Ion acceleration by ultrafast, relativistically intense CO_2 laser at BNL: A new window into laser plasma

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USA
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BNL: ***Igor Pogorelsky (Head of experiments), Vitaly Yakimenko, Markus Babzien, Michael Polyanskiy*** **Experiment**

University of Maryland ***Galina Dudnikova,*** **Computer simulations**

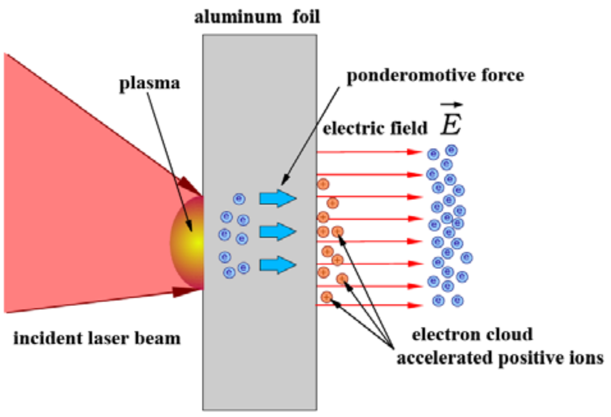
UK
University of Strathclyde, Glasgow: ***Paul McKenna, David Carroll*****, Experiment**
Rutherford Appleton Lab, Central Laser Facility, Oxford: ***David Neely*****, Experiment**
Imperial College, London: ***Zulfikar Najmudin, Charlotte Palmer, Nick Dover, A. E. Dangor,*** **Experiment and simulations**

Germany
Heinrich-Heine-Universitat Dusseldorf : ***Alexander Pukhov, Min Chen*****, Theory**
Max-Planck-Institut fur Quantenoptik: ***Joerg Schreiber*****, Theory**

Laser ion acceleration in thin solid films: TNSA

Acceleration by ***ultrashort-pulse***, ***relativistically intense*** lasers:

•multi-MeV
•collimated
•high-intensity
proton/ion beams



Vast majority of experiments so far:
λ~ 1 μm, ***linear polarization***
Thin (~ μm) solid film target

TNSA the main mechanism until high intensity 10^{23} W/cm^2

Laser beam accelerates electrons in plasma near the surface of a thin solid film and pushes them through the target.

*Emerging from the **cold rear surface**, electrons create a strong charge separation field, which ionizes target atoms and pulls out*

CO_2 laser at BNL: new horizons

Relativistically intense CO_2 lasers available for decades
BNL: first **picosecond** TW laser at 10 μm

Modest-size alternative to "national facility" solid-state lasers:
same hot electron energy ***($I\lambda^2$)*** at 1/100 of laser intensity

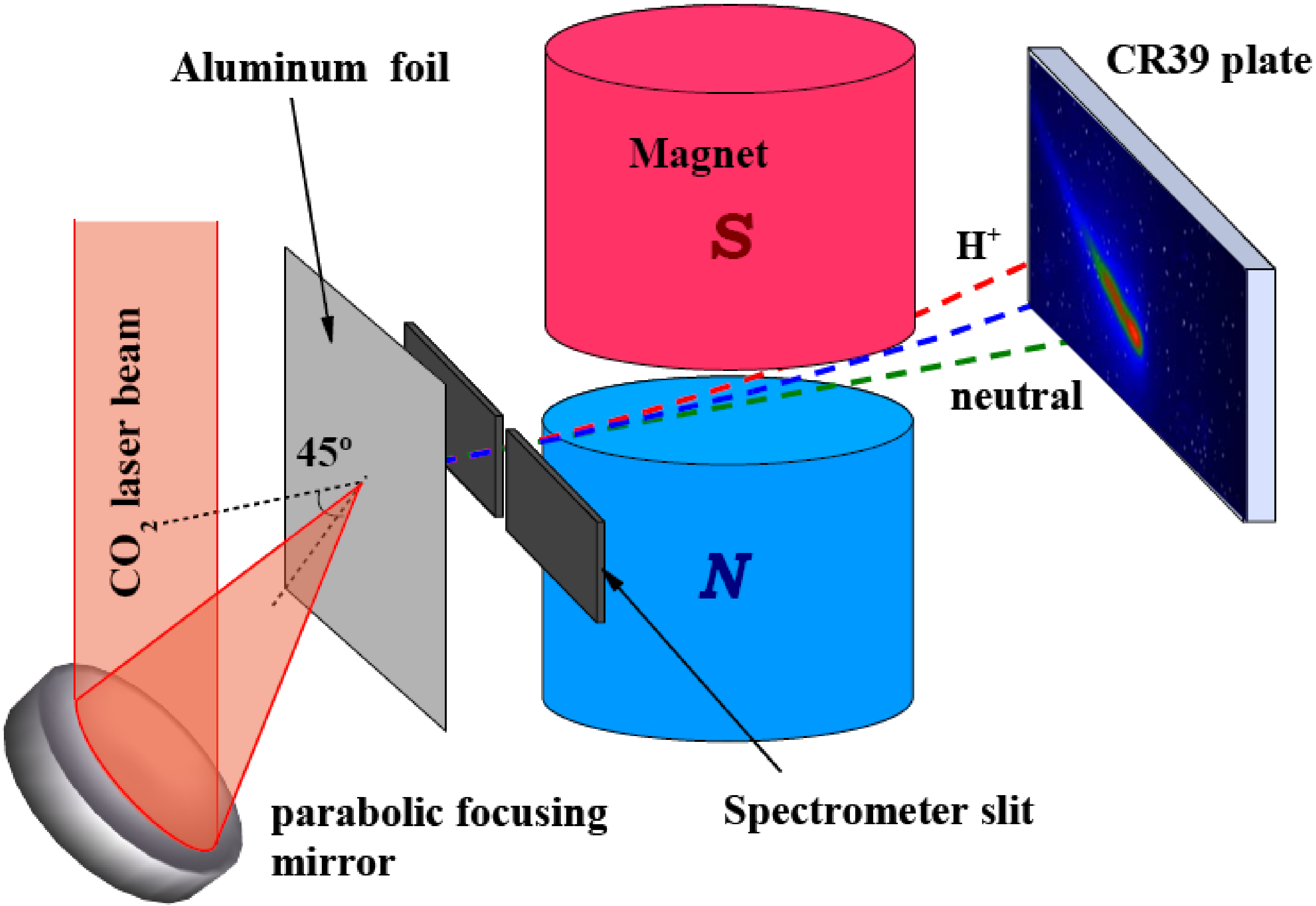
New domain in ultrashort high-intensity laser-matter interactions:
10 times larger wavelength

New road in the race to **practical laser ion accelerators**

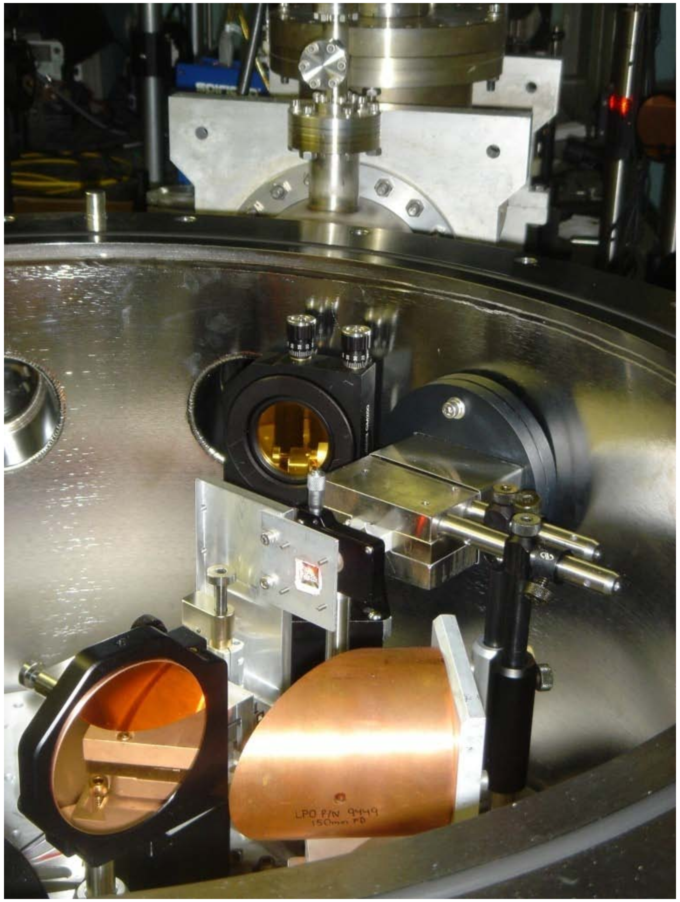
Our laser today:

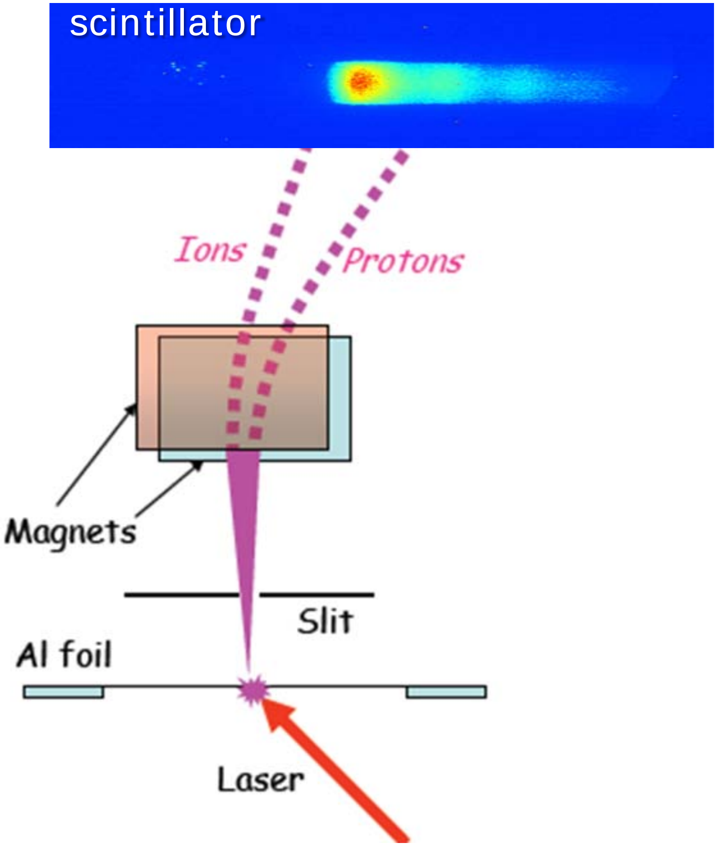
5J in 5 ps, 1 TW; focused intensity $I \sim 10^{16}$ W/cm^2
Ponderomotive potential of a λ= 1 μm laser at $I \sim 10^{18}$ W/cm^2
Inherently **circular polarization**

Setup for ion acceleration in thin foils



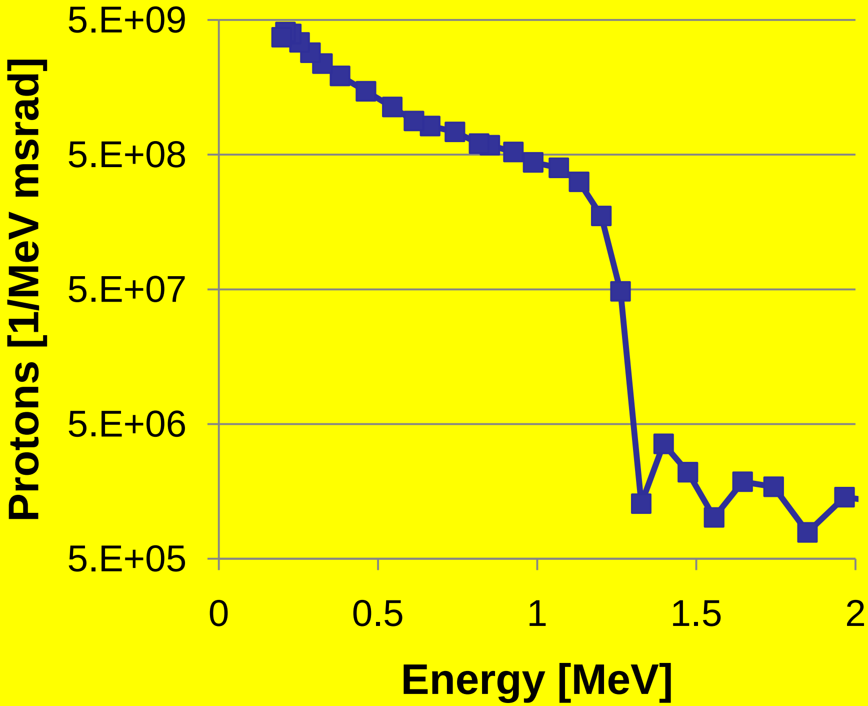
Circularly polarized laser beam in Al foil



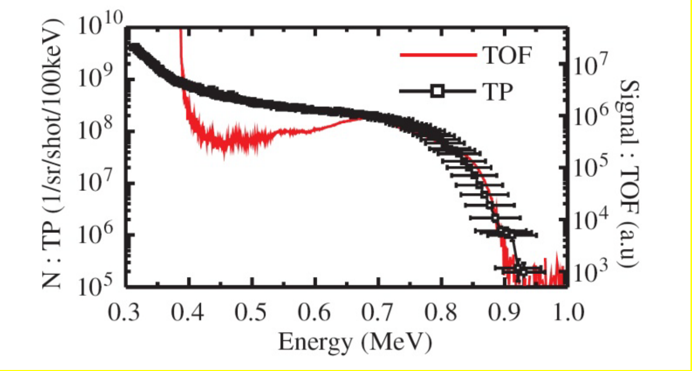


Old experiments with a new laser: Proton acceleration in a metal foil

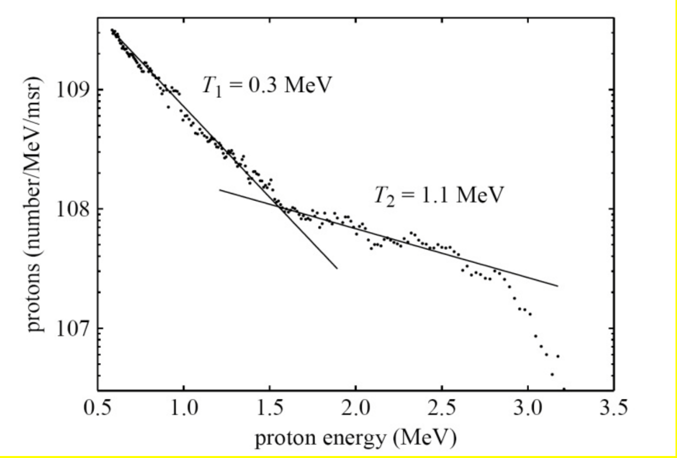
CO_2 laser 10^{16} W/cm^2, 3 J



S. Nakamura, 10^{18} W/cm^2, 0.35 J



P. McKenna, 10^{19} W/cm^2, 1 J



Consistent with $I\lambda^2$ scaling

What''s next with foils?

Continue to investigate the ***parameter space*** of laser acceleration in foils by **10 μm** laser for:

- higher laser power
- higher laser energy
- shorter laser pulse
- higher pulse contrast

as they become accessible. And for:

- thinner foils
- structured foils
- multi-component foils

Circular (native) and linear polarization

New target: gas jet

Why gas jets?

Exciting prospect to investigate **overcritical** laser plasma with **optical** diagnostics
Made possible by **100 times lower** critical plasma density for 10 μm radiation :

$$10^{19}\ \text{cm}^{-3}\ \textit{vs}\ 10^{21}\ \text{cm}^{-3}\ \text{for}\ \lambda=1\ \mu\text{m}$$

Fully ionized (1 free electron per molecule) **room air** is way **overdense** for CO_2 laser but perfectly **transparent** for e. g. Nd:YAG second harmonic (green)

No TNSA here: too slow plasma gradient
Only possible for modest intensities: **Radiation Pressure Acceleration**

RPA "primer" (over-simplified, for a reason…)

How it works. In a variety of ways, still under investigation :

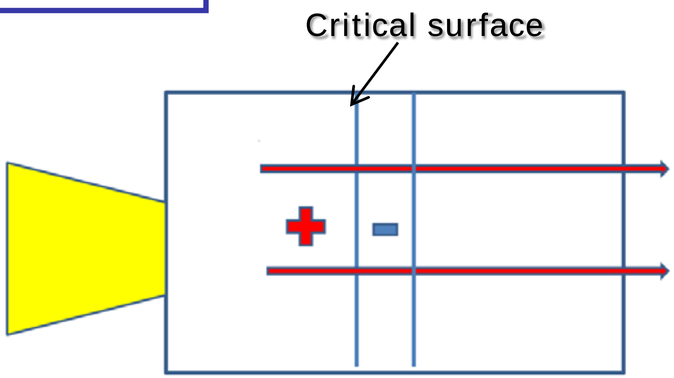
Ultra-thin targets: "light sail." Target, or a piece of it, moves as a whole
GeV/n ➔ a **"macroscopic" relativistic object on the table !**

"Thick" targets:
hole boring, shock waves, "laser piston," depending on the laser parameters

RPA in our experiments

Laser field pushes "cold" electrons inside a target, thus creating a charge separation field that accelerates ions. Further events depend on laser intensity, pulse length, target density,… --

A lot of research needed



Theory, simulations, and some experimenting with solid targets →

RPA dominates for circularly polarization (RPA-CP):
Circularly polarized light almost incapable of accelerating electrons

RPA-CP:
Quasi-monoenergetic ions
For short laser pulses, the ions acceleration occurs near the wave-breaking point, where all ions have ~ same energy

Many faces of RPA-CP

Two regimes:
"hole boring" for thick targets (non-transparent)

Maximum proton energy

$$E_{max}(MeV) \approx 4\ (n_{crit}/n_e)\ a_0^2$$

with $n_{crit} \sim n_e$ *(based on A. Macchi, T. Lyseikina, et al)*

→ ***linear (fast) scaling with intensity***

Quite tolerant of: **lower pulse contrast**
imperfect circular (ellipticity)
larger plasma gradient

The **first experiments** on RPA-CP(A. Henig et al, 12/2009: damage to ultra-thin target masked RPA benefits)

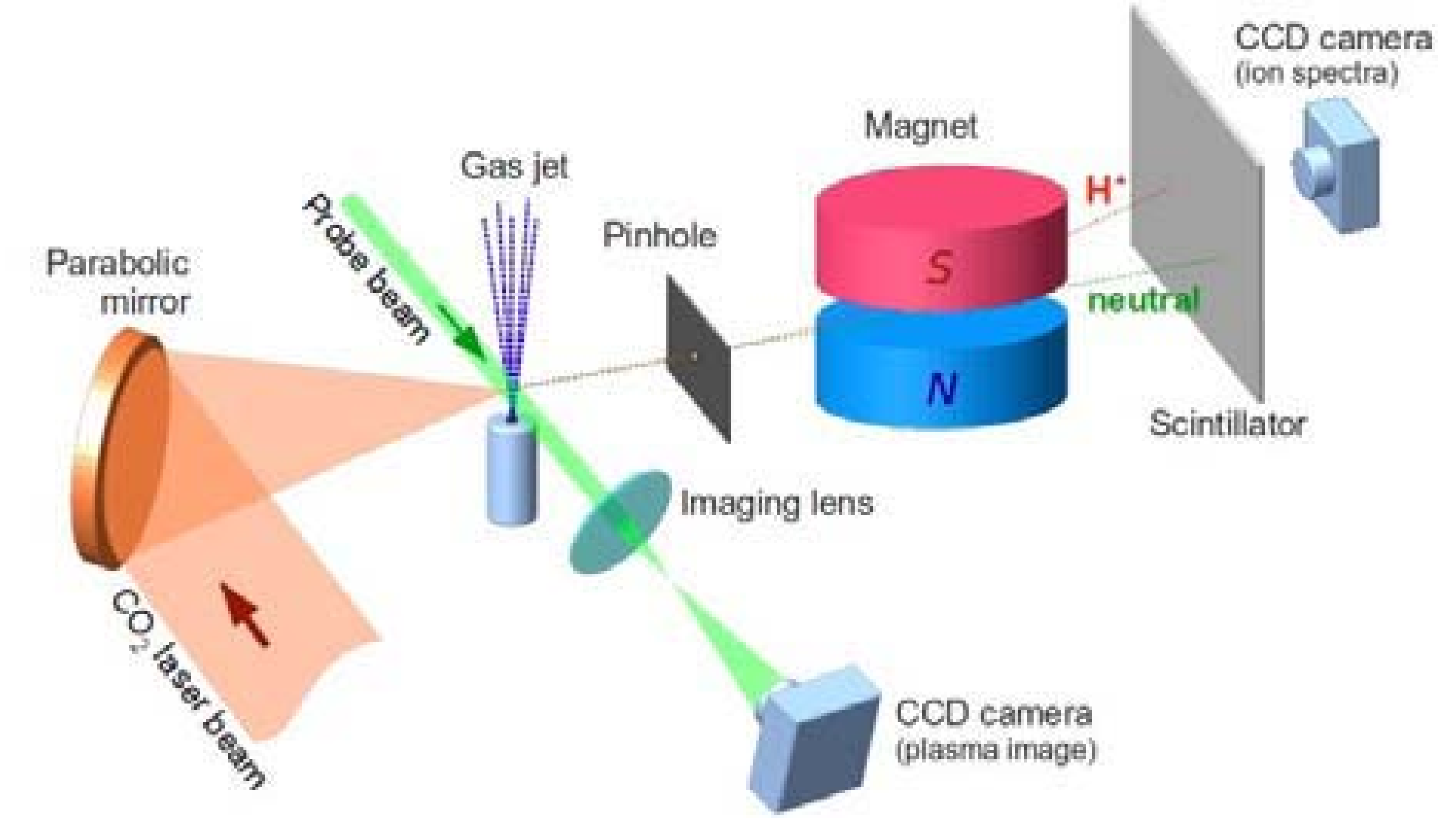
More gas jet benefits and conveniences

Available for CO_2 lasers only ☺

- **Can use H (that is, pure protons), He, and other species difficult to make solid**
- **Easily operate near critical density (higher maximum energy)**
- **Easy to pre-ionize in a controllable way**
- **Little debris after each shot**
- **Allow for quick change of target material**
- **Can run at high laser repetition rate.**

BNL CO_2 laser in hydrogen gas jets

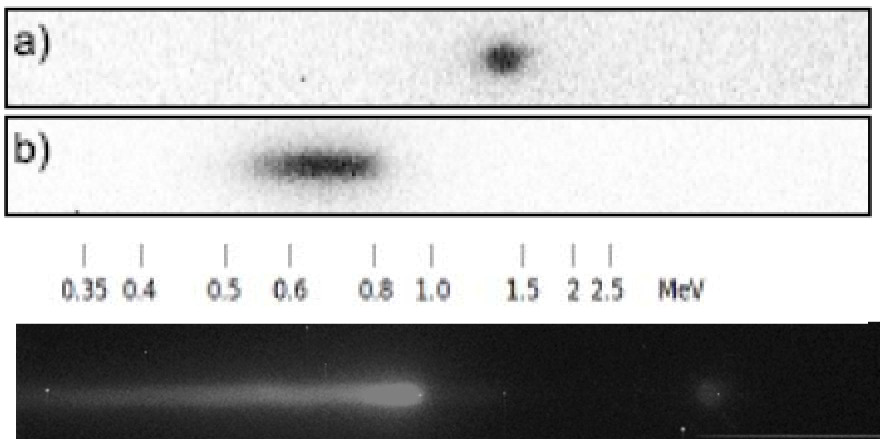
CO_2 laser: 5J in 5 ps; ~10^{16} W cm^{-2}
Hydrogen gas jet of (3-5)x10^{19} cm^{-3} →
Proton beams with energy in a **narrow range around 2 MeV,** in a reasonable agreement with RPA-CP predictions



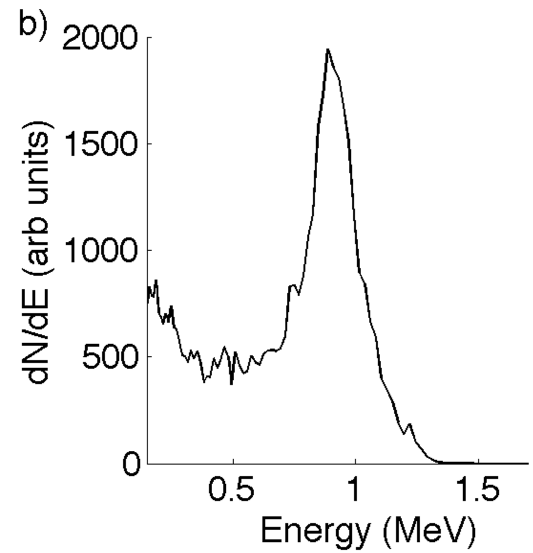
Proton energy spectra

Experiment

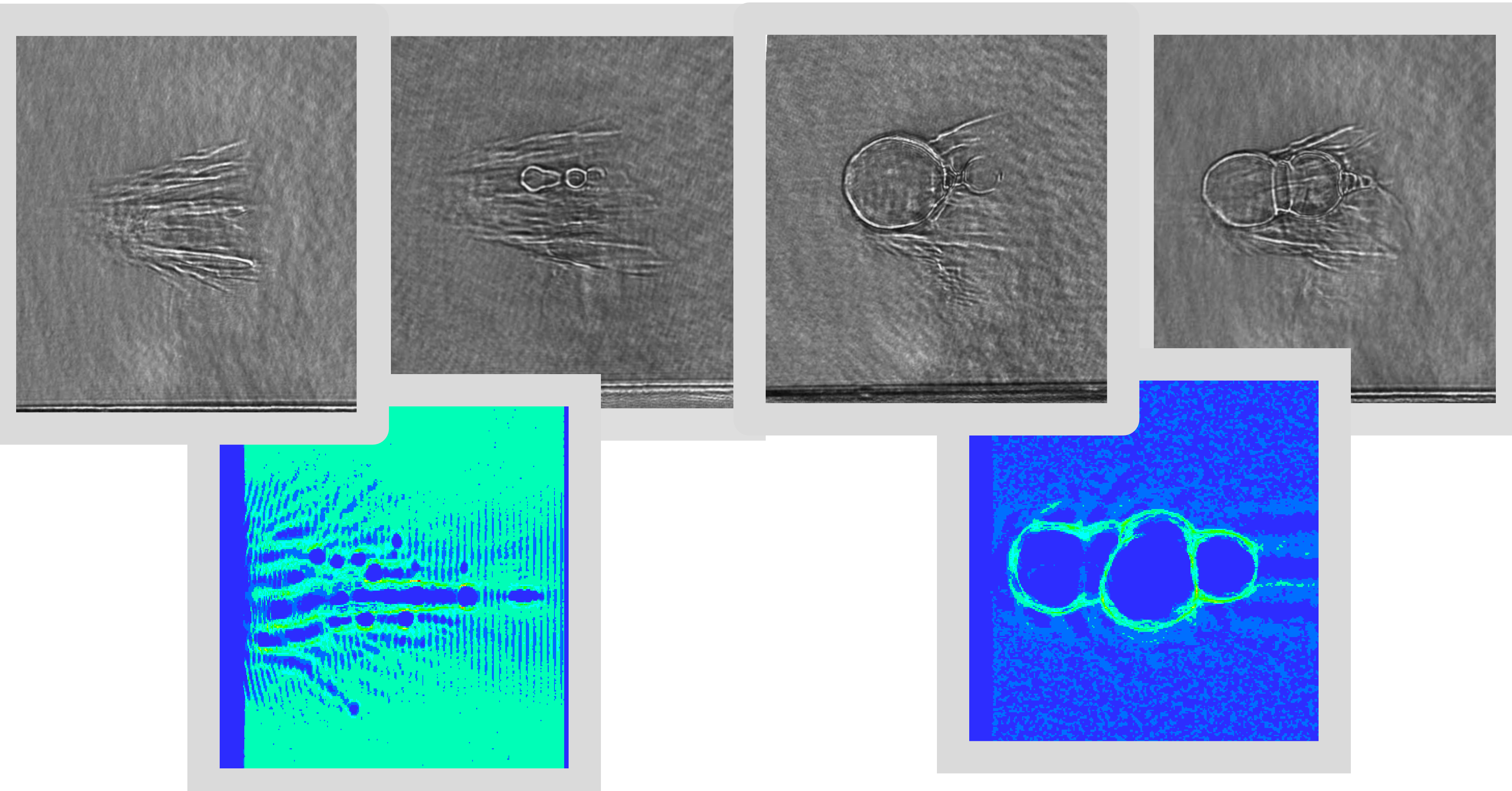
Top two images: RPA in gas jet
Bottom: TNSA in solid film



Simulations



Done with expected. Now – surprises (as announced at the start)



Plasma formations observed in experiment (upper raw) and simulated (bottom row)

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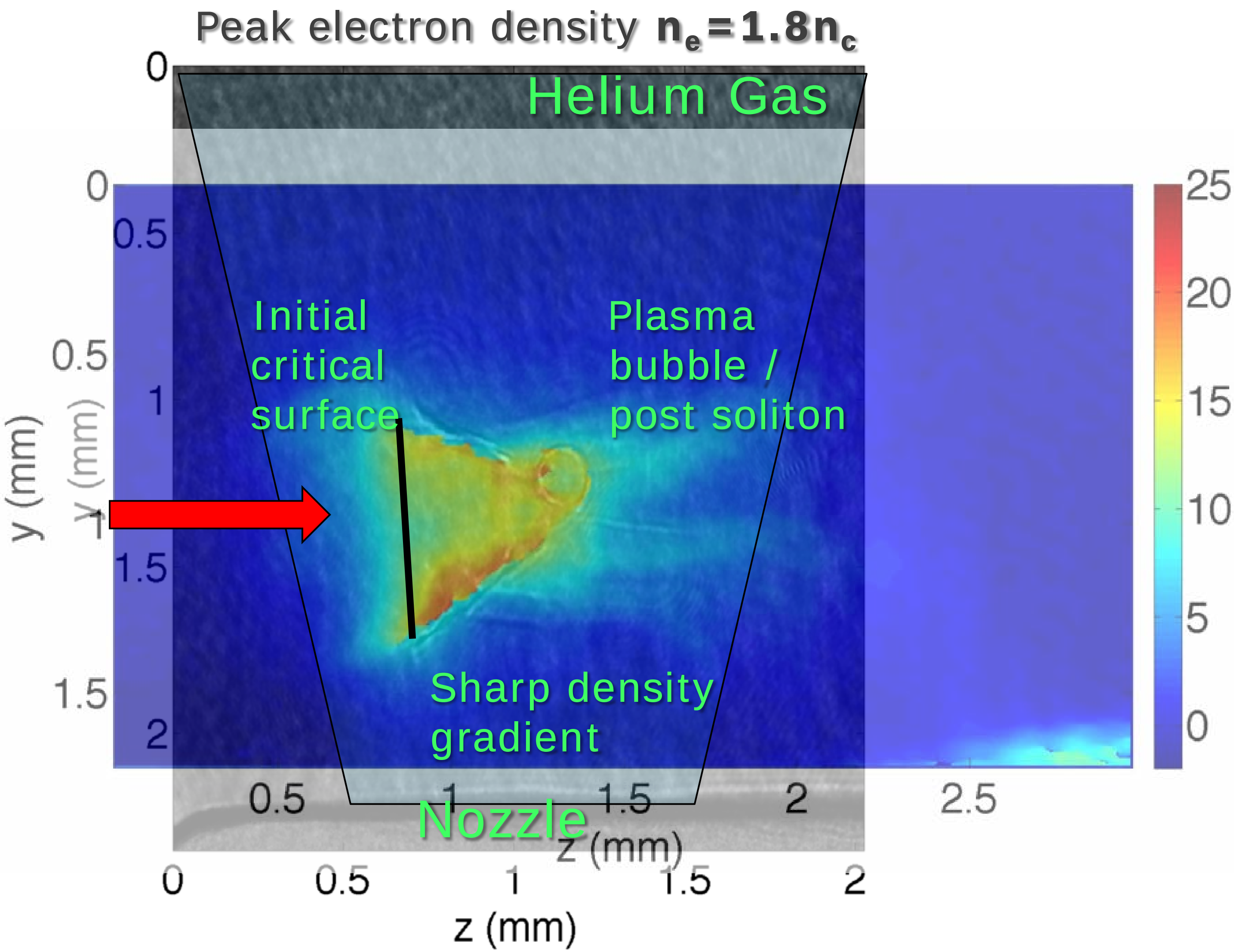

So, what is it? Laser-plasma solitons and post-solitons

Numerous predictions of **soliton formation**, for various conditions, below and above critical density.
In particular: solitons due to **relativistically-induced transparency** *(..., M. Tushentsov et al, 2001;.. A. E. Kaplan, 2010)*

-- Formed in **modestly over-critical plasma** $n_{crit} < n_e < 1.5 n_{crit}$

-- A few λ's in size, **stationary** (almost unmoving) on electron time scale

-- **Bubbles** of low electron density but **very strong EM field**

-- On ion time scale, grow into larger **post-solitons** *(N. M. Naumova et al, 2001)*

As with most anything, **very difficult to observe in solid-density plasma**
Indirect possible observation of post-solitons *M. Borghesi et al, 2002*

Most likely, **nothing to do with the ion acceleration**. But:
a good example of new effects we will **see** in overdense gas jet plasma

Ion acceleration by ultrafast, relativistically intense CO_2 laser at BNL: A new window into laser plasma

- **First ever** experiments on proton and ion acceleration by ultrafast lasers interacting with overcritical **gas jets plasma**
- First **direct** observations of **quasi-monoenergetic** protons accelerated by **radiation pressure**
- **First direct observations** of the plasma structures that evolved from relativistic laser-plasma solitons (post-solitons)

Plans and prospects near-term
RPA-CP in gas jets and solids
Increase the proton energy
Nature of solitons

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And a lot of other grants all over Europe