July 18-20, 2012 - 5th Int. Workshop on
"Thin Films Applied To Superconducting RF And New Ideas For Pushing The Limits Of RF Superconductivity" - Jefferson Lab, VA

Strong localization of ionization in high power impulse magnetron sputtering:

An enabling route to niobium plasma coatings of SRF cavities

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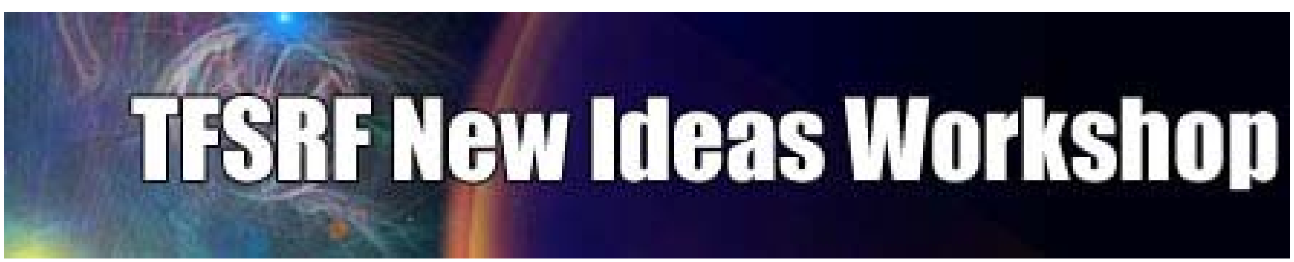
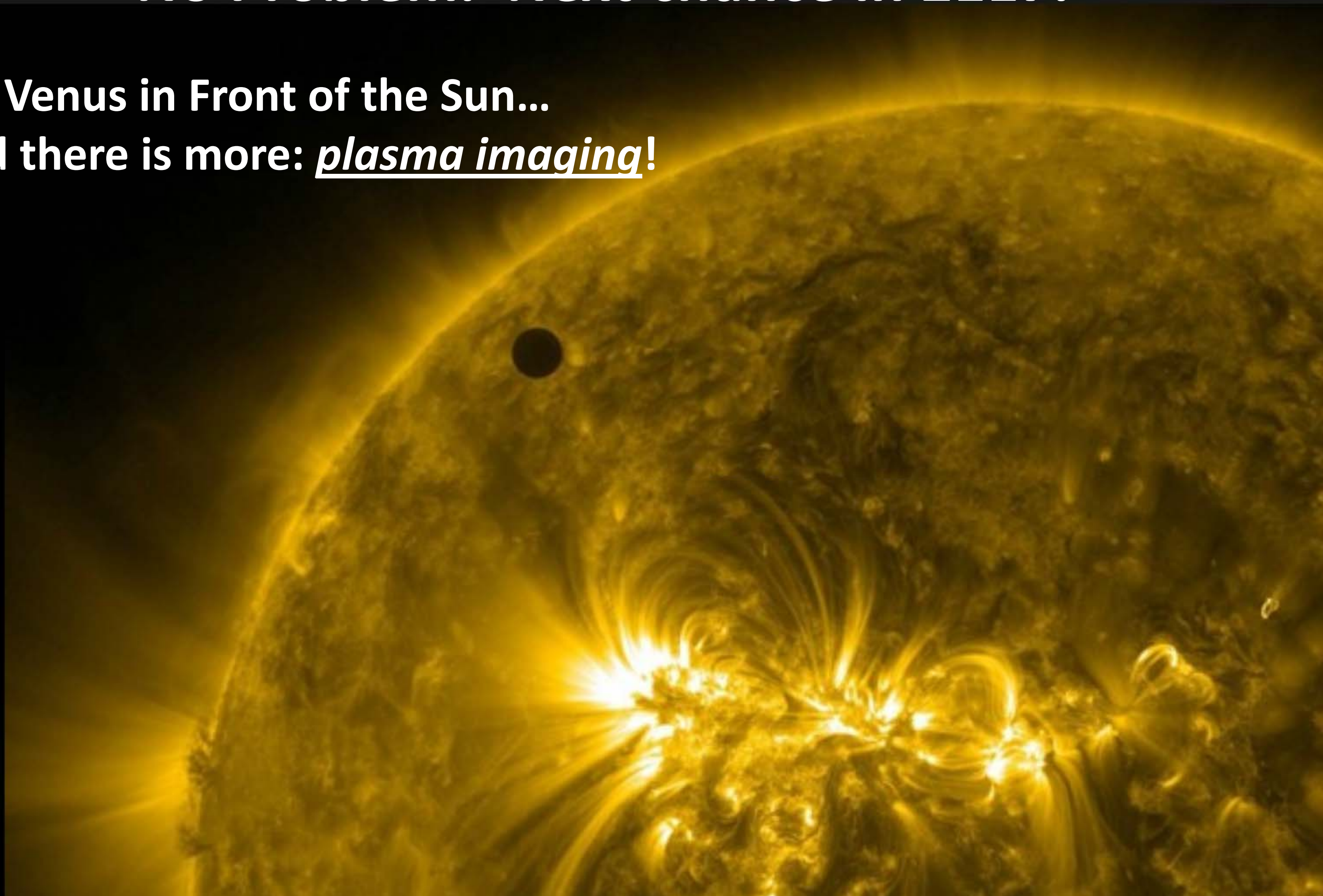


BERKELEY LAB

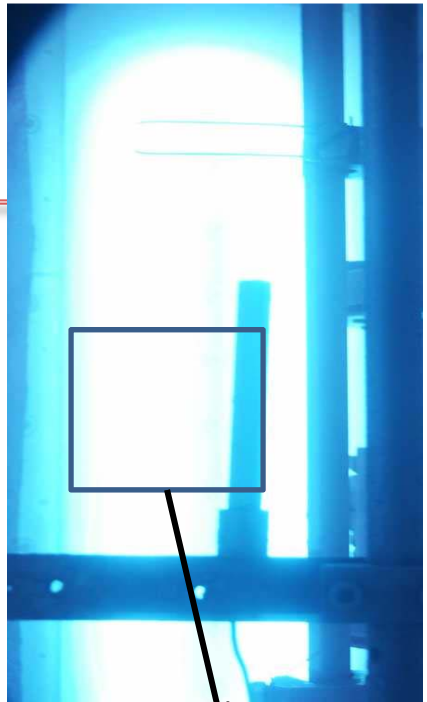
June 5, 2012: Did you miss it?
No Problem. Next chance in 2117.

Venus in Front of the Sun…
…and there is more: *plasma imaging*!

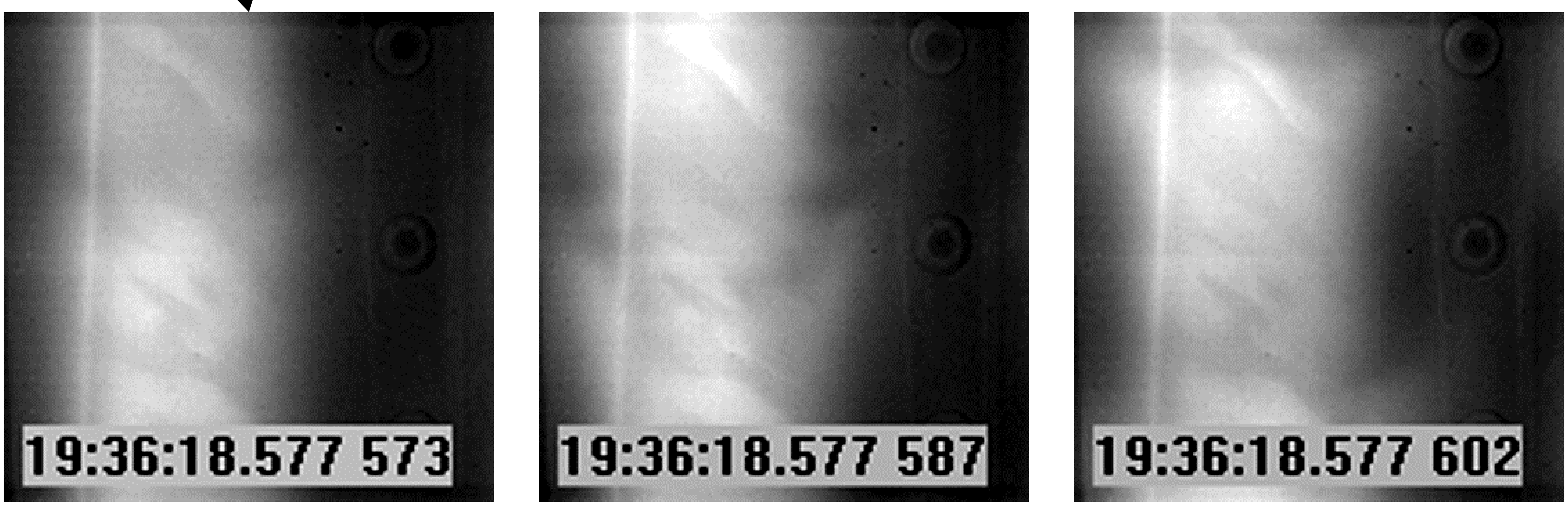


June 5, 2012
The planet Venus at the start of its transit of the sun. One of the rarest astronomical events occurs on Tuesday and Wednesday when Venus passes directly between the sun and Earth, a transit that won't occur again until 2117.
NASA / Reuters

Fast Camera Observations of HIPIMS Discharges Gave Early Indication for Structure in Plasma

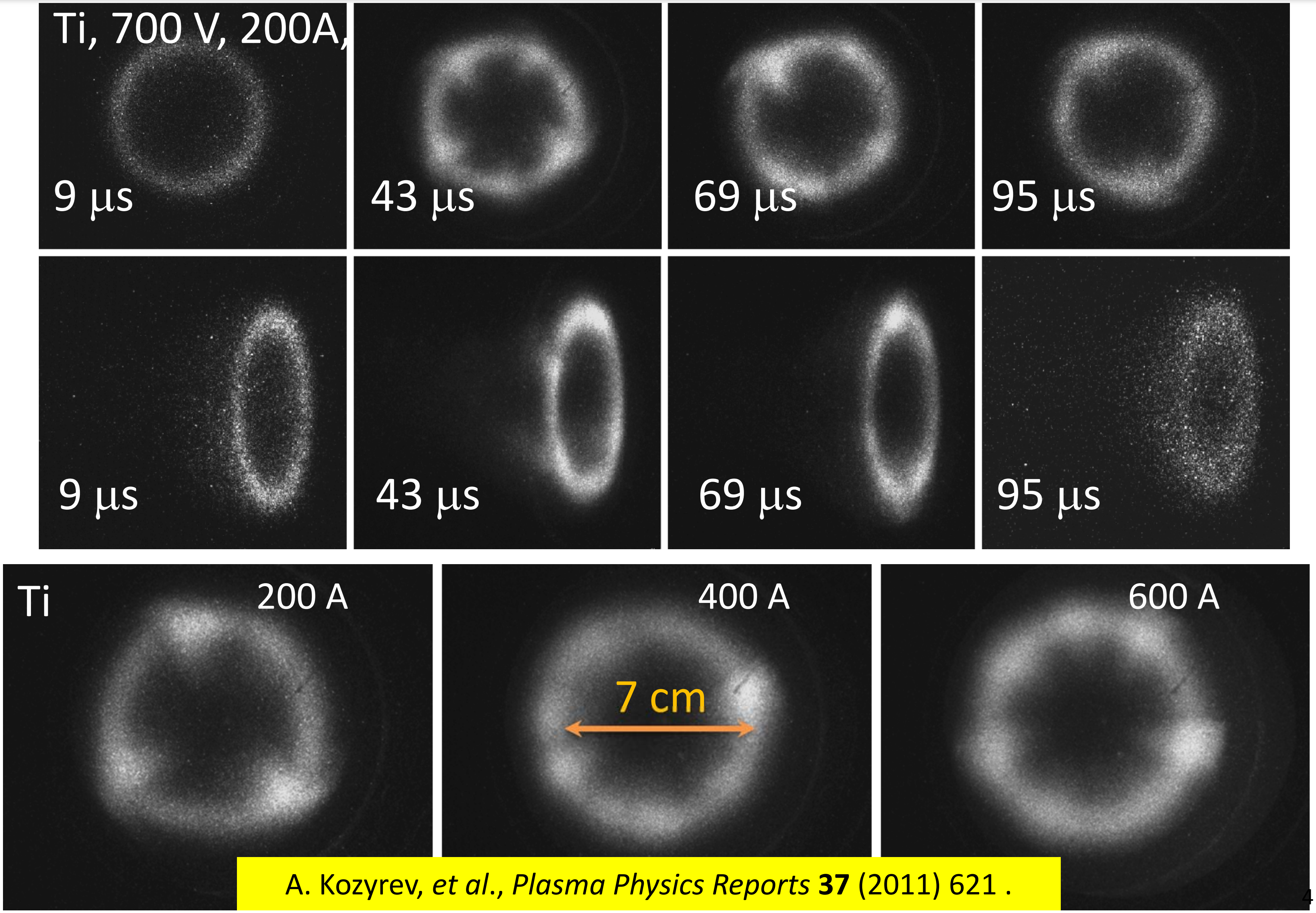


600 mm x 200 mm Vanadium target



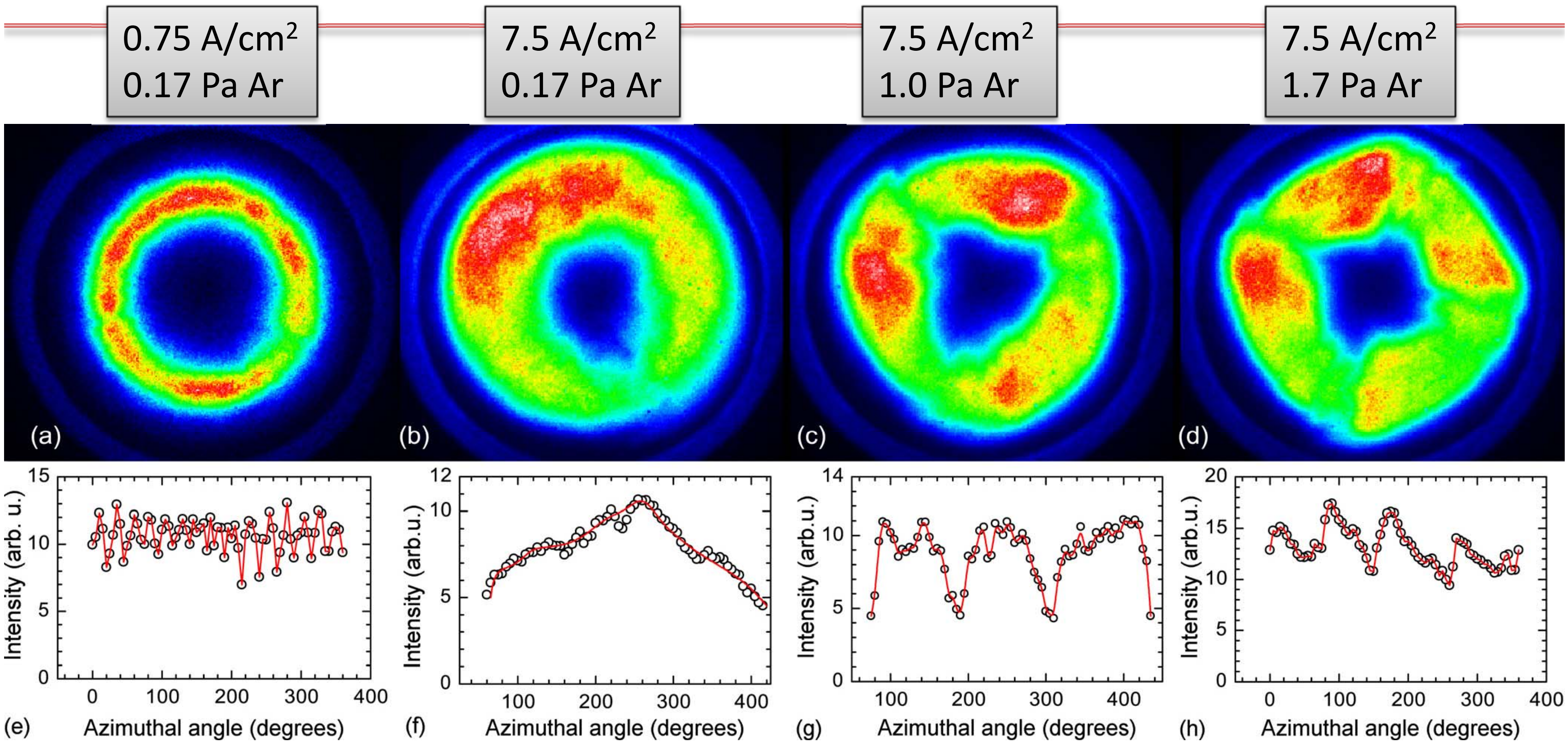
A.P. Ehiasarian, Chapter 2: HIPIMS, R. Wei (Ed.), Plasma Surface Engineering Research and its Practical Applications, Research Signpost, Kerala, (2008)

Moving Ionization Zones: Observed universally



A. Kozyrev, *et al.*, *Plasma Physics Reports* **37** (2011) 621 .

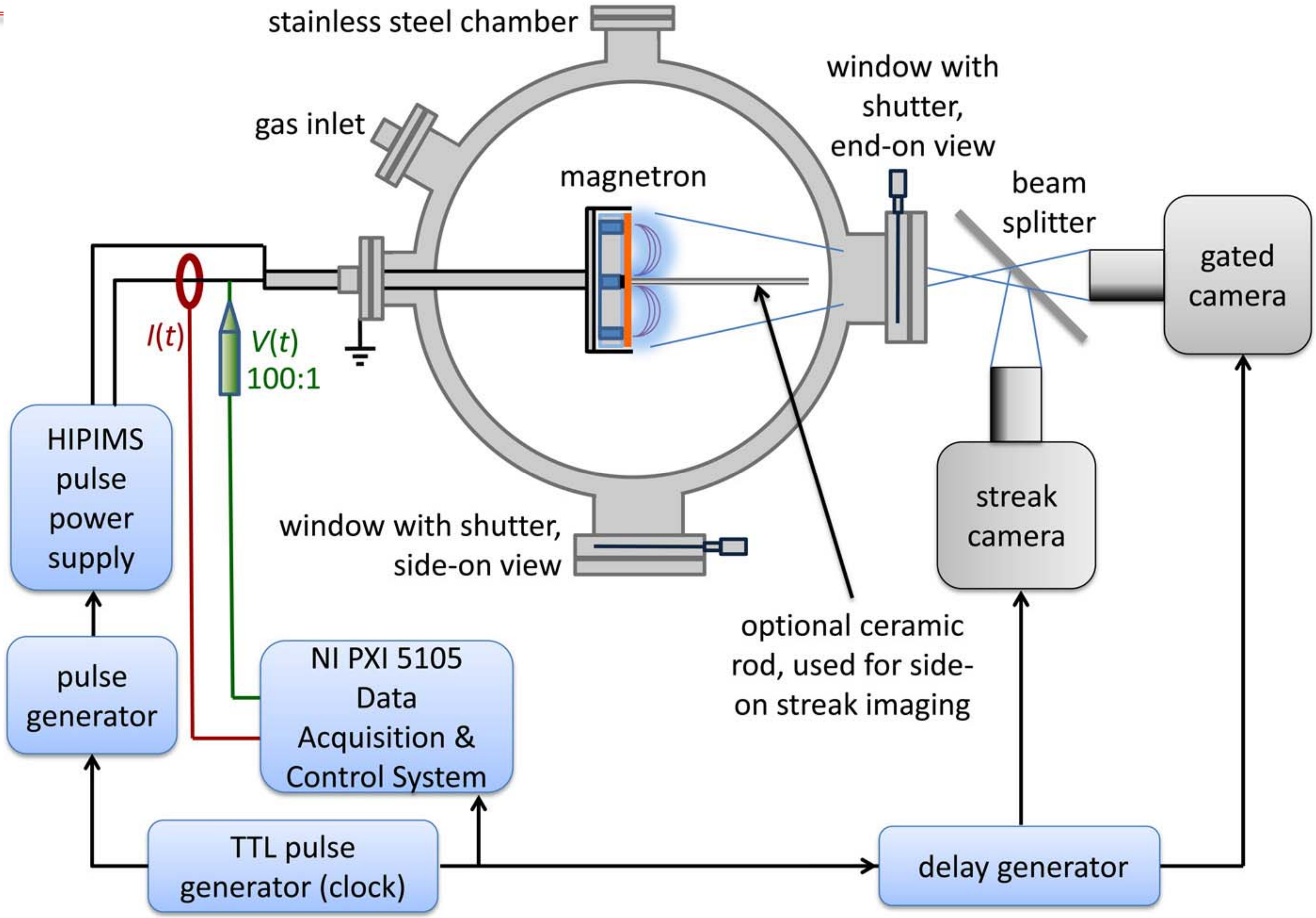
Self-organization in HIPIMS Plasma (Univ. Bochum)



- plasma zones rotate in ExB direction with about 10^4 m/s
- particle ejection ~ U_{fl} oscillations,
- probes pick up oscillations with ~ 200 kHz

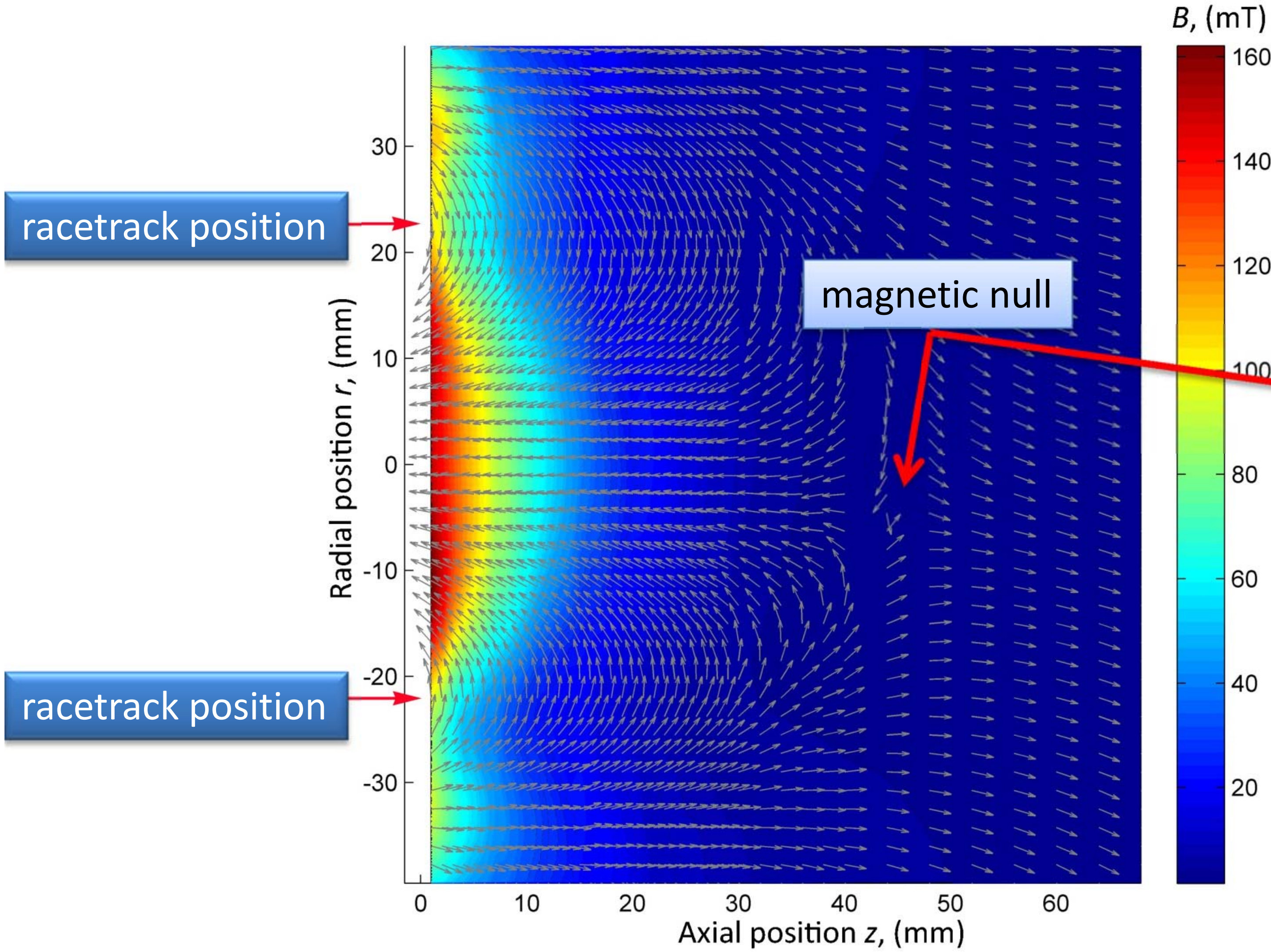
Ehiasarian, *et al.*, *Appl. Phys. Lett.* **100** (2012) 114101.

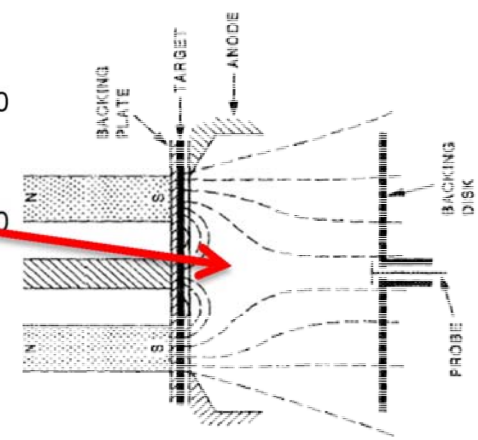
Fast Camera Observations of HIPIMS Discharges



A. Anders, *et al*., *J. Appl. Phys*. **111** (2012) 053304

Unbalanced Magnetron in Berkeley Experiments

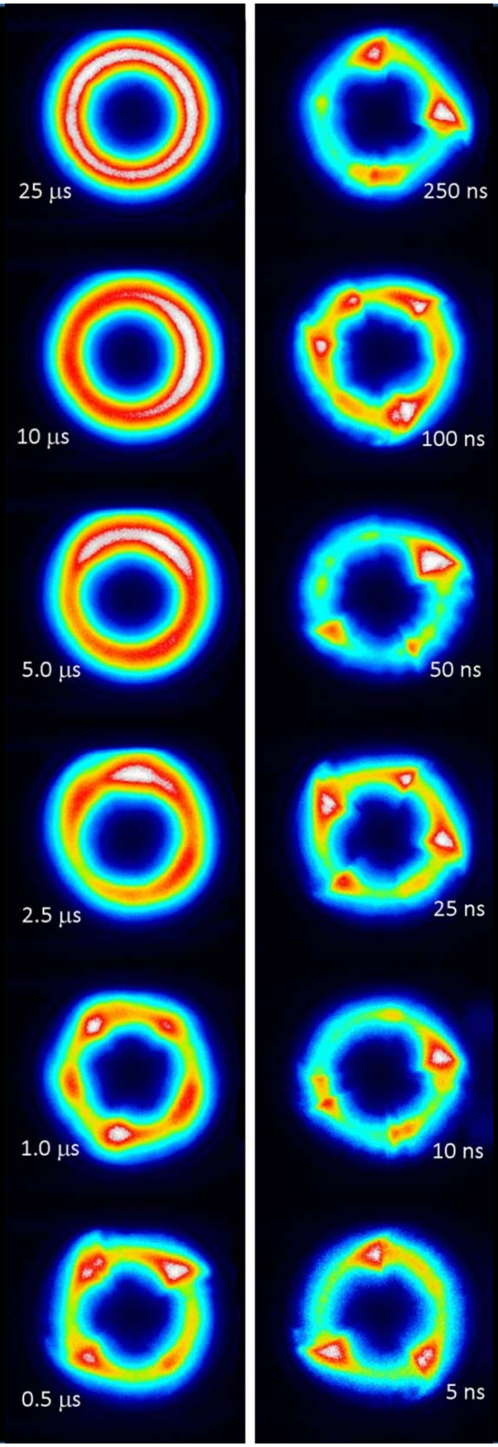




Windows and Savvides, *J. Vac. Sci. Technol. A* 4 (1986) 453.

A. Anders, *et al.*, *J. Appl. Phys*. **111** (2012) 053304

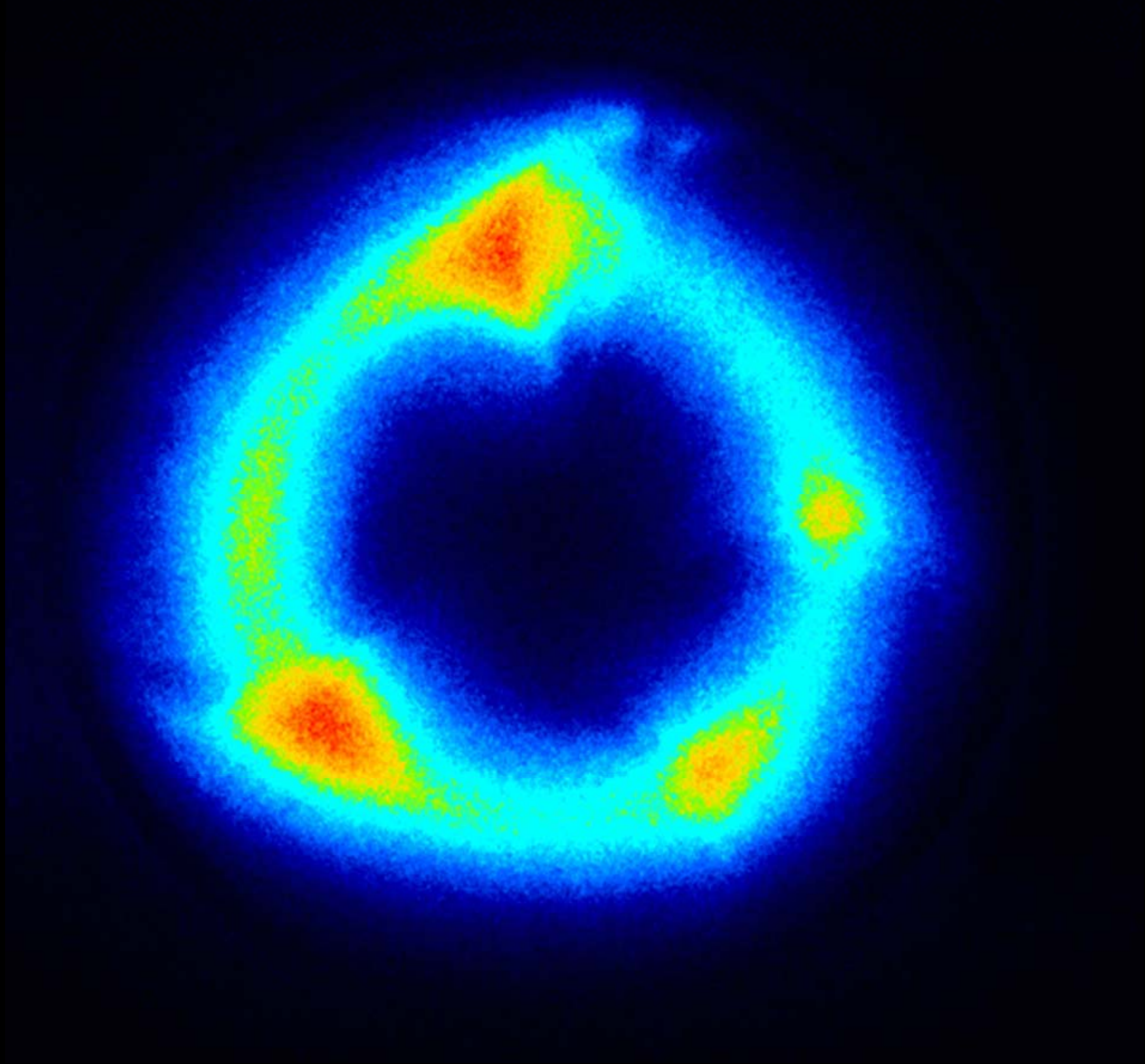
Moving Ionization Zones



- 3” Nb target, peak current ~ 200 A
- reduction of image exposure time gives immediate clues on rotational speed → ~ 10^4 m/s

A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

Localization of Ionization and Self-Organization

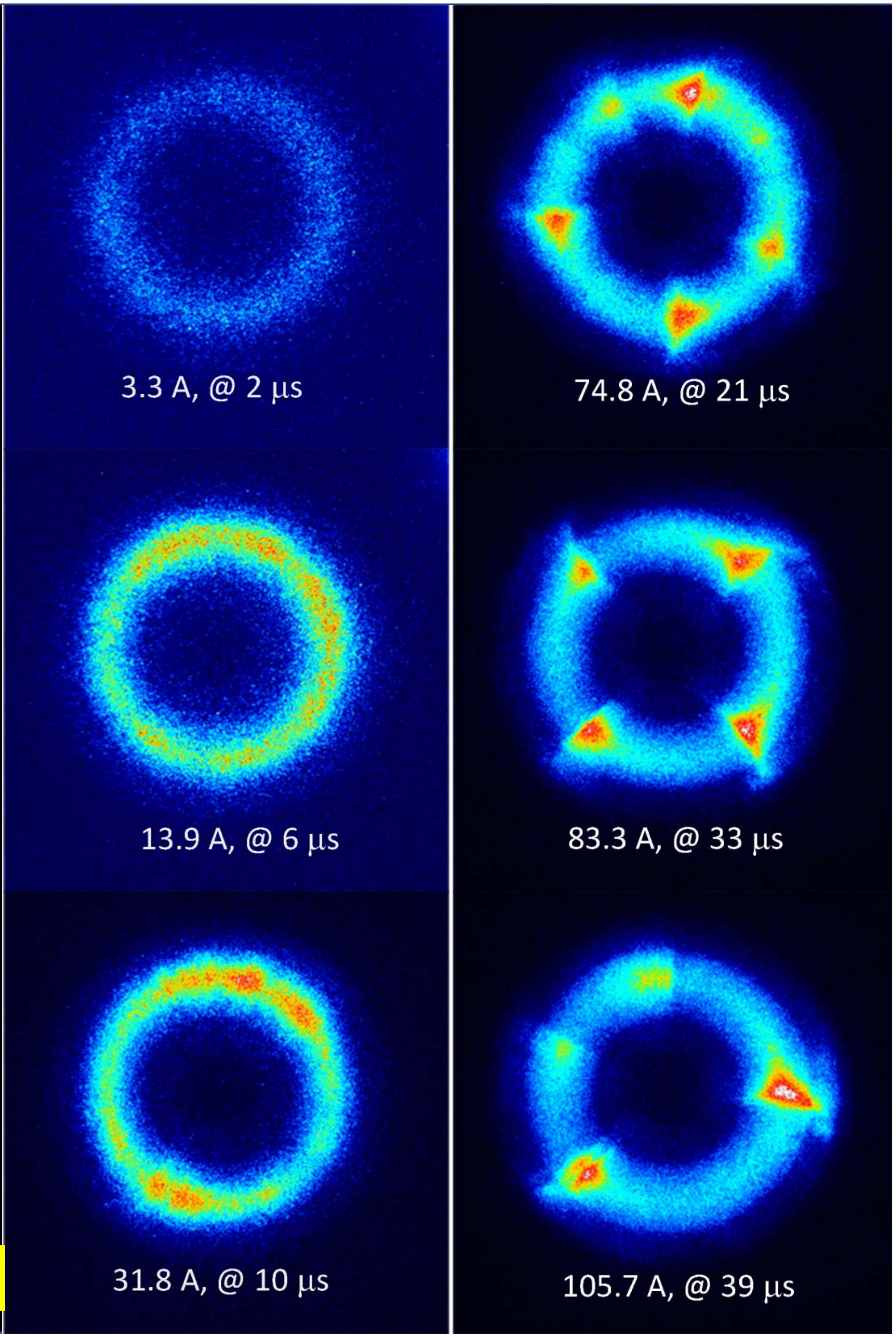


A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

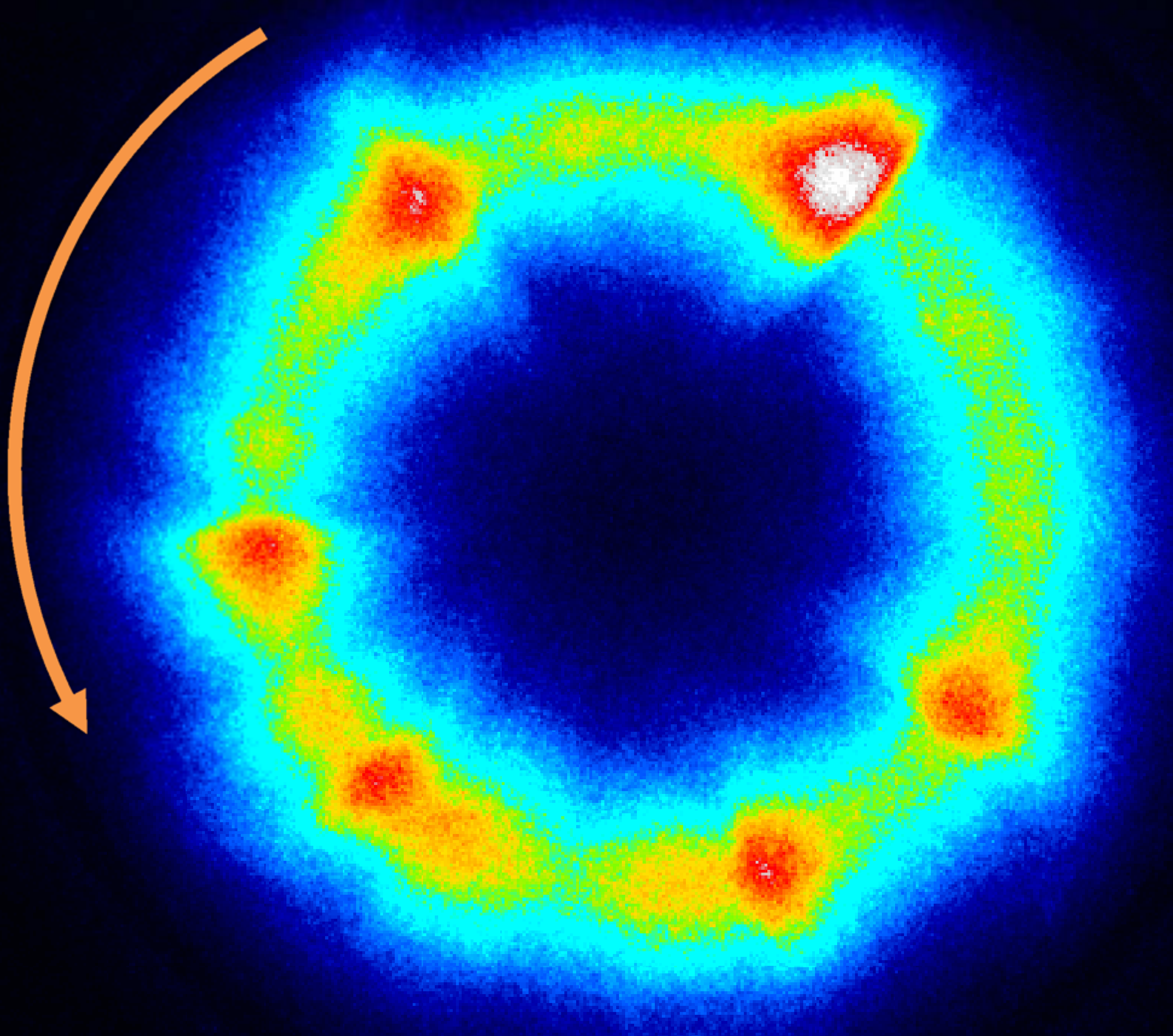
Ionization Zones: Evolution with Time and Current

- no ionization localization when current is just a few A
- at the 10 A level, bunching can be seen
- at the 100 A, well defined ionization zones exists

A. Anders, *Appl. Phys. Lett.* **100** (2012) 224104.



Interesting Clues: Wake of Ionization Zones



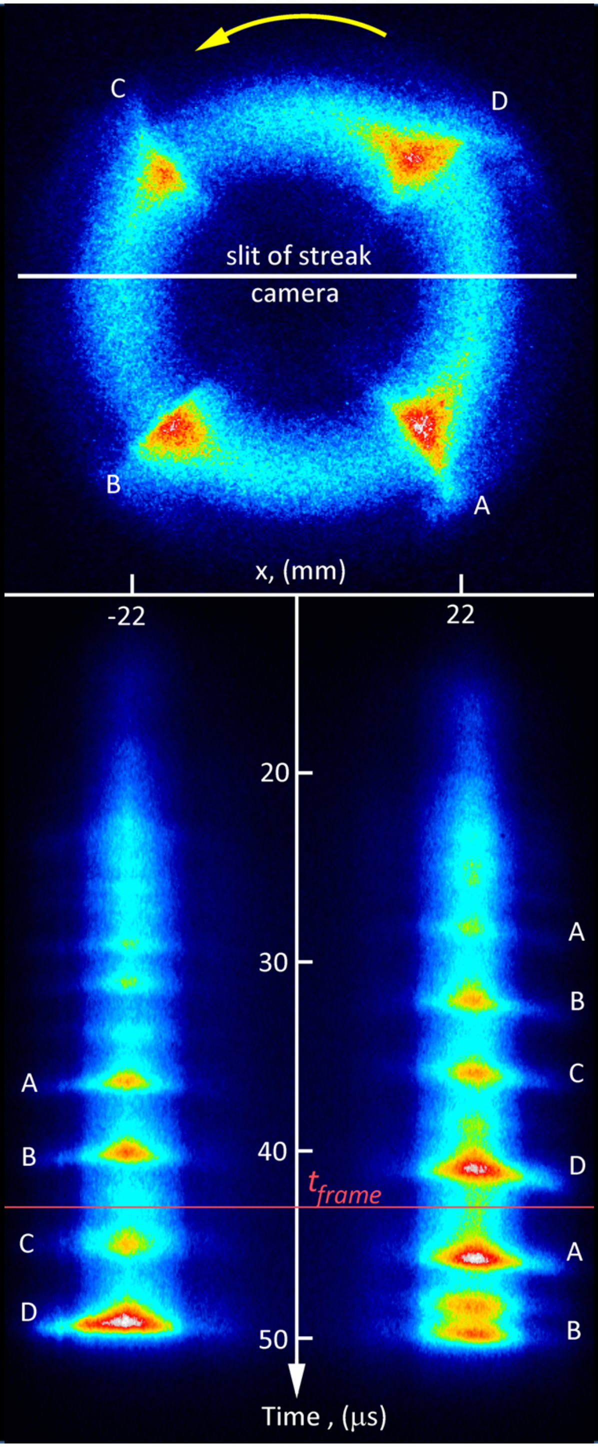
intense, dense zones tend to have more extended wakes

Nb in Kr 0.27 Pa @ 50 μs, 137.7 A

Frame and Streak Camera Combination

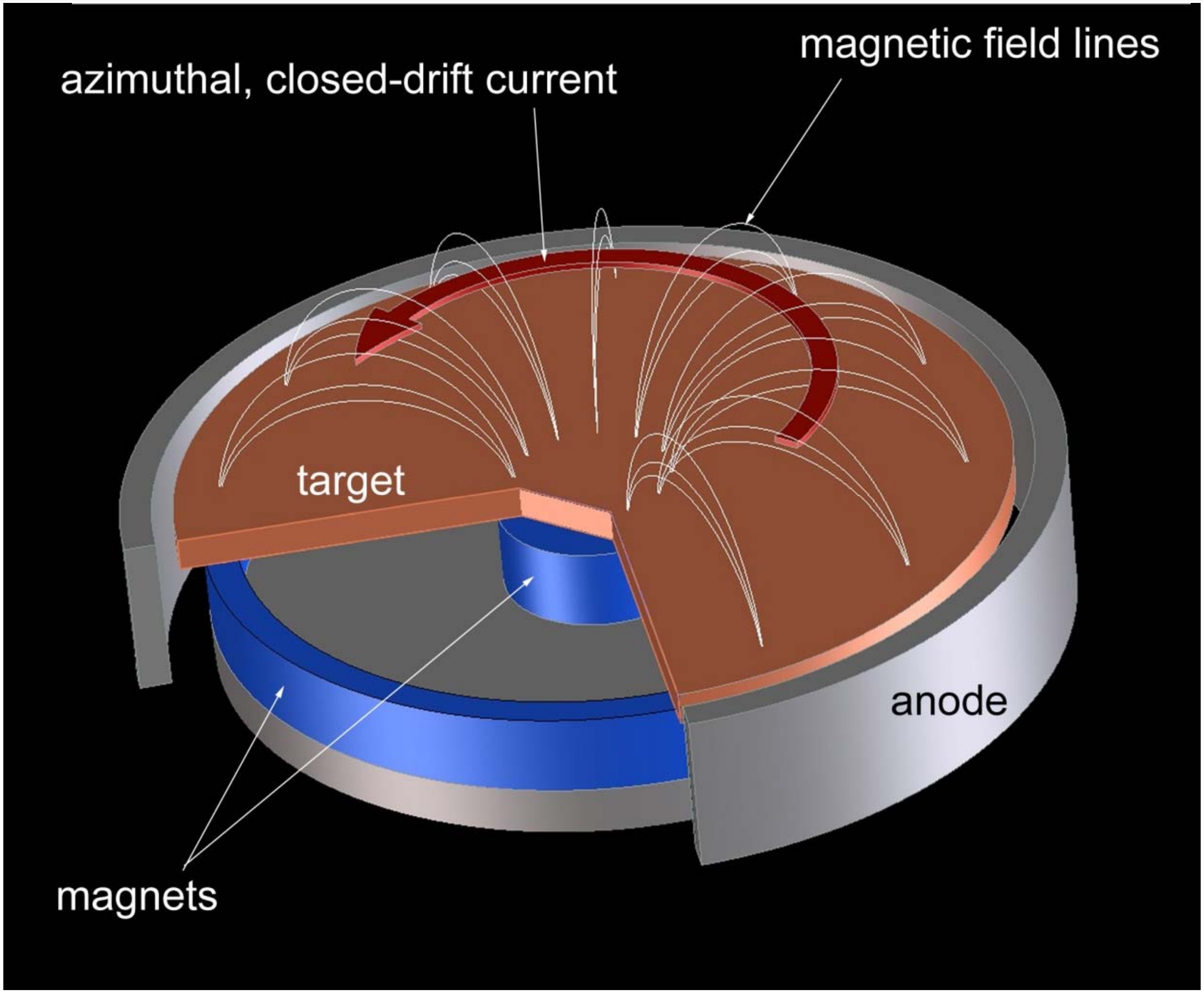
end-on view
frame image

end-on view
streak image



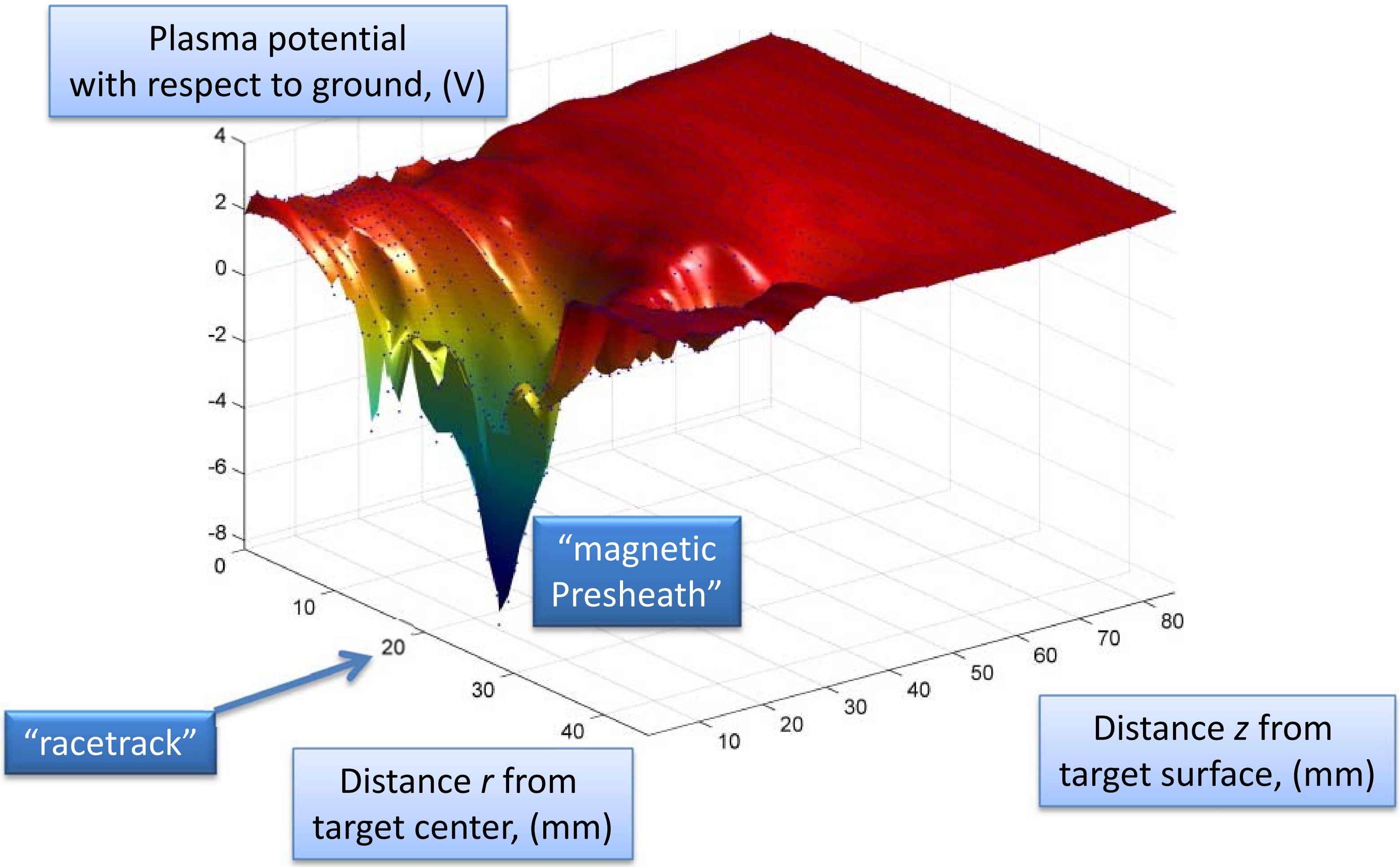
A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

Magnetron as an Electron Trap



Pulse-Averaged Electric Field in Plasma with Magnetic Field

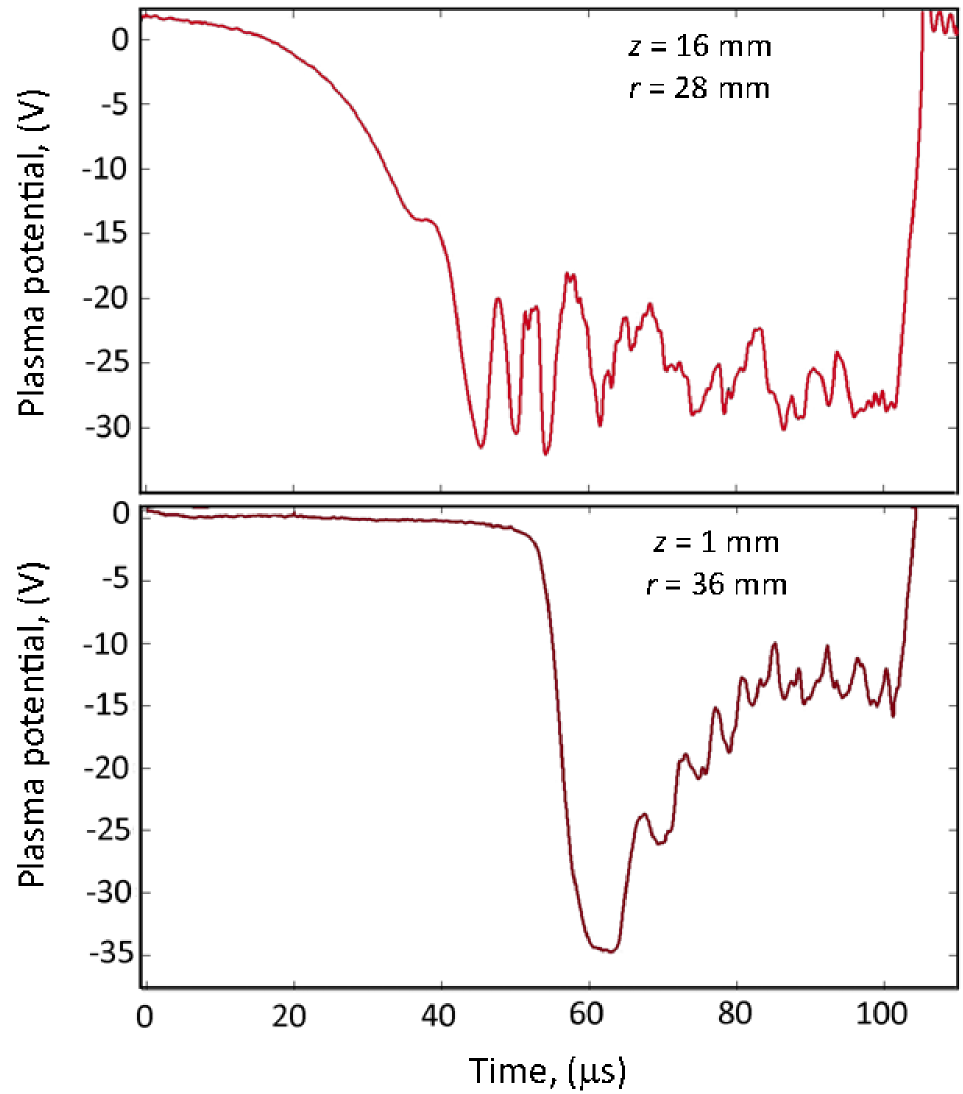
Plasma potential in front of a racetrack of a magnetron (Nb sputtered in Ar), measure with emissive probe → Average ion acceleration mostly toward to target



J. Sanders, *et al., Rev. Sci. Instrum.* **82** (2011) 093505;   A. Rauch *et al., J. Appl. Phys*. **111** (2012) 083302.

Electrical potential shows patterns

- All types of probes (floating, emissive, ion collectors, pick-up) show signals correlated with ionization zones.
- evidence for azimuthal electric field



A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

Strong azimuthal density gradient implies azimuthal electric field and formation of jets

$$\mathbf{j}_{Hall} = -en_e \mathbf{v}_{Hall}$$

current equation

$$\frac{\partial}{\partial \theta}\left(n_e v_{e\theta}\right) = 0$$

continuity equation

azimuthal coordinate

$$m_e v_{e\theta} \frac{\partial v_{e\theta}}{\partial \theta} = -eE_\theta$$

momentum equation

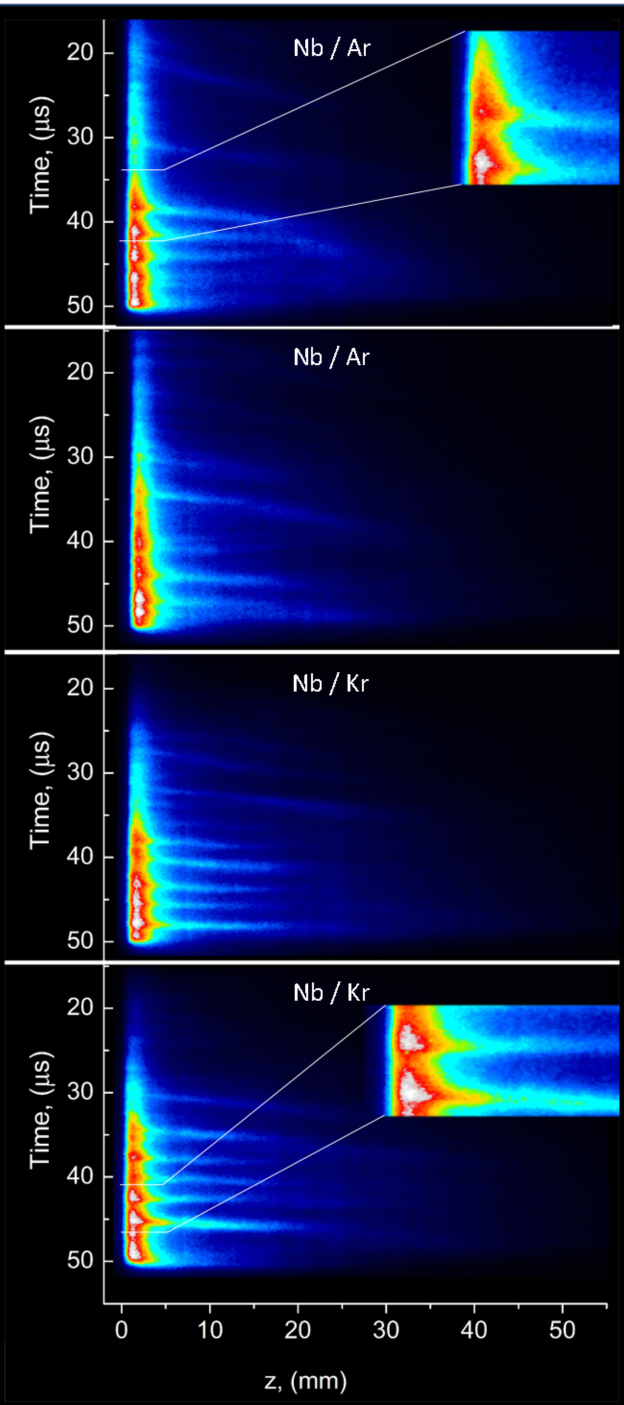
$$\mathbf{v}_z = \mathbf{E}_\theta \times \mathbf{B} / B^2$$

new ExB drift for electrons caused by new electric field component → electrons can move in z-direction away from target!

Side-on view streak

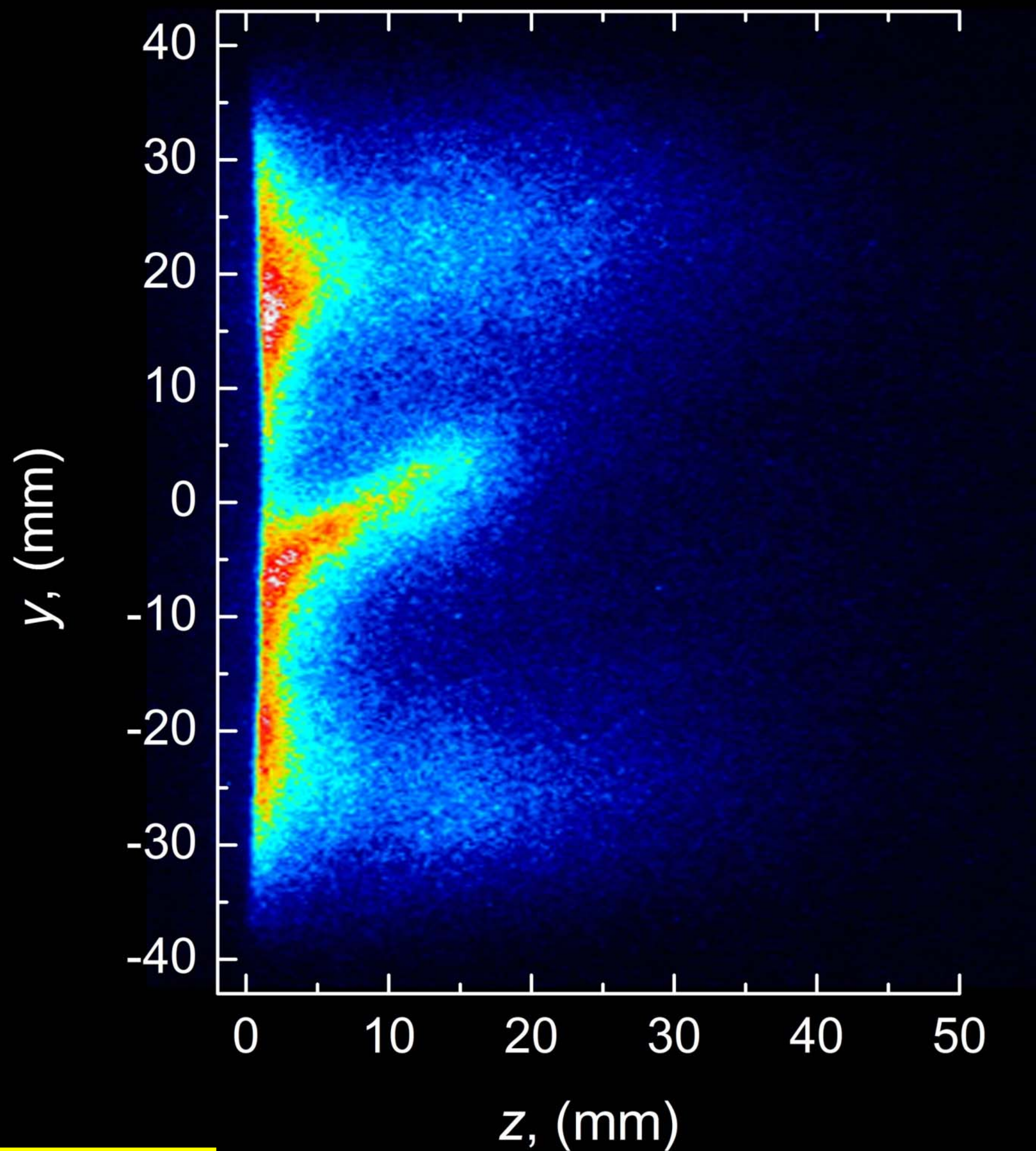
most intense jet formation at the location of strongest azimuthal gradient

$$m_e v_{e\theta} \frac{\partial v_{e\theta}}{\partial \theta} = -eE_\theta$$



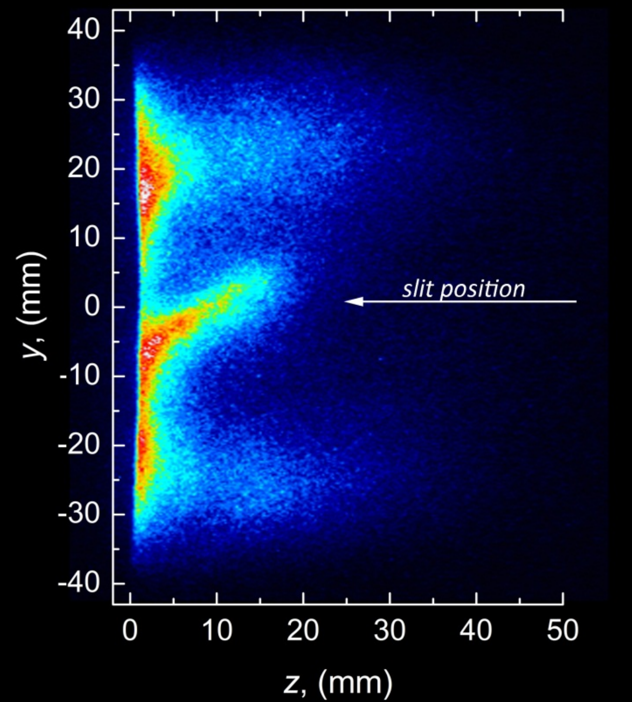
A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

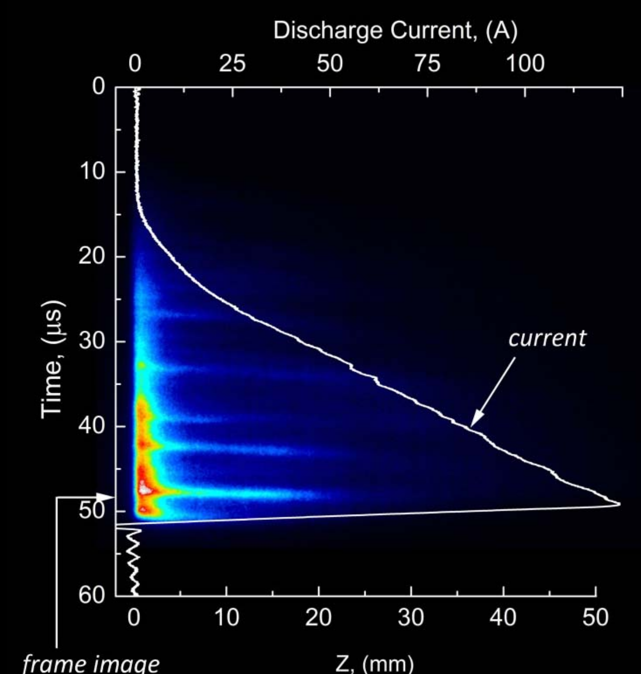
Side-on view frame



A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

Simultaneous
side-on frame view
and
side-on streak view

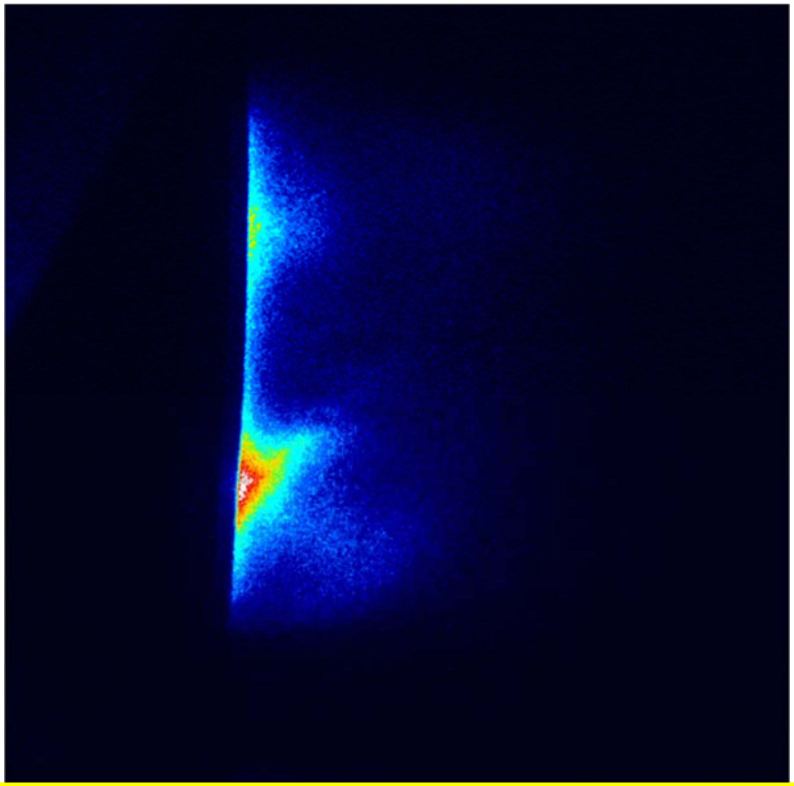




A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

Implications of jet formation: Enhanced "anomalous" discharge current

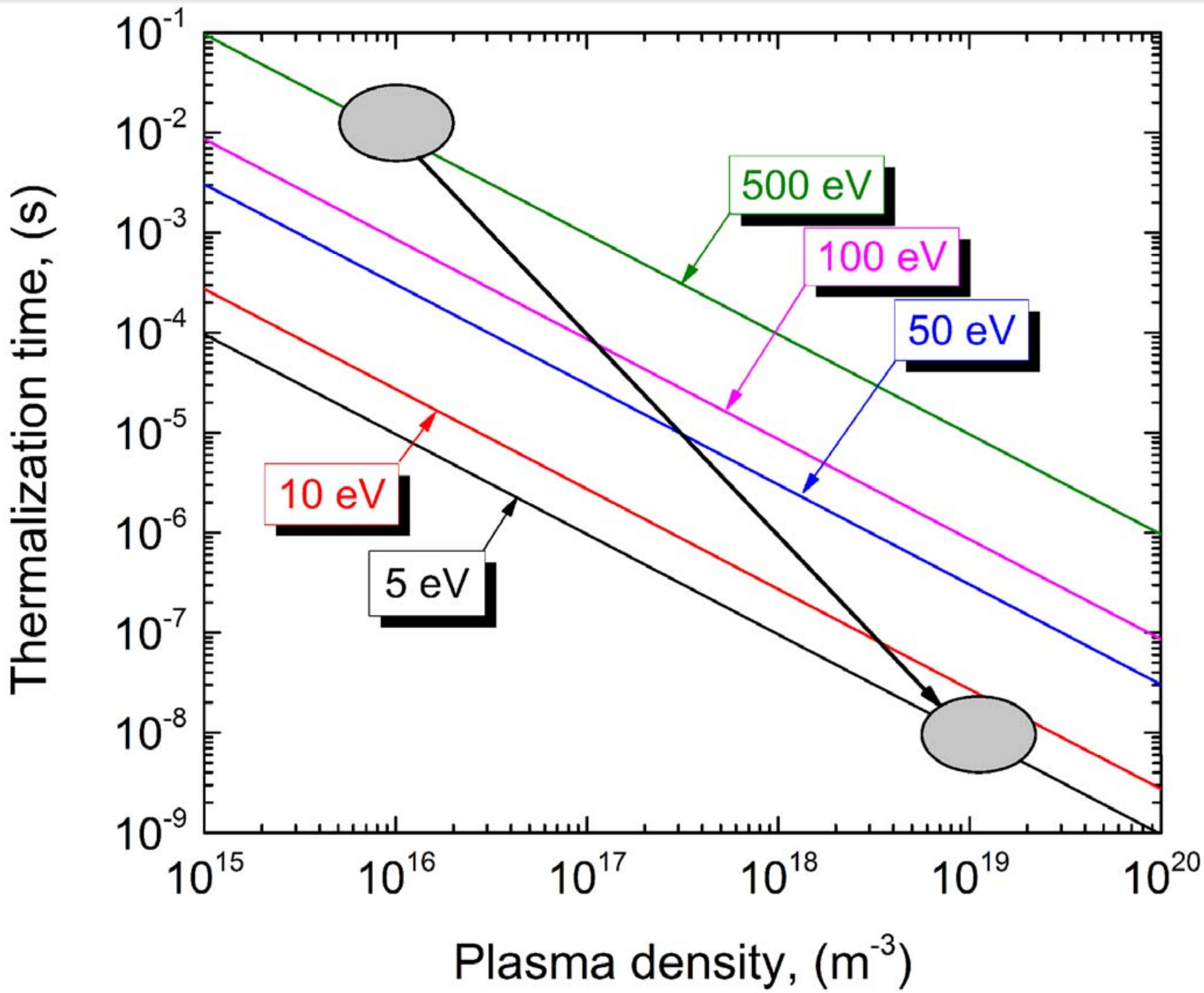
- classical cross-B transport is ~ B^{-2}
- Bohm (1949): semi-empirical cross-field transport ~ B^{-1}
- Magnetron and Hall thrusters and any of the gridless ion sources: "anomalous" transport. Facilitated by plasma fluctuations and instabilities.
- HIPIMS: ionization zones produce azimuthal electric field and electron jets



A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

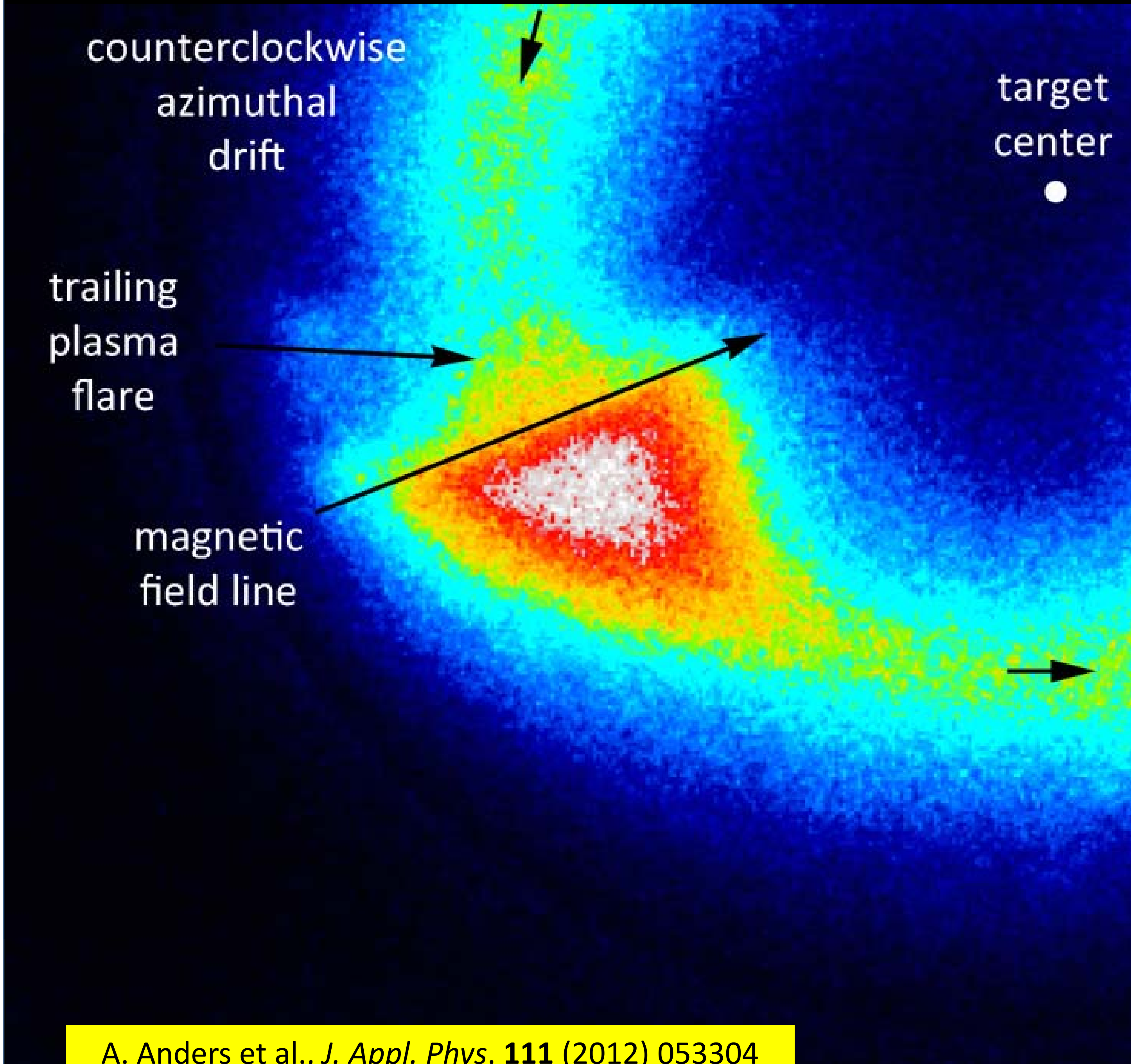
“Stopping power” of plasma for drifting electrons

many orders of magnitude!



A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

Shape of Ionization Zone



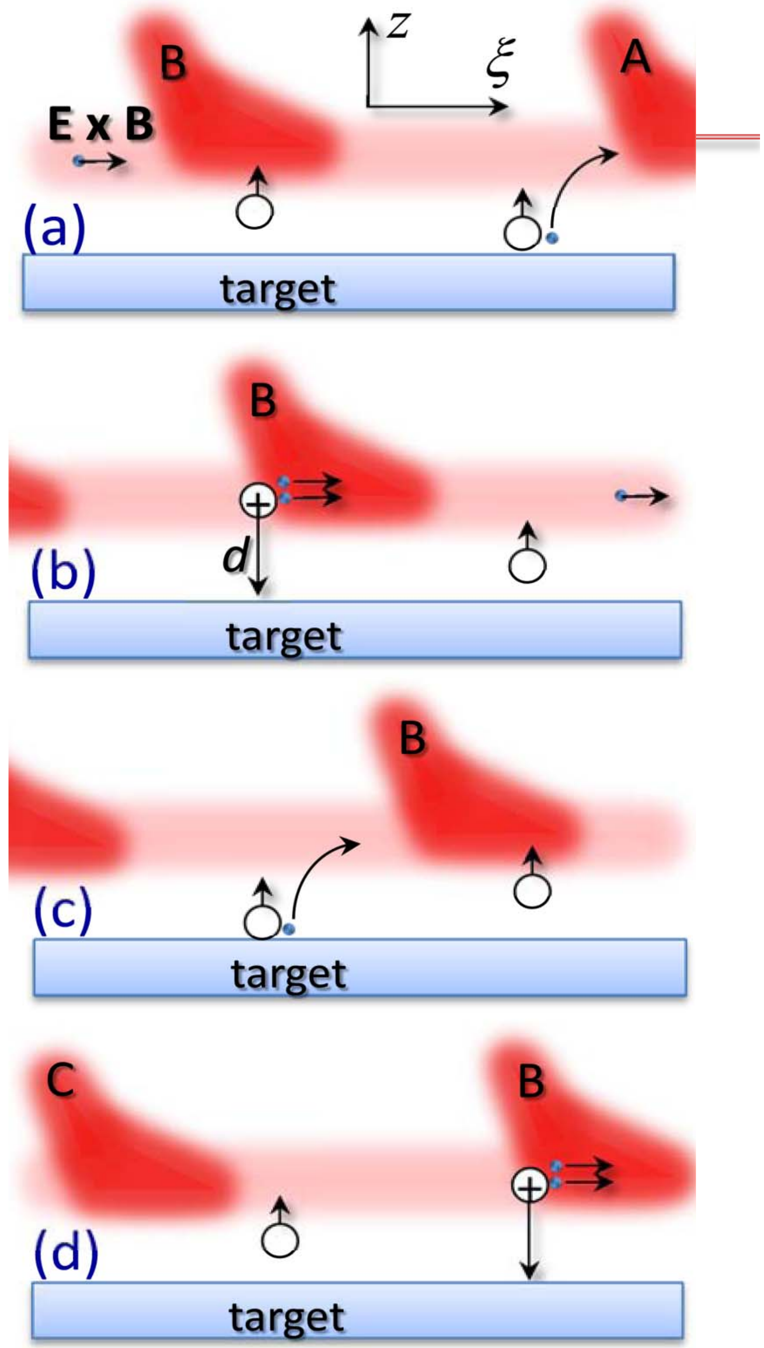
A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

Motion and Self-Organization of Ionization Zones

1. secondary electrons help amplifying the *same* zone that was the origin of the primary ion

2. sputtered atoms help amplifying the zone *following* the one of the primary ions

A. Anders, *Appl. Phys. Lett.* **100** (2012) 224104.



Velocity of the Ionization Zones

$$v_{IZ} = d\xi_{IZ} / dt$$

$$v_{IZ} \approx \Delta\xi_{IZ} / \Delta t_i$$

$$\Delta\xi_{IZ} \approx 2r_{g,e} = \frac{2m_e u_{e\perp}}{eB}$$

thin slab or slice of plasma about to be removed from the plasma region, characteristic lengths is 2 r_{ge}

$$\Delta t_i \approx \left(\frac{2d}{E_{mps}} \frac{m_i}{Qe} \right)^{1/2}$$

time of removal of ions is determined by inertia of ions accelerated in the local electric field

$$v_{IZ} = \frac{2}{B} \left(\frac{Q V_{sheath} E_{mps}}{d} \frac{m_e}{m_i} \right)^{1/2}$$

A. Anders, *Appl. Phys. Lett.* **100** (2012) 224104.

Velocity of the Ionization Zones

$$v_{IZ} = \frac{2}{B}\left(\frac{QV_{sheath}E_{mps}}{d}\frac{m_e}{m_i}\right)^{1/2}$$

Let's compare with experiments

- $B = 60$ mT
- $Q = 1$
- $V_{sheath} = 400$ V
- $E_{mps} = 5 \times 10^{4}$ V/m
- $m_i(\mathrm{Nb}) = 93 \times 1.66 \times 10^{-27}$ kg and $m_i(\mathrm{Ar}) = 40 \times 1.66 \times 10^{-27}$ kg
- $m_e = 9.1 \times 10^{-31}$ kg
- $d = 2$ mm

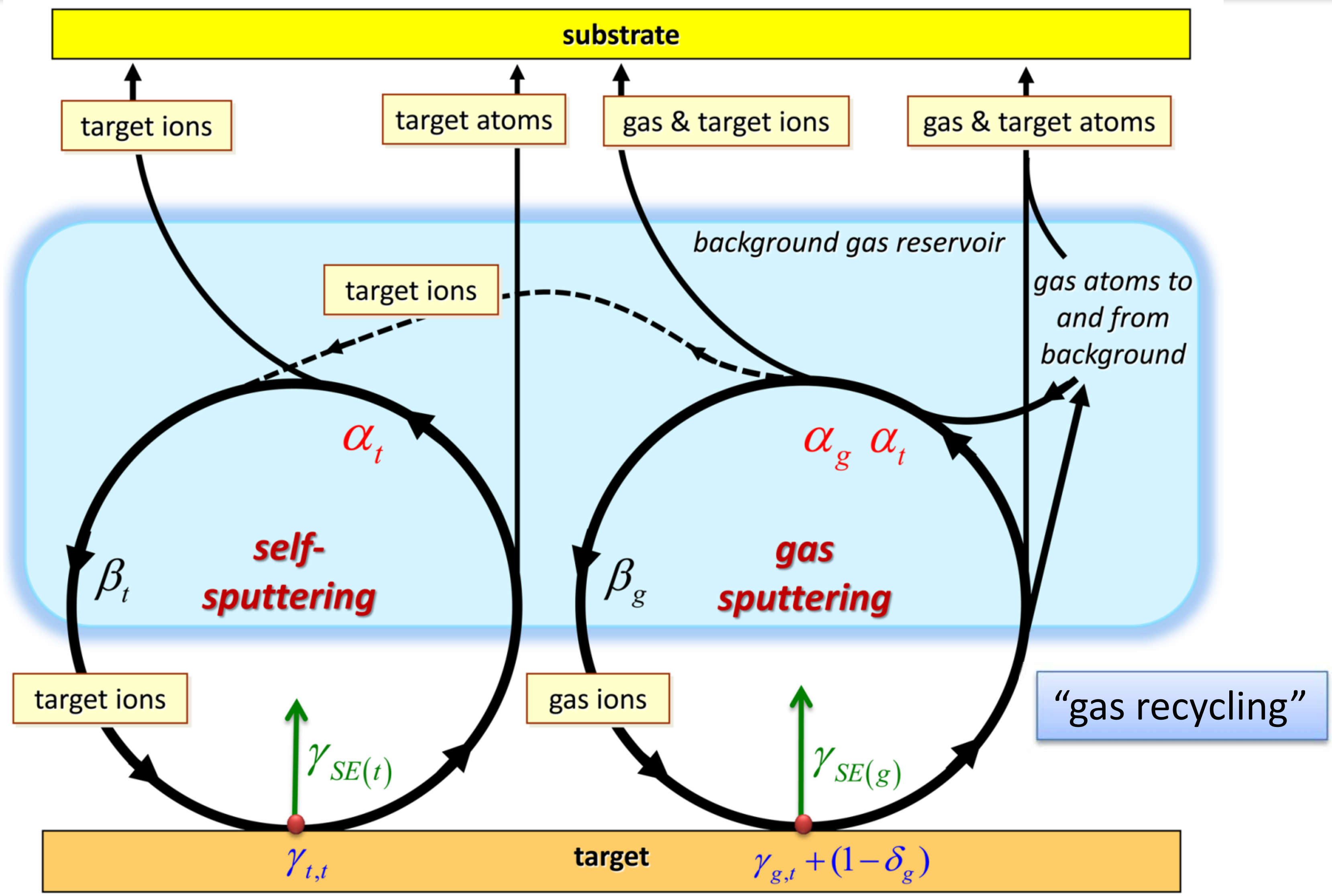
gives $\Delta t_i = 0.2 - 0.3\ \mu\mathrm{s}$ and $v_{IZ} \approx 10^4\ \mathrm{m/s}$

Velocity of Ionization Zones: Experiments

target			gas		observed azimuthal velocities (m/s)
	atomic mass (amu)	surface binding energy (eV)		atomic mass (amu)	
Al	30.0	3.19	Ar	39.9	8100 ± 300
Al	30.0	3.19	Kr	83.8	5400 ± 300
Cu	63.5	3.48	Ar	39.9	4200 ± 400
Cu	63.5	3.48	Kr	83.8	4200 ± 150
Nb	92.9	5.93	Ar	39.9	7000 ± 2000
Nb	92.9	5.93	Kr	83.8	5700 ± 700
W	183.4	8.7	Ar	39.9	6250 ± 300
W	183.4	8.7	Kr	83.8	4000 ± 300

A. Anders et al., *J. Appl. Phys*. **111** (2012) 053304

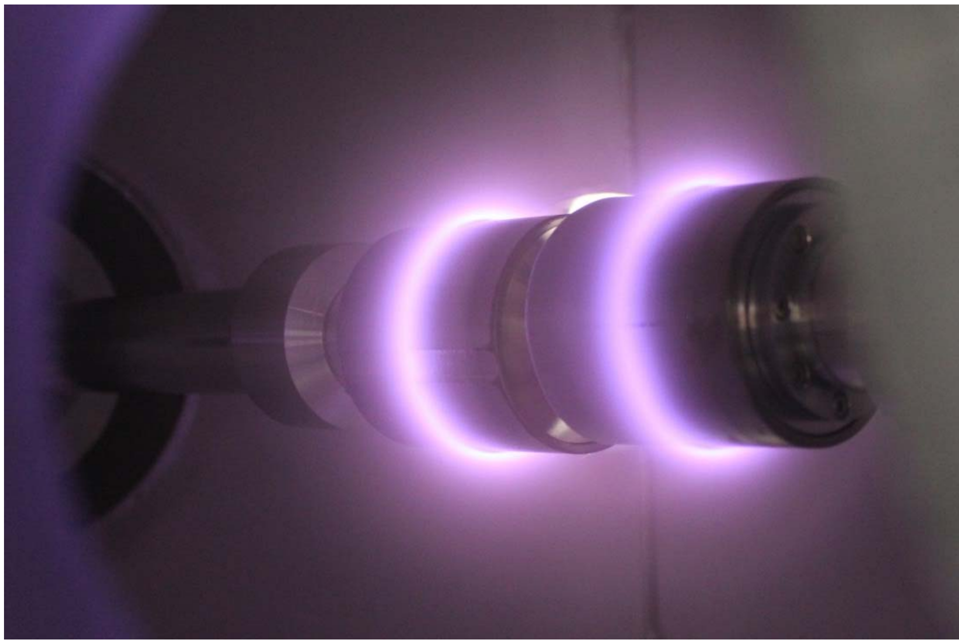
Mixed Metal / Gas Sputtering in HIPIMS



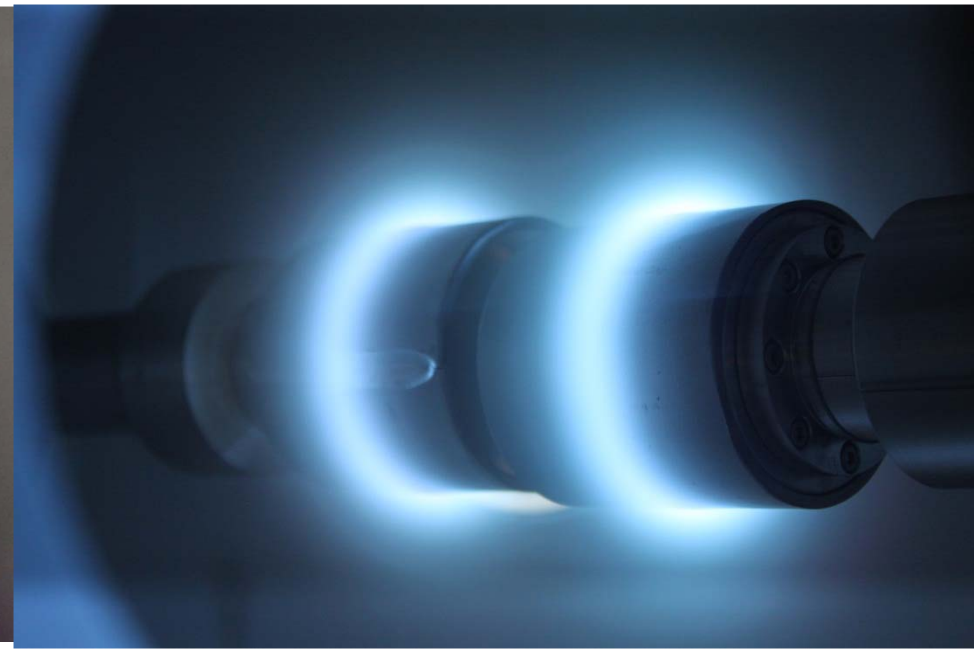
A. Anders, et al., J. Phys D: Appl. Phys. 45 (2012) 012003.

Dual-Magnetron HIPIMS
A Promising Coatings Technology for SRF Cavities

- experiments so far focused on plasma with planar magnetrons
- cylindrical magnetrons are suited for cavity coatings → see talk by Rueben Mendelsberg



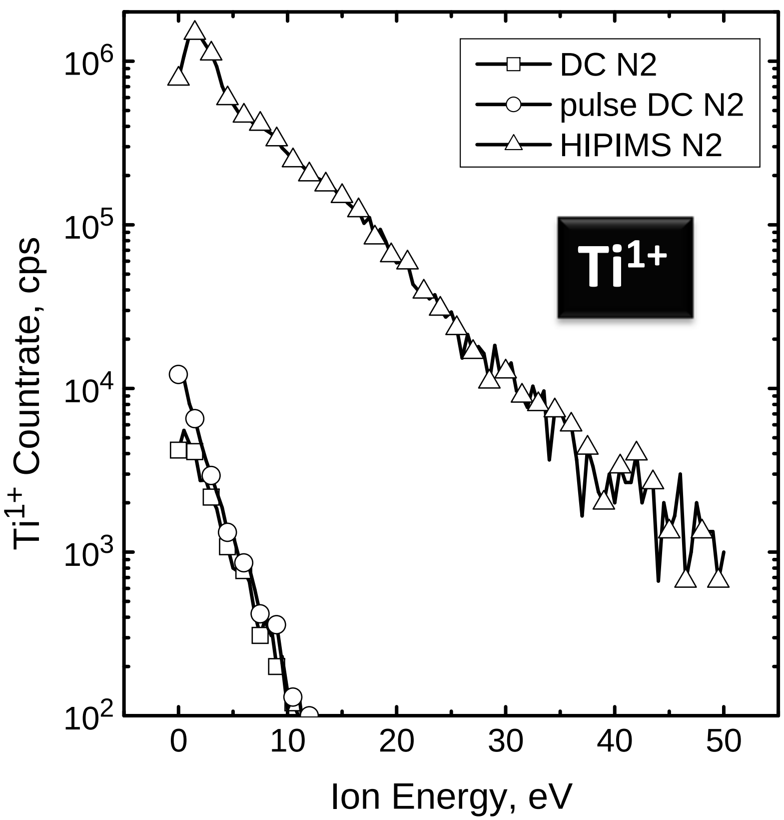
- dual cylindrical magnetron in at relatively low power sputtering mode
- Dominated by argon emission



- dual cylindrical magnetron in high power mode (above runaway threshold)
- Dominated by niobium emission

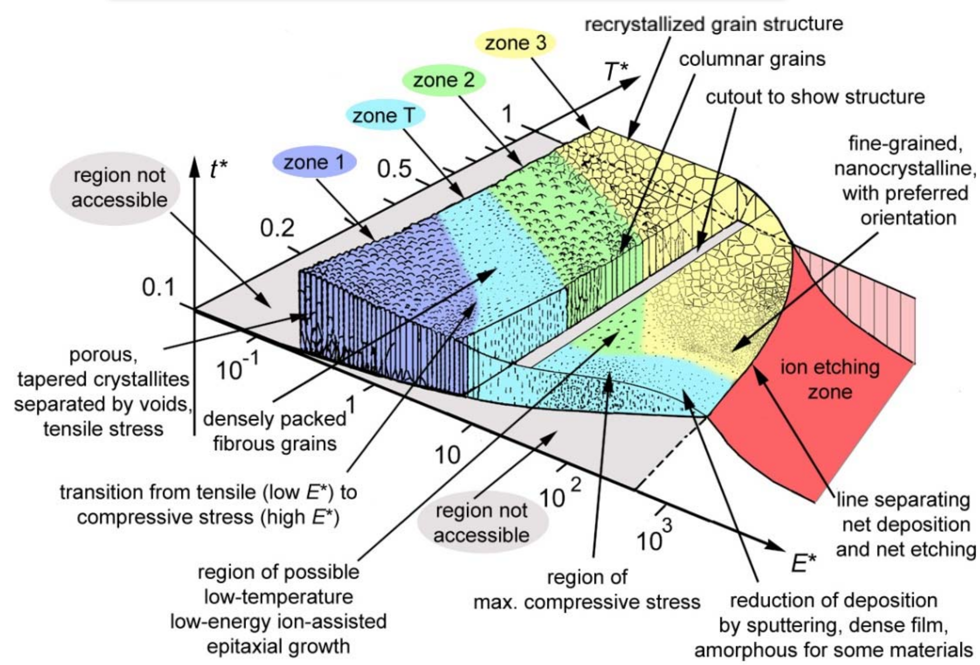
Why are Ionization Zones important for SFR?

Ion Energy Distribution Function



Enhanced power density is the key to the desired ionization of sputtered material: films are denser, smoother, and some grain texture control is possible.

"Structure Zone Diagram"



A. P. Ehiasarian, *et al.*, Plasma Processes and Polymers **4** (2007) S309

A. Anders, Thin Solid Films 518 (2010) 4087.

Summary

1. Positive feedback loop between electron mean free path and ionization leads to "bunching" of plasma in **ionization zones**
2. Ionization zones move in ExB direction because ions are "evacuated" from ionization zones by electric field, exposing new neutrals to ionization by drifting electrons
3. electrons drift according to the local E and B fields, perpendicular to both, and produce electron jets related to the azimuthal electric field of the plasma zone
4. the physically relevant power density of HIPIMS is much higher than the typically quoted average power density
5. **Ionization zones explain why HIPIMS works as observed, and offer "energetic condensation" in the context of sputtering and SRF coatings.**