Advanced and Novel Acceleration Techniques

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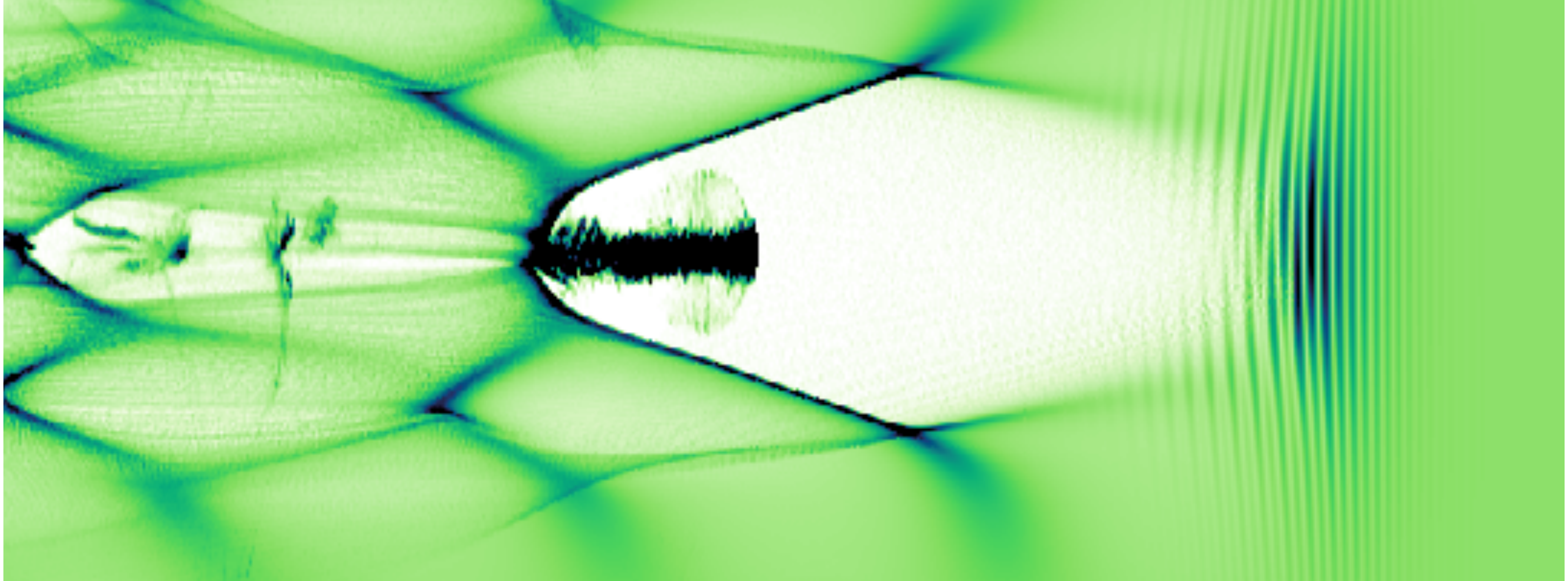
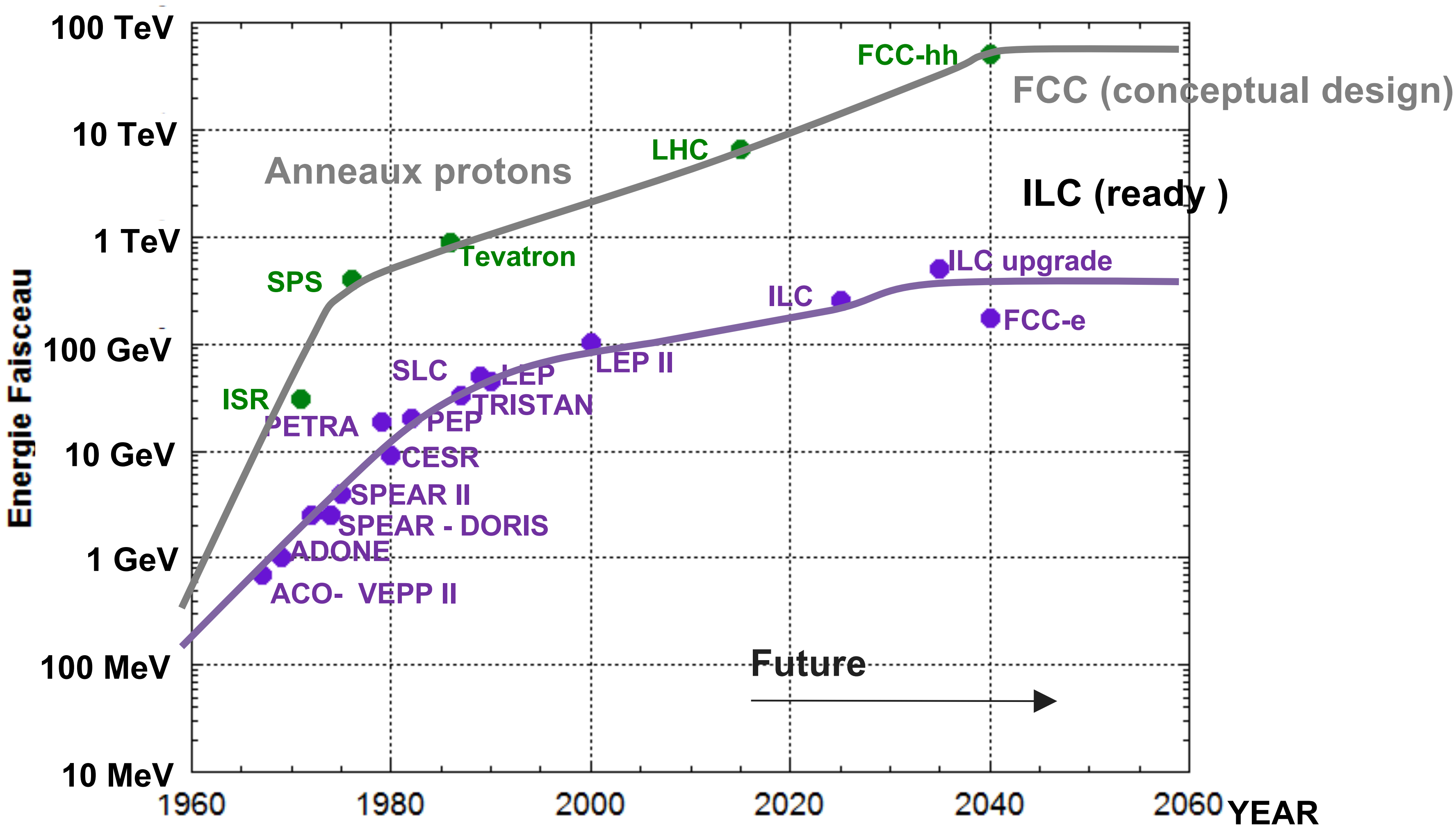


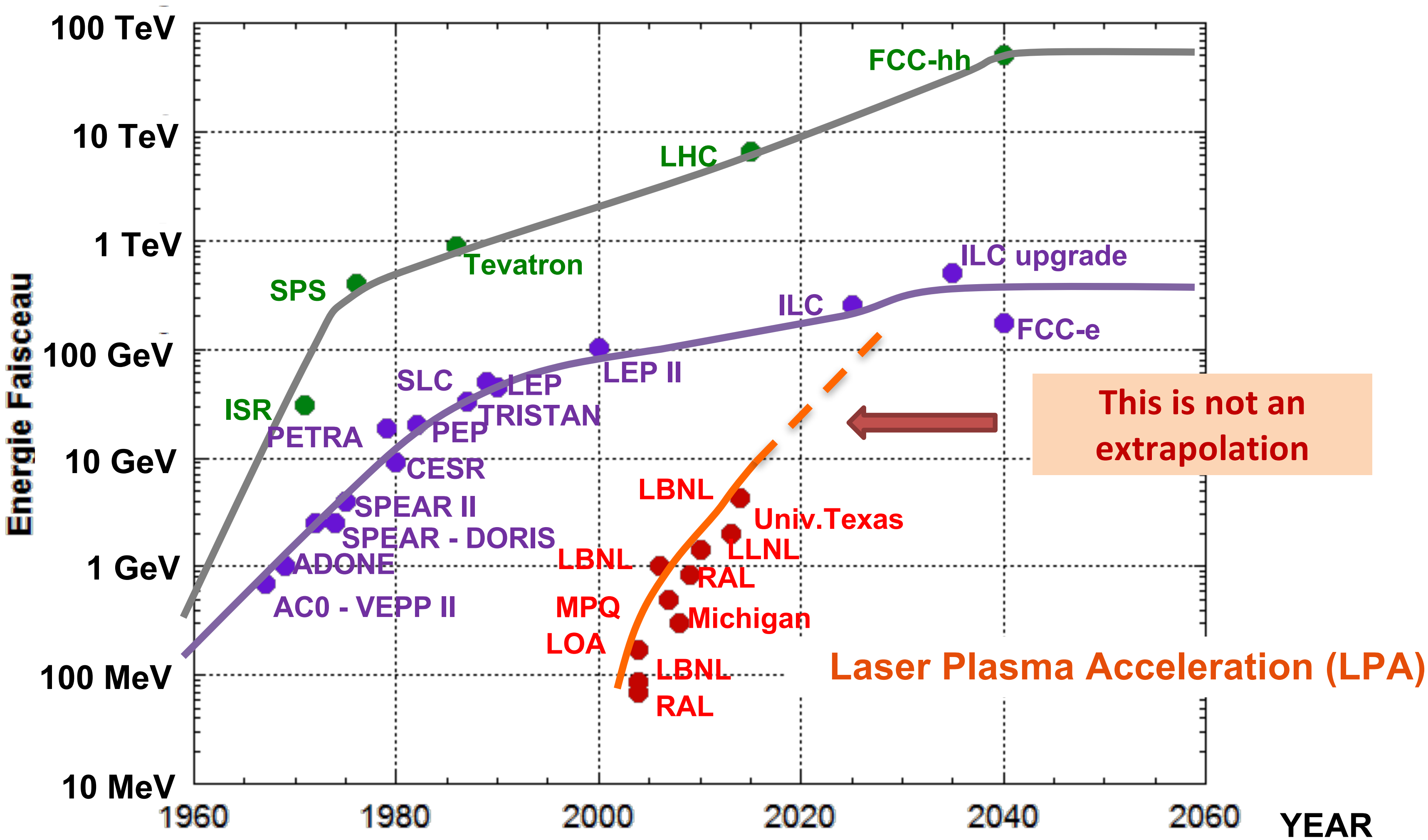
Many thanks to: Ralph Assmann, Arnaud Beck,Brigitte Cros, Mark Hogan, Wim Leemans, Andreas Maier, Alban Mosnier, Patric Muggli, Carl Schroeder, Andreas Walker, and many many more.

evolution of beam energy of colliders e+/e- et p/p



graph courtesy by A. Mosnier

«beam» energies in laser plasma acc. experiments



LPA gradients 10 to 100 times higher than conventional RF LINACs

$$W = q \times E \times L$$

Advanced and Novel Acceleration Techniques

acceleration of electrons (and positrons)

drive beam	plasma medium	accelerating structure
e+/e-beam	plasma wakefield acceleration (PWFA*) *) PWFA: historical misnomer	~~dielectric~~ structured wakefield acceleration (~~D~~SWFA)
proton beam	seeded self-modulation (SSM)	
laser beam	laser wakefield acceleration (LWFA)	dielectric laser acceleration (DLA)

laser plasma acceleration of protons (and ions)

Advanced and Novel Acceleration Techniques

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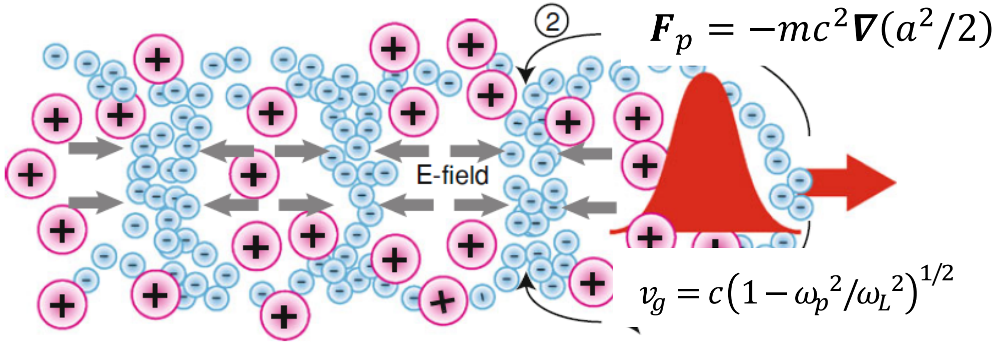
laser plasma acceleration of protons (and ions)

Plasma wave driven by strong electric fields

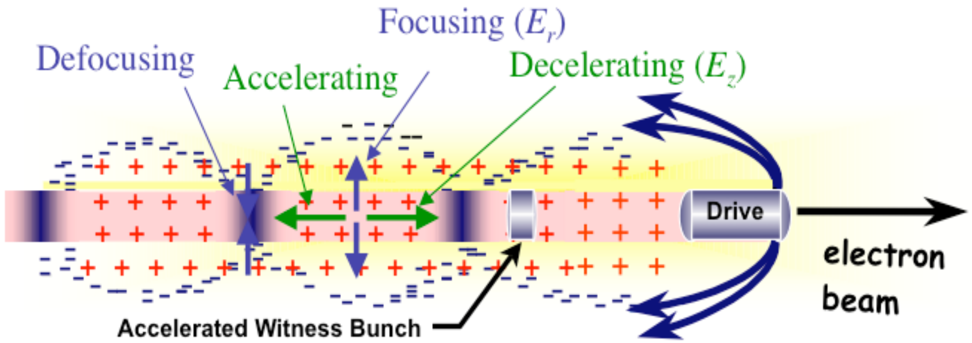
laser field (vector potential a)

T. Tajima & J.M. Dawson, Phys. Rev. Letter 43, 267 (1979)



particle beam field

P. Chen & J.M. Dawson, AIP Conf Proc **130**, 201 (1985)



1-D linear theory: plasma wave = forced electron density oscillation

1-D linear approximation $a^2 \ll 1$

$$\left(\frac{\partial^2}{\partial \xi^2} + k_p{}^2\right)\frac{\delta n}{n_0} = \nabla^2 \frac{a^2(\xi)}{2}$$

plasma wave — ponderomotive force

1-D linear approximation $n_b/n_0 \ll 1$

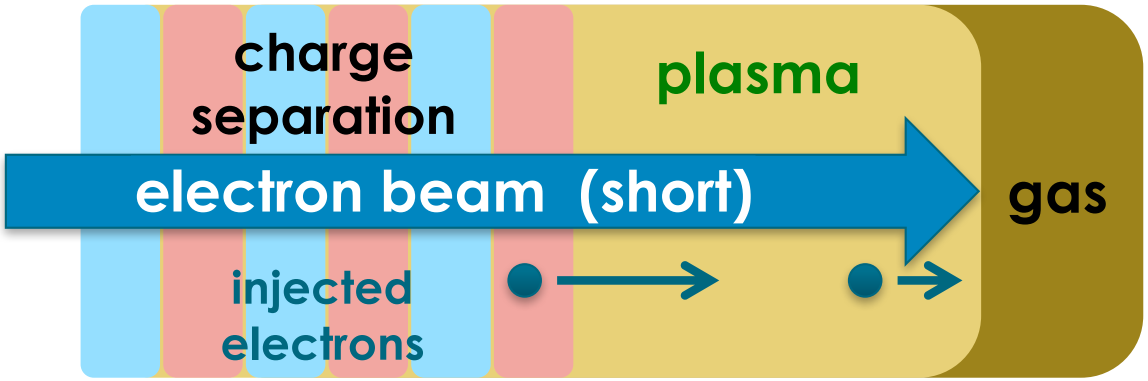
$$\left(\frac{\partial^2}{\partial \xi^2} + k_p{}^2\right)\frac{\delta n}{n_0} = -k_p{}^2\frac{n_b}{n_0}$$

space charge force

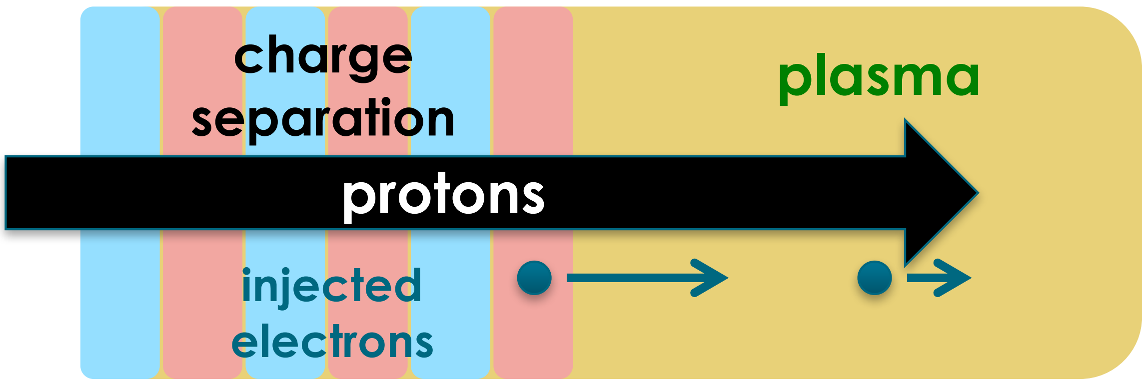
$\xi = z - ct$

Plasma waves can be excited by ANY drive beams

- **short electron or positron bunches (PWFA)**

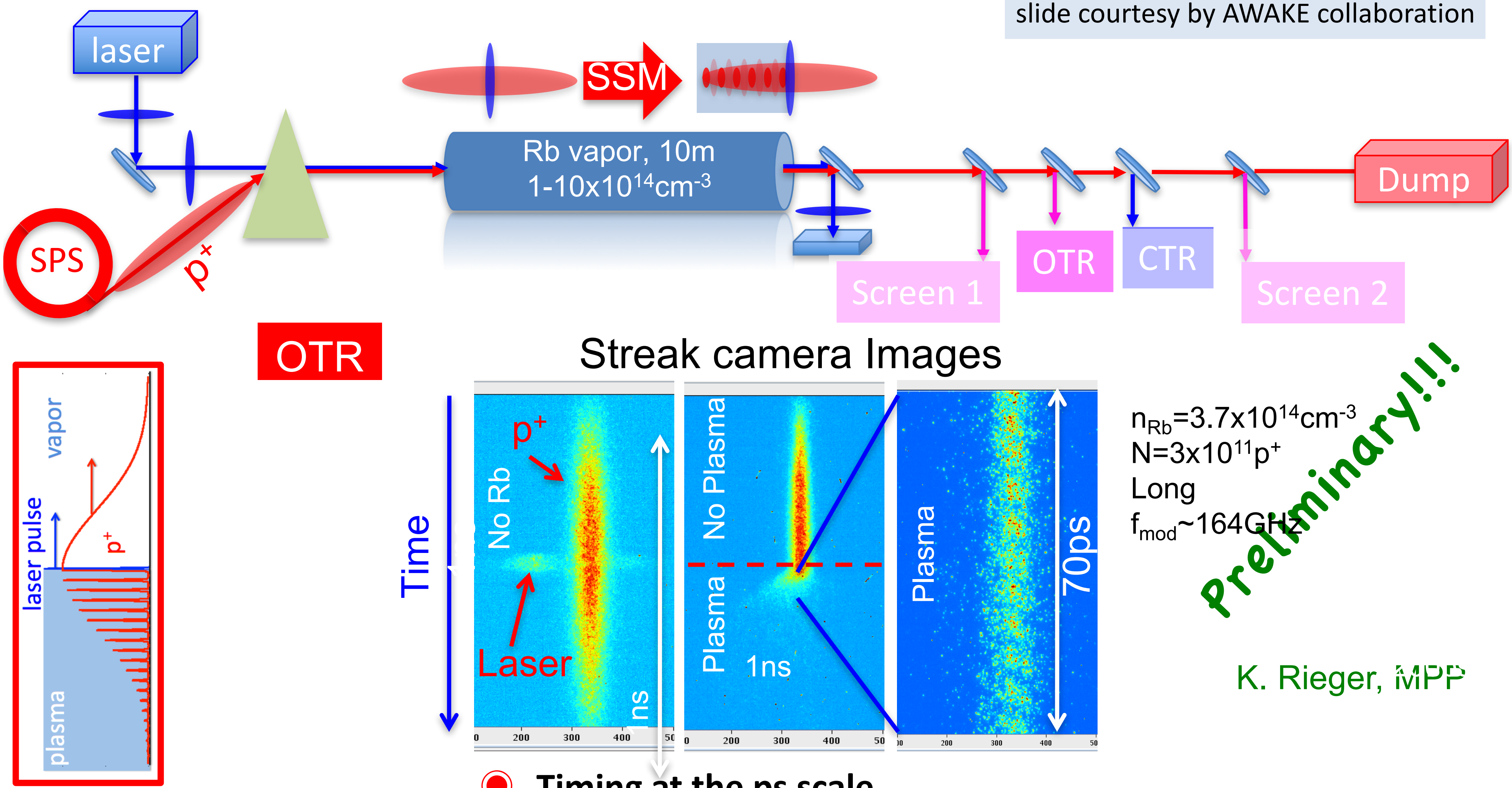


- **proton bunch: short bunch or seeded self- modulation (SSM)**



AWAKE experiment @ CERN: seeded self-modulation

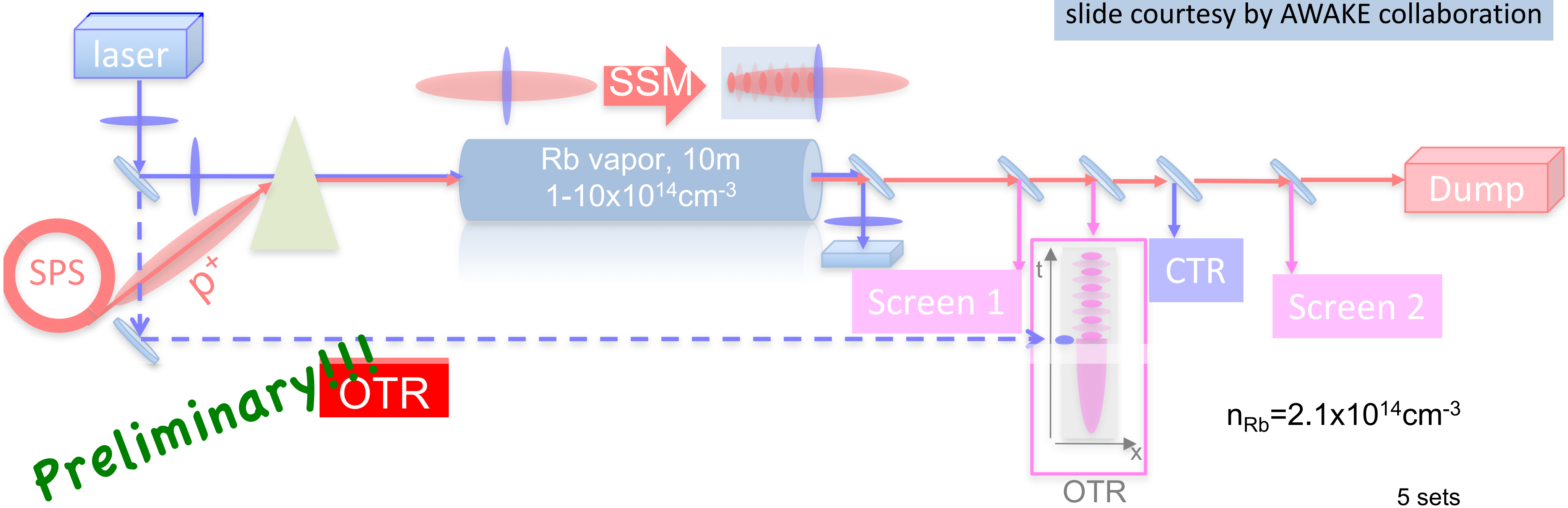
slide courtesy by AWAKE collaboration



- **Timing at the ps scale**
- **Effect starts at laser timing ® SM seeding**
- **Density modulation at the ps-scale visible**

AWAKE observes micro-bunch train after SSM

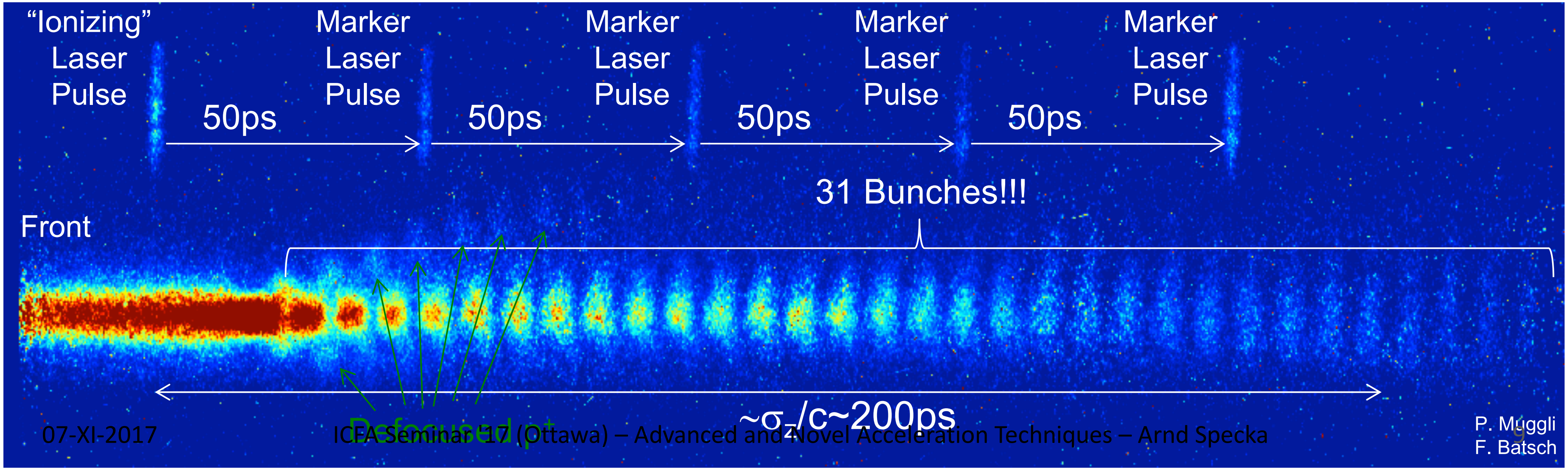
slide courtesy by AWAKE collaboration



n_{Rb}=2.1x10^{14}cm^{-3}

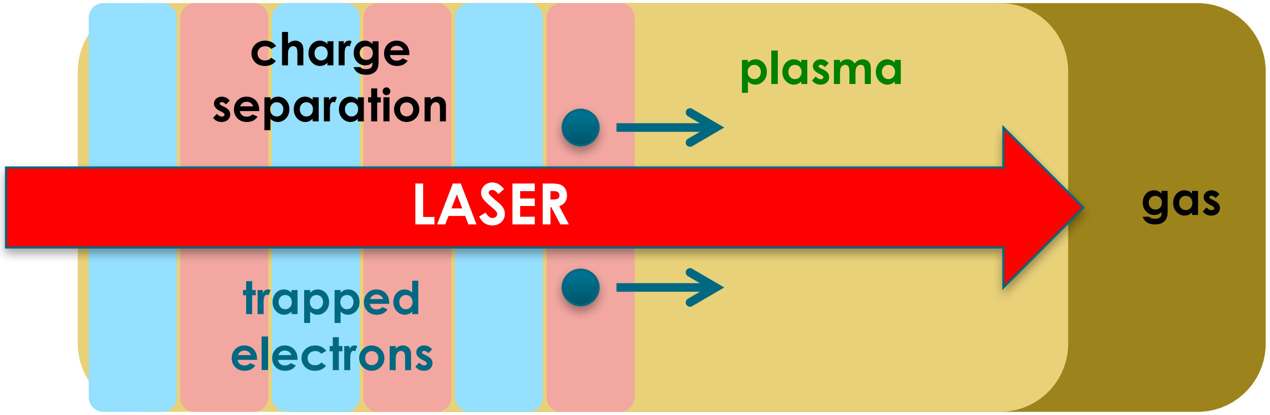
5 sets
10 events each

Streak camera Images



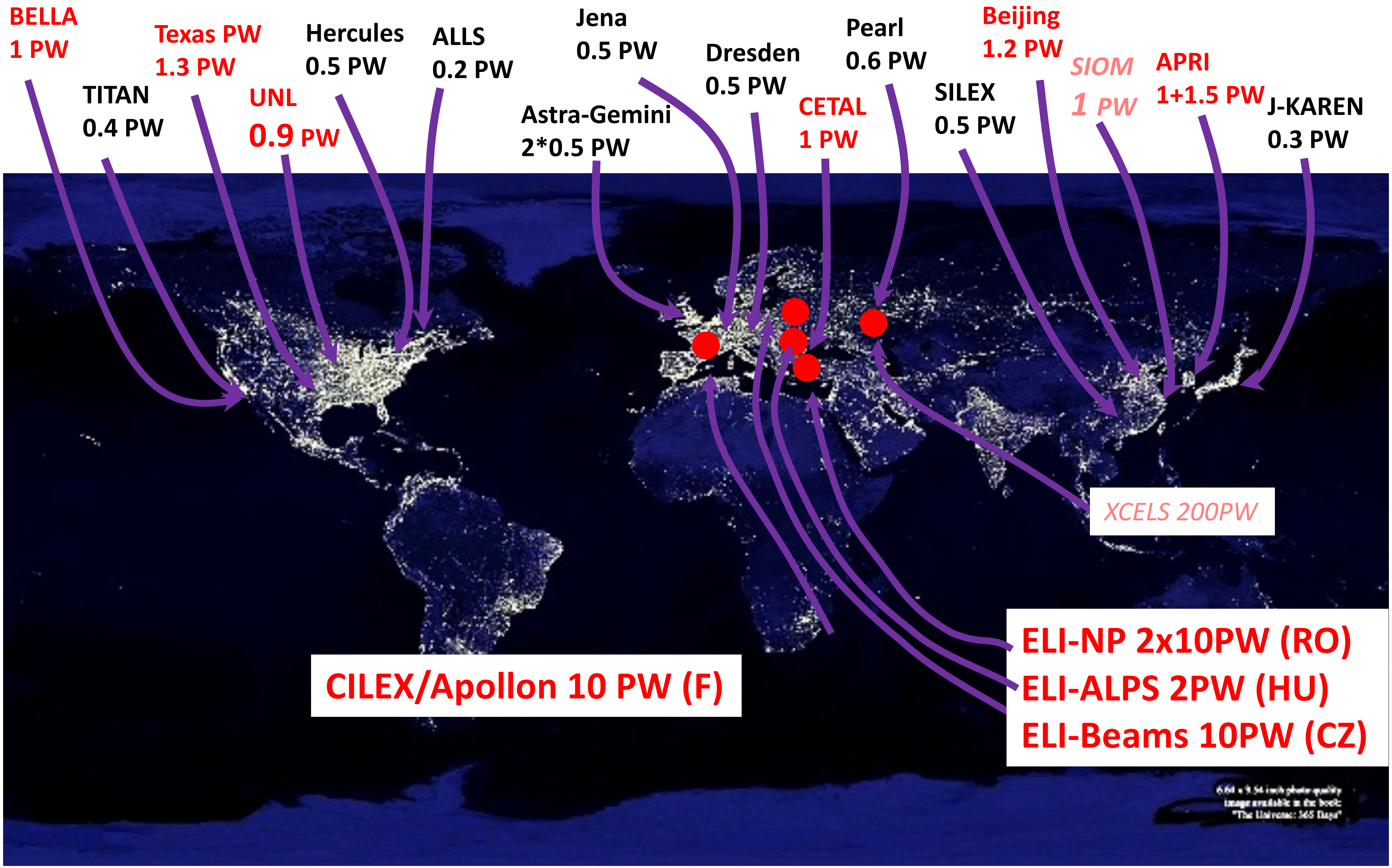
Physics principle of laser plasma wave acceleration

- **ultra-short pulse, high peak-power laser : >50TW, 20-100fs, >1 J, focused in a gas, e.g. hydrogen**



- **laser wakefield acceleration of electrons (LWFA)**
  - gaseous target (under-dense plasma) : n_e~$10^{16} – 10^{19}$ cm^{-3}
  - field effect ionization at the front of the laser pulse
  - charge separation -> plasma wave: λ_P ~ 300µm – 10µm
  - phase velocity v_{PH} (plasma wave) = v_G (group velocity laser) => relativistic wave

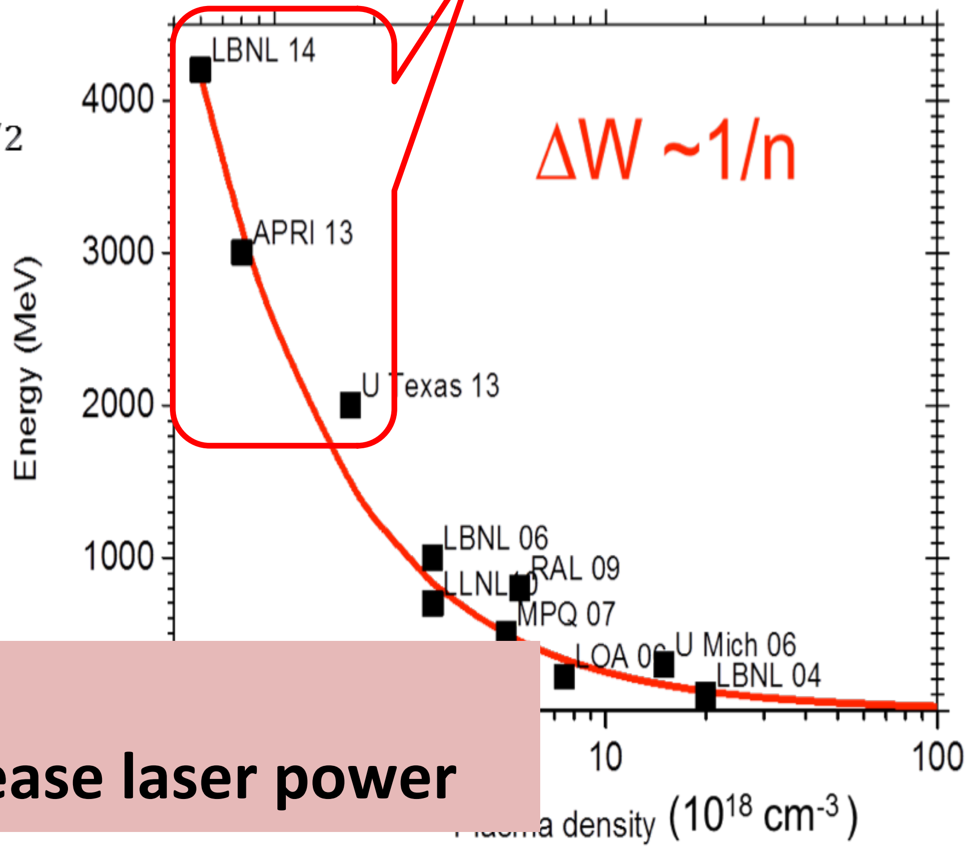
Proliferation of UHI laser Peta-Watt class lasers



Physics limitations of a single LWFA stage

- **Diffraction (Rayleigh range)**
  - **remedy: (self-focussing), laser guiding: channel, capillary, discharge**
- **Dephasing ($\gamma_{electrons} > \gamma_{plasma\ wave}$)** $L_{max} \propto n_0^{-3/2}$
  - **remedy : density downramp, staging**
- **Depletion** $L_{deplete} \propto \lambda_p^{\,3}/\lambda_L^{\,2} \propto n_0^{-3/2}$
- **gradient :** $G \sim E_0 = mc\omega_p/e \propto \sqrt{n_0}$
- **energy gain:** $\boldsymbol{W = G \times L_{acc} \propto 1/n_0}$
- **laser power:** $\boldsymbol{P_{laser} \propto 1/n_0}$

PW level
1-10 cm long plasma



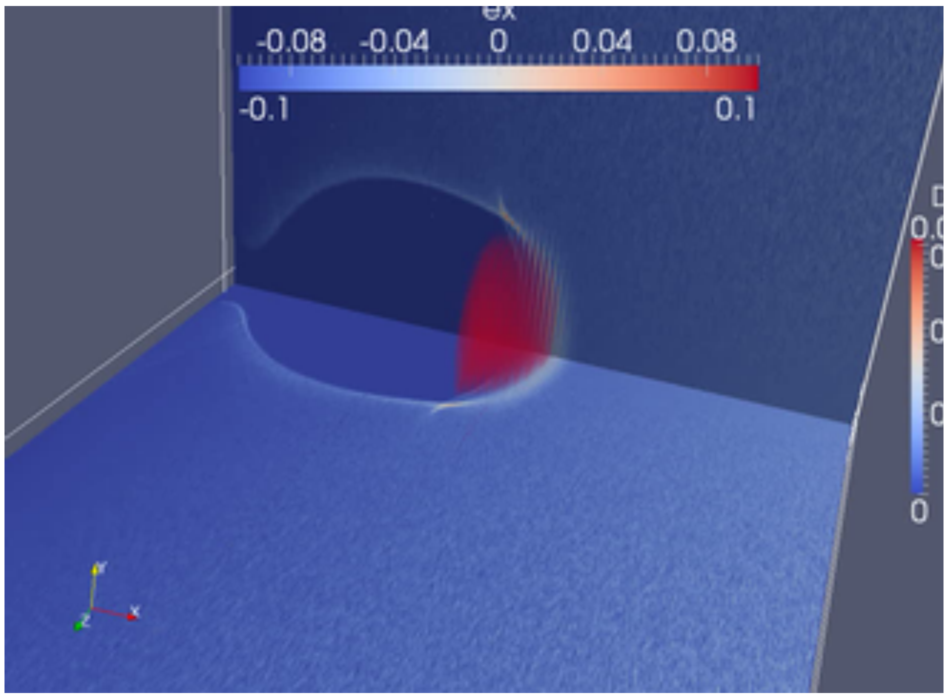
increase energy gain per stage
→decrease plasma density and increase laser power

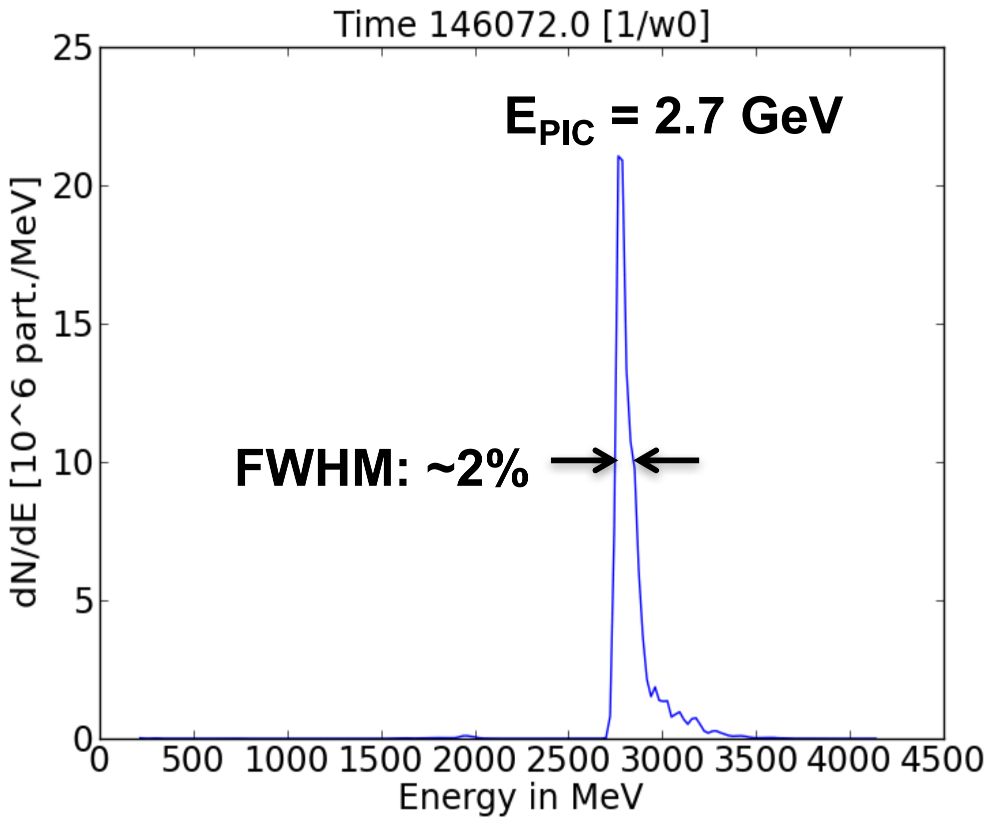
Blow-out regime LWFA : selfinjection and acceleration

A. Beck et al., NIM A 740 (2014).

- ❑ laser: 600TW 25fs (**CILEX/Apollon 1PW startup**)
- ❑ comoving window over 18mm
- ❑ bubble shrinks, then expands

energy spectrum of self-injected electrons





- **simulation shows stable acceleration even without guiding**
- **peaked energy spectrum around 3GeV after ~20mm**

Current Status of LWFA Electron Bunch Properties

slide courtesy by Mike DOWNER

Property	State of Art*	Reference	Remarks
Energy	**2 GeV** (± 5%, 0.1 nC) **3 GeV** (±15%, ~0.05 nC) **4 GeV** (±5%, 0.006 nC)	Wang (2013) - Texas Kim (2013) – GIST Leemans (2014) - LBNL	Accelerates from E ≈ 0
Energy Spread	**1%** (@ .01 nC, 0.2 GeV) **5-10%**	Rechatin (2009a) – LOA more typical, many results	0.1% desirable for FELs & colliders
Normalized Trans-verse emittance	**~ 0.1 π mm-mrad**	Geddes (2008) - LBNL Brunetti (2010) - Strathclyde Plateau (2012) - LBNL	Measurements at resolution limit
Bunch Duration	**~ few fs**	Kaluza (2010) – Jena (**Faraday**) Lundh (2011) – LOA; Heigoldt (2015) – MPQ/Oxford (**OTR**) Zhang (2016) – Tsinghua	Measurements at resolution limit
Charge	**0.02 nC** @ 0.19 GeV ±5% **0.5 nC** @ 0.25 GeV ±14%	Rechatin (2009b) – LOA Couperus (2017) - HZDR	Beam-loading achieved. FOM: **Q/ΔE** ?
Repetition Rate & Repeatability	~ **1 Hz** @ > 1 GeV **1 kHz** @ ~ 1 MeV	Leemans (2014) - LBNL He – UMIch ('15); Salehi ('17) – UMd; Guénot ('17) -- LOA	Limited by lasers & gas targets

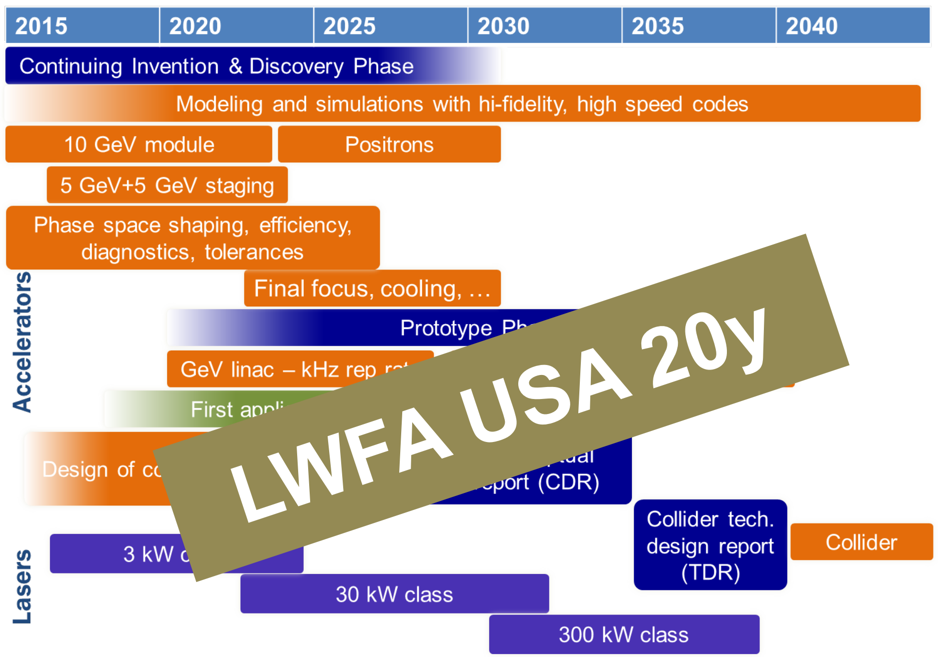
*** No one achieves all of these simultaneously!**

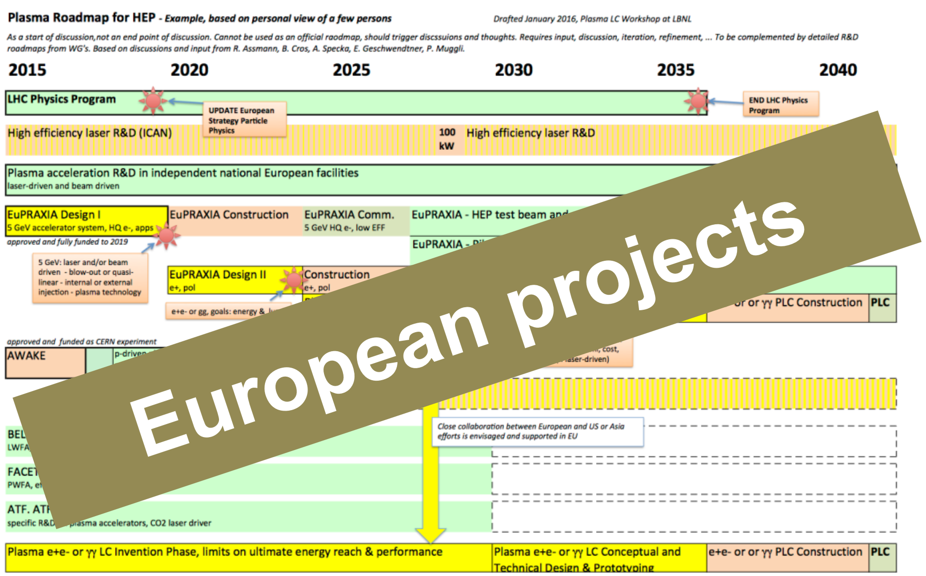
- Brunetti, *PRL* **105**, 215007 ('10)
- Couperus, *submitted* ('1
- Geddes, *PRL* **100**, 2150
- He, *Nat. Comms* **6**, 715

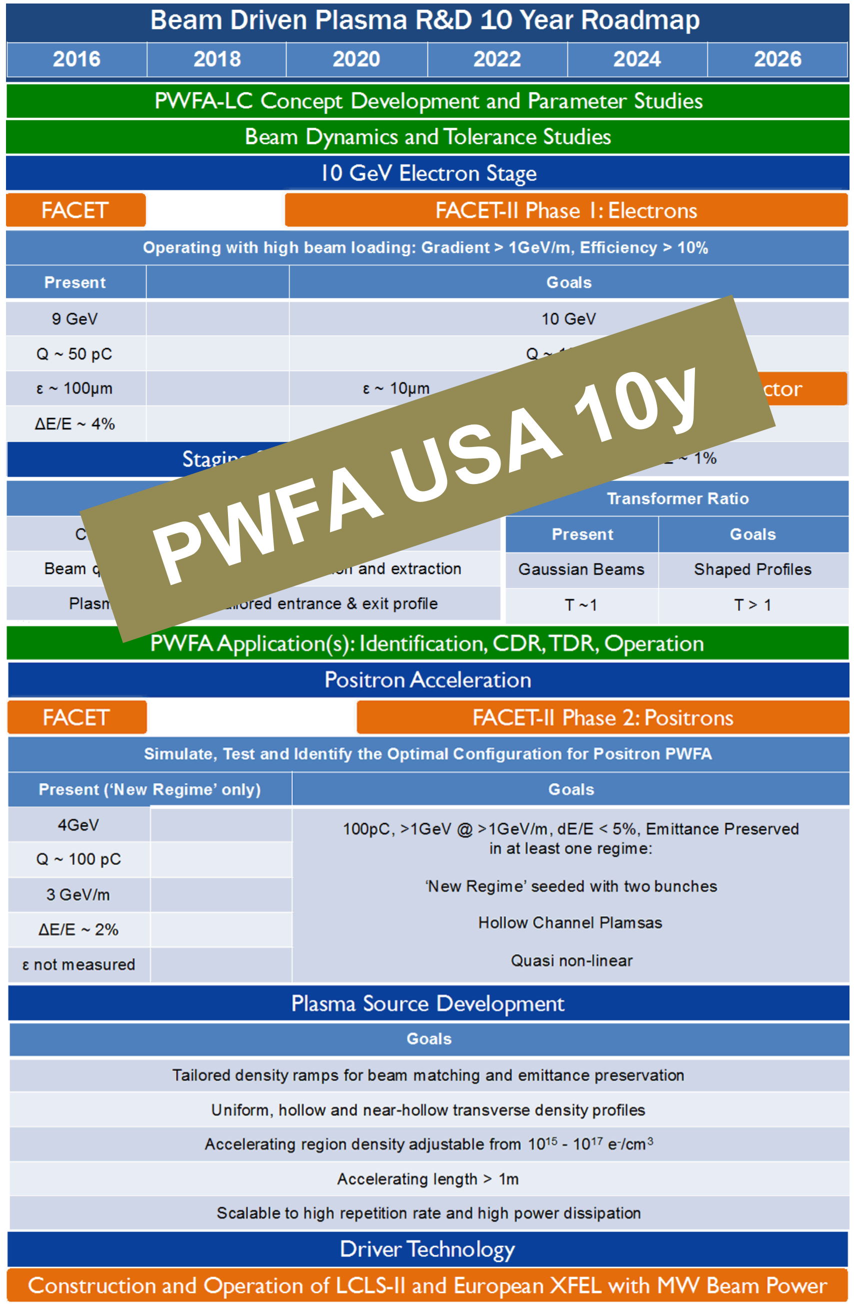
- Rechatin, *PRL* **103**, 194804 ('09b)
- *Opt. Lettt.* **42**, 215 ('17)
- *Nat. Comms* **4**, 1988 (2013)
- *PRST-AB* **19**, 062802 (2016)

Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop 2017
April 25-28, 2017 at CERN

strategy roadmaps







known challenges for plasma accelerators (e^-/e^+)

- energy spread -> luminosity, luminosity spectrum
- driver-to-beam efficiency and beam loading
- emittance preservation (transv. fields, scattering, ion motion)
- multi-staging (driver in/out-coupling, interstage transport
- positron acceleration
- spin polarization
- wall-plug energy efficiency of driver (especially laser)
- beam quality and stability (energy spread, emittance)

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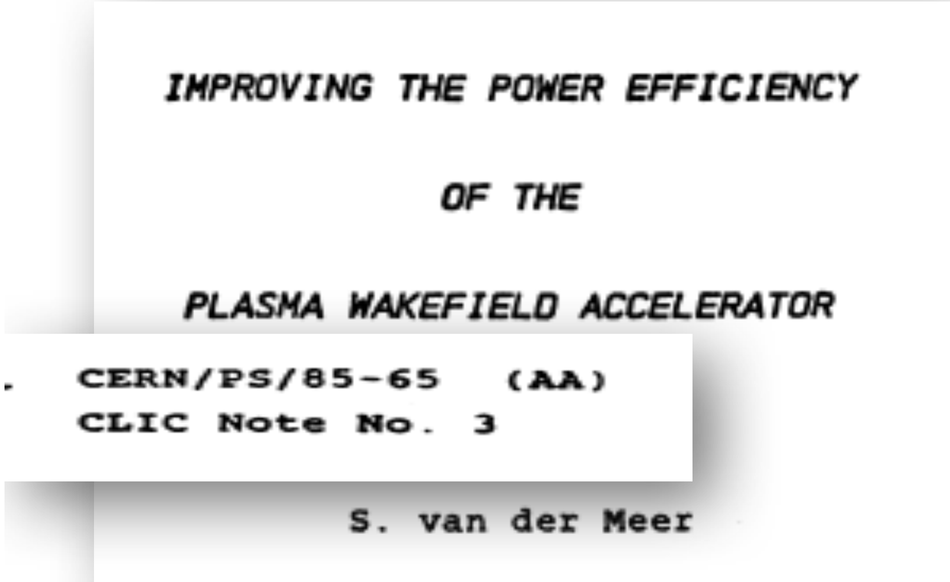
E efficiency and E spread: optimized beam loading


IMPROVING THE POWER EFFICIENCY

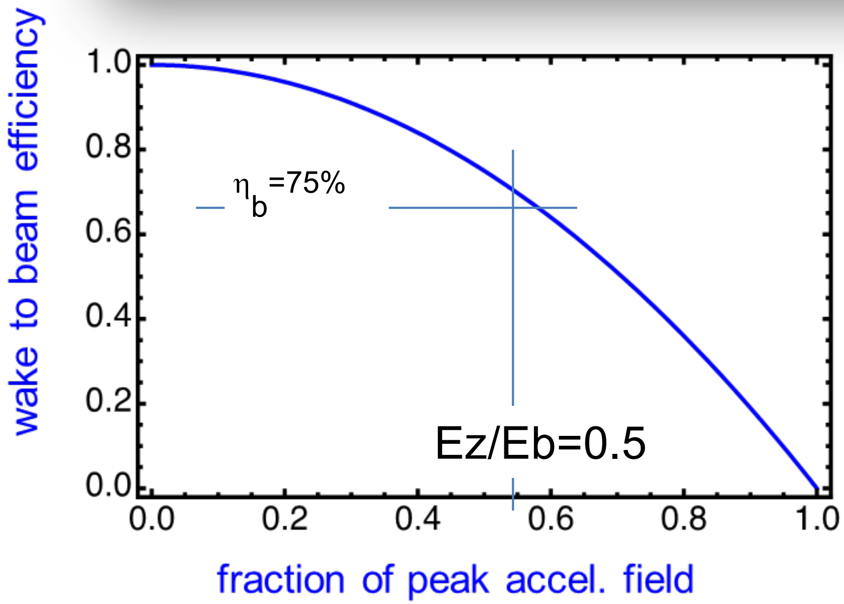
OF THE

PLASMA WAKEFIELD ACCELERATOR

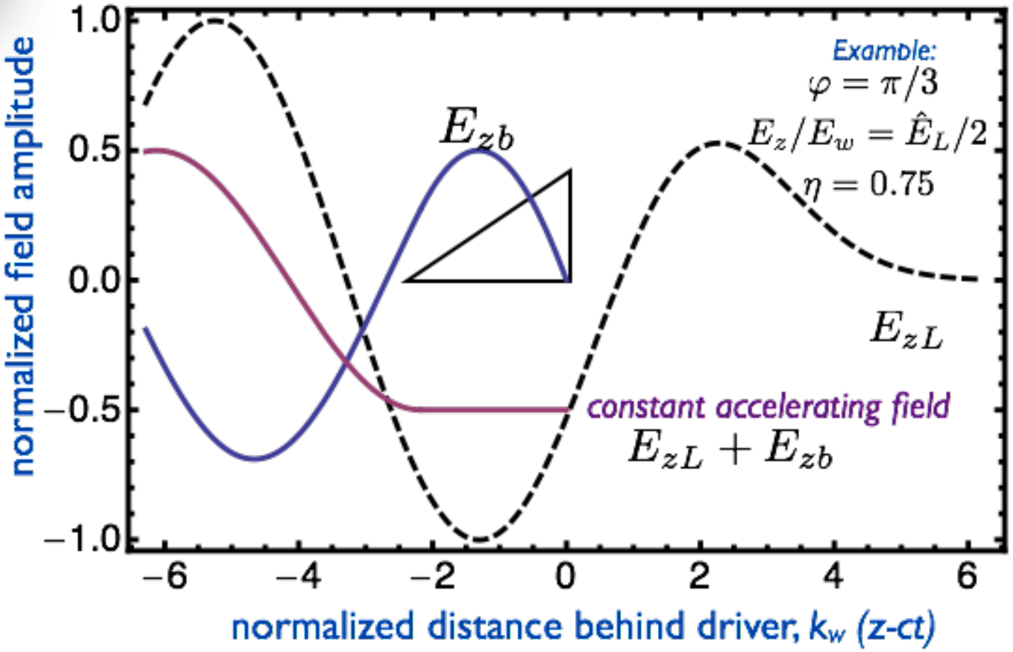
CERN/PS/85-65 (AA)
CLIC Note No. 3

S. van der Meer

- increase energy efficiency
  →shape drive beam (PWFA)
- minimize energy spread
  → shaped witness beams



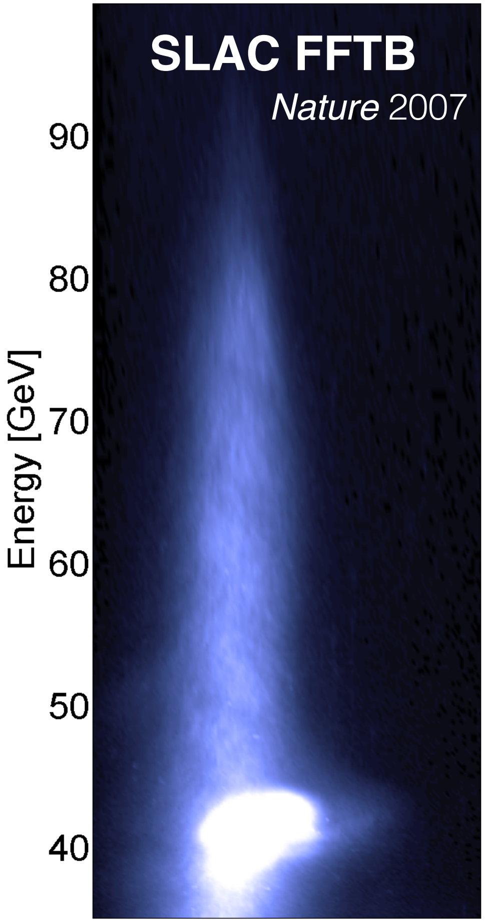
C. Schroeder et al, Phys. Plasma (2013)



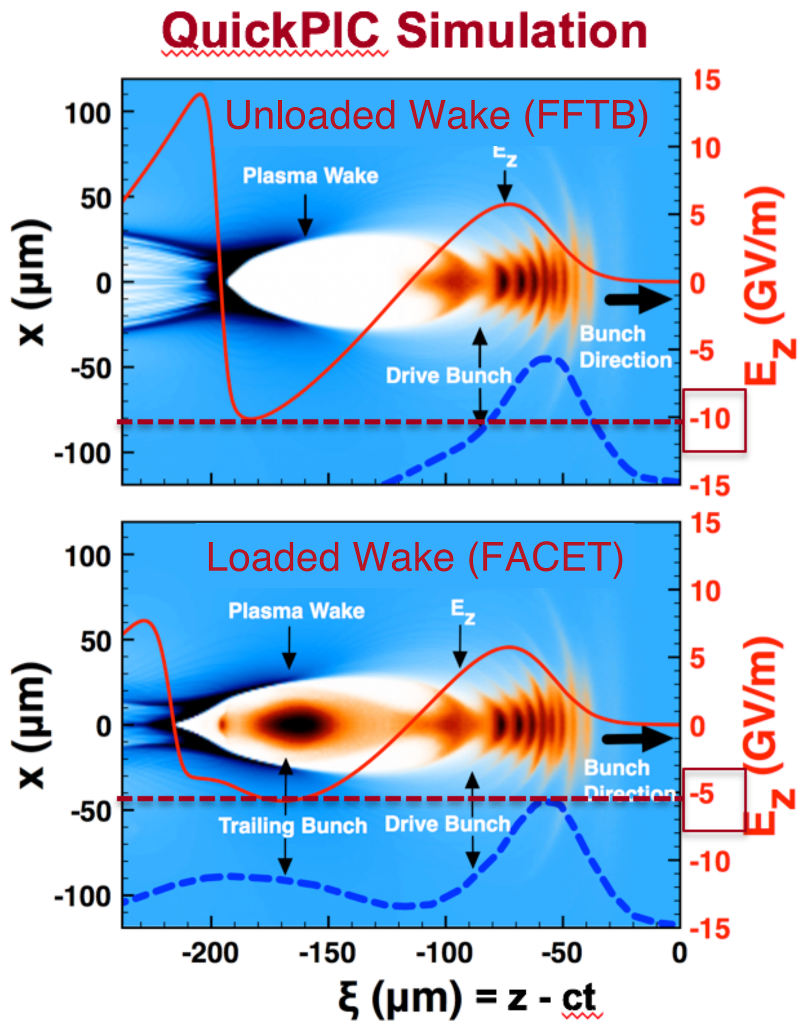
slide courtesy by M. Hogan

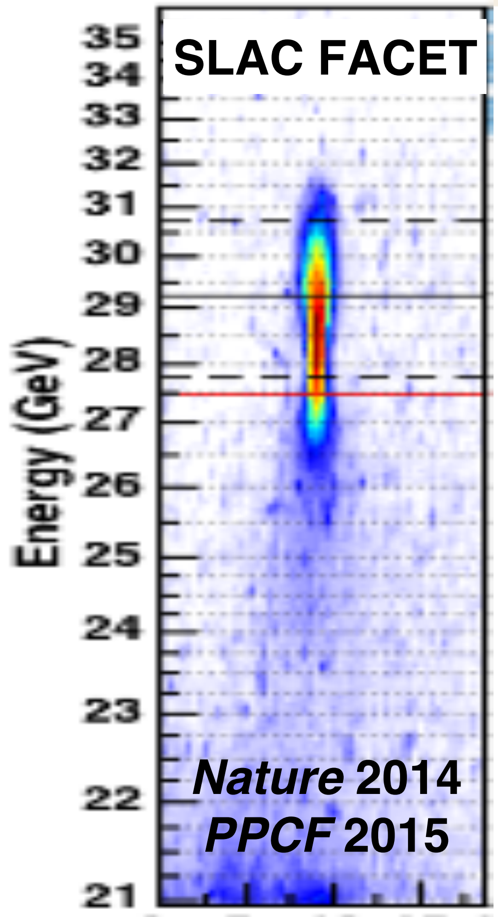
High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

UCLA SLAC



43 GeV
Energy Gain





9 GeV
Energy Gain

Narrow energy spread acceleration with high-efficiency has been demonstrated
Next decade will focus on simultaneously preserving beam emittance

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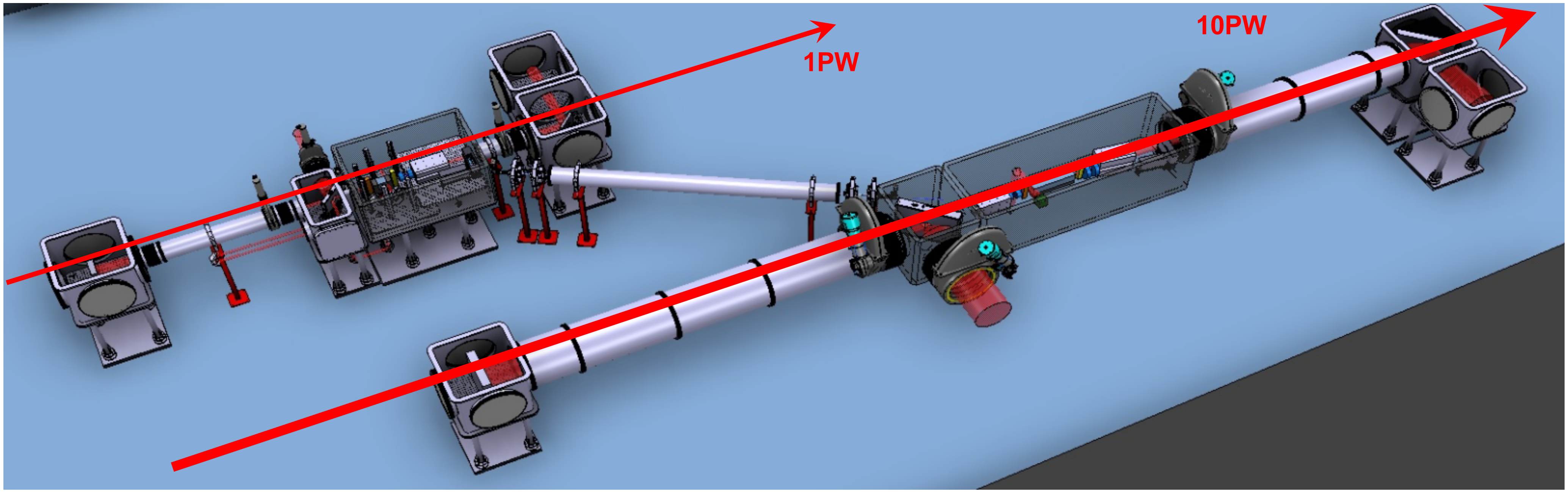
CILEX 10PW laser (F): planned 2 stage experiment

- **Challenges for staging scheme**
  - Large divergence + energy spread of beam produced by LPA
    ⇒ strong demand on beam optics
    ⇒ strong emittance growth in the drift after the plasma
  - Coupling of laser beams to the plasma structures in a narrow and busy room
- **Under study: EuPRAXIA, Cilex-Apollon, …**



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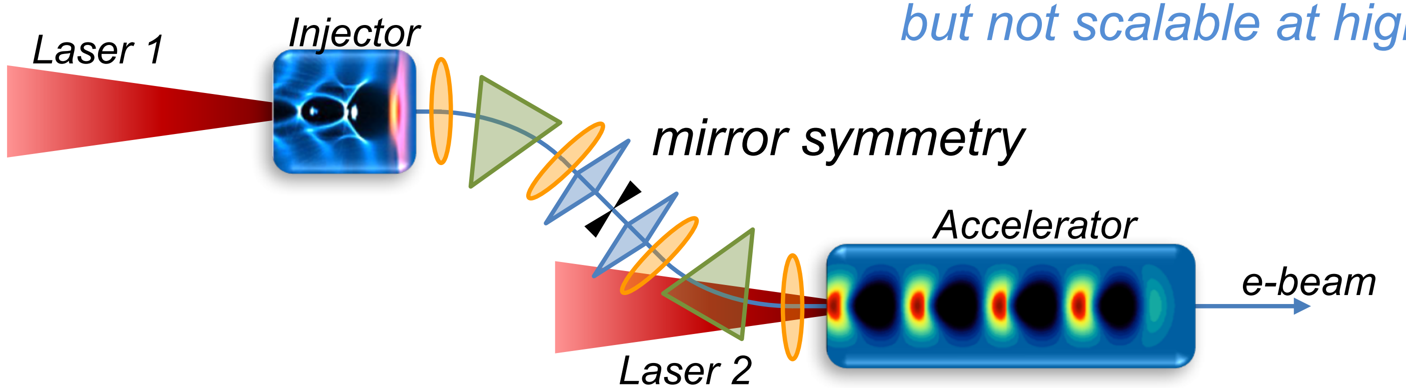
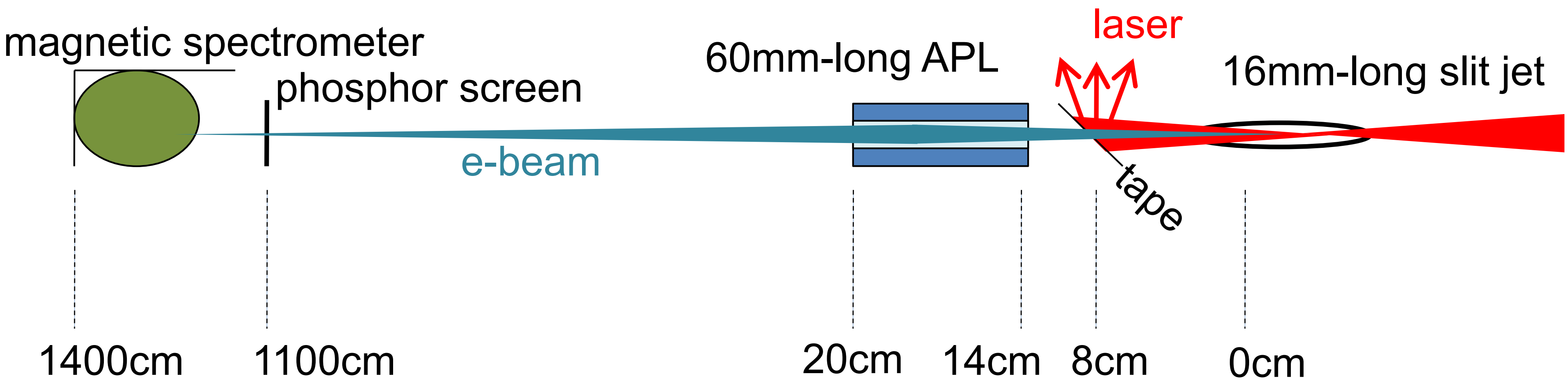
Example: 2-stage schema under study at Cilex-Apollon

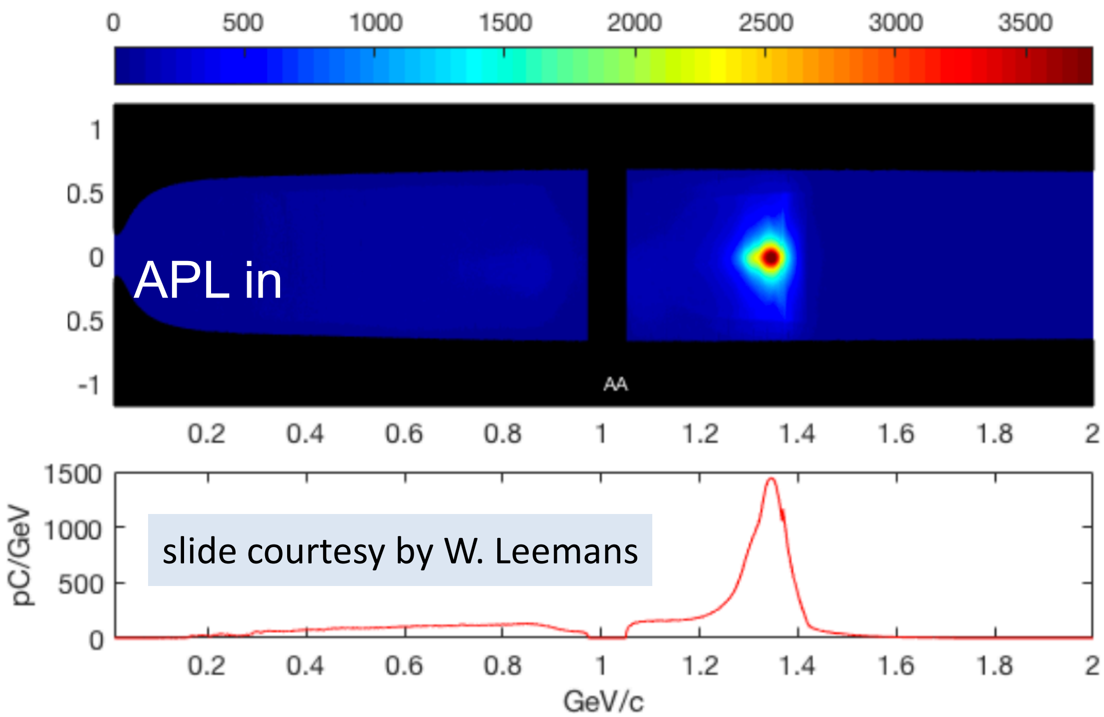
allows easier laser beam transpo
well suited at low energy
but not scalable at high energy

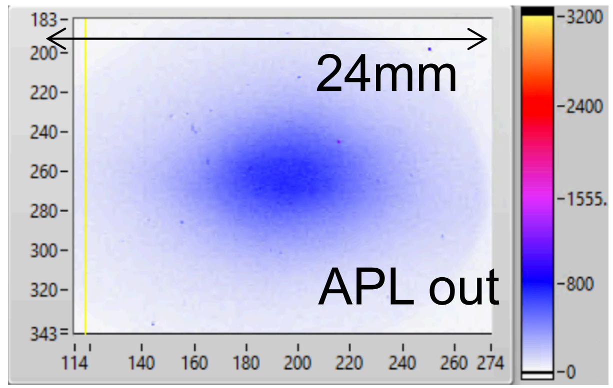


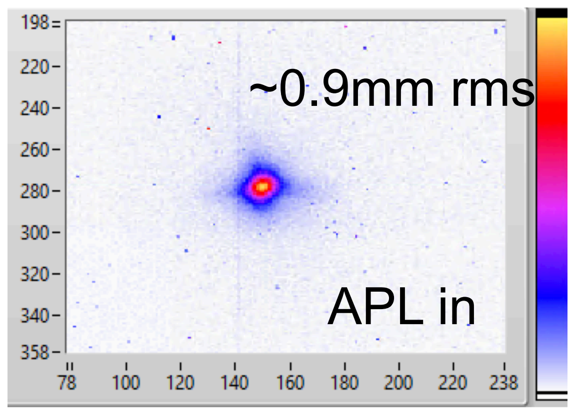
A. Chancé et al, NIM A 740 (2014)

Active Plasma Lens focuses 1.4 GeV beam onto phosphor screen at ~11 m from source and ~60 cm from source





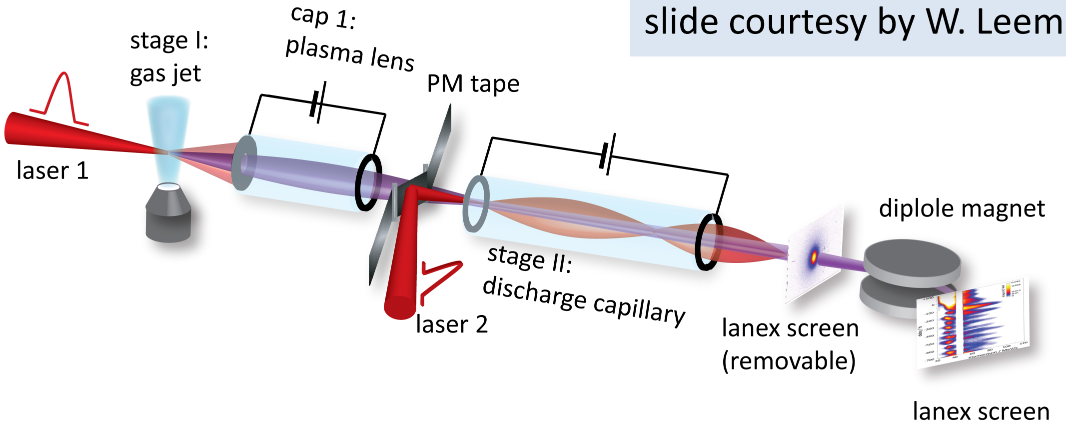




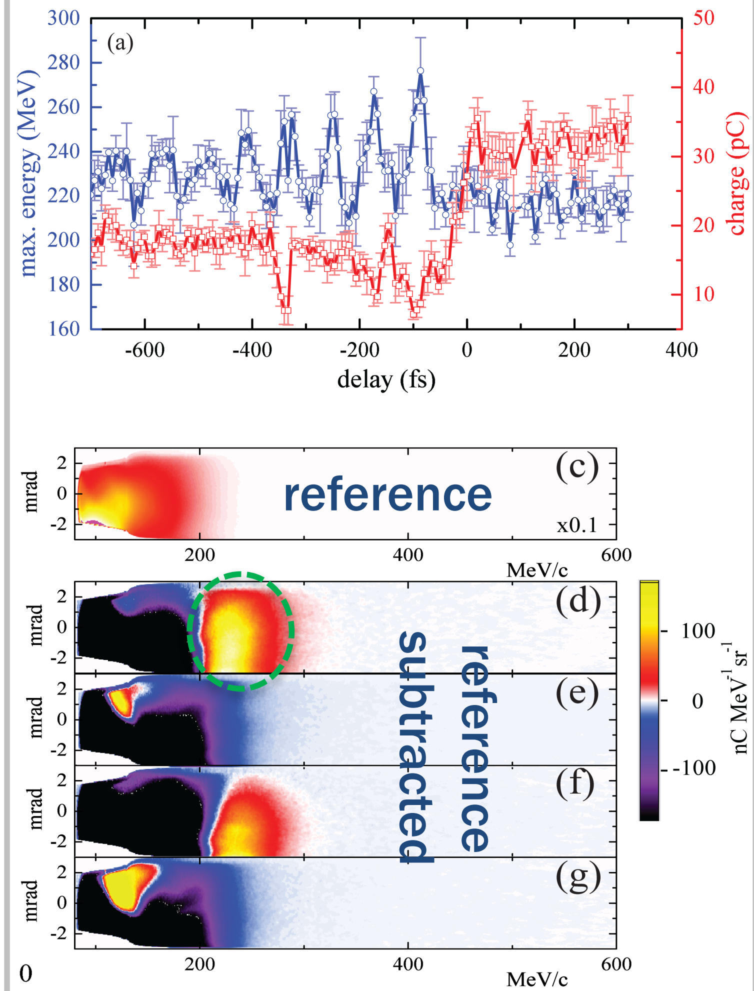
Collaboration with Feurer/Tarkeshian (UBern) for charge density monitoring

first independently powered staging of two consecutive laser plasma accelerators at BELLA Center of LBNL

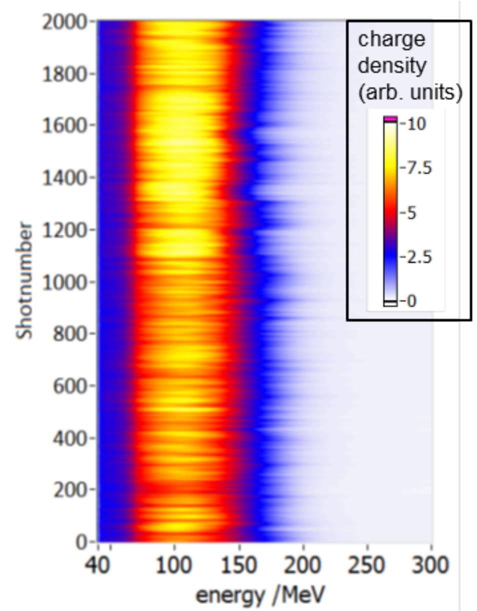
slide courtesy by W. Leemans



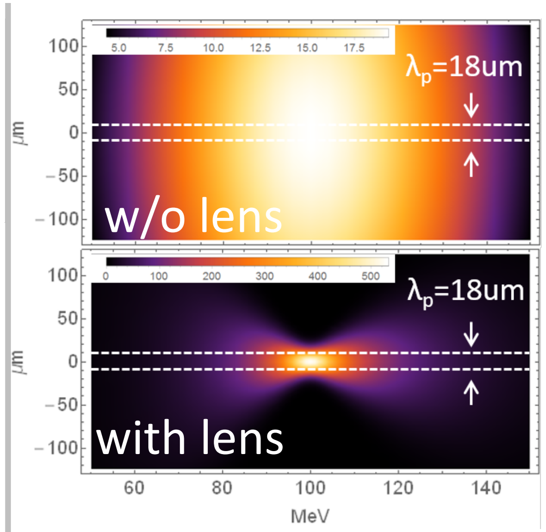
Staging Result



Stable Injector



Plasma Lens Transport



J. van Tilborg et al., PRL 184802 (2015)

S. Steinke et al., Nature 530, 190 (2016)

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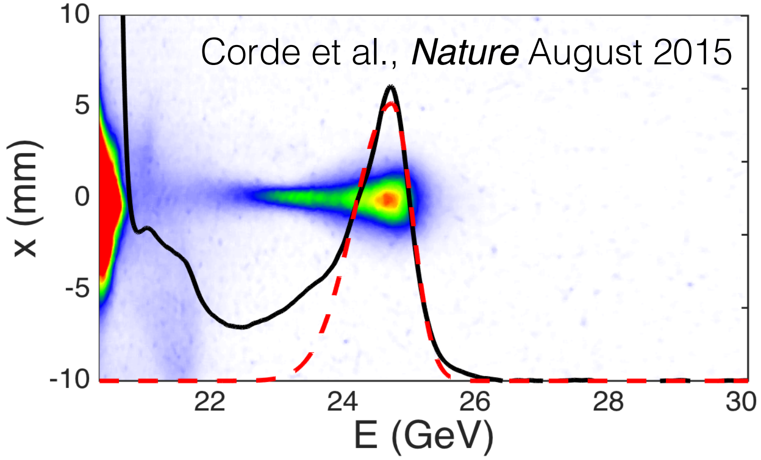
FACET/FACET-II Have a Unique Role in Addressing Plasma Acceleration of Positrons for Linear Collider Applications

slide courtesy by M. Hogan

Multi-GeV Acceleration in Non-linear wakes

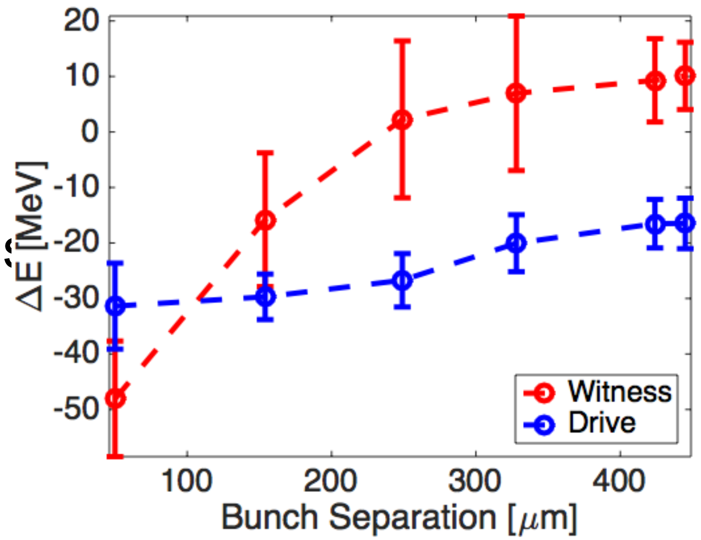
- New self-loaded regime of PWFA
- Energy gain 4 GeV in 1.3 meters
- Low divergence, no halo



Hollow Channel Plasma Wakefield Acceleratio

- Engineer Plasma to Control the Fields
- No focusing on axis
- Measured transverse and longitudinal wakefields

Gessner et al., *Nature* Communications 2016
Lindstrom et al., submitted 2017



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EuPRAXIA collaboration: conceptual design study

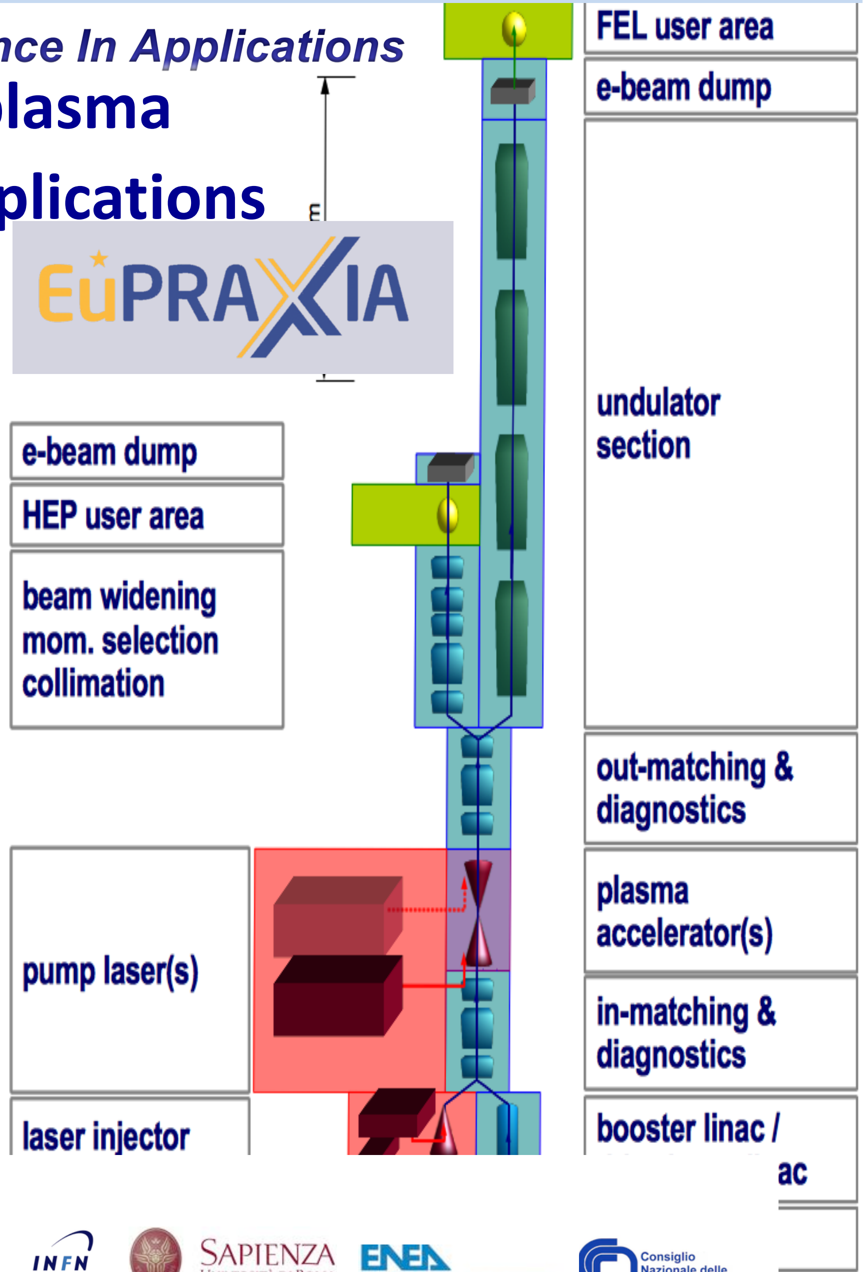
European Plasma Research Accelerator with eXcellence In Applications

design, propose, and build a dedicated plasma accelerator facility for R&D and pilot applications

- 2015-19: *conceptual design study (3M€)*
- 2020: on updated ESFRI
- 2025: startup

Electron beam energy	1-5 GeV
Charge per bunch	1 – 100 pC
Repetition rate	10-100 Hz
Bunch length	0.01 – 10 fs
Peak current	1 – 100 kA
Energy spread	0.1-1%
Norm. emittance	0.01 – 1 µm

EuPRAXIA



CNRS, CEA, SOLEIL Synchrotron, IST-ID, DESY, Universität Hamburg, University of Strathclyde Glasgow, Imperial College London, University of Oxford, University of Liverpool, Manchester 1824 The University of Manchester, Science & Technology Facilities Council, INFN, Sapienza Università di Roma, ENEA, Consiglio Nazionale delle Ricerche

Introduction: Structure, Roles

- Collaboration of **38 institutes**
  - **16 EU laboratories** are beneficiaries
  - **22 associated partners** from EU, Europe, Asia and US contribute in-kind, 4 of them joined after first year of project:
    KIT (Germany), FZJ (Germany),
    University Jerusalem (Israel), IAP (Russia)
- Collaboration brings together:
  - Big science labs: photon science, particle physics
  - Laser laboratories: high power lasers
  - International laboratories: CERN, ELI (associated)
  - Universities: accelerator research, plasma, laser
- Organized in **8 EU-funded work packages** and **6 in-kind work packages**
  - DESY is coordinator laboratory (R. Assmann)
- **125 scientists** in our work list

The Team

The EuPRAXIA team

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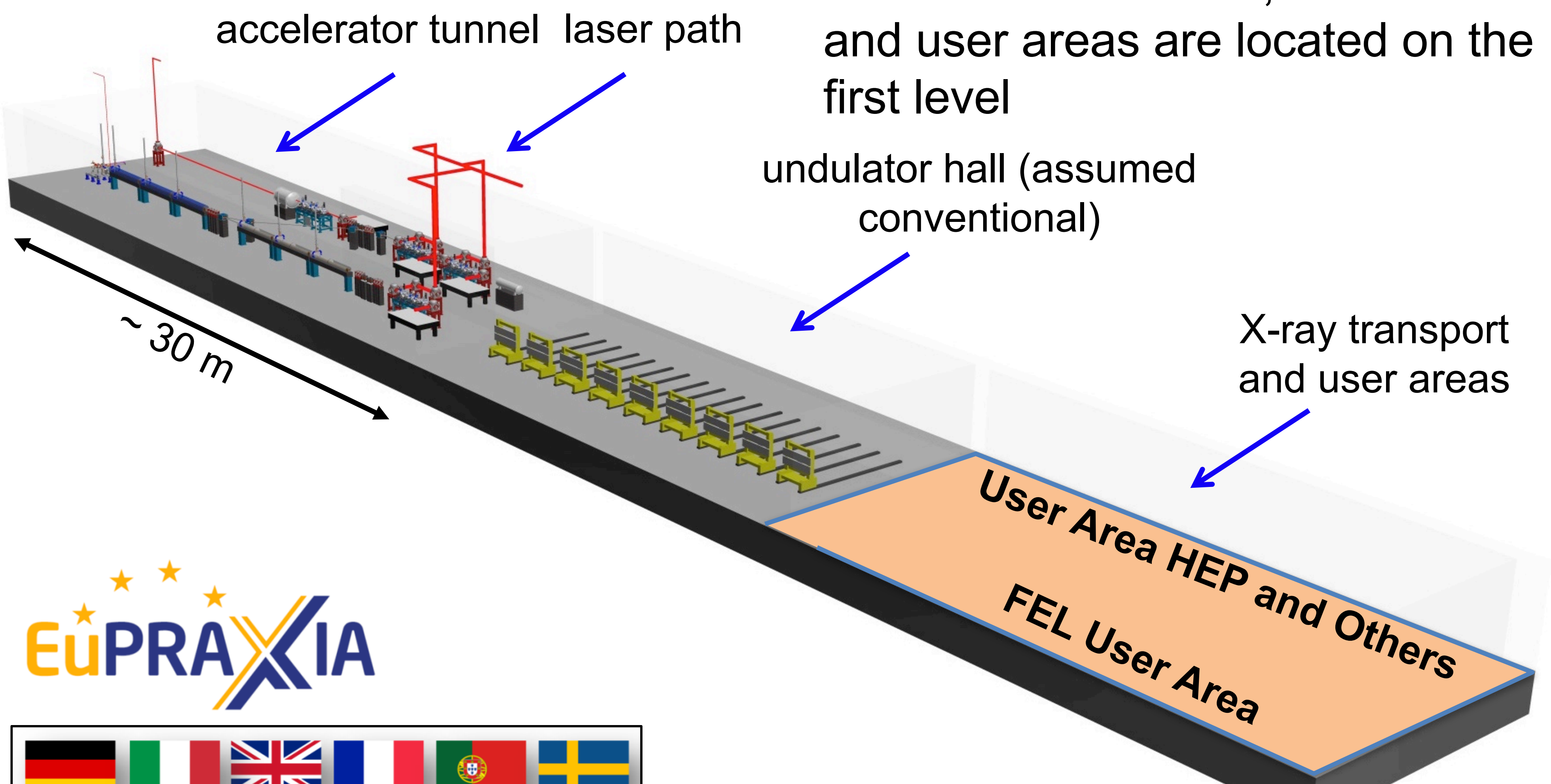
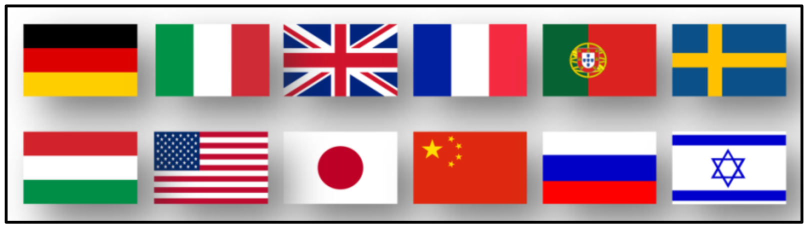
Overall layout status (ongoing)

Horizon 2020

Accelerator research, undulators and user areas are located on the first level

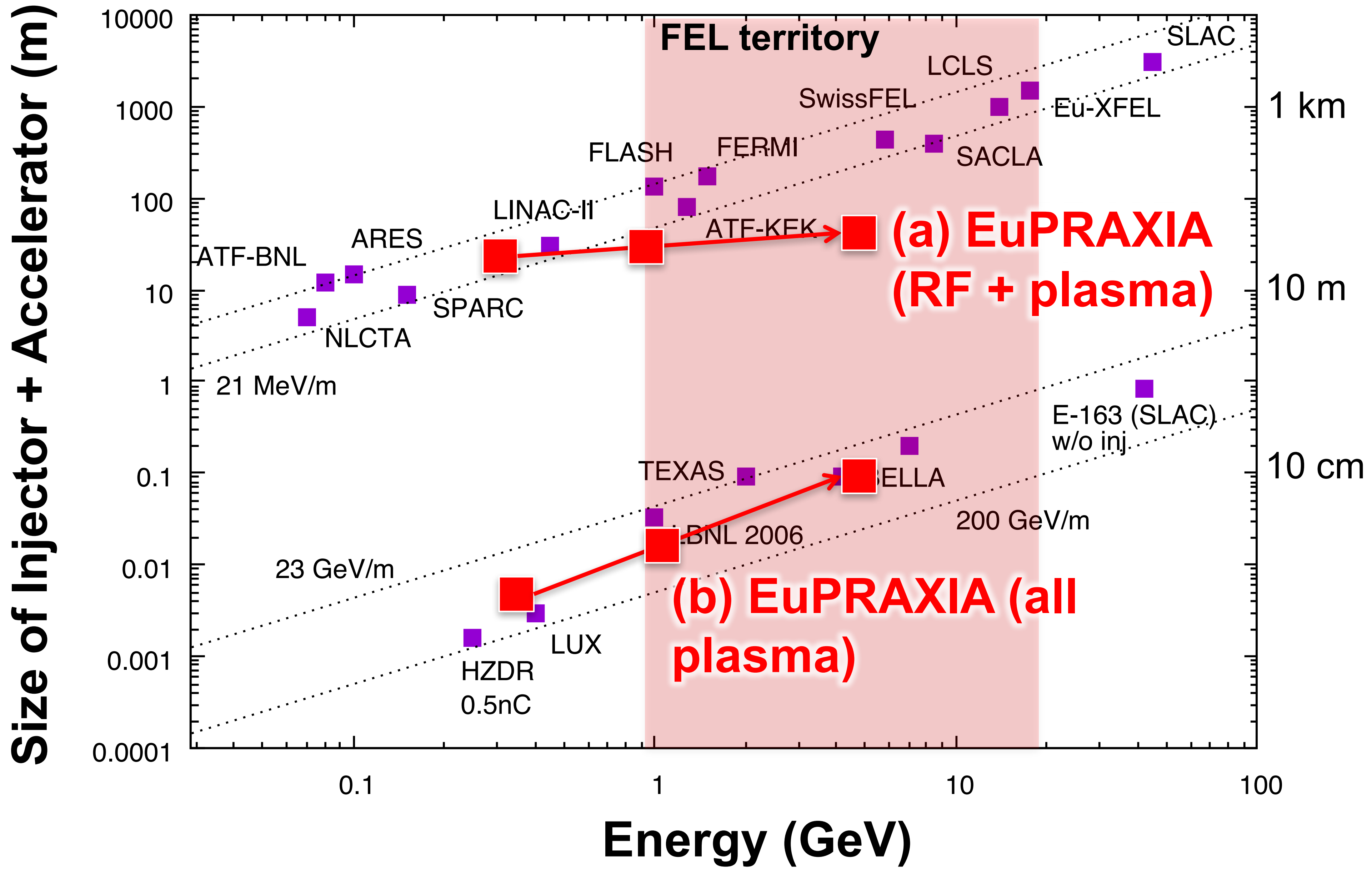




Design by A. Walker (DESY) and Dariusz Kocoń (ELI-Beams)

EuPRAXIA Development Paths

towards high quality electron beams



Summary and conclusions

- **wide variety of advanced acceleration schemes, physics simple**
- **plasma acceleration enters age of maturity**
- **complementarity between approaches (LWFA, PWFA, proton diven PWFA)**
- **plasma accelerator experiments and simulations address all collider and HEP relevant issues (or challenges):** ***efficiency, beam quality, staging, positrons, stability,….***
- **plasma accelerator driven light source as accelerator R&D facility should be the intermediate step from acceleration experiments and bunches to accelerators and beams**

EuPRAXIA overview paper: P. A. Walker *et al.*, 'Horizon 2020 EuPRAXIA design study', *J. Phys.: Conf. Ser.* **874**, 012029 (2017)
http://iopscience.iop.org/article/10.1088/1742-6596/874/1/012029
ANAR2017 Workshop report:
http://www.lpgp.u-psud.fr/icfaana/ana-publications-2017

Summary and conclusions

Thank you for your attention

- complementarity between approaches (LWFA, PWFA, proton diven PWFA)
- plasma accelerator experiments and simulations address all collider and HEP relevant issues (or challenges): *efficiency, beam quality, staging, positrons, stability,....*
- plasma accelerator driven light source as accelerator R&D facility should be the intermediate step from acceleration experiments and bunches to accelerators and beams

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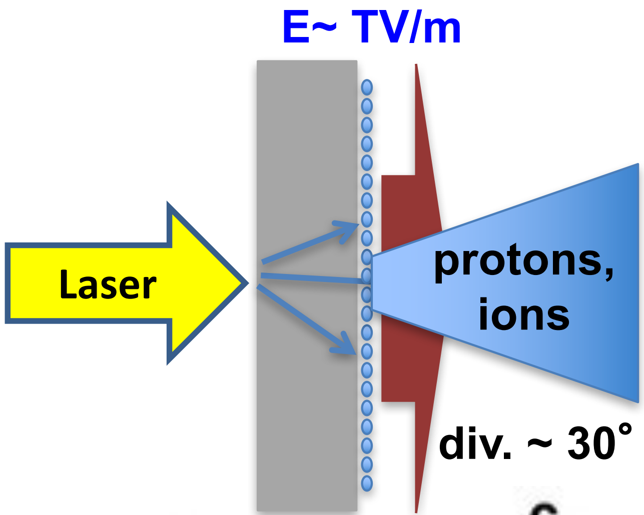
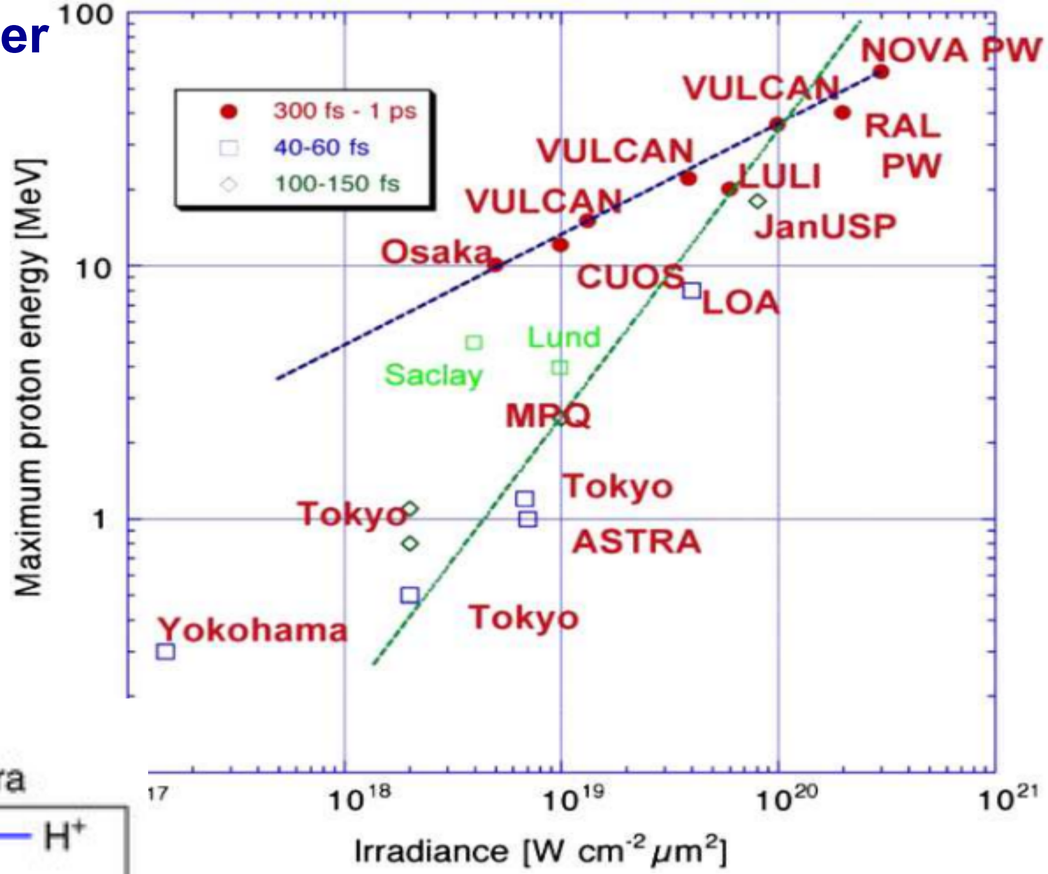
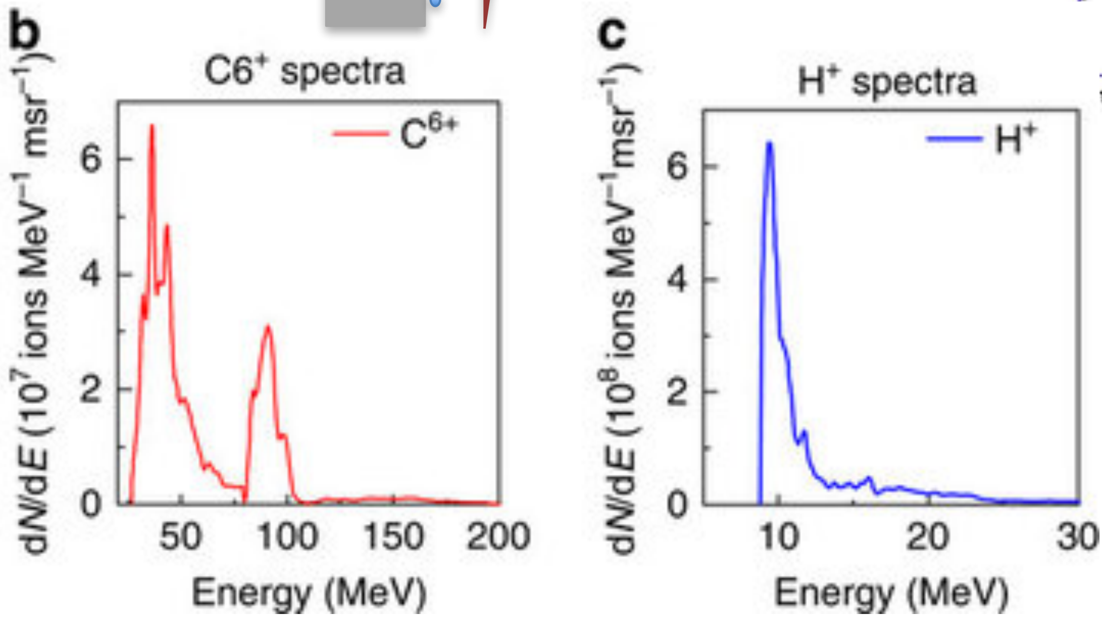
BACKUP SLIDES

Laser-plasma acceleration of protons (and ions)

Target Normal Sheath Acceleration: laser on solid targets (overdense plasma) acceleration on downstream surface





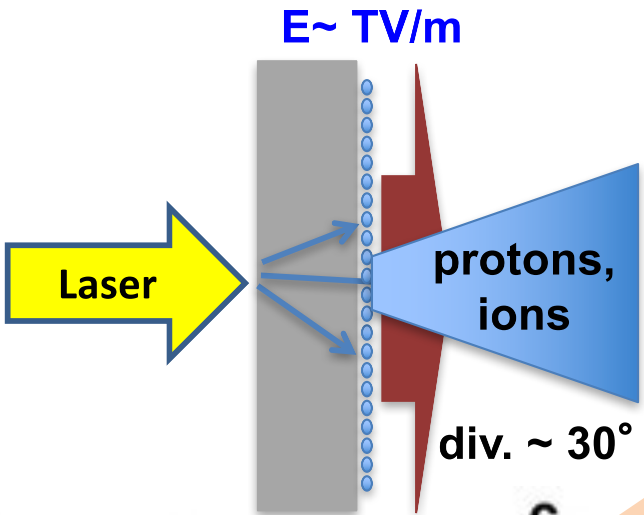


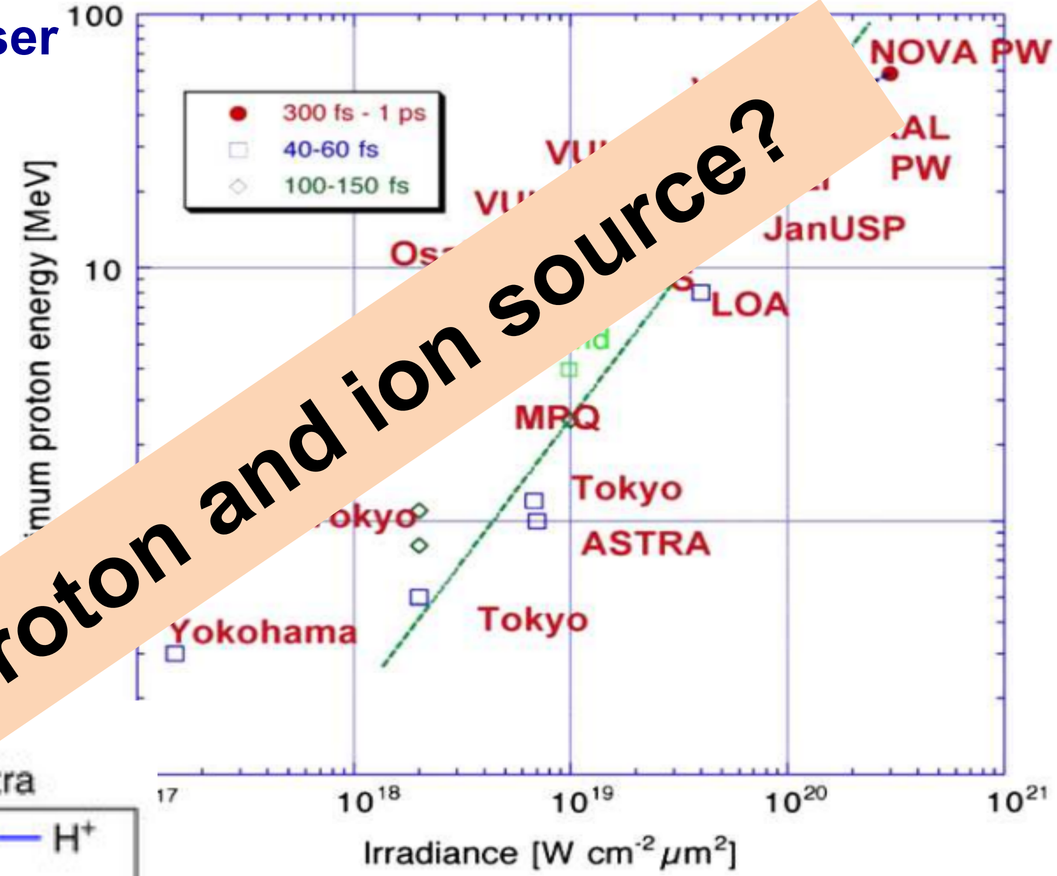
peaked ion spectra
nanometer thick, complex targets
volume acceleration?

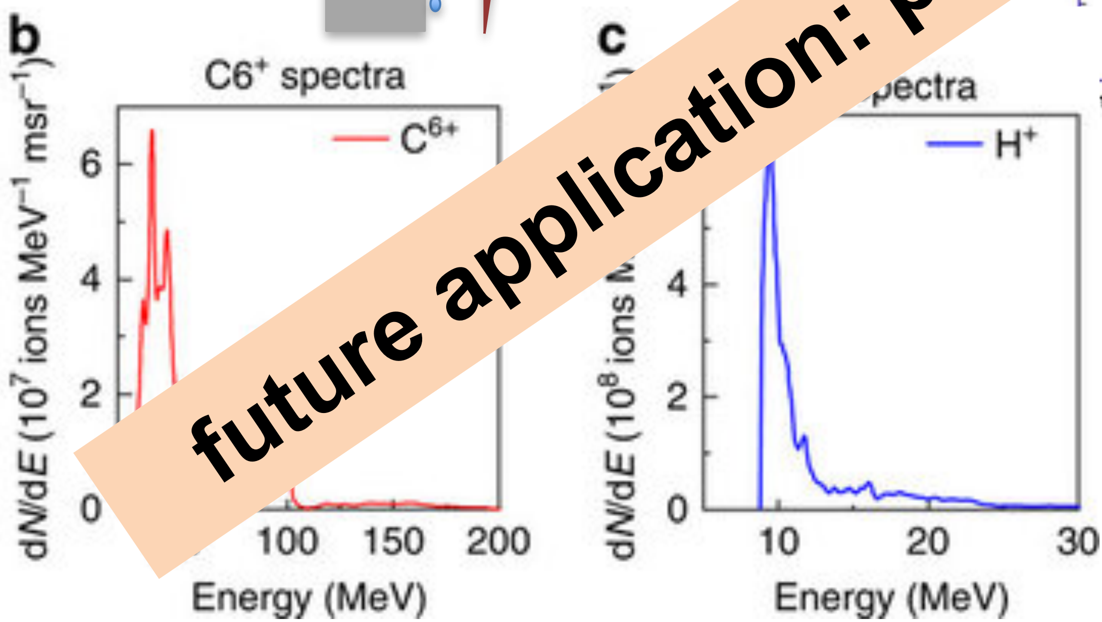
[S. Palaniyappan et al., Nature Communications 2015] LANL Trident Laser (80J, 650 fs)

Laser-plasma acceleration of protons (and ions)

Target Normal Sheath Acceleration: laser on solid targets (overdense plasma) acceleration on downstream surface







future application: proton and ion source?

peaked ion spectra
nanometer thick, complex targets
volume acceleration?

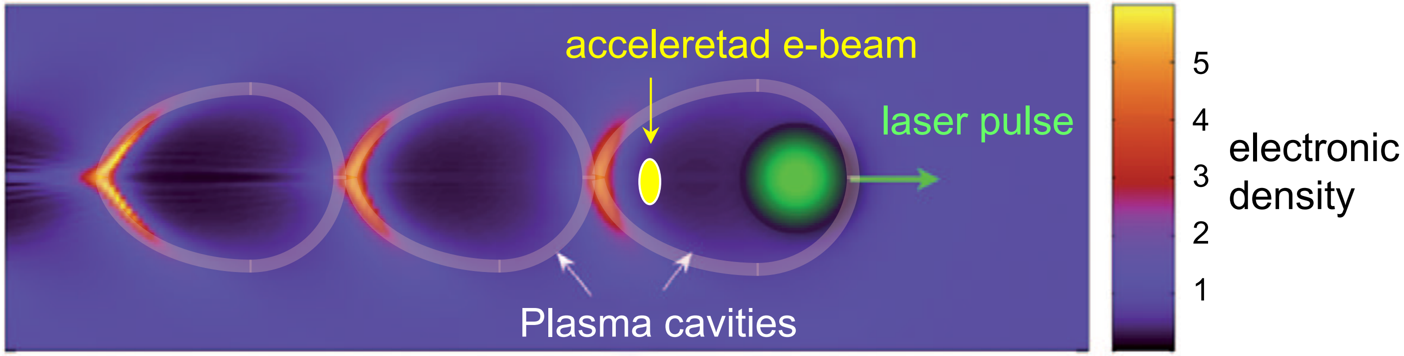
[S. Palaniyappan et al., Nature Communications 2015] LANL Trident Laser (80J, 650 fs)

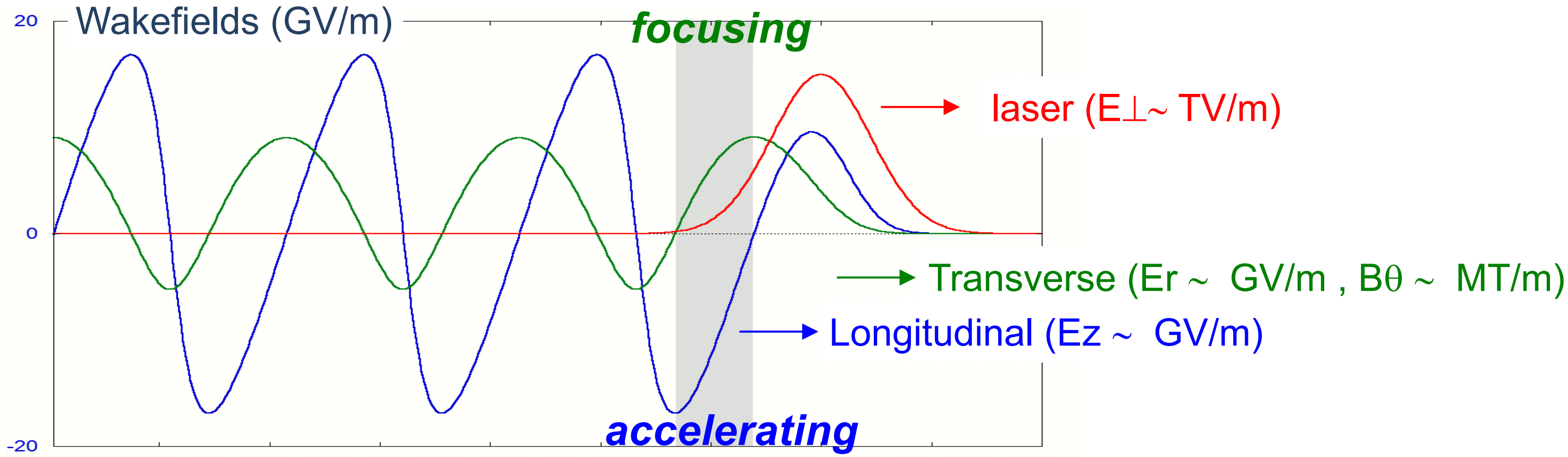
Acceleration - Focalisation

- **Electron beam should sit at the correct phase of**
  - the accelerating field $W_z = E_z$
  - the focusing field $W_\perp = E_r - cB_\theta$

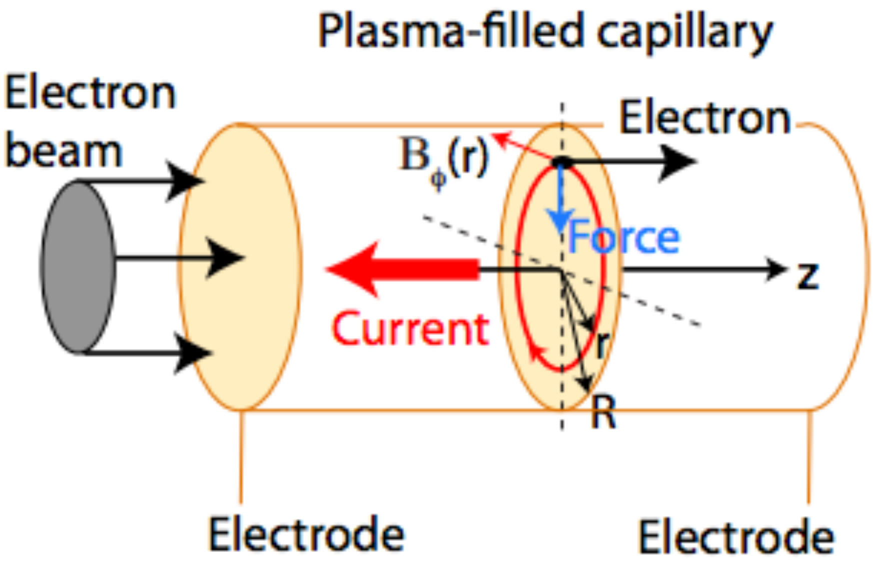
Relation Panofsky-Wenzel

$$\partial W_z/\partial r = \partial W_\perp/\partial \xi$$

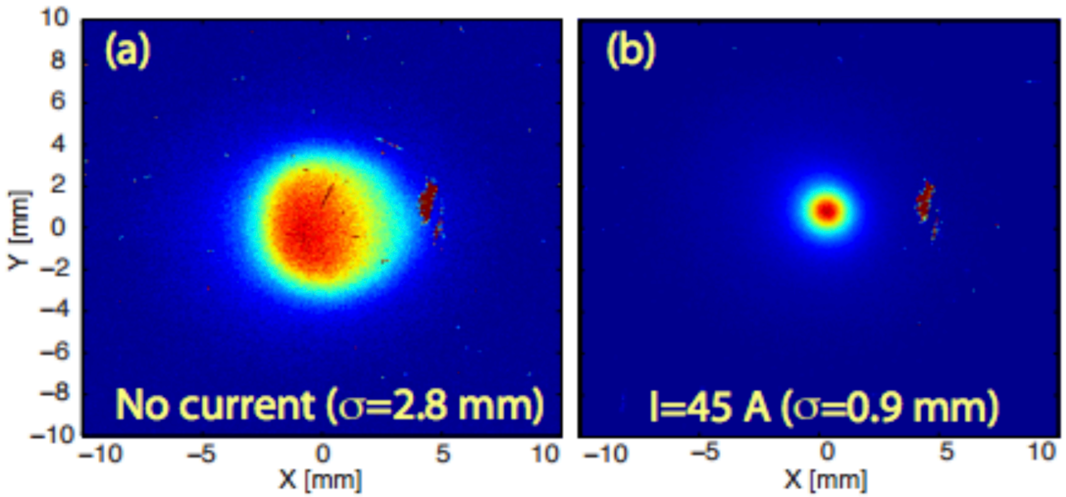




Capillary discharge guides laser pulses AND (de)focuses electron beams



Electron beam



- Symmetric focusing
- Tunable strength with peak gradients >3,000 T/m
- Low chromatic aberrations
- Small bore

J. Van Tilborg et al., PRL 2015

J. van Tilborg *et al*. PR-AB 20, 032803 (2017)