Ion Acceleration:
TNSA and beyond

Lecture 1

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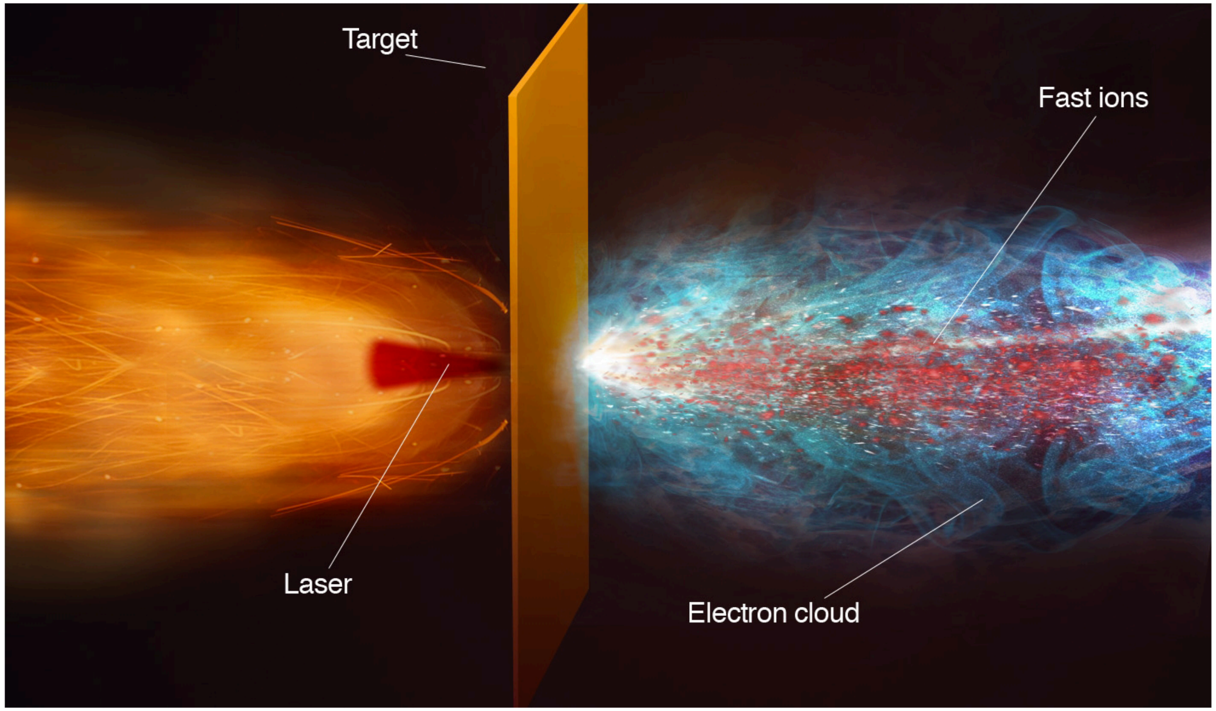
Centre for Plasma Physics,
School of Mathematics and Physics

The Queen's University of Belfast

Advanced Summer School on laser-driven sources of high energy particles and radiation
Anacapri, 10-16 July 2017

A-SAIL
ADVANCED STRATEGIES FOR ACCELERATING IONS WITH LASERS

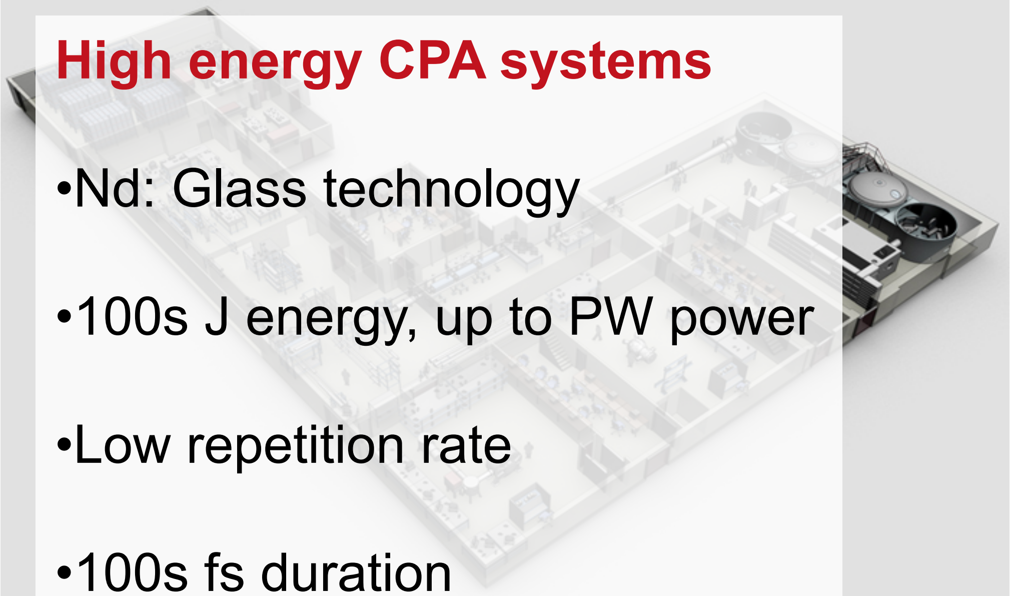
Ion acceleration : some general points



A.Macchi, M.Borghesi and M. Passoni, *Ion acceleration by superintense laser-plasma interaction*, Rev. Mod. Phys., **85**, 751 (2013)

- Several, fundamentally different mechanisms
- Large accelerating fields sustained by electron-ion separation in a plasma
- Very large fields (up to 10^{13} V/m) applied over very short distances (~μm)
- Mostly solids (high density targets)

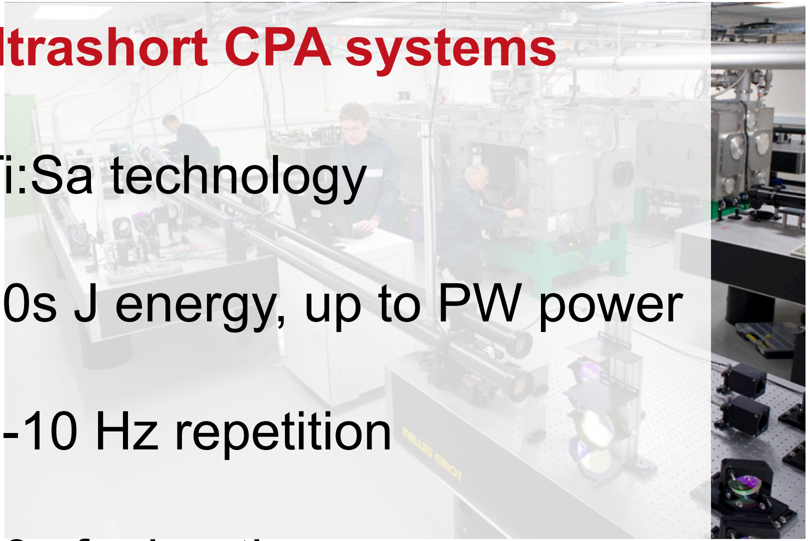
Two classes of lasers are mainly used for ion acceleration



High energy CPA systems

- Nd: Glass technology
- 100s J energy, up to PW power
- Low repetition rate
- 100s fs duration
- I_{max}~ 10^{21} Wcm^{2}

VULCAN, RAL (UK)
Phelix, GSI (De)
Trident, LANL (US)
Texas PW, Austin (US)
.....

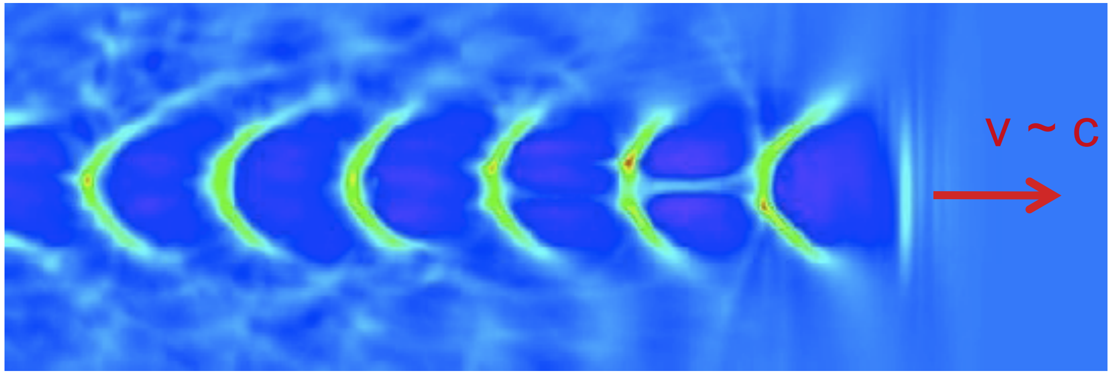


Ultrashort CPA systems

- Ti:Sa technology
- 10s J energy, up to PW power
- 1-10 Hz repetition
- 10s fs duration
- I_{max}~ 10^{21} Wcm^{2}

GEMINI, RAL (UK)
Draco, HZDR (De)
Pulser I, APRI (Kr)
J-Karen, JAEA (J)
.....

Laser-ion acceleration: why not use wakefield?

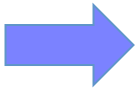


Standard laser wakefield methods cannot be used for accelerating ions

Issues:

1) $v_{ion} << v_{wake}$

2) v_{ion} varies as ion is accelerated



Need of “slow wave”

Need of accelerating structure with variable phase

Some ideas:

S. Masuda, T. Katsouleas and A. Ogata, Nucl. Instr. and Meth. A **455** (2000) 172 - 175.

Slow waves from Raman backscattering

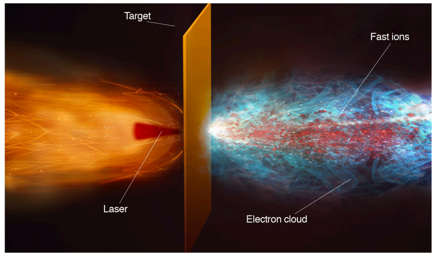
F. Peano, et al, New J. Phys., **10**, 033028 (2008)

Beat wave structure with variable phase velocity (frequency chirped pulses)

Breakdown of lectures

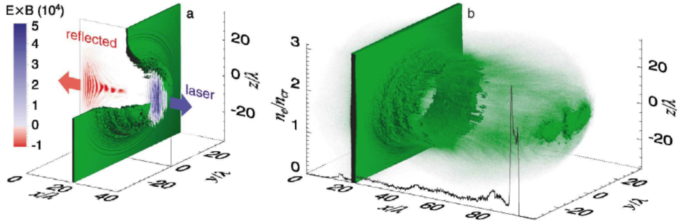
- Lecture 1 : **Sheath acceleration processes**

  (Tue, 9 am , 40 min)



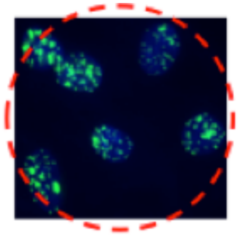
- Lecture 2: **Other mechanisms - new developments**

  (Thu, 3pm, 50 minutes)



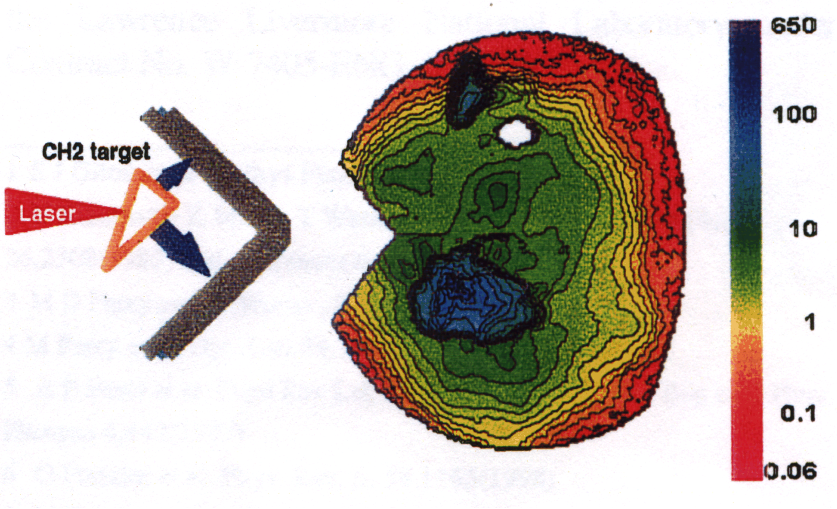
- Lecture 3: **Applications**

  (Friday, 6.30 pm, 30 minutes)



Outline of Lecture 1

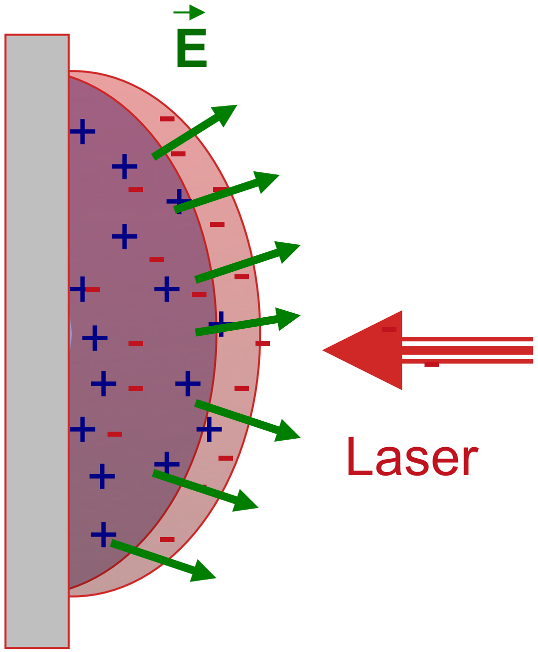
- ***Historical* introduction**
  - First observations
- **Target Normal Sheath Acceleration**
  - The basic process
  - State of the art and beam properties



Laser acceleration of ions from laser irradiated targets was studied from 1960s throughout the 90s

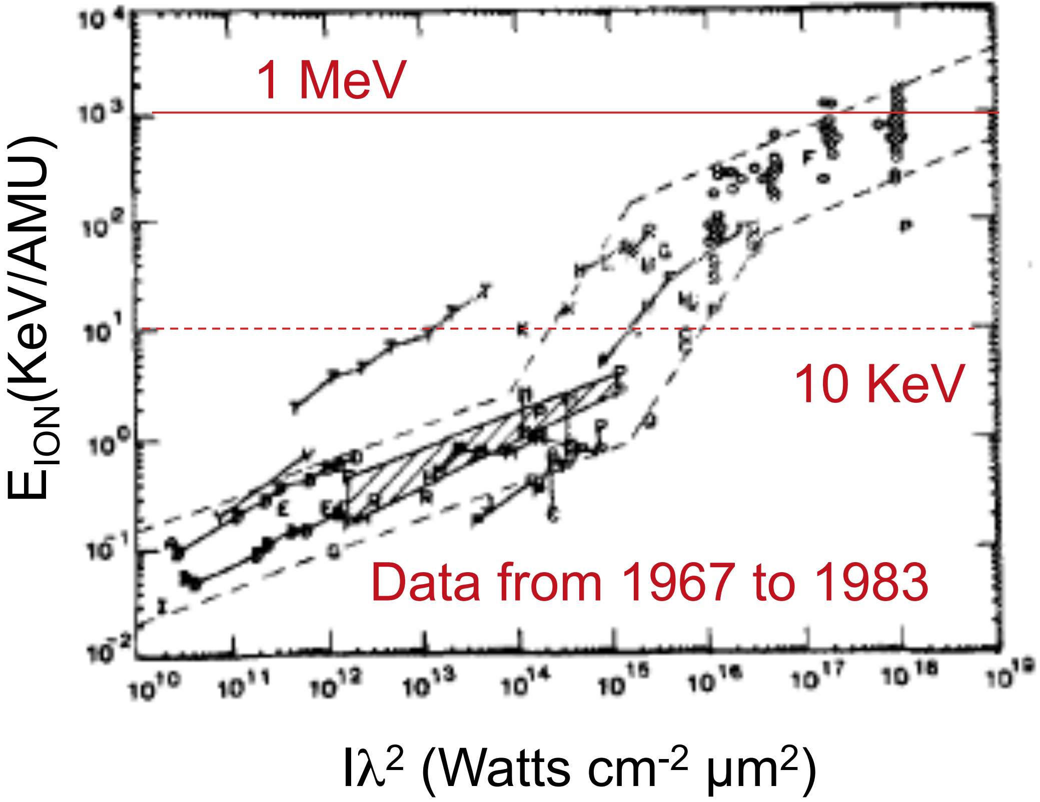
Laser couples energy into electrons

Faster electrons drag ions



A.V. Gurevich et al,
Sov. Phys. JETP, **22**, 449 (1966)

CO_2 lasers , ns, (λ~10 μm)

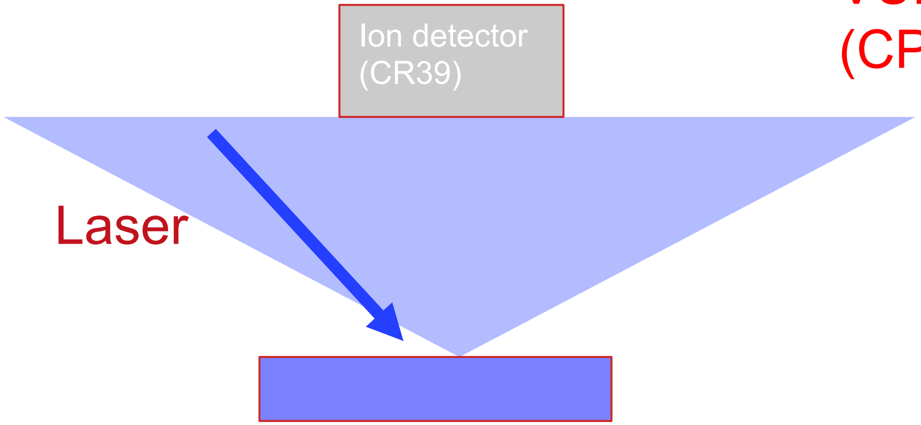


S.J. Gitomer et al,
Phys. Plasmas, **29**, 2679 (1986)

Ion acceleration was studied throughout the 90s

F. Beg et al, Phys. Plasmas, **4**, 447 (1997)

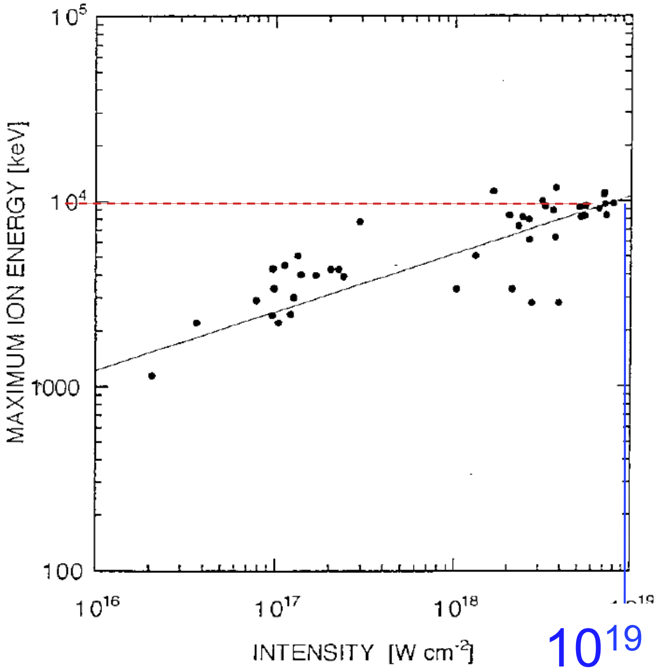
VULCAN laser (CPA)



Ion detector (CR39)

Laser

Target CH, Cu (15-25 μm thick)



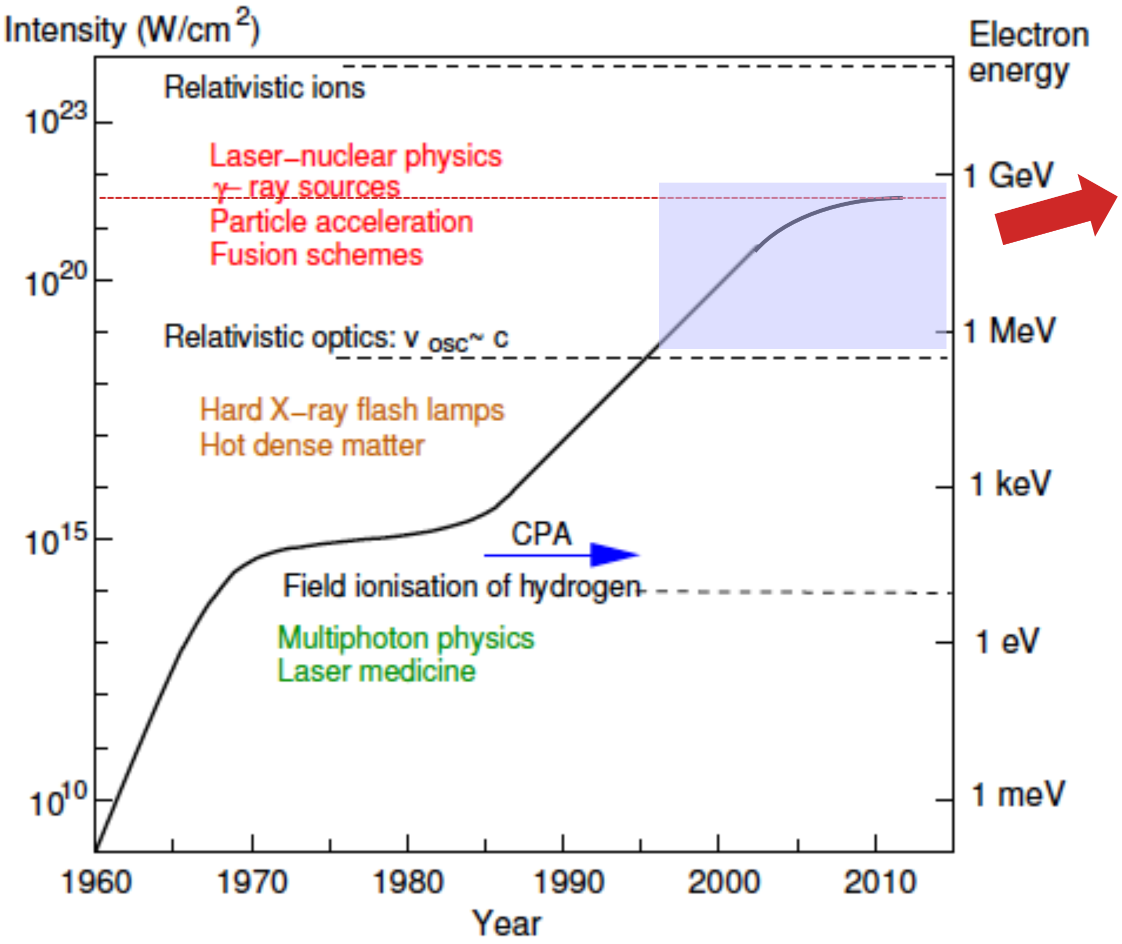
10 MeV

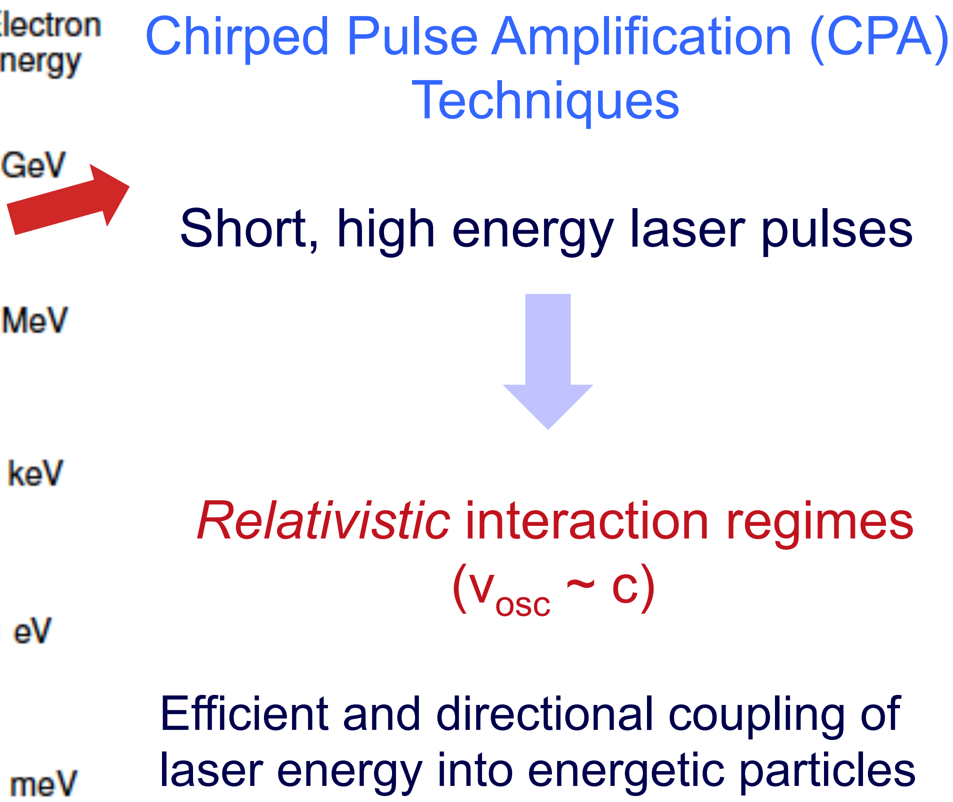
10^{19} W/cm^2

- •Protons originate from contaminants
- •Exponential spectrum with sharp cut-off
- •Ions accelerated during plasma expansion (isothermal rarefaction model)
- •Maximum energy of ions related to T_{hot}

$E_{max} \sim I^{0.3}$
(Beg's law)

Laser intensity is key to efficient particle acceleration





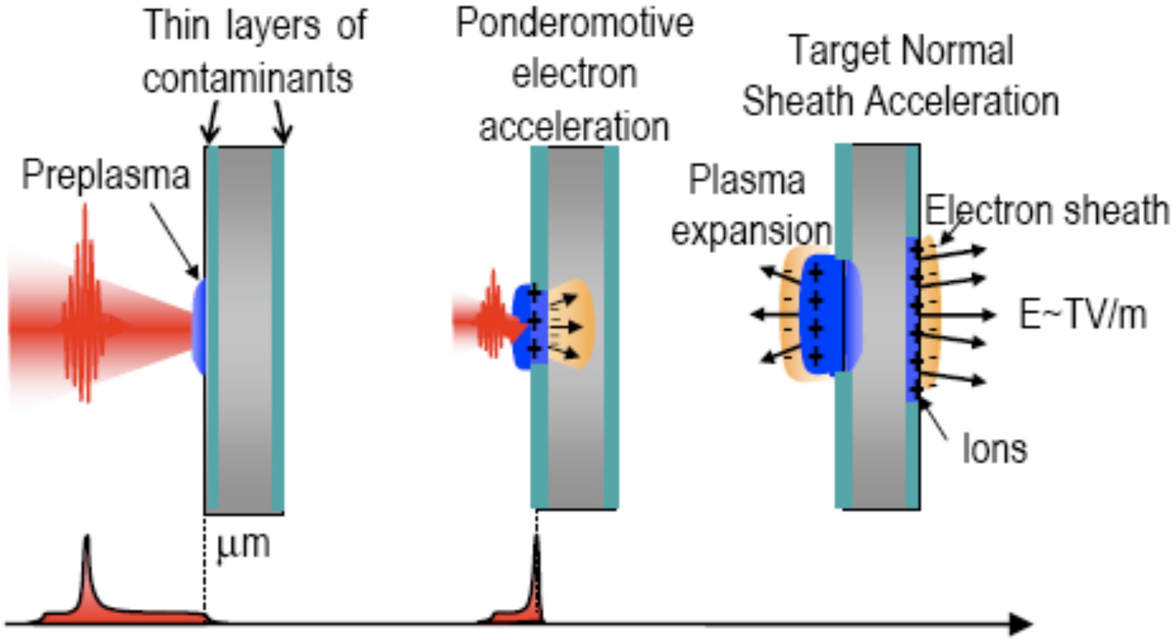
Chirped Pulse Amplification (CPA) Techniques

Short, high energy laser pulses

Relativistic interaction regimes ($v_{osc} \sim c$)

Efficient and directional coupling of laser energy into energetic particles

Target Normal Sheath Acceleration (TNSA) from the rear of thin foils was studied from ~ 2000



Clark et al, PRL, **84** ,670 (2000)

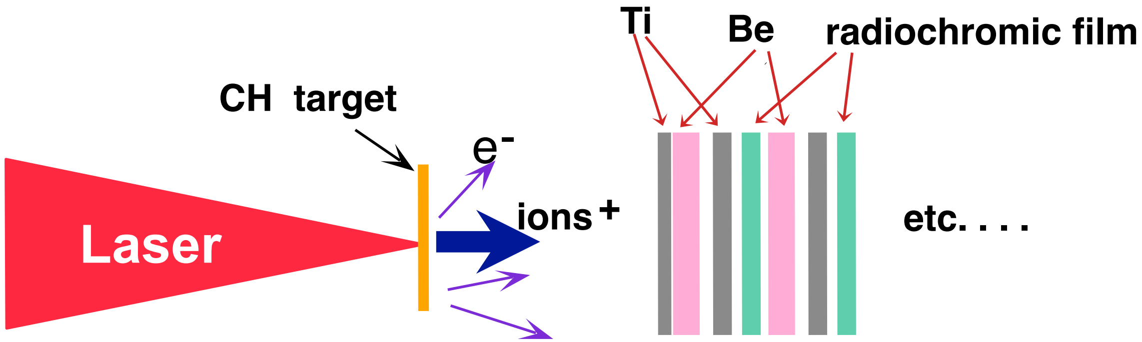
Maksimchuk et al, PRL, **84**, 4108 (2000)

Snavely et al, PRL, **85**,2945 (2000)

Intensities rising above 10^{19} W/cm^2 – electron acceleration to MeV energies
Thin foils allow electrons to reach the rear of the target and establish a field there
Protons (from contaminants) have *beam* features contrary to lower energy, isotropic emission previously observed from the front.

LLNL data were obtained with Radiochromic film techniques

R. Snavely et al., PRL, **67**, 84 (2000)



Counting activations

Ti^{48} (p,n) V^{48} $t_{1/2}$=16d, E_{thres}=5 MeV

gives absolute #'s of protons in several spectral bands.

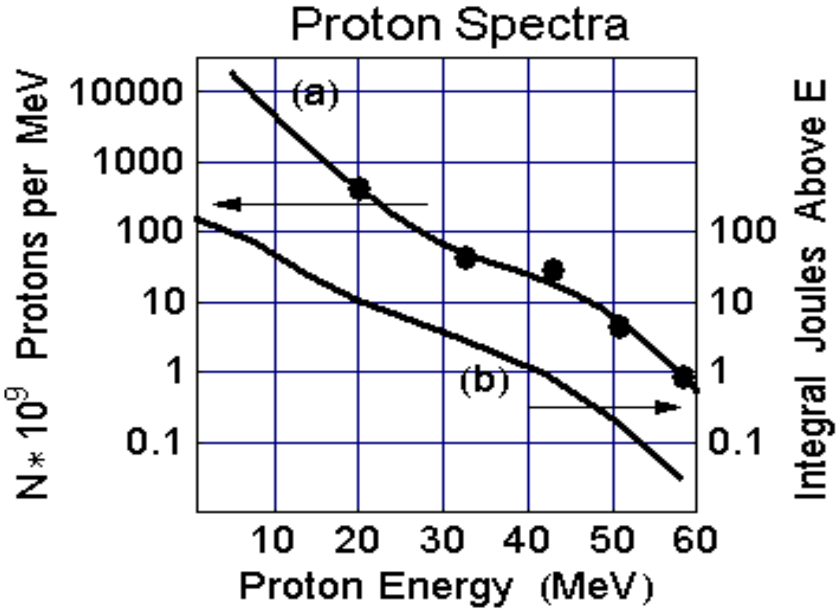
Spatial distribution of activation gives distribution of protons.

Radiochromic film layers:

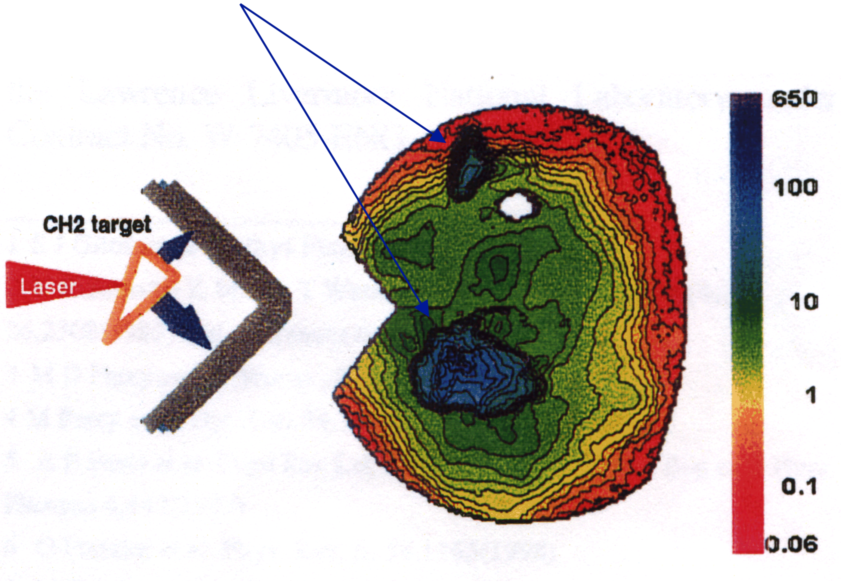
Autoradiographs of activated d Ti discs:

Lawrence Livermore National laboratory experiments

R.D.Snavely *et al* , Phys. Rev. Lett., **85,** 2945 (2000)



Proton beams

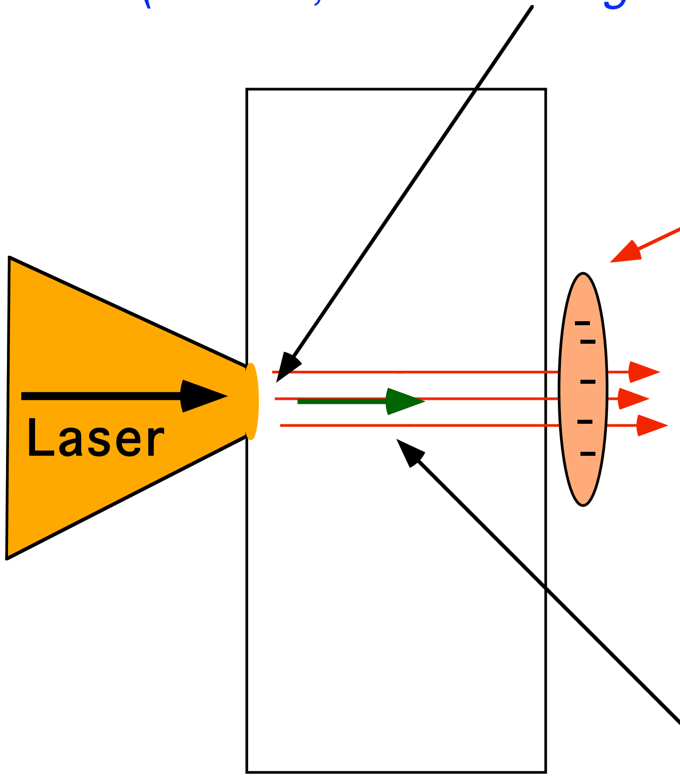


Radiochromic Film (Rads)

- Sharp edge proton beam with <u>cut off energy</u> of 50MeV and <u>slope</u> of 6MeV
- Higher energy protons were more collimated than lower energy
- The proton beam was <u>always normal to the back surface</u> of the target
- No protons > 8 MeV were observed from the front of the target

PW beam
500J, 0.5ps
I ~ $4x10^{20}Wcm^{-2}$

In 2000 there was controversy regarding the explanation of results ….



Ponderomotive acceleration (up to a few MeV) followed by electrostatic acceleration due to electron escape *(RAL-IC, CUOS Michigan)*

Fast electrons are held in proximity of the target by space charge effects.

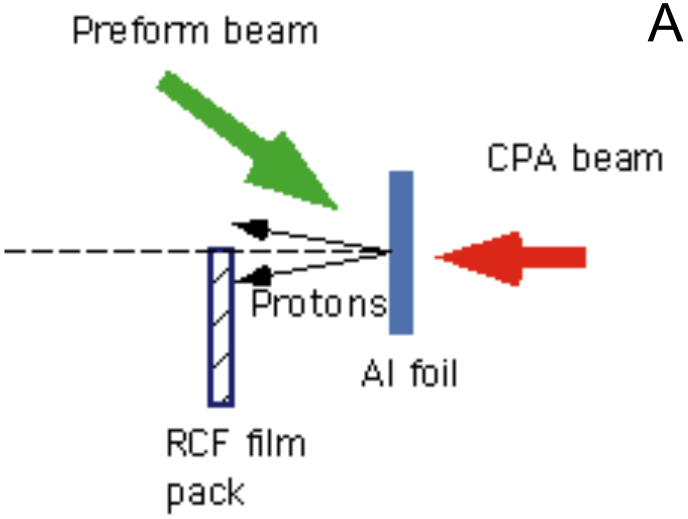
E-field at discontinuity estimated as $E \sim T_{hot}/(eL_{ion})$ can also accelerate ions *(LLNL, supported by PIC simulations)*

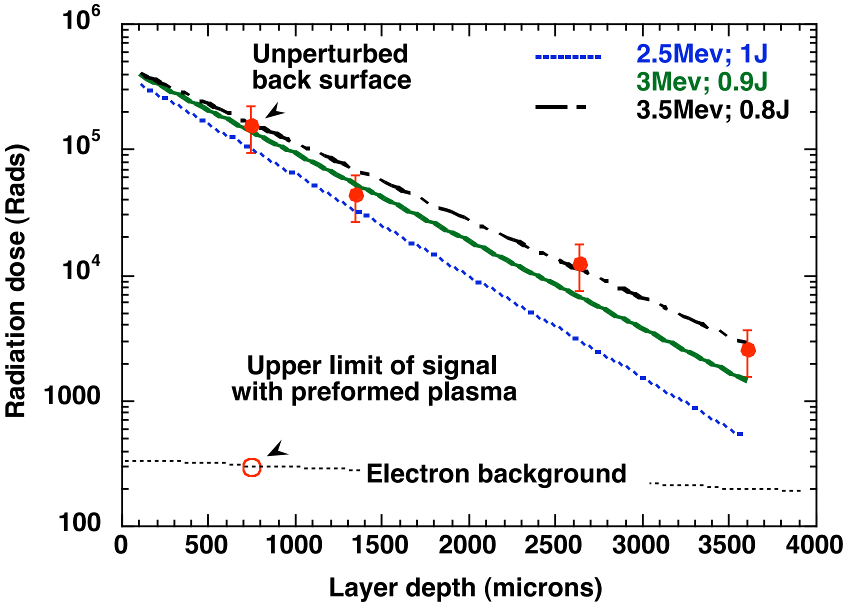
Acceleration by electric fields produced by the fast electrons travelling inside the target. *(RAL- IC)*

Several experiments have since shown that the dominant acceleration process for “thick” targets takes place at the target rear

Creating a gradient artificially on the rear surface changes very significantly the proton beam energy

A.J.Mackinnon *et al*, Phys. Rev. Lett, 86, 1769 (2001)





Also:
J.Fuchs et al, Phys. Rev. Lett., 99, 015002 (2007)
J.Fuchs et al, Phys. Rev. Lett, 94, 045004 (2005).

Lecture 1 - TNSA

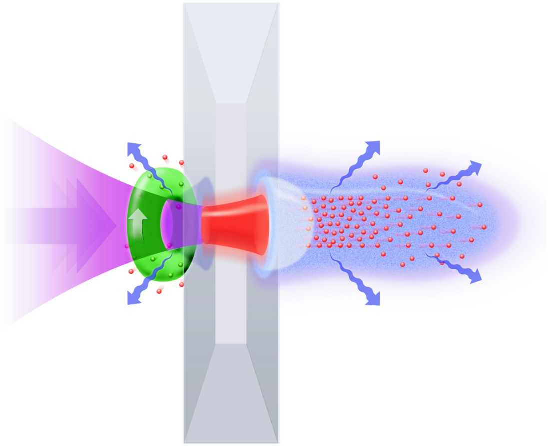
- **Historical introduction**

  First observations

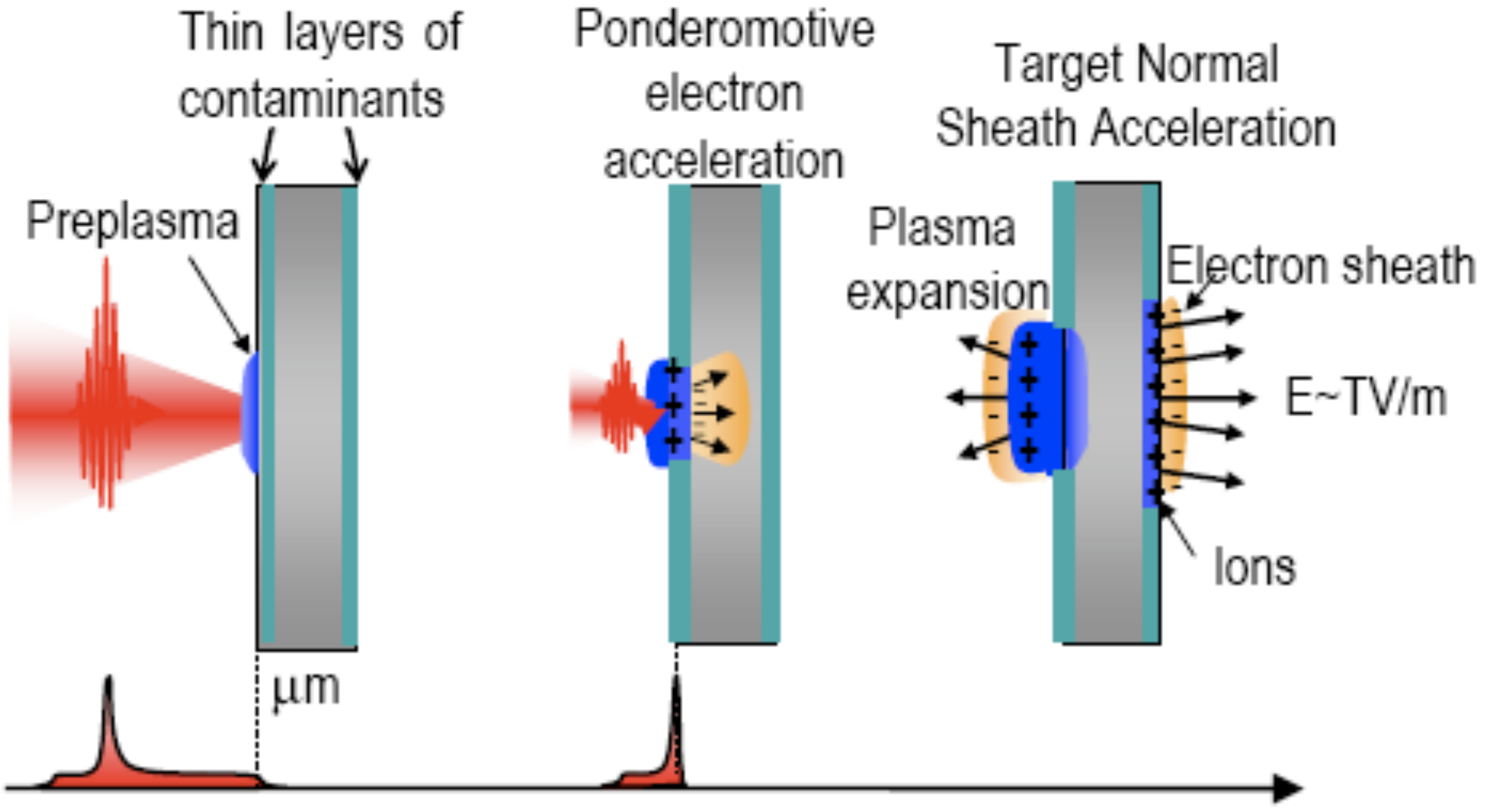
- **Target Normal Sheath Acceleration**

  The basic process

  State of the art and beam properties

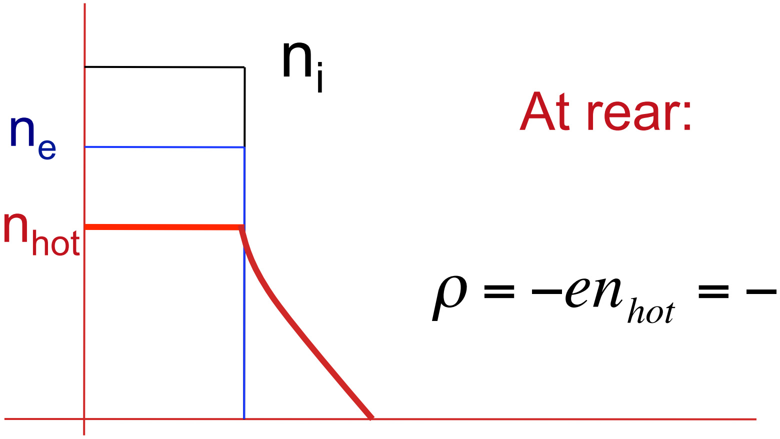


The established mechanism: Sheath Acceleration (TNSA)



High density, high energy electrons lead to ultralarge field

S. Wilks *et al*, PoP, **8**, 542 (2001)



At rear:

$$\rho = -en_{hot} = -en_0 \exp\left(-\frac{x}{\lambda_D}\right)$$

$$\nabla \cdot E = \frac{dE}{dx} = \frac{\rho}{\varepsilon_0}$$

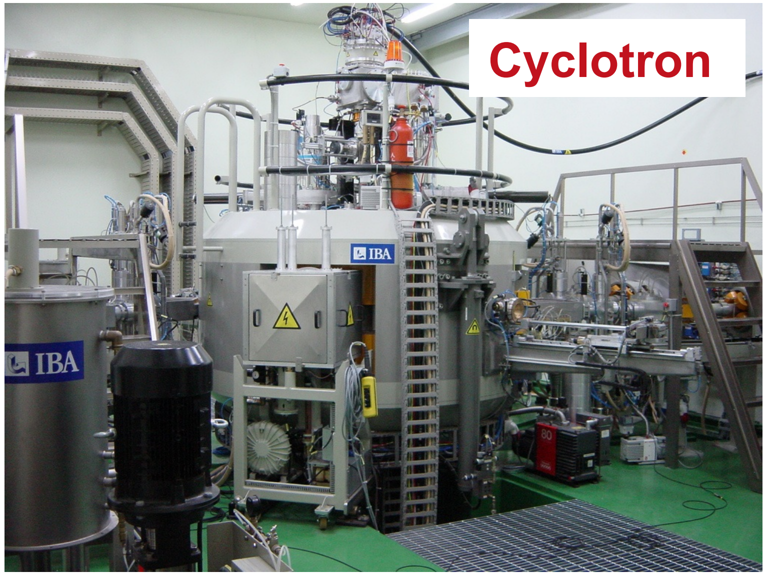
$$E(0) = \int_{\infty}^{0} \frac{\rho}{\varepsilon_0} dx$$

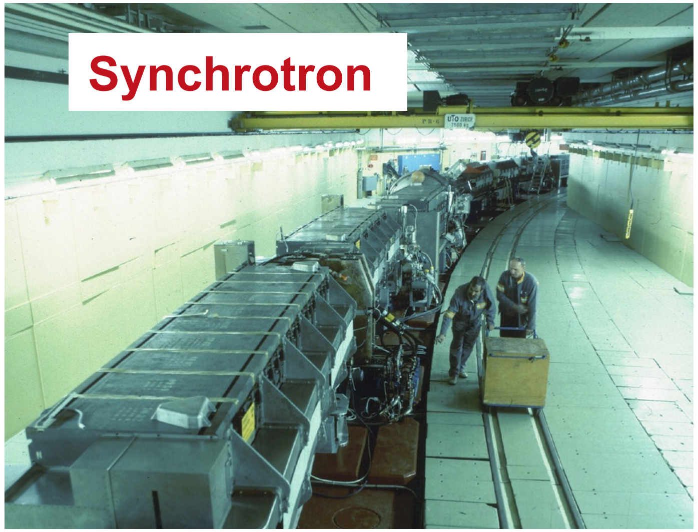
Typical values:
λ_D~ 1 µm
T_h ~ MeV

$$E(0) = \frac{KT_h}{e\lambda_D} = \sqrt{\frac{n_h KT_h}{\varepsilon_0}}$$

$$\boxed{E(0) = \frac{10^6 V}{10^{-6} m} \sim TV/m}$$

Conventional particle accelerators use much smaller fields





Acceleration by much smaller Electric fields associated to alternating voltages (at RF or microwave frequencies)

E_{max} ~ 50 MV/m

(more than 10,000 smaller than with lasers)

TNSA ion beam properties

- **Low emittance/ high laminarity**
- **Ultrashort duration** (~ ps at the source)
- **High brightness: 10^{11} –10^{13}** protons/ions in a single shot (> 3 MeV)
- **High current** (if stripped of electrons): kA range

- Divergent (~ 10s degrees)
- Broad spectrum

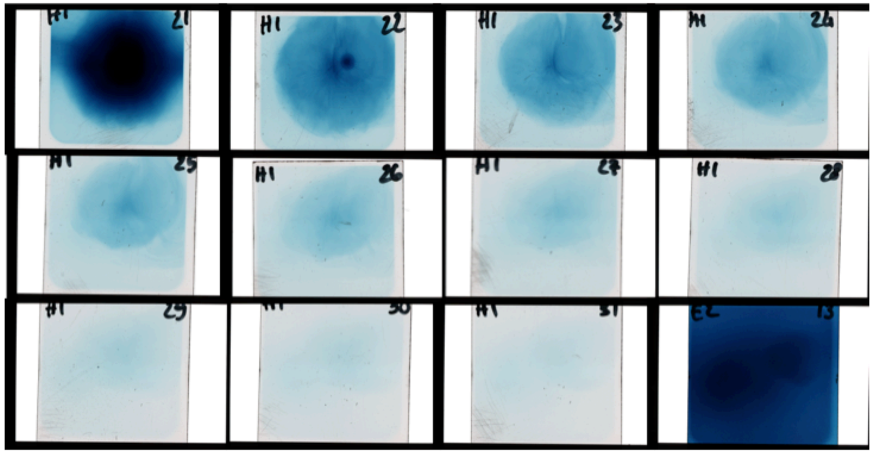
Very compact: E~1-10 TV/m
Acceleration lengths: ~ µm

Ion beam from TARANIS facility, QUB

E ~10 J on target in 10 µm spot

Intensity: ~10^{19} W/cm^2, duration : 500 fs

Target: Al foil 10um thickness



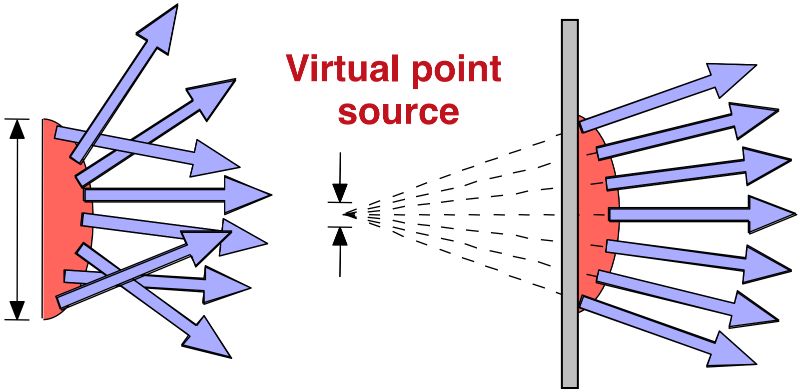
Laser driven beams have excellent emission quality

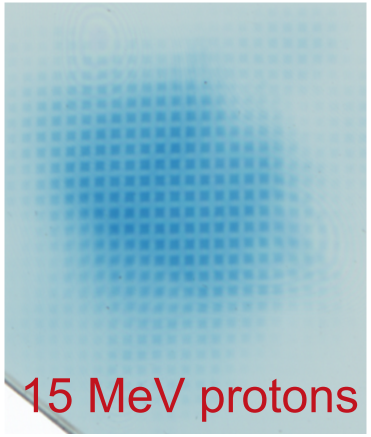
Highly laminar source (virtual point source of ~μm size << *real* source)

Ultralow emittance/ virtual source:

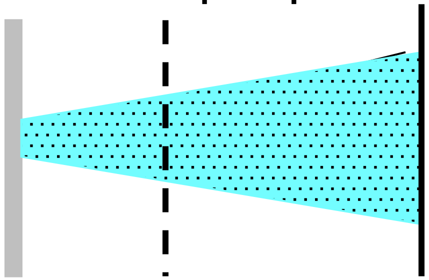
$\varepsilon_N < 0.1\ \pi$ mm.mrad @ 15 MeV

(< 0:004 mm-mrad;
T.Cowan et al, PRL, **92**, 204801, 2004)




15 MeV protons

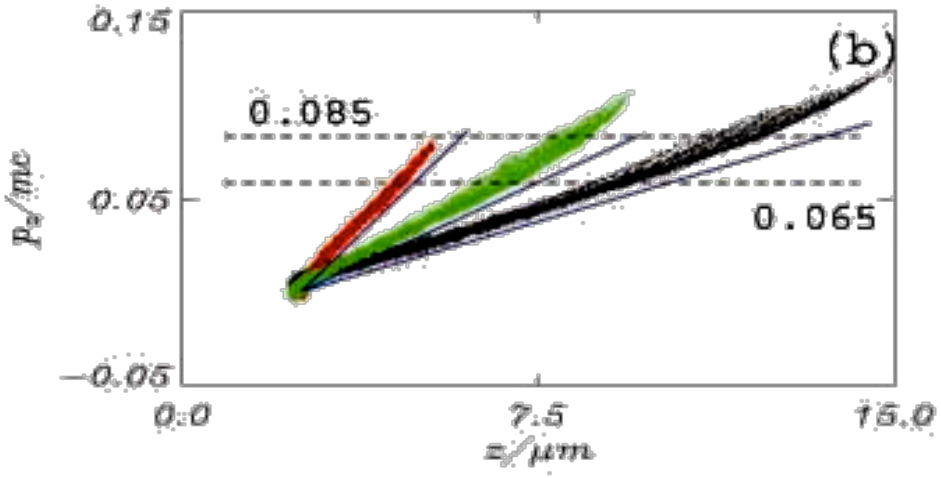
Mesh with 12 μm pitch



CERN proton rf-linac:
ε = **1.7** π mm-mrad

M.Borghesi et al, Phys Rev Lett., ***92****, 055003 (2004))*

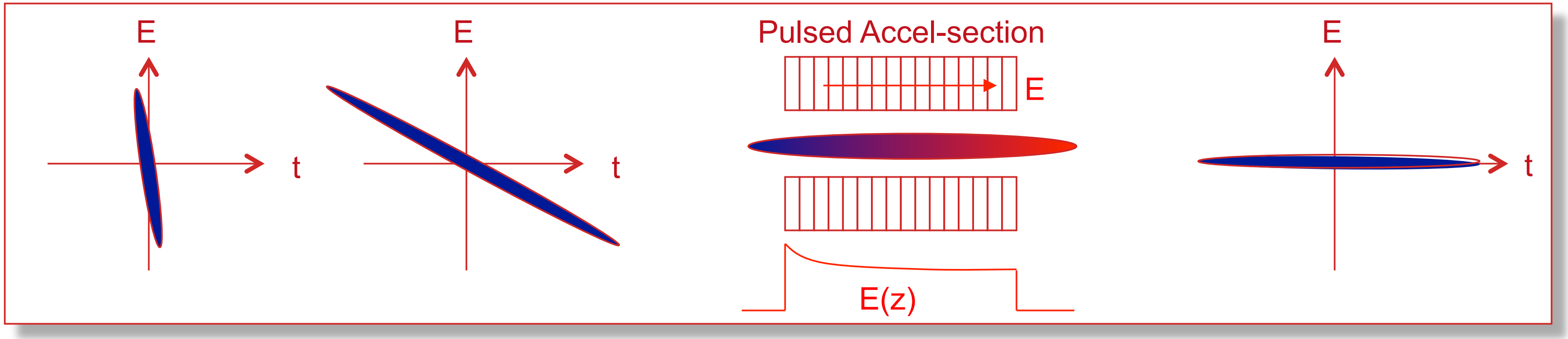
PIC simulations predict an excellent longitudinal emittance



Rapid acceleration produces strong ΔE-Δt correlation

ΔE-Δt < 10^{-6} eV-s

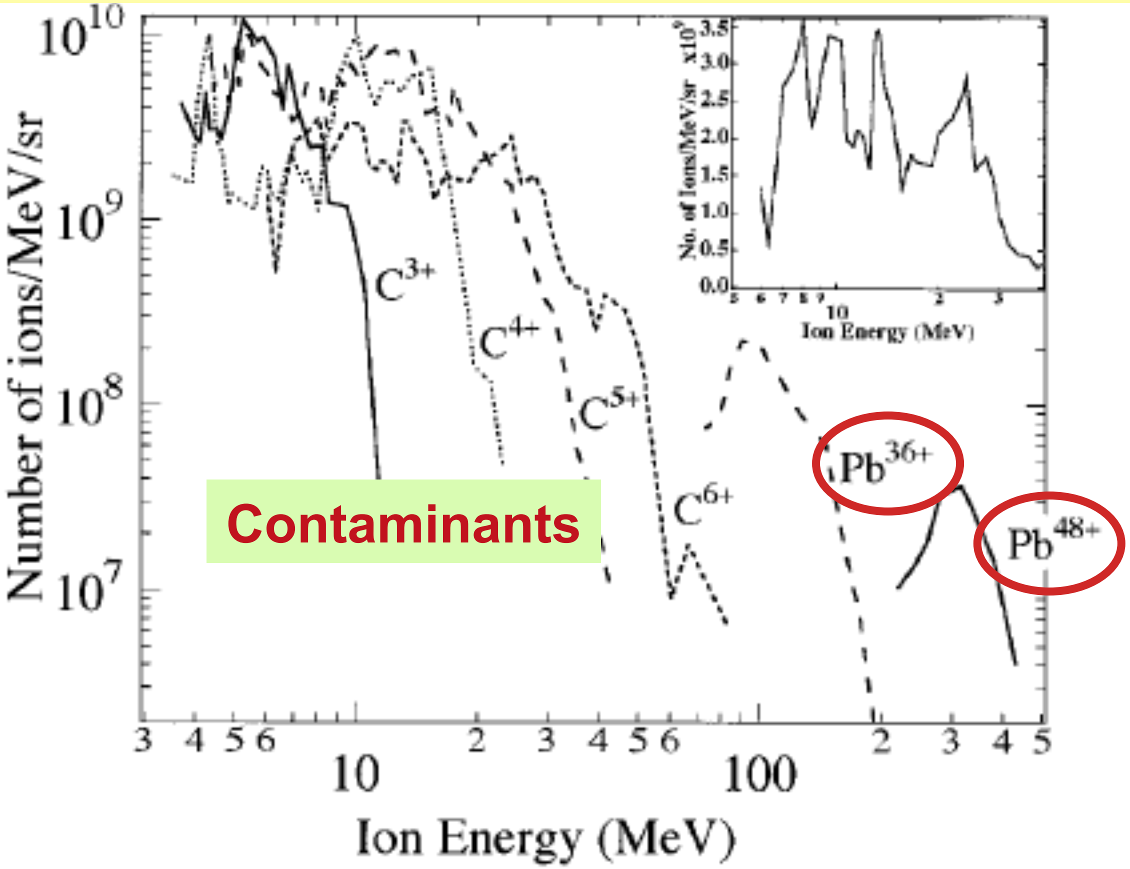
Energy- or time-bunching may be possible with post-acceleration



Not only protons but heavier ions also accelerated

Spectra from VULCAN 100 TW: Pb target irradiated @ 5 10^{19} W/cm^2

E.L.Clark *et al.,* Phys. Rev. Lett., **85**, 1655 (2000))



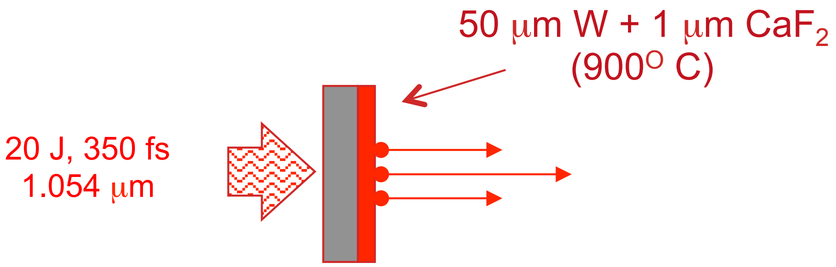
Contaminants

- Most of energy goes to protons
- Energy increases with charge

Varying the target, any ion can be accelerated (not straightfoward with RF accelerators)

High efficiency conversion of laser energy to heavy ions is achieved by removing hydrogen contaminants from target

M. Hegelich et al., Phys. Rev. Lett. **89**, 085002 (2002)

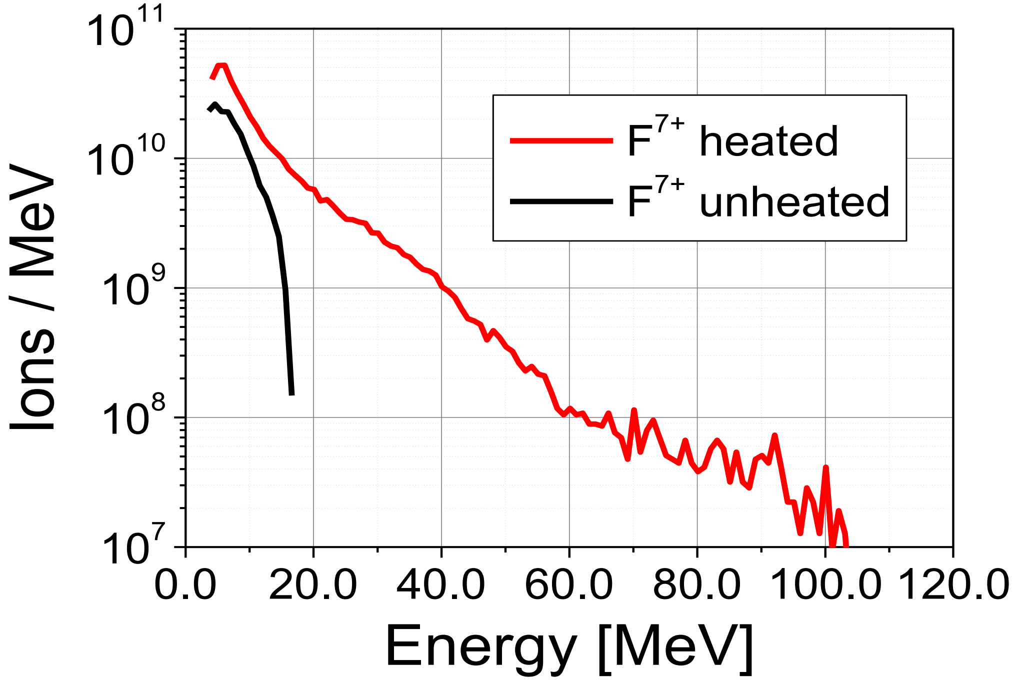


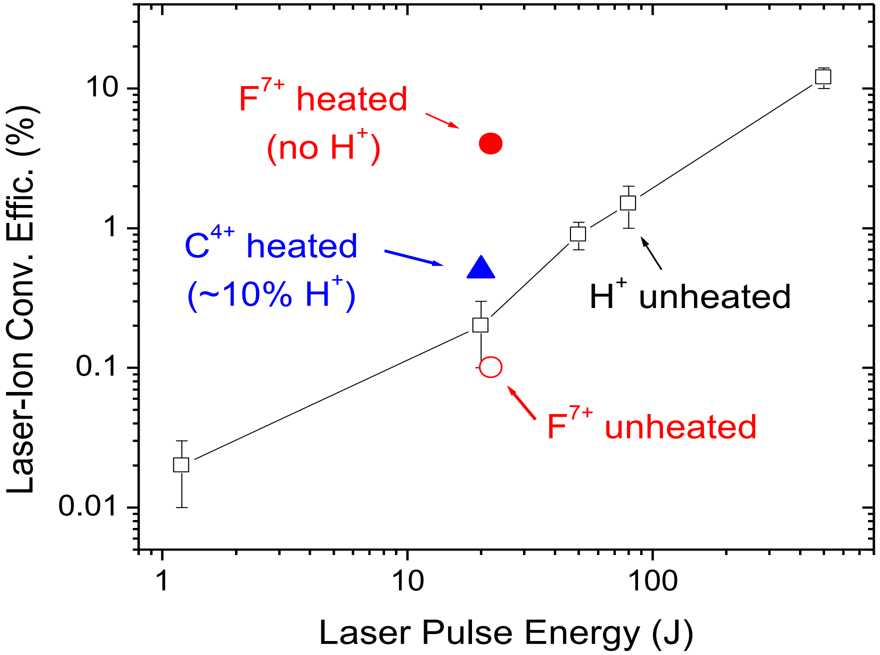
Contaminant removal:

Ohmic heating

Laser heating

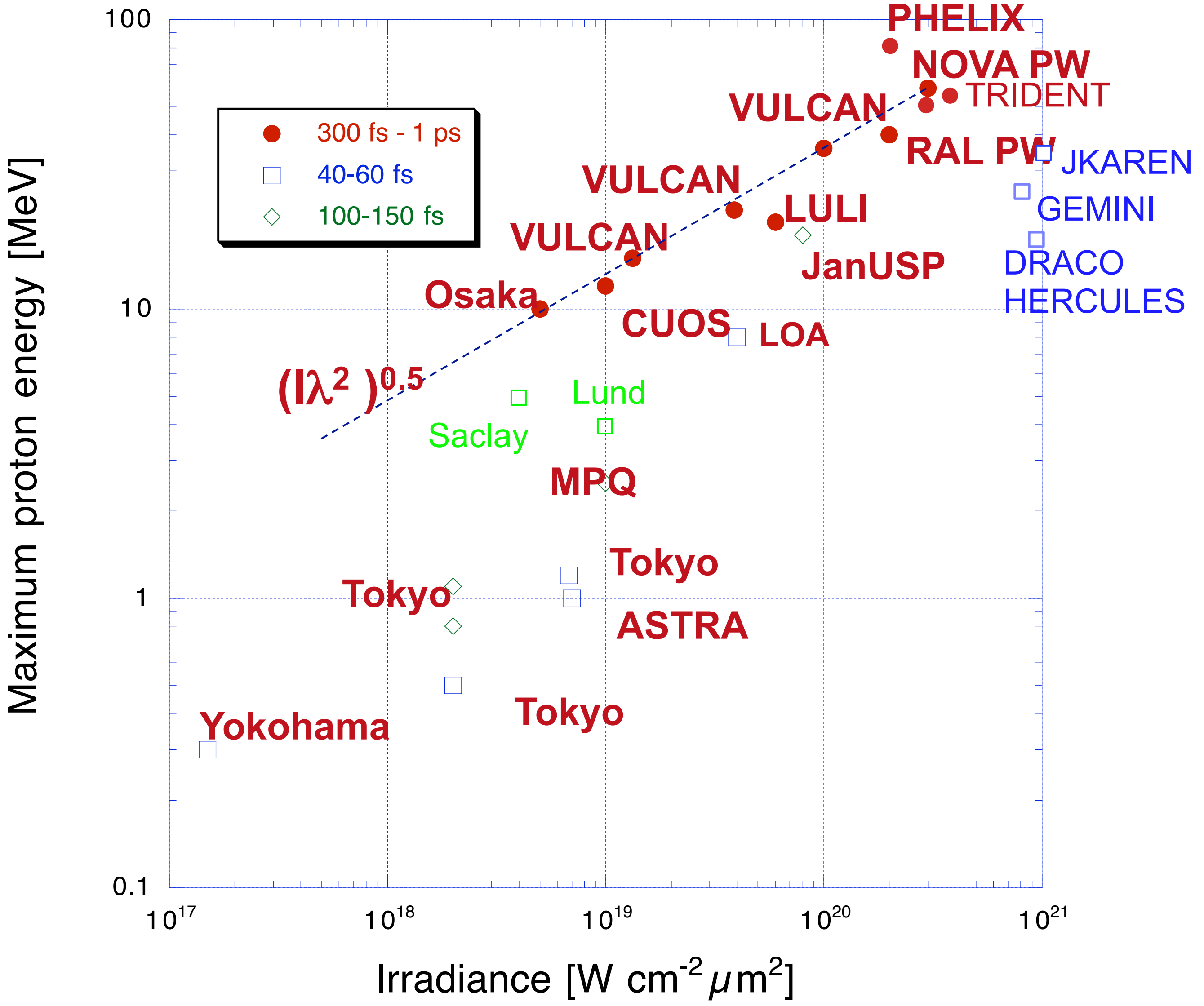
Laser ablation





TNSA energies – state of the art

A.Macchi, M. Borghesi, M. Passoni, Rev. Mod. Physics, **85**, 751 (2013)



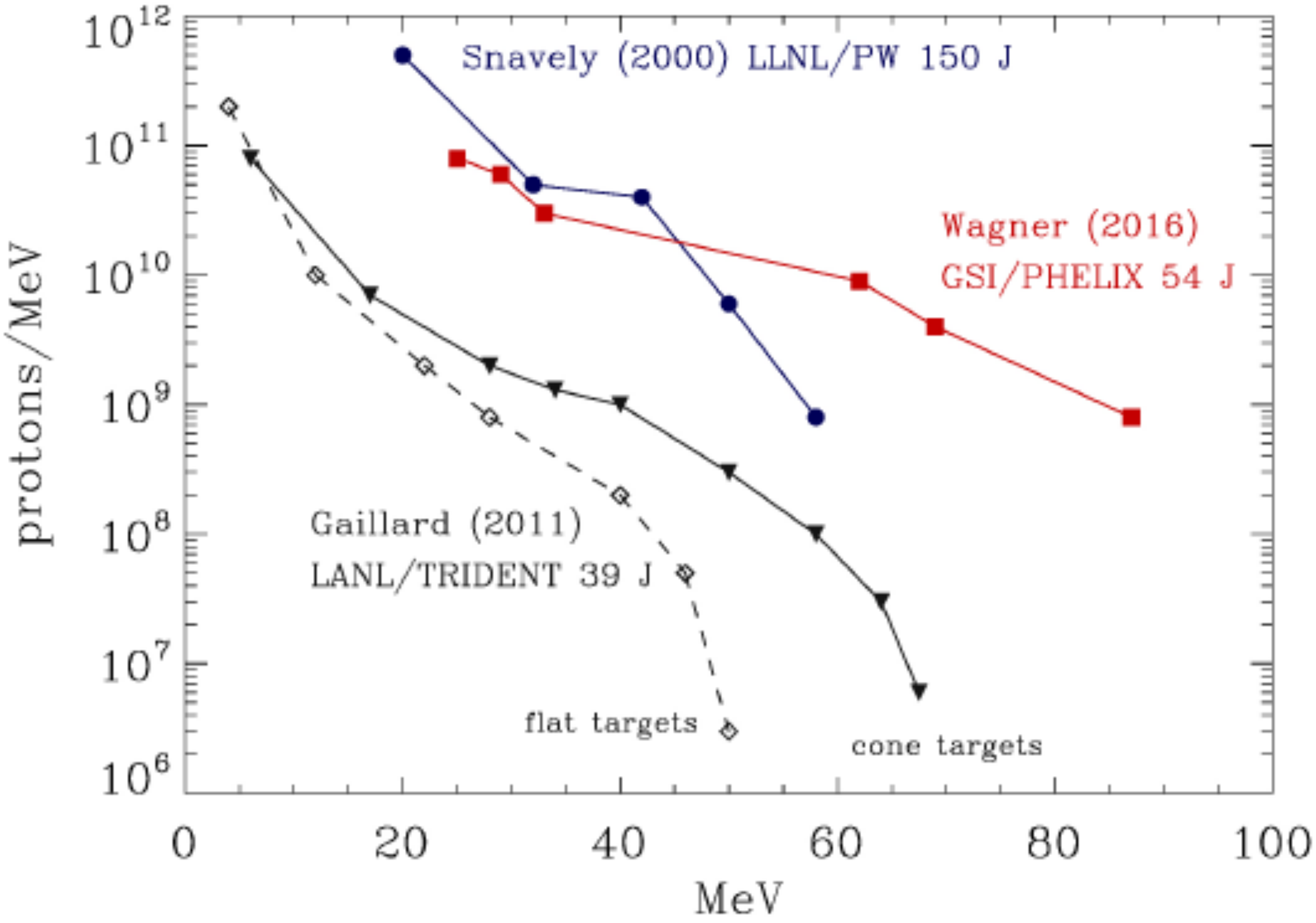
Maximum published energies: ~85 MeV

Conversion efficiency: ~ few %

Acceleration more effective with higher energy, longer pulses, at equal intensities

Effective on protons, less so on higher-Z species

“Record” spectra - long pulses (0.5-1 ps)



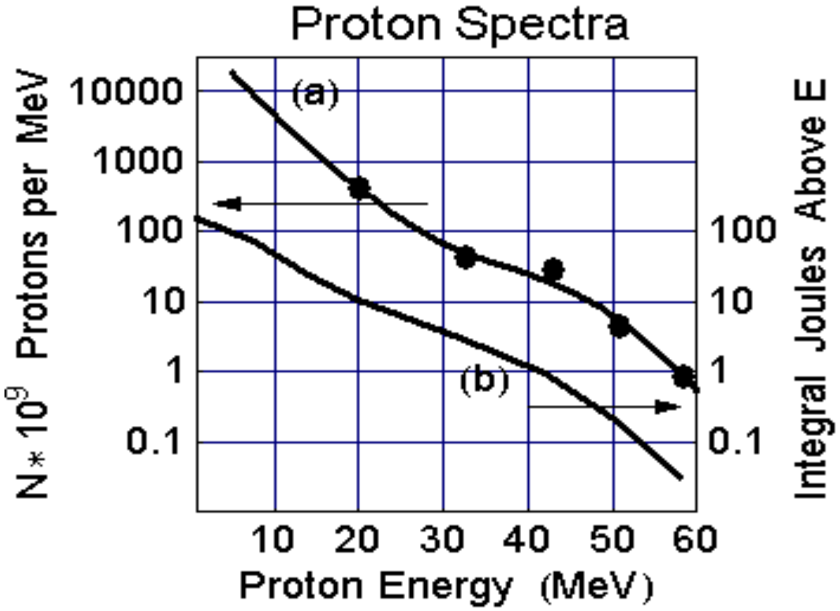
Large, high energy *systems*

RCF (and activation) measurements

I ~ mid 10^{20} W/cm^2

Improved control of the laser parameters can lead to significant improvement

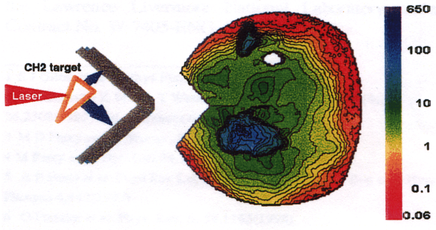
R.D.Snavely *et al* , PRL, 85, 2945 (2000)



NOVA PW, LLNL

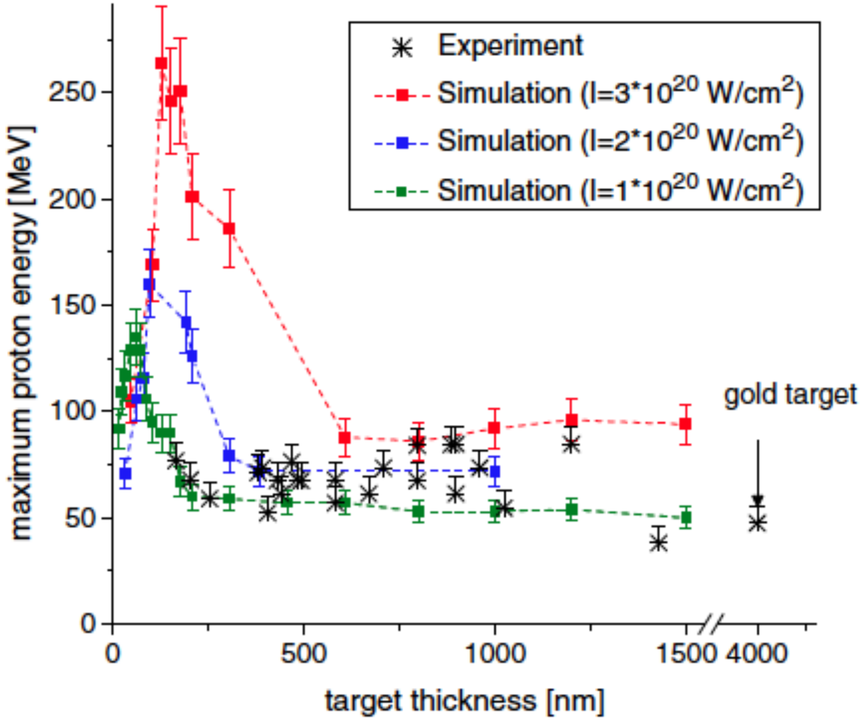
500J, 0.5ps

I ~ 4x10^{20}Wcm^{-2}



CH target, 100 μm thick

F.Wagner *et al* , PRL, 116, 205002 (2016)



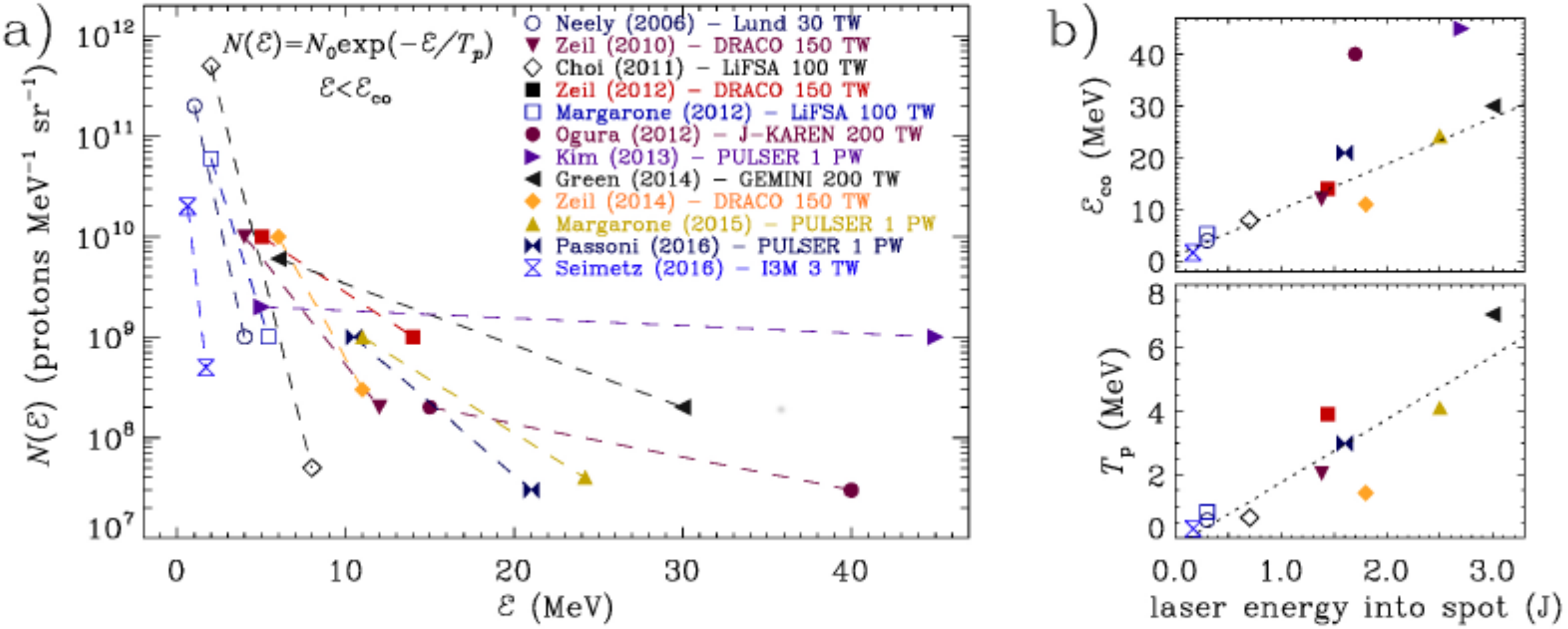
PHELIX, GSI

200J, 0.5 ps, I~ 2 10^{20} W/cm^2

CH$_2$ target, 0.9 μm

Better focusing, prepulse control….

Proton spectra from *short pulse* laser systems : ~ 20-50 fs



Near-linear scaling of proton energy with Laser energy/intensity (~ 9 MeV/J)

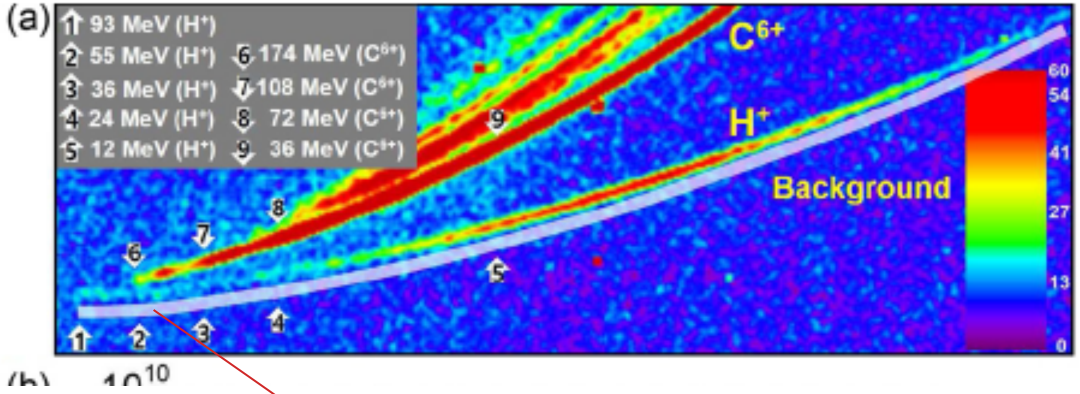
A Macchi, A Sgattoni, S Sinigardi, M Borghesi, and M Passoni, *PPCF*, **55**, 124020 (2013)

Some other high energy claims

PHYSICS OF PLASMAS **23**, 070701 (2016)

Radiation pressure acceleration of protons to 93 MeV with circularly polarized petawatt laser pulses

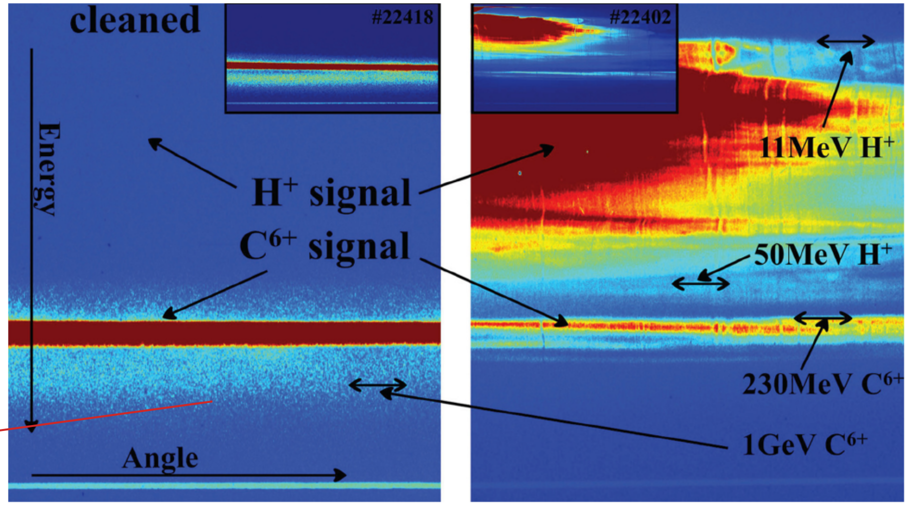
I. Jong Kim,[1,2,a)] Ki Hong Pae,[1,2] Il Woo Choi,[1,2] Chang-Lyoul Lee,[2] Hyung Taek Kim,[1,2]
Himanshu Singhal,[1] Jae Hee Sung,[1,2] Seong Ku Lee,[1,2] Hwang Woon Lee,[1]
Peter V. Nickles,[3] Tae Moon Jeong,[1,2] Chul Min Kim,[1,2,b)] and Chang Hee Nam[1,4,c)]



PHYSICS OF PLASMAS **20**, 083103 (2013)

Laser-driven 1 GeV carbon ions from preheated diamond targets in the break-out afterburner regime

D. Jung,[1,2,3,a)] L. Yin,[1] D. C. Gautier,[1] H.-C. Wu,[1] S. Letzring,[1] B. Dromey,[4] R. Shah,[1]
S. Palaniyappan,[1] T. Shimada,[1] R. P. Johnson,[1] J. Schreiber,[2,3] D. Habs,[2,3]
J. C. Fernández,[1] B. M. Hegelich,[1] and B. J. Albright[1]



Scattering noise interpreted as signal ?

Need for community established protocols
Rigour in analysis