IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

20 Years of the Ball-Pen Probe in Fusion and Non-Fusion Research

Jiri Adamek on behalf of the team

Working team with Ball-pen probe (s)

Jiří Adámek and J. Stöckel, M. Tichý, V. Rohde, H. W. Müller, J. Gunn, G. Van Oost, A. Herrman, R. Schrittwieser, C. Ionita, J. Brotánková, F. Mehlmann, C. Silva, J. Loureiro, V. Weinzettl, J. Seidl, M. Peterka P. Balan, J. Ryszawy, J. Horáček, A. Devitre, M. Komm, Z. Pekárek, R. Pánek, I. Duran, T. Gyergyek, M. Zanáška, J. Cavalier, R. Dejarnac, G. Popa, C. Costin, S. Costea, L. van de Peppel, E. Martines, M. Spolaore, R. Cavazzana, G. Serianni, M. Zuin, H. Fernandes, H. Figueiredo, P. Duarte, P. Kudrna, M. Ramisch, U. Stroth, M. Hron, I. Ďuran, P. Vondráček, P. Ondáč, B. Nold, B. Roth, A. H. Nielsen, N. R. Walkden, A. Kirk, S. Allan, B. D. Dudson, S. Elmore, G Fishpool, J Harrison, S. Murphy-Sugrue, P. Bryant, J. W. Bradley, B. J. Harris, M Smith, M. Boušek, D. Šesták, B. Kurzan, E. Havlíčková, P. Mácha, V. Svoboda, K. Hromasová, M. Dimitrova, Tsv. K. Popov, J. Kovačič, P. Ivanova, E. Hasan, D. Lopez – Bruna, P. Bílková, P. Böhm, M. Šos, M. Aftanas, A. Havránek, I. Khodurov, J. Varju, J. Strnad, J. Vlček, J. Lovell, P. Háček, J. Krbec, S. Zoletnik. M. Berta, M. Imríšek, O. Grover, D. I. Réfy, M. Tomeš, P. Junek, N. Vianello, S. Ptak, D. Cipciar, C. Killer, T. Klinger, T. Eich,

Working team with Ball-pen probe (s)

G. Grenfell, D. Brida, G. D. Conway, T. Nishizawa, P. Manz, D. Tskhakaya, R. Pitts, T. Markovič, D. Trunec, B. G. Csillag, L. Cinnirella, J. Lips, D. Lopez – Rodriguez, D. S. Sanchez, D. Medina, H. Lindl, L. Lobko, J. Malinak, J. Hečko, S. Meshkani, M. Mahjour, G. H. S. Durr-Legoupil-Nicoud, O. Zikmund, C. Theiler, G. Bousselin, J. F. Pautex, S. Heuraux, N. Lemoine, G. Bonhomme, L. Šalamon, G. Ikovic, B. Fonda, M. Bonisolli, D. Brioschi, L. Yu-Chih, A. Kumar, T. Březina, V. Sedmidubský, K. Nosek, C. Maestracci, D. Di Matteo, Y. Nagashima, A. Fujisawa, T. Nishizawa, T. Yamada, C. Moon and more in SUMTRAIC/EMTRAIC (146 colleagues and more)

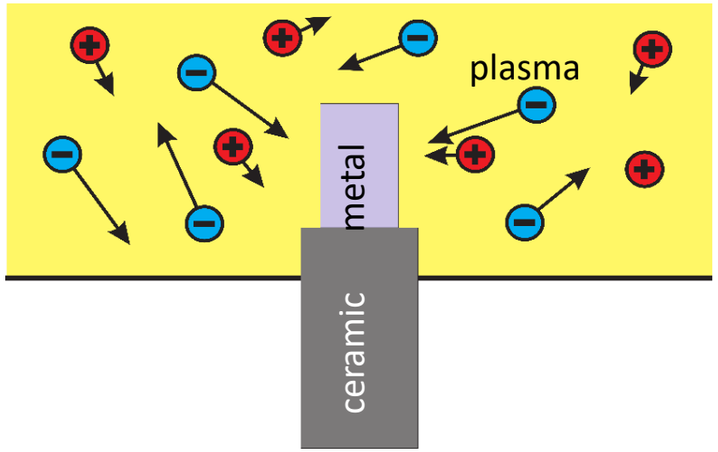
The Langmuir probe (I-V characteristic)

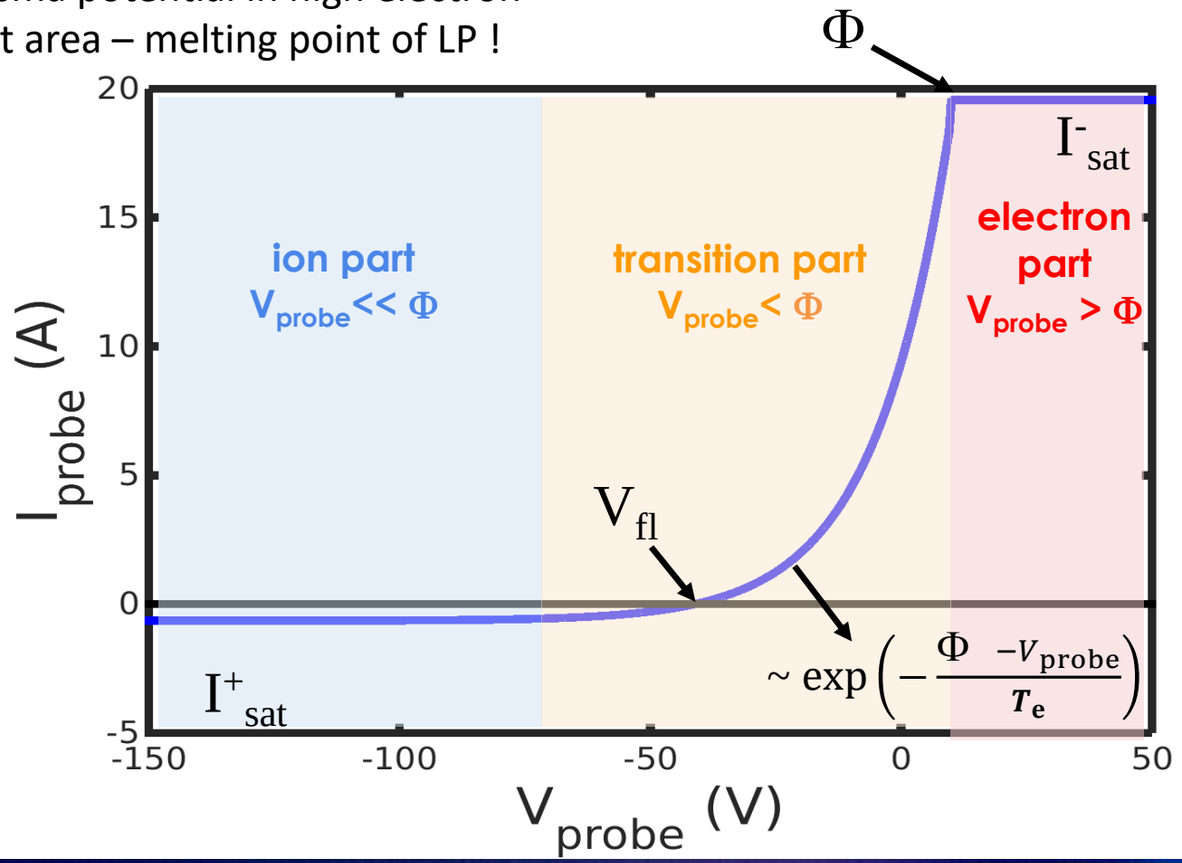
$$V_{fl} = \Phi - T_e \cdot \ln\left(\frac{I_{sat}^-}{I_{sat}^+}\right)$$

if you measure Φ

$$T_e = \frac{\Phi - V_{fl}}{\ln\left(\frac{I_{sat}^-}{I_{sat}^+}\right)}$$

The plasma potential in high electron current area – melting point of LP !

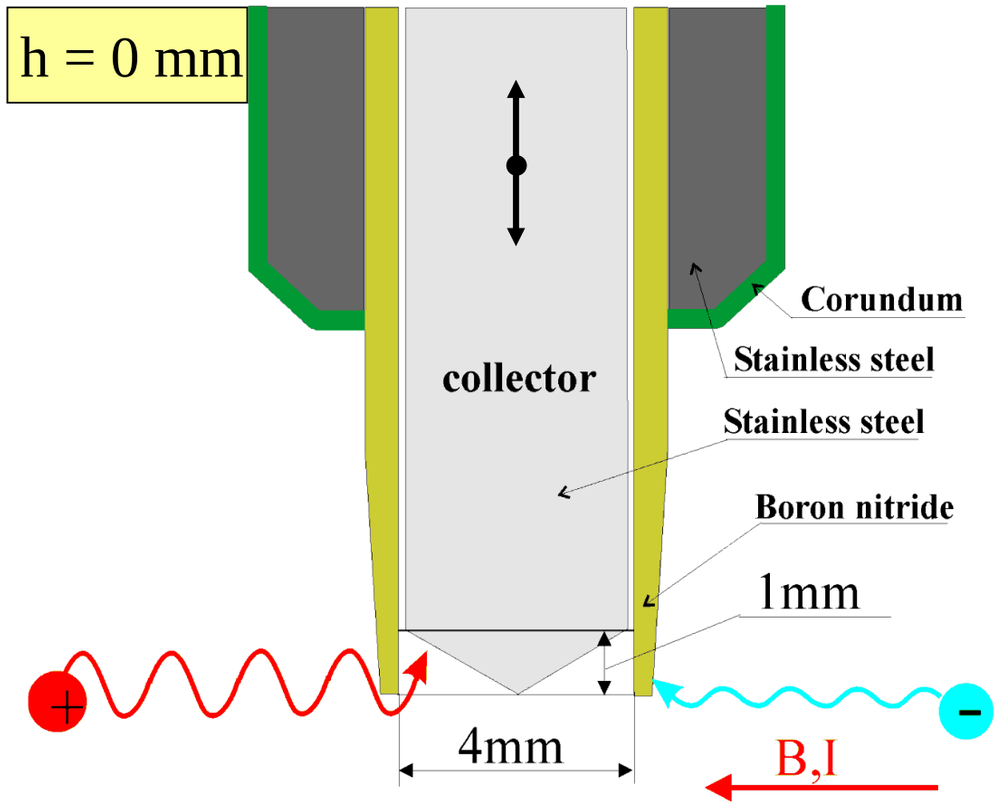




Ball-pen probe principle (BPP) (in magnetized plasmas)

$$V_{fl} = \Phi - T_e \cdot \ln\left(\frac{I_{sat}^-}{I_{sat}^+}\right)$$

$$\ln\left(\frac{j_{sat}^- \cdot A_e(h)}{j_{sat}^+ \cdot A_i(h)}\right) = 0 \;\Rightarrow\; V_{fl}^{\mathrm{BPP}} = \Phi$$



- ✓ Direct and **fast** plasma potential **Φ**
- ✓ "Direct" and **fast** electron temperature T_e

$$T_e = (\Phi - V_{fl}) / \Delta_{LP}$$

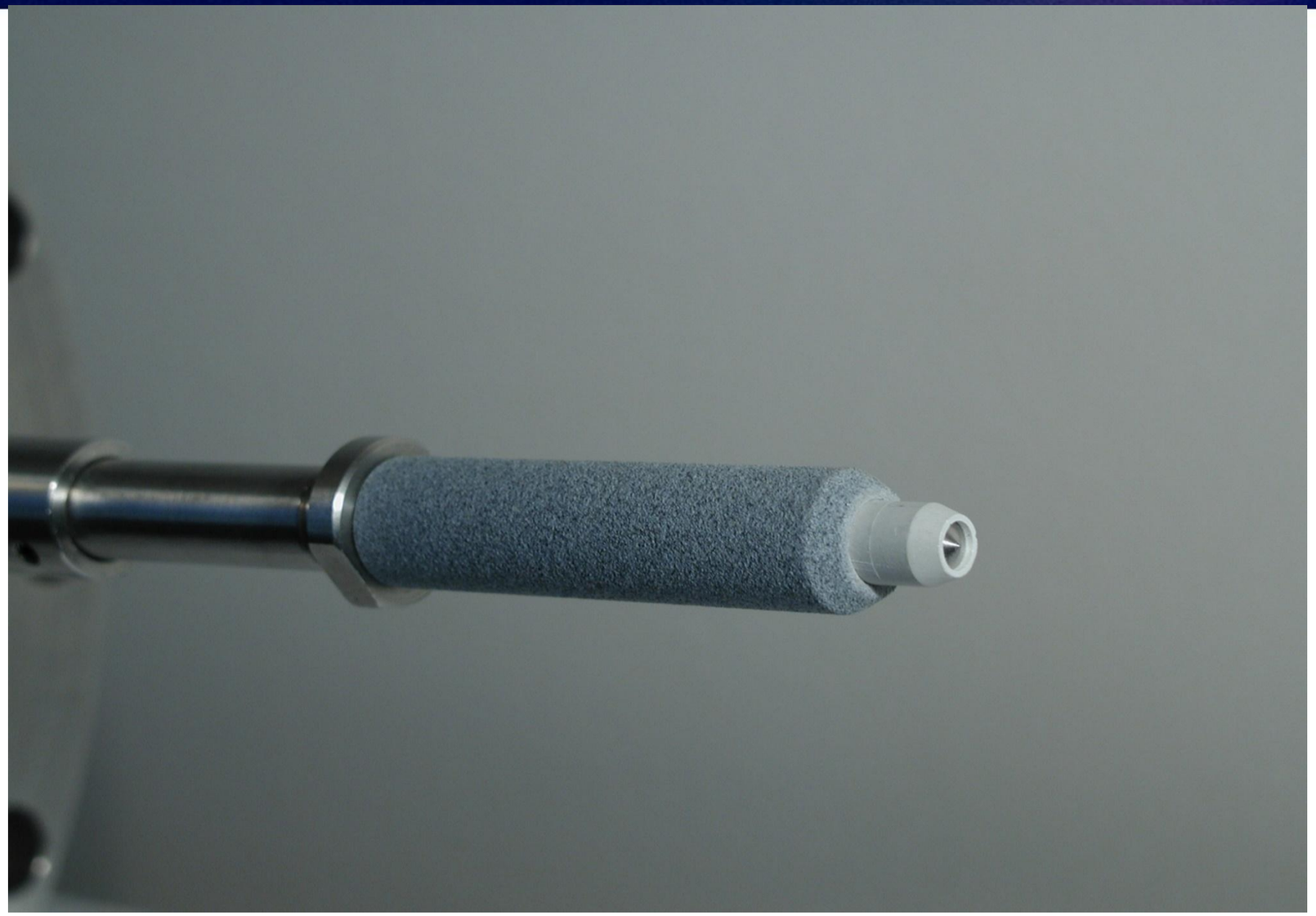
BPP LP

- ✓ "Direct" and **fast** electric field

$$E = -\nabla\Phi \text{ (two probes)}$$

- ✓ Estimation of the ion temperature T_i.

Ball-pen probe on CASTOR (2004, Prague)

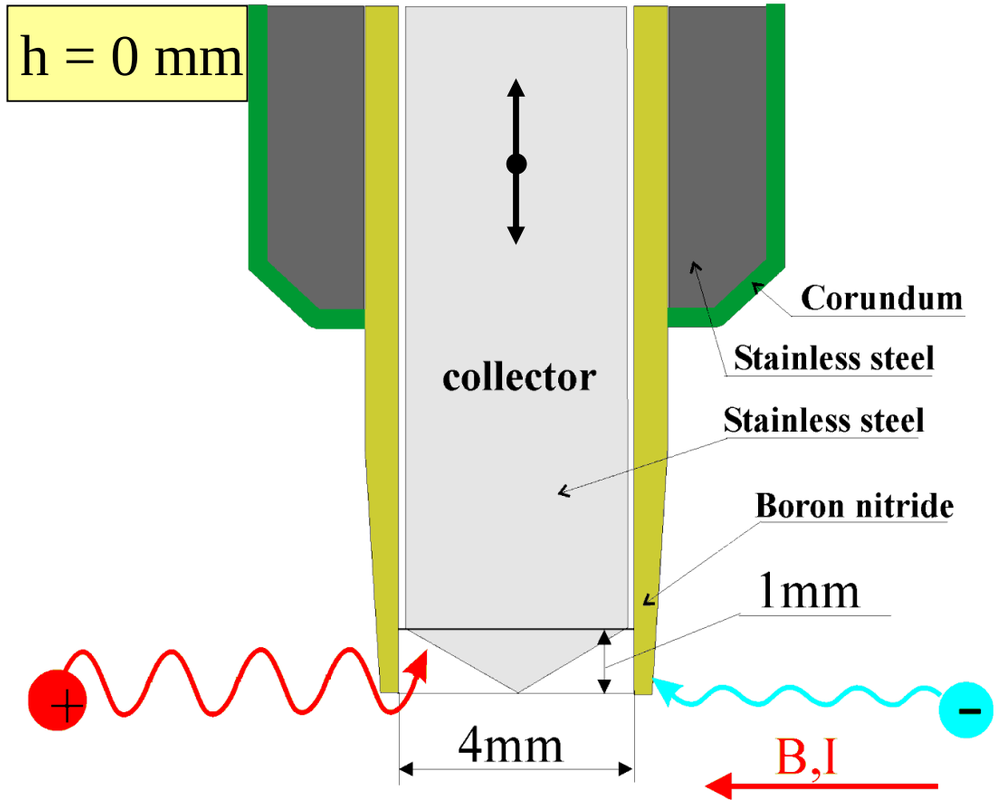


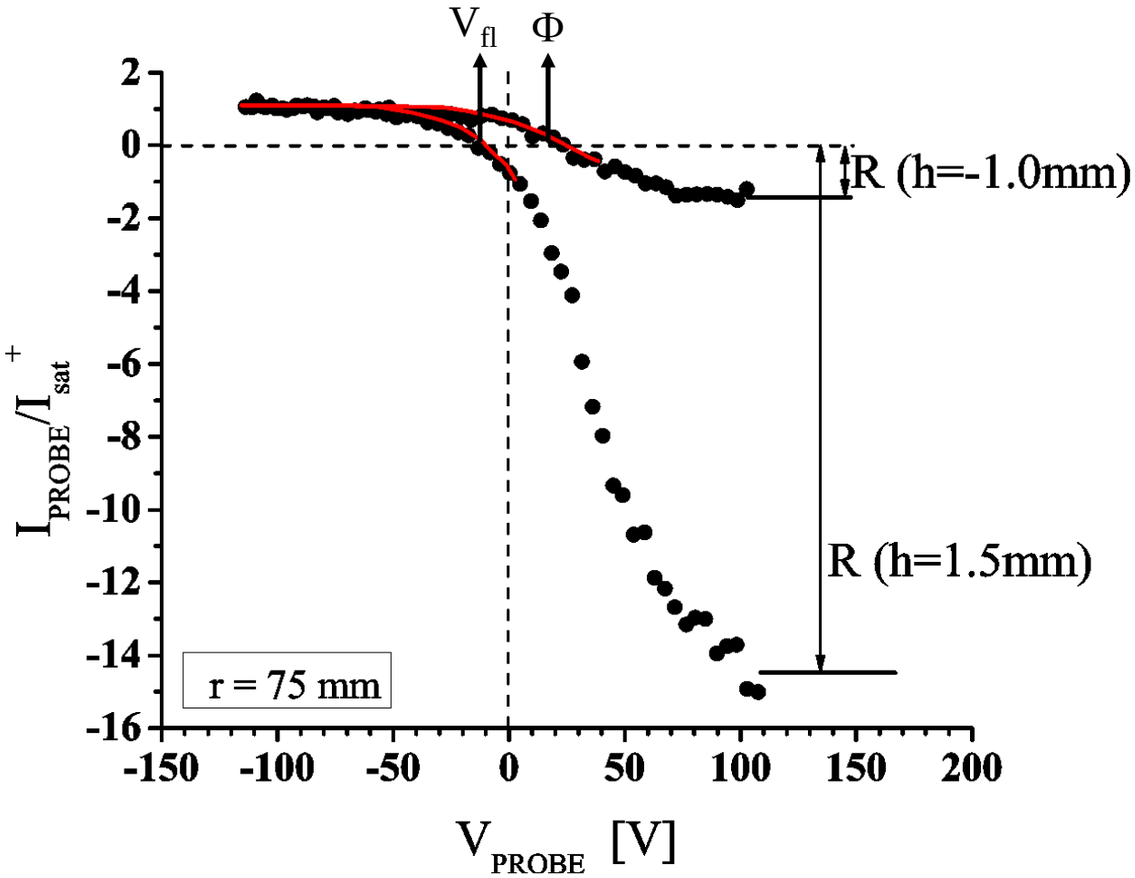
Ball-pen probe on CASTOR

(B=1 T, I_p=10 kA, R=0.4 m, r=85 mm, hydrogen plasma)

$$V_{fl} = \Phi - T_e \cdot \ln\left(\frac{I_{sat}^-}{I_{sat}^+}\right)$$

$$\ln\left(\frac{j_{sat}^- \cdot A_e(h)}{j_{sat}^+ \cdot A_i(h)}\right) = 0 \;\Rightarrow\; V_{fl}^{BPP} = \Phi$$





J. Adamek, J. Stöckel et al. *Czech J Phys*, **54** suppll.C (2004) C95-C99

Ball-pen probe on CASTOR (2004)

Adámek J., Stöckel J., Hron M., Ryszawy J., Tichý M., Schrittwieser R., Ionita C., Balan P., Martines E., Van Oost G.: A novel approach to direct measurement of the plasma potential. *Czechoslovak Journal of Physics* **54** supll.C (2004) C95-C99.

https://en.wikipedia.org/wiki/Ball-pen_probe

Ball-pen probe on RFX - Reversed field pinch (2007, Italy)

Ball-pen probes

100 mm

50 mm

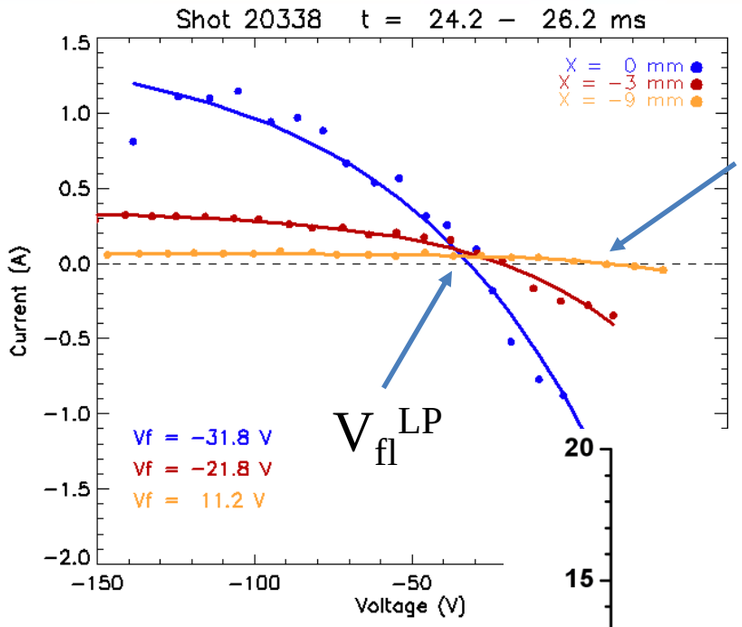
boron nitride

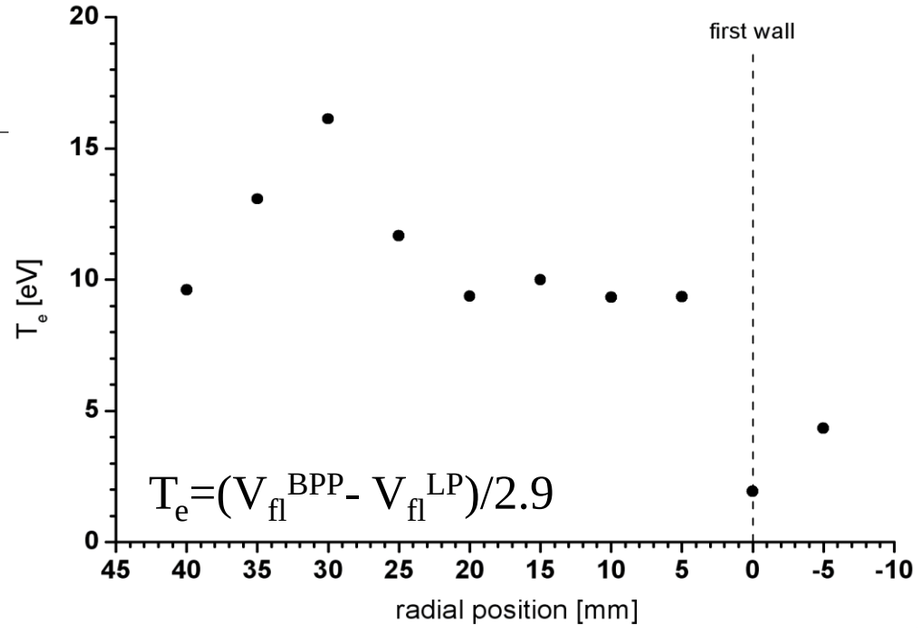
B = 0.1 T

h = 0 mm
h = -3 mm
h = -6 mm
h = -9 mm

VESPEL

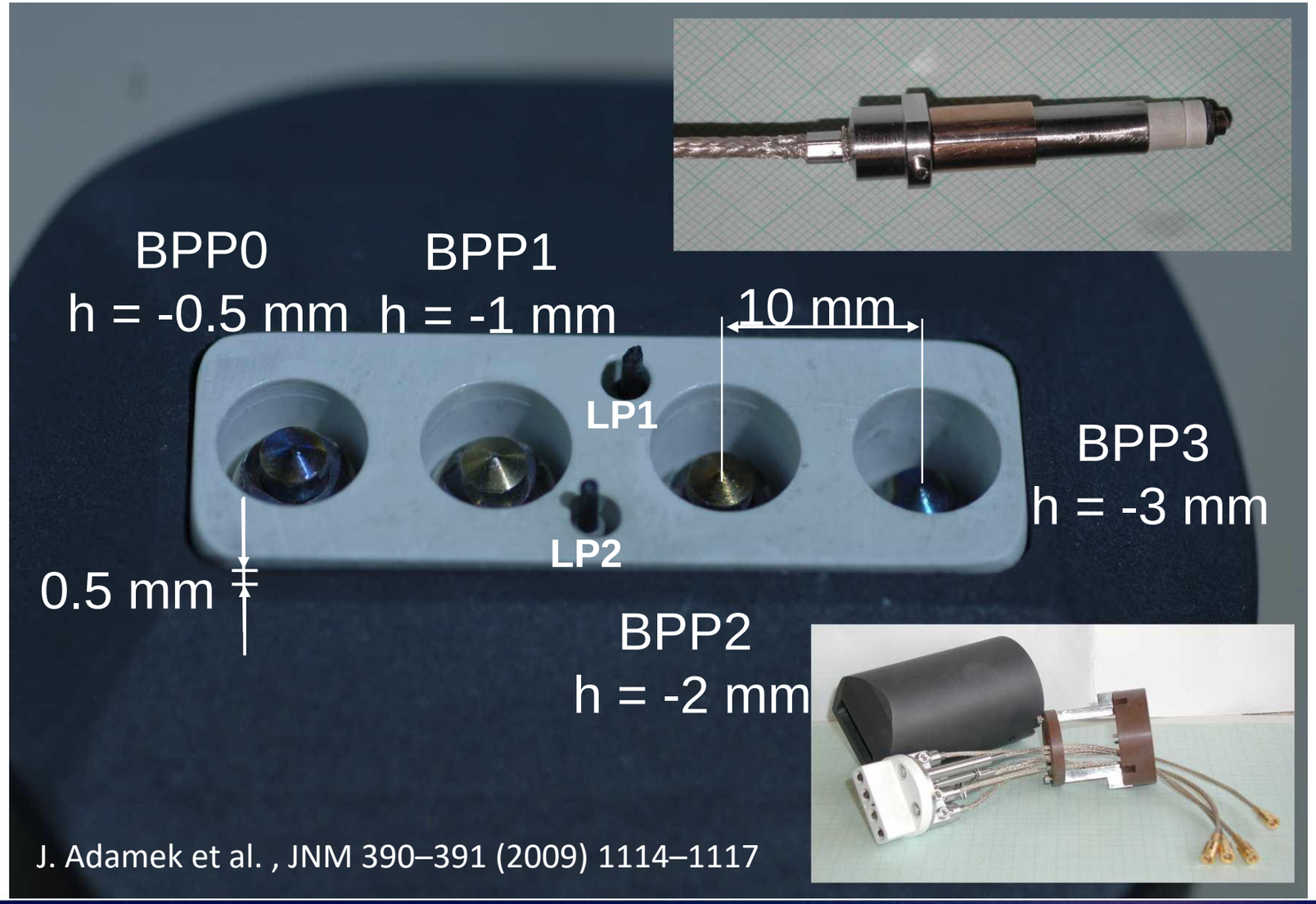
holder stainless steel



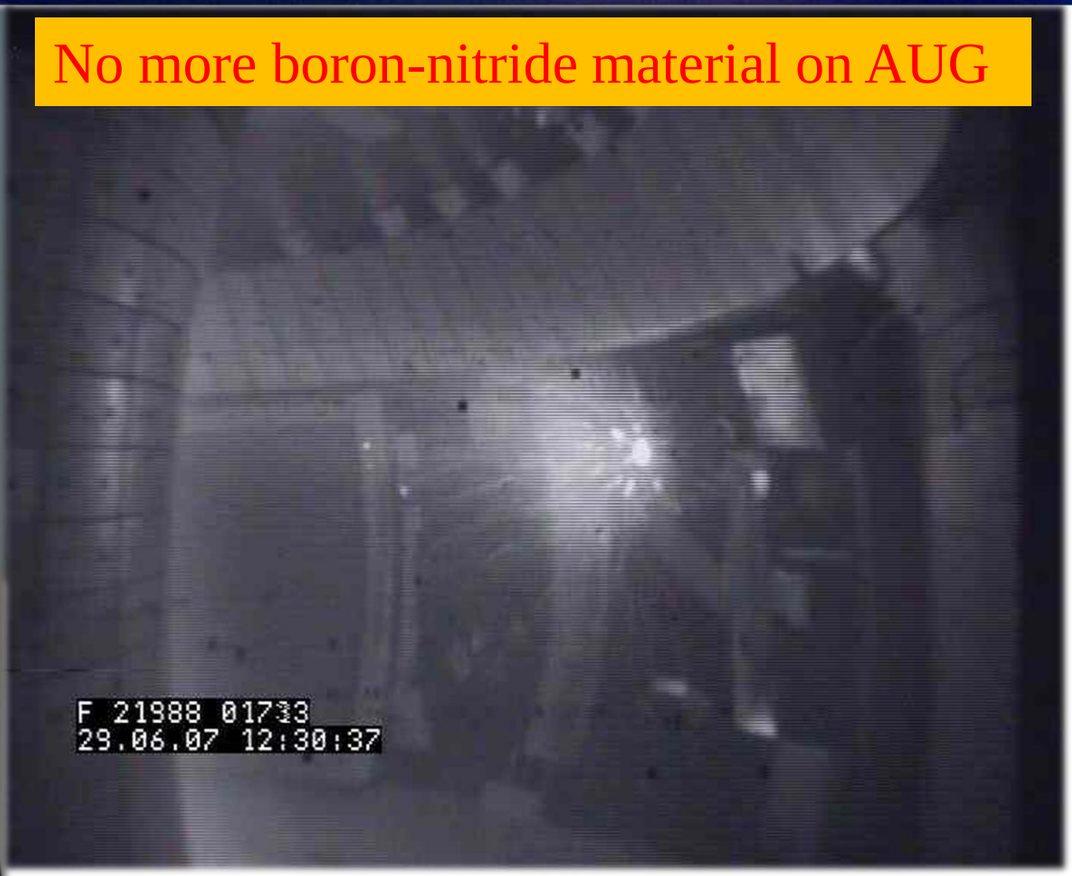


J. Brotankova et al. Voprosy Atomnoj Nauki i Tekhniki, no.1/59, p. 16-18

Ball-pen probe on ASDEX Upgrade (AUG) (2007, first design, Germany)

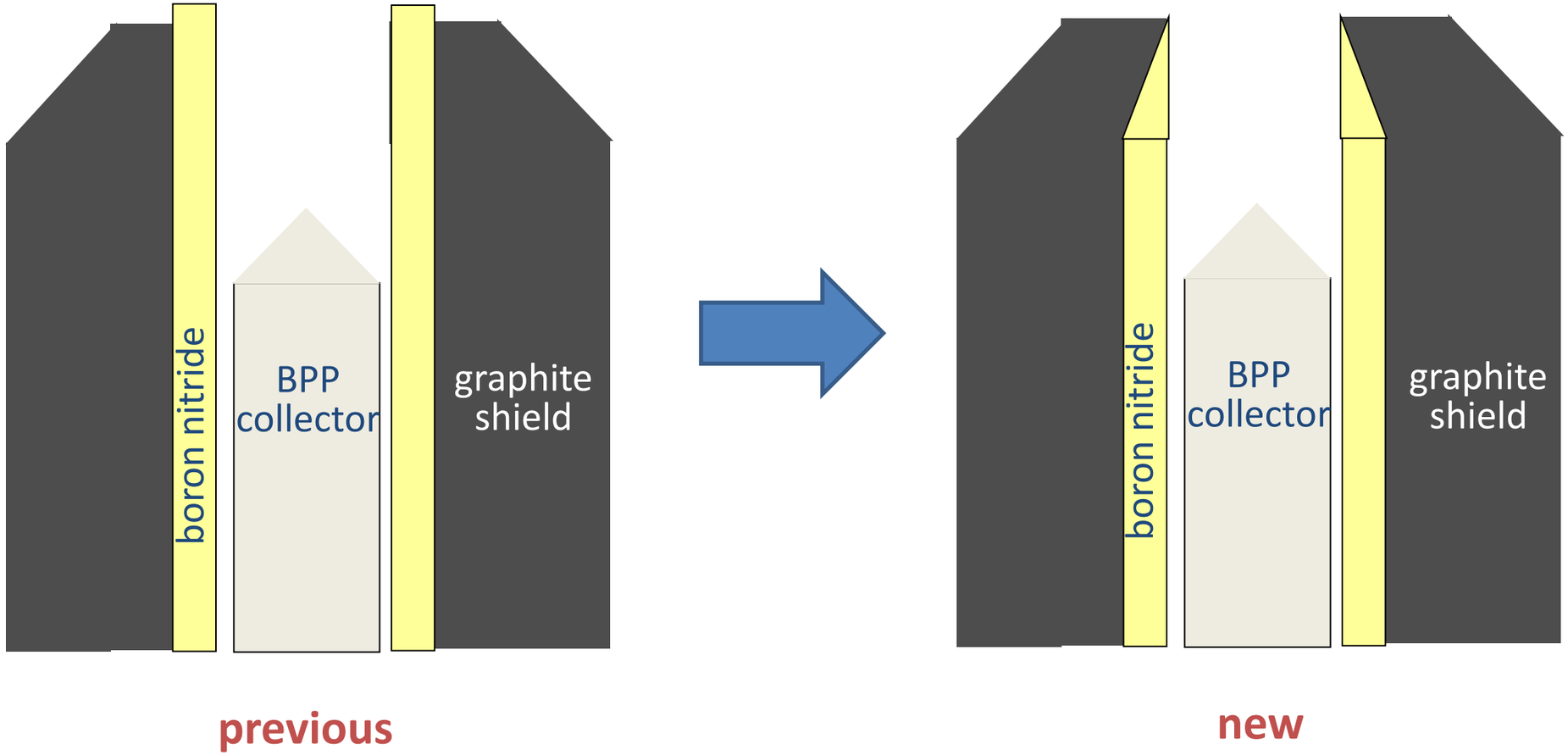


Ball-pen probe and strong erosion of material (2007, AUG)



J. Adamek, V. Rohde, H. W. Müller, A. Herrmann, C. Ionita, R. Schrittwieser, F. Mehlmann, J. Stöckel, J. Horacek, J. Brotankova, ASDEX Upgrade Team, “Direct measurements of the plasma potential in ELMy H-mode plasma with ball-pen probes on ASDEX Upgrade tokamak”, Journal of Nuclear Materials, Volumes 390–391, 15 June 2009, Pages 1114-1117.

Ball-pen probe head - new design



previous

new

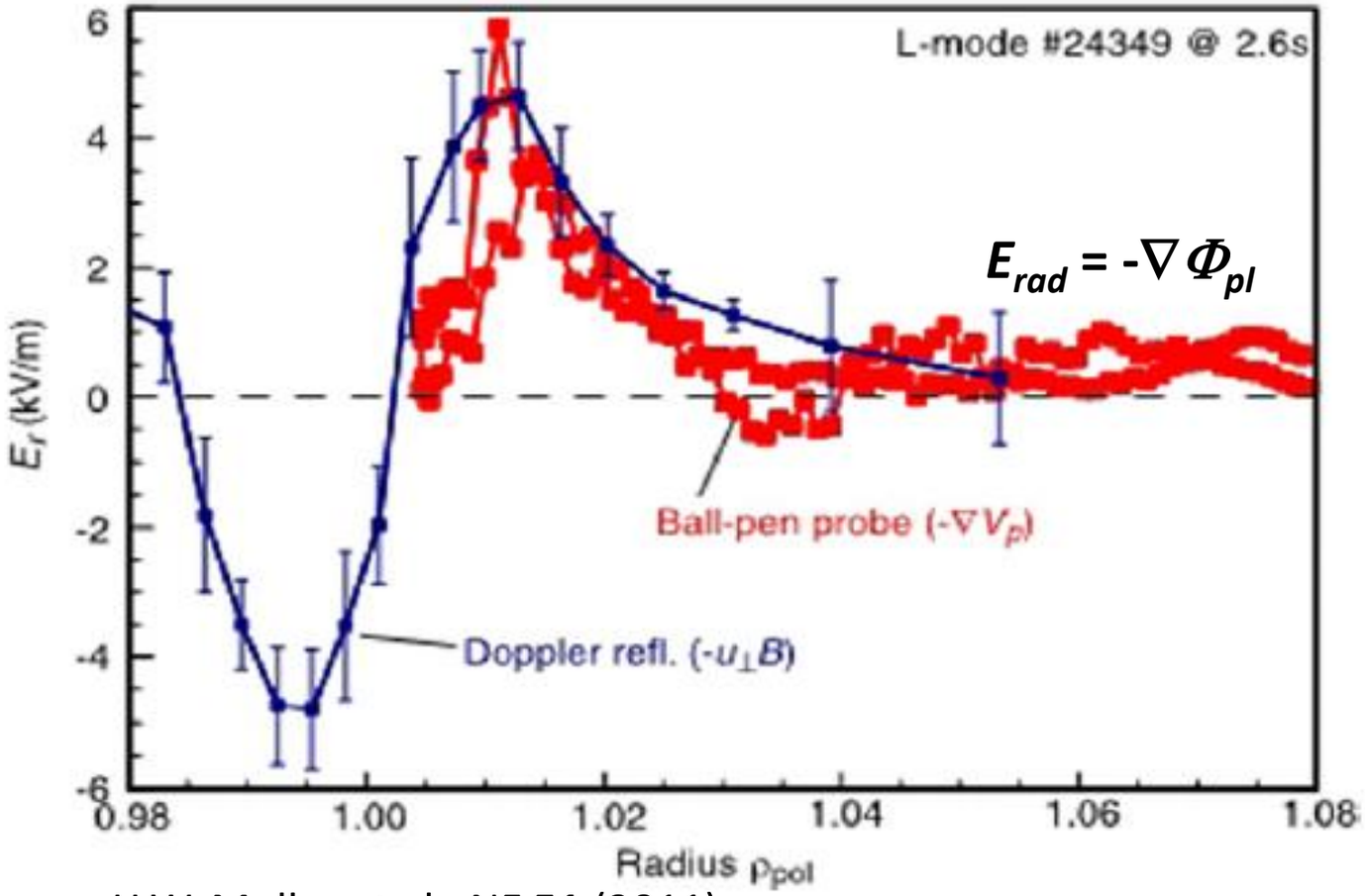
New design is patented in CR , J. Adamek & J. Stöckel

Ball-pen probe head - new design (2008, AUG)

Radial electric field in L-mode
(2009, AUG, BPP & Doppler reflectometer)

#24349, $\mathbf{B_T=2.5\ T}$, I_P=0.8 MA, n=3*10^{19} m^{-3}, P_{NBI}=1 MW

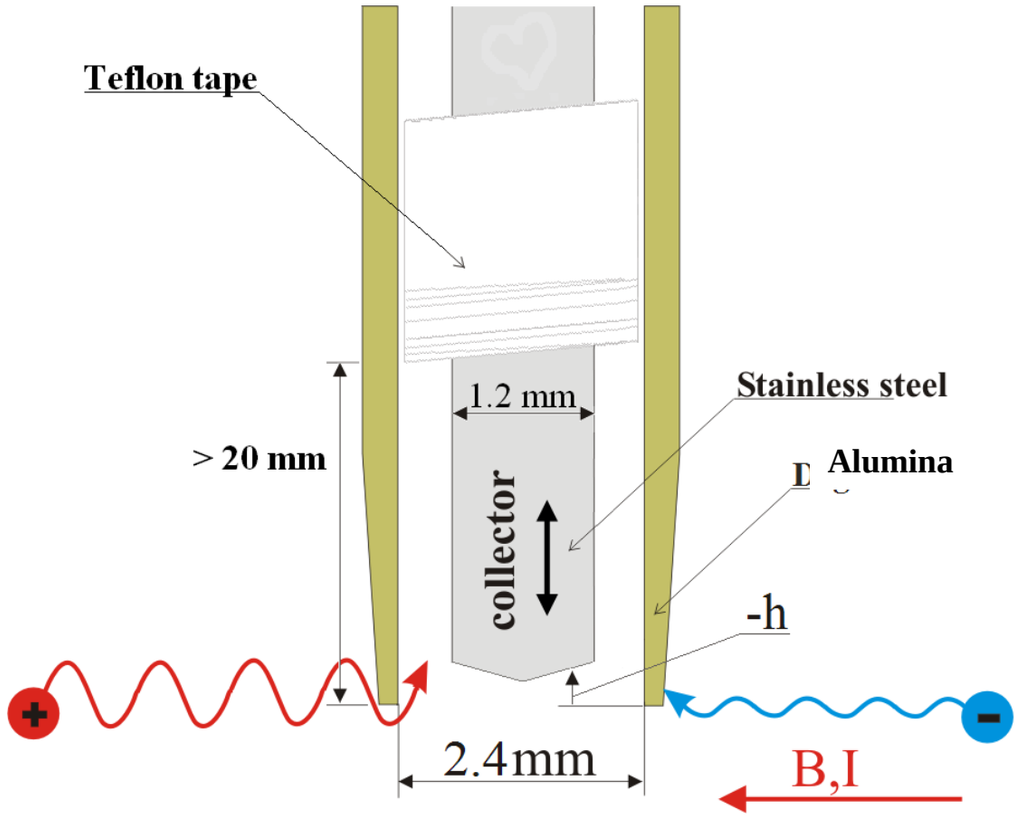
L-mode



H.W. Muller et al., NF **51** (2011)

Ball-pen probe for low-temperature plasma
(2010 – 2015, DC Magnetron, CU, Prague)

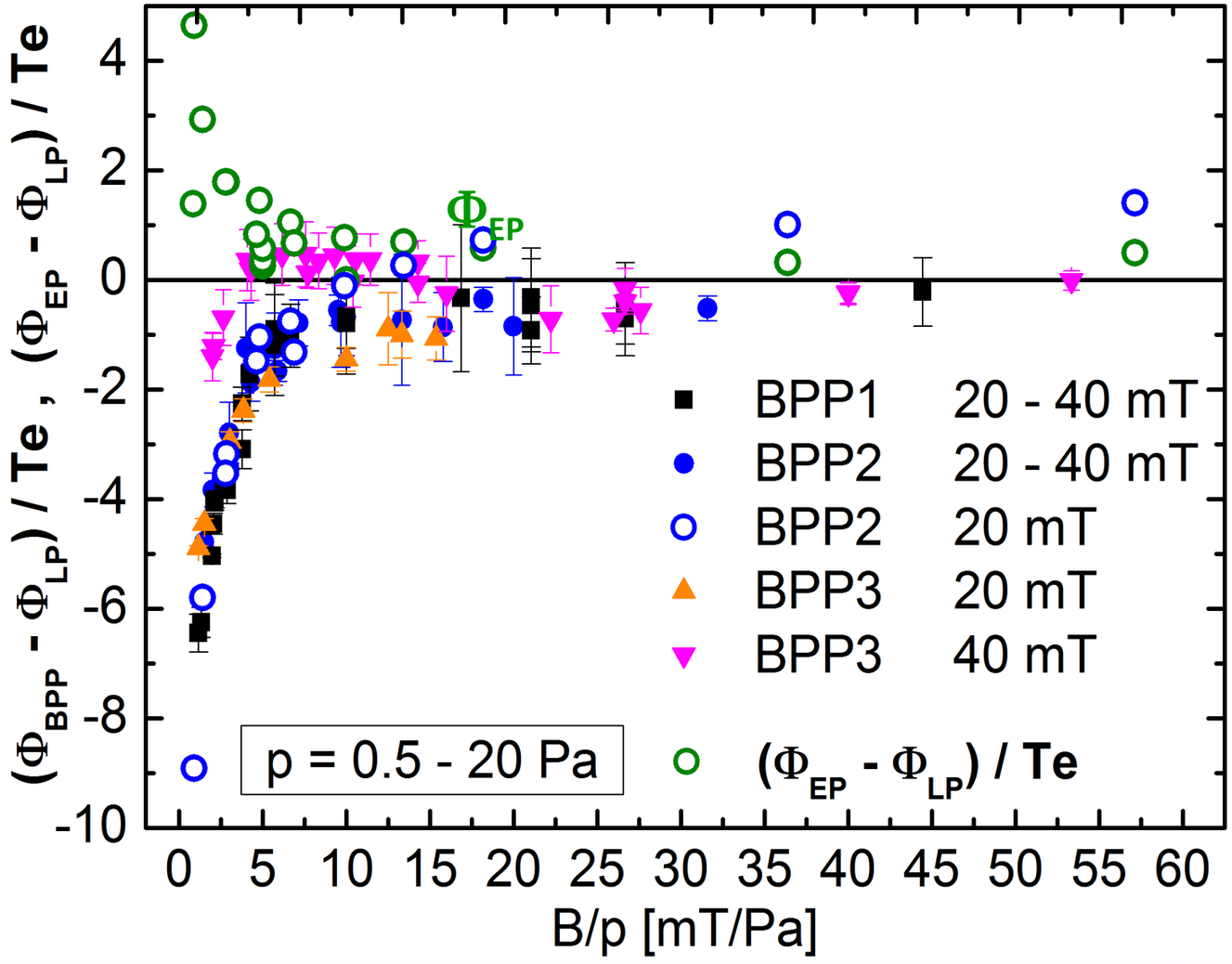
Ball-pen probe for low-temperature plasma (2010 – 2015, DC Magnetron, CU, Prague)



Probe type	Collector diameter/ length	Collector material	Ceramic support ID/OD
LP	50 μm/ 4 mm	Tungsten	Tube 0.3 mm ID /1 mm OD
EP	150 μm/ 6 mm	Tungsten	Square tube 1x3 mm
BPP1	1.2 mm/ variable	Stainless steel	Tube 2.4 mm ID /4 mm OD
BPP2	0.8 mm/ variable	Tungsten	Tube 2.4 mm ID /4 mm OD
BPP3	0.8 mm/ variable	Tungsten	Tube 1.5 mm ID /3 mm OD

M. Zanáška et al., PoP, **22** (2015)

Difference between the plasma potential Φ determined from three different teqchniques



Φ_{LP} … Langmuir probe, inflection point of the I-V
Φ_{EP} … Emissive probe
Φ_{BPP} … Ball-pen probe

Depicted data from 3 BPPs of different construction that have been gained over approximately one year of experimental effort.

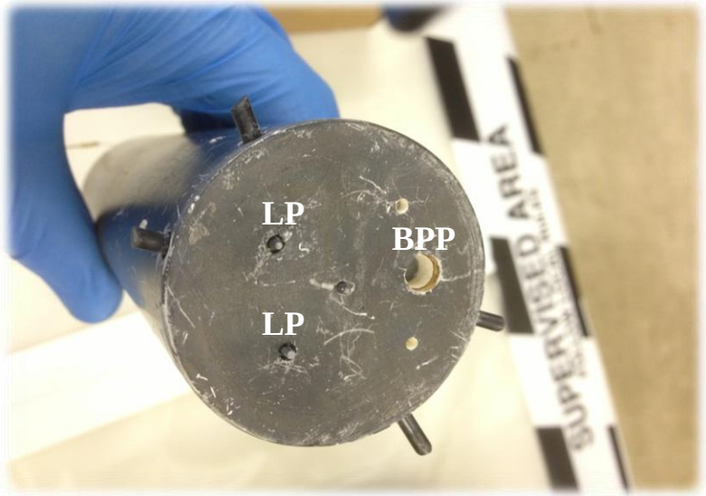
M. Zanáška et al., PoP, **22** (2015)
J. Adamek et al., CPP **53** (2013)

Ball-pen probe in low-temperature plasma (2010 – 2024, all devices)

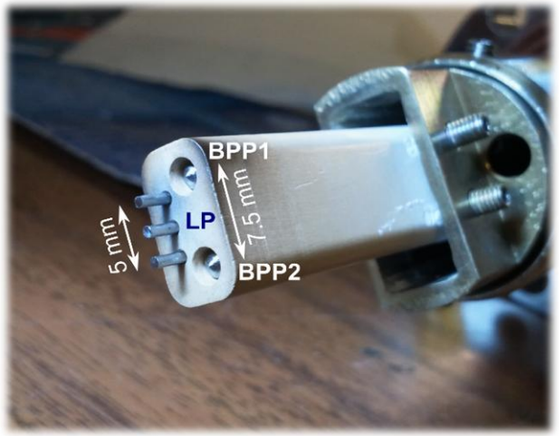
DC Magnetron, Prague	M. Zanáška et al., PoP 22 (2015)
TJ-K, Stuttgart, Germany	J. Adamek et al., CPP 53 (2013)
Mirabelle, Nancy, France	G. Bousselin et al., RSI 84 (2013)
Linear dev., Ljubljana, Slovenia	J. Adamek et al., CPP 53 (2013)
Linear dev., Liverpool, England	B. J. Harris et al., PSST 28 (2019)
Panta, Kyushu, Japan	C. Moon et al., JPFR 100 (2024)

Ball-pen probe on MAST and ISTTOK (2012-2013, England, Portugal)

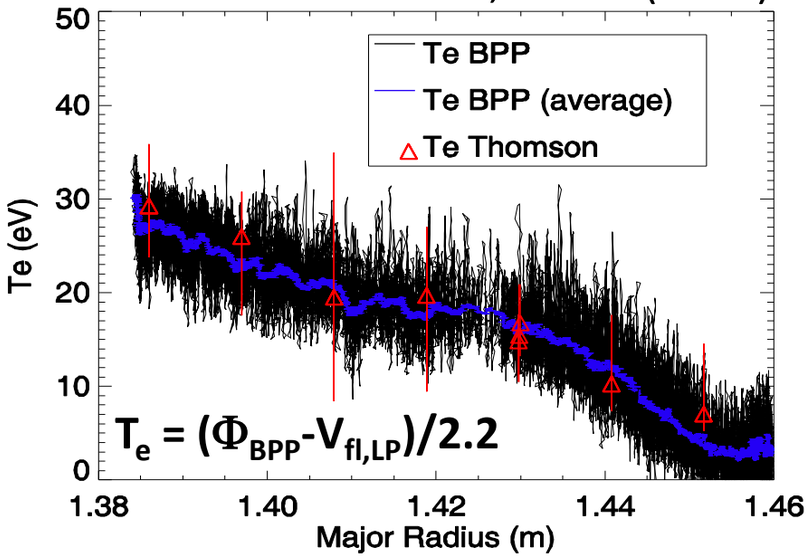
MAST, The electron temperature measurements (2013)



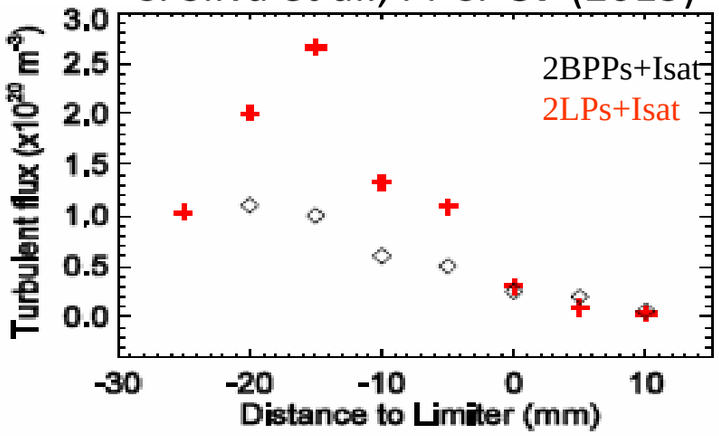
ISTTOK , Radial particle flux measurements (2012/2013)



N. Walkden et al., RSI **86** (2015)

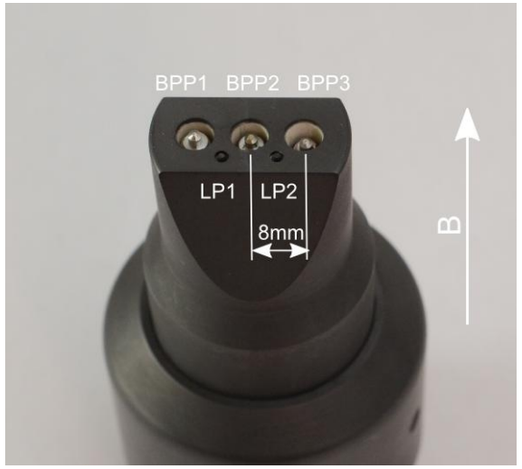


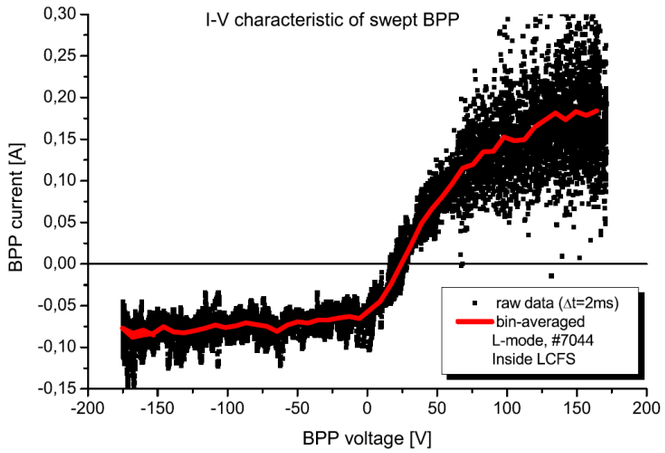
C. Silva et al., PPCF **57** (2015)



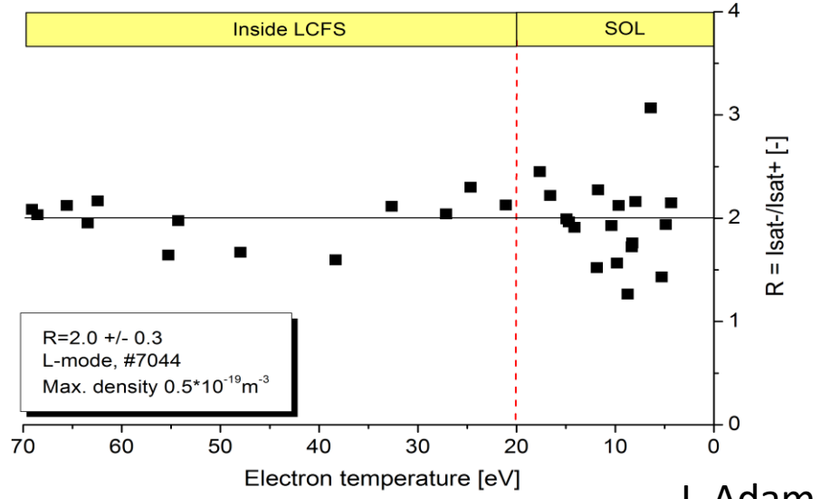
Ball-pen probe on COMPASS (2013-2020, Prague)

Probe head with 3 BPPs and 2 LPs





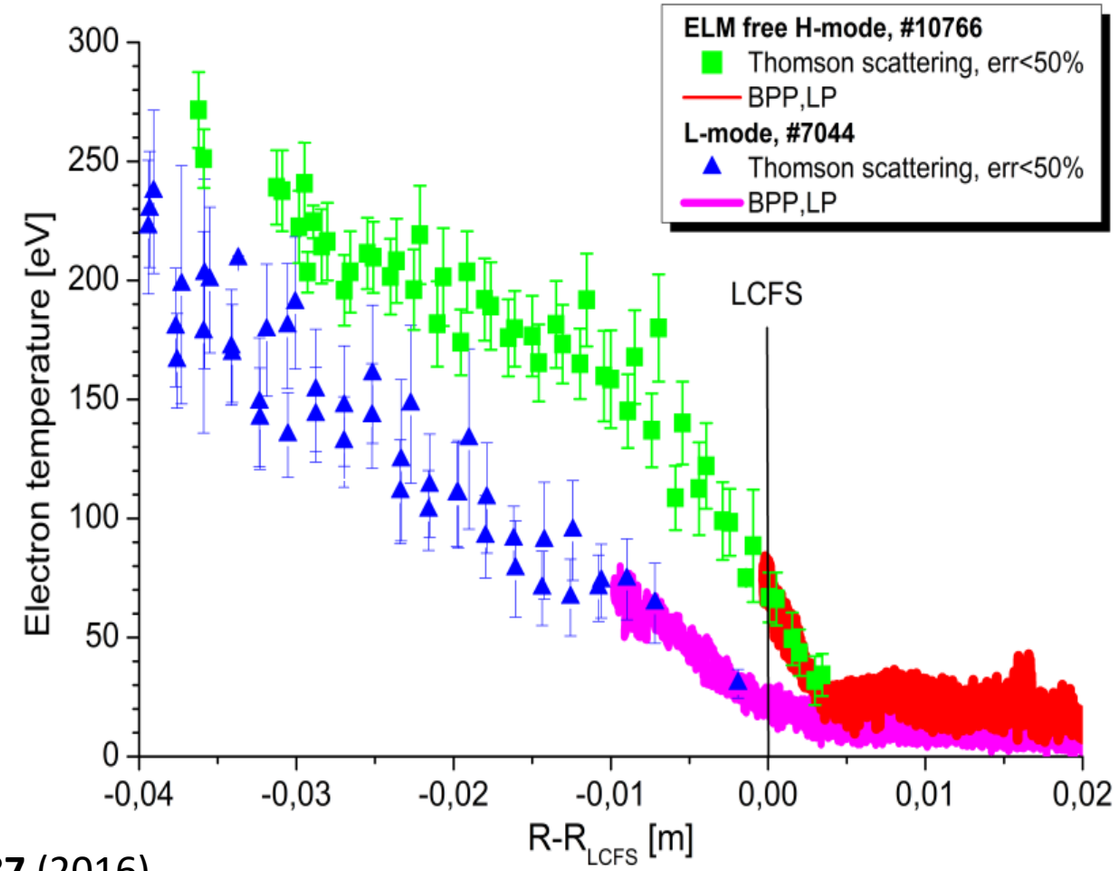
Current Isat-/Isat+ ratio vs electron temperature



Fast measurements of T_e (limited just by DAS)

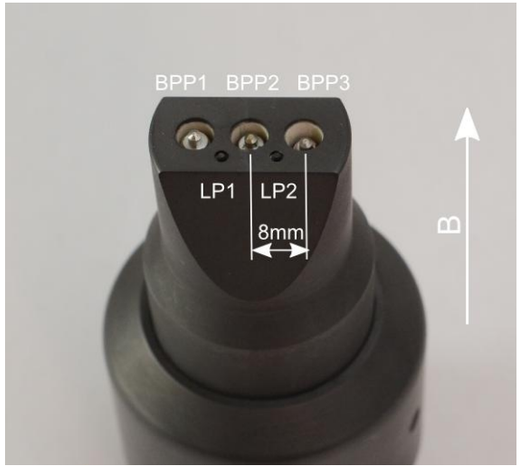
$$T_e = (\Phi - V_{fl,LP}) / \Delta$$

Δ = 2.2 for Deuterium plasmas – confirmed by TS



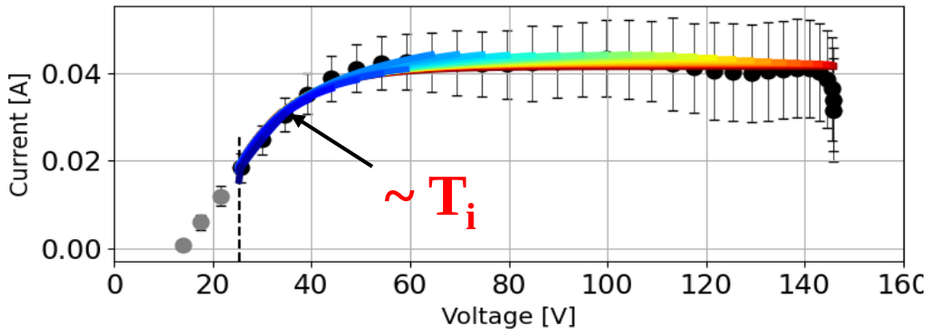
J. Adamek et al., RSI **87** (2016)

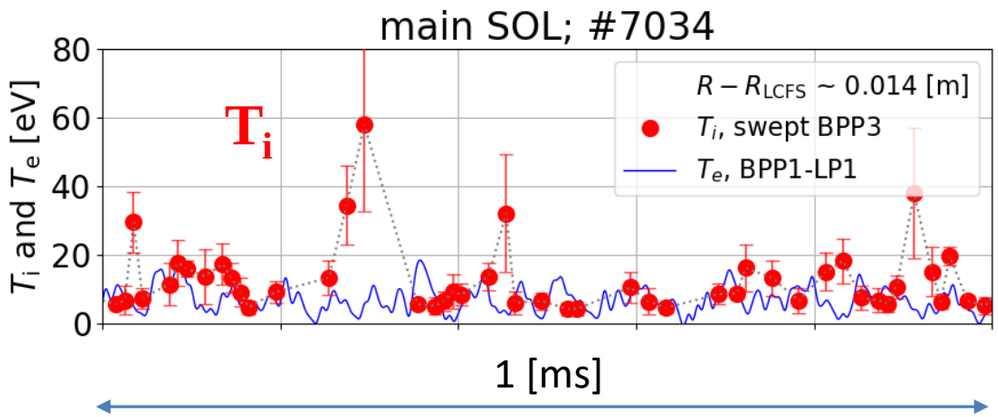
Ball-pen probe on COMPASS (2013-2020, Prague)

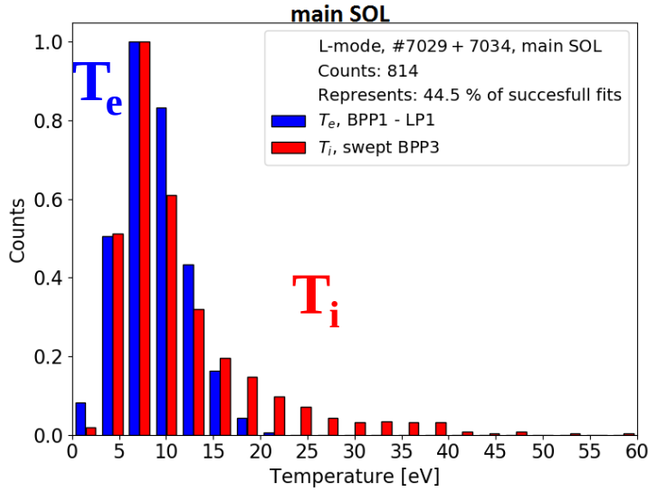


FAST SWEPT BALL-PEN PROBE

I-V with **10 µs** resolution, f sweeping = 50 kHz





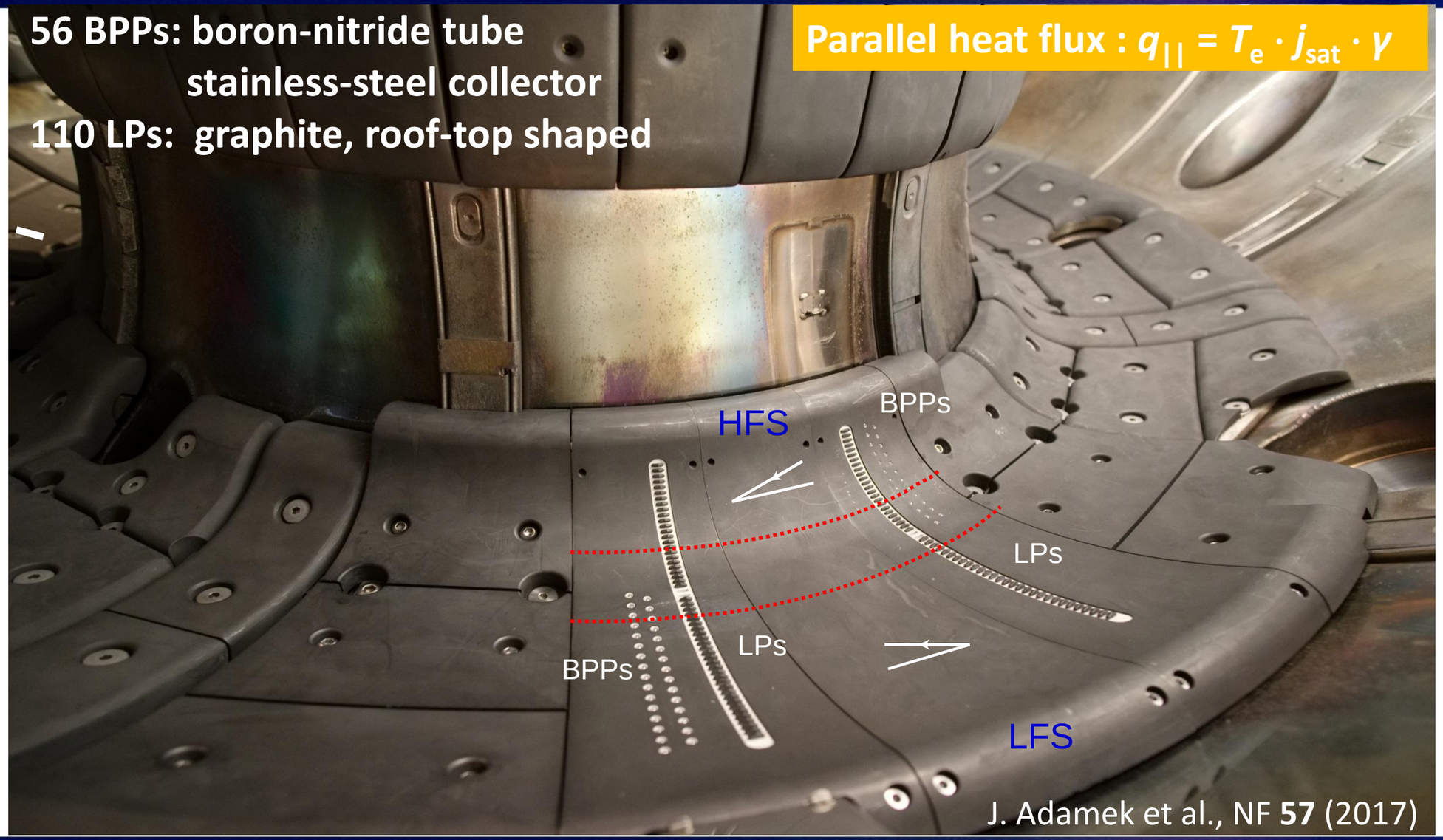


J. Adamek et al., NF **61** (2021) and D. Cipciar et al., PPCF **64** (2022).

New system of divertor probes for fast measurements of T_e and $q_{//}$ (2015)

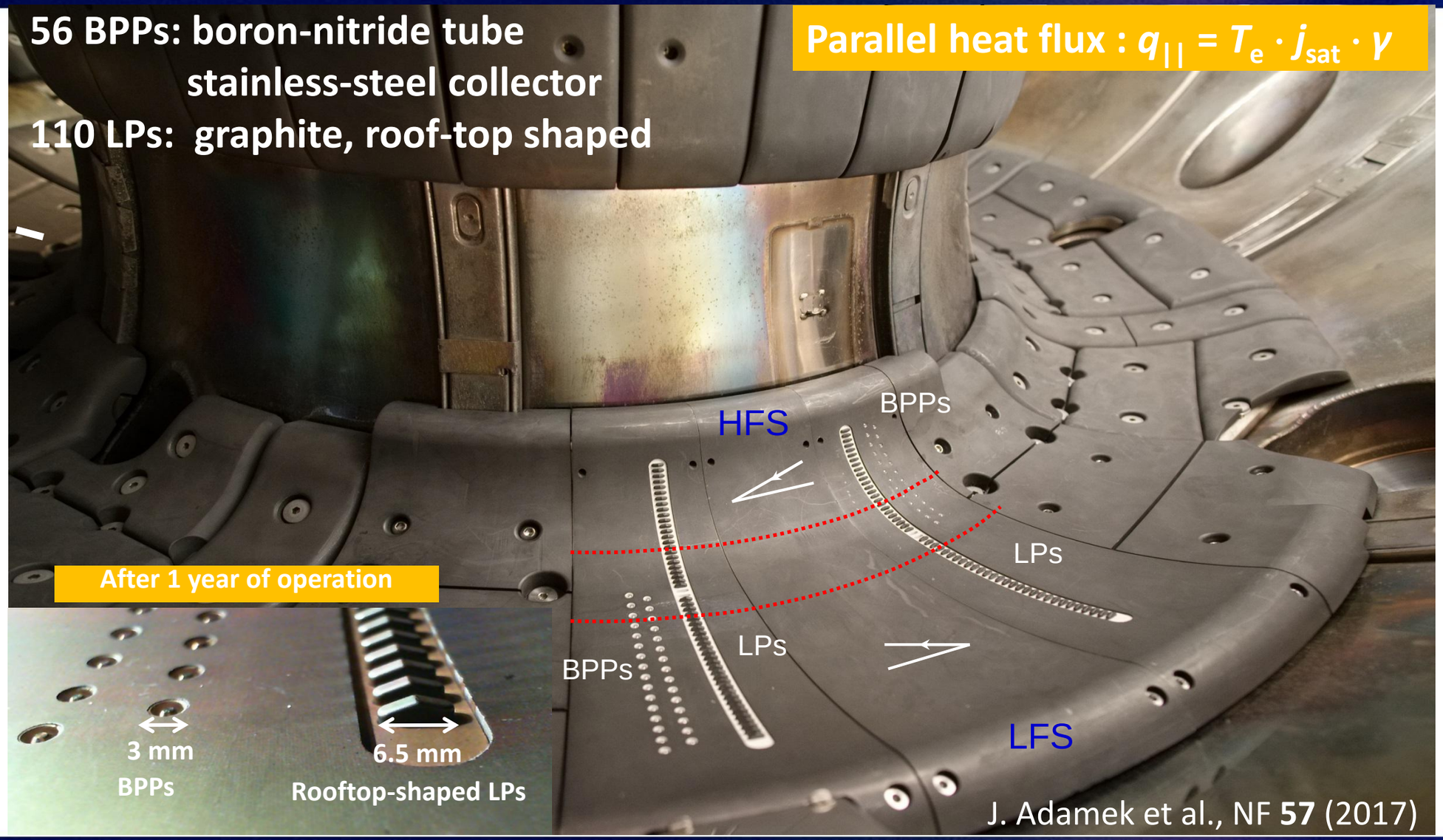
56 BPPs: boron-nitride tube
stainless-steel collector
110 LPs: graphite, roof-top shaped

Parallel heat flux : $q_{||} = T_e \cdot j_{sat} \cdot \gamma$



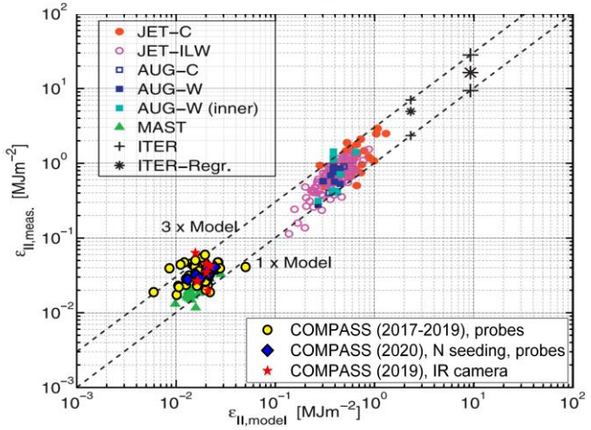
J. Adamek et al., NF **57** (2017)

New system of divertor probes for fast measurements of T_e and $q_{//}$ (2015)



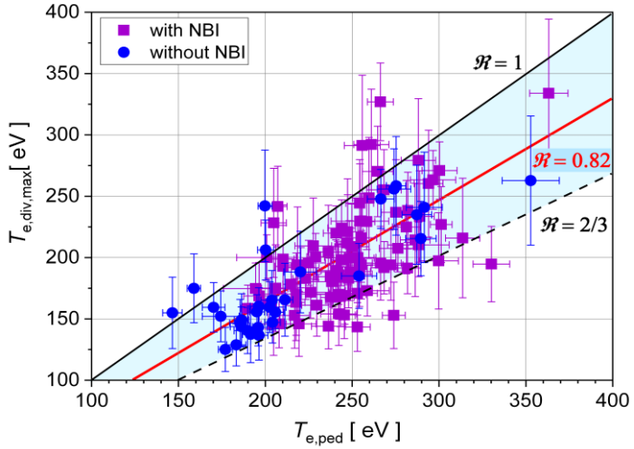
Fast measurements using new divertor probes (COMPASS, selected results)

ELM energy fluence



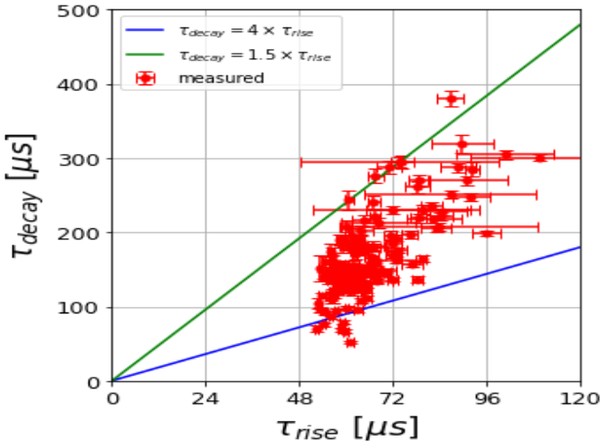
J. Adamek et al., NF **57** (2017)

Free-streaming model



J. Adamek et al., NF **60** (2020)

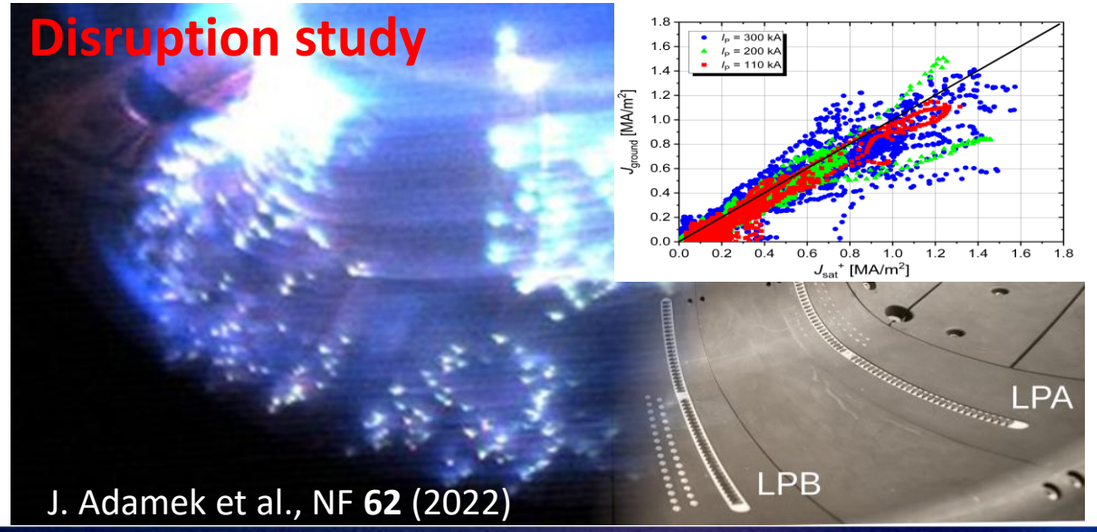
ELM characteristics



J. Adamek et al., NF **63** (2023)

- Power exhaust
- Nitrogen seeding
- ELM conditionaly averaged Te
- Langmuir probes – swept, Te
- Liquid metals
- Real-time feedback system
- Comparison with the modelling

Disruption study



J. Adamek et al., NF **62** (2022)

Ball-pen probes over the world

CASTOR

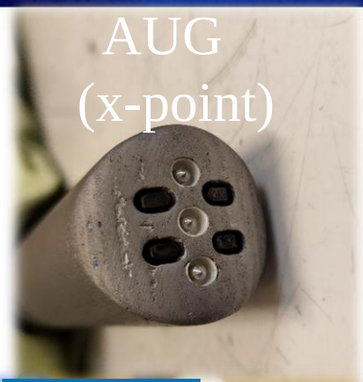
RFX
(Italy)

ASDEX Upgrade (AUG)

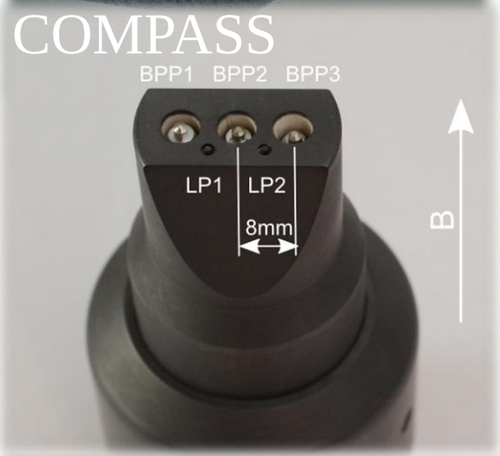
(Germany)

AUG/COMPASS

AUG
(x-point)

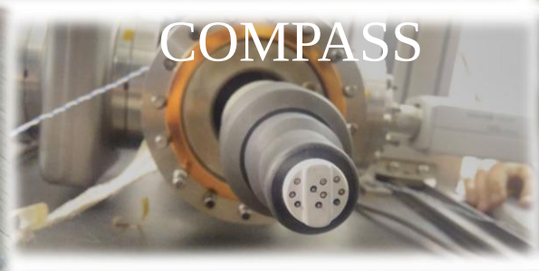


COMPASS

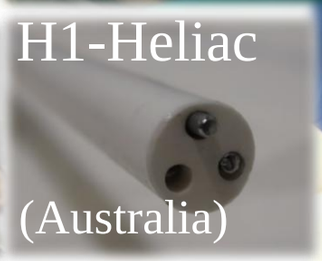


DC Magetron, Prague
TJ-K, Stuttgart, Germany
Mirabelle, Nancy, France
Linear dev., Ljubljana, Slovenia
Linear dev., Liverpool, England
Panta, Kyushu, Japan

COMPASS



H1-Heliac

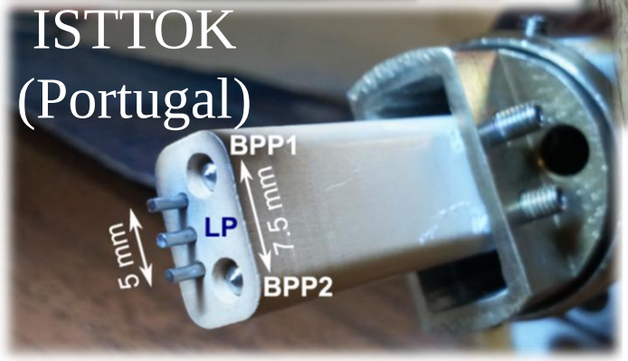


(Australia)

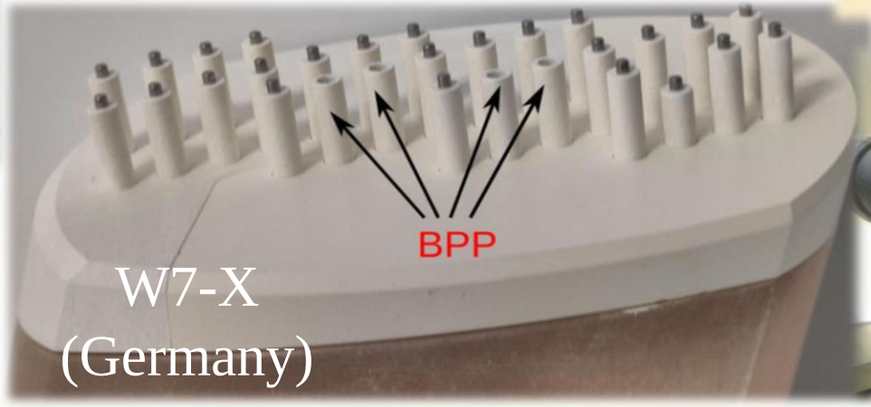
MAST

(England)

ISTTOK
(Portugal)



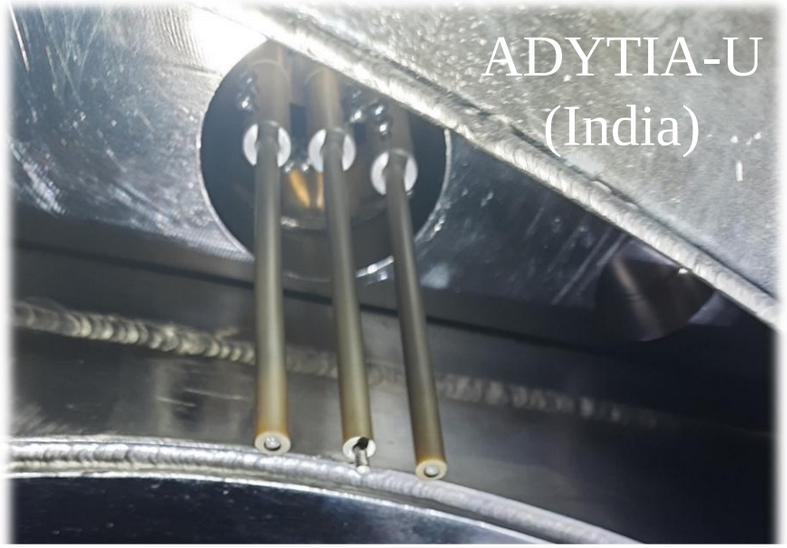
GOLEM
(CTU, Prague)

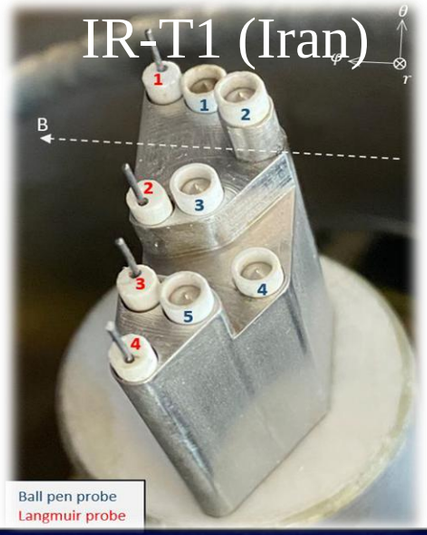


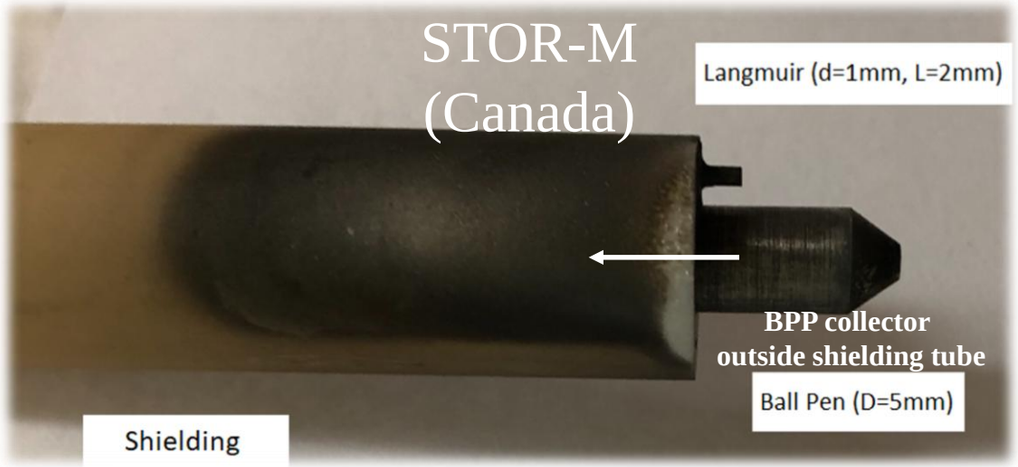
W7-X
(Germany)

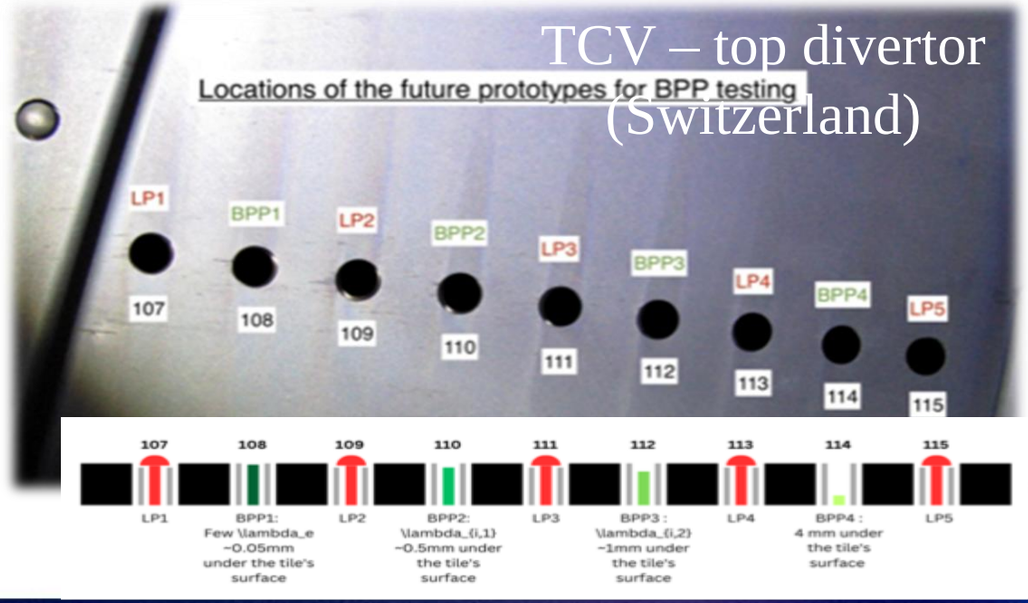
Tore-Supra
(France)

Ball-pen probes over the world







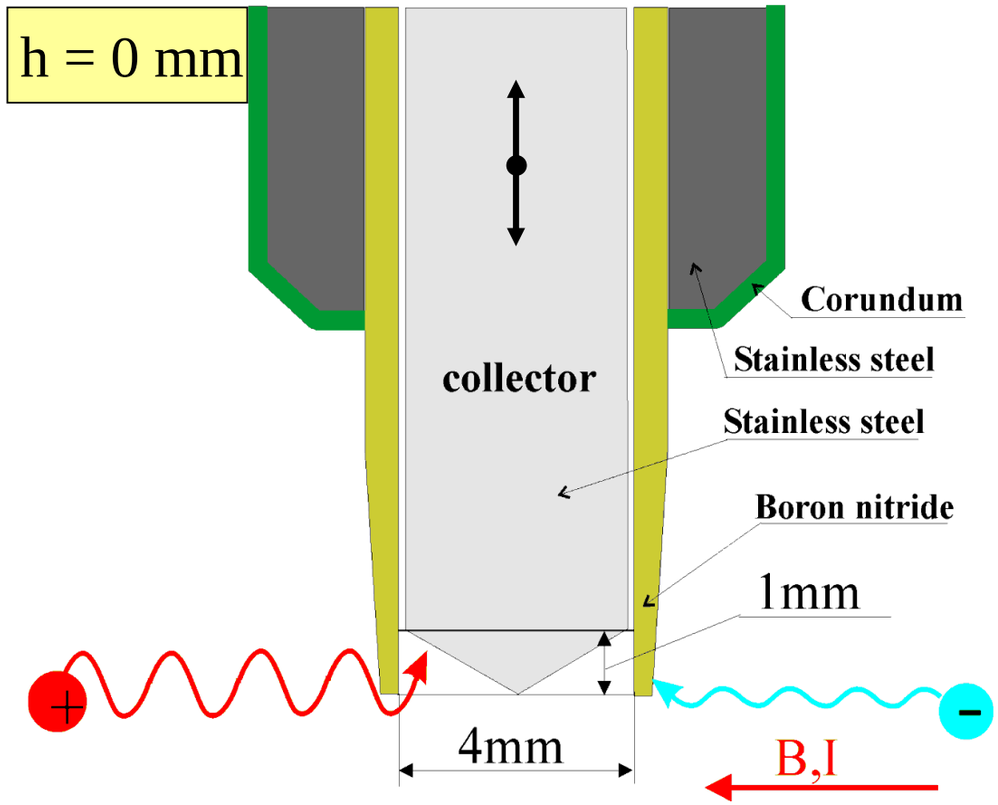


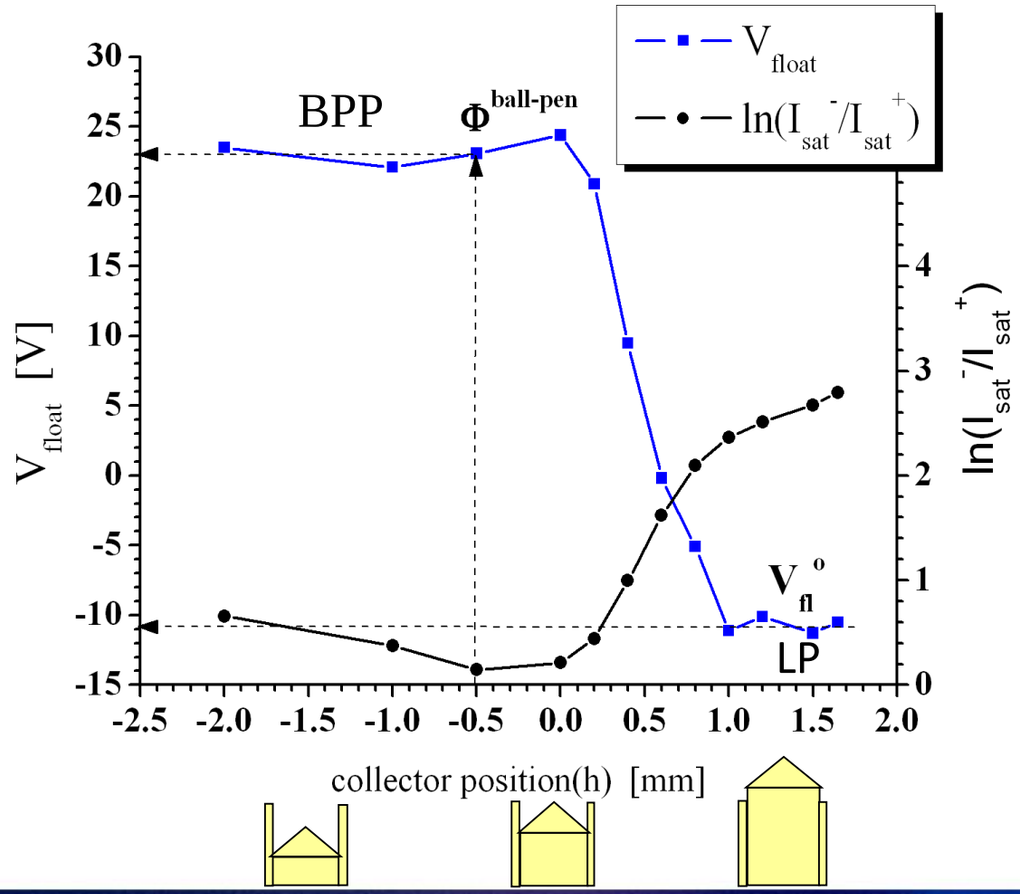
Ball-pen probe on CASTOR

(B=1 T, I_P=10 kA, R=0.4 m, r=85 mm, hydrogen plasma)

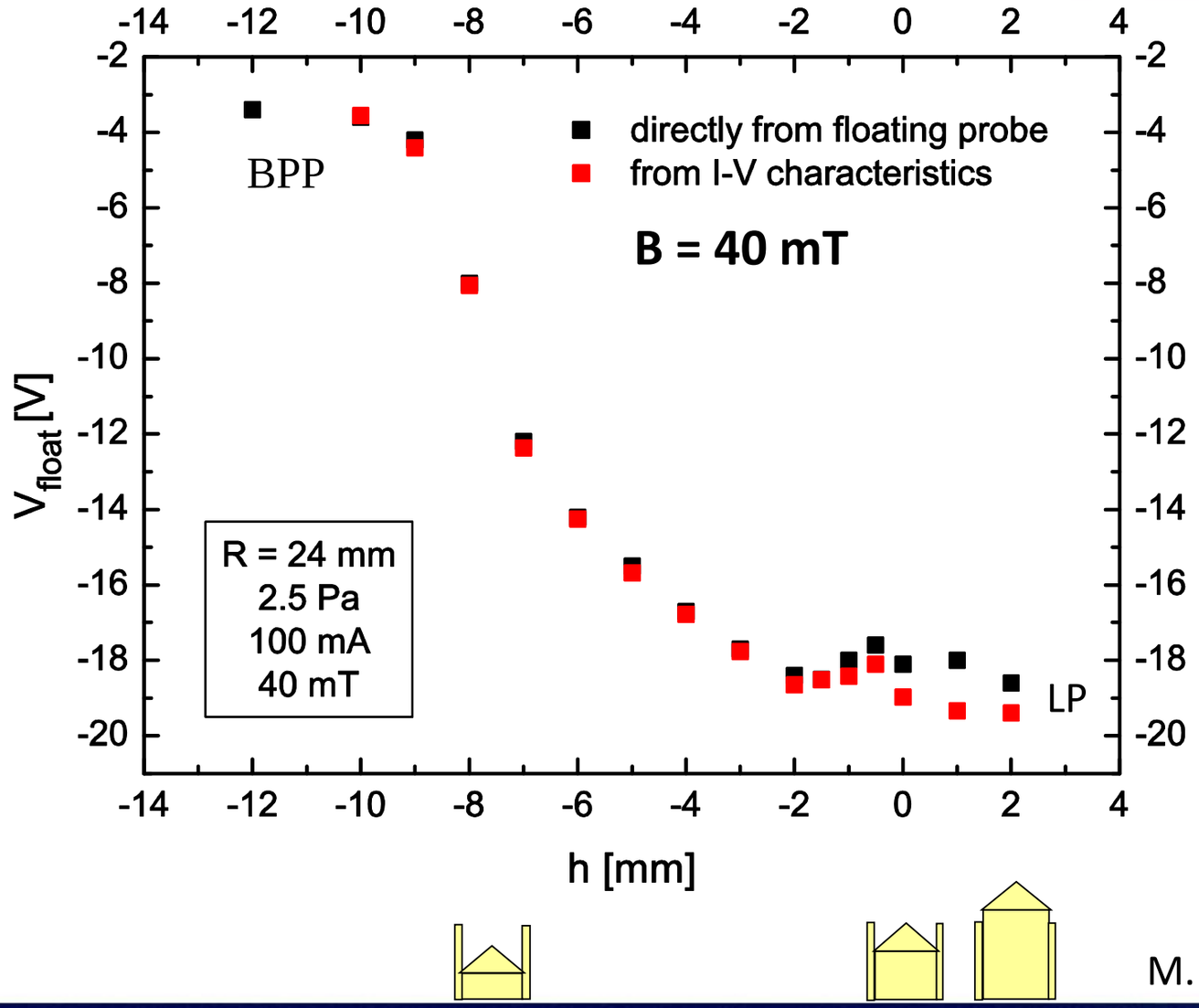
$$V_{fl} = \Phi - T_e \cdot \ln\left(\frac{I_{sat}^-}{I_{sat}^+}\right)$$

$$\ln\left(\frac{j_{sat}^- \cdot A_e(h)}{j_{sat}^+ \cdot A_i(h)}\right) = 0 \;\Rightarrow\; V_{fl}^{BPP} = \Phi$$



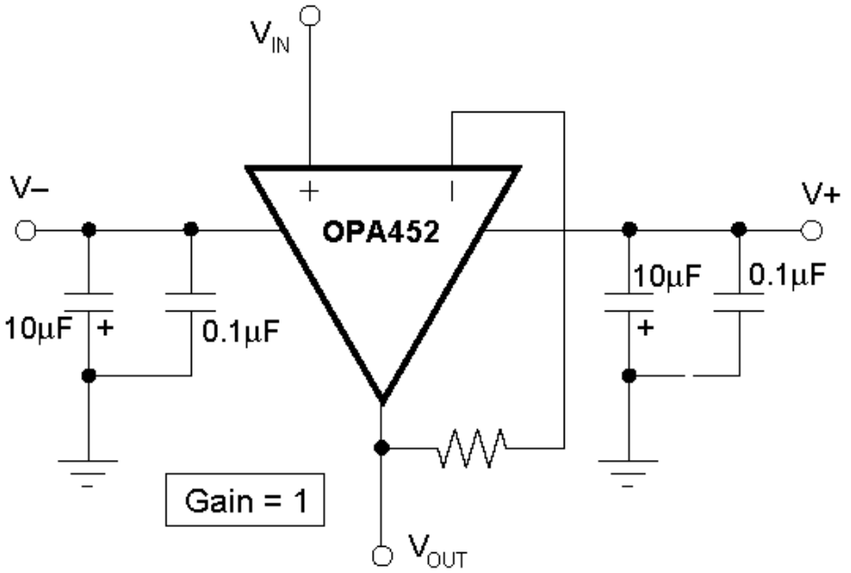


BPP floating potential scan with collector position (high input impedance voltmeter)



A voltage follower with

$$Z_{in} \approx 10^{12}\ \Omega$$



M. Zanáška et al., PoP **22**, 2015; J. Adamek et al., CPP **53,** 2013.