High-brightness picosecond ion beam source based on BNL TW CO_2 laser: Proof-of-principle experiments

We report initial results and the status of the

***first ever experiments** of proton and ion acceleration*

*by ultra-short, high-intensity **far-infrared** (10 μm) laser pulses in metal foils.*

***Proton energy** spectra reveal a broad but pronounced **energy peak at ~1 MeV**.*

*The peak, **never previously observed** with unstructured targets may be*

*the **first experimental** indication of direct **Radiation Pressure acceleration***

of protons by a circularly polarized laser.

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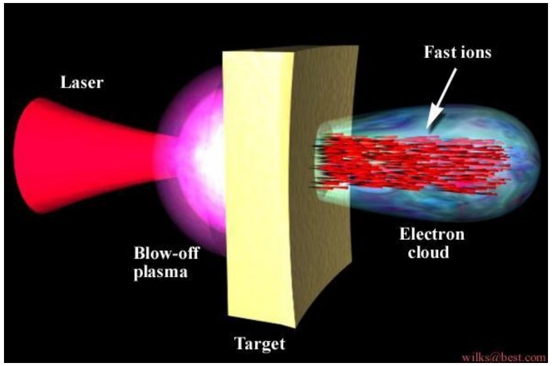
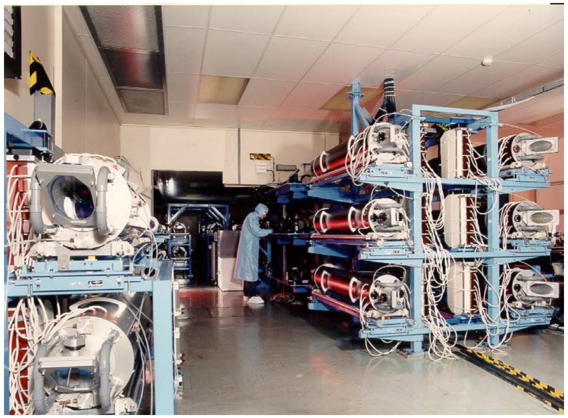
Background

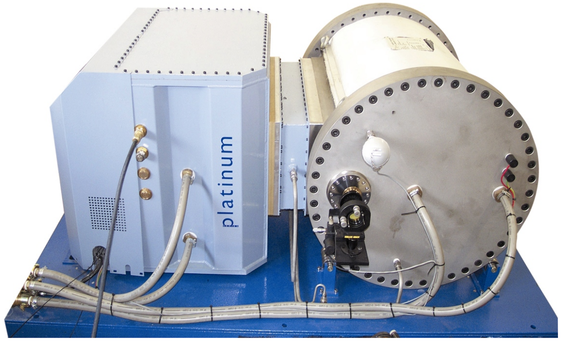
The effect
Thin foils irradiated by sub-picosecond laser pulses at relativistic intensities emit ions/protons at MeV energies in bright, well-collimated beams.



The current status of the field
Ultra-fast solid state lasers, at λ ~ **1 μm;**
usually **national facilities**.
Proton and heavier ions at 25-100 MeV (potentially GeV) at intensities 2 orders of magnitude larger than those at conventional accelerators.

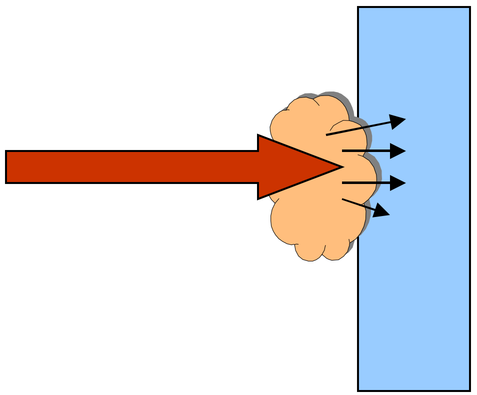


We propose
To build and study **a high-brightness multi-MeV ion and proton beam source** driven by the unique **picosecond TW CO_2** laser available at the ATF.

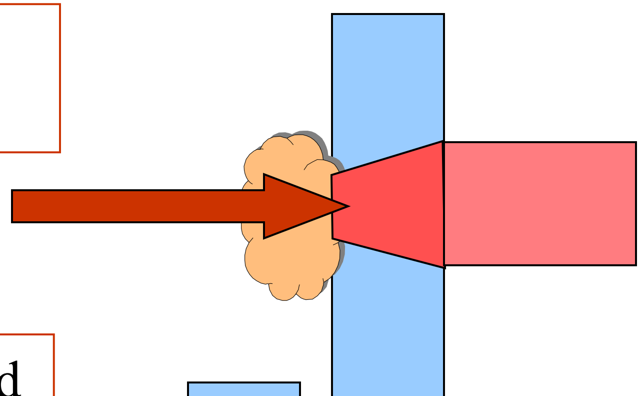


Physics of ion (proton) acceleration by a laser in a foil target: TNSA

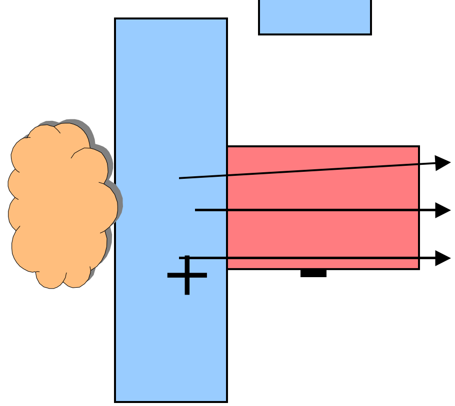
Stage 1. On the target surface, the laser beam creates plasma with **relativistic** electrons **moving into** the target



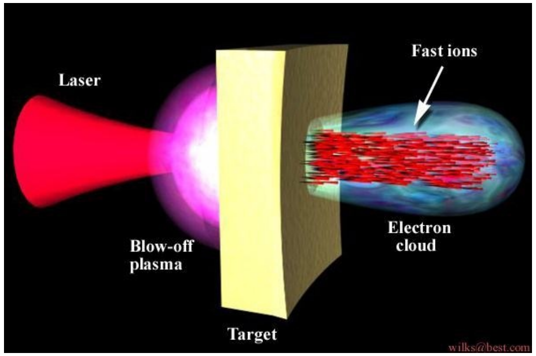
Stage 2. Relativistic electrons propagate through the target and form a dense cloud behind it



Stage 3. Electron cloud and the positively charged target create electric field (~ 10 GV/m), which ionizes atoms of the target back surface and pulls ions (protons) out, accelerating them



TNSA with CO_2 laser



TNSA with CO_2 laser:
potential pros and cons as compared to solid-state lasers

Pros: larger wavelength and longer pulses → more electrons; relatively high ponderomotive potential
Cons: larger wavelength and longer pulses → larger electron volume; target heating

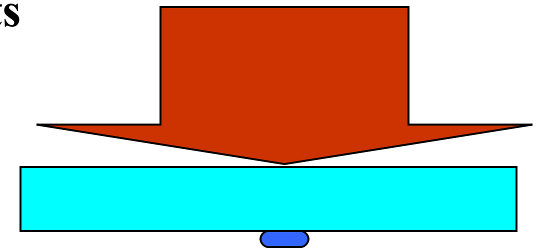
Bottom line:

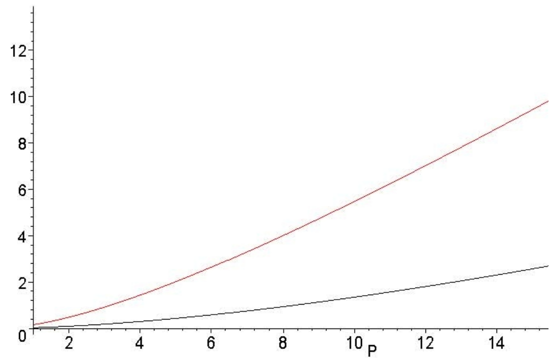
- *significant **promise** of the CO_2 laser*
- *need to thoroughly investigate **the physics in this new regime***

Unique potentials of ATF CO_2 laser

1. Uniform solid targets
Laser of moderate power
New physics: very little is known

2. Structured targets: H-rich microdots





Proton energy (MeV) vs laser power (TW). Red is for 10 µm, blue is for 1 µm

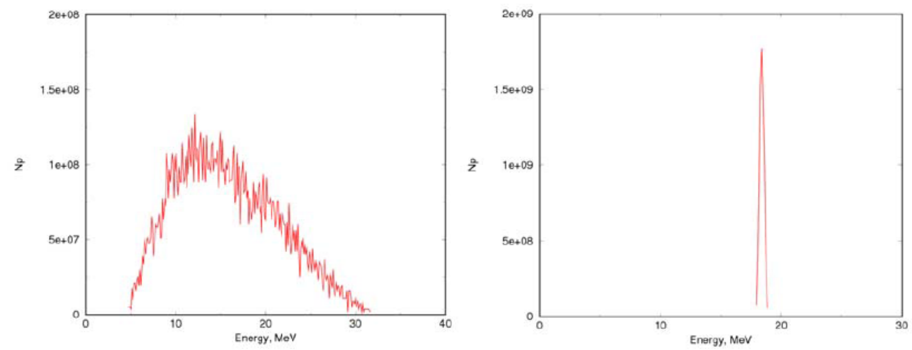
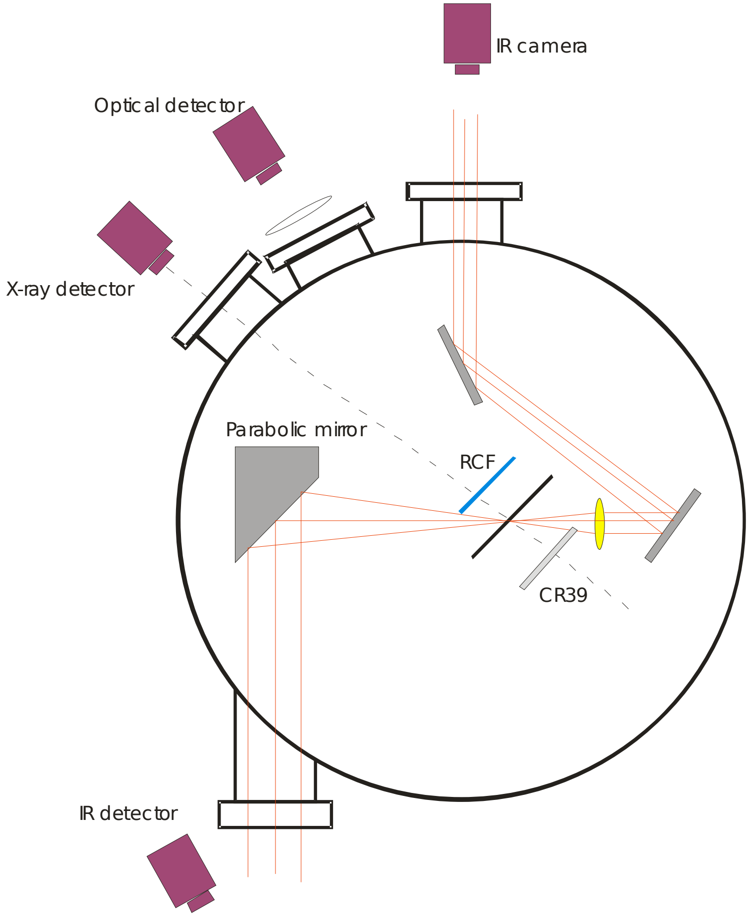
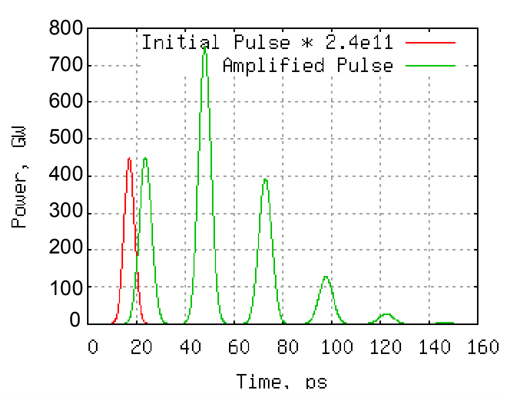


Fig. 8 Proton energy spectrum from a structured target. (a) Solid state laser with λ=1µm. (b) CO_2 laser with λ=10µm. The CO2 laser produces a much narrower proton spectrum because of the narrower phase space fill.

3. Low critical plasma density: 10^{19} cm
Gas jets as targets

Ion acceleration experiments





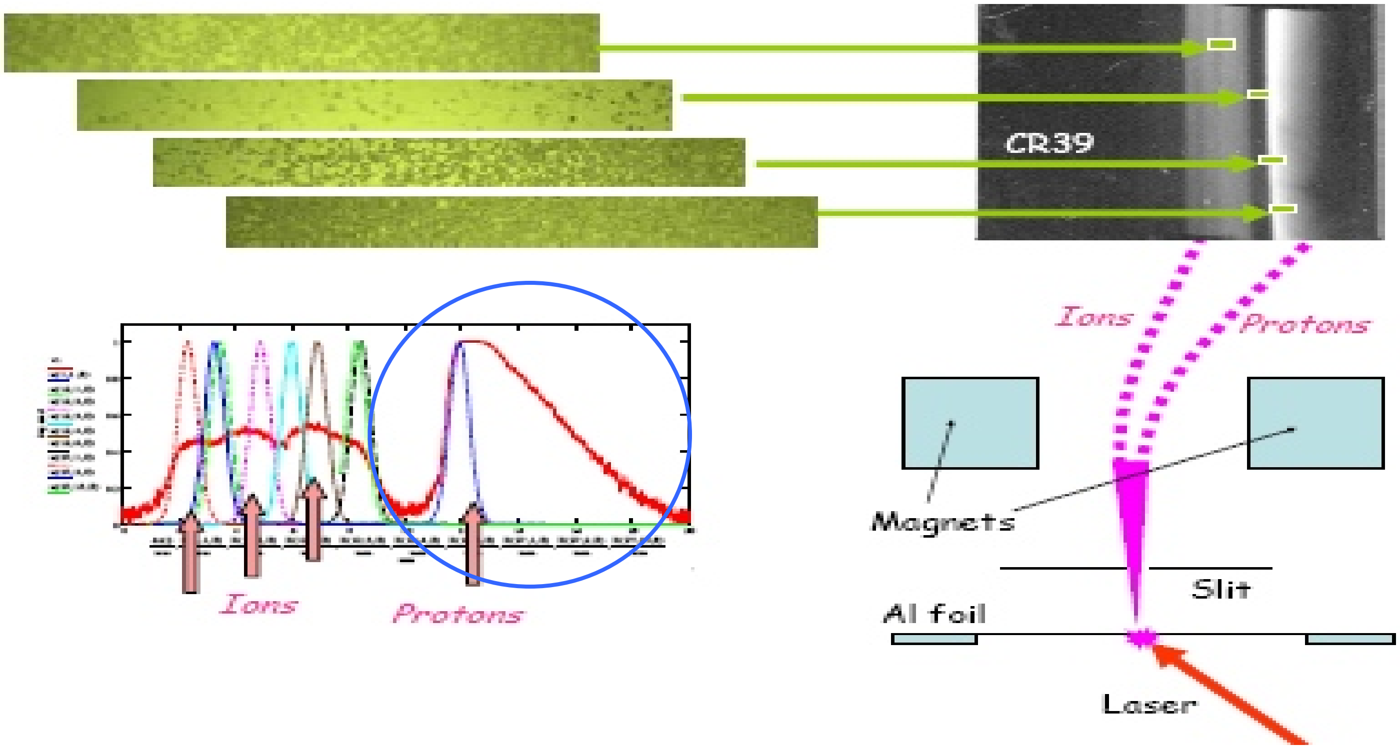
Temporal structure of the laser pulse

Circularly polarized CO_2 laser focused by an off-axis parabola #f=3 onto a 12-*m*m thick Al foil at the 45^0 incidence into a focal spot of w_0=65 microns (We plan to move to the normal incidence later)

Spectral modulation during amplification splits 6-ps seed pulse into **train of pulses separated by 20 ps**.

The 1st pulse turns part of the target into plasma; the 2nd, main pulse accelerates protons and ions.

Experimental observations



Proton and ion energies were diagnosed with a compact magnetic spectrometer followed by a CR39 plate. A density plot obtained with a scanner is overlaid with artificial peaks that illustrate the expected position and spread due to a finite spectrometer slit for the 1-MeV protons and any possible Al+n and C+n ions accelerated in the same field.

Circular vs linear laser polarization

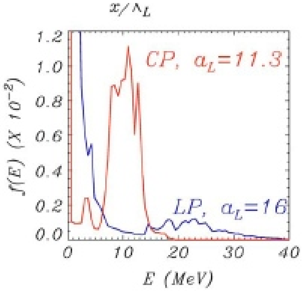
The ***peak*** nature of the proton spectra ***highly unusual*** for TNSA

Our laser radiation is **circularly** polarized → At normal incidence, electron heating suppressed → ***TNSA suppressed***

Practically **all** experiments so far – with **linear** laser polarization

Recent theoretical predictions (***T. Liseikina et al***)
Radiation pressure acceleration at the target's **front**

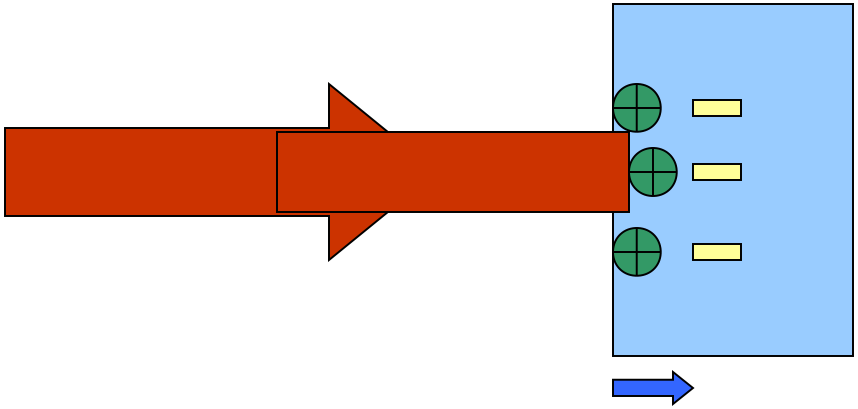
→**Peak in energy spectra; Not yet observed experimentally**



Our case **more complicated: circular polarization, but at 45^0**

Radiation pressure acceleration by a circularly polarized laser

Normal incidence: ***Very little electron heating by the laser directly***



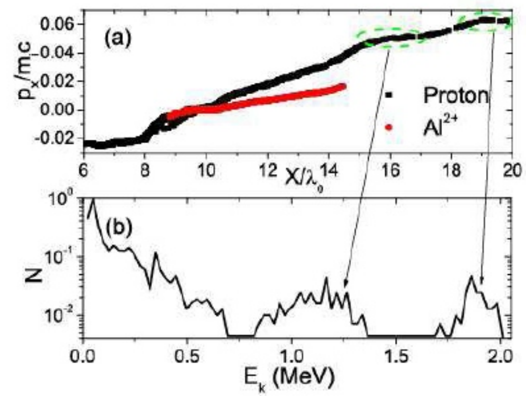
Maximum proton energy $E^p_{max}(MeV) \approx a_0^2$, $a_0^2 \approx 0.36\, I_{18}\, \lambda^2(\mu\text{m})$

Number of protons $N^p \approx \nu\pi\lambda/4\pi$

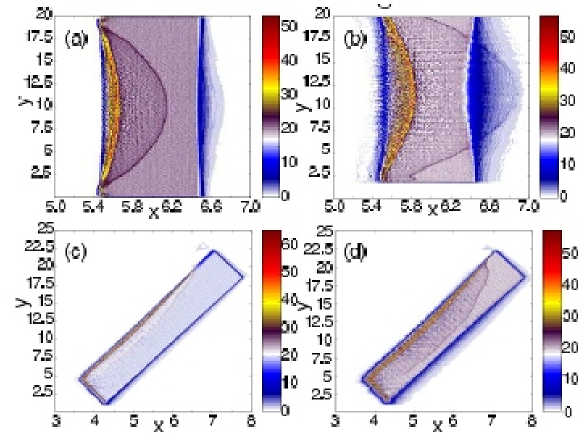
1D and 3D PIC simulations

Both mechanisms present
→ Need detailed computer simulations

1D (a) Proton and Al2+ distributions in the phase space at *t/T0* = 500. (b) Energy spectrum of the forward moving protons at *t/T0* =500



3D Distribution of ions at the time of *t/T0*=40 (a) and *t/T0*=60 (b) with the laser pulse normally incident onto the target;(c) and (d) correspond to the laser oblique incidence with the same time points



Bottom line: interplay of two mechanisms retains quasi-monoenergetic peaks

Conclusion and near-term plans

The first ever experiments of proton and ion acceleration ***by ultra-short, high-intensity far-infrared laser*** pulses interacting with metal foils.

Sub-TW, 6-ps, circularly polarized CO2 laser pulses focused onto 12 μm-thick Al foils drive ion acceleration in in the forward direction normal to the rear target surface.

The spectra of protons reveal a broad yet quite pronounced ***proton energy peak*** at ~1 MeV –never observed before with unstructured targets.

This peak may be the ***first experimental indication*** of direct RPA of protons by circularly polarized laser.

- Circular polarization at normal incidence
- Increase the laser output and futher suppress pre-pulses
- Tighter focusing
- Thomson spectrometer for ion beam diagnostics
- Real-time beam diagnostics

Work is supported by OHEP/DOE