Diagnostics of ion beams for space propulsion and industrial surface processing

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introduction (motivation)

(non-conventional) **plasma diagnostics** for the determination of

- **energy flux** from plasma to surface
  by calorimetric (thermal) probes
- **momentum transfer** during sputtering
  by interferometric force probe

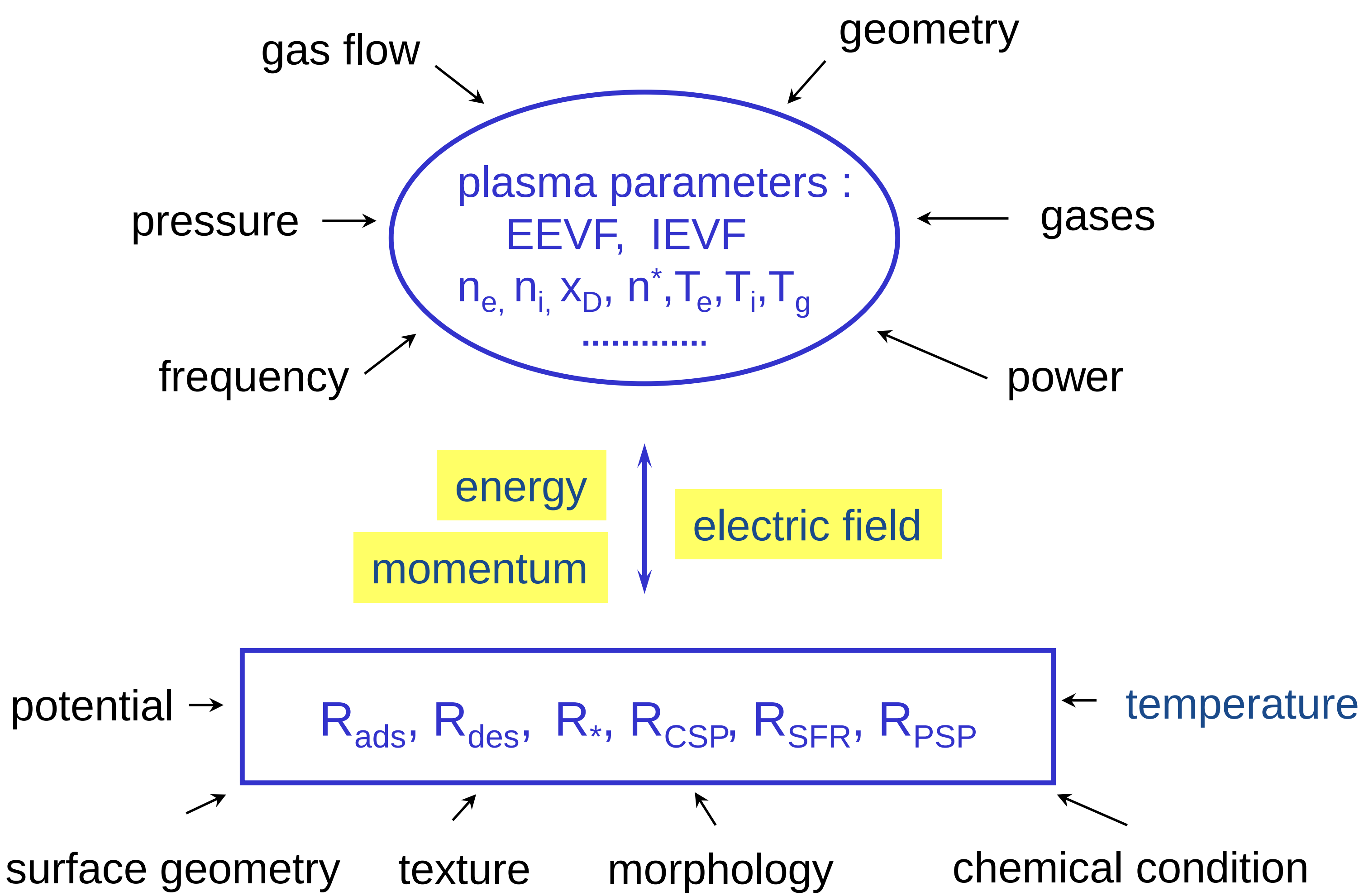
summary

introduction

(motivation)

introduction

plasma and substrate surface



methods for plasma diagnostics

- Langmuir probes, RFA, Faraday cup
- SEERS, MPR probe
- optical spectroscopy (emission, absorption, QCLAS, LIF)
- photometry of plasma sheath
- mass spectrometry / plasma monitoring
- V-I-probe
- microwave diagnostics
- etc. etc. etc.
- ***energy flux measurement **
- ***force measurement **
- *microscopic particle probes **

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

for planar geometry

current :

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

force :

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

power (thermal) :

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

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

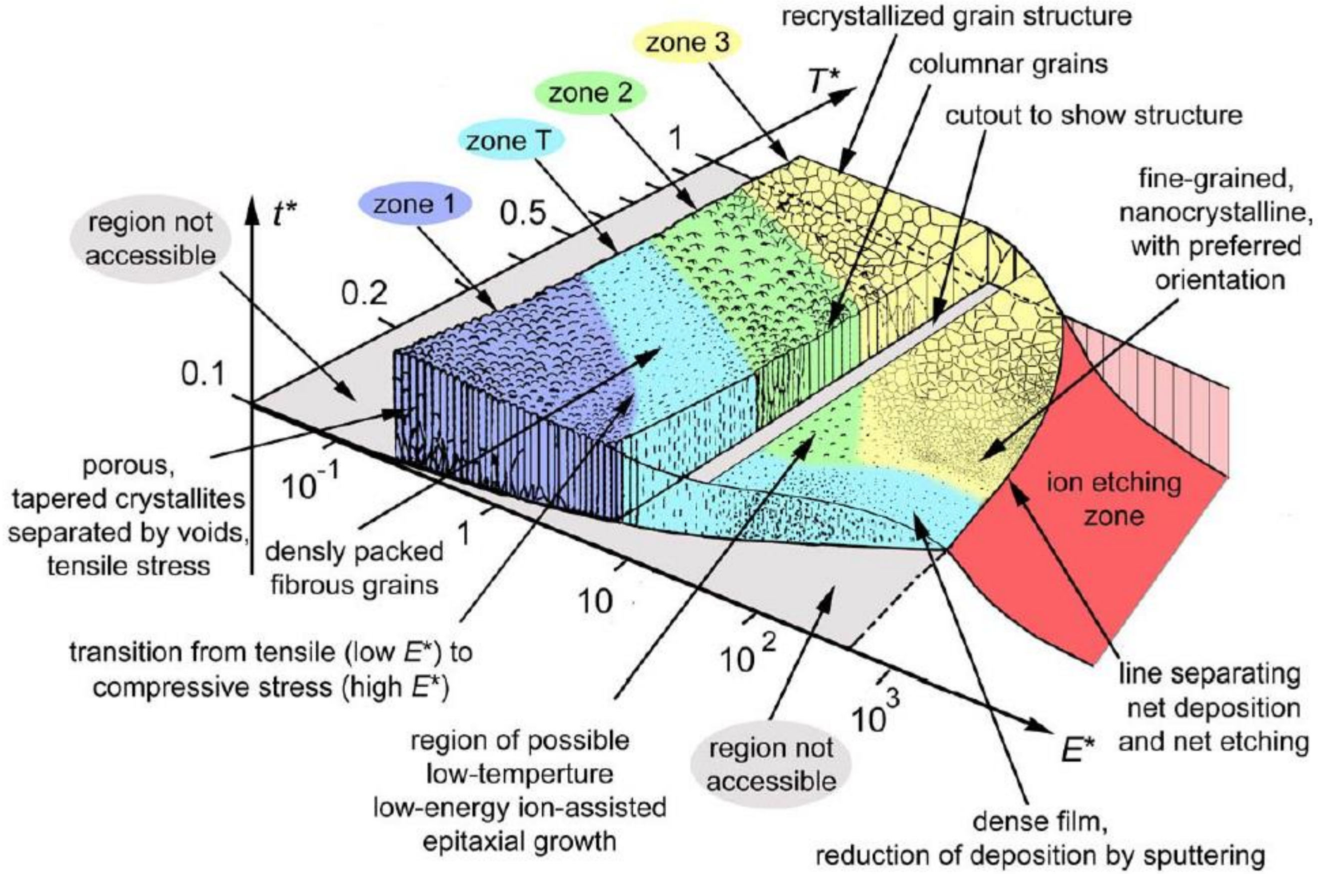
(non-conventional) **plasma diagnostics**

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

by calorimetric (thermal) probes

energy influx

thin films



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 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**

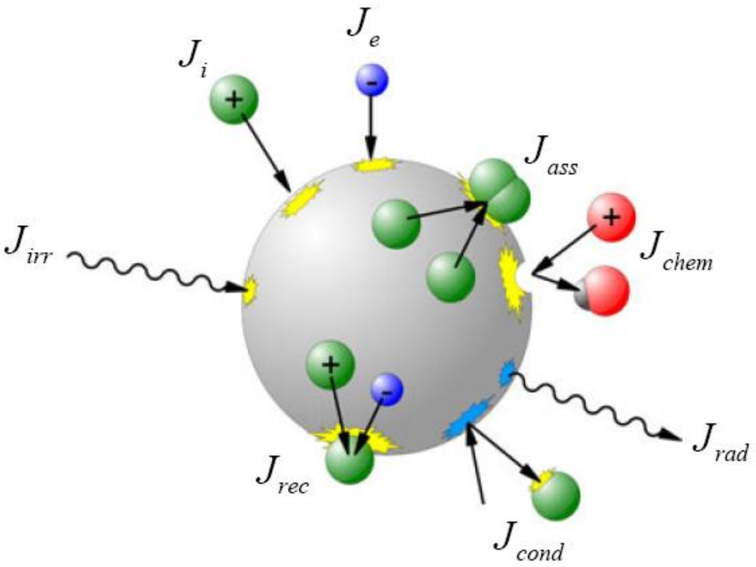
*P. R. i Cabarrocas, N. Chabane, A. V. Kharchenko and S. Tchakarov, PPCF **46**, B235 (2004).*
*P. R. i Cabarrocas, Y. Djeridane, T. Nguyen-Tran, E. V. Johnson, A. Abramov and Q. Zhang, PPCF **50**, 124037 (2008).*

*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).

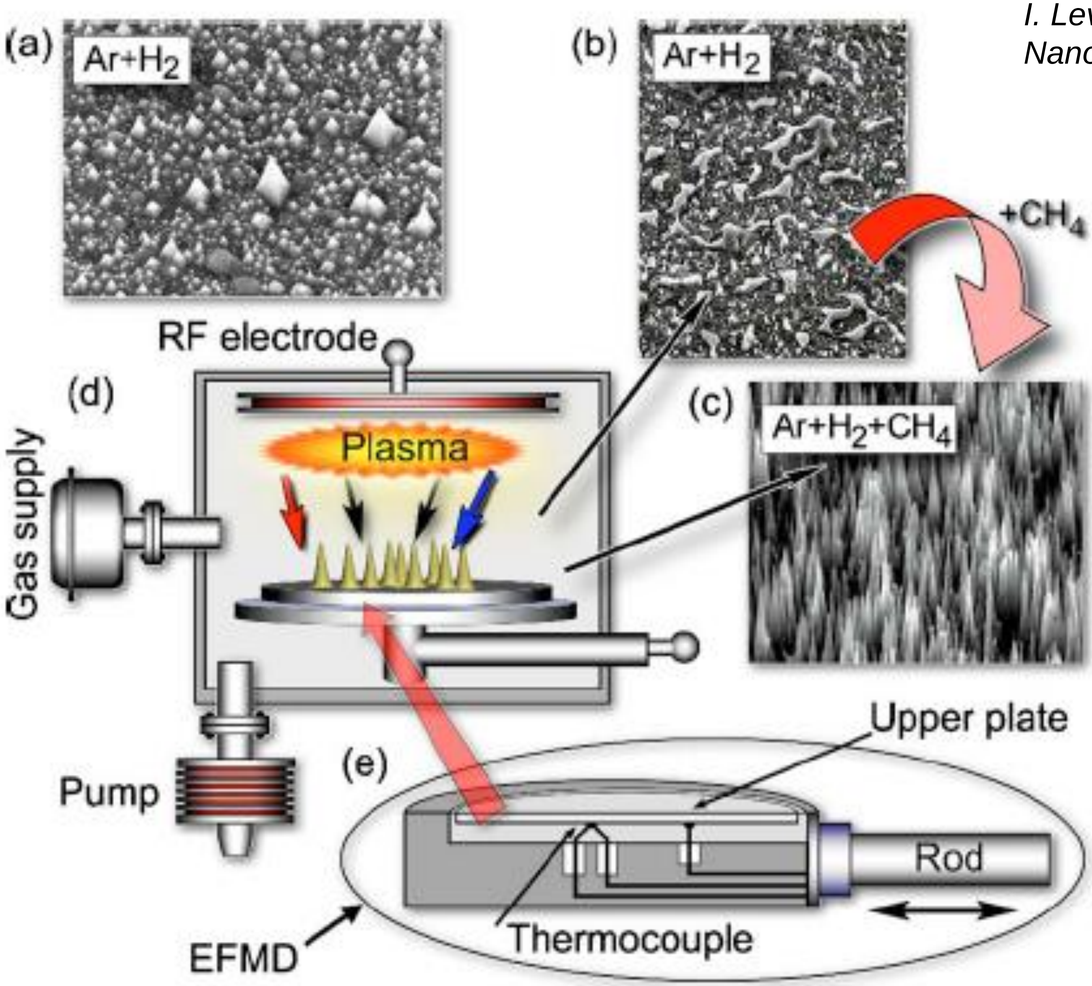
*A. Anders, J. Appl. Phys. **82**, 3679 (1997).*

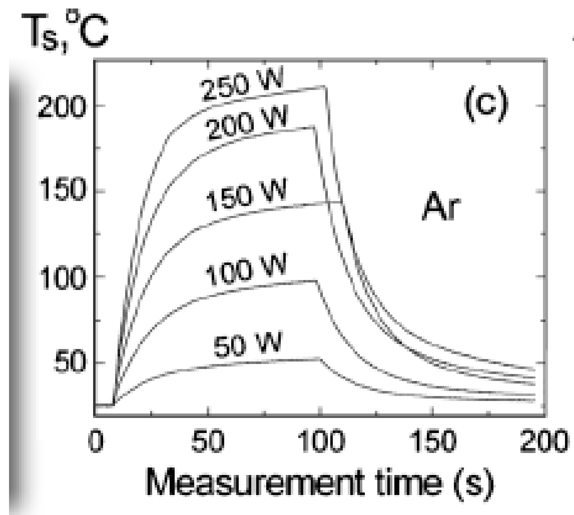


structure (fragmentation, growth)

M. Wolter, I. Levchenko, H. Kersten, K. Ostrikov, Appl. Phys. Lett. ***96****(2010), 133105.*

I. Levchenko, S. Y. Huang, K. Ostrikov, S. Xu, Nanotechnology ***21****, 025605 (2010).*

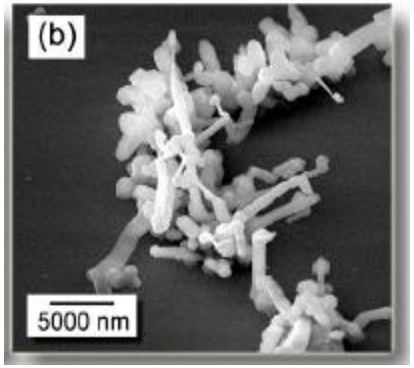


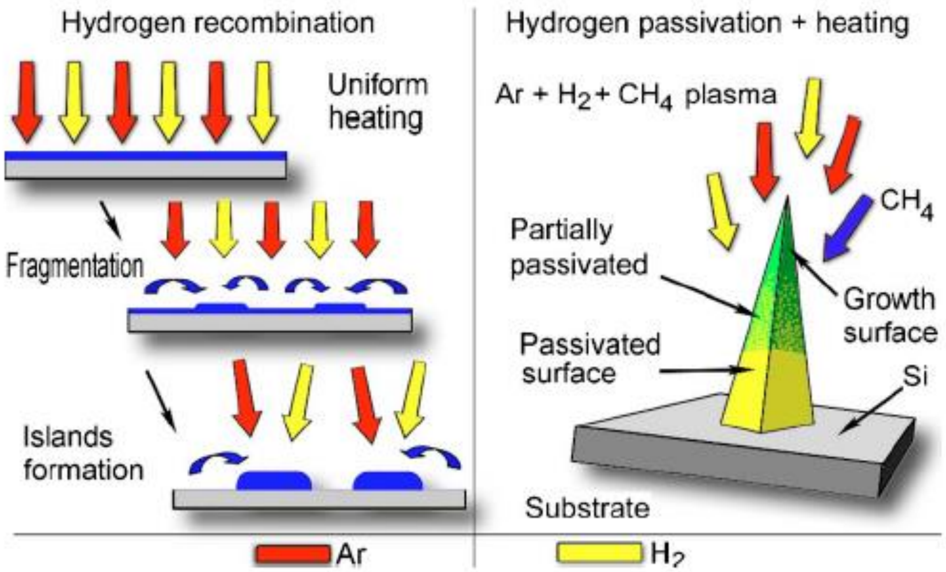


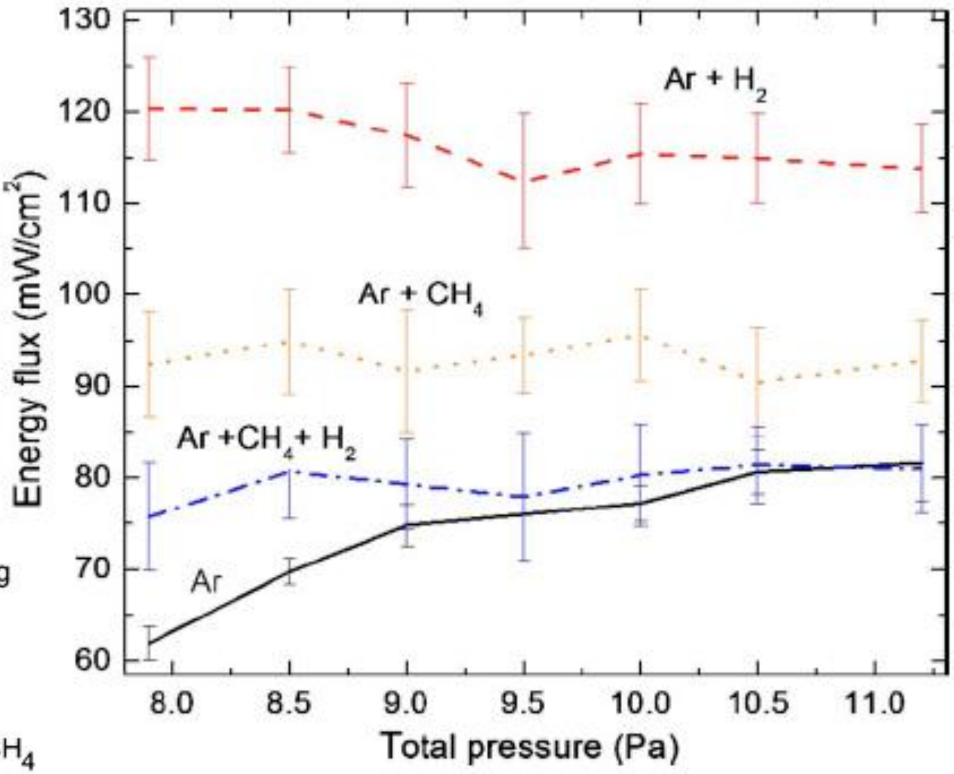
energy influx

nanostructure

structure (fragmentation, growth)







M. Wolter, I. Levchenko, H. Kersten, S. Kumar, K. Ostrikov,
J. Appl. Phys. ***108****(2010), 053302.*

M. Wolter, I. Levchenko, H. Kersten, K. Ostrikov,
Appl. Phys. Lett. ***96****(2010), 133105.*

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.*

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.

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

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.

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.

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 ...)*

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)

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

- kinetic energy of sputtered and reflected particles (J_n)

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

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

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

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

energy balance

contributions

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

$$Q_{rec} = j_i(E_{ion} - e_0\Phi) \cdot A \qquad J_{rec} = \frac{j_i}{e_0}\left(\Phi_{ion} - \Phi_{ewf}\right)$$

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

- radiation (J_{rad})

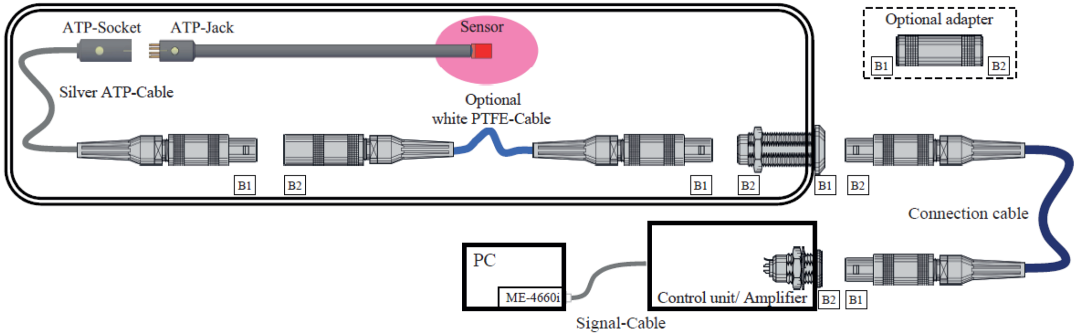
$$Q_{rad} = (\sigma(\varepsilon_T T_T^4 - \alpha_S T_S^4) + \xi_{abs} j_{rad} E_{ph}) \cdot A \qquad J_{phot} = \int \Phi_{pl}(\nu) \cdot h\nu \cdot A(h\nu) \cdot d\nu = \xi_{pl} j_{pl} E_{pl}$$

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

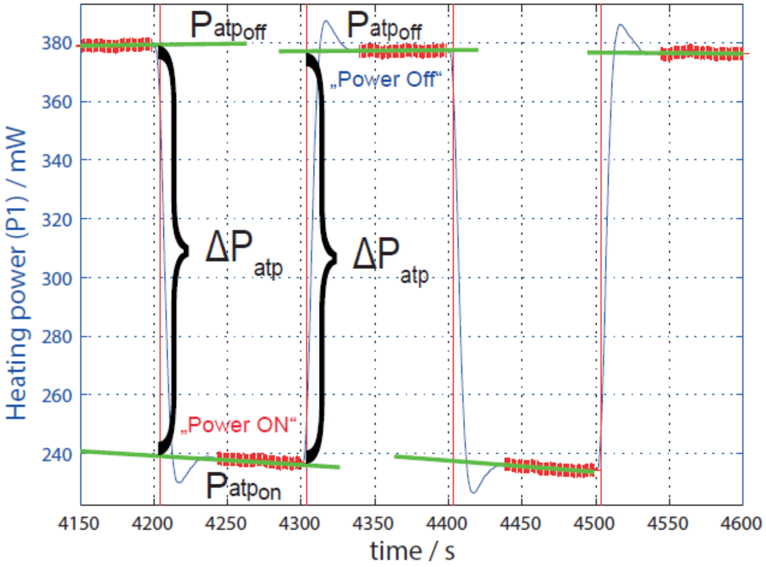
*J.A. Thornton, TSF **54**(1978), 23.*
*M. Andritschky, F. Guimaraes, V. Teixeira, Vacuum **44**(1993), 809.*
*R. Wendt, K. Ellmer, K. Wiesemann, JAP **82**(1997), 2115.*
*R. Piejak, V. Godyak, B. Alexandrovich, N. Tishchenko, PSST **7**(1998), 590.*
*T.P. Drusedau, T. Bock, T-M. John, F. Klabunde, JVST 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.*

energy influx : determination by active thermal probe (ATP)



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



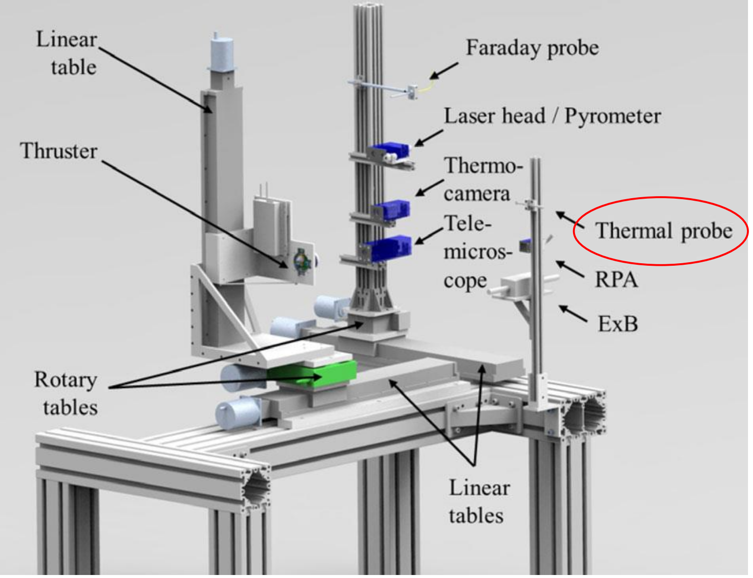
Wiese, R., Kersten, H.,
Wiese, G., Bartsch, R.,
EPJTI ***2****(2015), 2.*

measurement of energy influx

ATP

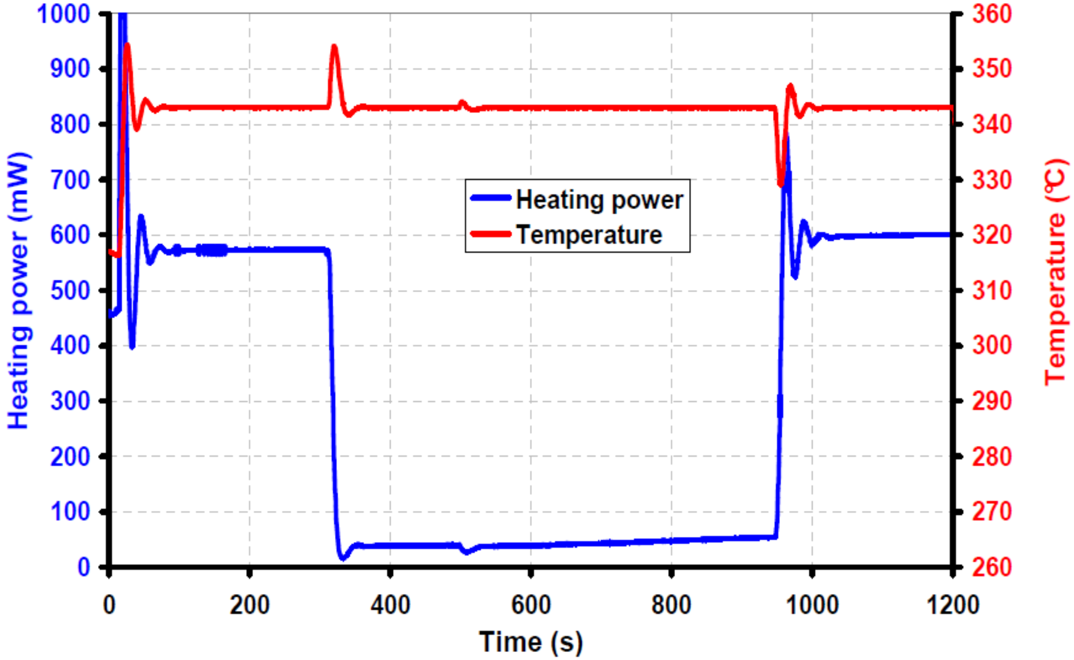
Bundesmann, C., et.al.,
„An advanced electric propulsion diagnostic (AEPD) platform for in-situ characterization of electric propulsion thrusters and ion beam sources“,
Eur. Phys. J. D ***70****(2016), 212.*

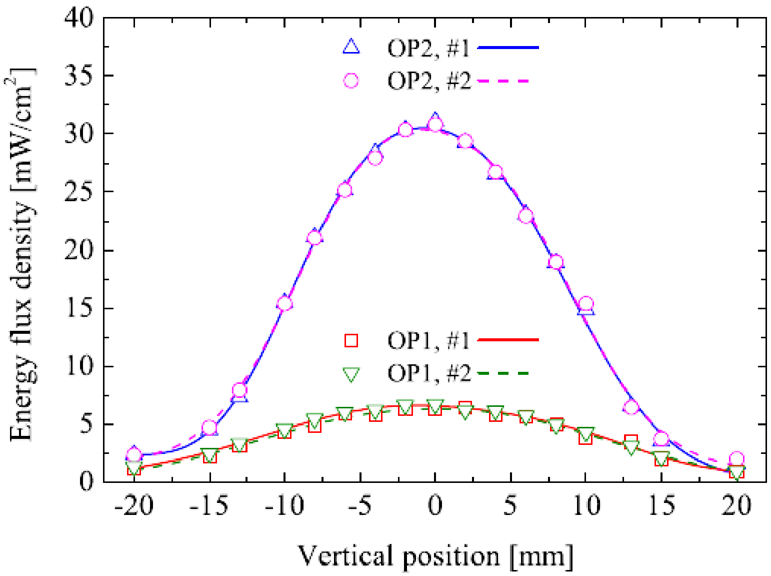
Parameter	OP1	OP2
Beam Voltage	1050 V	1700 V
Beam Current	4 mA	8 mA
Accelerator voltage	–200 V	–250 V
Nominal thrust	210 μN	540 μN



ion beam source:

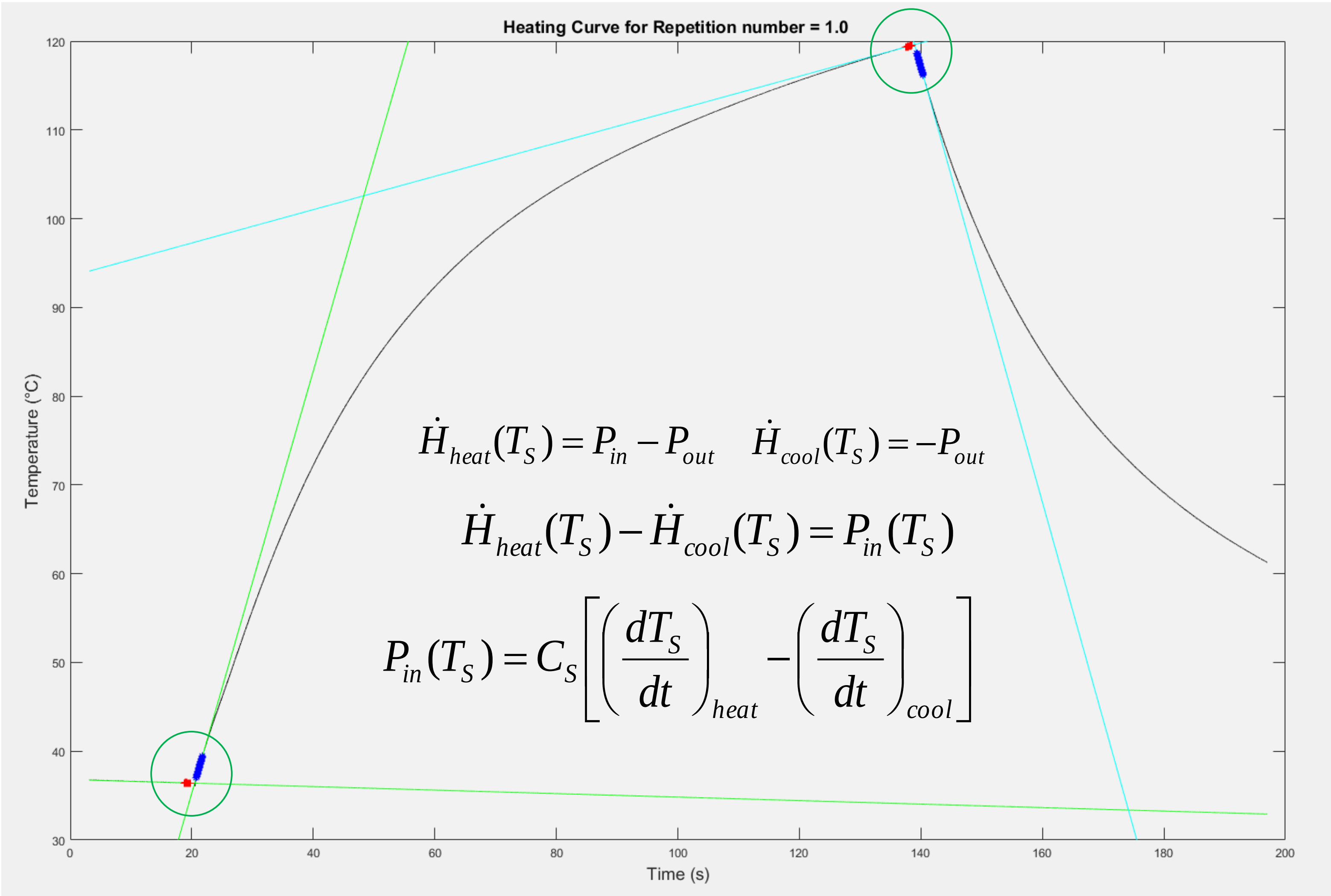
pressure: 0.04 Pa Ar, beam voltage: 500 V
beam diameter: 160 mm
distance: 225 mm





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)

evaluation method

Passive thermal probe

Determination of the energy flux density

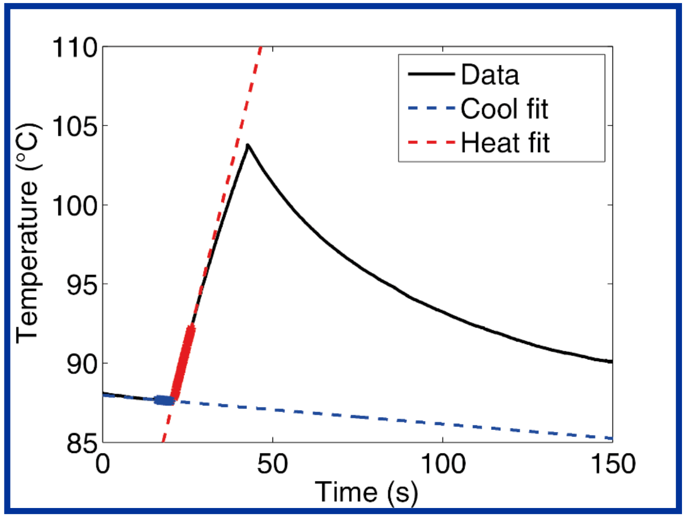
$$\frac{P_{in}}{A_S} = J_{in} = \frac{C_S}{A_S}\left[\dot{T}_h - \dot{T}_c\right]$$

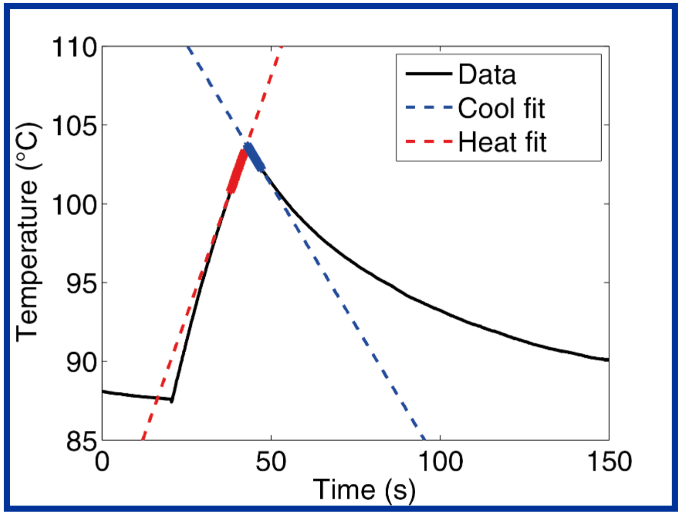
Evaluation around kinks

- Examination of short times around switching kinks of the temperature curve
- Approximation of temperature curve by linear fit
- Difference of slope gives: $\left[\dot{T}_h - \dot{T}_c\right]$

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.*



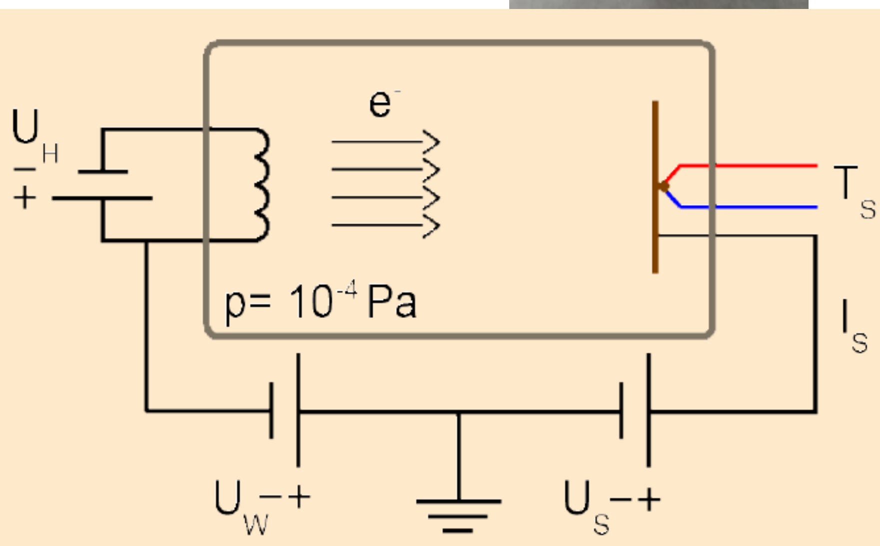


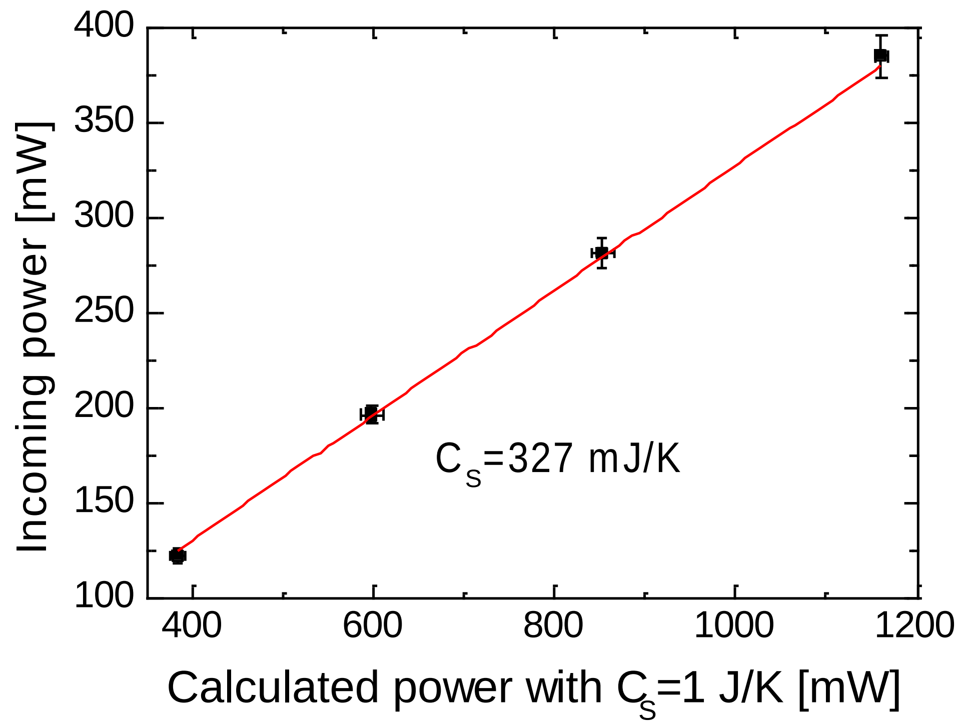
Measurement on ion beam experiment VIBEX: 700V anode voltage, 60% impulse width modulation, distance to source: 30 cm

passive thermal probe (PTP)

PTP

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

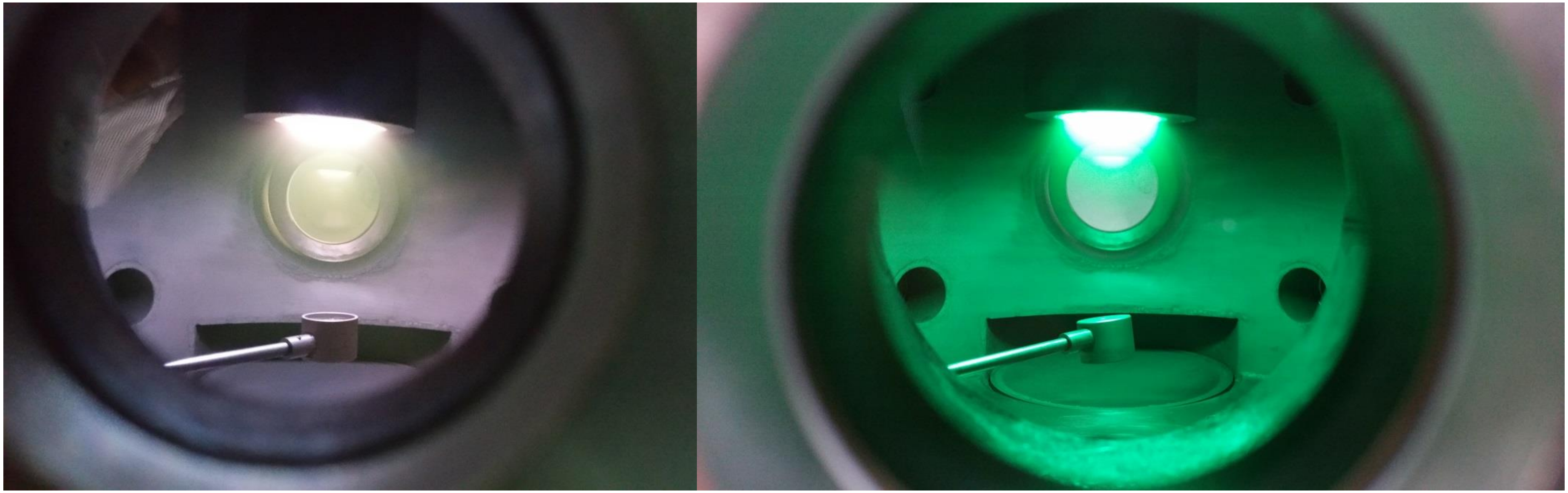




Stahl, M., Trottenberg, T., Kersten, H., Rev. Sci. Instr. ***81****(2010), 023504.*

HiPIMS vs. DCMS

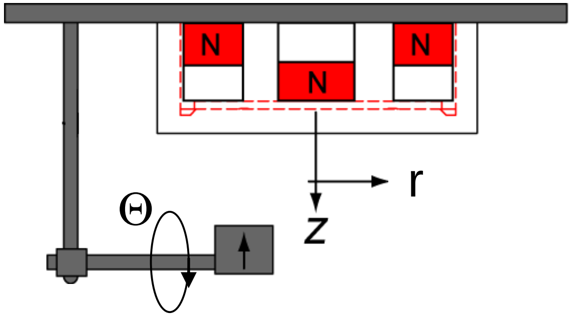
comparison DCMS and HiPIMS



Cu / Ar (DC)

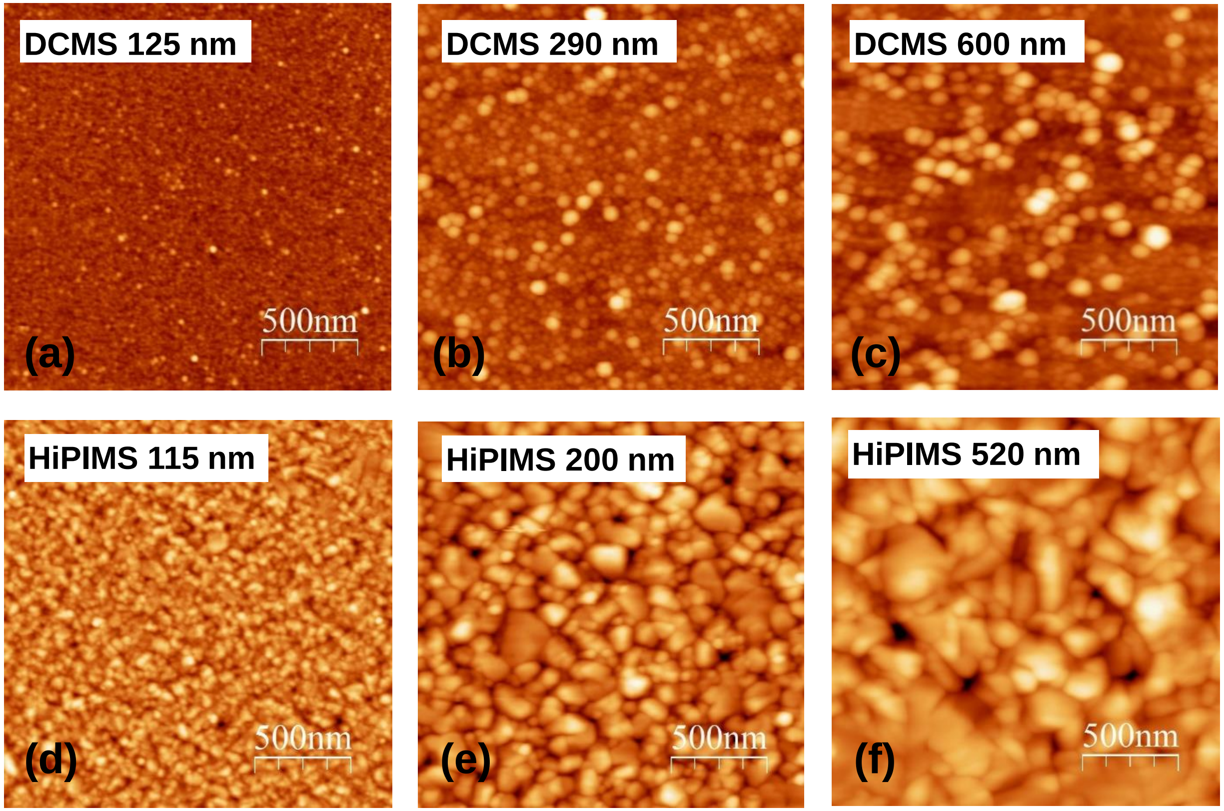
Cu / Ar (40µs, 500 Hz)

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



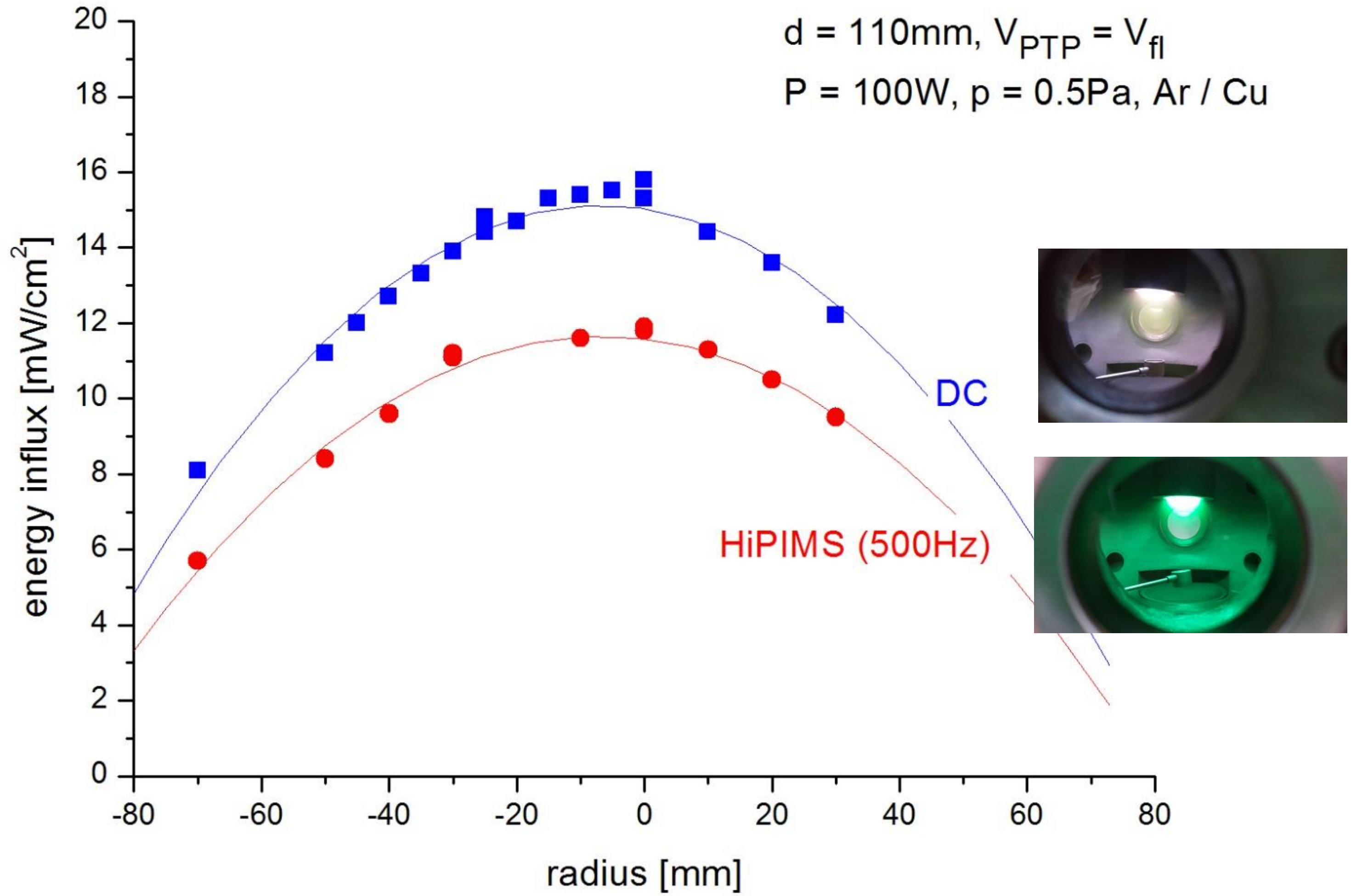
grain size modifications due to energetic ion bombardment

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

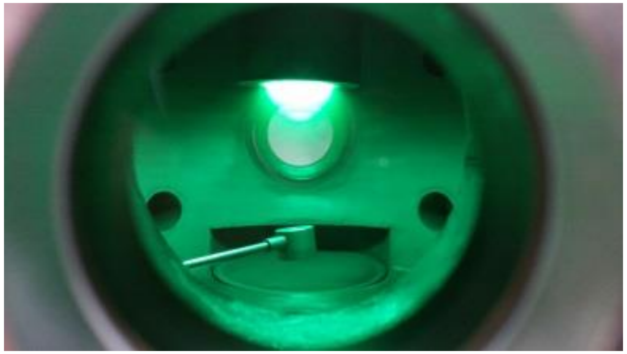
$J_{HiPIMS} / J_{DCMS} = 0,7$

e.g. lower heating rate

deposition $rate_{HiPIMS}$ / $rate_{DCMS}$ = 0,5

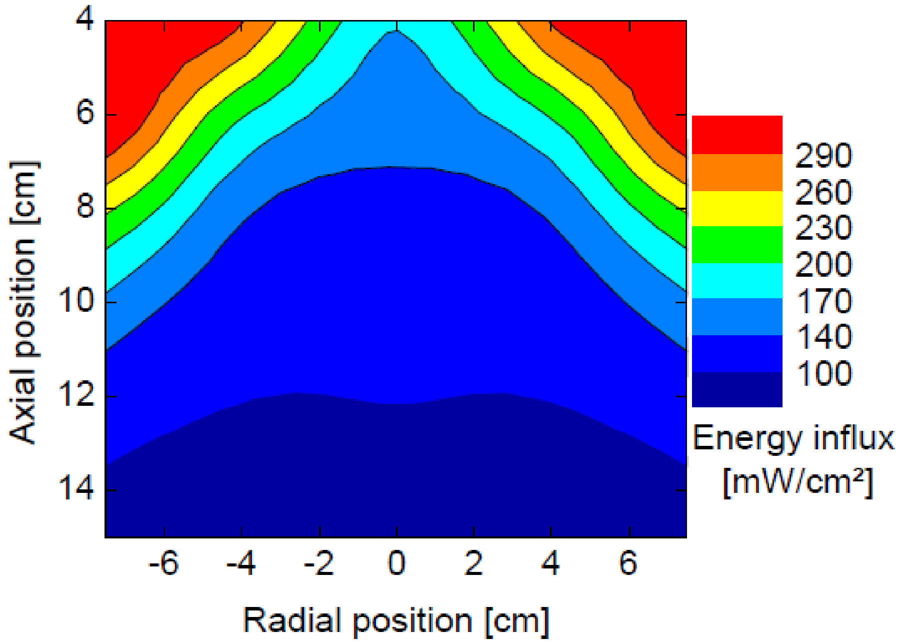
⇨ 1,4 times more energy per deposited particle

⇨ thin film properties



Ti / Ar

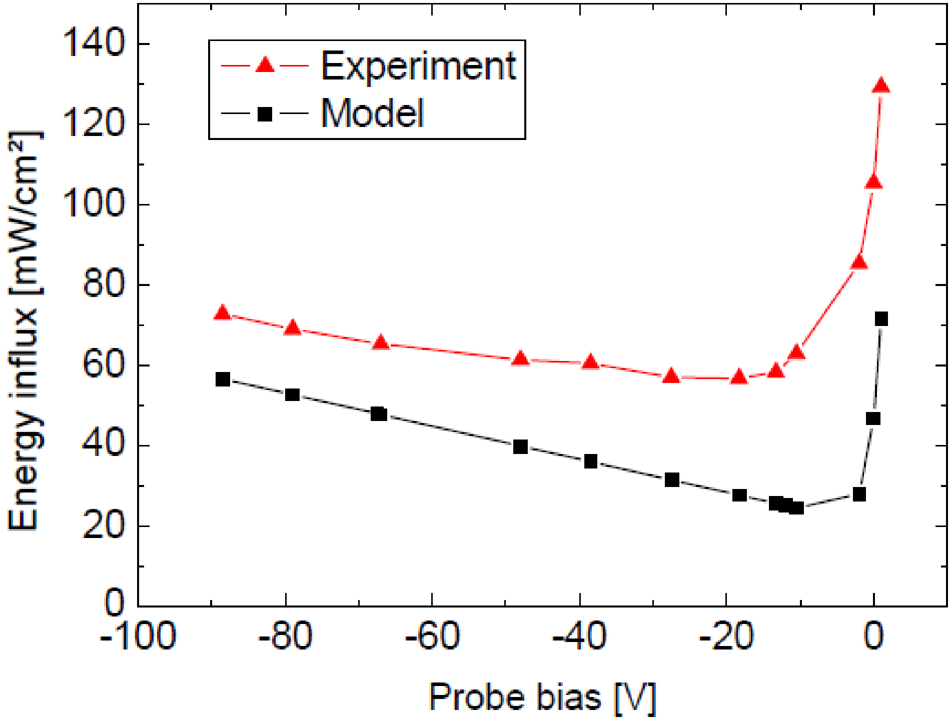
100µs
100Hz



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

energy fluxes in sputtering

effect of bias voltage



Model:

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

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

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

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

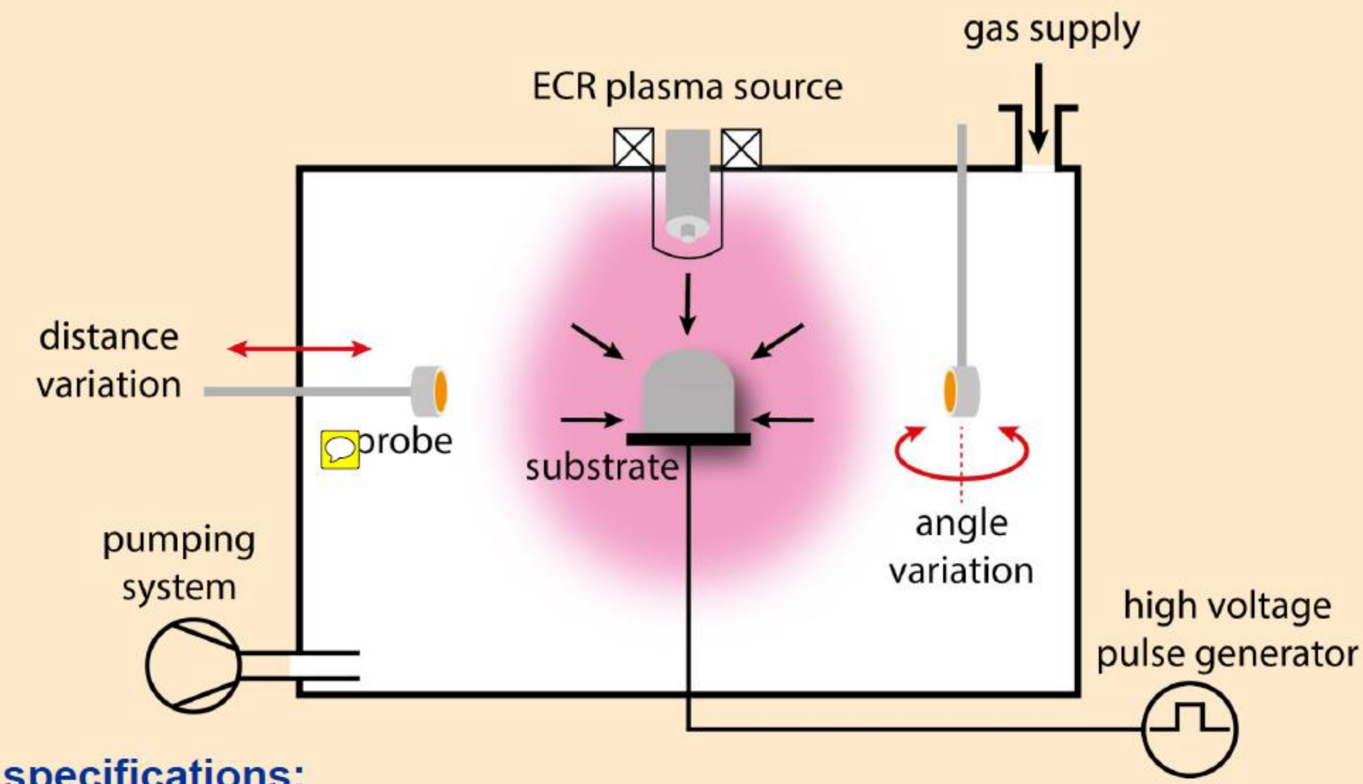
j_{ion}: Bohm-Fluss

$J_{kin,e}$: 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 PIII



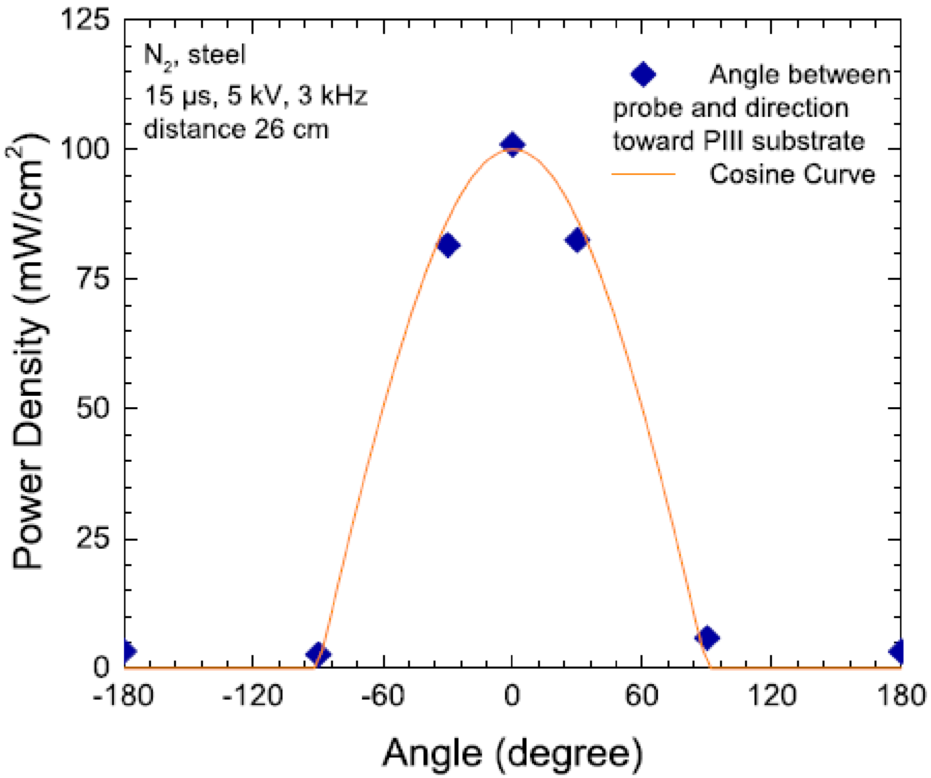
specifications:

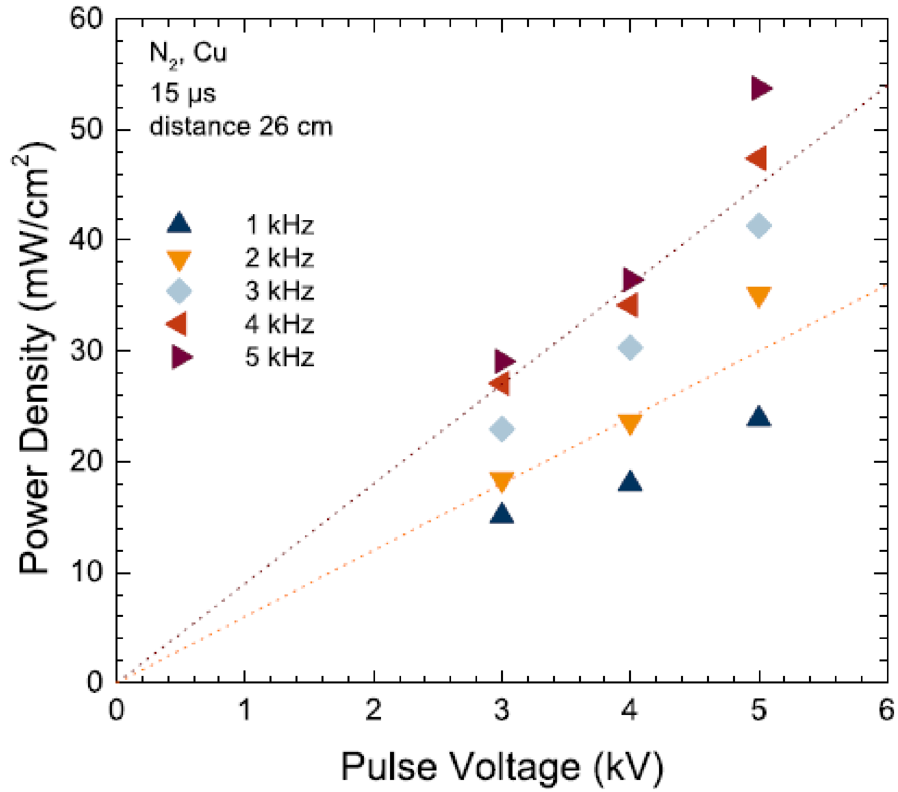
- volume = 165 l
- 3 plasma sources (2.45G Hz ECR, only centered one was used)
- pressure: 5.8 µbar

*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

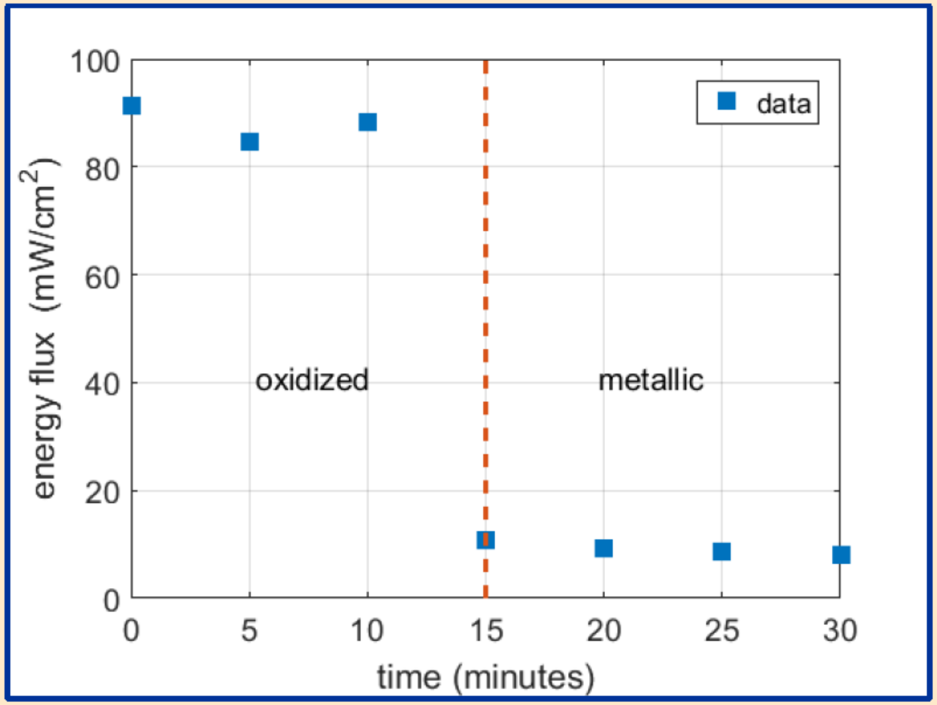




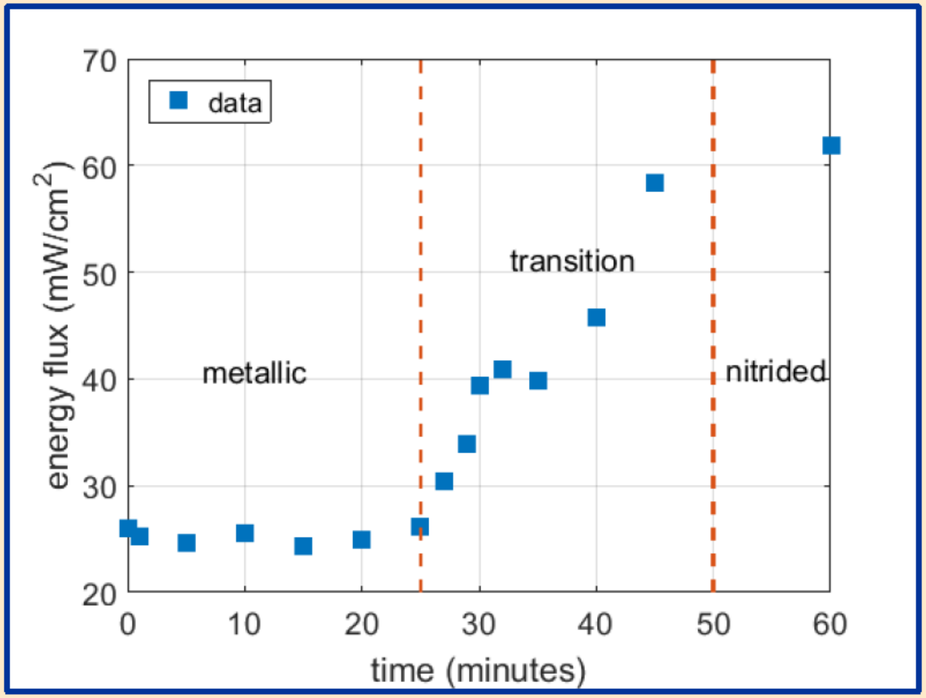
*Haase, F., Manova, D., Mändl, S., Kersten, H., Eur. Phys. J. D **70**(2016), 186.*

energy fluxes in PIII

SEE, surface state



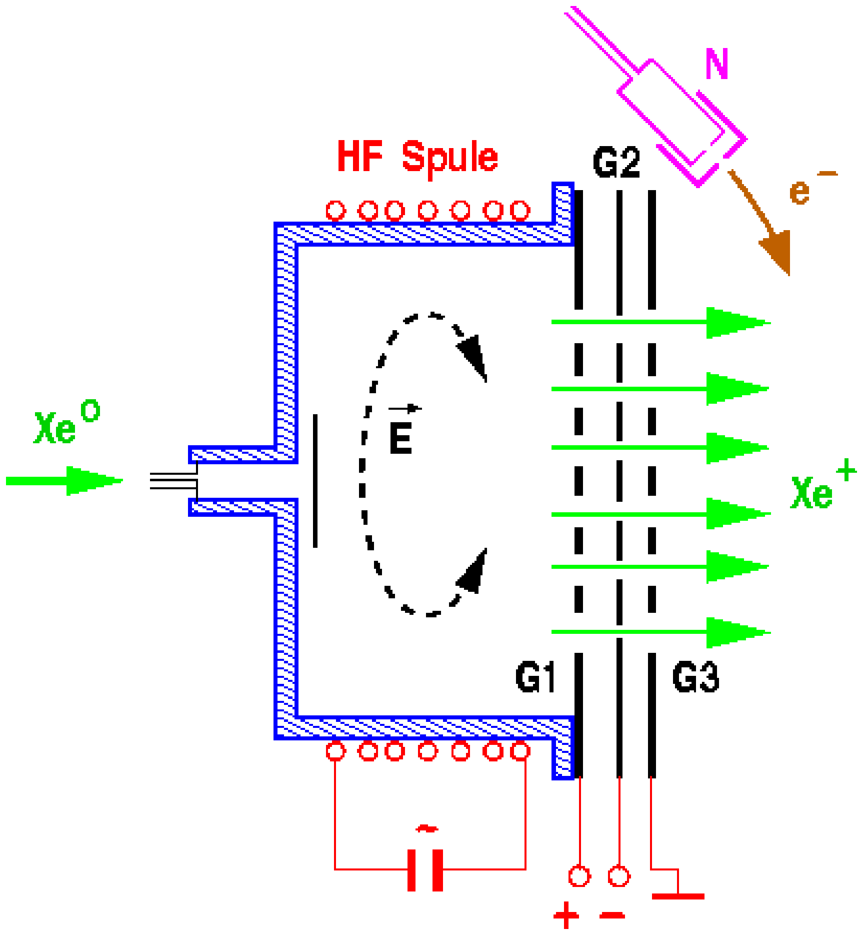
oxidized Mg, 15 µs, 3 kV, 5 kHz



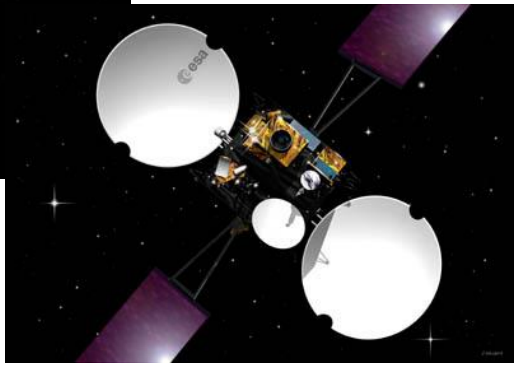
Mg, 15 µs, 3kV, 5 kHz

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

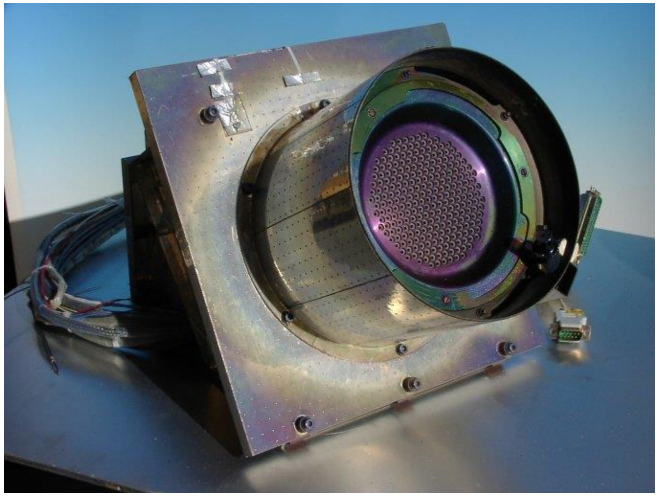
energy fluxes in ion beam



SMART 1



ARTEMIS

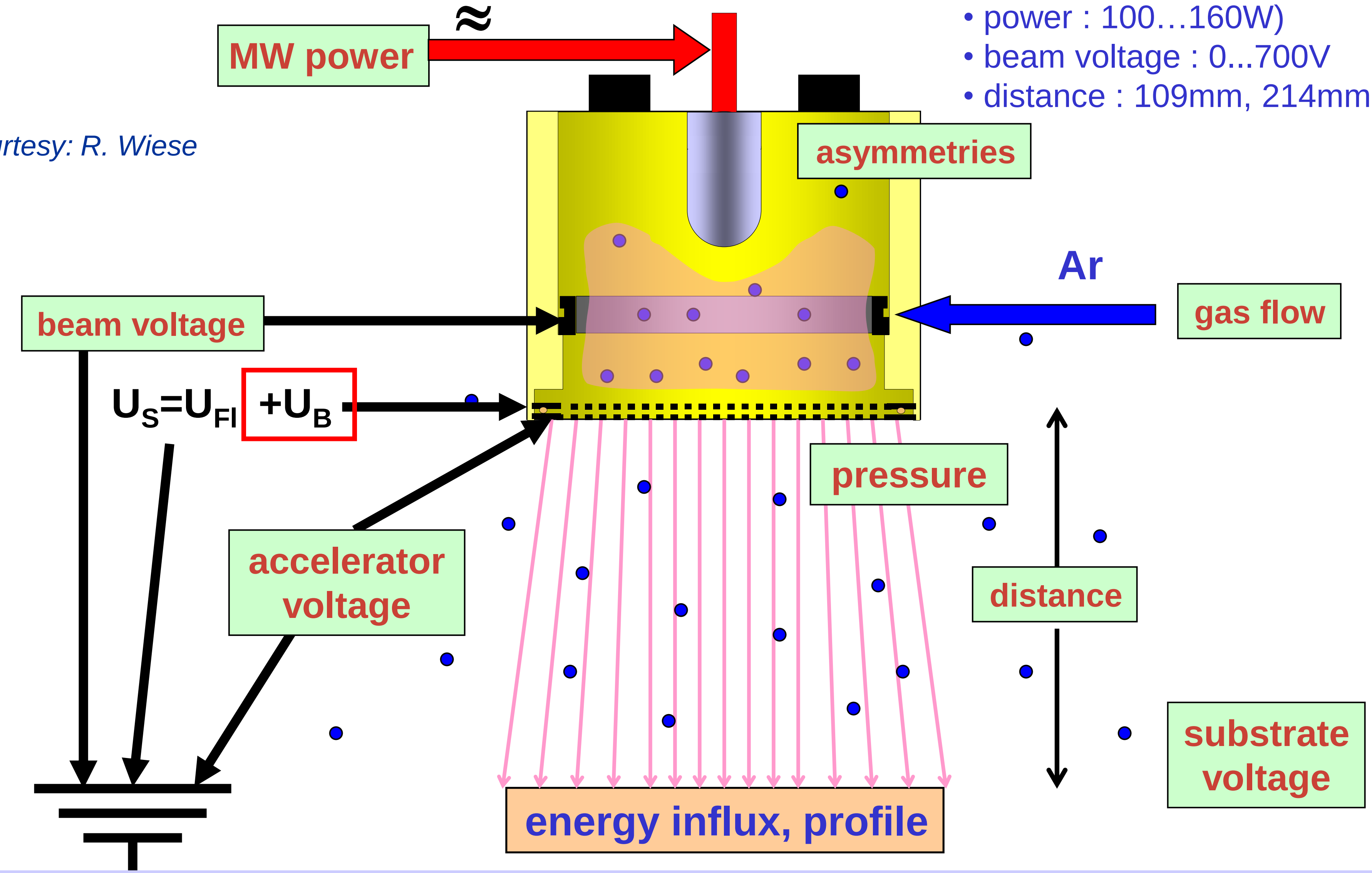


RIT 10

energy fluxes in ion beam

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

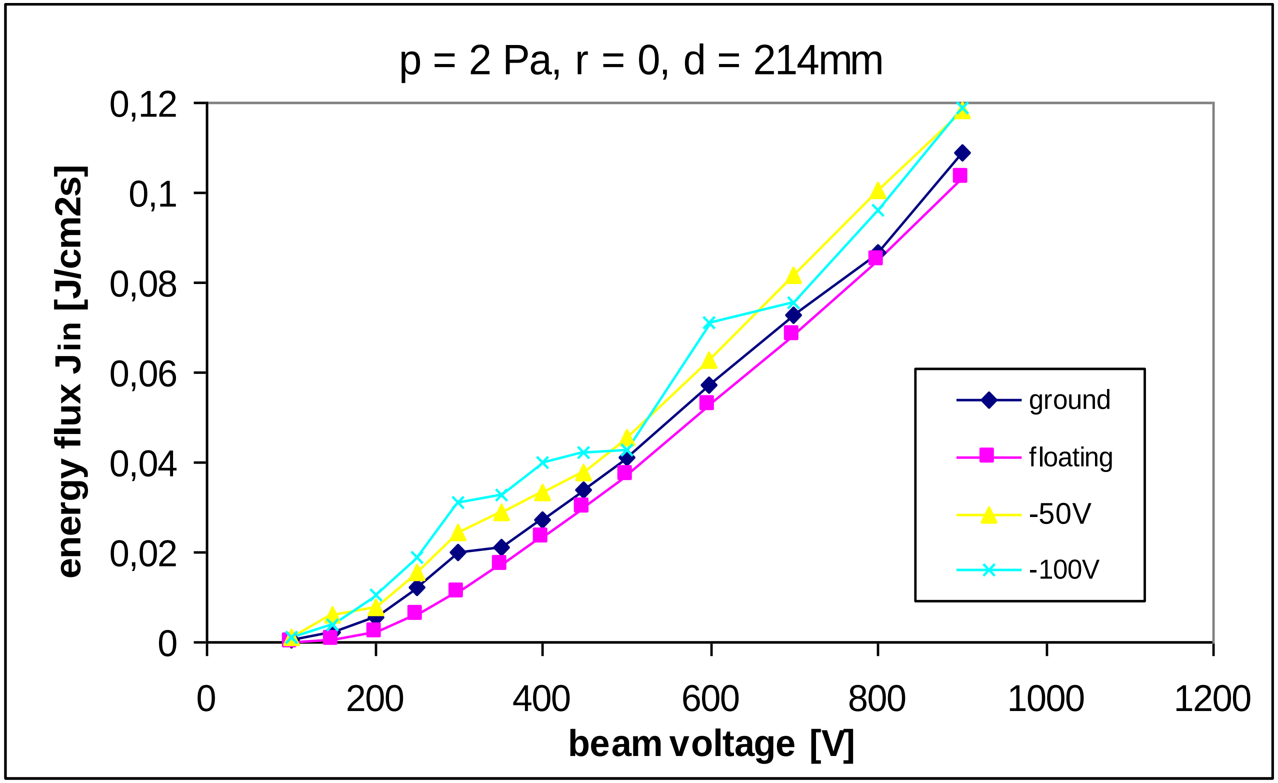
courtesy: R. Wiese



energy fluxes in ion beam

beam voltage

energy influx in dependence on beam voltage and substrate potential:



$J_{in} = f(V_{beam}, V_S)$

*Kersten, H., Wiese, R. et.al. SCT **200**(2005) , 809.*

beam voltage ➡ **potential difference** ➡ **ion energy**

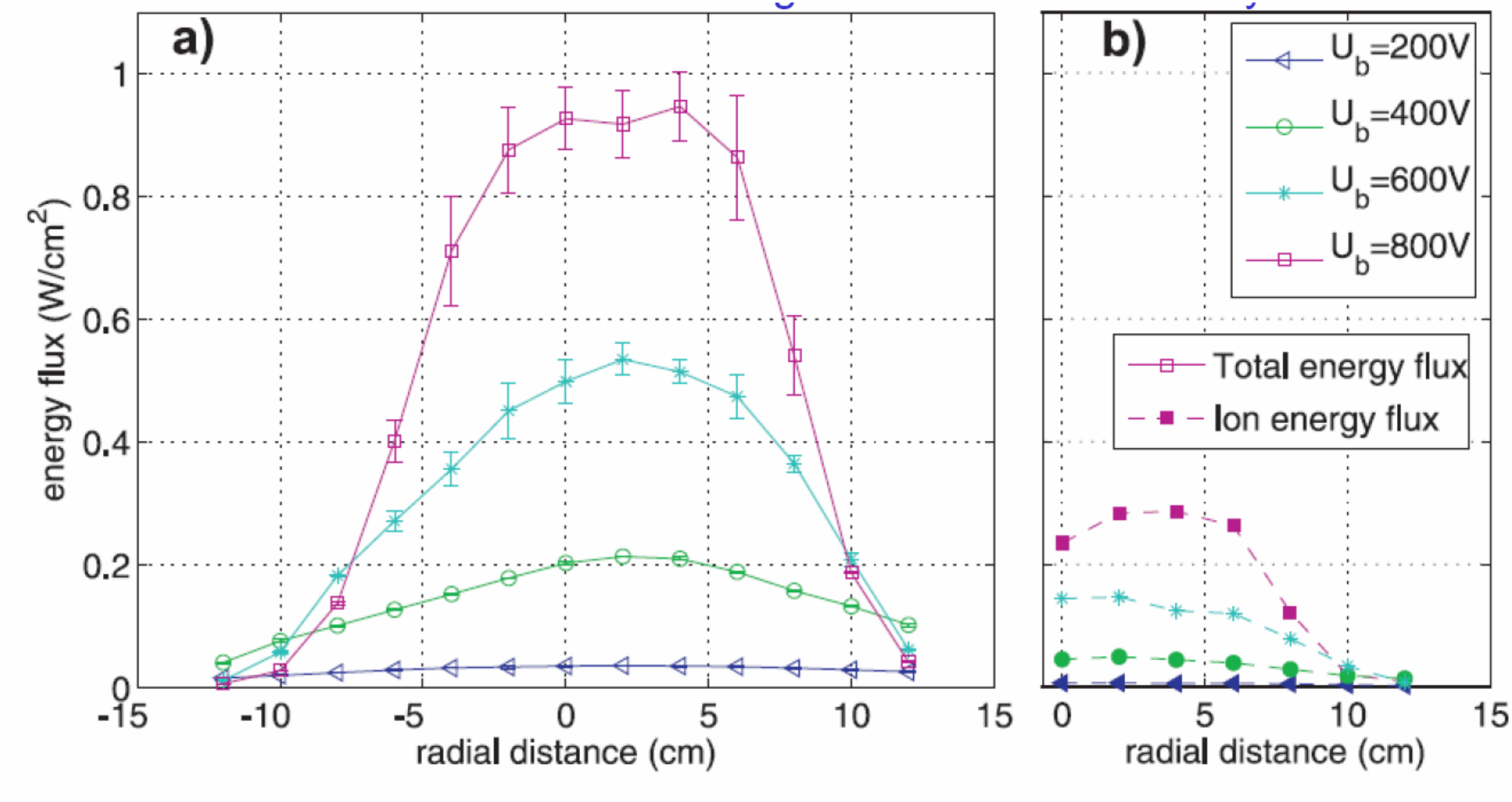
(affected by : pressure, radial position, substrate voltage)

energy fluxes in ion beam

radial profile

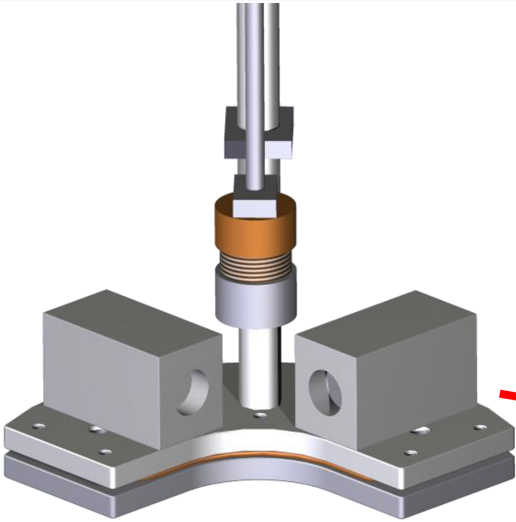
measured by thermal probe

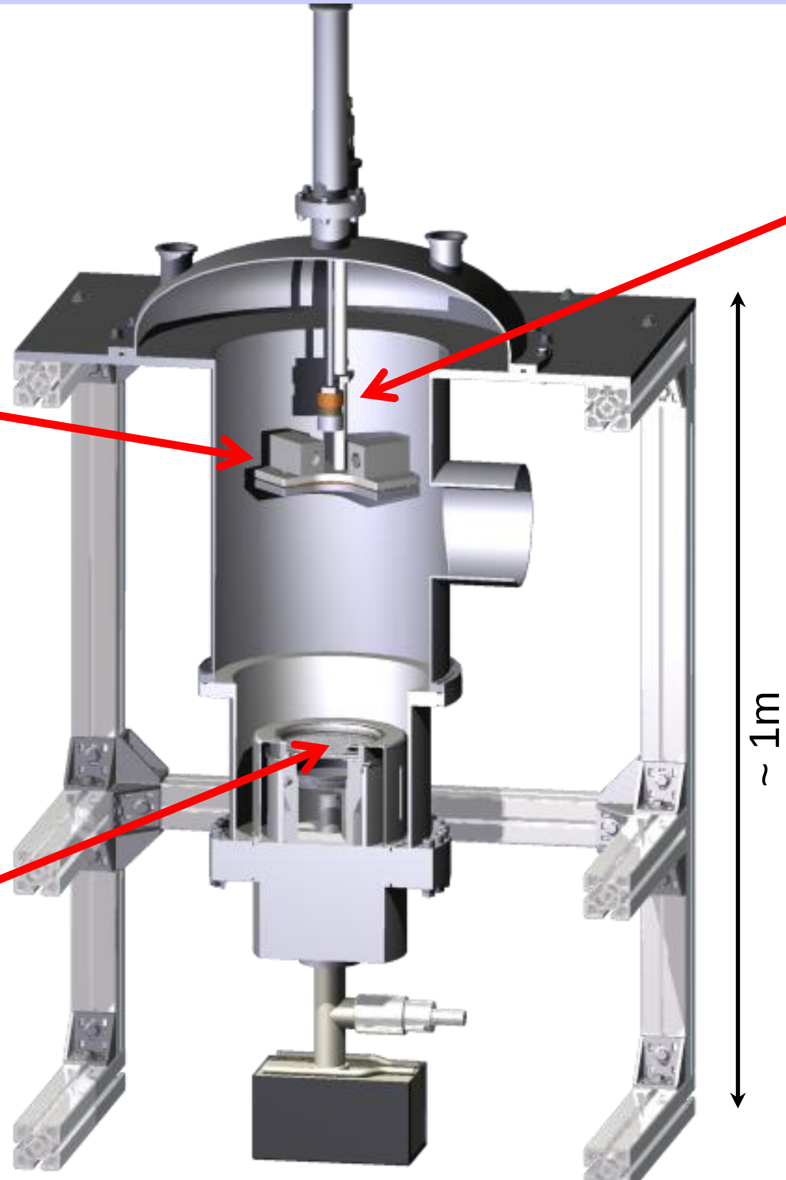
measured by Faraday cup

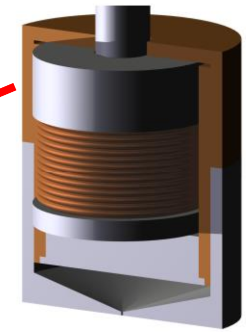


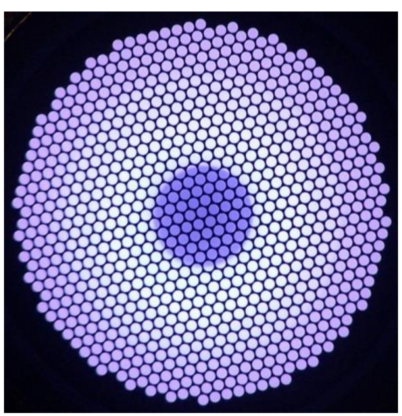
momentum transfer in ion beam

ion beam source









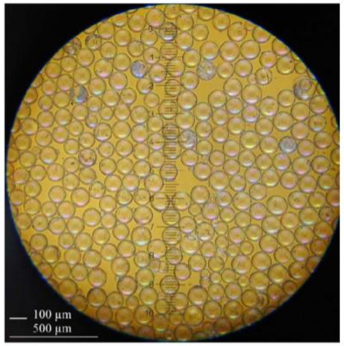
VIBEX:

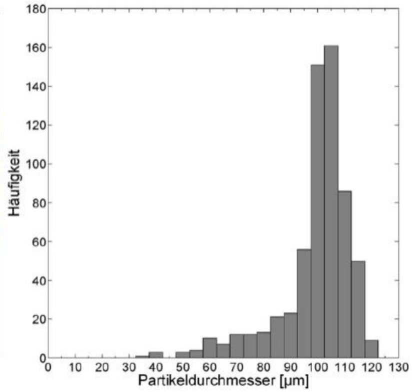
Vertical
Ion
Beam
Experiment

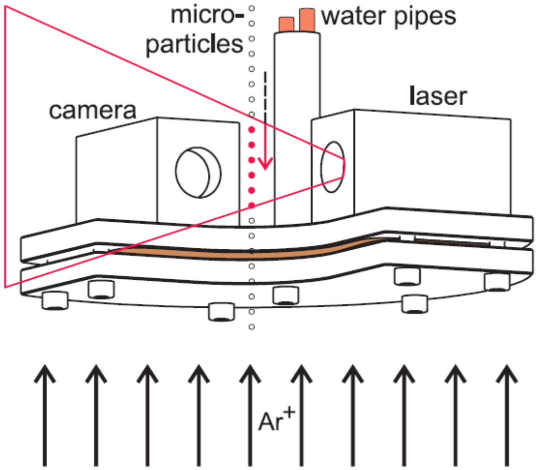
C | A | U

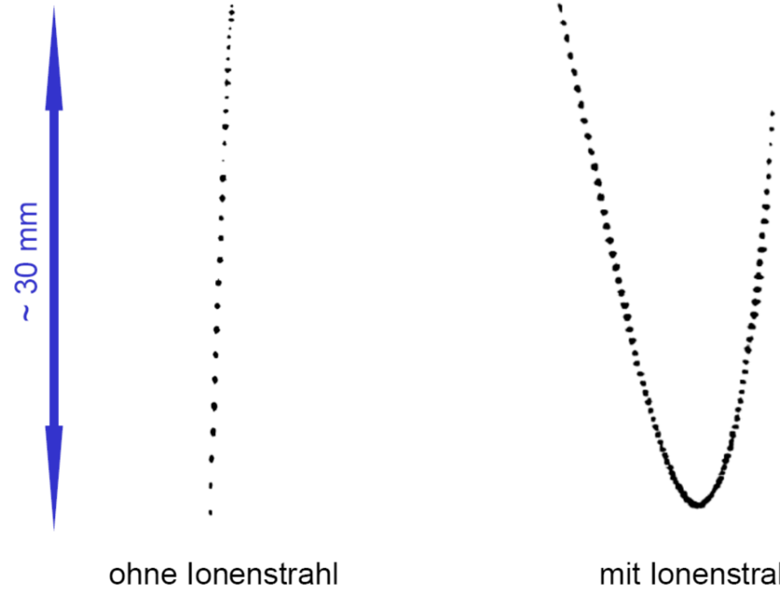
ion beam source

momentum transfer



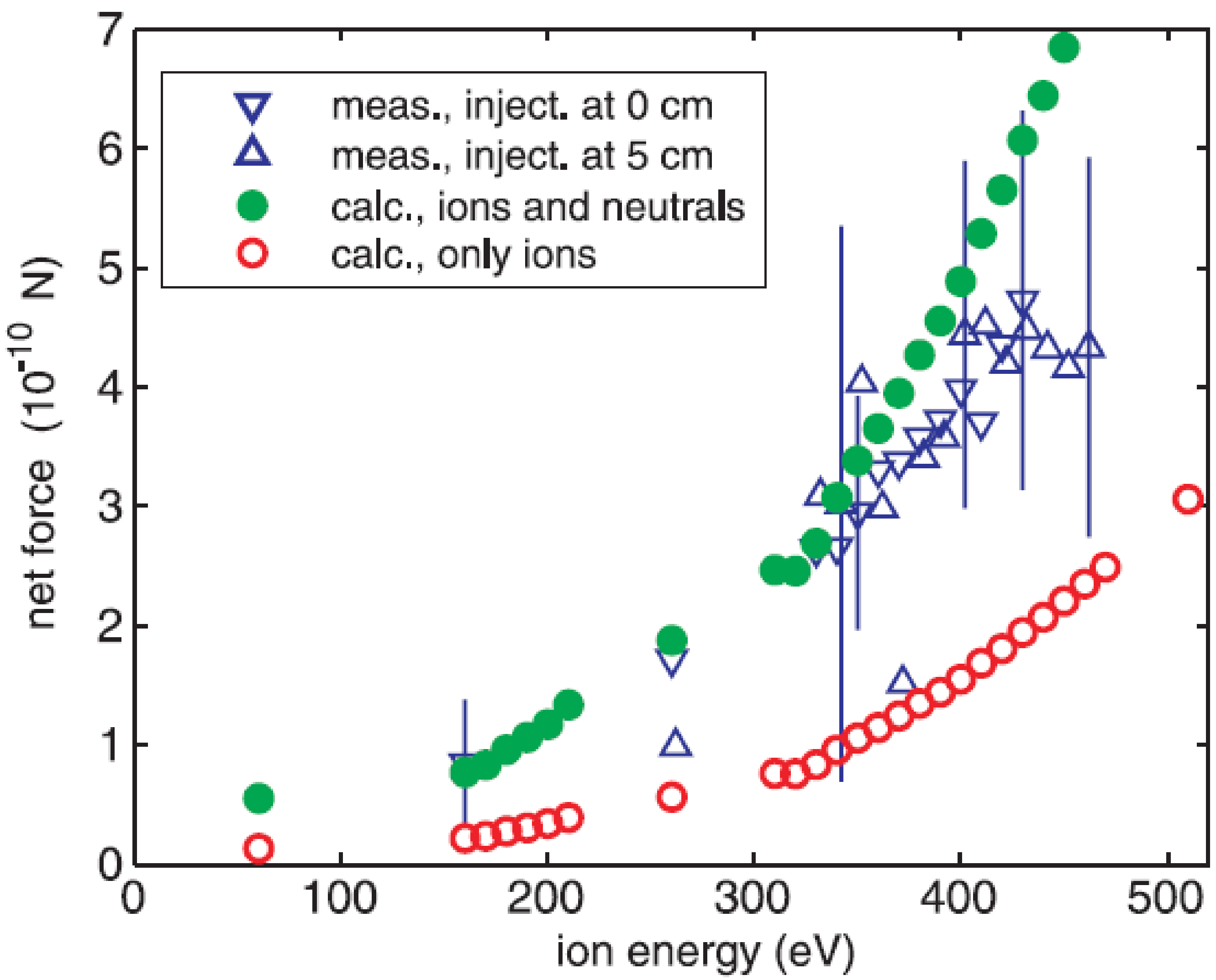






ion beam source

momentum transfer



Trottenberg, T., Schneider, V., Kersten, H.,
IEEE Plasma Sci. ***38****(2010), 774.*

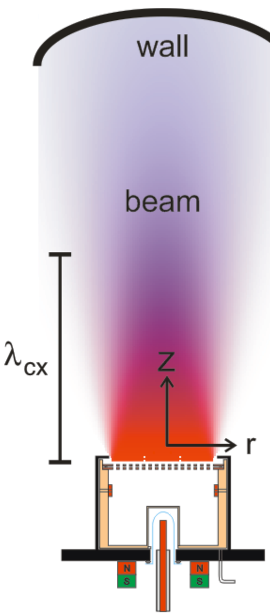
Schneider, V., Trottenberg, T., Teliban, I., Kersten,H.,
Rev. Sci. Instr. ***81****(2010), 013503*

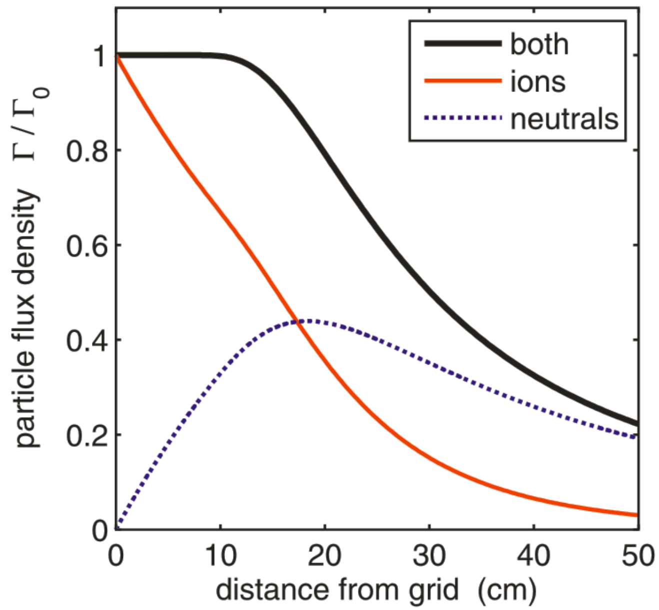
energy fluxes in ion beam

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

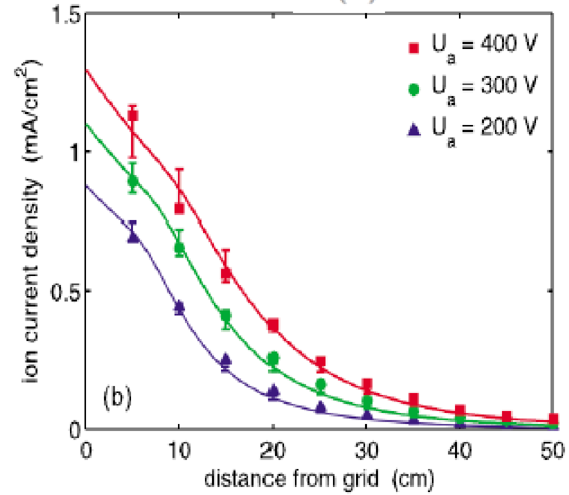
$$\Gamma_{\mathrm{n}}(z) = \Gamma_{\mathrm{beam}}(z) \left[1 - \exp\left(-\frac{z}{\lambda_{\mathrm{cx}}}\right)\right]$$

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

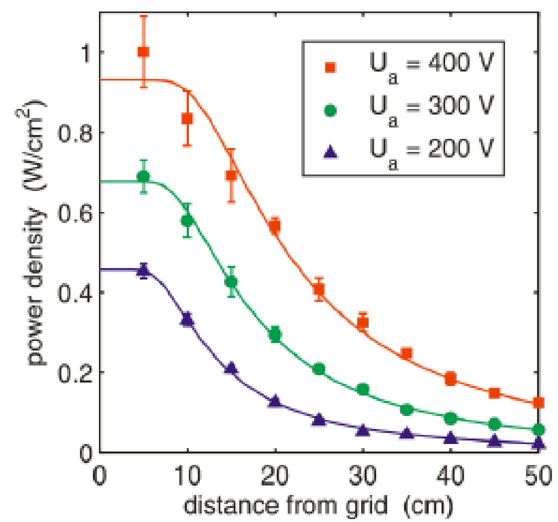




$j(z) = e\,\Gamma_{\mathrm{i}}(z)$

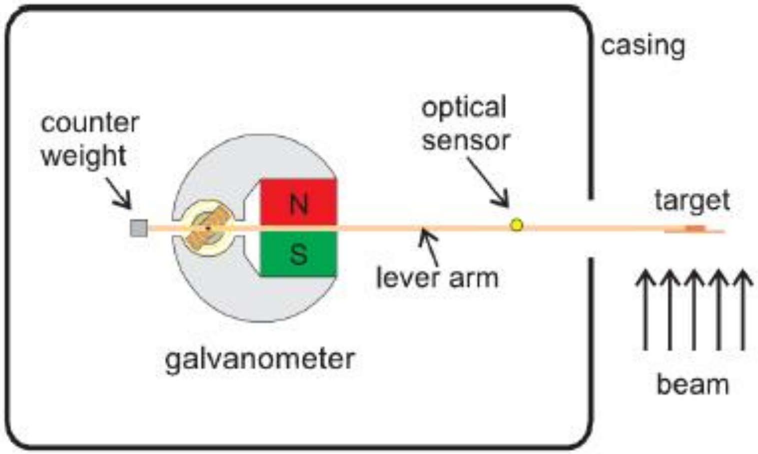


$w(z) = c_{\mathrm{heat}} E\, \Gamma_{\mathrm{beam}}(z)$



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

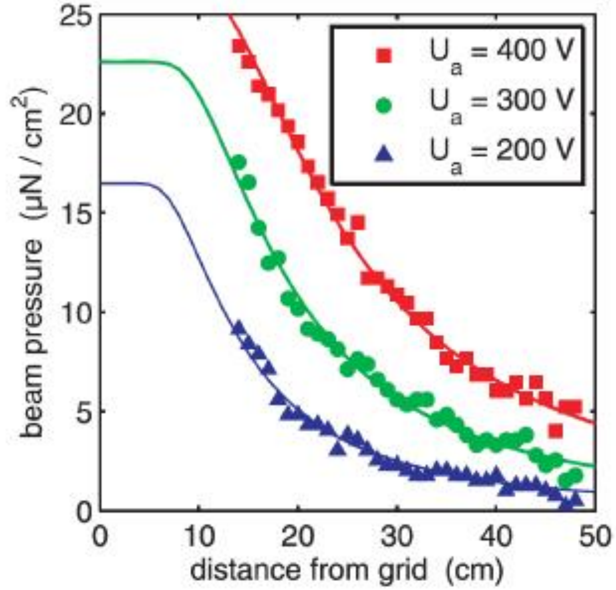


$$p(z) = c_{\text{force}}\,(2\,m\,E)^{\frac{1}{2}}\,\Gamma_{\text{beam}}(z)$$

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

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

galvanometric force probe



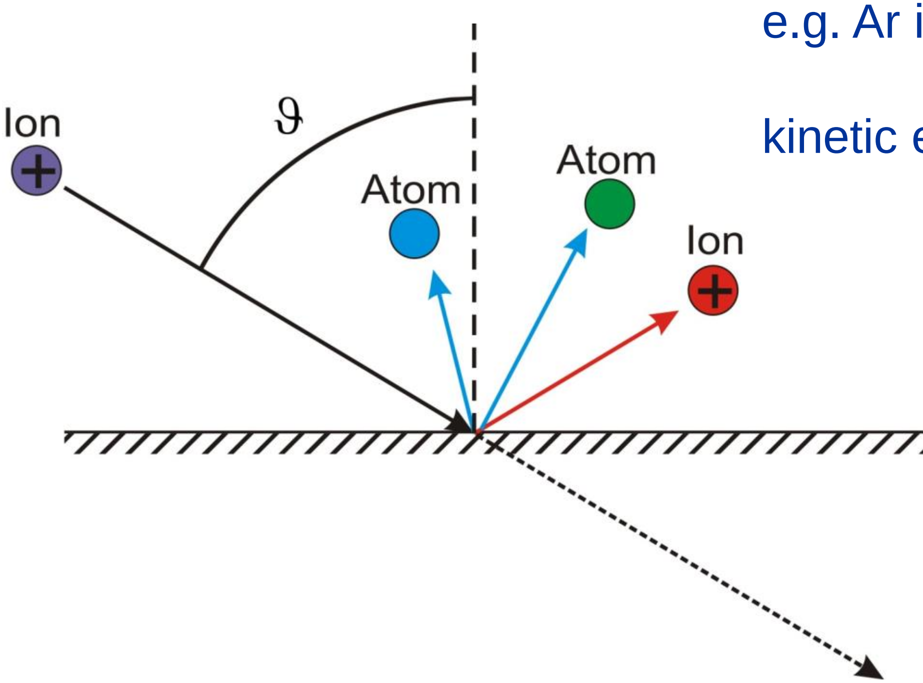
Spethmann, A., Trottenberg, T., Kersten, H., Rev. Sci. Instrum. ***86****(2015), 015107.*

(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 !

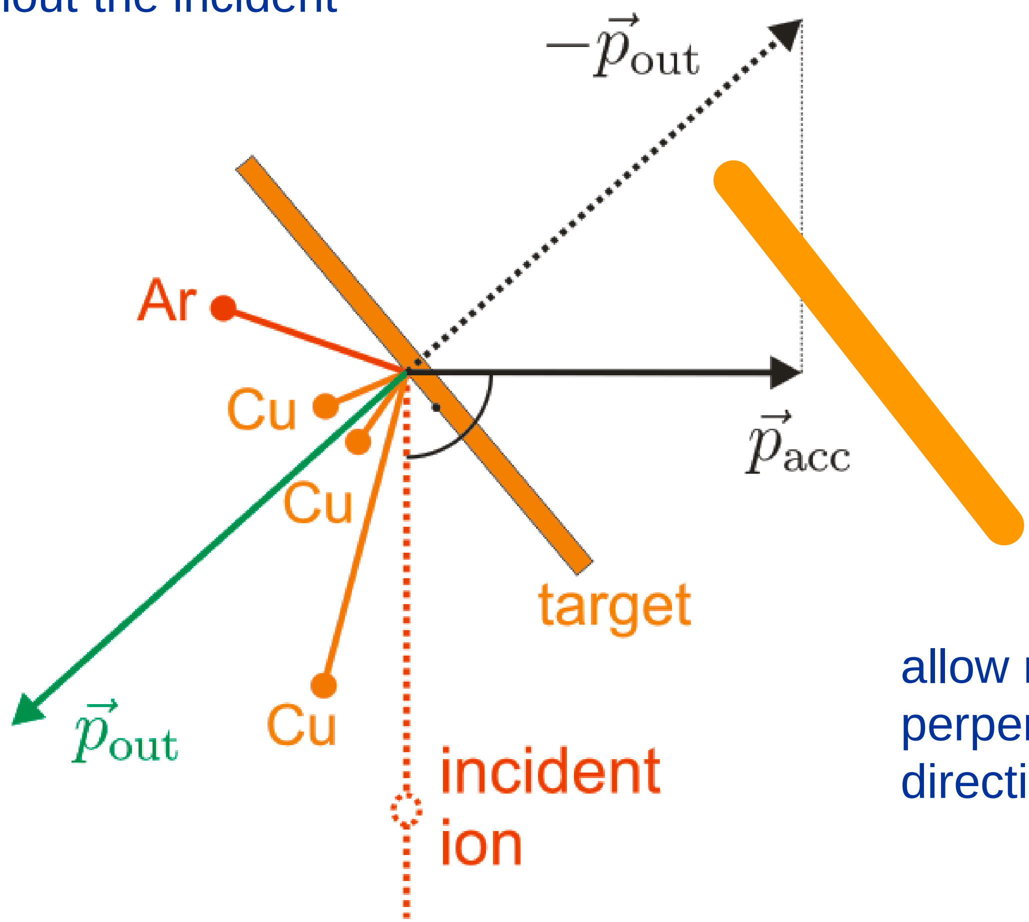
energy of reflected particles ?
angle distribution ?
momentum transfer ?
ions / neutrals ?

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

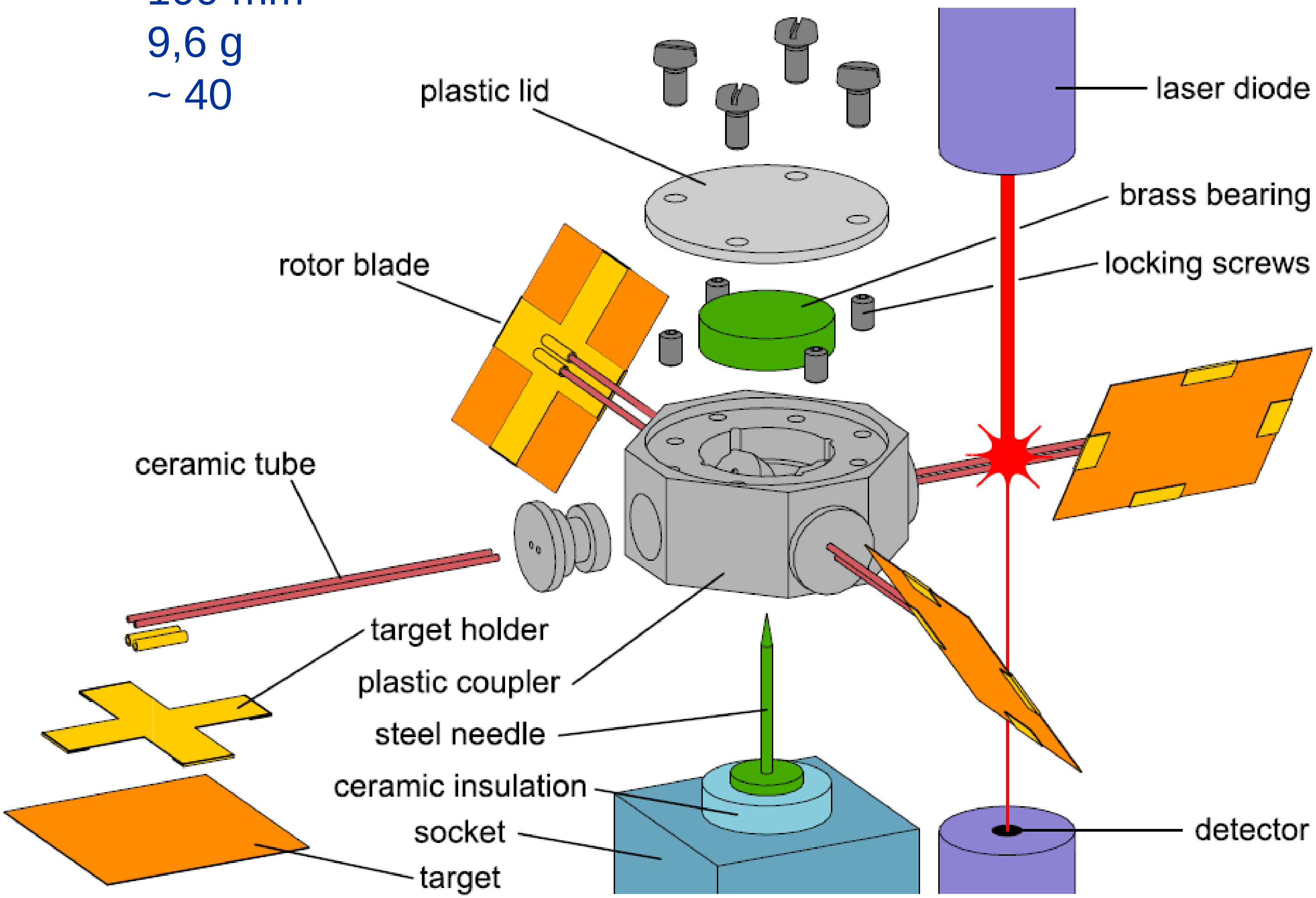
How to measure only the momenta from the released particles (reflected, sputtered), e.g. without the incident ion‘s momentum?



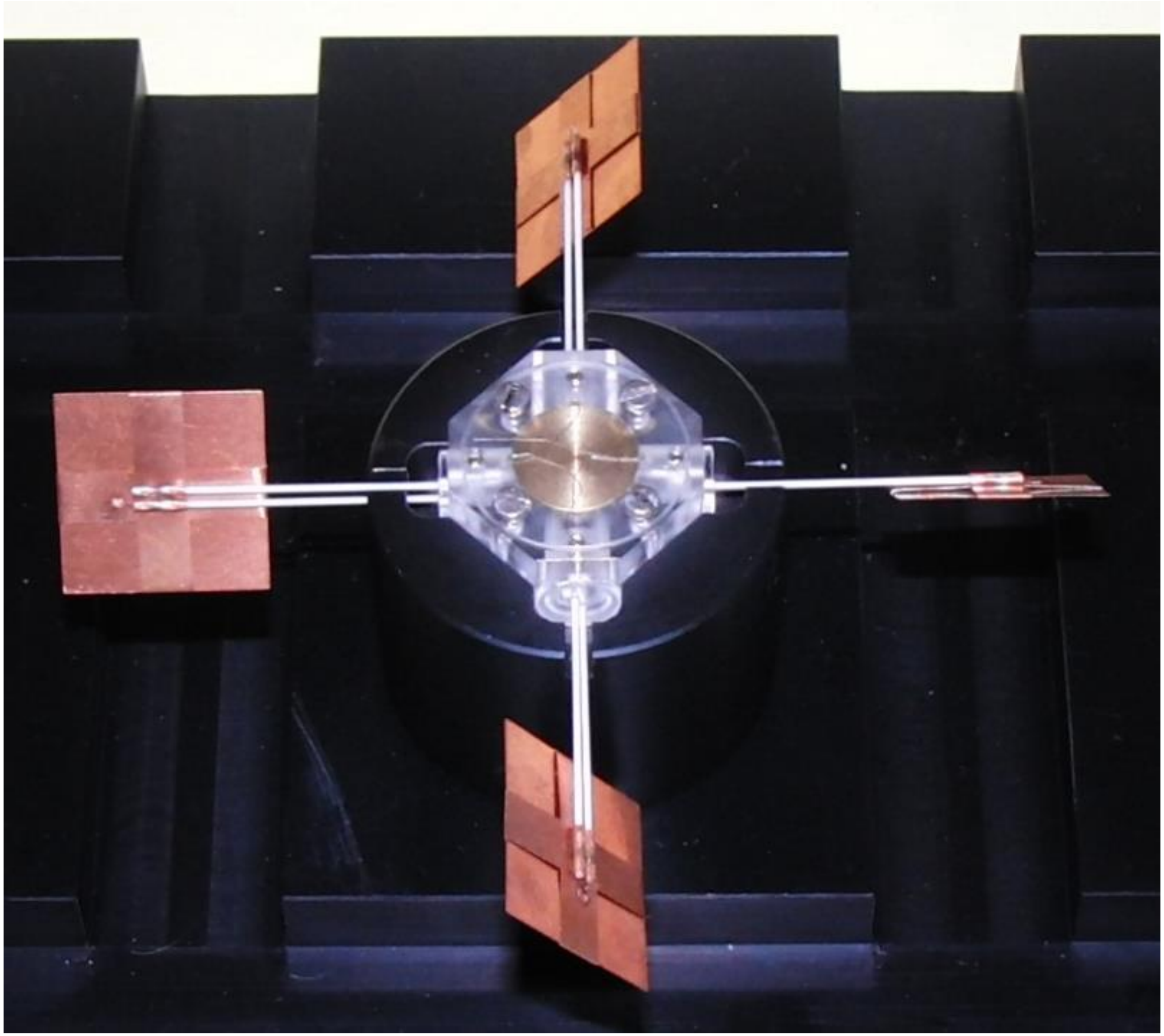
allow movement only perpendicular to ion beam direction

measurement of momentum transfer

diameter: 100 mm
mass: 9,6 g
parts: ~ 40

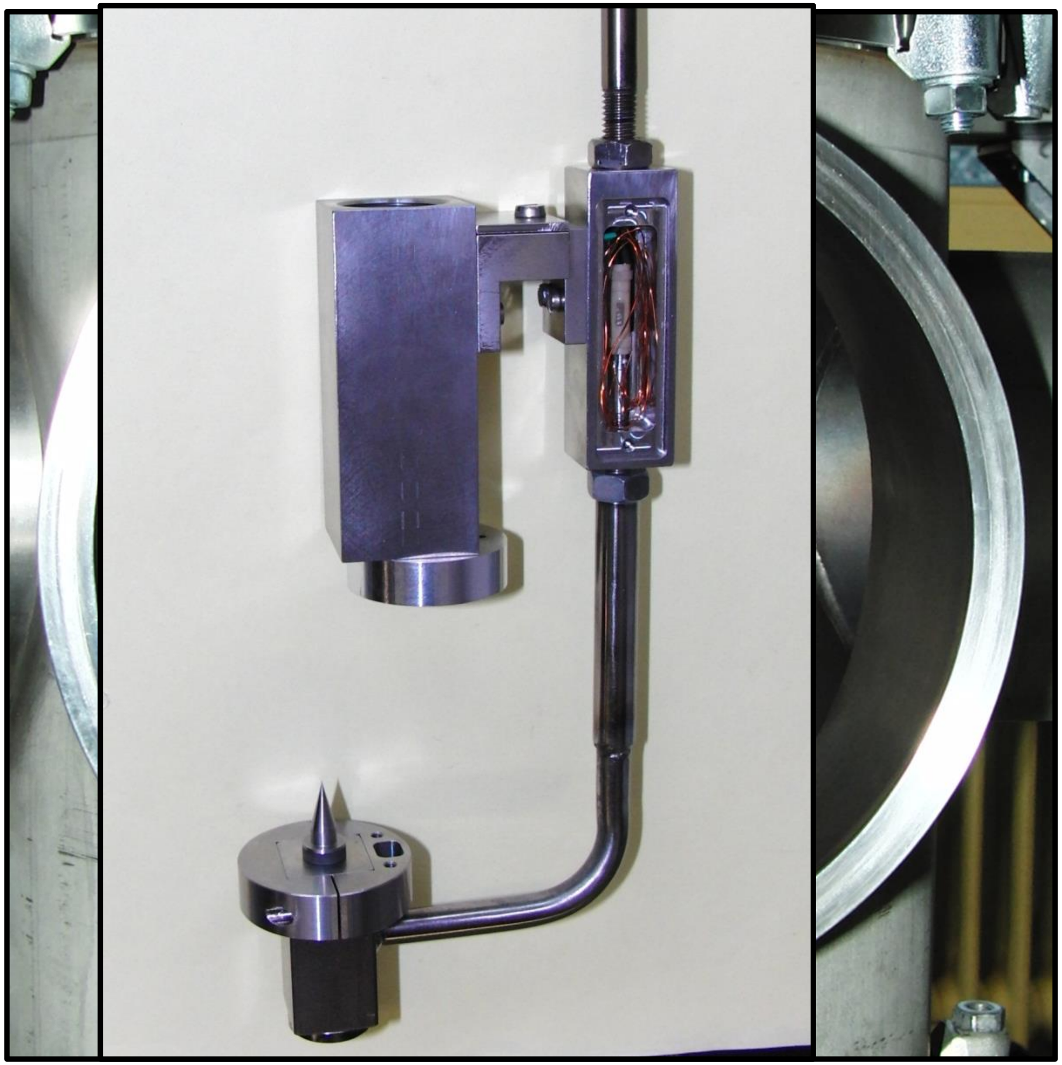


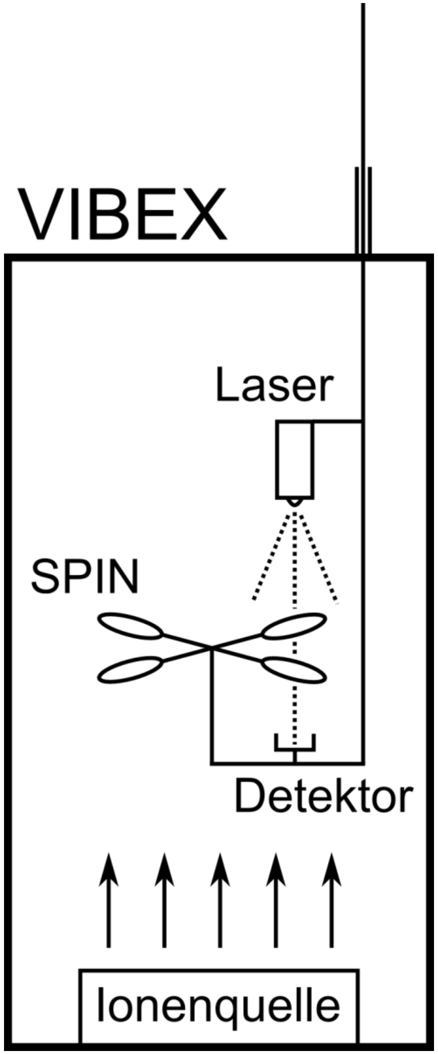
measurement of momentum transfer



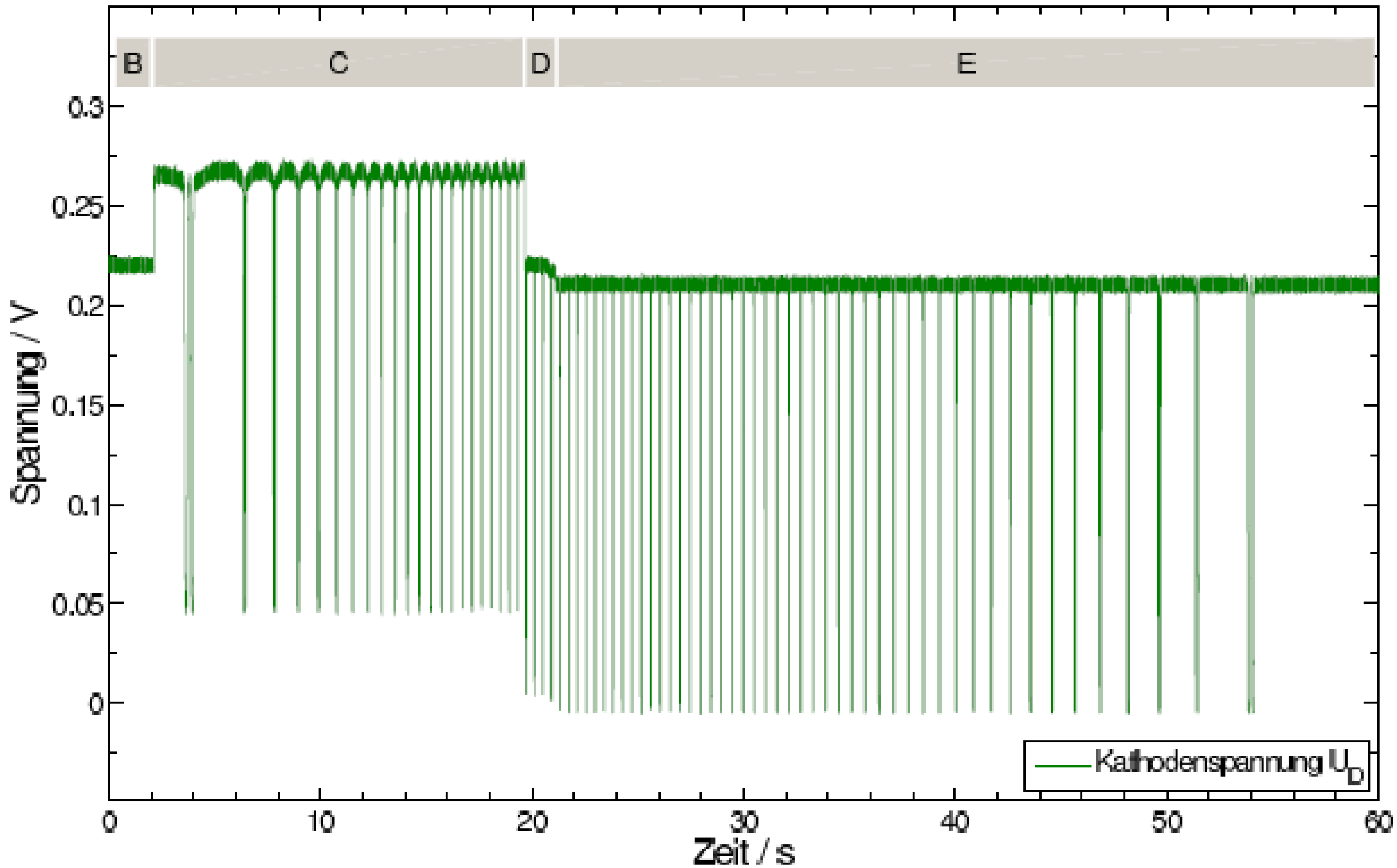
measurement of momentum transfer

SPIN

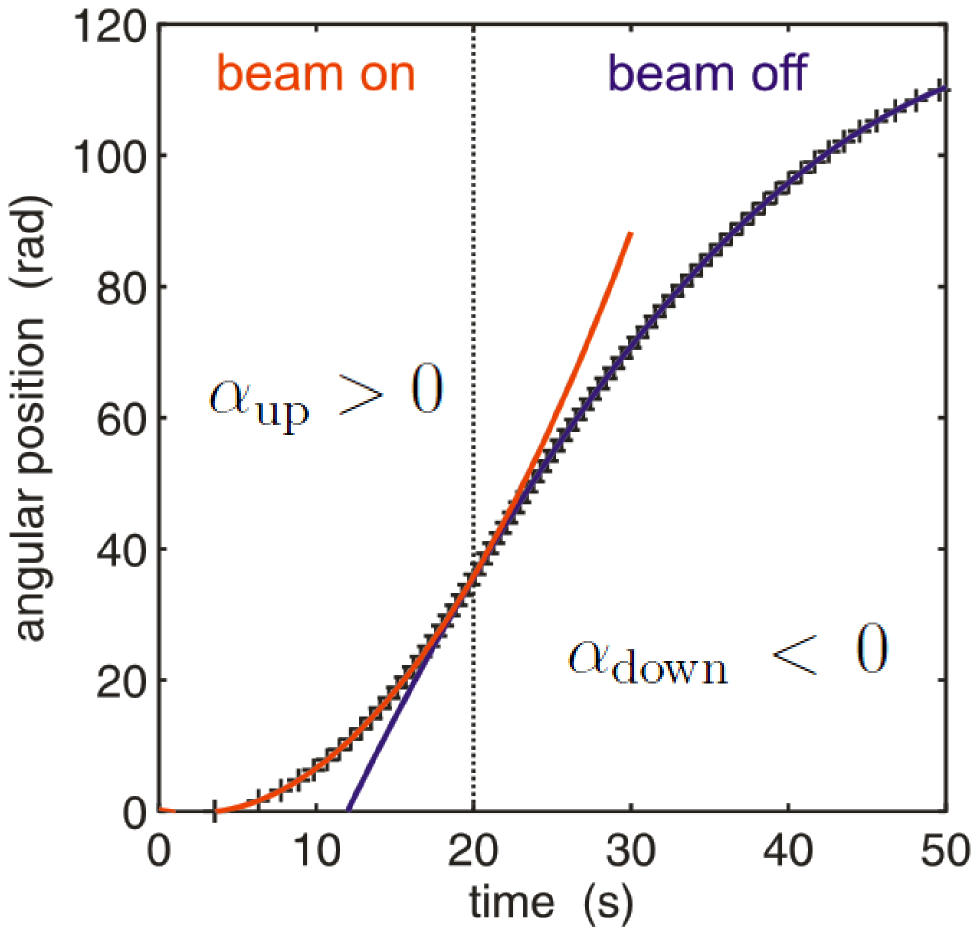




measurement of momentum transfer



measurement of momentum transfer



torsional moments:

$$M = M_{beam} - M_{fr}$$

$$M_{fr} = I\alpha_{down}$$

moment of inertia: I

radius of rotor blades:

$$r = 41\,\mathrm{mm}$$

$$F_{beam} = \frac{I}{r}(\alpha_{up} - \alpha_{down})$$

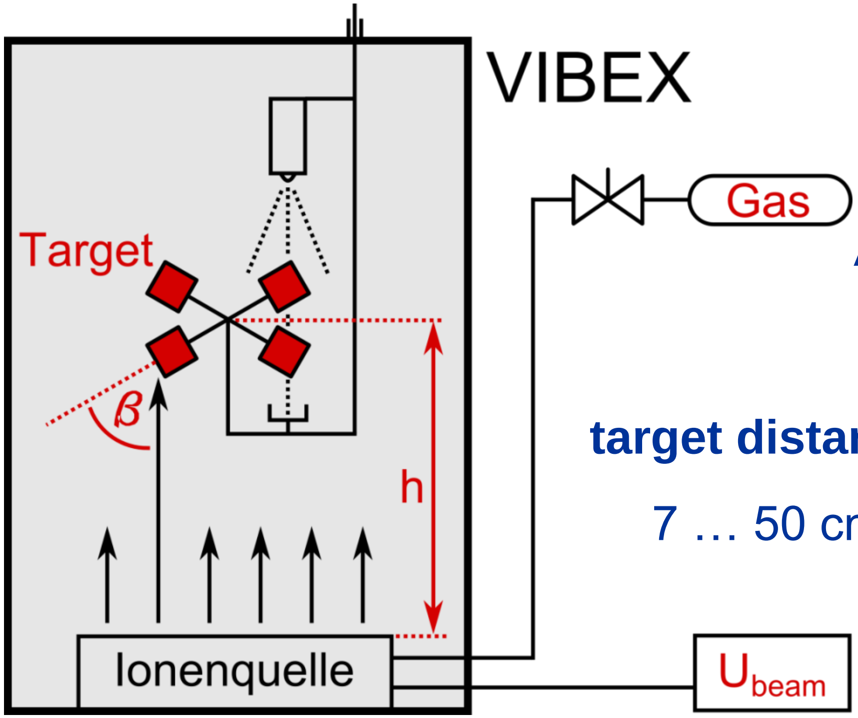
measurement of momentum transfer

target material:

copper, zinc, graphite

target angle:

0° … 90°



gas / plasma:

Argon, Neon, Krypton

target distance:

7 … 50 cm

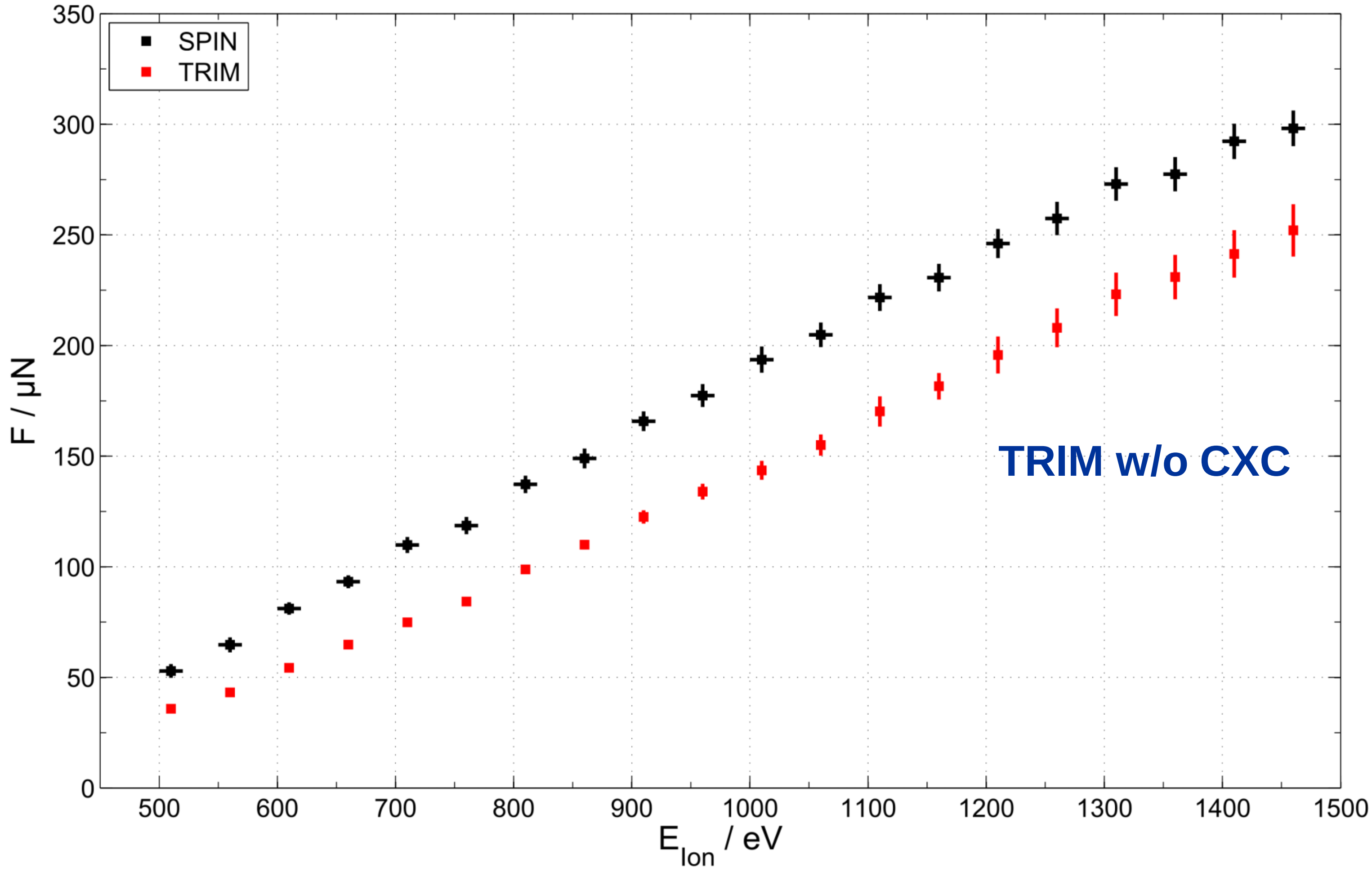
ion energy:

300 … 1500 V

J. Rutscher, T. Trottenberg, H. Kersten,
"An instrument for direct measurements of sputtering related momentum transfer to targets",
Nucl. Instr. Meas. Meth. In Phys. Res. B ***301****(2013), 47.*

measurement of momentum transfer

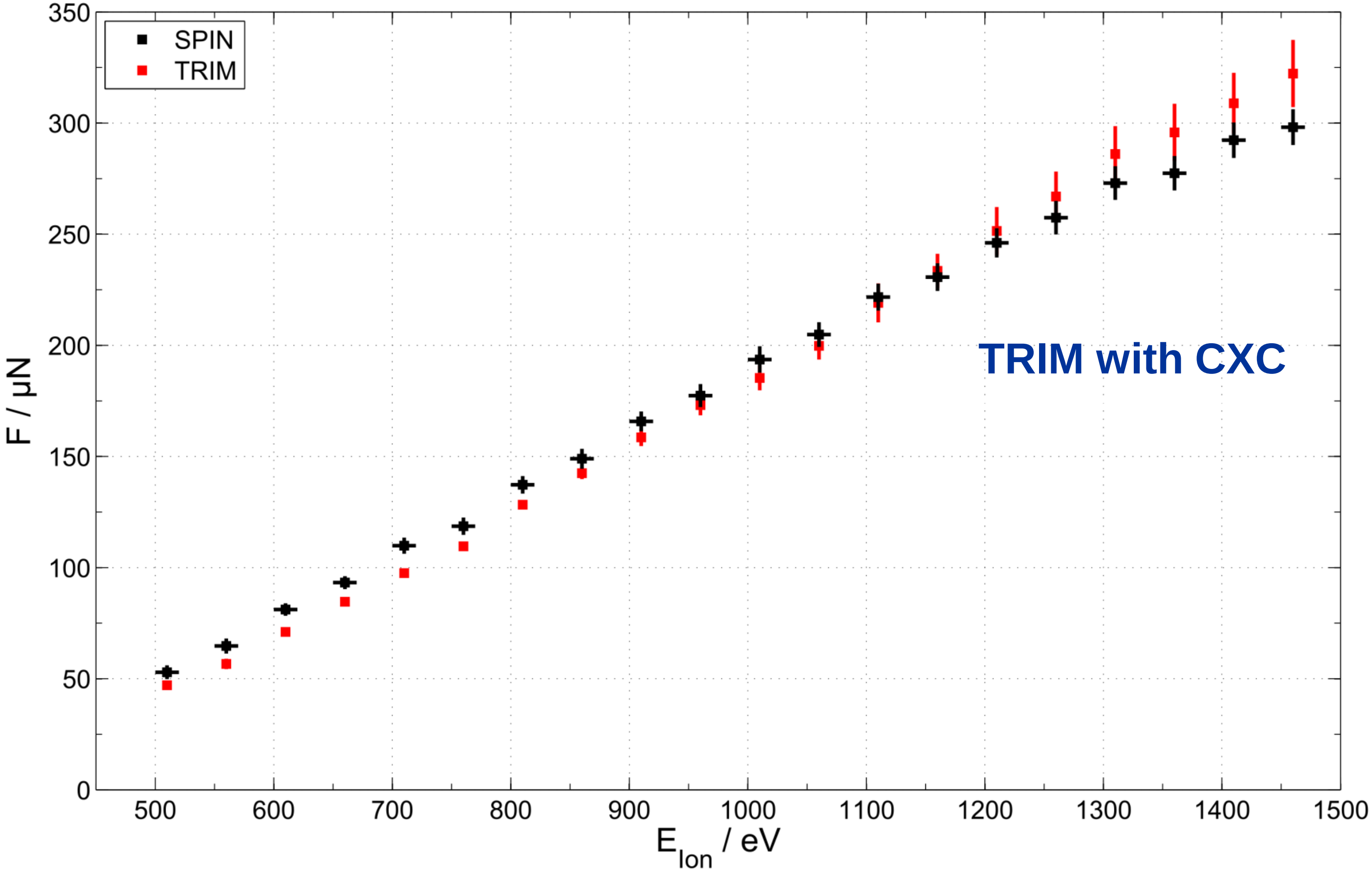
Ar - ions Cu - target β = 56° h = 26,3 cm p = 1,8e-2 Pa



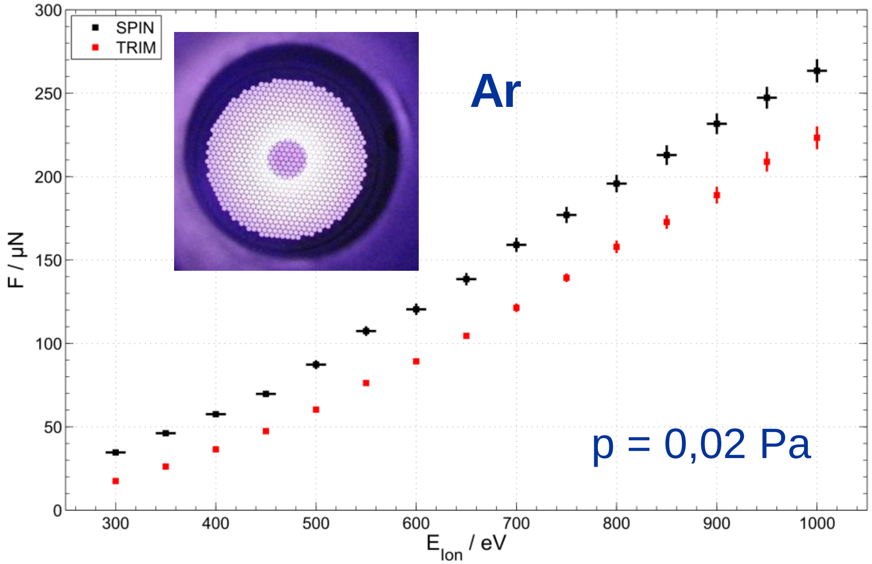
measurement of momentum transfer

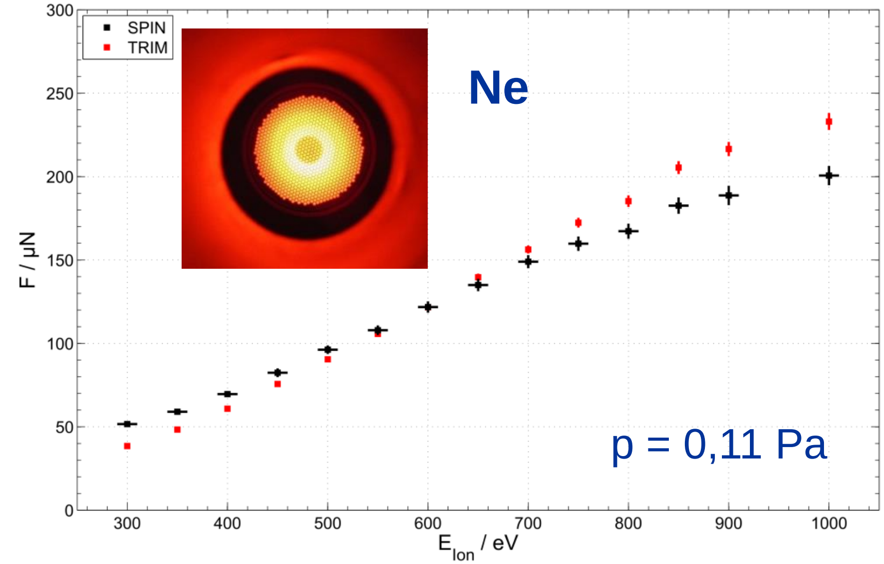
beam energy

Ar - ions Cu - target β = 56° h = 26,3 cm p = 1,8e-2 Pa



parametric study : gas / plasma

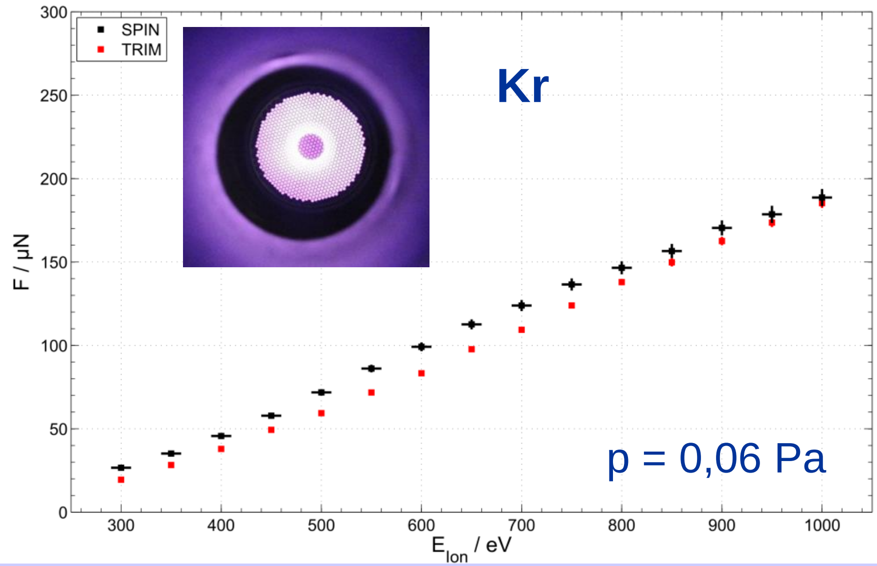




Cu target

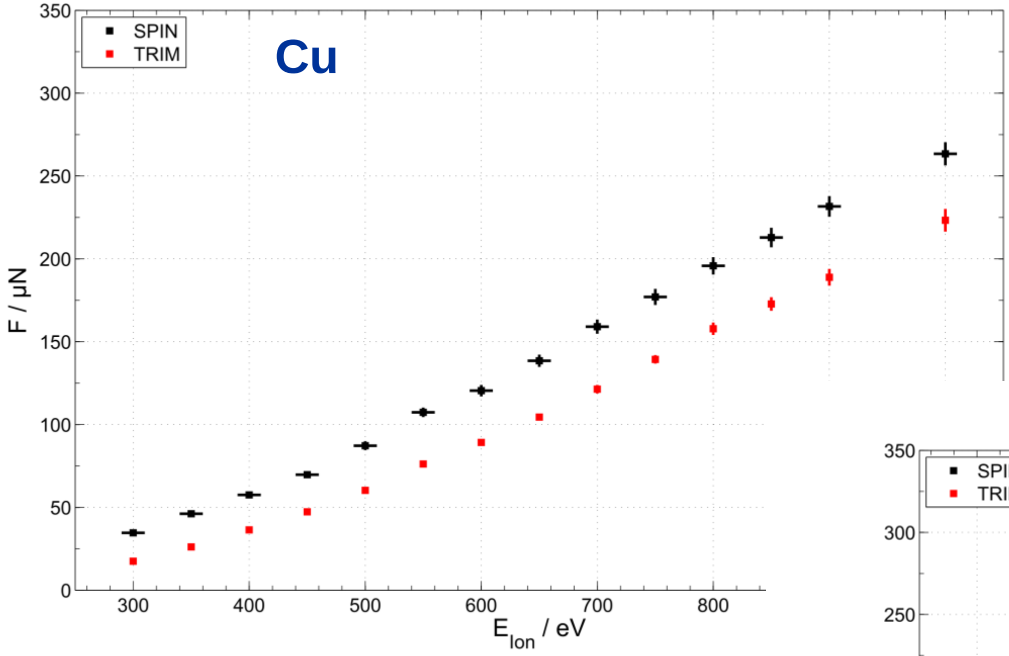
β = 56°

h = 19,2 cm



measurement of momentum transfer

target material

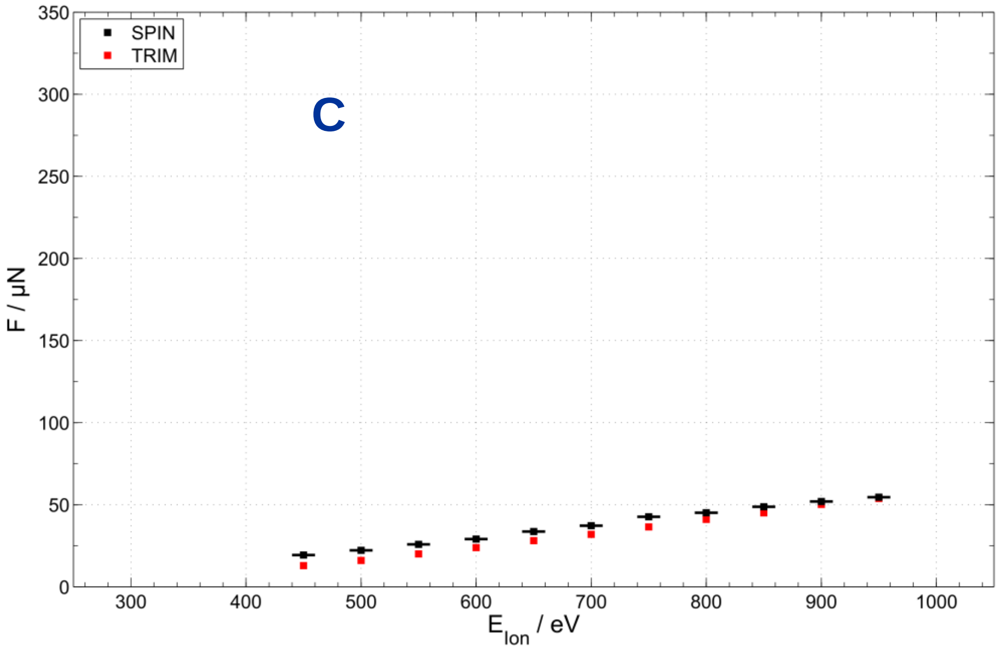


Ar - ions

β = 56°

h = 19,2 cm

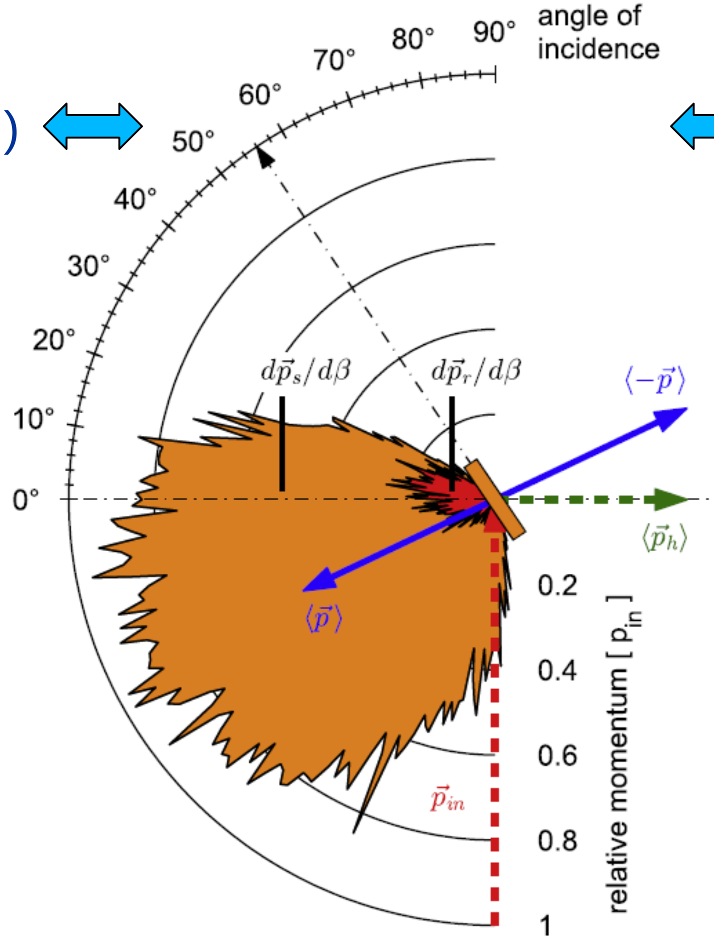
p = 1,8e-2 Pa



measurement of momentum transfer

SRIM vs. SPIN

simulation (TRIM / SRIM) ⟺



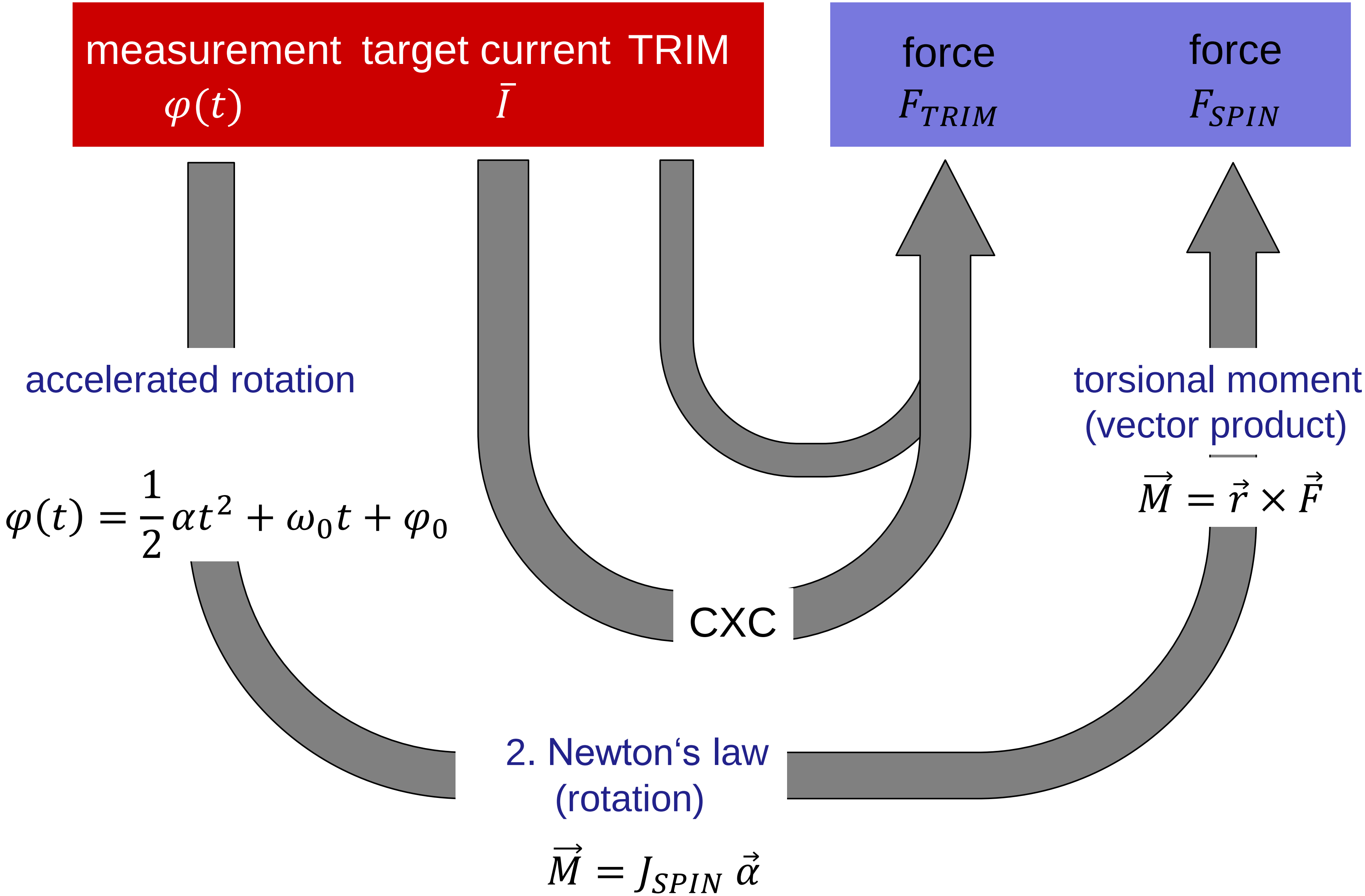
⟺ measurement (SPIN)

Spethmann, A., Trottenberg, T., Kersten, H., „Instrument for spatially resolved simultaneous measurements of forces and currents in particle beams", Rev. Sci. Instrum. ***86****(2015), 015107.*

Postprocessed simulation results based on a TRIM calculation for 100,000 argon ions with energies of 500 eV impinging on a copper target. The differential momentum of sputtered target atoms $d\vec{p}_s/d\beta$ as well as the differential momentum of reflected argon particles $d\vec{p}_r/d\beta$ were uniformly resized for better visibility.

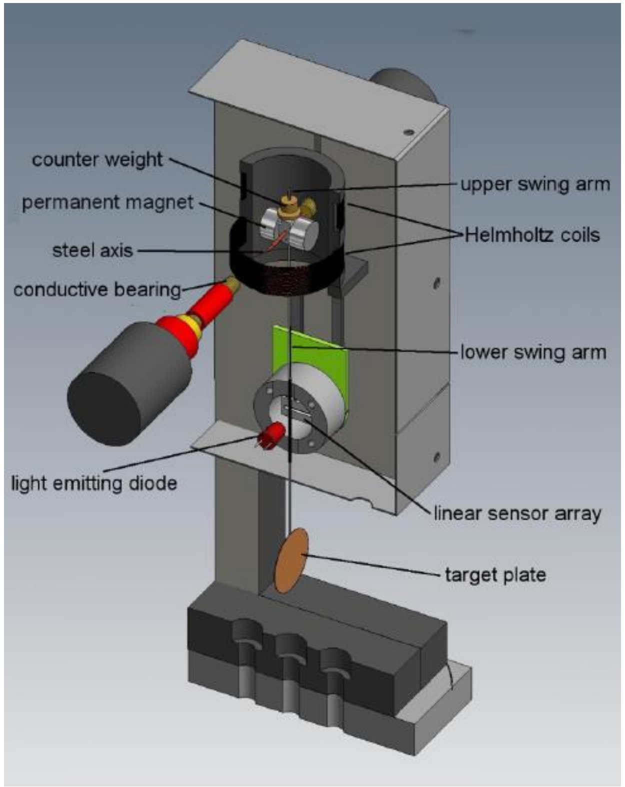
measurement of momentum transfer

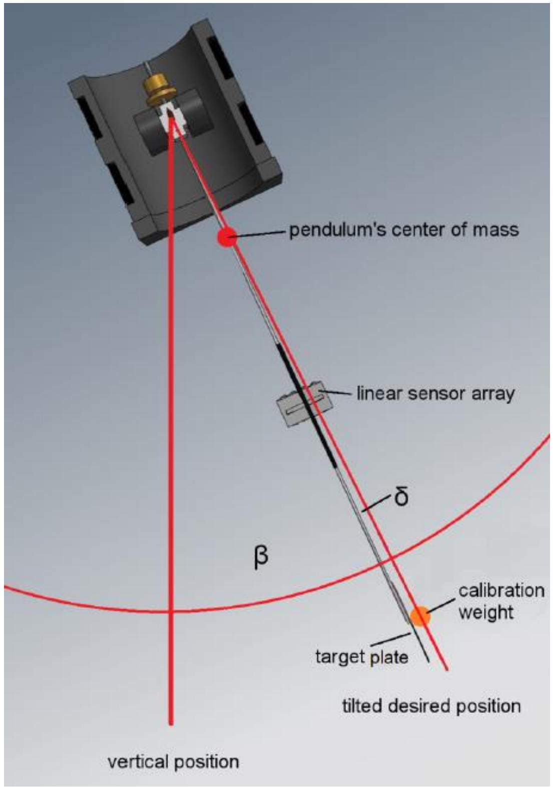
SRIM vs. SPIN



measurement of momentum transfer

- device for spatially resolved and simultaneous measurements of forces and currents in particle beams, especially in beams composed of ions and neutral atoms
- forces are exerted by the impinging beam particles on a plane circular conductive target plate mounted on a pendulum with electromagnetic force compensation
- force measurement in the µN range is achieved by electromagnetic compensation

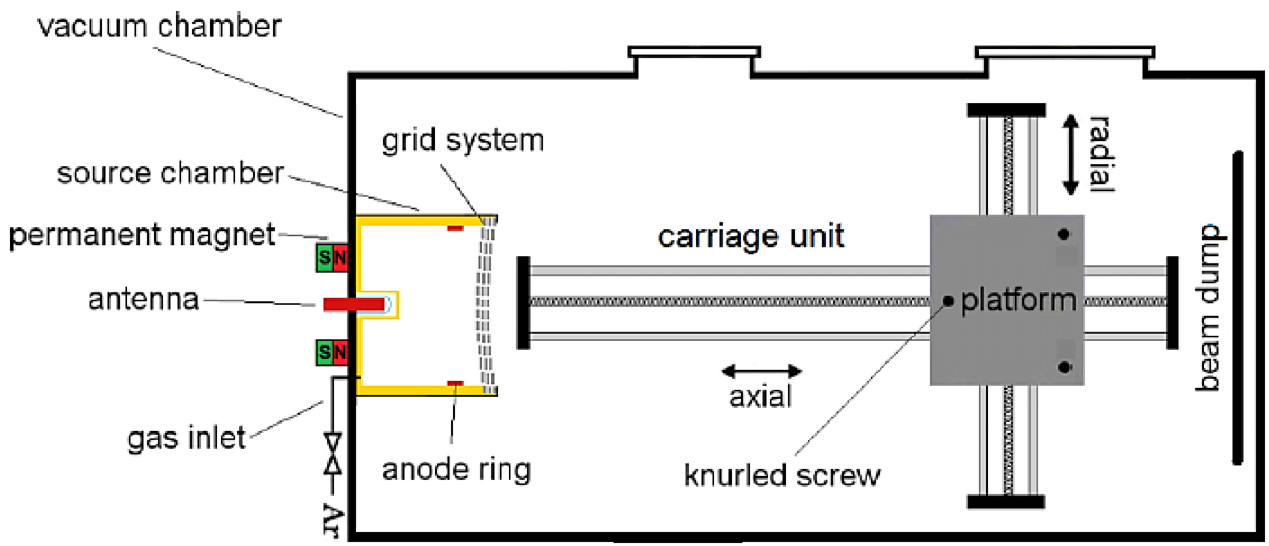


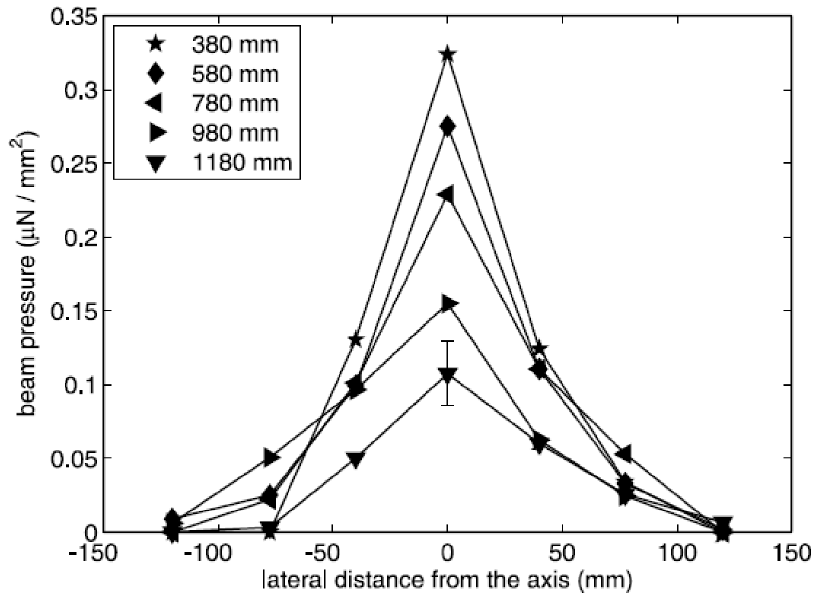


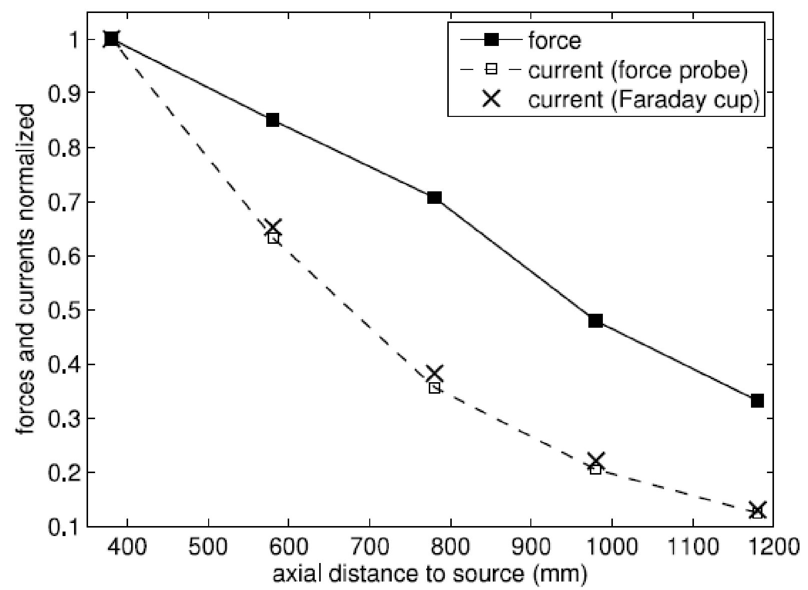
A. Spethmann, T. Trottenberg, H. Kersten
Rev. Sci. Instrum. ***86****(2015), 015107.*

measurement of momentum transfer

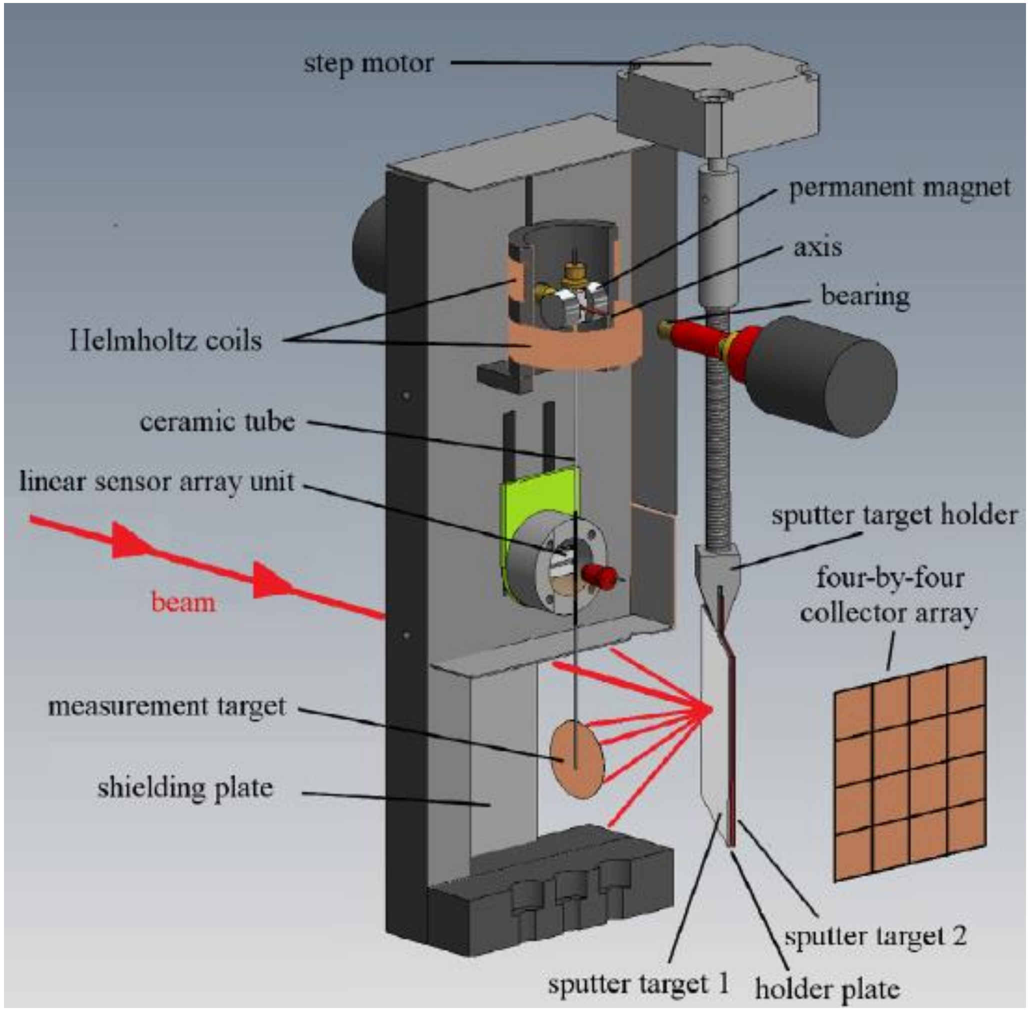
incident (primary) particles

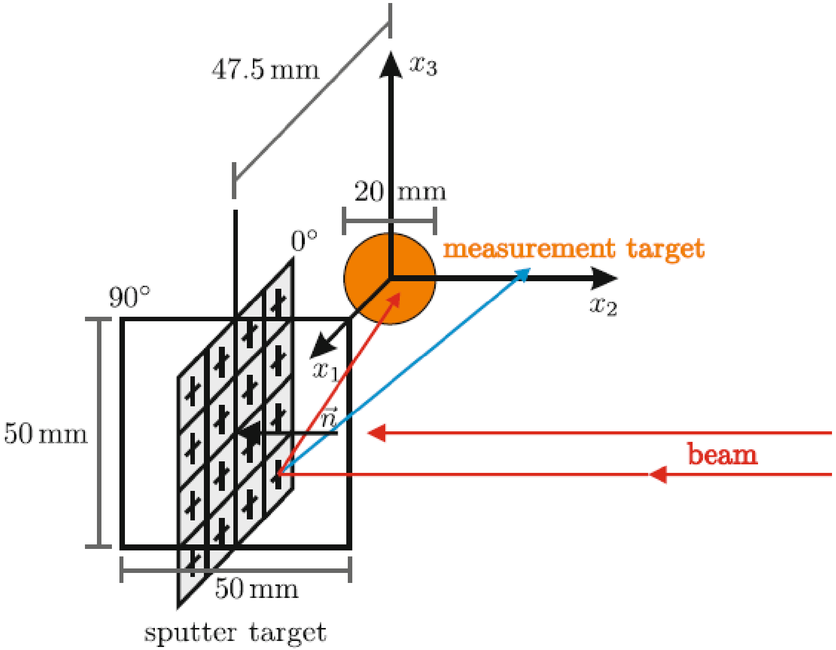




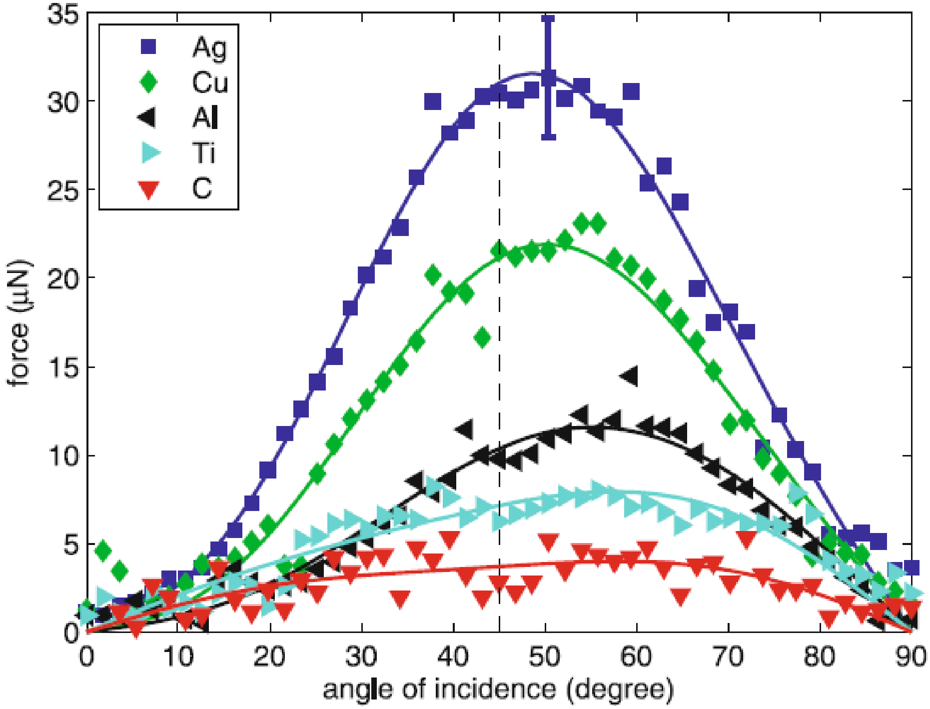


measurement of momentum transfer sputtered (secondary) particles





measurement of momentum transfer sputtered (secondary) particles

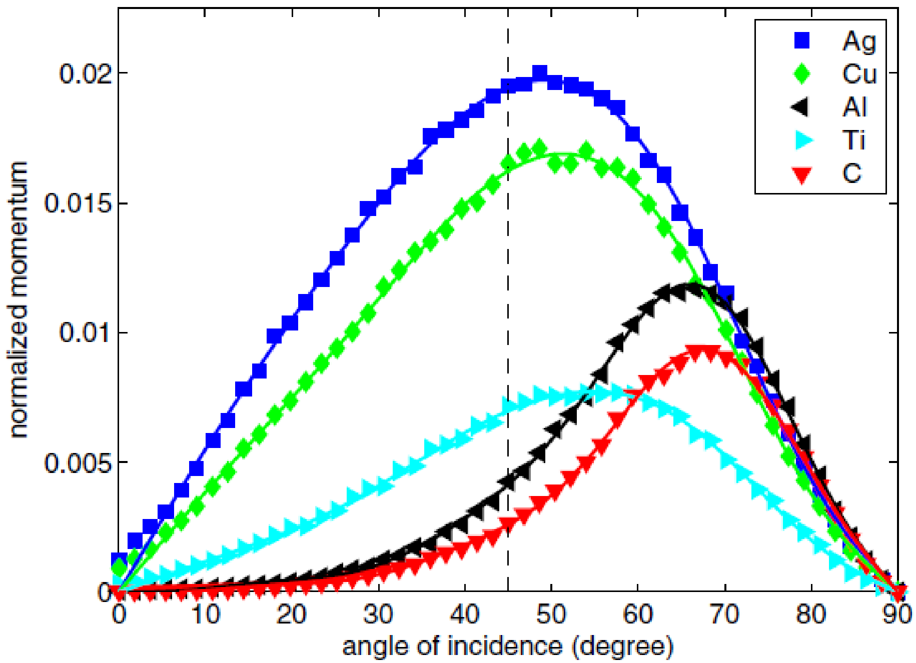


measured forces for different targets
exposed to an Ar beam with an energy of 1220 eV

Target material (mat)	Ag	Cu	Al	Ti	C
$F_{\mathrm{mat}}/F_{\mathrm{Ag}}$	1	0.71	0.32	0.20	0.09
$Y_{\mathrm{mat}}/Y_{\mathrm{Ag}}$	1	0.62	0.34	0.19	0.11

$$F(\alpha, n) = \sum_{i=1}^{n+1} c_i \sin(2i\alpha)$$

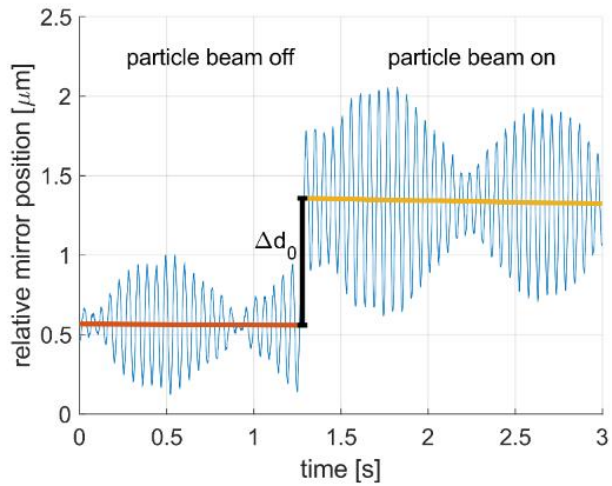
simulated momenta for different targets
exposed to an Ar beam with an energy of 1220 eV



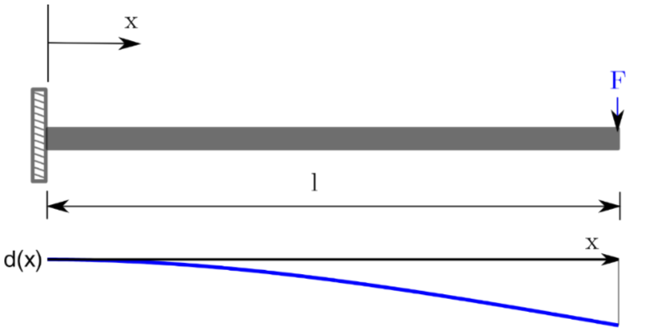
*Spethmann, A., Trottenberg, T., Kersten, H., Eur. Phys. J. D **70**(2016), 255.*

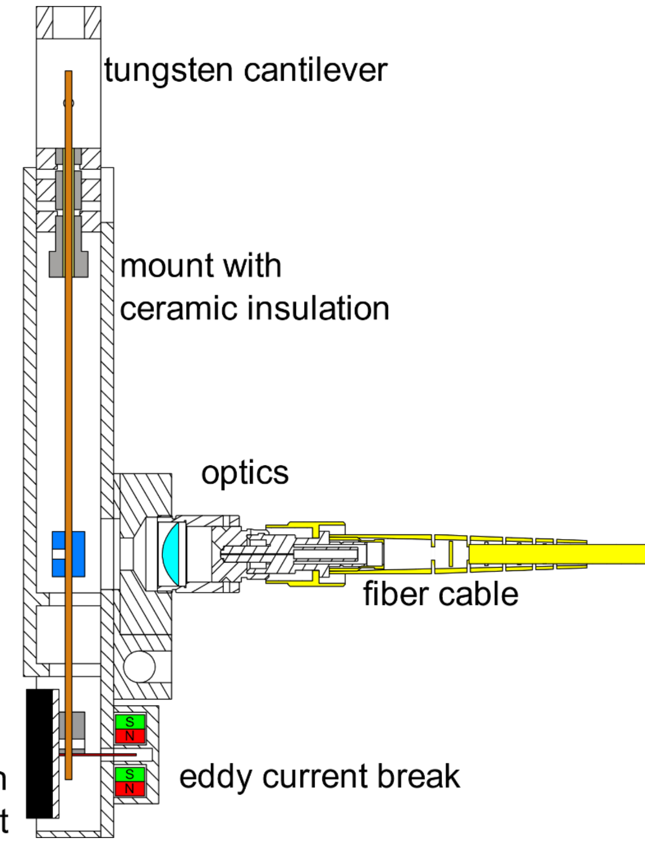
measurement of momentum transfer

interferometric measurement



New Force Probe Design





Euler–Bernoulli Beam Theory

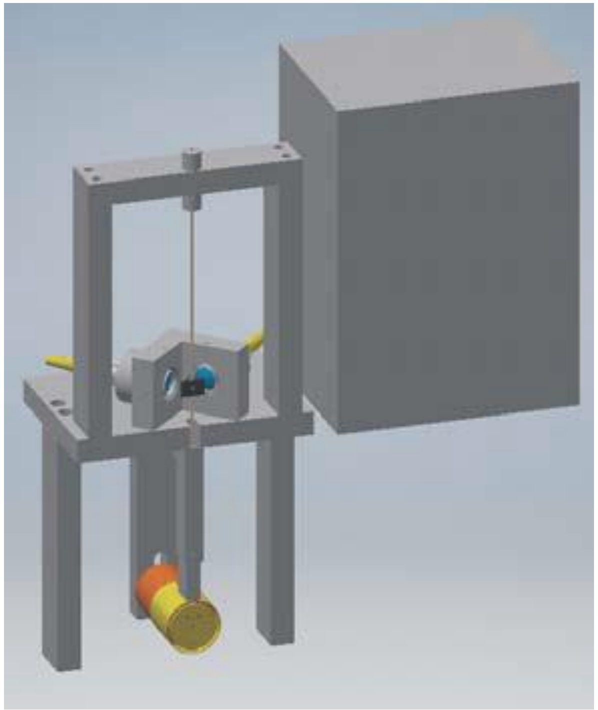
$$d(x) = \frac{Fx^2(3l - x)}{6EI}$$

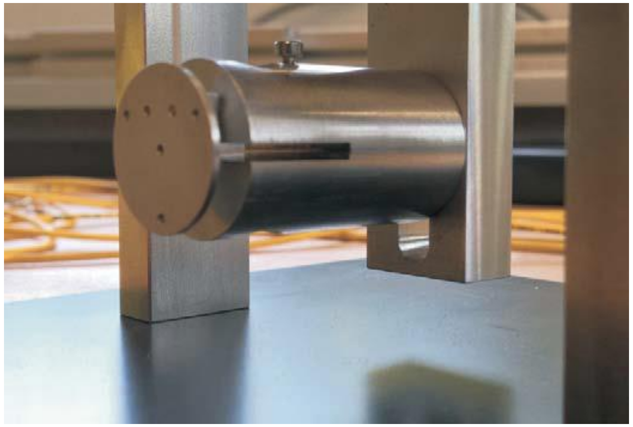
"Hooke's Law"

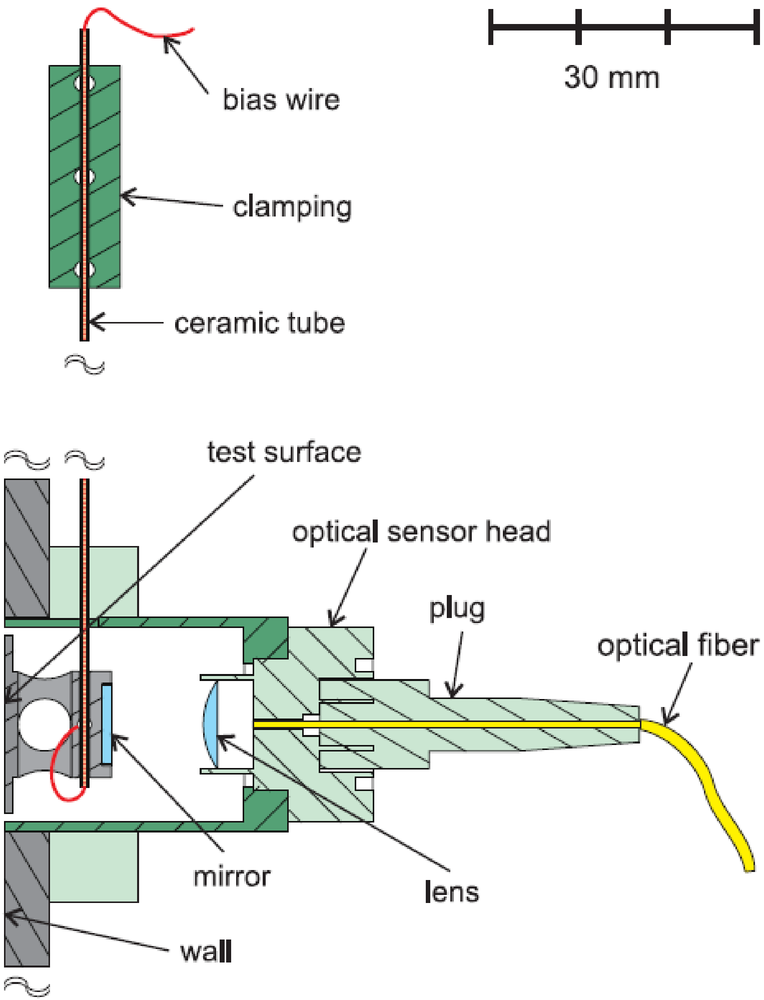
$$F = k(x_0)d_0 \text{ using } k(x) = \frac{6EI}{x^2(3l-x)}$$

measurement of momentum transfer

interferometric measurement



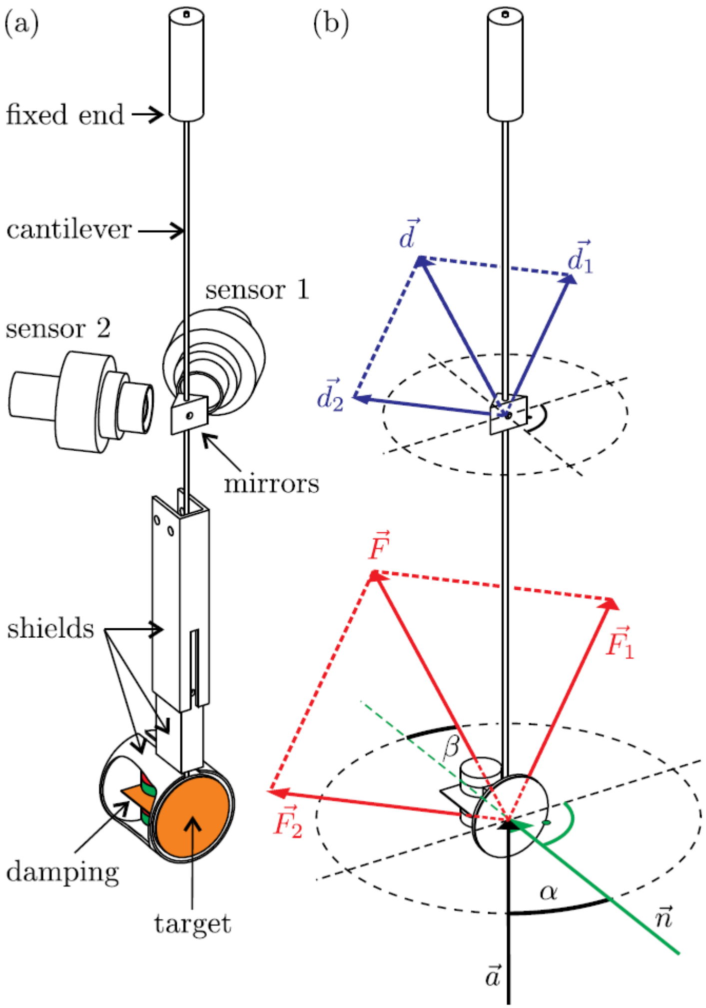


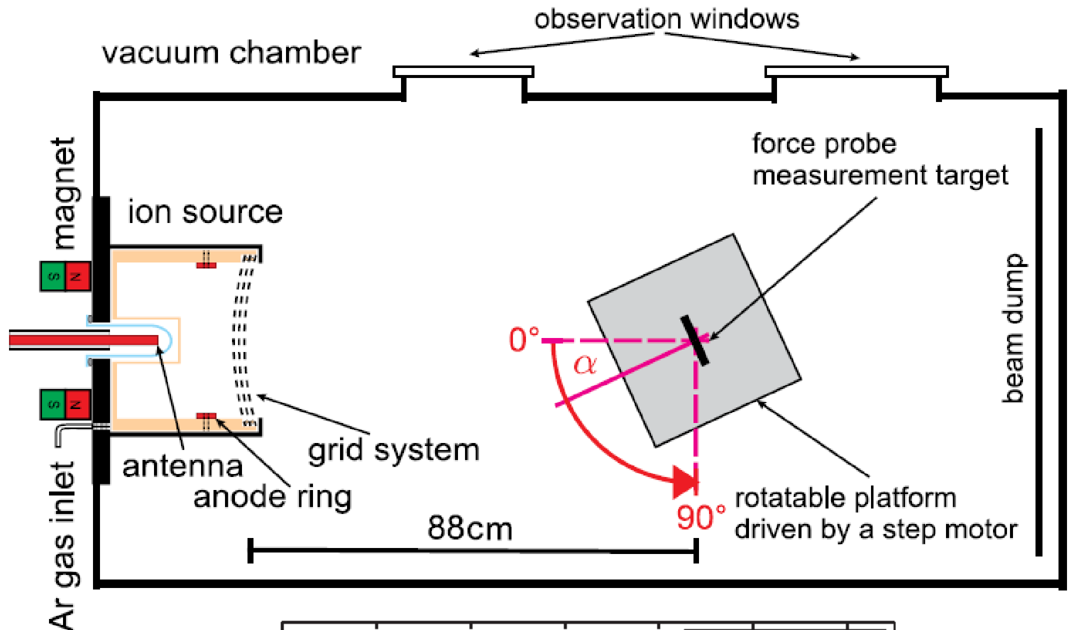


T. Trottenberg, H. Kersten,
Plasma Sources Sci. Technol. ***26****(2017), 055011.*
Trottenberg, T., Spethmann, A., Kersten, H.,
Eur. Phys. J. Techniques and Instrumentation ***5****(2018), 3.*

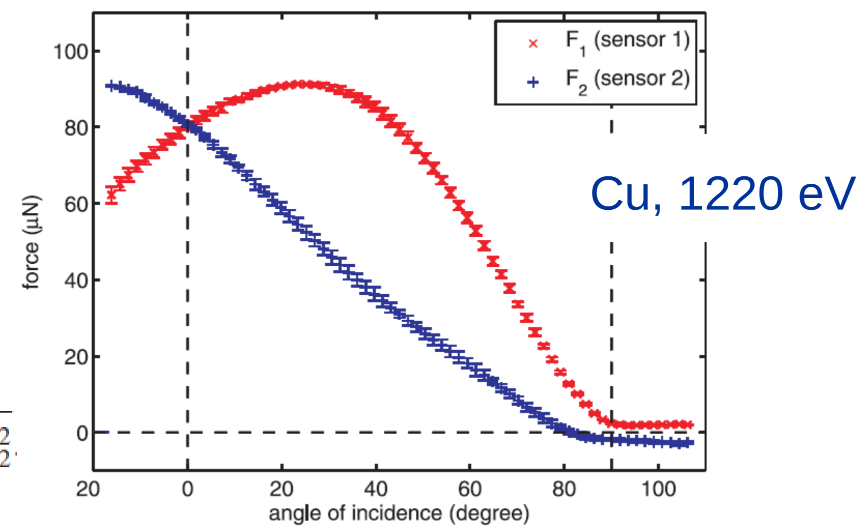
measurement of momentum transfer

interferometric measurement





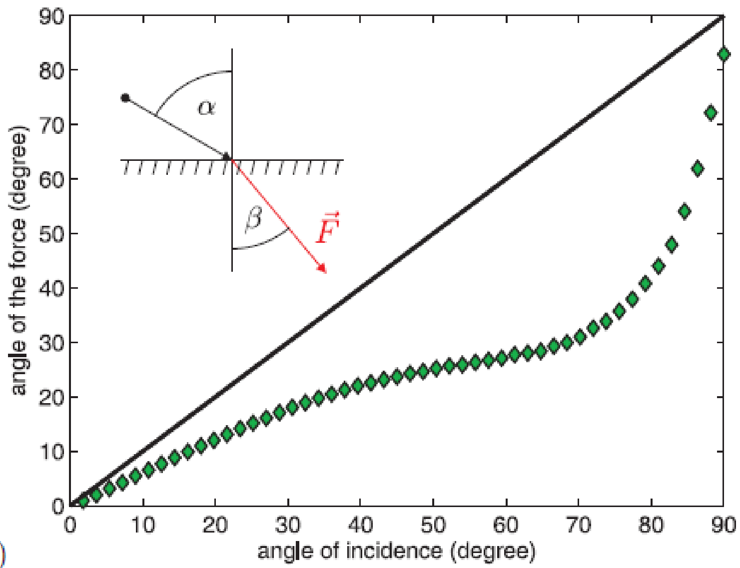
$$|\vec{F}| = \sqrt{F_1^2 + F_2^2}$$



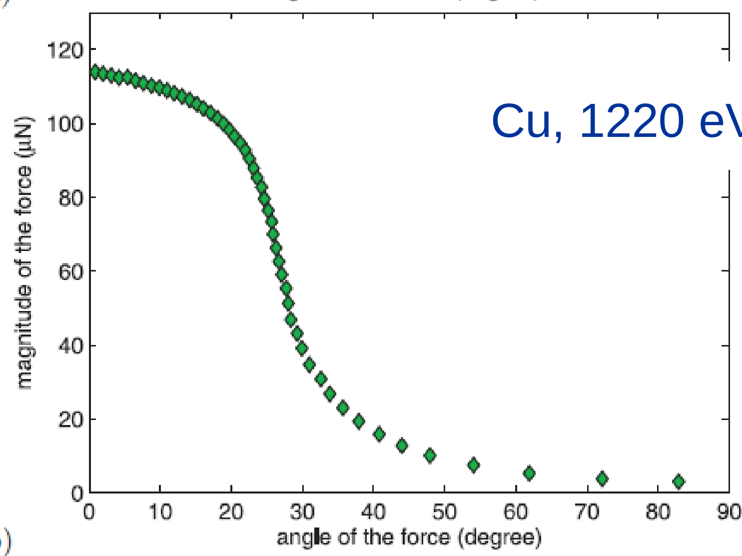
*A. Spethmann, T. Trottenberg, H. Kersten, Phys. Plasmas, **24**(2017), 093501.*

measurement of momentum transfer

by beam particles



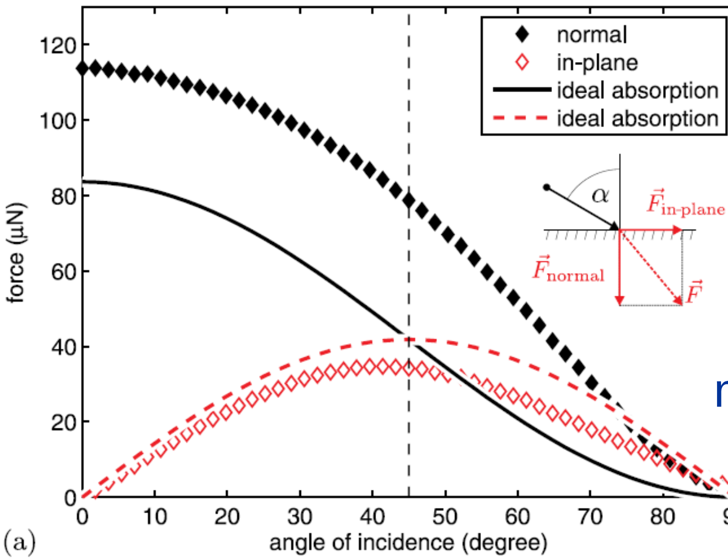
(a)



(b)

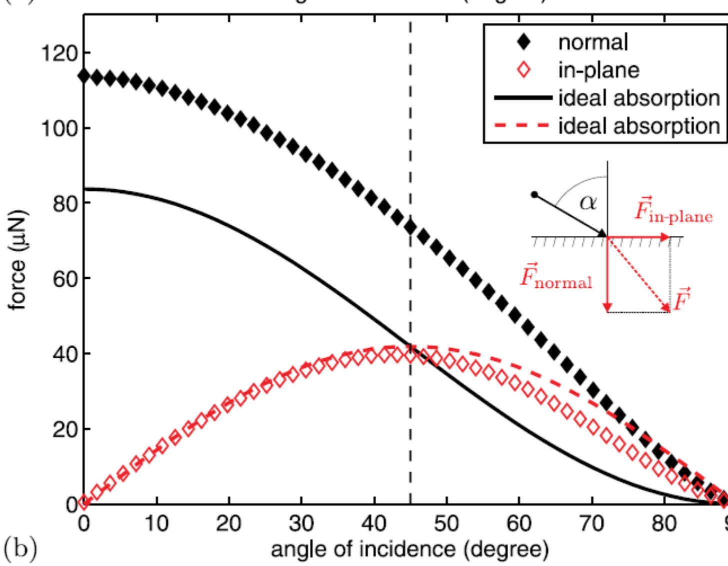
Cu, 1220 eV

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



(a)

measurement

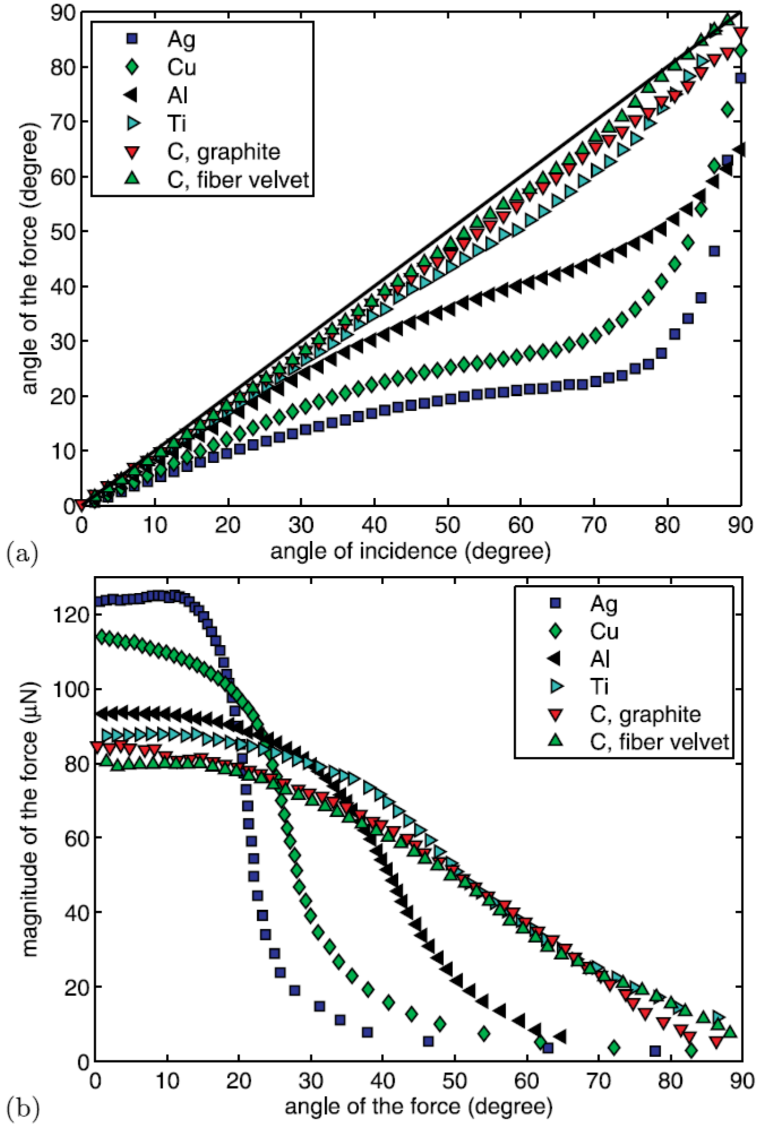


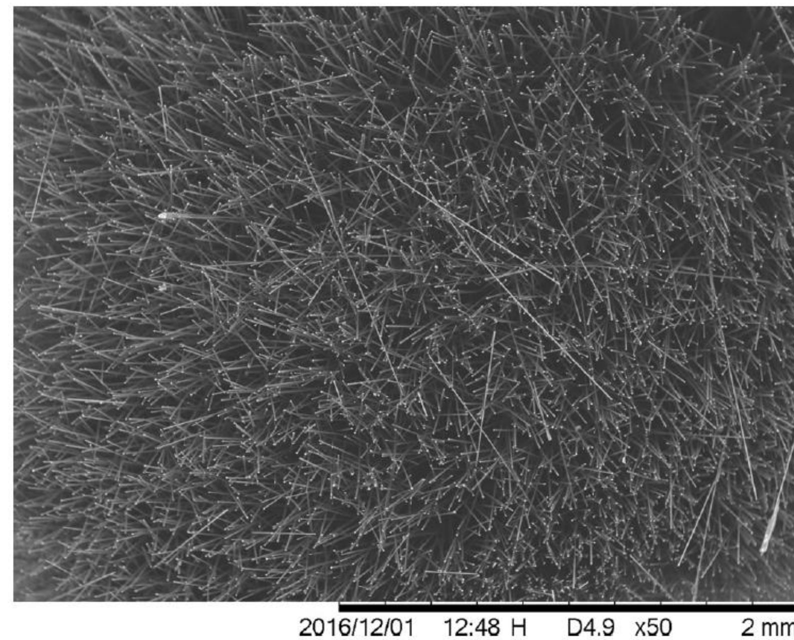
(b)

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

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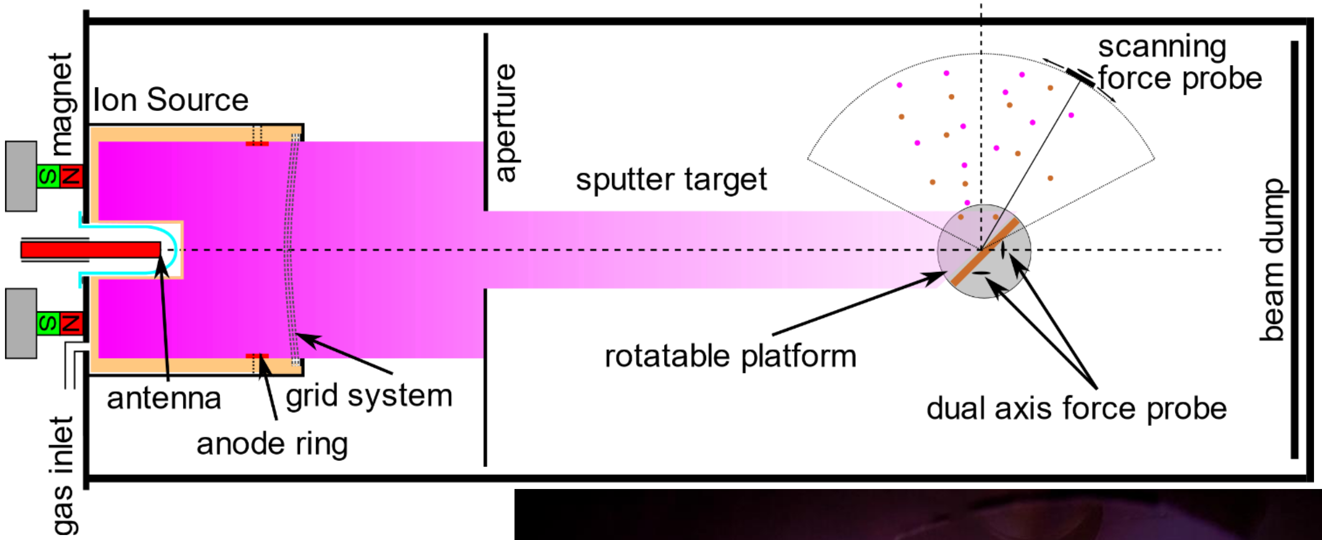
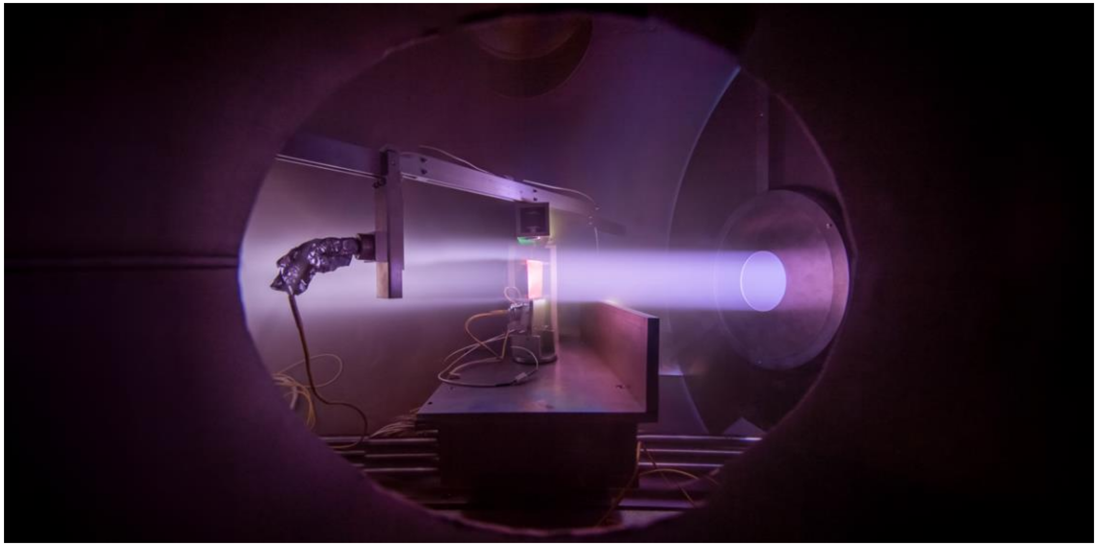
measurement of momentum transfer by sputtered particles





volume: 1.60 m, 0.65 m, 530 l

plasma source: 2.45 GHz ECR

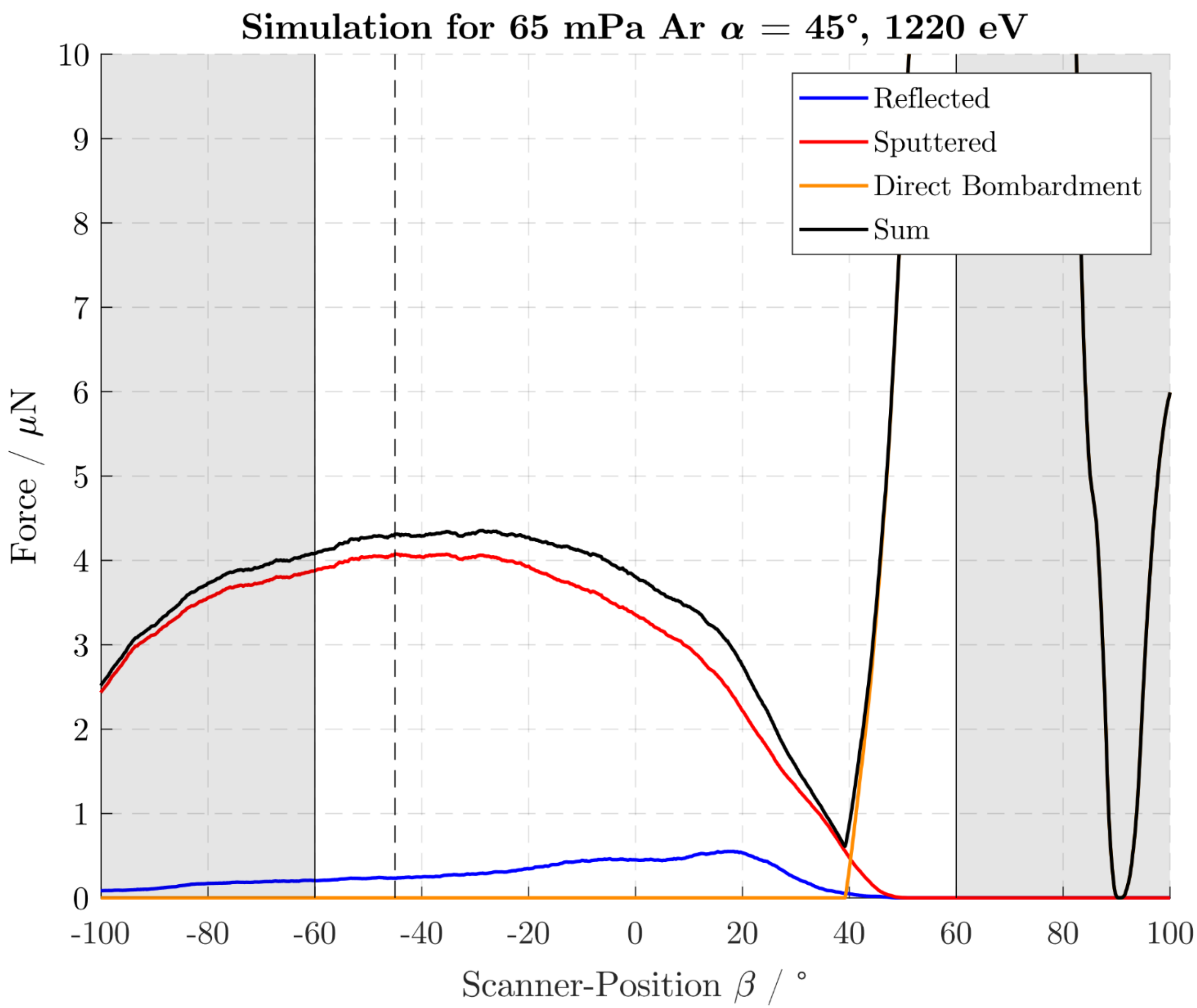
ion beam: 0 - 2000 eV, 1200 eV

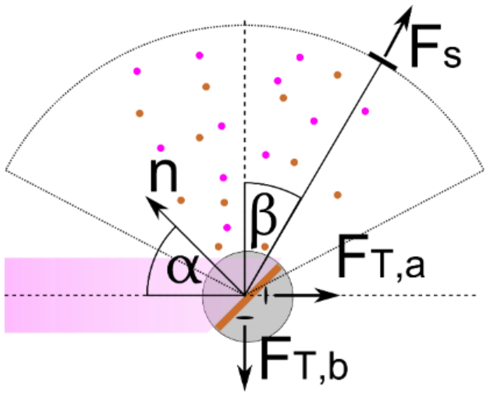
base pressure: 0,001 Pa

working pressure: 0,07 Pa, 5 sccm Ar

target: 5x5 cm copper, 50 cm distance

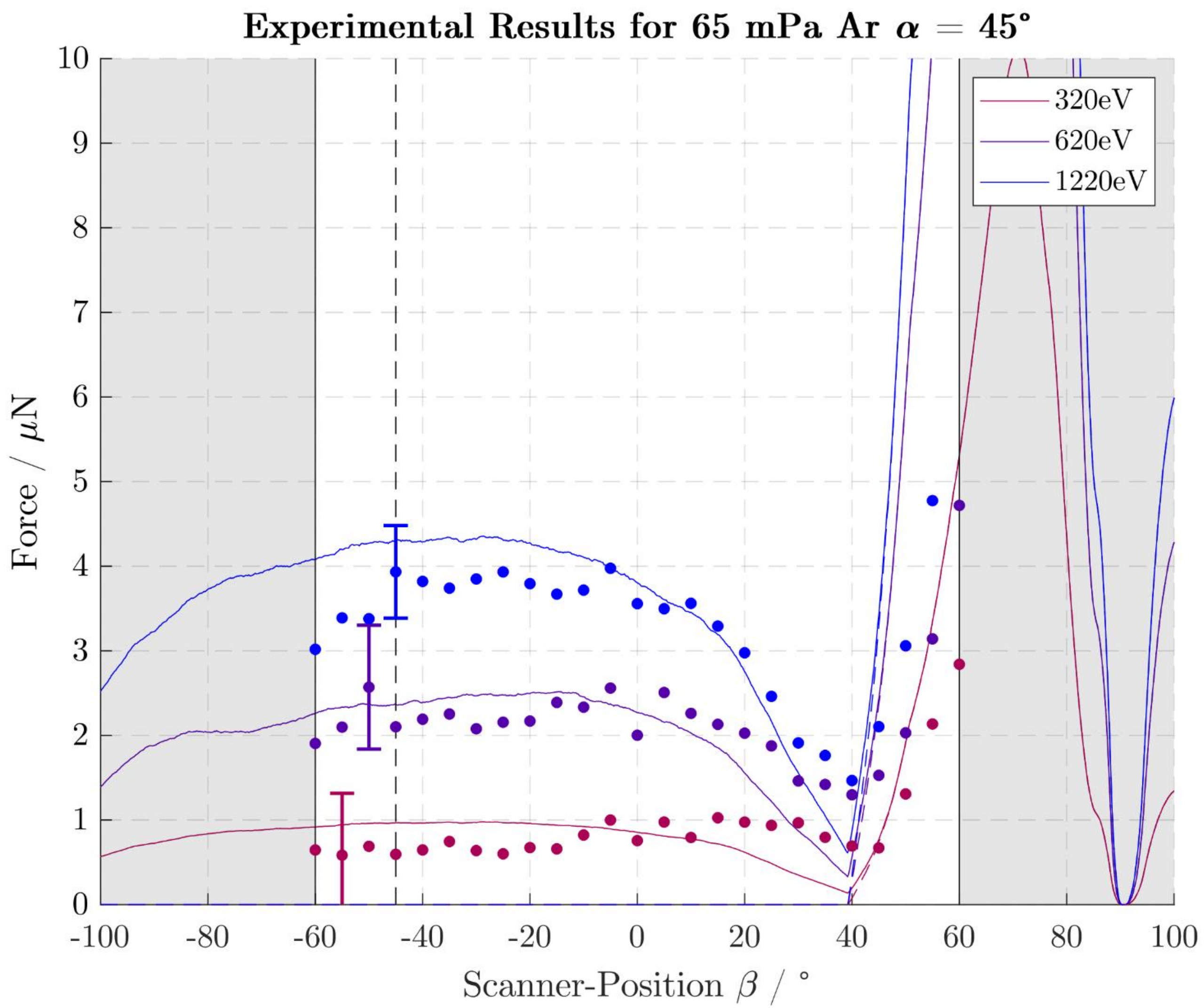
measurement of momentum transfer
by sputtered particles

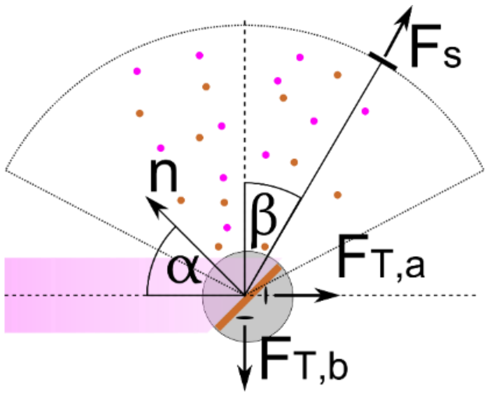




measurement of momentum transfer

by sputtered particles





summary

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• 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 (PTP)
- interferometric force probe

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

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