Santa Fe
July 28, 2009

Cluster fusion in a high magnetic field

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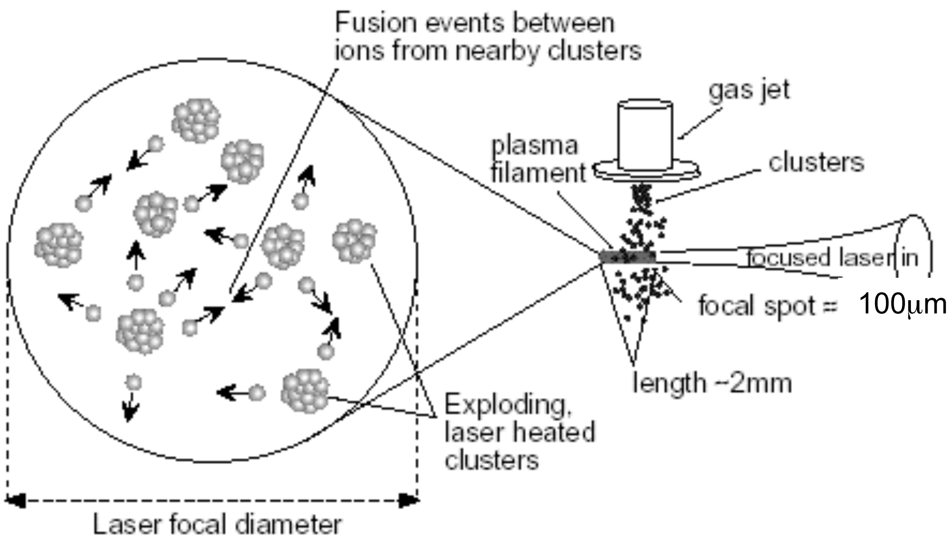
Earlier experiments

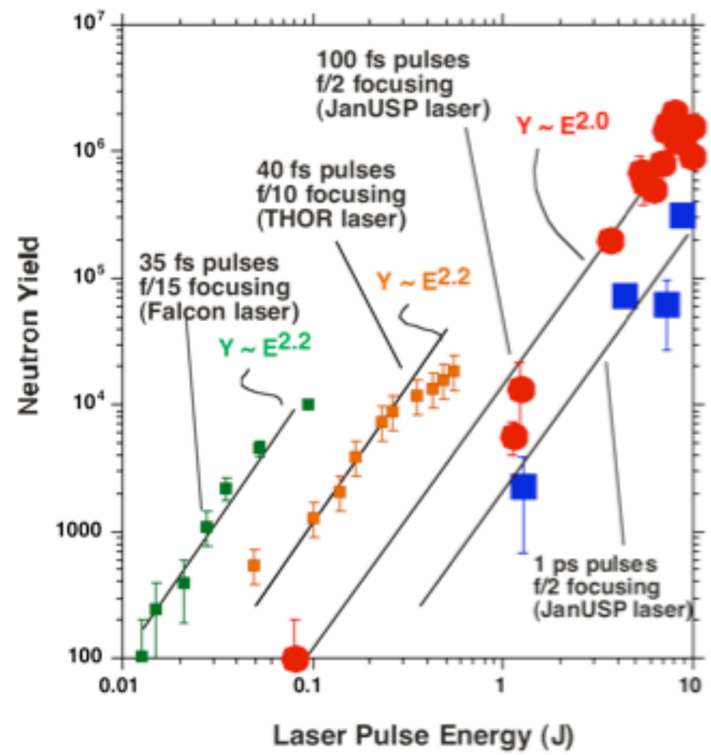
- Expanding supersonic deuterium jets produce clusters, that are liquid-density droplets a few nanometers in radius.
- The laser field quickly converts clusters into dense nanoplasmas.
- The resulting explosions produce fusion reactions, with a noticeable neutron yield measured experimentally.



T. Ditmire et al., Nature **398**, 489 (1999)

Neutron yield scaling

- Neutron yield scales with laser pulse energy and duration.
- Neutron production time ~100 ps.
- A large magnetic field may slow down radial transport and increase the neutron yield.



Magnetically confined plasma filament

- Neutron production in freely expanding filament:

$$N = \int n^2 \langle \sigma v \rangle dV dt \propto \int \frac{dt}{R^2(t) L(t)}$$

- Radial and axial expansion occur at sound speed:

$$R = R_0 + c_s t \qquad L = L_0 + c_s t \qquad \Rightarrow \quad N \propto \frac{1}{c_s} \frac{1}{R_0 L_0}$$

- Strong magnetic field suppresses radial expansion:

$$R = R_0 \qquad L = L_0 + c_s t \qquad \Rightarrow \quad N \propto \frac{1}{c_s} \frac{1}{R_0^2} \ln \frac{L_0 + c_s \tau}{L_0}$$

- A neutron yield enhancement factor of $L_0 / R_0 \sim 20 - 50$ is expected in long filaments from changes in transport

- Radial magnetic confinement will also slow down the ion cooling rate, which will maintain a higher reaction rate

Origin of neutrons

- D-D collisions in the gaseous plasma filament
- Collisions within clusters or between neighboring clusters with yield enhancement due to high local density
- Collisions of accelerated deuterium ions in the ambient gas jet
- Time-resolved neutron measurements can identify the dominant mechanism
- The applied magnetic field can facilitate only the first of the three mechanisms

Plasma confinement issues

- Any realistic magnetic field is too weak to affect cluster explosion as plasma pressure is extremely high inside the clusters
- However, a field of 100-200T can impede radial expansion of the plasma after the dense clusters expand and mix to become a gaseous plasma filament
- Ions are very difficult to magnetize. Their Larmor radii are typically greater than the envisioned radius of the plasma filament. Yet, the ions can be confined within the filament by the radial electrostatic field of the magnetically confined electrons.
- Magnetic mirrors at the ends may improve axial confinement.
- Violation of the frozen-in condition for electrons is a potential risk for radial confinement. The proposed experiments should clarify whether anomalous electron transport is preventable .

Experiment

- Joint program between Sandia National Lab [Ken Struve] and University of Texas at Austin [Roger Bengtson].
  - Funded by LDRD funds from Sandia.

- Present Status
  - Half size experiment is nearly designed. (SNL)
  - Experiments on cluster injection are close to operating.   (UT)
  - Lower field (10 T) experiment is near data. (UT)

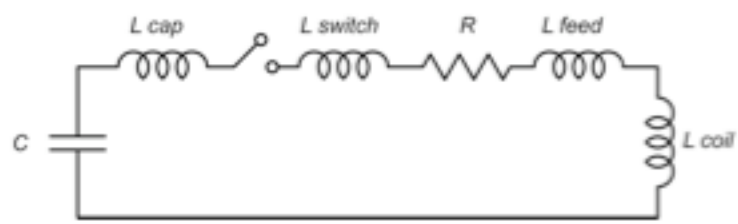
Experimental needs

- Plasma filament long enough to provide axial life-time of
  $t \sim 10^{-9}$-10^{-8}s.

- Magnetic field large enough to constrain plasma radially
  - For $n_e \sim 10^{19}$ cm^{-3} and $T_e = T_i \sim 10$ kV with $\beta = 1$,
    we need B ~100-200 T
  - Will have many electron Larmor radii and many Debye lengths in plasma radius but hardly one ion Larmor orbit
  - Since volume is small, energy requirements for B are within reach
  - Will have to replace coil every shot.

Electrical considerations

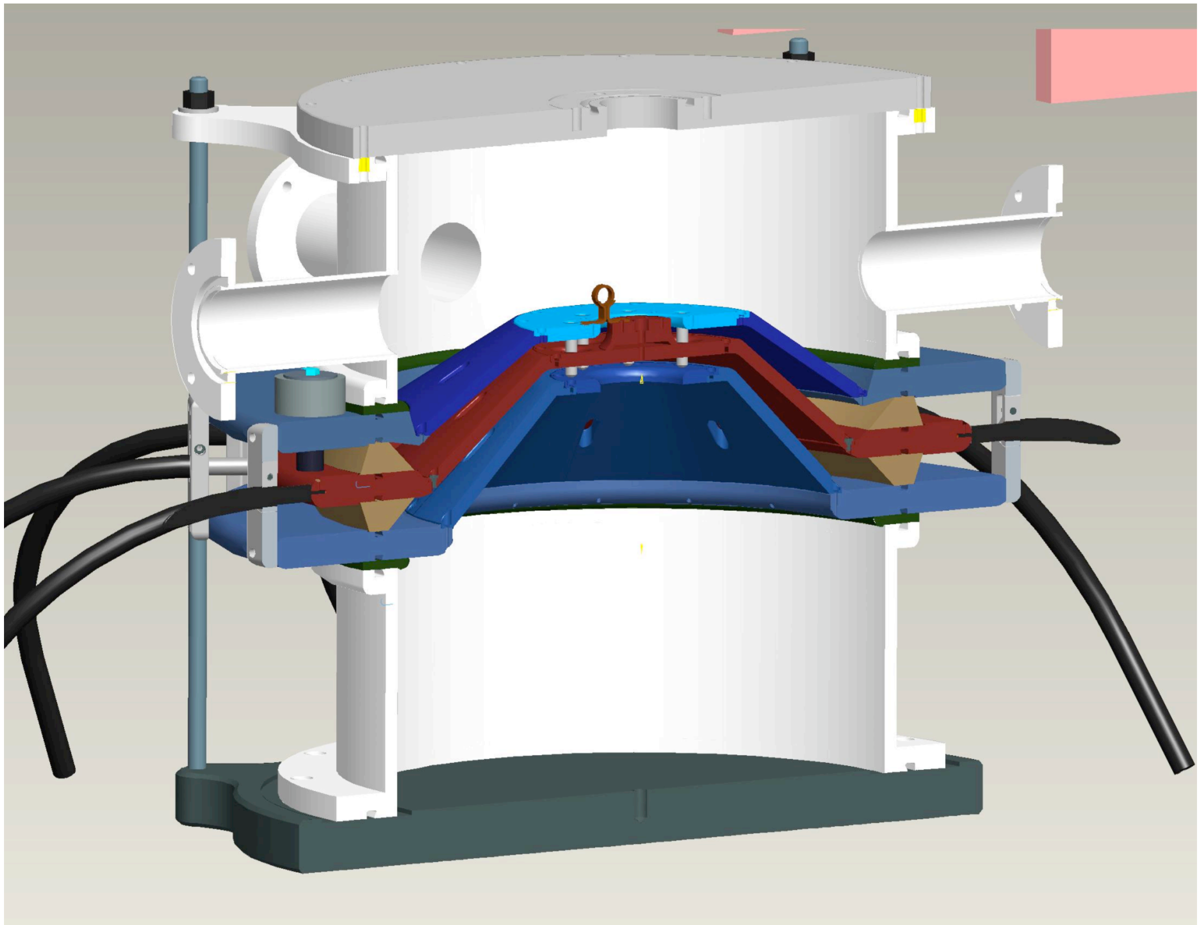
- Take coil radius ~ 5mm
- Times > 10^{-8} s
- Need currents 1-2 x 10^6 Amps



V_o (kV)	I_{peak} (MA)	B_{peak} (T) 10 mm dia coil	P_{peak} (GPa) (= $B^2/2\mu_o$)
25	0.55	49	0.97
50	1.1	98	3.9
75	1.6	150	8.7
100	2.2	200	15

One scenario
C = 24 μF
L = 50 nH
R = 5 mΩ
Max V = 100 kV
Max E = 120 kJ
L/R = 10 μs
τ_{peak} = 1.7 μs

Electromechanical setup



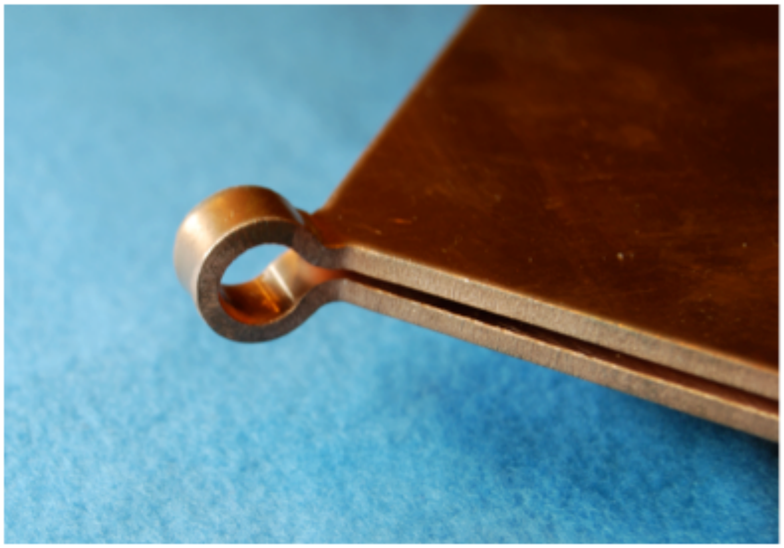
Laser considerations

- First experiments will be done with low energy laser [Ghost]
- Later experiments will move to petawatt laser either at UT or Sandia
  - Primary improvement in going to a petawatt laser is that larger energy at same intensity will provide a larger volume of hot plasma.

Worries on the experiment

- Injecting clusters into the coil
  - Will the inductive electric field E_θ ionize the gas inside coils?
  - What is gas pressure inside coils?
  - How often will we have to replace gas nozzle?
- How many shots per day?
- Most electrical worries seem to be solved
- Diagnostics
  - Neutron yield
  - Neutron time of flight
  - Schlieren interferometry with time delay to follow evolution

Pictures from LANL high field experiment



Before

After

1/8 in copper coil, B > 100 T

*Thanks to Chuck Mielke, National High Magnetic Field Laboratory, LANL

Physics questions

- Where do the 10 keV ions come from?
  - Coulomb explosion of fully stripped clusters
  - Ambipolar ion acceleration by hot electrons

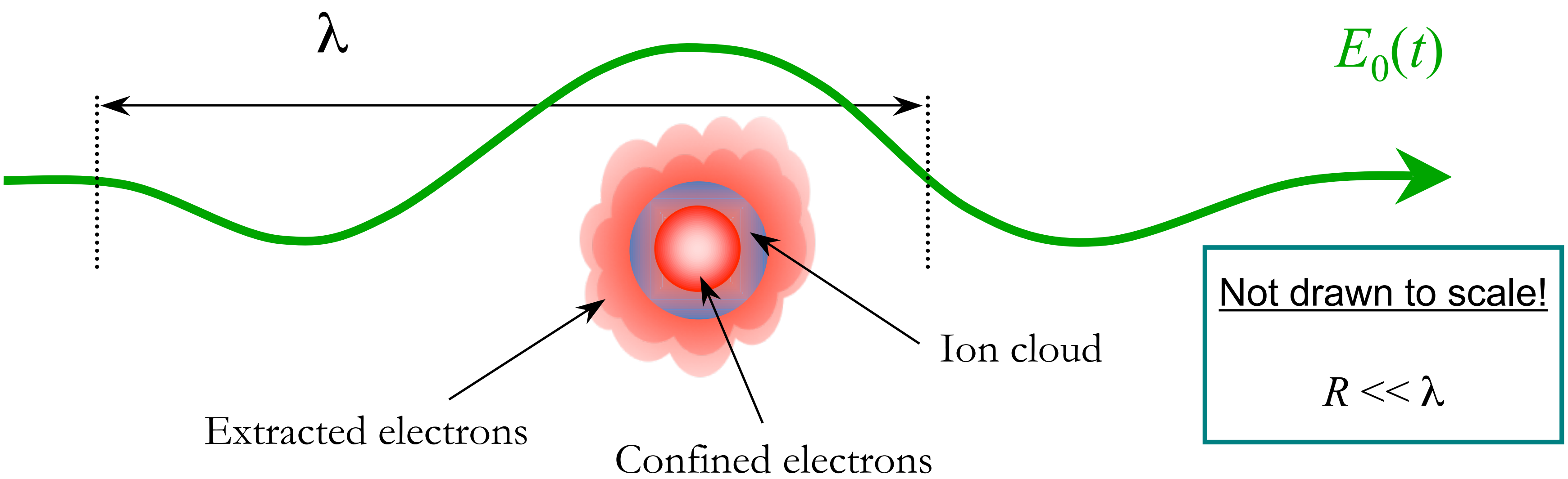
- Do fusion neutrons come from dense clusters or from gaseous plasma after clusters expand and mix?

- Can high magnetic field facilitate neutron production?
  - Magnetic confinement of electrons
  - Electrostatic confinement of fast ions

Large clusters and hot electrons

- Neutrons are produced by most energetic ions, which makes neutron yield sensitive to the tail of the ion distribution function.
- Coulomb explosion of a single cluster produces an ion distribution with a sharp cut-off (no tail).
- The plasma filament lifetime is too short for the ions to thermalize and become Maxwellian.
- Neutron yield comes predominantly from larger than average clusters, which points to the need to have control over cluster -size distribution.
- In large clusters, ion acceleration by hot electrons is of major importance.

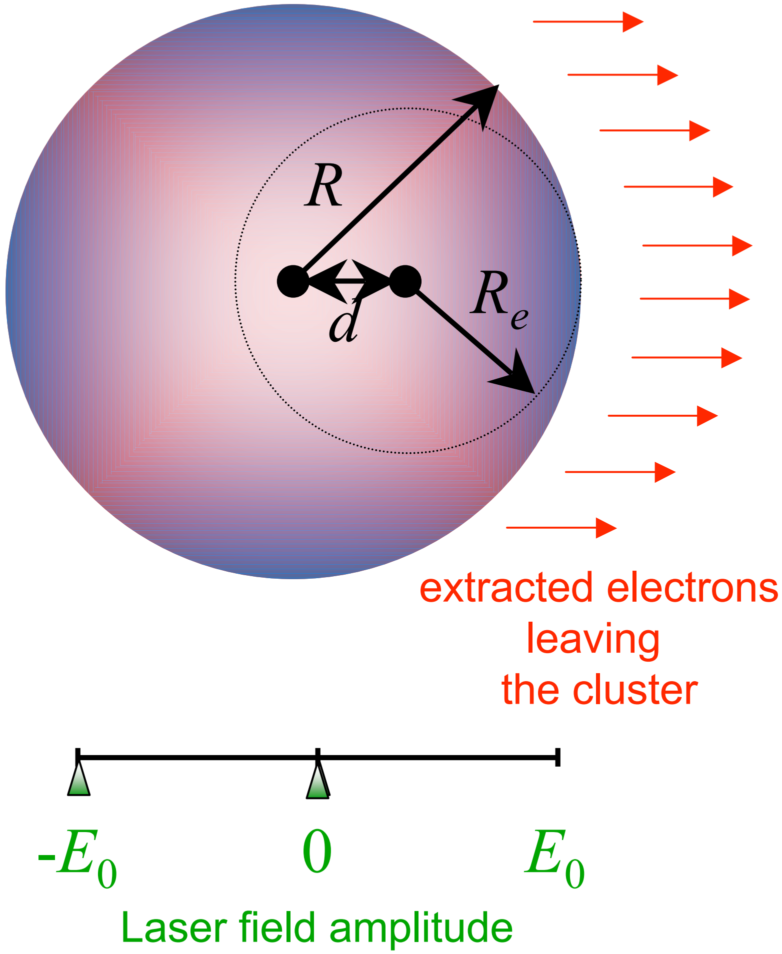
Two groups of electrons



- There are two groups of electrons: extracted and confined.
- Confined electrons behave as a perfectly conducting fluid, since $\omega \ll \omega_{pe}$.
- Electron response time is much shorter than the ion response time.

Electron extraction

- Laser field quickly ionizes the cluster, producing an ion cloud and an electron cloud.
- The space charge density is zero in the region where two clouds overlap.
- Increasing laser field extracts electrons keeping the total electric field zero inside the electron cloud.
- Confined electrons form a cold core with radius $R_e = R - d$, where $d=3|e|E_0/m_i\omega^2_{pi}$ is the cold core displacement.
- Ion shell of thickness d explodes after the pulse because of its own space charge.



B. Breizman and A. Arefiev, Plasma Phys. Rep. **29**, 593 (2003)

Ion energy gain after electron extraction

- If $R < d$, then all electrons are extracted out of the cluster.

- The corresponding ion energy gain is $\varepsilon_i = m_i \omega_{pi}^2 r_0^2 / 3$, where r_0 is the initial ion position.

- If $R > d$, then the cluster consists of a neutral core surrounded by a positive ion shell.

- The energy gain for the ions in the shell is $\varepsilon_i = m_i \omega_{pi}^2 \left[r_0^3 - (R - d)^3 \right] / 3r_0$.

- The maximum ion energy increases with R and for $R >> d$ it is $\varepsilon_i = 3|e|E_0 R$.

What happens to the extracted electrons?

- Extracted electrons accelerate in the laser field during half of the laser period and their characteristic kinetic energy is $\tilde{\varepsilon} \approx \frac{m_e}{2}\left(\frac{eE_0}{m_e\omega}\right)^2$.

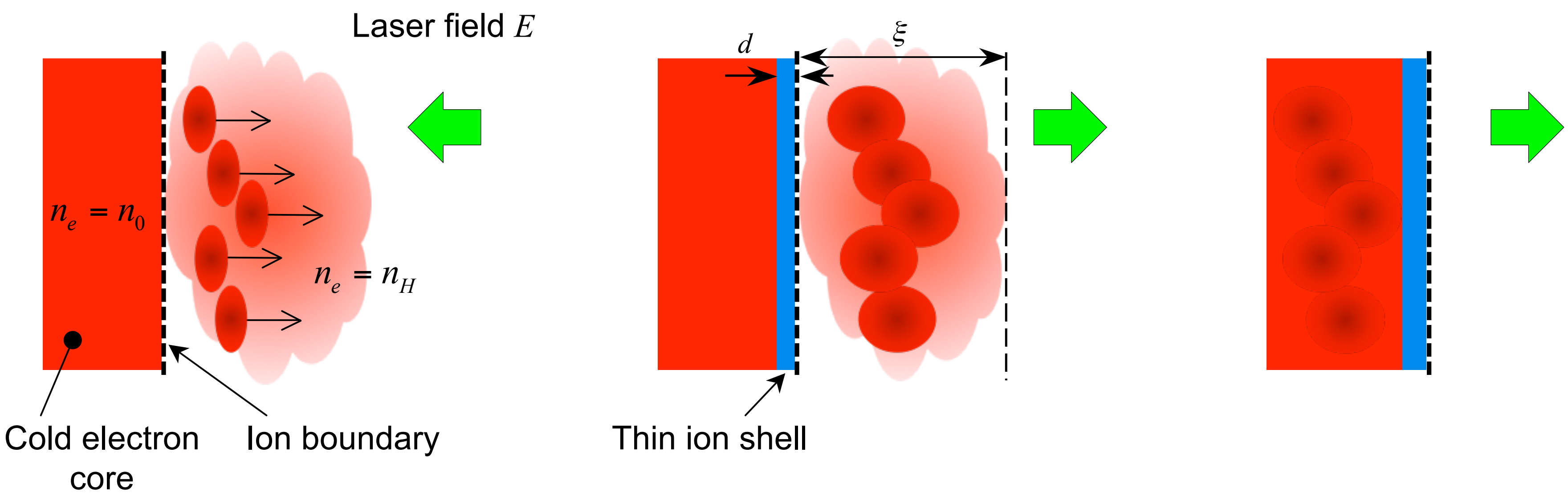
- **Escape condition:** extracted electrons fly away from the cluster only if the ponderomotive potential exceeds the Coulomb potential of the cluster.

- For a cluster with a thin ion shell, the escape condition reads $\tilde{\varepsilon} >> \max(\varepsilon_i) = 3|e|E_0R$.

- It is equivalent to $R << \xi$, where $\xi = |e|E_0/m_e\omega^2$ is the electron quiver amplitude.

- Extracted electrons remain bound to a large cluster ($R>>\xi$), because the Coulomb potential of the cluster exceeds the ponderomotive potential.

Brunel (vacuum) heating in large clusters



Electron are extracted by the laser field

Electrons turn around after E changes direction

$$n_H \xi \approx n_0 d \;\rightarrow\; n_H \approx n_0 \frac{\omega^2}{\omega_{p0}^2}$$

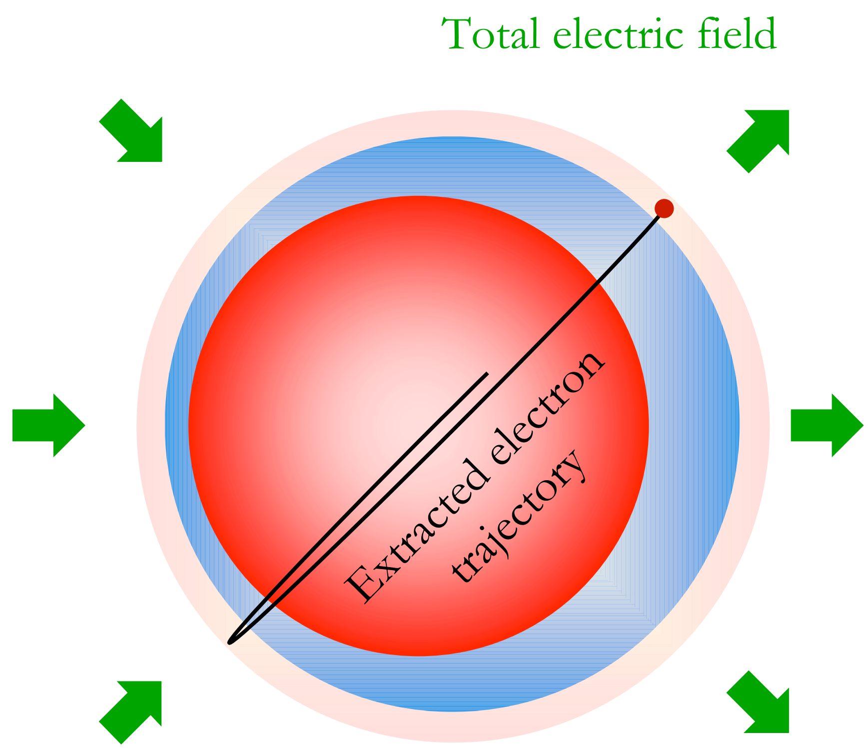
Electrons are driven into the cluster with

$$\varepsilon_e \approx \frac{m_e}{2}\left(\frac{eE_0}{m_e \omega}\right)^2$$

F. Brunel, Phys. Rev. Lett. **59**, 52 (1987)

Stochastic heating

- The vacuum heating generates a warm electron minority with density $n_0\ \omega^2/\omega_p^2$.
- Bouncing through the cluster, the warm electrons interact with the field only at the cluster edge.
- The interaction leads to additional stochastic heating.
- The resulting hot electron energy can significantly exceed the ponderomotive energy and be in the range of 10 keV and higher.



B. Breizman and A. Arefiev, Plasma Phys. Rep. **29**, 593 (2003); T. Antonsen et al., Phys. Plasmas **12**, 056703 (2005); B. Breizman, A. Arefiev, and M. Fomyts'kyi Phys. Plasmas **12**, 056706 (2005).

Hot electron distribution

- In the short pulse limit, the problem of ion acceleration is a problem of plasma expansion into a vacuum for a given initial electron distribution.

- We assume that the hot electrons have no angular momentum.

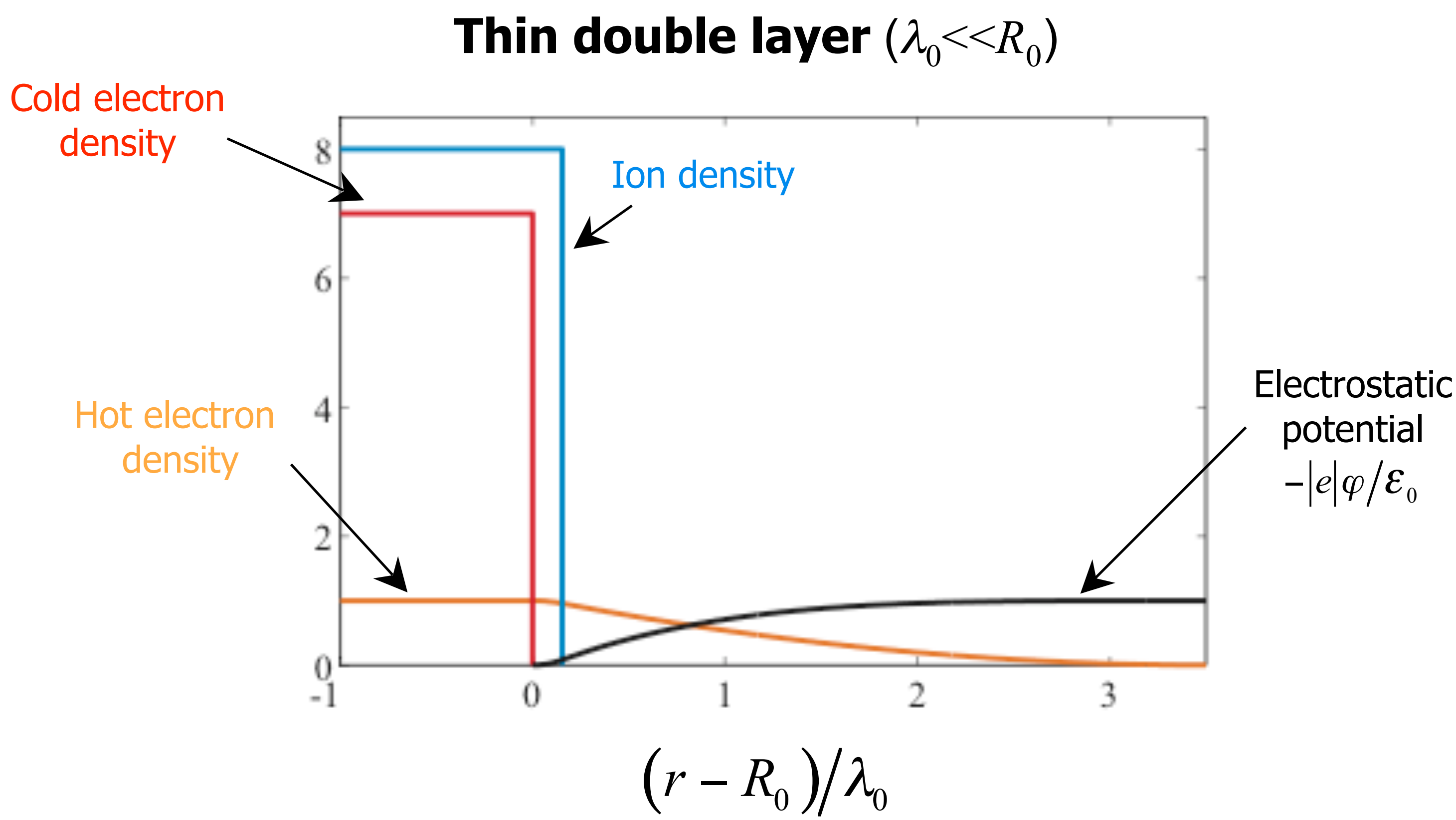
- We also assume an initial "water-bag" distribution

$$f_{eH} = C_0 \delta\left(M_\phi\right) \delta\left(M_\theta\right) H\left(I_0 - I\right) H\left(I\right)$$

  M_ϕ and M_θ are components of the angular momentum, I is the radial adiabatic invariant, and H is the Heaviside step function.

- The hot electrons generate fast ions via adiabatic collisionless expansion.

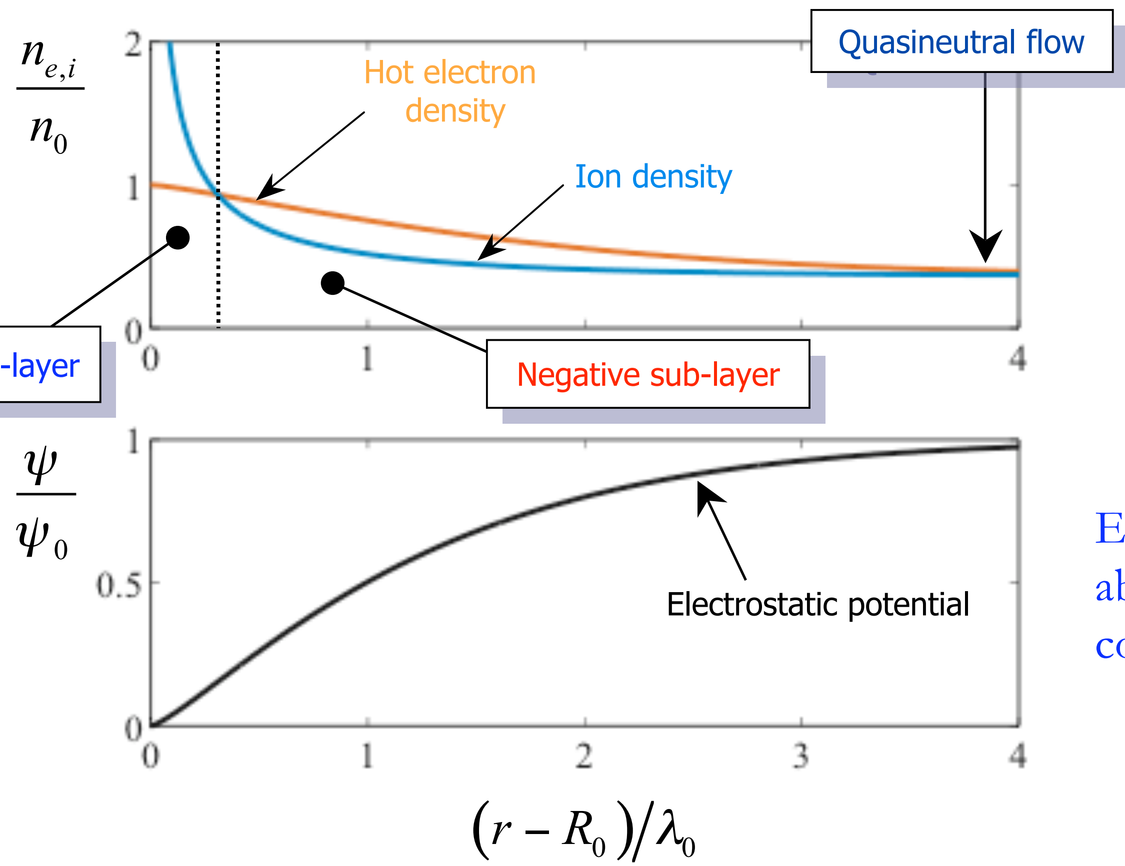
Initial cluster edge configuration



$\lambda_0 \equiv \sqrt{\varepsilon_0 / 4\pi n_0 e^2}$ - initial Debye length of the hot electrons; R_0 - initial cold core radius;

Steady-state double layer $(n_0/n_{i0} \to 0)$

- The electric field vanishes at the cold core surface.
- At the double layer exit, the electric field and the charge density vanish.
- We find that $\psi_0 = \sqrt{3}/2$ (Child-Langmuir law for a plane diode).



$$\psi \equiv -\frac{|e|\varphi}{\varepsilon_H}$$

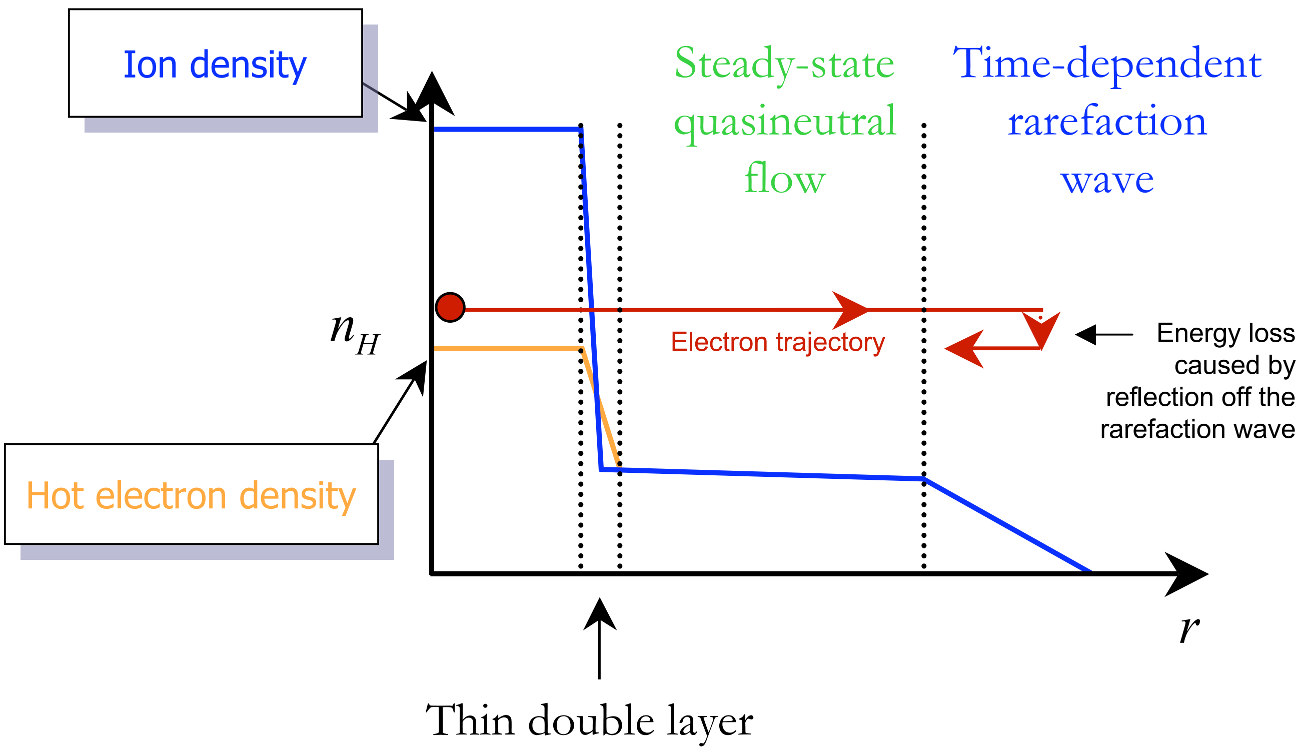
The outgoing flow is supersonic

Electrons with energies above $\psi_0 \varepsilon_H$ are not confined

Supersonic quasineutral flow

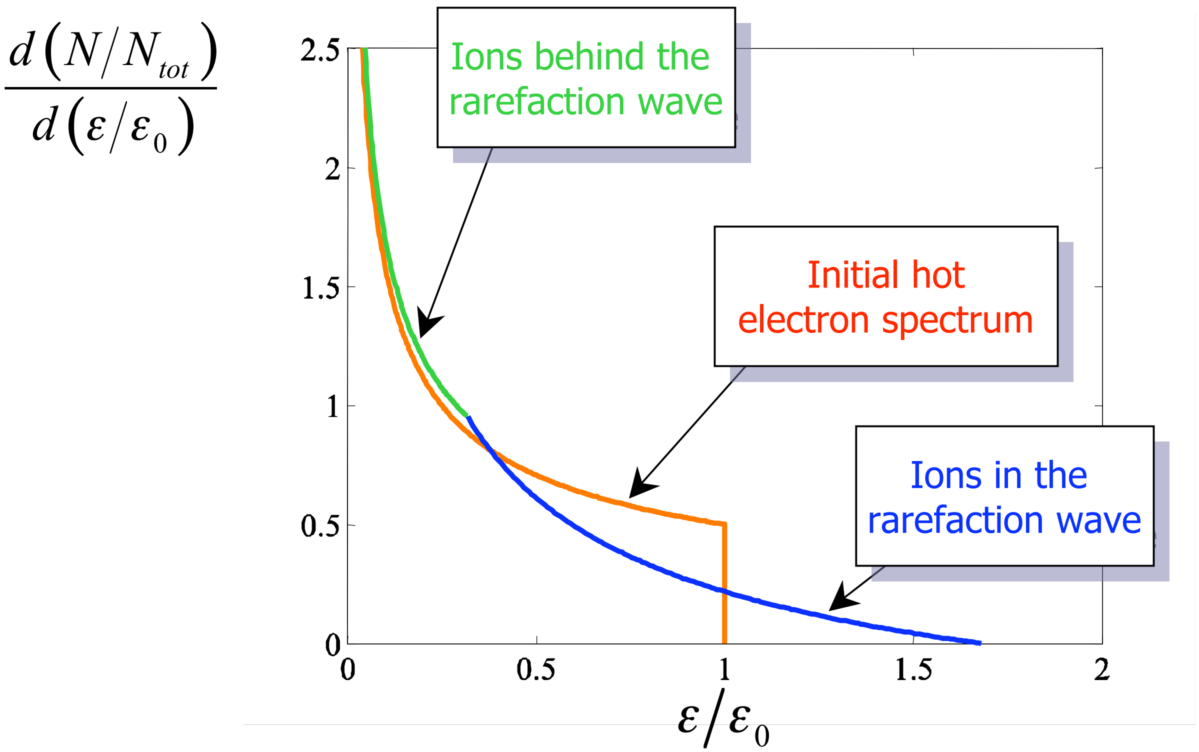
- Location of the double layer remains fixed in the limit of $n_0/n_{i0} \to 0$.
- The width of the double layer is effectively zero in the limit of $\lambda_D/R_0 \to 0$.
- Double layer acts as a boundary condition for the flow:

$$n(R_0,t) = n_i(t)$$
$$\mathrm{v}(R_0,t) = \mathrm{v}_i(t)$$



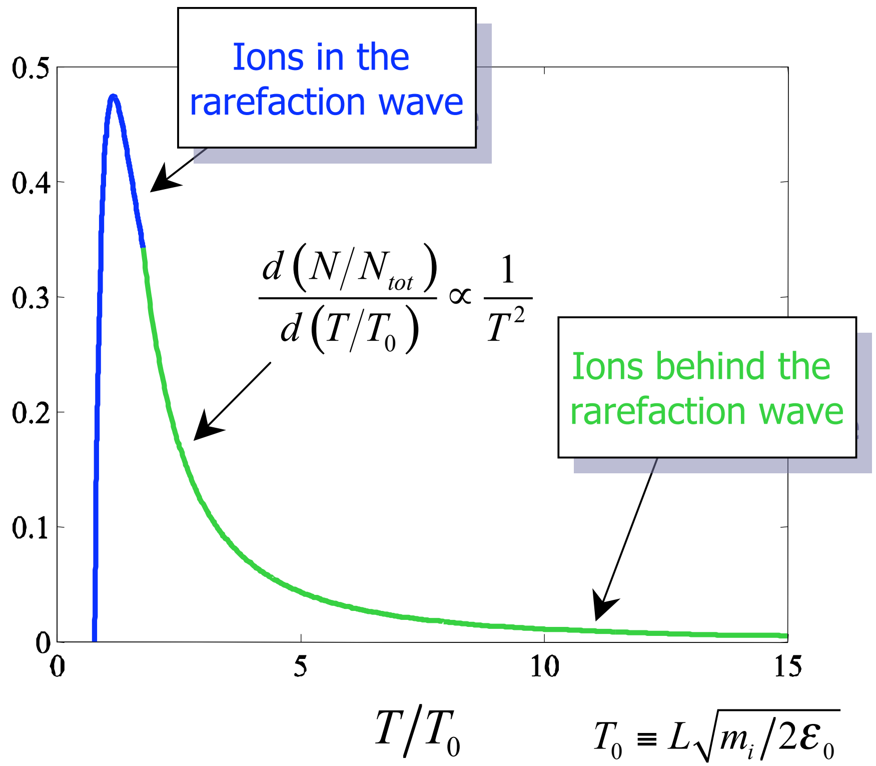
Ion energy spectrum

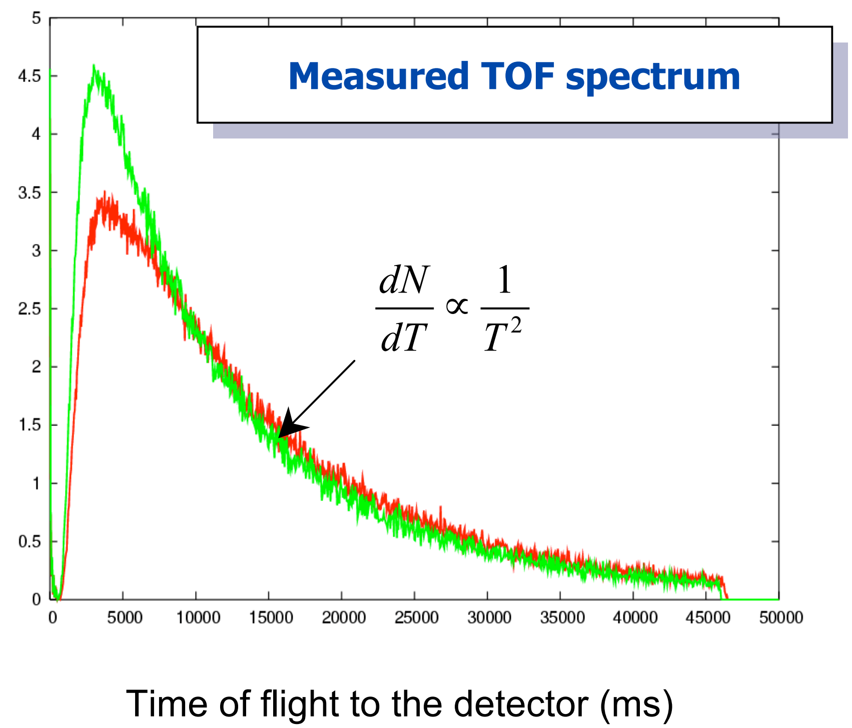
- Ion energy is of the order of the hot electron energy before the explosion.
- Maximum ion energy exceeds maximum electron energy.
- Ions gain as much as 50 % of their energy in the double layer.



Time-of-flight spectrum

B. Breizman and A. Arefiev, Phys. Plasmas **14**, 073105 (2007)





- T is the time of flight to the detector at a distance L for an ion with energy ε_i.
- The "one dimensional" electron distribution causes the $1/T^2$ dependence.

What we expect to study and learn

EXPERIMENT

- Ion & electron transport
- Neutron production
- How does neutron yield scale with laser power?
- Does magnetic field enhance neutron yield as expected?
- Mirror confinement without end walls

THEORY/SIMULATIONS

- Confinement of ions with large Larmor radii
- Hot electron production
- Anisotropy of energetic ions
- Stability of plasma filament
- Anomalous electron scattering and resistivity
- Ion acceleration by hot electrons