Exotic Concepts and HED: Working Group Summary

By R. Noble, T. Katsouleas

- Creative, paradigm changing ideas
- Confluence of HED, AAC and Applications
- Charge -- design proton injector

Exotic Concepts WG

- J. Alessi
- D. Umstadter
- K. Mima
- A. Ogata
- J. Fuchs
- P. Awtia
- P. Bolton
- J. Lewellen
- J. Kim
- G. Shvets
- I. Pogorelsky
- B. Bowes
- I. Pavlishin
- J. Smedley
- J. Wurtele
- P. Stoltz
- C. Toth
- T. Cowan
- R. Noble
- T. Katsouleas

From attendee list Day 1

We heard some nice talks…

- Proton/ion acceleration from laser-driven foils
  - Experiments: Lin, Bolton, Ogata, Fuchs, Cowan, Mima
  - Simulations: Silva, Mima, Messmer
  - Applications -- ***the charge***: Injectors (Alessi), HIF/HED (Cowan, Wurtele, Bowes)

We heard some nice talks… (II)

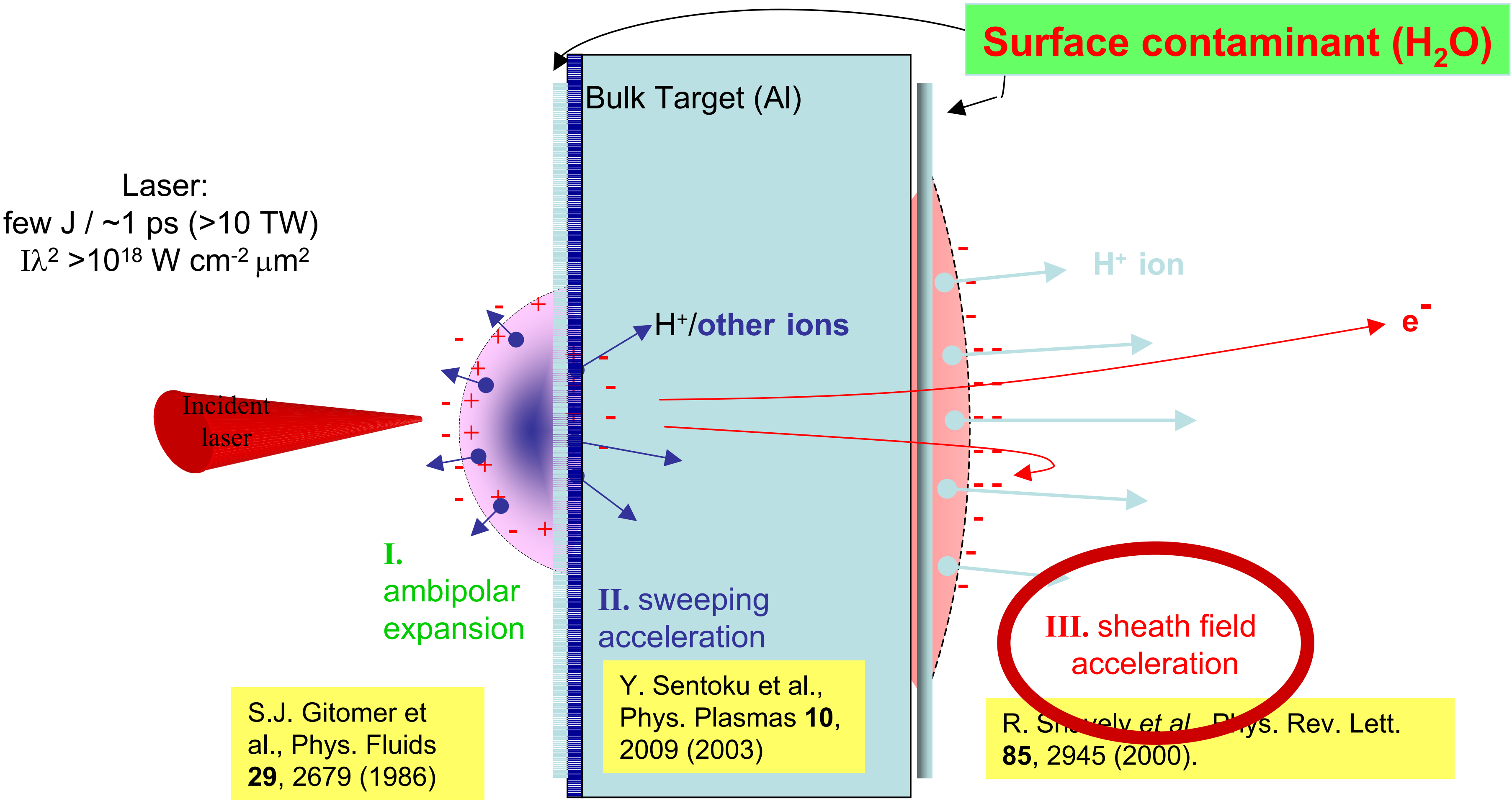
- Vacuum Acceleration (Umstadter, Nakajima)
- Active Medium Acceleration (Shachter)
- Ferroelectrics (Kanareykin)
- Beam conditioning for FELs (Wurtele, Esarey, Schroeder)

Addressing the Charge:

“Design a laser-ion source
that exceeds existing ion sources in some key parameter
for an application”

- Injector for an Ion Accelerator
  - for HEP, medicine, or fast physics
- Heavy Ion Fusion/High Energy Density Physics Driver

Mechanisms of laser-acceleration of *ions*

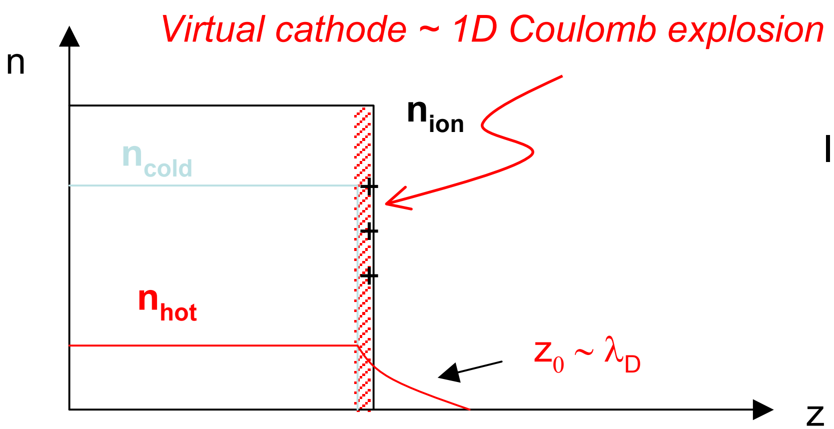


if target is heated ➔ efficient acceleration of heavy ions

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

Summary of rear-surface acceleration of protons

①

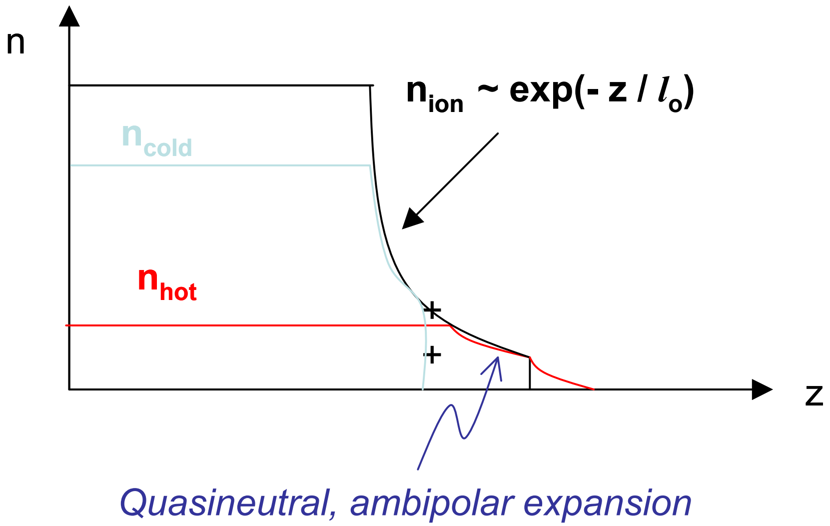


Initial Electric Field:

$E_z = kT_{hot}/e\lambda_D$

$\sim 10^{12}$ V / m

②



In expanding sheath:

$E_z(t) \sim kT_{hot}(t) / e\, l_o(t)$

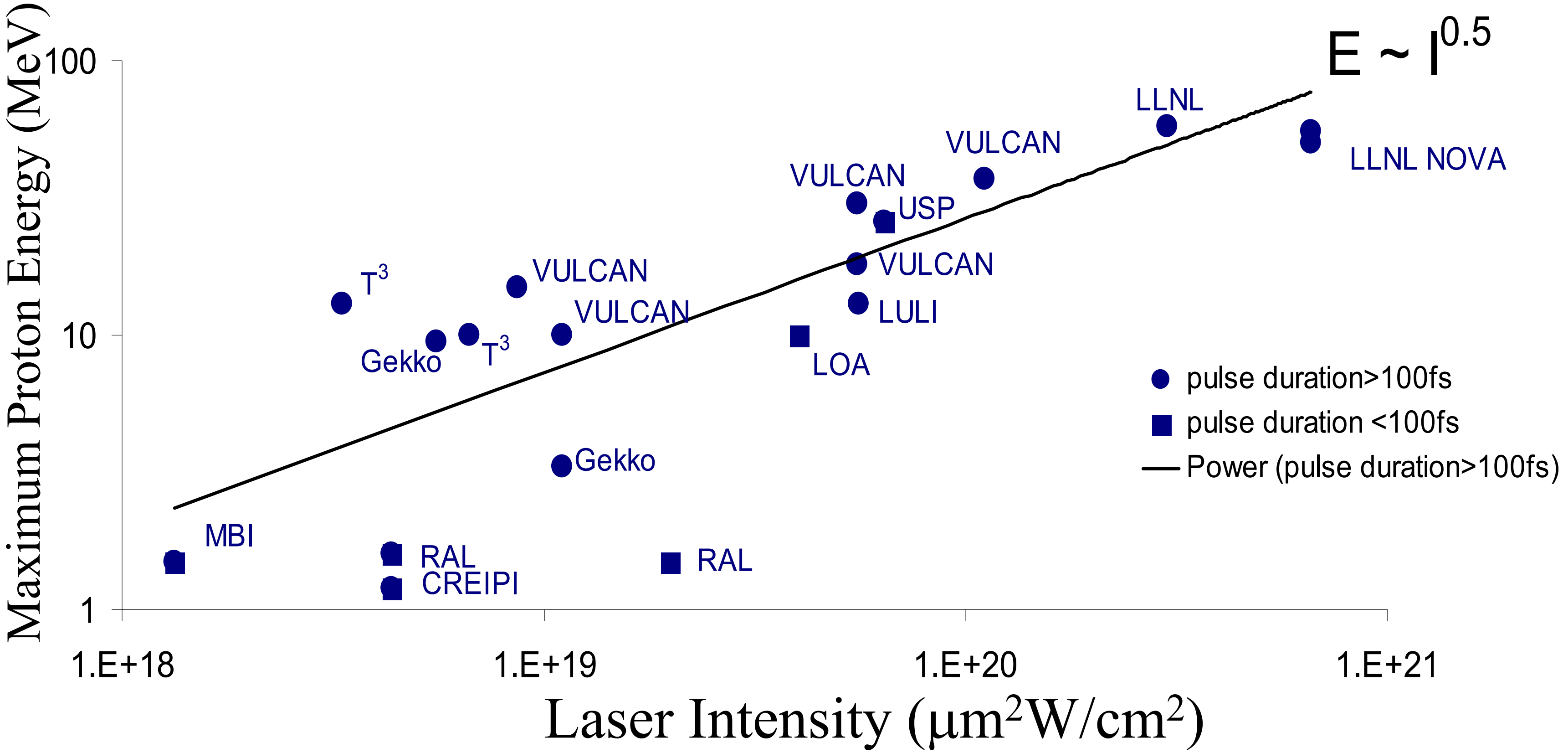
Self-similar expansion of isothermal plasma:

$l_o(t) = c_s\, t$

Then adiabatic:

E_z decreases from expansion, l_o and cooling of T_{hot} by transfer to ions.

Proton Energy Scaling (T. Lin)



We did some work…

Working Group Result:

$$T_h / mc^2 \sim .8 a_o$$ Forslund, 70's

$$V_{\max} = 2 c_s \ln(2\omega_{pi}\tau_p)$$ Mora,'03

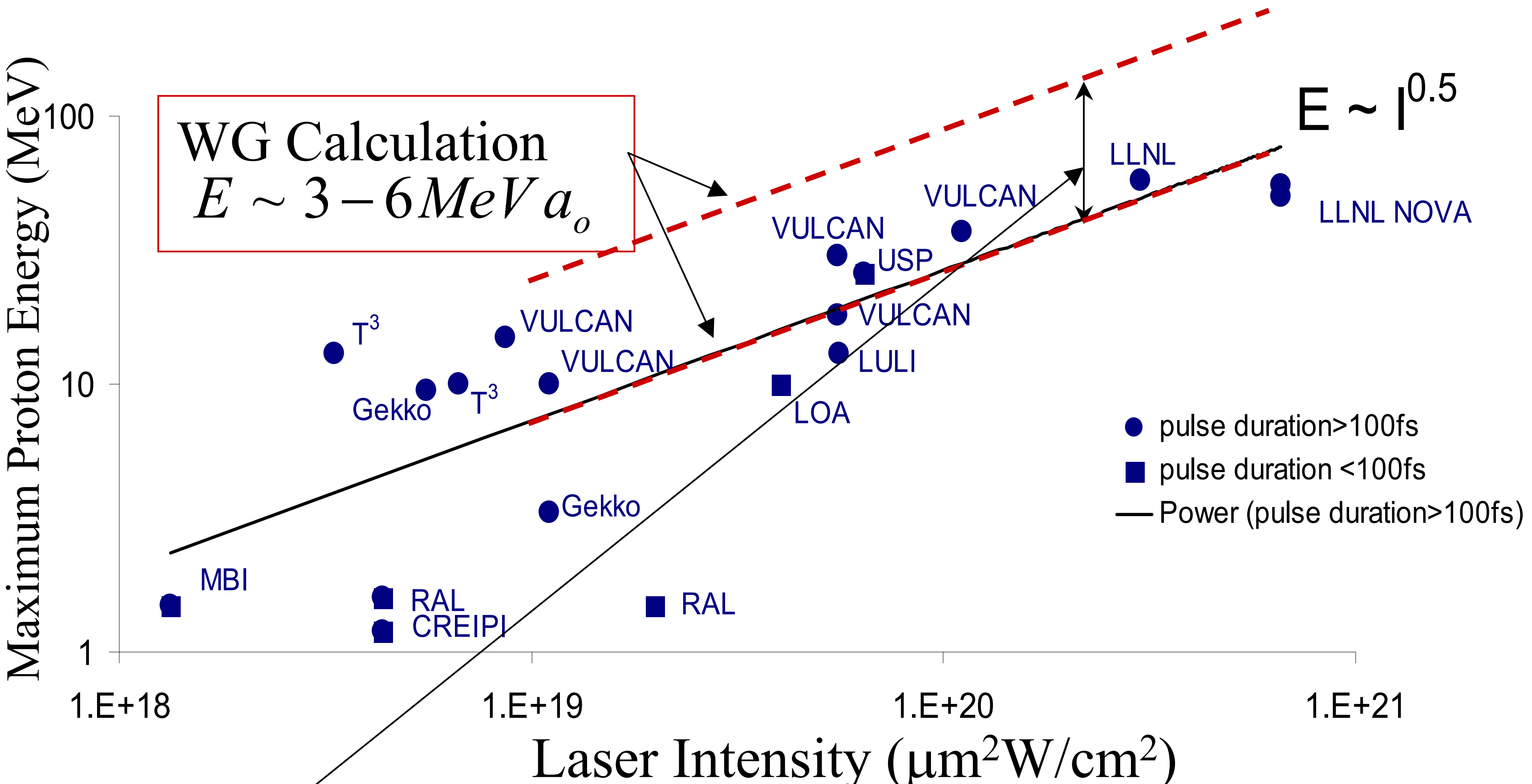
$$c_s = \sqrt{T_h / M}$$

$$E = \frac{1}{2} M V_{\max}^2$$

$$\Rightarrow E \sim 3 - 6 MeV\, a_o \quad a_o >> 1$$

Note: this is about 10x $\phi_{\mathbf{sheath}} \sim T_{\mathbf{h}}$

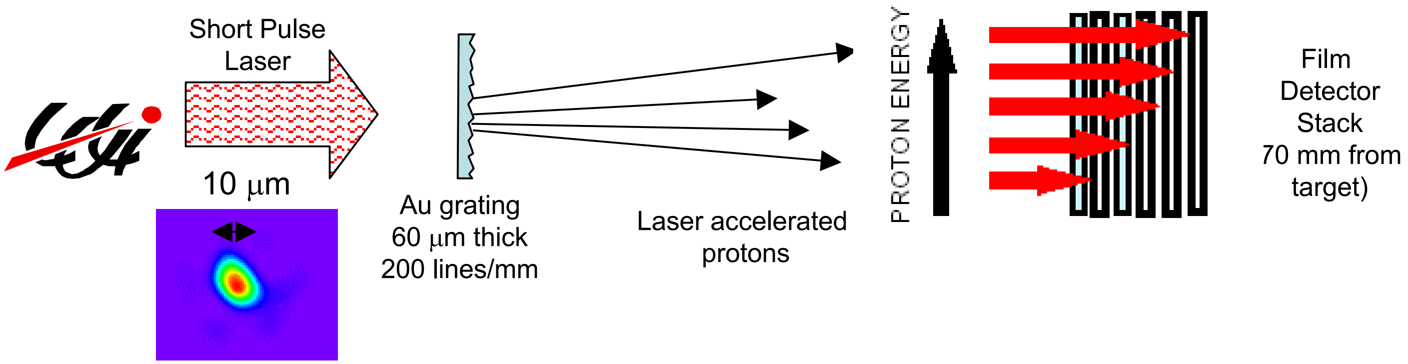
Proton Energy Scaling (T. Lin)



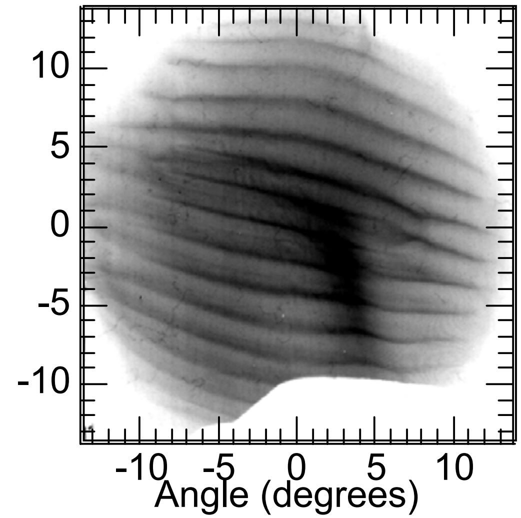
Pulse length dependence in theory ($\ln 2\omega_{pi}\tau_p$); Mora, PRL (2003)

Recent measurements show normalized ε < .004 mm-mrad!

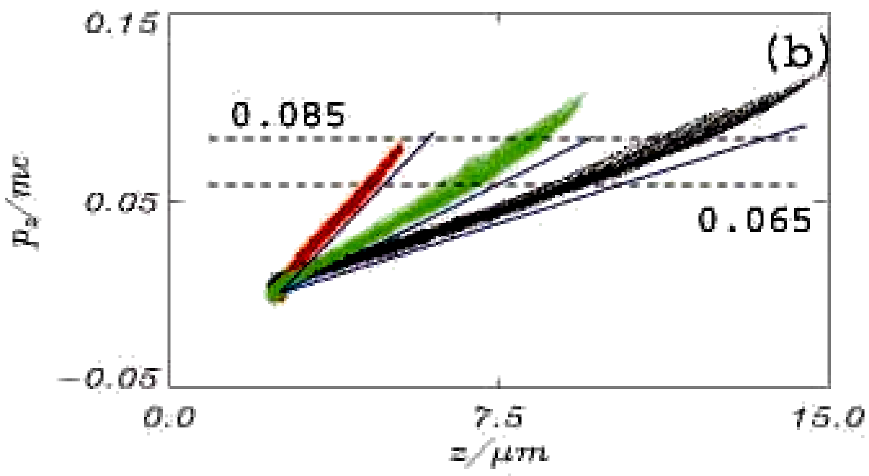
T. Cowan, J. Fuchs. H. Ruhl *et al.*, Phys. Rev. Lett. **92**, 204801 (2004).



8 MeV layer

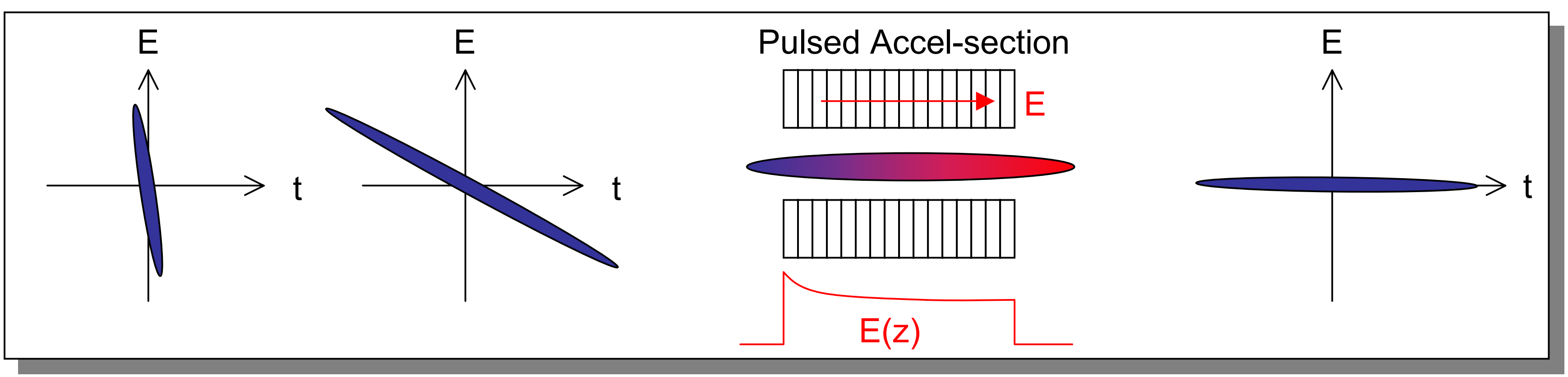


PIC simulations also show an excellent longitudinal emittance



Rapid acceleration produces strong ΔE-Δt correlation

Energy- or time-bunching possible with post-acceleration



Laser-accelerated ions as sources for conventional ion injectors ?

Noble, Alessi, Fuchs

Typical HE linac requirements (proton)

- 10^{13}-10^{14} p/pulse~10^4 nC
- pulse duration: 5-500 μs
  (bunch: <1 ns)
- $\Delta E/E < 10^{-2}$ at injection
- frep: 5-50 Hz
- Injection E: 50 keV
- emittance N: 0.05-0.5
  mm.mrad at injection

Laser-accelerated protons

- 10^{10}-10^{13} p/pulse [TW to PW]
- bunch duration: 1 ps at source
  debunches to 100 ps in cm
- $\Delta E/E \sim 1$ (E_{max}~10-50 MeV)
- 10 Hz - hour [TW to PW]
- 10 MeV
- emittance N: 0.005

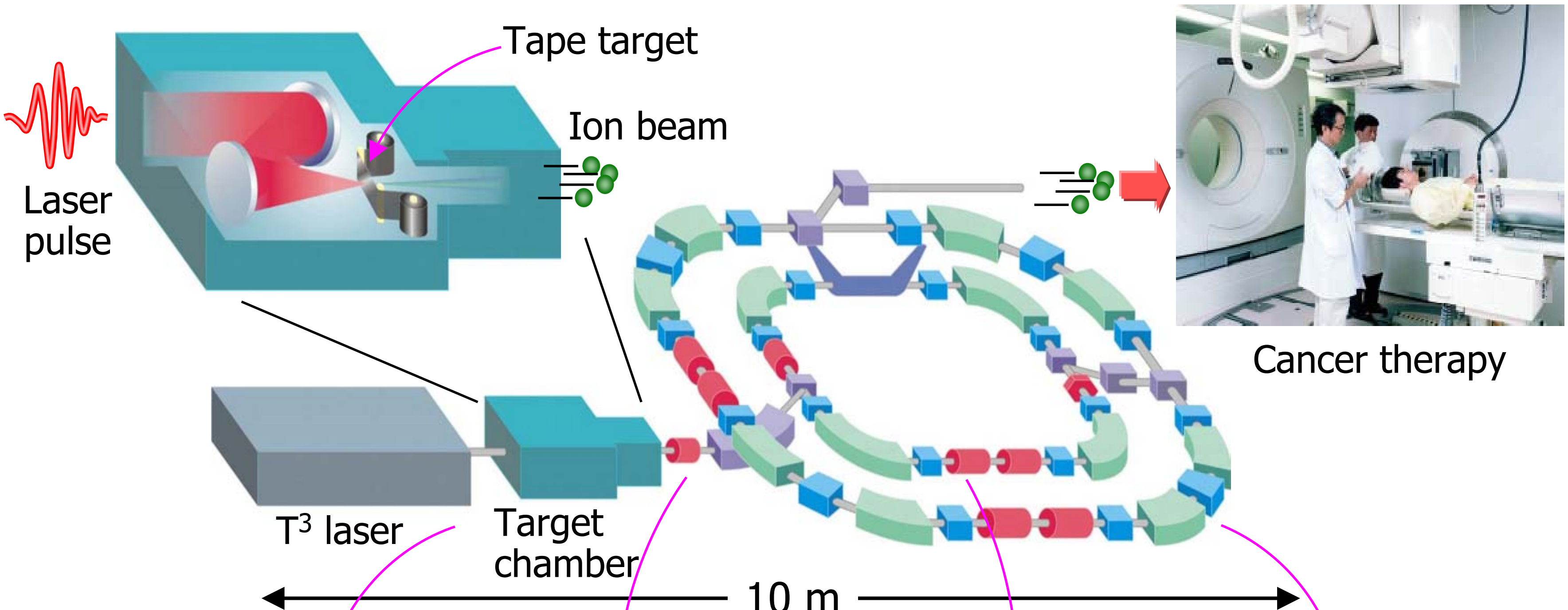
most Synchr. injectors use H^-

Laser-accelerated ions as sources for conventional ion injectors ?

- How can we get the needed charge?
  accelerator-10^4 nC/pulse vs. TW laser-1 nC/bunch
- Laser average power needs to increase
  - 10 Hz TW laser now ~ 1 W average power
  - Need 1-10 kW (semi-conductor lithog. Lasers)
- Phase-space rotation needed to reduce ΔE once naturally debunched
- Higher injection energy + smaller emittance could lead to higher brightness out of linac
- Other Applications:
  - low-av. current Carbon (others) medical use
  - short-duration source for pump-probe time-resolved exp.
  - time-resolved radiography (brightness but low number of charges)

Development of Compact Ion Accelerator

National Institute of Radiological Sciences, JAPAN

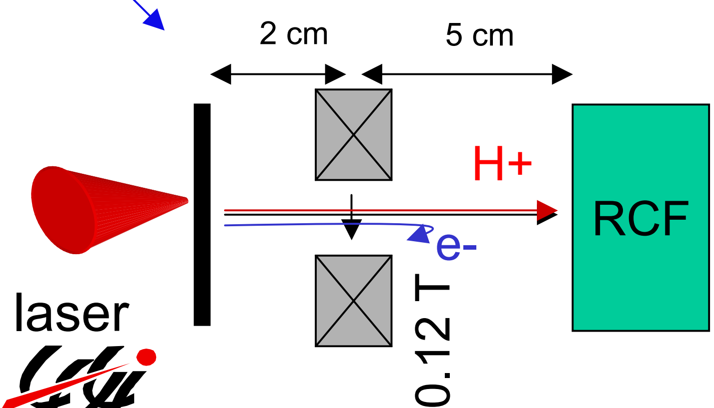


Laser plasma ion source	RF cavity for phase rotation	Electron beam cooler ring	Compact heavy ion synchrotron
2 MeV/u p (10^{10}/sec.) C ion (10^{9}/sec.)	Energy spread ~±1%	Energy spread ~±0.1%	200 MeV/u
JAERI, Univ. of Tokyo, Hiroshima Univ.	Kyoto Univ., JAERI	Kyoto Univ.	KEK

Fukumi, Ogata, …

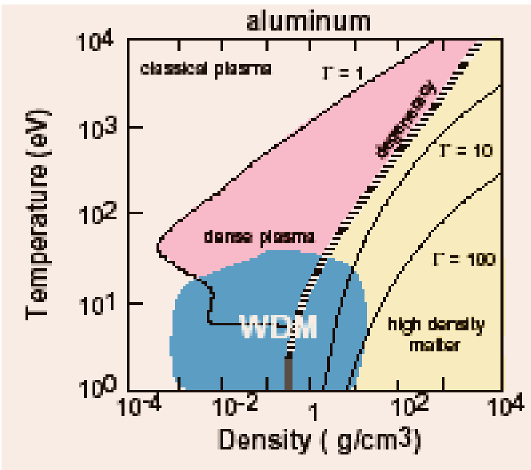
We identified some open questions…

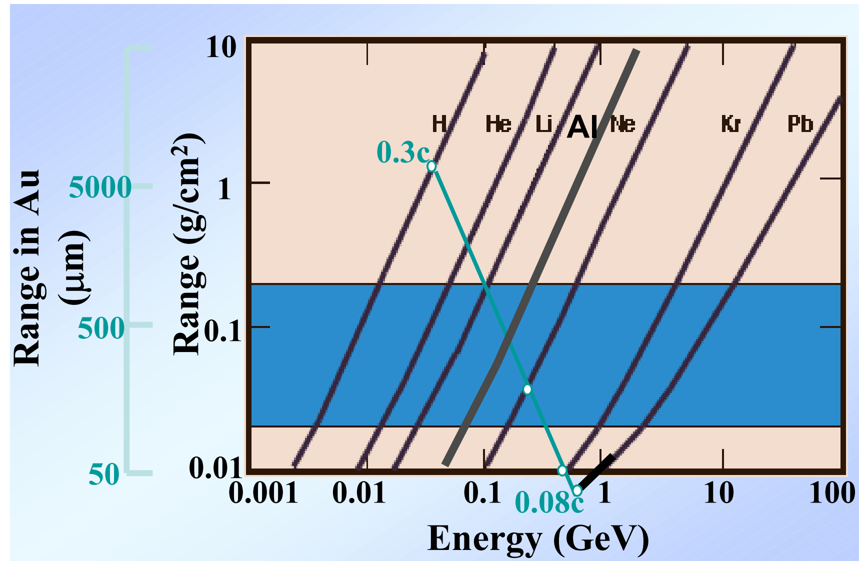
- Finer dependencies of E
  - (spot size, thickness, λ-- $C0_2$?)
- Can we extend the E ~ I scaling (at low a_o)?
  - Large pre-plasma (1-D sims ok, 2-D?)
- Can we tailor/control acc/energy spectra?
  - Multiple foils, droplets?
  - Tailored plasma density -- near critical density
- Key Milestone -- extract & post-accelerate to rotate p_z-z



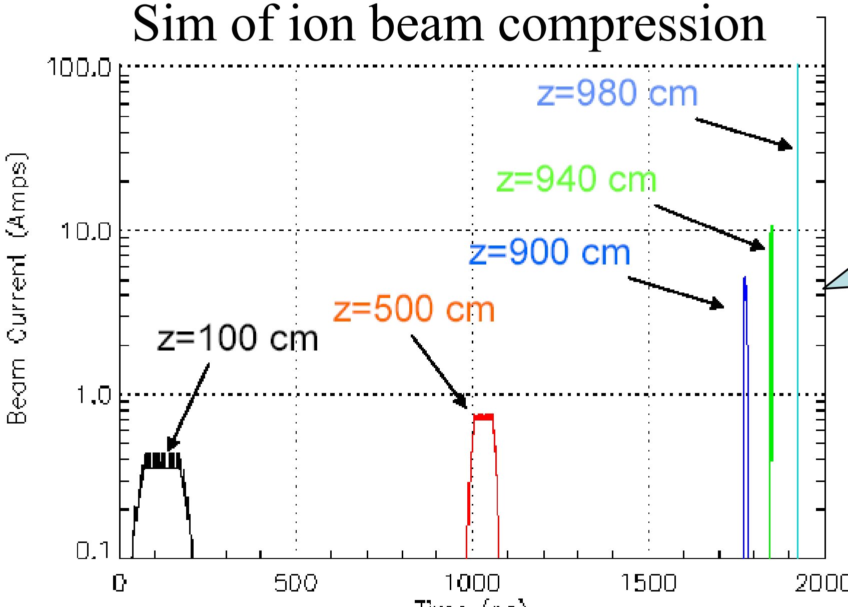
Heavy Ion High Energy Density Physics

What is the nature of "warm dense matter"?





Sim of ion beam compression

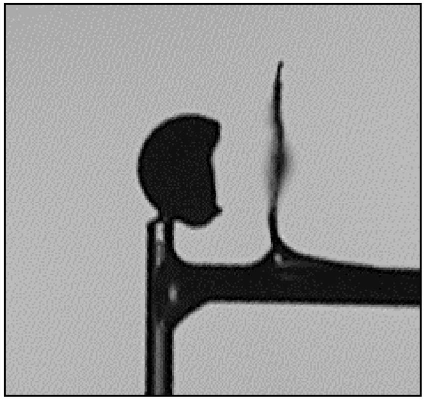


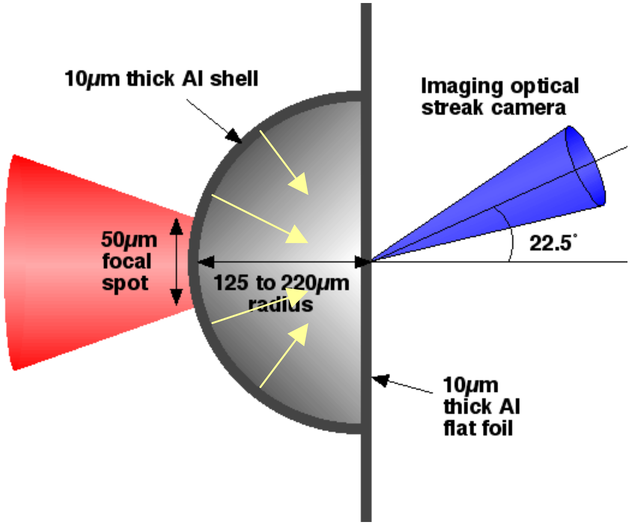
Ion beam range ideal for heating solid matter

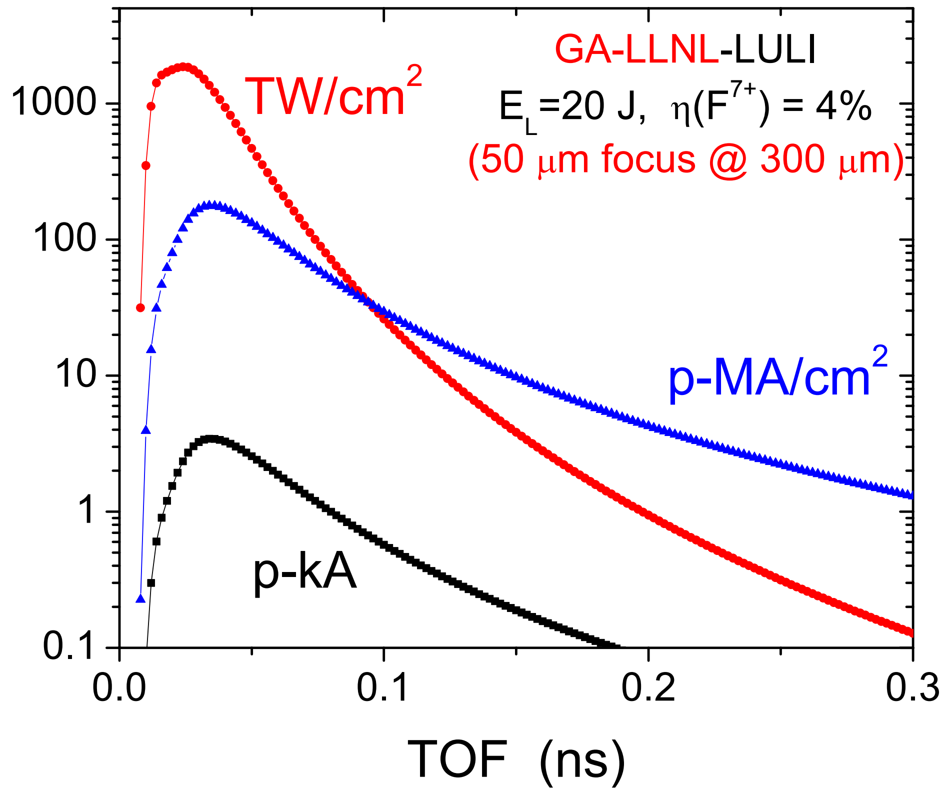
But pulse must be short to beat expansion requires neutralized transport

5 yr Goal: (10^{11} J/m^3)
100 p-MA/cm^2 !
10 MeV
1 ns

Can laser-irradiated foils do the job? (T. Cowan) >10^8 p-A/cm^2, and > 1000 TW/cm^2 on target





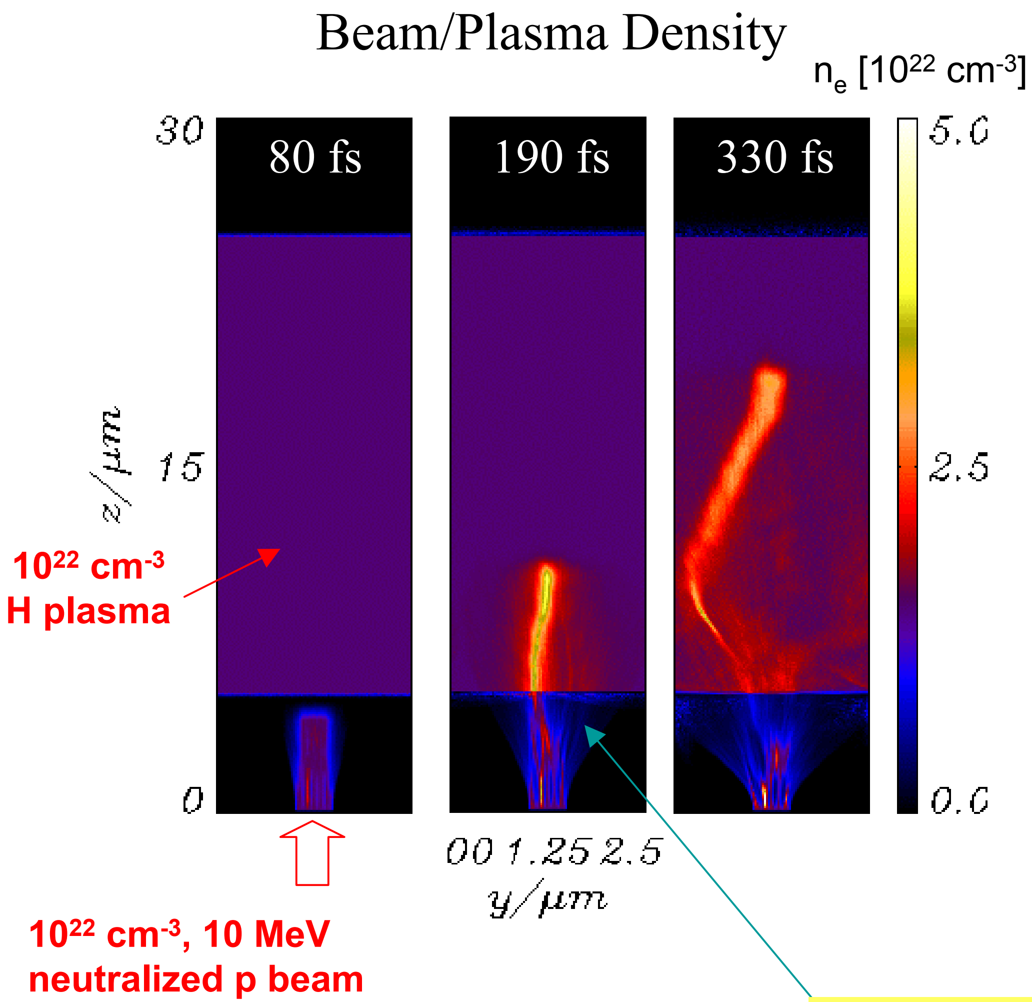


HED w/ Ion Beams Summary

5 yr Goal: (10^{11} J/m^3)	Now w/ 20J lasers
100 p-MA/cm^2	100 p-MA/cm^2
10 MeV	10 MeV
1 ns	10 ps

New 2kJ PW lasers (e.g., Sandia ZBL PW) should enable ion current densities relevant to HIF beams (Cowan)

Beam-plasma instabilities affecting neutralized beam transport might be studied with laser-foil beams



Electron two-stream disrupts neutralization, generates strong B, which drives hosing

H. Ruhl

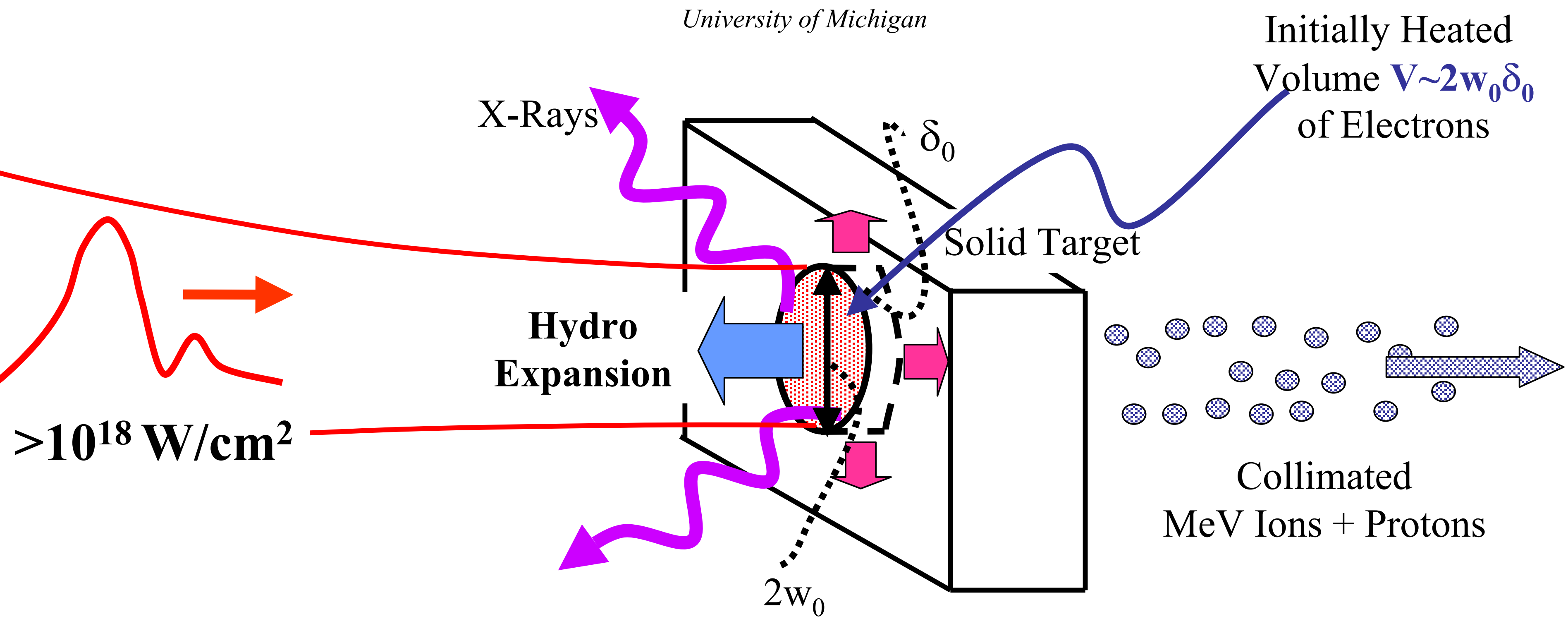
Highlights of Some Talks

Ultrafast 2-D radiative transport in a micron-scale aluminum plasma excited at relativistic intensity

Ben Bowes and M. C. Downer
University of Texas at Austin

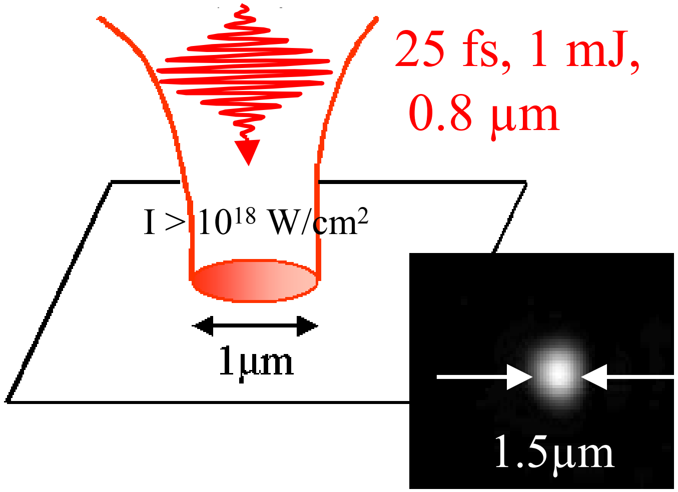
H. Langhoff
Physikalisches Institut der Universität Würzberg

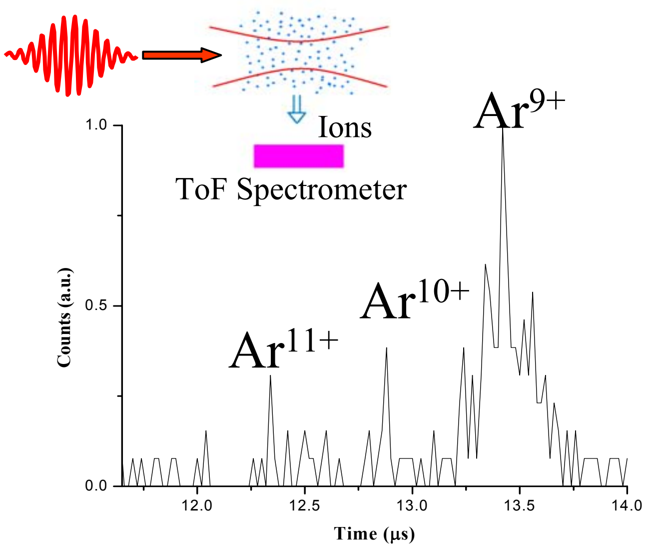
M. Wilcox, B. Hou, J. Nees and G. Mourou
University of Michigan



λ^3 laser system: relativistic intensity at 1 kHz

Albert, O.; *Opt. Lett.* **25** 1125 (2000)



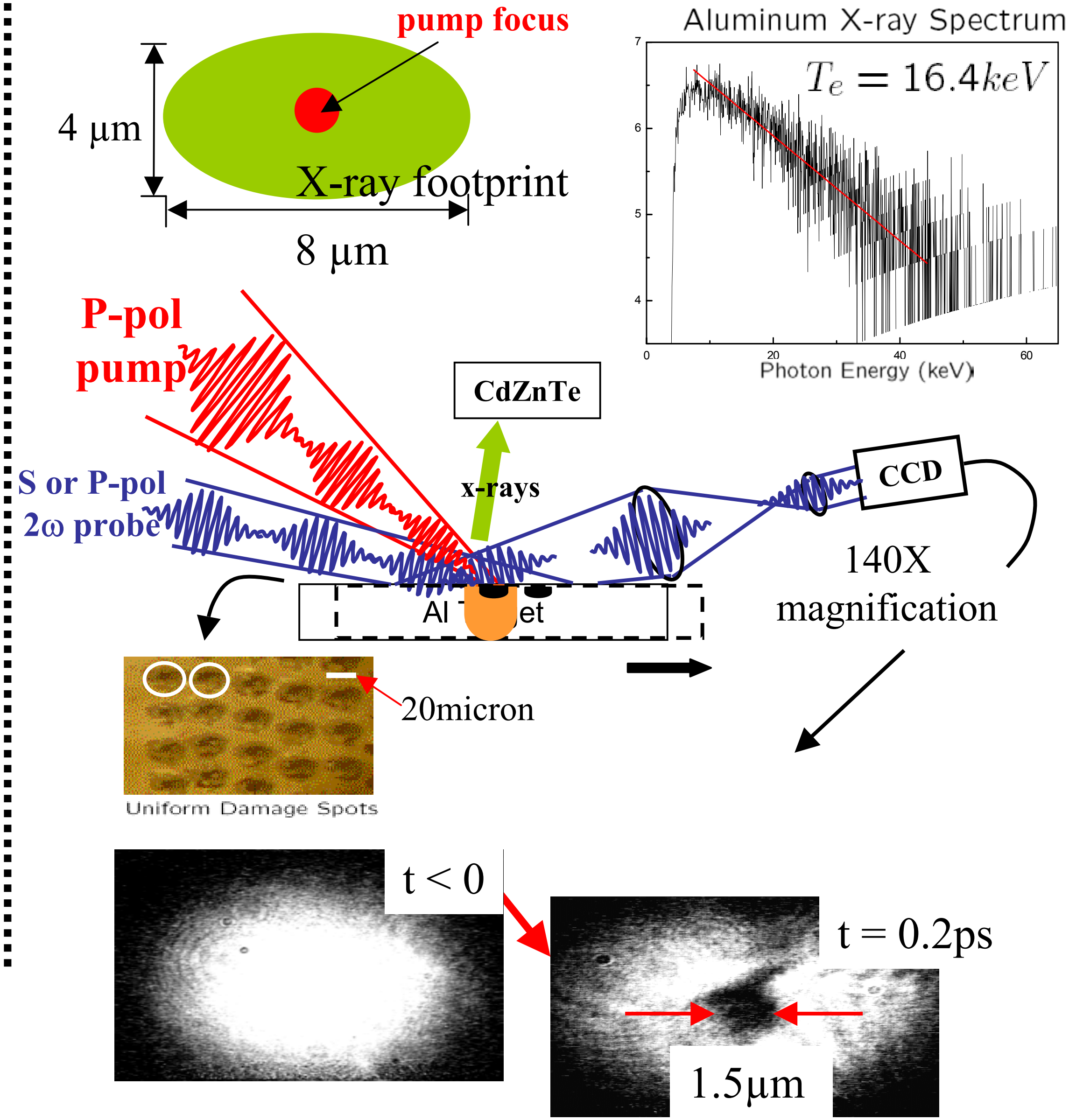


0.1% Ionization Rate for Ar^{11+}

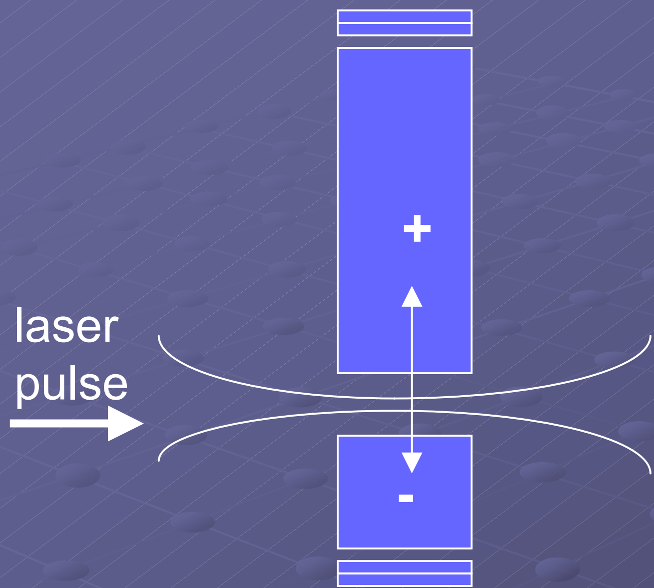
$\Rightarrow$ I= 3×10^{18} W/cm^2

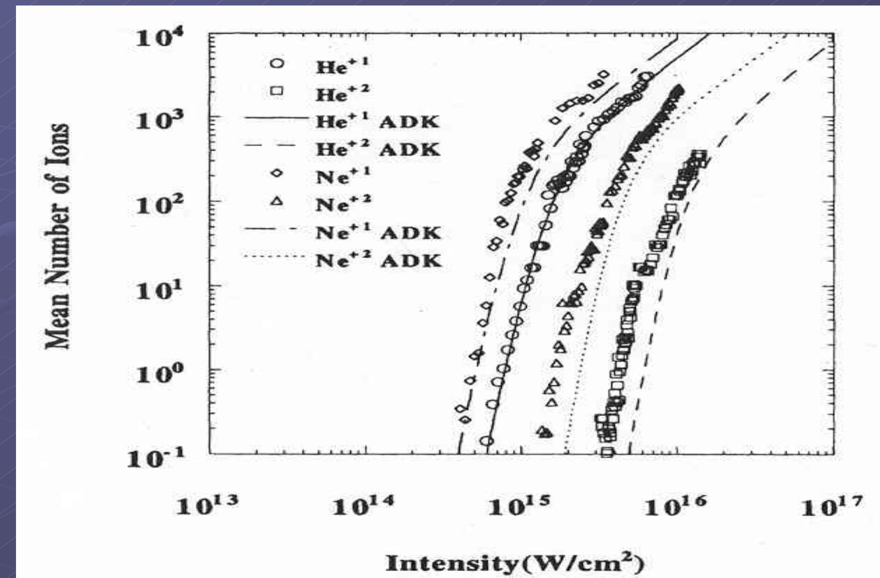
S. Augst; JOSA-B **8** 858 (1991)

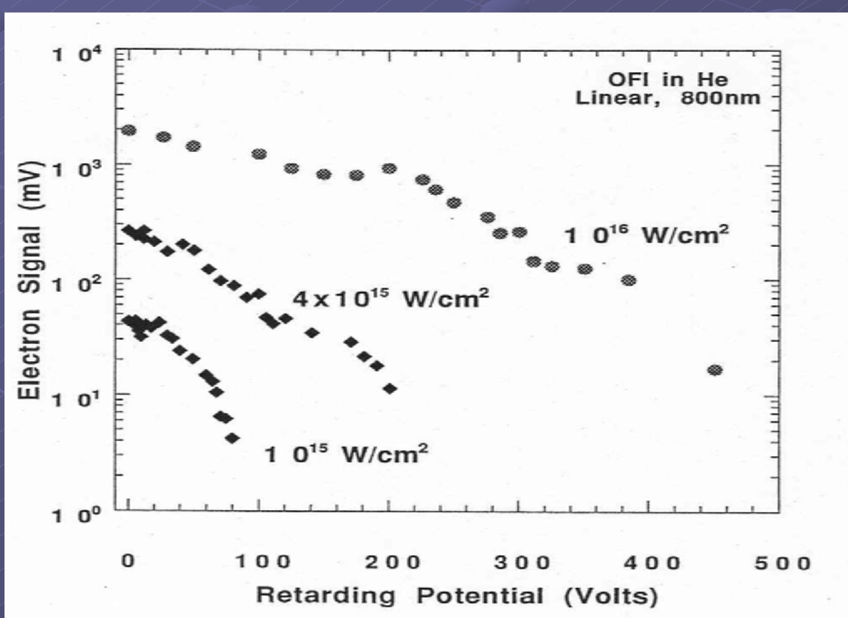
Experimental set-up for fs reflective imaging

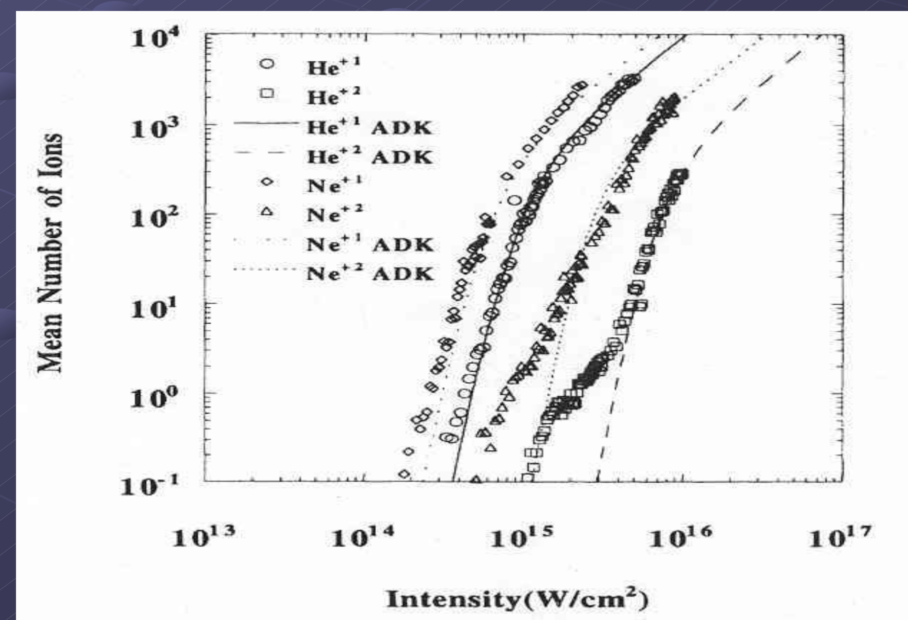


Multiple charge ions – P. Bolton



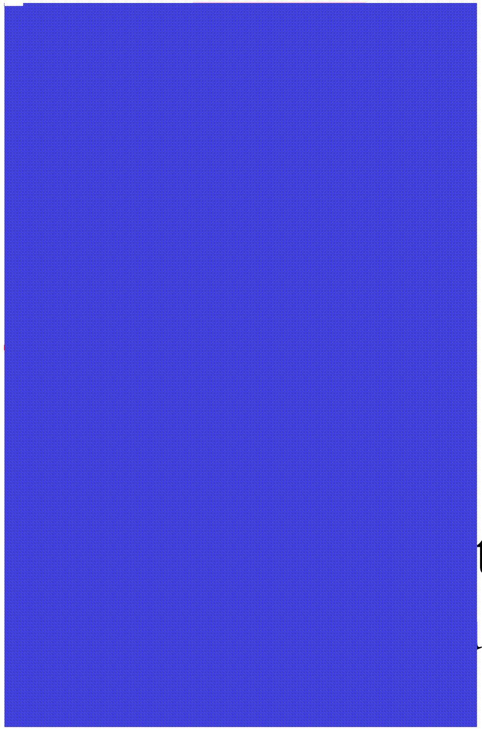






A. Ogata
Getting more acceleration with less laser

T^3 laser with a 10^{-3} prepulse



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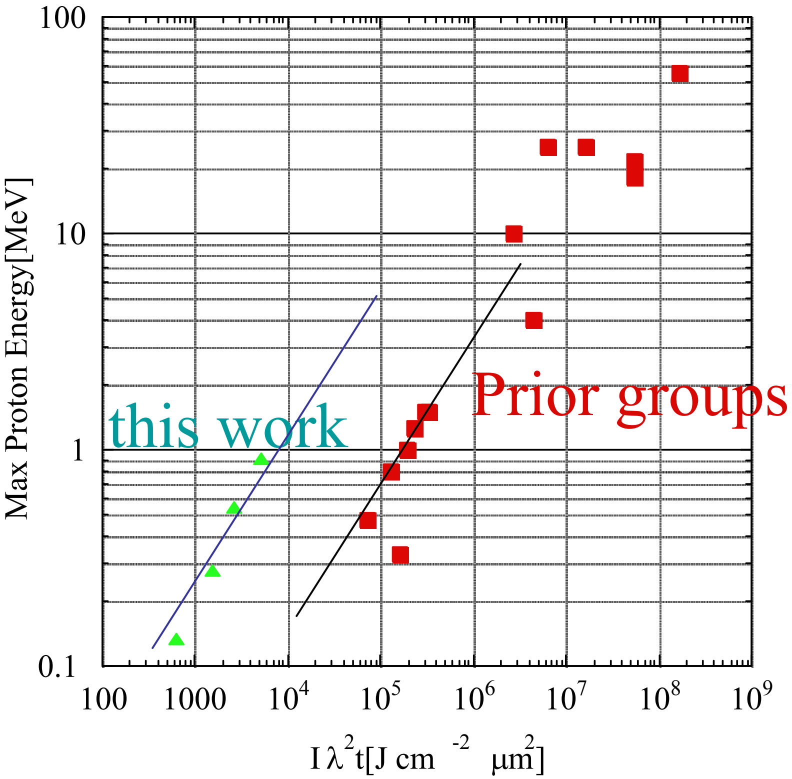
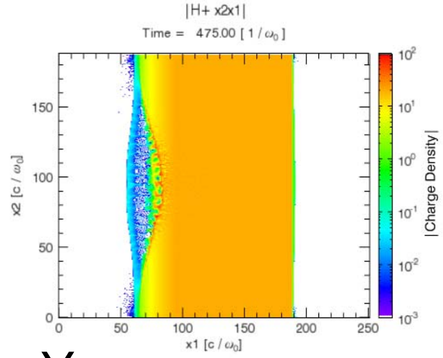


Shocks in laser-plasma interactions

Luís O. Silva
J. Davies, R. A. Fonseca, M. Marti, F. Peano
(IST/Portugal)

J. Fahlen, C. Ren, F. Tsung, W. B. Mori
(UCLA)



And **P. Messmer**, D. Bruwhiler, Tech-X
Shocks and THz generation

Acceleration mechanisms

No shock

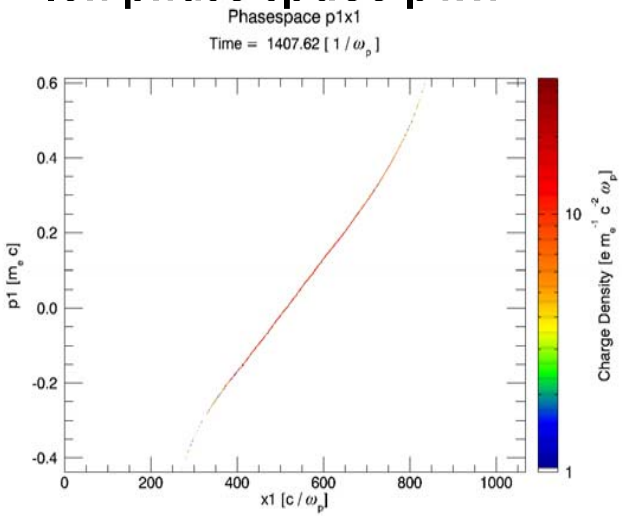
Shock with higher energy than rear

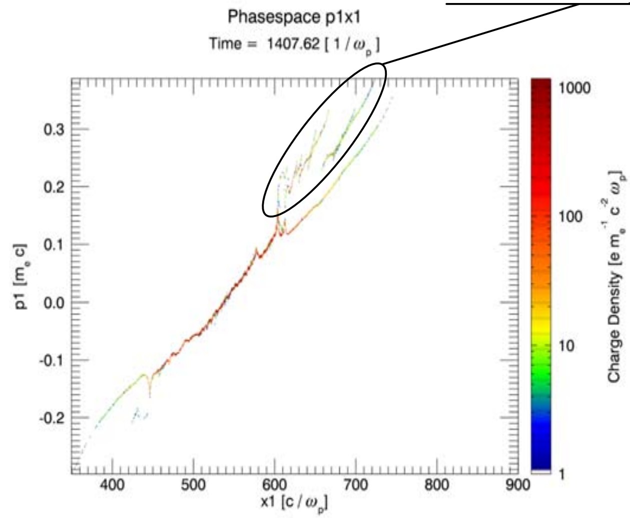
Shock with lower energy than rear

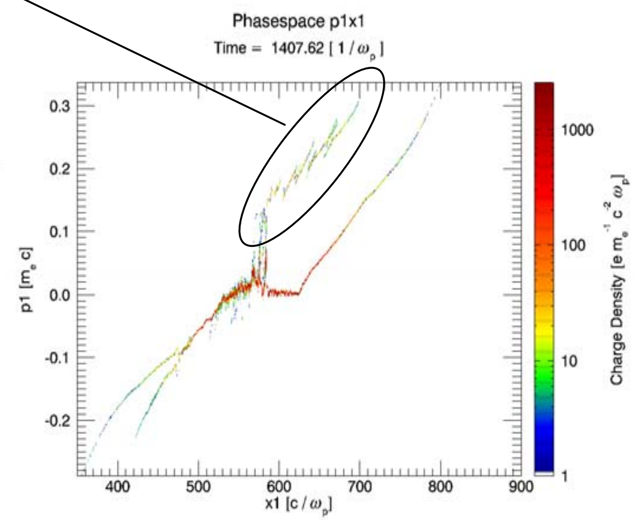
Diffusive/sheath acceleration

Ion phase space p1x1

shock acceleration





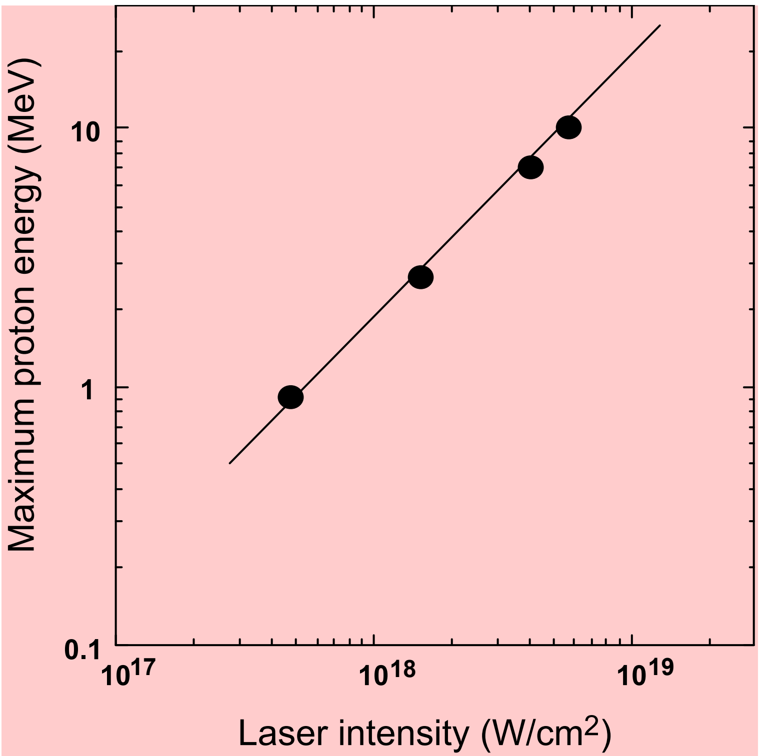


a0 = 16
Δ = 1 μm

a0 = 16
Δ = 6.2 μm

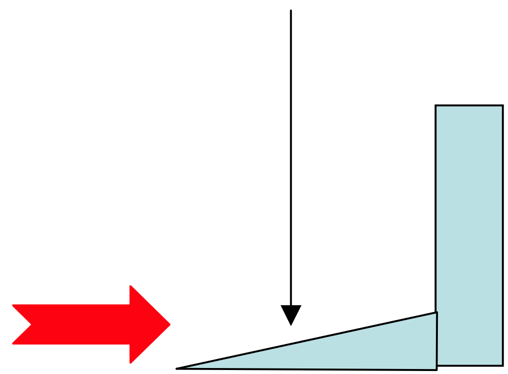
a0 = 16
Δ = 8.8 μm

CUOS Experiments Shows Maximum Proton Energy is Enhanced and Proportional to the Laser Intensity [3]



(1 ~10) TW Laser with intensity contrast ratio; $5 \cdot 10^{-5}$

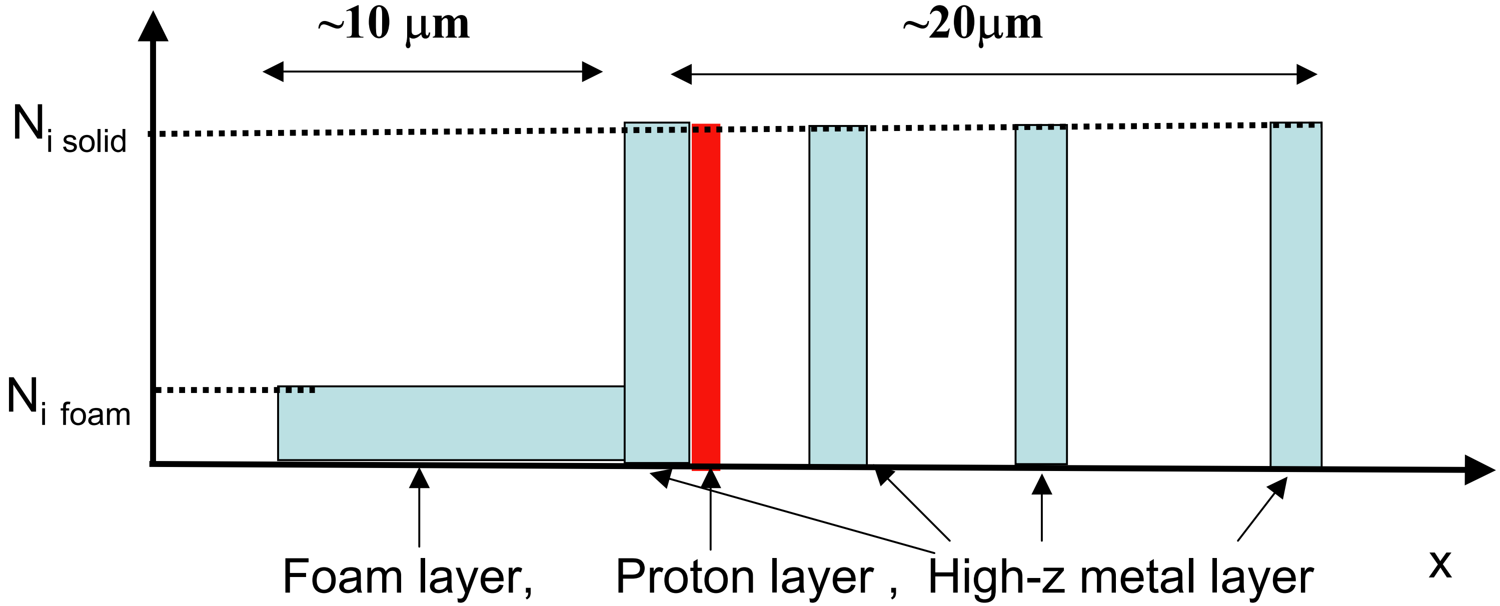
Estimated preplasma scale is ≤ 10 microns.



For prepulse level is 10^{-7} proton energy was much less.

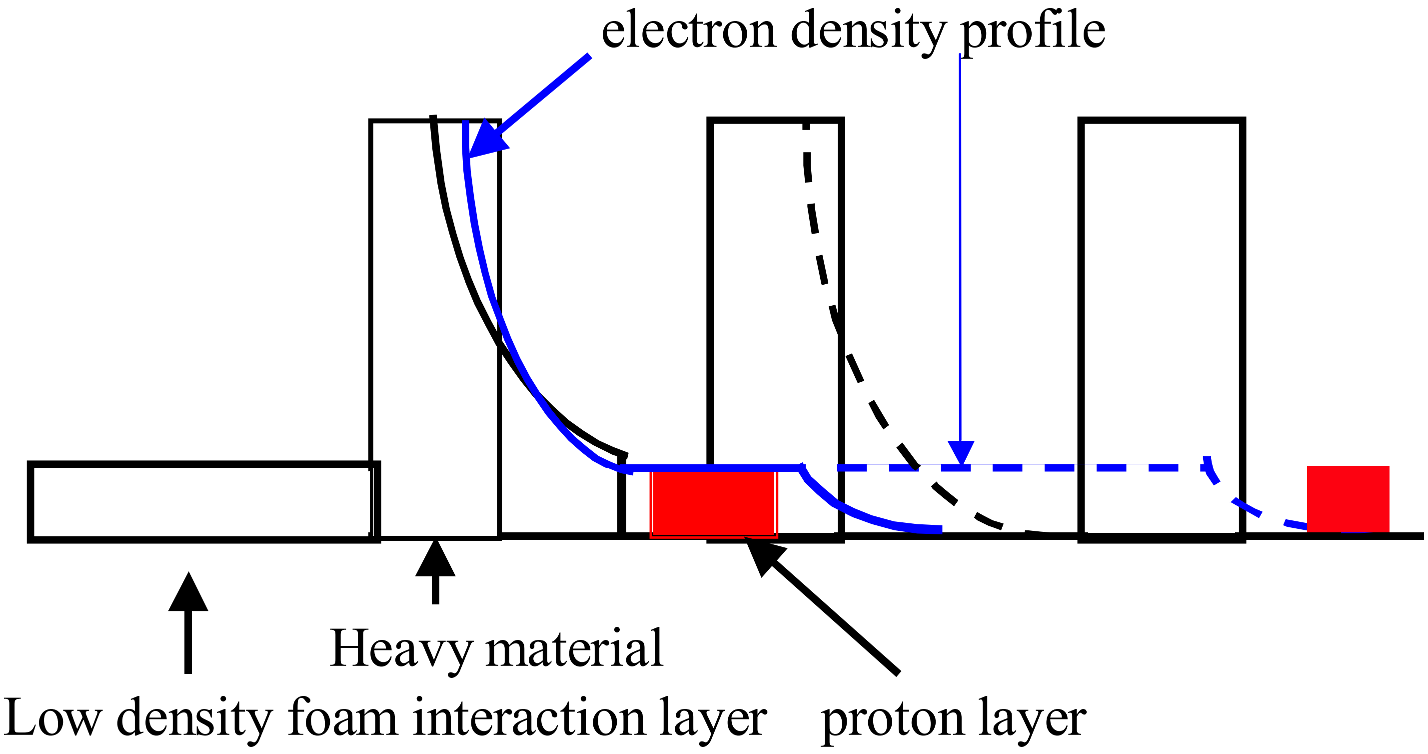
[3] K. Nemoto, A. Maksimchuk, S. Banerjee *et al*., Appl. Phys. Lett. **78,** 595 (2001).

[Concluding Remark]
Target for high energy and monochromatic proton acceleration



$Zn_{i\ foam} < \gamma n_c$, $T_h \sim a^2 mc^2 /2$ ⟶ $I_L > 10^{21}$ W/cm^2
For 300 MeV proton

Multi-foil Expansion Processes



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- Active Medium Acceleration (Shachter)
- Ferroelectrics (Kanareykin)
- Beam conditioning for FELs (Wurtele, Esarey, Schroeder)

Beam Conditioning for FELs

1. Jonathan Wurtele -- conv. Approach to an exotic idea

LBNL/UCB

Co-workers: G. Penn, A. Wolski, A. Sessler

2. E. Esarey et al. -- Plasma LWFA approach

3. C. Schroeder et al.-- Thomson Scattering laser approach

The Problem

FEL resonance:

$$\lambda = \left(1 - \frac{\overline{\mathrm{v}}_Z}{c}\right)\lambda_W \approx \frac{1+K^2}{2\gamma^2}\lambda_W$$

$$\frac{\overline{\mathrm{v}}_Z^2}{c^2} = 1 - \frac{1}{\gamma^2} - \frac{\overline{\mathrm{v}}_\perp^2}{c^2} = 1 - \frac{1+K^2}{\gamma^2}$$

Zero canonical momentum

$$\lambda = \frac{1}{2}\left(\frac{1+K^2}{\gamma^2} + \frac{2J_x}{\beta_x} + \frac{2J_y}{\beta_y}\right)\lambda_W$$

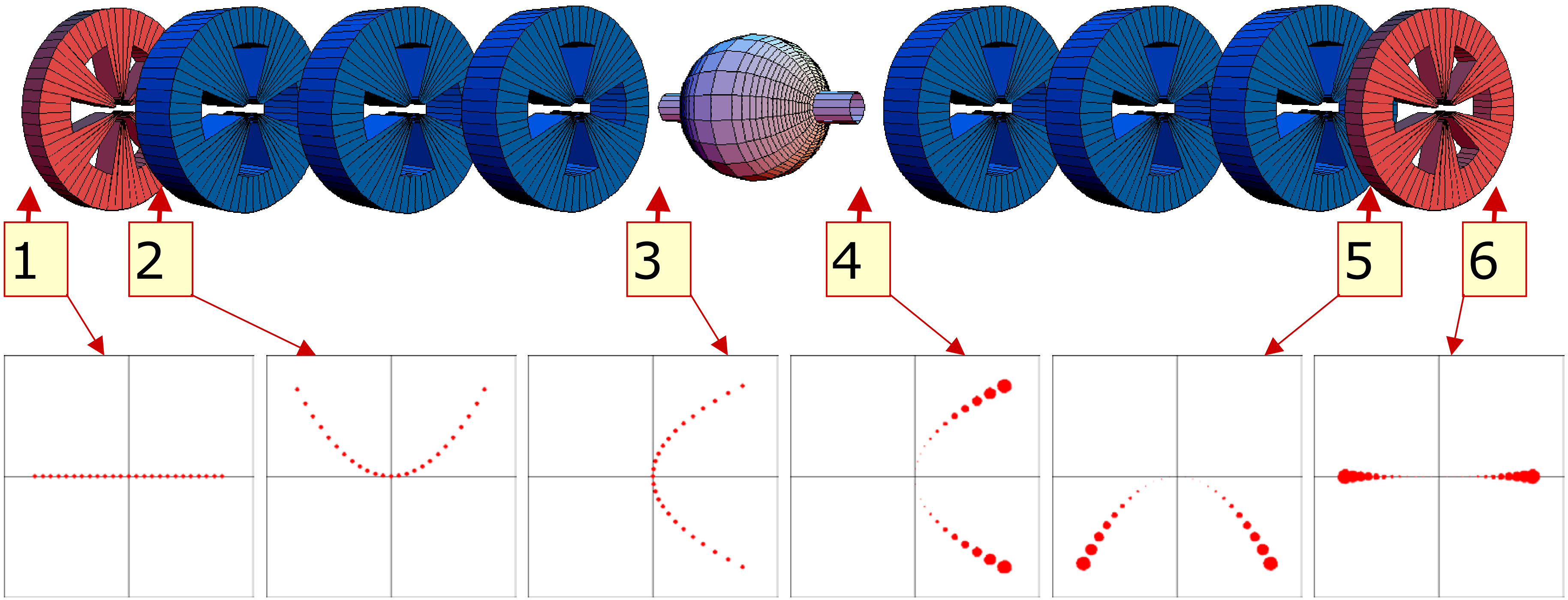
Typical particle

$$J_x = \frac{1}{2}\left[\frac{x^2}{\beta_x} + \beta_x\left(\frac{p_x}{P_0} + \frac{\alpha_x x}{\beta_x}\right)^2\right],$$

Emittance is beam average of J

FEL requires:
1)Particle relative motion be less than one wavelength in a gain length a
2)Emittance be less than radiation wavelength (overlap).

Example: Sextupole + TM_{110} cavity Conditioner

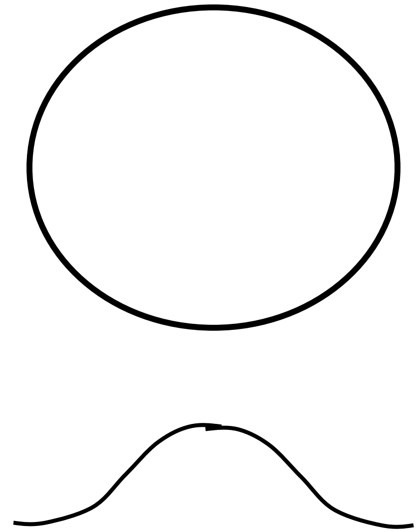


1. A “matched” beam enters the conditioner.
2. The first sextupole distorts the horizontal phase space.
3. The phase space is rotated through π/2.
4. The cavity gives a correlation between *x* and pz.
5. The phase space is rotated through a further π/2.
6. The final sextupole removes the phase space distortion.

A. Wolski, et al, to appear in PRST-AB

Works but weak E requires many stages

3 Alternate Approaches:

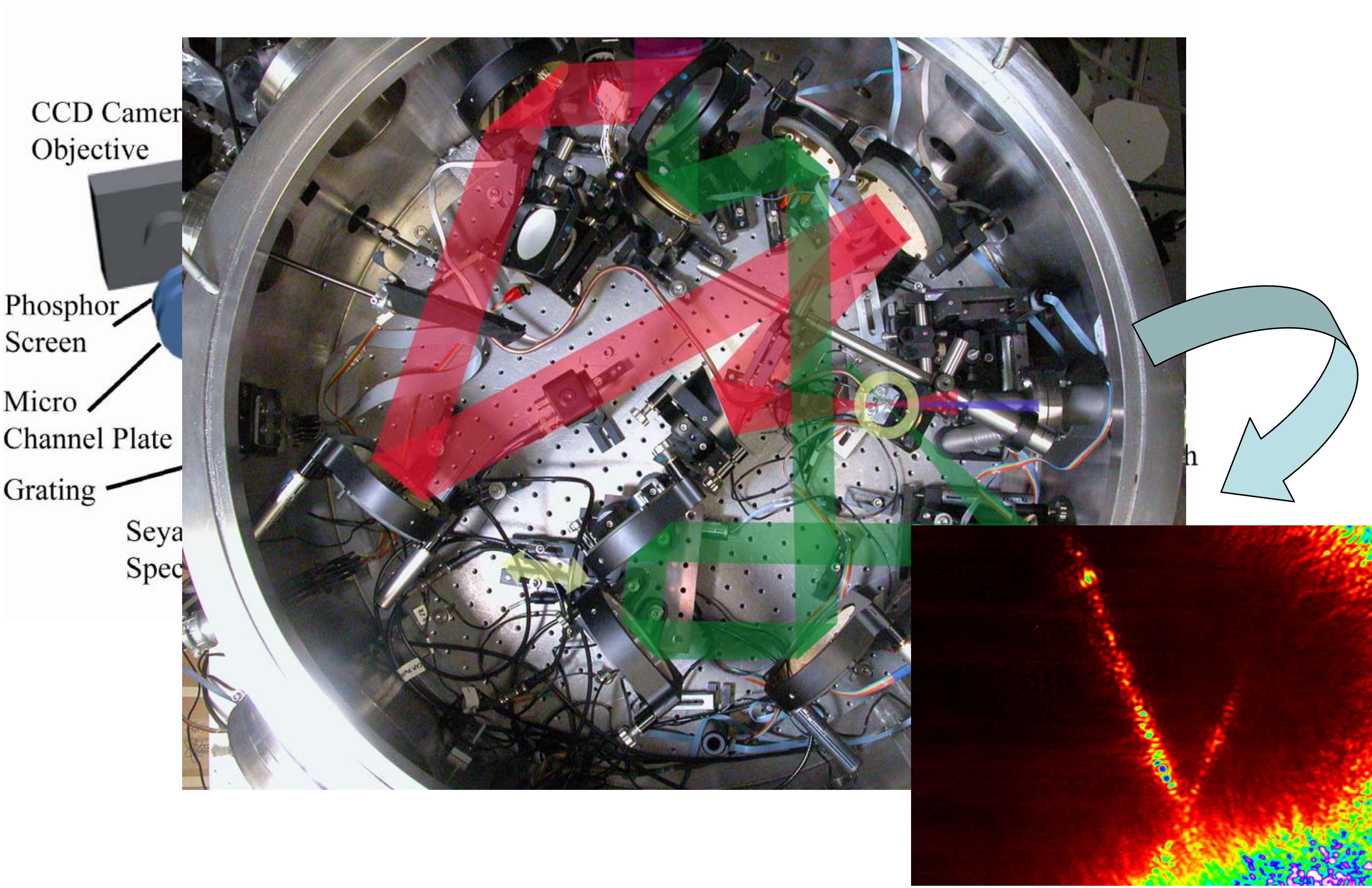


beam

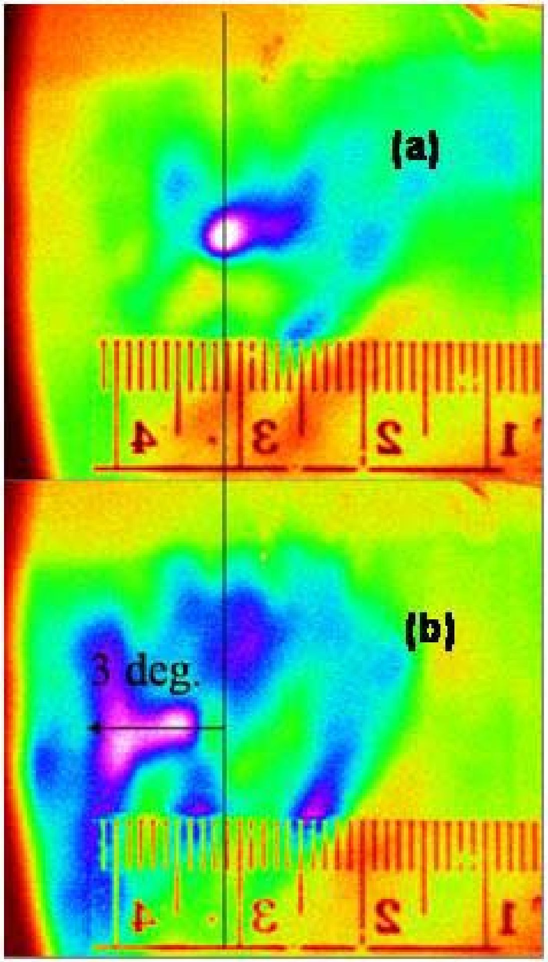
profile of decelerator field

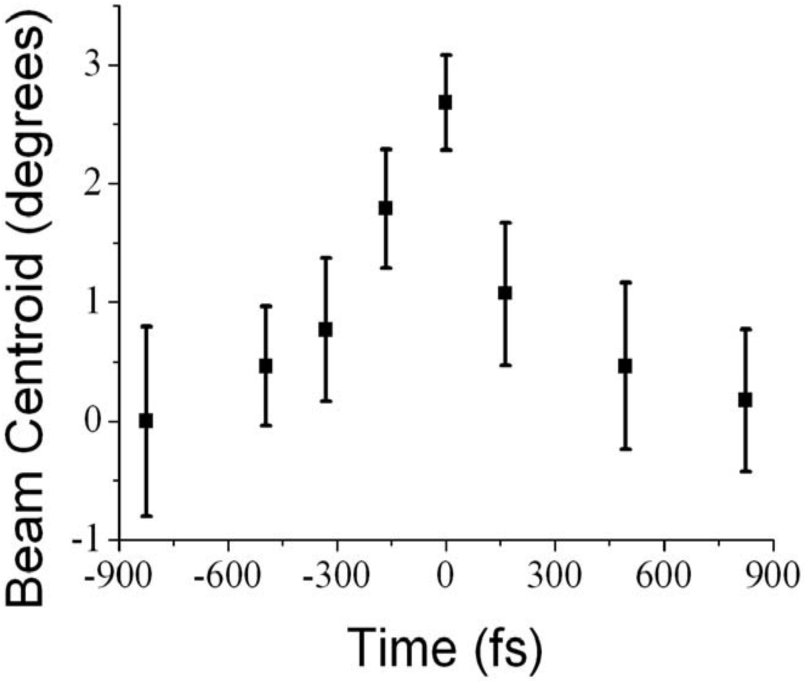
1. Esarey -- LWFA, good but wide laser => 700 TW
2. Schroeder -- Thomson laser => 300 TW
3. Working Group -- passive plasma (PWA deceleration)
   0 TW!
   but longitudinal dependence
   -- use shaped bunch before compressing?
   --throw away all but small slice of bunch?

Vacuum Acceleration -- Umstadter, UM



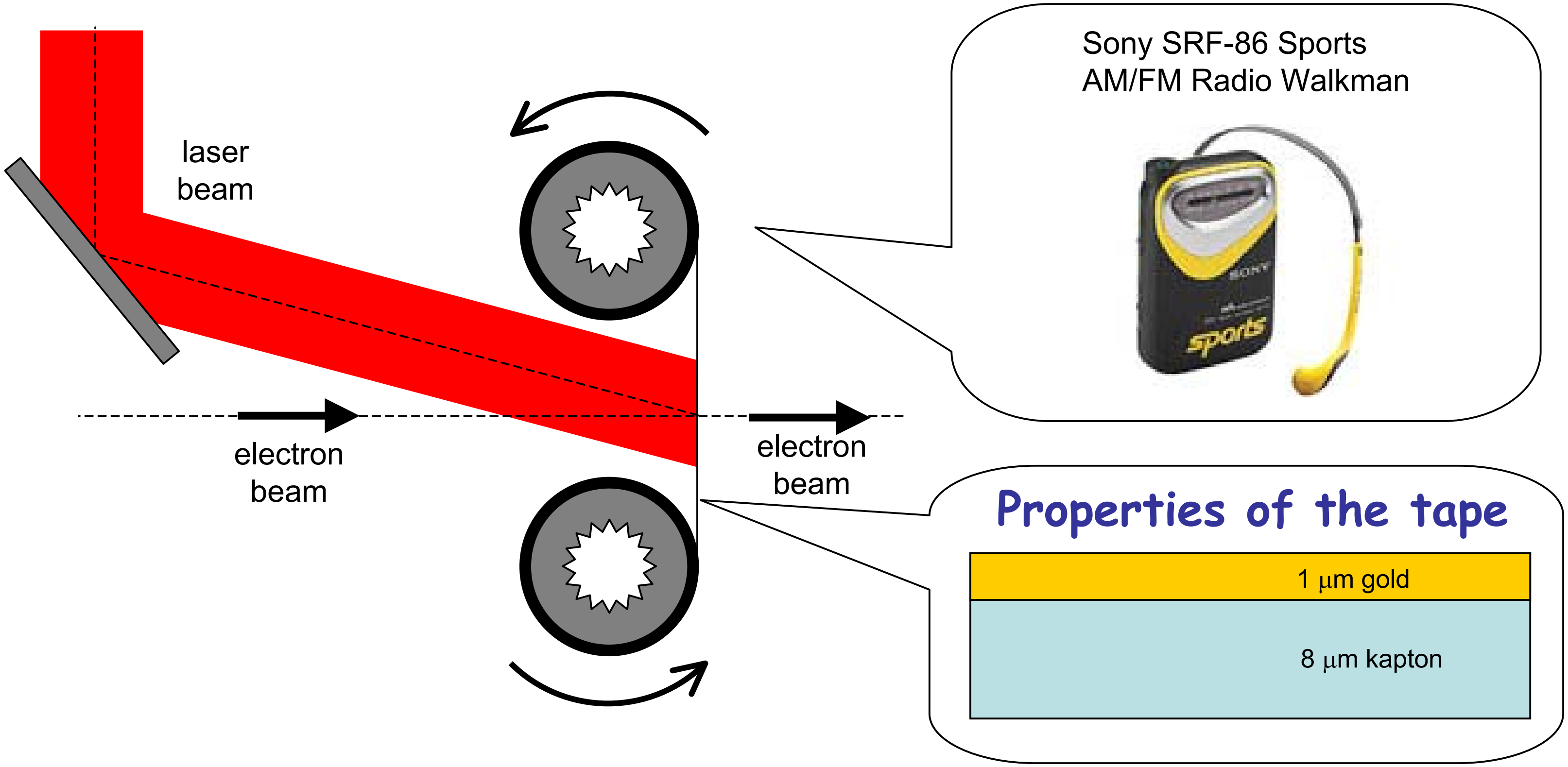
Ponderomotive deflection of electron beam





Cross-correlation of laser-wakefield accelerated electron beams

The "Walkman" particle accelerator -- LEAP, Plettner



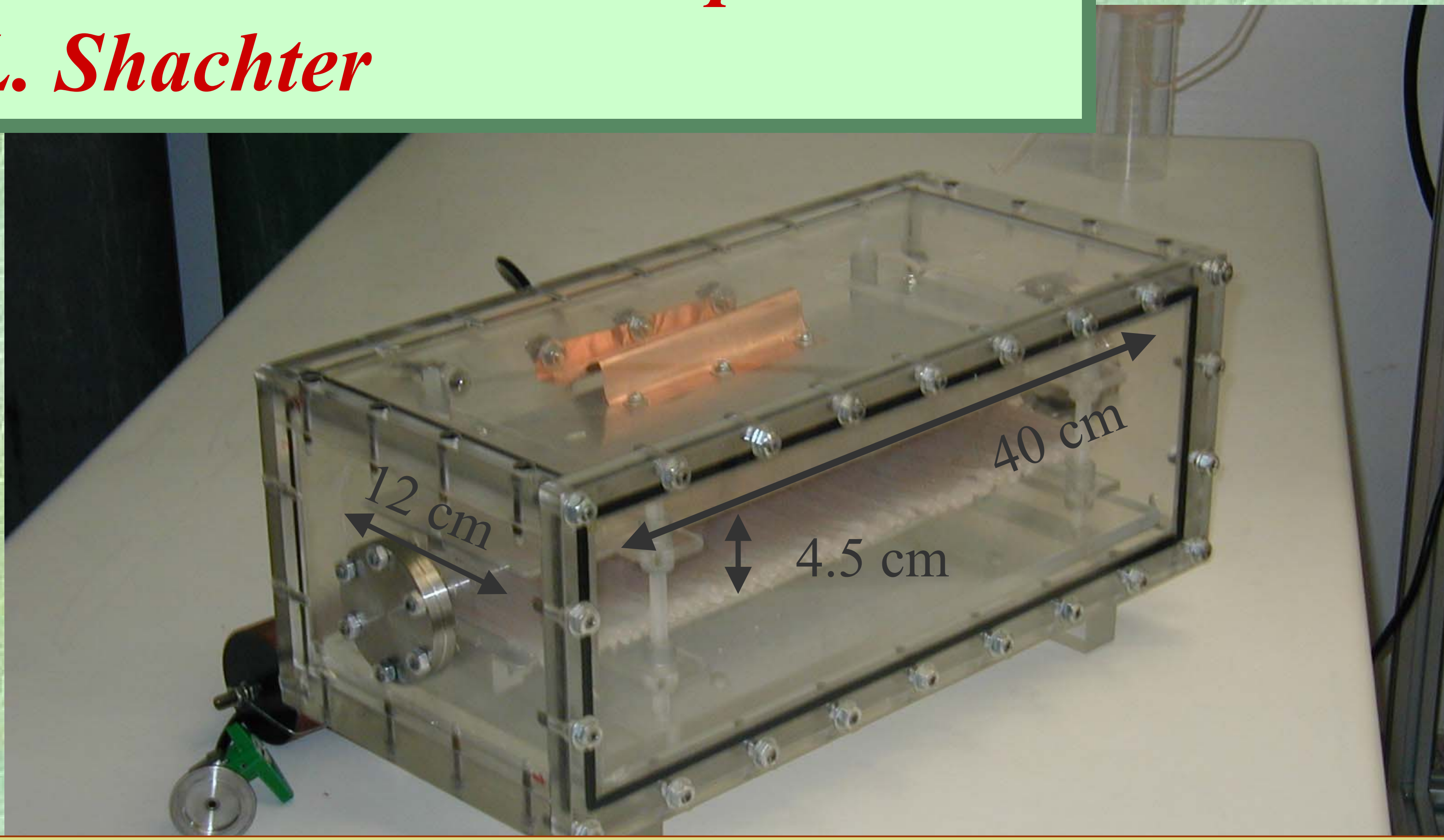
Key modifications

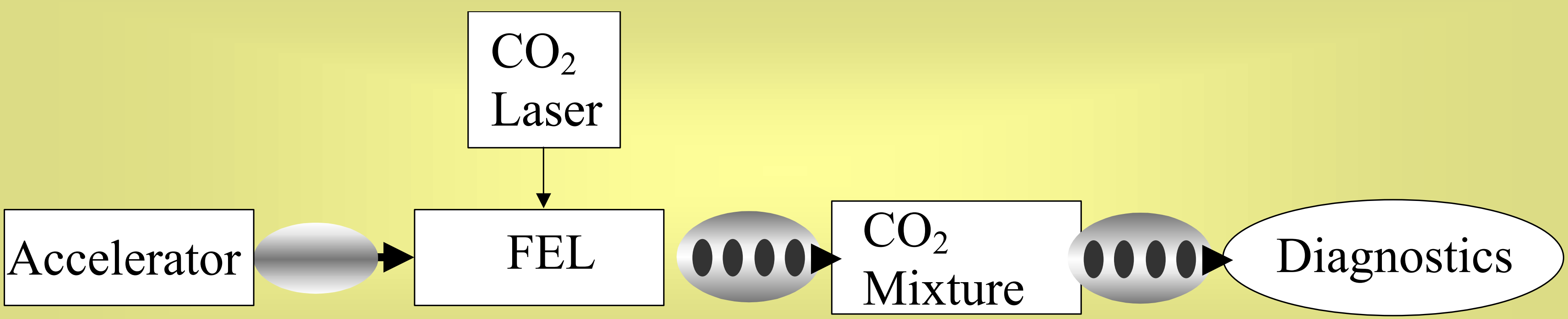
1. Slit is lost (e^- traverses matter)
2. One laser beam focused on the surface of the tape
3. Damage threshold constraint is removed

New problems

1. e^- traverses matter
2. potential contamination from laser-ablated material
3. Potential interference of the acceleration effect due to the presence of plasma

BNL-ATF PASER experiment- L. Shachter





Exotic Concepts Conclusion

"As our field matures, there is still room for innovation in all AAC areas: drivers, materials, combinations thereof." G. Shvets

"We came, we saw, we calculated." Anonymous

"I proclaim these the best games ever."

Juan Antonio Samaranch

Thank you Ilan and Brookhaven National Lab!