Exotic Acceleration Concepts and High Energy Density Physics:

Working Group Summary from the 2004 Advanced Accelerator Concepts Workshop, Stony Brook

by Tom Katsouleas (USC) and Bob Noble (SLAC)

- Creative, paradigm changing ideas
- Confluence of HED, AAC, and Applications

Exotic Concepts WG Participants

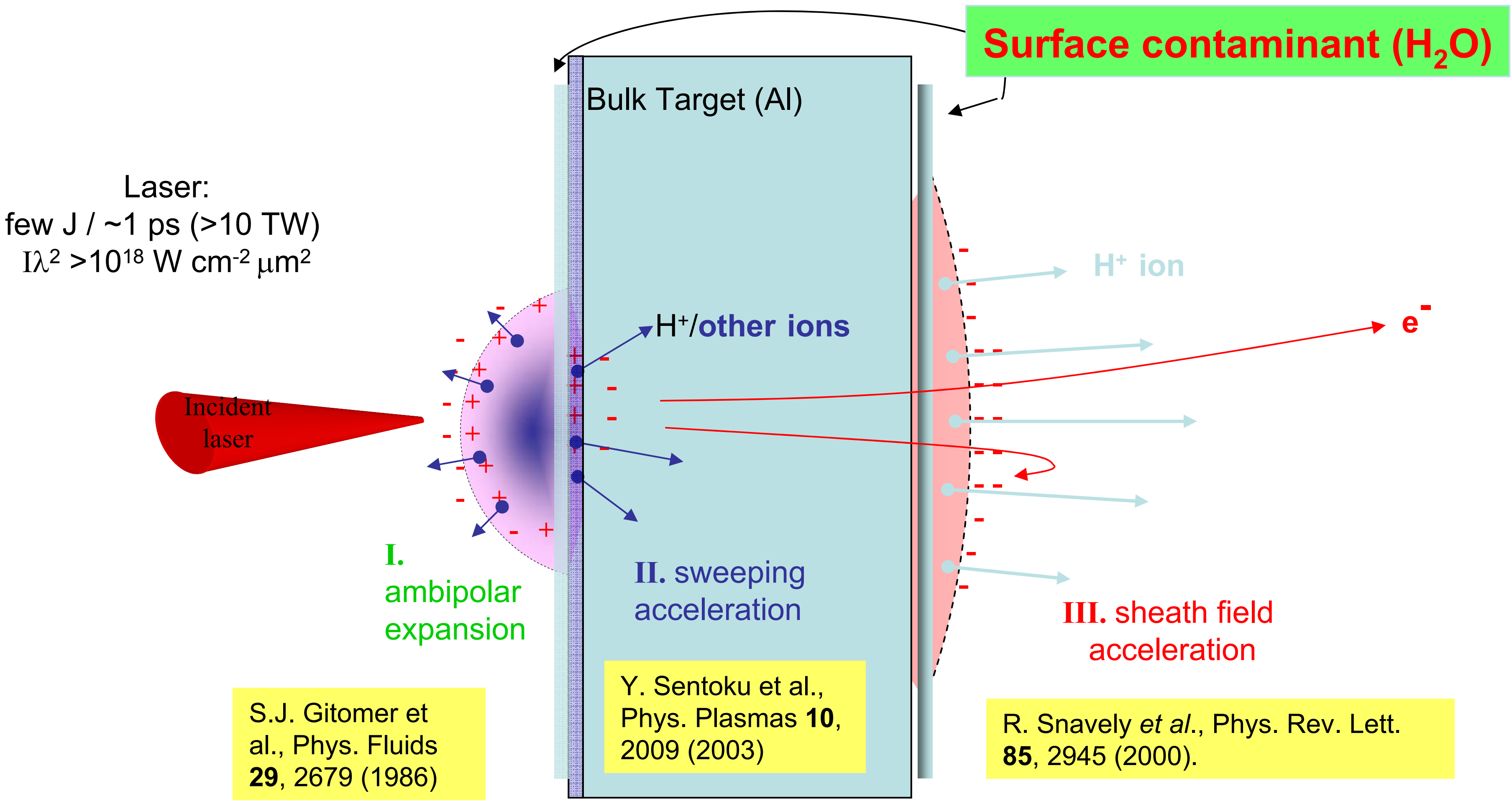
- J. Alessi
- D. Umstadter
- K. Mima
- A. Ogata
- J. Fuchs
- P. Awtia
- P. Bolton
- J. Lewellen
- J. Kim
- G. Shvets
- K. Nakajima
- C. Schroeder
- A. Kenareykin
- I. Pogorelsky
- B. Bowes
- I. Pavlishin
- J. Smedley
- J. Wurtele
- P. Stoltz
- C. Toth
- T. Cowan
- R. Noble
- T. Katsouleas
- L. Schachter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

We heard some fascinating talks…

17 presentations during 3 days

- Proton/ion acceleration from laser-driven foils
  - Experiments: Lin, Bolton, Ogata, Fuchs, Cowan, Mima
  - Simulations: Silva, Mima, Messmer
  - Applications: Proton Injectors (Alessi), Heavy Ion Fusion/HED Physics (Cowan, Wurtele, Bowes)
- e- Laser Acceleration in Vacuum (Umstadter, Plettner)
- Active Medium Acceleration (Schachter)
- Ferroelectrics (Kanareykin)
- Beam conditioning for Free Electron Lasers (Wurtele, Esarey, Schroeder)

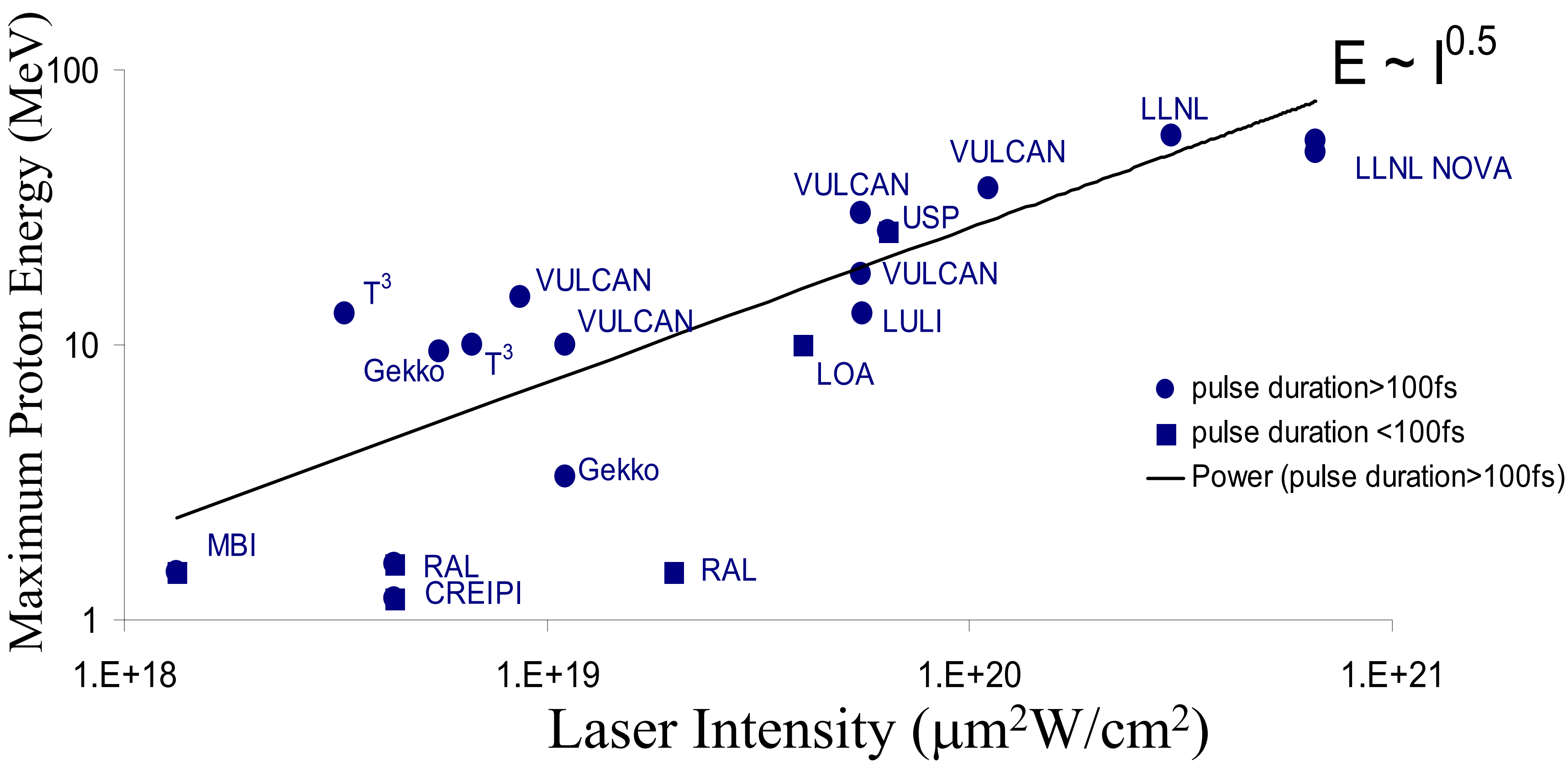
Mechanisms of laser-acceleration of *ions*



if target is heated ➔ efficient acceleration of heavy ions

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

Proton Energy Scaling (T. Lin)



We did some work…

Working Group Result:

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

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

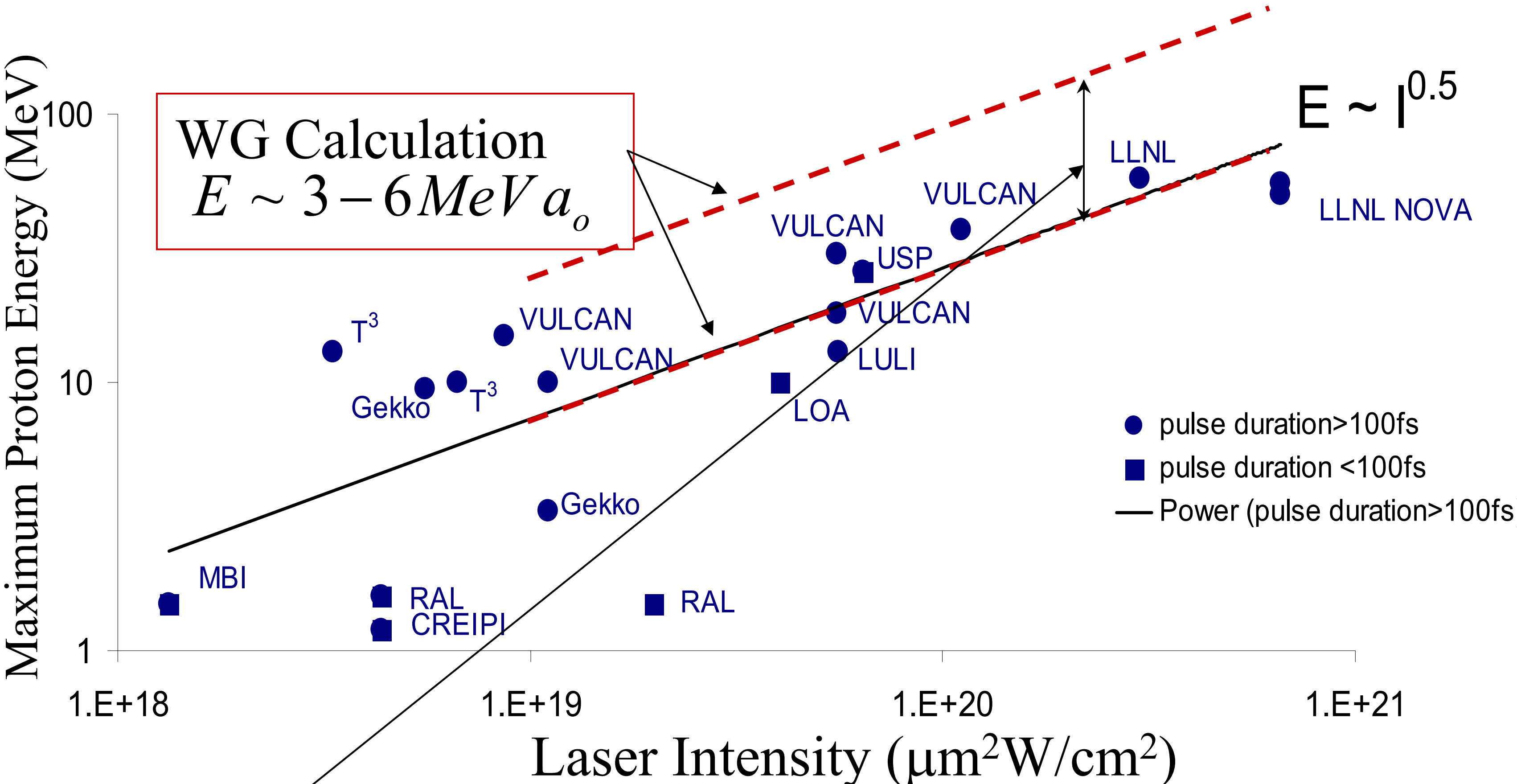
$$c_s = \sqrt{T_h / M}$$

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

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

Note: this is about 10x $\phi_{sheath} \sim T_h$

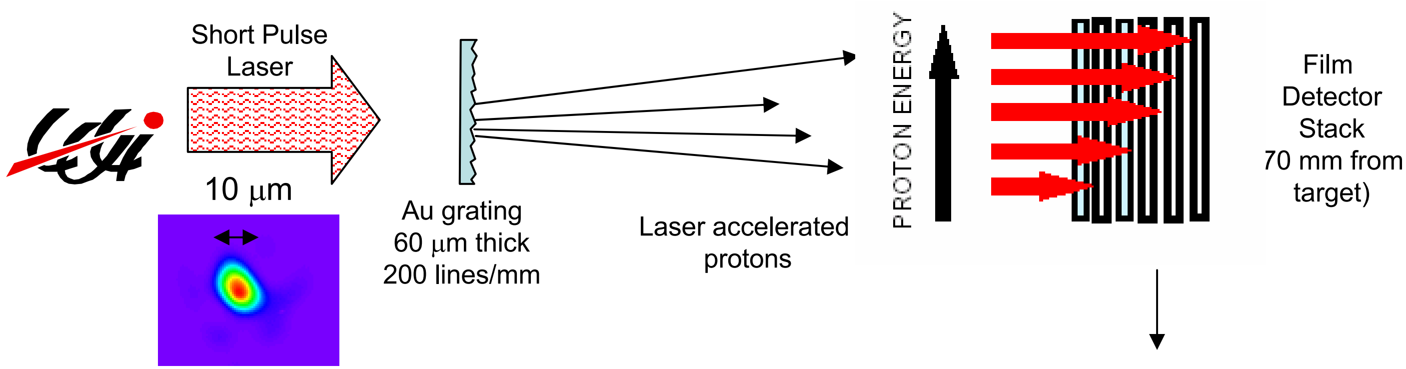
Proton Energy Scaling (T. Lin)

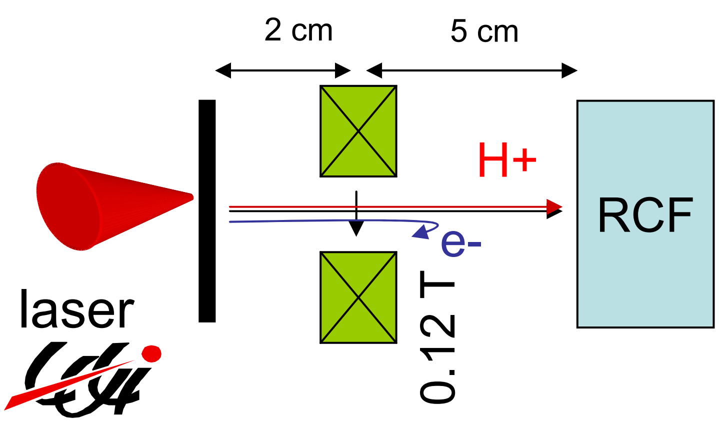


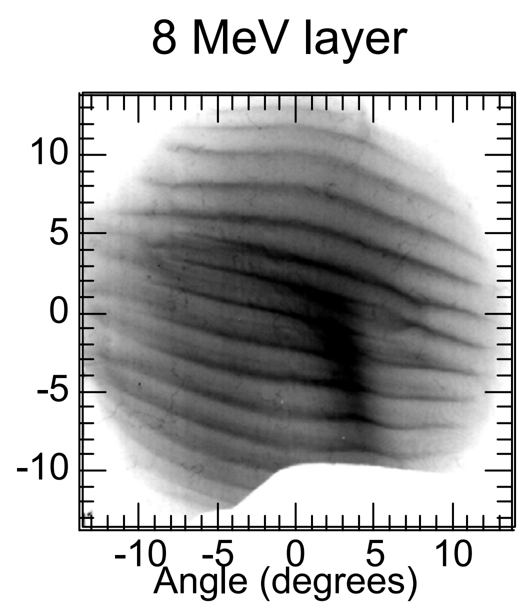
Pulse length dependence in theory ($\ln 2\omega_{pi}\tau_p$); Mora, PRL (2003)

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

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







Laser-accelerated ions as sources for conventional ion injectors ?

Alessi, Fuchs, Noble

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

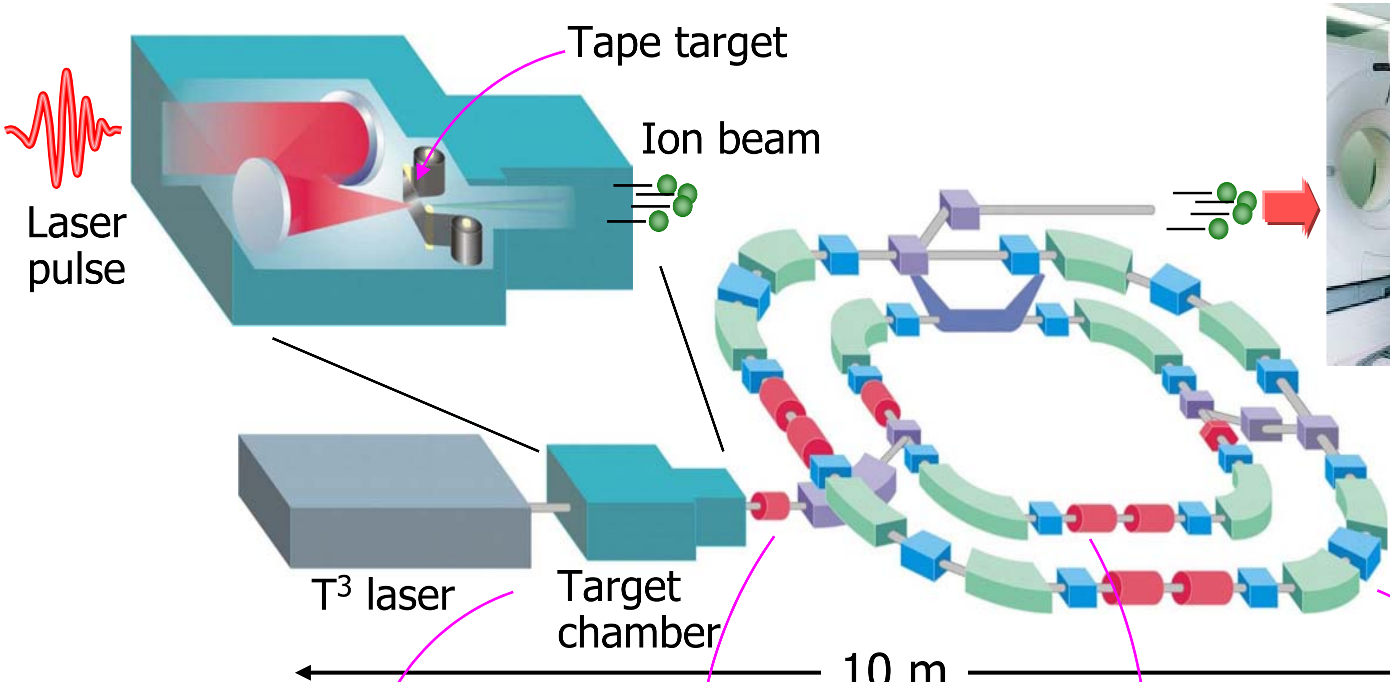
Laser-accelerated protons

- 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^-

Development of Compact Ion Accelerator

National Institute of Radiological Sciences, JAPAN



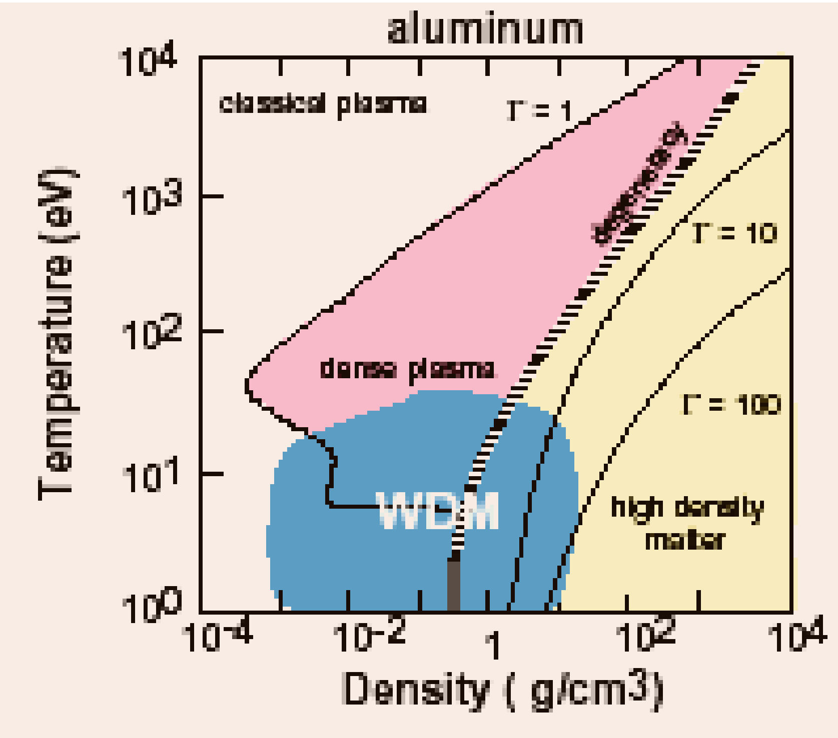
Cancer therapy

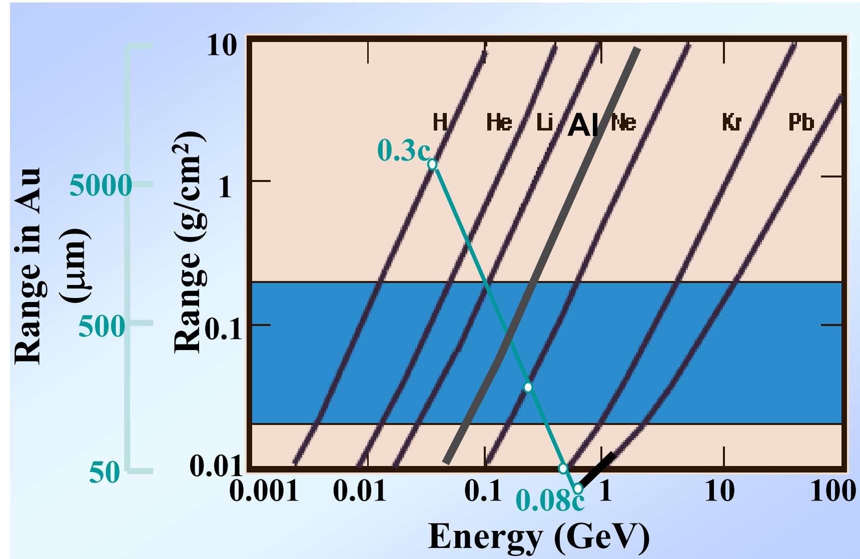
Laser plasma ion source	RF cavity for phase rotation	Electron beam cooler ring	Compact heavy ion synchrotron
2 MeV/u p (10^{10}/sec.) C ion (10^{9}/sec.)	Energy spread ~±1%	Energy spread ~±0.1%	200 MeV/u
JAERI, Univ. of Tokyo, Hiroshima Univ.	Kyoto Univ., JAERI	Kyoto Univ.	KEK

Fukumi, Ogata, …

Heavy Ion - High Energy Density Physics

Physics motivation: What is the nature of "warm dense matter"?



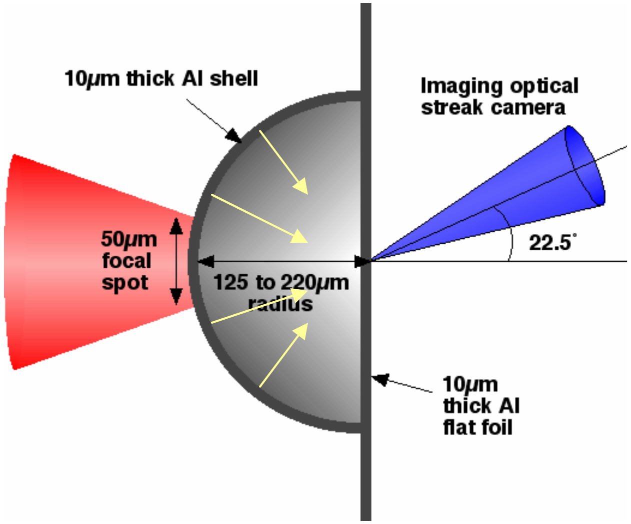


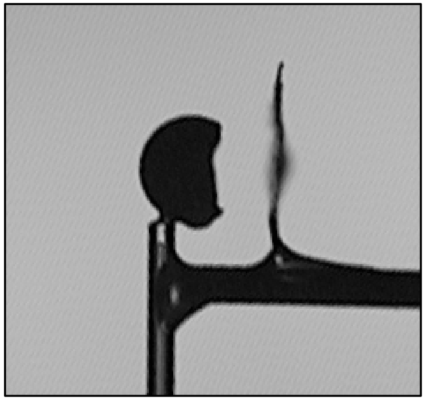
Ion beam range ideal for heating solid matter

But pulse must be short to beat expansion,
requires neutralized transport

5 yr Goal: 10^{11} J/m^3

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



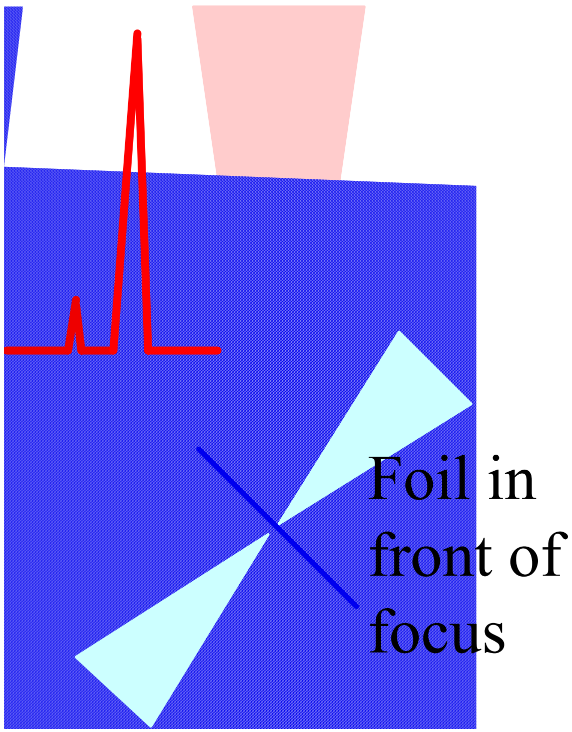


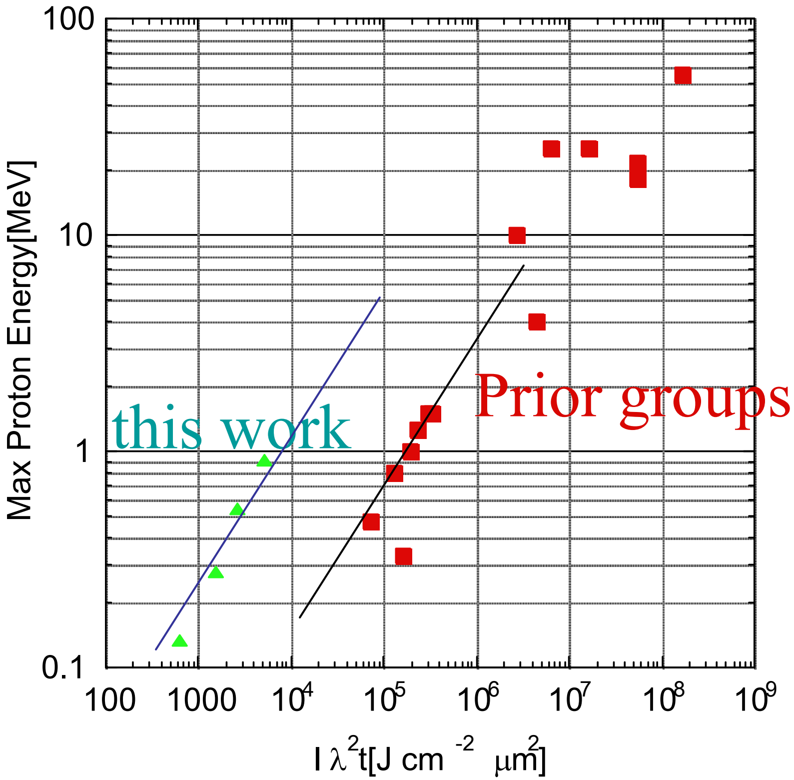
5 yr Goal: (10^{11} J/m^3)	Now w/ 20J lasers (10^9 J/m^3)
100 p-MA/cm^2	100 p-MA/cm^2
10 MeV	10 MeV
1 ns	10 ps

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

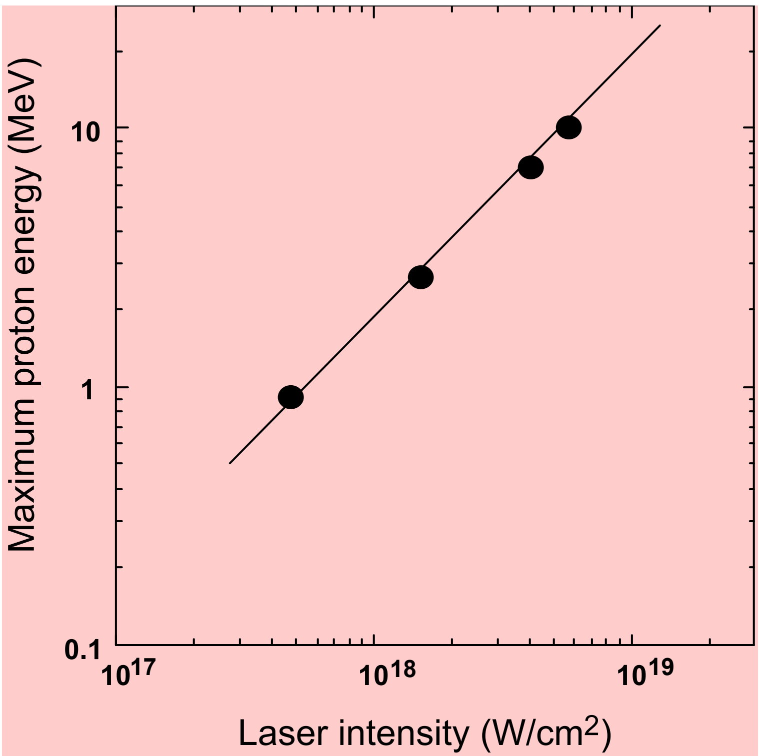
A. Ogata (Hiroshima Univ.): Getting more ion acceleration with less laser

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



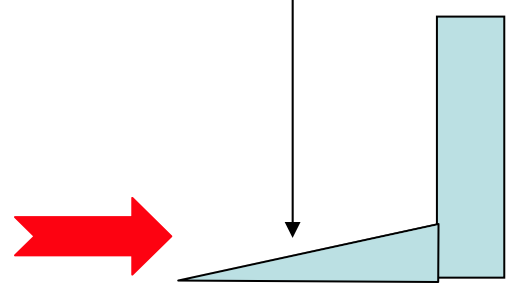


CUOS Experiments Shows Maximum Proton Energy is Enhanced and Proportional to the Laser Intensity [3]



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

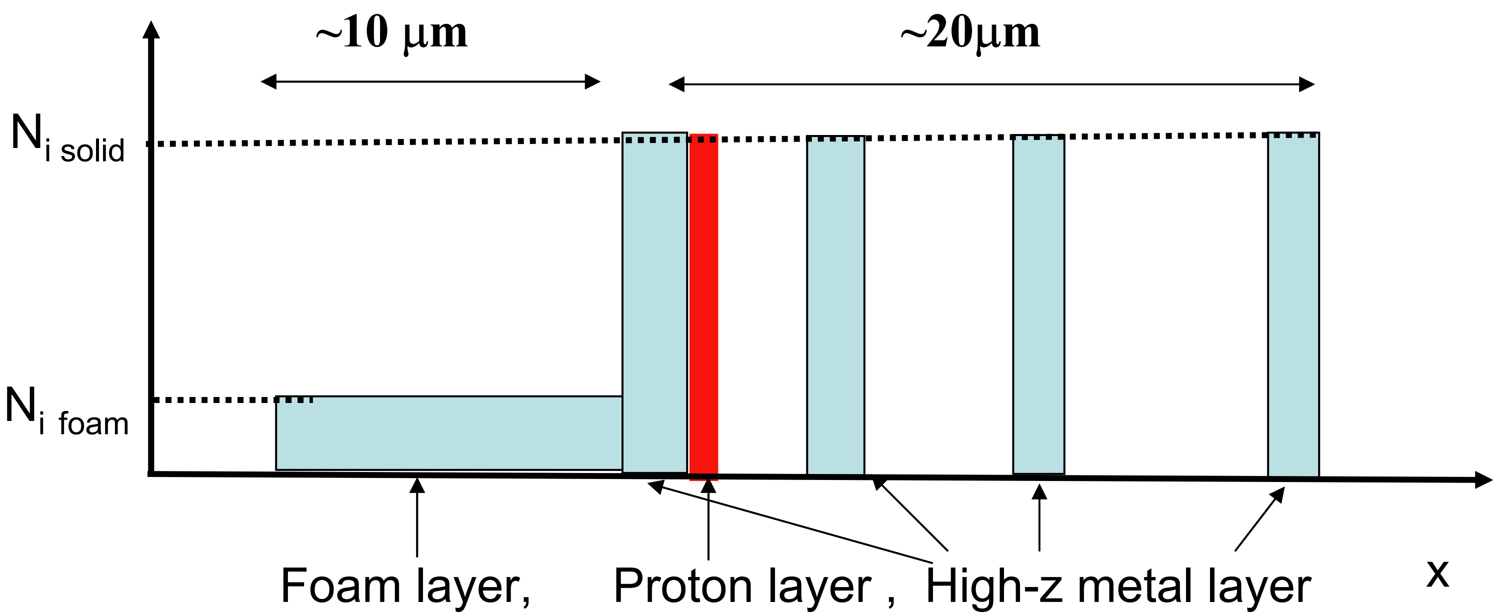
Estimated preplasma scale is ≤ 10 microns.



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).

Possible target for high energy and monochromatic proton acceleration (K. Mima)



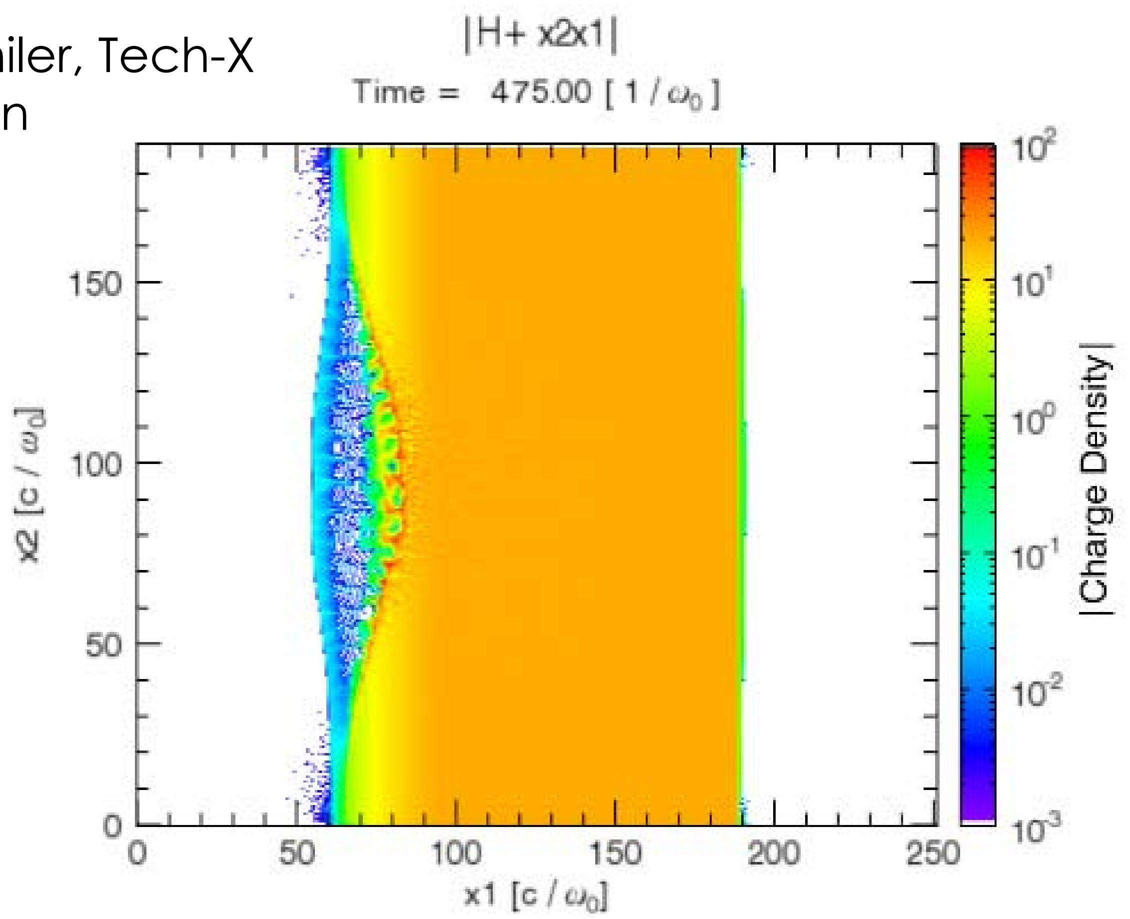
$Zn_{i\,foam} < \gamma n_c$, $T_h \sim a^2\, mc^2/2$ → $I_L > 10^{21}$ W/cm^2 For 300 MeV proton

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



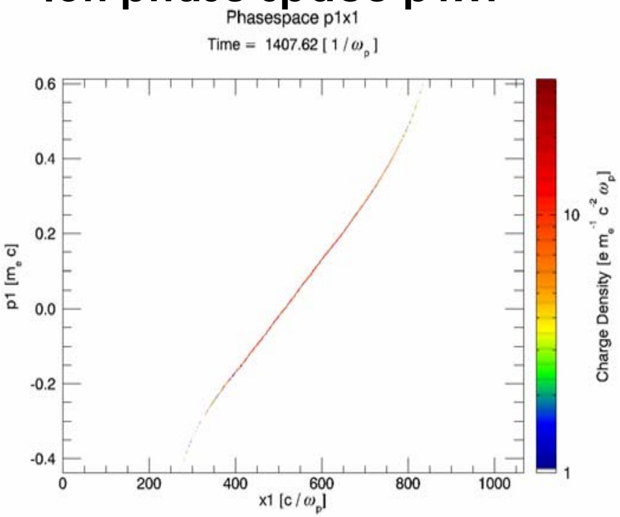
Acceleration mechanisms

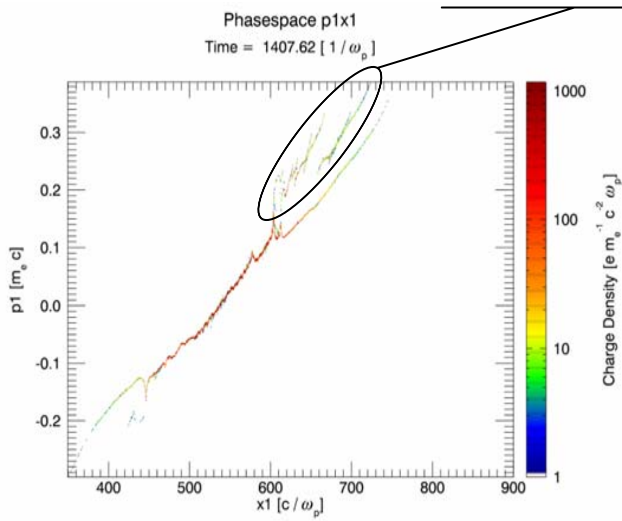
No shock	Shock with higher energy than rear	Shock with lower energy than rear

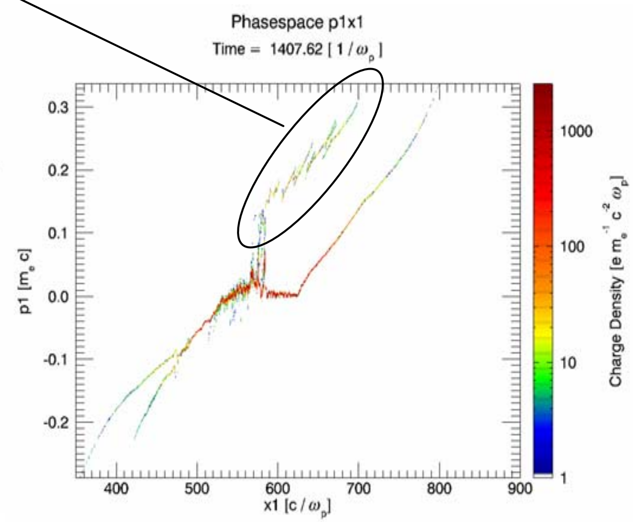
Diffusive/sheath acceleration

shock acceleration

Ion phase space p1x1







a0 = 16	a0 = 16	a0 = 16
Δ = 1 μm	Δ = 6.2 μm	Δ = 8.8 μm

Beam Conditioning for Free Electron Lasers

1. J. Wurtele, G. Penn, A. Wolski, A. Sessler -- Conventional approach to an exotic idea
2. E. Esarey et al. -- Plasma LWFA approach
3. C. Schroeder et al.-- Thomson Scattering laser approach

FEL resonance: $$\lambda = \left(1 - \frac{\overline{v}_z}{c}\right)\lambda_w \approx \frac{1+K^2}{2\gamma^2}\lambda_w$$

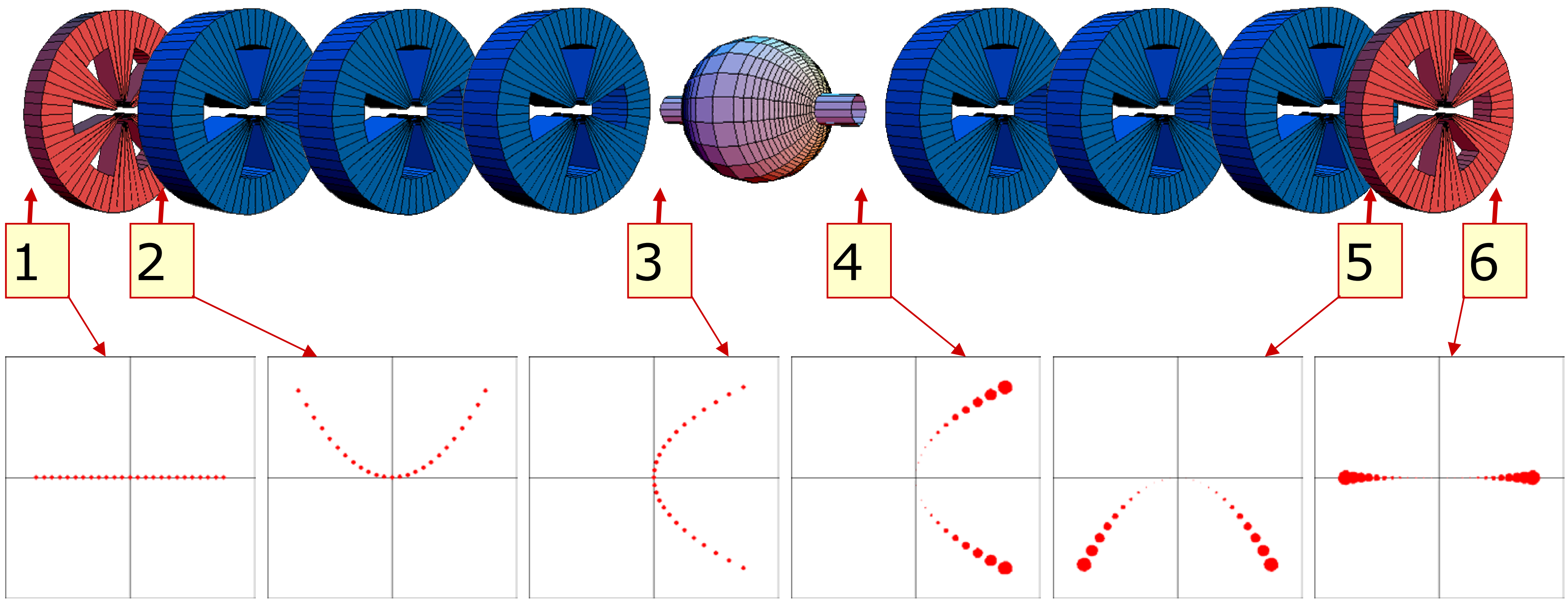
Ideally want all e- to radiate same λ, but typical particles have different energies and transverse oscillation amplitudes:

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

So if you can arrange for particles with larger x to also have larger energy, then you can arrange for nearly same resonant λ for all particles.

Example: Sextupole + TM_{110} cavity Conditioner



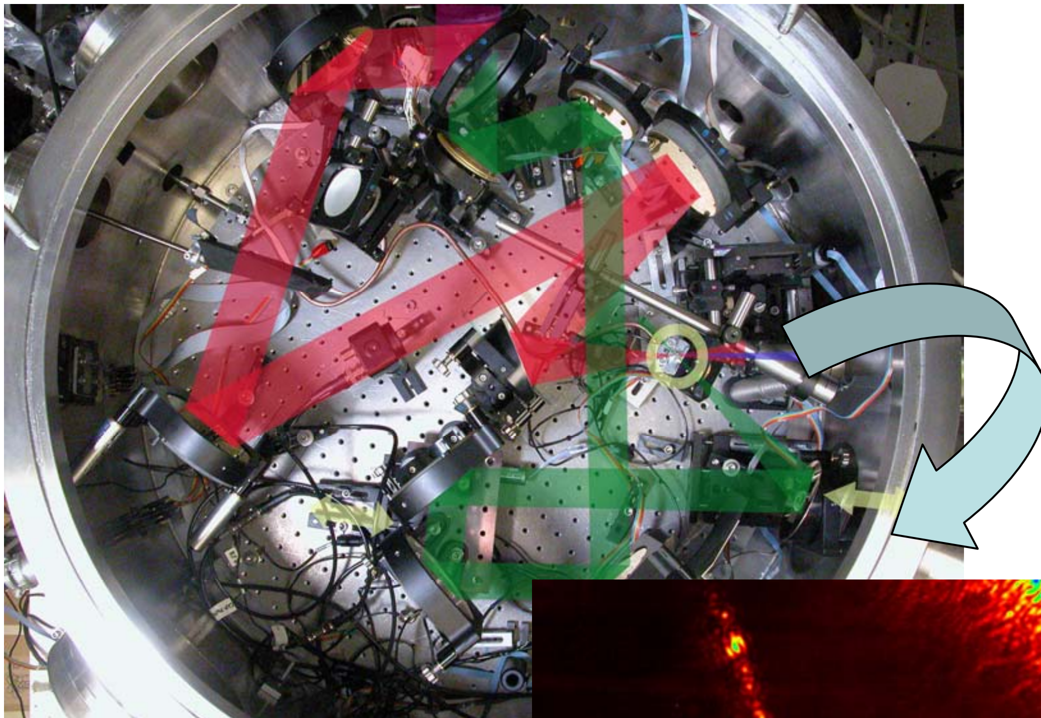
1. A “matched” beam enters the conditioner.
2. The first sextupole distorts the horizontal phase space.
3. The phase space is rotated through π/2.
4. The cavity gives a correlation between *x* and pz.
5. The phase space is rotated through a further π/2.
6. The final sextupole removes the phase space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

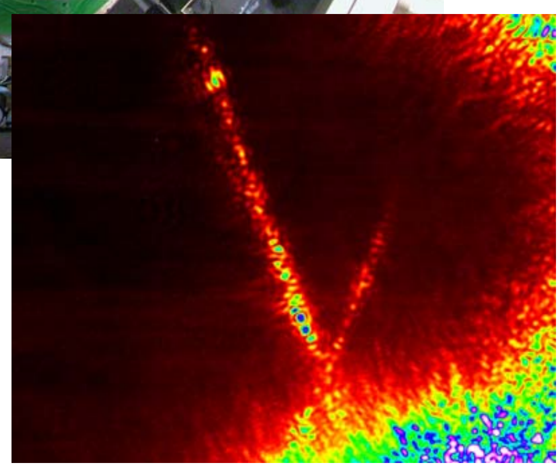
A. Wolski, et al, to appear in PRST-AB

Works but weak E in rf cavity requires many stages.
3 Alternate Approaches:

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?

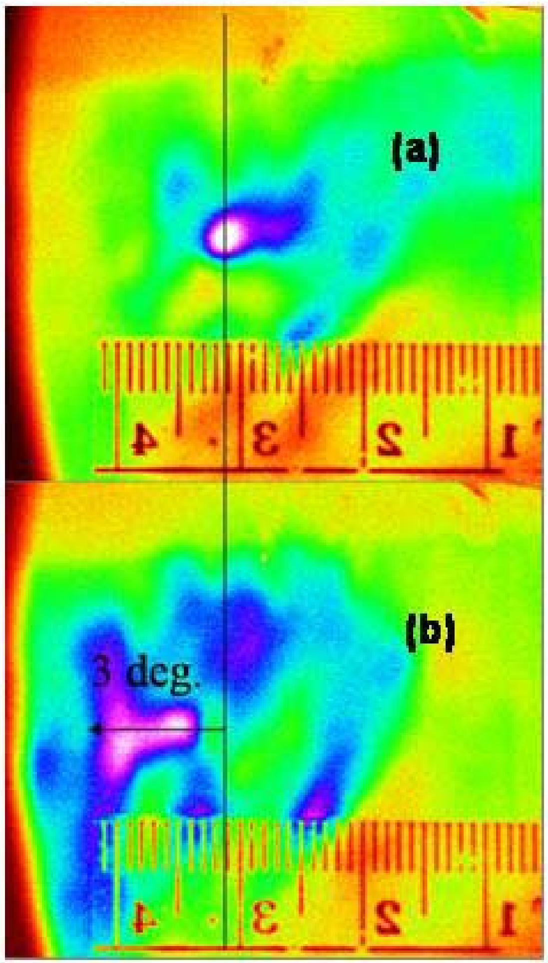
e- Vacuum Acceleration – D. Umstadter, U Mich

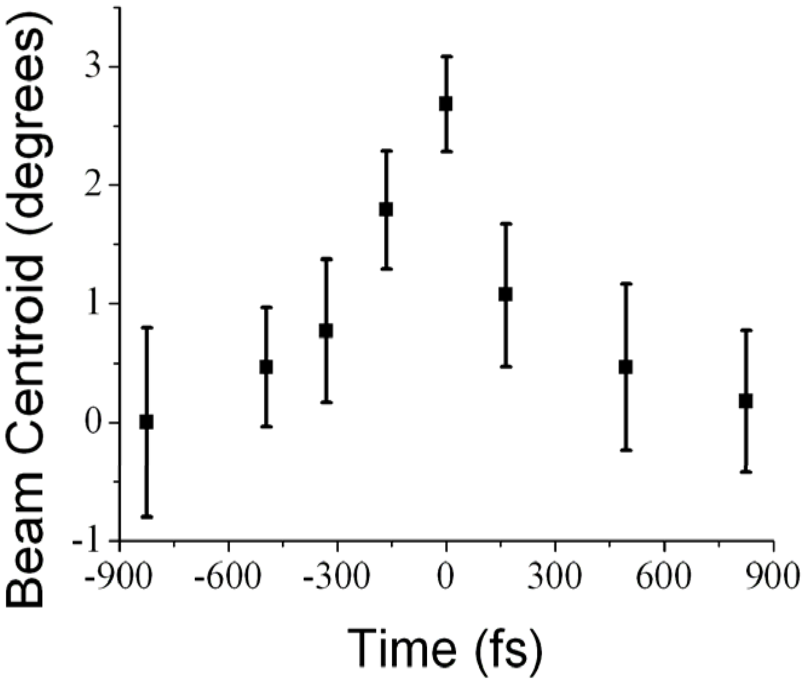




Transversely propagating optical pulse imparts momentum to electron beam, causing it to deflect in vacuum.
Results are in good agreement with theoretical model that takes account of longitudinal fields present when Gaussian pulse is tightly focused.
May be useful technique to characterize sub-picosecond e- bunch.

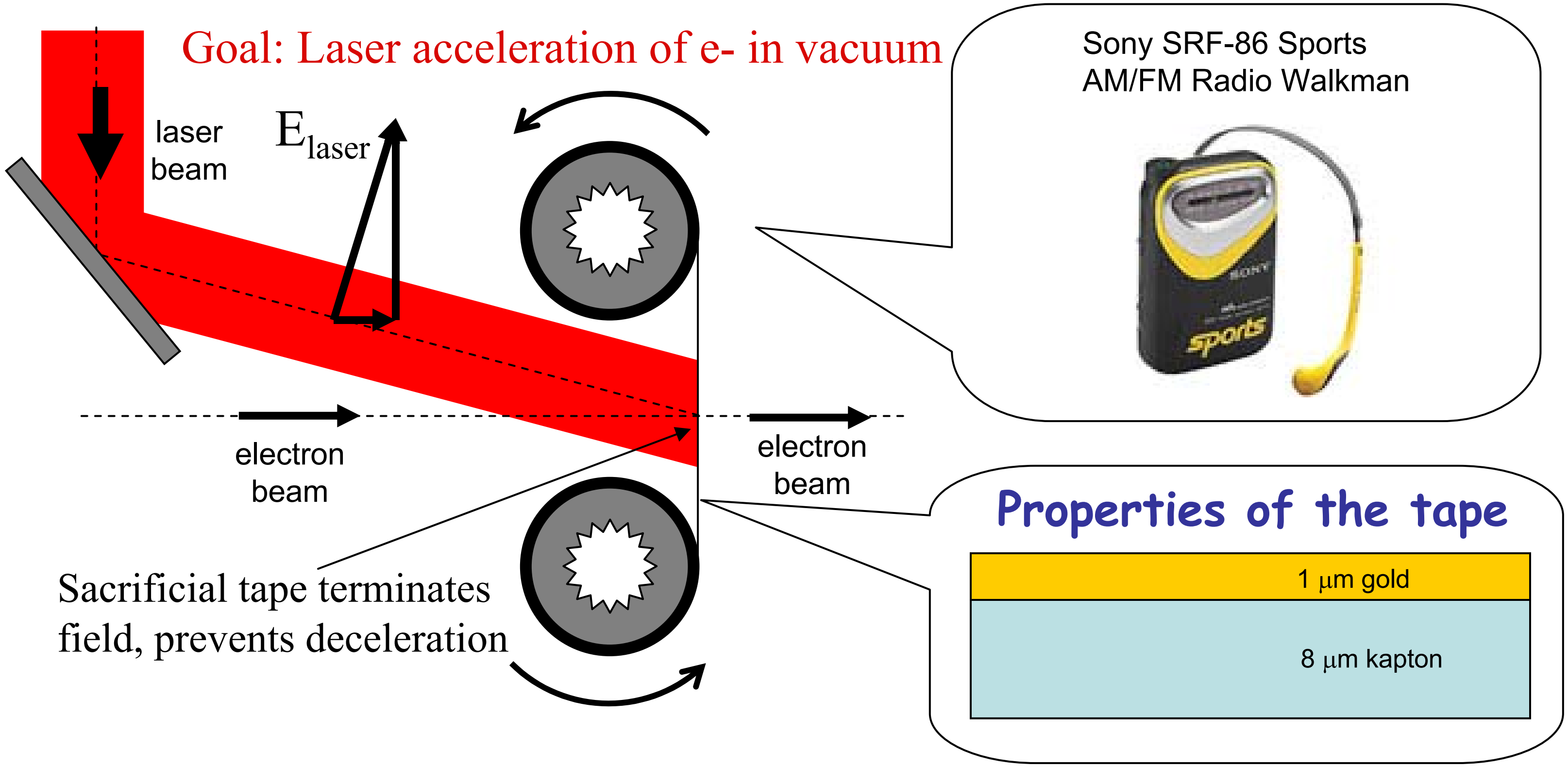
Ponderomotive deflection of electron beam





Cross-correlation of laser-wakefield accelerated electron beams

The "Walkman" particle accelerator -- LEAP, T.Plettner



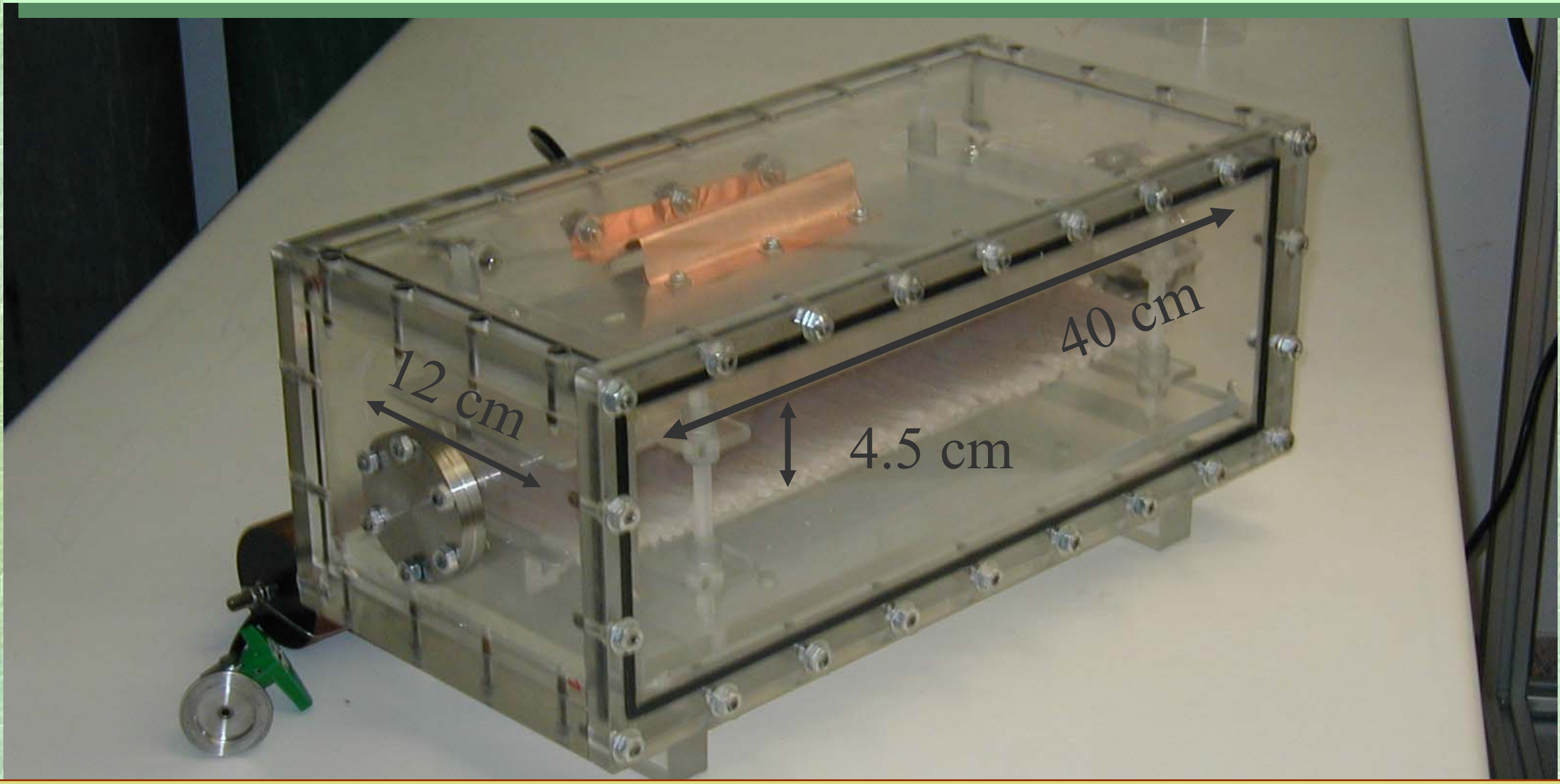
Key modifications

1. Beam exit slit is absent
2. One laser beam focused on the surface of the tape
3. Damage threshold constraint on delicate optical surfaces is removed

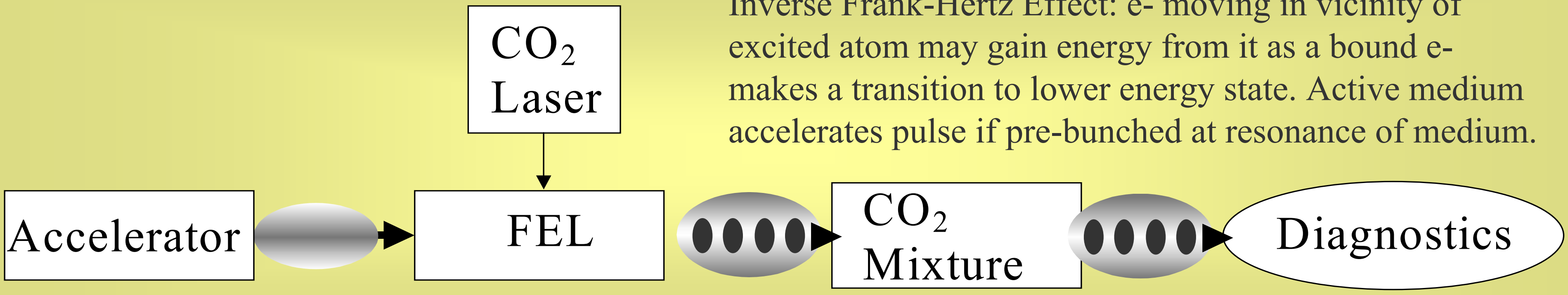
New problems

1. e^- traverses matter
2. Potential contamination from laser-ablated material
3. Potential interference to the vacuum acceleration effect from the plasma's presence

Planned BNL-ATF experiment on active media acceleration - Levi Schachter



Inverse Frank-Hertz Effect: e- moving in vicinity of excited atom may gain energy from it as a bound e- makes a transition to lower energy state. Active medium accelerates pulse if pre-bunched at resonance of medium.



Exotic Concepts WG Conclusions

“As our field matures, there is still room for innovation in all Advanced Accelerator Concept areas: drivers, materials, combinations thereof.” Gennady Shvets

“We came, we saw, we calculated.” Anonymous

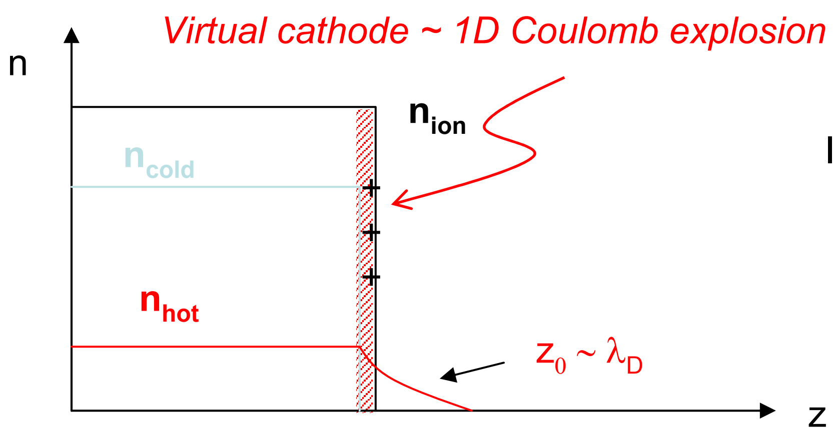
“I proclaim these the best games ever.”

Juan Antonio Samaranch

“The Exotic Concepts WG is like a box of chocolates – you never know what you’re gonna get.” Forest Gump

Summary of rear-surface acceleration of protons

①

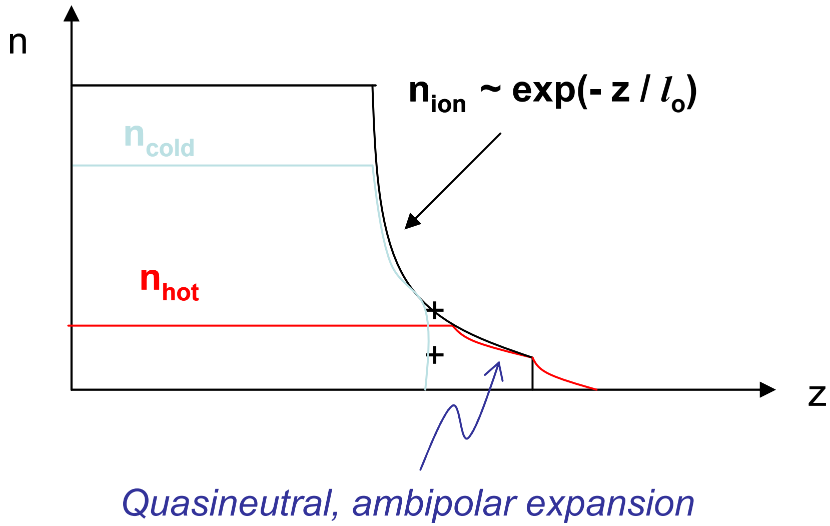


Initial Electric Field:

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

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

②



In expanding sheath:

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

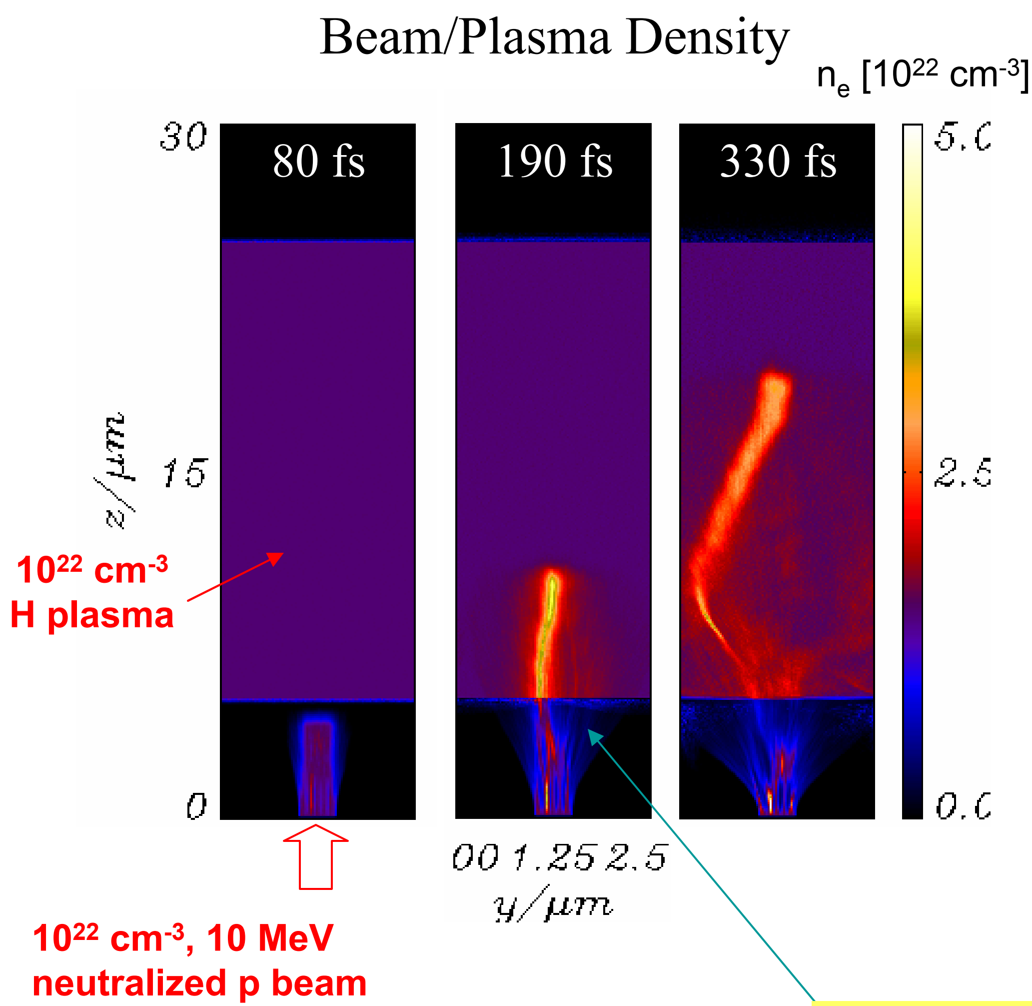
Self-similar expansion of isothermal plasma:

$l_o(t) = c_s\, t$

Then adiabatic:

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

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