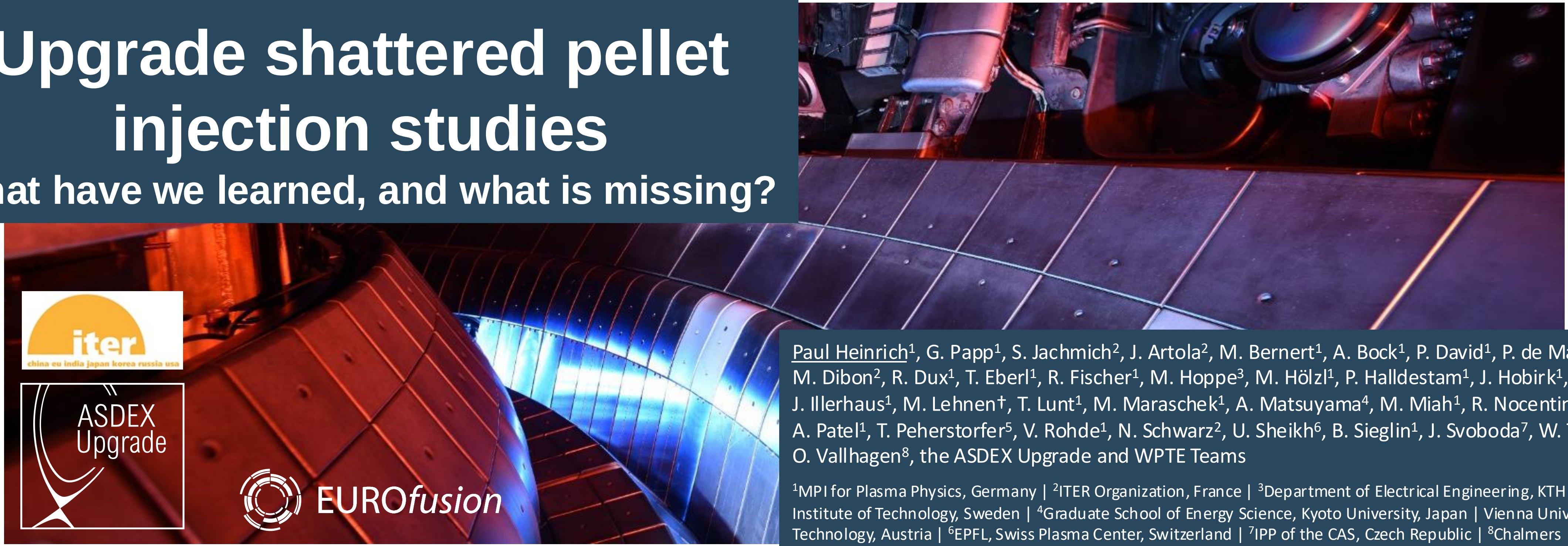
Overview of the ASDEX Upgrade shattered pellet injection studies

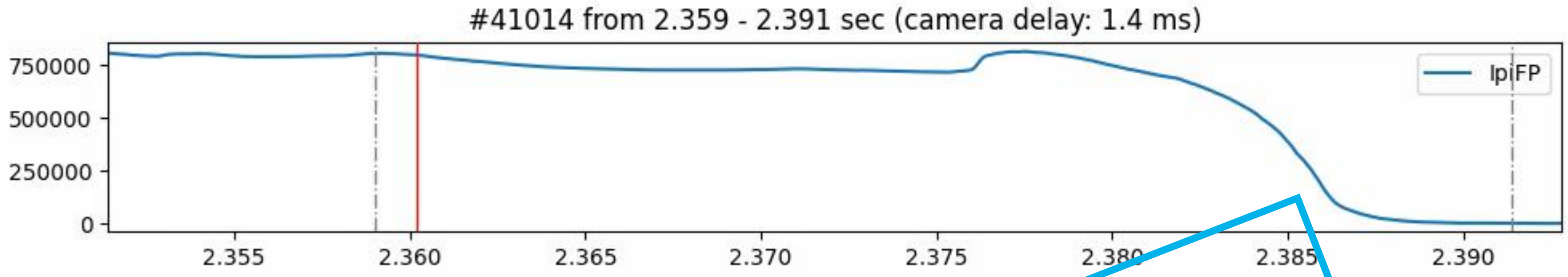
What have we learned, and what is missing?



Paul Heinrich[1], G. Papp[1], S. Jachmich[2], J. Artola[2], M. Bernert[1], A. Bock[1], P. David[1], P. de Marné[1], M. Dibon[2], R. Dux[1], T. Eberl[1], R. Fischer[1], M. Hoppe[3], M. Hölzl[1], P. Halldestam[1], J. Hobirk[1], J. Illerhaus[1], M. Lehnen†, T. Lunt[1], M. Maraschek[1], A. Matsuyama[4], M. Miah[1], R. Nocentini[1], A. Patel[1], T. Peherstorfer[5], V. Rohde[1], N. Schwarz[2], U. Sheikh[6], B. Sieglin[1], J. Svoboda[7], W. Tang[1], O. Vallhagen[8], the ASDEX Upgrade and WPTE Teams

[1]MPI for Plasma Physics, Germany | [2]ITER Organization, France | [3]Department of Electrical Engineering, KTH Royal Institute of Technology, Sweden | [4]Graduate School of Energy Science, Kyoto University, Japan | Vienna University of Technology, Austria | [6]EPFL, Swiss Plasma Center, Switzerland | [7]IPP of the CAS, Czech Republic | [8]Chalmers University of Technology, Sweden | †Deceased

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. ITER is the Nuclear Facility INB no. 174. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization. This work was performed in collaboration with the ITER DMS Task Force and received funding by the ITER Organization under contracts IO/CT/43-2084, IO/CT/43-2115 and IO/CT/43-2116.


#41014 from 2.359 - 2.391 sec (camera delay: 1.4 ms)
750000
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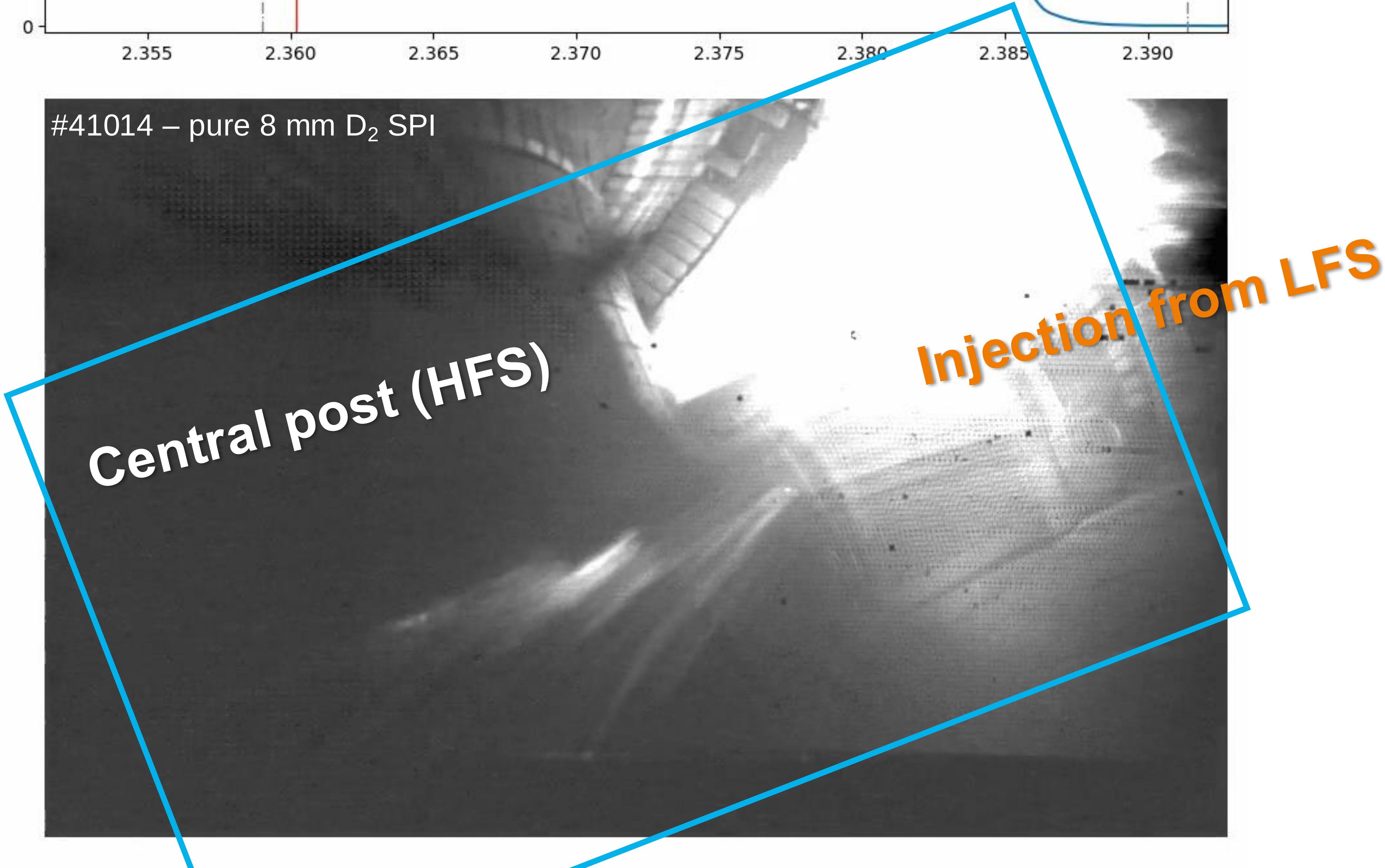
2.385
2.390
IpiFP


#41014 – pure 8 mm D_2 SPI
Central post (HFS)
Injection from LFS

Outline

- ❖ **What is SPI supposed to deliver?**
- ❖ **What is the specific goal of the ASDEX Upgrade SPI system?**
- ❖ **What did we learn from the AUG SPI project so far?**
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  - **AUG SPI experiments in 2022 & AUG SPI modelling**
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    - Radiation asymmetries
    - Radiated energy fraction (f_{rad})
    - Is there an „optimal“ shatter head for all purposes?
- ❖ **Shatter head setup for the 2025 experimental campaign**

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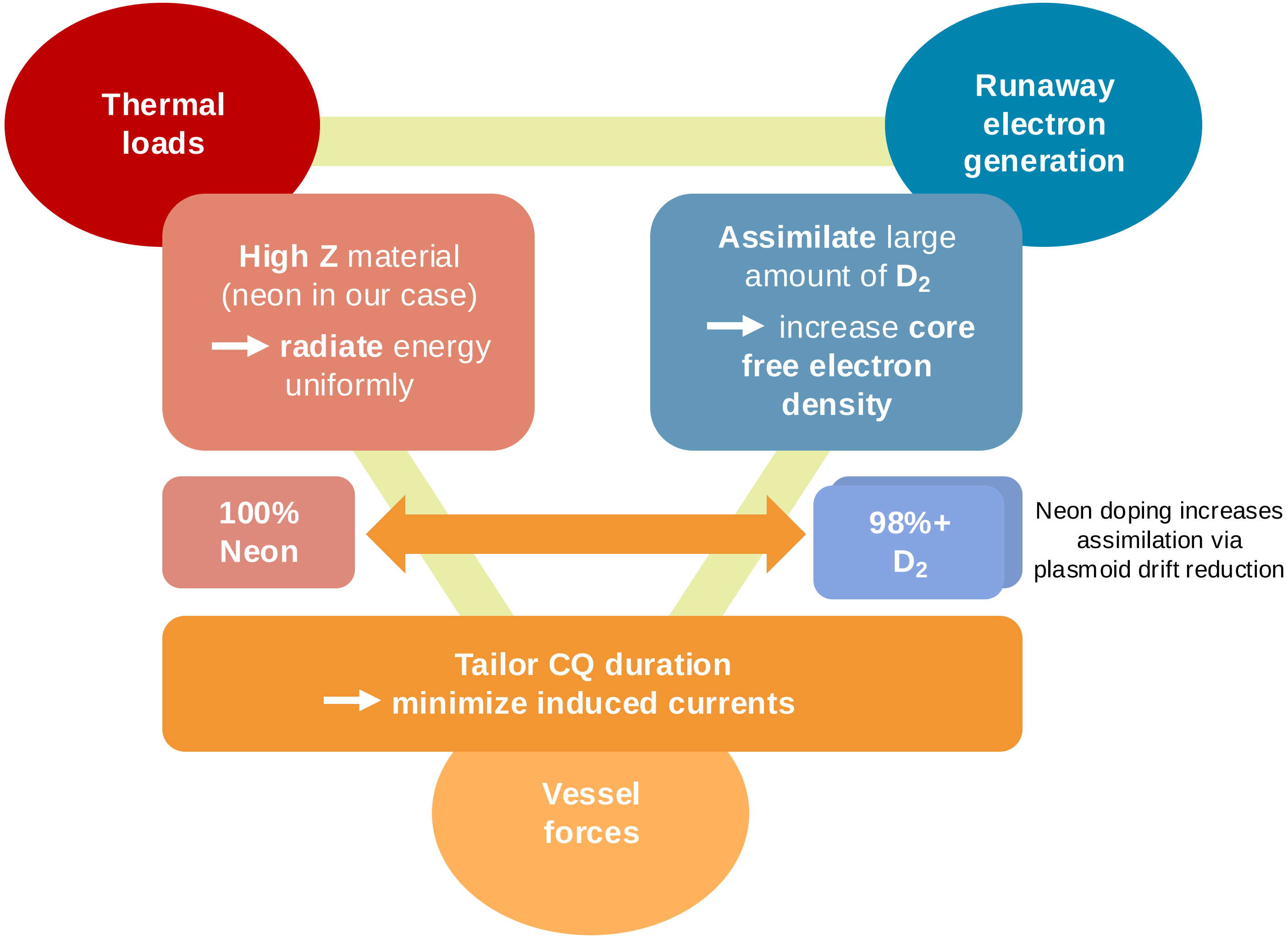
The goals of shattered pellet injection (SPI)



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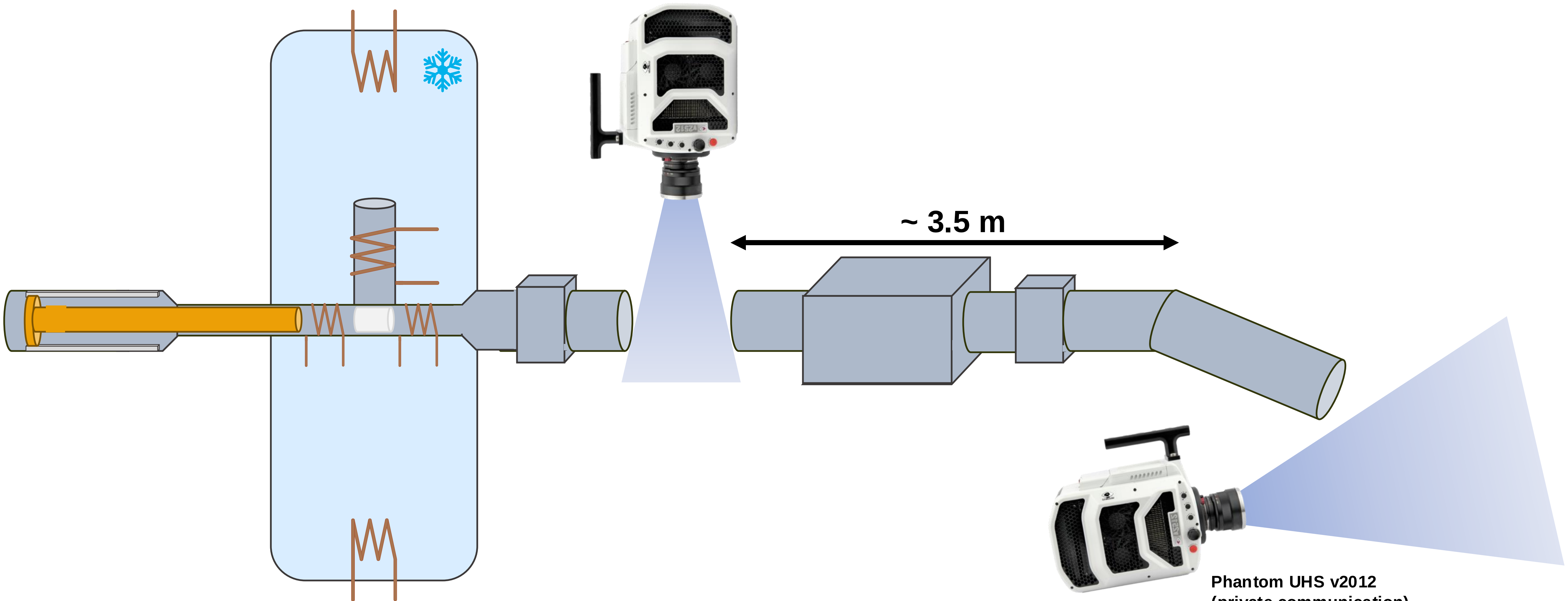
How does the AUG SPI system work?



Phantom UHS v2012
(private communication)
https://www.phantomhighspeed.com/

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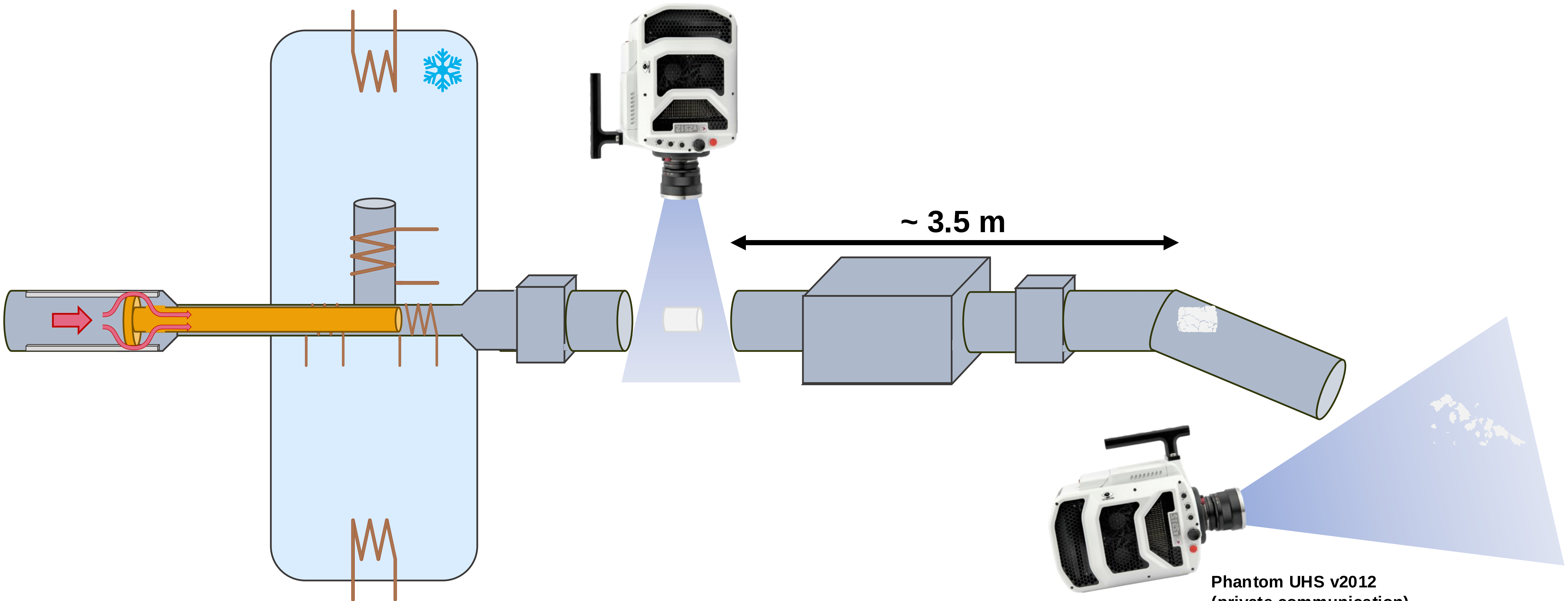

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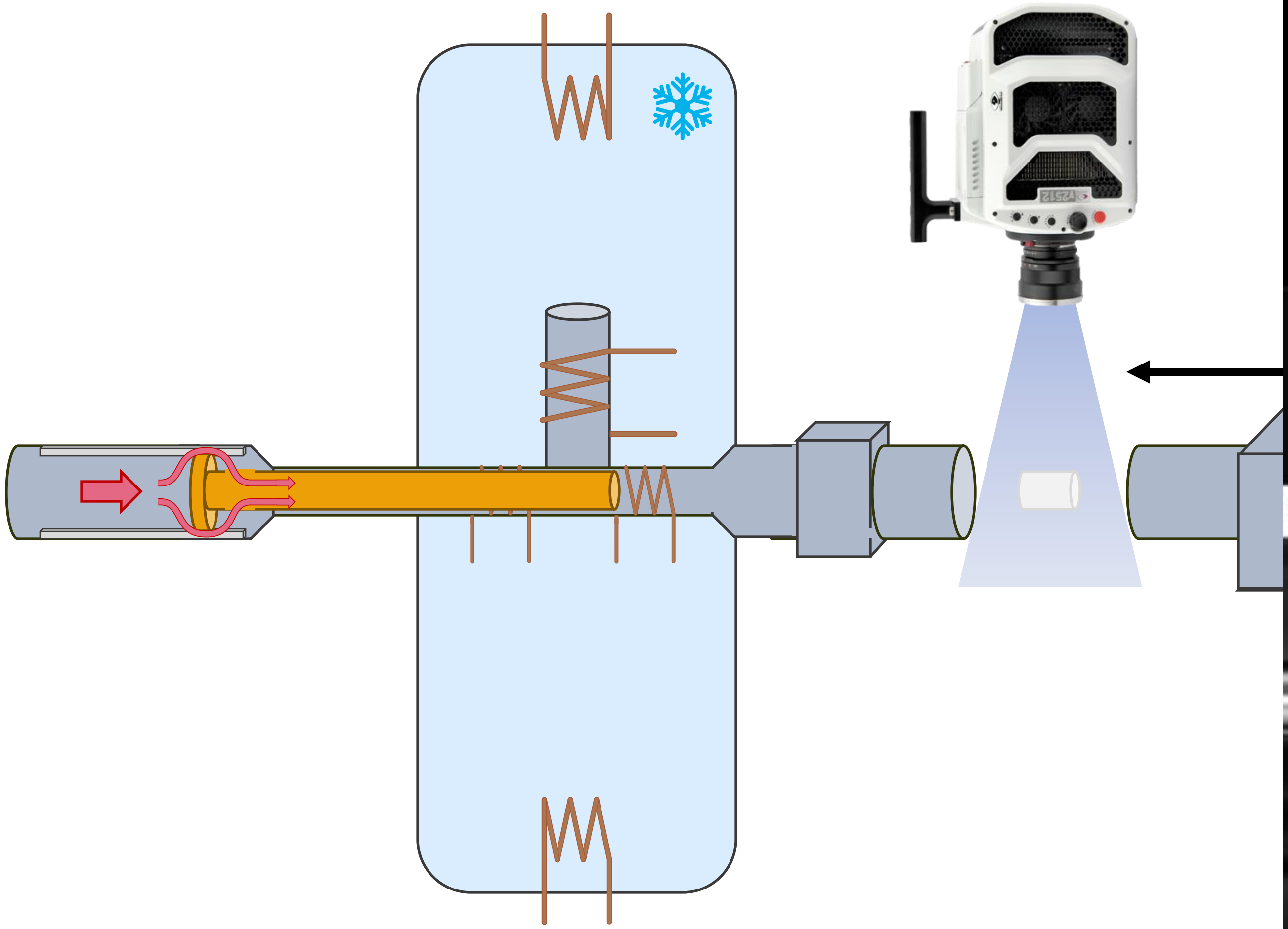
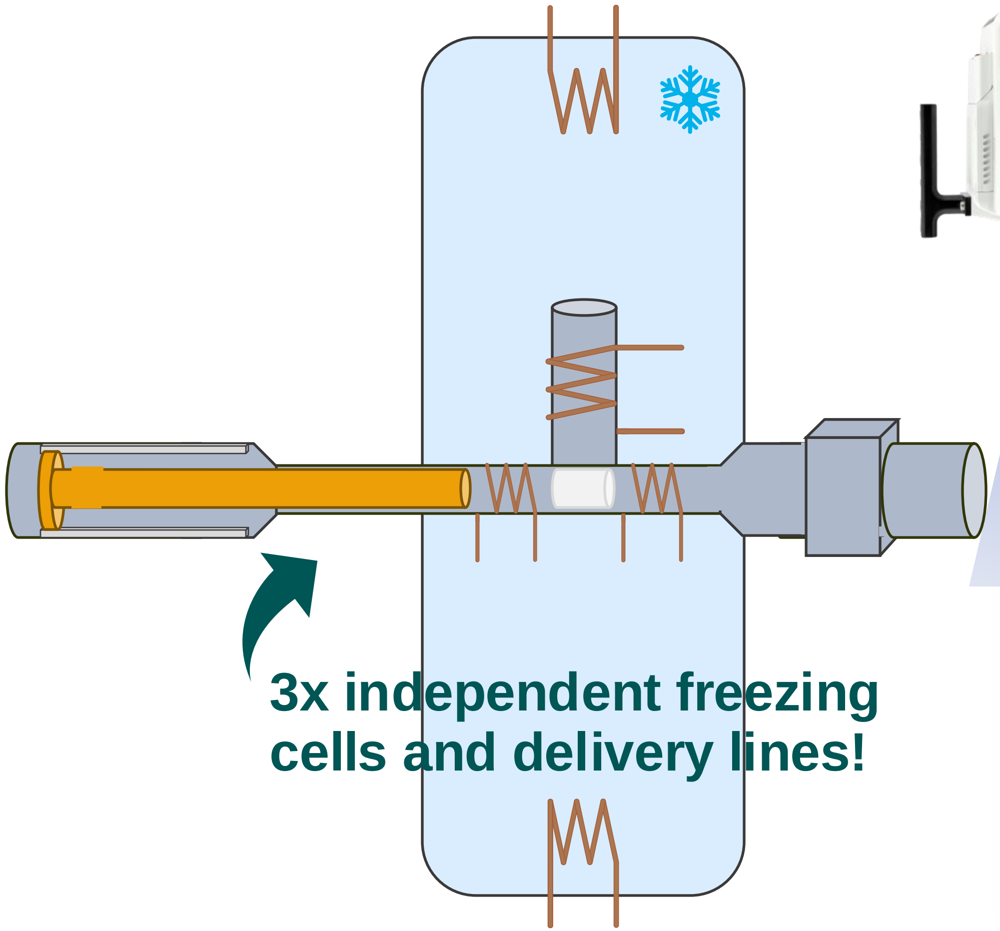


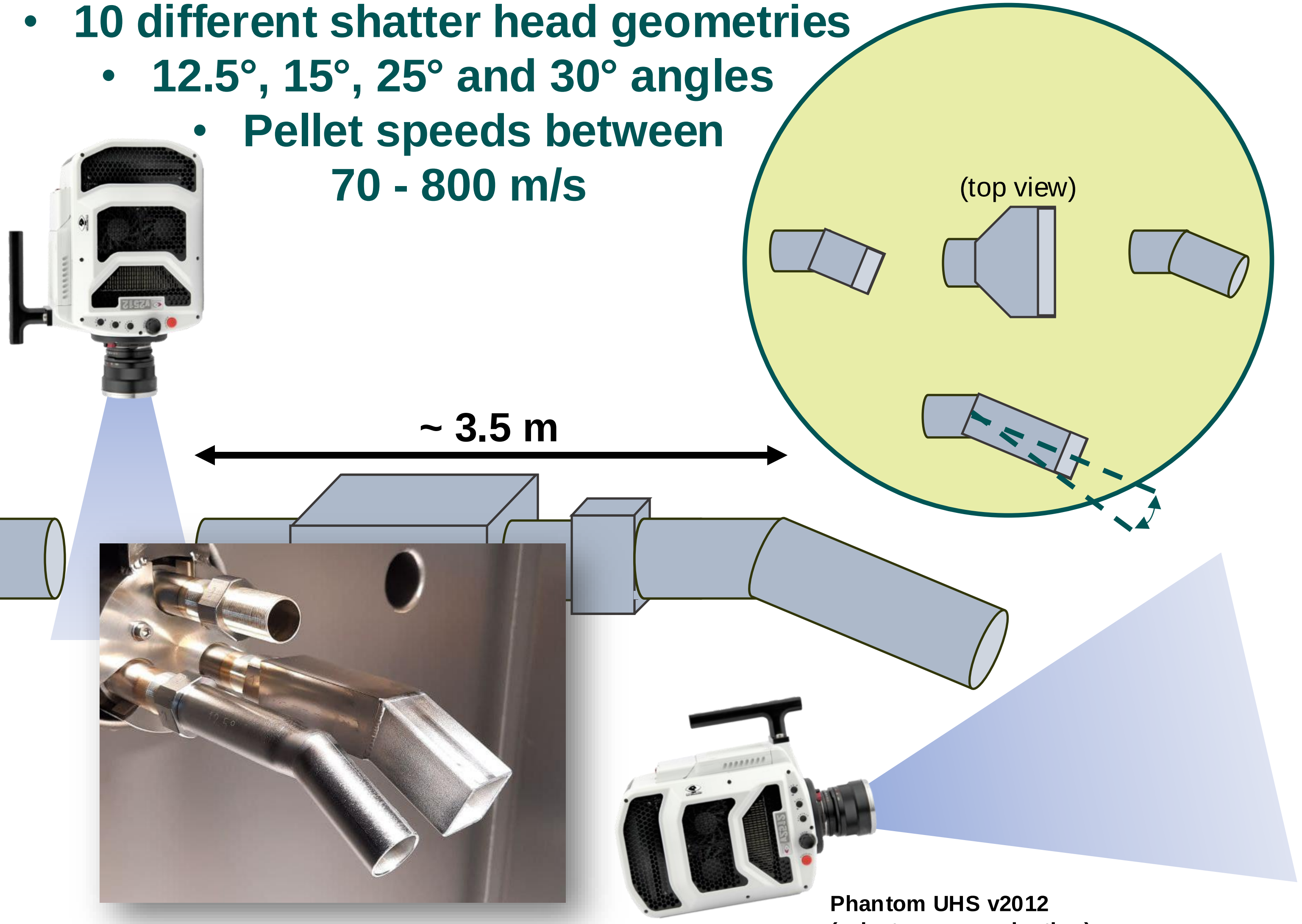
How does the AUG SPI system work?

What is special about the SPI system at AUG?

- 10 different shatter head geometries
  - 12.5°, 15°, 25° and 30° angles
    - Pellet speeds between 70 - 800 m/s

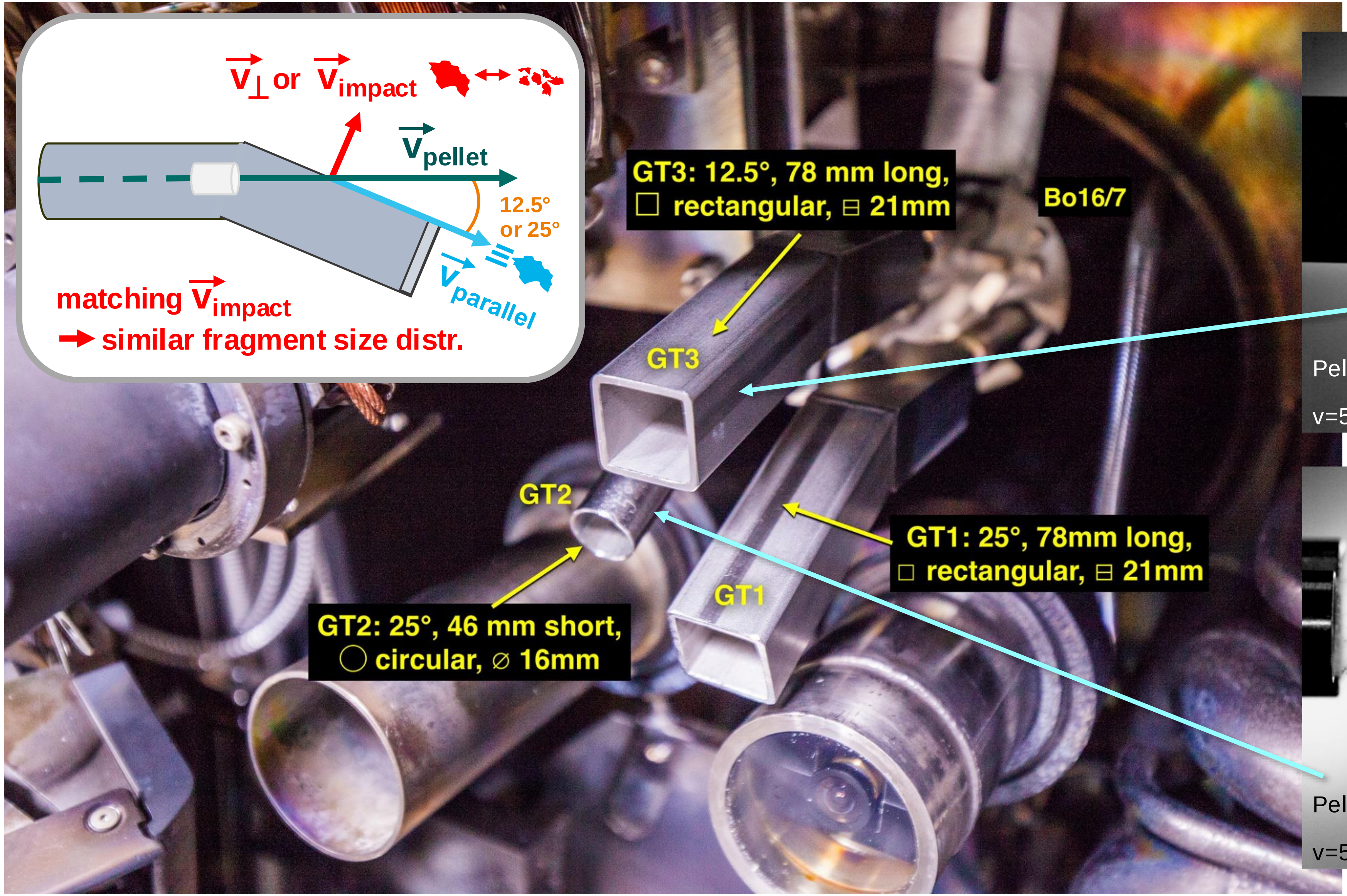


3x independent freezing cells and delivery lines!

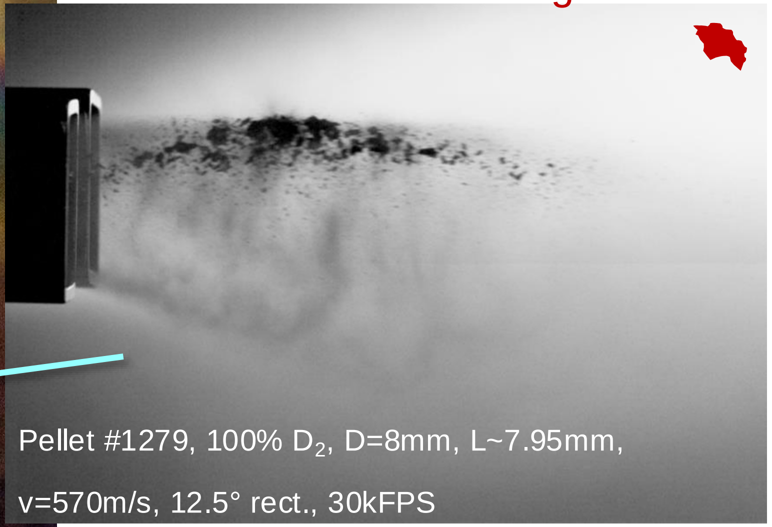


Phantom UHS v2012
(private communication)
https://www.phantomhighspeed.com/

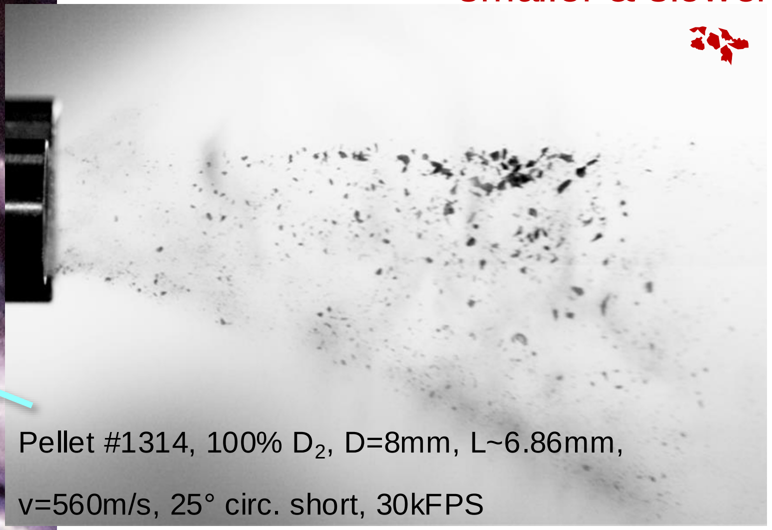
Shatter heads at ASDEX Upgrade in 2022



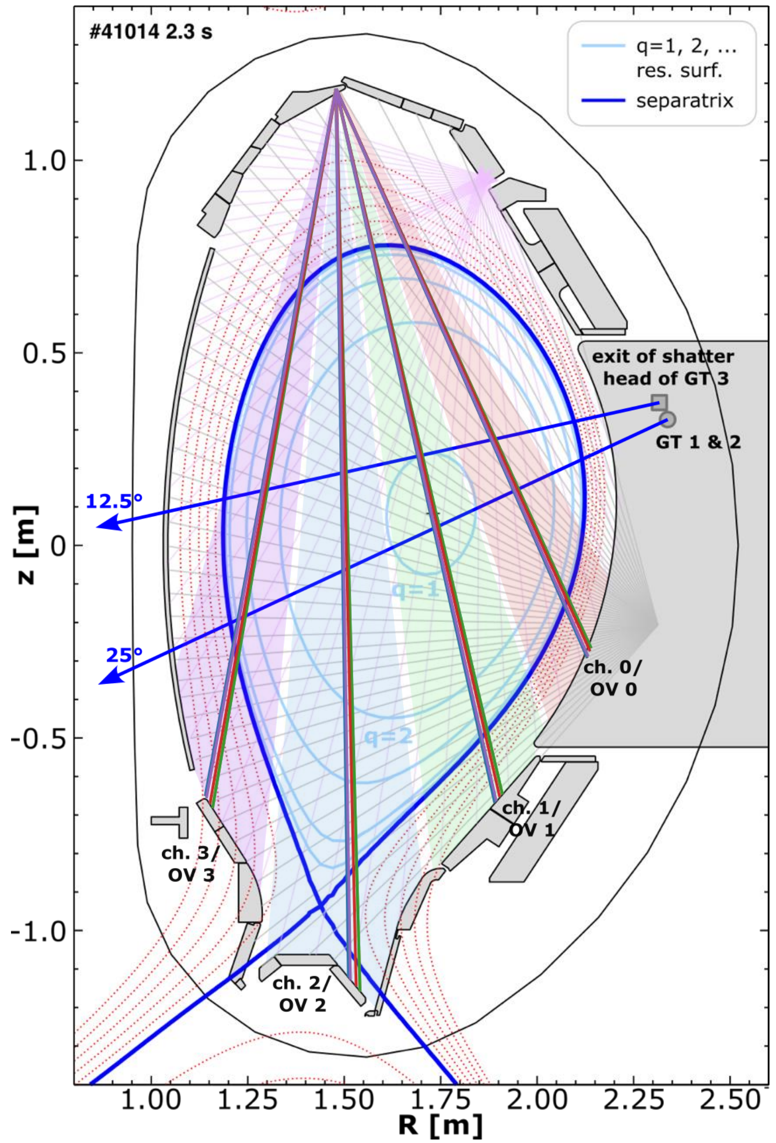
larger & faster

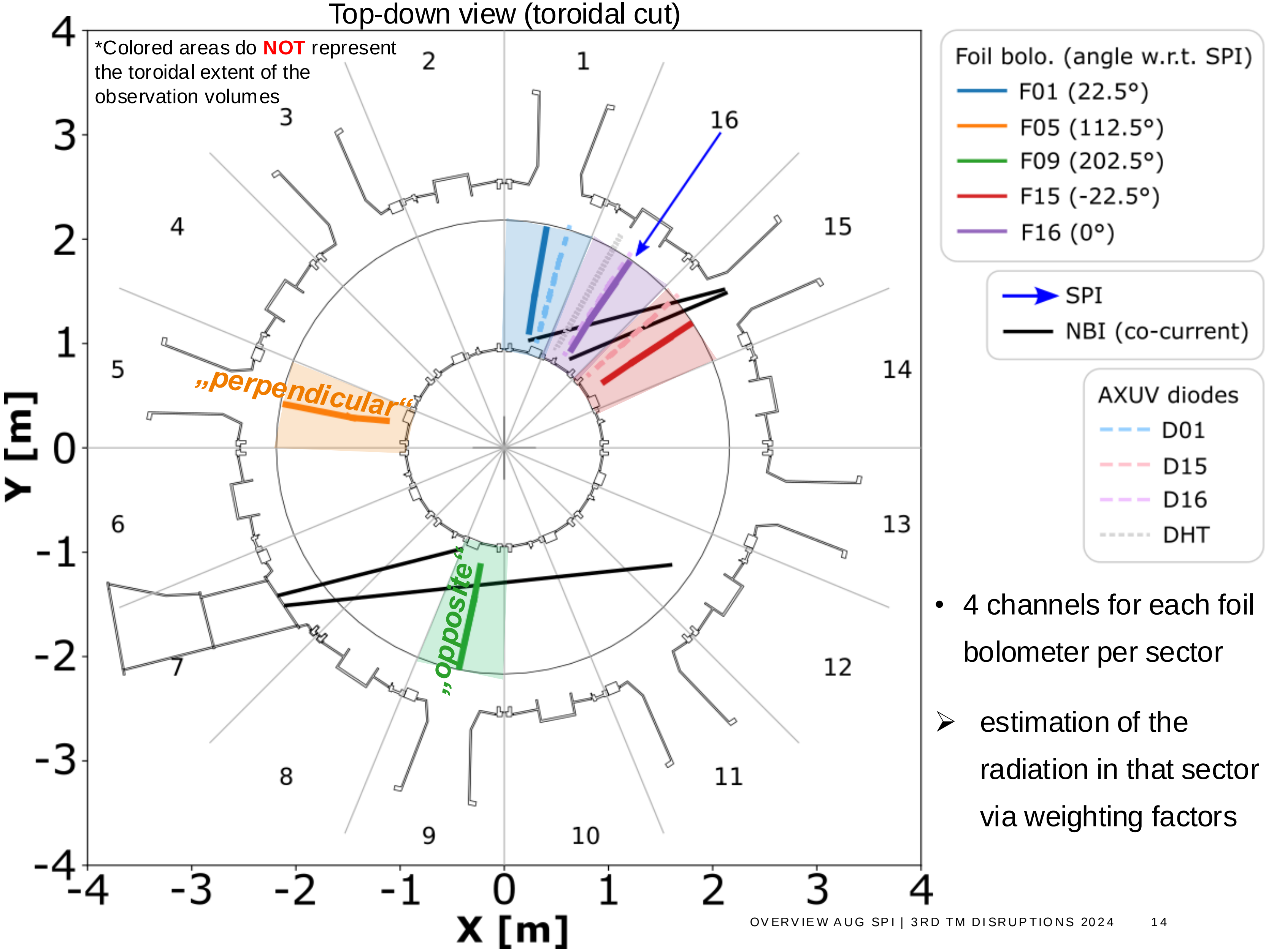


smaller & slower



AUG radiation measurements





- 4 channels for each foil bolometer per sector
  - ➢ estimation of the radiation in that sector via weighting factors

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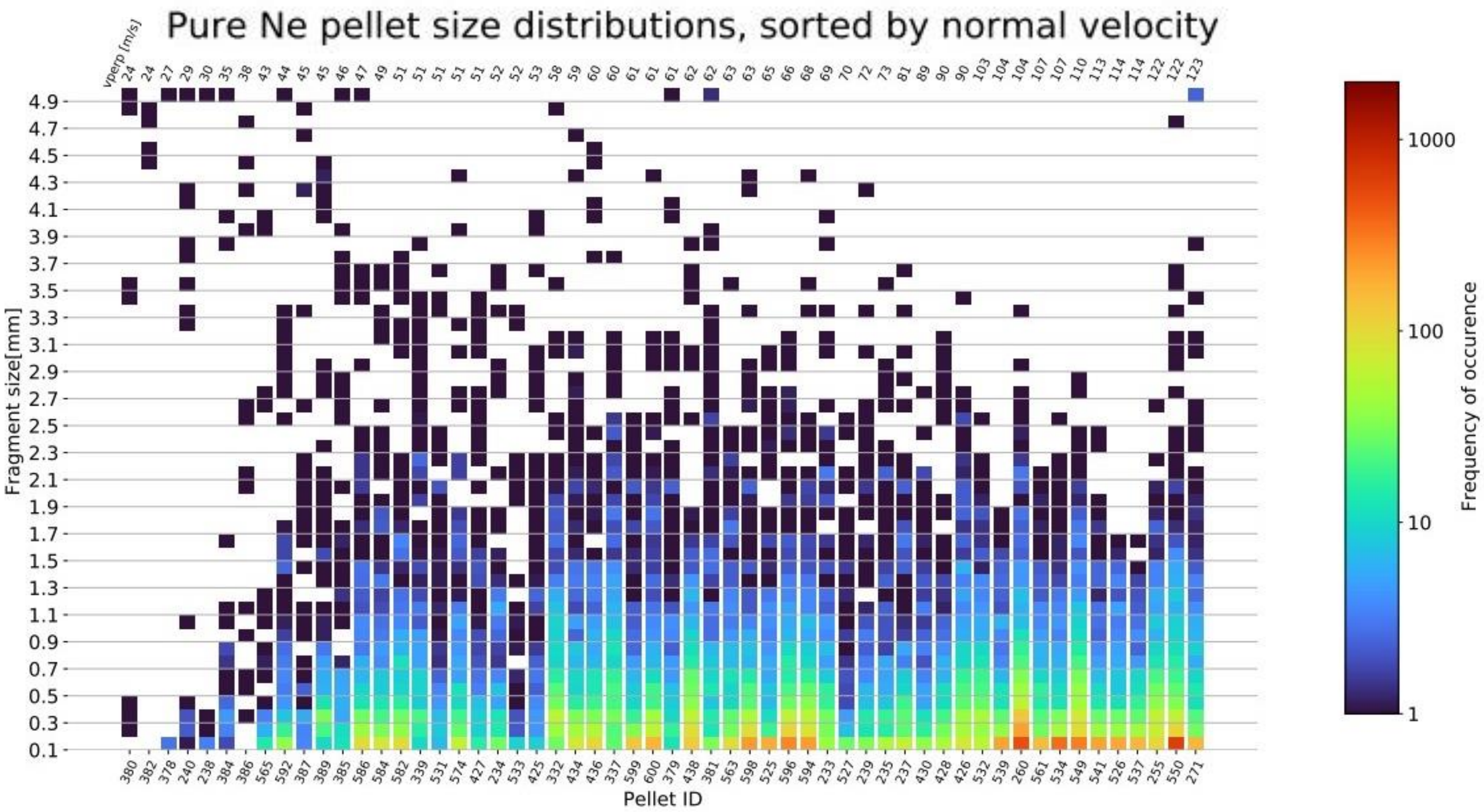
Fragment count for experimental data

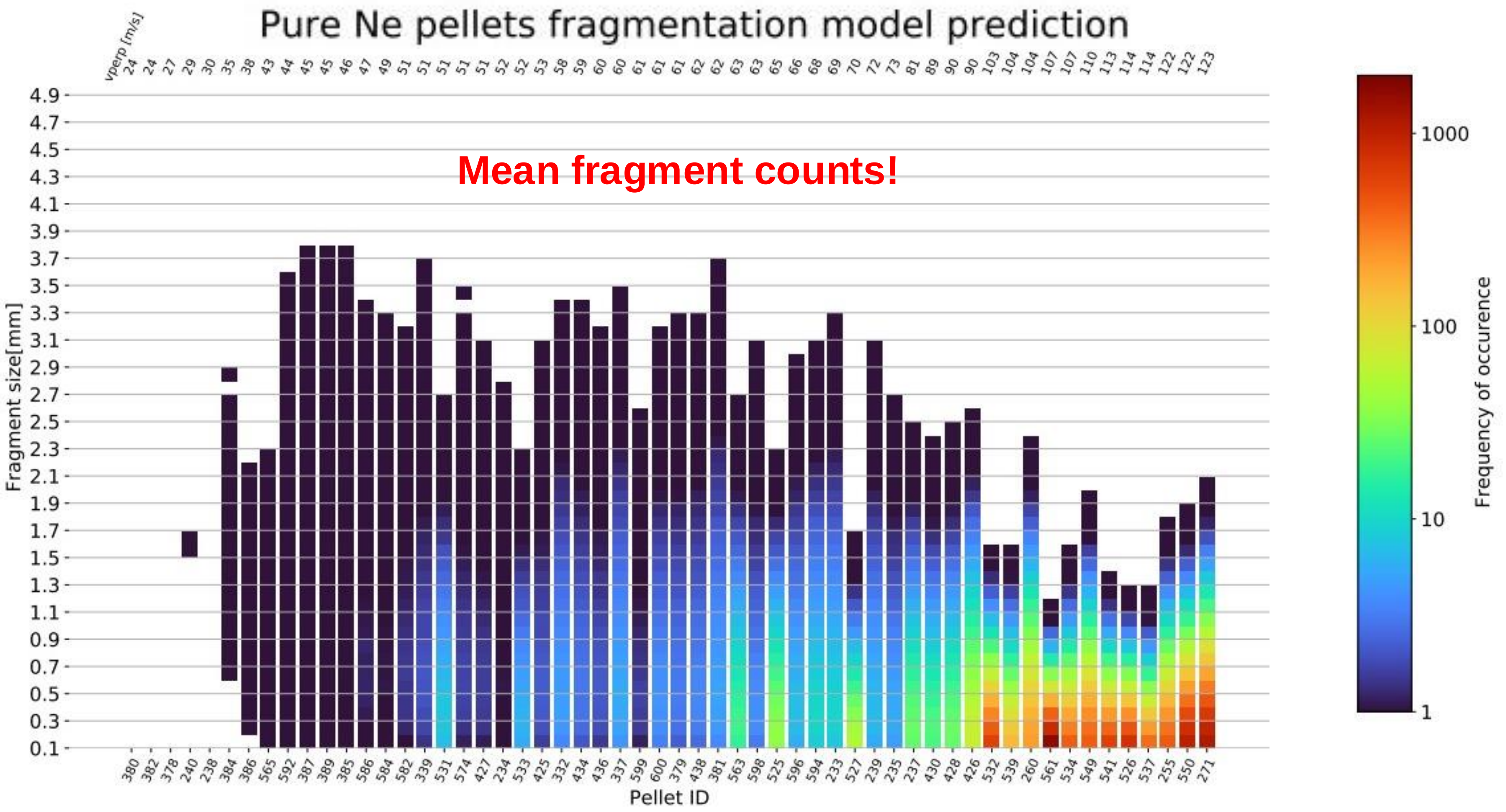
T. Peherstorfer, M.Sc. thesis (2022)



Tobias Peherstorfer (TU Wien)

Mean fragment count for Parks model prediction

T. Peherstorfer, M.Sc. thesis (2022)



Mean fragment counts!

Parks model

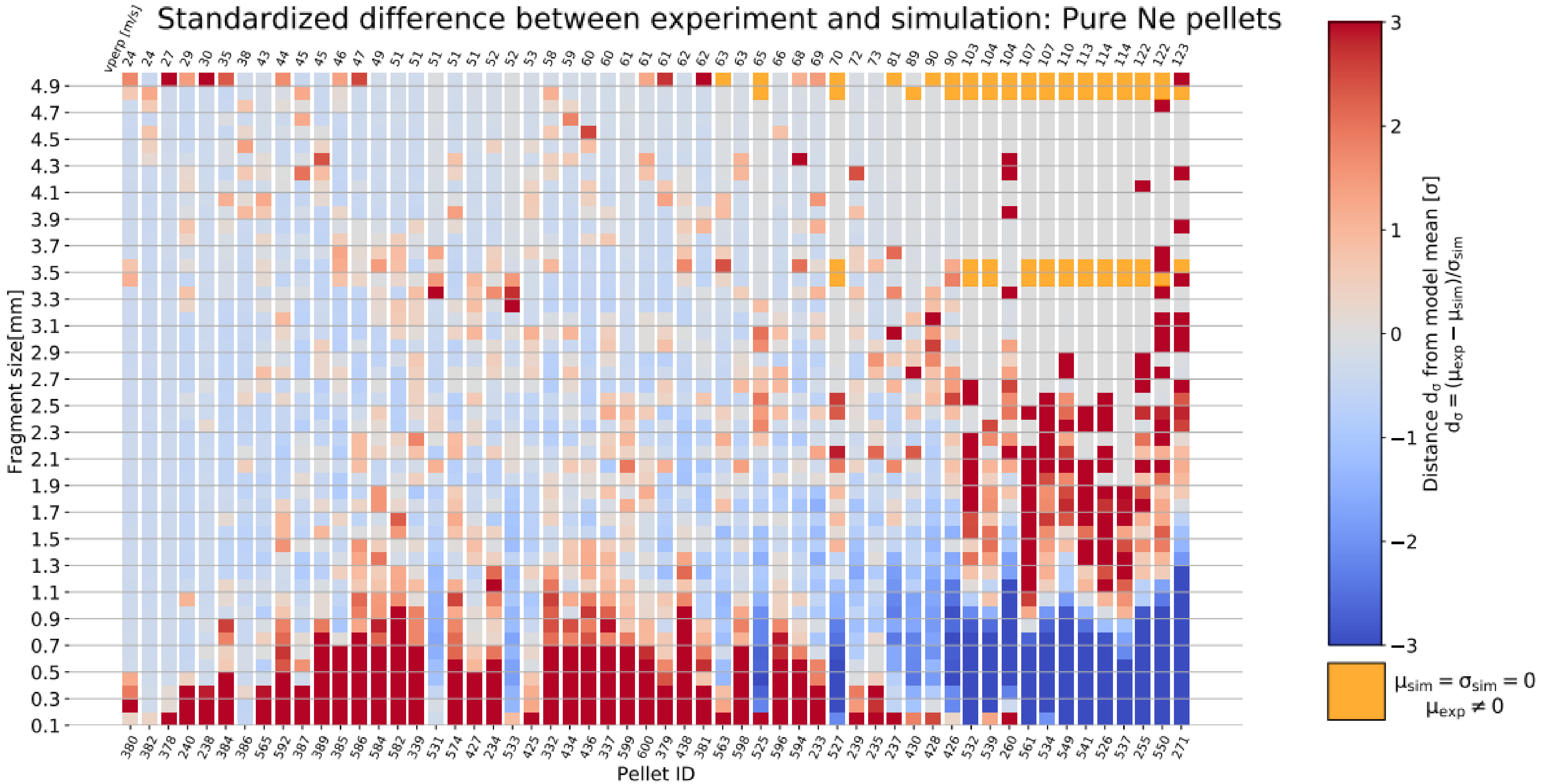
Tobias Peherstorfer (TU Wien)

Difference of model predictions to experimental data

T. Peherstorfer, M.Sc. thesis (2022)

Red: Model under-estimates

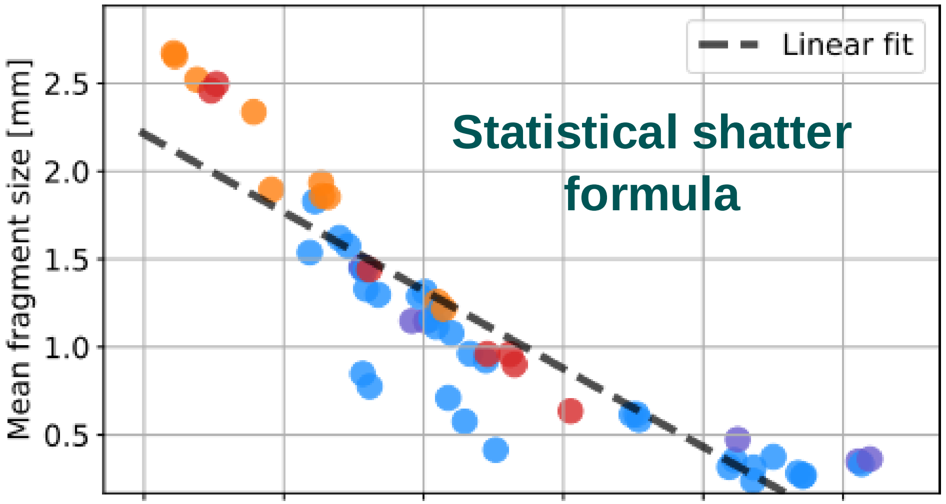
Blue: Model over-estimates

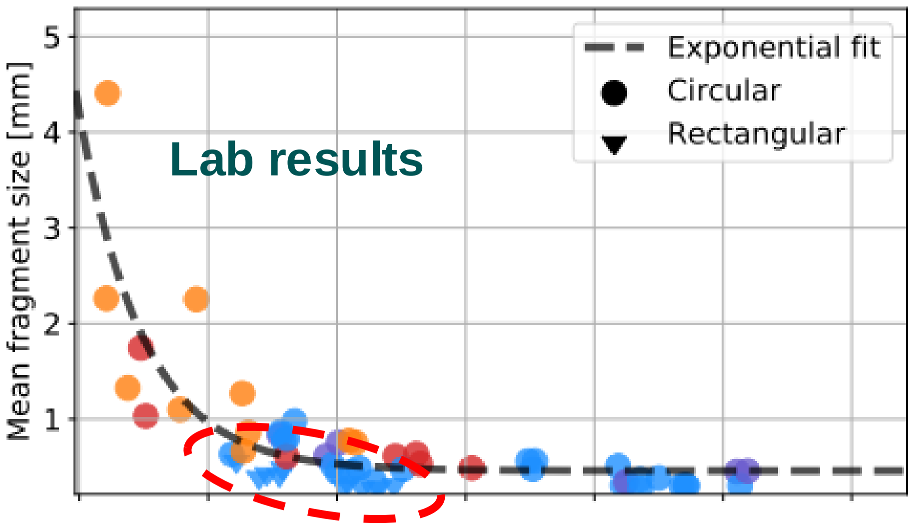


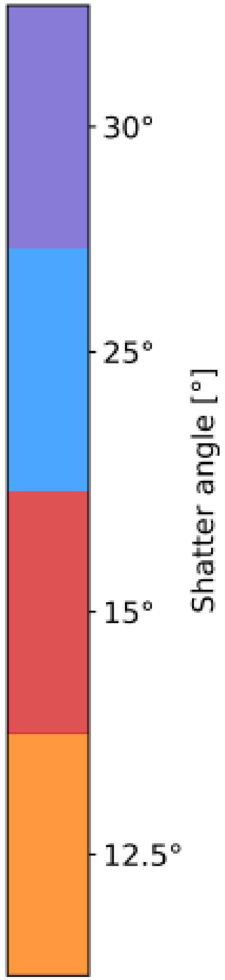
Tobias Peherstorfer (TU Wien)

Statistical shatter formula[1] and lab fragment detection[2]

100% neon, 4mm

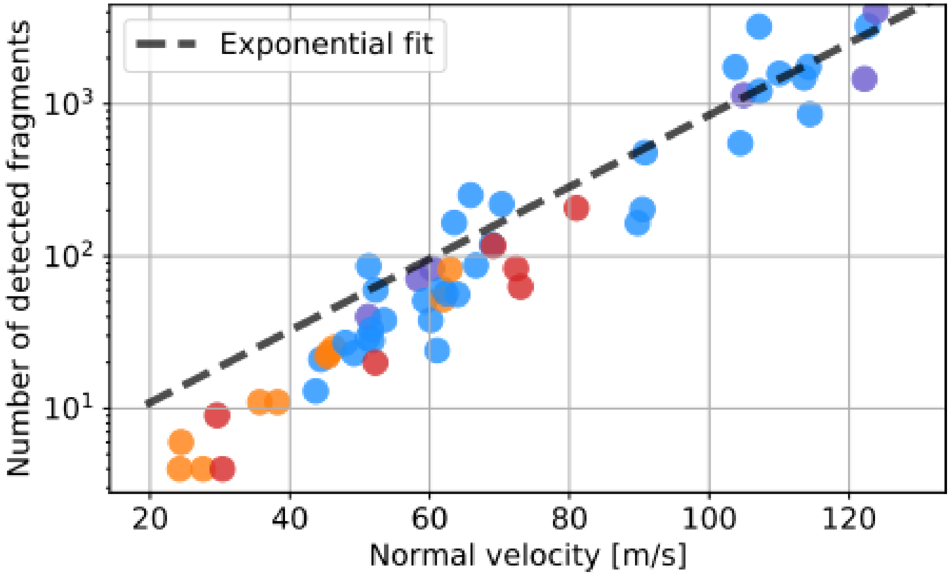


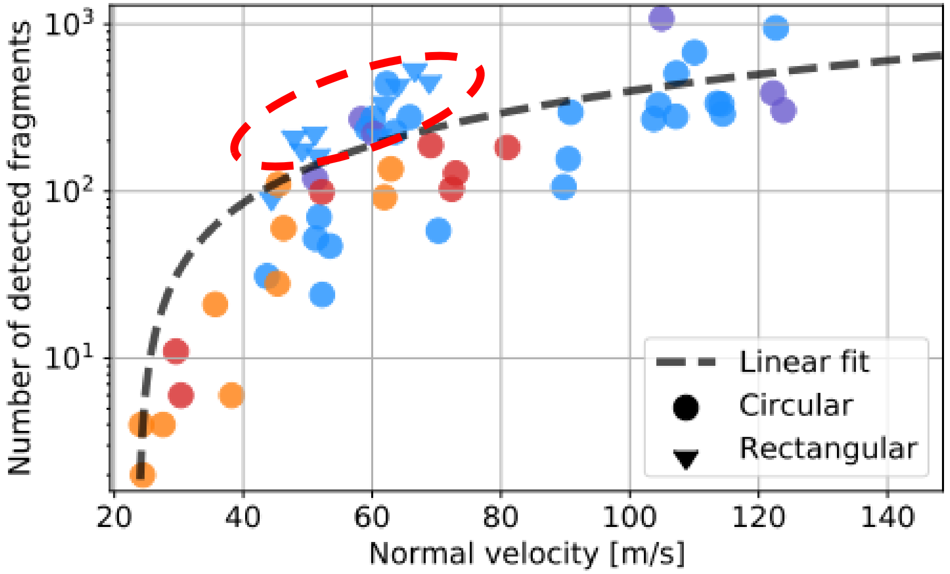




[1][Parks, 2016]

[2][Peherstorfer, M.Sc. thesis (2022)]



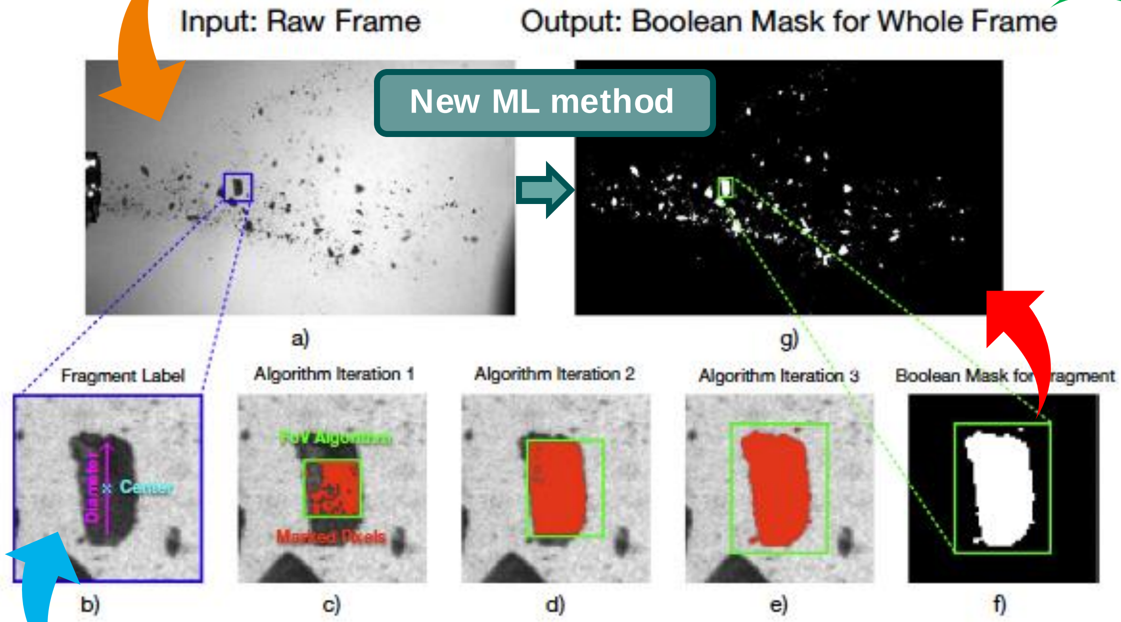


Johannes Illerhaus & Mohammad Miah (IPP)

New fragment detection based on Machine Learning

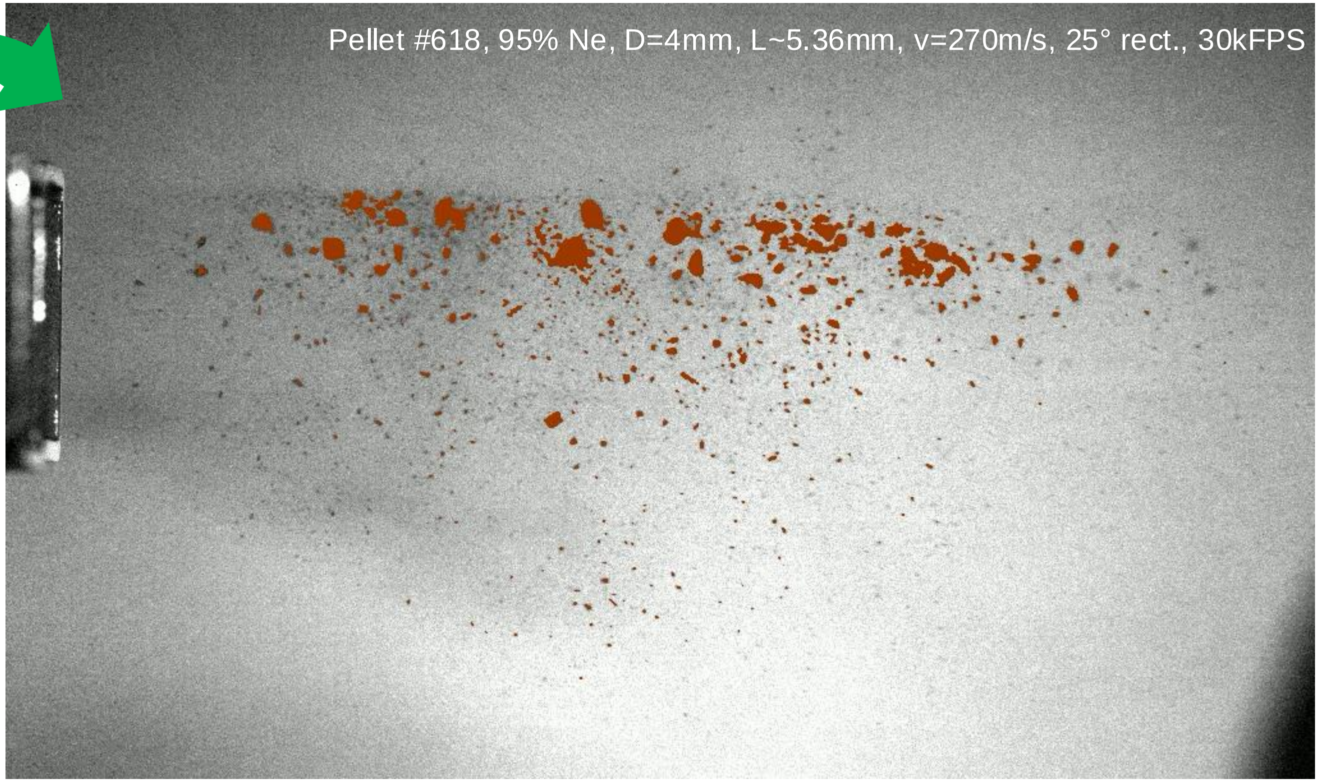
Lab data

Boolean masks act as training data



[Illerhaus et al., Journal of Fusion Energy 43:14 (2024)]

Label from previous detection method (T. Peherstorfer)



With the help of Machine Learning (model: U-Net; EfficientNet B0 backbone) ➡ Generation of Boolean masks for fragment tracking

➡ **Possible to analyse all 1100 lab videos without manual parameter adjustments (Mohammad Miah)**

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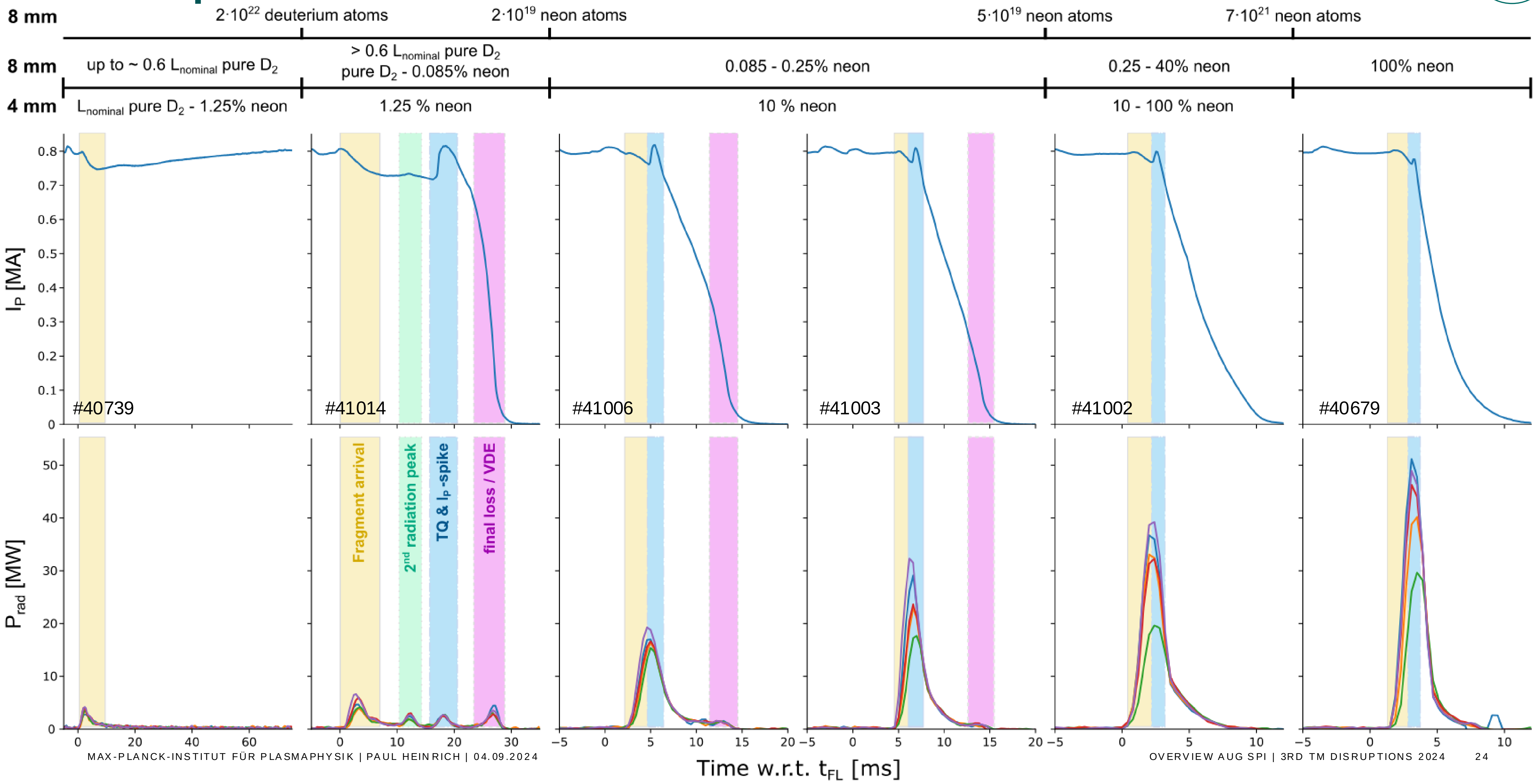
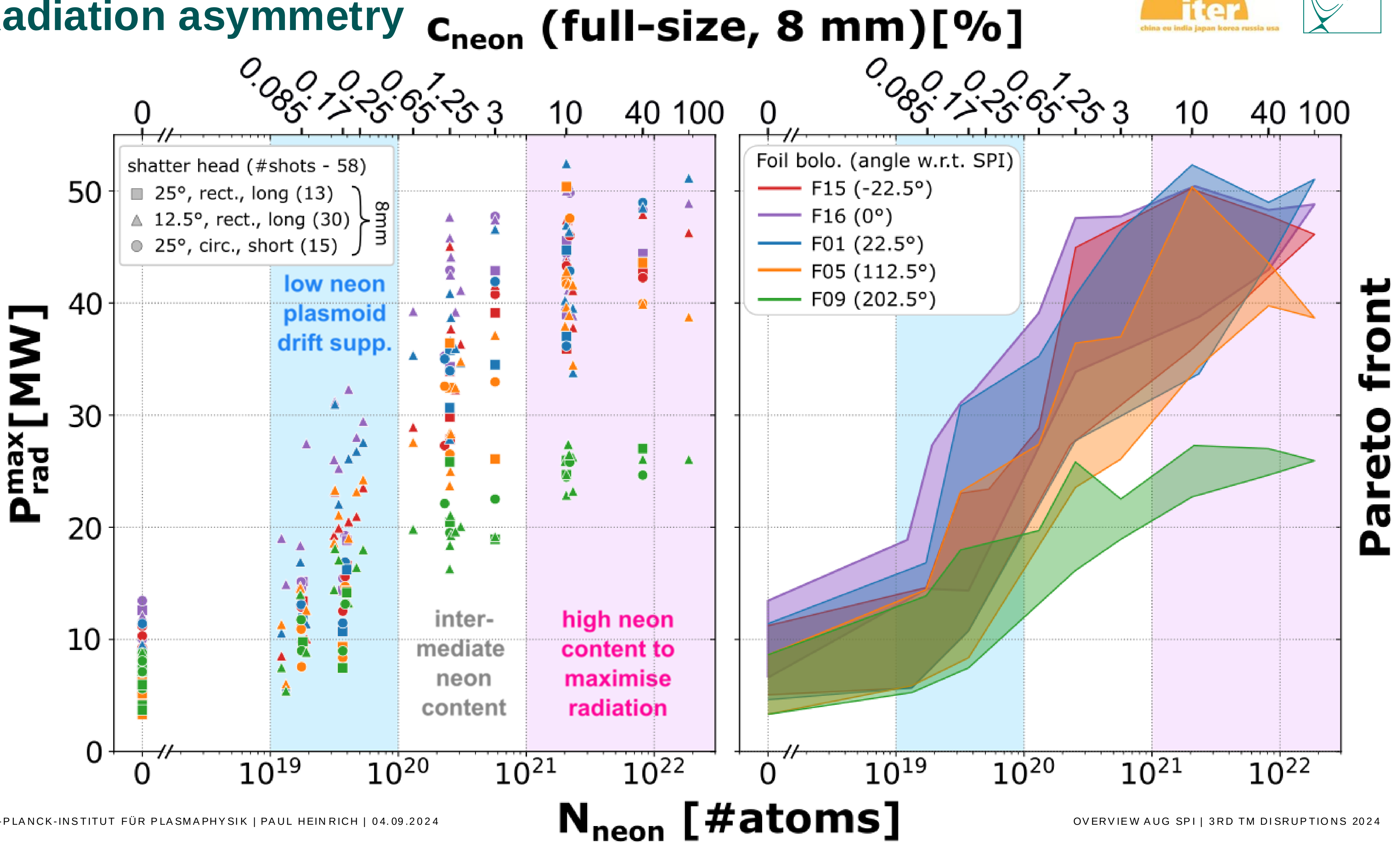
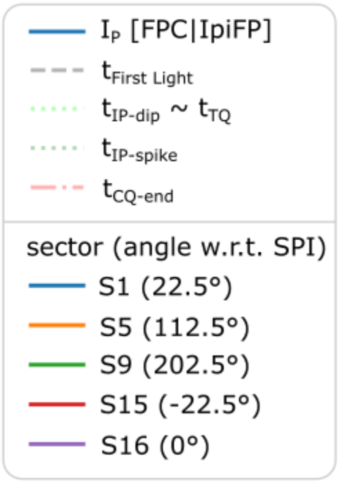
Disruption evolution



Radiation asymmetry

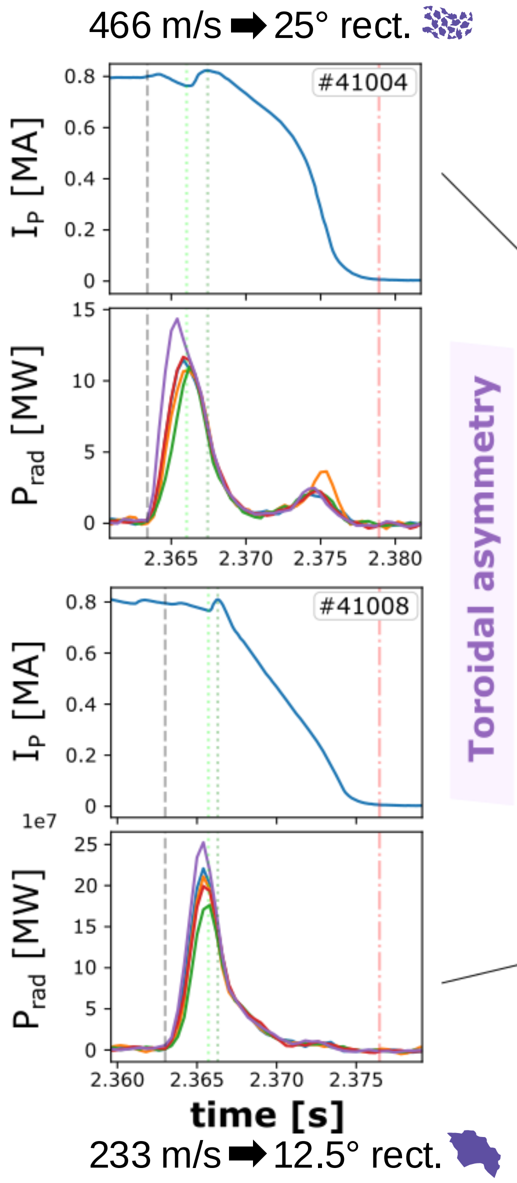


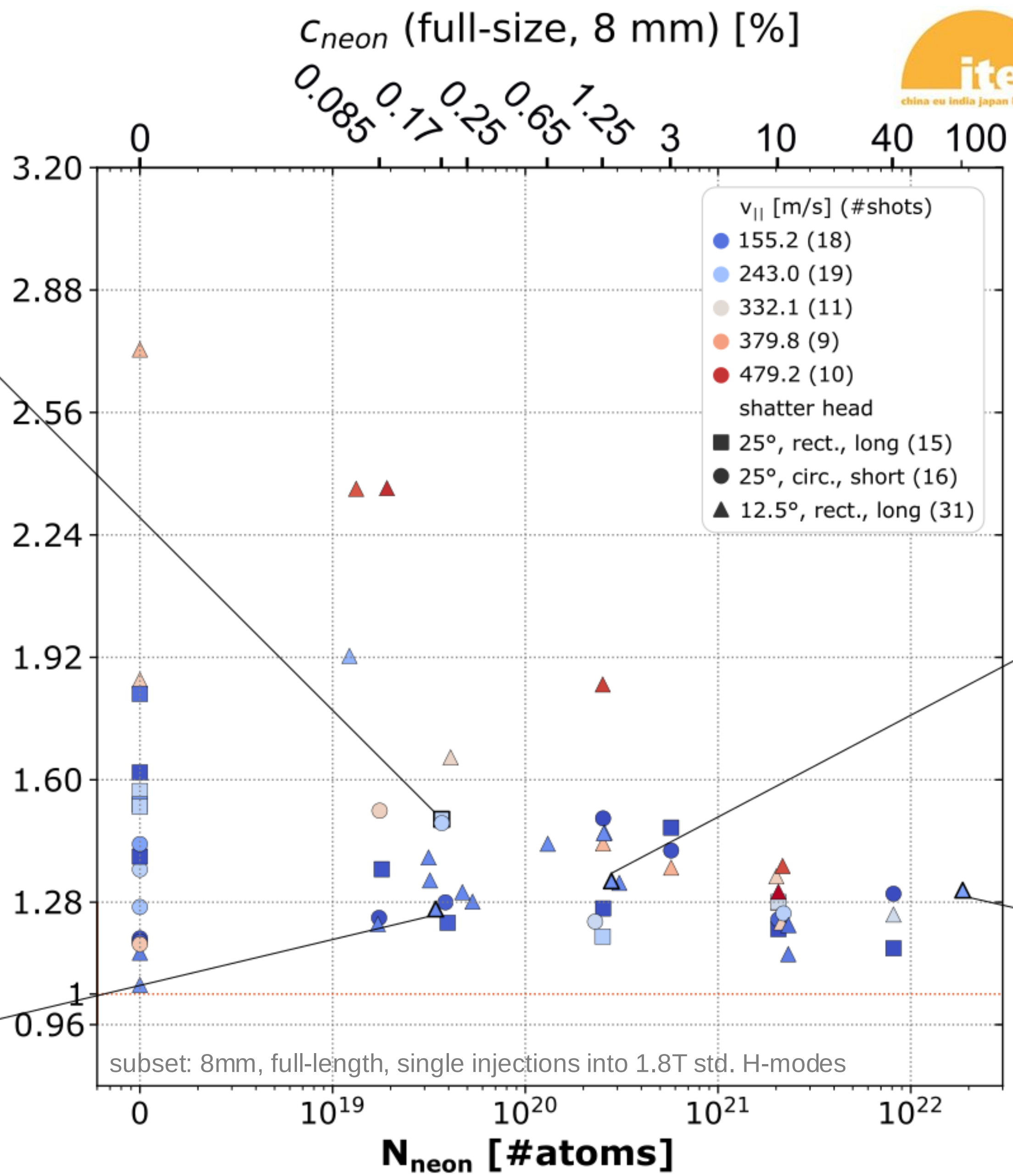
Toroidal asymmetries

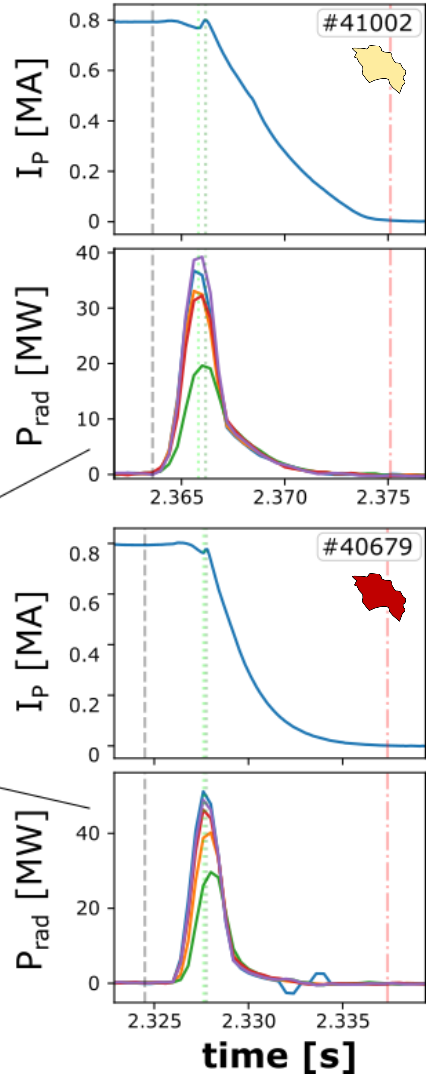


Tor. asym.

$$\frac{P_{rad}^{max}}{\sum_{i=0}^{16} \frac{P_{rad,\,i}}{16}}$$







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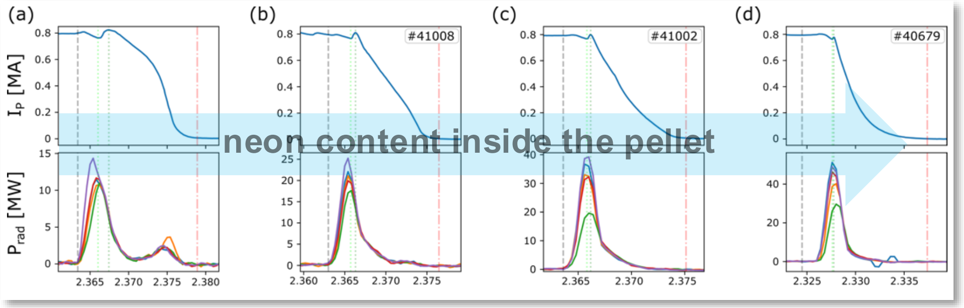

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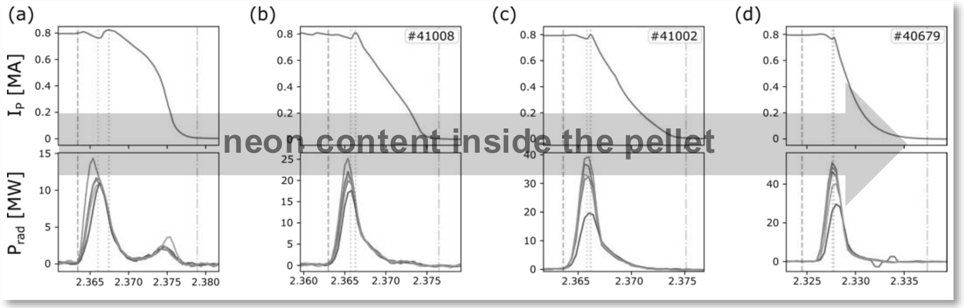


Radiated energy fraction (f_{rad})

W_{mag}		W_{th}
$W_{coupled}$	W_{rad}	W_{cond}
energy coupled into the structure (e.g. coils, vessel)	energy radiated (derived from foil bolometers)	energy conducted to the PFCs (mainly divertor)

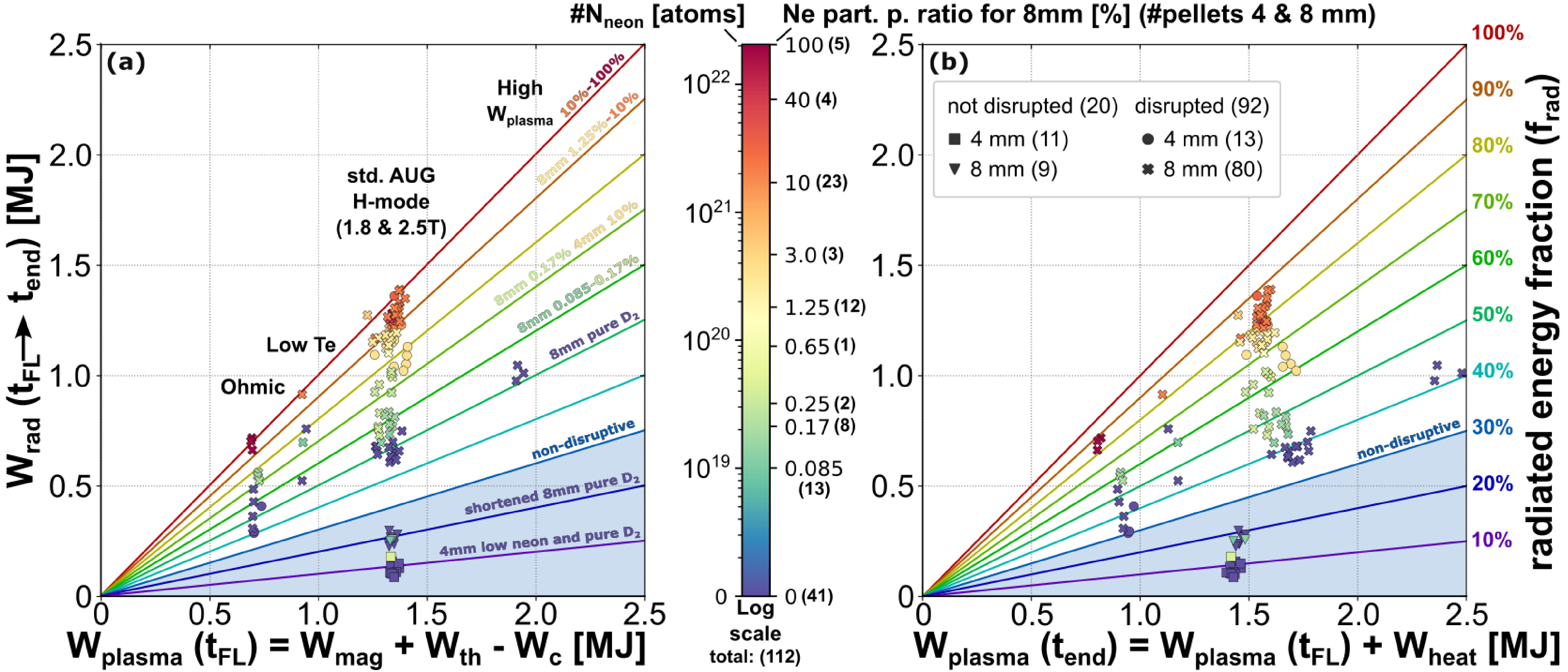
$$W_{mag} + W_{th} + W_{ext.\ heat.} = W_{rad} + W_{coupled} + W_{cond} + W_{RE}$$

$$f_{rad} = \frac{W_{rad}}{W_{mag} + W_{th} + W_{heat.} - W_{c}} = \frac{W_{rad}}{W_{rad} + W_{cond}}$$

[Lehnen et. al., Nucl. Fusion 53 (2013) 093007]

Radiated energy fraction (f_{rad})

$$f_{rad} = \frac{W_{rad}}{W_{plasma}} = \frac{W_{rad}}{W_{mag} + W_{th} + W_{heat} - W_c} = \frac{W_{rad}}{W_{rad} + W_{cond}}$$



[Heinrich et. al., in preparation]

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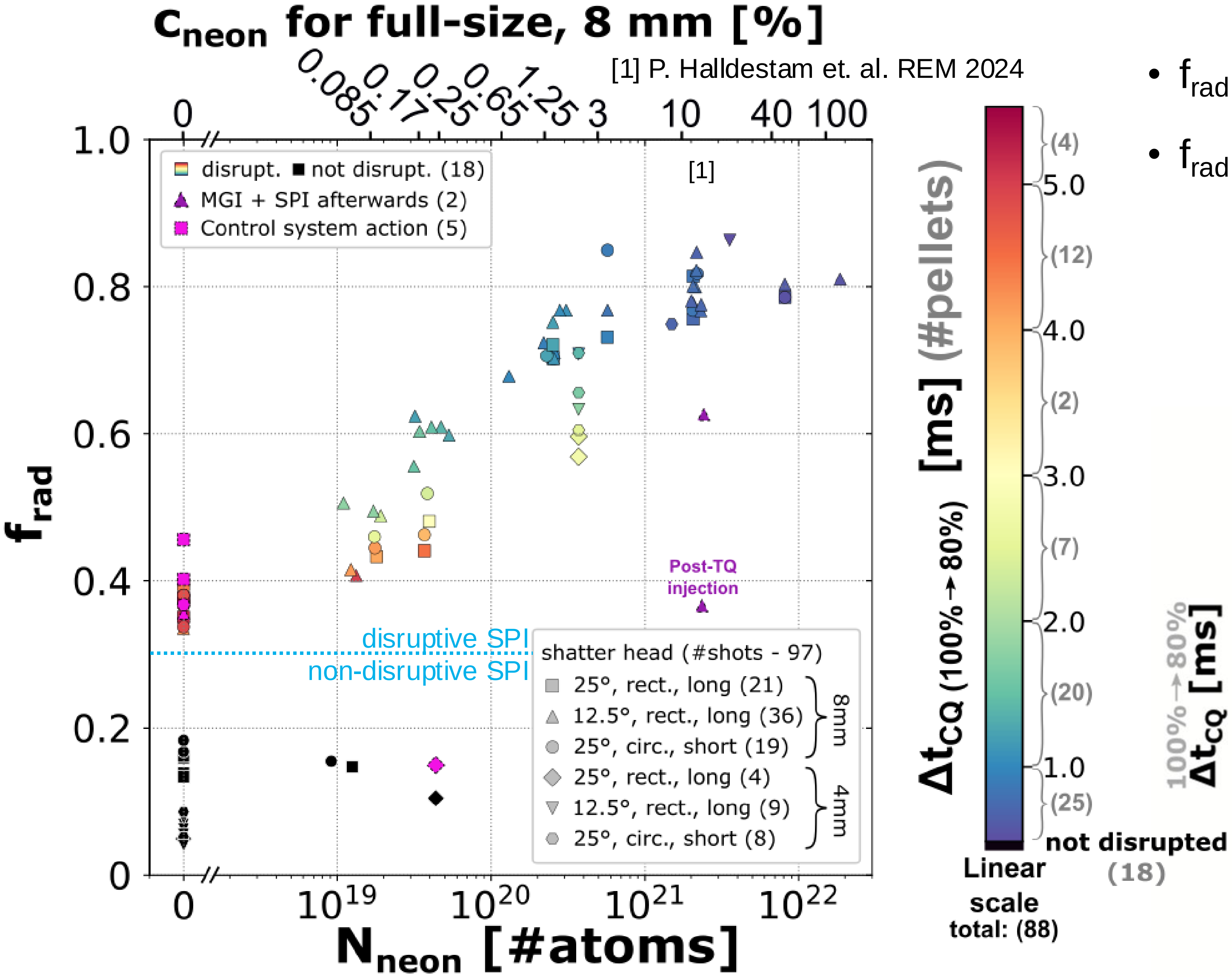
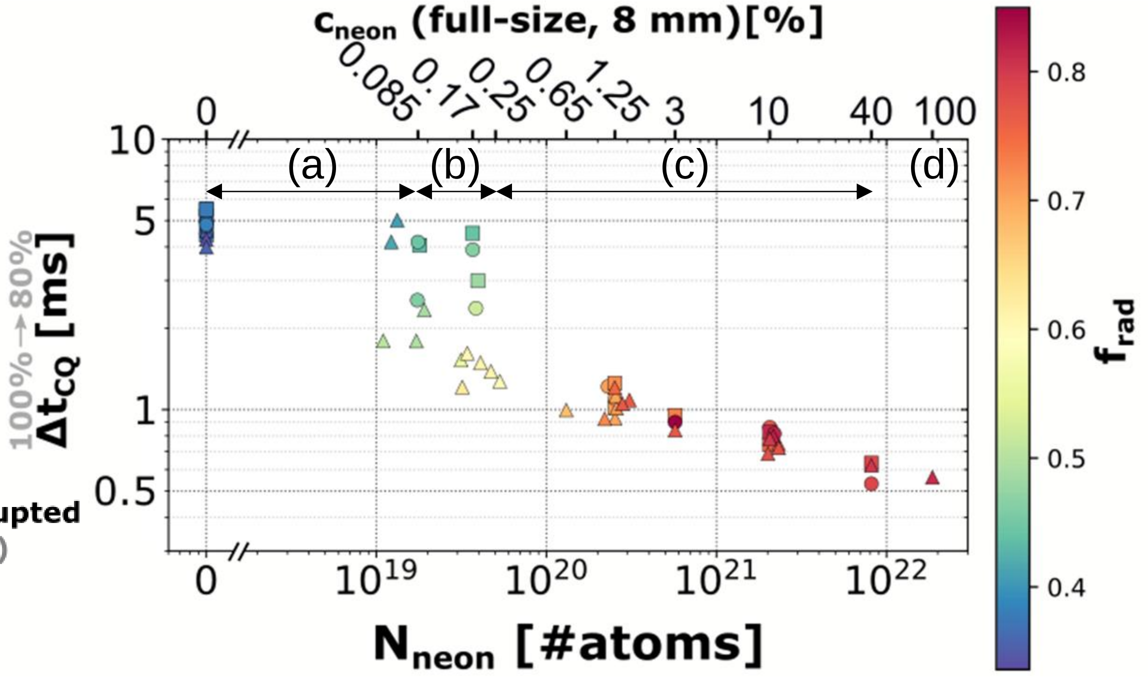


- f_{rad} dominated by the impact of the neon amount
- f_{rad} of disruptive SPI $\geq 35\%$, non-disr. $\leq 20\%$



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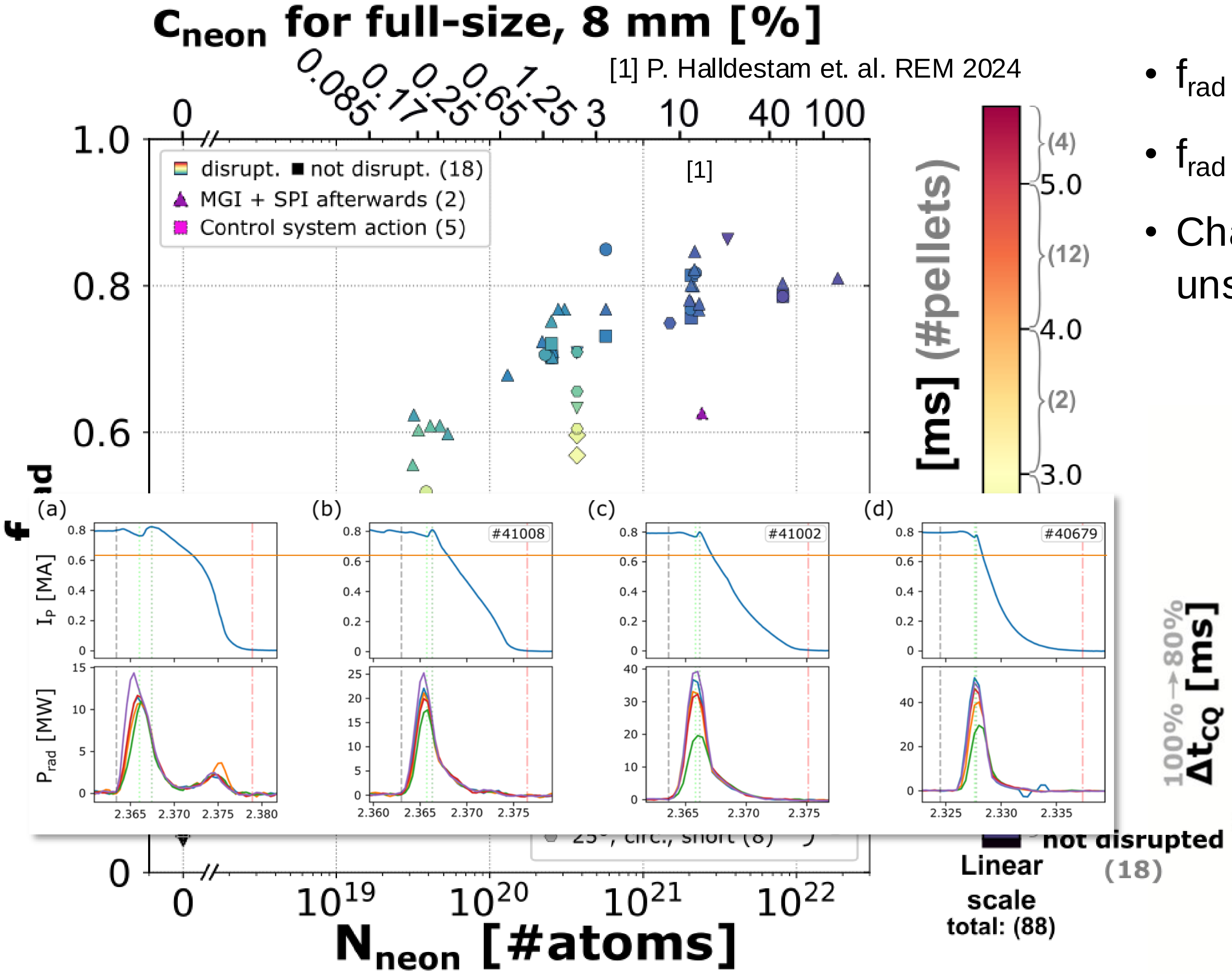

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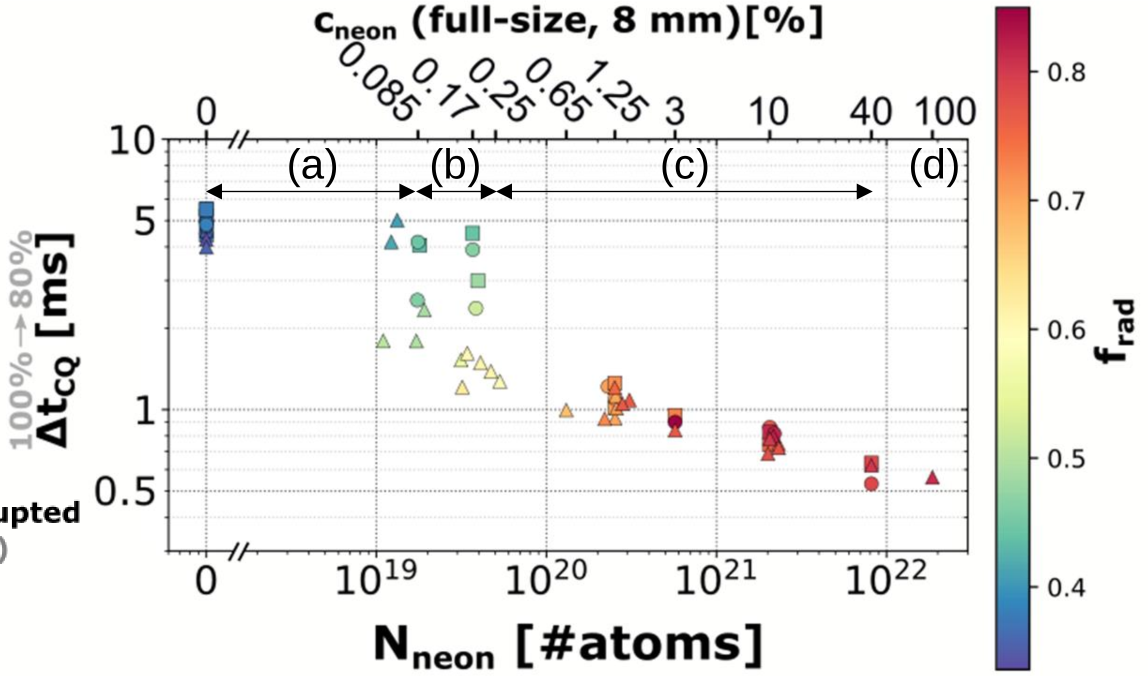
- Change in CQ-shape reflected in discontinuity of unscaled $\Delta t_{CQ}^{100\% \rightarrow 80\%}$



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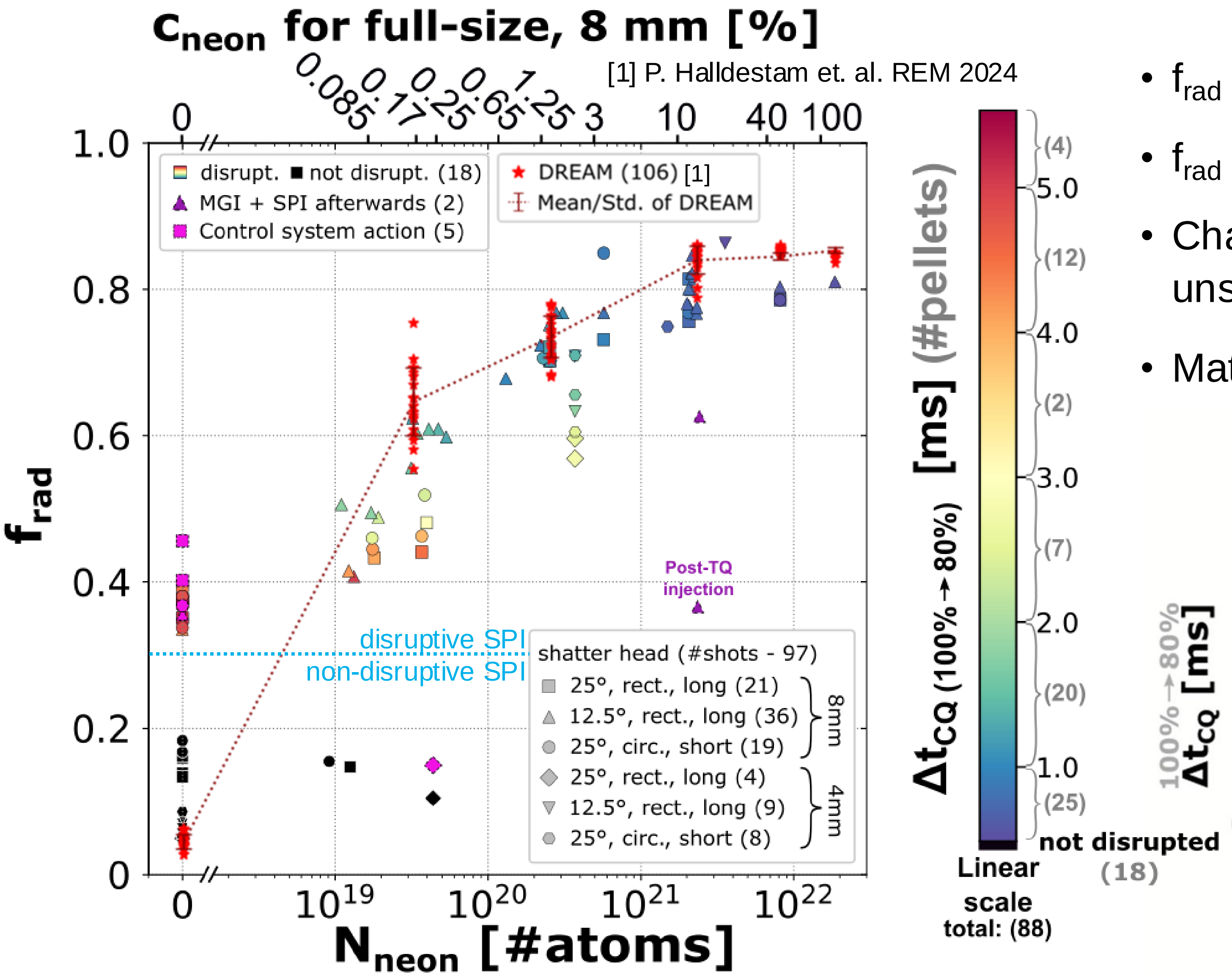

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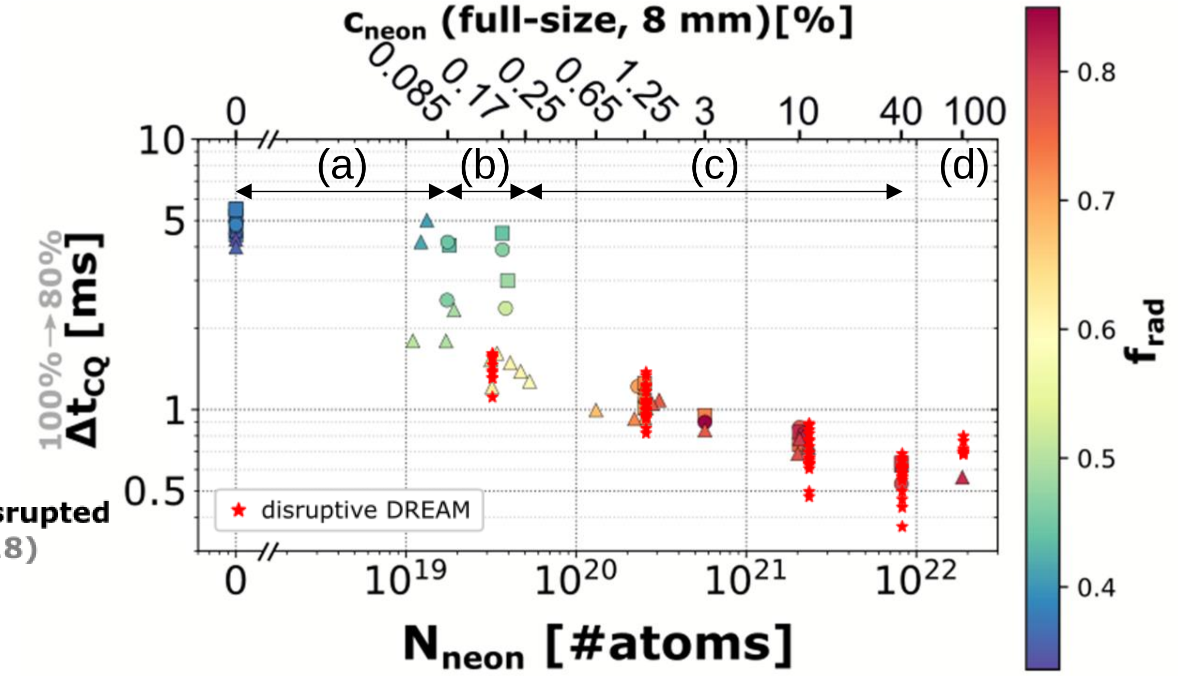
- f_{rad} of disruptive SPI $\geq 35\%$, non-disr. $\leq 20\%$
- Change in CQ-shape reflected in discontinuity of unscaled $\Delta t_{CQ}^{100\%\rightarrow 80\%}$
- Matches DREAM simulations well! (VDEs not simulated)



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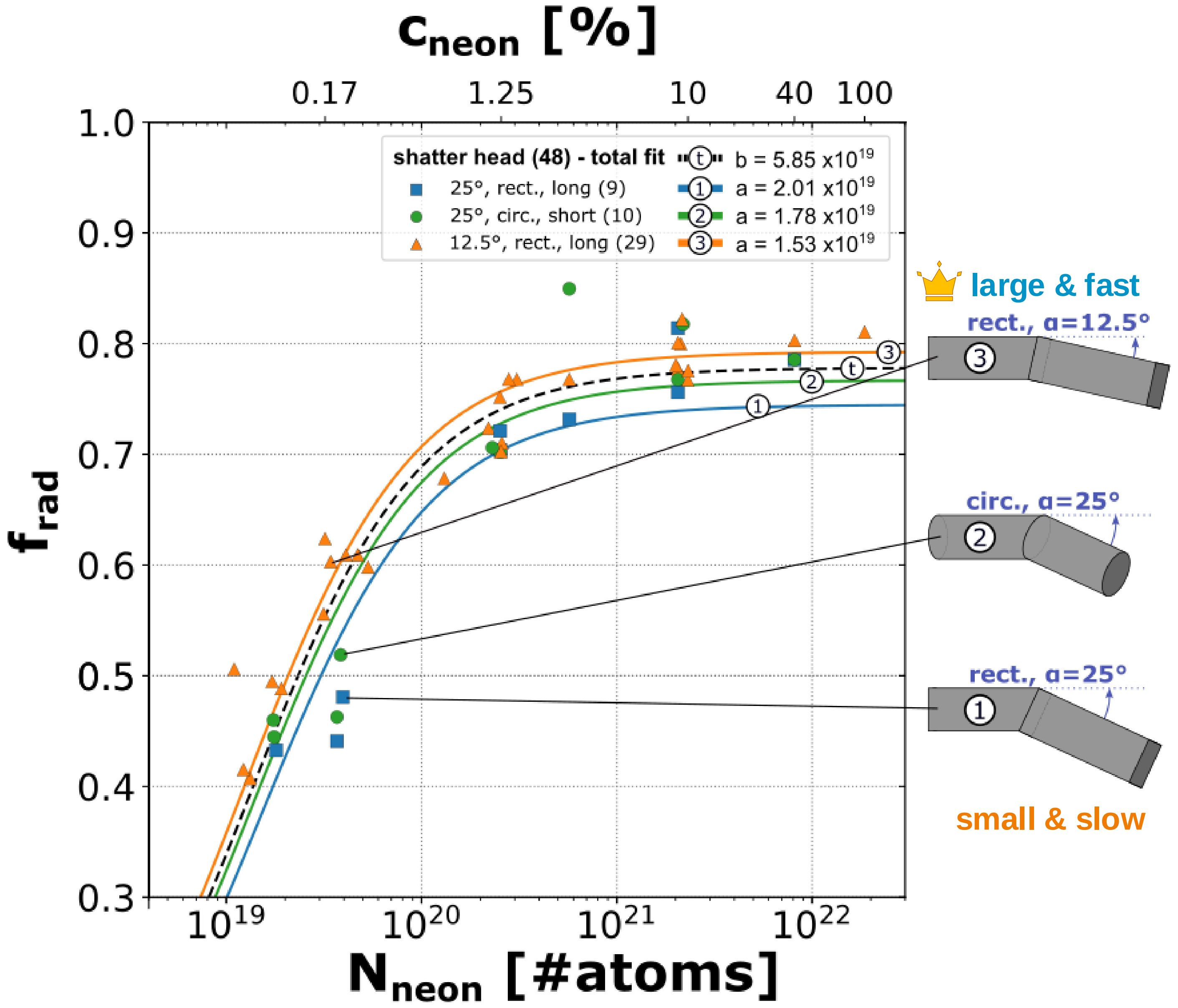
„Optimal" 👑 shatter head geometry



Fit function* $y = \left(1 + \frac{a \cdot \left(1 + \left(\frac{b}{N_{\text{injected neon}}}\right)\right)}{b}\right)^{-1}$

Overall, the **12.5° rectangular** shatter head shows the highest values of f_{rad}

$$^{*}f_{rad} = \frac{P_{rad}}{P_{rad} + P_{thFW}} = \frac{1}{1+x}$$

with thermal heat fluxes onto the PFCs $P_{thFW} \propto n_e \cdot T_e^{3/2}$,

$$P_{rad} \propto n_e \cdot n_{imp} \cdot L_{rad}(T_e) ,$$

$$x \propto \frac{T_e^{3/2}}{L_{rad}(T_e)} \cdot \frac{1}{n_{imp}} = G_{rad}(T_e) \cdot \frac{1}{n_{imp}} \text{, and}$$

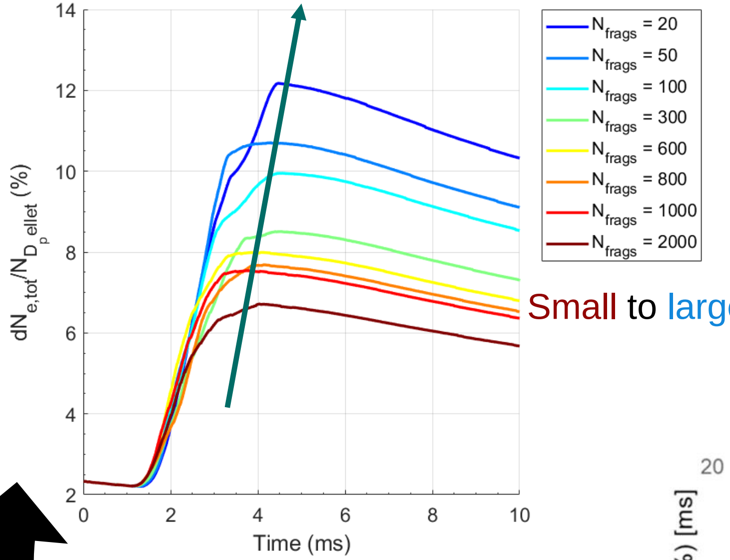
$$n_{imp} \propto N_{\text{assimilated neon}} = b/(1 + b/N_{\text{injected neon}})$$

$$\rightarrow f_{rad} = \frac{1}{1 + \frac{B \cdot G_{rad}(T_e)}{N_{\text{assimilated neon}}}} = \frac{1}{1 + \frac{a(1+(b/N_{\text{injected neon}}))}{b}}$$

„Optimal“ fragment size

- Low neon doping (< 10^{21}):

Pure D_2 INDEX: Number of fragments (fragment size) scan

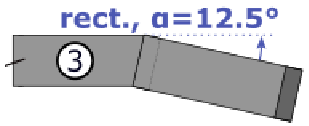


Small to large

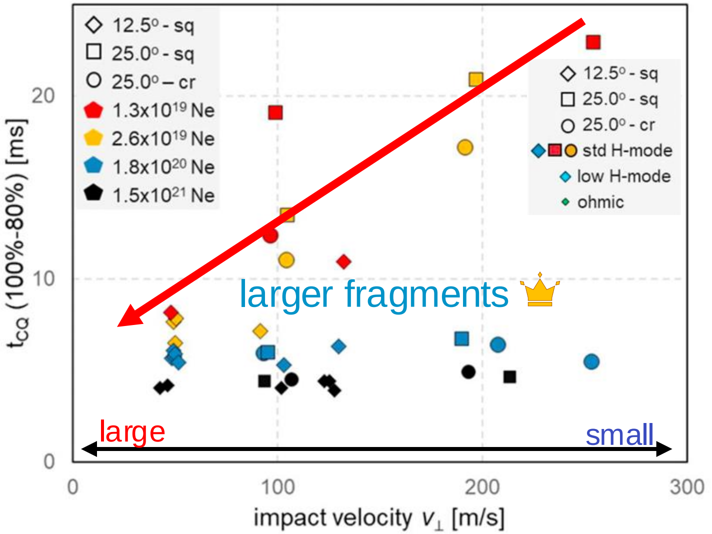
A. Patel, M.Sc. thesis (2023)

material assimilation

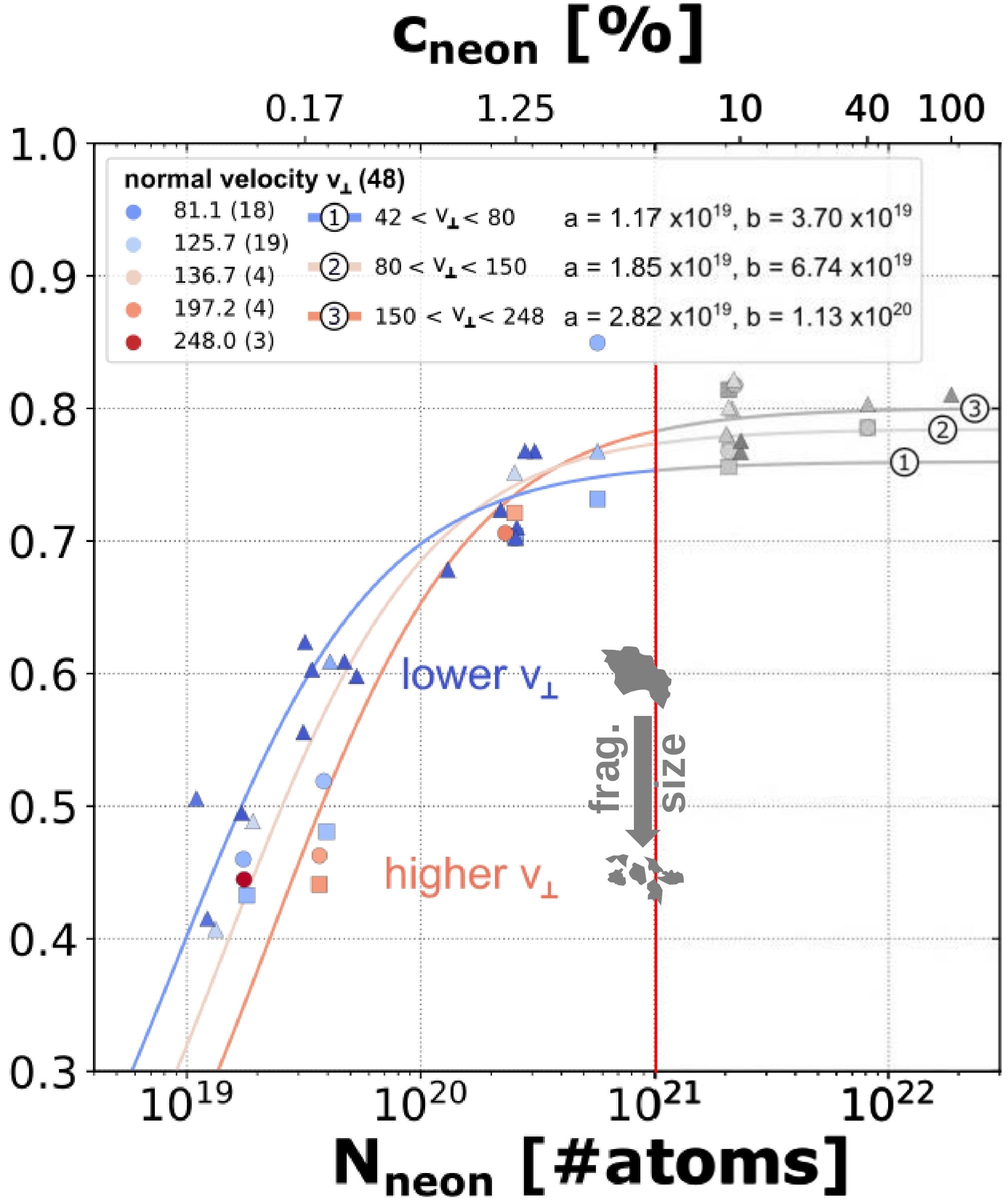
large & fast



Experiment



Jachmich et al., 49th EPS (2023)



„Optimal“ fragment size

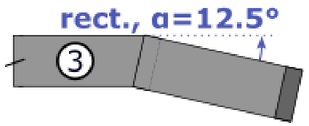
- Low neon doping (< 10^{21}):

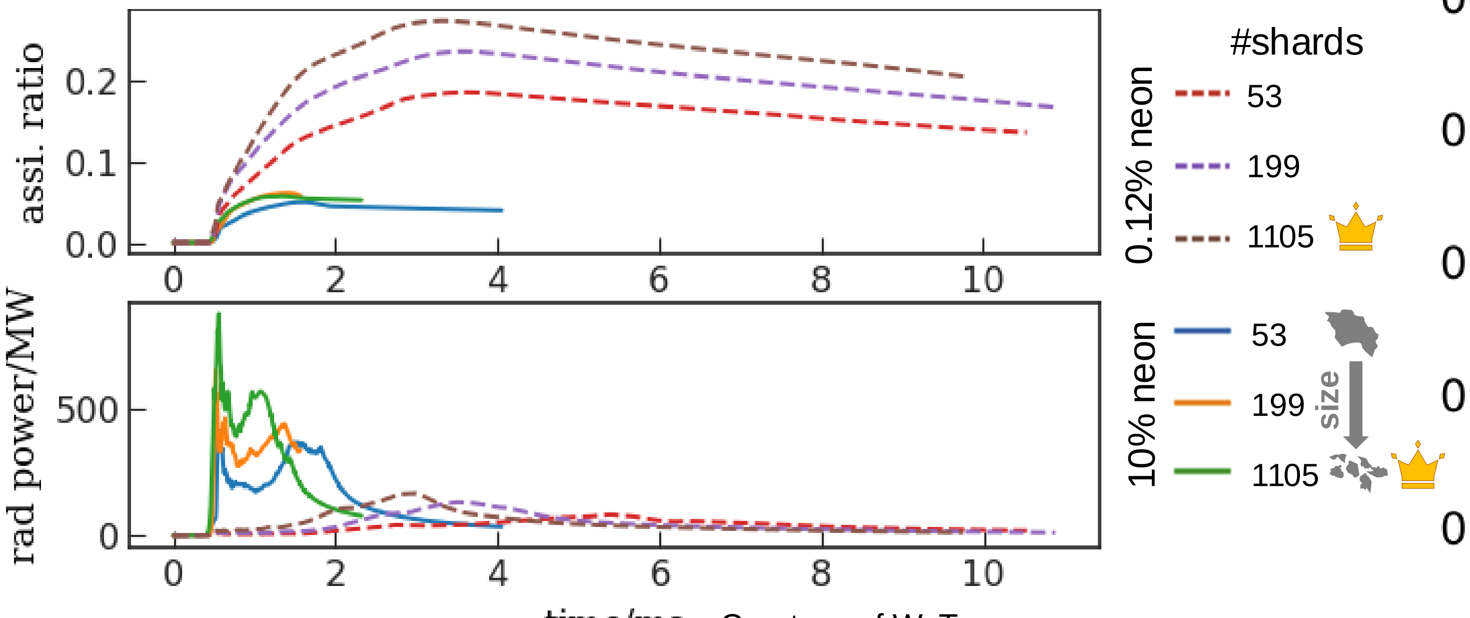
  large (lower $v_\perp$) fragments (shallow angle)

- High neon (8 mm, 10% or 2×10^{21}):

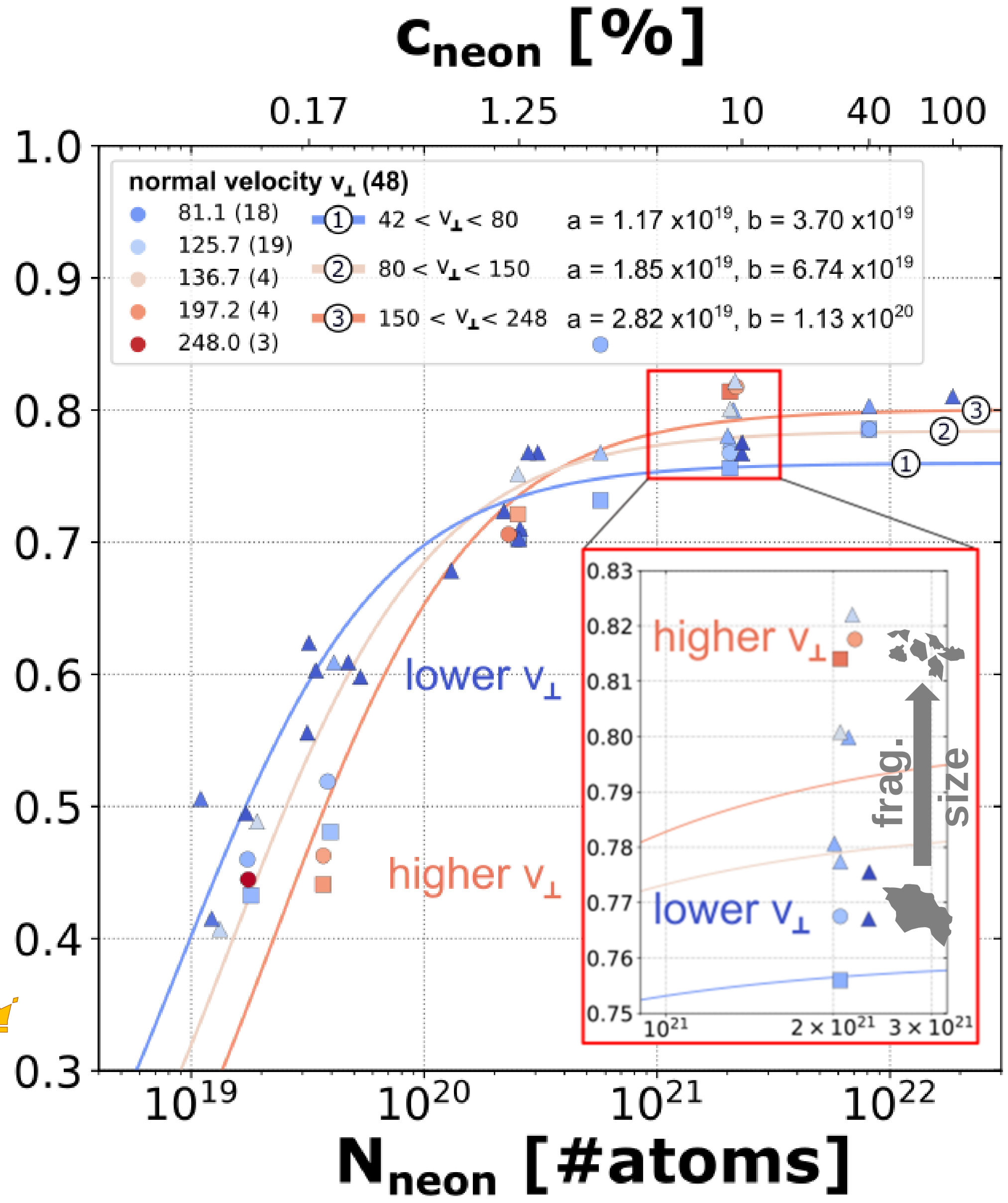
First hints: small (larger $v_\perp$) fragments (further studies needed)

- JOREK: small fragments for **all** neon ranges





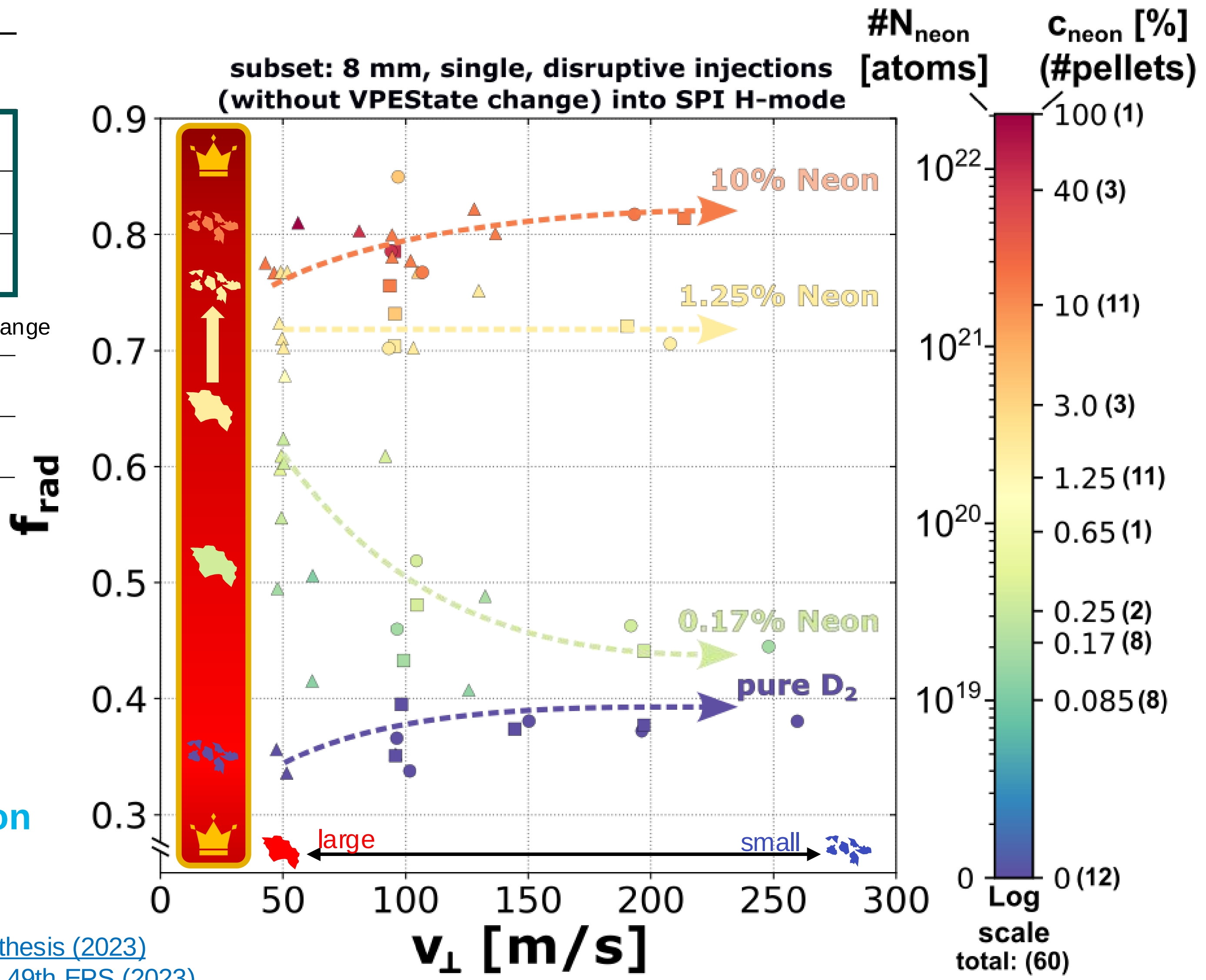
Courtesy of W. Tang



Which is now the „optimal“ fragment size?

		pure D_2	low neon	high neon
goal		D_2 assimilation for suppression of REs	plasmoid drift suppr. for high D_2 assim.	max. radiation for load mitigation
frad	Exp.			
	INDEX			
	JOREK		= no difference [3]	[3]
assimilation	Exp.	[2]	[2]	only minor Δt_{CQ} change
	INDEX	[1]	unclear [1]	[1]
	JOREK		[3]	[3]
		D_2 assimilation	Ne assimilation	Ne assimilation

- Depending on the goal (max. frad or D_2 assimilation), smaller or larger fragments may be considered „optimal“
- Small fragments seem beneficial for **maximising frad** (high neon)
- Large fragments seem better for pure D_2 SPI **assimilation**
- Mismatch in neon assimilation for neon doped pellets in experiment ( ) and JOREK ( )



[1] A. Patel, M.Sc. thesis (2023)
[2] Jachmich et al., 49th EPS (2023)
[3] Courtesy of W. Tang

Outline

❖ What is SPI supposed to deliver?

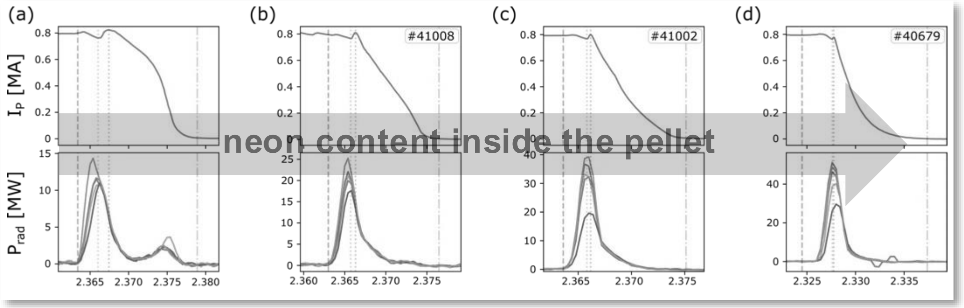
heat loads: max. radiation | **forces**: tailor CQ rate | **runaway electrons (REs)**: max. assimilation (density increase)

❖ What is the specific goal of the ASDEX Upgrade SPI system?

Highly flexible system (angle and velocity) ➡ unique for characterizing fragment size & velocity effects!

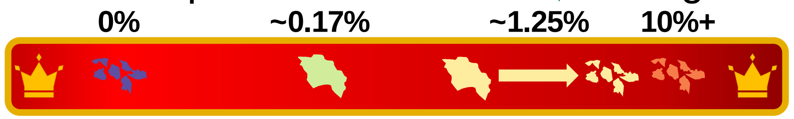
❖ **What did we learn from the AUG SPI project so far?**

- **Commissioning (Lab) phase** The Parks model does **not** seem to fit **our** observed fragment distributions well
- **AUG SPI experiments in 2022 & AUG SPI modelling**



  - Disruption evolution convex —incr. neon content→ concave CQ shape
  - Radiation asymmetries asym. ↓ & S5/S9 asym. ↑ with neon ↑
  - Radiated energy fraction (f_{rad}) **strong** function of neon content, 2nd order effect of geometry: 12.5° rect.
  - Is there an „optimal" shatter head for all purposes? **optimal** fragment size depends on **neon %** ➡ SPI-goal

frad



❖ Shatter head setup for the 2025 experimental campaigns

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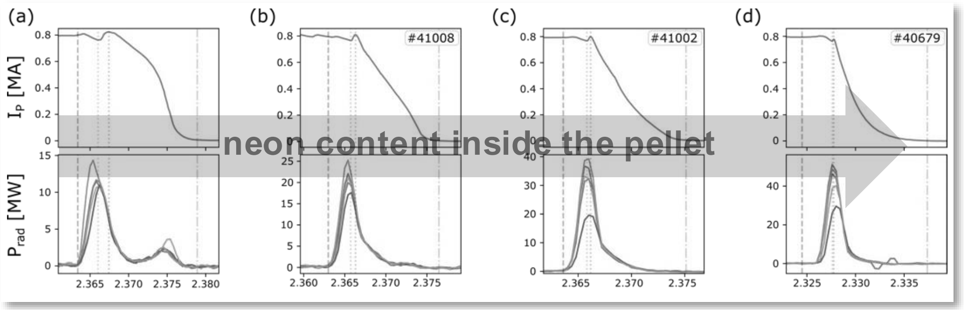

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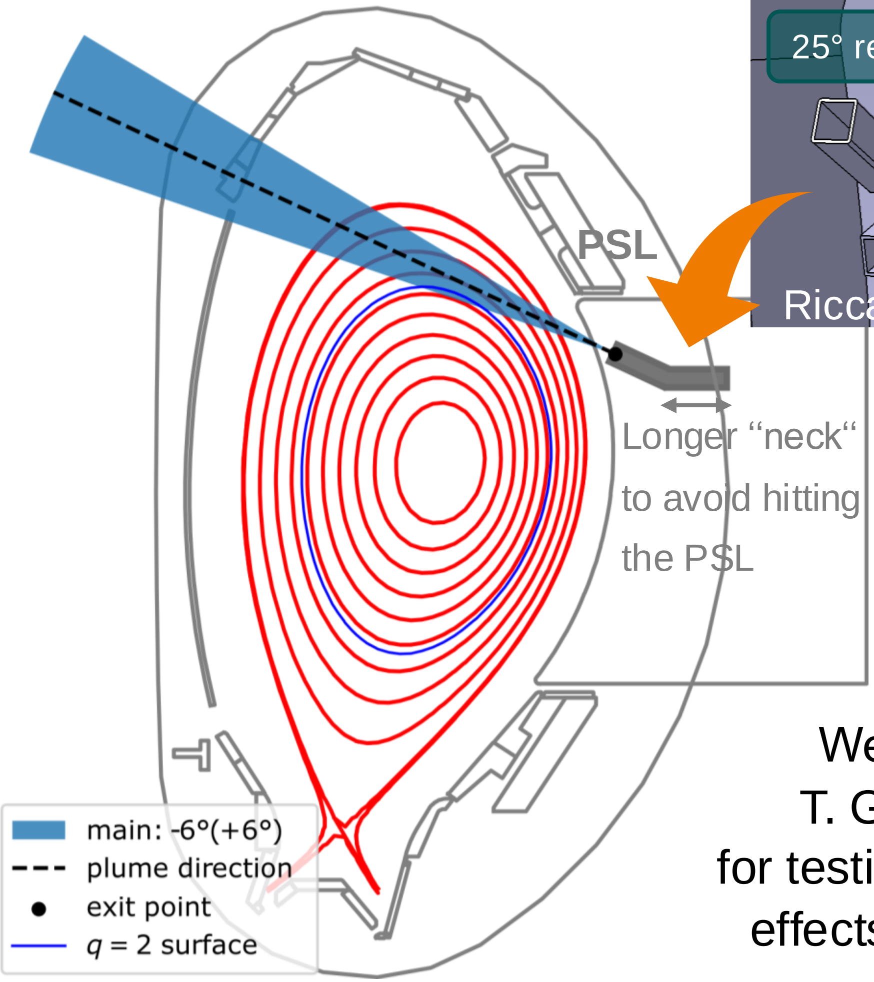
❖ **Shatter head setup for the 2025 experimental campaigns**

frad

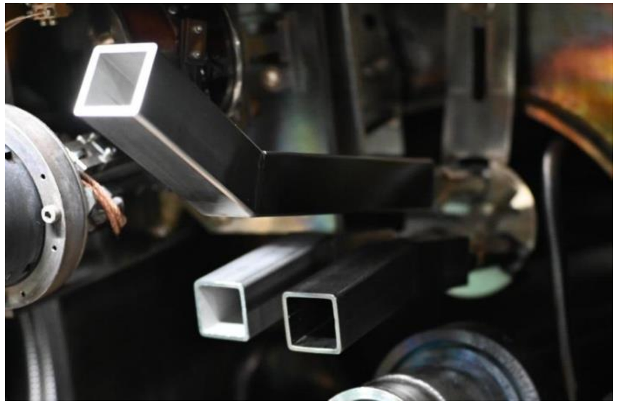
Shatter head setup for the 2025 experiments

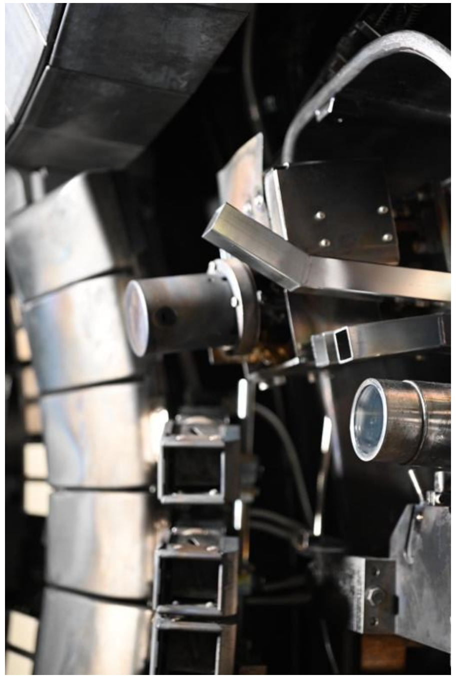
What if we miss q=2 ?

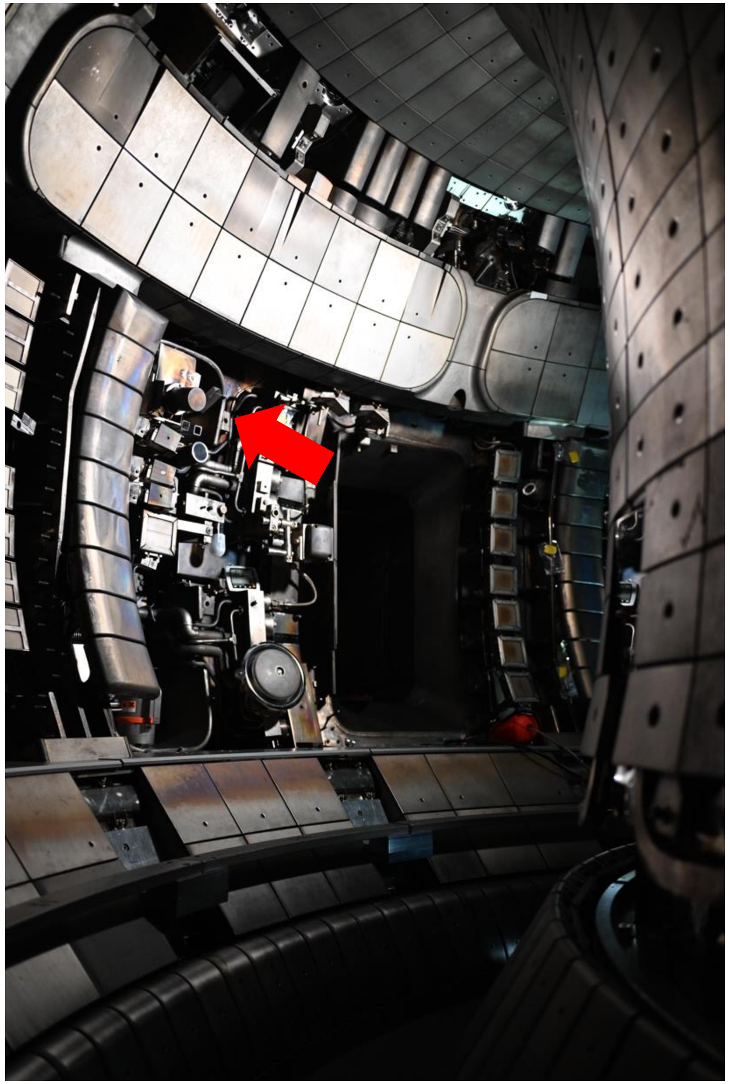
(P: head pointing upwards)



Peter Halldestam







We‘d like to thank
T. Gebhart (ORNL)
for testing fragment impact
effects on the PSL tiles!

Outline

- What is SPI supposed to deliver?

<u>heat loads</u>:	<u>forces</u>:	<u>runaway electrons (REs)</u>:
max. radiation	tailor CQ rate	max. assimilation (density increase)

- What is the specific goal of the ASDEX Upgrade SPI system?

SPI animation

Highly flexible system (angle and velocity) ➡ unique for characterizing fragment size & velocity effects!

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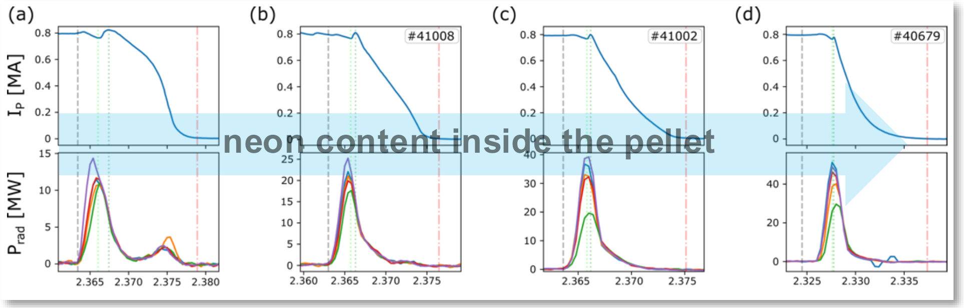

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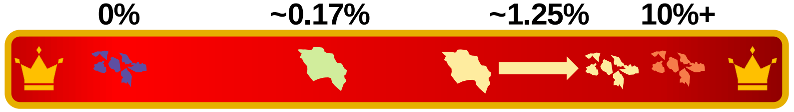
frad



- Shatter head setup for the 2025 experimental campaigns

Upside-down shatter head to study the SPI performance in case of missing the q = 2 rational surface