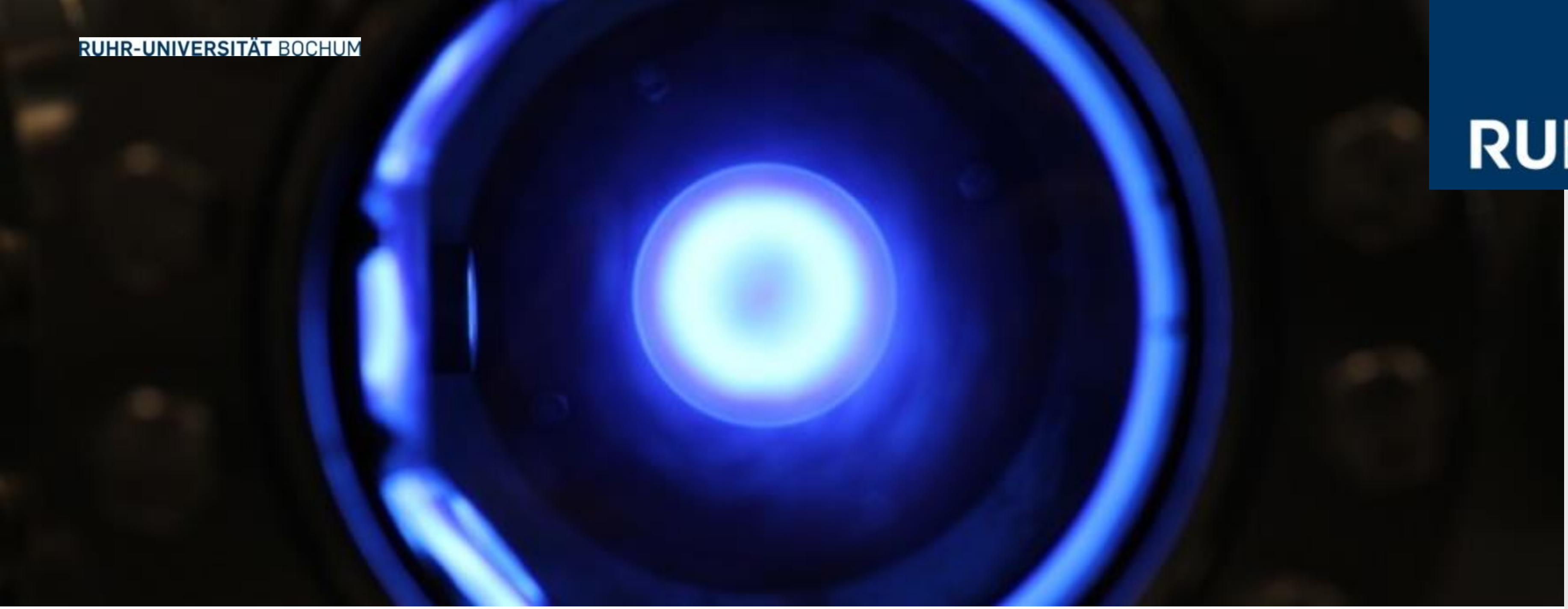


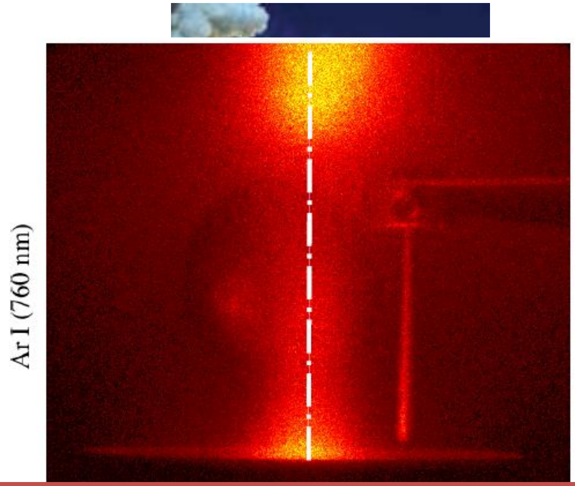
From Target to Substrate – About the Generation of Energetic Ions in HiPIMS Discharges

A. von Keudell, C. Maszl, W. Breilmann, J. Held, V. Schulz-von der Gathen, A. Hecimovic
Experimental Physics II, Ruhr University Bochum, Germany

Acknowledgements SFB-TR 87

Challenge HiPIMS

Space Shuttle Heat Shield Re-Entry

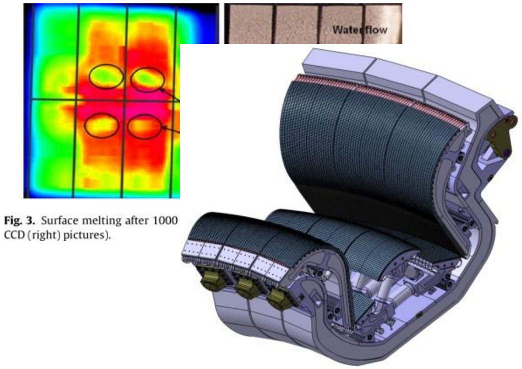


1 MW/m²   10 MW   50 MW/m² …… 600 MW/m²   MW/m²

(homogeneous)   (spokes)

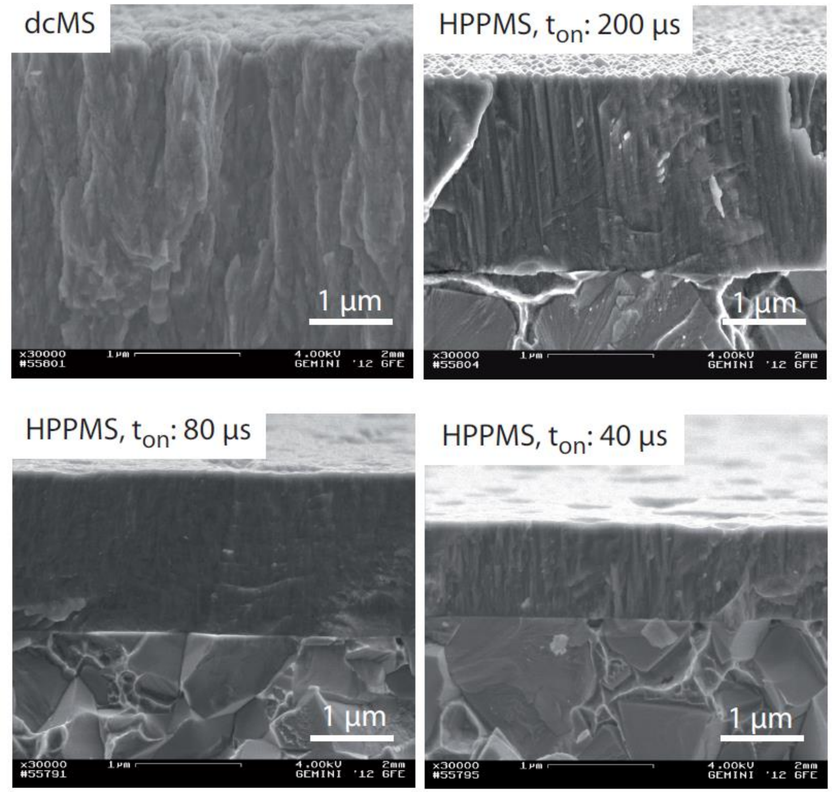
Rolls Royce Flight Engine

Divertor ITER



ITER Transients

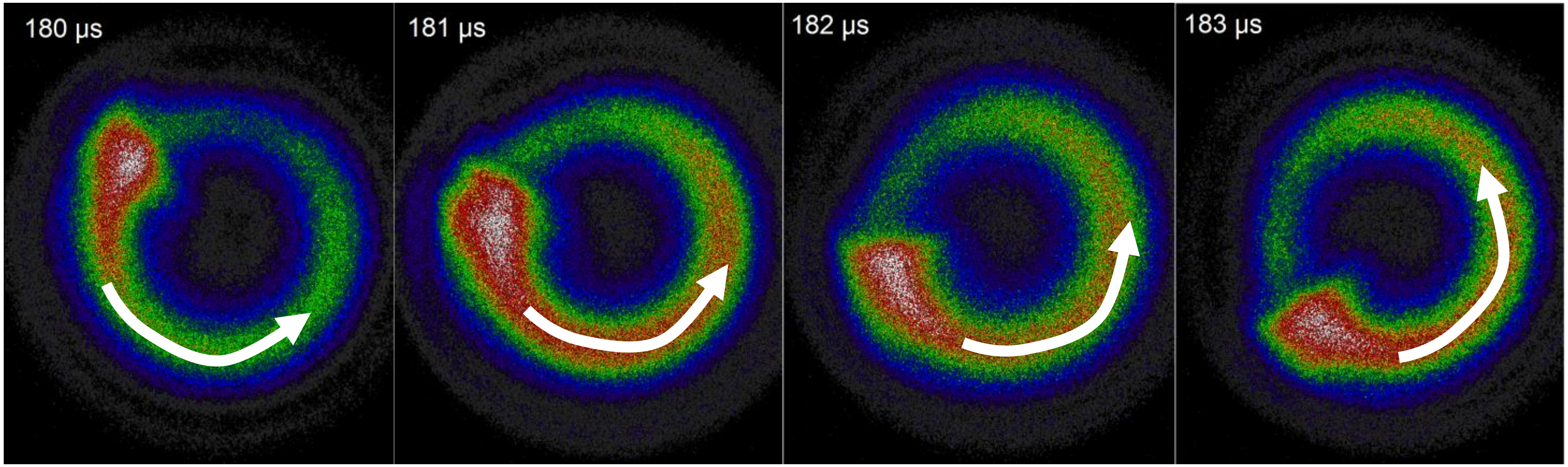
Controlling energy input during deposition in HiPIMS

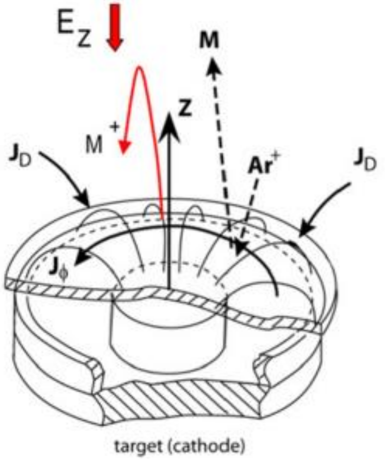


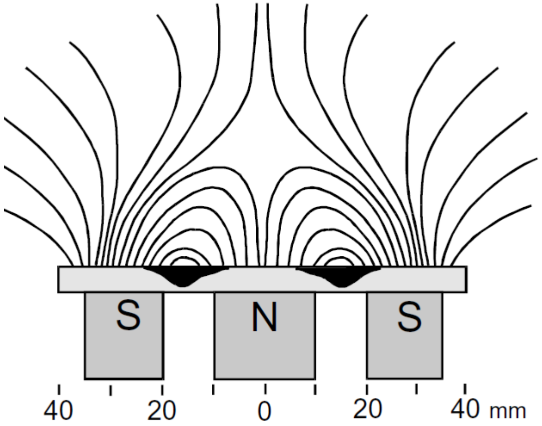
HPPMS results in smaller grains and smoother films compared to dcMS

N.Bagcivan,K.Bobzin,G.Grundmeier,C.Kunze,R.H.Brugnara,
Thin Solid Films (2013) http://dx.doi.org/10.1016/j.tsf.2013.06.036

HPPMS-Plasmas Azimuthal Movement of Plasma Spokes in ExB direction

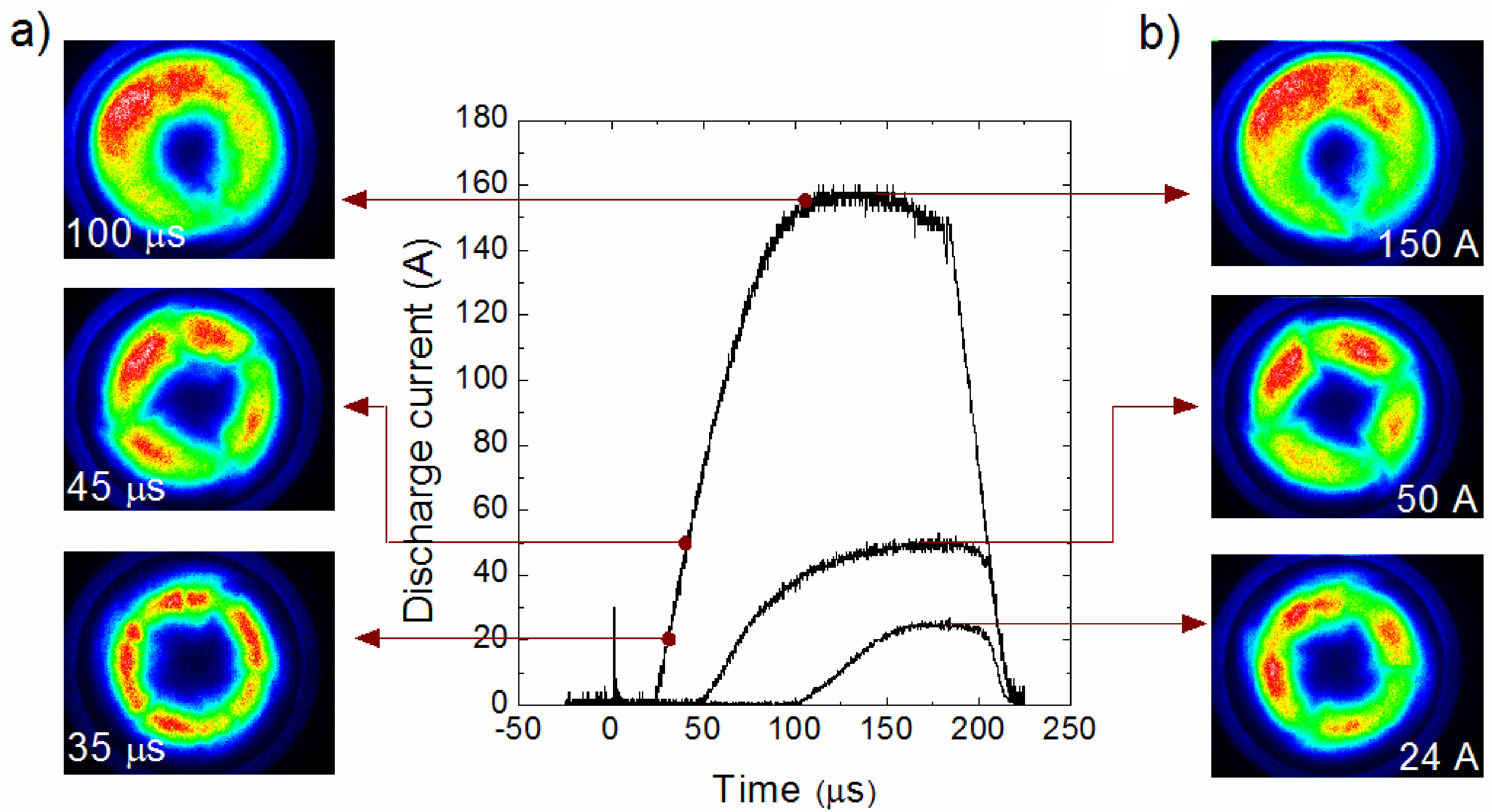






Ehiasarian AP, Hecimovic A, de los Arcos T, New R, Schulz-von der Gathen V, Böke M, et al. Applied Physics Letters 100, 114101 (2012)
Hecimovic A, de los Arcos T, Schulz-von der Gathen V, Böke M, Winter J. Plasma Sources Science and Techonology 21, 035017 (2012)
Winter J, Hecimovic A, de los Arcos T, Böke M, Schulz-von der Gathen V. Journal of Physics D: Applied Physics. 46, 084007 (2013)

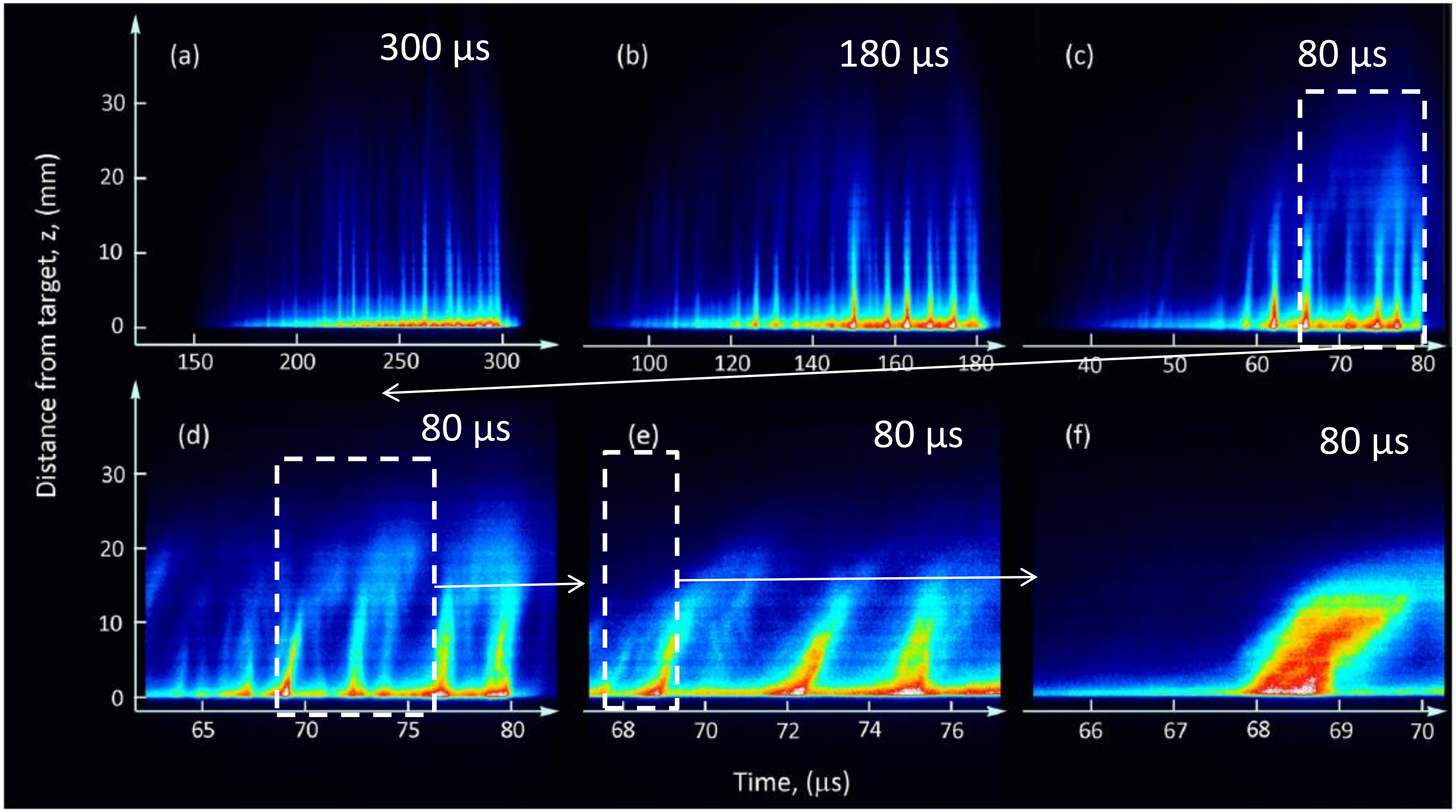
HPPMS – Spokes Top View



Many Publications on Spokes by Anders, Ehiasarian, Lundin, Brenning, Gudmundson,…

Ehiasarian AP, Hecimovic A, de los Arcos T, New R, Schulz-von der Gathen V, Böke M, et al. Applied Physics Letters 100, 114101 (2012)
Hecimovic A, de los Arcos T, Schulz-von der Gathen V, Böke M, Winter J. Plasma Sources Science and Techonology 21, 035017 (2012)
Winter J, Hecimovic A, de los Arcos T, Böke M, Schulz-von der Gathen V. Journal of Physics D: Applied Physics. 46, 084007 (2013)

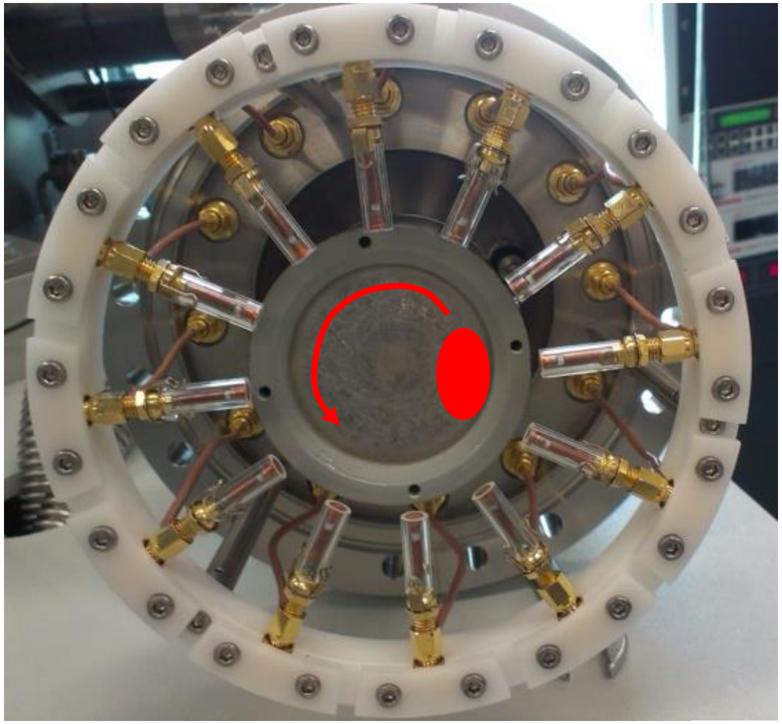
HPPMS – Spokes Side View

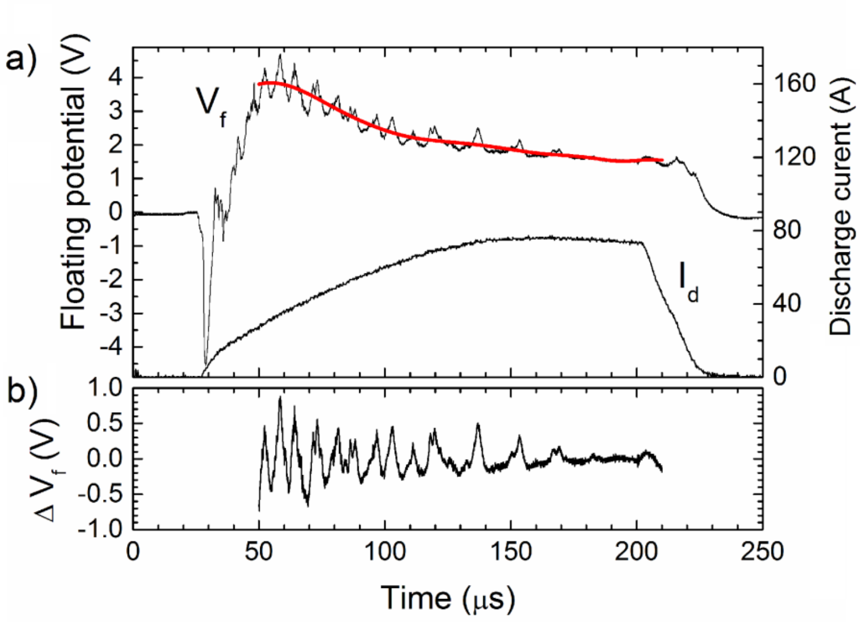


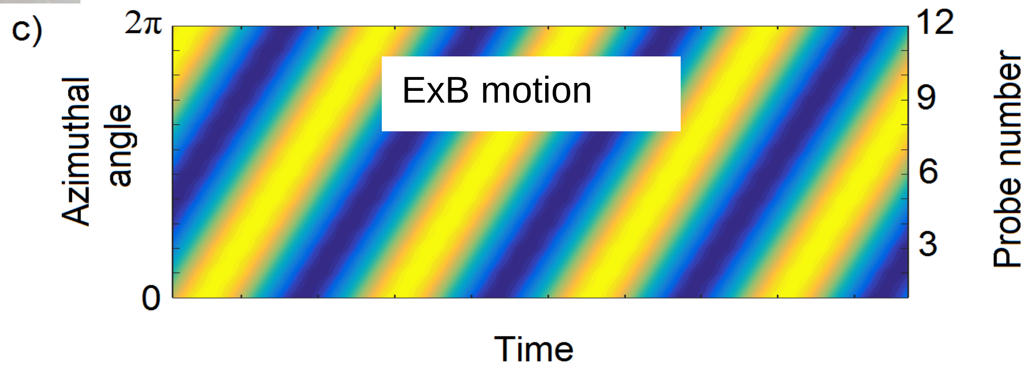
Plasma Flares in HiPIMS Ar (630-680 V, 500 A)

P. Ni, C. Hornschuch, M. Panjan, A. Anders, Appl. Phys. Lett. **101**, 224102 (2012);

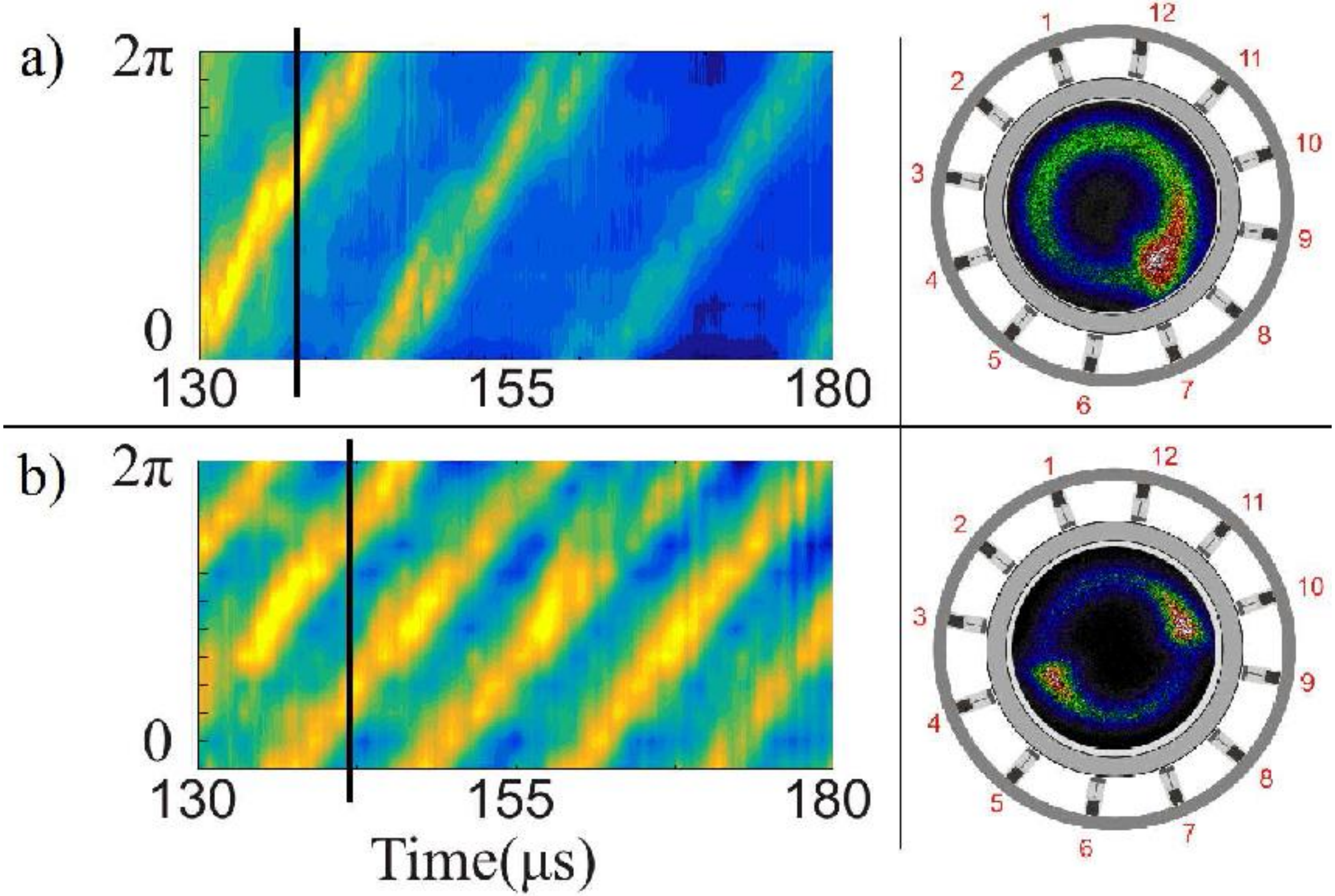
Following the Spoke Dynamic in Single Pulses by a Probe Array







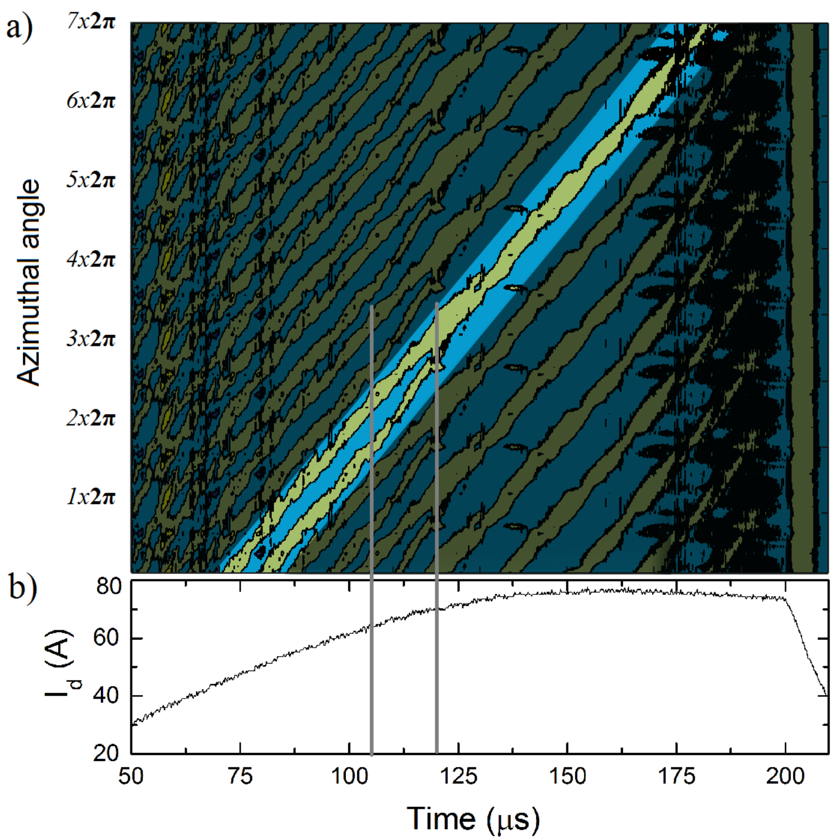
Following the mode number with the probe array



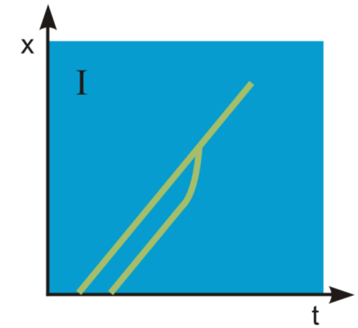
Following Spoke Mode Transitions in a single Plasma Pulse

Trai

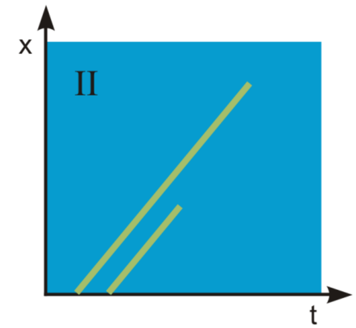
spo



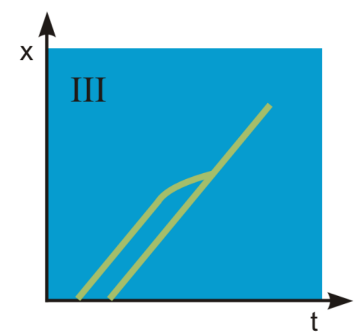
One spoke speeds up



One spoke disappears



One spoke slows down



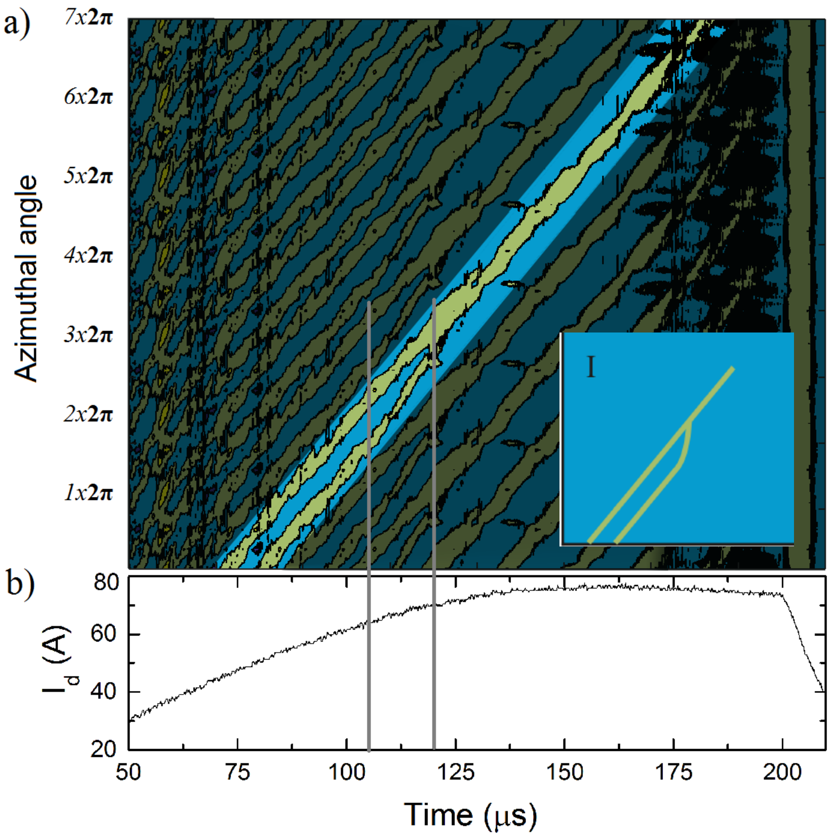
A. Hecimovic, C. Maszl, V. Schulz-vpn der Gathen, M. Böke, A. von Keudell, Plasma Sources Sci. Technol (2015).

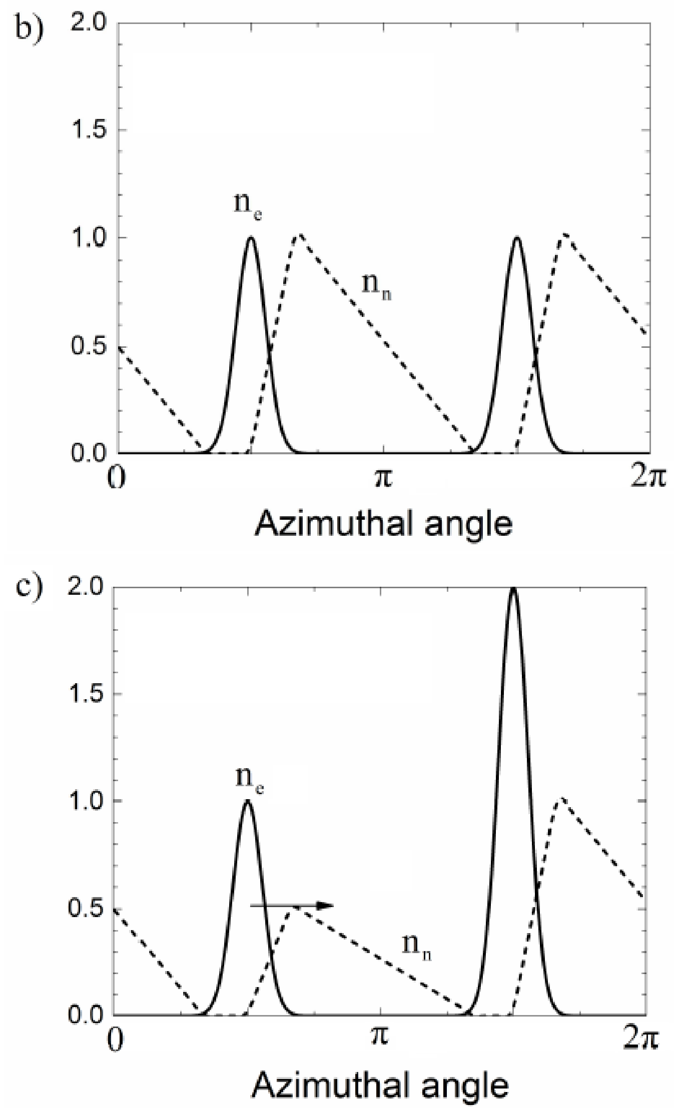
RUB

Following Spoke Mode Transitions in a single Plasma Pulse

Tra

spo

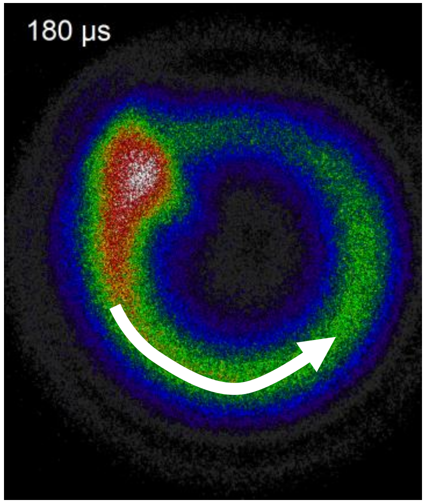


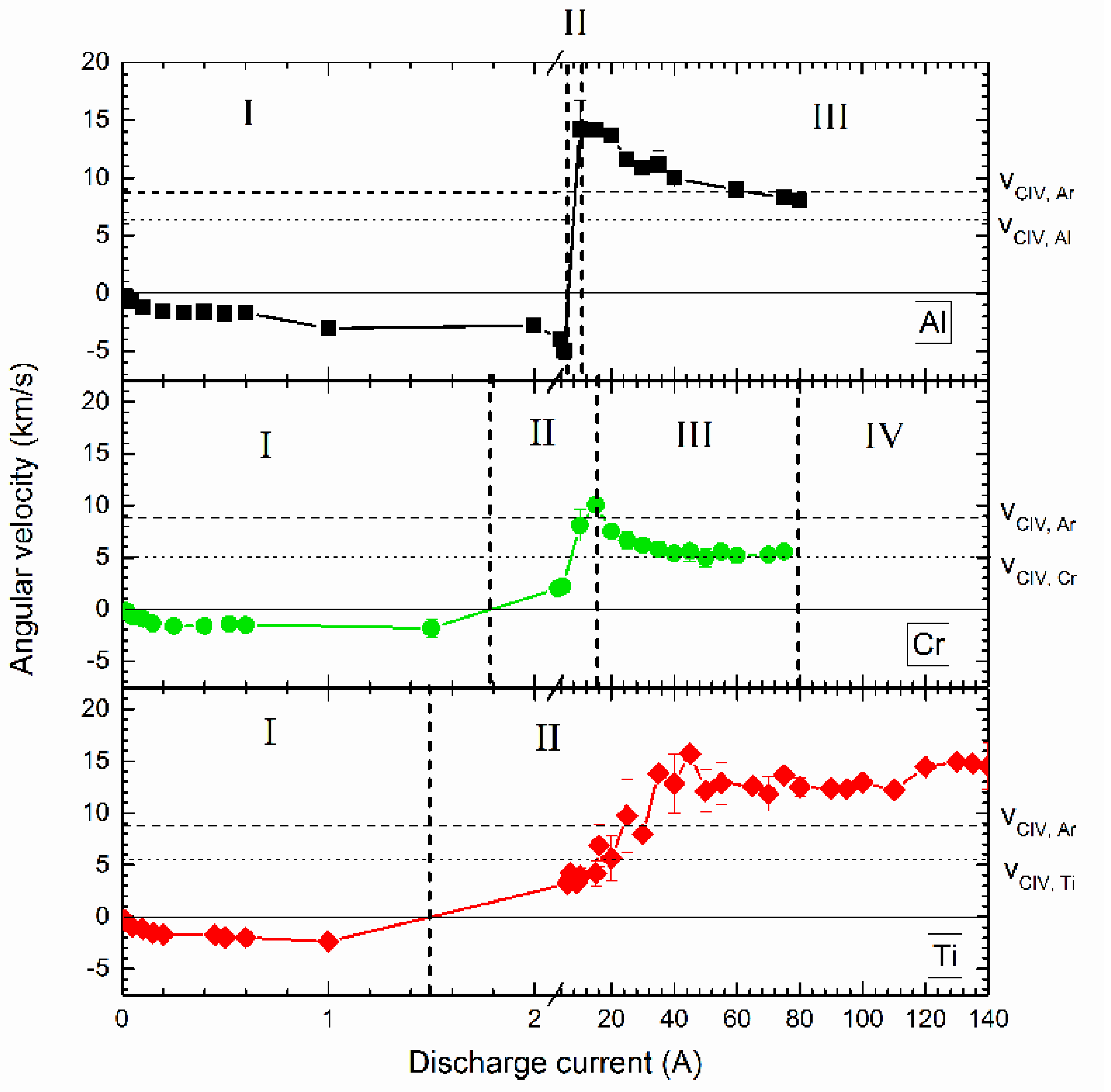


Gallian et al., Plasma Sources Sci. Technol. 22 (2013) 055012

A. Hecimovic, C. Maazl, V. Schulz-vpn der Gathen, M.Böke, A. von Keudell, Plasma Sources Sci. Technol (2015).

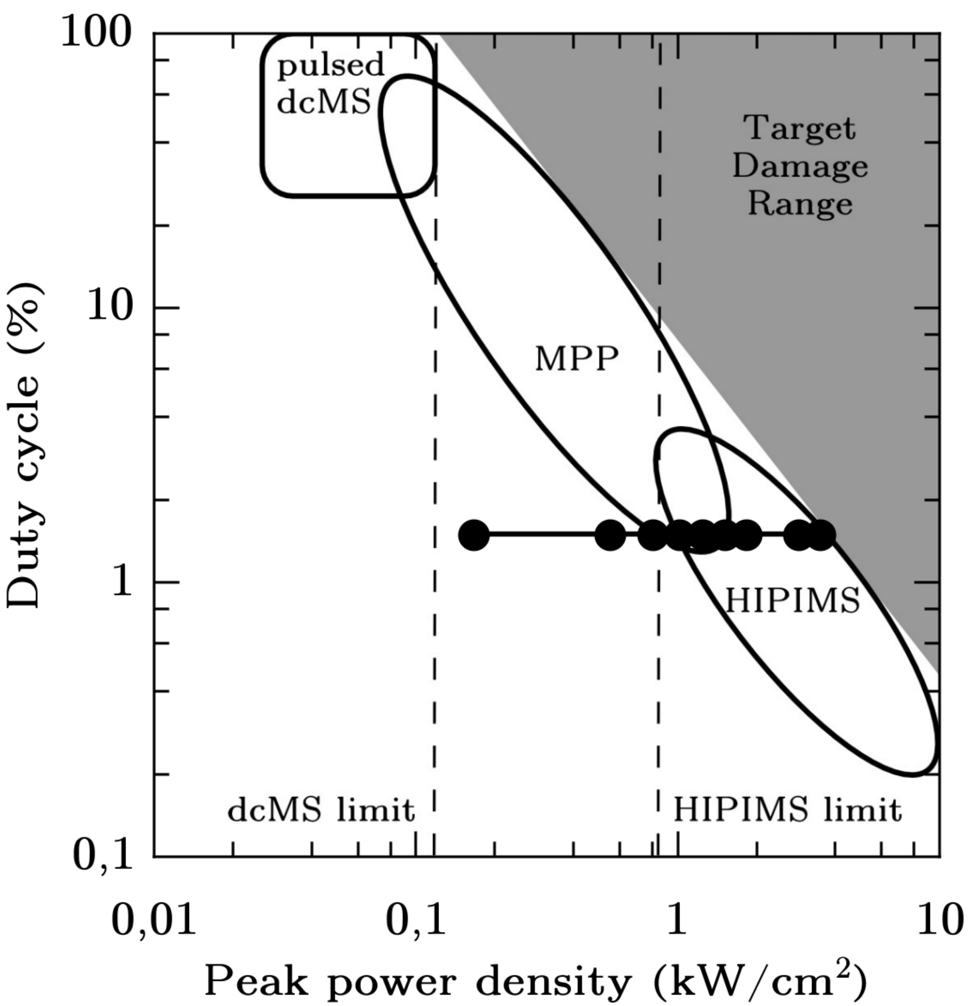
Velocity of the Spokes

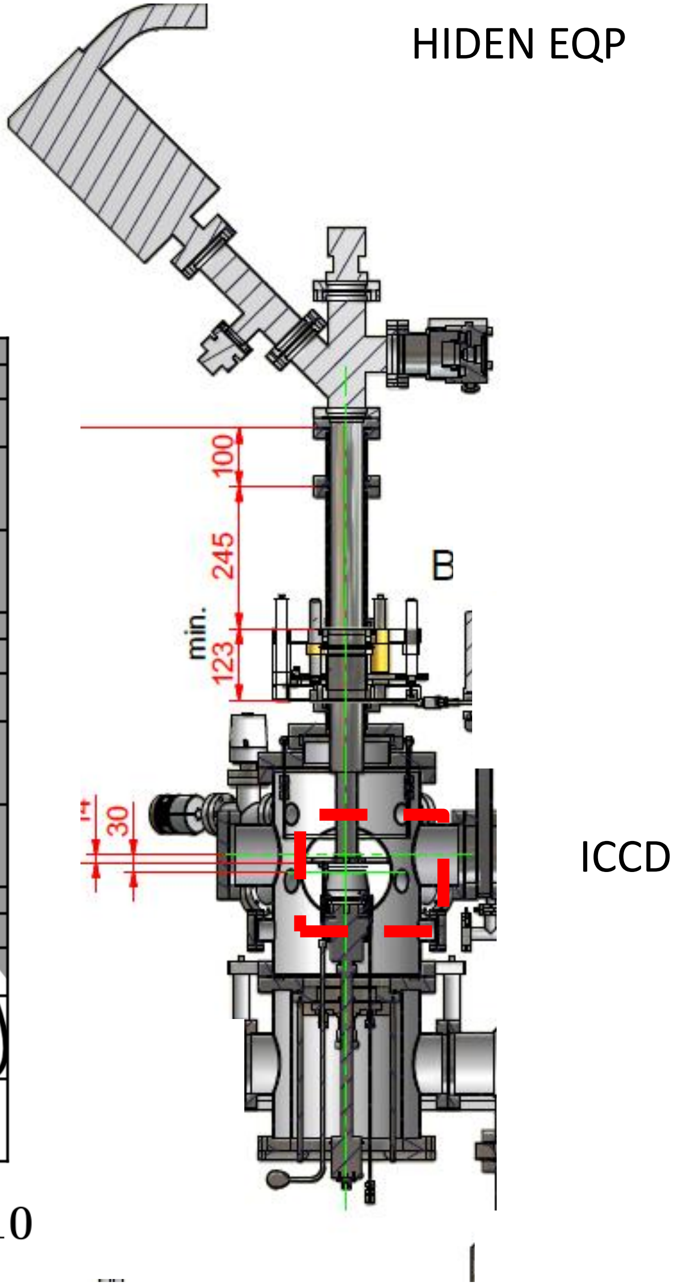




A Hecimovic, C Maszl,
V Schulz-von der Gathen,
M Böke and A von Keudell
Plasma Sources Science and
Technology 06/2016; 25(3):035001

Correlation to plasma diagnostics: Ion mass spec and PROES





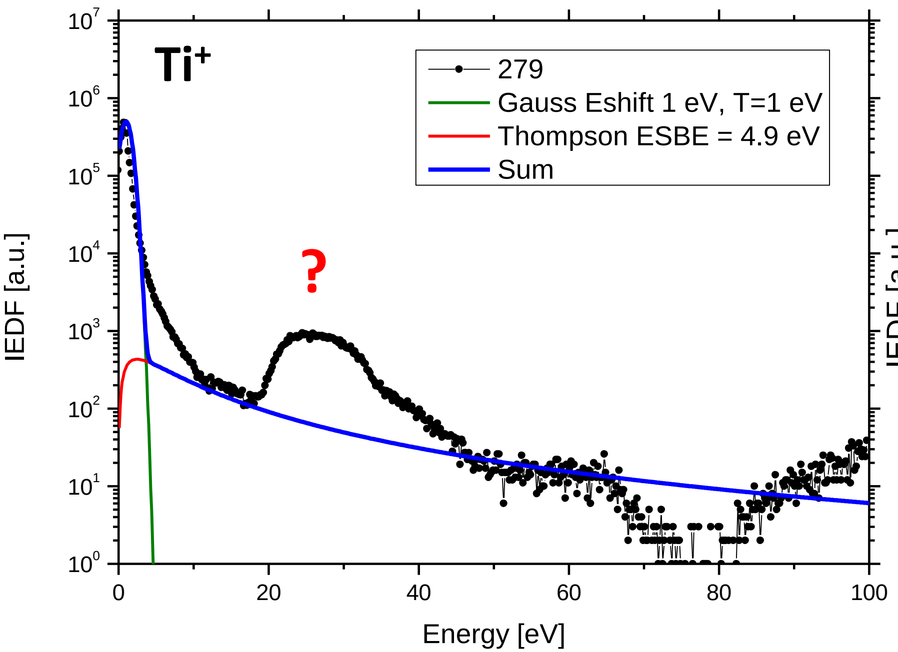
IEDFs during HiPIMS of Ti^+ ions

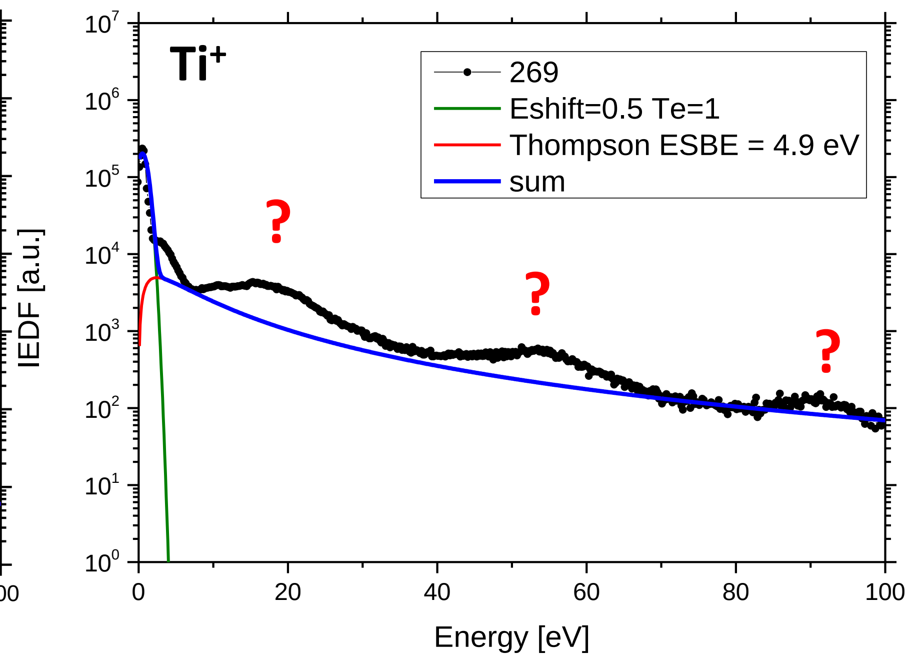
RUB

0.98kW/cm²

2964 W/cm2

0.5 Pa, Ar





thermalized Ti^+ dominant
energetic Ti only 0.1% of ion flux

Ti^+ from sputter wind dominant
energetic Ti 10% of ion flux

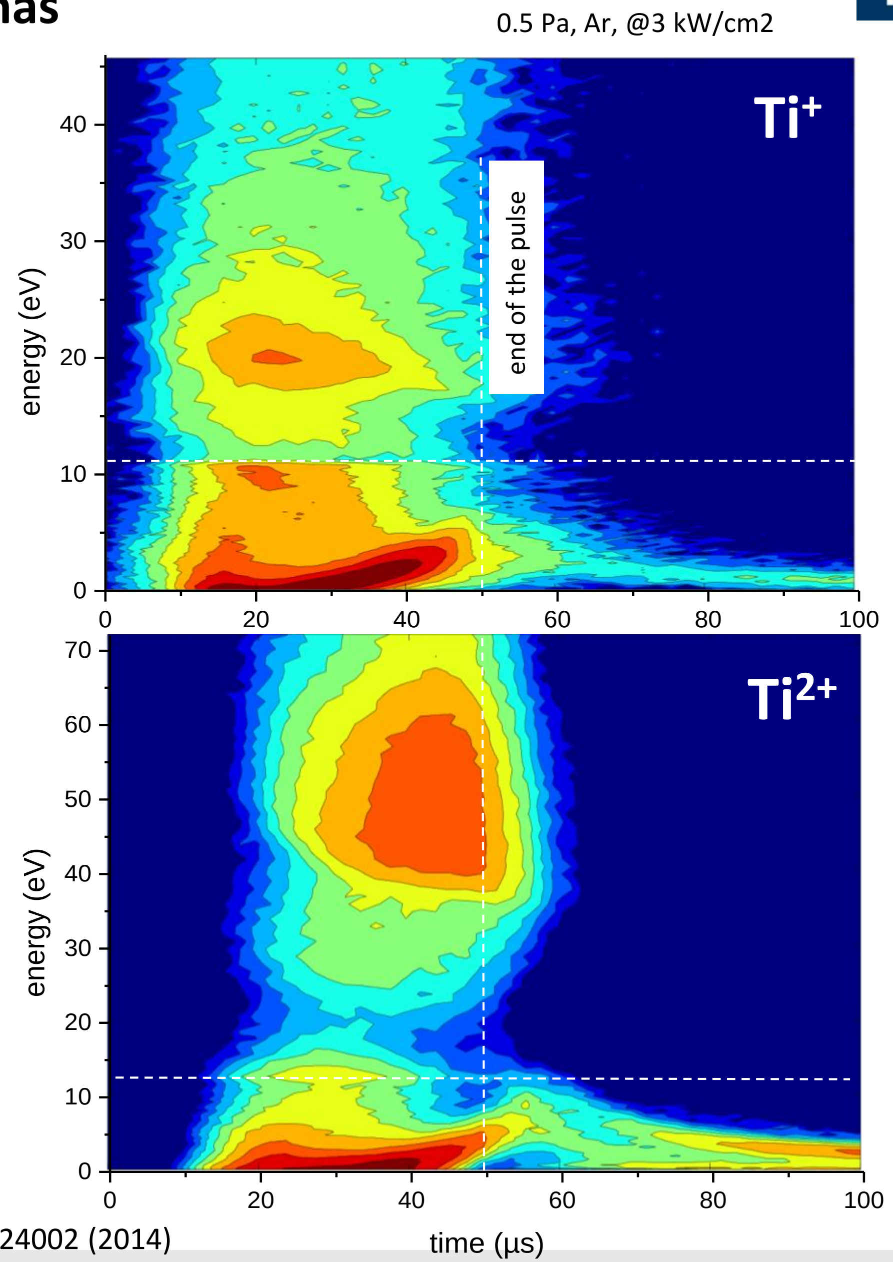
Distinct energetic peaks ?

W. Breilmann, C. Maszl, A. von Keudell *Plasma Sources Sci. and Technol. (2017) DOI: https://doi.org/10.1088/1361-6595/aa56e5*

From pulsed dc-MS to HPPMS plasmas

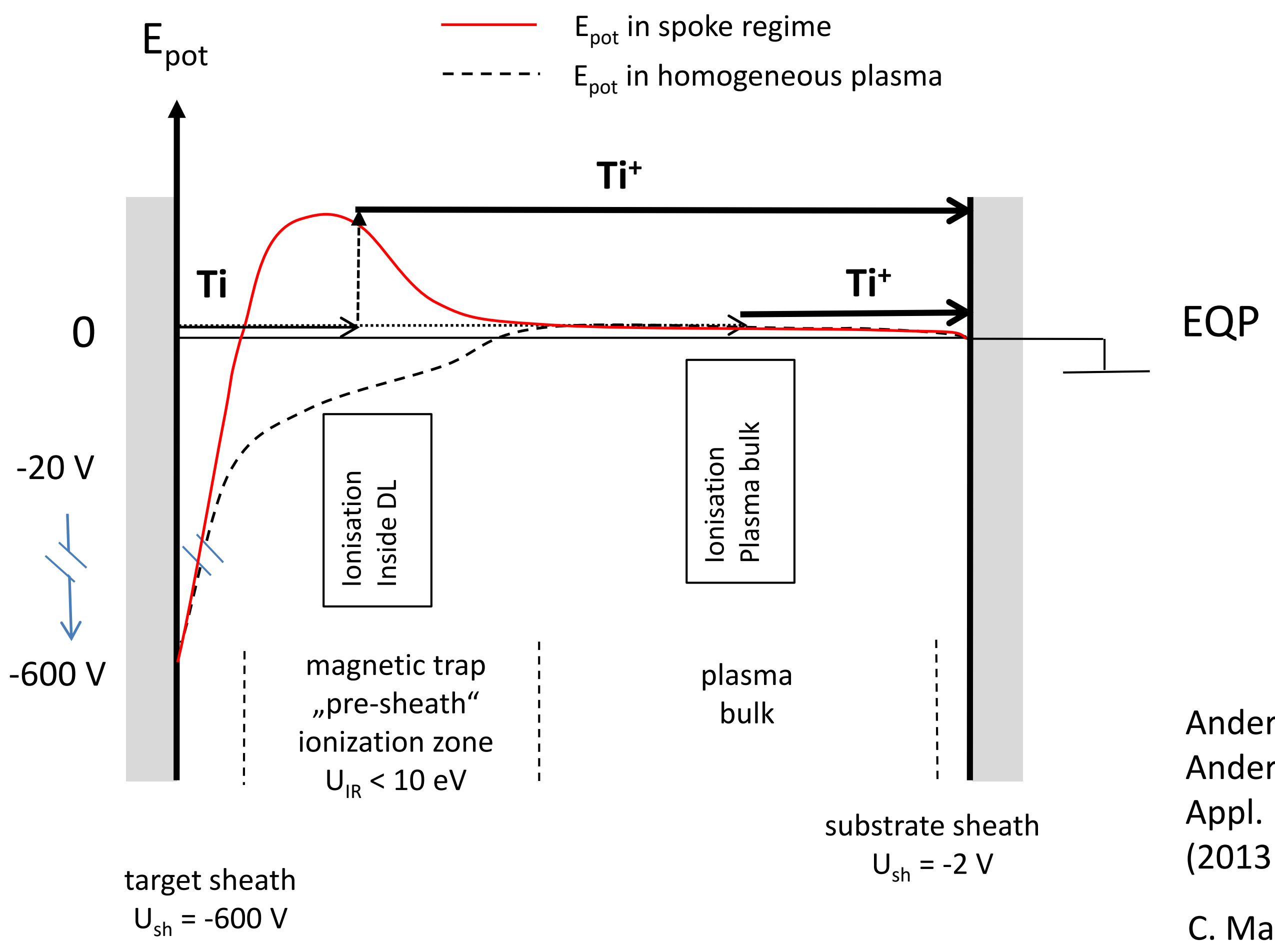
- Group of higher energy ions (HE) appears simultaneously with low energy ions (LE)
- LE ions increase in energy at later stages of the HiPIMS pulse
- HE ions remain at constant energy, only the distribution broadens

Most easiest explanation
Two groups of ions (HE and LE) are created at two distinct positions of electrical potential



C. Maszl, W. Breilmann, J. Benedikt, A. von Keudell, J. Phys. D 47, 224002 (2014)

Plasma potential model to explain distinct HE and LE peaks



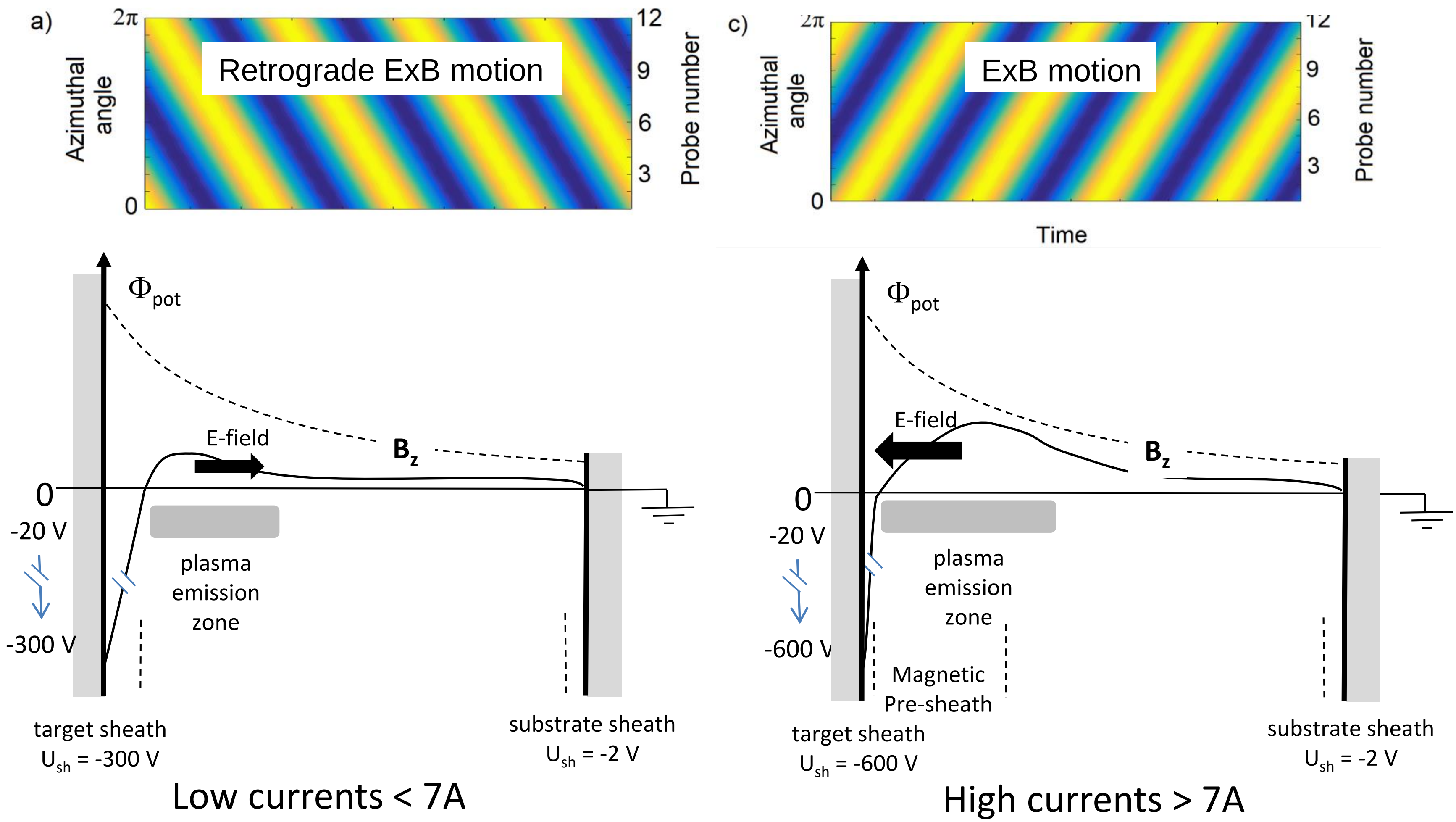
Anders A, Panjan M, Franz R, Andersson J and Ni P
Appl. Phys. Lett. 103 144103 (2013)

C. Maszl, W. Breilmann, J. Benedikt, A. von Keudell,
J. Phys. D 47, 224002 (2014)

Rotation of Spokes

The dominating E-field surrounding the spoke determines its rotation*

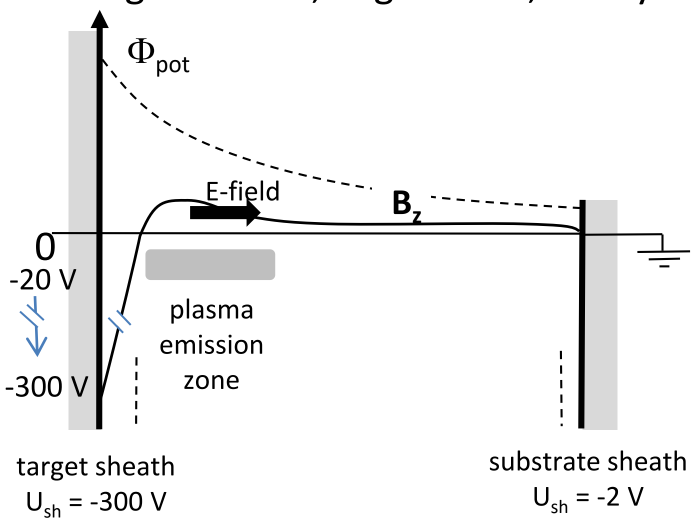
(following PoP Frias, Kaganovich, Smolyakov, Raitses)

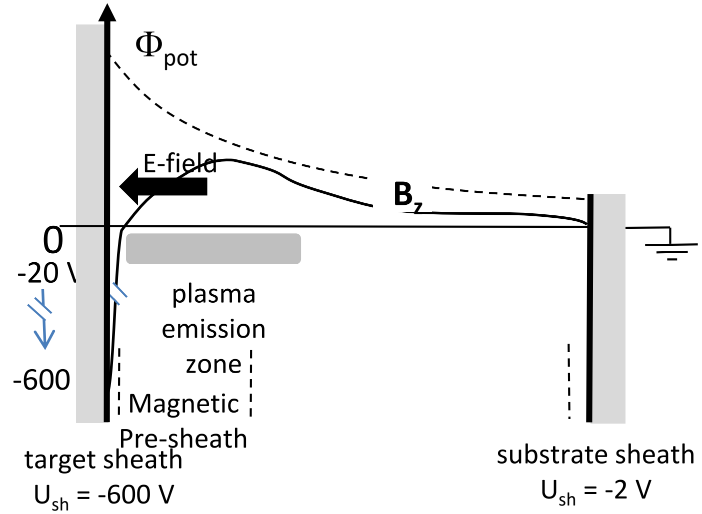


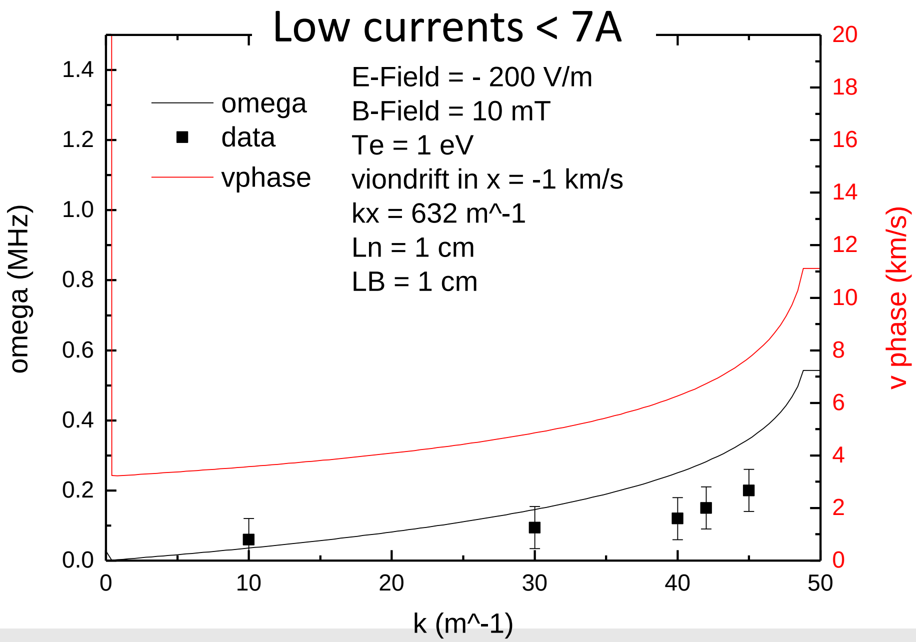
A Hecimovic, C Maszl, V Schulz-von der Gathen, M Böke and A von Keudell
Plasma Sources Science and Technology 06/2016; 25(3):035001

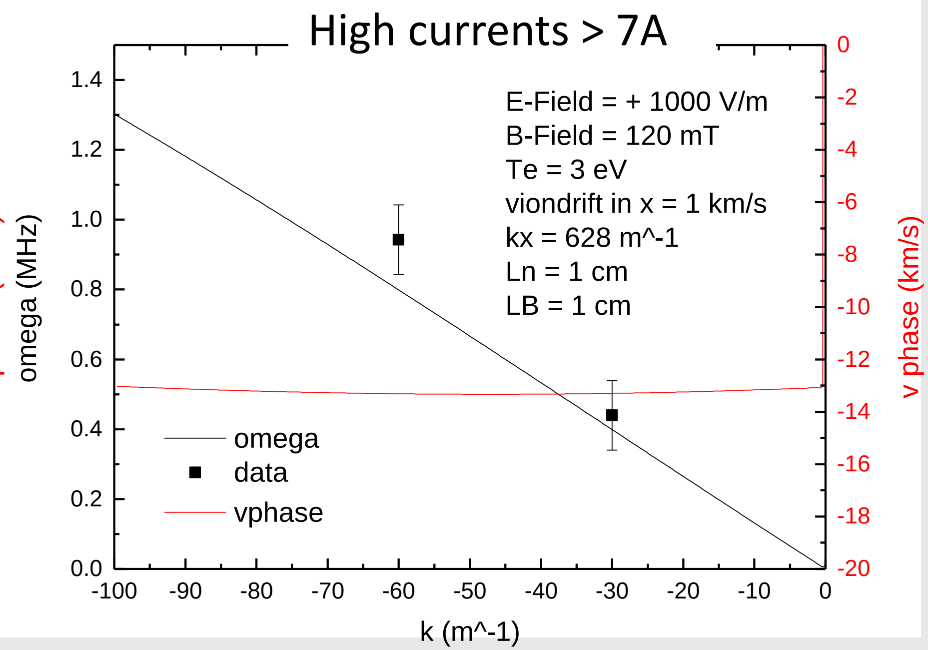
Drift waves to explain direction of motion and velocities*

(following PoP Frias, Kaganovich, Smolyakov, Raitses)





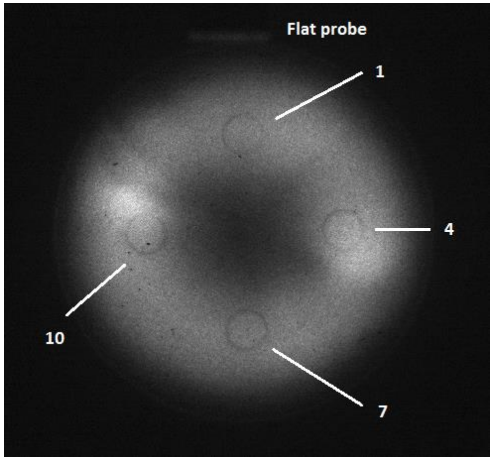


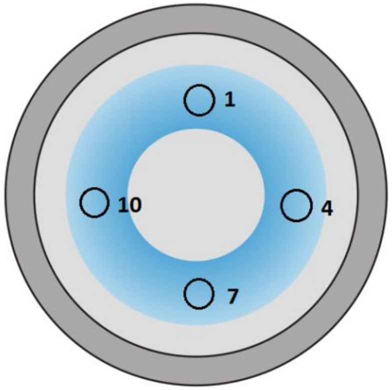


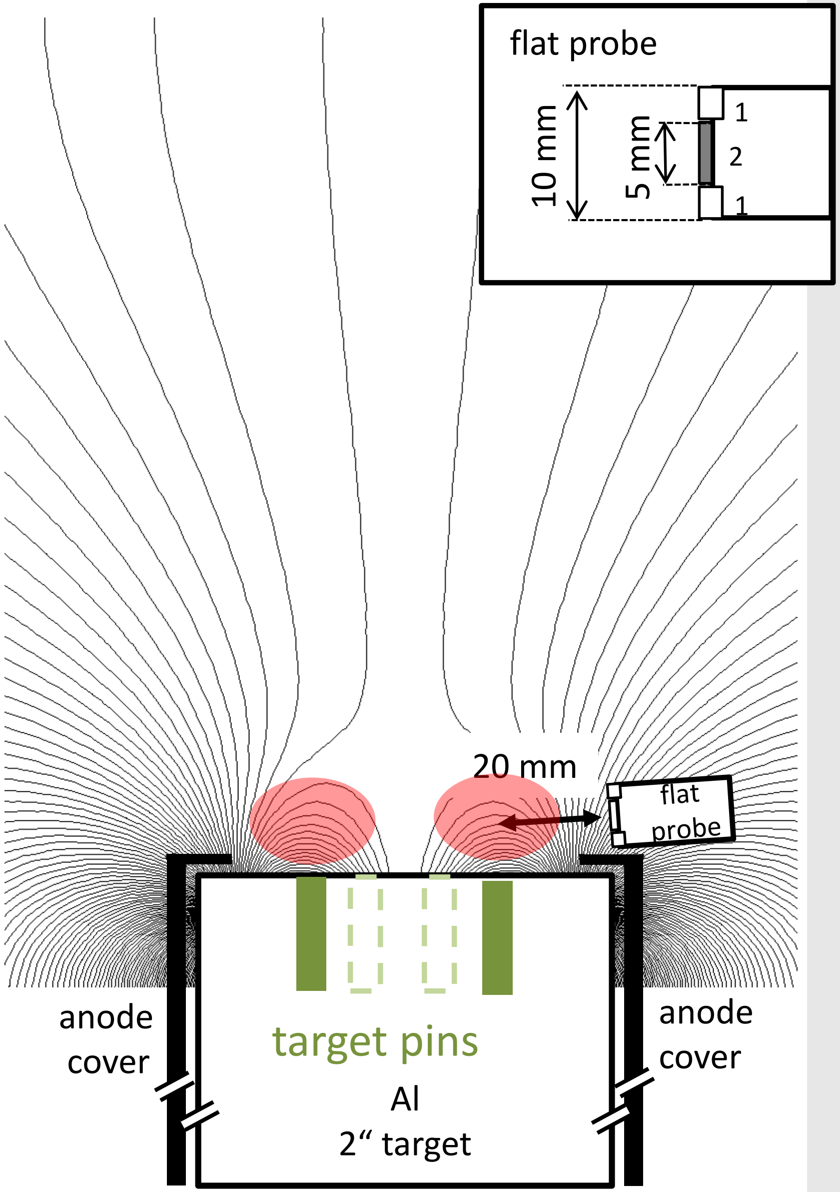
Measurement of the distributed current in the target

- Flat probe -36 V bias, 1 mm from the anode cover edge
- 12 pins in target (4.9 mm pin diameter), same potential

Al target, **4 pins**,
Ar 0.5 Pa, pulse 200 µs,
10 Hz, ICCD – 100 ns @ 190 µs

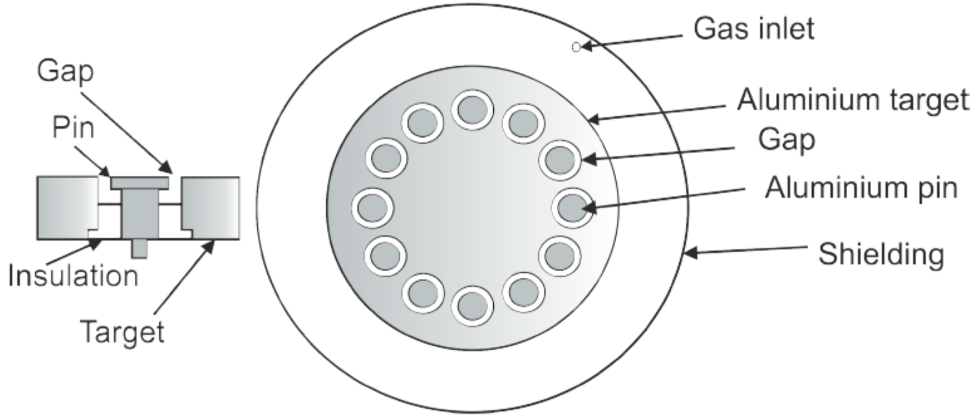


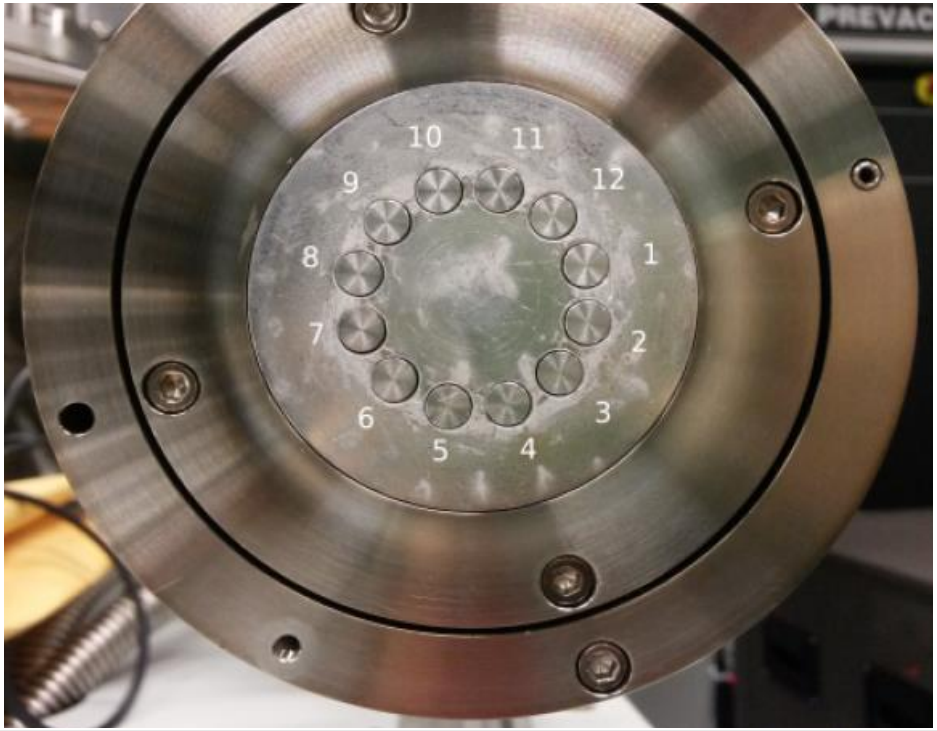


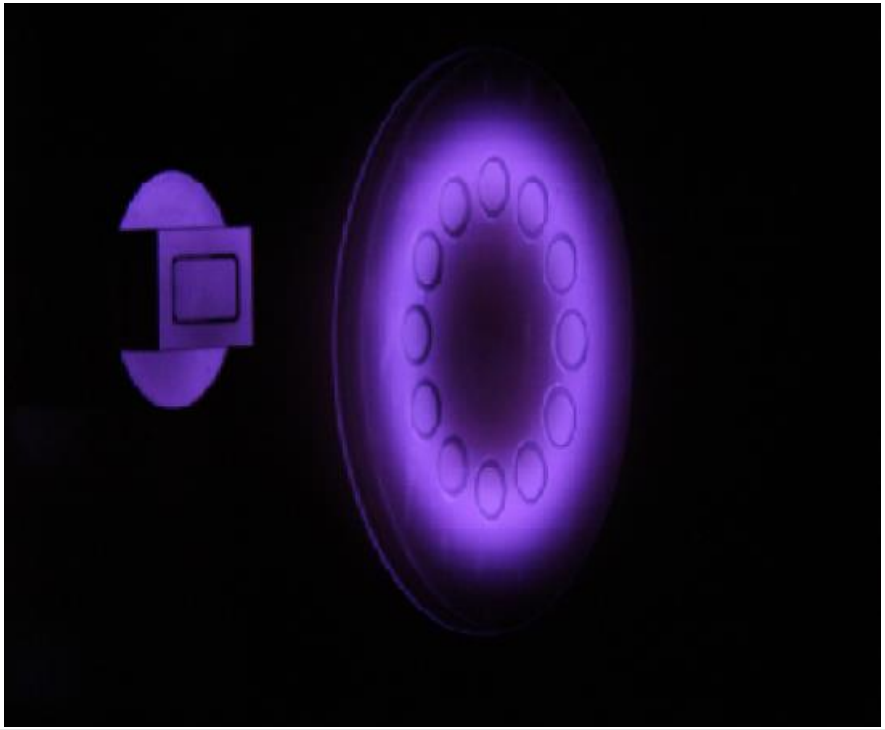


Measurement of the distributed current in the target

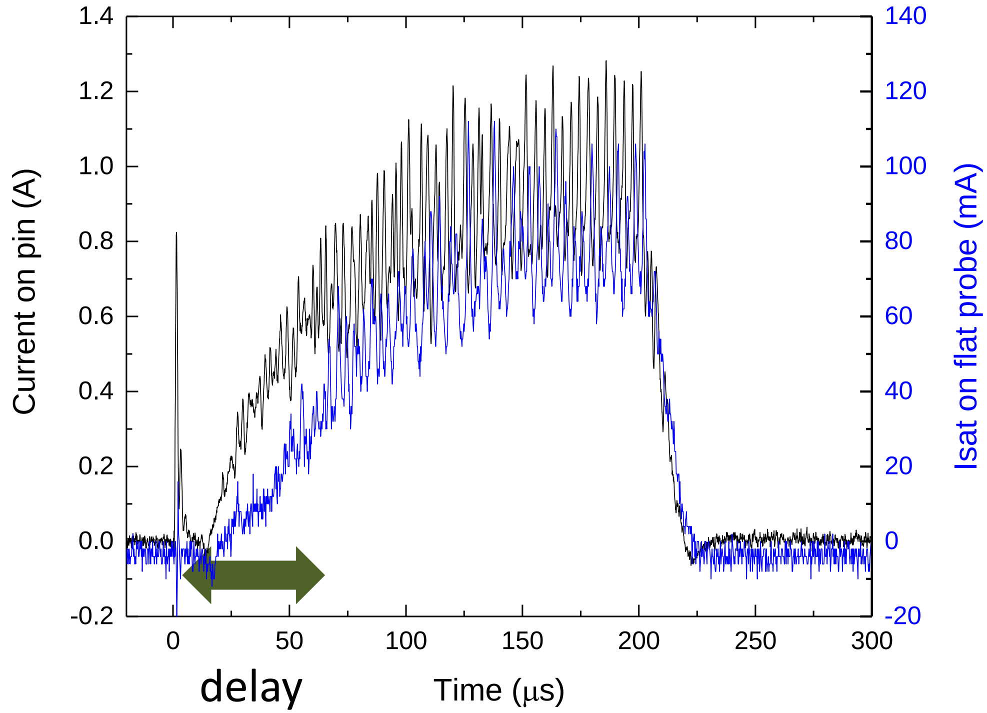
Difficulty is to avoid Arcing and hollow cathode effects



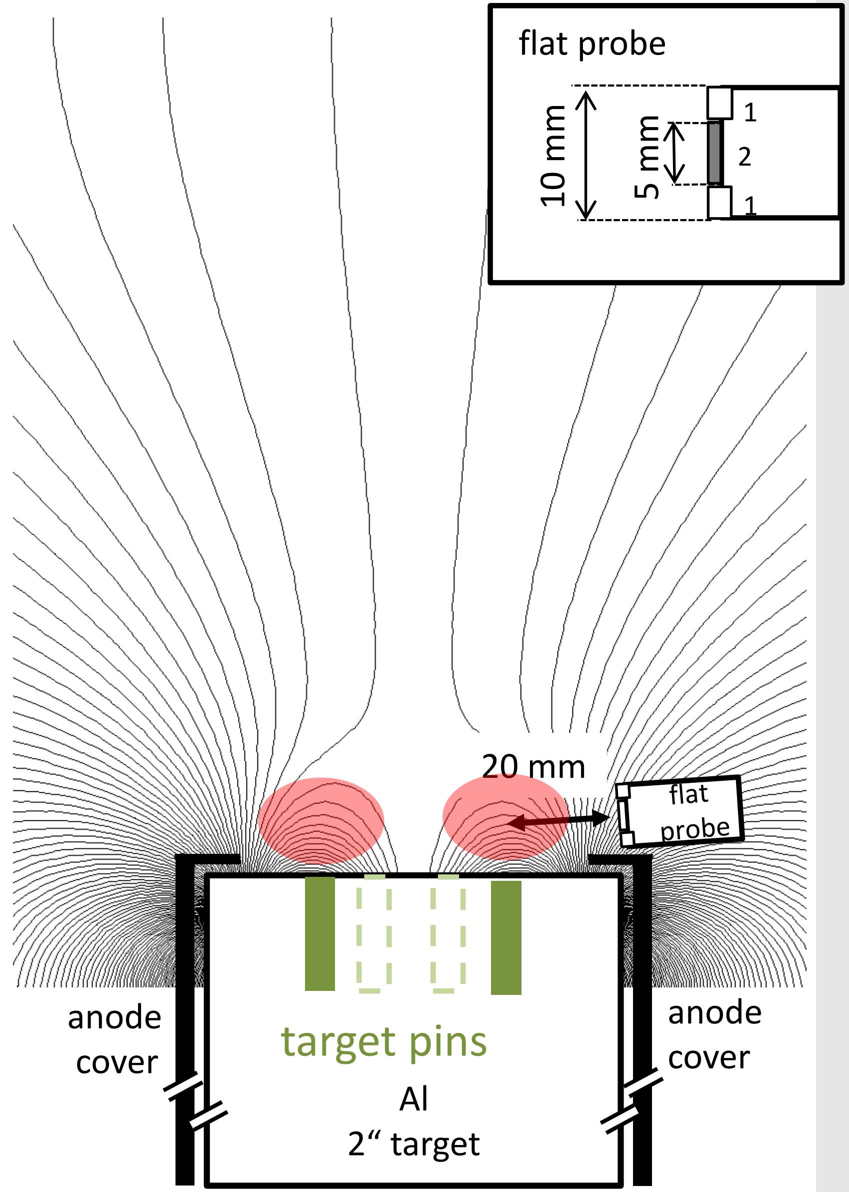




Measurement of the distributed current in the target

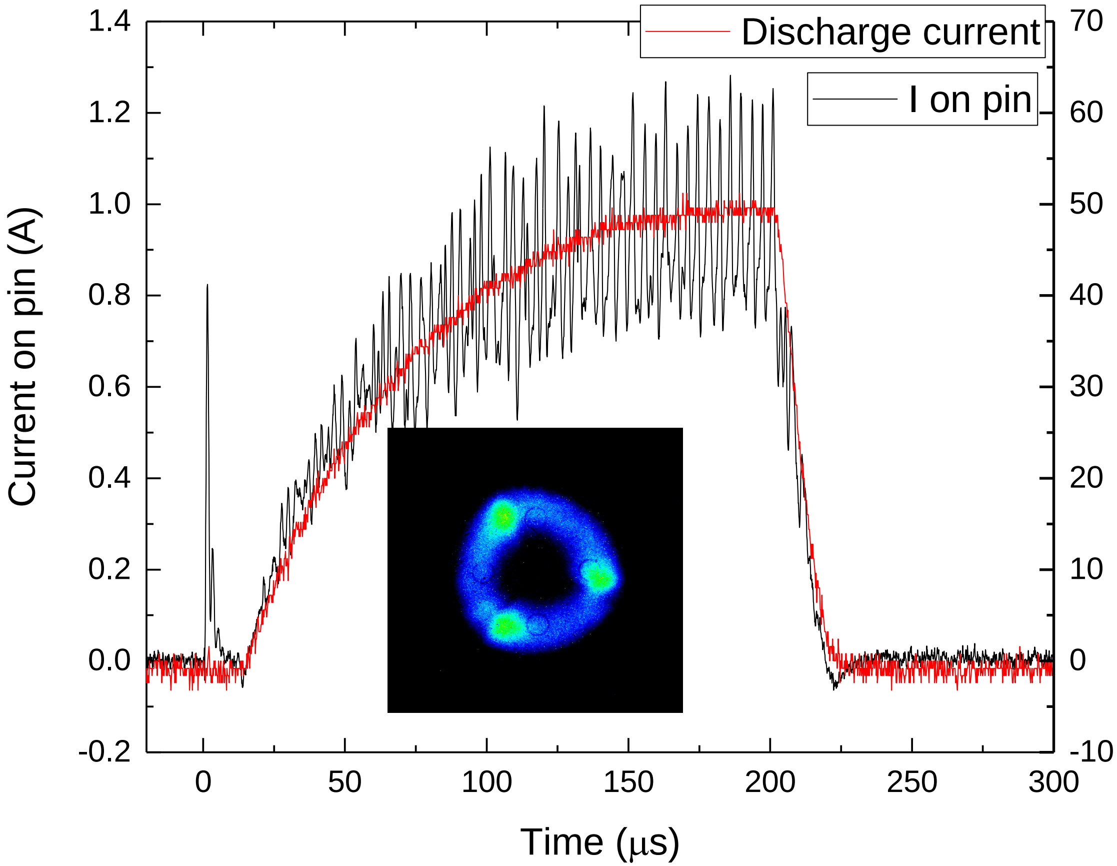


- Build up of current at pin probe sooner than at flat probe (delay)
- Current on pin up to 1.2 A
- Simultaneously the flat probe measures about 100 mA



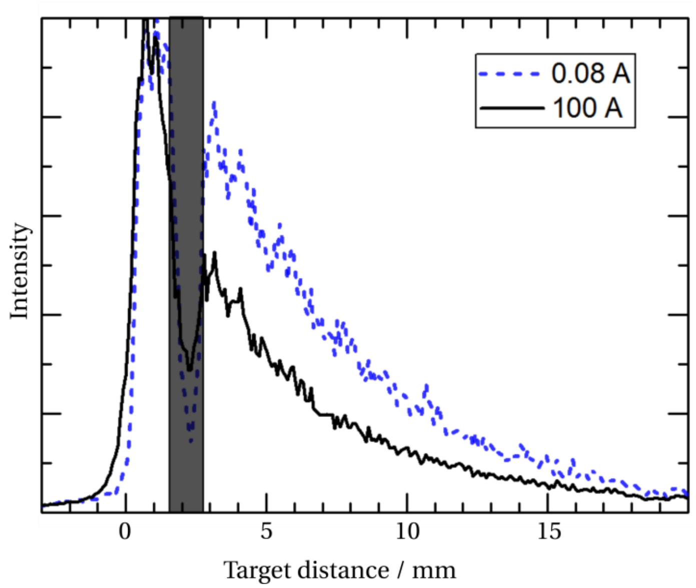
Measurement of the distributed current in the target

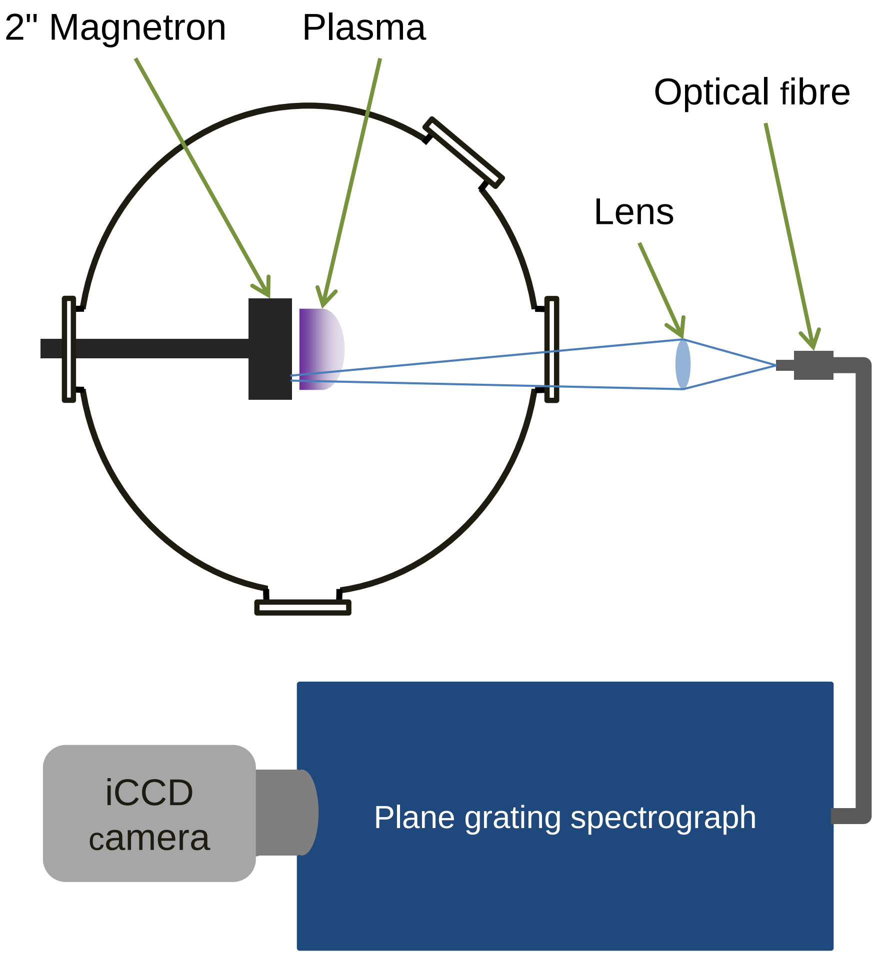
I_d ~ 50 A, m = 3, Al target



- Current on pin I_p and discharge current I_d exhibit similar trend
- I_p is never zero* Modulation ~ 30% (*Qualitatively similar to Poolcharuansin JAP **117**, 163304 (2015),)
- Current density **j** over pin is about 6 A/cm^2
- **This yields plasma density at sheath edge of ~ 10^{20} m^{-3} from Bohm criterion**

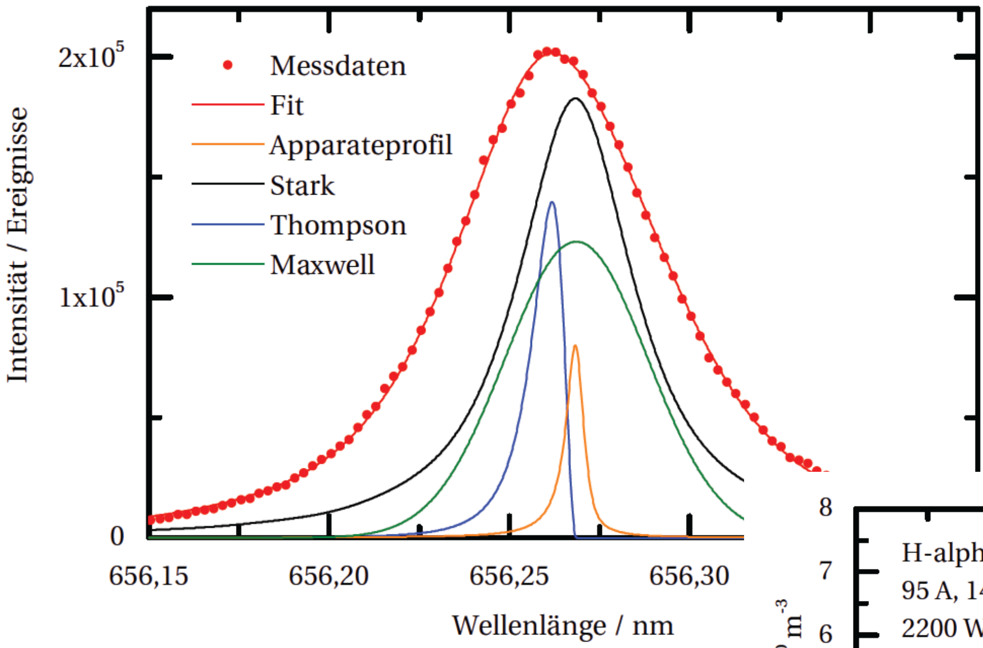
Diagnostic Challenge HiPIMS – Measurement inside a spoke

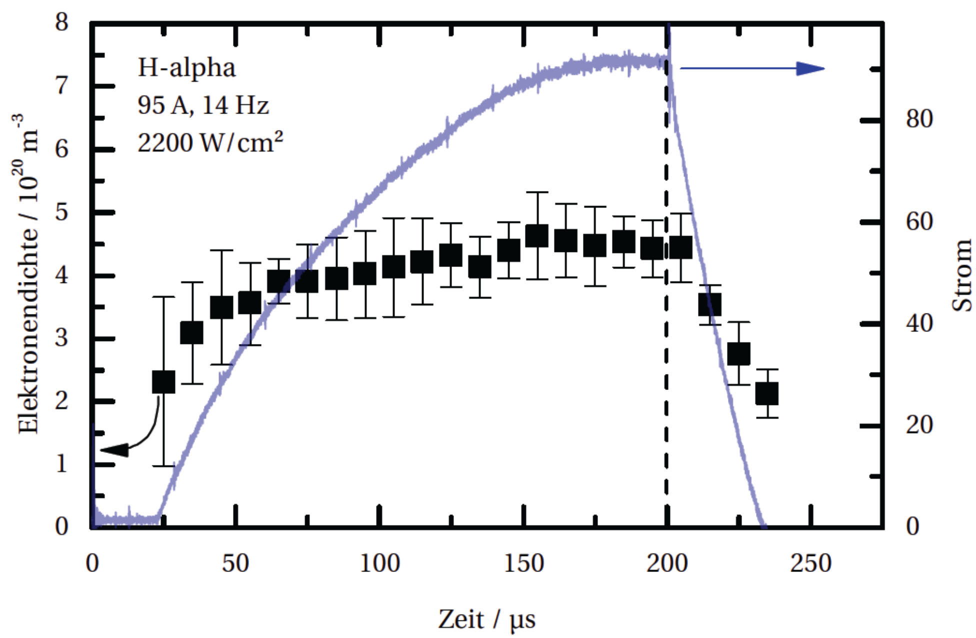




RUB

Diagnostic Challenge HiPIMS – Measurement inside a spoke

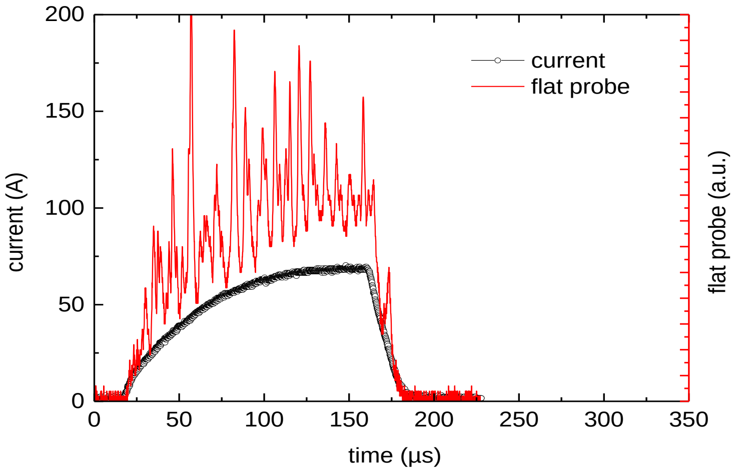


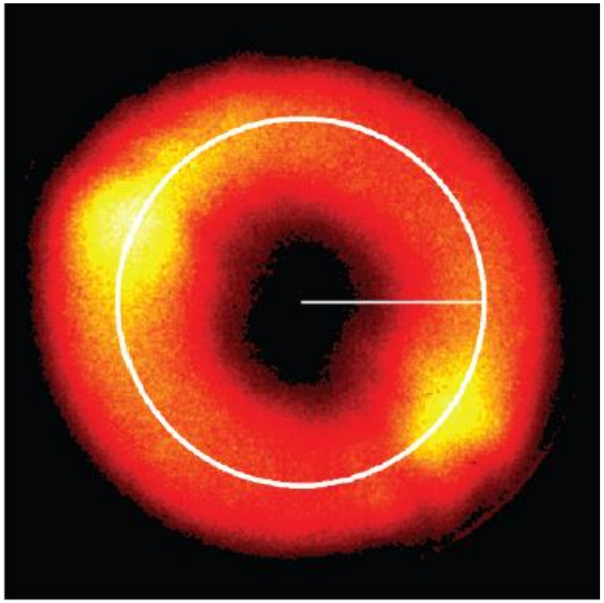


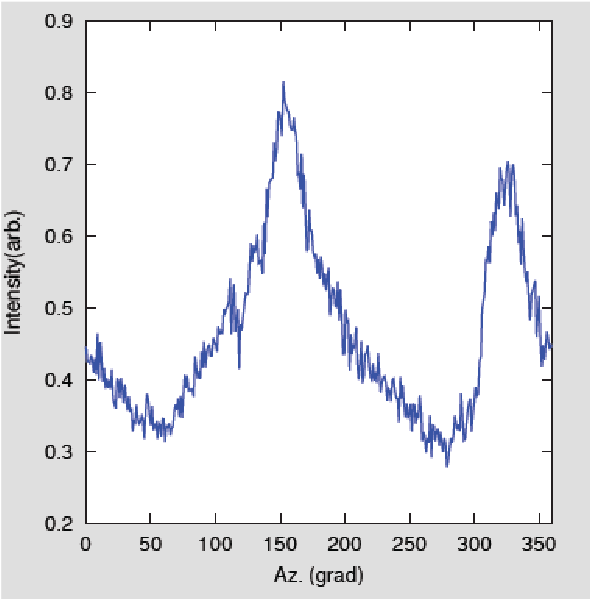
Stark-Broadening ~ 1/m

Diagnostic Challenge HiPIMS – Measurement of a Dynamic plasma

Triggering at 2 times necessary
- Beginning of the pulse
- Presence of a spoke in the diagnostic window



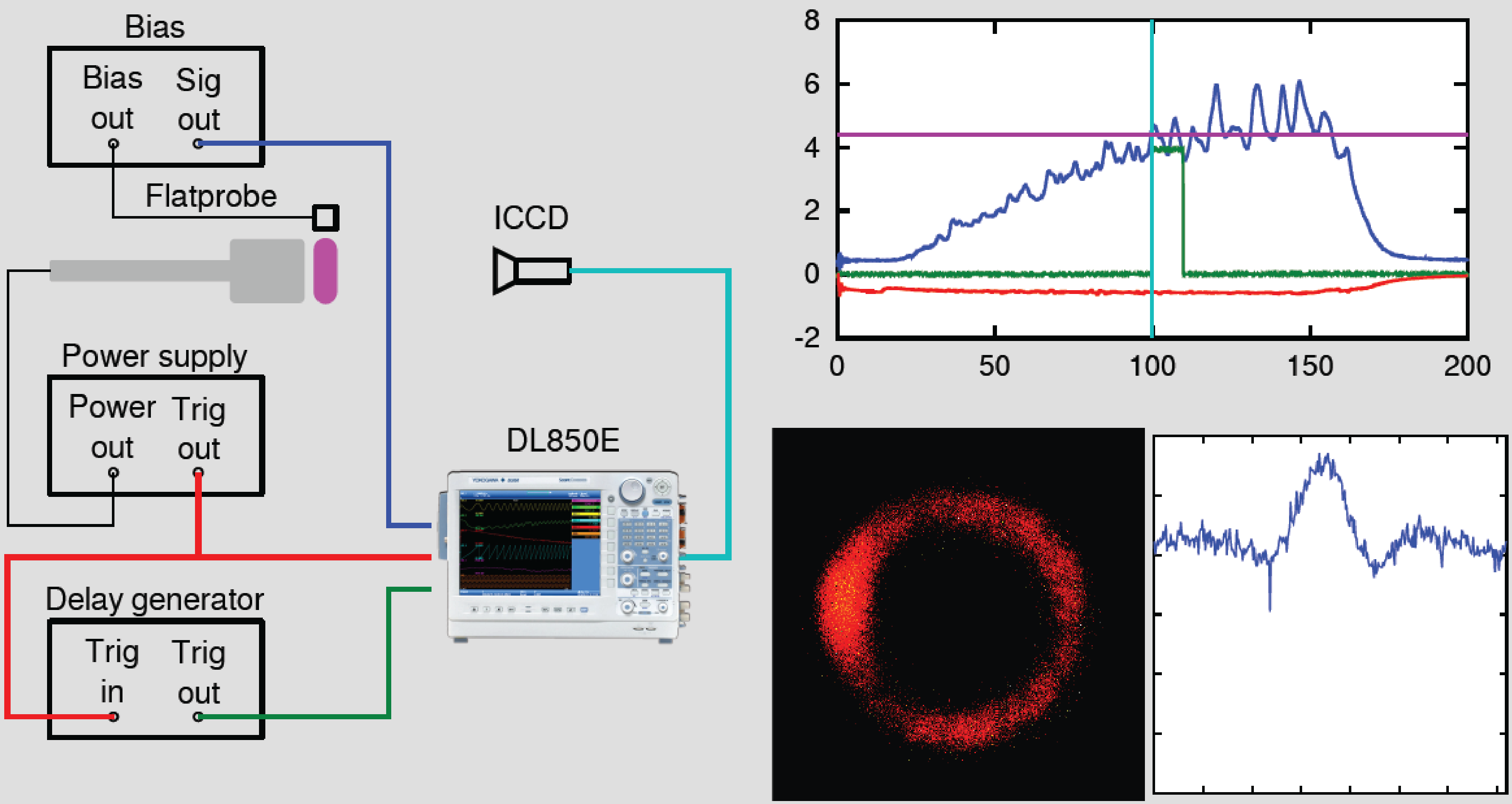




Diagnostic Challenge HiPIMS – Measurement of a Dynamic plasma

Triggering at 2 times necessary

- Beginning of the pulse
- Presence of a spoke in the diagnostic window



Spoke Phenomenon – the Unknowns

Experimental

- Electrical potential - no data inside the spoke available
- Electron density – sparse data by Stark broadening or Interferometry
- Modulation of the current ~ 30% + x -
  Plasma emission is not equivalent to plasma current density

Plasma Modeling

- Fluid Model seems to be applicable, good agreement with drift waves, but saturation values? Long mean free paths?
- Models need to invoke dynamic variation of gas rarefaction
- IRM - type Global Models for an inherent 3D phenomenon
- PIC – models not yet capable to cover 3D dynamic at high plasma density

Energy of the Ions in HiPIMS Plasmas

Properties of Spokes

1) Electrical Structure in the plasma determines direction of propagation

2) Electrical Structure as origin of energetic ions

3 Questions

1) Importance of the “spoke” phenomenon ?

2) Contribution of multiple charged ions ?

3) Influence of Reactive Gases ?

Conclusions

Spokes are an electrical structure in HiPIMS plasmas

Gradients determine velocity and direction
Internal electrical fields determine energy of the ions at the substrate

- At very high powers, homogeneous plasma is reached,
  High ion energies unaffected
- Multiple charged ions cause CX ions with higher energies
- Reactive HiPIMS hysteresis disappears for very high powers
- Reactive admixtures may cause and enhancement of the return effect

Acknowledgements SFB-TR 87