Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

PW laser and meter-scale gas jets at Berkeley Lab Laser Accelerator (BELLA)

16/12/2024

C.R. ENEA Frascati, Aula Brunelli

Outline

1. BELLA laser facility
   The PW laser facility, a quick overview

2. Motivation
   LWFA, increasing energy and repetition rate

3. Gas jet simulation and measurements
   Simulation tools, gas density measurements and throat adjustment

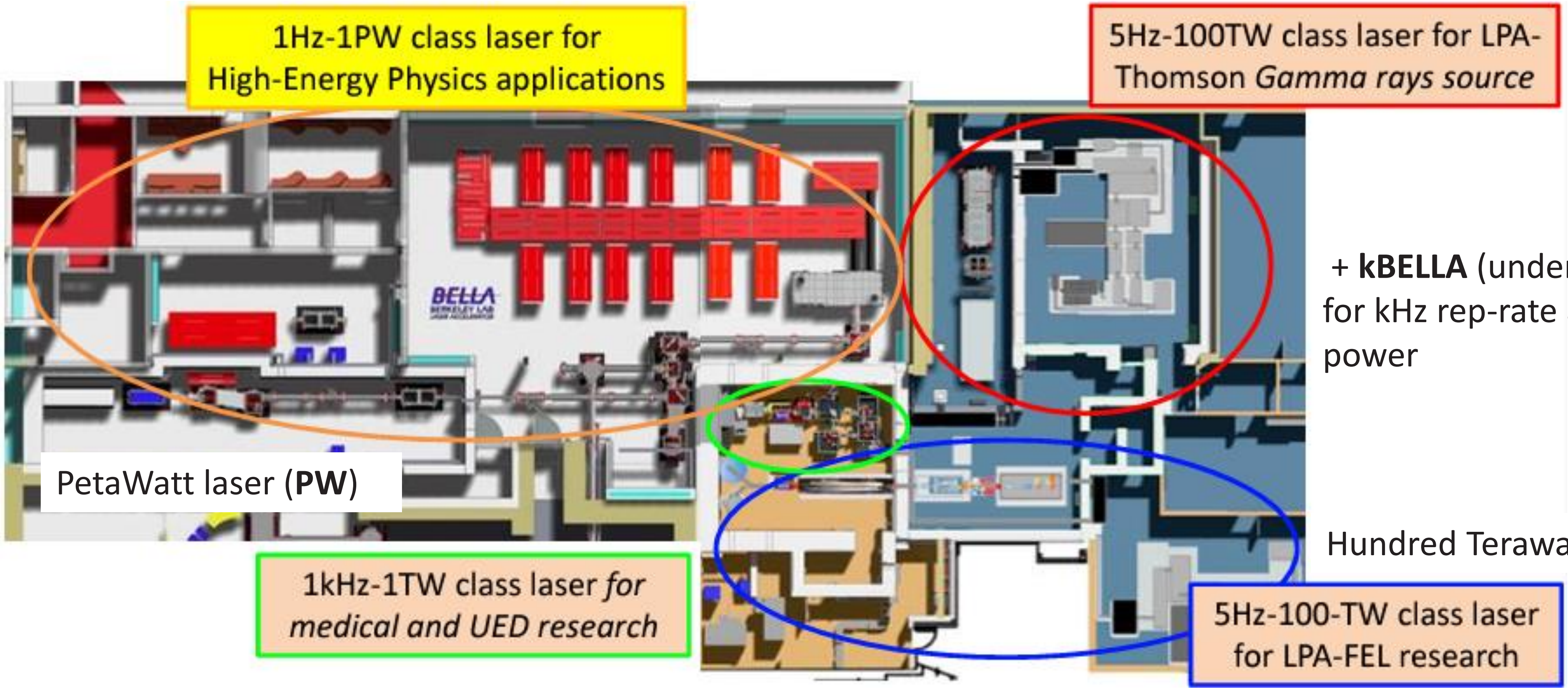
4. Results and future work
   New geometries for gas jet and vacuum improvement

BELLA Laser Facility

Berkeley Lab Laser Accelerator (**BELLA**) is a laser built by the Thales Group and owned and operated by the Lawrence Berkeley National Laboratory (**LBNL**).

It houses 4 (+1) different laser systems:

Hundred Terawatt Thomson (**HTT**)

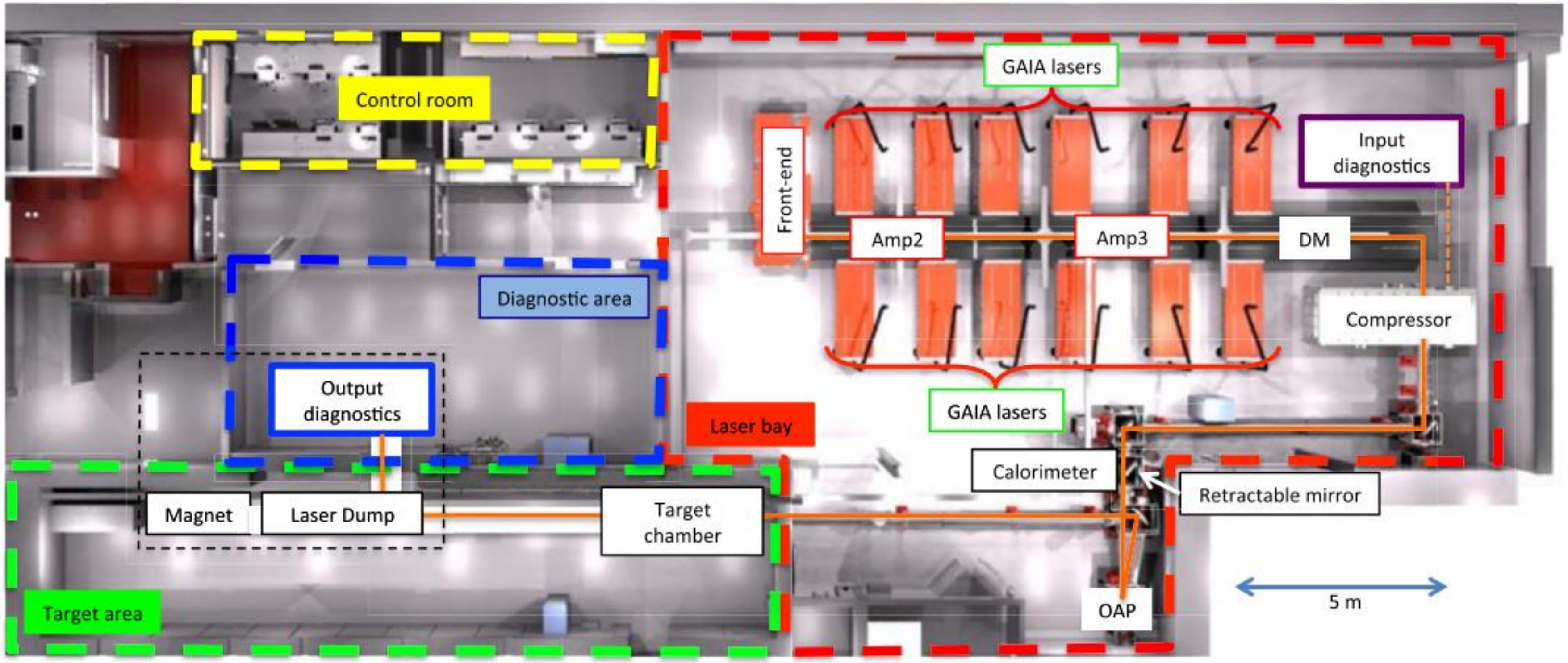


+ **kBELLA** (under development) for kHz rep-rate and kW average power

Hundred Terawatt Undulator (**HTU**)

BELLA Laser Facility: PW laser

The BELLA Petawatt (**PW**) Laser is a Ti:sapphire CPA laser system providing laser pulses at petawatt-level peak power and was the first system to deliver them at 1 Hz rep-rate in 2012.



The laser consists of a front-end followed by two final amplifiers operating at a 1 Hz repetition rate.

Pulses are transported from the laser table to the first target chamber via two pulse transport lines named first (**1BL**) and second (**2BL**) beamline.

The final uncompressed pulse energy is > 65 J. This is sent to a grating-based optical compressor that produces >40 J, 30 fs.

K. Nakamura et al., IEEE J. Quantum Electron. 53, 1200121 (2017)

BELLA Laser Facility: PW laser

Two target chambers are available:

In the first, the laser is focused with a long focal length (f/65) off-axis paraboloid mirror into the first target chamber. It is mainly used for LWFA experiments.

The iP2 extension uses the first beamline laser pulse that provides a laser focus with an intensity of > 10^{21} W/cm^2, using a short-focal length OAP (f/2.5) and is used, e.g., for solid target experiments and HEDP.

	Parameter	Value	Unit	Additional Information			
	Center Wavelength	815	nm				
	Pulse duration (FWHM)	30	fs				
	Max energy on target	40	J				
	Shot energy stability	2.5	%	r.m.s.			
	Focal spot at target						
LB1	F/number	65					
	intensity FWHM	65	µm				
	Strehl ratio	>0.9					
	Energy containment	75	%	within	67	µm	radius
iP2	F/number	f/2.5					
	focal spot FWHM	2.7	µm				
	Strehl ratio	0.77					
	Energy containment	67	%	within	3	µm	radius
	Pointing Stability	1.3	µrad	r.m.s.			
	Pre-pulse contrast						
	ns scale	10^{-9}		@	1	ns	
	ps scale	10^{-6}		@	5	ps	
	Repetition Rate	1 Hz					

$$\frac{40\ J}{30\ fs} \sim 1\ PW$$

Obst-Huebl, L., et al. "BELLA PW 1 Hz Laser Experiments for Short Pulse Laser-based Ion Fast Ignition for IFE." (2022).

Turner, M., et al. "Strong-field QED experiments using the BELLA PW laser dual beamlines." The European Physical Journal D 76.11 (2022): 205.

Steinke S, et al. " Multistage coupling of independent laser-plasma accelerators. " Nature. 2016;530(7589):190–3.

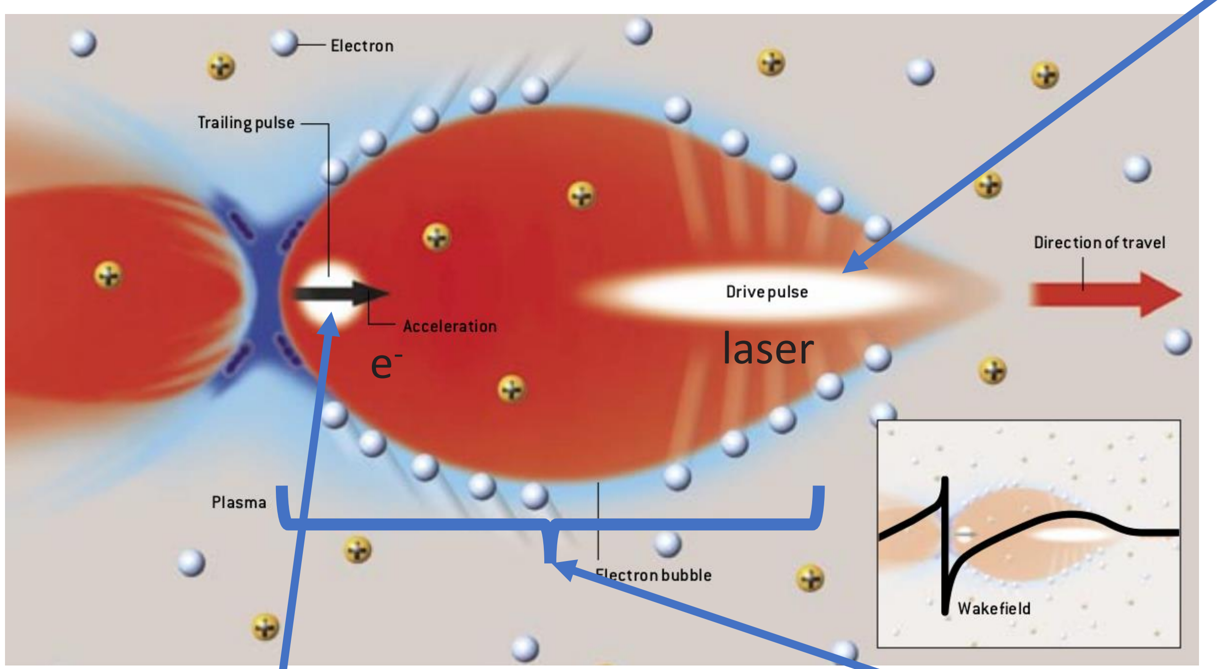
ccelerat

Motivation: Laser Wakefield Acceleration (LWFA)

In the Laser Wakefield Acceleration (LWFA):

- **short** ($c\tau \leq \lambda_p$)
- **intense** ($>10^{18}$ W/cm^2)

laser pulse drives a plasma wave which can accelerate an electron bunch.



'Trapped' electrons can be accelerated

The «bubble» length is $\sim\lambda_p$

Ponderomotive force

$$\vec{F}_p = -\frac{e^2}{4m\omega^2}\nabla \vec{E}^2$$

Plasma can sustain fields of the order of the hundreds of GV/m, several order of magnitude higher than RF based accelerators.

Accelerating gradient

$E[V/m] \approx E_0 \approx 96\, n_0[cm^{-3}]^{1/2}$

$\omega_p = \sqrt{n_0 e^2 / \varepsilon_0 m_e}$ e- plasma frequency

$\lambda_p = 2\pi c / \omega_p$ Plasma wavelength

$E_0 = c m_e \omega_p / e$ nonrelativistic wavebreaking field

Motivation: Laser Wakefield Acceleration (LWFA) limitations

Limitations

- **Diffraction :** $Z_R = \pi r_0^2 / \lambda$

  Laser has diffraction after the focus

- **Dephasing :** $L_d = (\lambda_p / \lambda)^2 \lambda_p / [1 + (\lambda_p / \pi r_0)^2]$

  Electron bunch advances in phase and moves into a decelerating region of the plasma wakefield

- **Energy depletion :** $L_e = \ell_L a_0^2 (\lambda_p / \lambda)^2 (E_{wb} / E_{z0})^2$

  Laser loses significative part of its power and cannot drive any wake

Typically: $Z_R < L_d < L_e$

$\sim cm \quad \sim 20cm \quad \sim 10m$

Solutions

Guiding in Plasma Channel

Taper the plasma density/the plasma boundaries to guide the laser pulse

Tapered Channel

Varying the plasma density along the laser/particle propagation axis

Staging

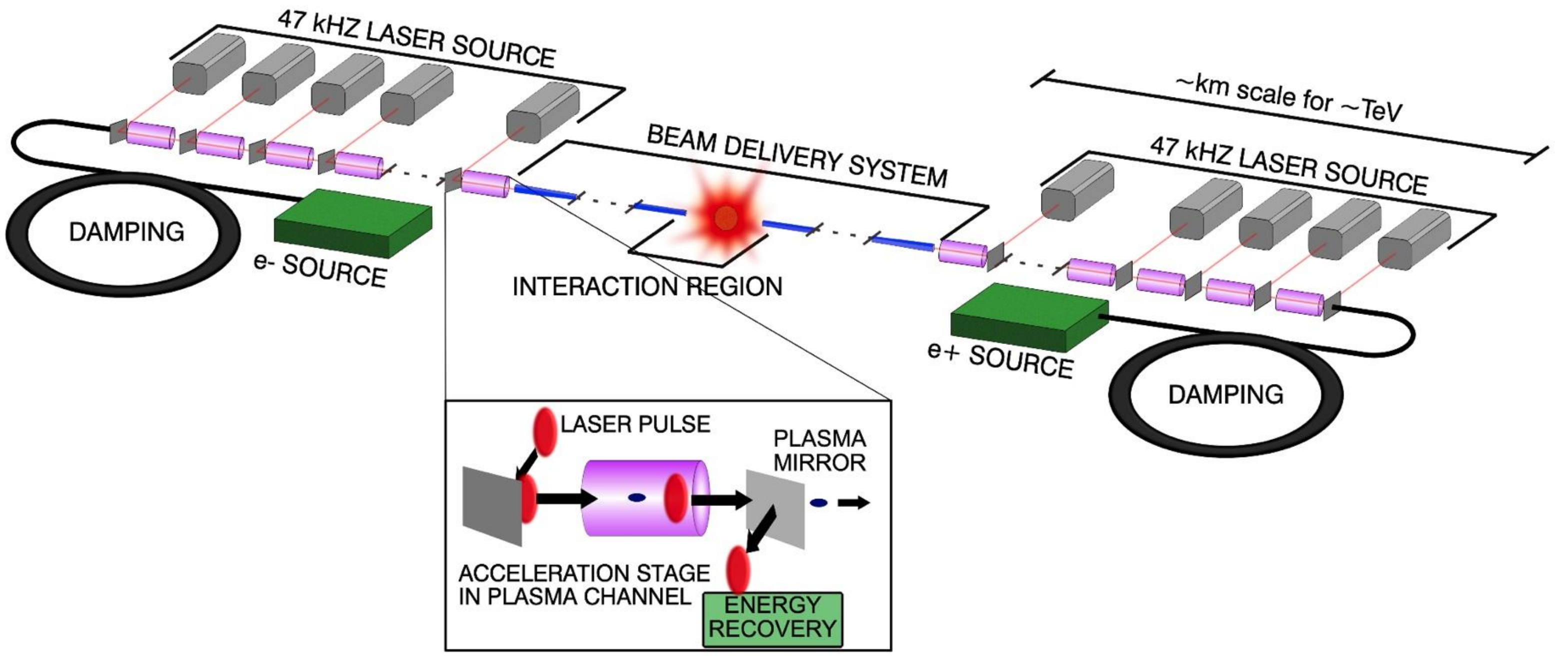
Placing several consecutive plasma-based sections fed with laser different pluses

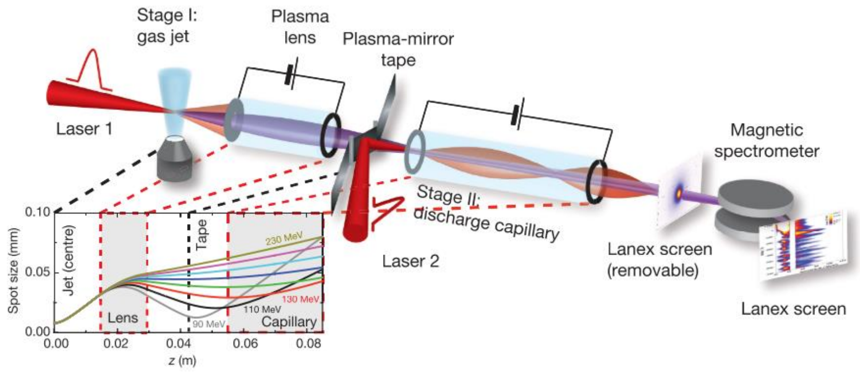
Motivation: Laser Wakefield Acceleration (LWFA) goals

Acceleration of electrons up to 10 GeV has been achieved in few cm plasmas.

LPA is asttractive in many applications, ranging from biomedical treatment to free-electron-lasers research centers to nuclear nonproliferation. Ultimately they might even be the basis for a new generation of colliders, orders of magnitude smaller than today’s, for high-energy physics.

The present goal is to further **increase the energy** and the **repetition rate** (now struck at few Hz), keeping the **quality** of the electrons controllable and reproducible.





Steinke S, van Tilborg J, Benedetti C, Geddes CGR, Schroeder CB, Daniels J, et al. Multistage coupling of independent laser-plasma accelerators. Nature. 2016;530(7589):190–3.

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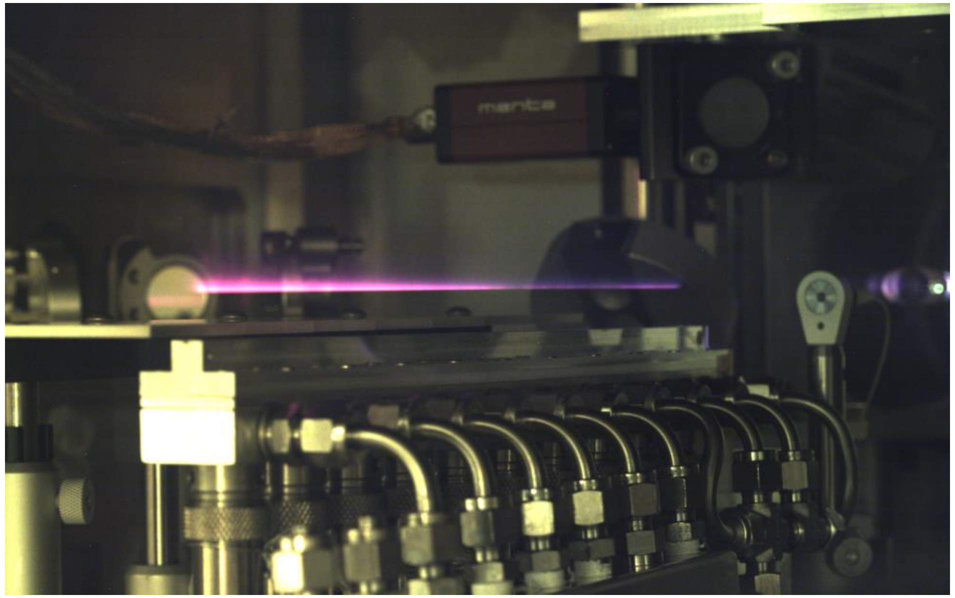
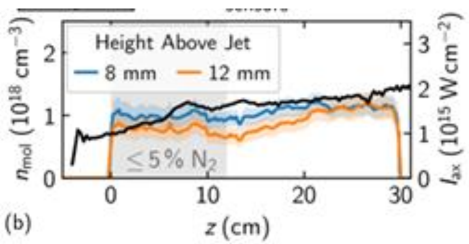
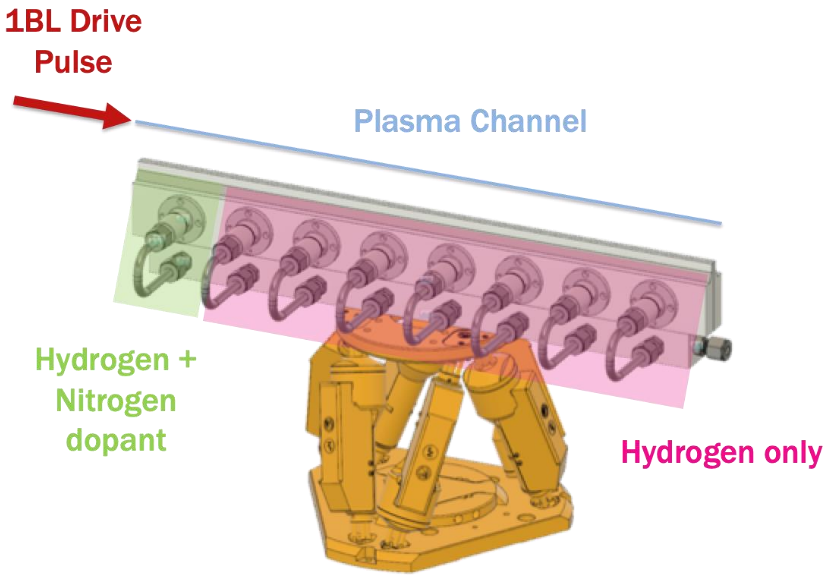
Gas-jet for increasing energy and repetition rate

In previous experiments, fixed-length glass or sapphire tubes called “capillaries” has been used to shape the plasma.
Now, at BELLA, **gas-jets** are preferred due to their **resilience** to the plasma and laser stress (increasing rep-rate).
Gas jets based on elongated converging-diverging (de Laval) nozzles have been demonstrated at meter-scale lengths. This allow to finely tune the plasma and change its length (increasing the energy).



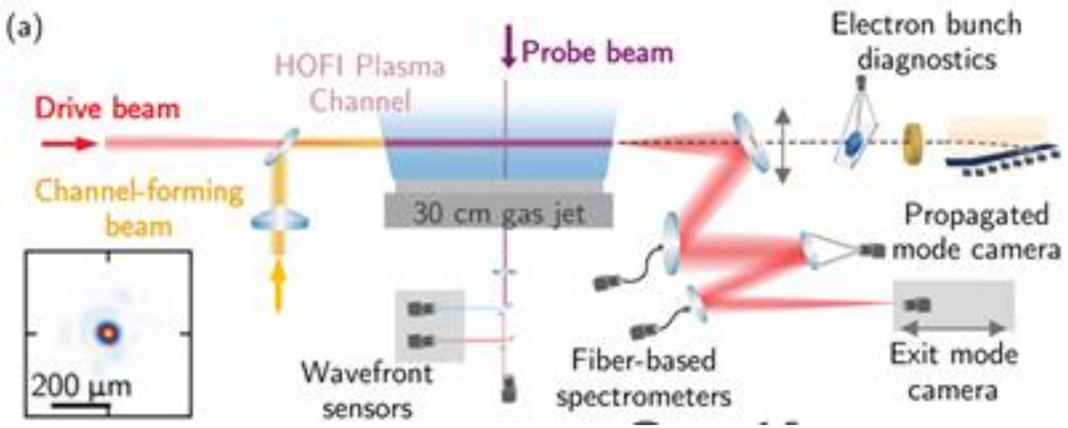


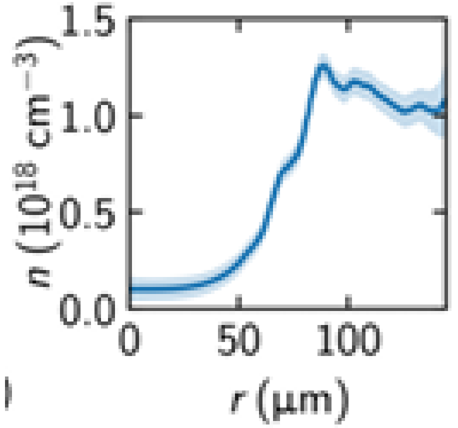


30 cm long gas jet with localized dopant will be used to enable **ionization injection**.

Gas-jet for increasing energy and repetition rate

To limit the **diffraction** and guide the laser for several centimeters a plasma channel is produced due to hydrodynamic optical field ionization (**HOFI**).
A <100fs **heating laser** ionizes the gas before the driver laser. A cylindrical column of plasma is formed in the laser line and expands radially. When an intense drive laser is focused into the plasma channel, the leading edge ionizes the neutral gas surrounding the expanding shock front to create a deep, thick-walled plasma channel.





Measured «parabolic» density profile

$$n(r) = n_0 + \Delta n \frac{r^2}{r_{ch}^2}$$

Laser spot must be matched with the parabolic profile to be guided along the capillary

$$w_m = \left(r_{ch}^2 / \pi r_e \Delta n\right)^{1/4}$$

Beam waist

Classical electron radius

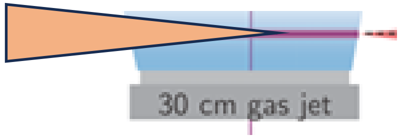
$$r_e = e^2/mc^2$$

Picksley A et al. "Matched guiding and controlled injection in dark-currentfree, 10-GeV-class, channel-guided laser plasma accelerators". arXiv:2408.00740 [physics.plasm-ph] (2024)

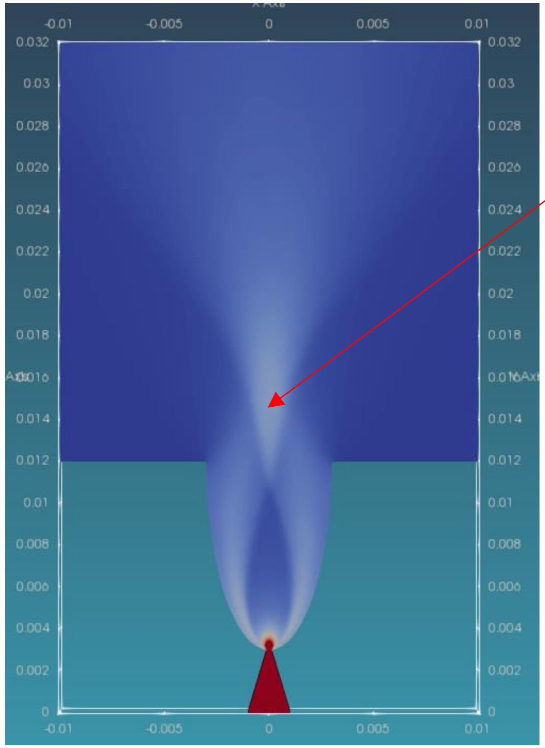
Gas-jet for increasing energy and repetition rate

Characteristics required for the stable production of 10 GeV electron bunches:

- Longer jet (from current 20cm up to 80cm)
  - Requires reduced gas load / improved pumping
    Less gas diffused into the vacuum chamber compared to the one used to produce the plasma
  - Mitigate heater beam blockage
    The higher can be produced the channel, the further is the laser from the edge of the gas-jet wall



Bell-shape nozzle



The bell curvature can create highly focused density regions, tens-of-mm far from the exit of the nozzle, with density of the order of ~10^{17} cm^{-3}

Simulation of is a powerful tool for prototyping and for a qualitative estimation of the gas density profile

Zhou O, et al. "Effect of nozzle curvature on supersonic gas jets used in laser-plasma acceleration". Phys Plasmas. 2021;28(9).

Gas jet simulation: OpenFoam

OpenFOAM is a free, open-source Computational Fluid Dynamic (CFD) software.

Pros

- Free download available online
  https://www.openfoam.com/
- It works on different OS and platforms
- Since it is open source, the code (including solvers) may be modified
- A large community may provide feedbacks or solution to specific cases
- Ancillary external softwares can be used for some steps (like the geometry design or meshing)

Cons

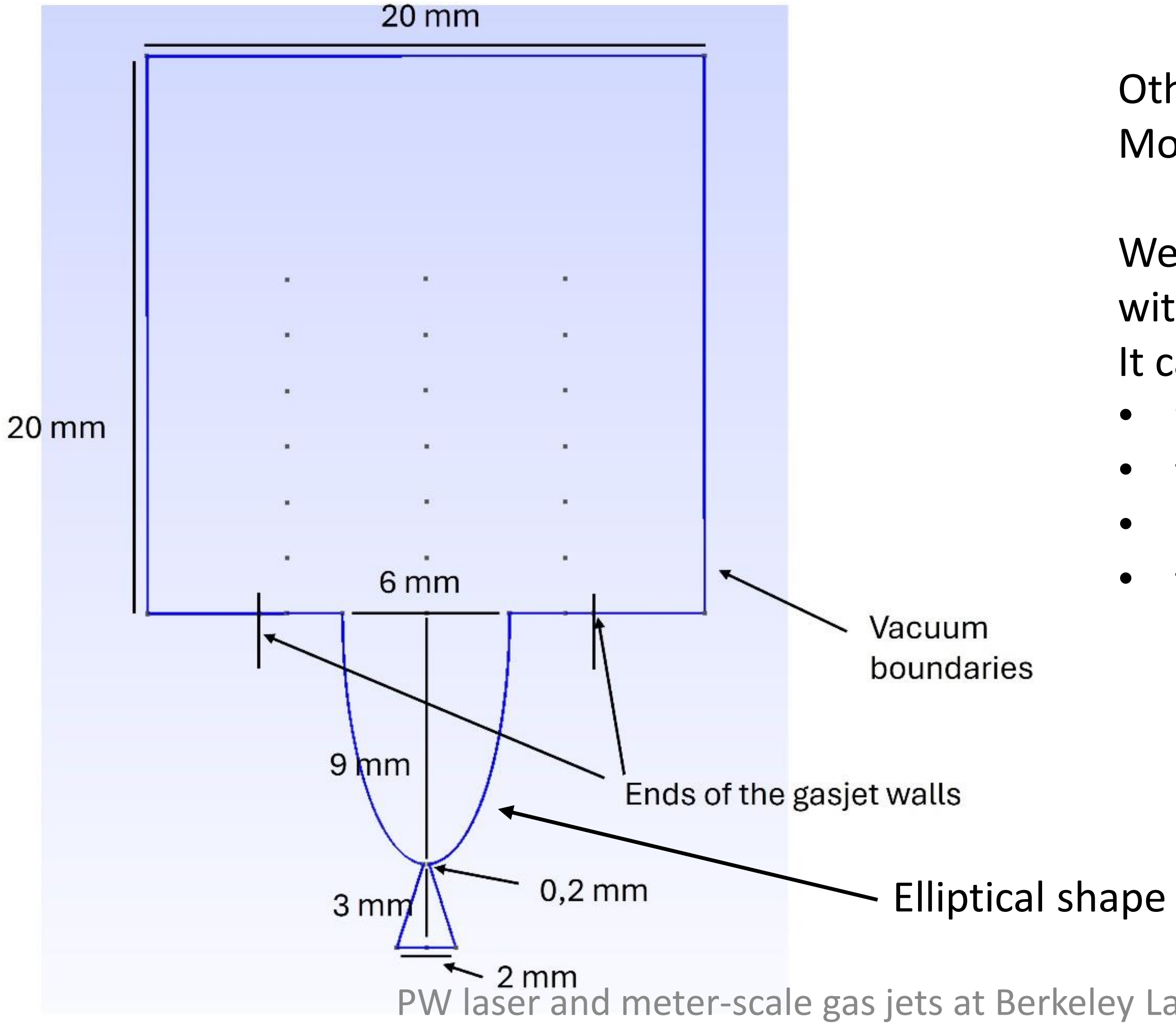
- Doesn't have a proper CAD interface (some external software may provide it)
- Meshing of externally designed objects are challenging with built-in functions (but meshes may be uploaded)
- Assistance is provided by user community, not by a company

Steps for the simulation

- Define the geometry
- Do/upload the mesh
- Set the initial and boundary conditions
- Launch the solver

Gas jet simulation: geometry definition with Gmsh

OpenFOAM provides some built-in tools for creating geometries and mesh. However, the design cannot be done interactively.

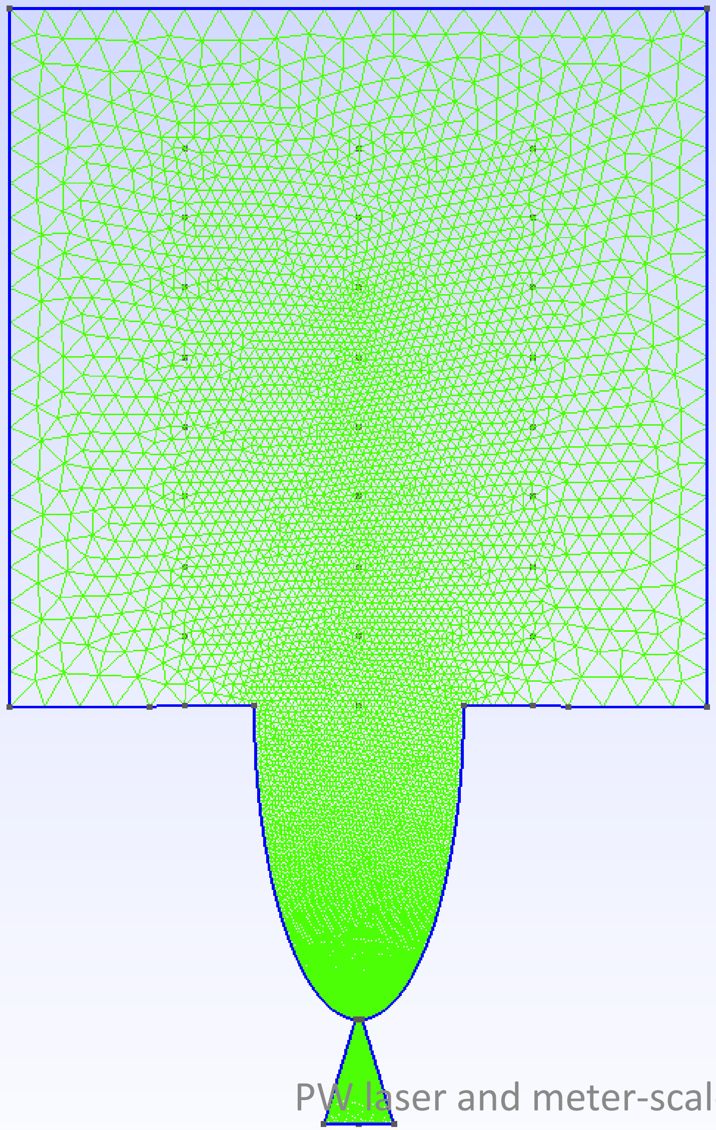


Other software are usually used to design complex geometries. Most used are Fluent, Blender and GMSH.

We used **Gmsh**, a three-dimensional finite element mesh generator with a build-in CAD engine and post-processor.
It can be controlled either:

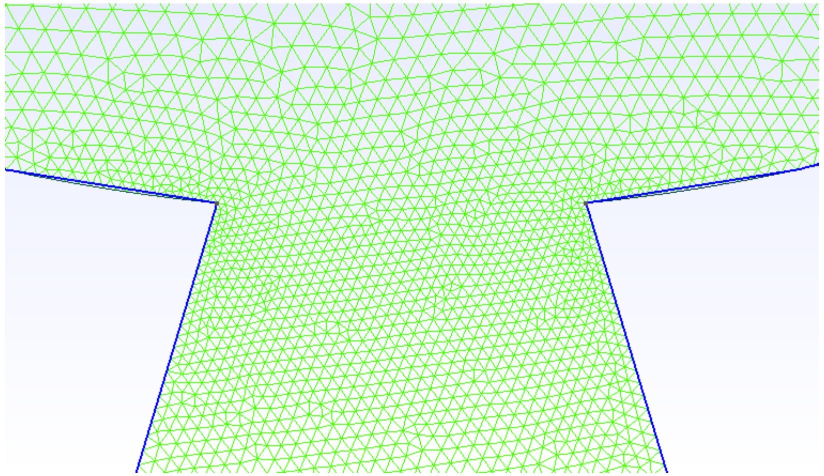
- with the graphical user interface
- from the command line
- using text files (.geo files)
- through the C++, C, Python, Julia and Fortran application programming interface.

Gas jet simulation: meshing with Gmsh



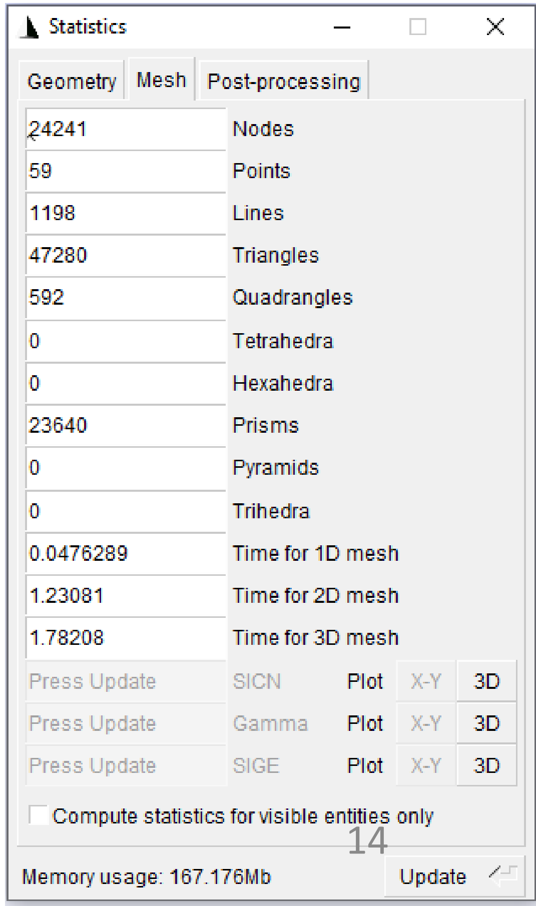
Meshes have been generated with **Gmsh.**

We used 2D triangular mesh (Frontal-Delaunay). It allows to vary the density of the mesh in the different region of the geometry.



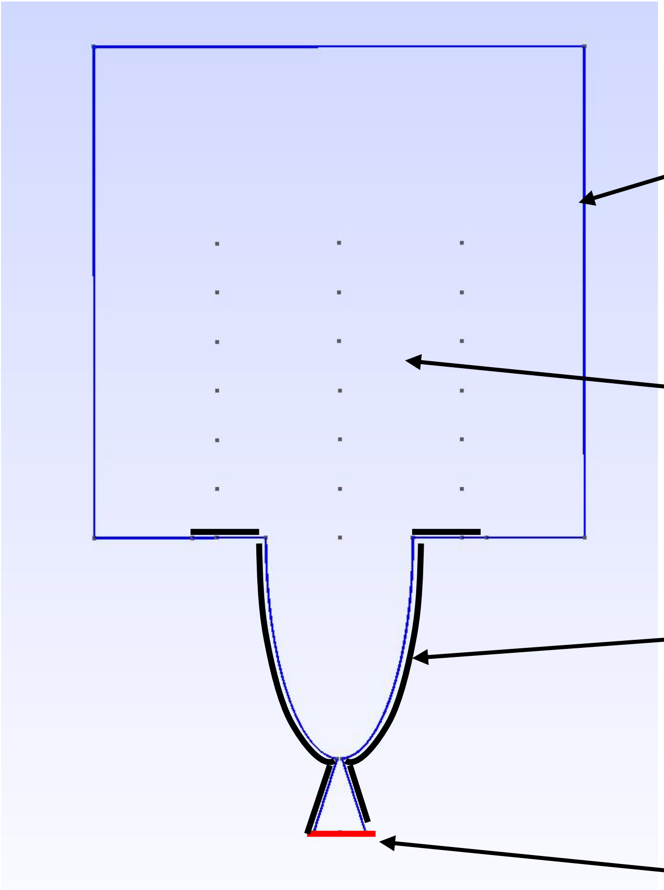
Mesh resolution at the throat: ~50 points

Size of the .msh file: 3.6 MB



Gas jet simulation: Boundary conditions

Boundary conditions:



Outlet: wave transmissive boundaries

Inner space: initial uniform pressure (‘environmental pressure’)

Gas jet: wall conditions

Inlet: pressure ramp from environmental pressure to 200 psi
It reaches target pressure after 1 us

Gas jet simulation: OpenFOAM solver

The so-generated geometry can be uploaded in OpenFoam for the simulation

Solver
It has been used **rhoCentralFoam**.
Turbulence model: Reynolds Averaged Simulation (**RAS**), **kepsilon**

rhoCentralFoam.

- is a **density-based** solver designed for transient simulations of **compressible** flow.
- It handles laminar and **turbulent** flow.
- It is suitable for transonic and **supersonic** flow, including shock waves
- **Single-phase** simulations
- Allows for **solver limiters** which improve the stability (Velocity and Temperature limiter)

Recommended applications:

Solver: rhoCentralFoam

Application

Aerospace

- High-speed Aircraft Aerodynamics
- High-speed Airplanes Wing Profiles
- Rockets Entry to the Atmosphere

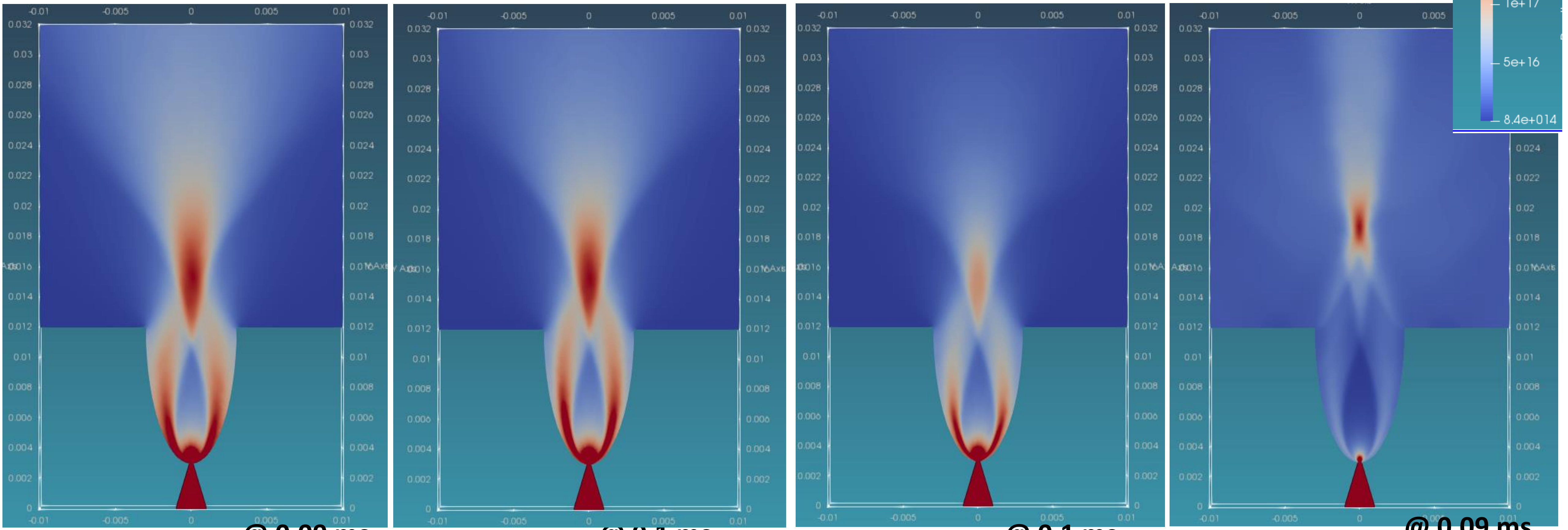
Military

- Bullets and Missiles
- Converging-diverging Nozzles in Engines

Gas jet simulation: tests with different background pressure

Qualitative density distribution by varying the chamber pressure. The backing pressure was set to **200 psi**.

7E-3 Torr | **7E-2 Torr** | **0,7 Torr** | **7 Torr**



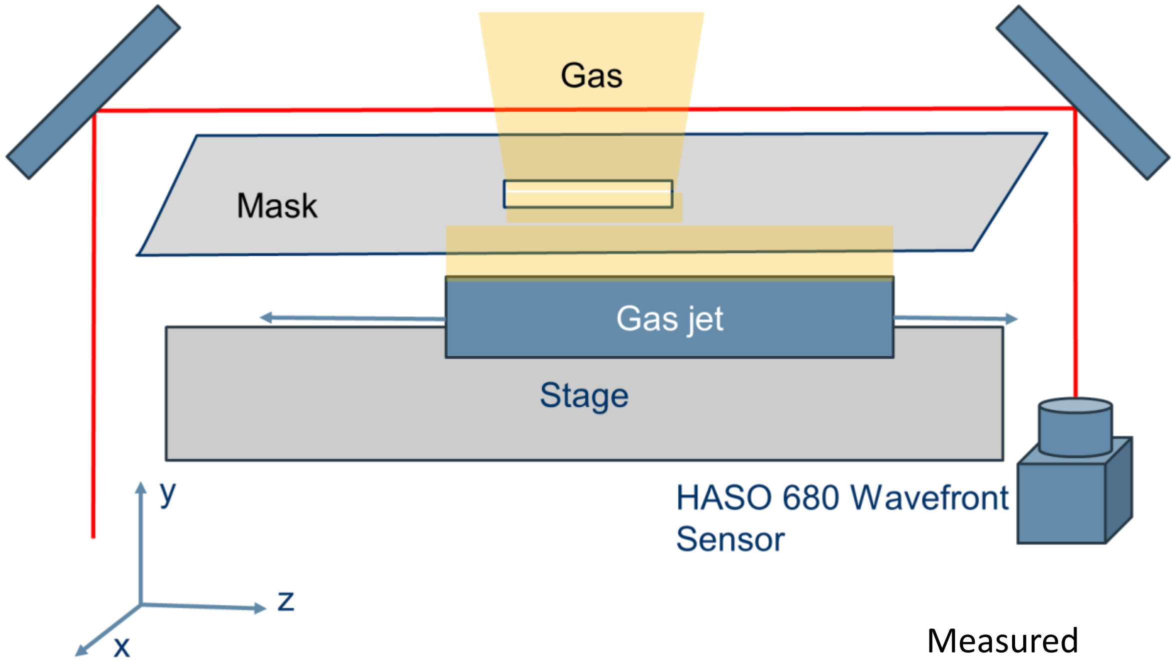
@ 0,09 ms | **@ 0,1 ms** | **@ 0,1 ms** | **@ 0,09 ms**

Simulations need to run further to verify that the flow reached the steady state.

It seems a dependency of the focus position on the environmental pressure.

Gas jet measurements: neutral density measurement

A high-resolution wavefront sensor (Imagine Optic HASO LIFT 680) was used to measure the phase offset caused by the different index of refraction between the neutral gas and vacuum.



- A thin metal plate with a small (~few cm's) hole is used as a mask to only allow gas flow above a specific part of the gas jet
- By blocking most of the gas flow with the mask, the longitudinal gas density profile can be measured
- By measuring the phase difference between gas and vacuum, the density of the gas can be determined
- Gas jet was moved at different position under the plate, to scan different positions along the gas jet.

Gas density can be calculated with the following formula:

$$n(x,y) = \frac{2\varepsilon_0}{\alpha}\frac{\phi(x,y)\lambda}{2\pi L}$$

Measured phase shift ($\phi(x,y)$)

Laser wavelength (λ)

Length o the hole in the mask (L)

polarizability of the gas (α)

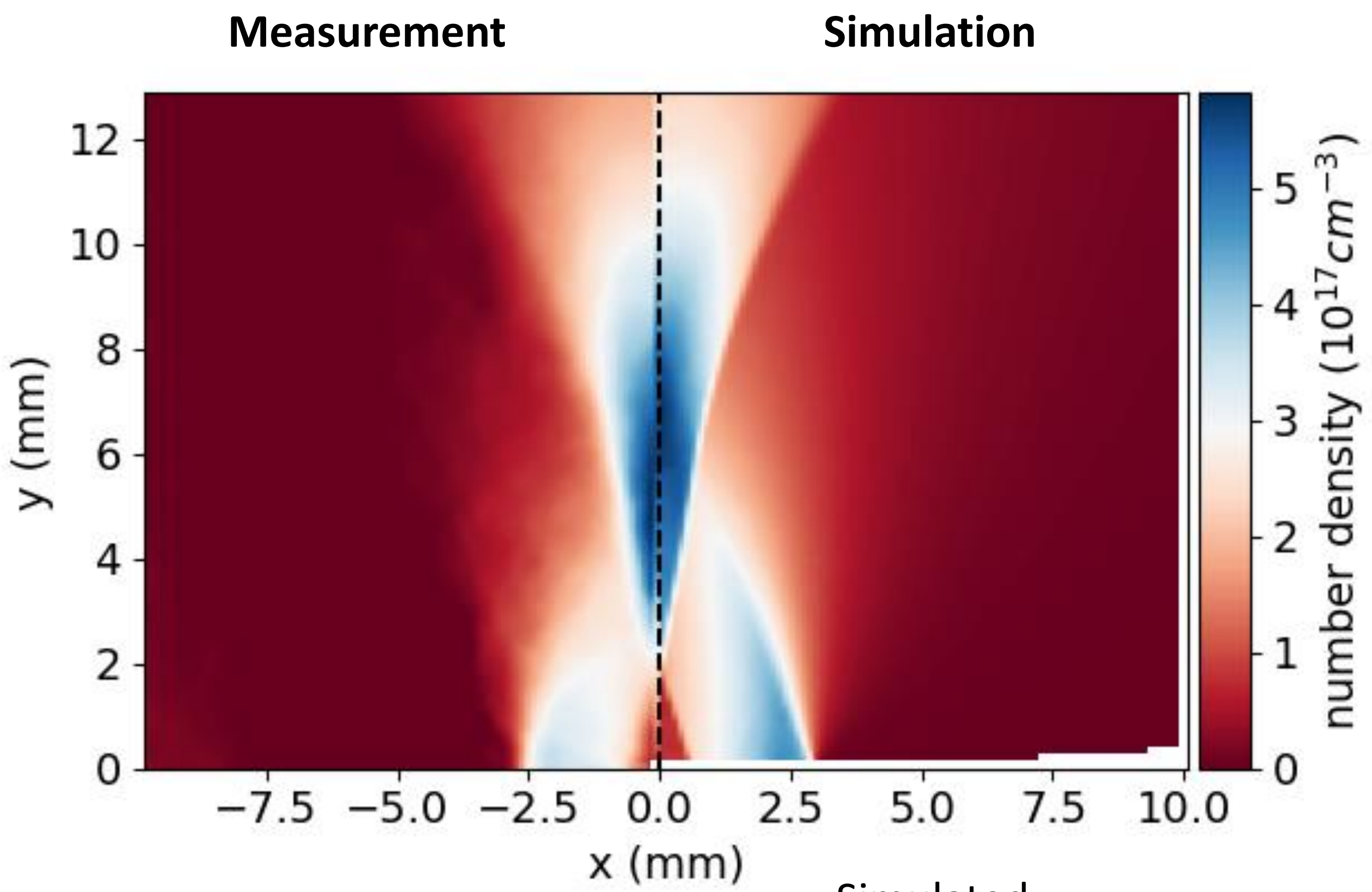
We used HeNe CW laser (633 nm)
N^2 gas

$\alpha \simeq 19.62\times10^{-41}$ F m^2

R. Li et al. Development and characterization of meter scale gas jets suitable for ≥10 GeV electron acceleration in HOFI plasma channels. AAC 2024

Preliminary results: comparison with measurements

Qualitative agreement between the simulations and the experimental measures has been achieved.



Simulated density divided by 10

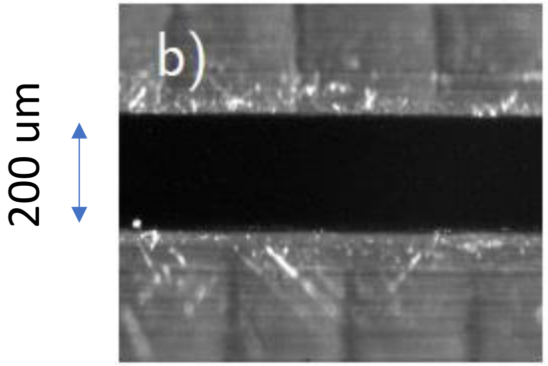
Image made by **Raymond Li**.

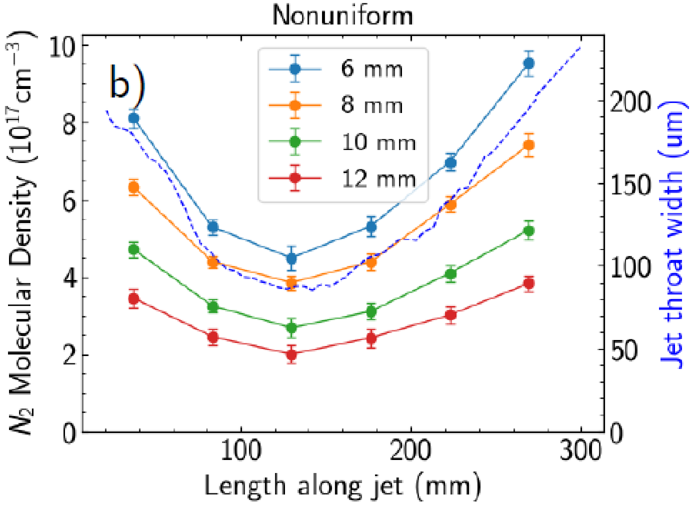
R. Li et al. “Longitudinal tapering in meter-scale gas jets for increased efficiency of laser plasma accelerators”. TBP

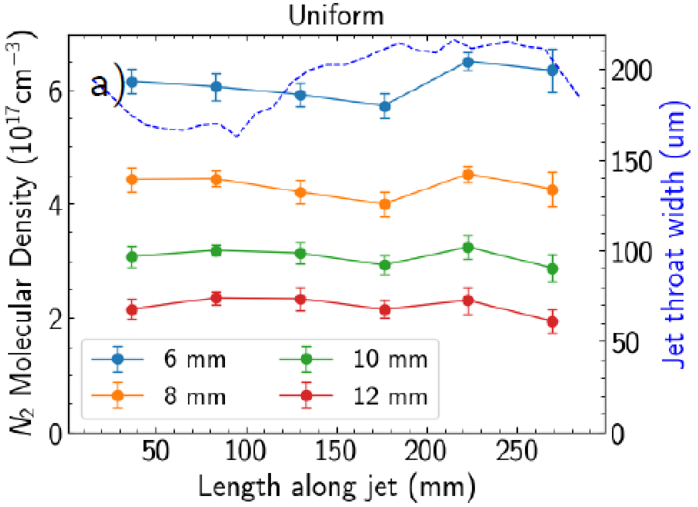
Preliminary results: fine tune of the throat width

We measured the actual aperture of the throat with a microscope, then we finely adjust it to obtain a uniform aperture along the gas-jet.

Microscopic image of the throat







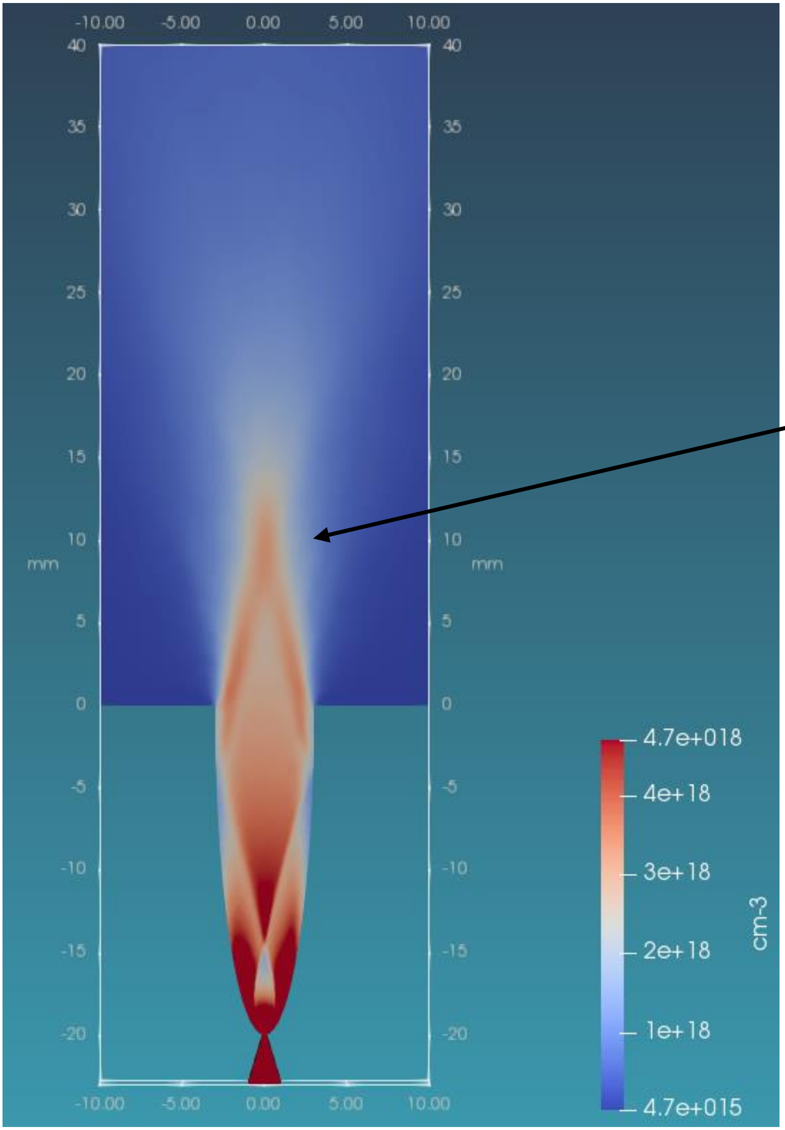
There is a linear correlation between nozzle throat width and molecular density

The data indicate there are two simple methods for varying the density profile:

- changing the throat width
- tilting the gas jet.

By tilting a constant throat width nozzle, we can achieve a linearly tapered density profile.

Ongoing: simulation of new geometries

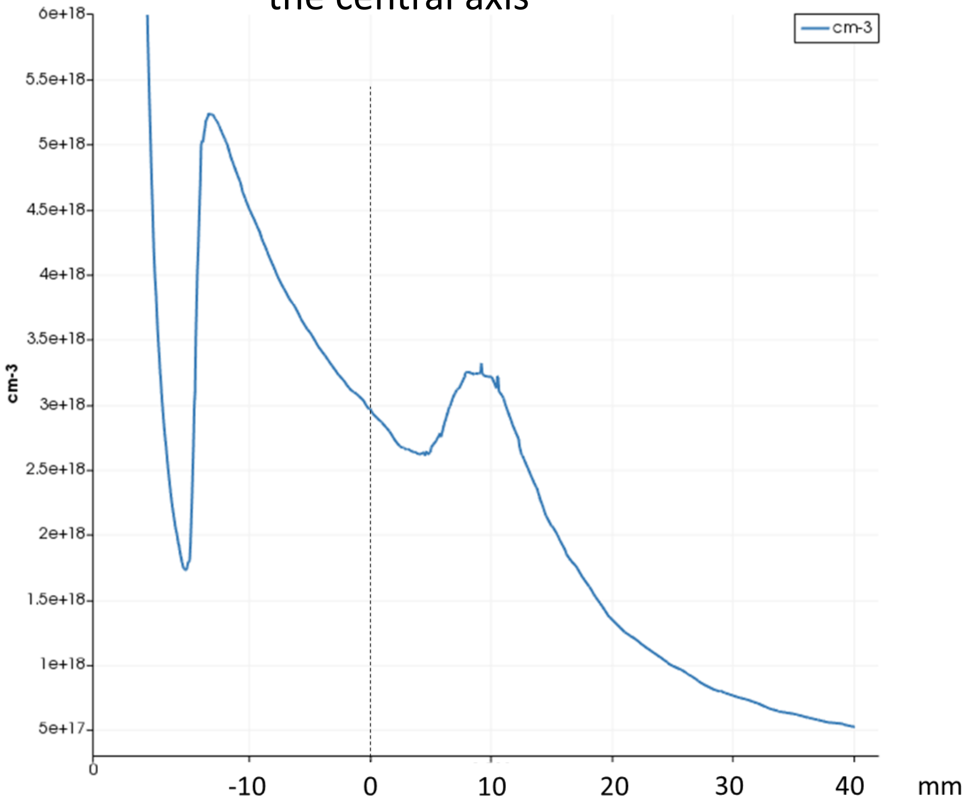


We simulated other “bell-shape” gas-jet varying the length of the “bell”.

Simulations are ongoing, here there is the result of a 20 mm long bell.

There is a density “focus”.
Max density about 10 mm over the gas jet edge

Molecular gas density in the central axis



Conclusion and next steps:

1. We set up a tool for the simulation of gas jets profiles for 2D (3D) geometries which qualitatively matches the gas profile of the measured gas-jet

2. We measured the gas density profile along the gas-jet and we studied the effects of the throat width onto the gas density profile

3. Collaboration is ongoing. We design/simulate different geometries for further upgrades (and vacuum «trap» is one of the possible future topic)

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THANKS FOR YOUR ATTENTION!

FFilippi@lbl.gov
Francesco.Filippi@enea.it