Introduction to plasma acceleration

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On behalf of the SPARC_LAB collaboration

16.05.204

Outline

- Motivation to plasma based accelerators
- What is a plasma?
- Plasma based acceleration
- Plasma source
- Beam driven scheme
- What is a high power laser?
- Laser scheme
- Plasma acceleration @LNF: SPARC_LAB
- EuPRAXIA and EuAPS projects

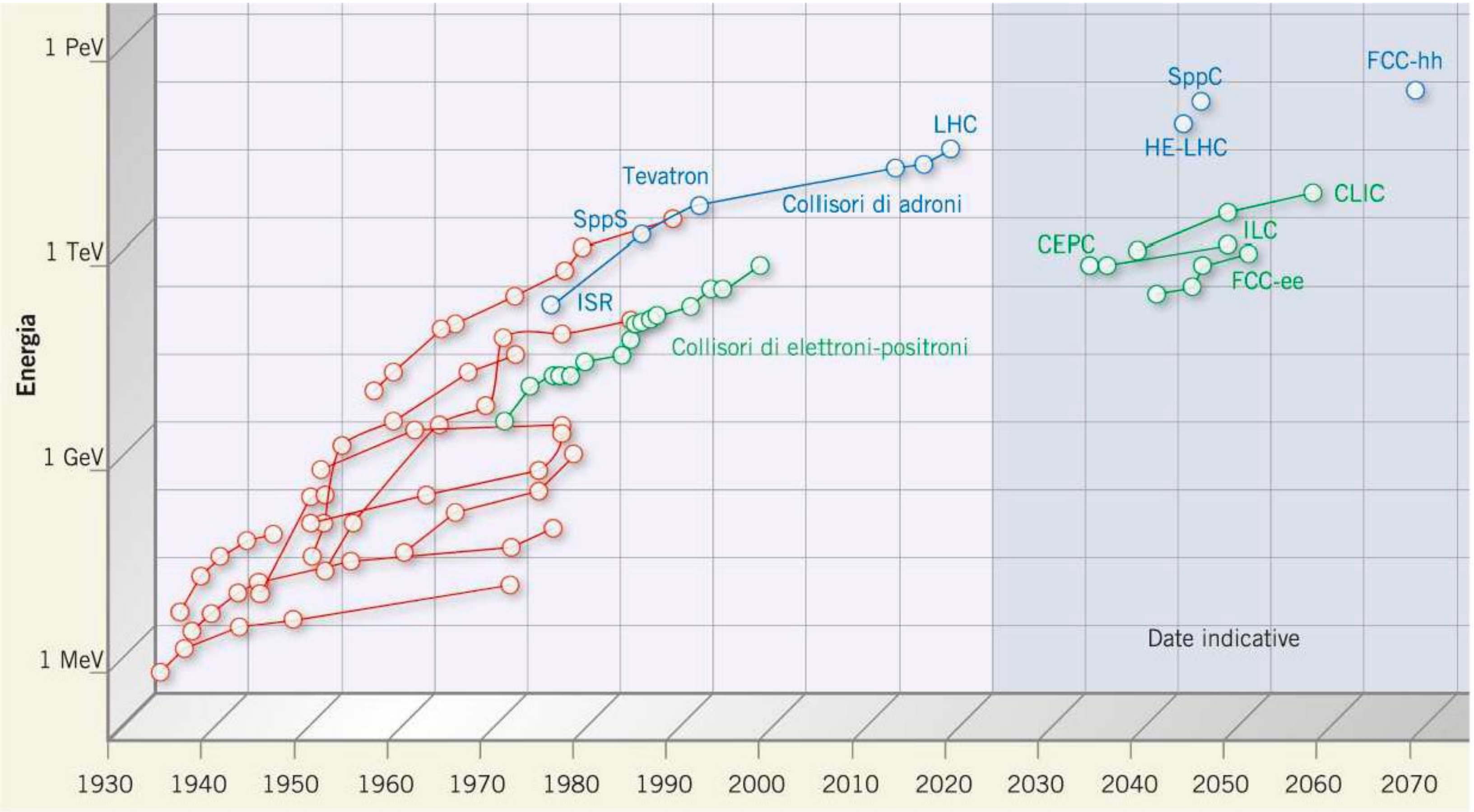
Motivation to plasma based accelerators

Accelerators		1994	2014
Industrial		>4500	27 000
	Electron accelerators >300 keV	1500	~5000
	Electron accelerators <300 keV	>1000	~8000
	Ion implanters and ion analysis	>2000	~12 000
	Neutron generators		~2000
Science		~1000	~1200
Medicine		~4200	~14 000
	Electron accelerators	~4000	~13 000
	Proton and ion accelerators	17	~59
	Production of radioisotopes	~200	~1100
TOTAL		**>9700**	**42 000**

Chernyaev, A. P., and S. M. Varzar. "Particle accelerators in modern world." Physics of Atomic Nuclei 77.10 (2014): 1203-1215.

Motivation to plasma based accelerators

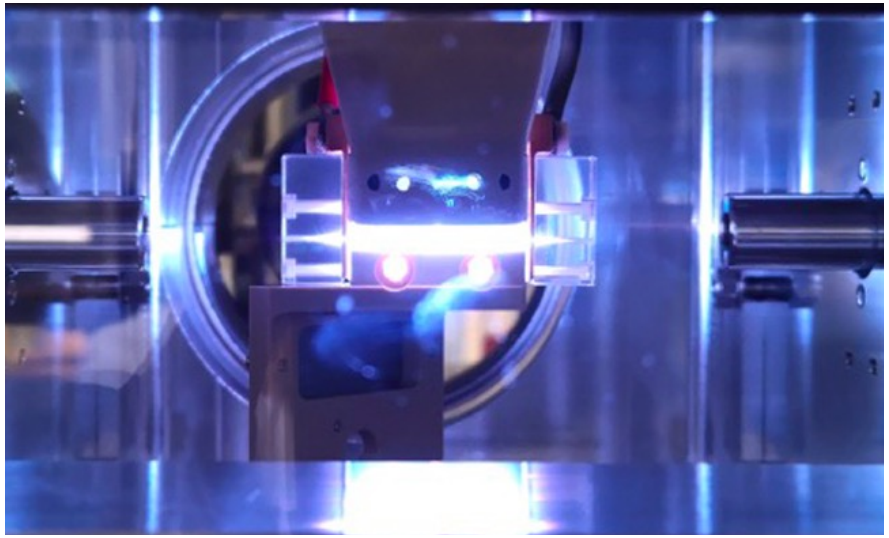
The accelerating gradients have more or less remained constant over the past few decades, in the order of 20 –50 MV/m



Motivation to plasma based accelerators

Conventional RF structures:

(20 – 40) MV/m
range *m - km*

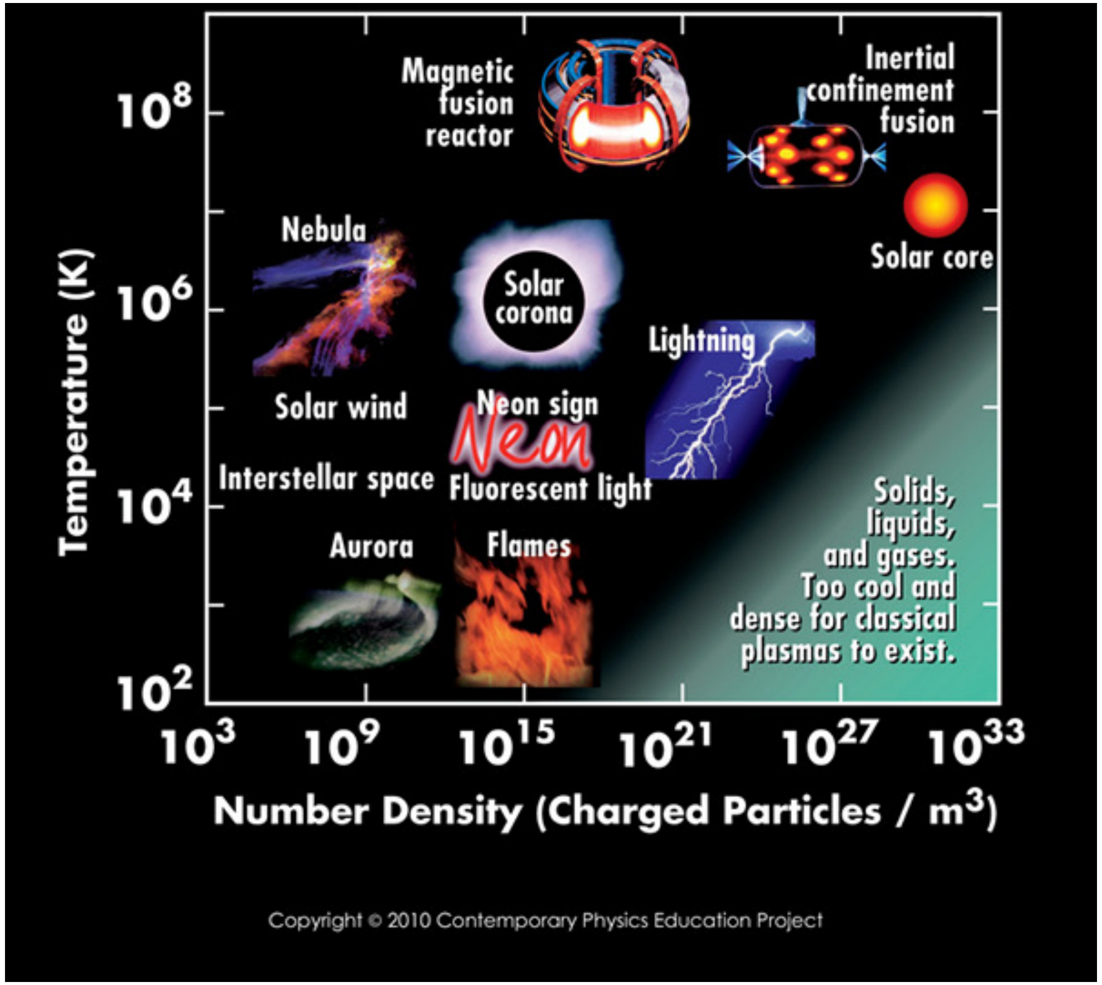


Plasma module:

$E\ [GV/m] = 96\ (n_e\ [cm^{-3}])^{1/2}$
$n_e = 10^{18}\ cm^{-3} \Rightarrow 100\ GV/m$
range *mm - cm*

What is a plasma?

- Quasi-neutral gas of charged particles showing collective behavior
- Local balance inside a plasma: $n_e = Z\, n_i$



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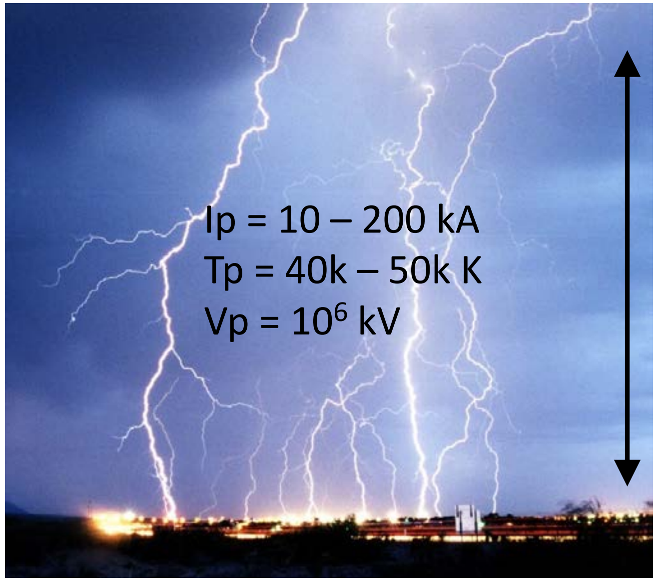
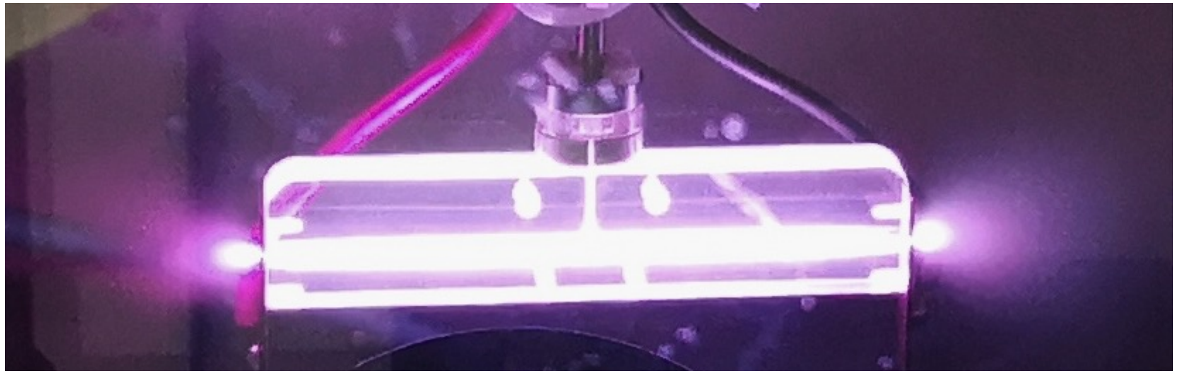
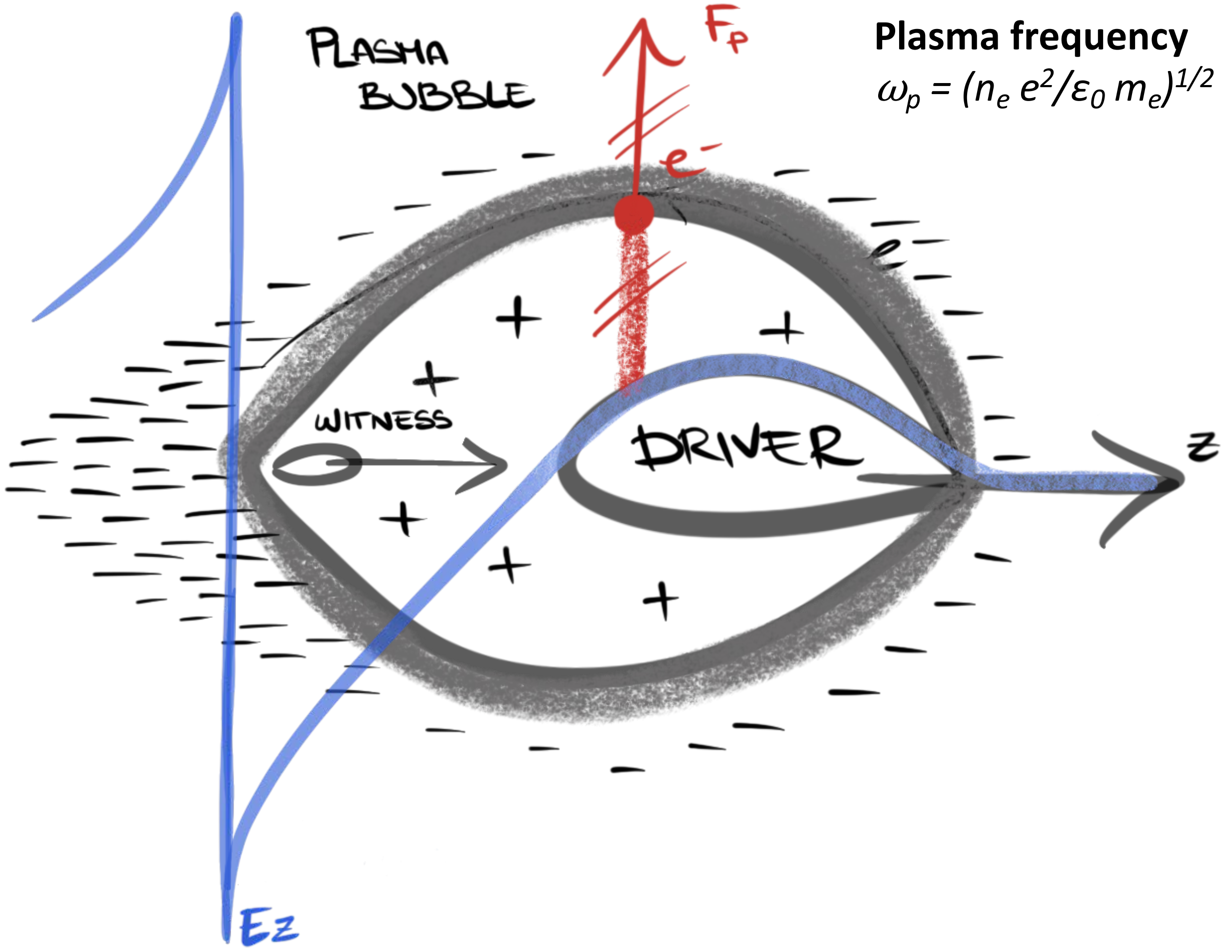

I_p = 10 – 200 kA
T_p = 40k – 50k K
$V_p = 10^6$ kV

Plasma source for accelerators:
I_p = 0.3 – 2 kA
T_p = 20k – 100k K
V_p = 5 – 20 kV



Plasma based acceleration



Plasma frequency

$\omega_p = (n_e e^2/\varepsilon_0 m_e)^{1/2}$

Electron beam

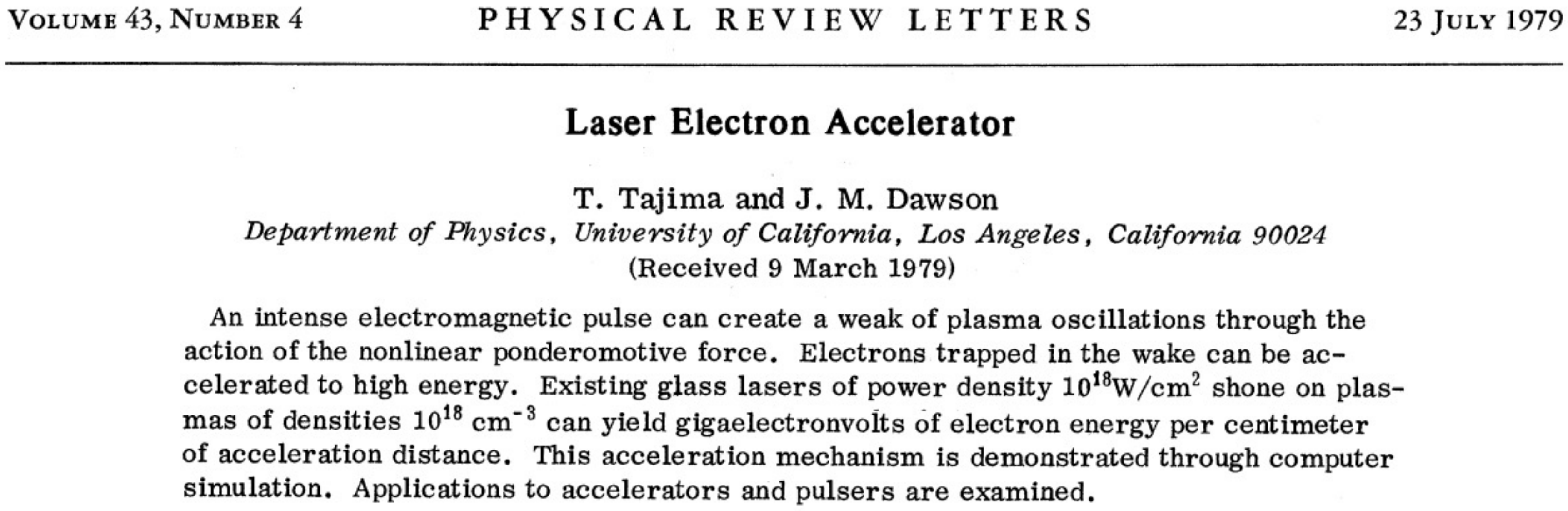
or

Laser pulse

$I = 10^{18}$ W/cm^2 and $c\tau < \lambda_p/2$

cold wave-breaking
Self-injection

Plasma based acceleration



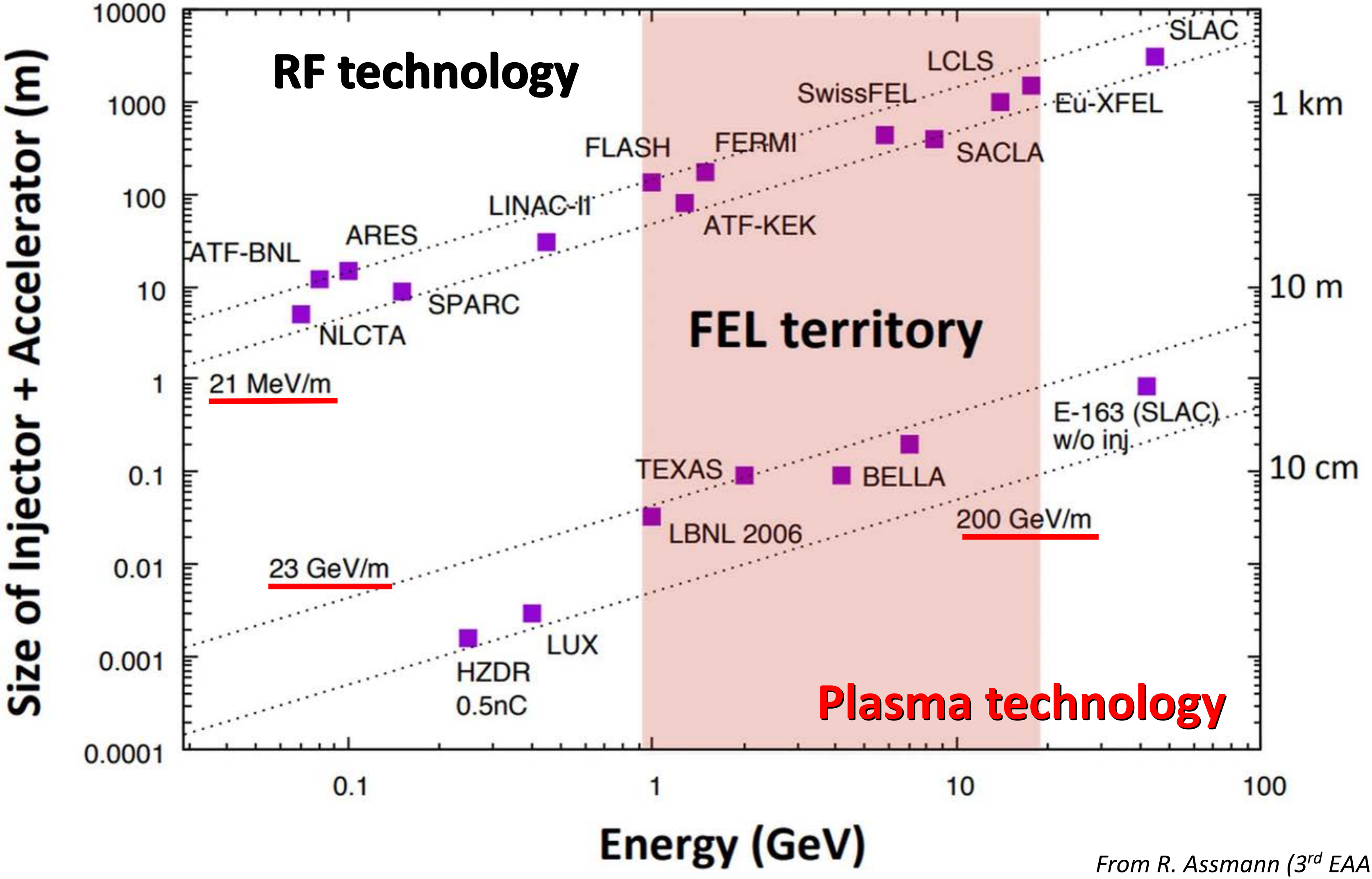
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

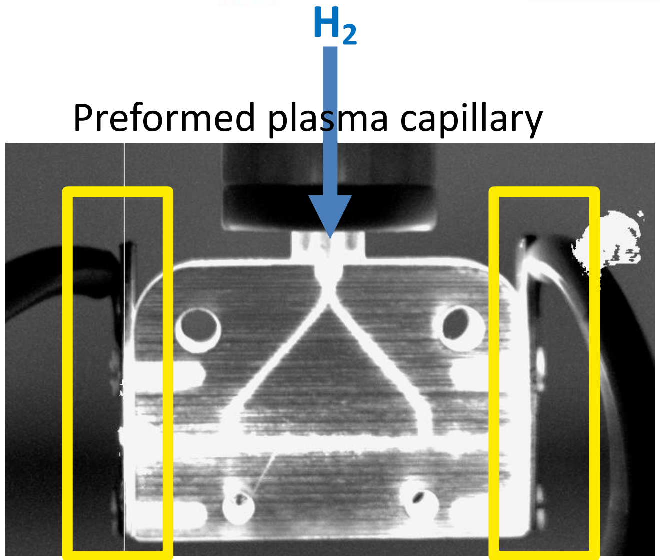
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

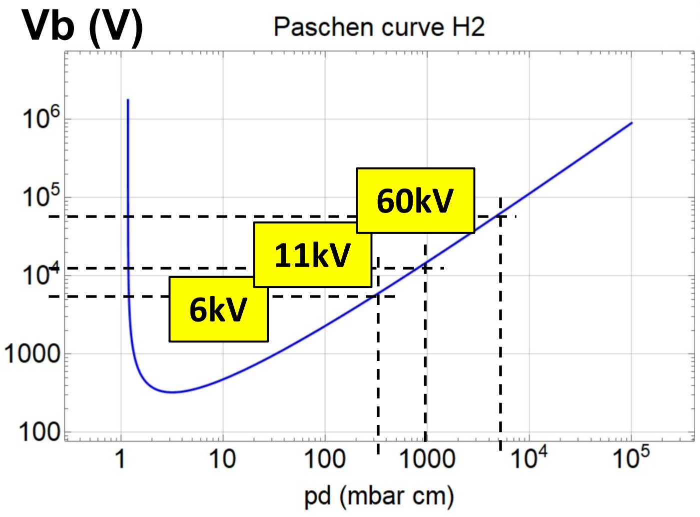
Standard vs Plasma accelerators

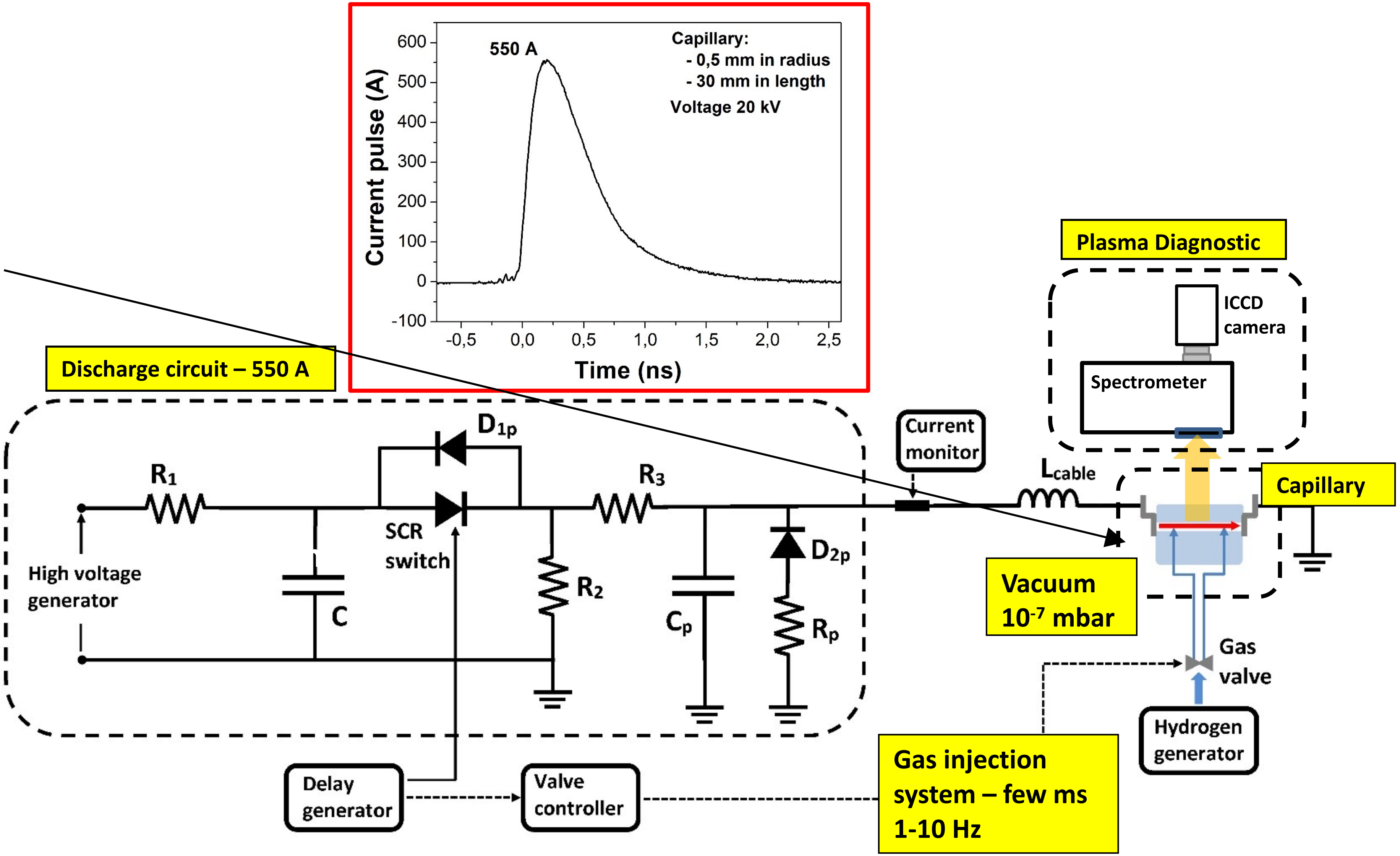


From R. Assmann (3rd EAAC Workshop, 2017)

Plasma source





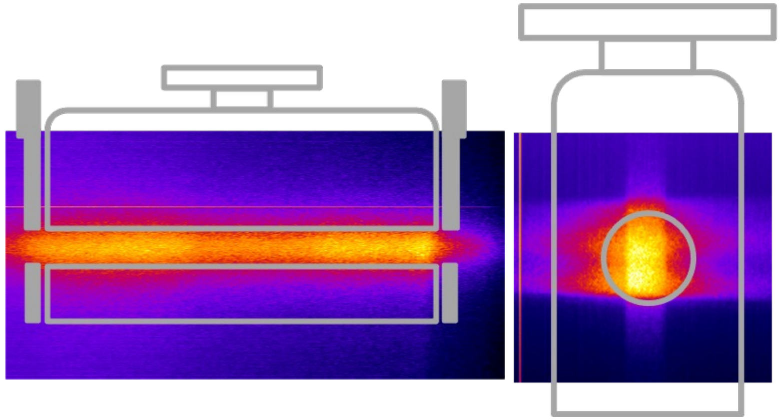


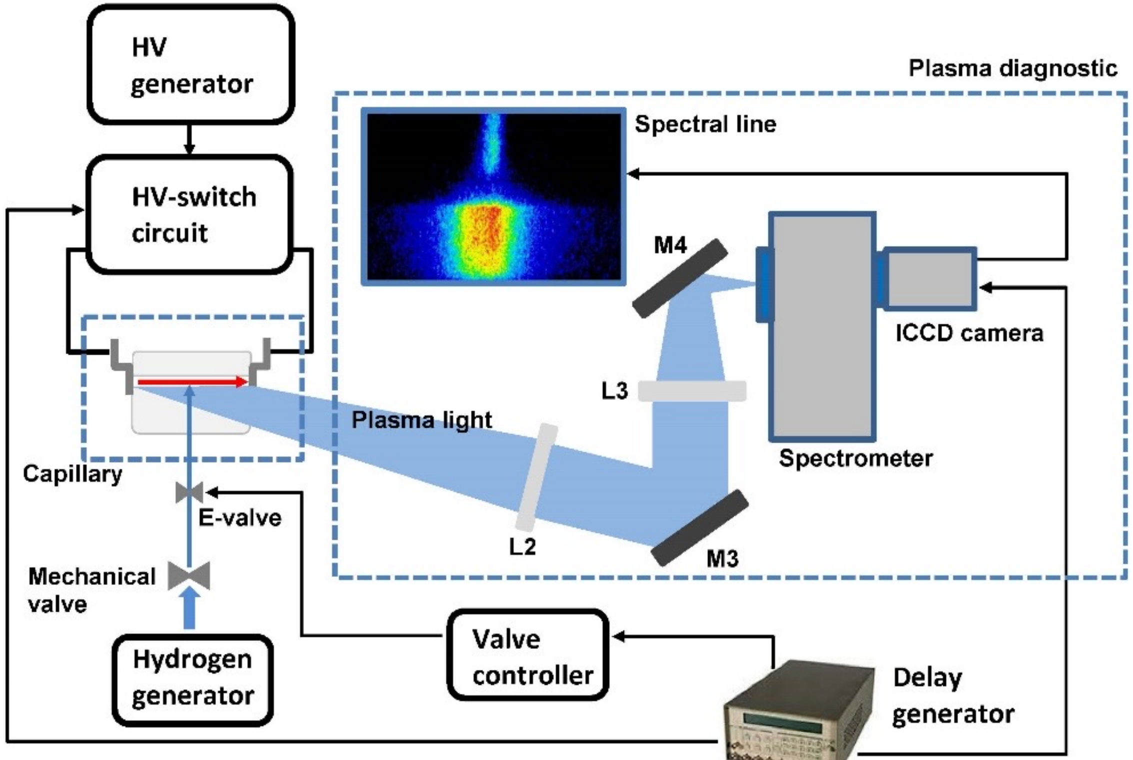
Plasma source

Stark Broadening:

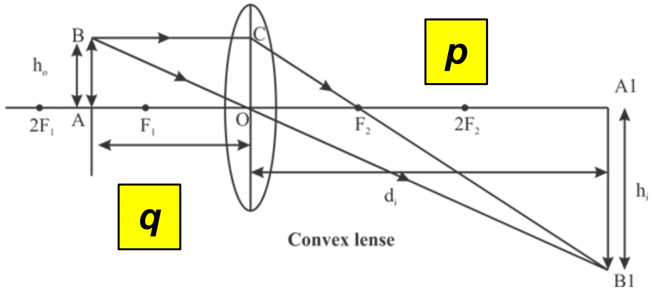
$$n_e = 8.022 \times 10^{12} \left(\frac{\Delta\lambda}{\alpha}\right)^{\frac{3}{2}} cm^{-3}$$

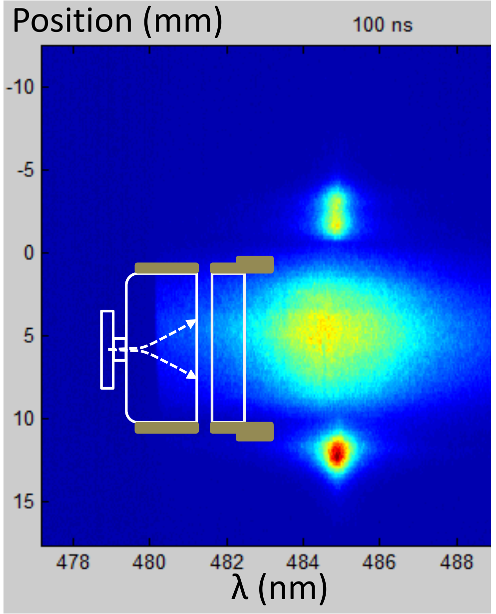
- $\Delta\lambda$ = FWHM $H_{\alpha\beta}$
- H_α = 656 nm, H_β = 486 nm
- α = const.





$1/f = 1/p + 1/q$



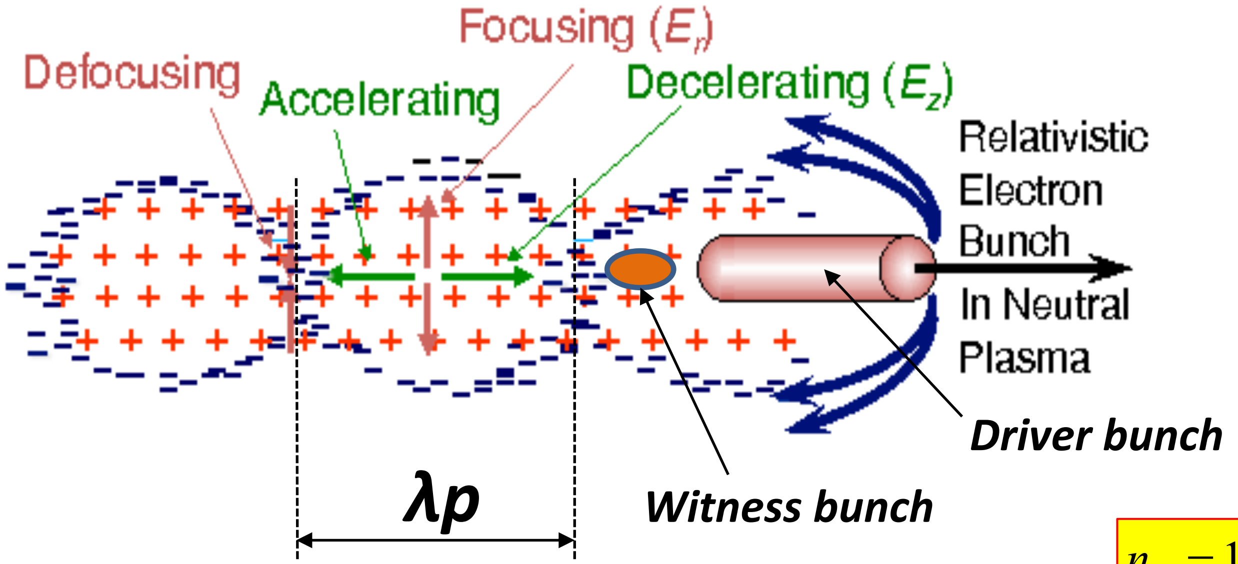


Beam driven plasma acceleration

$$\omega_p = \sqrt{\frac{n_p e^2}{m_e \varepsilon_0}}$$

$$\lambda_p = \frac{2\pi c}{\omega_p}$$

$$E_{cold,wb}[V/m] = \frac{m_e \omega_p c}{e} \approx 96\sqrt{n_0[cm^{-3}]}$$



$$\alpha = \frac{n_{bunch}}{n_p}$$

Linear regime	**(nb < np)**
Weakly NL regime	**(nb = np)**
Non-linear regime	**(nb>>np)**

$n_p = 10^{17}\ cm^{-3}$

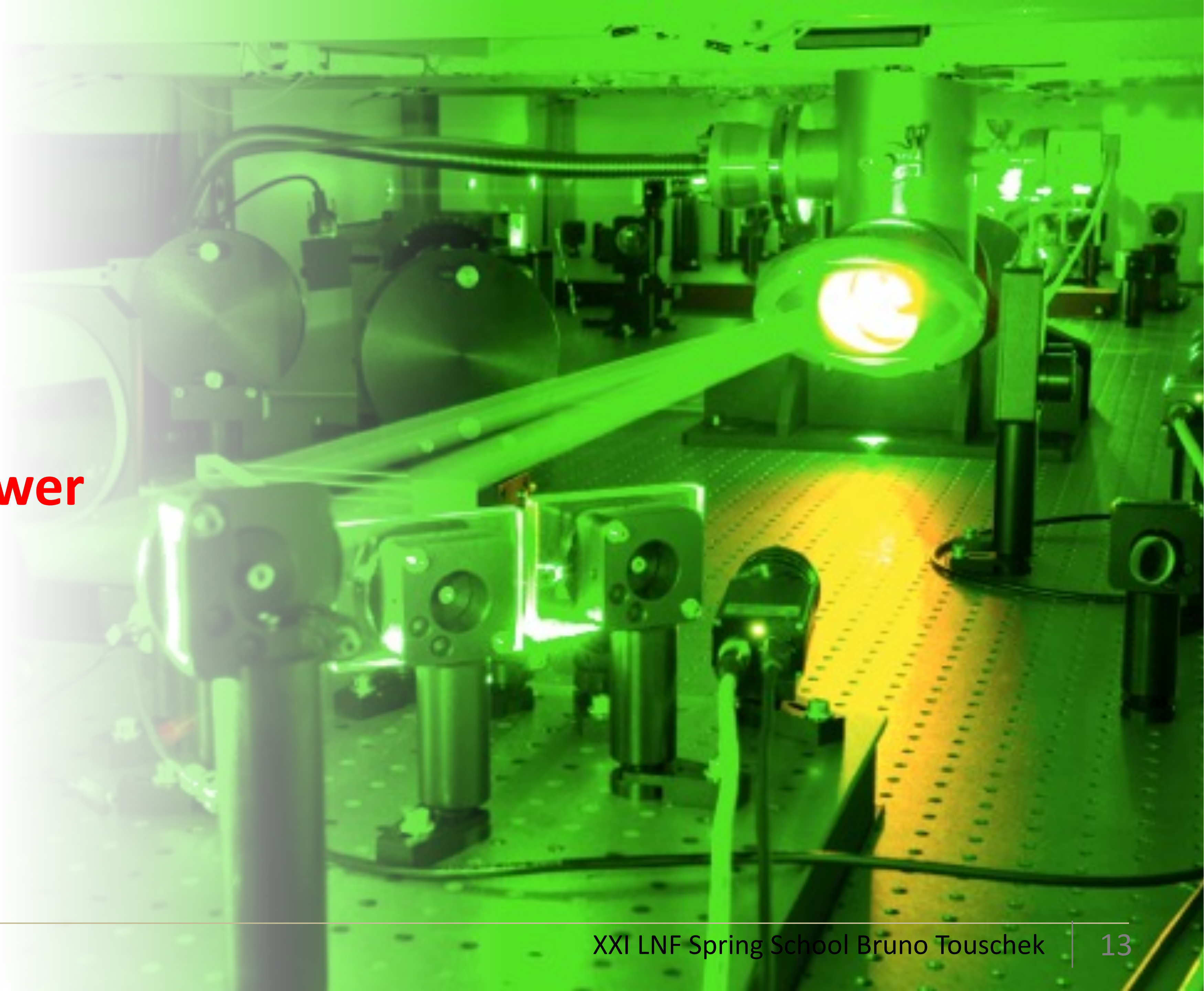
$\omega_p = 2 \times 10^{13}\ Hz$

$E_0 = 30\ \frac{GV}{m}$

$\lambda_p = 100\ \mu m\ (300\ fs)$

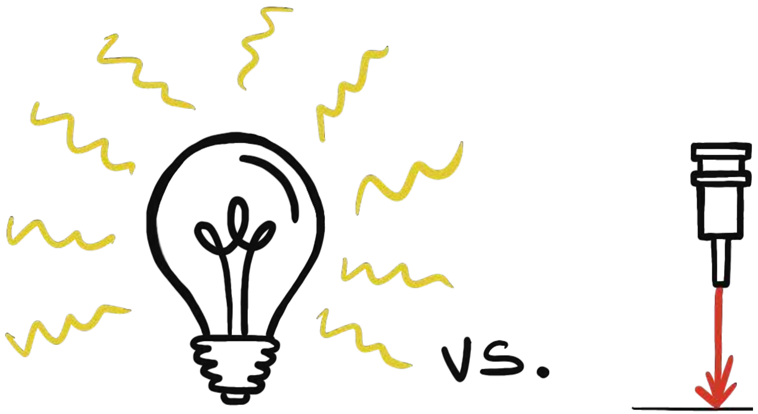
$\sigma_{zD} \approx 25\ \mu m\ (75\ fs)$

$\sigma_{xD} \approx 2\ \ \mu m$

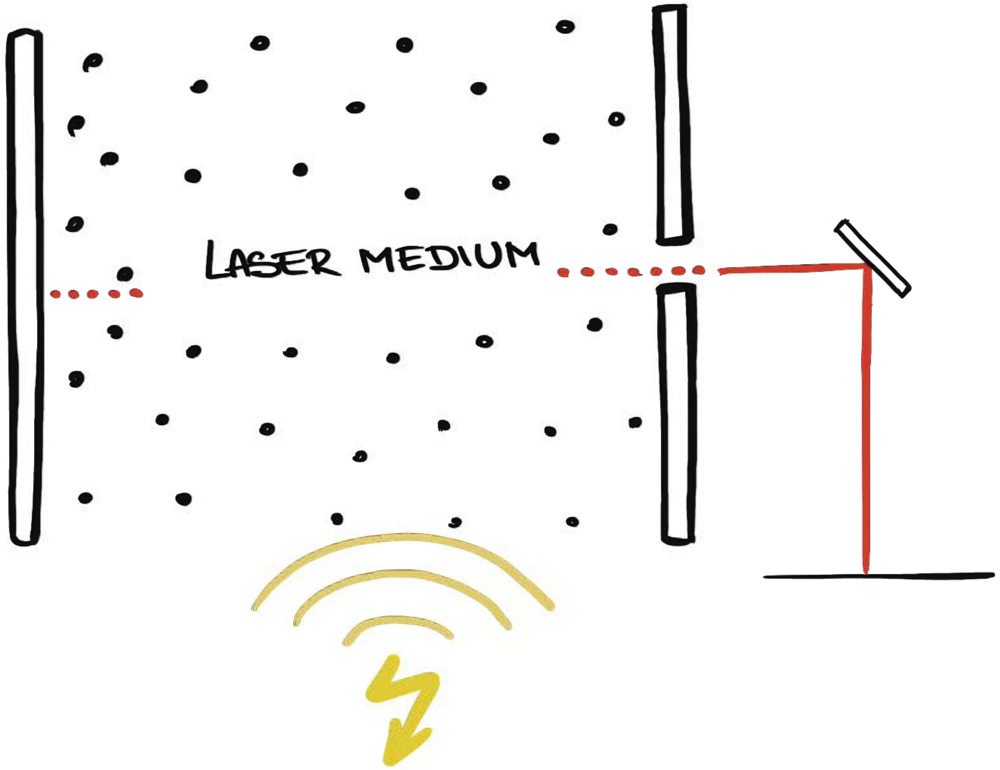


How can we get an **ultra-short high-power** pulse?

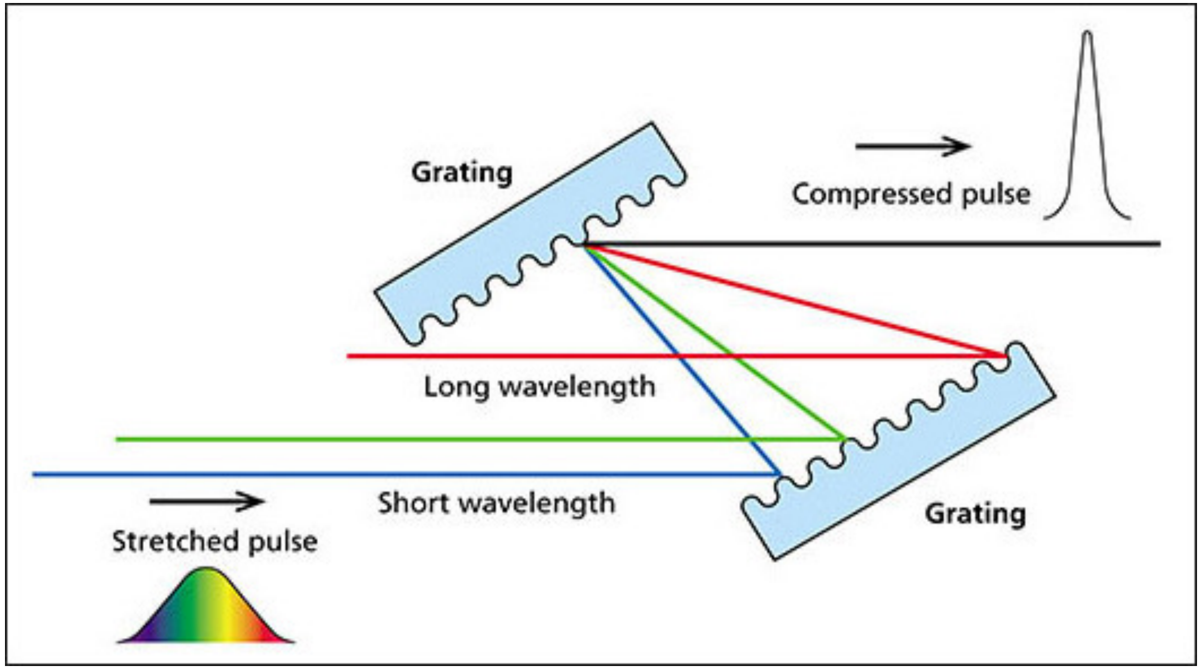
What is a laser?



LIGHT
AMPLIFICATION
BY **S**TIMULATED
EMISSION
OF **R**ADIATION



What is a high power laser?



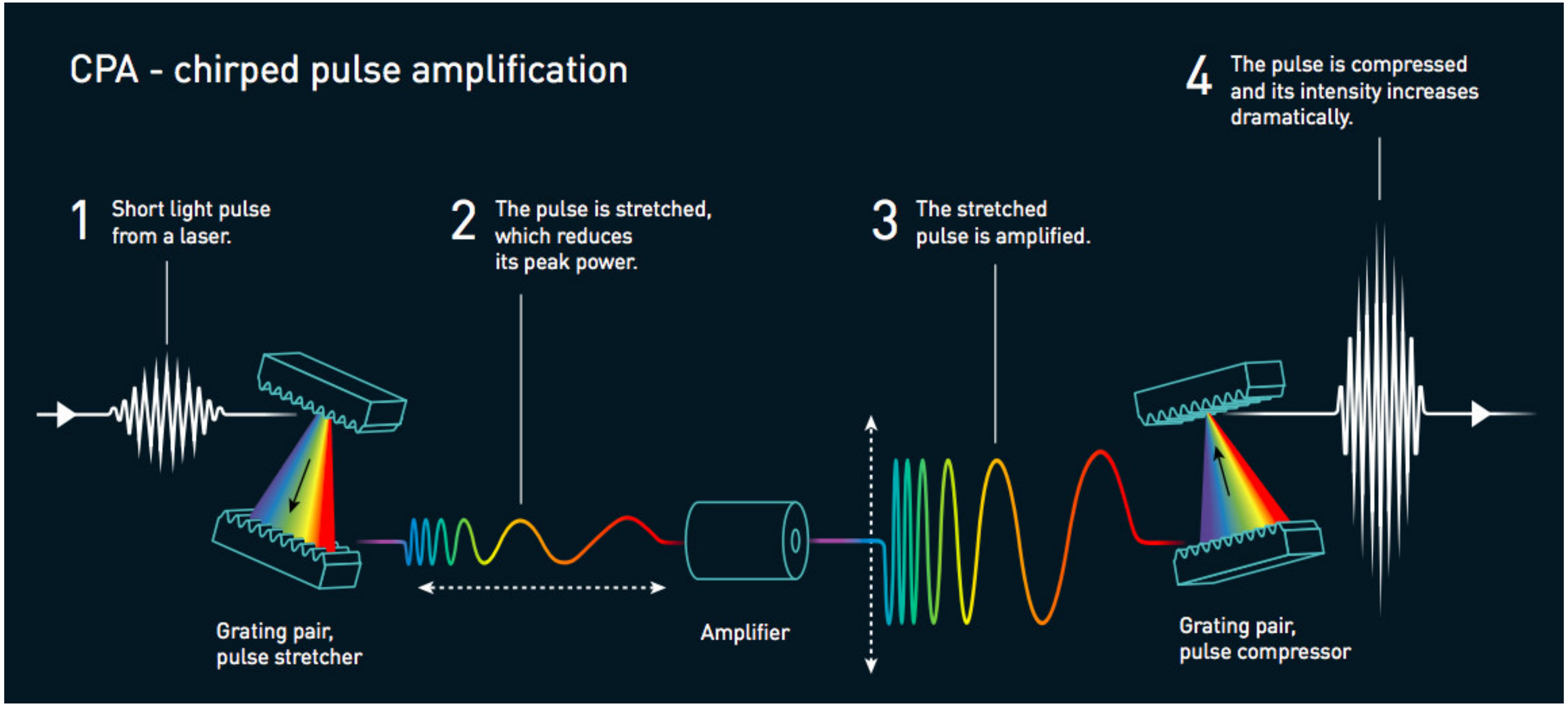
Grating compressor

Red light→ longer distance → closer to blue

Blue light → shorter distance → catches up

What is a high power laser?

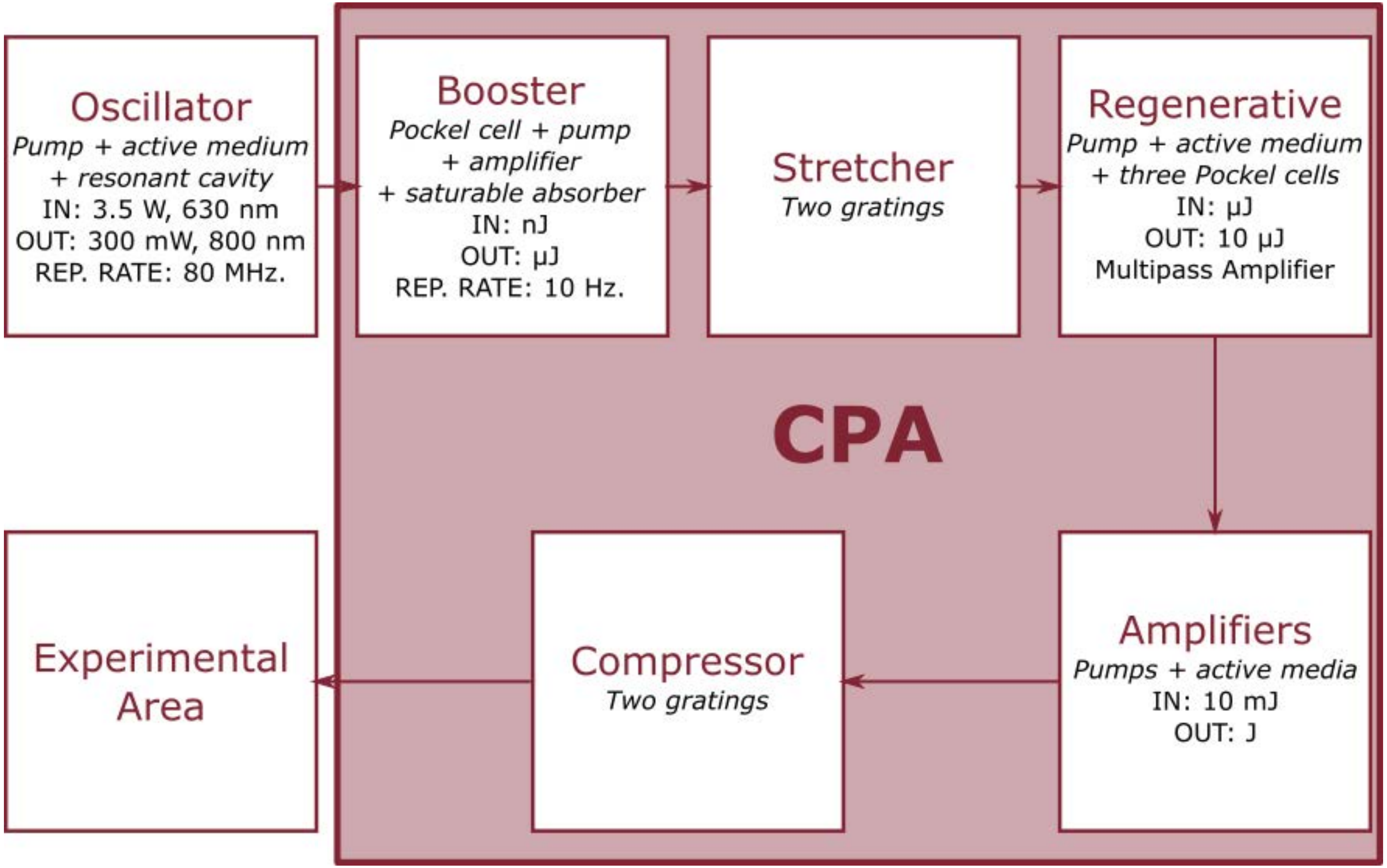
Chirped Pulse Amplification



Physics NOBEL PRIZE 2018

Short pulse → Stretch in time (chirp) → Amplify → Compress in time

What is a high power laser?



Oscillator
Pump + active medium + resonant cavity
IN: 3.5 W, 630 nm
OUT: 300 mW, 800 nm
REP. RATE: 80 MHz.

Booster
Pockel cell + pump + amplifier + saturable absorber
IN: nJ
OUT: μJ
REP. RATE: 10 Hz.

Stretcher
Two gratings

Regenerative
Pump + active medium + three Pockel cells
IN: μJ
OUT: 10 μJ
Multipass Amplifier

CPA

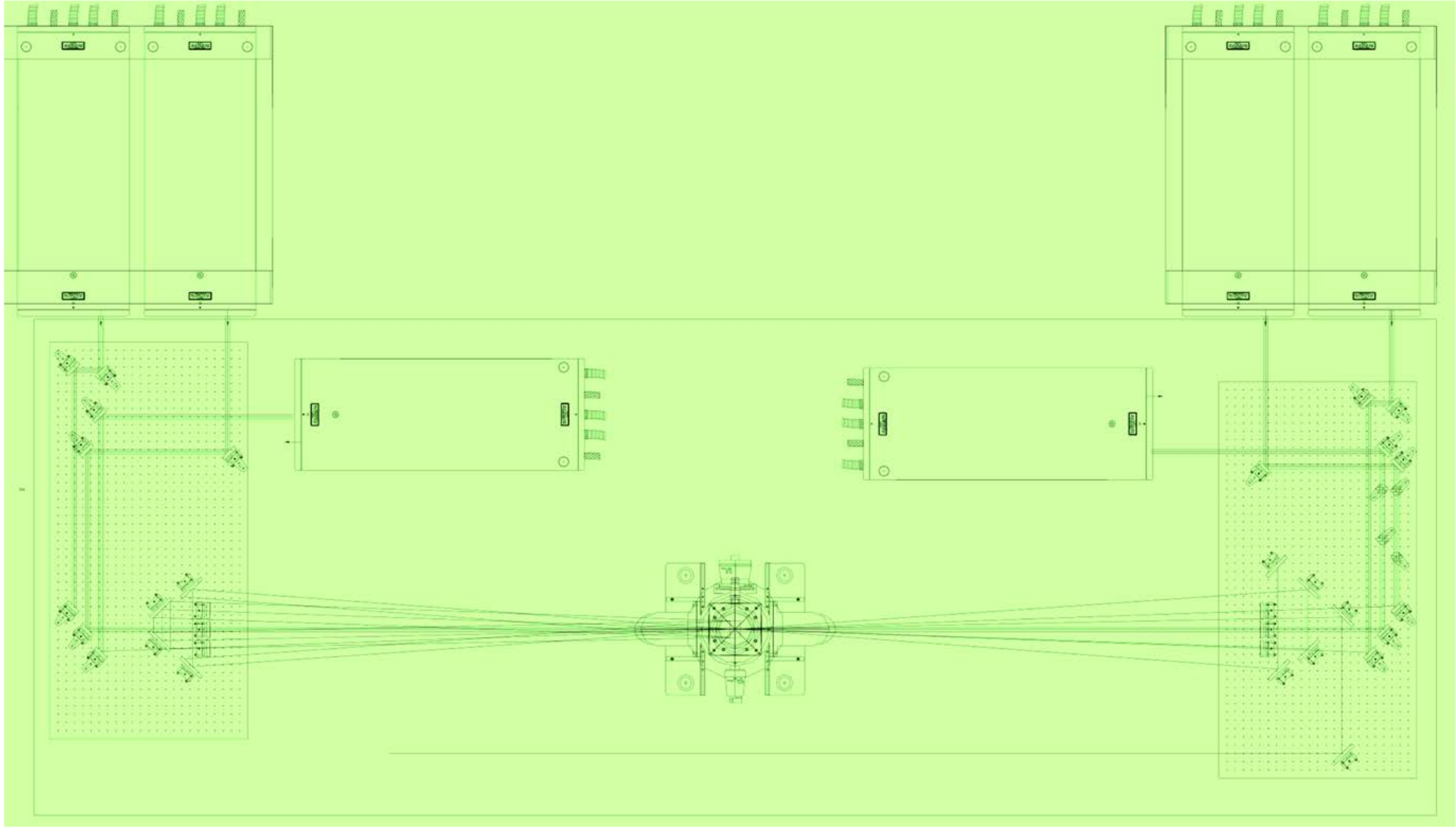
Amplifiers
Pumps + active media
IN: 10 mJ
OUT: J

Compressor
Two gratings

Experimental Area

What is a high power laser?

example of a Multipass Amplifier



Laser plasma acceleration

Normalized laser intensity $a_0 = eE_0/(m_e\omega_p c)$

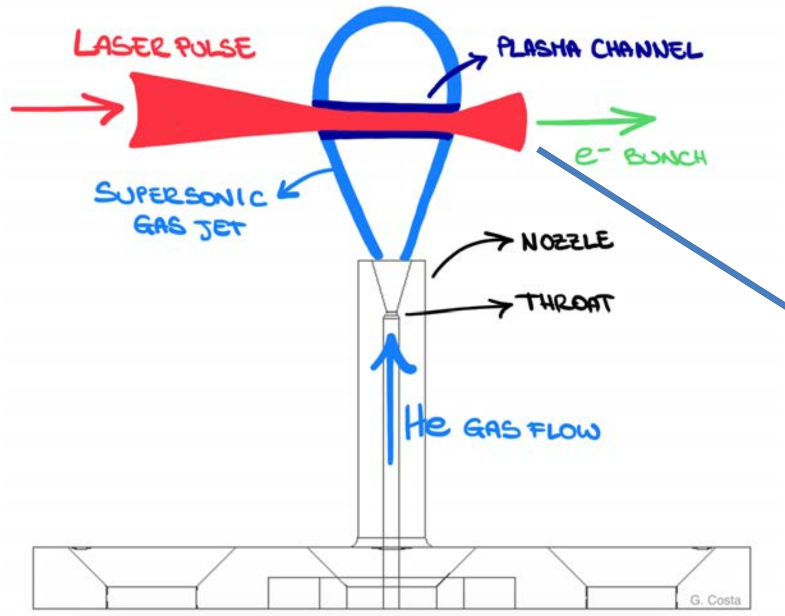
Electron motion in a laser field oscillation in the direction of the electric field

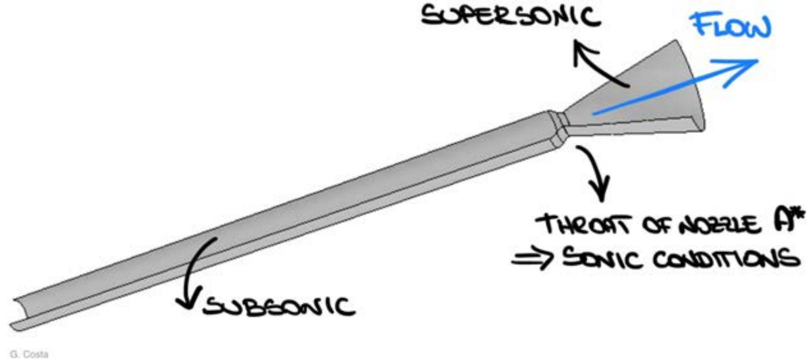
velocity $\beta = -a_0 \sin(\omega_p t)$

- $a_0 < 1$ linear regime ⇒ no wavebreaking
- $a_0 \approx 1$ non-linear regime ⇒ $v_e \approx c$ ⇒ self-injection
- $a_0 \gg 1$ strongly non-linear regime ⇒ plasma bubble can focus and accelerate electrons to high energies

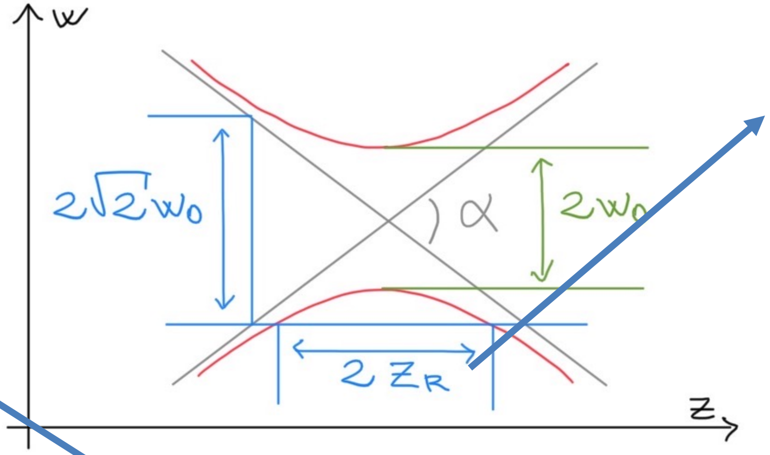
Laser plasma acceleration

Gas jet flow within a **supersonic** nozzle





Along the propagation direction of a laser beam that is focused



Rayleigh length z_R

distance from the laser waist w_0 to the point where the cross-sectional area is doubled

Laser with intensity transverse gradient

↓

plasma refractive index acts as a convex lens

↓

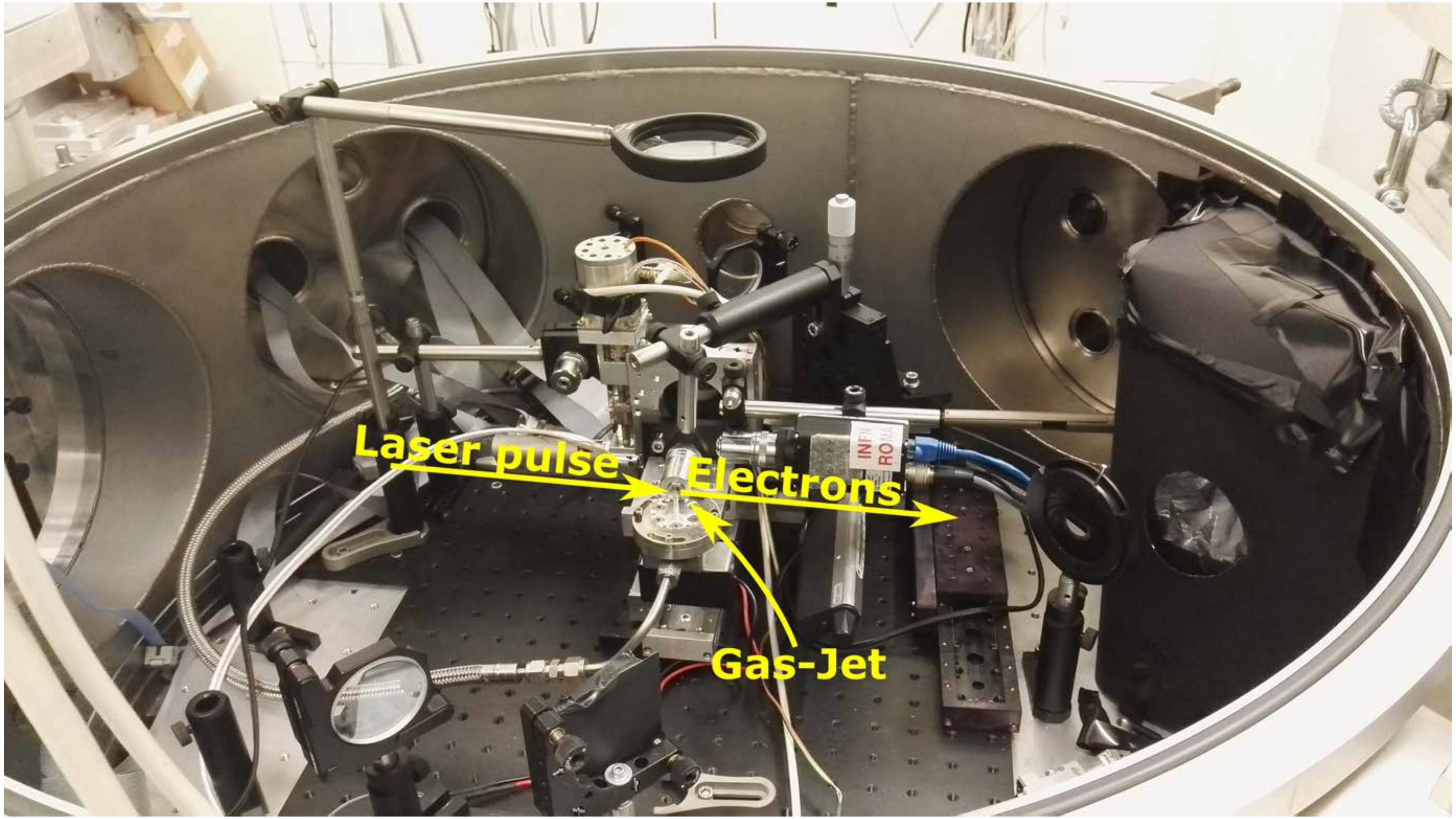
Laser **self-focusing** in plasma

↓

increasing the pulse confinement length

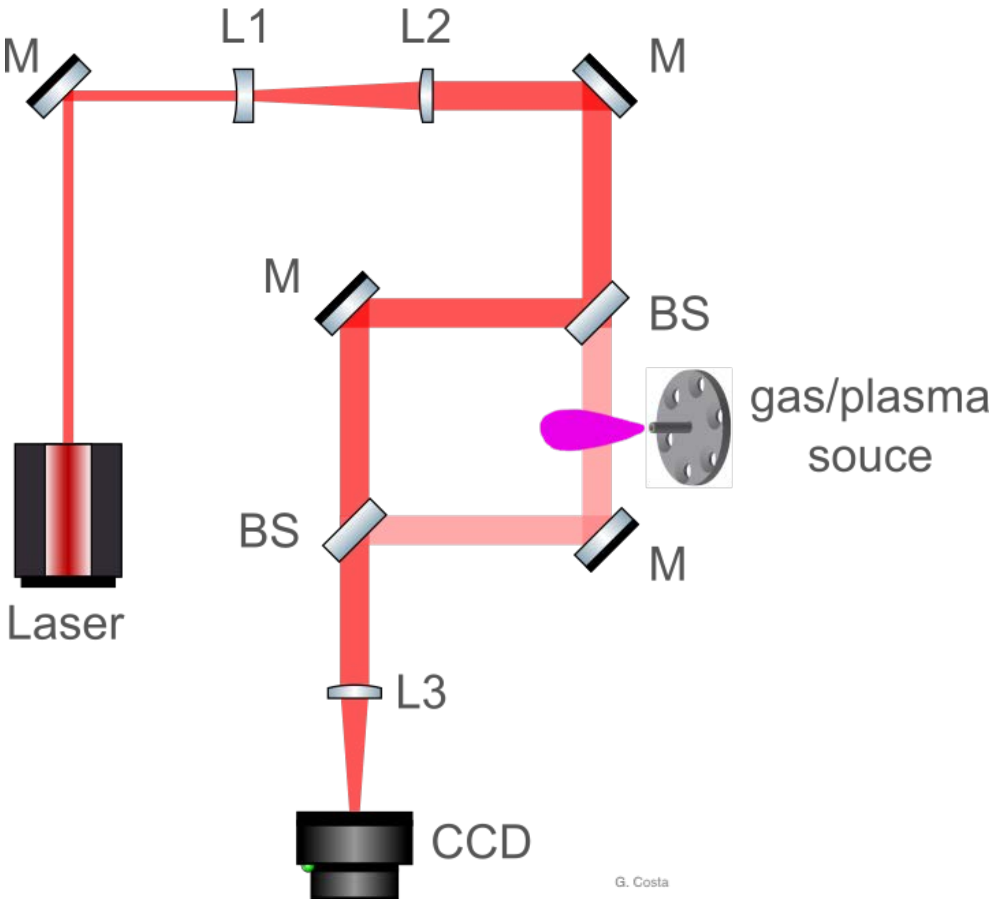
Laser plasma acceleration

Laser interaction chamber



Laser plasma acceleration

Plasma density interferometric measurements



Mach Zehnder interferometer:

Path difference between probe and reference laser

⇩

interference fringes

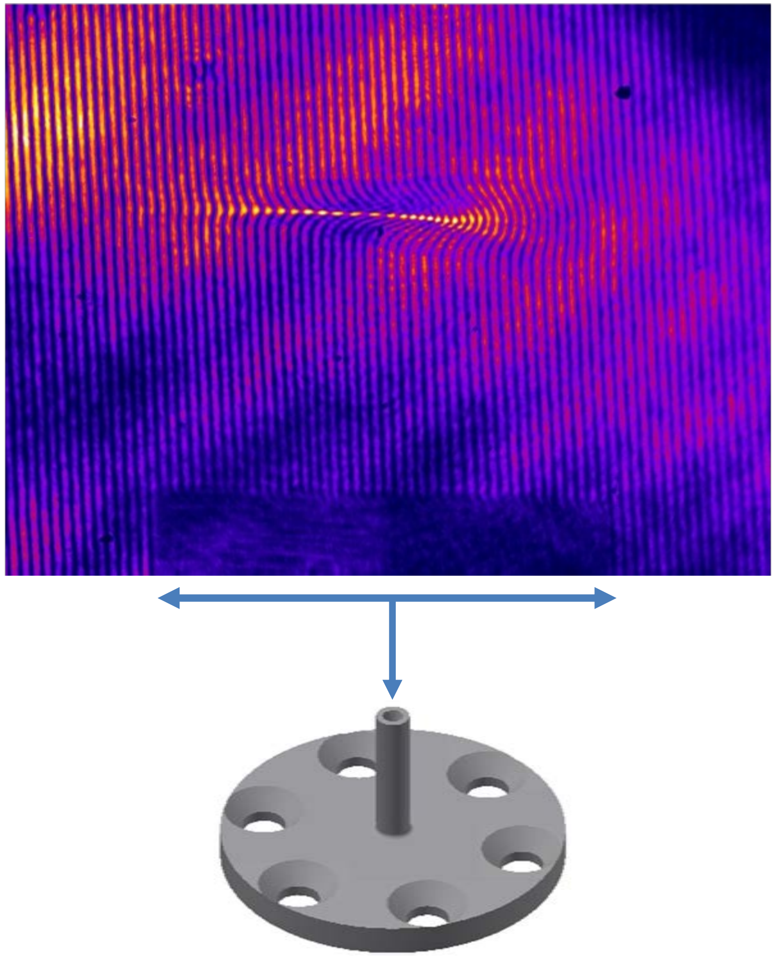
Plasma refractive index

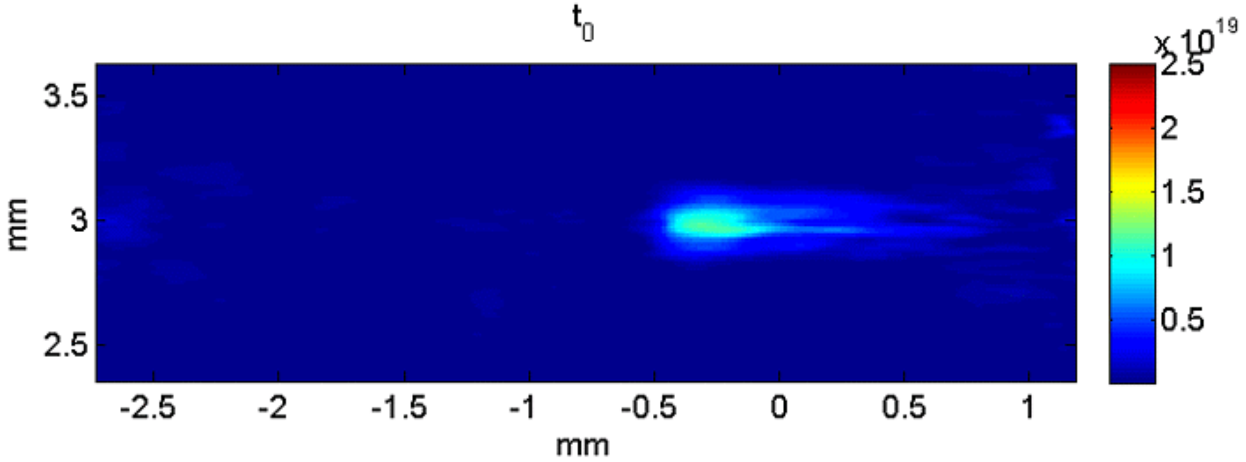
$$\eta = \left(1 - \frac{n_e}{n_c}\right)^{\frac{1}{2}}$$

- n_e = e^- plasma density
- n_c = critical e^- density

Laser plasma acceleration

High power pulse: few J – 25 fs – 20 µm @focus → Laser intensity 10^{19} W/cm²





typical densities ~ 10^{19} cm^{-3} → self-injection!

Quality of produced and accelerated electron bunches:

- divergence
- energy spread -> emittance

Limitations of this scheme:

- diffraction
- pump depletion
- dephasing

Laser plasma acceleration

e$^-$ energy gain ∝ Acceleration field × Acceleration length $\longrightarrow \pi Z_R$

$\Downarrow$

Rayleigh length
=> Diffraction $Z_R = \pi \dfrac{r_i^2}{\lambda_0}$

optical guiding in plasma

ex: for $r_i = 60\ \mu m$

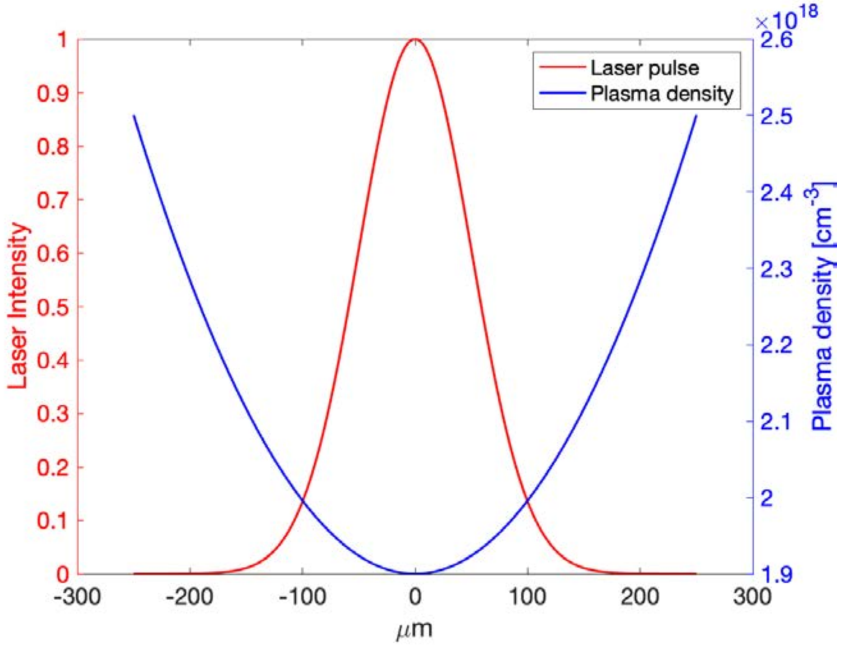
- $n_0 \sim 2.5 \times 10^{18}\ cm^{-3}$
- $n_d \sim 6 \times 10^{17}\ cm^{-3}$

- gaussian intensity laser pulse $I(r) = I_0 e^{-\left(\frac{2r^2}{r_i^2}\right)}$
- parabolic density distribution plasma channel

$$n(r) = n_0 + \left(\frac{r}{r_m}\right)^2 n_d \quad \text{for} \quad r \leq r_m$$

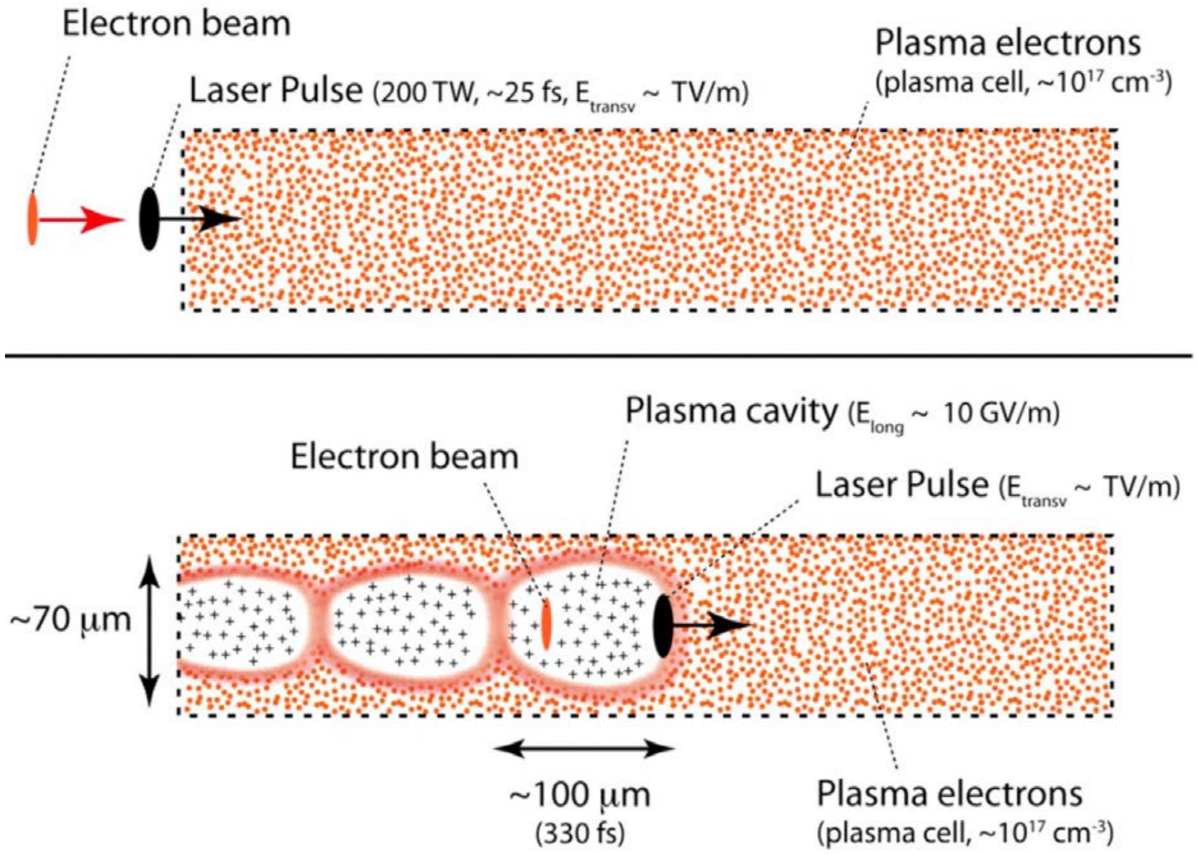
- if waist radius $r_i = r_m = (\pi\, r_e n_d)^{-\frac{1}{2}}$

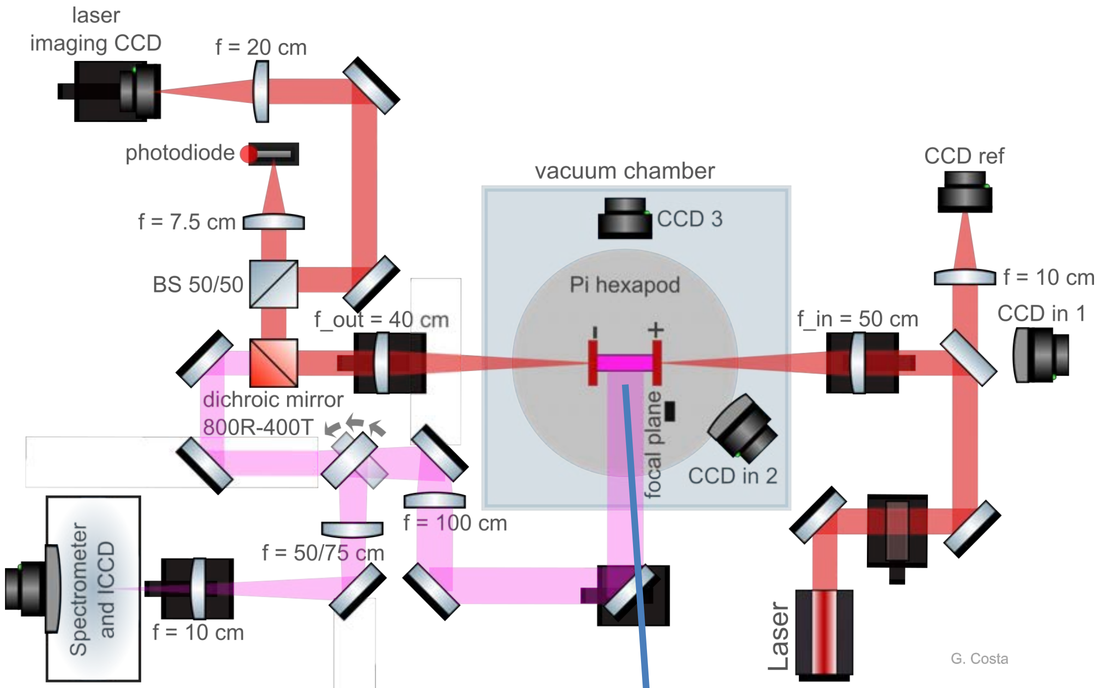
  - λ_0 = laser wavelength
  - r_m = matching radius
  - r_e = e$^-$ radius
  - n_0 = plasma density on the axis
  - n_d = density difference axis-walls

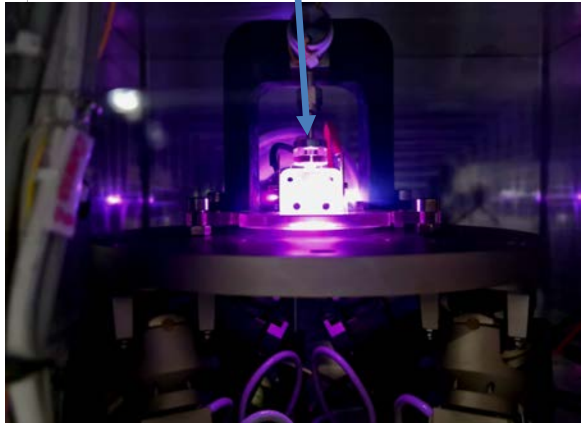


Laser plasma acceleration

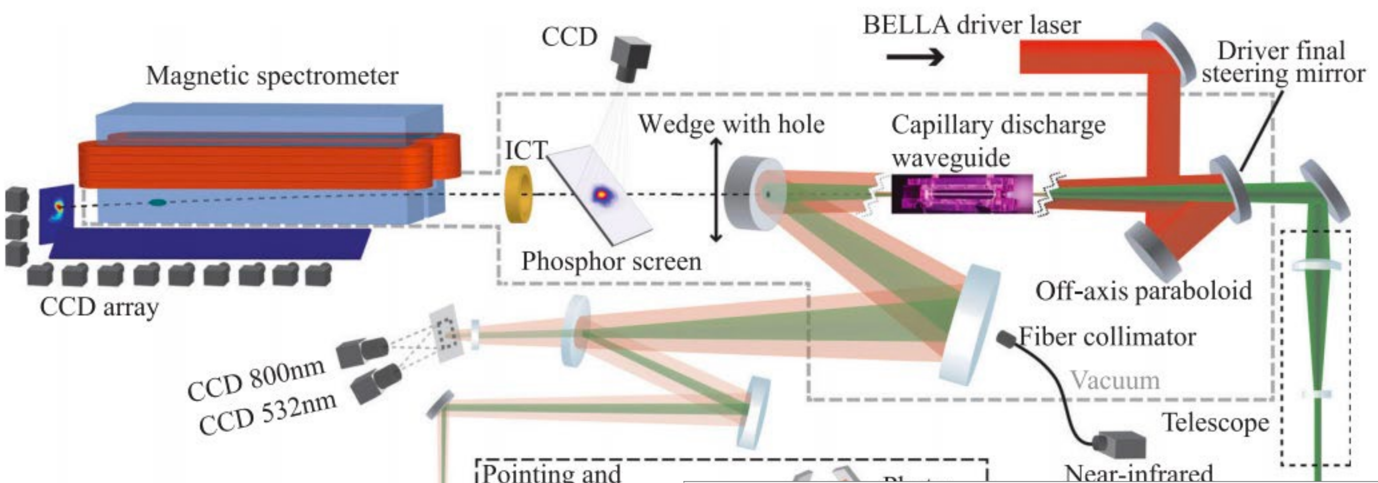
Laser external injection scheme



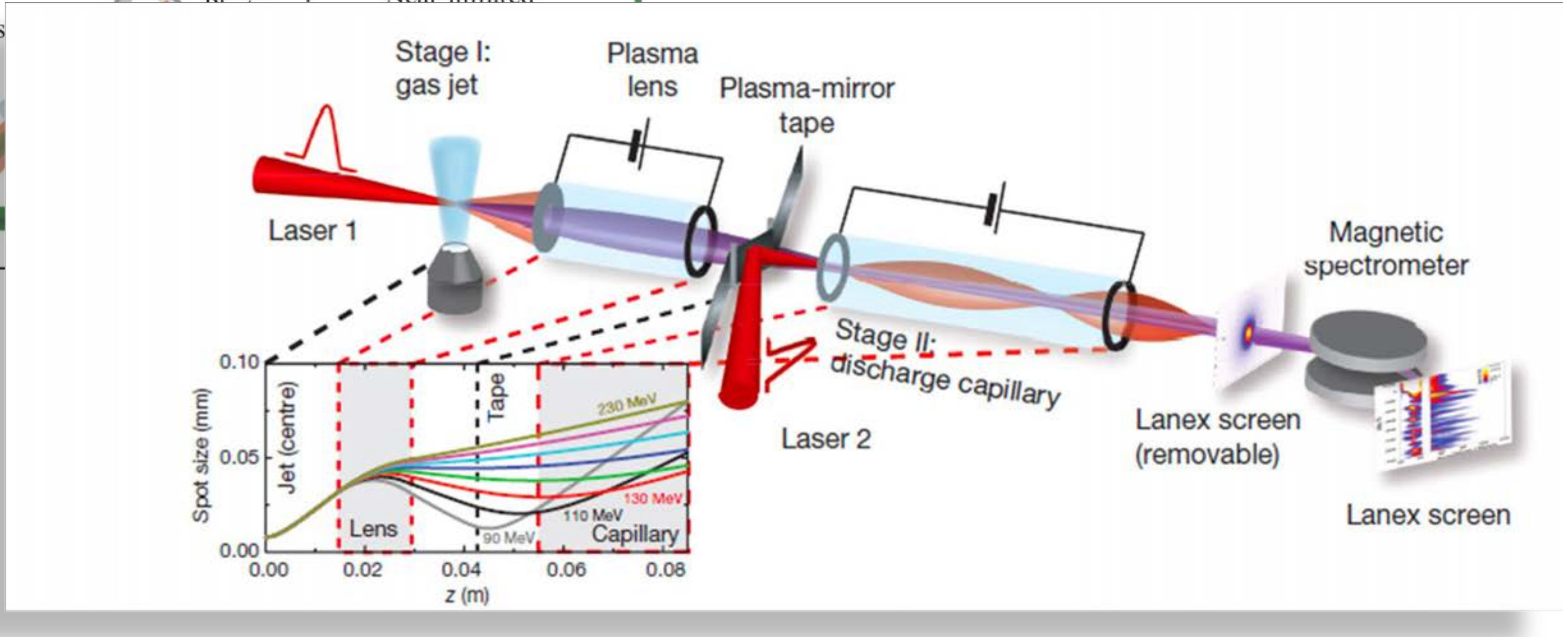




Laser plasma acceleration



7.8 GeV in 20 cm
Gonsalves, A. J., et al. "Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide."*Physical review letters*122.8 (2019): 084801.

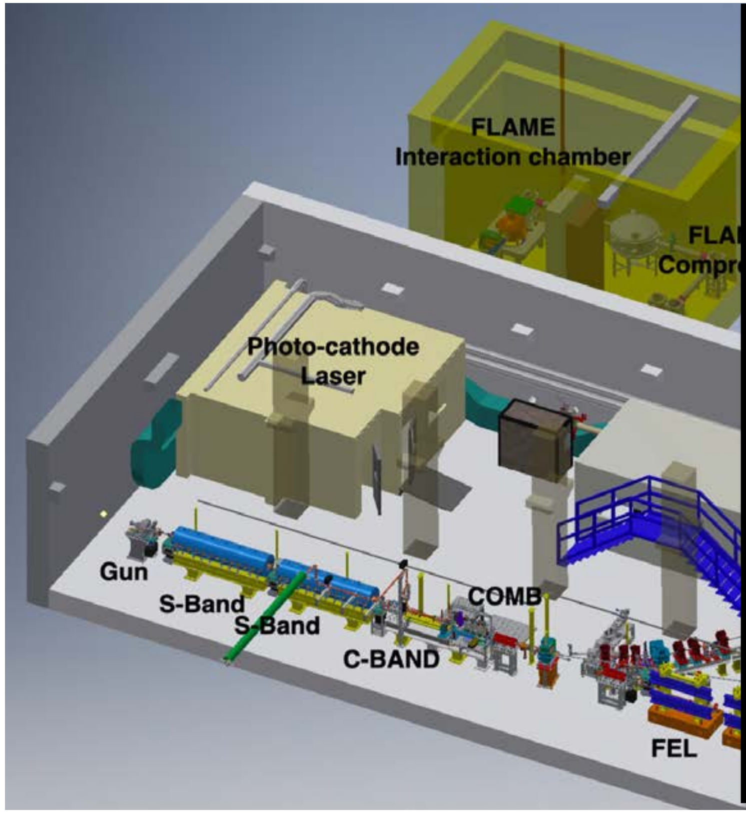


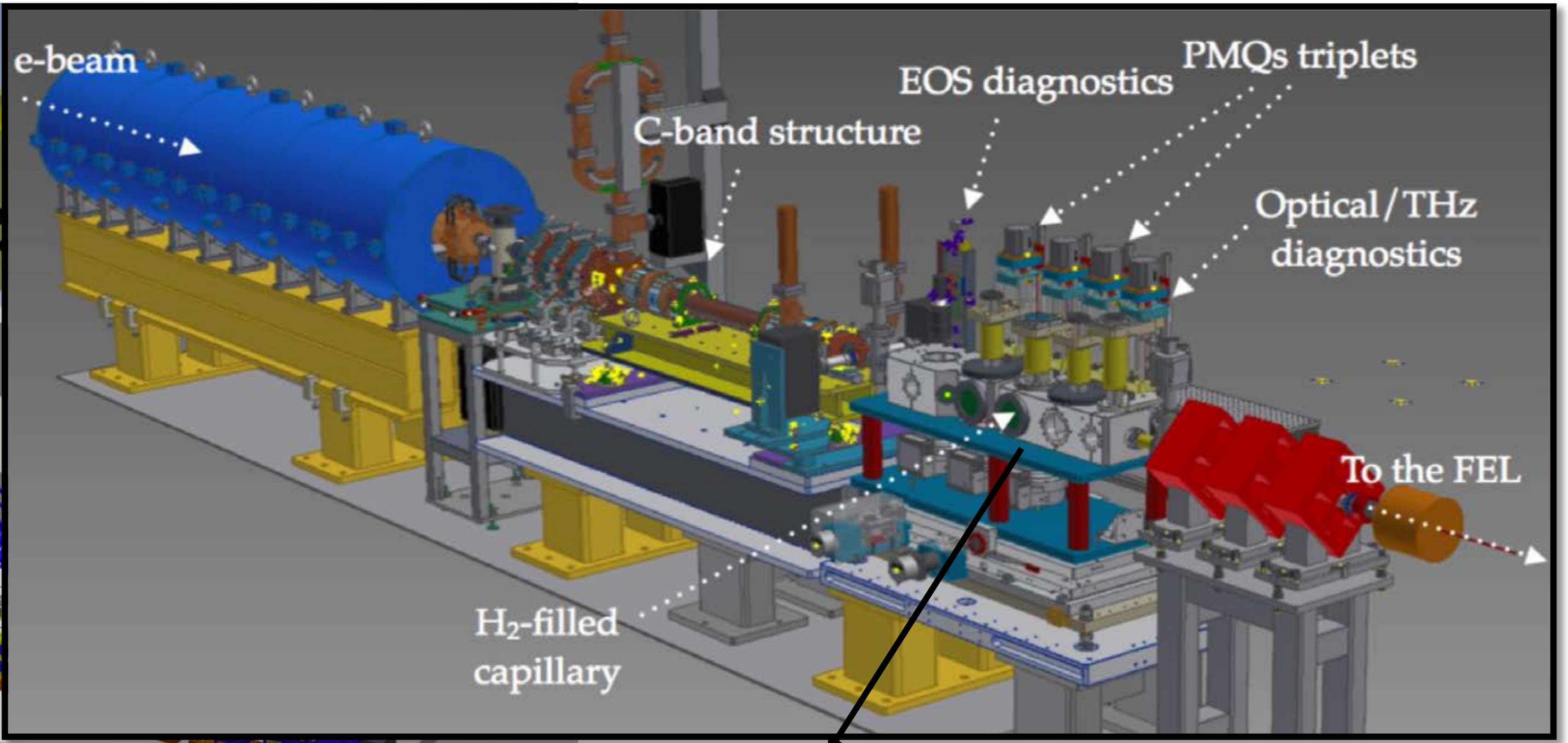
Staging
*Nature*530.7589 (2016): 190-193.

Recap different schemes of plasma acceleration

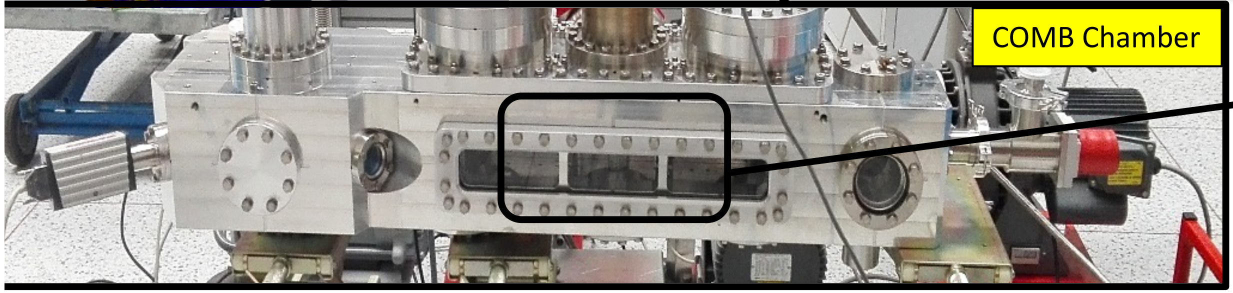
- Laser only: *easiest* to implement, requires to tune the laser and the target, **but** difficult control over the whole process
- Electrons only: easier implementation than external injection, no need for independent synchronization system and driver guiding, **but** it depends heavily on the ability to properly tailor the driver(s) and witness phase spaces
- Laser + electrons: in principle has the best potentialities in term of e-beam brightness and energy, **but** it is the hardest to implement for laser guiding and synchronization issues

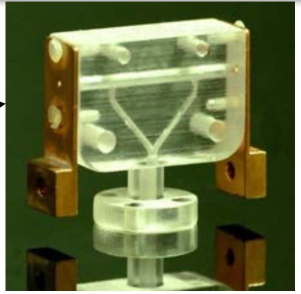
Plasma acceleration @LNF: SPARC_LAB test facility





Energy	$(30-180)\ MeV$
Energy Spread	$\simeq 0.01\%-1\%$
Charge	$10\ pC-1\ nC$
Bunch length range (FWHM)	$50\ fs-10\ ps$
Normalised Emittance	$(1-3)\ mm\ mrad$
Max Rep. Rate	$10\ Hz$





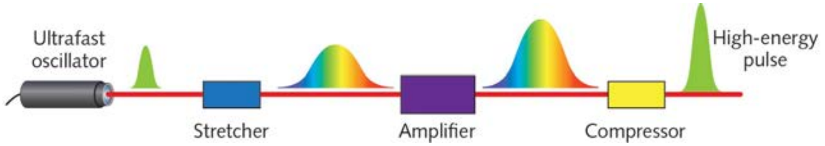
Plasma acceleration @LNF: SPARC_LAB test facility

FLAME Laser

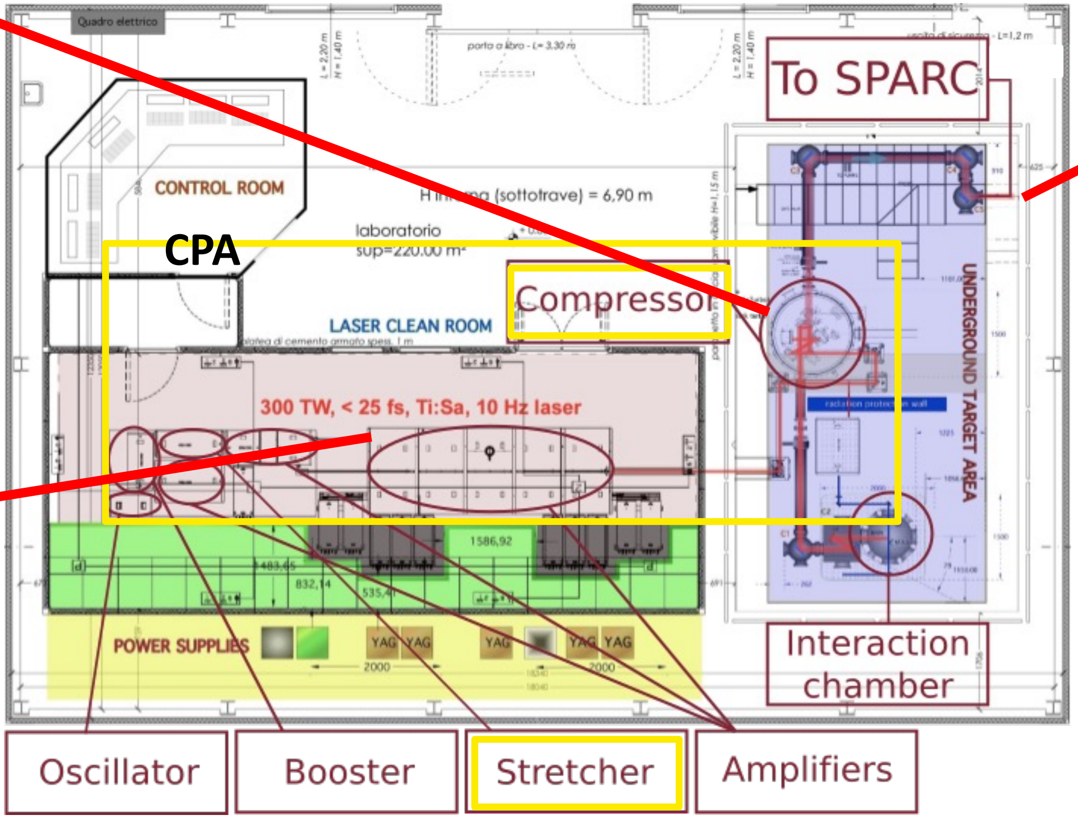
MAIN PULSE	
Peak power	250 TW
Energy on target	7 J
Rep. rate	10 Hz
Temporal length	25 fs
FW 1/e^2 @ focus	20 µm
Intensity	10^{19} W/cm^2
Contrast-ratio	10^{10}

PROBE PULSE	
Energy on target	10 mJ
Temporal length	50 fs
FW 1/e^2 @ focus	120 µm
Intensity	10^{16} W/cm^2

High-power Ti:Sa based laser, ultra-short CPA based pulse

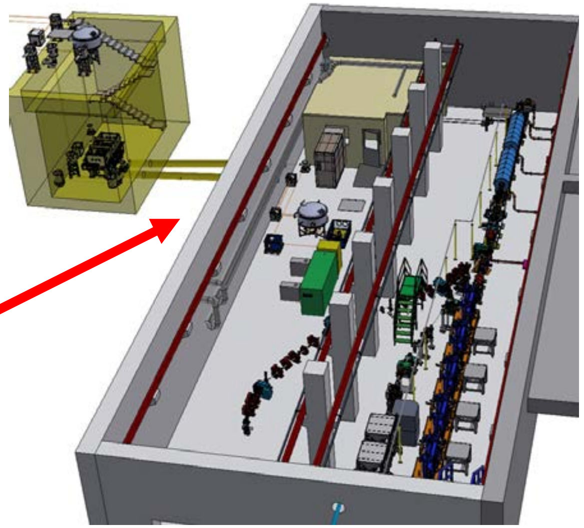


Strickland and Mourou 1985
Nobel Prize in Physics 2018

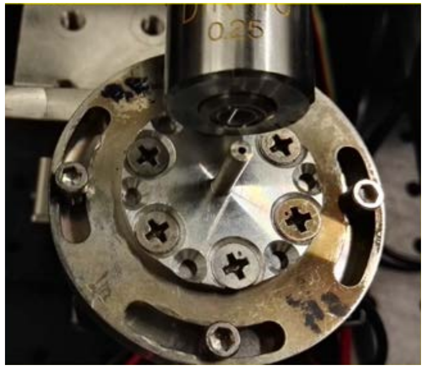


80 MHz, 220 mW

FG Bisesto, et al., doi:10.1016/j.nima.2018.02.027

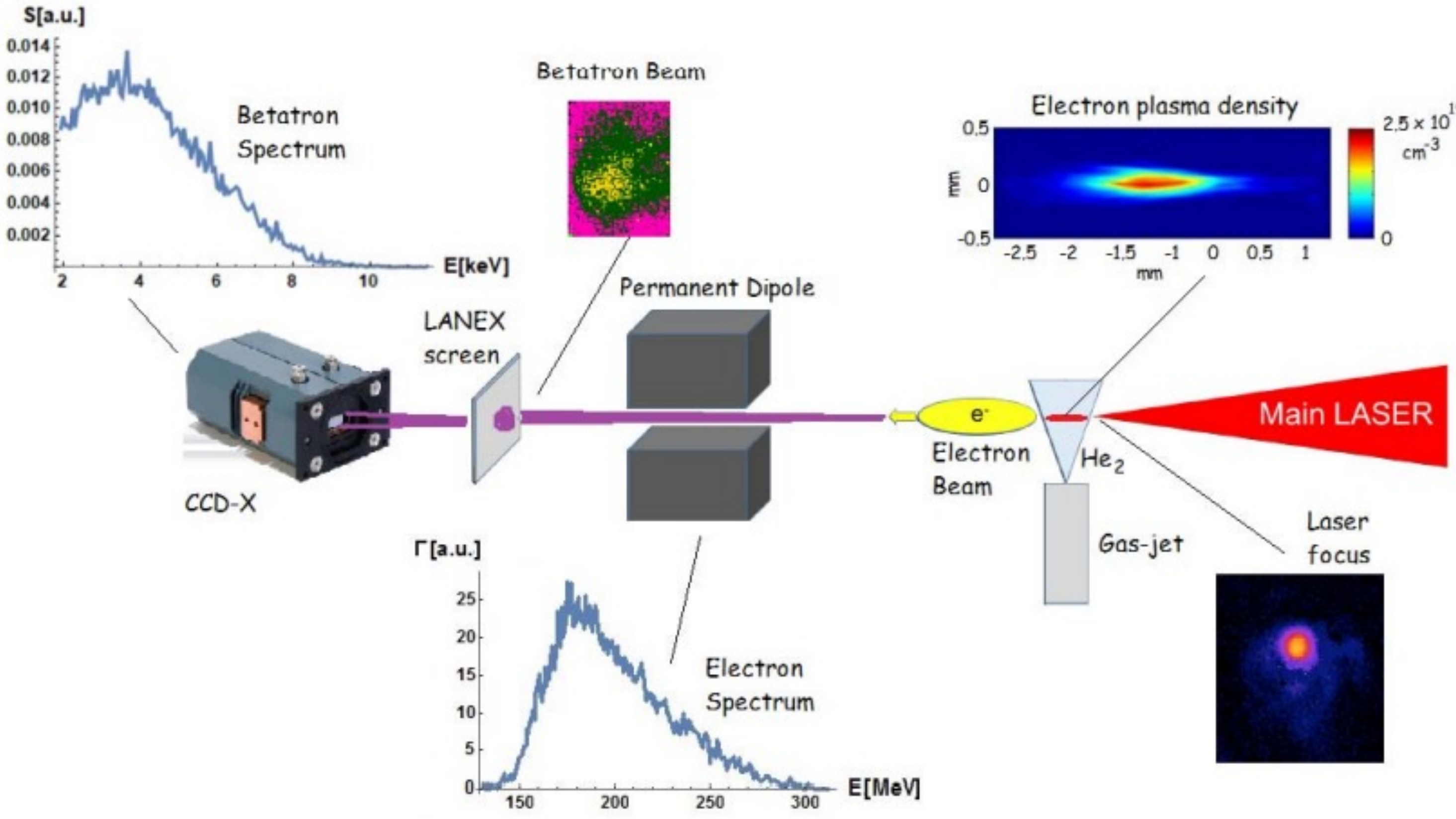


supersonic nozzle for self-injection experiments and X-rays radiation emission

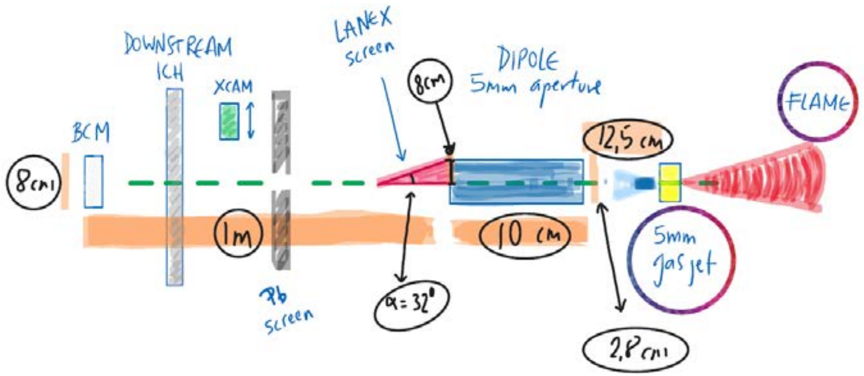


Plasma acceleration @LNF: SPARC_LAB test facility

FLAME experimental setup per plasma acceleration

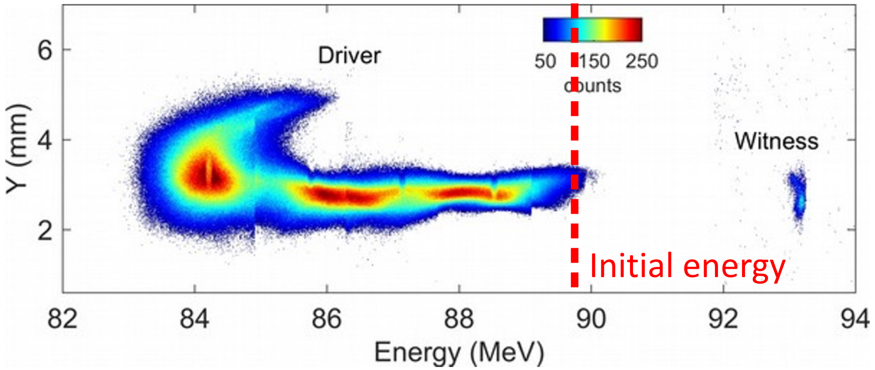


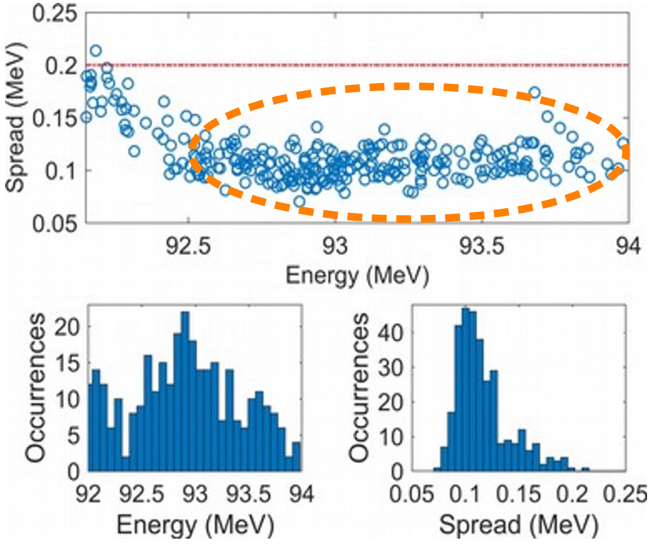
- Laser energy *6 J*
- Laser temporal length *30 fs FWHM*
- Laser focal spot *18-20* μm *FWHM*



Courtesy M Galletti

Plasma acceleration @LNF: SPARC_LAB test facility





Plasma acceleration results @SPARC_LAB

- Two-bunches configuration produced directly at the cathode with laser-comb technique
- 200 pC driver (charge increased up to 350 pC) followed by witness bunch (20 pC)
- 4 MeV acceleration in 3 cm plasma with 200 pC driver
- Ultra-short durations (200 fs + 30 fs) obtained with velocity-bunching technique
- 133 MV/m accelerating gradient
- 2 x 10^{15} cm^{-3} plasma density
- Demonstration of projected energy spread compensation: spread from 0.2% to 0.12%

nature physics

LETTERS

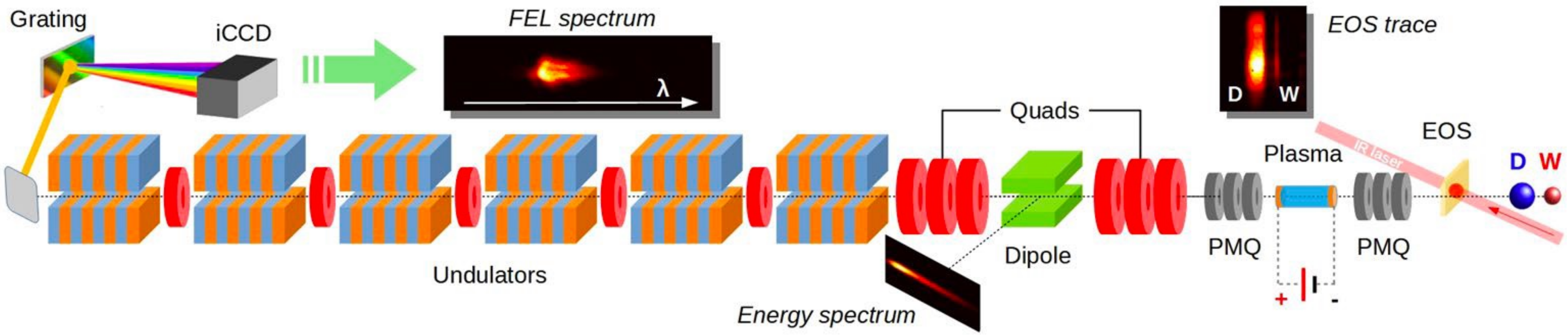
https://doi.org/10.1038/s41567-020-01116-9

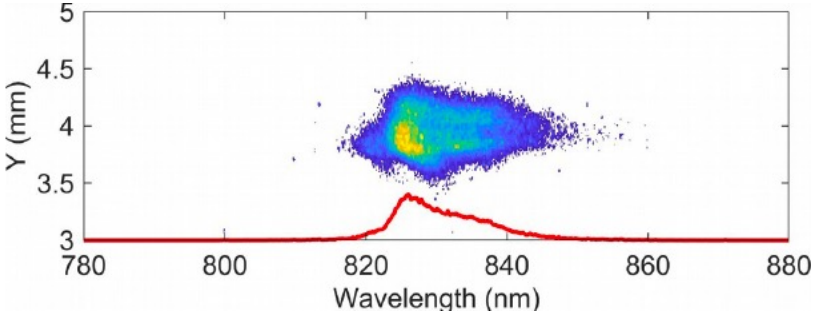
Check for updates

Energy spread minimization in a beam-driven plasma wakefield accelerator

R. Pompili[1]✉, D. Alesini[1], M. P. Anania[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], F. G. Bisesto[1], M. Cesarini[1,2], E. Chiadroni[1], A. Cianchi[3], G. Costa[1], M. Croia[1], A. Del Dotto[1], D. Di Giovenale[1], M. Diomede[1], F. Dipace[1], M. Ferrario[1], A. Giribono[1], V. Lollo[1], L. Magnisi[1], M. Marongiu[1], A. Mostacci[2], L. Piersanti[1], G. Di Pirro[1], S. Romeo[1], A. R. Rossi[4], J. Scifo[1], V. Shpakov[1], C. Vaccarezza[1], F. Villa[1] and A. Zigler[1,5]

Plasma acceleration @LNF: SPARC_LAB test facility



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Article | Published: 25 May 2022

Free-electron lasing with compact beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, ... M. Ferrario + Show authors

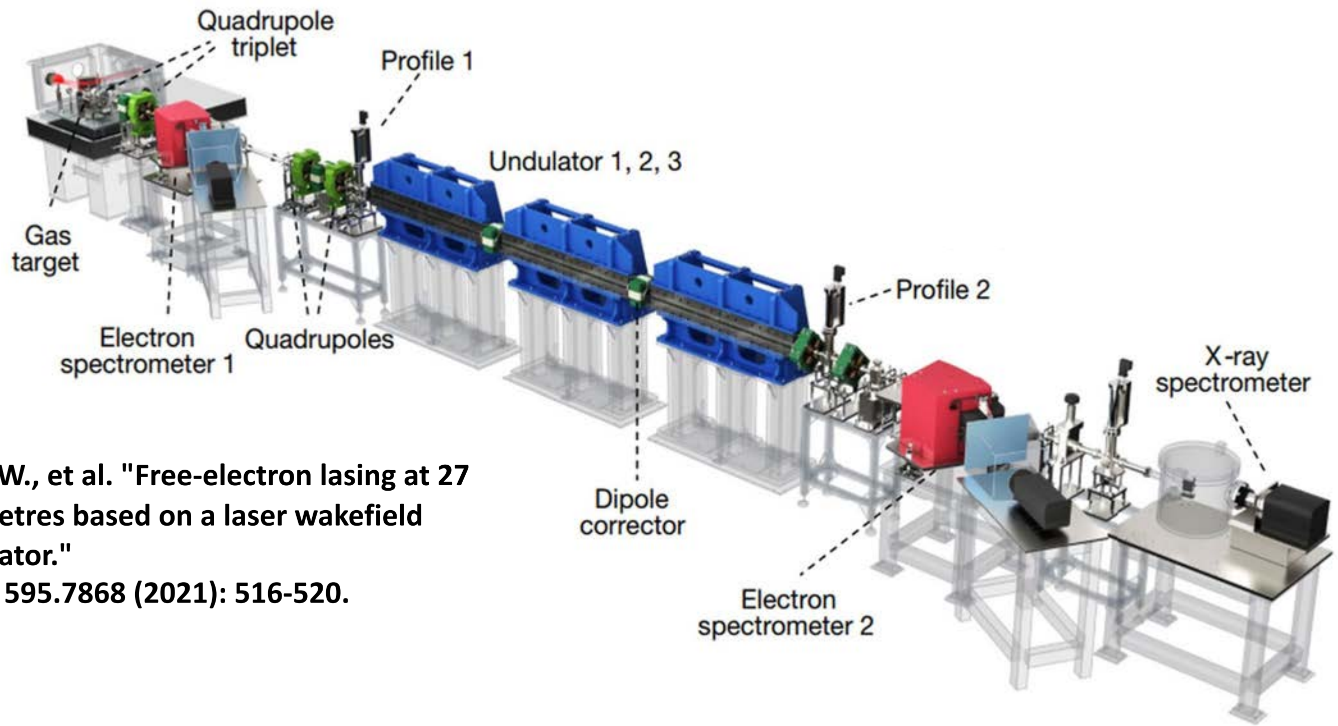
Nature **605**, 659–662 (2022) | Cite this article

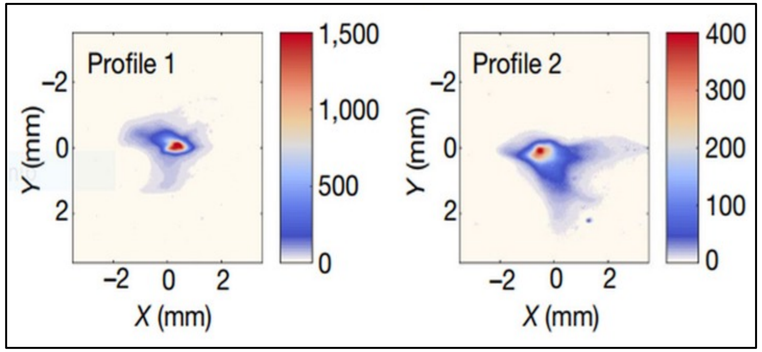
Proof of SASE and Seeded FEL driven by PWFA @SPARC_LAB

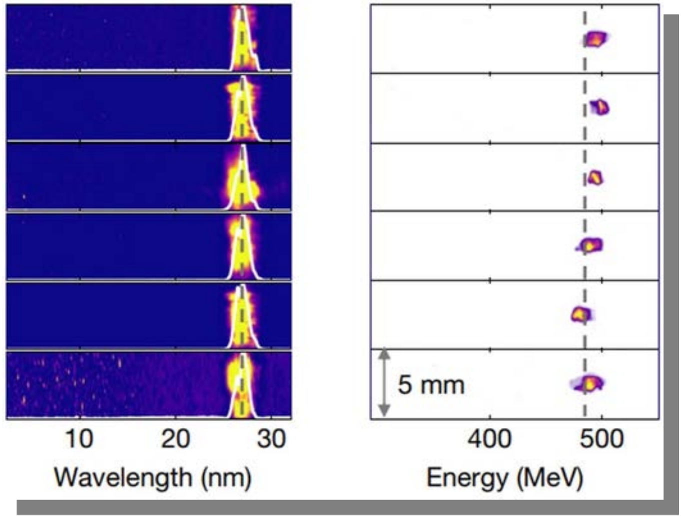
- Proof-of-principle experiment to demonstrate high-quality PWFA acceleration able to drive a Free-Electron Laser
- Witness is completely characterized (energy, spread, X/Y emittance) allowing to match it into the undulators beamline
- Jitter is online monitored with Electro-Optical Sampling (EOS) diagnostics
- Imaging spectrometer with iCCD used to detect FEL radiation
- Spectrum of the SASE FEL radiation emitted at 830 nm

In collaboration with

Laser plasma acceleration







Wang, W., et al. "Free-electron lasing at 27 nanometres based on a laser wakefield accelerator." Nature 595.7868 (2021): 516-520.

- <u>laser focused on a gas-jet</u>
- <u>Electron beam generated from a 200 TW (I~4x10^{18} W/cm^2)</u>

✓ Peak energy ~ 490 MeV, 0.5% spread (measured), emittance 0.5 um (estimated)

✓ Radiation energy from 0.5 to 150 nJ

Plasma acceleration @LNF: SPARC_LAB test facility

Focusing with active-plasma lenses

Pompili, R., et al., Physical review letters 121.17 (2018): 174801.
Pompili, R., et al., Applied Physics Letters 110.10 (2017): 104101.

Focusing produced by electric discharge in plasma-filled capillary

Magnetic field follows Ampere Law

$$B_\phi(r) = \frac{\mu_0}{r}\int_0^r J(r')\,r'\,dr'$$

Weak chromaticity

Like in quadrupoles → K~1/γ

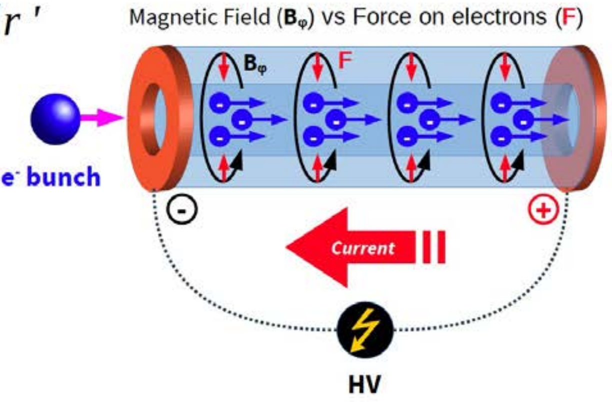
Radially symmetric

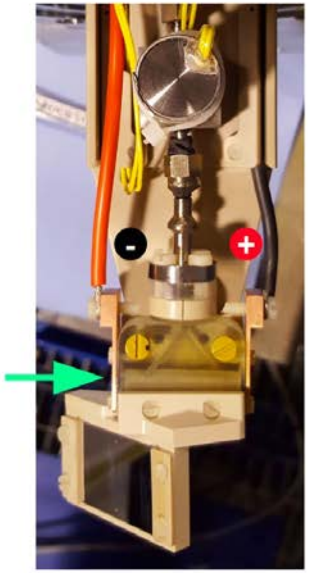
Like in solenoids

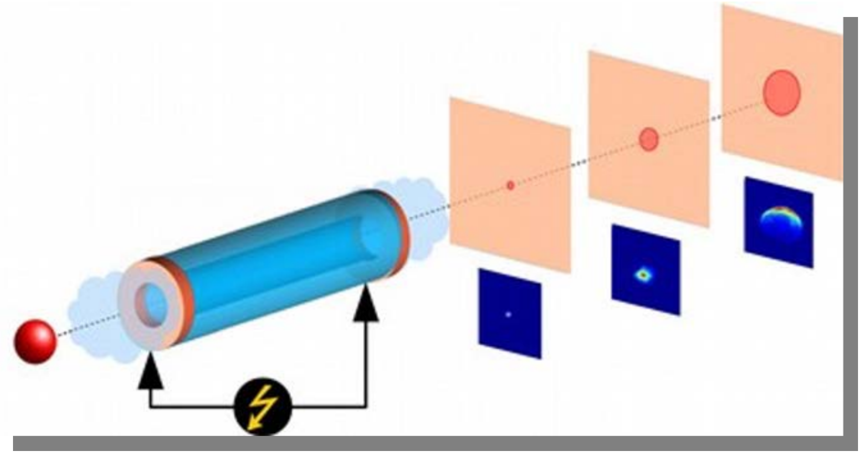
Compactness

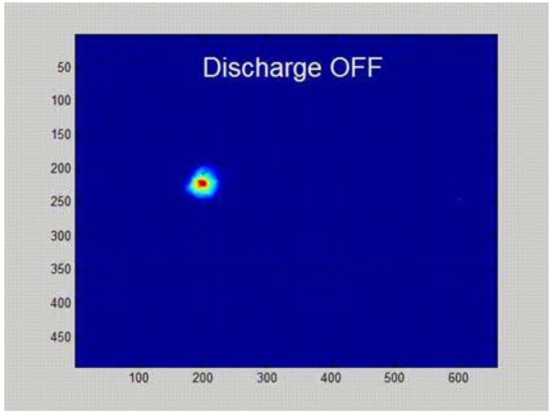
kT/m magnetic field → much larger than strongest quadrupoles available (PMQ)

Not sensitive to beam distribution





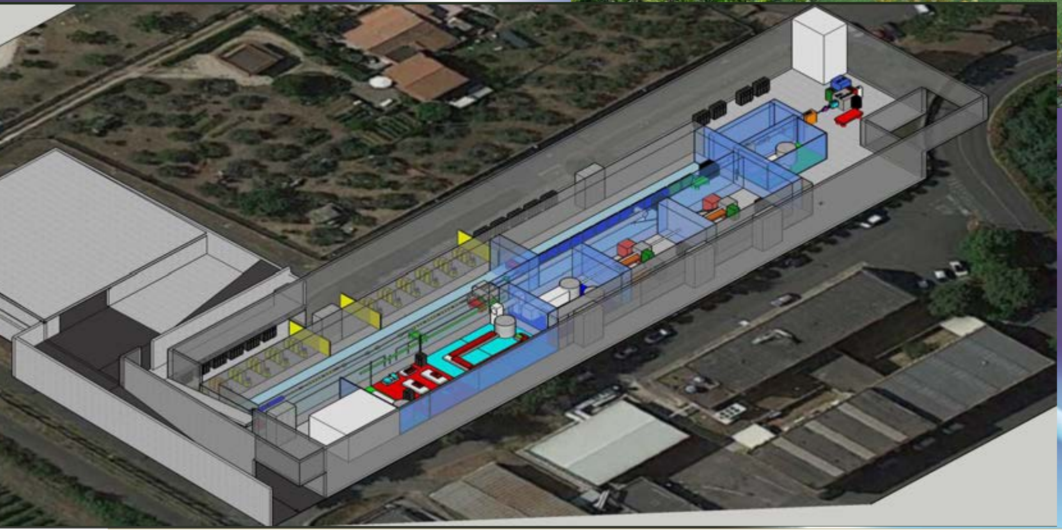




Courtesy R Pompili

Plasma acceleration @LNF: EuPRAXIA user facility

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS



- Frascati future facility
- Beam-driven plasma accelerator
- Europe most compact and most southern FEL
- The world most compact RF accelerator (X band with CERN)

- Electron energy 1-5 GeV
- FEL user facility 1 GeV – 3 nm
- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only

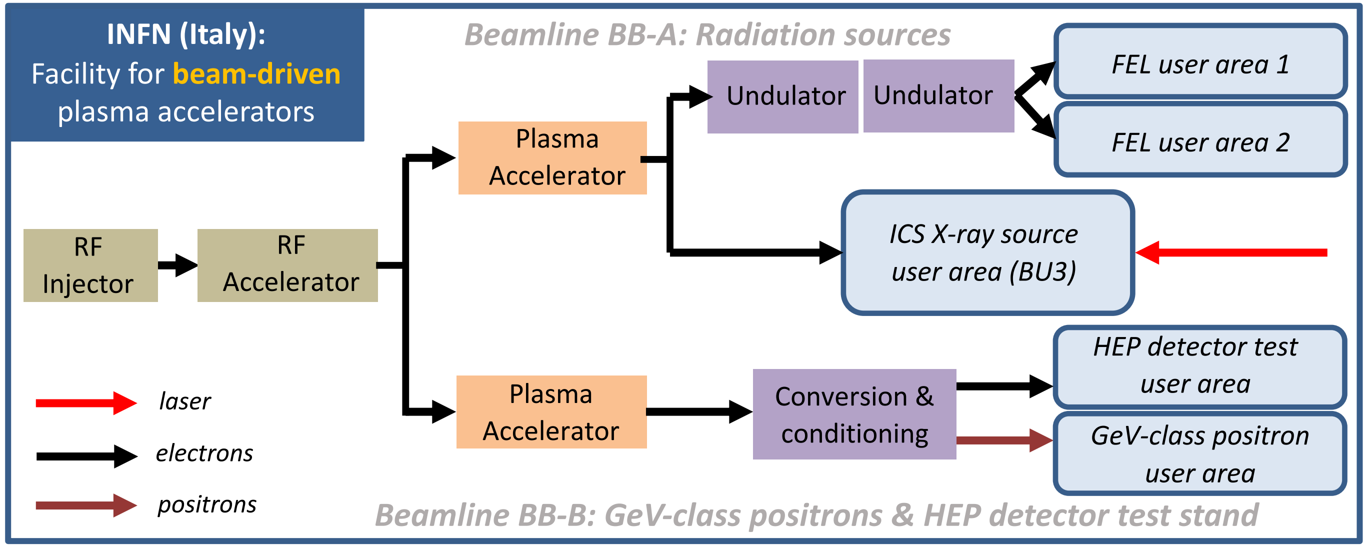
Plasma acceleration @LNF: EuPRAXIA user facility


INFN
Istituto Nazionale di Fisica Nucleare

CDR-1, April 2018

EuPRAXIA@SPARC_LAB

Conceptual Design Report


INFN (Italy):
Facility for **beam-driven**
plasma accelerators

Beamline BB-A: Radiation sources

RF Injector

RF Accelerator

Plasma Accelerator

Undulator

Undulator

FEL user area 1

FEL user area 2

ICS X-ray source user area (BU3)

Plasma Accelerator

Conversion & conditioning

HEP detector test user area

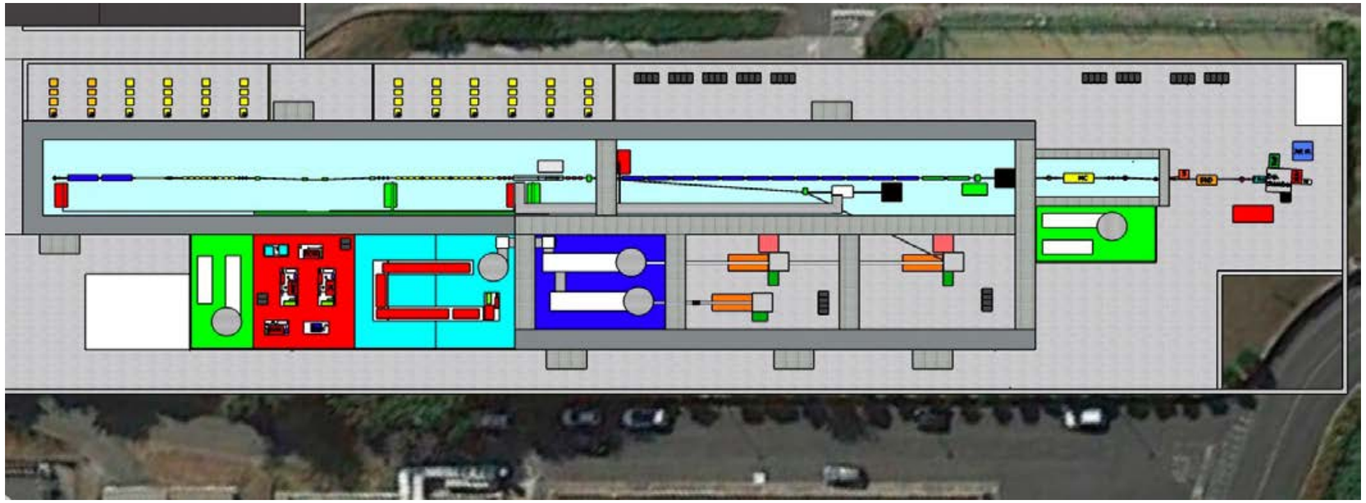
GeV-class positron user area

laser

electrons

positrons

Beamline BB-B: GeV-class positrons & HEP detector test stand



Plasma acceleration @LNF: EuAPS user facility

The PNRR EuAPS Project WP2

EuAPS will be the first brick of EuPRAXIA, a user facility based on the radiation emitted by electrons plasma accelerated

- The source will be hosted at LNF-INFN
- Several parts will be realized at CNR (Photon Diagnostics) and at Tor Vergata (User end Station)
- INFN-Mi will take care of simulation and data analysis
- Trieste University focuses on applications

Where	Target
INFN-Mi	Simulation & Data Analysis
LNF-INFN	Plasma source
LNF-INFN	Synchronization
CNR-Potenza	Photon Diagnostics
Tor Vergata	End user station
CNR- Montelibretti	Photon time diagnostics

Parameter	Value	unit
Electron beam Energy	*100 - 500*	*MeV*
Plasma Density	10^{18} - 10^{19}	cm^{-3}
Photon Critical Energy	*1 - 10*	*keV*
Number of Photons/pulse	10^{6} - 10^{9}	
Repetition rate	*1 - 5*	*Hz*
Beam divergence	*3 - 20*	*mrad*

Courtesy A Cianchi

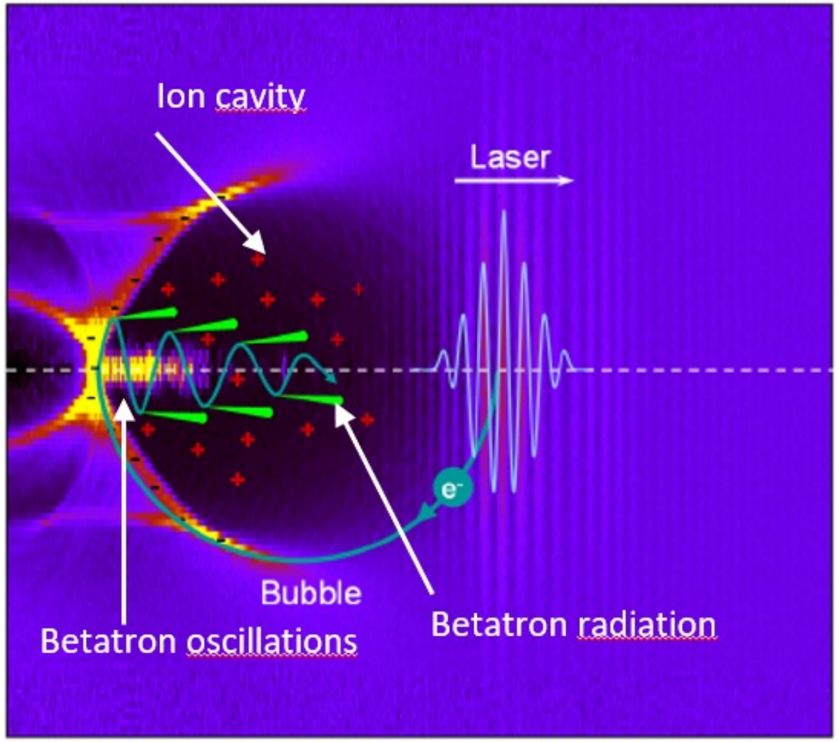
Plasma acceleration @LNF: EuAPS user facility

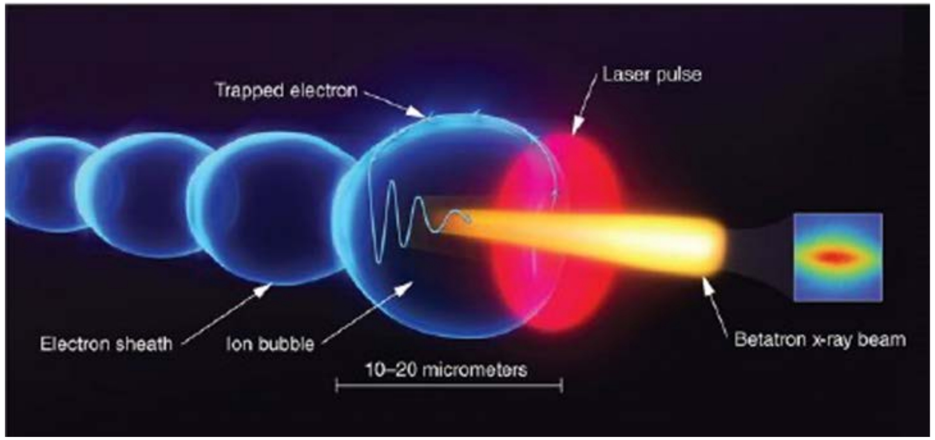
Betatron radiation emission

Longitudinal electric field → acceleration along the laser propagation axis

Radial electric field → oscillations around the reference trajectory

Emission of synchrotron-like radiation = **Betatron radiation**





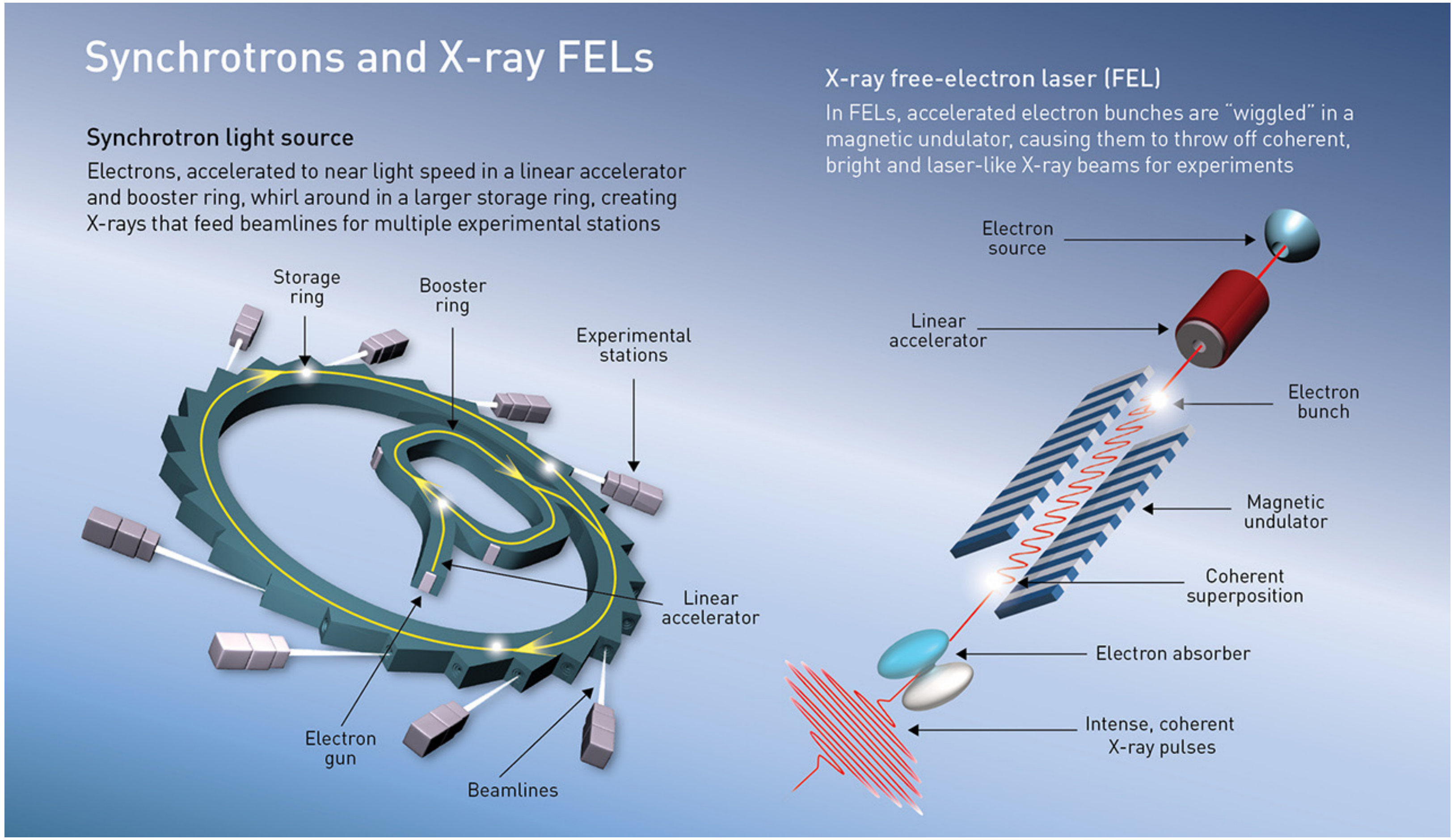
- Energy from soft to hard X-rays
- High peak brilliance

$$B \approx 10^{20} \frac{Photons}{s \cdot mm^2 \cdot mrad^2 \cdot 0.1\%\ BW}$$

- Spatially coherent
- Temporally incoherent
- Pulse ~ few fs

Plasma acceleration @LNF: EuAPS user facility

Synchrotrons vs FELs



Betatron radiation:

- Large bandwidth like a Synchrotrons
- Short pulse duration like a FEL

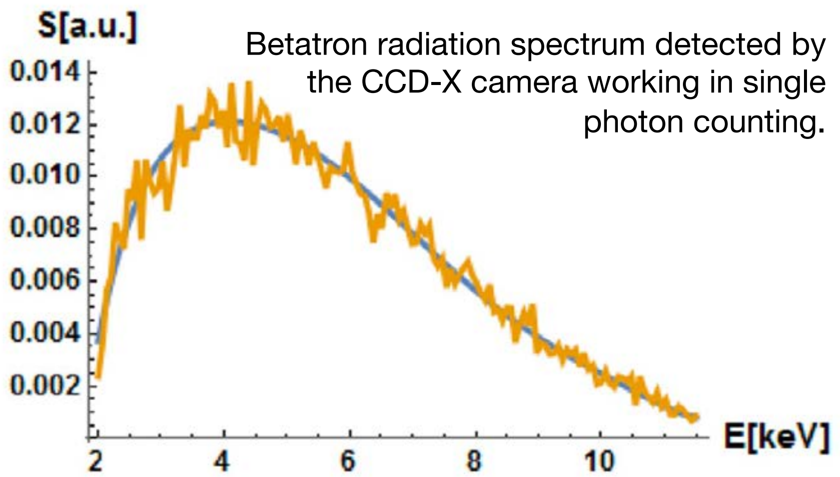
$$B = \frac{d^4 N}{dt\, d\Omega\, dS\, d\lambda / \lambda}$$

Ph/ (s mm² mrad² 0.1% of bandwidth)

Patricia Daukantas Synchrotron Light Sources for the 21st Century Optics & Photonics News Settembre 2021

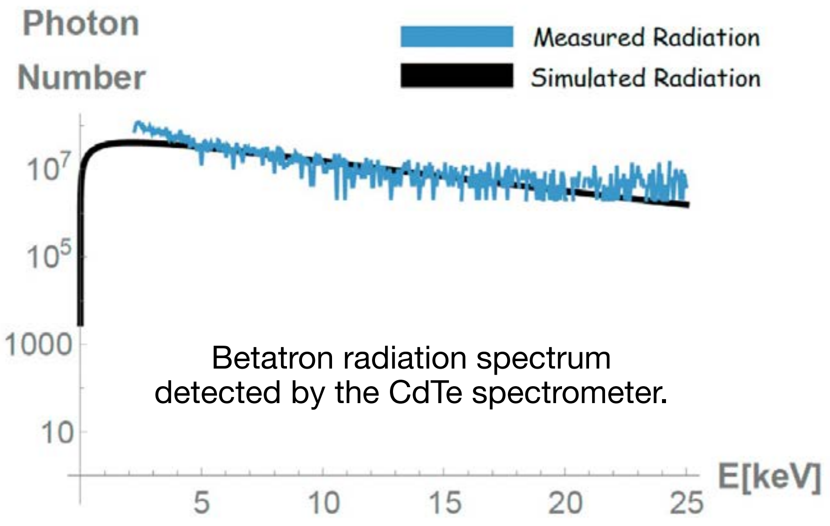
Plasma acceleration @LNF: EuAPS user facility

Betatron radiation test @FLAME



Betatron radiation spectrum detected by the CCD-X camera working in single photon counting.

- Laser energy *1 J* - temporal length *30 fs* - focal spot rms 5 μm
- Plasma density *10^{19} cm^{-3}* - acceleration length *1.1 mm*
- e^- energy *300 MeV* - energy spread *20%* - bunch charge *5 pC*



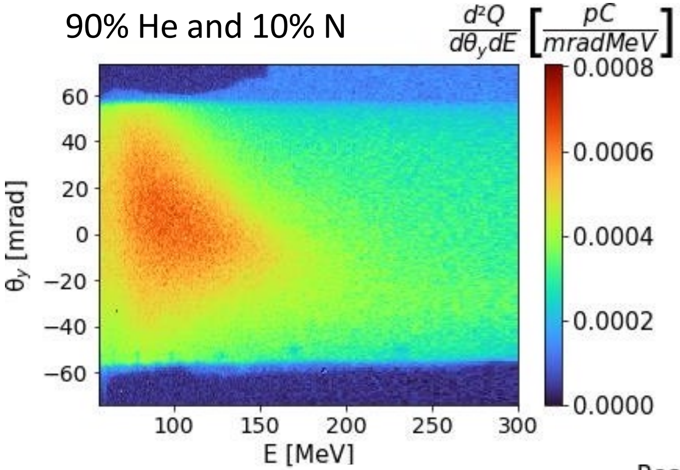
Betatron radiation spectrum detected by the CdTe spectrometer.

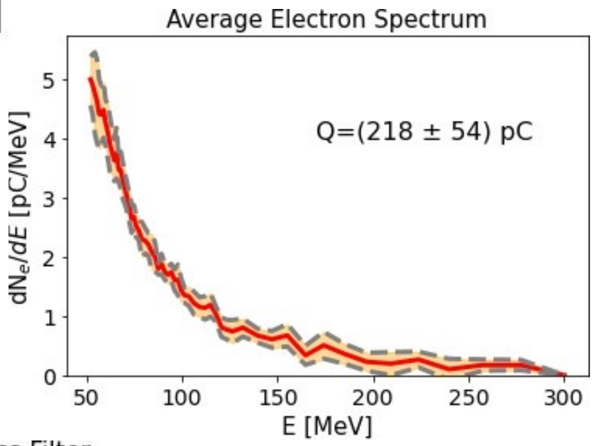
- Laser energy *1.5 J* - temporal length *35 fs* - focal spot rms 5 μm
- Plasma density *6 x 10^{18} cm^{-3}* - acceleration length *1 mm*
- e^- energy *200 MeV* - energy spread *30%* - bunch charge *5 pC*

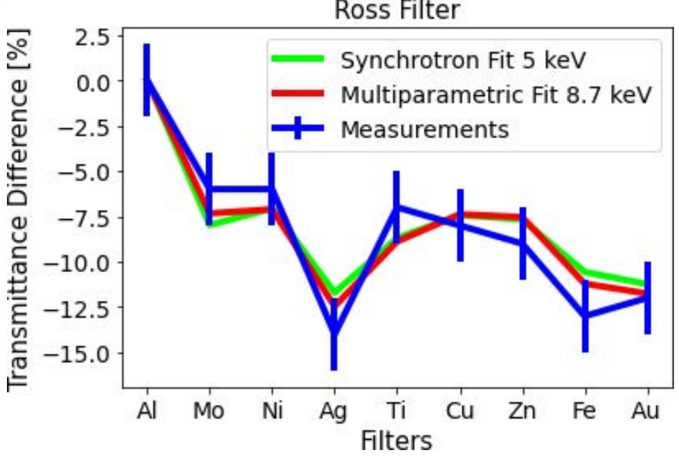
A. Curcio et al., First measurements of betatron radiation at FLAME laser facility, Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.03.106

Plasma acceleration @LNF: EuAPS user facility

Ongoing betatron radiation test @FLAME



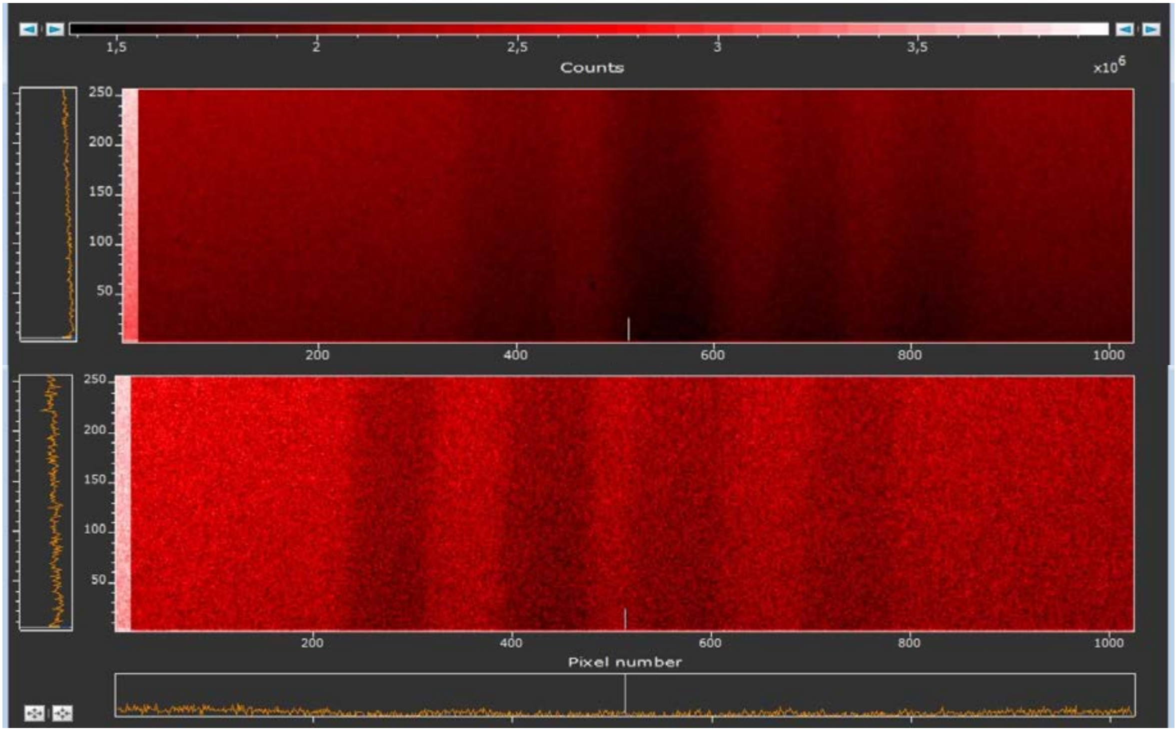




Ross-filter:

Ti 15 μm – Ag 33 μm – Ni 7 μm – Mo 4 μm

Au 6 μm – Fe 25 μm – Zn 10 μm – Cu 8 μm

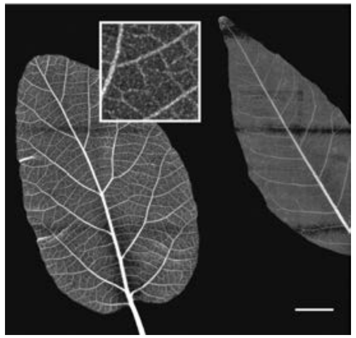


Betatron radiation applications

Photon Science from betatron radiation

- Imaging of biological and cultural heritage samples: Exploits the brilliance and coherence of betatron radiation, requires small divergence and good focusing
- Static X-ray Spectroscopy and Ultra-fast X-ray spectroscopies: The second one requires timing between pump and probe pulses, exploits the fs pulse duration
- Wide angle scattering, diffraction: Requires monochromatic beams with high flux

Imaging – The pilot experiment

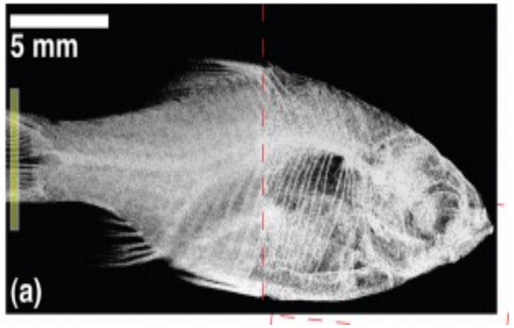


X-ray imaging of leaves (and wood) aiming at the (tens of) microns resolution.

Experiments performed with the broad radiation spectrum filtered by different materials to obtain difference maps emphasizing the presence of heavy metal contaminants → pollution control.

Reale et al. - MIDIX Soft X-rays microradiography

Single shot phase contrast X-ray imaging:



X-ray absorption contrast image of an orange tetra fish. The spectrum is synchrotron like with a critical energy $E_c \sim 10$ *keV*. The phase contrast images are taken in a single shot *30 fs* exposure.

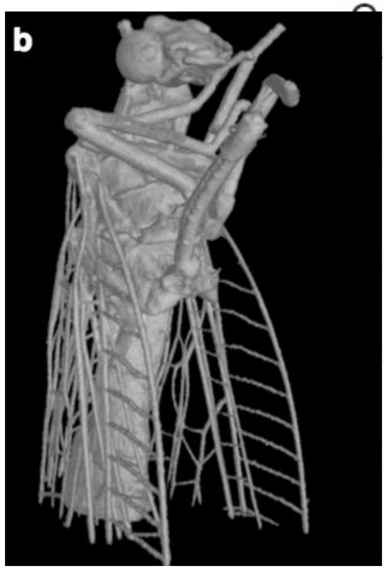
Ref. Kneip, S., et al. "X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator." **APL** 99.9 (2011): 093701.

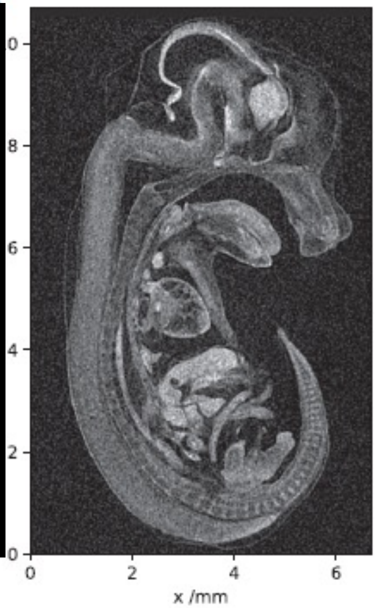
Courtesy F Stellato

Betatron radiation applications

Imaging, Tomography and Phase Contrast

Betatron sources can fill the gap between synchrotrons and X-ray tubes for imaging and **Computer Tomography** (CT)

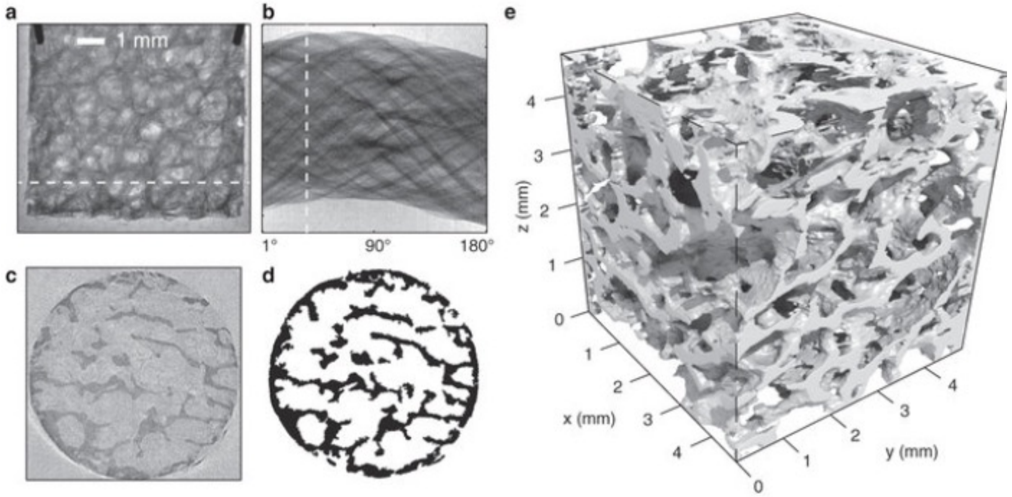




Betatron sources have a spatial coherence that allows performing Phase Contrast Imaging (PCI). In PCI, it is measured the difference in wavefront, while in traditional imaging, it is measured the difference in the X-ray absorption coefficient between different objects.

PCI provides better contrast than radiography, especially when dealing with biological samples.

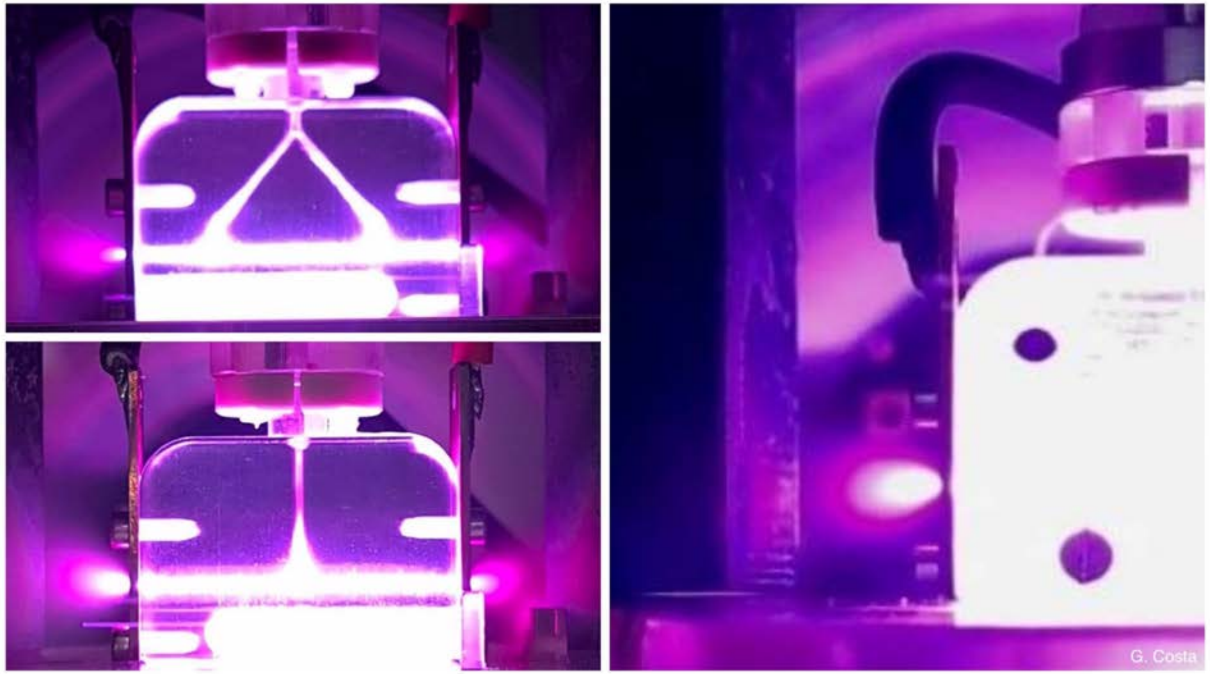
Guo *et al.* Scientific Reports 2019
Cole *et al.* PNAS 2018
Wenz *et al.* Nature communications 2015



3D medical imaging: Tomographic reconstruction of bone sample: (a) A raw image of the bone sample recorded on the xray camera. (c) Application of the inverse Radon transform to the sinogram in (b). (d) Pixels are classified as bone (black) or vacuum (white). (e) Stacking together 1300 slices generates a 3 D voxel map of the bone sample. An isosurface marking the detailed structure of the bone surface is constructed, rendered using a ray-tracing method.

Ref. Cole, J. M., et al. "Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone." *Scientific reports* 5.1 (2015): 1-7.

Thank you for the attention!



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