MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Wendelstein
7-X

Why does a fast plasma decay trigger the W7-X quench detection system?

M. Endler, K. Riße, M. Schneider, K. Rahbarnia

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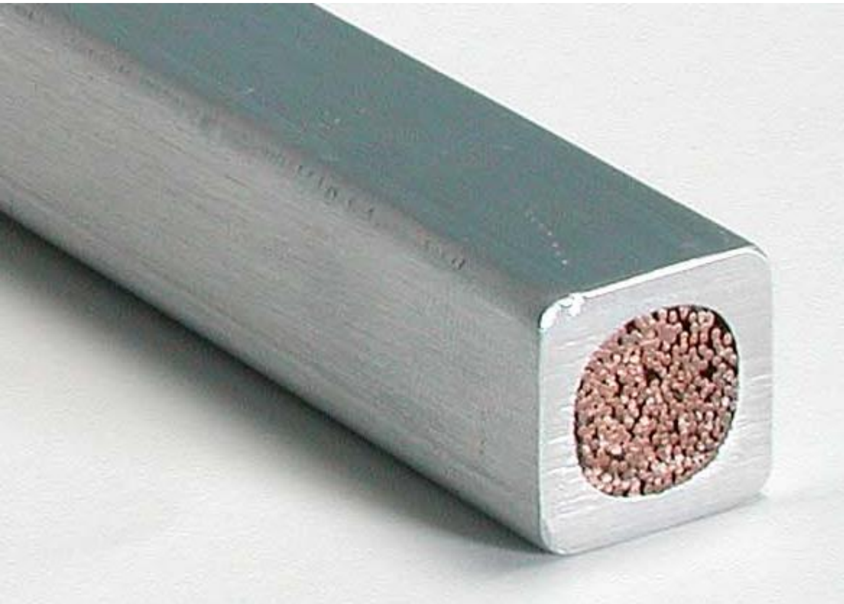
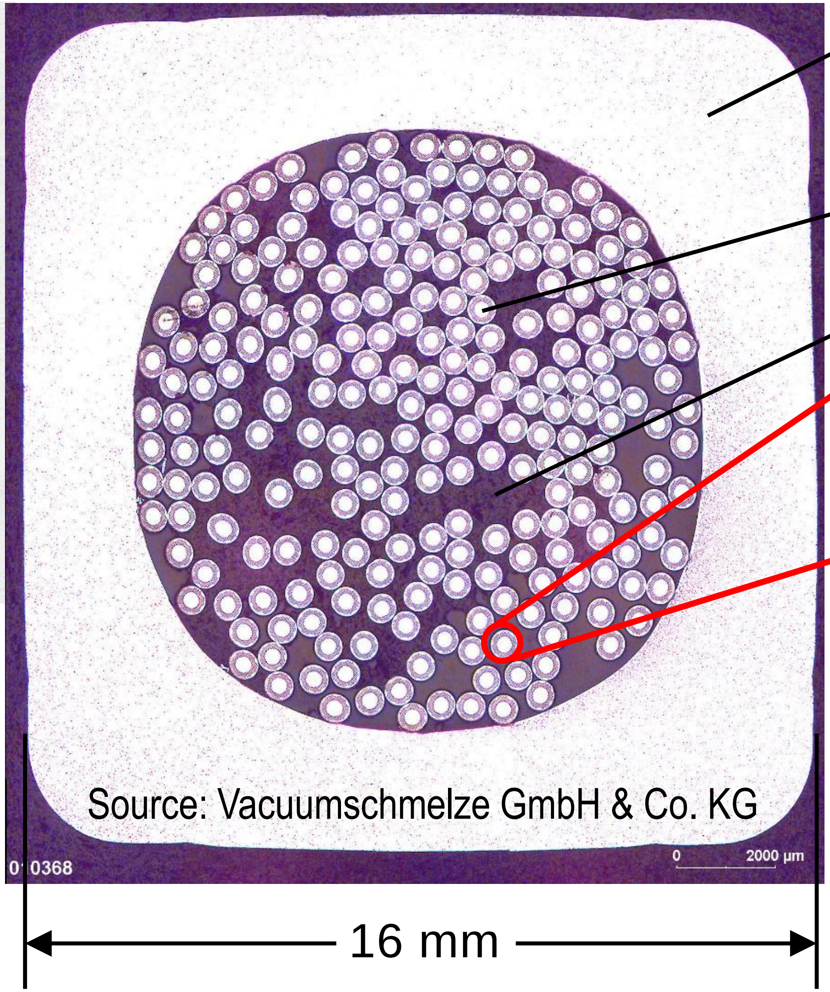
1. Motivation
2. The W7-X field coils and their QD system
3. Electromagnetic interaction between plasma and coil system
    a. The field coils as diamagnetic loops
    b. The subdivision in double layers and qualitative considerations
    c. Simulating voltages in the QD system
    d. Quantitative reproduction of measurements
4. Are there alternative setups of the QD system?
5. Summary

Correction in this version of the presentation (6.2.2024): On p. 20, the statement " ... the induced voltage ... is independent of precise shape of winding [and] distance of winding from plasma column" has been changed into " ... the induced voltage ... is only weakly dependent on precise shape ... "

1. Motivation – The W7-X superconductor



Cable-in-conduit conductor (CICC) used for the W7-X superconducting coils and bus system

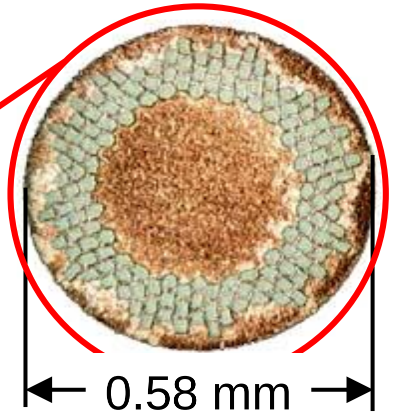


Source: Vacuumschmelze GmbH & Co. KG

AlMgSi jacket

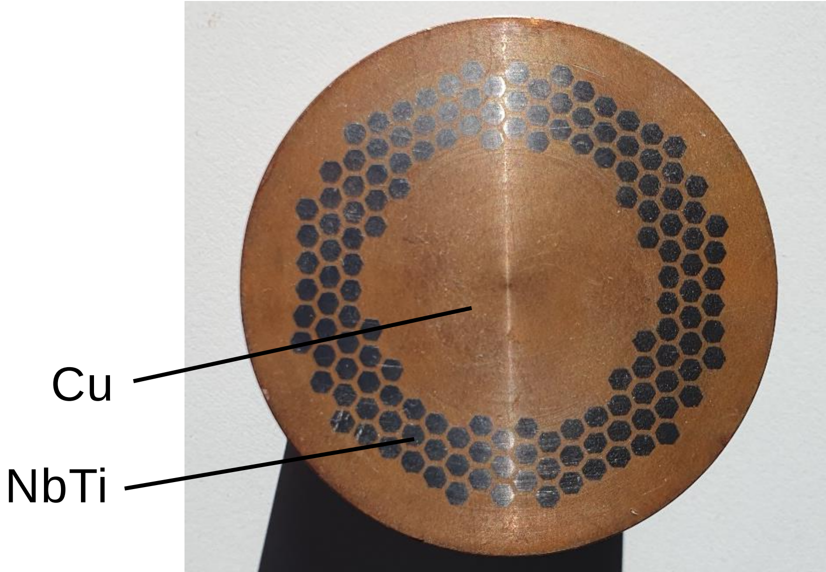
243 strands

37 % void fraction for He flow



Single strand

Before drawing the strand:



Refs.: K. Riße et al., Fus. Eng. Des. **66–68** (2003) 965;
T. Rummel et al., IEEE Trans. Plasma Sci. **40** (2012) 769

Purpose of the quench detection (QD) system

Quench: Supercoductivity locally lost → ohmic heating → loss of superconductivity spreads

Consequence:

- High thermal stress causes local damage
- Eventually local melting of coil

Remedy: Remove coil current quickly enough

QD system:

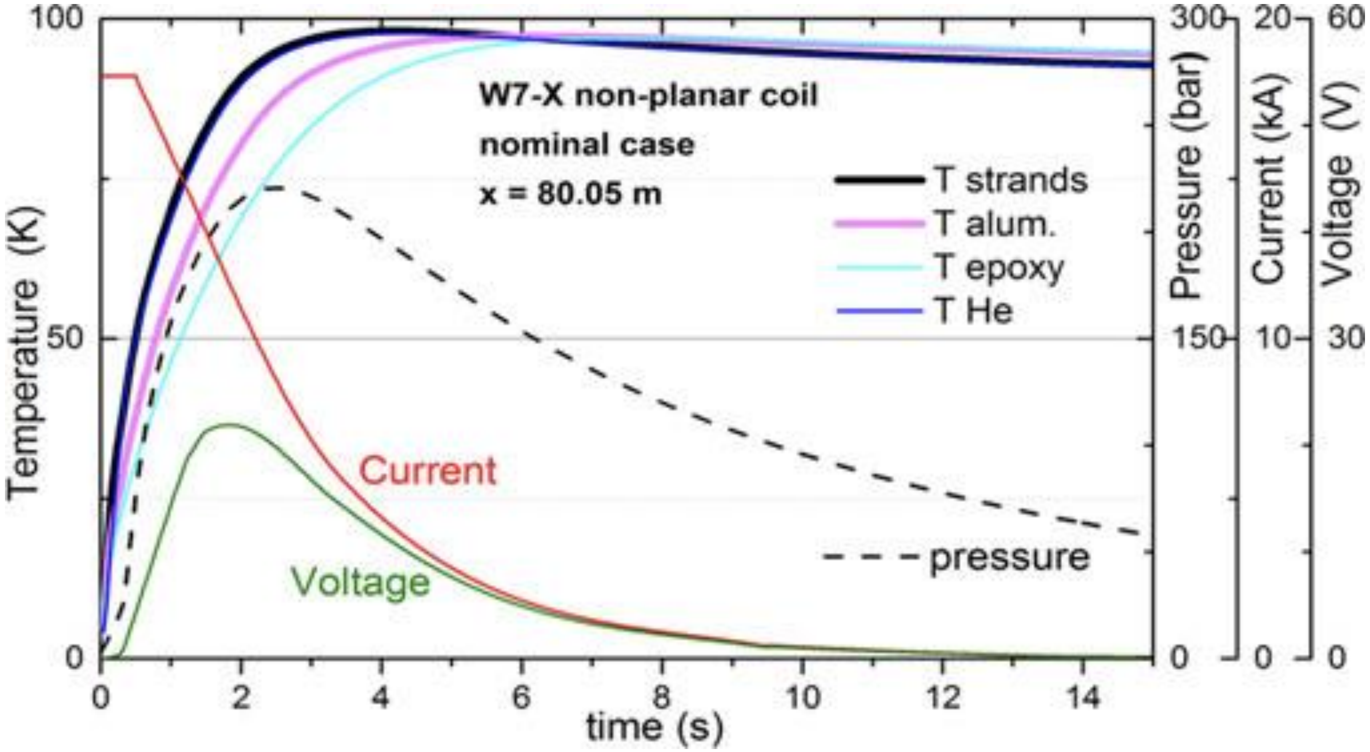
- Detects voltage caused by final conductance in quench area
- Initiates fast ramp down of coil current by switching to external resistors
- ~ 500 MJ of magnetic energy are dumped into resistors within several seconds (value for $B_0 = 2.5$ T)

(This corresponds to: ~ 300 t at 200 km/h *or* ~ 500 t falling 100 m *or* heating of ~ 1 t of water from 0° C to 100° C.)

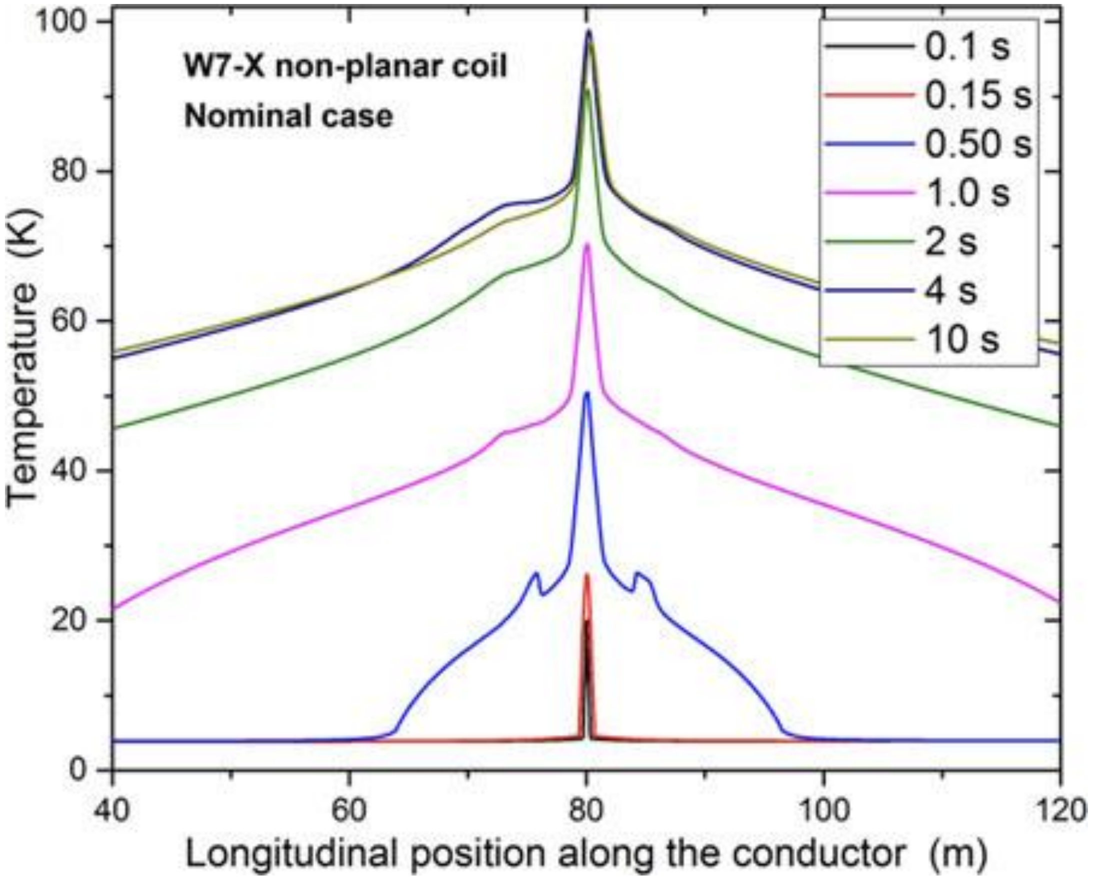
Timing of the QD system (1)

- Data simulated with original settings of the W7-X QD system
- Quench is initiated by depositing 2 J on 10 cm of superconductor within 0.1 s

Time evolution



Spreading of temperature along superconductor

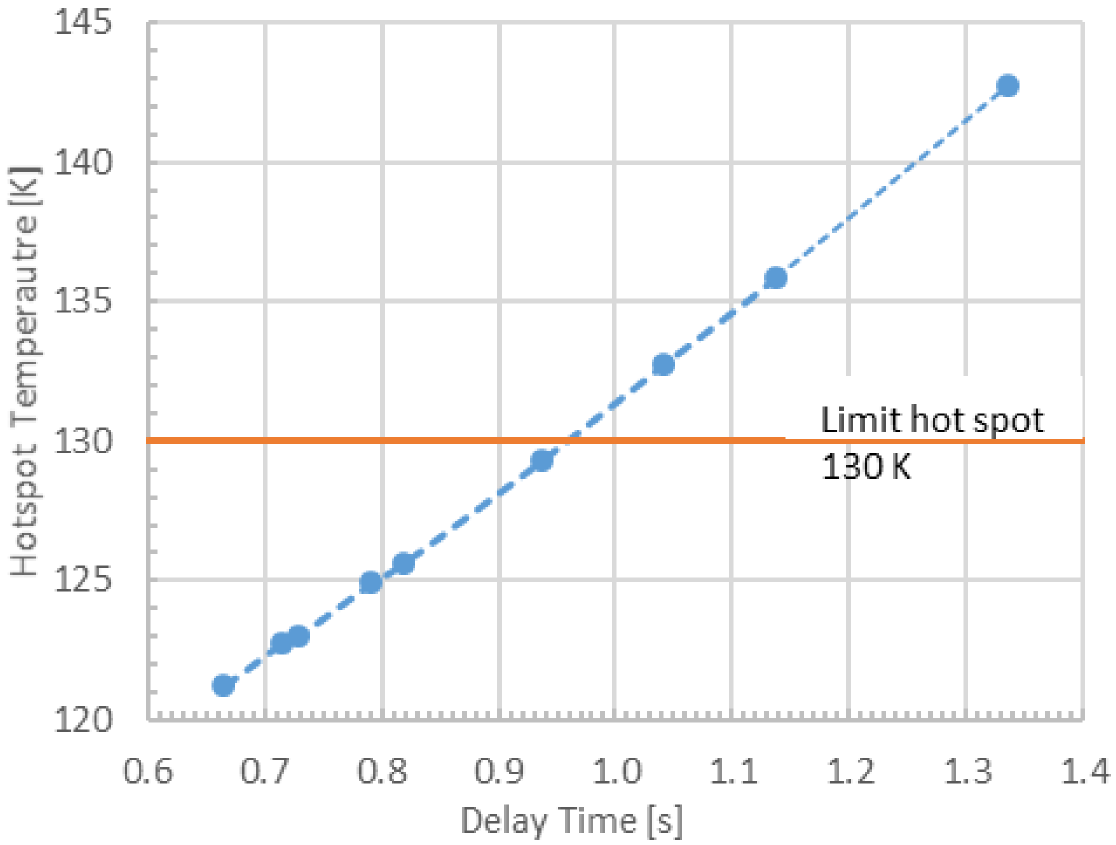


Figs. from: K. Sedlak et al., IEEE Trans. Applied Supercond. **28** (2018) 4200905

Timing of the QD system (2)

Delay time before current ramp down starts:

- time before voltage reaches threshold
- validation time before QD system initiates ramp down (50 ms in the initial setup)
- plus switching time of the current breakers (350 ms)



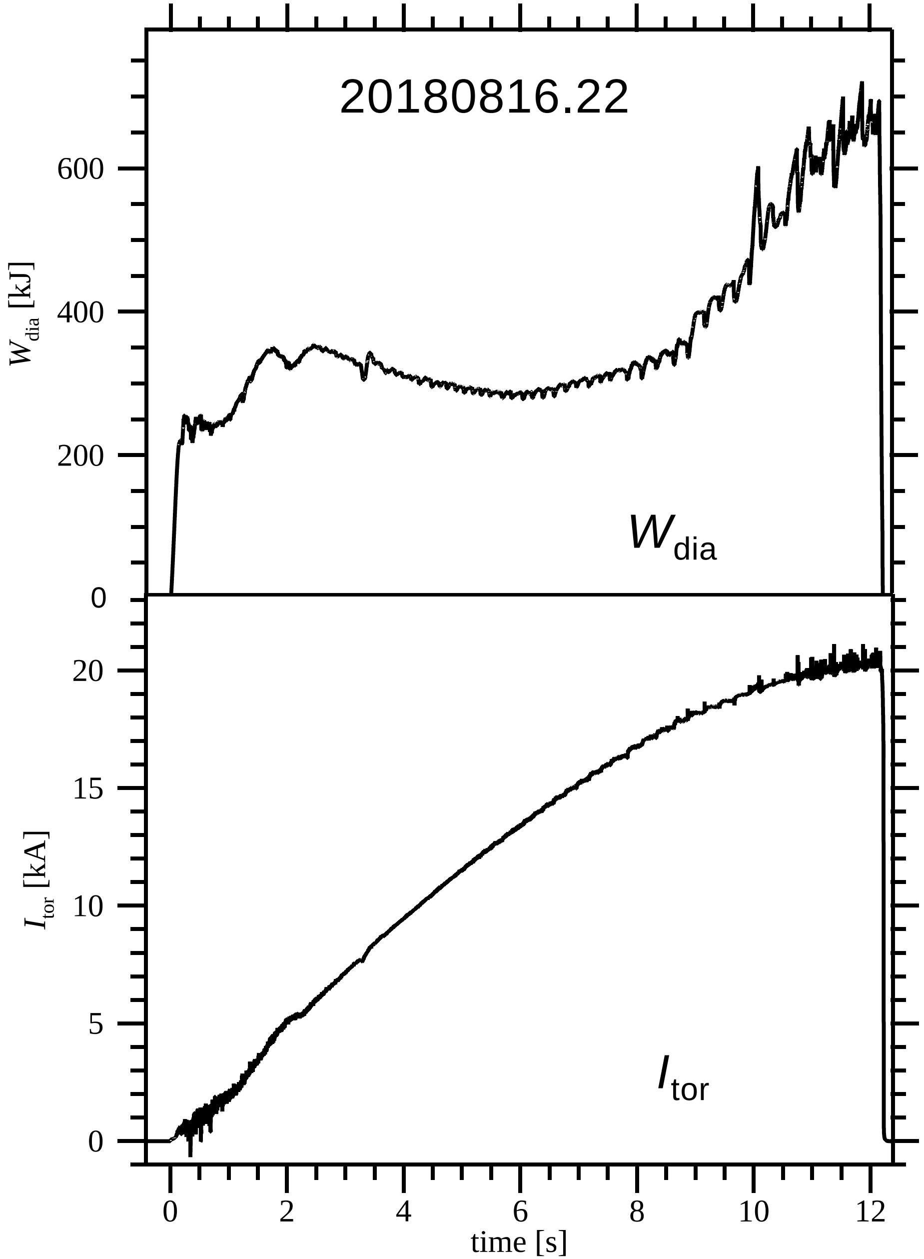
Maximum temperature within quenching coil

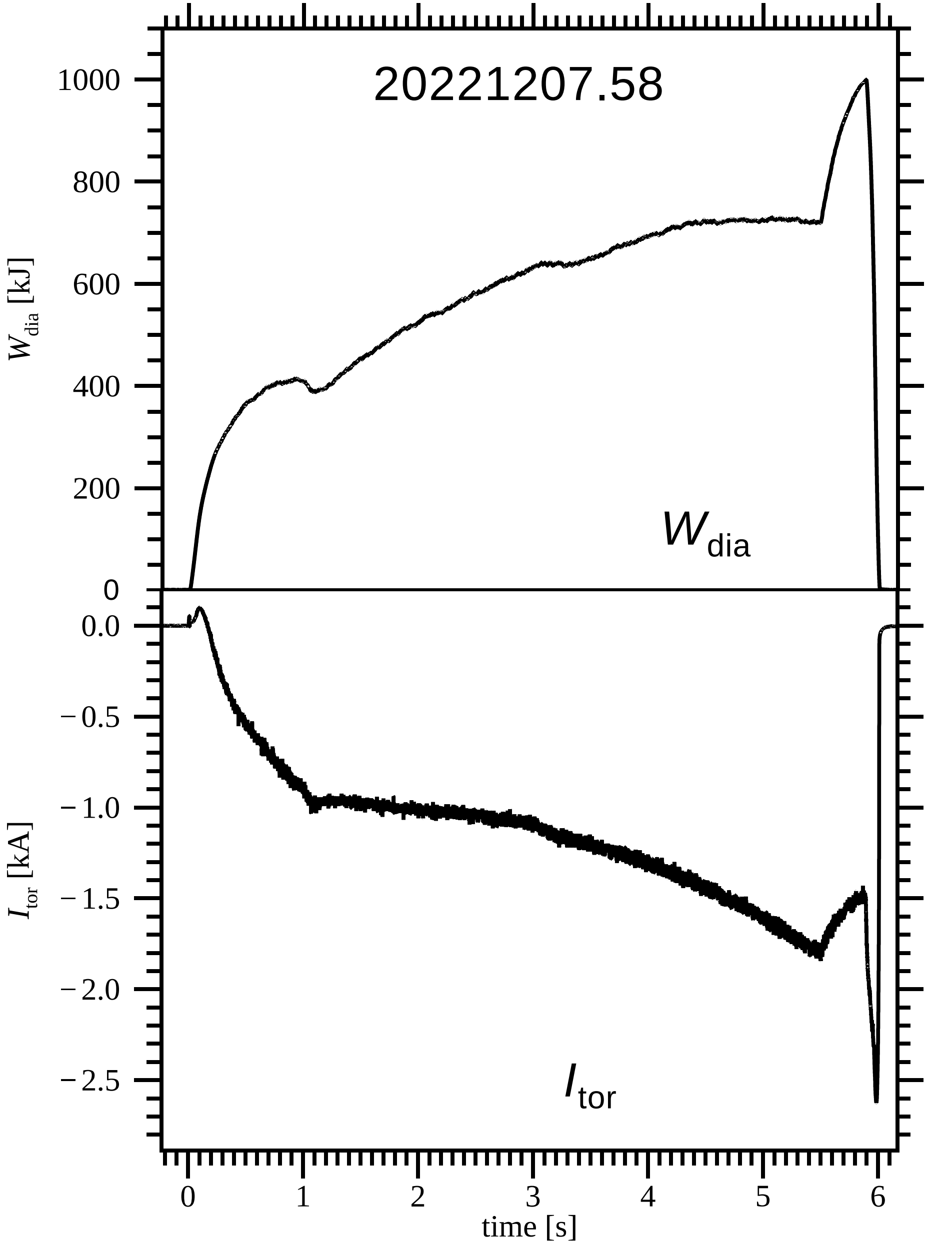
Fig. from: K. Riße et al., 28th International Conference on Magnet Technology (2023), submitted to IEEE Trans. Applied Supercond.

Consequences of the action of the QD system

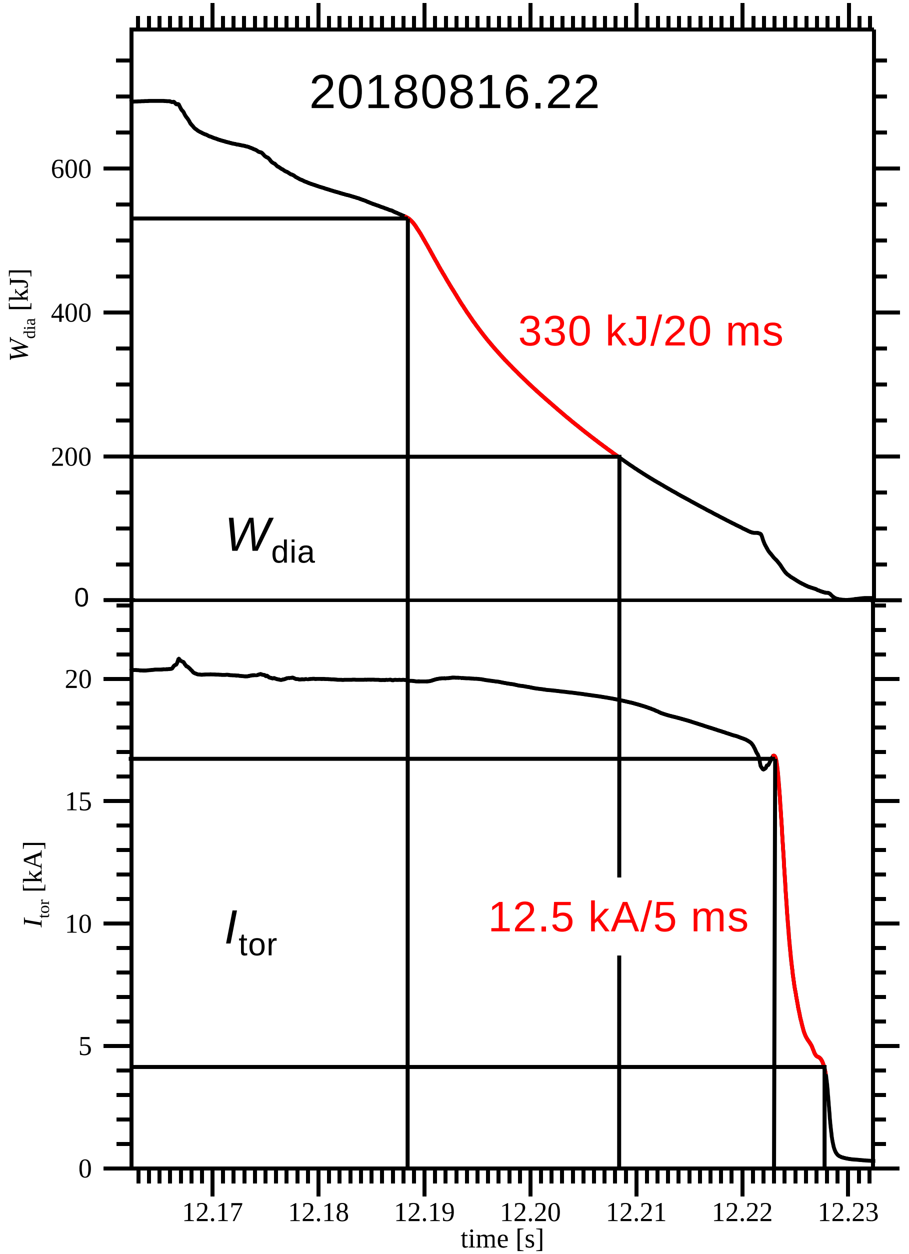
- A quench would destroy the coil if not detected
- The mere triggering of a fast current ramp down should do no harm, however ...
  - High voltages (up to ~ 1.9 kV, half of this against ground)
  - Stop of operation, usually for at least the rest of the day
- So far, a fast current ramp down has been triggered typically once per operation campaign, due to different reasons
- Thereof, twice a plasma event (fast decay of plasma) has triggered the QD system

Two plasma events with triggering of the QD system (1)

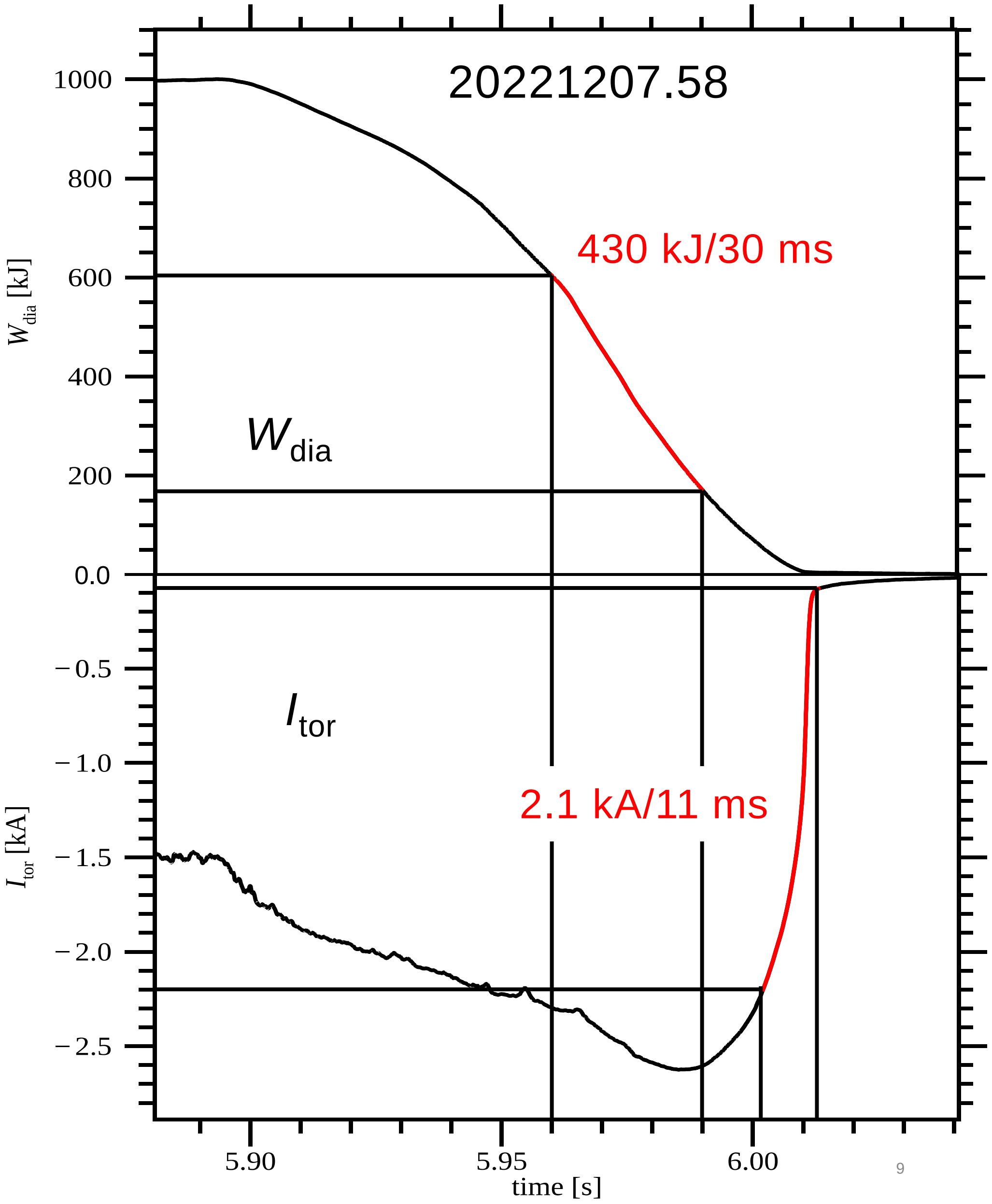




Two plasma events with triggering of the QD system (2)

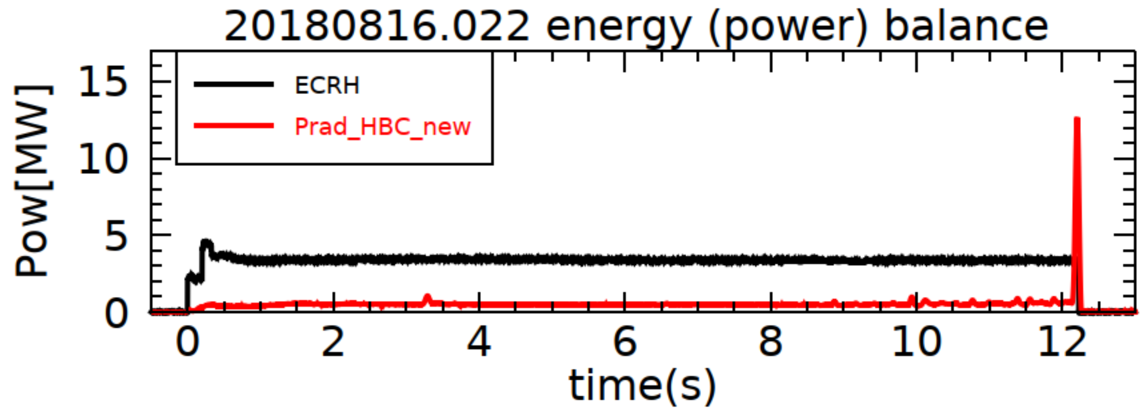


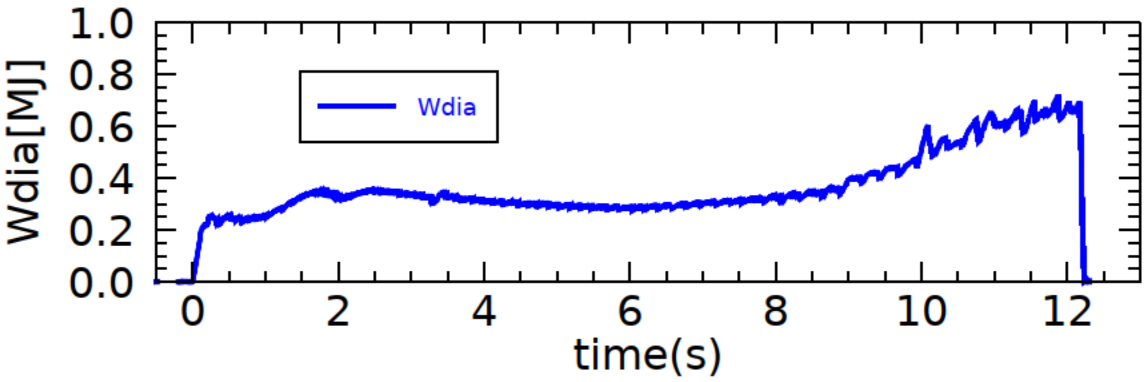
Plasma decay enlarged

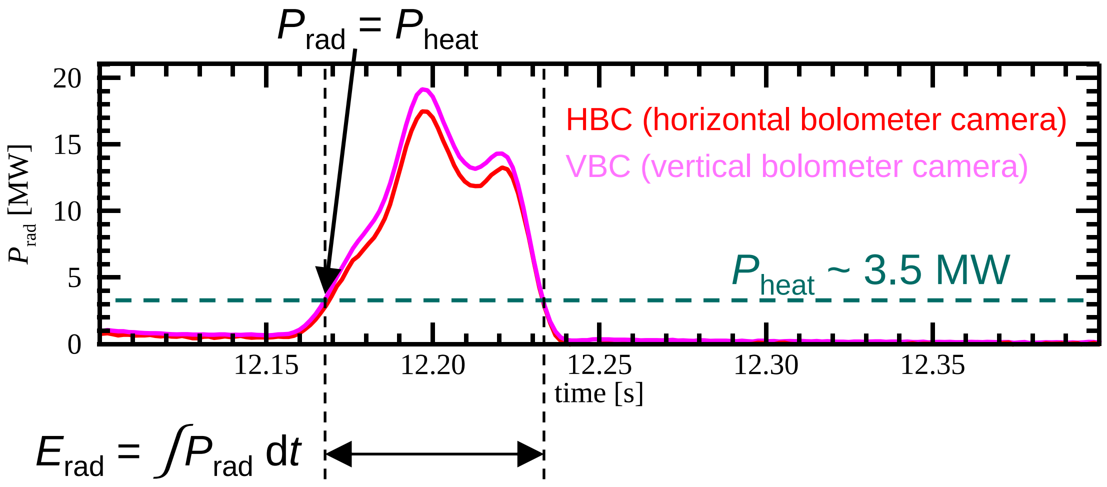


Digression (1) – Reason for fast plasma decay: Impurity radiation – 20180816.022

Comparing loss of diamagnetic energy with radiated energy from bolometry – by D. Zhang:





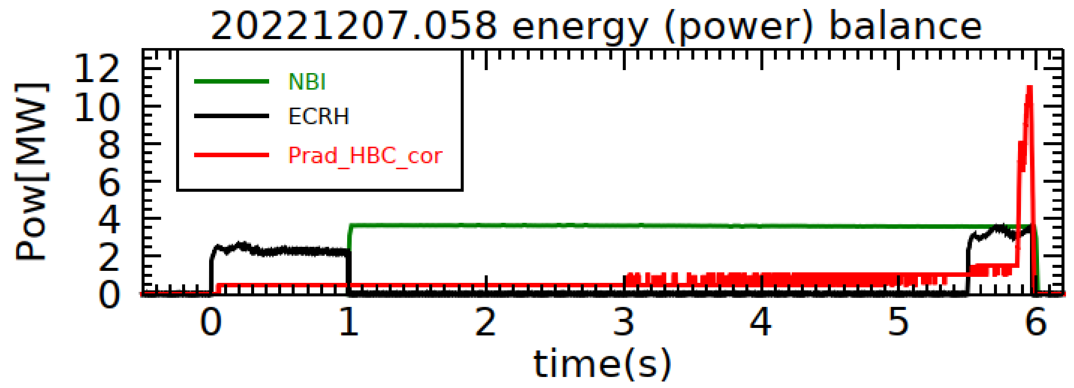


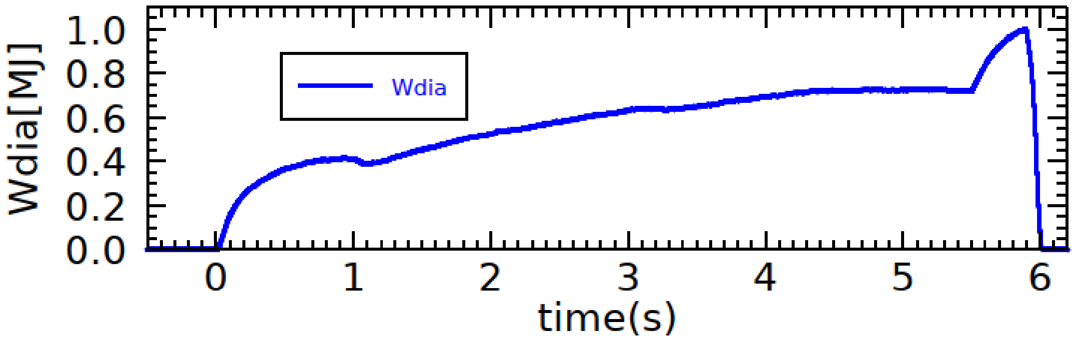
Conclusion of D. Zhang:

- Integrating P_{rad} from 12.16 s to 12.24 s: E_{rad} = 0.7–0.8 MJ ≈ $W_{dia}(t = 12.15\ \mathrm{s}) \approx 0.7$ MJ
- Exact amount of absorbed ECRH power during collapse phase is unknown
- Assuming no increased heat load on targets for $t > 12.16$ s (small, detached plasma) – confirmed by Y. Gao

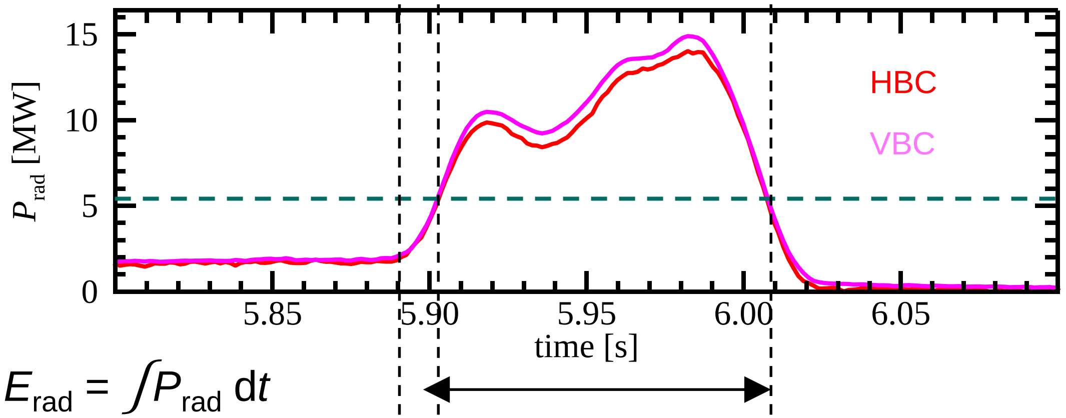
Digression (2) – Reason for fast plasma decay: Impurity radiation – 20221207.058

Comparing loss of diamagnetic energy with radiated energy from bolometry – by D. Zhang:


20221207.058 energy (power) balance



P_{heat} ~ 5.5 MW (3 MW ECRH + 70 % of 3.6 MW NBI)



$E_{rad} = \int P_{rad}\, dt$

Conclusion of D. Zhang:

- Integrating P_{rad} from 5.89 s to 6.02 s: $E_{rad} \approx 1.2$ MJ or integrating P_{rad} from 5.90 s to 6.02 s: $E_{rad} \approx 1.0$ MJ ≈ $W_{dia}(t = 5.89$ s$) \approx 1.0$ MJ
- Exact amounts of absorbed ECRH and NBI power during collapse phase are unknown (estimate: 30 % of $P_{heat} \approx 0.2$ MJ)
- Assuming no heat load on targets for $t > 5.9$ s (small, detached plasma) – confirmed by Y. Gao

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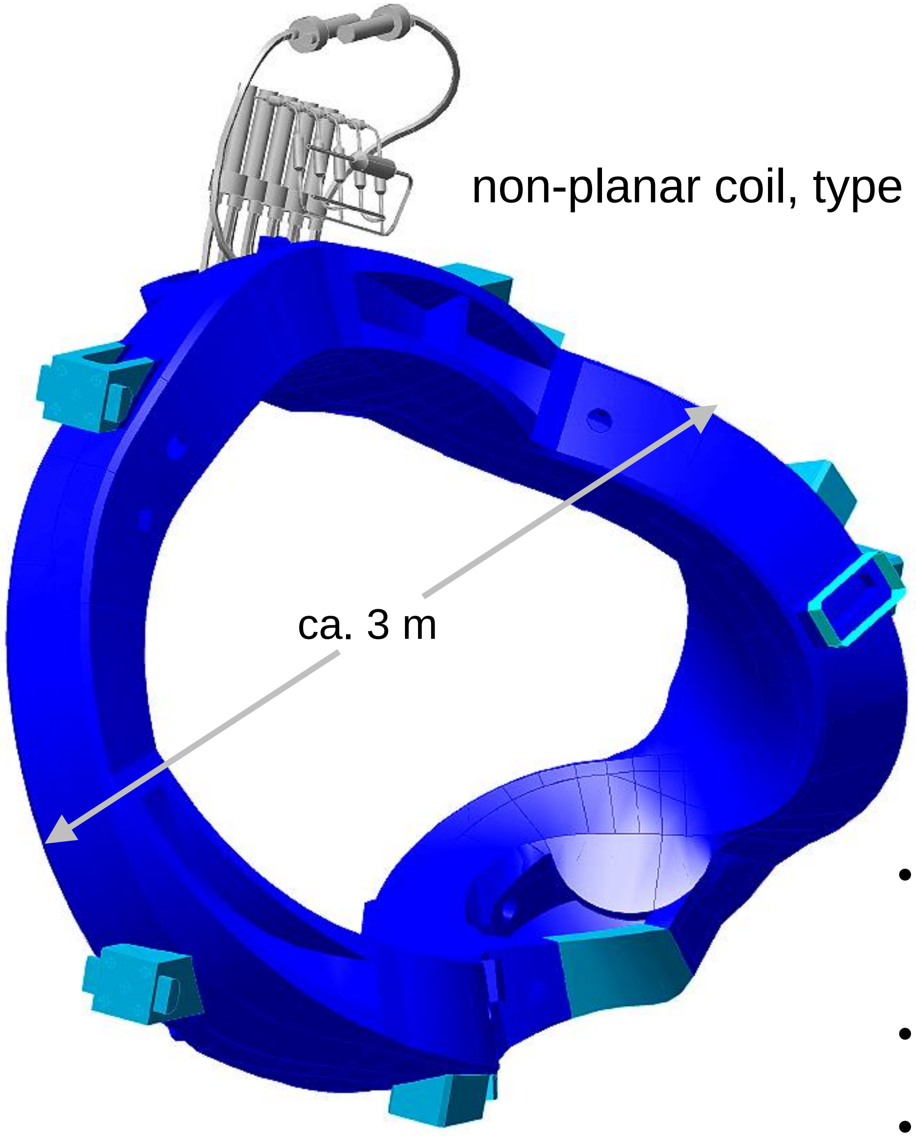
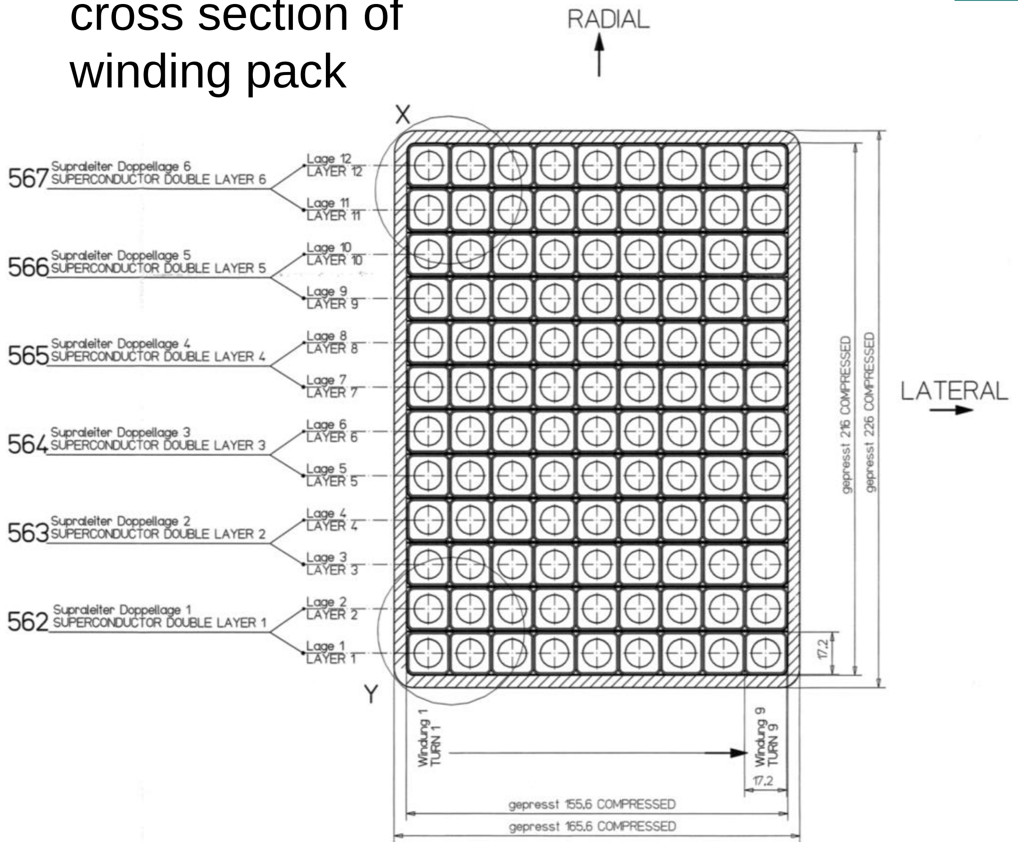
The W7-X field coils

non-planar coil, type 5



cross section of winding pack



- The winding pack of a non-planar coil consists of 6 double layers (DLs) in series, arranged radially
- There are 5 types of non-planar coils and 2 types of planar coils
- For each coil type, 10 coils are connected in series

Ref.: L. Wegener et al., Fus. Eng. Des. **58–59** (2001) 225

The quench detection (QD) system (1)

Setup for non-planar coils (primary system = “original” system):

Quench detection units (QDE) measure the difference of voltages across adjacent double layers (DL)

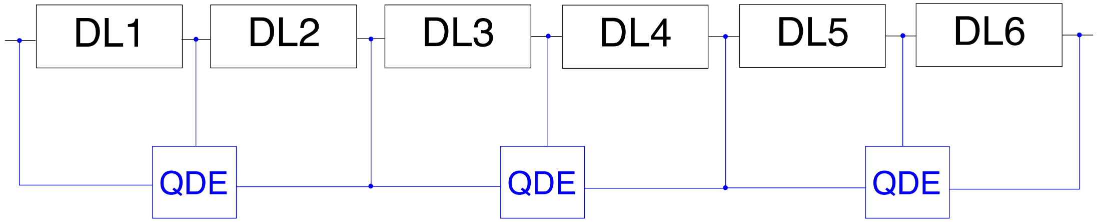
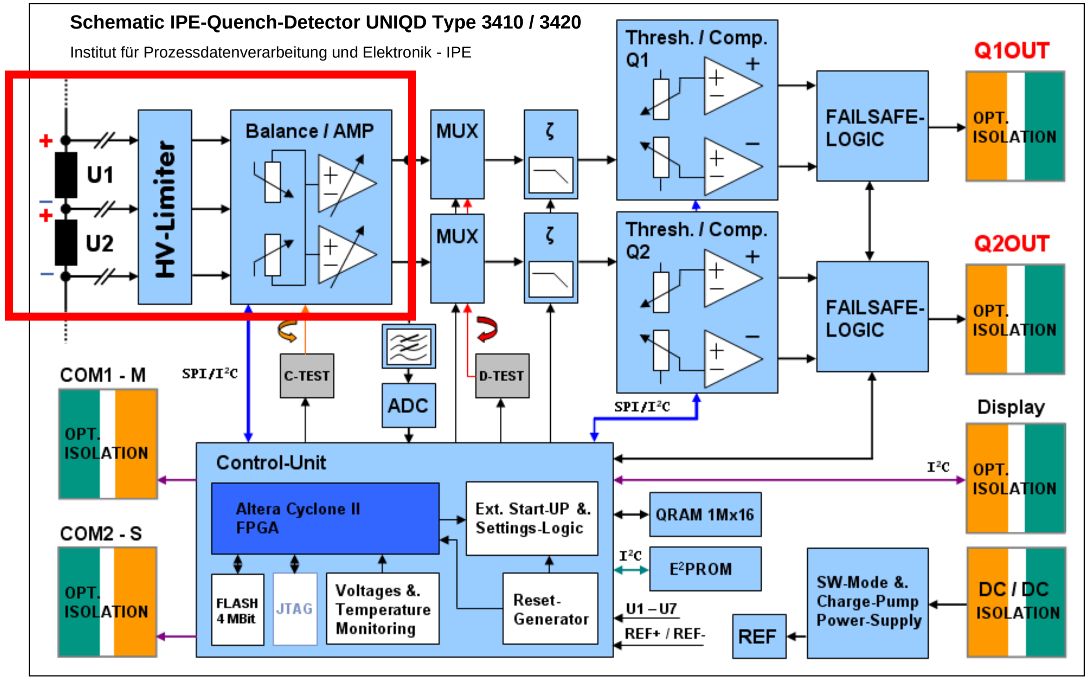


Fig. from: 1-AAM-T0103.11, p. 20

Schematic of one QDE:



© 2005 - 2014 Karlsruher Institut für Technologie - KIT

Fig. from: Bedienungsanleitung Quenchdetektionssystem UNIQD TYP 3410 / 3420, KIT 2014, p. 62

Refs. with overall description of QD system:
D. Birus et al., Fus. Eng. Des. **82** (2007) 1400;
D. Birus et al., Fus. Eng. Des. **84** (2009) 457

The quench detection (QD) system (2)

One QDE can be used either in differential mode (as realised for the coils)

or in absolute mode (by connecting one of the terminals to the central terminal, as realised for the bus sections)

For redundancy, there exists a secondary system (“backup” system) – for each non-planar coil, one QDE compares the voltage across DL1–2 with the voltage across DL3–6:

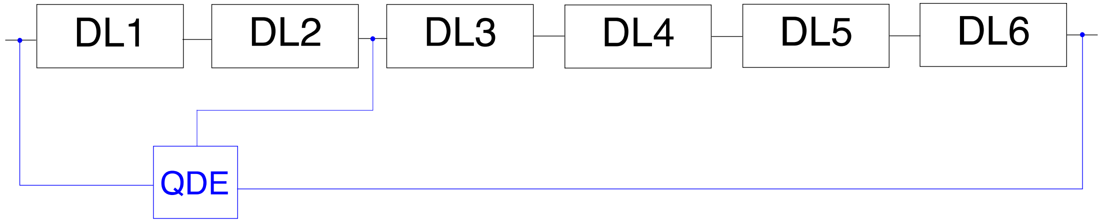


Fig. from: 1-AAM-T0103.11, p. 21

Data acquisition of the QD system

- System is independent of “normal” data acquisition
- Data acquisition rate 100 kHz per channel, absolute time precision ~ 1 ms
- Data are only stored in a 10 s interval around the trigger time:

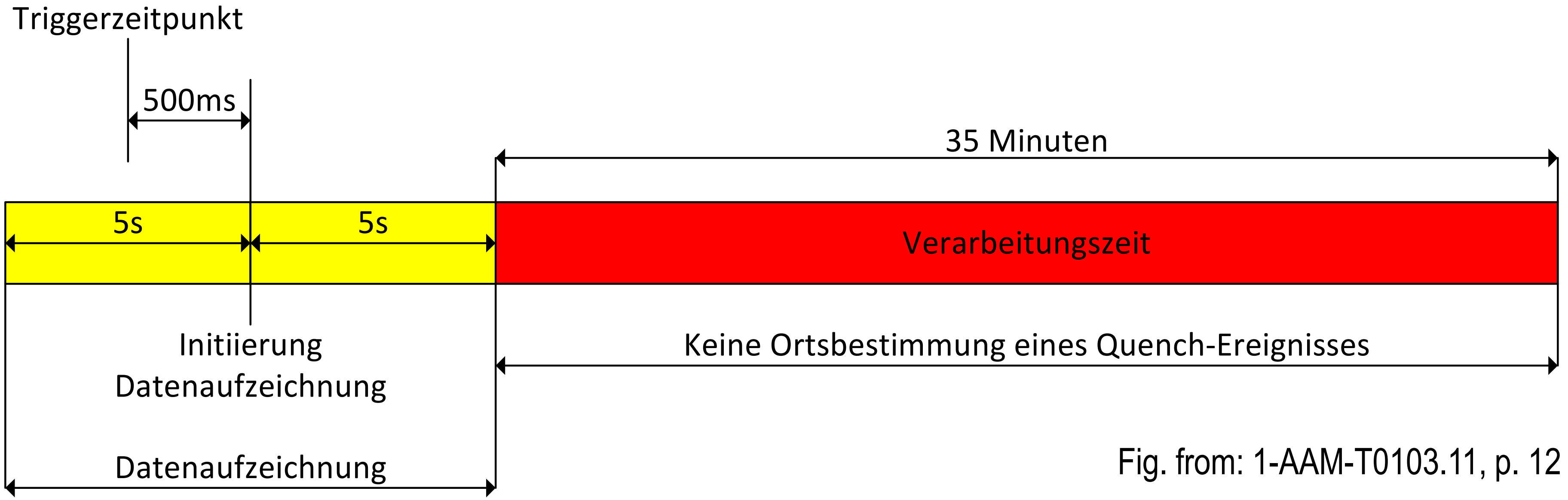


Fig. from: 1-AAM-T0103.11, p. 12

- Data storage takes approximately 35 min
- Data are temporarily stored on local system and transferred to W7-X archive after processing to obtain correct voltages and timing

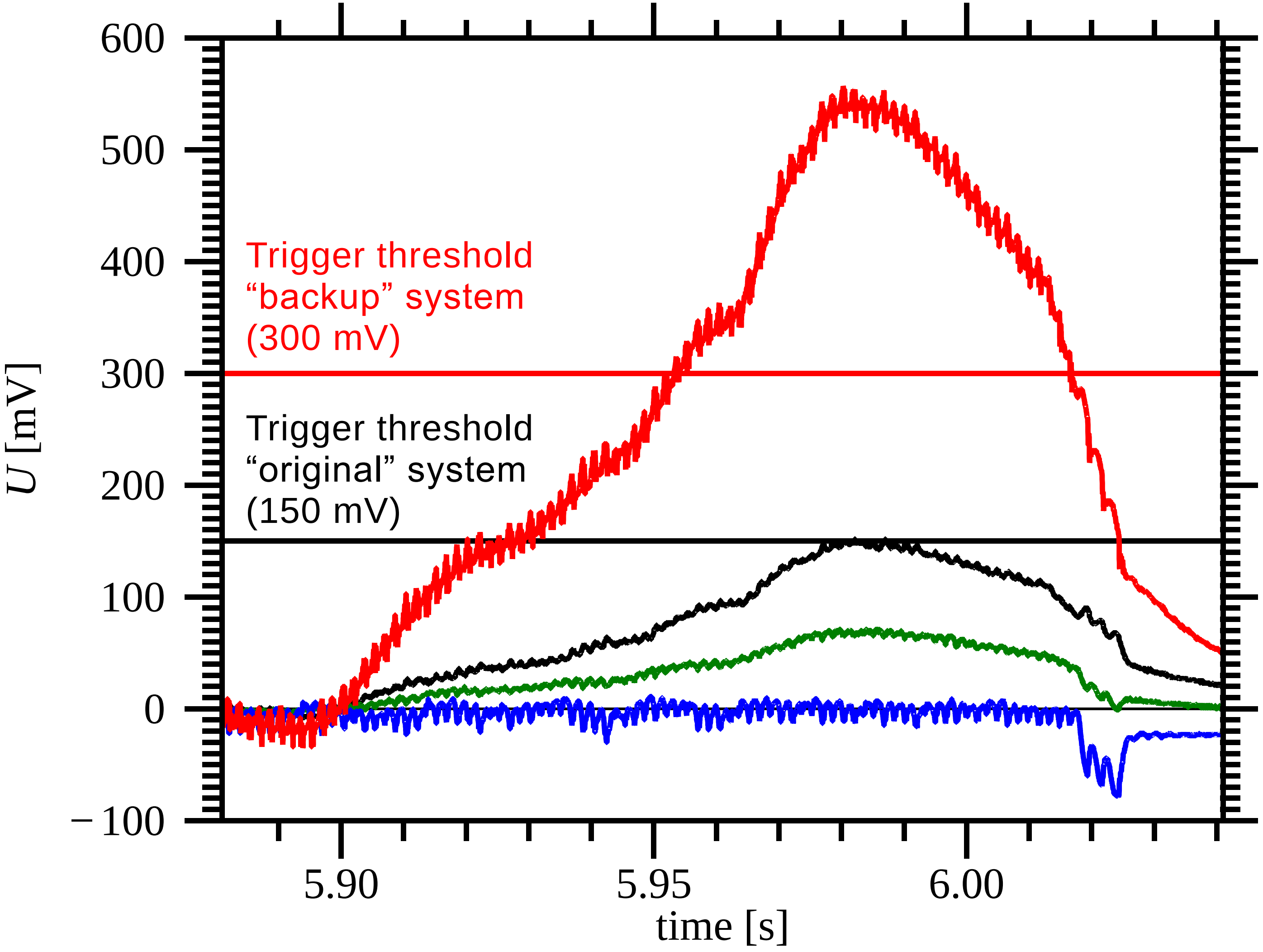
QD data during fast plasma decay

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

Voltage differences between

- DL1 and DL2
- DL3 and DL4
- DL5 and DL6
- DL1+2 and DL3+4+5+6 (“backup” system)

Other coils show similar signal amplitudes!



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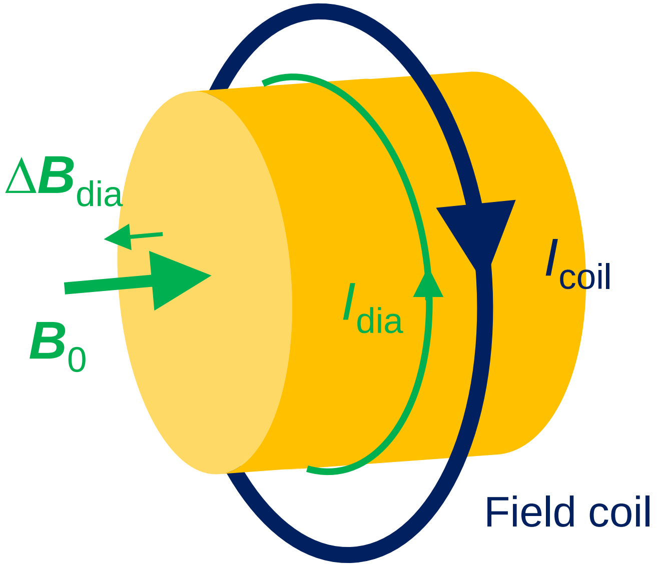
Diamagnetic effect of the plasma



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:

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

Use of this effect is made when measuring the plasma energy by recording the induced voltages in a diamagnetic loop

In W7-X, for a plasma energy of 5 MJ at 2.5 T (corresponding to $\beta \sim 4.4$ %): $\Phi_{\text{dia}} \approx -50$ mVs

Outside the plasma column, the diamagnetic effect is equivalent to a poloidal surface current I_{dia} on the plasma column, which generates the same change in toroidal magnetic flux.

In a toroidal solenoid with 5.5 m major radius and 0.5 m minor radius, this is achieved by a total current $I_{\text{dia}} \approx 1.7$ MA

The field coils as diamagnetic loops

As in a diamagnetic loop, a change of plasma energy should also induce a voltage in the field coils

Indeed, the use of toroidal field coils as diamagnetic loops was demonstrated at the PDX tokamak
[P. Thomas, report PPPL-1979, 1983]

The plasma vessel (PV) shields fast changes of the magnetic flux. The typical decay time constant for poloidal currents in the PV is ~ 15 ms. The field coils therefore see a minimum decay time of the diamagnetic flux of ~ 15 ms.

Apart from that, the induced voltage $d\Phi_{dia}/dt$, is only weakly dependent on

- precise shape of winding
- distance of winding from plasma column

Why should different voltages be induced in different double layers of the field coils???

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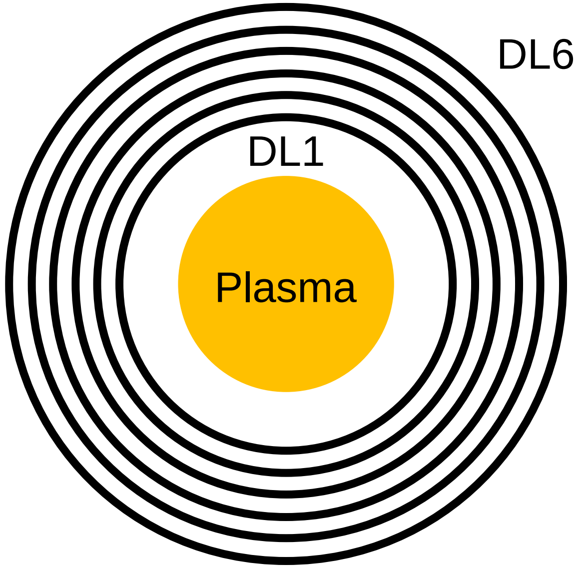
The subdivision in double layers and qualitative considerations

- The double layers (DLs) of a coil are arranged radially and therefore enclose different areas
- The change in coil current due to the induced voltage acts differently on the different DLs



- A_1, A_2, ..., A_6 are the areas enclosed by DL1–6
- The DLs are connected in series and carry the same coil current I
- Assume that each DL contributes equally to the magnetic field inside, therefore the change in flux due to DL no. j within DL no. k is

  $\mathrm{d}I/\mathrm{d}t\ C\ N_{\mathrm{DL}}\ A_j$ if $j \leq k$

  $\mathrm{d}I/\mathrm{d}t\ C\ N_{\mathrm{DL}}\ A_k$ if $j > k$

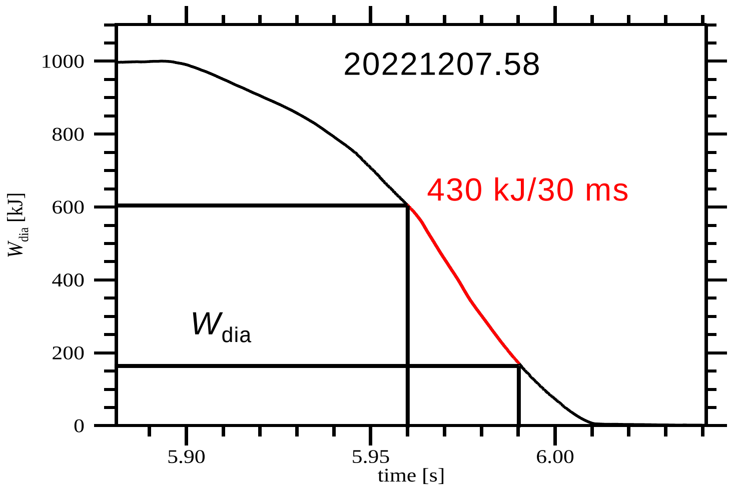
Estimate of voltages across DLs (1)

$$
\begin{aligned}
\mathrm{DL1}: \quad 0 &= \frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{\mathrm{DL}} + \frac{\mathrm{d}I}{\mathrm{d}t} C N_{\mathrm{DL}}\, 6A_1 + U_1 \\
\mathrm{DL2}: \quad 0 &= \frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{\mathrm{DL}} + \frac{\mathrm{d}I}{\mathrm{d}t} C N_{\mathrm{DL}}\, (A_1 + 5A_2) + U_2 \\
\mathrm{DL3}: \quad 0 &= \frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{\mathrm{DL}} + \frac{\mathrm{d}I}{\mathrm{d}t} C N_{\mathrm{DL}}\, (A_1 + A_2 + 4A_3) + U_3 \\
&\vdots \\
\mathrm{DL6}: \quad 0 &= \frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{\mathrm{DL}} + \frac{\mathrm{d}I}{\mathrm{d}t} C N_{\mathrm{DL}}\, (A_1 + A_2 + A_3 + A_4 + A_5 + A_6) + U_6
\end{aligned}
$$

$\sum_{j=1}^{6} U_j = 0$ (no external resistance, symmetry of all coils in a circuit)

$$\Longrightarrow \quad \frac{\mathrm{d}I}{\mathrm{d}t} = -6\,\frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} \cdot \frac{1}{C} \cdot \frac{1}{11A_1 + 9A_2 + 7A_3 + 5A_4 + 3A_5 + A_6}$$

Estimate of voltages across DLs (2)



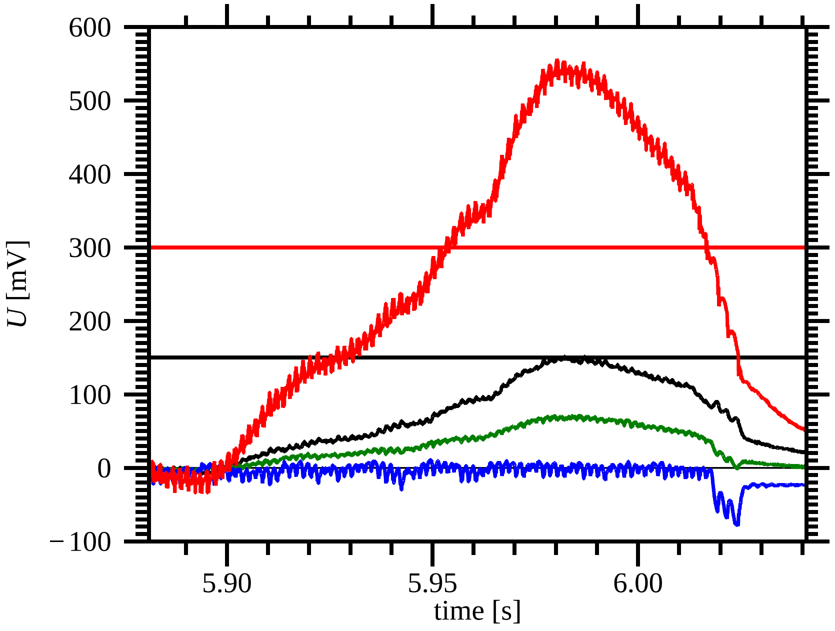
→ $d\Phi_{PG}/dt \approx 150$ mV

Assume R_{coil} = 1.2 m and radially 36 mm between the centres of the DLs

↓

U_1	–253 mV
U_2	–119 mV
U_3	–8 mV
U_4	+78 mV
U_5	+136 mV
U_6	+167 mV

↓



↔

DL2–DL1	134 mV
DL4–DL3	86 mV
DL6–DL5	30 mV
(DL3+DL4+DL5+DL6)–(DL1+DL2)	745 mV

Estimate of voltages across DLs (3) – summary

- In contrast to a diamagnetic loop, the superconducting coils have low resistivity (almost 0)
- Due to the change in coil current in response to the change of diamagnetic flux, the DLs in their radial pile do no longer see the same loop voltage
- A simple geometrical consideration, together with an analysis of the coil circuit, can explain the measured voltages in the QD system fairly well

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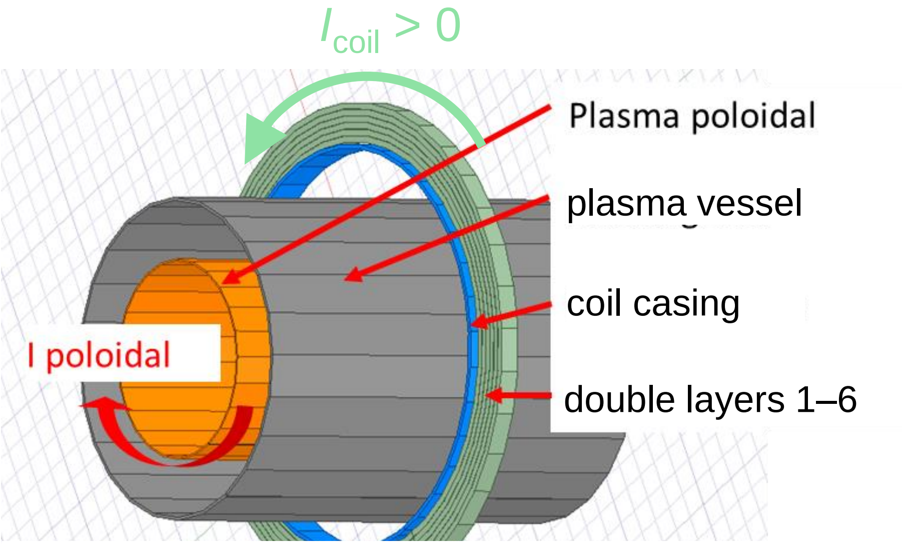
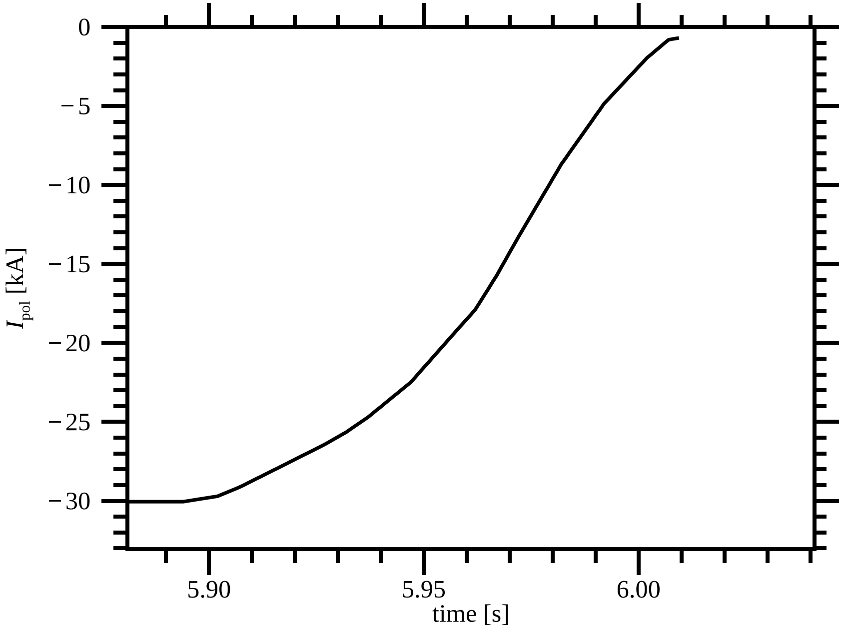
Simulating plasma, plasma vessel, coil casing and coil windings with ANSYS® Electromagnetics Suite (Maxwell3D) (1)

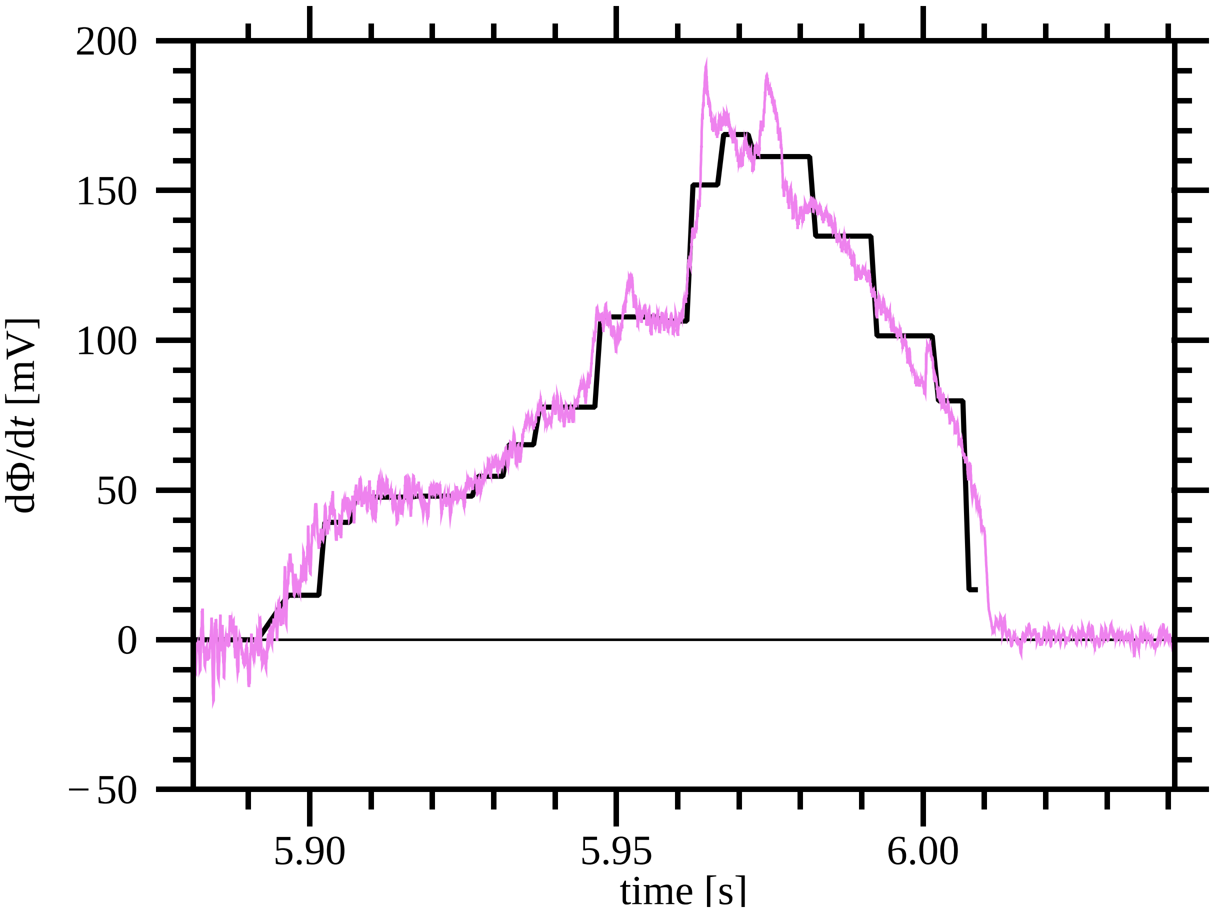
- Geometrically simple approximation:
  - Cylinder with azimuthal current representing the plasma with diamagnetic effect
  - Cylindrical approximation of plasma vessel
  - Circular coil with 6 layers, cross section of each layer corresponds to DL of non-planar coil
  - Coil casing represented by one further layer with suitable ohmic resistance
- Plasma current $I_{poloidal}$ is prescribed to change from –30 kA to 0 with time trace derived from measured diamagnetic energy of 20220712.58





Simulating with ANSYS Maxwell3D (2)

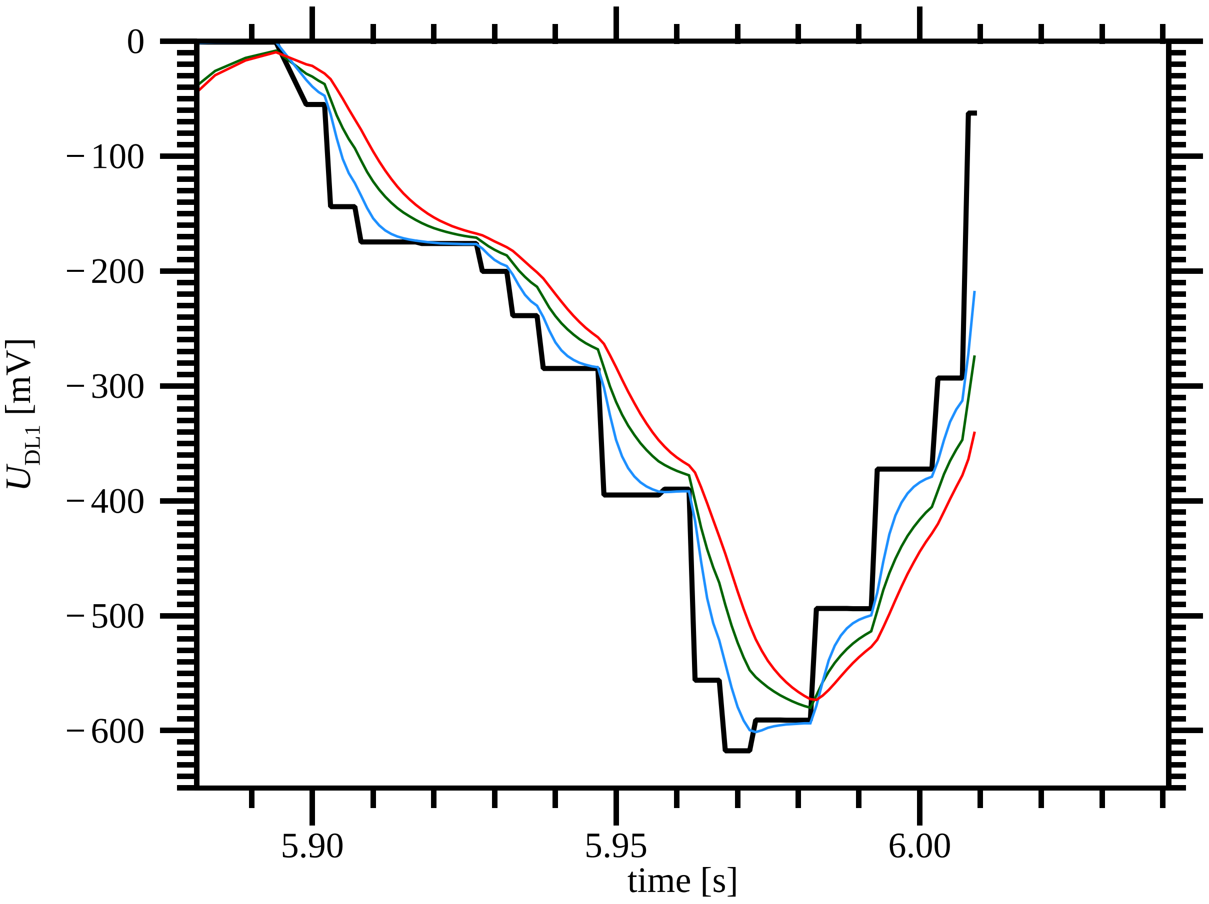
Resulting change in magnetic flux (single loop voltage)



ANSYS simulation

calculated from (compensated) W_{dia} signal

Calculated voltage in DL1



without plasma vessel and coil casing

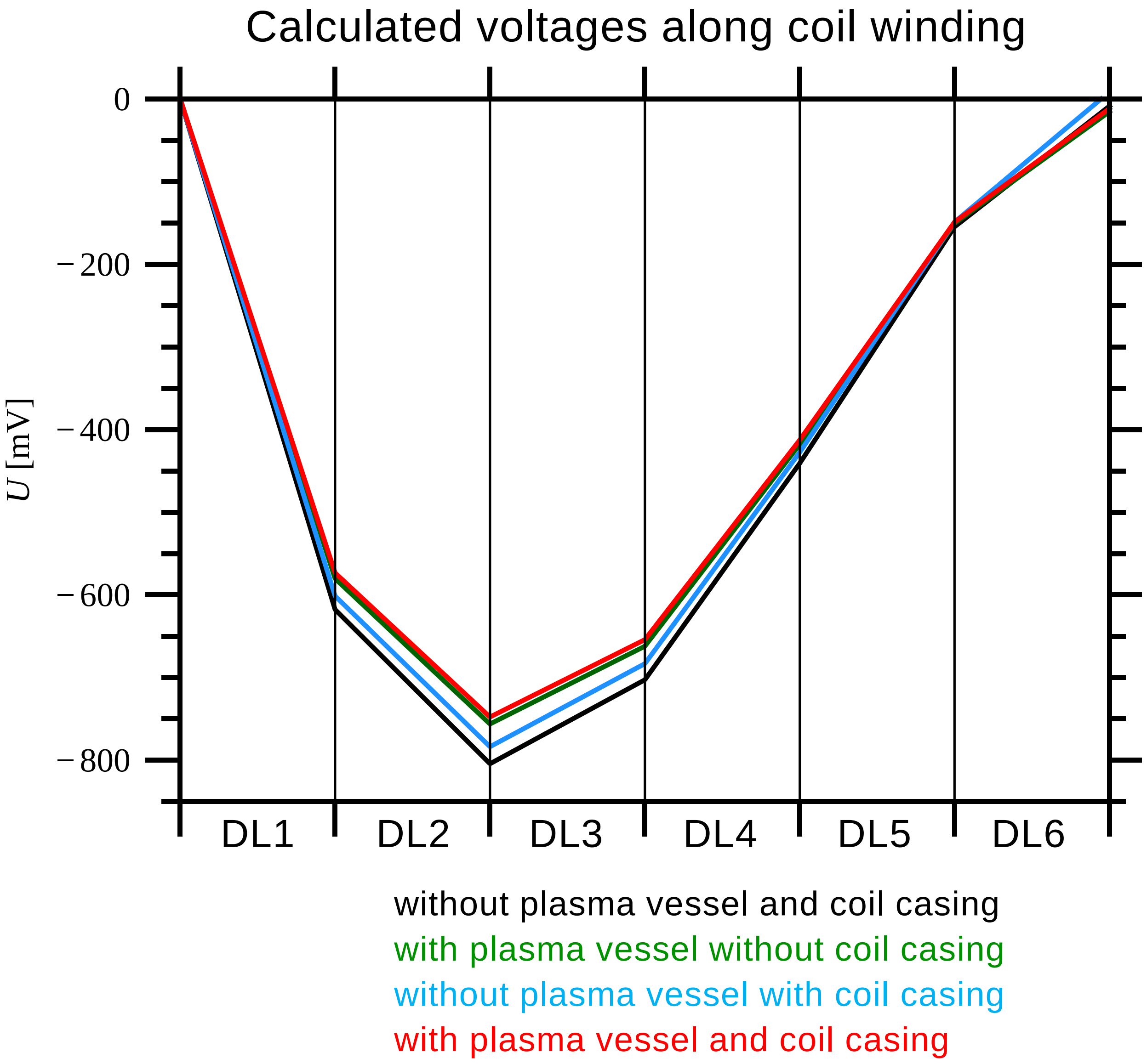
with plasma vessel without coil casing

without plasma vessel with coil casing

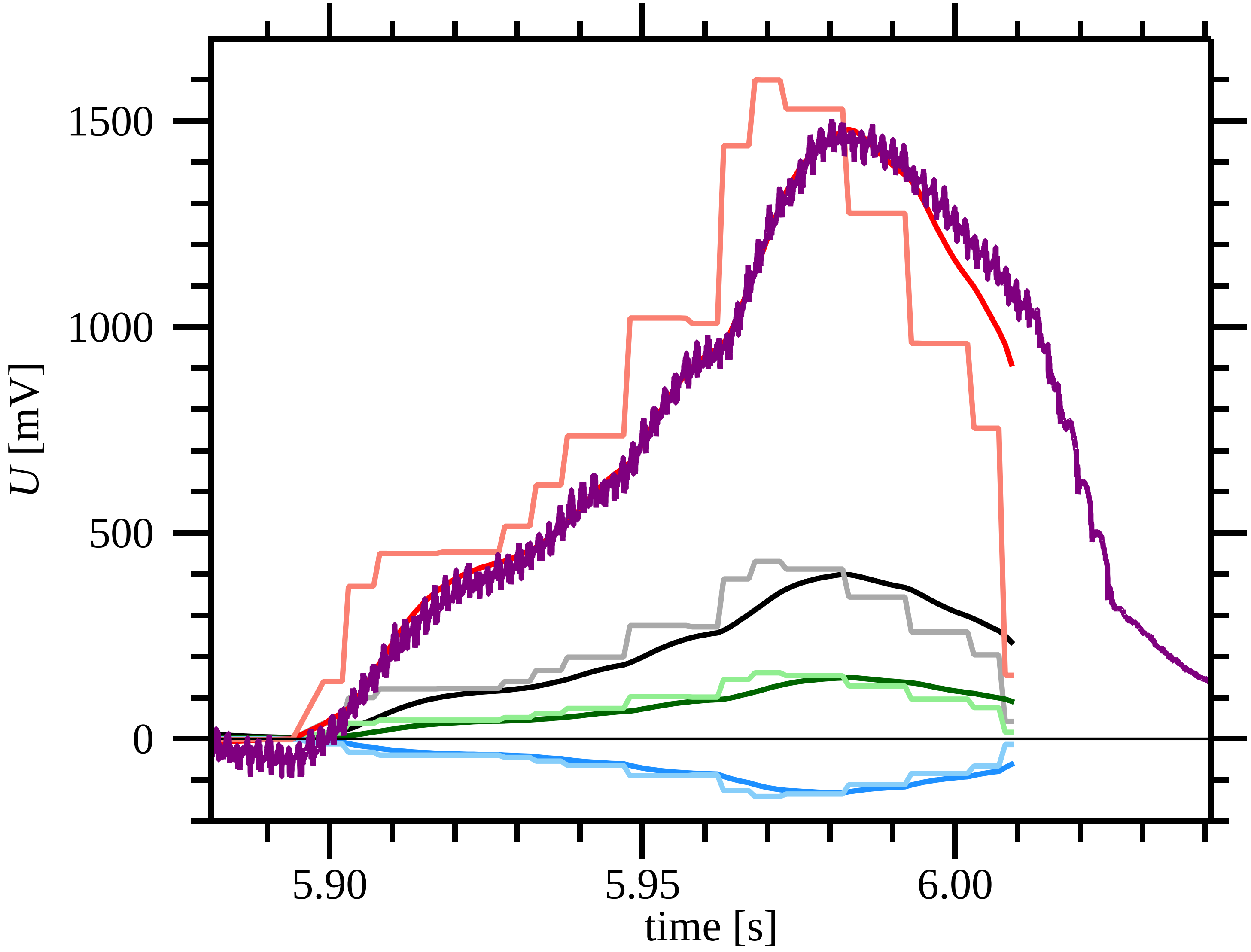
with plasma vessel and coil casing

Simulating with ANSYS Maxwell3D (3): Calculated voltages across DLs

peak values	without PV and coil casing	with PV and coil casing
U_1	–618 mV	–573 mV
U_2	–187 mV	–174 mV
U_3	+102 mV	+94 mV
U_4	+262 mV	+242 mV
U_5	+286 mV	+264 mV
U_6	+146 mV	+137 mV



Simulating with ANSYS Maxwell3D (4): Voltages measured by the QD system



Voltage differences between

- DL1 and DL2
- DL3 and DL4
- DL5 and DL6
- DL1+2 and DL3+4+5+6 ("backup" system)
- **2.7 x** measured voltage on "backup" system

Solid colours are with plasma vessel and coil casing

Light colours are without plasma vessel and coil casing

Simulating with ANSYS Maxwell3D (5) – summary

- Plasma vessel and (to a lesser degree) coil casing have a damping and delaying effect on the voltage induced in the superconducting winding (decay time of poloidal currents in the plasma vessel: ~ 15 ms!)

- For our example 20221207.58 with decay time scale ~ 30 ms, this effect is moderate but clearly visible

- The waveform observed in the QD system can very well be simulated

- The amplitude of the simulated voltages in the QD system is too large by a factor of almost 3 – the agreement is not as good as with the “qualitative consideration” before!

- This may be due to the neglect of the toroidal geometry with the other coils (which was implicit in the “qualitative consideration”)

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    c. Simulating voltages in the QD system
    d. Quantitative reproduction of measurements
4. Are there alternative setups of the QD system?
5. Summary

Electrotechnical description of coil circuits (1): Excitation and de-excitation of coil system

- We have 7 coil circuits 1, 2, 3, 4, 5, A, B
- Depending on the chosen magnetic configuration, the currents should be fixed multiples $I_j = f_j\, I_1$ ($j = 1, 2, 3, 4, 5, \mathrm{A}, \mathrm{B};\ f_1 = 1$)

$$0 = U_{j\,\mathrm{ext}} - \sum_k L_{jk} \frac{\mathrm{d}I_k}{\mathrm{d}t} = U_{j\,\mathrm{ext}} - \sum_k L_{jk} f_k \frac{\mathrm{d}I_1}{\mathrm{d}t}$$

The $U_{j\,\mathrm{ext}}$ are the voltages applied to the complete circuits j to achieve the desired current ramps $\mathrm{d}I_j/\mathrm{d}t$

The L_{jj} are the self inductances of the complete circuits j

The L_{jk} are the cross inductances between the complete circuits j and k

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

cross inductances of DL *m* with other circuits

$$-\frac{\mathrm{d}I_j}{\mathrm{d}t}\left(L_{jJm,\,jJm} + \sum_{n\neq m} L_{jJm,\,jJn} + \sum_{K\neq J} L_{jJm,\,jK}\right) - \sum_{k\neq j} \frac{\mathrm{d}I_k}{\mathrm{d}t} L_{jJm,k}$$

self inductance of DL *m*

cross inductances of DL *m* with other coils of same type

cross inductances of DL *m* with other DLs of same coil

Electrotechnical description of coil circuits (2): Calculating the required inductances

Challenge: we have “lost” all experts which were able to spontaneously calculate the required inductances

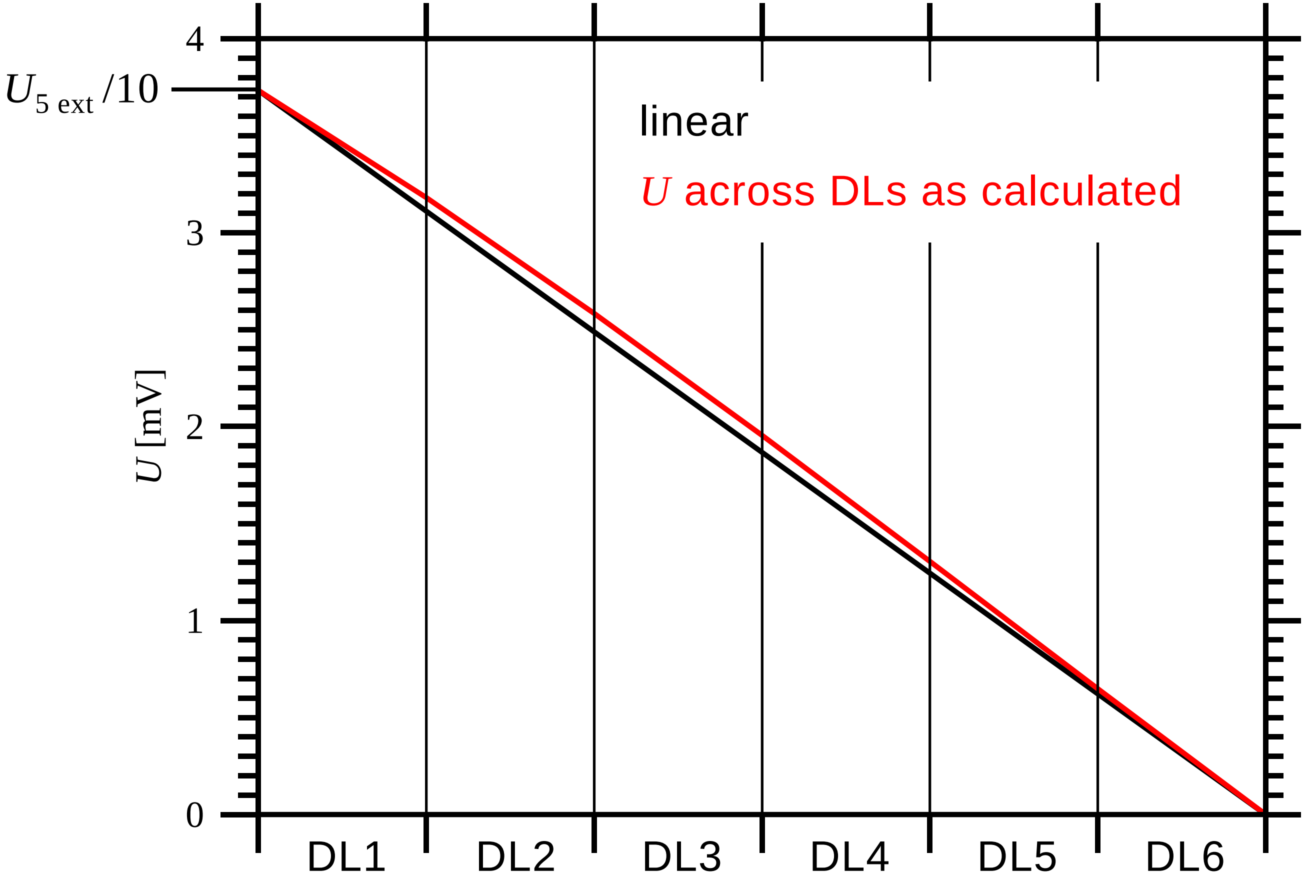
We have available from several “old” documents

- Inductance matrix of the 7 coils within one half module
- Inductance matrix of the 7 complete coil circuits
- Inductance matrix of DLs of one type of non-planar coil (indications exist that it is type 4)
- We can calculate cross inductances between current filaments with the MAG3D web service. Comparison with the available inductance matrices shows that this is sufficiently precise for cross inductances between DLs of different (even adjacent) coils but not for DLs of the same coil

By combining this information and appropriate scaling, all required inductances can be derived except for the self and cross inductances of individual DLs within the planar coils

Electrotechnical description of coil circuits (3): Excitation Example

Excitation of coil type 5 circuit with 40 A/s (12 kA reached after 5 min, required voltage ~ 40 V)



U_1	–552 mV
U_2	–597 mV
U_3	–629 mV
U_4	–649 mV
U_5	–656 mV
U_6	–649 mV

DL2–DL1	–44 mV
DL4–DL3	–20 mV
DL6–DL5	+8 mV
(DL3+DL4+DL5+DL6)–(DL1+DL2)	–1434 mV

Electrotechnical description of coil circuits (4): Fast decay of diamagnetic energy – coil currents

Comparison of coil excitation with fast decay:

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

$\mathrm{d}I_k/\mathrm{d}t$ are predetermined, necessary $U_{j\,\mathrm{ext}}$ are calculated

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

$\mathrm{d}\Phi_{\mathrm{PG}}/\mathrm{d}t$ and $N_{j\,\mathrm{tot}}$ are predetermined, necessary $\mathrm{d}I_k/\mathrm{d}t$ must be calculated

$\Longrightarrow$ Solve system of linear equations in the $\mathrm{d}I_k/\mathrm{d}t$

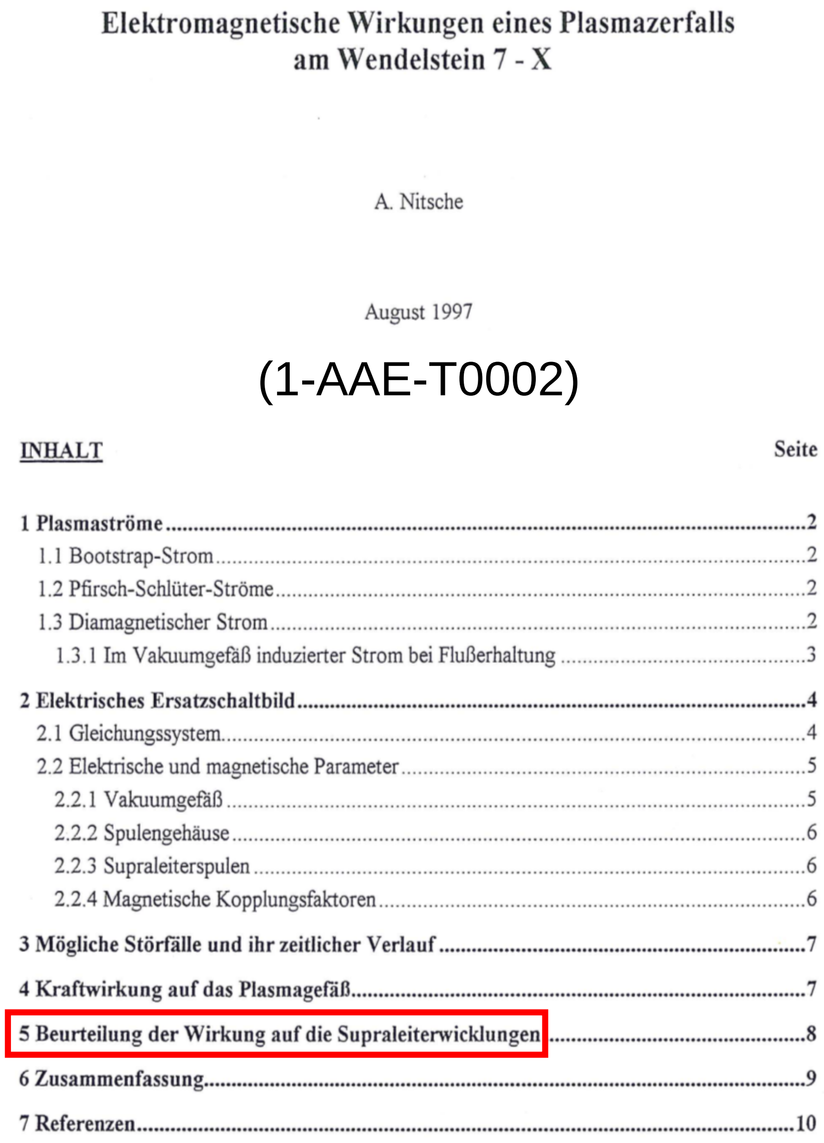
Since it is a linear system, $I_j = f_j\, I_1$ ($j = 1, 2, 3, 4, 5, \mathrm{A}, \mathrm{B}; f_1 = 1$) can again be used

Note:

- $\mathrm{d}I_j/\mathrm{d}t$ is very similar for all non-planar coils $j = 1, \ldots, 5$ (as expected)
- $\mathrm{d}I_j/\mathrm{d}t$ is larger by a factor of 3–4 than in the coil excitation example (40 A/s)

$\mathrm{d}I_1/\mathrm{d}t$	–156 A/s
$\mathrm{d}I_2/\mathrm{d}t$	–156 A/s
$\mathrm{d}I_3/\mathrm{d}t$	–163 A/s
$\mathrm{d}I_4/\mathrm{d}t$	–159 A/s
$\mathrm{d}I_5/\mathrm{d}t$	–148 A/s
$\mathrm{d}I_\mathrm{A}/\mathrm{d}t$	–73 A/s
$\mathrm{d}I_\mathrm{B}/\mathrm{d}t$	–116 A/s

Digression: What was expected in the design of W7-X?



Elektromagnetische Wirkungen eines Plasmazerfalls am Wendelstein 7 - X

A. Nitsche

August 1997

(1-AAE-T0002)

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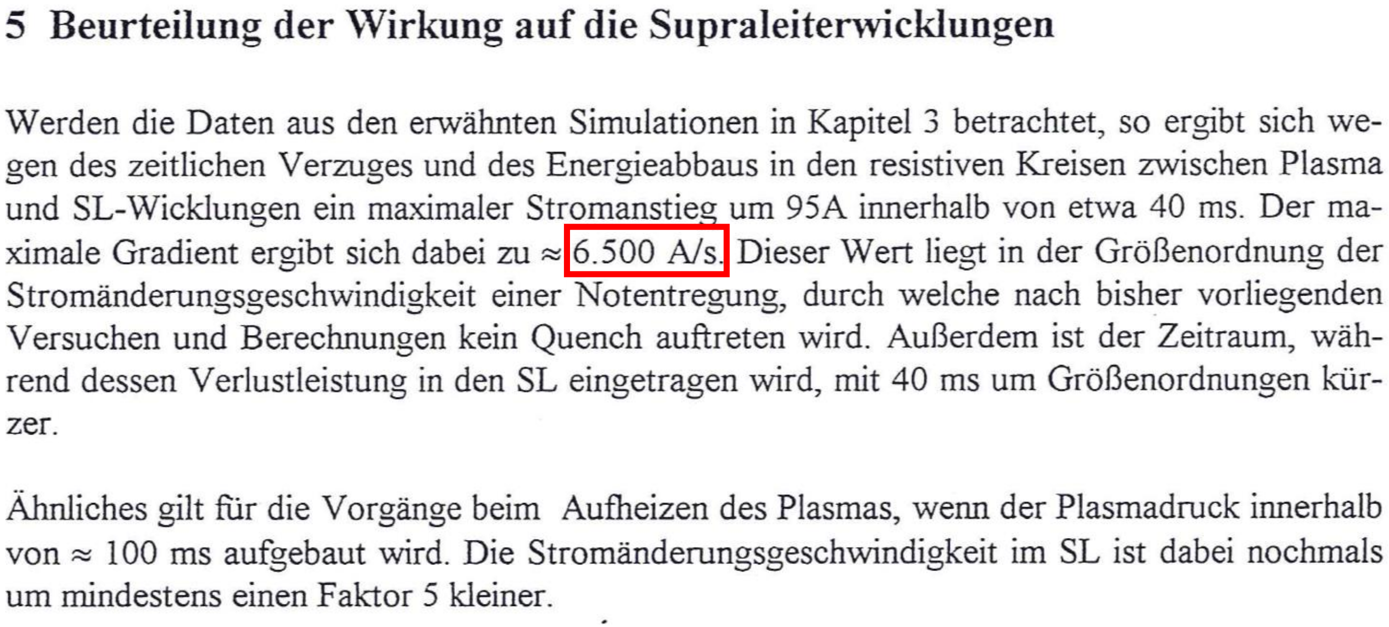


5 Beurteilung der Wirkung auf die Supraleiterwicklungen

Werden die Daten aus den erwähnten Simulationen in Kapitel 3 betrachtet, so ergibt sich wegen des zeitlichen Verzuges und des Energieabbaus in den resistiven Kreisen zwischen Plasma und SL-Wicklungen ein maximaler Stromanstieg um 95A innerhalb von etwa 40 ms. Der maximale Gradient ergibt sich dabei zu ≈ 6.500 A/s. Dieser Wert liegt in der Größenordnung der Stromänderungsgeschwindigkeit einer Notentregung, durch welche nach bisher vorliegenden Versuchen und Berechnungen kein Quench auftreten wird. Außerdem ist der Zeitraum, während dessen Verlustleistung in den SL eingetragen wird, mit 40 ms um Größenordnungen kürzer.

Ähnliches gilt für die Vorgänge beim Aufheizen des Plasmas, wenn der Plasmadruck innerhalb von ≈ 100 ms aufgebaut wird. Die Stromänderungsgeschwindigkeit im SL ist dabei nochmals um mindestens einen Faktor 5 kleiner.

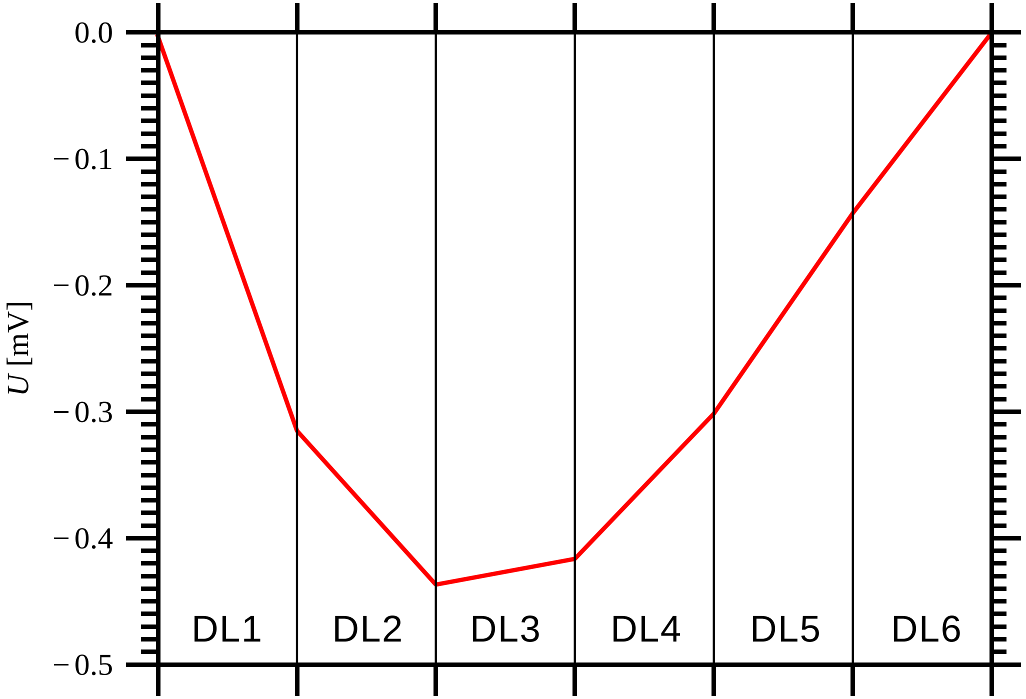
Electrotechnical description of coil circuits (5): Fast decay of diamagnetic energy – DL voltages

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

$$-\frac{\mathrm{d}\Phi_{\mathrm{PG}}}{\mathrm{d}t} N_{j\,\mathrm{DL}} - \frac{\mathrm{d}I_j}{\mathrm{d}t}\left(L_{jJm,jJm} + \sum_{n\neq m} L_{jJm,jJn} + \sum_{K\neq J} L_{jJm,jK}\right) - \sum_{k\neq j} \frac{\mathrm{d}I_k}{\mathrm{d}t} L_{jJm,k}$$

U_1	–312 mV
U_2	–122 mV
U_3	+20 mV
U_4	+115 mV
U_5	+159 mV
U_6	+143 mV

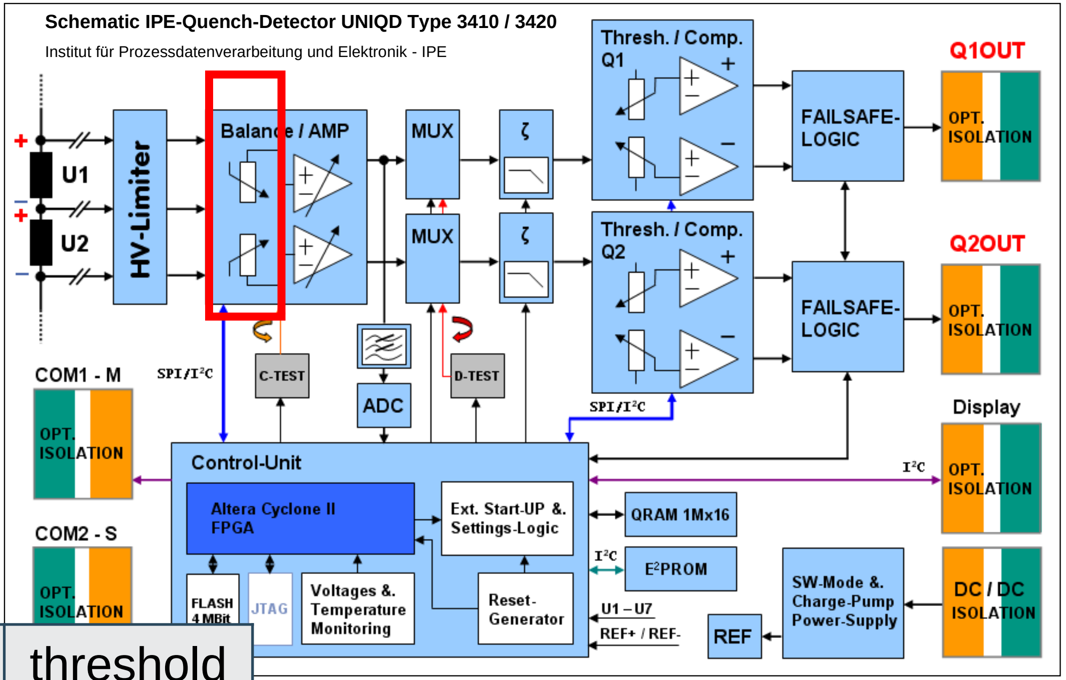
Again: example of coil type 5



DL2–DL1	+190 mV
DL4–DL3	+94 mV
DL6–DL5	–16 mV
(DL3+DL4+DL5+DL6)–(DL1+DL2)	+870 mV

Electrotechnical description of coil circuits (6): Excitation example – voltages recorded by QDUs

Remember: Quench detection units have optional tunable damping at input of differential amplifiers!



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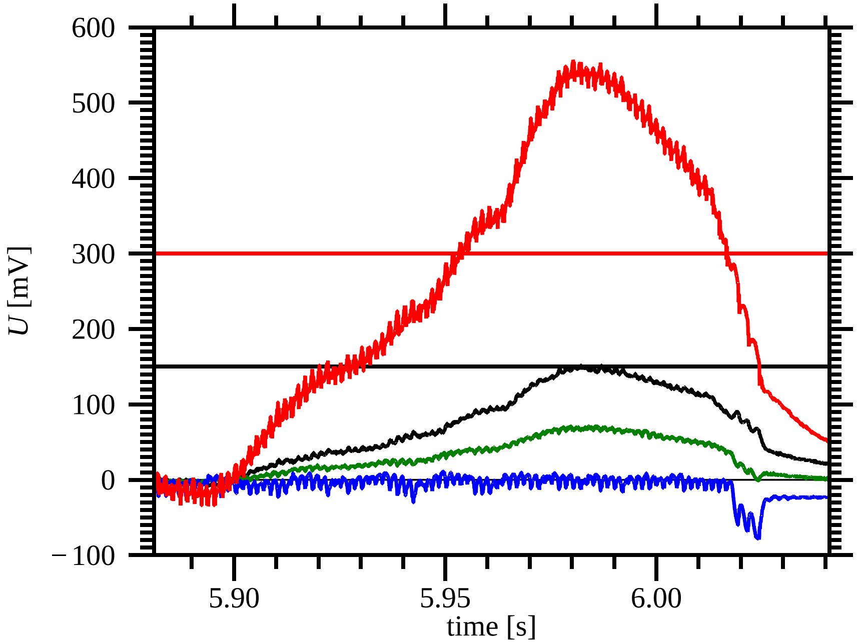
Example with settings of coil AAB16 for coil excitation:

Coil excitation example, 40 A/s	before damping	after damping	threshold
DL2–DL1	–44 mV	+39 mV	±150 mV
DL4–DL3	–20 mV	+6 mV	±150 mV
DL6–DL5	+8 mV	–38 mV	±150 mV
(DL3+DL4+DL5+DL6)–(DL1+DL2)	–1434 mV	–65 mV	±300 mV

Electrotechnical description of coil circuits (7):
Fast decay of diamagnetic energy – voltages recorded by QDUs

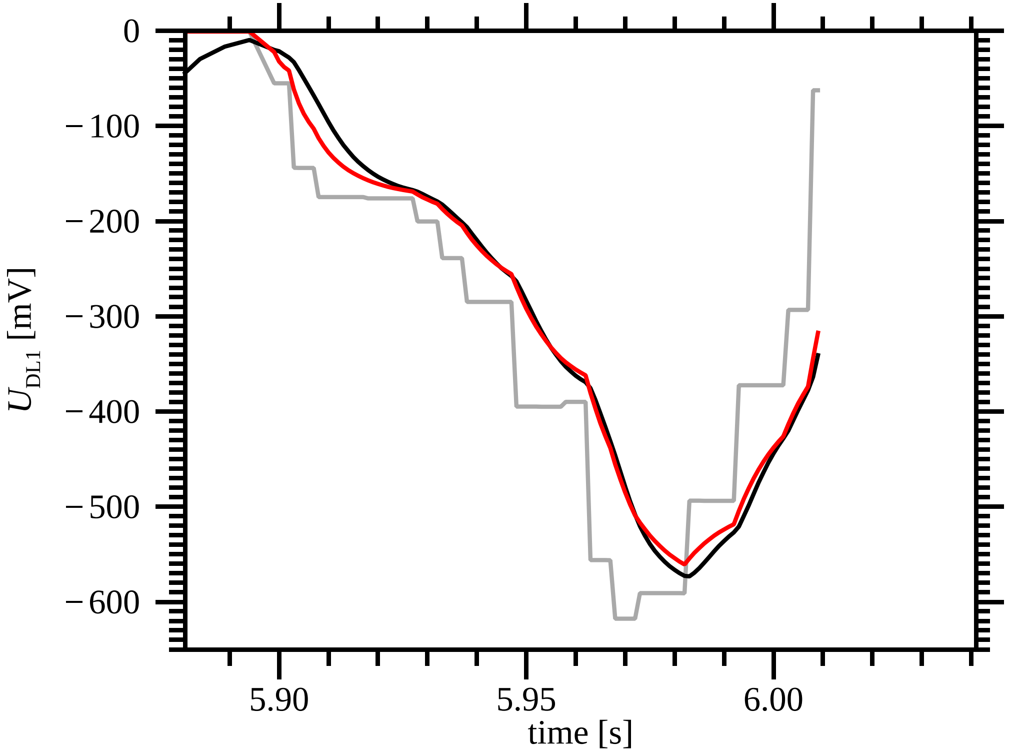
Fast decay, 20221207.58, AAB16	before damping	after damping	threshold
DL2–DL1	+190 mV	+207 mV	±150 mV
DL4–DL3	+94 mV	+90 mV	±150 mV
DL6–DL5	–16 mV	–5 mV	±150 mV
(DL3+DL4+DL5+DL6)–(DL1+DL2)	+870 mV	+639 mV	±300 mV



Plan: Use again the compensated W_{dia} signal to calculate the loop voltage, then use this model to derive the QD signals and compare them with the measured signals.

Electrotechnical description of coil circuits (8): Simulating effect of plasma vessel and coil casing

Effect of plasma vessel and coil casing on waveform can be approximated by filter

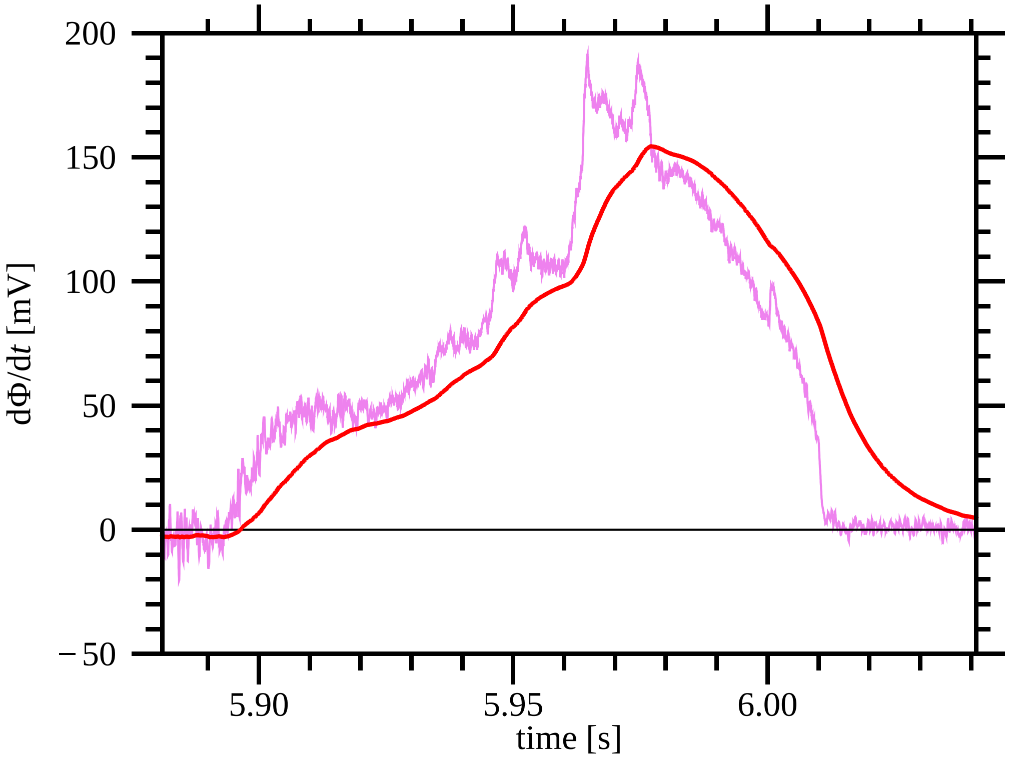


Signal 1: ANSYS without plasma vessel and coil casing

Signal 2: ANSYS with plasma vessel and coil casing

Signal 1 with filter (running average with exponential weighting of past samples with time constant τ = 10 ms)

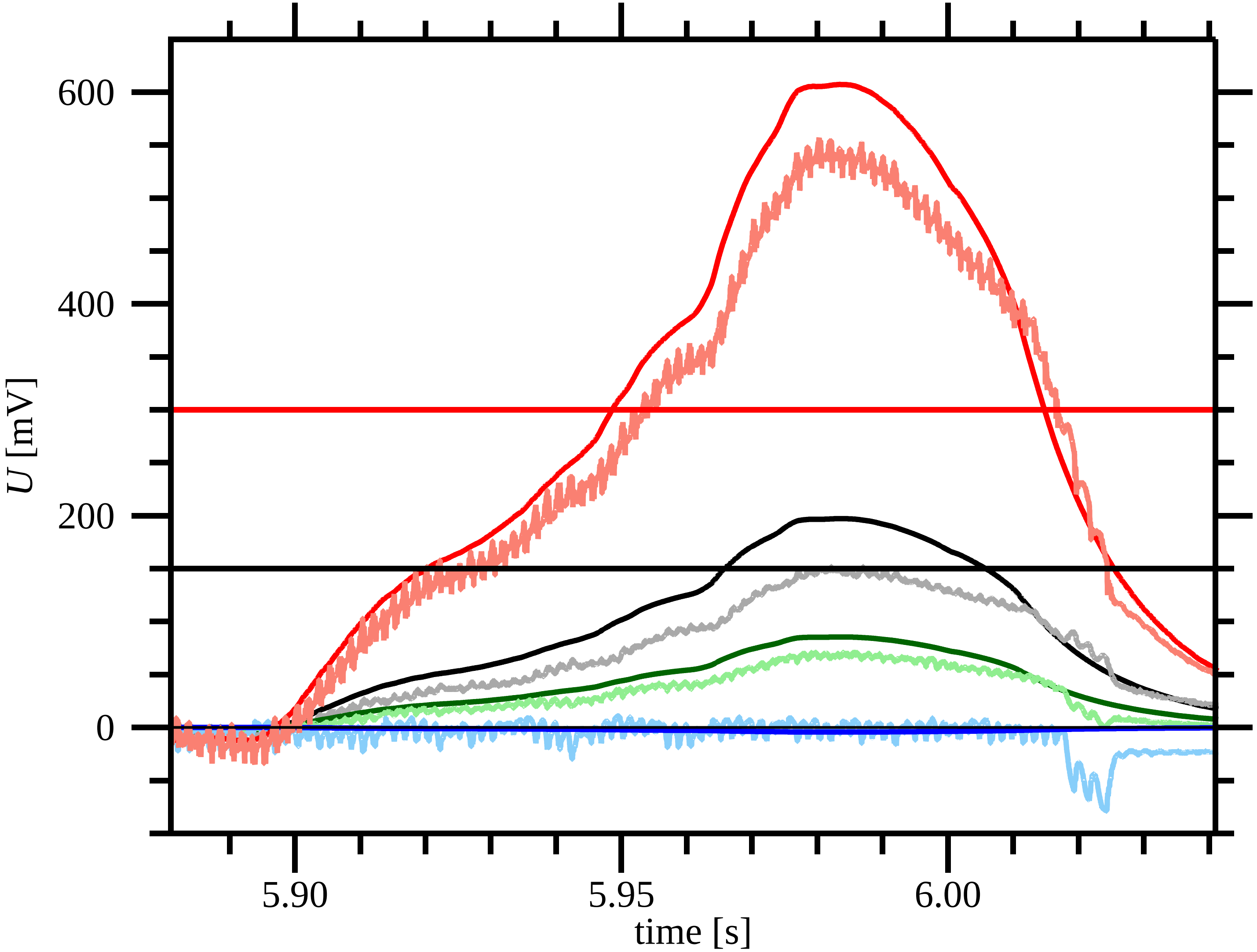
Application of same filter to dΦ/d*t*



dΦ/d*t* from compensated W_{dia} signal

after application of filter

Electrotechnical description of coil circuits (8): Simulation versus signals recorded by QDUs



Voltage differences between

- DL1 and DL2
- DL3 and DL4
- DL5 and DL6
- DL1+2 and DL3+4+5+6 (“backup” system)

Solid colours are simulated with filtered $d\Phi_{dia}/dt$ signal (τ = 15 ms) and calculated DL voltages

Light colours are measured on coil AAB16

Intermediate summary

We can calculate the voltages across the different DLs of the W7-X field coils during a fast plasma decay.

The results are confirmed by quantitatively correct predictions of the voltages measured by the QD system.

With the present setup and settings, we expect the QD system to initiate a fast discharge of the magnet system again if a comparably fast decay rate of plasma energy occurs.

There is no reason why future higher energy discharges should decay slower in the case of similar events.

Without special event, the plasma energy is expected to decay with $\mathrm{d}W/\mathrm{d}t \sim W/\tau_E \sim P_{\mathrm{heat}}$. Above 10–15 MW, even a “normal” plasma shutdown would induce a poloidal loop voltage of 100–150 mV and thus trigger the QD system.

Why does a fast plasma decay trigger the W7-X quench detection system?

Contents:

1. Motivation
2. The W7-X field coils and their QD system
3. Electromagnetic interaction between plasma and coil system
   a. The field coils as diamagnetic loops
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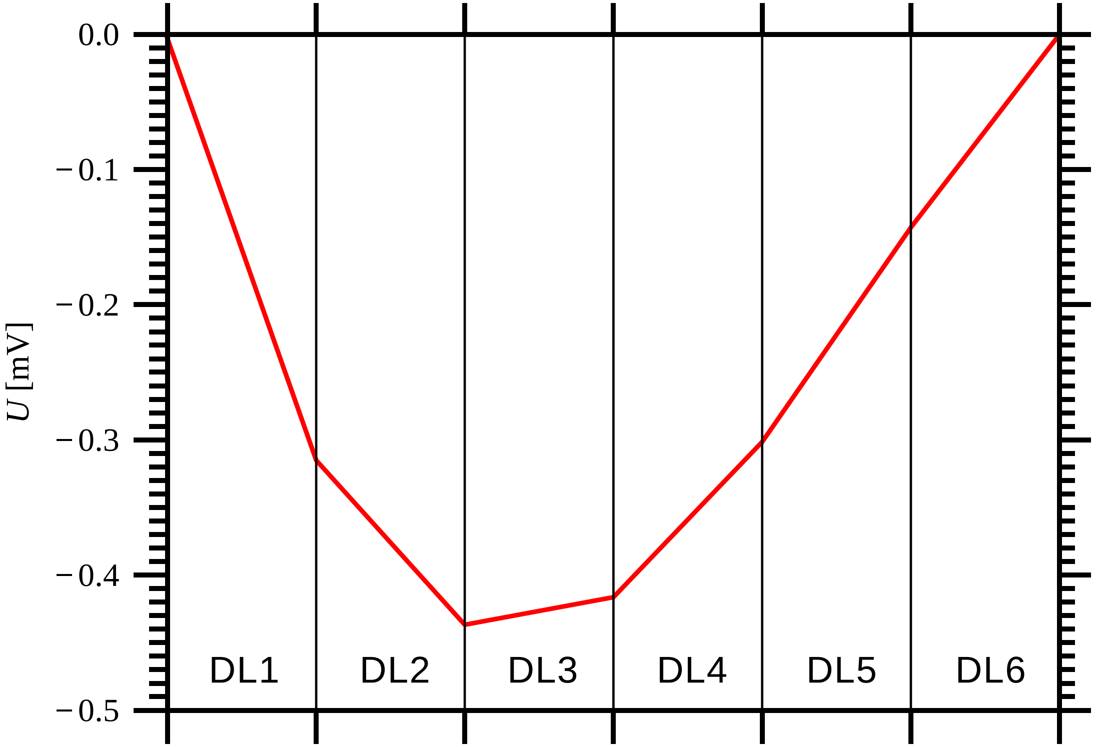
Are there alternative setups of the QD system? Analysis of challenges

Backup system: Due to reversal of voltages across DLs in fast plasma energy decay, comparing inner with outer DLs will always give large voltage differences. Comparing voltage across DLs 1+2 versus DLs 3+4+5+6 is the worst choice!

“Original” system: DL1 versus DL2 is most critical. This will still trigger the QD system if a sufficiently fast change of plasma energy occurs.

Remember – calculated voltages along coil type 5 for 20221207.58:



Are there alternative setups of the QD system? (2)

Hypothetical solutions

- Arrange DLs in superconducting coils toroidally rather than radially ...
- Compare identical DLs in different coils of same type – not possible with present design of QDUs

Changing the logic of the QD system

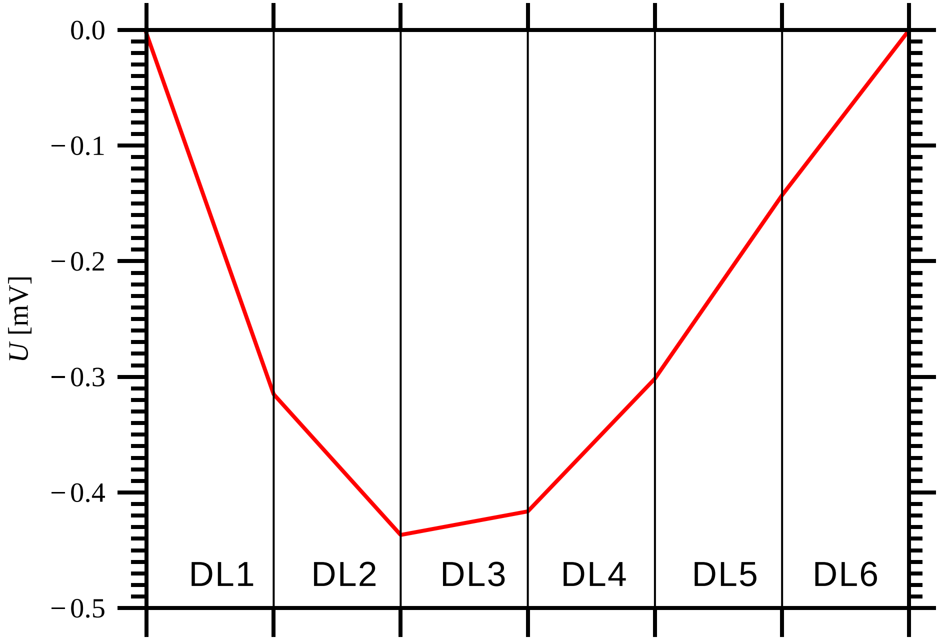
- Do not trigger a fast discharge of the coil system, if diamagnetic loop has detected fast change of plasma energy "at the same time"
- Do not trigger a fast discharge of the coil system, if another coil is about to trigger at the same time

In both cases, you may miss triggering on a true quench, if it occurs in the time window tagged invalid by the "auxiliary" signal – therefore suggestions of this type were dismissed

Are there alternative setups of the QD system? (3)

Short term solution as planned now: Change thresholds – it is presently foreseen to raise the threshold for the “original” system from ±150 mV to ±196 mV and for the backup system from ±300 mV to ±333 mV

Longer term solution for the Backup system: It is foreseen to replace the present backup system by a duplication of the “original” system



Alternatives for backup system with slight improvement:

	coil excitation example, 40 A/s		fast plasma decay example	
	before damping	after damping	before damping	after damping
(DL3+DL4+DL5+DL6)–(DL1+DL2)	–1434 mV	–65 mV	+870 mV	+639 mV
(DL5+DL6)–(DL1+DL2+DL3+DL4)	+1222 mV	–92 mV	+600 mV	+451 mV
(DL4+DL5+DL6)–(DL1+DL2+DL3)	–176 mV	–132 mV	+830 mV	+622 mV

Damping of (1, 0.5) and (0.75, 0.75), respectively, was used for the two alternatives – not yet optimised.

Are there alternative setups of the QD system? (4)

Alternative for original system:

Introduce higher damping into “original” system for DL12?

DL2–DL1, AAB16	coil excitation example, 40 A/s	fast plasma decay example
without damping	–44 mV	+190 mV
present damping (1, 0.86)	+39 mV	+207 mV
damping (0.5, 1)	–321 mV	+34 mV
damping (0.5, 0.8)	–201 mV	+59 mV

If the coil excitation and de-excitation rates are reduced, the threshold could even be lowered to make up for the damping factor!

Are there alternative setups of the QD system? (5)

Task:

- Use existing hardware as far as possible
- Use characteristic pattern of voltages induced by fast plasma decay
- Do not blind the system even temporarily against true quenches

(Don’t forget: By replacing the present “backup” system by a duplication of the “original” system we may lose the ability to detect simultaneous quenches in two adjacent DLs!)

Option to think about:

Use a module which calculates the ratio between two QD signals and suppresses triggering a fast discharge if the ratio of voltages is within a predefined narrow range

- must be deployed per coil
- will not suppress in case of true quench because ratio of signals will be outside range
- must be failsafe: only output suppression signal if it works correctly

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Summary

- A change in the diamagnetic energy induces different voltages in the different DLs of a W7-X field coil
- We can quantitatively reproduce the resulting voltages measured by the QD system
- With the newly implemented settings, still
  - above $|dW_{dia}/dt| \sim 8$ kJ/ms by more than $\Delta W_{dia} \sim 800$ kJ, the QD “backup” system will trigger a fast discharge of the magnet system
  - above $|dW_{dia}/dt| \sim 14$ kJ/ms by more than $\Delta W_{dia} \sim 700$ kJ, the QD “original” system will trigger a fast discharge of the magnet system
  - these conditions can be satisfied even without special plasma event, if a full heating power above 10–15 MW is switched on or off at once
- It may be possible to modify the QD system, such that these conditions are detected without blinding it for true quenches