Non-conventional probe diagnostics for plasma processing

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Online Low Temperature Plasma Seminar (OLTP)

November 30, 2021

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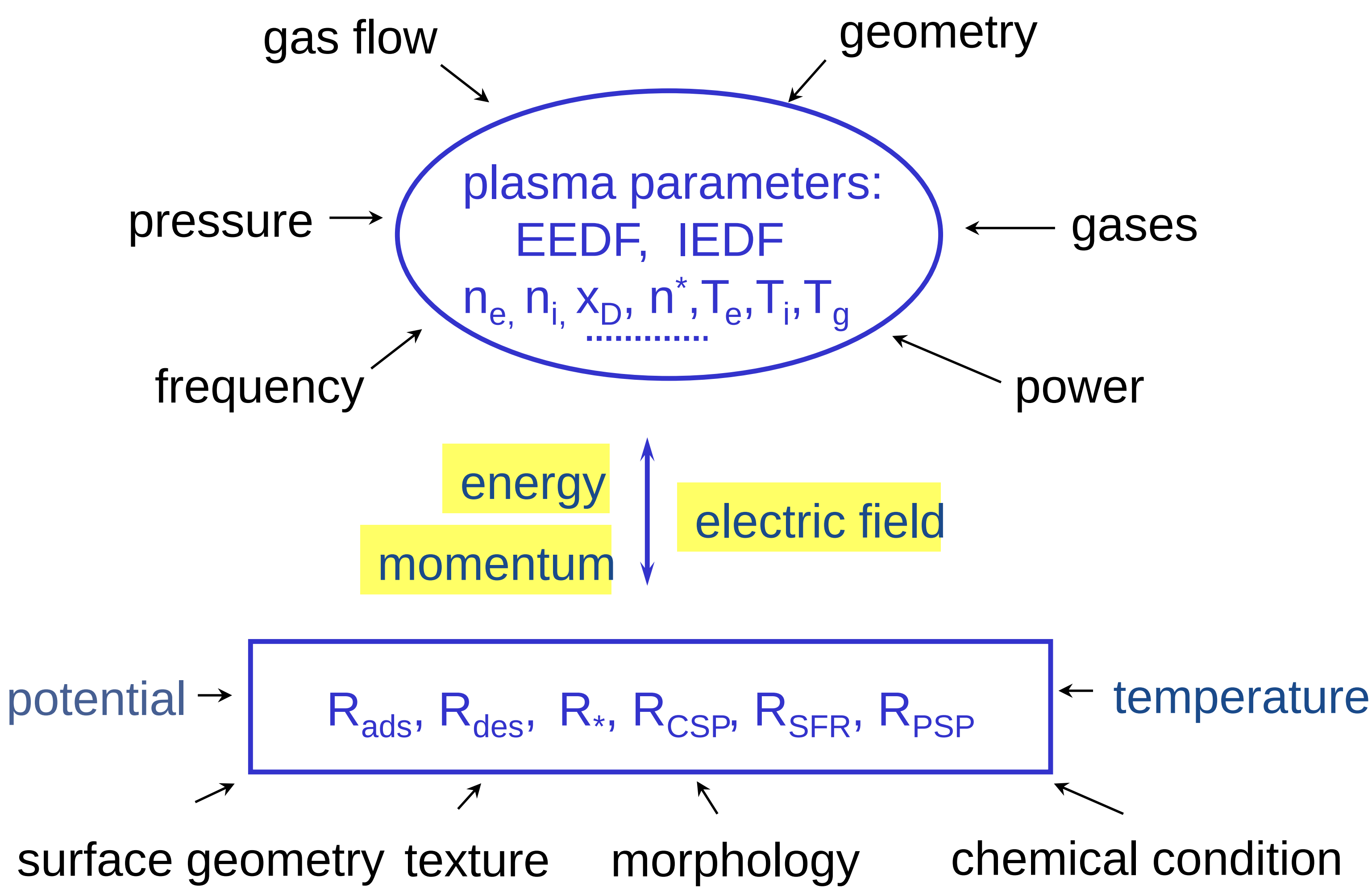
introduction

(motivation)

introduction

plasma and substrate surface



introduction

for planar geometry

$$n(\vec{r},t) = \int f^{(3)}(\vec{r},\vec{v},t)\,\mathrm{d}^3v$$

current:

$$I = jA \sim Anv \sum_{j=i,e} q_j$$

$$I = A \sum_{j=i,e} q_j \int_{-\infty}^{+\infty} v_x\, f_j(v_x) dv_x$$

force:

$$F = pA \sim Anv^2 \sum_{j=i,e,n} m_j$$

$$F = A \sum_{j=i,e,n} m_j \int_{-\infty}^{+\infty} v_x^2\, f_j(v_x) dv_x + F_E$$

power (thermal):

$$P = J_{in}A \sim Anv^3 \sum_{j=i,e,n} m_j$$

$$P = \frac{1}{2} A \sum_{j=i,e,n} m_j \int_{-\infty}^{+\infty} \left(v_x^2 + \langle v_y^2 \rangle + \langle v_z^2 \rangle\right) v_x\, f_j(v_x) dv_x + P_{rad} + P_{cond} + P_{chem} + P_{evap} + P_{sputt}$$

*Trottenberg, T., Richter, T., Kersten, H., Eur. Phys. J. D **69**(2015), 91.*
*Trottenberg, T., Kersten, H., Plasma Sources Sci. Technol. **26**(2017), 055011.*

methods for plasma diagnostics

- optical spectroscopy (emission, absorption, QCLAS, LIF)
- photometry of plasma / sheath
- V-I-probe
- microwave diagnostics
- Langmuir probes (LP), retarding field analyzer (RFA), Faraday cup (FC)
- self-excited electron resonance spectroscopy (SEERS), multipole resonance (MRP)
- mass spectrometry / plasma monitoring
- etc. etc. etc.
- ***energy flux measurement ****
- ***force measurement ****
- *microscopic particle probes **

Benedikt, J., Kersten, H., Piel, A.,
Plasma Sources Sci. Technol. ***30***(*2021), 033001.*
(Topical Review)

** „non-conventional“ plasma and sheath diagnostics*

(non-conventional) plasma diagnostics

for the determination of **energy influx** from plasma to surface

by calorimetric (thermal) probes

energy influx

N.Hershkowitz et.al. *JVST A**11**(1993), 1283 , ISPC-12, 1995, 533* :

"... plasma processing characteristics are similar ... when only a limited number of plasma parameters are identical at the plasma-wafer sheath boundary. Identical values of ***energy flux*** and particle concentration result in identical rates."

J.G.Han *J. Phys. D: Appl. Phys. **42**(2009), 043001* :

„ …the energy delivered to the surface for nucleation and growth during magnetron sputtering should be measured and analysed by integrated diagnostics of the plasma parameters which are closely associated with the process parameters and other external process conditions."

PSI at LPPP is affected by :

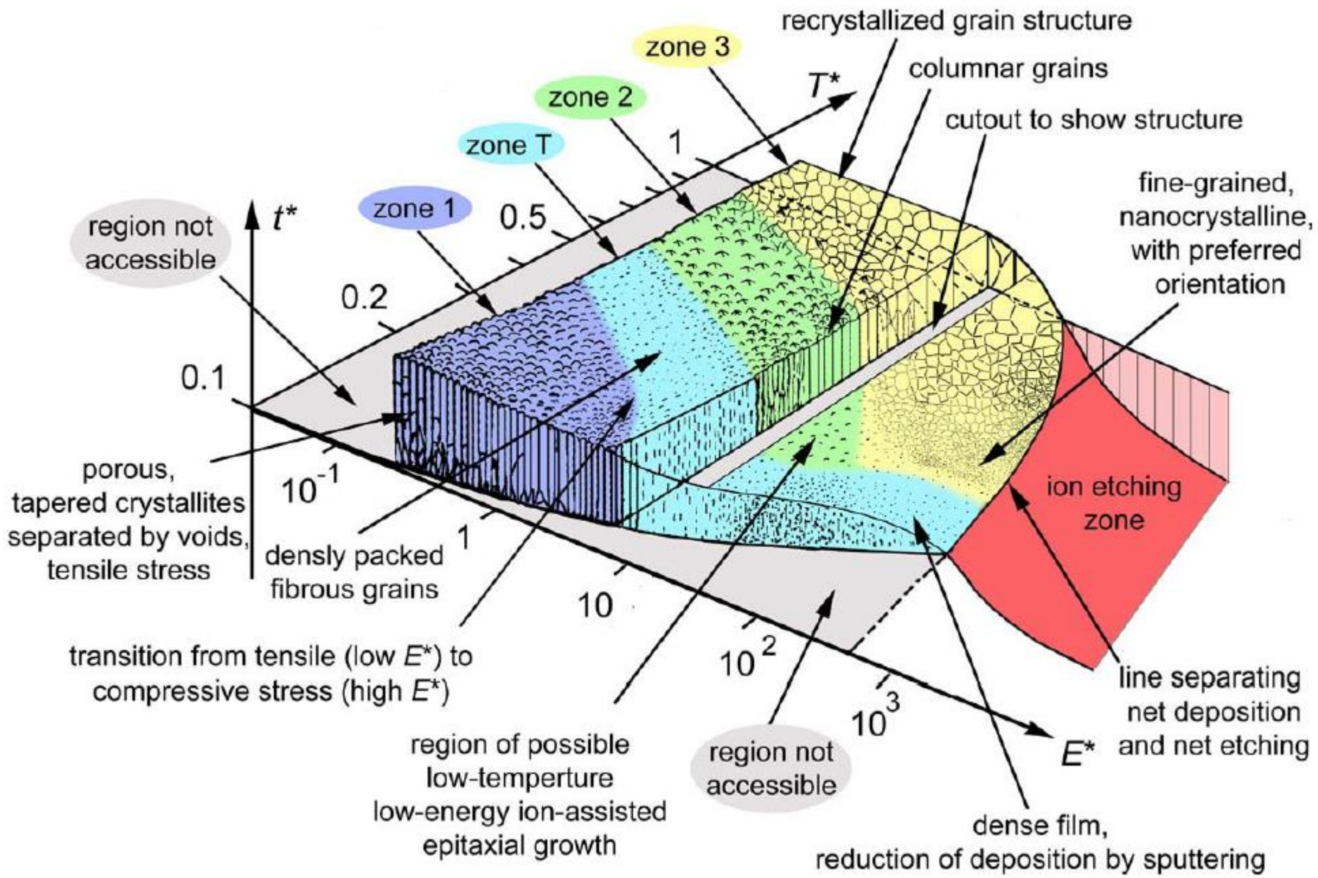
- *energy (E) of impinging particles (energy transfer)*
- *particle flux density(j) towards the substrate (momentum transfer)*

energy influx (J)

➡ *temperature of the substrate surface (T_S)*

thermal / energetic conditions at substrate surface in plasma processing determine …

- *elementary processes (adsorption, diffusion, desorption ...)*
- *chemical reactions (CSP, SFR ...)*
- *composition (stoichiometry ...)*
- *structure (morphology, crystal orientation ...)*



Movchan, B.A., Demchishin, A.V., Fizika Metallov i Metallovedenie (Physics of Metals and Metallography) ***28****(1969), 653.*
Thornton, J.A., J. Vac. Sci. Technol. ***11****(1974) 666.*
Anders, A., Thin Solid Films ***518****(2010), 4087.*

energy influx

nanoparticles

• nanoparticles produced in low-temperature plasmas are often found with crystalline structure, which suggests rather high temperatures during synthesis
• this even applies to particles of high-melting-point materials, which is surprising, because the gas temperature in these plasmas is often close to room temperature and particles may reside in the plasma only for a short duration

• **nanoparticle heating in plasmas through energetic surface reactions**

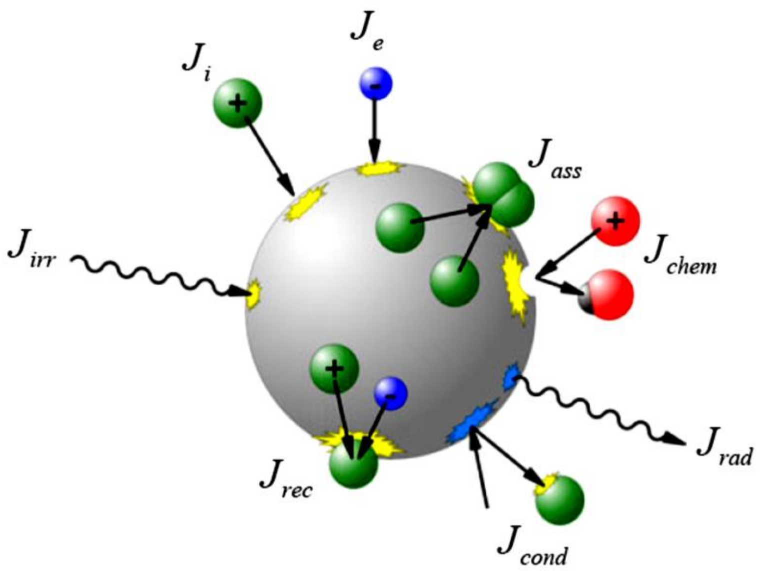
*P. R. i Cabarrocas, N. Chabane, A. V. Kharchenko and S. Tchakarov, PPCF **46**, B235 (2004).*
*P. R. i Cabarrocas, Y. Djeridane, T. Nguyen-Tran, E. V. Johnson, A. Abramov and Q. Zhang, PPCF **50**, 124037 (2008).*

*U. Kortshagen, J. Phys. D: Appl. Phys. **42**, 113001 (2009).*
*L. Mangolini, U. Kortshagen, Phys. Rev. E **79**, 026405 (2009).*

*J. Beckers, W. W. Stoffels and G.M.W. Kroesen, J. Phys. D: Appl. Phys. **42**,155206 (2009).*

*H.R. Maurer, H. Kersten, J. Phys. D: Appl. Phys. **44**, 174029 (2011).*
H.R. Maurer, H. Kersten, in: "Plasma Procesing of Nanomaterials", ed. By R.M. Sankaran, CRC Press , 309 (2012).

*A. Anders, J. Appl. Phys. **82**, 3679 (1997).*



energy balance

contributions of energy influx at substrate surface :

- irradiation (plasma, walls, sources)
- kinetic energy of charge carriers (electrons, ions)
- energy of neutrals (kinetic energy, excitation energy,
  heat of adsorption, condensation, resp.)
- exothermic chemical reactions
- recombination (charge carriers, atoms)
- external heating

energy losses at substrate surface :

- radiation (environment)
- heat conduction and convection (substrate holder, gas)
- desorption
- endothermic chemical reactions
- sputtering of particles and secondary electron emission
- external cooling

Kersten, H., Deutsch, H., Steffen, H., Kroesen, G.M.W., Hippler, R., Vacuum ***63*** *(2001), 385.*
Bornholdt, S., Kersten, H., Eur. Phys. J. D ***67****(2013), 176-187.*
Gauter, S., Haase, F., Kersten, H., Thin Solid Films ***669****(2019), 8.*

energy balance

substrate heating during PECVD
due to energy influx by several contributions :

$$Q_{in} = \int_{A_S} J_{in} dA \qquad J_{in} = J_n + J_c + J_e + J_i + J_{rec} + J_{rad} + J_{react} + \ldots$$

- condensation of deposited material (J_c)

$$Q_C = q_C \cdot \rho \cdot R_{dep} \cdot A \qquad J_c = \frac{\rho R}{m} \alpha E_{bind} \qquad \alpha \approx 1$$

- kinetic energy of sputtered and reflected particles (J_n)

$$Q_n = j_C \cdot E_{n,kin} = R_{dep} \frac{N_A \rho}{M} \cdot E_{n,kin} \cdot A \qquad J_n = \frac{\rho R}{m} \bar{E}_{n,kin}$$

- kinetic energy of electrons (J_e) and ions (J_i)

$$Q_e = n_e \sqrt{\frac{k_B T_e}{2\pi m_e}} \exp\left\{ -\frac{e_0 V_{bias}}{kT_e} \right\} \cdot 2 k_B T_e \cdot A \qquad J_e = 2 \frac{j_e}{e_0} k_B T_e$$

$$Q_i = n_e \sqrt{\frac{k_B T_e}{m_i}} \exp\{-0.5\} \cdot e_0 V_{bias} \cdot A \qquad J_i = \frac{j_i}{e_0} \left(\Phi_{pl} - V_{probe} \right)$$

energy balance

- neutralisation / recombination of electrons and ions (J_{rec})

$$Q_{rec} = j_i (E_{ion} - e_0 \Phi) \cdot A$$

$$J_{rec} = \frac{j_i}{e_0} \left(\Phi_{ion} - \Phi_{ewf} \right)$$

- association / reaction of molecules (J_{react})

- radiation (J_{rad})

$$Q_{rad} = (\sigma (\varepsilon_T T_T^4 - \alpha_S T_S^4) + \xi_{abs} j_{rad} E_{ph}) \cdot A$$

$$J_{phot} = \int \Phi_{pl}(\nu) \cdot h\nu \cdot A(h\nu) \cdot d\nu = \xi_{pl} j_{ph} E_{ph}$$

$$\boxed{J_{in} = J_n + J_c + J_e + J_i + J_{rec} + J_{rad} + J_{react} + \ldots}$$

$$Q_{in} = \int_{A_S} J_{in} dA$$

\# *J.A. Thornton, TSF **54**(1978), 23.*
\# *M. Andritschky, F. Guimaraes, V. Teixeira, Vacuum **44**(1993), 809.*
\# *R. Wendt, K. Ellmer, K. Wiesemann, JAP **82**(1997), 2115.*
\# *R. Piejak, V. Godyak, B. Alexandrovich, N. Tishchenko, PSST **7**(1998), 590.*
\# *T.P. Drusedau, T. Bock, T-M. John, F. Klabunde, JVST A**17**(1999), 2896.*
\# *S.D. Ekpe, S.K. Dew, JVST A**21**(2003), 476.*
\# *M. Čada, P. Virostko, S. Kment, Z. Hubicka, Vacuum **83**(2008), 738.*

\# *H. Kersten, H. Deutsch, H. Steffen, G.M.W. Kroesen, R. Hippler, Vacuum **63**(2001), 385.*

measurement of energy influx

methods for determination of (integral) energy influx J_{in} :

- measurement *dT/dx* :
  spatial gradient

 # Tandian, N.P., Pfender, E., PCPP ***17****(1997), 353.*
***Gardon, R****., RSI* ***24****(1953), 366.*
 # Ellmer, K., Mientus, R., SCT ***116-119****(1999), 1102.*
 # Welzel,T., Kellermeier, M., Harbauer, K., Ellmer, K., APL ***102****(2013), 211605.*
*# Steffen,H., Kersten, H., Wulff,H., JVST A****12****(1994), 2780.*
 # Kersten,H., Snijkers, R, Schulze, J., Kroesen, G.M.W, Deutsch, H., deHoog, F.J., APL ***64****(1994), 1496.*

- measurement dT_S/dt :
  temporal slope (passive), PTP

***Thornton, J.A****., JVST* ***11****(1974),666.*
 # Wendt, R., Ellmer, K., Wiesemann, K., JAP ***82****(1997), 2115.*
*# Ekpe, S.D., Dew, S.K., JVST A****22****(2004), 1420.*
 # Thomann, A.L.,Semmar, N., Dussart, R., Mathias, J., Lang,V., RSI ***77****(2006), 033501.*
 # Čada, M., Bradley, J., Clarke, G., Kelly, P.J., JAP ***102****(2007), 063301*
 # Kersten, H., Kroesen, G.M.W., Contrib.Plasma Phys. ***30****(1990), 725.*
 # Kersten, H., Deutsch, H., Steffen, et.al., Vacuum ***63*** *(2001) 385.*
 # Gauter, S., Haase, F., Kersten, H., Thin Solid Films ***669****(2019), 8.*

- measurement Q_{in} :
  power compensation (active), ATP

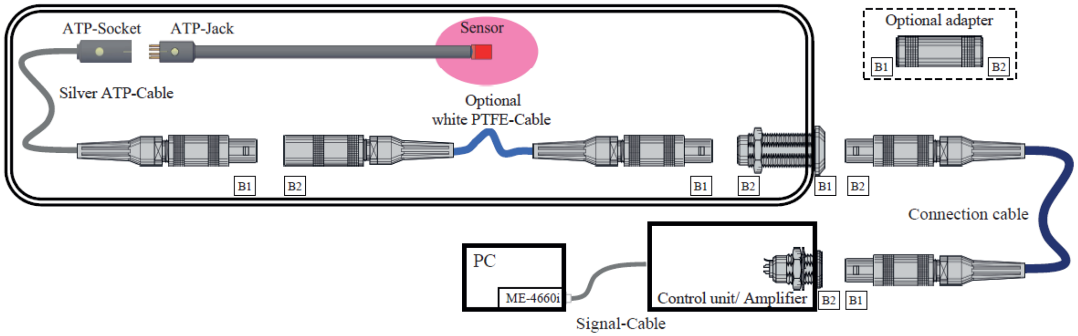
 # Wiese, R., Kersten, H., Galvanotechnik ***99****(2008), 1502.*
 # Wiese, R., Kersten, H., Wiese, G., Bartsch, R., EPJTI ***2****(2015), 2.*

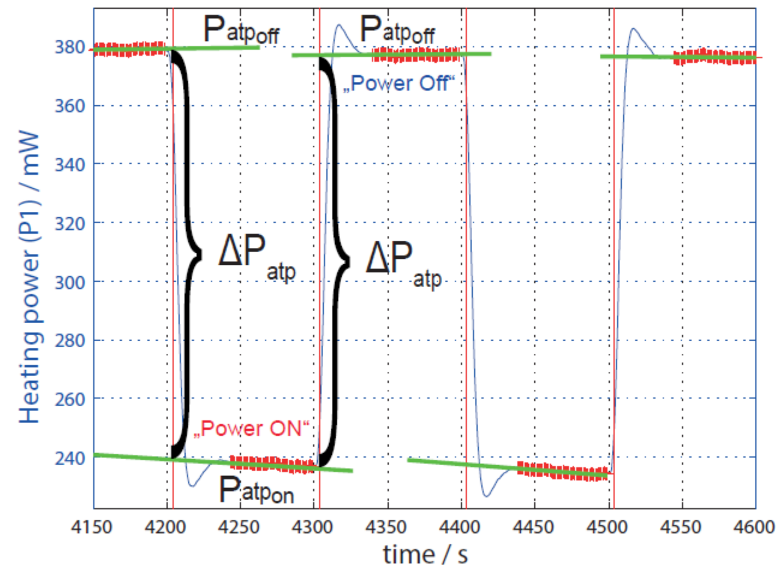
- measurement T_p :
  particle fluorescence

*# Daugherty, J.E., Graves, D.B., JVST A****11****(1993), 1126.*
 # Swinkels,G., Kersten,H.,Kroesen,G., Deutsch,H. JAP ***88****(2000), 1747.*
 # Maurer, H., Basner, R., Kersten, H., RSI ***79****(2008), 093508.*

measurement of energy influx

Wiese, R., Kersten, H.,
Galvanotechnik ***99****(2008), 1502.*
Wiese, R., Kersten, H., Wiese, G., Häckel, M.,
Vakuum in Forschung und Praxis ***23****(2011), 20.*



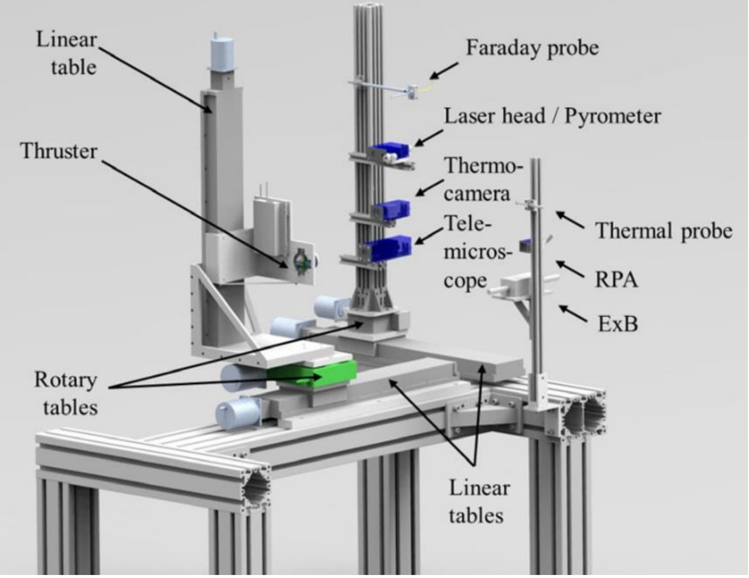


Wiese, R., Kersten, H.,
Wiese, G., Bartsch, R.,
EPJTI ***2****(2015), 2.*

measurement of energy influx

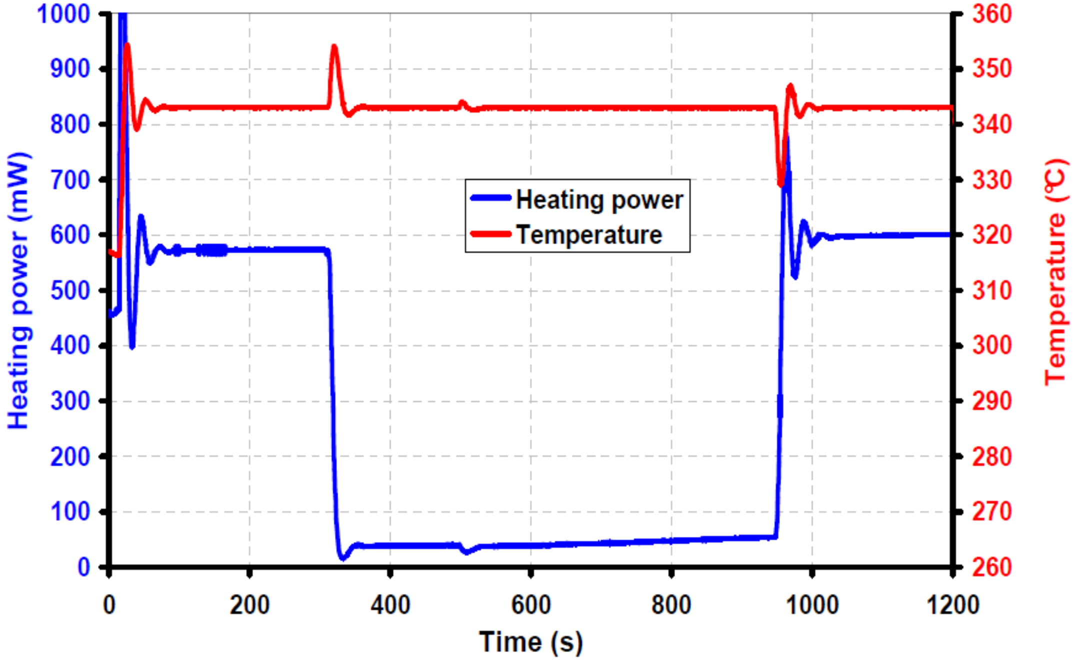
Bundesmann, C., et.al.,
„An advanced electric propulsion diagnostic (AEPD) platform for in-situ characterization of electric propulsion thrusters and ion beam sources“,
*Eur. Phys. J. D **70**(2016), 212.*

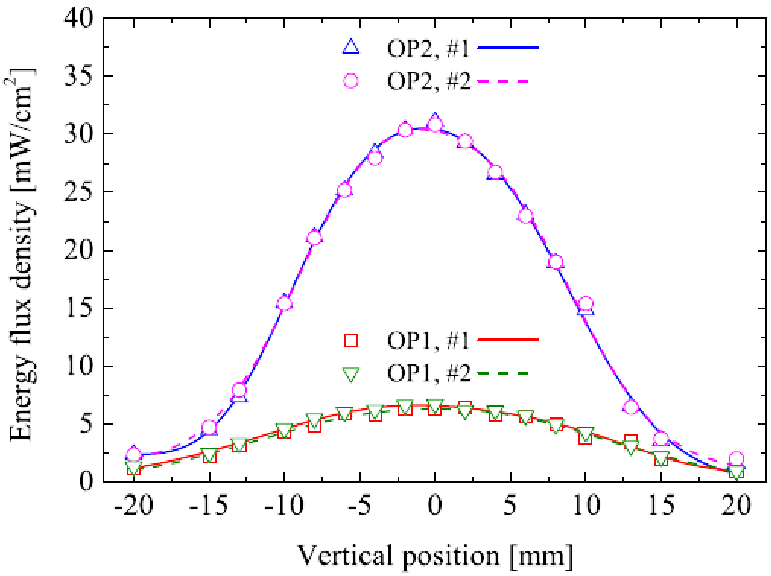
Parameter	OP1	OP2
Beam Voltage	1050 V	1700 V
Beam Current	4 mA	8 mA
Accelerator voltage	–200 V	–250 V
Nominal thrust	210 μN	540 μN



ion beam source:

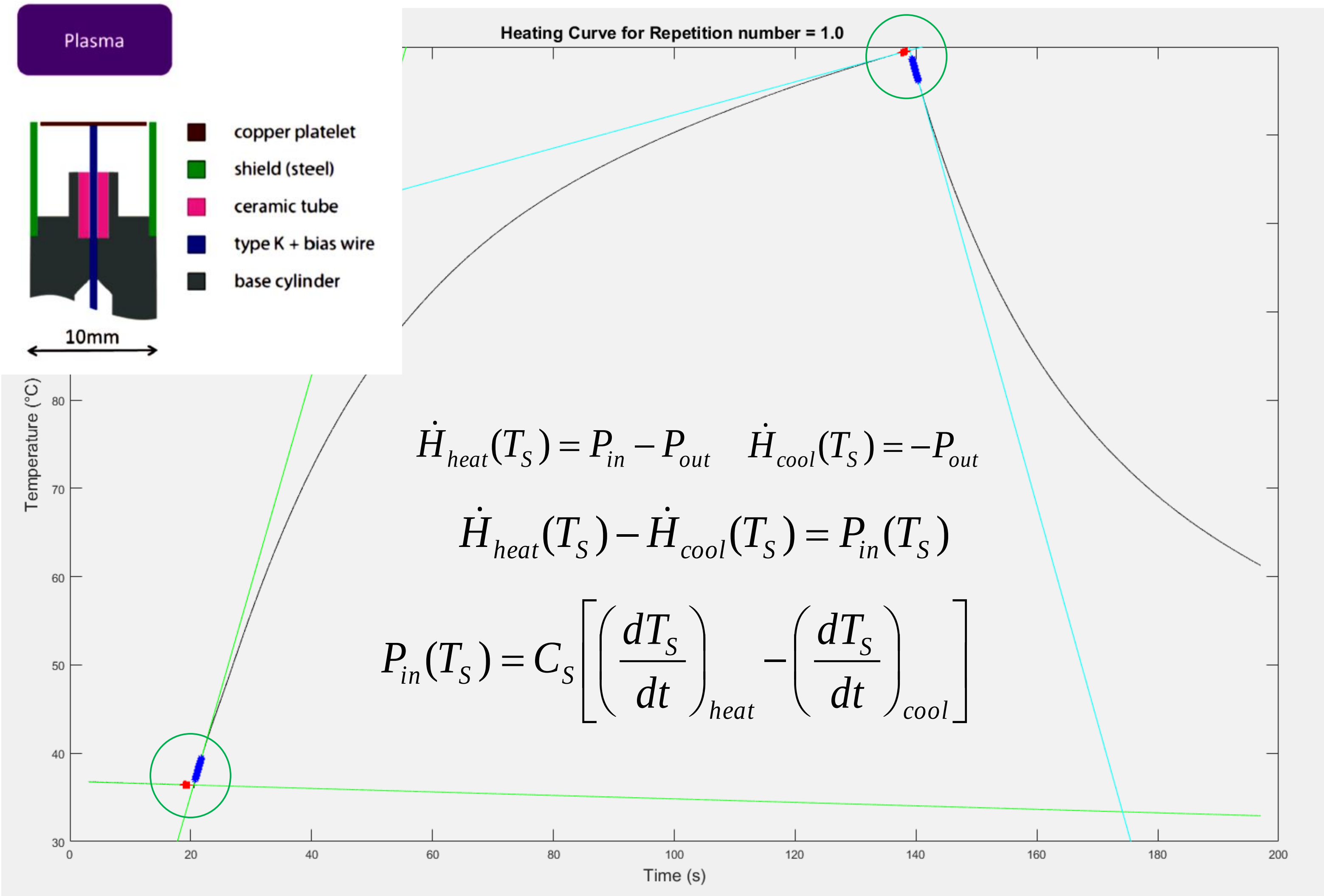
pressure: 0.04 Pa Ar, beam voltage: 500 V
beam diameter: 160 mm
distance: 225 mm





passive thermal probe (PTP)

procedure



$$\dot{H}_{heat}(T_S) = P_{in} - P_{out} \qquad \dot{H}_{cool}(T_S) = -P_{out}$$

$$\dot{H}_{heat}(T_S) - \dot{H}_{cool}(T_S) = P_{in}(T_S)$$

$$P_{in}(T_S) = C_S\left[\left(\frac{dT_S}{dt}\right)_{heat} - \left(\frac{dT_S}{dt}\right)_{cool}\right]$$

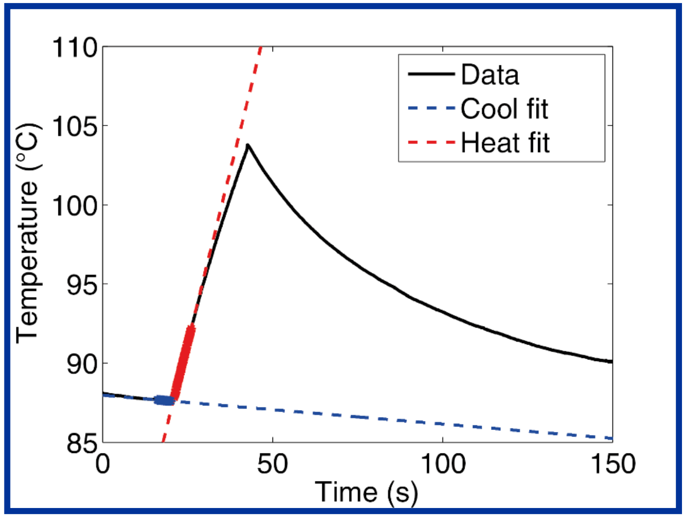
*S. Bornholdt, H. Kersten, Eur. Phys. J. D, **67**(2013), 176.*
*F. Haase, D. Lundin, S. Bornholdt, H. Kersten, Contrib. Plasma Phys. **55**(2015), 701.*

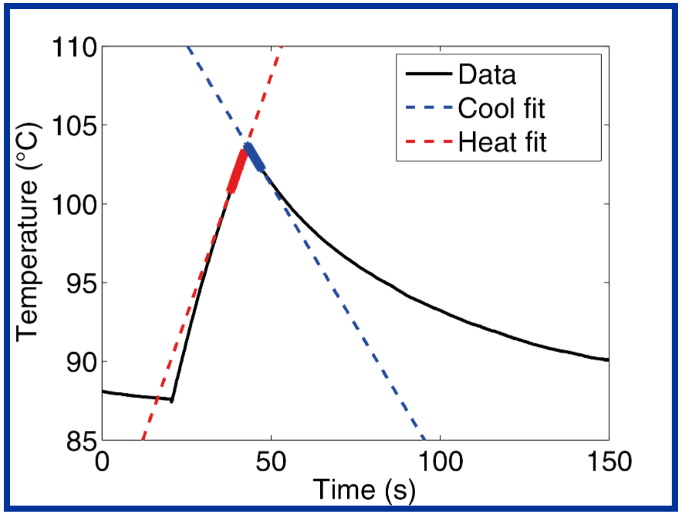
passive thermal probe (PTP)

Passive thermal probe

Determination of the energy flux density

$$\frac{P_{in}}{A_S} = J_{in} = \frac{C_S}{A_S}\left[\dot{T}_h - \dot{T}_c\right]$$





Measurement on ion beam experiment VIBEX: 700V anode voltage, 60% impulse width modulation, distance to source: 30 cm

Evaluation around kinks

- Examination of short times around switching kinks of the temperature curve
- Approximation of temperature curve by linear fit
- Difference of slope gives:

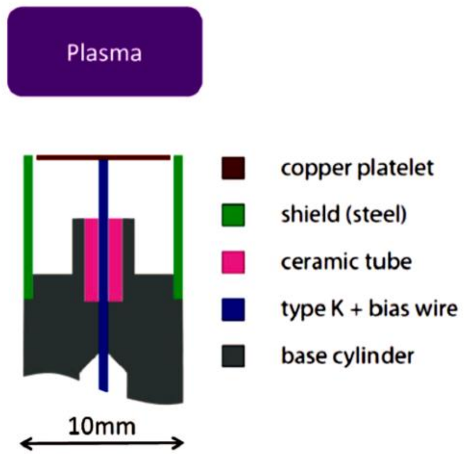
Gauter,S., Haase,F., Solar,P., Kylian,O., Kus,P., Choukourov,A., Biederman,H., Kersten,H., J. Appl. Phys. ***124****(2018), 073301.*

Gauter, S., Fröhlich, M., Kersten, H., SCT ***352****(2019), 663.*
Gauter, S., Haase, F., Kersten, H., Thin Solid Films ***669****(2019), 8.*

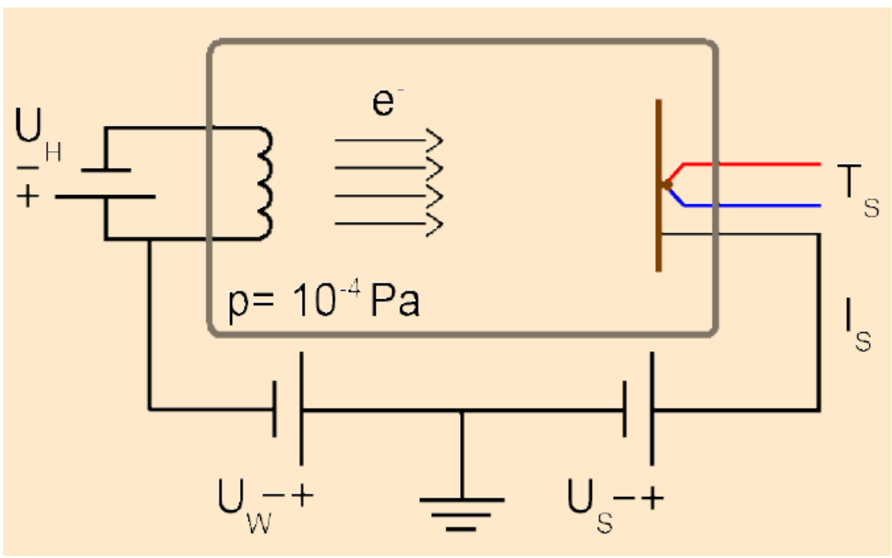
passive thermal probe (PTP)

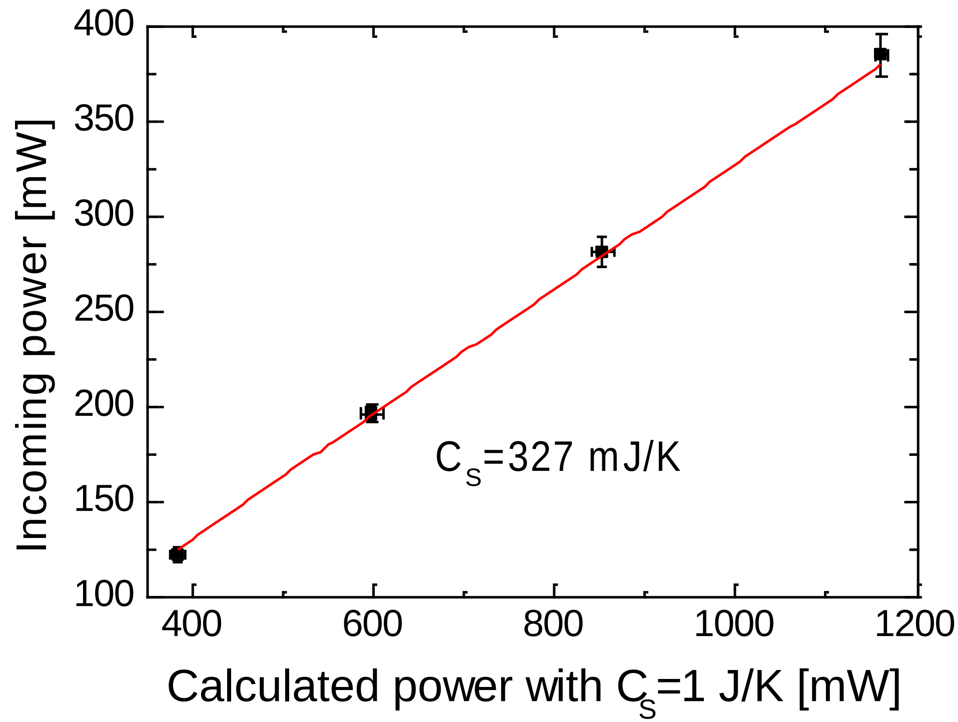
calibration

PTP



$$P_{in}(T_S) = C_S \left[\left(\frac{dT_S}{dt} \right)_{heat} - \left(\frac{dT_S}{dt} \right)_{cool} \right]$$

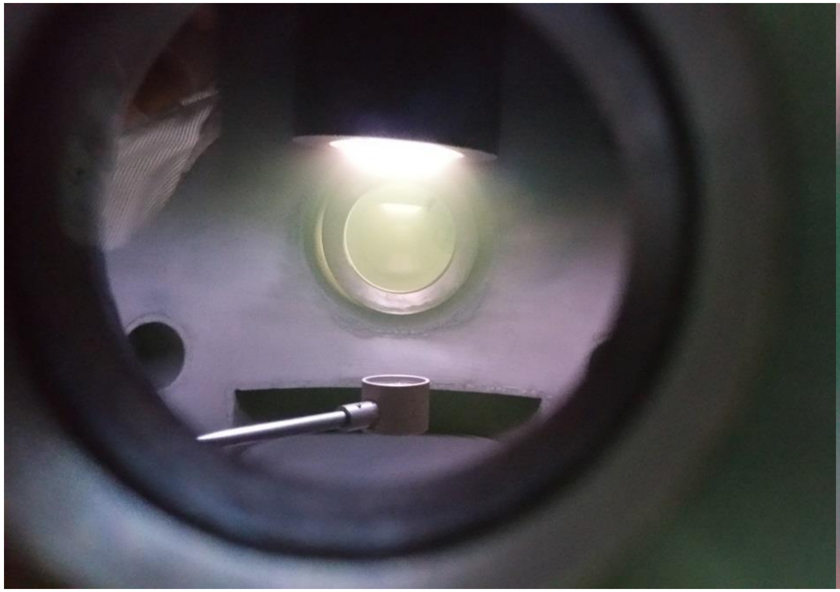




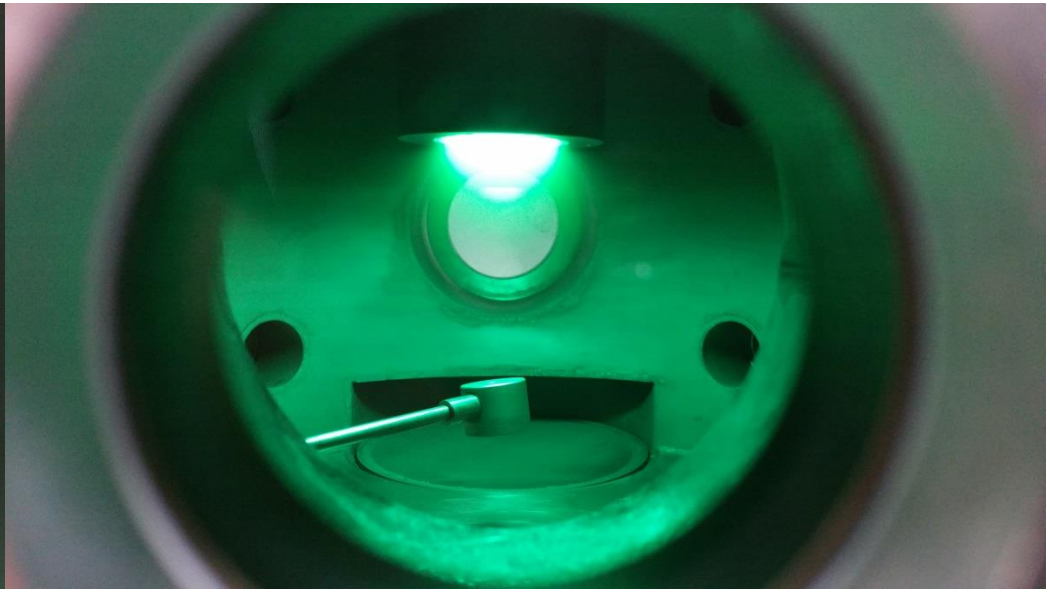
Stahl, M., Trottenberg, T., Kersten, H., Rev. Sci. Instr. ***81****(2010), 023504.*

HiPIMS vs. DCMS

comparison DCMS and HiPIMS

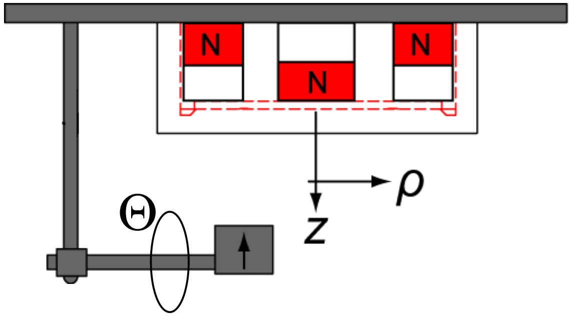


Cu / Ar (DC)



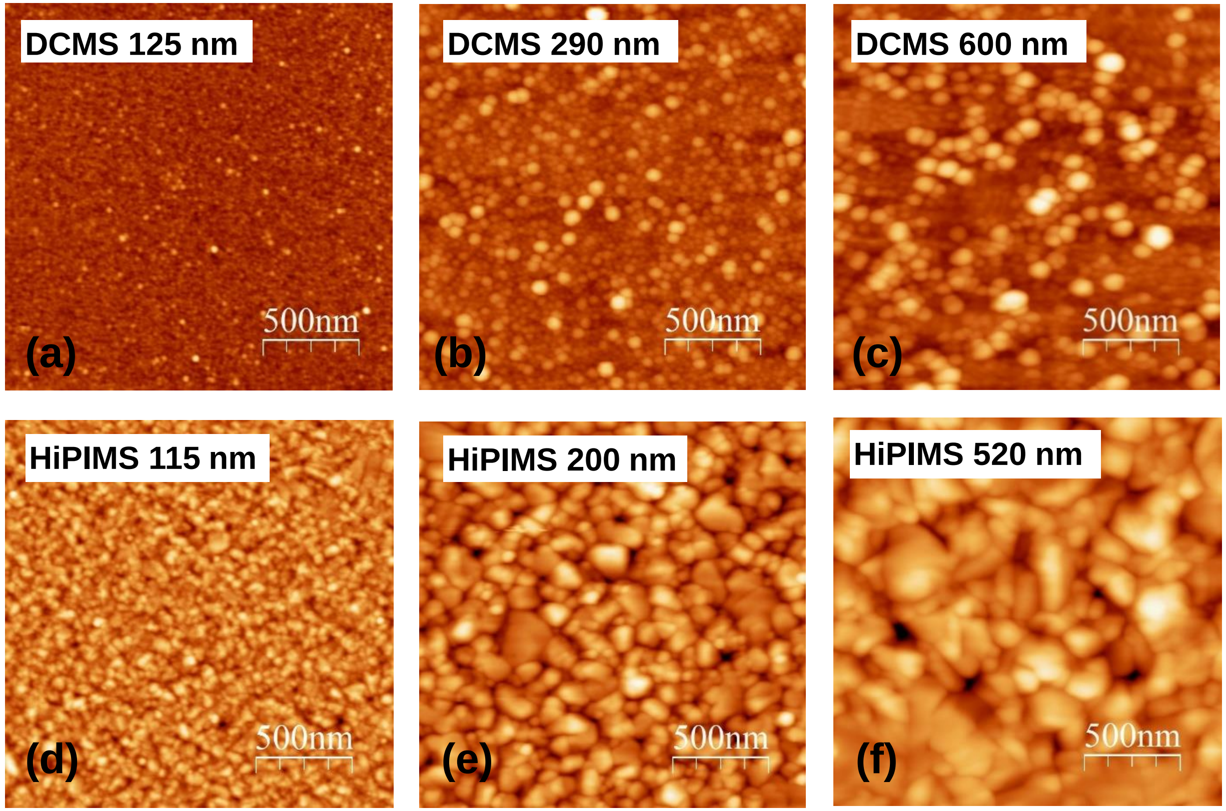
Cu / Ar (40µs, 500 Hz)

D. Lundin, T. Minea, et.al.
(U Paris-Sud)



r = - 80 ... + 80 mm
z = 55, 110 mm
Θ = - 90° ... + 90°
V_{PTP} = - 200 ... V_{fl} ... + 20 V

HiPIMS vs. DCMS



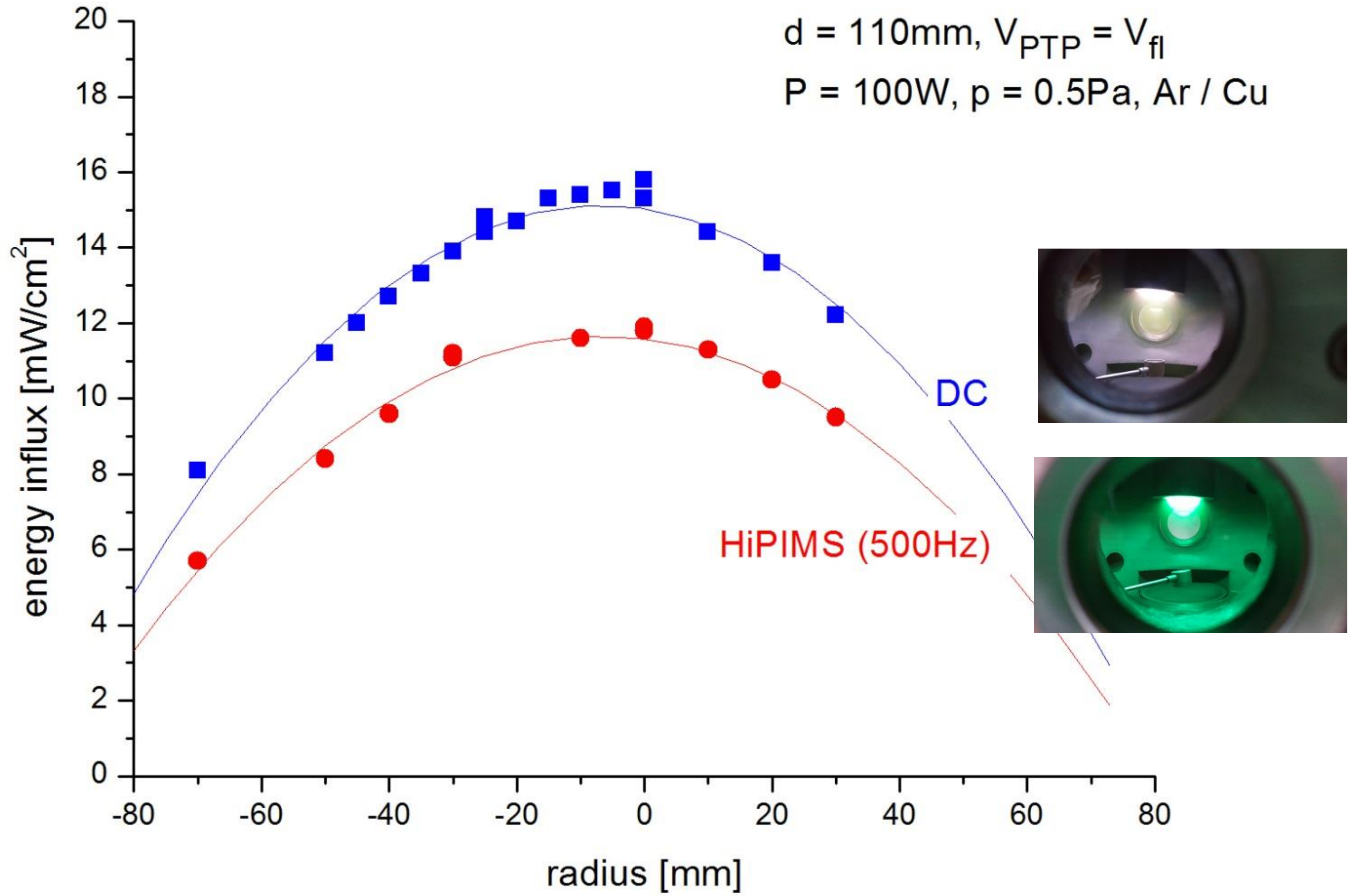
grain size modifications due to energetic ion bombardment

D. Lundin, T. Minea, et.al. (U Paris-Sud)

Stryhalski,J., Fontana,L.C., Odorczyk,M.F., Scholtz,J.S., Sagas,J.C., Recco,A.A.C., Materials Research ***17****(2014).*

energy fluxes in HiPIMS

radial



energy fluxes in HiPIMS vs. DCMS

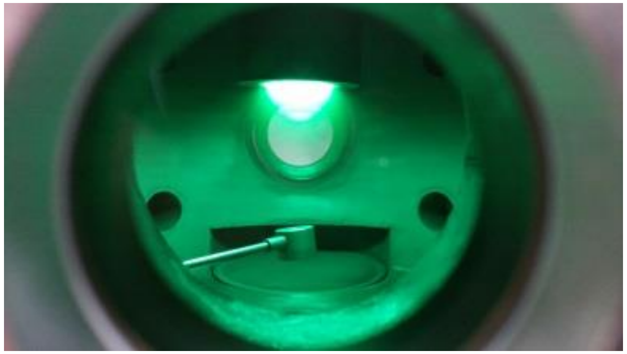
$J_{HiPIMS} / J_{DCMS} = 0.7$

e.g. lower heating rate

deposition rate$_{HiPIMS}$ / rate$_{DCMS}$ = 0.5

⇨ 1.4 times more energy per deposited particle

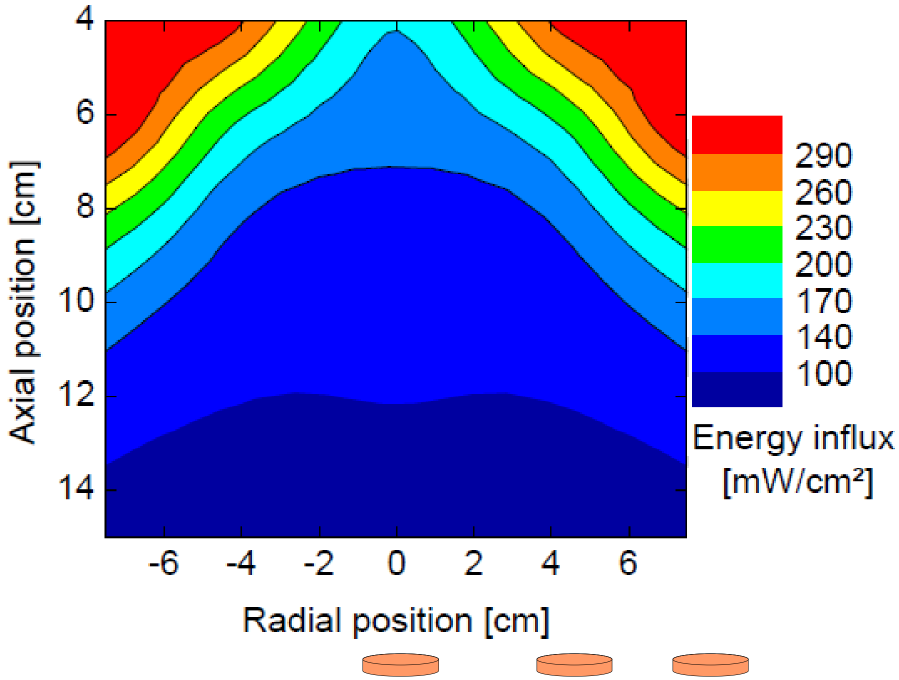
⇨ thin film properties



Ti / Ar

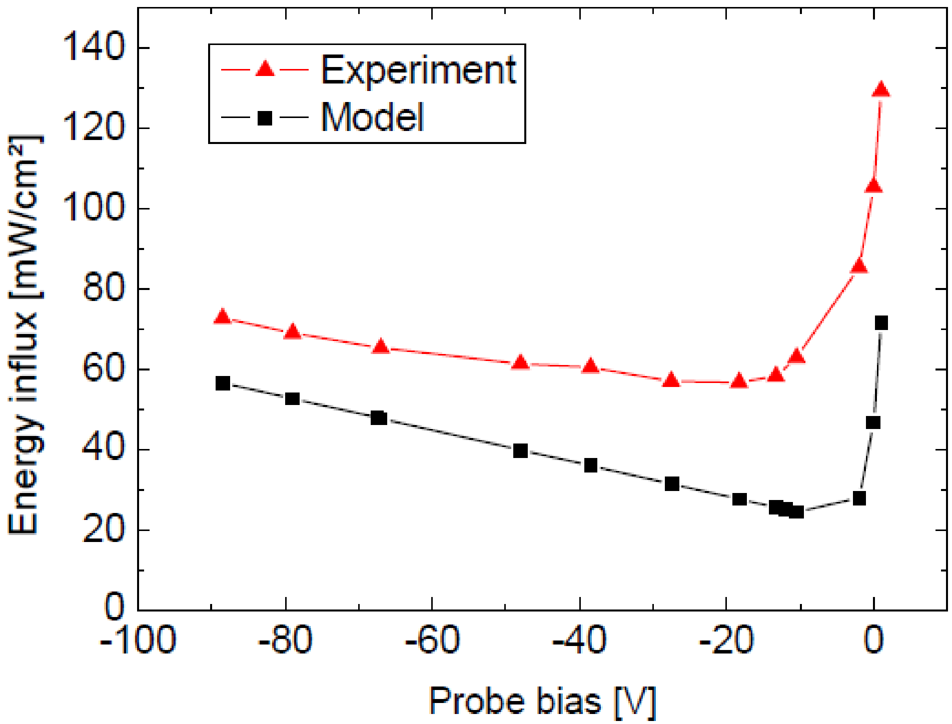
100µs
100Hz

- J_{tot} not homogeneous at target
- radial transport
- homogeneous for z > 100mm



energy fluxes in sputtering, DCMS

effect of bias voltage



Model:

$$J_{tot} = J_{kin,i} + J_{kin,e} + J_{rec} + J_{e,sec}$$

$$J_{kin,i} = j_{ion} \cdot q(V_{pl} + V_S)$$

$$J_{rec} = j_{ion} \cdot \bar{E}_{rec}$$

$$J_{e,sec} = j_{ion} e \cdot \gamma (V_S + V_{cat})$$

j_{ion}: Bohm-Fluss

$J_{kin,e}$: Maxwell-Verteilung

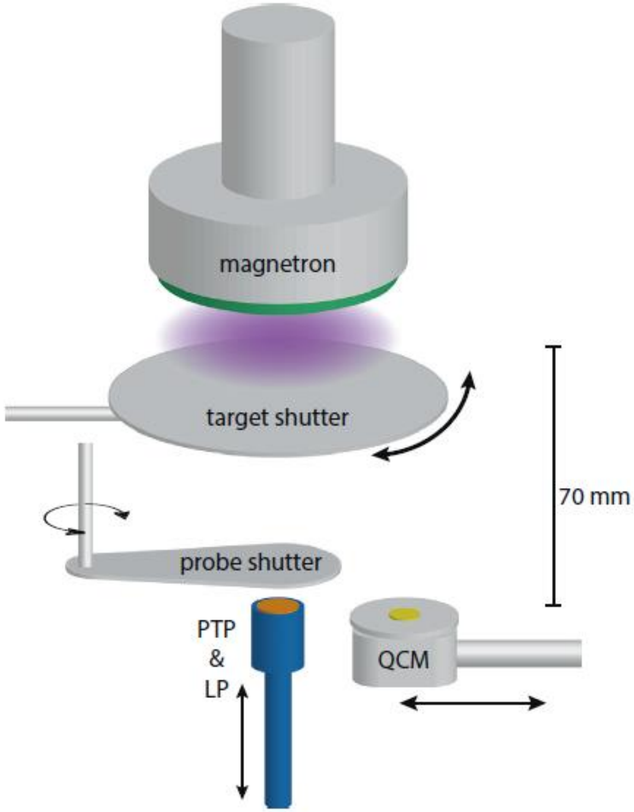
→ difference due to neutrals, film growth and radiation

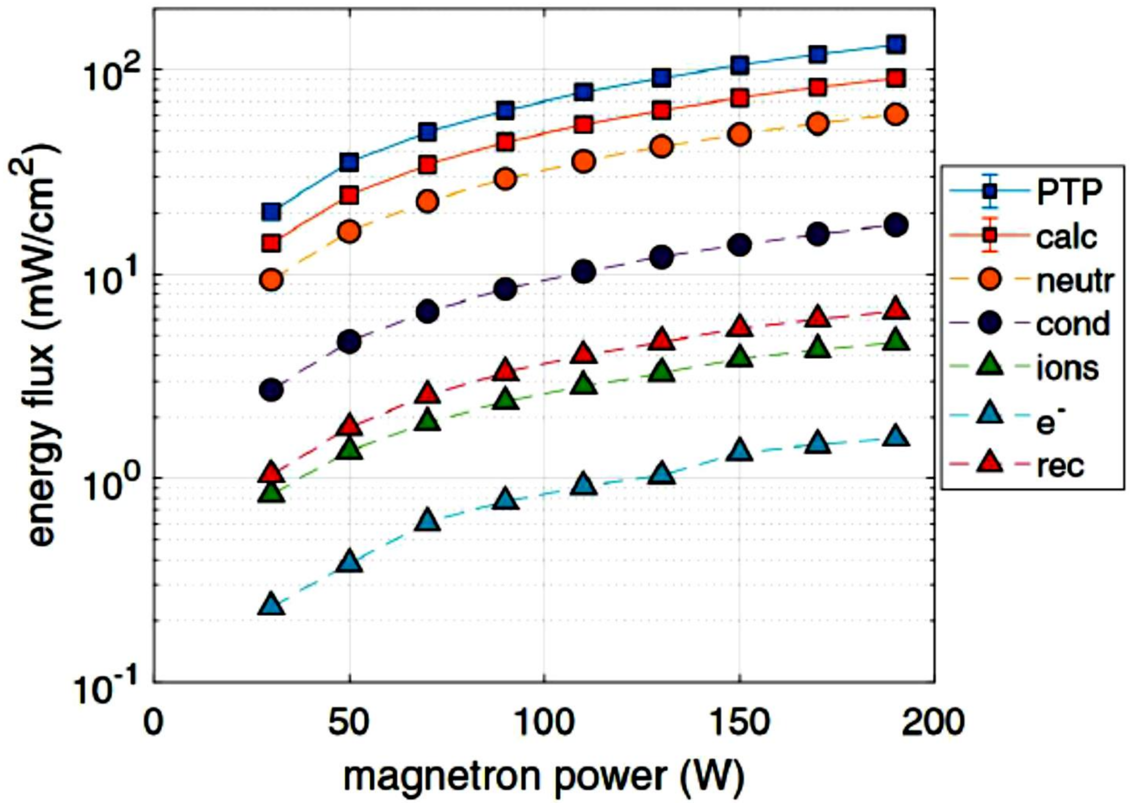
*H. Kersten, D. Rohde, J. Berndt, H. Deutsch, R. Hippler , TSF **377-378** (2000), 585.*

energy fluxes in sputtering, DCMS

contributions

$$J_{in} = J_n + J_c + J_e + J_i + J_{rec} + J_{rad} + J_{react} + \ldots$$

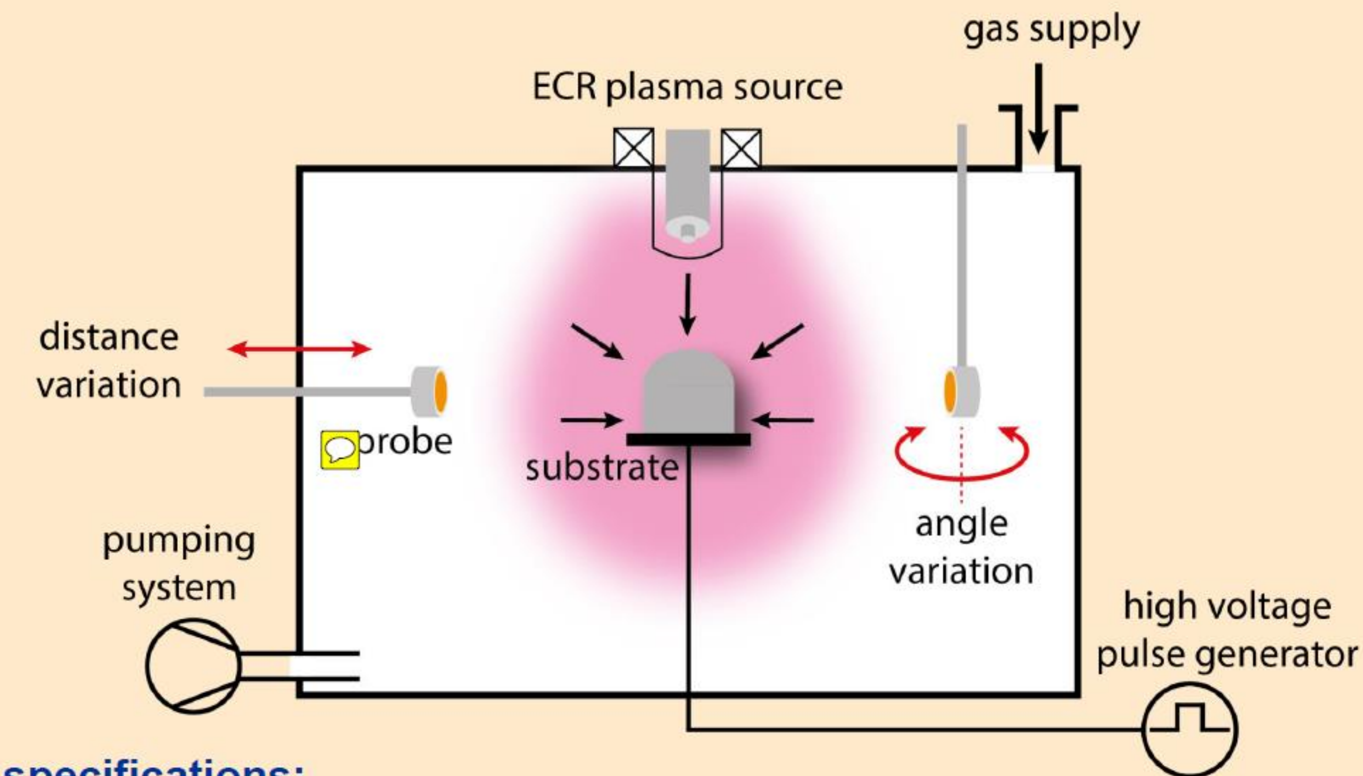




*Gauter, S., Haase, F., Kersten, H., Thin Solid Films **669**(2019), 8.*

*Benedikt, J., Kersten, H., Piel, A., Plasma Sources Sci. Technol. **30**(2021), 033001.*

energy fluxes in PIII



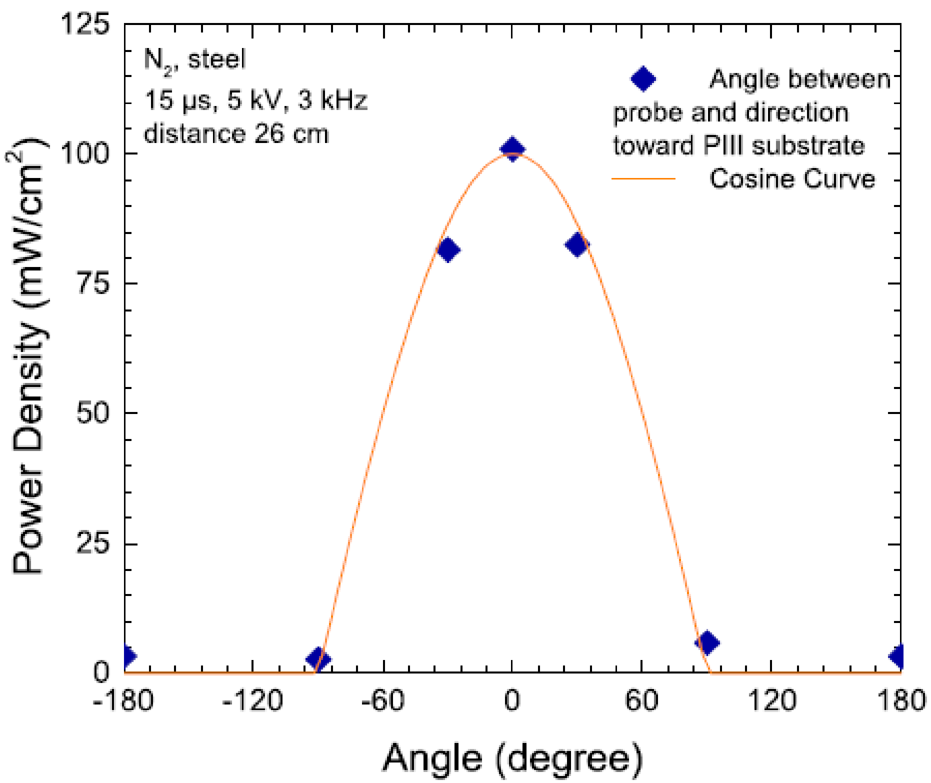
specifications:

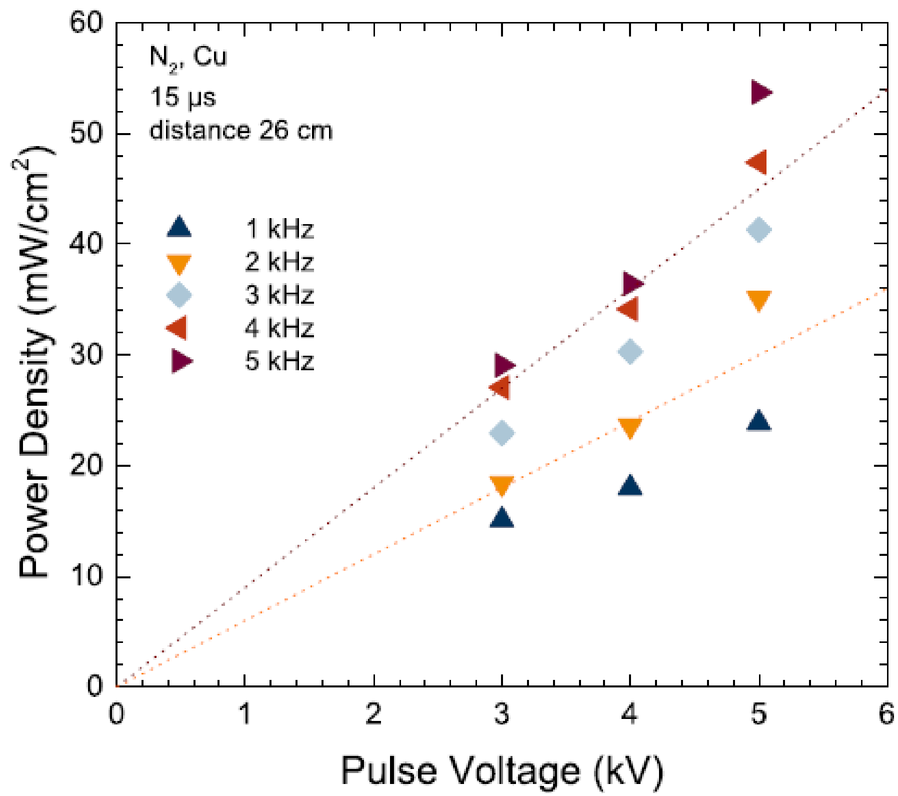
- volume = 165 l
- 3 plasma sources (2.45G Hz ECR, only centered one was used)
- pressure: 5.8 µbar

Haase, F., Manova, D., Mändl, S., Kersten, H., Eur. Phys. J. D ***70****(2016), 186.*
Haase, F., Manova, D., Hirsch, D., Mändl, S., Kersten, H., Plasma Sources Sci. Technol. ***27****(2018), 044003.*

energy fluxes in PIII

SEE: angle, frequency

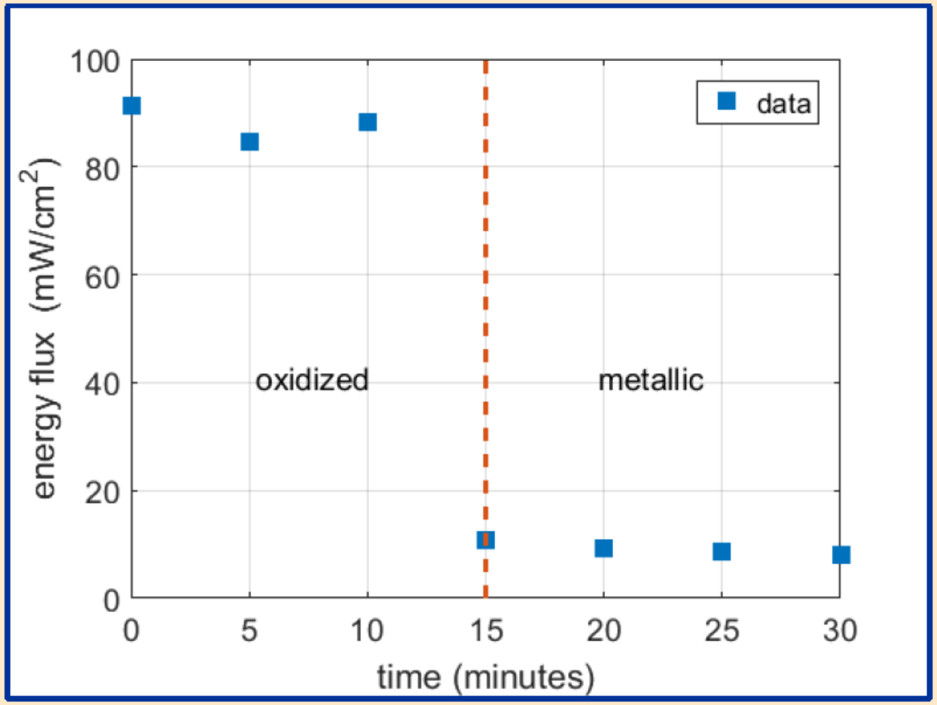




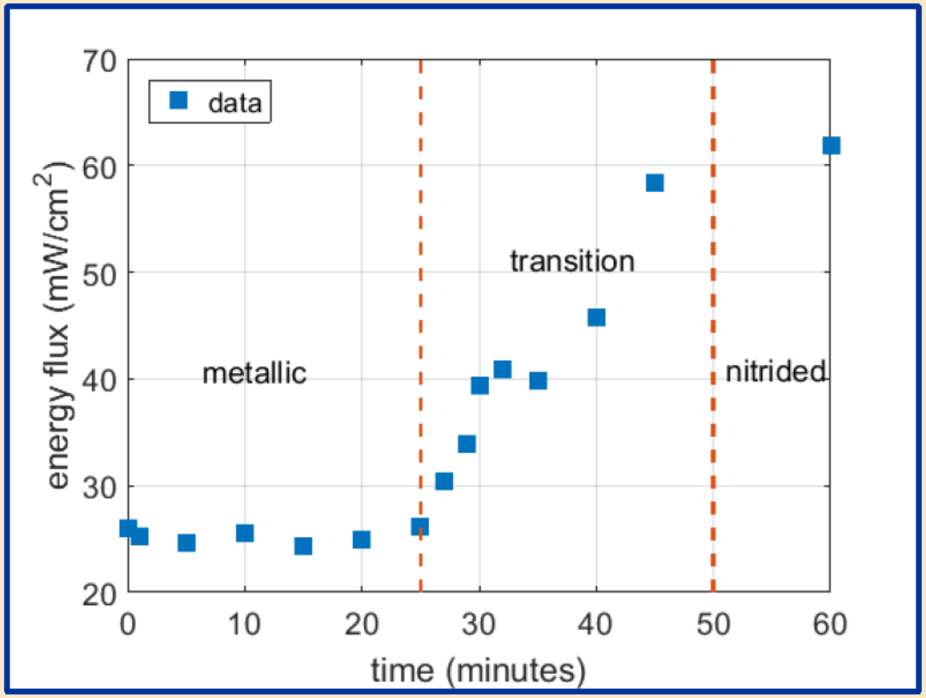
*Haase, F., Manova, D., Mändl, S., Kersten, H., Eur. Phys. J. D **70**(2016), 186.*

energy fluxes in PIII

SEE, surface state



oxidized Mg, 15 µs, 3 kV, 5 kHz

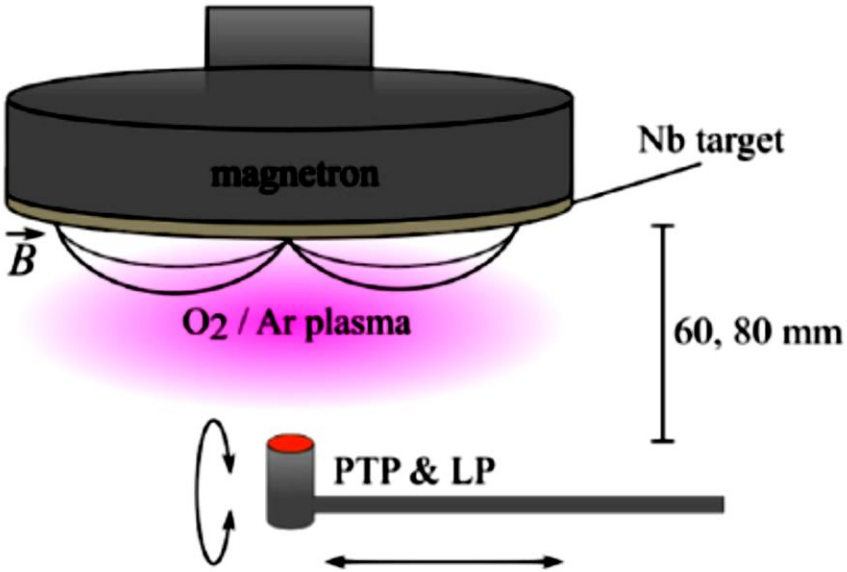


Mg, 15 µs, 3kV, 5 kHz

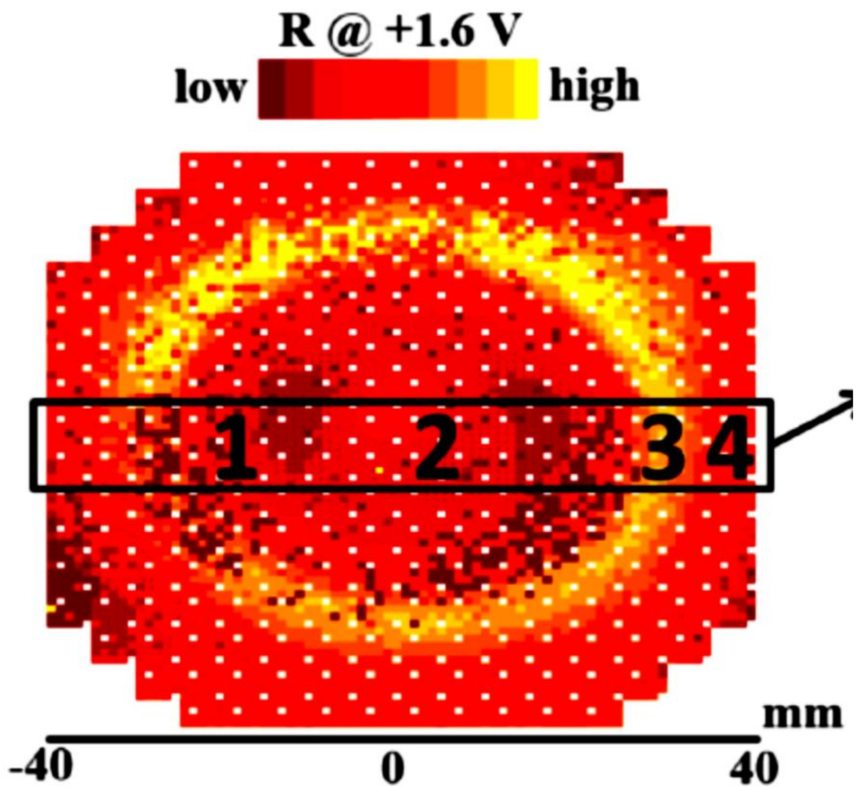
Haase, F., Manova, D., Hirsch, D., Mändl, S., Kersten, H., Plasma Sources Sci. Technol. ***27****(2018), 044003.*

energy fluxes in sputtering

NbOx for memristive devices



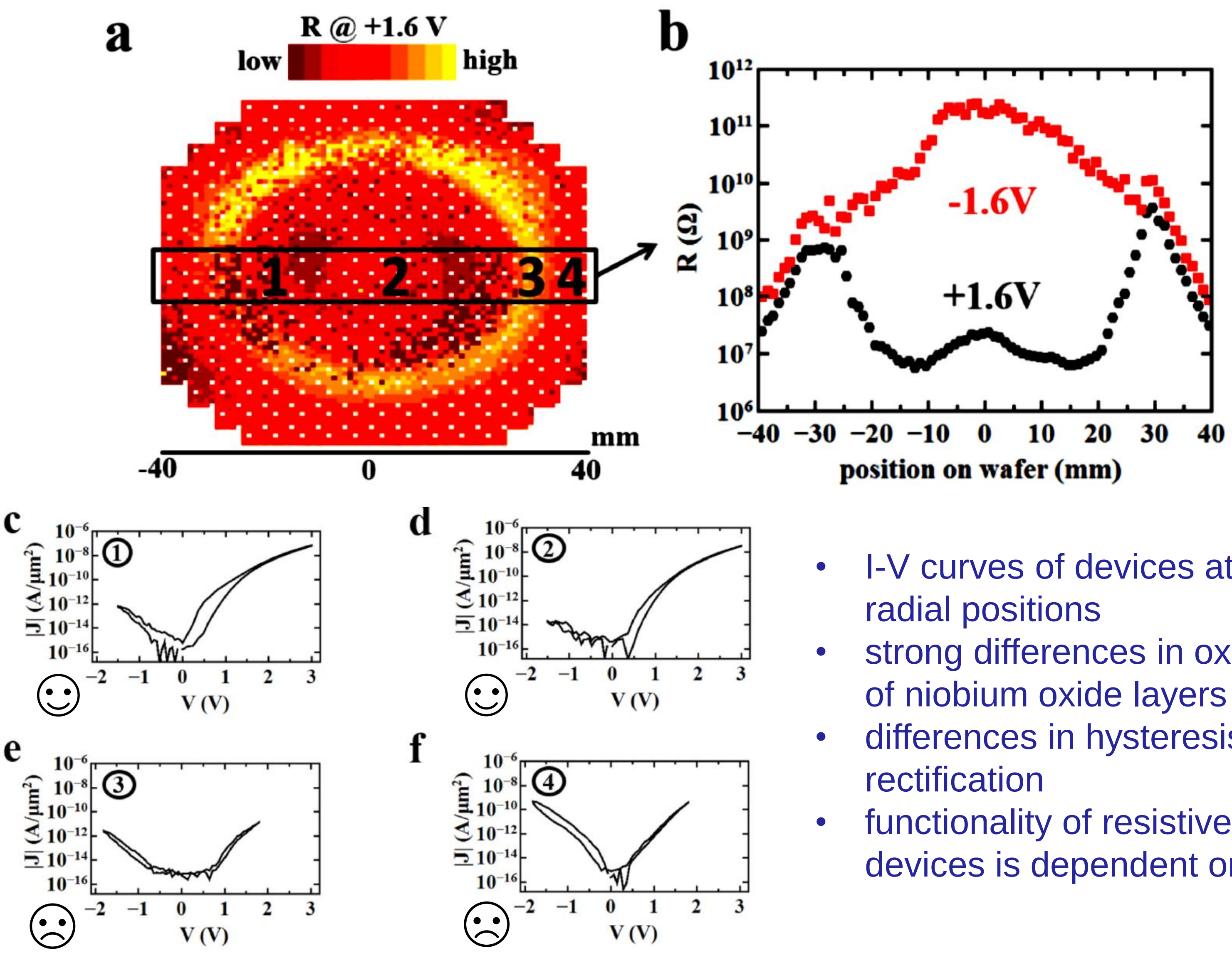
- NbOx thin film sputtering for double-barrier memristive devices
- resistive map of devices



Zahari, F., Schlichting, F., Strobel, J., Dirkmann, S, Cipo, J., Gauter, S., Trieschmann, J., Marquardt, R., Haberfehlner, G., Kothleitner, G., Kienle, L., Mussenbrock, T., Ziegler, M., Kersten, H., Kohlstedt, H.,
J. Vac. Sci. Technol B ***37****(2019), 061203.*

energy fluxes in sputtering

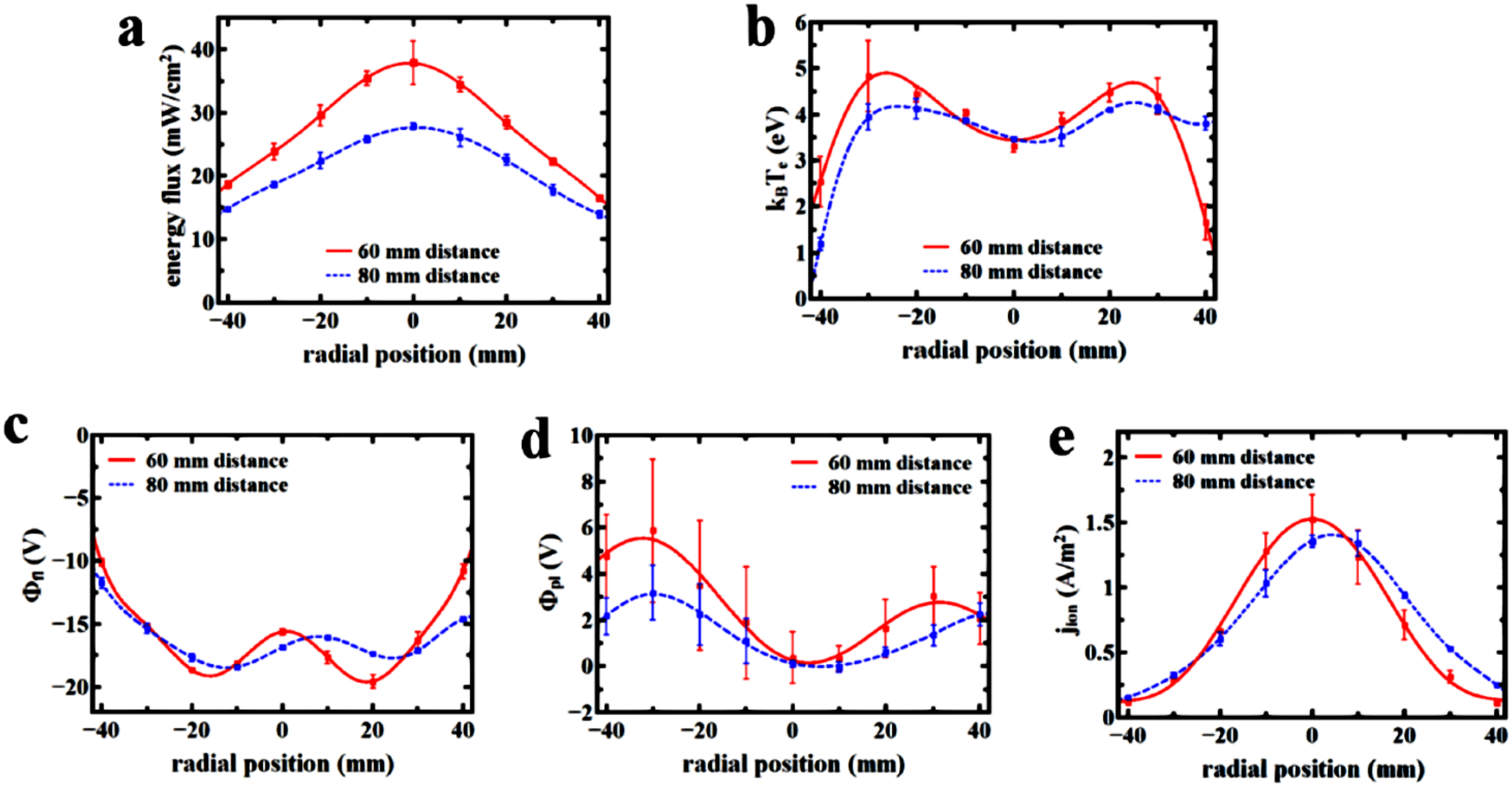
NbOx for memristive devices



- I-V curves of devices at different radial positions
- strong differences in oxidation state of niobium oxide layers were found
- differences in hysteresis and rectification
- functionality of resistive switching devices is dependent on position

energy fluxes in sputtering

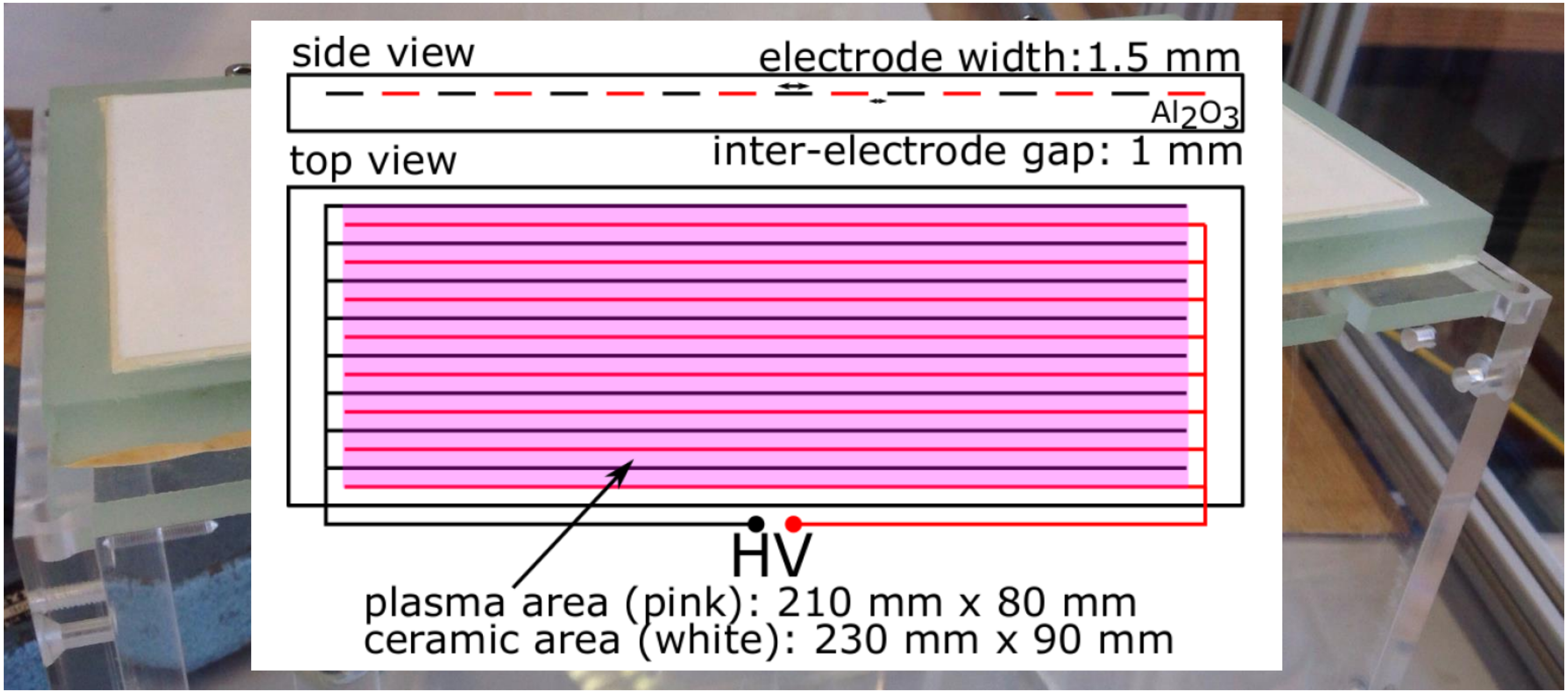
NbOx for memristive devices



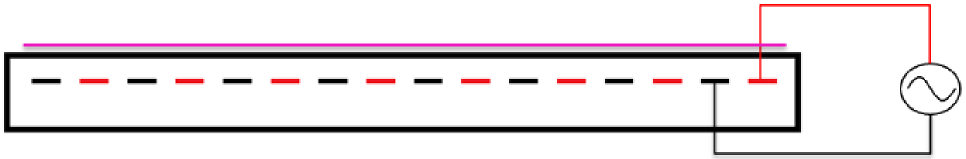
- functionality of resistive switching devices is dependent on position
- these findings are correlated to the energy (and potential) conditions on the sample surface

*Zahari, F., et.al., J. Vac. Sci. Technol B **37**(2019), 061203.*

energy fluxes in DCSBD



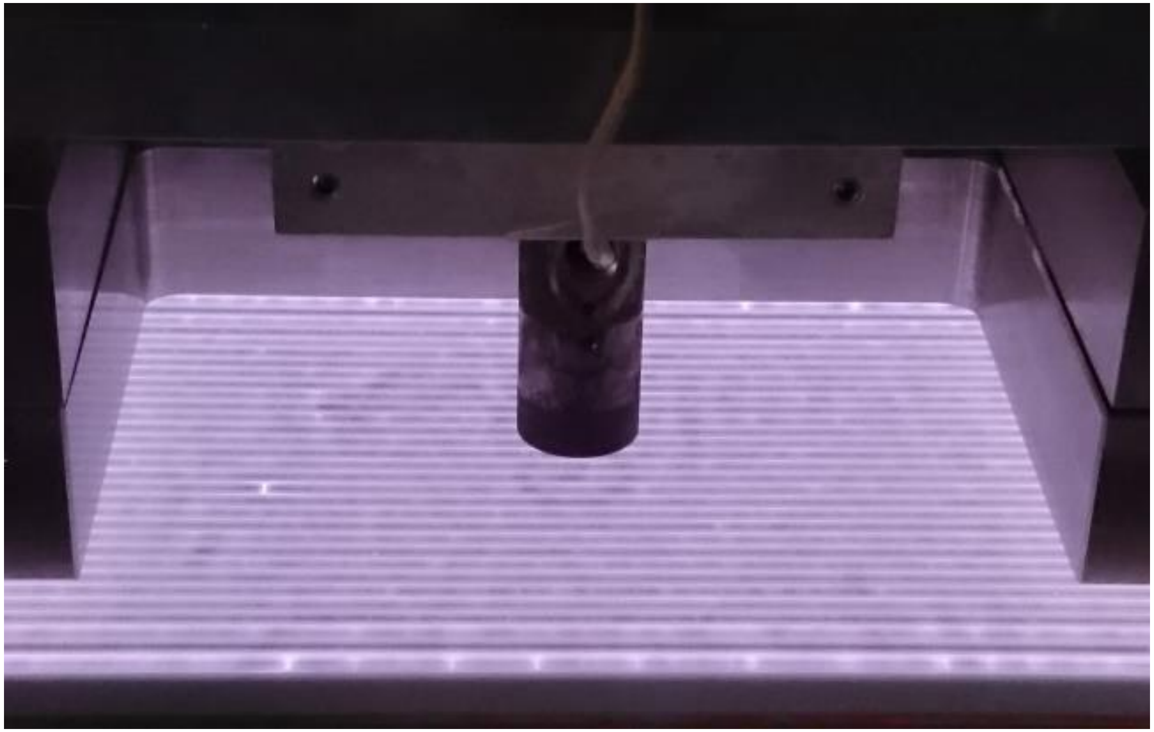
http://www.roplass.de

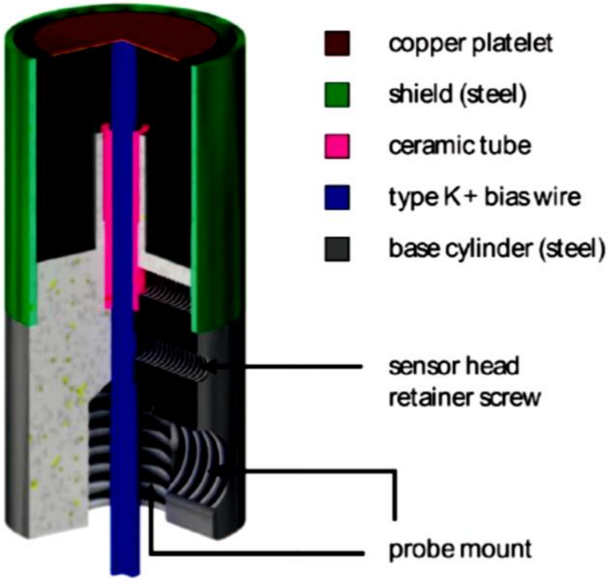


- DCSBD 400 (Roplass, CZ)
- Input power: 380 W
- Applied voltage: 20-30kVpp
- Frequency: 14-18 kHz (sine)

Homola et.al., Appl. Surf. Sci. ***258****(2012), 7135-7139.*
Kormunda et.al., Poly. Deg. & Stab. ***97****(2012), 547-553.*
Homola et.al., Plasma Chem. Plasma Process., ***33****(2013), 881-894.*

energy fluxes in DCSBD





*Bornholdt, S., Wolter, M., Kersten, H., „Eur. Phys. J. D **60**(2010), 653-660.*

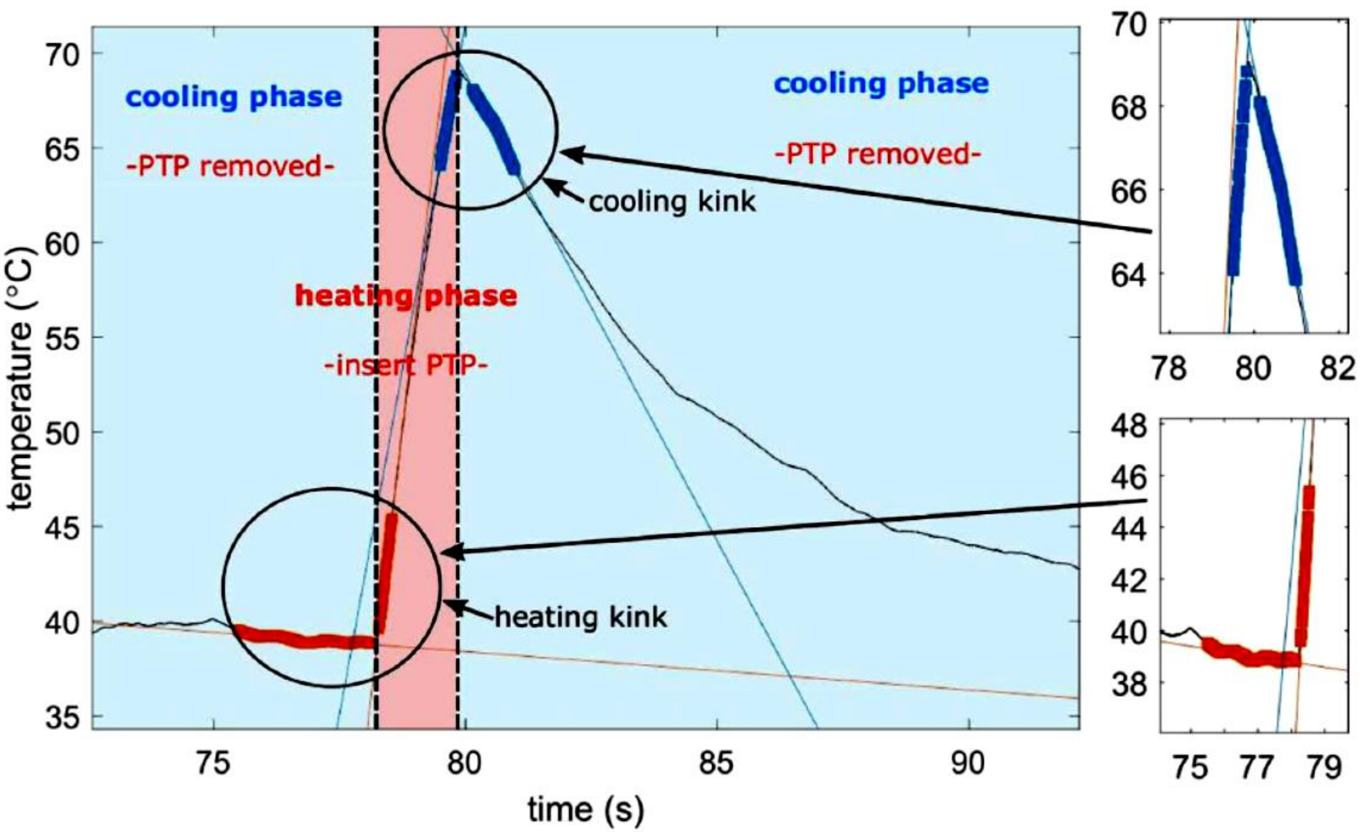
*Gauter, S., Haase, F., Kersten, H., Thin Solid Films **669**(2019), 8-18.*

- calorimetric probe: **Passive Thermal Probe (PTP)**
- experimental investigation of DCSBD:

  variation distance DCSBD – PTP (gas flow, chemistry)

  variation of process gas (air, N_2, O_2, Ar)

energy fluxes in DCSBD



Before switching off → Steady state

Energy flux values of both kinks usually match

Directly after switching on → Process start

Energy flux density

$$J_{in} = \frac{P_{in}}{A_s} = \frac{C_s\left(\frac{dT_{s_{heat}}}{dt} - \frac{dT_{s_{cool}}}{dt}\right)}{A_s}$$

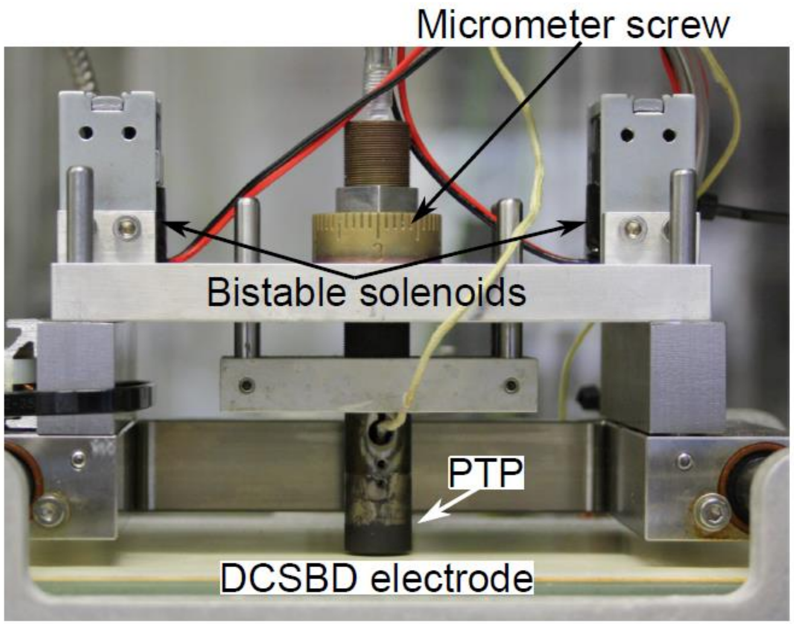
Stahl, M., Trottenberg, T., Kersten, H., Rev. Sci. Instr. ***81****(2010), 023504.*

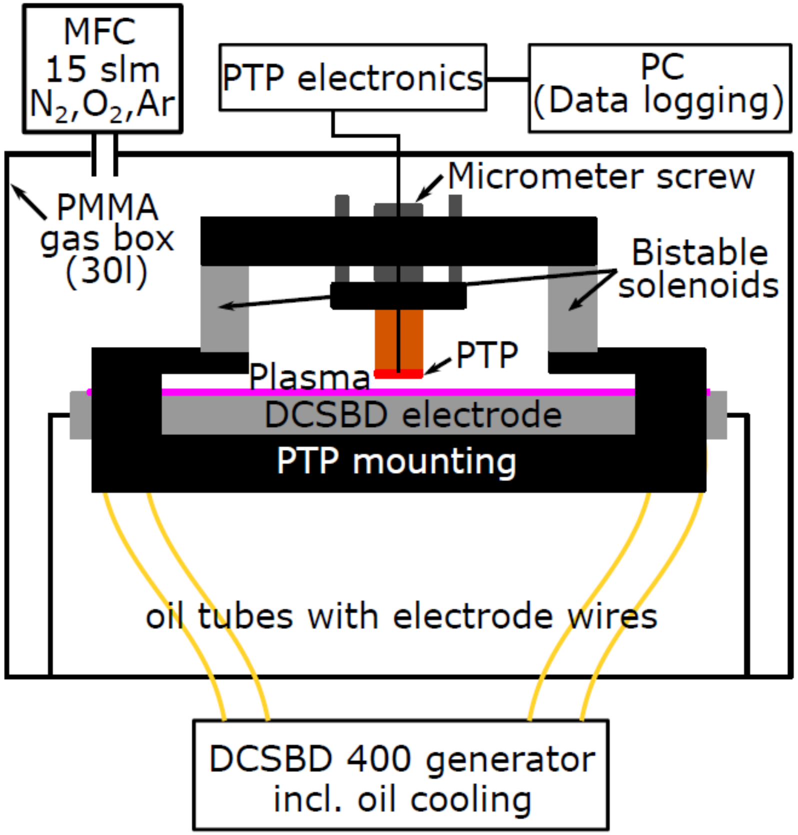
Gauter, S., Haase, F., Kersten, H., Thin Solid Films ***669****(2019), 8-18.*

energy fluxes in DCSBD

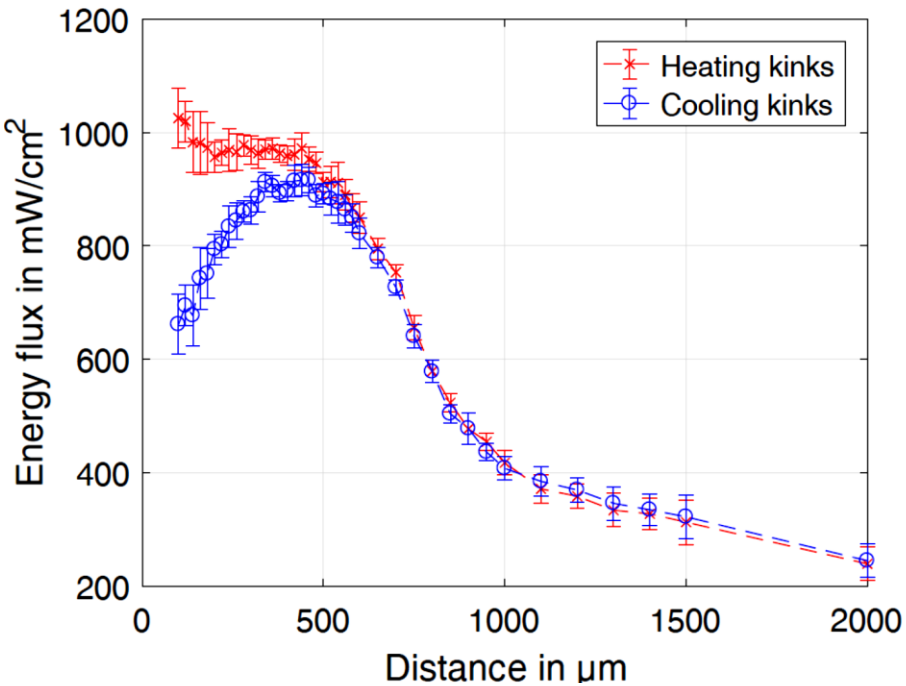
Hansen, L., Reck, K., Kersten, H.,
J. Phys. D: Appl. Phys. ***52****(2019), 325201.*

- PTP modified by dielectric silicone resin coating
- second calibration using an ion beam





energy fluxes in DCSBD



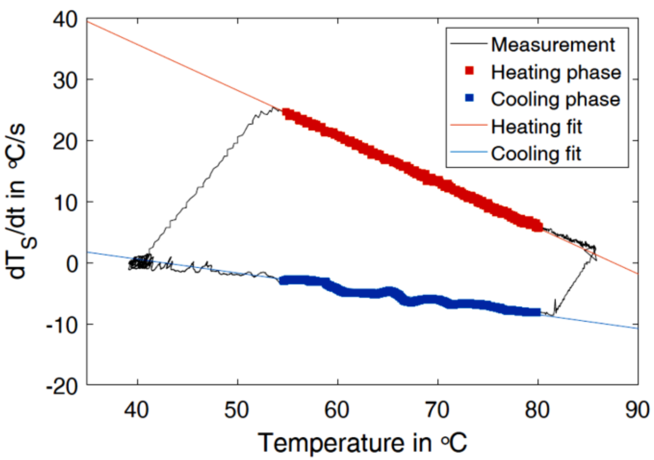
- unexpected mismatch between heating and cooling kinks for small distances

$$P_{out} = \alpha(T_S - T_{eq})$$

- cooling coefficient α
- temperature change described by

$$\frac{\mathrm{d}T_h}{\mathrm{d}t} = -\frac{\alpha}{C_S}T_h + \frac{P_{in}+\alpha T_{eq}}{C_S}$$
$$\frac{\mathrm{d}T_c}{\mathrm{d}t} = -\frac{\alpha}{C_S}T_c + \frac{\alpha T_{eq}}{C_S}$$

Hansen, L., Reck, K., Kersten, H., J. Phys. D: Appl. Phys. ***52****(2019), 325201.*
Rosenfeldt, L., Hansen, L., Kersten, H., IEEE Trans. Plasma Sci. ***49****(2021), 3325-3335.*

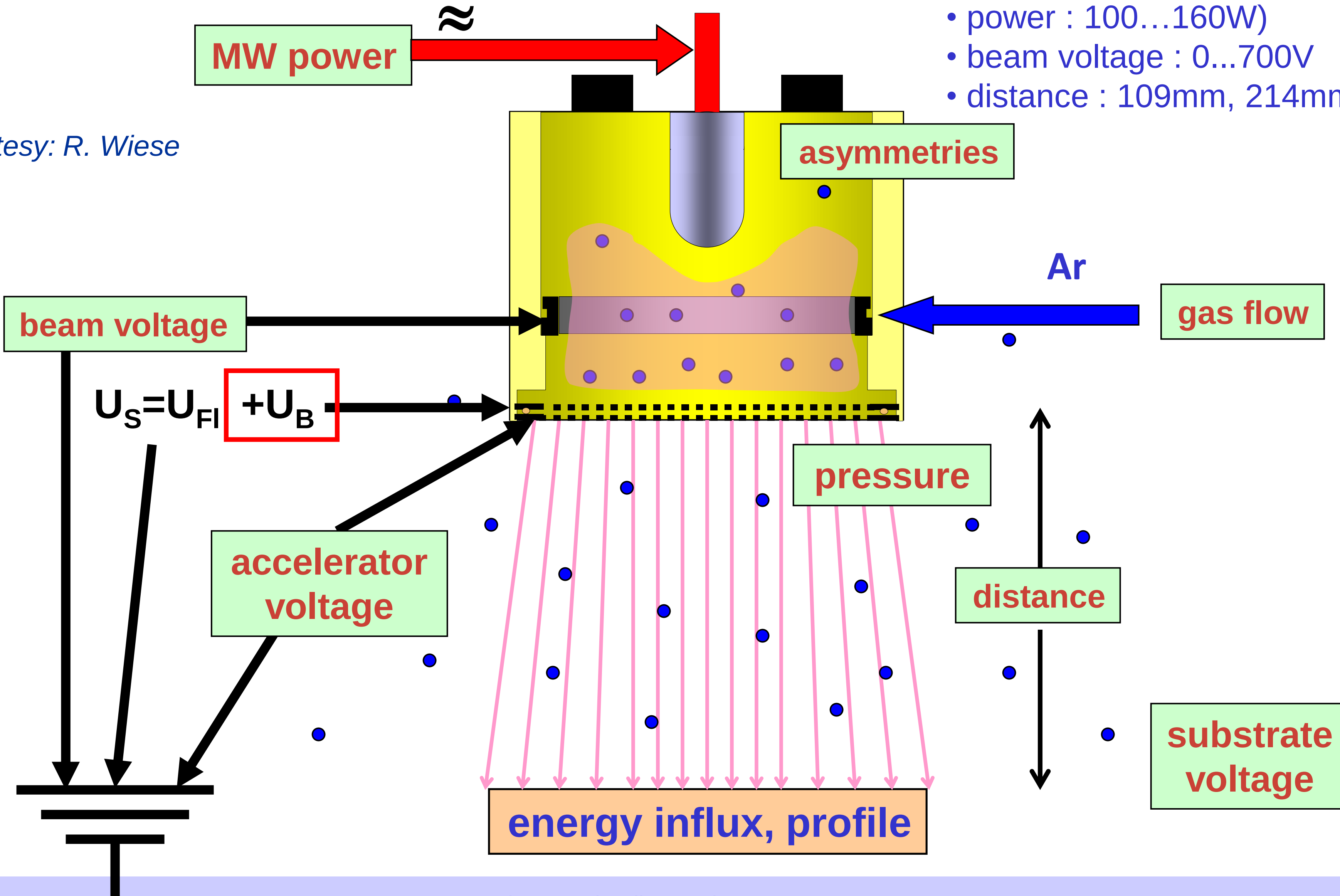


- active substrate cooling term at small distances
→ increased gas convection due to filament ignition and less space underneath the probe to transport the expanded volume
- cooling kinks represent transferred energy
- good agreement with free surface energy

energy fluxes in ion beam

- Ar pressure : 10^{-2} … 10^{-1}Pa
- power : 100…160W)
- beam voltage : 0...700V
- distance : 109mm, 214mm

courtesy: R. Wiese

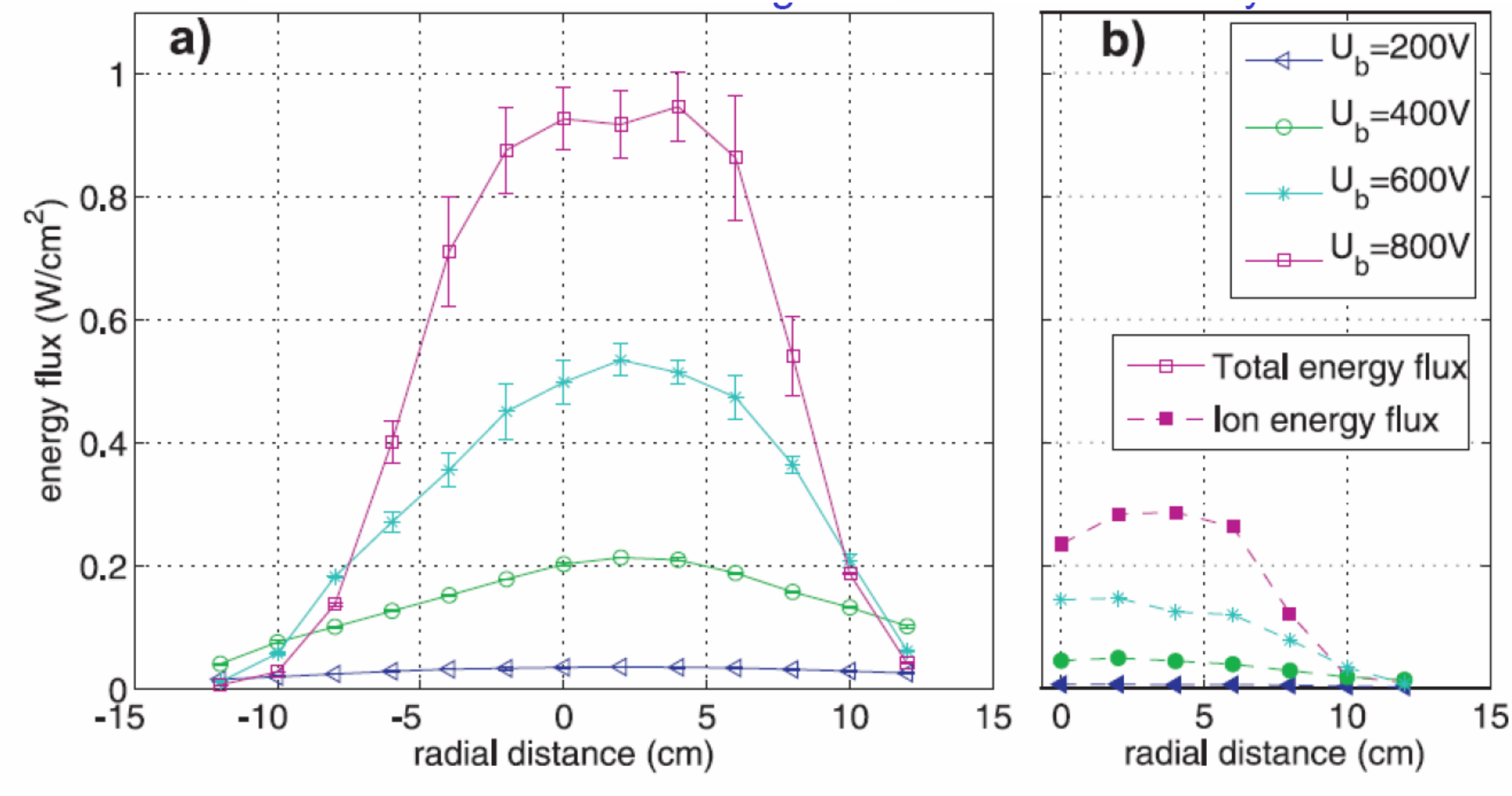


energy fluxes in ion beam

radial profile

measured by thermal probe

measured by Faraday cup

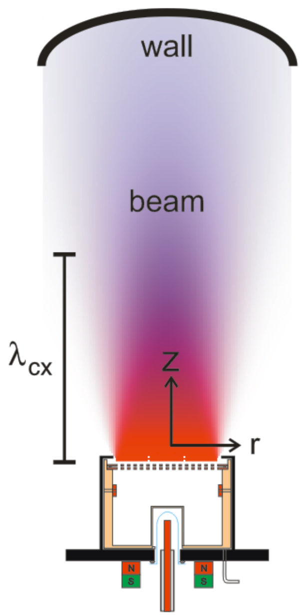


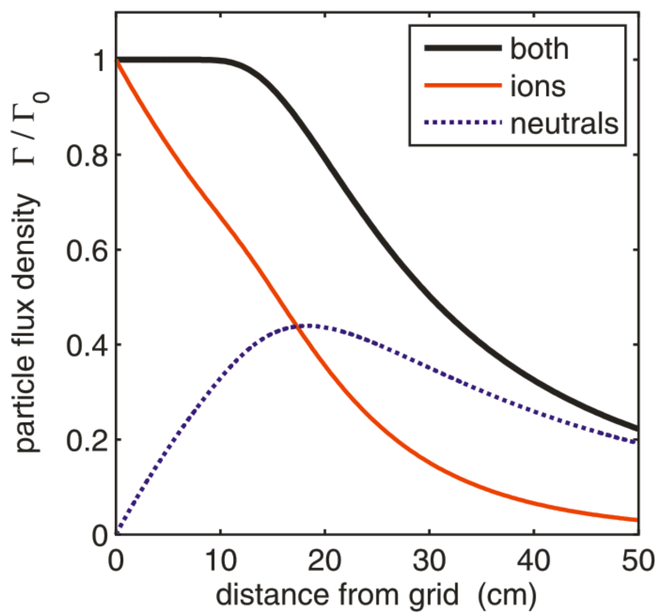
energy fluxes in ion beam

$$\Gamma_\mathrm{i}(z) = \Gamma_\mathrm{beam}(z)\exp\left(-\frac{z}{\lambda_\mathrm{cx}}\right)$$

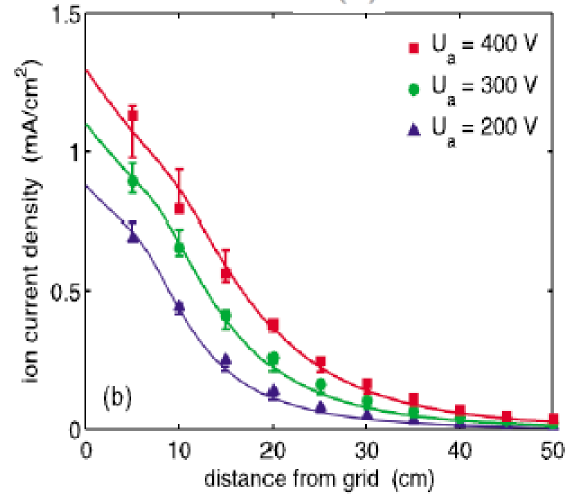
$$\Gamma_\mathrm{n}(z) = \Gamma_\mathrm{beam}(z)\left[1 - \exp\left(-\frac{z}{\lambda_\mathrm{cx}}\right)\right]$$

$$\Gamma_\mathrm{beam}(z) = \left[1 - \exp\left(-\frac{R^2}{2z^2\tan^2\vartheta}\right)\right]\Gamma_0$$

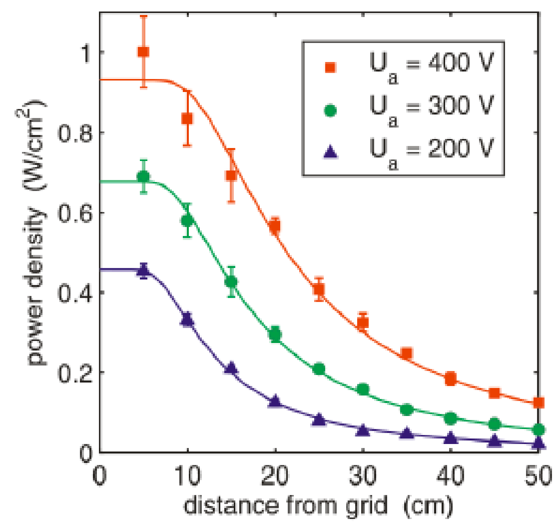




$$j(z) = e\,\Gamma_\mathrm{i}(z)$$

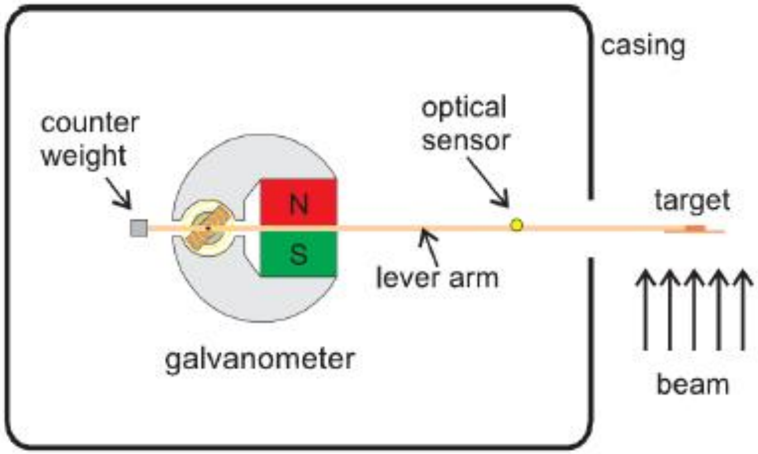


$$w(z) = c_\mathrm{heat} E\,\Gamma_\mathrm{beam}(z)$$



*Trottenberg, T., Schneider,V., Kersten, H., Phys. Plasmas **17**(2010), 103702.*
*Phelps, A.V., J. Appl. Phys. **76**(1994), 747.*

momentum fluxes in ion beam

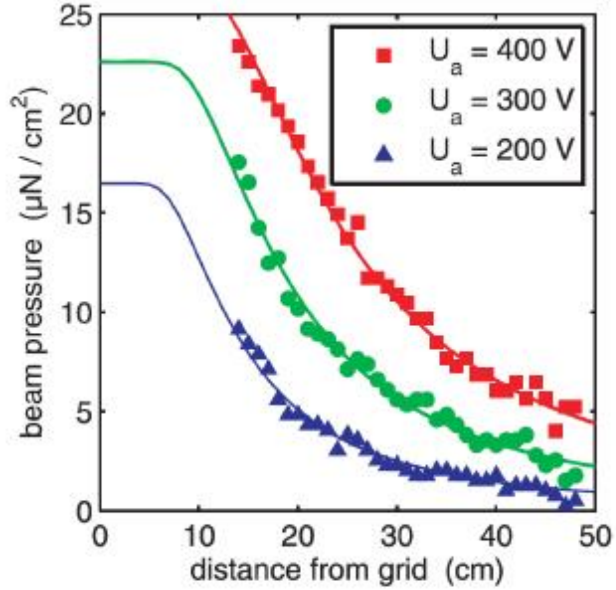


$$p(z) = c_{\mathrm{force}}\ (2\,m\,E)^{\frac{1}{2}}\ \Gamma_{\mathrm{beam}}(z)$$

$$1 \leq c_{\mathrm{force}} \leq 2$$

$$\Gamma_{\mathrm{beam}}(z) = \left[1 - \exp\left(-\frac{R^2}{2z^2\tan^2\vartheta}\right)\right]\Gamma_0$$

galvanometric force probe

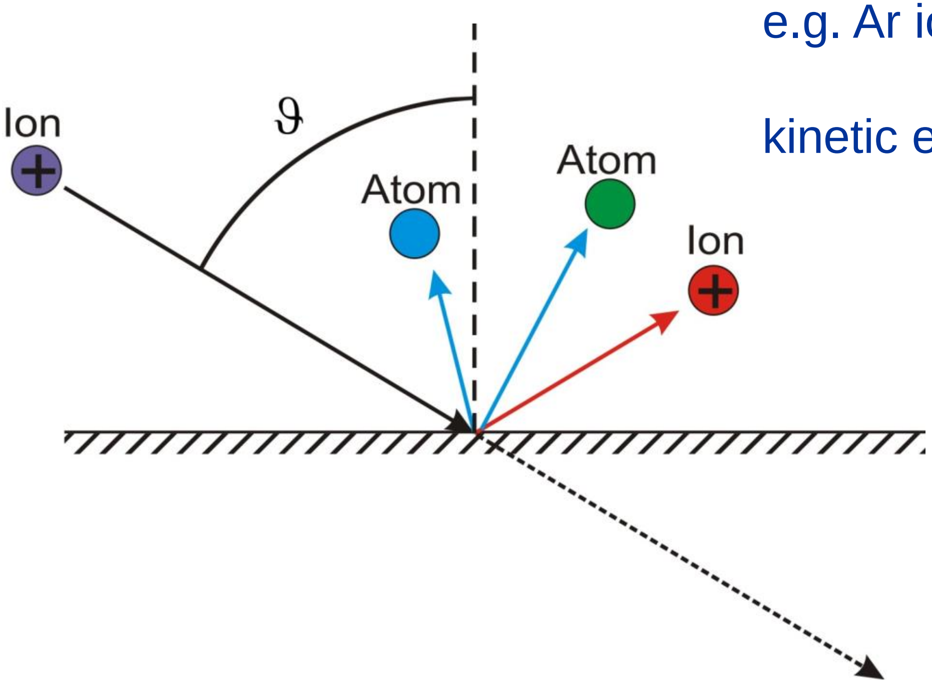


Spethmann, A., Trottenberg, T., Kersten, H., Rev. Sci. Instrum. ***86****(2015), 015107.*

(non-conventional) **plasma diagnostics**

for the determination of momentum transfer during sputtering by interferometric force probe

simulation of sputtering



simulation with SRIM (TRIM, TRYDIN …) code :
e.g. Ar ions (100 … 2000 eV) on Cu target

kinetic energy + binding energy = loss (cooling)

sputtering yield !
energy of sputtered particles !

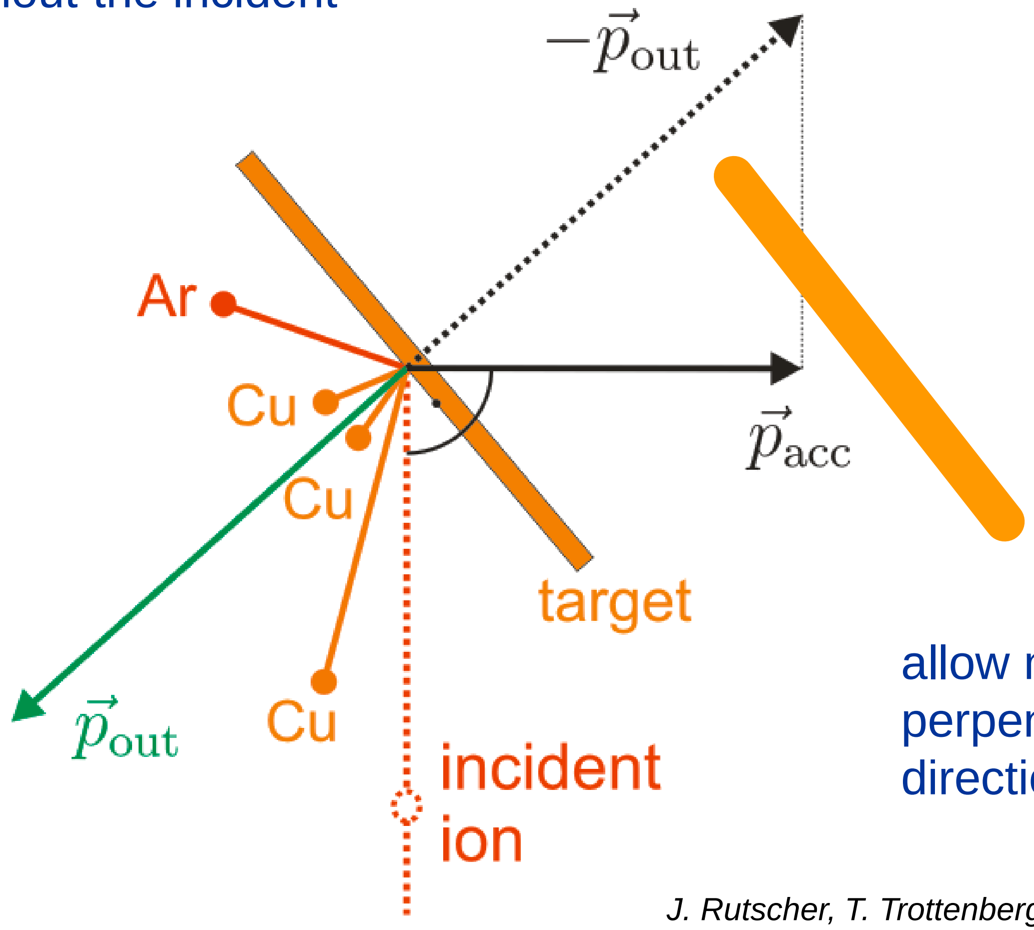
energy of reflected particles ?
angle distribution ?
momentum transfer ?
ions / neutrals ?

James F. Ziegler, Jochen P. Biersack, and Matthias D. Ziegler. SRIM Co., Chester, Maryland, 2008.

J.P. Biersack and L.G. Haggmark. *Nucl. Instr. and Meth.*, 174:257, 1980.

measurement of momentum transfer

How to measure only the momenta from the released particles (reflected, sputtered), e.g. without the incident ion‘s momentum?

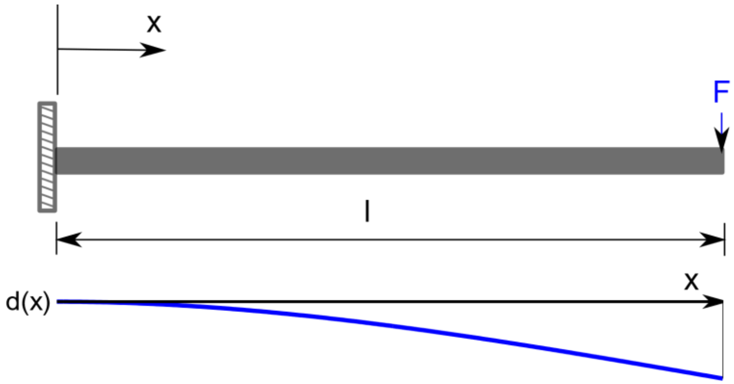


allow movement only perpendicular to ion beam direction

J. Rutscher, T. Trottenberg, H. Kersten,
Nucl. Instr. Meas. Meth. In Phys. Res. B ***301****(2013), 47.*

measurement of momentum transfer

interferometric measurement

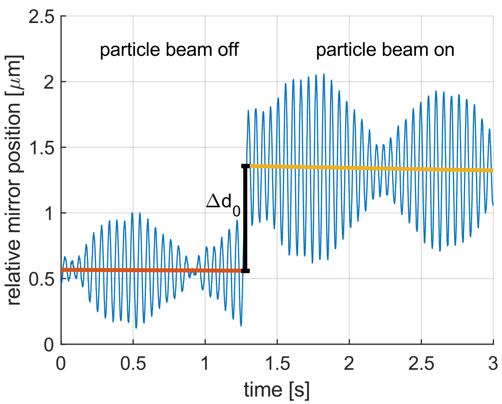


Euler–Bernoulli Theory

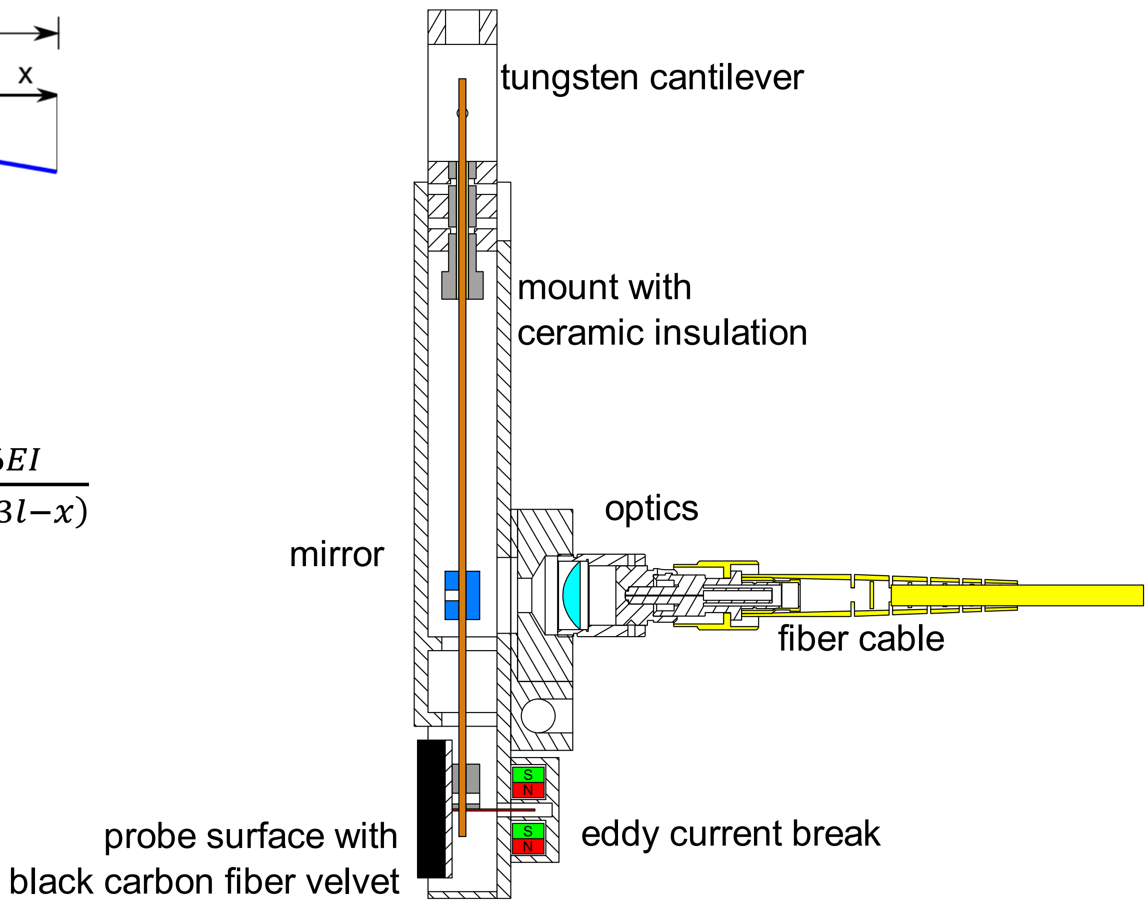
$$d(x) = \frac{Fx^2(3l - x)}{6EI}$$

"Hooke's Law"

$F = k(x_0)d_0$ using $k(x) = \frac{6EI}{x^2(3l-x)}$

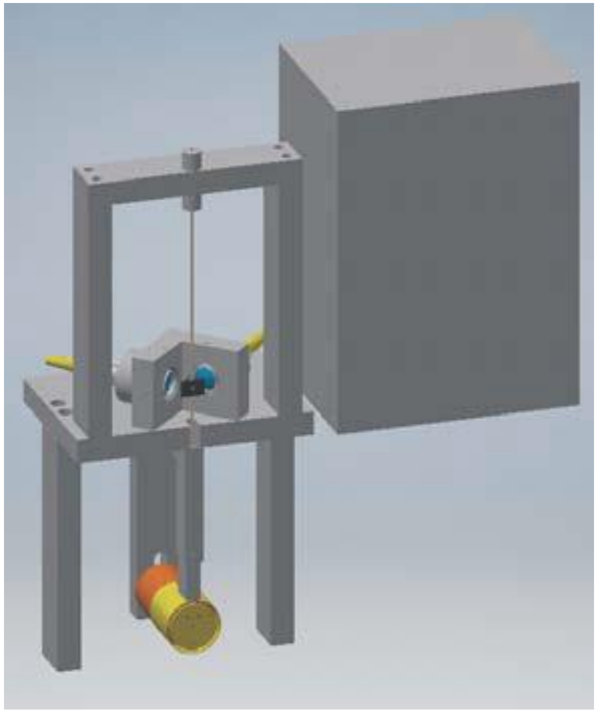


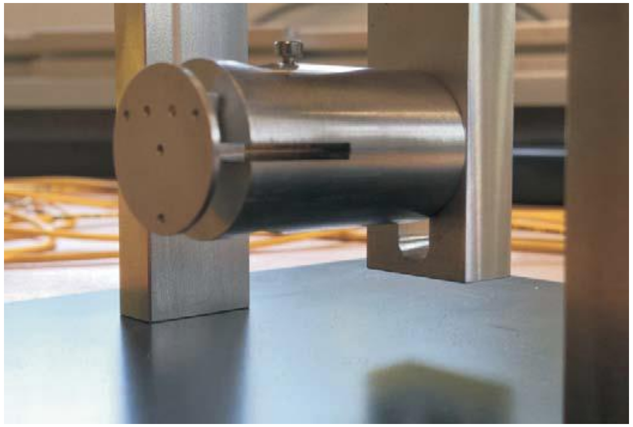
New Force Probe Design

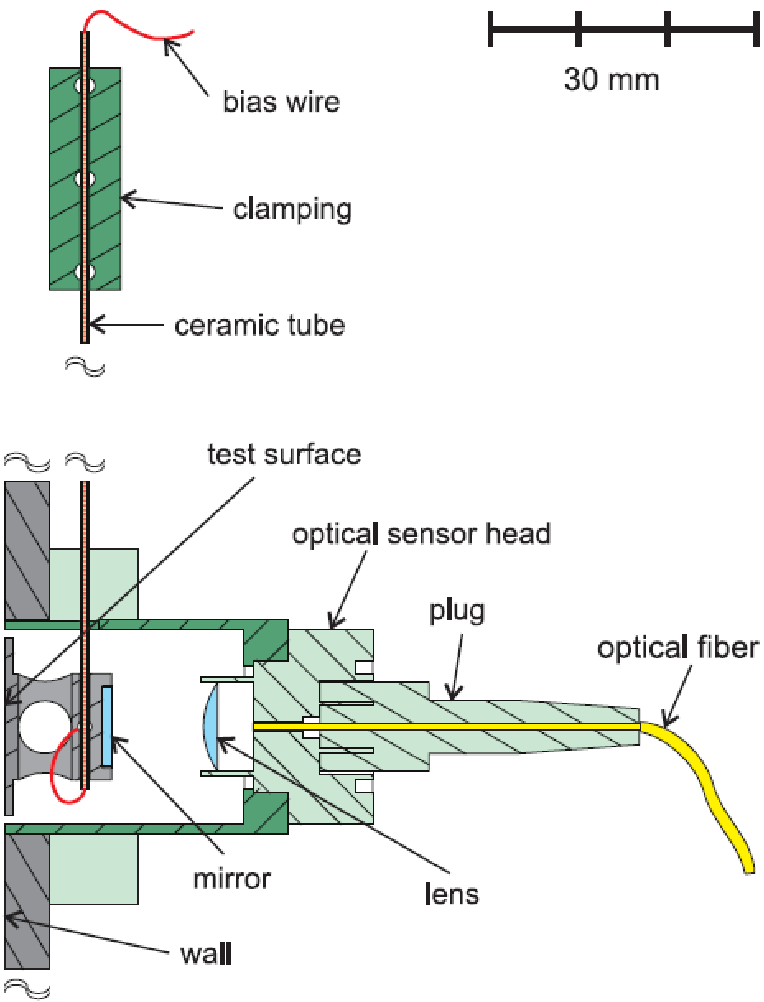


measurement of momentum transfer

interferometric measurement



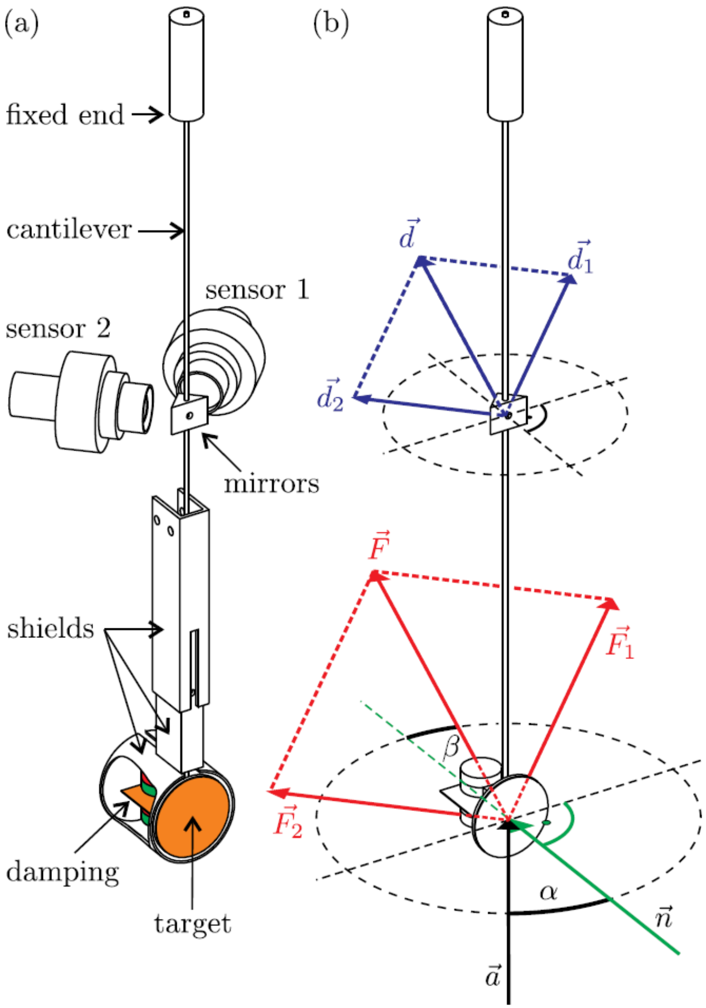


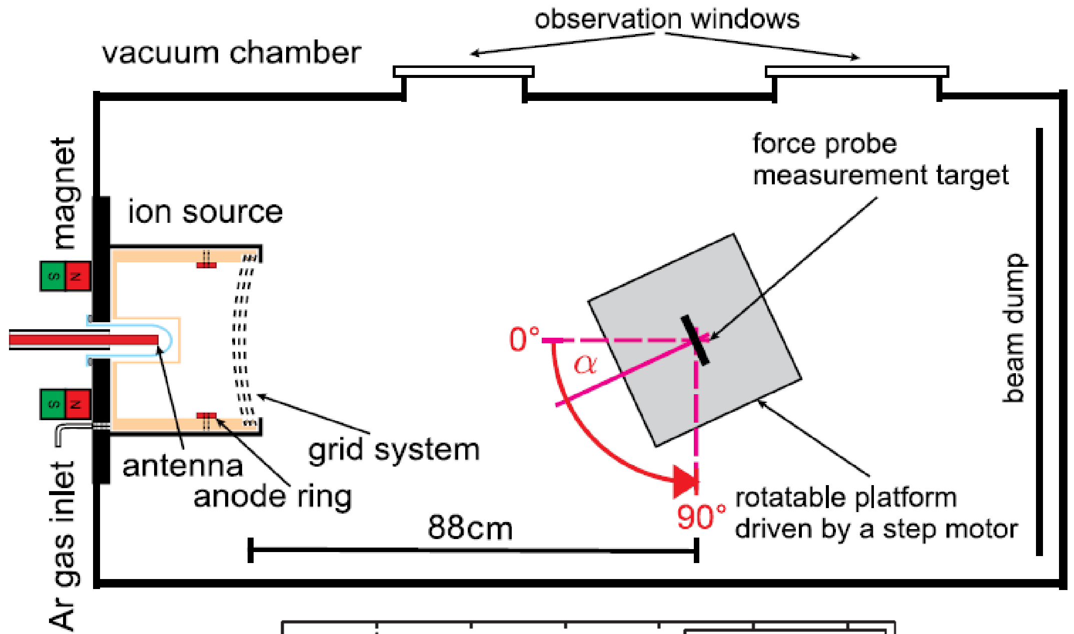


T. Trottenberg, H. Kersten,
Plasma Sources Sci. Technol. ***26****(2017), 055011.*
Trottenberg, T., Spethmann, A., Kersten, H.,
Eur. Phys. J. Techniques and Instrumentation ***5****(2018), 3.*

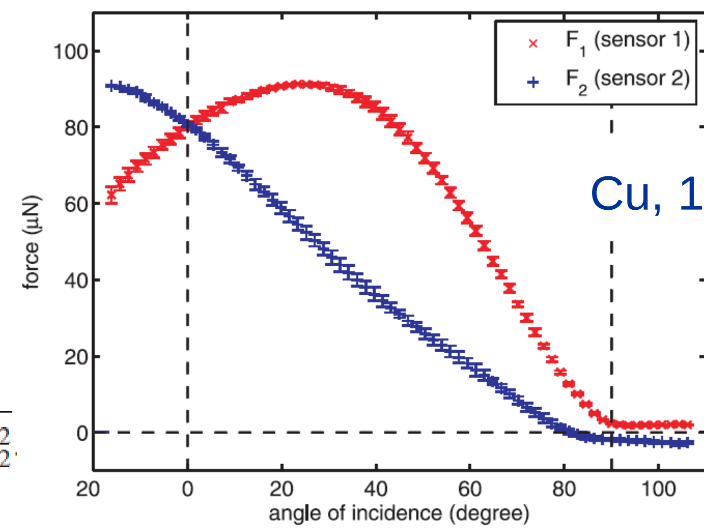
measurement of momentum transfer

interferometric measurement





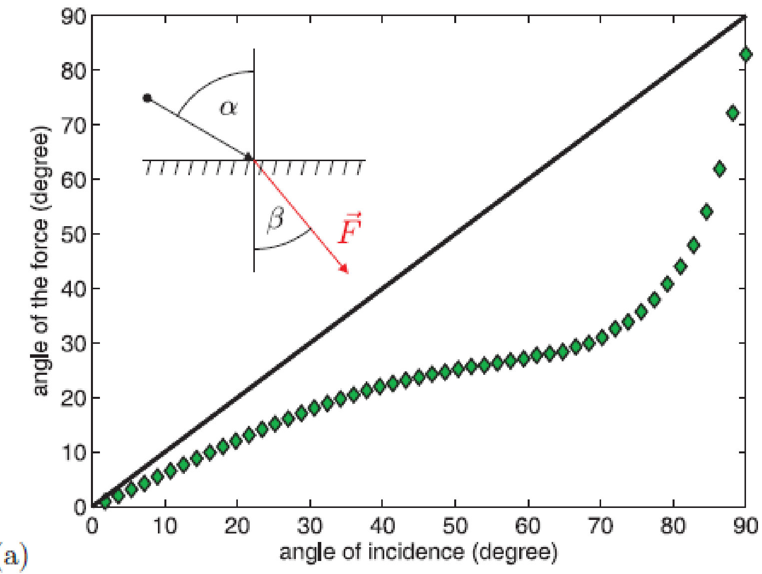
$$|\vec{F}| = \sqrt{F_1^2 + F_2^2}$$



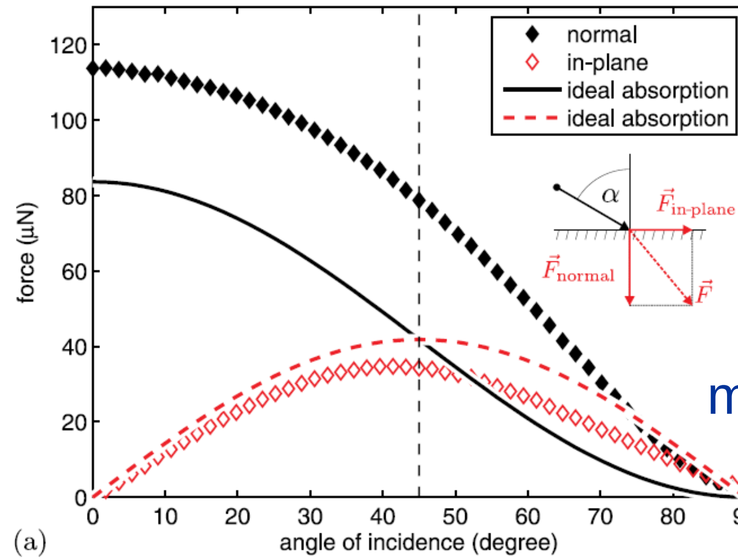
*A. Spethmann, T. Trottenberg, H. Kersten, Phys. Plasmas, **24**(2017), 093501.*

measurement of momentum transfer

by beam particles



(a)

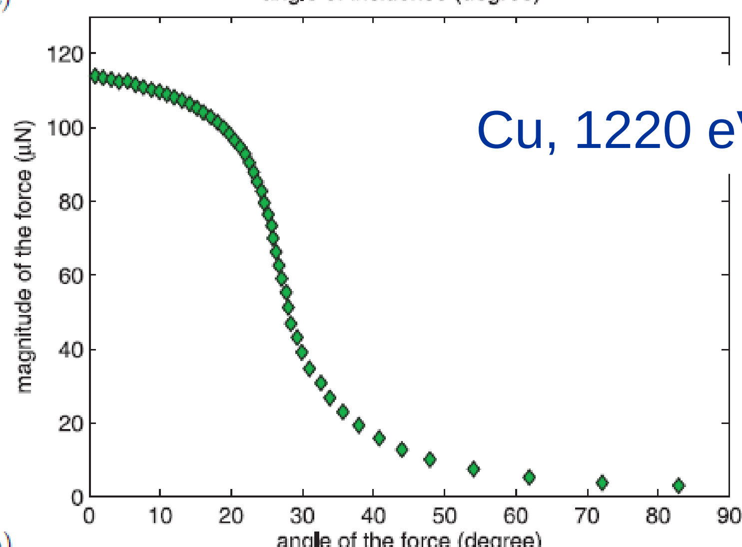


(a)

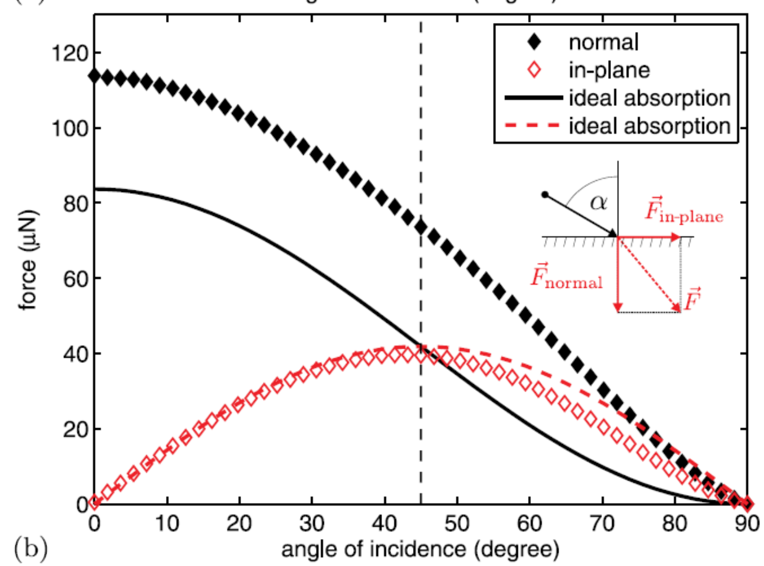
$$F_{\text{normal}} = |\vec{F}| \cos \beta$$
$$F_{\text{in-plane}} = |\vec{F}| \sin \beta.$$

measurement

Cu, 1220 eV



(b)



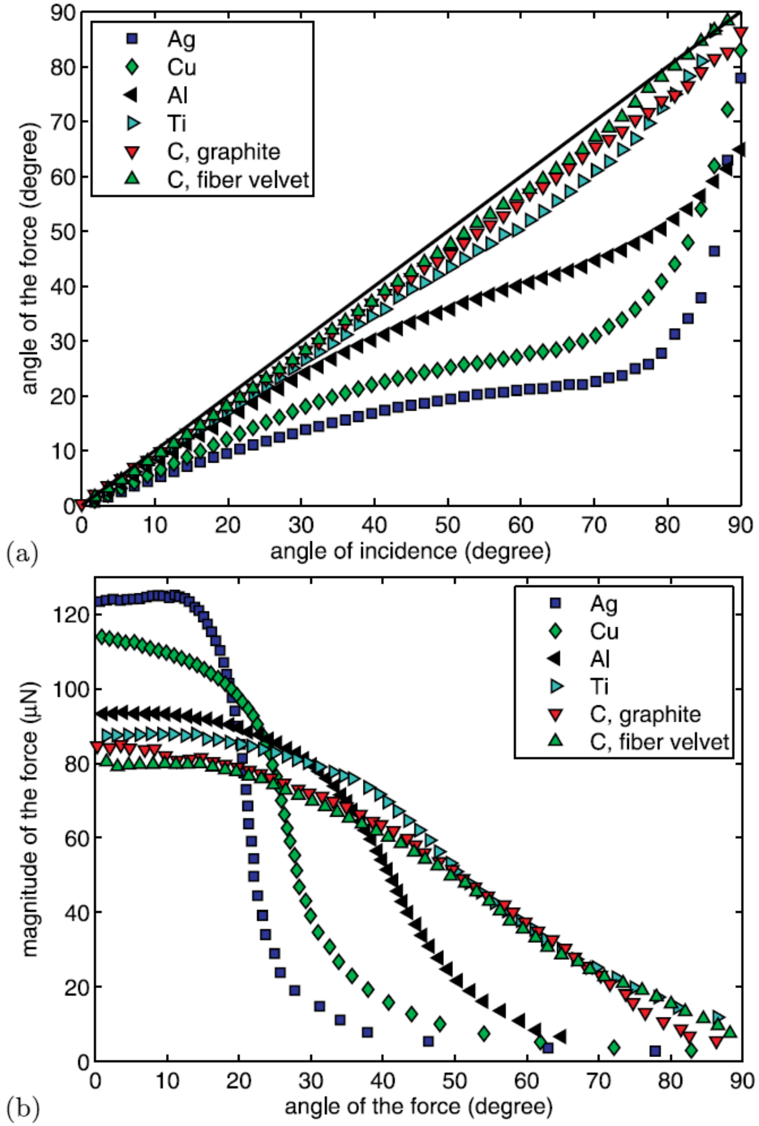
(b)

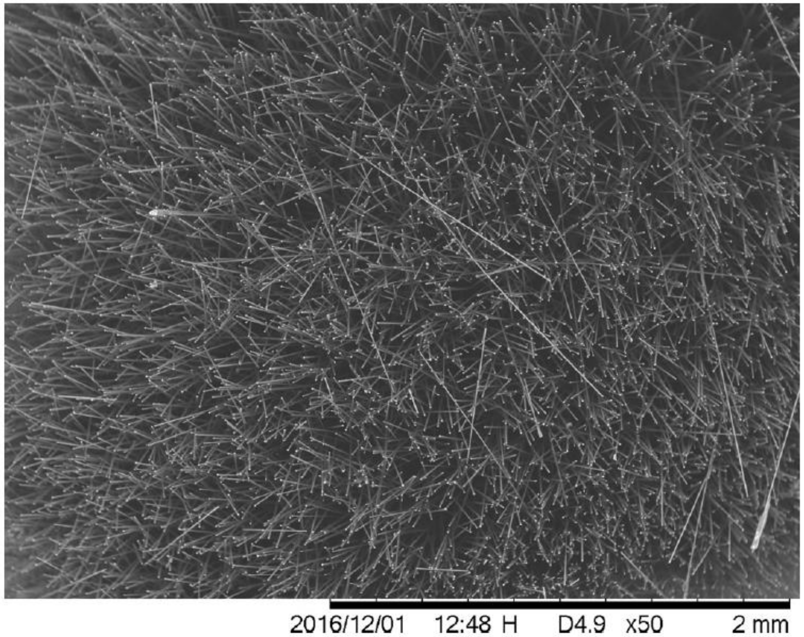
SRIM

simulation

measurement of momentum transfer

by beam particles





1220 eV

Target material	Ag	Cu	Al	Ti	C_g	C_{fv}
$F_{measured}$ (μN)	122.3	113.8	92.1	87.1	84.6	79.9
$F_{simulated}$ (μN)	125.7	113.8	92.1	89.5	86.7	
$Y_{empirical}$	4.1	3.1	1.7	0.8	0.3	
Mass numbers	107, 109	63, 65	27	46–50	12	12

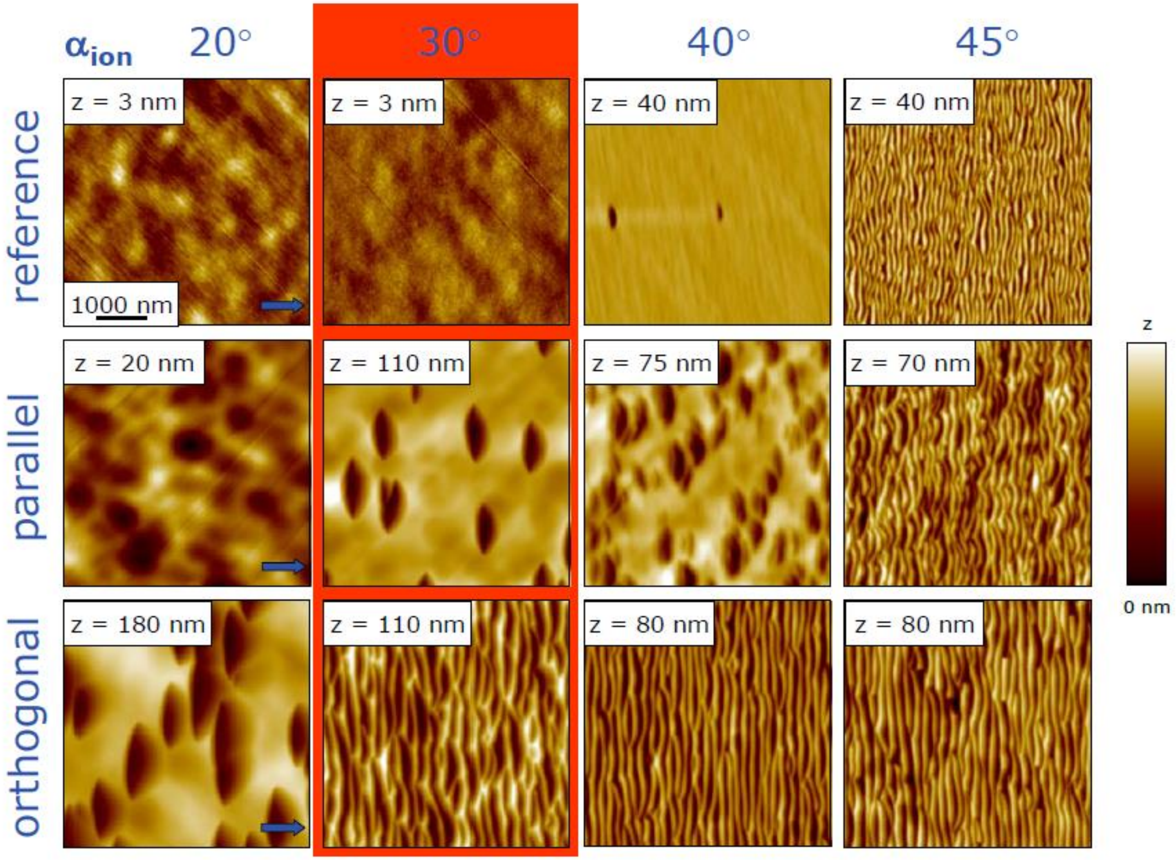
A. Spethmann, T. Trottenberg, H. Kersten, Phys. Plasmas, ***24****(2017), 093501.*

ion beam sputtering

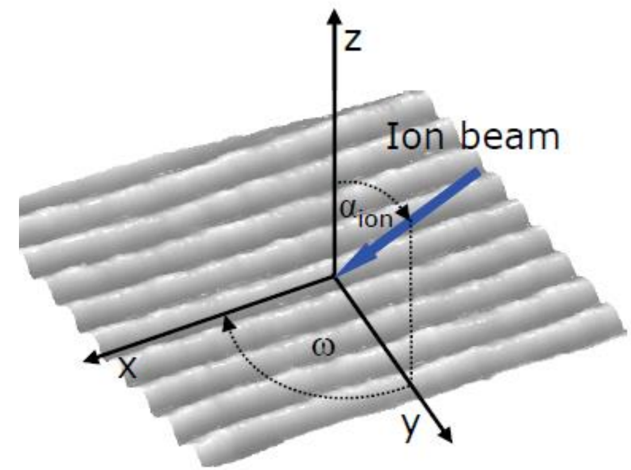
surface morphology

Surface evolution vs. α_{ion}

Constant parameters:
Ar^+, Kr^+, Xe^+, E_{ion} = 1600 eV, 2000 eV, j_{ion} = 300 μA cm^{-2}



t = 60 min



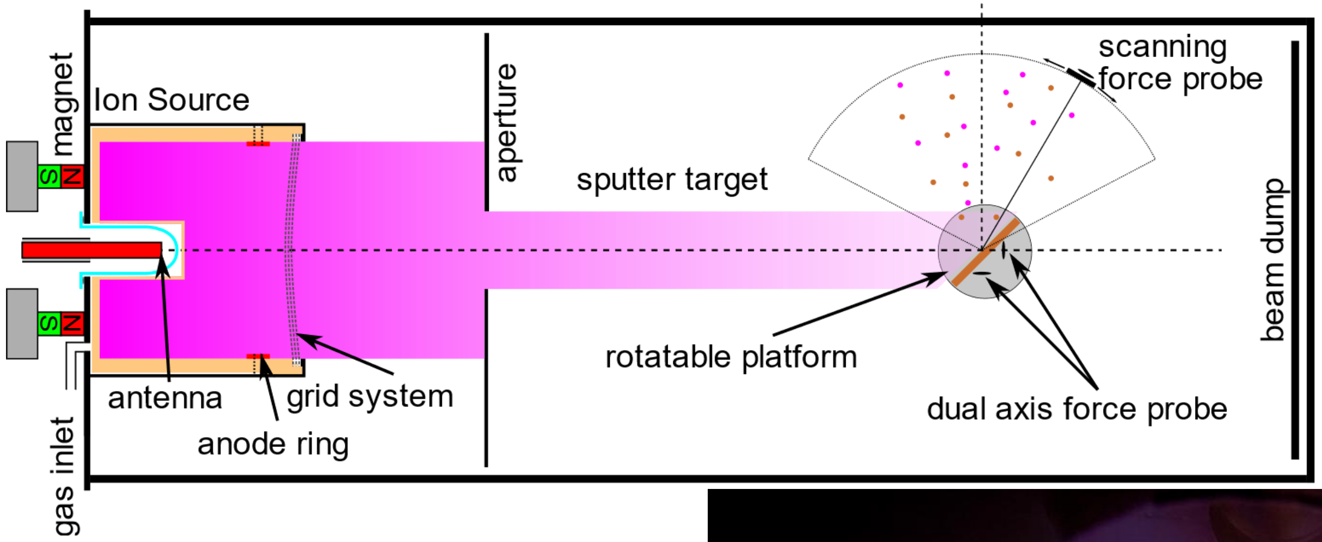
orthogonal (⊥)
ω = 0°

parallel (||)
ω = 90°

with rotation ( )
dω/dt = const.

J. Völlner, B. Ziberi, F. Frost, B. Rauschenbach, J. Appl. Phys. ***109****, 043501 (2011).*

measurement of momentum transfer by sputtered particles



volume: 1.60 m, 0.65 m, 530 l

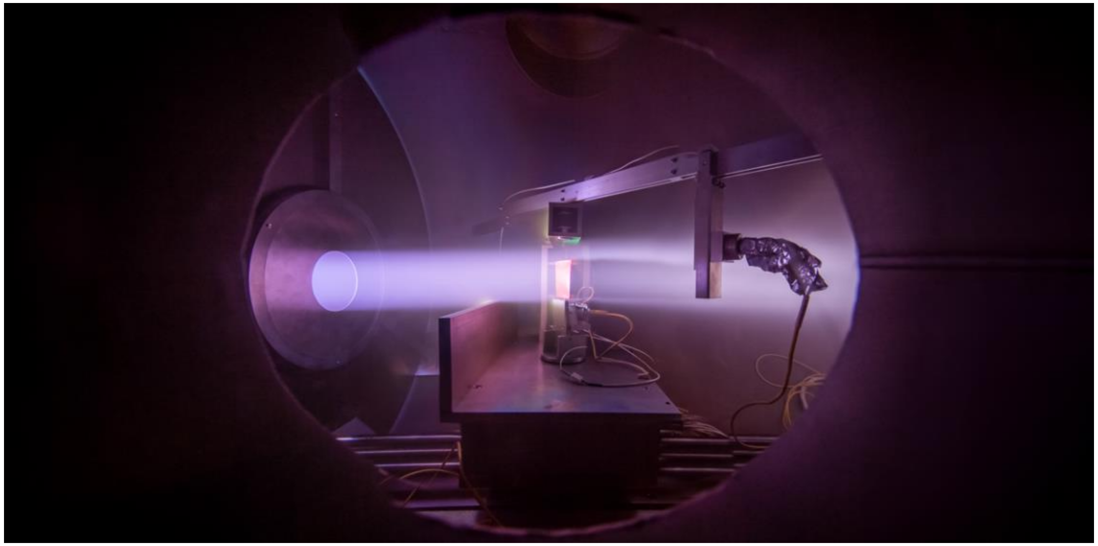
plasma source: 2.45 GHz ECR

ion beam: 0 - 2000 eV, 1200 eV

base pressure: 0,001 Pa

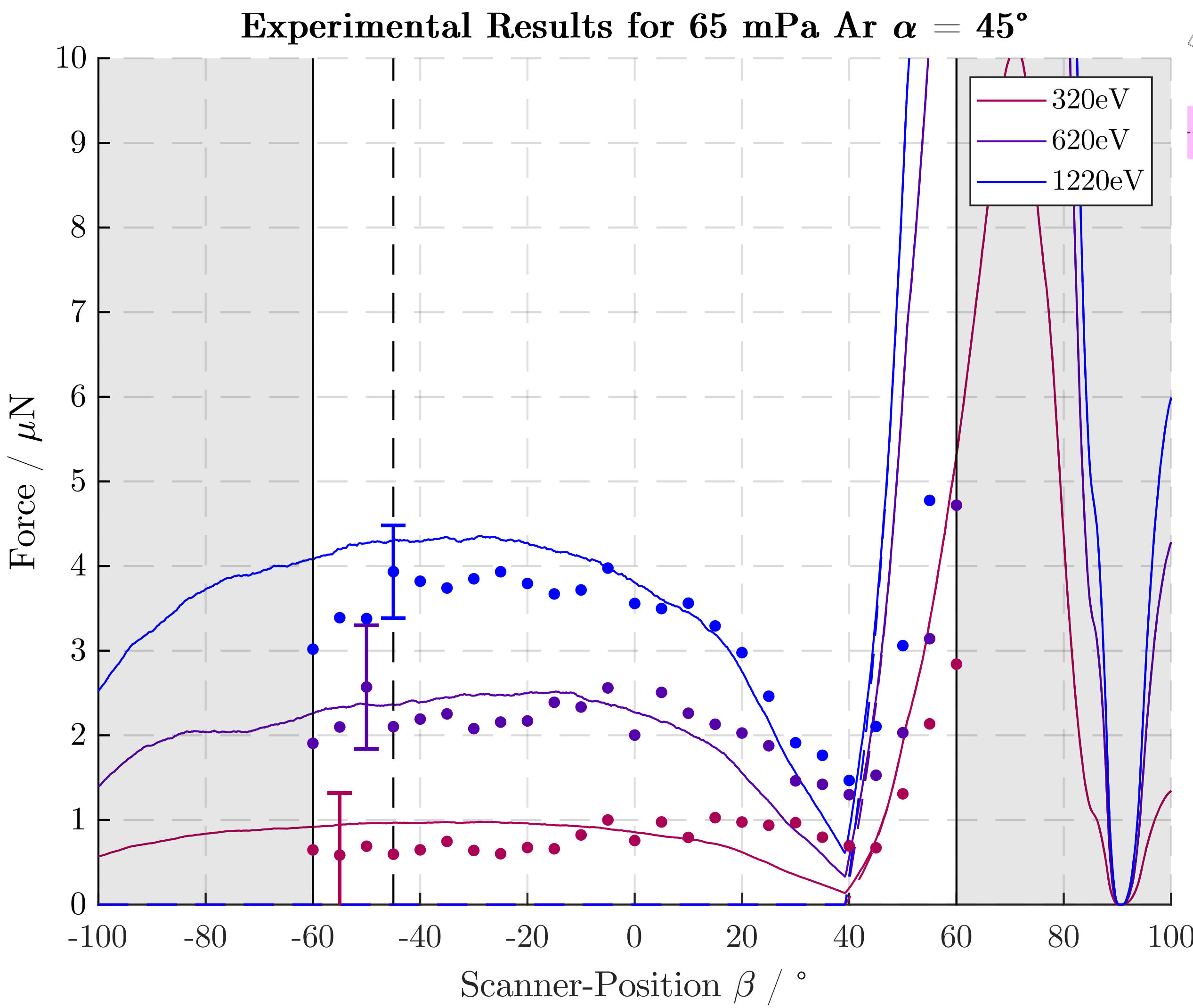
working pressure: 0,07 Pa, 5 sccm Ar

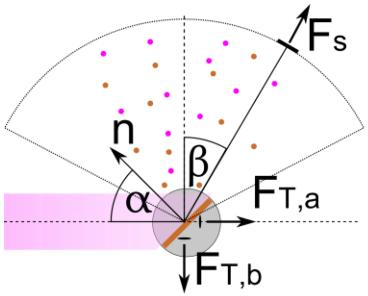
target: 5x5 cm copper, 50 cm distance



Klette, M., Maas, M., Trottenberg, T. Kersten, H., J. Vac. Sci. Technol. A ***38****(2020), 033013.*

measurement of momentum transfer
by sputtered particles





simulation

(sputtered + reflected)

SRIM

vs.

measurements

summary

summary

• detailed knowledge of plasma-surface interaction is necessary for optimizing the processes

• **non-conventional plasma diagnostics** in addition to common diagnostics for

energy influx / substrate heating due to plasma operation

force transfer due to momentum flux by particles at (ion beam) sputtering

by - calorimetric (thermal) probes (CP)
- interferometric force probe (FP)

- supplement for electrostatic diagnostics:
  measurement of otherwise not directly accessible quantities

- however: for quantitative non-electrostatic diagnostics
  understanding of plasma-surface interaction is required

kersten@physik.uni-kiel.de

Atom- und Plasmaphysik: LA250 & ATILA