DIRECTIONS FOR THE FUTURE

SUCCESSIVE ACCELERATION OF POSITIVE AND NEGATIVE IONS APPLIED TO SPACE PROPULSION

Laboratoire de Physique des Plasmas

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Acknowledgments

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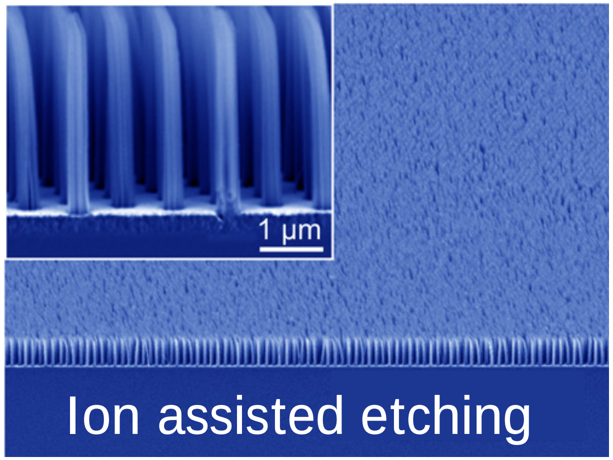
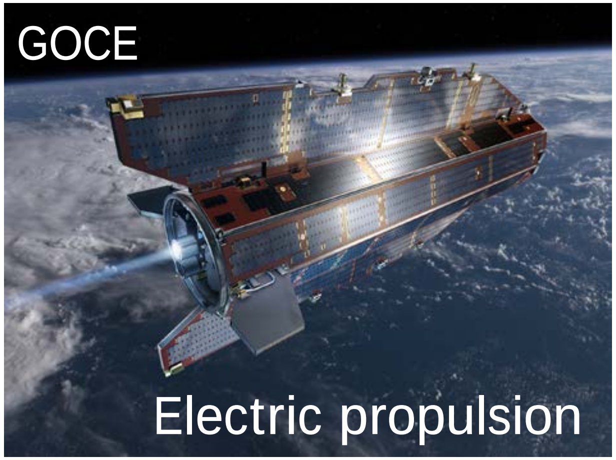
Electrons – Pros & Cons

Electrons required for plasma **generation** and beam **neutralization**

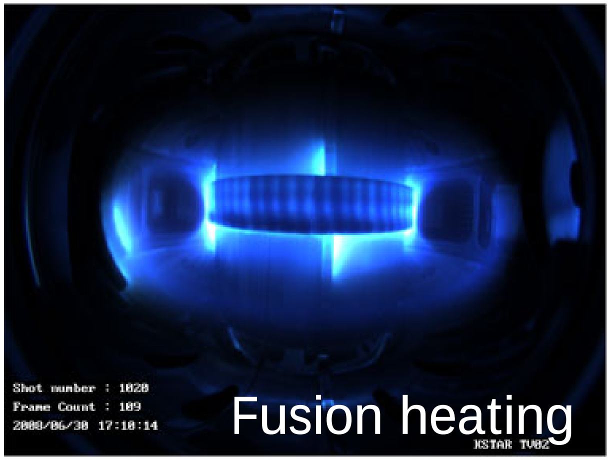
Electrons cause problems by surface and differential **charging** and slow ion-electron **recombination**



Ion assisted etching



Electric propulsion



Fusion heating

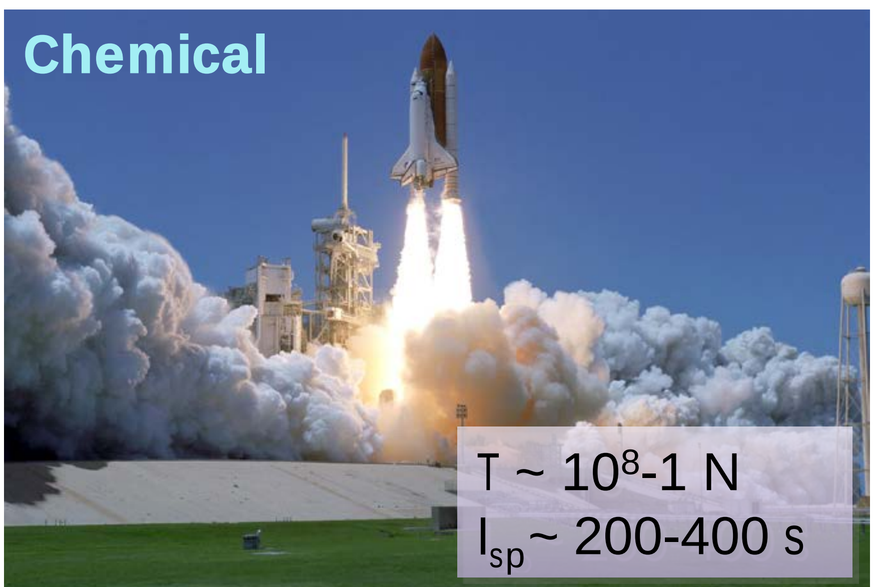
Space propulsion

acceleration by ejecting mass

$$m\frac{dv}{dt} = -\frac{dm}{dt}v_g$$

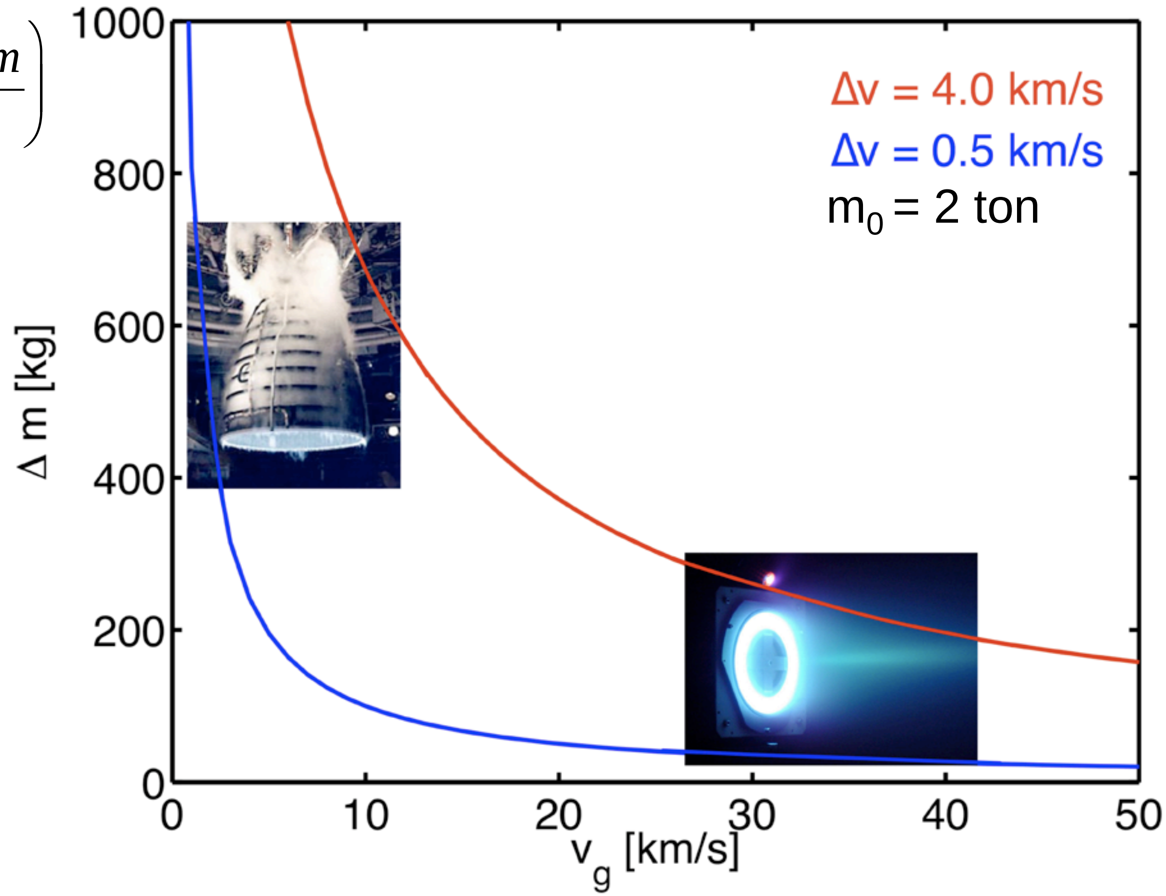
Trust $$T = \frac{dm}{dt}v_g$$

Specific Impulse $$I_{sp} = \frac{v_g}{g_0}$$

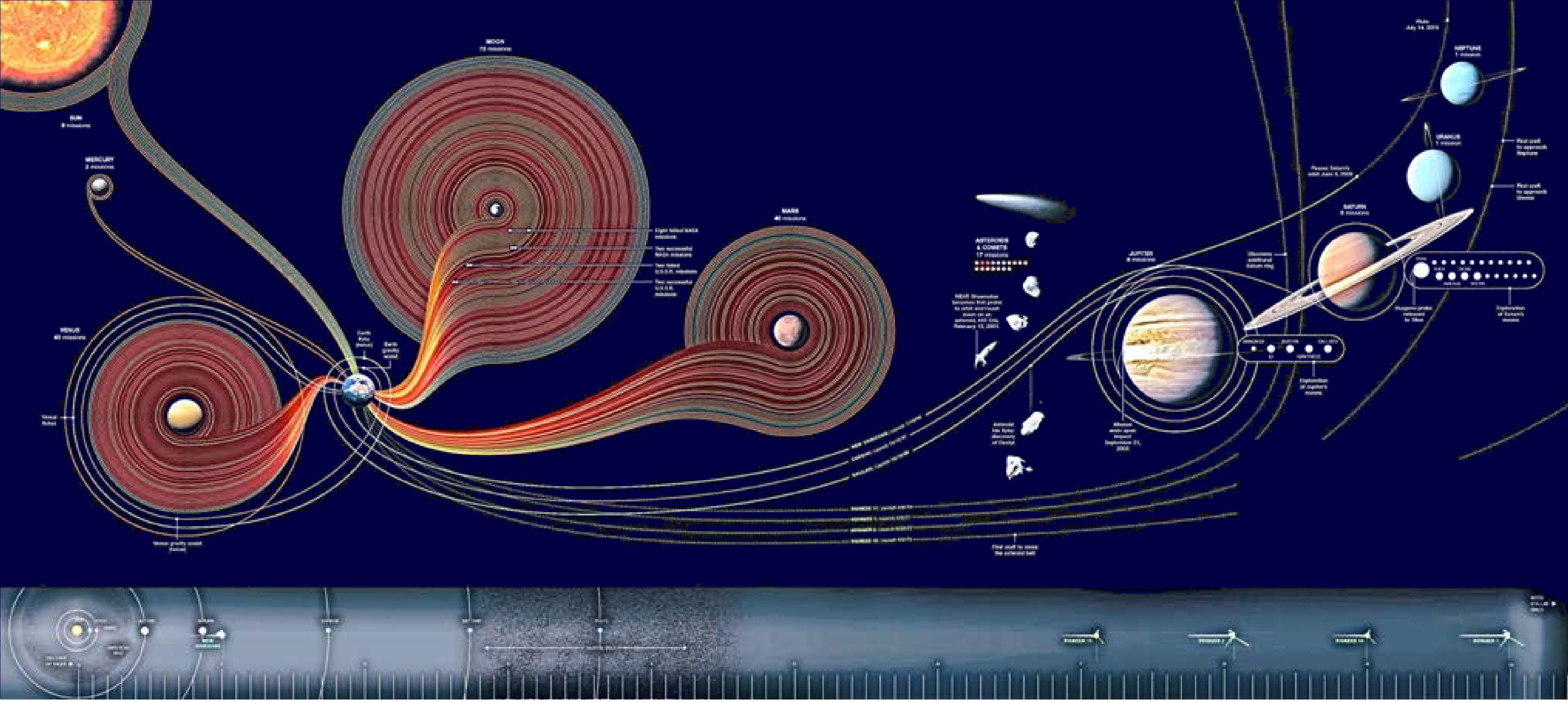


Mass consumption
Chemical versus Electric Propulsion

$$\Delta v = v_g \ln\left(\frac{m_0 - \Delta m}{m_0}\right)$$



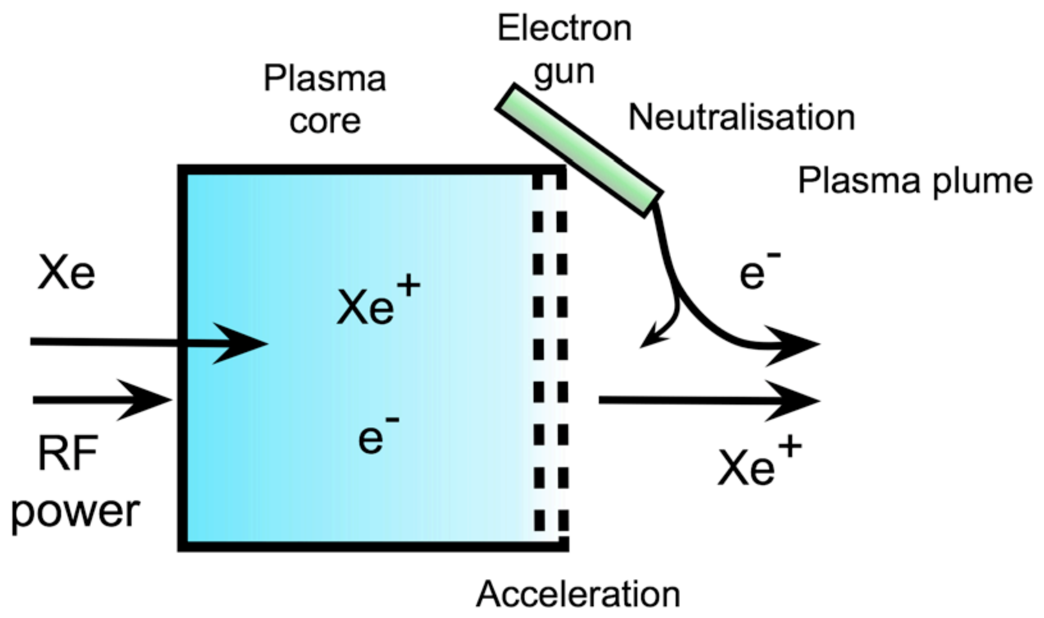
Cost to sent 1 kg to LEO is ~ 20 k€ !



Source: National Geographics

SPACE MISSIONS SINCE THE 1950'S

Principle of Electric Propulsion



Two weak points:

1) Hollow cathode – limited lifetime and stability

2) Back scattering and sputtering

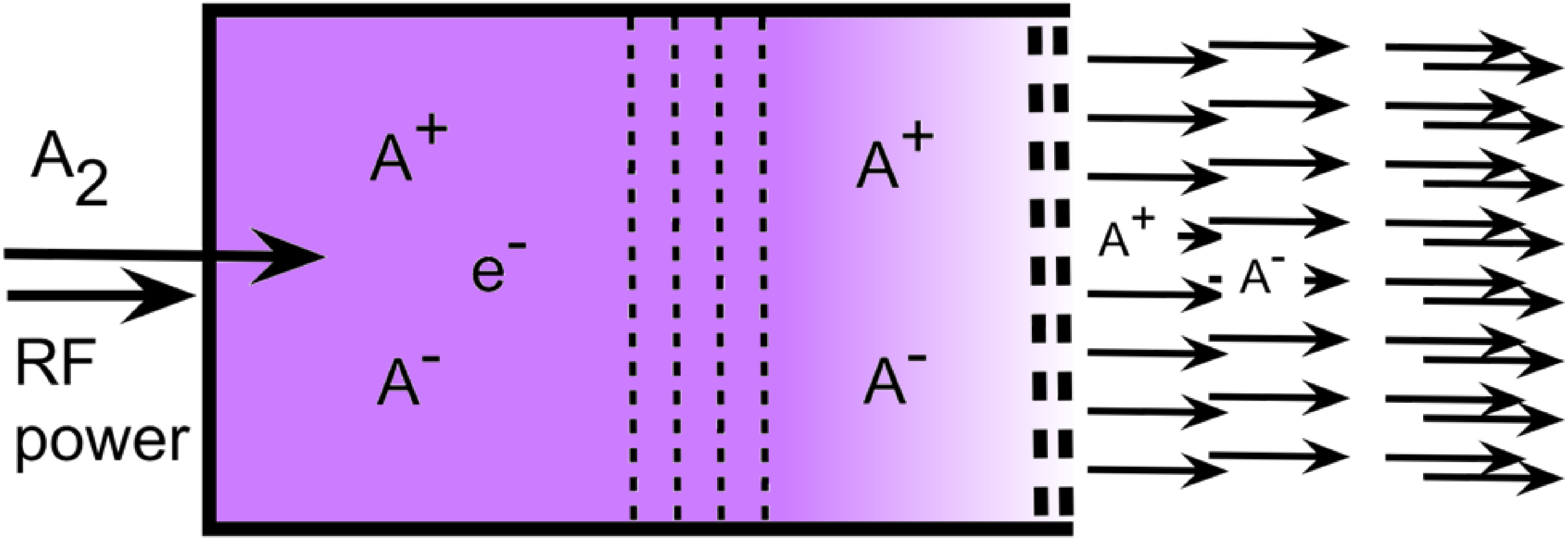
PEGASES

Plasma propulsion with electronegative gases

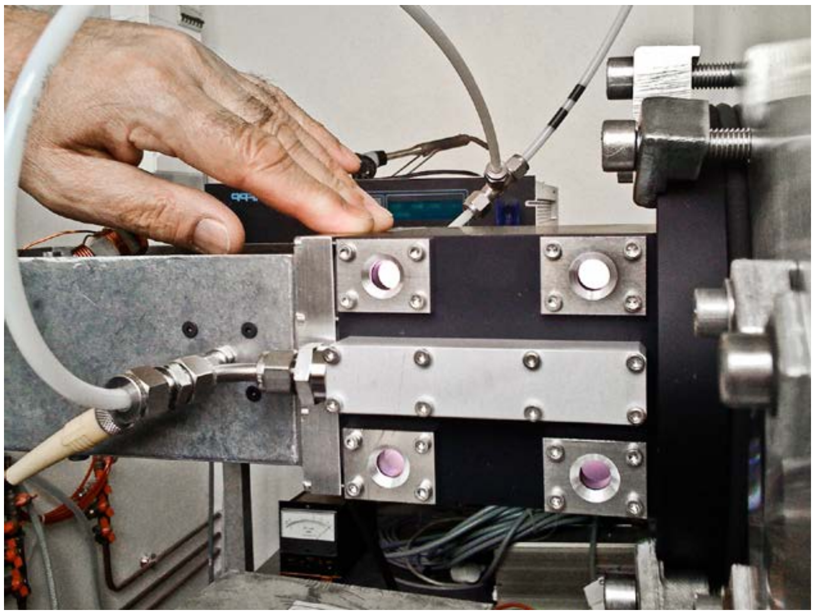
Stage 1
Plasma discharge, power coupling

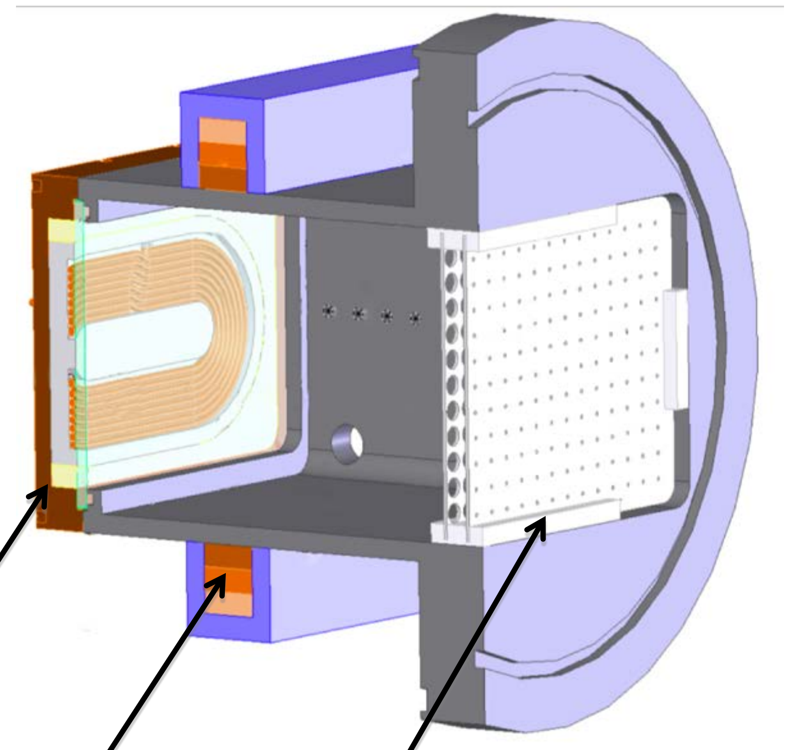
Stage 2
Electron filtering, ion-ion formation

Stage 3
Acceleration and recombination



PEGASES Prototype





Stage 1
ICP source

Stage 2
Magnetic barrier

Stage 3
Gridded alternate acceleration

STAGE 1

PLASMA DISCHARGE WITH ELECTRONEGATIVE GASES

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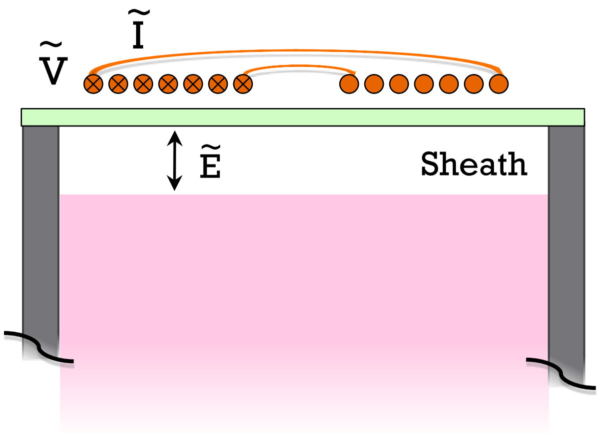
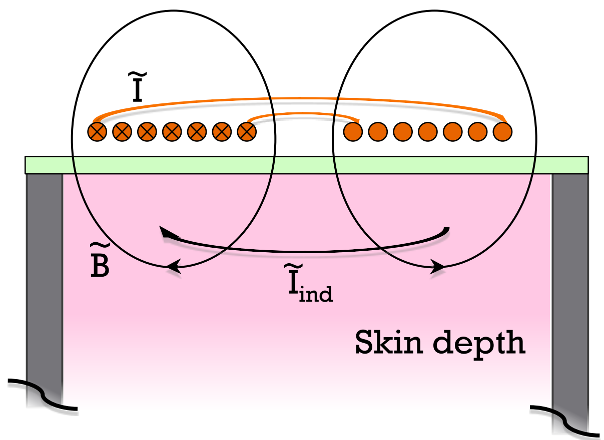
RF plasma discharges

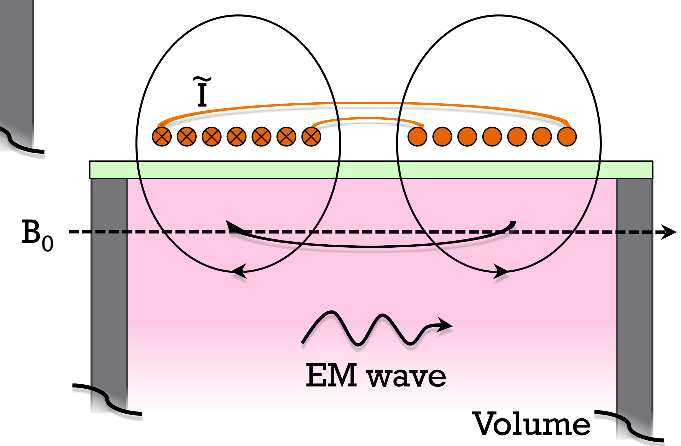
Capacitive E-mode



Inductive H-mode



Wave W-mode

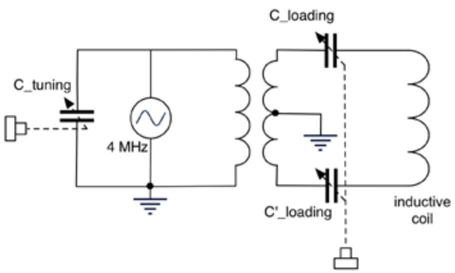


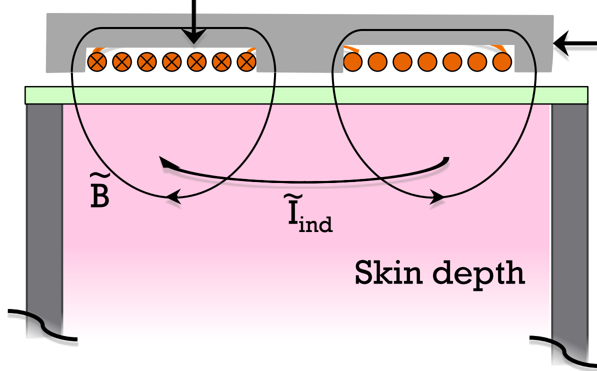
Inductively coupled plasma (ICP) with high efficiency

RF frequency: **4 MHz**

Z-matching: **Step-down transformer**

Inductor coil embedded in a **ferrite** material





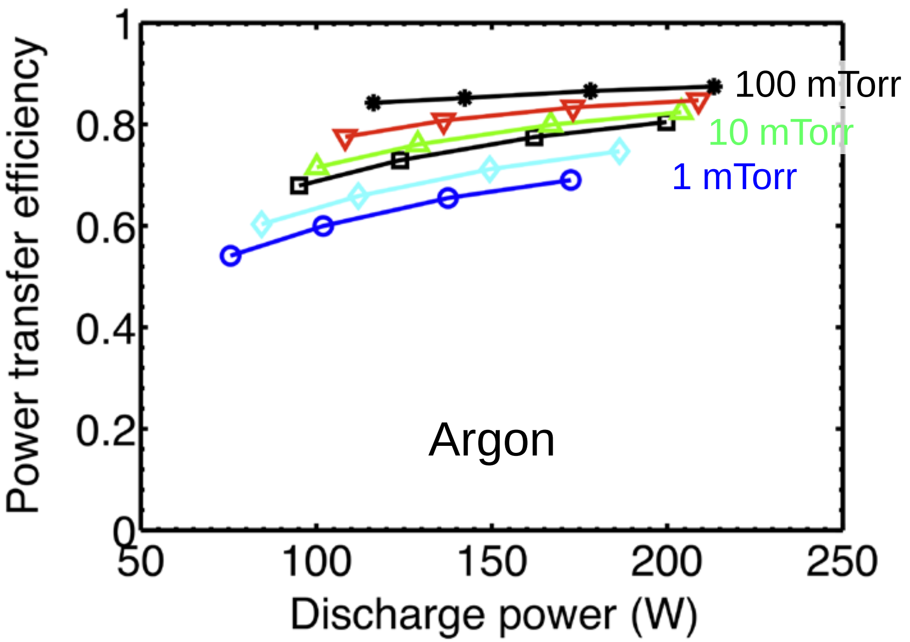
Requirements for space applications:

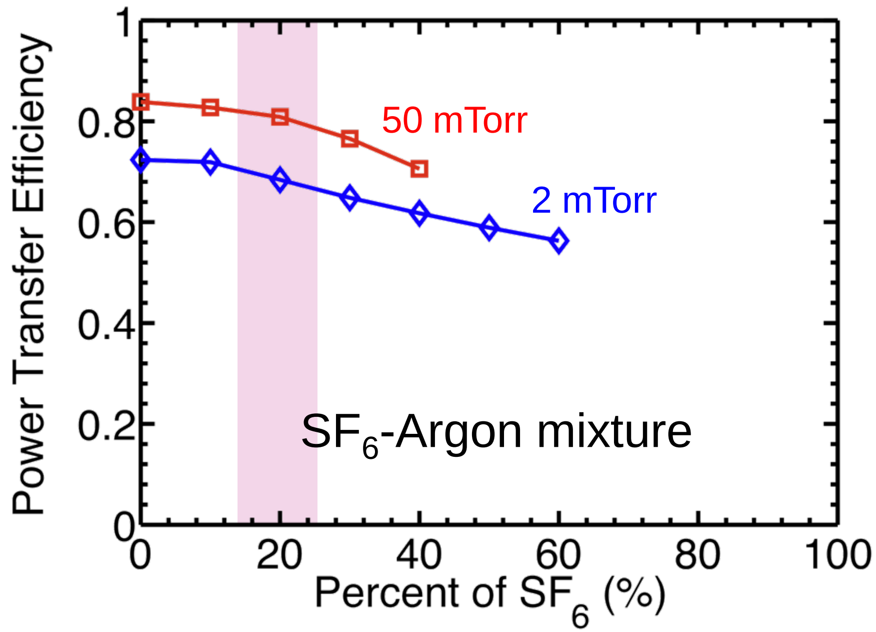
Small and light

Minimal energy loss

Large parameter space in T and Isp

Power transfer efficiency in PEGASES





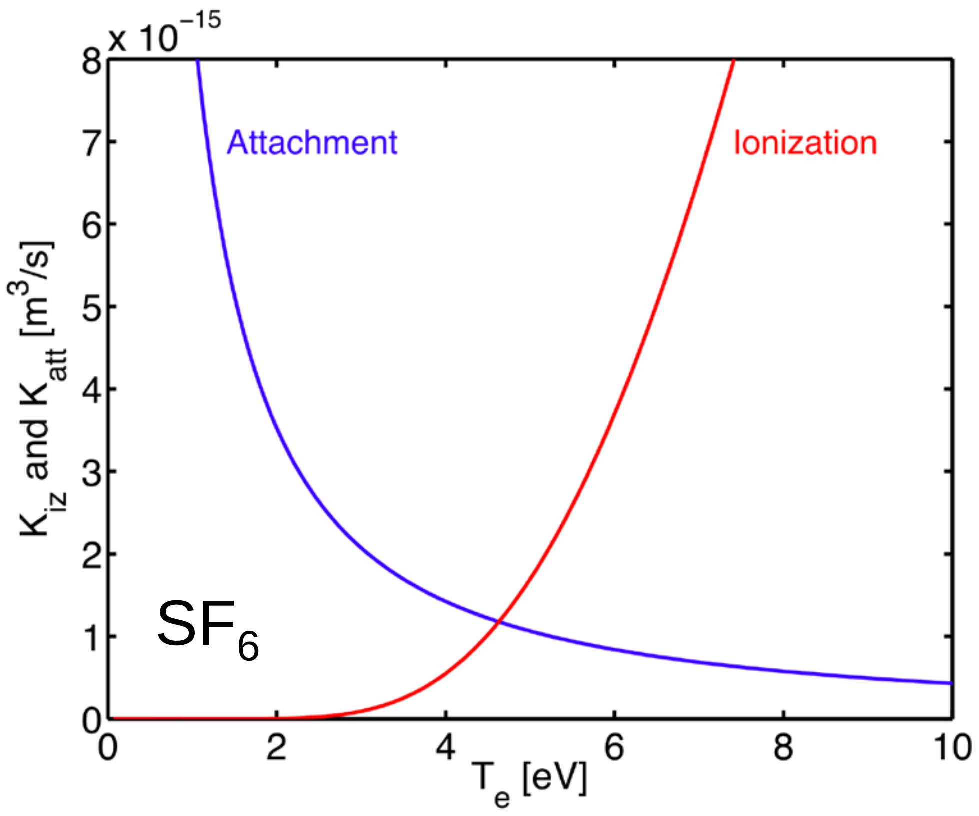
Up to 90 % power transfer efficiency in Argon

70 – 85 % efficiency in current PEGASES condition

Electronegative volume produced plasma

Ionization: $A_2 + e^- \rightarrow \mathbf{A_2^+} + 2e^-$

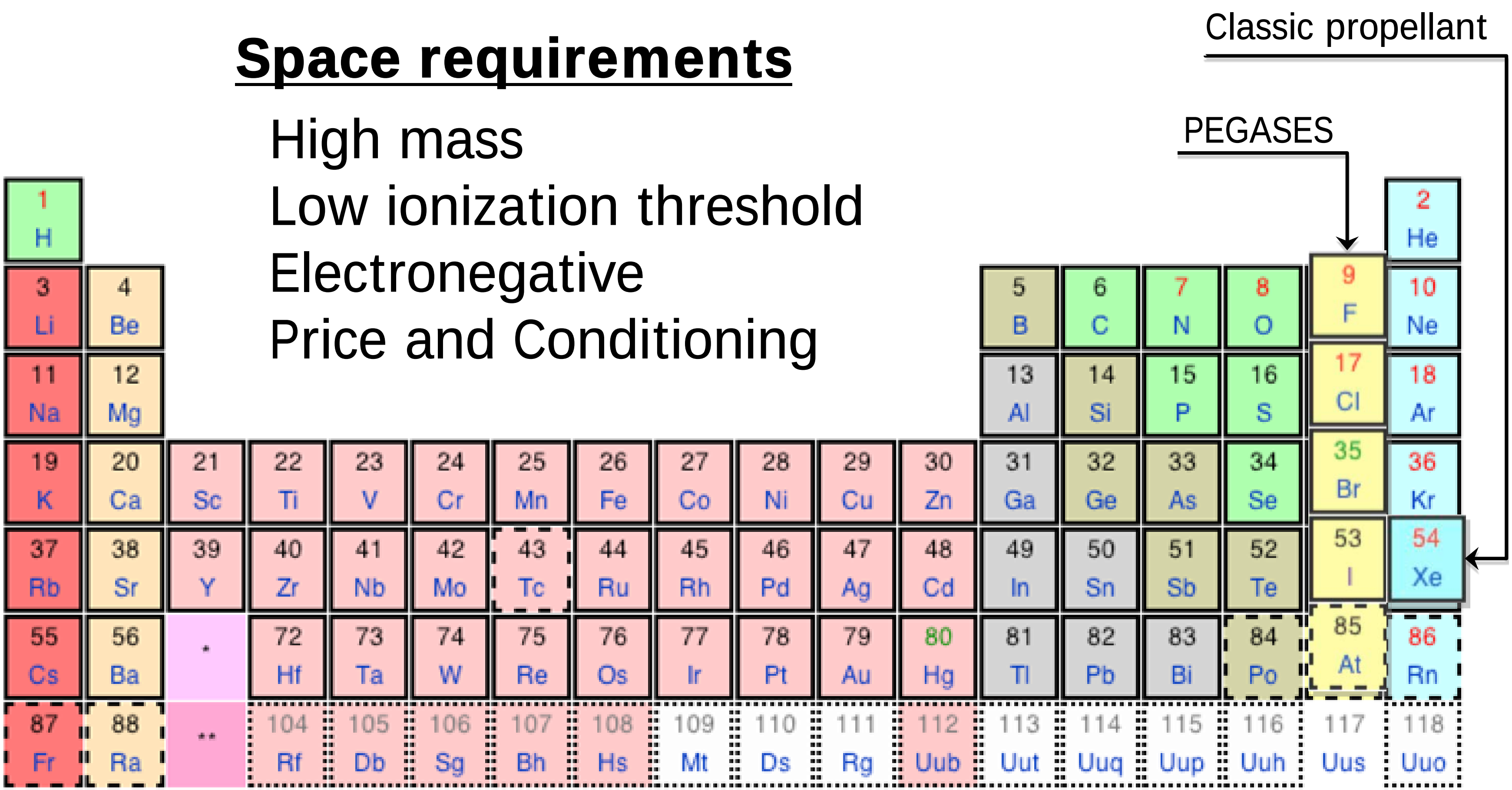
Attachment: $A_2 + e^- \rightarrow \mathbf{A^-} + A$



Propellant in the PEGASES thruster

Space requirements

High mass
Low ionization threshold
Electronegative
Price and Conditioning



STAGE 2

MAGNETIC FILTER AND ION-ION FORMATION

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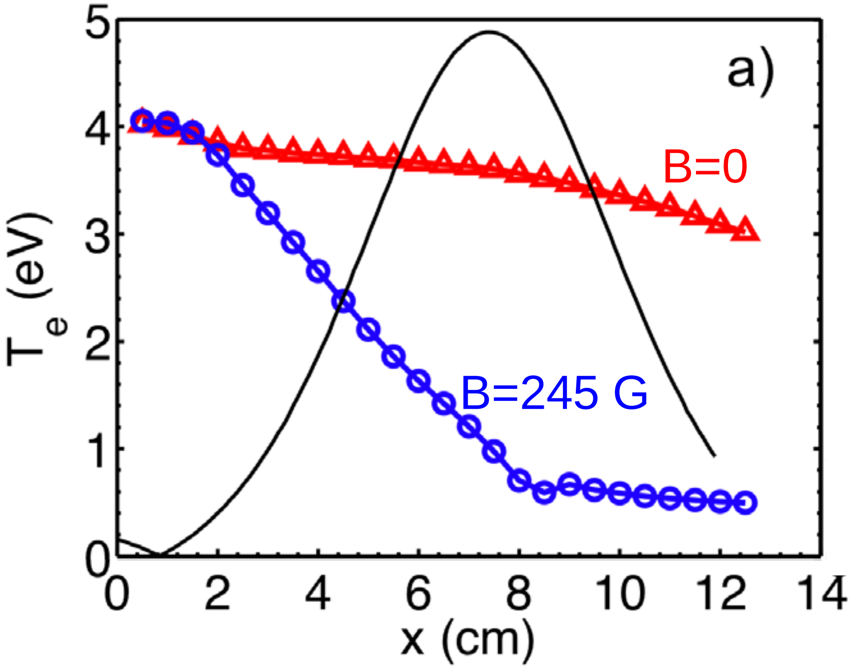
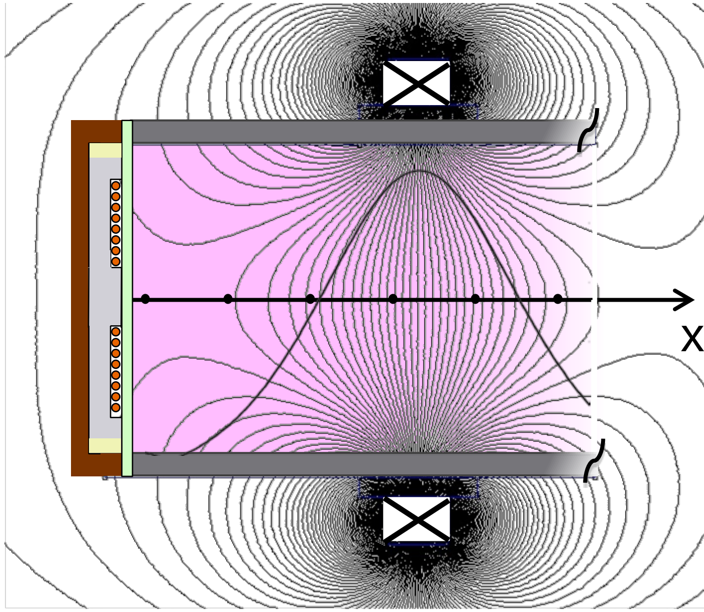
Control of the electron temperature

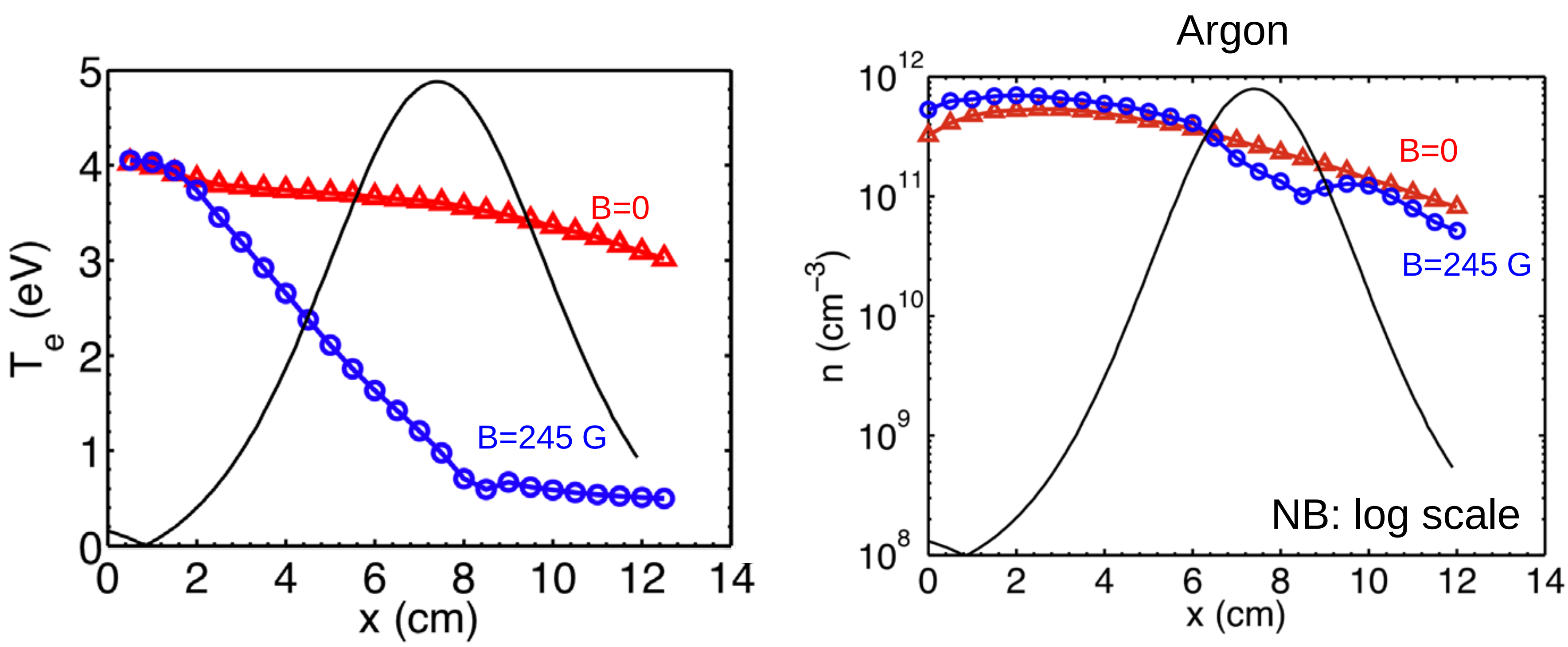




Cool down the electrons

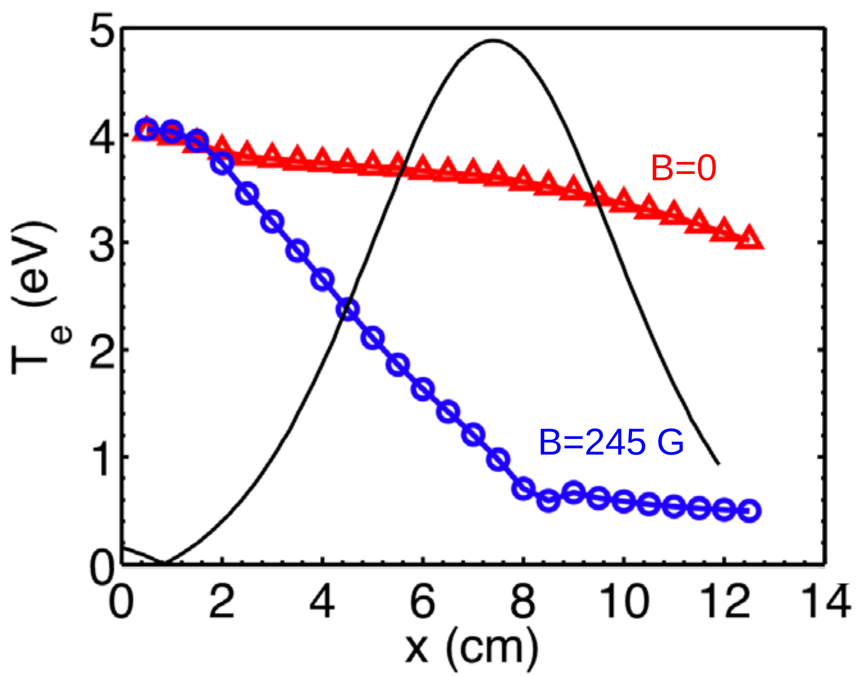
Control of high and low T_e region by pressure and B-field

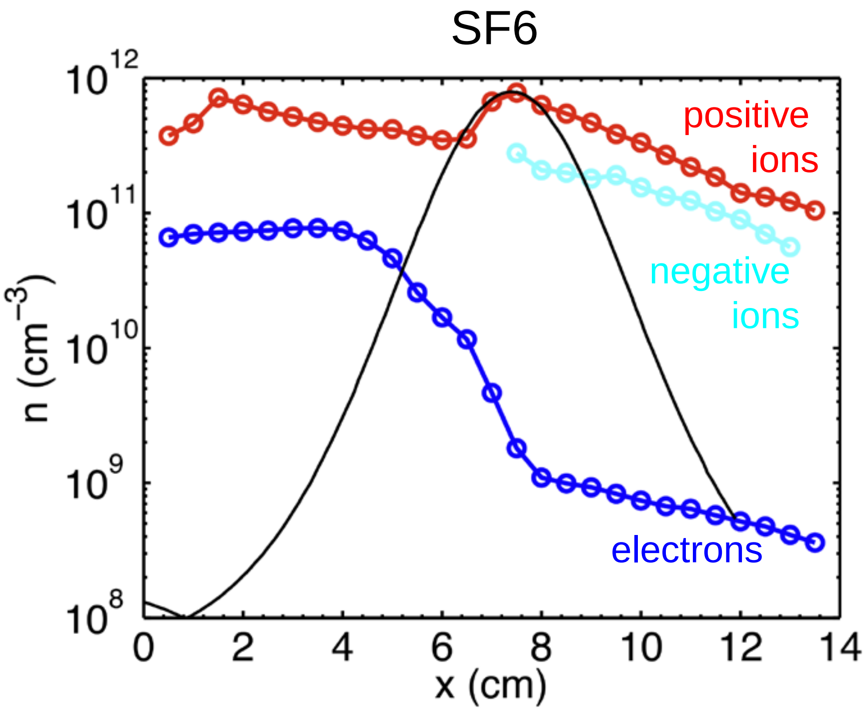
Plasma density in the magnetic barrier



In **electropositive plasmas** the plasma density decreases strongly in the filter region

Ion-Ion plasma in the magnetic barrier

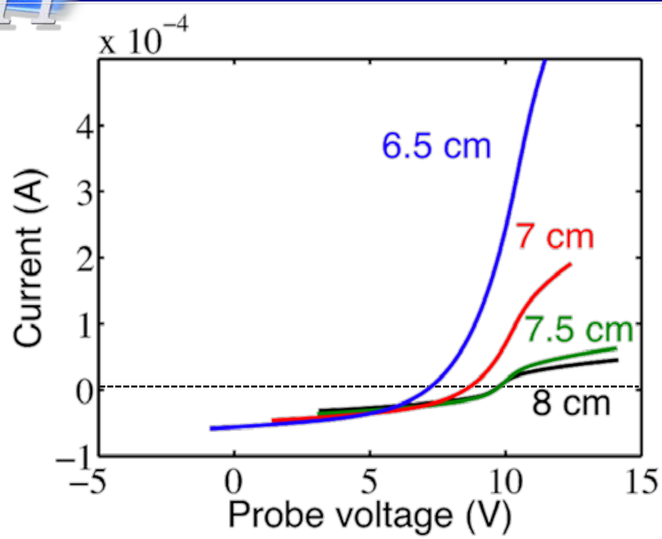


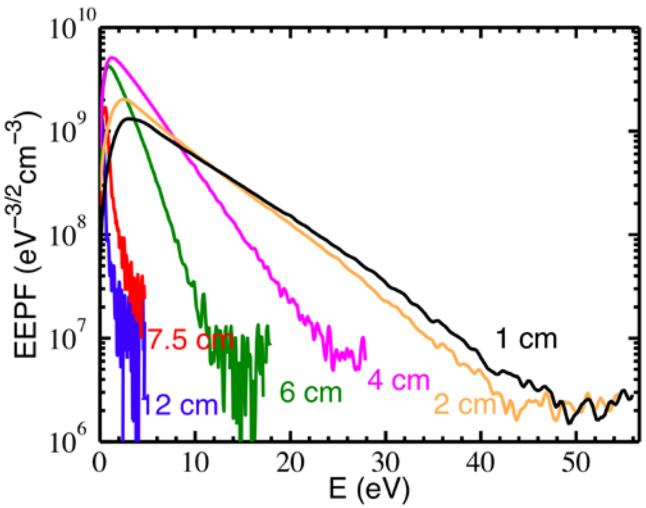


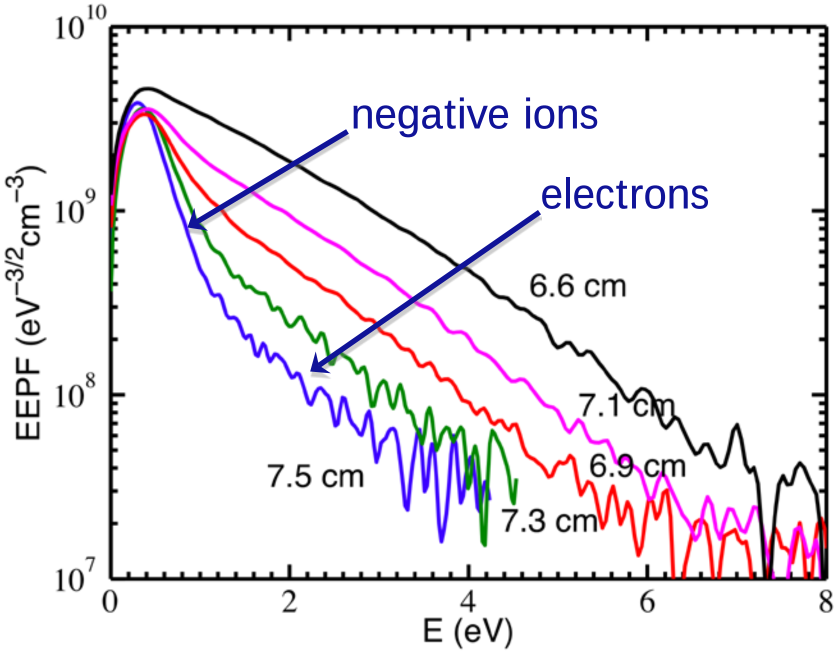
In **electronegative plasmas** the ion density remain high

$n_i \sim 5 \times 10^{11}\ cm^{-3}$ at 150 W

Langmuir probes
in electronegative plasmas







STAGE 3

ALTERNATE ION ACCELERATION

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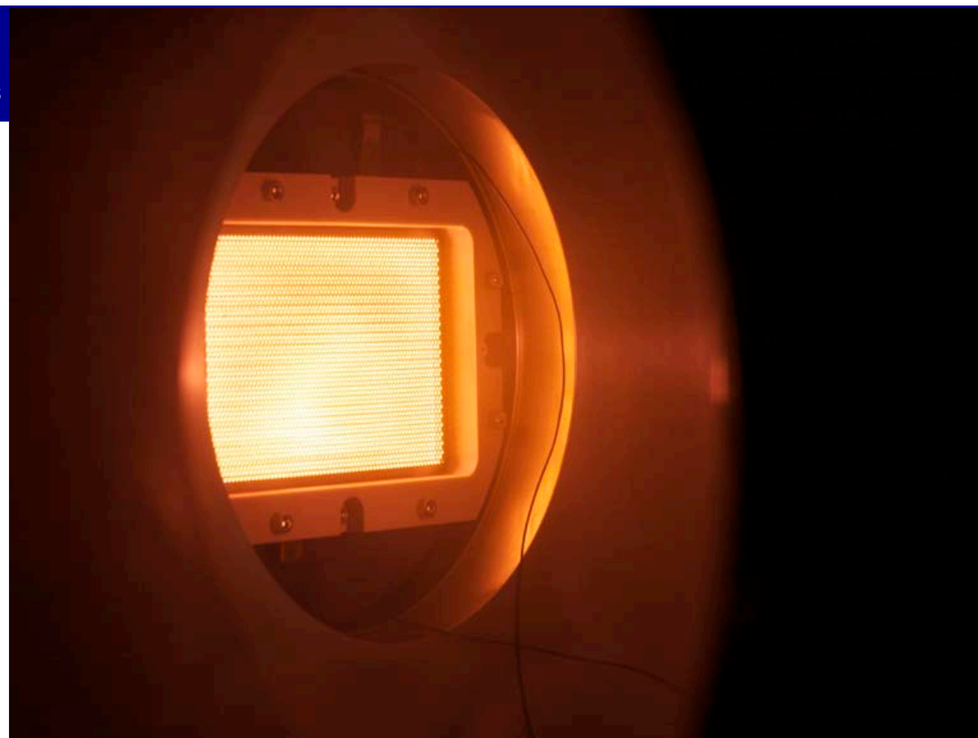
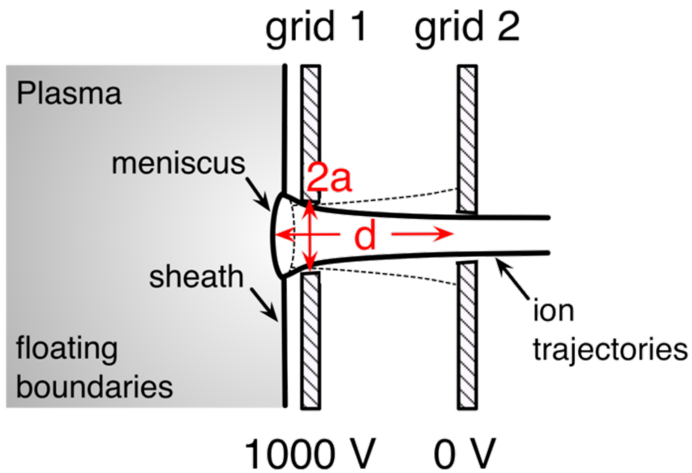
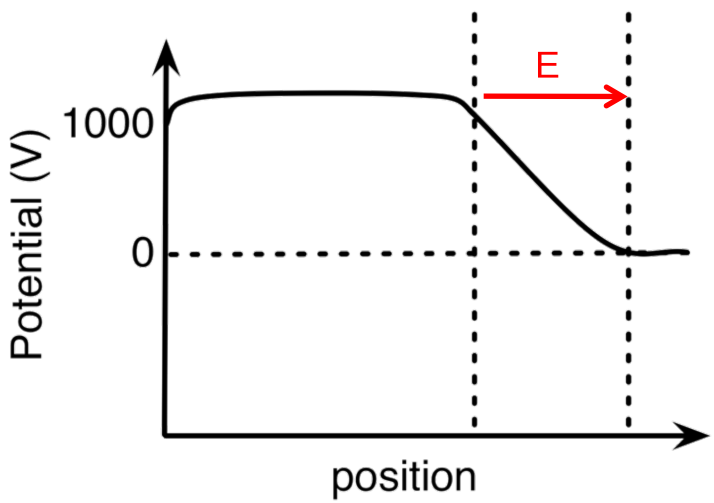


Classical gridded acceleration





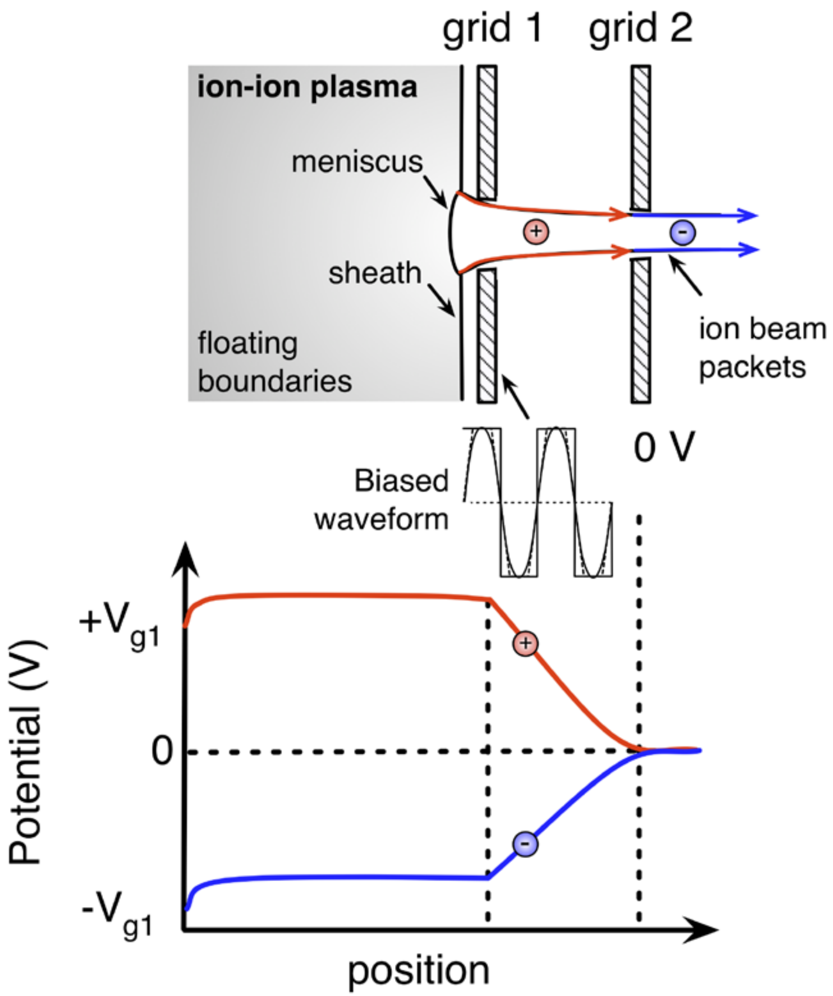
The Child-Langmuir space charge limited current controls the **maximum Thrust**

$$J_{CL} = \frac{4\varepsilon_0}{9}\left(\frac{2e}{M}\right)^{1/2}\frac{V^{3/2}}{d^2}$$

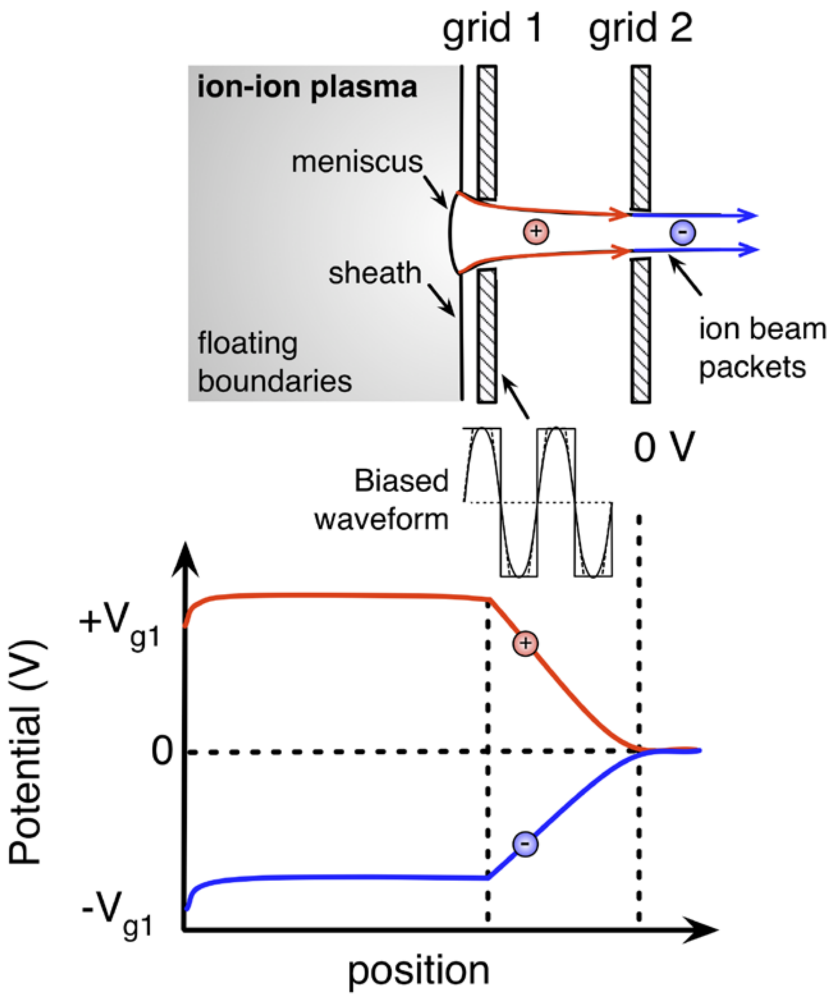
$$T \equiv v_i \frac{dm}{dt} = v_i \frac{I_b M_i}{e} = I_b \sqrt{\frac{2 M_i V_b}{e}}$$

$$T_{\max} = \frac{8\varepsilon_0}{9}\frac{A_g T_g}{d^2} V_b^2$$

Alternate acceleration – Concept



Alternate acceleration – Requirements



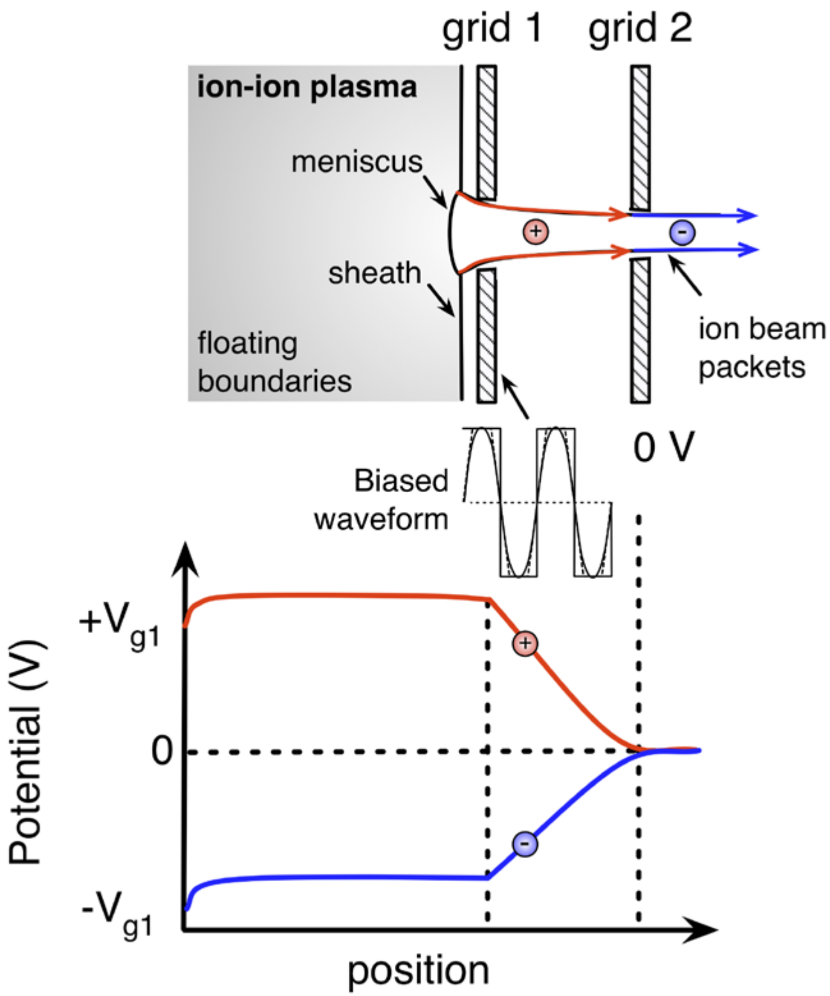
Waveform requirements

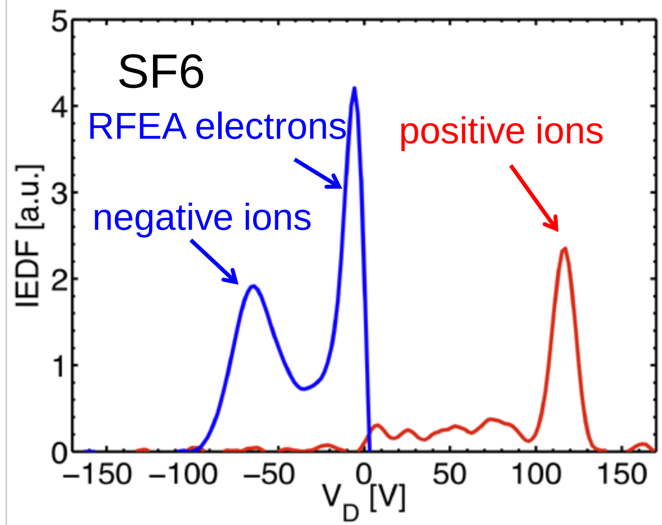
Upper limit:
$\omega < \omega_{pi} \sim$ 10-20 MHz
$\omega < 1/\tau_{tof} \sim$ 1 MHz

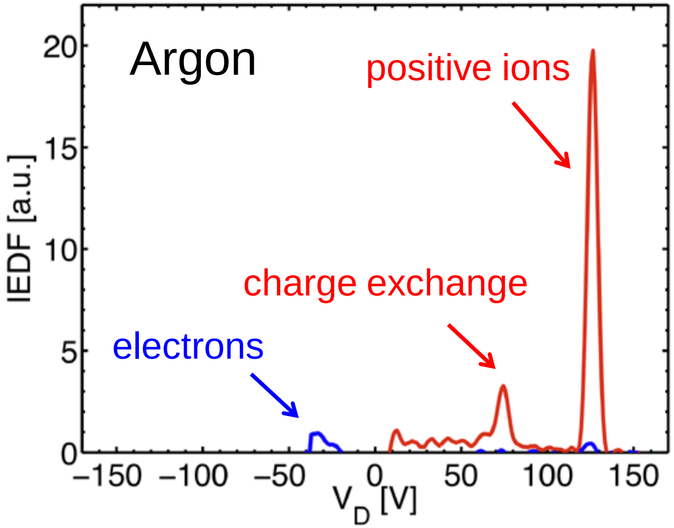
Lower limit:
Beam packet blowup
Beam oscillations
Estimated ω > kHz

Optimization:
square waveforms
variable rise time and periods

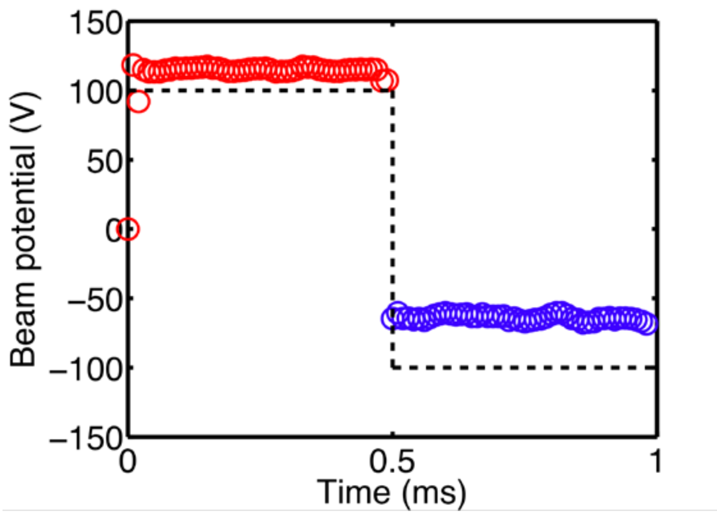
Alternate acceleration
Proof-of-Concept with ±100 V at 1 KHz

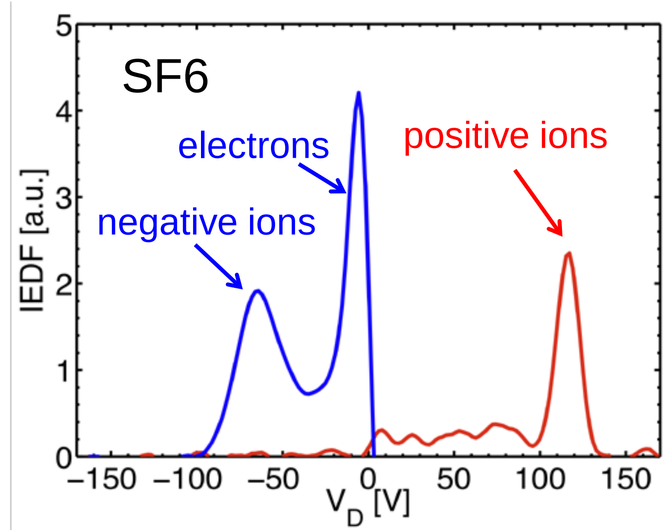


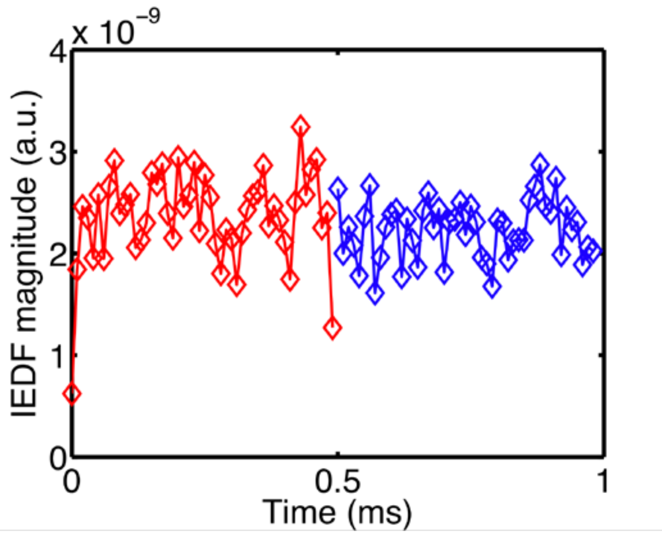




Alternate acceleration
Ion beam energy



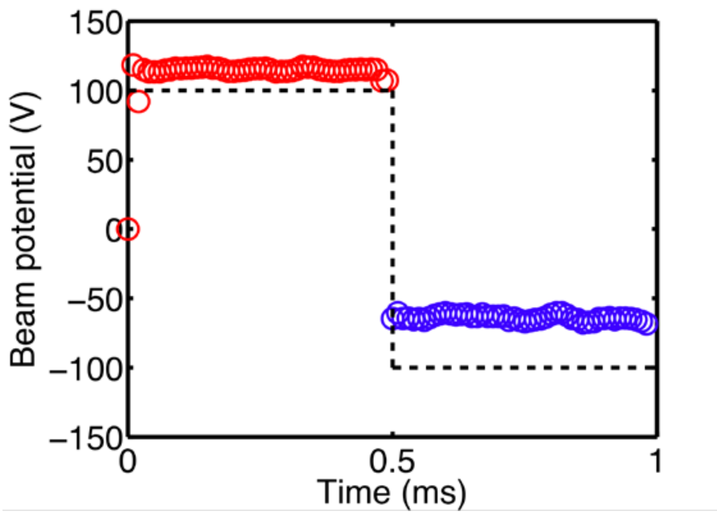


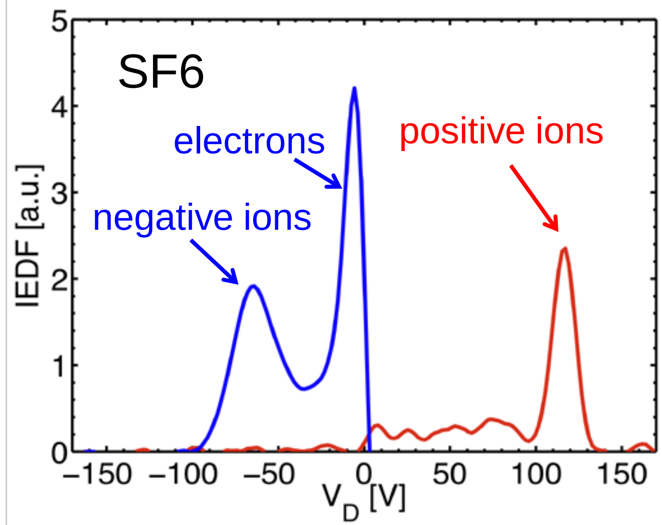


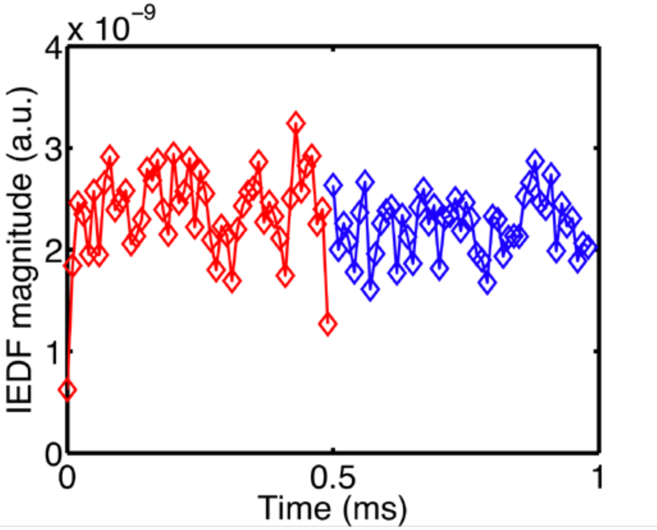
Positive ion beam at **+114 V**,

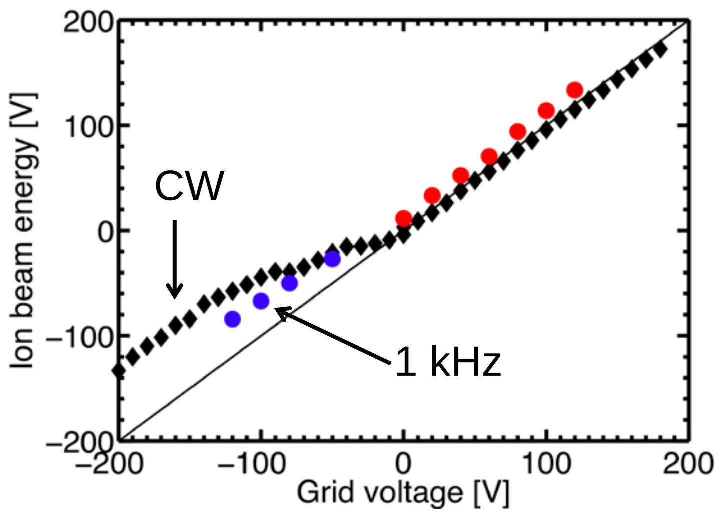
Negative ion beam at **– 67 V**

Alternate acceleration
Ion beam energy versus grid potential

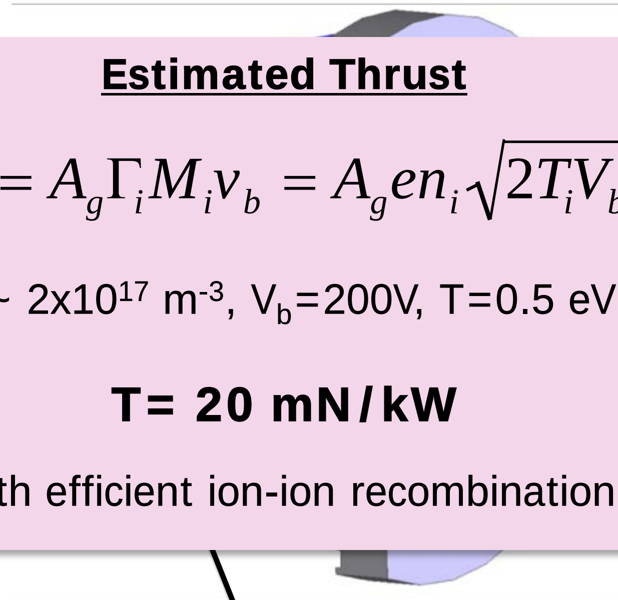








PEGASES – from concept towards reality



Estimated Thrust

$$T = A_g \Gamma_i M_i v_b = A_g e n_i \sqrt{2 T_i V_b}$$

$n_i \sim 2\text{x}10^{17}\ \text{m}^{-3}$, V_b=200V, T=0.5 eV

T= 20 mN/kW

with efficient ion-ion recombination

Stage 1

•Ferrite enhanced ICP source

•**70-85 %** power efficiency in current PEGASES conditions

Stage 2

•Segregation of the electronegative plasma

•Formation of ion-ion plasma

•High density **$5\text{x}10^{11}$ cm^{-3}** at only 150 W

Stage 3

•Dual ion acceleration

•First **proof-of-concept**

THANK YOU FOR YOUR ATTENTION

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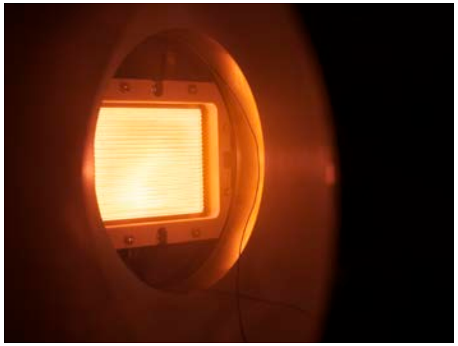
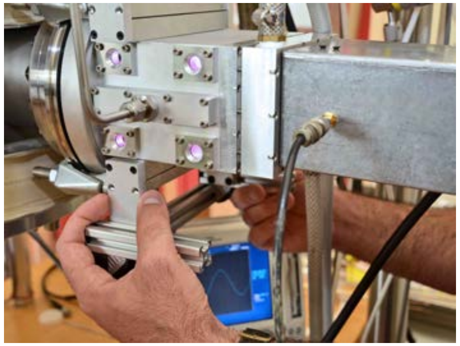
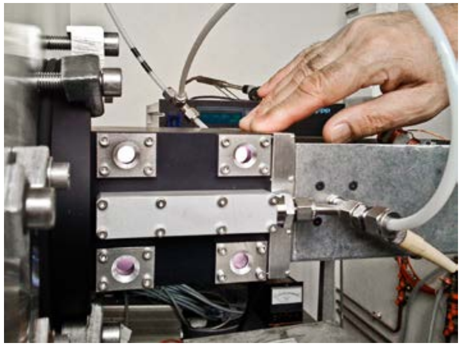


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