

# DOUBLE BEAM SATELLITE PROPULSION



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# Space propulsion



## JPL MISSION HISTORY

over 100 missions launched  
mission launch date x area of study  
past / present / future / proposed

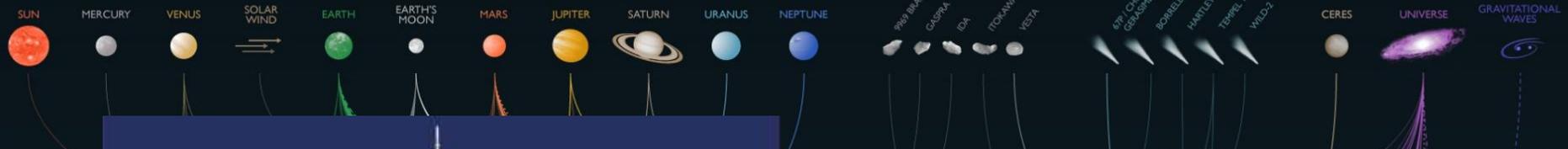


Image credit: NASA/JPL-Caltech

$V$  (chemical)  $\sim 3$  km/s,  $T > 10^5$  N

$V$  (plasma)  $\sim 30$  km/s,  $T < 1$  N

$$\Delta V \equiv V_{ex} \ln(m_0/m_1)$$

2 ton spacecraft, 1 km/s delta V:

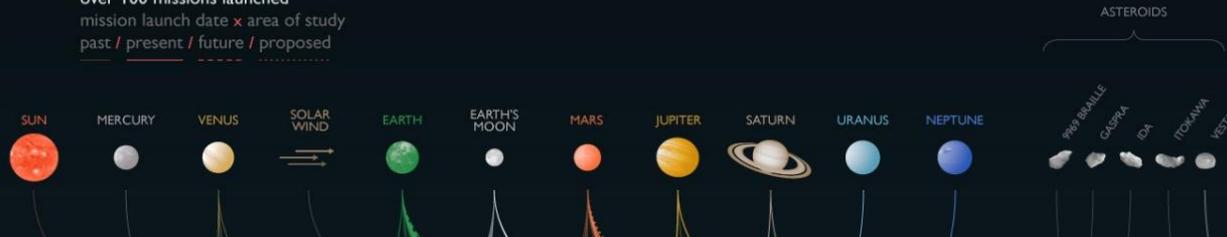
- Chemical propulsion  $\sim 1$  ton of fuel
- Electric propulsion  $\sim 50$  kg of fuel

# Space propulsion



## JPL MISSION HISTORY

over 100 missions launched  
mission launch date x area of study  
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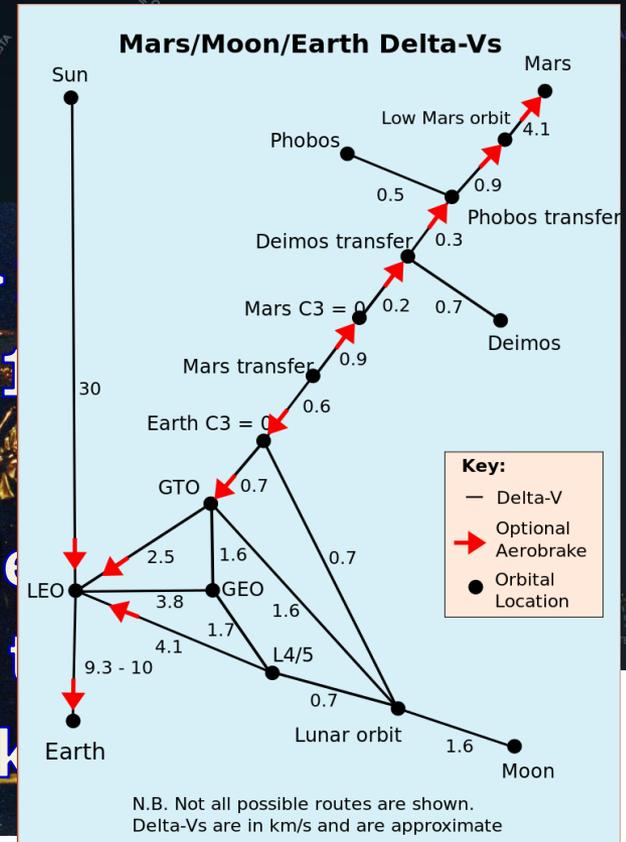


$V$  (chemical)  $\sim 3$  km/s,  $T >$   
 $V$  (plasma)  $\sim 30$  km/s,  $T <$   
 $\Delta V \equiv V_{ex} \ln(m_0/m_1)$

2 ton spacecraft, 1 km/s de

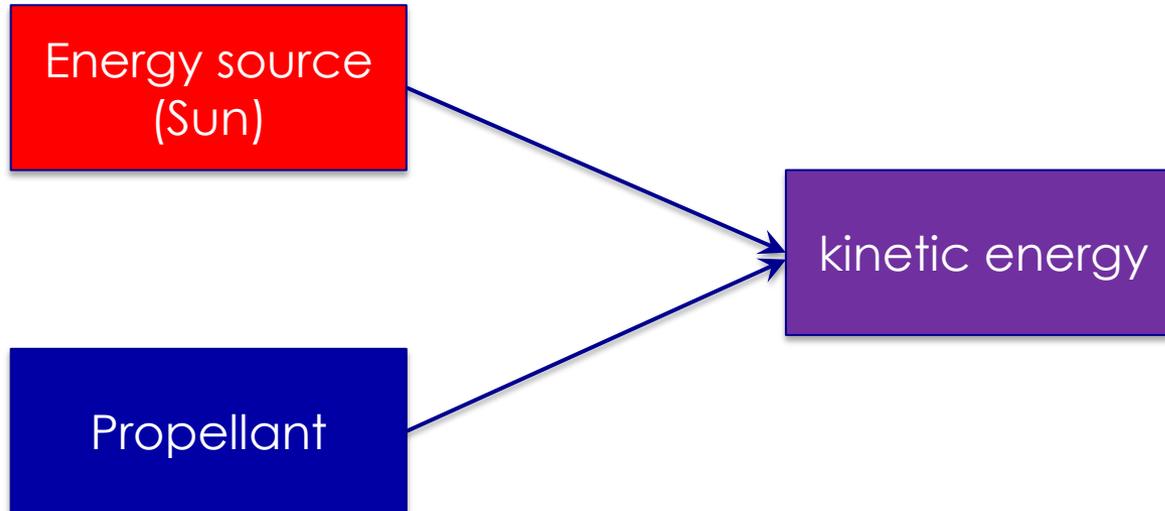
- Chemical propulsion  $\sim 1$
- Electric propulsion  $\sim 50$

Image credit: NASA/JPL-Caltech

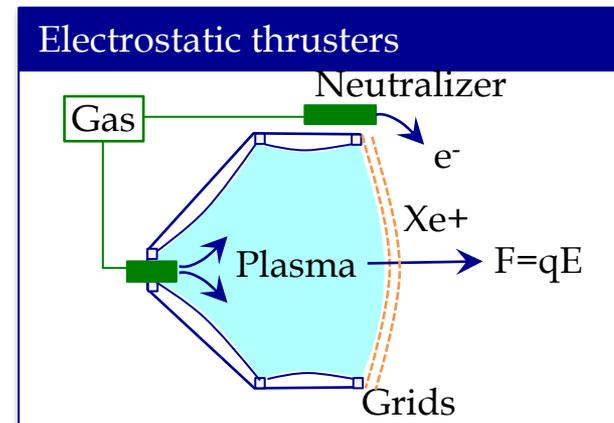


"Delta-Vs for inner Solar System" by Wolfkeeper - Public Domain via Wikimedia Commons

# Electric Propulsion



Gridded Ion thrusters  
Hall thrusters  
 $V_{ex} \sim 15 - 40 \text{ km/s}$   
 $T \sim 0.1 - 1000 \text{ mN}$



# Propulsion basics



## Ion engine performance

$$T = m' V_{ex} \approx I_{ion} (2m_i V_{acc} / q)^{1/2}$$

$$V_{ex} = (2qV_{acc} / m_i)^{1/2}$$

## Mission capabilities

$$\Delta V = V_{ex} \ln(m_0 / m_1)$$

$$\Delta t \approx \Delta V m_0 / T$$

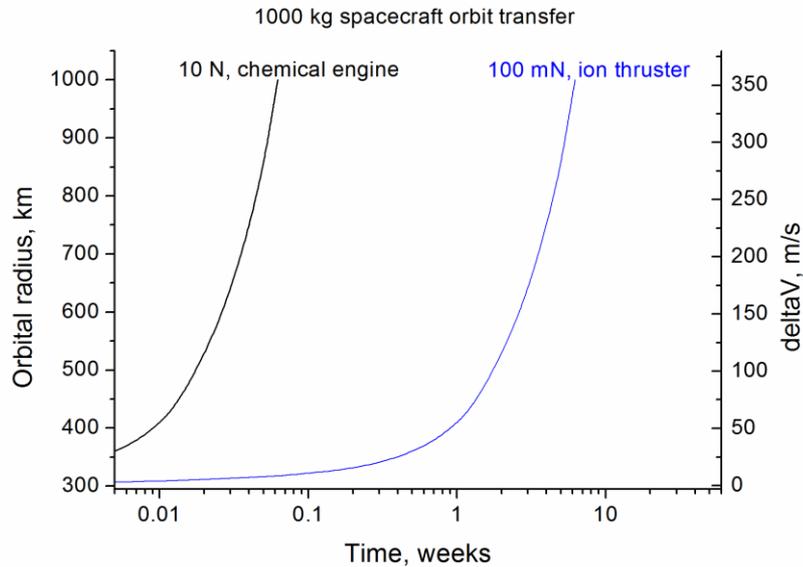
***!  $\Delta V$  required with high thrust <  $\Delta V$  (low thrust)***

- Hohmann transfer
- Oberth effect

# Propulsion basics



## Ion engine performance

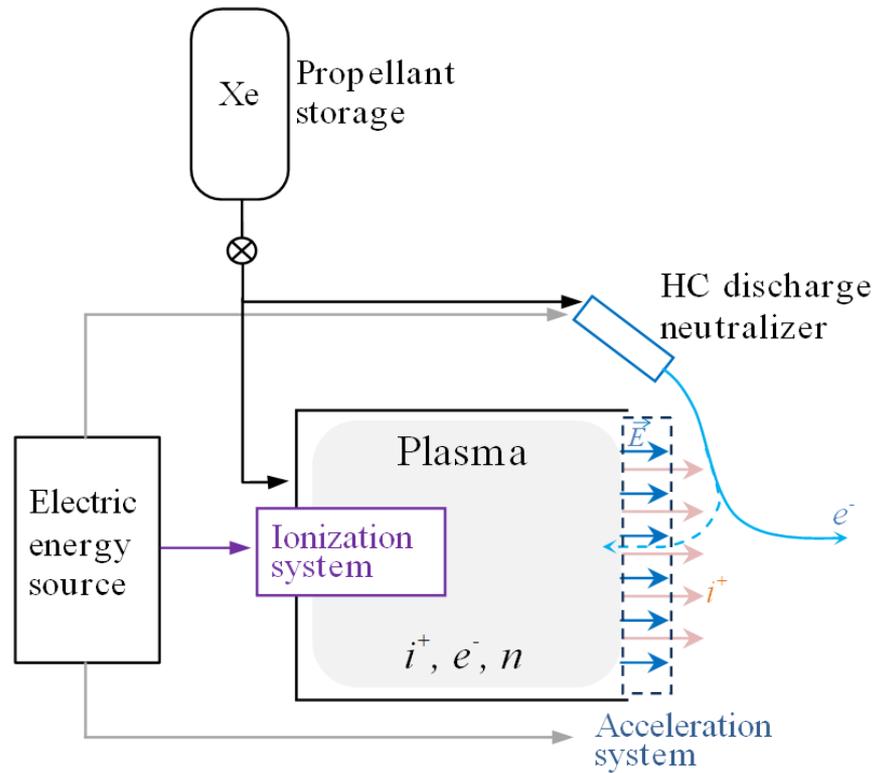


$$\Delta t \approx \Delta V m_0 / T$$

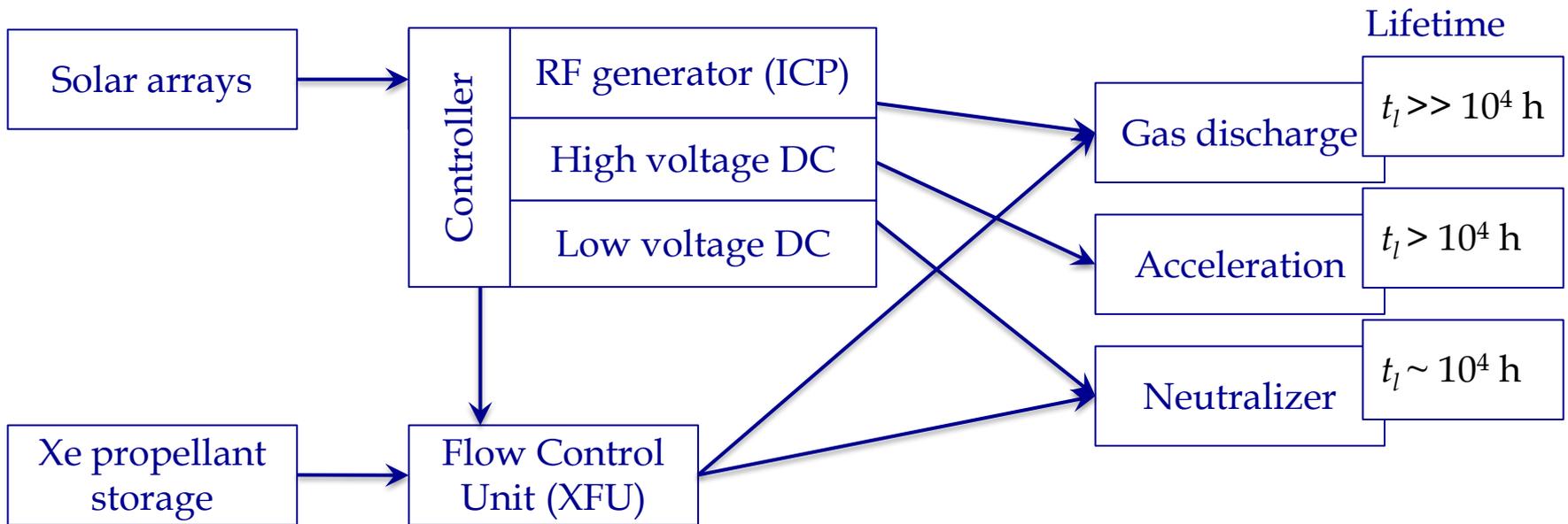
***!  $\Delta V$  required with high thrust <  $\Delta V$  (low thrust)***

- Hohmann transfer
- Oberth effect

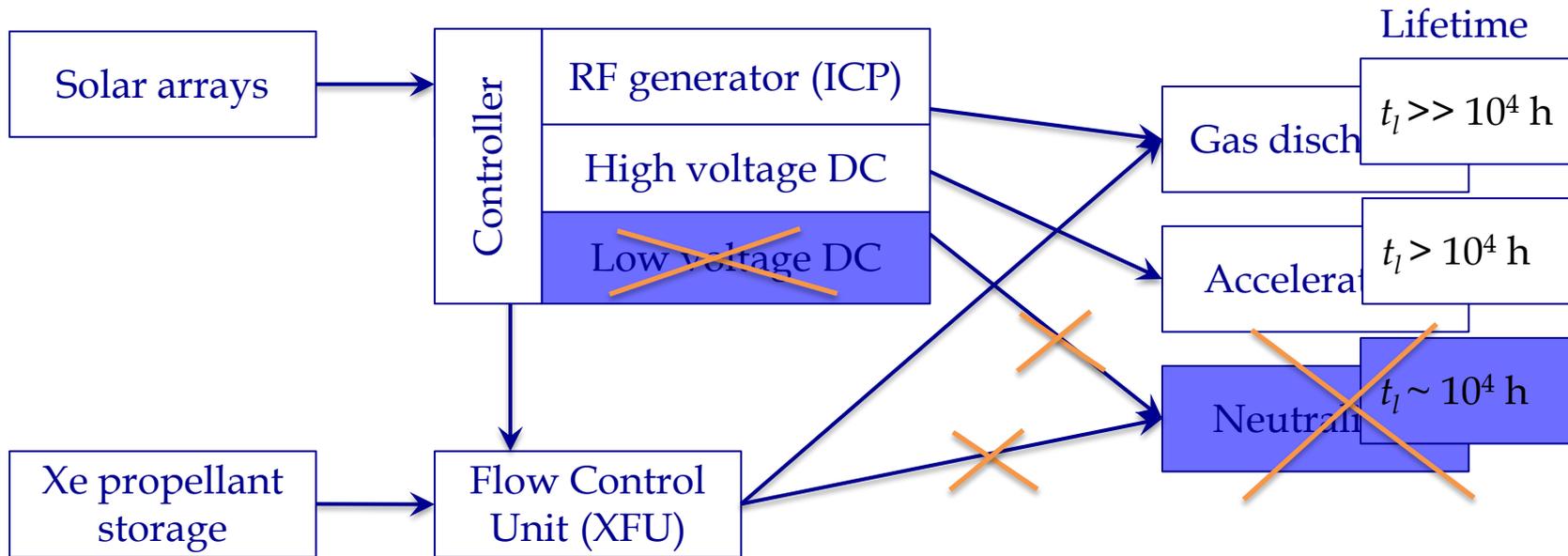
# Electric Propulsion system



# Electric Propulsion system



# Neutralizer-free systems



- +Lifetime and robustness
- +Downscaling

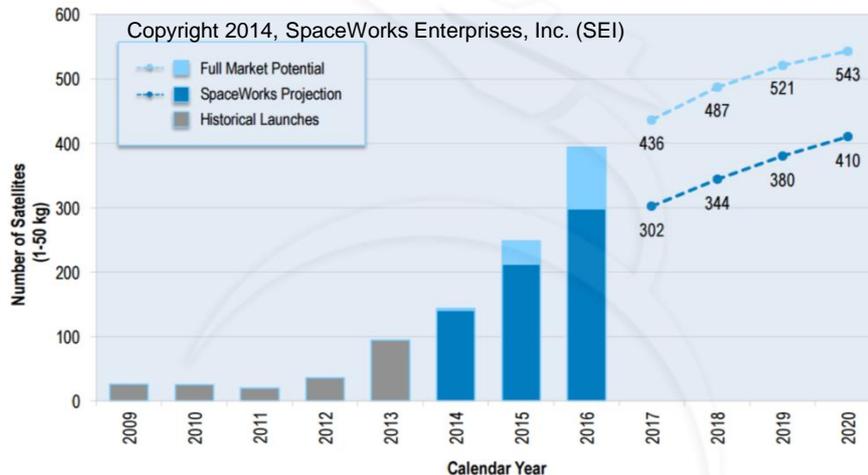
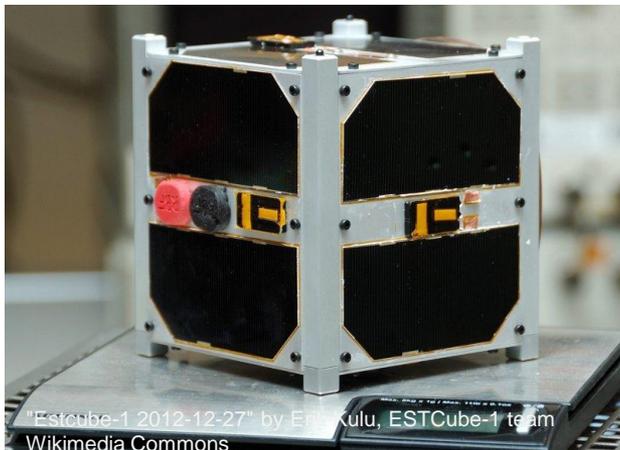
# Electric Propulsion: new challenges



- Lifetime and robustness for longer missions



- Downscaling the EP for small satellites



The Full Market Potential dataset is a combination of publically announced launch intentions, market research, and qualitative/quantitative assessments to account for future activities and programs. The SpaceWorks Projection dataset reflects SpaceWorks' expert value judgment on the likely market outcome.

# Neutralizer-free systems



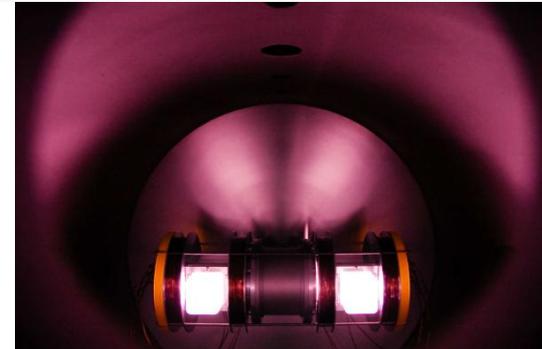
Acceleration of oppositely charged particles

Plasma acceleration concepts:  
• Plasma expansion  
•  $j \times B$  acceleration

Dual beam acceleration concepts:  
• Spatial separation  
• Temporal separation



J Jarrige, P-Q Elias, F Cannat, D Packan, 33rd International Electric Propulsion Conference, 2013 (IEPC-2013-420)



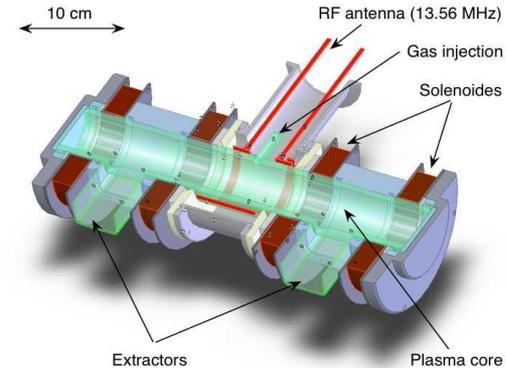
Aanesland A, et al.: *Journal of Physics: Conference Series*, 162 012009 (2009)

# Dual beam with positive/negative ions



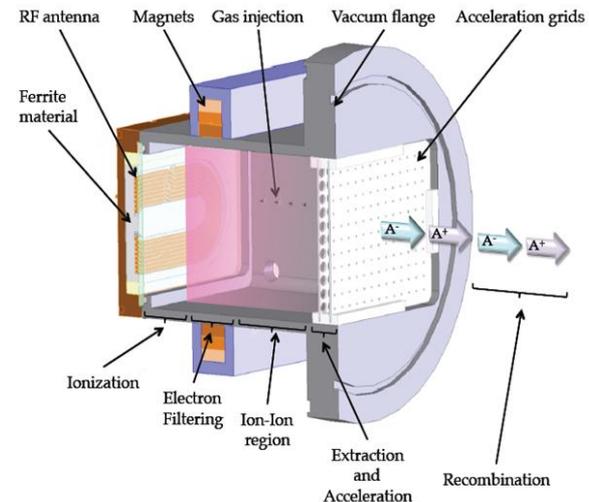
## PEGASES I:

Two beams of oppositely charged ions extracted from the same plasma source



## PEGASES II:

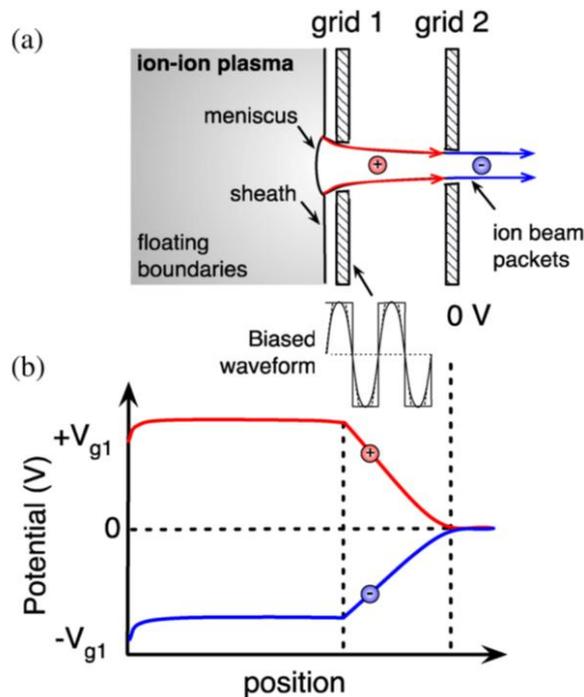
One beam with alternated extraction of oppositely charged ions



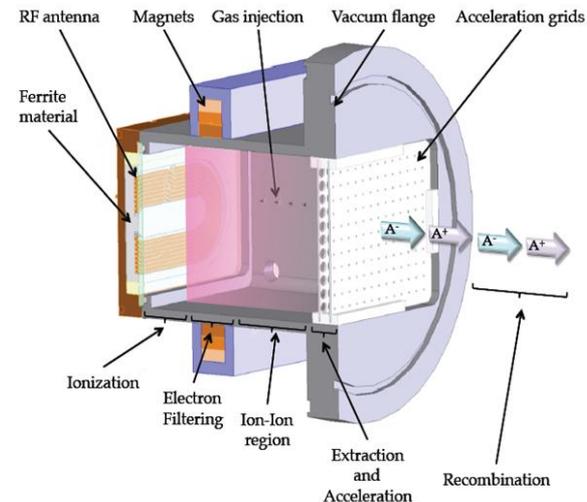
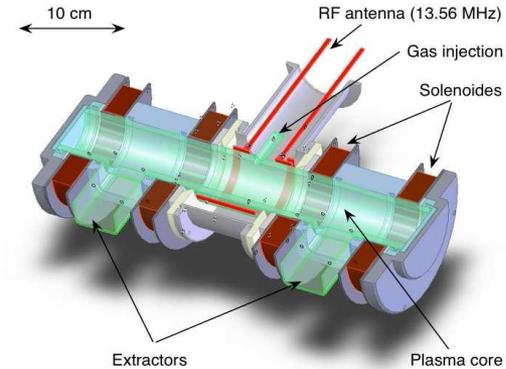
# Dual beam with positive/negative ions



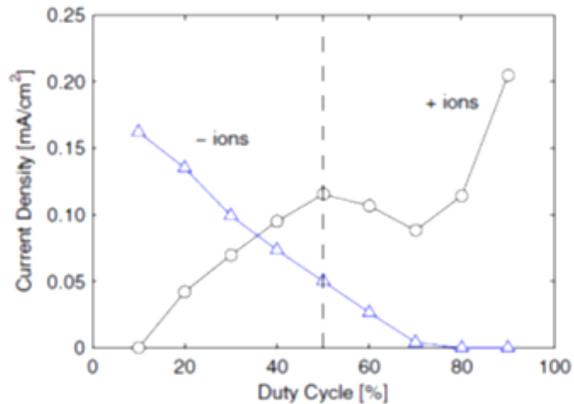
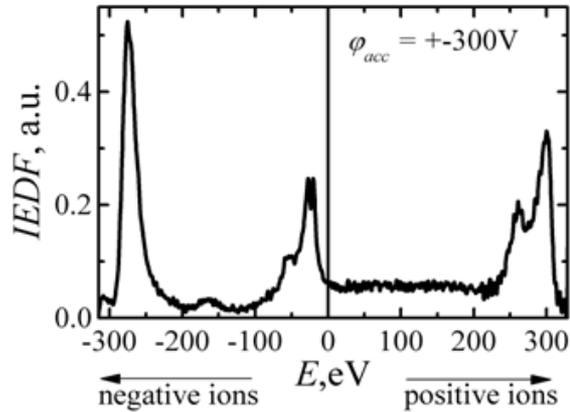
## Ion-ion plasma



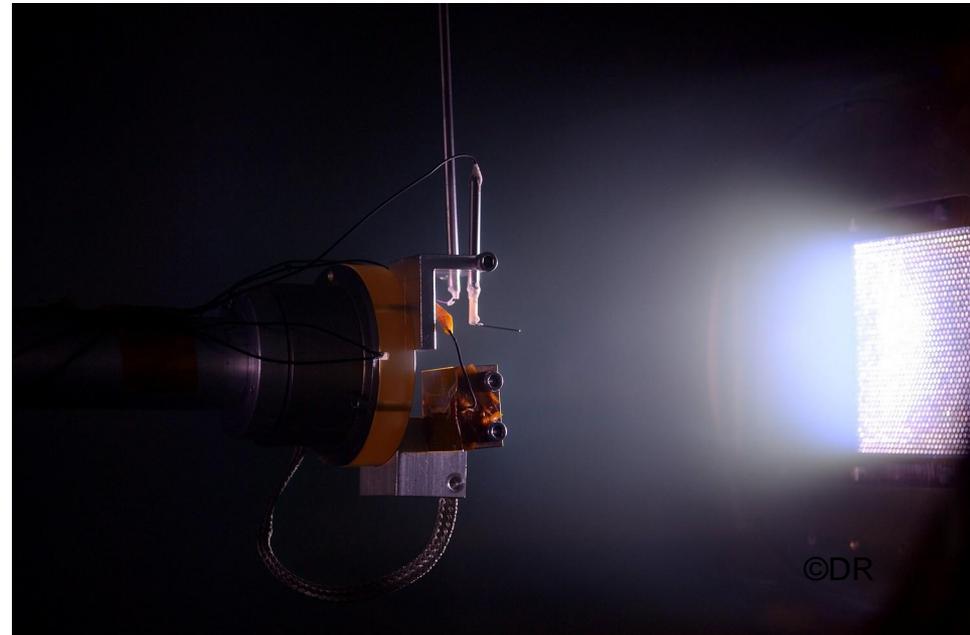
- $n_i/n_e \sim 5000$
- Zero plasma potential
- Similar response to +/- biases



# Dual beam with positive/negative ions



Running dual beam ion source (SF<sub>6</sub>)



[First patent](#) 2006

[Proof of principle](#) 2015

# Dual beam with positive/negative ions



## Propellant restrictions

Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.8
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967			
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]			

+Heavy  
+Easy to ionize  
-Storage  
-Cost

+Heavy  
+Easy to ionize  
+Storage  
+Cost  
-Corrosive

Xe, 100 bar



I<sub>2</sub>, 0 bar

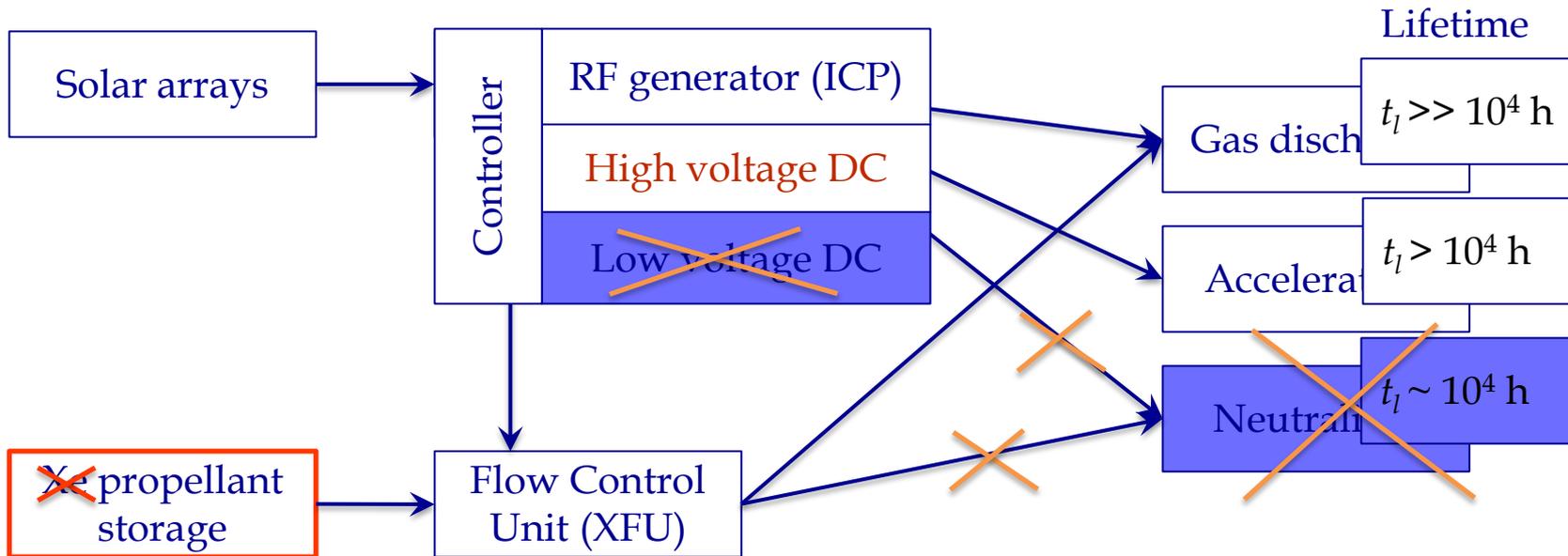


PEGASES  
"Plasma propulsion with electronegative gases"

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide
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scienceofspace.org

# Dual beam with positive/negative ions



- +Lifetime and robustness
- +Downscaling
- +Propellant storage
- Propellant flexibility

# Dual beam with positive ions/electrons

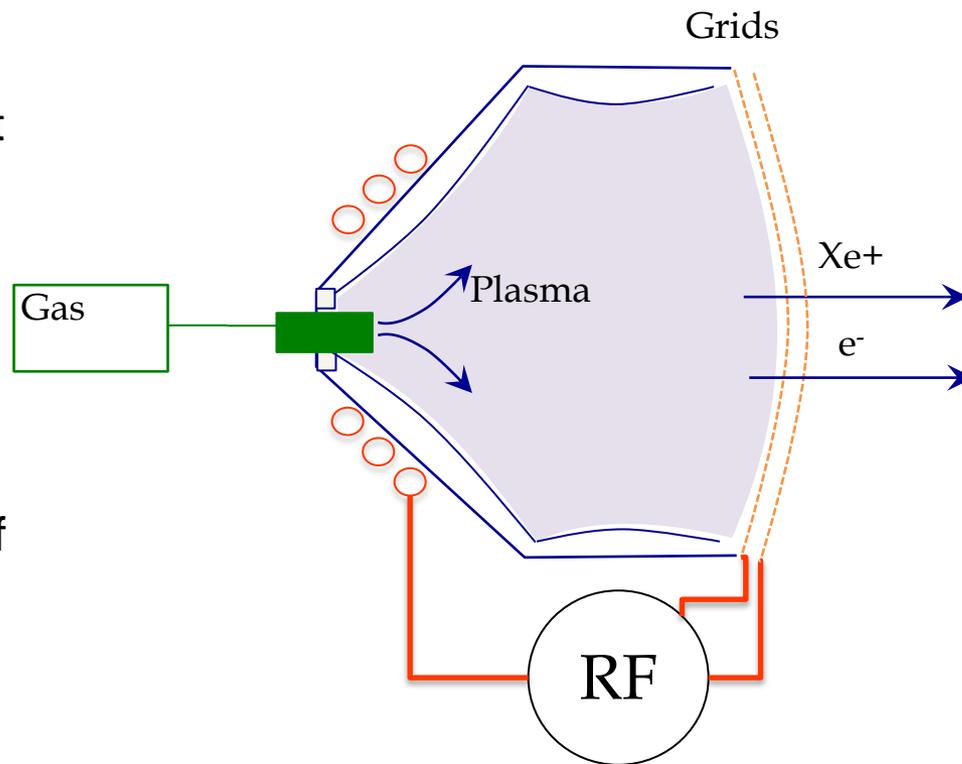
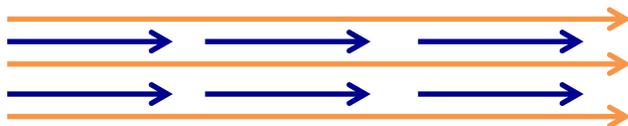


## Principle

ion-electron acceleration in the RF sheath due to self-bias effect

## Beam

Composed of continuous flow of ions and pulsed electrons

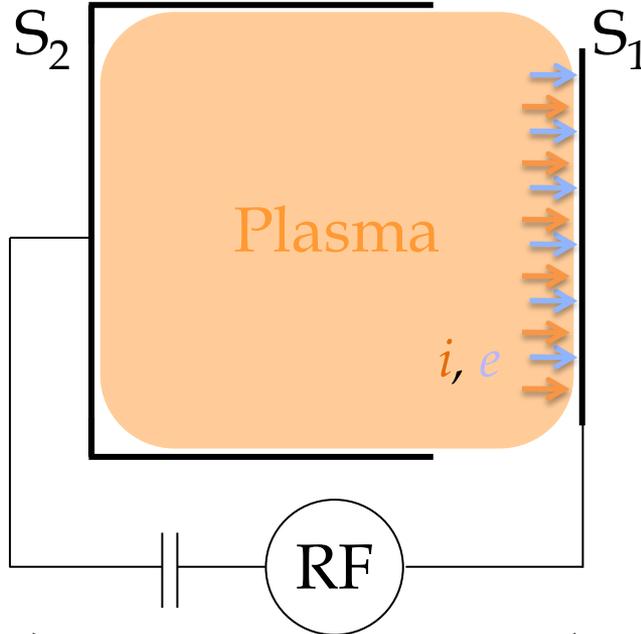


# Dual beam with positive ions/electrons

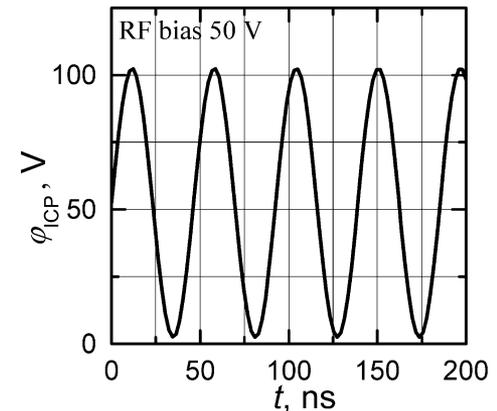
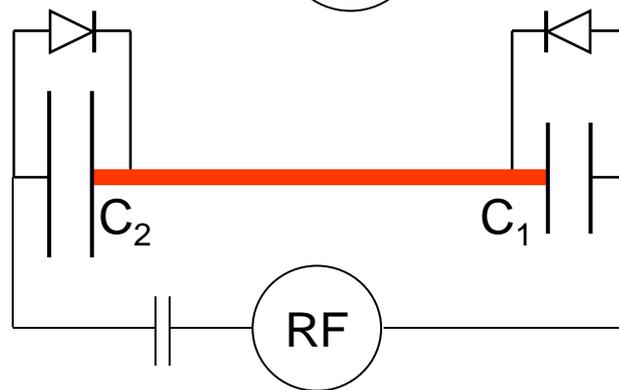


$S_1 < S_2$   
 $\omega_{pi} < \omega_{RF} < \omega_{pe}$   
 blocking capacitor  
 $I_e \equiv I_i$

## Asymmetric RF discharge



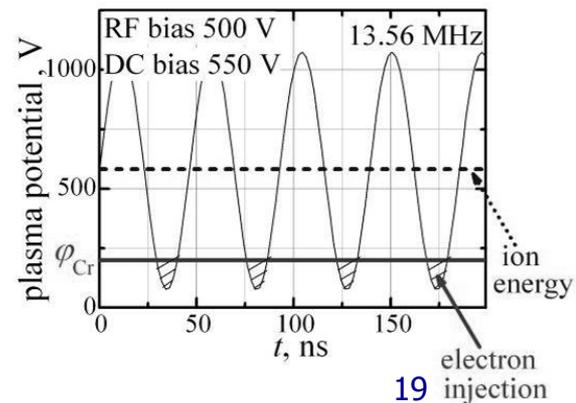
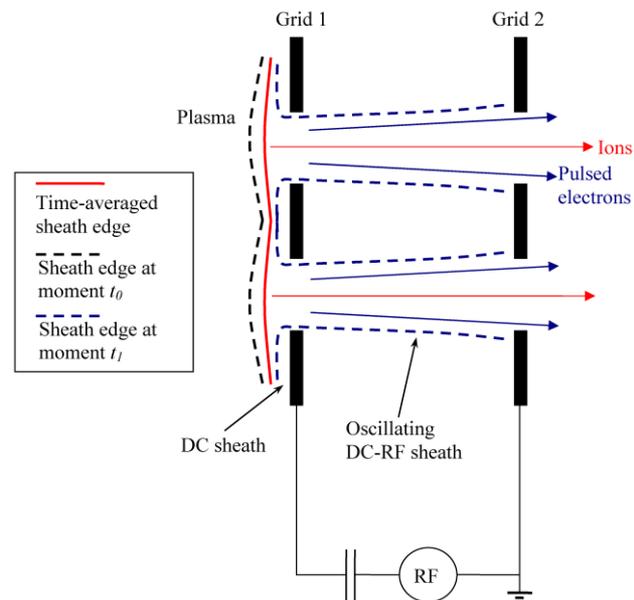
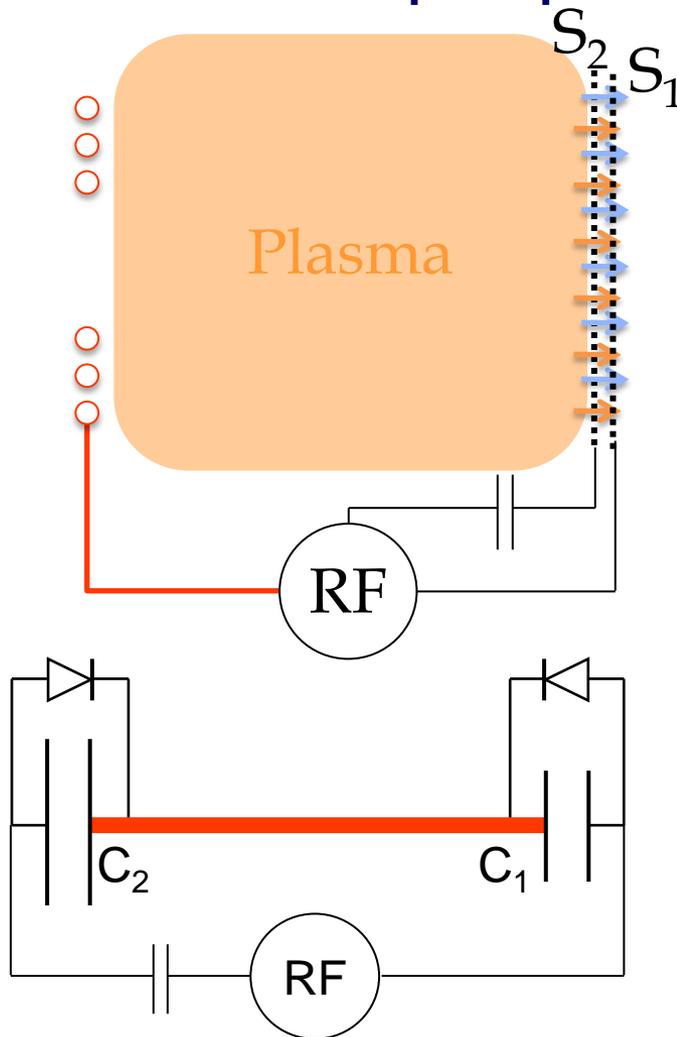
$C_1 < C_2$   
 $V_1 \gg V_2$   
 $V_1 \sim V_{RF} + V_{DC}$   
 due to "diode"



# Dual beam with positive ions/electrons



## RF acceleration principle



# Dual beam with positive ions/electrons



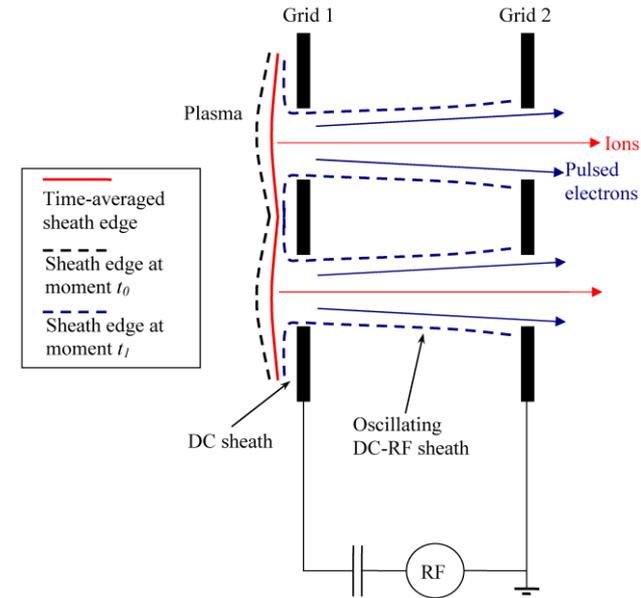
Blocking capacitor:

$$I_e \equiv I_i$$

The space charge limited current is:

$$J_{CL} = X_C \frac{2e \bar{v}^{3/2}}{M \bar{v}} \frac{1}{d^2}$$

$$X_{DC} = \frac{4}{9} = 0.44 \quad X_{RF} = \frac{200}{243} = 0.82 \quad [1]$$

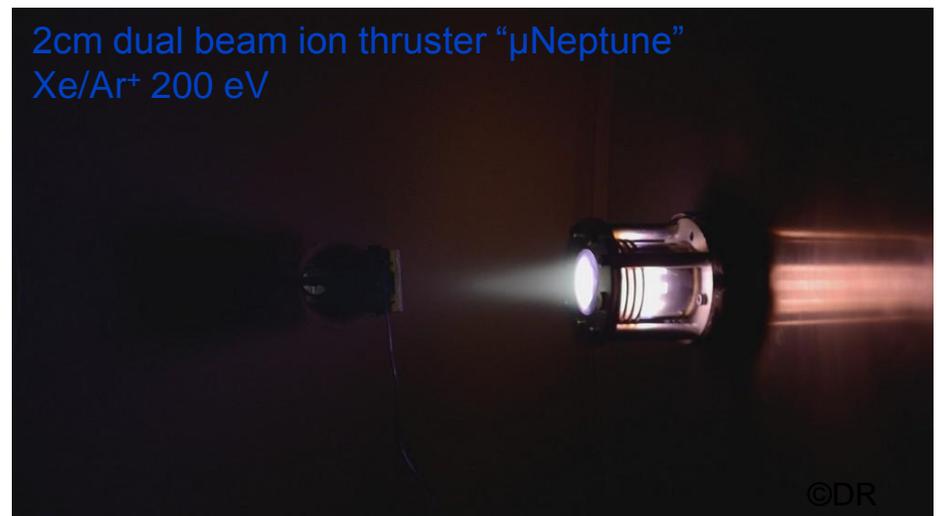
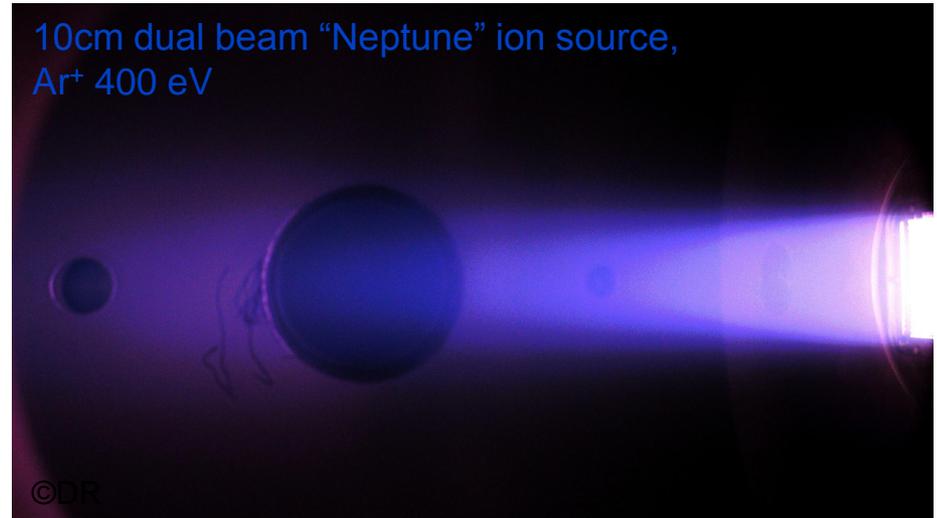
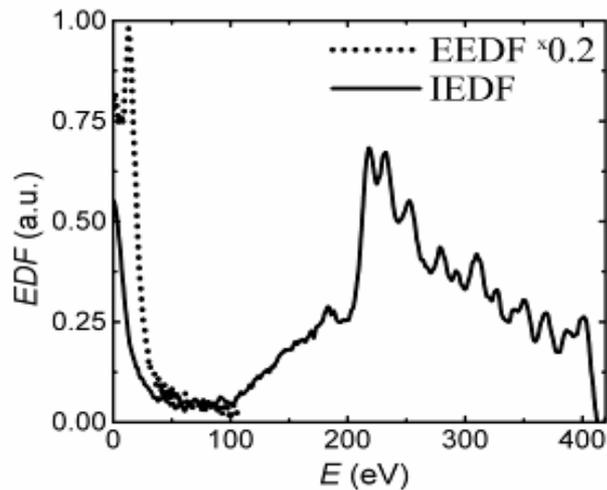
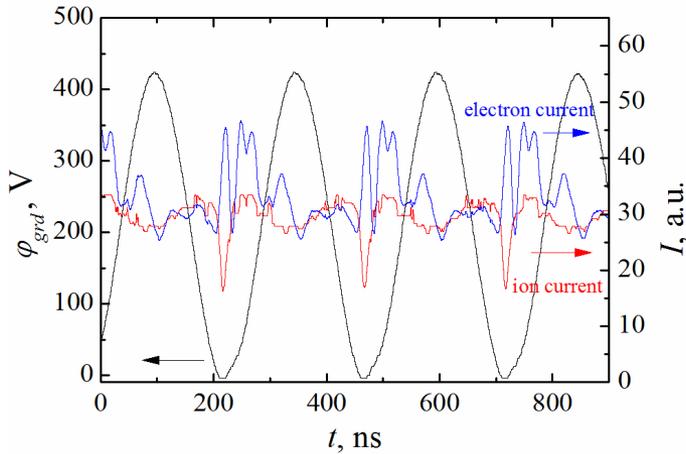


- Emitted net charge is always zero
- Extracted ion current can be up to x2 the one for DC

# Dual beam with positive ions/electrons



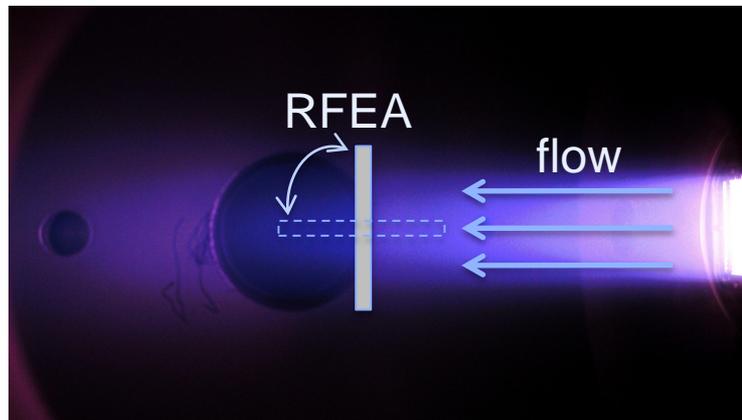
RF acceleration  
Quasi-simultaneous extraction



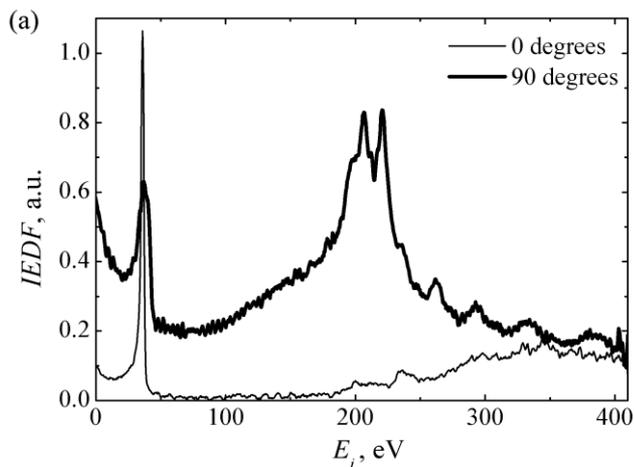
# Dual beam with positive ions/electrons



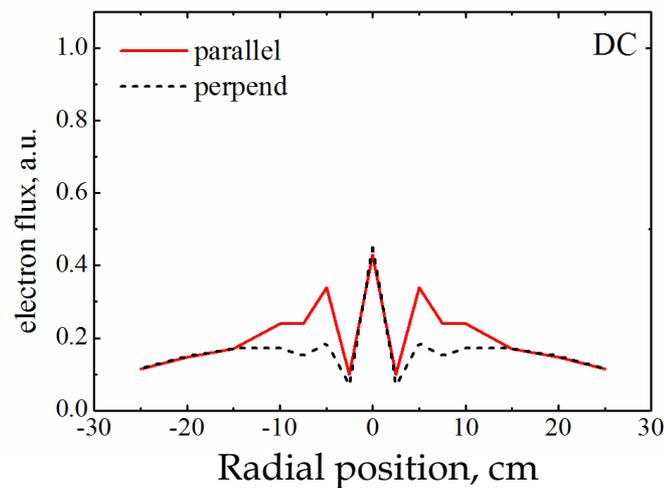
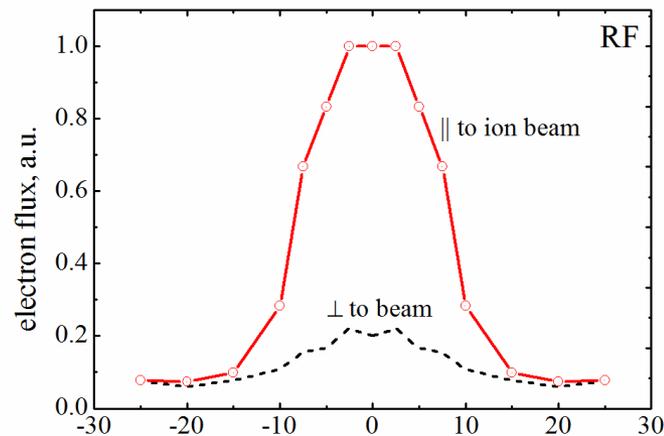
### The flow directionality



### Ions



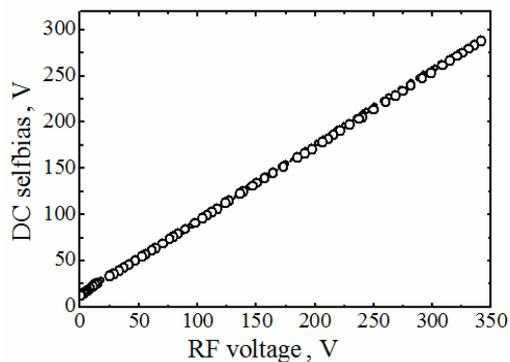
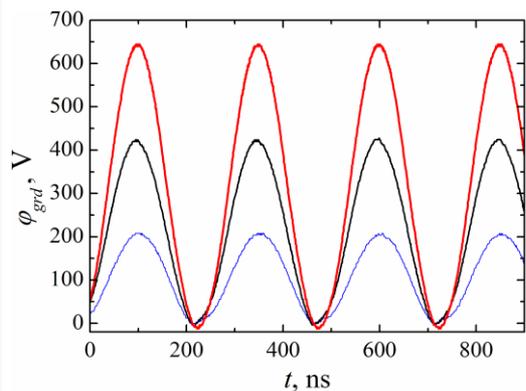
### Electrons



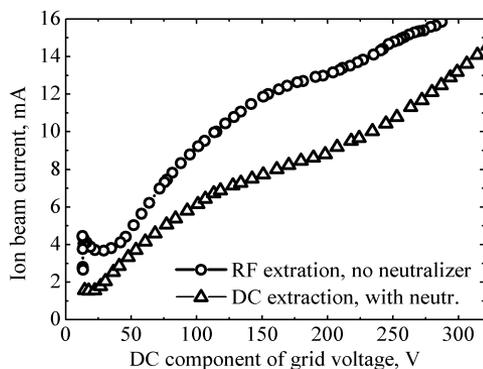
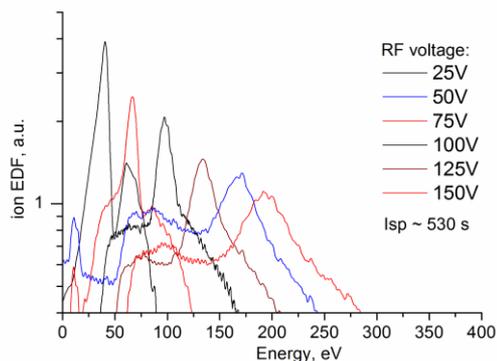
# Dual beam with positive ions/electrons



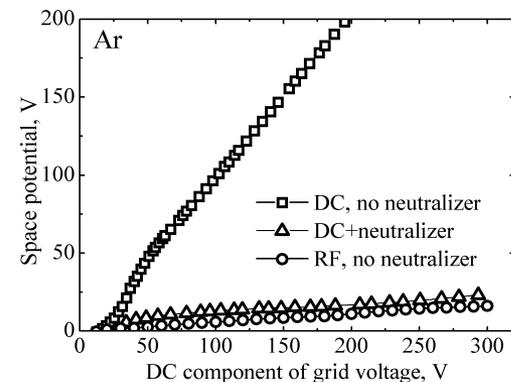
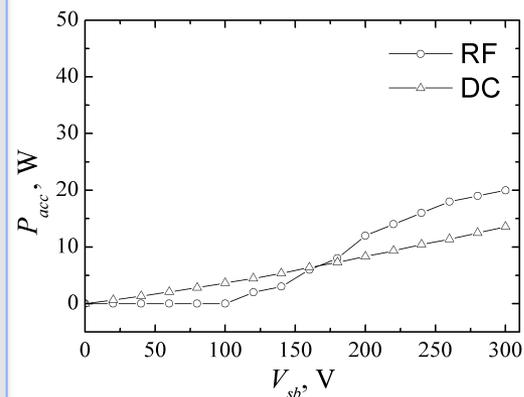
## Stability



## Control

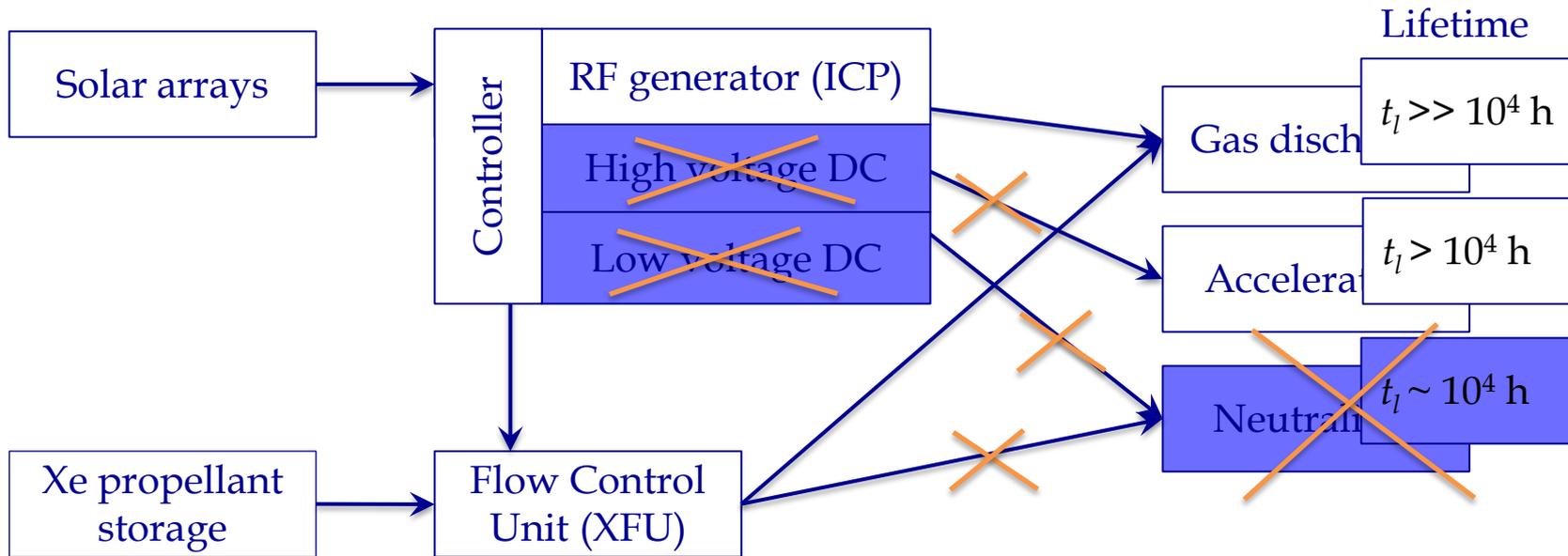


## RF vs DC



Find more information in *Phys. Plasmas*, **22**, 063502 (2015)  
and *J. Phys. D : Appl. Phys.*, **47**, 495203 (2014)

# Dual beam with positive ions/electrons



- +Lifetime and robustness
- +Significant downscaling
- +Propellant flexibility

# Dual beam with positive ions/electrons

## - disruptive technology for space



### Reasons:

- Strong technology heritage
- No cathode neutralizer
- Beam current can be x2 the one for a DC system
- System is simplified - only one RF power supply
- Scaling flexibility
- Zero emitted net charge
- Highly directional flow
- Suppressed background plasma
- Can be used as a plasma accelerator

# Dual beam space propulsion: conclusions



- Dual beam is promising technology for space propulsion
- Dual beams can be formed using temporal or spatial separation of the extraction, can be composed of +/- ions or ions and electrons
- Coincident beams provide precise control of the beam and transport (space potential, induced potential, fluxes)
- Potential use in technologies due to high anisotropy and surface potential control

# References



- [1] M A Lieberman and A J Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, 2nd ed. (Wiley, New York, 2004).
- [2] *Works on rocket technology by K.E. Tsiolkovskiy*, ed. by M.K. Tikhonravov, Publishing House of the Defense Industry, Moscow, 1947. NASA Technical Translation TT F-243
- [3] "Electronegative plasma motor" P Chabert, US Patent App. 12/096,534, 2006
- [4] D Rafalskyi, L Popelier and A Aanesland *J. Appl. Phys.*, **115**, 053301 (2014)
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- [6] D Koda, H Kuninaka, Ion Engine Combining Positive and Negative Ions, Paper IEPC-2015-317, *Joint Conference of 30th ISTS, 34th IEPC and 6th NSAT, Kobe-Hyogo, Japan, July 4 – 10, 2015*
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- [8] "Dispositif de formation d'un faisceau quasi-neutre de particules de charges opposes" D Rafalskyi, A Aanesland, French Patent application no. 14 53469, from 17.04.2014
- [9] E Stuhlinger, *Ion propulsion for space flight*, New York: McGraw-Hill, 1964.

# Thank you for attention



Laboratoire de Physique des Plasmas

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