The HEMP Thruster - An Alternative to Conventional Ion Sources ?

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Feasibility study sponsored by DLR

Thrust measurements at ONERA, Palaiseau, sponsored by CNES
Ion beam characterisation in cooperation with IOM, Leipzig

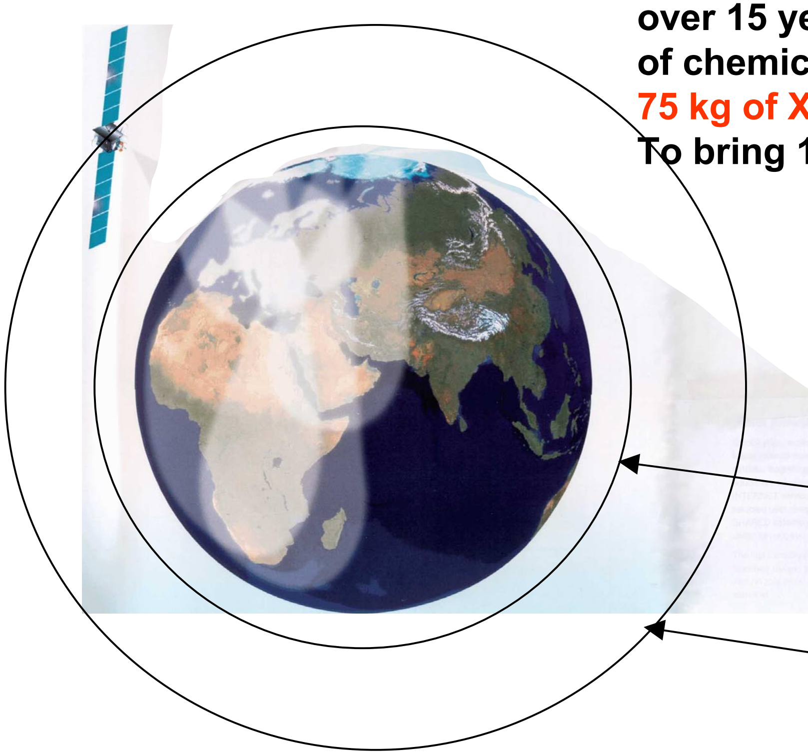
Why electric (ion) propulsion ?

To maintain a GEO communication satellite over 15 years on its position requires 775 kg of chemical propellant (Hydrazin), but only 75 kg of Xe for electric propulsion.

To bring 1 kg into GEO orbit costs 55.000.- $

Saving in launch costs: 38.5 Mio $

Alternatively more payload channels.



LEO or MEO- Satellite Orbit
(low earth or medium earth orbit)

Geo-Orbit (geostationary earth orbit)

Basic relations for electric (ion) propulsion (I)

Thrust

$$T = \dot{m}_{prop} \cdot v_{\|} = \dot{m} \cdot v \cdot \cos\alpha_{eff} \propto M_{prop} \cdot I_{ion} \cdot \sqrt{U_{eff}} \cdot \cos\alpha_{eff}$$

Thrust Power

$$P_T = \frac{1}{2} \cdot \dot{m}_{prop} \cdot v_{\|}^2 = \frac{T^2}{2 \cdot \dot{m}} \propto M_{prop} \cdot I_{ion} \cdot U_{eff} \cdot \cos^2\alpha_{eff}$$

Specific Impulse

$$I_{sp} = \frac{T}{\dot{m}_{prop} \cdot g} \propto \sqrt{U_{eff}} \cdot \cos\alpha_{eff}$$

Thrust-to-Power Ratio

$$TTPR = \frac{T}{P} \propto \sqrt{\frac{M_{prop}}{U_{eff}}} \cdot \frac{1}{\cos\alpha_{eff}}$$

Total Efficiency

$$\eta_{tot} = \frac{T^2}{2 \cdot \dot{m}_{prop} \cdot P}$$

Ionisation Efficiency

$$\eta_{ion} = \frac{\sum_i I_{ion^{i+}}}{e \cdot \frac{\dot{m}_{prop}}{M_{prop}}}$$

Thermal (=beam power) Efficiency

$$\eta_{therm} = \frac{P_{beam}}{P}$$

$$\Rightarrow \eta_{tot} = \eta_{ion} \cdot \eta_{therm} \cdot \cos^2\alpha_{eff}$$

M_{prop} = propellant molecular mass,
dm_{prop}/dt = propellant mass flow,
$v_{\|}$, v = mean (axial) propellant velocity,
α_{eff} = effective ion beam angle
U_{eff} = effective acceleration voltage,
I_{ion} = ion current,
g = 9.81 m/s²,
P_{beam} = total ion beam power

Basic relations for (ion) electric propulsion (II)

Conclusions:

(i) The higher the propellant molecular mass M_{prop}, the higher the thrust-to-power ratio *TTPR.* Typically Xenon is used as propellant, which also exhibits a low ionisation energy.

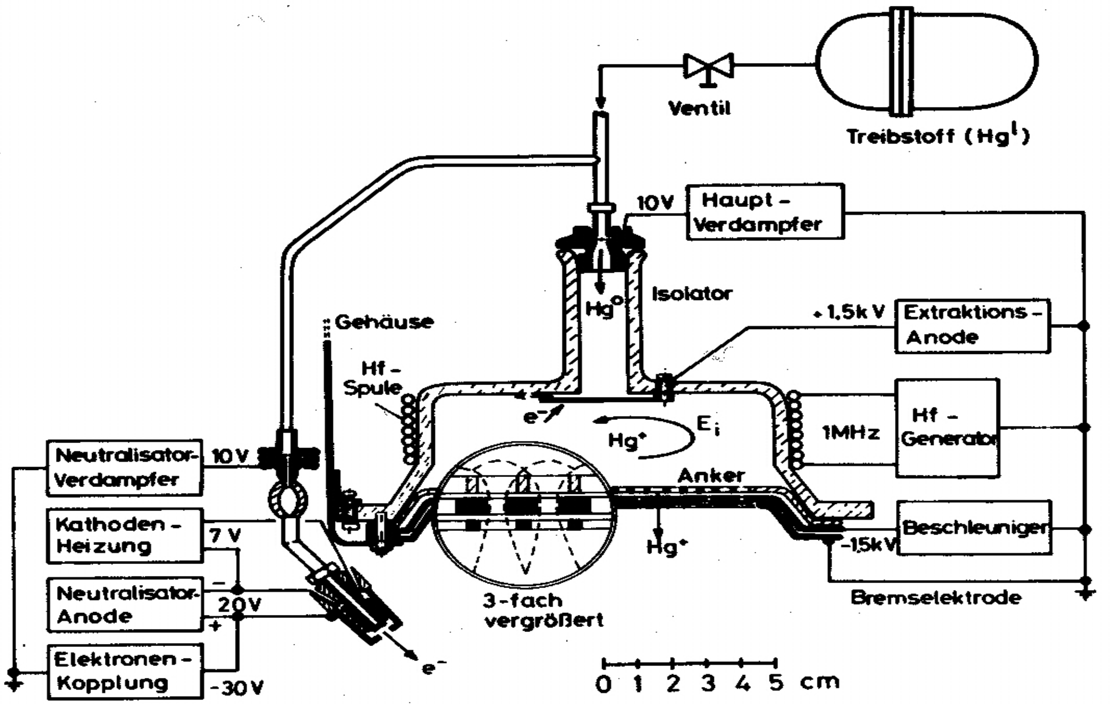
(ii) In order to obtain a maximum total efficiency η_{prop}, a high amount of the propellant flow has to be ionised, the thermal efficiency η_{therm} has to be as high and the effective ion beam angle α_{eff} as low as possible (desirable below 20°).

(iii) The higher the specific impulse I_{sp}, the lower the total mass consumption.

(iv) However a high I_{sp} requires a high effective acceleration voltage U_{eff} and thus lowers the thrust-to-power ratio *TTPR*.

(iii) & (iv) The best compromise between I_{sp} and TTPR depends on the corresponding mission parameters (available electric power on board, satellite mass, required life time and manoeuvre requirements). Typically I_{sp} is chosen around ~ 2500 s.

Conventional Concepts: I. Gridded Ion Thrusters GITs



Scheme of a Radio Frequency sustained Ion Thruster RIT

Advantages: - high I_{sp}, high h_{tot} in restricted operational range

Drawbacks: - space charge limitation limits thrust density (up-scaling critical)
- grid erosion

THALES

Conventional Concepts: II. Hall Effect Thrusters HETs

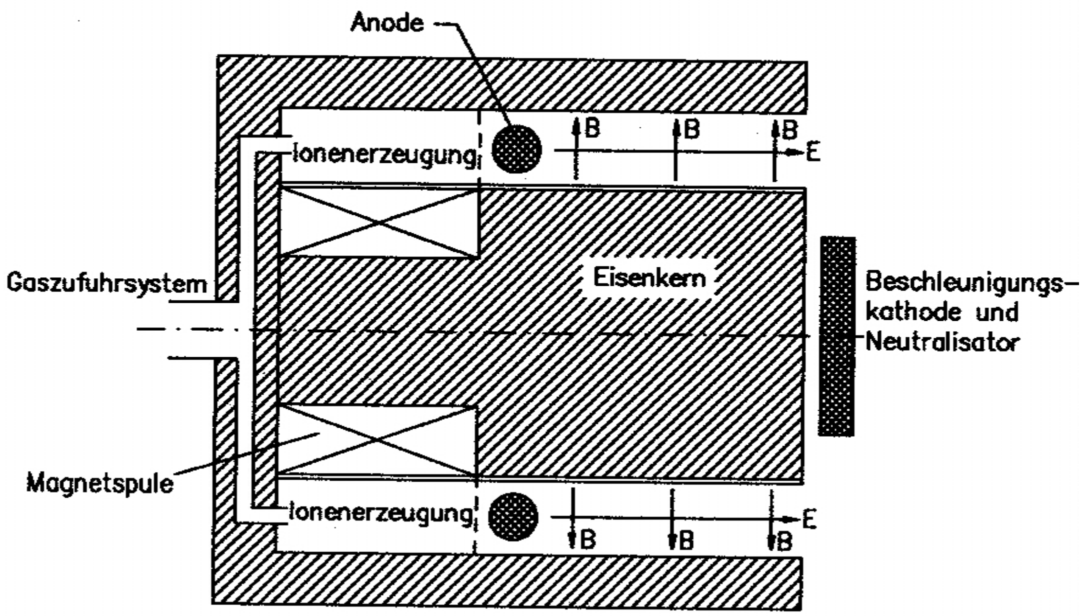


Bild 7.40: Prinzip eines Hallionentriebwerks mit getrennter Plasmaquelle.

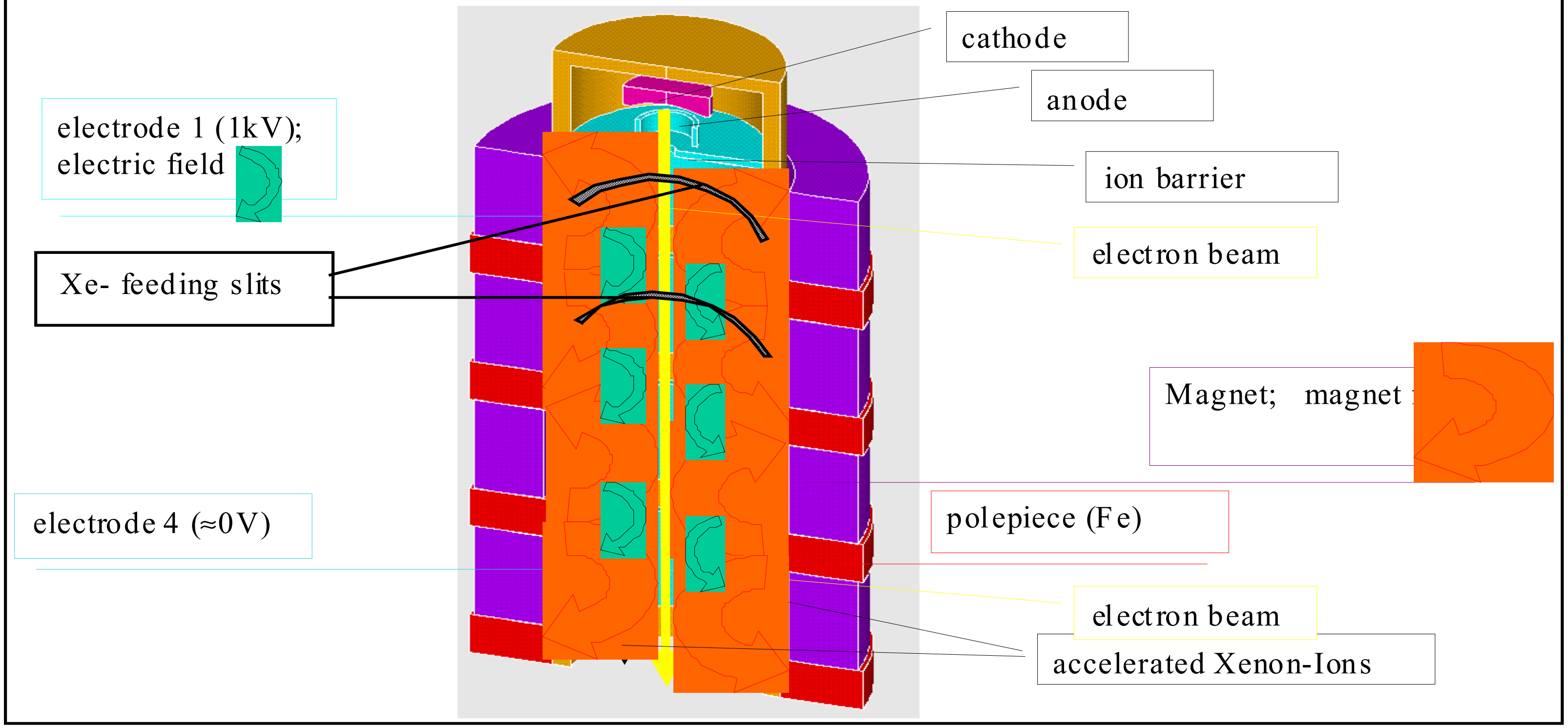
Advantages: - high TTPR, moderate h_{tot} in restricted operational range

Drawbacks: - low to moderate I_{sp}

- pronounced channel erosion (limits applicable U_A , I_{sp})

New Concept: HEMP thruster (THALES Electron Devices GmbH patent)

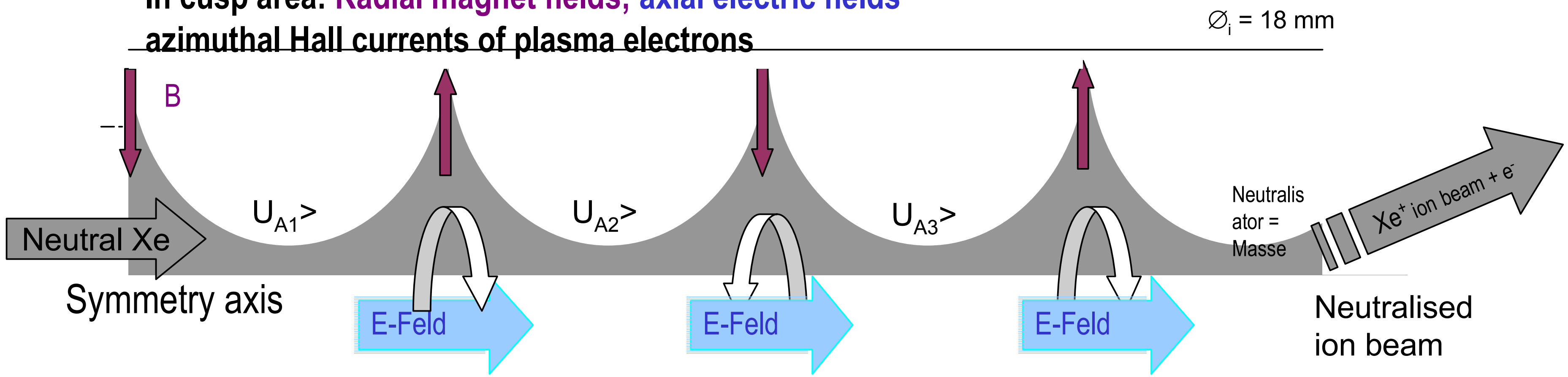
High Efficient Multistage Plasma Thruster
HEMP-Thruster Concept



Operational principle of the HEMP-thruster (I)

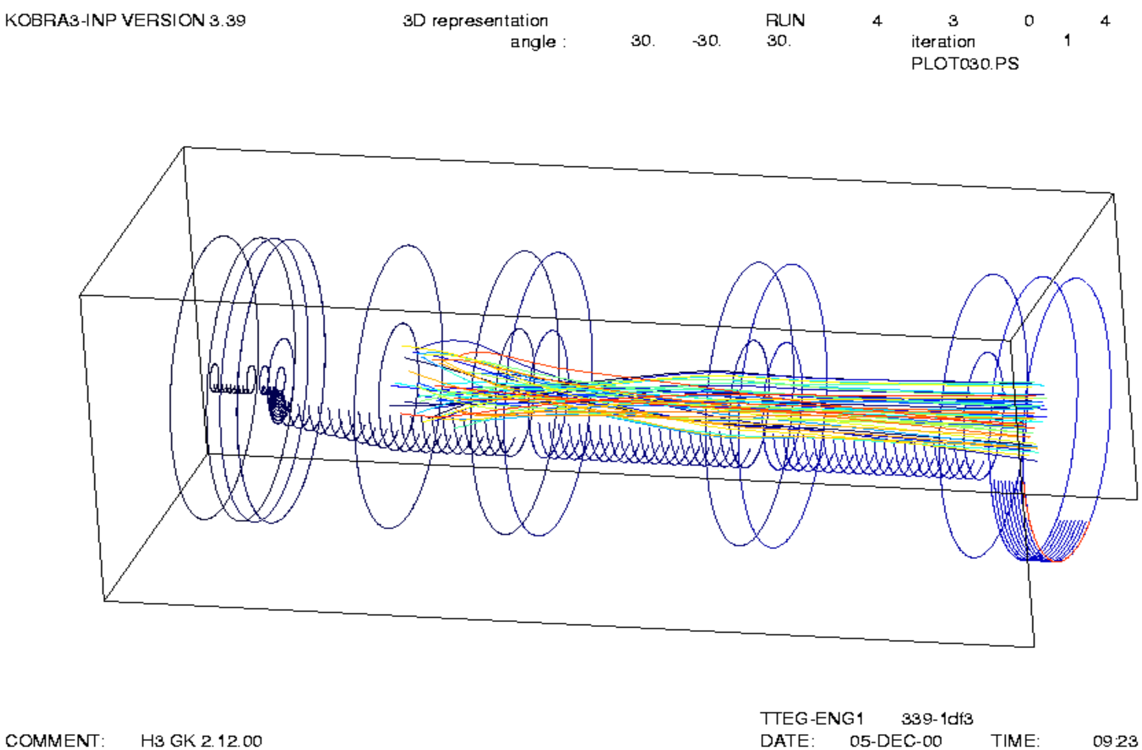
- A permanent periodic magnet structure focuses the Xe plasma, on the axis and thus prevents losses on the ionisation chamber wall.
- The applied plasma potentials U_{A_i} between the Cusps decrease towards the exit. The resulting electrical fields accelerate the Xe ions.
- A neutraliser may provide at the exit the electrons for neutralisation of the ion beam current but is not necessary for thruster operation.
- Due to the crossed electric and magnetic fields in the cusp area the plasma electrons are orbiting and mirrored in closed, azimuthal Hall currents loops, which maintains a quasi-neutral space charge distribution in the plasma chamber and lead to a high ionisation rate.

In cusp area: Radial magnet fields; axial electric fields
azimuthal Hall currents of plasma electrons



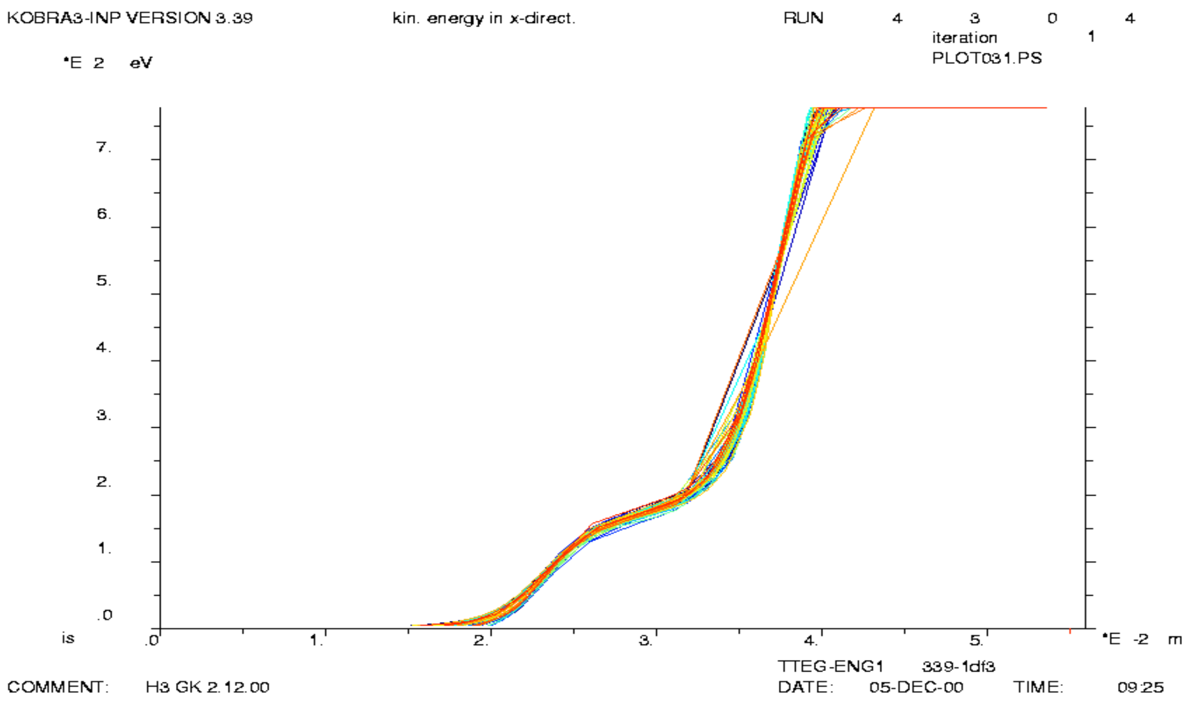
Operational principle of the HEMP-thruster (II)

Results from KOBRA trajectory code: Xe^{1+} trajectories, 1st iteration



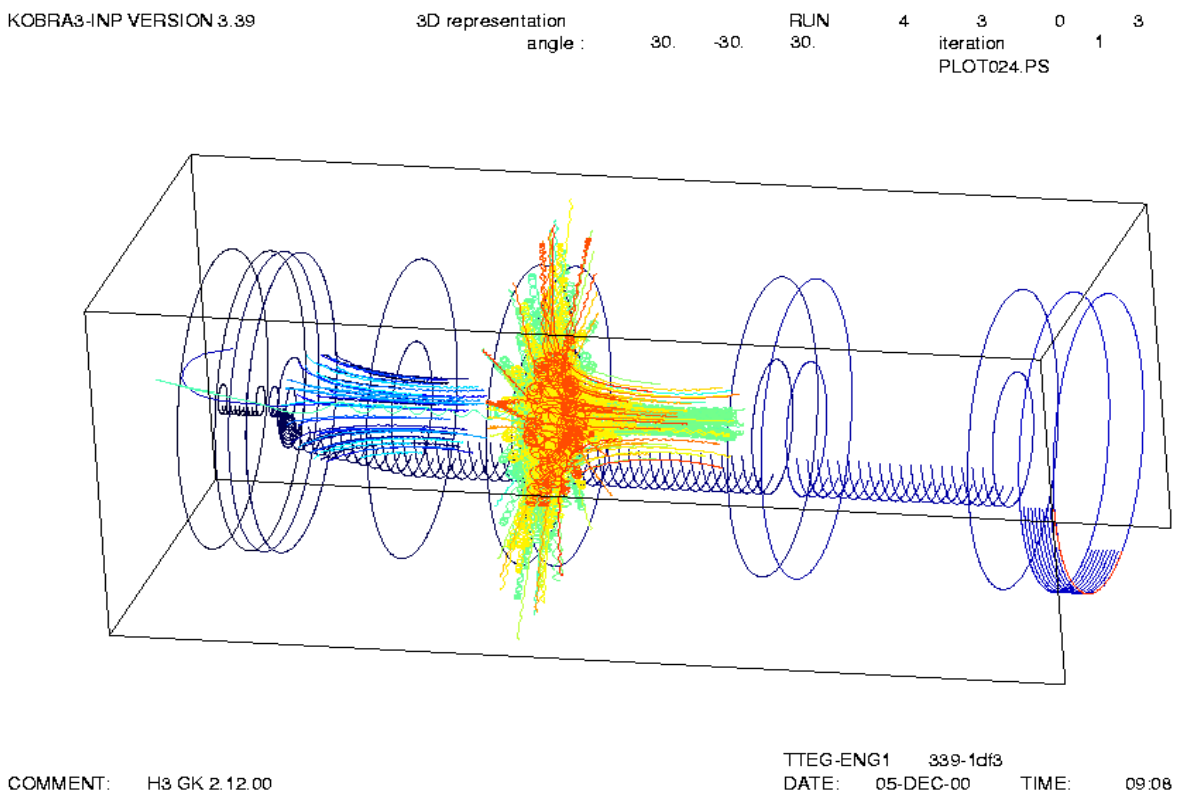
Operational principle of the HEMP-thruster (II)

Results from KOBRA trajectory code: axial kinetic energy of Xe^{1+}, 1st iteration



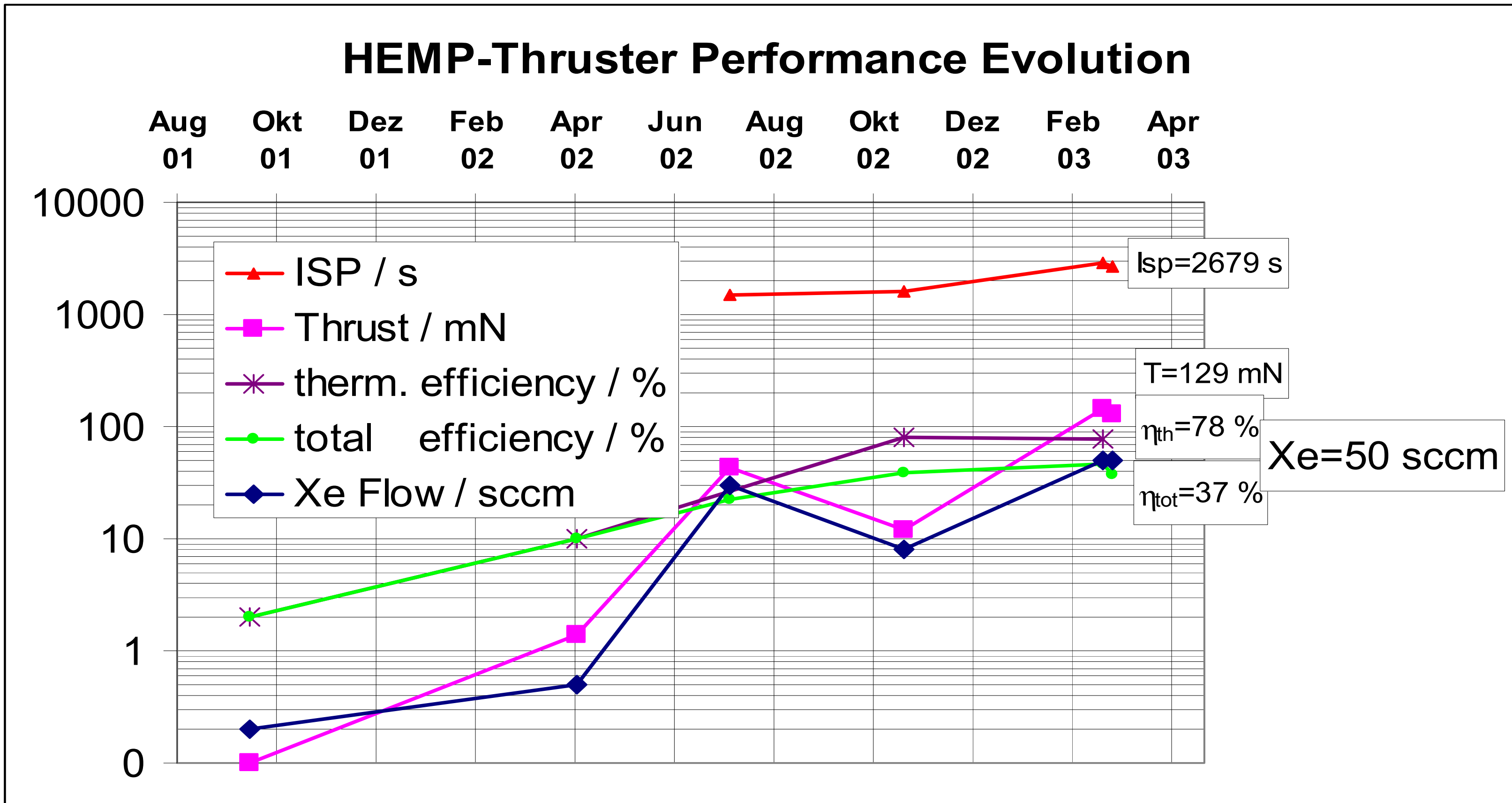
Operational principle of the HEMP-thruster (II)

Results from KOBRA trajectory code: secondary e⁻ trajectories, 1st iteration



HEMP thruster development (I)

Achievements within the feasibility study:



HEMP thruster development (II)

Theoretical approaches – numerical simulations:

- **KOBRA: trajectory code (TEDG code)**
  - 3D, short computational time
  - non self-consistent treatment of collisions and space charges

- **1D fluid model (in cooperation with G. Emsellem, Ecole Politechnique)**
  - 1D, short computational time
  - self-consistent treatment of collisions and space charges via transport equations & Townsend theory

- **XOOPIC (in cooperation with IOM Leipzig, see talk S. Jankuhn et al.)**
  - 2.5D, self-consistent treatment of collisions and space charges from first principles
  - long computational time, no self-consistent solution for steady-state situation yet

HEMP thruster development (III)

Available diagnostic tools for experimental characterisation:

- **Solid angle resolved thermal diagnostics @ TEDG, Ulm**
  - ϕ 80 cm x l 1000 cm vacuum chamber, S_{eff} = 1000 l/s for Xe via turbo molecular pump
  - 3Hz online readout and evaluation of heating velocity and cooling down characteristics allows for determination of beam power and thrust power within 5% and 10% precision, respectively

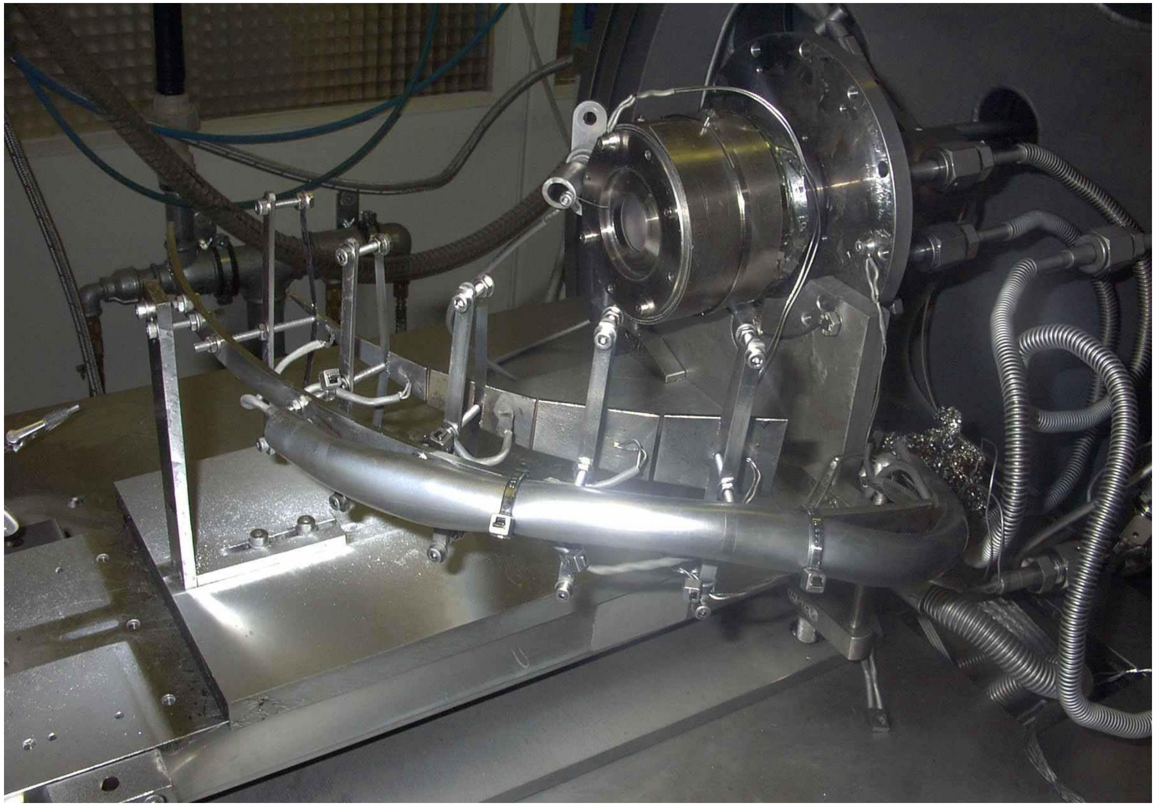
- **Direct thrust measurements @ ONERA, Palaiseau, F**
  - ϕ 60 cm x l 1000 cm hatch + ϕ 1000 cm x l 6000 cm main vacuum chamber, S_{eff} = 8000 l/s for Xe via turbo molecular and cryo pumps
  - balance for direct thrust measurements with intrinsic calibration mechanism allows for determination of thrust at 0.25 mN level

- **Ion beam characterisation @ IOM Leipzig (see talk S. Jankuhn et al.)**
  - ϕ 120 cm x l 5000 cm vacuum chamber, S_{eff} = 4000 l/s for Xe via turbo molecular pumps
  - energy selective mass spectrometry and Faraday cup based ion current measurements

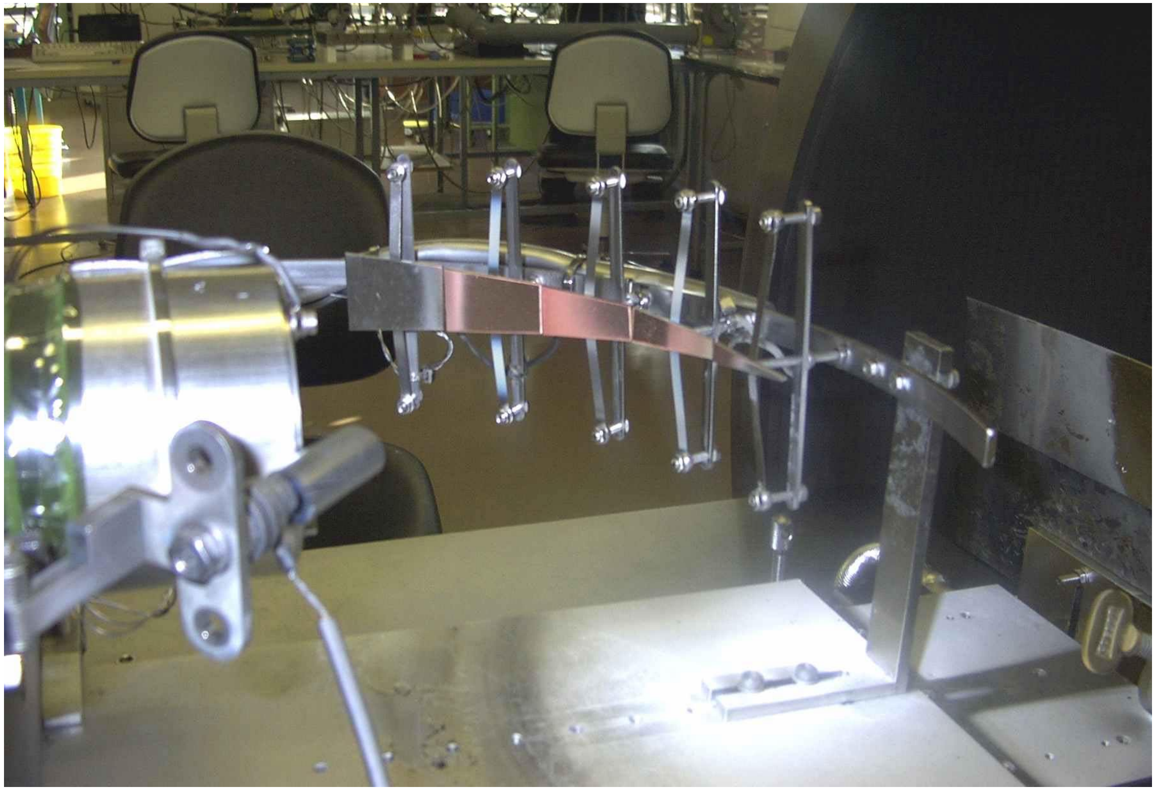
Solid angle resolved thermal diagnostics @ TEDG, Ulm (I)

Dimension of the TEDG test chamber

Solid angle resolved thermal diagnostics @ TEDG, Ulm (II)

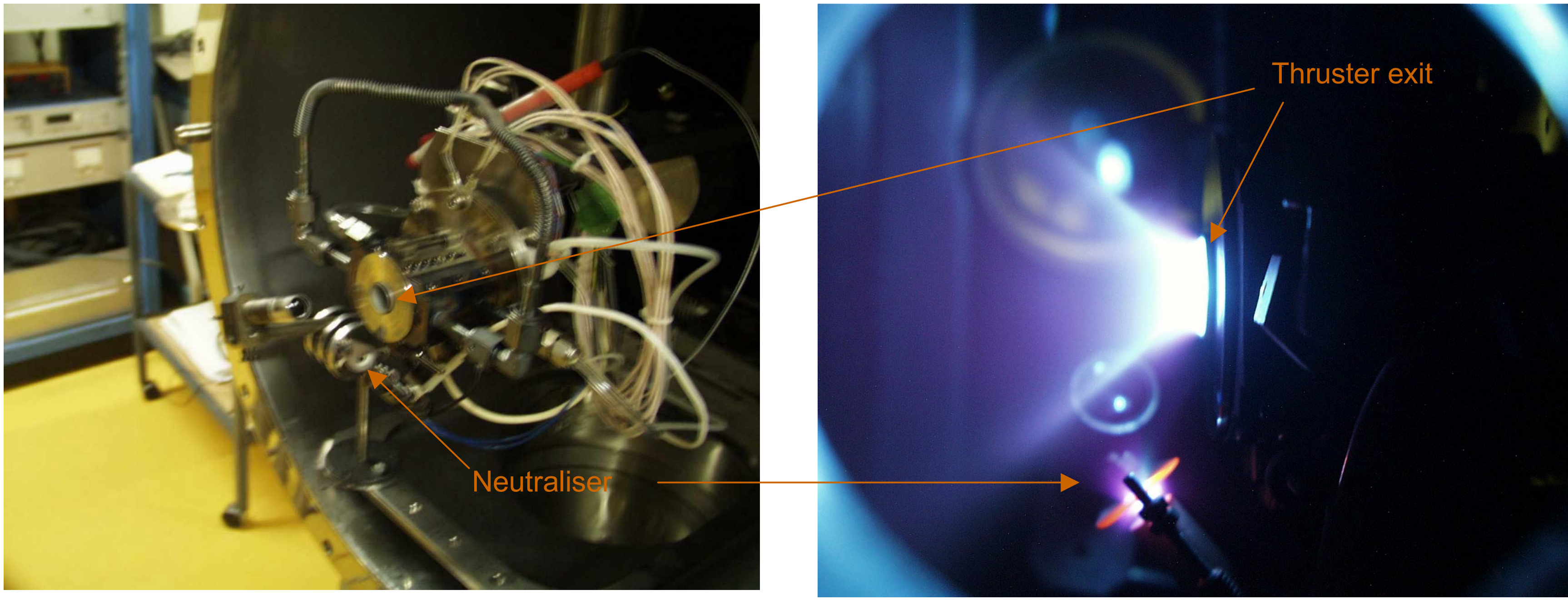


Solid angle resolved thermal diagnostics @ TEDG, Ulm (III)



Thrust measurements at ONERA, Palaiseau, F, July 2002 (I)

Experimental set up & thruster installation



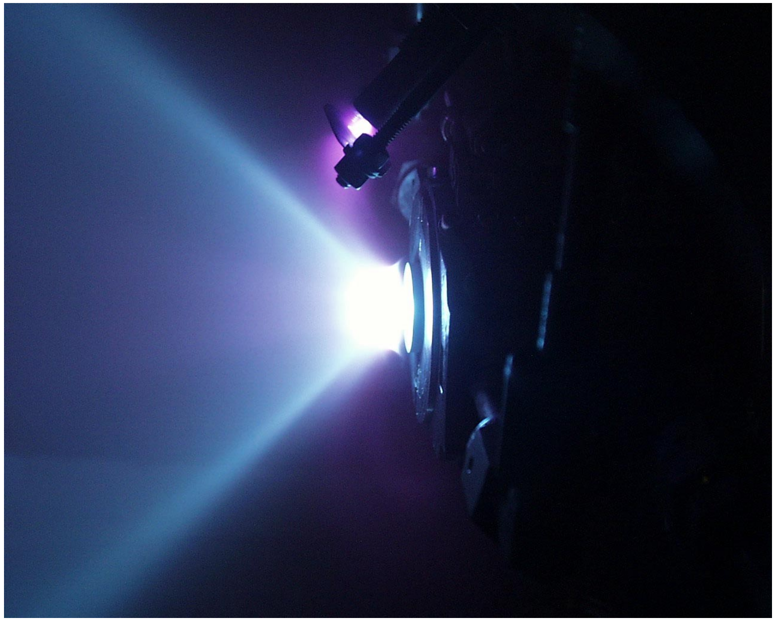
View on the DM3a MS 1-2 at installation in the thrust balance of ONERA Palaiseau

HEMP DM3a MS1-2 in ONERA's test station in operation,
Side view through window in vacuum chamber

- **up to 43 mN thrust from 2,5 cm² exit area**
- **up to 70% thermal efficiency and**
- **32% total efficiency**

Thrust measurements at ONERA, Palaiseau, F, July 2002 (II)

2 different thruster configurations tested



DM3a-MS2:

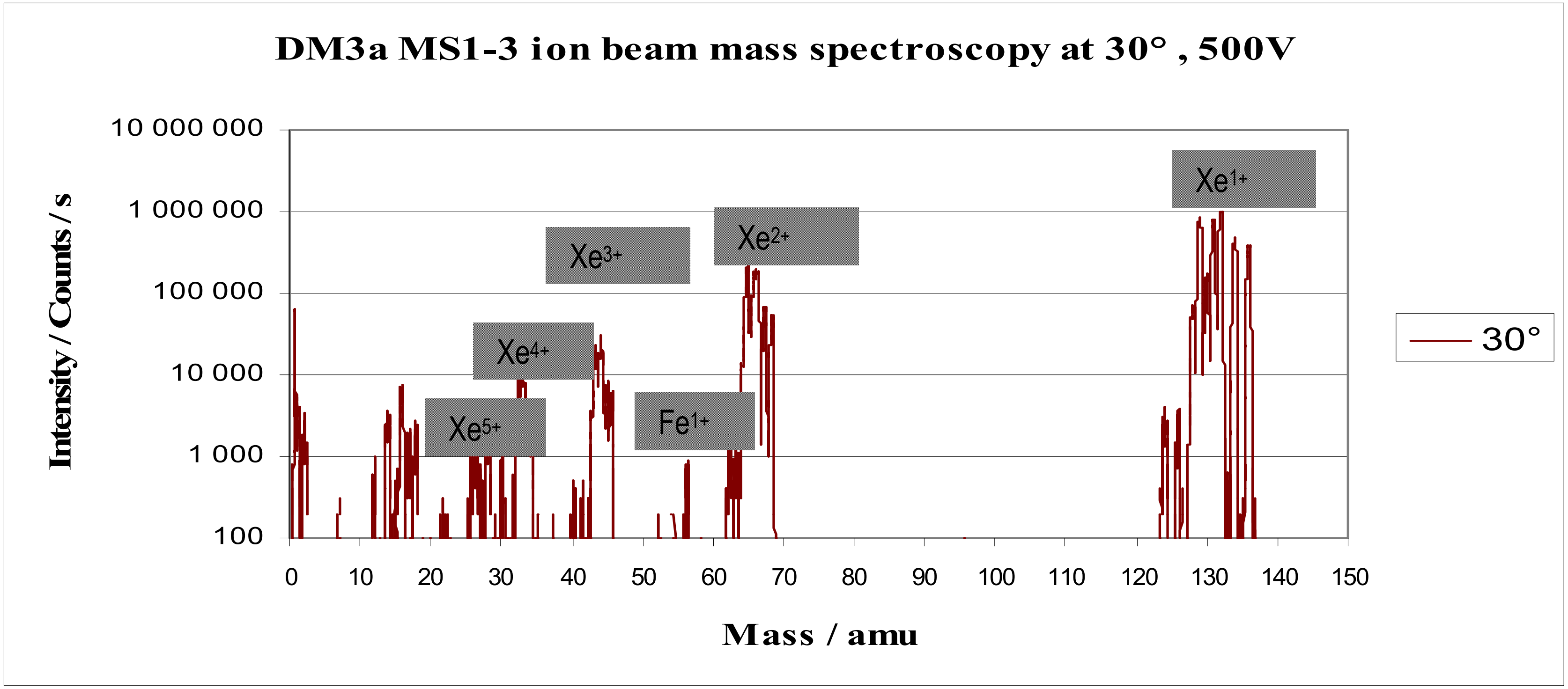
α_v = 40..50°, α_{eff} = 50…65°,
larger beam angle,
lower thrust efficiency,
but very wide operational range

DM3a-MS1-2:

α_v = 30..45°, α_{eff} = 40…55°,
lower beam angle,
higher thrust efficiency,
but restricted operational range

Ion beam characterisation @ IOM Leipzig, Nov 2002 (I)

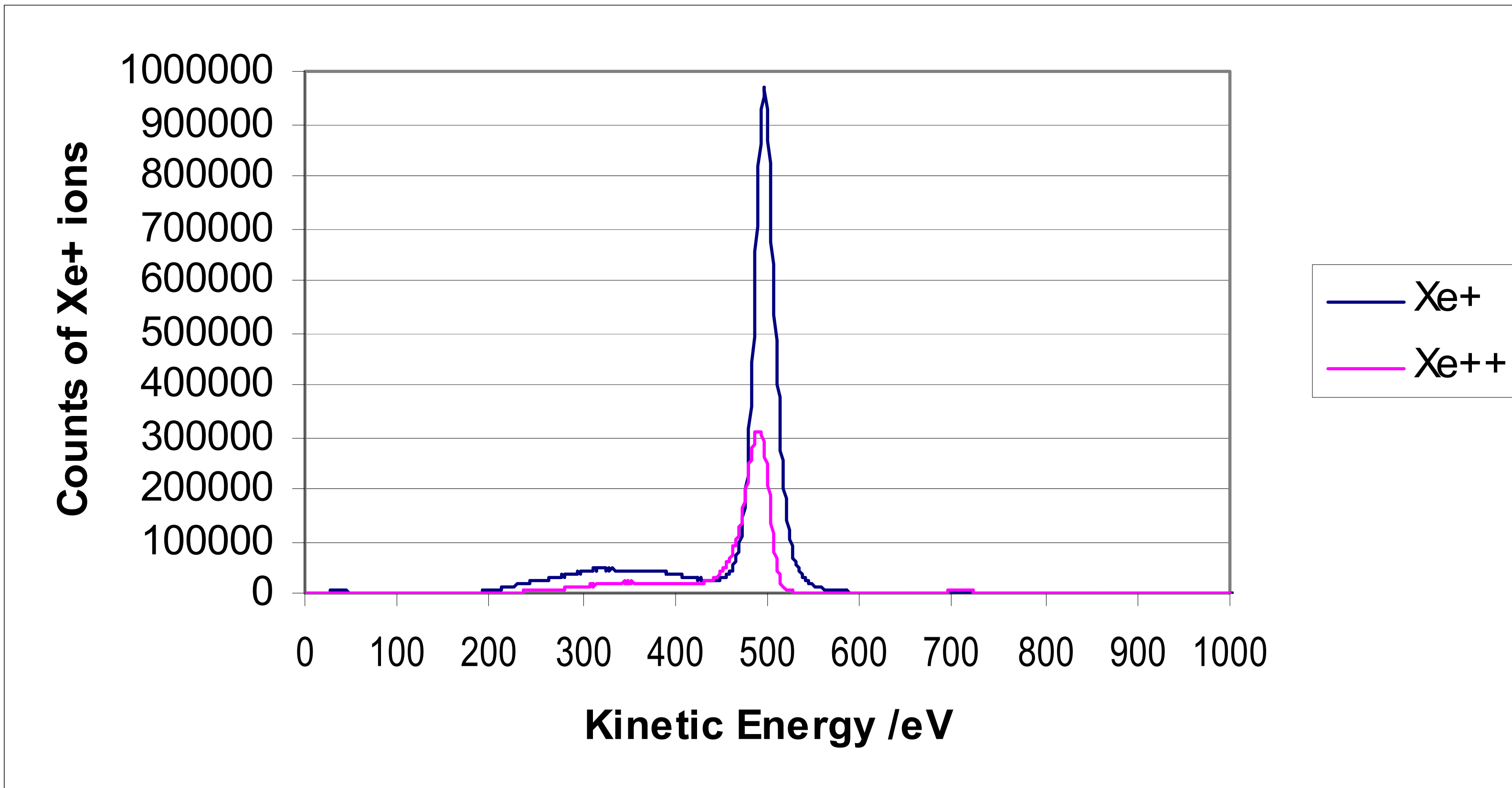
DM3a MS1-3 @ polar angle 30°, ion energy 500 eV



- multiple charged propellant ions up to Xe^{5+}
- no material from discharge channel observed (--> no erosion !!!)

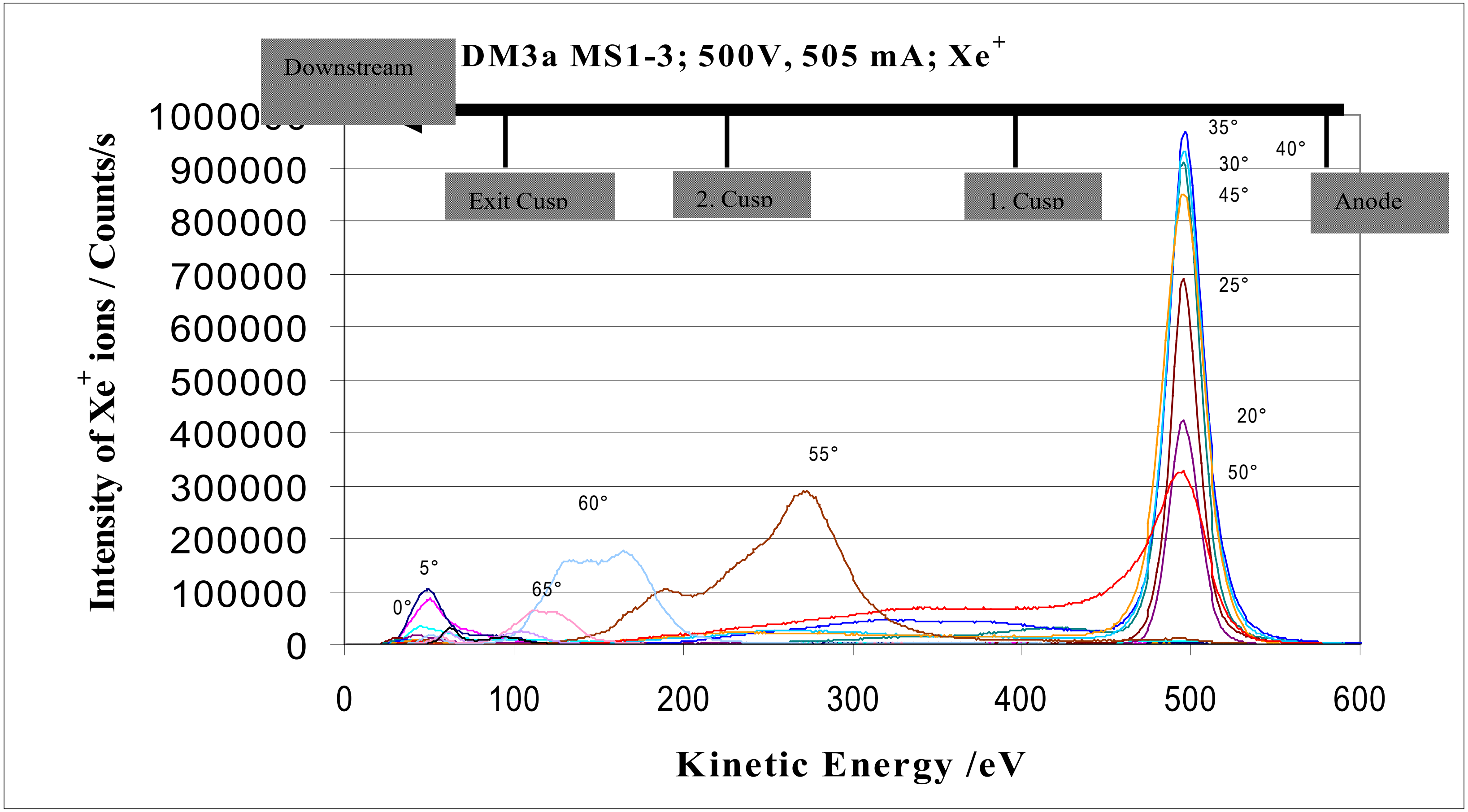
Ion beam characterisation @ IOM Leipzig, Nov 2002 (II)

DM3a MS1-3, energy spectrum of Xe+ and Xe++ ions at 35°, anode voltage 500V



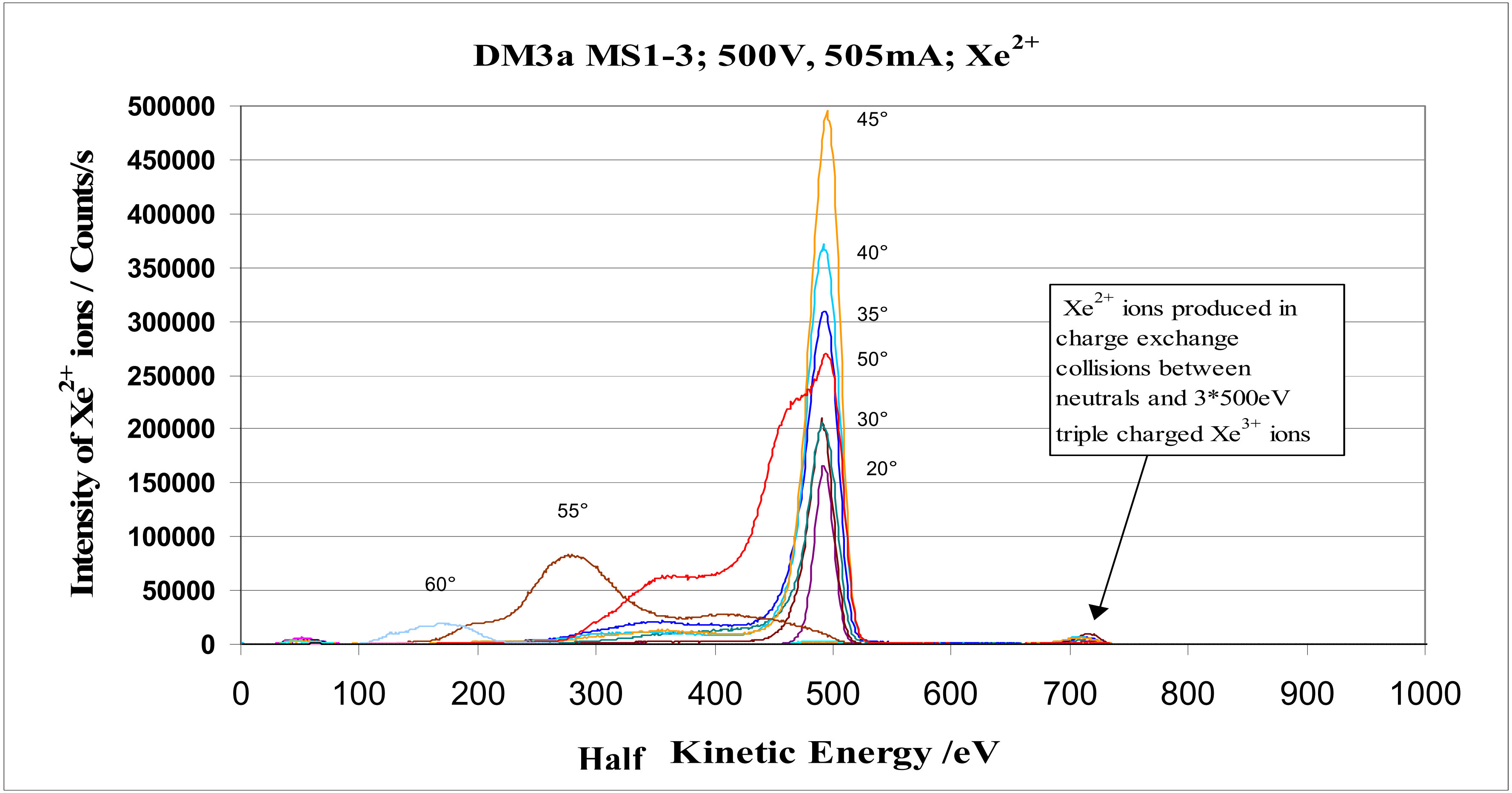
Ion beam characterisation @ IOM Leipzig, Nov 2002 (III)

DM3a MS1-3, polar angle and energy distribution of Xe^{1+}



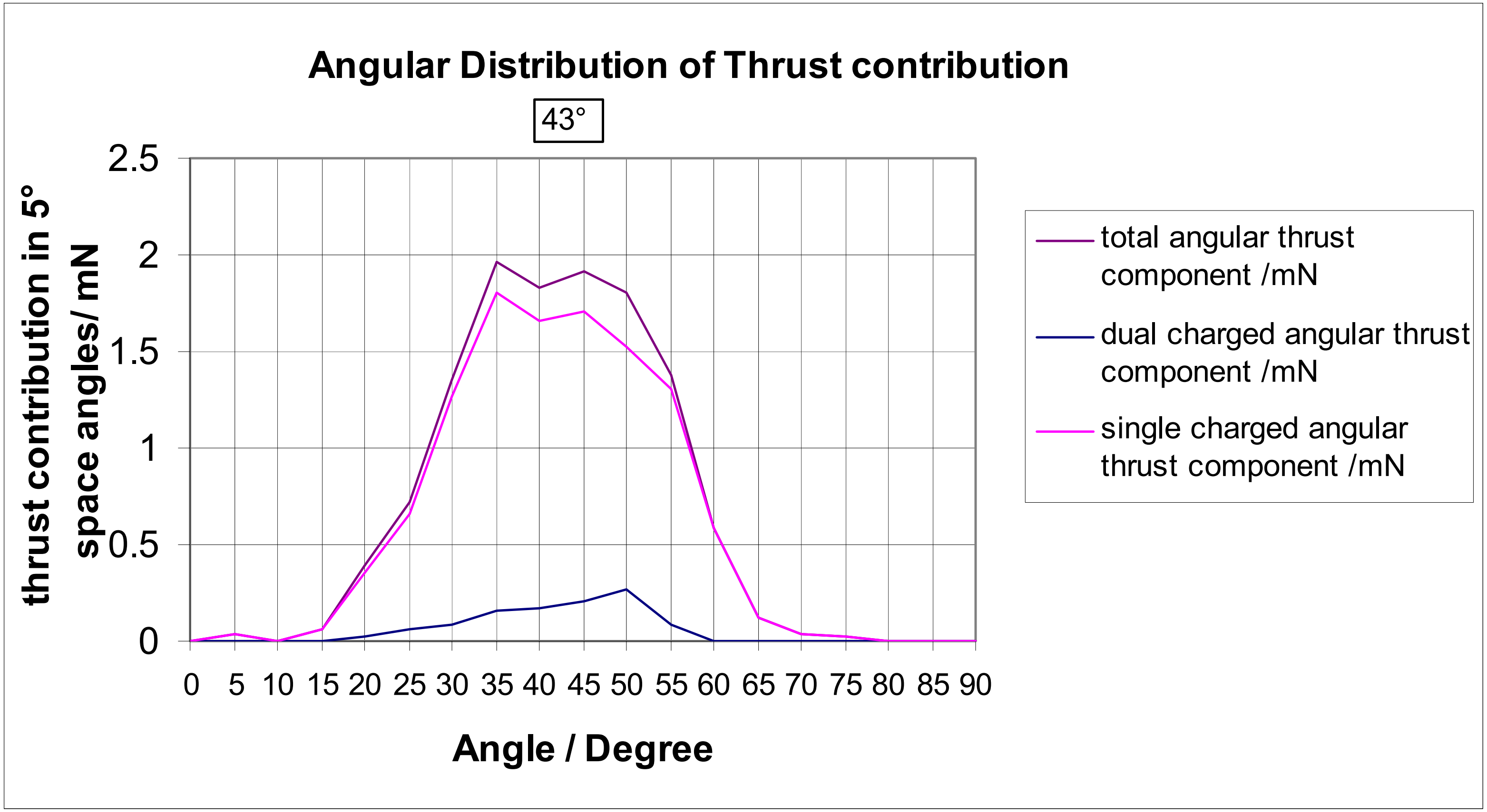
Ion beam characterisation @ IOM Leipzig, Nov 2002 (IV)

DM3a MS1-3, polar angle and energy distribution of Xe^{1+}



Ion beam characterisation @ IOM Leipzig, Nov 2002 (V)

DM3a MS1-3, angular thrust contribution of Xe^{1+} and Xe^{2+}



Example: Key issues in development from DM3a to DM6
(period June 2001- March 2003)

1.) DM3a-MS2:

- broad operational range, input power up to 1.5 kW
- T = 43 mN & I_{sp} = 1750s @ η_{tot} = 0.22 (ONERA data)
- thermal efficiency up to 85% (TEDG data)
- strong increase of α_{eff} (50...65°) with mass flow and anode voltage

2.) DM3a-MS1-2:

- restricted operational range, input power up to 1.2 kW
- T = 25 mN @ η_{tot} = 0.32 (ONERA data)
- thermal efficiency up to 80% (TEDG data)
- strong increase of α_{eff} (40...55°) with mass flow and anode voltage

3.) DM3a-MS1-3:

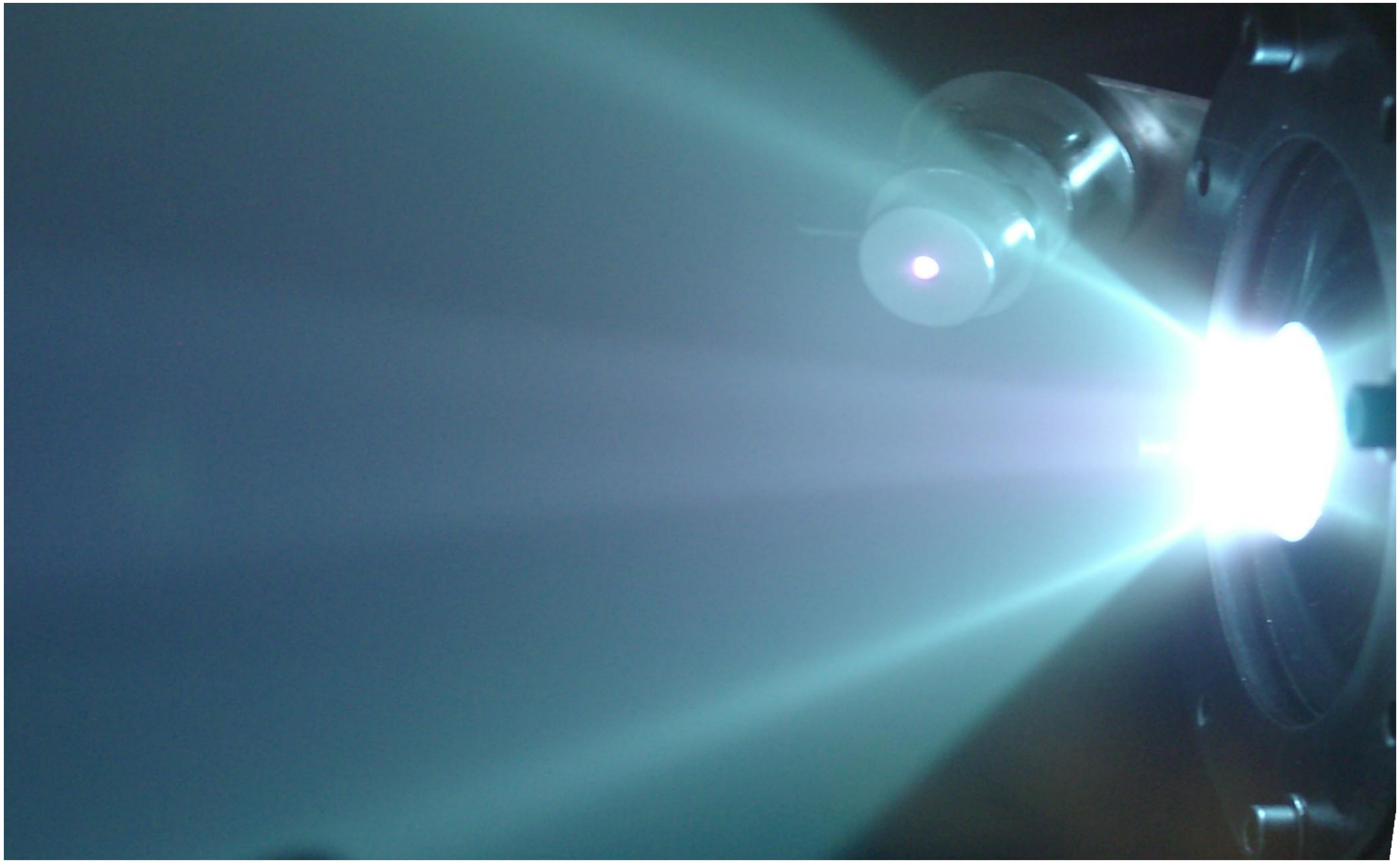
- restricted operational range, input power up to 1.2 kW
- T = 12mN @ η_{tot} = 0.38 (IOM & TEDG data)
- thermal efficiency up to 80% (TEDG + IOM data)
- reduced increase of α_{eff} (38...50°) with mass flow and anode voltage

3.) DM6-MSJ5/6:

- broad operational range, input power up to 4.5 kW
- T = 129mN & I_{sp} = 2700s @ η_{tot} = 0.38 / 0.43 (ONERA / TEDG data)
- maximum η_{tot} = 0.55 (TEDG data)
- thermal efficiency up to 90% (TEDG data)
- only modest increase of α_{eff} (33...40°) with mass flow and anode voltage

Latest Demonstrator Modell: DM6, Versions MS5 & MS6 (I)

Side view into TEDG vacuum chamber

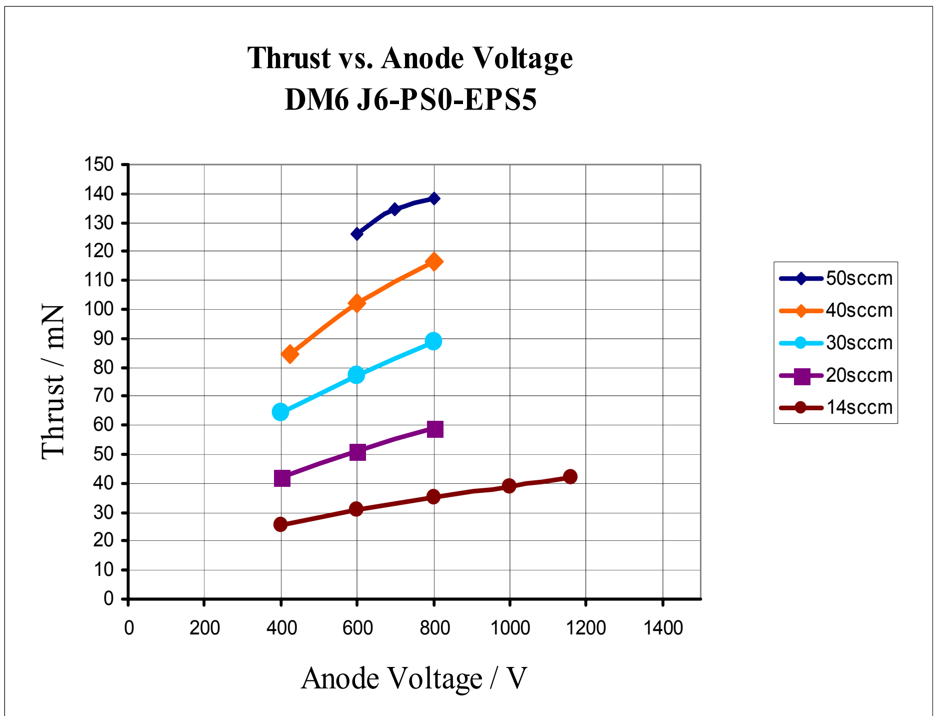


2 cm

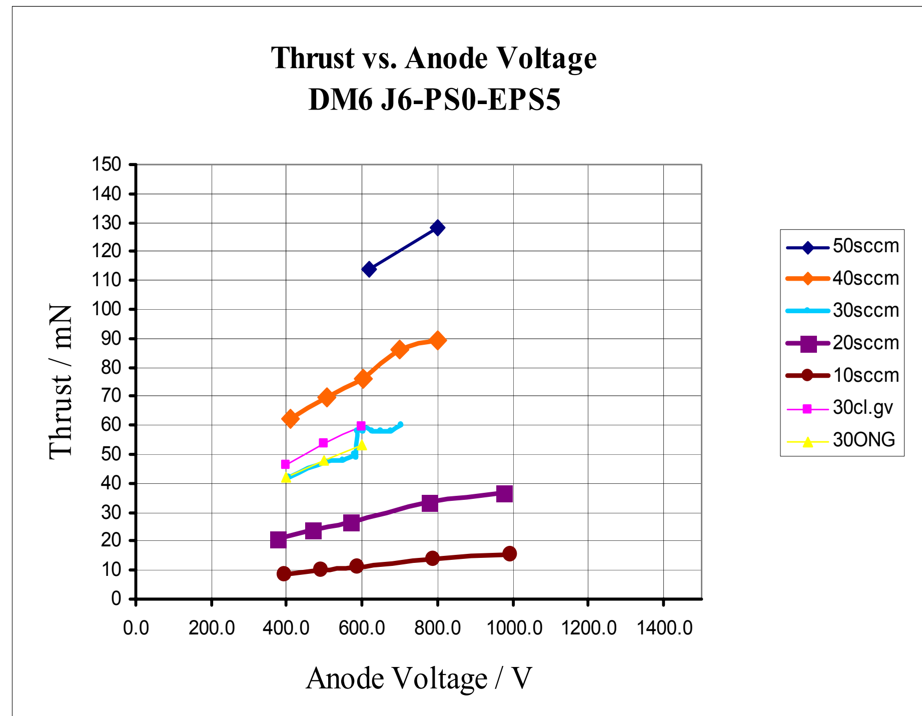
Latest Demonstrator Modell: DM6, Versions MS5 & MS6 (II)

Comparision of results obtained from

thermal diagnostics @ TEDG (March 2003)



thrust balance @ ONERA (March 2003)



Latest Demonstrator Modell: DM6, Versions MS5 & MS6 (III)

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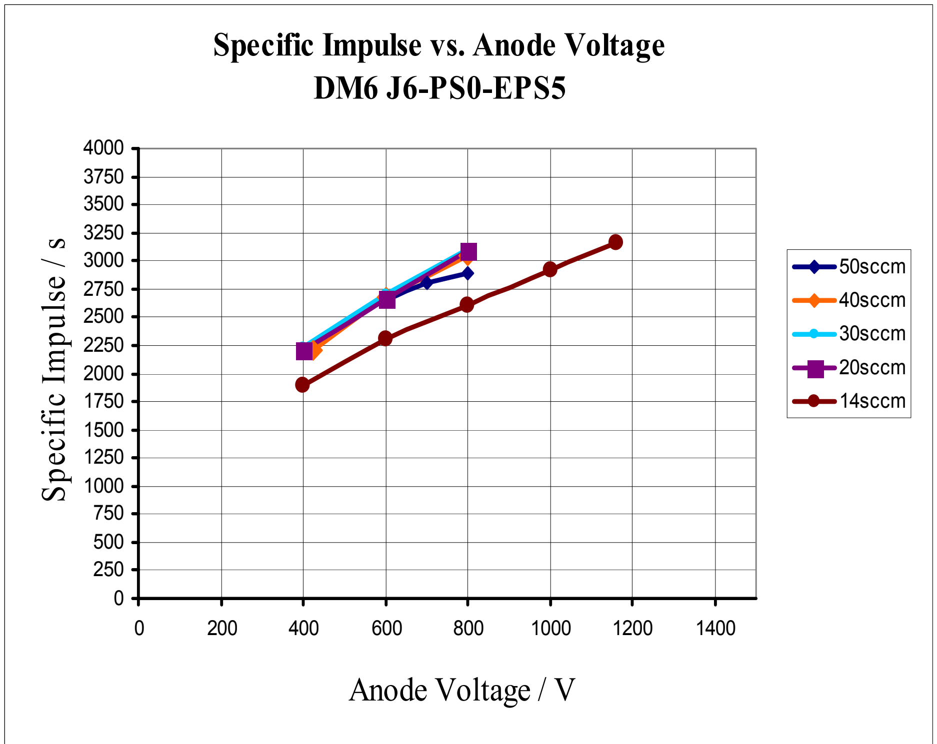

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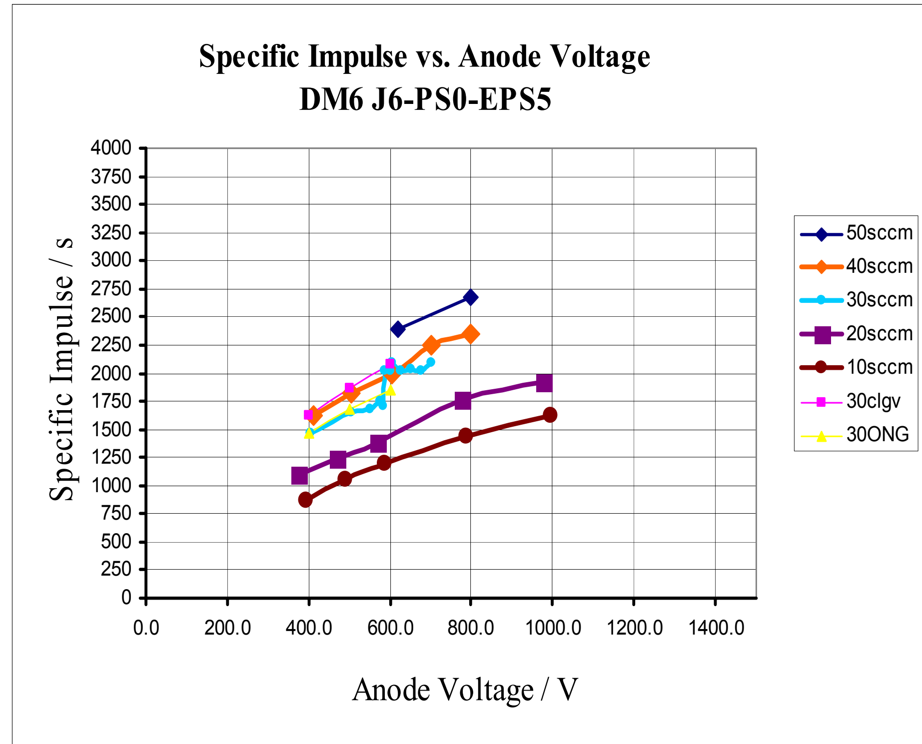
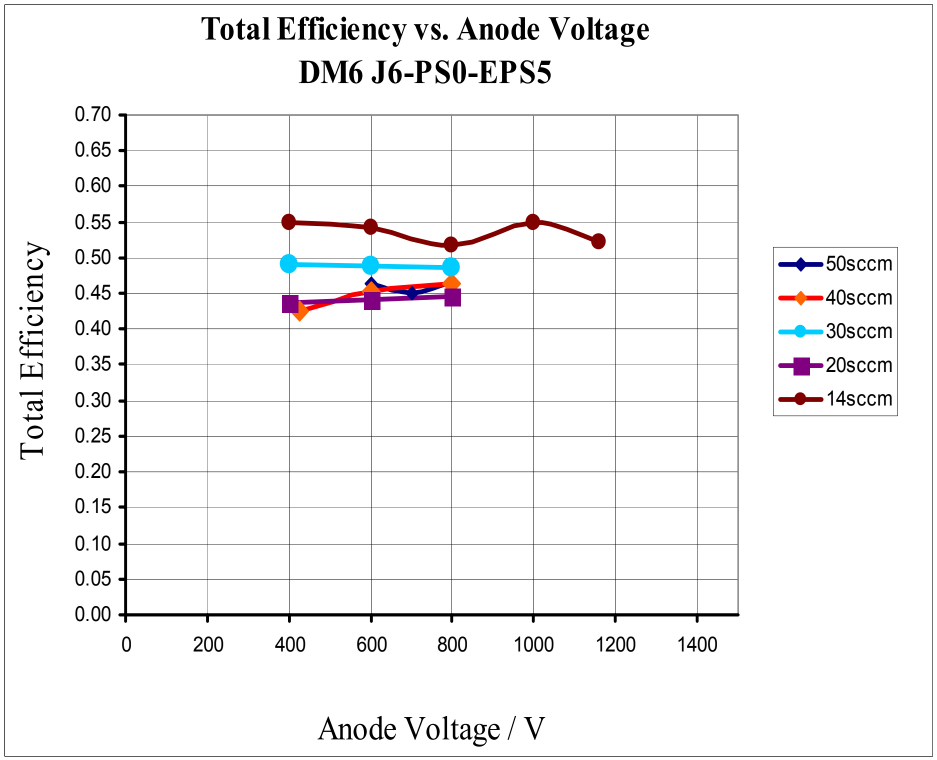


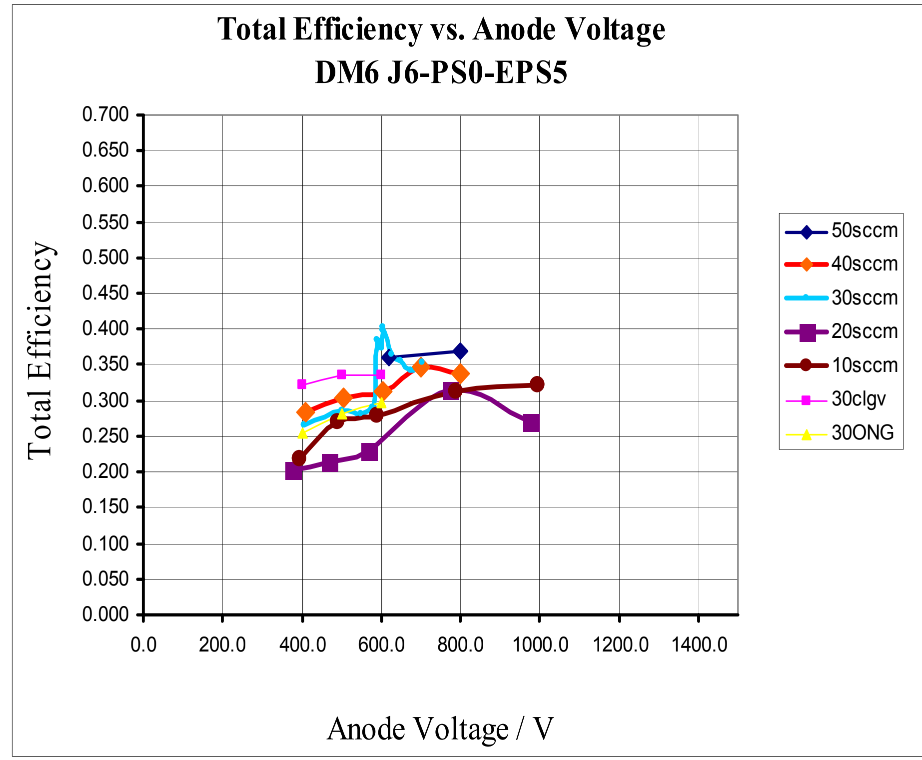
Latest Demonstrator Modell: DM6, Versions MS5 & MS6 (IV)

Comparision of results obtained from

thermal diagnostics @ TEDG (March 2003)



thrust balance @ ONERA (March 2003)



Comparison of HEMP thruster performance with state of the art HETs and GITs

Parameter	GIT	HET	HEMP Thruster
Plasma thrust density	0.2...0.4 mN/cm²	~2mN/cm²	>25 mN/cm² (32 mN/cm² achieved)
Mass & Volume	large	medium	small
Acceleration grids required	yes	no	no
Ion emission space charge limited	yes	no	no
Neutraliser required	optionally no (depends on space plasma density)	yes	optionally no (depends on space plasma density)
Erosion effects	at grids	strong at channel walls	none...minimum (<-> PPM focussing)
Additional supplies required for:	RF-source	magnet coils	no
Power supply & control unit	complex	complex	simple
Total efficiency	good(50...80%)	modest (30...55%)	modest(40...60%) at present, good >75% future potential
Divergence & effective beam angle	< 15° & <10°eff.	~45° & ~25°eff.	~50° & 33...40°eff. at present <40° & <25° future potential
Specific impulse / s	2000 to 4000	1000 to 2000	1000 to 3500 at present 1000 to >4000 future potential
Flexible application & adjustability with respect to high TTPR or high I_{sp}	good to medium	low	very good

HEMP thruster characteristics applied as ion source (I)

➤ Performance data

- Ion energy range	200 …. 2000 eV
- Current density	up to 3000 mA / cm^2 @ source exit
	up to 30 mA / cm^2 @ 15 cm from source exit
- Type of gases	Xe, Ar, He, Air (demonstrated)
	all others: feasibility of application expected
- Operational pressure in process chamber	up to 5 x 10^{-3} mbar

➤ Additional features

- No erosion of source components (grid, discharge channel, etc.)
- Compact size
- Minimum number of components required for source operation (DC power supply & flow controller)

HEMP thruster characteristics applied as ion source (II)

➢ Potential benefits for end-user

- High flexibility in ion energies fills gap between gridded and hall type sources (> reduction in complexity of plasma sytem)
- Reduced process time due to high current density (> swap from batch to in-line processing)
- Easy integration in existing process chamber due to compact design
- No increase of pumping speed at 100 to 1000 times higher ion currents needed due to high residual pressure tolerance
- Only low effort required for control of HEMP source operation due to stable & reproducible behaviour and minimum number of components

Could the HEMP thruster be(come) an alternative to currently applied ion sources ?