Introduction to Laser Wakefield Acceleration

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ELI ERIC ELI-Beamlines Facility

EuPRAXIA-DN School on Plasma Accelerators @ Orto Botanico, Roma

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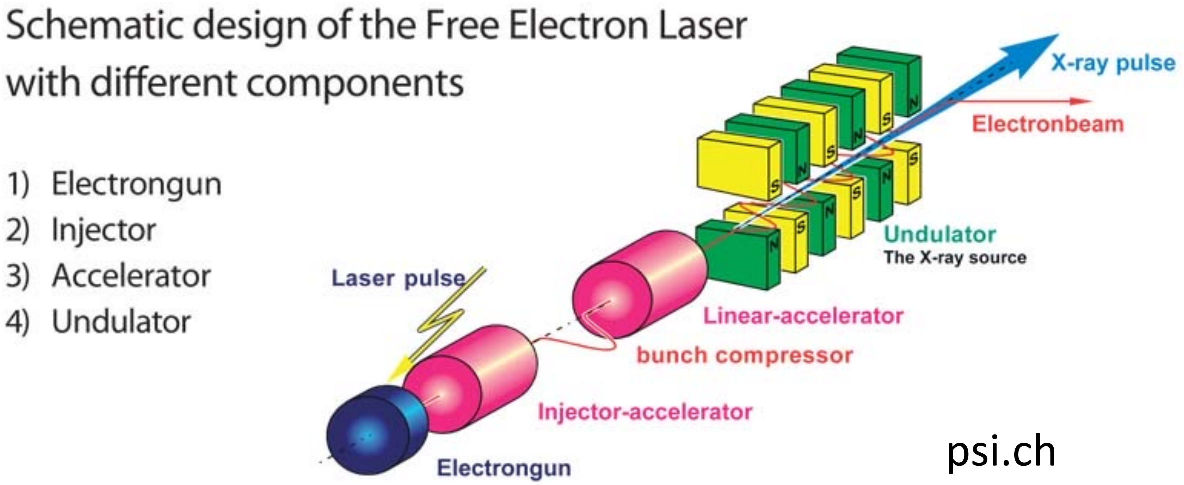
A European Research Infrastructure Consortium

Rationale

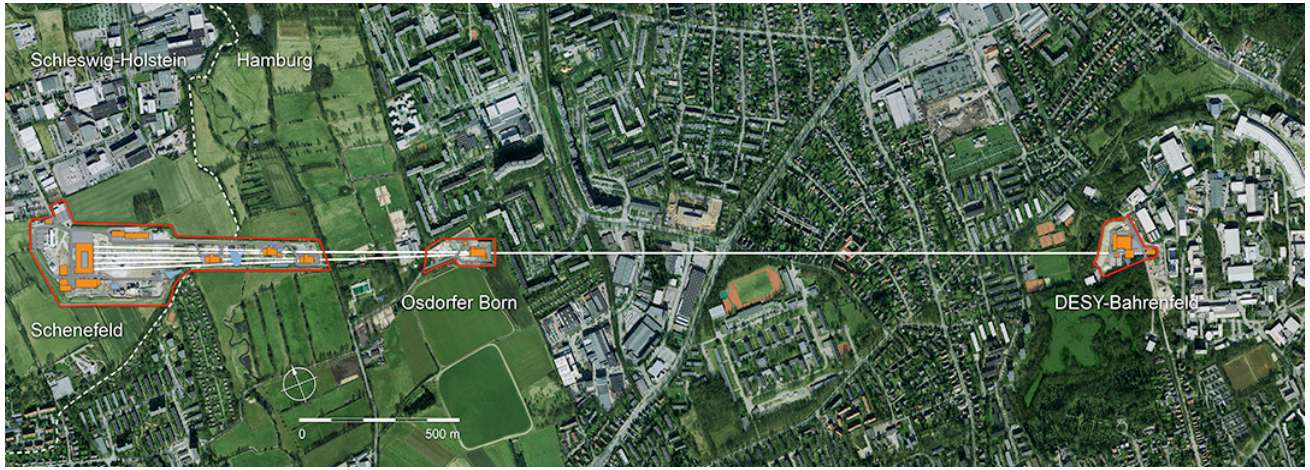
Electron accelerators are a cornerstone technology of modern society. In their variations, they are daily used as an instrument to enable scientific explorations, and as strategic tools at the disposal of the healthcare system for medical imaging and cancer treatment.

Electron beams are produced by radio-frequency machines, that accelerate up to 100 MV/m (typ. 10 MV/m). This becomes a limit for GeV accelerators, which are the key technology for last generation light source (synchrotron radiation and free electron lasers).

Laser Wakefield acceleration is the most compact technique to generate GeV electron beams. They also have other unique features.



psi.ch



European XFEL in Hamburg, 17 GeV, 3 km long

Tajima and Dawson's paper

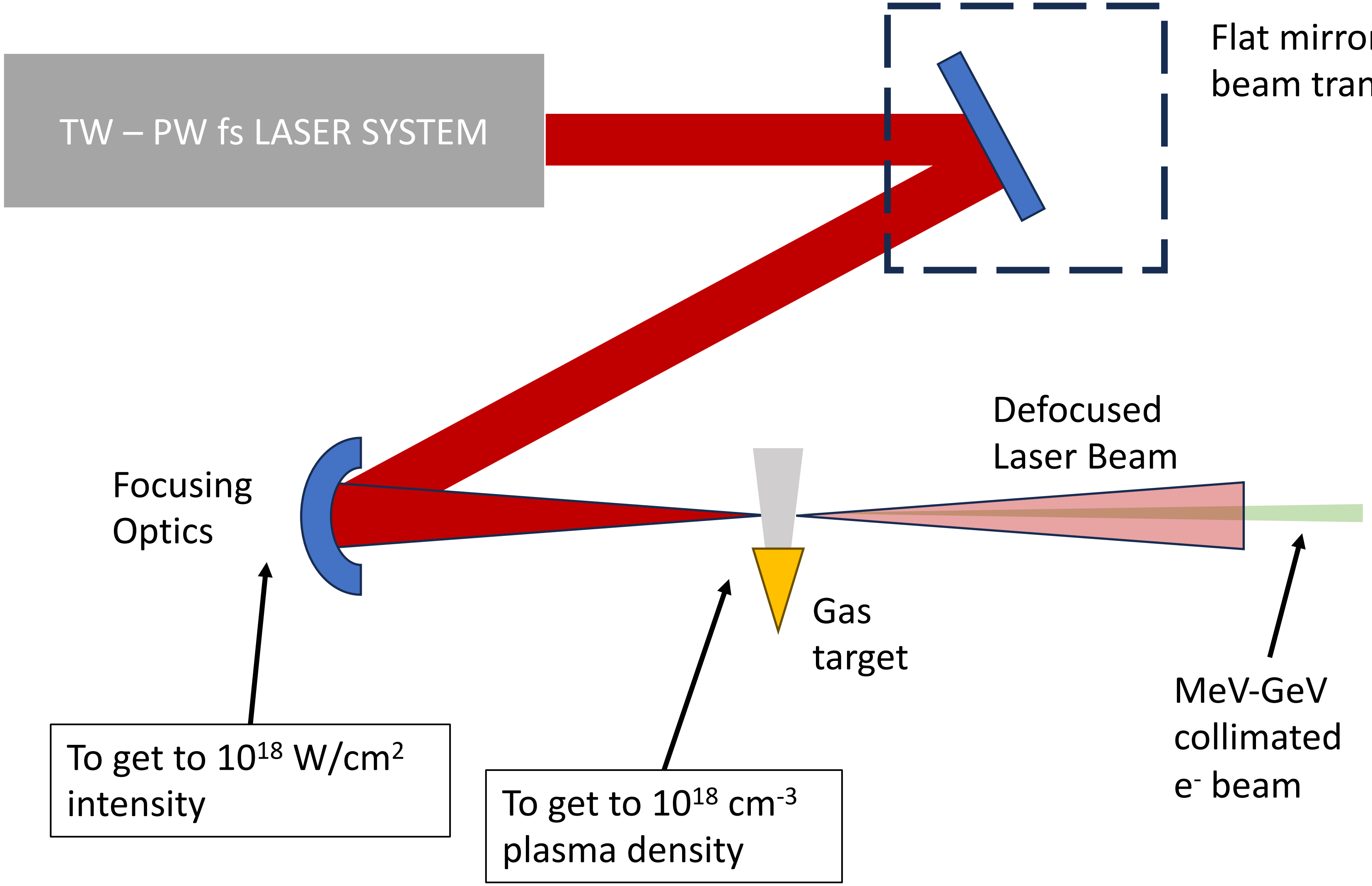
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

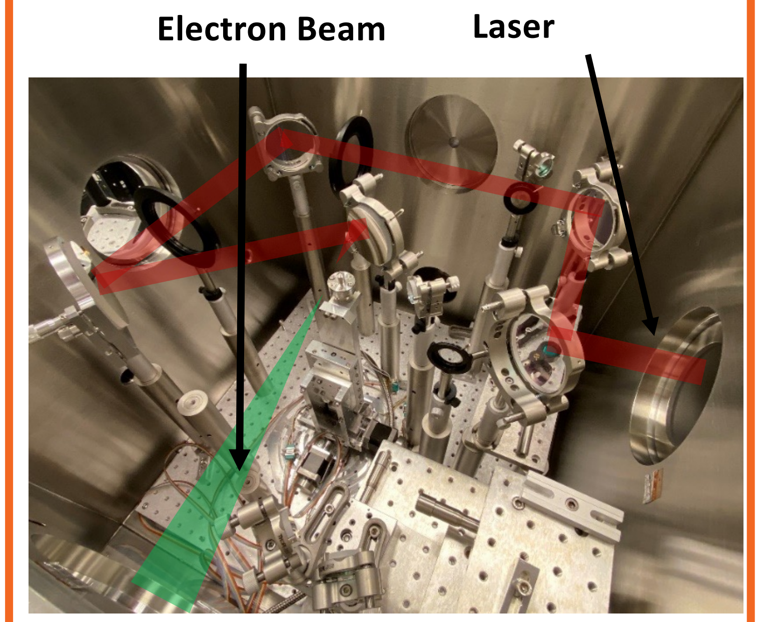
Laser Electron Accelerator

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.

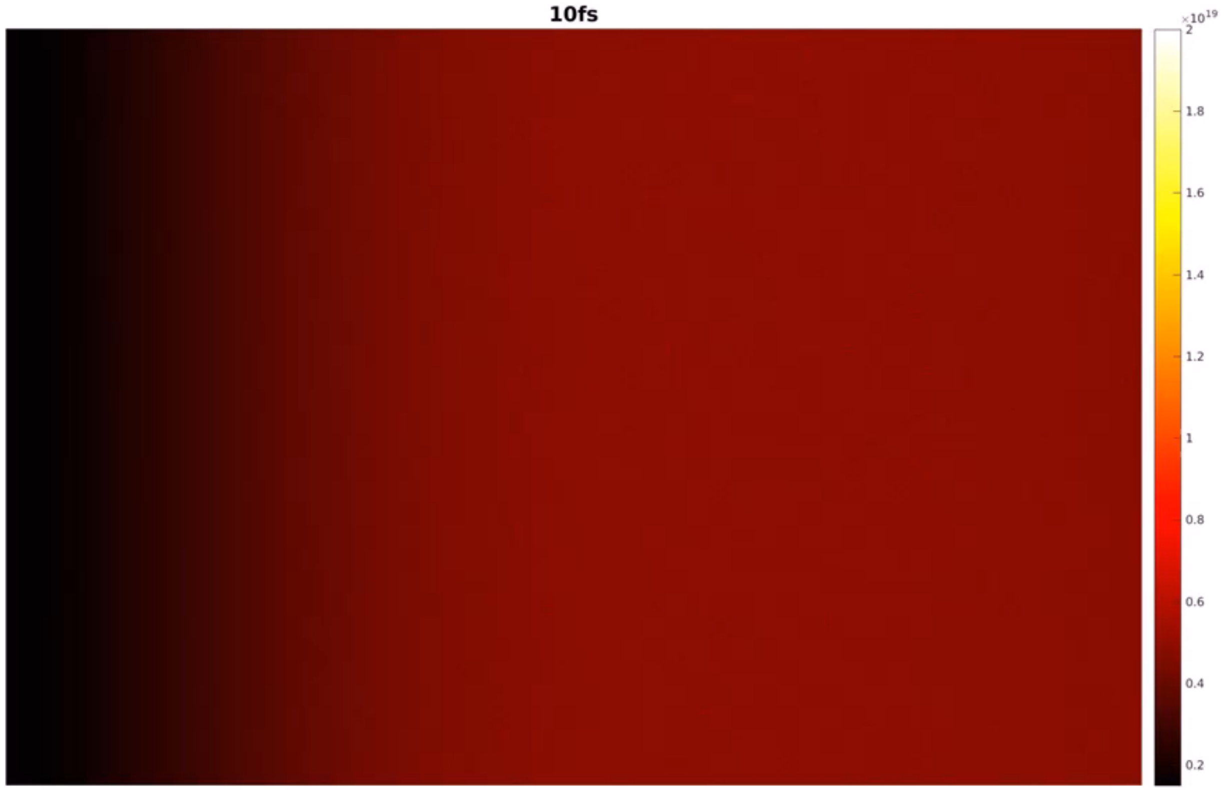
Laser Wakefield Acceleration at-a-glance





Electron injection in the plasma wave

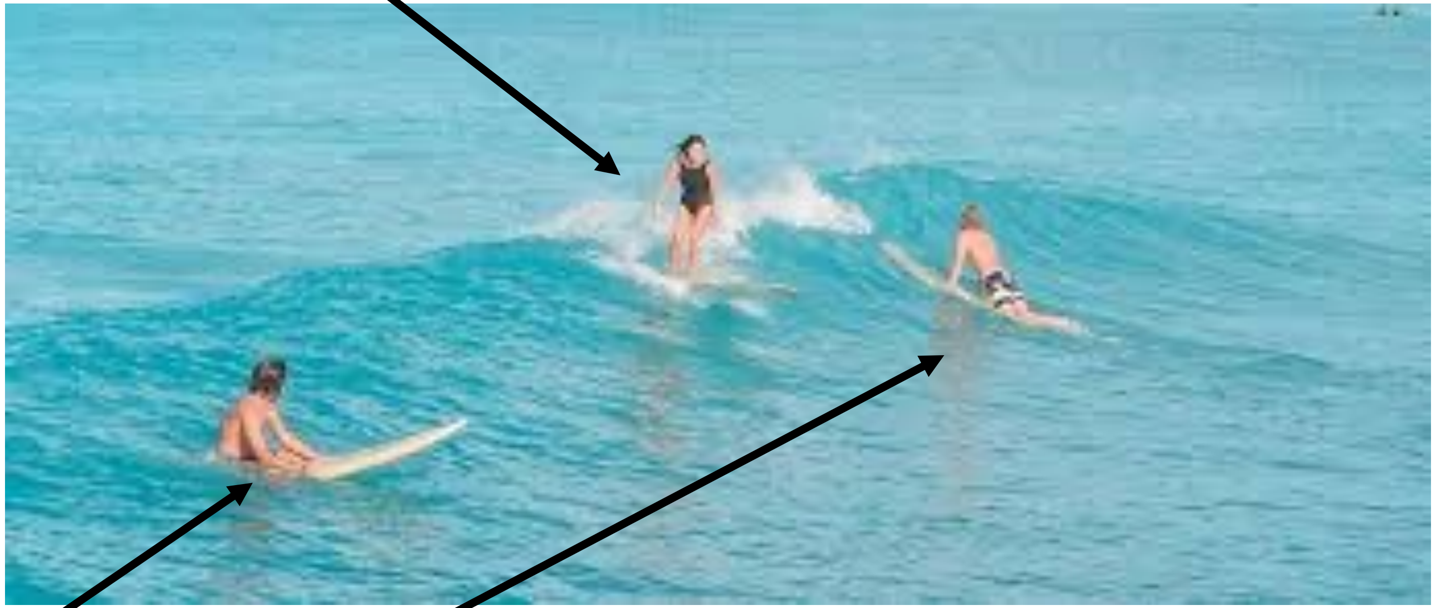
In LWFA both the ‘’injector’’ and the ‘’accelerating cavity’’ are re-created at every laser ‘’shot’’. It is not hard to inject electrons in the plasma wave in a not-controlled way (self-injection). But to get high quality beams, the electron injection inside the accelerating plasma cavity must be controlled.



Catching a wave

Pre-acceleration required to catch the wave

Fast enough



They will oscillate and stay in the same position

Electron injection schemes

We need to help the electrons catch the wave. And we need to do it trying to keep the plasma wave formation process not affected. We have two ingredients: the laser and the plasma target.

Optical injection schemes

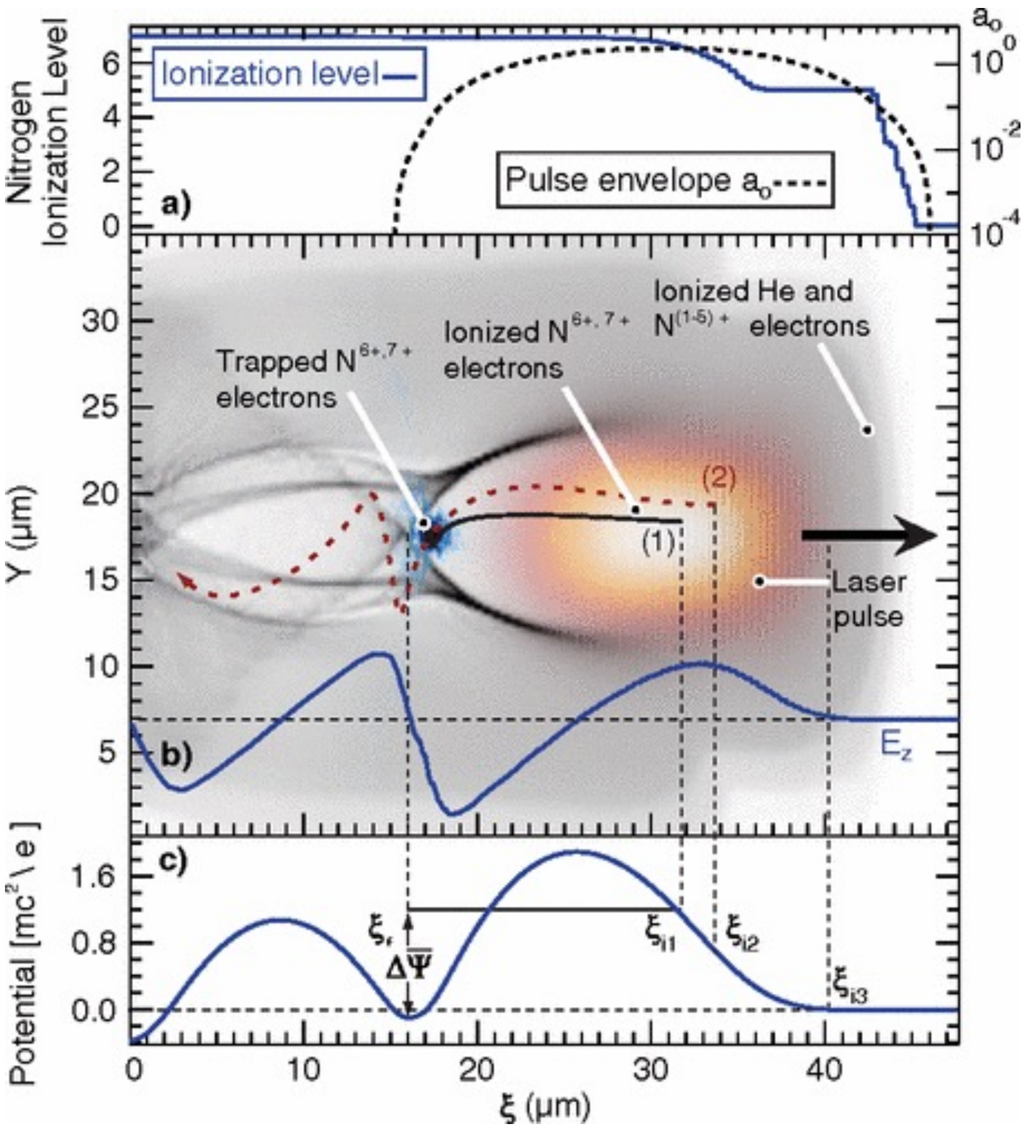
- Ionization injection
- Colliding pulse injection

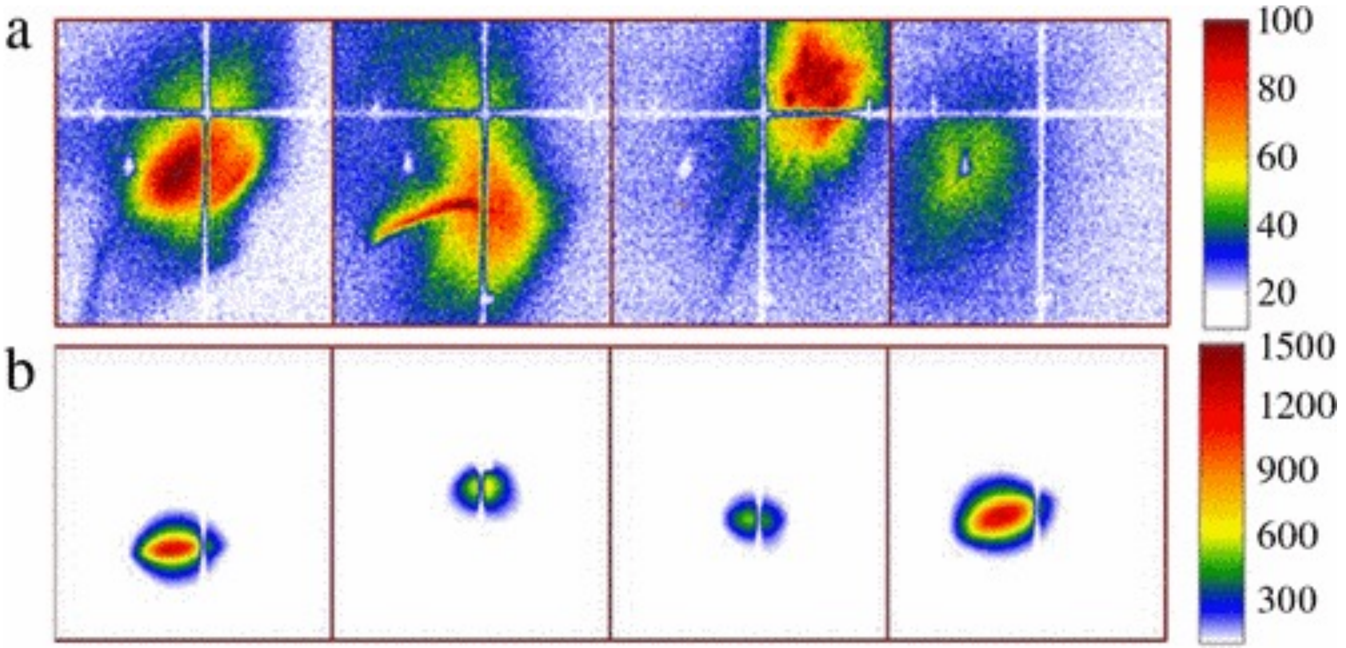
Plasma injection schemes

- Downramp/shock injection
- Density bump

And their combination(s):
i.e. shock-assisted ionization injection (Thaury, Sci. Rep. 2015)

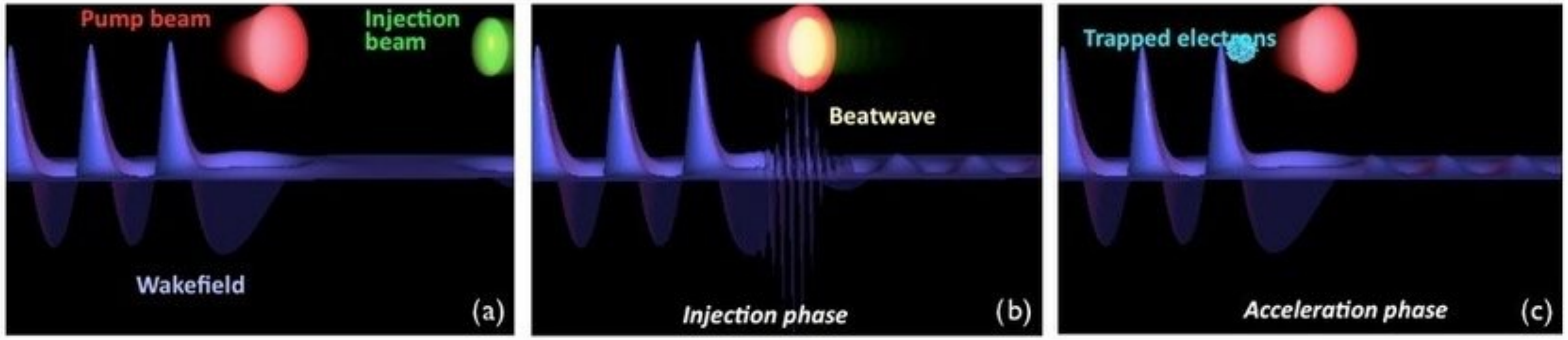
Ionization injection



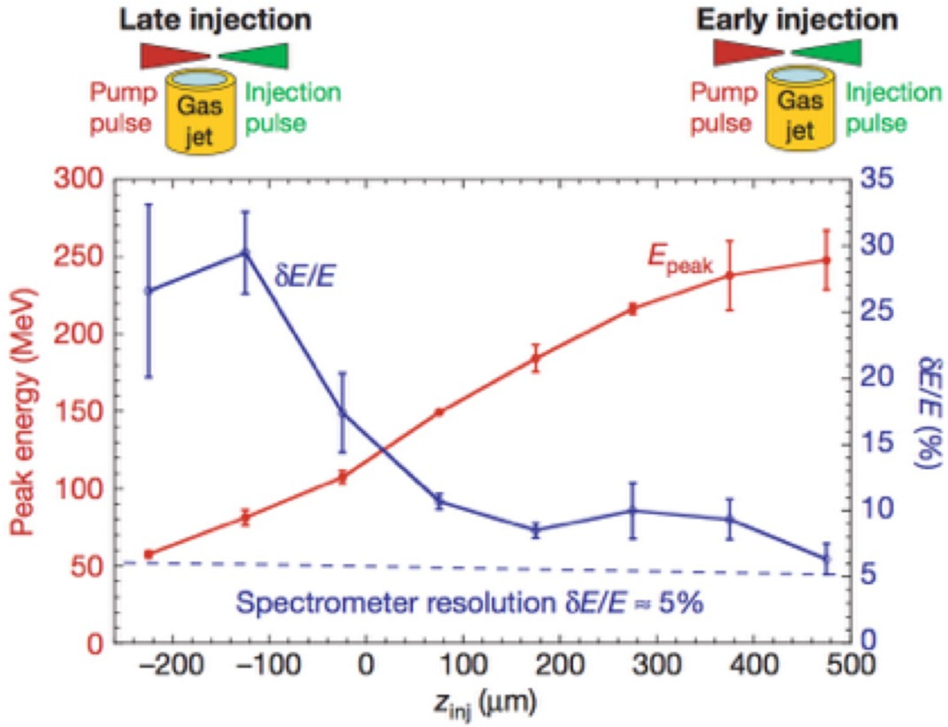


Pak PRL 2010, Mc Guffey PRL 2010

Colliding Pulse Injection

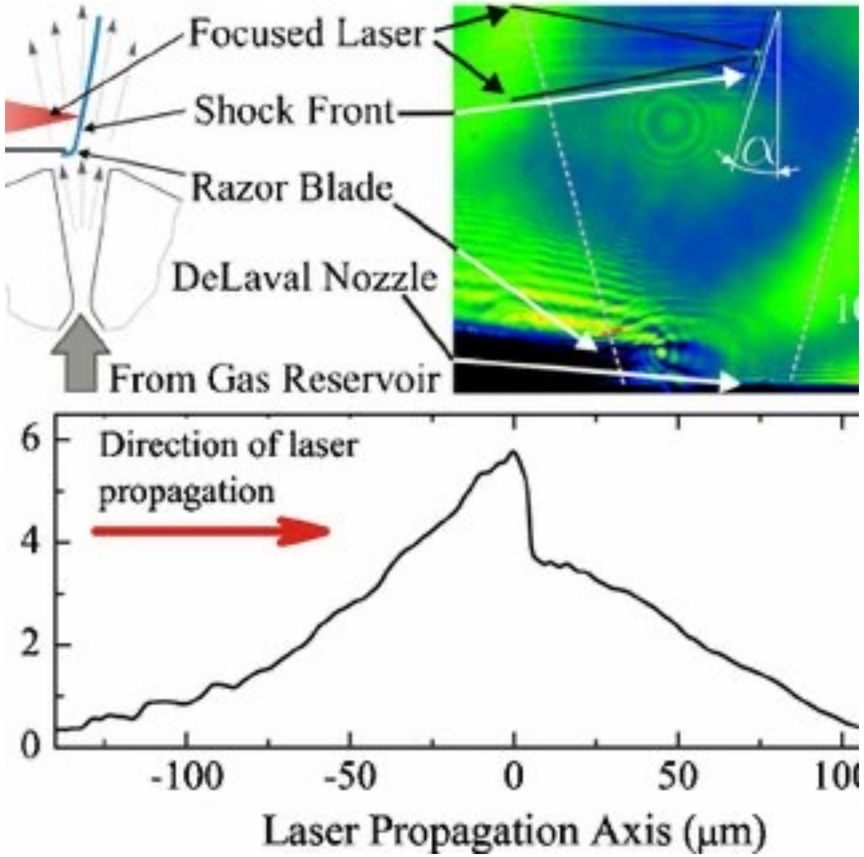


Faure Nature 2006

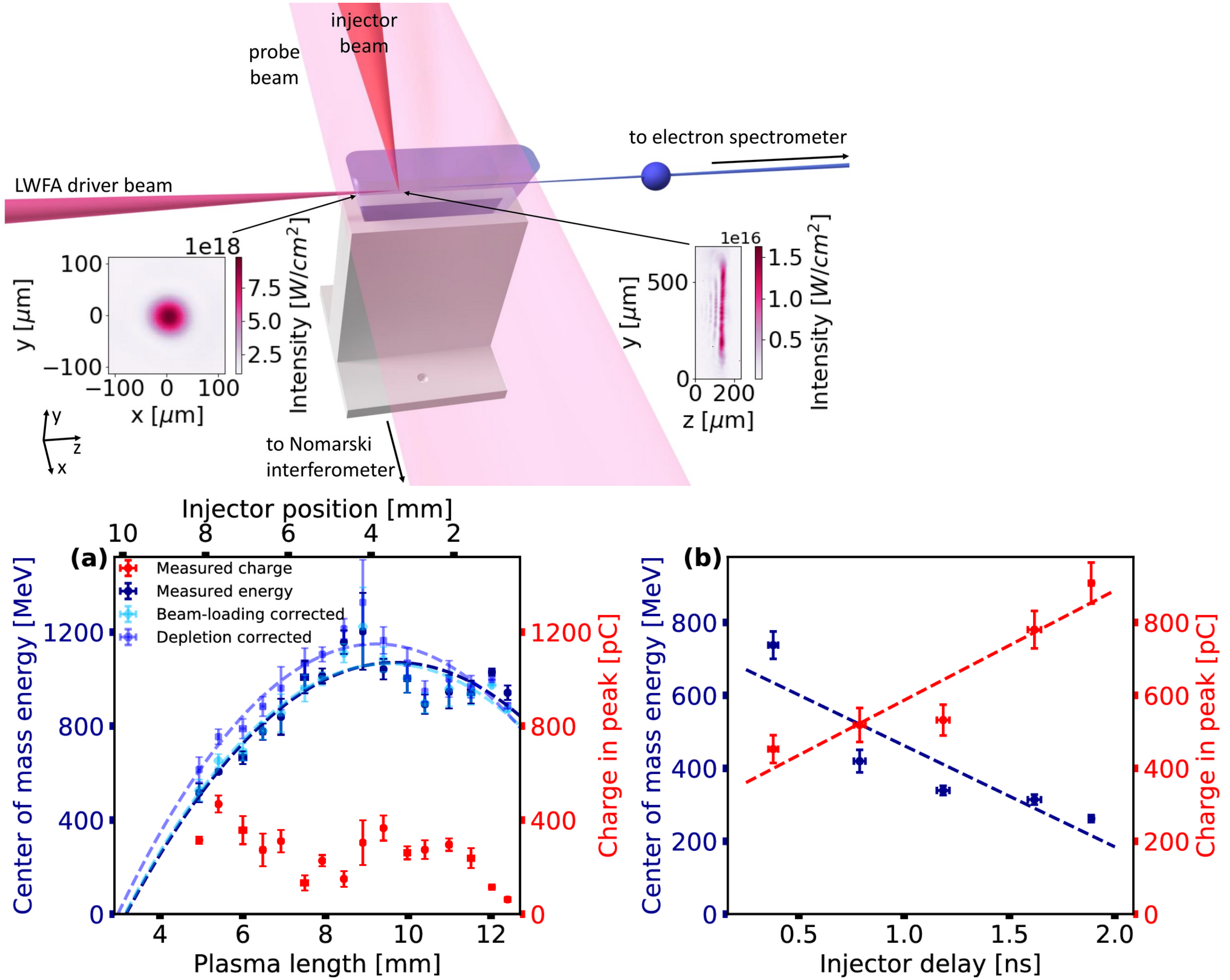


Downramp/Shock injection

Mechanical Shock

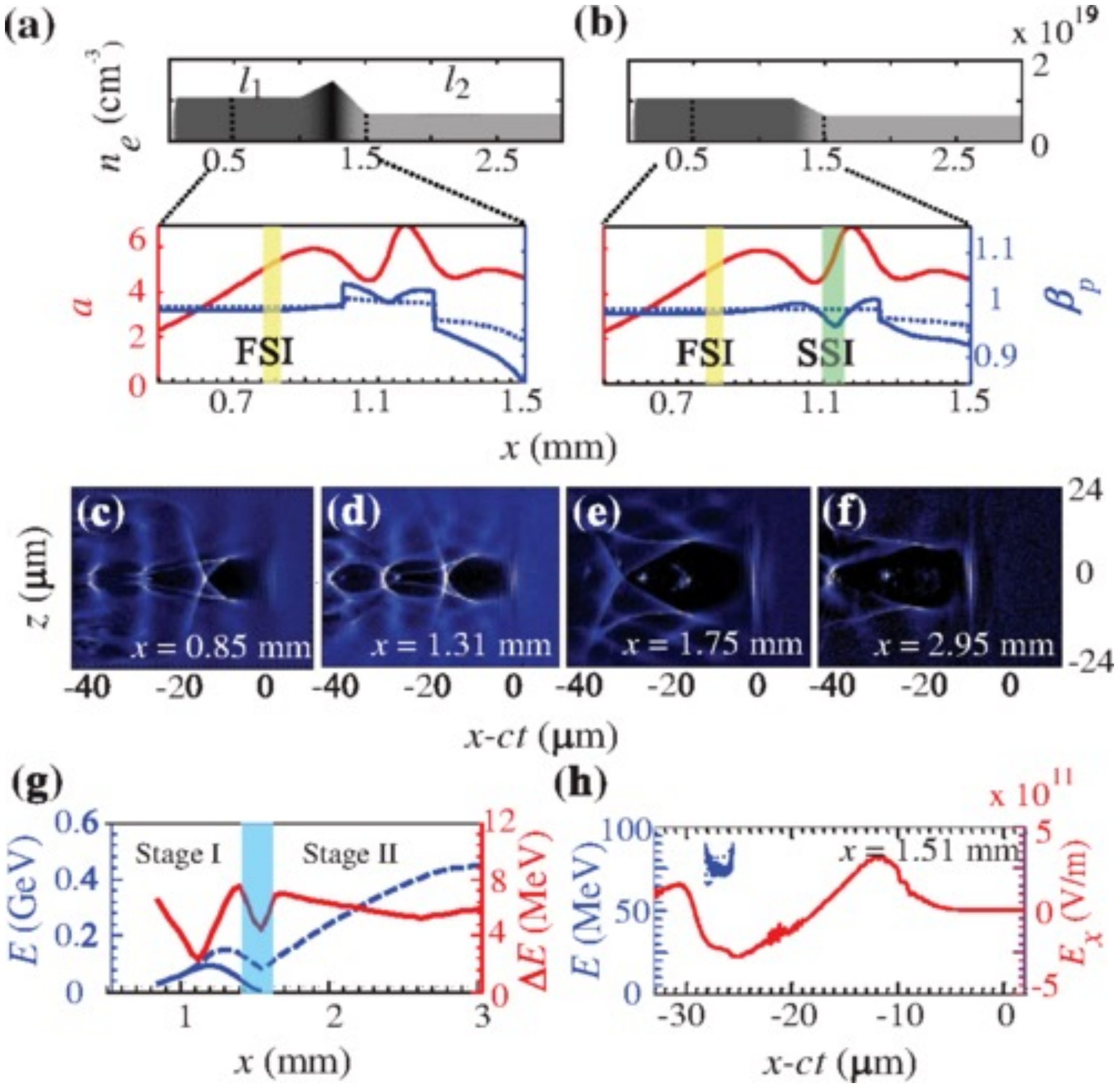


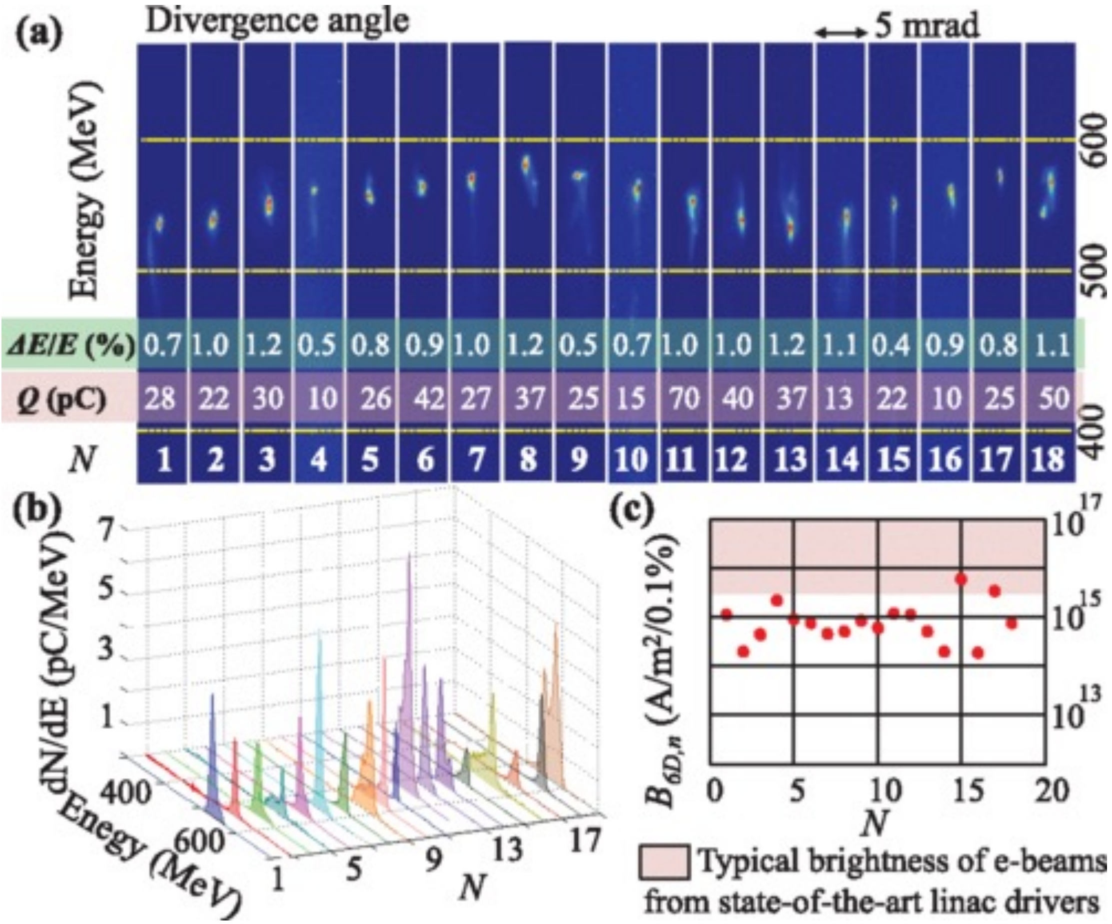
Optical Shock



Bulanov PRE 1998, Schmid PR STAB 2010, Grafenstein Sci. Rep. 2023

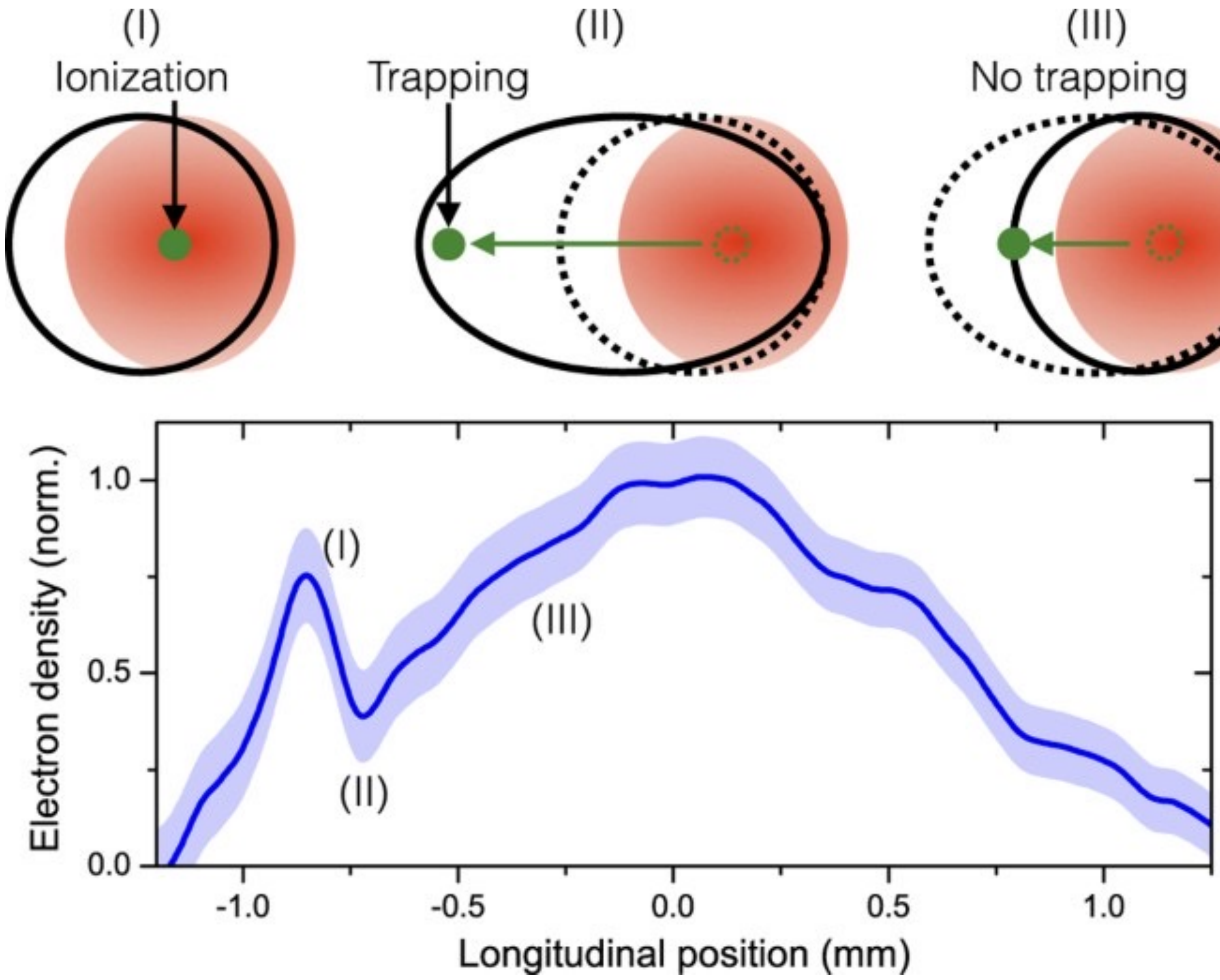
Density bump injection

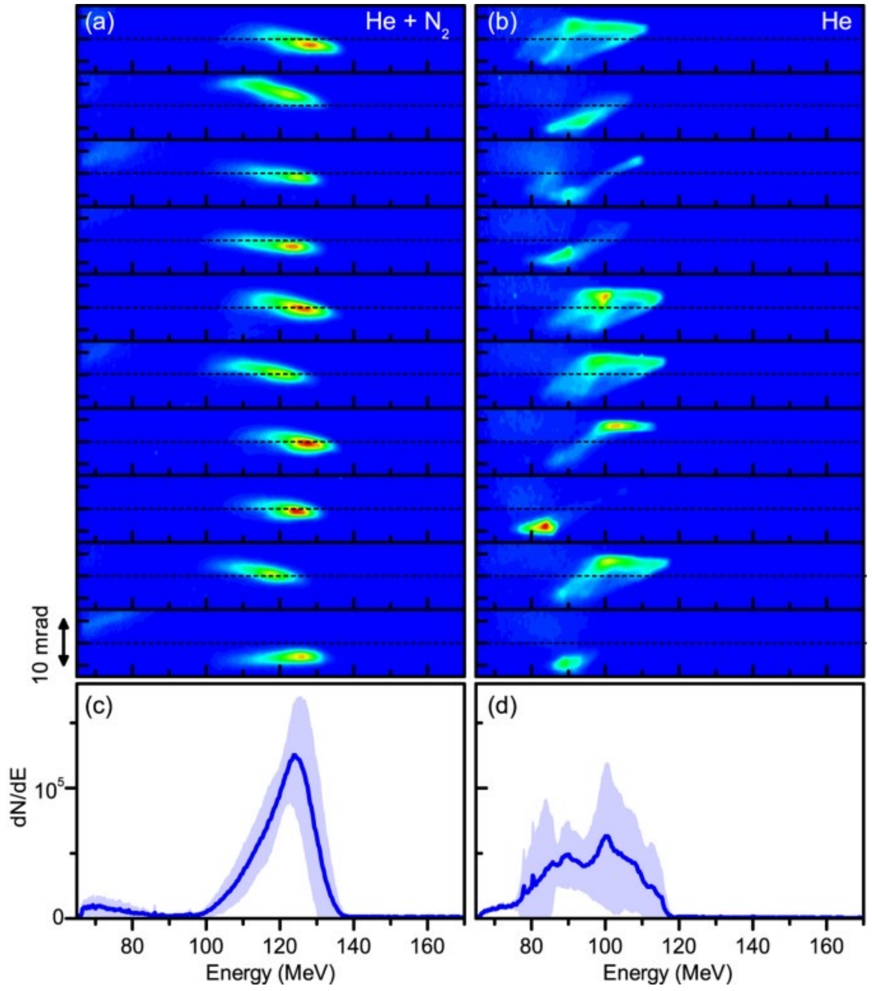




Wang PRL 2016

Shock-assisted ionization injection





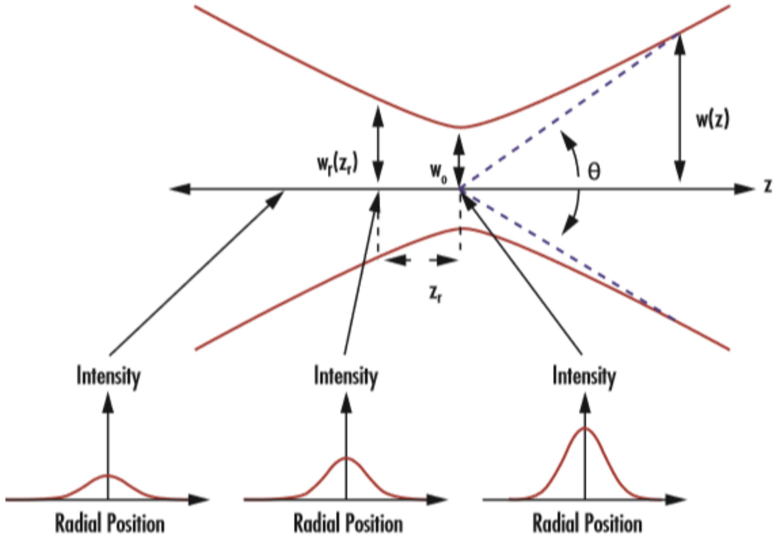
Thaury Sci. Rep. 2015

LWFA Fundamental Limits: laser diffraction

In LWFA the accelerating cavity is generated in the laser focus.
The electron beam energy gain is given by:

$$\Delta E_e[GeV] = V[GV/cm] \cdot L_{acc}[cm]$$

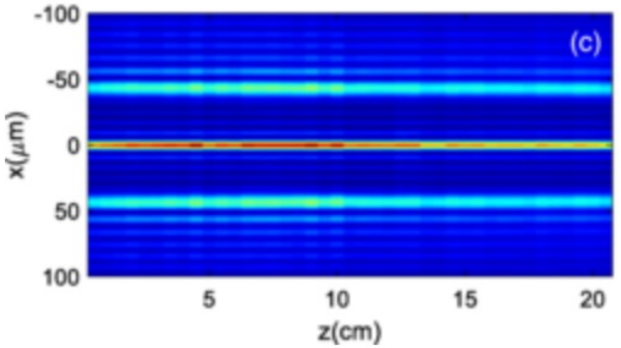
Therefore, the strong accelerating gradient is not enough to get to GeV energies if we do not extend the region where the laser is focused as much as we can.



Self-guiding

$$P_c = 17.5 \cdot \frac{n_{cr}}{n_p} GW = 17.5 \cdot \frac{{\lambda_p}^2[\mu m]}{{\lambda_L}^2[\mu m]} GW = 17.5 \cdot \frac{{\lambda_p}^2[\mu m]}{0.64} GW$$

Pre-formed plasma waveguide



Self-guiding

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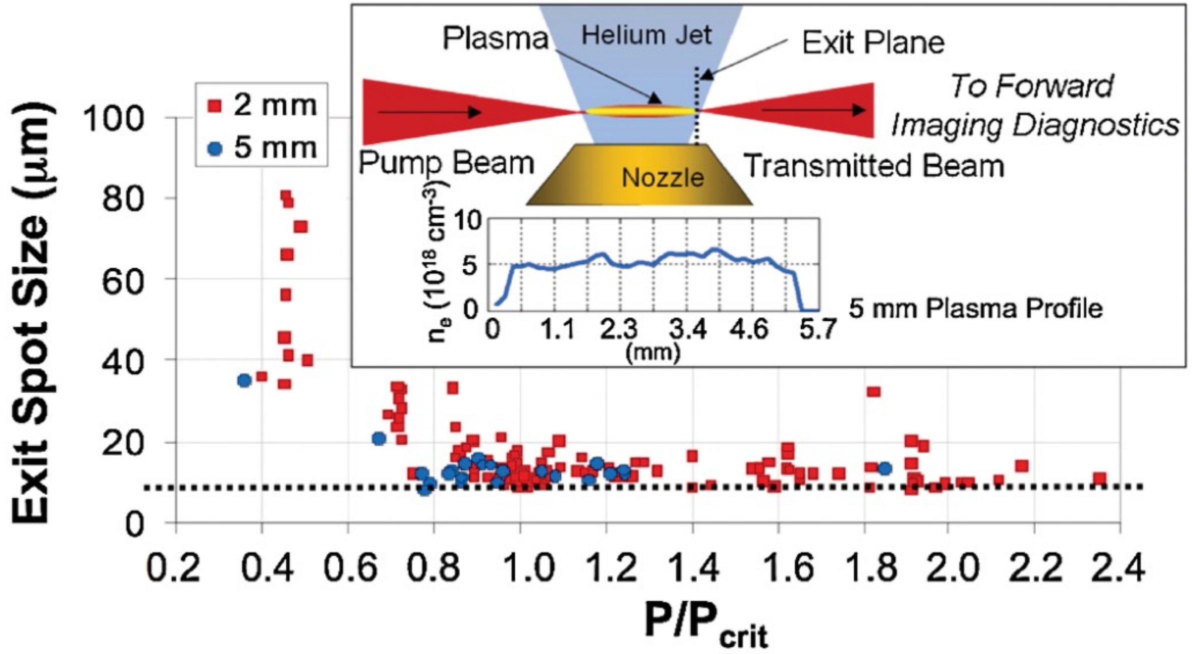
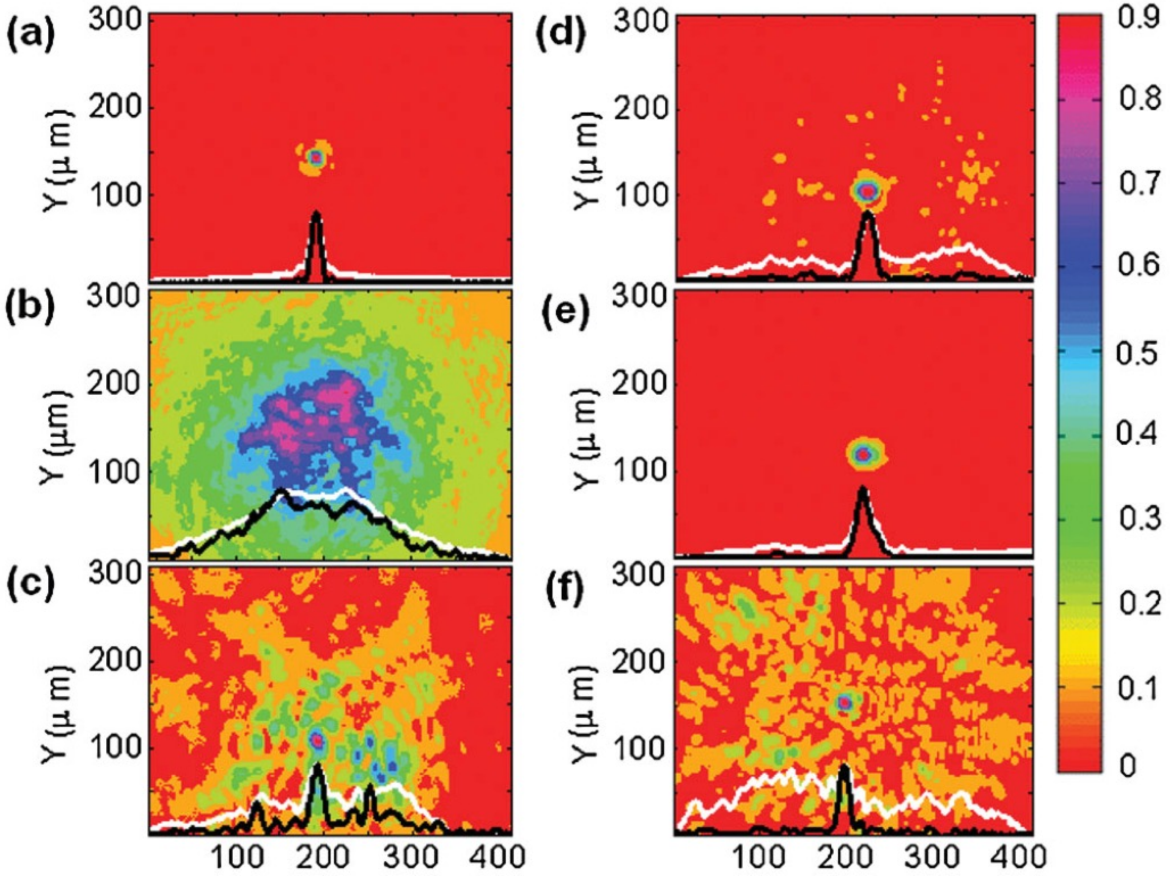
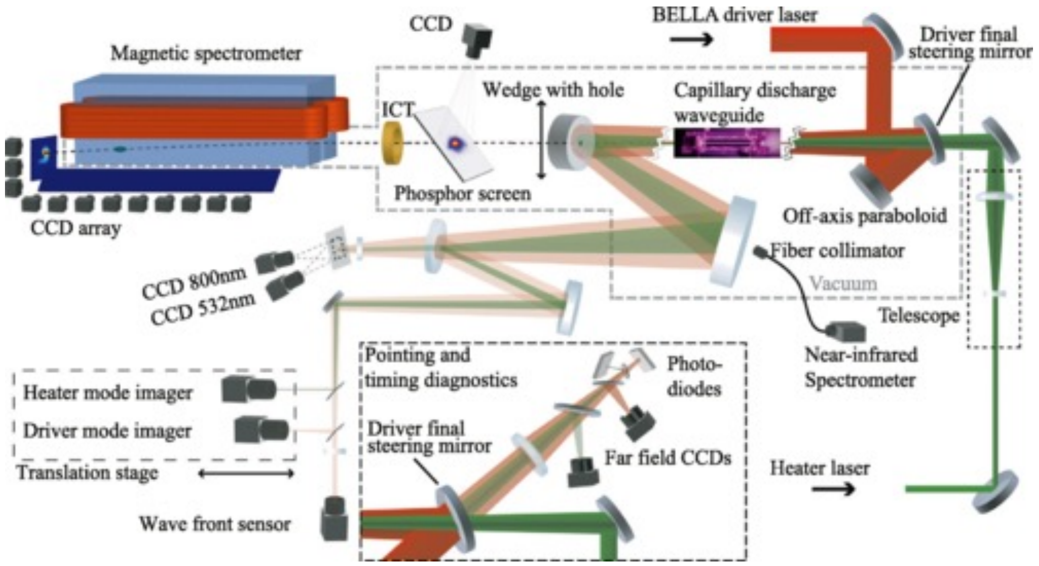




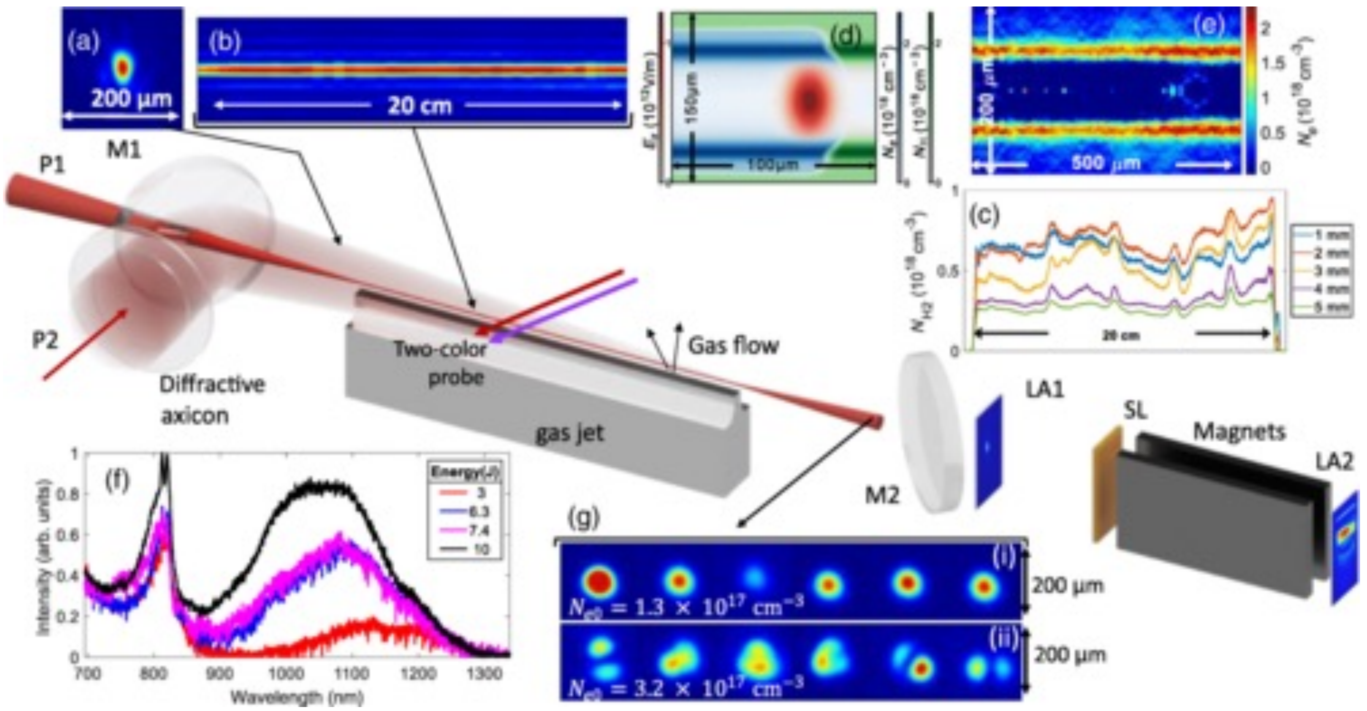
Ralph PRL 2009

Plasma waveguide

Capillary Discharge



Bessel Beam



Leemans PRL 2014, Goncalves PRL 2019, Miao PRX 2022

Dephasing: the acceleration is over

LWFA Fundamental Limits: dephasing

The light inside a plasma travels slower than in vacuum:

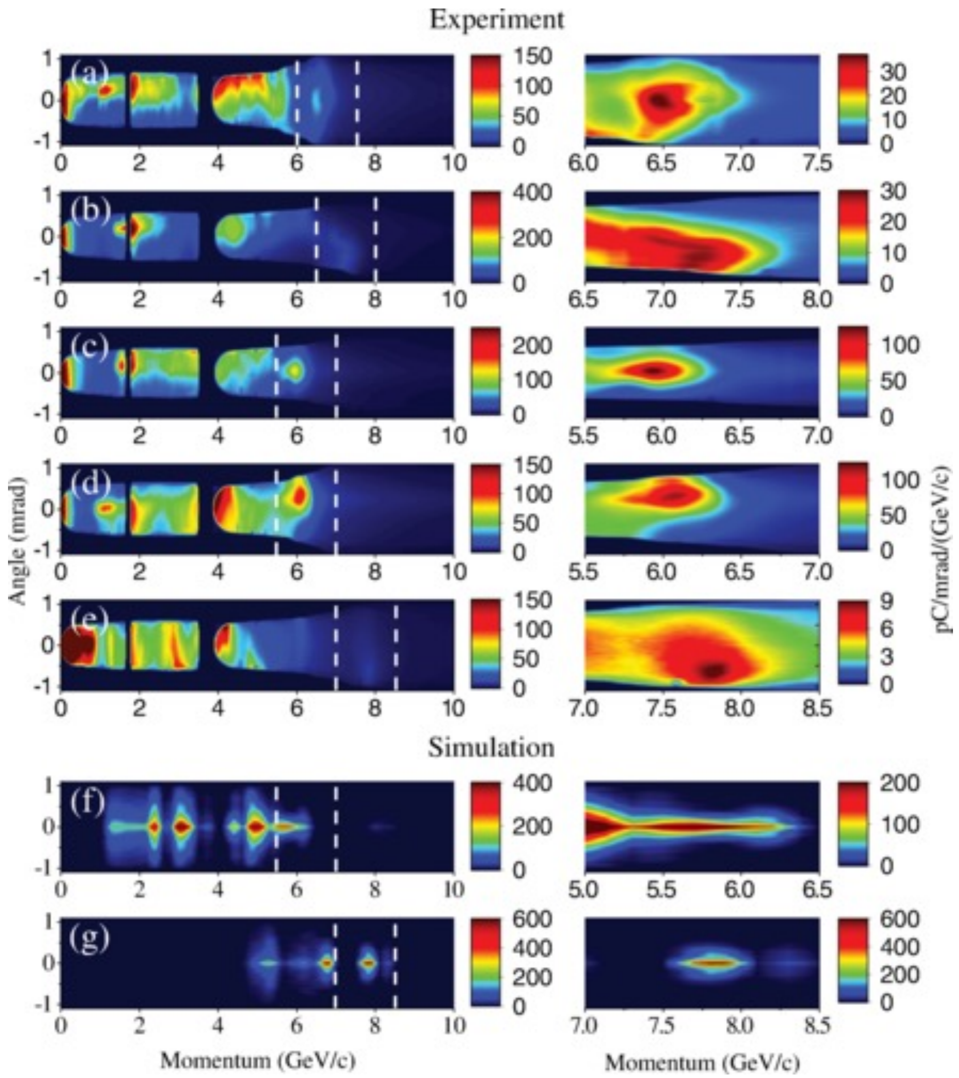
$$v = c \cdot n = c \cdot \left(1 - \frac{n_e}{n_c}\right)^{1/2}$$

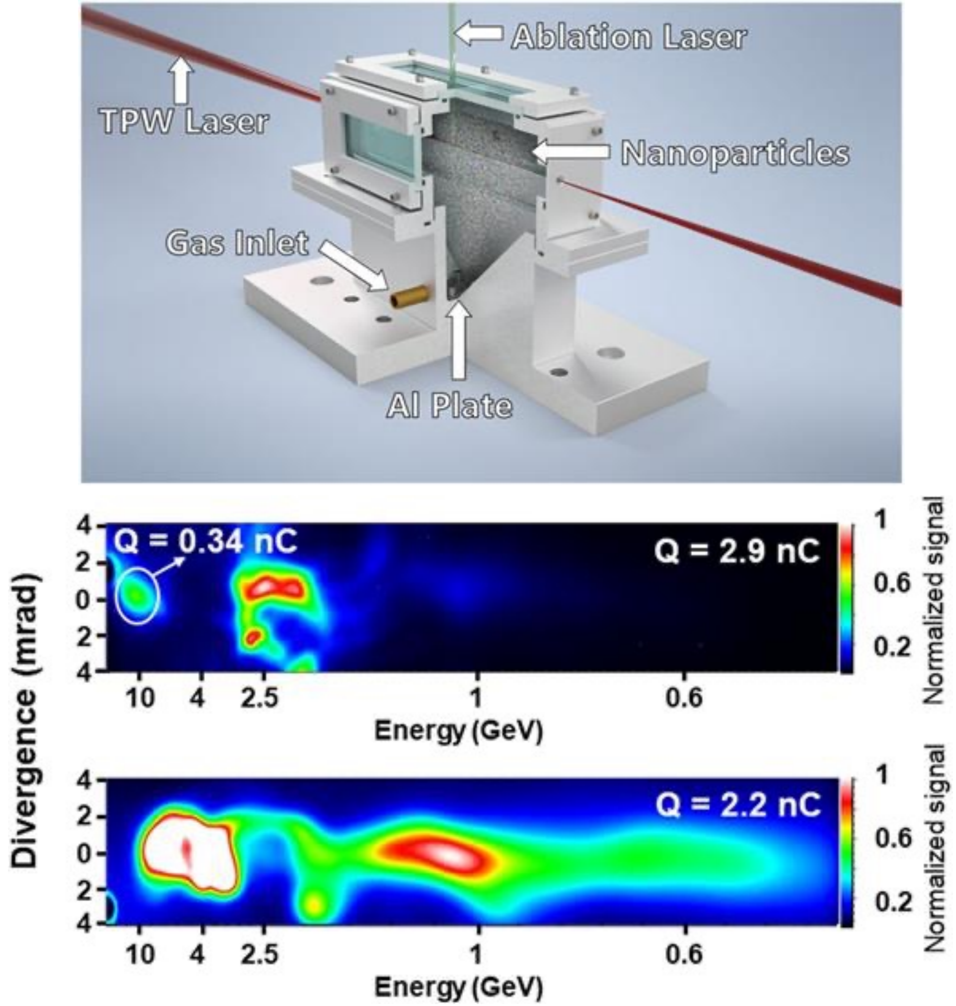
This implies a hard limit on the maximum speed of the accelerating cavity, and on the maximum energy that the electron beam can gain. From this fundamental argument, it is possible to derive the dephasing length for a laser wakefield accelerator:

$$L_d[cm] \sim \frac{3.9}{\lambda_L^2[\mu m] n_e[10^{18} cm^{-3}]}$$

Typically, single stage LWFA energy gain is limited by dephasing for laser energy of J-level and more. The dephasing length sets the length of the gas target (it has to be taken into account also at which longitudinal position injection is expected to happen).

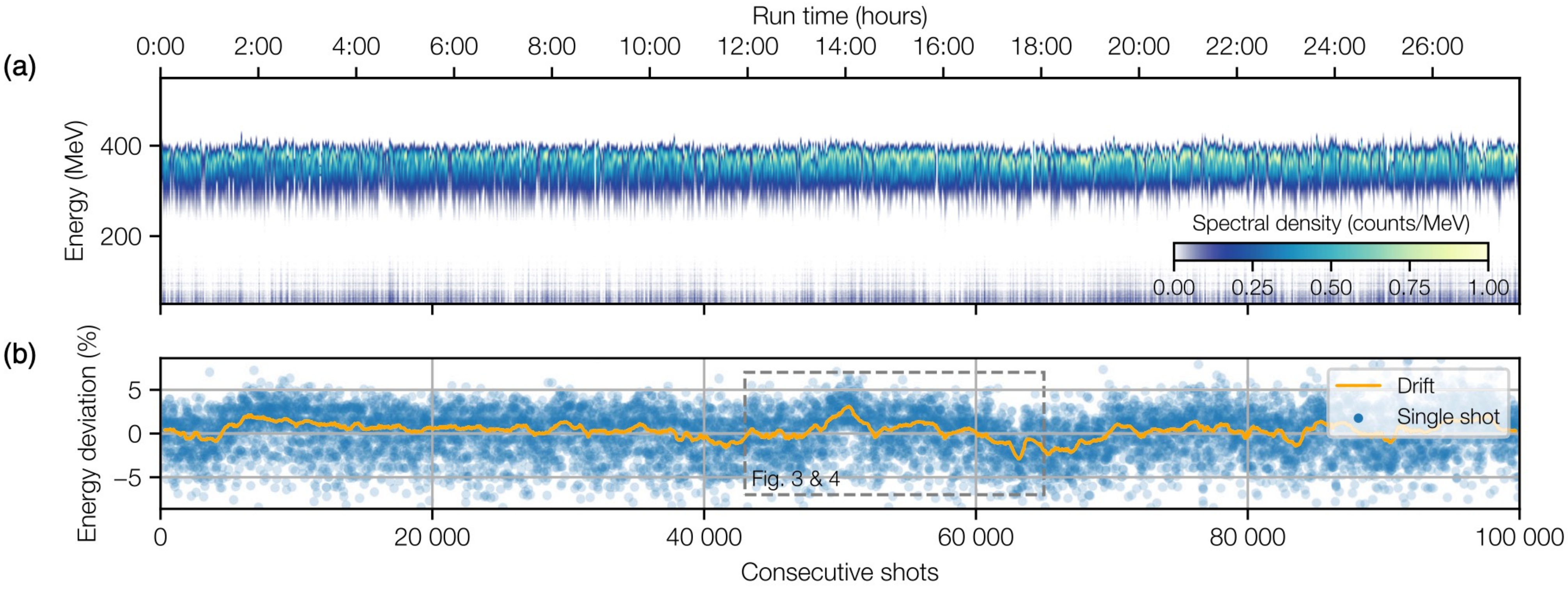
Highest Energy LWFA





Goncalves PRL 2019, Aniculaesei MRE 2024

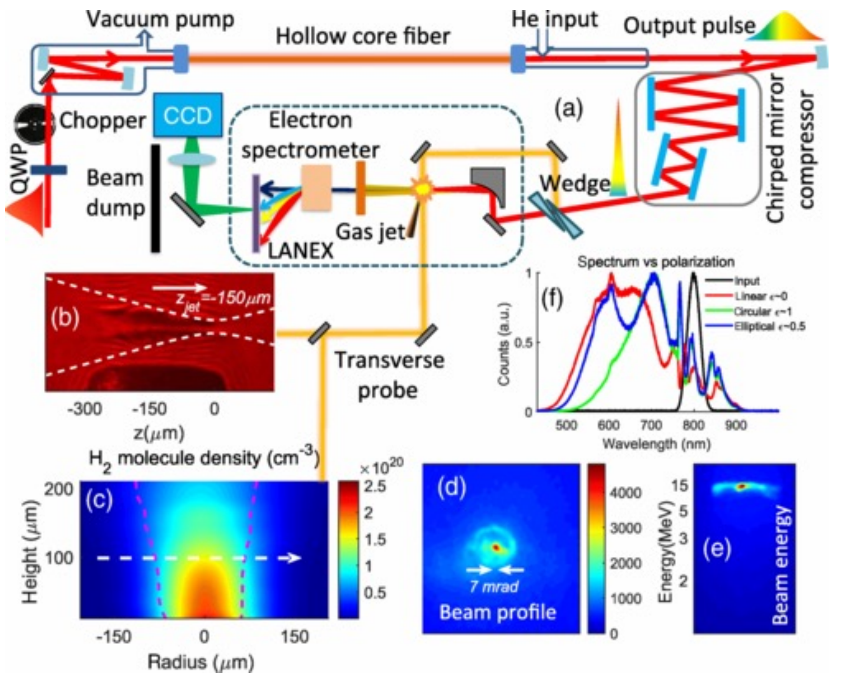
Demonstration of LWFA robustness

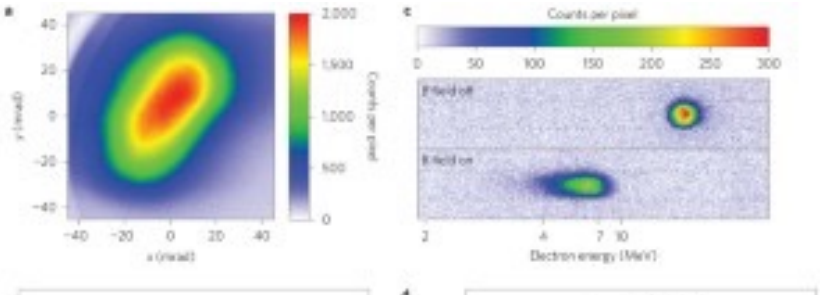


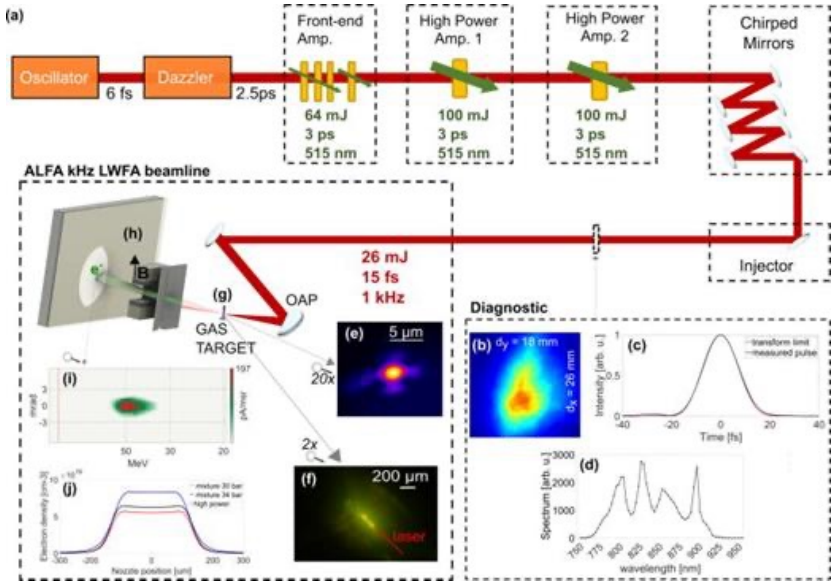
Maier PRX 2020

Highest Rep Rate LWFA - kHz

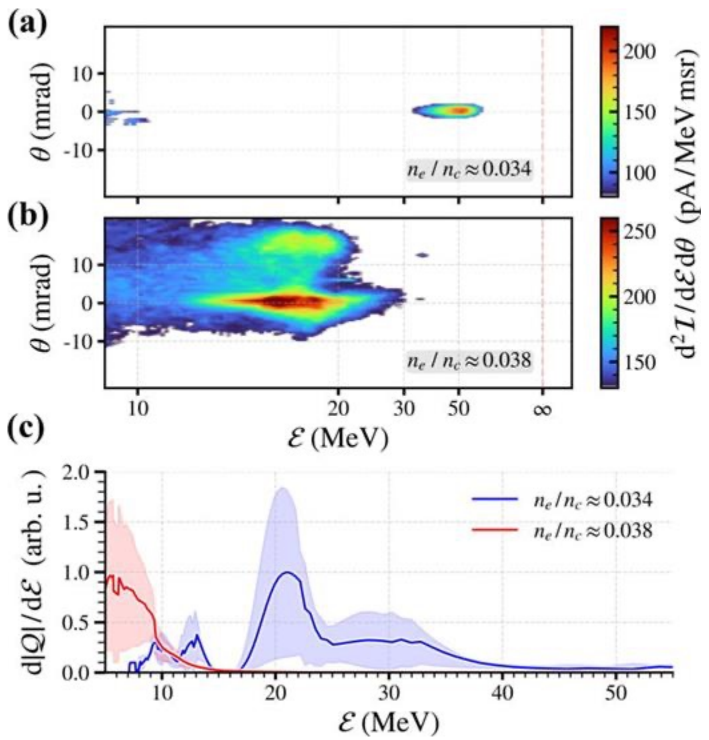
Laser Post-compression – not scalable







OPCPA Laser System:
Scalable!



Guenot Nat. Phot. 2017, Salehi PRX 2021, Lazzarini PoP 2024

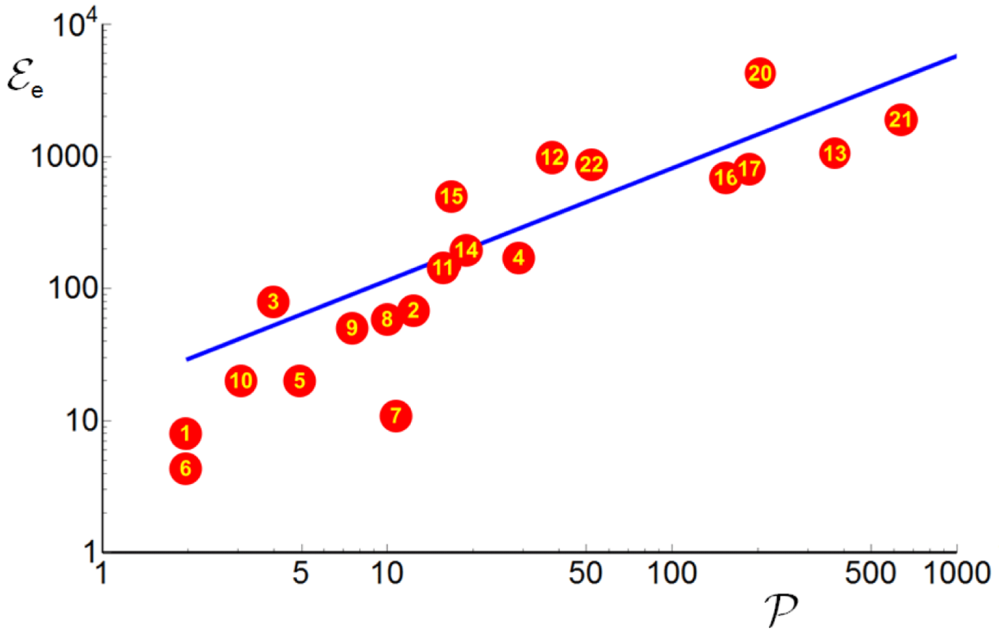
VERY GOOD!

YOU NOW KNOW ALL THE DETAILS OF LWFA!

IS TIME TO GO TO THE LAB!

Scaling laws and comparison with rf beams

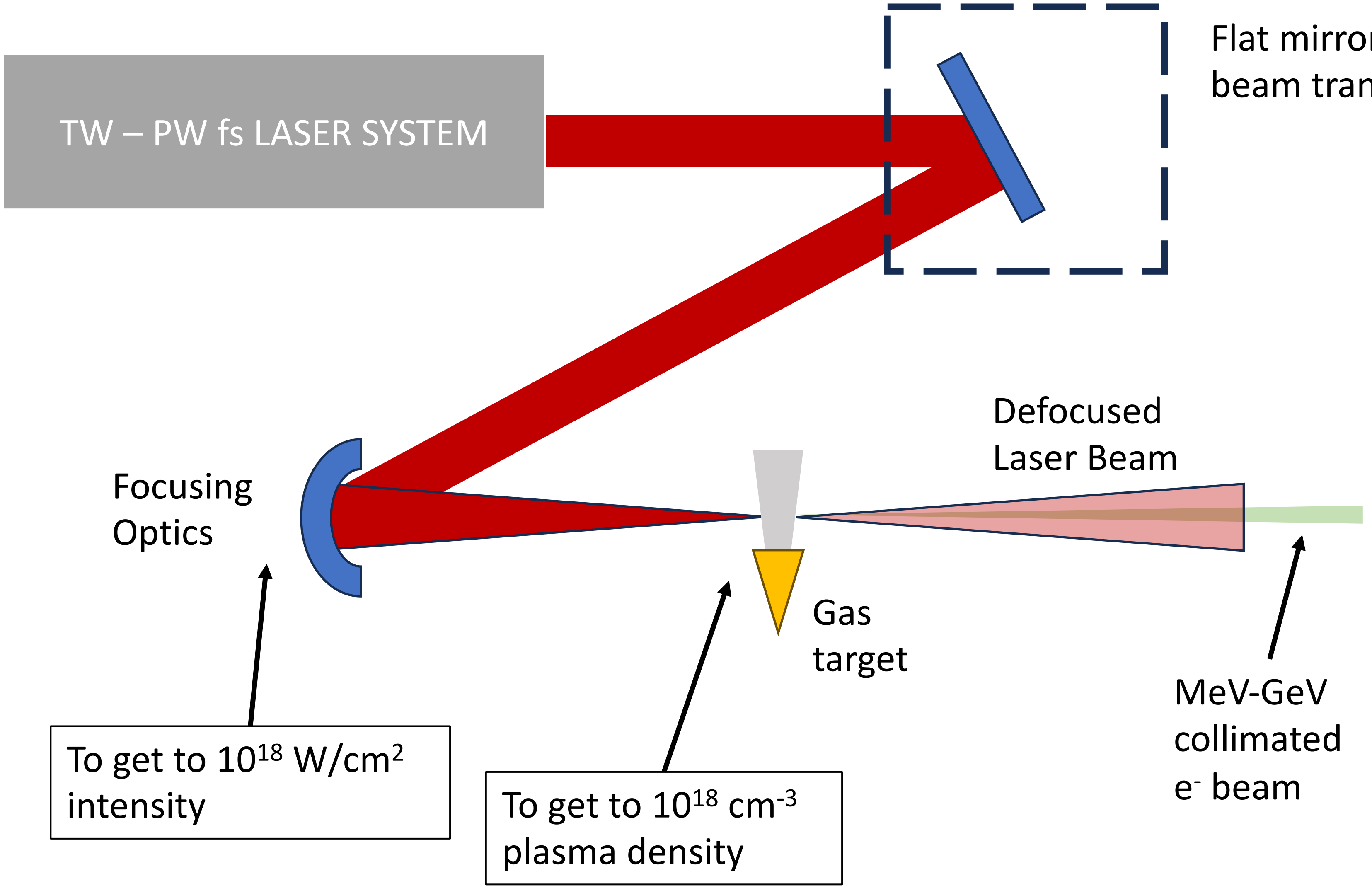
$$E_e[GeV] \sim 1.7 \left(\frac{P[TW]}{100}\right)^{\frac{1}{3}} \left(\frac{1}{n_p[10^{18} cm^{-3}]}\right)^{\frac{1}{3}} \left(\frac{0.8}{\lambda_0[\mu m]}\right)^{\frac{4}{3}}$$

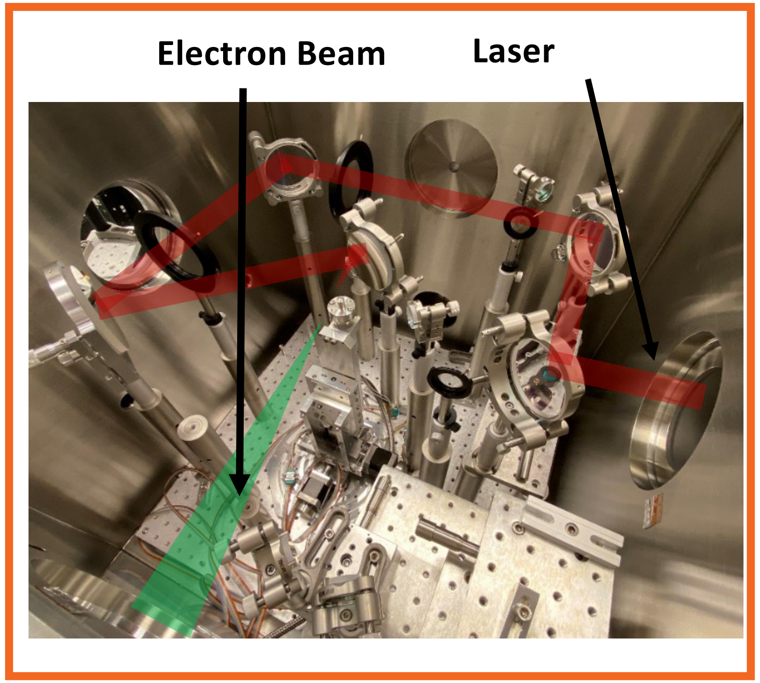


PARAMETER	LWFA	RF ACCELERATOR
ACC. GRADIENT	1 GV / cm	0.1-1 MV /cm
ENERGY SPREAD	0.5%	0.01%
PULSE DURATION	1 fs	ps - ns
CHARGE/PULSE	pC - nC	pC - nC
AVG. CURRENT	nA	μA - mA

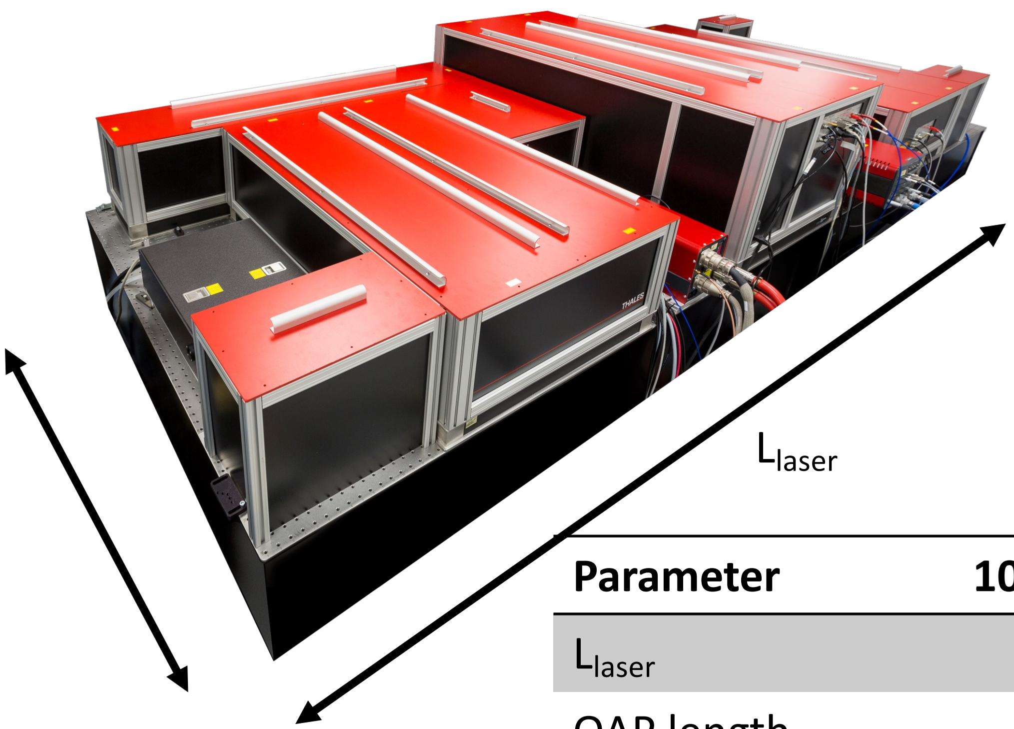
Lu PR STAB 2006, Bulanov J. Plasma Phys 2016

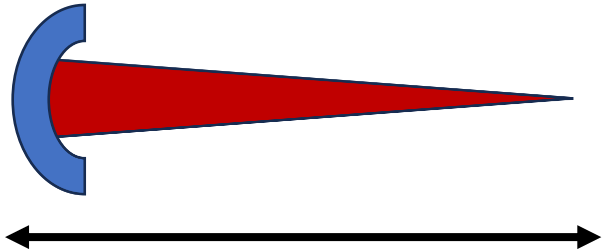
Laser Wakefield Acceleration at-a-glance



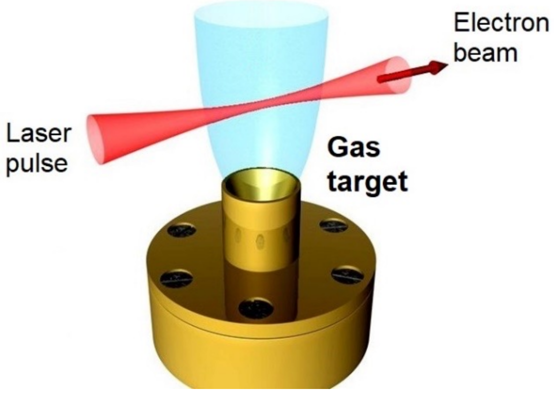


The real size of a LWFA machine





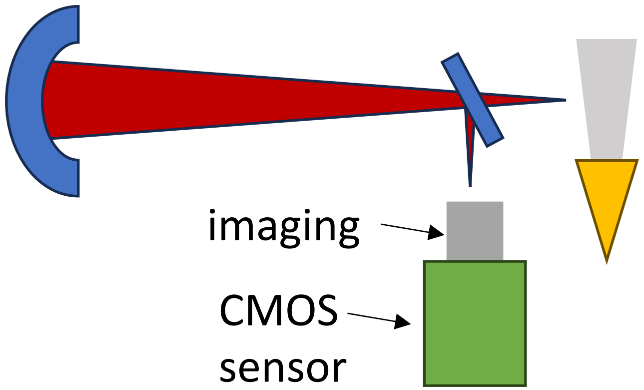
Off-axis Parabola focal length



Gas Target length (typically what we refer to)

Parameter	10s mJ - TW	J – 100 TW	PW	10 PW
L_{laser}	1 m	3 m	10 m	30 m
OAP length	0.1 m	1 m	10 m	100 m
L_{acc}	0.0001 m	0.01 m	1 m	10 m
Electron Energy	10s MeV	100s MeV	Multi-GeV	10s GeV
Total	~ 1 m	~ 5 m	~ 20 m	~ 150 m
Label	Table-top	University Lab	Research Lab	National Lab

Laser focusing

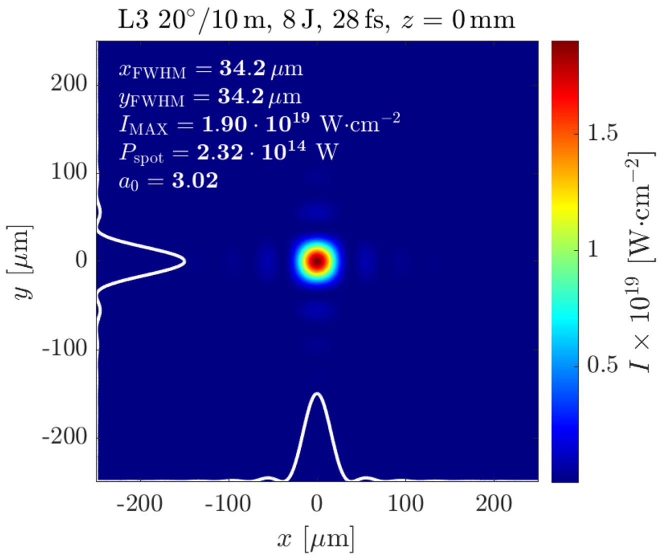


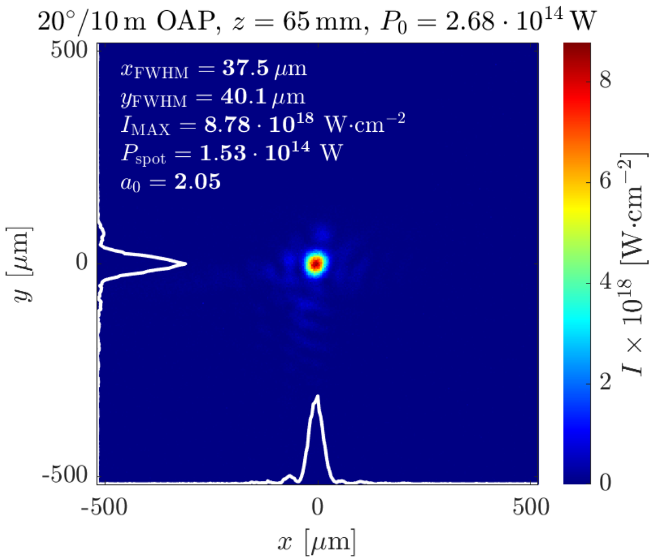
The laser energy in the focal spot E_{FS} is estimated as follows:

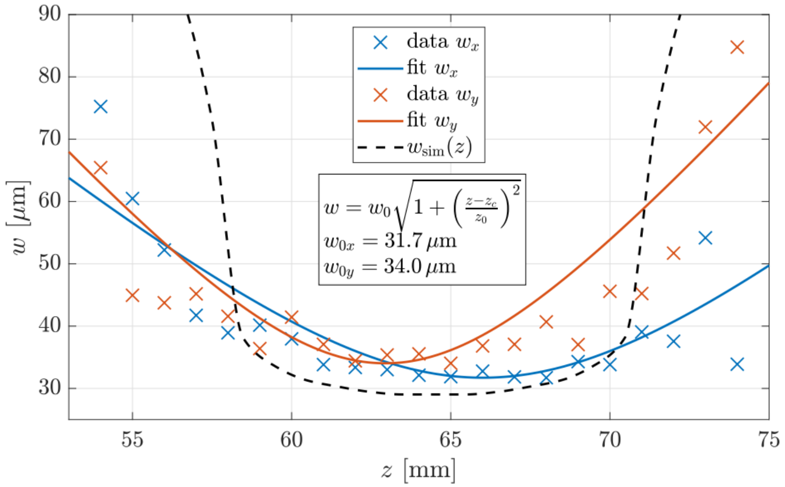
$$E_{FS} = E_{fb}\epsilon_{sb}\epsilon_{wf}$$

where, E_{fb} is the laser energy in the full beam at the compressor output, ϵ_{sb} is the fraction of the energy that the laser beam can put into the focal spot, and ϵ_{wf} is the fraction of the laser enegy that can go into the focal spot due to non-ideal wavefront. E.g. a square beam sets $\epsilon_{sb} = 0.85$, and ϵ_{wf} is typically in the 0.2 – 0.7 range.

COMPARISON OF SIMULATION VS. MEASUREMENT ON L3-HAPLS (Ti:Sa)

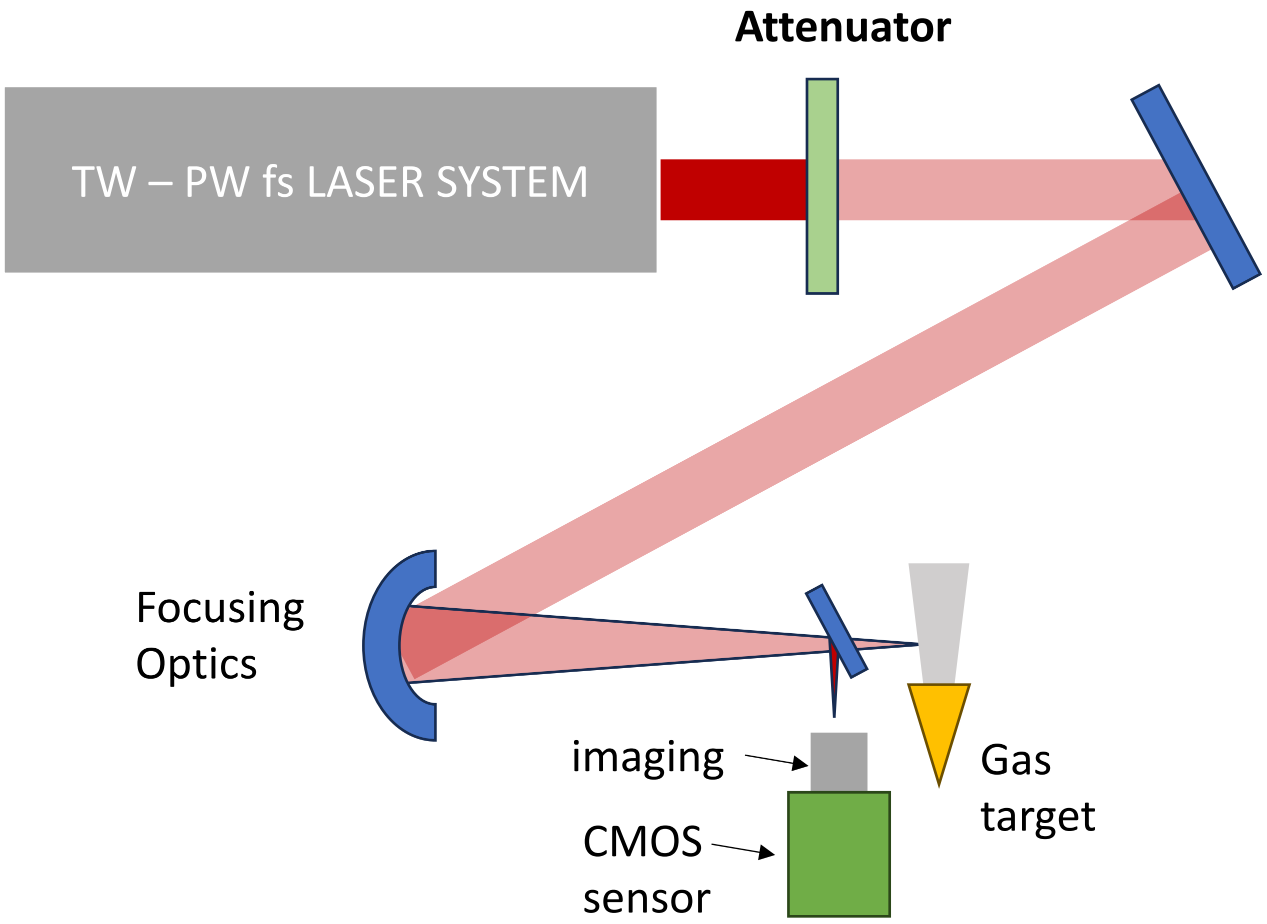




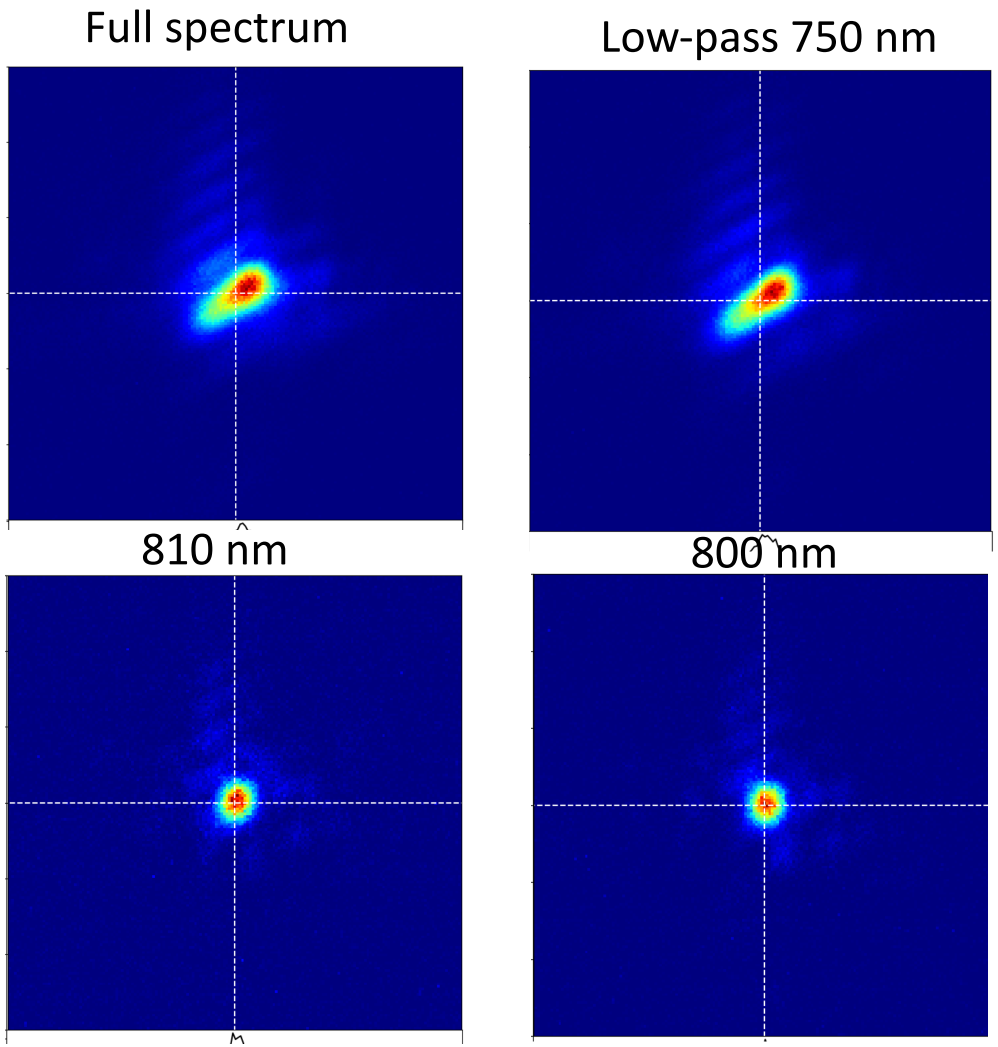


How to measure laser focus?

Full Power Characterization

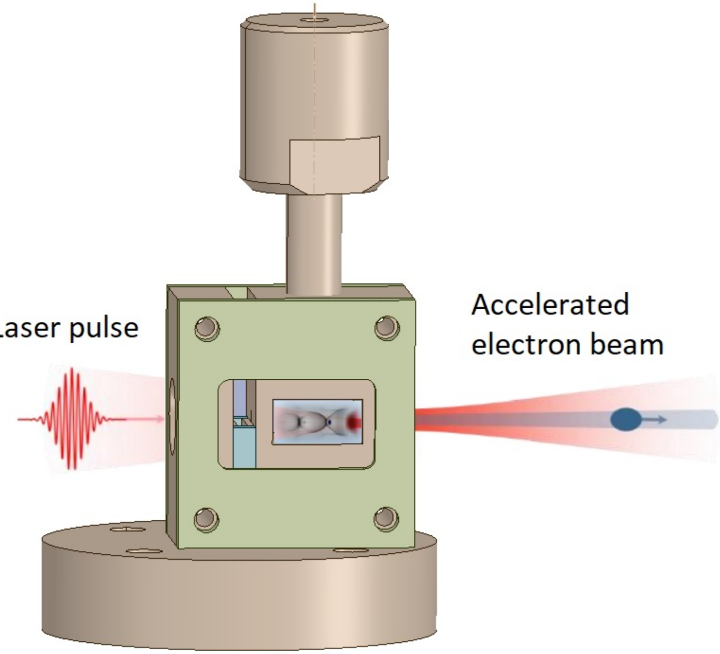


Measurement at different wavelengths

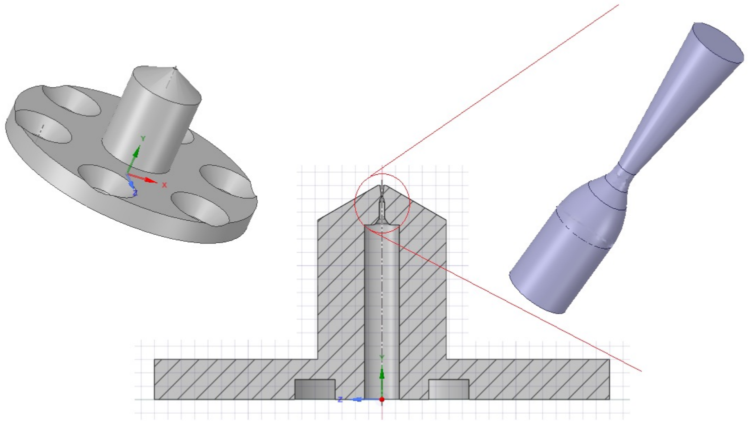


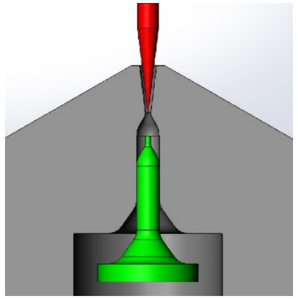
Gas targets

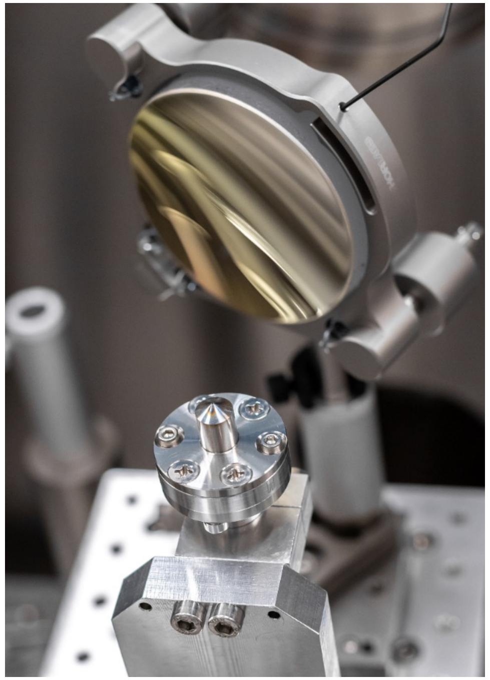
Closed Volume



Open Volume

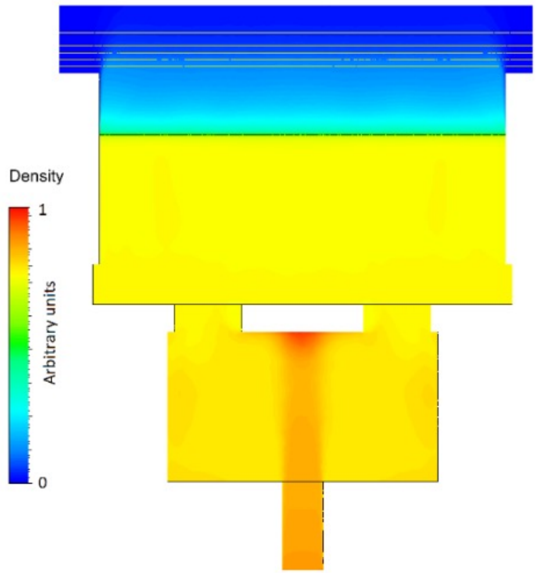


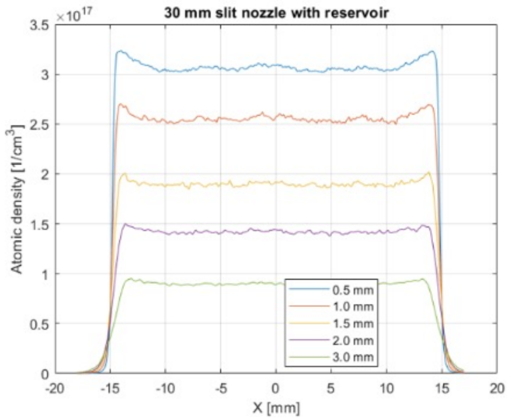




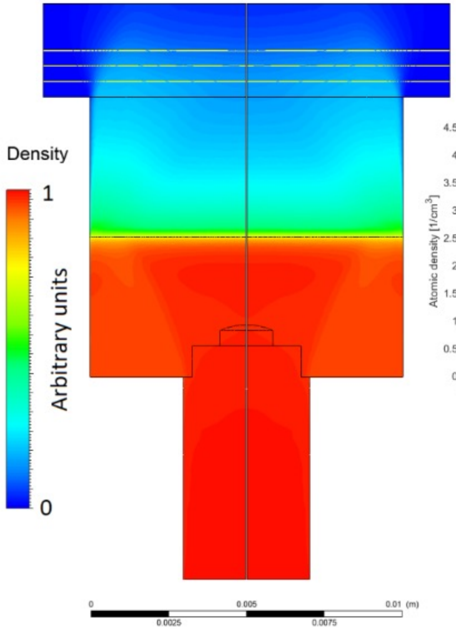
Gas targets

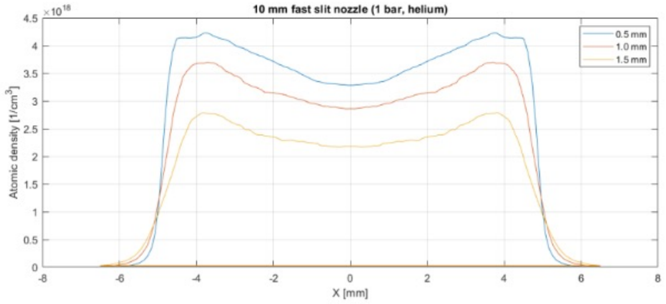
Good density profile





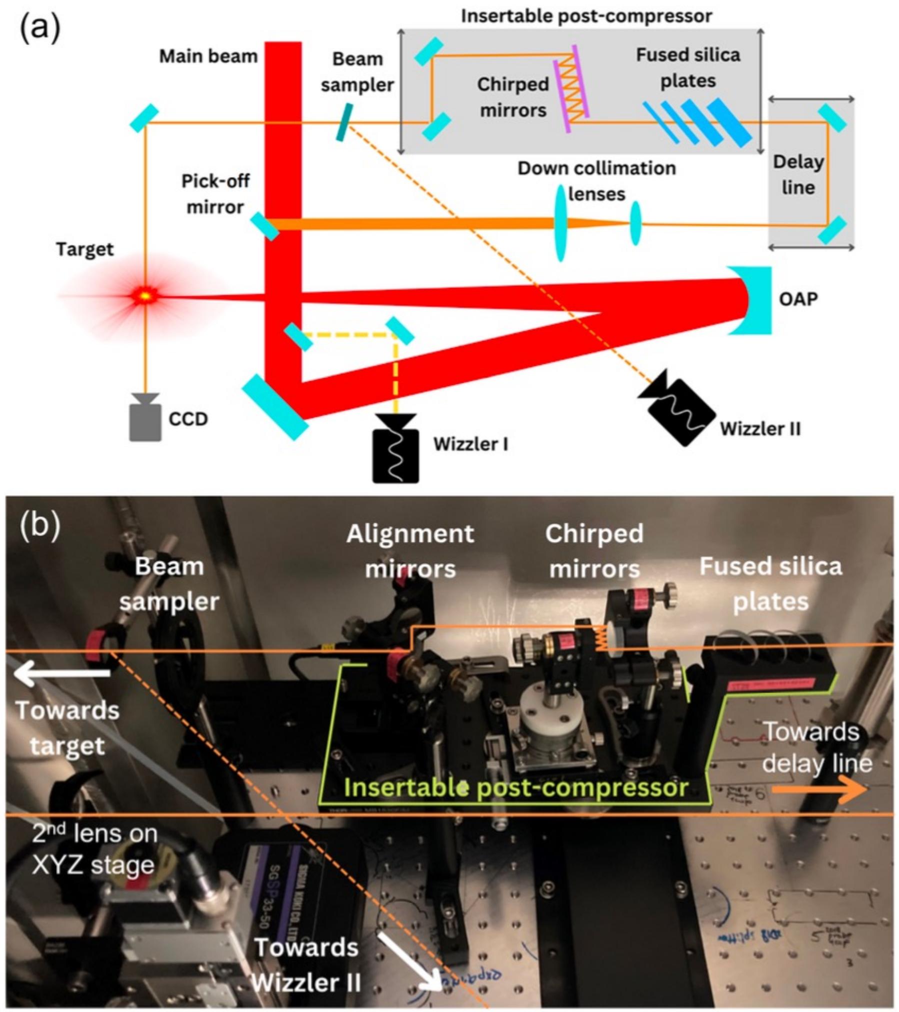
Fast flow



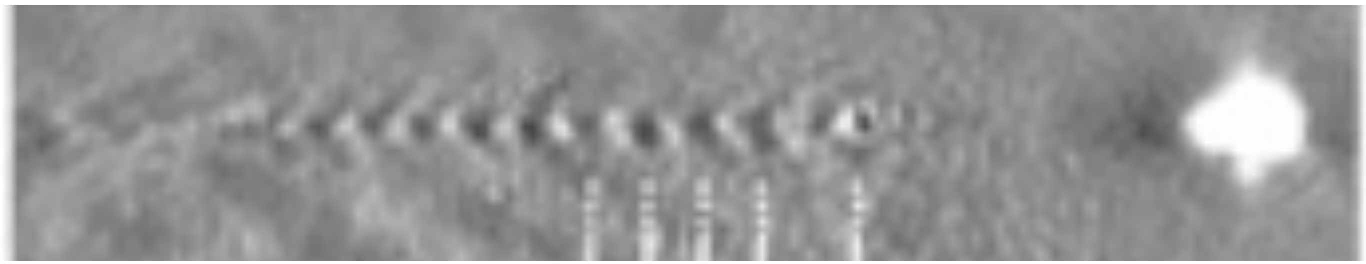


Imaging the accelerating cavity

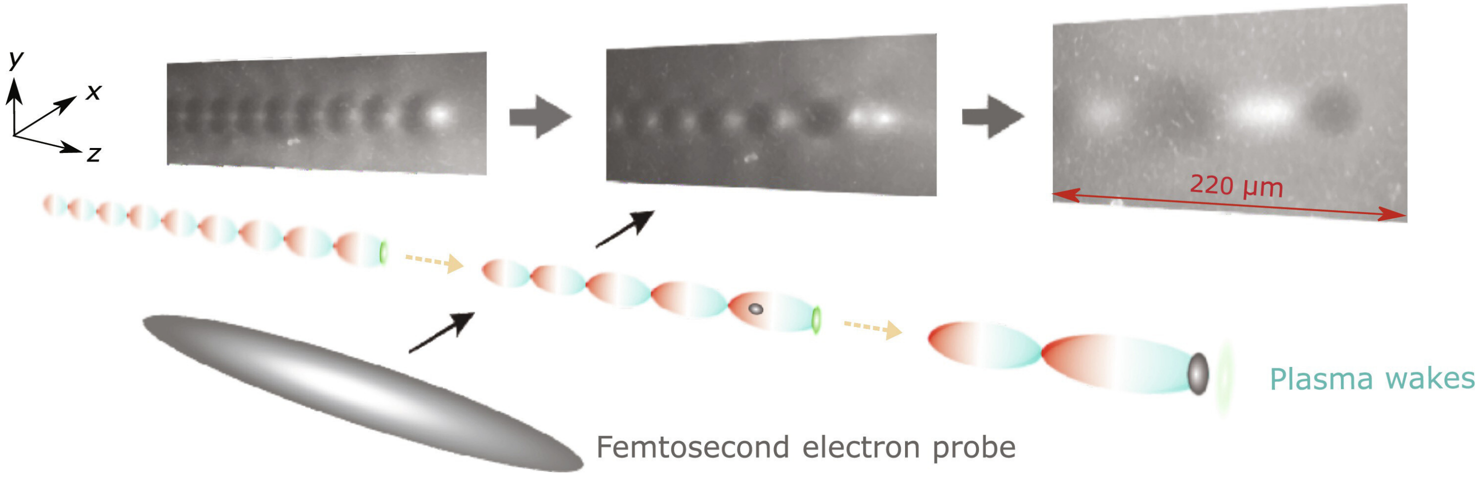
fs probe beam



Laser probe beam

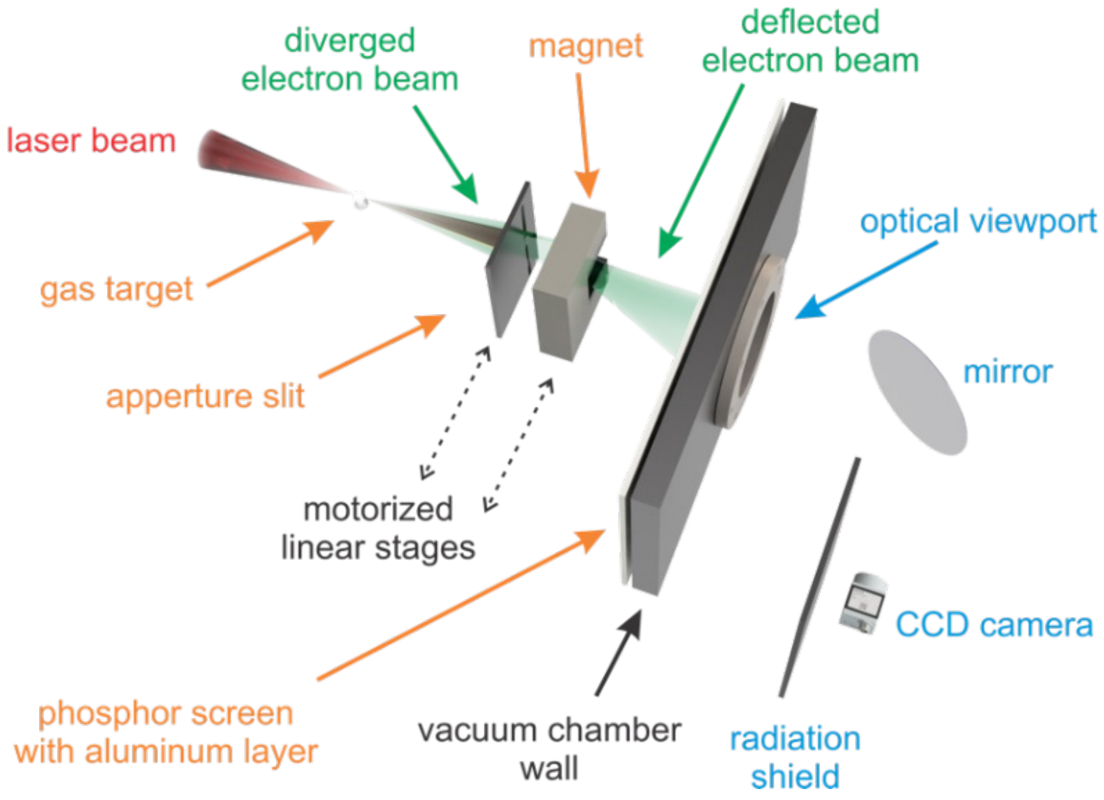


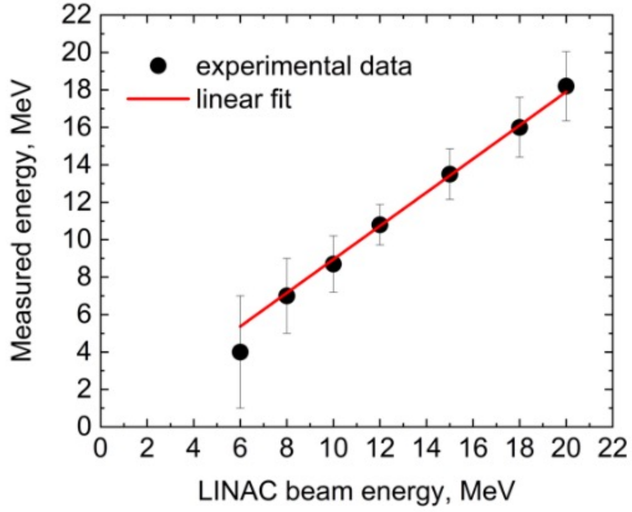
Electron probe beam



Savert PRL 2015, Wan Science Advences 2024, Lorenz 2024

Electron Beam Characterization





Screen	Absolute calibration (10^9 photons/sr/pC)	$N_{scint}/N_{CLS,20\ ms}/Q$ (pC^{-1})	ρ_{sat} (see Sec. III C) (pC/mm^2)
KODAK Biomax MS	14.8 ± 1.3	5.79 ± 0.26	21.8 ± 5.0
CAWO OG 16	12.4 ± 1.1	4.86 ± 0.21	32.9 ± 6.6
KODAK Biomax Transcreen HE	7.85 ± 0.67	3.02 ± 0.13	47 ± 10
KODAK Lanex Regular	6.95 ± 0.60	2.72 ± 0.12	66 ± 33
KONICA KR	6.58 ± 0.56	2.58 ± 0.11	>100
KODAK Biomax Transcreen LE	1.79 ± 0.15	0.700 ± 0.031	>100
KODAK Lanex Fine	1.75 ± 0.15	0.686 ± 0.030	>100
KONICA KF	1.54 ± 0.13	0.602 ± 0.027	>100

Glinec RSI 2006, Buck RSI 2010, Zymak 2024

LWFA Applications

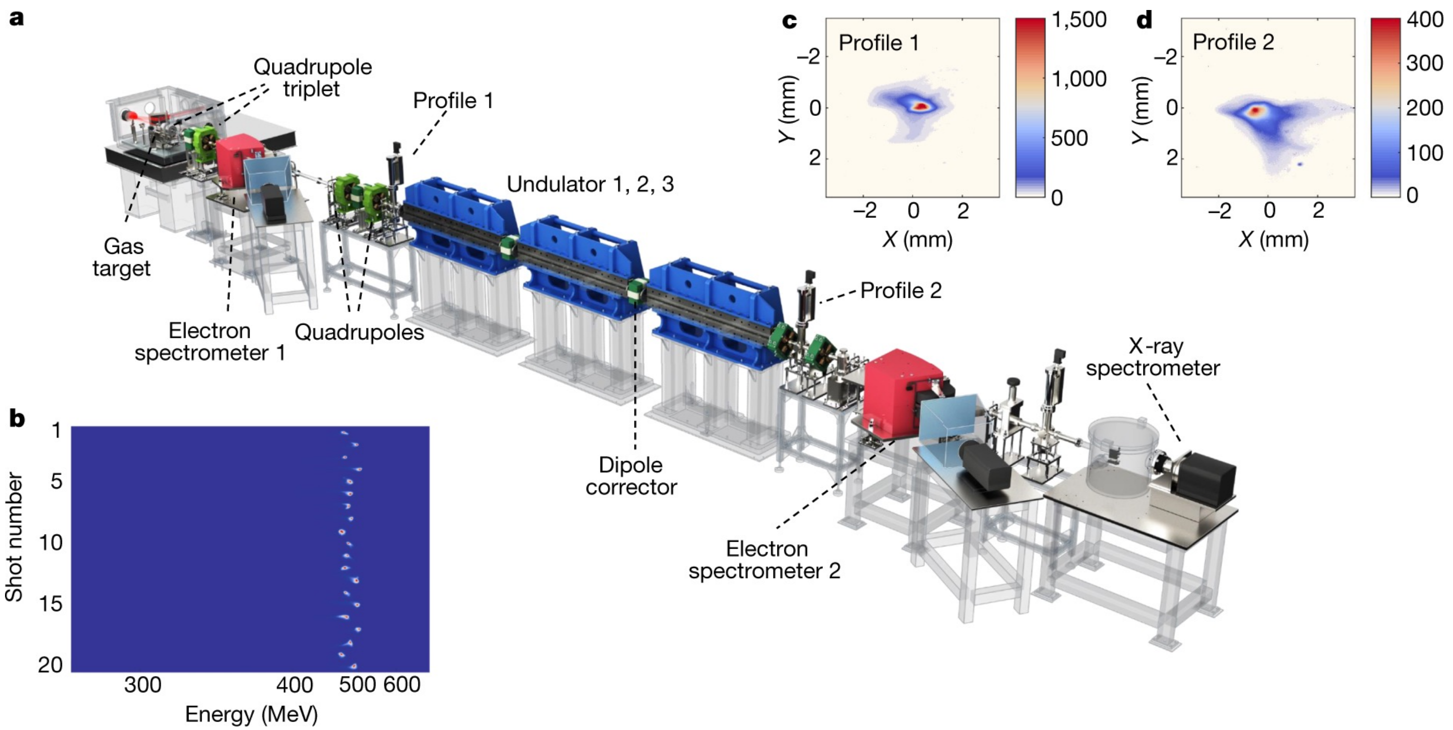
Compact and tunable accelerators

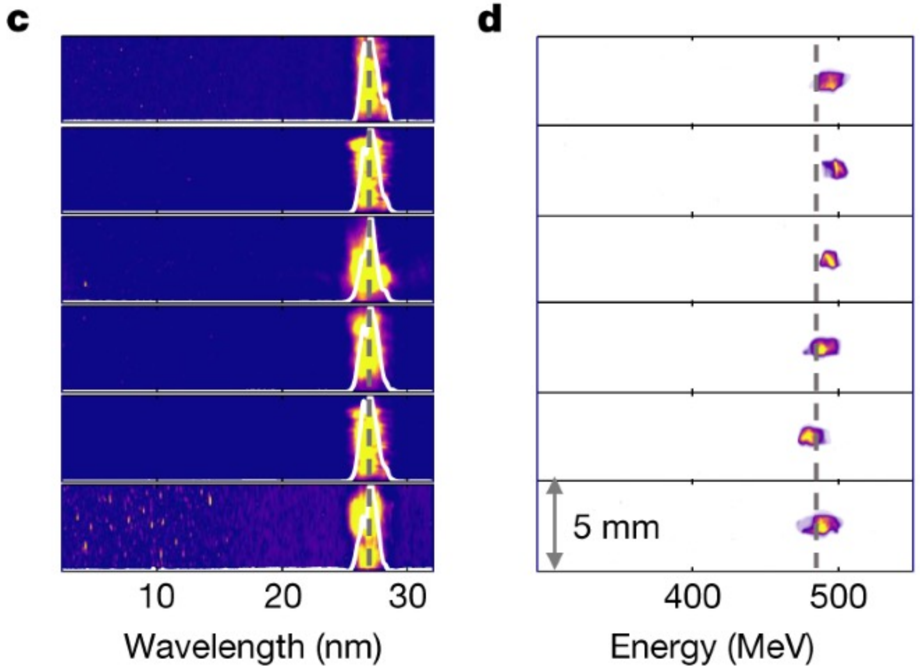
- Compact Free Electron Laser
- Compact and tunable light source for medical imaging and non-destructive testing
- Compact VHEE radiotherapy device
- Compact muon source

Enabling new science

- Laser – Electron Colliders
- Ultra-fast radiobiology
- Dual electron beams

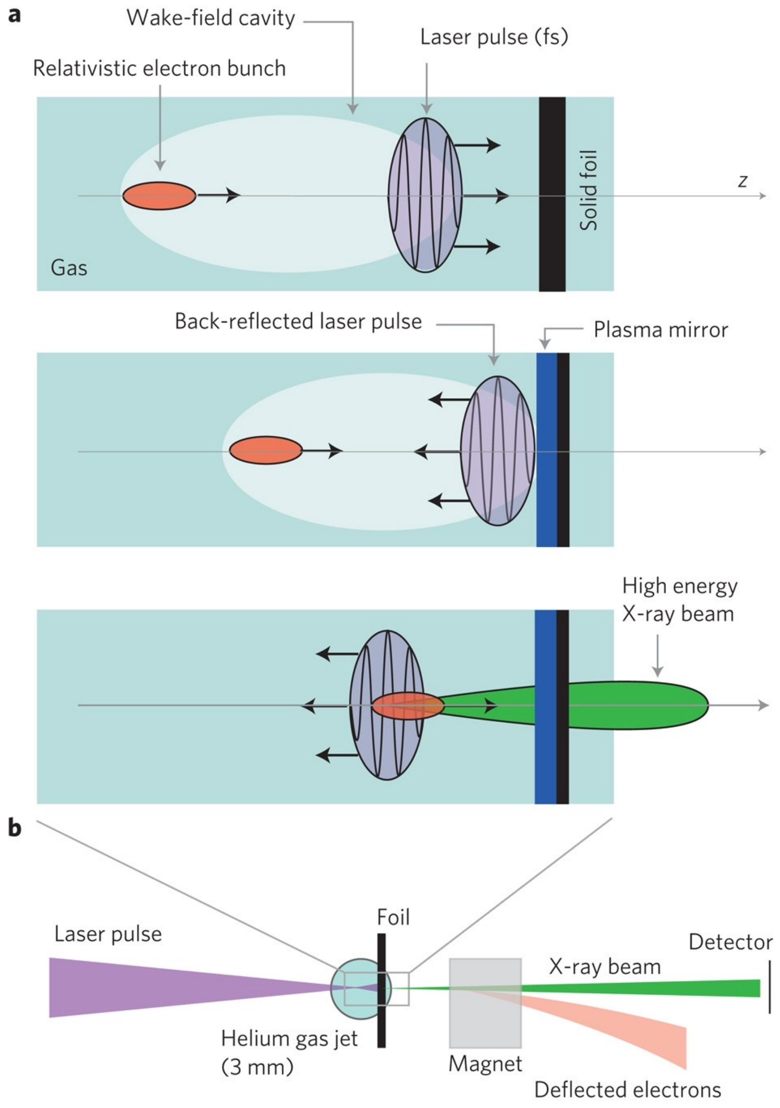
Laser-Driven Compact Free Electron Laser

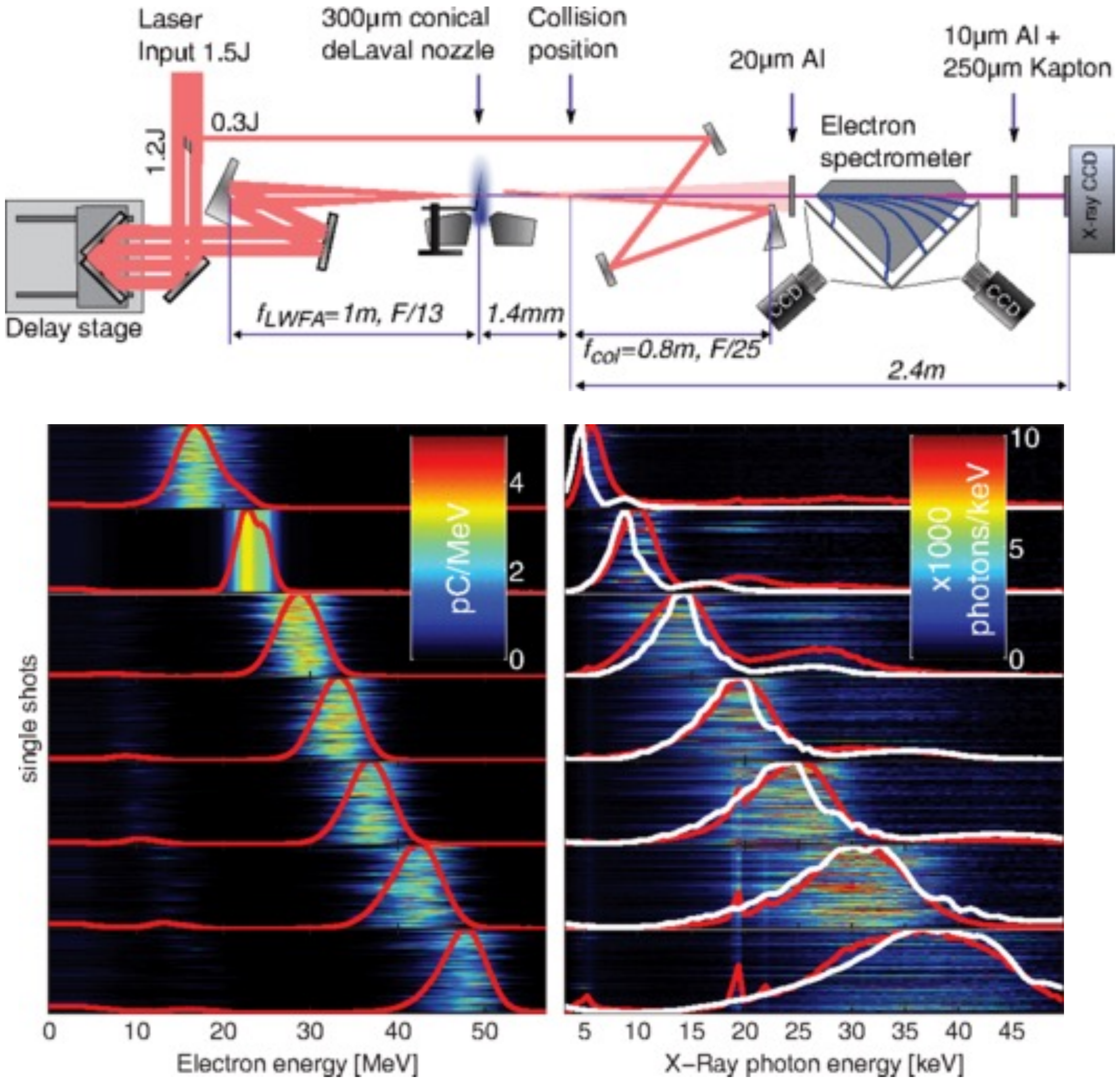




Wang Nature 2021, Labat Nat. Phot. 2023

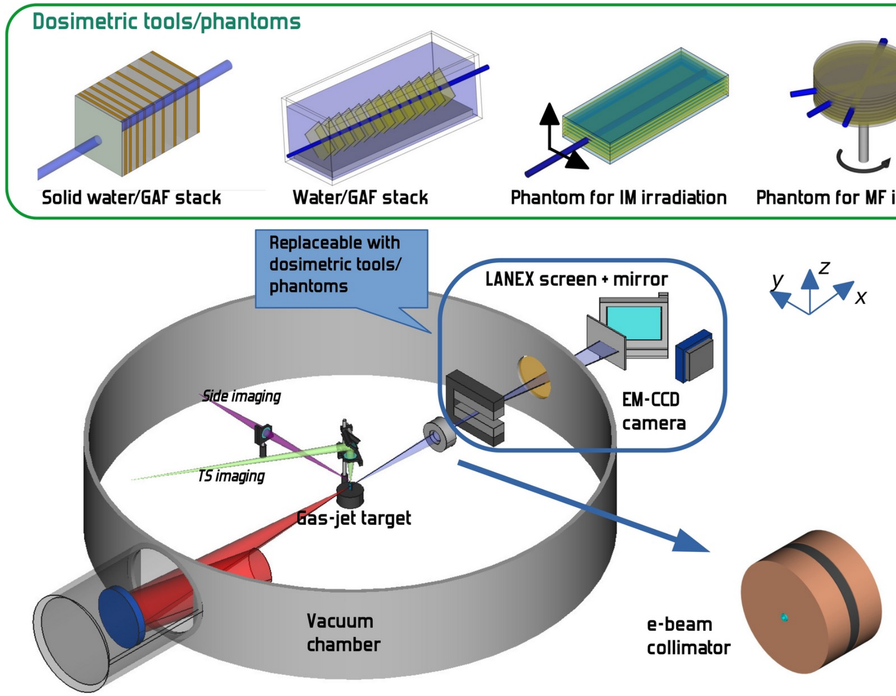
Compact X-ray sources



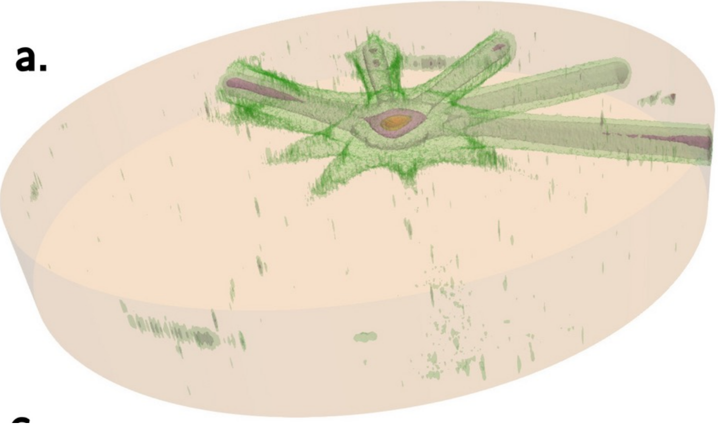


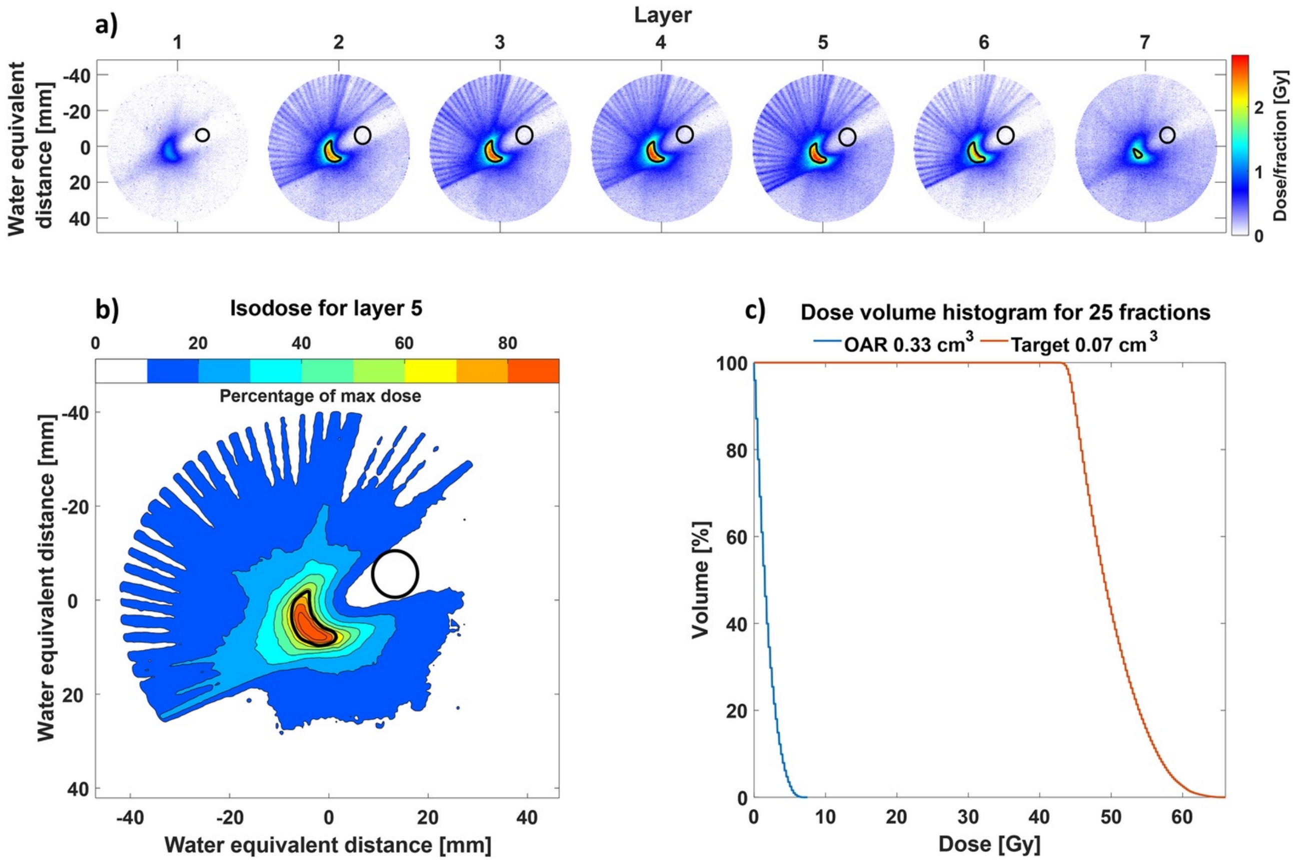
Ta Phuoc Nat. Phot. 2012, Khrennikov PRL 2015

Laser-driven VHEE radiotherapy device



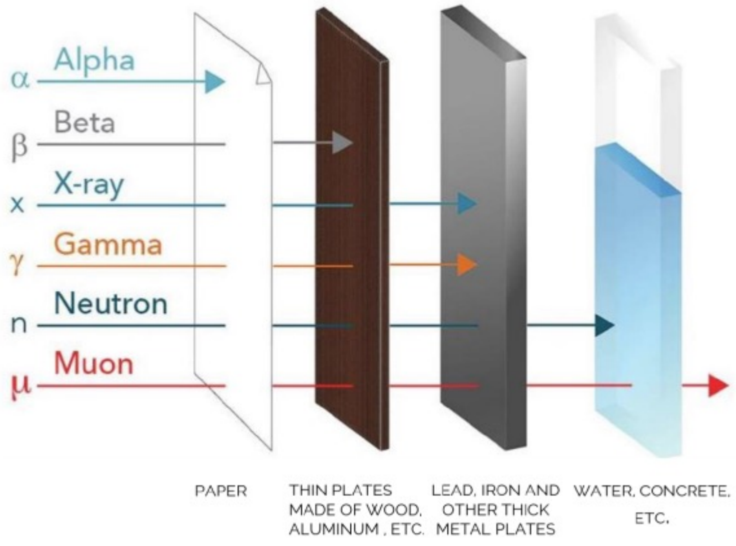
a.





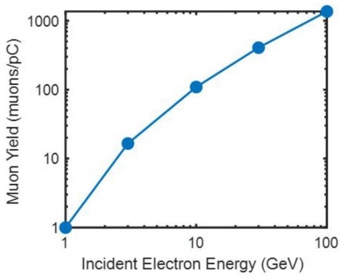
Labate Sci. Rep. 2020, Svendsen Sci. Rep. 2021

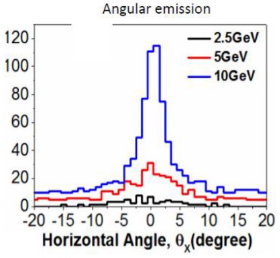
Compact Muon Source



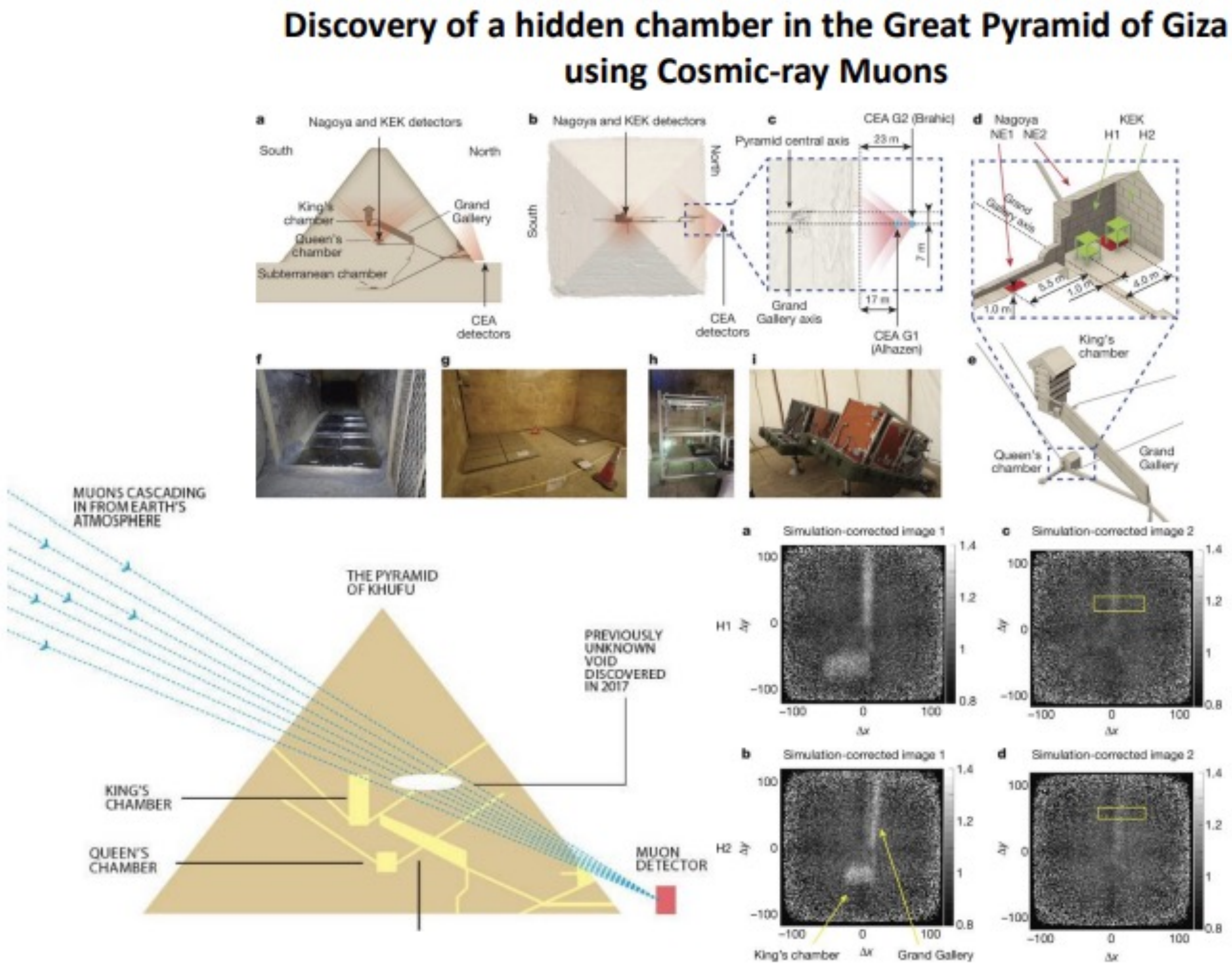
Bethe-Heitler Pair Production: Create bremsstrahlung radiation by impacting electrons onto a high atomic number target and produce muon pairs

$$\left.\begin{array}{l} e^- + N \rightarrow e^{-*} + N + \gamma \\ \gamma + N \rightarrow N + \mu^- \mu^+ \end{array}\right\}.$$



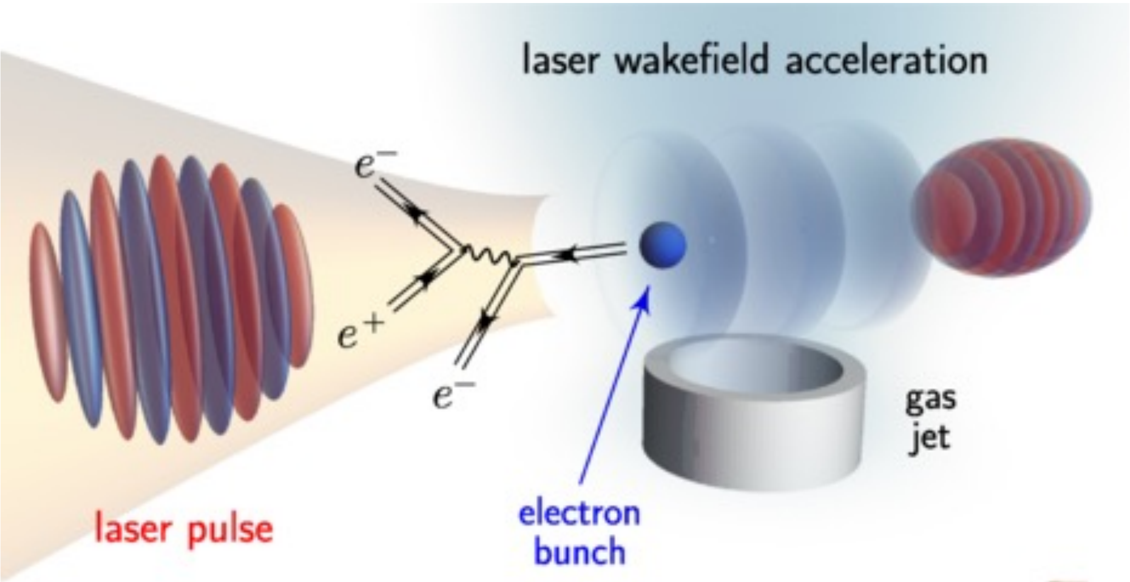


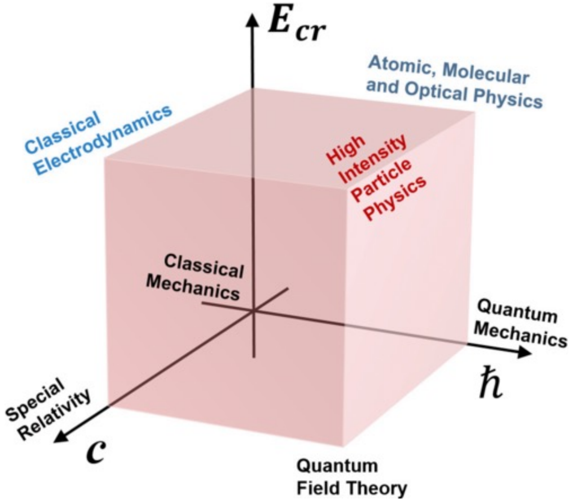
Rao et al. Plasma Phys. Control Fusion (2018)

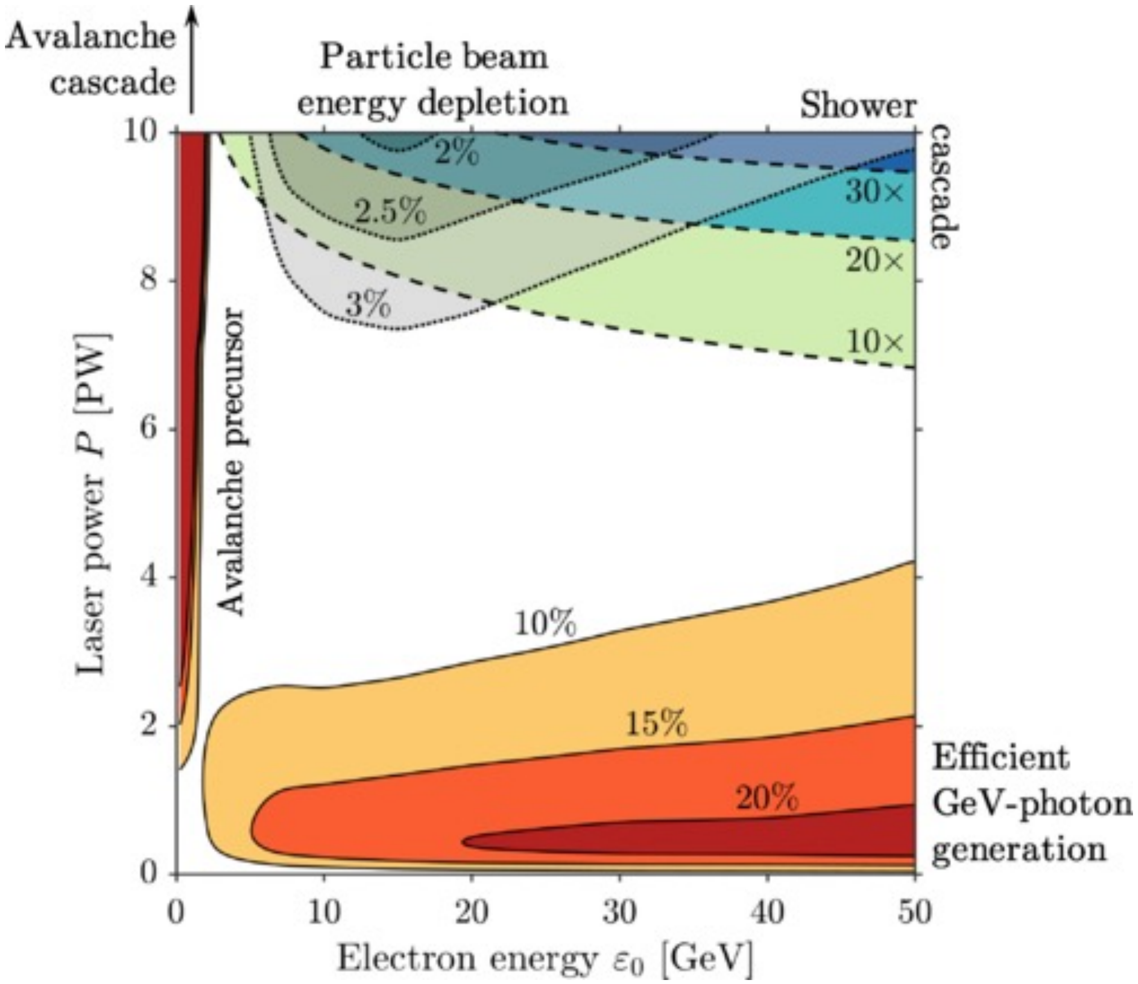


Morishima Nature 2017

Laser – Electron Colliders

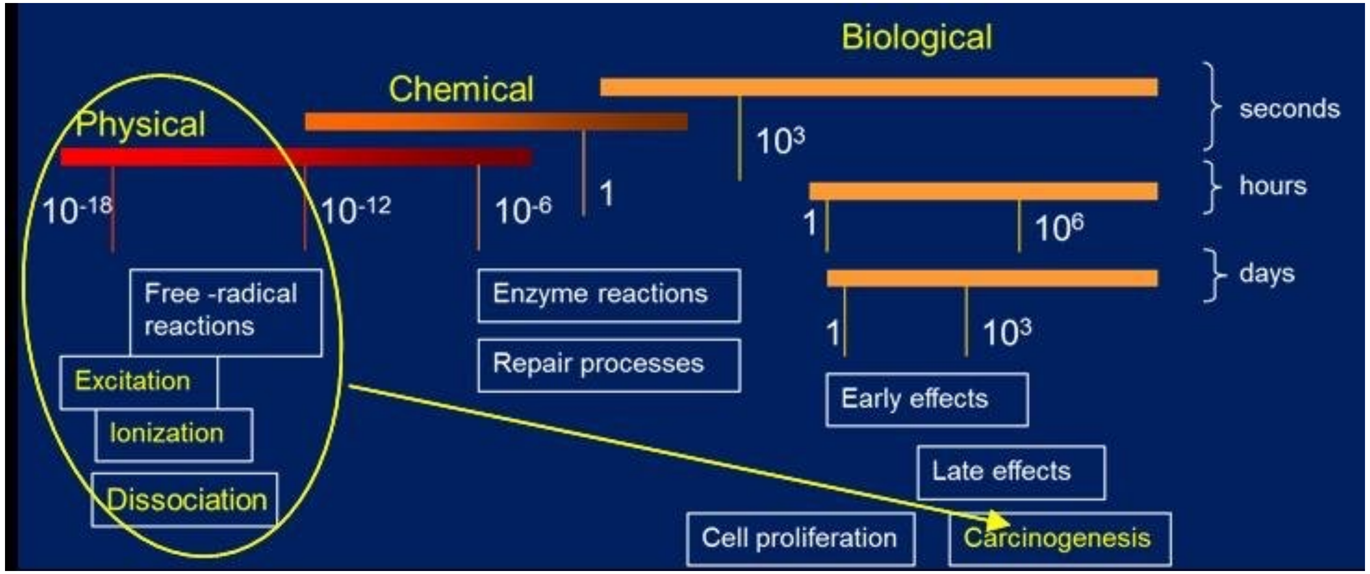


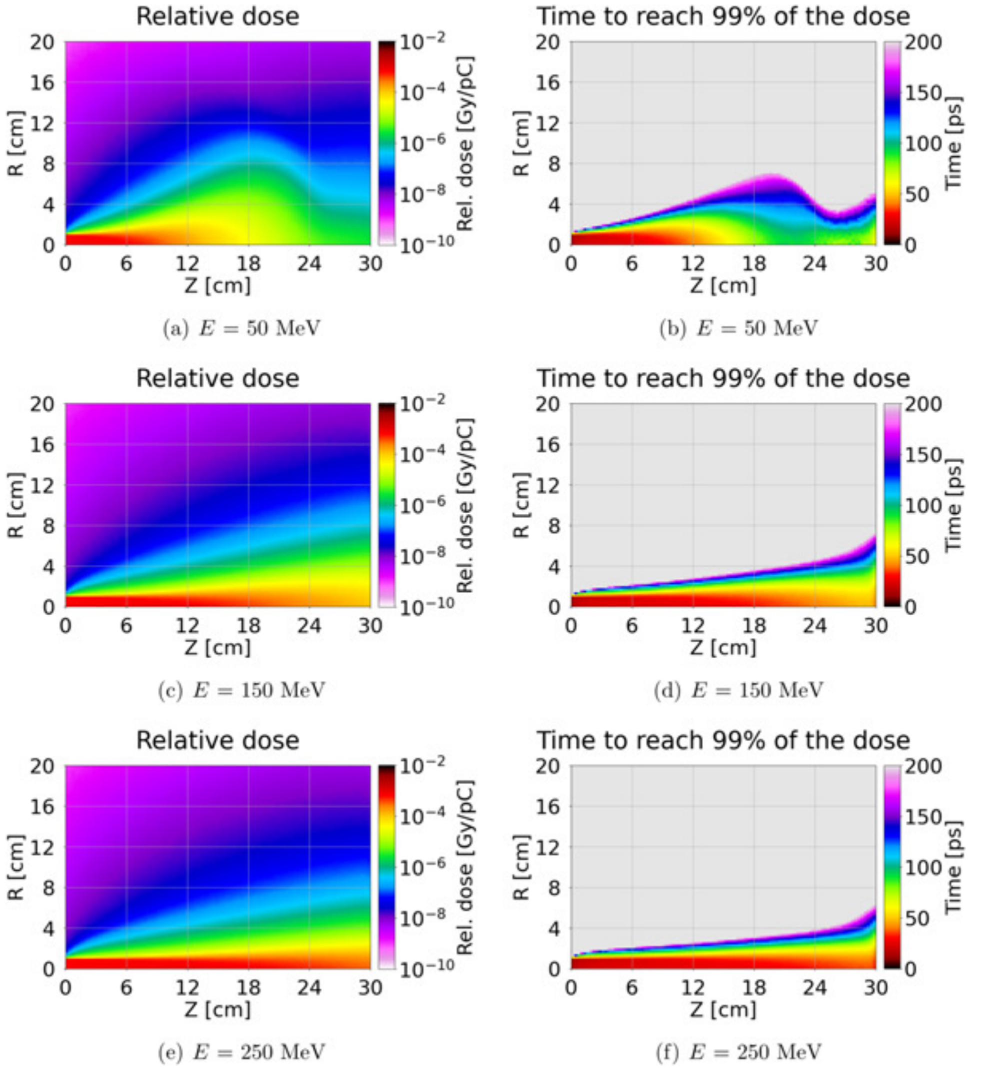




Gonoskov RMP 2022

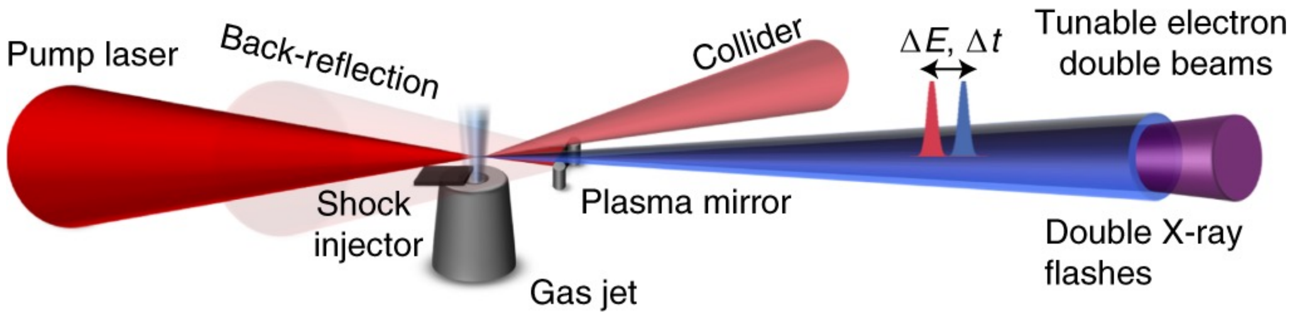
Ultra-fast Radiobiology

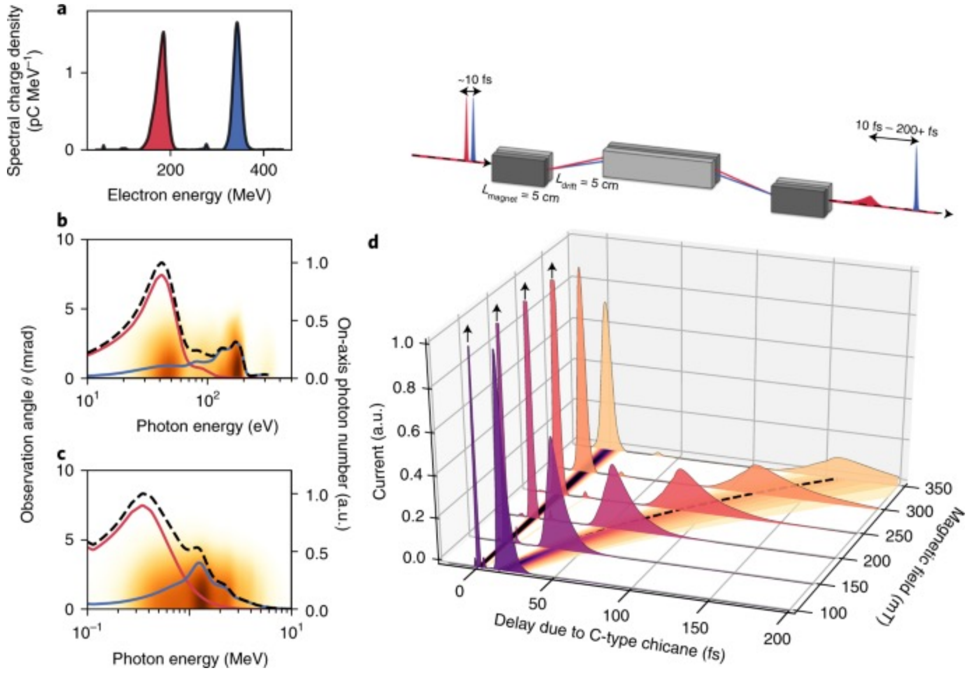


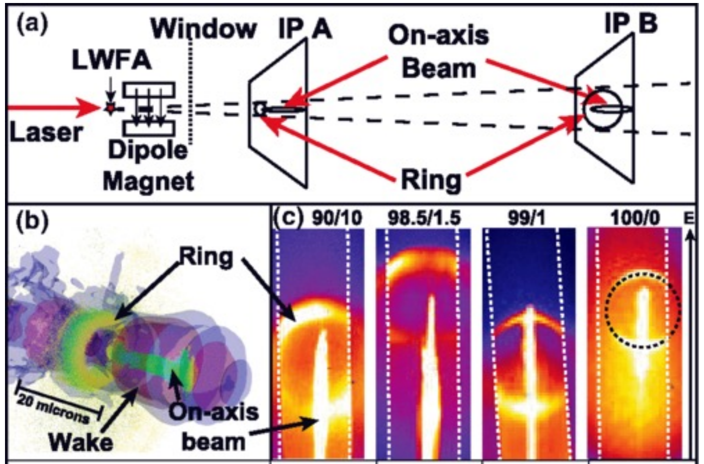


Gauduel Eur. J. Phys 2010, Gauduel J. Phys. 2011, Horvath Phys. Med. Biol. 2023

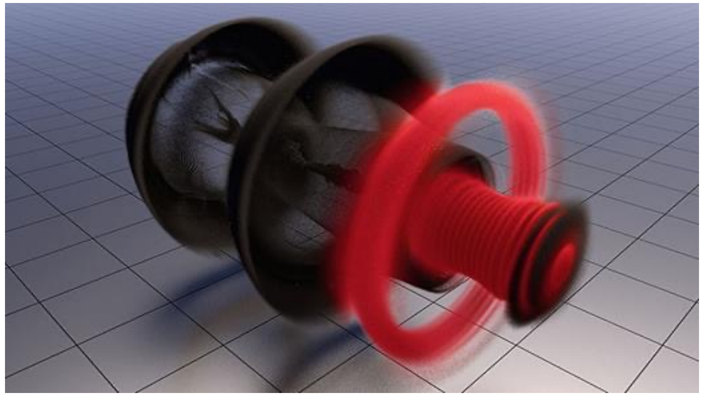
Special Electron Beams







Electron Density (10^{18} cm^{-3})	5	7	5	7
Total Laser Power (TW)	108	128	113	113
Ring Energy (MeV), ΔE/E (%)	215, 14	280, 25	170, 5.9	249, 4.8
Ring Expansion Angle (mrad)	65	78	55	49
Ring Charge (pC)	18	16	3.3	1.0



Wenz Nat. Phot. 2019, Pollock PRL 2015, Valenta PoP 2021

THANK YOU FOR YOUR ATTENTION!