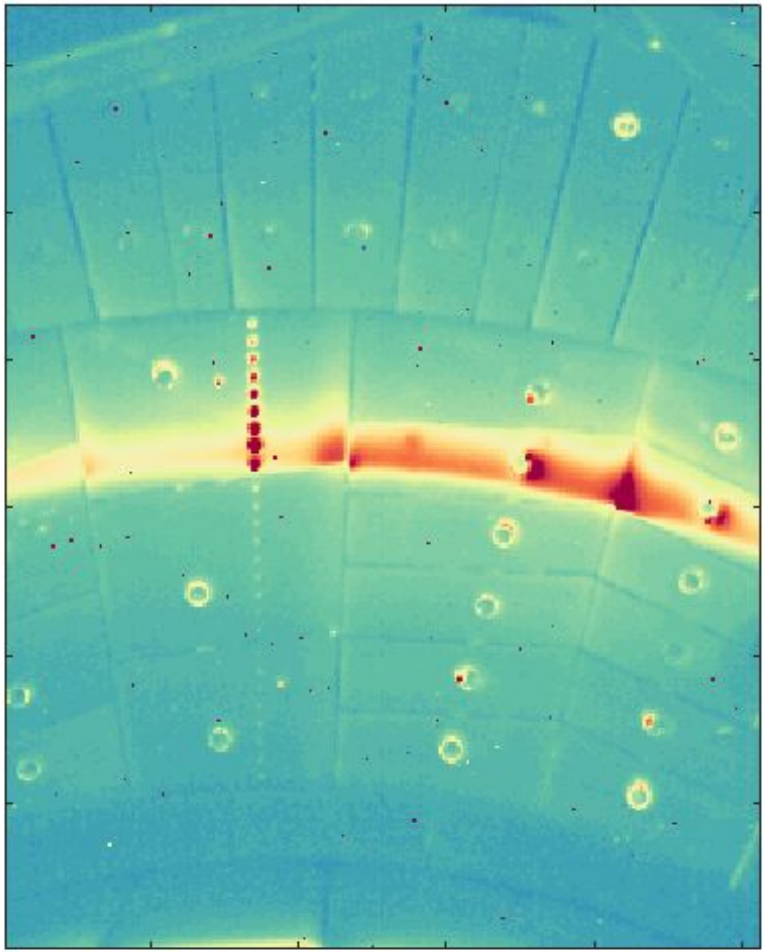
EPFL Swiss Plasma Center



Recent improvement in the infrared thermography diagnostic of TCV

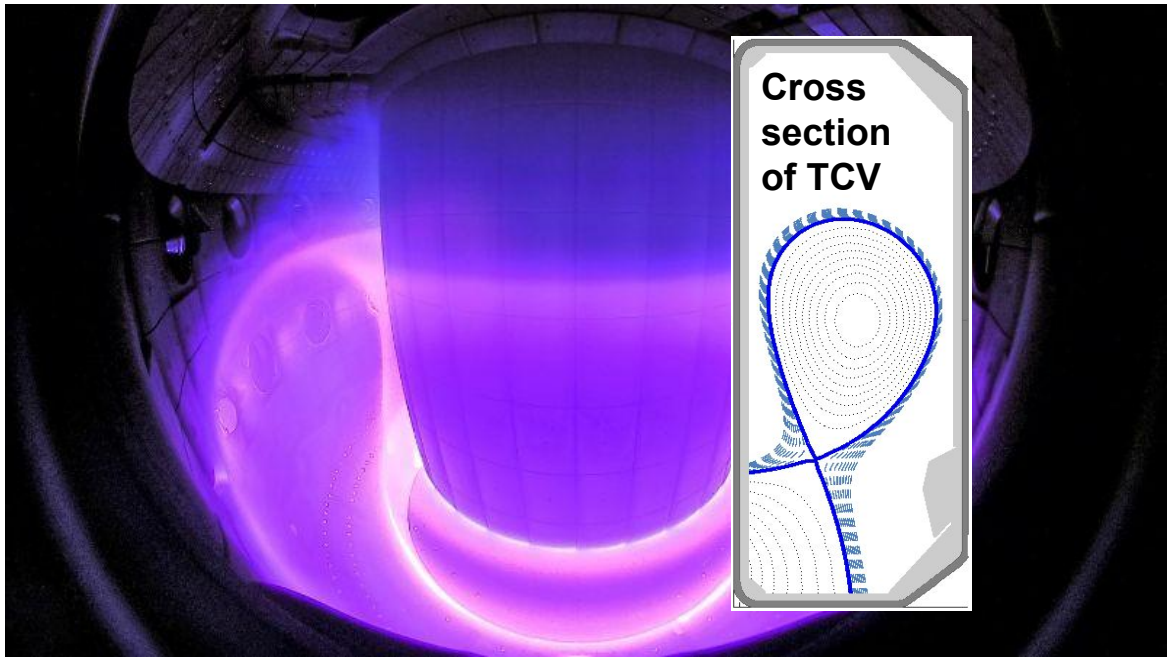
Martim Zurita

with Claudia Colandrea, Holger Reimerdes, Dmytry Mykytchuk, Marta Pedrini, and the TCV team

Joint Annual Meeting of the Swiss & Austrian Physical Societies, 8 September 2023, Universität Basel, Switzerland

Plasmas and tokamaks

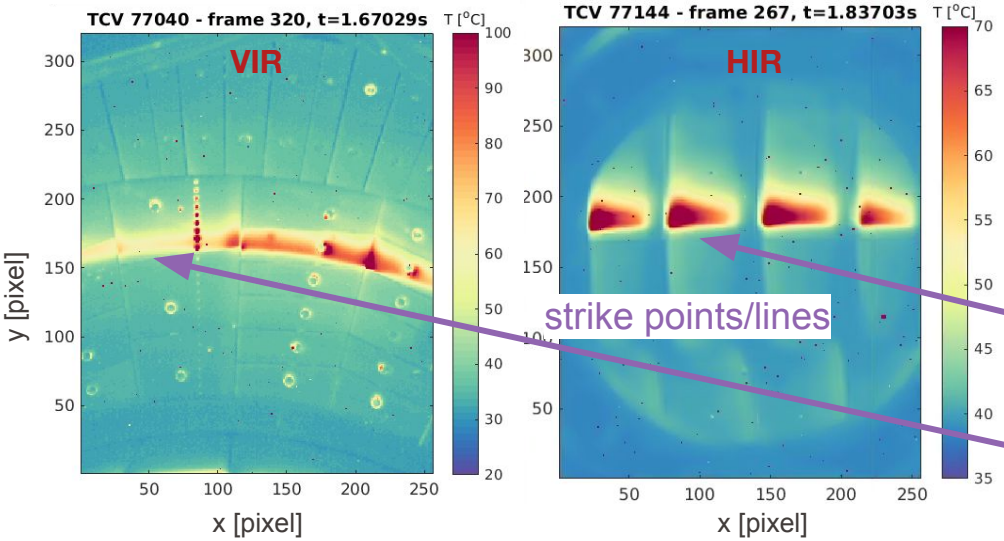
- Plasmas are ionised gases
- Tokamaks are devices that confine plasmas using magnetic fields
- The Tokamak *à Configuration Variable* (TCV) is located at EPFL

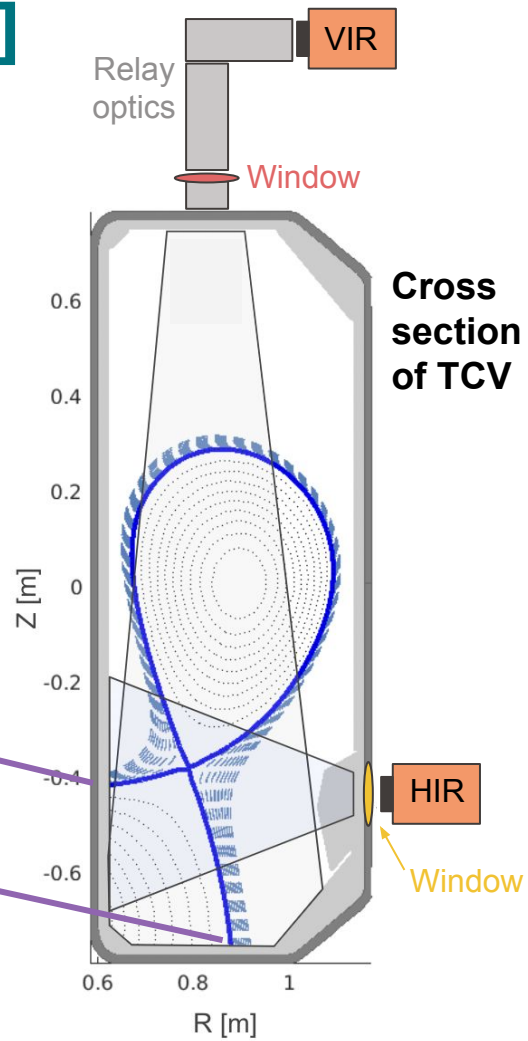


TCV interior during operation. Photo by Curdin T. Wüthrich.

Infrared thermography in TCV [1]

- Infrared thermography: images infrared radiation to get surface temperature
- Vertical infrared (**VIR**) camera: measures **temperature** on the tokamak floor
- Horizontal infrared (**HIR**) camera: measures temperature on the tokamak inner wall

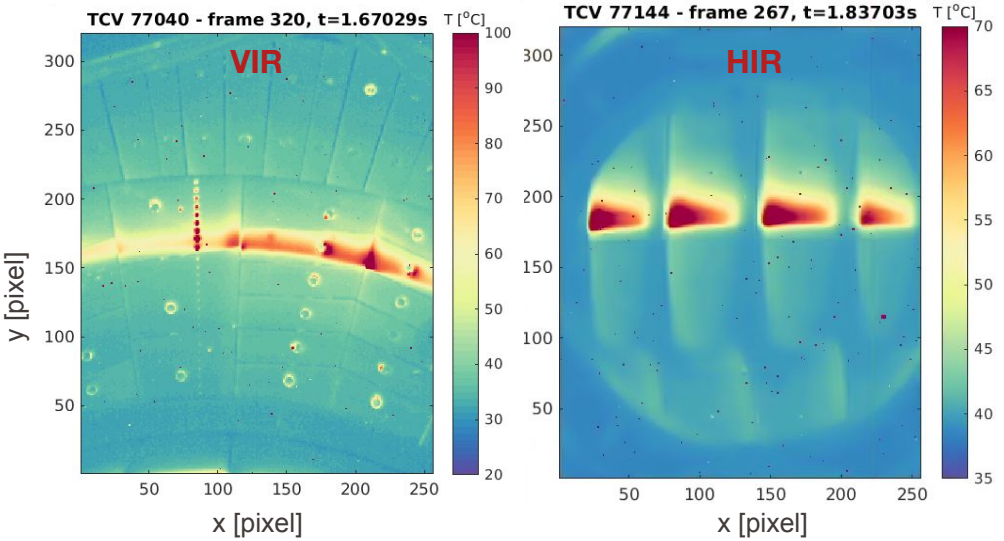


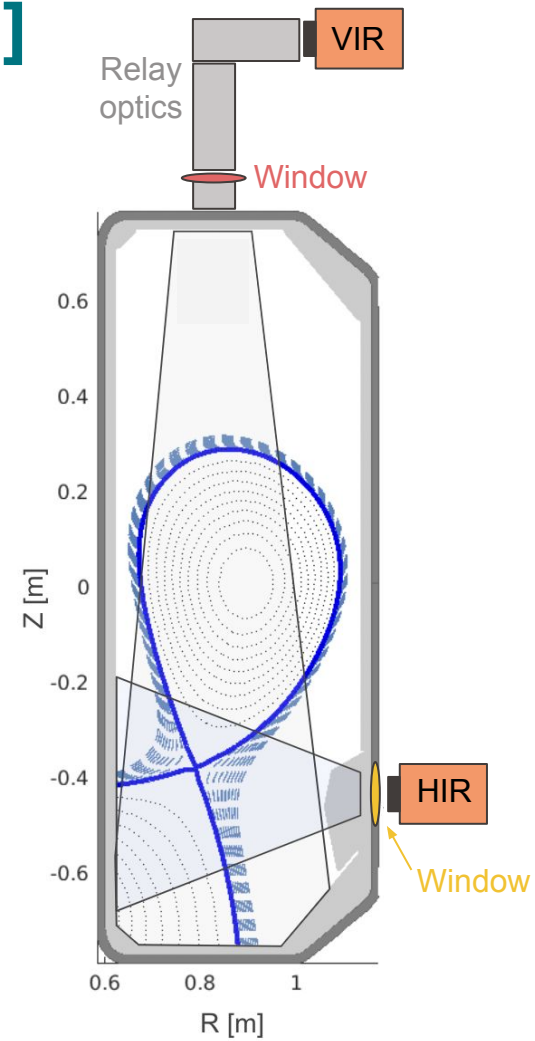


[1] Roberto Maurizio's PhD thesis, EPFL (2020)

Infrared thermography in TCV [1]

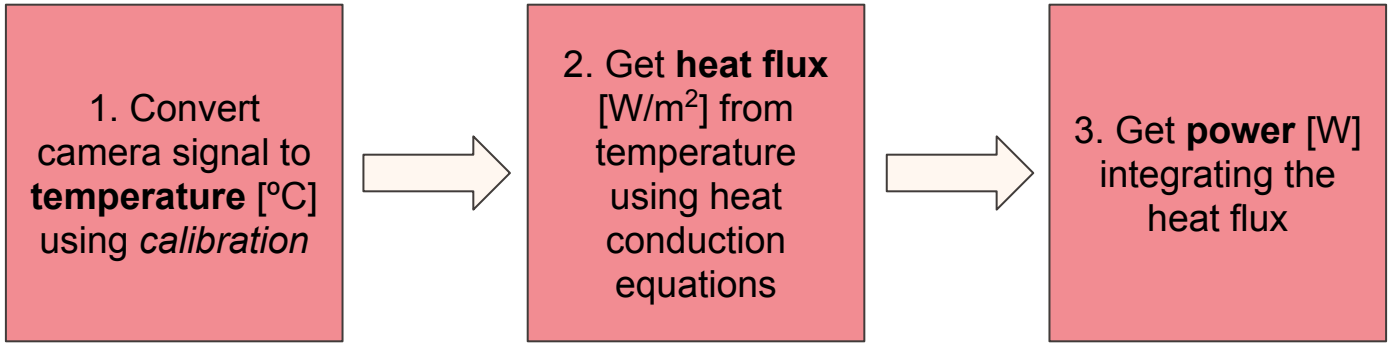
- Infrared thermography: images infrared radiation to get surface temperature
- Plasma is almost transparent in the infrared range measured by the cameras





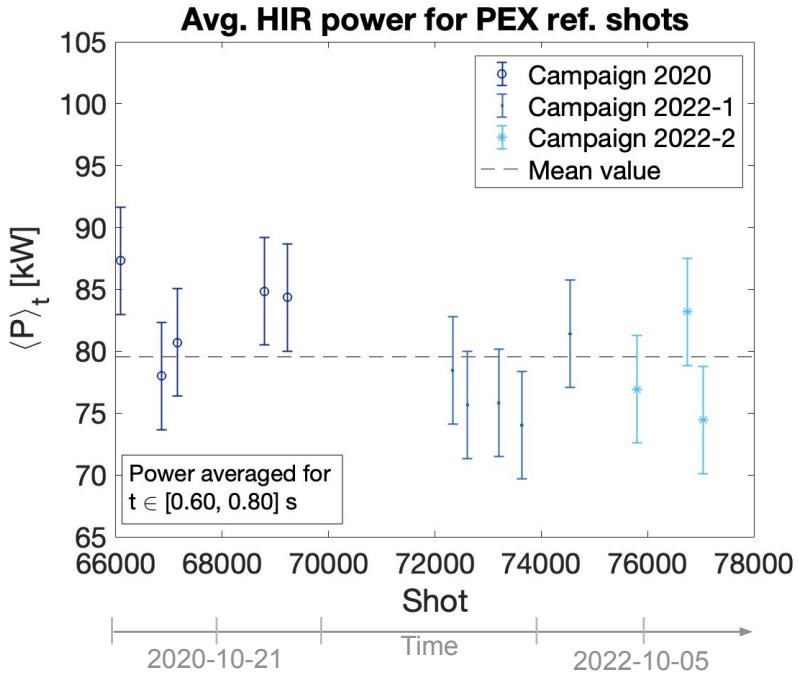
[1] Roberto Maurizio's PhD thesis, EPFL (2020)

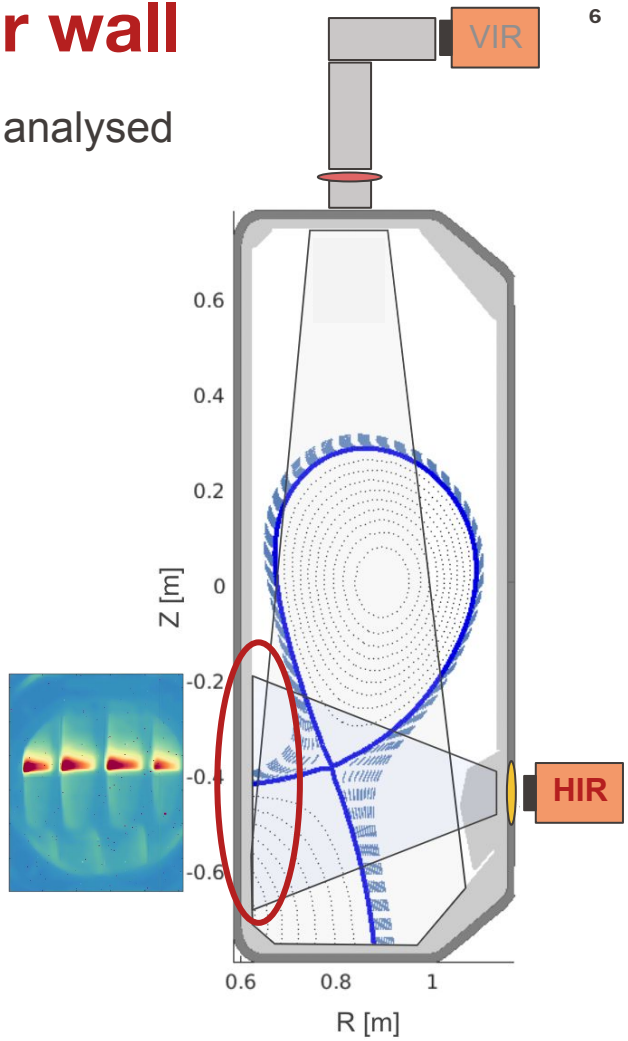
Infrared thermography (IR) workflow to measure power impinging on the wall



Ref. shots: power reaching inner wall

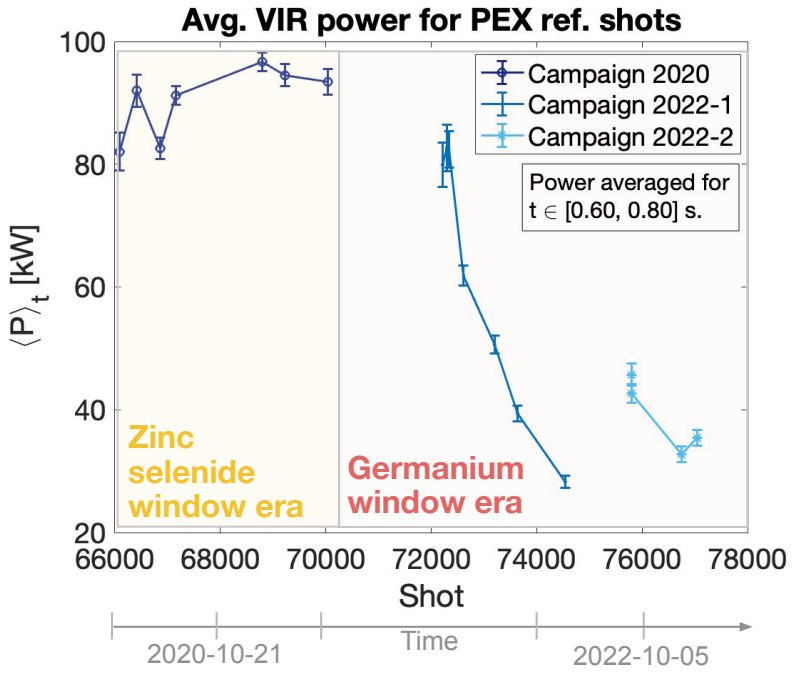
- Experiments (shots) with **same configurations** were analysed
- Power measured by HIR was approximately constant

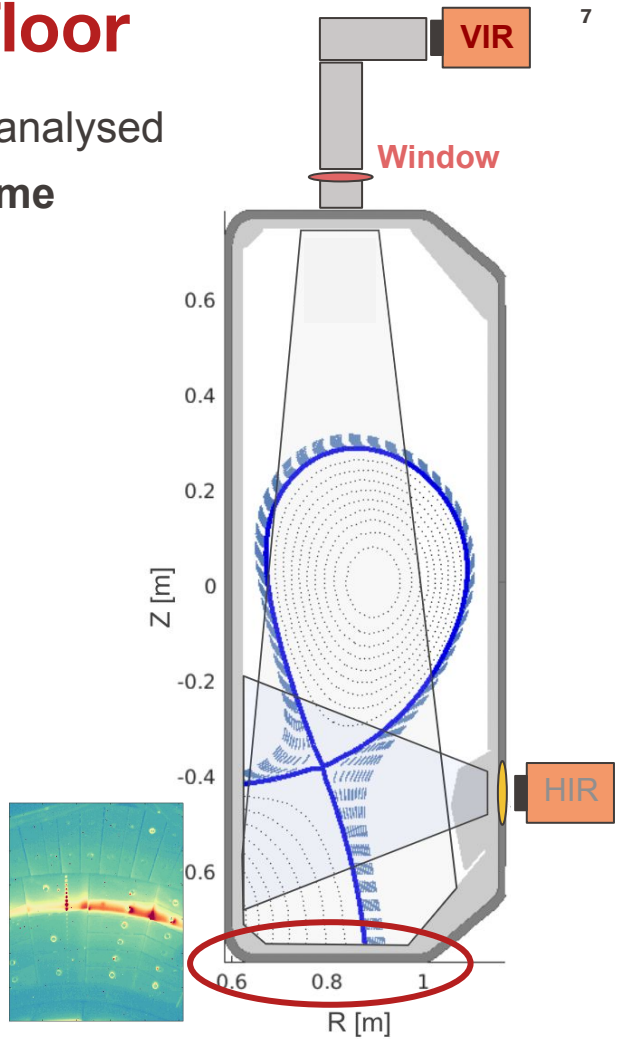




Ref. shots: power reaching the floor

- Experiments (shots) with **same configurations** were analysed
- **Power measured by VIR started decreasing with time when the window changed!**





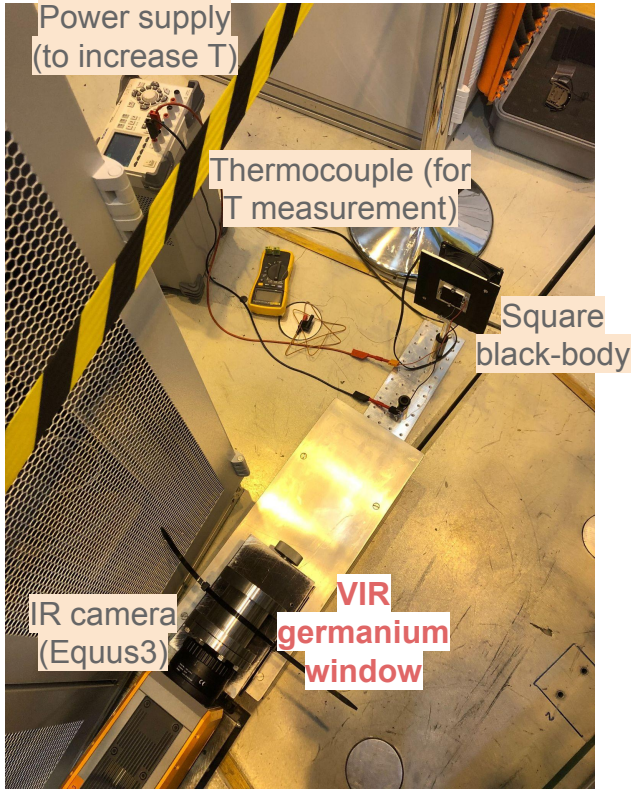
Components of the IR camera signal

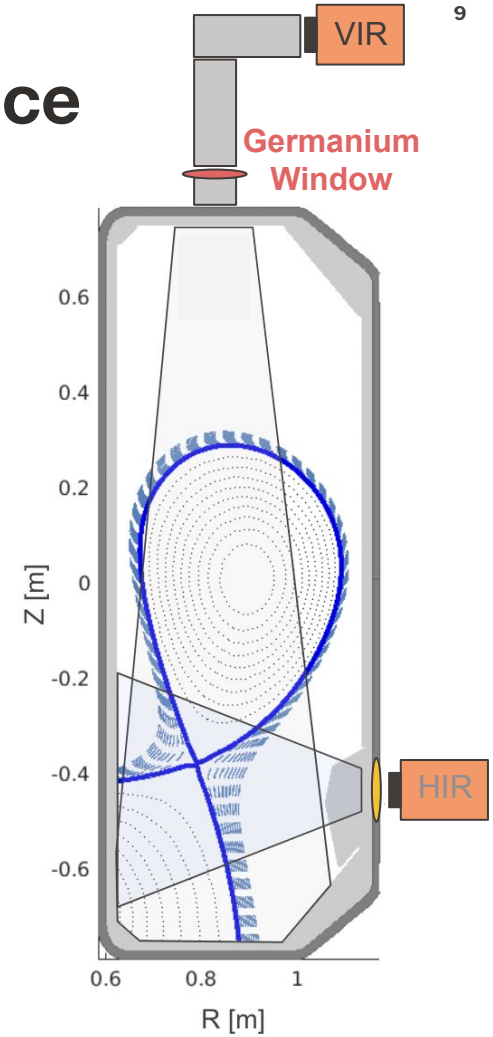
- Components of the IR camera signal, N:

$$N_{counts} = a_{HT}\,\Delta t_{int}\,I_{bb}(T) + B_{HT}(\Delta t_{int})$$

- N_{counts}: camera signal [counts]
- Δt_{int}: camera integration time (adjustable) [ms]
- I_{bb}: black body radiation intensity [$sr^{-1}m^{-3}$]
- T: Tile temperature [K or ºC]
- a_{HT}: signal gain coefficient [counts sr m^3 ms^{-1}]
  - Proportional to tile emissivity, transmittance of optical system, etc.
- B_{HT}: other sources+electronic noise [counts ms^{-1}]

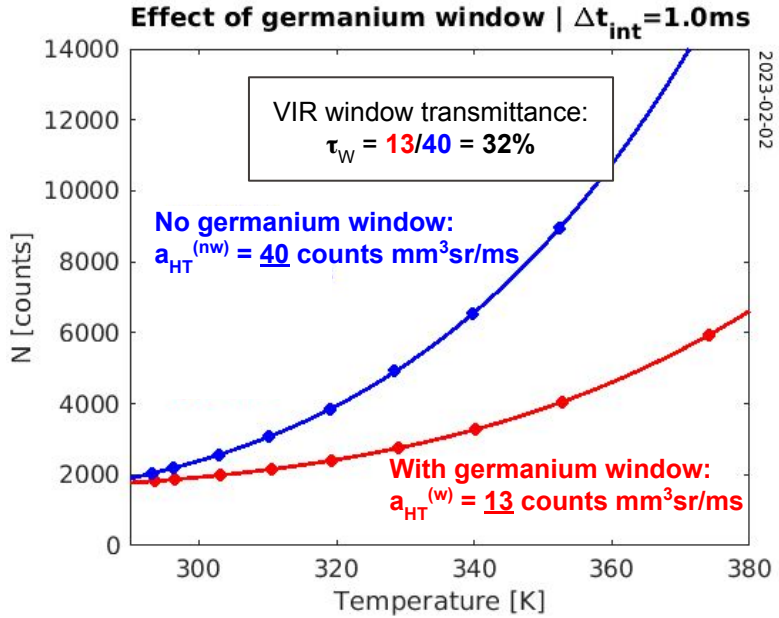
Experiment to determine the VIR germanium window transmittance

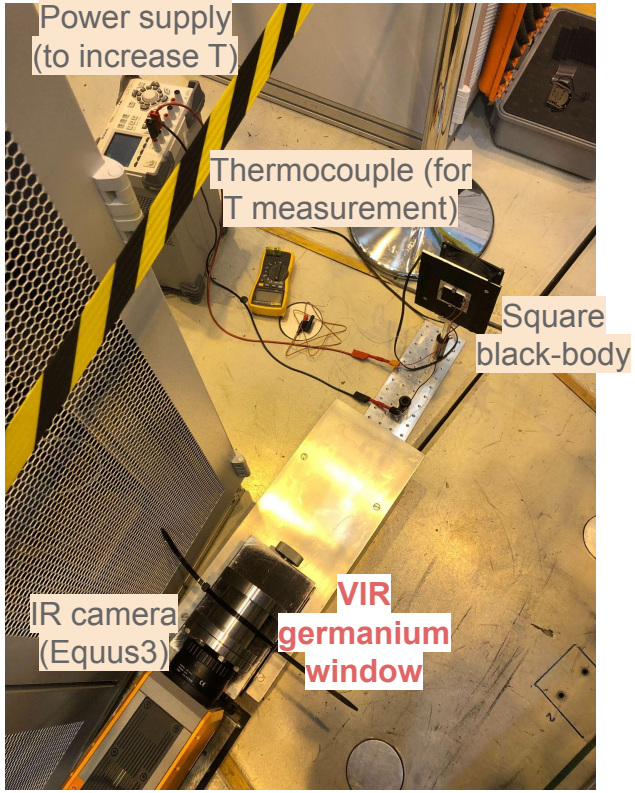




VIR germanium window transmittance decayed

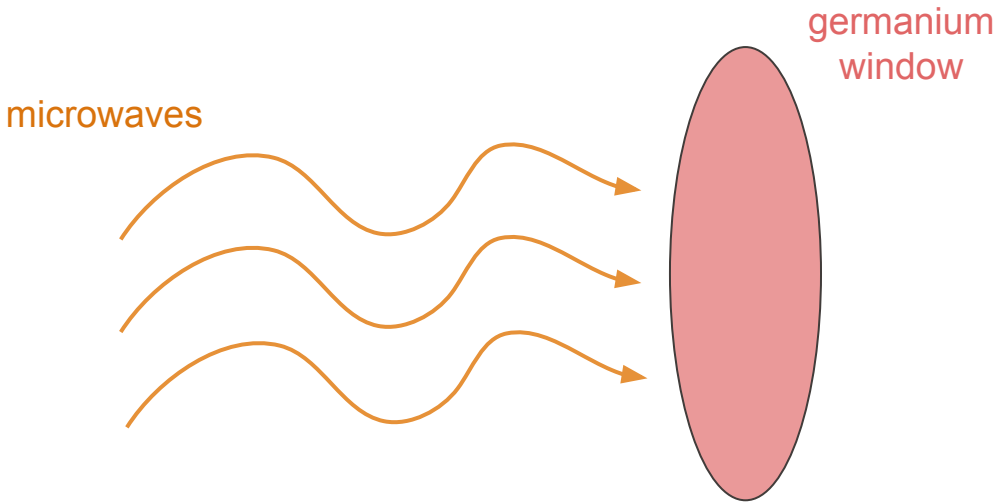
- According to the vendor, window transmittance was originally 95(1)% when installed (Feb. 2021)
- However, **window transmittance decayed to 32%** in Feb. 2023!
- $N_{counts} = a_{HT} \Delta t_{int} I_{bb}(T) + B_{HT}$





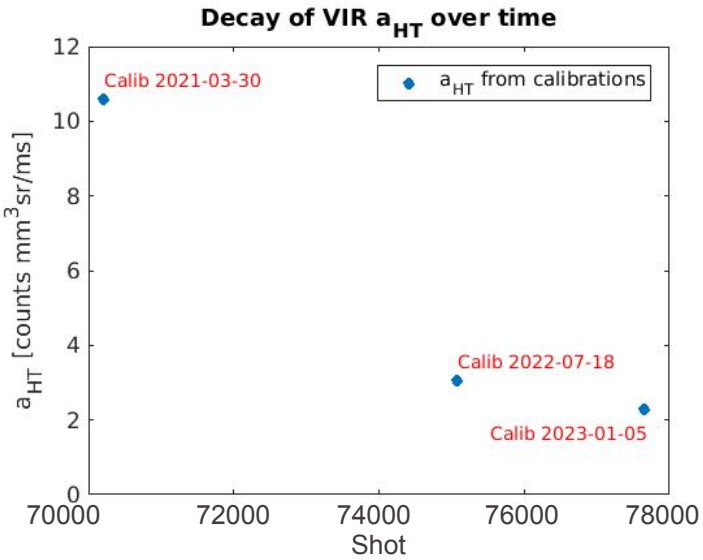
Main hypothesis for VIR germanium window transmittance decay: microwaves

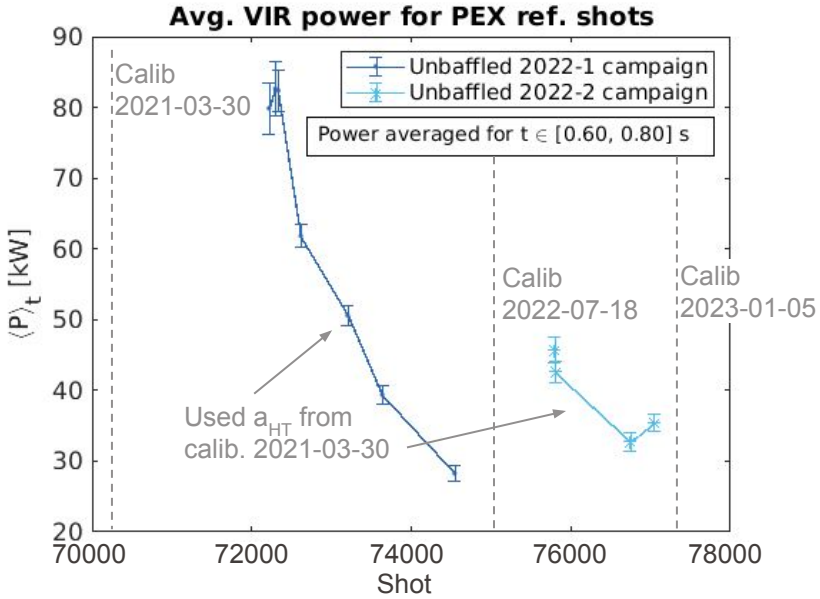
- Another identical germanium window cracked in TCV in 2022
  - It's microwave absorption was measured as high
- Therefore microwaves probably also altered the structure of the VIR window



So how can we save the VIR data?

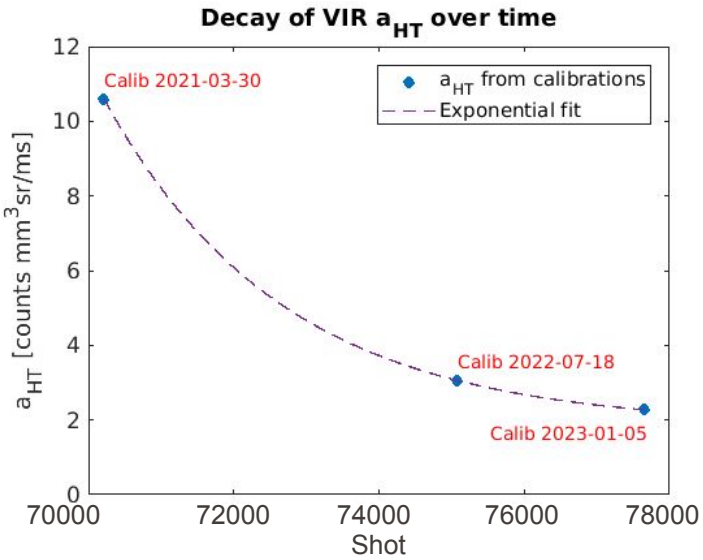
- Signal decayed from March-2021 (germanium window installed) to Jan-2023
- We have three calibrations from this period

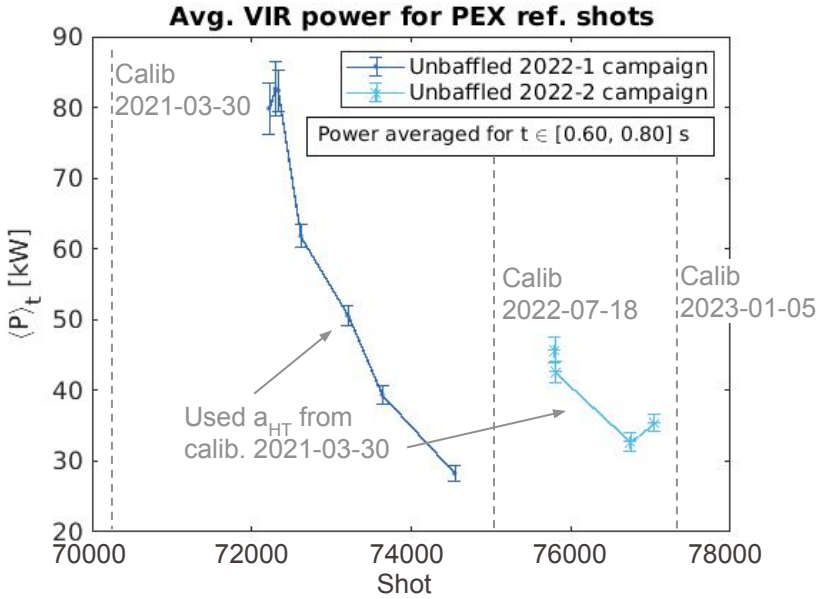




So how can we save the VIR data?

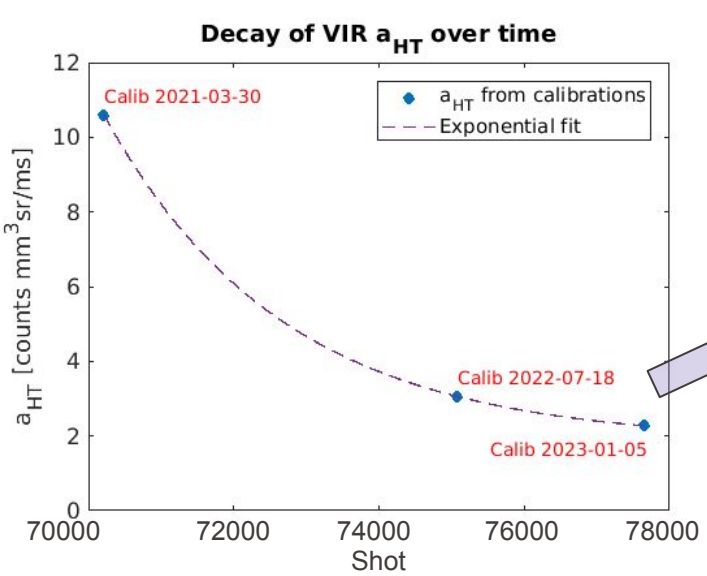
- Signal decayed from March-2021 (germanium window installed) to Jan-2023
- We have three calibrations from this period
- Trying to fit the three known values of a_{HT} together…

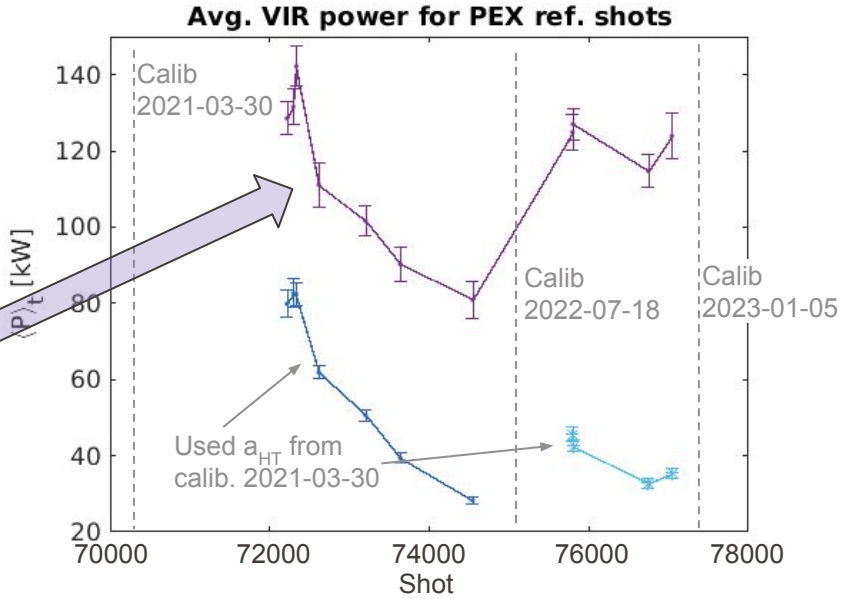




So how can we save the VIR data?

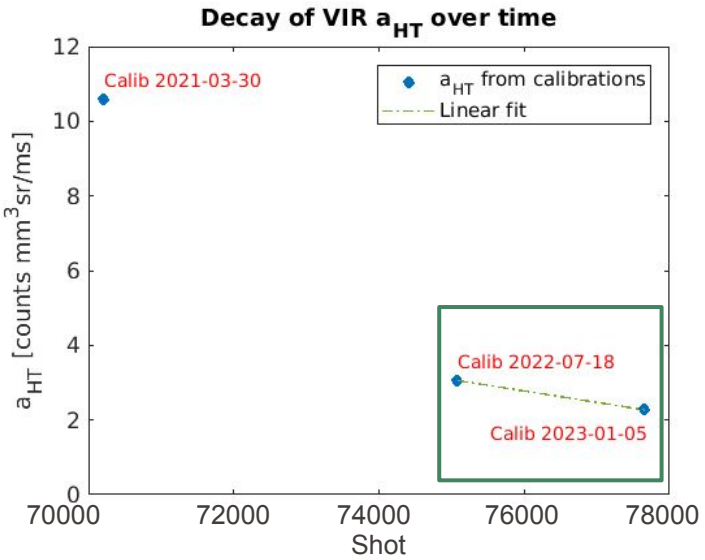
- Signal decayed from March-2021 (germanium window installed) to Jan-2023
- We have three calibrations from this period
- Trying to fit the three known values of a_{HT} together… still gives biased results

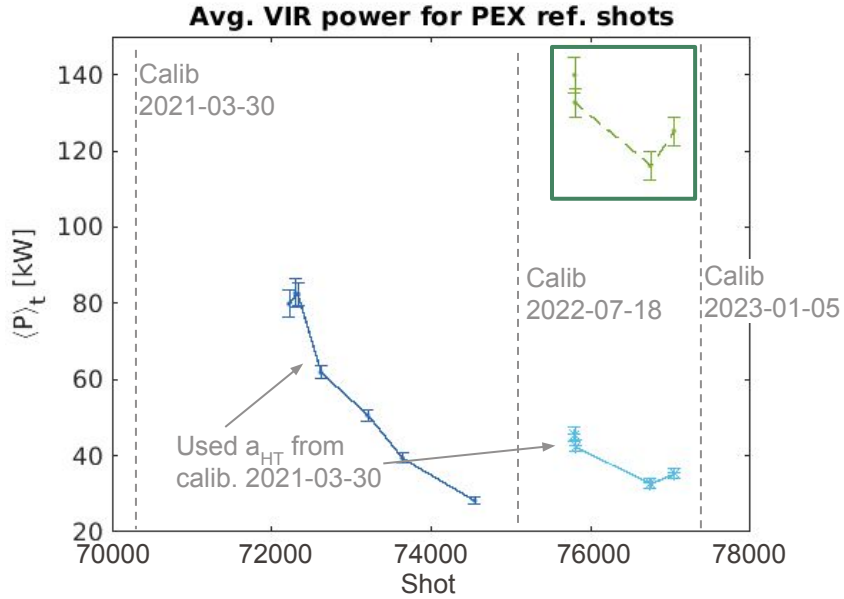




So how can we save the VIR data?

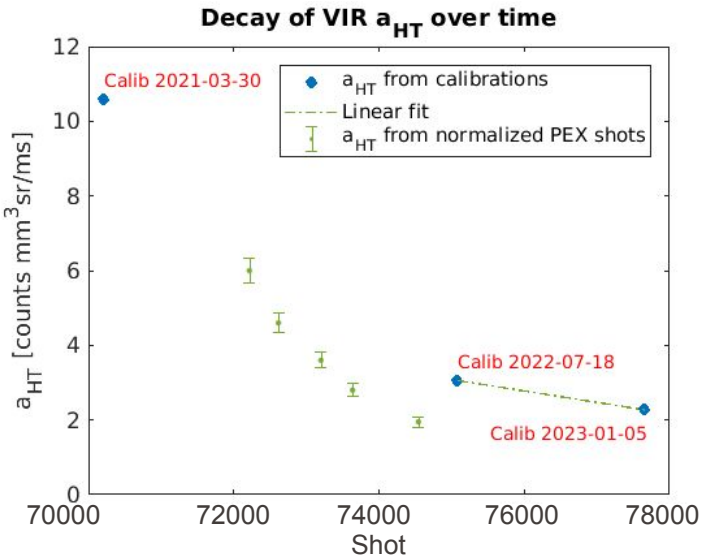
- Signal decayed from March-2021 (germanium window installed) to Jan-2023
- We have three calibrations from this period
- It is possible to linear-interpolate a_{HT} from the last two calibrations

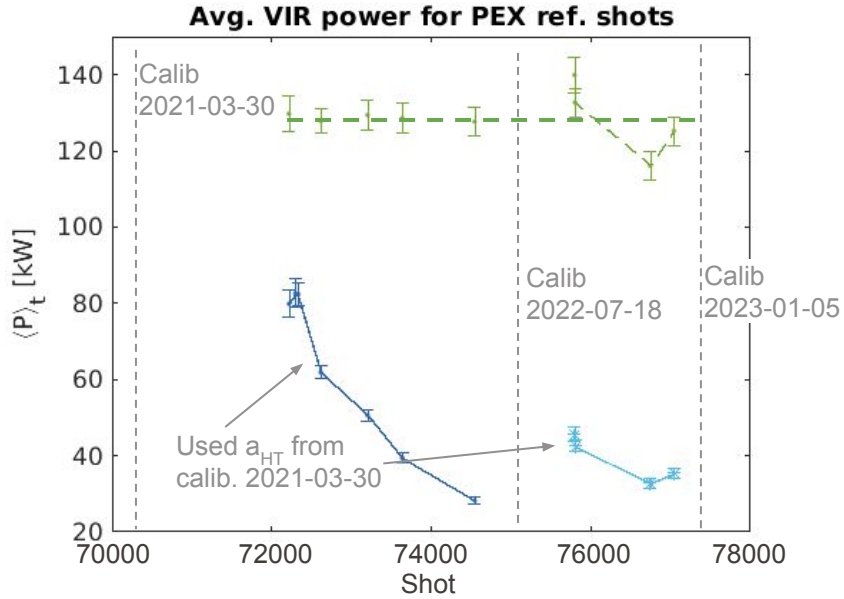




So how can we save the VIR data?

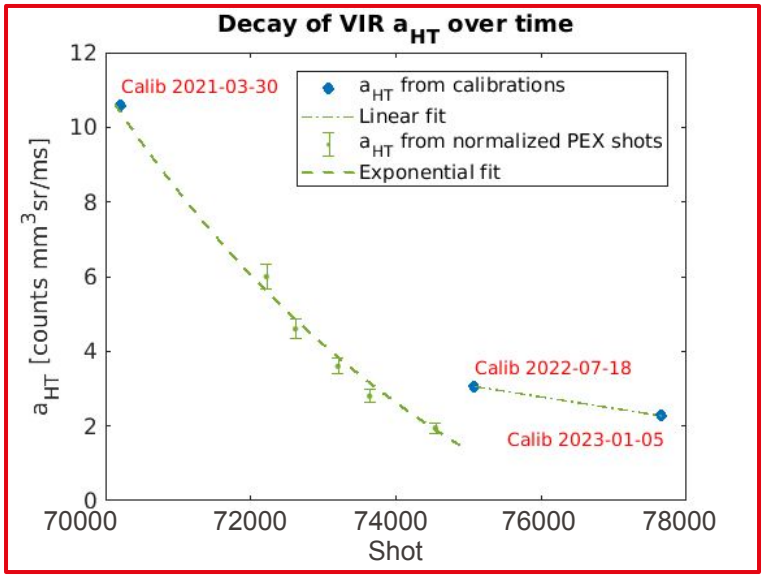
- Signal decayed from March-2021 (germanium window installed) to Jan-2023
- We have three calibrations from this period
- It is possible to linear-interpolate a_{HT} from the last two calibrations
- And then use the avg. power from 2022-2 to normalize the power of the others

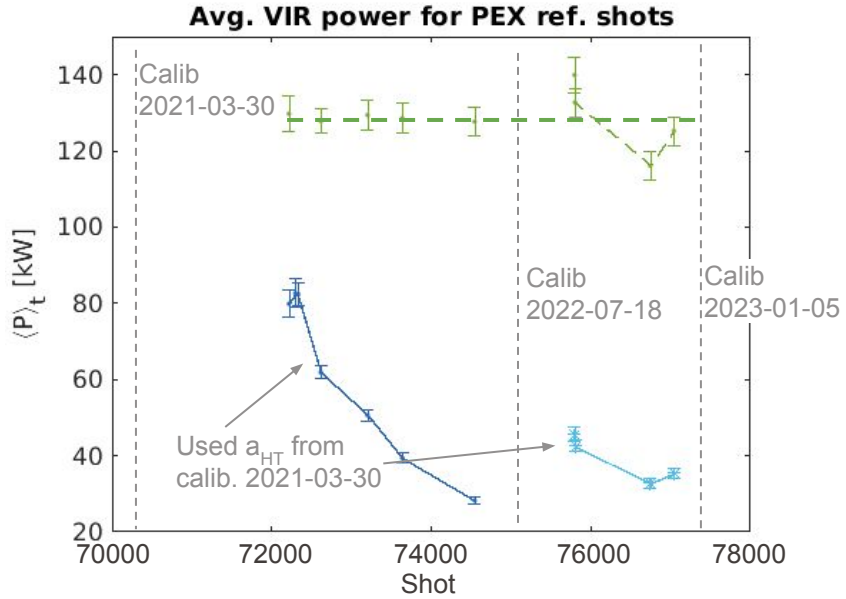




So how can we save the VIR data?

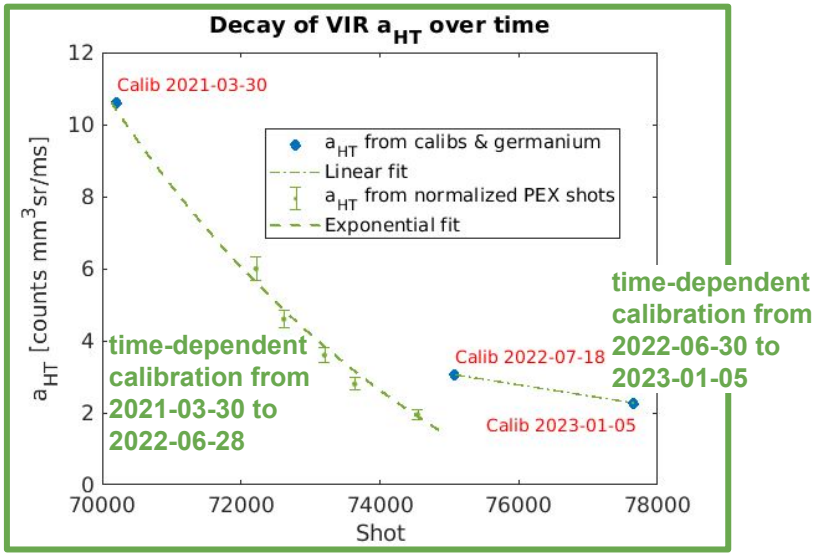
- It is possible to linear-interpolate a_{HT} from the last two calibrations
- And then use the average power value to normalize the power of the others
- It is then possible to fit an exponential curve for the 1st period of shots





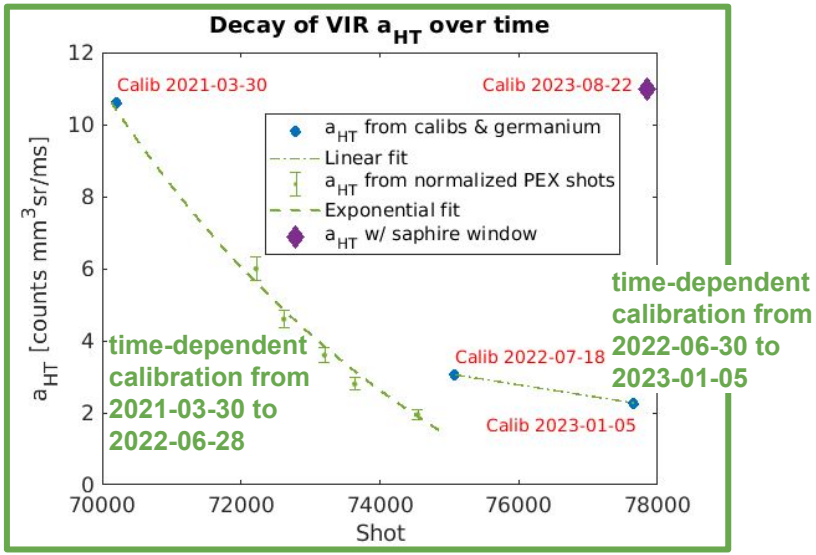
Conclusions

- The **VIR signal decreased** from March 2021 to January 2023
  - VIR germanium window transmittance dropped by a factor of 3
- **Time-dependent calibrations** were developed to correct the 2021-2023 data



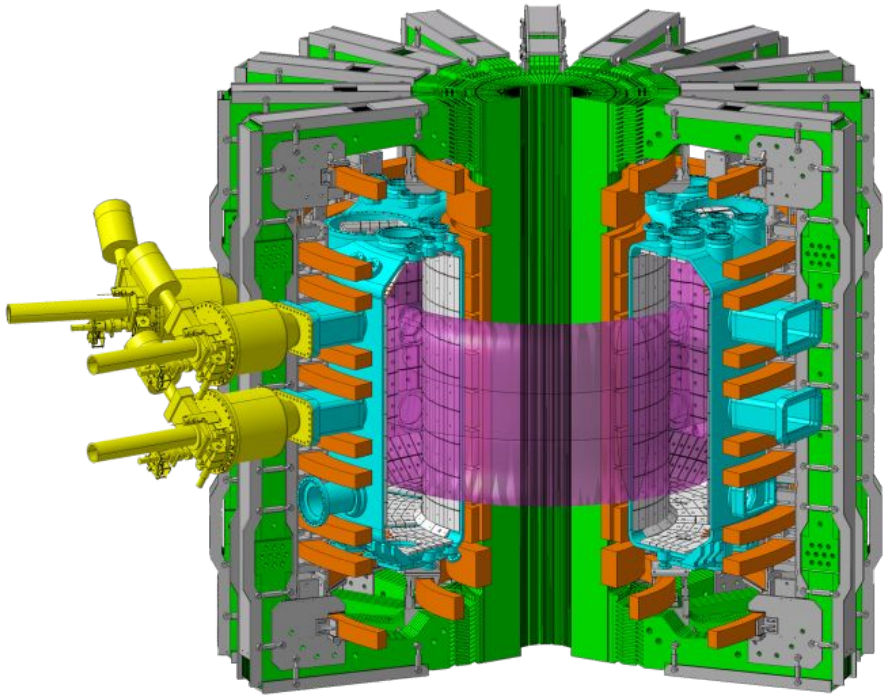
Conclusions and epilogue

- The **VIR signal decreased** from March 2021 to January 2023
  - VIR germanium window transmittance dropped by a factor of 3
- **Time-dependent calibrations** were developed to correct the 2021-2023 data
- Also: A **new sapphire window** has been installed for the 2023 campaign.
  - a_{HT} as high as in the beginning of 2021 was recovered

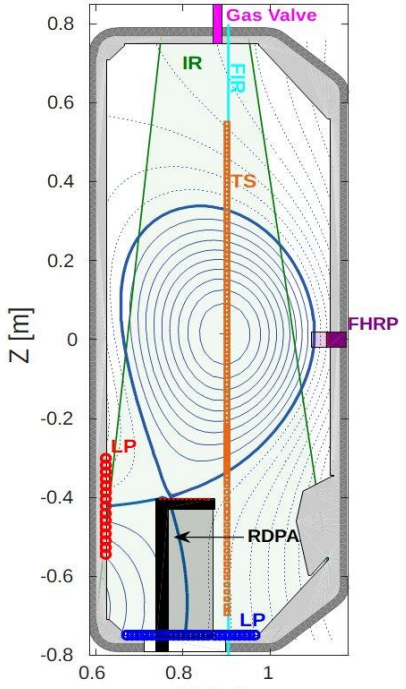


Extra slides

The TCV tokamak



CAD drawing of the TCV tokamak by Matthieu Toussaint.



Some diagnostics used to measure TCV's SOL [D.S. Oliveira, NF 2022]

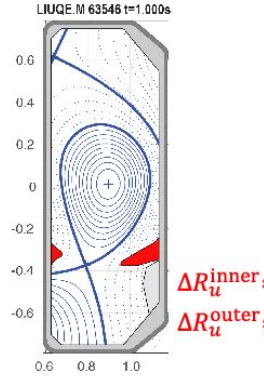
Baffle campaigns

Short and Long Inner and Outer baffles create configurations with variable divertor closure

19

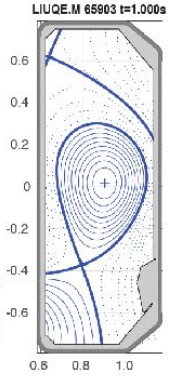
- Tested various combinations in dedicated experimental campaigns

2019	2020	2021	2022	2023
SINO, SILO	Unbaffled	SILO, SISO	Unbaffled, LILO, Unbaffled	



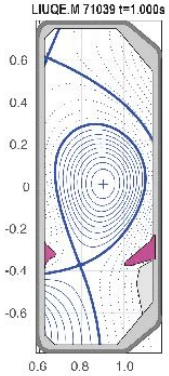
$\Delta R_u^{inner} \approx 23mm$
$\Delta R_u^{outer} \approx 30mm$

Short inner – long outer (SI-LO)

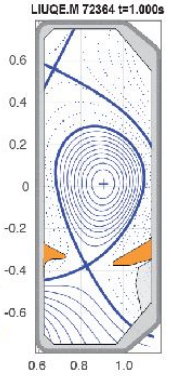


Unbaffled

$\Delta R_u^{inner} \approx 24mm$
$\Delta R_u^{outer} > 44mm$



Short inner – short outer (SI-SO)



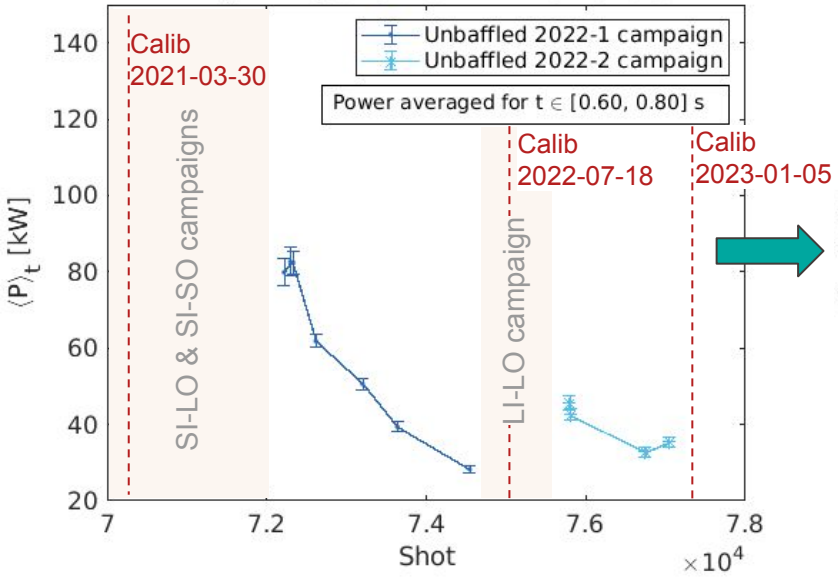
$\Delta R_u^{inner} \approx 18mm$
$\Delta R_u^{outer} \approx 18mm$

Long inner – long outer (LI-LO)

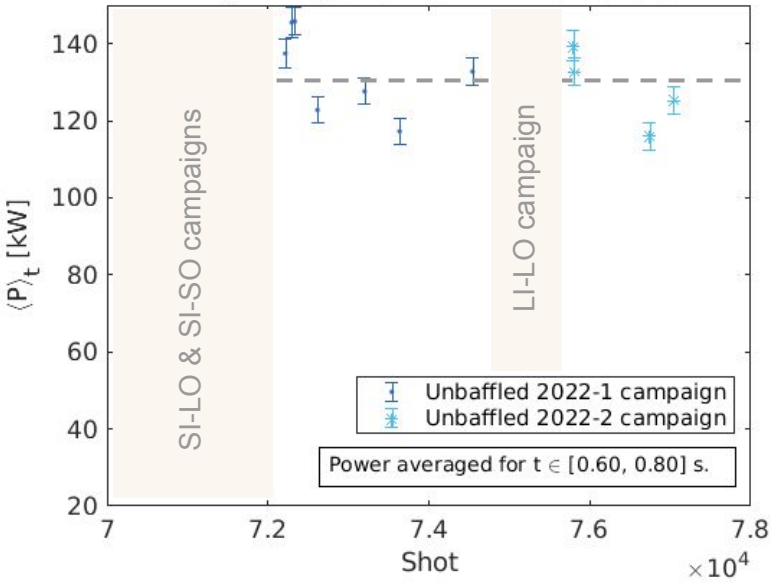
Final results: correcting the power

- The VIR gain of the TCV shots from 2021 to 2022 was corrected with the new **time-dependent calibration**
- The **power** of the ref. shots is **now** compatible with a **constant**

Power with old calibrations

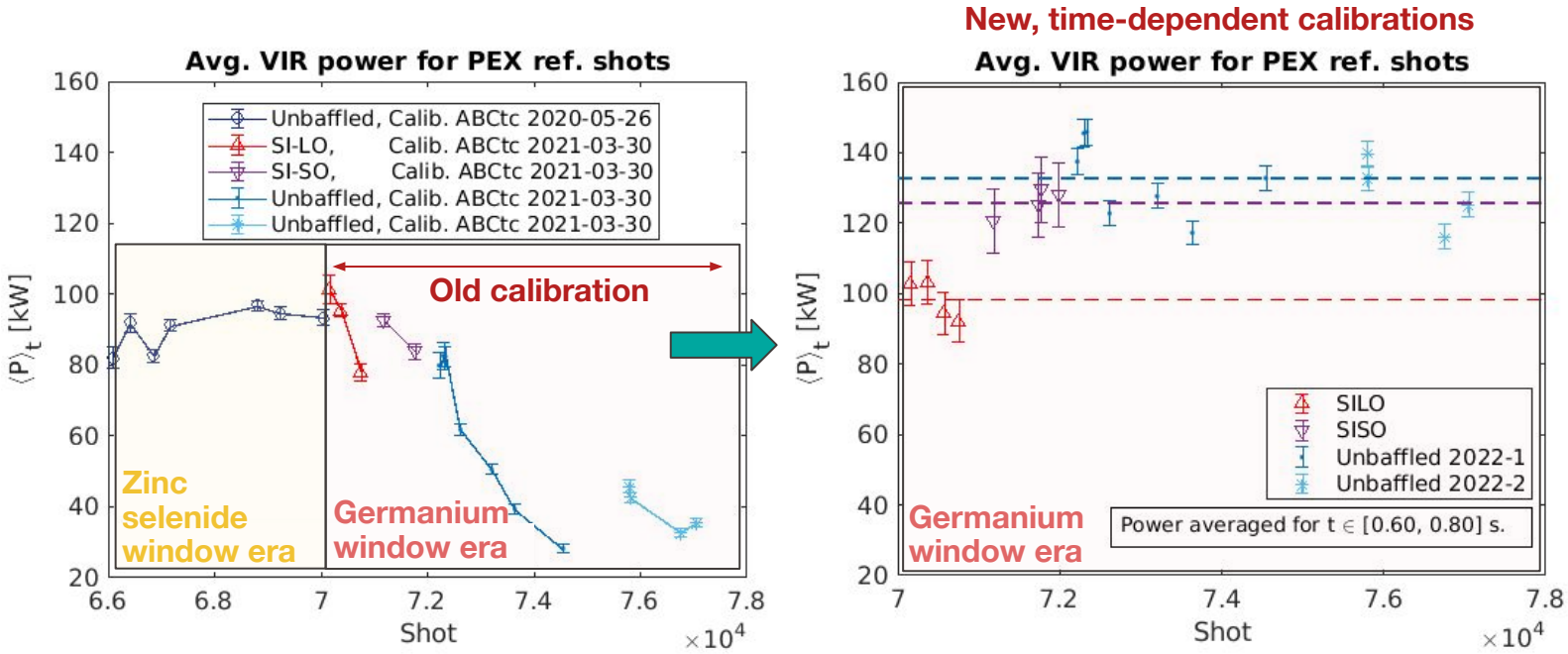


Power with new, time-dependent calibrations



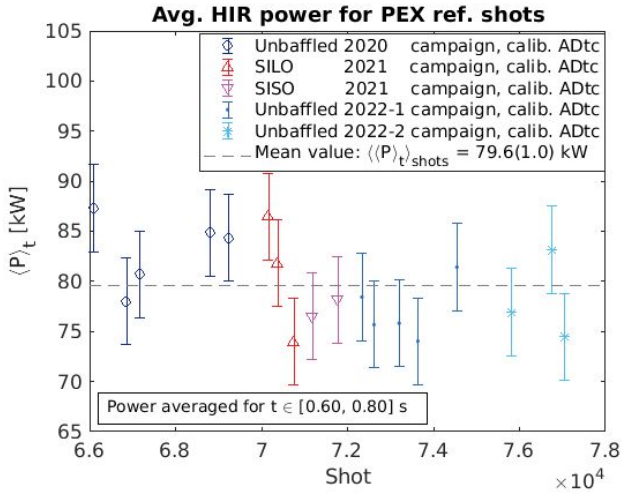
PEX ref. shots: power reaching the floor

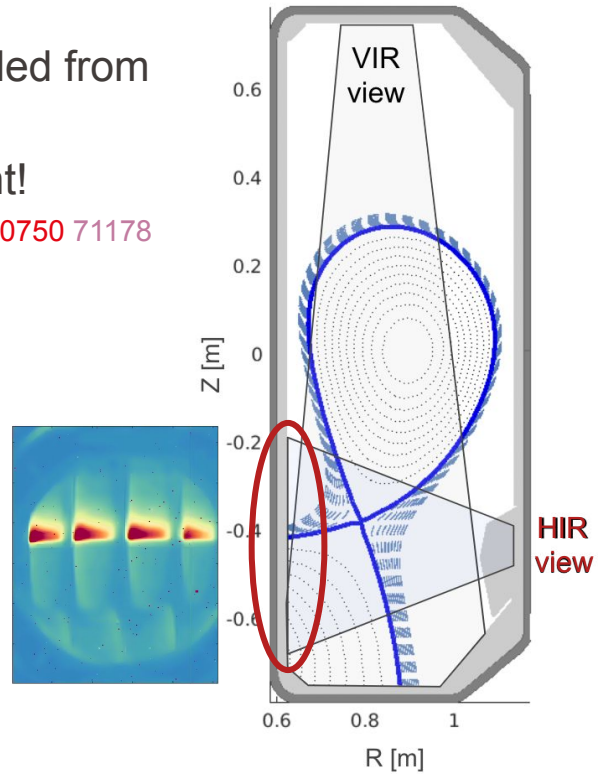
- Power of PEX ref. shots became constant after applying new time-dep. calibration
- The 2020 mystery: why is the heat flux so much lower than in 2021–2022?
- Shots used: [66092 66415 66857 67162 68795 69230 70042, 70156 70367 70571 70750, 71178 71731 71764 71979, 71764 72216 72296 72333 72615 73201 73636 74543, 75795 75800 76745 77040]



PEX ref. shots: power reaching inner wall

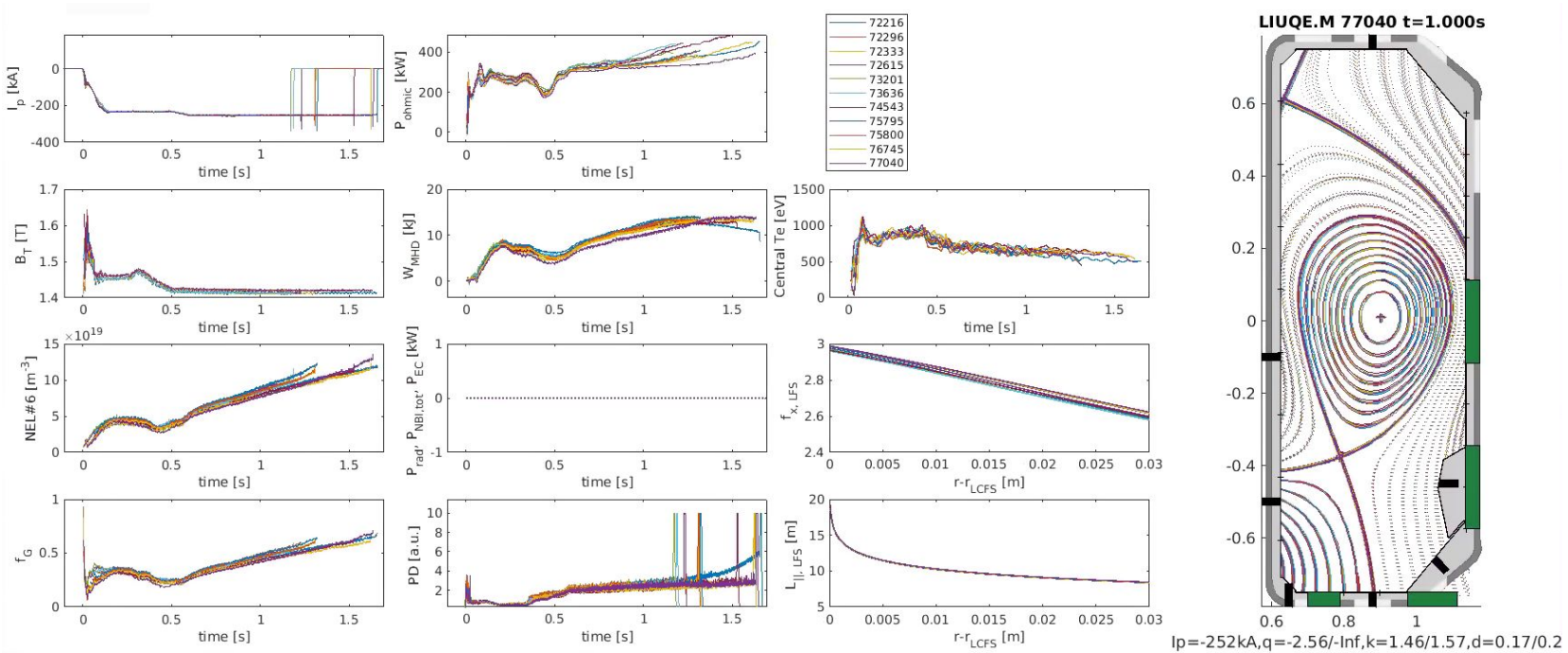
- The shots had the *same configurations*
- Including baffled shots (SI-LO & SI-SO) and unbaffled from 2020
- Inner target power is still compatible with a constant!
  - Analysed shots: [66092 66857 67162 68795 69230 70156 70367 70750 71178 71764 72333 72615 73201 73636 74543 75800 76745 77040]



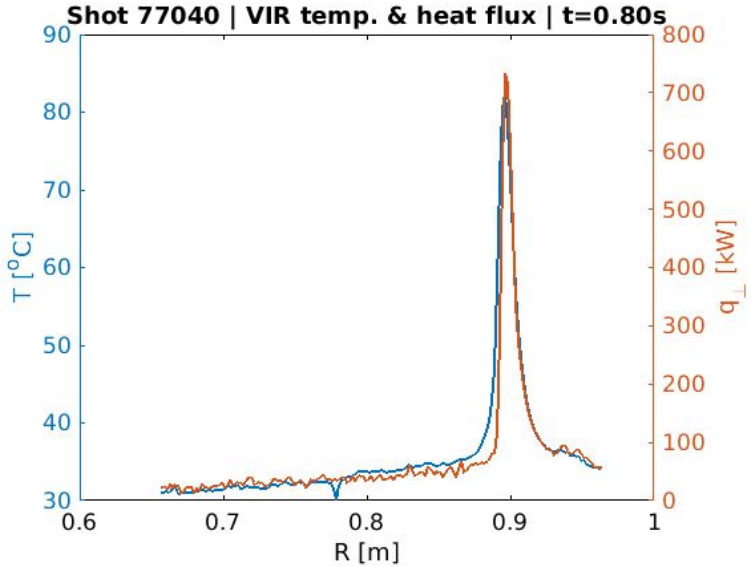


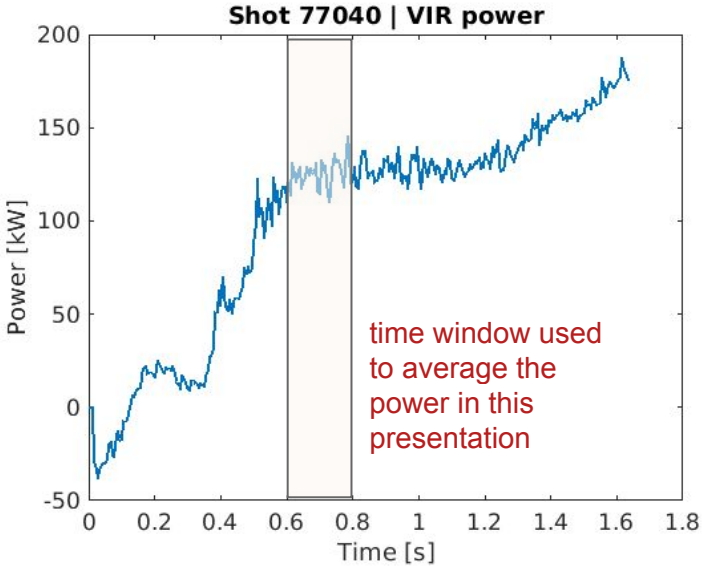
PEX reference shots

- PEX (power exhaust) ref. shots were analysed
- The shots had the **same configurations**
  - Analysed shots: [72216 72296 72333 72615 73201 73636 74543, 75795 75800 76745 77040]



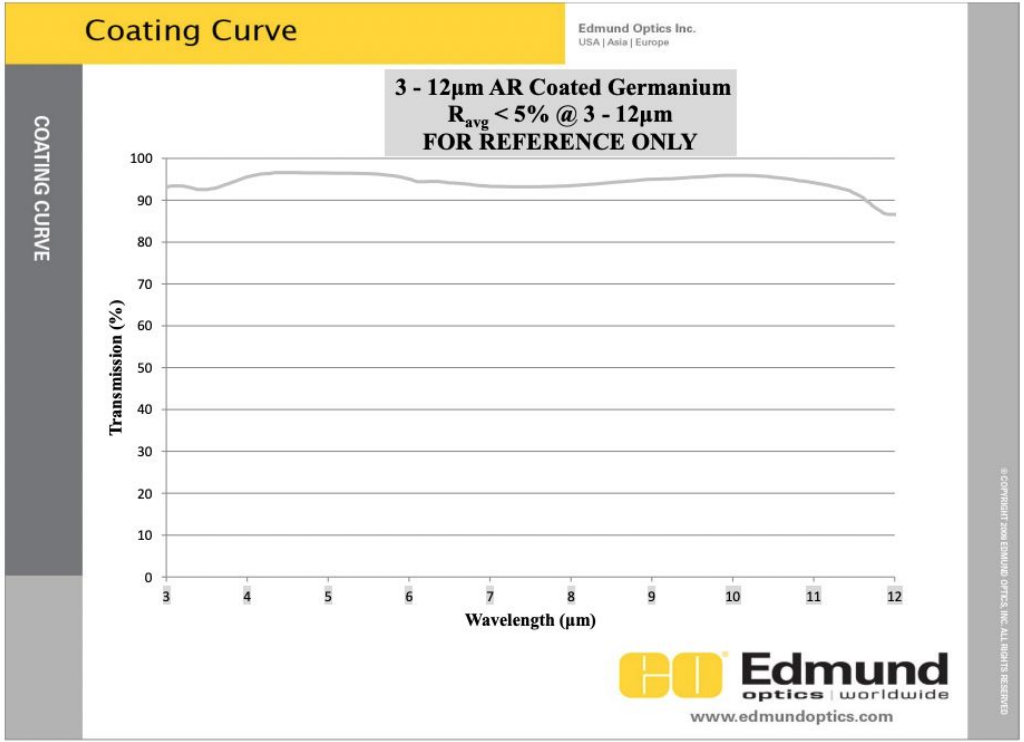
Infrared thermography temperature, heat, and power profiles for PEX ref. shots



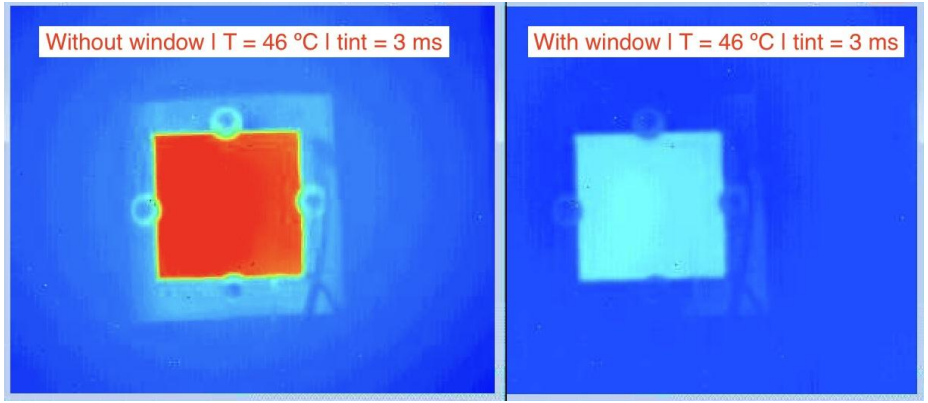


Old germanium window

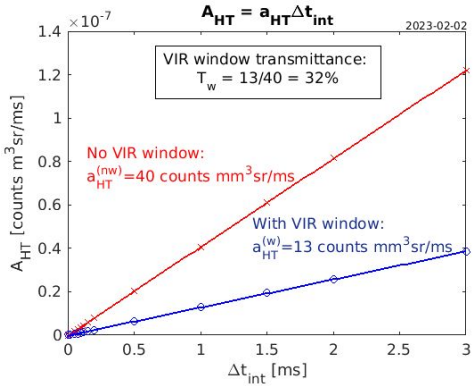
- According to the vendor, the germanium window initially had more than 90% transmittance
- Info about the window: https://spcwiki.epfl.ch/wiki/images/2/2c/20201222-Edmund-Optics-WINDOW_GE_75MM_3-5_UM_AR_CTD_TS.pdf

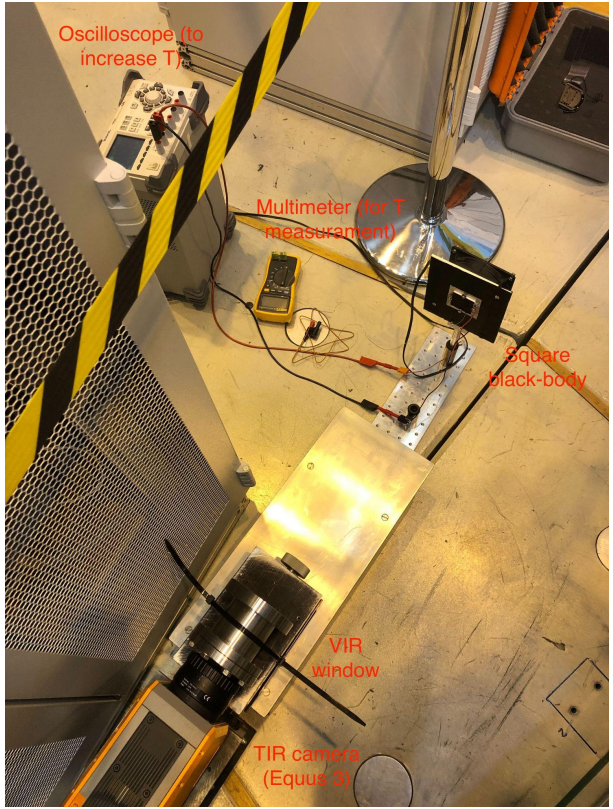


VIR experiment to measure window transmittance decay



Camara images

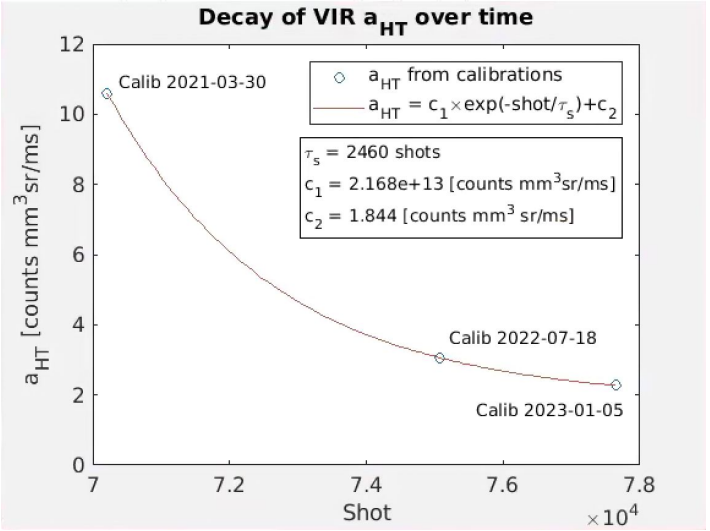


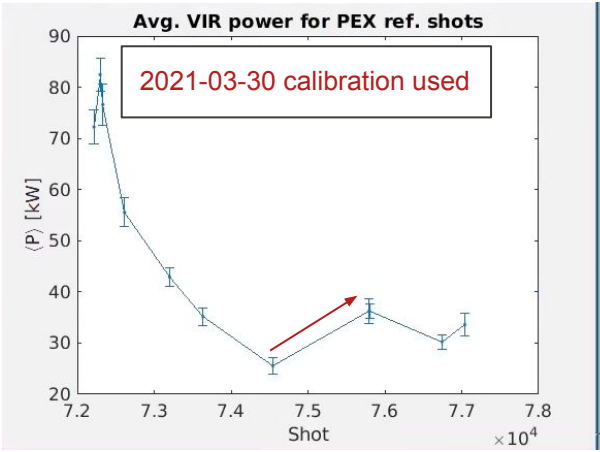


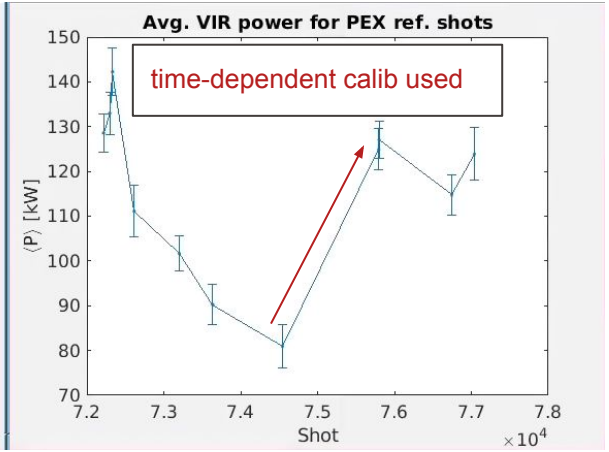
Experimental setup

Trying to “fit” an exponential to the 3 calibrations aHT

- Jump in signal in between unbaffled campaigns increased with this time-dependent calibration

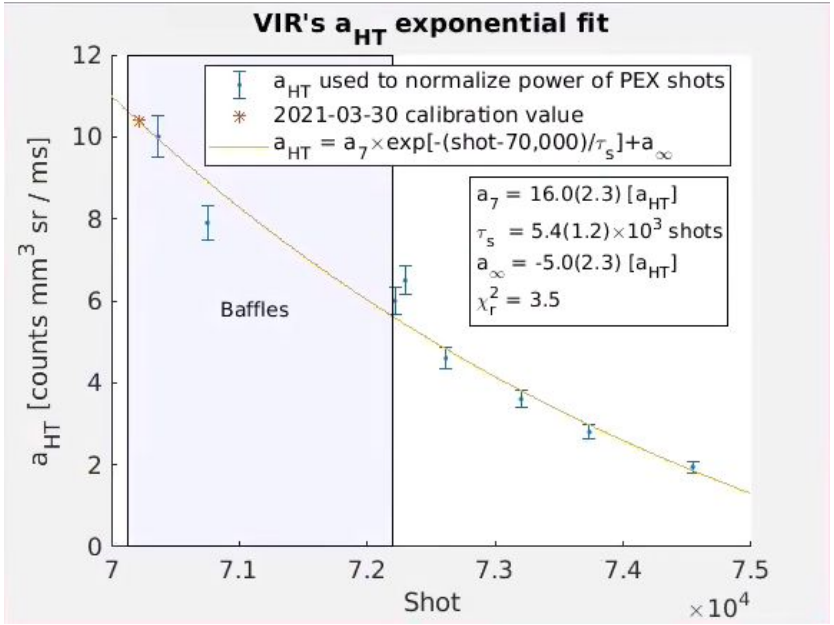






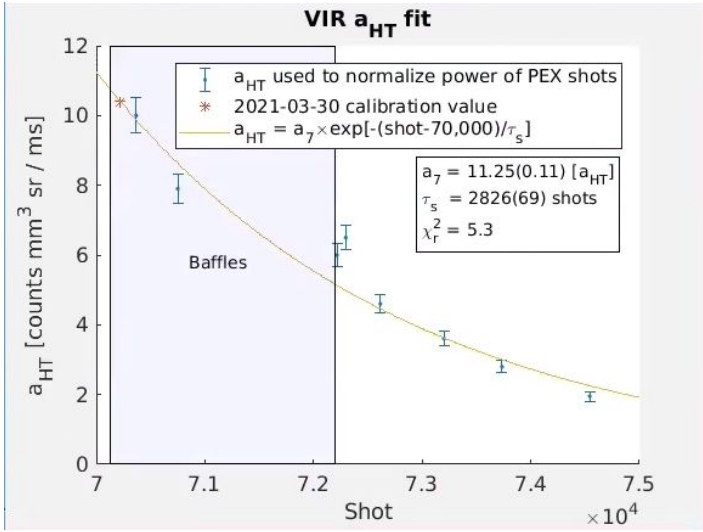
What we really fitted

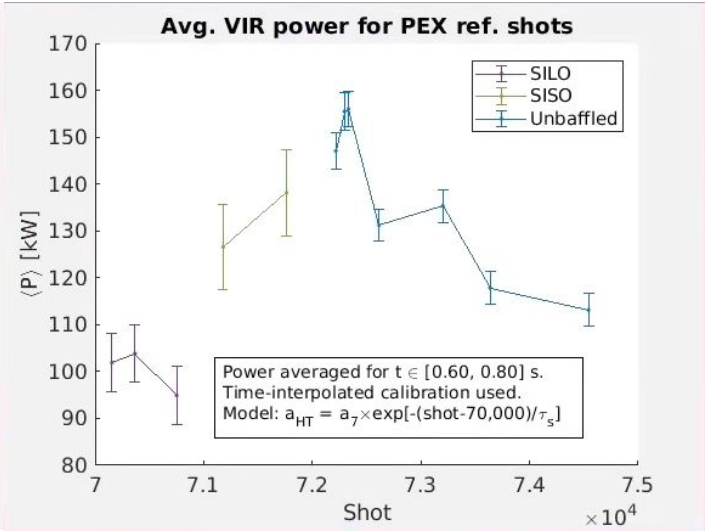
- Two SI-LO baffled shots were also considered
- One SI-LO shot very close to the 2021-03-30 calibration was considered as reference for power (not shown in the figure, as it was not fitted).



What about an exponential with 0 offset?

- Power still decreases in the unbaffled phase





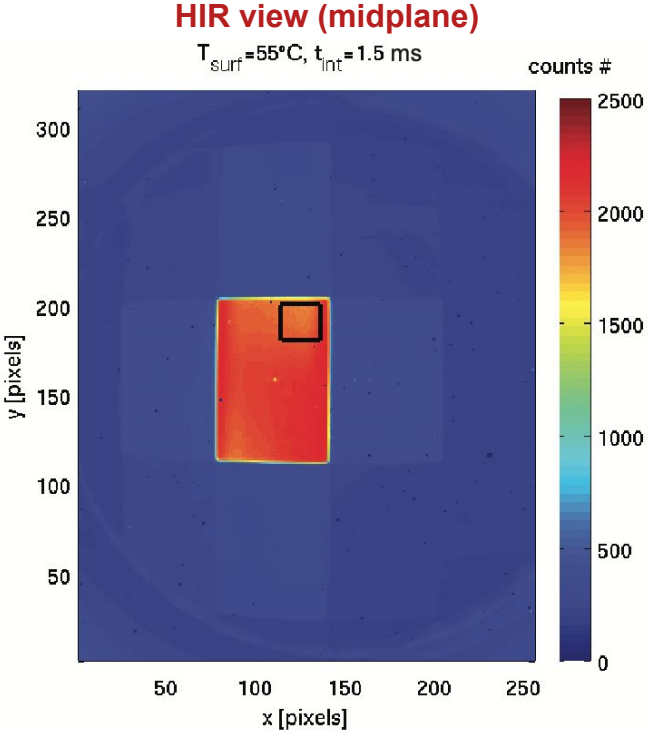
IR cameras: calibration to temperature

- Conversion from raw data (digitized photon counts) to temperature is done via calibration

$$N_{raw} = a_{HT}\,\Delta t_{int}\,I_{bb}(T) + b_{HT}\,\Delta t_{int} + c_{HT} \Rightarrow$$

$$T = I^{-1}[(N_{raw} - b_{HT}\,\Delta t_{int} - c_{HT})/(a_{HT}\,\Delta t_{int})]$$

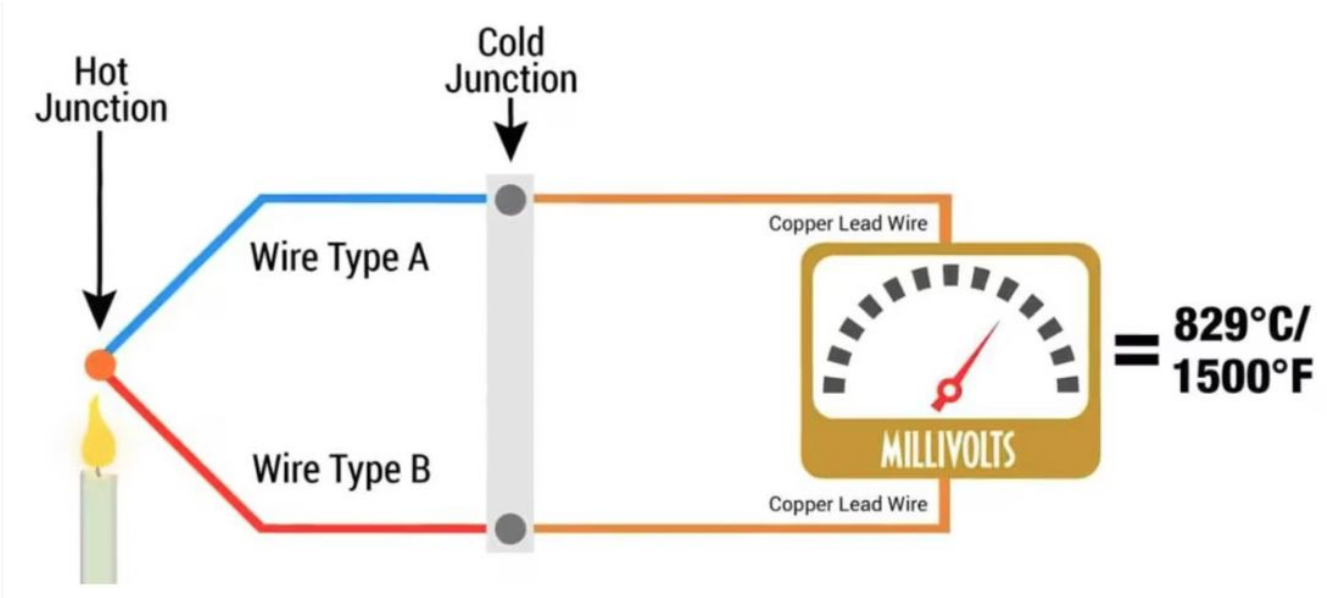
- N_{raw}: raw counts [counts]
- Δt_{int}: camera integration time (adjustable) [ms]
- I_{bb}: black body integral [$sr^{-1}m^{-3}$]
- T: Temperature [K or ºC]
- a_{HT}: signal gain factor [counts sr m^3 ms^{-1}]
- b_{HT}: dark currents/other sources [counts ms^{-1}]
- c_{HT}: electronic noise component [counts]



Federico Nespoli's PhD thesis (2017), Fig. 2.12.

Thermocouples (TCs)

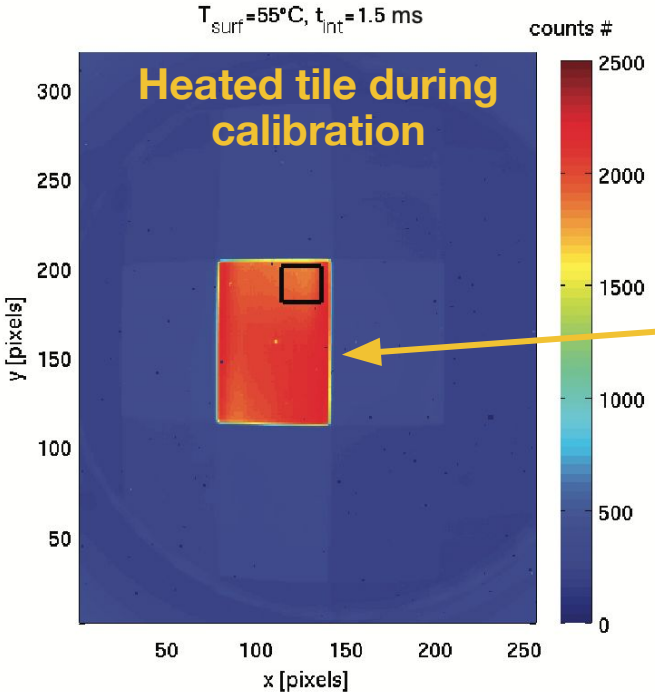
- Thermocouples are used to **measure temperature**.
- Heating up a joint of two dissimilar metal wires produces a voltage proportional to the temperature difference between the hot and cold junctions.



Source: omega.com

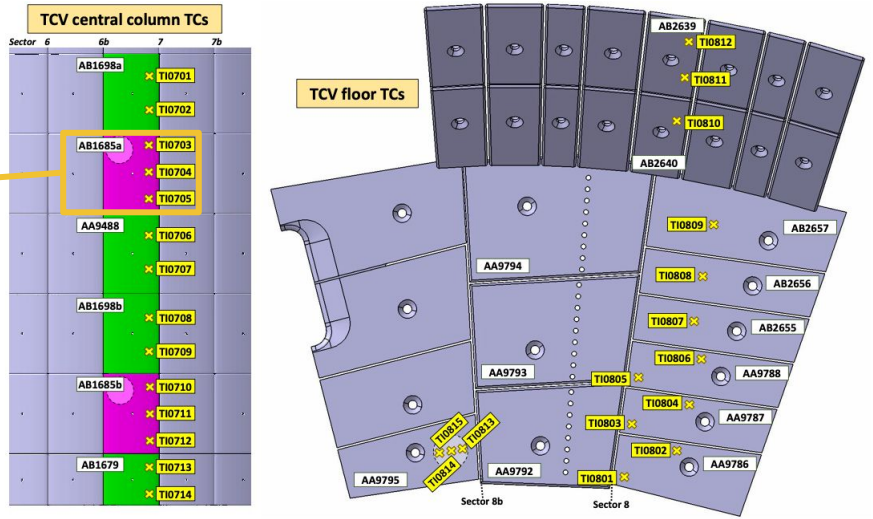
Thermocouples (TCs) & heated tiles in TCV

- Thermocouples are used to **measure temperature**.
- Together with **heating elements** embedded in tiles, TCs can **calibrate the IR cameras**.



Federico Nespoli's PhD thesis (2017), Fig. 2.12.

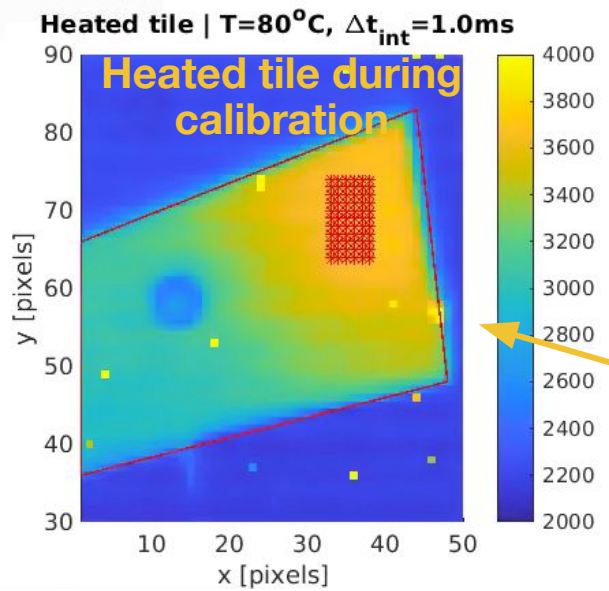
Thermocouples in TCV (HIR & VIR views)



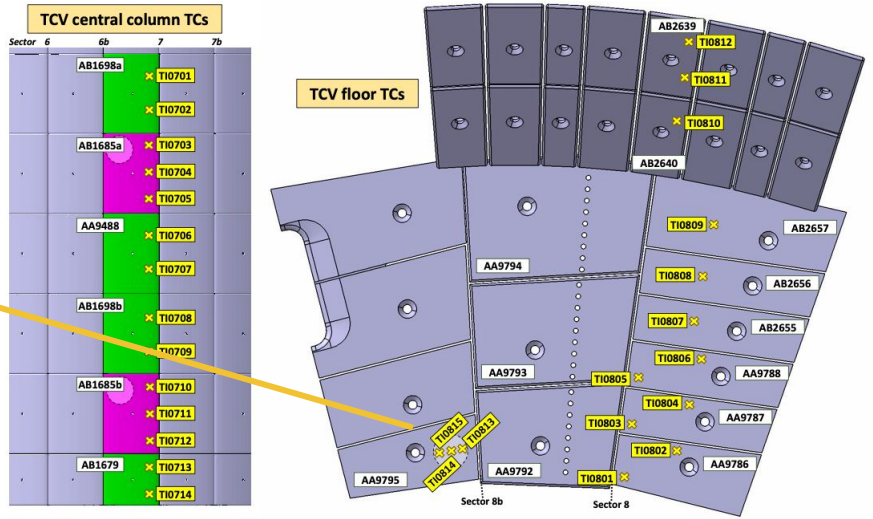
Roberto Maurizio's PhD thesis (2020), Fig. 2.10.

Thermocouples (TCs) & heated tiles in TCV

- Thermocouples are used to **measure temperature**.
- Together with **heating elements** embedded in tiles, TCs can **calibrate the IR cameras**.



Thermocouples in TCV (HIR & VIR views)



Roberto Maurizio's PhD thesis (2020), Fig. 2.10.

Thermocouple-corrected calibration

Calibration

5

H. Reimerdes

- **ABC calibration: Background term varies during the day**
- ➢ **Use thermocouple measurement (TC) to correct *B* for each discharge**
  - Use measurement of diagnosed tile (index TC) at time t_0 to determine momentary value $B_{\mathrm{TC}}(t_0)$

$$N_{\mathrm{TC}}(t_0) = A_{\mathrm{TC}}\, I\big(T_{\mathrm{TC}}(t_0)\big)\,\Delta t_{\mathrm{int}} + B_{\mathrm{TC}}(t_0)\,\Delta t_{\mathrm{int}} + C_{\mathrm{TC}}$$

$$\Leftrightarrow \quad B_{\mathrm{TC}}(t_0)\,\Delta t_{\mathrm{int}} = N_{\mathrm{TC}}(t_0) - A_{\mathrm{TC}}\, I\big(T_{\mathrm{TC}}(t_0)\big)\,\Delta t_{\mathrm{int}} - C_{\mathrm{TC}}$$

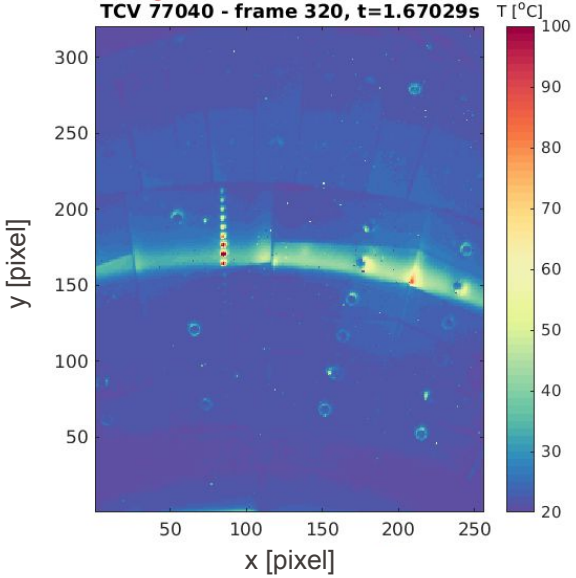
  - Derive correction coefficient for pixel dependent B_{xy}

$$N_{xy}(t) = A_{xy}\, I\left(T_{xy}(t)\right)\Delta t_{\mathrm{int}} + \frac{B_{\mathrm{TC}}(t_0)\,\Delta t_{\mathrm{int}}}{B_{\mathrm{TC}}\,\Delta t_{\mathrm{int}}} B_{xy}\,\Delta t_{\mathrm{int}} + C_{xy}$$

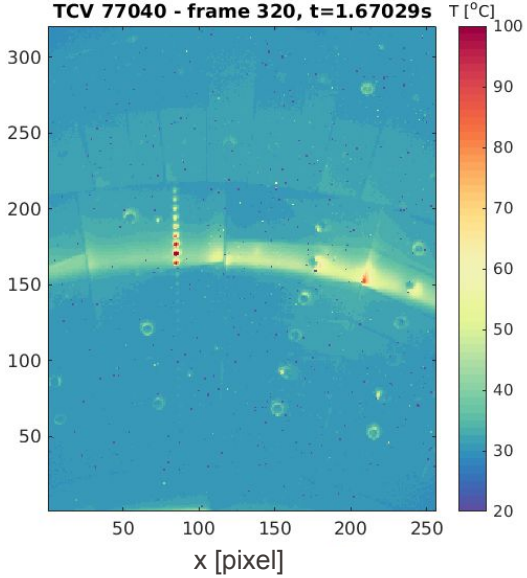
  - Can be extended to C_{xy}, if needed

Comparison between calibrations

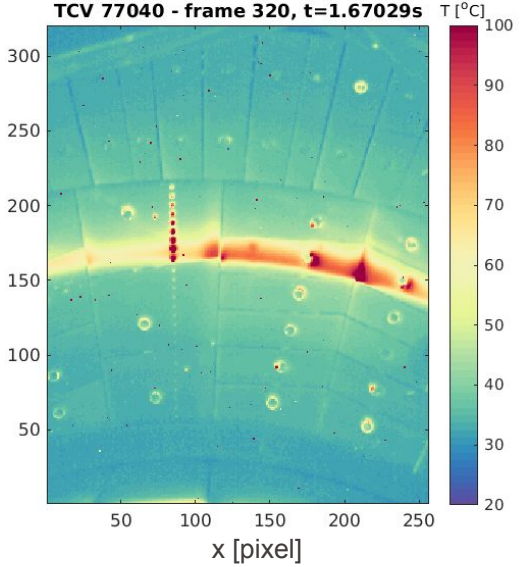
Using 2021-03-30 calibration



Using TC-corrected 2021-03-30 calibration

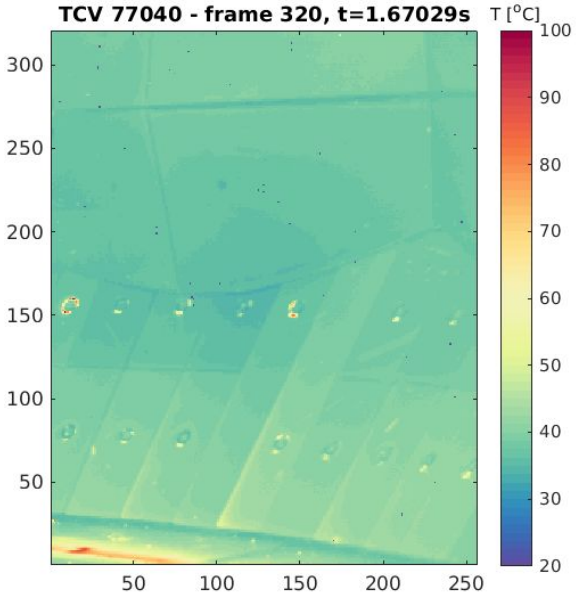


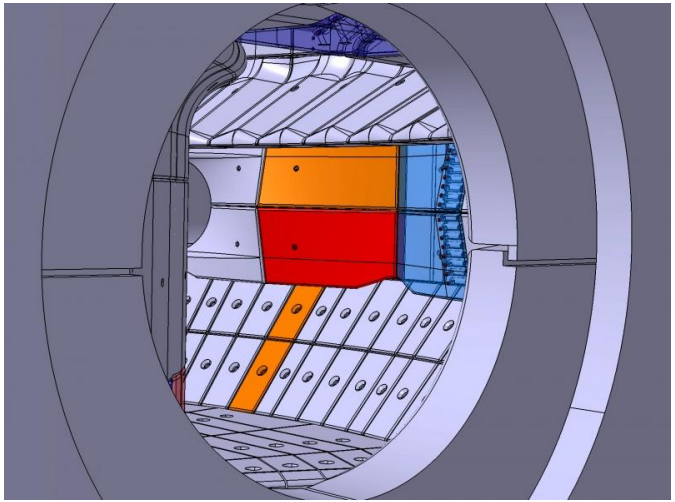
Using TC-corrected, time-dependent 2022-2023 calibration



Tangential infrared (TIR) camera [1]

- Measures **temperature** on the tokamak outer wall



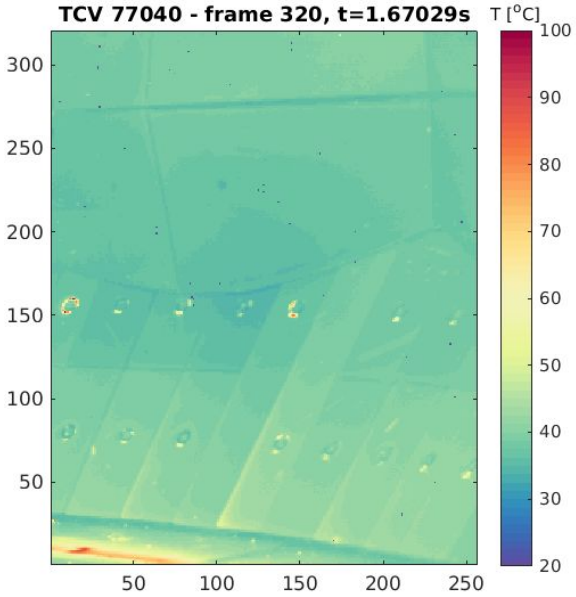


[1] Roberto Maurizio's PhD thesis (2020)

TIR vs VIR

- **Temperature discrepancies** between VIR and TIR motivated the investigation on the calibration

TIR | 2021-03-30 calibration



VIR | 2021-03-30 calibration