Monoenergetic Proton Beams from Laser Driven Shocks

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Outline

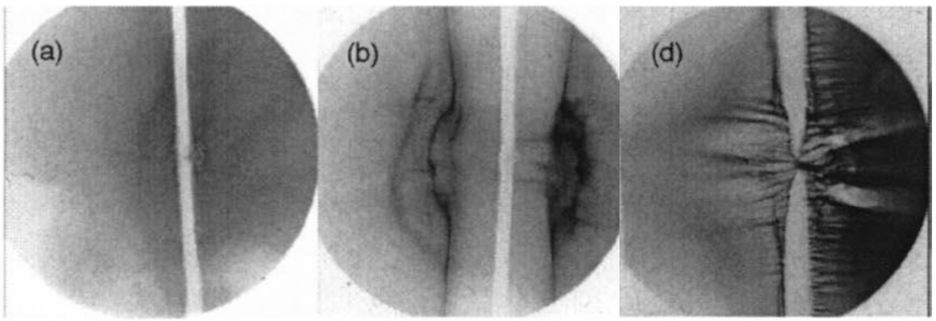
- Applications of Laser Driven Ion Acceleration (LDIA) : Hadron cancer therapy
  - Localized energy deposition : Bragg Peak
  - Therapy centers : conventional accelerators vs. lasers
  - Ion source requirements
- Collisionless Shock Wave Acceleration (SWA) of protons
  - 1D OSIRIS Simulations
  - Laser driven case
- UCLA proton acceleration experiment : CO_2 laser and a H_2 gas jet target
  - Results : Spectra, emittance
  - Interferometry : Plasma density profile
- 2D OSIRIS simulations
  - Modeling the experiment
  - Scaling to higher power lasers
  - Using 1μm laser systems
- Conclusion

Laser Driven Ion Beam Applications

Probing of strong electric fields in dense plasma on the picosecond timescale

- ~1μm resolution, 5-20MeV

- *Borghesi, Phys. Plasmas (2002)*
  - 50μm Ta wire
  - Imaging with 6-7MeV protons



-15ps -5ps 5ps

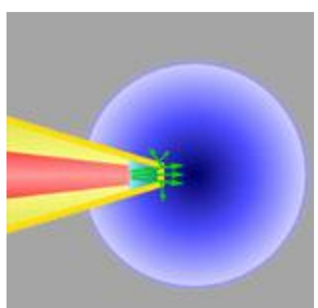
← VULCAN Laser, 20J, 10^{19}W/cm^2

Picosecond injectors for conventional accelerators

- 1-10MeV, <.004 mm·mrad, <10^{-4} eV·s [*Cowan, Phys. Rev. Lett. (2004)*]

Fast Ignition

- 15-23MeV
- <20ps
- Eff = 10%

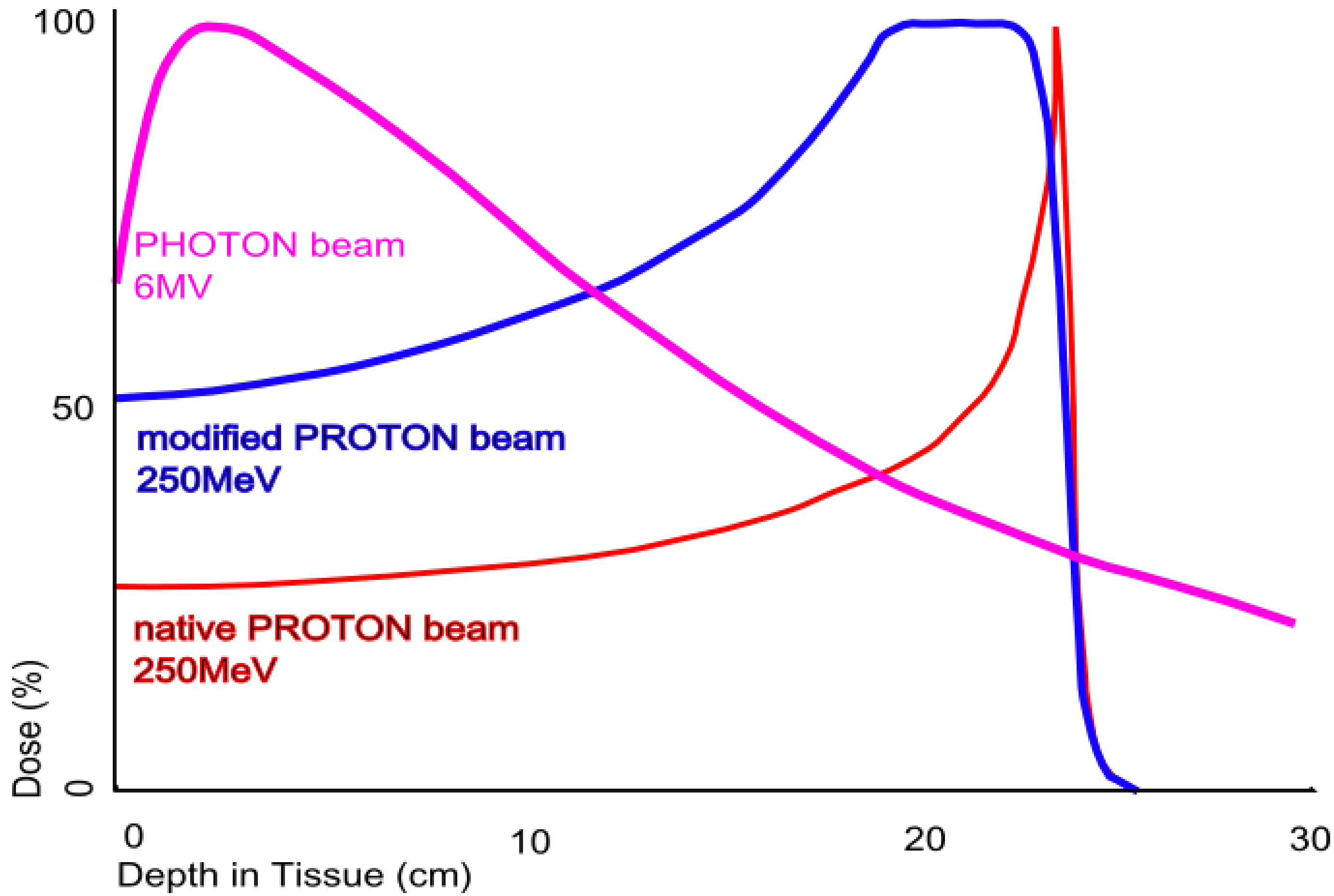


Hadron Cancer Therapy

- 250MeV, 10^9-10^{10} protons/s
- $\Delta E/E \leq 5\%$

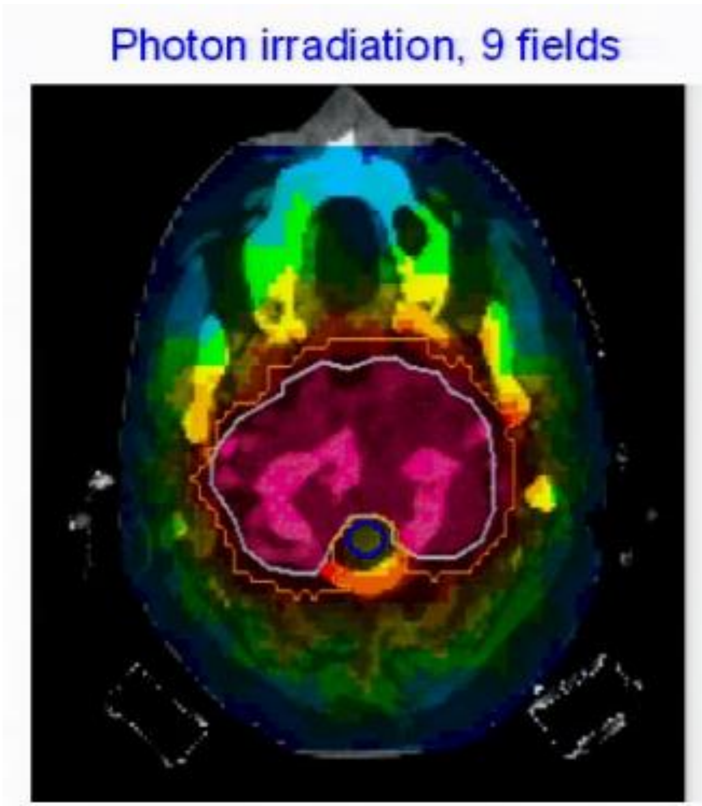
Energy Deposition : Ions vs. Photons

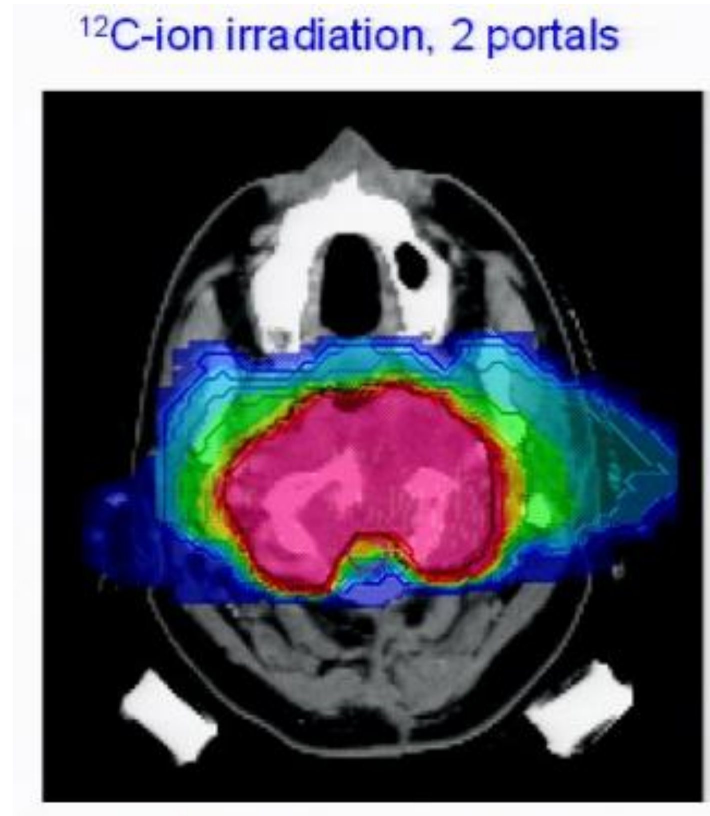
Bragg Peak for ions results in localized energy deposition



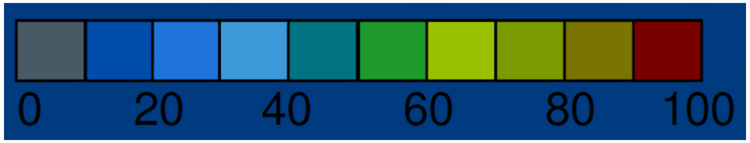
Multi-beam Localization

Simulations of Irradiating the Human Skull



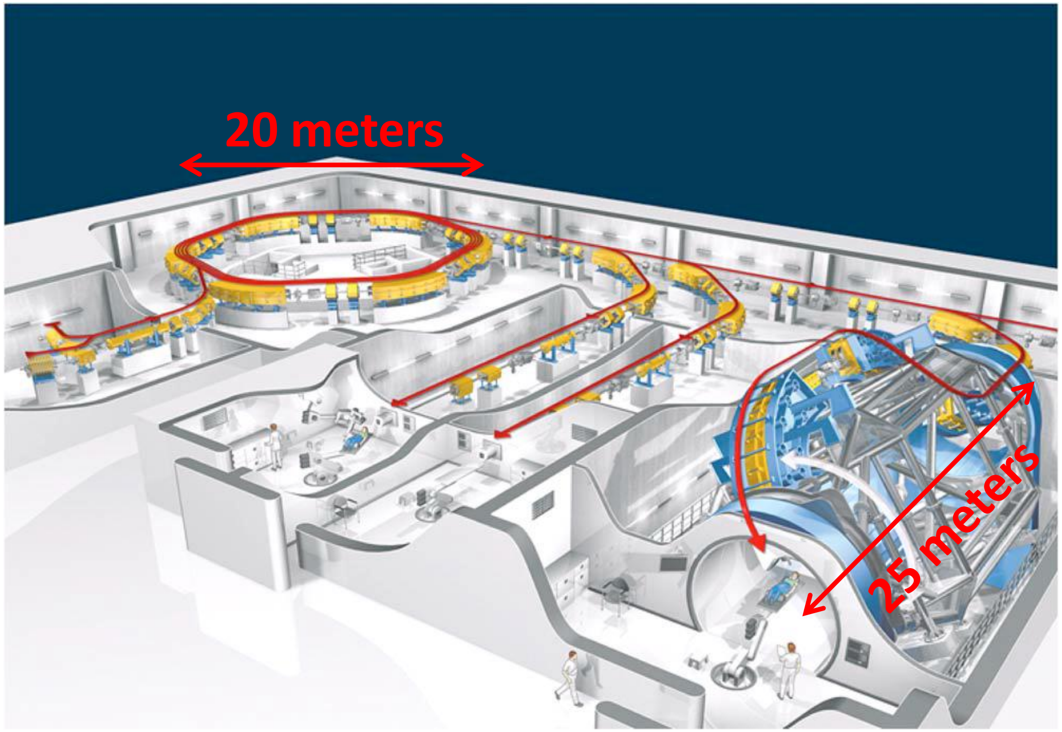


Radiation dose relative to peak (100%)



GSI Helmholtz Centre for Heavy Ion Research in Darmstadt
http://www.weltderphysik.de/gebiet/leben/tumortherapie/warum-schwerionen/

Problem : Cost and Size



Cost : ~200 Million USD

- Accelerator ring (20m)
- Transport magnets
- Complicated Gantry
- Radiation shielding

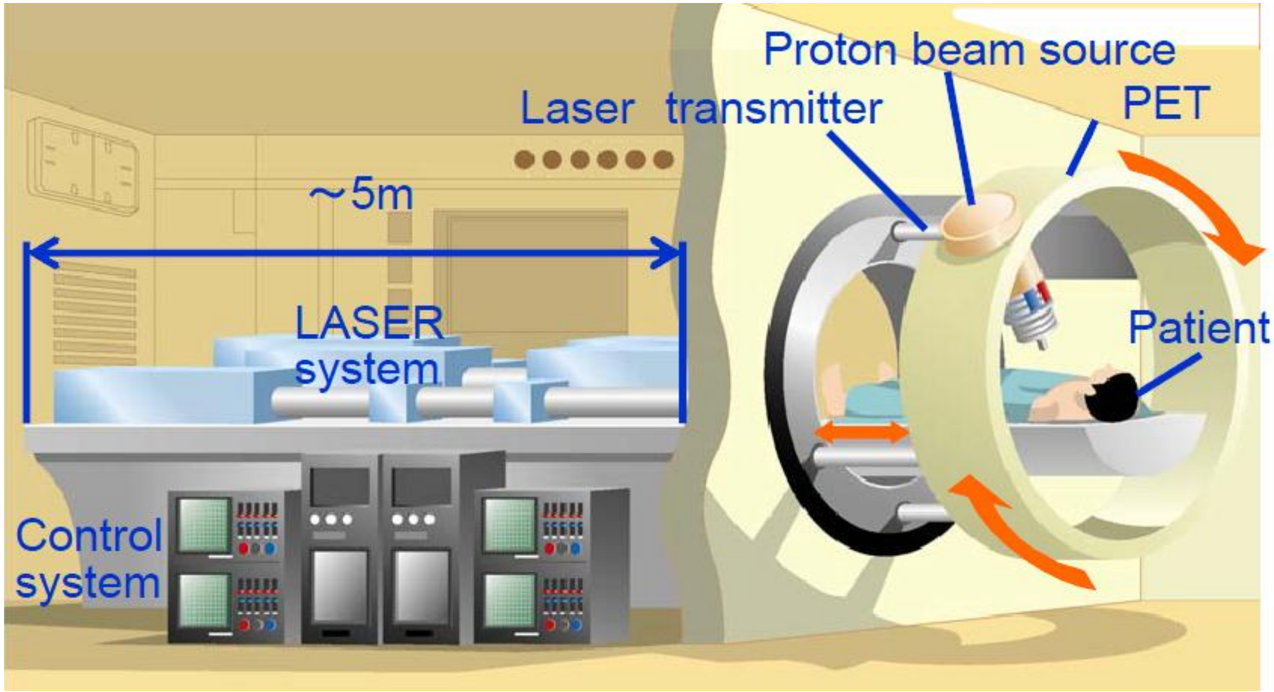
Only a few in operation along with ~30 small facilites

- 10's of thousands of people treated
- Need more than an order of magnitude more therapy centers

Heidelberg Ion-Beam Therapy Center, Commissioned in 2009

http://www.klinikum.uni-heidelberg.de/Welcome.113005.0.html?&L=1

Solution : Laser Based Accelerators



Goal Cost : 10-20 million USD

Table top laser system (developing)

Transportation : Mirrors

Only has focusing magnet

Gantry : small, protons generated in direction of patient

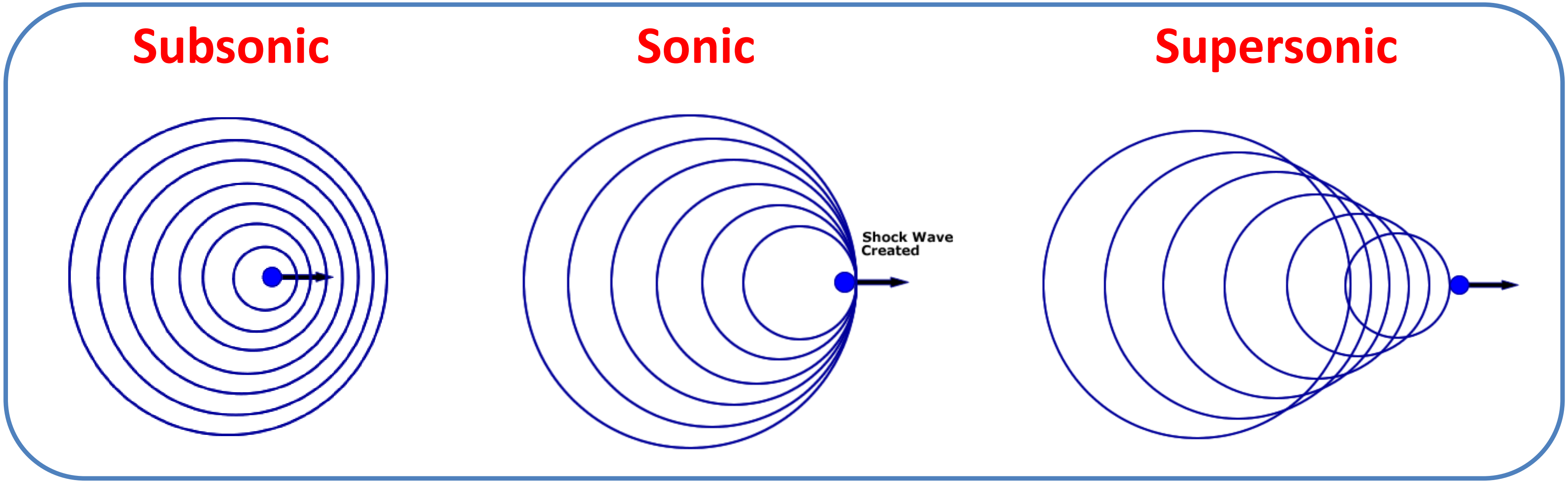
M. Murakami, et al., AIP Conf. Proc. 1024 (2008) 275, doi:10.1063/1.2958203

Proton Beam Requirements

	Radiation Beam Requirements	Laser Driven Ion Acceleration (LDIA)
Dose	2 Gray in 1 liter tumor in a few minutes -Translates to 10^{10} protons per second	Lasers can accelerate up to 10^{12} protons in a single shot
Energy	Proton energies in range of 250 MeV	Worlds most powerful lasers have produced 75 MeV protons
Energy Spread	Energy Spread of ~5%	Vast majority of beams have continuous energy spread
	Focusability, Energy Accuracy, Energy Variability, Dose Accuracy, etc.	Future Work

What is a Shock Wave?

A disturbance that travels at supersonic speeds through a medium



- At supersonic speeds, pressure will build at the front of a disturbance forming a shock
- Characterized by a rapid change in pressure (density and/or temperature) of the medium

In a plasma, a shock wave is characterized by a propagating electric field at speeds useful for ion acceleration ($V_{sh} > 0.01c$)

1D OSIRIS Simulations

In Plasmas, the driver is a potential or electric field

Expansion Shocks

Ambipolar electric field of Plasma 1 is driven into Plasma 2

Plasma 1
n_{e1}
T_e
Cold Ions

Plasma 2
n_{e2}
T_e
Cold Ions

Driven Shocks

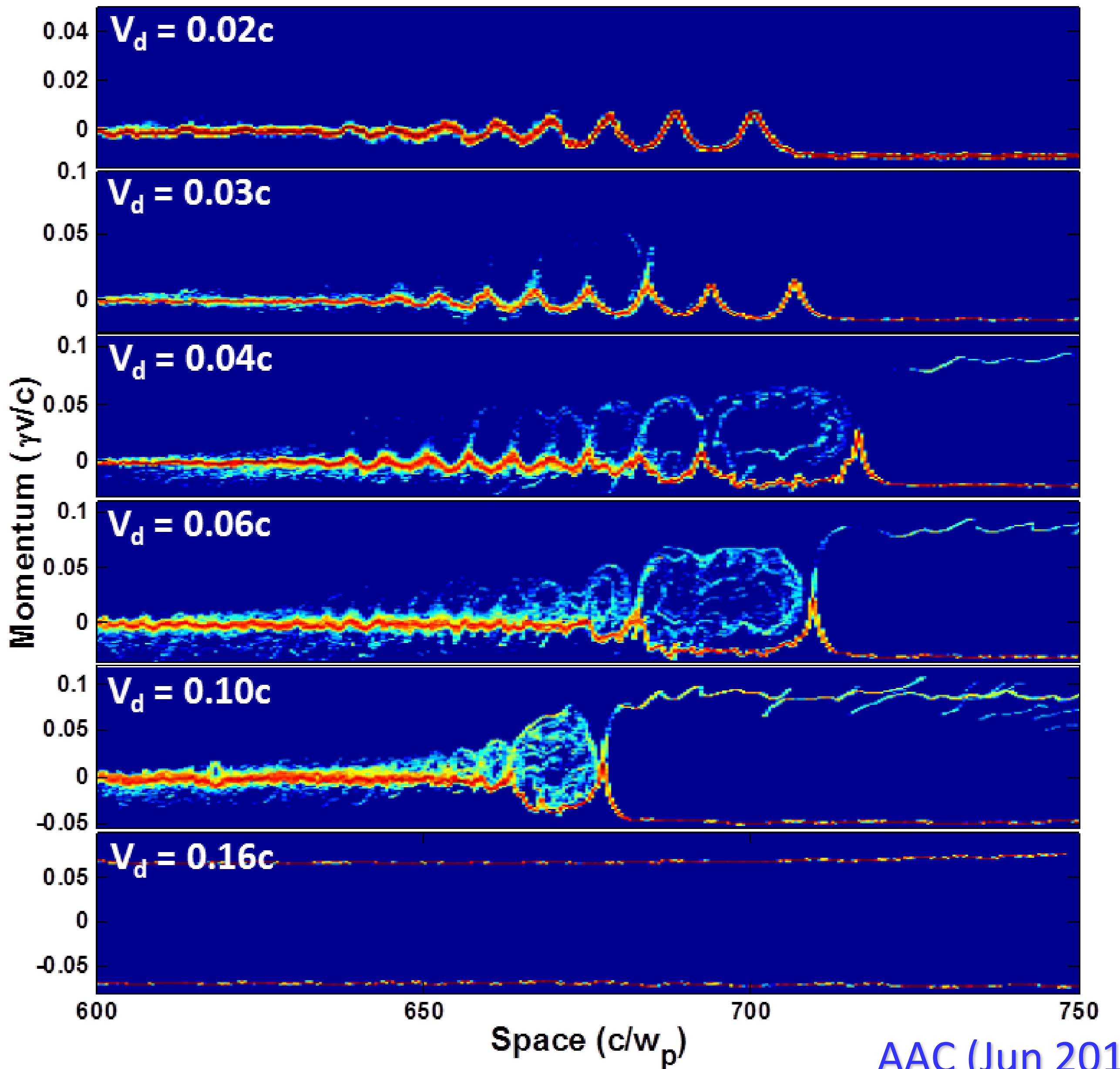
Initial drift causes overlap; overlap causes local density increase and again ambipolar electric field is driven into the plasma

$V_d/2 \rightarrow$ $\leftarrow V_d/2$

Plasma 1
$n_{e1} = n_{e2}$
T_{e1}
Cold Ions

Plasma 2
$n_{e1} = n_{e2}$
T_{e1}
Cold Ions

1D Sims : Driven Shocks (T_e = 511 keV C_s = 0.0233c).



Wave train response

Proton trapping begins

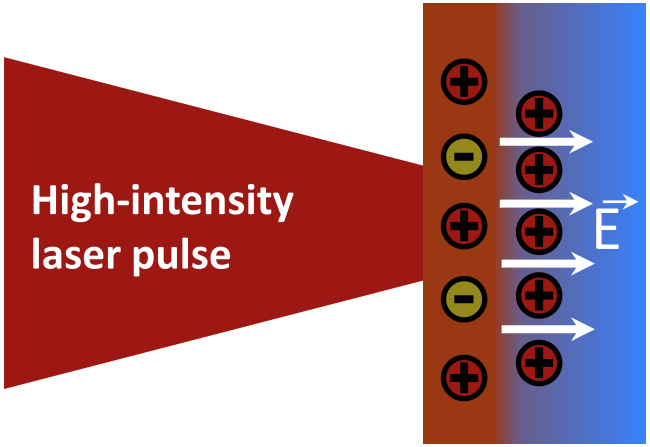
Proton reflection begins

Strong damping of wave

Reflection Condition
$e\phi > 1/2mv^2$

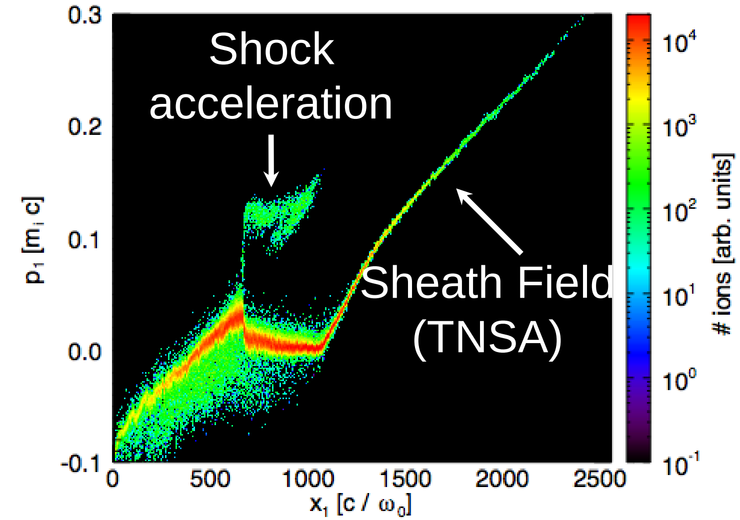
No interaction

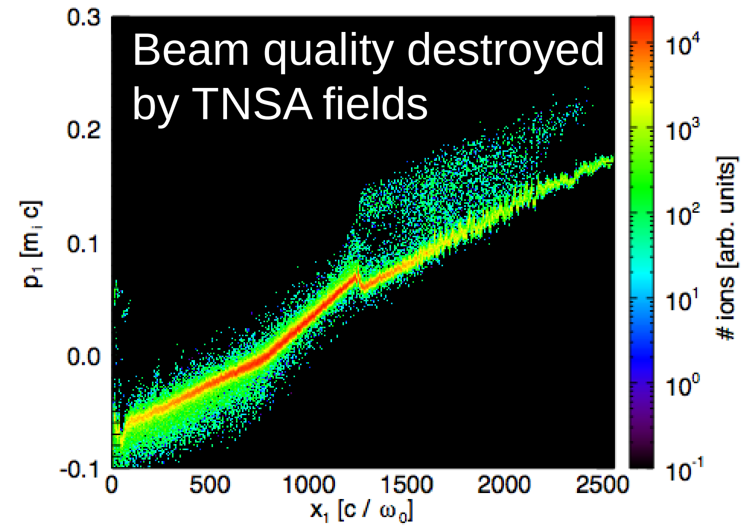
Shock formation in laser driven plasmas



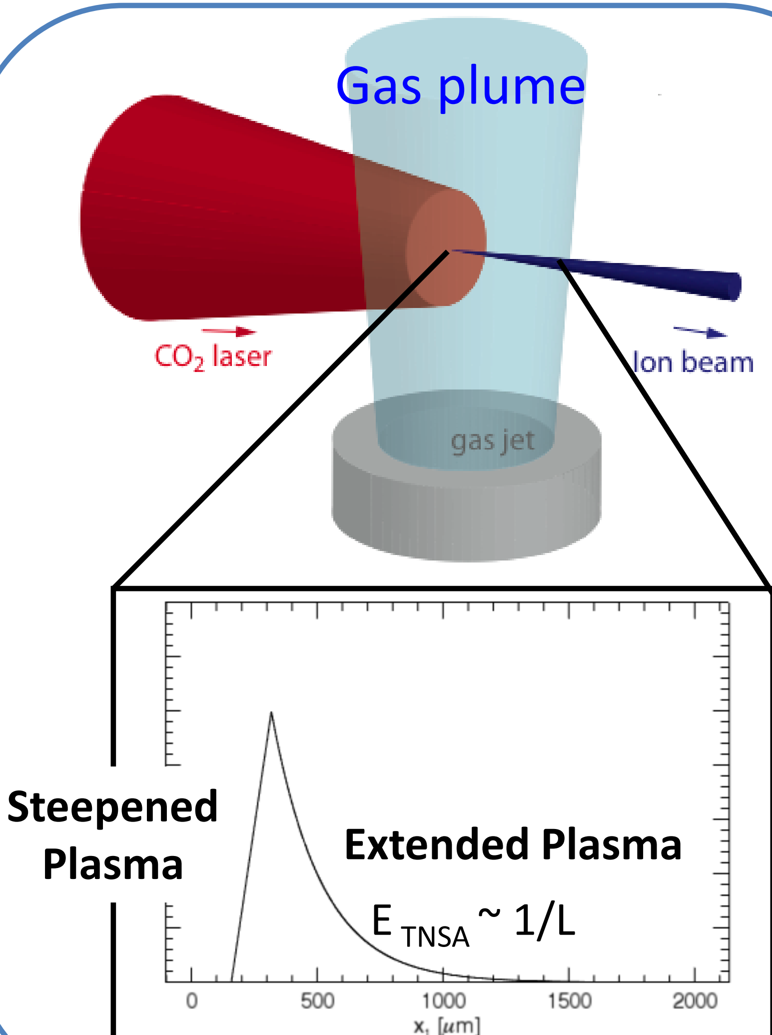
- Linearly polarized laser incident upon an overcritical target creates and heats the plasma
- Ponderomotive force creates density spike and imparts a velocity drift on surface plasma

Denavit PRL 1992, Silva PRL 2004





CO_2 Laser Interacting with a Gas Jet Target



Gas jet target advantages for Shock Wave Acceleration (SWA)

- Gas jets can be operated at or above 10^{19} cm^{-3} (n_{cr} for 10μm)
- Long scale length plasma on the back side of the gas jet inhibits strong TNSA fields preserving proton spectrum
- High repetition rate source
- Clean source of ions (H_2, He, N_2, O_2, Ar, etc…)
- Low plasma densities allows for probing of plasma dynamics using visible wavelengths

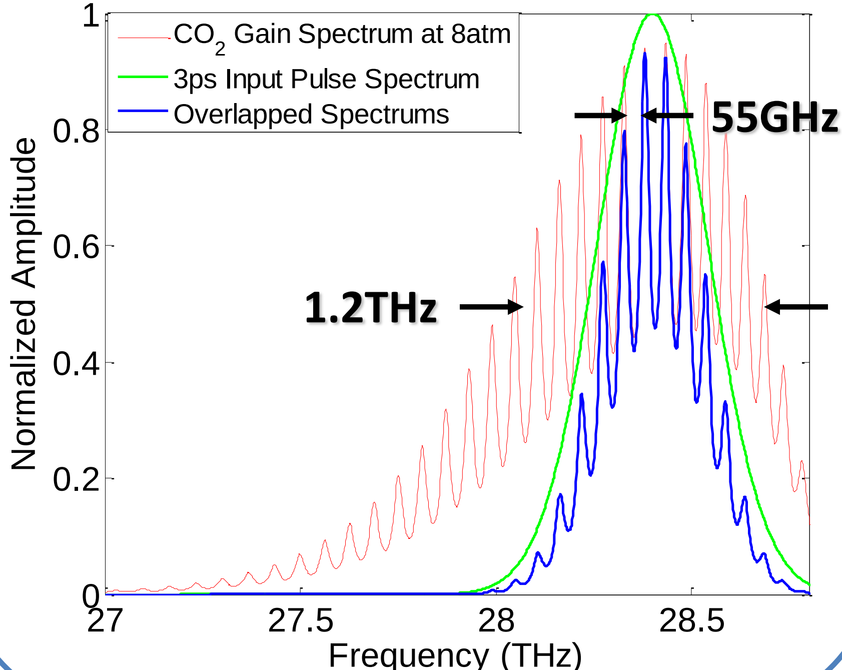
CO_2 Laser Pulse Temporal Structure

Calculated CO_2 Gain Spectrum

Pressure = 8atm

Line Separation = 55GHz

Line Center : 10.6µm



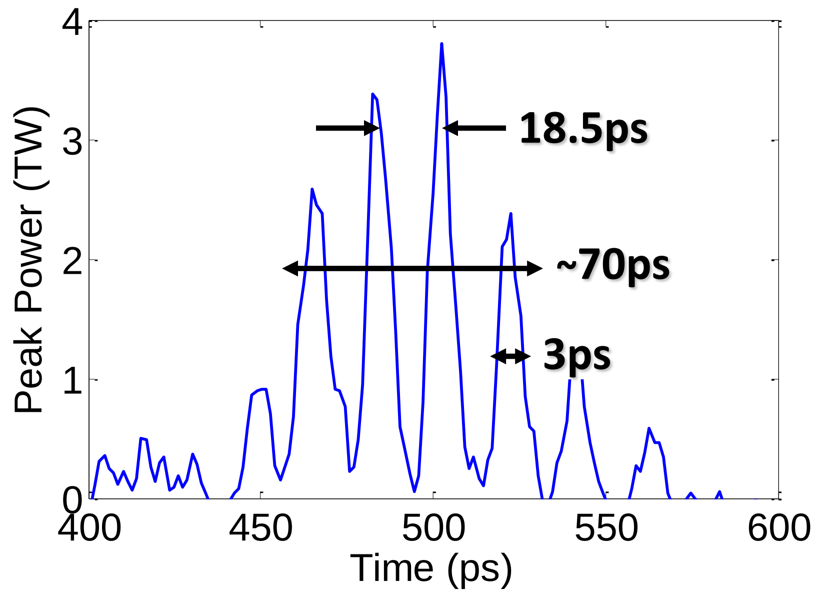
Experimentally Measured Temporal Profile

E = 50 J

P_{peak} = 4TW

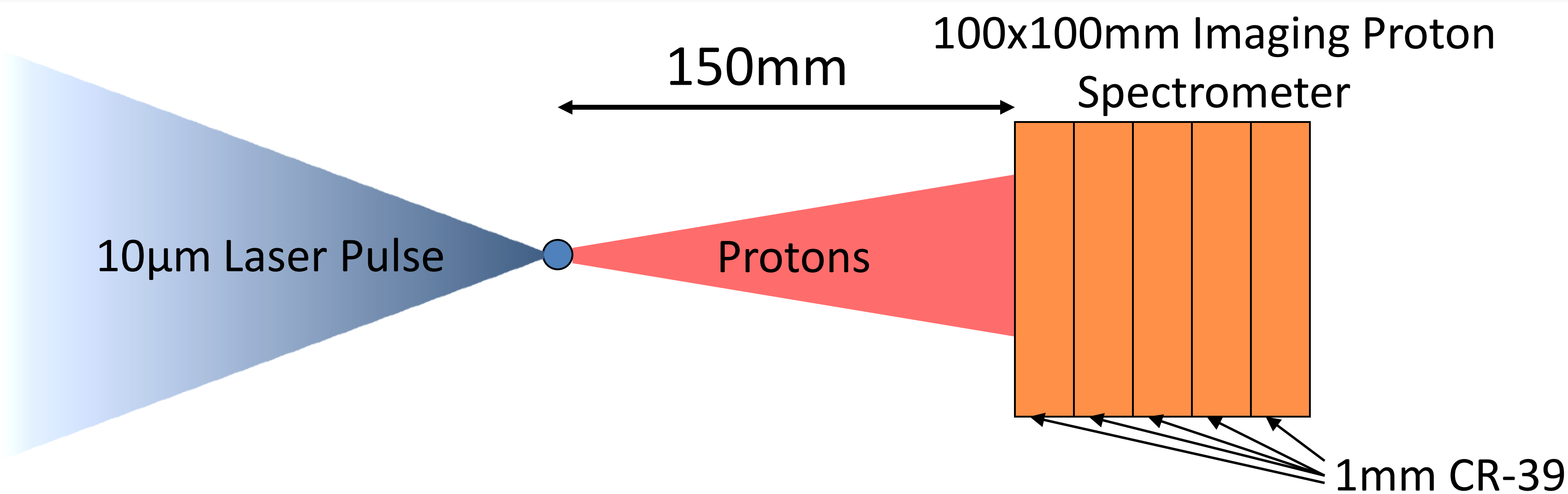
Pulse Separation = 1/55GHz = 18.5ps

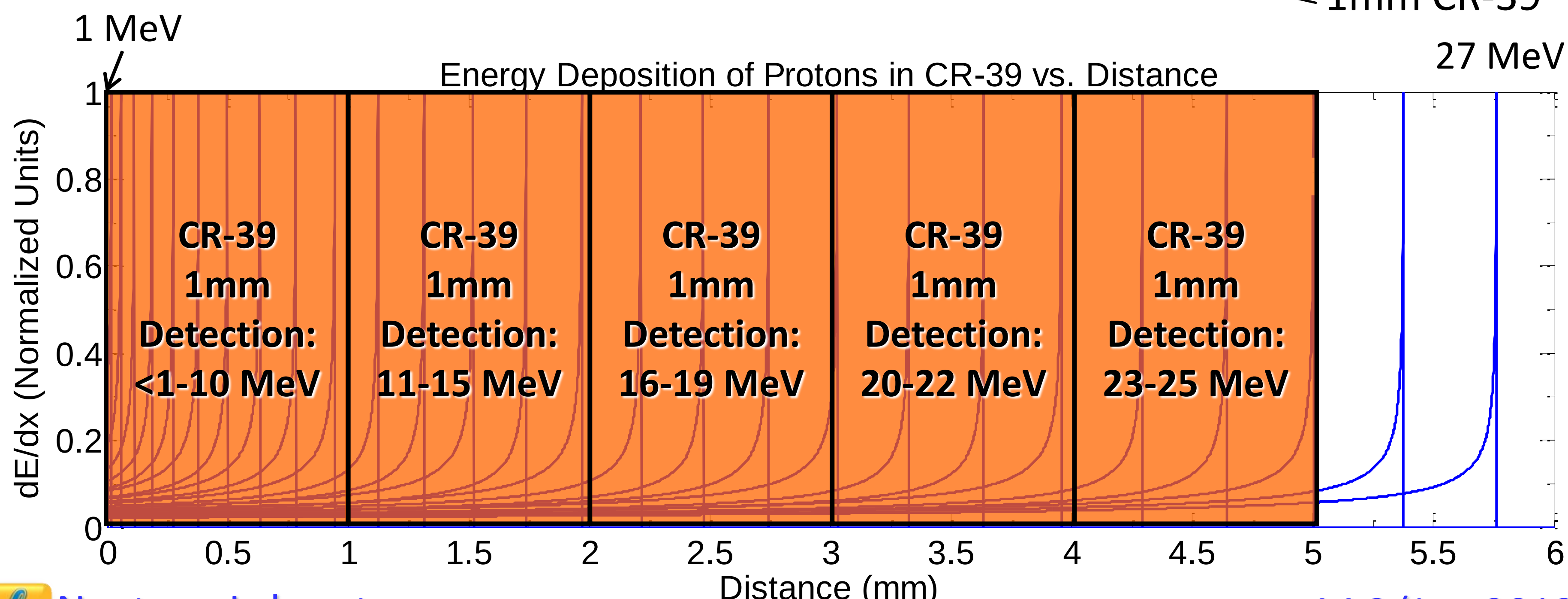
7-10 pulses long



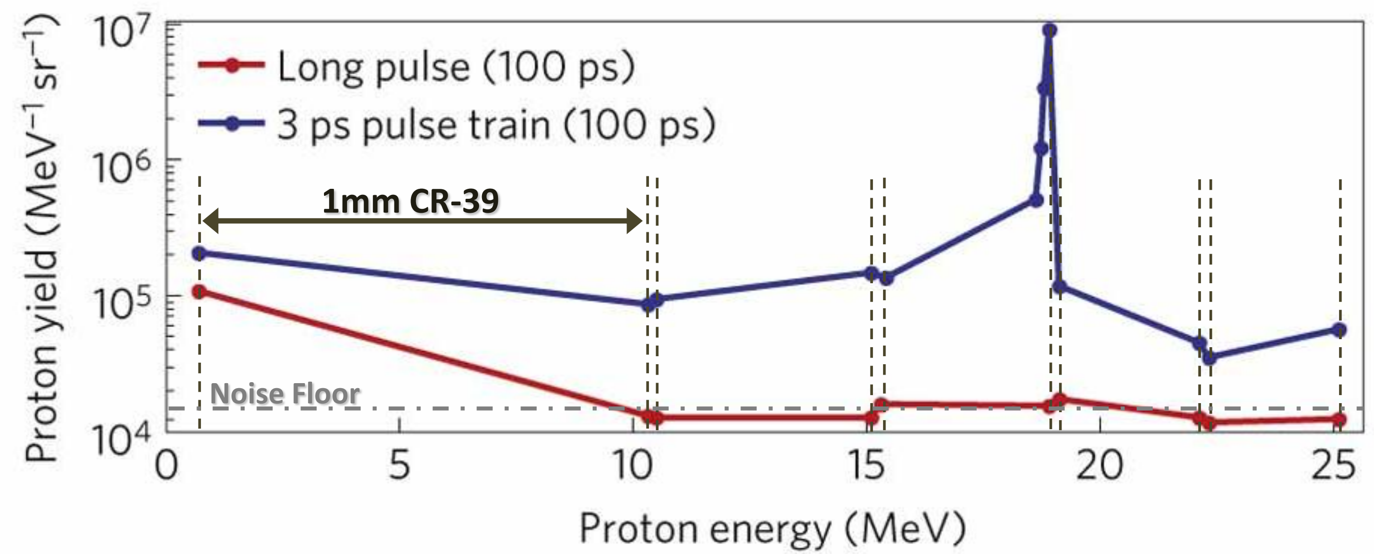
D. Haberberger et al., Opt. Exp. 18, 17865 (2010)

CR-39 Proton Detection

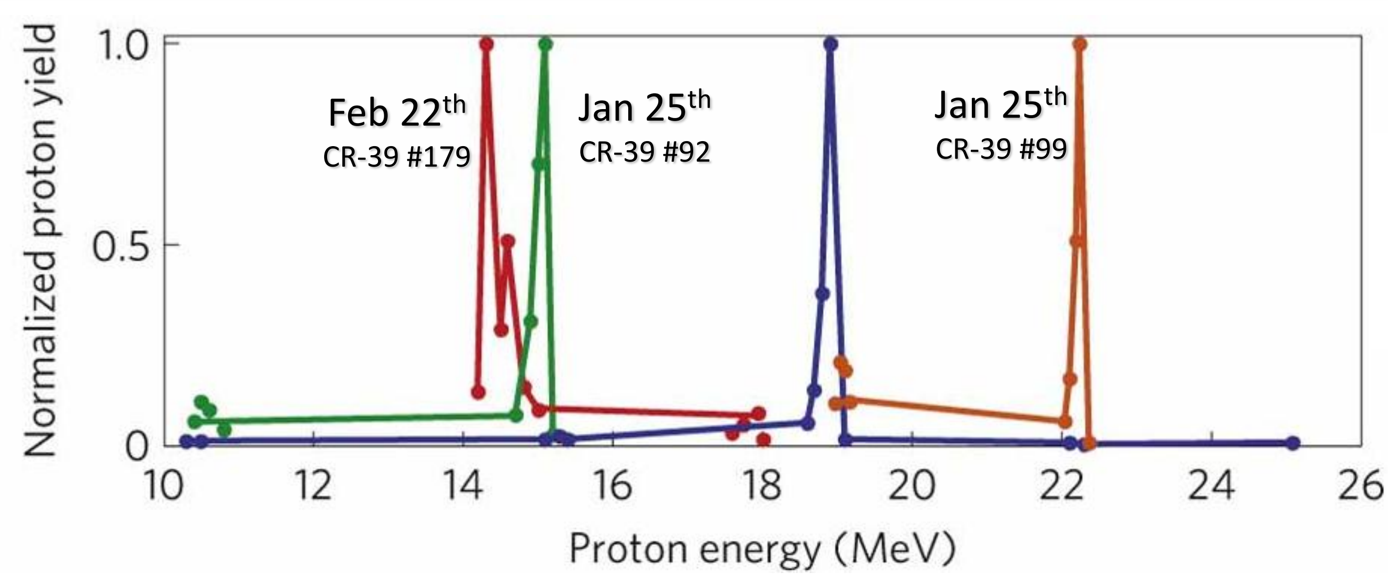




CO_2 Laser Produced Proton Spectra

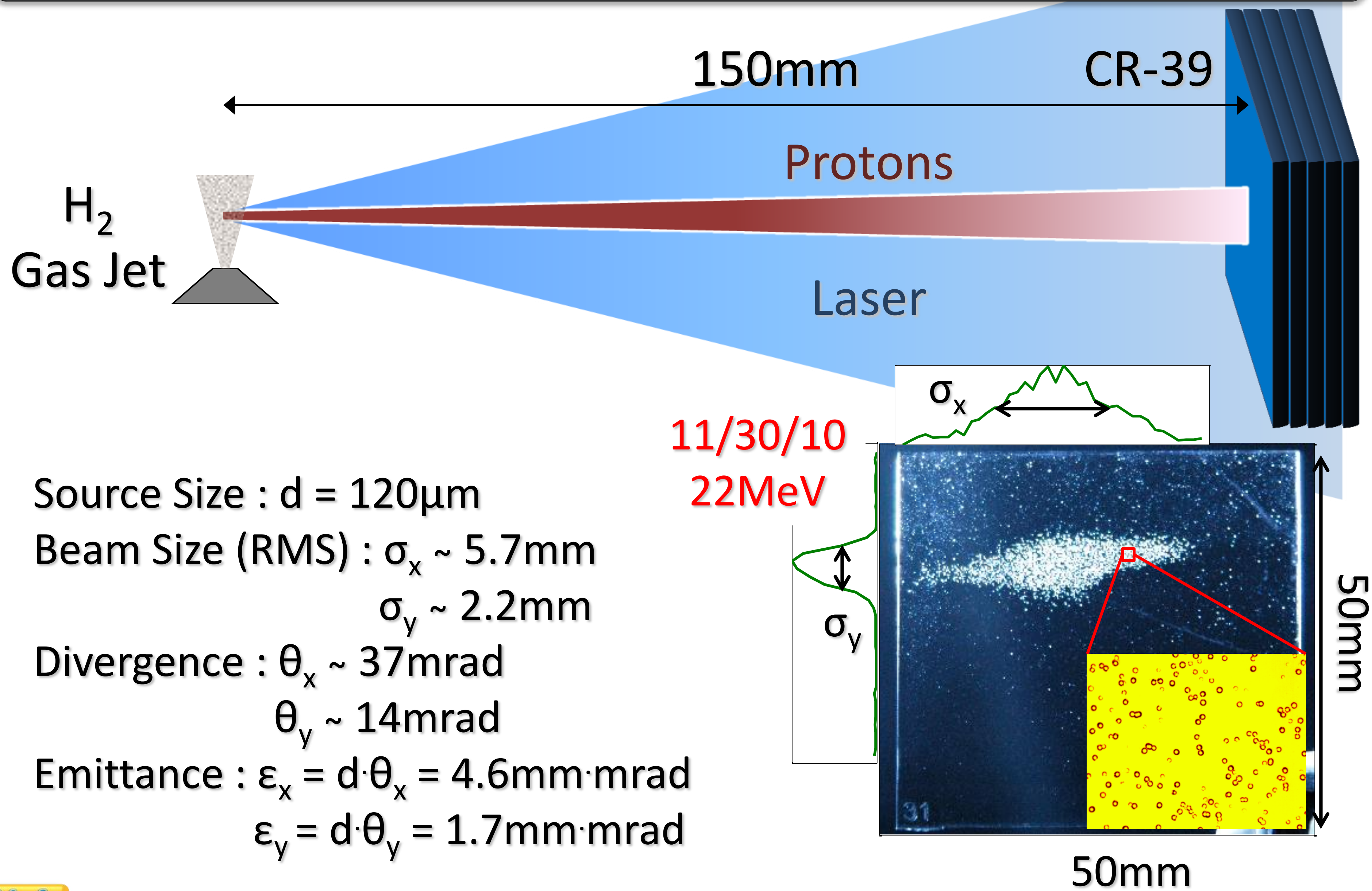


Energy spreads measured to be FWHM ΔE/E ~ 1%



Haberberger, Tochitsky, Fiuza, Gong, Fonseca, Silva, Mori, Joshi, Nature Phys., 8, 95-99 (2012)

Emittance Estimation



Source Size : d = 120μm

Beam Size (RMS) : σ_x ~ 5.7mm

σ_y ~ 2.2mm

Divergence : θ_x ~ 37mrad

θ_y ~ 14mrad

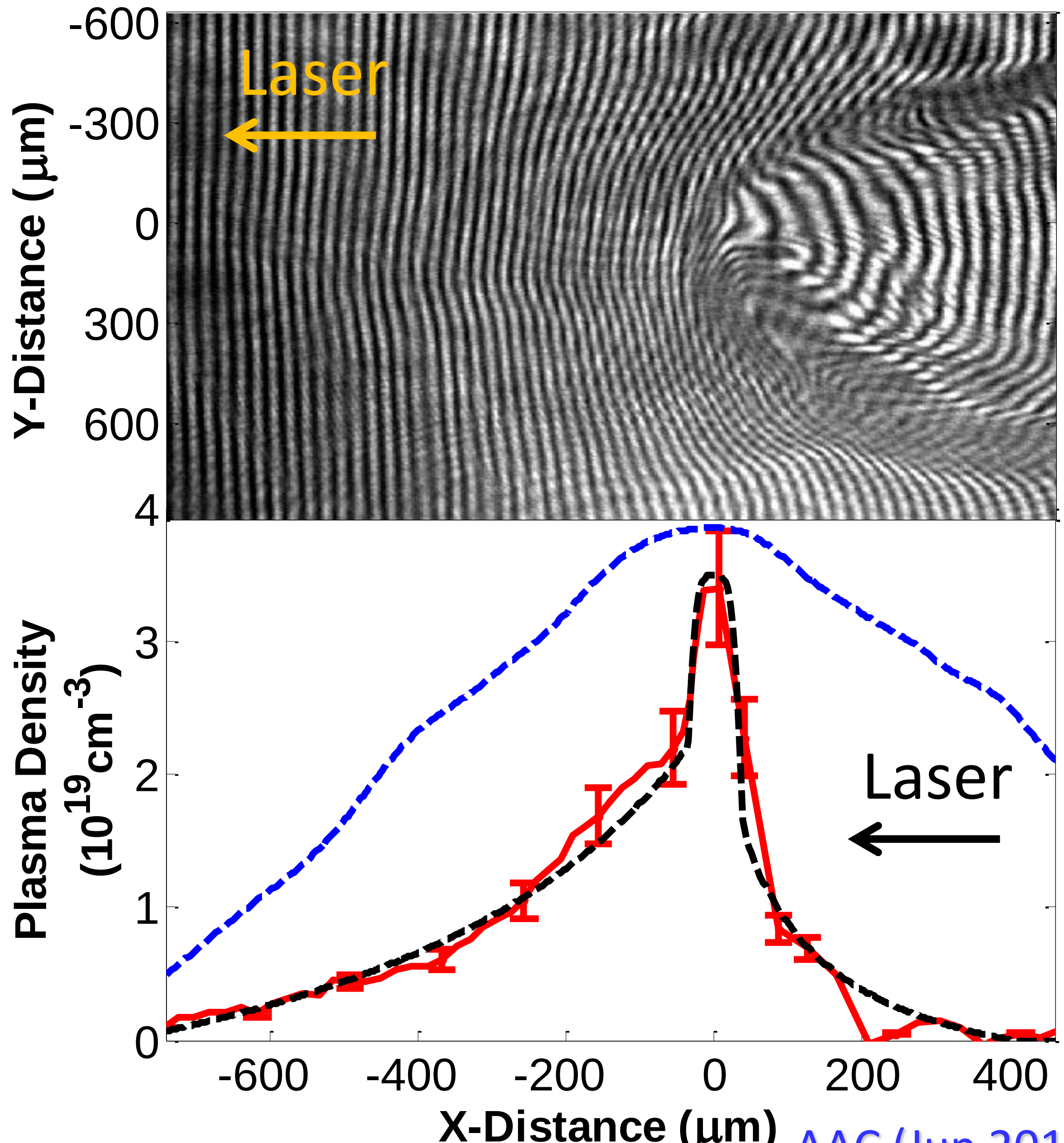
Emittance : $\varepsilon_x = d\cdot\theta_x$ = 4.6mm·mrad

$\varepsilon_y = d\cdot\theta_y$ = 1.7mm·mrad

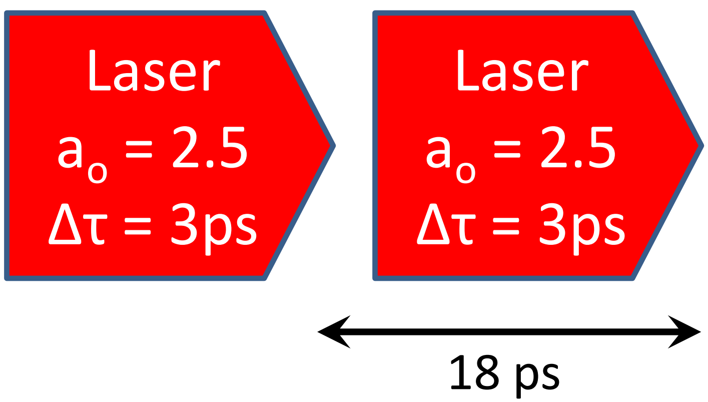
Plasma Density Profile

Observations

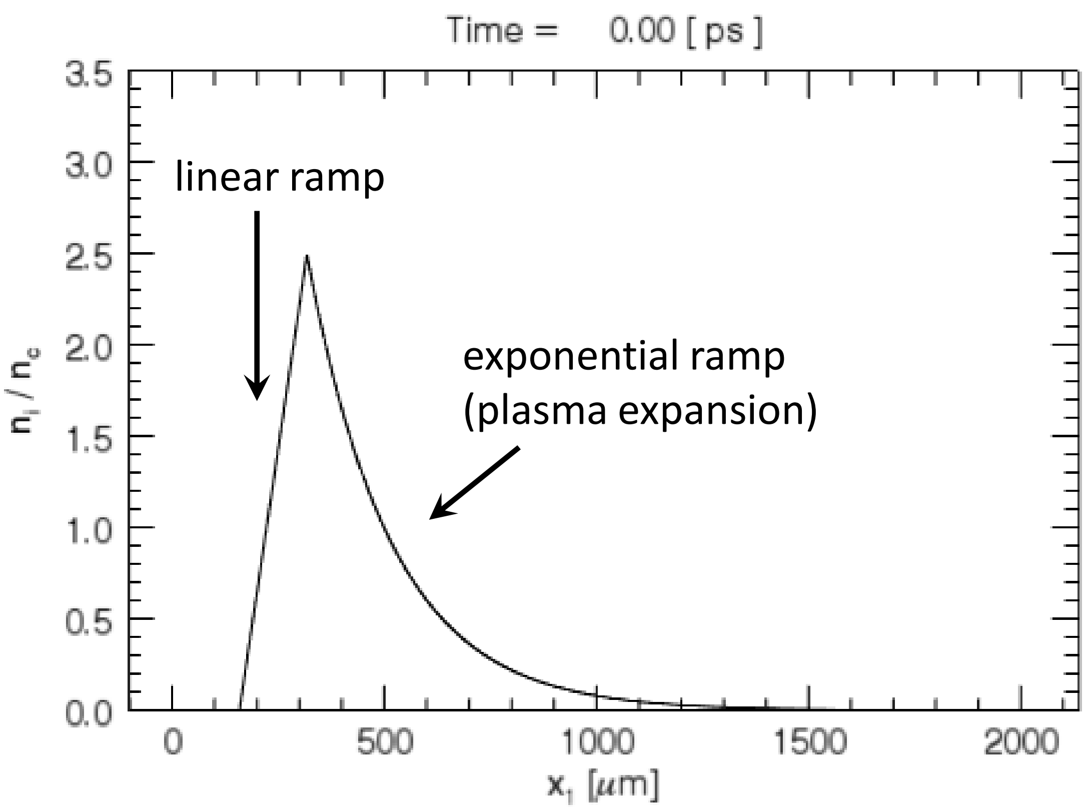
1. **Strong profile modification on the front side of the plasma : hole boring**
2. **Sharp rise (10λ) to overcritical plasma where laser pulse is stopped**
3. **Long (1/e 30λ) exponential plasma tail**



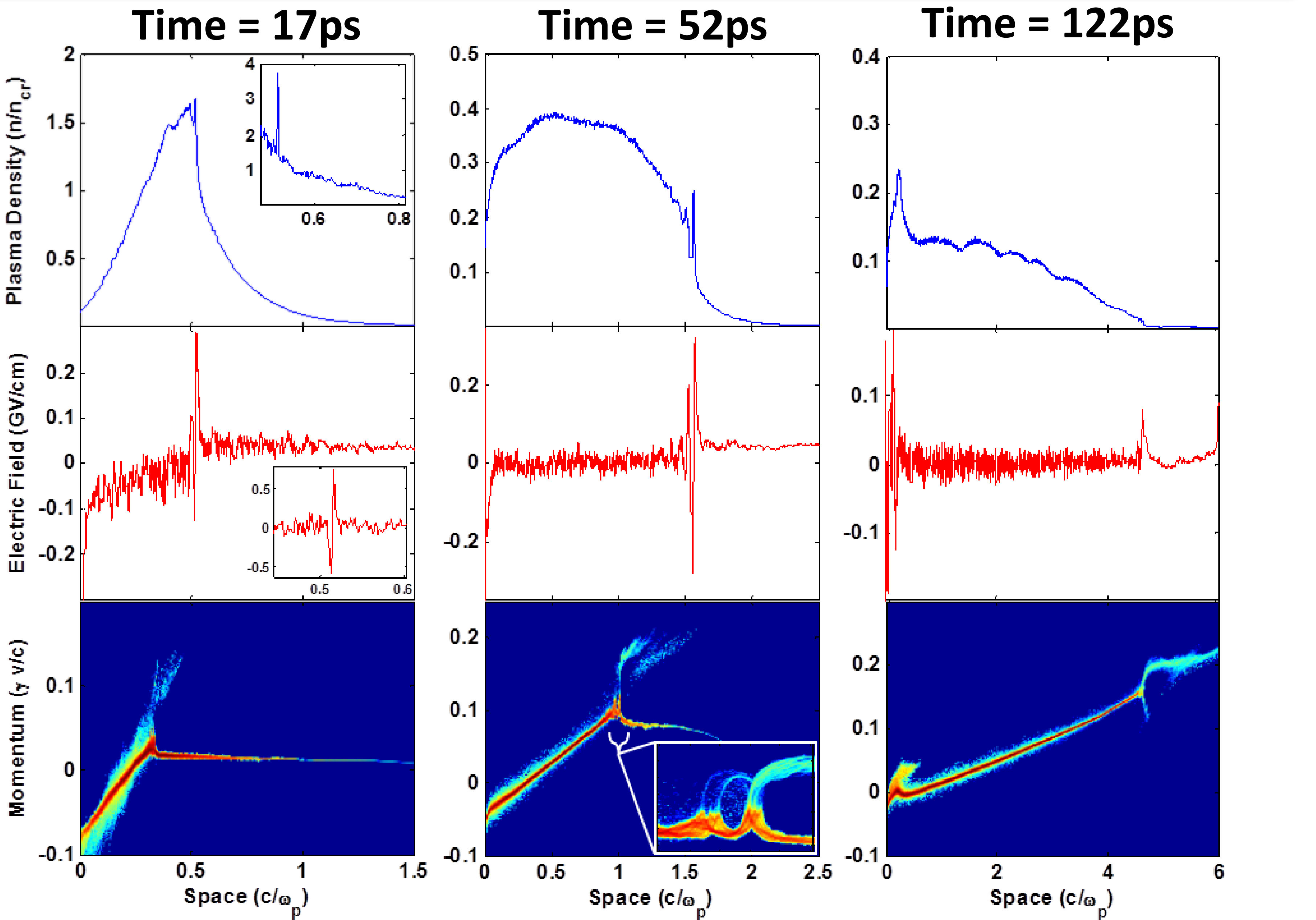
2D OSIRIS Simulations : Input Deck



Initial Plasma Profile

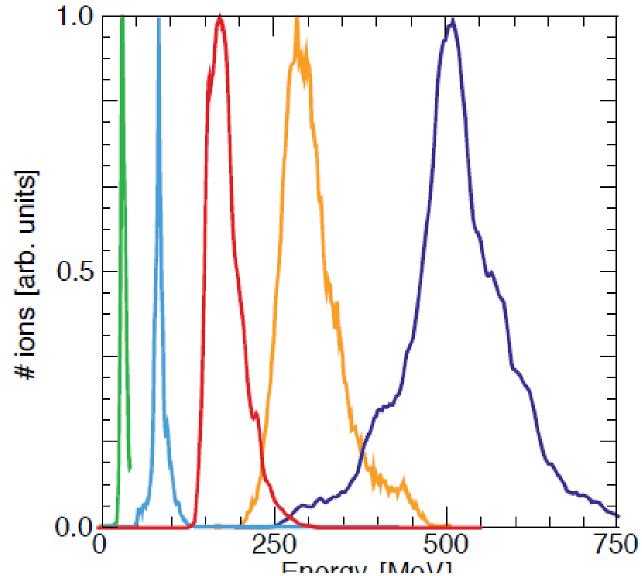


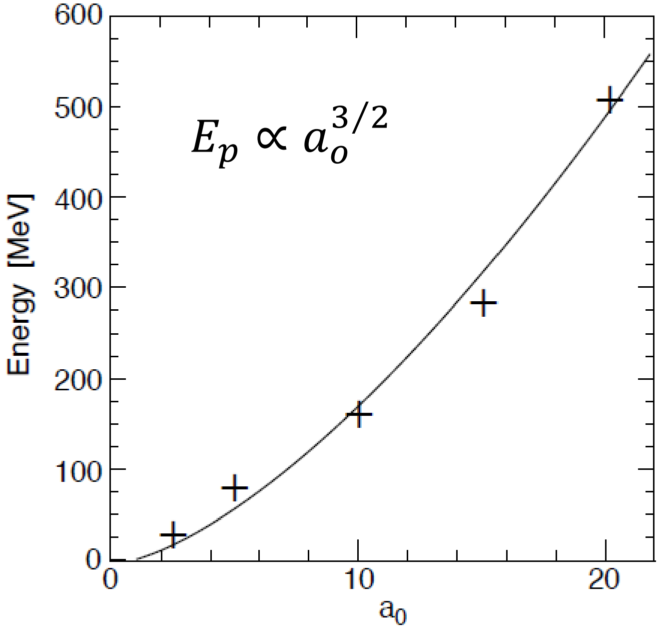
2D OSIRIS Simulations : Results

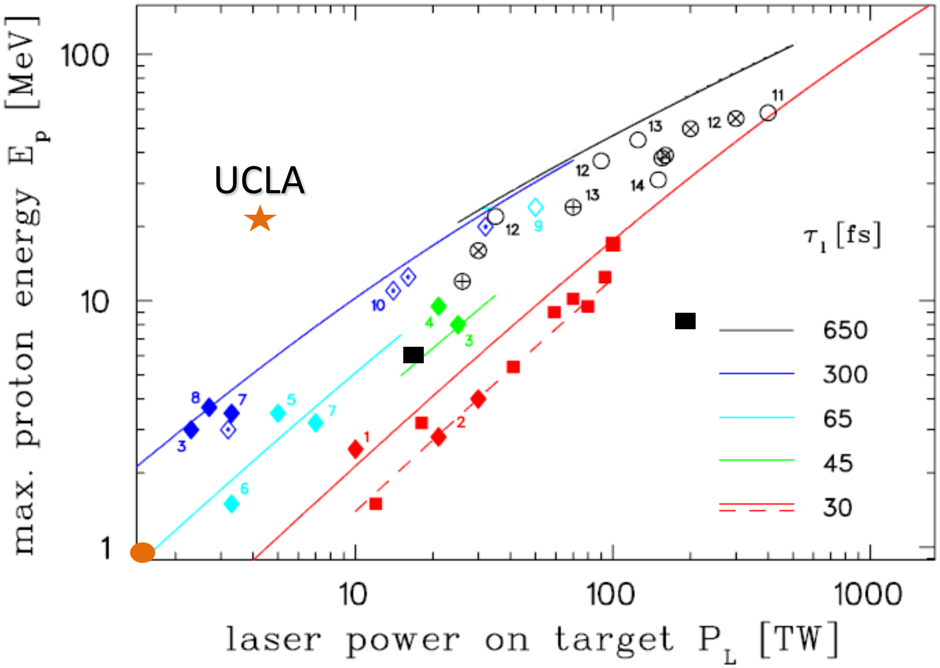


2D Simulations : Energy Scaling

-F. Fiuza, Phys. Rev. Lett., Submitted



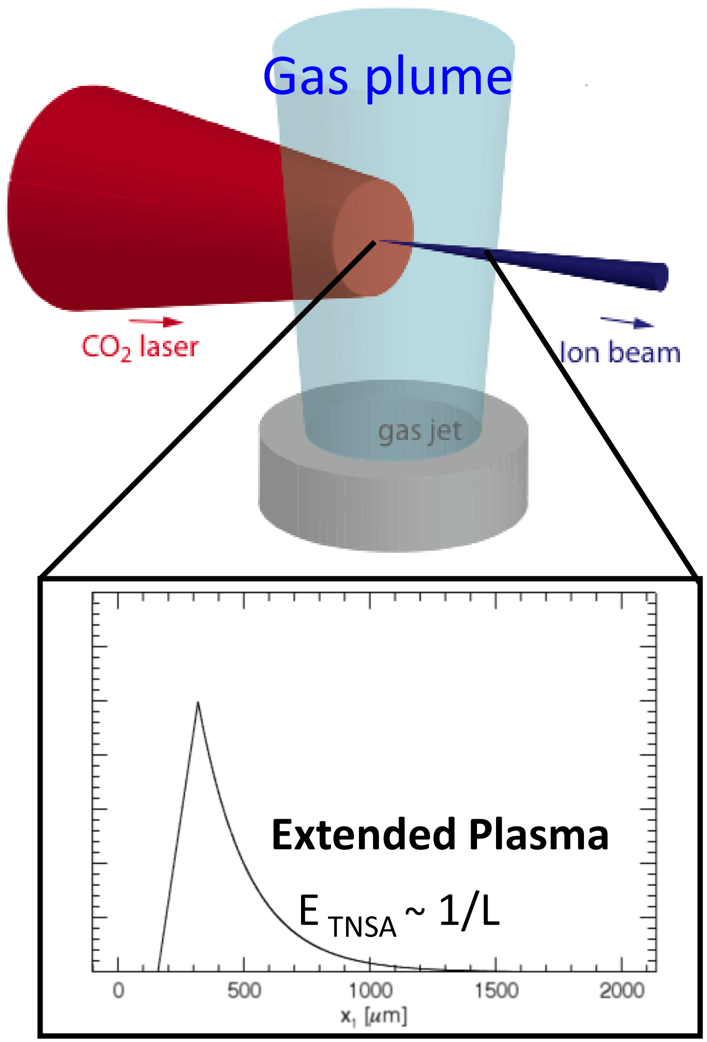




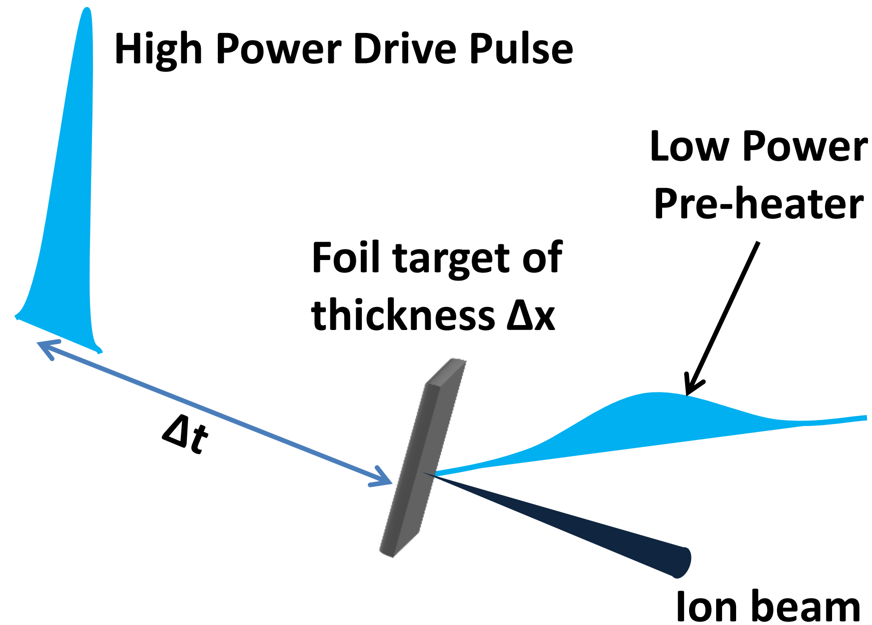
-K. Zeil et. al., New J. Phy 12, 045015 (2010)

Proposed Shock Wave Acceleration at 1µm

10µm Laser – Gas Jet Target



1µm Laser – Exploded Foil Target



Δx and Δt

- Peak density for Drive Pulse is 5-15n_{cr} = 5-15 x 10^{21} cm^{-3}
- Extended plasma profile (1/e - 30λ)

Conclusions

Laser-driven, electrostatic, collisionless shocks in overdense plasmas produce monoenergetic protons at high energies

- **Protons accelerated to 15-22 MeV (at $I_L \sim 4\text{x}10^{16}$ W/cm^2)**
- **Energy spreads as low as 1% (FWHM)**
- **Emittances as low as 2x4 mm·mrad**
- **Interferometry uncovers unique plasma profile**
- **Plasma simulations elucidate shock wave acceleration of protons through the backside of the plasma**

Step towards achieving 200-300 MeV protons needed for cancer therapy

- **Simulations show scaling to ~300 MeV with a laser a_o = 15**
- **Proposed method of exploding foil target for 1μm laser systems**