Innovative concepts for extreme heat load tokamak divertor

IPP
COMPASS INSTITUTE OF PLASMA PHYSICS ASCR
Jan Horacek

1. Mitigation ELMs by fast strike point sweeping → 3-5x is achievable on EU DEMO

1. Liquid Li/Sn divertor survives steady & transients by evaporating … which will cool plasma

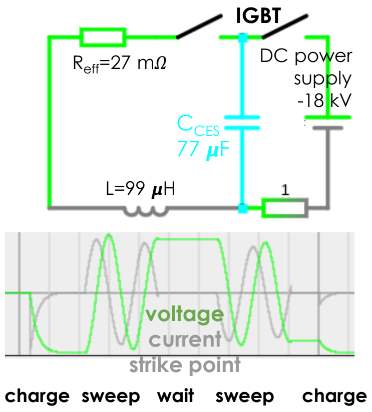
1. Why must PFC survive $q_{\perp}$>>10 MW/m^2

1. Conceptual experiment of PFC surviving ~60 MW/m^2

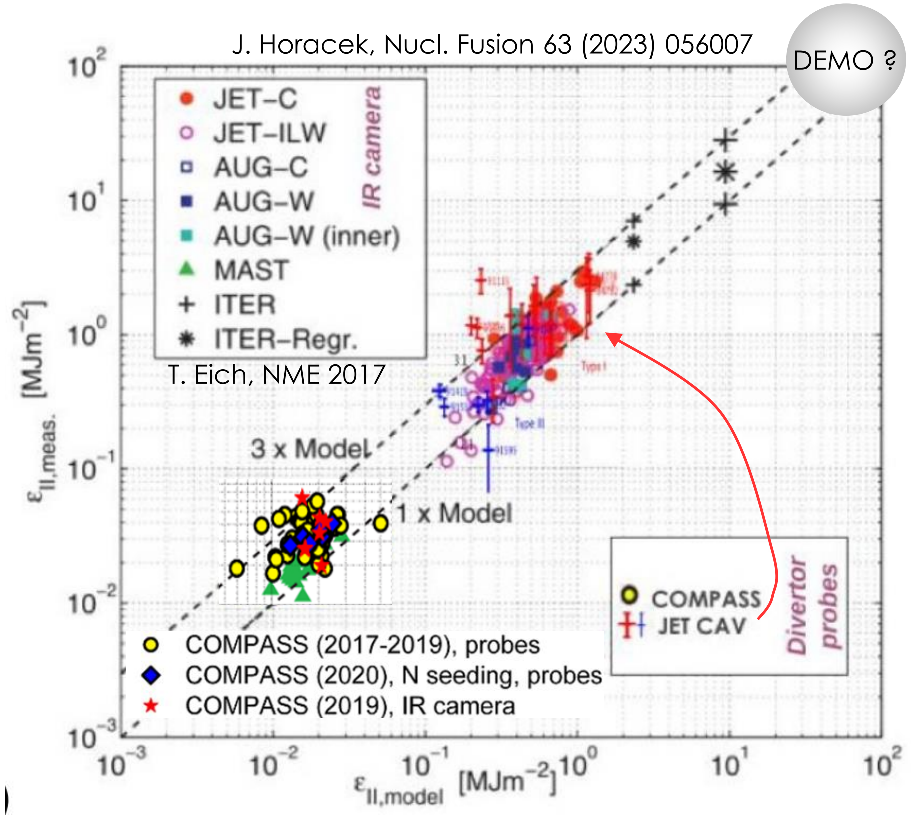
ISFNT15 INTERNATIONAL SYMPOSIUM ON FUSION NUCLEAR TECHNOLOGY

Fast divertor strike point sweeping

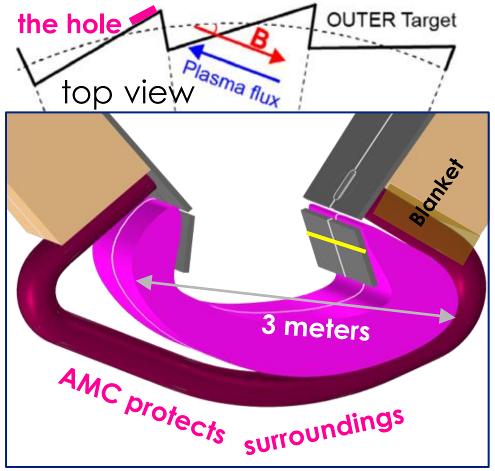
- Tungsten melts at 0.7 MJ/m^2 [J. Coenen, NF 2015], cracks at 0.4
- Multiply known ELM mitigation techniques (RMP, impurity seeding) with our new engineering concept:
- Fast sweep the strike point spreading the power within the ELM (or QCE filaments) space-time scales

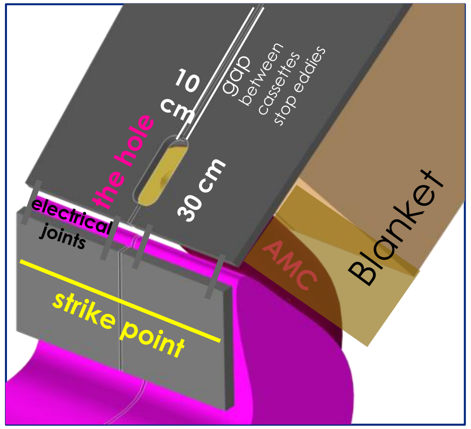


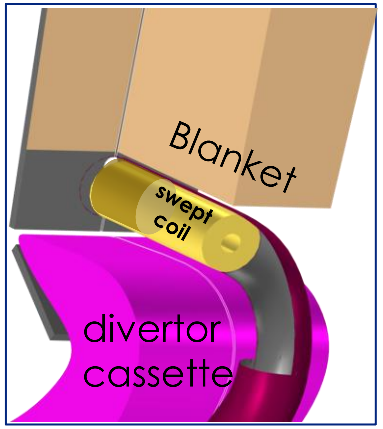
Trigger by ELM divertor current



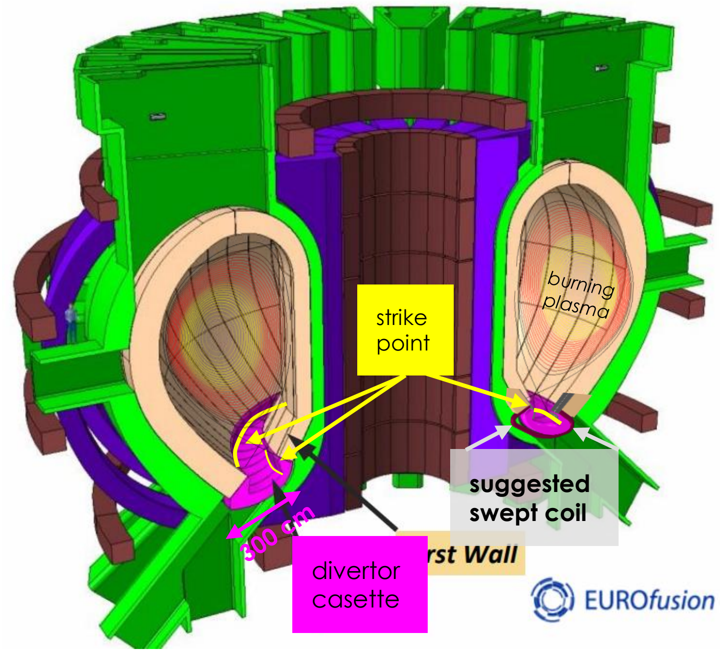
EU DEMO geometry





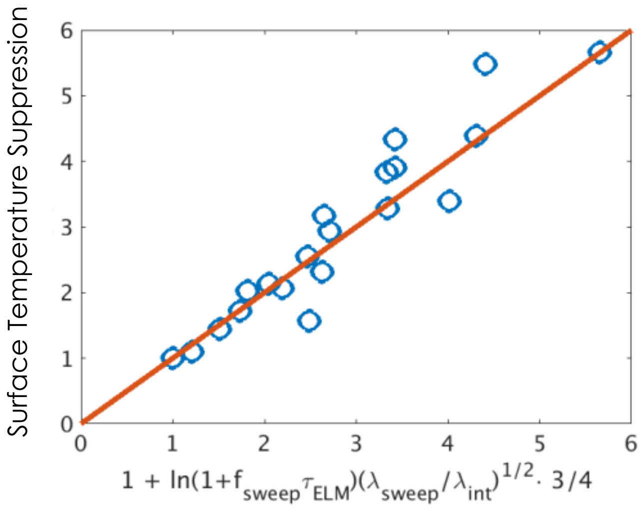


Electrical insulation may be tricky at 2 dpa/year [J.H. You, *FED* 2017]



6mm thick Litz conductor

Horacek, J. *Fusion Eng. Des.* **123** (2017) 646–649



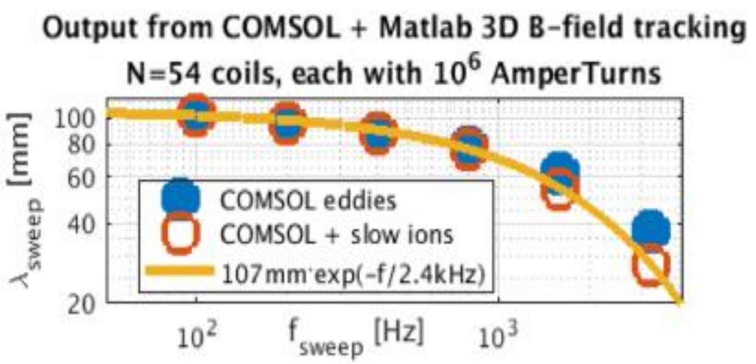
Dynamic simulations of 3D magnetic field

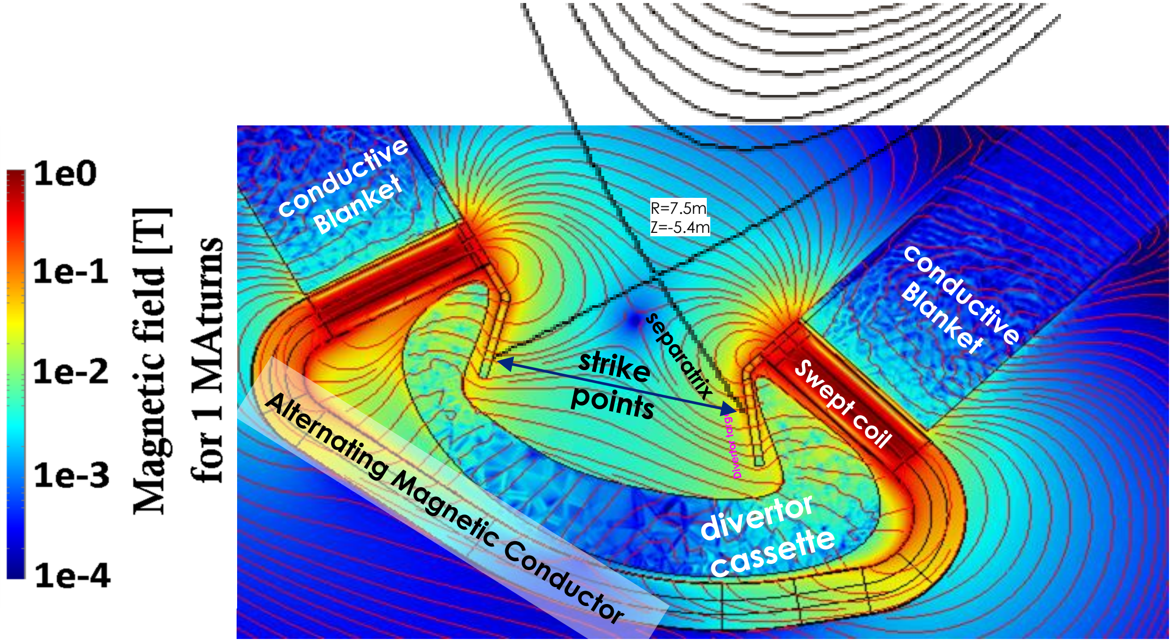
COMSOL:

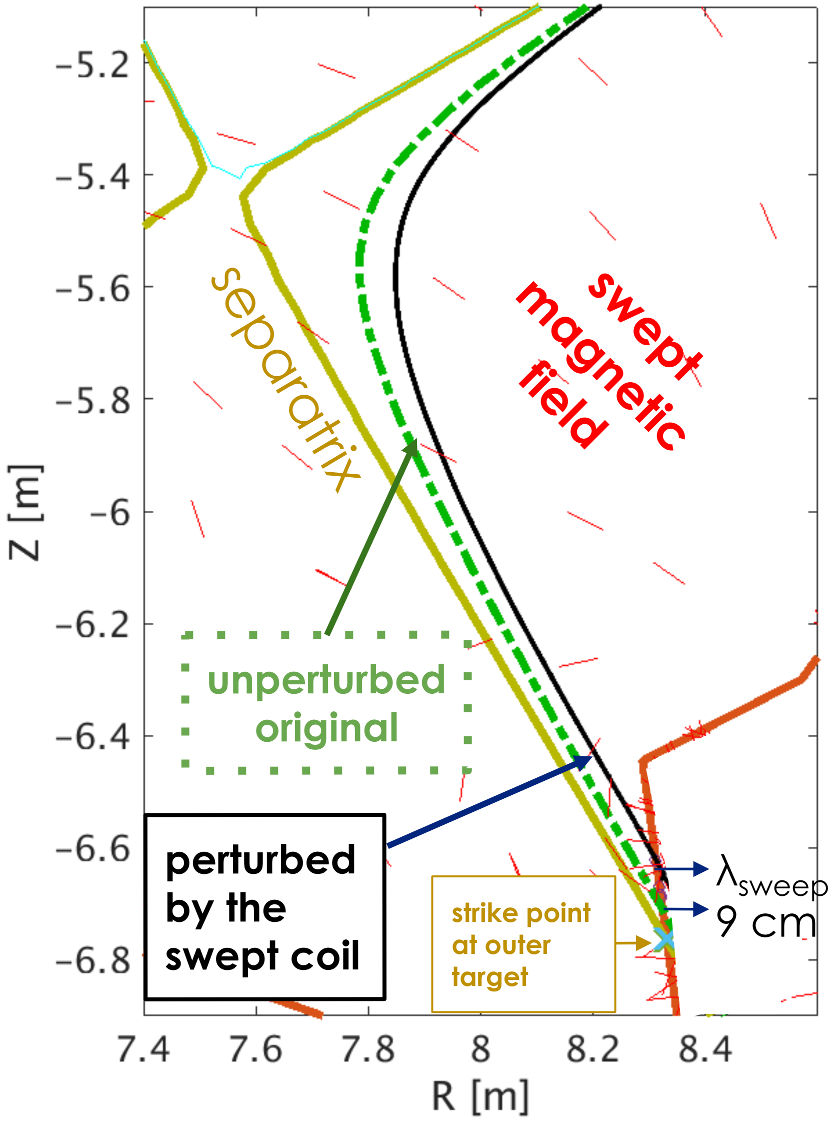
- 3D B-field of the double swept coil
- inside an AC magnetic conductor
- 0.1 mm vibrations due to $I_{sweep} x B_{tor}$

Matlab: 3D tracking from midplane to strike point

- EFIT of COMPASS plasma (rescaled to DEMO
- passing through 54 C-coils







Requirements for fast sweeping

scientific reports (2022) 12:17013

Check for updates

OPEN

Novel concept suppressing plasma heat pulses in a tokamak by fast divertor sweeping

J. Horacek[1]✉, S. Lukes[2], J. Adamek[1], J. Havlicek[1], S. Entler[1], J. Seidl[1], J. Cavalier[1], J. Cikhardt[1,3] & V. Sedmidubsky[4]

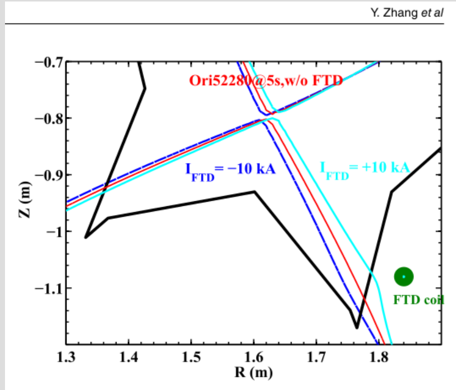
Study outputs			
Voltage U_0 amplitude	± 18	± 120	kV
Optimal coil number of turns	63	100	
λ_{swp} swept strike point amplitude	±6	±16	cm
CES parasitic inductance L_{CES}	70	25	nH
the circuit parasitic resistance $R_{eff} = R_{IGBT} + R_{capacitor} + R_{coil}$	11	25	mΩ
Capacity $C_{CES} + C_{cable}$	105	23	µ F
$L = L_{capacitor} + L_{coil} + L_{cable} + L_{IGBT}$	0.14	0.3	mH
Resonant Sweep frequency $f_{swp} = \frac{U_0}{2\pi \cdot L \cdot I_0} = (2\pi\sqrt{LC})^{-1}$	1.3	1.9	kHz
2N coils Ohmic losses $E^{tot}_{\Omega/ELM} = \frac{1}{2} R_{eff} I^2_{coil} \tau_{ELM} = E_{eddy} + E^{RLC}_{circuit}$	0.22	2.2 !	MJ
AC Current I_{coil} amplitude	±16	±33	kA
Coil and Cable D_{Litz} diameter	6	5	mm
Copper weight of 1 coil + cable	80	60	kg
Relative energy dissipation within 1 ELM $\frac{E^{tot}_{\Omega/ELM}}{E}$	0.24	0.25	
The predicted surface temperature suppression factor by the fast sweeping during an ELM F_{STS}	3.1	5.1	

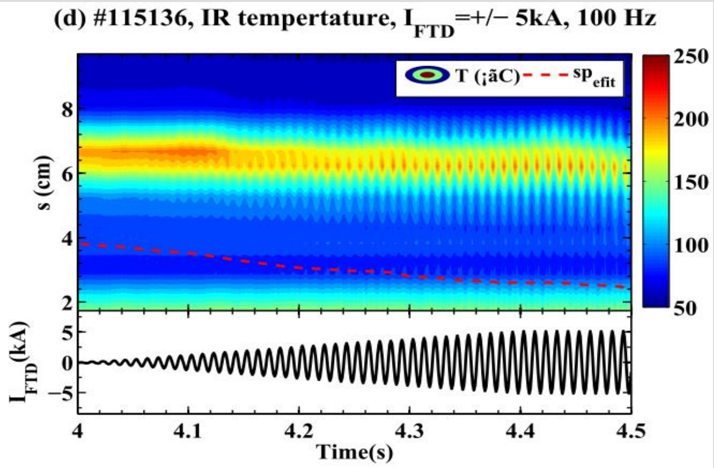
More effective on bigger tokamaks because

- λ_q doesn't scale with R_0
- there's much more space
  - under divertor target for the coil
  - for divertor leg to bend

Feasible for EU DEMO and worth for ELM suppression by 3-5x.
Needs further investigation, especially

- EU DEMO machine integration
- Experimental verification Y. Zhang, *Nucl. Fusion* **63** (2023) 086006
  - EAST tokamak installed poloidal divertor coil similar to Horacek *Fus.Eng.Des.* **123**, 646–649 (2017)
  - swept with 10-100 Hz w/o ELMs
  - ELMs planned for 2023





Outline

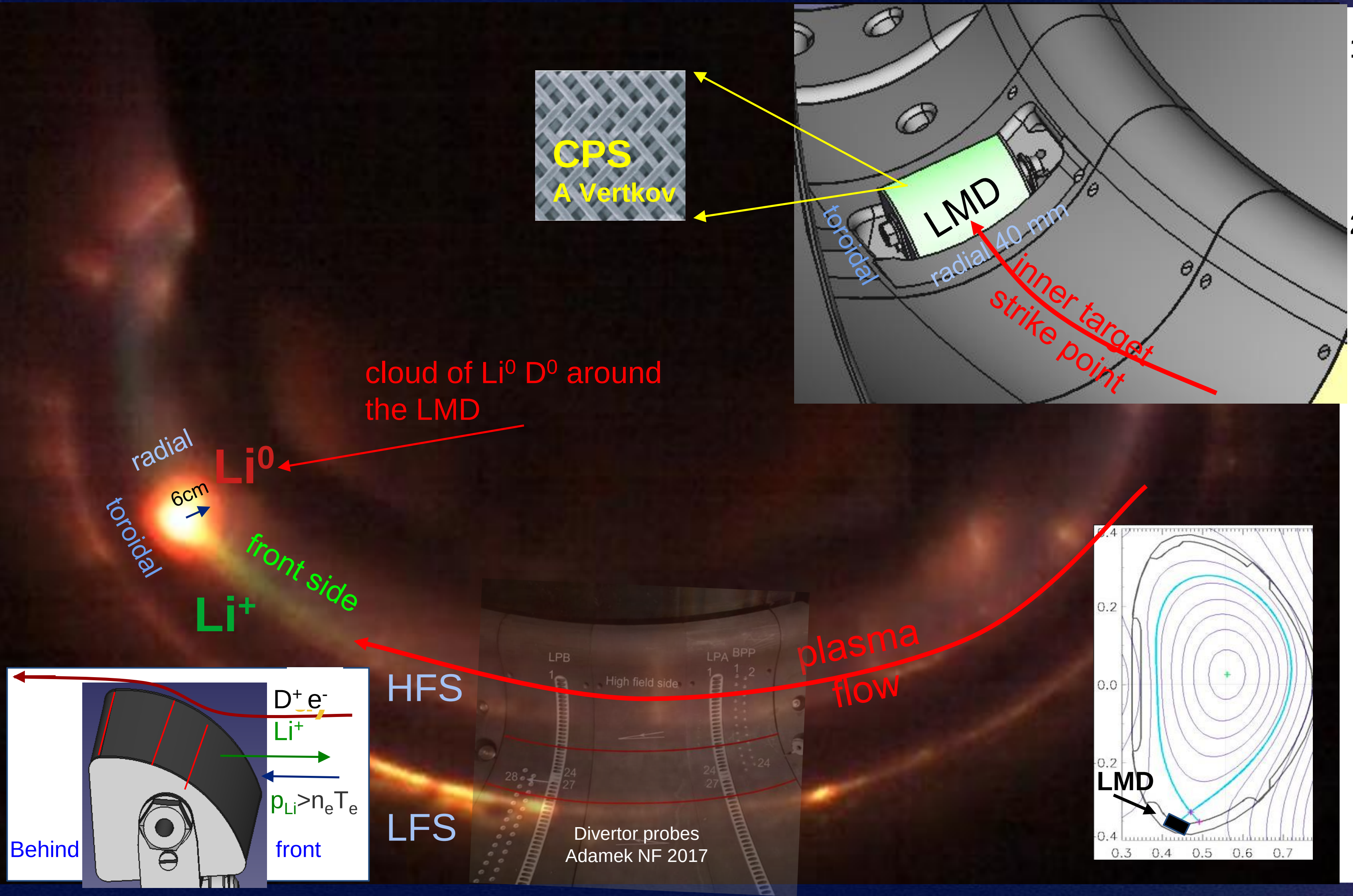
1. Suppressing ELMs by fast strike point sweeping → suppression 3-5x is achievable on EU DEMO

1. **Liquid Li/Sn divertor survives steady & transients by evaporating … which will cool plasma**

1. Why must PFC survive $q_{\perp}$>>10 MW/m^2

1. Conceptual experiment of PFC surviving ~60 MW/m^2

LMD on tokamak COMPASS

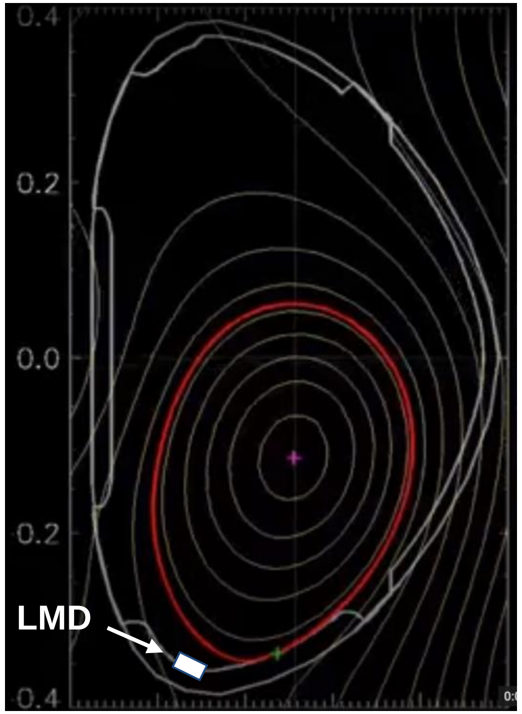


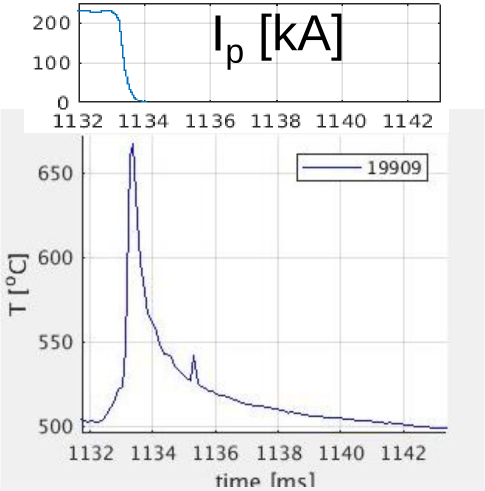
1. **Li**: part of surface oxidized →droplets sliding off the edge. Li_2O sputtered out → CPS mesh melted :-(
2. **LiSn alloy** performed excellently under $q_{\perp}$=12-15 MW/m^2 world record in tokamak ELMy (15 kJ/m^2) H-mode
   - CPS not damaged :-)
     - even after VDE disruption
   - Plasma not affected
   - No droplets splashing
   - Observed release of Li, not Sn

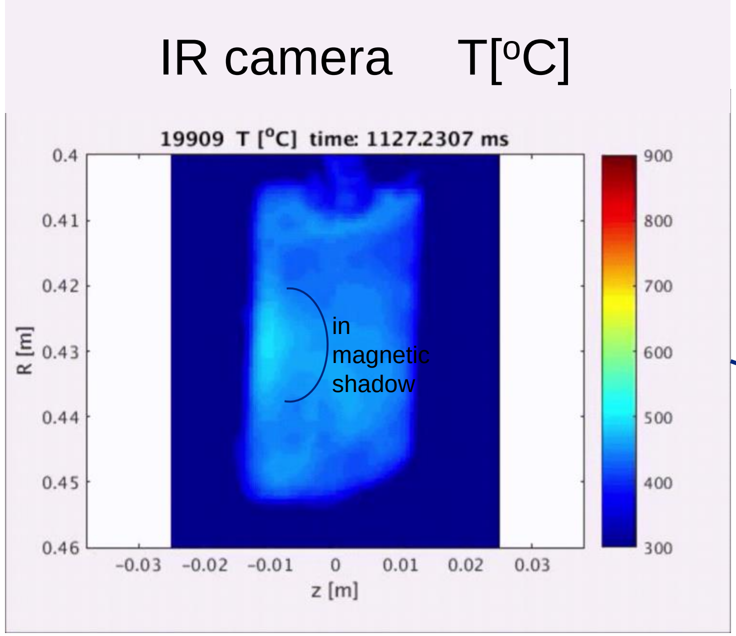
P.Veis, Nuc. Mat. Energy 25 (2020) 100809
R. Dejarnac, Nuc. Mat. Energy 25 (2020) 100801

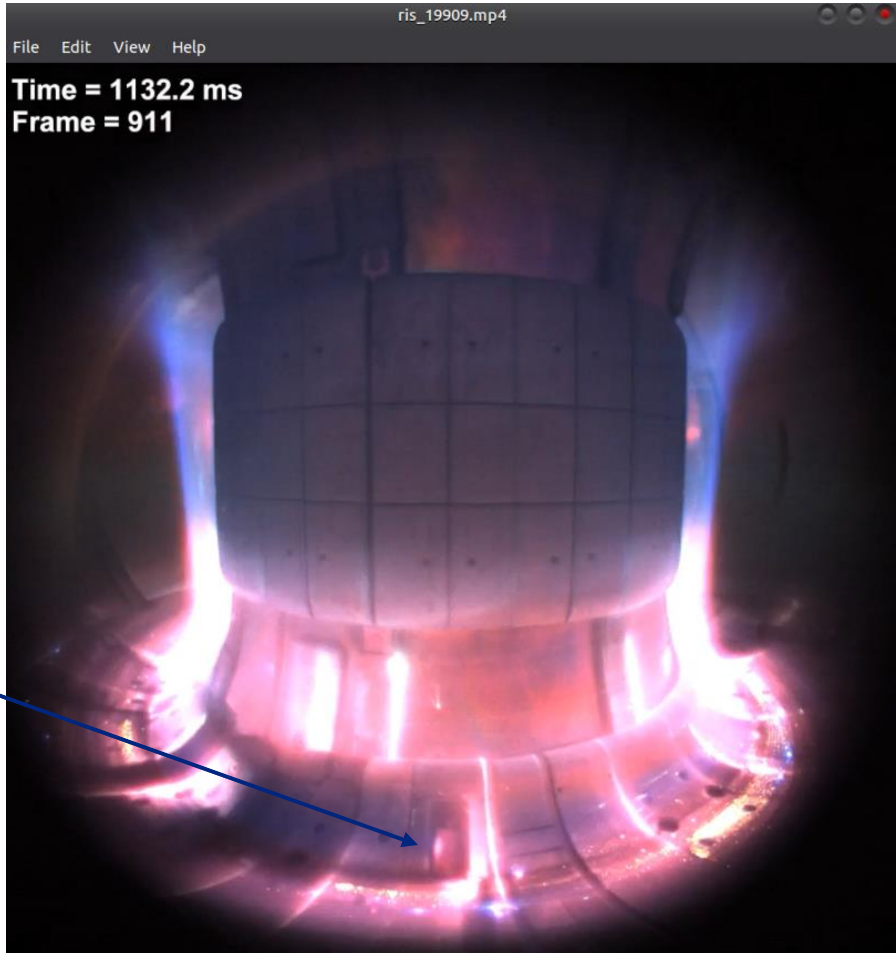
Survival of disruption VDE

LMD **survived** major disruption









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Modeling of COMPASS tokamak divertor liquid metal experiments

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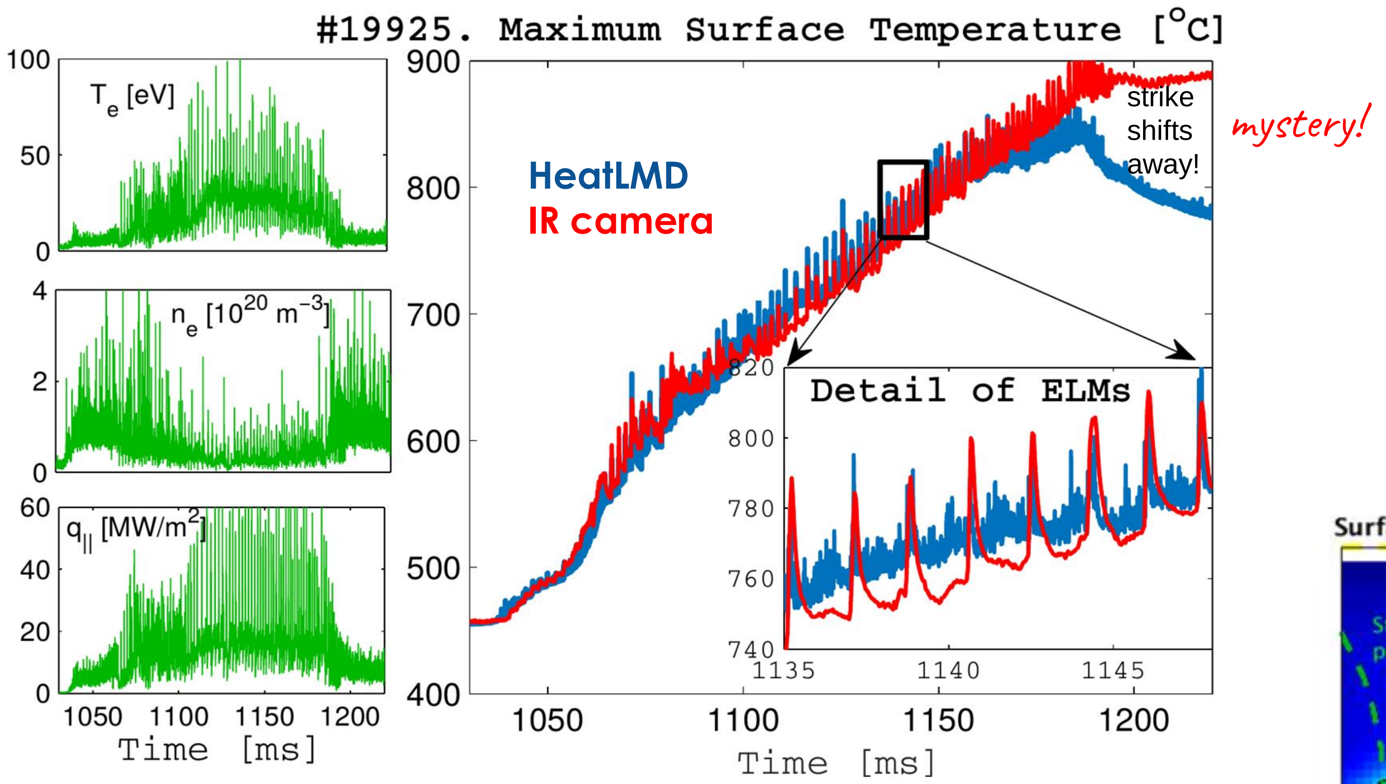
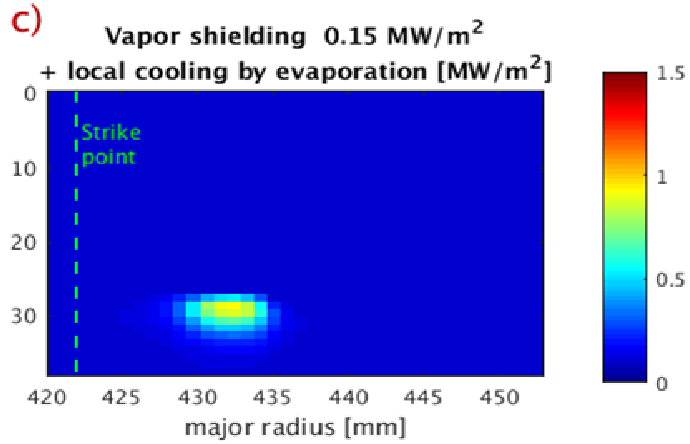
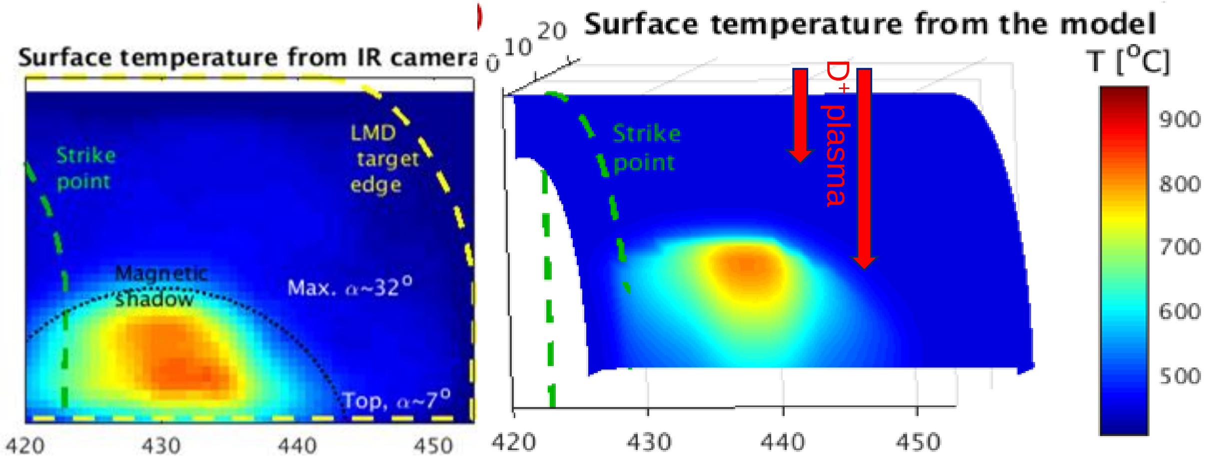


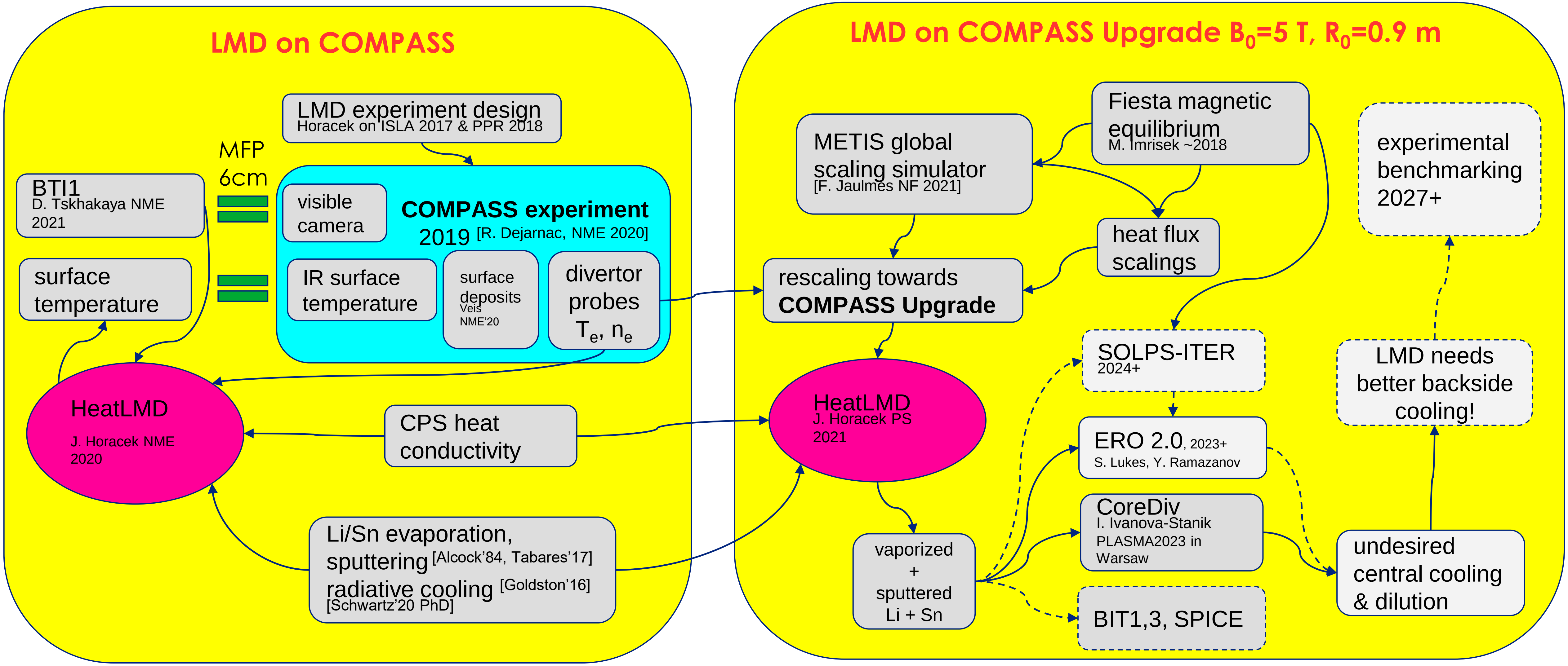




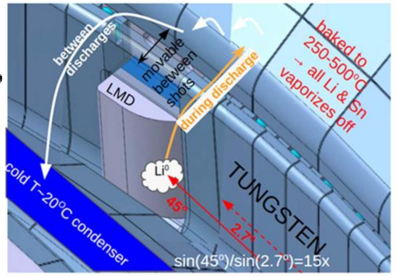
15 kJ/m^2 ELMs reveal strong surface thermal insulation of the CPS: 1 MW/m^2/K. If absent, dT~3K! Why? Is it a general CPS property?

mystery!

LMD program on COMPASS(-U) to sustain extreme heat load density



J Horacek[1], J Cecrdle[2,*], D Tskhakaya[1], R Dejarnac[1], J Schwartz[3], M Komm[1], J Cavalier[1], J Adamek[1], S Lukes[2,*], V Veselovsky[1], J Varju[1], P Barton[1], S Entler[1], Y Gasparyan[4], E Gauthier[5], J Gerardin[1], J Hromadka[1], M Hron[1], M Iafrati[6], M Imrisek[1], M Jerab[1], K Kovarik[1], G Mazzitelli[6], D Naydenkova[1], G Van Oost[4,7,8], R Panek[1], A Prishvitsin[4], J Seidl[1], D Sestak[1], M Tomes[1], Y Vasina[4], A Vertkov[9], P Vondracek[1] and V Weinzettl[1]



Predictive modelling of liquid metal divertor: from COMPASS tokamak towards Upgrade. *Physica Scripta* **96** (2021) 124013
Will be published

liquid metal *prompt redeposition*	**unit**	**Li** *R=0*	**Li** *R=0*	**LiSn** *R=0*	**Sn** *R=0.9*	**LiSn** *R=0*	**Sn** *R=0.9*		**LiSn** *R=0*	**LiSn** *R=0*	**Sn** *R=0.9*
plasma mode	Set-up	**L-mode[3100]**	**R_0=0.9 m, medium power H-mode [#3210], 2.5 T, 0.8 MA, P_{in}= 2_{NBI} + 0.6_{Ω} MW**								
divertor target		**At manipulator with T_{back}=250°C, hot spot only few cm^2**						**full toroidal divertor 1000 cm^2 at 3° from Fiesta**			
Cooling		**1 mm CPS on 4 mm Copper cooling pipe**				**¼ mm CPS on 2 mm Copper cooling pipe**		**1 mm CPS on 4 mm Copper cooling pipe**		**inertial** heat sink into 2 cm W in 2 s	
Equilibrium temperature	°C	700	900 850 ELMs	1050 1000 ELM	1900 2000 ELMs	1000 950 ELMs	1700 2000 ELMs	700		800	1350
Plasma heat flux $q_{\perp}$	Inter-ELM Energy fluxes MW/m^2	+36	**attached DEMO-like: +160**					**+16**			
Copper conduction + absorption in water		-18	-15	-25	-45	-70	-130	-16	-8	-3	-14
Sputtering		-15	-45	-15	-15	-30	-15	0-1	-4	-5	-1
Evaporation		-3	-100	-120	-100	-60	-15	0-1	-4	-8	-1
released	atoms	lithium			tin	lithium	tin		lithium	lithium	tin
Sputtered + Vaporized	grams / sec atoms / sec	0.04 $3x10^{21}$	0.4 $3x10^{22}$		0.006 $3x10^{19}$	0.2 $1.5x10^{22}$	0.0006 $3x10^{18}$		1.3 10^{23}	4 $3x10^{23}$	0.006 $3x10^{19}$
I.I. Stanik: **CoreDiv** **plasma2023.ipplm.pl** **Warsaw**	global plasma conse-quences	n/n= 2 %	core concentration = 9 % →dilution of fusion reactions P_{rad}^{Li} ~ 0.9 MW		**core cntr 10^{-3}** f_{rad}=0.8, Z_{eff}=1.5? P_{rad}^{Sn}~5 MW **→radiative collapse!**	**core cntr 8%** f_{rad}=0.5, Z_{eff}=1.8 P_{rad}^{Li} ~ 0.5 MW	**core cntr 10^{-4}** f_{rad}=0.5, Z_{eff}=1.45, P_{rad}^{Sn}=0.4 MW		acceptably strong	**radiative collapse!**	**core cntr 10^{-3}** f_{rad}=0.8, Z_{eff}=1.5? P_{rad}^{Sn}~5 MW →radiative collapse!

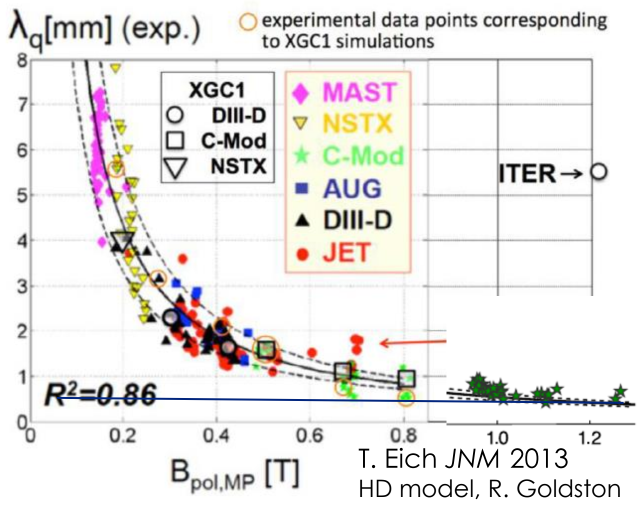
Baseline prediction for ITER

$q_\perp = (1-f_{rad})P_{SOL} / (2\pi R_0 \lambda_{int} f_x 2)$, $\boldsymbol{\lambda_{int} \sim 2\lambda_q}$

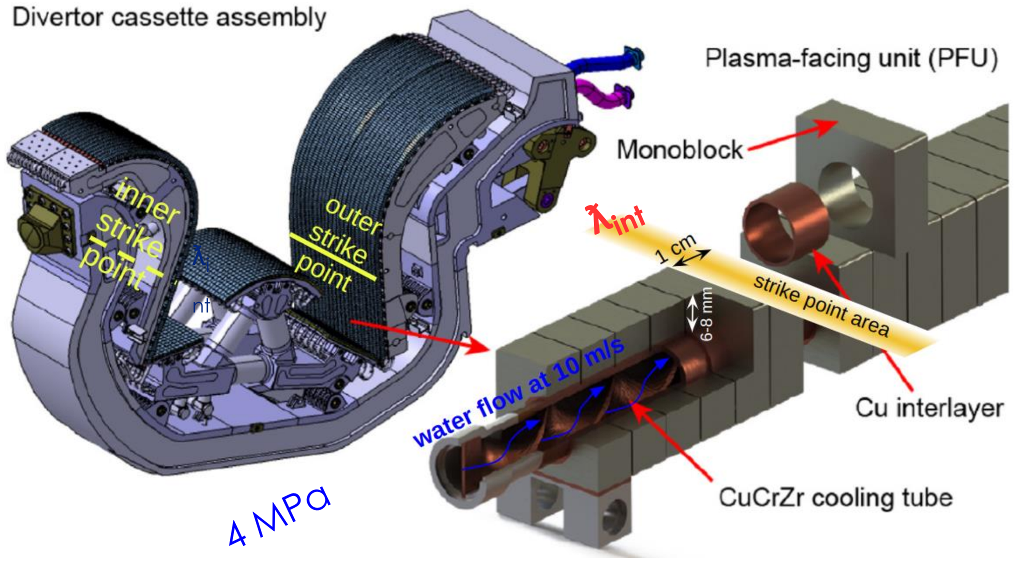
L-mode (just before L/H transition) Horacek, Nucl.Fus. 2020 attached f_{rad}=0.3, P_{fusion}~0 → $q_\perp$~10 MW/m^2

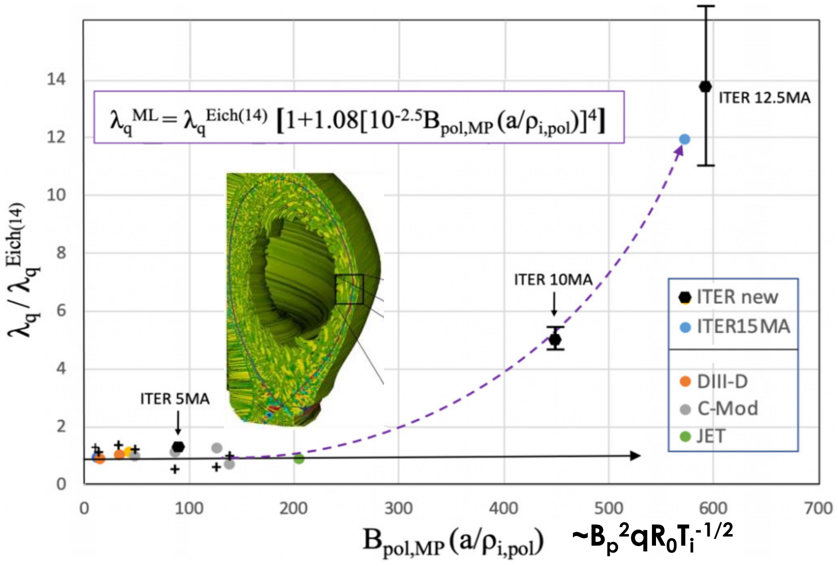
H-mode Q=10: P_{SOL}=100 MW → λ_q^H~½ mm Eich JNM 2013 → $q_\perp=(1-f_{rad})$*200 MW/m^2 … decreased by:

1. XGC1 consistent with experiments [C.S. Chang, Nucl. Fusion 57 (2017), Phys. Plasmas (2021)] predict λ_q^H=6mm, λ_q~R_0 thanks to "new turbulence" dominated by ITG mode → acceptable $q_\perp$<20 MW/m^2 Pitts, NME 2019. Accessible only in large enough B^2R_0 → experimental verification impossible until ITER
2. ELM-free f_{rad}=0.95 M. Bernert *Nucl. Fus.* **2021** by X-point radiator



ITER divertor survives
10 MW/m^2 (forever)
20 MW/m^2 (transients)





Outline

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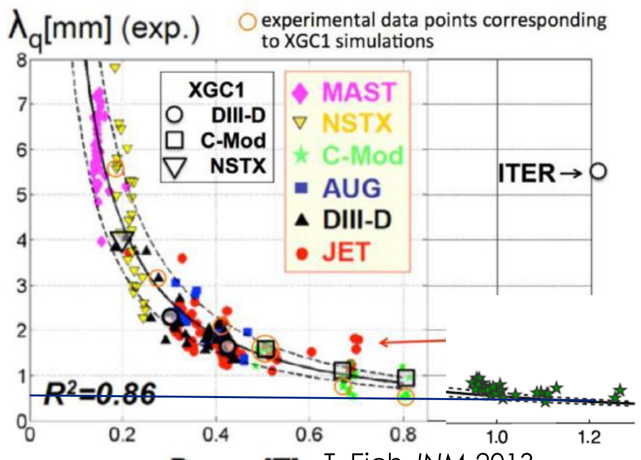
1. Liquid Li/Sn divertor survives steady & transients by evaporating … which will cool plasma :-(

1. **Why must PFC survive $q_\perp$>>10 MW/m^2**

1. Conceptual experiment of PFC surviving ~60 MW/m^2 → either liquid tin or W are feasible

Pessimistic turbulence & empirical predictions



T. Eich *JNM* 2013
HD model, R. Goldston

EU DEMO: 4x higher $q_\perp$ than ITER

Spherical tokamaks → small B^2R_0 → no enhanced turbulence as in XGC1

- **SPARC: $q_\perp$~350 MW/m²** A.Q.Kuang Plasma Phys. (2020) assuming f_{rad}=0.5
- **STEP: $q_\perp$~480 MW/m²** S.L. Newton IAEA ™ 2022 at inner target with f_{rad}=0.

GBS: excellent match with COMPASS [P. Macha EU-US TTF 2023]

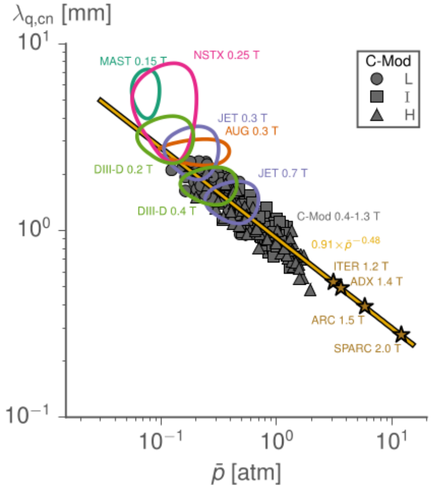
No free parameter in contrary to SOLPS.

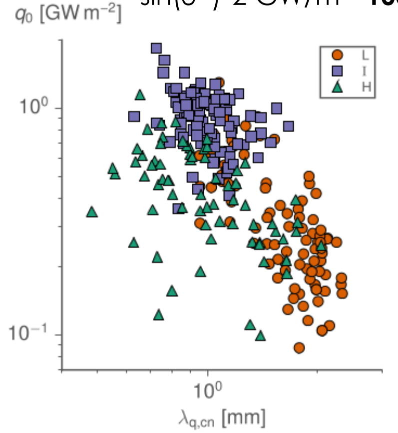
Simulation of ITER impossible.

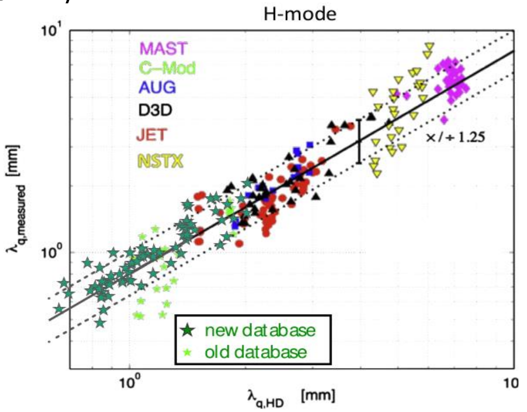
[Giacomin NF 2021] derived:

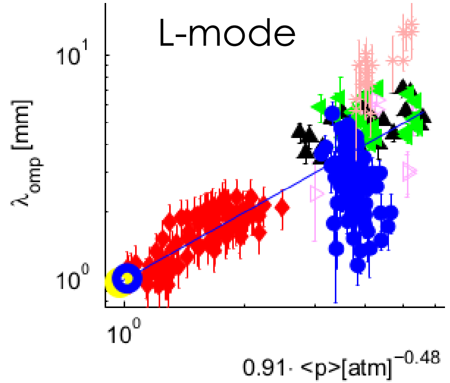
$$L_p \simeq 5.6 A^{1/17} q^{12/17} R_0^{7/17} P_{\rm SOL}^{-4/17} a^{12/17} \times (1+\kappa^2)^{6/17} n_{\rm e}^{10/17} B_T^{-12/17},$$

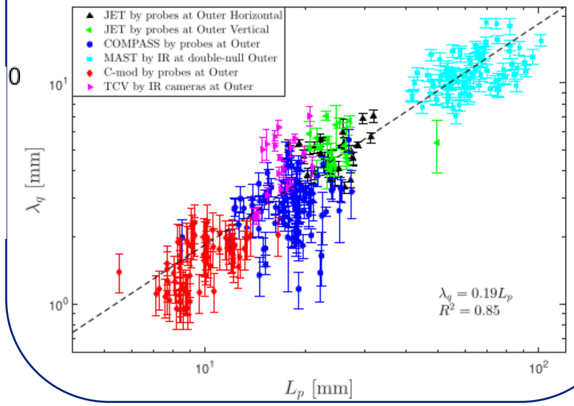
D. Brunner P_{fusion}=0
Alcator C-mod on divertor
sin(3°)*2 GW/m²=**100 MW/m²**











→ new engineering solutions surviving >> 20 MW/m² wanted!

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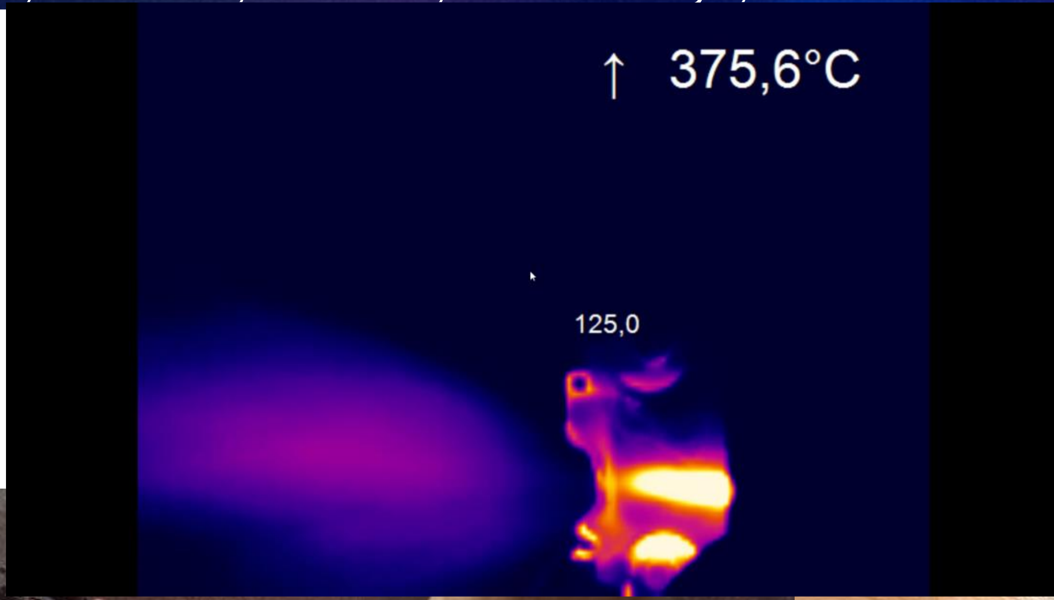
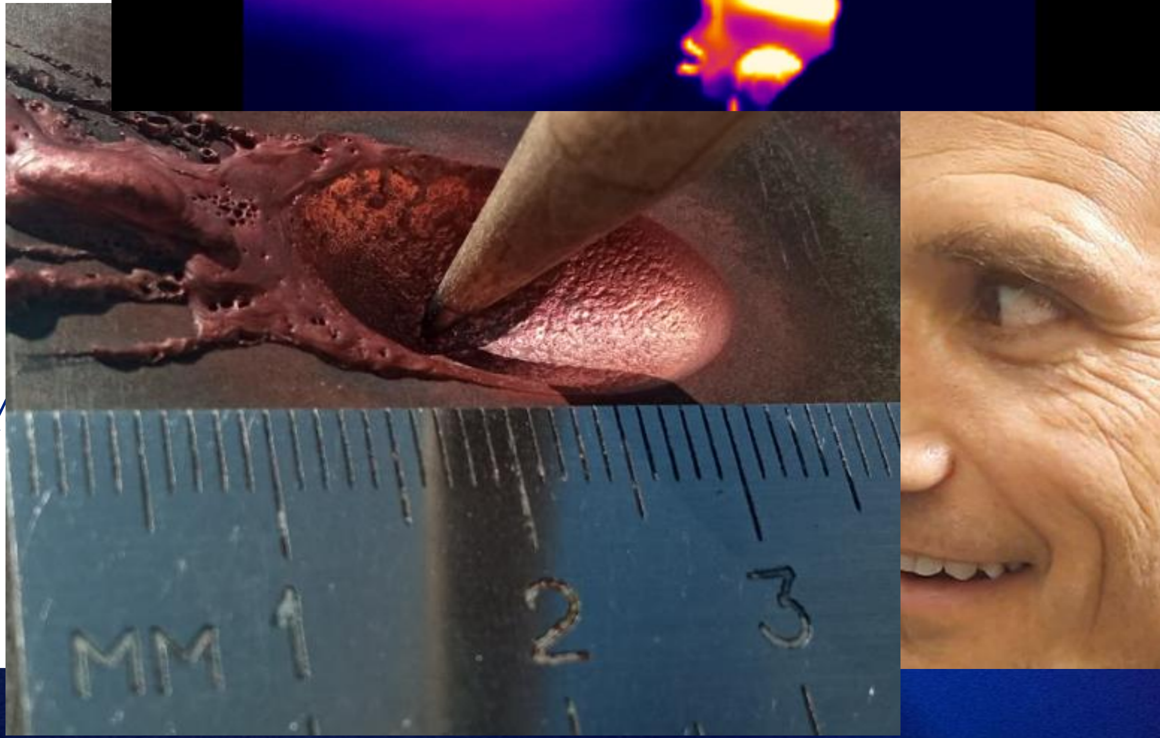
1. **Conceptual experiment of PFC surviving ~60 MW/m^2**

Water-cooled plasma-facing component survives 60 MW/m^2

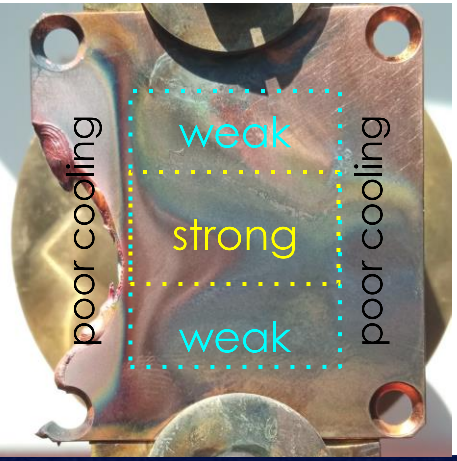
J. Horacek, T. Radnic, S. Lukes, V. Sedmidubsky, A. Horachek, D. Sestak, M. Bousek, Z. Kutílek, M. Janata, Sedlacek, S. Entler, D. Tskhakaya, V. Weinzettl

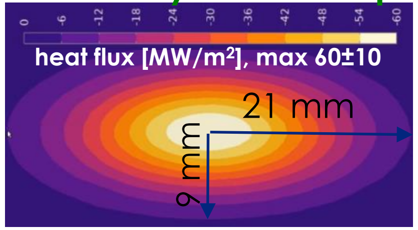




16 kW

Conceptual experiment at air plasmatron cooled by water at speed 0.8 m/s, zero pressure





IR video of graphite bloc (reaching 3800°C in 0.6 s)

COMSOL Multiphysics 3D+time heat conduction.

Asking for a national project for systematic study & closing the water flow

Summary

- ★ Unmitigated ITER ELMs sin(4.5°)·15 MJ/m² melt tungsten
  - ○ Fast strike point sweeping 7 cm, 1.3 kHz, 18 kV → surface temperature suppression by a factor of 3 on EU DEMO. Can be multiplied by RMP & seeding,

J. Horacek, J. *Fusion Eng. Des.* **123** (2017) 646–649

J. Horacek, Scientific Reports (2022) 12:17013

Czech liquid metal divertor tokamak program since 2017:

- ★ **COMPASS:** single ***LiSn*** **PFC survived**
  - ○ 12-16 MW/m²
  - ○ 15 kJ/m² ELMs
  - ○ major VDE disruption
  - ○ plasma unaffected
  - ○ vapor shielding unreached ←short discharge
  - ○ *LiSn* doesn't oxidize
  - ○ *LiSn* evaporates only *Li*
- ★ **COMPASS-U:** Fiesta+Metis+scalings+HeatLMD+CoreDiv **simulations**:
  - ○ full toroidal divertor (1000 cm²) with 16 MW/m²: acceptable with cooling max. 4 mm under W surface, better with pure Tin
    - ■ easy inertial cooling: unacceptable after 1 second
  - ○ single LMD (few cm²) at 45° exposed to 160 MW/m² H-mode
    - ■ Li(Sn): acceptably low plasma cooling but 9% core plasma dilution → lower P_{fusion}
    - ■ Sn: radiative collapse with conventional cooling
      - ● acceptable only with backside cooling with 130 MW/m² → ¼ mm CPS + 2 mm Cu

R. Dejarnac, *Nuc. Mat. Energy* **25** (2020) 100801

J. Horacek, *Nuc. Mat. Energy* **25** (2020) 100860

P.Veis, *Nuc. Mat. Energy* **25** (2020) 100809

J. Horacek, Physica Scripta 96 (2021) 124013

- ★ ITER expects in detached Q=10:
  - ○ 190 MW/m² from empirical scalings
  - ○ <16 MW/m² thanks to much wider divertor footprint from ITG turbulence in XGC1, accessible likely in ITER only
- ★ Decreased 20x in AUG X-point radiator in 2021
- ★ Attached STEP & SPARC divertors expect 350-480 MW/m²
- ★ ITER divertor survives 10 (forever) - 20 MW/m² (shortly)

→ our innovative water PFC concept survived plasma jet 60±10 MW/m² !

→ asking for a national project, your email support appreciated :-).

Thanks for your attention, questions welcome

RESERVES for discussion

INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

Innovative concepts for extreme heat load tokamak divertor

J. Horacek

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Dynamic simulation of heat conduction in tungsten target

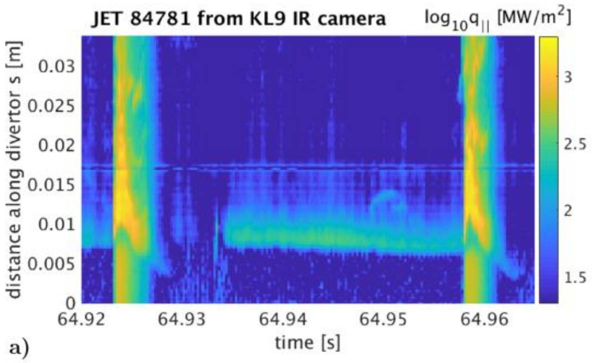
Horacek, J. *Fusion Eng. Des.* **123** (2017) 646–649

Inputs:

- **JET IR camera in Type-I ELMy H-mode**
- **Rescaled to DEMO**

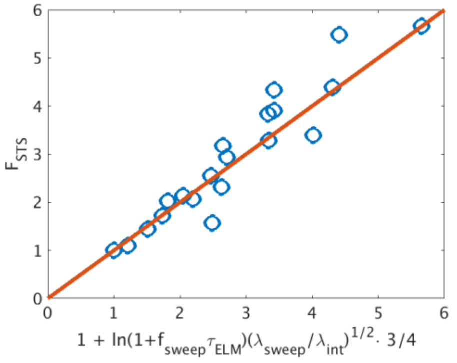
space: $\lambda_q^{JET}/\lambda_q^{DEMO} \sim (B_{pol}^{JET}/B_{pol}^{DEMO})^{-1.5} \sim 3$

time: $L_{||}^{DEMO}/L_{||}^{JET}(T^{ped,JET}/T^{ped,DEMO})^{1/2} \sim 3{:}1/(1{:}6)^{½}=1.$



Output Surface Temperature Suppression rise, F_{STS} ratio

- **swept strike point**
- **normal fixed strike point**



Empirical scaling found:

used for further system optimization

ITER divertor cooling

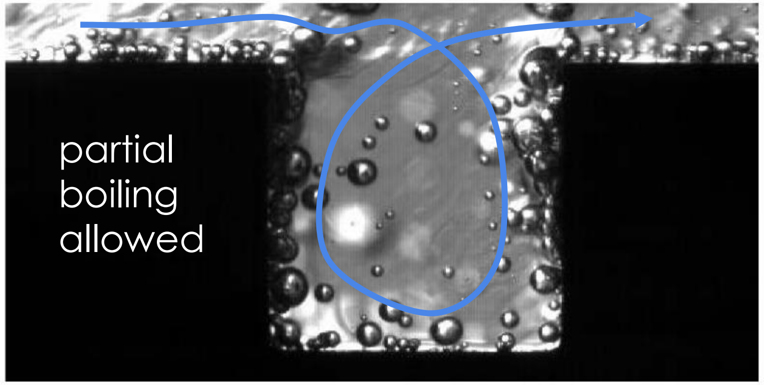


Figure 31: Vapour production in HyperVapotron-like cavity (p=3.5MPa, V=0.2m/s, T_w-T_{sat} = 4.3K)

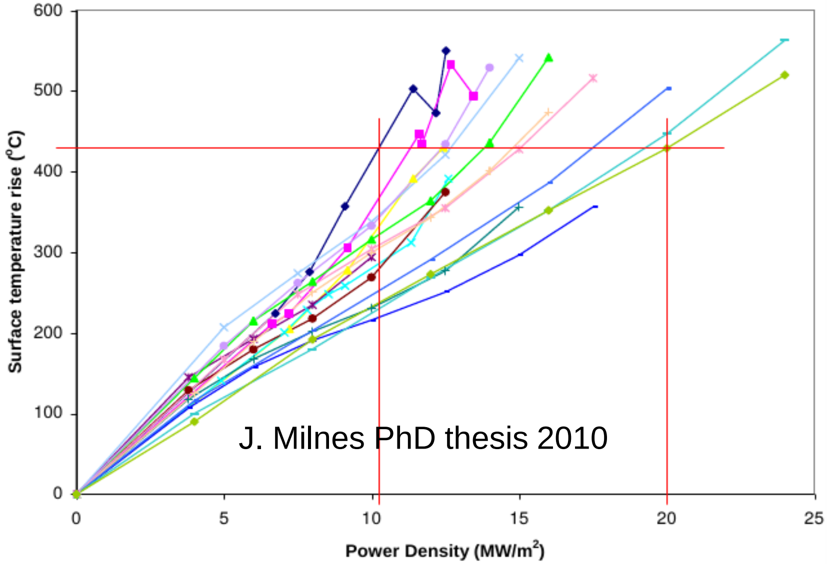
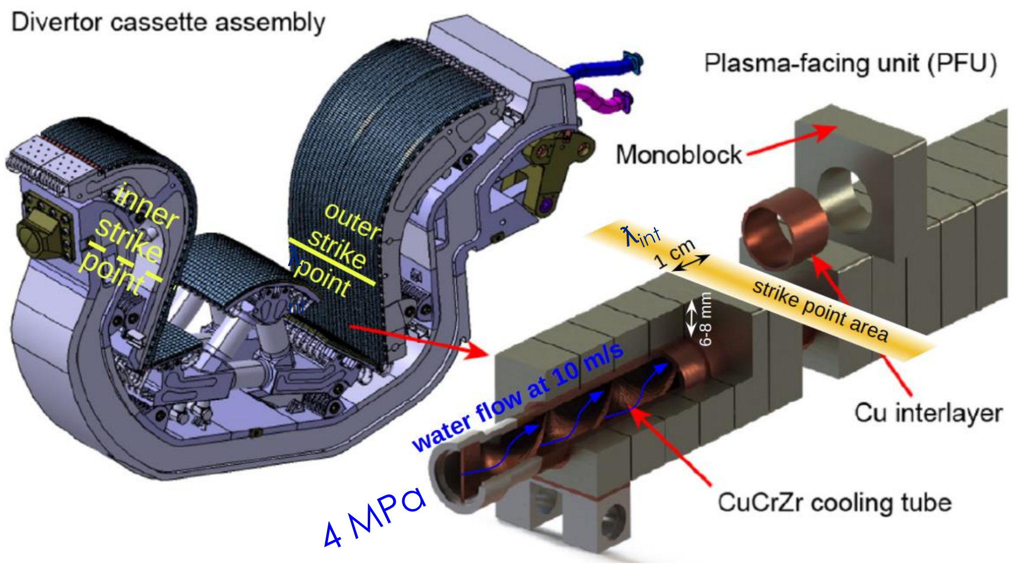
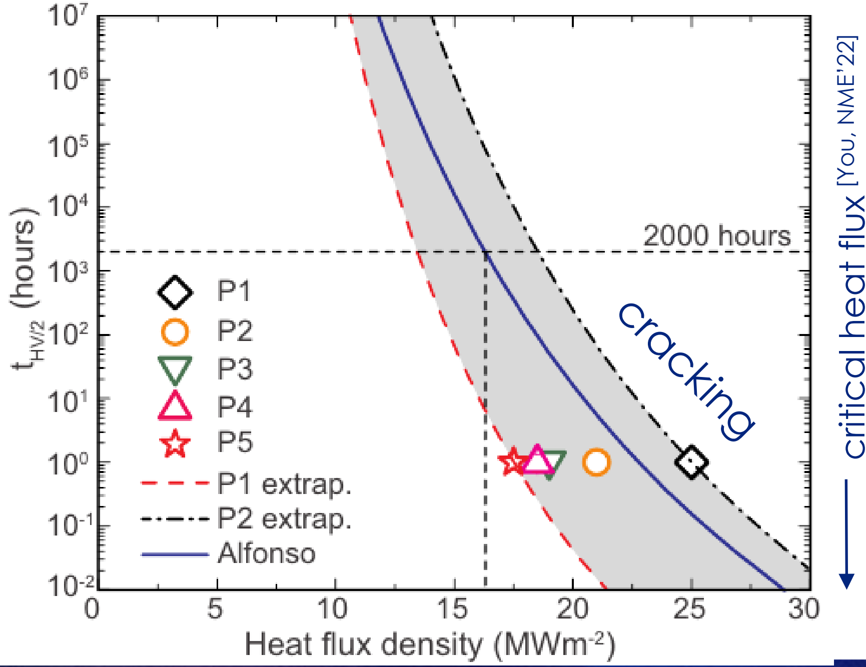


Figure 34: HyperVapotron performance comparison (normalised to 3mm fro

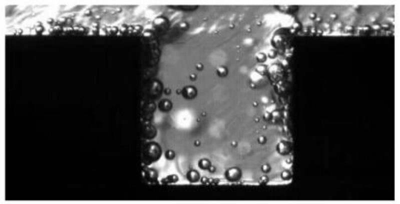


W surface temperature (~100x heat flux) determines the lifetime of the heat shield



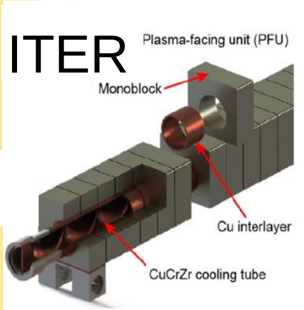
Predicted & Survived heat loads

Hypervapotron



soft limit

ITER



hard limit

EUROFER-97

Survived cooling capability

Liquid metals have no limit, however, if not partially cooled, its vapor cools the plasma

Water-steam supercooling First experiment

No

10^0 10^1 **W/mm² = MW/m²** 10^2 10^3

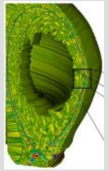
Predicted plasma divertor heat flux $q_\perp$

EU DEMO 1^{st} wall [Wenninger 2017]

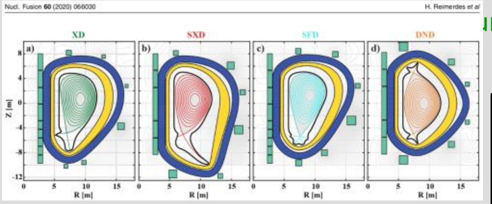
ITER attached L-mode Q=0 by scalings

ITER detached H-mode Q=10 SOLPS

New kinetic effect turbulence in large enough $B_{pol}a/\rho_{i,pol}$ in extremely demanding 3D kinetic simulation [Chang 2021] increasing λ^{mid}_q from ½ mm to ½ cm



Real-time controlled impurity seeded (X-point) radiator Bernert 2021



...urations

Measured on Alcator C-mod

attached!

ITER H-mode Q=10 by scalings

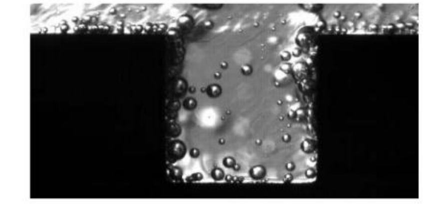
SPARC [Kuang 2019]

STEP [S.L. Newton]

lots of effort (-: effort)-:

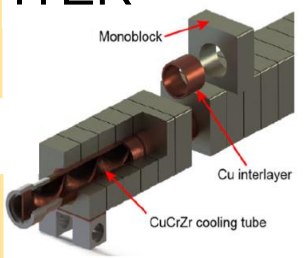
Predicted & Survived heat loads

Hypervapotron



soft limit

ITER



hard limit

Liquid metals have no limit, however, if not partially cooled, its vapor cools the plasma

Our Conceptual experiment

- impact water flow
- nucleate boiling
- no water pressure :-)

Survived cooling capability

0 50 $W/mm^2 = MW/m^2$ 100 150

Predicted plasma divertor heat flux $q_\perp$

ITER attached L-mode Q=0 by scalings

ITER detached H-mode Q=10 SOLPS

may be strongly decreased by

1. enhanced turbulence observable only for large enough $B_{tor} * R_0$ in extremely demanding 3D kinetic simulation → λ^{mid}_q increases from ½ mm to ½ cm
2. real-time controlled impurity seeded (X-point) radiation (1st observed in 2021)

ITER attached H-mode Q=10 by scalings

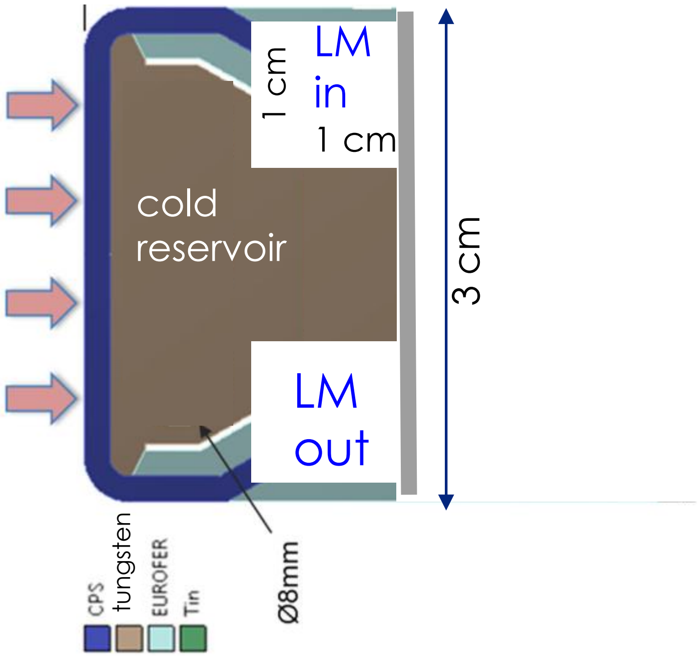
350 MW/m^2 predicted for attached SPARC, 480 MW/m^2 for STEP

Geometry of LMD

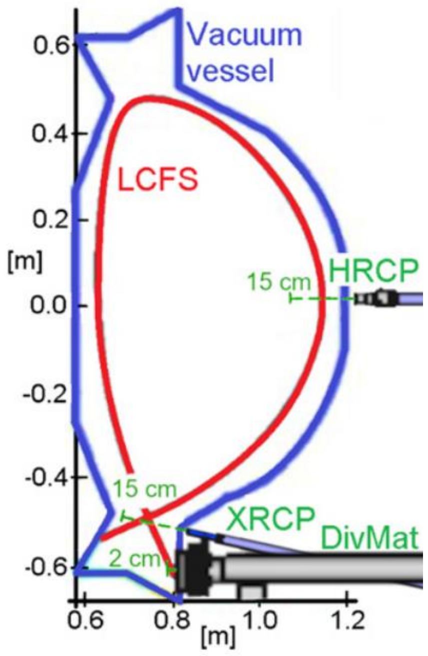
Inspired by [Roccella *J.Nucl.Mat.* 2020]

1. until ~2028 make it simple: no pipes
   a. → inertial cooling only
   b. → cannot use pure Li
2. keep space for pipes & cold trap later

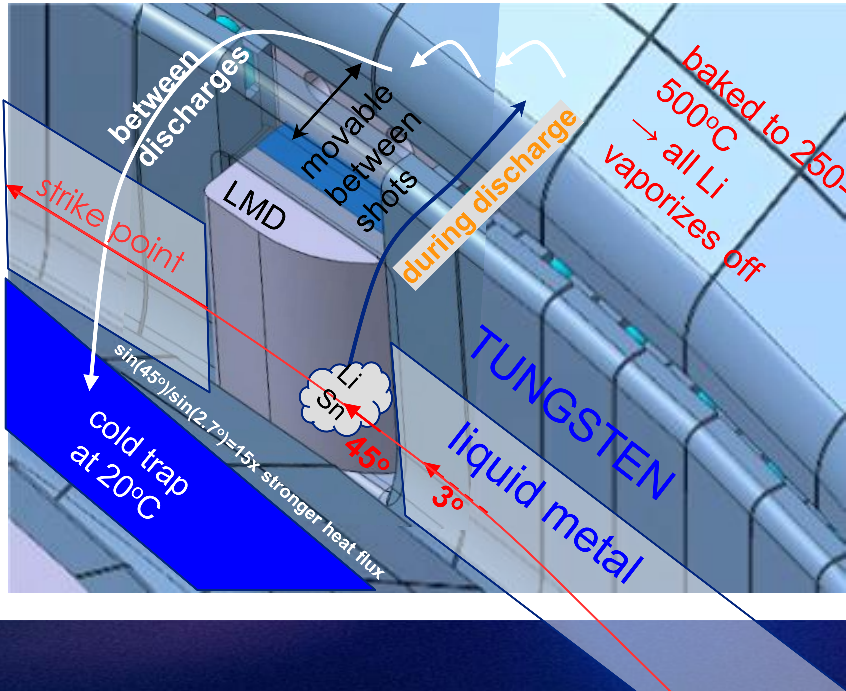
20 cm^3 of LiSn per discharge sputtered & evaporated
Without pipes, its enough for 1 only week operation :-(
For Tin, it's enough for years



S. Lukes, 2022 JINST 17 C02007

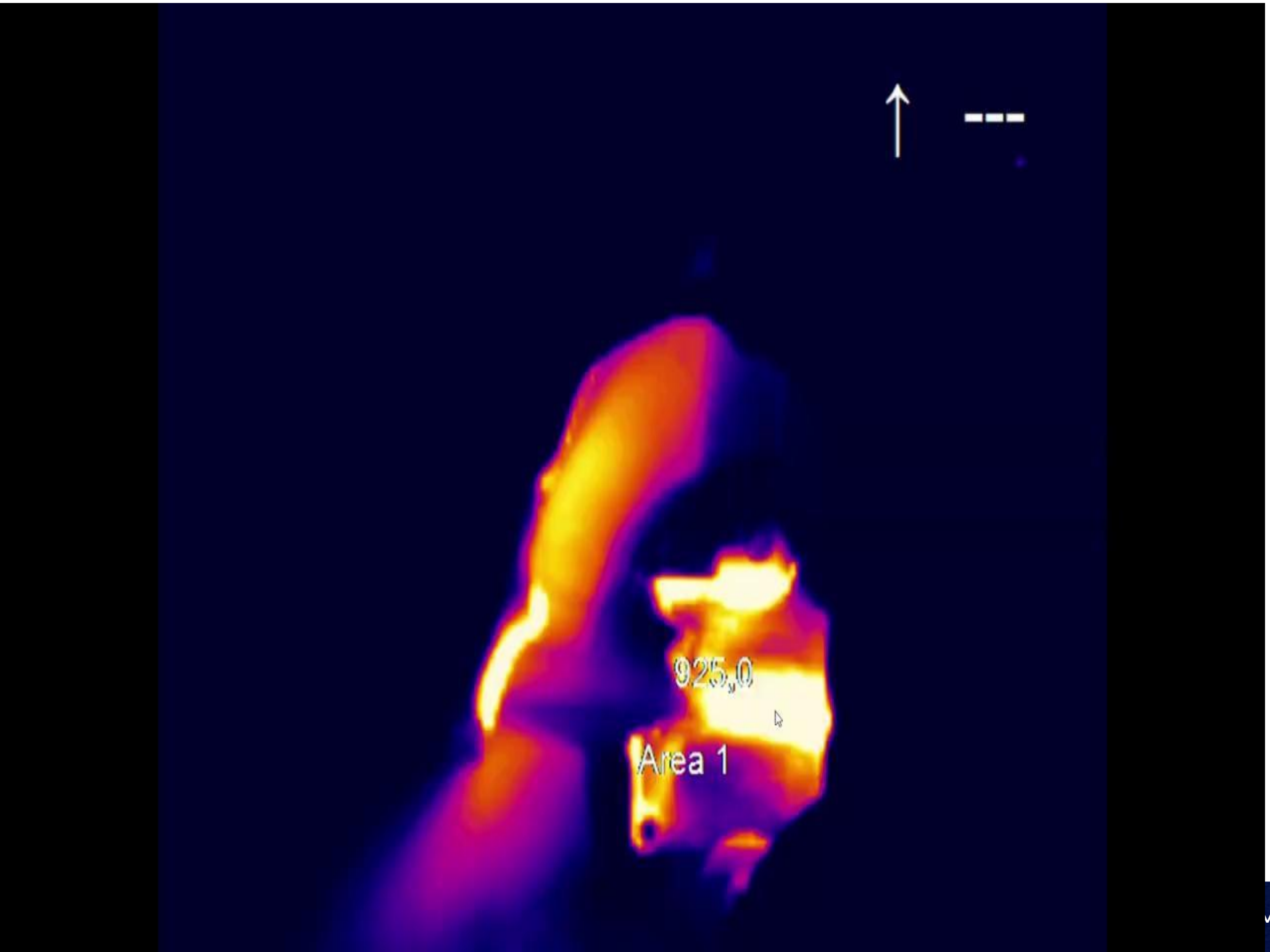


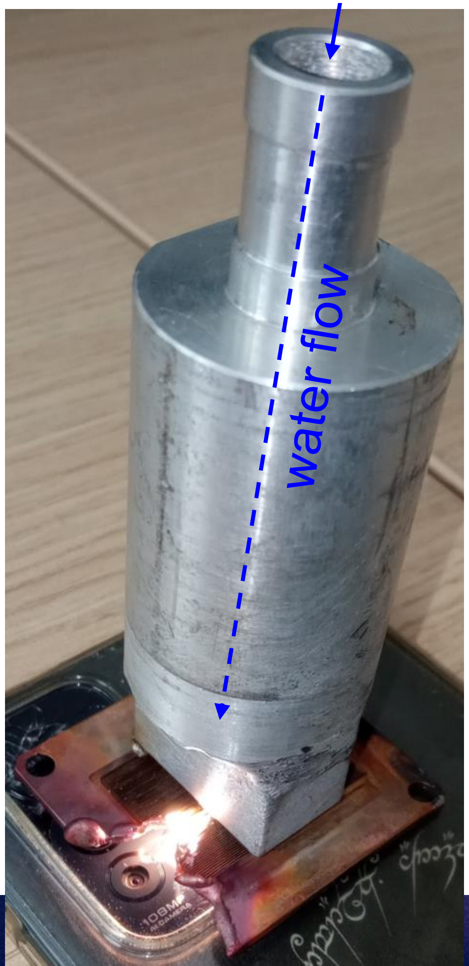
Condensation of Li/Sn on the wall and the cold trap will be simulated by SOLPS + ERO 2.0. Will this work ?

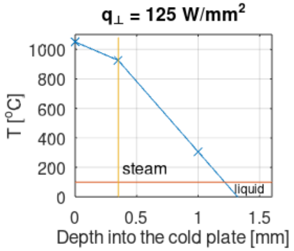


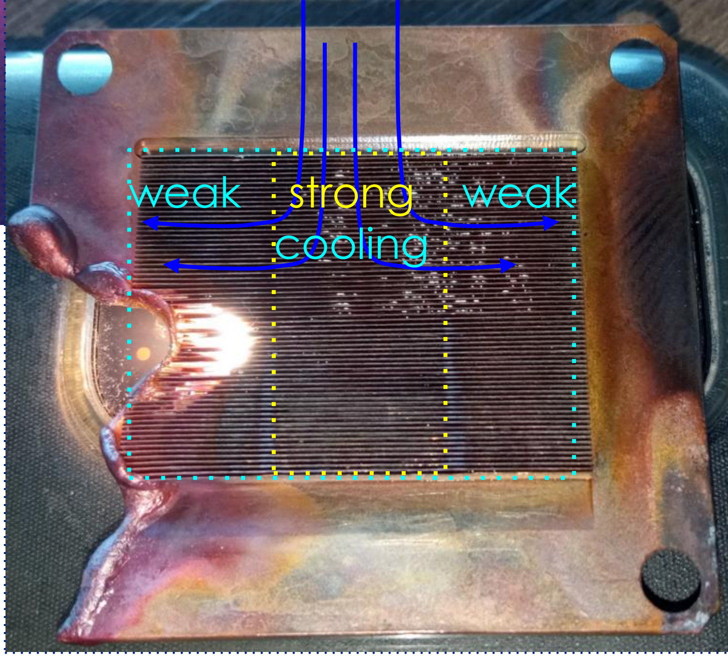
Plasmatron Exp.11: 5 cm off jet nozzle. 125±28 W/mm². 1.5 s

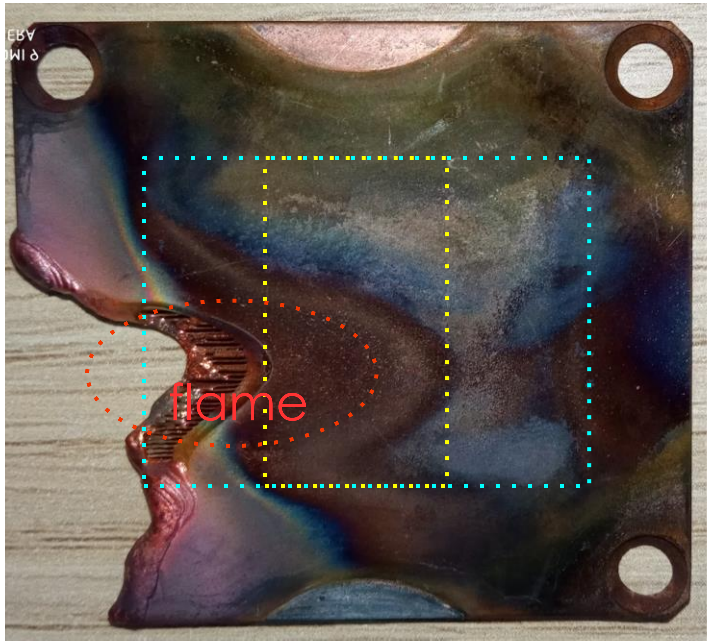
Melted only outside the perpendicular flow cooled area

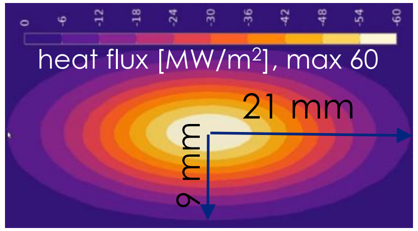


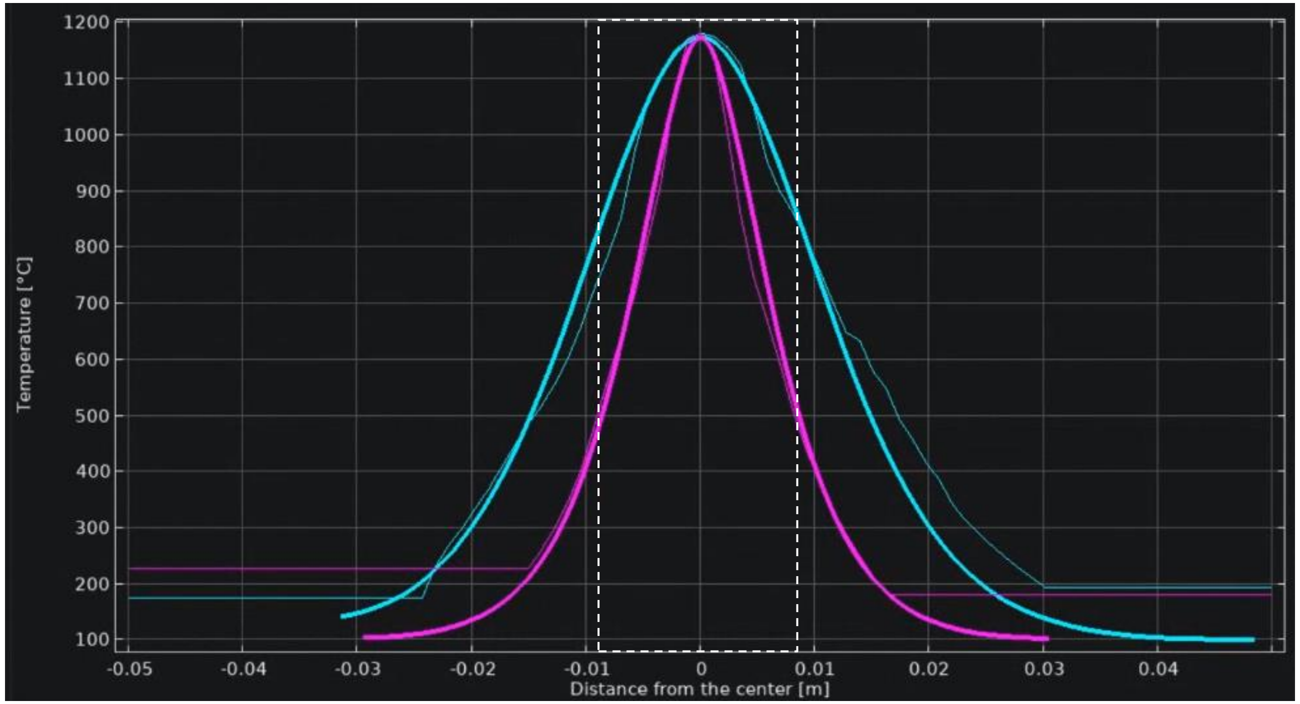


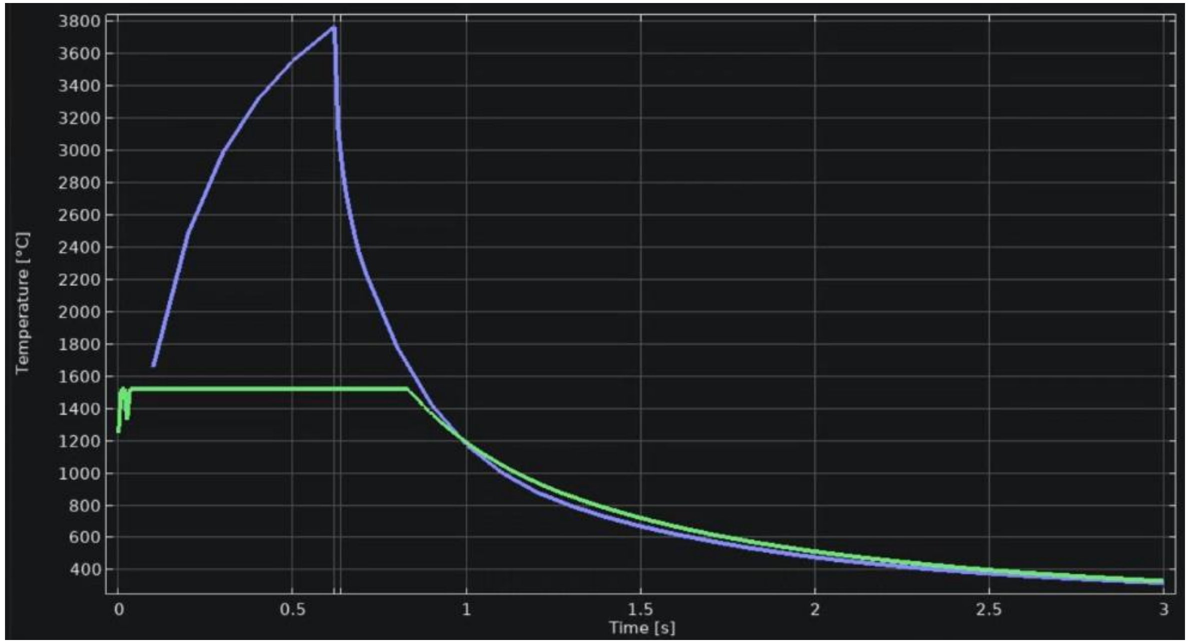







heat flux [MW/m2], max 60
0 -6 -12 -18 -24 -30 -36 -42 -48 -54 -60
21 mm
9 mm


Temperature [°C]
1200
1100
1000
900
800
700
600
500
400
300
200
100
-0.05 -0.04 -0.03 -0.02 -0.01 0 0.01 0.02 0.03 0.04
Distance from the center [m]


Temperature [°C]
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
0 0.5 1 1.5 2 2.5 3
Time [s]

Uncertainty: C-coil from a Litz wire conductor

- Litz wire passes AC current with the same resistance as DC
- DEMO neutron flux (~1 dpa/year in the divertor area!) → can not insulate each strand

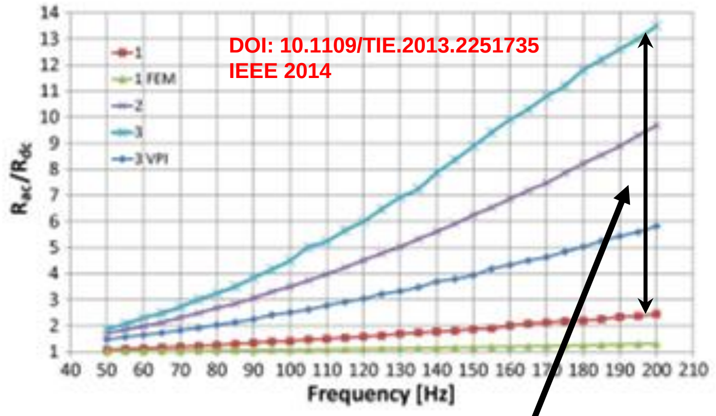
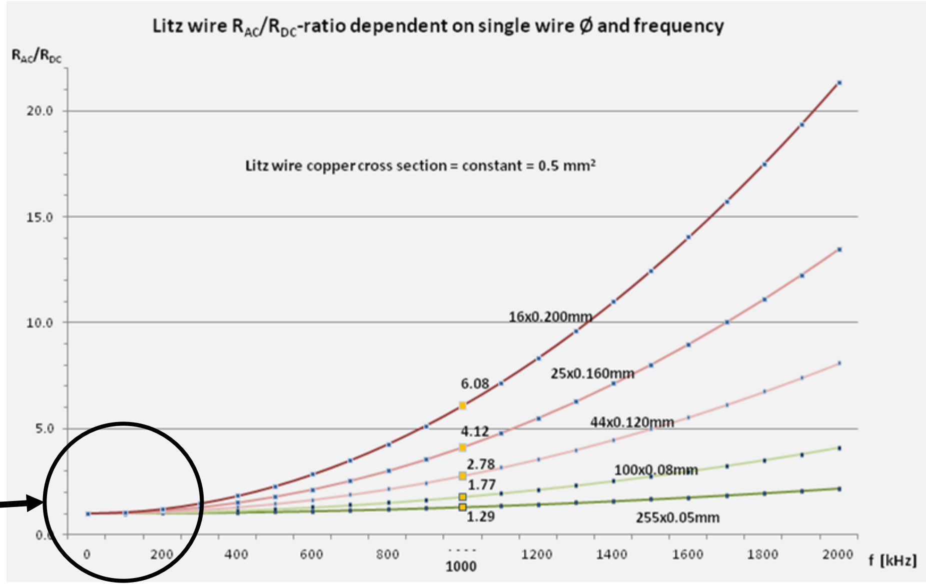
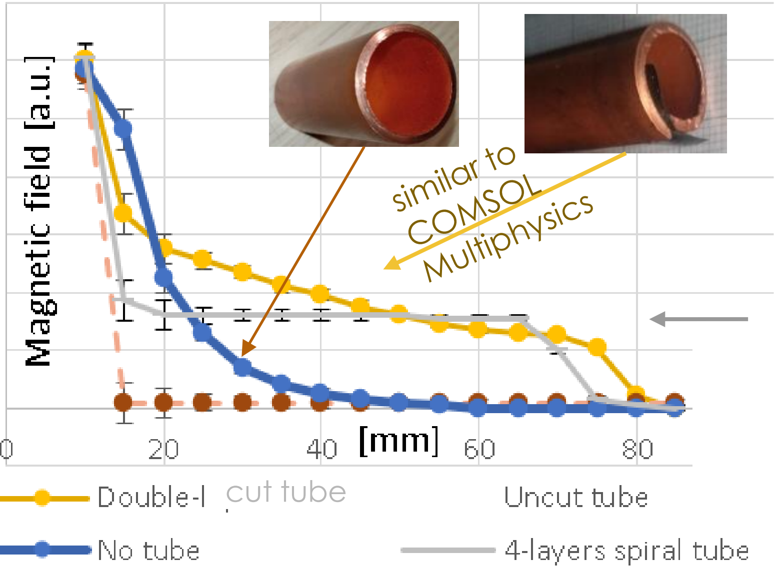


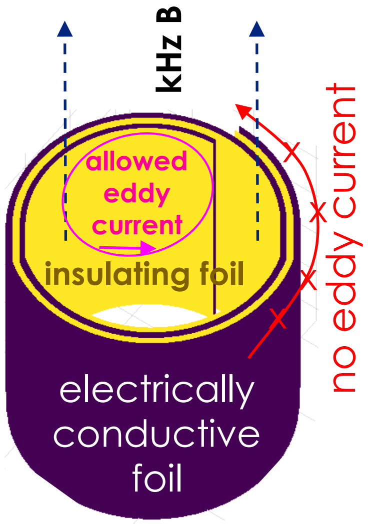
Fig. 10. Resistance factors from measurements and FEM. See legends in Table I.

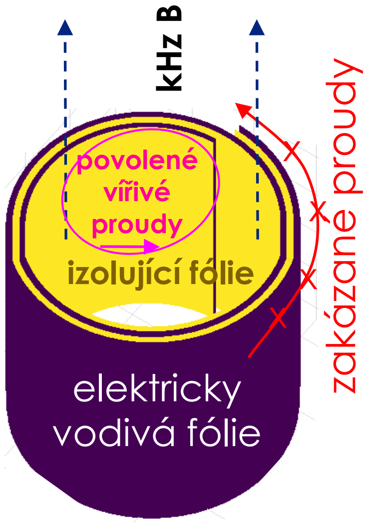


- Uninsulated Litz wire (Stranded wire) is ~6× worse, but for ~kHz still $R_{AC}/R_{DC}=1$

Experimental test of the AC B-conductor (GOLEM Tokamak Wiki - TrainingCourses/FTTF/2020-2021/SamuelLuk/index (cvut.cz))







Invented AC magnetic conductor to guide kHz B-field through a tube

- a simple axially-cut copper tube:
  - eddy currents suppress kHz B-field penetration
  - cut along its length elliminates poloidal eddy currents

COMSOL at DEMO scale:

- AC B-conductor increases B-field around X-point by **3**, maybe more

HeatLMD of LiSn full toroidal LMD in medium H-mode COMPASS-U