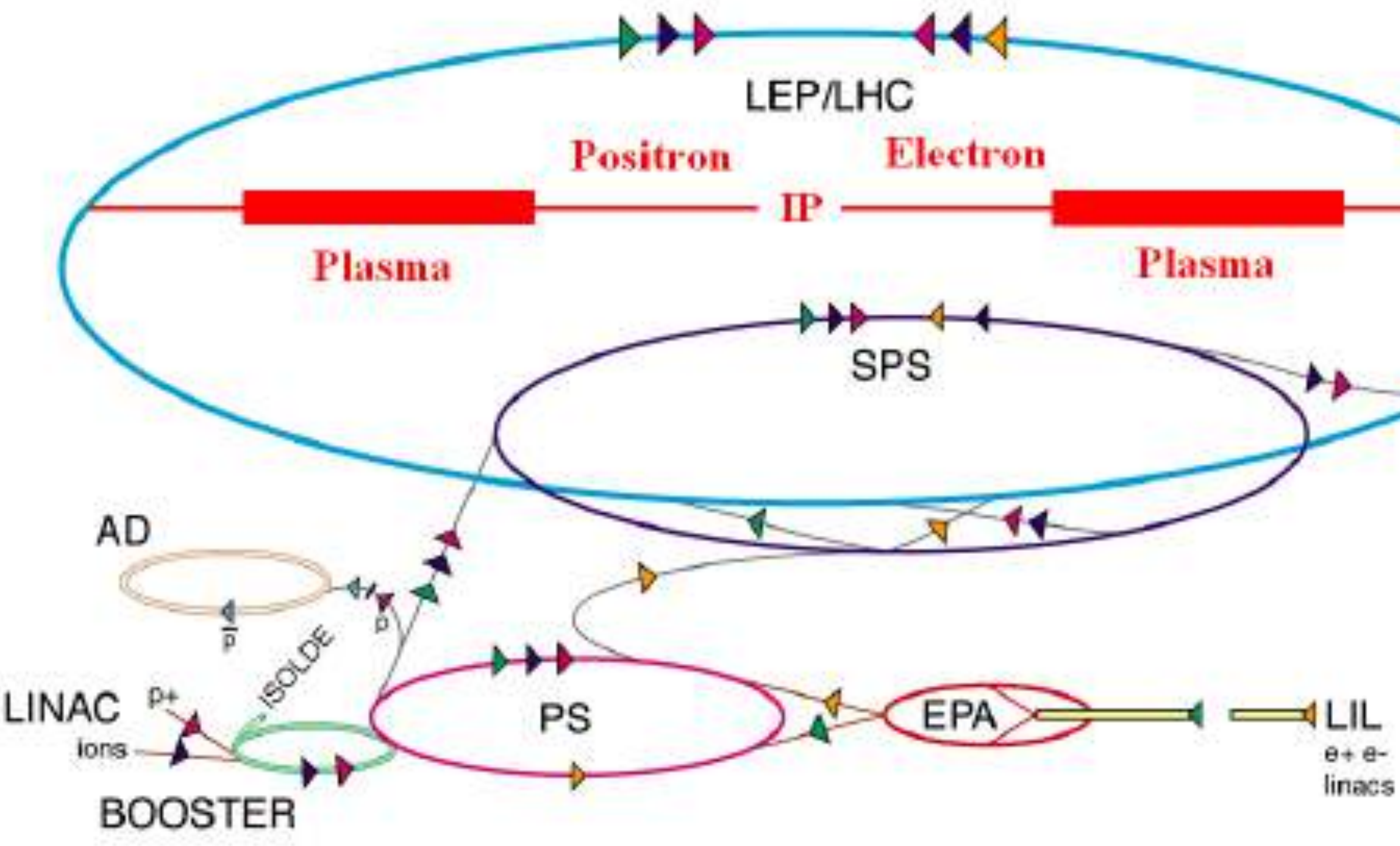
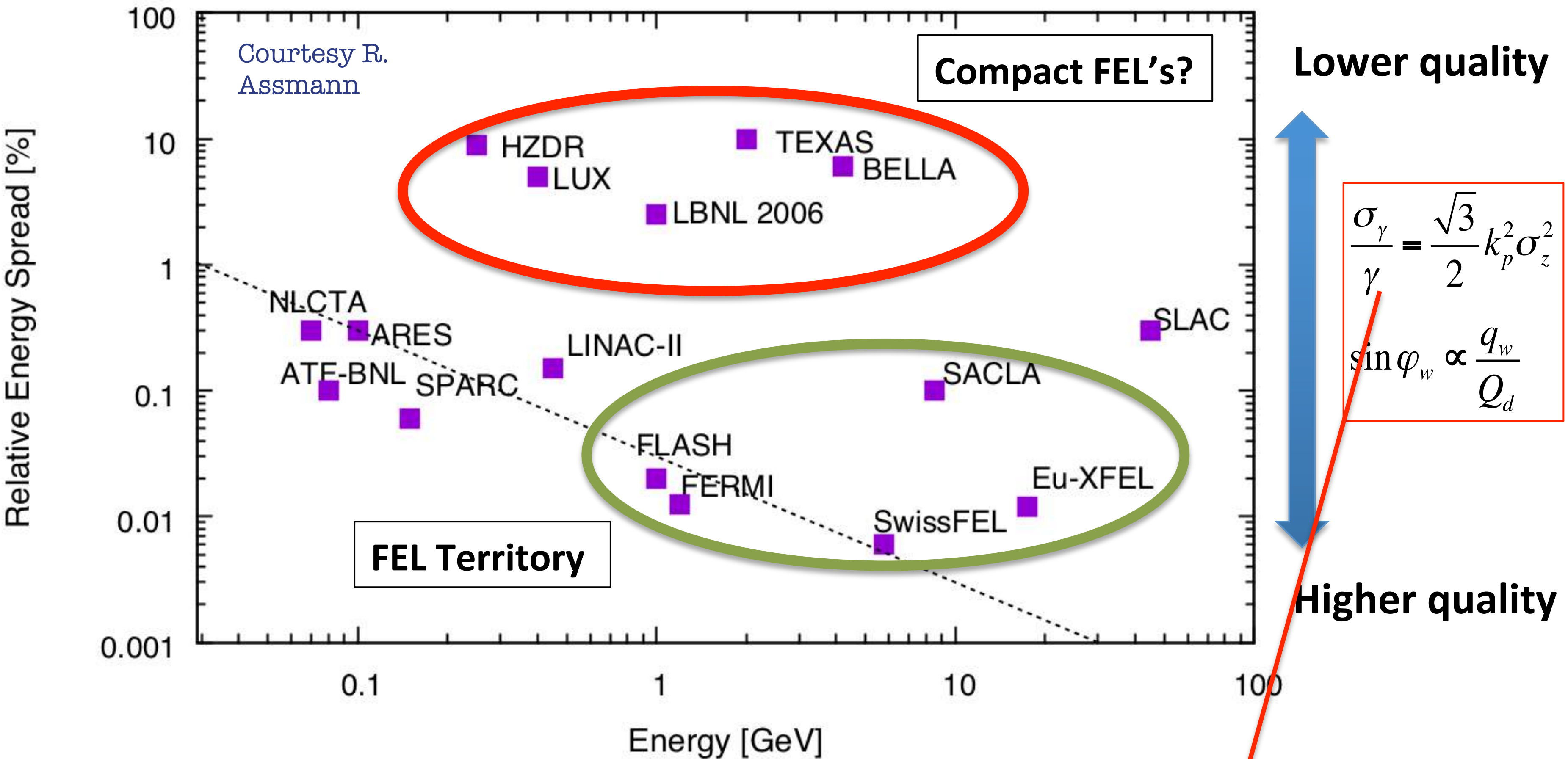


Figure 1: Schematic layout of a 2 TeV CoM electron-positron linear collider based on a modulated proton-driven plasma wakefield acceleration.

The near future

Quality: Example Energy Spread



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

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

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

M. Migliorati et al, Physical Review Special Topics,Accelerators and Beams 16, 011302 (2013)
K. Floettmann, PRSTAB,6, 034202 (2003)

When the correlations between the energy and transverse positions are negligible (as in a drift without collective effects) we can write:

$$\varepsilon_{n,rms}^2 = \langle \beta^2\gamma^2 \rangle \langle x^2 \rangle \langle x'^2 \rangle - \langle \beta\gamma \rangle^2 \langle xx' \rangle^2$$

Considering now the definition of relative energy spread:

$$\sigma_\gamma^2 = \frac{\langle \beta^2\gamma^2 \rangle - \langle \beta\gamma \rangle^2}{\langle \beta\gamma \rangle^2}$$

which can be inserted in the emittance definition to give:

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

Assuming relativistic electrons (β=1) we get:

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

PRESENT PLASMA E- ACCELERATION EXPERIMENTS

Demonstrating **100 GV/m** routinely

Demonstrating many **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, ...

PLASMA ACCELERATOR PRODUCTION FACILITIES

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

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

Medical, industrial applications soon

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

EuPRAXIA scientific goals
Compact Free Electron Laser et al.

- **Single and multi-stage** acceleration of electrons to **1 – 5 GeV,** transverse emittance of **1 mm-mrad**, energy spread between **% to 10^{-3}**
- **Highly compact** machine layout (factor 3 gain in floor space, up to factor 10)
- **PW pulsed lasers** developed together with industry and laser institutes. → Operation with high stability at **20 – 100Hz**.
- **Compact beam driver** based on X-band RF technology from CERN.
- **Versatile user area**

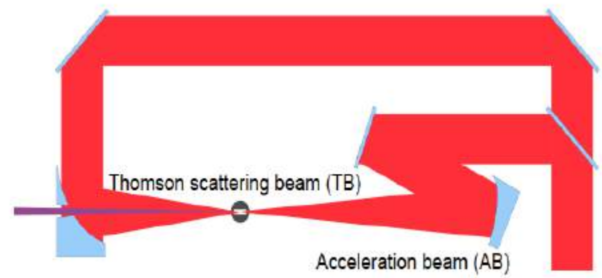
Electron beam parameters at the undulator

Quantity	Symbol [Unit of Meas.]	Target parameters
Energy	E [GeV]	1 - 5
Charge	Q [pC]	30
Bunch length (FWHM)	t_{FWHM} [fs]	10
Peak current	I [kA]	3
Repetition rate	f [Hz]	10
# of bunches	N	1
Transverse Norm. emittance	$\varepsilon_{n,x}, \varepsilon_{n,y}$ [mm mrad]	<1
Total energy spread	σ_E/E [%]	1
Slice Norm. emittance	$\varepsilon_{n,x}, \varepsilon_{n,y}$ [mm mrad]	<<1
Slice energy spread	$\sigma_{E,s}/E$ [%]	~0.1
Slice length	L_{Slice} [μm]	0.75 - 0.12

Other applications of plasma accelerators

- Free Electron Lasers
- Synchrotron sources
- Compton sources
- High Field Physics
- Positron Sources
- High Energy Physics

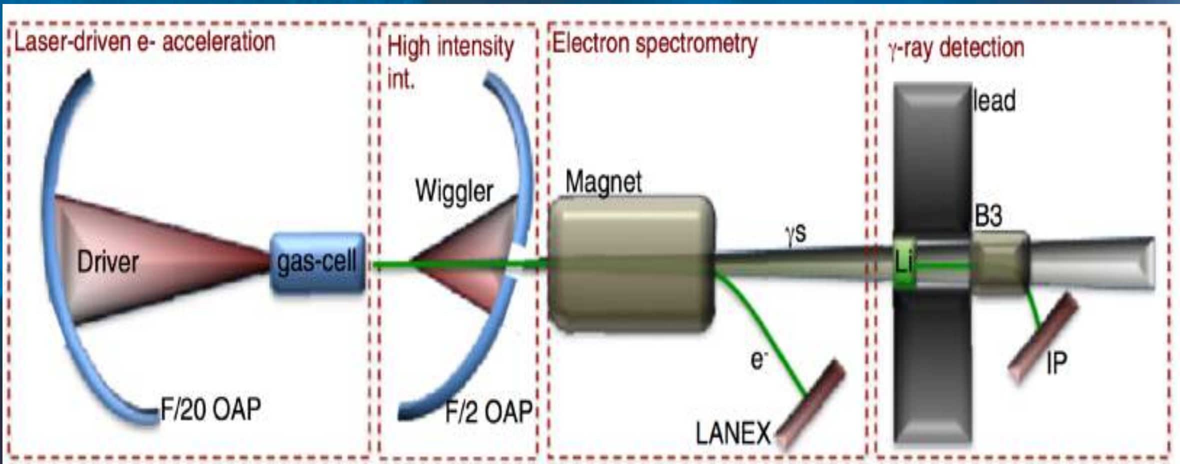
A possible simple setup for Thomson scattering experiments with self-injected electrons [1/2] (~*compatible with existing setup*)



Main params:

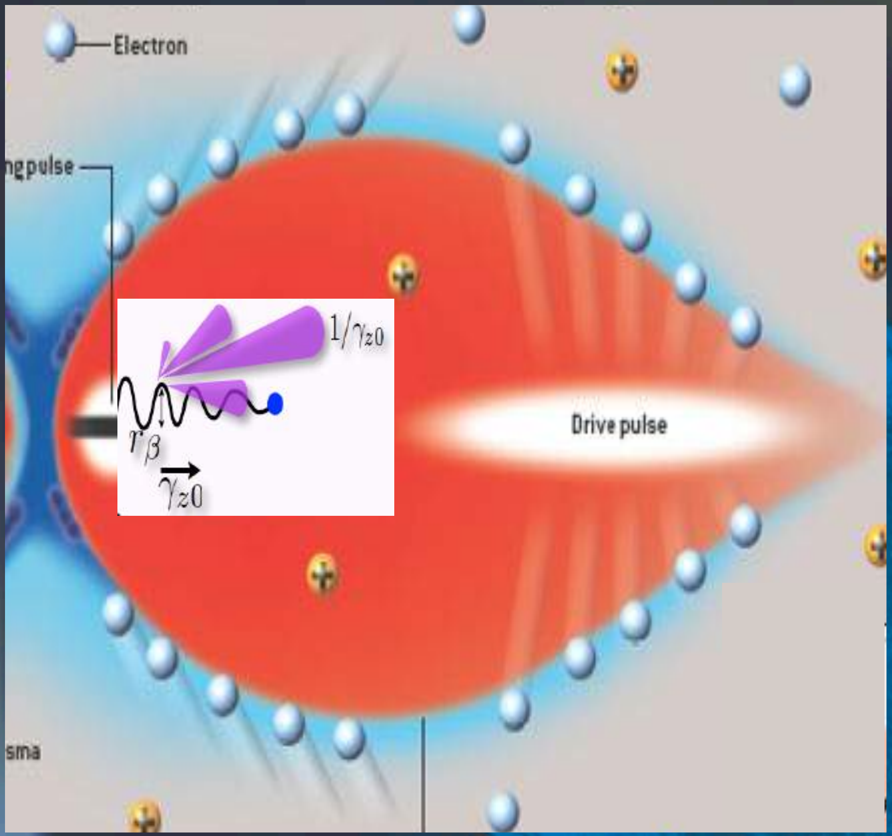
- **AB** OAP: f/10, a_0~4-5
- **TB** OAP: to be defined (see below), a_0~0.5, but size (→ energy) depending on the e- beam emittance

Sarri, G. et al, Nat. Commun. 6, 6747 (2015).

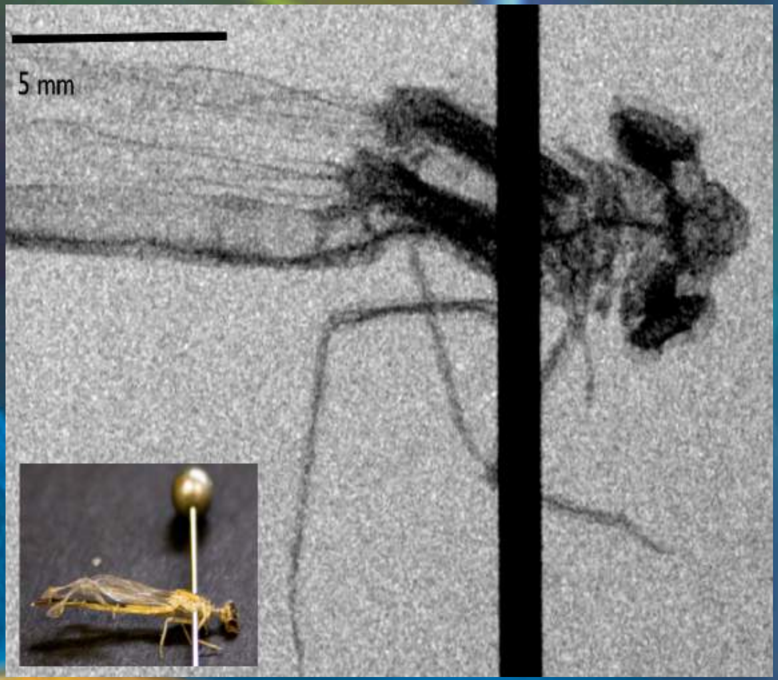


$$E_s = 4\gamma^2 \hbar\omega$$

Betatron Radiation Source



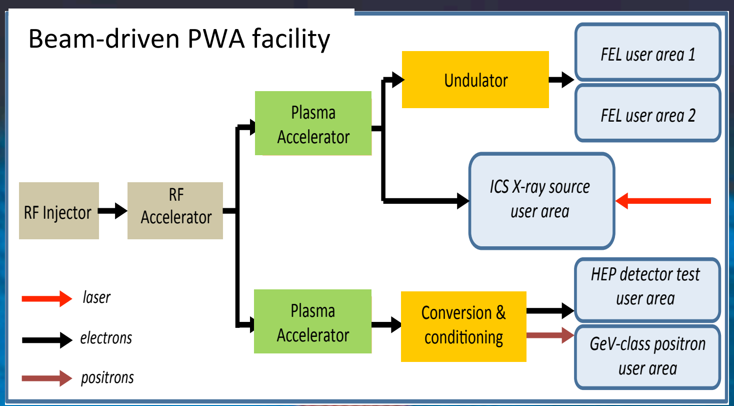
E Esarey PRE 65, 056505 (2002)
Kneip, Appl. Phys. Lett. 99, (2011).

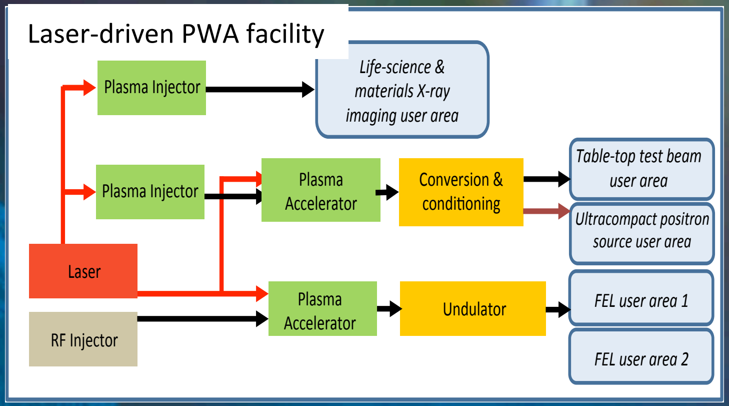


Photon energy > 25 keV, investigating dense material, biological materials
Small source size (~ µm), intrinsically high resolution, exhibits spatial resolution
Small divergence (~ 10 mRad)
Short pulse (~10s fs), suitable for ultrafast dynamics
Bright (>109 photons per shot), suitable for single shot imaging

EuPRAXIA future

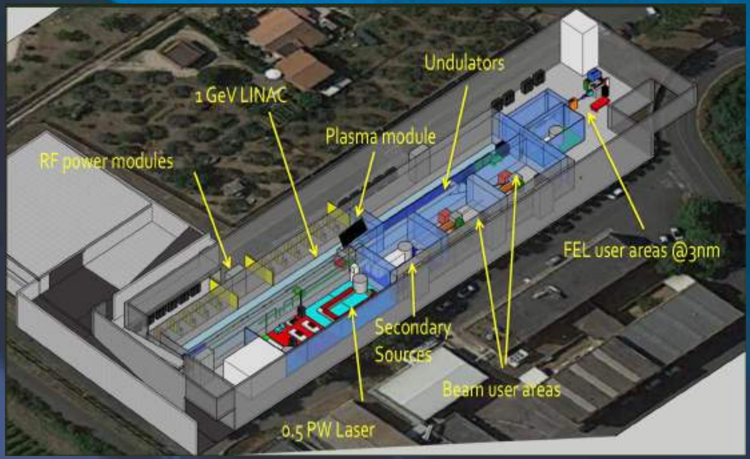
Two facilities will be proposed as the required intermediate step between proof of principle and user facility!





EuPRAXIA@SPARC_LAB

EuPRAXIA@SINBAD



Conclusions

- 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.
- **Novel Acceleration Techniques and Plasma-based, high gradient accelerators 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 USER FACILITIES Needed**


Thanks for your attention