Characteristics of Capillary Z-pinch Discharge Light Source

***Eiki Hotta, Inho Song, Mitsuo Okamoto, Keita Kitade, Yasushi Hayashi, Masato Watanabe, Akitoshi Okino, Koichi Yasuoka and Kazuhiko Horioka**

Tokyo Institute of Technology

Nagatsuta, Midori-ku, Yokohama 226-8502, JAPAN

***E-mail: ehotta@es.titech.ac.jp**

Objectives

- **Development of High Quality, High Power EUV Source**
  - **Output＝ECE×（Energy／Shot）×Rep-rate**
    - **For example, 0.5%×2 J/Shot×10 kHz =100 W**
  - **Improvement of ECE**
  - **Decrease of input energy/shot ⇒ Debris mitigation**
  - **High rep-rate > 7-10 kHz ⇒ High power**
- **Plasma physics ⇒ Improvement of ECE**
- **Development of high rep-rate, fast pulse modulator**
  - **Fast semiconductor switch with magnetic assist**
    - **Relation between current rise time and plasma property？**
    - **Pre-ionization : Optimum condition?**
      - **Stability, plasma property？**

    ⇒ Improvement of ECE ⇒ Minimum input energy ⇒ Debris mitigation
- **Simulation : Plasma dynamics of Z-pinch plasma**
  - **Matching between power supply and plasma dynamics**

    ⇒ Improvement of ECE ⇒ Minimum input energy ⇒ Debris mitigation
- **Gas curtain ⇒ Debris mitigation**

Technical Issues of DPP Light Source

Tokyo Institute of Technology

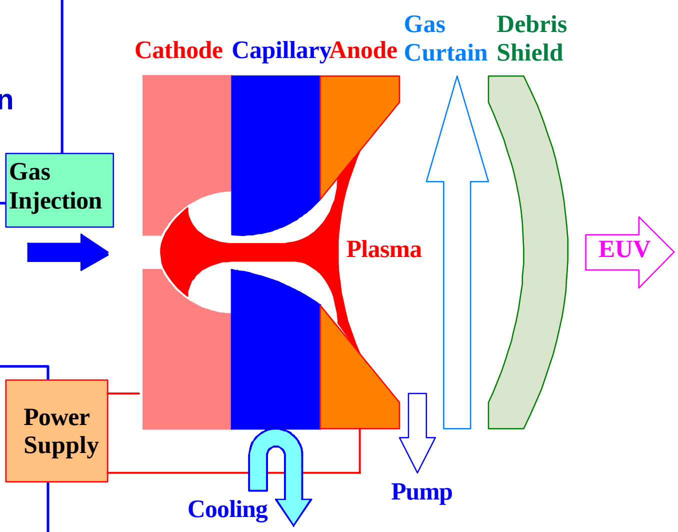
- **Electrode**
  - Material
    - High melting point, Low sputter
  - Structure
    - Wide electrode surface
      - Low current density
      - Prevent current concentration by pre-ionization
    - Location, Cooling

- **Gas injection**
  - Gas dynamics

- **Pulse modulator：>7 kHz**

  High hold-off voltage, High current, Low loss
  - High rep-rate >7 kHz
    - ◆Semiconductor switch
      - IGBT, FET, SI Thyristor（NGK)
  - Low inductance：Fast rise
  - Pre-ionization
  - Magnetic pulse compression

- **Discharge tube：Length 2-10 mm, diameter 2-4 mm**
  - Material
    - High melting point , Low sputter, High heat cond.
  - Structure: Gas dynamics



- **Debris mitigation**
  - Gas curtain
  - Thin film filter
  - Foil trap
  - Capillary plate

- **Plasma physics：Heating, confinement, stability**
  - Simulation:Plasma dynamics

    compression→Heating, radial confinement of

    High temperature・High density plasma

    → Improvement of ECE
  - Preionization→stabilization, debris mitigation

Plasma Confinement

Tokyo Institute of Technology

•**Required plasma** : Xe^{+10} ; T_e : 20 - 40 eV, $n_e \sim 1\times10^{24}$ - 10^{25} m^{-3}, $n_i \sim 1\times10^{24}$ m^{-3}

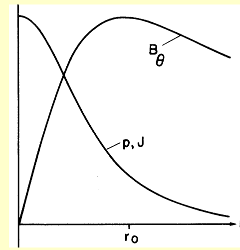
•Radial confinement → Supression of debris generation from tube wall

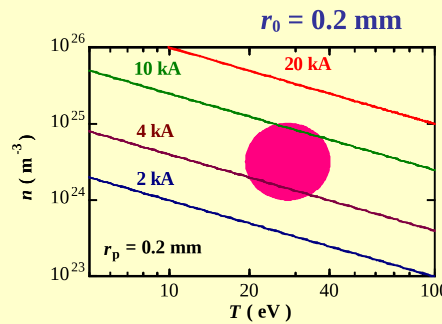
Bennett profiles (Bennett, 1934)

$$B_\theta = \frac{\mu_0 I_0}{2\pi}\frac{r}{r^2 + r_0^2}$$

$$J_z = \frac{I_0}{\pi}\frac{r_0^2}{(r^2 + r_0^2)^2}$$

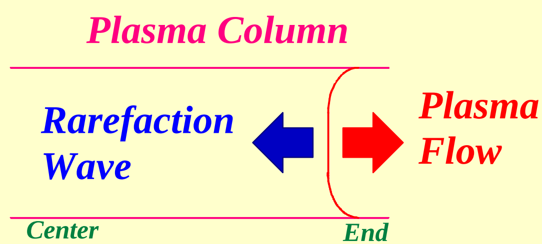
$$p = \frac{\mu_0 I_0^2}{8\pi^2}\frac{r_0^2}{(r^2 + r_0^2)^2}$$





•Axial confinement time

$$t_c \approx \frac{\ell}{2V_A} = \frac{\ell}{2\sqrt{B_q / m_0 r_m}}$$



Tube length = 3 mm

Xe : $n = 1\times10^{24}$ m^{-3}, I = 10 kA, r_p = 0.2 mm

⇨ $\tau_c \sim$ **40 ns**

Pinch Dynamics and Stability

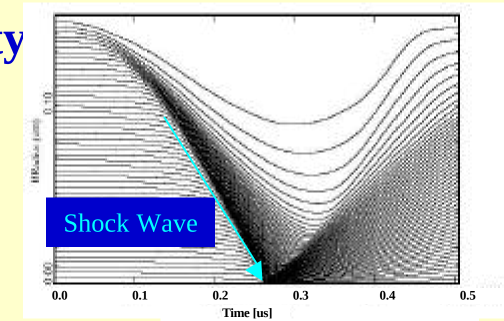
Tokyo Institute of Technology

•Pinch time : Compression speed～Alfven velocity

$$t_p \approx \frac{r_p}{V_A} = \frac{r_p}{\sqrt{B_q / m_0 r_m}}$$

Tube radias :2 mm, Xe : $n_0 = 1\times10^{22}$ m^{-3}, I = 10 kA

⇨ τ_p～100 ns



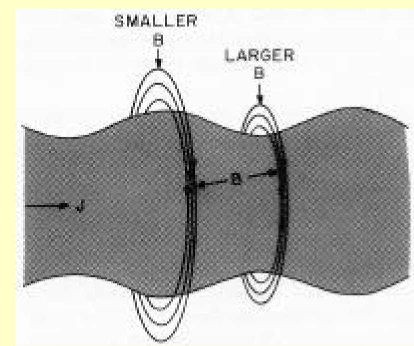
Capillary: ϕ3 mm
Current: 8 kA (peak), 1 μs (period)
Pressure: 0.8 Torr

•m=0 instability （Sausage instability）
Linear growth rate （Surface current model）

$$\frac{g^2}{k^2} \approx \frac{B_q^2}{m_0 r_m} \cdot \frac{1}{kr_p} \cdot \frac{I_0'(kr_p)}{I_0(kr_p)}$$

if $kr_p << 1$

$$\frac{g^2}{k^2} \approx \frac{1}{2} \cdot \frac{B_q^2}{m_0 r_m}$$



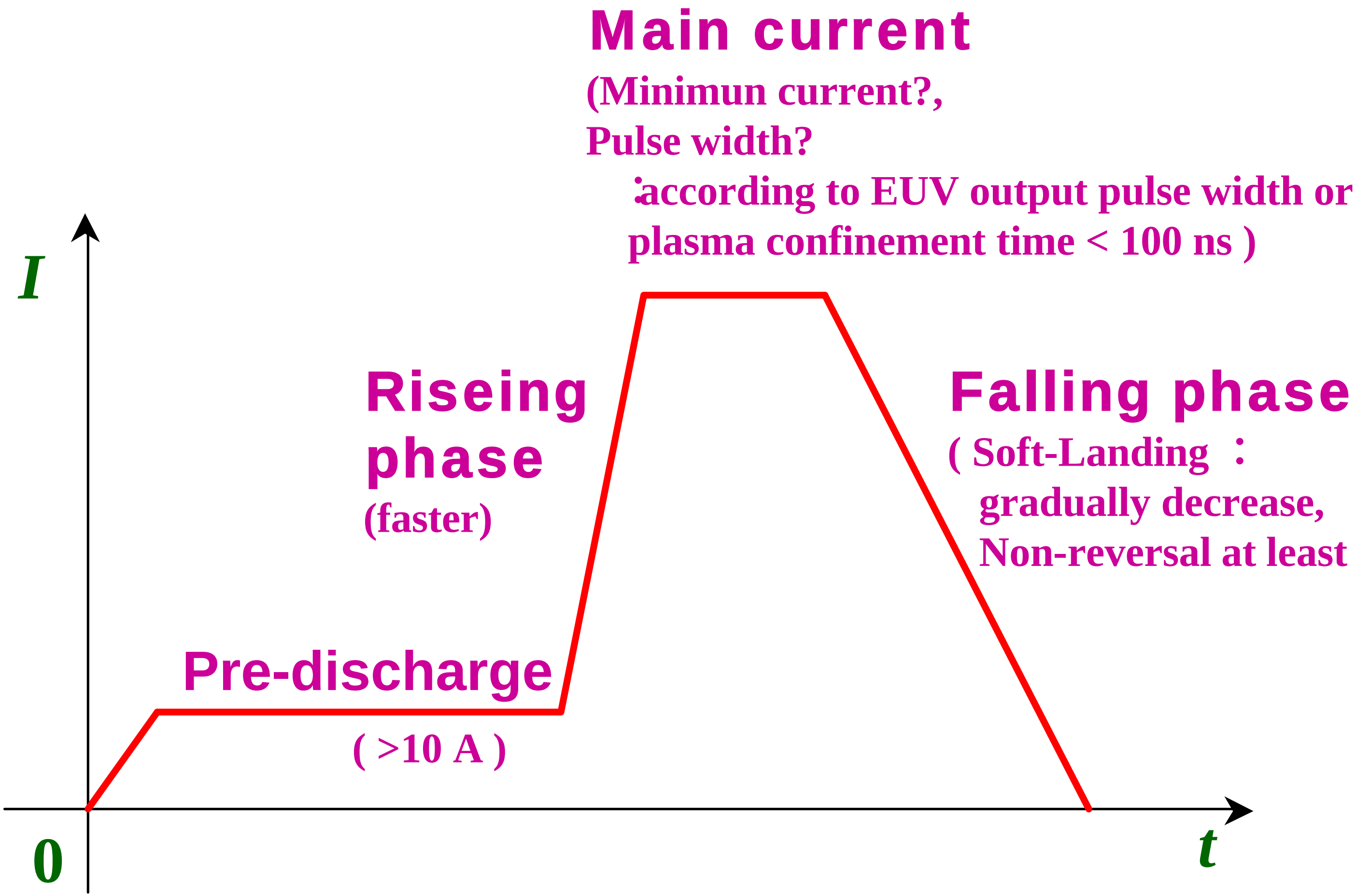
Sausage instability

Tube length =3 mm, Xe : $n = 1\times10^{24}$ m^{-3}, I = 10 kA, r_p = 0.2 mm

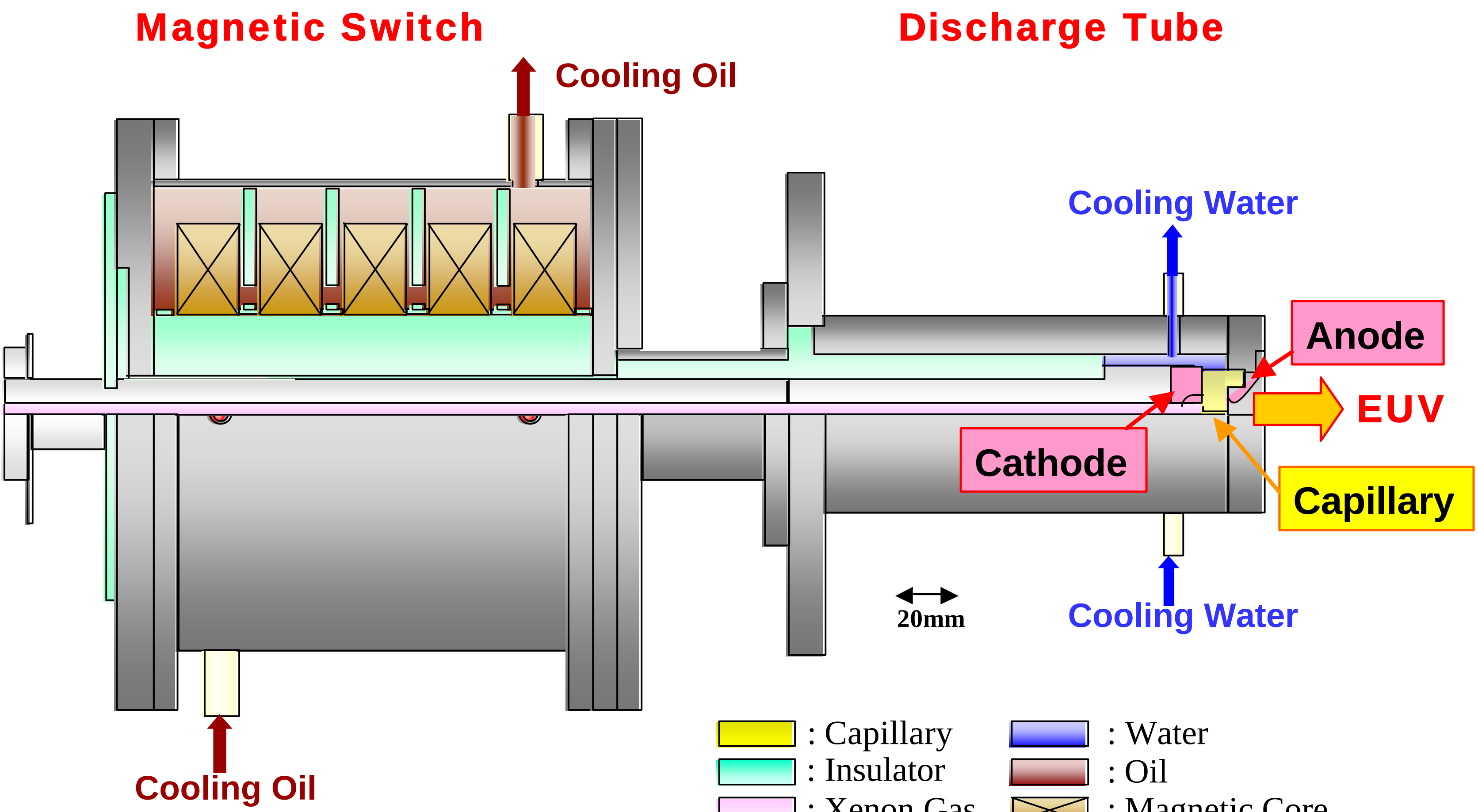
⇨ $\tau = 1/\gamma$～50 ns

Supression of initial disturbance by pre-ionization
→ Supression of instability

Required Current Waveform

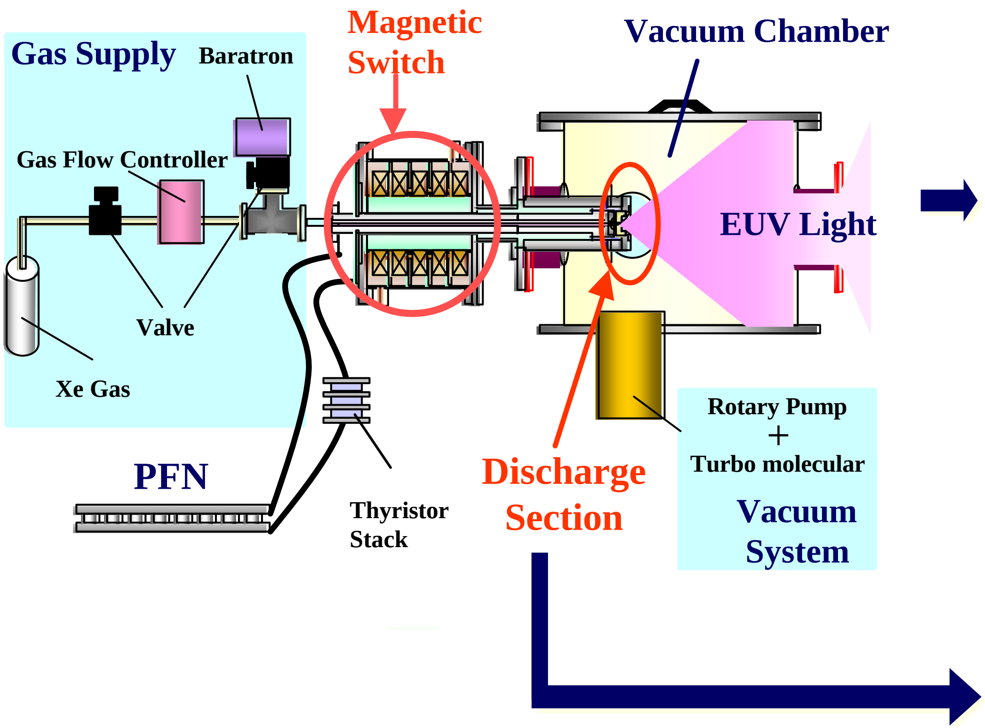


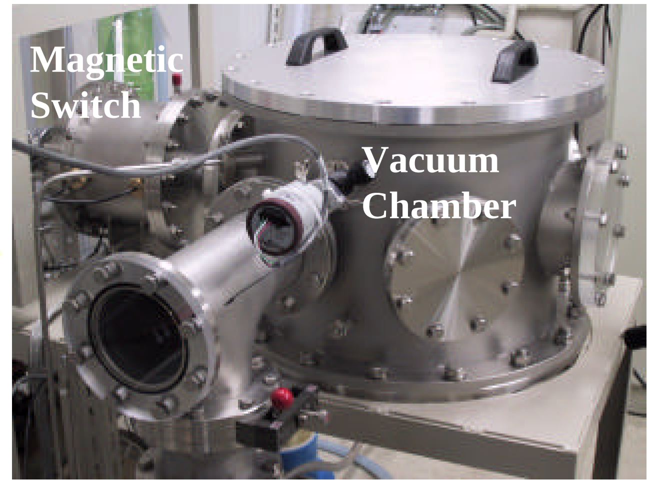
Design of Device

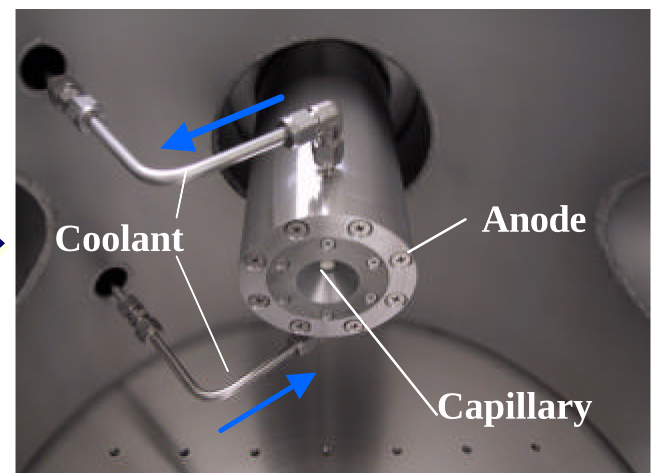


Experimental Setup

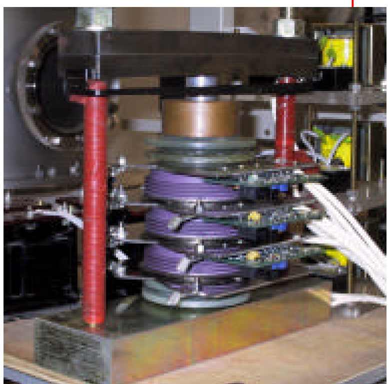
Tokyo Institute of Technology

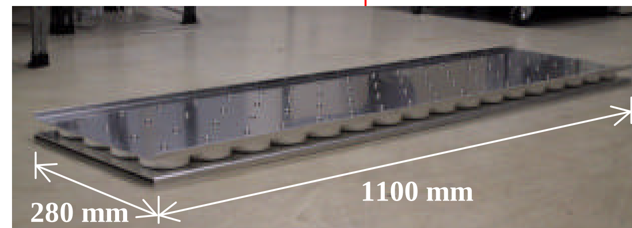


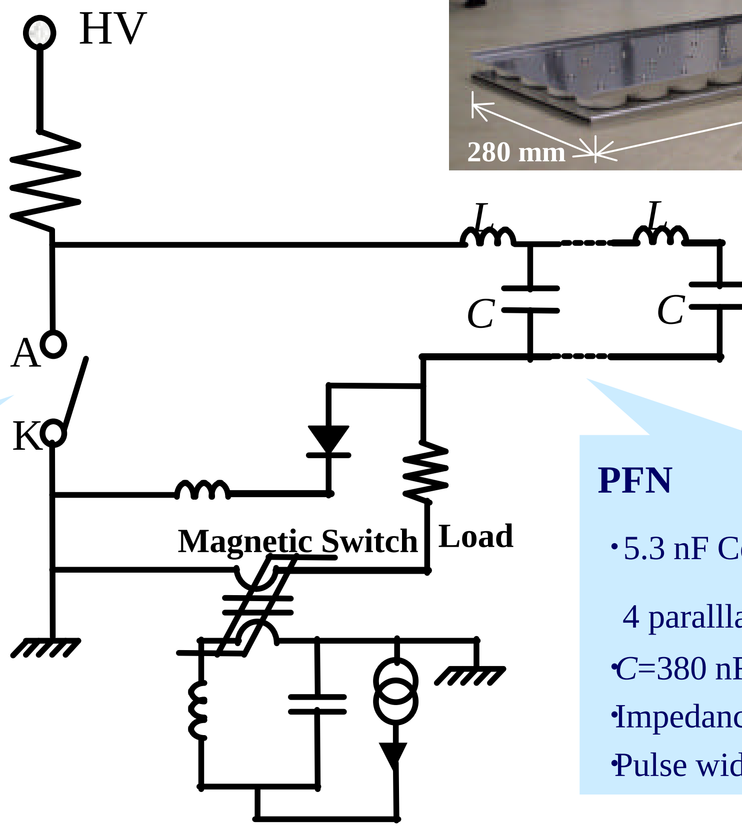




Pulse Modulator







Reset Circuit

SI(Static Induction) Thyristor

- Hold off voltage: 4.0 kV
- 3 SI Thyristors connected in series
- Effective on current: 400 A
- Surge on current: >10 kA

PFN

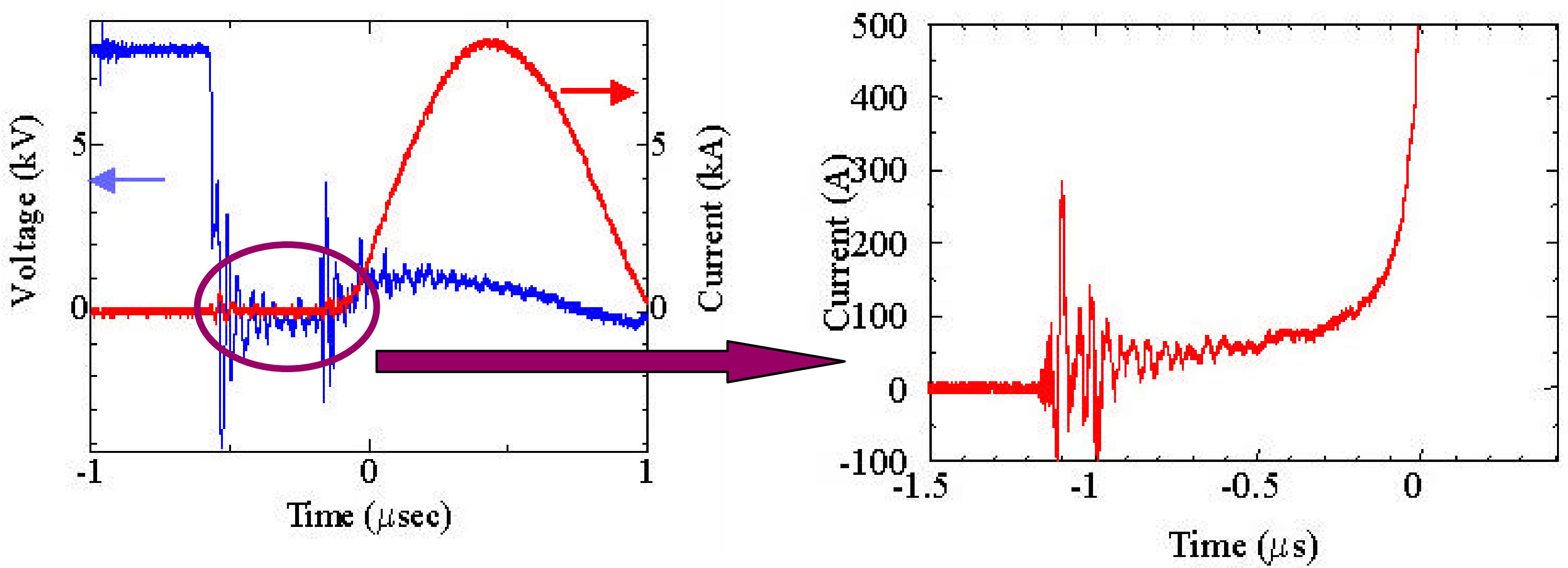
- 5.3 nF Ceramic Capacitors

  4 paralllal, 17 stages
- *C*=380 nF, 20 kV
- Impedance *Z*=0.44 O
- Pulse width = 372 nsec

Voltage and Current Waveforms

Tokyo Institute of Technology

Voltage and Current | **Preionization Current**



Charging Voltage = 8 kV, Xe: 40 Pa
Current Risetime: ∼ 500 ns
→ Inductance: ∼ 270 nH

Bias Current: 2 A
→ Predischarge Current: ∼ 100 A
Duration: ∼ 1 ms

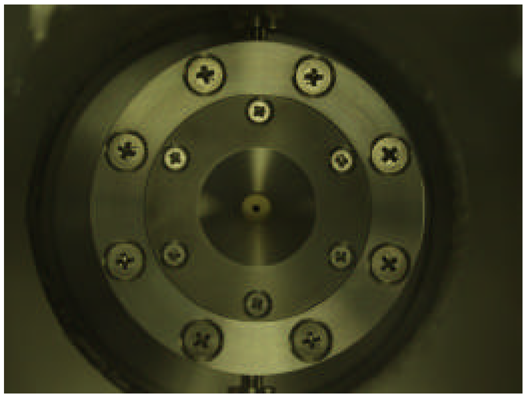
Preionization current has been confirmed.

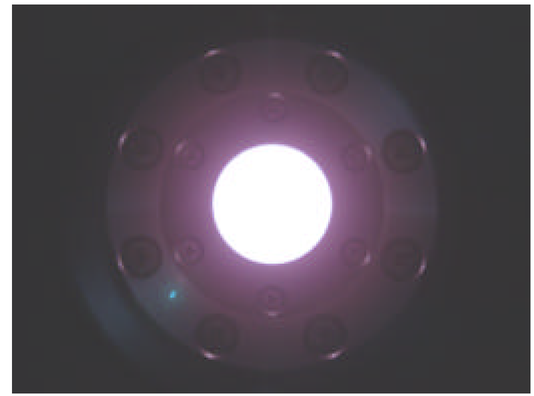
Time-integrated Photographs

Tokyo Institute of Technology

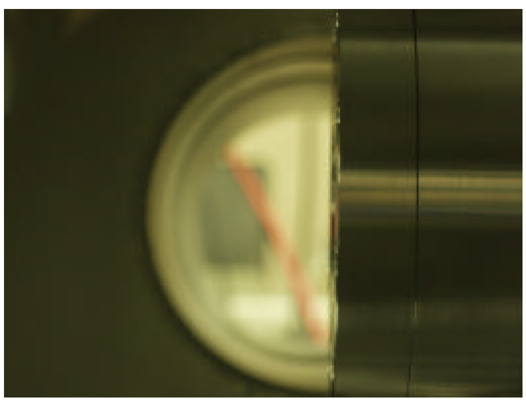
Charging voltage: 3 kV, Xe Pressure: 40.4 Pa

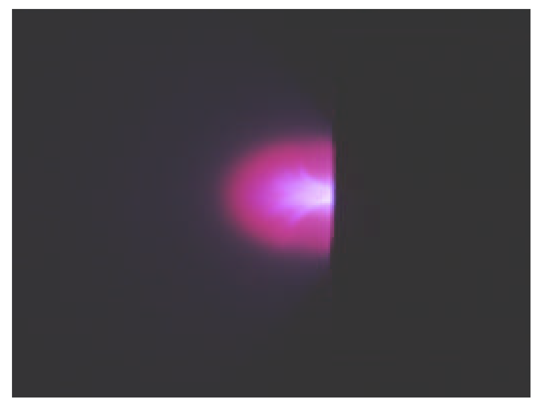
Front view





Side view

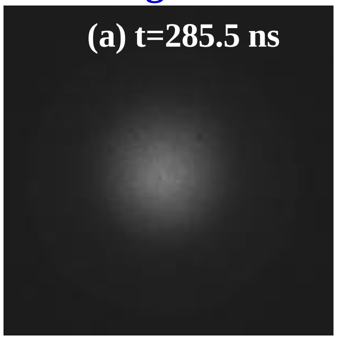


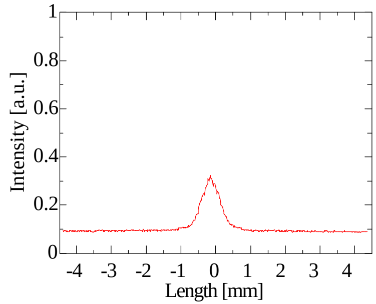


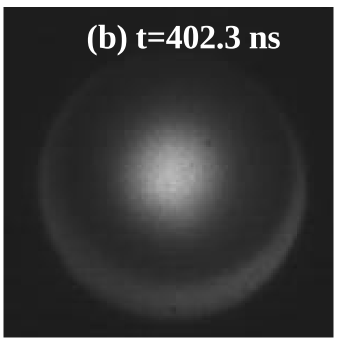
Framing Photographs

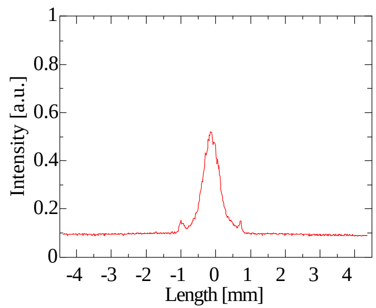
Tokyo Institute of Technology

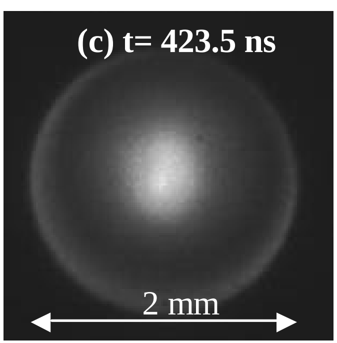
Framing Photo | **Intensity**

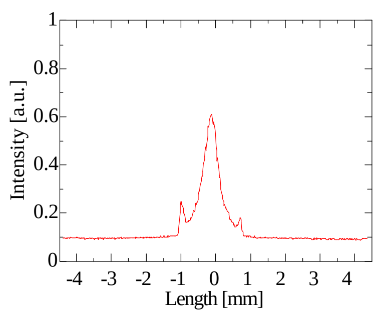








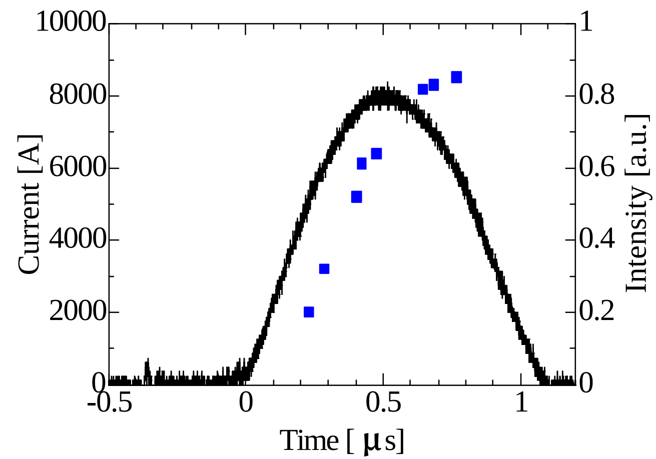




Capillary : ϕ2 mm

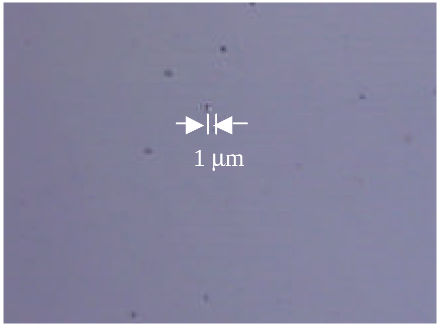
Charging voltage ：8 kV,

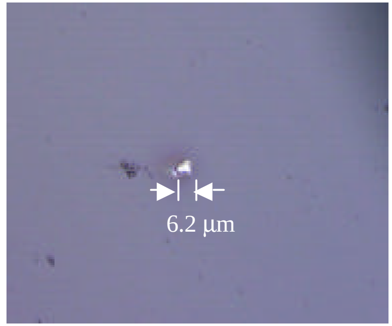
Xe pressure ：40 Pa

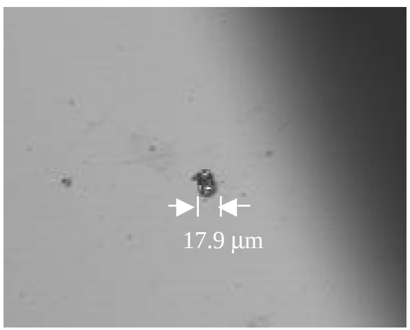


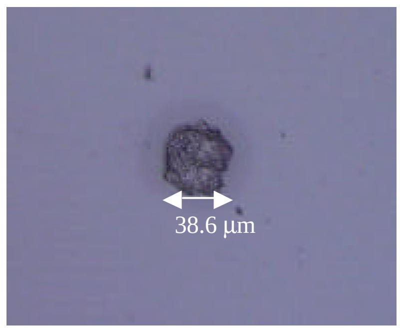
10 pixels correspond to 50 mm

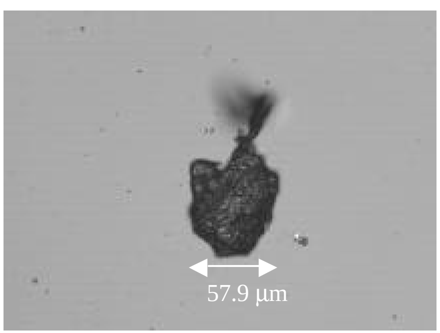
Debris Observation











Debris on Zr filter

Location of filter ：25 cm from capillary

Filter size : 10 mm ×10 mm

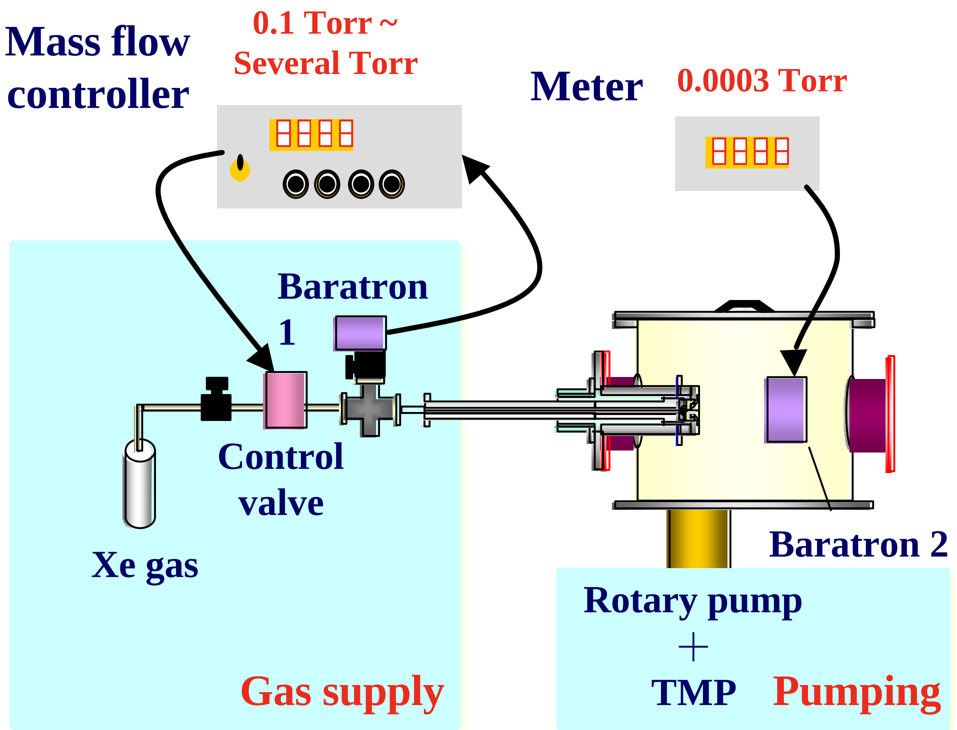
Number of discharge : about 500 shots

Tools : Color 3D profile microscope

VK-9500 (KEYENCE)

Debris size	Number of debris
» 1 mm	> 100
» 6 mm	several tens
» 17 mm	< 5
» 38 mm	< 5
» 57 mm	1

Pressure Distribution



Mass flow controller Setting value	Xenon gas inlet Pressure	Chamber Pressure	Warm up: one and a half hours
0.1 V	0.1 Torr (13.3 Pa)	7.5×10^{-5} Torr (0.01 Pa) ~ 2.3×10^{-4} Torr (0.03 Pa)	0.8 mV ~ 2.3 mV Within the tolerance error
1.0 V	1.0 Torr (133.3 Pa)	Same	
2.0 V	2.0 Torr (266.6 Pa)	Same	

Gas Dynamics in Discharge Tube

Tokyo Institute of Technology

Target of rep. rate → f～10 kHz

Length of discharge tube → L～1 cm

Then required gas speed is

$u \sim CR \times L \times f \sim 200$ m/sec (CR～2)

Mach number of gas $M \sim u/a_{Xe} \sim 1.11$

where a_{Xe} is sound speed of Xe （～180 m/secat 300 K）

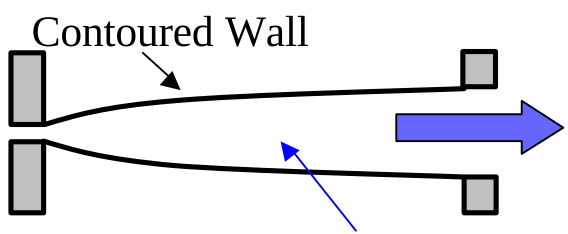
⇩

Gas dynamics is important！

Gas Dynamics

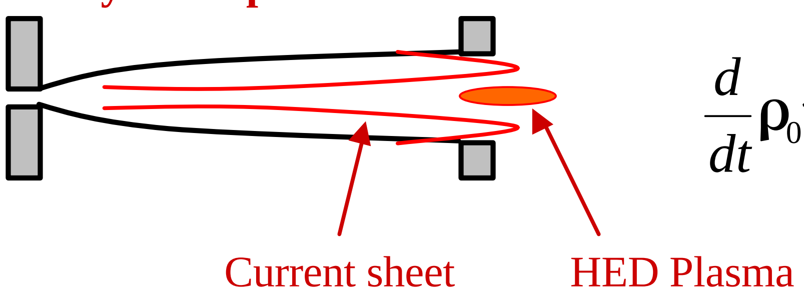
Tokyo Institute of Technology

- **Gas injection**
- **Heating and cooling by gas dynamics**



$$\frac{A}{A^*} = \frac{1}{M}\left[\frac{(\gamma - 1)M^2 + 2}{\gamma + 1}\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

$$\frac{P_0}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

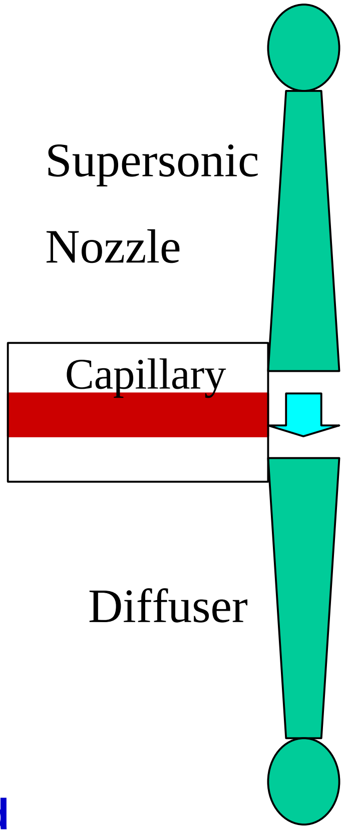


$$\frac{d}{dt}\rho_0 \pi\left(r_0^2 - r(t)^2\right)\dot{r}(t) = -\frac{\mu_0 I(t)^2}{2\pi r(t)} + p(t)$$

Gas Dynamic Curtain

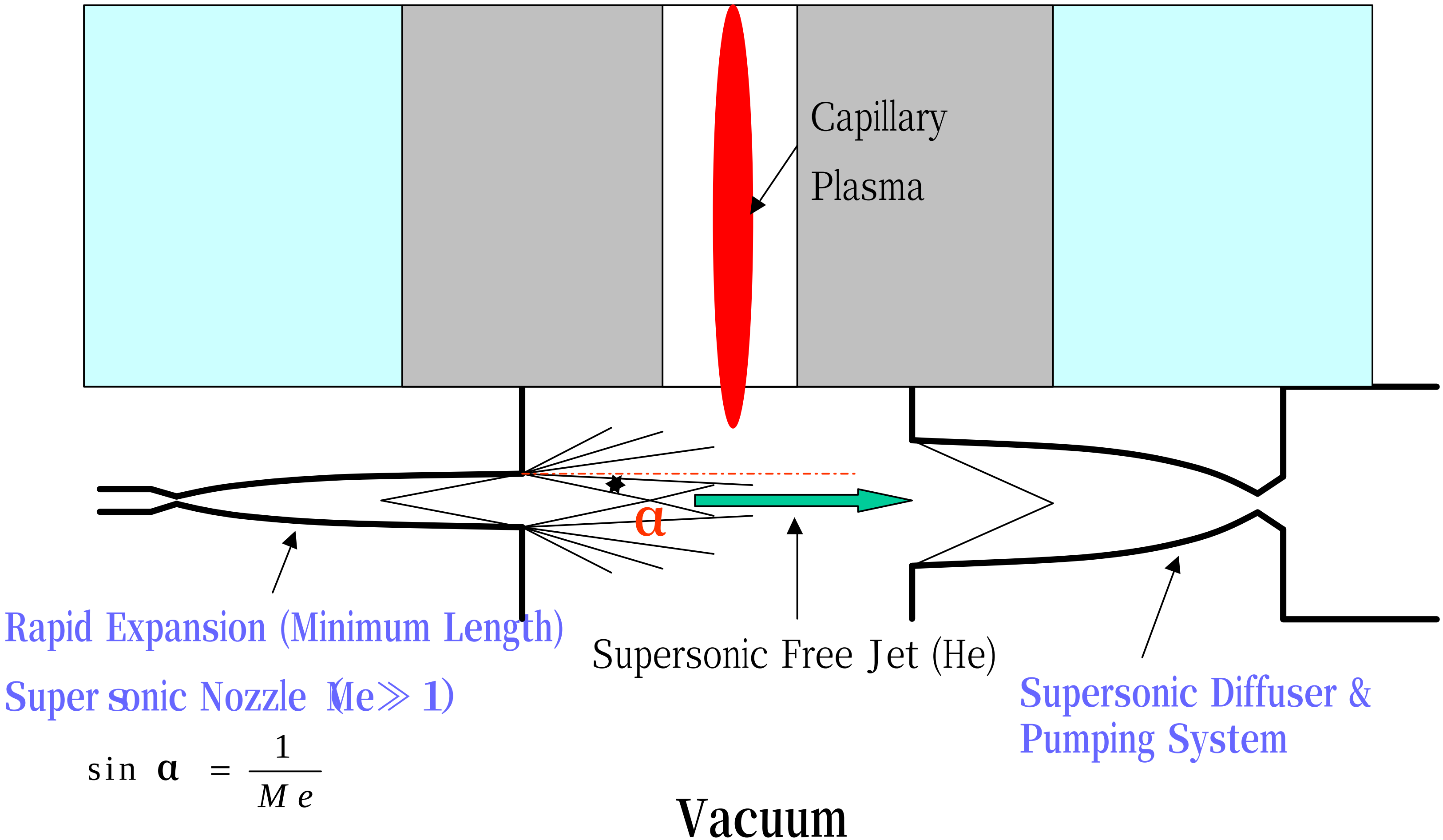
- **Basic concept and characteristics**
  - **Steady state operation**
  - **Matching of pressure at outlet of nozzle**
    - **Stable discharge**
    - **Minimum caliber（Smaller load）**
  - **Slit type supersonic jet with high Mach number**
  - **Nozzle with rapid expansion structure**
    - **Excellent optical performance**

- **Issues**
  - **Debris shield effect**
    - **Shield effect on gas density at outlet of nozzle**
  - **Gas density distribution in operation**
    - **Effect on discharge, presssure in tube and back pressure**
  - **High efficient pressure recovery (diffuser shape) and gas circulation**



Concept of Supersonic Gas Curtain

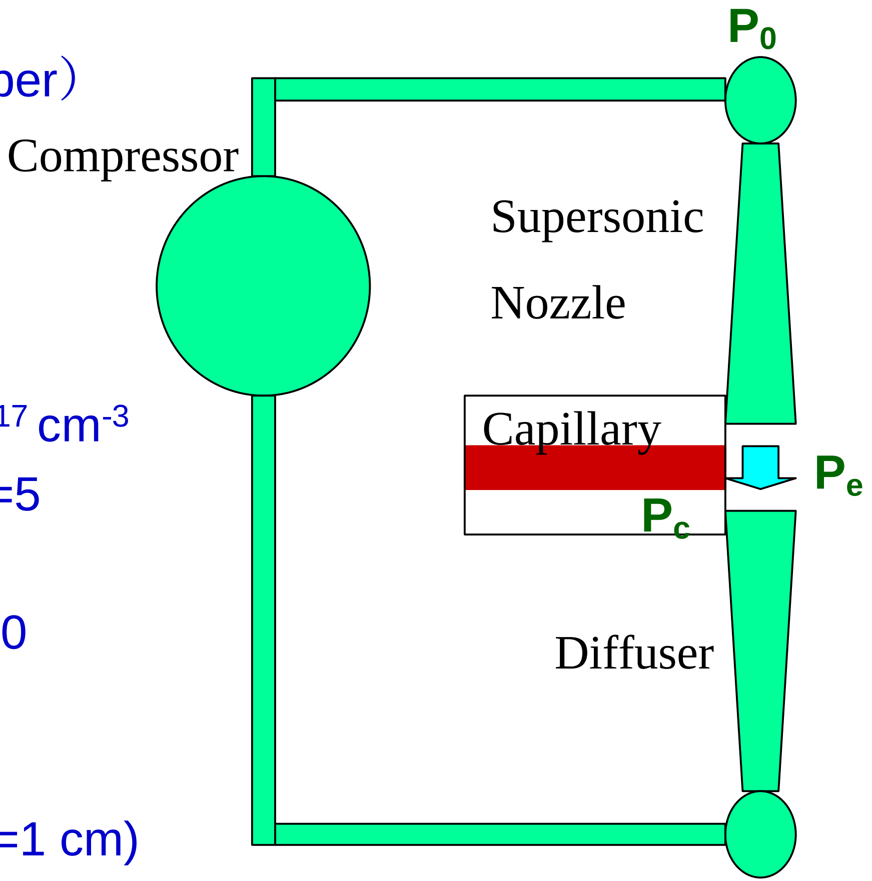
Tokyo Institute of Technology



Design Example of Gas Dynamic Curtain

Tokyo Institute of Technology

- Example of design parameter
  (High Mach number)
- $P_e \sim P_c \sim 100$ Pa
- $n_e L s \sim O(1)$, $s \sim 10^{-16}$ cm^2
  $\rightarrow n_e L \sim 4.5 \times 10^{16}$ cm^{-2}
- $L \sim 2$ mm $\rightarrow n_e = 2.25 \times 10^{17}$ cm^{-3}
- $P_e = n_e k T_e \rightarrow T_e = 32$ K $\rightarrow M=5$
- γ (He) ~ 1.66
- $M=5 \rightarrow n_0/n_e \sim 29.4$, $A_e/A^* \sim 10$
- $P_0 = n_0 k T_0 \rightarrow 2.74 \times 10^4$ Pa
- Particle Flow Rate $\sim n^* a^* A^*$
  $\sim 8.6 \times 10^{21}$ Particle/sec (W=1 cm)



Conclusions and Acknowledgment

- **Conclusions**
  - Device has been constructed
  - Principle of preionization current generation was confirmed
  - Pinch formation was observed
  - Debris was observed

- **Acknowledgment**

This work is supported by METI/NEDO.