Laser Plasma Acceleration at Low Plasma Densities

R. Assmann

DESY

Apollon FIRE User's Meeting

11.02.2016, Paris, France

European Network EuroNNAc for Novel Accelerators

EuPRAXIA

Accelerator Research and Development ARD

A program by the Helmholtz association

EuCARD²

LAOLA.

HELMHOLTZ ASSOCIATION

DESY

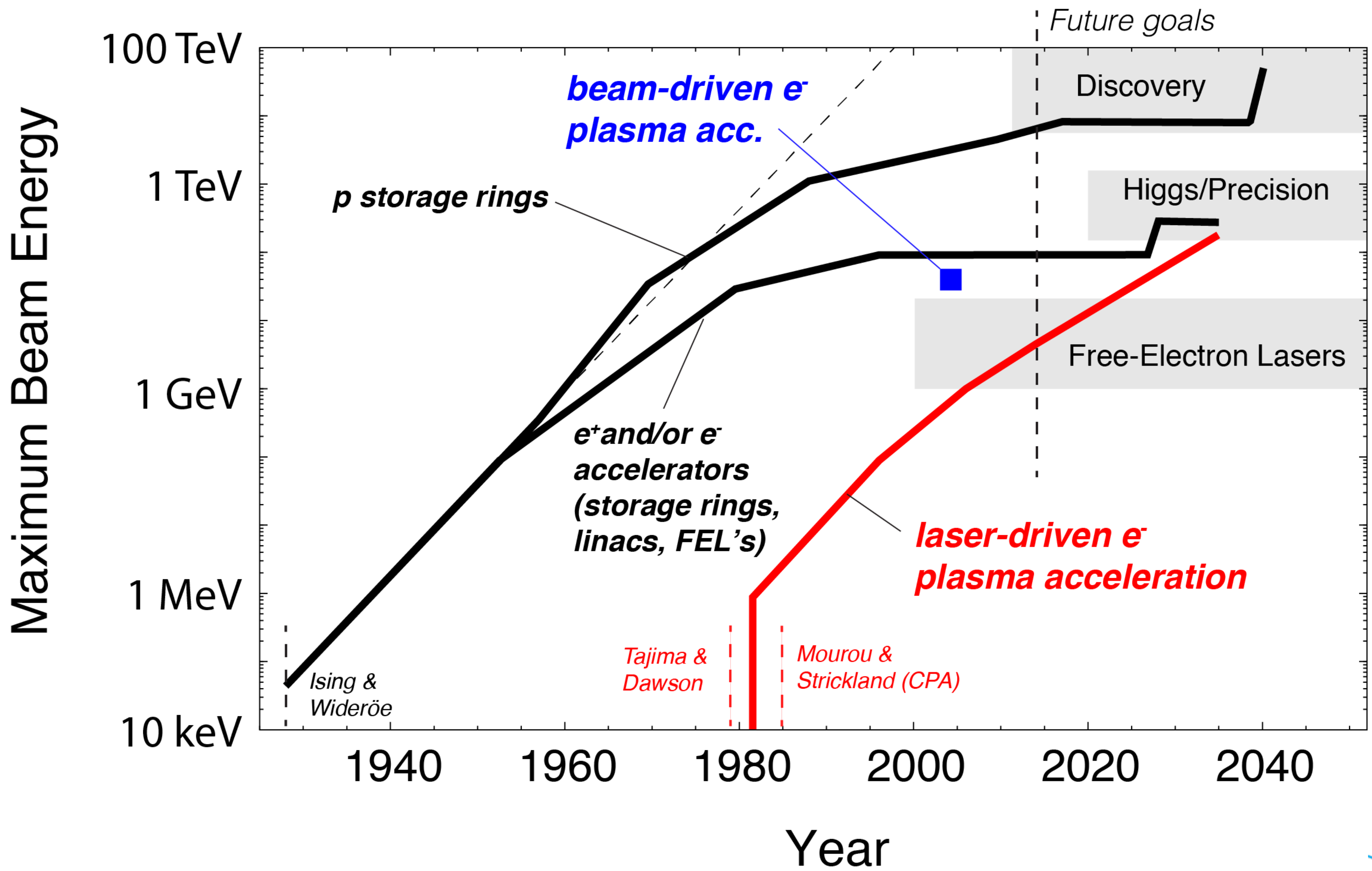
Introduction

- **Apollon Fire will provide laser capabilities at the frontier of the technical possibilities.**
- The laser-driven generation and acceleration of **electron beams** has seen great success over the last years:
  - **Publication of results in journals with highest impact factor** (Nature, PRL, ...) → academic success and recognition.
  - **Production of "serious" beams that attract more and more interest from big science (particle physics, photon science)** → potential of laser-driven beam facilities opening new territory and possibilities for scientific research with e- beams
- DESY has joined a strongly growing community on advanced accelerator research and is setting up research facilities in Hamburg:
  - Leading, state-of-the-art electron beams (this is our core expertise)
  - Thales 200 TW Ti:Sa Laser (much lower than Apollon Fire)
- In parallel: Strongly involved in community activities. See Horizon2020 project EuPRAXIA. **Strong interest to involve ourselves in experiments at other institutes** → APOLLON Fire

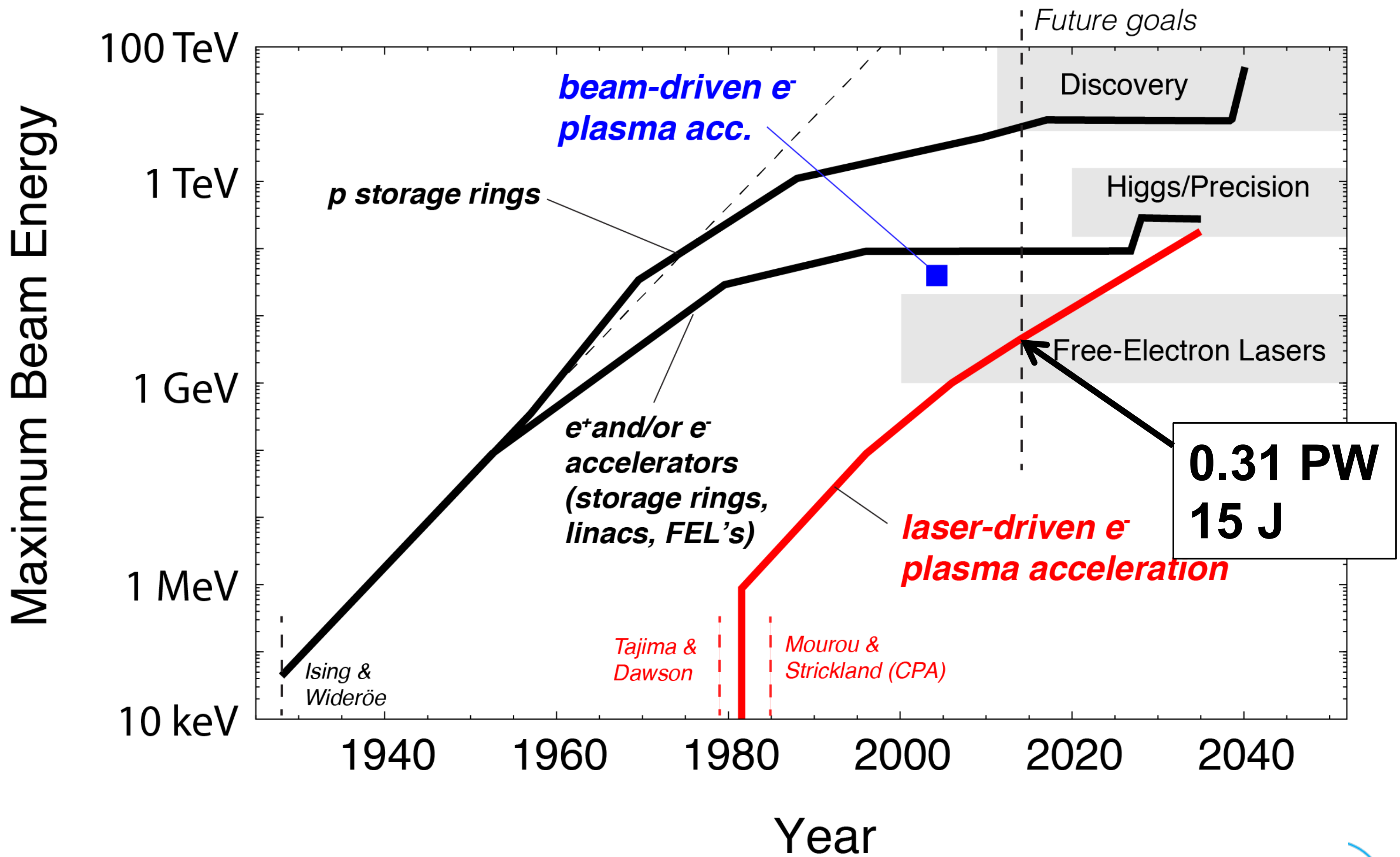
Apollon (from workshop web site)

- Apollon* laser facility designed in collaboration between several partners of the Université Paris-Saclay and their industrial partners, on the Plateau de Saclay, South of Paris (France), is expected to reach for the 10 Petawatt level.
- **The facility will include two short-pulse laser beams (F1 at 10 PW nominally, with a first step at 5 PW, and F2 at 1 PW, both at 15 fs duration), a chirped laser pulse (up to 250 J, 1 ns) and a probe beam (up to 100 mJ, 20 fs minimum), all available at a repetition rate of one shot per minute at full power and in a stable manner.**
- Two target areas will be serviced by these laser beams in alternate mode: the LFA, dedicated to long-focal length focusing experiments (6 to 30m for F1), and the SFA, dedicated to short-focal length focusing (1m for F1) and achievement of the highest intensity on target. The facility will be open to users European as well as international users.

Livingston Curve Accelerators



Livingston Curve Accelerators



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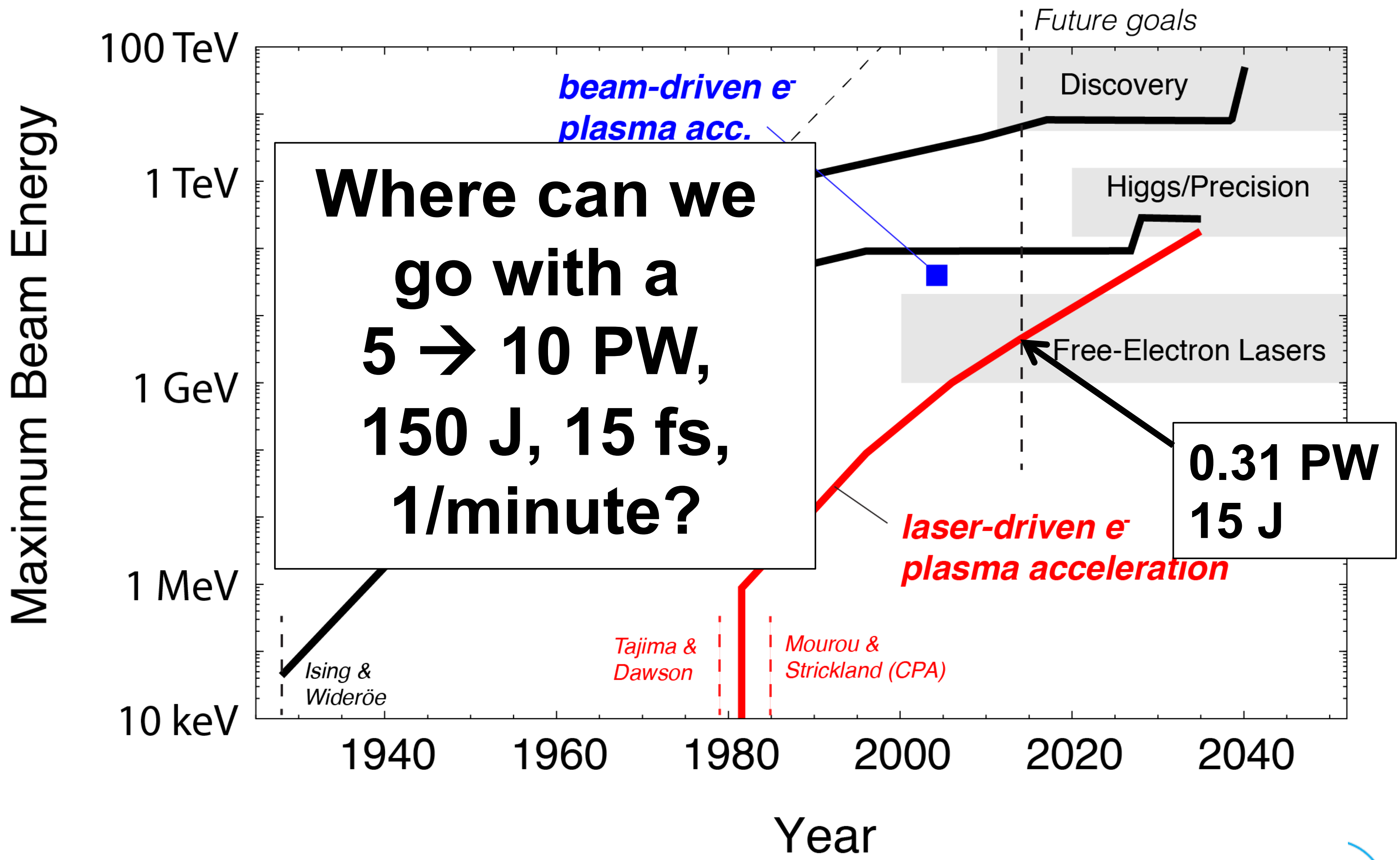
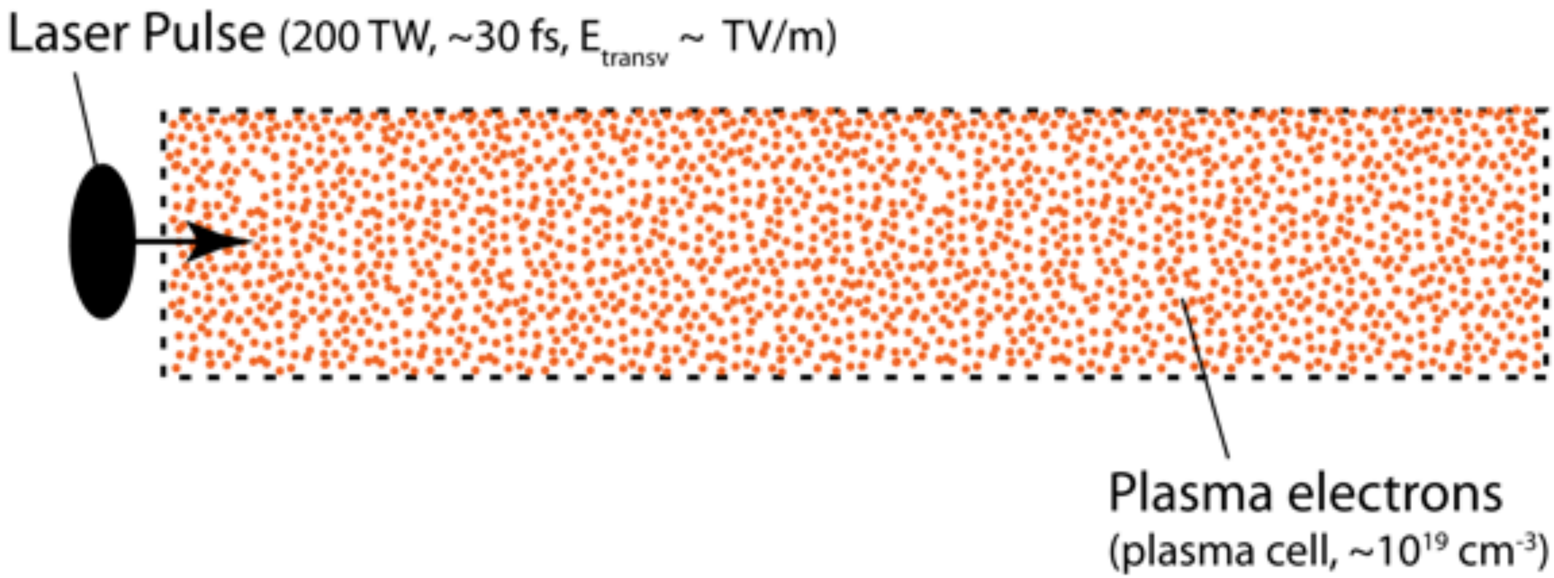


Reminder: Plasma-Acceleration (Internal Injection)



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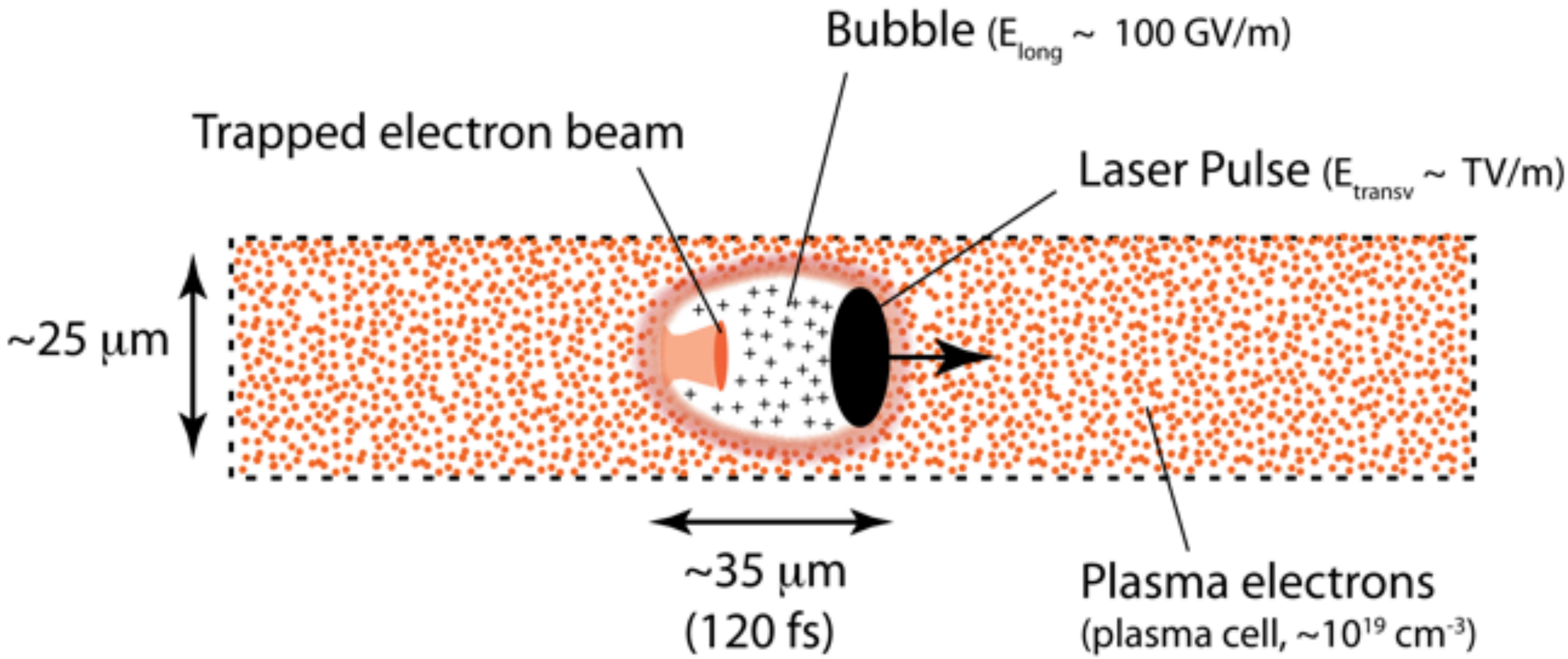


This accelerator fits into a human hair!

Plasma Accelerator Physics I

> **Most important scales in plasma acceleration are density-dependent**

- Accelerating gradient: $$E_0[\mathrm{V/m}] \approx 96\sqrt{n_0[\mathrm{cm}^{-3}]}$$

- Size of the accelerating plasma 'cavity' ($\frac{1}{4}\lambda_p$) $$\lambda_p = \frac{2\pi c}{\sqrt{\epsilon_0 m_e/e^2}} \frac{1}{\sqrt{n_0}}$$

- Required size of the accelerated bunch (requires ultra-short bunches) $$\ll \lambda_p$$

- Acceleration length (depends on diffraction and dephasing) $$\propto n_0^{-3/2}$$

Plasma Accelerator Physics I

1) Lower plasma density reduces accelerating gradient

> **Most important scales in plasma acceleratio**[...]**t**

> Accelerating gradient: $$E_0[\mathrm{V/m}] \approx 96\sqrt{n_0[\mathrm{cm}^{-3}]}$$

> Size of [...] plasma

2) Lower plasma density increases size of cavity

$$\lambda_p = \frac{2\pi c}{\sqrt{\epsilon_0 m_e / e^2}} \frac{1}{\sqrt{n_0}}$$

> Required size of the accelerate[...] (requires ultra-short bunches)

3) Lower plasma density allows longer bunches

$$\ll \lambda_p$$

> Acceleration length (de[...] and dephasing)

4) Lower plasma density increases length of acceleration

$$\propto n_0^{-3/2}$$

Towards Highest Beam Energy Gain ΔE

4) Lower plasma density increases **length of acceleration**

$$\propto n_0^{-3/2}$$

Acceleration increases linearly when plasma density is reduced *(compromising accelerating gradient)*

→ Progress in recent experiments along this line

Plasma Accelerator Physics II

> The ion channel left on axis, where the beam passes, induces an **ultra-strong focusing field**. In the simplest case:

$$g = 960\,\pi \cdot \left(\frac{n_0}{10^{14}\ \mathrm{cm}^{-3}}\right)\ \mathrm{T/m}$$

300 kT/m for 10^{16} cm^{-3}

> This can be converted into a **optical beta function** (lower density is better , as beta function is larger)::

$$k_\beta^2 = 0.2998\,\frac{g}{E} \qquad \beta = \frac{1}{k_\beta}$$

β = 1.1 mm for 100 MeV

> The **phase advance** in the plasma channel is rapid:

$$\psi(s) = \int k_\beta s\ \mathrm{d}s \propto \sqrt{E}$$

Plasma Accelerator Physics II

> The ion channel left on axis, where th[…] an **ultra-strong focusing field**. In the simples[…]

5) Lower plasma density decreases transverse fields

$$g = 960\,\pi \cdot \left(\frac{n_0}{10^{14}\ \mathrm{cm}^{-3}}\right)\ \mathrm{T/m}$$

300 kT/m for 10^{16} cm^{-3}

> This can be converted into a **optica**[…]ensity is better , as beta function is larger)::

6) Lower plasma density increases beta function

$$k_\beta^2 = 0.2998\,\frac{g}{E} \qquad \beta = \frac{1}{k_\beta}$$

β = 1.1 mm for 100 MeV

> The **phase advance** in the plasma channel is rapid:

$$\psi(s) = \int k_\beta s\, \mathrm{d}s \propto \sqrt{E}$$

7) Lower plasma density decreases phase advance

Plasma Accelerator Physics III

- The **matched beam size** in the ion channel is small:

$$\sigma_0 = \sqrt{\beta \varepsilon}$$

σ_0 = 1.3 μm for γε = 0.3 μm

- Offsets between laser and beam centres will induce betatron oscillations. Assume: full dilution into emittance growth (energy spread and high phase advance).

- Tolerances for **emittance growth** due to offsets Δx = σ_x:

$$\frac{\Delta\varepsilon}{\varepsilon_0} = \left(\frac{\sigma_x}{\sigma_0}\right)^2$$

100% for 1.3 μm offset

Assmann, R. and K. Yokoya. Transverse Beam Dynamics in Plasmas. NIM A410 (1998) 544-548.

Plasma Accelerator Physics III

- The **matched beam size** in the ion channel is small:

$$\sigma_0 = \sqrt{\beta \varepsilon}$$

σ_0 =

8) Lower plasma density increases matched beam size

- Offsets between laser and beam centres will induce betatron oscillations. Assume: full dilution into emittance growth (energy spread and high phase advance).

- Tolerances for **emittance growth** due to offsets $\Delta x = \sigma_x$:

$$\frac{\Delta\varepsilon}{\varepsilon_0} = \left(\frac{\sigma_x}{\sigma_0}\right)^2$$

9) Lower plasma density relaxes transverse tolerances, reduces emittance growth, increases stability, better quality

Assmann, R. and K. Yokoya. Transverse Beam Dynamics in Plasmas. NIM A410 (1998) 544-548.

Major Goal: High Quality GeV Class Beam

9) Lower plasma density relaxes transverse tolerances, reduces emittance growth, increases stability, better quality

For example, offset tolerance for emittance doubling:

$$\Delta x_{tol} \propto \frac{1}{\sqrt[4]{n_0}}$$

Just one of several error sources – all improve with lower plasma density!

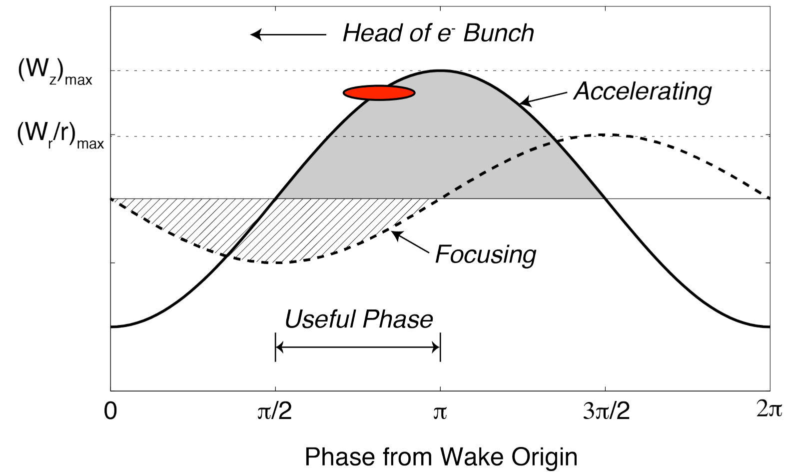
Quality: Energy Spread Minimization (before beam loading compensation of energy spread a la S. van der Meer)

Reduce energy spread (head to tail → correlated with z)

↓

Minimize: Ratio of accelerated bunch length over ¼ plasma wavelength!

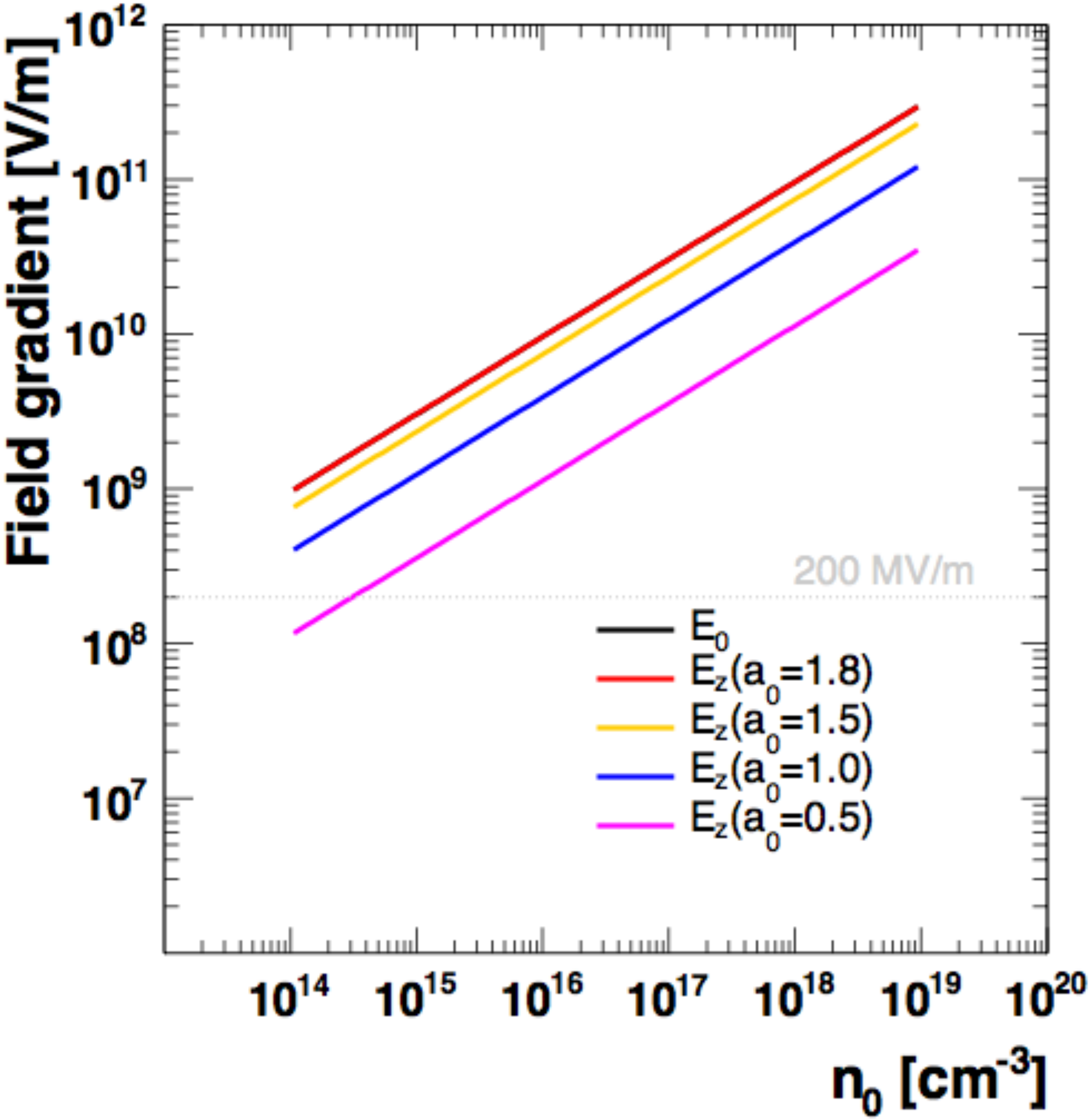
Minimize length accelerated bunch	and/or	Increase plasma wavelength
↓		↓
Ultra-short bunches (fs, as)		Lower plasma density
↓		↓
Ultra-fast science		Lower accelerating gradient



1 fs = 0.3 μm

when travelling with light velocity c

Low Plasma Density I



Plasma density [cm^{-3}]	E_0 GV/m
10^{19}	303
10^{18}	96
10^{17}	30.3
10^{16}	9.6
10^{15}	3.03
10^{14}	0.96

Laser strength parameter a_0

$$E_z/E_0 = \frac{a_0^2/2}{\sqrt{1 + a_0^2/2}}$$

Low Plasma Density II

- Optimum **matched laser pulse length L_{rms}** is determined by plasma wavelength λ_p with some dependence from laser shape:

$$L_{rms} \approx \frac{\lambda_p}{2\pi} = \frac{1}{k_p}$$

- Low plasma density requires longer laser pulse or will result in reduced amplitude of wakefield.

[1] I. Kostyukov, A. Pukhov and S. Kiselev, *Phenomenological theory of laser-plasma interaction in "bubble" regime*, Phys. Plasmas 11, 5256 (2004)

[2] W. Lu et al., *Nonlinear Theory for Relativistic Plasma Wakefields in the Blowout Regime*, Phys. Rev. Lett. 96, 165002 (2006)

[3] W. Lu et al., *Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime*, Phys. Rev. STAB 10, 061301 (2007)

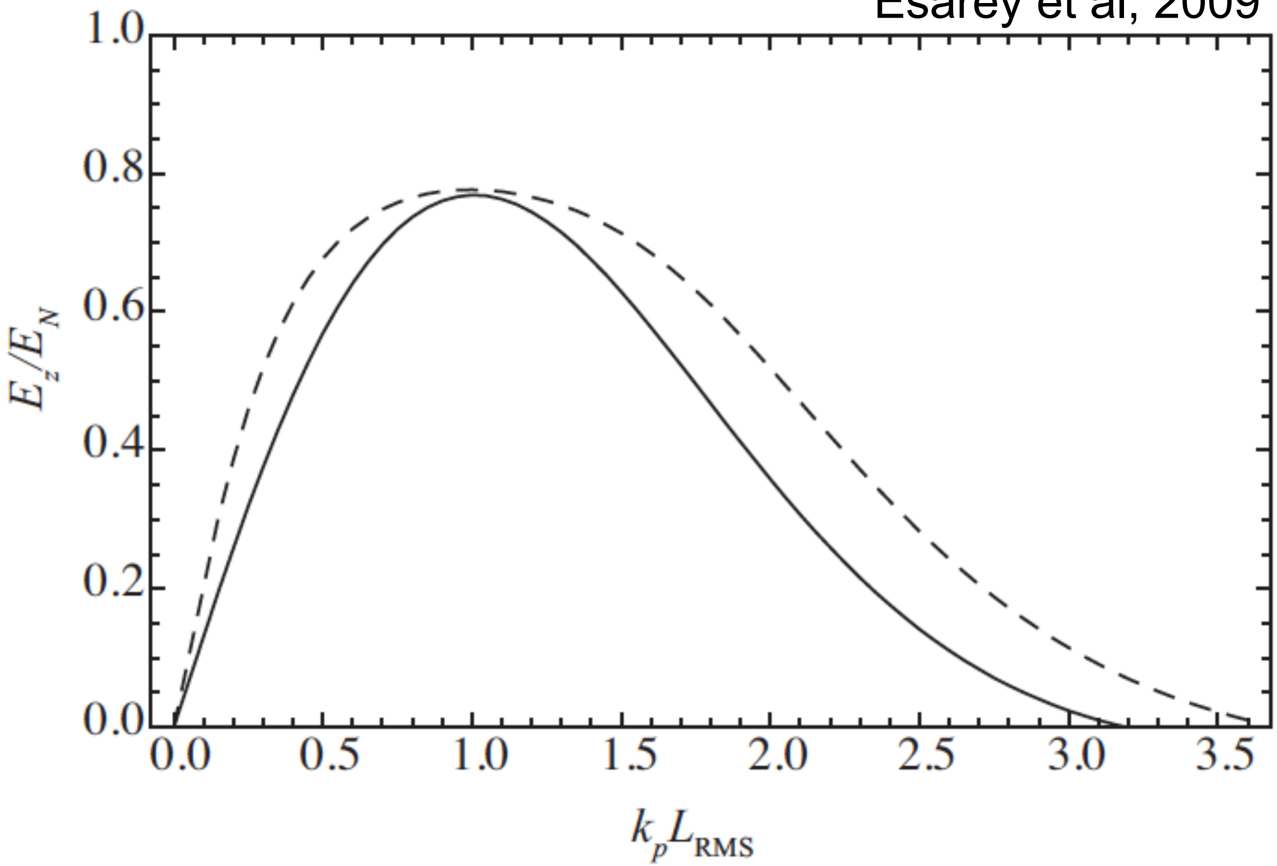
Low Plasma Density III

Plasma density [cm^{-3}]	Wavelength λ_p	Period	$L_{rms} \approx \frac{\lambda_p}{2\pi}$
10^{19}	10.6 μm	35.3 fs	1.68 μm
10^{18}	33.4 μm	101.3 fs	5.31 μm
10^{17}	106 μm	353.3 fs	16.8 μm
10^{16}	334 μm	1.0 ps	53.1 μm
10^{15}	1.06 mm	3.53 ps	0.168 mm
10^{14}	3.34 mm	10.0 ps	0.531 mm

15 fs = 4.5 μm

Drop in Gradient for Non-Optimum Laser Length

Esarey et al, 2009



REVIEWS OF MODERN PHYSICS, VOLUME 81, JULY–SEPTEMBER 2009

Physics of laser-driven plasma-based electron accelerators

E. Esarey, C. B. Schroeder, and W. P. Leemans

Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

FIG. 9. Amplitude of axial electric field E_z [normalized to the maximum amplitude of a flat-top pulse $E_N=(a_0^2/2)/(1+a_0^2/2)^{1/2}$] plotted as a function of laser pulse length $k_p L_{\mathrm{rms}}$ for the LWFA examples shown in Fig. 8: $a_0=0.5$ (solid curve) and $a_0=2.0$ (dashed curve). The laser pulse envelope is $a=a_0 \exp(-\zeta^2/4L_{\mathrm{rms}}^2)$.

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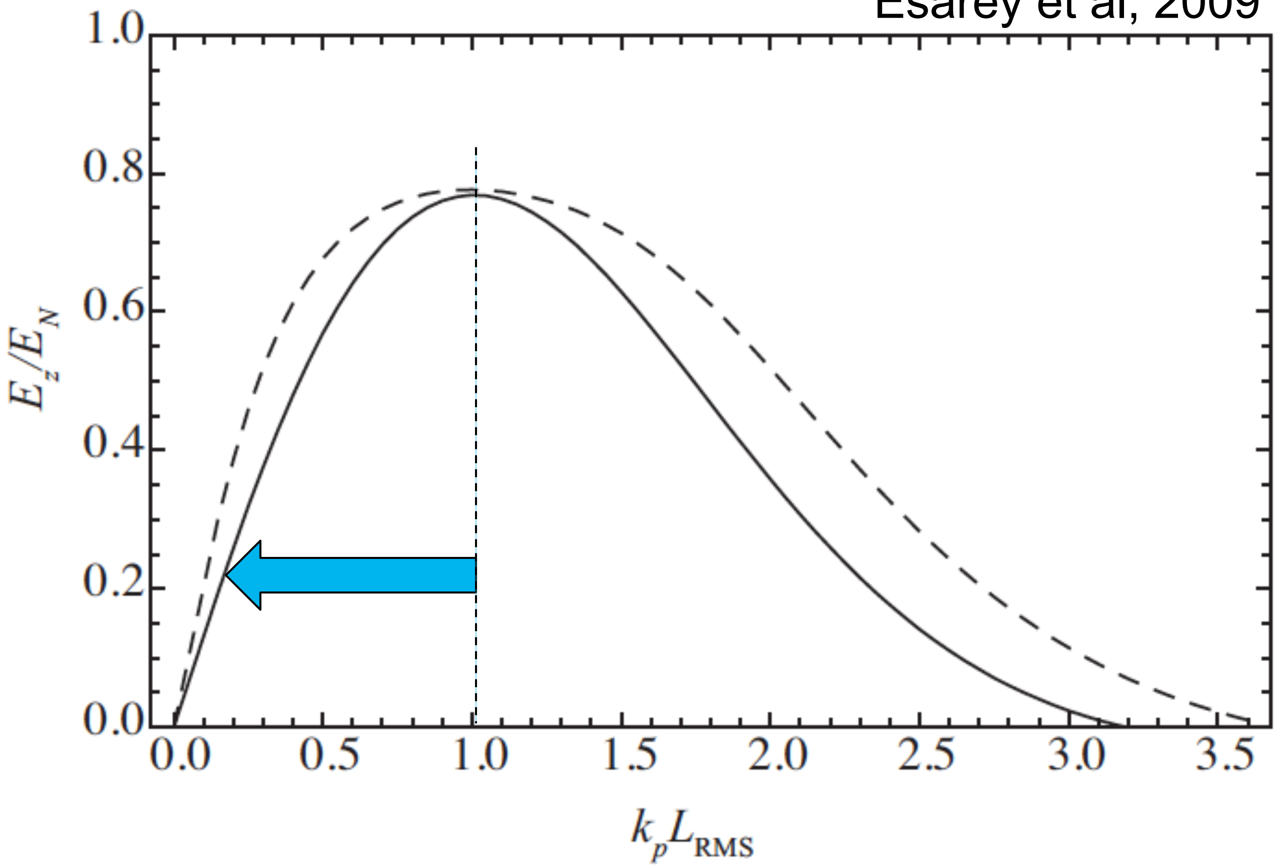

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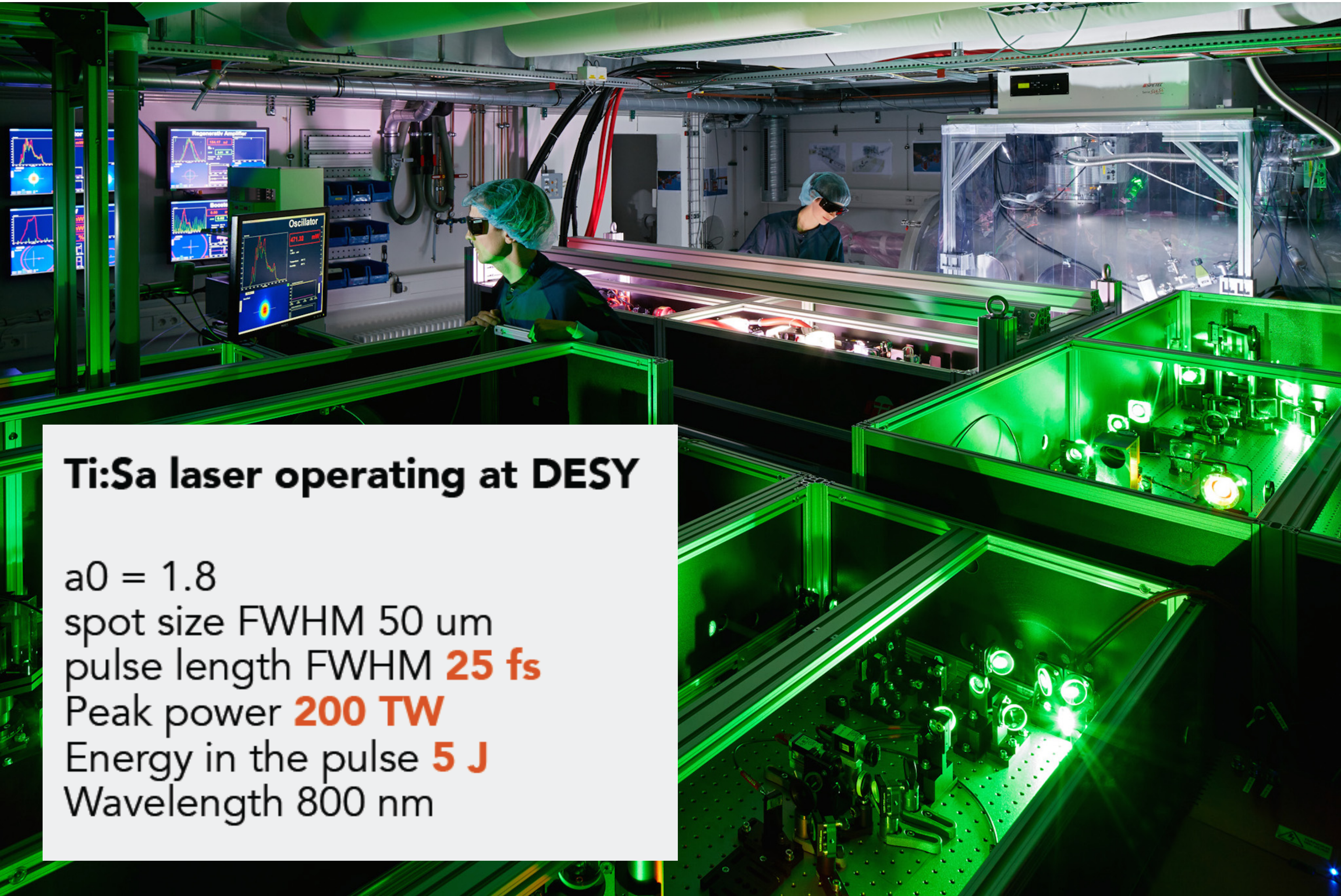
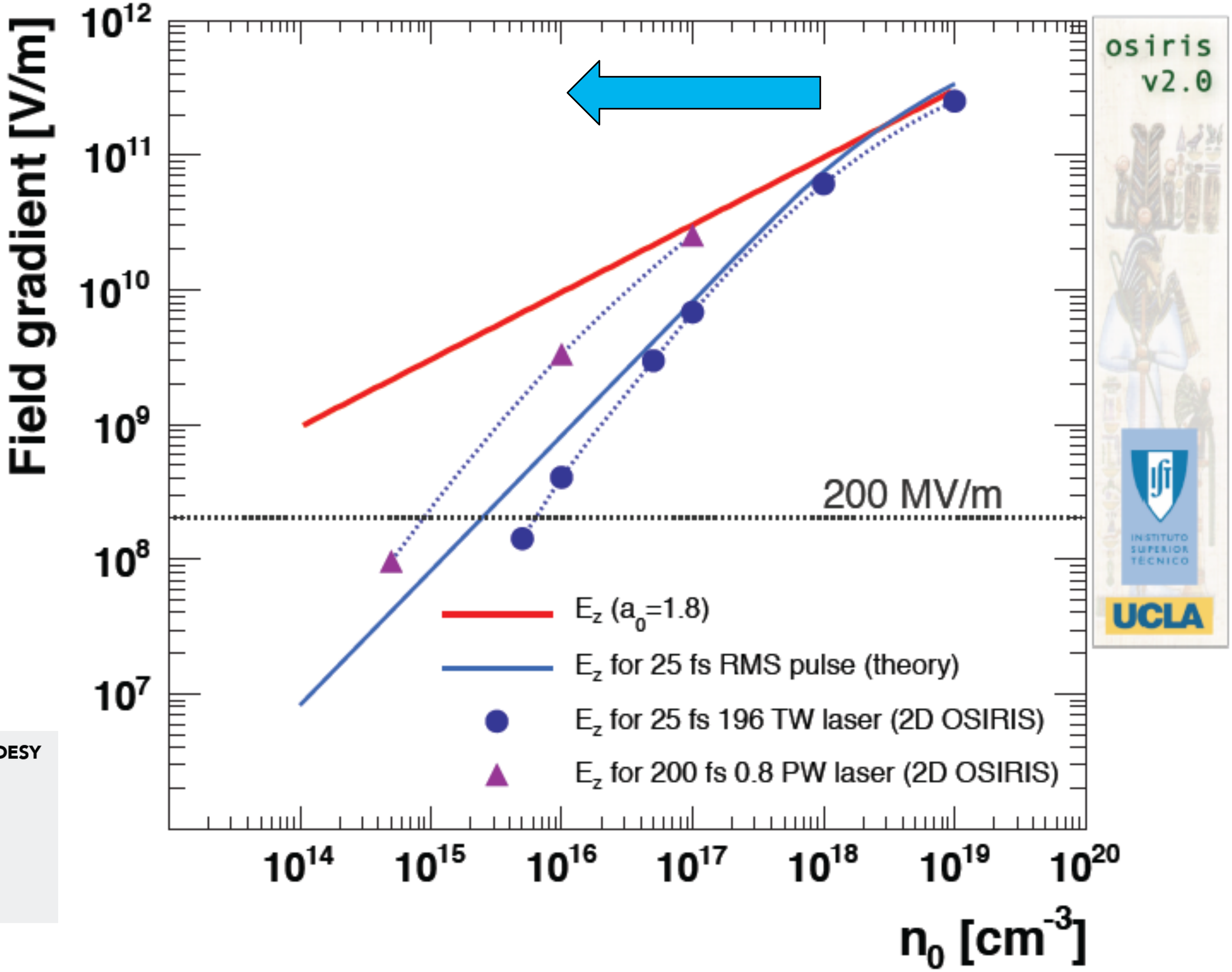
Simulation for DESY/Uni HH Laser



Ti:Sa laser operating at DESY

a0 = 1.8
spot size FWHM 50 um
pulse length FWHM **25 fs**
Peak power **200 TW**
Energy in the pulse **5 J**
Wavelength 800 nm

Simulation for 200 TW and 800 TW Lasers



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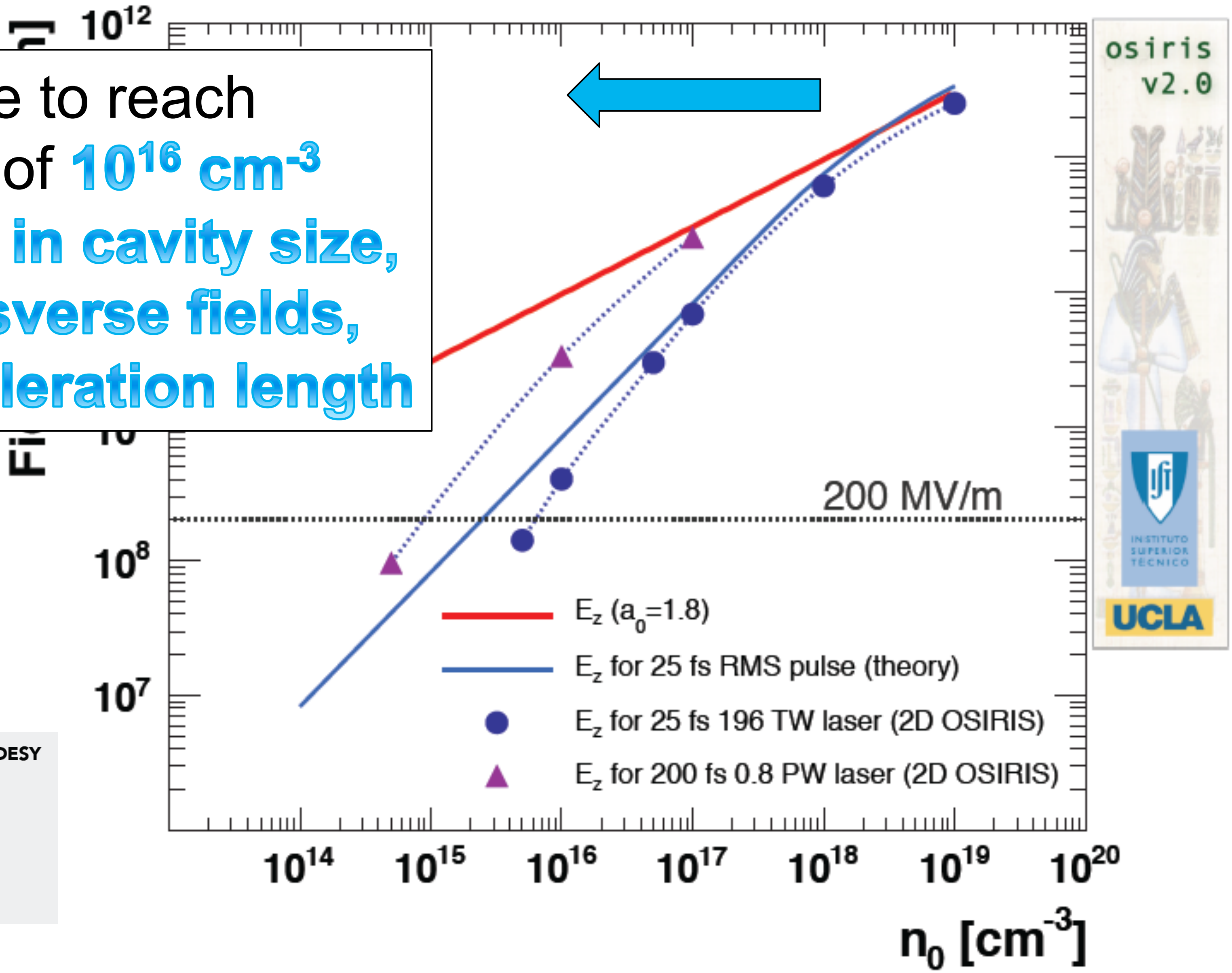
Simulation for 200 TW and 800 TW Lasers

Possible to reach density of 10^{16} cm^{-3}
→ **gain in cavity size, in transverse fields, in acceleration length**



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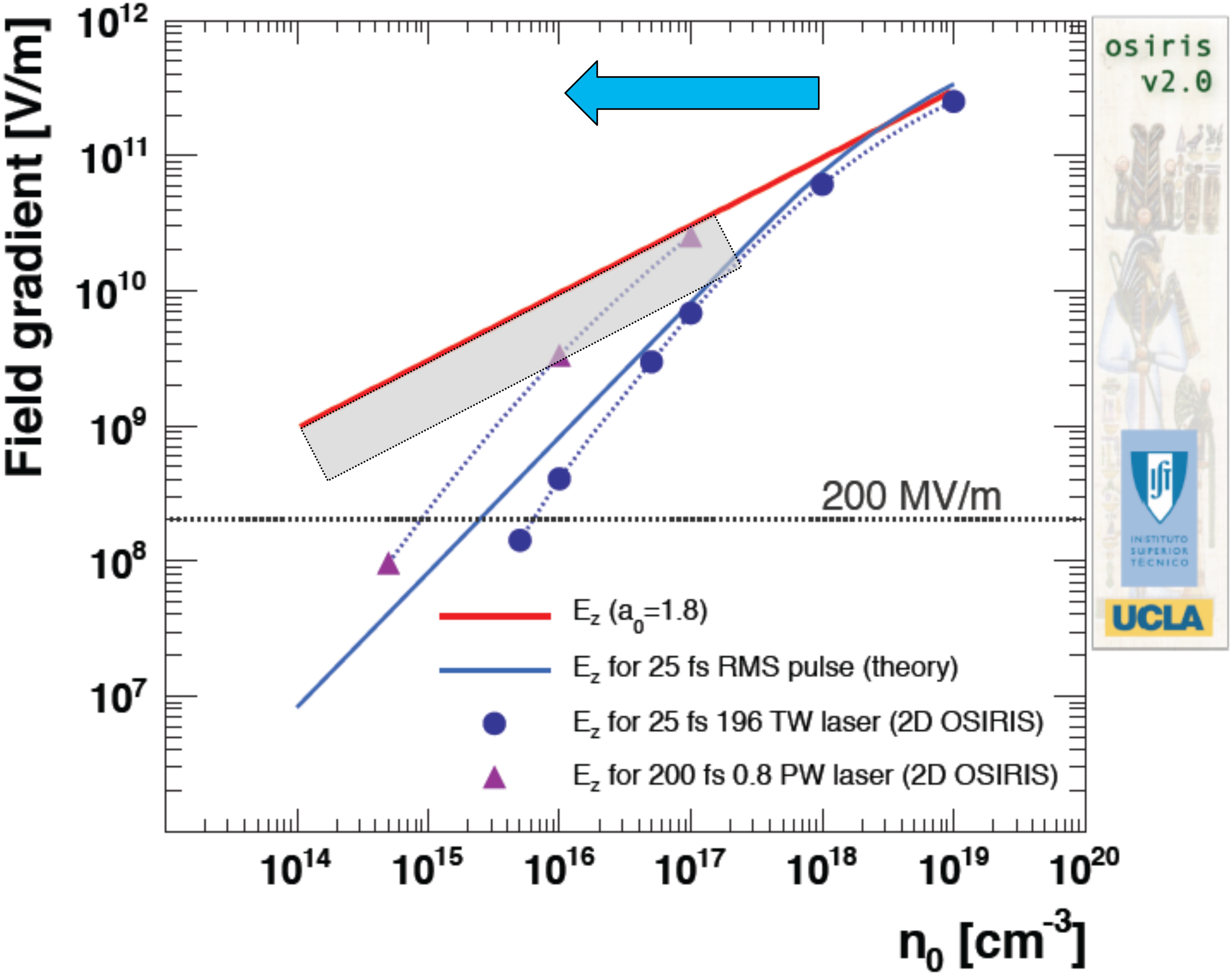
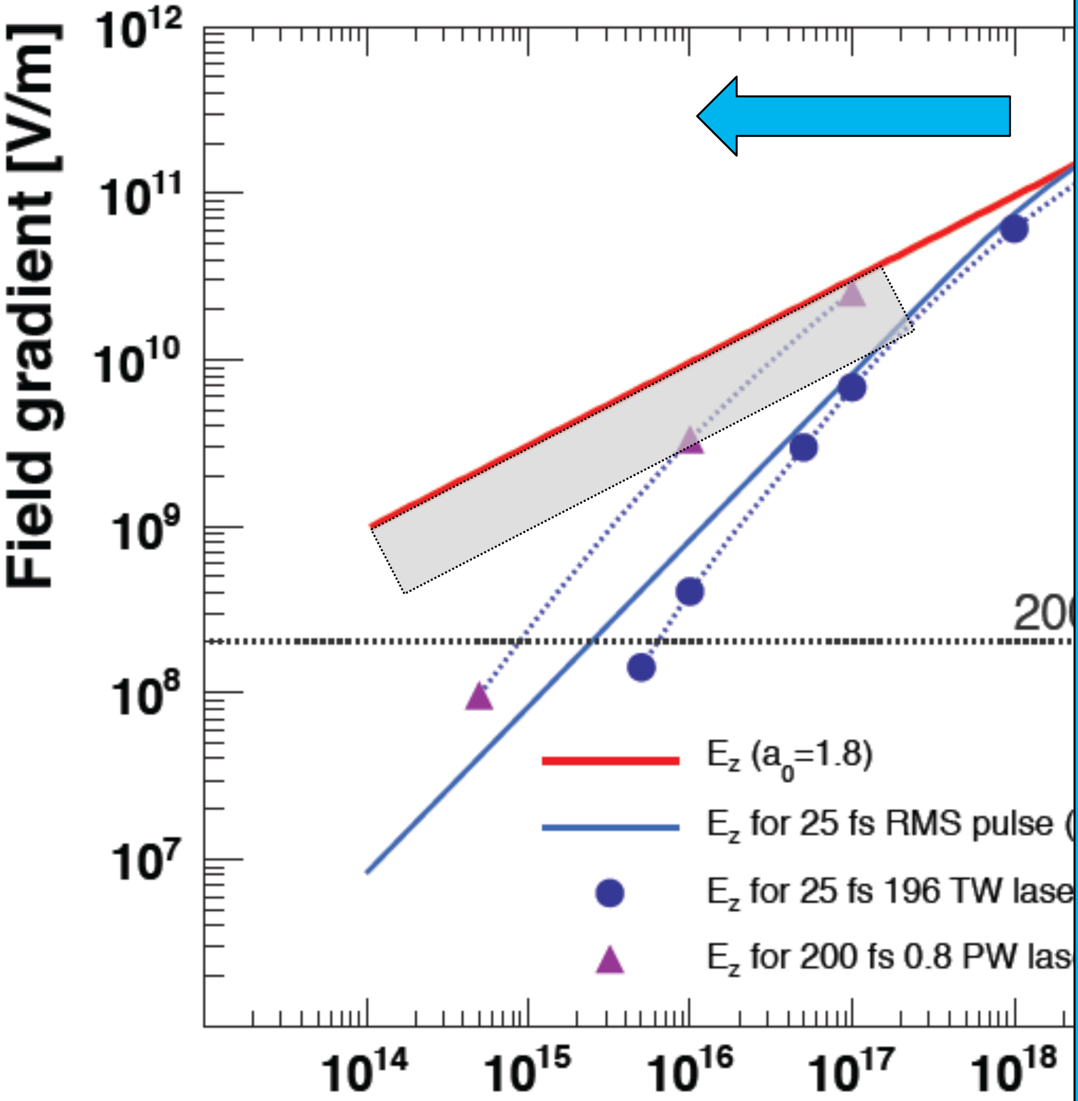
Possible Apollon Reach



Possible Apollon Reach



Missing for LWFA breakthrough: about 10 times better quality

The Apollon Reach:

- LWFA with ≥ 1 GV/m
- Longer acceleration length
- 100 – 1,000 times lower plasma density possible
- Much reduced transverse fields → easier matching
- Relaxed tolerances
- Larger plasma cavity → less RF curvature → lower energy spread
- Space (200m) for long-term application tests (e.g. FEL)

Addresses many of accelerator physicists' hopes and dreams

The Apollon Case → Opening New Territory

- The Apollon laser can **use its unprecedented power to explore lower plasma densities** than possible elsewhere:
  - Longer acceleration lengths → higher absolute energies...
  - Reduced transverse fields and relaxed tolerances → **higher quality beams**...
- Our interest:
  - **Explore the unique capabilities of the Apollon laser for exploring the benefits and limits of low plasma densities.**
- Issues to be addressed:
  - **Full simulation** of Apollon case and experiments: show unique features and possibilities (e.g. energy spread advantages – not discussed here).
  - Beam generation:
    1) from wavebreaking regime into **triggered injection at lower densities**
    2) **two stage setup** (high density injection and low density acceleration)

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EuPRAXIA

http://eupraxia-project.eu

NOVEL FUNDAMENTAL RESEARCH

COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

Find Out More

OUR TECHNOLOGY

EuPRAXIA brings together novel acceleration schemes, modern lasers, the latest correction technologies and large-scale user areas.

LEARN MORE

PARTICIPANTS

A consortium of 16 laboratories and universities from 5 EU member states has formed to produce a conceptual design report.

LEARN MORE

WORK PACKAGES

The project is structured into 14 work packages of which 8 are included into the EU design study.

LEARN MORE

MANAGEMENT

The management bodies will organise, lead and control the project's activities and make sure that objectives are met

LEARN MORE

OPENING NEW HORIZONS

EUPRAXIA IS A LARGE RESEARCH INFRASTRUCTURE BEYOND THE CAPABILITIES OF A SINGLE LAB

DESY

cnrs

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Consiglio Nazionale delle Ricerche

SOLEIL SYNCHROTRON

IST-ID Associação do Instituto Superior Técnico para a Investigação e Desenvolvimento

MANCHESTER 1824 The University of Manchester

INFN

UNIVERSITY OF LIVERPOOL

ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development

UNIVERSITY OF OXFORD

SAPIENZA UNIVERSITÀ DI ROMA

University of Strathclyde Glasgow

Imperial College London

UHH Universität Hamburg

Science & Technology Facilities Council

plus 18 associated partner institutes

Horizon2020 Design Study EuPRAXIA

COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

Design report for a 5 GeV facility by end of 2019, including science case for pilot users, cost and site study. Second design study ("plan B") after FCC/EuroCirCol.

Conclusion

The Apollon Facility opens a new regime with many scientific achievements and break-throughs to be expected.

It could be the place to demonstrate a laser-driven plasma accelerator with **unprecedented quality of the produced electron beam** → exploring benefits of low plasma density!

Convert laser power into superior quality of GeV e- beam!

This would be the **transformative step** the field is missing and many scientists wait for.

This could **pave the way for EuPRAXIA**, our common European project, and open many new opportunities.

We are interested to participate in **working out a detailed proposal** for an experiment in the presented direction and to help setting it up...

Thanks for attention

*Acknowledgements to the ARD accelerator physics team in Hamburg, in particular **J. Grebenyuk** with whom I worked a lot on this, but also **Ulrich Dorda and Barbara Marchetti** and all the others...*

References:

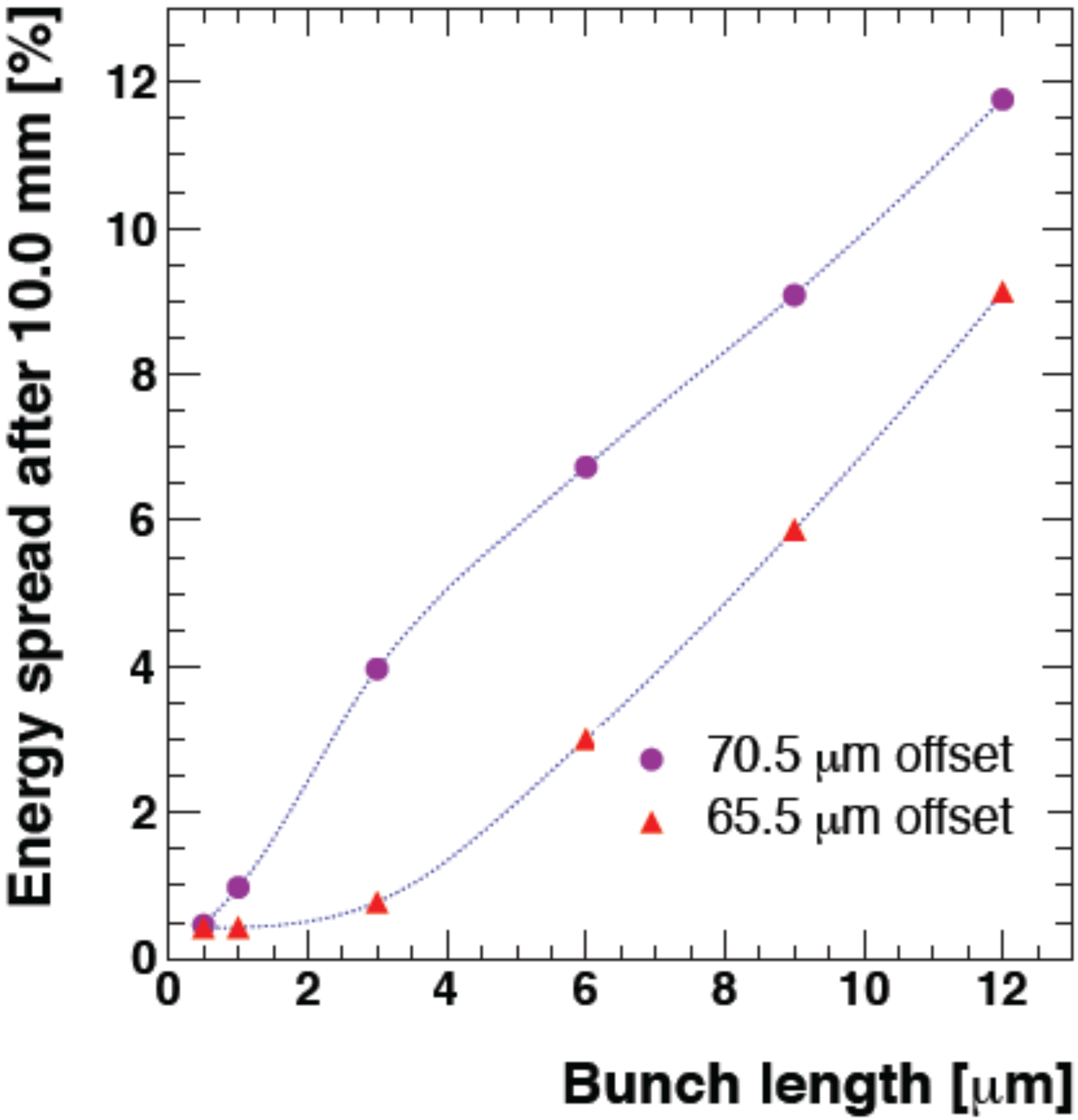
R. Assmann and J. Grebenyuk, “Accelerator Physics Challenges Towards a Plasma Accelerator with Usable Beam Quality”, Proc. IPAC 2014.

J. Grebenyuk, R. Assmann, U. Dorda, B. Marchetti, “Laser-Driven Acceleration with External Injection at SINBAD”, Proc. IPAC 2014.

and references therein

Backup slides →

Towards sub % Energy Spread



Electrons, Plasma and Laser: Parameters

e- beam for injection

Parameter	Unit	Value
Energy	MeV	100
Charge	pC	0.5 – 12
Energy spread	%	0.1
Norm. emittance	mm-mrad	0.3
Transv. size	μm	5
Bunch length	μm	3 – 12

Plasma

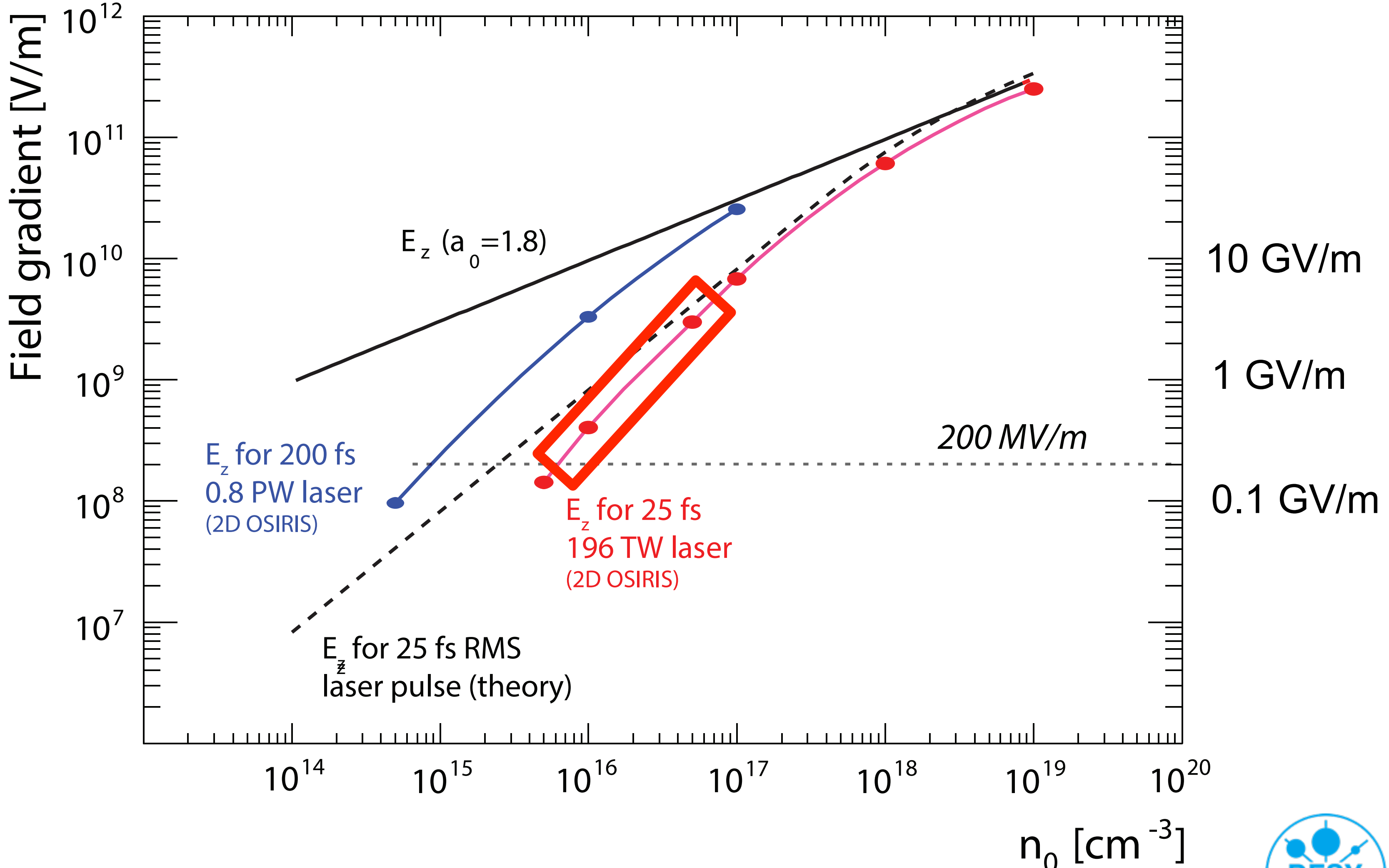
Density	cm^{-3}	0.5×10^{16}-10^{18}

Laser (Thales)

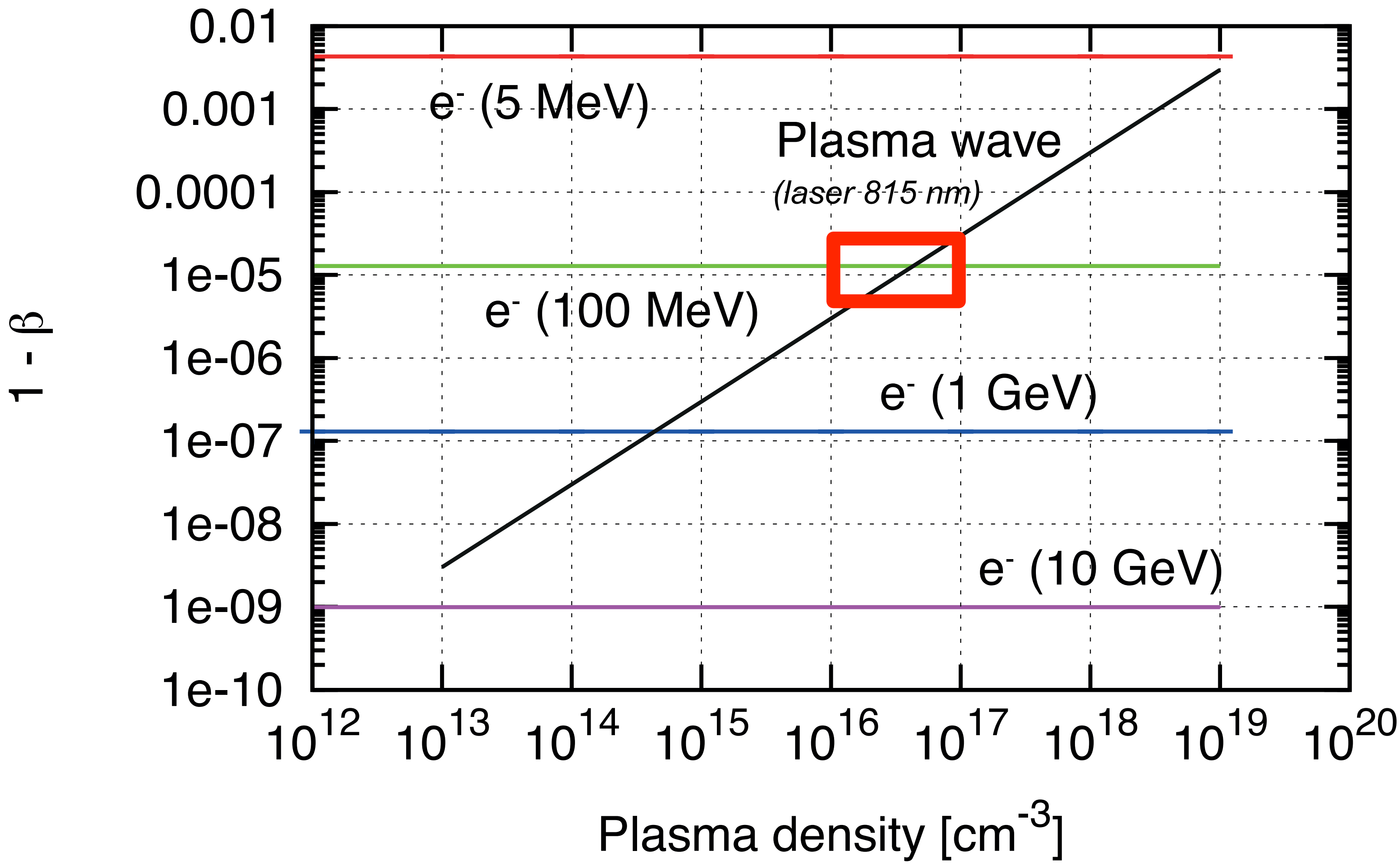
Parameter	Unit	Value
Wavelength	nm	815
Pulse length	fs	25
Spot size	μm	50
Energy	J	5
Peak power	TW	200
Pointing stability	μrad	3
Energy stability	%	1.5

Minimum Useful Plasma Density

> Depends on technology to excite plasma. **Here we consider laser-driven…**



Beam Energy for Injected Electron Bunch



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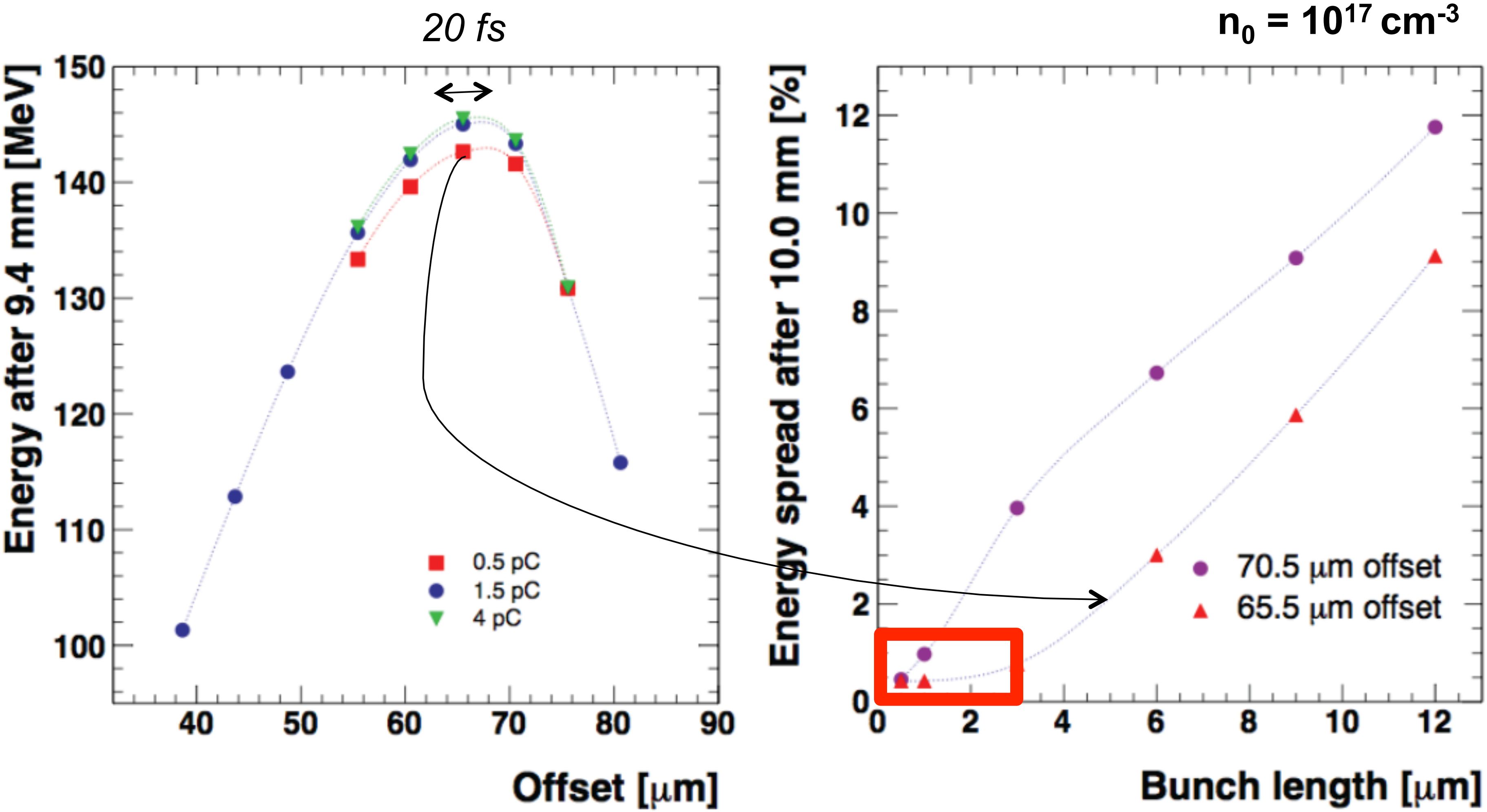
Energy + Energy Spread after ≈ 1 cm Plasma



See also TUPME064

Beam Loading to Flatten Wakefield

S. van der Meer – T. Katsouleas

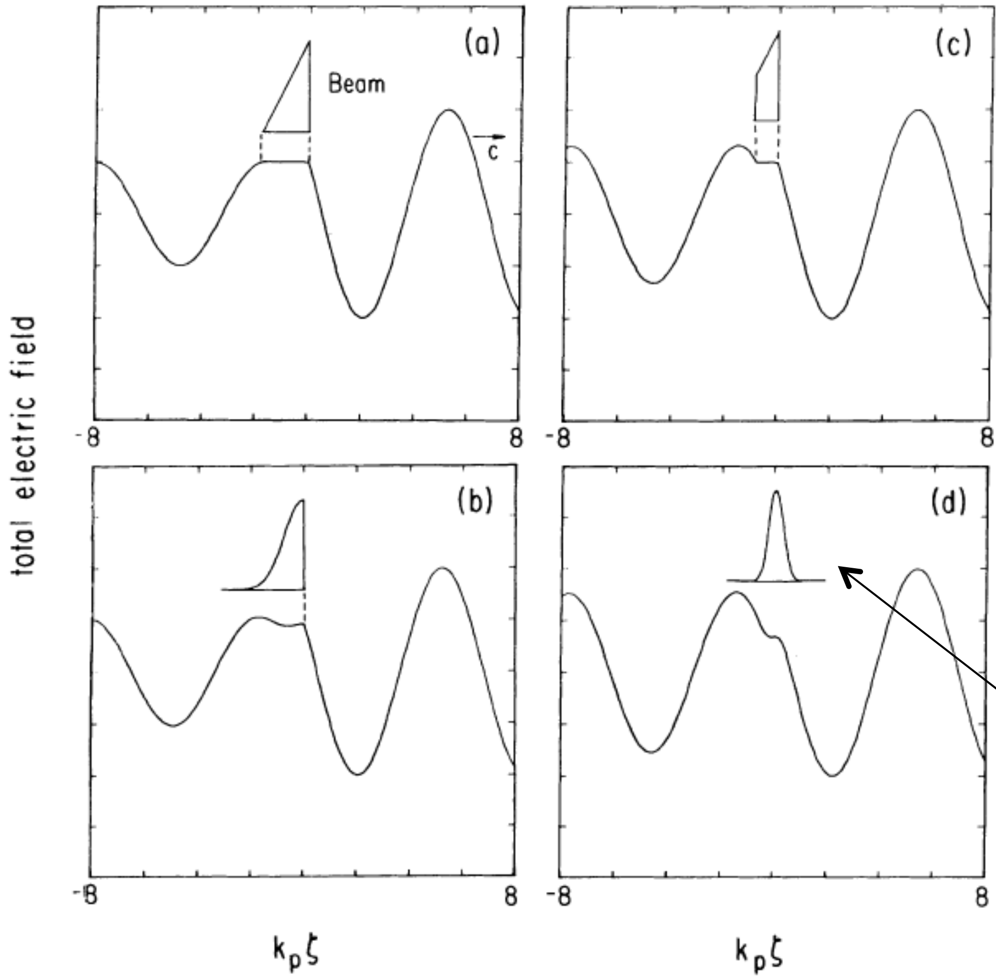


FIGURE 4 Total electric field for various beam shapes: (a) triangle [Eq. (22), $N = 3N_0/4$, $k_p\zeta_0 = \pi/3$), (b) half-Gaussian of same number of particles, (c) truncated triangle ($N = 9N_0/16$), and (d) Gaussian of same number as (c).

- Idea: Simon van der Meer – CLIC Note No. 3, CERN/PS/85-65 (AA) (1985).
- Shape the electron beam to get optimized fields in the plasma, e.g. minimize energy spread.
- Study: Tom Katsouleas.

This case we simulated. Other cases to come.

Katsouleas, T., et al. Beam Loading in Plasma Accelerators. Particle Accelerators, 1987, Vol. 22, pp. 81-99 (1987)