Development of IPPLM's Krypton HET

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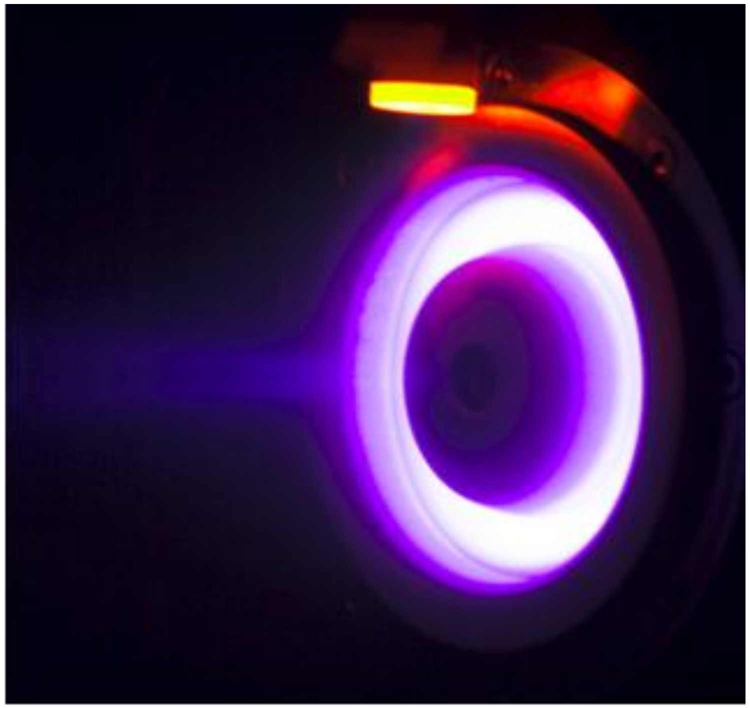

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Institute of Plasma Physics and Laser Microfusion

… research in plasma physics

- inertial confinement fusion,
- pulsed high power technology,
- magnetic confinement fusion.

The majority of IFPiLM's projects is implemented within cooperation in the framework of the fusion programme of Euratom Community, HiPER project and other European projects:

PF-1000 experiment …

vacuum chamber:

D=1.4 m, *L*=2.5 m

U_0 = 20-40 kV, E_0 = 250-1000 kJ,
I_{sc}=12 MA, $T_{1/4}$ = 6 μs, R_0 = 2.6 mΩ,
C_0 = 1.332 mF, L_0 = 15 nH

... heritage ...

In 2008, within the new application oriented strategy of IPPLM, the **Group of Plasma Accelerators (PAG)** was established to kick-off studies on electric propulsion.

PAG's research program is a natural continuation of the investigations initiated about 20 years ago in the Institute of Fundamental Technological Research of the Polish Academy of Sciences (PAS) in cooperation with CNRS-France and which primarily concerned Hall effect thrusters (HETs).

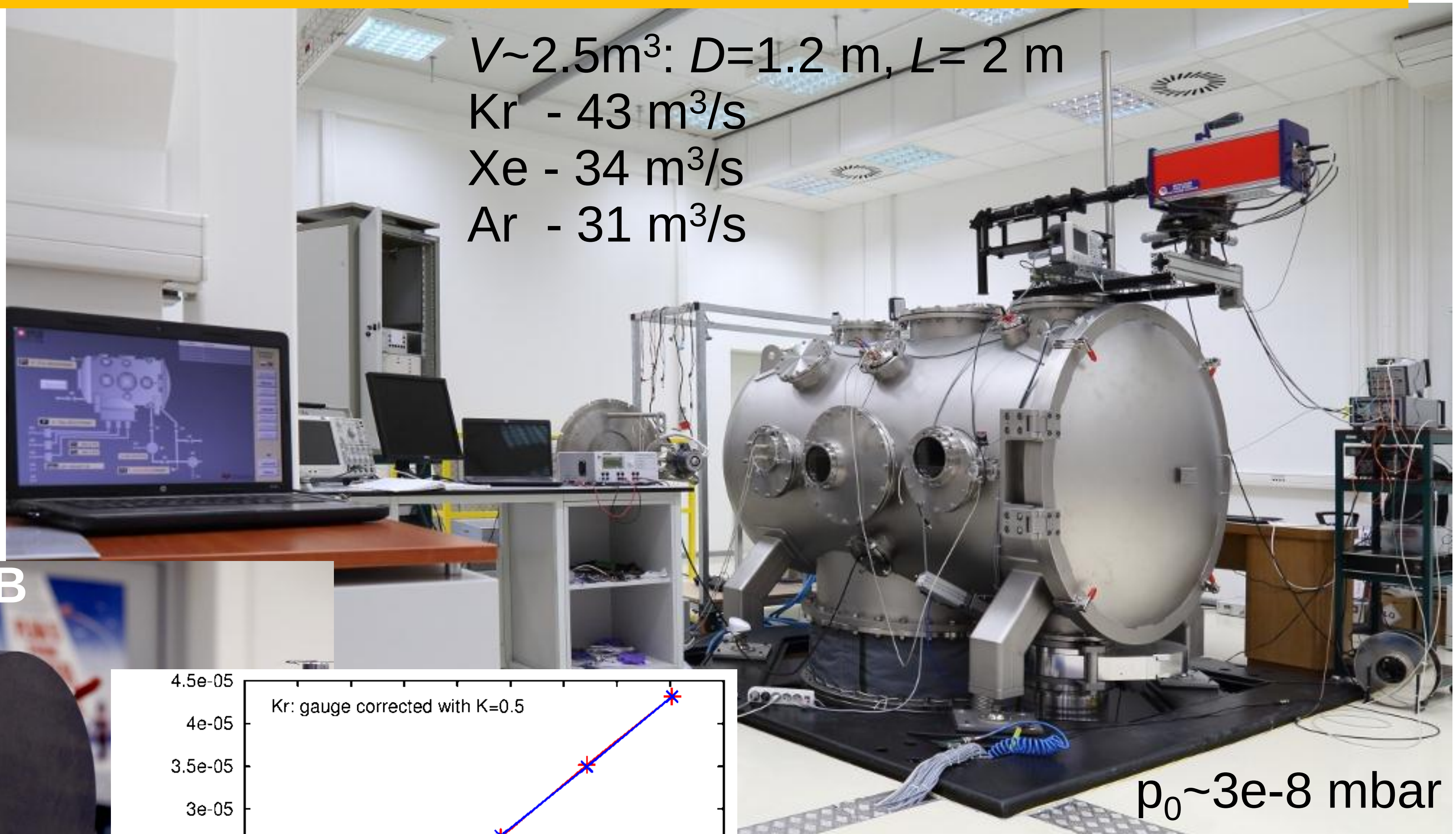
IPPLM, being involved in three European EP projects (HiPER/FP7, L-µPPT/FP7 and KLIMT/PECS-ESA), has created its own infrastructure by setting up **PlaNS Laboratory** for investigation of plasma thrusters.

It was thought as an experimental base for the L-µPPT and KLIMT projects which were geared towards development prototype design of

- pulsed micro-thruster (**PPT** addressed to nanostaellites) and
  - a 0.5 kW class **HET** (KLIMT)

... IPPLM's PlaNS Laboratory ...

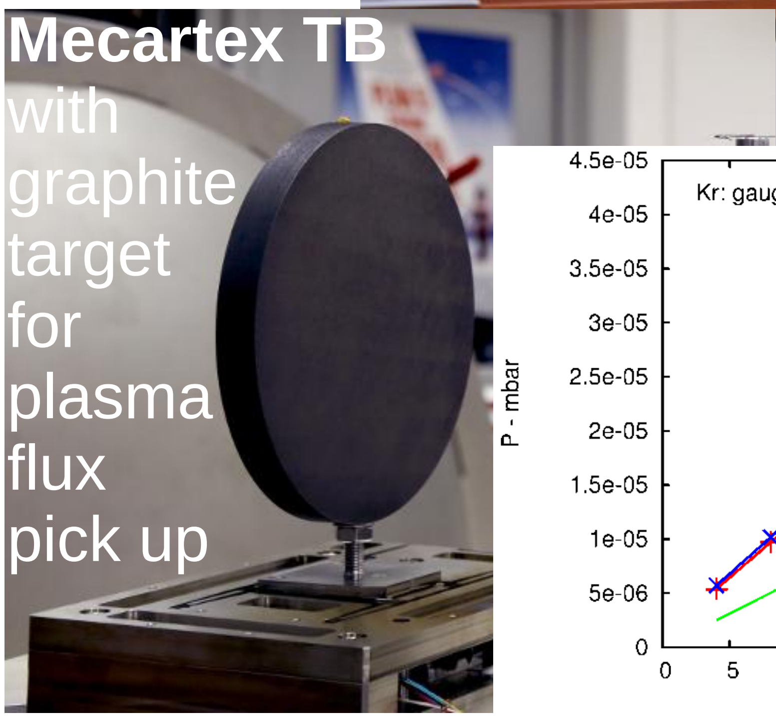
Vacuum facility designed in the frame of FP7 LμPPT project

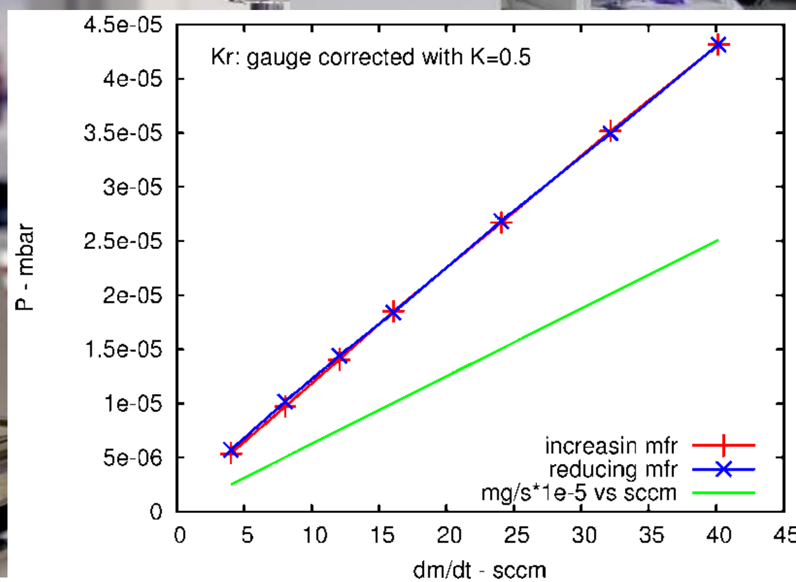


V~2.5m^3: D=1.2 m, L= 2 m
Kr - 43 m^3/s
Xe - 34 m^3/s
Ar - 31 m^3/s

p_0~3e-8 mbar

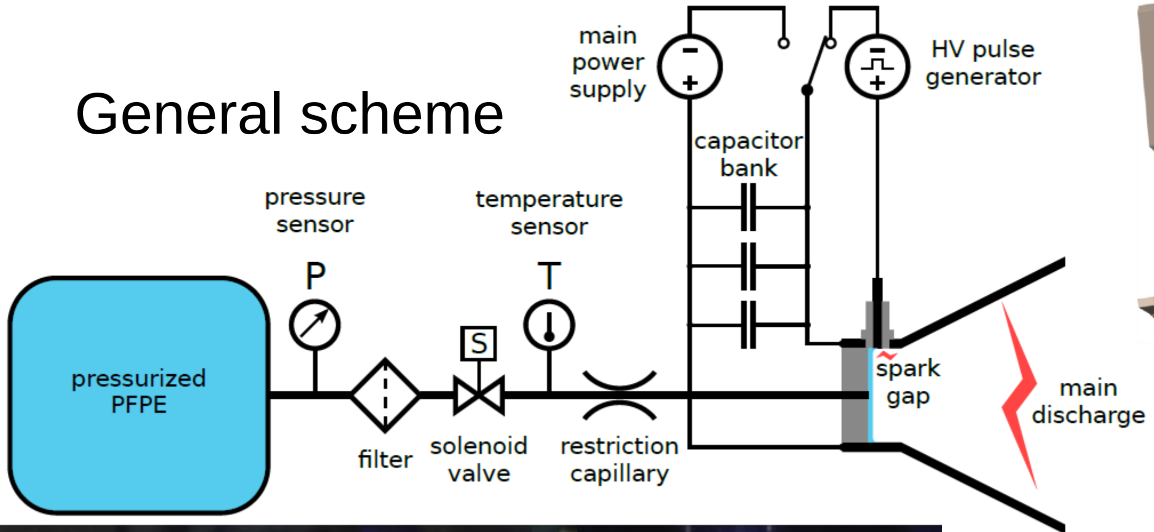
Mecartex TB with graphite target for plasma flux pick up

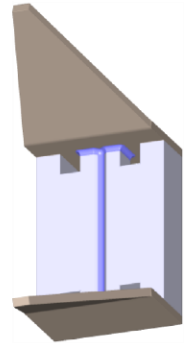


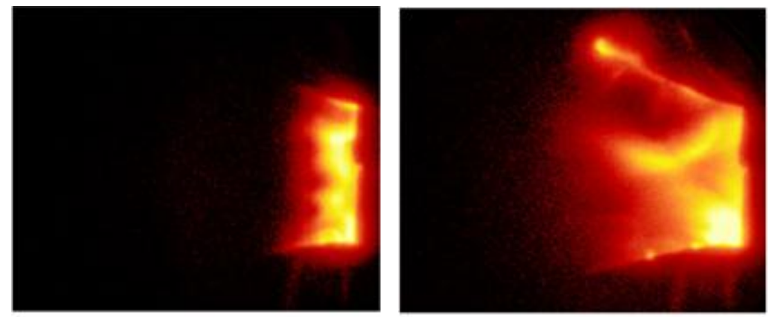


forevacuum pump up 450 m^3/h,
TM pump ~3000 l/s
cryogenic pump HSR (Balzers)
Velco Xe900; pumping speed:
36 m^3/s for air, 93 m^3/s for H_2O.

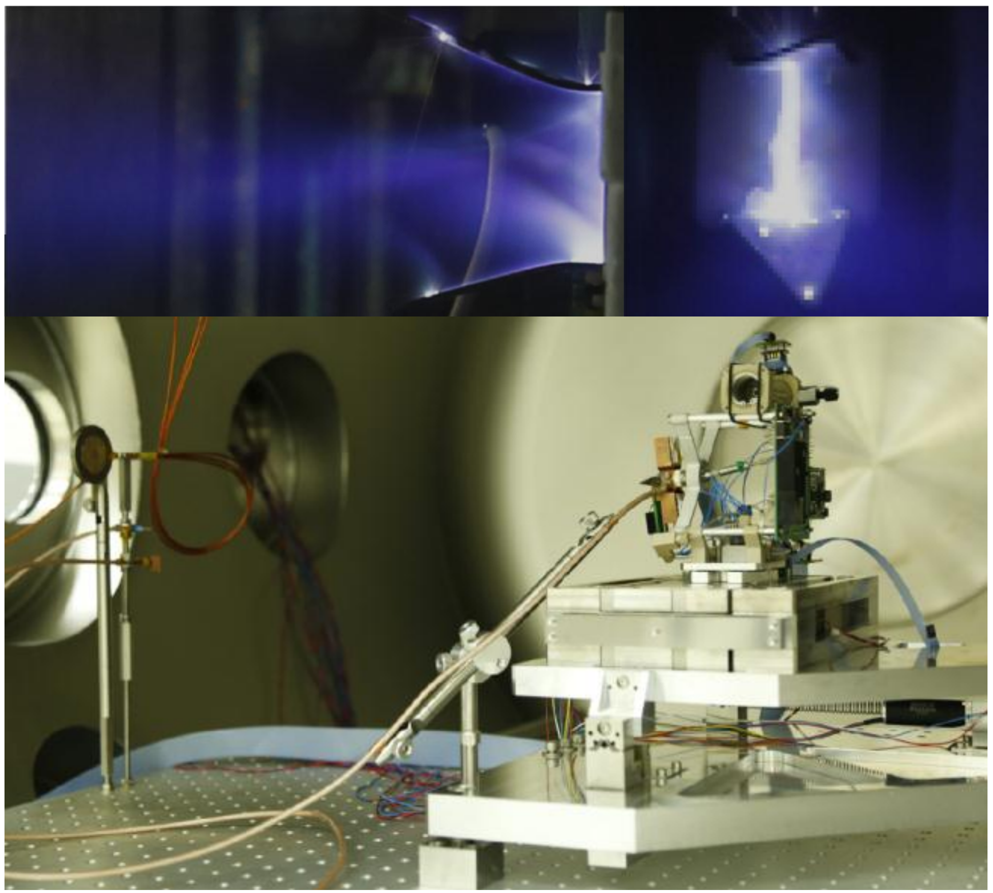
...L-μPPT – implementation ...

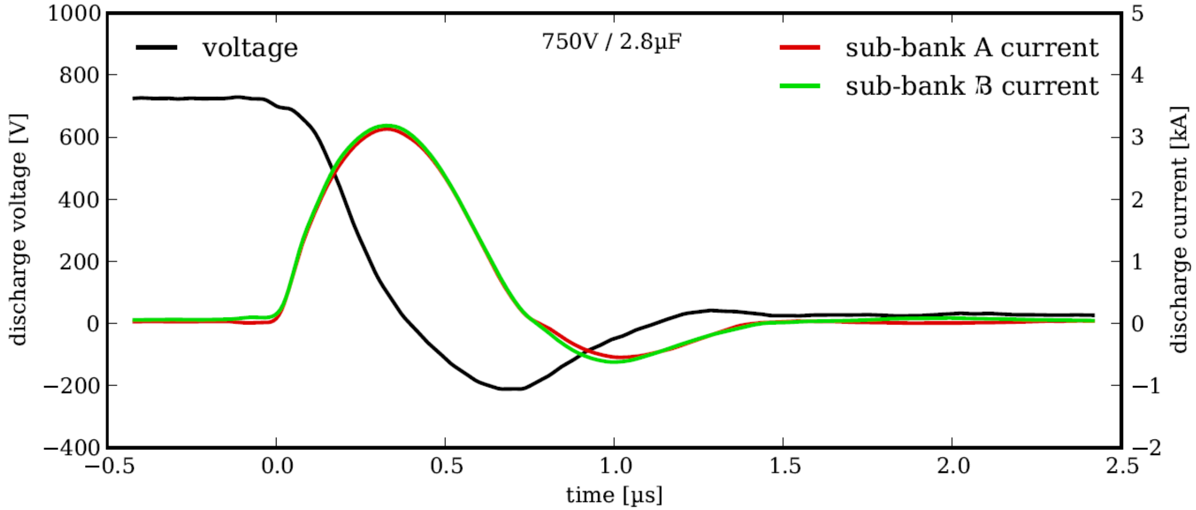






Fast camera photos (in pseudo-colors), frame-time: 10 ns.





(a) 750 V

$$I_{bit} \sim 17\ \mu\text{Ns},\quad I_{sp} = \frac{I_{bit}}{m_{bit} g_0} \sim 1000\ \text{s},$$

$$\eta = \frac{1}{2}\frac{I_{bit}^2}{m_{bit} E} \sim 10\%,\quad T/P \sim 17\ \mu\text{N/W}$$

... KLIMT project summary ...

Short description:

- incremental development and optimization of a **krypton** propellant Hall effect thruster (~0.5 kW class);

alternative propellant suggestion

- **three optimization steps** were assumed; each one consisted of the design and manufacturing phases followed by a test phase;
- **three measurement campaigns** at ESA Propulsion Laboratory (ESTEC) were predicted with the aim at critical assessment of the developed versions and for collecting data for the modifications to be implemented at each subsequent stage of the project.

Project output: ~0.5 kW-class Hall thruster dedicated for operation with krypton propellant.

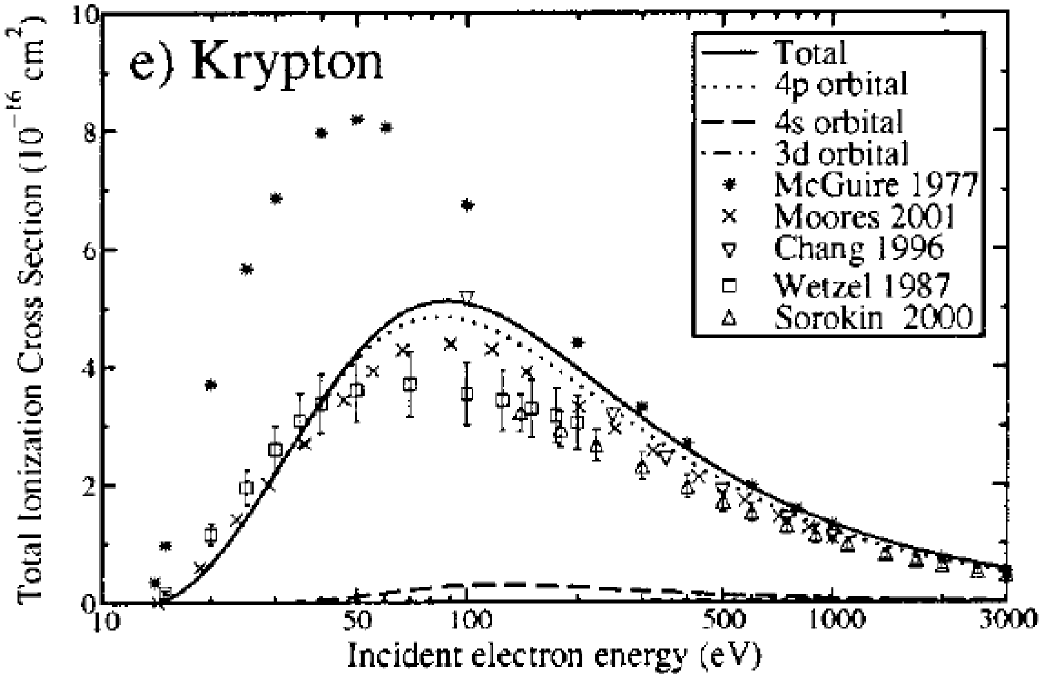
ESA Contract No. 4000107746/13/NL/KML

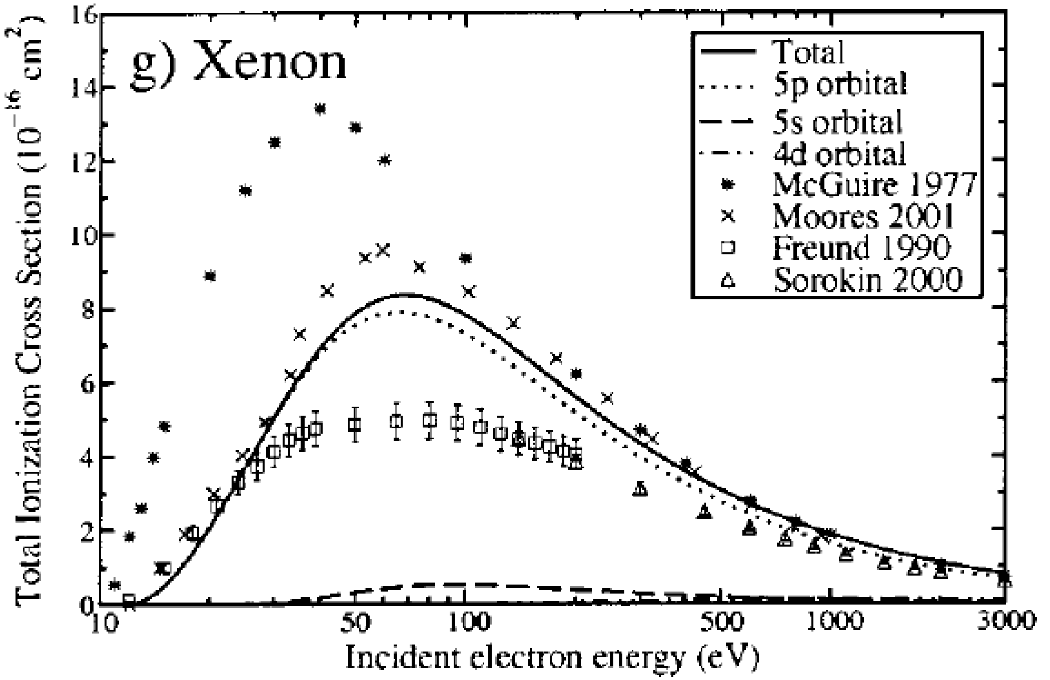
... basing on the former analysis ...

The smaller ionization cross section of krypton than that of xenon has to be compensated by increased krypton number density for keeping invariant value of λ_i/L ratio (*ionization length to discharge channel length*) what eventually results in the growth of discharge current and power.

Previous experimental findings as well as physical considerations lead to the conclusion that switching to krypton will result in the **growth of heat loads**, if the required efficiency is to be kept.

The new design had to be geared to withstand the increased heat loads.

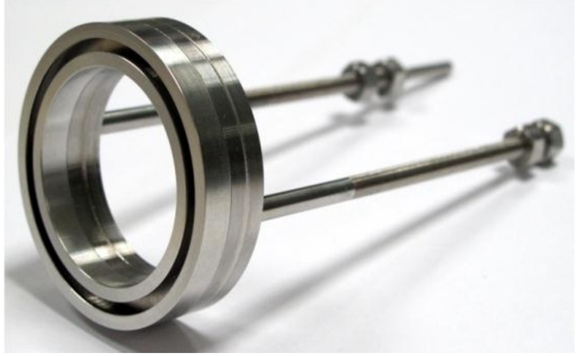


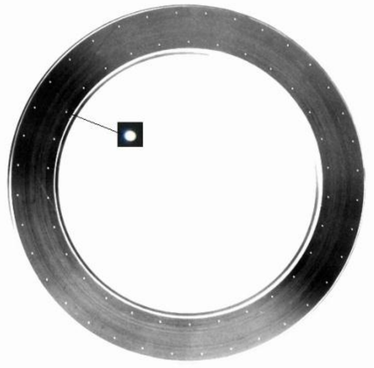


... KLIMT – Krypton Large IMpulse Thruster ...

Objectives:

- **goal**: evaluate **krypton** as a cost-effective alternative to xenon for Hall thrusters,
- thruster designed from the ground up to **accommodate high thermal loads**, high mass flow rate operation,
- prototype development: IPPLM’s *kick-off* project + ESA/PECS 3-year contract (from March 2013)





KLIMT is assumed to be a laboratory model and a research tool .

The given design is modular and should maintain the operation in several configurations by:

- anode & cathode positioning

- usage of different magnetic poles

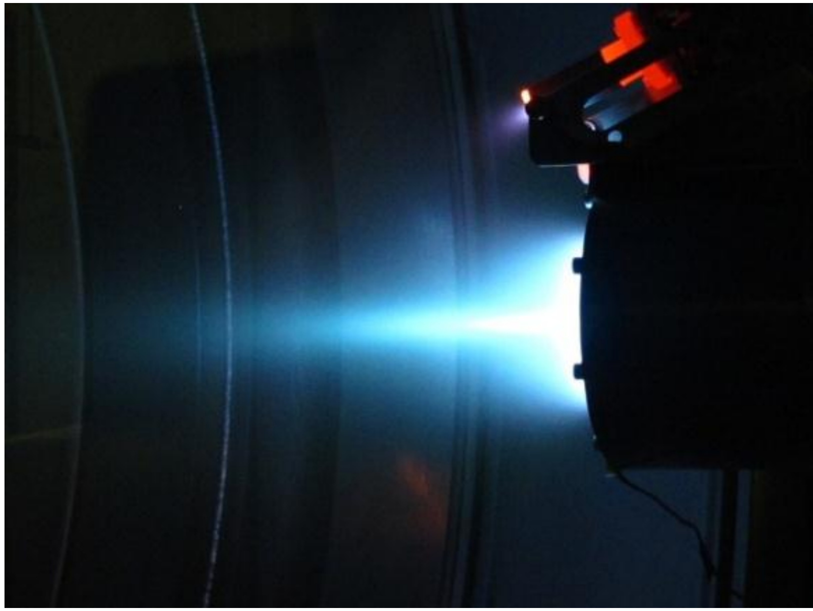
Technical highlights:

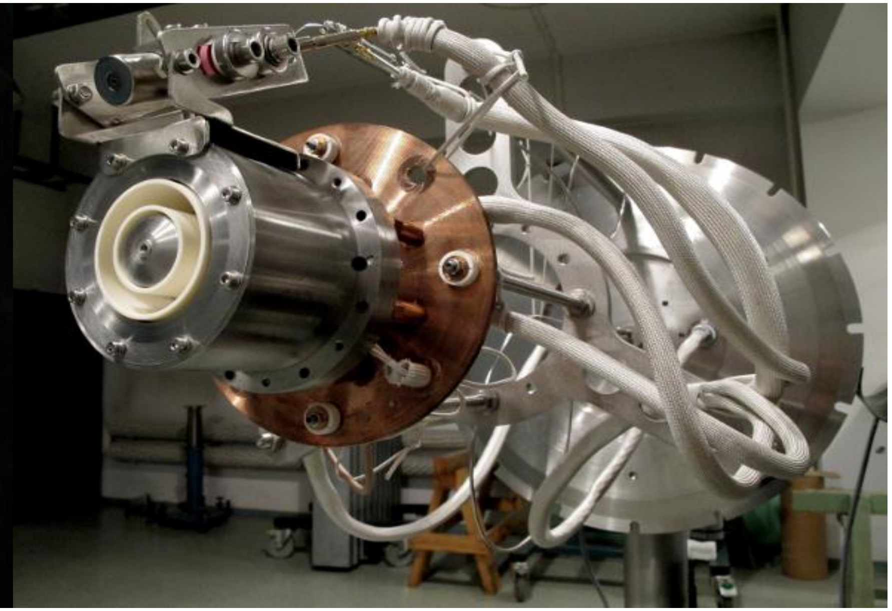
„radial scaling” results in:

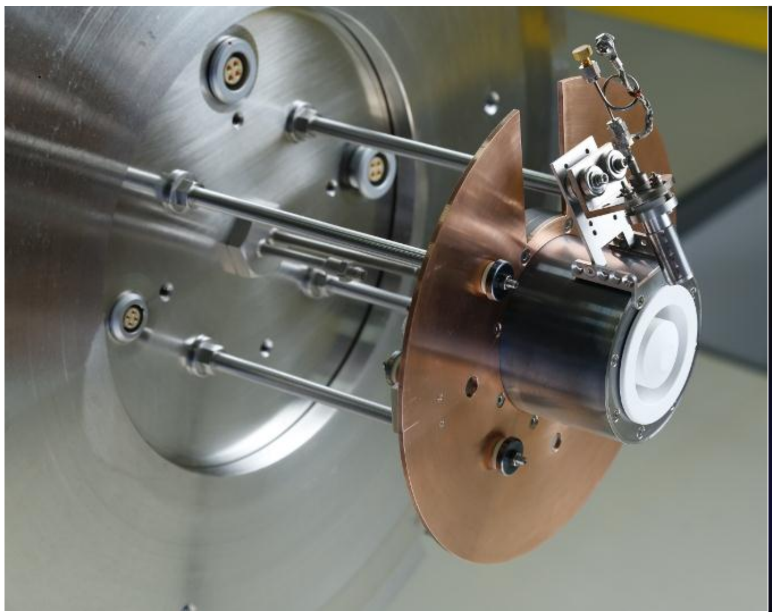
- **nominal power: up to ~0.5kW,**
- **outer channel diameter: 50mm,**
- **channel width: 8mm,**
- **mass flow rate 1-2mg/s**

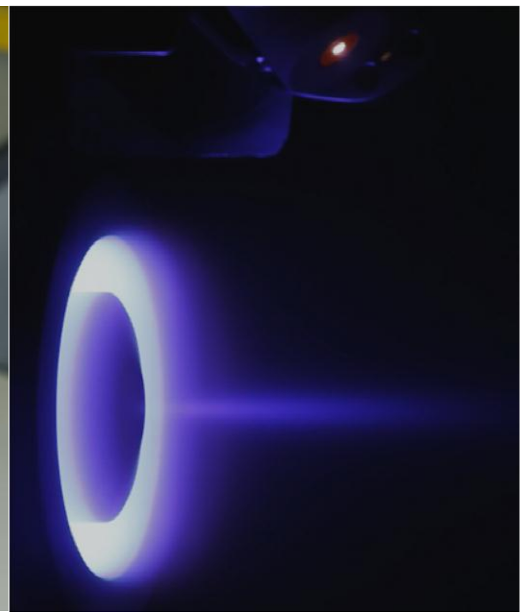
... design evolution ...

First prototype operating with Xenon at ESA Propulsion Laboratory.



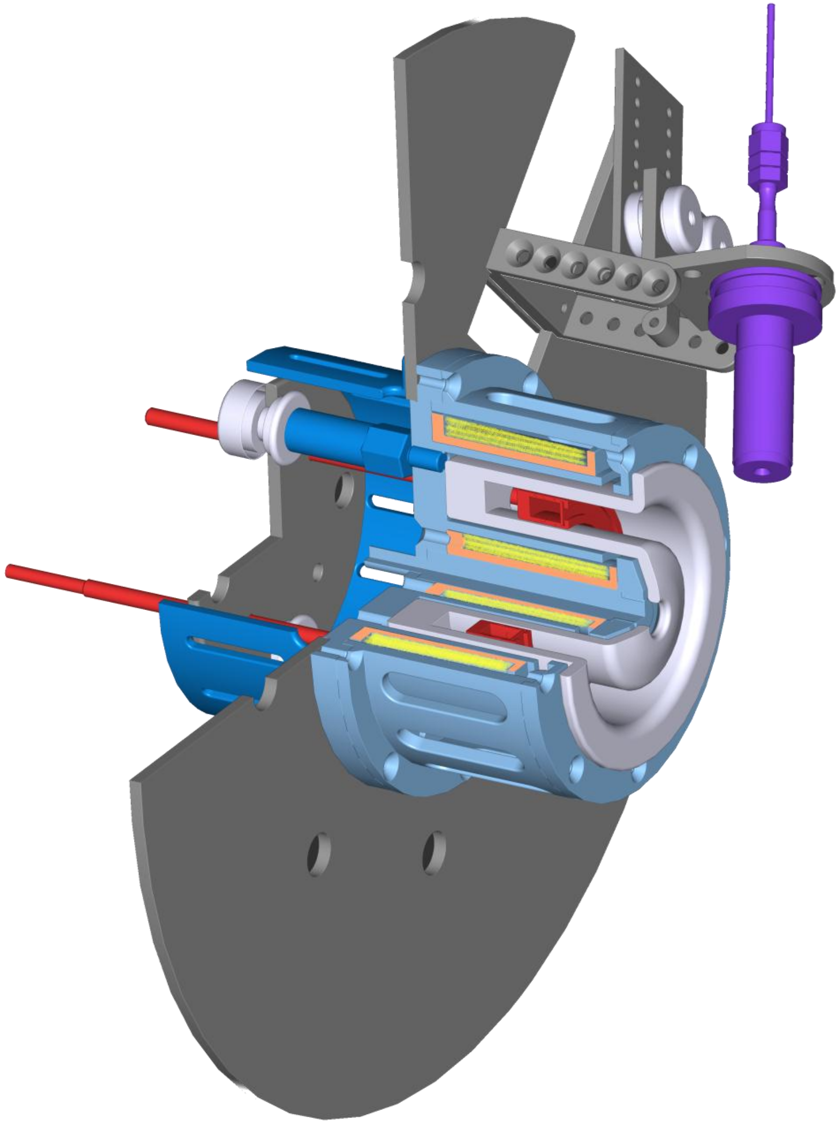


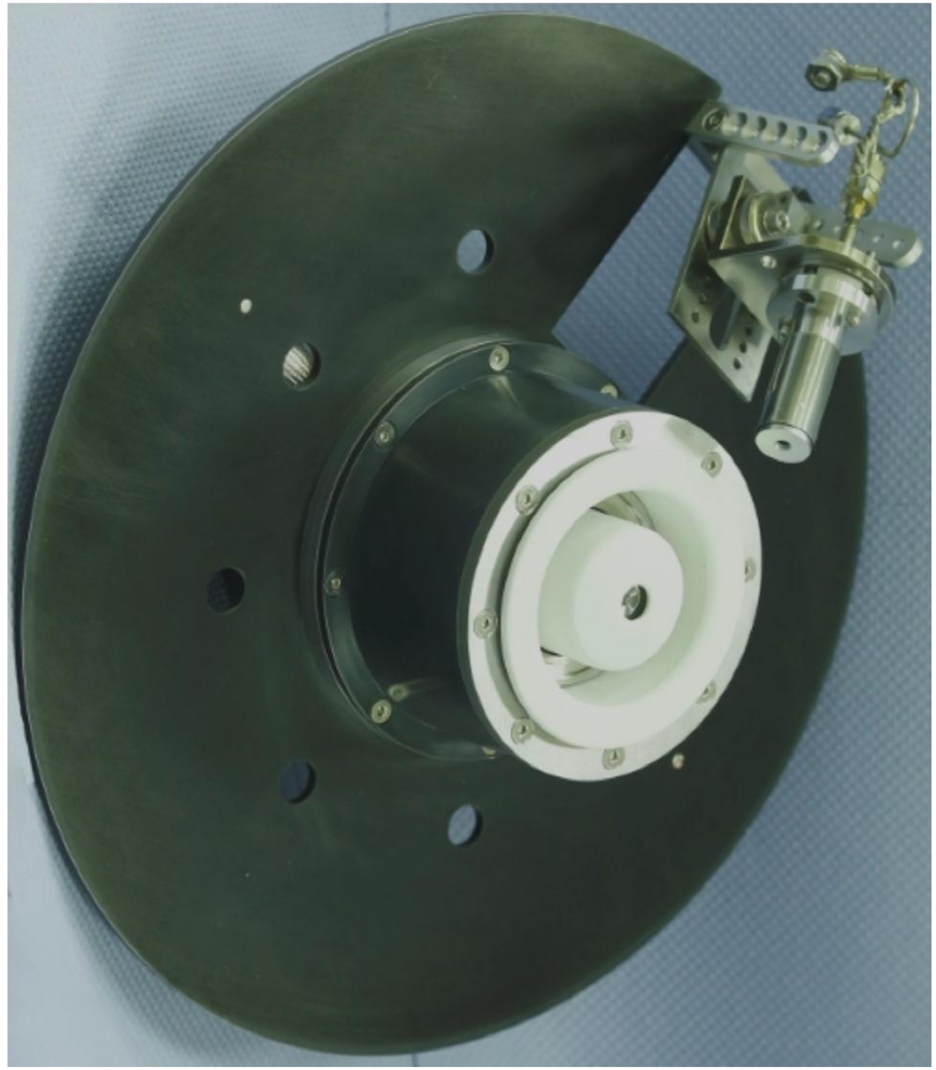




Second prototype operating with Krypton at IPPLM PlaNS Lab. SDHC 1000 (heaterless) and HWPES 250 hollow cathodes were tested.

... KLIMT – final (3rd) version ...





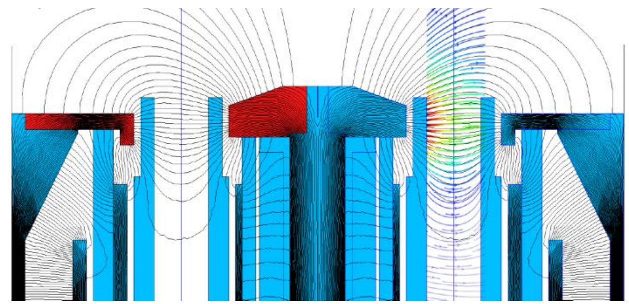
- Concentric outer magnetic coil was chosen.
- It is still a laboratory model.

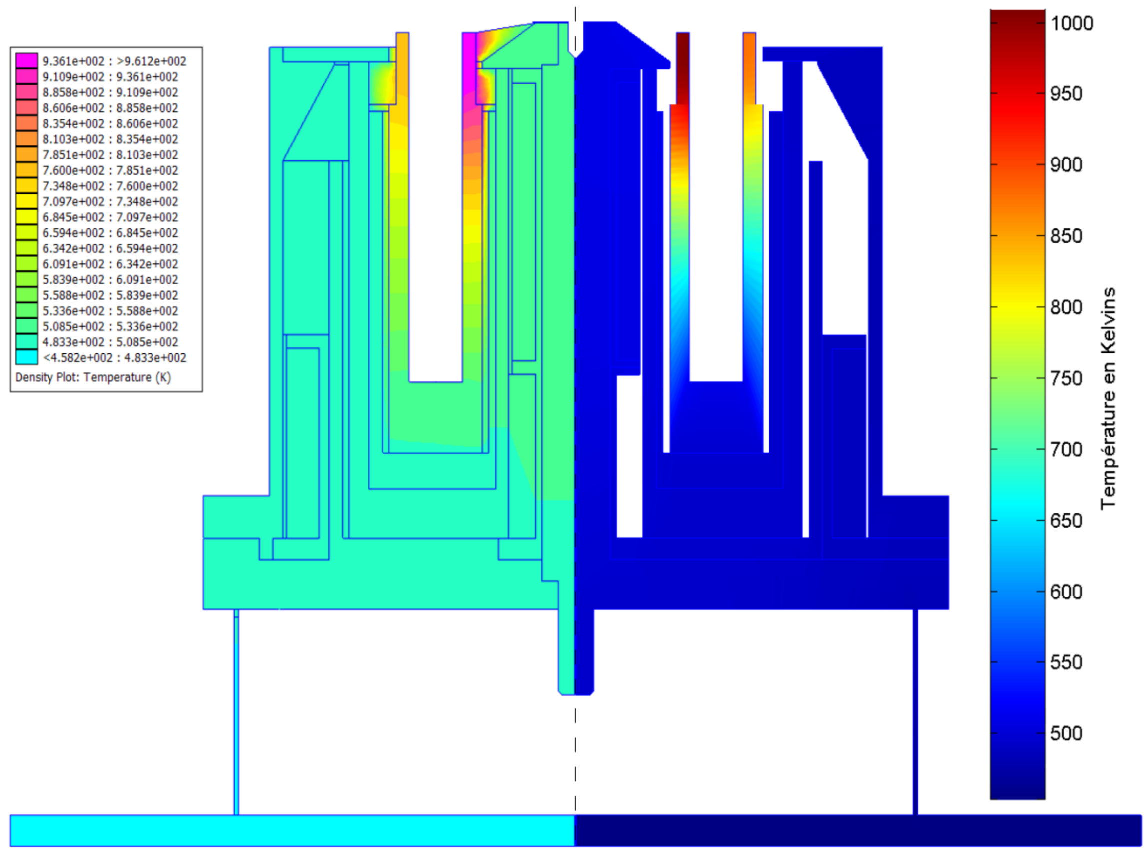
... magnetic and thermal design ...

Design optimization:

- **magnetic field configuration** based on photographic scaling (with respect to SPT-100) and optimized with the “G-criterion” (color lines in the upper figure correspond to the measured B-field distribution)

- **thermal behavior:** conduction-radiation modeling (using FEMM heat module and the CRATHER code) optimization of thermal bridges



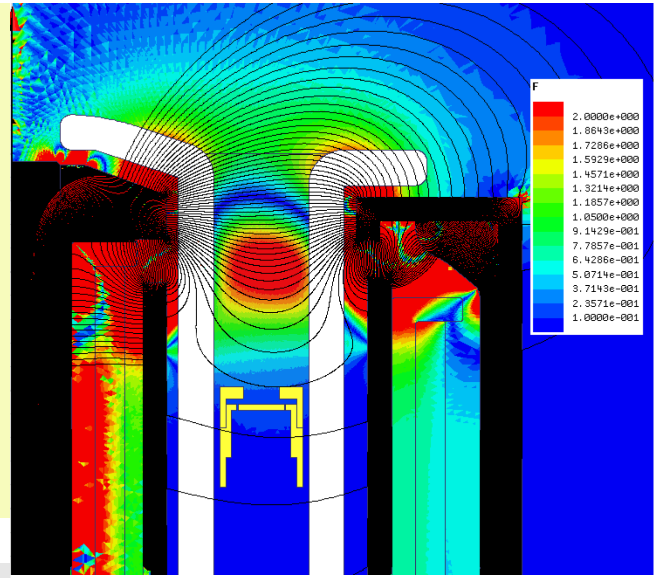


... G-criterion ...

$F(\boldsymbol{r})$ function[1] describes the rate of **B** field variation in the direction perpendicular to the magnetic field lines

$$F(\boldsymbol{r}) = \left| \frac{\boldsymbol{B}(\boldsymbol{r}) \times \nabla B(\boldsymbol{r})}{B^2(\boldsymbol{r})} \right|$$

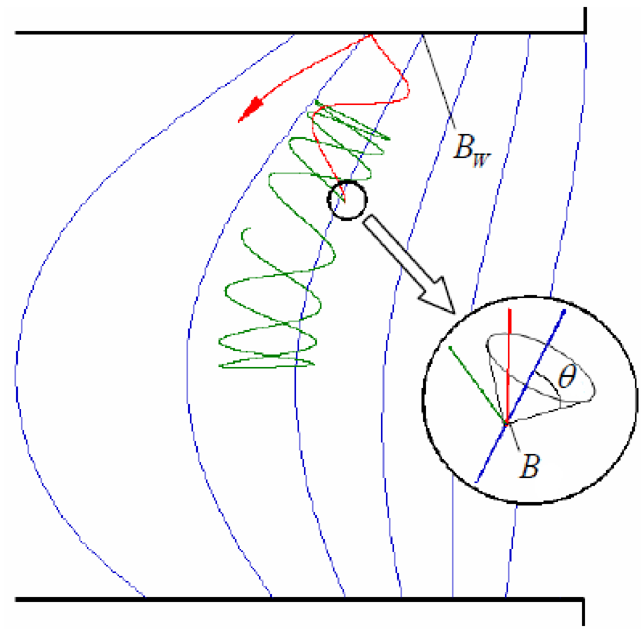
***Experimental finding**: a region of the most intense ionization coincides with the zone of* $\max(grad(|B|)$



Magnetic mirror effect: electrons may be reflected if their velocities are directed outside the escape cone with angle θ, and thus remain within the solid angle:

$$\Omega(\boldsymbol{r}) = 4\pi \cos\theta, \qquad \text{where} \quad \sin^2\theta = B(\boldsymbol{r})/B_w$$

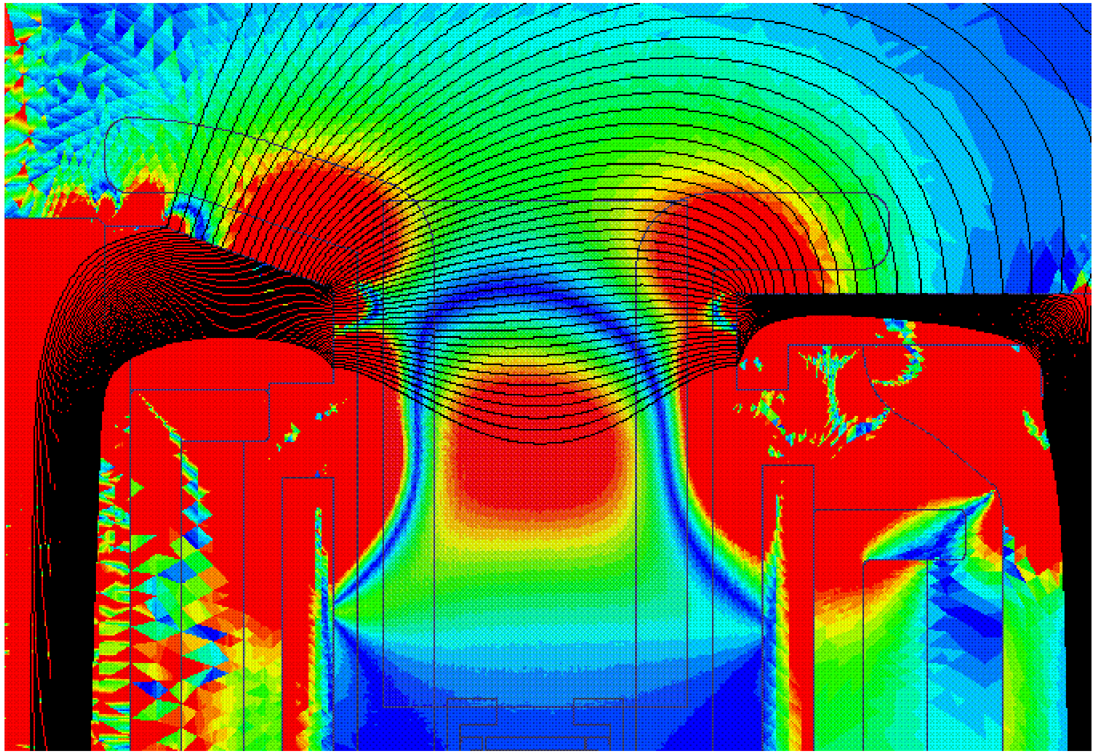
If $G^* = \int_{S_i} F(\boldsymbol{r})\Omega(\boldsymbol{r})d\boldsymbol{r} / \int_{S_i} F(\boldsymbol{r})d\boldsymbol{r}$ *reaches maximum value, **B** field topography is optimal*

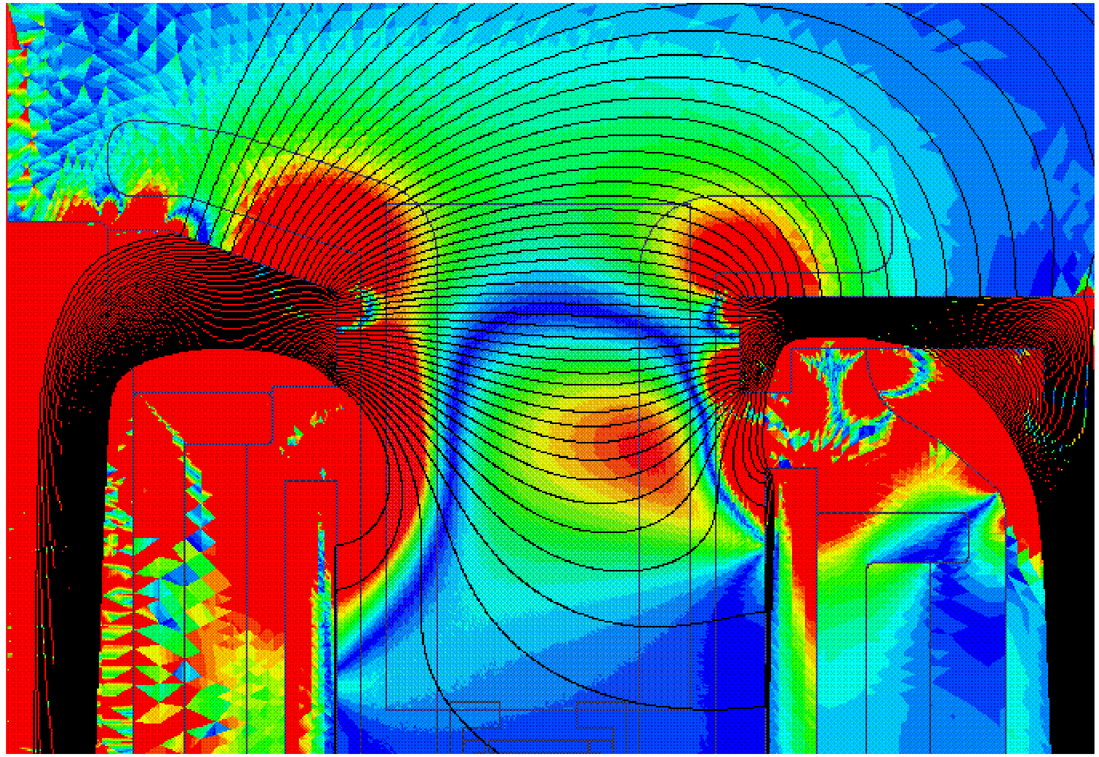


1. Please note, that: $\boldsymbol{v}_{drift} \cong \frac{m{v^2}_\perp}{2qB} \frac{(-\nabla_\perp B) \times \boldsymbol{B}}{B^2}$

Belikov *et al.*, IEPC 30-129-2007

... G-criterion – F(r,z)-function field ...





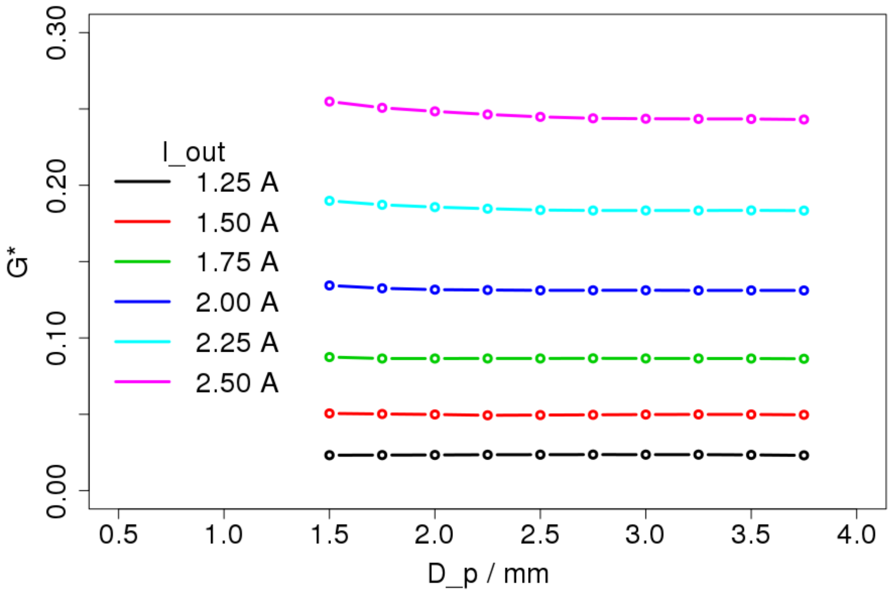
Variable pole thickness:
D_p=1. 25-3.75 mm, step 0.25
I_{inn}=5 A, I_{out}=1.75, 2.0, 2.5 A

Variable inner coil current:
I_{inn}=1. 5-2.5 A, step 0.25
I_{out}=5 A, D_p=1.5, 2.5,3.75 mm

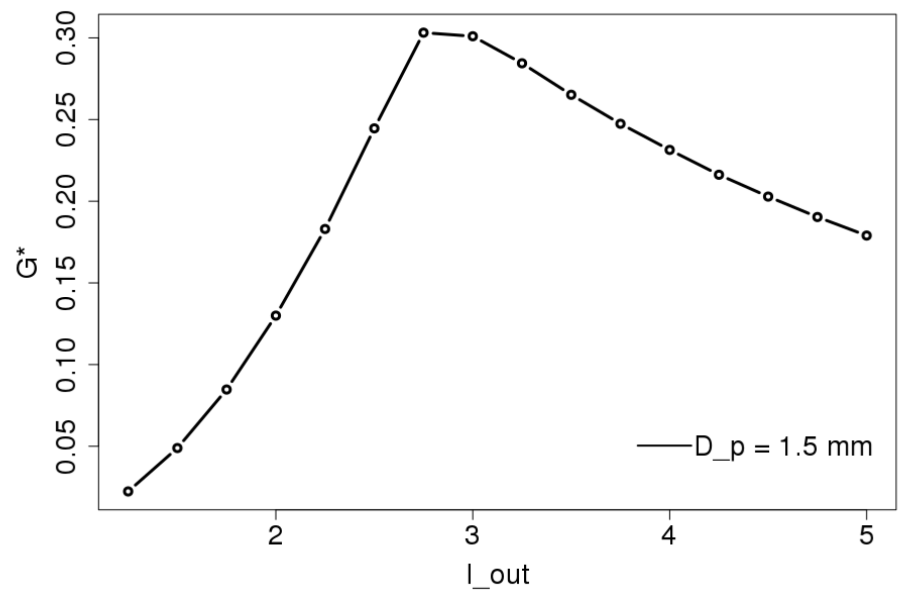
$$F(\boldsymbol{r}) = \left| \frac{\boldsymbol{B}(\boldsymbol{r}) \times \nabla B(\boldsymbol{r})}{B^2(\boldsymbol{r})} \right|$$

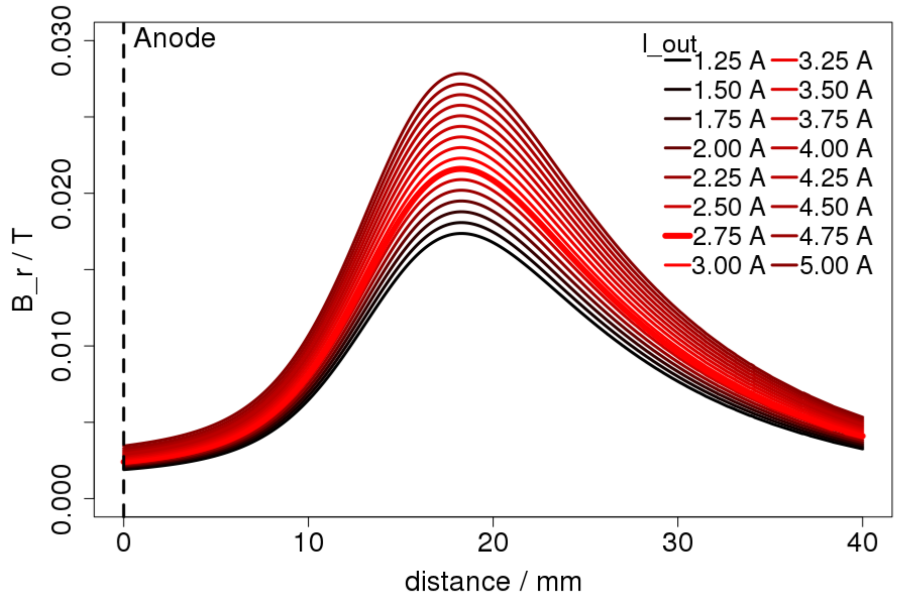
... G-criterion – searching for the maximum

Variable pole thickness;
I_{inn}=5.0 A.



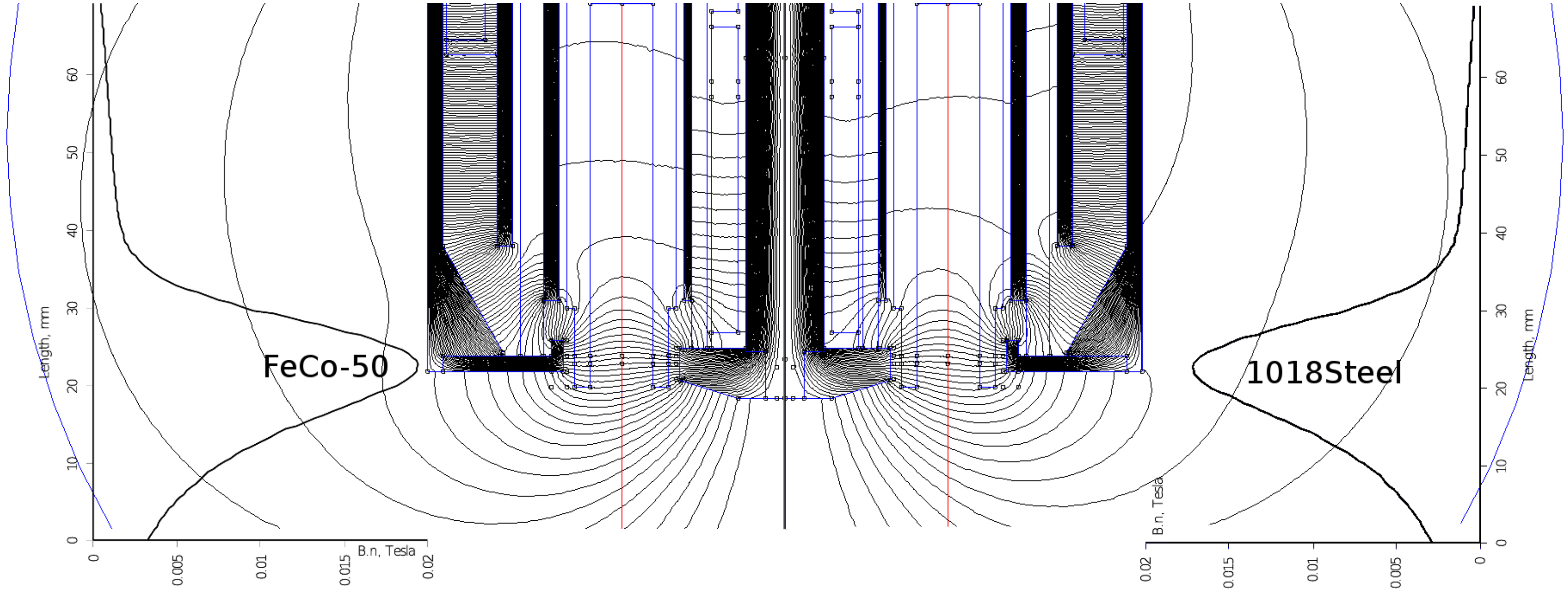
Variable outer coil current:
I_{inn}=5.0 A, D_{p}=1.5 mm





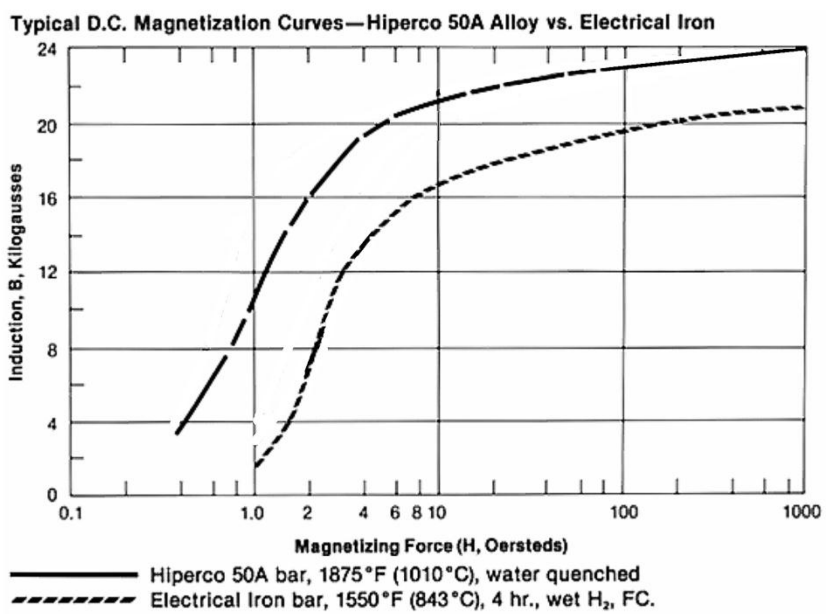
$$G^* = \int_{S_i} F(\mathbf{r})\Omega(\mathbf{r})d\mathbf{r} \Big/ \int_{S_i} F(\mathbf{r})d\mathbf{r}$$

... towards better magnetic circuit ...

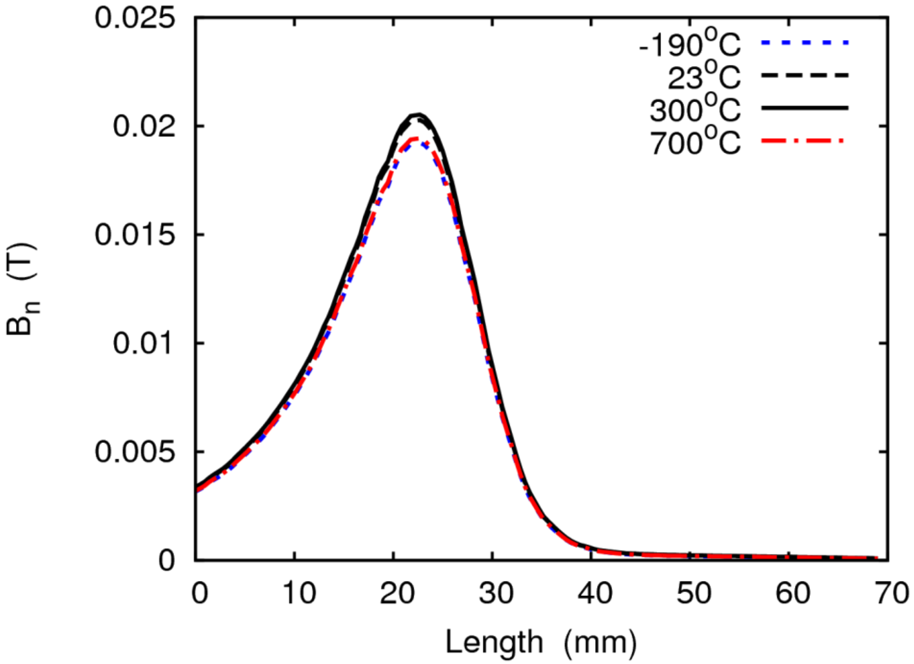


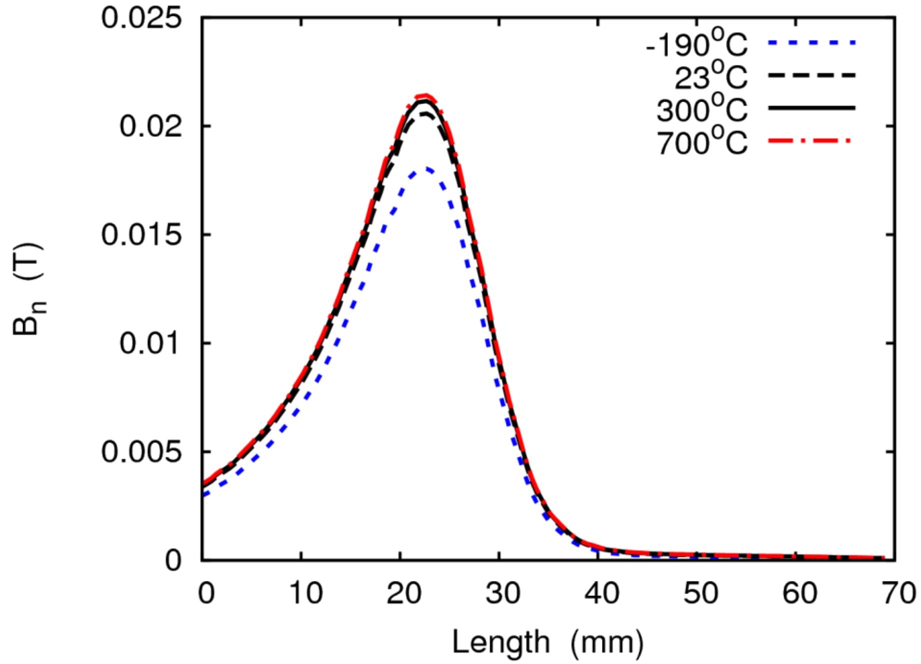
Magnetic field distribution for the first (right) and the second (left) prototype (the same coil currents are set).

magnetization curves for pure iron and FeCo alloy

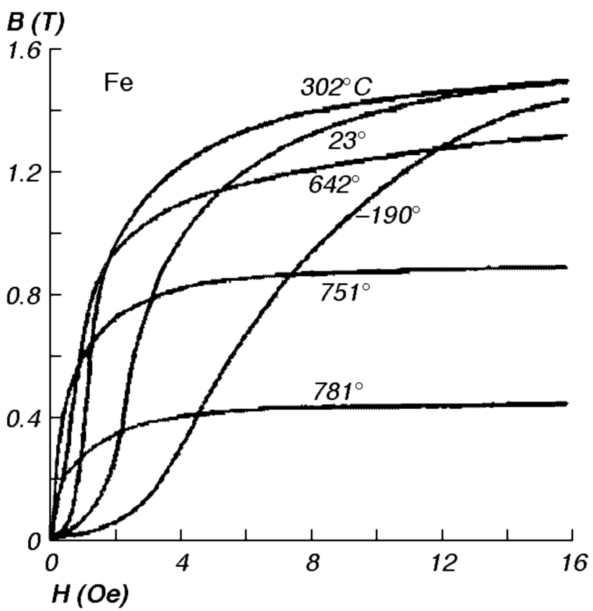


... temperature impact ...





Axial distribution $B_r(z)$ at the channel center line parameterized with T of poles; the residual part of magnetic circuit was kept at 23^{o}C



Temperature dependence of magnetization curves for pure iron

Dependence of Fe-Co alloy magnetization curve on temperature was calculated applying analytical approximation suggested as an alternative to quantum-mechanical computations.

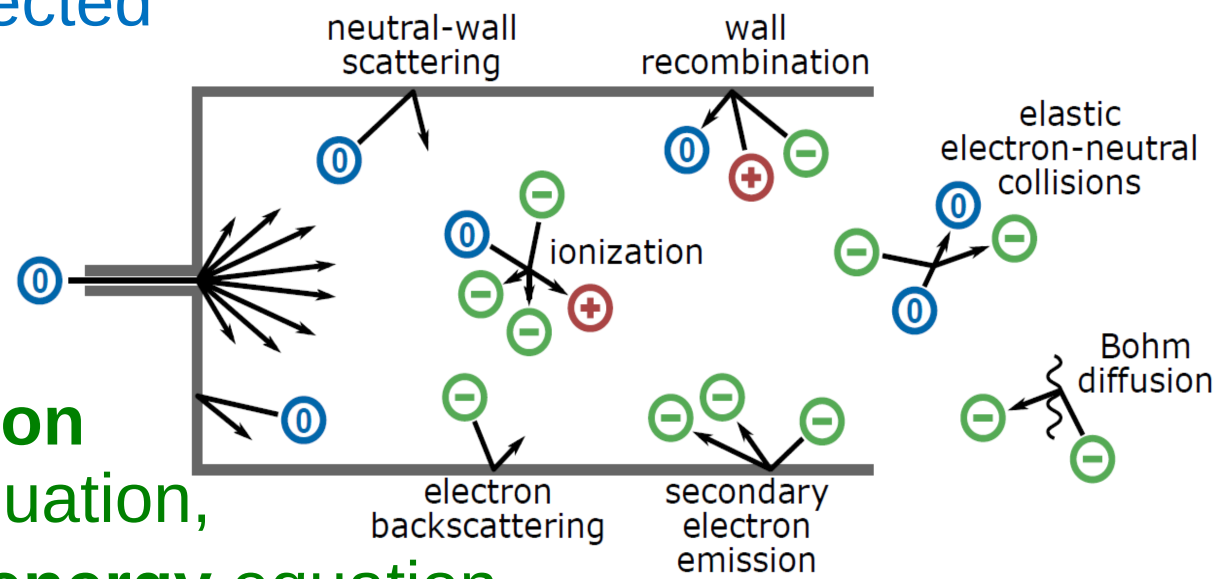
Z. Włodarski, *COMPEL*, **17** (1998) 402

... computer aided design concept assessment ...

HETMAn = **H**all **E**ffect **T**hruster **M**odeling & **An**alysis

a fast, 1D, time dependent simulating code; ***author: Serge Barral***

1ms simulation == 1min CPU



- **neutrals**: diffiused and injected population distinguished,
- complete Ohm's law with
- **electron** pressure term,
- time-dependent and gradient-dependent **electron azimuthal momentum** equation,
- time-dependent **electron energy** equation with orthotropic **electron temperature tensor** ($T_{e\parallel}$, $T_{e\perp}$),
- anomalous transport and self-consistent near-wall transport,
- channel and near-field plume domain,
- separate anode and gas injection, external RLC circuit.

Financial support: FP7 "HiPER" project (2009–2011), Snecma (2012)

... comparative analysis for Kr and Xe ...

Parametric calculations with the HETMAn code:

5-D space spanned by:

$$U_D, \quad \dot{m}, \quad B_{0,}$$

$$L_C = x_c - x_a,$$

$$K_{Ch}, \quad K_p = 2K_{Ch}$$

… assumed:

- fixed ratio of heat conductivity coefficients: $\lambda_\perp$ and $\lambda_\parallel$
- axial profile of **B**-field as measured in experiment
- fixed values of the external electric circuit parameters

…searching for

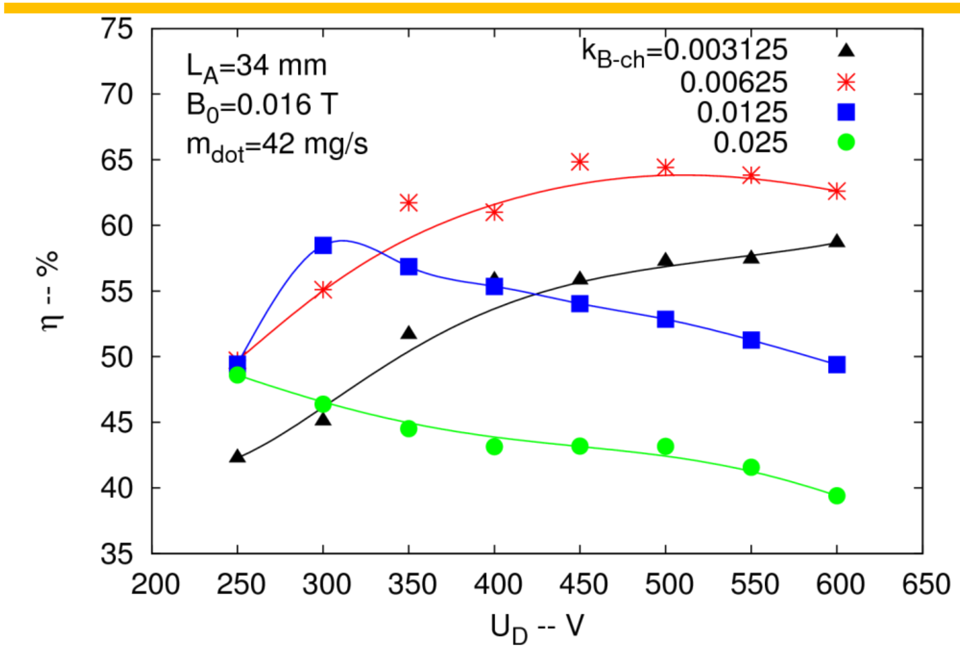
- performance and
- discharge characteristics:

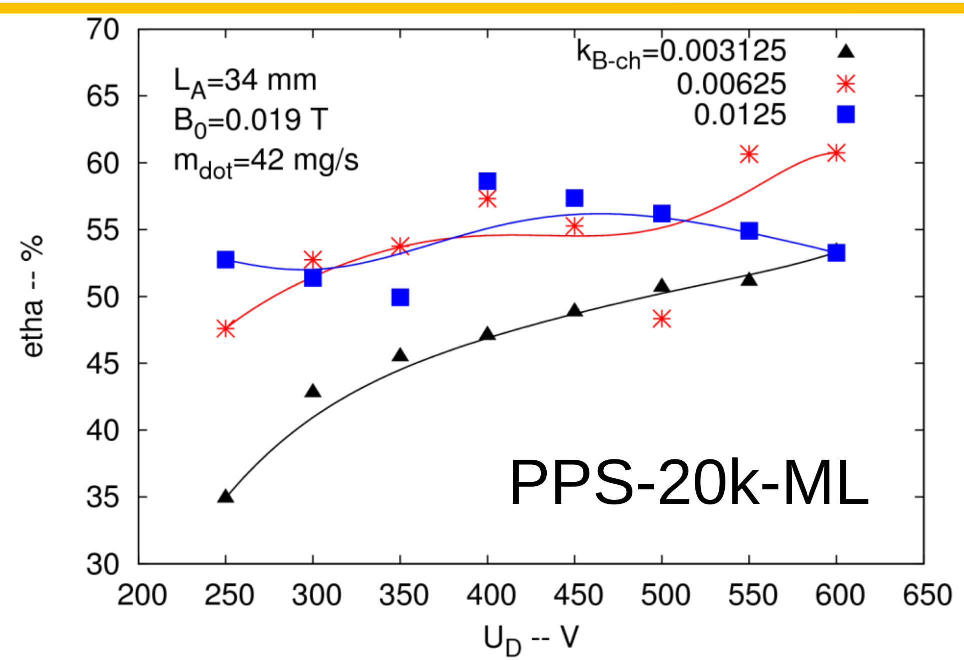
$$T, \quad I_{sp}, \quad \eta,$$

$$I_D, \quad P_D, \quad P_W,$$

$$T_e, \quad n_e, \quad \nu, \quad etc.$$

... Bohm transport coefficient evaluation ...





Bohm coefficients belong to free parameters of the model…

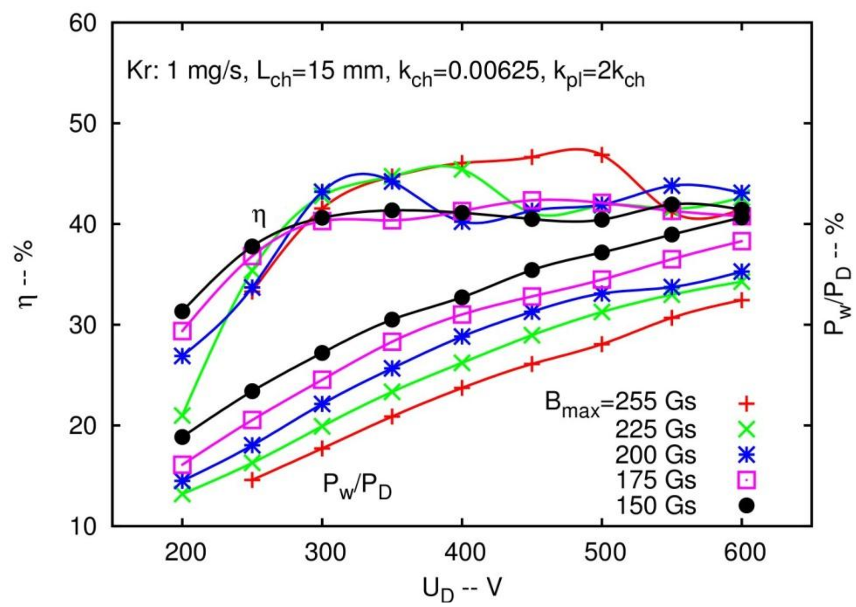
$k_B^{plume} = 2k_B^{channel} = 1/80$ correspond to anomalous electron mobility $\mu_\perp \sim K/16B$ if K=0.1 and 0.2

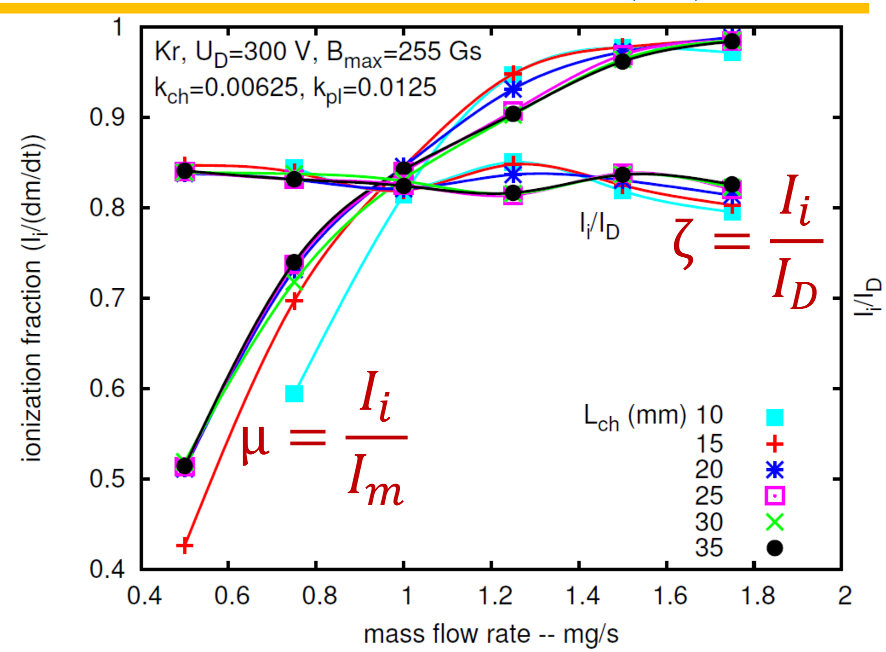
These values provided **for maximum efficiency** of the modeled thruster **in the widest range of the operating parameters**.

It happened ? that for these parameters the results of modeling fitted to PPS-20k-ML thruster characteristics as measured in experiment.

These k_B values were also used for KLIMT discharge modeling.

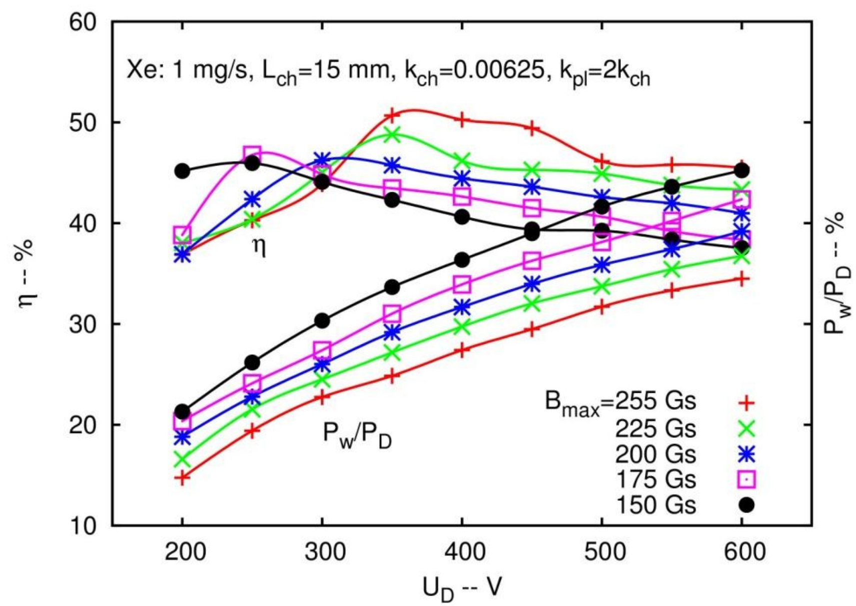
... KLIMT – Kr-Xe HETMAn simulation (2) ...

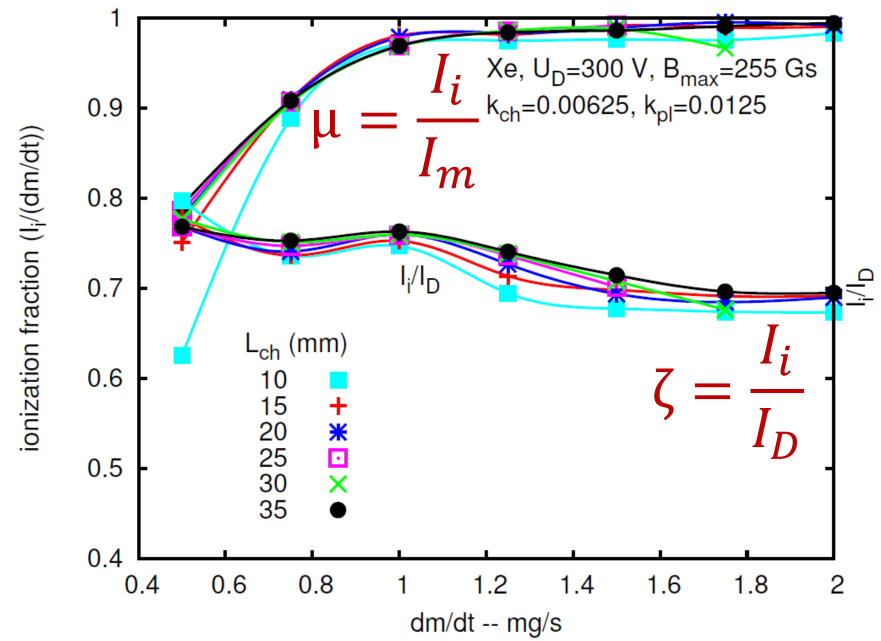




Krypton

Xenon





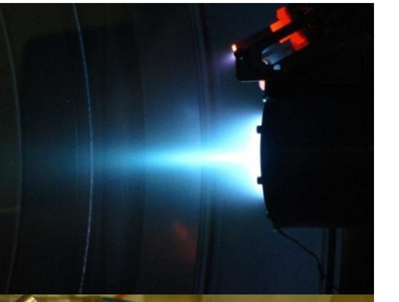
Efficiency & power lost to walls vs discharge voltage

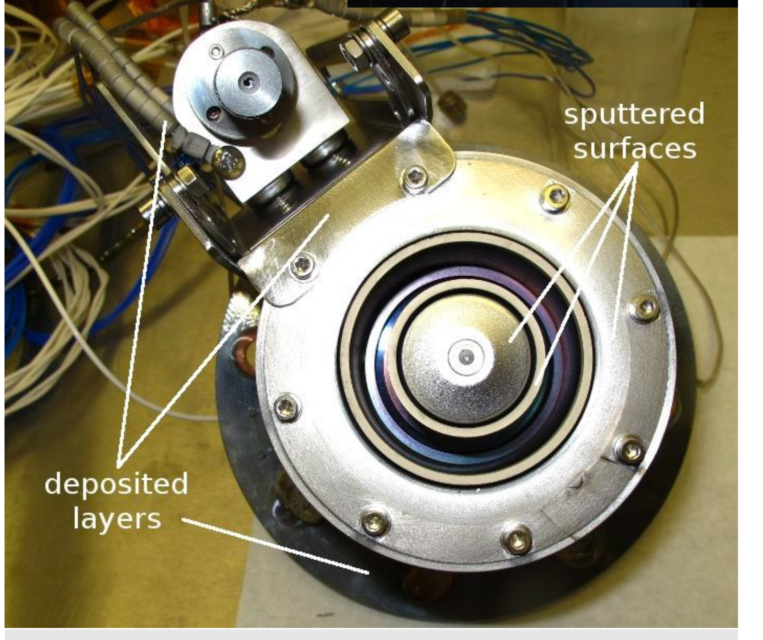
Propellant utilization and ion current fraction

... KLIMT's 1st version performance ...

dm /dt mg/s	U_D V	P_D W	I_D *readout* mA	*F* mN	I_{sp} S	η %
1	300	245	818	12.1±0.8	1240	30
1	300	247	822	12.4±1.0	1270	31
1.1	300	271	904	14.7±0.9	1370	36
1.1	300	272	907	15.6±0.9	1450	41
1.1	350	322	921	14.5±0.8	1340	30
1.1	450	456	1013	18.2±0.8	1690	33
1.5	200	267	1335	19.1±0.9	1300	46
1.5	250	331	1324	20.3±0.9	1380	41

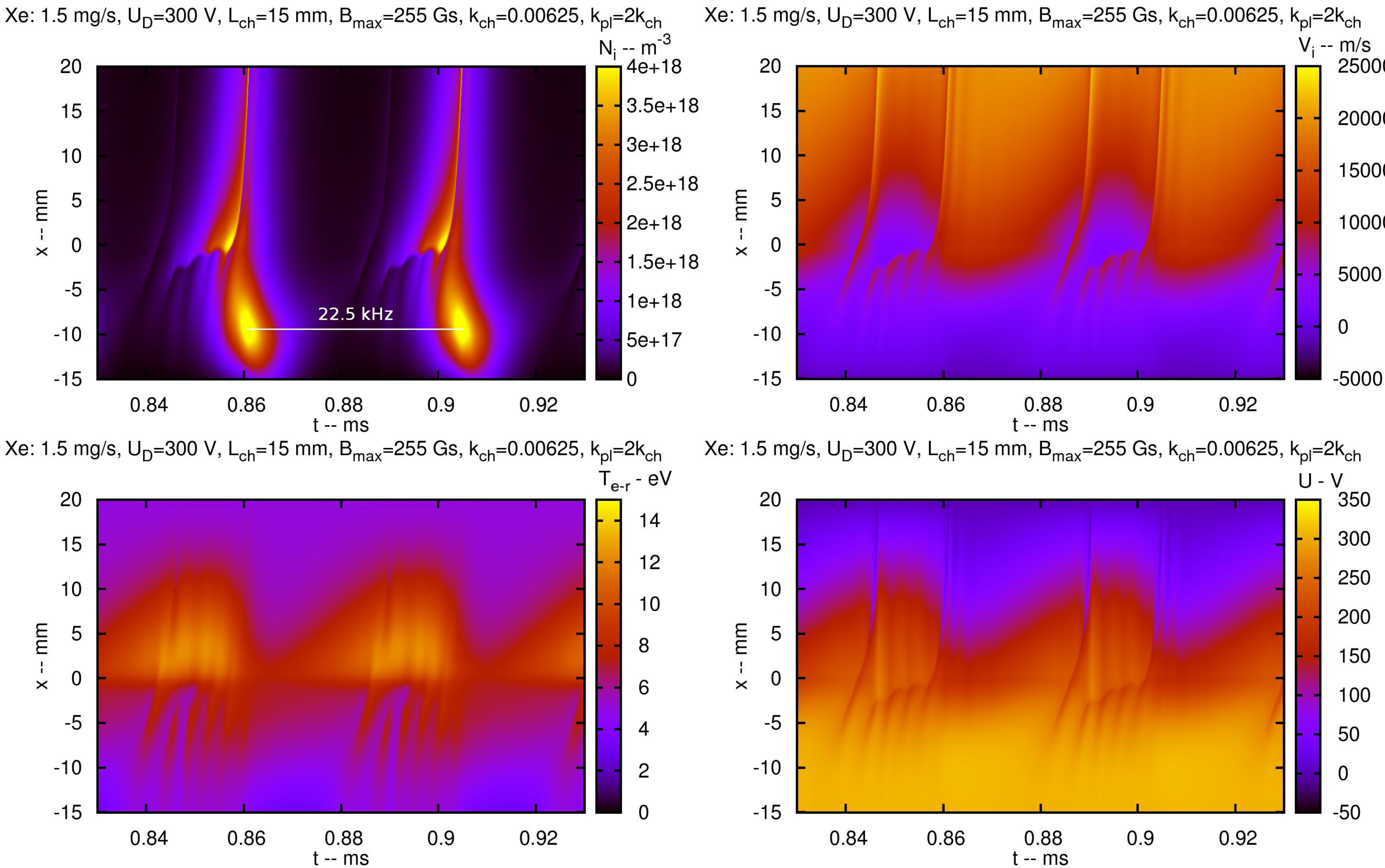
Xenon



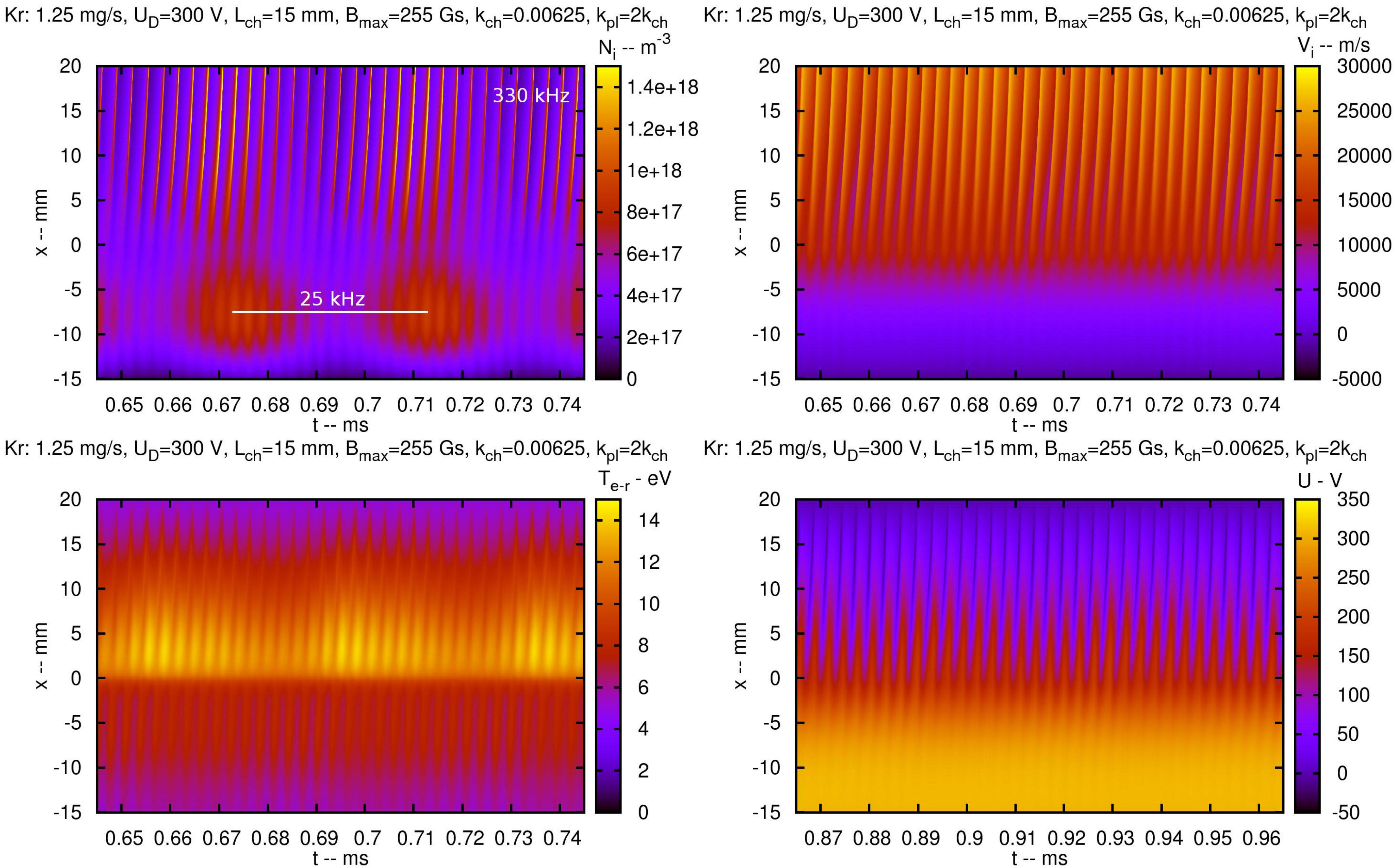


KLIMT as dismounted from the thrust stand after the campaign in EPL. Deposited layers and sputtered surfaces are shown.

... *discharge oscillations: breathing mode* ...



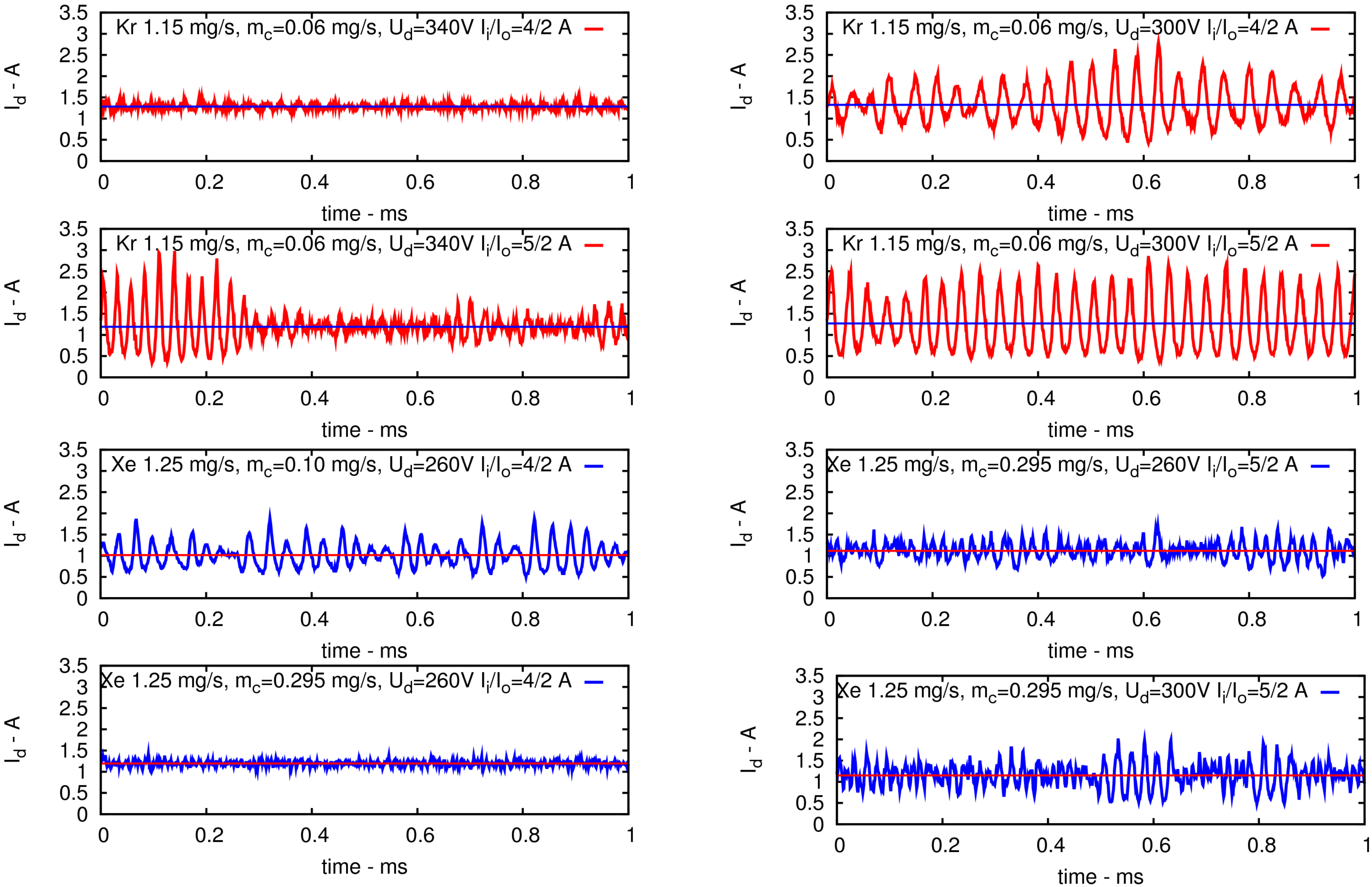
...discharge oscillations: „transit-time (?)”...



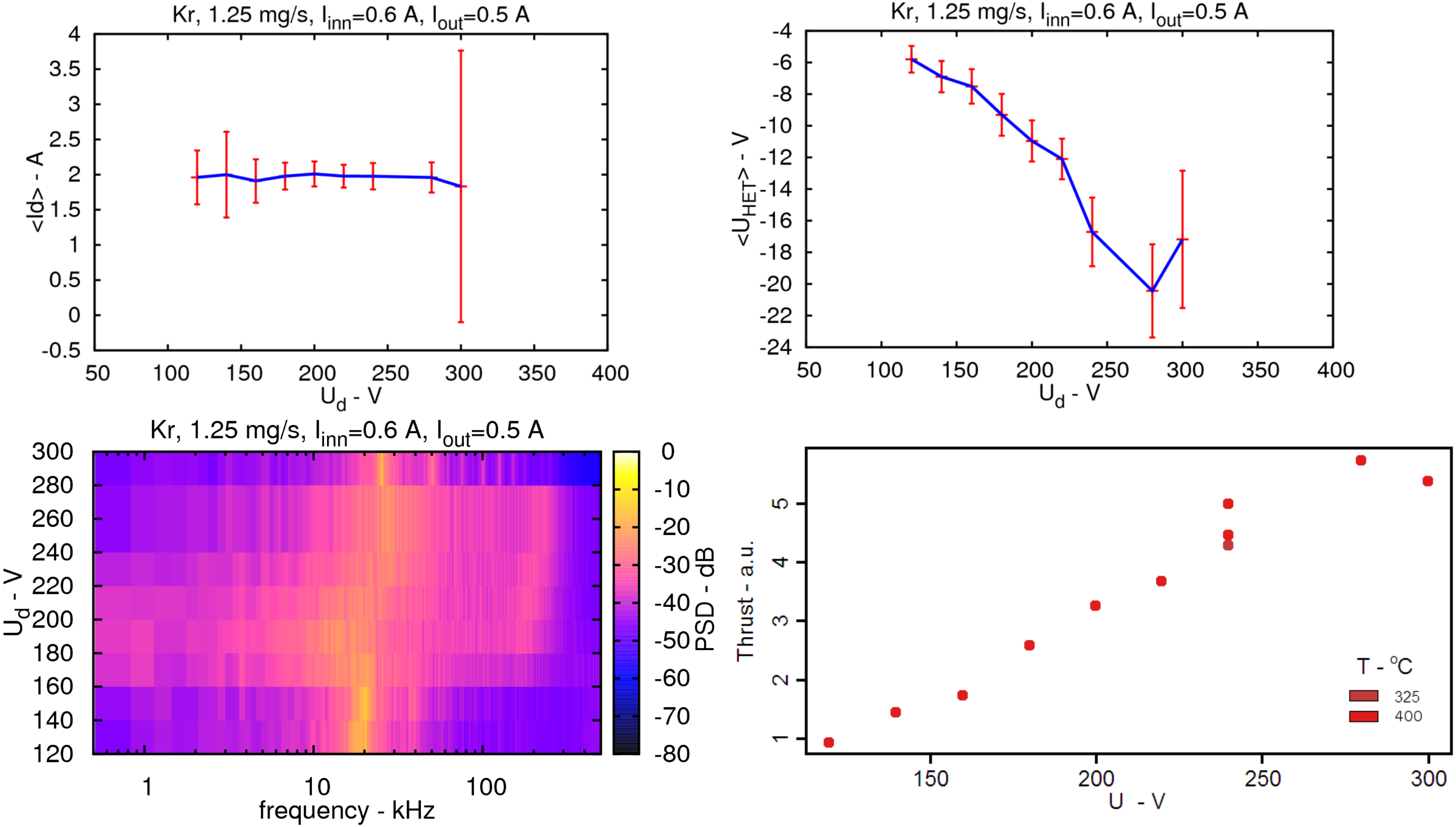
... 2nd measurement campaign (at IPPLM) ...

- Tests were performed for krypton mass flow rates of 0.5, 0.63, 0.75, 1.0, 1.25 and 1.5 mg/s.
- For each mass flow rate **discharge voltage** was varied in the widest possible range that provided stable thruster operation. The lowest discharge voltage for which the thruster had been examined was set to **80 V** while the highest to **350 V**.
- Coil currents were adjusted to keep stable thruster operation in the extended range of discharge voltages.
- Momentum flux as measured for all operating conditions.
- The temperature effect on thruster behavior and performance was examined.

… discharge current: B-field effect …



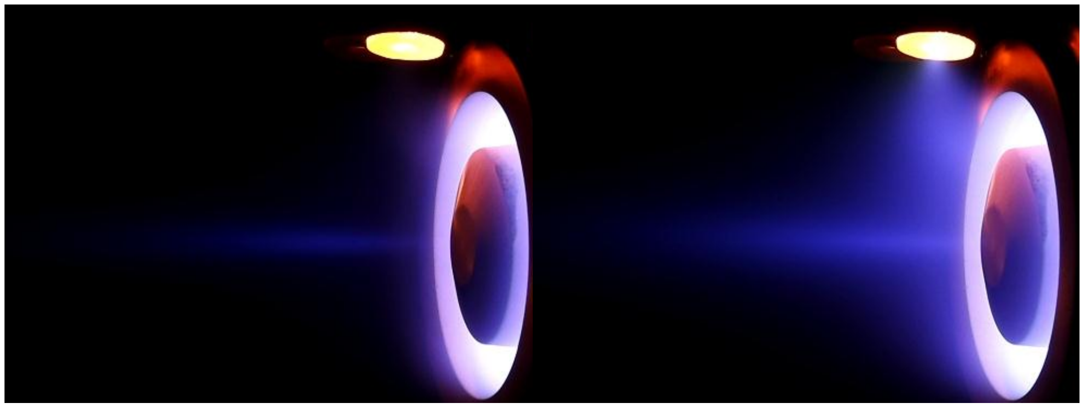
... basic discharge characteristics ...

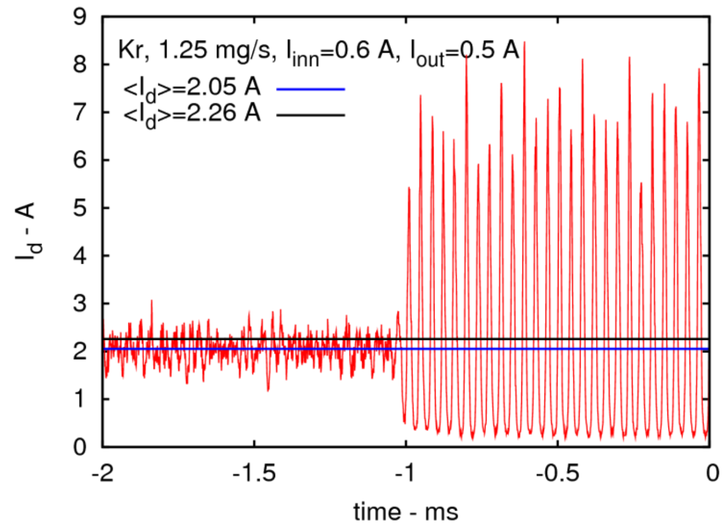


a) I-V characteristic, b) floating potential, c) PSD, d) thrust

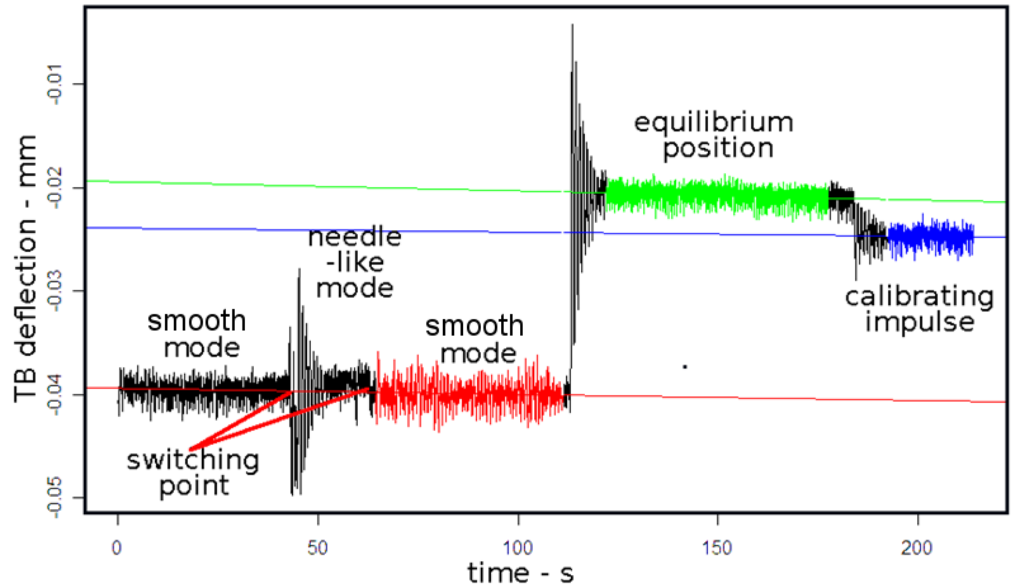
... searching for operating envelope ...

operating parameters range	
Krypton flow rate - mg/s	0.50-1.50 (8.6-25.9 sccm)
Discharge voltage U_d – V	80-350
Inner coil current - A	0.30-0.75
Outer coil current - A	0.15-0.60





KLIMT operating in a smooth mode at Ud=240 V and in deeply modulated breathing-type mode at Ud=300 V *Heatwave Labs* HWPES-250 cathode is used.

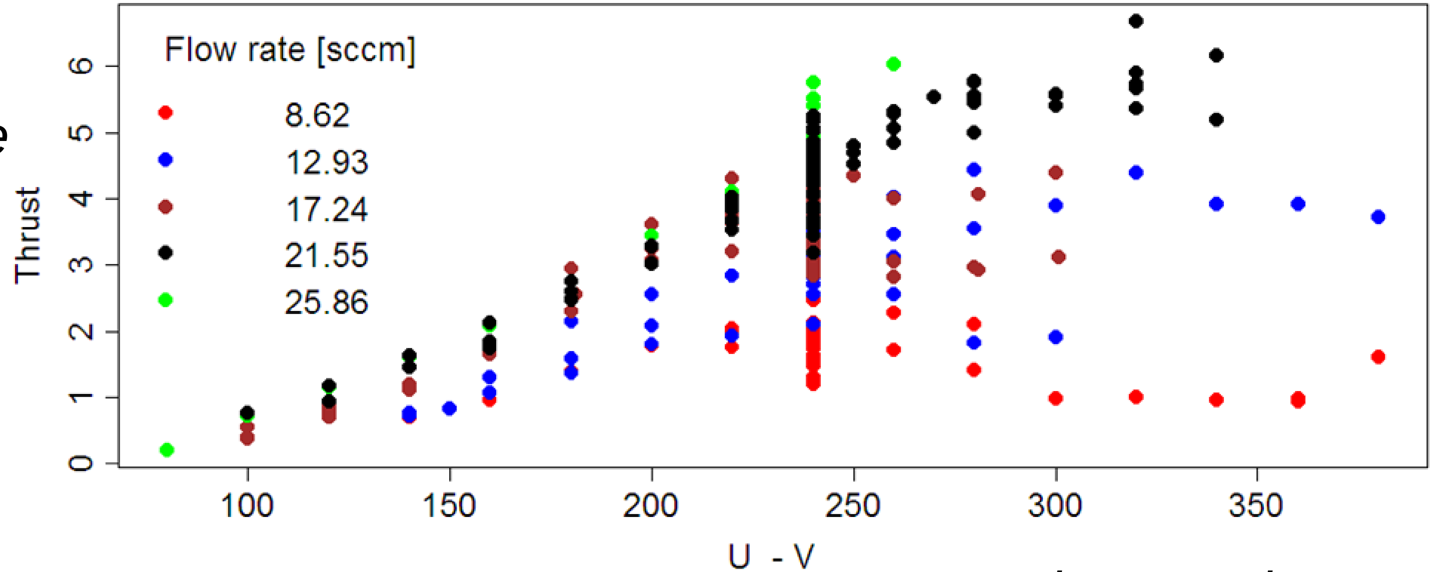


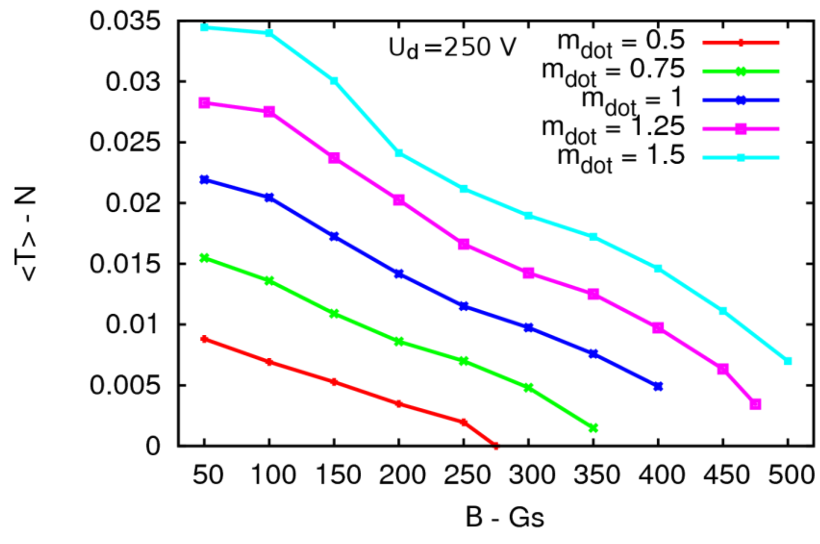
Switching between modes

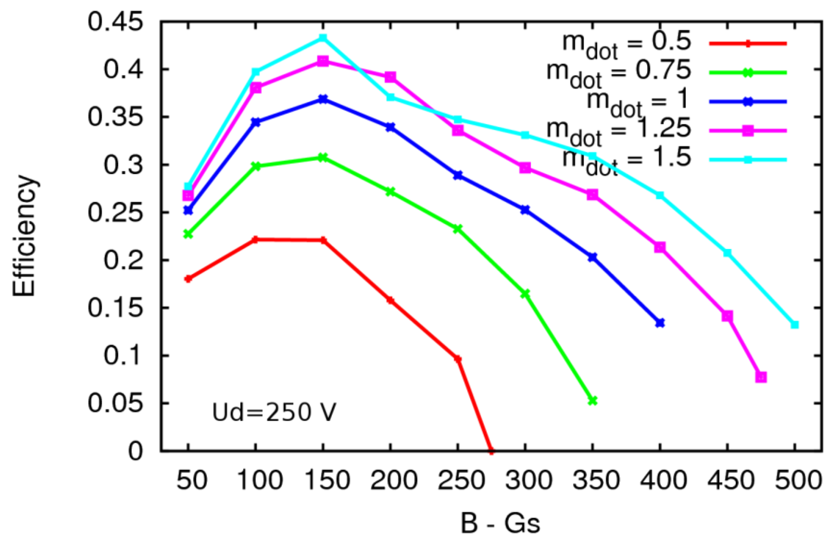
... thrust production ...

The maximum value of thrust as measured with our **indirect** method coincides with voltage close to 240 V for smaller mass flow rates. For massive gas flows it is shifted towards higher voltages.

Momentum flux (indirect thrust measure) vs. discharge voltage as recorded with Mecartex TB in all operating conditions. Normalizing coefficient (1 mN) corresponds to calibrating impulse.







Thrust and efficiency as predicted with HETMAn code for the preferred operating conditions as established in experiment

... guidelines for the 3rd prototype...

- Magnetic field topology was proved to be chosen properly and should be preserved.
- **Thermal design of the thruster should be still improved – better heat evacuation is required**.
- The thruster weight should be reduced.
- The inner structure of the magnetic circuit should be simplified.

***Modeling of magnetic field distribution and heat problem resulted in the new design for which*:**

– the outer diameter of the thruster and its channel length are reduced;

– BN insulator is further modified;

– magnetic screens make an union with the magnetic yoke;

– the coils are modified for better heat evacuation towards the back of the thruster;

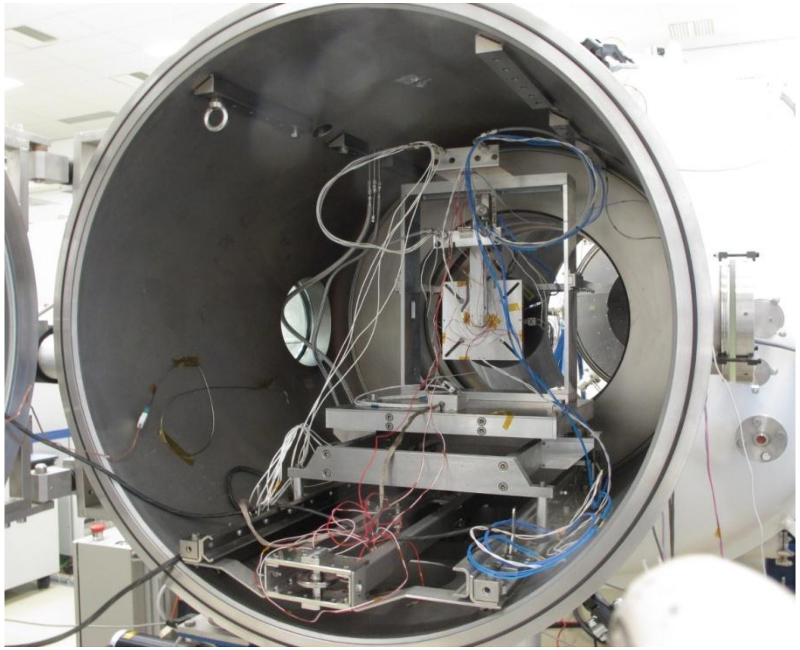
– cathode and anode ensembles are redesigned.

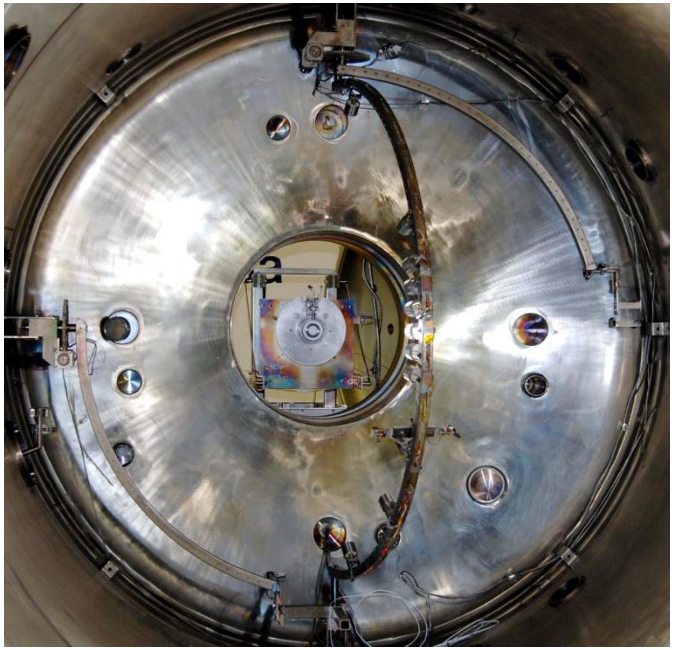
... testing 3rd prototype at EPL ...

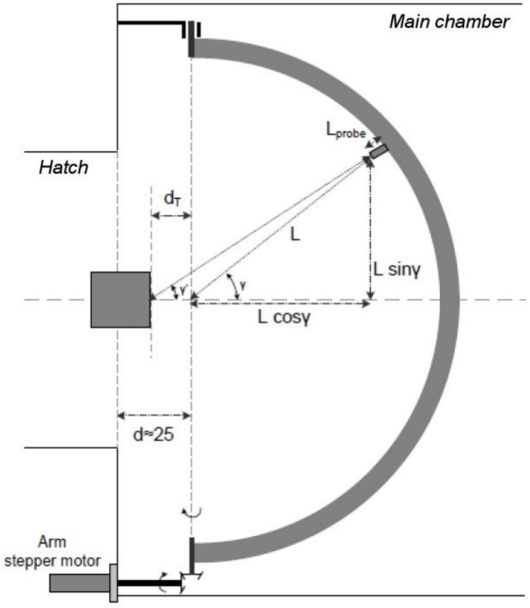
The goal of the tests at EPL was **assessment of KLIMT’s performance** and determination of the relevant operational envelope in terms of thrust produced, specific impulse and efficiency.

Additionally thermal stability of the new design and its short time characteristics (for power spectra calculation) were examined.

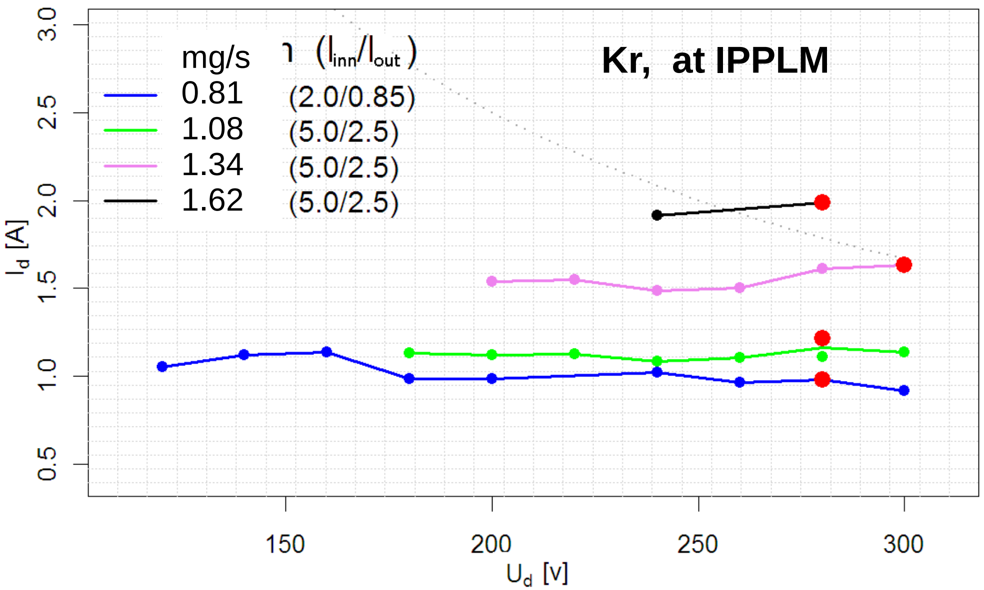
Investigation of the expelled plasma divergence was performed only for Krypton.

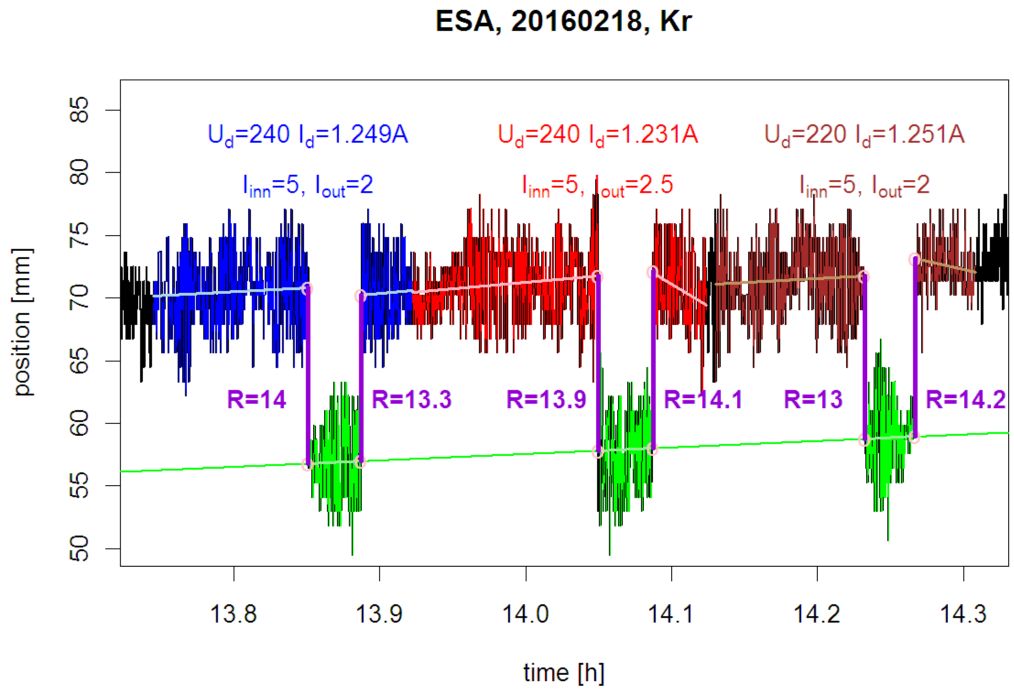


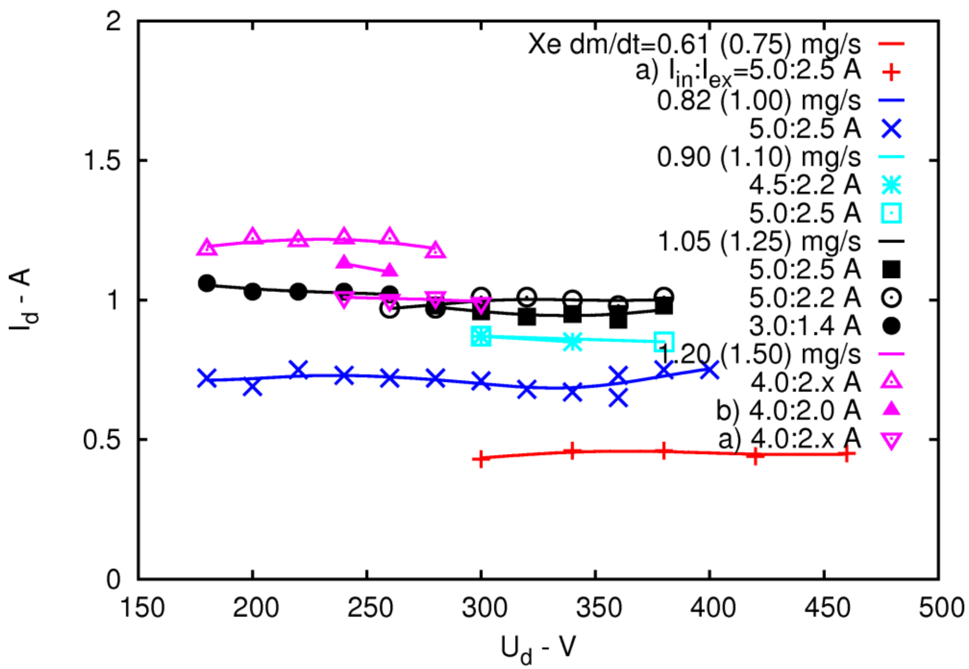


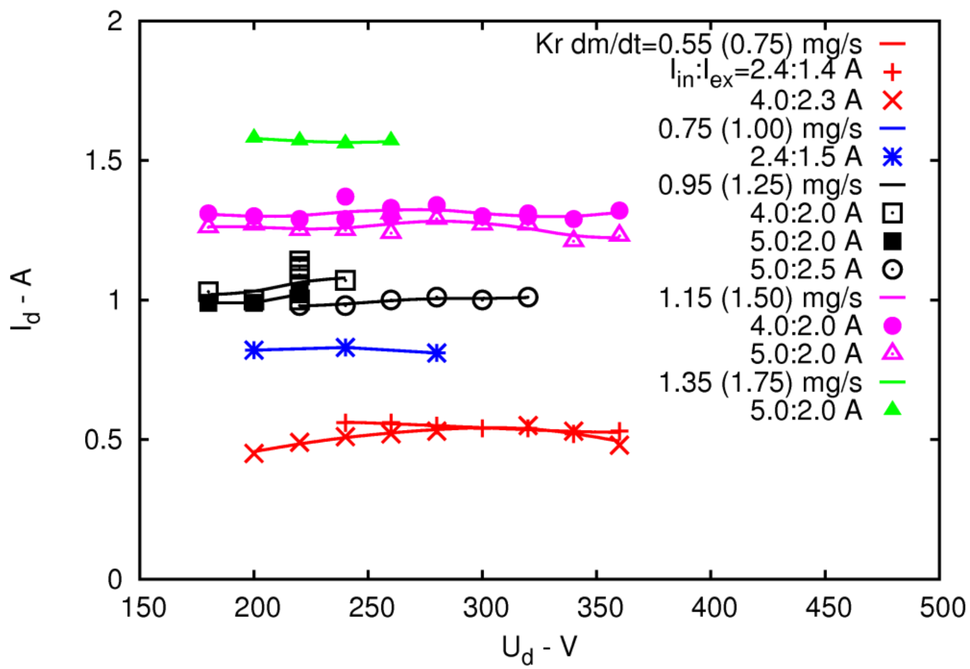


... 3rd version characterization ...

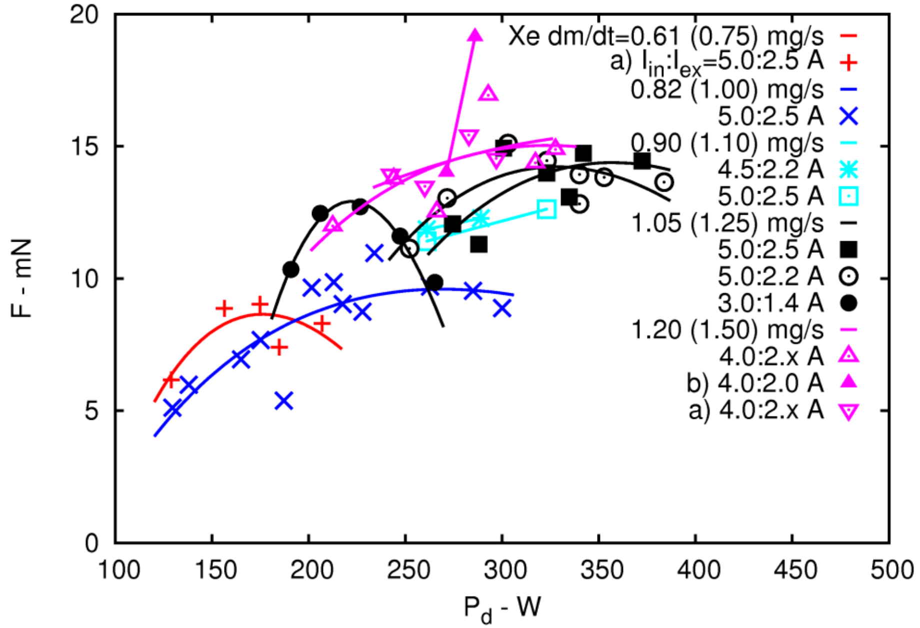


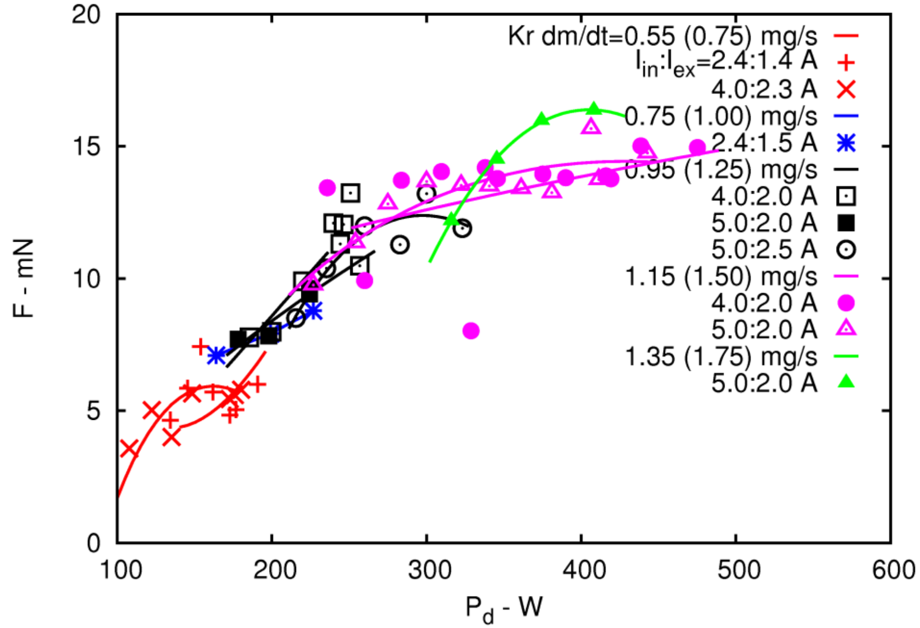


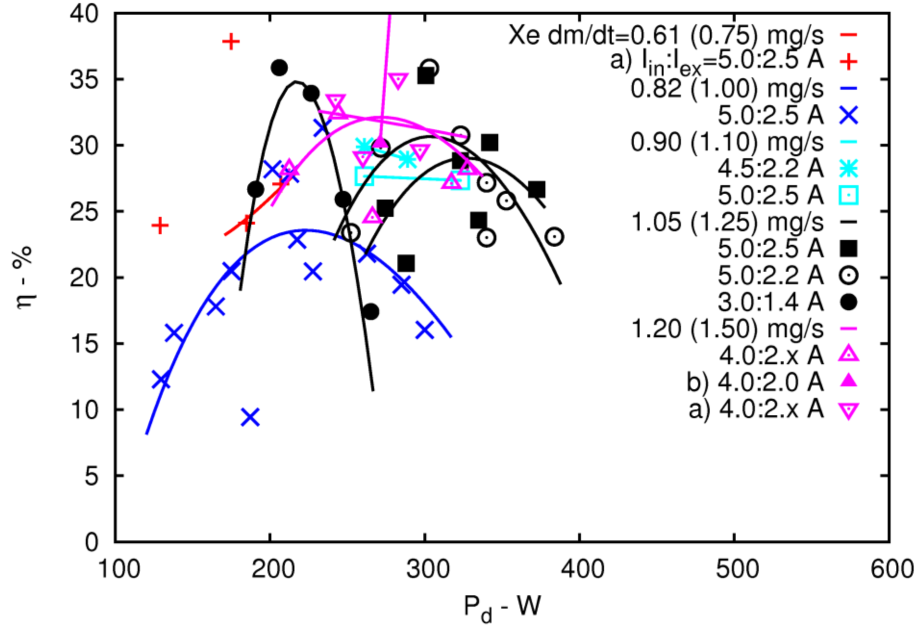


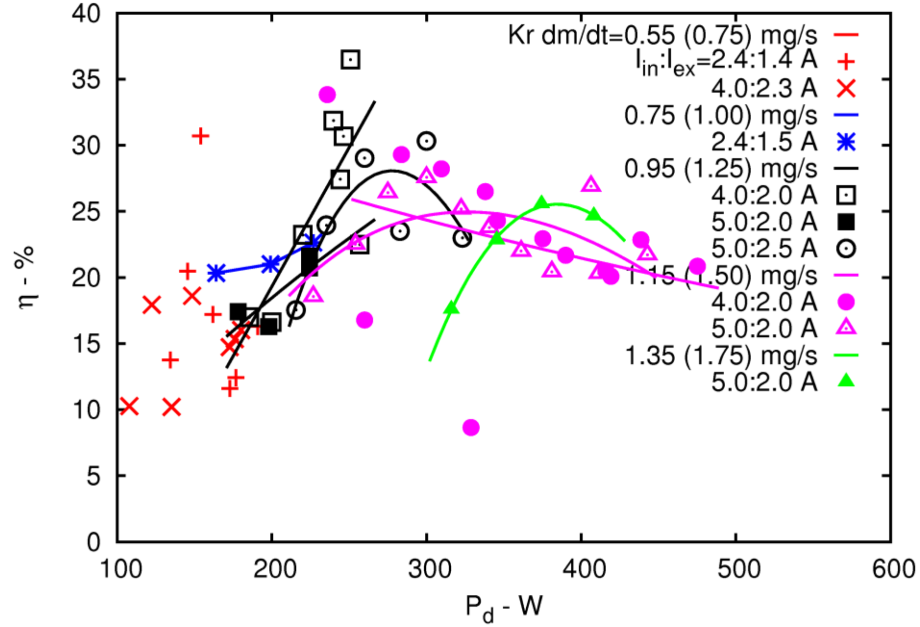


... 3rd version performance ...

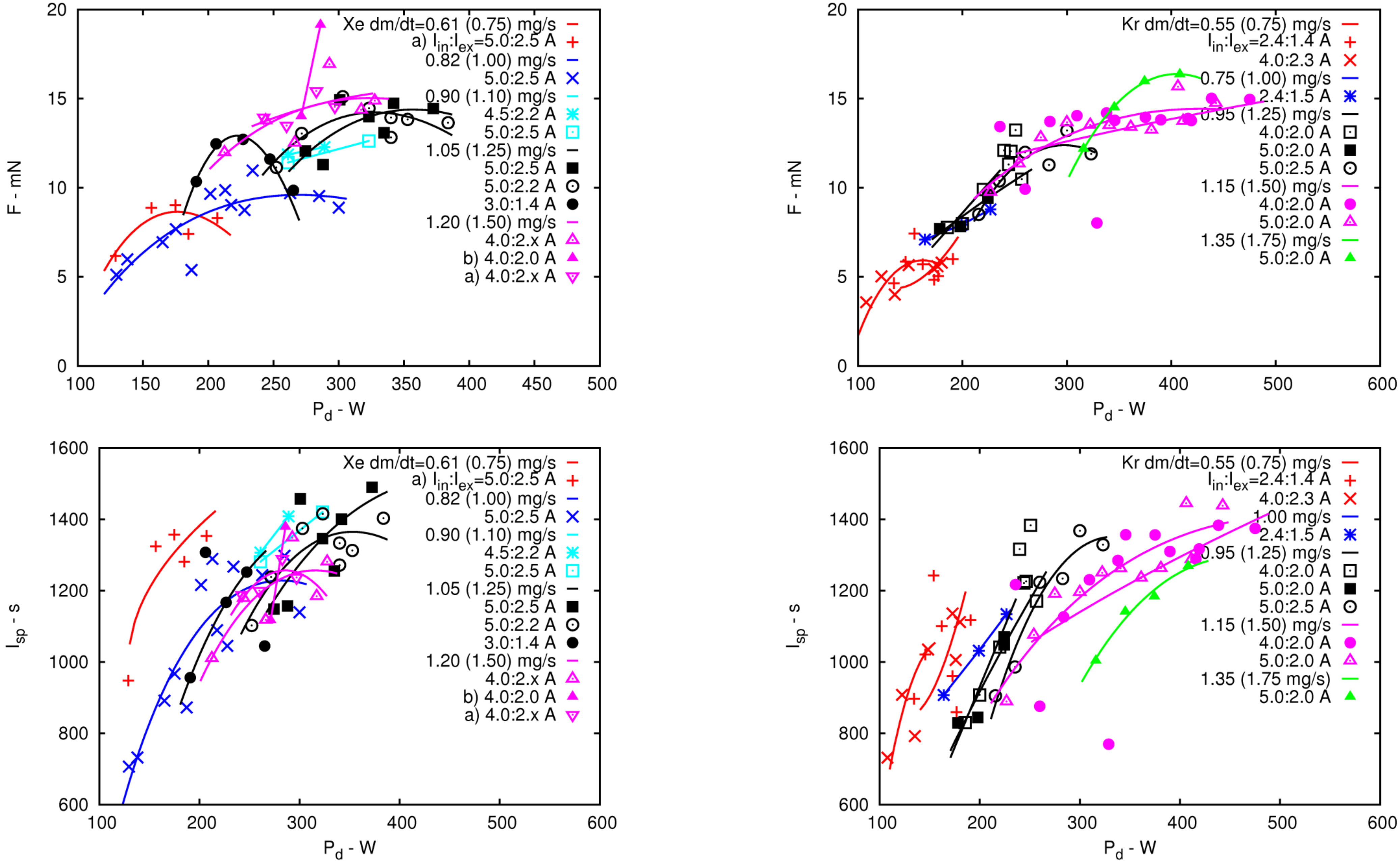






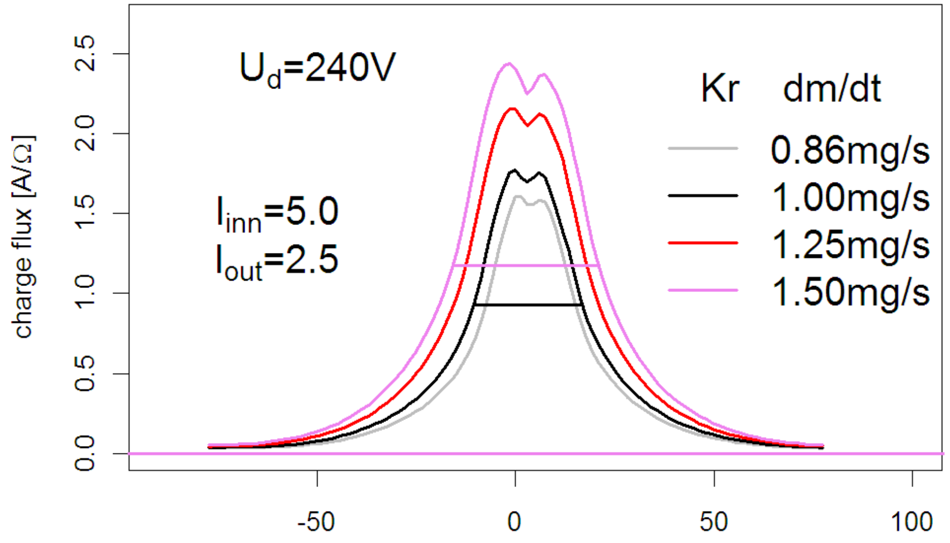


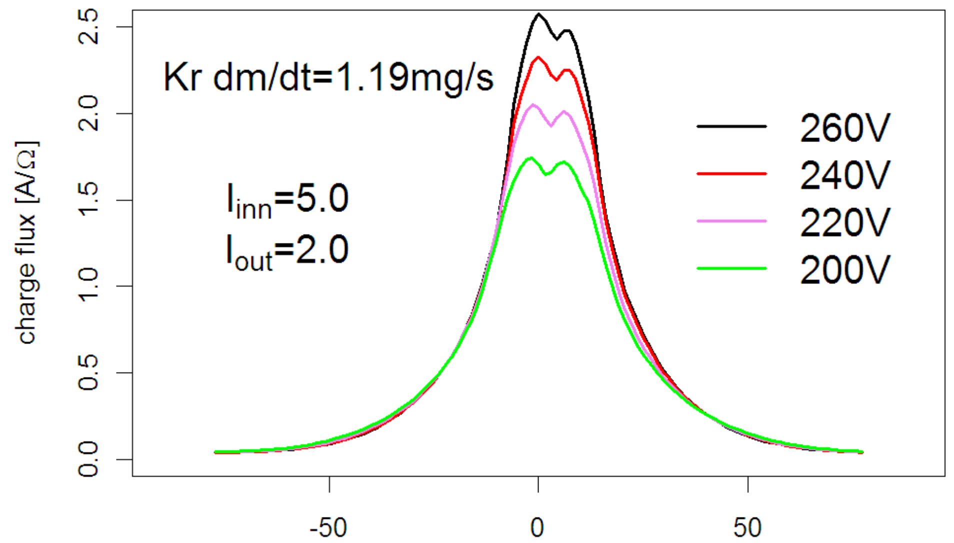
... 3rd version performance II

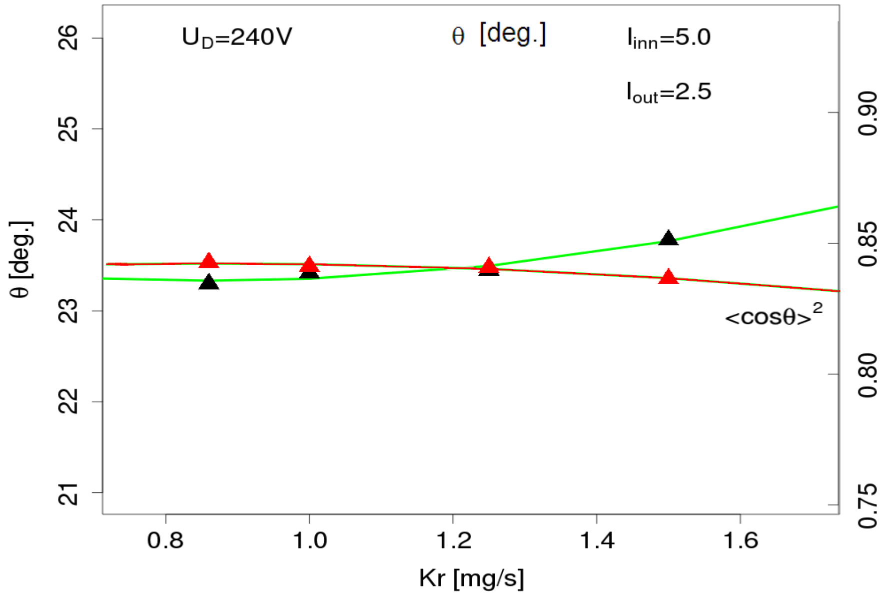


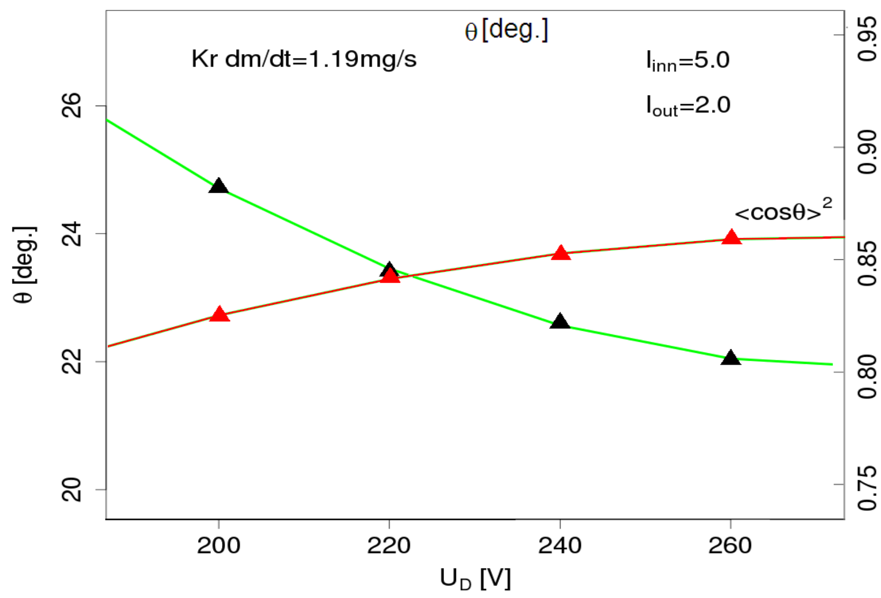
... Beam divergence: ADF, angle & <cosθ>^{2}...

ADF extent in terms of maximum and FWHM values



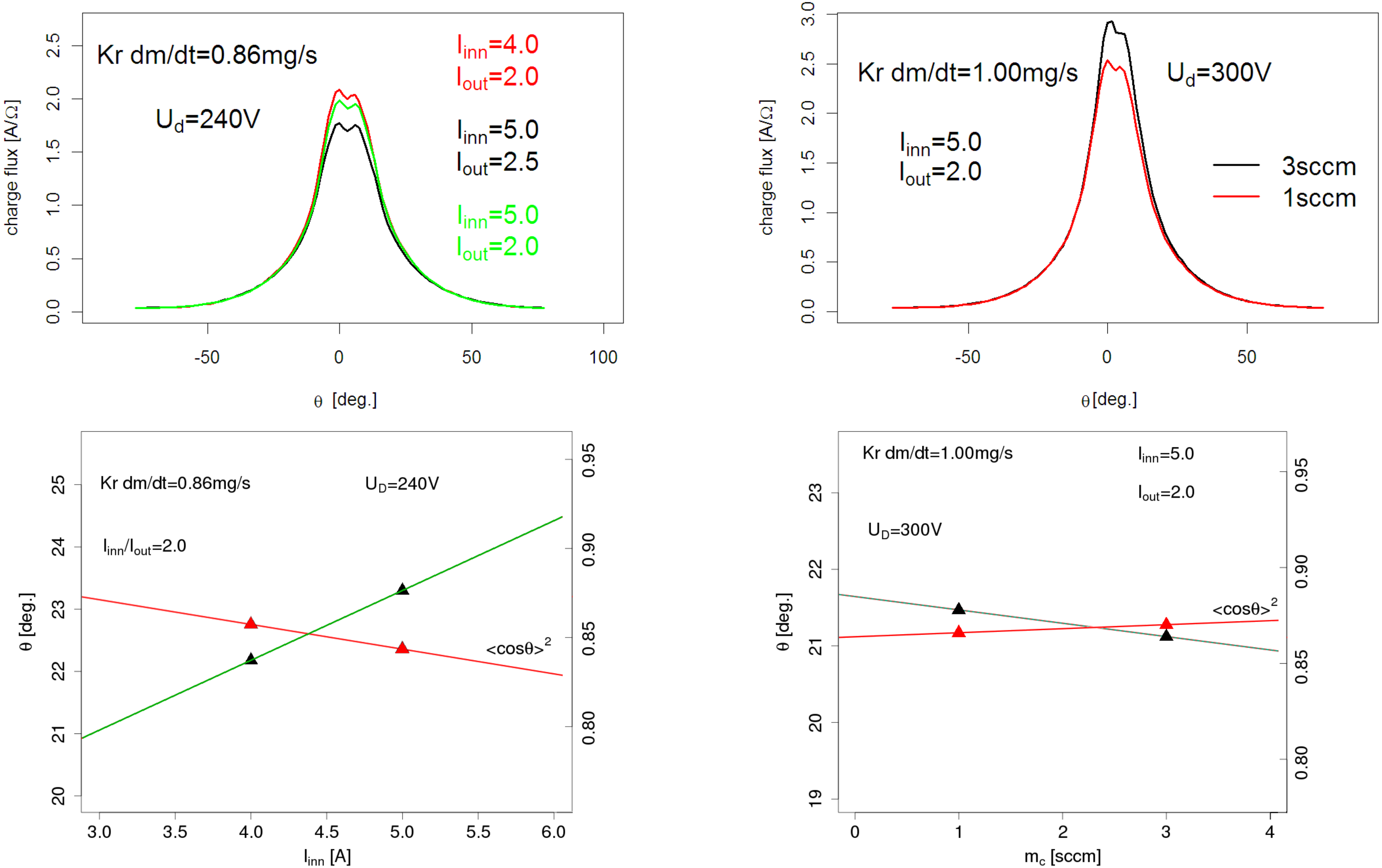




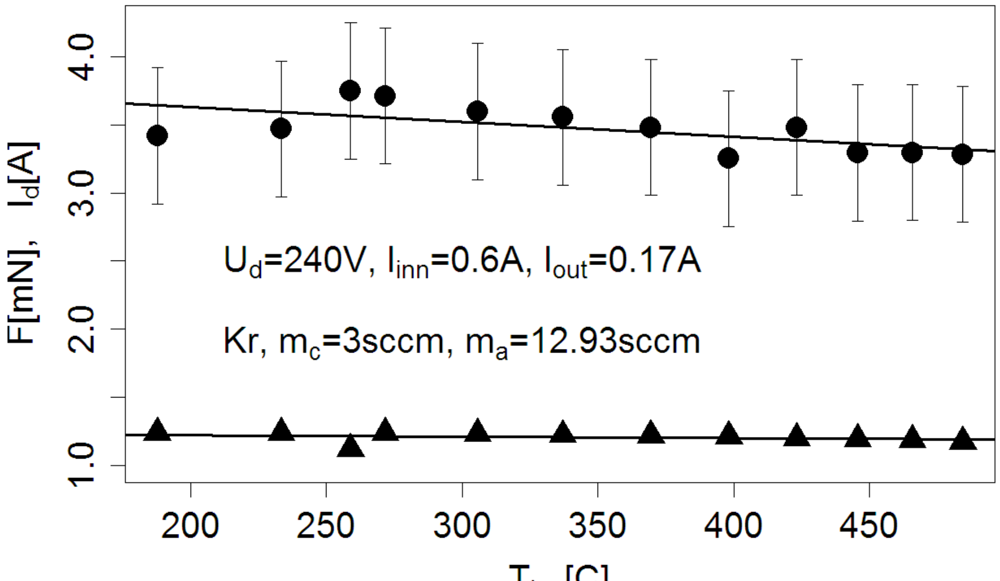


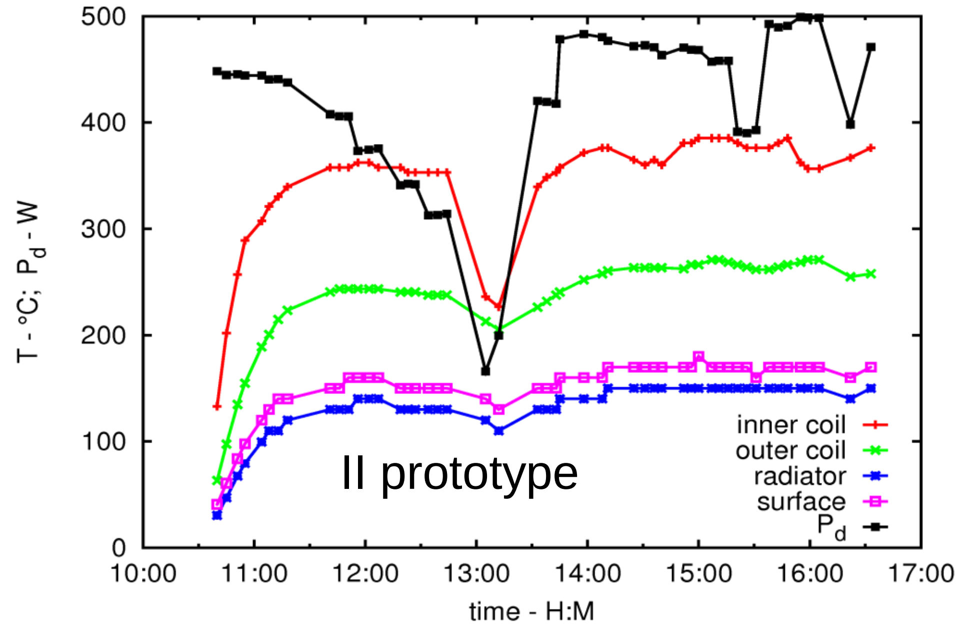
Square of mean cosine and relevant angle

… Beam divergence: ADF, angle & <cosθ>² …

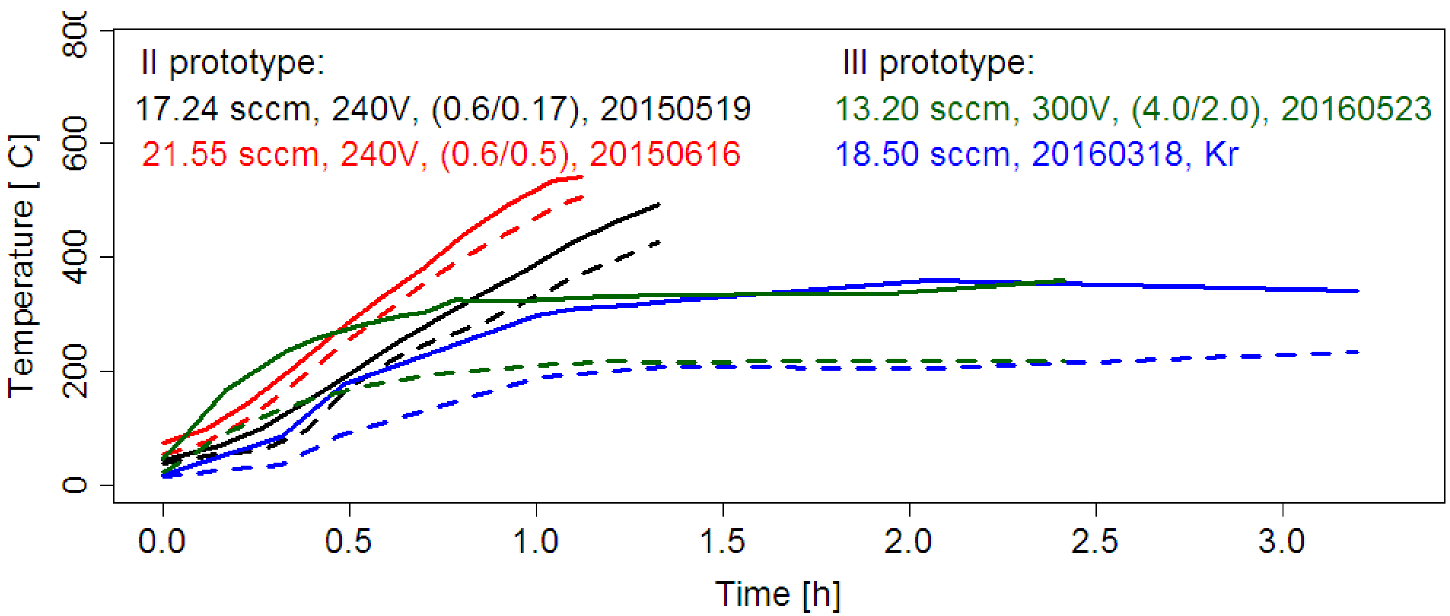


... *thermal equilibrium* ...





Discharge current and momentum flux *vs* temperature (II prototype)



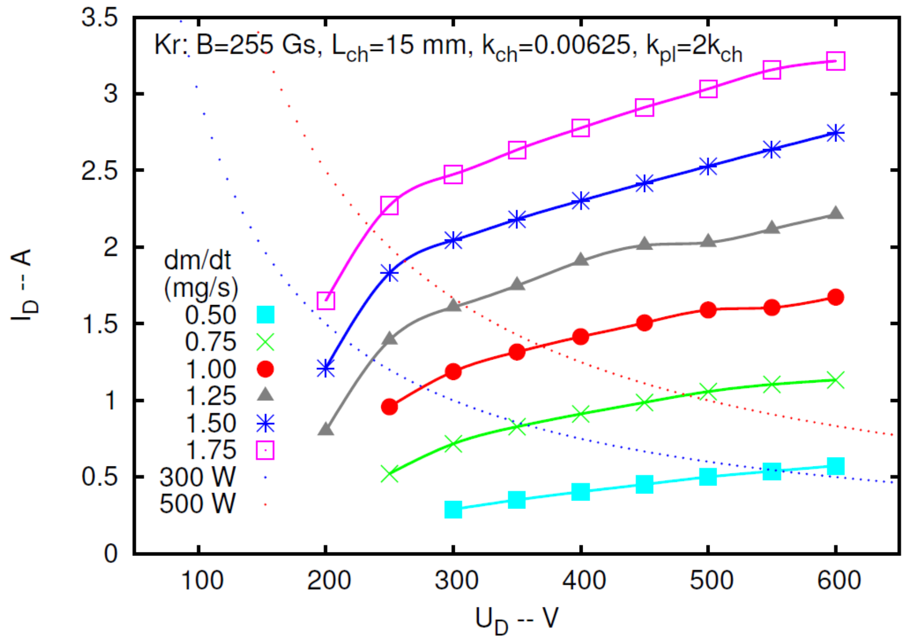
Thermal history as measured at EPL (upper right plot) and at IPPLM (bottom figure) for different operating parameters

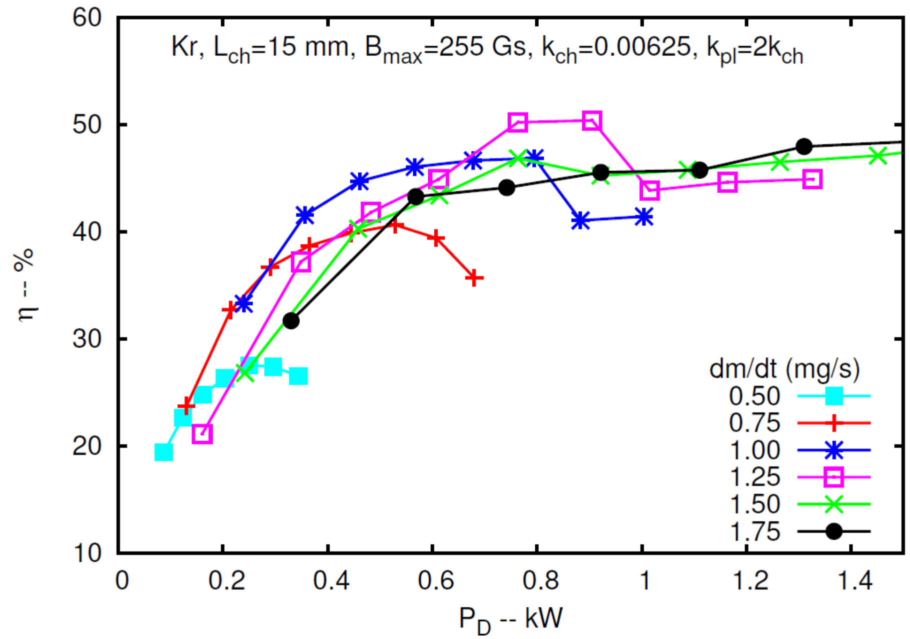
...conclusion...

1. Heat loads simulation allowed to gain thermal stability of the thruster. Correctness of the guidelines for the **KLIMT**'s design has been shown – the thruster can operate with **krypton propellant** (as well as with xenon) **stably** as long as it is required reaching **thermal equilibrium.**
2. The operating envelope has been probed in the wide range of parameters giving the prefered values recommended as nominal parameters.
3. The performance is satisfactory for HET of this size
4. Improvement will be continued

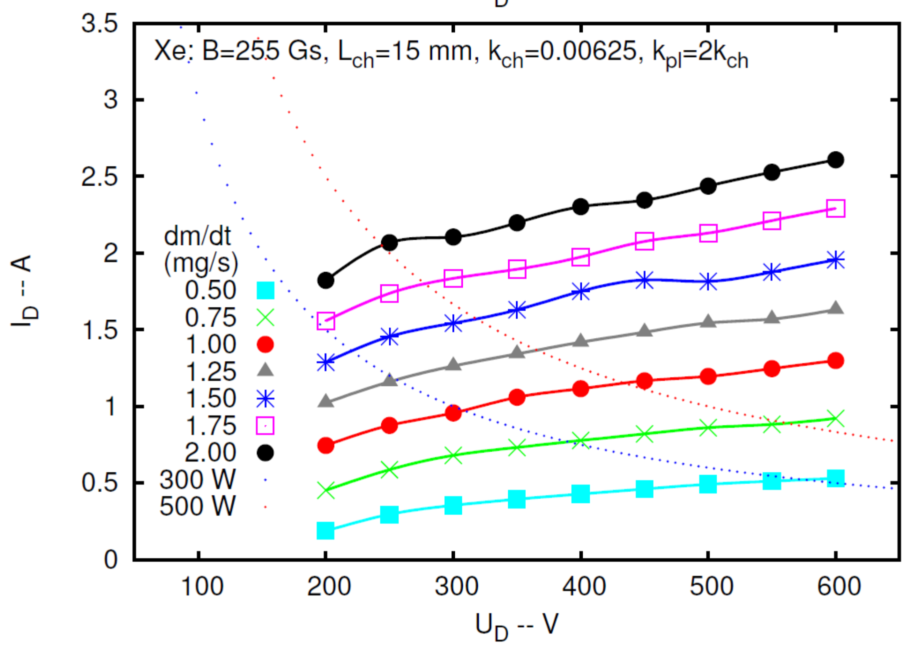
...thank you ...

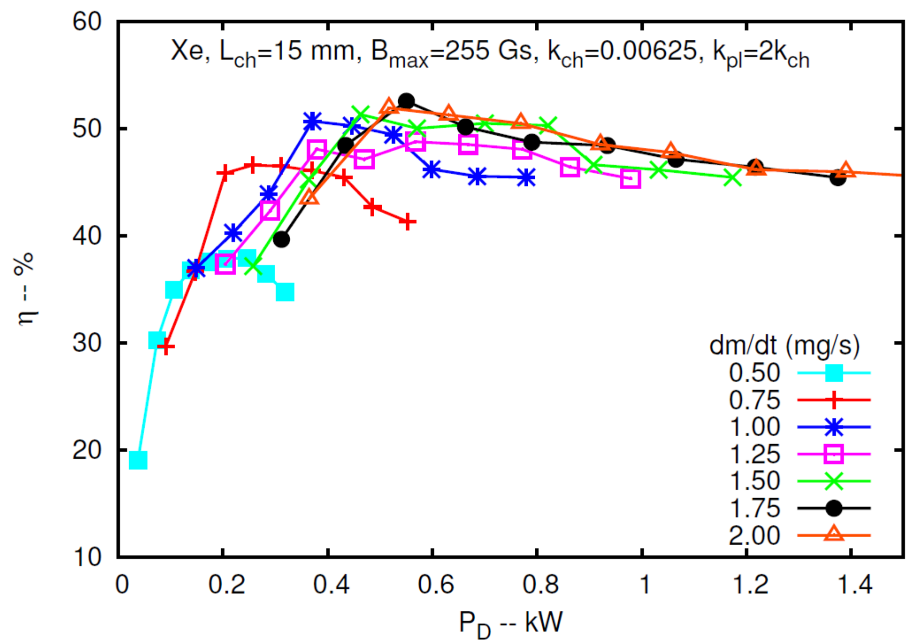
Appendix 1: KLIMT- Kr-Xe HETMAn simulation





Krypton



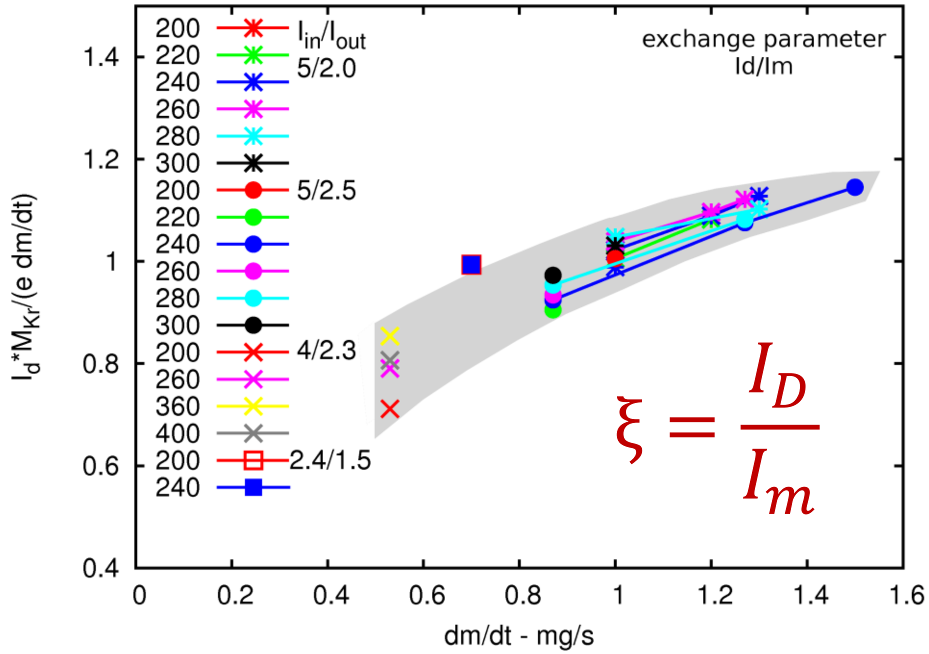


Xenon

Current-voltage characteristics

Efficiency vs discharge power

Appendix 2:exchange parameter & erosion…



Before and after the session at EPL – shown is a significant erosion effect.