Using the superconducting field coils of W7-X as diamagnetic loops

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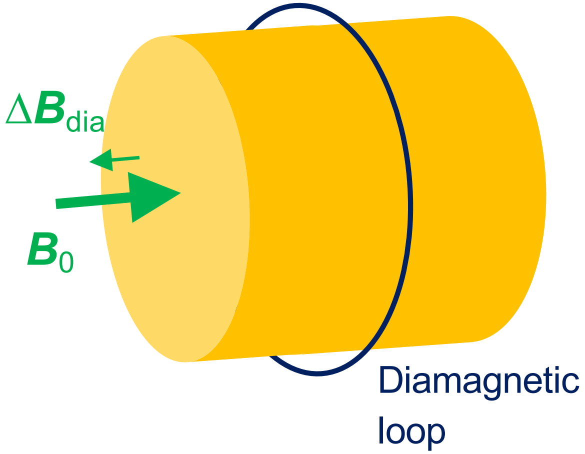
Using the superconducting field coils of W7-X as diamagnetic loops

Contents:

1. Motivation – Why should we use something else than our diamagnetic loops? (1)

Reminder: How does a diamagnetic loop measure the diamagnetic energy?



The magnetic field B_0 is reduced by the plasma diamagnetism

The total change in magnetic flux through a poloidal cross section is proportional to the plasma energy W:

$$\Phi_{\mathrm{dia}} = \Delta B_{\mathrm{dia}} A = -\mu_0 W/(3\pi R B_0)$$

Only $d\Phi/dt$ can be measured by a diamagnetic loop

⟹ $d\Phi/dt$ must be integrated from the start of the plasma to have W_{dia} at every moment of the discharge

⟹ Integration of the diamagnetic loop voltage signal

Why should we use something else than our diamagnetic loops? (1)

Measurement of W_{dia} is

- sensitive against offset voltages

  ⟹ determine and subtract offset

  ⟹ hardware design of diamagnetic loops and cabling to avoid thermovoltages

- sensitive against drifts of offset voltages

  ⟹ sophisticated electronics design [A. Werner et al., Rev. Scientific Instrum. **77** (2006) 10E307]

- sensitive against changes of magnetic flux other than from changes in W_{dia}

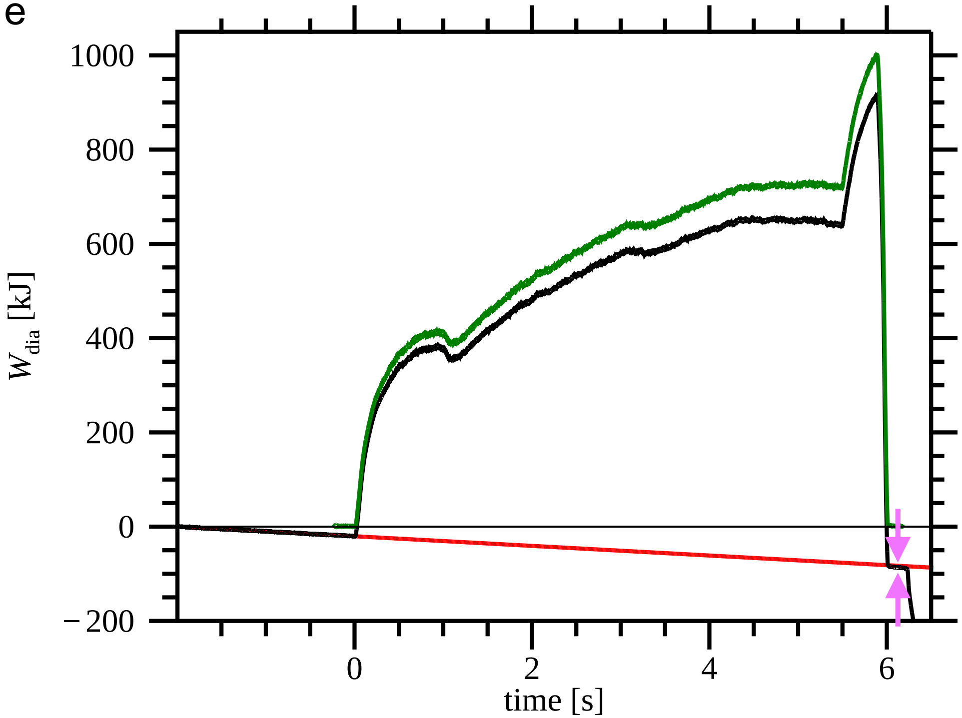
  ⟹ compensation loops, compensating for flux changes due to current changes in the field coils and in the plasma vessel

  ⟹ change of effective area of diamagnetic and/or compensation loops due to thermal expansion?
  [M. Endler et al., Fus. Eng. Des. **100** (2015) 468, section 4.2]

Temperature change of plasma vessel by 10 K – corresponding to ~ 130 kJ

Why should we use something else than our diamagnetic loops? (2)

Drifts in diamagnetic signal can still be corrected after the end of the discharge by subtracting a regression line



Compensated W_{dia} signal

Regression line from 2 s before t1 (could be used for real-time correction)

Corrected W_{dia} signal after end level is known

Remaining error after 6 s: small

The real-time signal used for interlock is still affected by the drift!

Why should we use something else than our diamagnetic loops? (3)

The real-time signal used for interlock is still affected by the drift!

⟹ A well thermalised loop attached to a well thermalised carrier would be nice – unfortunately we did not install one in the cryostat ... – except for the superconducting coils

Further motivation for trying to use the field coils: It was already done [P. Thomas, report PPPL-1979, 1983]:

systems makes the measurement feasible. The main difficulty arises from the change in the TF coil resistance due to Joule heating, compounded by the nonlinearity and sharp temperature dependence of the resistance of the joints in the TF coils. The measurement method, details of the experimental system,

⟹ We should not have these problems!

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2. Which signals are required? (1) – Method A

Reminder: comparison of coil excitation with fast decay:

$$0 = U_{j\,\mathrm{ext}} - \sum_k L_{jk} \frac{\mathrm{d}I_k}{\mathrm{d}t}$$

Coil excitation and de-excitation: $\mathrm{d}\Phi_{\mathrm{PG}}/\mathrm{d}t$ due to plasma is not considered

$$0 = -\frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{j\,\mathrm{tot}} - \sum_k L_{jk} \frac{\mathrm{d}I_k}{\mathrm{d}t}$$

Fast changes of $\mathrm{d}\Phi_{\mathrm{PG}}/\mathrm{d}t$ due to plasma: $U_{j\,\mathrm{ext}}$ is neglected

$\Longrightarrow$ Complete equations:

$$0 = U_{j\,\mathrm{ext}} - \frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{j\,\mathrm{tot}} - \sum_k L_{jk} \frac{\mathrm{d}I_k}{\mathrm{d}t}$$

7 equations for the 7 coil circuits $j = 1, 2, 3, 4, 5, \mathrm{A}, \mathrm{B}$ – each can be solved for $\mathrm{d}\Phi_{\mathrm{PG}}/\mathrm{d}t$

$\Longrightarrow$ We need the voltages and currents of the current supplies of the superconducting coils

Which signals are required? (2) – Method B

Reminder: Voltage induced in DL no. m of coil of type j in HM J:

$$\begin{aligned} U_{Jjm} &= -\frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{j\,\mathrm{DL}} - \frac{\mathrm{d}I_j}{\mathrm{d}t}\left(L_{jJm,jJm} + \sum_{n\neq m} L_{jJm,jJn} + \sum_{K\neq J} L_{jJm,jK}\right) - \sum_{k\neq j} \frac{\mathrm{d}I_k}{\mathrm{d}t} L_{jJm,k} \\ &= -\frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{j\,\mathrm{DL}} - \sum_k K_{jk} \frac{\mathrm{d}I_k}{\mathrm{d}t} \end{aligned}$$

50 x 6 + 20 x 3 equations for all double layers – each can be solved for $\mathrm{d}\Phi_{\mathrm{PG}}/\mathrm{d}t$

The QD signals (difference between double layers) still contain $\mathrm{d}\Phi_{\mathrm{PG}}/\mathrm{d}t$

- due to the balancing of input voltages (different damping) in the QD units
- due to the different numbers of double layers in the “backup” system

$\Longrightarrow$ We need the voltages mesured by the QD units and the currents of the current supplies of the superconducting coils

Which signals are required? (3) – Summary and further procedure

- After integration of the equations, both methods require all coil currents (7 circuits) and the integration of one voltage signal
- The coil current of that circuit which delivers the voltage signal will be strongest weighted
- The voltages measured by the QD system are not normally available (not even after the discharge)

⟹ Compare the quality of a W_{dia} signal generated by these methods with the signal obtained from a diamagnetic loop

- For fast changes of plasma energy (when the power supplies hardly contribute to dI/dt)
- For long time scales (when the current measurement should be no problem, but the quality of voltage integration counts)

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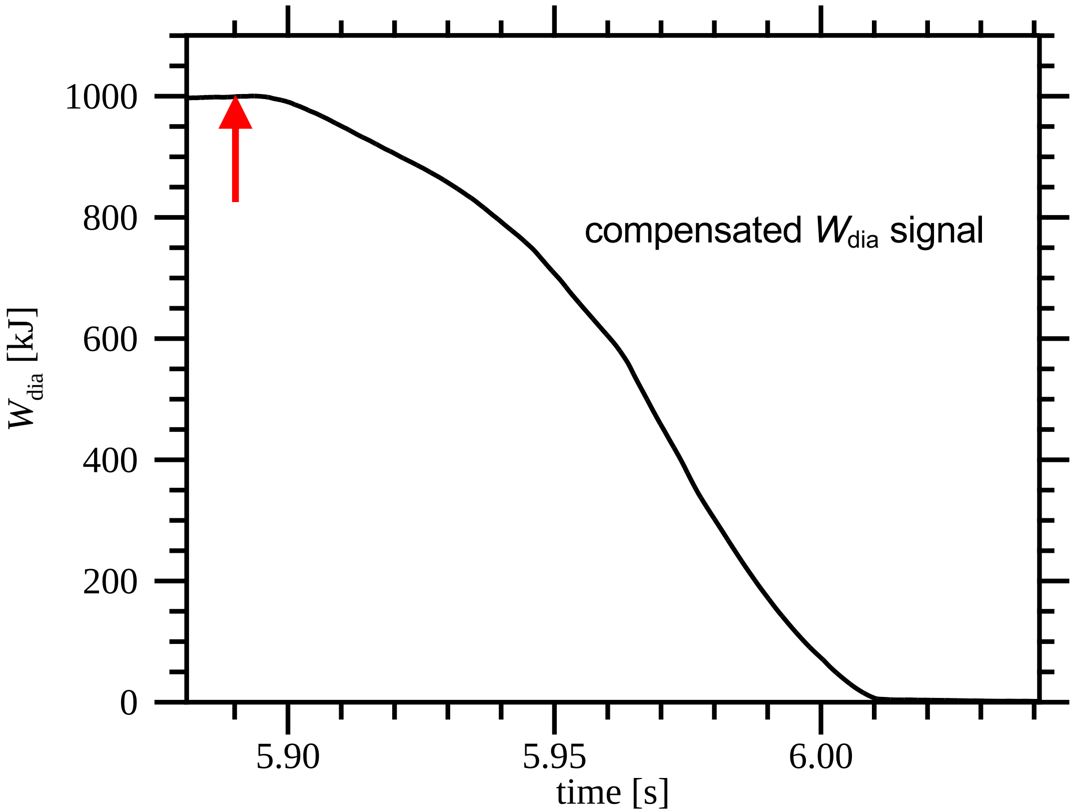
3. Comparing methods in case of fast changes of plasma energy

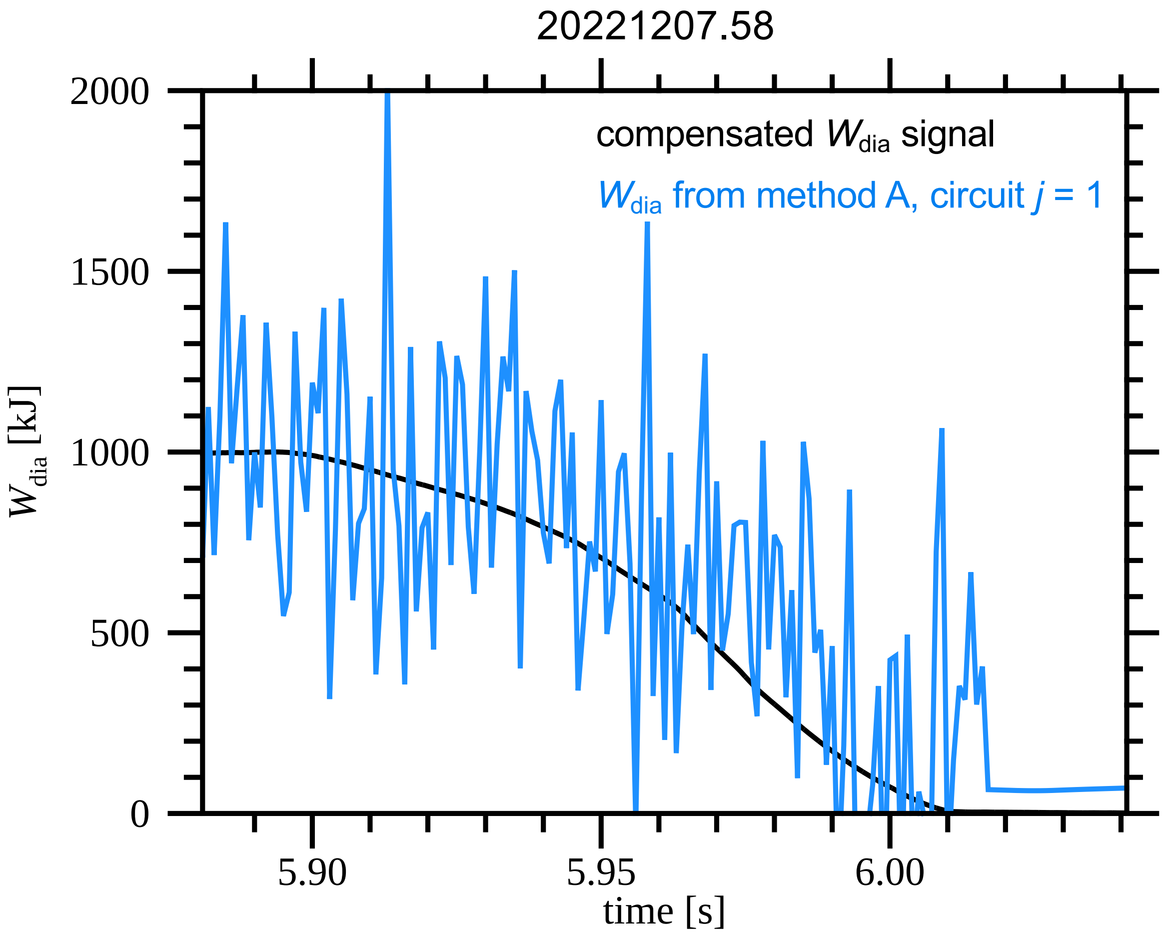
For comparison, choose fast plasma decay terminating 20221207.58, which triggered a fast discharge of the magnet system



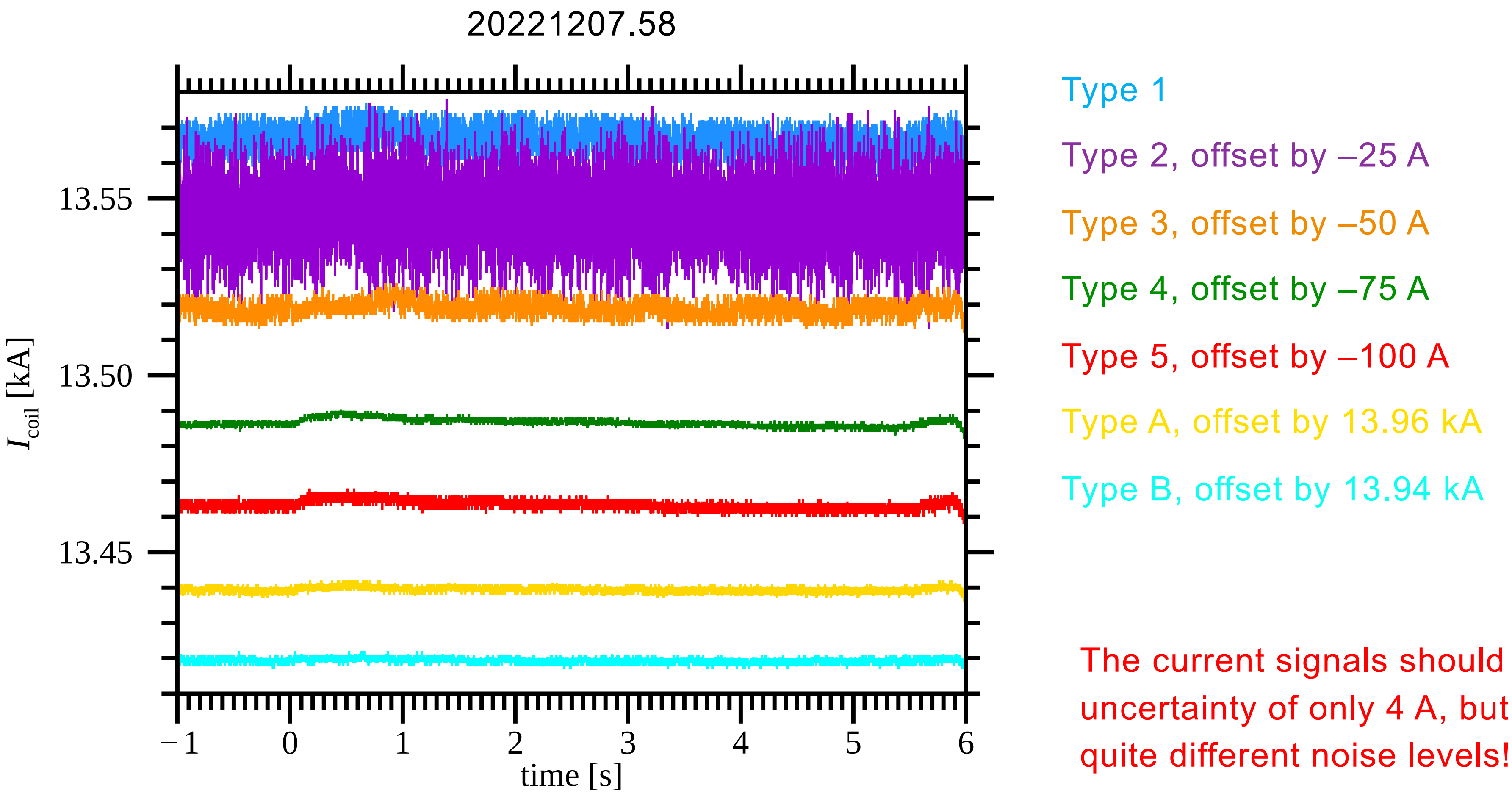
For comparison of different signals, they will be shifted to W_{dia} value at t = 5.89 s

Comparing methods in case of fast changes of plasma energy – Method A (1)

$$0 = U_{j\,\mathrm{ext}} - \frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{j\,\mathrm{tot}} - \sum_k L_{jk} \frac{\mathrm{d}I_k}{\mathrm{d}t}$$



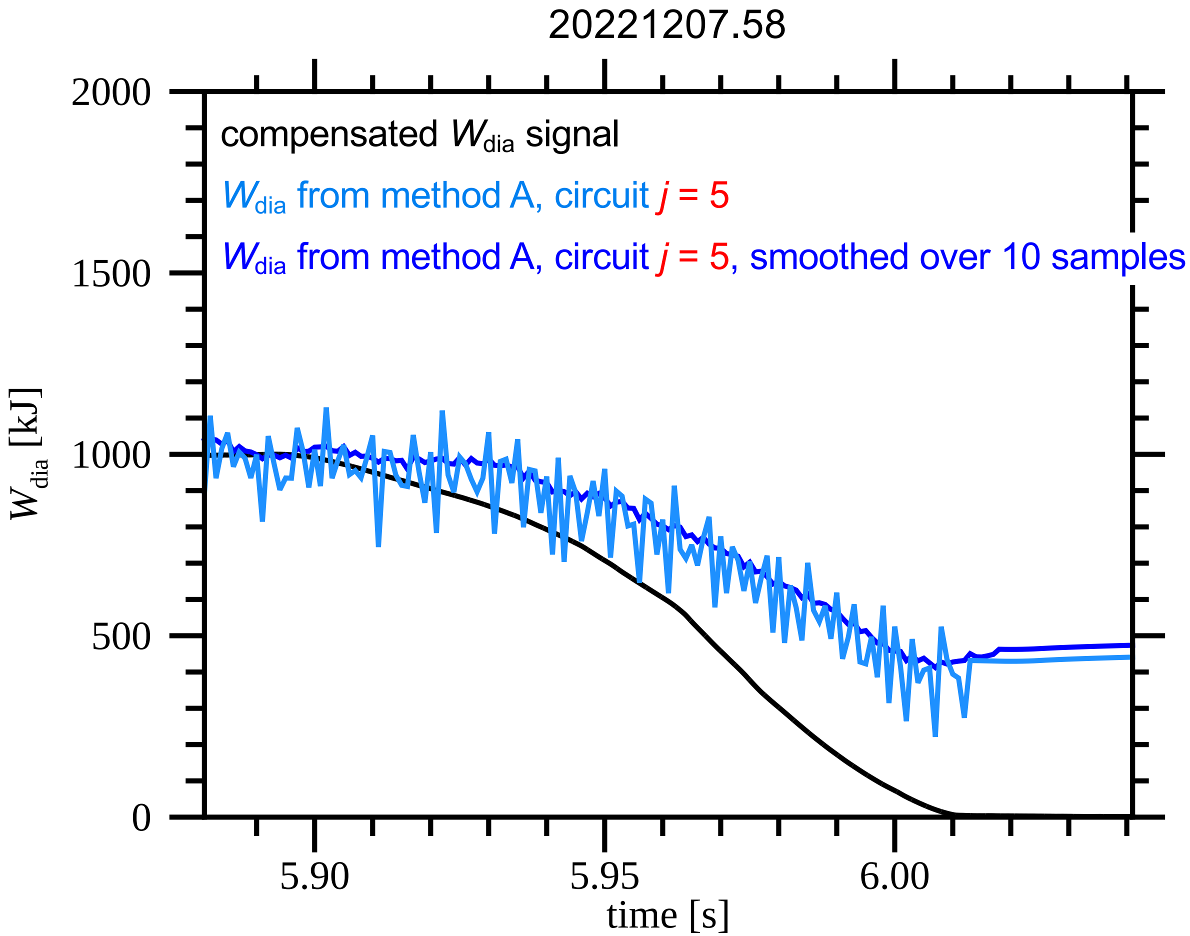
Noise level on coil current signals (Idx1-1)



The current signals should have an uncertainty of only 4 A, but exhibit quite different noise levels!

Comparing methods in case of fast changes of plasma energy – Method A (2)

$$0 \;=\; U_{j\,\mathrm{ext}} - \frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t}\,N_{j\,\mathrm{tot}} - \sum_k L_{jk}\,\frac{\mathrm{d}I_k}{\mathrm{d}t}$$



Comparing methods in case of fast changes of plasma energy – Method A (3): comparing results based on all coil circuits

$$0 \;=\; U_{j\,\mathrm{ext}} - \frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{j\,\mathrm{tot}} - \sum_k L_{jk} \frac{\mathrm{d}I_k}{\mathrm{d}t}$$

Compensated W_{dia} signal

Coloured time traces: W_{dia} based on currents and voltages, smoothed over 10 samples, of different circuits *j*:

Type 1

Type 2

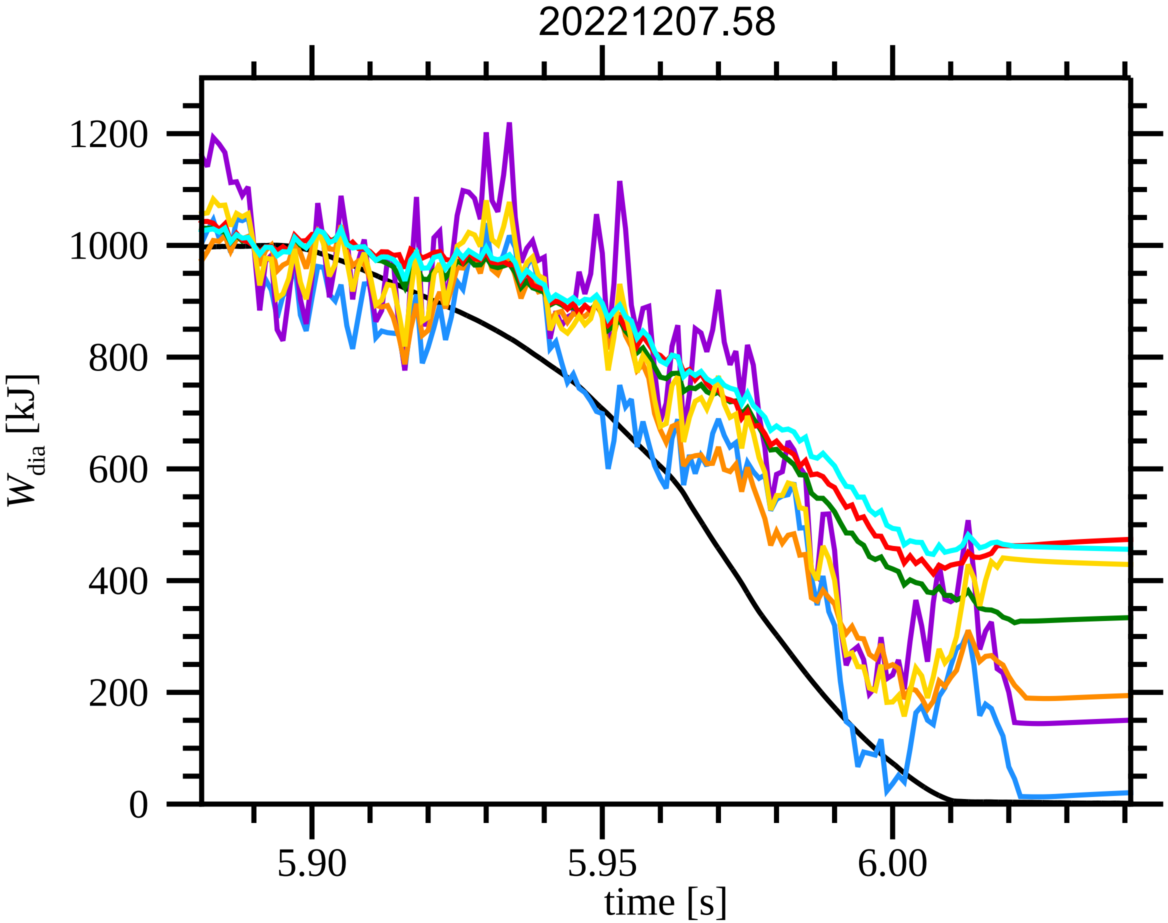
Type 3

Type 4

Type 5

Type A

Type B

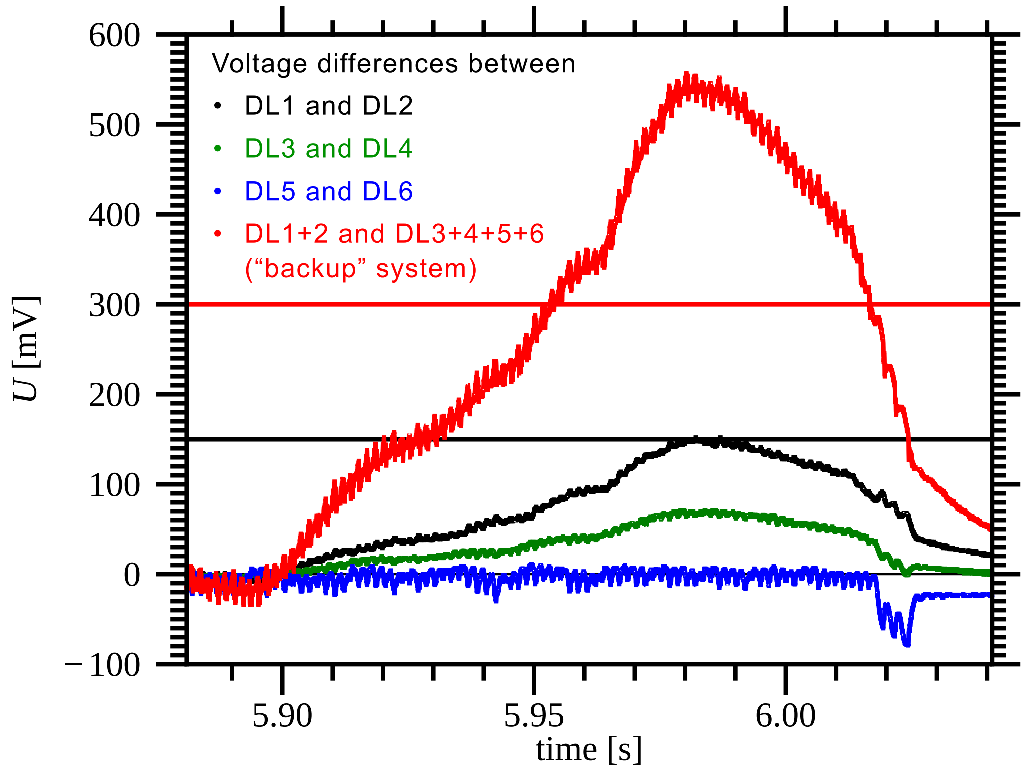


Comparing methods in case of fast changes of plasma energy – Method B (1): choice of signals

$$U_{Jjm} \;=\; -\frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t}\,N_{j\,\mathrm{DL}} - \sum_k K_{jk}\,\frac{\mathrm{d}I_k}{\mathrm{d}t}$$

- Overall 360 DL voltages U_{Jjm} – but only 260 voltage differences are accessible as QD signals
- Focus on QD signals with highest amplitudes: QD “backup” system and DL12 difference of “original” system
- For now, we restrict ourselves to the AAB16 signals

Reminder: QD signals in 20221207.58 from coil AAB16 (coil of type 5 in HM30)



Comparing methods in case of fast changes of plasma energy – Method B (2)

$$U_{Jjm} \;=\; -\frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t}\,N_{j\,\mathrm{DL}} - \sum_k K_{jk}\,\frac{\mathrm{d}I_k}{\mathrm{d}t}$$

- For short time scales, the $U_{j\,\text{ext}}$ can be neglected; then the $\mathrm{d}I_k/\mathrm{d}t$ can be calculated from

  $0 \;=\; -\frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t}\,N_{j\,\mathrm{tot}} - \sum_k L_{jk}\,\frac{\mathrm{d}I_k}{\mathrm{d}t}$, and $\mathrm{d}\Phi_{\mathrm{PG}}/\mathrm{d}t$ can be expressed by the U_{Jjm} only $\rightarrow$ method “BS”

- We shall compare methods B and BS, using the DL12 and the “backup” signal

Comparing methods in case of fast changes of plasma energy – Method B (3)

$$U_{Jjm} \;=\; -\frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t}\,N_{j\,\mathrm{DL}} - \sum_k K_{jk}\frac{\mathrm{d}I_k}{\mathrm{d}t}$$

Compensated W_{dia} signal

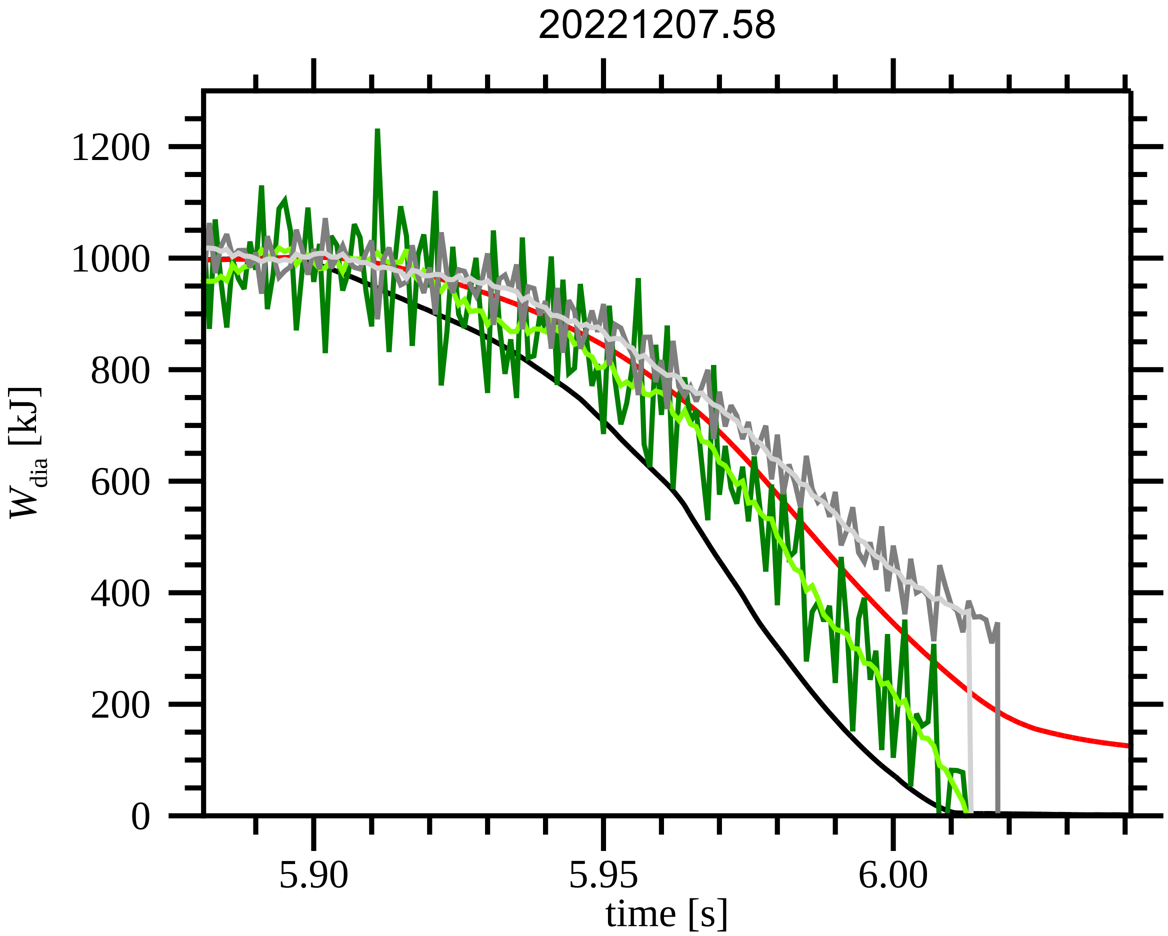
W_{dia} based on AAB16 QD “backup” signal and calculated currents (method BS)

W_{dia} based on AAB16 QD “backup” signal and measured currents

Same but smoothed over 10 samples of current signals

W_{dia} based on AAB16 QD DL12 signal and measured currents

Same but smoothed over 10 samples of current signals



Comparing methods in case of fast changes of plasma energy – Overall comparison

Compensated W_{dia} signal

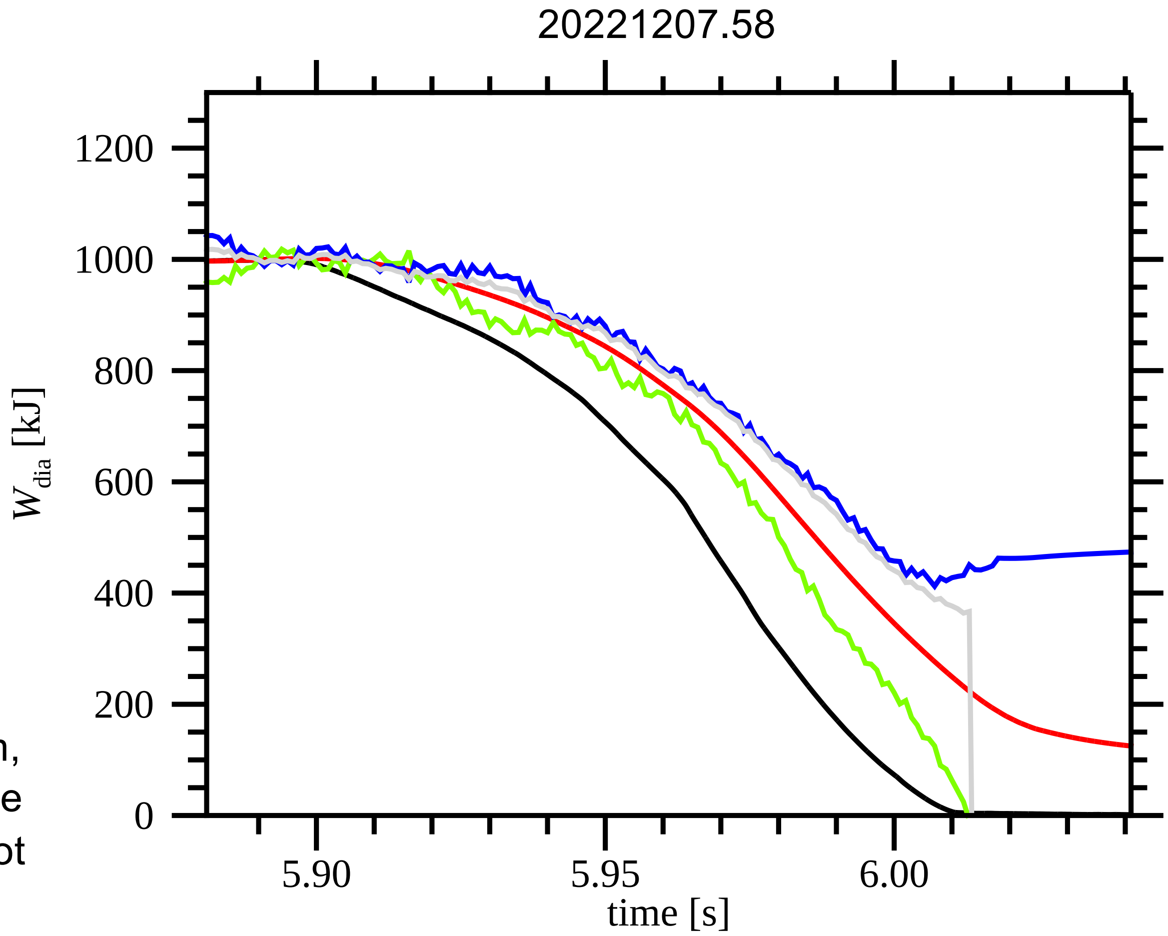
W_{dia} based on measured currents and measured external voltage of circuit 5 (method A), smoothed

W_{dia} based on AAB16 QD "backup" signal and calculated currents (method BS)

W_{dia} based on AAB16 QD "backup" signal and measured currents (method B), smoothed

W_{dia} based on AAB16 QD DL12 signal and measured currents (method B), smoothed

- Fair agreement, taking into account the delay due to the plasma vessel currents
- Due to the fast discharge of the coil system, the final level of the calculated W_{dia} after the end of the plasma in methods A and B is not available



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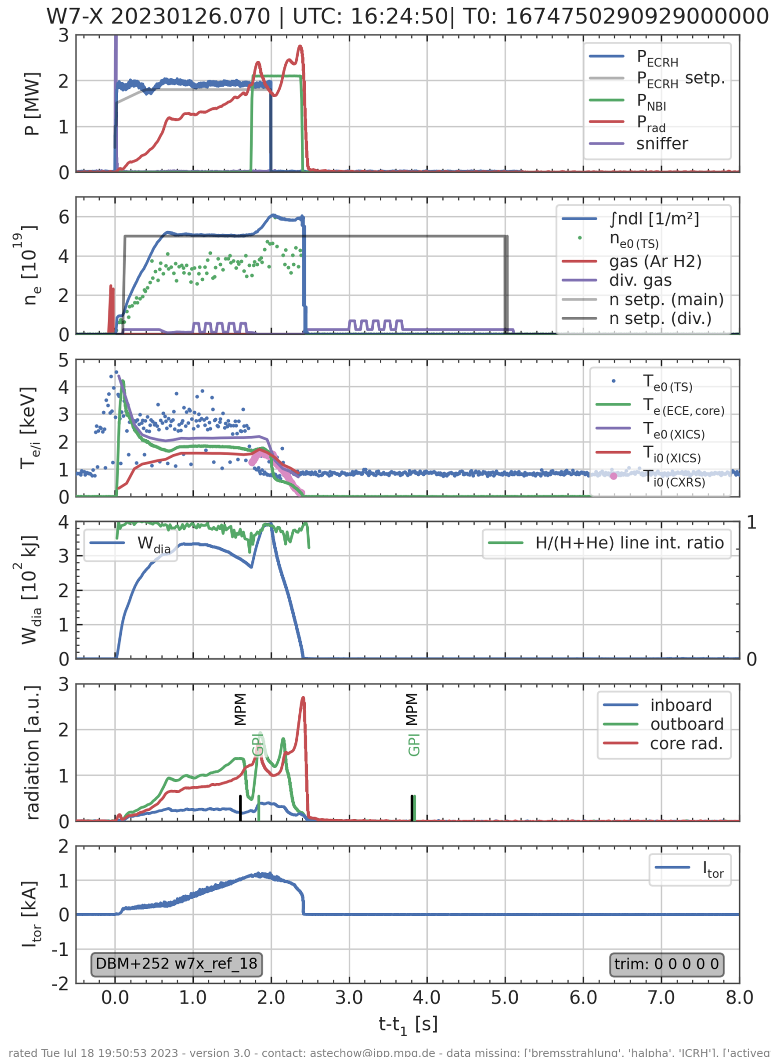
4. Comparing methods for long time scales (1)

- As noted earlier, this would be the actual application for using the superconducting field coils as diamagnetic loops
- There is only one discharge where QD data are available *before and after* the plasma: 20230126.70



Comparing methods for long time scales (2)

Compensated W_{dia} signal

W_{dia} based on measured currents and measured external voltage of circuit 5 (method A)

Same but smoothed over 10 samples

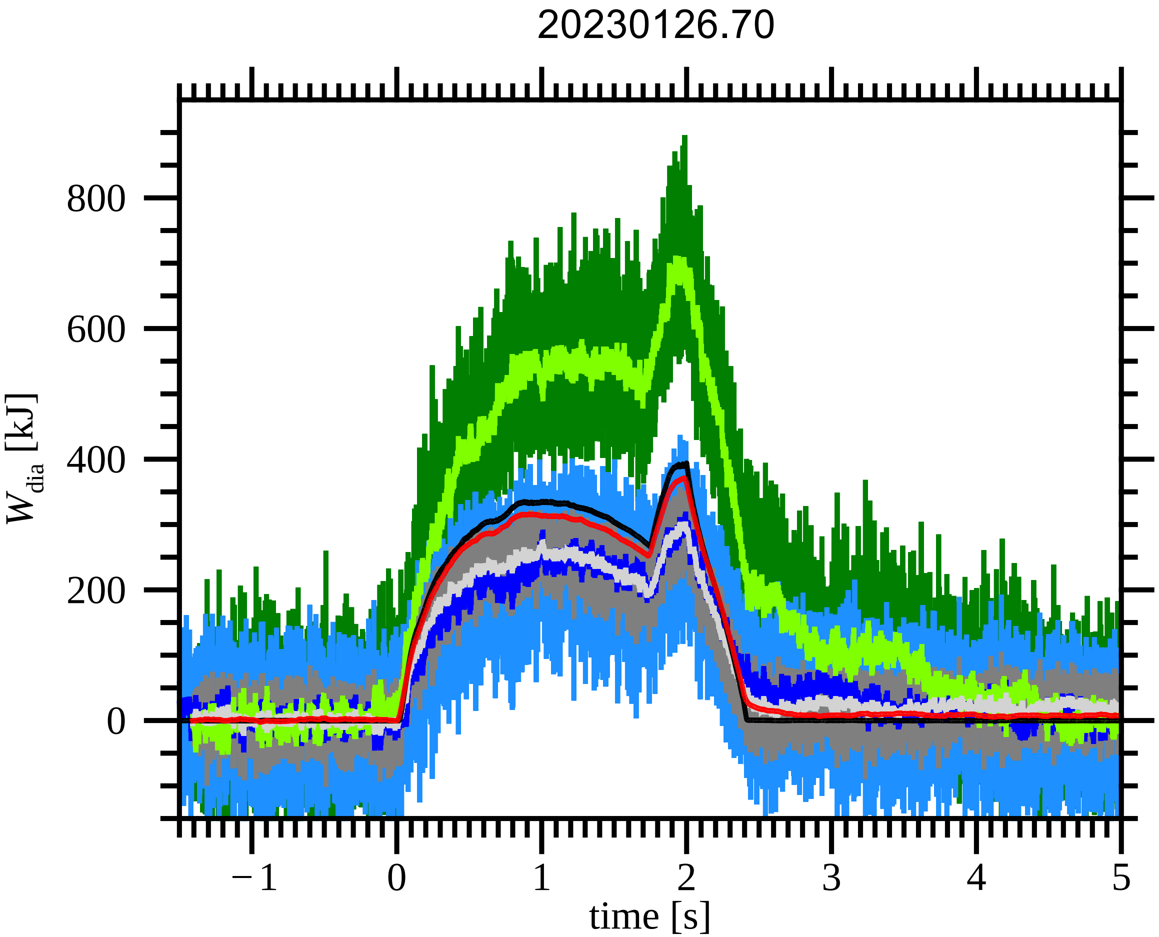
W_{dia} based on AAB16 QD “backup” signal and measured currents (method B)

Same but smoothed over 10 samples of current signals

W_{dia} based on AAB16 QD DL12 signal and measured currents (method B)

Same but smoothed over 10 samples of current signals

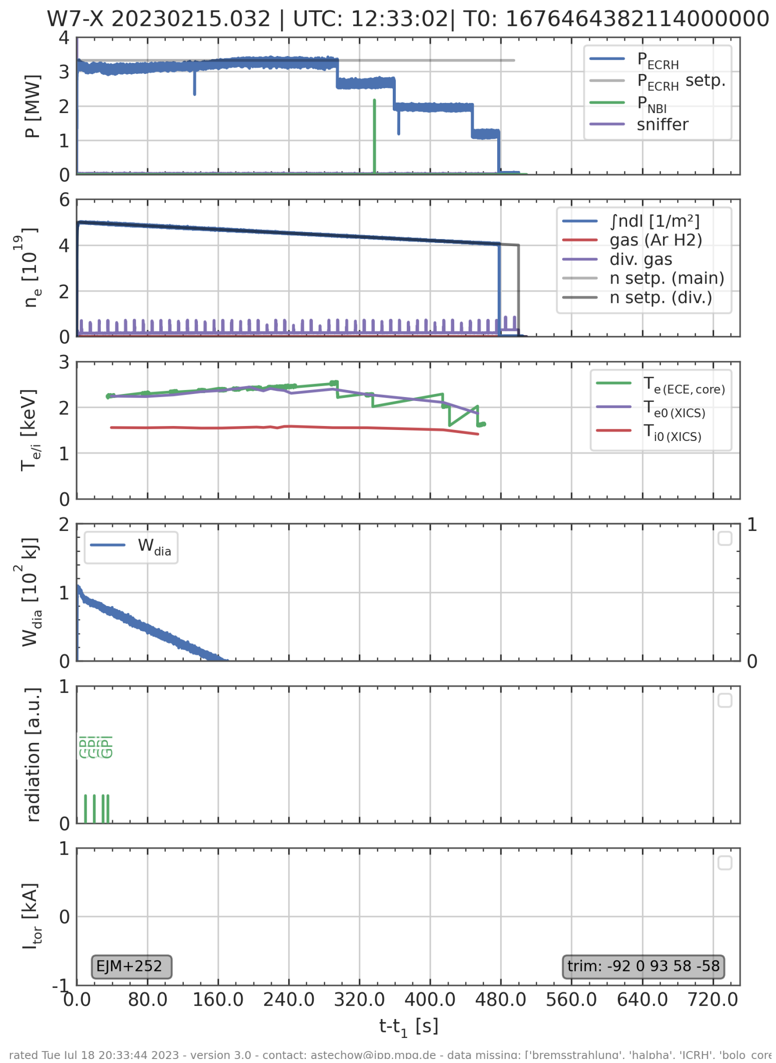
W_{dia} based on AAB16 QD “backup” signal and calculated currents (method BS)



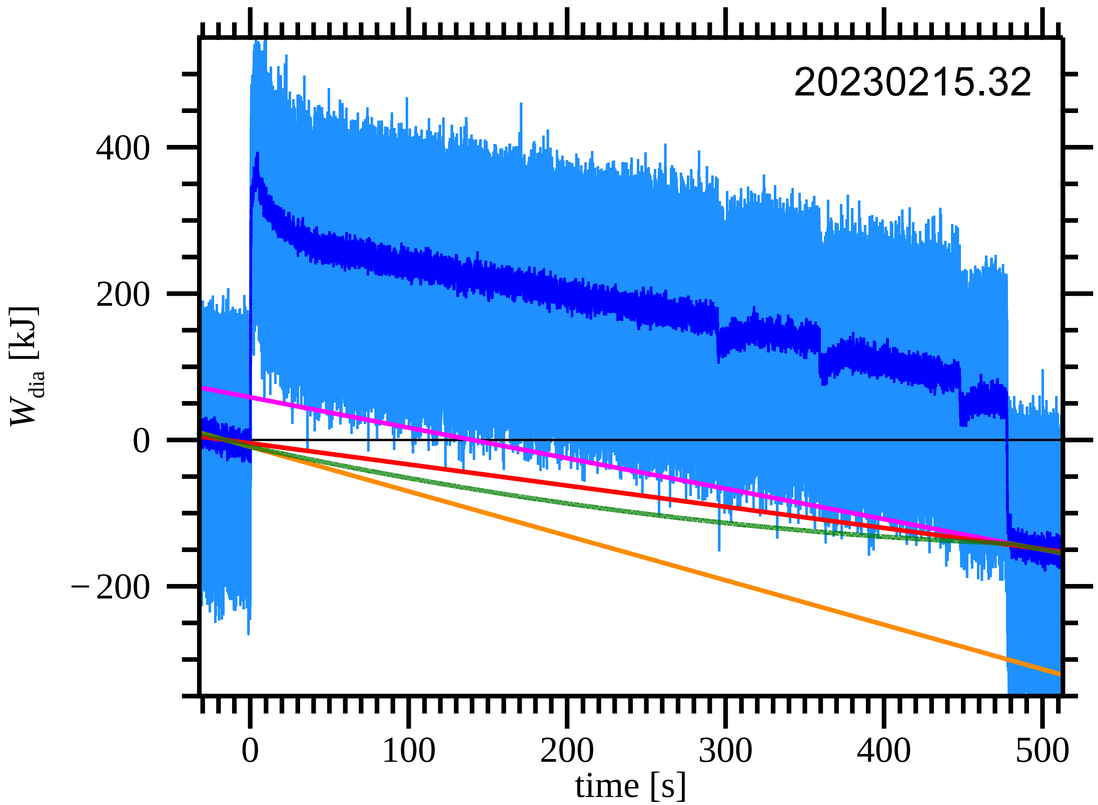
- Still fair agreement, even for method BS
- Here, for method B, DL12 signal gives better agreement than “backup” system
  $\Longrightarrow$ watch out for small differences between damping factors in denominator!

Comparing methods for long time scales (3)

- Does the method also work for very long discharges?
- QD signals not available – only use coil currents and voltages for comparison

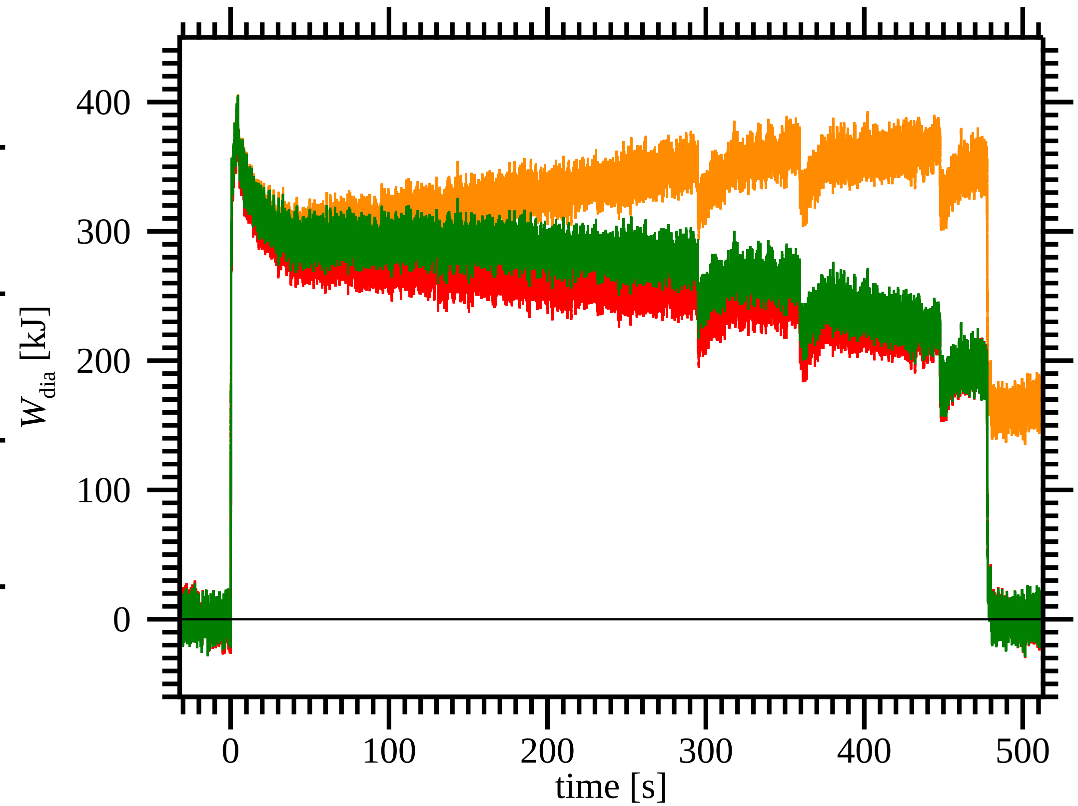


Comparing methods for long time scales (4)



W_{dia} based on measured currents and measured external voltage of circuit 5 (method A)

Same but smoothed over 50 samples



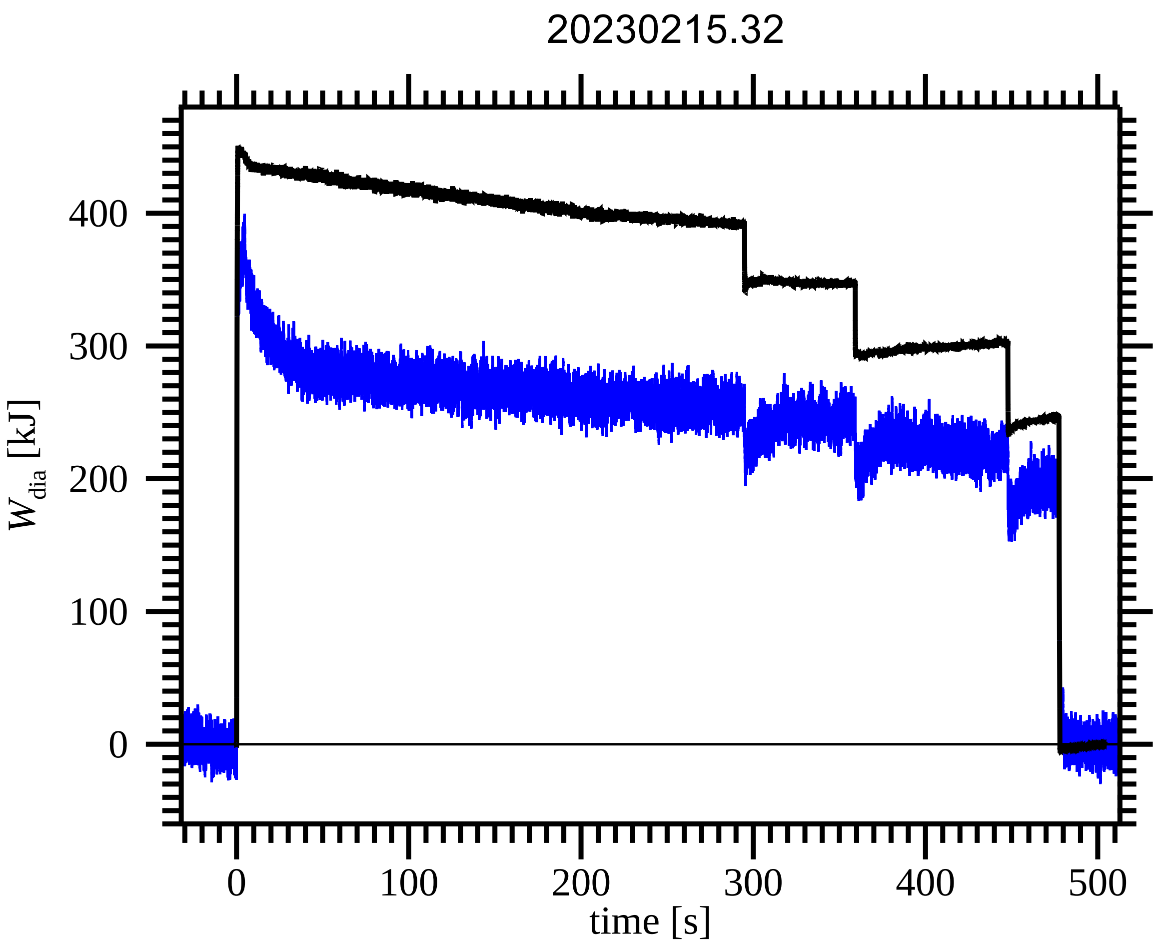
Smoothed signal after detrending with the different lines

Comparing methods for long time scales (5)

Compensated W_{dia} signal

W_{dia} based on measured currents and measured external voltage of circuit 5 (method A), smoothed over 50 samples

- Signal based on coil currents and voltage was corrected by subtracting a regression line combined from samples before and after plasma



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5. Conclusions and Summary

- The diamagnetic energy signals determined from currents and voltages in the superconducting coil system agree fairly well with the signal calculated from diamagnetic loop and compensation loops
- The current signals of the coil circuits have different noise levels, very high for particular circuits, but require no integration for calculating the diamagnetic energy
- Two methods to obtain the W_{dia} value from the coil circuits have been demonstrated
- The QD voltage signals are not regularly available but could be promising
- The voltage signals of the coil circuits are also suitable
- All voltage signals must be integrated; it remains to be investigated whether a sufficiently low offset drift can be achieved, e. g., by using the front end of the magnetics electronics
- It was not yet investigated which of the various channels is best suited, or whether some average should be used
- A correction for the online diamagnetic energy interlock signal for long time scales could therefore be developed from the superconducting coil current and voltage signals
- Such a correction might be of interest if errors due to thermal expansion of the diamagnetic loop and/or compensation loops occur