Real time feedback on plasma radiation at W7-X

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Recap

What's the bolometer at W7-X?

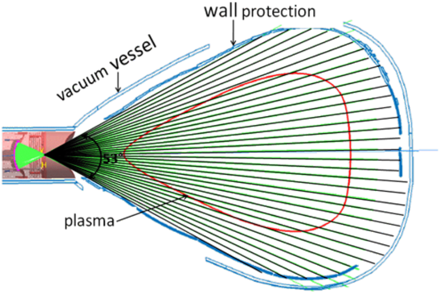
– a two camera system using metal film resistive detector arrays to measure plasma radiation based on thermal effects

Goals:

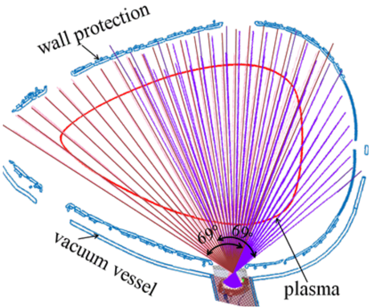
1. - global power balance: investigation of total radiation power loss, mainly from impurities, and its distribution
2. - local power balance: radiation profiles for transport studies (using tomographic inversion)

+ multi-camera system with 113 channels combined: 32@HBCm and 2 x 24@VBC subdetectors (+ differently coated/filtered channels)

HBCm

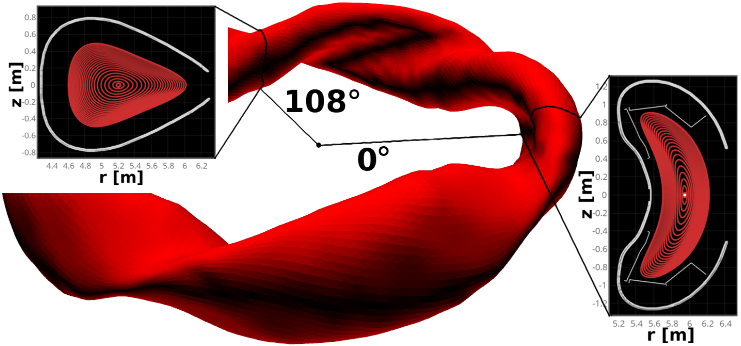


VBCr/VBCl



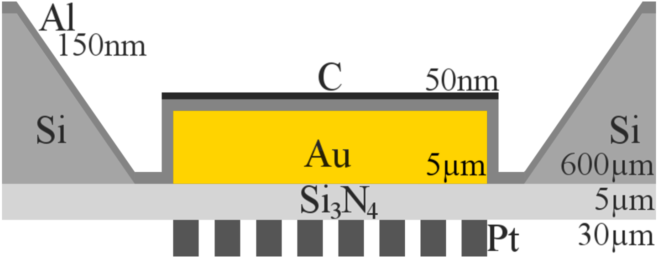
(Lines of sight with individual apertures, retracted into the vacuum vessel)

+ multi-camera system with 113 channels combined: 32@HBCm and 2 x 24@VBC subdetectors (+ differently coated/filtered channels)



(W7-X equilibrium fluxsurfaces from VMEC)

- $+$ spatial resolution of 5 cm & temporal resolution of 0.8 ms to 6.4 ms, spectral range between 600 nm to 0.2 nm
- $+$ detectors of gold-foil absorbers with carbon coating on silicon-nitrate substrate and gold meander for 200 nW resolution



(Single detectior channel scheme with holder), D. Zhang, P. Hacker et al.

Equations

Plasma radiation

$$P_{rad,bolo} \propto \sum_{Z} n_e \cdot n_Z \cdot L_Z$$

L_Z: line radiation function of impurity Z

$\ldots = f\,(T_e,\ T_i,\ T_Z,\ wall\ material/conditions,\ \ldots)$

Equations

Plasma radiation

$$P_{rad,bolo} \propto \sum_{Z} n_e \cdot n_Z \cdot L_Z$$

$$\ldots = \frac{V_{P,tor}}{V_{cam}} \cdot \sum_{ch} \frac{V_{ch}}{K_{ch}} \cdot \frac{P_{ch}}{f_{OT}}$$

V_{ch}: polygon volume of detector ch

$V_{P,tor}$: estimated plasma volume (EMC3/VMEC simulation)

K_{ch}: geometrical factor for channel ch

Equations

Plasma radiation

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$$\ldots \quad = \frac{V_{P,tor}}{V_{cam}} \cdot \sum_{ch} \frac{V_{ch}}{K_{ch}} \cdot \frac{P_{ch}}{f_{OT}}$$

Bolometer equation:

$$P_{ch} = F_{ch} \cdot \left(\tau_{ch} \frac{\mathrm{d}(\Delta U)}{\mathrm{d}t} + f_\tau \cdot (\Delta U) \right)$$

$\Delta U \propto \Delta T$ the change in absorber temperature

$F_{ch} = f$ (detector electrical properties, excitation, cables ...)

$f_\tau = f$ (detector impedance, heat capacity ...)

Plasma radiation

Bolometer equation:

$$P_{ch} = F_{ch} \cdot \left(\tau_{ch} \frac{\mathrm{d}(\Delta U)}{\mathrm{d}t} + f_\tau \cdot (\Delta U) \right)$$
$$\approx 25.737 \cdot \frac{\mathrm{W}}{\mathrm{V}} \left(\mathrm{d}(\Delta U_{ch}) + 0.014 \cdot \Delta U_{ch} \right)$$

channel & cabel resistances $R_{ch} \approx 1\,\mathrm{k}\Omega$, $R_{cab} \approx 40\,\Omega$

cooling/relaxation time of the gold foil $\tau_{ch} \approx 110\,\mathrm{ms}$

heat capacity $\kappa_{ch} \approx 0.8\,\mathrm{mW/k}\Omega$

scaling $f_\tau \approx 1$

temporal sampling in measurement 1.6 ms

Plasma radiation

Bolometer equation:

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$$\approx 25.737 \cdot \frac{\mathsf{W}}{\mathsf{V}} \left(\mathsf{d}(\Delta U_{ch}) + 0.014 \cdot \Delta U_{ch} \right)$$

$\Rightarrow$ for non-collapsing plasma scenarios: $\Delta U \approx 10^{-3}$ V
signal derivative for sampling time d$(\Delta U) \approx 10^{-5}$ V

Previously on ...

Goals

1.- Verifying and improve the evaluation of measurement data

2.- instantaneous/direct tomographic inversion after discharge $\Rightarrow$ investigation of impurity transport processes and discharge feedback

3.- providing feedback signal for other diagnostics/CoDaC through fast (5 ms) calculation of P_{rad} estimate

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Feedback

1.- adjust heat loads, investigate radiation regimes, maybe improved detachment

2.- find gas puff to radiation scaling law, i.e. importance of intrinsic/extrinsic impurities

Dataflow

plasma radiation & DAQ

↓

calculation, i.e. FIFO, filter

↓

single/multi-channel feedback

↓

two BNC/glas fiber lines to
thermal helium beam diagnostic

↓

plasma feedback

↓

change in radiation, density etc.

Feedback: Example

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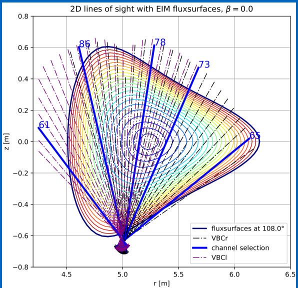

P.Hacker et al.

$$P_{rad} = f \frac{V_{P,tor}}{V_{cam}} \sum_{S} \frac{V_{ch}}{K_{ch}} \frac{P_{ch}}{53\%}$$

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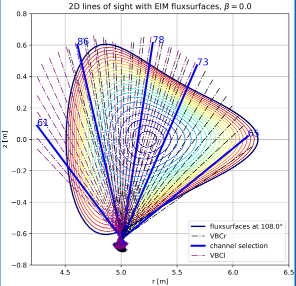

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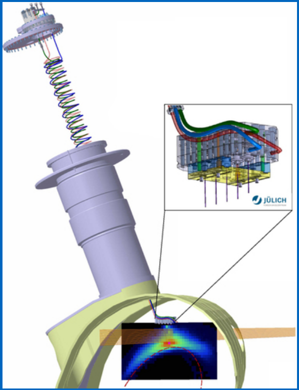

(Thermal helium beam diagnostic with piezo valves) M.Krychowiak et al.

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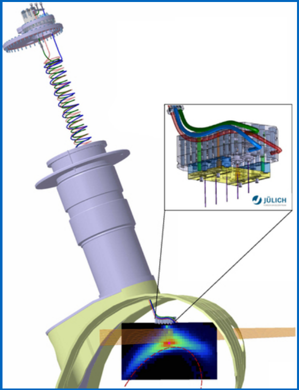

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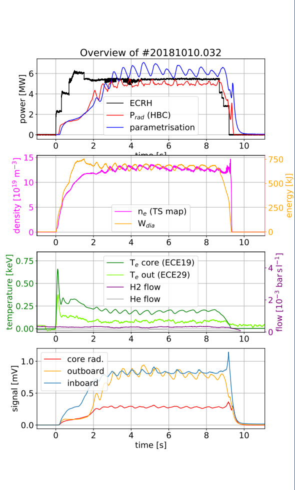
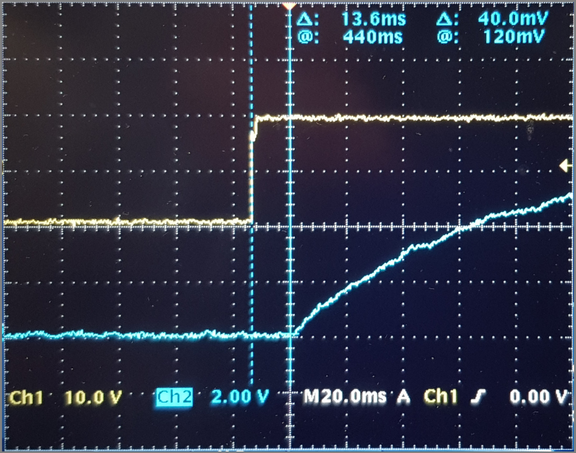


Feedback: Example

Sanity check . . .



(Testing feedback system internally prior to campaign, using an oscilloscope and closely defined 7 mW laser pulse)

Implementation

Sanity check . . .

+ defined solid-state laser pulses with cycle frequency 1 Hz - 1 kHz and 7 mW power onto detector
+ limit the system to a temporal response of $\geq$14 ms
+ mainly $F \cdot \Delta t$, Δt is sample rate and F the number of *FIFO* array elements
+ shallow slope due to detector response

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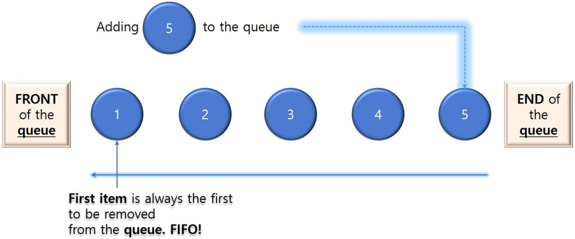

https://www.thecodingdelight.com/

In the aftermath: Who said that we need to "calculate" P_{rad}?

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Semi-experimental scaling

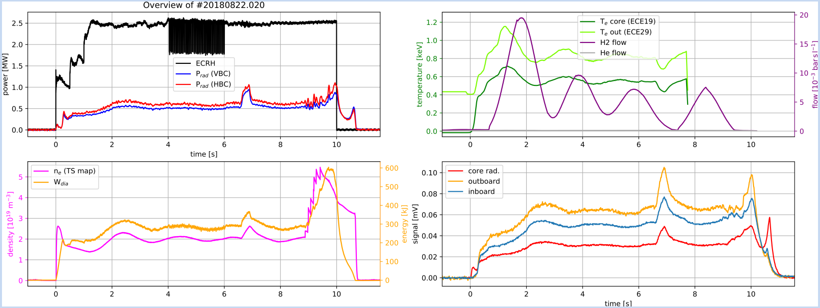
- find scaling between ECRH, density, fueling and radiation, i.e. instead of expensive & slow feedback
- making simple 3 parameter $\{a, b, c\}$ inference assumption like:

$$P_{rad}[\mathsf{MW}] \propto a\{n_e[10^{19}\mathsf{m}^{-3}]\}^b\{P_{ECRH}[\mathsf{MW}]\}^c$$

or

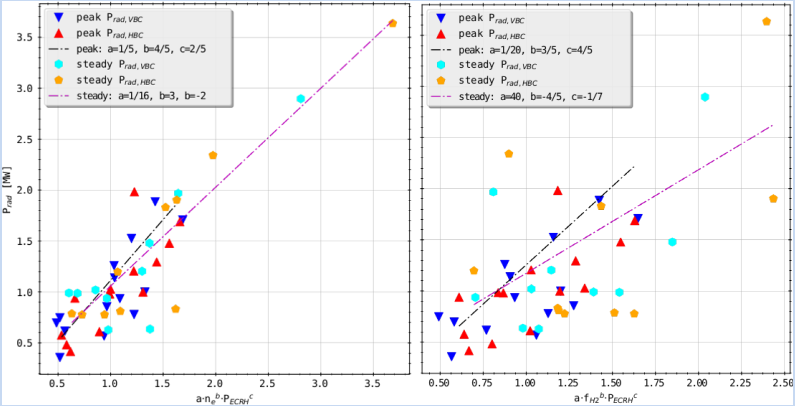
$$\propto a\{f_{H2}[\mathsf{mbar\,s/l}]\}^b\{P_{ECRH}[\mathsf{MW}]\}^c$$

Results: manual selection on main gas valve



Example of discharges in dataset for analysis, P.Hacker et al.

Results: manual selection on main gas valve



Possible scaling between ECRH, density/main gas fueling in H_2 and radiation loss, P.Hacker et al.

To find or not to find...

+ no common scaling found, parameters all over the place
+ further analysis would maybe require to find additional dependencies, but that would be the "needle in the hay stack"
+ originally forseen scaling based off of thermal helium gas inlet too complicated for now

– ALSO: differentiation between intrinsic/extrinsic impurities totally neglected here, but seriously important anyhow

New agenda: construction ...

Correlation analysis

+ find most relevant channel combination to predict P_{rad}, i.e. the best channels for divertor gas insertion experiments
+ localisation and sensitivity of channels in response divertor valves, maybe $n_e(P_{rad})$, $P_{rad}(n_e)$
  $\Rightarrow$ spatial sensitivity for tomography?

$$P_{prediction} = \frac{V_{P,tor}}{V_S} \cdot \sum_{ch}^{S} \frac{V_{ch}}{K_{ch}} \cdot \frac{P_{ch}}{53\%}$$

$$V_S = \sum_{ch}^{S} V_{ch}$$

New agenda: construction ...

Example: “Standard deviation”-method

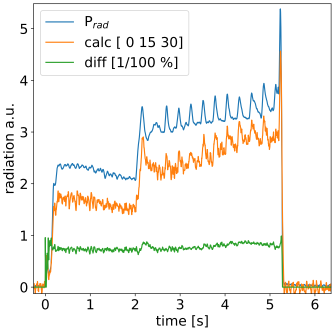
$$d_{diff}(t) = \|P_{rad}(t) - P_{prediction}(t)\|$$

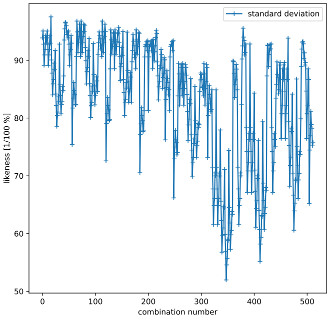
$$\varepsilon(t) = \left\{ \begin{array}{ll} 1 - \frac{d_{diff}(t)}{P_{rad}(t)} & , d_{diff} < P_{rad} \\ 0 & , \text{else} \end{array} \right\}$$

$$\vartheta = \overline{\varepsilon(t)}$$

New agenda: construction ...

Example: testing against P_{rad}(HBCm)





Goals

- x Verifying and improve the evaluation of measurement data

1.- instantaneous/direct tomographic inversion after discharge
$\Rightarrow$ investigation of impurity transport processes and discharge feedback

- x providing feedback signal for other diagnostics/CoDaC through fast (5 ms) calculation of P_{rad} estimate

2.- local sensitivity analysis of bolometer system with regards to feedback and configuration/scenarios

Thank you for your attention.
Now: questions.

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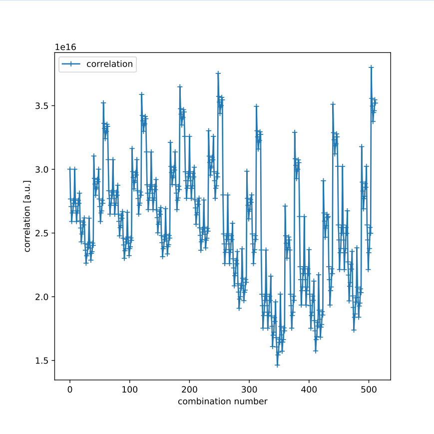
Cross correlation-method

$$C_{corr} = \int (P_{rad} * P_{prediction})(\tau)\mathsf{d}\tau$$

$$= \iint P_{rad}(t)P_{prediction}(t+\tau)\mathsf{d}t\mathsf{d}\tau$$

Example: testing against P_{rad}(HBCm)



Correlation: Coherence

Coherence

$$C_{x,y} = \frac{\|(P_{x,y}\|^2}{P_{x,x} \cdot P_{y,y}}$$

$P_{x,x}$ and $P_{y,y}$ are power spectral density estimates of $X = P_{rad}$ and $Y = P_{prediction}$,
and $P_{x,y}$ is the cross spectral density estimate of X,Y

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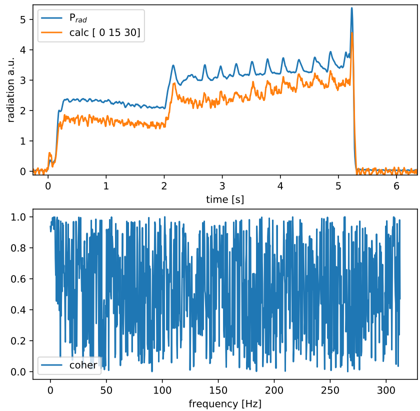

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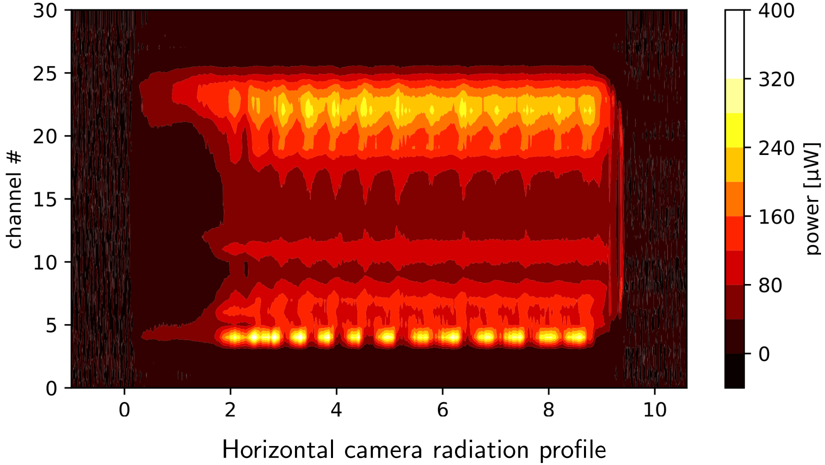

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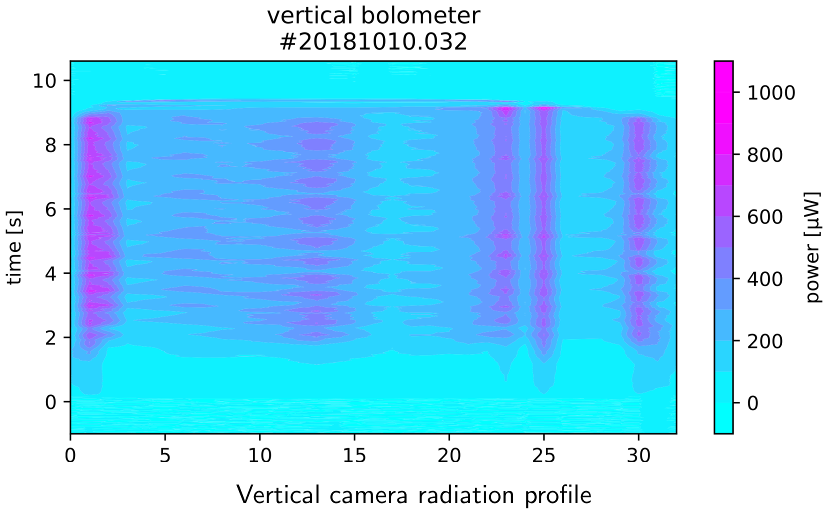

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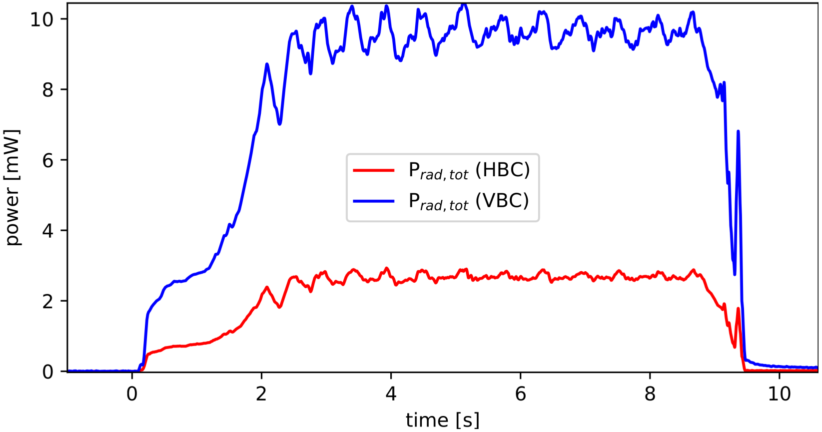
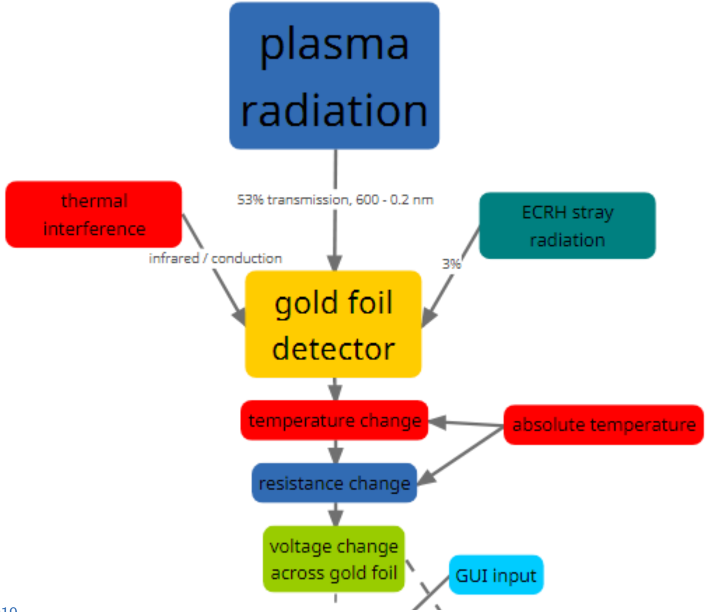


Line integrated power for each camera

System schematics



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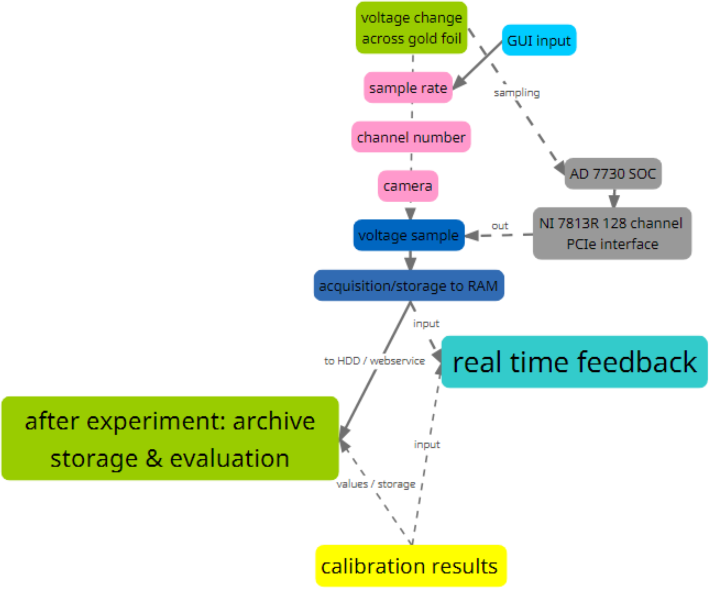

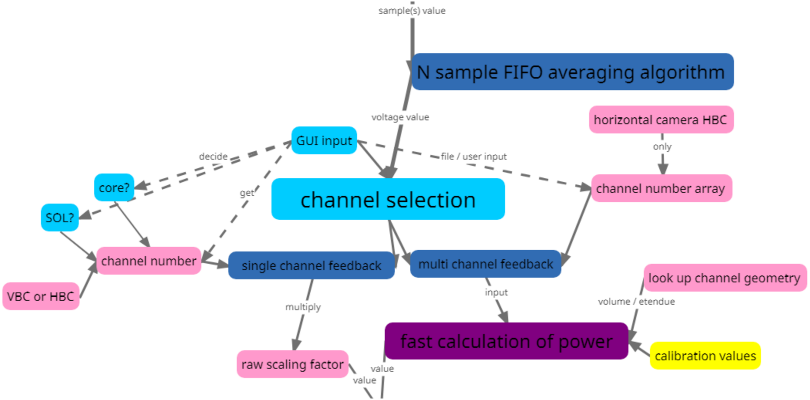

sample(s) value
N sample FIFO averaging algorithm
voltage value
horizontal camera HBC
only
GUI input
decide
file / user input
core?
get
channel selection
channel number array
SOL?
channel number
single channel feedback
multi channel feedback
look up channel geometry
VBC or HBC
input
multiply
volume / etendue
fast calculation of power
calibration values
raw scaling factor
value
value

System schematics