29-30, Nov, 2016, Paris

Efficient Ion acceleration from nanometer targets

X.Q.Yan

State Key Lab of Nuclear Phy and Tech, Institute of Heavy Ion Physics (IHIP), Peking Univeristy, China

International Centre for Zetta-Exawatt Science and Technology (IZEST)

*x.yan@pku.edu.cn

Outline

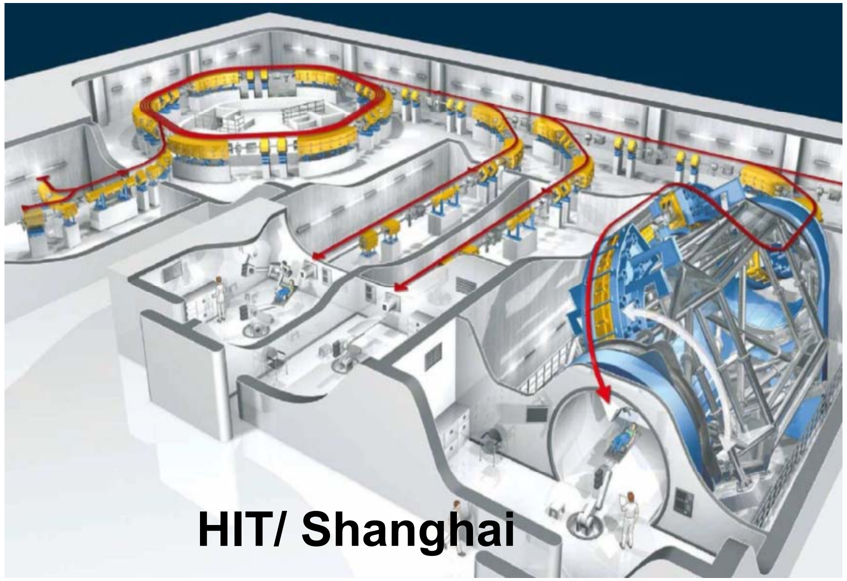
1. Motivation of proton/ion acceleration
2. Experiments using state of art CPA laser

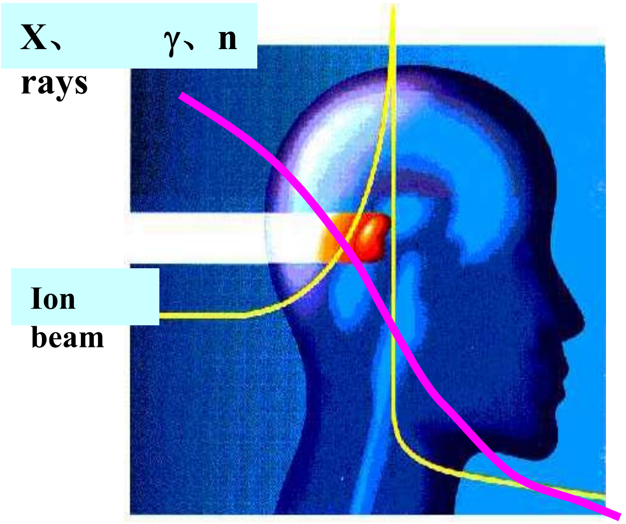
   2.1 Generation of quasi-mono-energetic ion bunch via ionization dynamics

   2.2 Acceleration of heavy Ion by two layer target (carbon nanotube +DLC)
3. Generation of proton beam in an instability-free regime by a single-cycle laser pulse
4. Compact LAser Plasma Acceleration (CLAPA) MOST-project

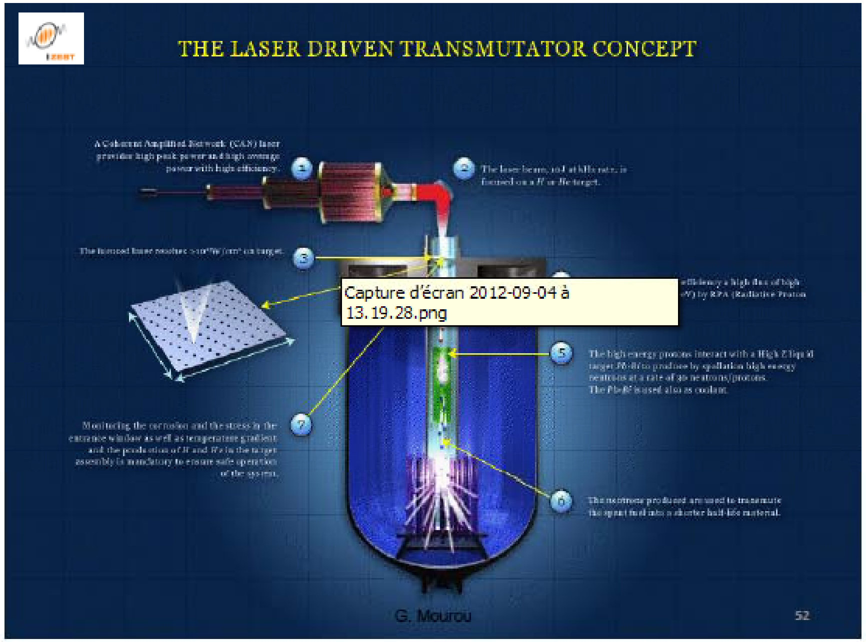
Motivation

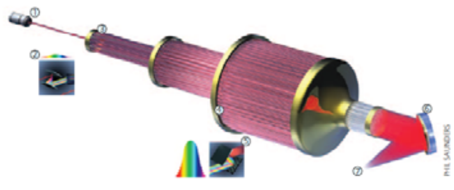
~200MeV proton/400MeV/u Carbon





~GeV proton





The future is fibre accelerators

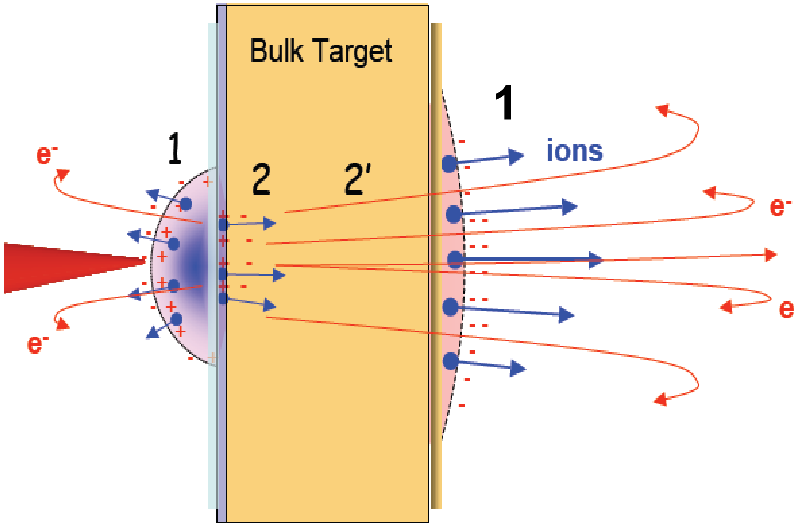
Gerard Mourou, Bill Brocklesby, Toshiki Tajima and Jens Limpert

Could massive arrays of thousands of fibre lasers be the driving force behind next-generation particle accelerators? The International Coherent Amplification Network project believes so and is currently performing a feasibility study.

The challenge of producing the next generation of particle accelerators, for both fundamental research at laboratories such as CERN and more applied tasks such as proton therapy and nuclear transmutation, has been taken up by the high-intensity laser community. With the advent of chirped pulse amplification (CPA) in 1985[1] came the ability to generate ultrashort laser pulses with intensities in excess of 10^{18} W cm^{-2}. At these intensities, the electromagnetic field drives electrons into relativistic motion, opening the door to useful effects like wakefield acceleration[2] and hard X-ray production by bremsstrahlung, Compton or betatron emission[3]. Ion motion becomes relativistic[4] at intensities above 10^{22} W cm^{-2} — an intensity regime demonstrated or anticipated with

Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).

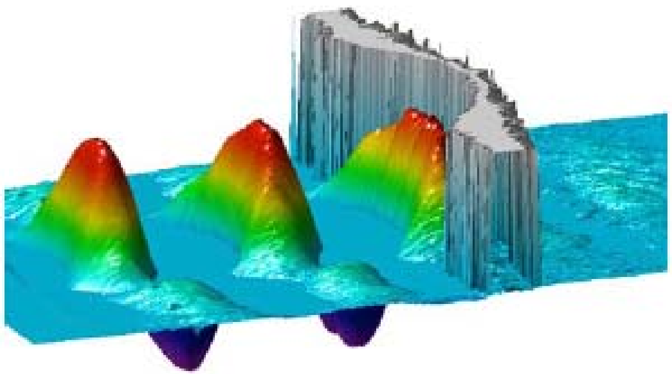
Ion acceleration mechanisms



E~TV/m

1)TNSA

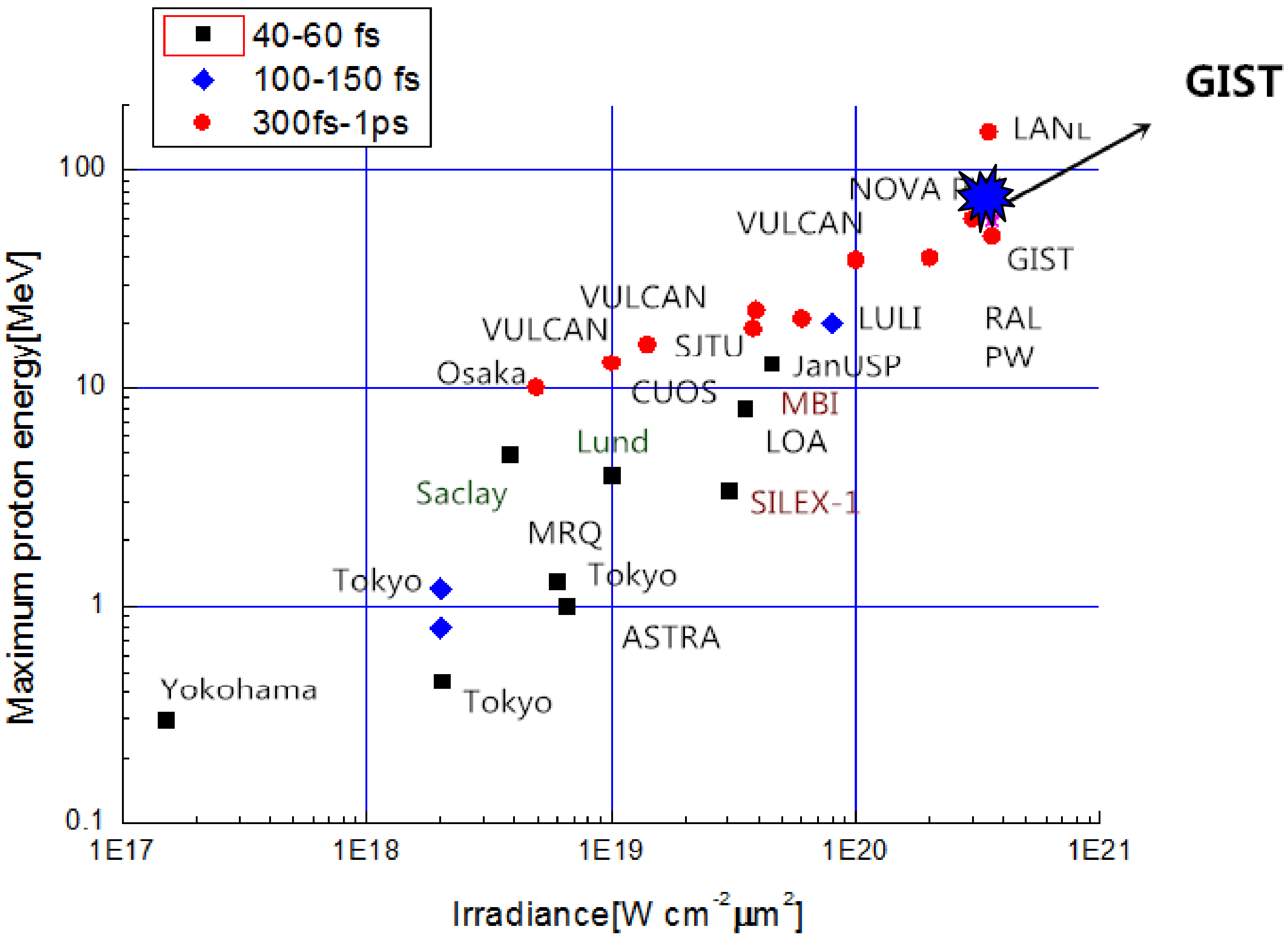
micron thick targets



2)RPA

nanotargets

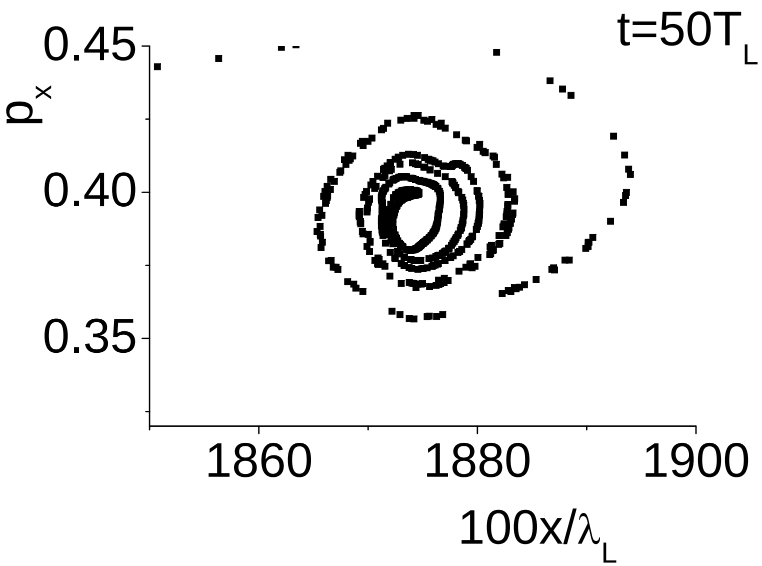
Proton scaling



Radiation Pressure Acceleration

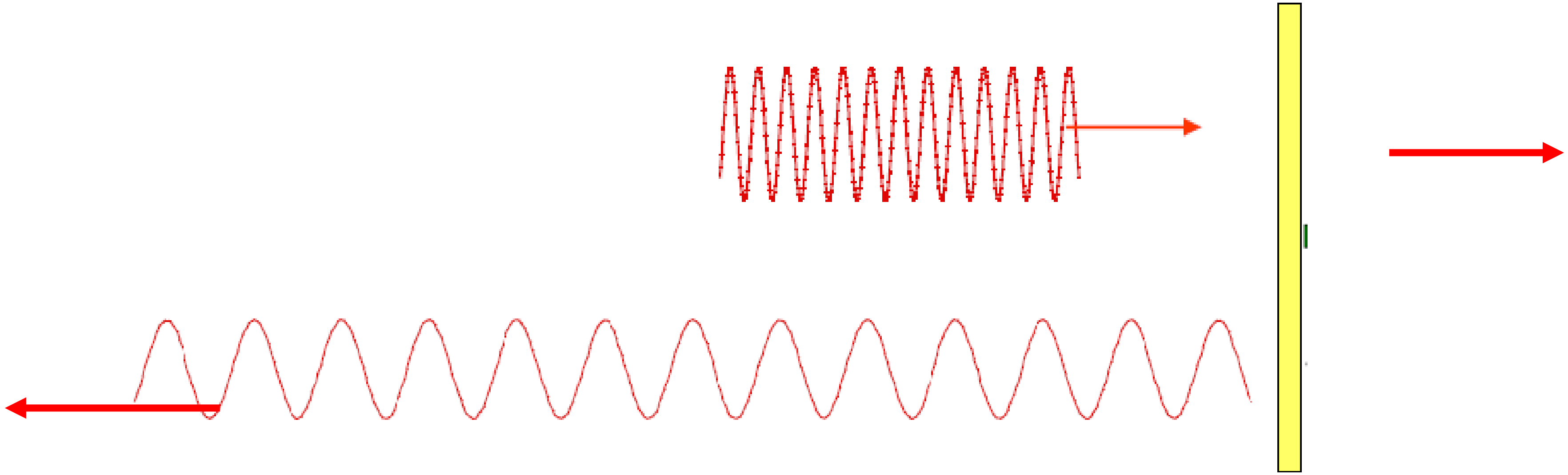
- Esirkempov, et al., PRL 92, 175003 (2004)
- A. Macchi, et al, PRL 94, 165003 (2005)
- X.Zhang, et al, PoP, 14, 123108 (2007)
- X.Q.Yan et al , PRL, 100, 135003 (2008)
- Rykovanov, et al, NJP. 10, 113005 (2008)
- Klimo et al, PRST 11, 031301 (2008)
- Robinson et al, NJP 2008
- A. Macchi, et al, PRL 103.085003 (2009).
- M. Chen et al., PRL 103, 024801 (2009).
- A.Henig et al. PRL 103, 245003 (2009)
- B.Qiao et al., PRL 102, 145002 (2009)
- X.Q. Yan, et al., PRL. 103, 135001 (2009)
- S.Bulanov, et al, PRL 104, 135003 (2010)
- D.Jung,et al. PRL 107, 115002 (2011)
- S.Kar. et al., PRL 109,185006(2012)
- Kim et al., PRL 2015/PoP 2016
- … …

RPA (nanometers) Mono-energetic ion beam



Synchrotron oscillation

Conversion Efficiency (CE)

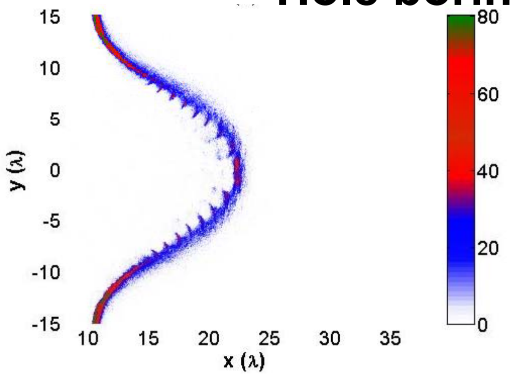


$$CE = 1 - \frac{1}{4\gamma^2} \sim 100\%$$

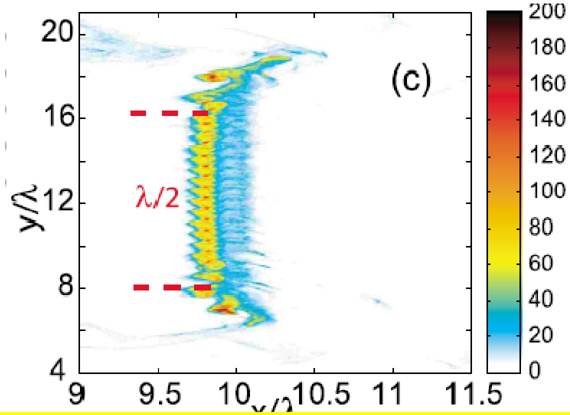
A. Einstein, Annalen der Physik 17, 891 (1905)

Sail broken by "violent storm" of laser

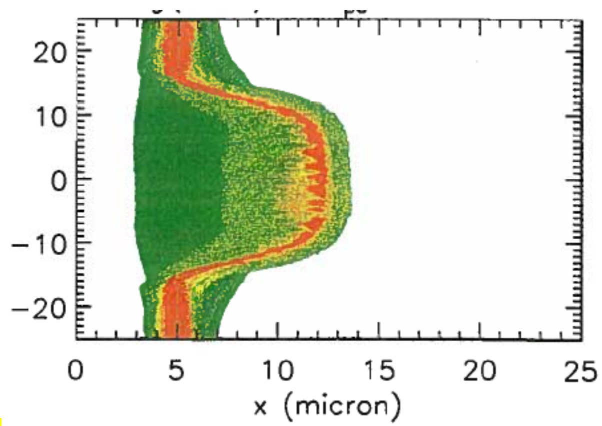
Hole boring and Instabilities are not gentle breeze



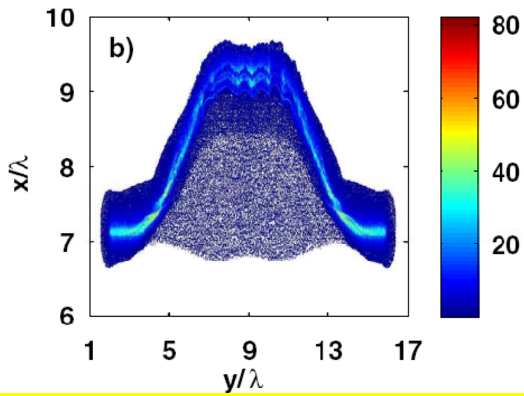
X.Yan, et al., PRL, 103, 135001, (2009)



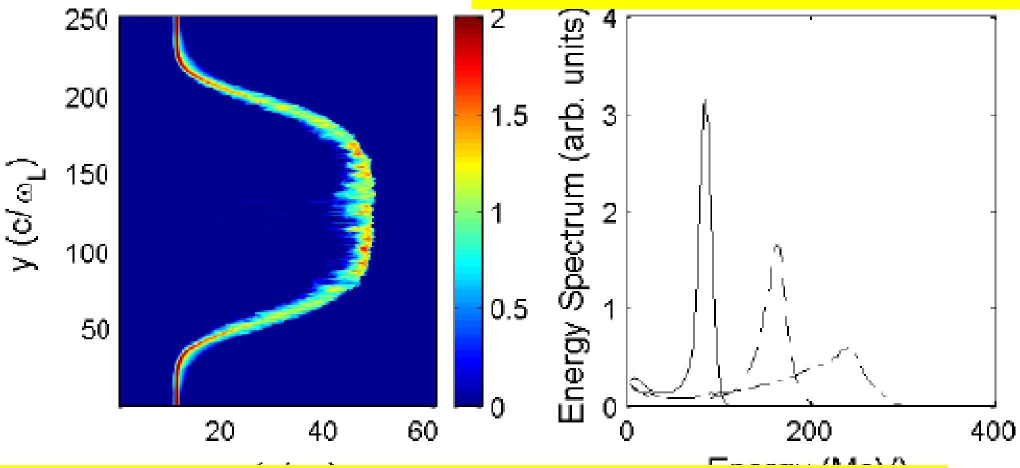
M.Chen et al PoP, 15, 113103, 2008



M.Hegelich and L.Yin

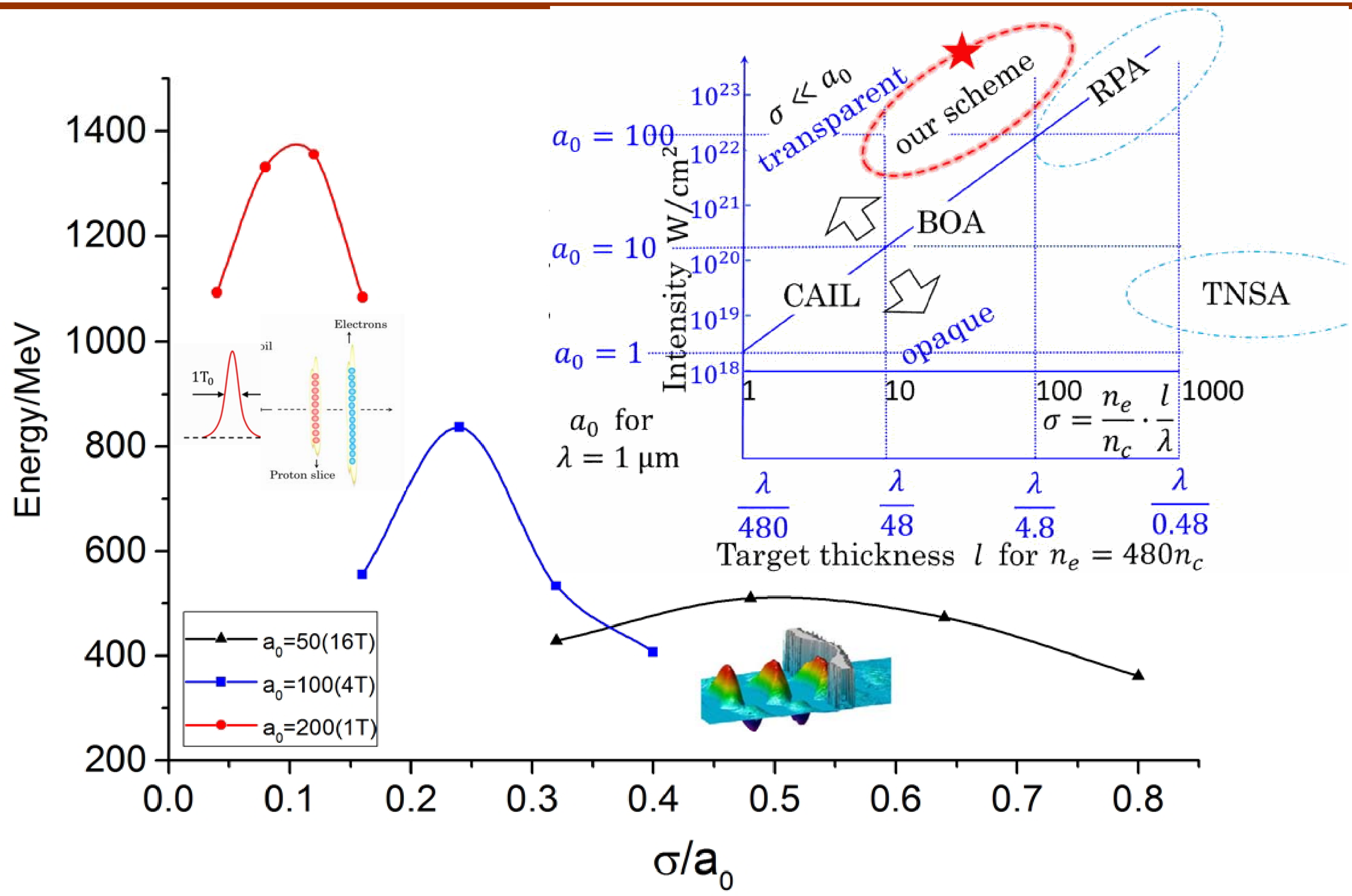


Klimo et al, **Phys. Rev. ST AB** 11, 031301 (2008)



A P L Robinson et al 2008 **New J. Phys.** 10 013021

TNSA、 RPA and new regime



M. L. Zhou, et al., Phys. Plasmas 23, 043112 (2016)

Outline

1. Motivation of proton/ion acceleration
2. Experiments using state of art CPA laser

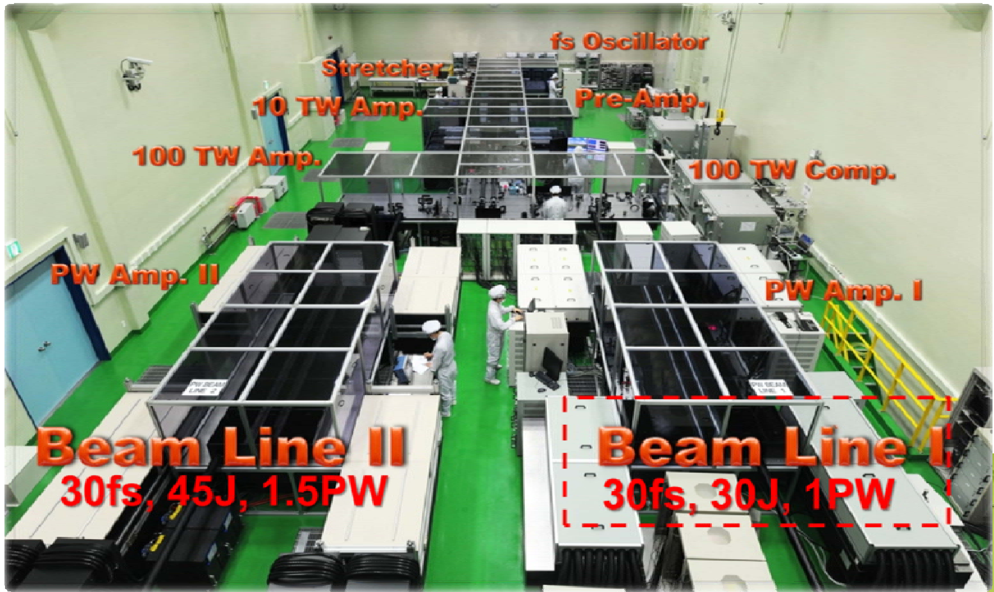
   2.1 Generation of quasi-mono-energetic ion bunch via ionization dynamics

   2.2 Acceleration of heavy Ion by two layer target (carbon nanotube +DLC)
3. Generation of proton beam in an instability-free regime by a single-cycle laser pulse
4. Compact LAser Plasma Acceleration (CLAPA) MOST-project

higher intensity and new nanotargets

Experiments were performed using the CoReLS PW Laser in Korea (Prof. C. H. Nam).

PW Ti:Sapphire Laser (PULSER)



1.5 PW laser (PULSE) in Center for Relativistic Laser Science(IBS), Korea

X. Q. Yan C.H. Nam

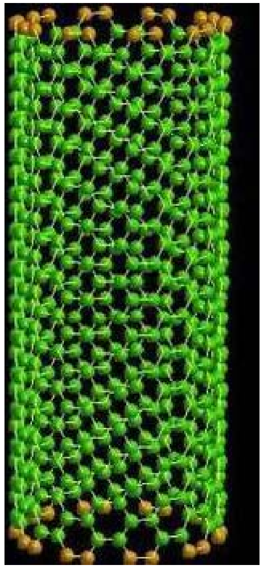
25fs-30fs,
Double plasma mirror, 9.2J on targets for LP,
$I = 5.45 \times 10^{20}\ W/cm^2$

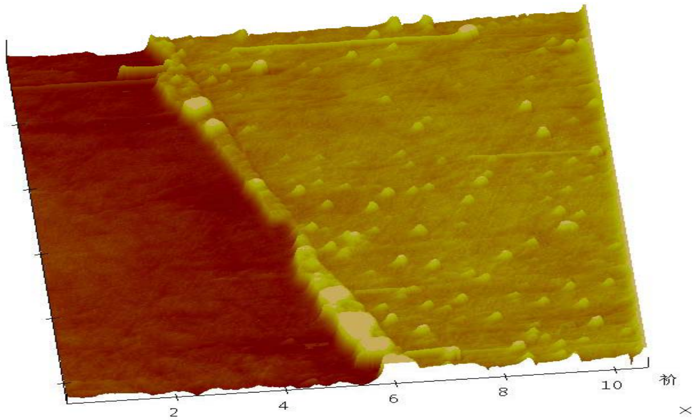
2015.03

Nano-targets (nanotube foam, DLC)

•Carbon Nanotube Foam (uniform, 0.1-10 n_c, thickness :1-100 um)

•Diamond Like Carbon foil (uniform, 800 n_c , thickness: 3-50nm)





Contamination of H2O, 3-5nm

Ion acceleration experiments

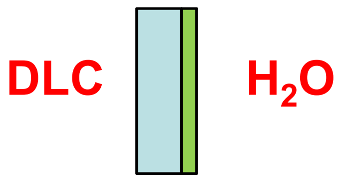
GIST CoReLS Laser parameters

Using double plasma mirror, 33fs and ~40J before PW compressor,
Compressor efficiency : 75%, 9.5-degree incidence angle.

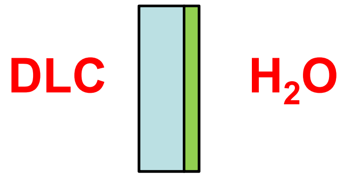
Focus spot: 4.5 um (12.4 pixel) focal spot using F/3 OAP

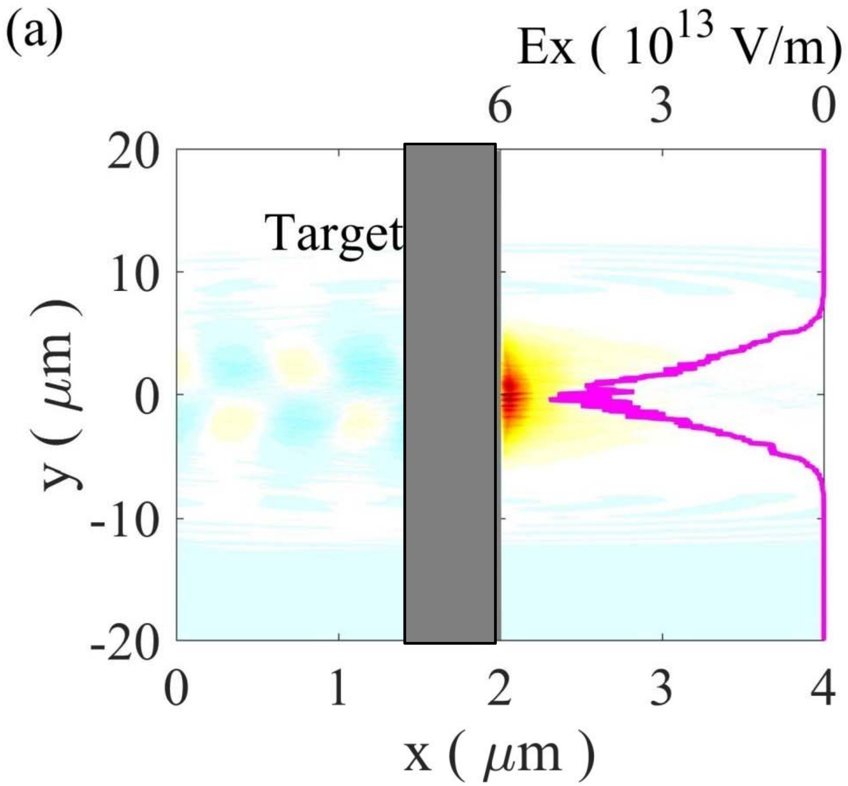
Energy on targets: LP ~9.5J

Targets: DLC foil (5~20nm) with H_2O contamination



Ionization dynamics of nm-film (pre-expanded)



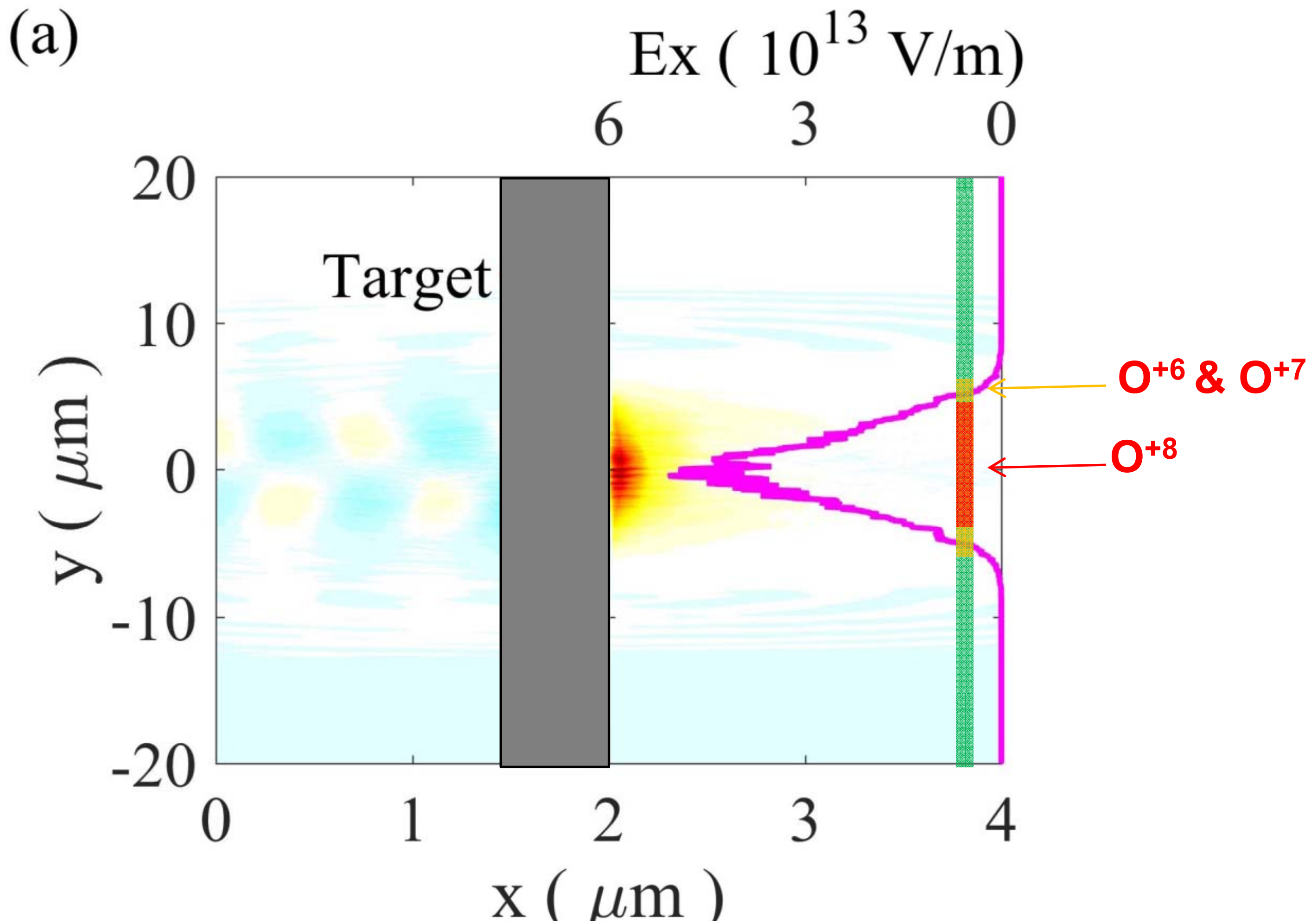


Sheath field distribution

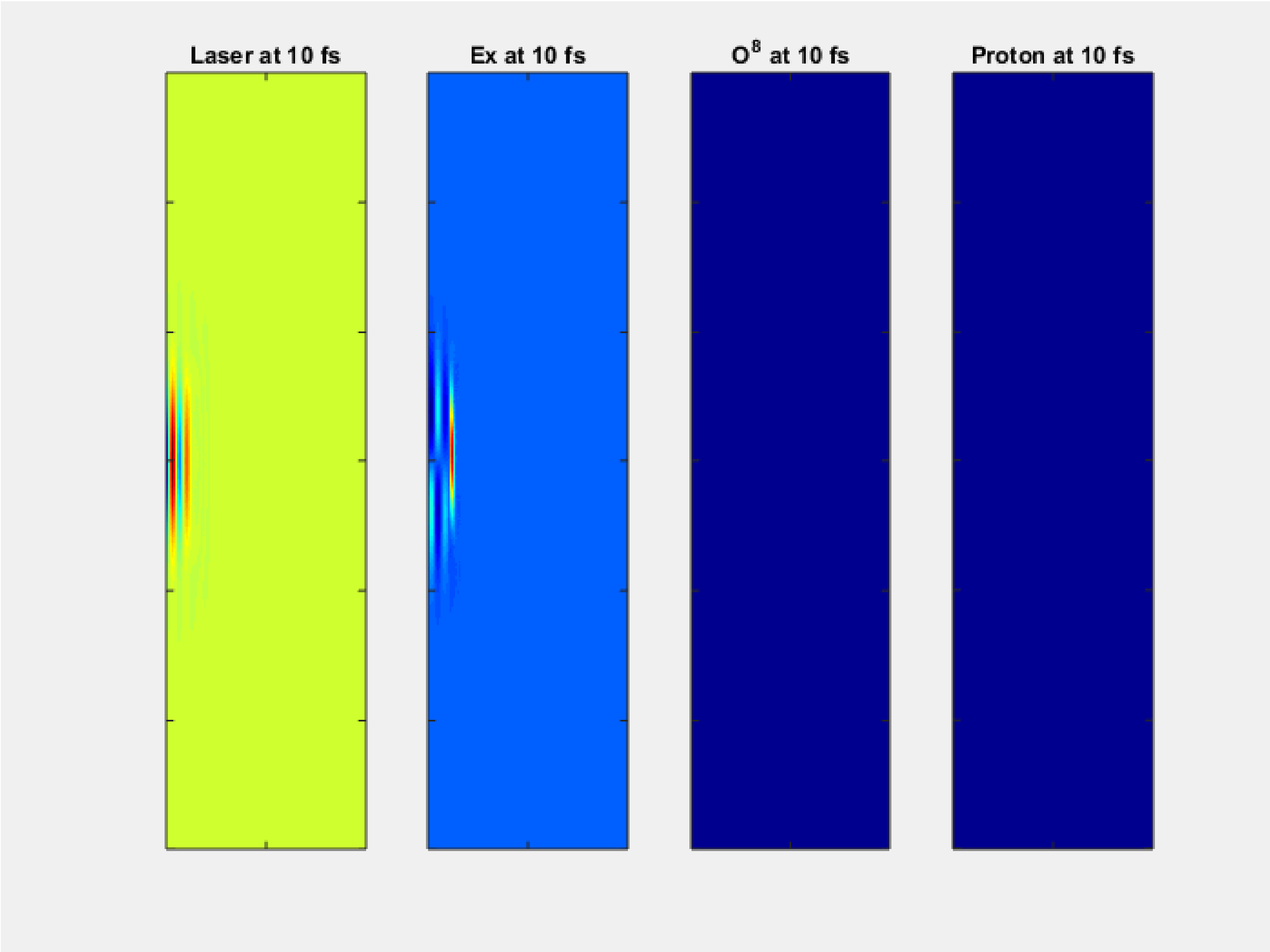
Ion type	Threshold field (V/m)
H^{+1}	3.19×10^{10}
C^{+4}	1.8×10^{11}
C^{+6}	6.9×10^{12}
O^{+6}	2.1×10^{12}
O^{+8}	1.6×10^{13}
Al^{+13}	7.0×10^{13}
Si^{+14}	8.8×10^{13}

Ionization dynamics of nm-film

Nature of micro-structured target due to contamination



Movie for generation of O8+ ions



C.Lin et al., (2016)

Outline

1. Motivation of proton/ion acceleration
2. Generation of quasi-mono-energetic ion bunch via ionization dynamics
3. Acceleration of heavy Ion by two layer target (carbon nanotube +DLC)
4. Generation of proton beam in an instability-free regime by a single-cycle laser pulse
5. Compact LAser Plasma Acceleration (CLAPA) MOST-project

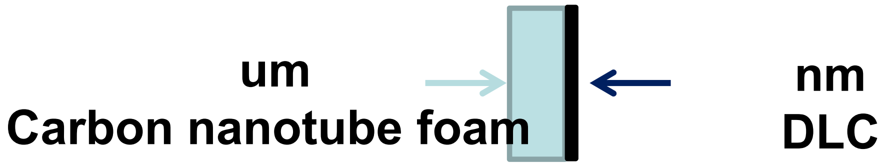
Outline

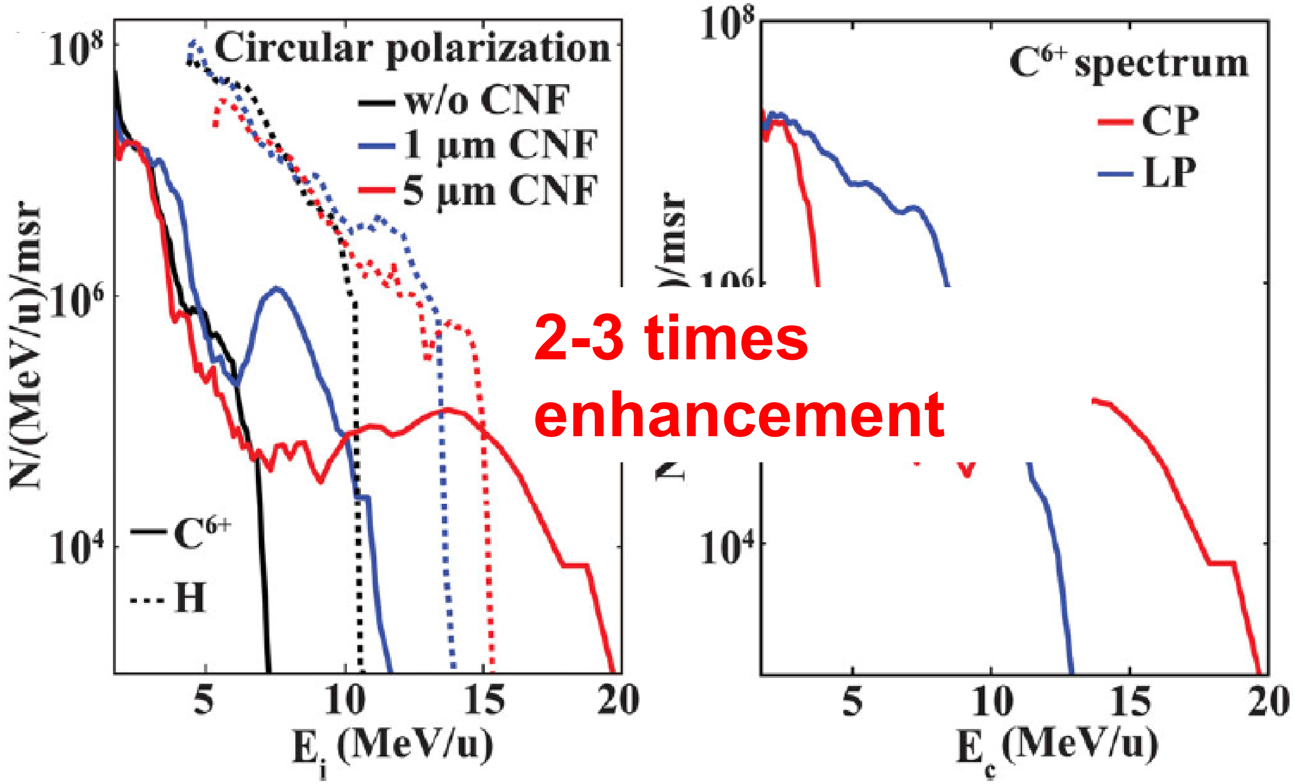
1. Motivation of proton/ion acceleration
2. Two experiments using state of art laser

   2.1 Generation of quasi-mono-energetic ion bunch via ionization dynamics

   2.2 Acceleration of heavy Ion by two layer target (carbon nanotube +DLC)
3. Generation of proton beam in an instability-free regime by a single-cycle laser pulse
4. Compact LAser Plasma Acceleration (CLAPA) MOST-project

Carbon nanotube foam +DLC





2-3 times enhancement

J.H.Bin*, W.J.Ma*,H.Y.Wang, X.Q.Yan et. al. “Ion Acceleration Using Relativistic Pulse Shaping in Near-Critical-Density Plasmas”. *Physical Review Letters 115, 064801 (2015).*

Enhanced Ion acceleration experiments

GIST CoReLS Laser parameters

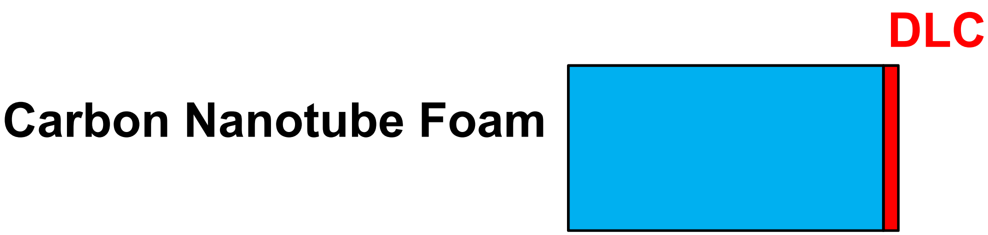
Using double plasma mirror, 33fs and ~40J before PW compressor,
Compressor efficiency : 75%, 9.5-degree incidence angle.

Energy on targets: LP ~9.5J

Focus spot: 4.5 um (12.4 pixel) focal spot using F/3 OAP

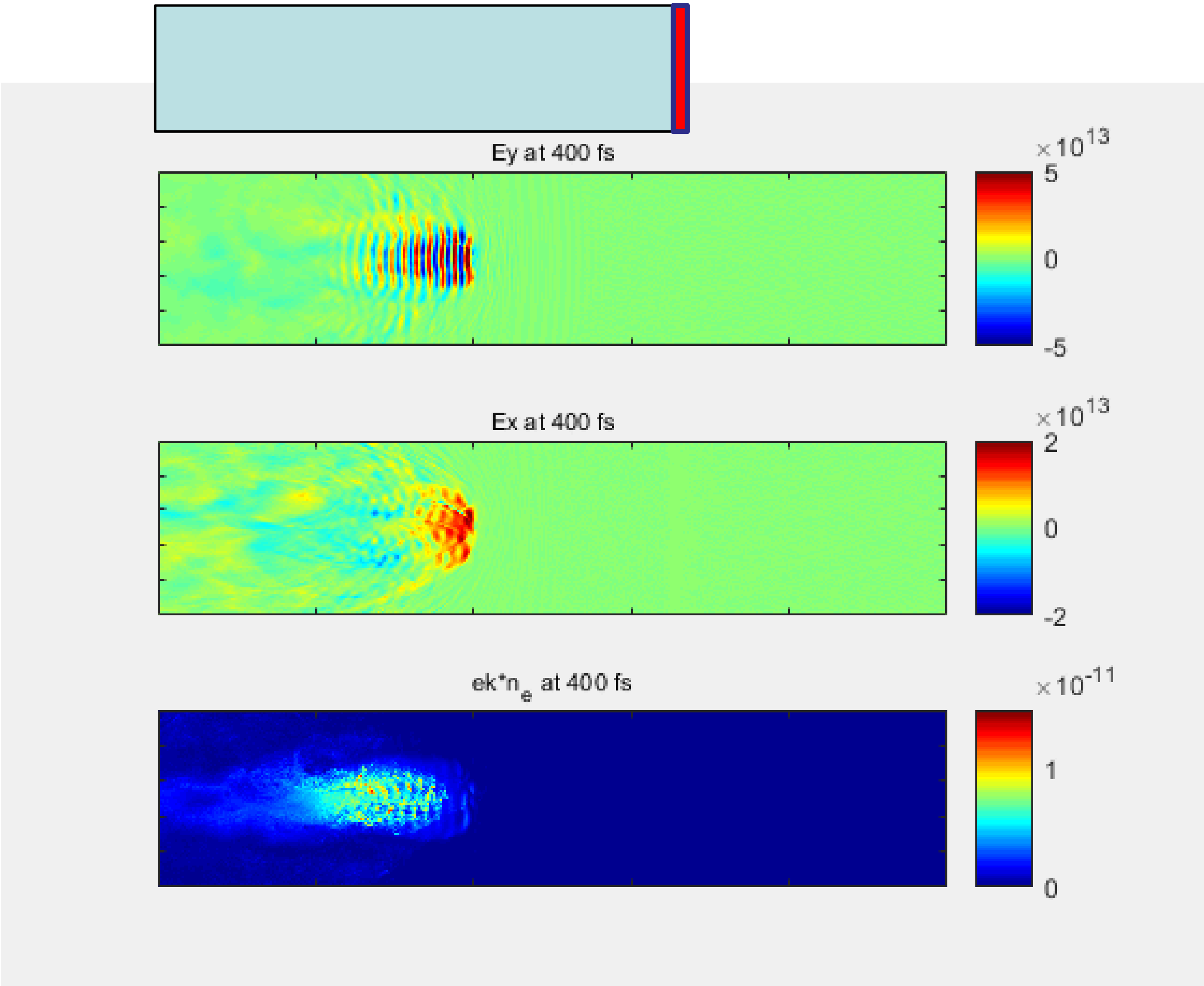
Targets:
Carbon nanotube foam, Thickness : 3 μg/cm^2~36 μg/cm^2 (10~120um)
Density : 2±0.5 mg/cm^3, corresponding to 0.25~0.4 nc if fully ionized

DLC foil (5~20nm)



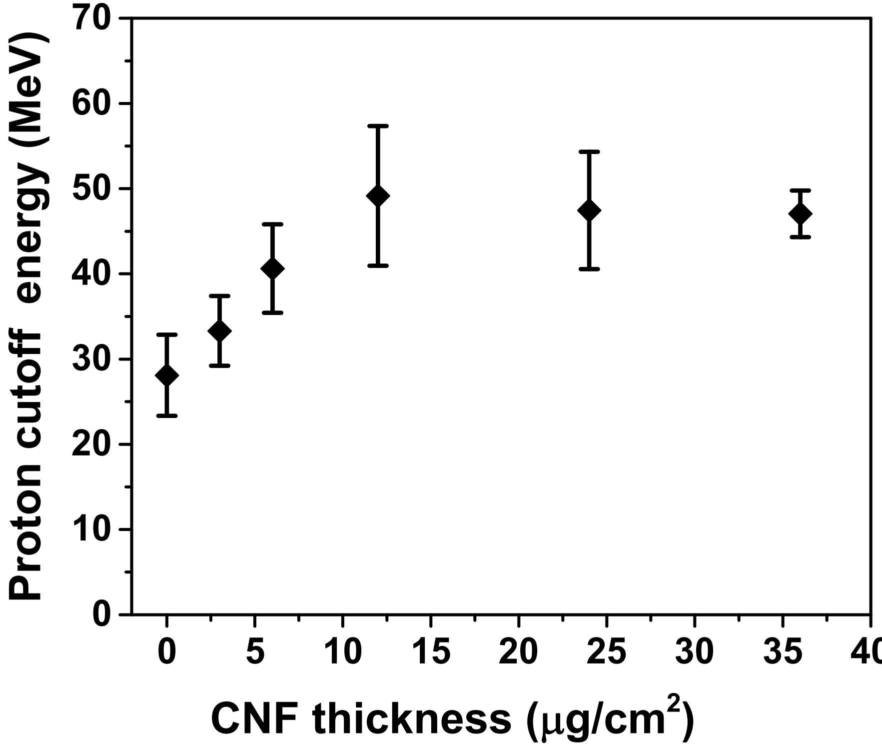
Carbon ions are dominant,
O is neglected

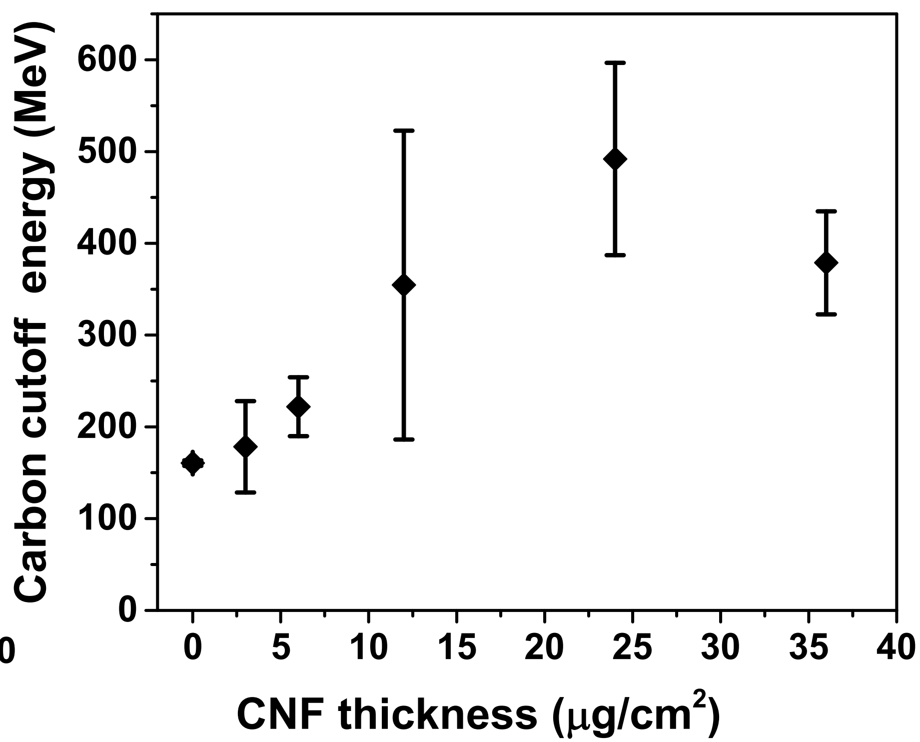
Carbon Nanotube faom **DLC Carbon**



Carbon Nano-Tube (as NCD lens) + DLC foil

Experiments were performed using the CoReLS PW Laser in Korea (Prof.C.H.Nam).





linear polarization

Carbon ions are dominant, Oxygen is neglected.

By Yan ,Ma, Lin, Schreiber, Zepf, Kim && Nam et al.,

Outline

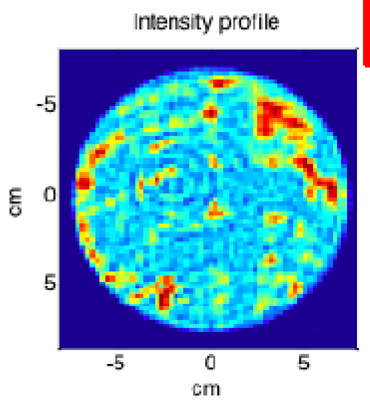
1. Motivation of proton/ion acceleration
2. Two experiments using state of art laser

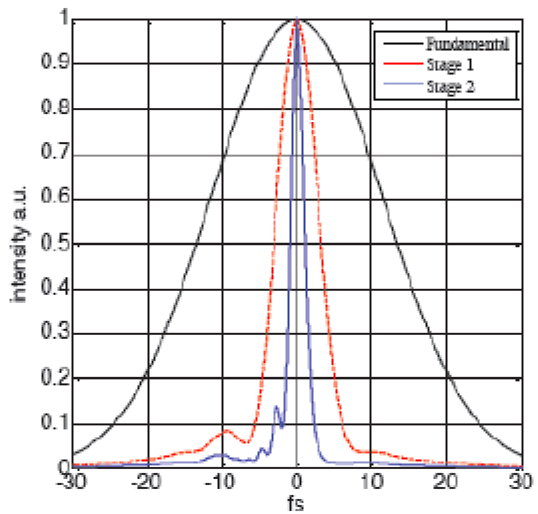
   2.1 Generation of quasi-mono-energetic ion bunch via ionization dynamics

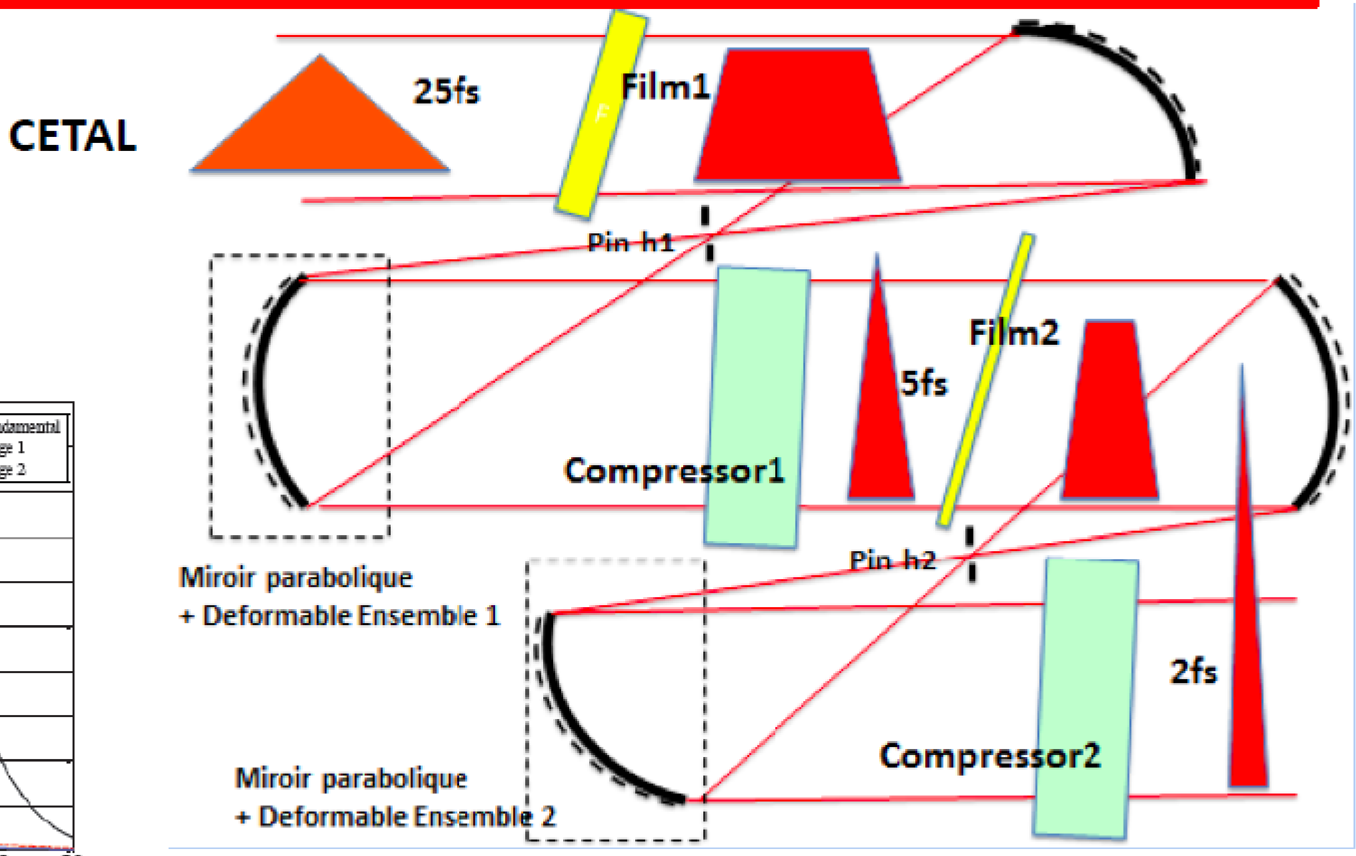
   2.2 Acceleration of heavy Ion by two layer target (carbon nanotube +DLC)
3. Generation of proton beam in an instability-free regime by a single-cycle laser pulse
4. Compact LAser Plasma Acceleration (CLAPA) MOST-project

Single Cycle Thin Film Compressor

Laser with Uniform beam Amplitude and Phase

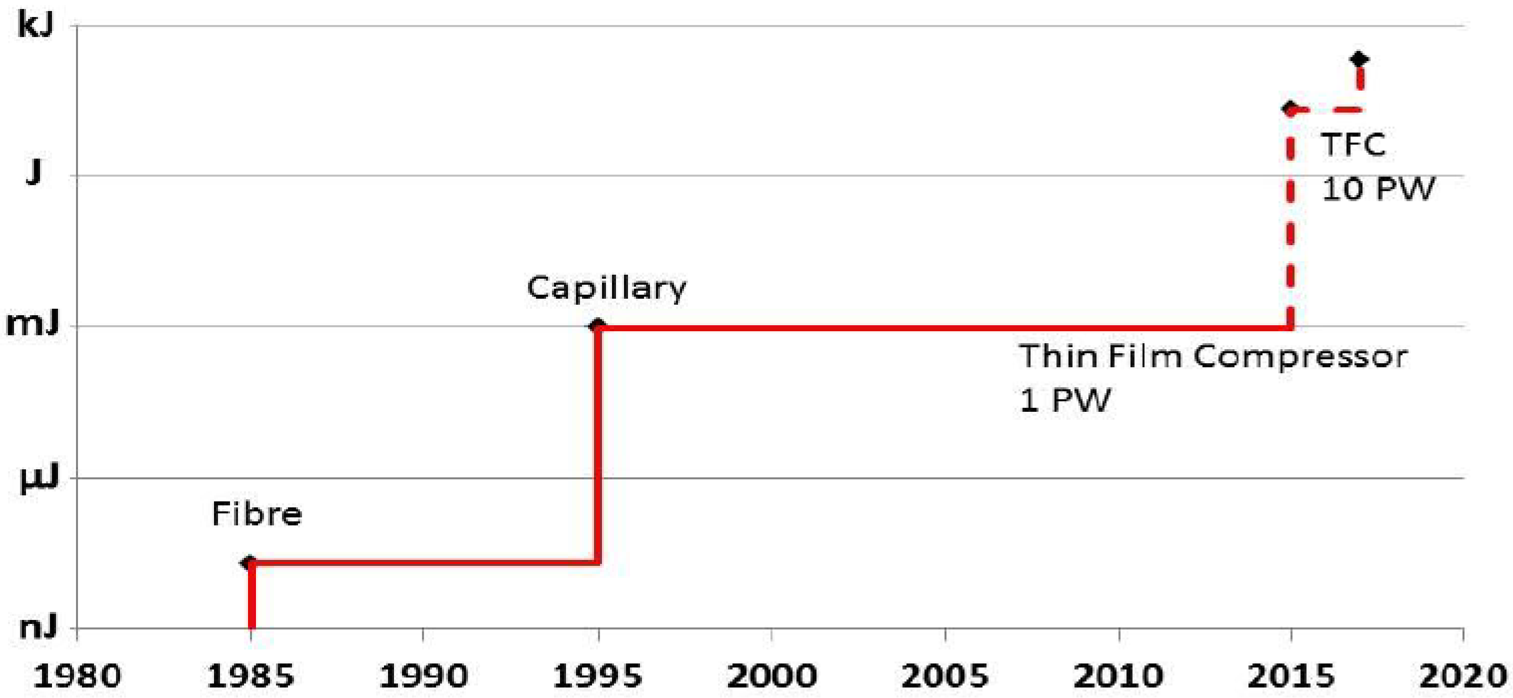






G. Mourou, S. Mironov, E. Khazanov and A. Sergeev, Single cycle thin film compressor opening the door to Zeptosecond-Exawatt Physics , Eur. Phys. J. Special Topics, 223, 1181(2014)

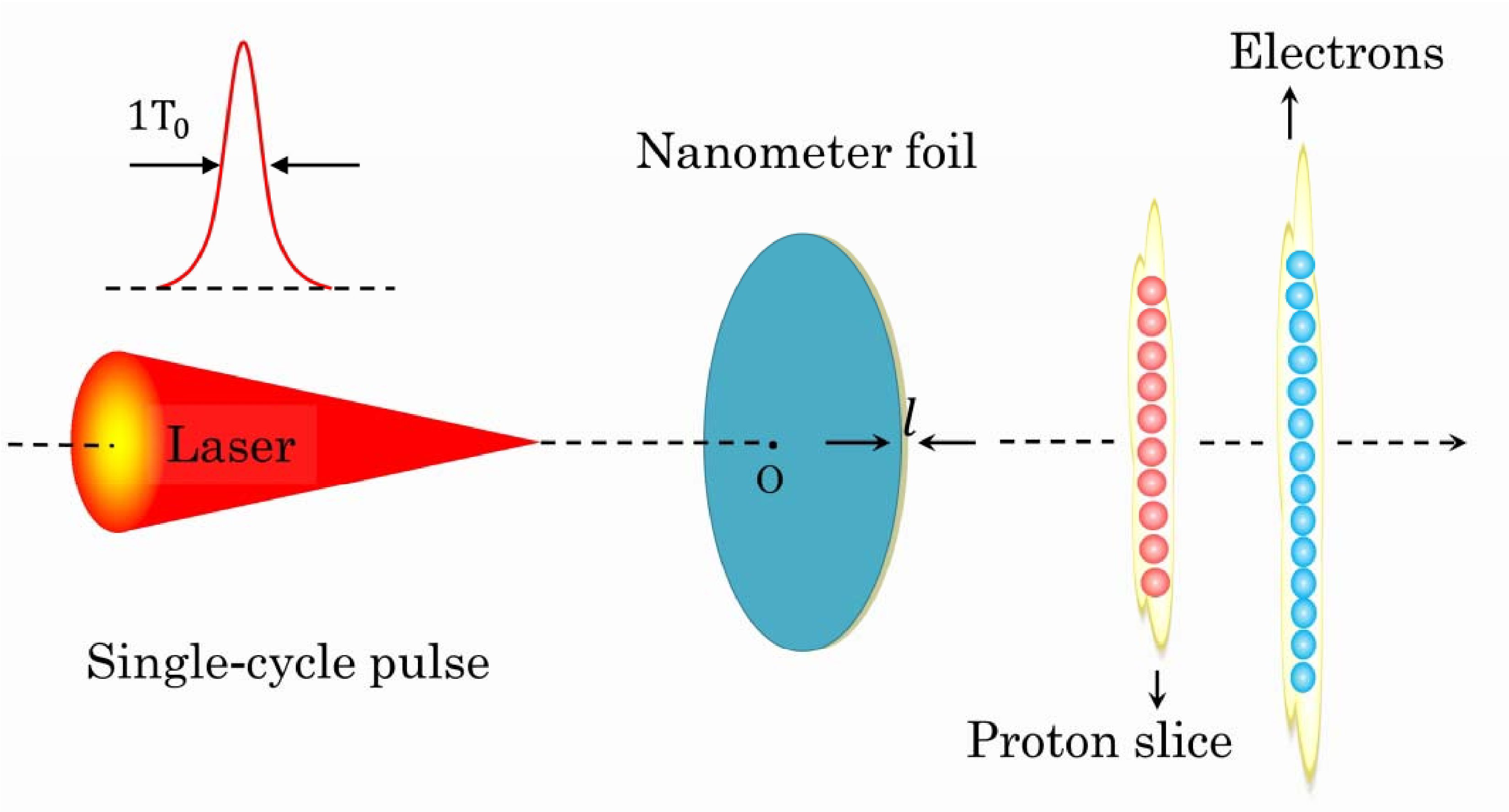
Single Cycle Compression of High Energy Pulse: History



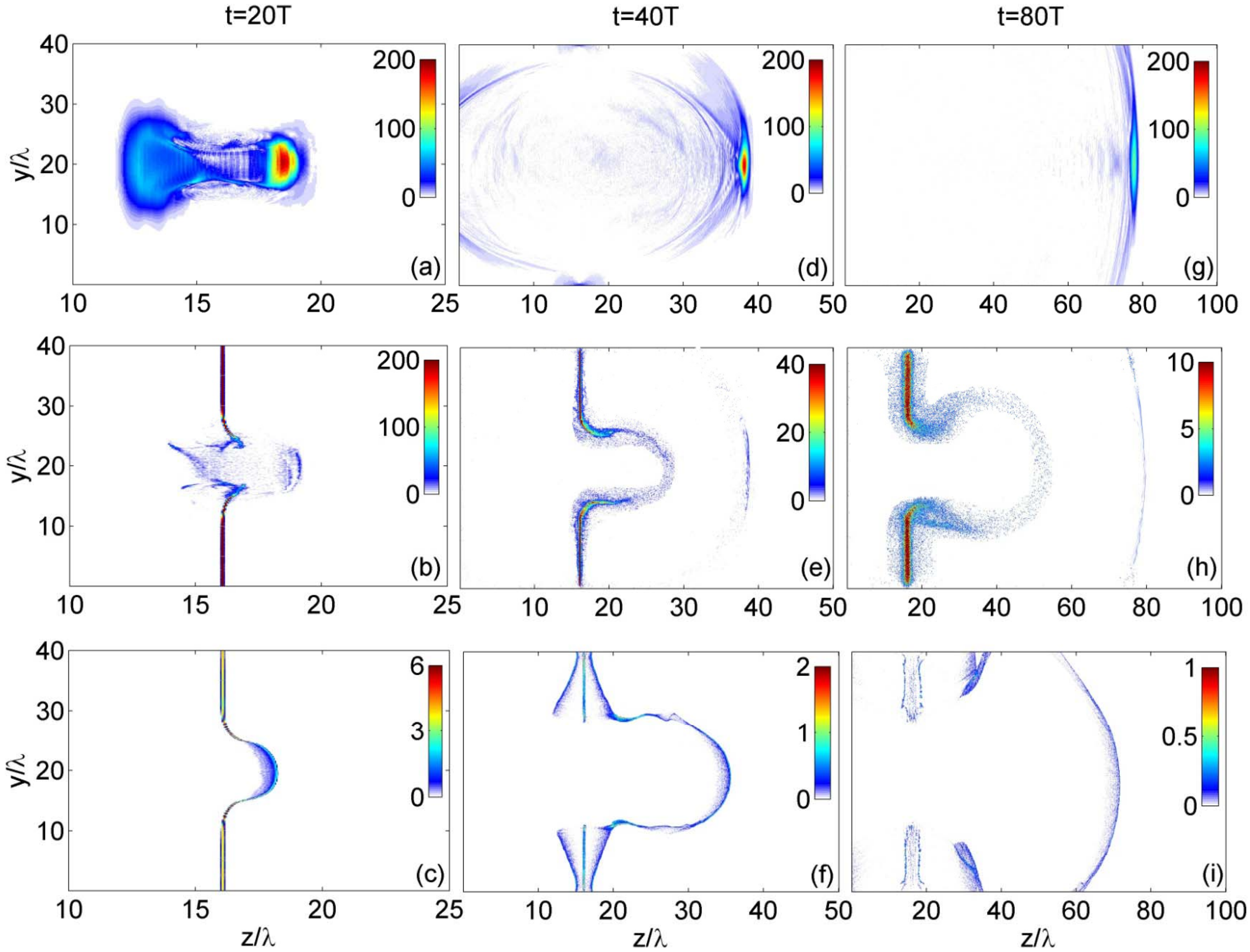
From G.Mourou

single cycle pulse ion acceleration regime

a~[50, 200], CP/LP,   Carbon+H



No instabilities at all!

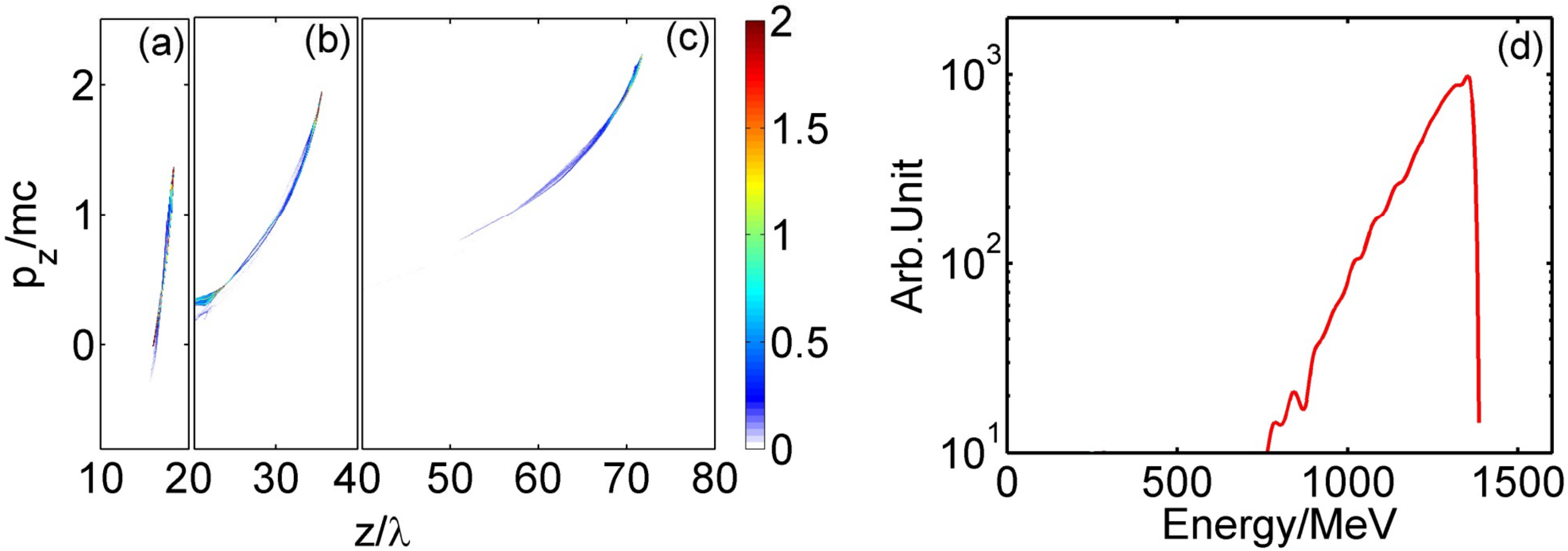


Transverse electric field

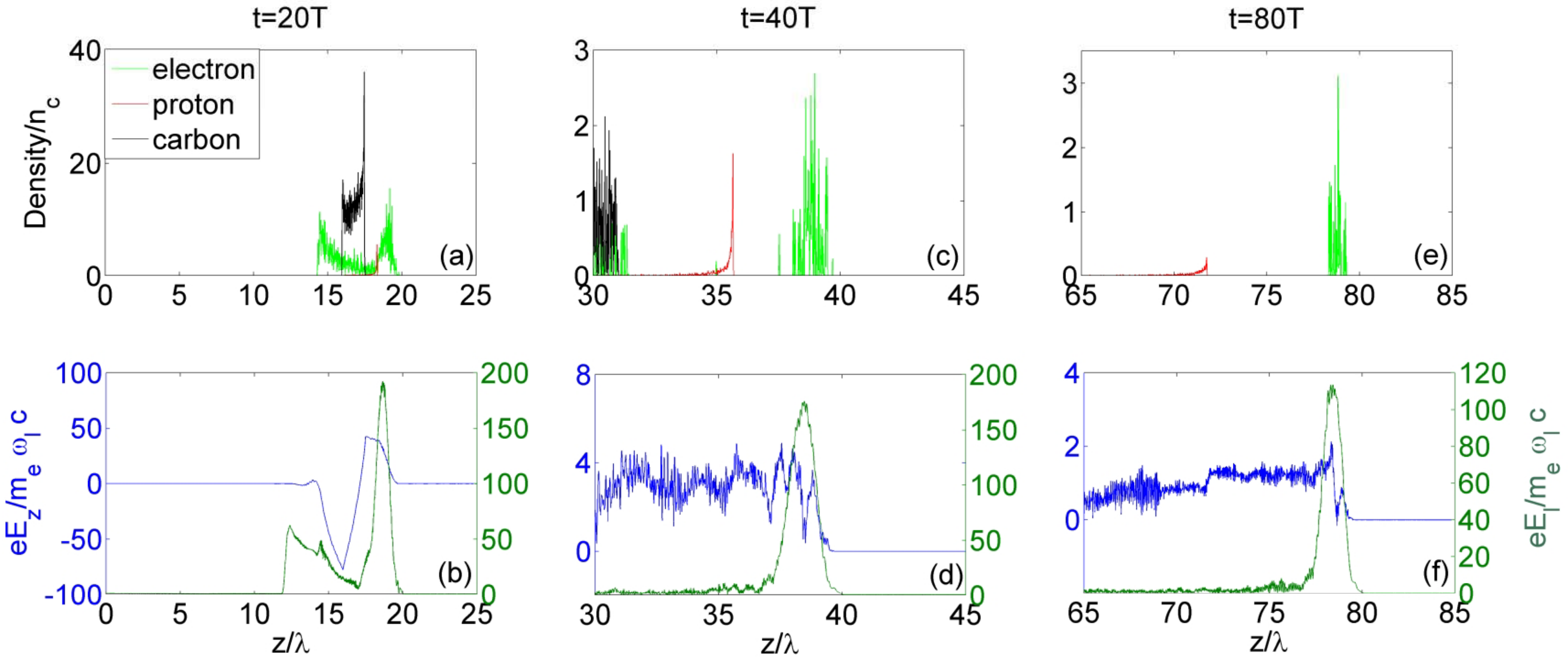
electrons density

proton density

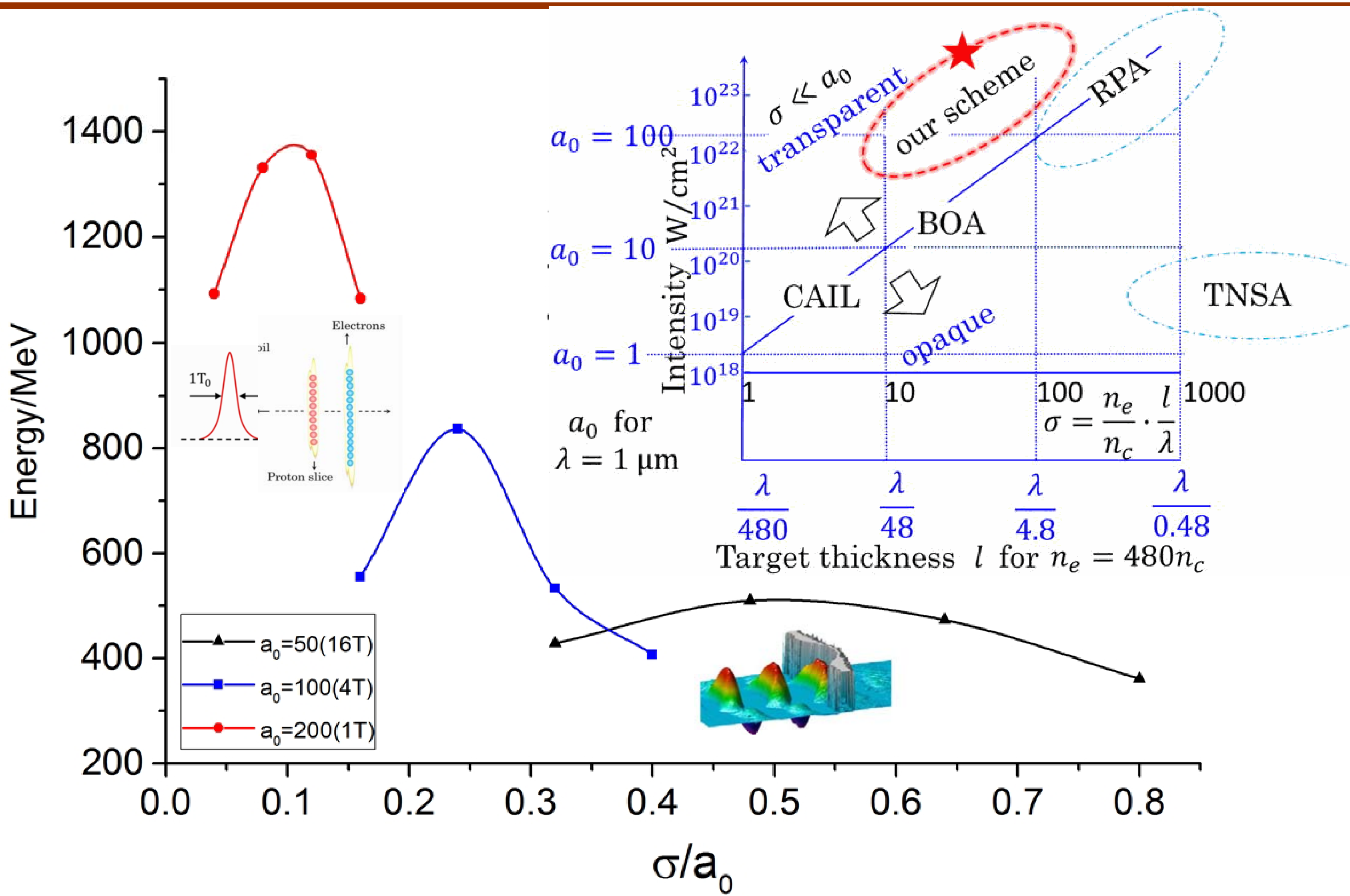
Proton spectrum and phase space



Acceleration distance: ~60um

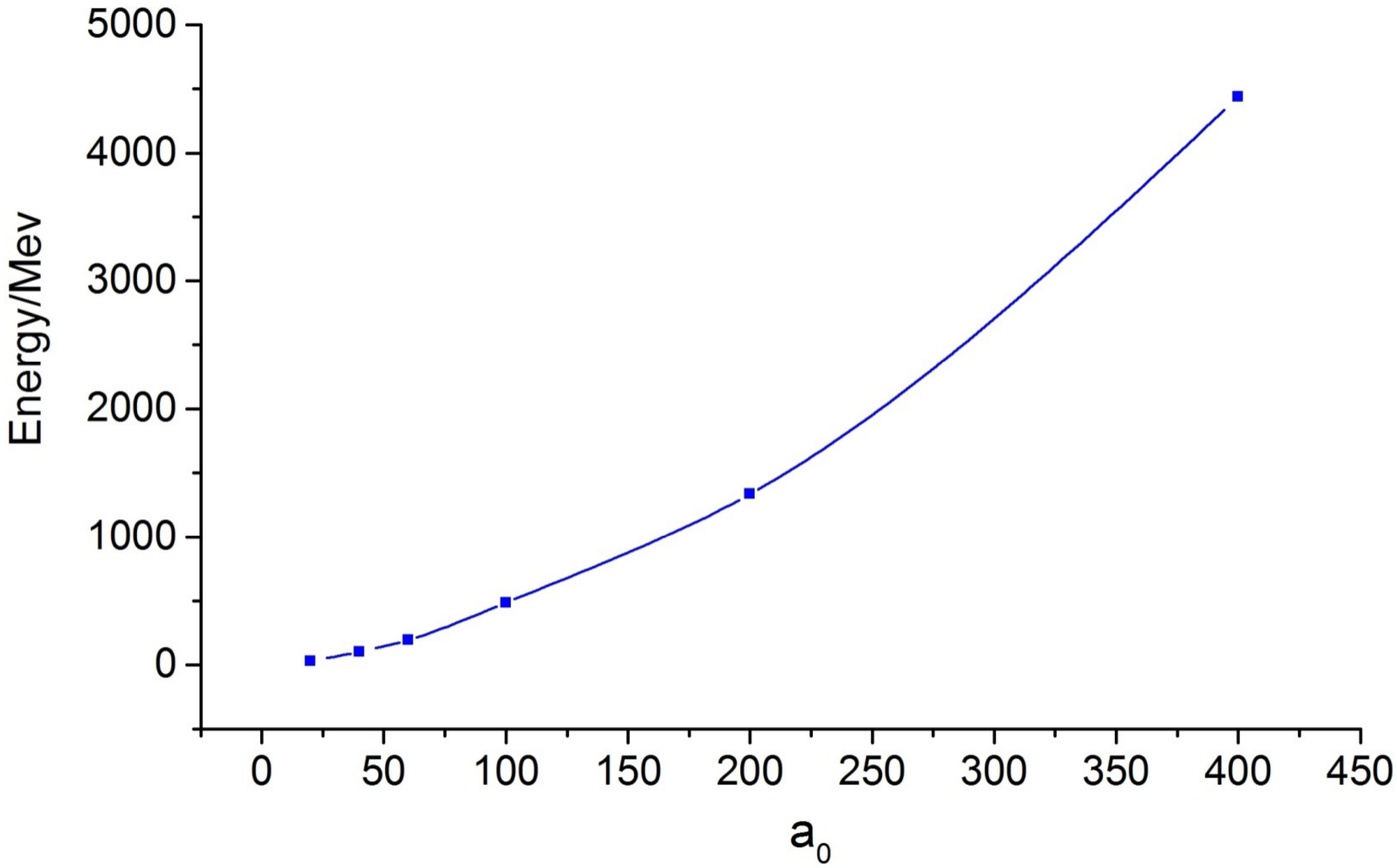


TNSA、 RPA and our regime



M. L. Zhou, et al., Phys. Plasmas 23, 043112 (2016)

Scaling of proton energy



FEATURES of our regime

- With a Gaussian pulse and simple thin planar foil, the acceleration structure is stable, **avoid such as the transverse instabilities (RTI),** which was the bottle neck happened in RPA.
- the optimal value of σ/a is much smaller (0.1)than in the traditional value (~0.5), more efficient acceleration!
- a quite short pulse(less than 1 micrometer).
- Hundreds-GeV proton beam may be used in proton cancer therapy or ADS.

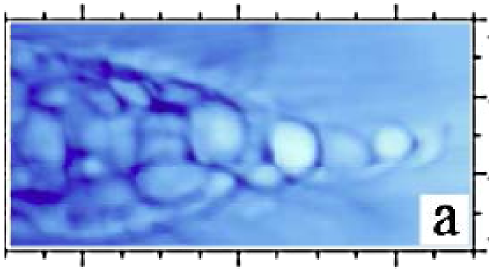
Outline

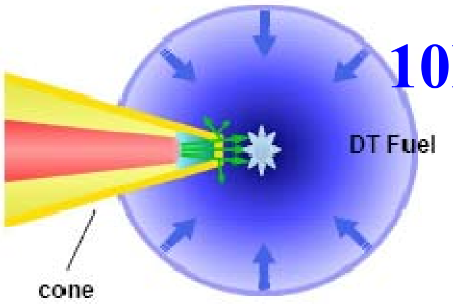
1. Motivation of proton/ion acceleration
2. Two experiments using state of art laser
   2.1 Generation of quasi-mono-energetic ion bunch via ionization dynamics
   2.2 Acceleration of heavy Ion by two layer target (carbon nanotube +DLC)
3. Generation of proton beam in an instability-free regime by a single-cycle laser pulse
4. Compact LAser Plasma Acceleration (CLAPA) MOST-project

CLAPA at Peking University

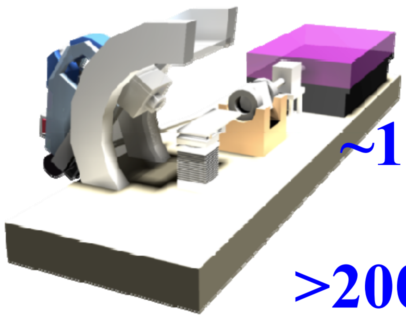
(Compact LAser Plasma Accelerator)

MOST Grand project: YQ2012030142, ~10M$



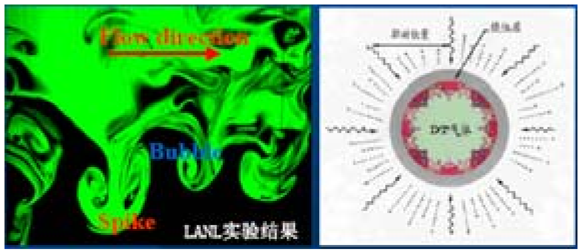


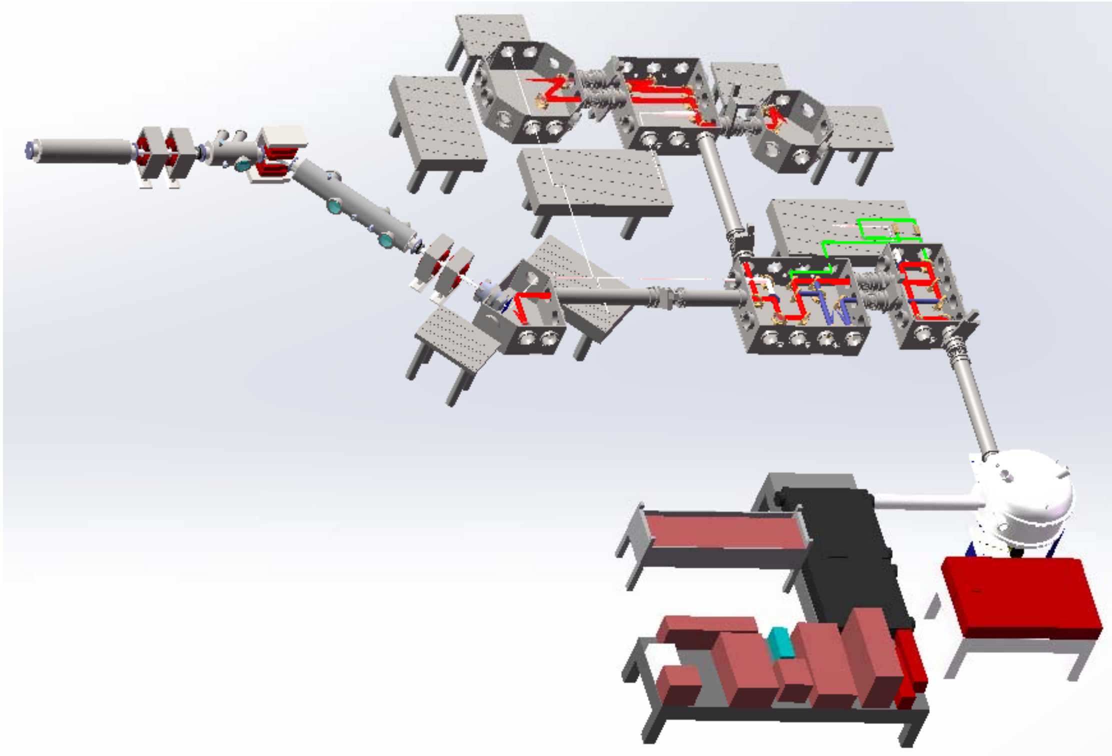
10MeV



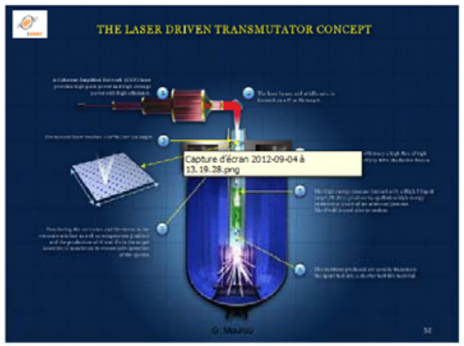
~100MeV

>200MeV





ADS: ~1GeV

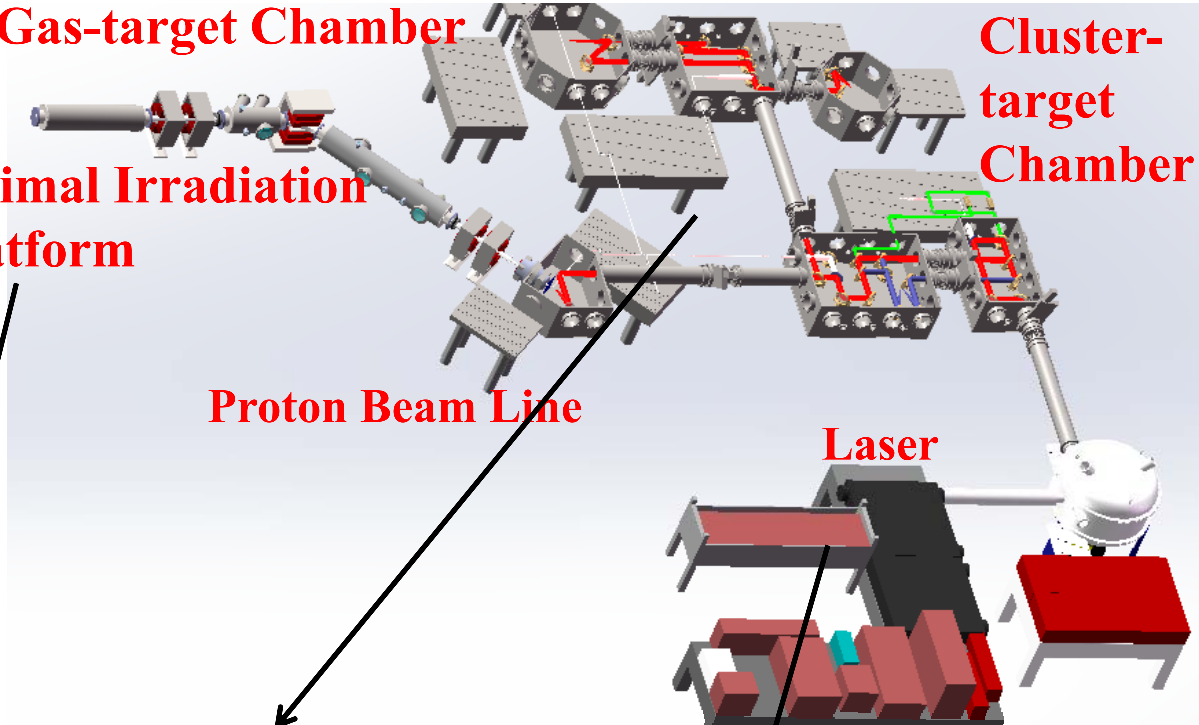


- Gamma ray
- Novel light source
- fs neutron
- QED

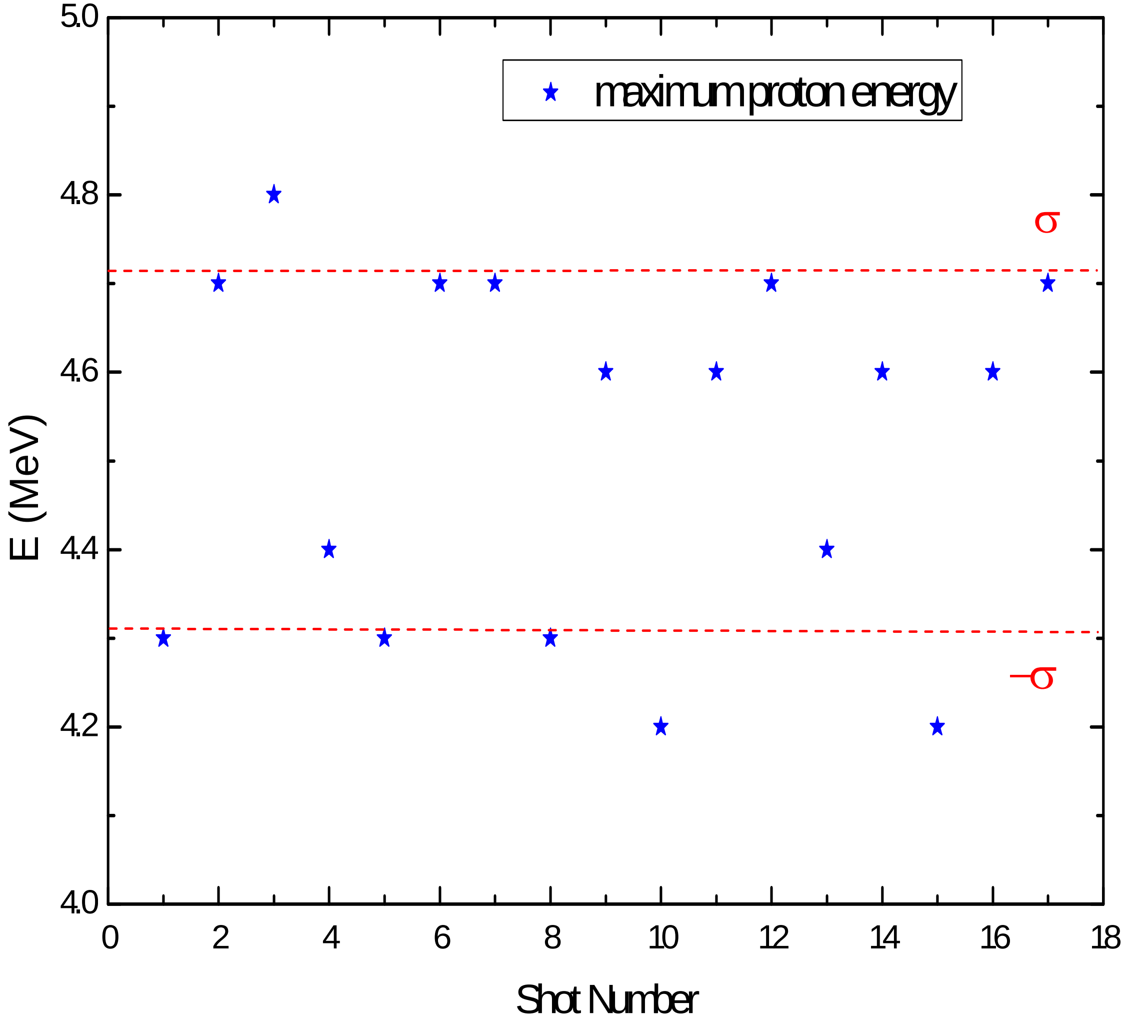
CLAPA is ready!

CLAPA Laser Parameters

Pulse Energy:	5 J /5Hz
Pulse Duration:	< 25 fs
Wavelength:	800 nm
Contrast Ratio:	10^{10}:1 @ 100 ps 10^{9}:1 @ 20 ps 10^{6}:1 @ 5 ps 10^{3}:1 @ 1 ps



Shot-to-Shot Variation of Proton Energies



Experiment Parameters

Laser ~30TW, 25fs, F/3.5 OAP

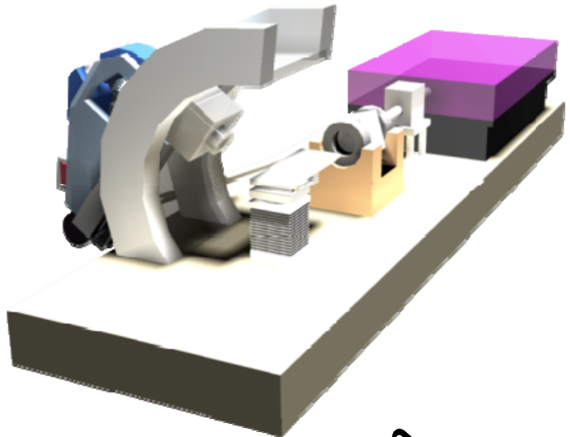
Target 0.8um, Al

Repetition rate 30s per target

E_ave = 4.52MeV

σ = 0.2MeV

What kind of laser for 200MeV proton therapy?



~ 10 m

100J Thales laser?

50J TFC one cycle laser?

Acknowledgement

- C.Lin, H.Y.Lu, W.J.Ma, X.T.He , J.E.Chen
- GIST: **Dr.Kim, Prof.Nam**
- Ecole Poly. T.Mourou,J.Wheeler
- UCI: T.Tajima
- MPQ/LMU: J. Schreiber, J.Bin
- Jena Uni. M.Zepf
- IAPCM: B.Liu, J.Liu
- SHJU/IOP: Z.M.Sheng, Y.T.Li, J.Zhang
- Shanghai Uni: H.Y.Wang

CLAPA @PKU

PostDoc and tenure track positions are open!
Welcome to join CLAPA@ Peking Uni!
Please email to: x.yan@pku.edu.cn