最終講義　２０２０年３月２日

発散型ガスパフ、そして発散型ワイヤアレイ

Divergent Gas-Puff, and Divergent Wire-Array

プラズマ科学研究室
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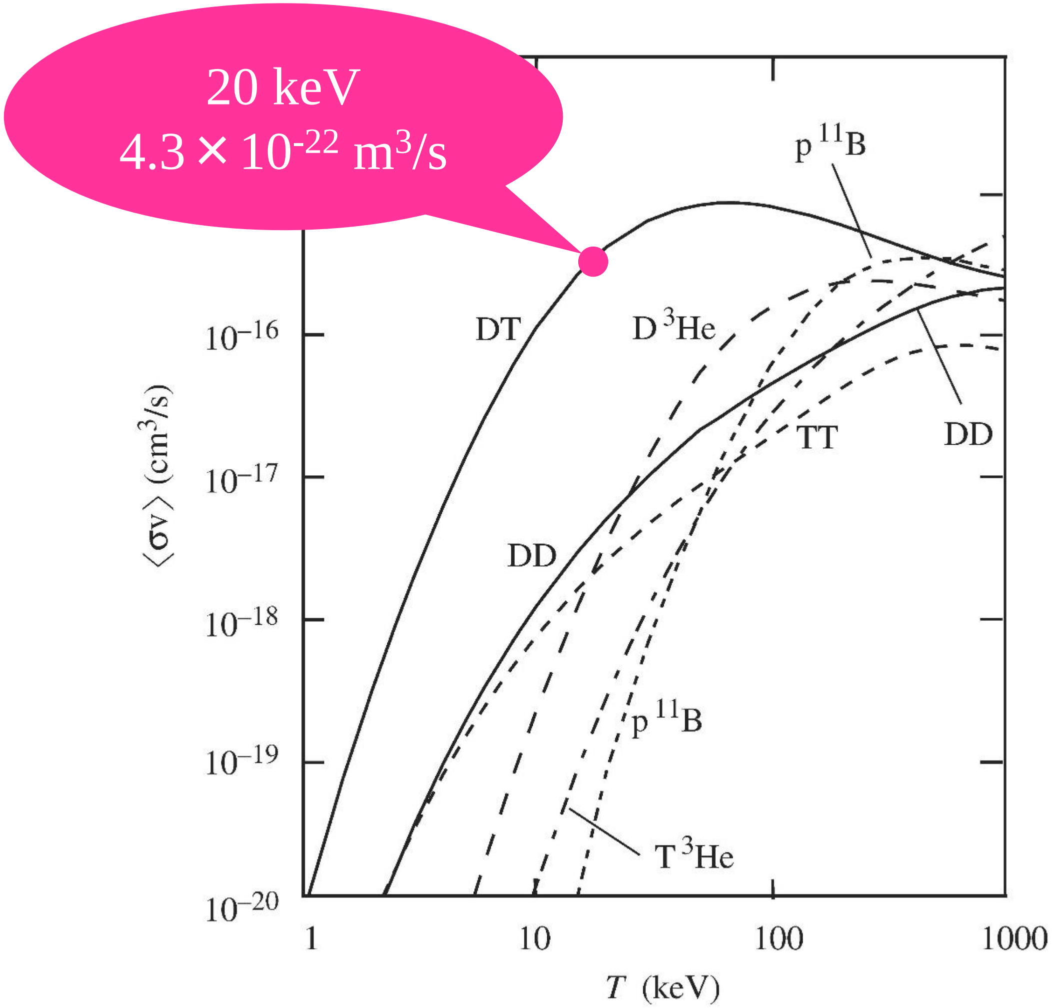
あいさつ

高杉恵一

核融合反応



20 keV
4.3×10^{-22} m^3/s

S. Atzeni and J. Meyer-ter-vehn, The Physics of Inertial Fusion, Oxford, 2004

D-T核融合反応

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n}$$

3.52 MeV 14.06 MeV

$$2\mathrm{g} + 3\mathrm{g} \rightarrow 1.7 \times 10^{12}\ \mathrm{J}$$

(TNT 370 t、1GW×28m)

磁場閉じ込め核融合

1GWの出力を取り出すため

温度 $T = 20$ keV

密度 $n_D = n_T = 10^{20}$ m^{-3}

体積 $V = 80$ m^3

が必要となる。$Q = 10$ とすると

閉じ込め時間 $\tau = 1$ s

が要求される

慣性核融合

温度 $T = 20\ \mathrm{keV}$ のとき燃焼率は

$$\varphi = \frac{\rho r}{\rho r + 100}$$

となる。燃焼率 $\varphi = 1/3$ を得るため

$$\rho r = 50\ \mathrm{kg/m^2}$$

が必要となる。

慣性核融合

質量 $M = 1.2 \times 10^{-5}\ \mathrm{kg}$

半径 $r = 2.4 \times 10^{-5}\ \mathrm{m}^3$

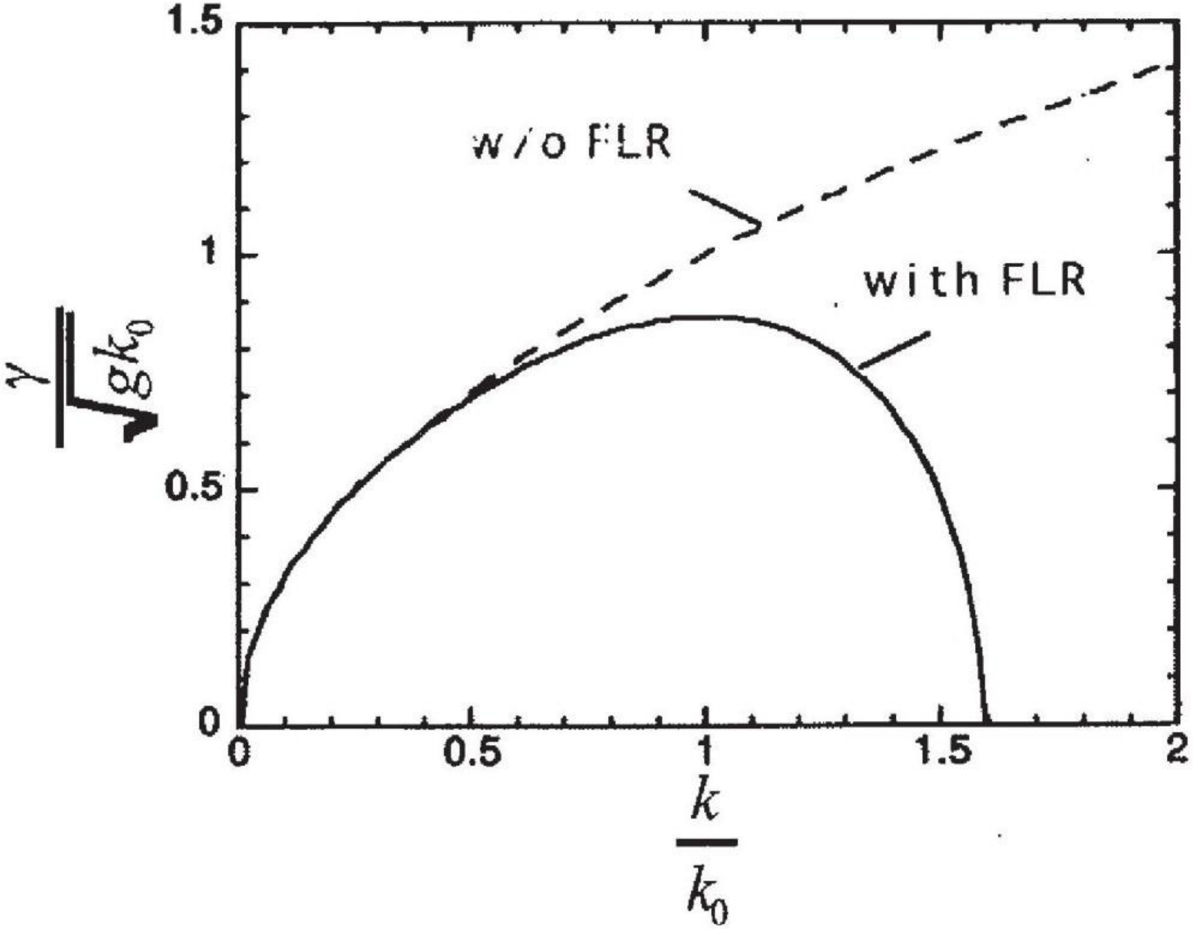
密度 $\rho = 2.1 \times 10^{5}\ \mathrm{kg/m}^3$

のとき

出力 $W = 1.3 \times 10^{9}\ \mathrm{J}$

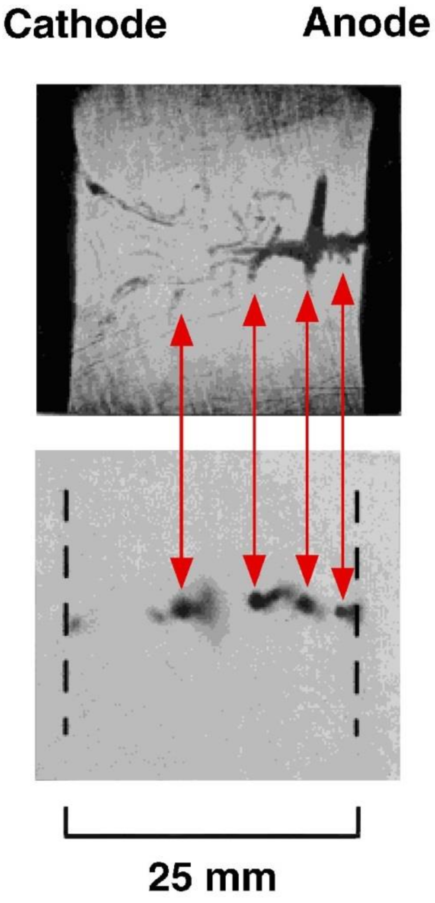
が得られる。1.3秒ごとに反応を起こせば、1GWの平均出力となる

Rayleigh-Taylor不安定性



K. Takasugi et al., AIP Conf. Proc. 299, 251, 1993

Rayleigh-Taylor不安定性



K. Takasugi et al., AIP Conf. Proc. 299, 251, 1993

収縮を伴う系に要求されること

Rayleigh-Taylor 不安定性の波長を短くする

$\Rightarrow$

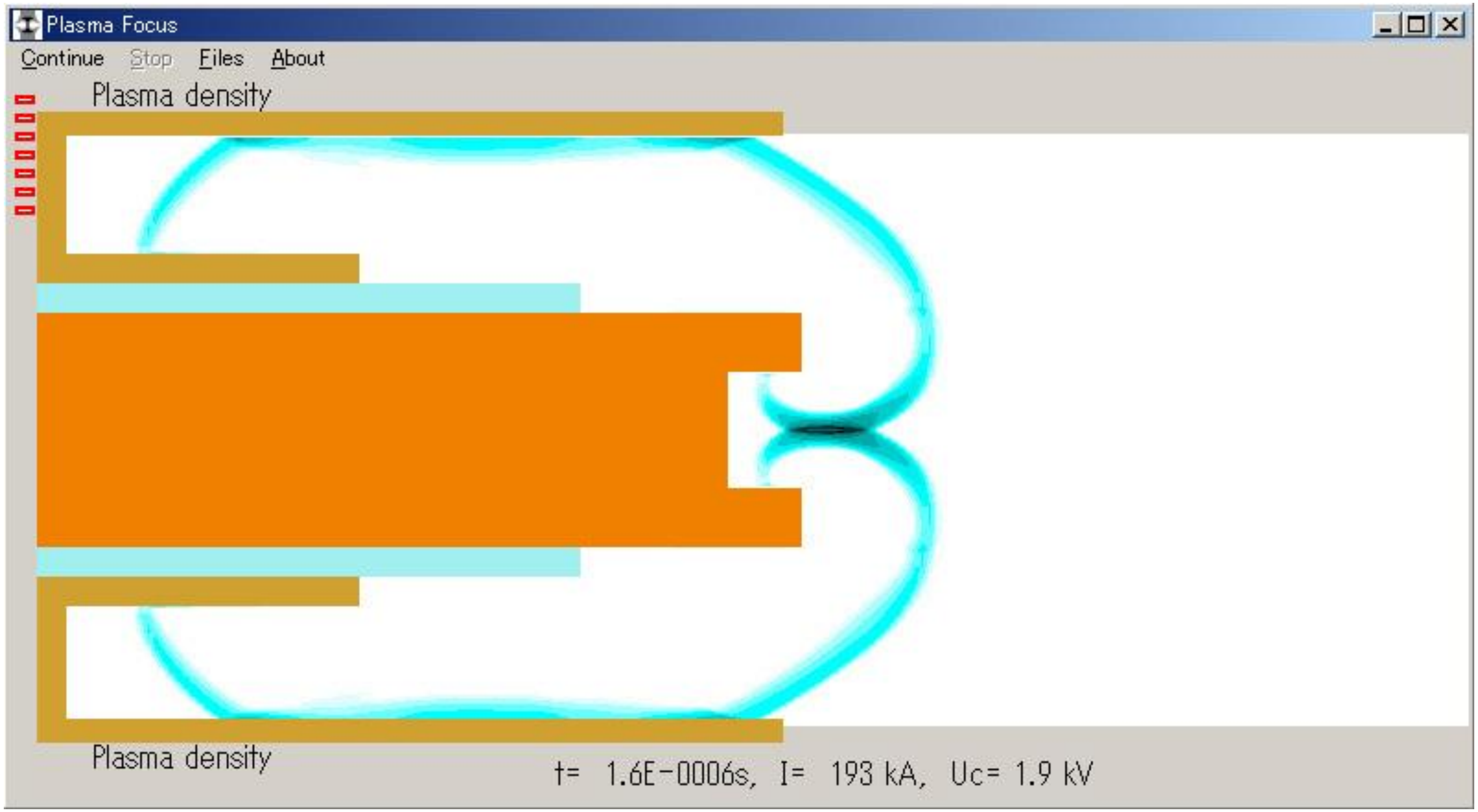
収縮時に温度を上げない

短時間に強い収縮を行う

$\Rightarrow$

パルスパワーが必要とされる

プラズマフォーカス



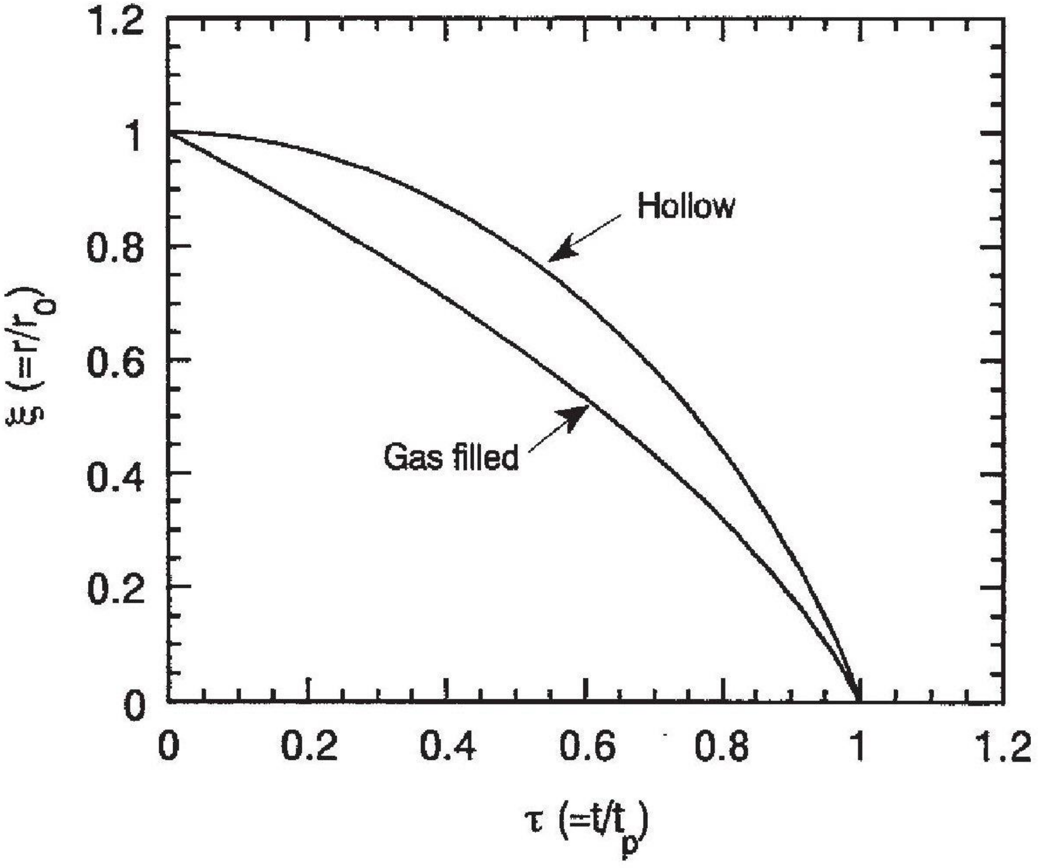
t= 1.6E-0006s, I= 193 kA, Uc= 1.9 kV

MHD Code by Viktor Vikhrev

プラズマフォーカスの特徴

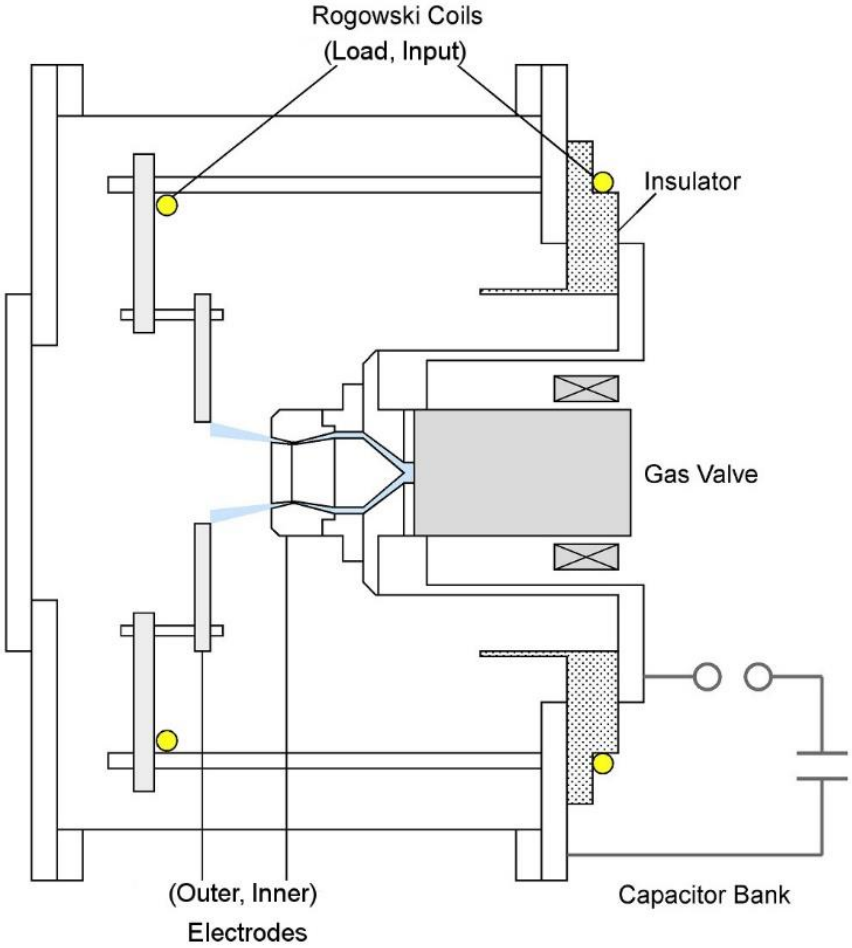
- パルスパワーを必要とせず、通常のコンデンサバンクでプラズマは一点に収束する
- 軸方向加速のフェーズでは不安定性が発生しない
- 簡単に核融合反応が起きるが、熱的ではなくビームによるものと理解されている
- 沿面放電を利用するため、絶縁物が劣化する

円環ガスパフによる収縮速度の向上



K. Takasugi et al., NIFS Proc. 18, 163, 1994

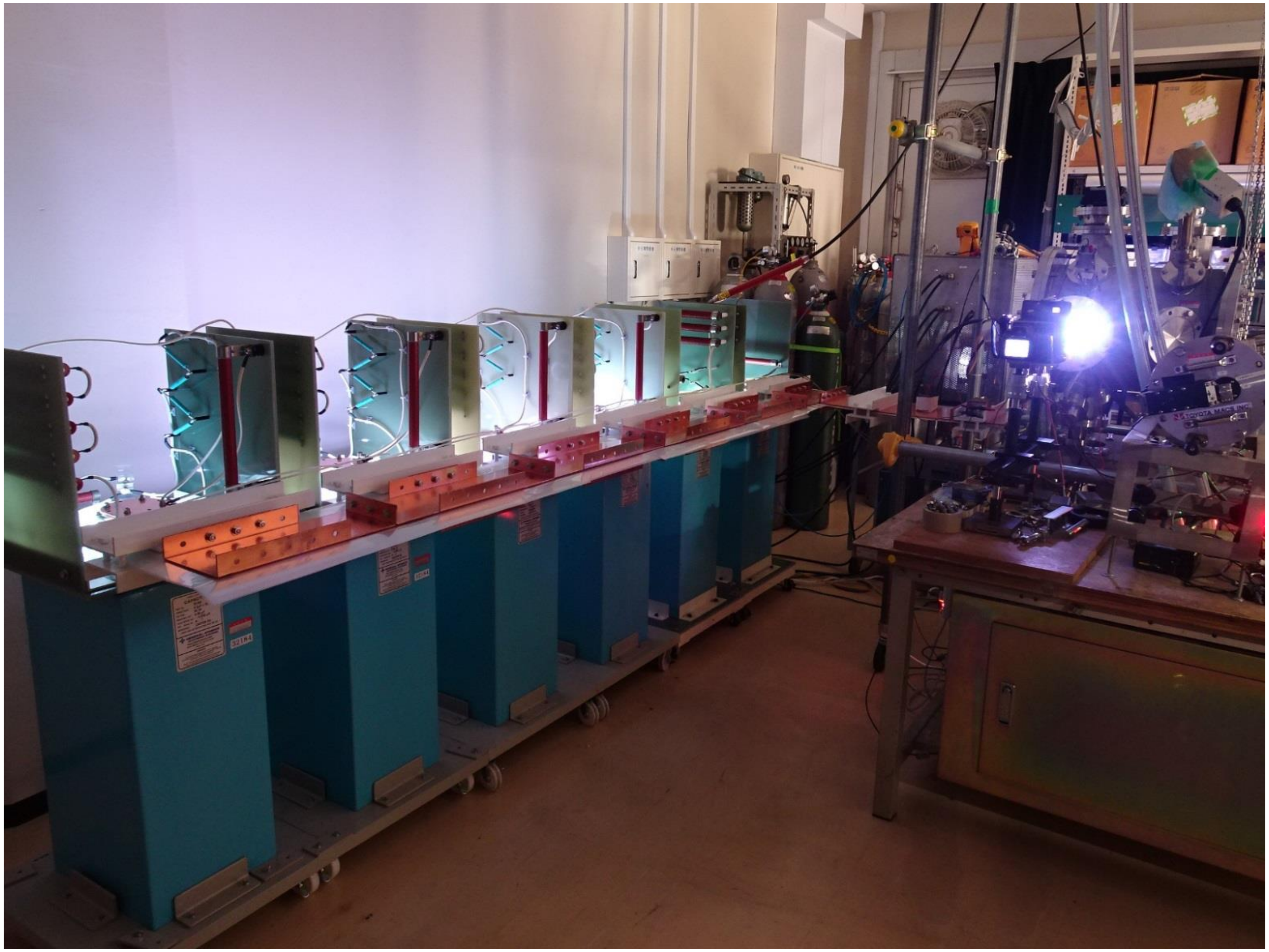
SHOTGUN III-U Z-Pinch Device



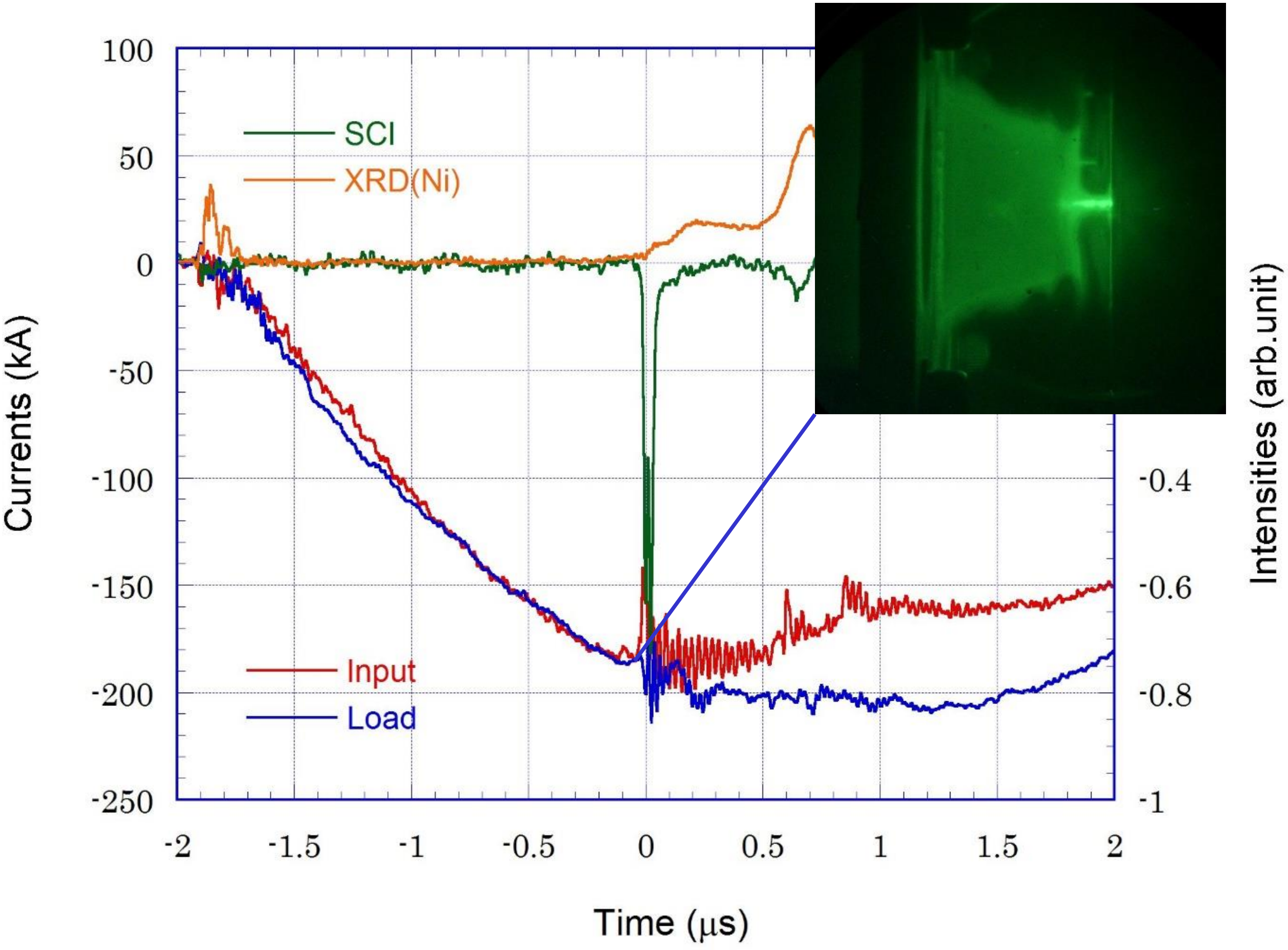
36μF ±40 kV

電極間隔 30 mm

SHOTGUN III-U Z-Pinch Device

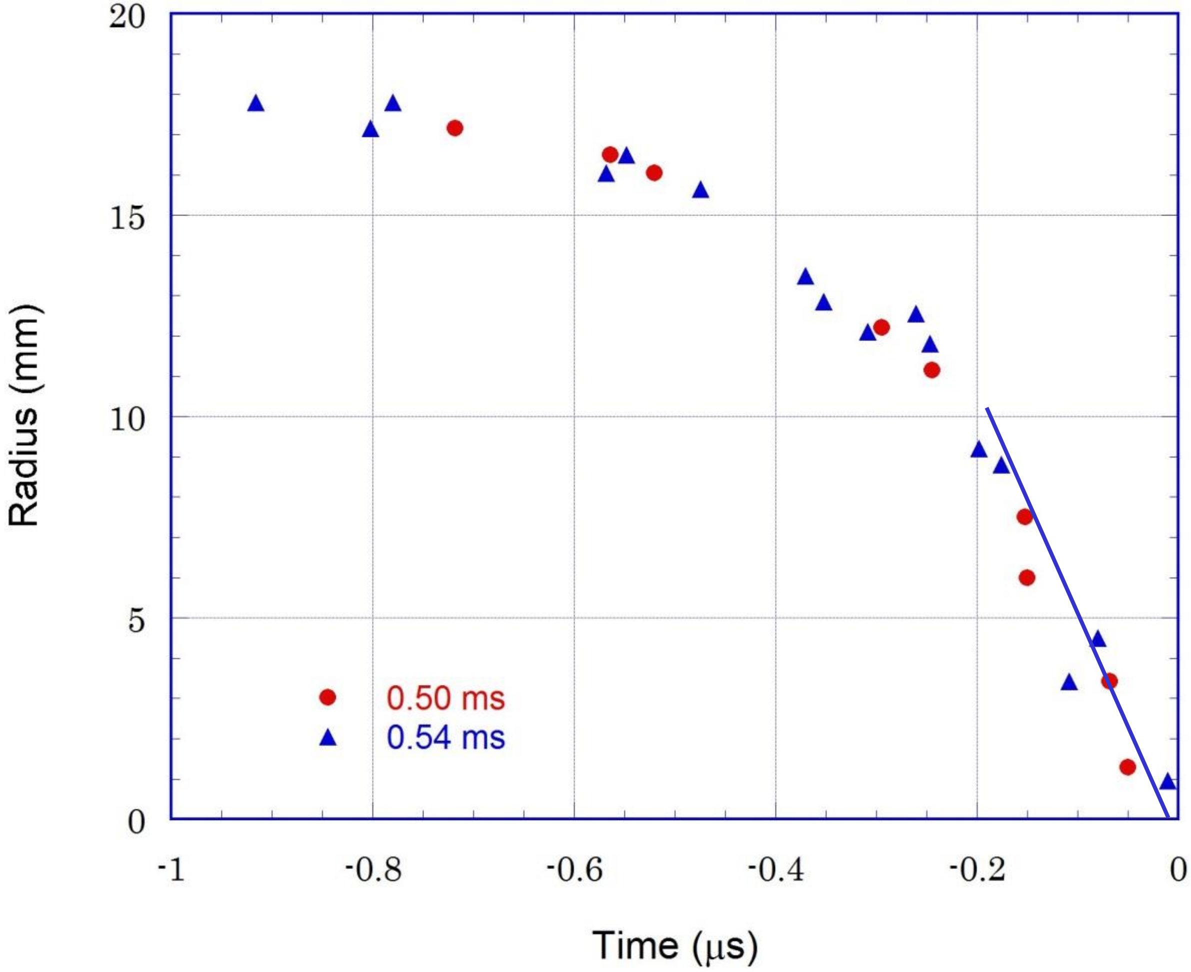


Gated Image of the Pinch Plasma



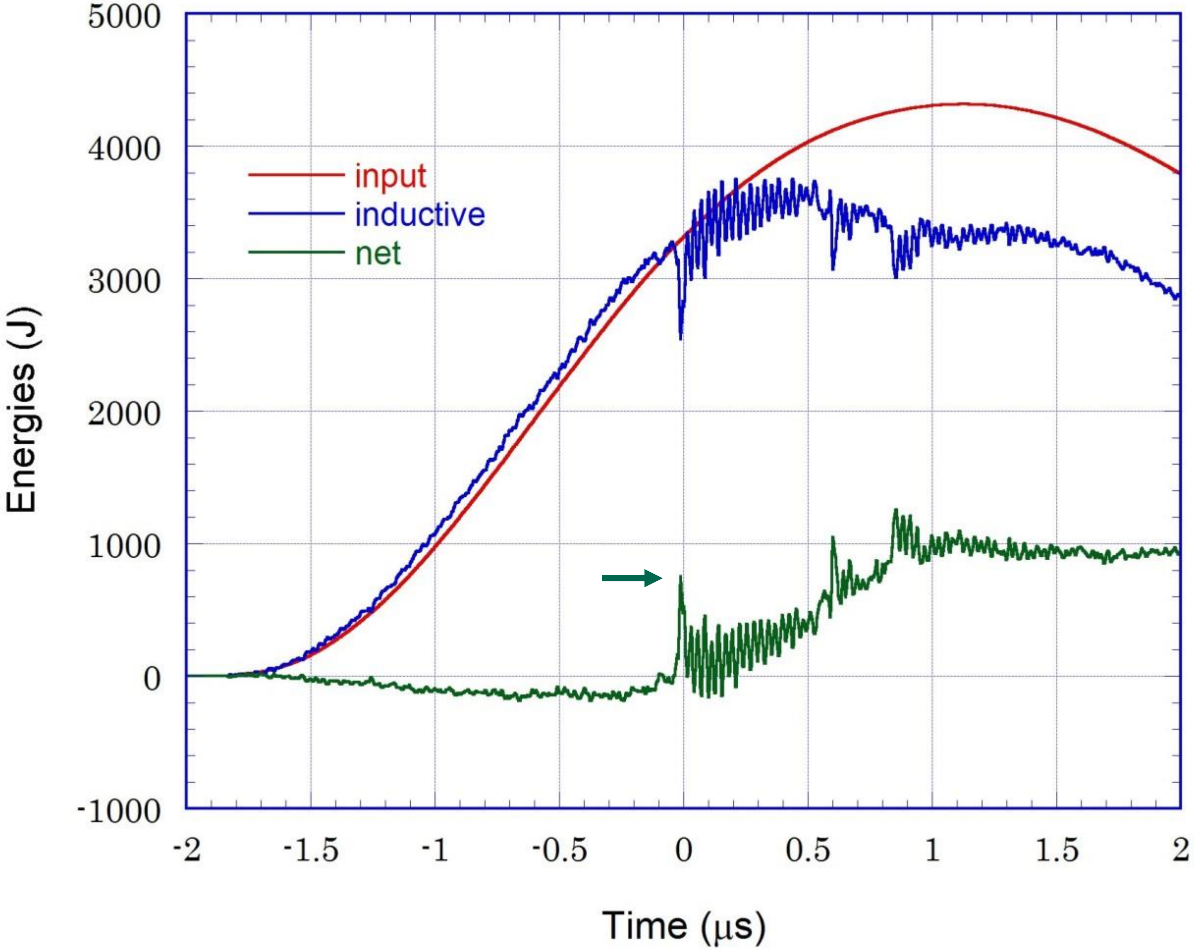
-50 ns

Radial Motion of the Pinch Plasma



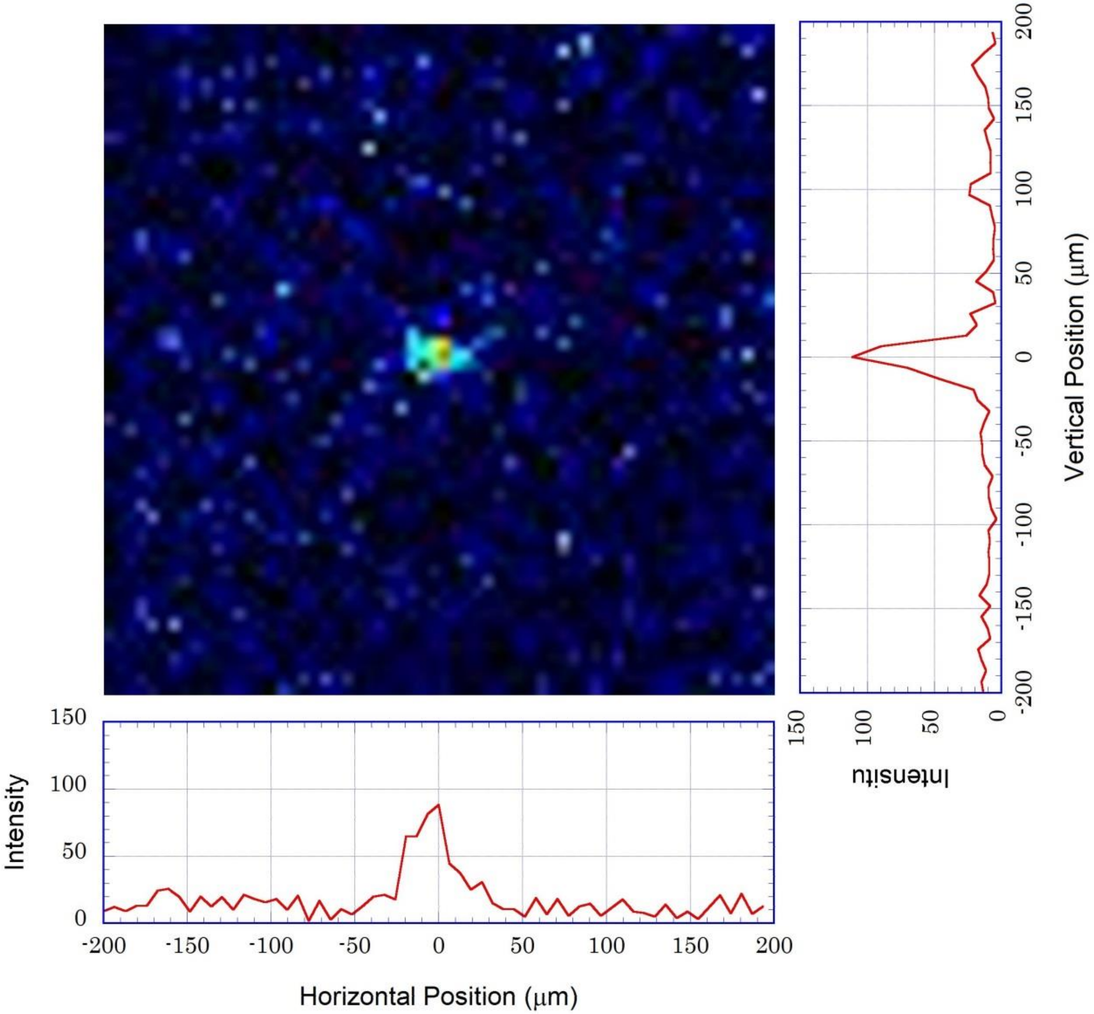
Collapsing velocity 5.5×10^4 m/s

Energy Transfer to the Pinch Plasma



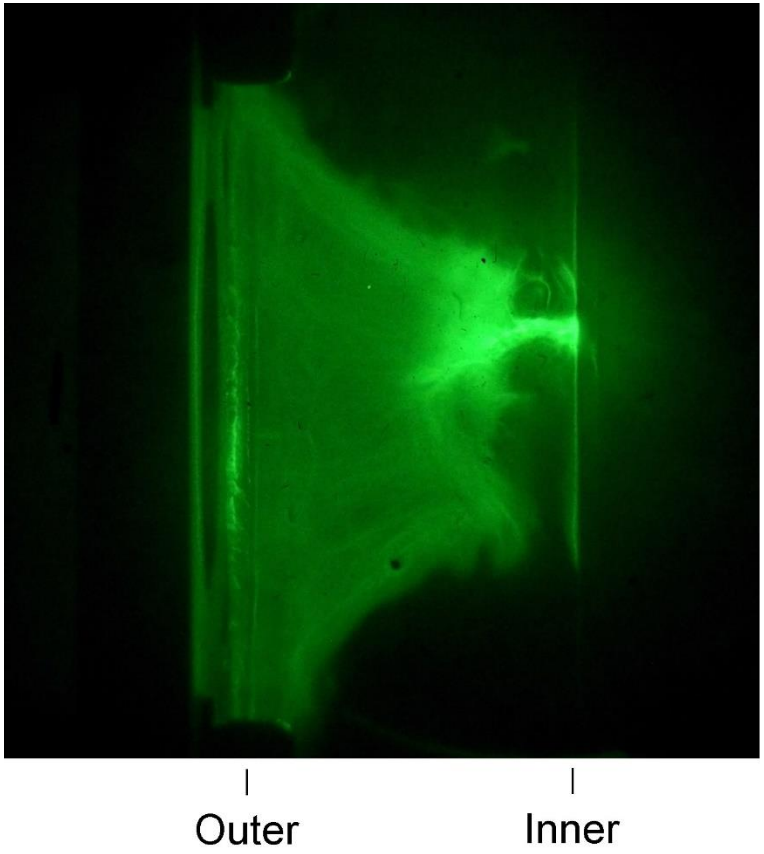
Net input energy 750 J (13 % of the stored energy 5.6 kJ)

Hot Spot Image on the CCD

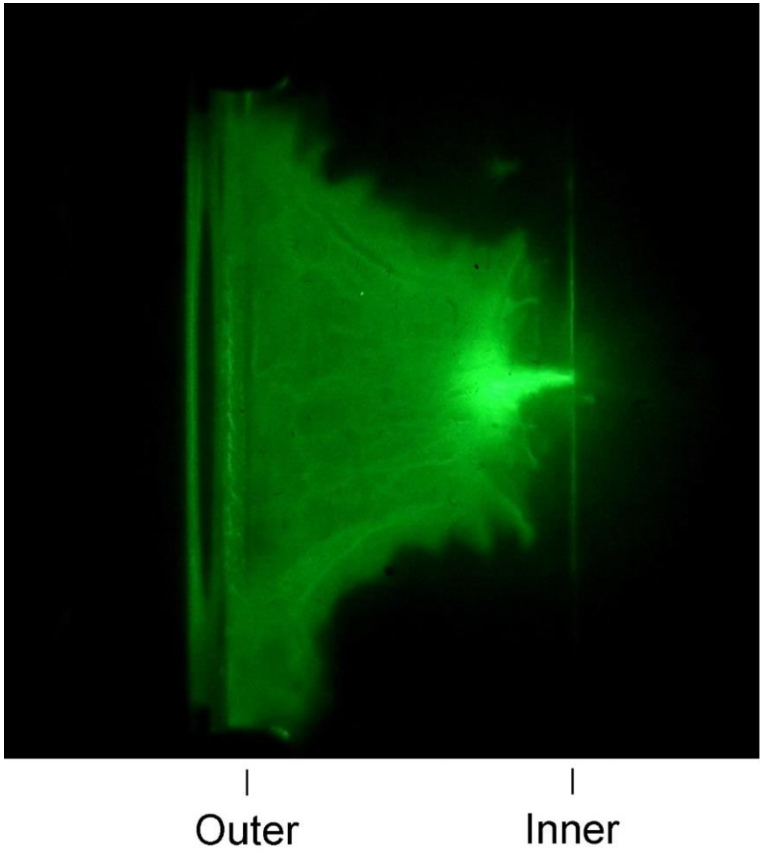


Horizontal 56 μm, Vertical 35 μm, Resolution 7 μm

ピンチプラズマの形状

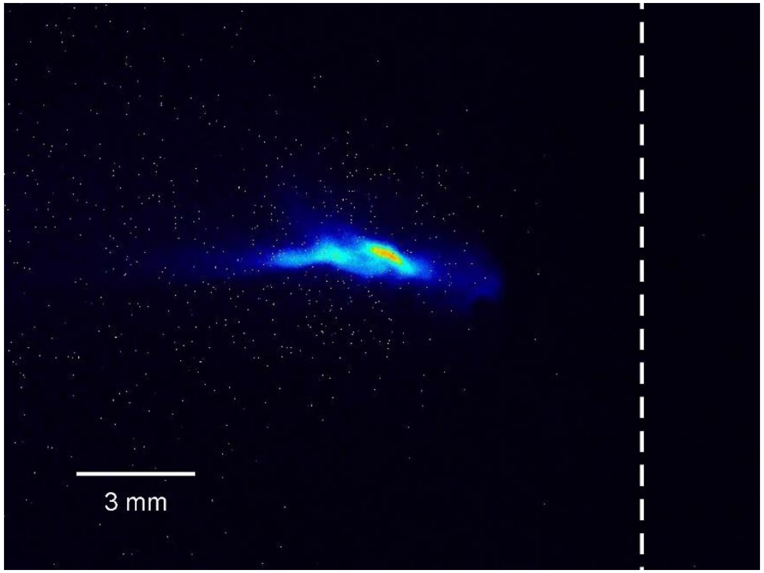


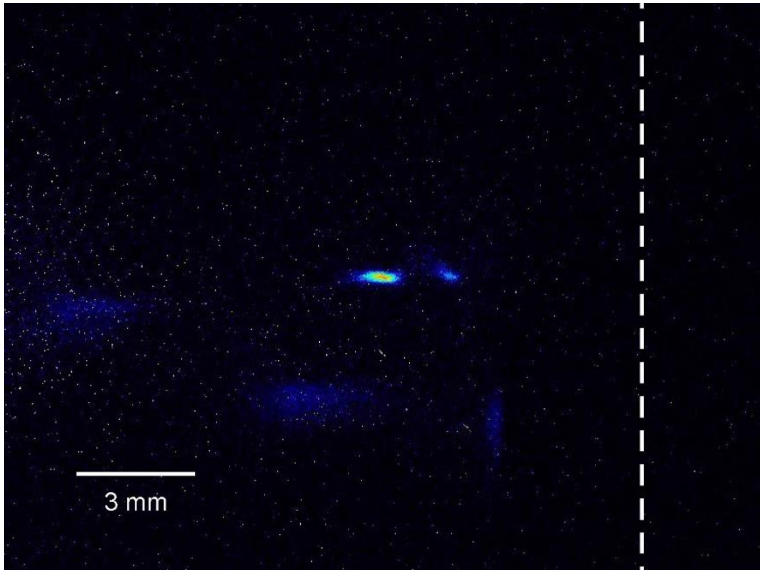
N_2



C_3H_8

ホットスポットの形状

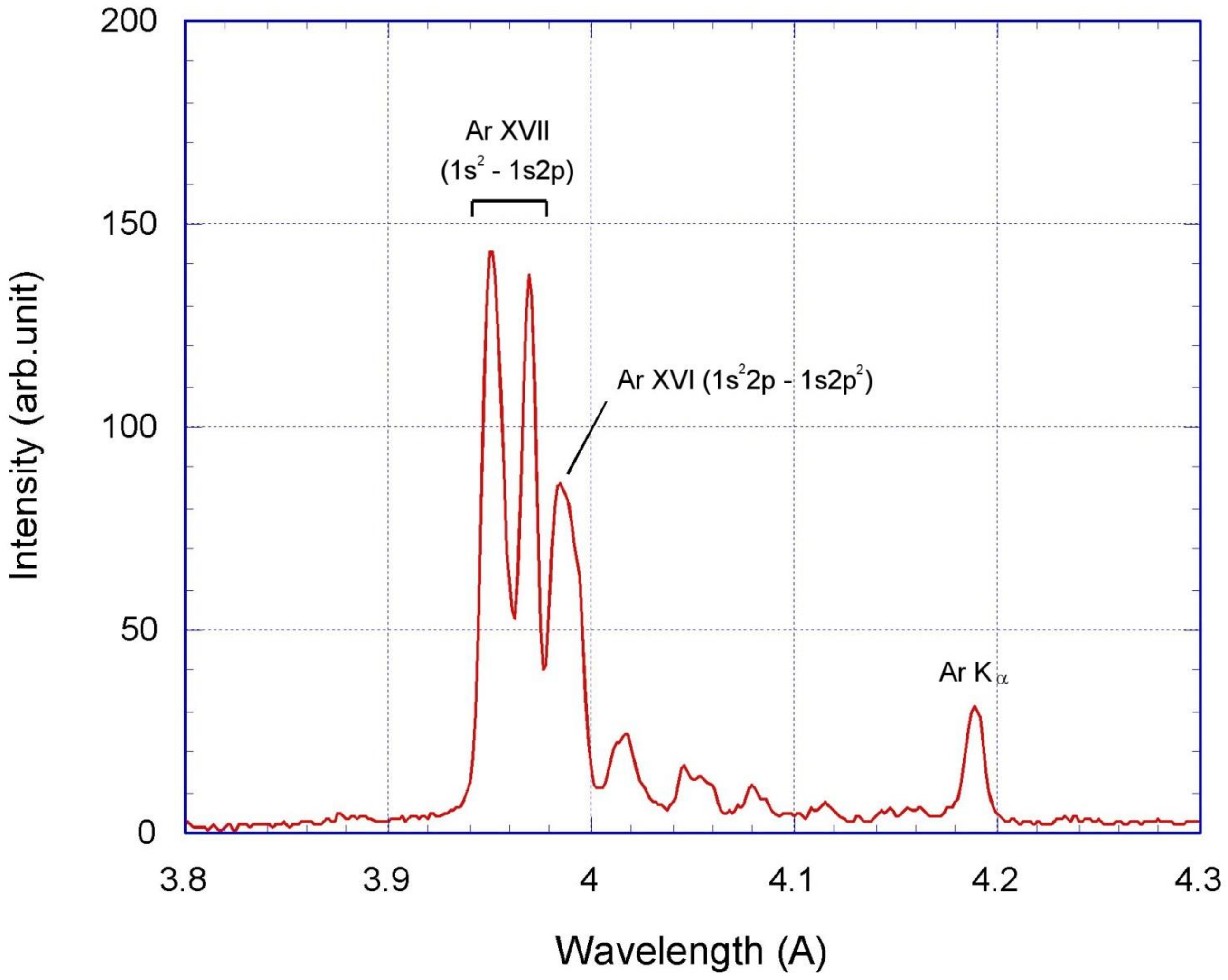




N_2

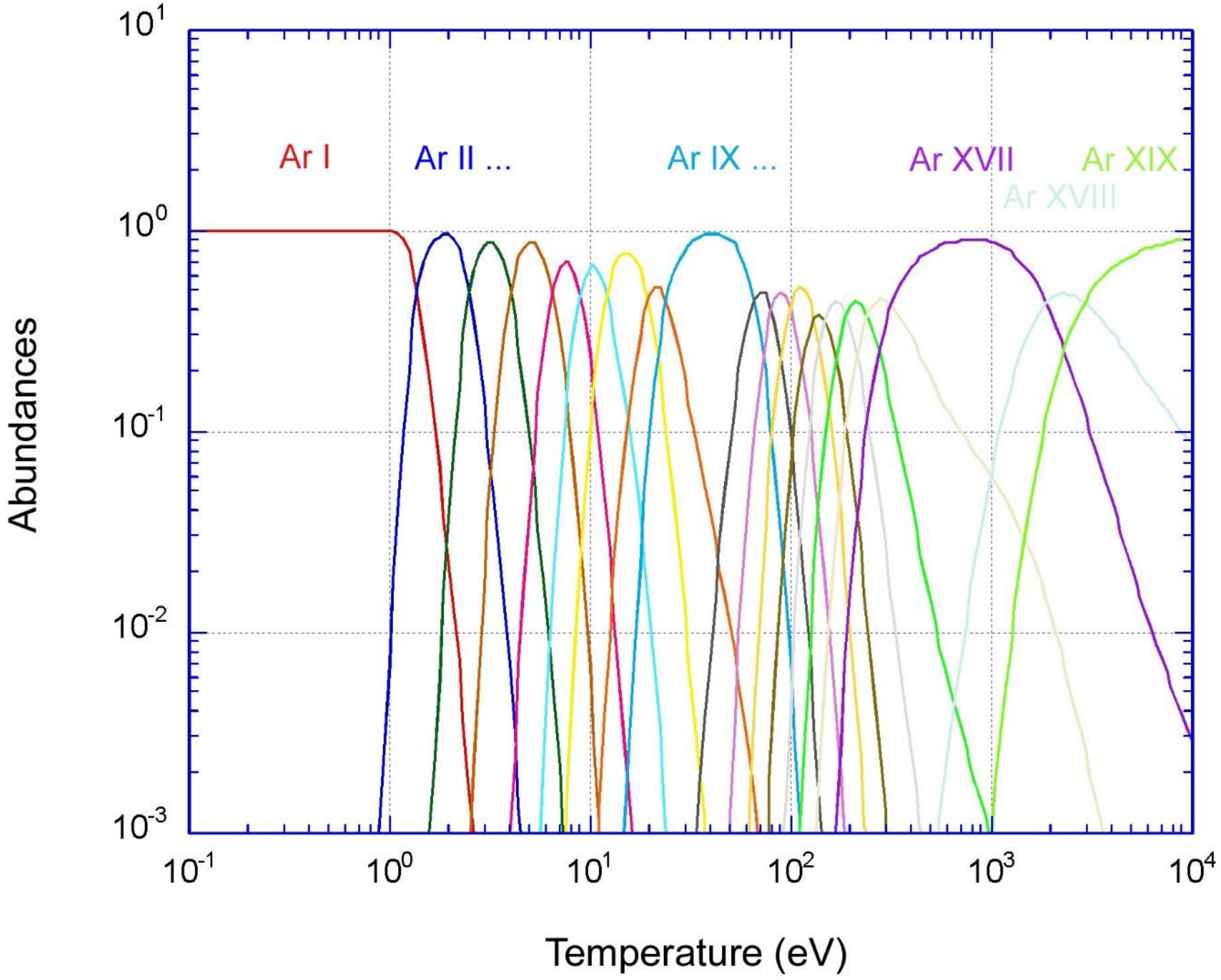
C_3H_8

ArイオンのK殻放射

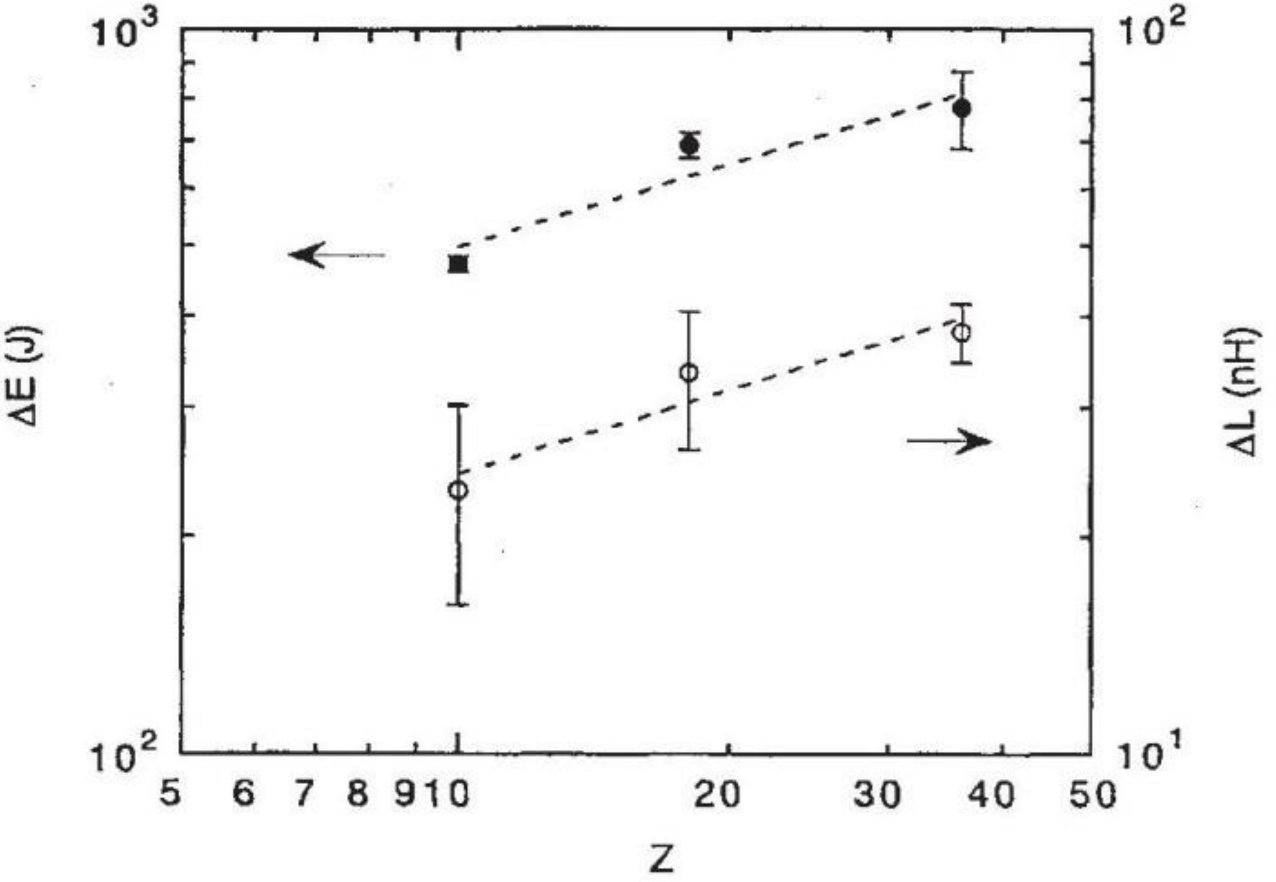


Ar XVII
(1s^2 - 1s2p)
Ar XVI (1s^{2}2p - 1s2p^2)
Ar K$_\alpha$
200
150
100
50
0
Intensity (arb.unit)
3.8
3.9
4
4.1
4.2
4.3
Wavelength (A)

Arイオンの占有密度

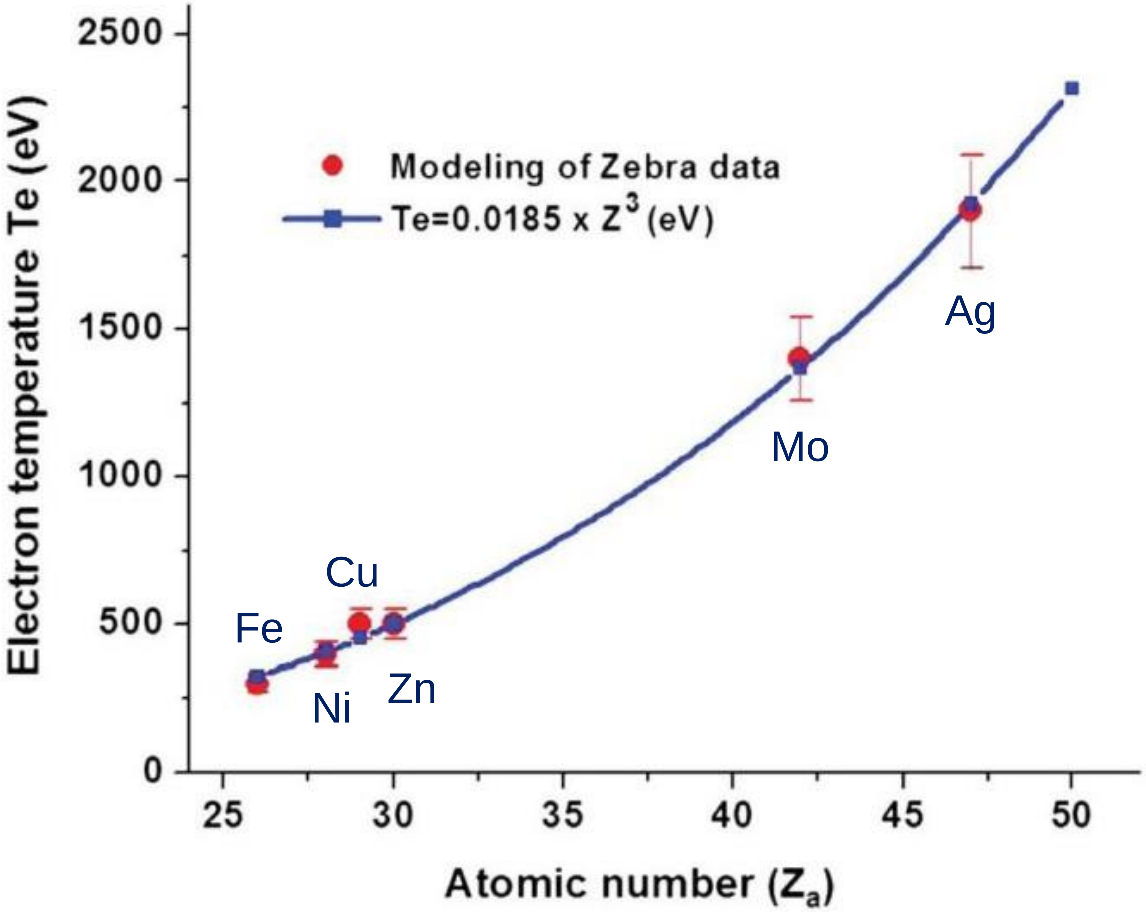

Ar I
Ar II ...
Ar IX ...
Ar XVII
Ar XIX
Ar XVIII
Abundances
10^1
10^0
10^-1
10^-2
10^-3
10^-1
10^0
10^1
10^2
10^3
10^4
Temperature (eV)

入力エネルギーの原子番号依存性



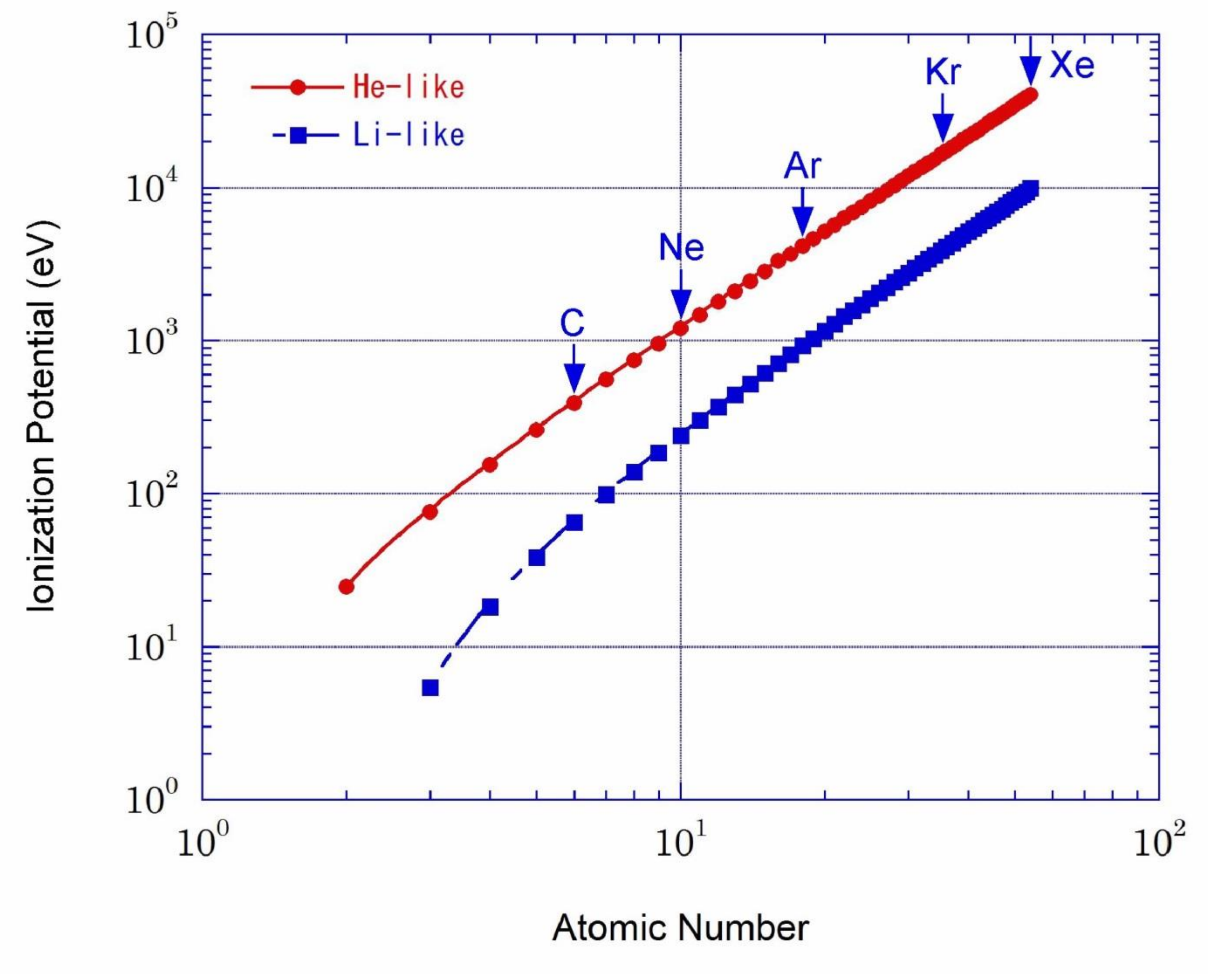
K. Takasugi et al., Jpn. J. Appl. Phys. 35, 4051, 1996

電子温度の原子番号依存性

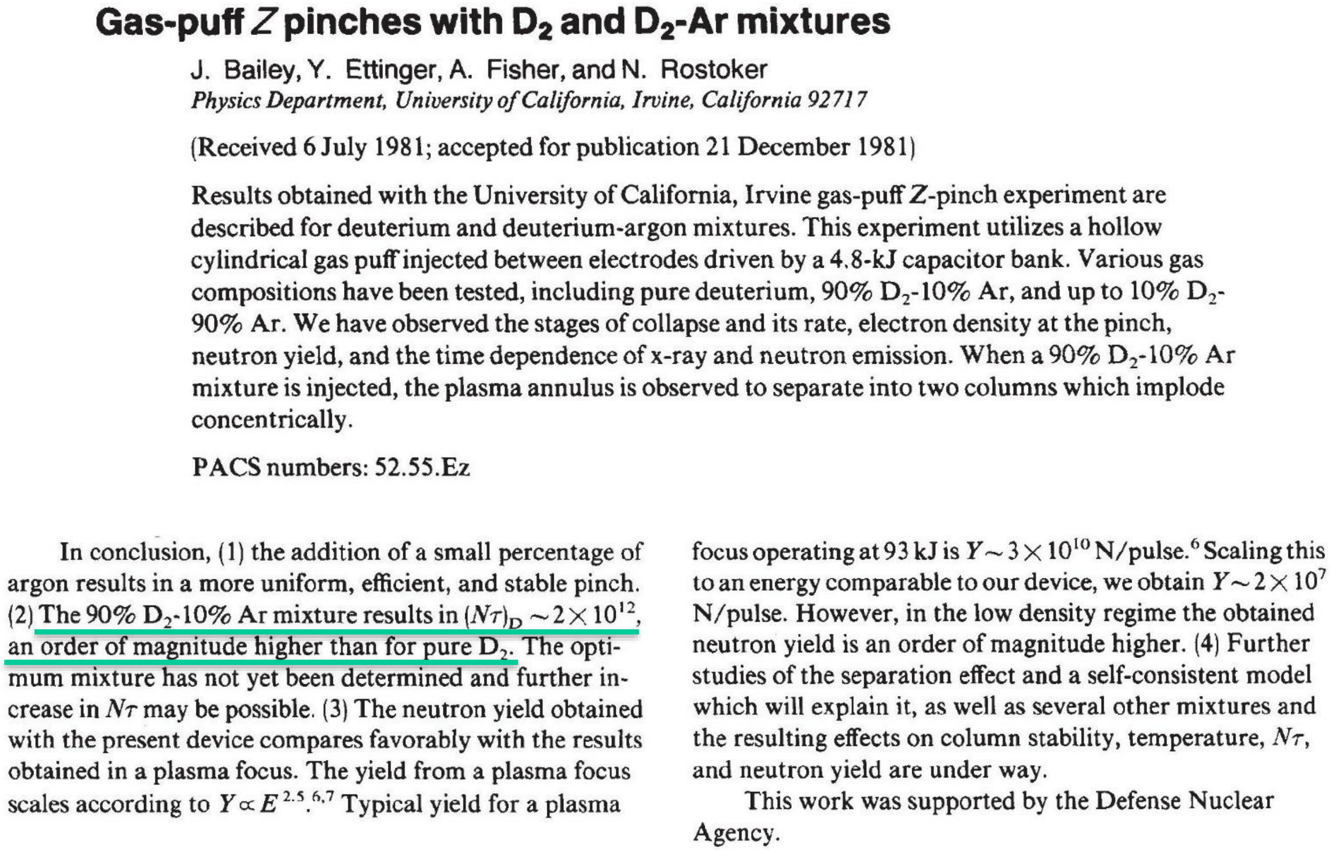


A. Safronova et al., IEEE TPS 40, 3347, 2015

多価イオンの電離ポテンシャル



D_2とArの混合ガス実験



Gas-puff *Z* pinches with D_2 and D_2-Ar mixtures

J. Bailey, Y. Ettinger, A. Fisher, and N. Rostoker
Physics Department, University of California, Irvine, California 92717

(Received 6 July 1981; accepted for publication 21 December 1981)

Results obtained with the University of California, Irvine gas-puff *Z*-pinch experiment are described for deuterium and deuterium-argon mixtures. This experiment utilizes a hollow cylindrical gas puff injected between electrodes driven by a 4.8-kJ capacitor bank. Various gas compositions have been tested, including pure deuterium, 90% D_2-10% Ar, and up to 10% D_2-90% Ar. We have observed the stages of collapse and its rate, electron density at the pinch, neutron yield, and the time dependence of x-ray and neutron emission. When a 90% D_2-10% Ar mixture is injected, the plasma annulus is observed to separate into two columns which implode concentrically.

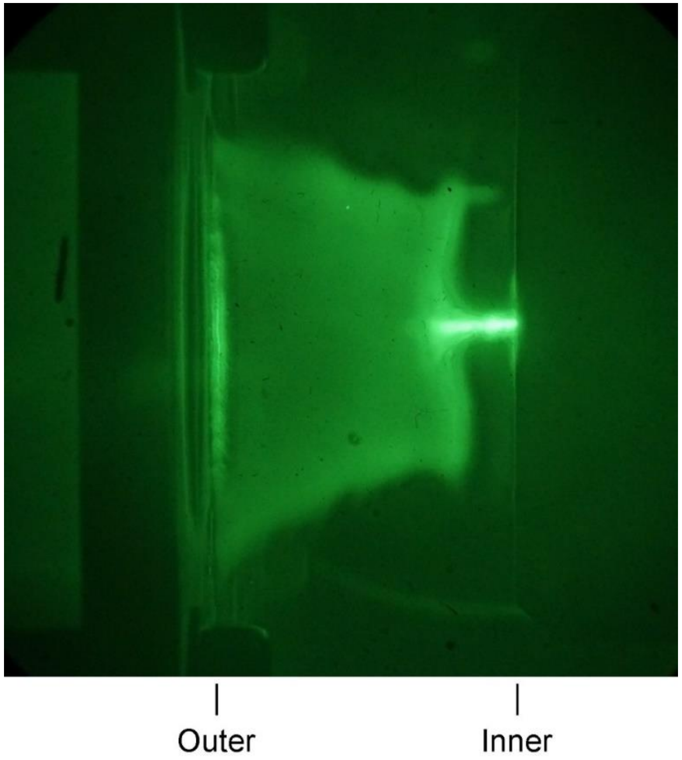
PACS numbers: 52.55.Ez

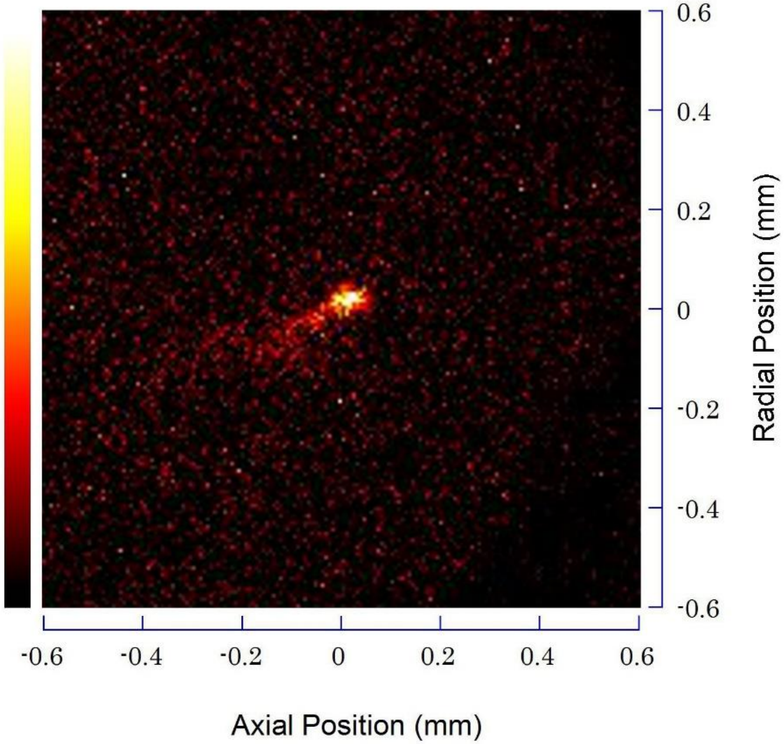
In conclusion, (1) the addition of a small percentage of argon results in a more uniform, efficient, and stable pinch. (2) The 90% D_2-10% Ar mixture results in $(N\tau)_D \sim 2\times 10^{12}$, an order of magnitude higher than for pure D_2. The optimum mixture has not yet been determined and further increase in $N\tau$ may be possible. (3) The neutron yield obtained with the present device compares favorably with the results obtained in a plasma focus. The yield from a plasma focus scales according to $Y \propto E^{2.5}$.[6,7] Typical yield for a plasma focus operating at 93 kJ is $Y \sim 3\times 10^{10}$ N/pulse.[6] Scaling this to an energy comparable to our device, we obtain $Y \sim 2\times 10^{7}$ N/pulse. However, in the low density regime the obtained neutron yield is an order of magnitude higher. (4) Further studies of the separation effect and a self-consistent model which will explain it, as well as several other mixtures and the resulting effects on column stability, temperature, $N\tau$, and neutron yield are under way.

This work was supported by the Defense Nuclear Agency.

J. Bailey et.al., Appl. Phys. Lett. 40, 460, 1982

Ar : H_2　(5 : 0)

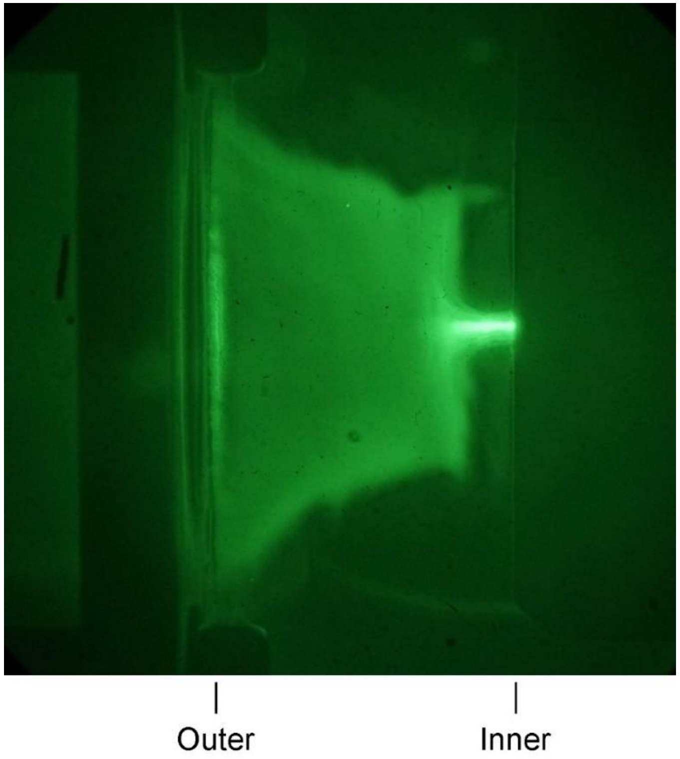


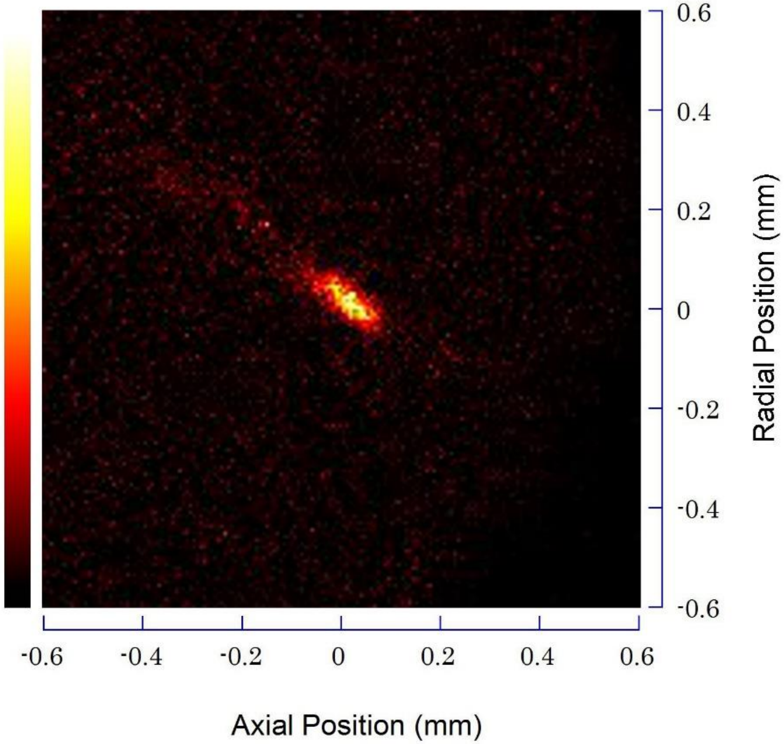


ピンチプラズマ

軟X線像

$Ar : H_2$ (4 : 1)

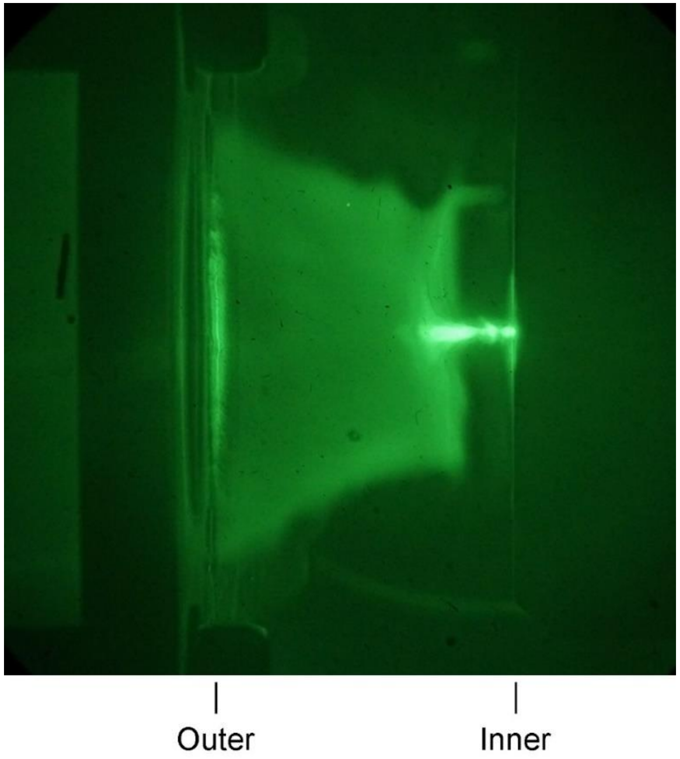




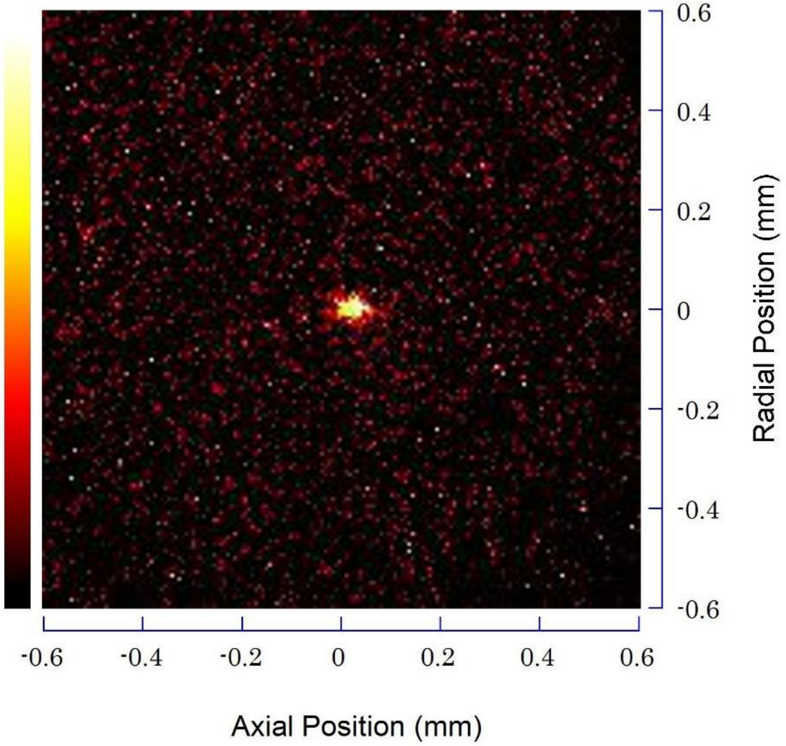
ピンチプラズマ

軟X線像

Ar : H_2 (3 : 2)

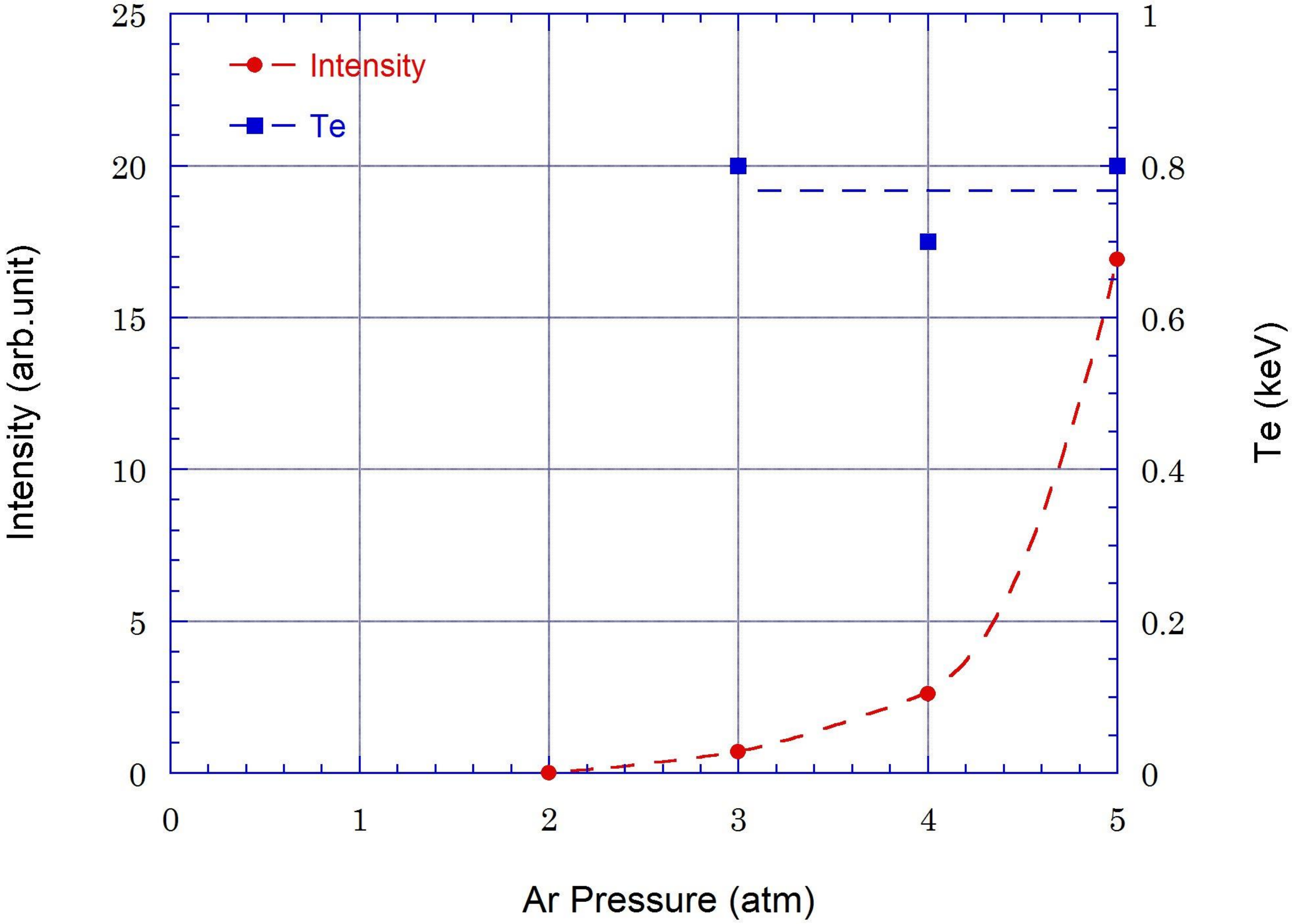


ピンチプラズマ



軟X線像

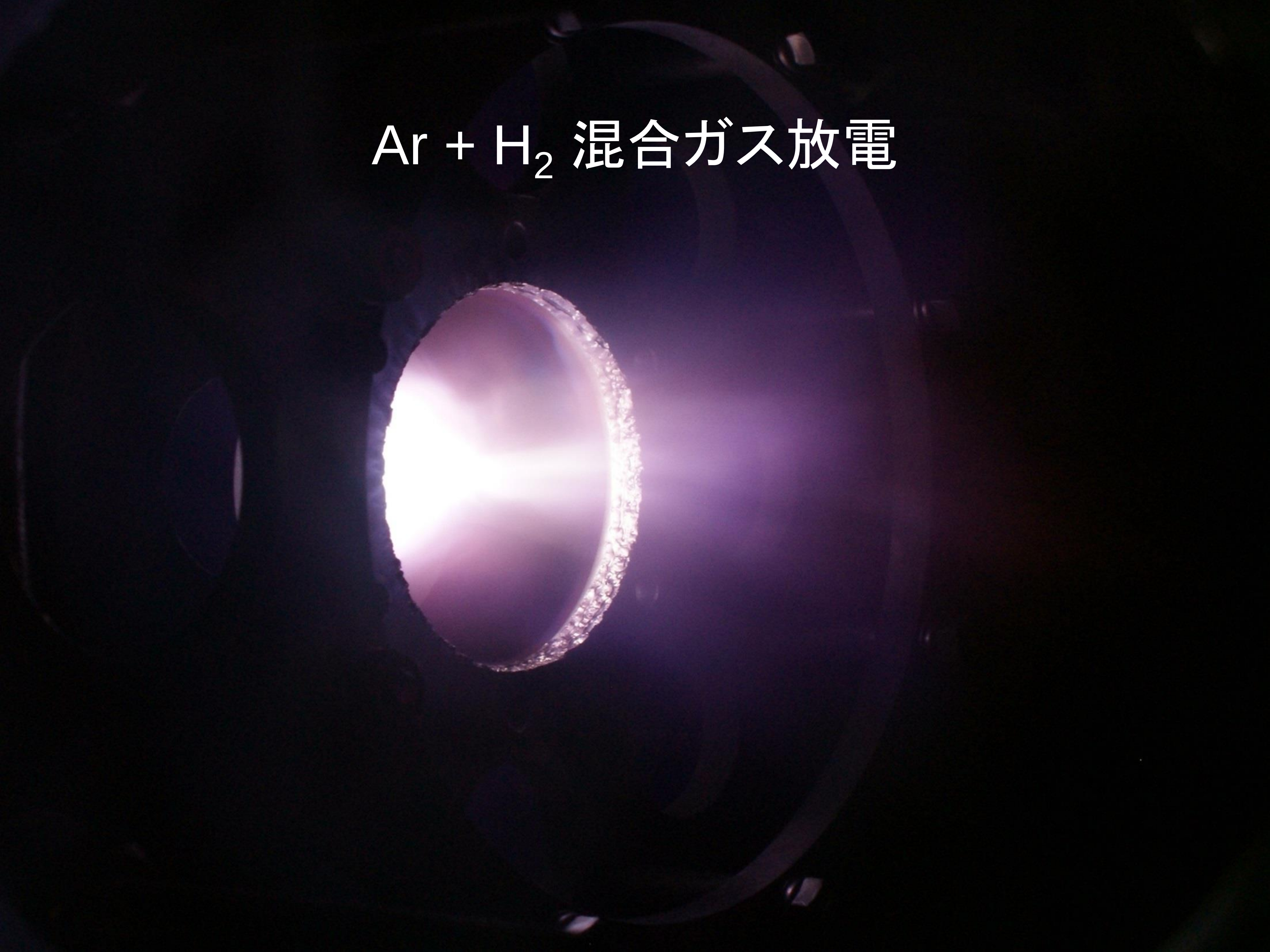
軟X線放射強度のAr分圧依存性



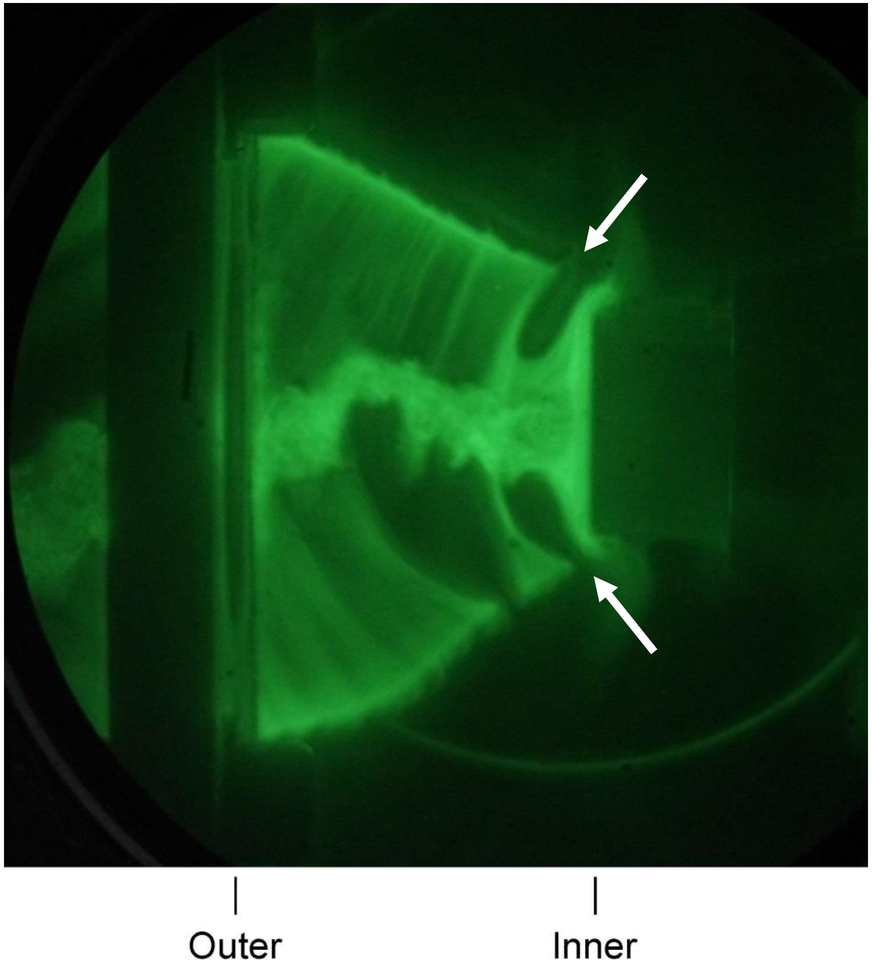
仮　説

- 原子番号の大きな元素を用いると放射冷却によって収縮時に温度が上がらず、強く収縮することができ、大きなエネルギー入力を得て、結果的に高温になる。
- 核融合燃料に原子番号の大きな元素を混合することにより、強く収縮させることができて高温が得られる。
- Xeを用いることにより、１０keVのピンチプラズマが得られ、核融合の点火が達成される。

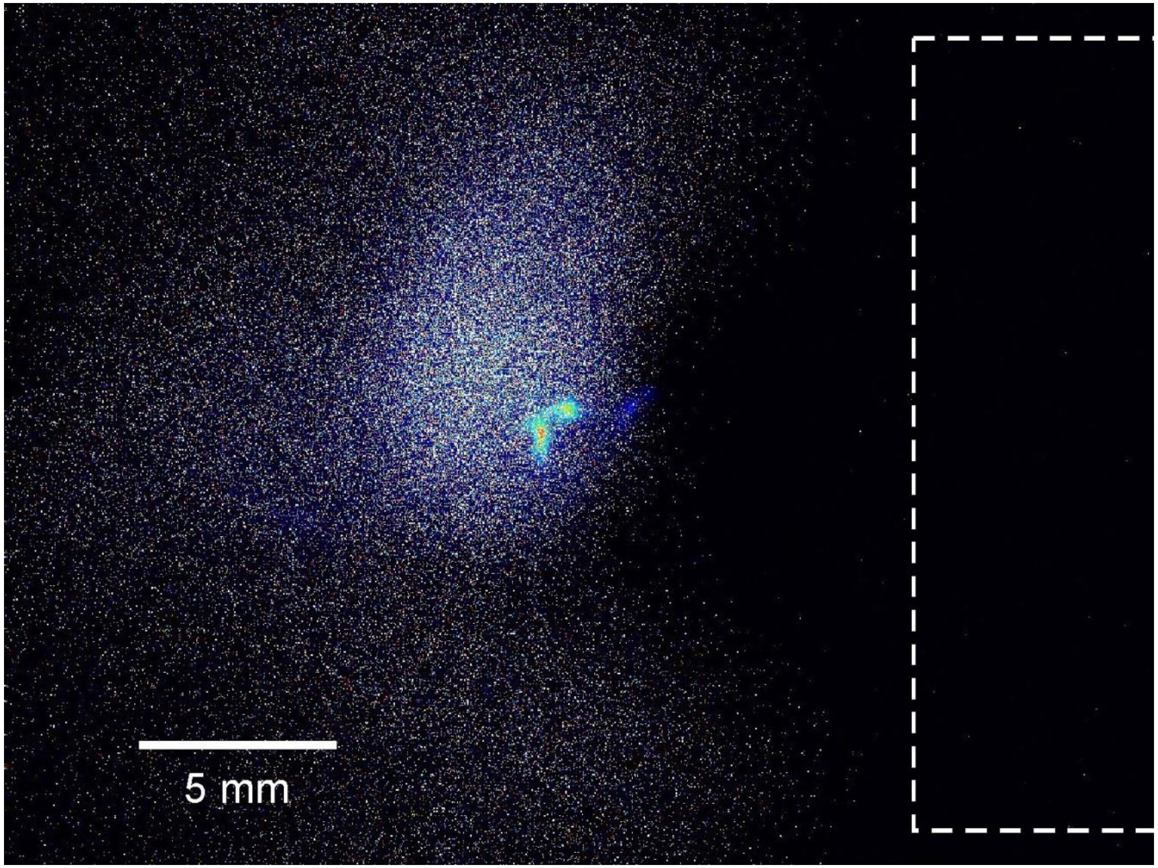
Ar + H_2 混合ガス放電

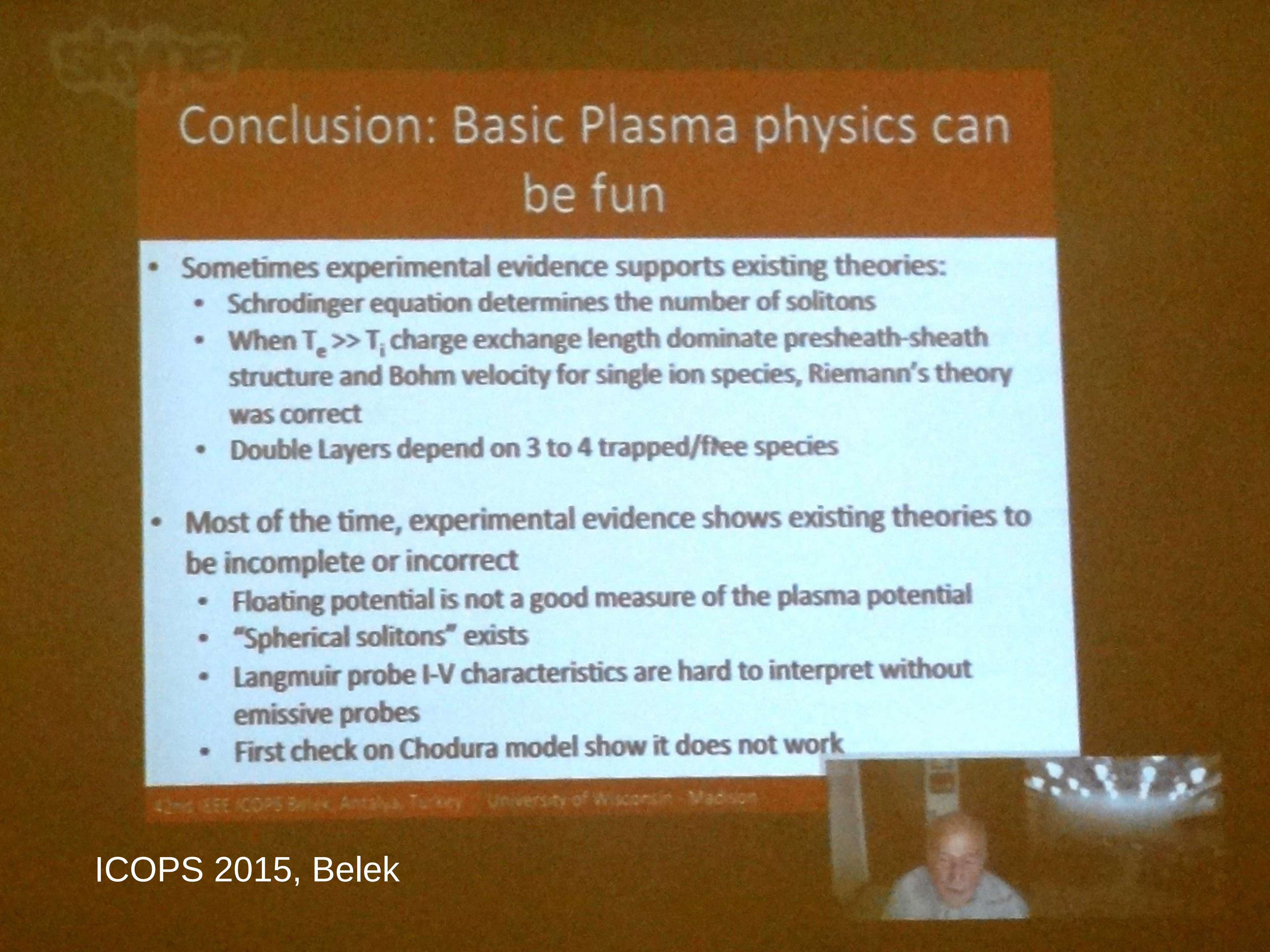


発散型Cuワイヤアレイ Zピンチ



発散型Cuワイヤアレイzピンチ





Conclusion: Basic Plasma physics can be fun

- Sometimes experimental evidence supports existing theories:
    - Schrodinger equation determines the number of solitons
    - When $T_e >> T_i$ charge exchange length dominate presheath-sheath structure and Bohm velocity for single ion species, Riemann's theory was correct
    - Double Layers depend on 3 to 4 trapped/free species

- Most of the time, experimental evidence shows existing theories to be incomplete or incorrect
    - Floating potential is not a good measure of the plasma potential
    - "Spherical solitons" exists
    - Langmuir probe I-V characteristics are hard to interpret without emissive probes
    - First check on Chodura model show it does not work

ICOPS 2015, Belek