20 years since the first laser plasma accelerated dream beams and a look forward

Wim Leemans

DESY and Universität Hamburg

IPAC'24, Nashville TN

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IPAC 24
NASHVILLE, TENNESSEE
USA
MAY 19-24, 2024
IEEE NPSS APS

Overview

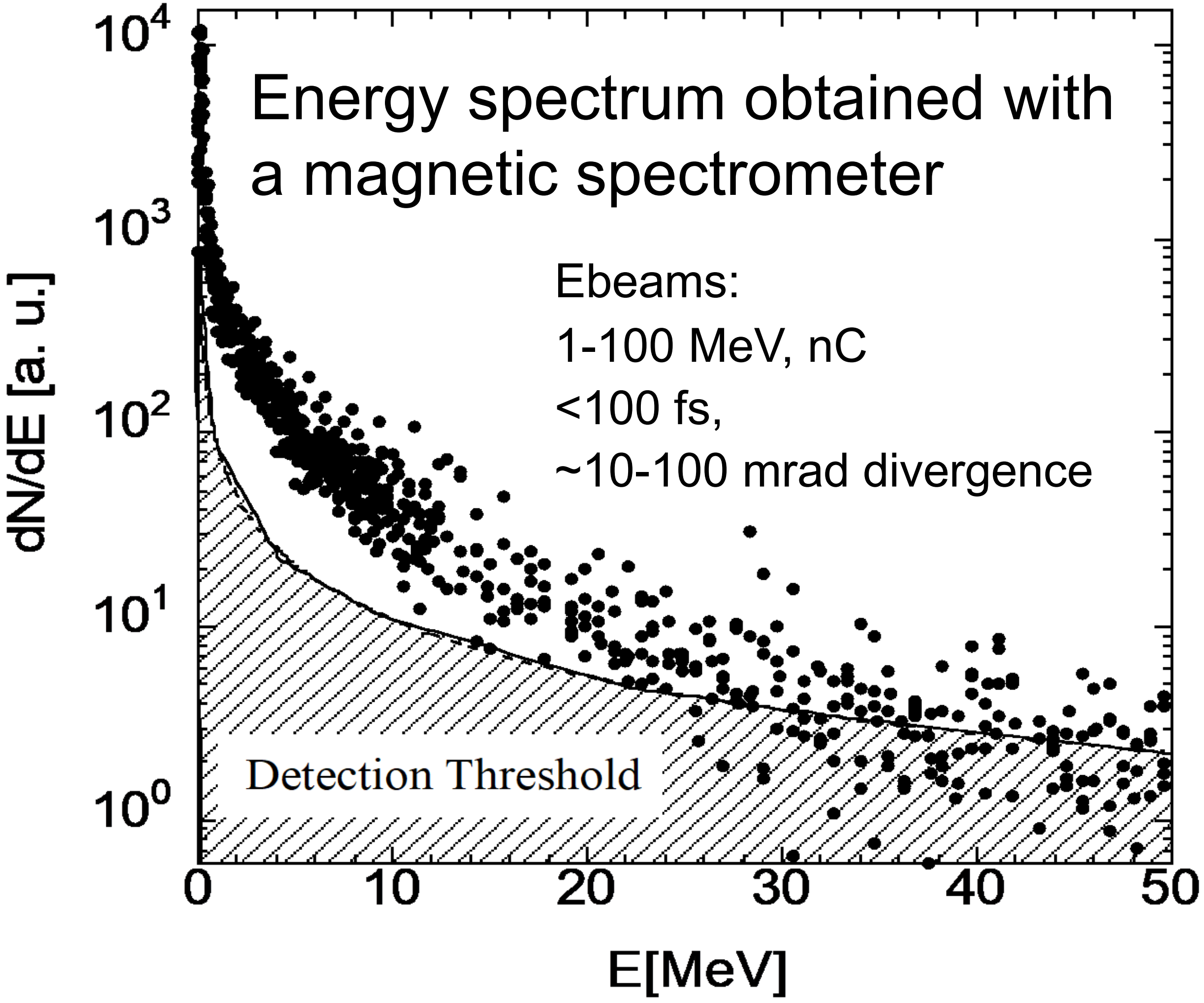
- Quick review of the 2004 results
- Reaching higher electron beam energies
- Controlling injection and beam quality
- Focus on applications
  - Colliders
  - Light sources
  - Storage ring injector

Disclaimer:

- Only electrons from a laser plasma accelerator
- Impossible to do a comprehensive review in 30 minute talk
- Topics that are exciting but I won’t cover:
  - kHz rep rate, few mJ driven laser plasma accelerators
    - E.g., J. Faure’s work
  - Progress in simulation tools over the past two decades
  - Medical applications

Mid 90's -2003: lasers generate electron beams with 100 % energy spread

Laser technology evolved from CO_2 lasers to Nd:glass to Ti:Al_2O_3 short pulse solid state lasers

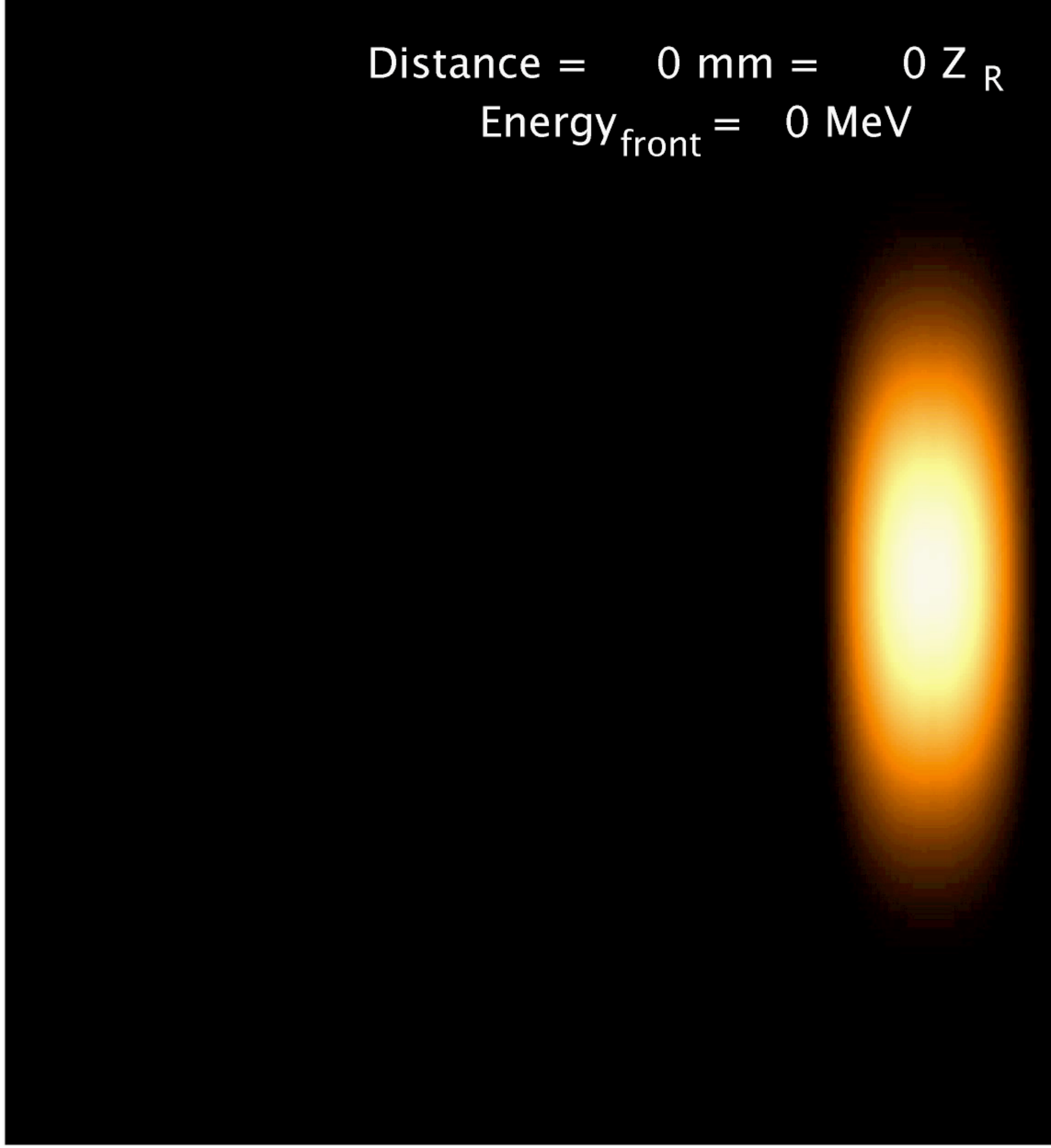


- 2-3 mm gas jet, ~100 MeV electrons
- Confirms large E_z

Modena et al. (95); Nakajima et al. (95); Umstadter et al. (96); Ting et al. (97); Gahn et al. (99); Leemans et al. (01); Malka et al. (02)

In 2002, the bubble or blow-out regime is studied via simulations

High quality electron beams could be generated in the highly non-linear regime

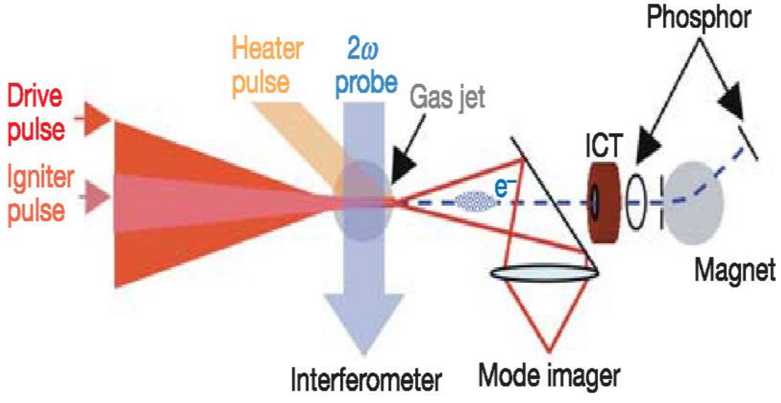


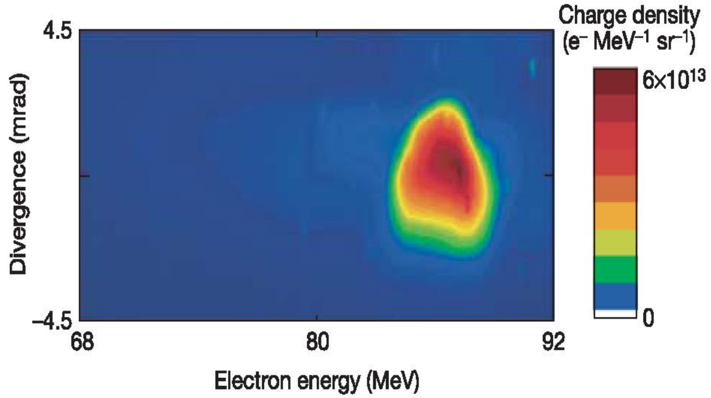
Movie courtesy of W. Mori, UCLA

- Pukhov, A., Meyer-ter-Vehn, J. Laser wake field acceleration: the highly non-linear broken-wave regime . Appl Phys B 74, 355–361 (2002)
- W. Lu et al., Phys. Rev. ST Accel. Beams 10(6) (2007) 061301. http://dx.doi.org/10.1103/PhysRevSTAB.10.061301

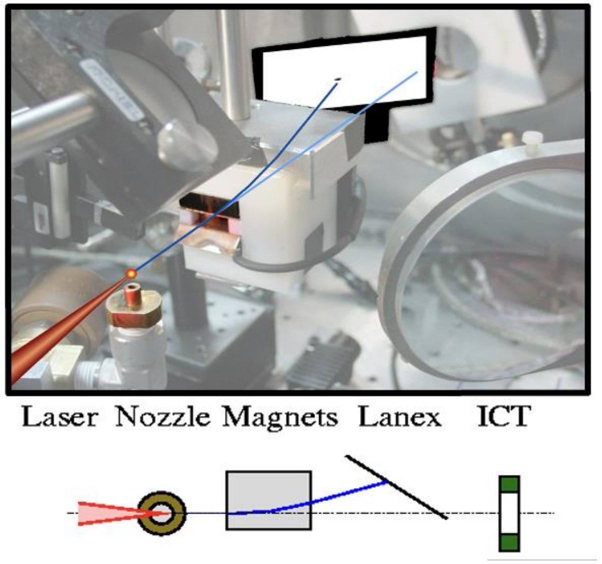
2004: Three independent groups report narrow energy spread beams in the ~100 MeV range with ~100 pC charge

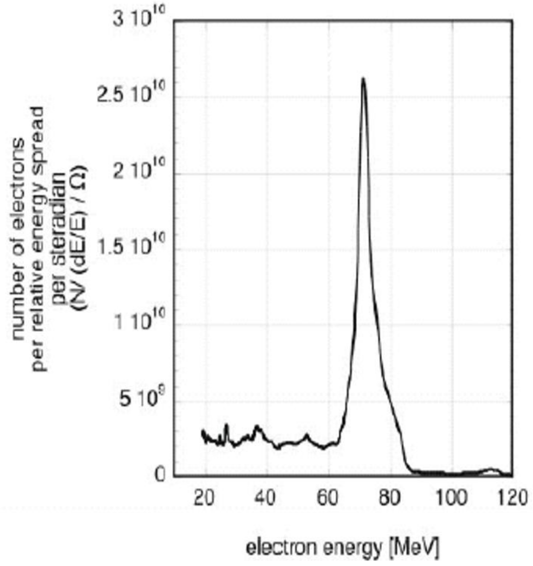
With channel guiding





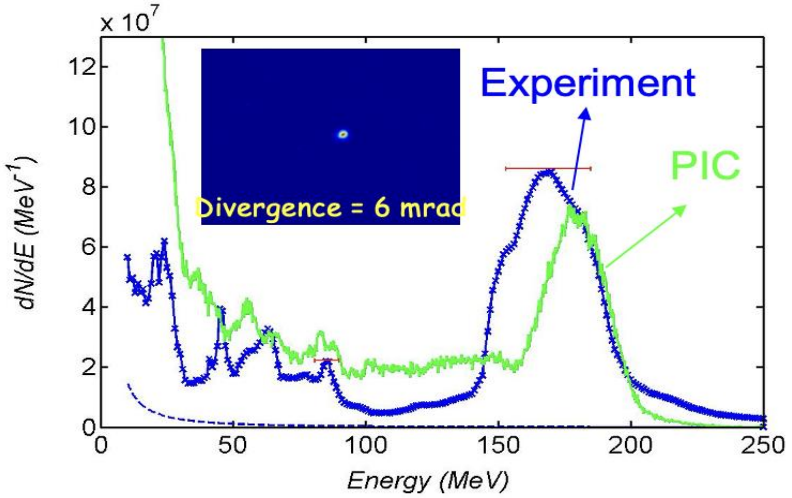
C. G. R. Geddes, *et al.*, Nature, 431, p538 (2004)





S. Mangles *et al.*, Nature 431, p535 (2004)

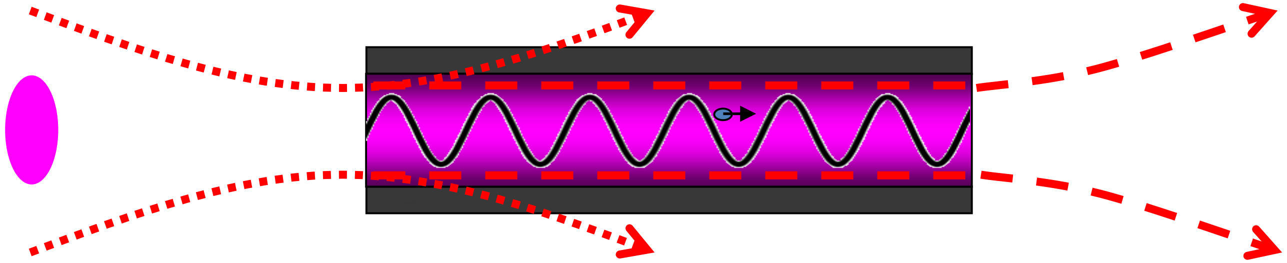
Without channel guiding



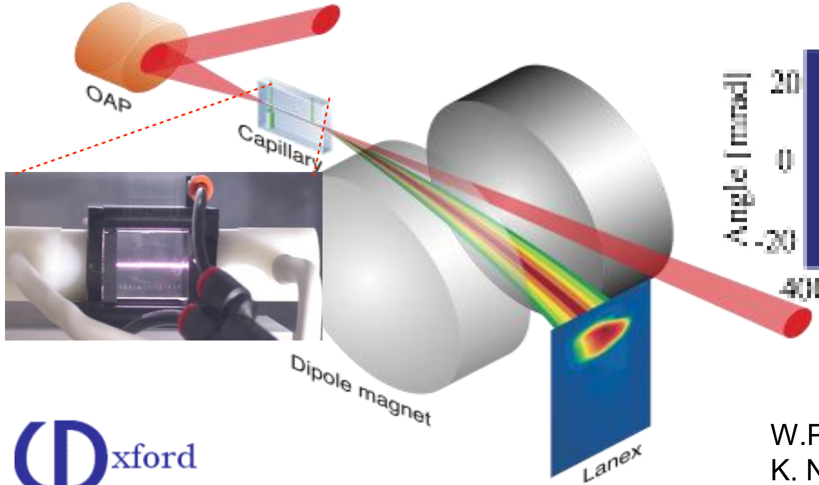
J. Faure *et al.*, Nature 431, p541 (2004)

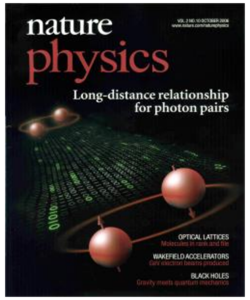
Extending the acceleration length by controlling the distance over which the drive laser is guided in low density plasmas results in GeV beams

Diffraction:



2006 result: 40 TW laser, cm-scale plasma



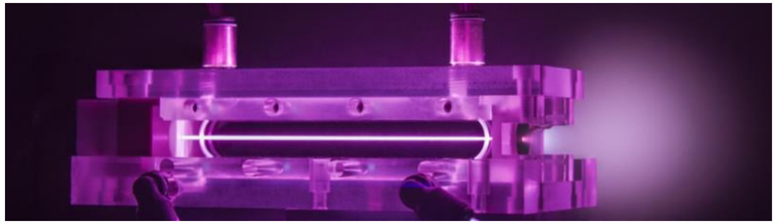


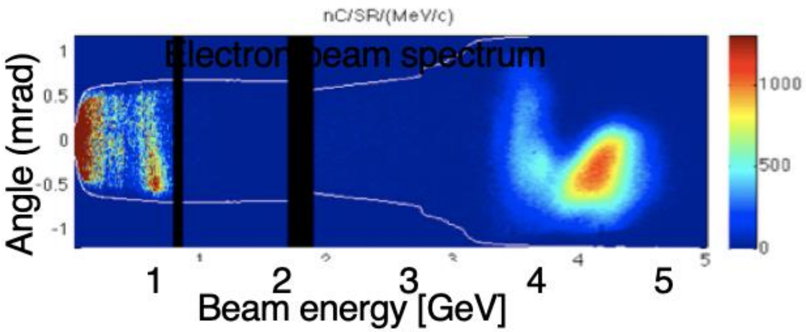
W.P. Leemans *et al.*, *Nature Physics* **2**, p696 (2006)
K. Nakamura *et al.*, Phys. Plasmas **14,** 056708 (2007)

Modematching proved to be a key challenge to overcome

Laser confinement requires high density and optimizing acceleration requires low(er) density

2014 result: 310 TW laser, 9 cm-scale plasma



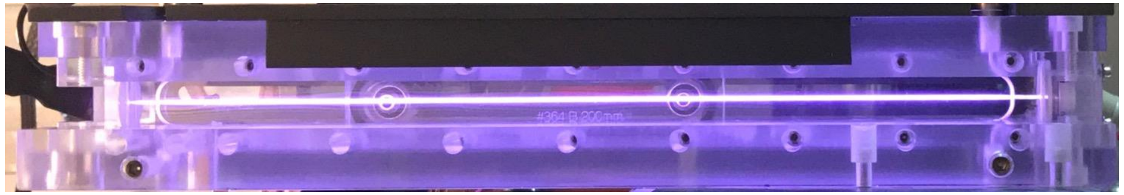


Leemans et al., PRL 2014

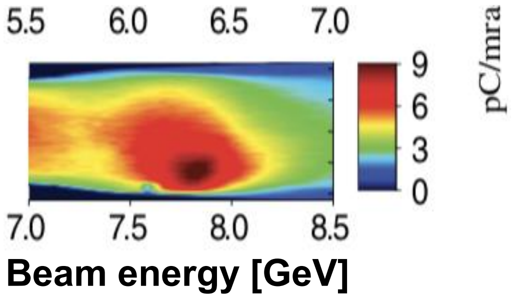
Loss of guiding damages capillary

- Implemented heater beam to deepen out channel: PRL 2019

2019 result: 1 PW laser, 20 cm-scale plasma



Gonsalves *et al.*, PRL 2019

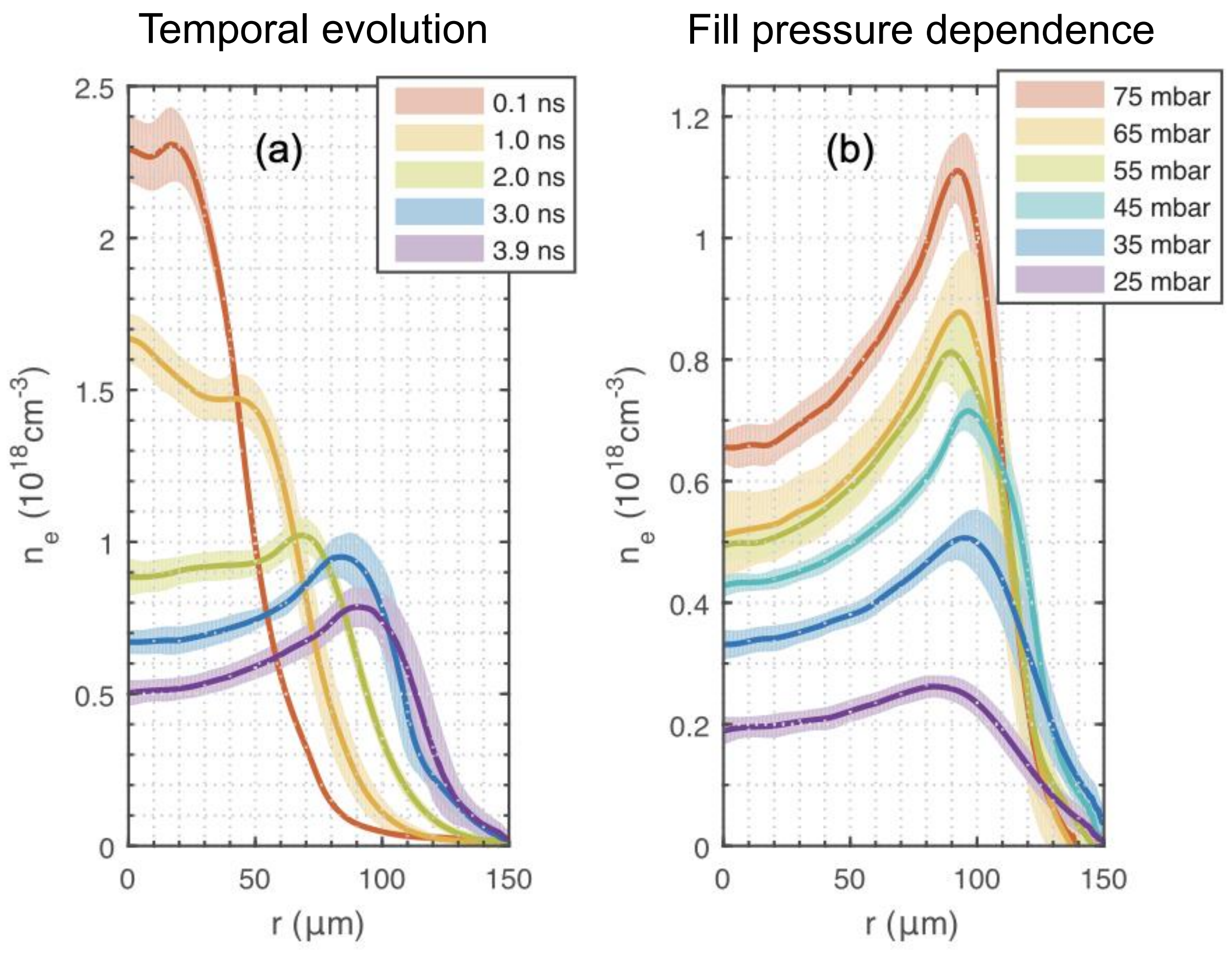


Channel technology that enables guiding of 30-50 micron beam size at 1-2 x10^{17} cm^{-3} is needed: HOFI channels (?)

Formation of laser pre-formed hydrodynamically expanding plasma waveguides has evolved over the past three decades

- **Methods relying on collisional heating require high plasma density**
  - Single pulse for ionization and collisional heating via inverse Bremsstrahlung: C. Durfee and H.M. Milchberg PRL1993
  - Two pulse (ignitor-heater): P. Volfbeyn,E. Esarey and WPL, 1998 – Used in LBNL Dream Beam paper

- **Method suitable for low density plasmas:**
  - Single pulse with elliptical polarization for formatior of hydrodynamic optical field ionization channel: R. Shalloo et al. PRE 2018

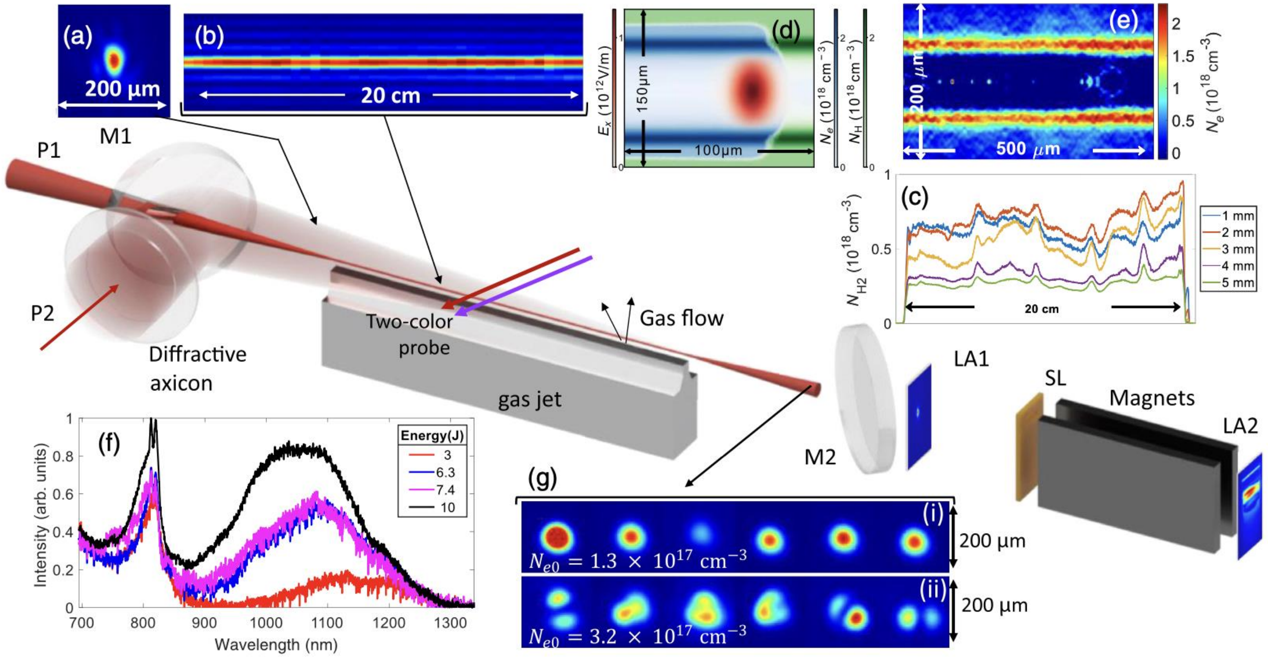


From R. Shalloo *et al.*, PRE 2018

Combining a channel and a <15 J wakefield drive pulse produced 5 GeV electron beams

Reproducibility limited by pointing fluctuations

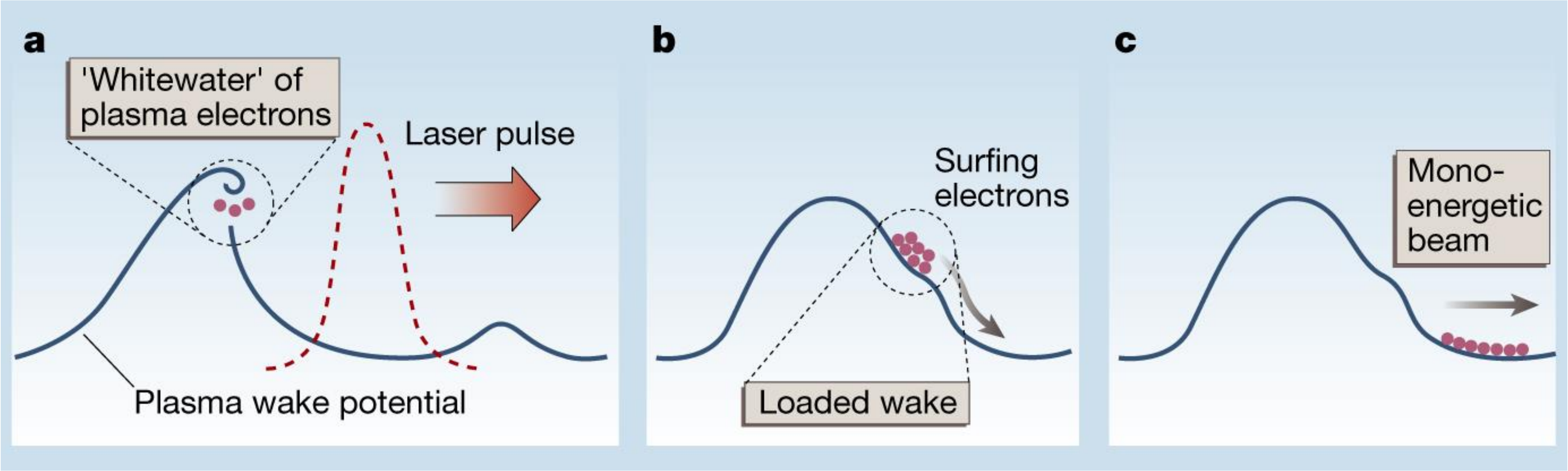
MULTI-GEV ELECTRON BUNCHES FROM AN ALL-OPTICAL … PHYS. REV. X **12,** 031038 (2022)



B. Miao et al., PRX 2022

- No damage issues
- Modematching of relatively small laser beams can be achieved
- Alignment stability is an experimental challenge

Key ingredients for quasi-mono-energetic beams are injection, adequate beam loading, and ending structure before dephasing decelerates the beam



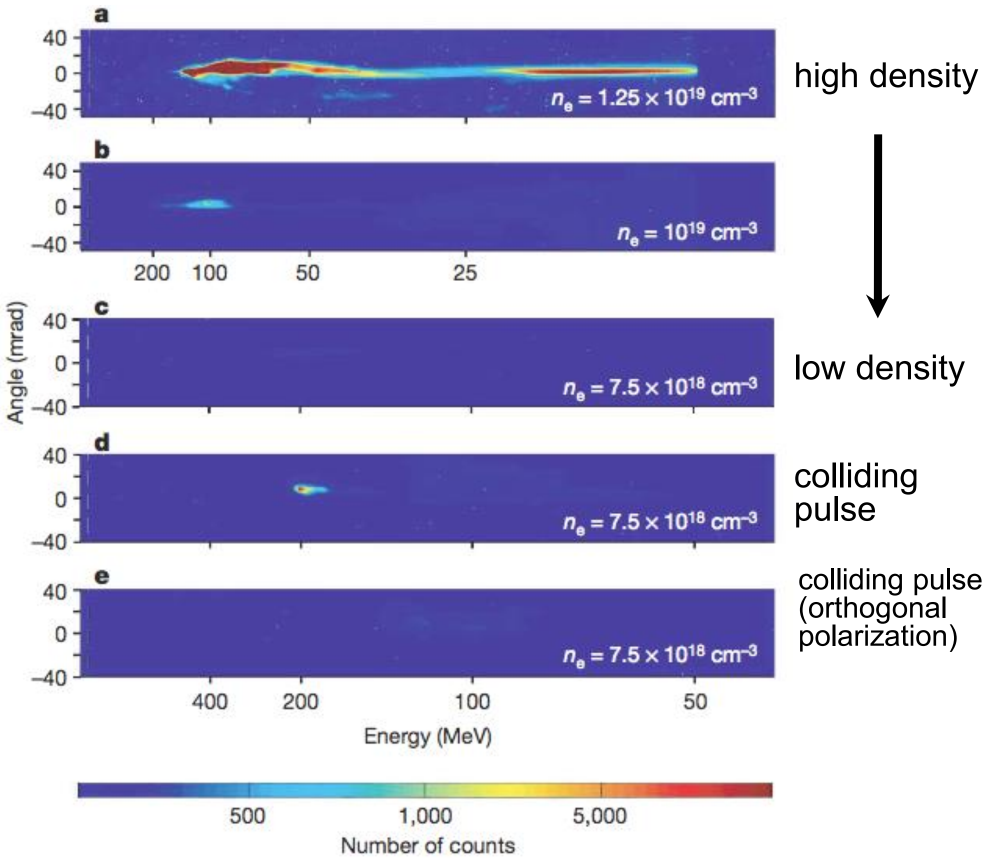
From: Th. Katsouleas, Nature, 431, 515 (2004)

Esarey, Schroeder, Leemans, RMP 2009

Controlling injection is/was a key challenge

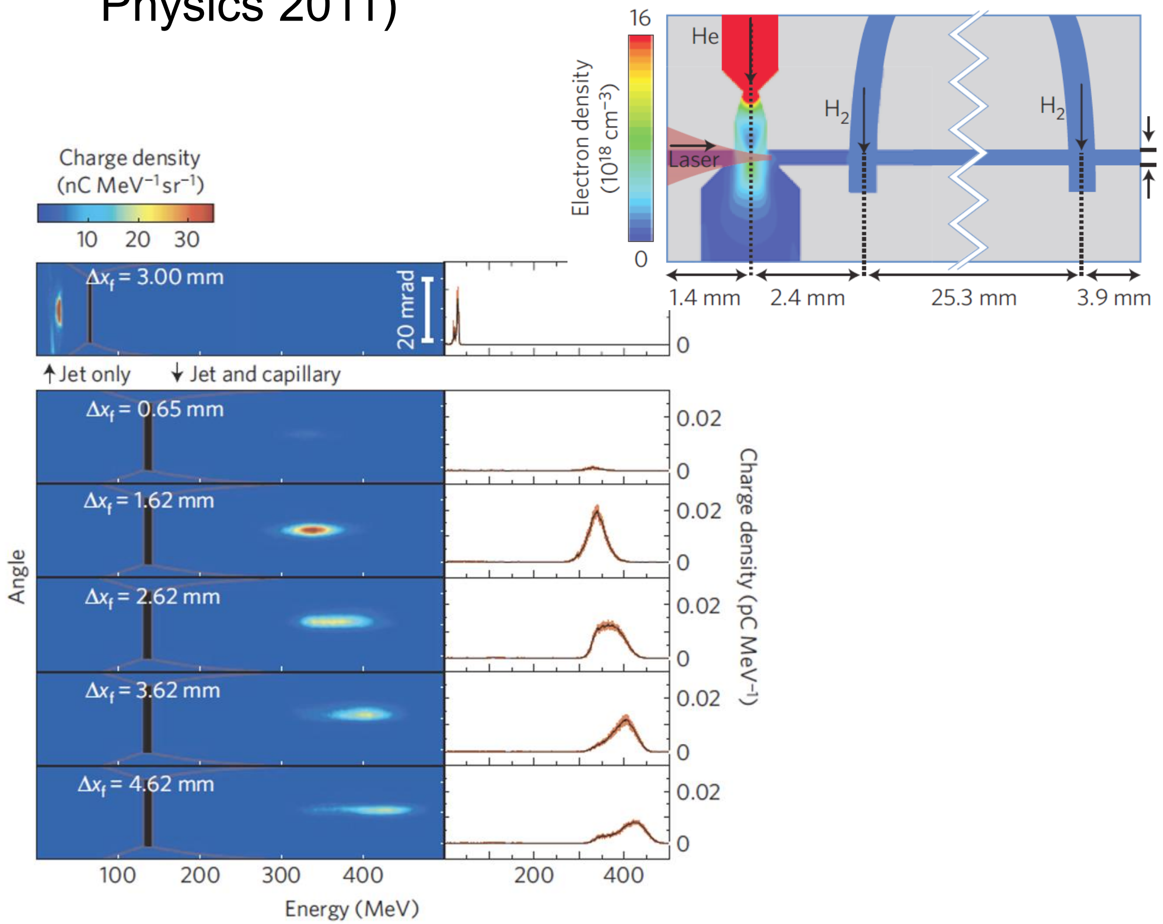
Optical control of electrons or phase velocity of the wave was shown effective

- Boosting the electrons to catch the wave: colliding pulse injection (J. Faure et al., Nature 2006)



From: Faure et al., Nature (2006)

- Slowing the wave down for electrons to catch it (C.Geddes et al., PRL 2008; A. J. Gonsalves Nature Physics 2011)

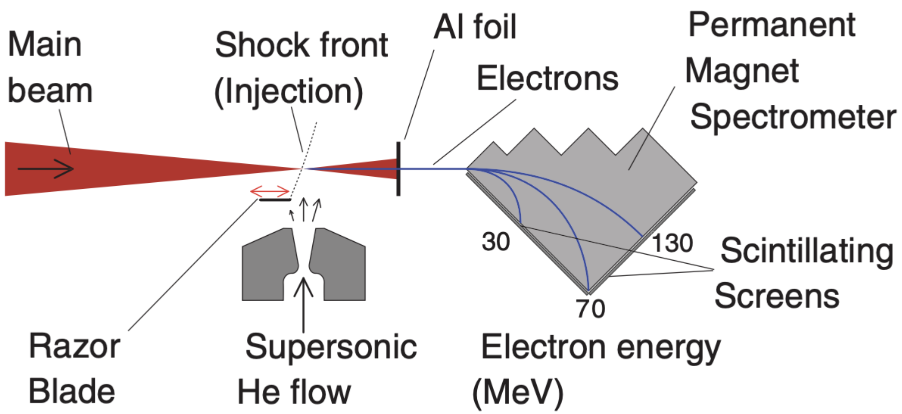


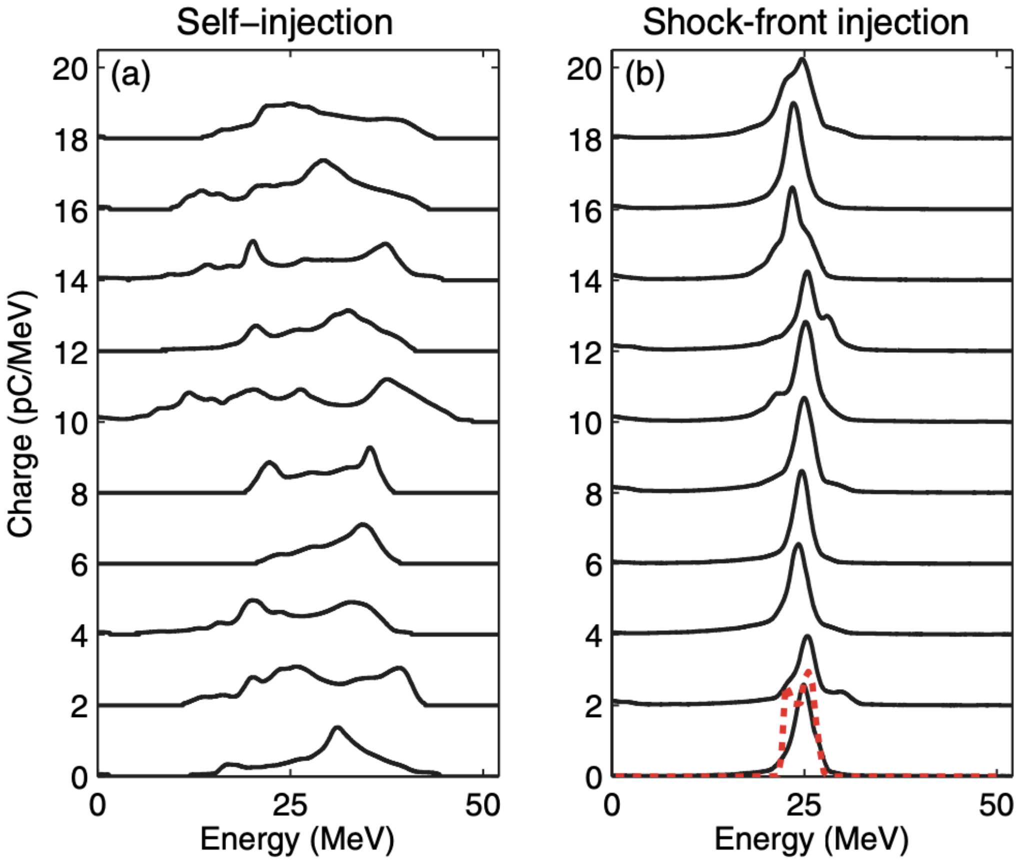
Gonsalves et al., Nature Phys. (2011)

Controlling injection is/was a key challenge – part 2

Injecting electrons via ionization or via localized wavebreaking are simple techniques

- **Ionization injection (A. Pak et al., PRL 2010)**
- **Causing localized wavebreaking (A. Buck *et al.*, PRL 2013, K. Swanson *et al.*, PRAB 2017)**



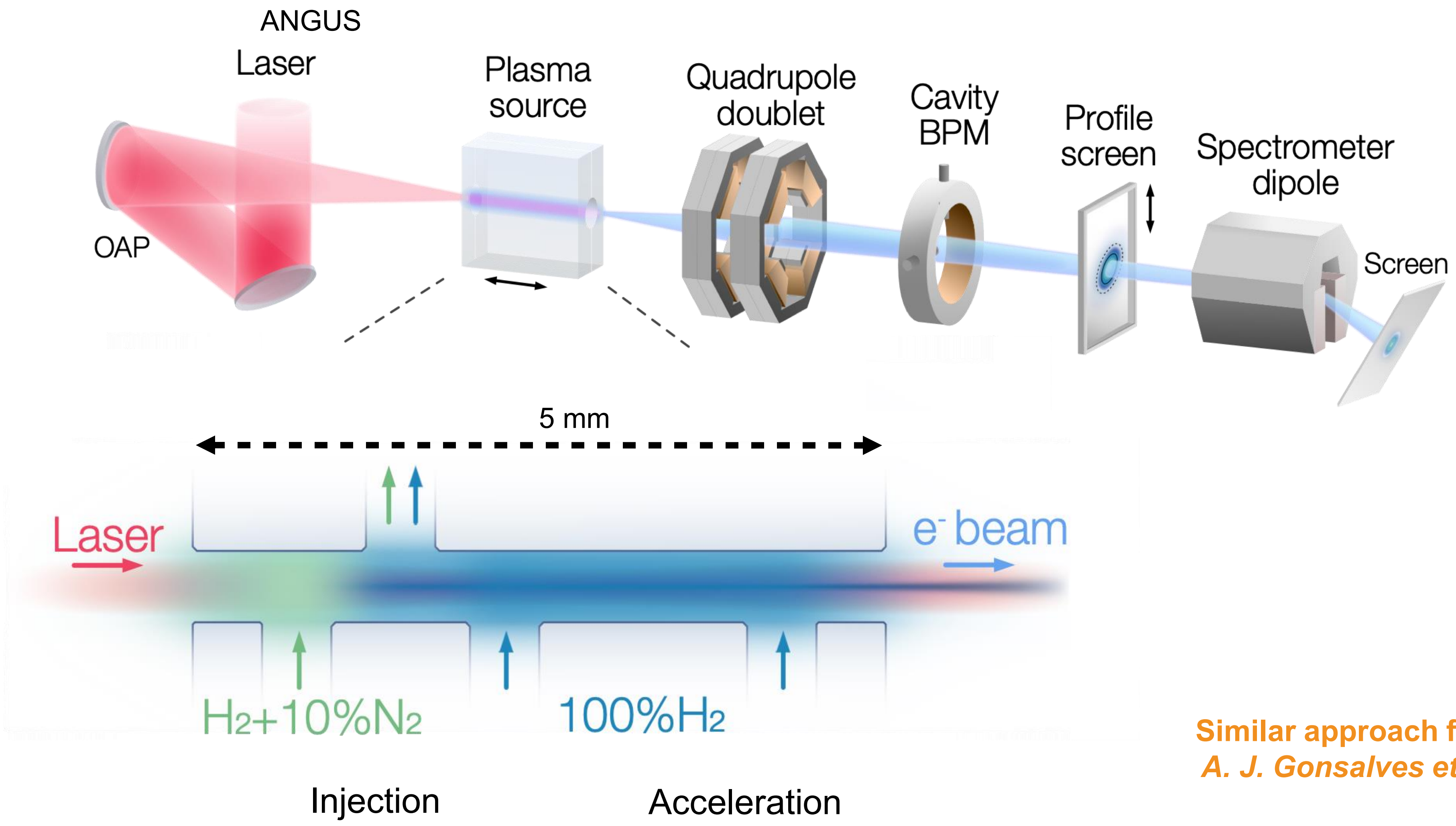


From A. Buck *et al.*, PRL 2013

Tailored gas based target was implemented to allow fine control

Down-ramp assisted localized ionization injection

M. Kirchen et al., PRL 126, 174801 (2021)



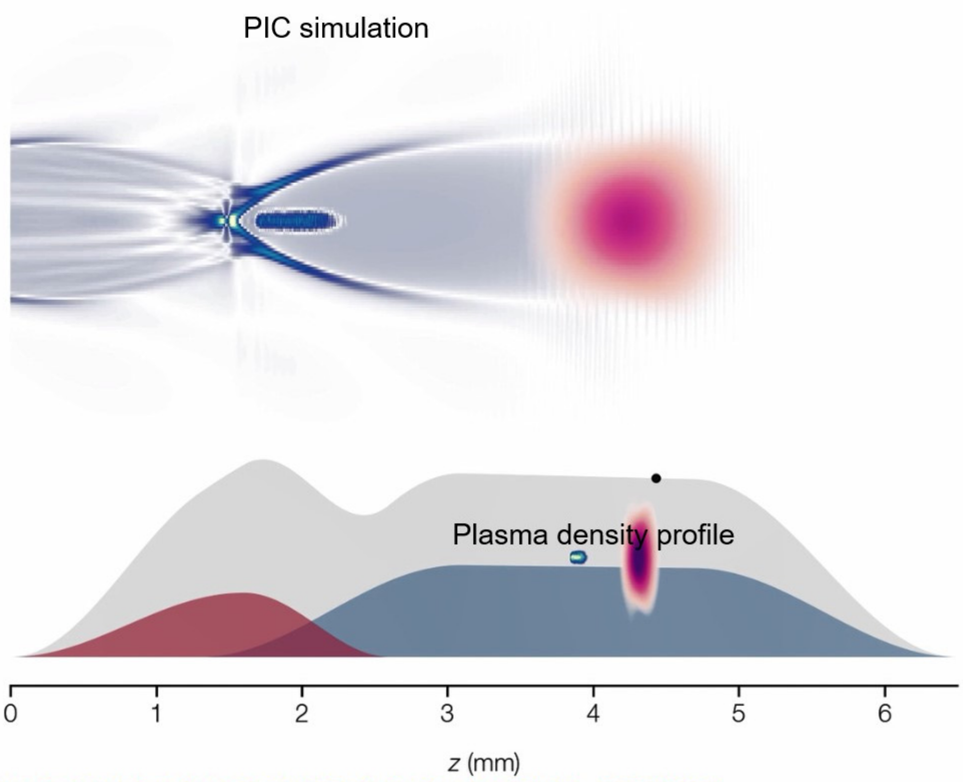
Similar approach followed at BELLA:
***A. J. Gonsalves et al.*, PoP 27, 053102 (2020)**

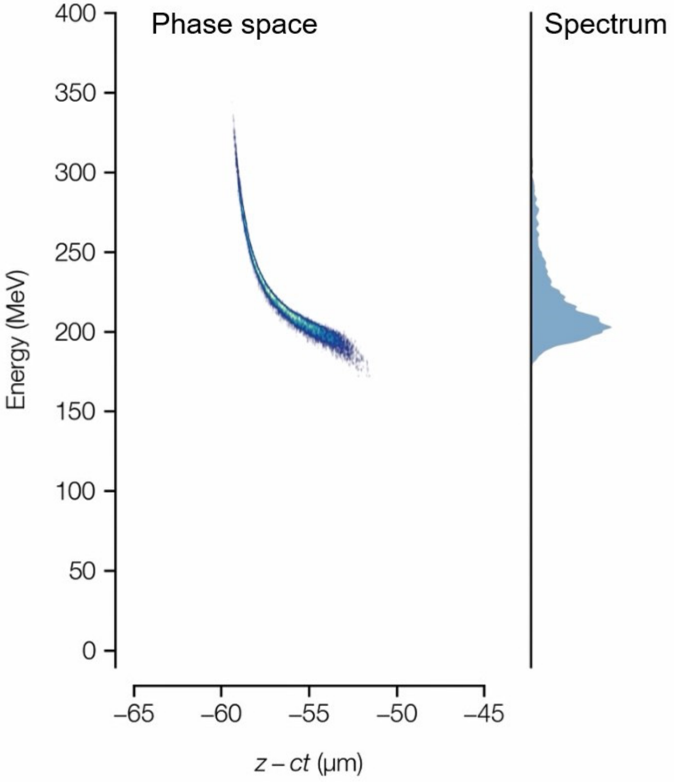
Courtesy: Andreas R. Maier

High-quality electron beams were obtained

M. Kirchen et al., PRL 126, 174801 (2021)

Optimal beam loading is key to narrowing the spectrum



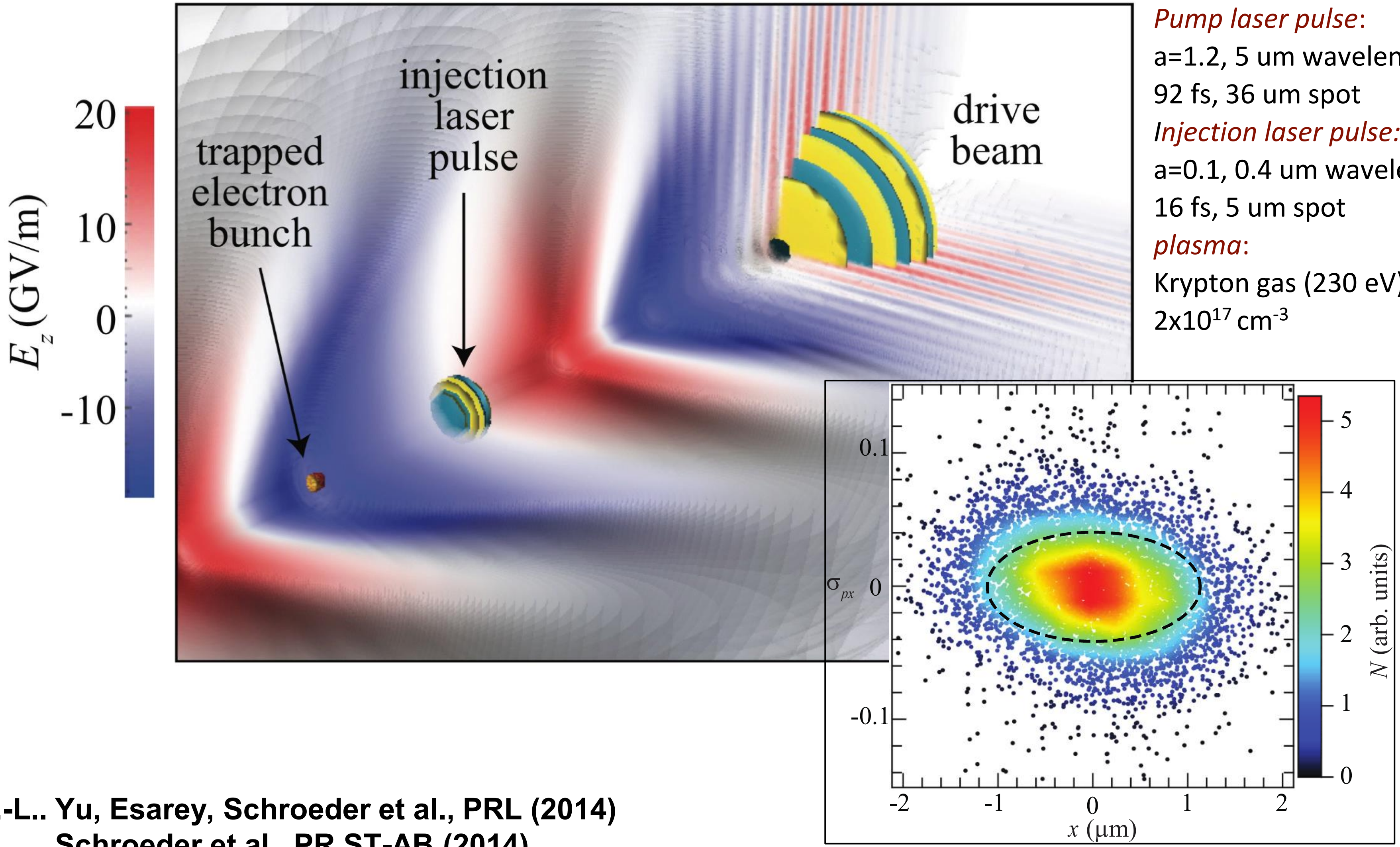


T. C. Katsouleas et al., Part. Accel. 22, 81 (1987); *M. Tzoufras et al.*, PRL 101, 145002 (2008);
C. Benedetti, AAC 2018, WG 1; *J. Götzfried et al.*, PRX 10, 041015 (2020);
J. P. Couperus, Nat. Comm. 8, 487 (2017) ; *C. Rechatin et al.*, PRL 103, 194804 (2009)

Courtesy of Andreas R. Maier

Two color ionization can yield normalized emittances below 0.02 micron

This method has not yet been experimentally demonstrated

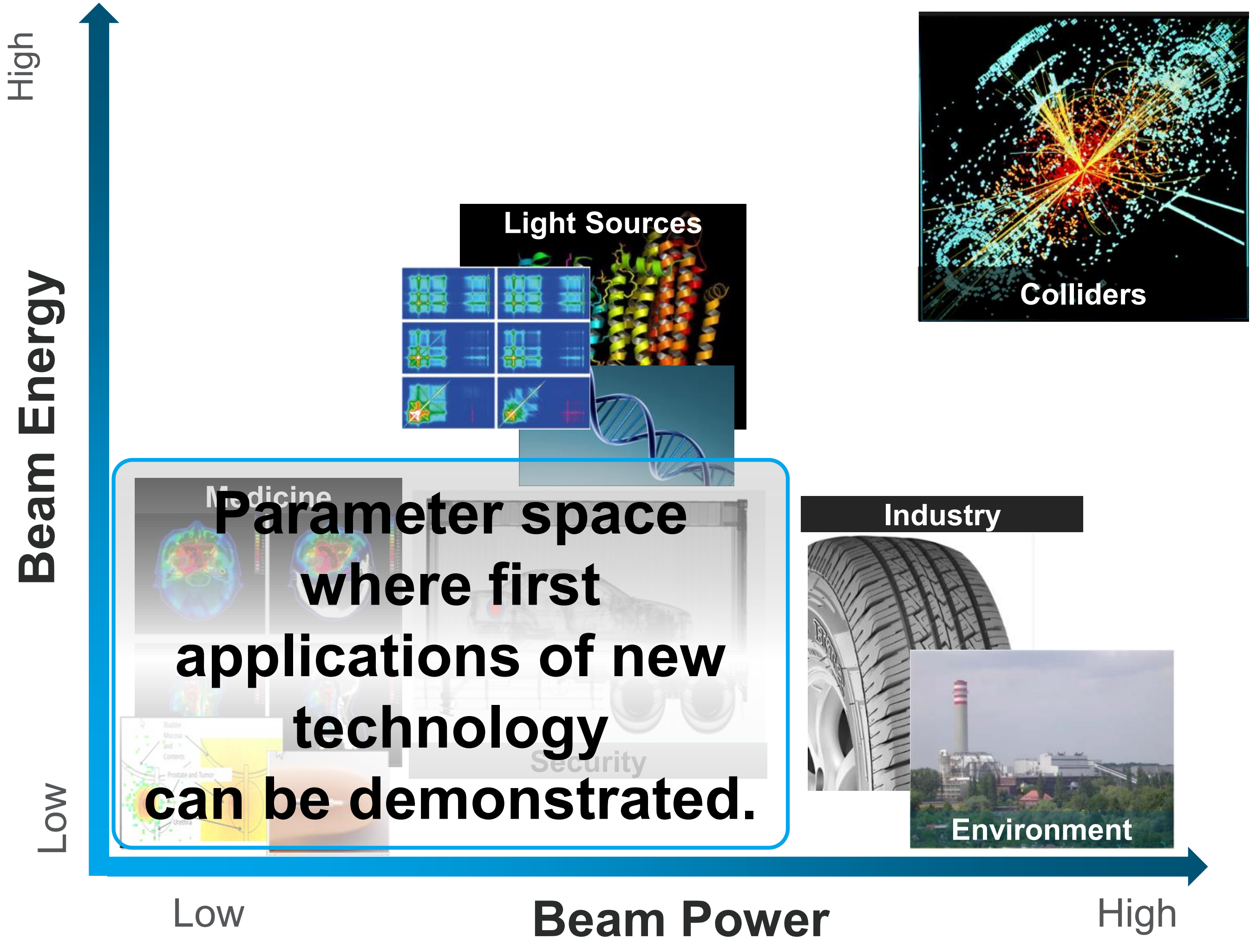


Pump laser pulse:
a=1.2, 5 um wavelength
92 fs, 36 um spot
Injection laser pulse:
a=0.1, 0.4 um wavelength
16 fs, 5 um spot
plasma:
Krypton gas (230 eV)
2x10^{17} cm^{-3}

L..-L.. Yu, Esarey, Schroeder et al., PRL (2014)
Schroeder et al., PR ST-AB (2014)

High gradient accelerators will have broad impact

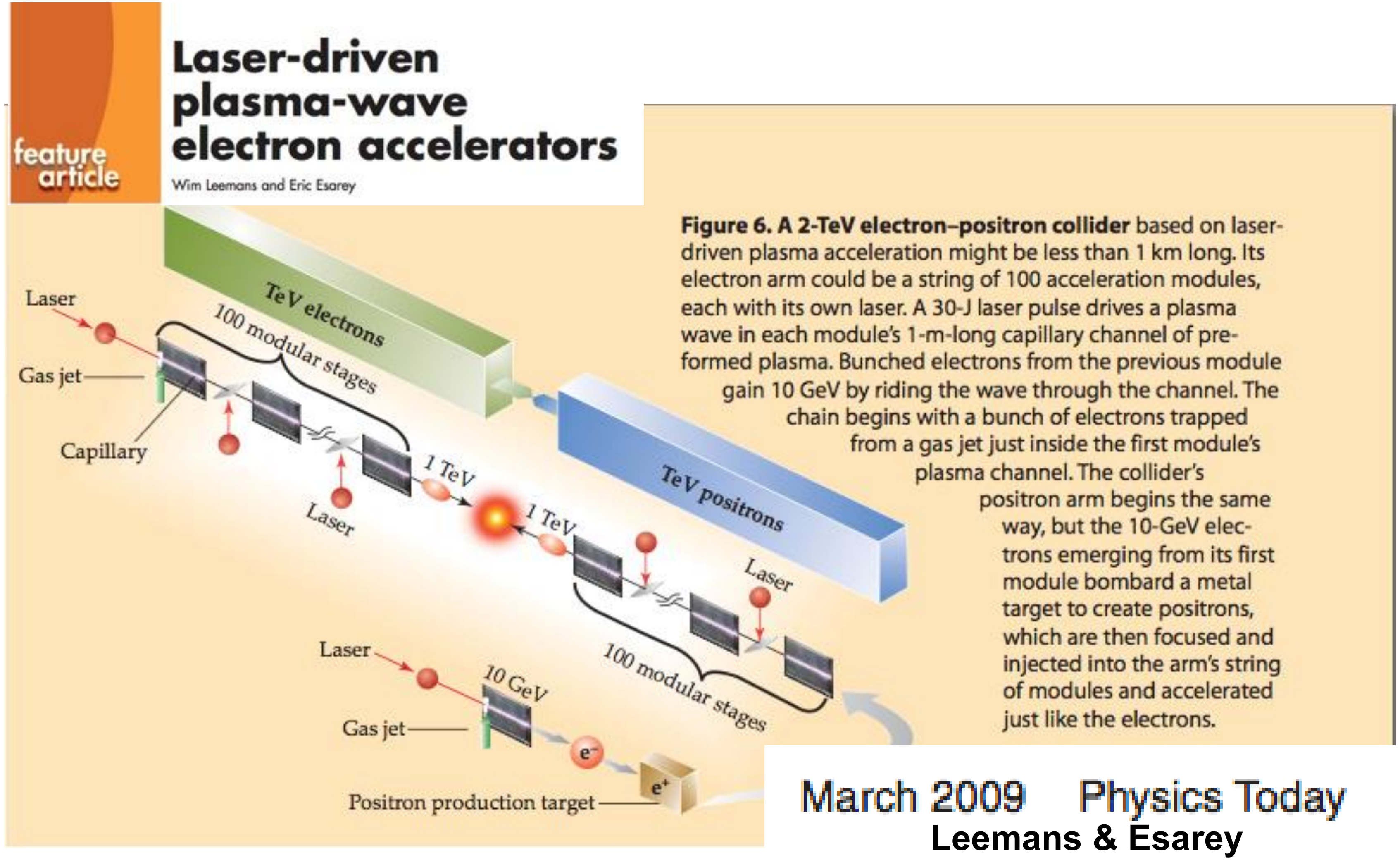
Key will be to operate at higher average power levels



Bring the machine to the problem

A laser-driven collider strawman concept was proposed 15 years ago

Staging many 10 GeV modules and lasers that run at 10's of kHz providing ~100 kW average power


feature article

Laser-driven plasma-wave electron accelerators

Wim Leemans and Eric Esarey

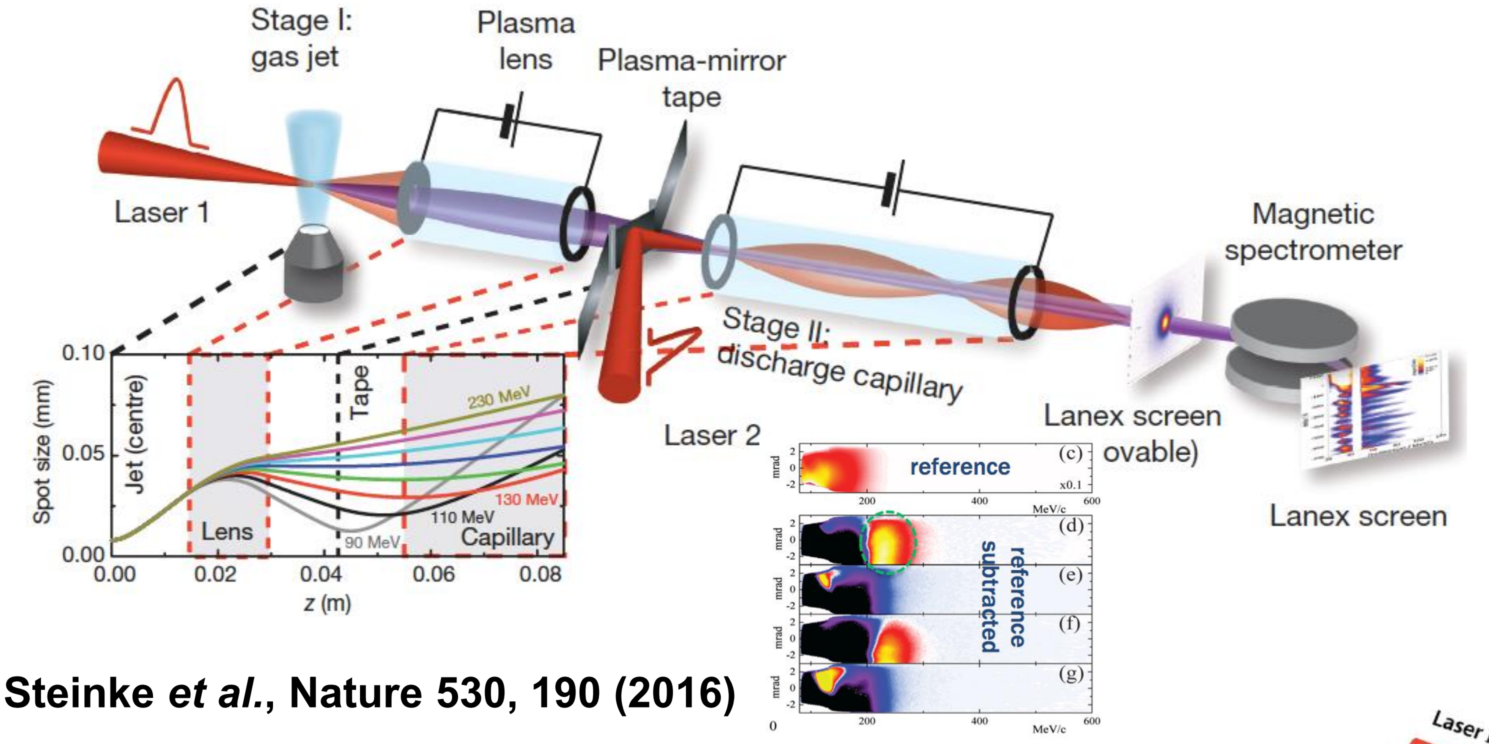
Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

March 2009 Physics Today

Leemans & Esarey

- Conceptually staging was demonstrated in 2016 (S. Steinke et al., Nature 2016) but approach not collider scalable
- Current laser performance insufficient
- **Need** multi-stage experiments and high peak and average power, high wall-plug efficiency lasers

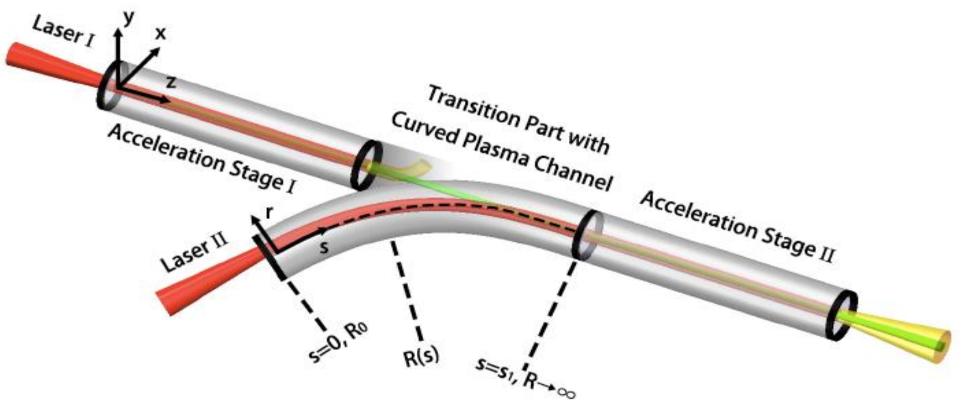
A first staging experiment was performed but many challenges remaining



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

- Low capture efficiency
- Limited rep rate of incoupling plasma mirror
- Efficiency of laser incoupling

- Novel concepts need to be explored: e.g. curved plasma channels

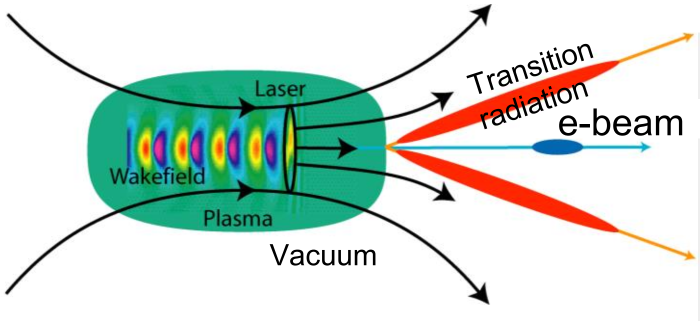


Luo *et al.*, PRL 120, 154801 (2018)

Laser plasma accelerators can provide radiation covering a broad range of the electromagnetic spectrum

From THz to hard X-rays have been obtained

Also: MeV gamma rays and muons

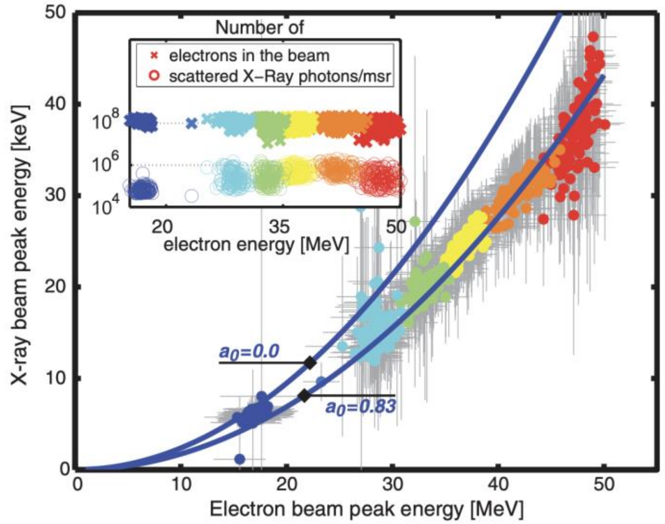


Coherent, multi-microJoule single cycle pulses, 1-10 THz

W.P. Leemans et al., PRL 2003
J. van Tilborg et al., PRL 2006

Broadband 1-10's of keV betatron X-rays, 10^6-10^8/shot

*Cole et al, PNAS **115** (2018)*



Tunable Thomson scattering

K. Khrennikov et al., PRL 2015
T. Brümmer et al., Scientific Reports 2022

Laser-plasma accelerator-based FEL demonstration at 27 nm

W. Wang *et al.*, Nature Vol 595 | 22 July 2021

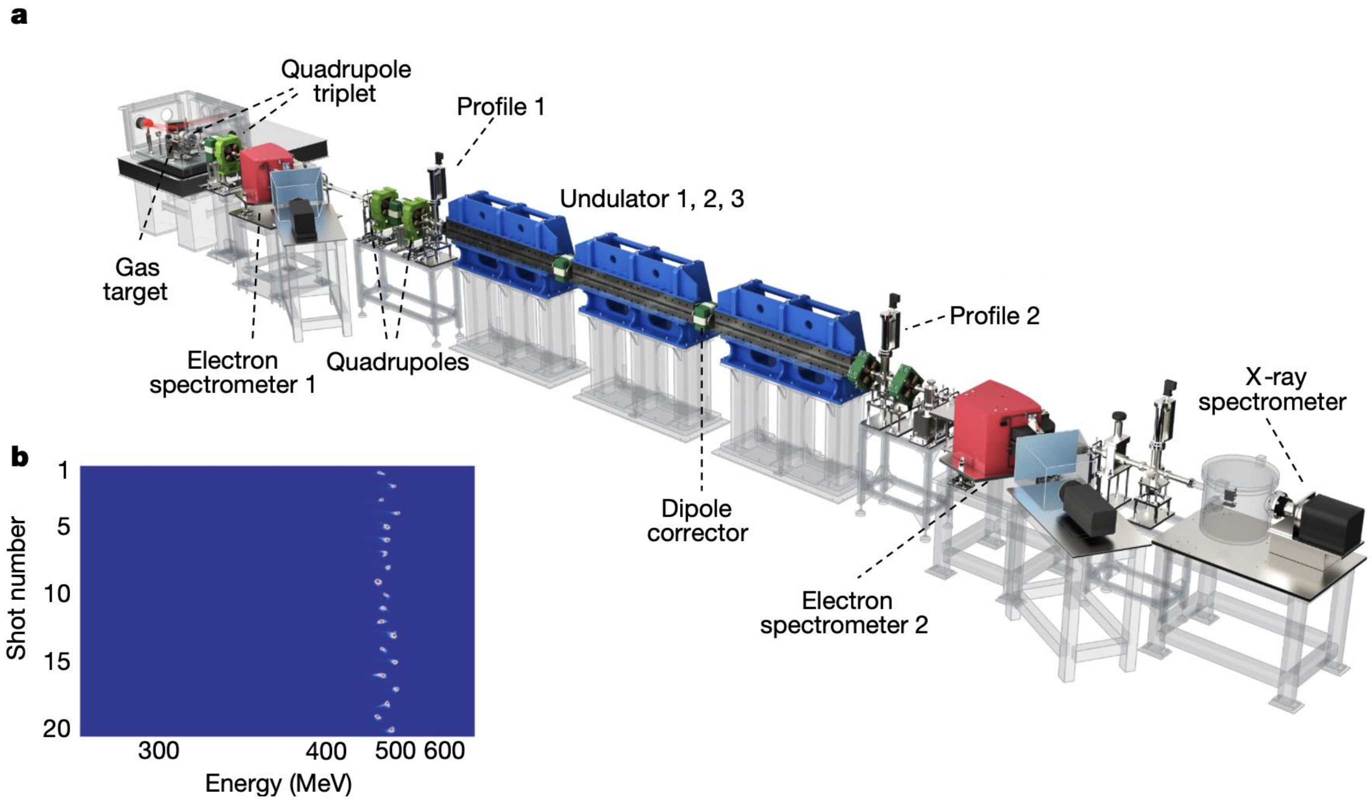
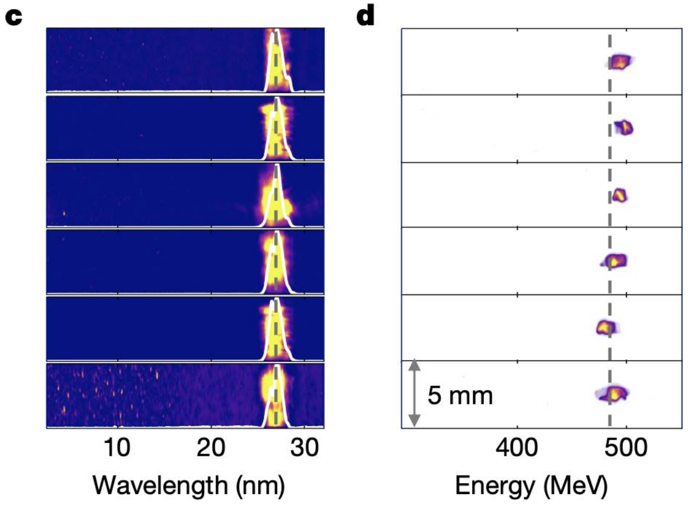


Fig. 1 | Schematic layout of LWFA-based free electron laser experiment. **a**, Undulator beamline with a total length of approximately 12 m from the gas target for the LWFA to the X-ray spectrometer. **b**, Typical spectra of electron beams from the LWFA for 20 consecutive shots.

c, **d**, Measured radiation spectra (**c**) and the corresponding electron-beam energy spectra (**d**)



3 %

energy jitter

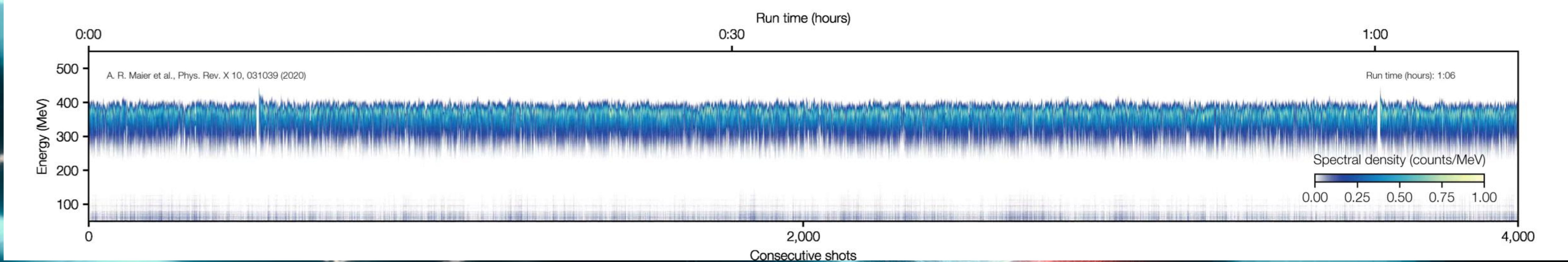
- Beam parameters of FEL-quality shots (~300):
- 30pC, 0.5% energy spread, sub-μm emittance.
- 3% energy jitter.

Also: **<u>seeded</u>** FEL -- SOLEIL SYNCHROTRON @ HZDR

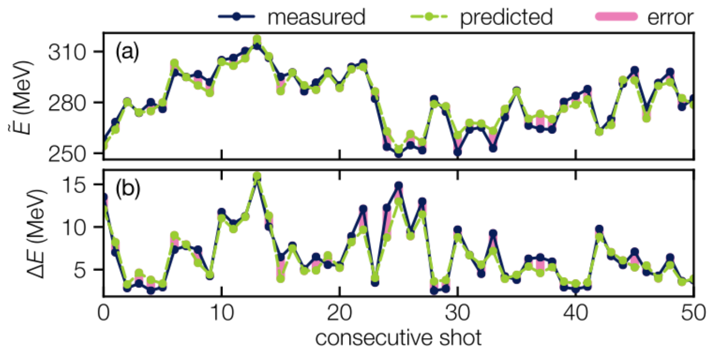
Stable operation has enabled decoding sources of variability

Combined with machine learning, a reliable LPA is approaching

Andreas R. Maier *et al.*, Physical Review X, 2020

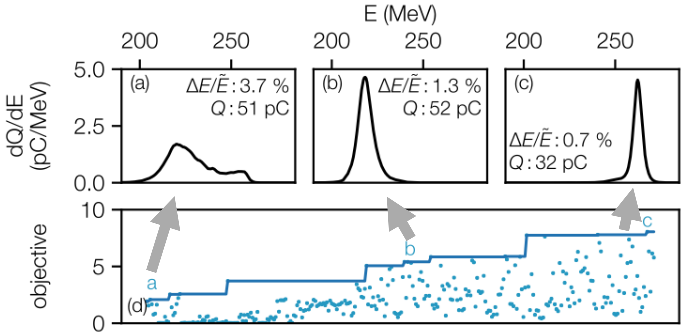


Science case active stabilization



M. Kirchen *et al.*, PRL 126, 174801 (2021)

Autonomous tuning

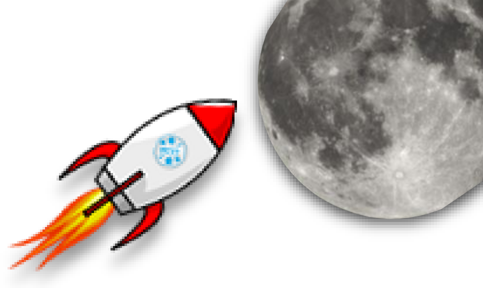


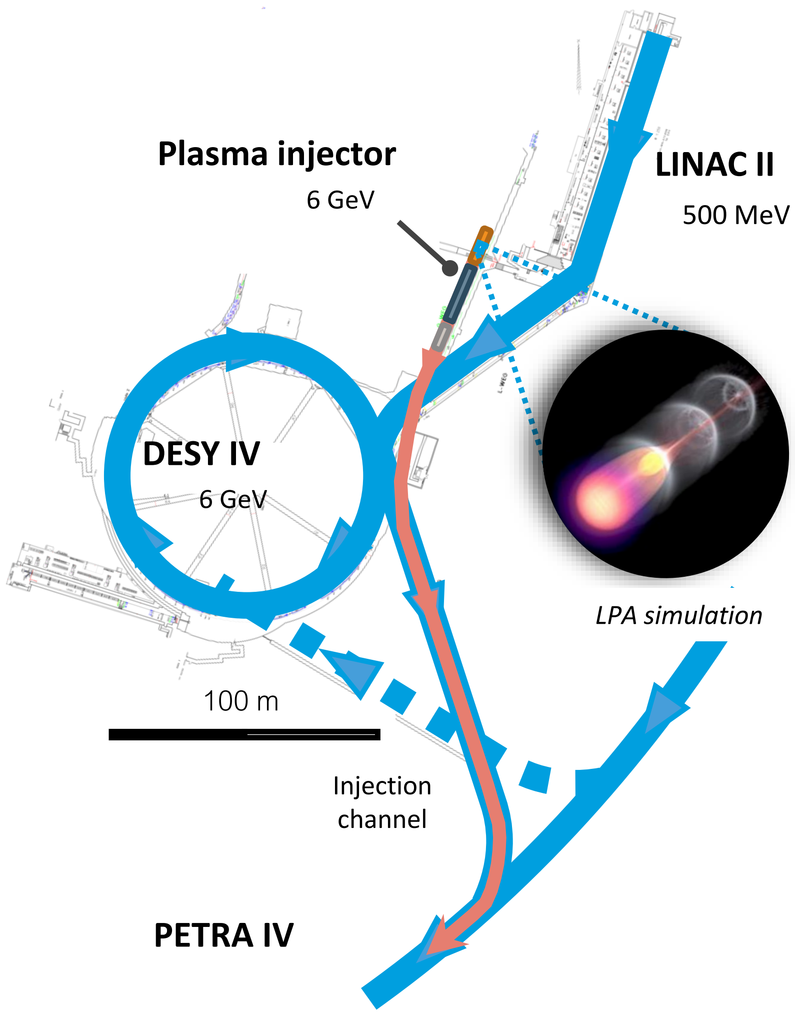
S. Jalas *et al.*, PRL 126, 104801 (2021)

Pic: Science Communication Lab

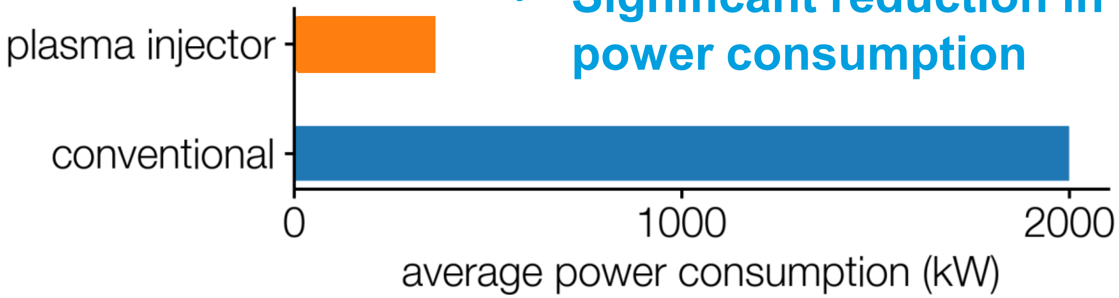
Our Moonshot: Plasma Injector for PETRA IV.

Competitive, compact and cost-effective alternative to conventional technology





- **Compact:**
  - ➢ Plasma injector + beamline: < 50 m
- **Energy of 6 GeV:**
  - ➢ Has been demonstrated using guiding
- **Challenge:** 99 % user availability
  - ➢ Charge injection rate: 2.7 nC/s

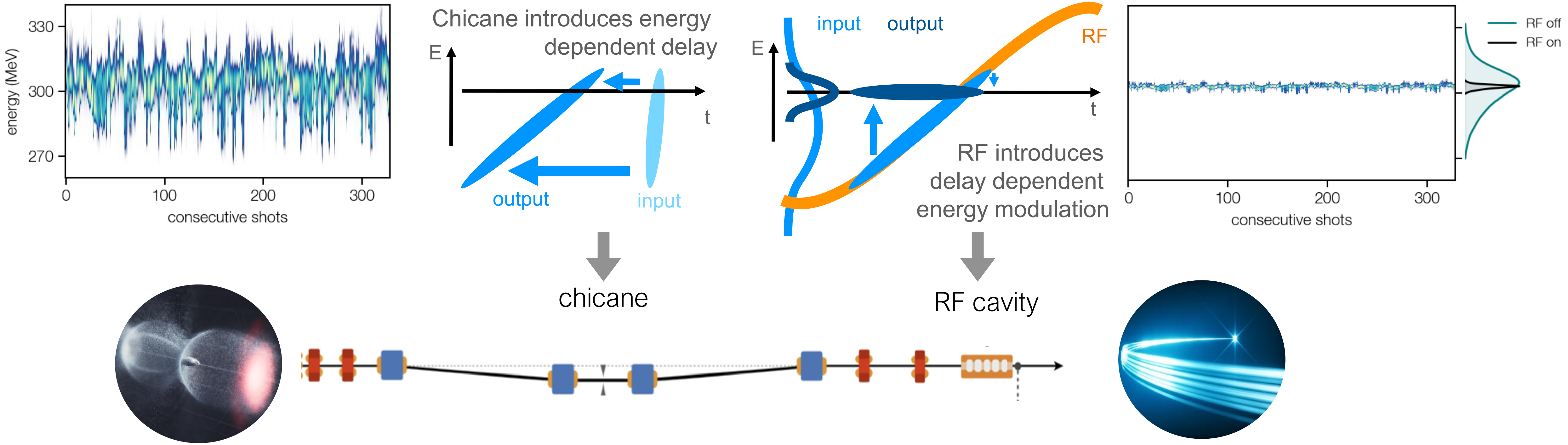


- **Significant reduction in power consumption**

Concept: Energy Compression Beamline

Imprint longitudinal chirp with a dipole chicane and remove it inside an RF field at 0-phase

original energy stability	chirp	dechirp	compressed energy stability



S. Antipov *et al.*, PRSTAB 24, 111301 (2021)

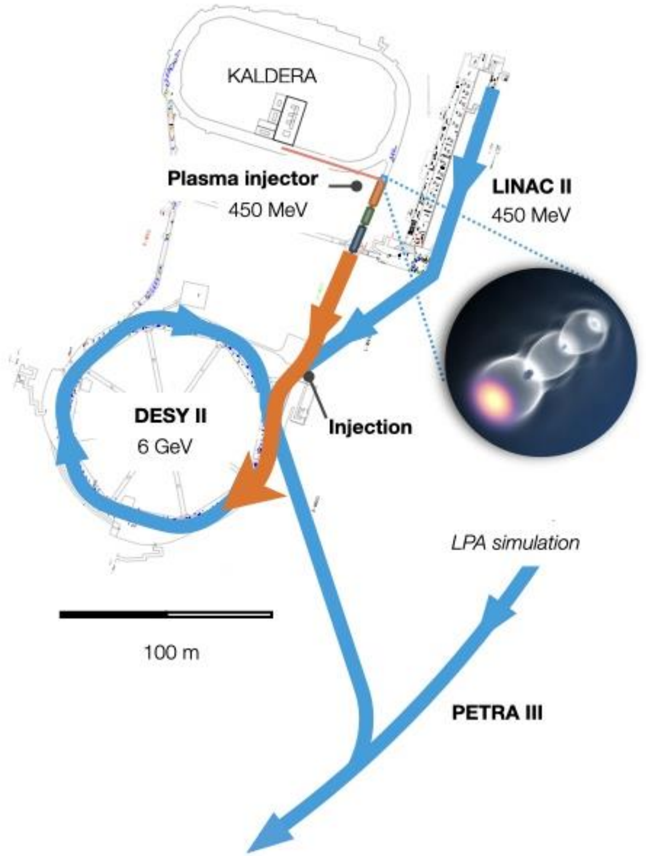
A. Ferran Pousa *et al.*, PRL 129, 094801 (2022)

We will use it to inject into our current 6 GeV booster.

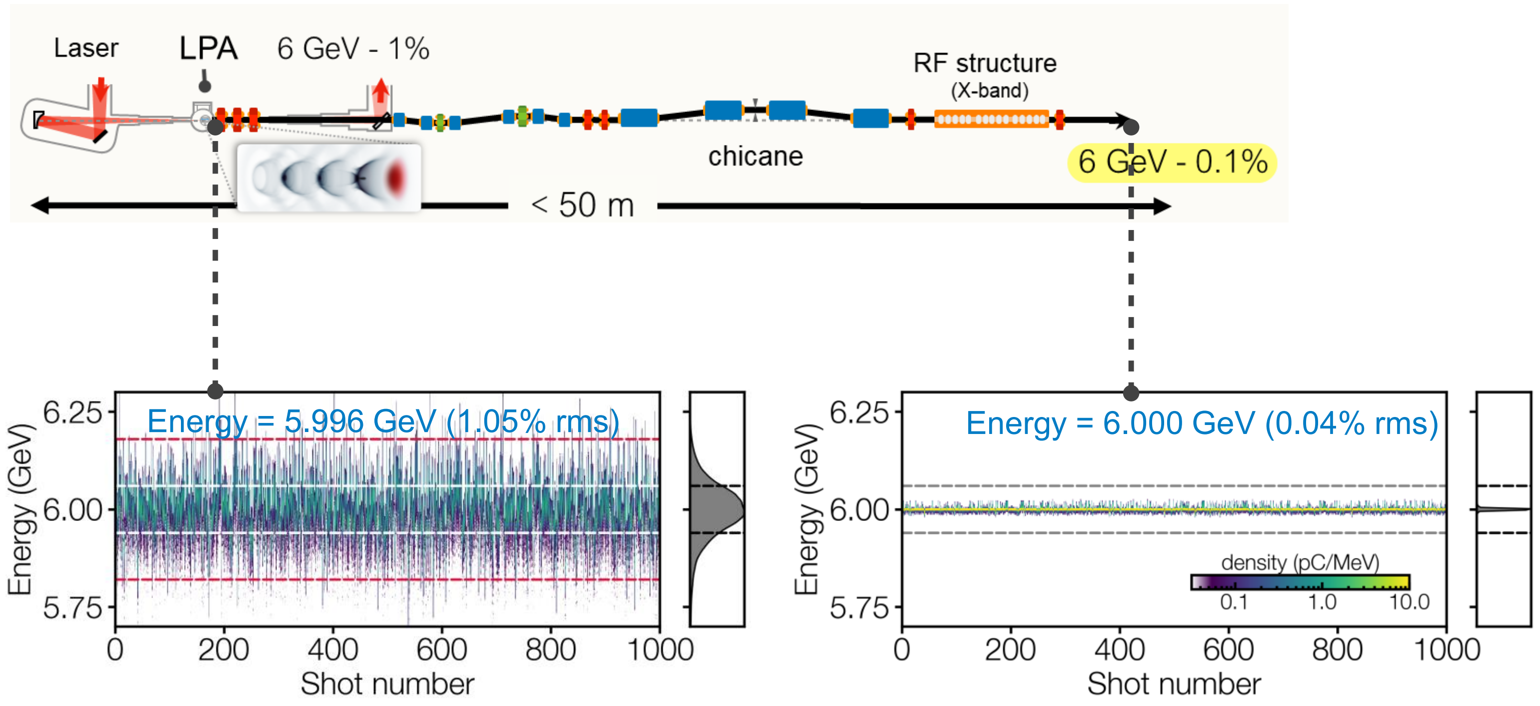
PETRA IV pre-project: Technology demonstrator, injection into PETRA III

Demonstrator of laser technology capable of 24/7 operations at >99 % availability

PETRA III plasma injector



Plasma injector schematic for PETRA IV



KALDERA LaserLab completed, and laser development has started

Transformation of LPAs into a technology ready to drive real-world applications

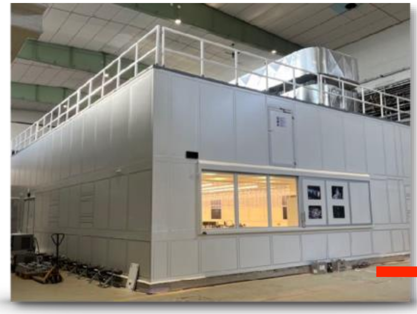
HiACTS | Helmholtz Innovation Platform for Accelerator-based Technologies and Solutions

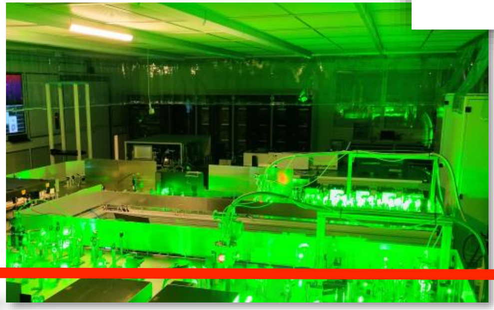
KALDERA

Science Case:
- Active Stabilization
- Competitive Technology
- Technology Demonstrator

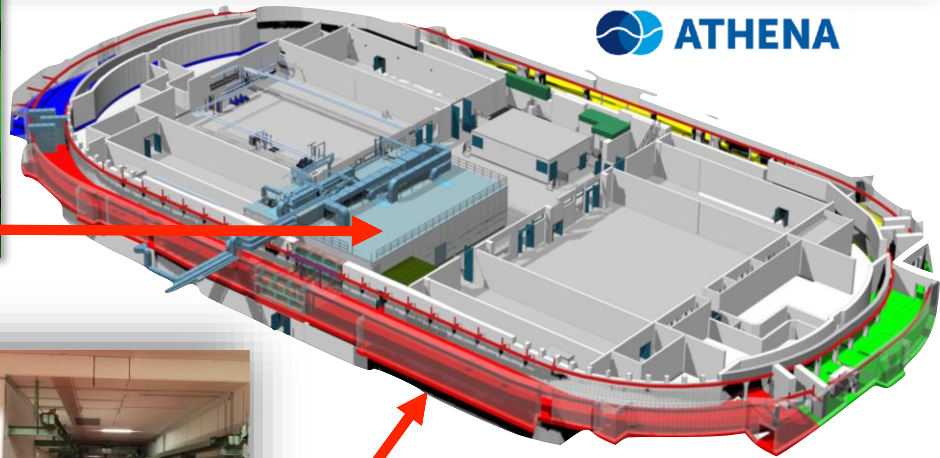
Specifically
- New LPA Drive Laser
- 100 TW at 1 kHz rep rate, 3 J in 30 fs
- Goal: FEL-quality electron beams @ 1 GeV

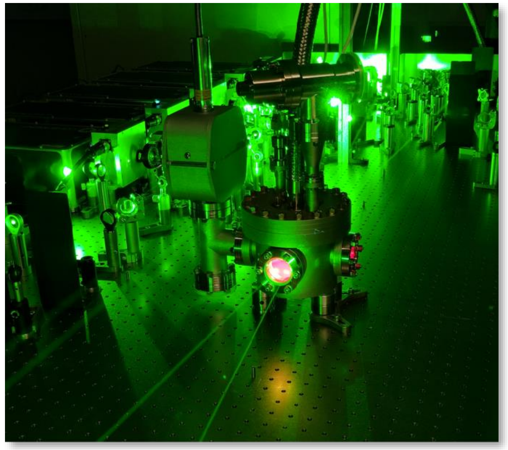
Project coordinator:
Andreas R. Maier





Laser Lab
- 400m^2 ISO5/6 clean room
- 0.1° temperature stability
- Lab completed end 2022





Laser (under dev.)
- 100 TW @ 1 kHz
- 3J in 30 fs
- Active stabilisation & feedback

KALDERA Tunnel
- Generic infrastructure for experiments (many different experiments over time)
- Supports up to 1GeV @ 1kHz

KALDERA . PLASMABESCHLEUNIGER

Summary

- Tremendous progress over the past two decades
- Main focus now on reliable, controllable, stable operating devices
- Short term goal is a fully functional injector for a storage ring
- Will require a continued (r)evolution in laser technology

“Those that say it cannot be done should not interrupt those that are doing it”

George Bernard Shaw

Thank you

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Andreas Maier
and his team

Victor Malka

And former LBNL colleagues