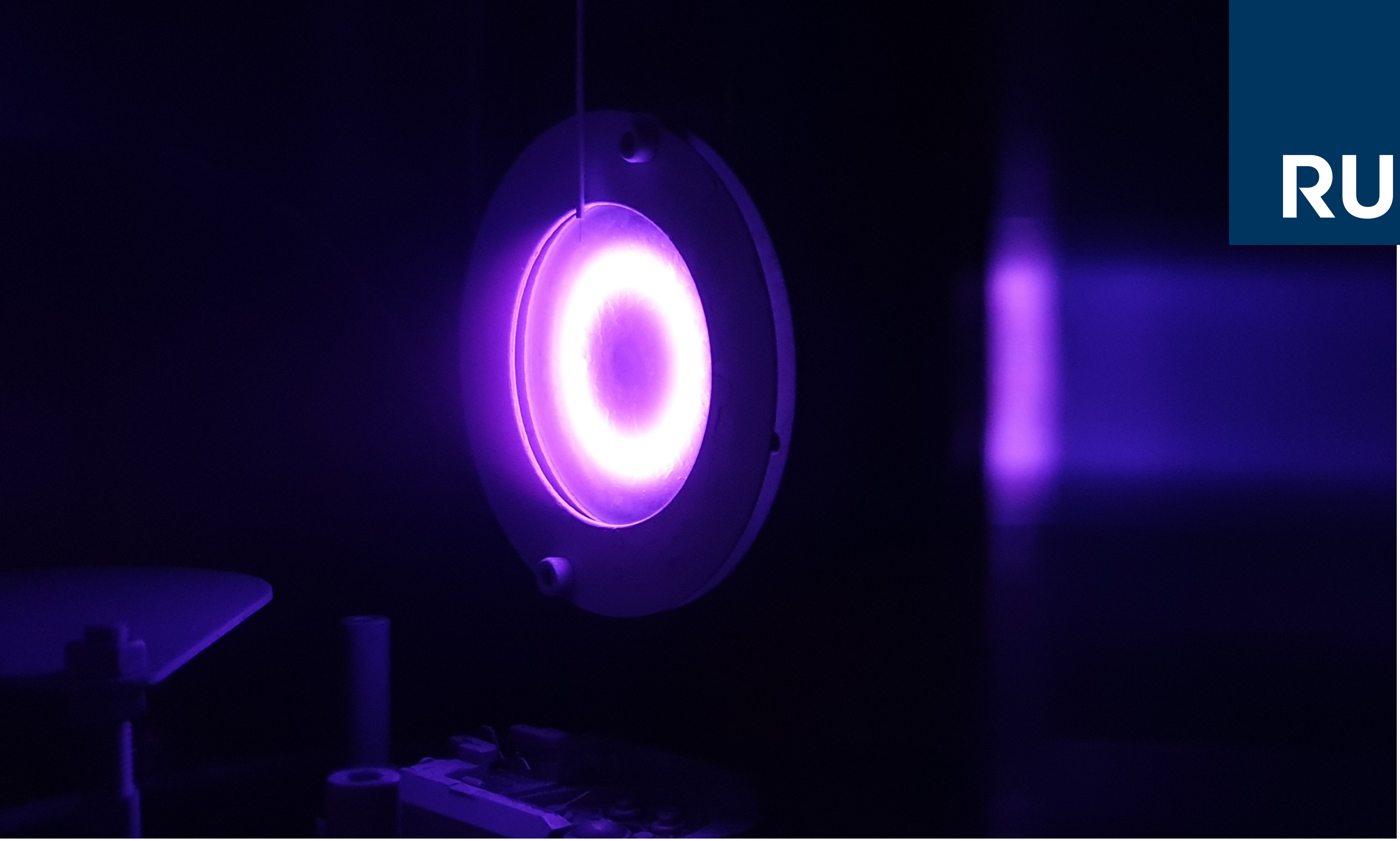


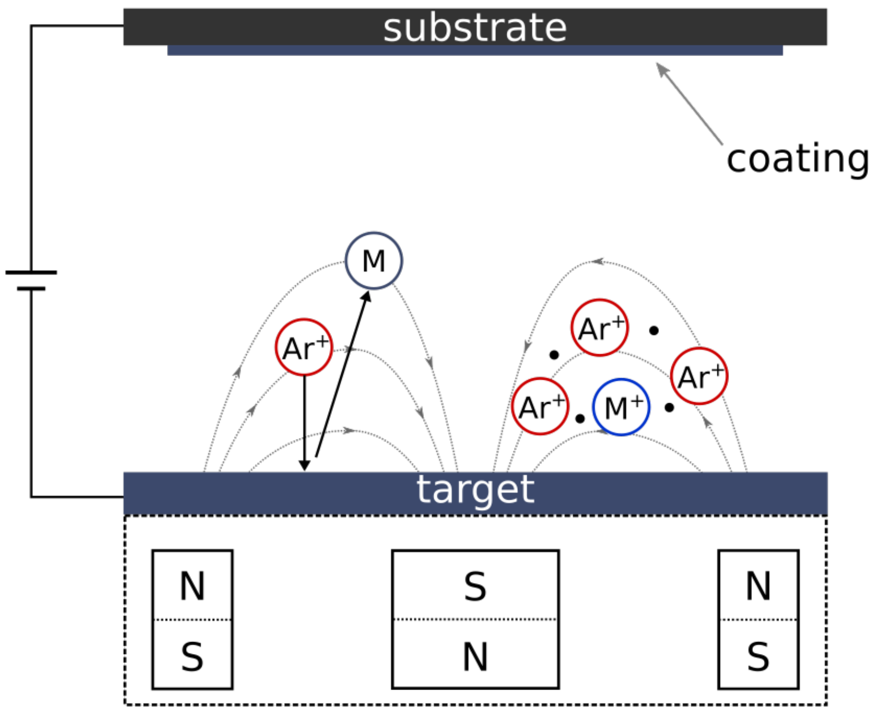
RUHR-UNIVERSITÄT BOCHUM

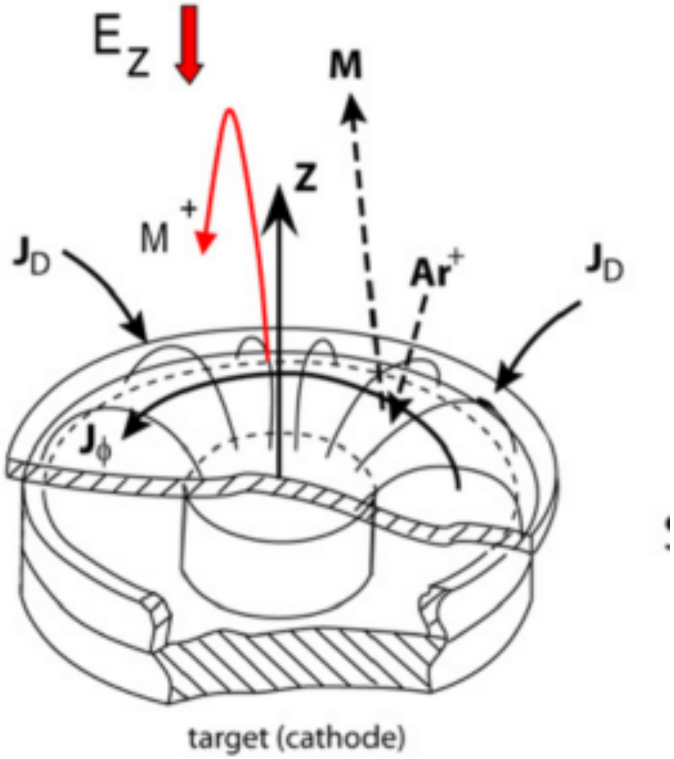
Azimuthal Ion Movement in HiPIMS: Hall Current or Spokes?

S Thiemann-Monjé, J Held, S Schüttler and A von Keudell

SFB-TR 87

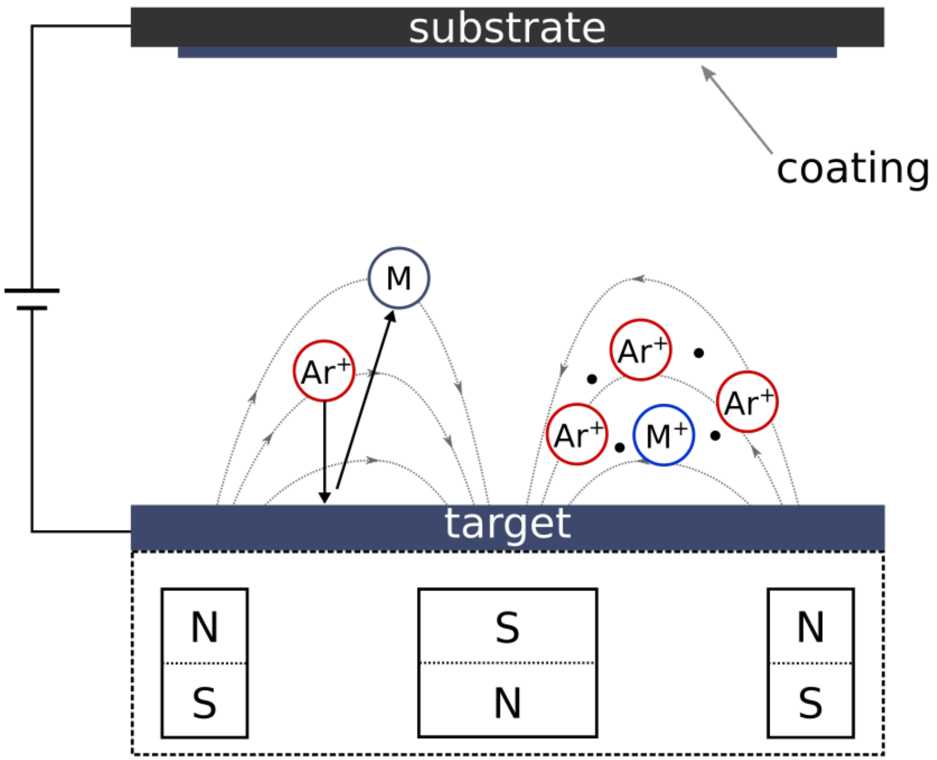
Introduction | High Power Impulse Magnetron Sputtering

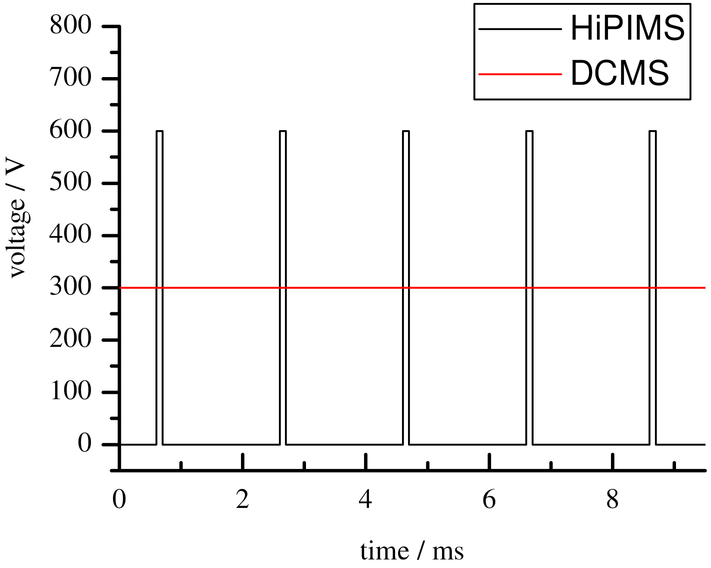




N. Brenning et. al., PSST 21 025005 (2012)

Introduction | High Power Impulse Magnetron Sputtering



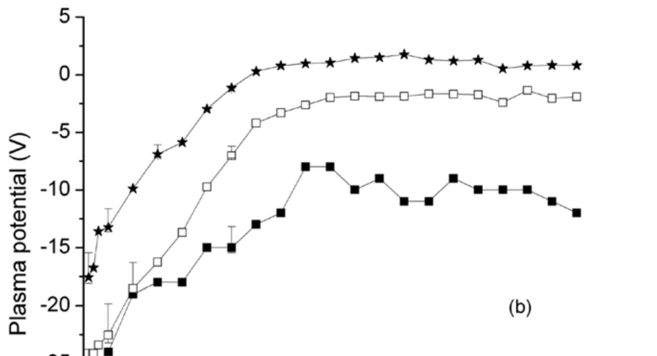


HiPIMS:
Higher ionization degree → better coatings.

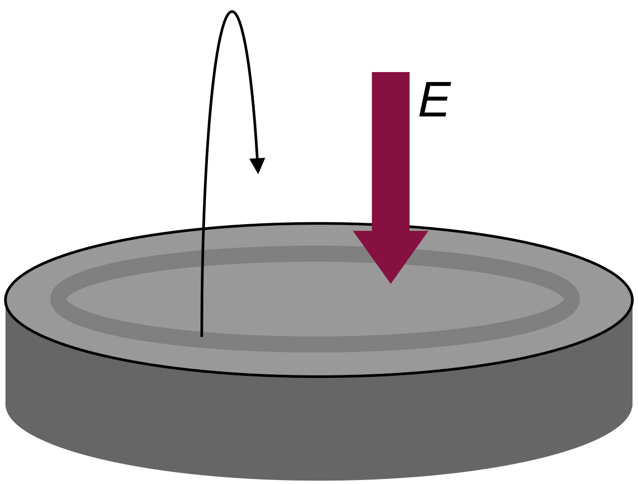
Ion movement is much more complex than neutrals.

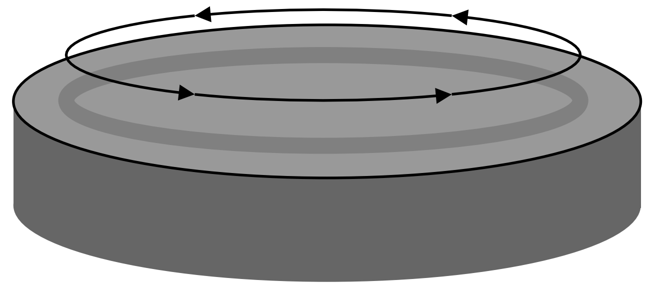
S Thiemann-Monjé, J Held, S Schüttler and A von Keudell

Introduction | Ion transport in HiPIMS



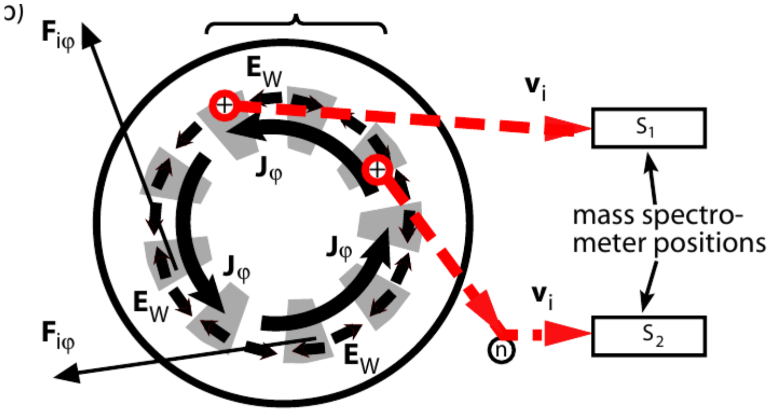
Mishra et al, PSST **19** (2010) 045014



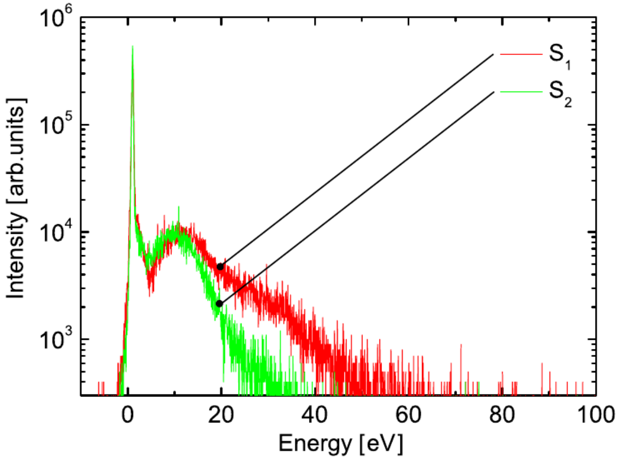


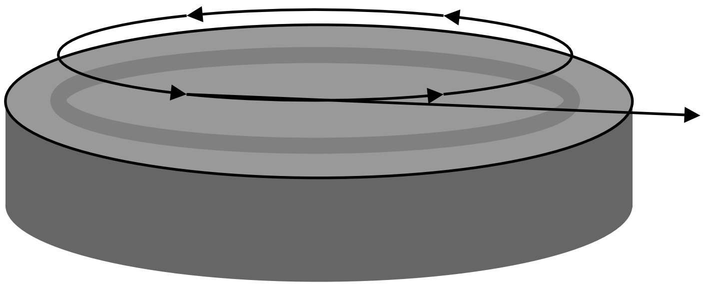
Ions also move in azimuthal direction.

Introduction | Azimuthal Ion Movement



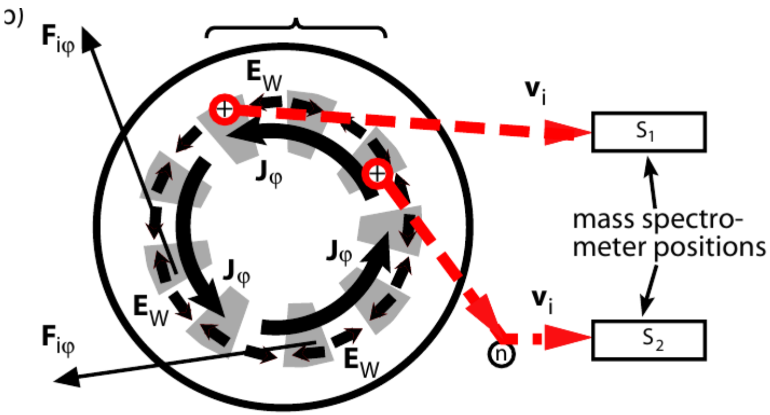
Lundin *et al*, Plasma Sources Sci. Technol. **17** (2008) 035021



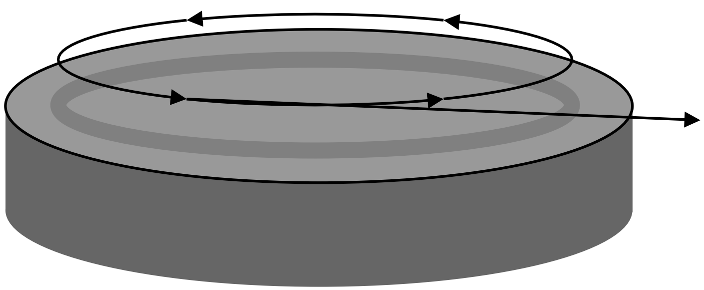


Ions are seemingly *flung out* of the racetrack.

Introduction | Azimuthal Ion Movement: Why?



Lundin *et al*, Plasma Sources Sci. Technol. **17** (2008) 035021



Hall current caused by electron drifts:

$$\mathbf{v}_D \equiv -\frac{\nabla p \times \mathbf{B}}{qnB^2} \qquad \mathbf{v}_E \equiv \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

$$F_{i,\phi} = -\eta e^2 n(v_D + v_{E\times B})$$

In HiPIMS, the Hall current is usually two or three times the discharge current.

I_D = ~50 A → I_{Hall}= ~100A

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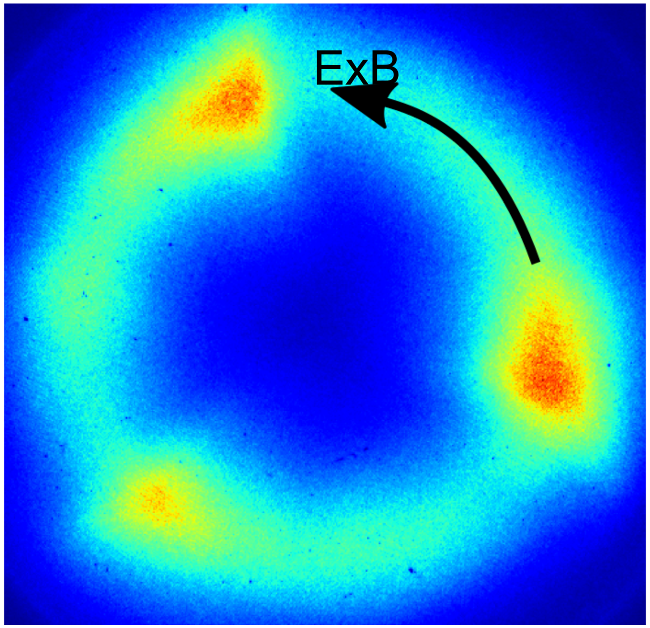
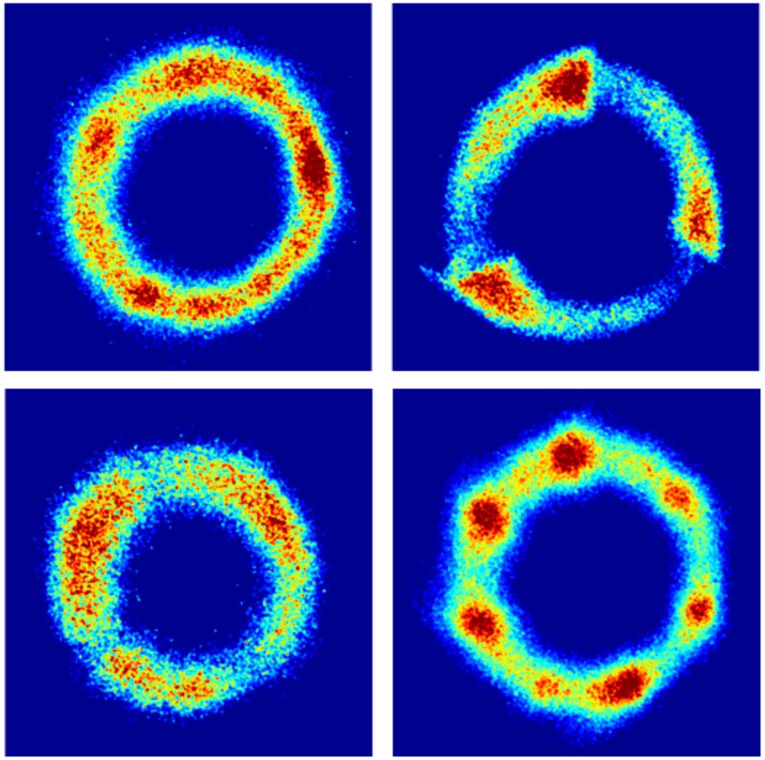
Introduction | Spokes



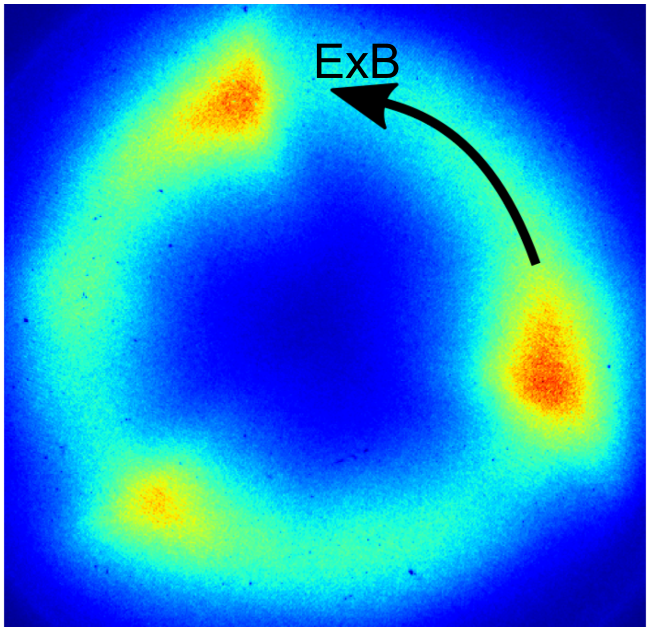
Rotating with 5 – 10 km/s in ExB direction



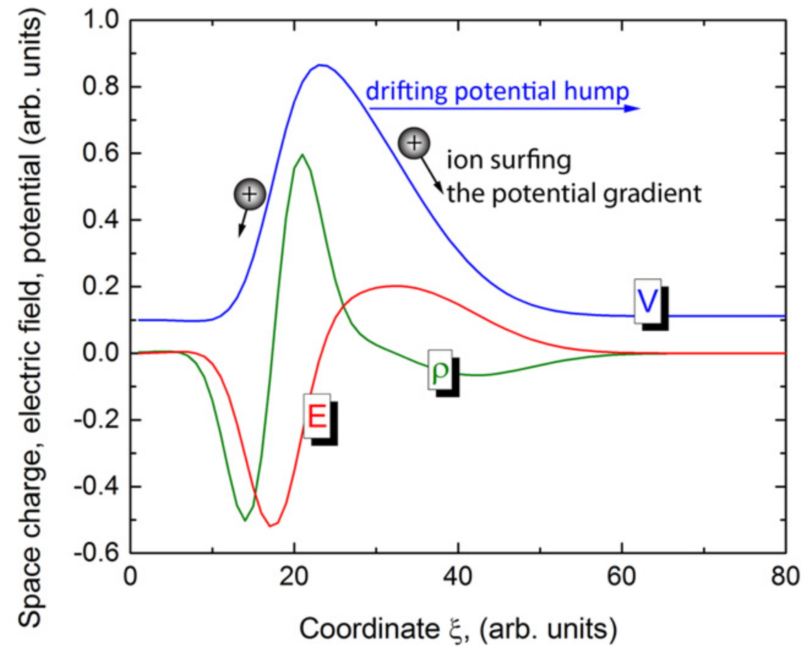
Hnilica, Klein, Šlapanská, Fekete, Vašina
J. Phys. D: Appl. Phys. **51** (2018) 095204

Spokes: wave phenomenon, moving in ExB direction.

Introduction | Spokes



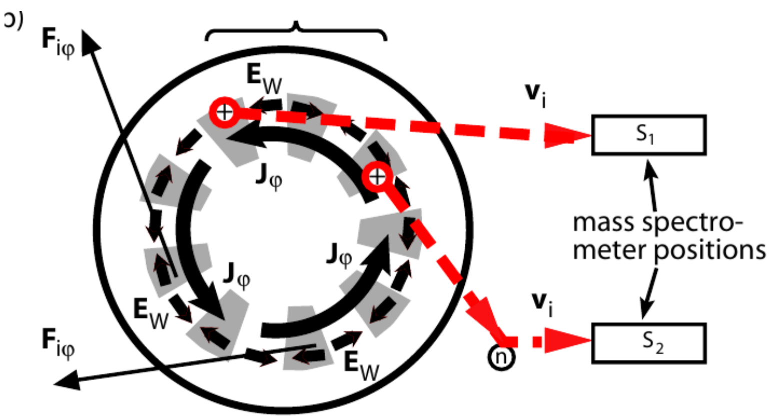
Rotating with 5 – 10 km/s in ExB direction

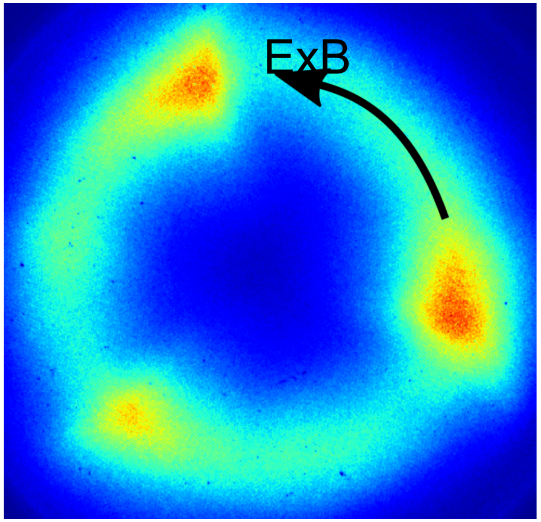


Panjan, Franz, Anders (2014) PSST **23** 025007

Spokes can also cause azimuthal ion movement.

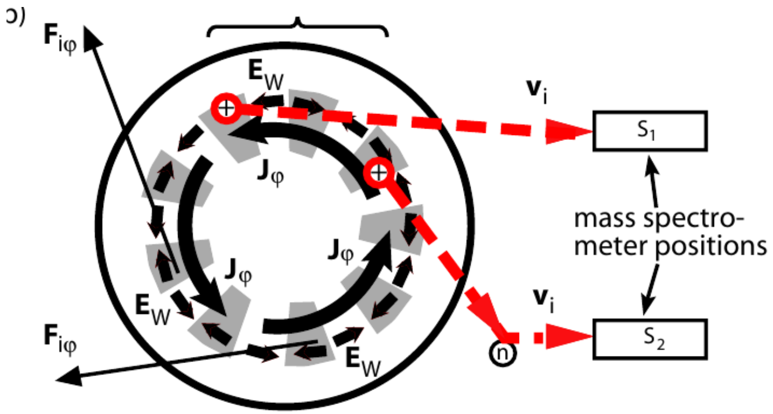
Introduction | Azimuthal Ion Movement in HiPIMS





Hall current or Spokes?

Introduction | Azimuthal Ion Movement in HiPIMS

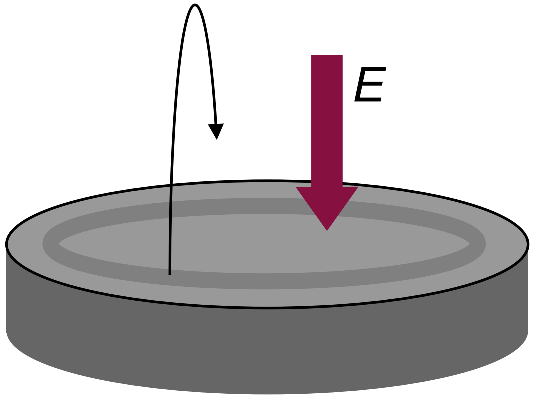


Hall current or spokes:
What do we need?

1. Better measurements of ion movement.

2. An estimation of the Hall-current drag force

3. Quantitative measurements of Spoke electric field and density.



PART ONE

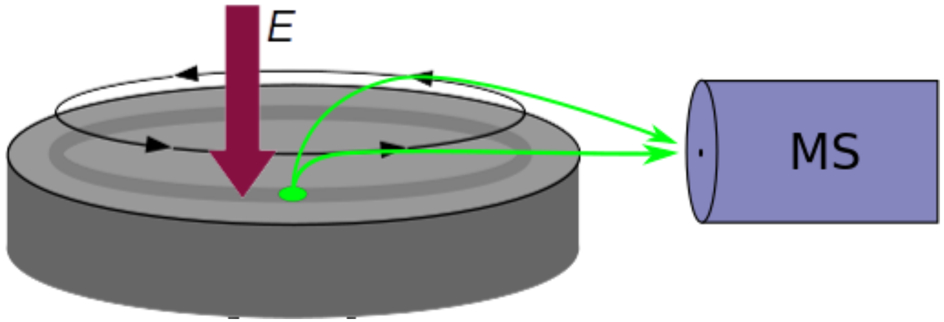
MEASUREMENT OF AZIMUTHAL ION VELOCITY

Measurement of Azimuthal Ion Velocity | MS measurements

Problems with mass spectrometry :

Measurement outside of plasma

Pre selection of particles due to time varying E-field



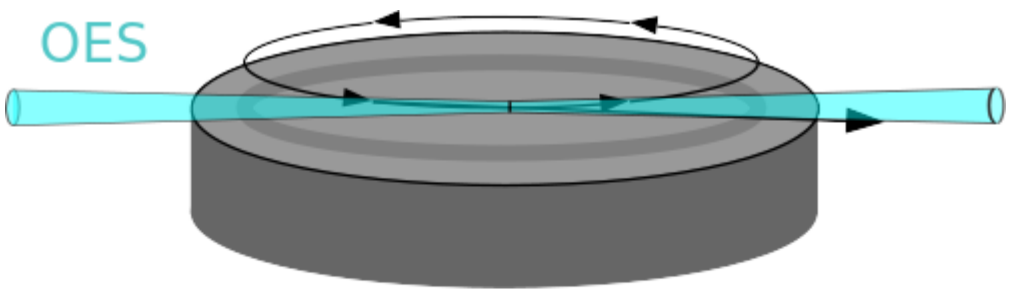
Measurement of Azimuthal Ion Velocity | OES

Using Optical Emission Spectroscopy:

non-intrusive

Spatially resolved

Time resolved



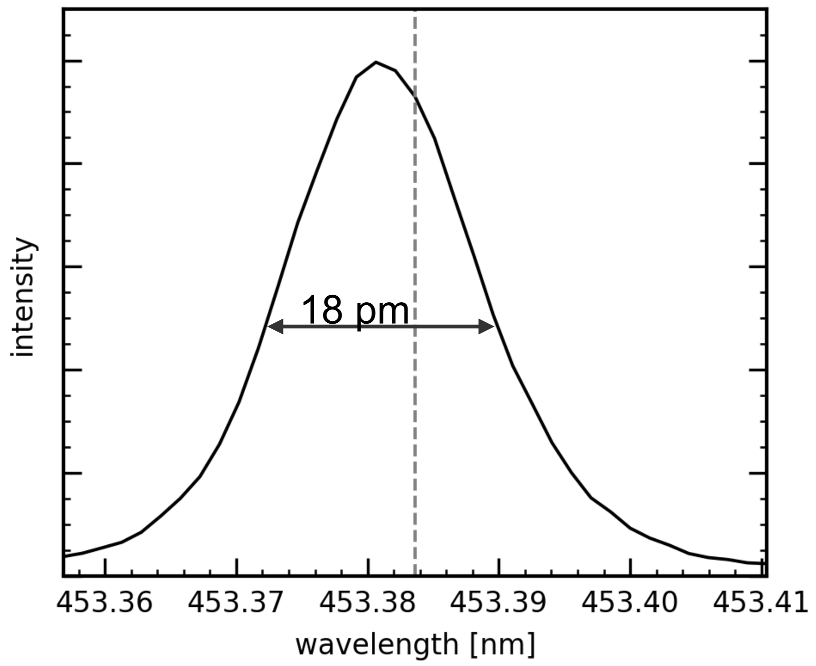
Measurement of Azimuthal Ion Velocity | OES

Optical Emission line profile:

Natural: ~ 0.1 pm
Stark: < 1 pm
Zeeman: ~ 1 pm

Instrument: ~ 6 pm
Doppler: ~ 15 pm

Line profile is dominated by Doppler broadening.



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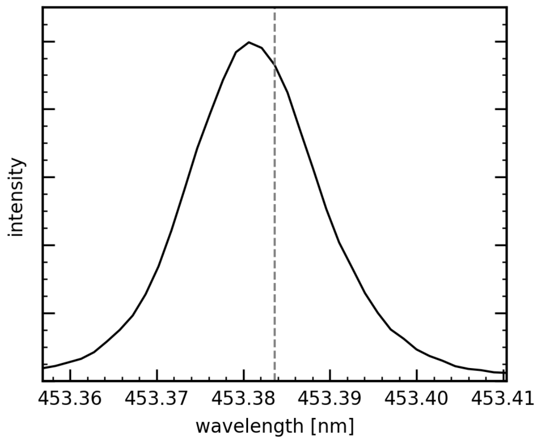
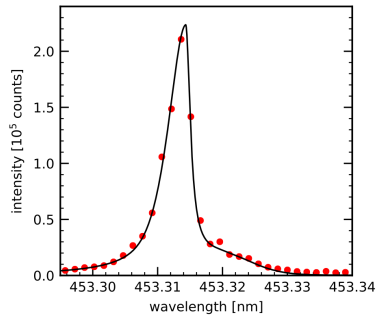
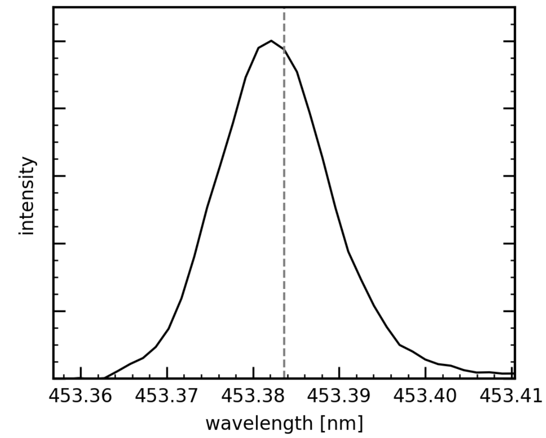
Measurement of Azimuthal Ion Velocity | OES

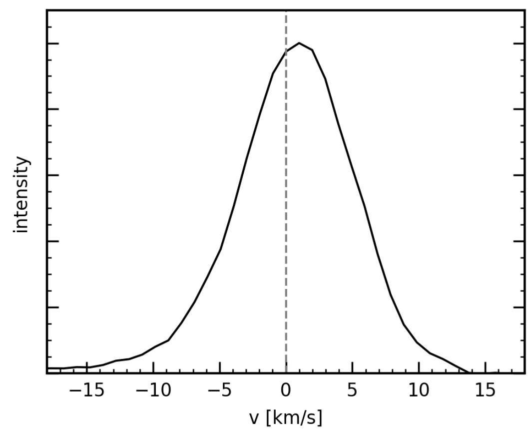




remove
Instrumental
profile



$$v = c(1 - \lambda/\lambda_0)$$



VDF can directly be obtained from emission line profile.

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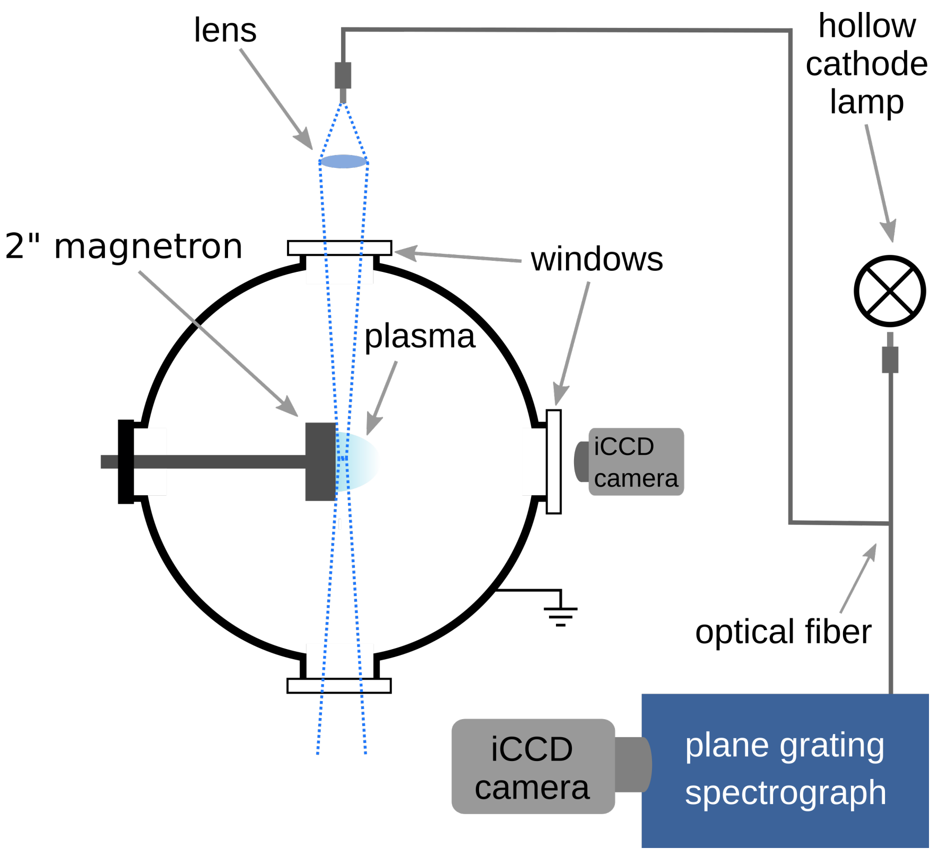
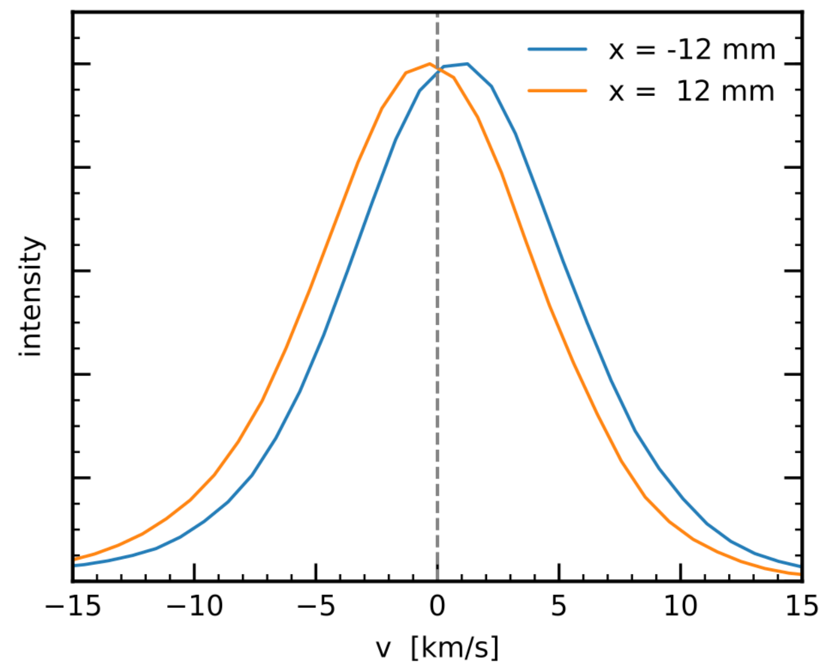
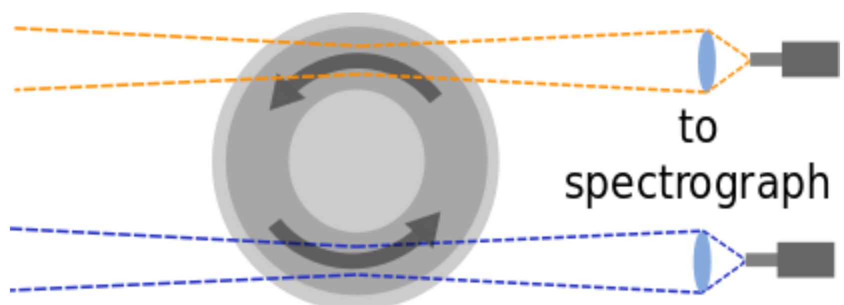
Measurement of Azimuthal Ion Velocity | OES







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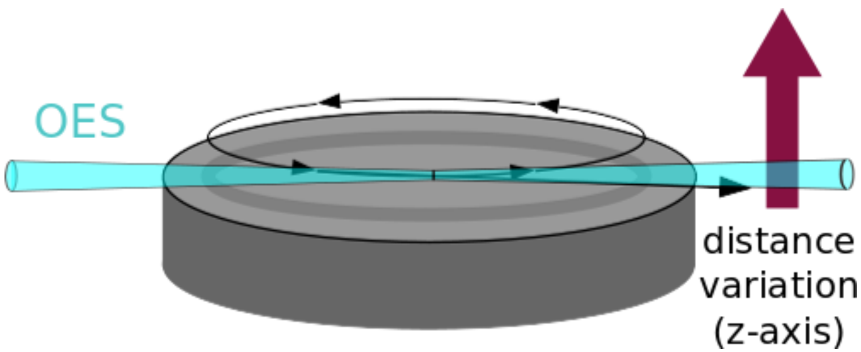
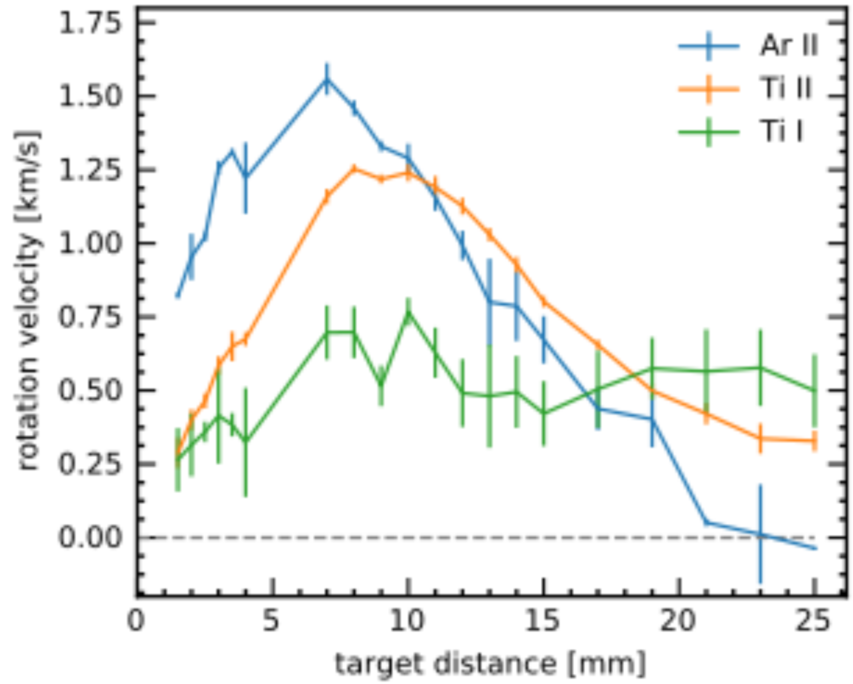
Measurement of Azimuthal Ion Velocity | OES





Maximum Ion rotation velocity is about 1.2–1.5 km/s at 8-10 mm distance from target

PART TWO

HALL CURRENT

Part Three | Azimuthal force

Parameters of Hall current drag force:

B – measured (plasma off)

T_e – measured 4.5 eV (z=8mm)

E – estimation needed

n_e – estimation needed

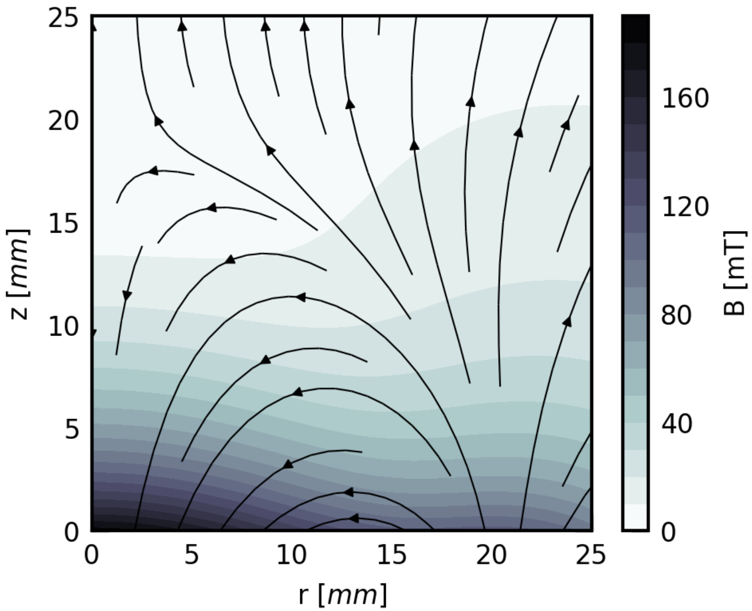
$$F_{i,\phi} = -\eta e^2 n (v_D + v_{E\times B})$$

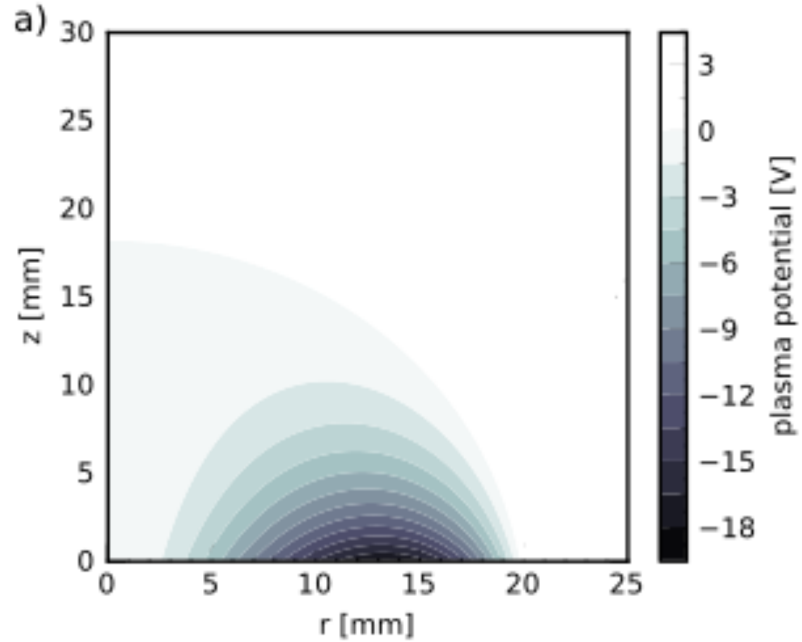
$$\mathbf{v}_D \equiv -k_B T \frac{\nabla n \times \mathbf{B}}{qnB^2}$$

$$\mathbf{v}_E \equiv \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

Estimations of E-field and density needed

Part Three | Electric Field

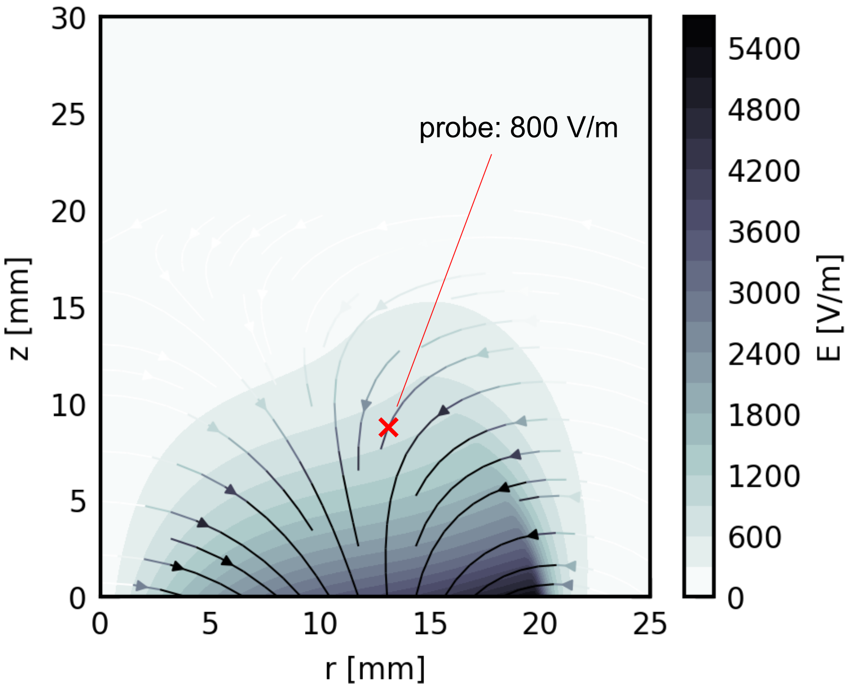


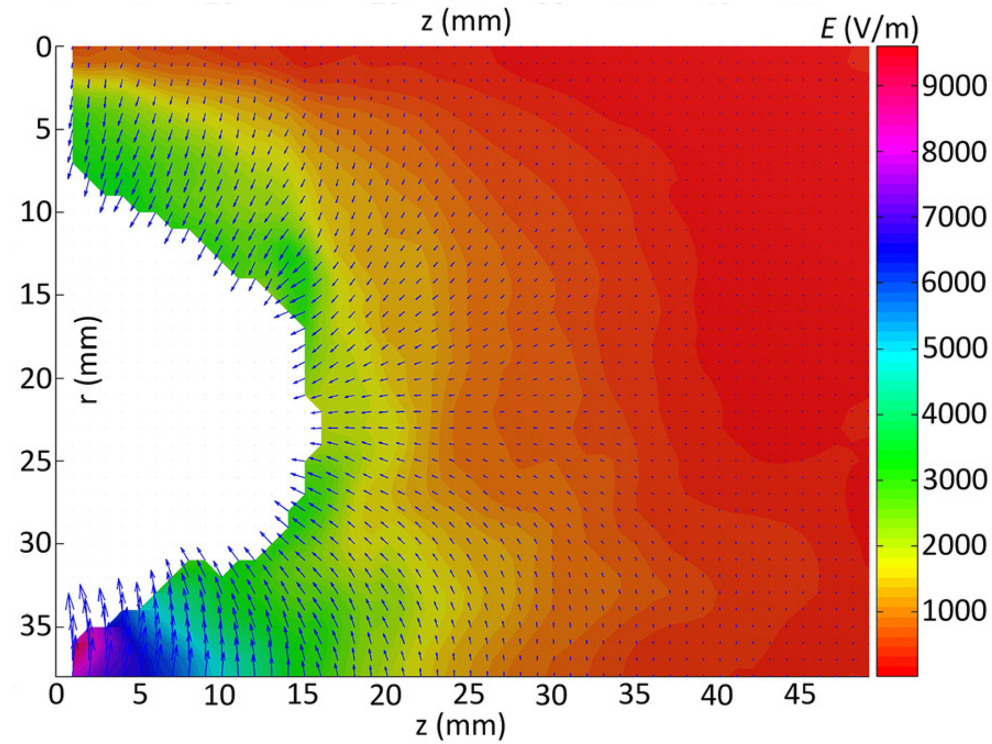


Guess of plasma potential:

- No potential differences possible along B-Field lines
- Usage of magnetic flux coordinates **Ψ** introduced by Brinkmann and Krüger
  [R. P. Brinkmann and D. Krüger, "Axisymmetric magnetically enhanced discharges described in terms of flux coordinates", Physics of Plasmas 27, 053504 (2020)]
- **Ψ** = const. represents magnetic field lines
- Guess: plasma potential proportional to magnetic flux coordinates

Part Three | Electric Field





Rauch *et al* J Appl Phys (2012) **111** 083302

E-field fits to measurements
but remains a weak estimation

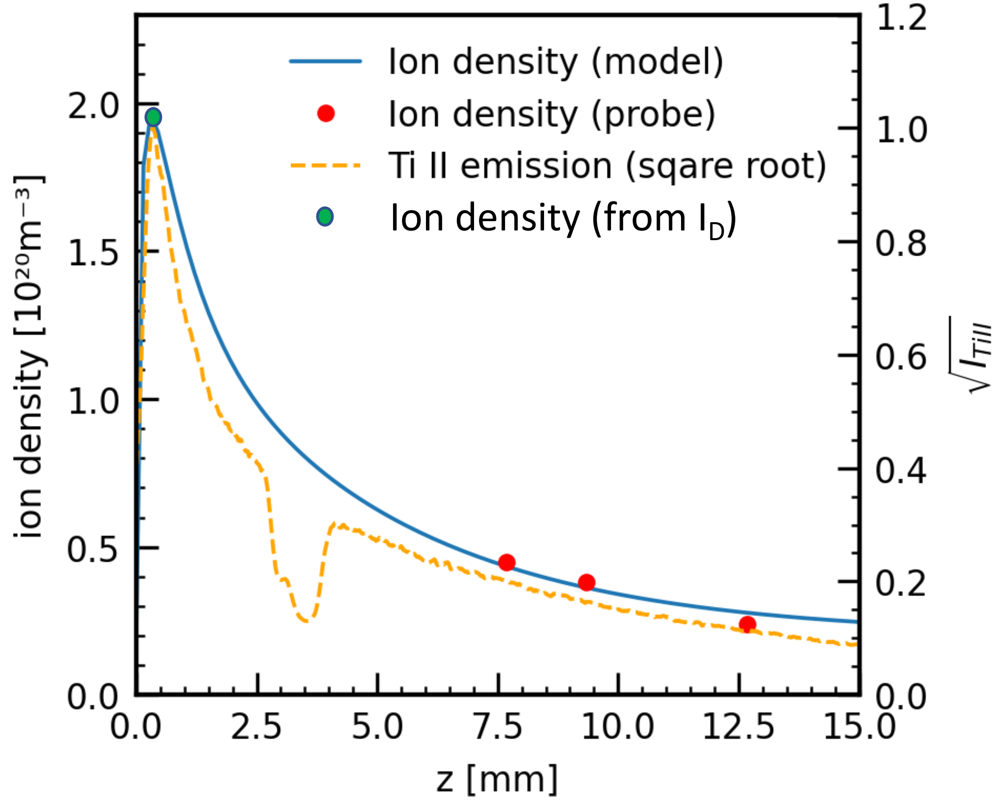
Part Three | Ion Density

Model of Ion density:

Peak density from discharge current

Exponential decay to fit probe data

Shape similar as square root of abel inverted emission



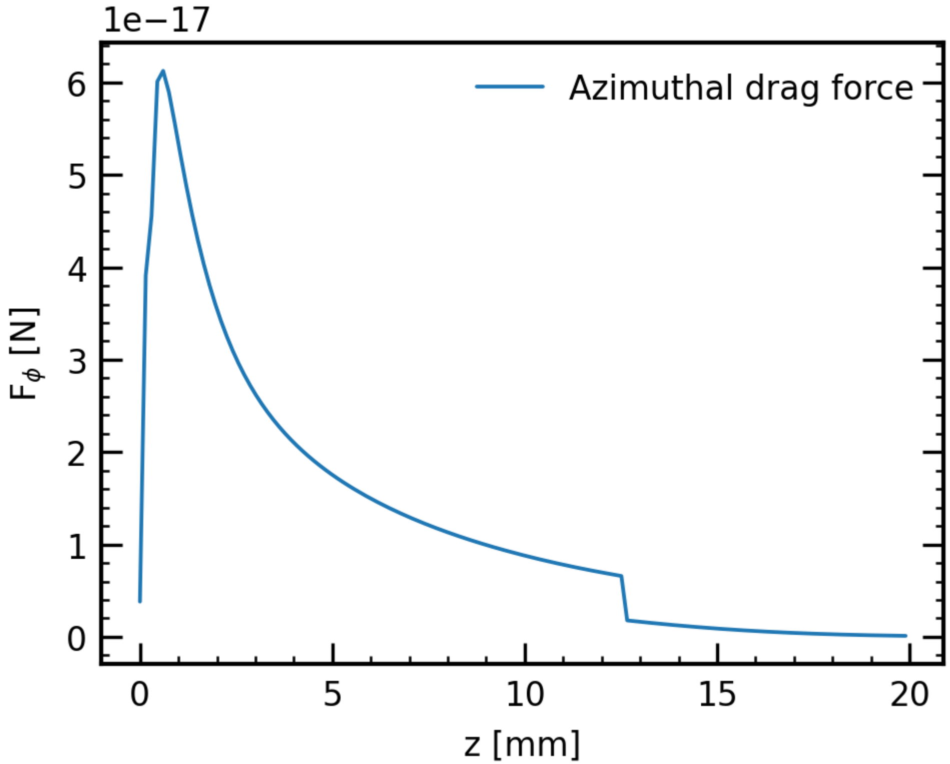
Suitable estimation reached

Part Three | Ion Density

$$F_{i,\phi} = -\eta e^2 n(v_D + v_{E\times B})$$

$$\mathbf{v}_D \equiv -k_B T \frac{\nabla n \times \mathbf{B}}{qnB^2}$$

$$\mathbf{v}_E \equiv \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$



Shape of drag force mostly influenced by the density

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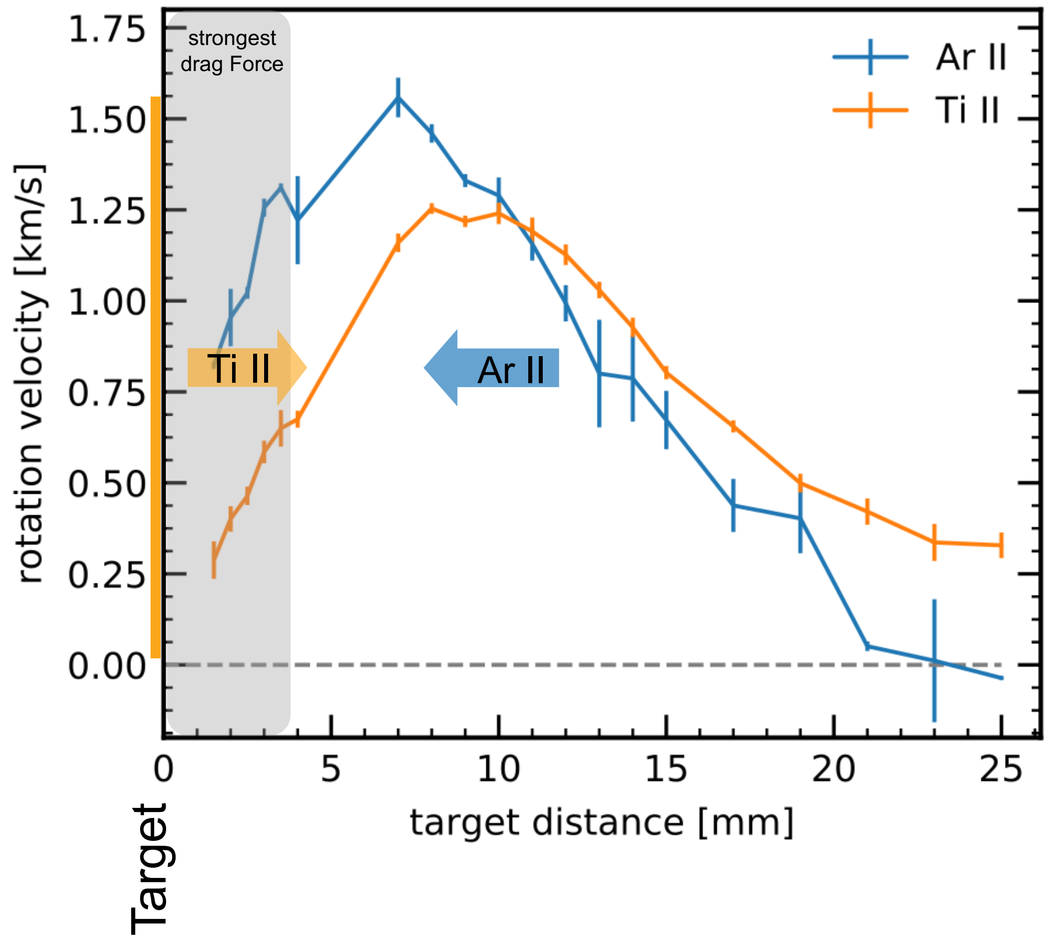
Measurement of Azimuthal Ion Velocity | OES

z > 10 mm:

- coupling of Ti II and Ar II due to collisions
- Slowing by Ion-Neutral collisions

z < 10 mm:

- Unknown residence time
- Ti II:
  - short residence time near target
  - accumulation of rotation velocity
- Ar II:
  - strong coupling with Ti II via collisions



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Measurement of Azimuthal Ion Velocity | OES

Estimation of resulting velocity:

z = 8 mm:

- From [1] e⁻ confinement time:

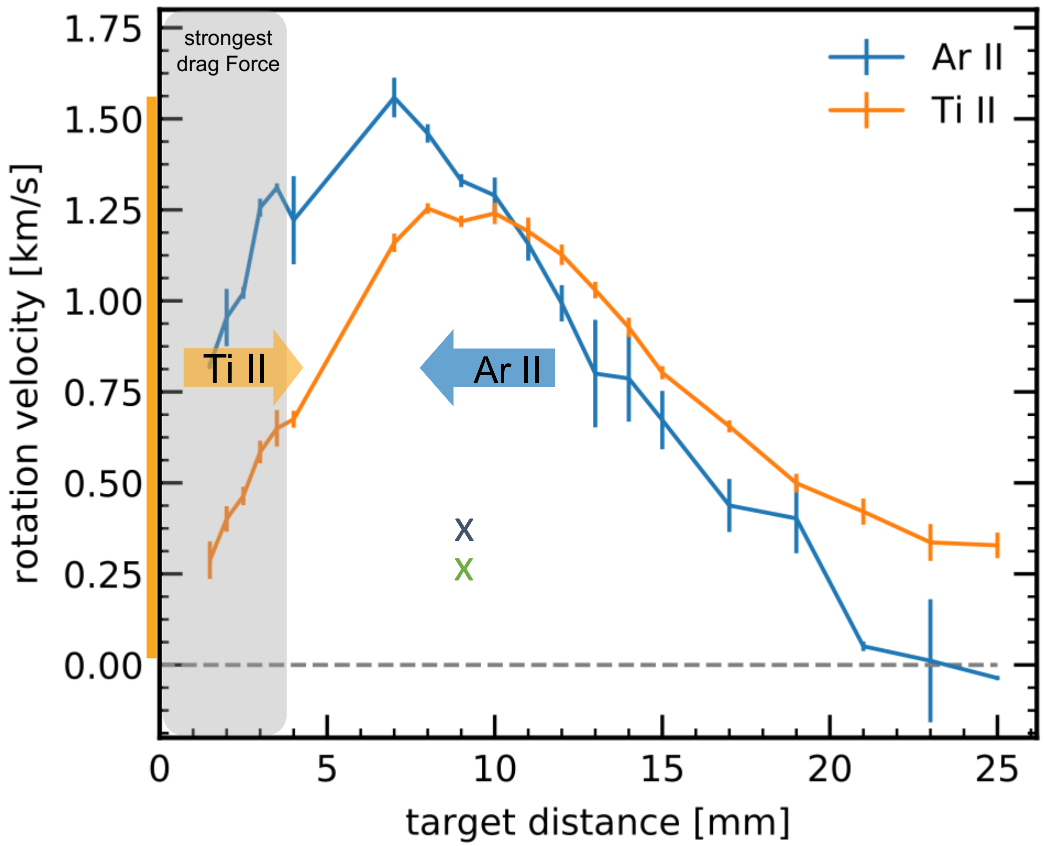
$$\tau_e(E) = 1.76 \times 10^4 \text{ eV} \frac{1}{E\, \nu_m(E)}$$

$$\tau_e(E) \approx 2\ \mu s$$

- Same confinement time for electrons and ions

$$v_{rot} = \frac{F_{drag}\tau_i}{m_{ion}}$$

- Ti II: $v_{rot} \approx 250\ m/s$
- Ar II: $v_{rot} \approx 300\ m/s$

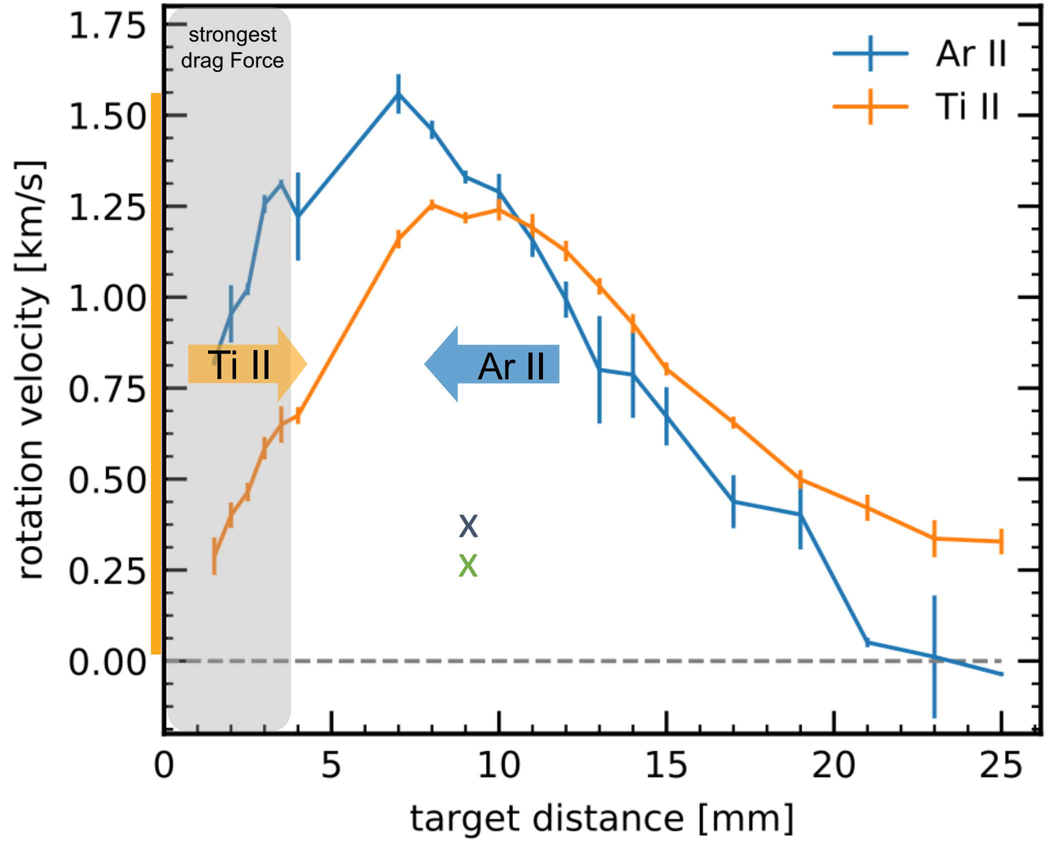


[1]: R. P. Brinkmann and D. Krüger, “Axisymmetric magnetically enhanced discharges described in terms of flux coordinates”, Pl Plasmas 27, 053504 (2020)

Measurement of Azimuthal Ion Velocity | OES

Problems:

- accumulation of rotational velocity during movement in z direction
- Coupling of ArII and TiII due to collisions
- Spokes?



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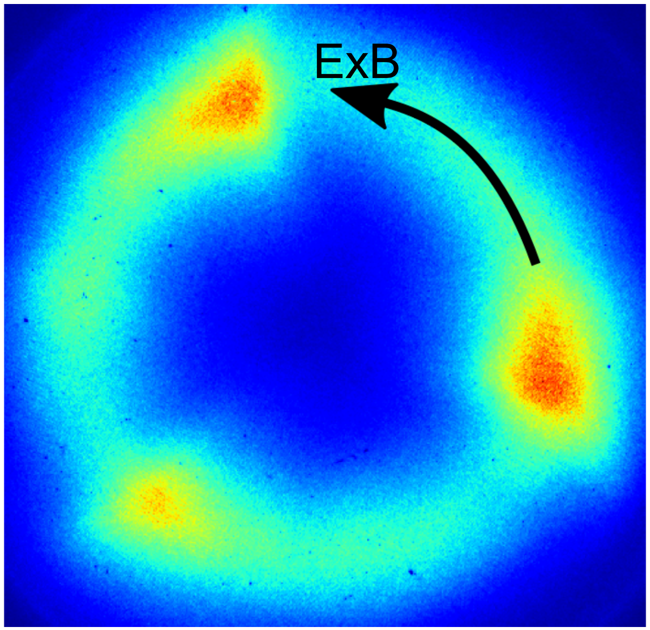
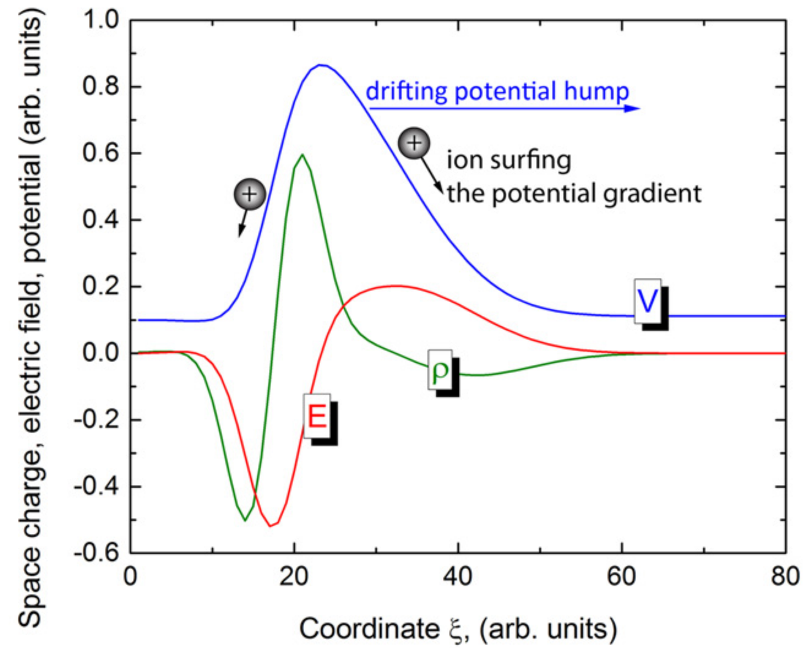
PART THREE

SPOKES

Introduction | Spokes





Panjan, Franz, Anders (2014) PSST **23** 025007

Rotating with 5 – 10 km/s in ExB direction

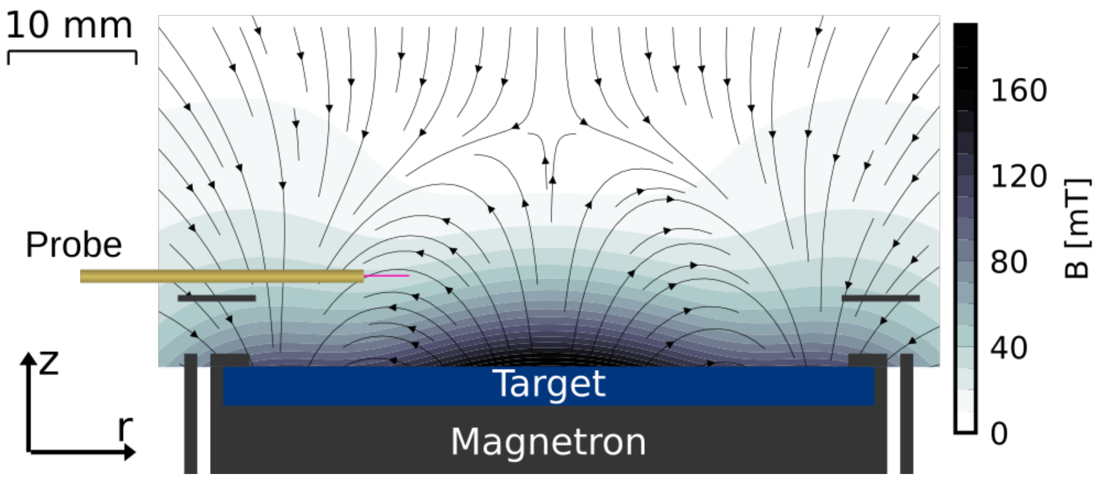
Spoke resolved probe
measurements needed

Part Two | Plasma Parameters? Langmuir Probe!

Two problems:

1. Magnetic fields
   → Magnetized Probe Theory

2. Spoke synchronization



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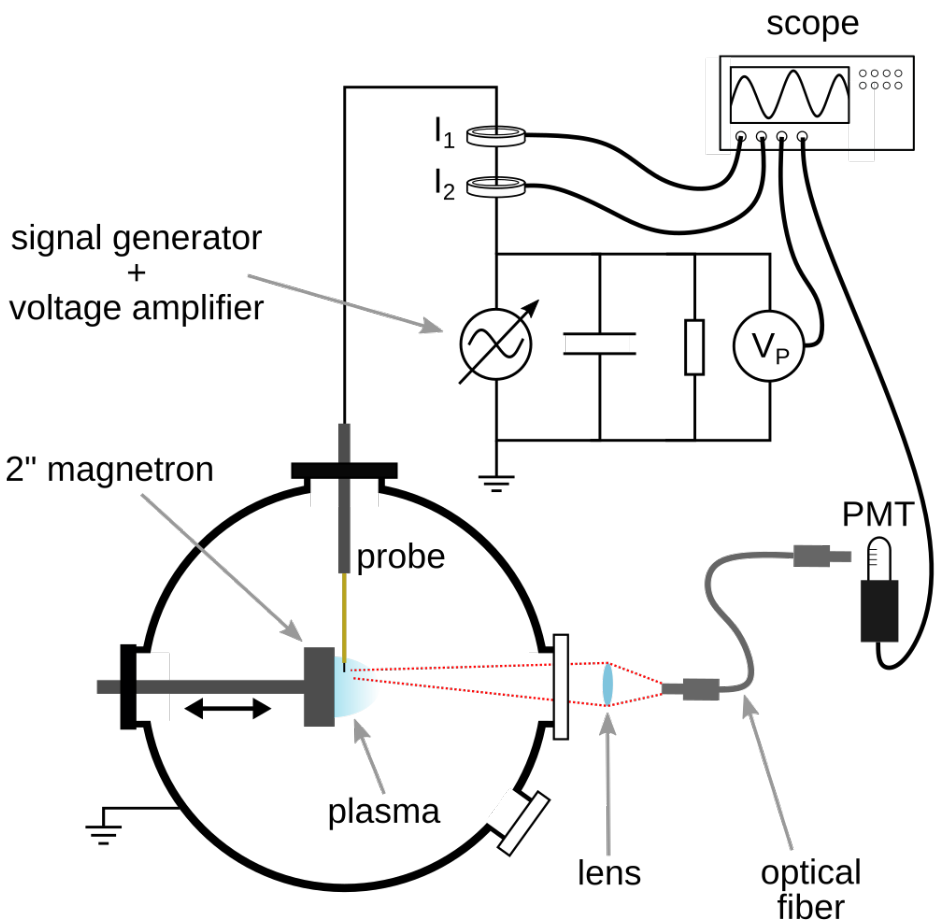
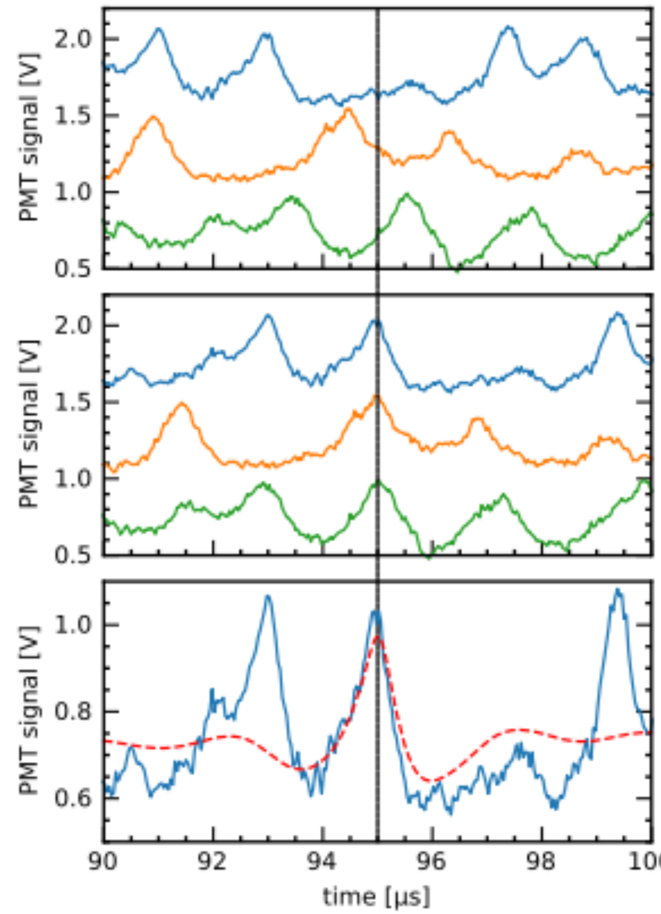
Part Two | Spoke Synchronization





Time shift averaging to preserve spoke information under averaging

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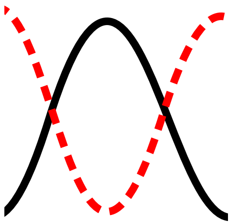
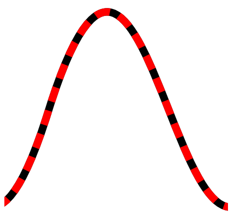
Part Two | Plasma Parameters

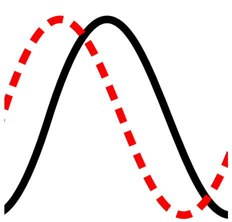


Potential (—) and density (- - -) waves phase shift:

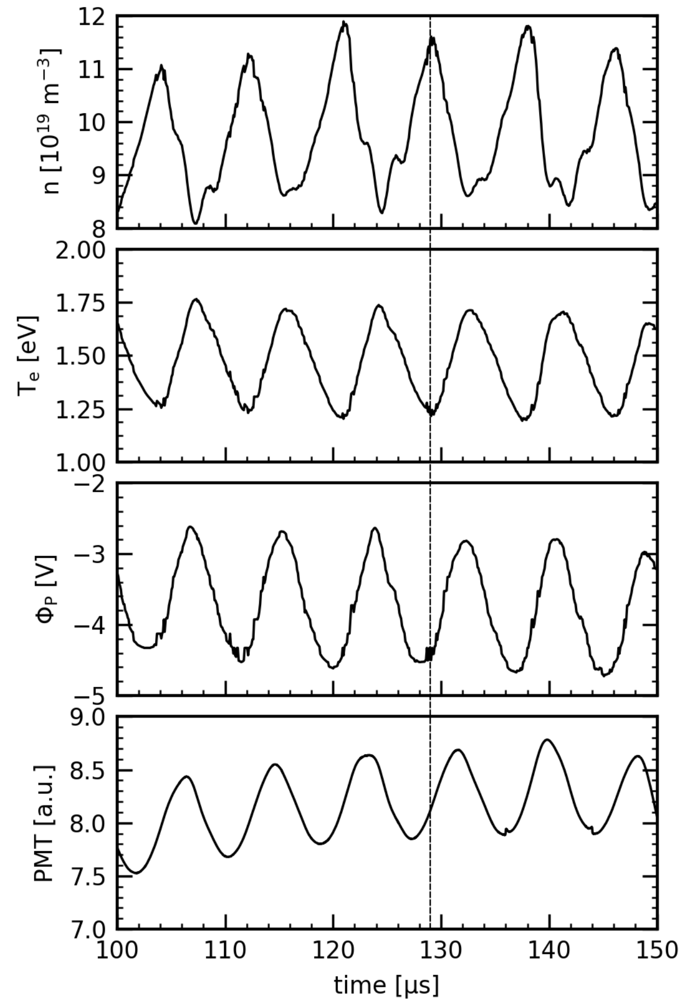
π - no transport



0 – no transport

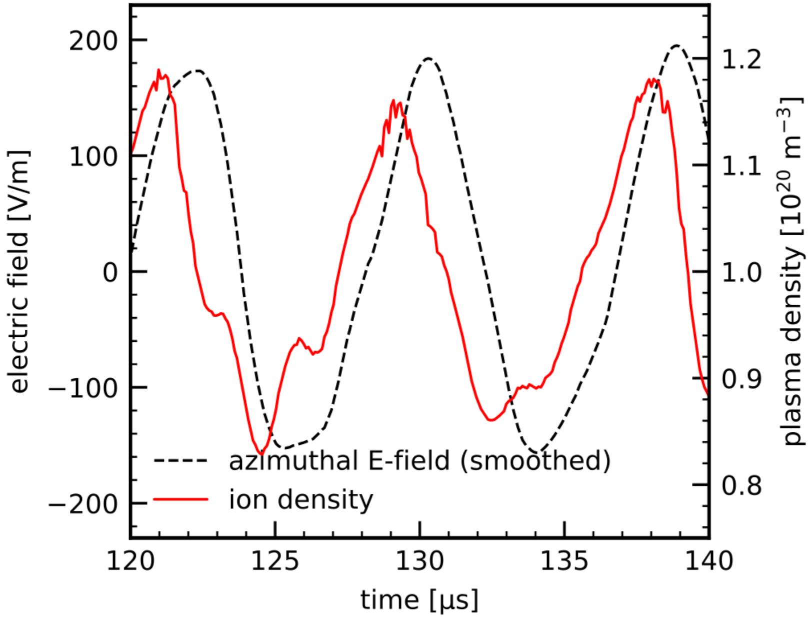


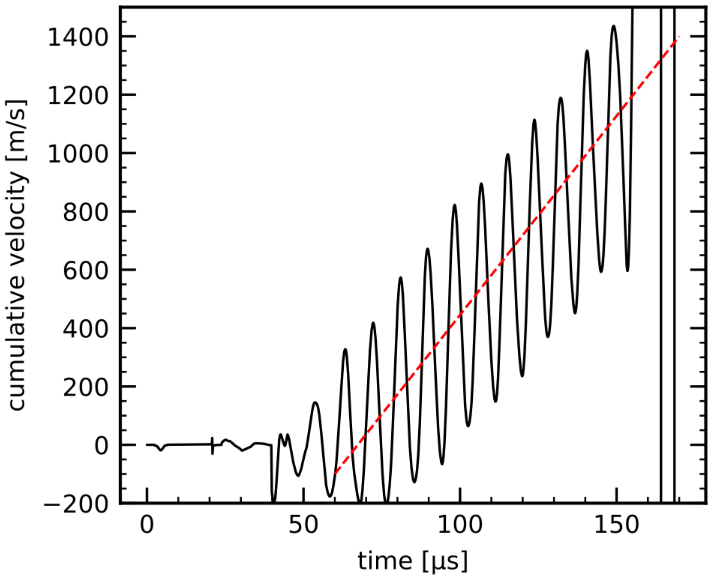
π/2 – transport!



Part Two | Plasma Parameters

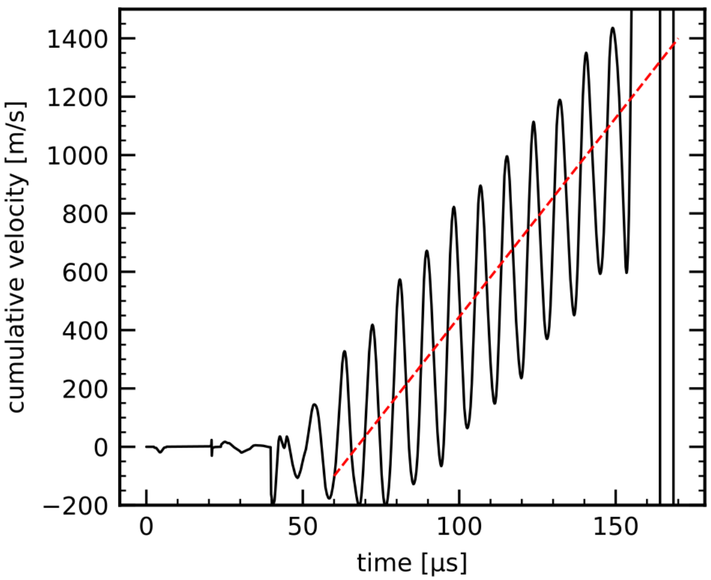
$$E_\phi = \frac{1}{v_s}\frac{\mathrm{d}V_P}{\mathrm{d}t} \qquad \Gamma_\phi = n_i \frac{eE_\phi}{m} t$$

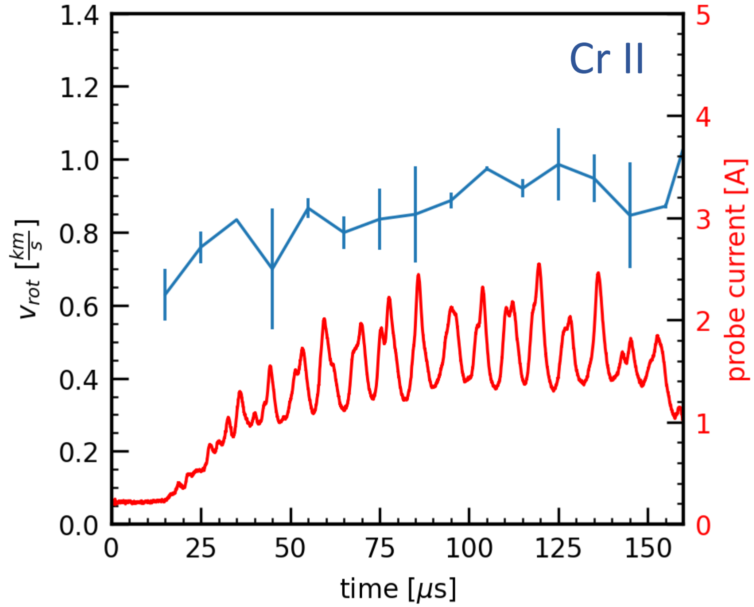




Spokes cause azimuthal ion rotation in the order of 1 km/s, *eventually*.

Part Two | Plasma Parameters





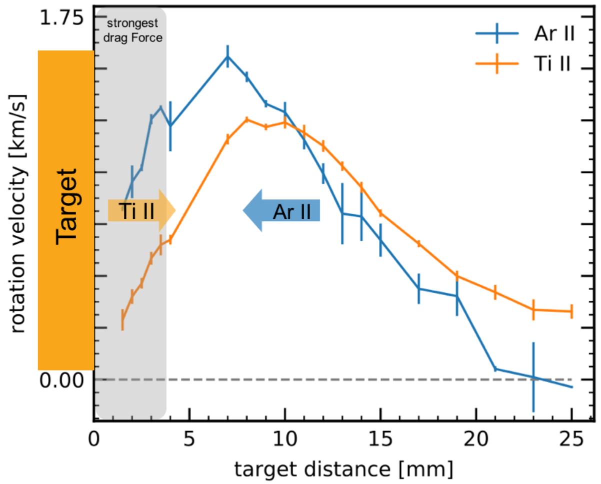
No cumulative effect over
whole discharge visible

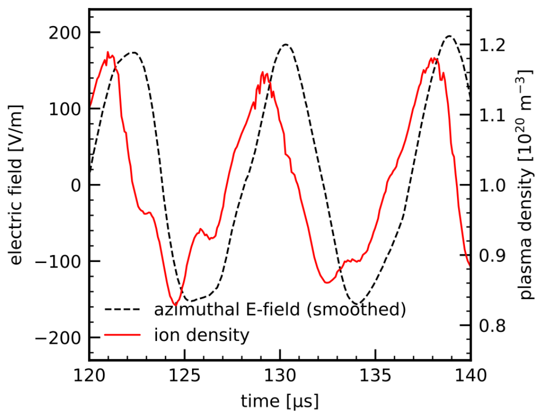
CONCLUSION

HALL CURRENT OR SPOKES?

Summary

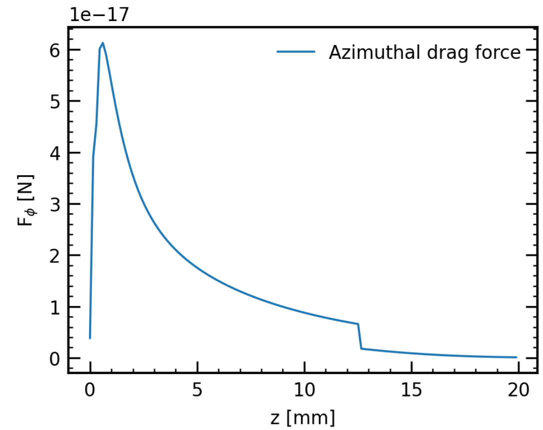
A better measurements of ion movement, based on high-resolution OES, is possible.
We find azimuthal velocities in the order of 1 km/s for ions.





Spoke-synchronized Langmuir probe measurements show strong oscilations in ion density, electron temperature and plasma potential. The shift between density and potential fluctuations strongly implies a net transport in the direction of spoke movement.

Estimations of the electron hall-current show almost constant values within the magnetic trap region. The shape of the azimuthal drag force therefore mimics the shape of the density. Having a maximum near the surface and decaying to further distances



S Thiemann-Monjé, J Held, S Schüttler and A von Keudell

Conslusion | Azimuthal Ion Movement in HiPIMS

Hall current or spokes?

Probably both!

V Layes *et al* Appl Phys Lett (2017) **110** 081603
J Held *et al* PSST 2018 **27** 105012
J Held and A von Keudell: Plasma Chem Plasma Process (2019) **38**
J Held *et al* PSST (2020) **29** 025006