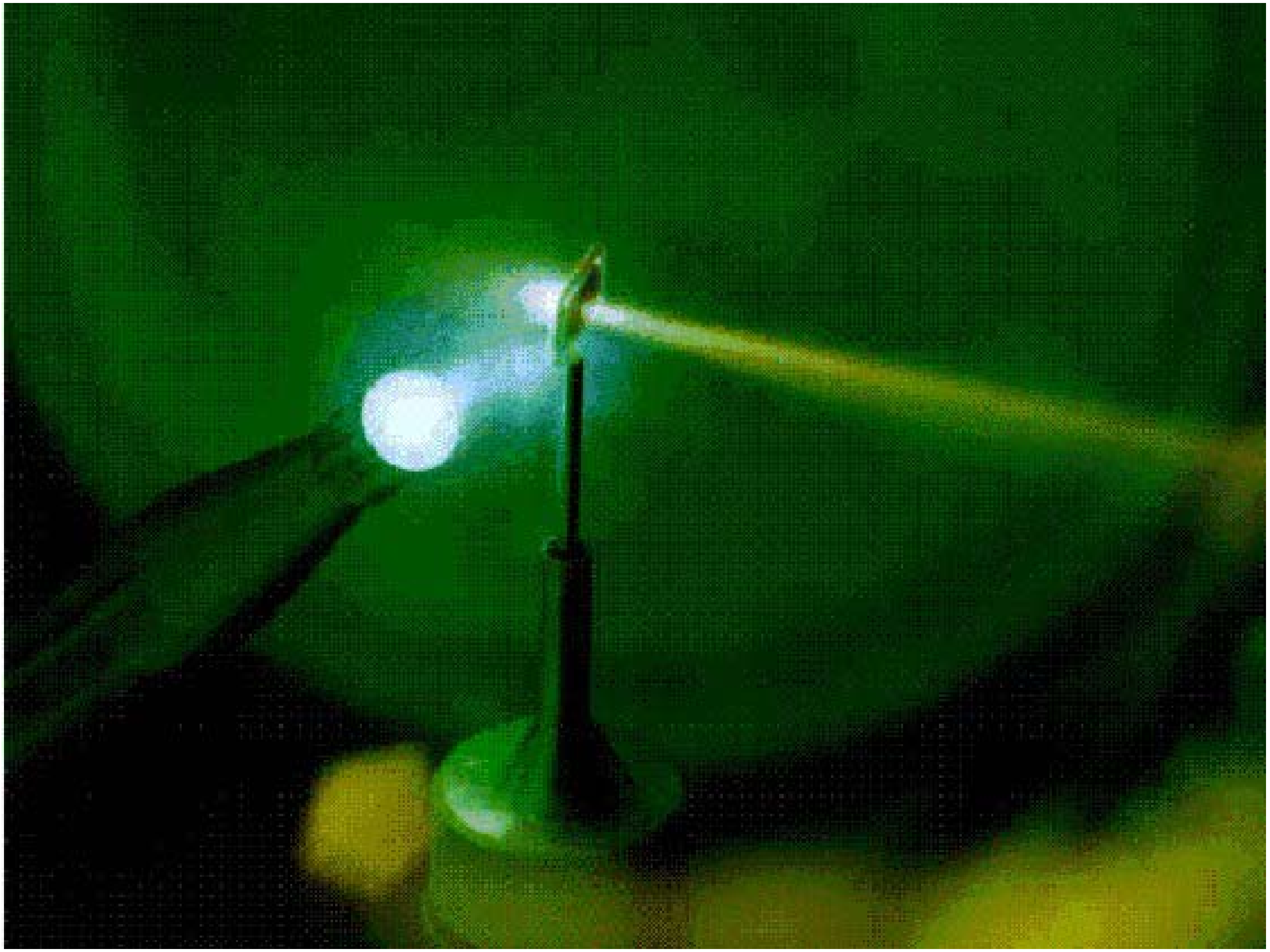
Laser-Cooling and Laser acceleration of Ion Beams



Markus Roth

Institut für Kernphysik

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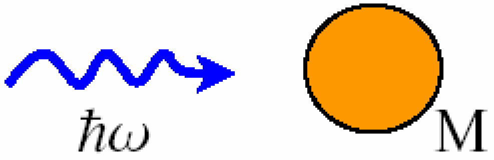
Talk: EPAC 2004

Laser Cooling (courtesy of U. Schramm and D. Habs)



The atom acquires momentum:

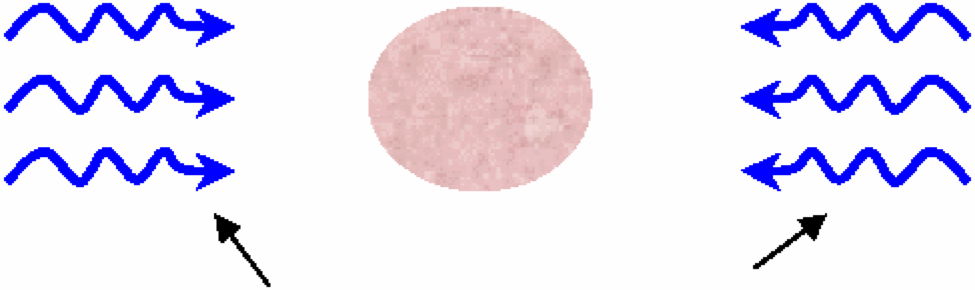
$$M \cdot v = \frac{\hbar\omega}{c}\,.$$

The corresponding energy is (for a sodium atom with mass number A=23):

$$E = \frac{p^2}{2M} = \frac{\hbar^2\omega^2}{2Mc^2} \sim \frac{(2\,eV)^2}{2\cdot 23\cdot 10^9\ eV} \approx 10^{-10}\ eV\,.$$

$$T_{1\gamma} \approx 10^{-10}\ eV \cdot 10^4\,\frac{K}{eV} \approx 1\,\mu K \qquad \text{(for Na).}$$

Atomic Gas

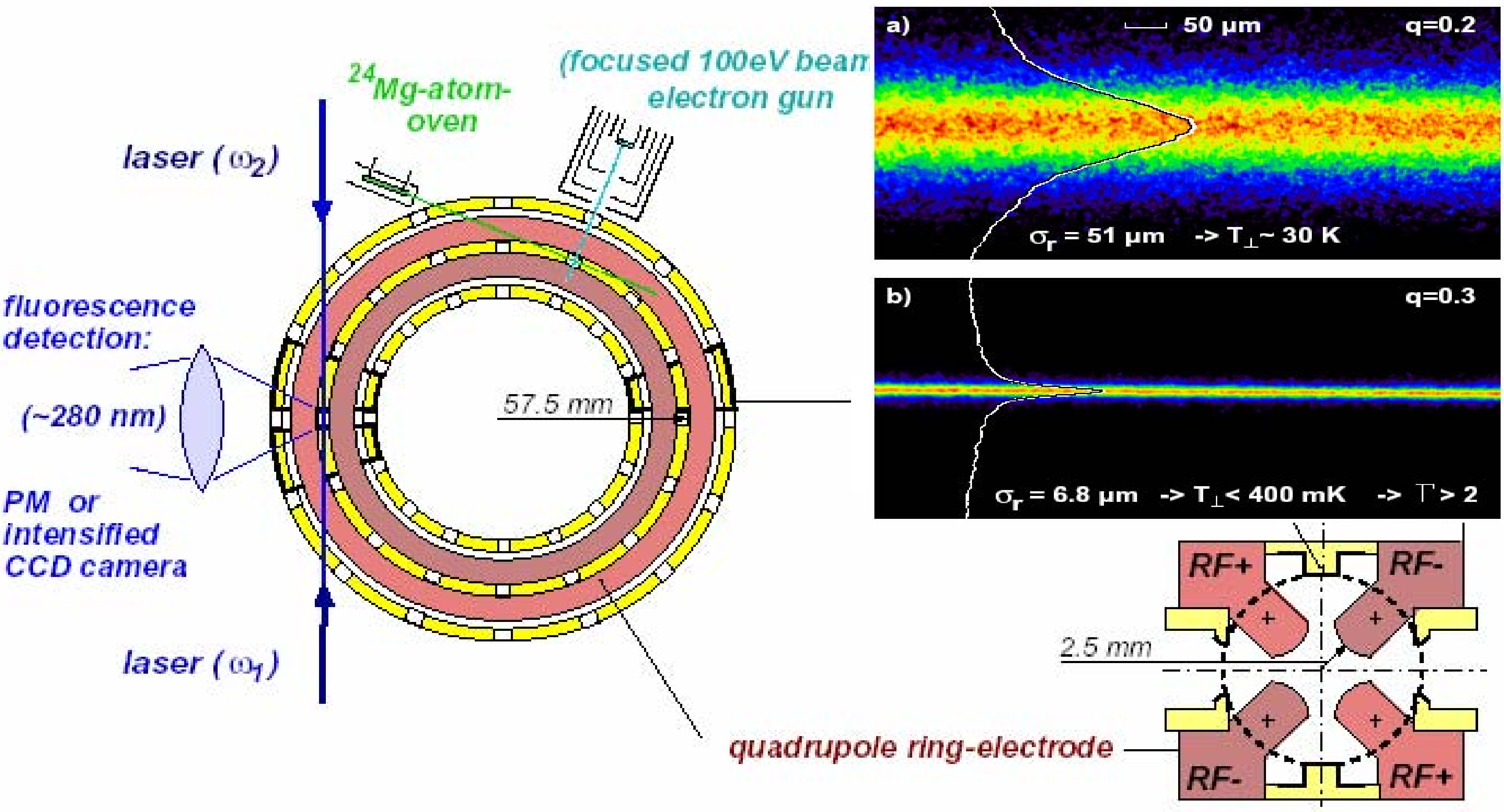


Red-detuned laser beams

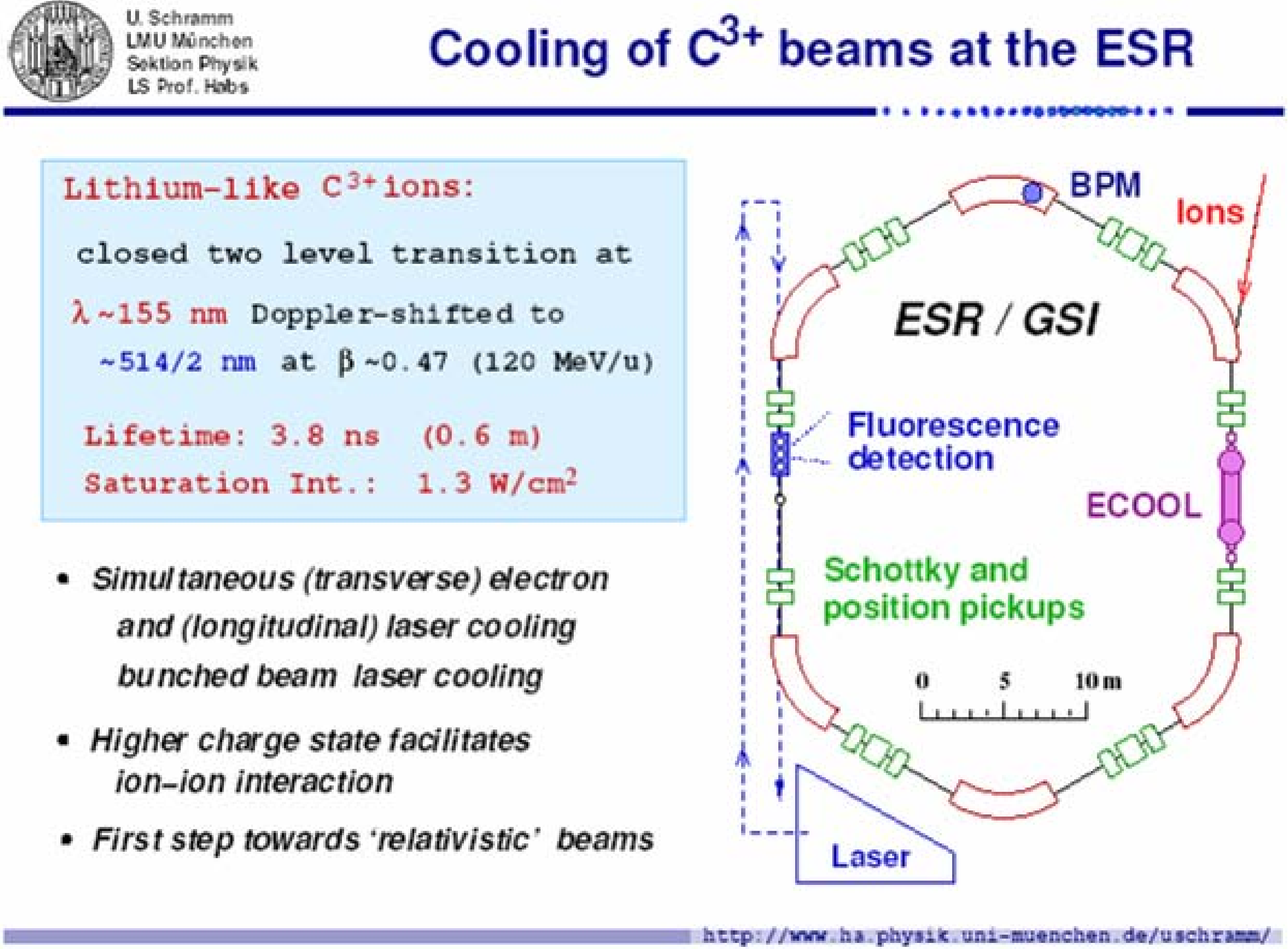
RFQ storage ring PALLAS*
(experimental setup)

T. Schätz
U. Schramm

PALLAS



* PAuL Laser cooling Acceleration System



U. Schramm
LMU München
Sektion Physik
LS Prof. Habs

Cooling of C^{3+} beams at the ESR

Lithium-like C^{3+} ions:

closed two level transition at

$\lambda \sim 155$ nm Doppler-shifted to

$\sim 514/2$ nm at $\beta \sim 0.47$ (120 MeV/u)

Lifetime: 3.8 ns (0.6 m)

Saturation Int.: 1.3 W/cm^2

- *Simultaneous (transverse) electron and (longitudinal) laser cooling bunched beam laser cooling*
- *Higher charge state facilitates ion–ion interaction*
- *First step towards 'relativistic' beams*

http://www.ha.physik.uni-muenchen.de/uschramm/

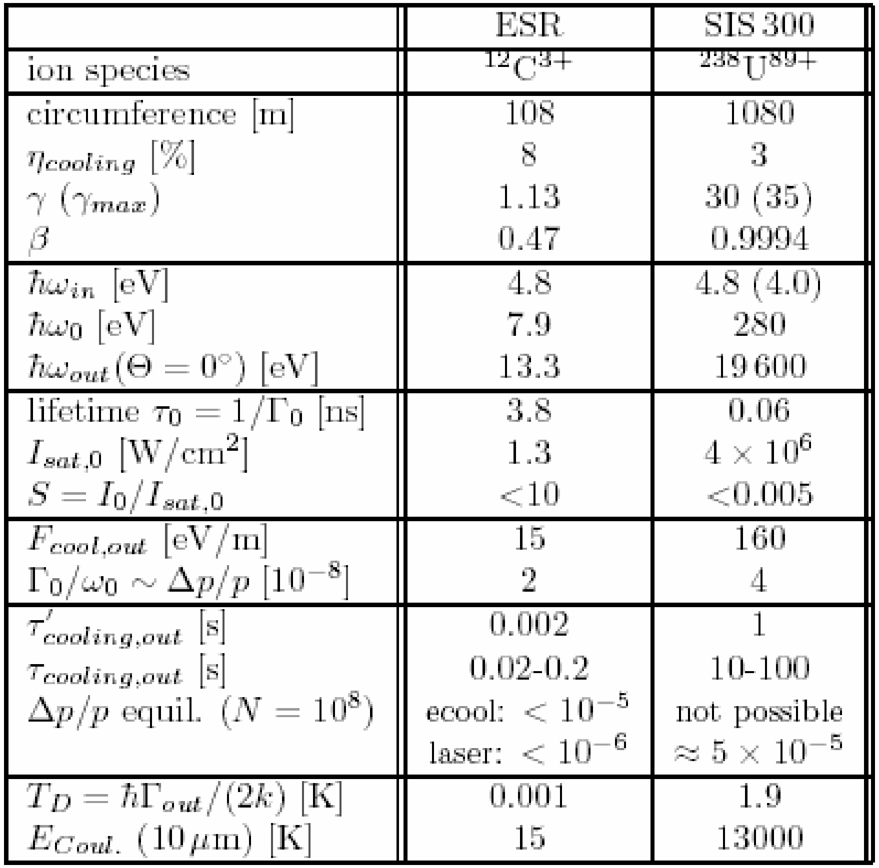
Talk: EPAC 2004

Laser Cooling of relativistic Ion Beams

(courtesy of U. Schramm and D. Habs)

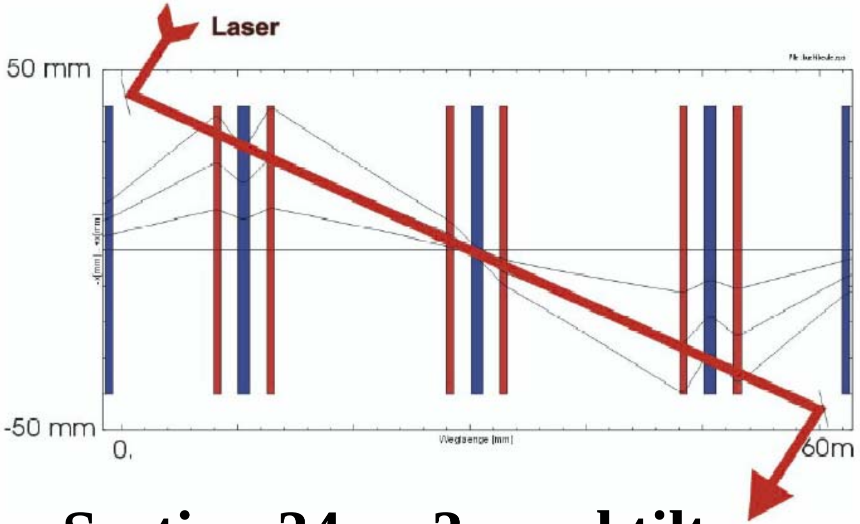
Electron beam cooling can not be applied to rel. Beams anymore

For counterpropagating beams with γ>>1 cooling force is increased by γ^3. (Momentum of reemitted photon $4\gamma^2$; lifetime shortened by γ)



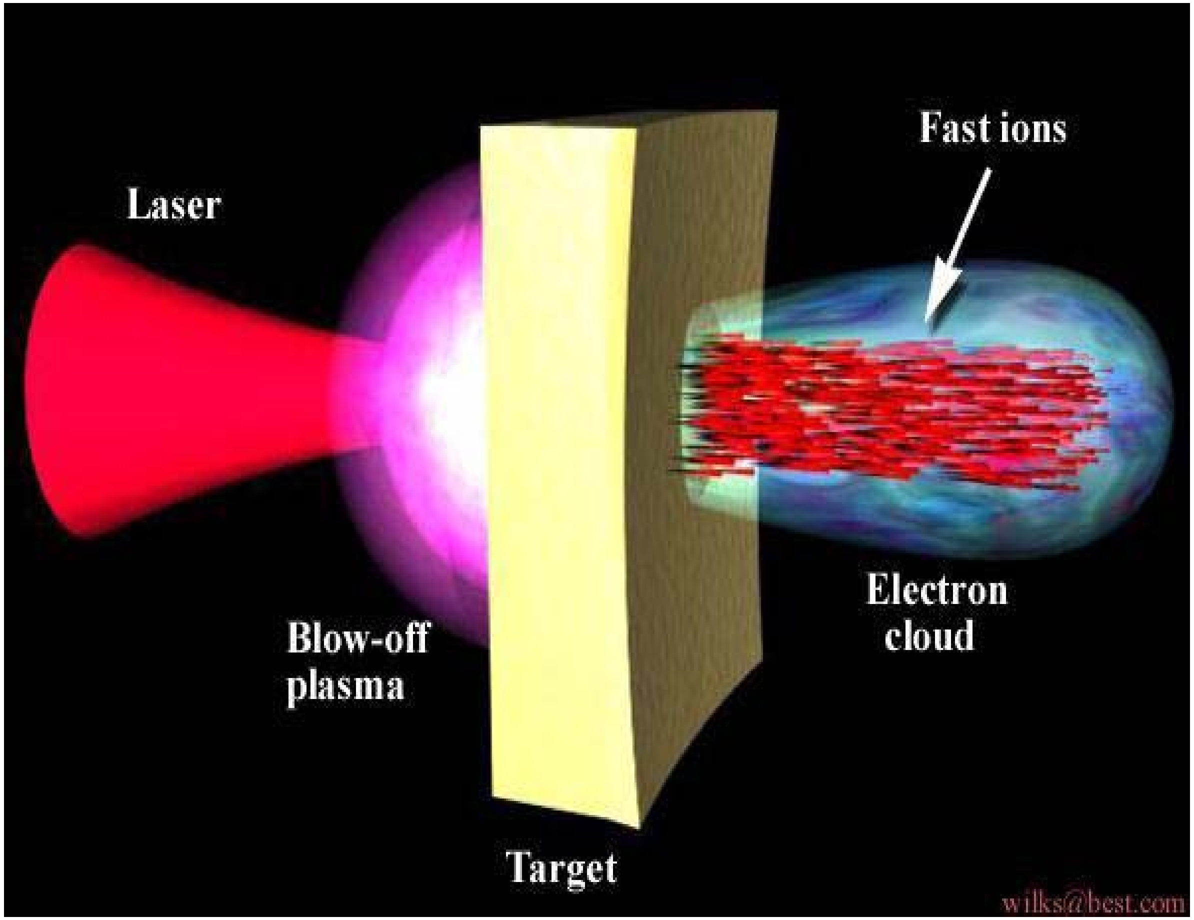
	ESR	SIS 300
ion species	$^{12}\mathrm{C}^{3+}$	$^{238}\mathrm{U}^{89+}$
circumference [m] $\eta_{cooling}$ [%] γ (γ_{max}) β	108 8 1.13 0.47	1080 3 30 (35) 0.9994
$\hbar\omega_{in}$ [eV] $\hbar\omega_0$ [eV] $\hbar\omega_{out}(\Theta = 0^\circ)$ [eV]	4.8 7.9 13.3	4.8 (4.0) 280 19 600
lifetime $\tau_0 = 1/\Gamma_0$ [ns] $I_{sat,0}$ [W/cm^2] $S = I_0/I_{sat,0}$	3.8 1.3 $<$10	0.06 4×10^6 $<$0.005
$F_{cool,out}$ [eV/m] $\Gamma_0/\omega_0 \sim \Delta p/p$ [10^{-8}]	15 2	160 4
$\tau'_{cooling,out}$ [s] $\tau_{cooling,out}$ [s] $\Delta p/p$ equil. ($N = 10^8$)	0.002 0.02-0.2 ecool: $< 10^{-5}$ laser: $< 10^{-6}$	1 10-100 not possible $\approx 5 \times 10^{-5}$
$T_D = \hbar\Gamma_{out}/(2k)$ [K] $E_{Coul.}$ (10 μm) [K]	0.001 15	1.9 13000

Use of pulsed lasers may increase the intensity and bandwidth



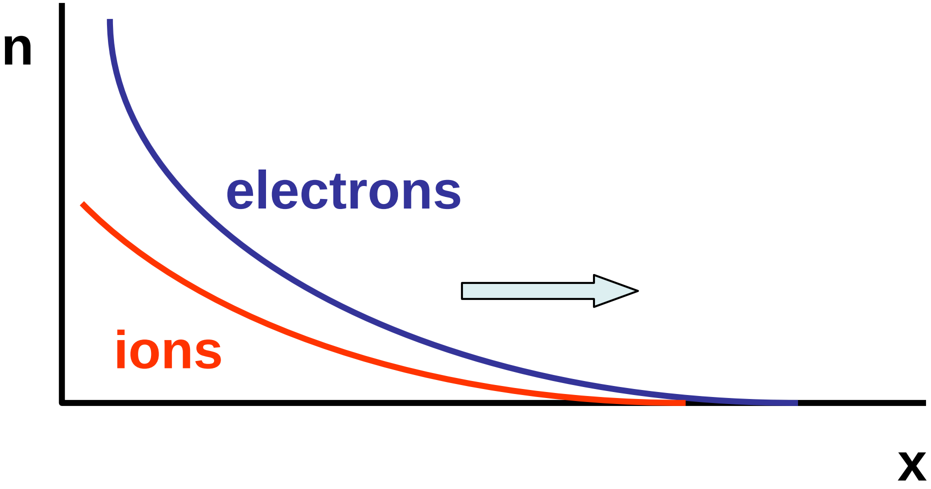
Section 34m; 3mrad tilt

Accelerating ions by ultra-intense laser pulses



- the mechanisms -

Plasma Expansion into a Vacuum

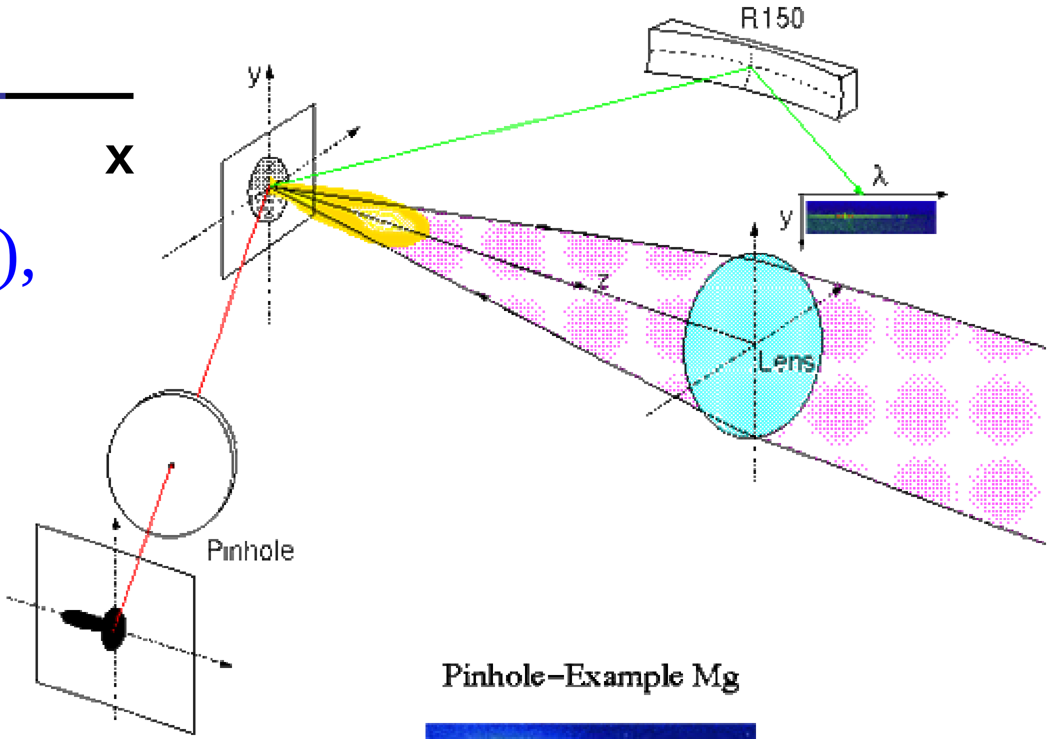


$$n_e = Zn_i = Zn_0 \exp(-(\xi + 1)),$$

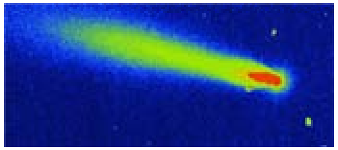
$$v = c_s(\xi + 1),$$

$$e\phi = -T_e(\xi + 1),$$

$$\xi = x / c_s t$$



Pinhole–Example Mg



Laser development

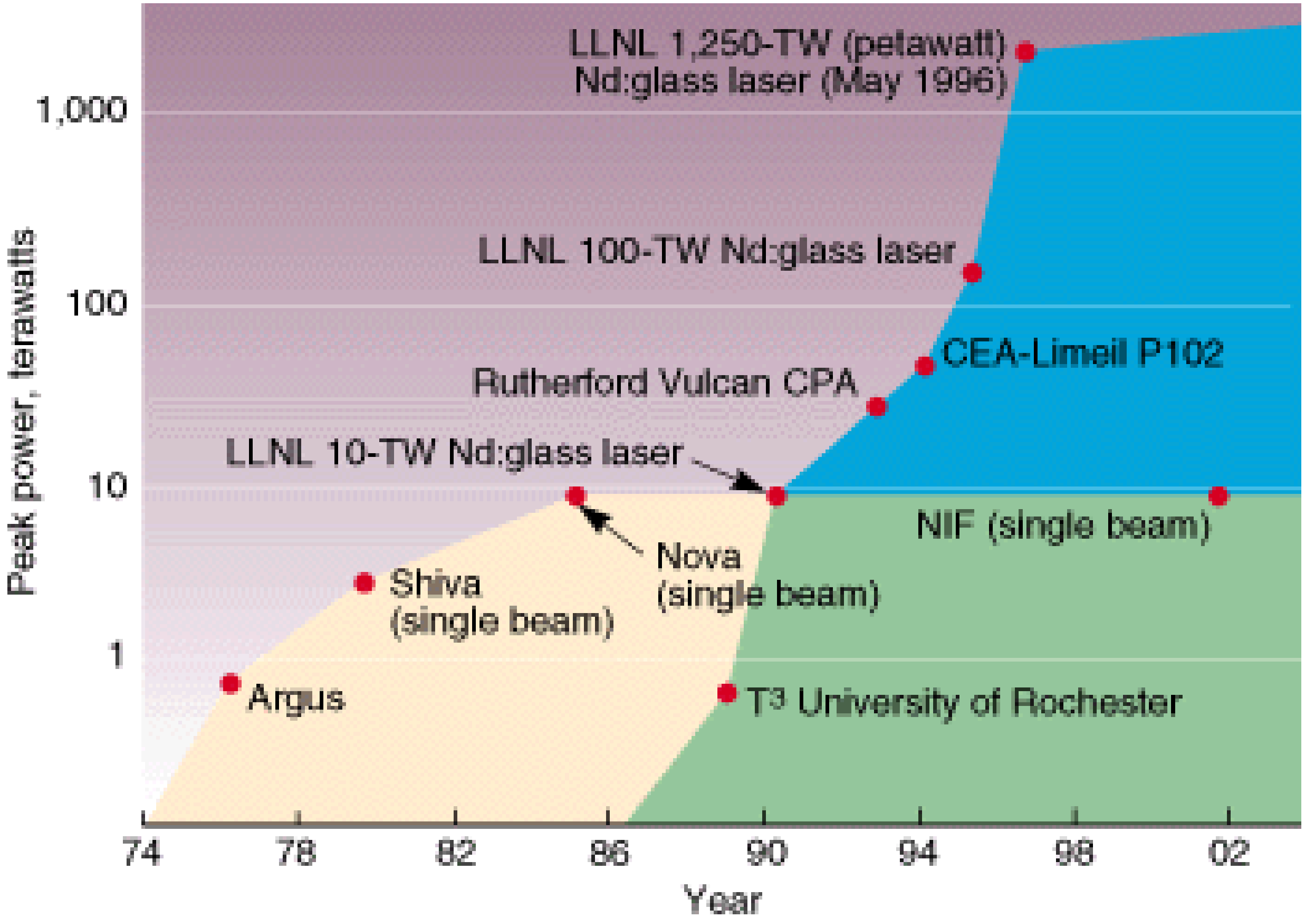


Figure 2. Milestones in laser development: early lasers (yellow), long-pulse technology (green), and chirped-pulse amplification technology (blue).

NOVA Laser

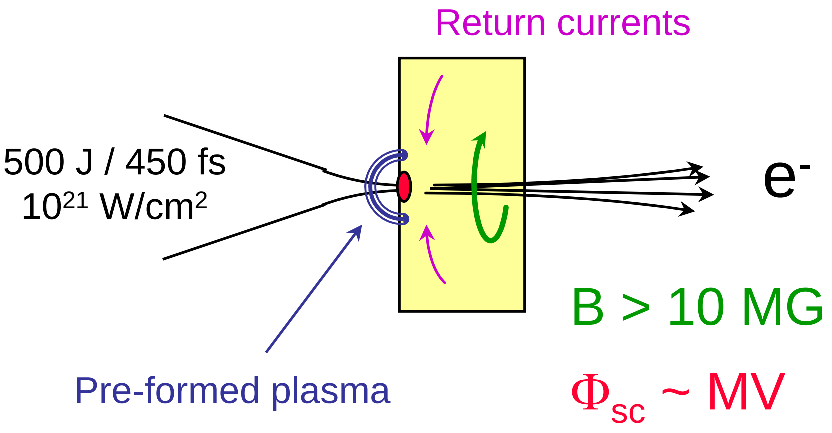
Table Top Terawatt (T^3)

The Petawatt opens a new regime of ultra-relativistic laser-matter interactions

Enormous EM fields

at $I = 10^{21}$ W/cm^2 :

- $E \sim I^{1/2}\,\lambda = 10^{14}$ V/m
- $B = E/c = 3\text{x}10^{5}$ Tesla
- $P_{rad} = I/c = 3\text{x}10^{10}$ J/cm^3
  $= 300$ GBar



Laser-plasma effects

- filamentation
- self-focusing
- plasma acceleration

» dependence on pre-pulse

Relativistic Electron Motion

- Cycle-averaged oscillation energy:

$$E_{avg} = mc^2[1 + a_o^2/2]^{1/2}$$

- $a_o = eA/mc^2 = [I/(1.37\text{x}10^{18})]^{1/2}\lambda(\mu m)$
- at 10^{21} W/cm^2, $a_o \sim 27$, $\mathbf{E_{avg} > 10}$ **MeV**

Electron & bremsstrahlung energies can greatly exceed nuclear excitation & pair-creation thresholds

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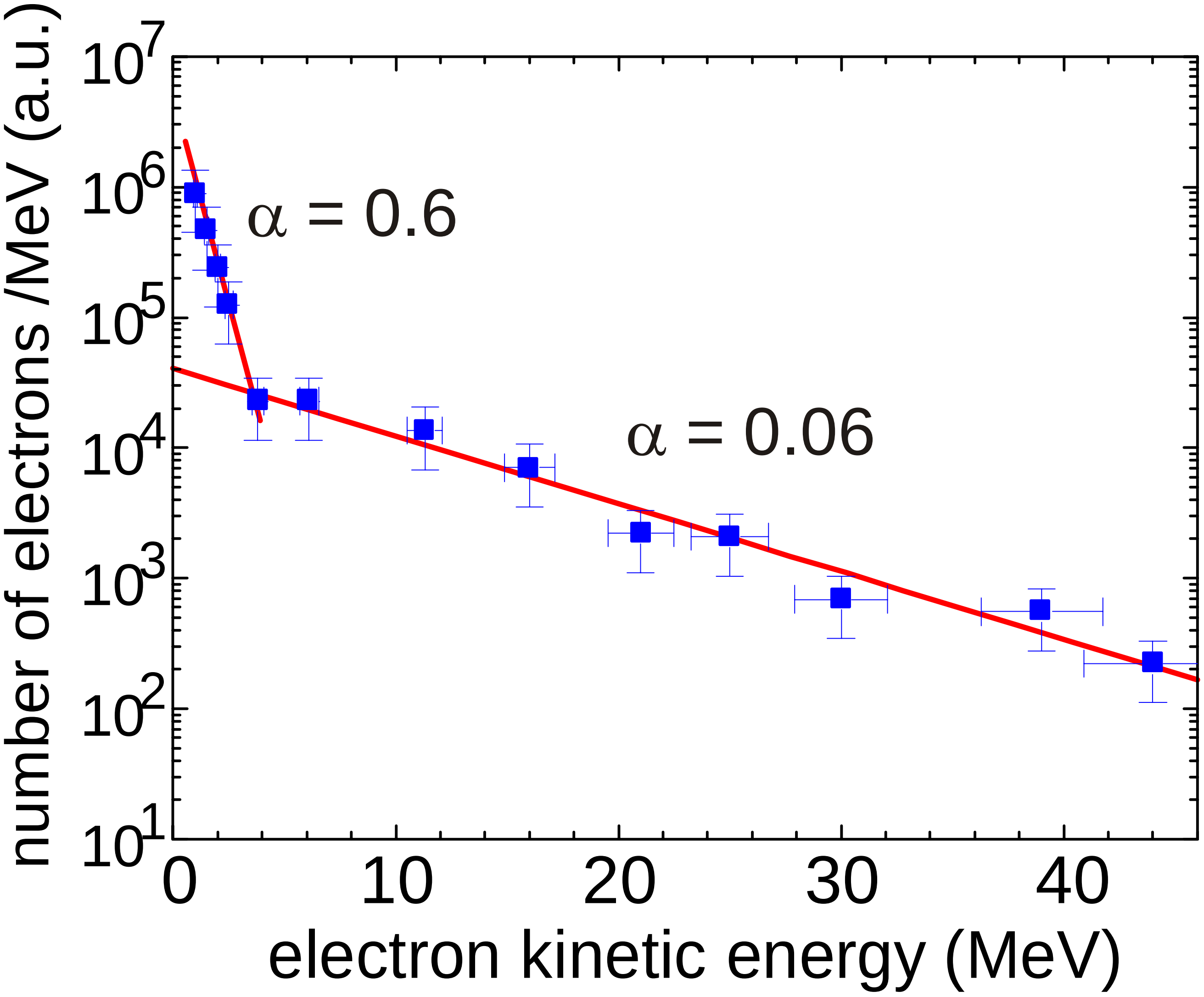
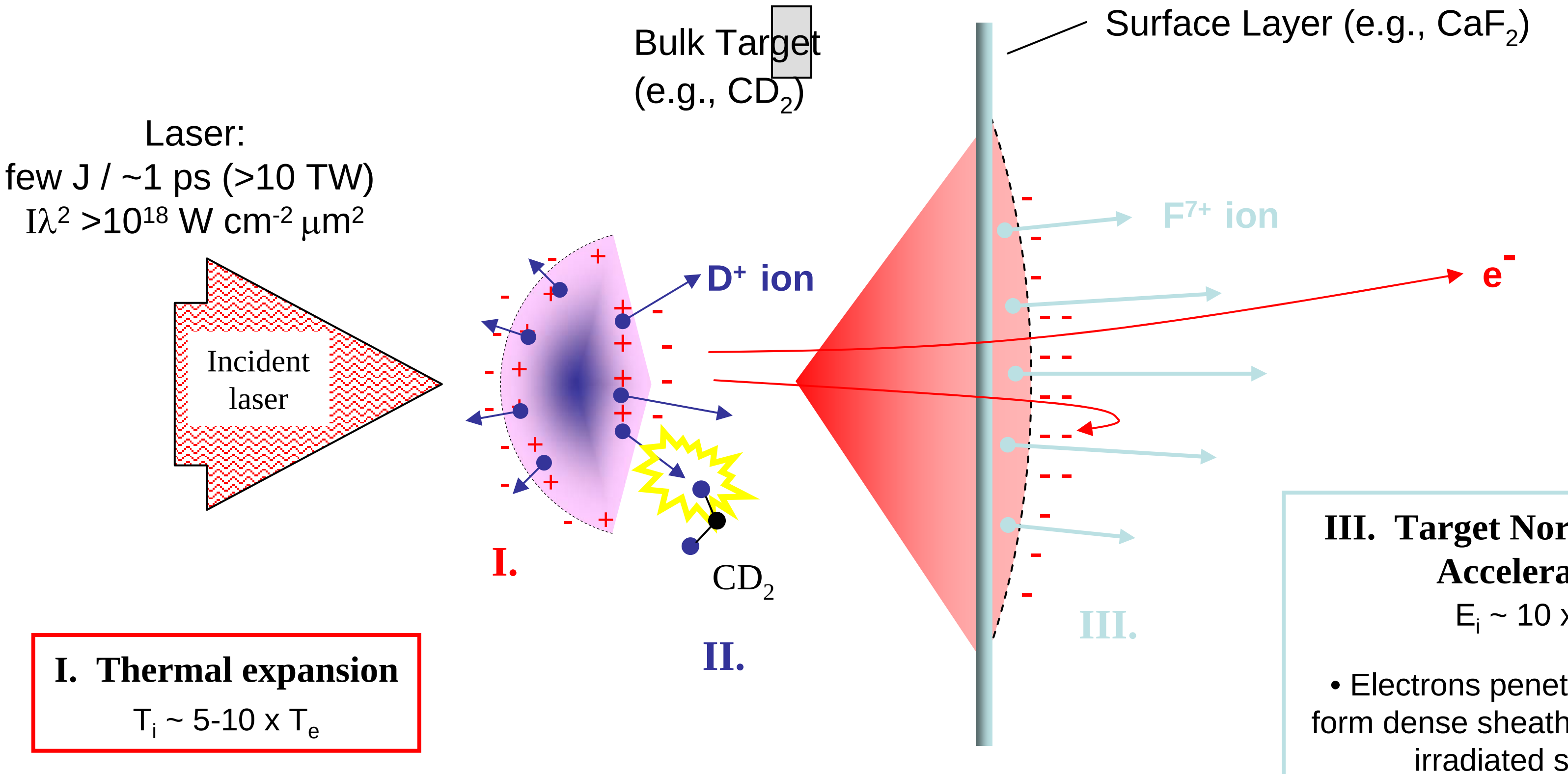
Two-temperature Distribution



Protons and ions are accelerated in relativistic laser-solid interactions by three principal mechanisms



I. Thermal expansion

$T_i \sim 5\text{-}10 \times T_e$

II. Front-surface charge separation

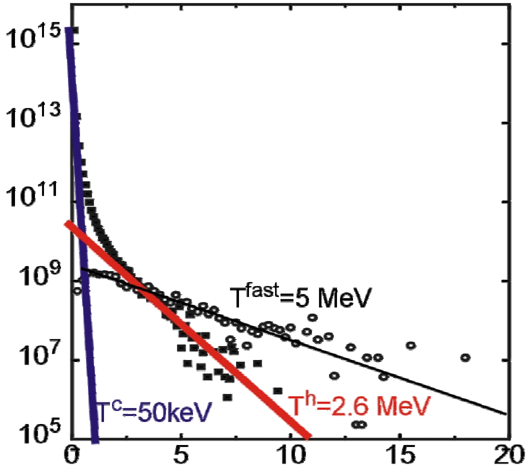
Static limit: $T_i \sim T_e$

III. Target Normal Sheath Acceleration

$E_i \sim 10 \times T_e$

- Electrons penetrate target & form dense sheath on rear, non-irradiated surface
- Strong electrostatic sheath field ionizes surface layer ($E_o \sim kT / e\lambda_d \sim$ MV/μm)
- Rapid (~ps) acceleration in expanding sheath produces very laminar ion beam

Scheme of the TNSA mechanism

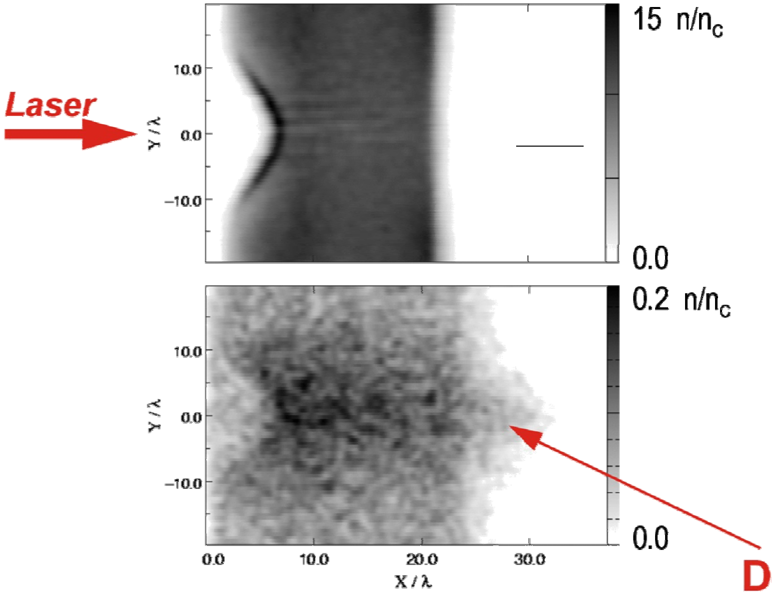


Electron spectrum

Two temperatures

T_{cold} = 50 keV

T_{hot} = 2.6 MeV



Cold electron component

Hot electron component

Debye sheath

3d PIC simulations, A.Pukhov, Theorie, MPQ,

Virtual Laser Plasma Lab

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The energy and density of the hot electrons set the scales of things in the physics

1. Length: Debye length of hots

$$\ell_0 \equiv \sqrt{\frac{T_{hot}}{4\pi e^2 N_{hot}}} = 2.4\mu m \left(\frac{T_{hot}}{1MeV}\right)^{1/2} \left(\frac{N_{hot}}{10^{19}}\right)^{-1/2}$$

a few µm!

2. Time:

$$\tau \equiv \sqrt{\frac{\ell_0^2 m_{ion}}{T_{hot}}} = 0.24\,ps \left(\frac{N_{hot}}{10^{19}}\right)^{-1/2}$$

a few ps!

3. Sheath Electric field:

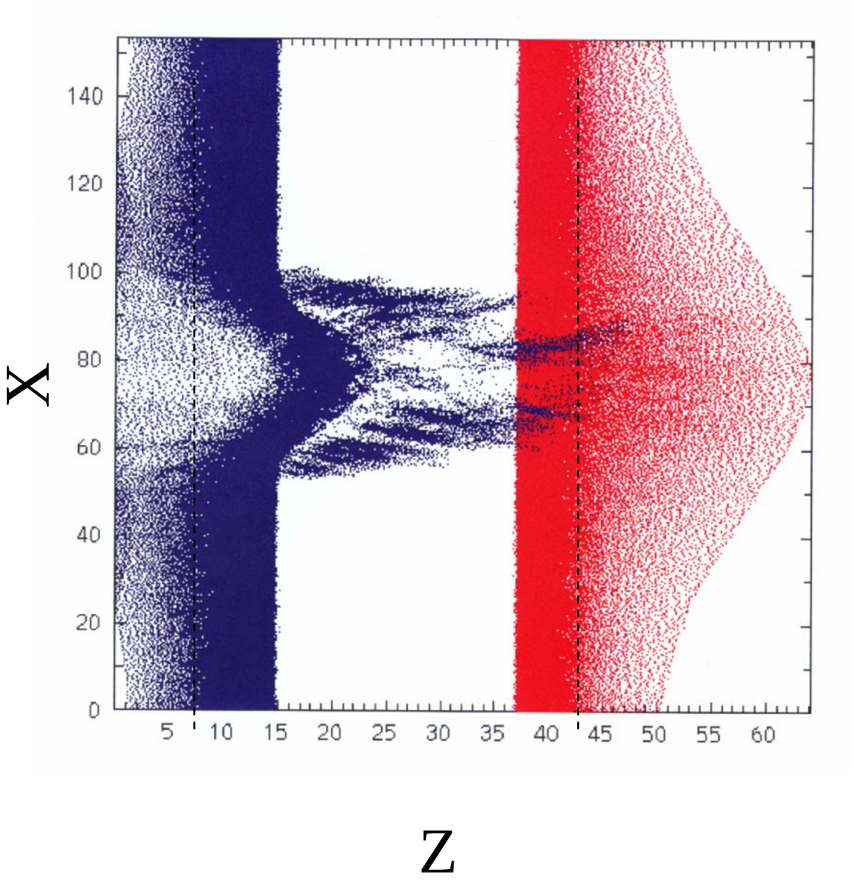
$$E \approx \frac{T_{hot}}{e\ell_0} = \frac{MegaVolts}{microns}$$

several TV/m!

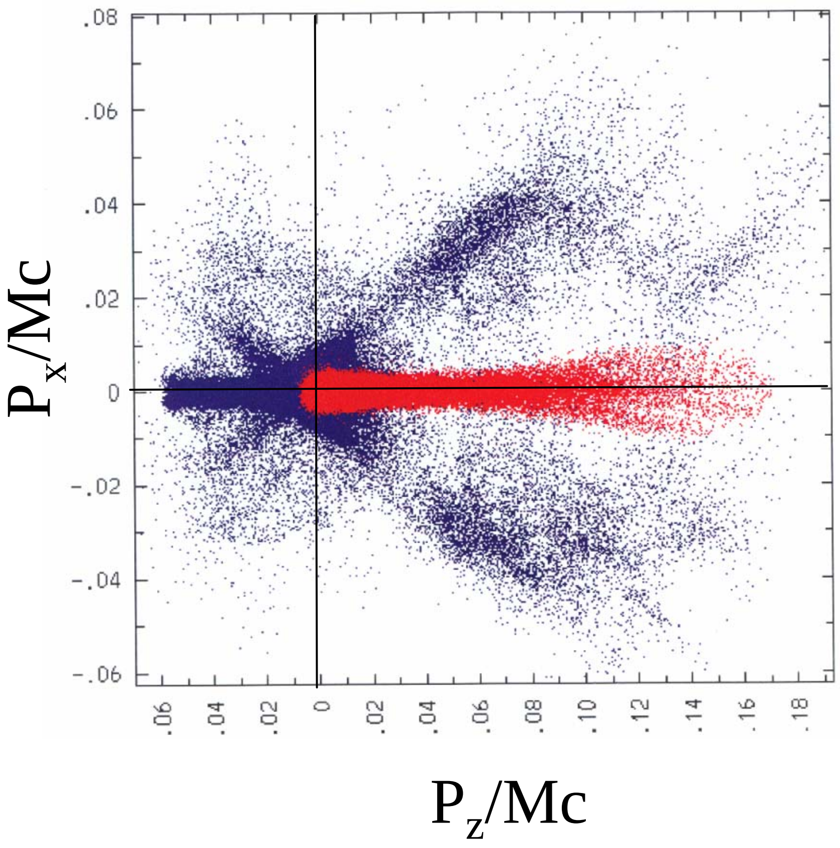
Conditions like at the surface of a neutron star!

Scaled PIC simulations show ion acceleration from the front and back surfaces of a thin target

Coordinate Space

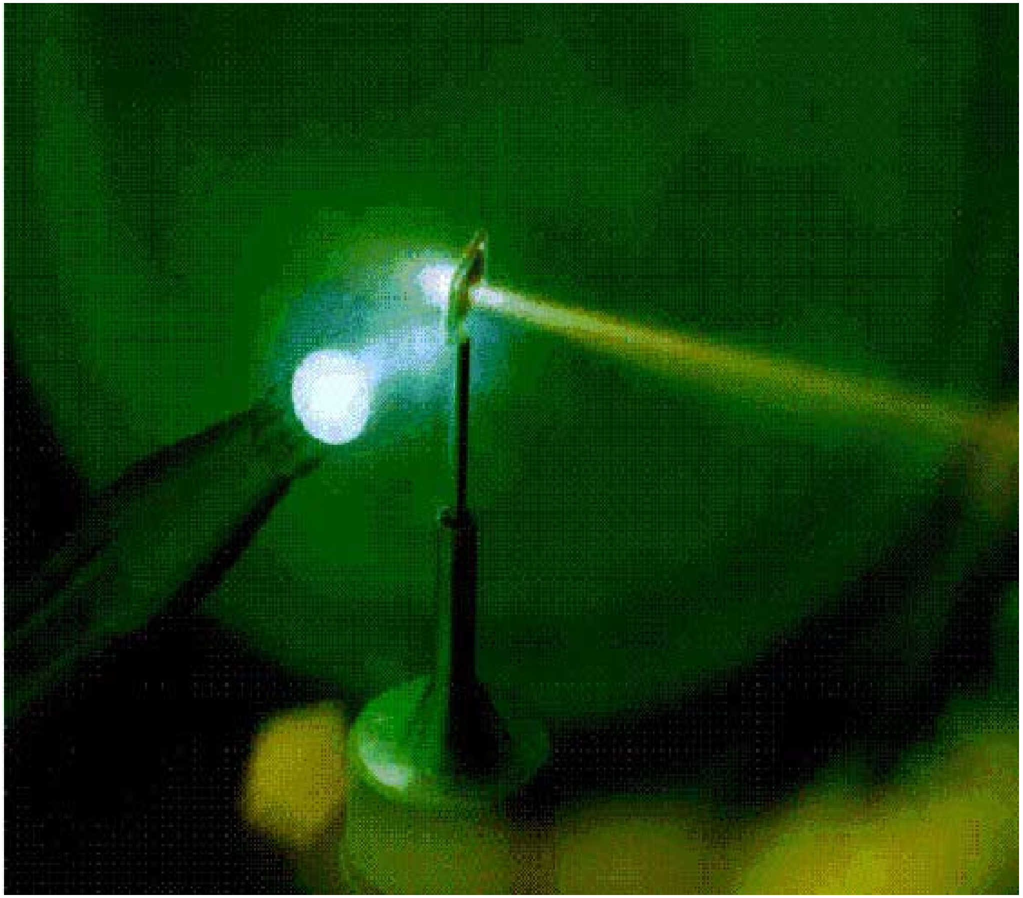


Momentum Space



Longitudinal and radial acceleration of ions from rear target surface are determined by initial distribution of hot electrons. Laminar, low-divergence beams are expected.

Ion Beam Properties



Petawatt experiments 3/99

Number of accelerated protons:
10^{13} (LLNL- Petawatt)

Pulse duration:
several Picoseconds

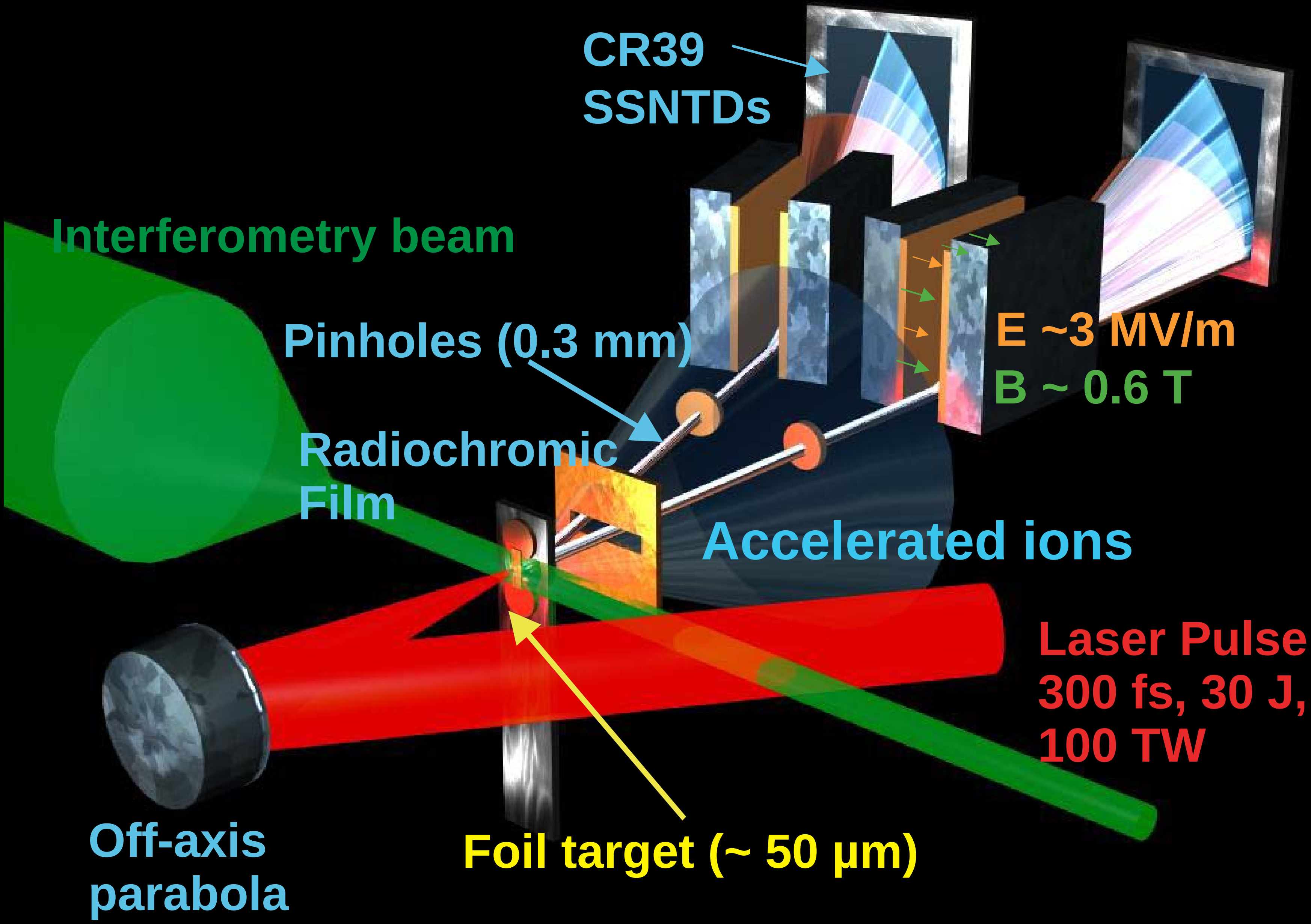
Maximum energy:
60 MeV (LLNL Petawatt)

Divergence:
<10° for high energy part

always normal to the rear surface

fully space charge and current neutralized

origin of protons: surface contaminants


CR39
SSNTDs
Interferometry beam
Pinholes (0.3 mm)
E ~3 MV/m
B ~ 0.6 T
Radiochromic
Film
Accelerated ions
Laser Pulse
300 fs, 30 J,
100 TW
Off-axis
parabola
Foil target (~ 50 µm)

Dependence of beam quality on target material must be understood to control the acceleration process

through 500 μm Ta
(E_p > 20 MeV)

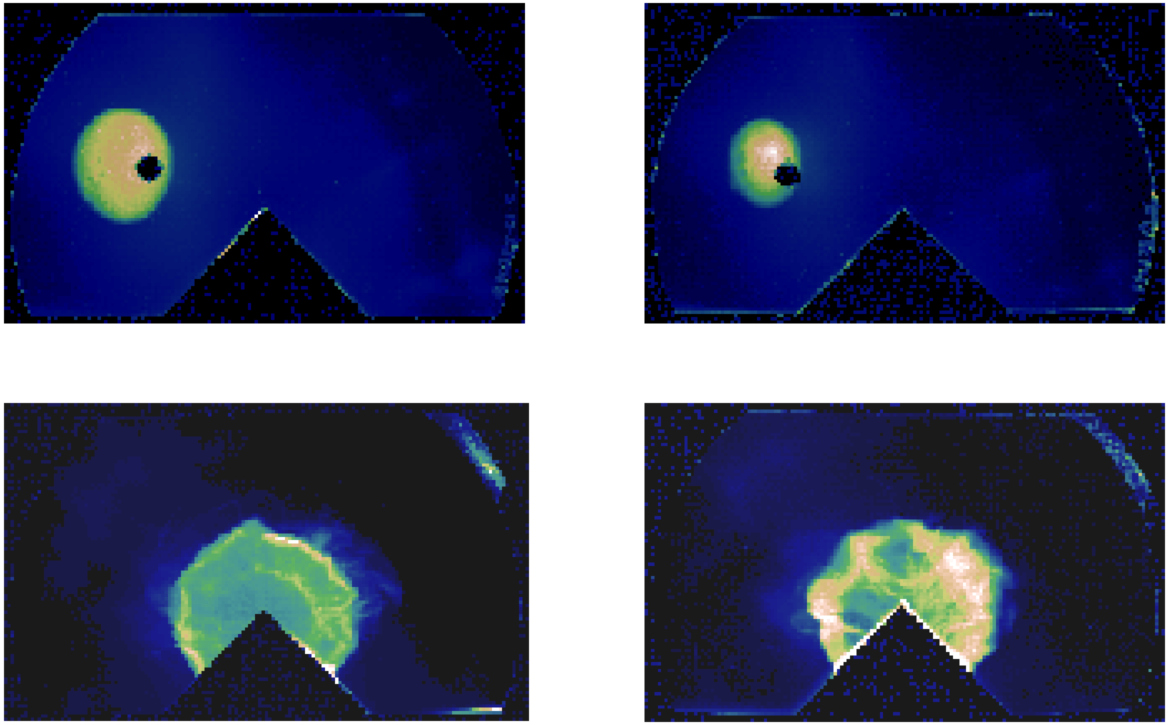
through 800 μm Ta
(E_p > 29 MeV)

125 μm Au foil

(~10^{12} protons, smooth beam)

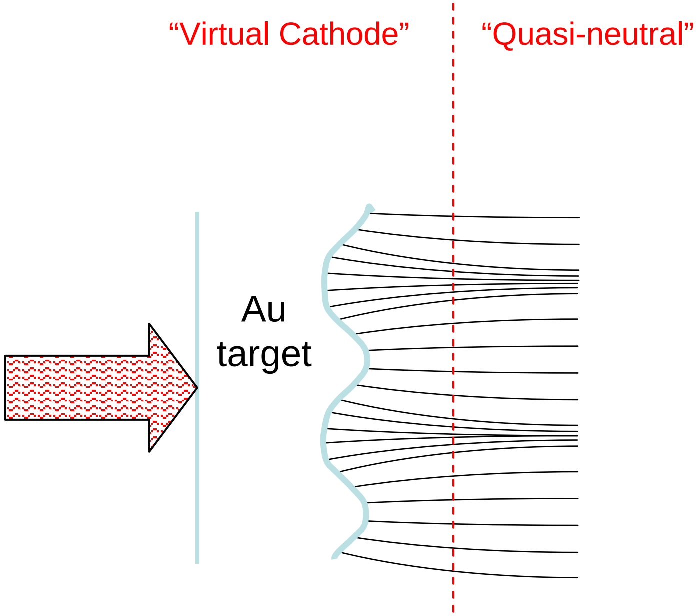
60 μm CH foil

(~10^{13} protons, structured beam)

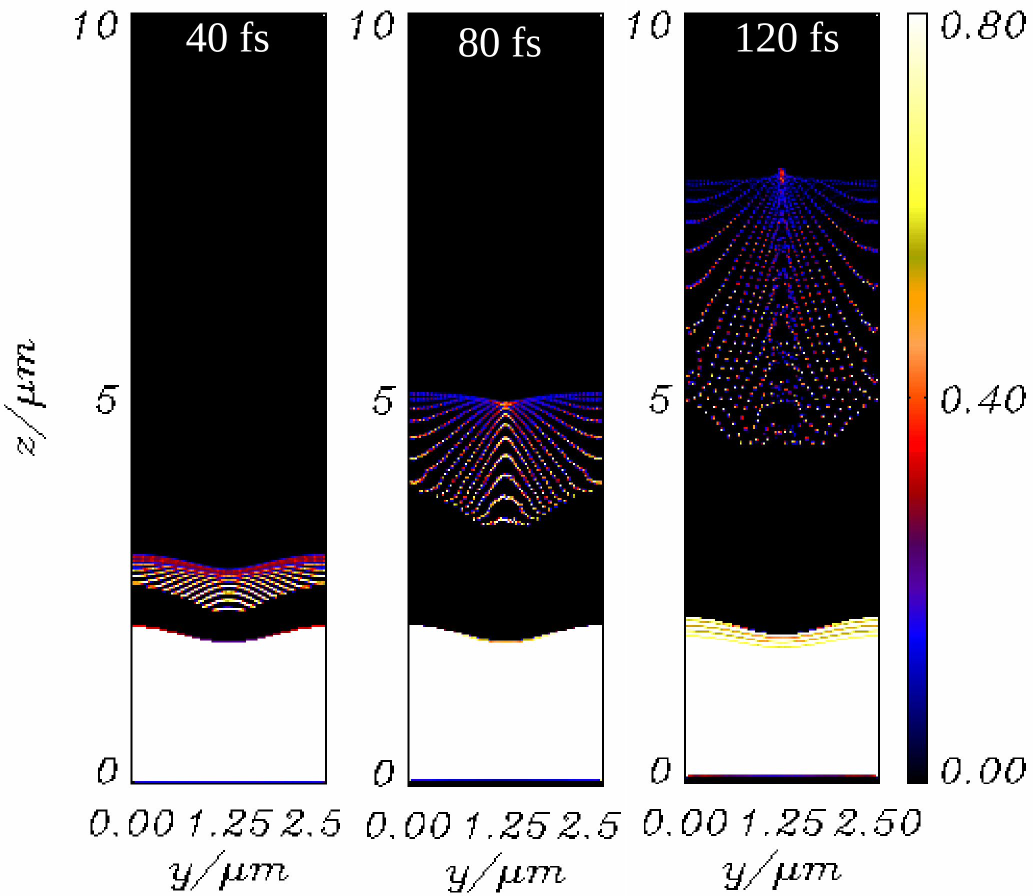


(LLNL-Petawatt data, R.A. Snavely, S.P. Hatchett *et al*.)

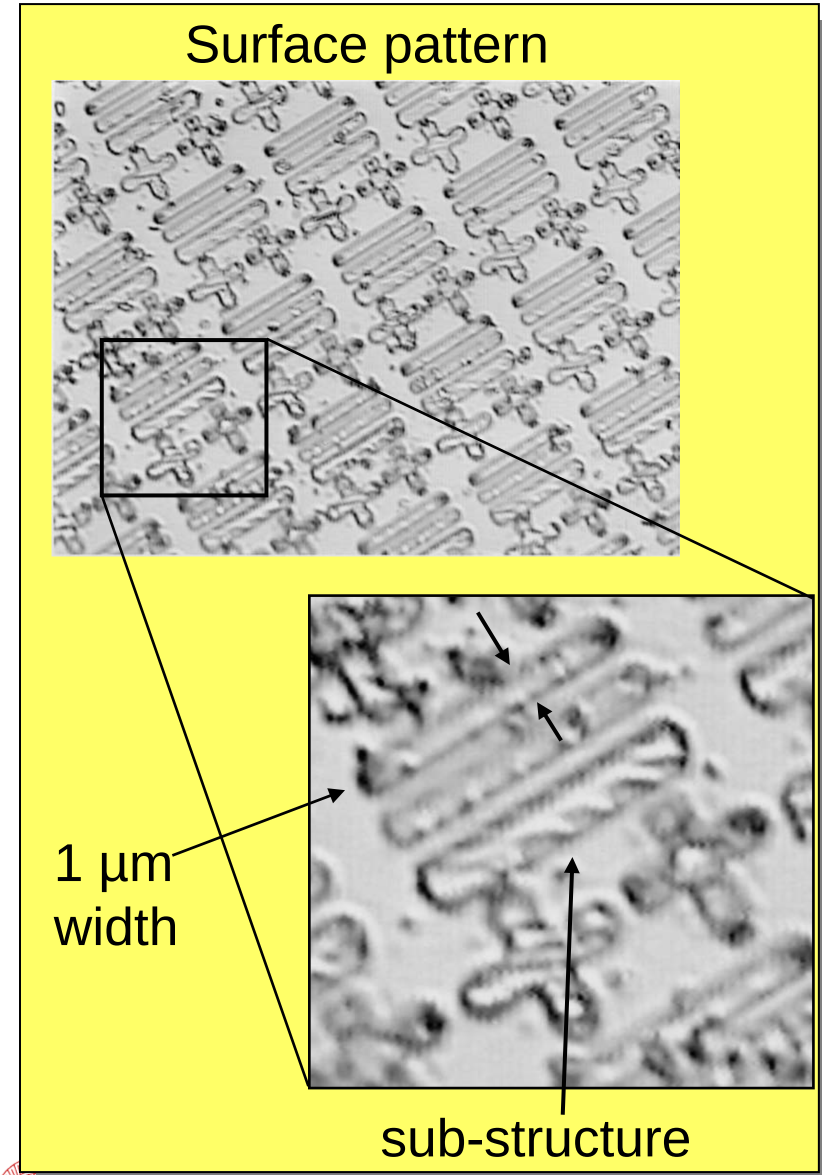
Nano-focusing is understood with help of PIC simulation of hydrogenous contaminant on a structured gold foil

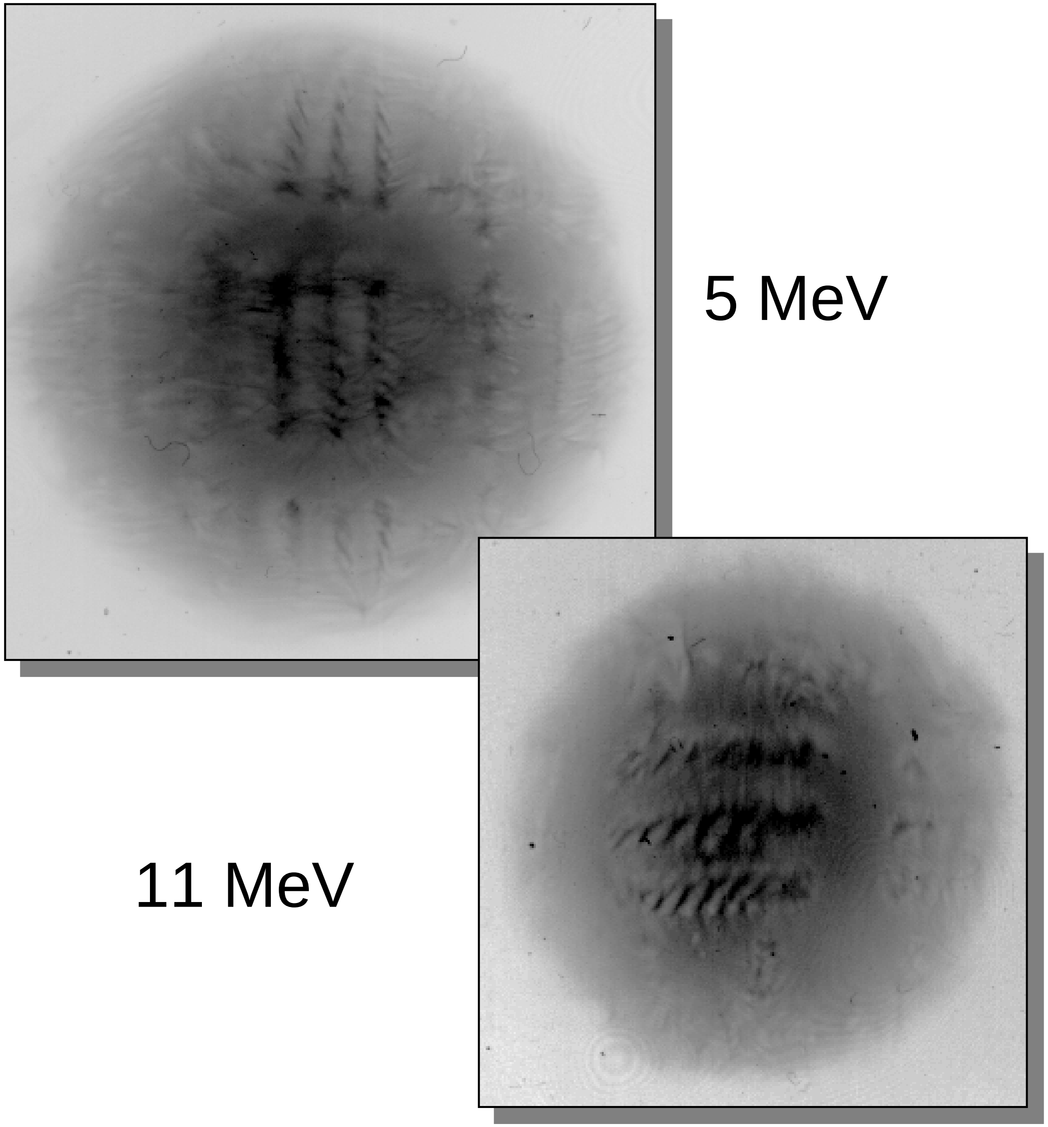


Proton beam-lets focused to ~100 nm (rms)

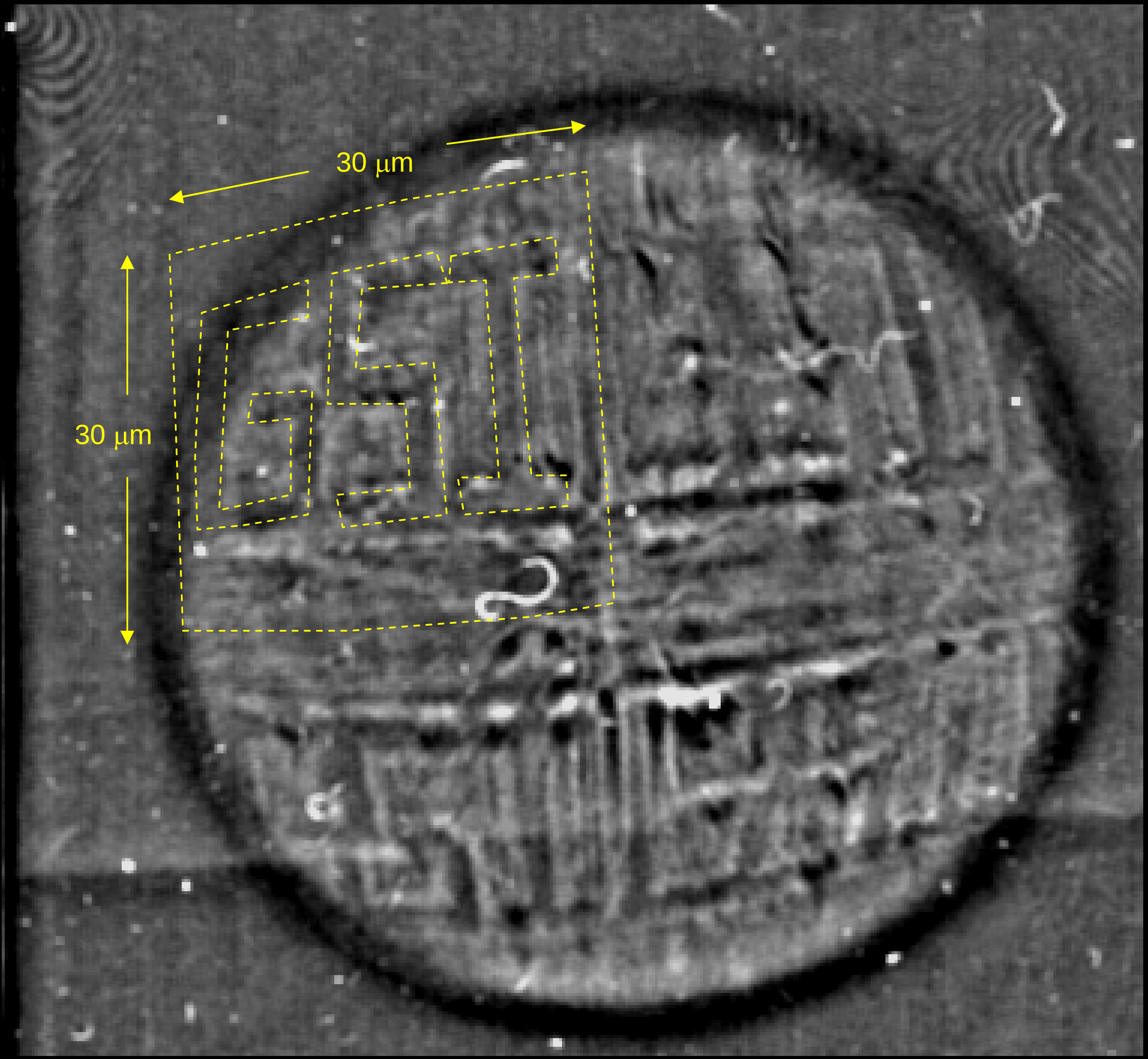


Sub-structures below one micrometer have been observed

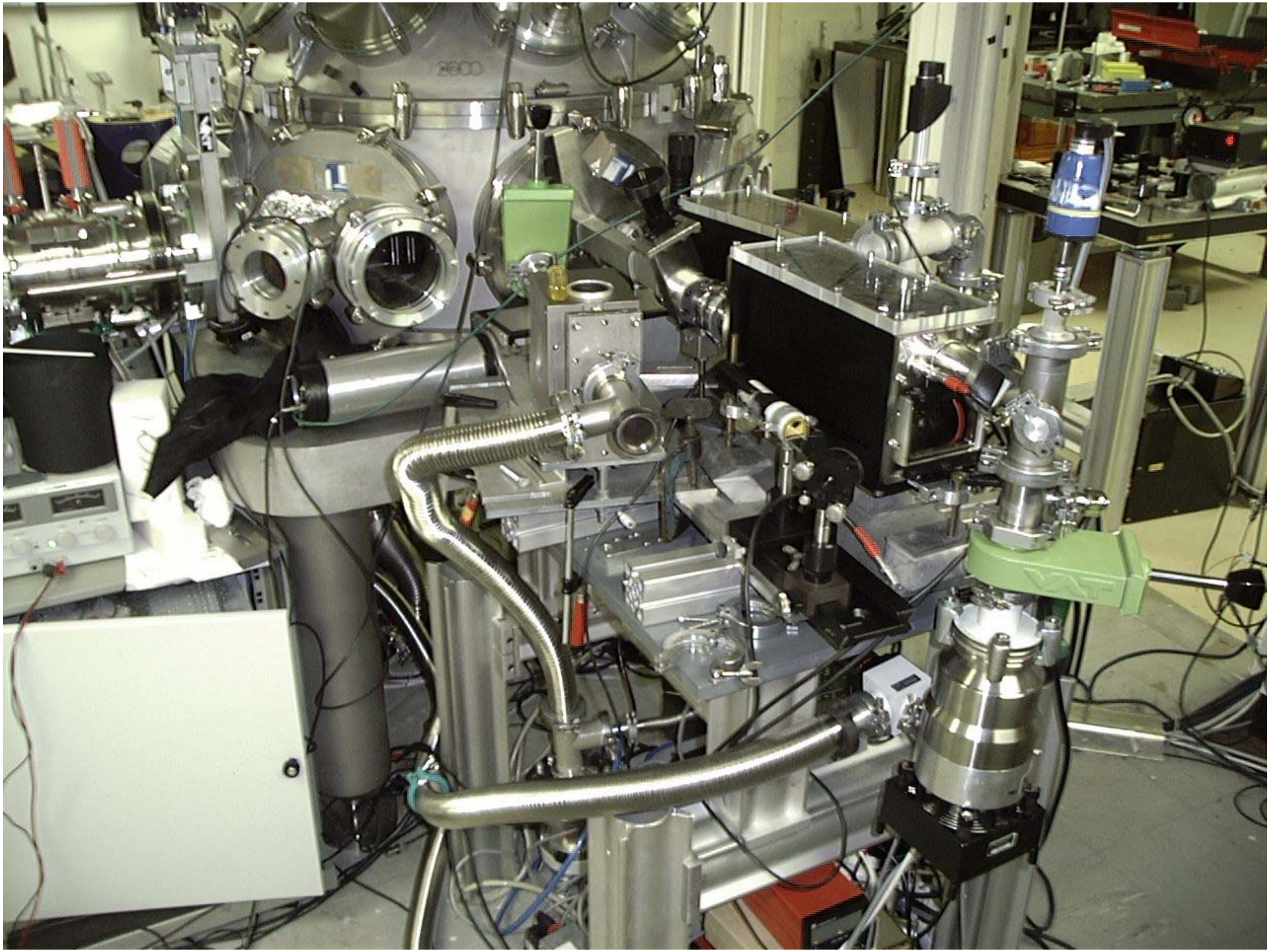




Complex ion “lithography” patterns are produced in a single shot



Heavy Ion Acceleration

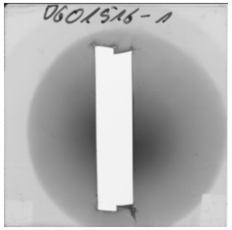


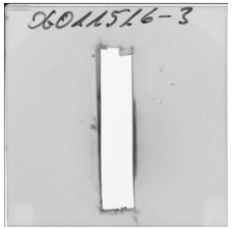
CaF_2 target

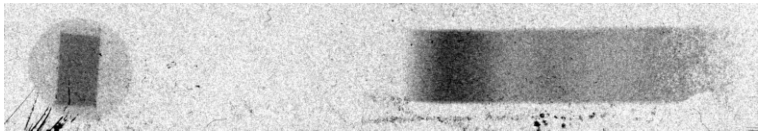
not heated

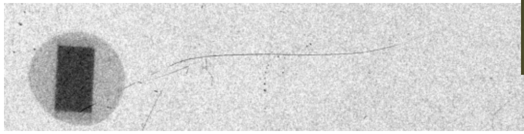
Target: W 50 µm backside coated with 0.3 µm CaF_2

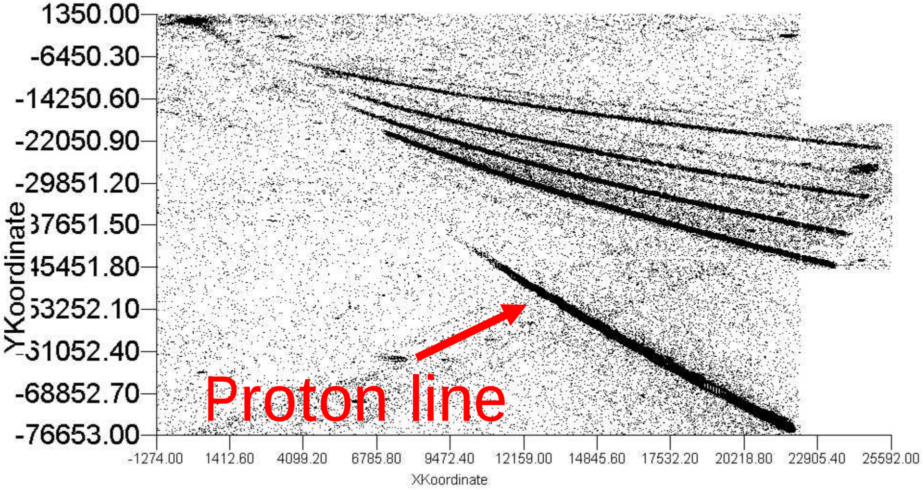
resivetively heated



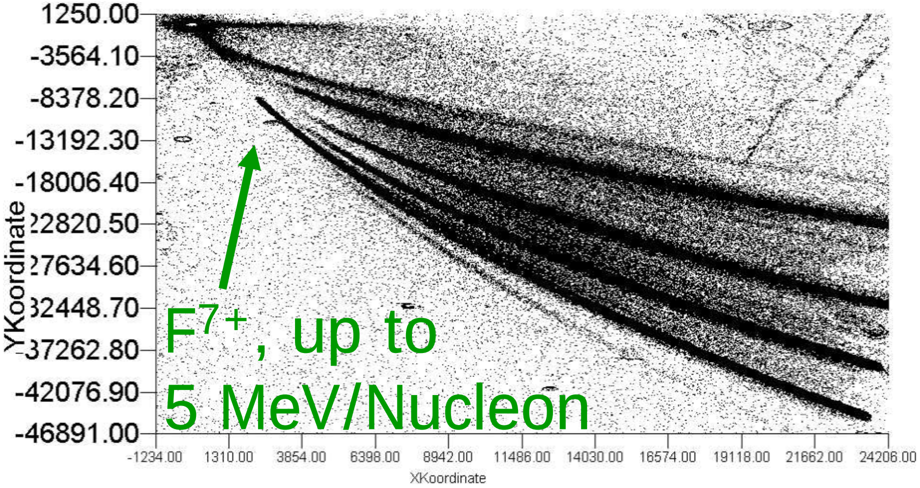






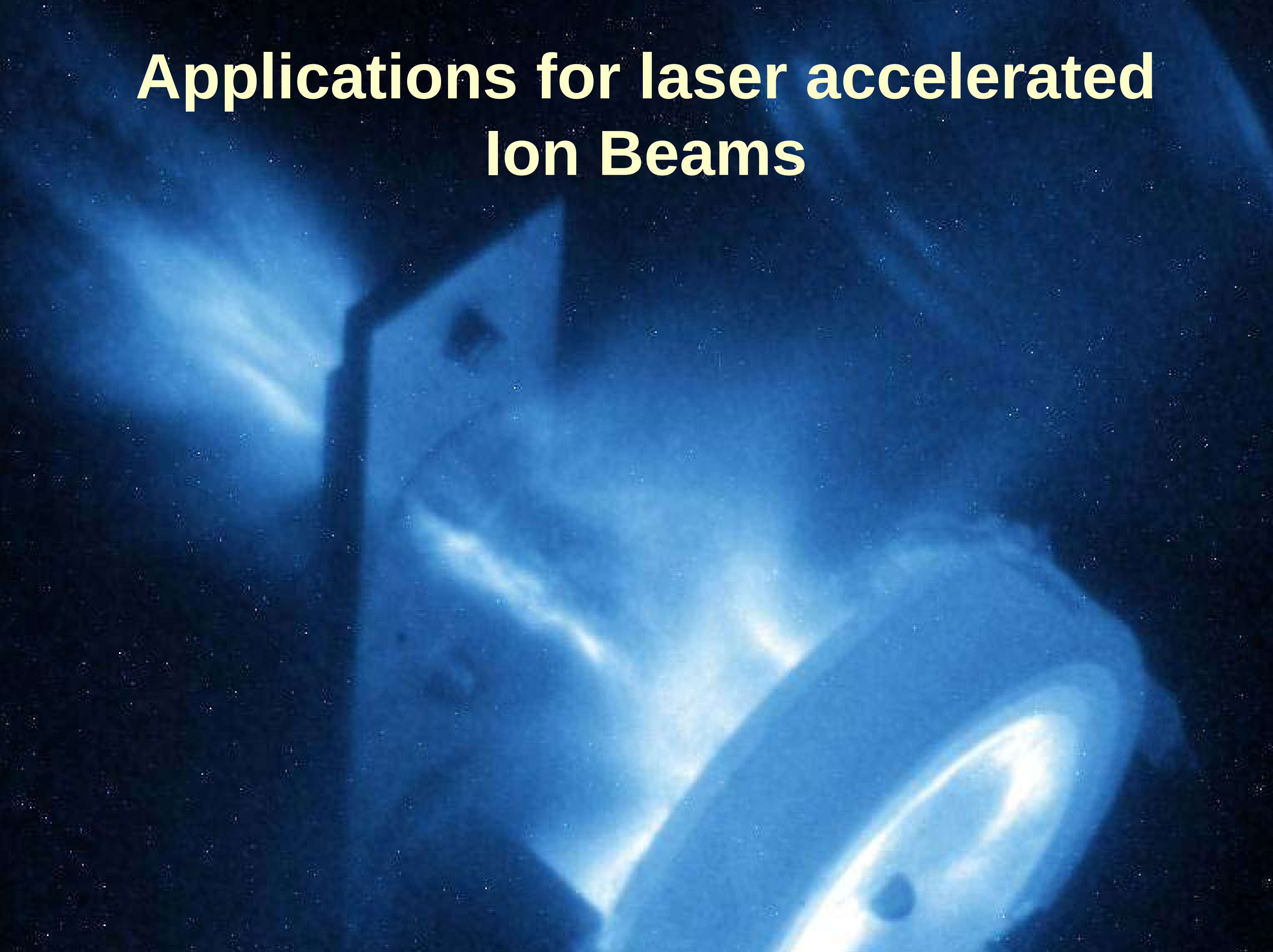


Proton line



F^{7+}, up to 5 MeV/Nucleon

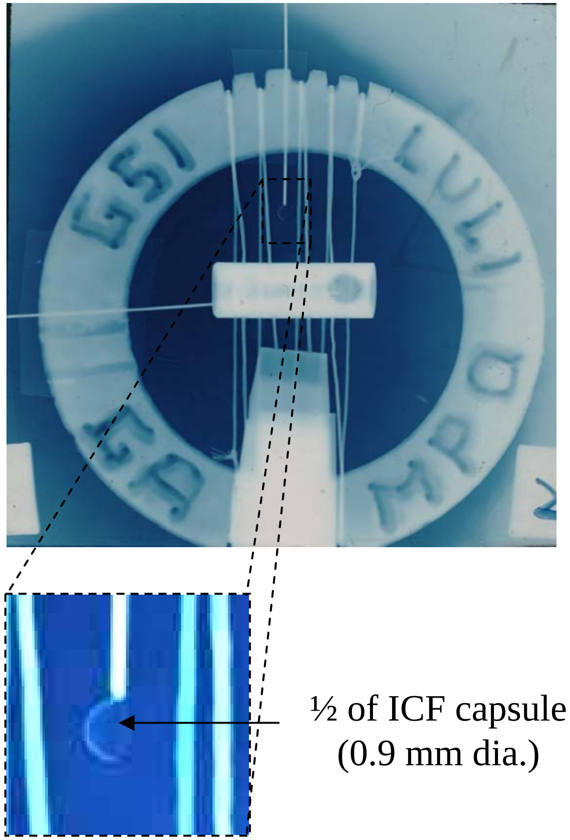
Applications for laser accelerated Ion Beams



The ultra-low emittance of laser-accelearated protons allows radiography of dense objects with excellent spatial resolution

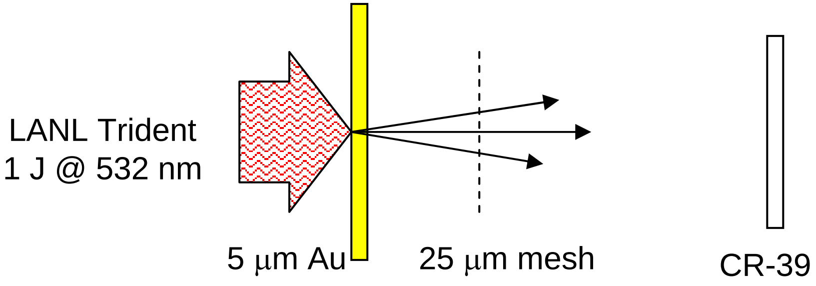
Laser-Accelerated Proton Radiography

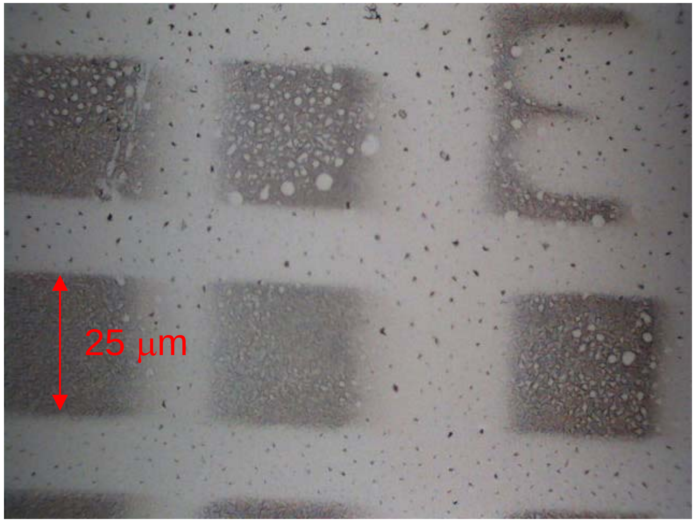
(~8 MeV protons)



½ of ICF capsule
(0.9 mm dia.)

Roth, Cowan, Audebert et al.
(GSI-GA-LULI-MPQ)
Phys. Rev. ST Accel. Beams 5, 061002 (2002)



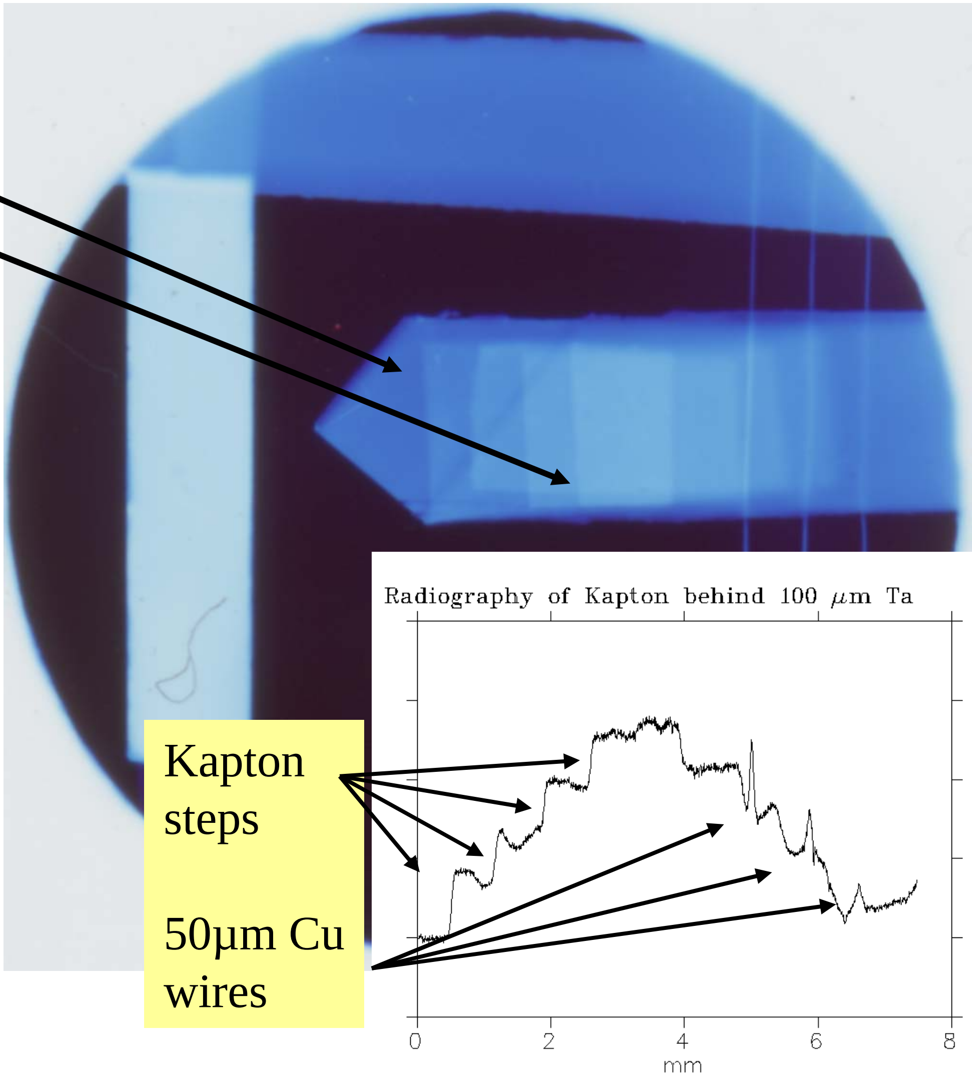


Object Plane Resolution **< 2.5 µm**
(1 MeV protons)

J. Cobble, J. Fernandez (LANL),
N. LeGalloudec (UN Reno), M. Allen, T. Cowan (GA)
J. Appl. Phys. 92, 1775 (2002)

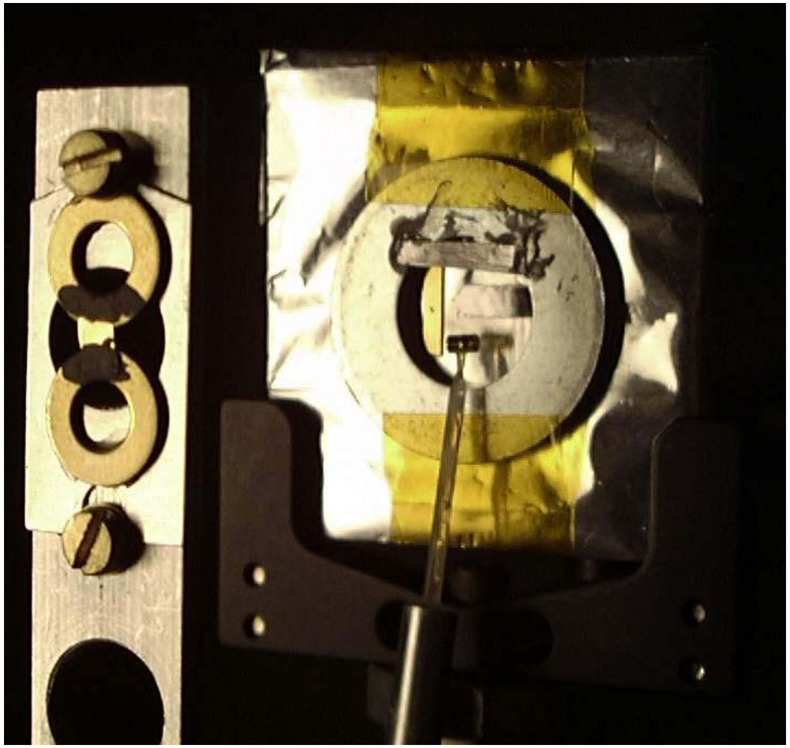
Low-Z material behind high-Z shielding resembles future GSI targets

100 µm Tantalum
50 µm Layers CH



Kapton steps

50µm Cu wires

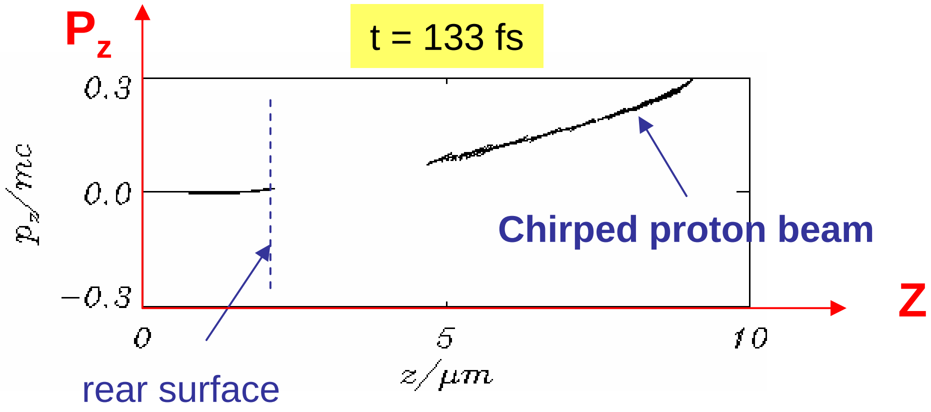


Next Generation Ion Sources ?

Beam characteristics of laser-virtual cathode sheath accelerators

- **Transverse emittance:** $< 0.002\ \pi$ mm-mrad (cf. RF Linacs ~ $1\ \pi$ mm-mrad)
- **Longitudinal emittance:** $< 10^{-6}$ eV-s
  (velocity correlated; synchrotrons ~ 0.1 eV-s)
- **Energy spread:** 100%
- **Bunch charge:** 10^{11} – 10^{13} protons or ions
- **Source diameter:** ~50 μm (fwhm)
- **Charge state purity:** >80% He-like
- **Ion current:** ~10 kA (at source)
- **Rep-rate:** determined by laser driver
- **Laser-ion efficiency:** > 1% (4-20% observed)

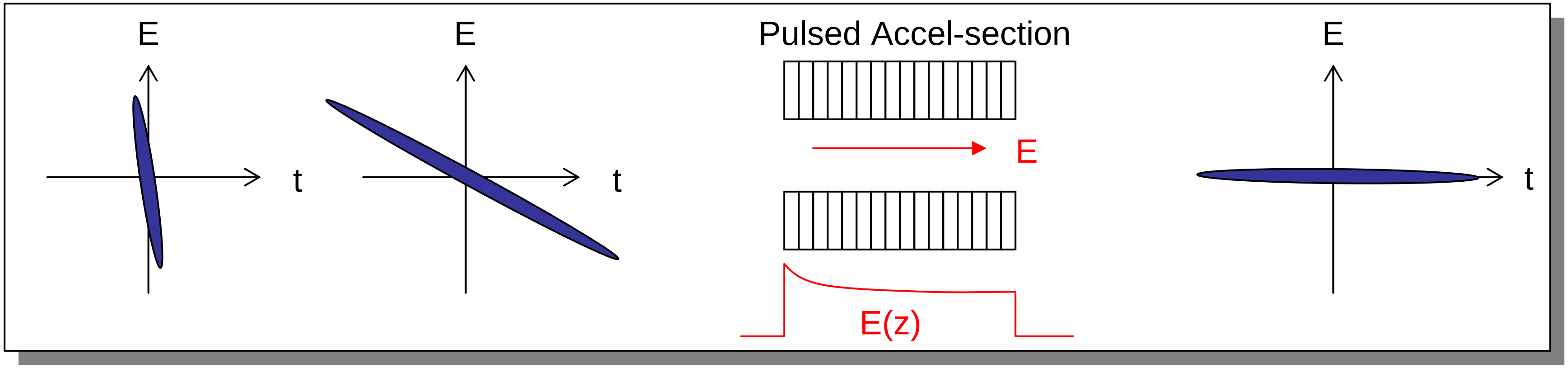
Short pulse duration produces small longitudinal emittance



- Rapid acceleration produces strong ΔE-Δt correlation
- Longitudinal phase space comparable to RF linacs

ΔE Δt < MeV-ps ~ keV-ns PIC suggests $<10^{-7}$ eV-s

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



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Key scientific challenge is to Separate Ions from co-moving Electrons while preserving excellent beam quality

Beam properties

4×10^{11} particles in F7+:

C = 0.45 μC, E > 1 J

@ x = 0:

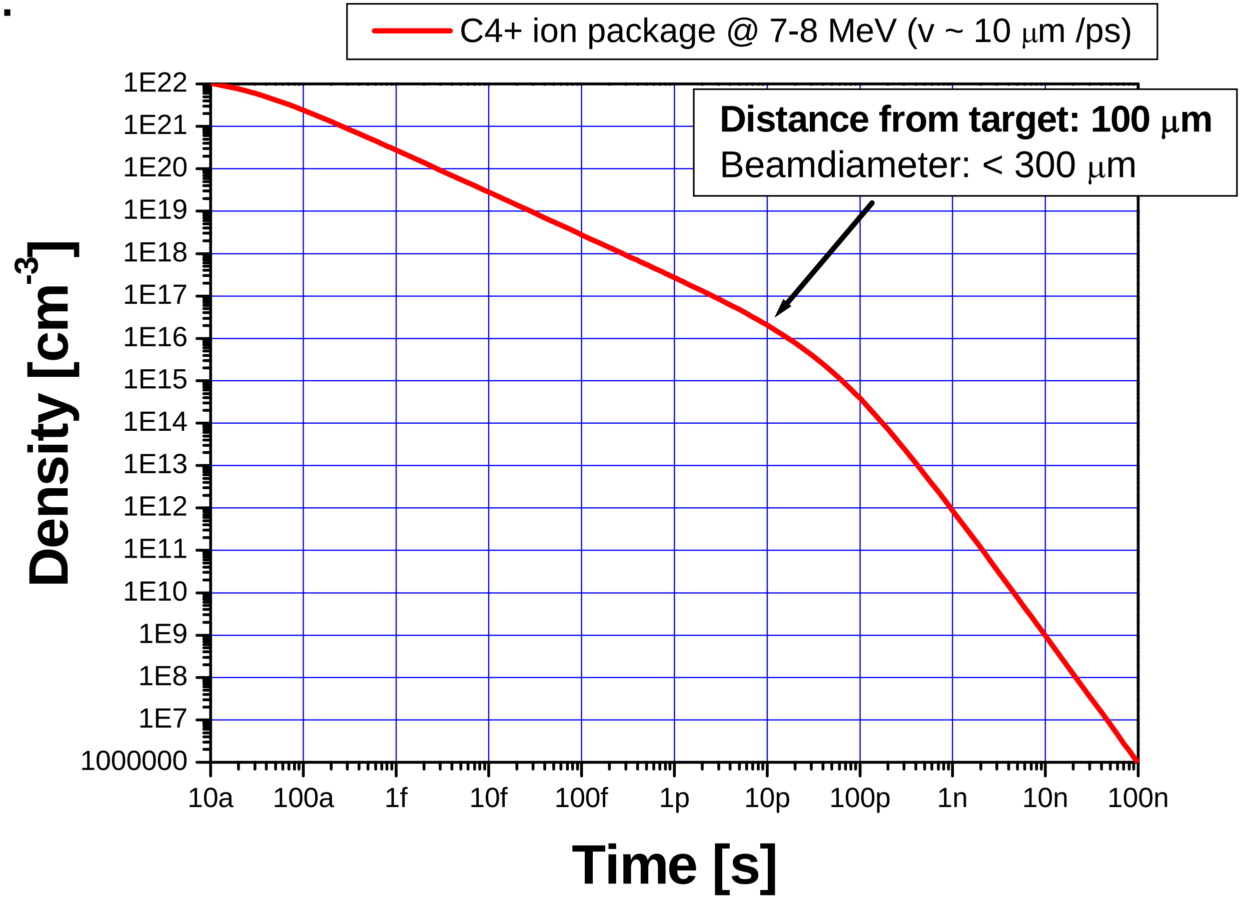
t = 350 fs: I = 1.3 MA

@ x = 100 μm:

t = 10 ps: I = 30 kA

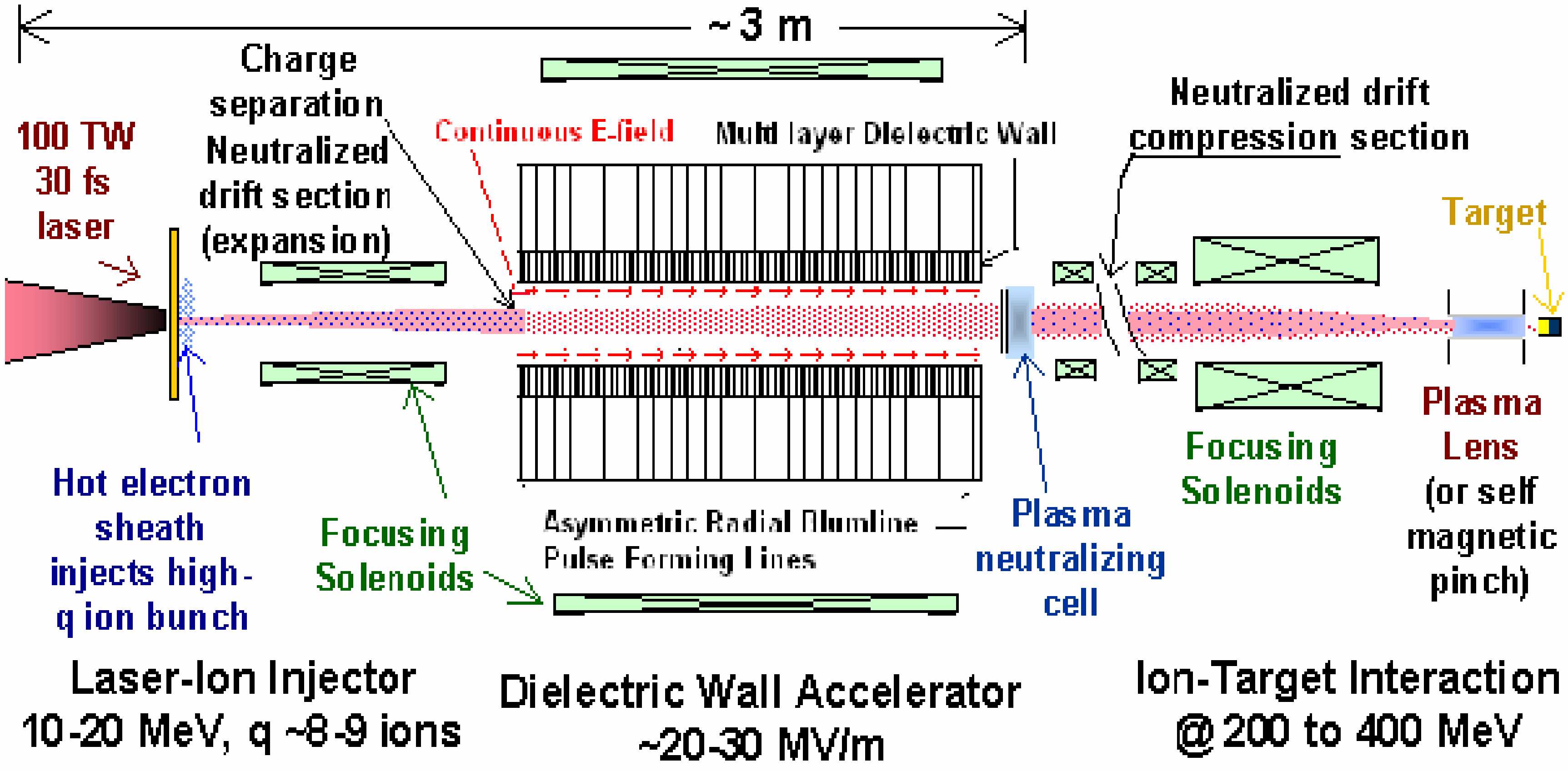
@ x = 1m:

t = 150 ns: I = 3 A



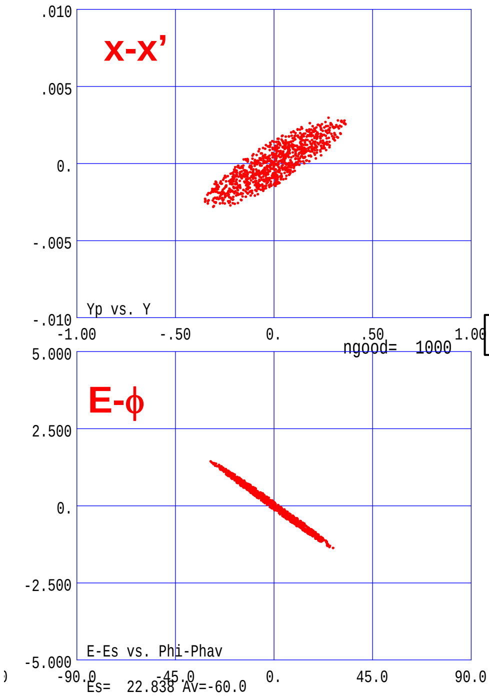
New accelerator concepts

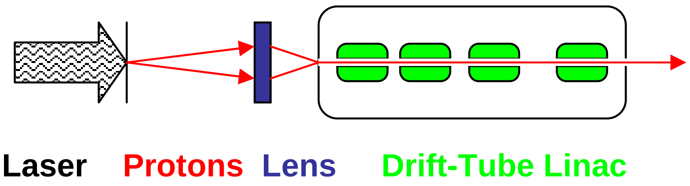
Idea for a new 200 MeV Heavy-ion- test accelerator including a laser ion source and a “Dielectrict Wall Accelerator”

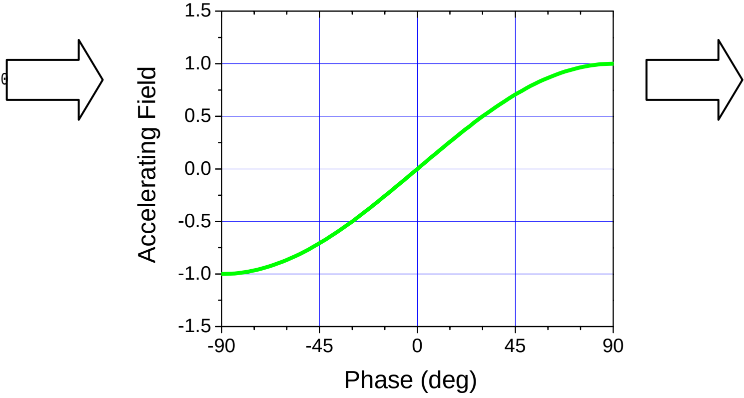


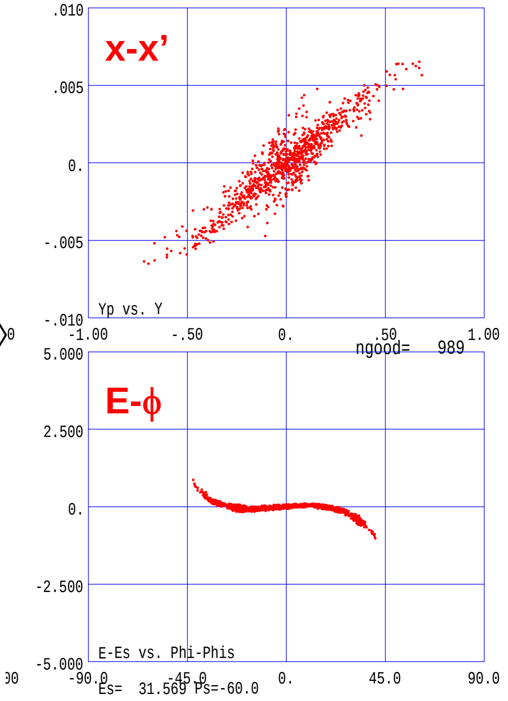
Logan, Caporasso, Roth, Cowan, Ruhl et al. (LBNL-LLNL-GSI-GA)

Injection of a modest energy band in a synchronous structure may be feasible (SNS drift-tube linac, tank 3)



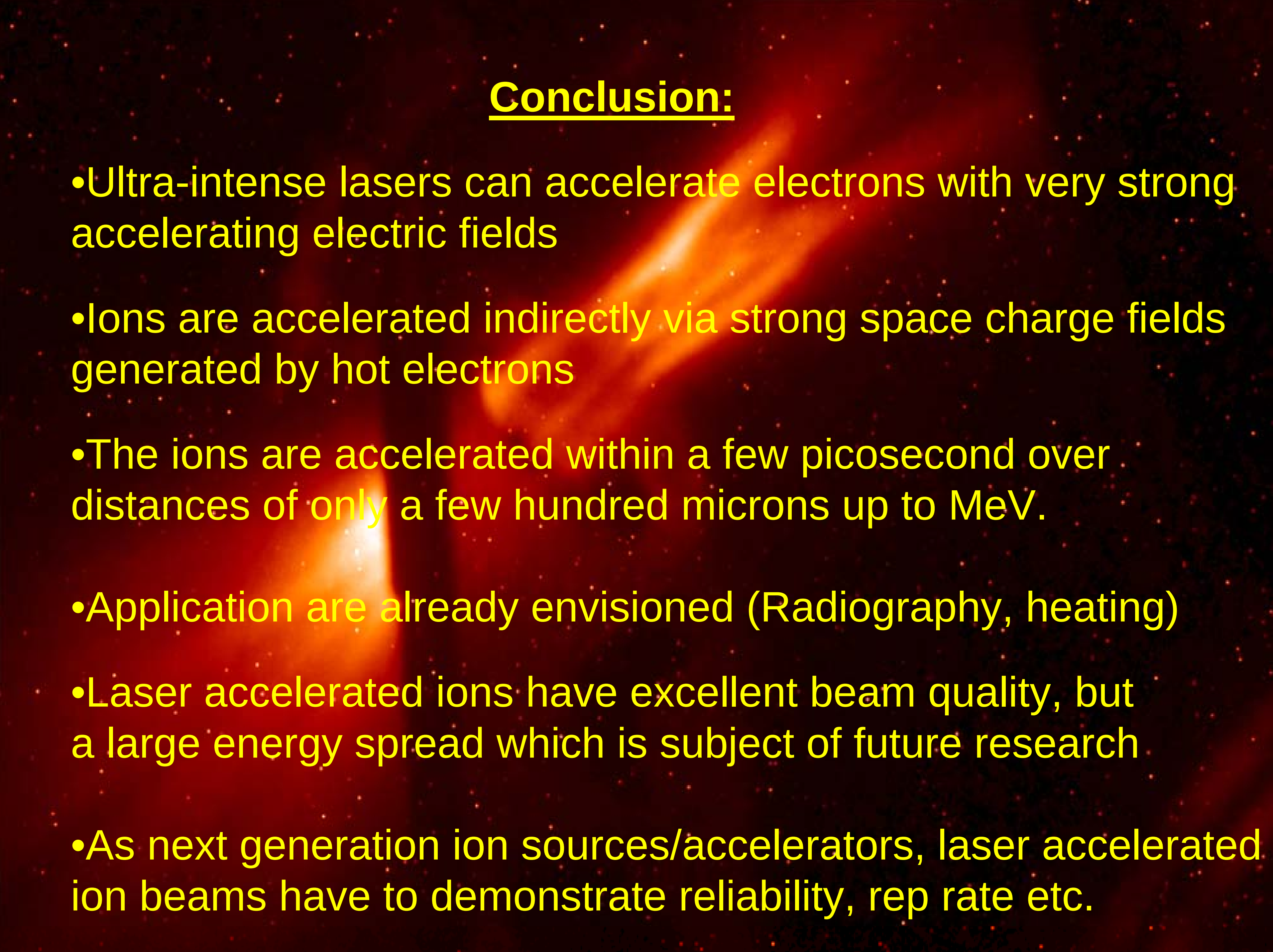






PHELIX at GSI is an outstanding opportunity!

G. Le Sage, T.E. Cowan (LLNL)



Conclusion:

- Ultra-intense lasers can accelerate electrons with very strong accelerating electric fields
- Ions are accelerated indirectly via strong space charge fields generated by hot electrons
- The ions are accelerated within a few picosecond over distances of only a few hundred microns up to MeV.
- Application are already envisioned (Radiography, heating)
- Laser accelerated ions have excellent beam quality, but a large energy spread which is subject of future research
- As next generation ion sources/accelerators, laser accelerated ion beams have to demonstrate reliability, rep rate etc.