ACCELERATOR PHYSICS CHALLENGES TOWARDS A PLASMA ACCELERATOR WITH USABLE BEAM QUALITY

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DESY

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European Network EuroNNAc for Novel Accelerators

Accelerator Research and Development ARD A program by the Helmholtz association

HELMHOLTZ ASSOCIATION

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UHH DESY LAOLA.

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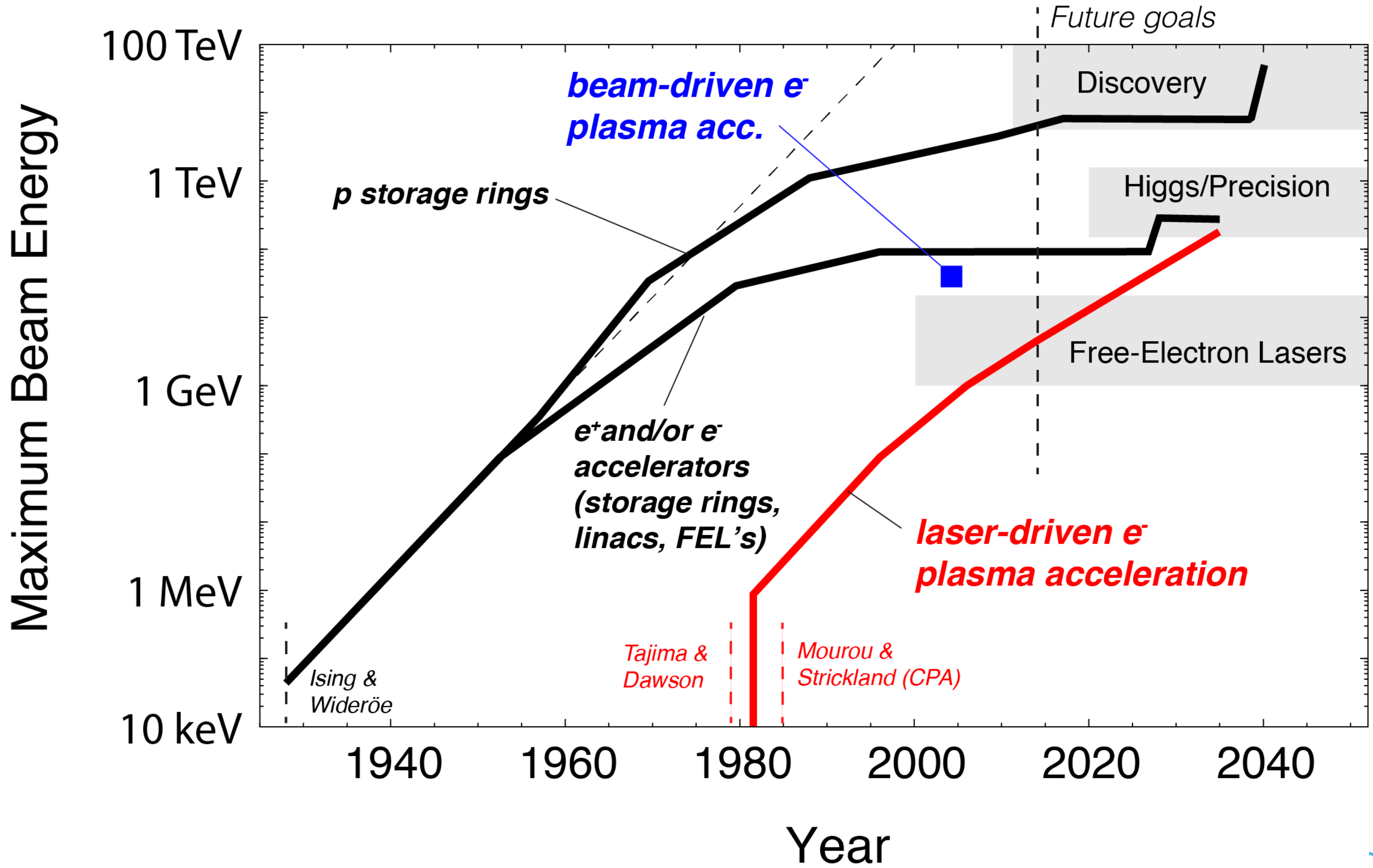
Content

1. Progress in Plasma-Based Accelerators
2. Accelerator Physics Challenges
3. Plasma Accelerator Projects
4. Conclusion

Livingston Curve Accelerators



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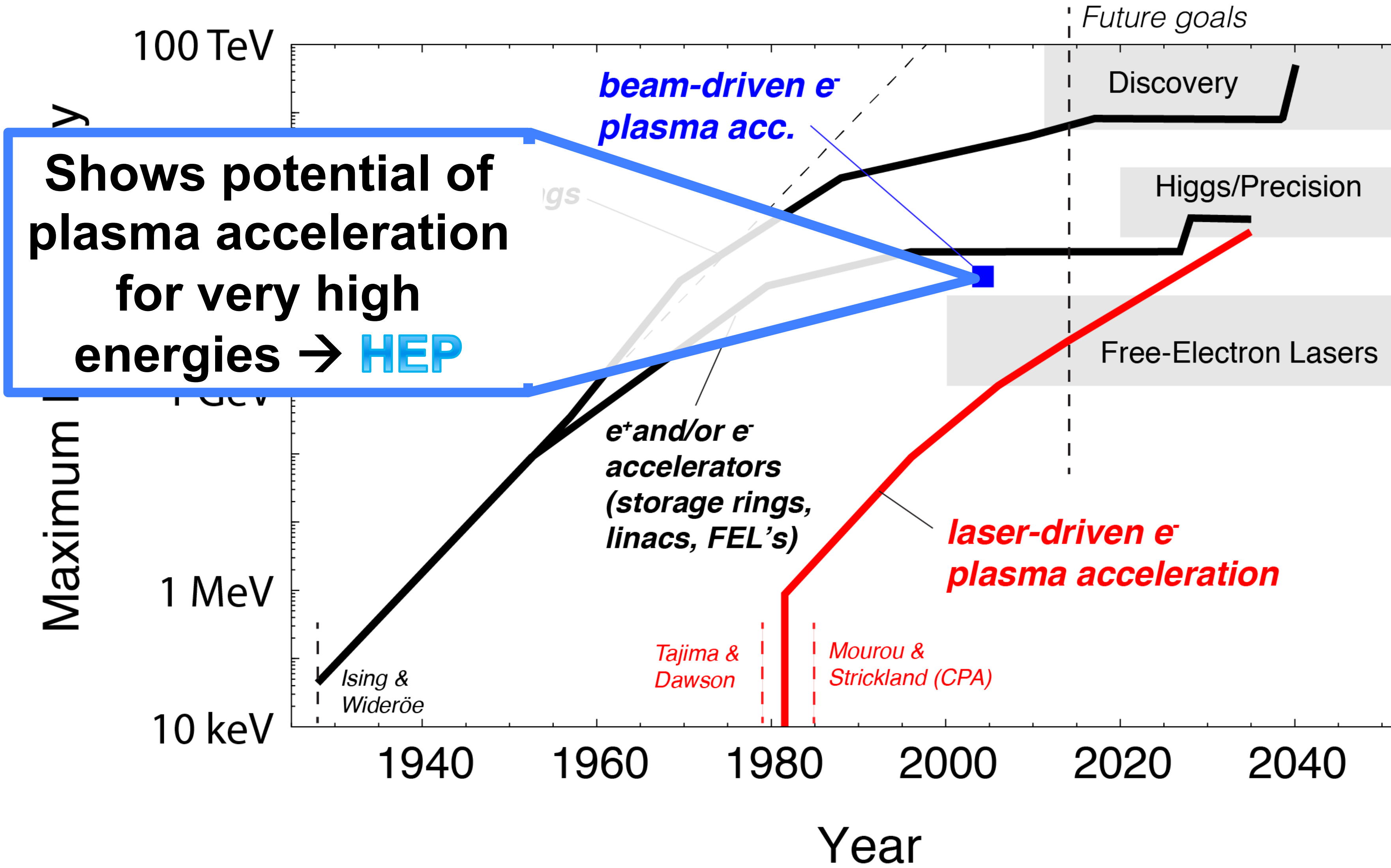

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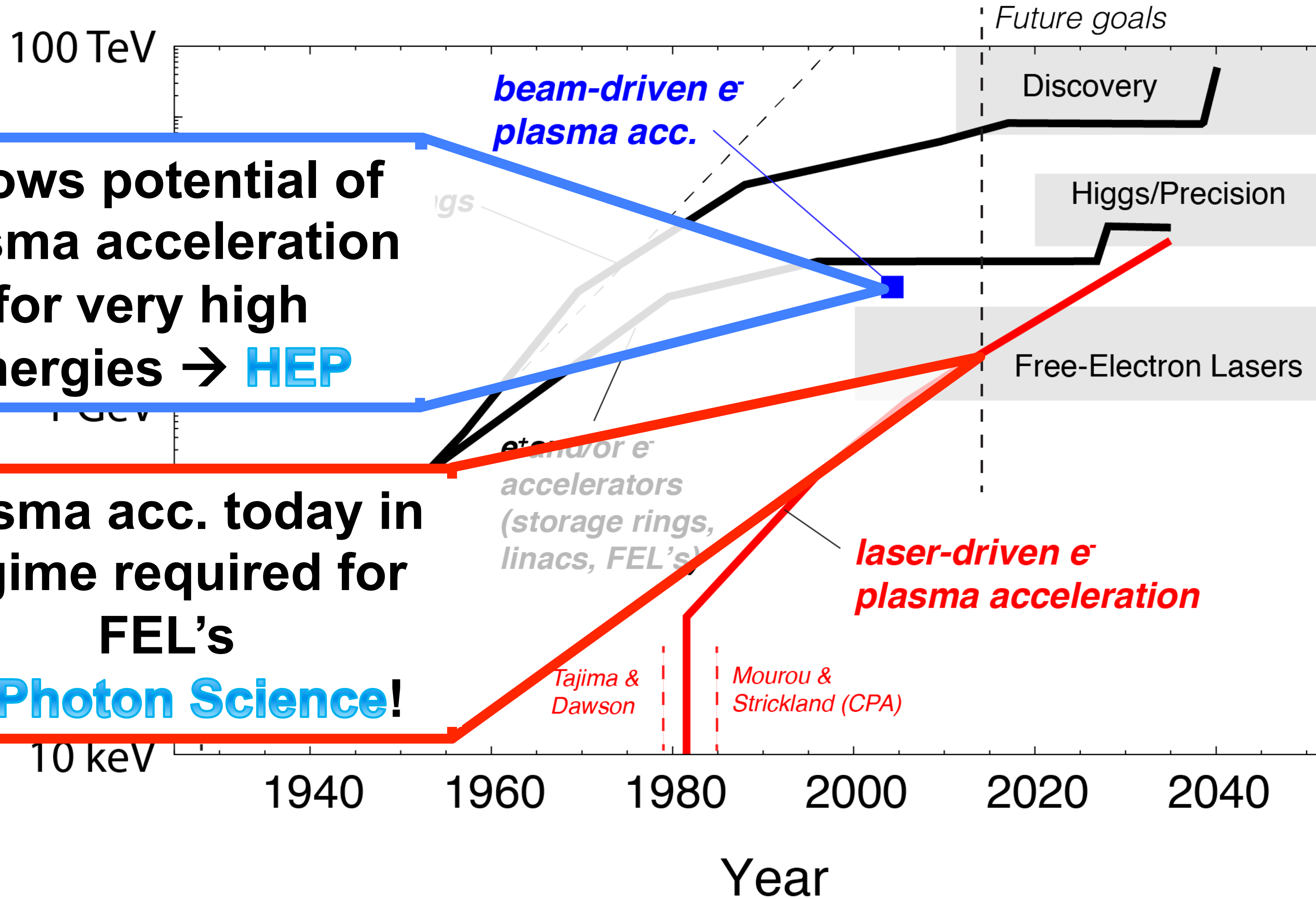

Shows potential of plasma acceleration for very high energies → HEP

Plasma acc. today in regime required for FEL's → Photon Science!

Status

- Several – many **GeV beam energy indeed being produced** within a few cm to 1 m! Energy is compatible with user needs in photon science. Reproducible …
- Field is progressing rapidly, with an **exponential increase of beam energy versus time for laser-driven plasma acceleration** (driven by progress in high power lasers).
- Then: **Why is there no user facility relying on plasma accelerator technology?**
- Technical reasons: Low average power, low efficiency → being worked on e.g. in laser projects. Not discussed here.
- Accelerator physics reasons: **Beam quality…**

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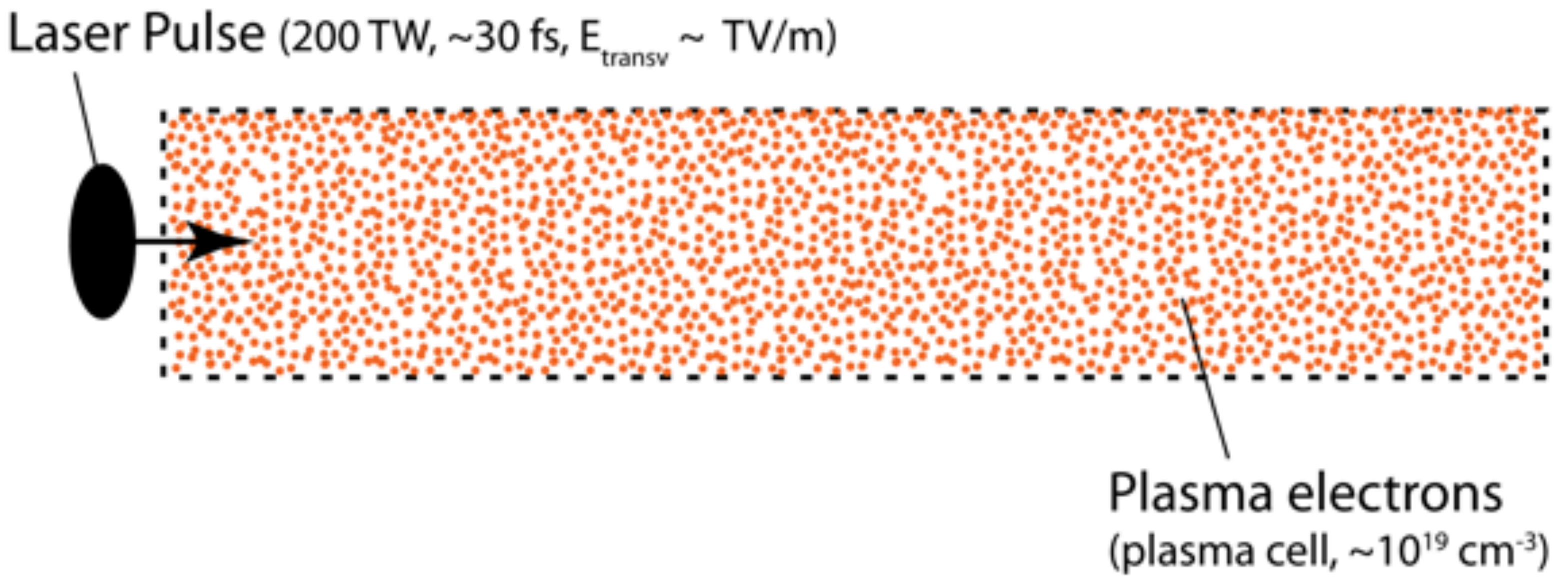
Reminder: Plasma-Acceleration (Internal Injection)



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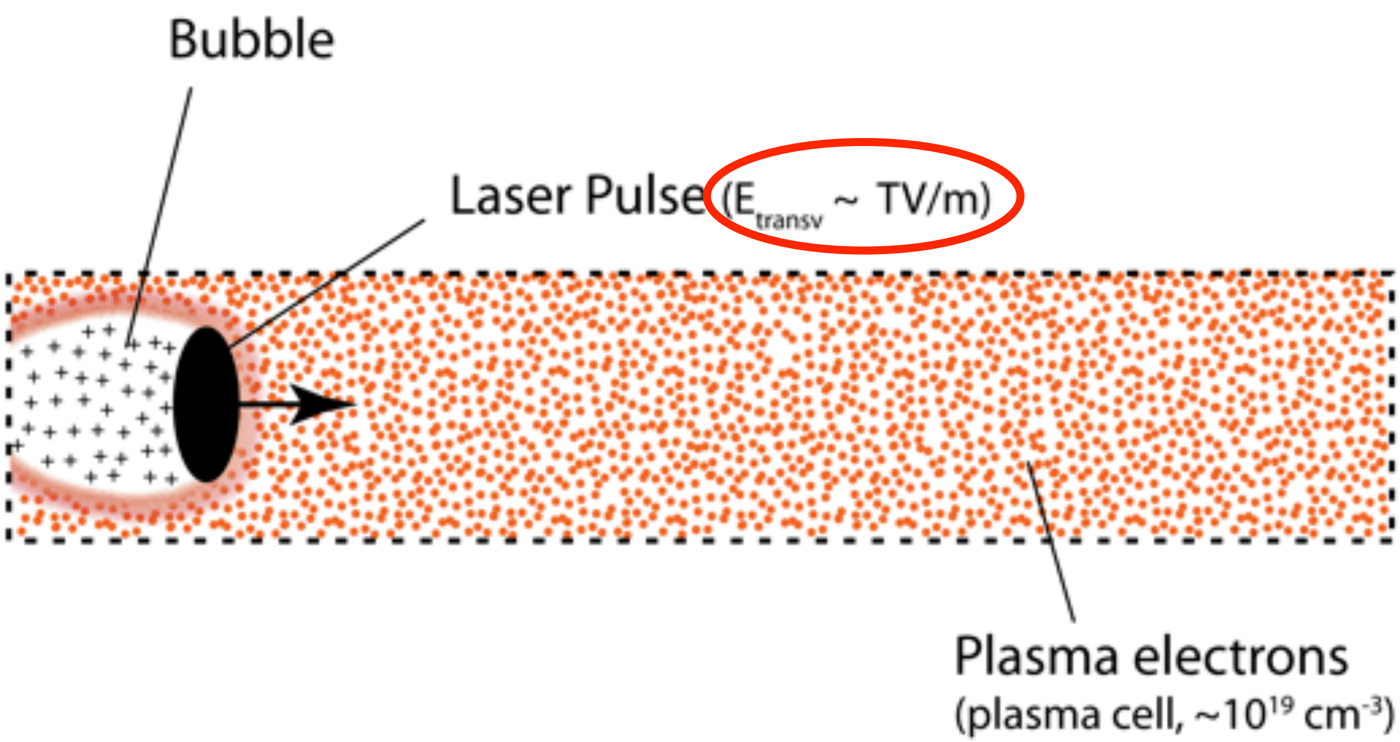

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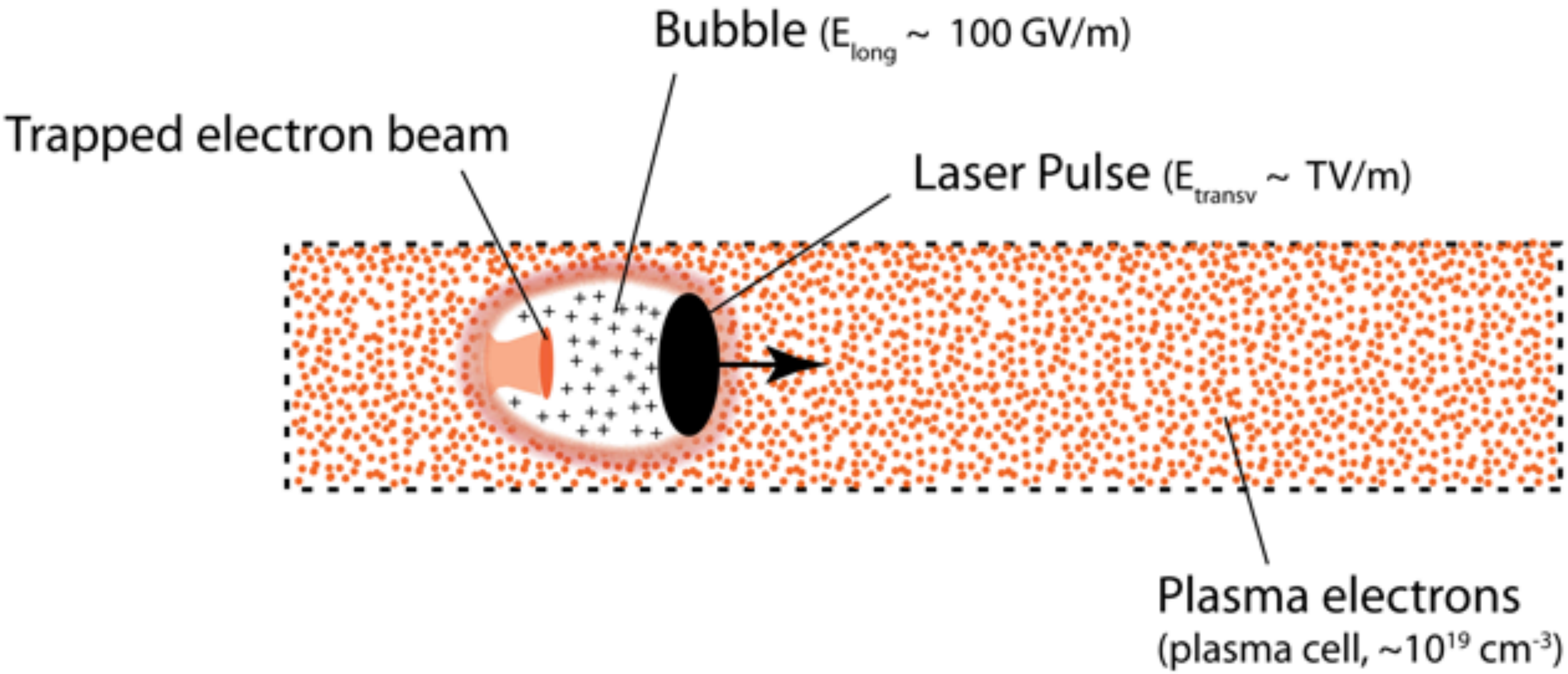

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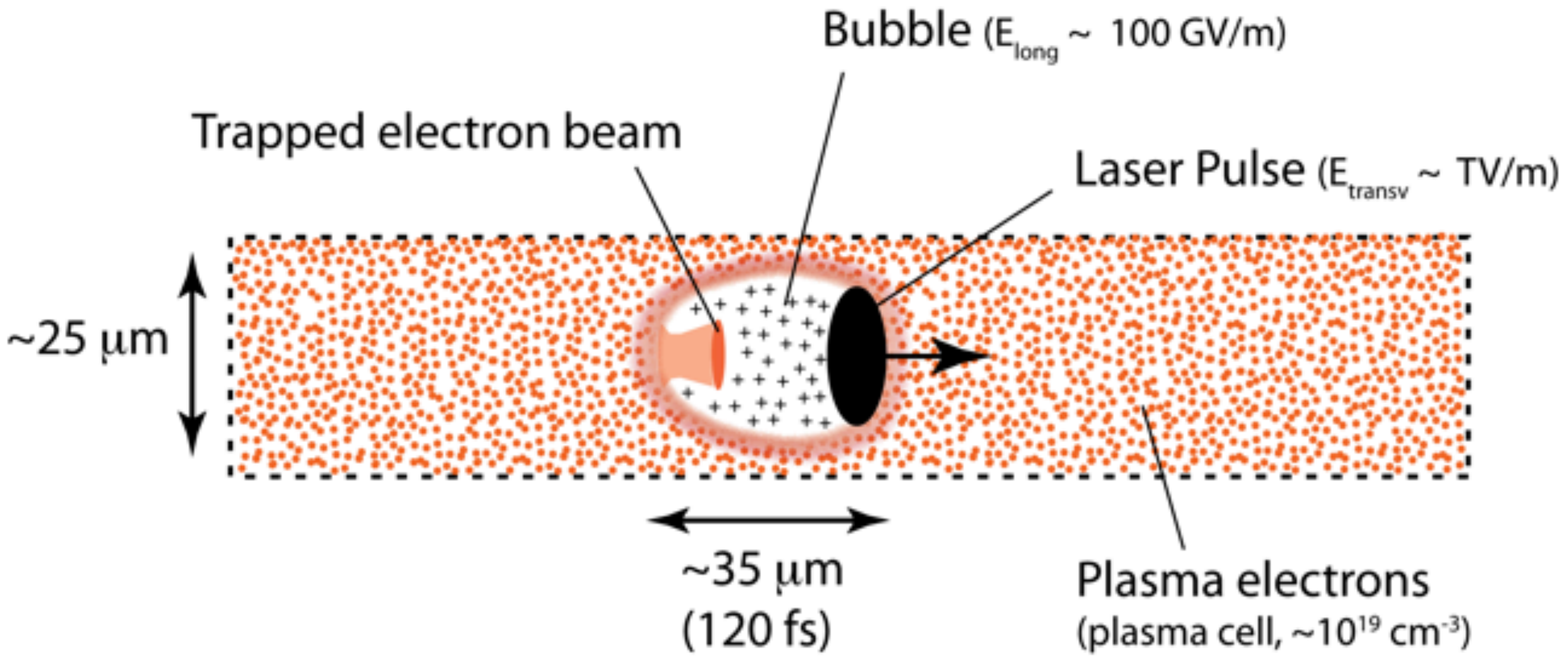
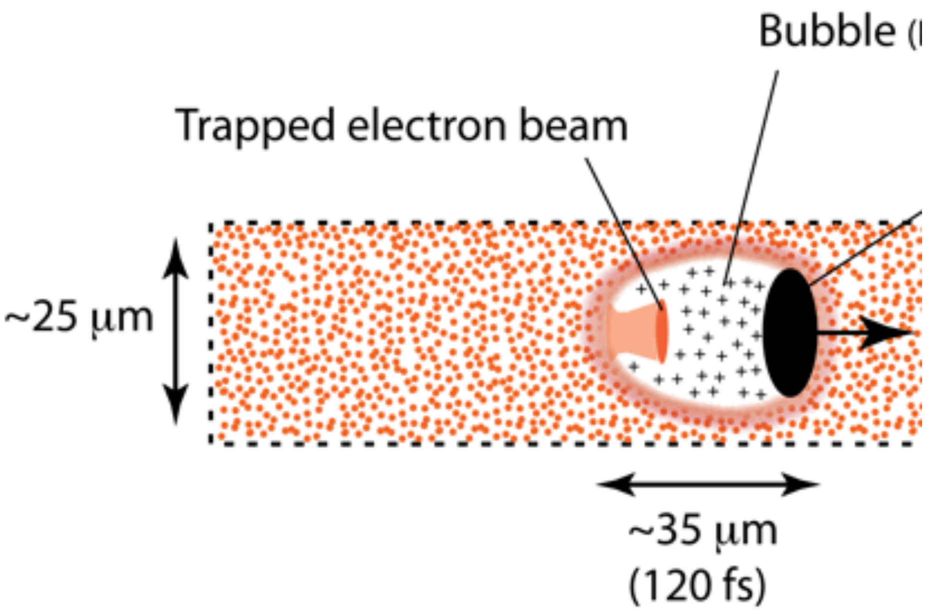


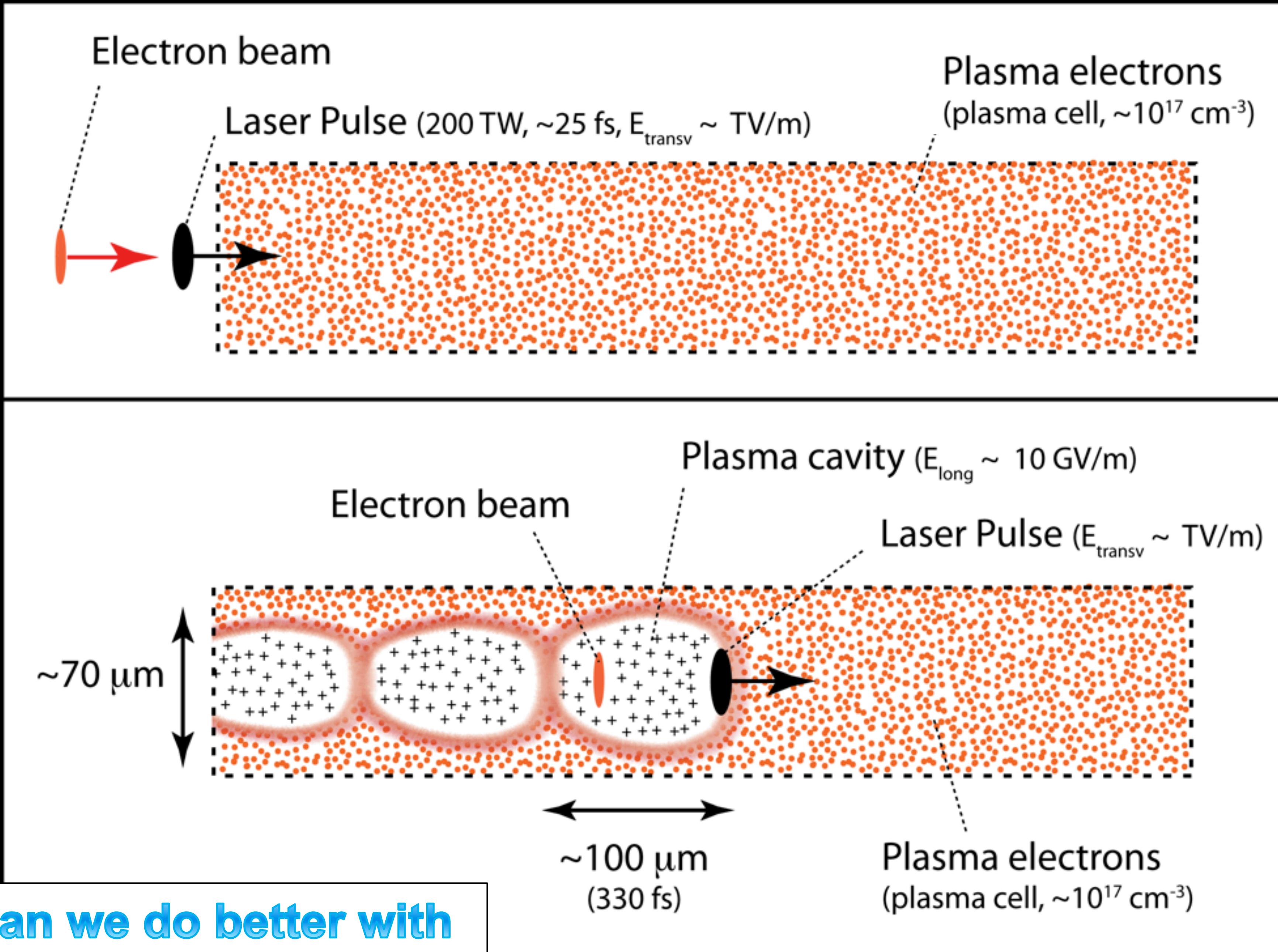
This accelerator fits into a human hair!

Reminder: Plasma-Acceleration (Internal Injection)



- This proved highly successful with electron bunches of **up to 4.5 GeV produced over a few cm**.
- Small dimensions involved → few **micron tolerances**!
- Highly compact but also **highly complex** accelerator: generation, bunching, focusing, acceleration, (wiggling) all in one small volume.
- Energy spread and stability at the few % level.

External Injection…



Can we do better with external injection?

Plasma Accelerator Physics I

- A plasma of density n_0 (same density electrons - ions) is characterized by the **plasma frequency**:

$$\omega_p = \sqrt{\frac{n_0 \; e^2}{\epsilon_0 \; m_e}}$$

- This translates into a **wavelength** of the plasma oscillation:

$$\lambda_p \approx 1\mathrm{mm} \cdot \sqrt{\frac{10^{15}\mathrm{cm}^{-3}}{n_0}}.$$

0.3 mm for $n_0 = 10^{16}$ cm^{-3}

- The wavelength gives the longitudinal size of the plasma cavity… Lower plasma density is good: larger dimensions.

Plasma Accelerator Physics II

- The plasma oscillation leads to **longitudinal accelerating fields** with a gradient of (higher plasma densities are better):

$$W_z = 96 \ \frac{\mathrm{V}}{\mathrm{m}} \cdot \sqrt{\frac{n_0}{\mathrm{cm}^{-3}}}$$

9.6 GV/m for 10^{16} cm^{-3}

- The **group velocity of the laser in a plasma** is as follows ($\omega_p << \omega_l$. Note: ω_l is laser frequency):

$$v_g = c \cdot \sqrt{1 - \frac{\omega_p^2}{\omega_l^2}}$$

- The laser-driven wakefield has a lower velocity than a fully relativistic electron → slippage and dephasing. Lower densities are better.

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

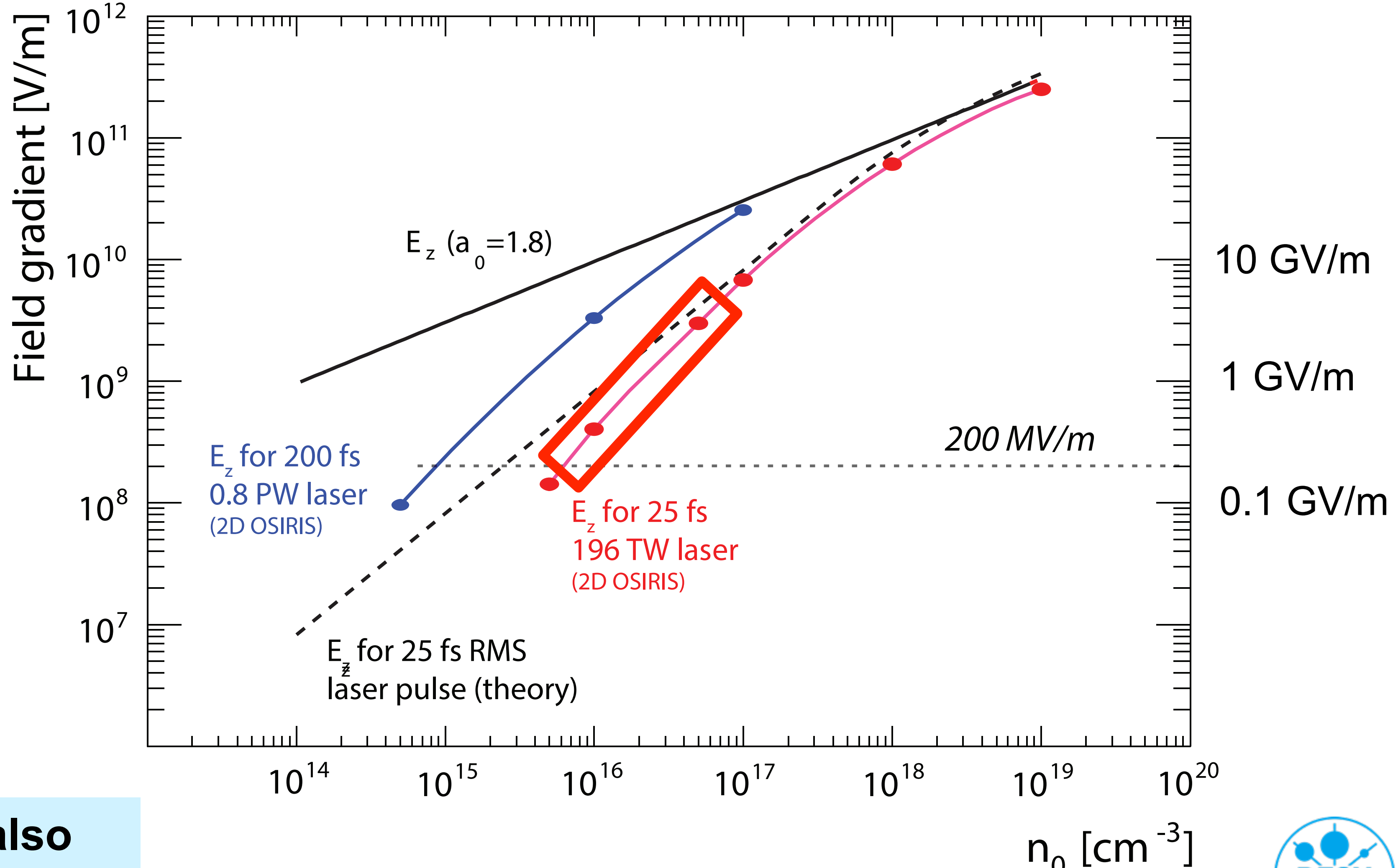
Density	cm^{-3}	0.5×10^{16}-10^{18}

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

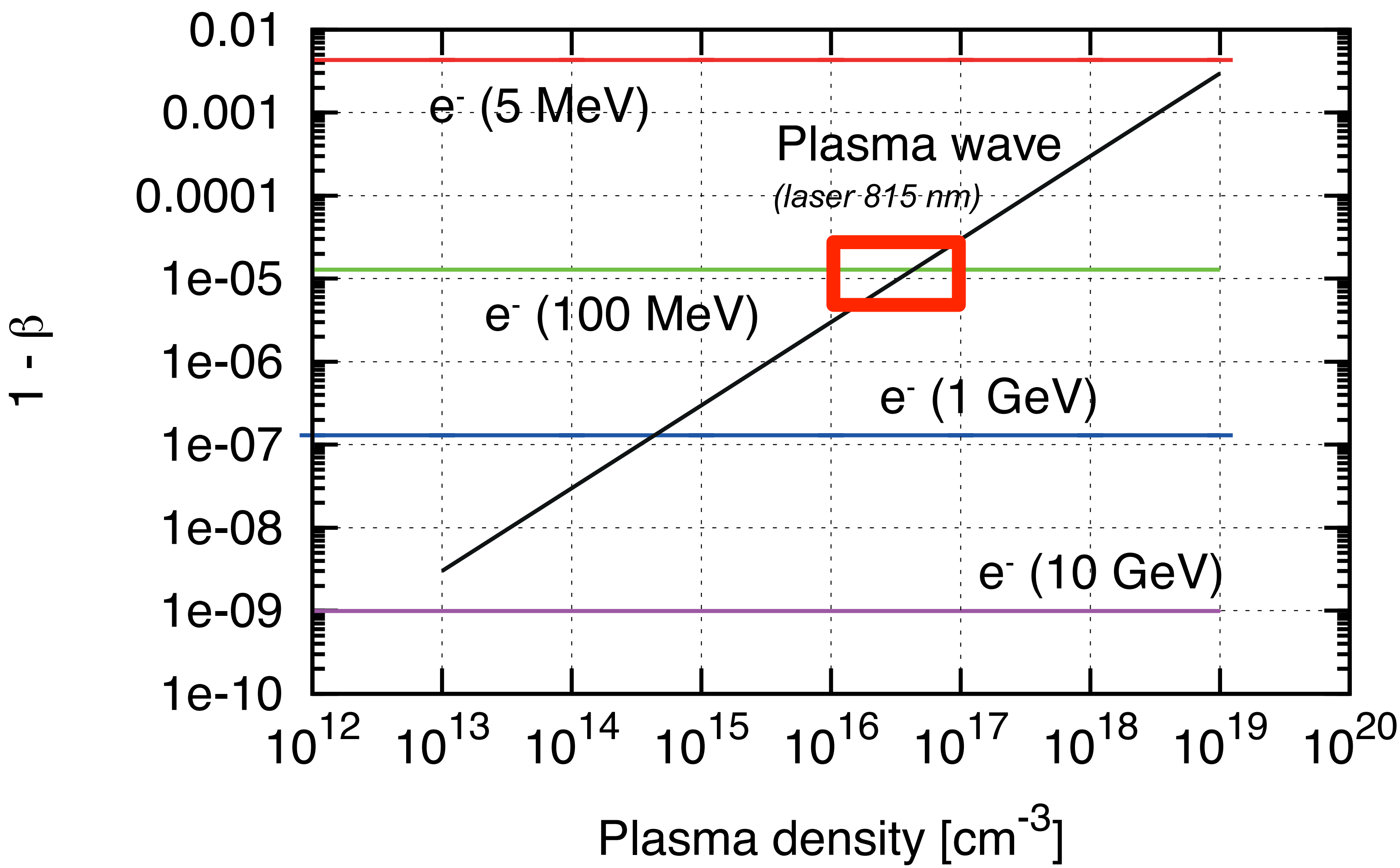
Minimum Useful Plasma Density

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



See also TUPME064

Beam Energy for Injected Electron Bunch



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Plasma Accelerator Physics III

- 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:

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

Plasma Accelerator Physics IV

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

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

σ_0 = 1.3 μm for $\gamma\varepsilon$ = 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 $\Delta x = \sigma_x$:

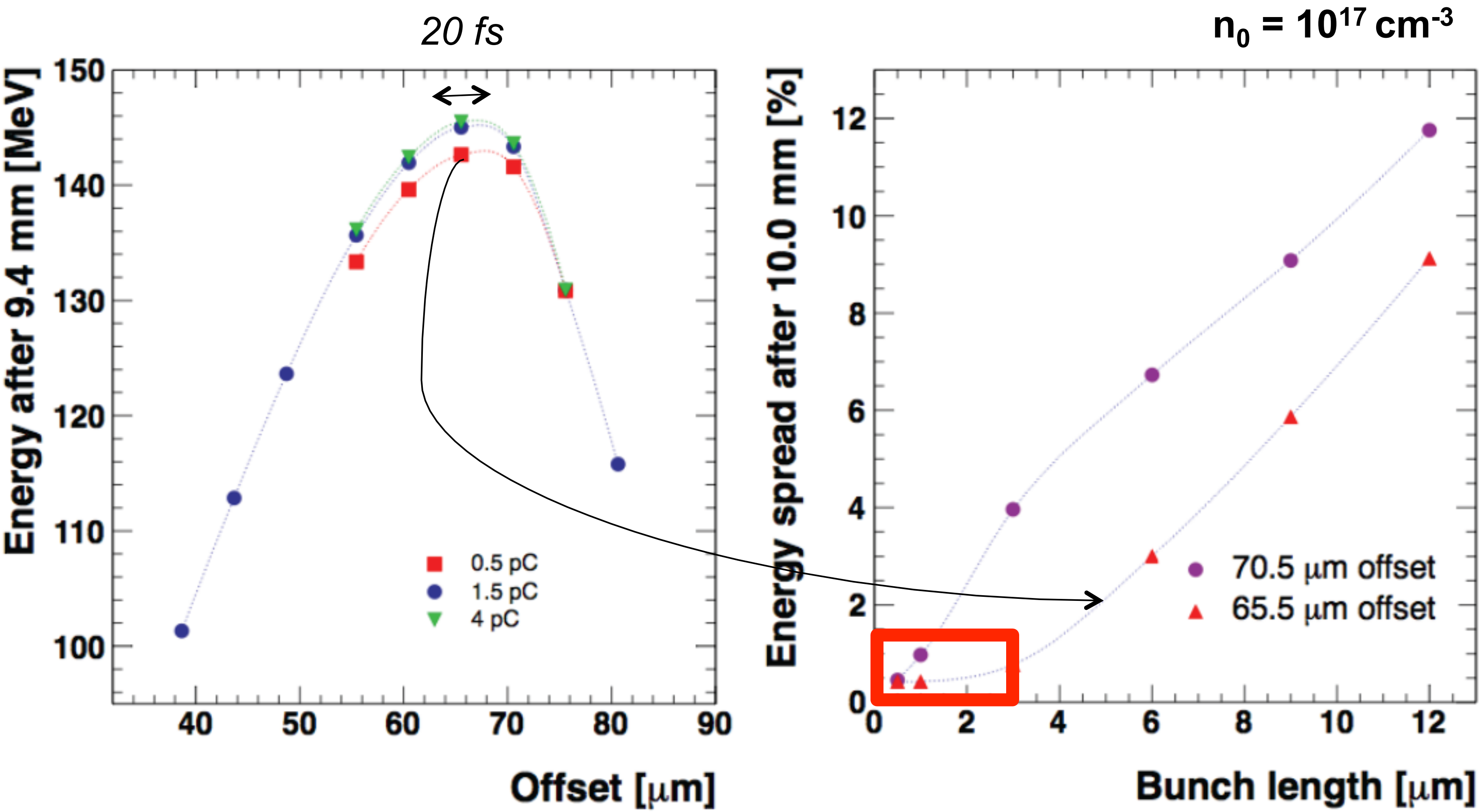
$$\frac{\Delta\varepsilon}{\varepsilon_0} = \left(\frac{\sigma_x}{\sigma_0}\right)^2$$

100% for 1.3 μm offset

- Lower plasma density better: larger matched beam size, bigger tolerances.

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

Energy + Energy Spread after ≈ 1 cm Plasma



See also TUPME064

Beam Loading to Flatten Wakefield *S. van der Meer – T. Katsouleas*

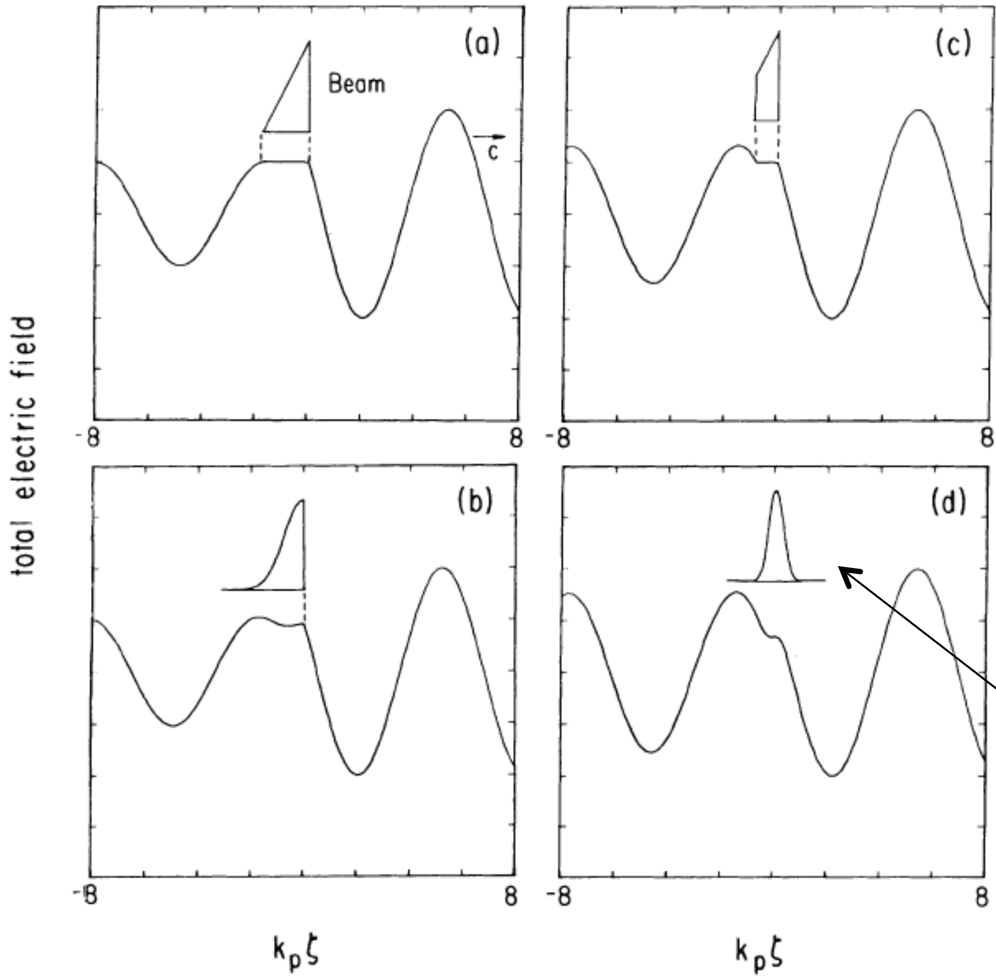


FIGURE 4 Total electric field for various beam shapes: (a) triangle [Eq. (22), $N = 3N_0/4$, $k_p\zeta_0 = \pi/3$), (b) half-Gaussian of same number of particles, (c) truncated triangle ($N = 9N_0/16$), and (d) Gaussian of same number as (c).

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

- 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.

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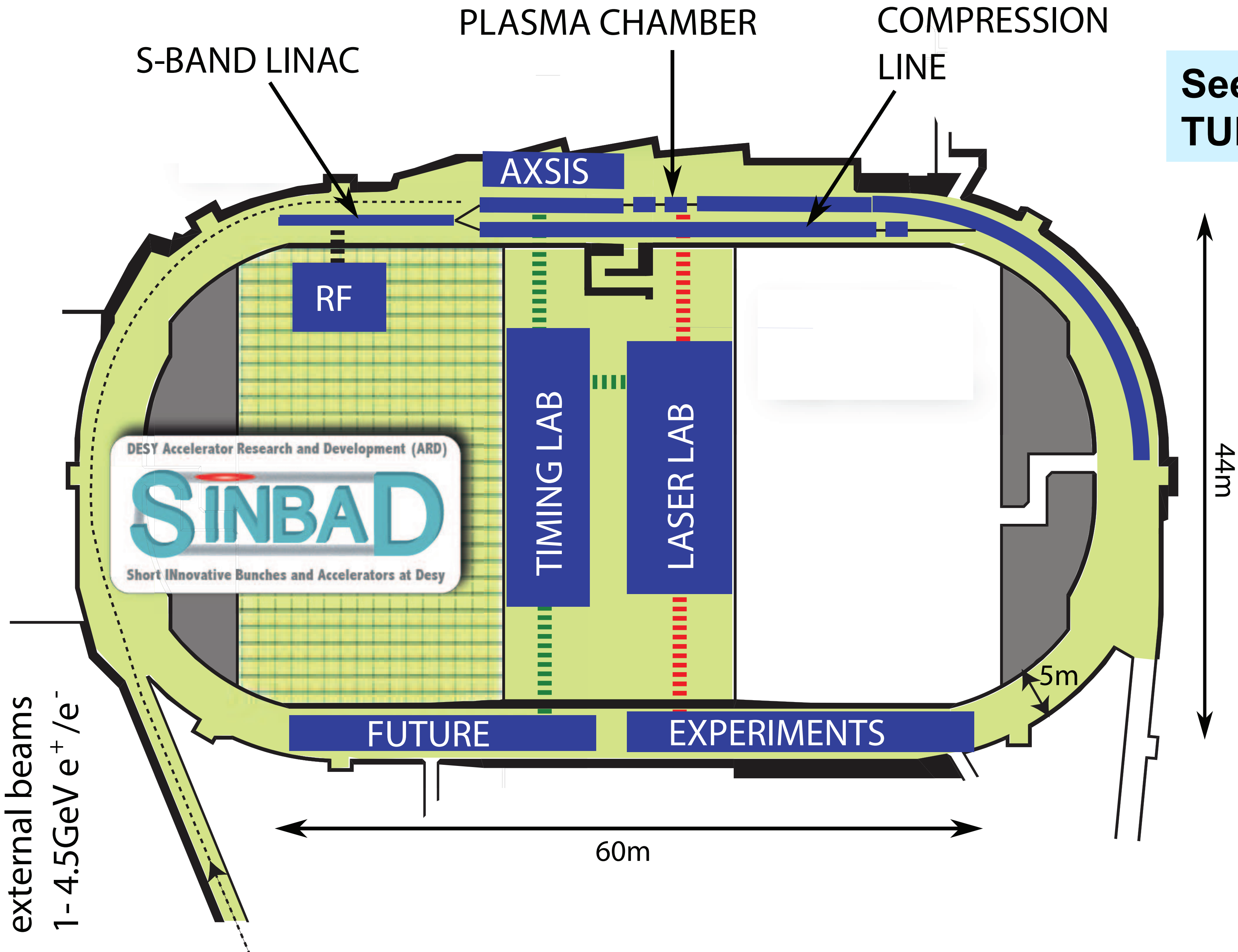
Plasma Accelerator Projects

- Our **vision for going towards user capabilities**:
  - Prepare external injection. Advantages: known beam in, measure the transfer function of the plasma, scans possible (Q, offset, length), can be staged,… Disadvantages: tolerances
  - Generate short injected bunch (≤ 10 fs), shaping of bunch shape (van der Meer), small emittance (photo injector), fs synchronization (photon science), small beta function (HEP squeeze). We think we can get close or match the requirements with latest technology.
  - As low as possible plasma densities to start in most simple conditions. Larger matched beam size, relaxed tolerances, … Adiabatic matching into plasma (Whittum, 1989).
  - The success will be all in accuracy, tolerances, precision! We mastered this in conventional accelerators.
- Now: **Build the suitable e^- injector for plasma…**
  Some projects (not complete overview – many more)…

SINBAD – Short Innovative Bunches & Accelerators at DESY

See also TUPME047



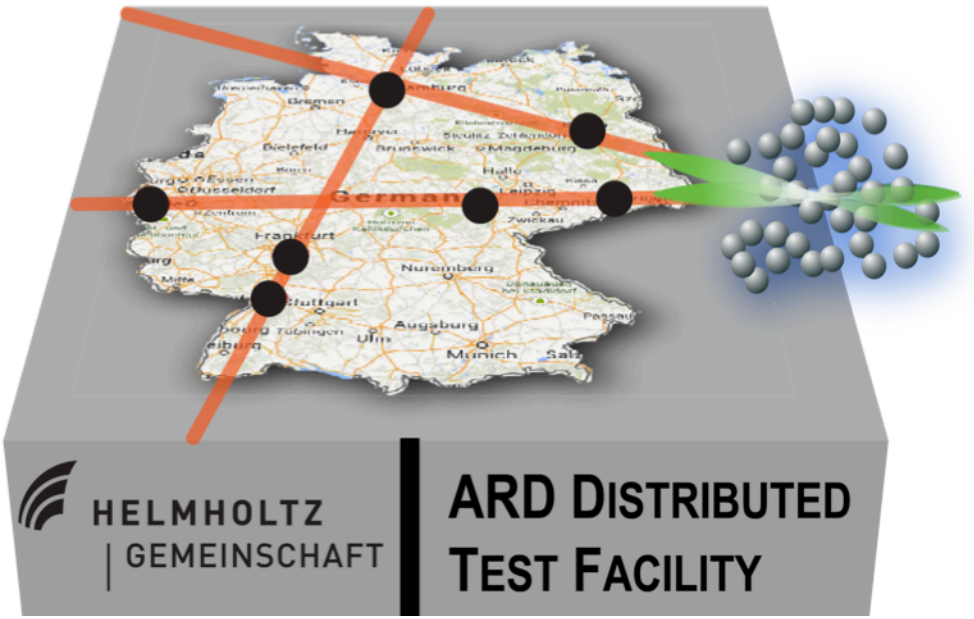
DRAFT

Old DORIS collider will be converted into SINBAD (2016 onwards)

SINBAD: Concept and Idea

- SINBAD **multi-purpose accelerator R&D** facility (PL: U. Dorda).
- Presently ≈ half the space distributed for projects:
  - ARES: Ultra-short and dense electron bunches (PL: B. Marchetti).
  - AXSIS: THz driven waveguides for atto-second science (EU ERC funded)
  - **PLASMA(a): Use ARES beam for injection into laser-driven plasma accelerator.**
  - PLASMA(b): Use ARES beam for driving beam-driven plasma wakefields.
- Quality goes first: **ARES built for maximum quality**. No major compromise allowed.
  - Still considering different RF technologies: what gives best quality?
- Focus is on stability and quality. No new energy records.
- Medium term: FEL applications. Long term: HEP.

Proposal: Helmholtz Distributed ARD Test Facility – Germany



The preparation team:

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See Talk R. Brinkmann
FRYBA01

- Theme 1: **Collaboration**

  Networking of existing research infrastructure.

- Theme 2: **Synergy**

  Extension of facilities for common usage.

- Thema 3: **Leadership**

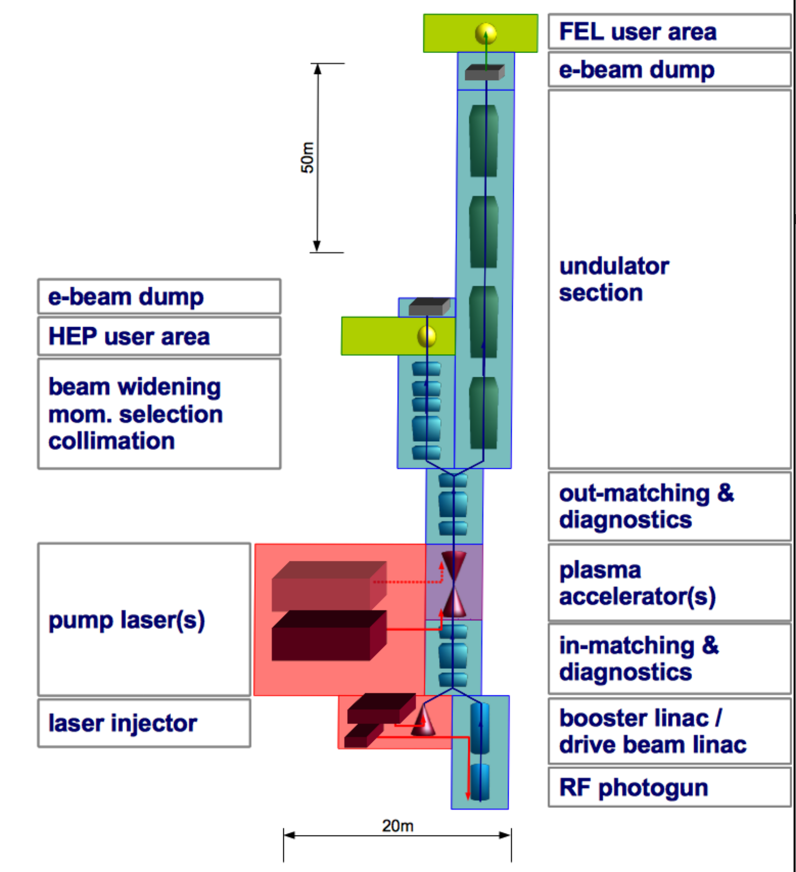
  2 – 3 flagship projects for internationally leading research with the **aim of ultra-compact accelerators and radiation sources** (plasma acceleration major player).

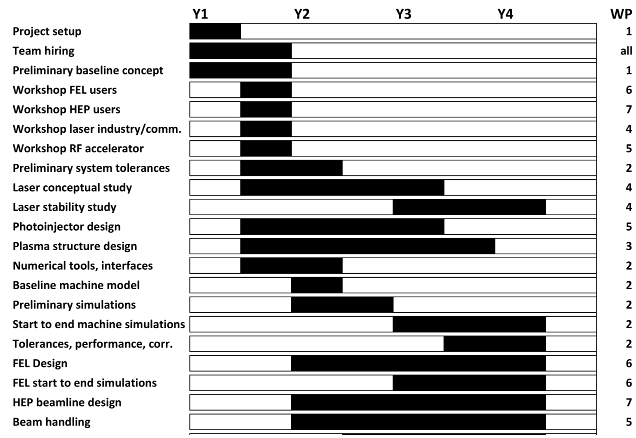
TUPME047
MOPRO106
WEPRO113
THOBA03
MOPRO066
TUPME030
S hort IN novative B unches & A ccelerators at D esy
ARD Spitzen-forschung im alten DORIS Komplex
durch optimale Nutzung der Infra-struktur
Kompakte Atto-Sekunden Lichtquelle
50 as, ICS
ERC Synergy Grant, DESY, Uni HH, Arizona
Ultrakurzer Elektronenpuls
< 1 fs mit konventioneller Technologie
ARD, DESY, Uni HH, KIT
Nutzbarkeitsstudien Plasma-beschleuniger, Skalierbarkeit
> 1 GeV/m, nutzbare Strahlqualität, FEL?
LAOLA, ARD, DESY, Uni HH
PIER
Ralph Aßmann | SINBAD | 24.01.2014 | Page 16
bERLinPro centre for high power cw beams in sc accelerators
bERLinPro = Berlin Energy Recovery Linac Project
100 mA / low emittance technology demonstrator
bERLinPro
Helmholtz-Zentrum Berlin
beam dump
6.5 MeV, 100 mA = 650 kW
linac module
44 MeV
booster
4.5 MeV
srf-gun
1.5-2 MeV
merger
dogleg
Jülich Short-Pulse Particle and Radiation Centre
JÜLICH
Particle physics
Synchrotron radiation
JuSPARC
Material research
Markus Büscher
Kiel
Rostock
Lübeck
Stade
Hamburg
Bremerhaven
Bremen
Pasewalk
Berlin
Hanover
Steglitz-Zehlendorf
Bielefeld
Brunswick
Magdeburg
Büren
Halle
Essen
Dusseldorf
Leipzig
Riesa
Germany
Chemnitz
Dresden
Zwickau
Frankfurt
Nuremberg
Stuttgart
Augsburg
Tübingen
Ulm
Munich
Passau
ELBE center for high power radiation sources
Beam driven sources (THz, FEL, ...) at ELBE
ELBE
150TW
Draco PW
HZDR
The LIGHT test-stand at GSI: coupling of laser-accelerated ions into conventional accelerators
Principle: manipulation of laser-accelerated ions
HI Jena
GSI
HZDR
1. Laser-driven ion acceleration
2. beam conditioning (collimation)
3. drift line and phase-space rotation
ion source (TNSA)
solenoid/ quadrupols
spiral resonator
Current results:
FLUTE: ARD-Forschung am KIT
KIT
Ultrakurze
Grosser B
Kohärente
iologische Anwendungen
Entwicklung/Tests von Kurzpuls-Strahldiagnose und Instrumentierung
Kooperation KIT, PSI, DESY
Ferninfrarot Linac- U
FLUTE
FLUTE, a Linac-Based THz Source at KIT
Helmholtz-Institute Jena
relative z-position (μm)
Development and application of novel
A. Sävert et al., submitted (2013)

EuPRAXIA – EU Design Study Proposal

- EuPRAXIA = **European Plasma Research Accelerator with eXcellence In Applications**
- Planning a proposal as EU design study to the EU in September.
- If successful, then this could result in a **European construction project (Large Infrastructure) by the early 2020's**.
- Involved institutes: About **20 European labs and universities**.
  - Bringing together research infrastructure, expertise, brainpower
  - Build one European plasma accelerator at one location.
  - Distribute the resources and the work (like a big particle physics detector).
- Foresee some associate institutes from US, Asia, Russia.

EuPRAXIA





Today

Multi GeV e- bunches in plasma acc. (30 m)

EuPRAXIA 5 GeV FEL & HEP test beam 250 m

2020's

Plasma Linear Coll. 3000 – 5000 m

2030's

Ultra-Compact FEL 10 – 100 m

Ultra-Compact e- medical accelerator

Conclusion

- Plasma-based accelerators have made very nice progress. The **achieved beam energy follows an exponential function** (Livingston).
- Beam **quality is still insufficient** for users. Plasma cavities are small and have ultra-strong fields. Interesting accelerator physics…
- Conventional **accelerator physicists can help: Build the best possible injector** for a laser-driven plasma accelerator.
- Pick up on the work of famous accelerator physicists, e.g. van der Meer who suggested **specially shaped e- bunches** for injection into plasma.
- Requirements are being defined. Present status presented.
- We think we can master the challenges.
- Several **projects are being set up** along the lines discussed. I have mentioned SINBAD at DESY, Helmholtz ARD Distributed Facility and EuPRAXIA (EU design study).

Thank you for your attention…