AVS Seminar - Plasma Applications Group

Santa Clara, CA, May 12, 2011

High Power Impulse Magnetron Sputtering:

A journey from early research to advanced processing

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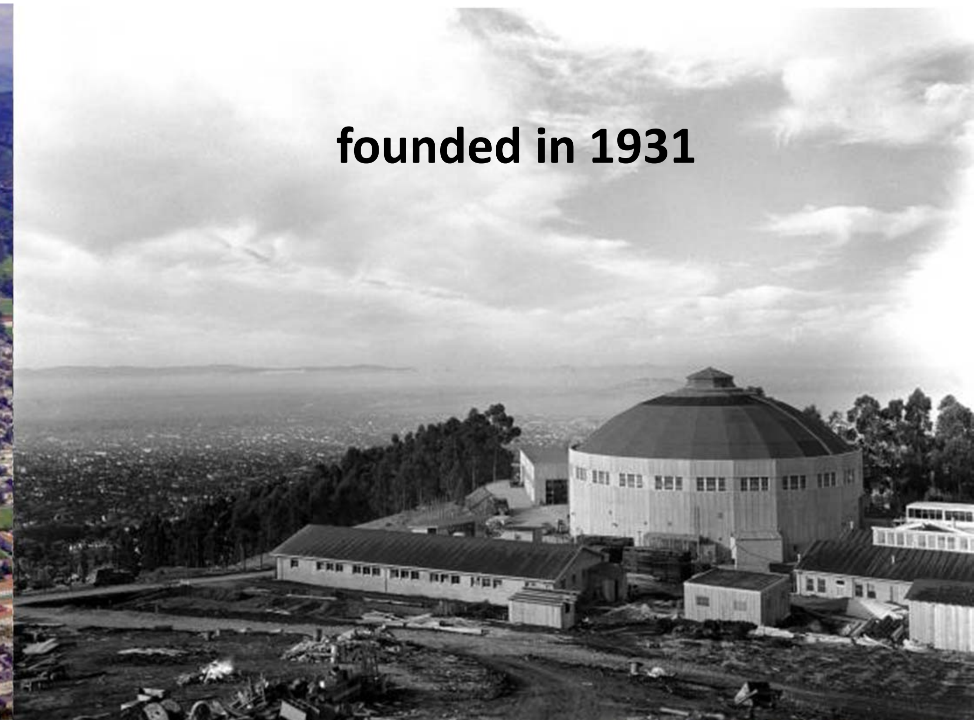
BERKELEY LAB


Berkeley Lab


founded in 1931


here are 7 (of now 10) Nobel Laureates


PAG @ Berkeley
CALIFORNIA

Story Line

- Define HIPIMS. Why do we care?
- A very brief journey through 250 years of history
- HIPIMS: state of the art

HIPIMS: A Form of "Ionized Sputtering." One Approach to "Energetic Deposition."

"What distinguishes HIPIMS from the long-practiced pulsed sputtering?"

Technical Definition:
HIPIMS is pulsed sputtering where the peak power exceeds the average power by typically two orders of magnitude.

(implies a long pause between pulses, hence the term "impulse")

Physical Definition:
HIPIMS is pulsed sputtering where a very significant fraction of the sputtered atoms becomes ionized.

(implies that self-sputtering occurs, which may or may not be sustained by target ions)

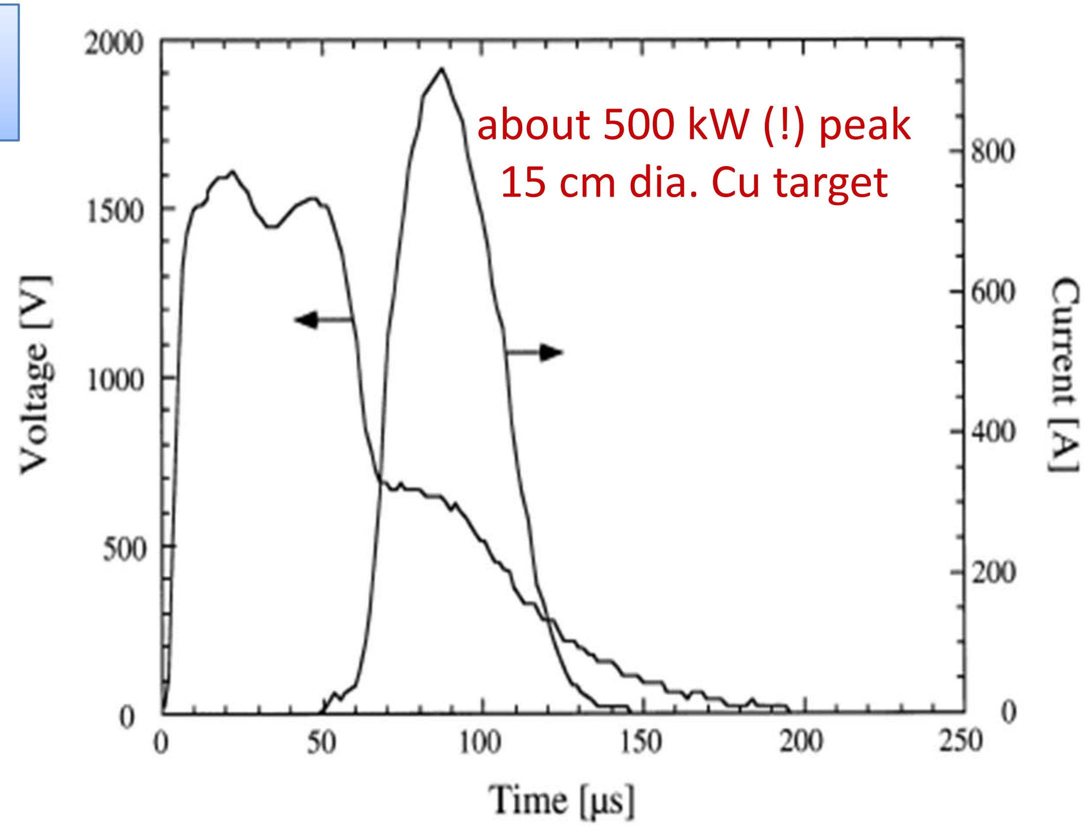
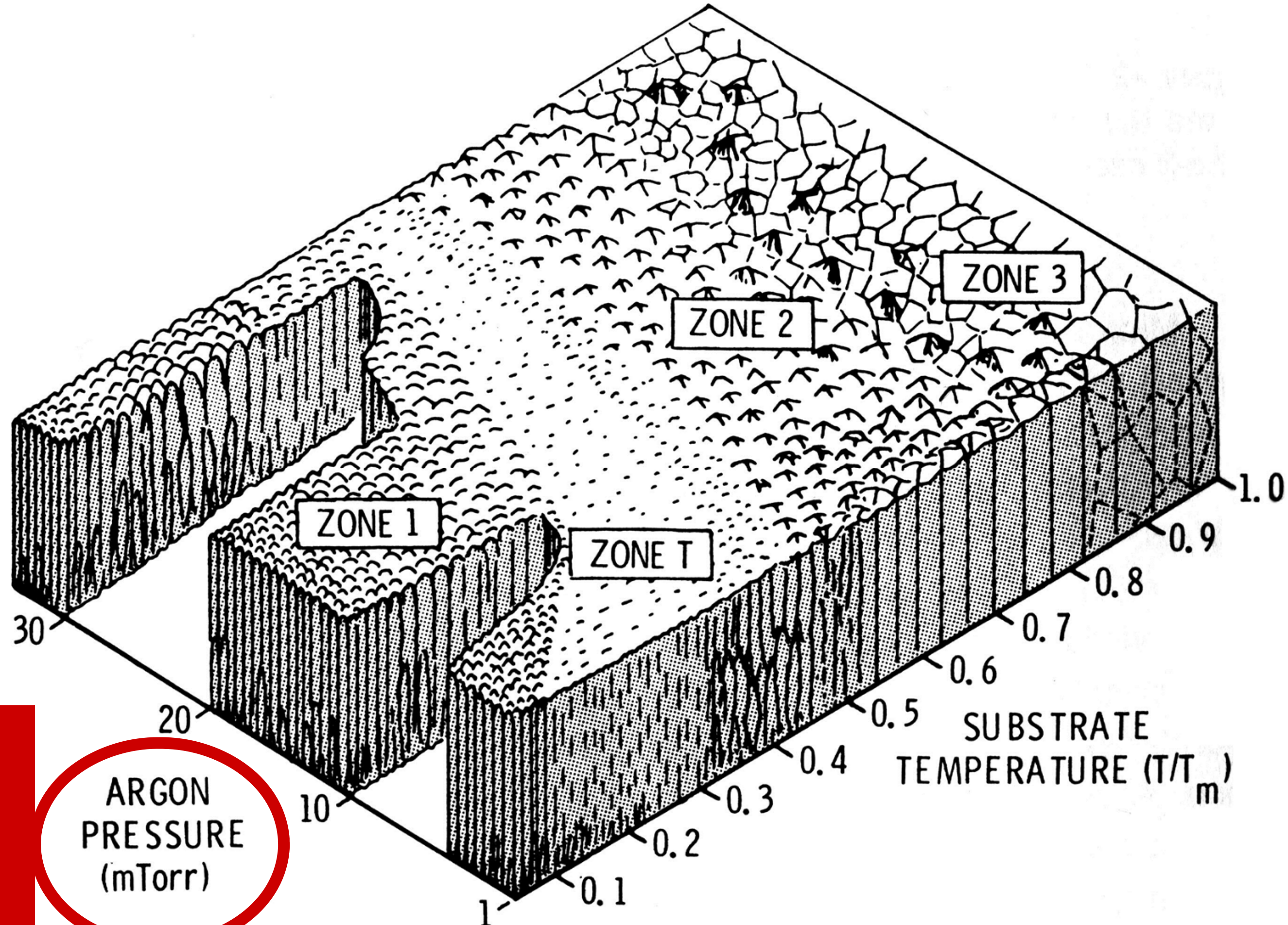


image from the seminal (but not first) paper: V. Kouznetsov, *et al.*, Surf. Coat. Technol. **122** (1999) 290

Thorton's Structure Zone Diagram for Sputtering



Contains the effects of energetic particle bombardment

J. A. Thornton, *J. Vac. Sci. Technol.* **11** (1974) 666

Biasing: Controlling the Kinetic Energy of Ions upon Arrival on the Substrate Surface

- Final kinetic energy is enhanced by acceleration in sheath adjacent to the substrate surface

$$E_i = E_0 + Qe\left(V_{plasma} - V_{surface}\right)$$

E_0: kinetic energy in plasma before acceleration

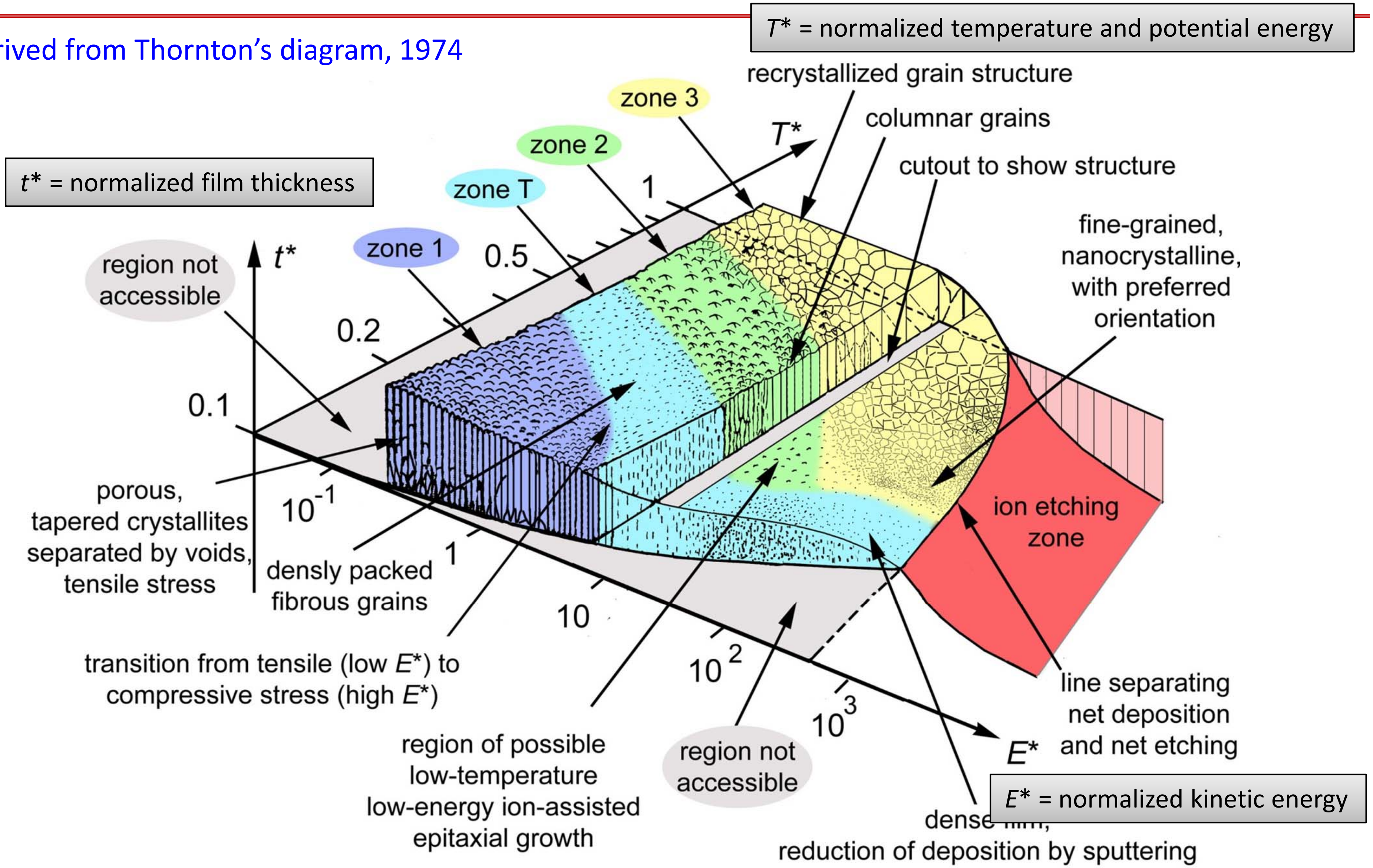
Q: ion charge state number

$V_{plasma} - V_{surface} = V_{sheath}$ is usually determined by bias

- High kinetic energy ($\geq$ 1000 eV) for pretreatment (ion etch)
- Low kinetic energy (10 eV…100 eV) for ion assist of growth

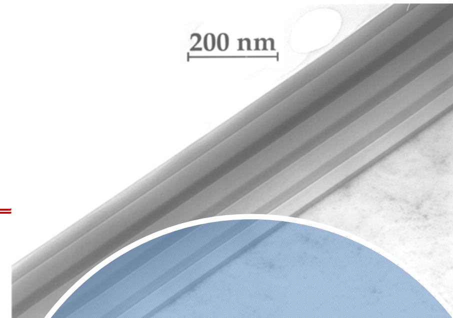
Generalized Structure Zone Diagram including the Effects of Plasma Assistance on Films

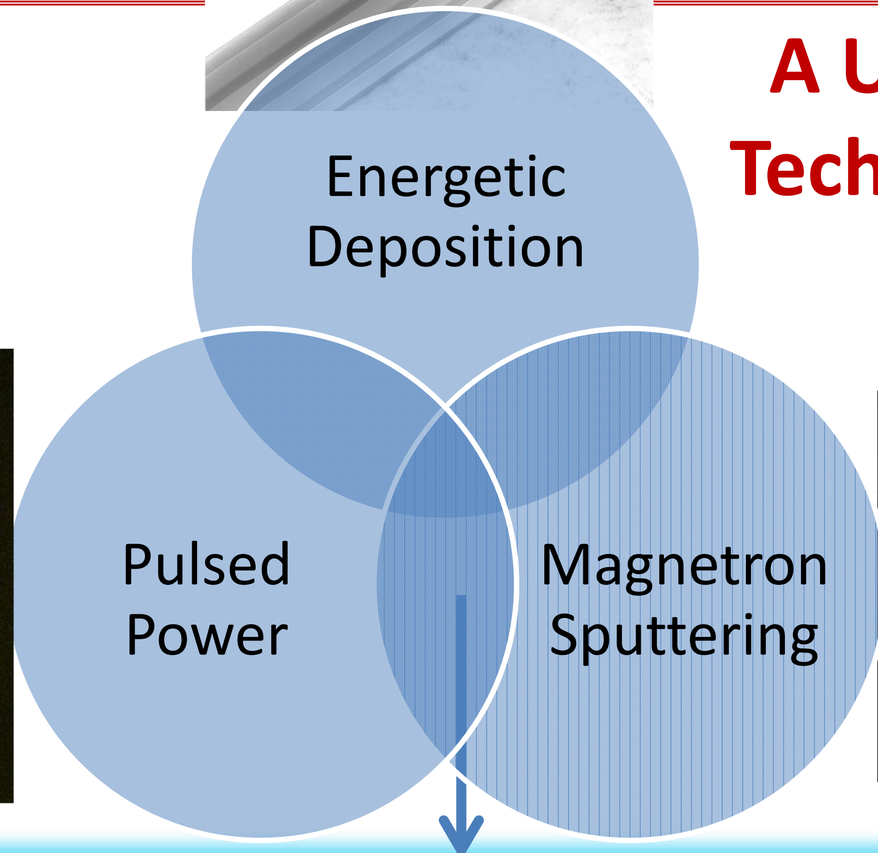
derived from Thornton's diagram, 1974

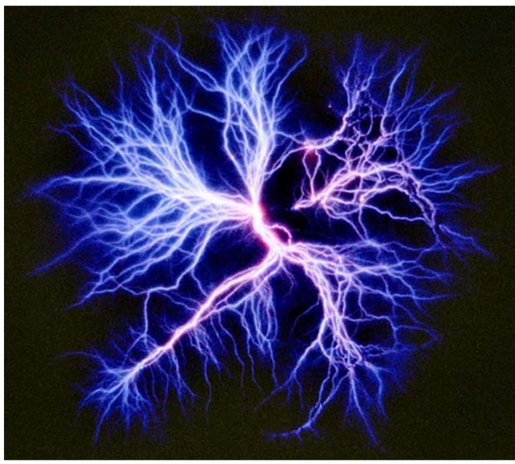


A. Anders, Thin Solid Films **518** (2010) 4087

A Union of Technologies

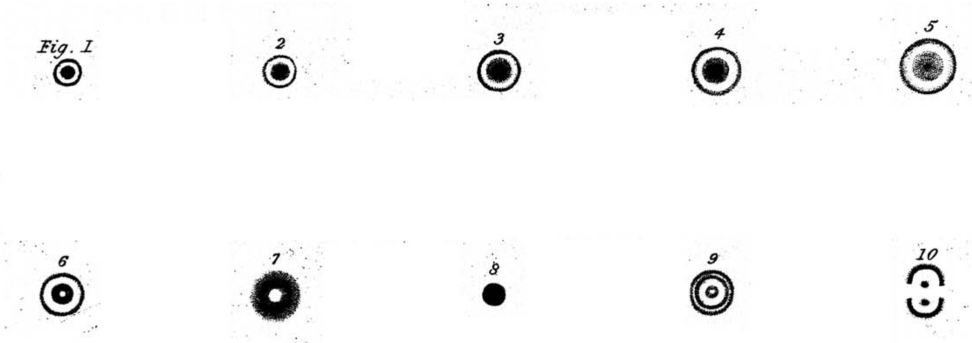




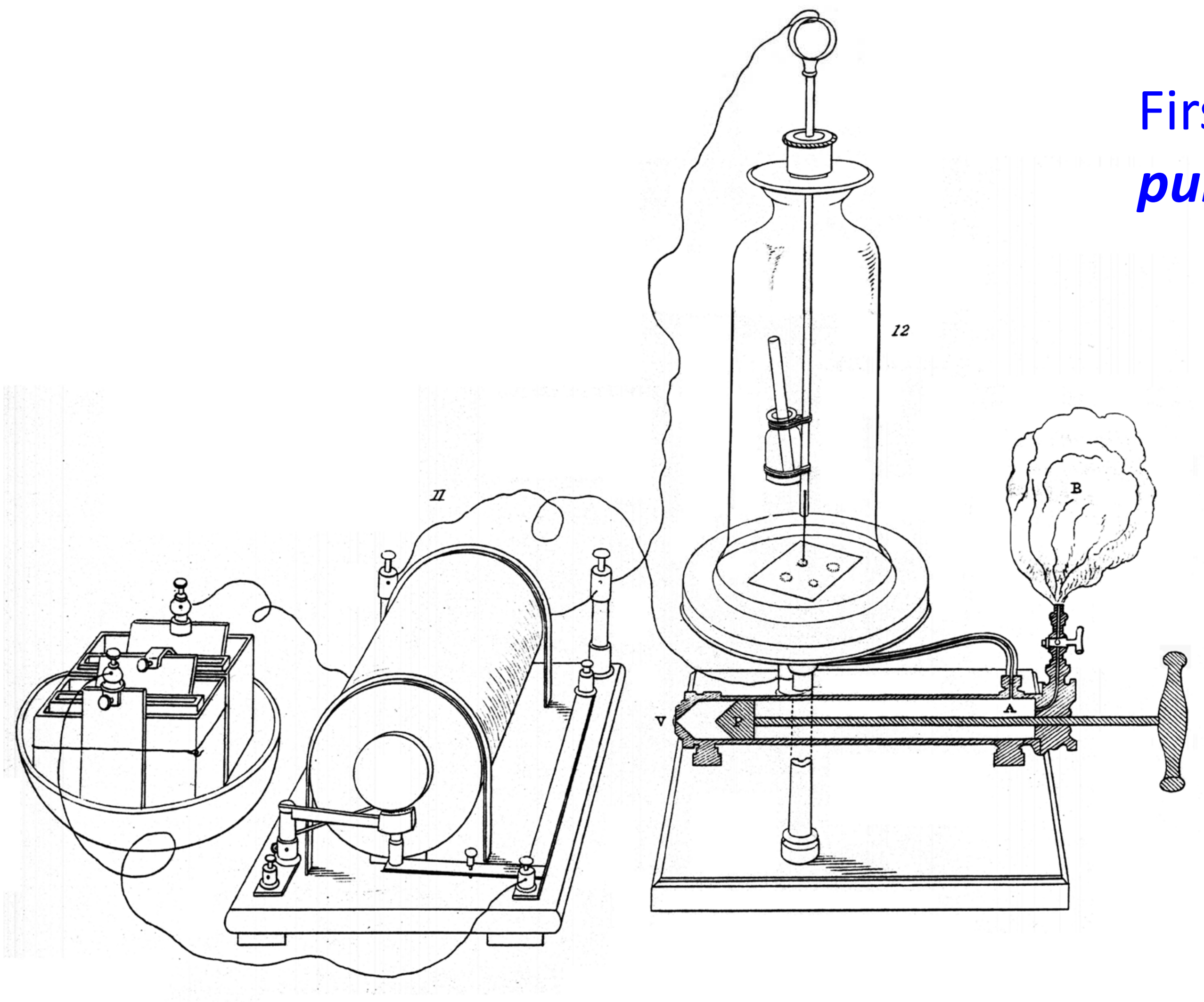


High Power Impulse Magnetron Sputtering

Grove 1852: Sputtering



First sputtering was ***pulsed*** sputtering!

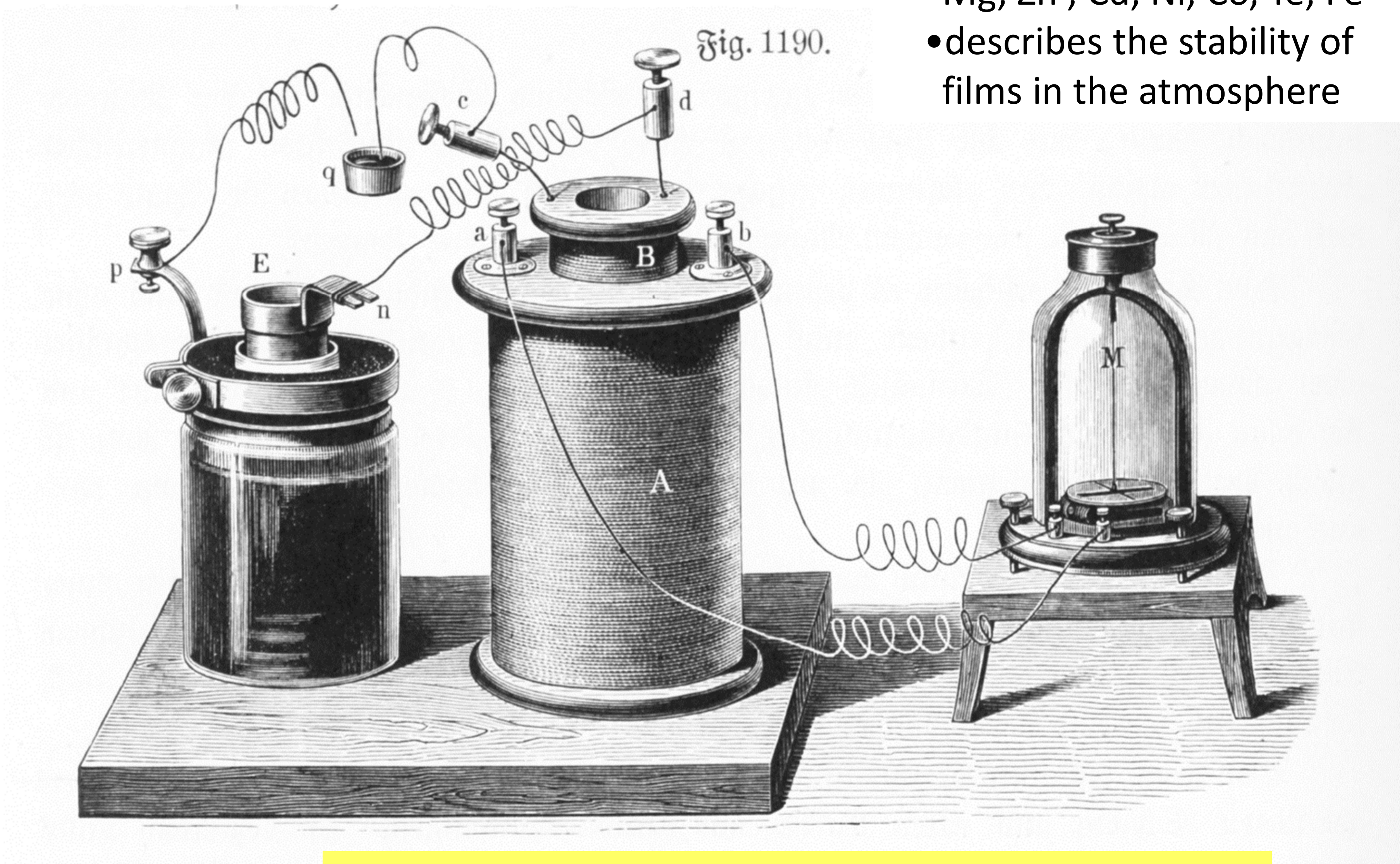


W. R. Grove, Phil. Mag. (1852) 498

Pulsed Diode Sputtering (at relatively high pressure)

Arthur Wright, 1877 deposited numerous films:

- Pt, Au, Co, Bi, Pd, Pb, Al, Sn, Mg, Zn , Cd, Ni, Co, Te, Fe
- describes the stability of films in the atmosphere



A.W. Wright, American J. Sci. - Third Series, vol. XIII, no. 78 (1877) 49

1884-1894: Edison's arc plating patents

- First patent application claiming arc plasma deposition
- although filed 1884 , granted in part in 1894: limited to a *continuous* arc process in light of Wright's pulsed work of 1877

T.A. Edison, ca. 1878

UNITED STATES PATENT OFFICE.

THOMAS A. EDISON, OF LLEWELLYN PARK, NEW JERSEY, ASSIGNOR TO THE EDISON PHONOGRAPH COMPANY, OF NEW JERSEY.

PROCESS OF DUPLICATING PHONOGRAMS.

SPECIFICATION forming part of Letters Patent No. 484,582, dated October 18, 1892.

Original application filed January 5, 1888, Serial No. 259,895. Divided and this application filed January 30, 1888. Renewed March 30, 1892. Serial No. 427,011. (No specimens.)

To all whom it may concern:

Be it known that I, THOMAS A. EDISON, of Llewellyn Park, in the county of Essex and State of New Jersey, have invented a certain new and useful Process for Duplicating Phonograms, (Case No. 751,) of which the follow-

covered by a more rapid process to give strength and body to the covering. A further covering of metal may be produced by electroplating a metal upon the vacuous deposit in the usual manner of electroplating, or the vacuous deposit may be backed up by

UNITED STATES PATENT OFFICE.

THOMAS A. EDISON, OF MENLO PARK, NEW JERSEY.

ART OF PLATING ONE MATERIAL WITH ANOTHER.

SPECIFICATION forming part of Letters Patent No. 526,147, dated September 18, 1894.

Application filed January 28, 1884. Serial No. 118,942. (Specimens.)

To all whom it may concern:

Be it known that I, THOMAS A. EDISON, of Menlo Park, in the county of Middlesex and State of New Jersey, have invented a new and useful Improvement in the Art of Plating One Material with Another, (Case No. 615,) of which the following is a specification.

The object of this invention is to produce a coating of one material upon another; and said invention consists in producing such a coating by throwing the material to be deposited into the form of a vapor in a vacuum, by means of a continuous current, the object to be coated or plated being within the vacuous chamber so that the material is deposited upon it from the vapor.

sheets so fine as to be transparent and yet even and homogeneous can readily be produced.

It is found especially advantageous in coating glass for mirrors as a very even deposit can be obtained in a very simple manner.

Alloys or compositions of different metals or substances may be produced by making each electrode of a different metal.

To produce a more rapid deposition two or more arcs may be formed in the chamber.

The invention may be applied to the manufacture of metallic foil especially gold, silver, and platinum foil. To accomplish this a cylinder of polished glass, coated internally with a film of material soluble in alcohol or

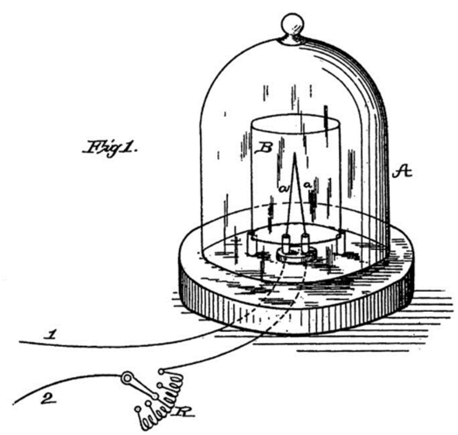
(Specimens.) 2 Sheets—Sheet 1.

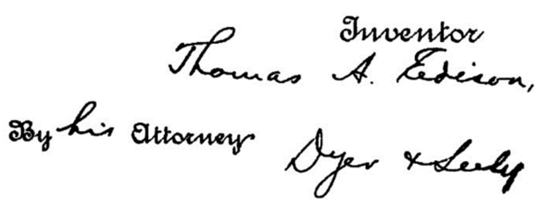
T. A. EDISON.

ART OF PLATING ONE MATERIAL WITH ANOTHER.

No. 526,147. Patented Sept. 18, 1894.

Fig 1.





Plasmas can satisfy the need for better films…

Sputtering on its journey to an ion-assisted deposition process

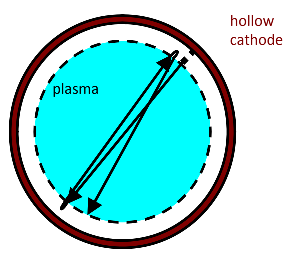
- ❑ we know: densification of films can be accomplished by particle bombardment of the growing film
- ❑ to take advantage of the energetic particles in a sputtering process will require going to less collisions than what is done in diode sputtering → This is achievable by lowering the pressure.

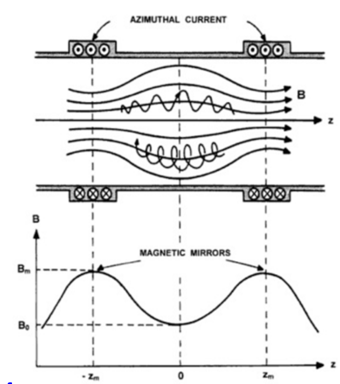
But then how to overcome the issue

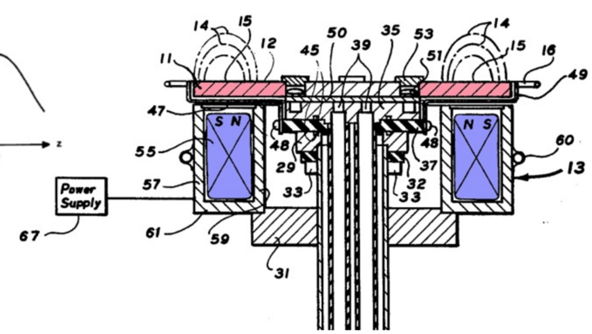
mean free path for ionization >> system size ?

Trapping and repeated "recycling" of charged particles!

1. electrostatic trap
2. magnetic trap
3. combined electrostatic and magnetic traps

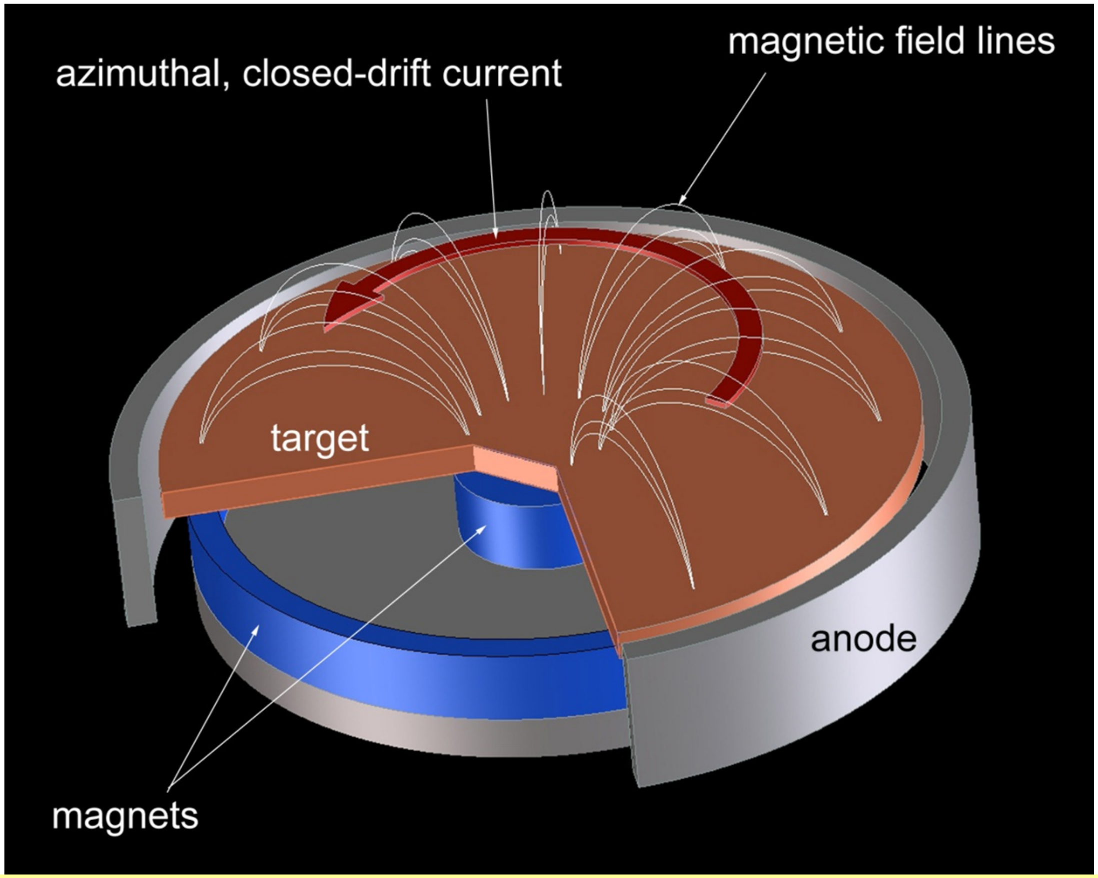






Magnetron as an Electron Trap

- target zone is a *magnetic mirror* as well as an *electrostatic reflector*
- electron *cyclotron motion* around field lines, resulting in closed azimuthal drift, the *magnetron motion*
- electrons cause ionization, and the "race track" appears under the drift zone due to sputtering by ions



rendering adapted by J. Slack from N. Brenning et al., Phys. Rev. Lett., **103** (2009) 225003

1980s: Unbalanced Magnetron

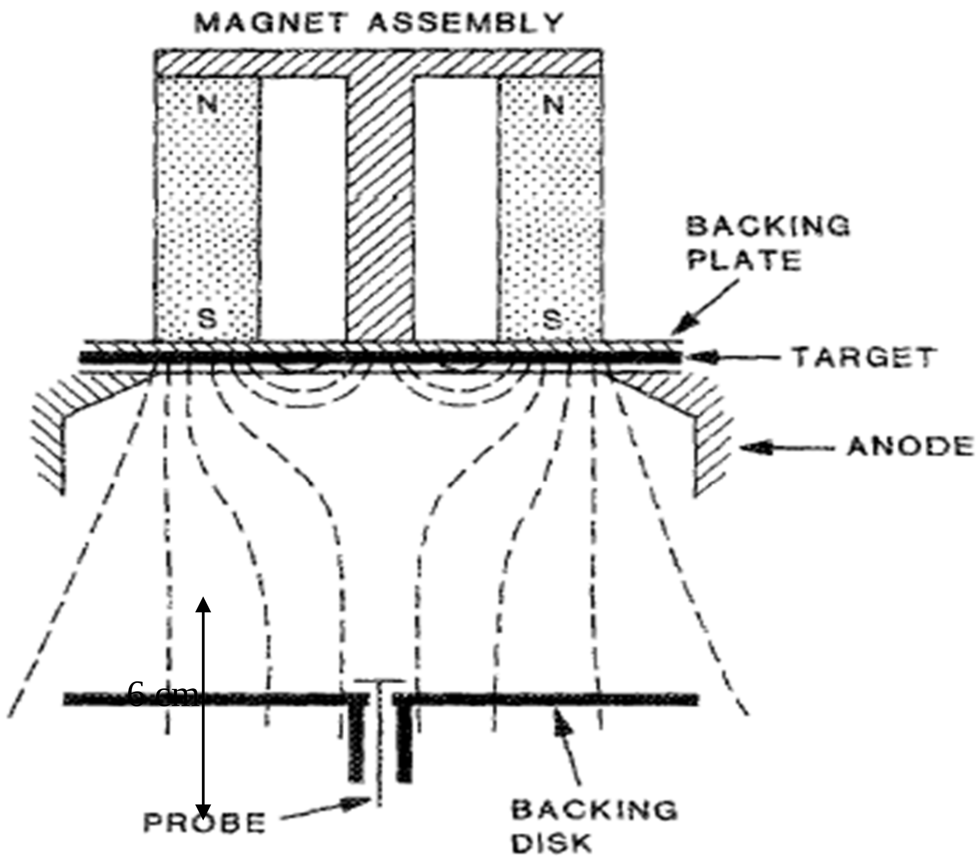
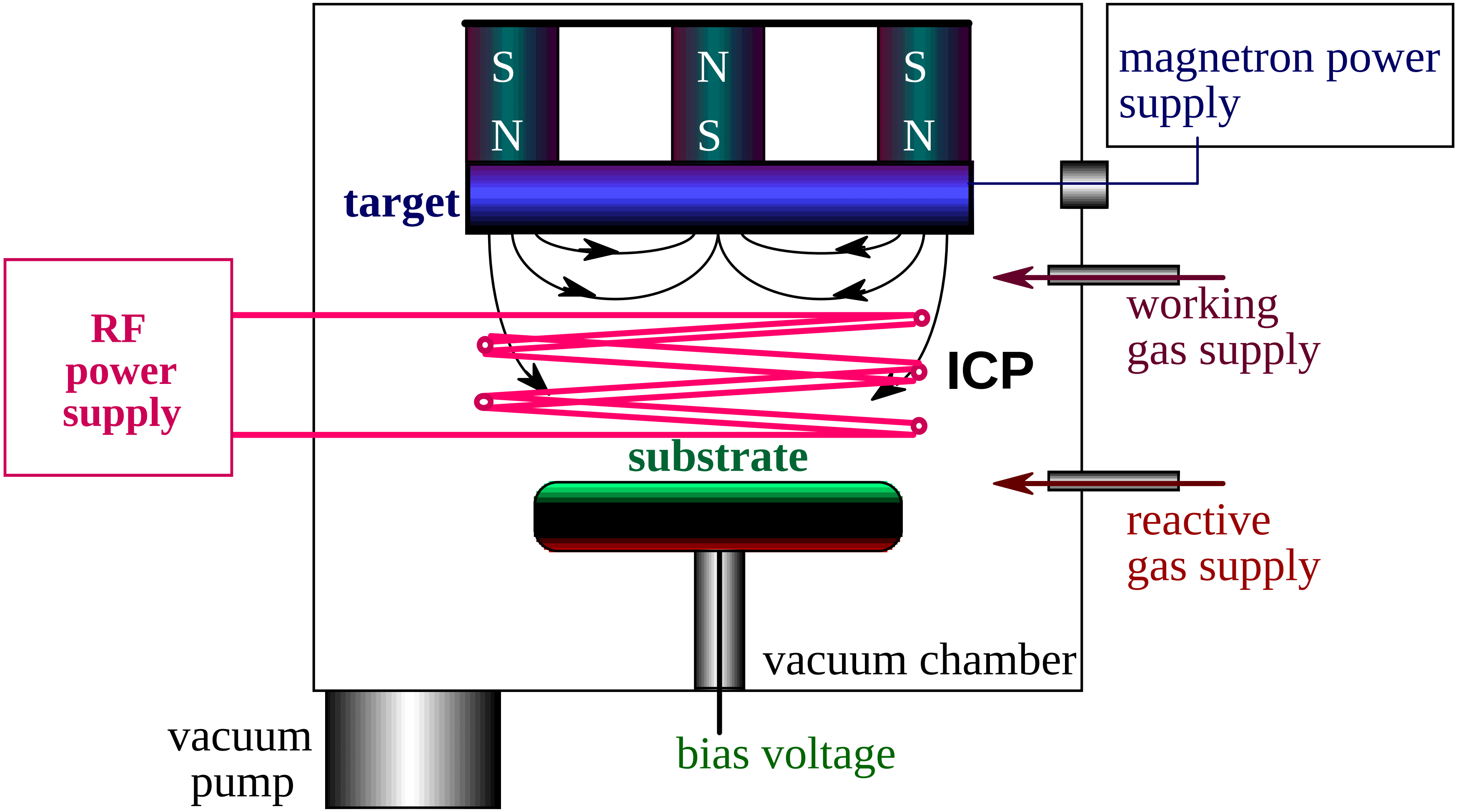


FIG. 1. Magnetron and probe assembly are shown schematically. For the measurements reported here the target to probe distance was maintained at 60 mm.

- Unbalanced magnetic field allows electrons and ions to escape from target, providing a means of ion assistance
- $n_e \sim 10^{12}$, for up to a distance of 10 cm.

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

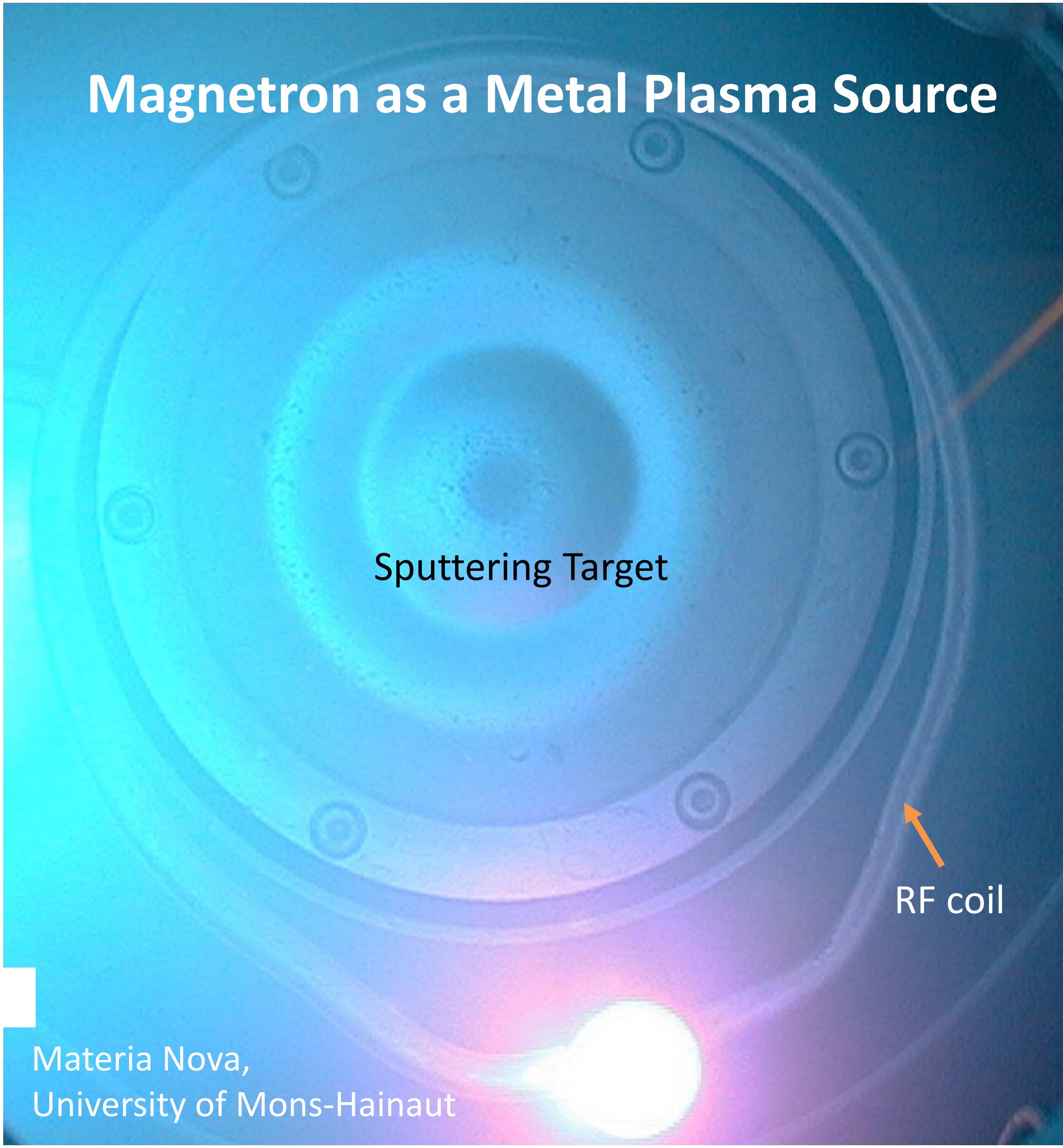
i-PVD: Magnetron Discharge with Ionization



S. M. Rossnagel and J. Hopwood, Appl. Phys. Lett. 63 (1993) 3285-3287

Ionized Physical Vapor Deposition; *Vol.*, edited by J. A. Hopwood (Academic Press, San Diego, CA, 2000).

Magnetron as a Metal Plasma Source



- ❑ conventional magnetron delivers (neutral) sputtered atoms
- ❑ flux of gas (argon) ions depends on “balancing” of the magnetic field
- ❑ Magnetron can be a plasma source when equipped with RF coil for post-ionisation
  - ❑ 70% ionised metal flux, high ion energy
  - ❑ more efficient at high pressures and low sputtering rates

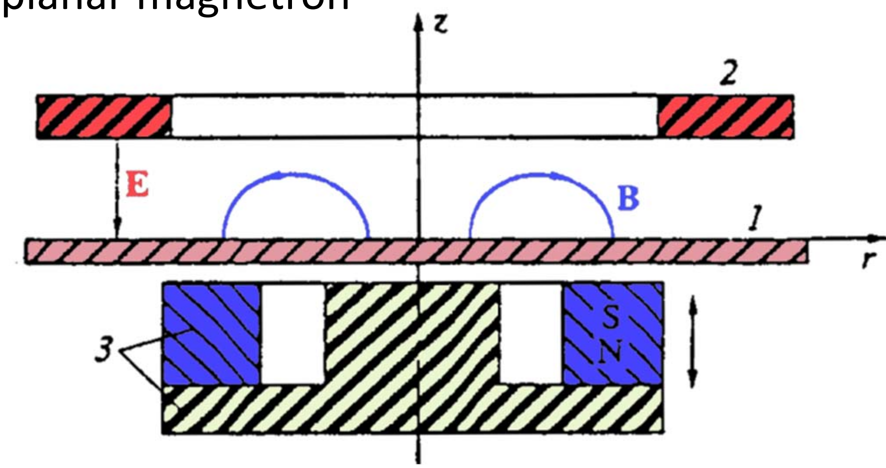
Plasma Physics Reports, Vol. 21, No. 5, 1995, pp. 400 - 409. Translated from Fizika Plazmy, Vol. 21, No. 5, 1995, pp. 422 - 433.

LOW-TEMPERATURE PLASMA

High-Current Low-Pressure Quasi-Stationary Discharge in a Magnetic Field: Experimental Research

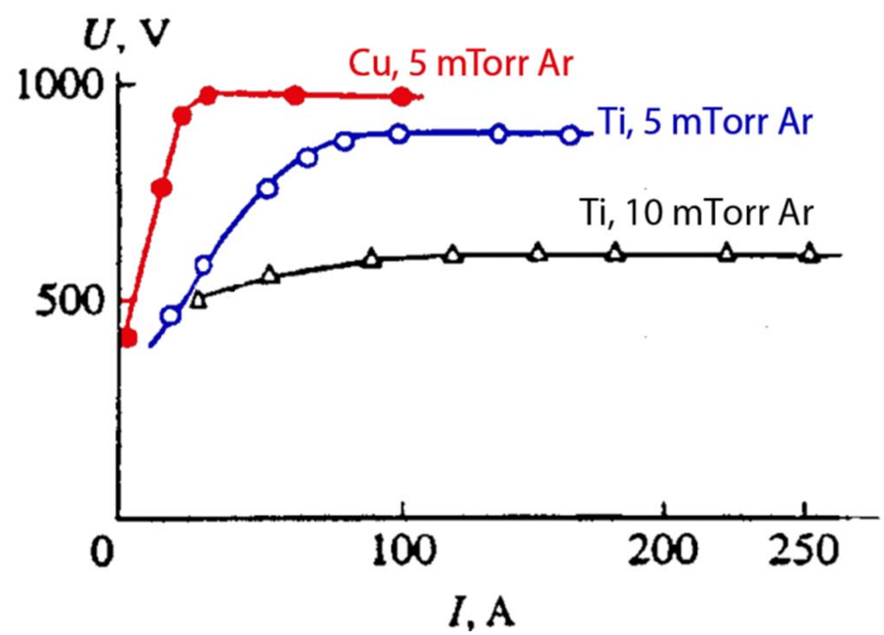
D. V. Mozgrin, I. K. Fetisov, and G. V. Khodachenko
Moscow Engineering Physics Institute, Kashirskoe sh. 31, Moscow, 115409 Russia
Received October 22, 1993; in final form, July 12, 1994

planar magnetron



1993

a self-sputtering or HIPIMS mode!

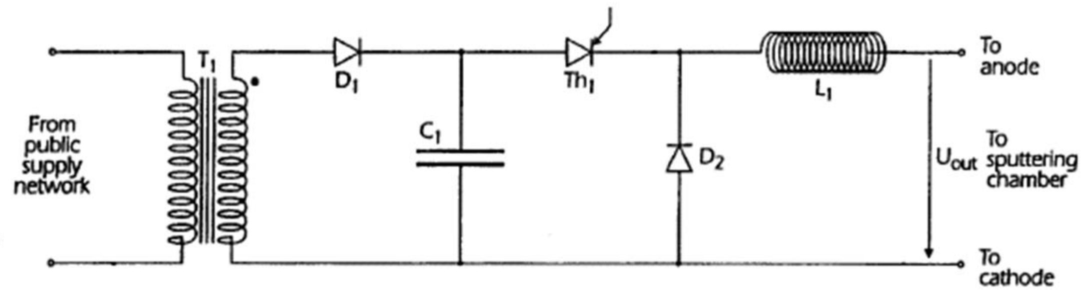


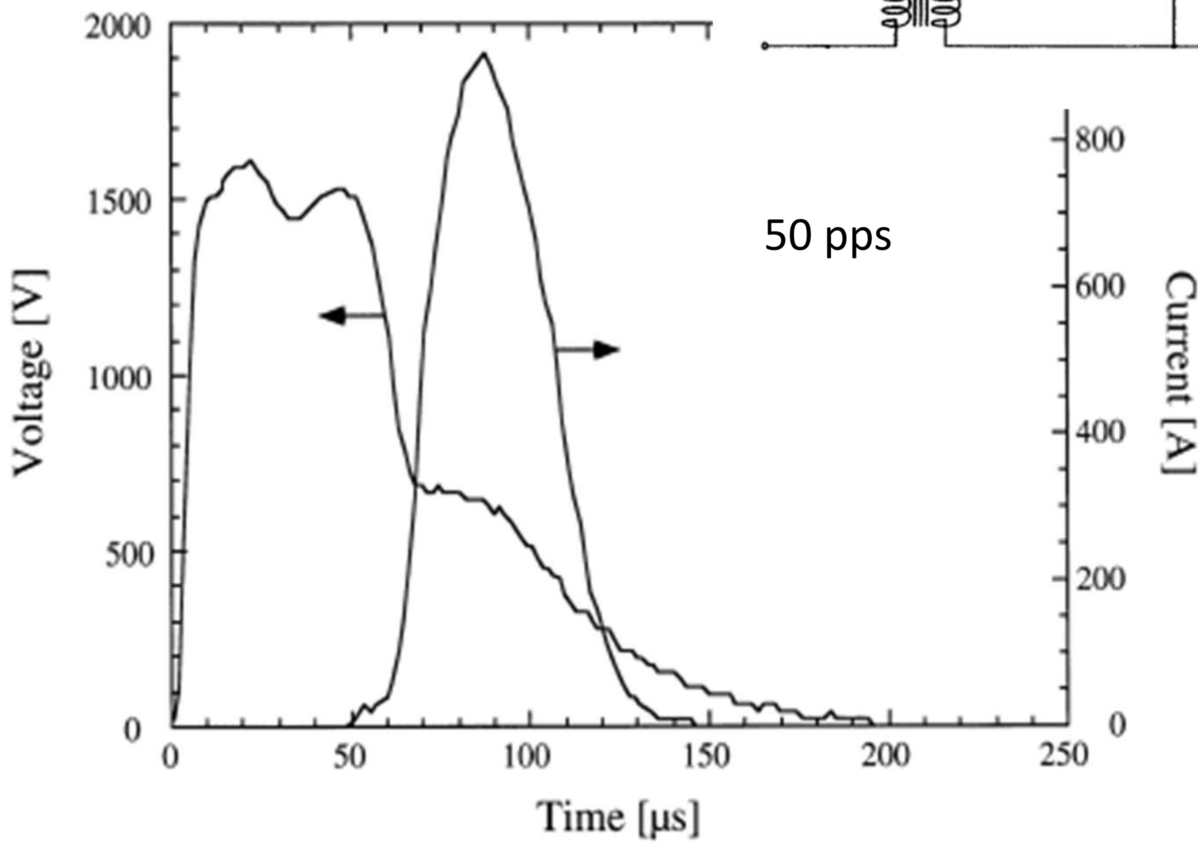
follow-up paper of same group:

Fetisov I.K., et al. “Impulse irradiation plasma technology for film deposition”, Vacuum, 53 (1999) 133-136.

1999: High Power Impulse Magnetron Sputtering

about 500 kW (!) peak power
on a 15 cm diameter Cu target





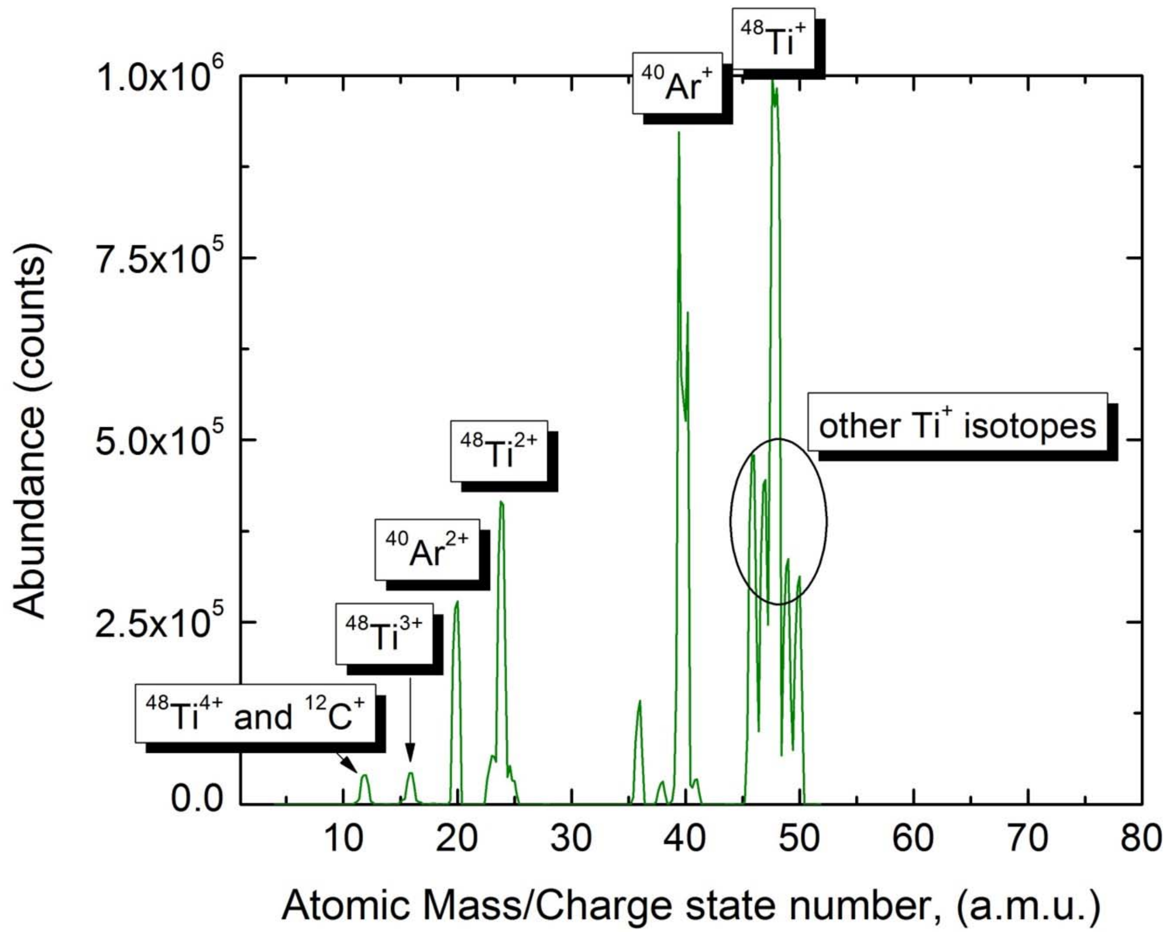
50 pps

US 6296742

from the seminal (but not first!) paper: V. Kouznetsov, *et al.*, Surf. Coat. Technol. **122** (1999) 290

Plenty of Evidence for Metal Ionization in HIPIMS

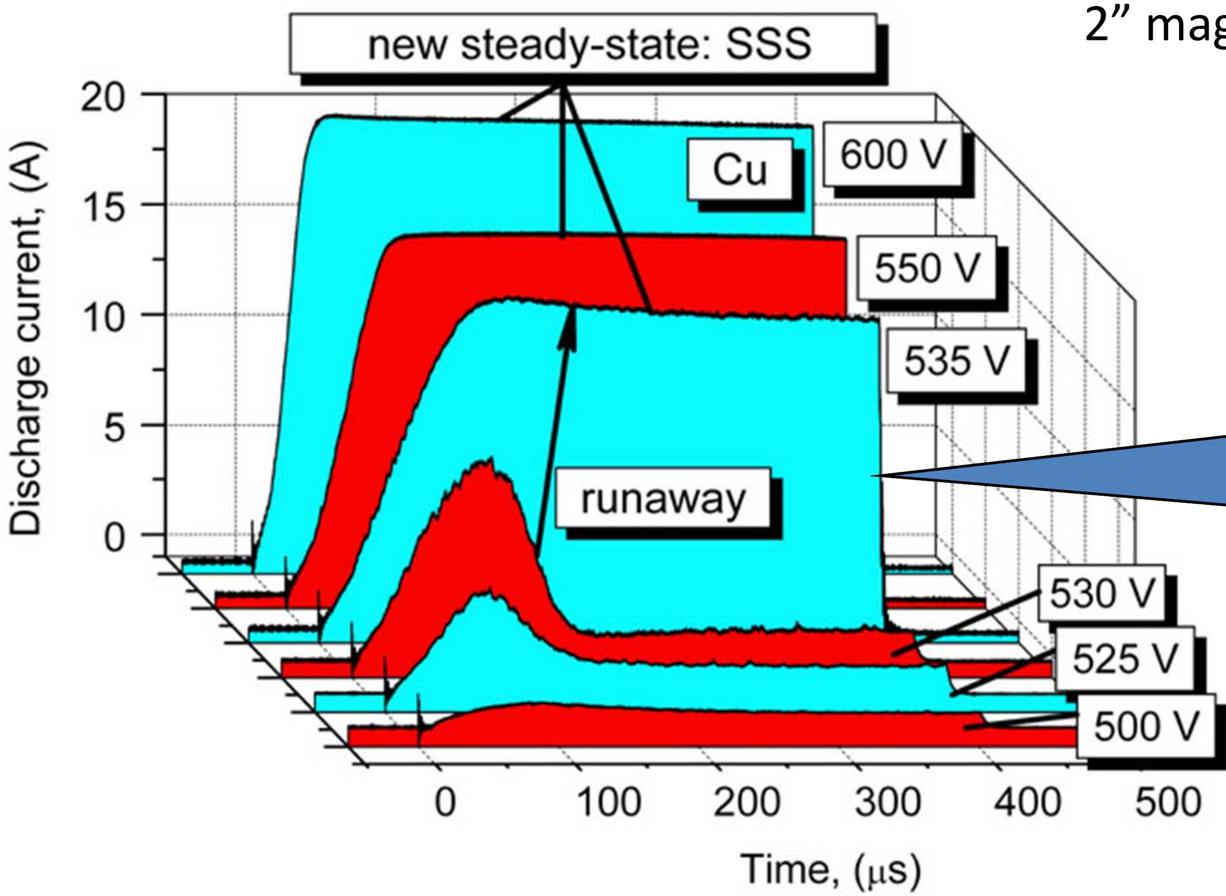
- Example: Ti target, ∅ 5 cm, Ar, 850 V, 60 A after 50 μs
- m/q spectrum sampled for the 100-150 μs window of the 150 μs discharge



- metal can dominate the plasma
- singly charged ions are most frequent
- even higher charge states are present

J. Andersson, et al., Appl. Phys. Lett. **93** (2008) 071504.

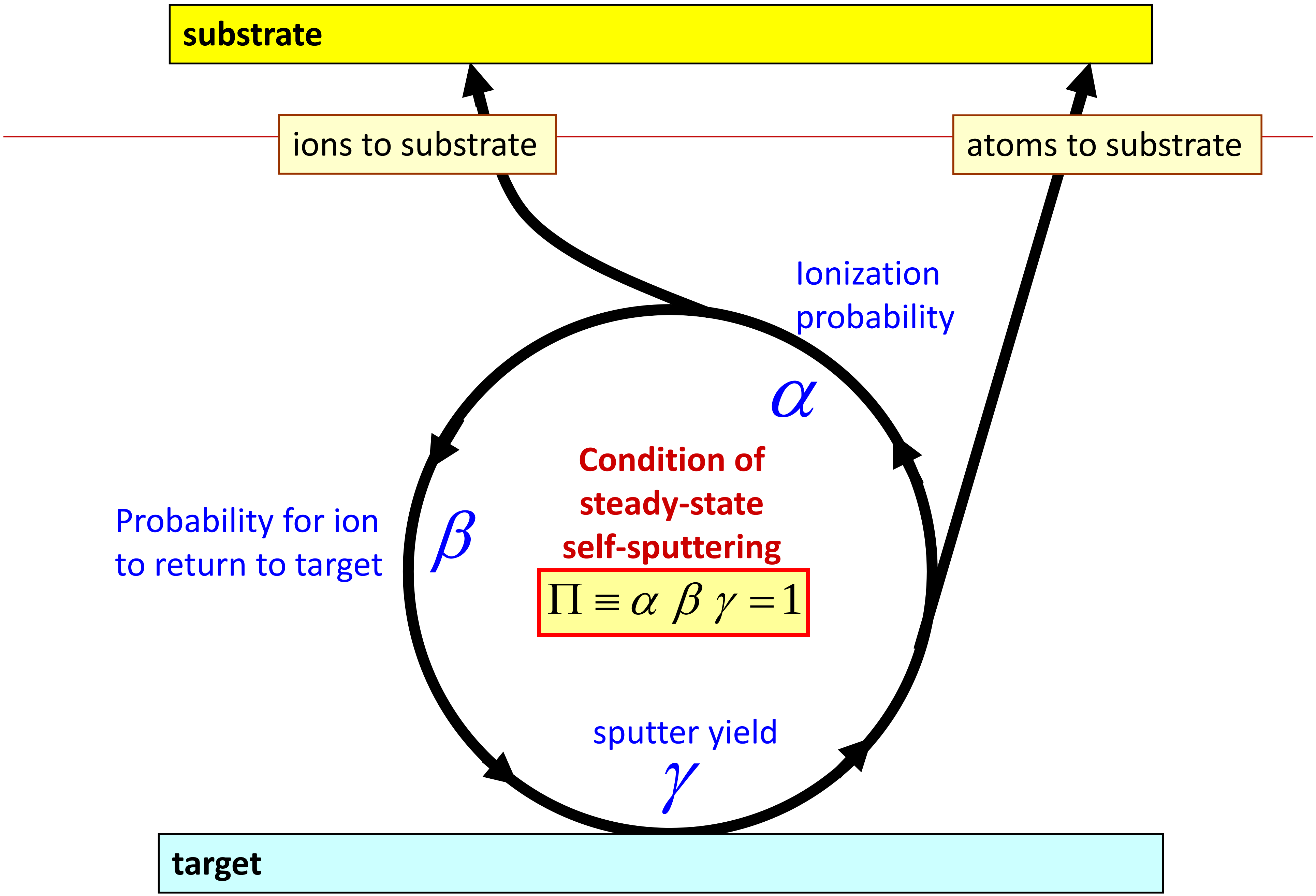
Runaway of Self-Sputtering



Copper target,
2” magnetron

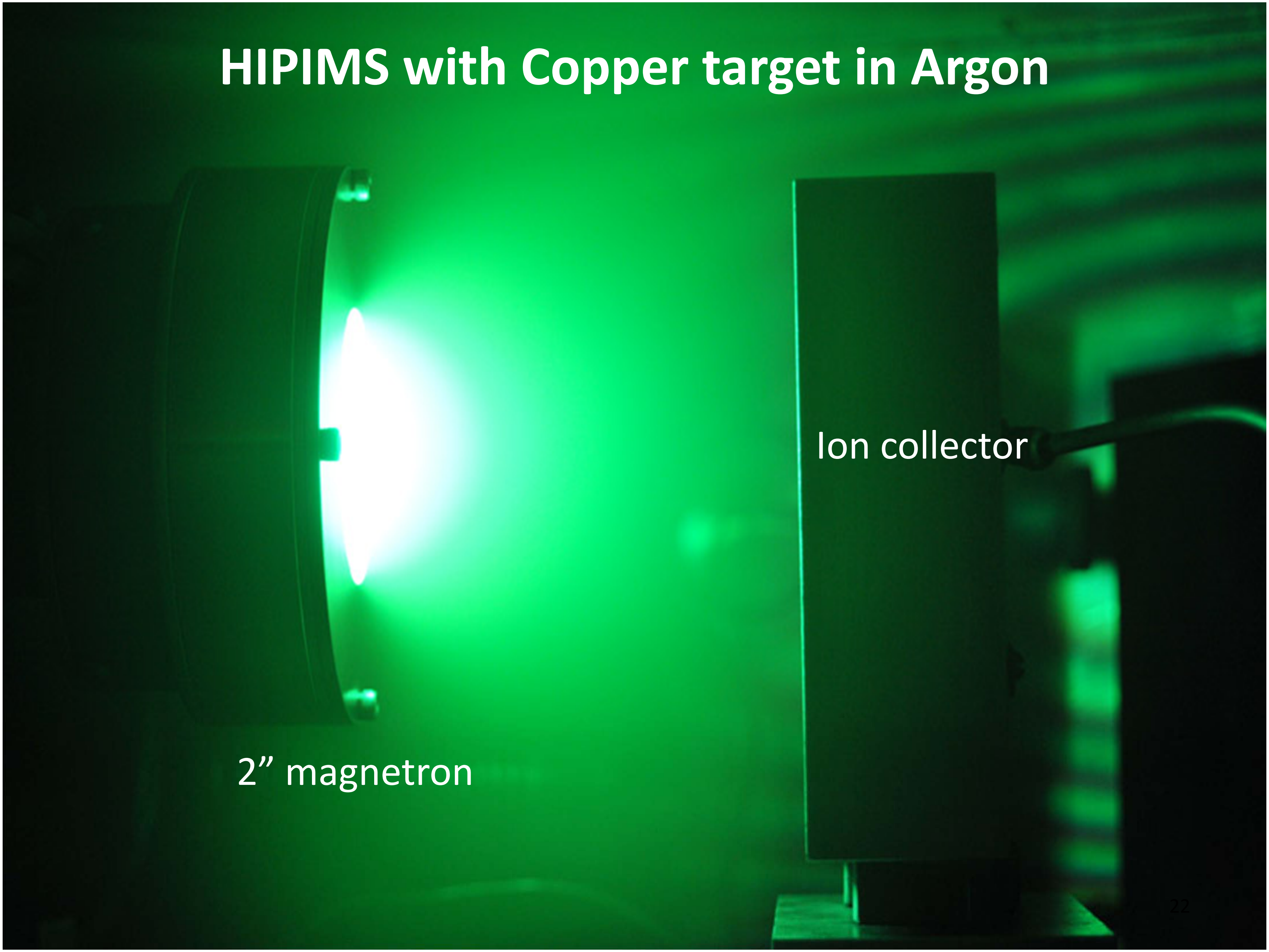
Look for this small change in voltage but huge effect in current!

A. Anders, et al., J. Appl. Phys. **103** (2008) 039901

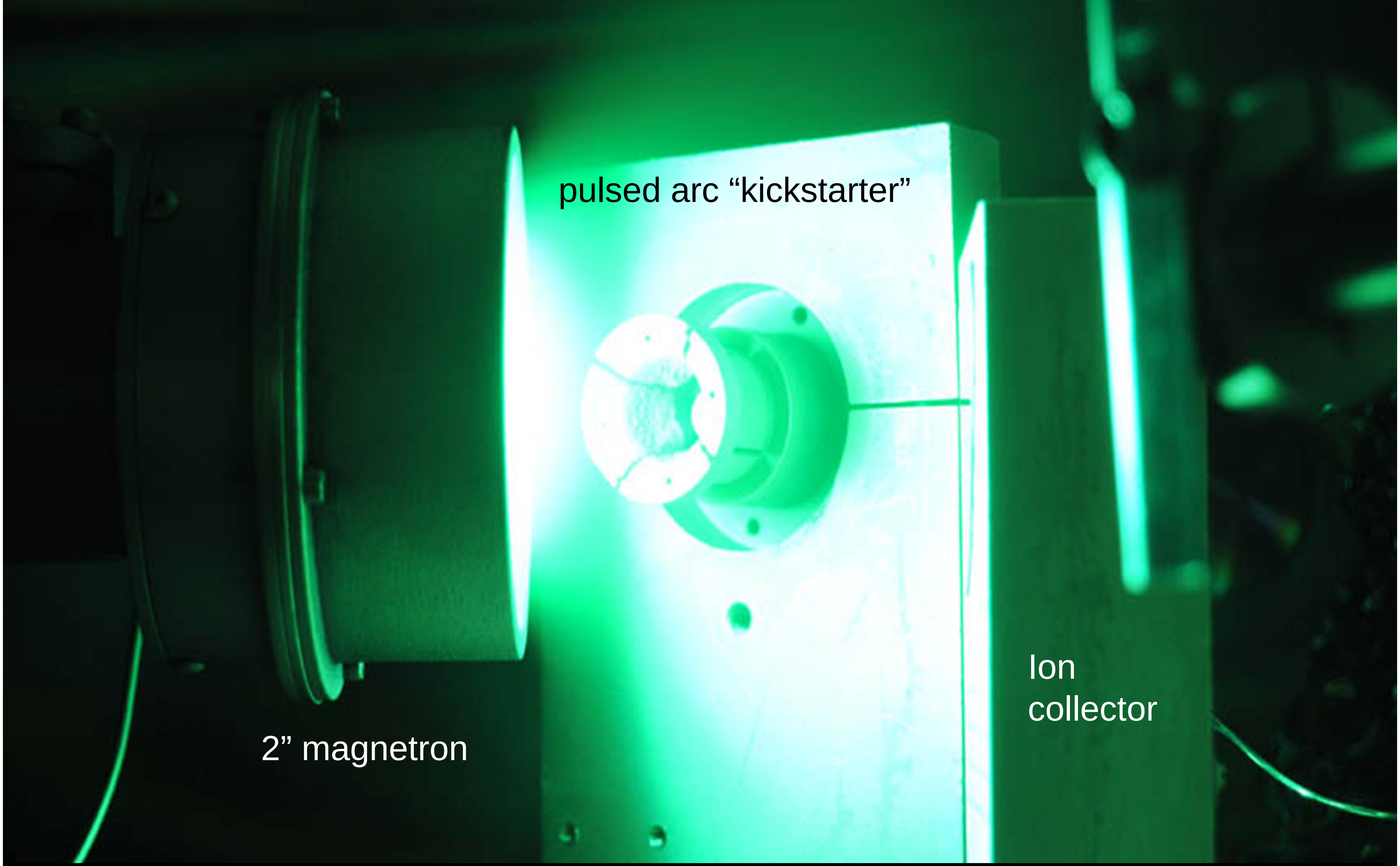


A. Anders, J. Vac. Sci. Technol. A **28** (2010) 783

HIPIMS with Copper target in Argon

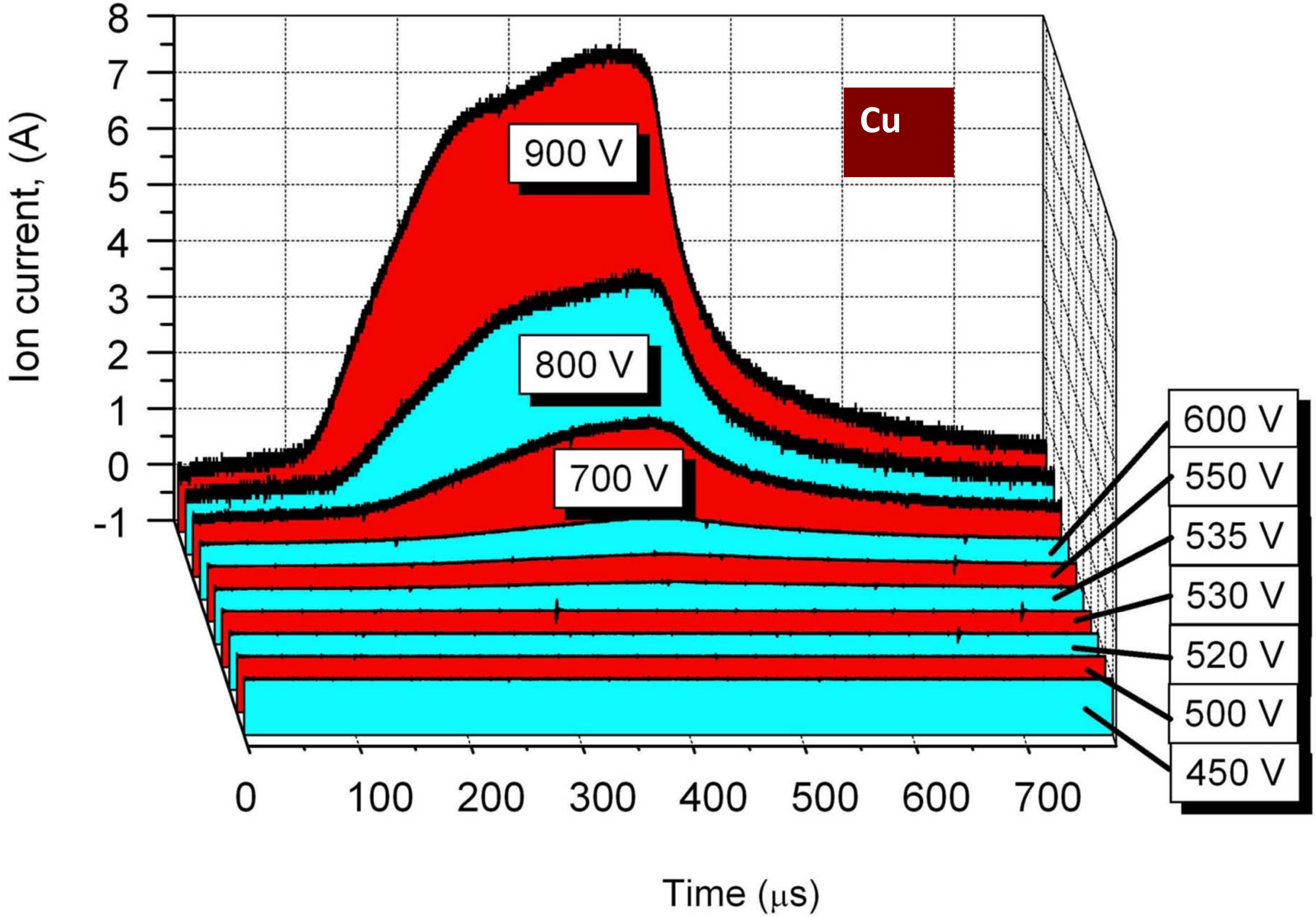


HIPIMS without any gas: Pure Self-Sputtering in Vacuum



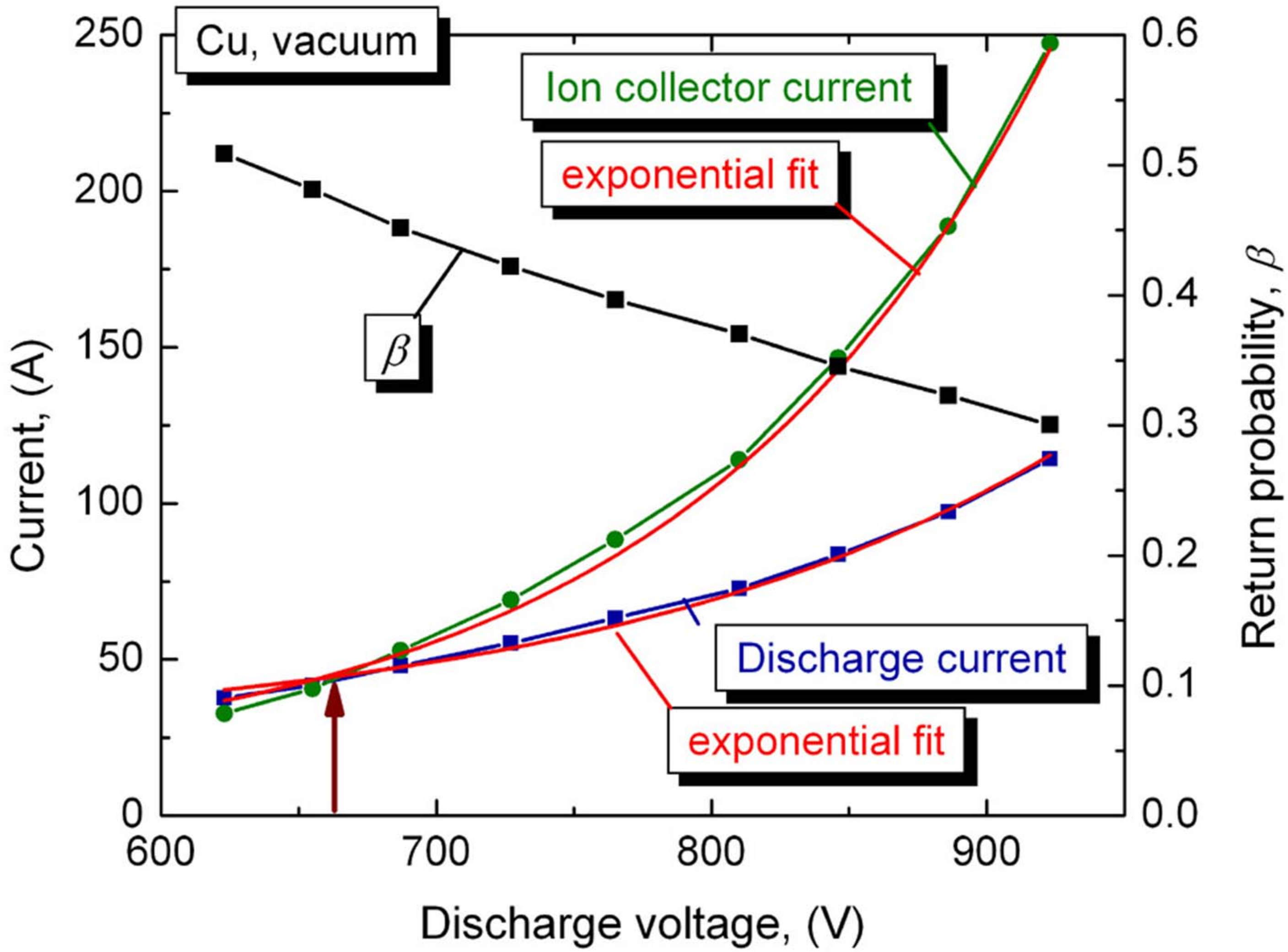
J. Andersson and A. Anders, Appl. Phys. Lett. **92** (2008) 221503
J. Andersson and A. Anders, Phys. Rev. Lett. **102** (2009) 045003

Ion Current at Substrate can be Very Large



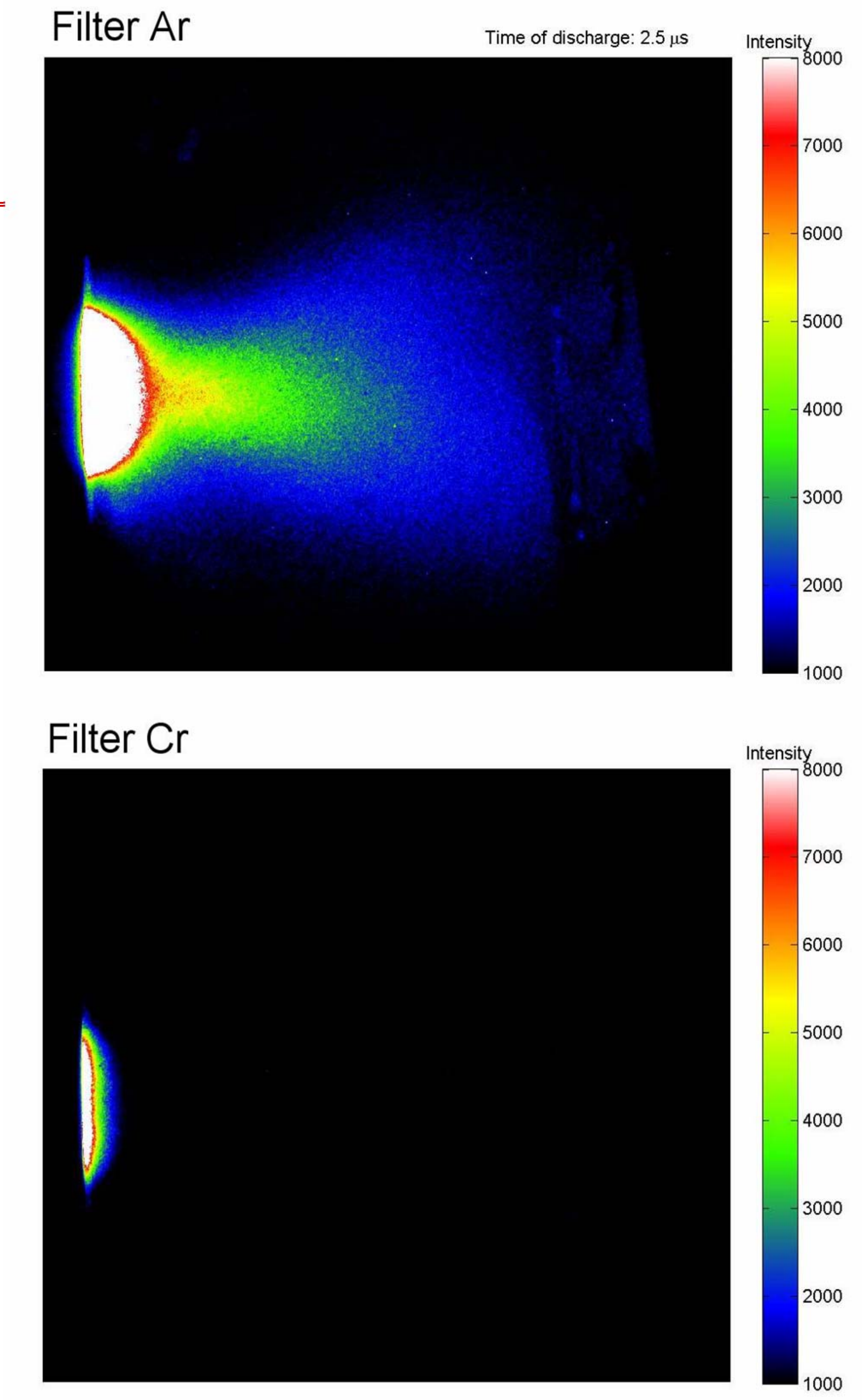
A. Anders et al, J. Appl. Phys. 102 (2007) 113303

Observed Exponential Growth of Available Ion Current with Voltage, and Reduction of Return Probability



J. Andersson and A. Anders, Phys. Rev. Lett. **102** (2009) 045003.

Spectroscopic Diagnostics of HIPIMS

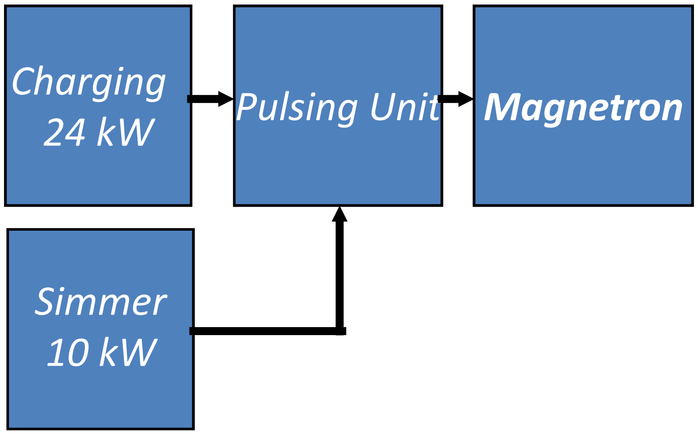


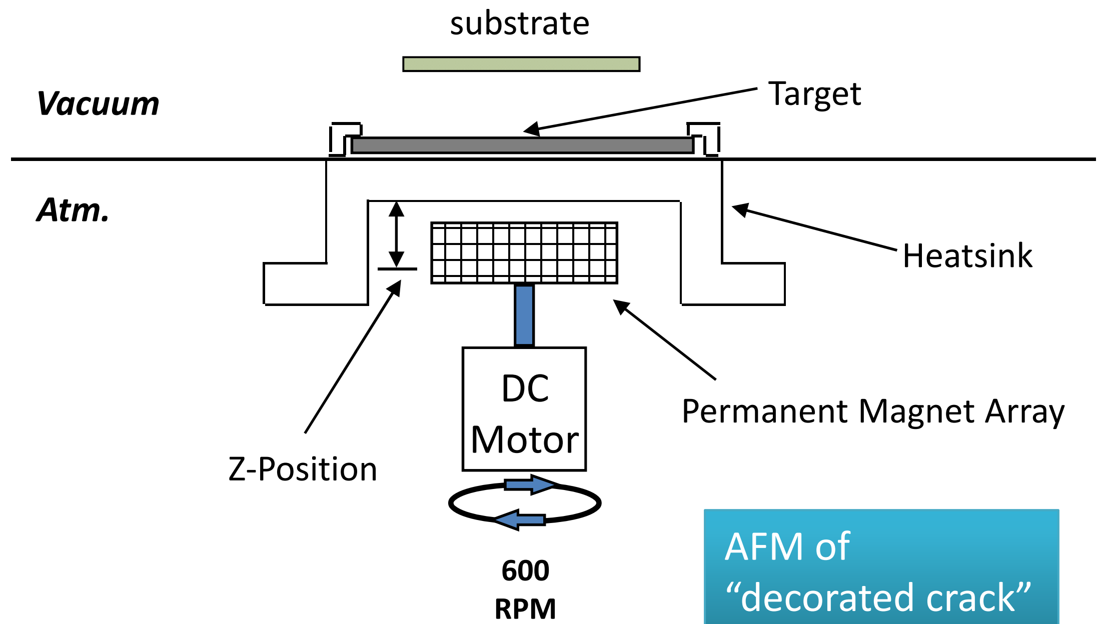
4 Pa, Ar, apply 2000 V

→ Video clip courtesy of Matej Hala.

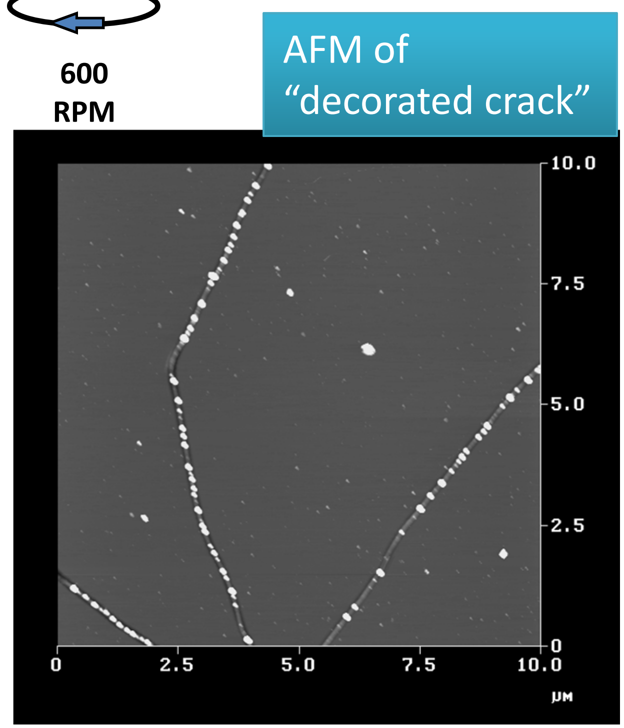
M. Hála, et al. , IEEE Trans. Plasma Sci. 38 (2010) 3035.

2003: First HIPIMS experiments for Diamond-like Carbon





- Pulse width 60 - 120 μs
- Frequency 10 to 200 Hz
- Plasma impedance 0.5 - 3.0 Ω
- Charge voltage 500 - 2000 V
- ~ 5 kW average power
- Simmer supply capability to maintain low power plasma (<1 kW) between pulses
- α,β,γ < 1, no sustained self-sputtering possible



B. M. DeKoven, et al., 46th Ann. Techn. Conf. Proc., Society Vacuum Coaters, San Francisco, CA, 2003.

Examples of HIPIMS Commercial Supplies and Systems

TRUMPF

HÜTTINGER Electronic
generating confidence

SOLVIX
People and Power electronics

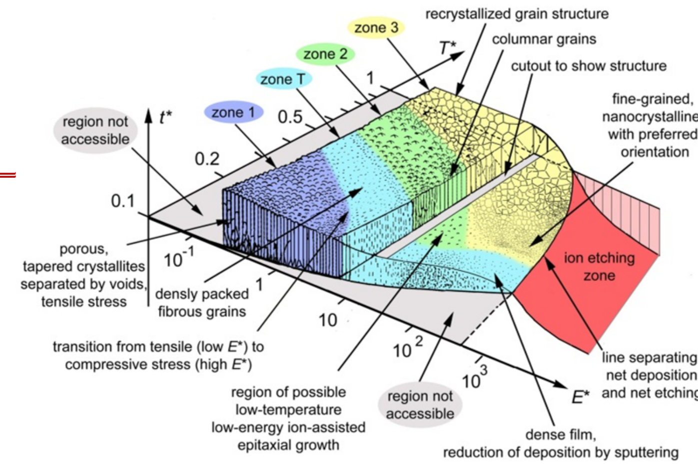
ZPULSER
plasma generator

SYSTEC

MELEC

Made in Taiwan
SHENCHANG ELECTRIC CO., LTD.

Summary



- HIPIMS has its roots in
  - energetic deposition using plasmas
  - (magnetron) sputtering
  - pulsed power technology
- HIPIMS: magnetron becomes a plasma source → self-ion assisted deposition for
  - densification
  - improvement of adhesion (often with pretreatment step)
  - control of phase and texture
  - influence stress
  - enabling certain coatings and properties, e.g. the “diamond-likeness” of DLC coatings
- HIPIMS is still emerging yet has already become a commercially available technology; it will find greatest acceptance where the “value added” is needed for the application