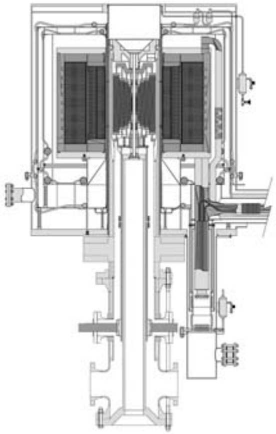


Analysis of Observations during Operation of the NHMFL 45-T Hybrid Magnet System

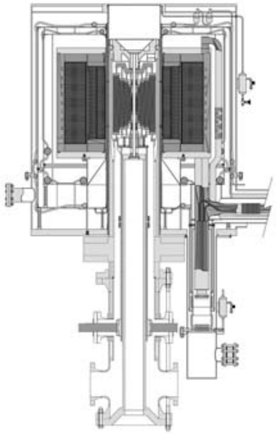
CHATS Workshop

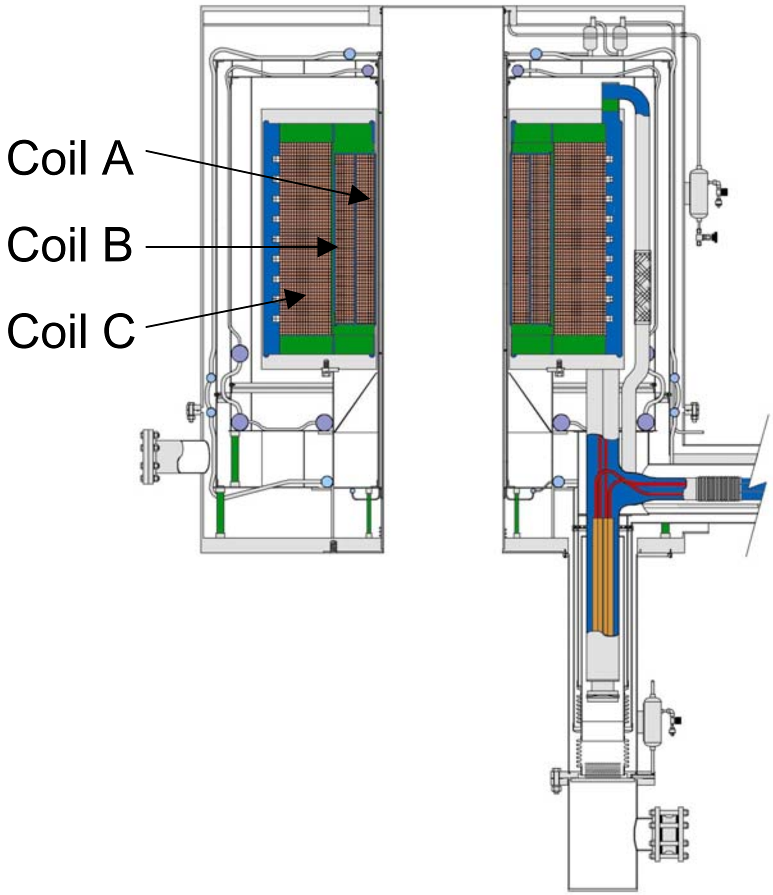
Kernforschungszentrum Karlsruhe

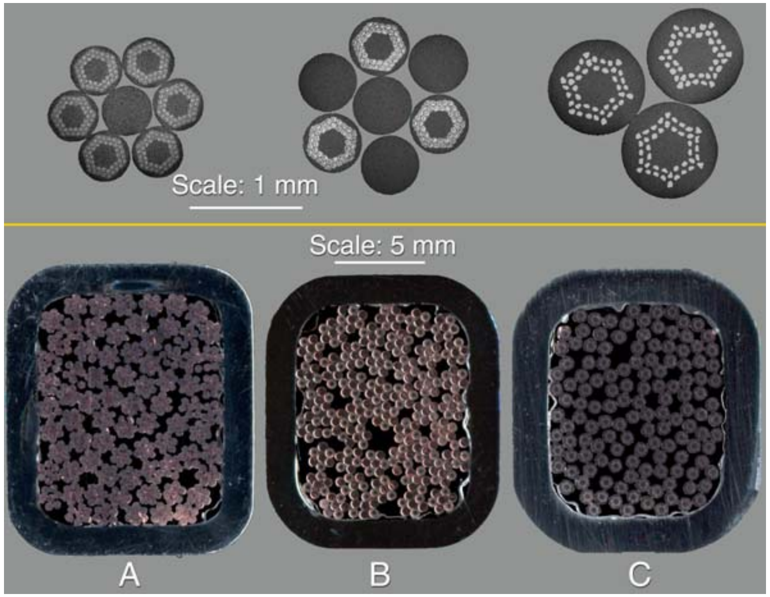
16-18 September 2002

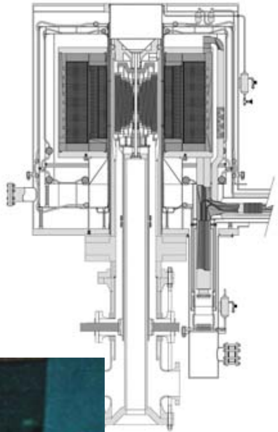
J.R. Miller, Y.M. Eyssa, S.D. Sayre, and C.A. Luongo

Superconducting outsert coils and conductors

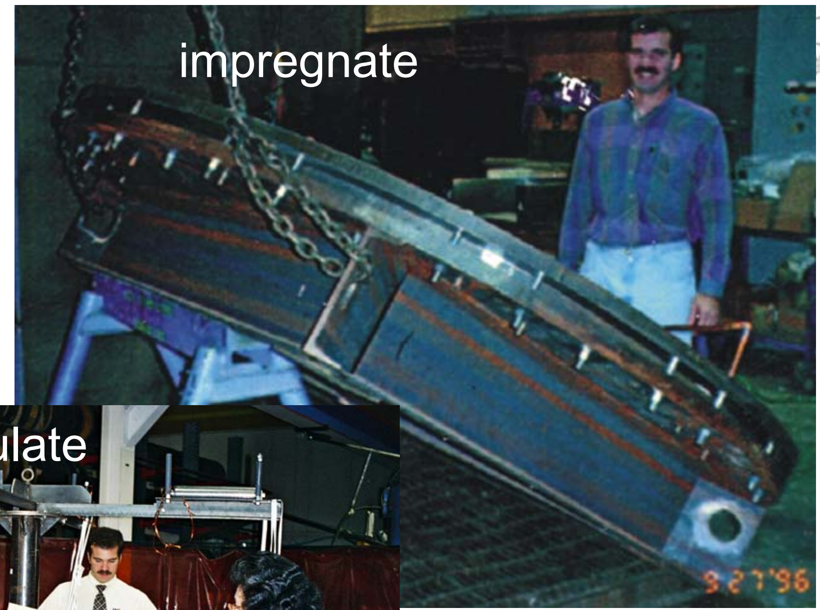


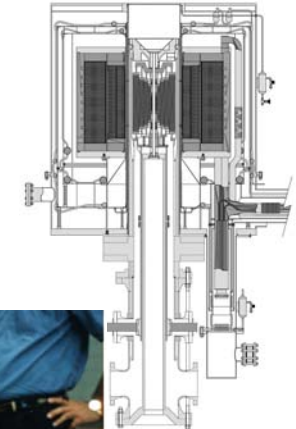




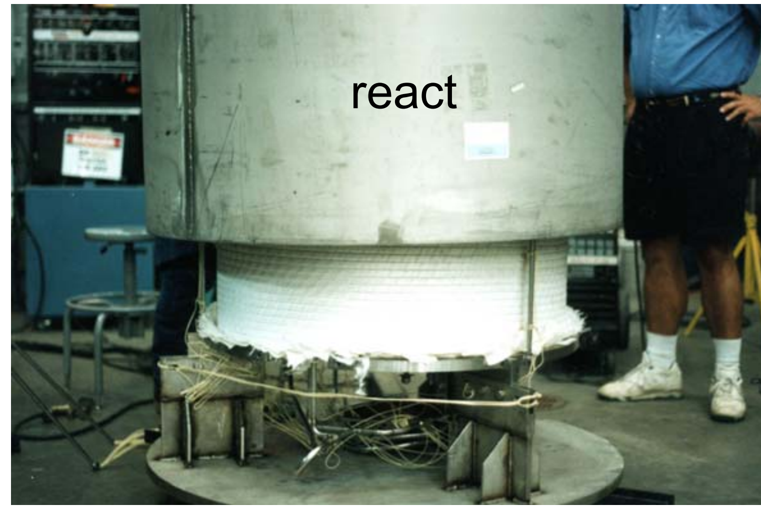


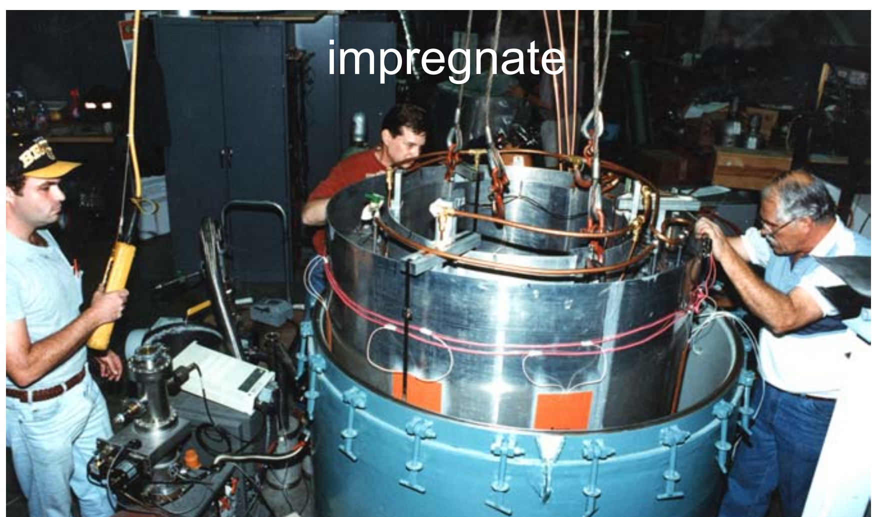
NbTi-coil manufacture



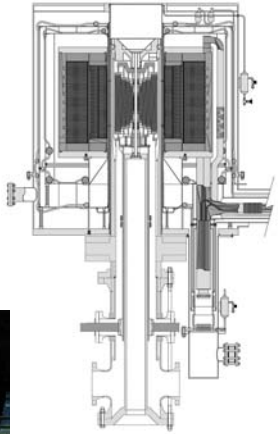


Nb_3Sn-coil manufacture

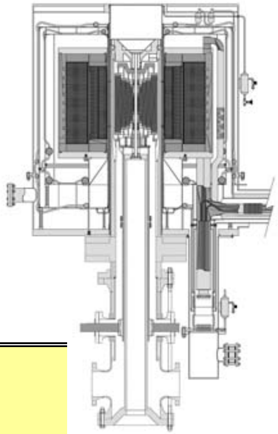




Outsert assembly



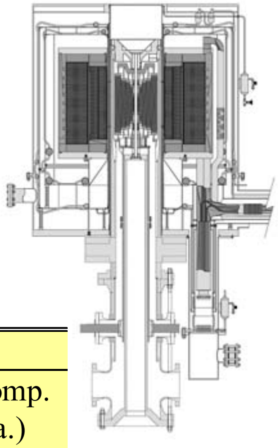
General features of the superconducting outsert



Configuration	3 series-connected subcoils		
Nominal operating current (kA)	10		
Individual coil characteristics:	**Coil A**	**Coil B**	**Coil C**
Type of winding	Layer, wind-and-react	Layer, wind-and-react	Double pancake
Conductor type	Nb_3Sn CICC	Nb_3Sn CICC	NbTi CICC
Number of turns	303 (6 layers x approx. 51 turns/layer)	376 (7 layers x approx. 54 turns/layer)	1025 (29 pancakes x 35 turns/pancake, plus crossovers and joints)
Length of conductor (m)	759	1186	4574
Inner diameter of windings (mm)	710	908	1150
Outer diameter of windings (mm)	888	1115	1680
Height of windings (mm)	869	868	992
Winding pack current density (A/mm^2)	39.6	44.3	38.6
Maximum field at the windings (T)	14.1 [a] 15.7 [b]	10.9 [a] 11.7 [b]	8.4 [a] 8.5 [b]
Field contribution at center (T) (individual coils)	3.3	3.6	7.4
Field contribution at center (T) (combined coils)	14.3		
Combined inductance (H)	1.96		
Combined stored energy (MJ)	98		

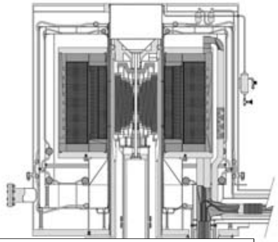
[a] Insert and outsert on, both at full current
[b] Outsert only at full current

Outsert conductor parameters

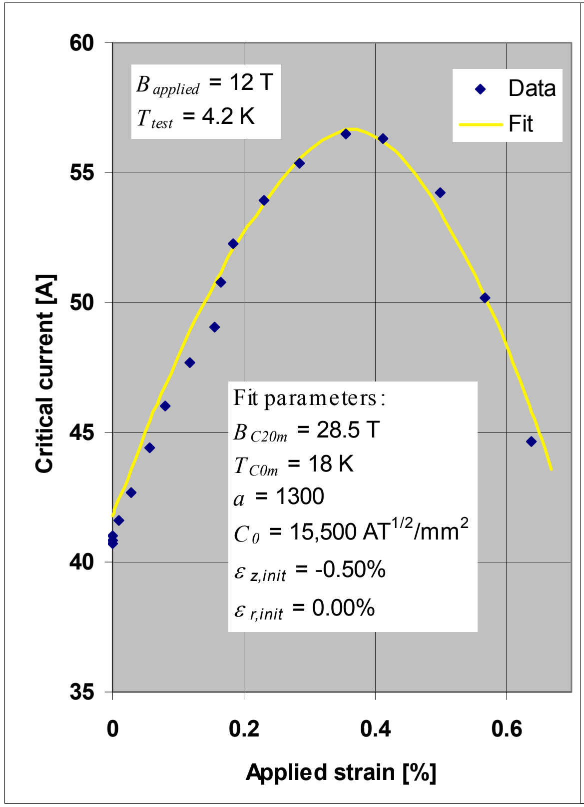


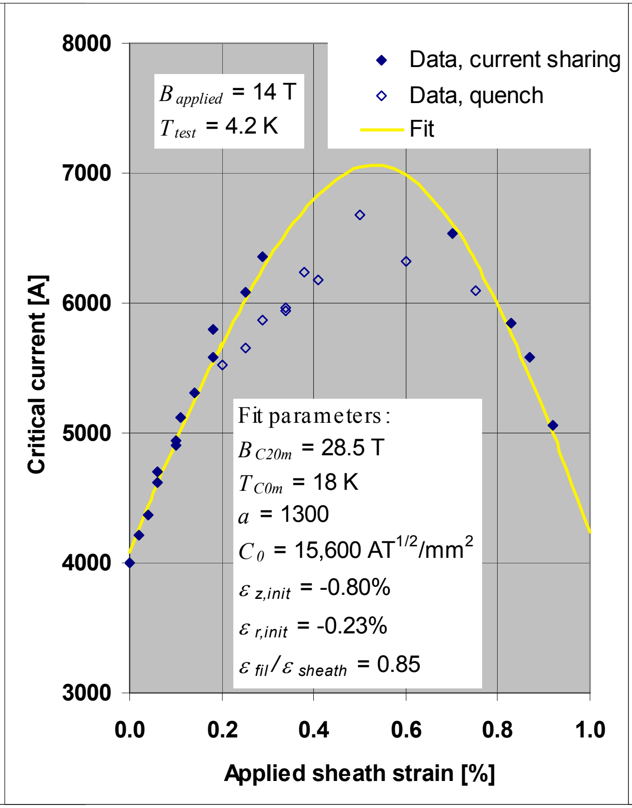
Parameter	Coil A	Coil B	Coil C
Cable patterns	5 x 5 x 3 x (6 Nb_3Sn comp. + 1 Cu wires, 0.433-mm dia.)	5 x 3 x 3 x (3 Nb_3Sn comp. + 4 Cu wires, 0.513-mm dia.)	5 x 3 x 3 x (3 NbTi comp. wires, 0.810-mm dia.)
Cable cross-section (projection ⊥ long axis of conductor)	79.44 mm^2 ($54.25\ mm^2$ Cu, $25.19\ mm^2$ non-Cu)	66.22 mm^2 ($55.66\ mm^2$ Cu, $10.56\ mm^2$ non-Cu)	70.49 mm^2 ($59.14\ mm^2$ Cu, $11.35\ mm^2$ non-Cu)
Foil wrap cross-section	2.51 mm^2	2.33 mm^2	1.89 mm^2
Void cross-section	50.30 mm^2	42.55 mm^2	36.50 mm^2
Jacket cross-section	80.20 mm^2 (16.22 mm x 13.71 mm, 1.64-mm wall, 3.40-mm outer corner)	72.86 mm^2 (15.25 mm x 12.97 mm, 1.64-mm wall, 4.01-mm outer corner)	89.30 mm^2 (15.85 mm x 13.74 mm, 2.00-mm wall, 4.77-mm outer corner)
Projected critical current (at field, temperature, and strain of normal operation)	15.8 kA[a] (at 15.7 T, 1.8 K, and 0.25% jacket strain)	14.7 kA[a] (at 11.7 T, 1.8 K, and 0.25% jacket strain)	21.7 kA[b] (at 8.5 T and 1.8 K)
Projected current-sharing temperature (at current, field and strain of normal operation)	4.34 K (at 10 kA, 15.7 T, and 0.25% jacket strain)	4.86 K (at 10 kA, 11.7 T, and 0.25% jacket strain)	4.01 K (at 10 kA and 8.5 T)

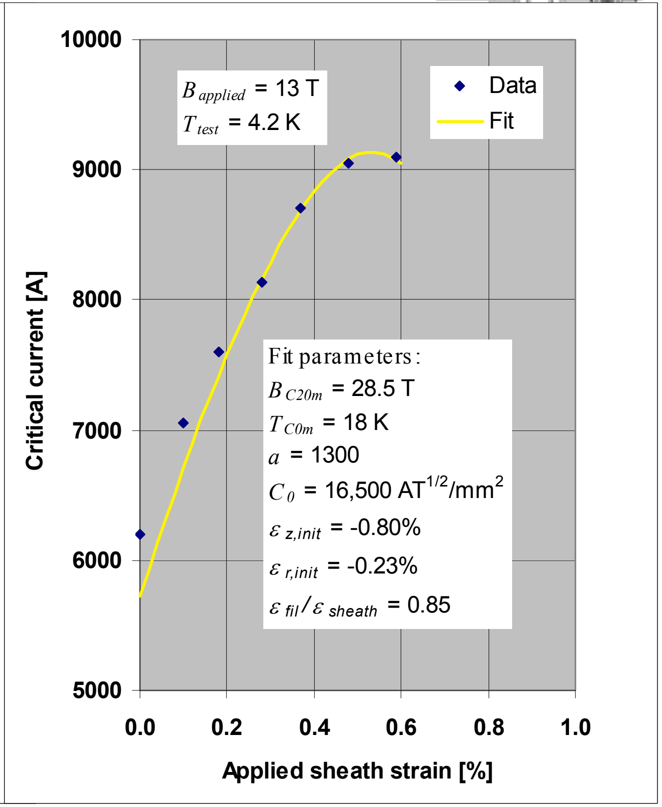
[a] Extrapolated from measurements reported in Ref. [7].
[b] Extrapolated from measurements reported in Ref. [6].



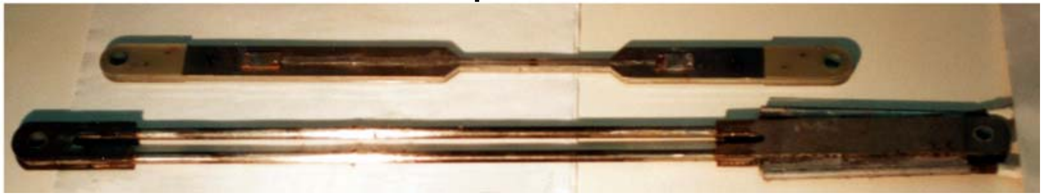
Critical current measurements





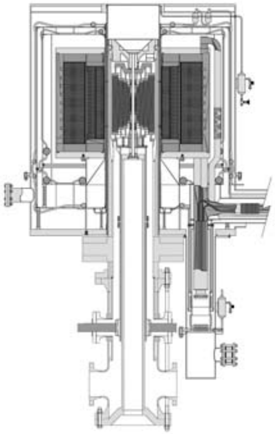


Single wire on substrate Developmental CICC Witness CICC



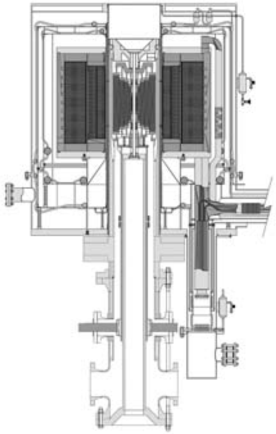
J.R. Miller *et al.*, "Characterization of High-Current Nb3Sn Cable-in-Conduit Conductors vs Applied Sheath Strain," in *Advances in Cryogenic Engineering*, vol. 44B, U. Balachandran *et al.*, Eds., New York:Plenum Press, 1998, pp. 967-974.

History of early high-current operations



Date	Max. Current	Ramp time	Hold time	Result
9 Dec. 1999	10 kA	80 min.	40 min.	Dump to test protection circuit.
10 Dec. 1999	10 kA	100 min.	2 hr.	Combined test with RI, 44.2 T. Normal ramp down.
11 Dec. 1999	10 kA	80 min.	2 hr.	Normal ramp down.
12 Dec. 1999	10 kA	100 min.	7 hr. 30 min.	User service, normal ramp down.
12 Dec. 1999	10 kA	80 min.	17 min.	Quench, RI reversed.
22 June 2000	10 kA	120 min.	8 min.	Crowbar, VCL over voltage.
26 June 2000	10 kA	30 min.	2 hr. 30 min.	Combined test with RI, 45.2 T. Normal ramp down.
3 July 2000	10 kA	30 min.	50 min.	Normal ramp down.
6 July 2000	10 kA	30 min.	8 hr.	User service, normal ramp down.
7 July 2000	10 kA	30 min.	7 min.	Dump! Quench or instrumentation glitch?
10 July 2000	10 kA	30 min.	5 min.	Unprotected quench.
2 Aug. 2000	9.5 kA	6 hr. 30 min.	0 min.	Slow ramp to assess damage. Quench.
4 Aug. 2000	9 kA	7 hr.	2 hr.	Slow ramp. Assess new operating margins. Normal ramp down.

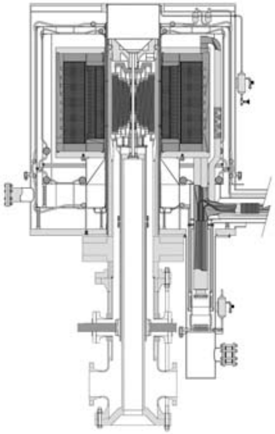
Based on results from the latter run, the superconducting outsert was approved to operate continuously at 8 kA for service to NHMFL users.

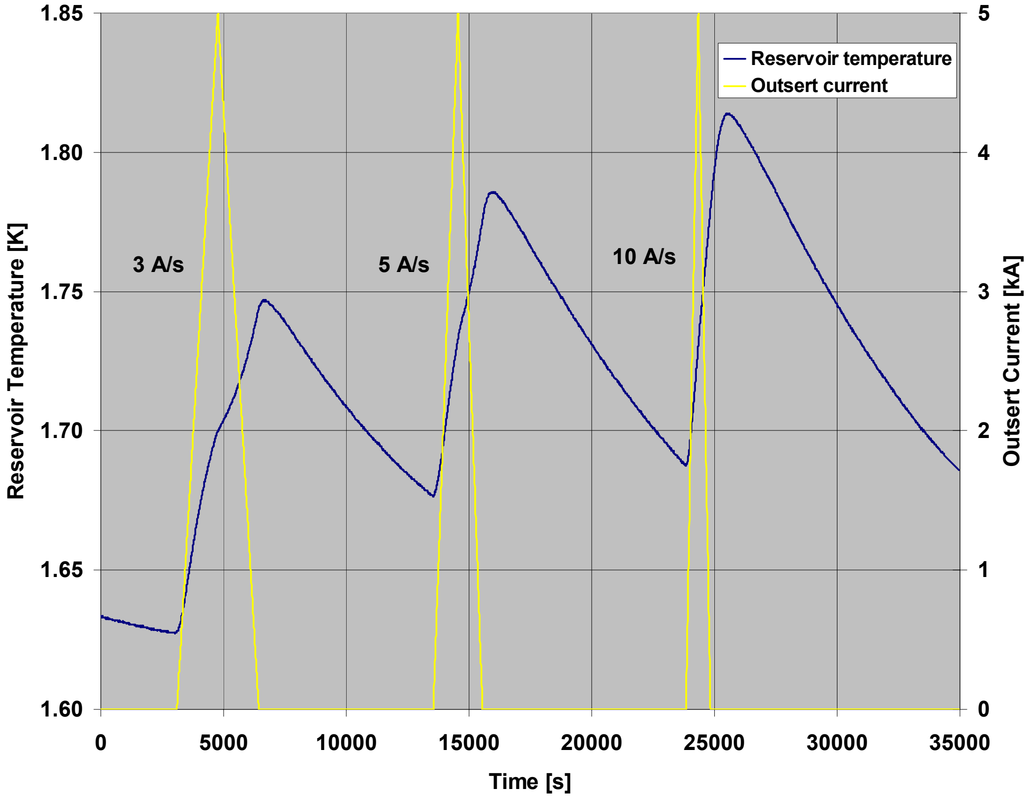


Instrumentation

- Since the 45-T Hybrid is a facility for scientific research rather than a test article for magnet development, there is no instrumentation internal to the magnet windings
- There are, however, voltage taps attached to every layer and every pancake via the helium flow connections
- And, there are calibrated temperature sensors in the HeII reservoir
- These are adequate for providing an understanding the magnet's performance

Temperature response in the HeII reservoir to 0-5-0kA outsert-current ramps





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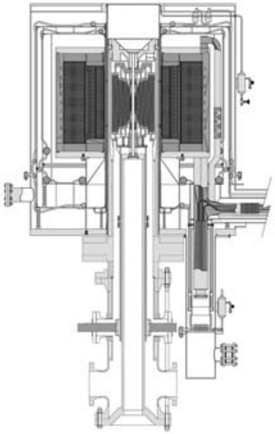
Conversion of temperature-response data to corrected energy deposition



After cessation of heating, temperature is observed to recover according to

$$T(t) = (T_{init} - T_{base})e^{-\left(\frac{t}{\tau}\right)} + T_{base}$$

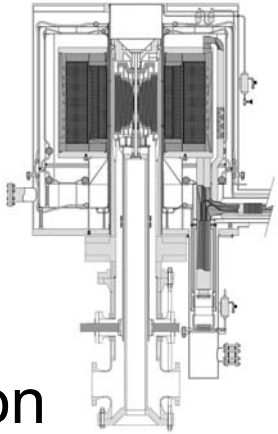
as if the reservoir is connected to a sink with temperature T_{base}. In that case, the instantaneous heat flow at temperature T is

$$\dot{Q}_{out}(T) = C_{p,HeII}(p,T)V_{reservoir}\frac{T - T_{base}}{\tau}$$

and the corrected heat deposition in the reservoir causing a rise from T_0 to T is

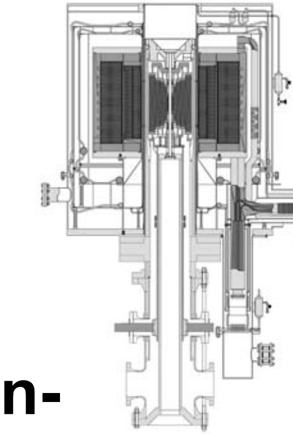
$$Q_{corrected}(T,t) = V_{reservoir}\int_{T_0}^{T} C_{p,HeII}(p,T)dT + \int_0^t \dot{Q}_{out}dt - \int_0^t I^2 R(I)dt$$

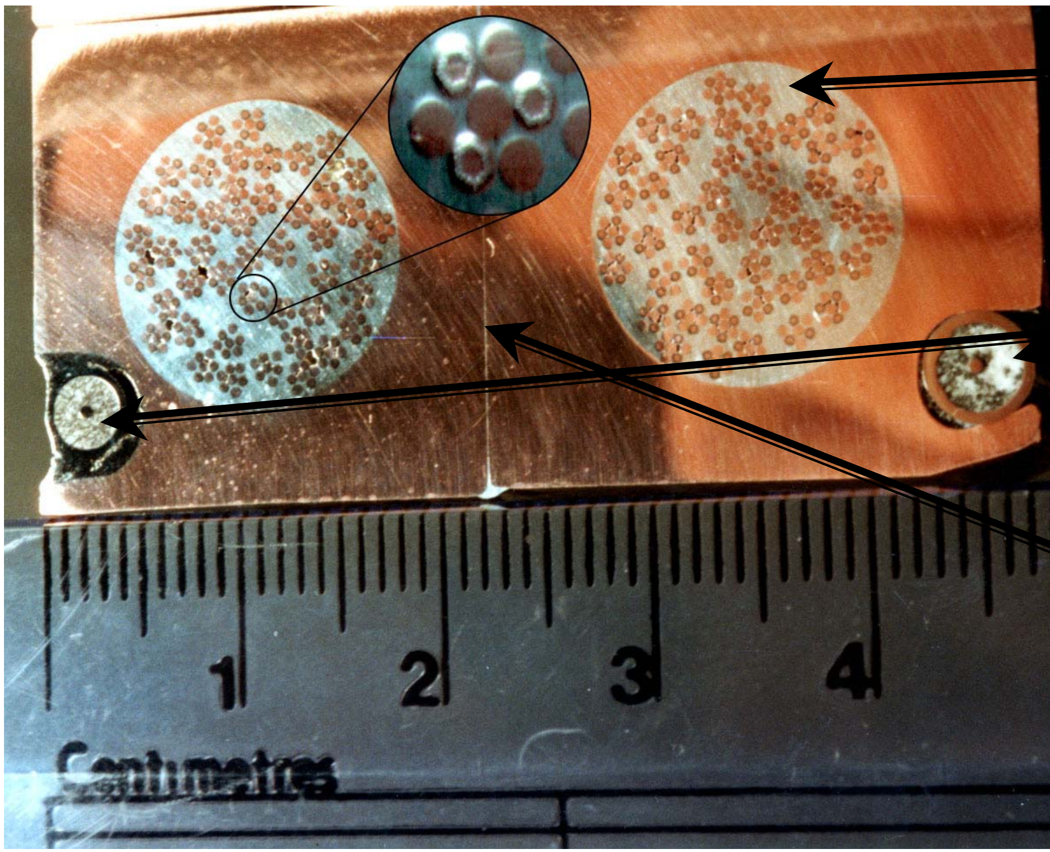
Corrected energy deposition
(continued)



- The last term in the previous relation is a correction for joint heating
- *R(I)* represents the total joint resistance corrected for magneto-resistance
- The magneto-resistance correction is relatively simple because 30 of the 38 joints in the HeII space are on the outer diameter of Coil C, where the field for any particular current is the same within about 10%
- All joints are of similar construction with resistance determined in a relatively simple way by properties of constituents: Cu, SnAg, and SnPb

A typical joint





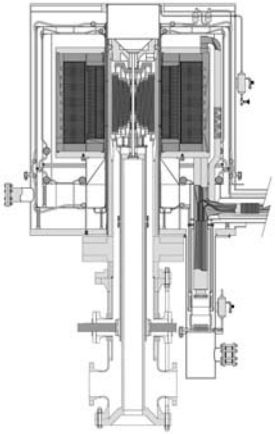
95Sn-5Ag solder

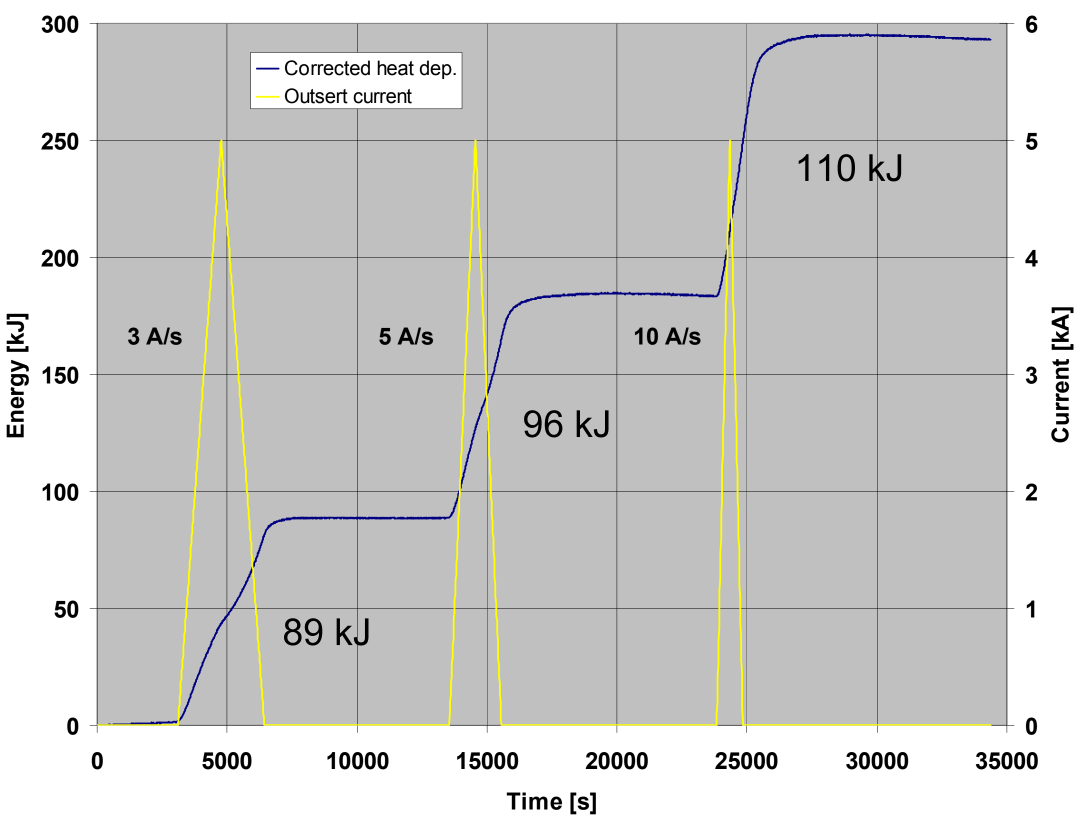
Imbedded heaters

60Sn-40Pb solder

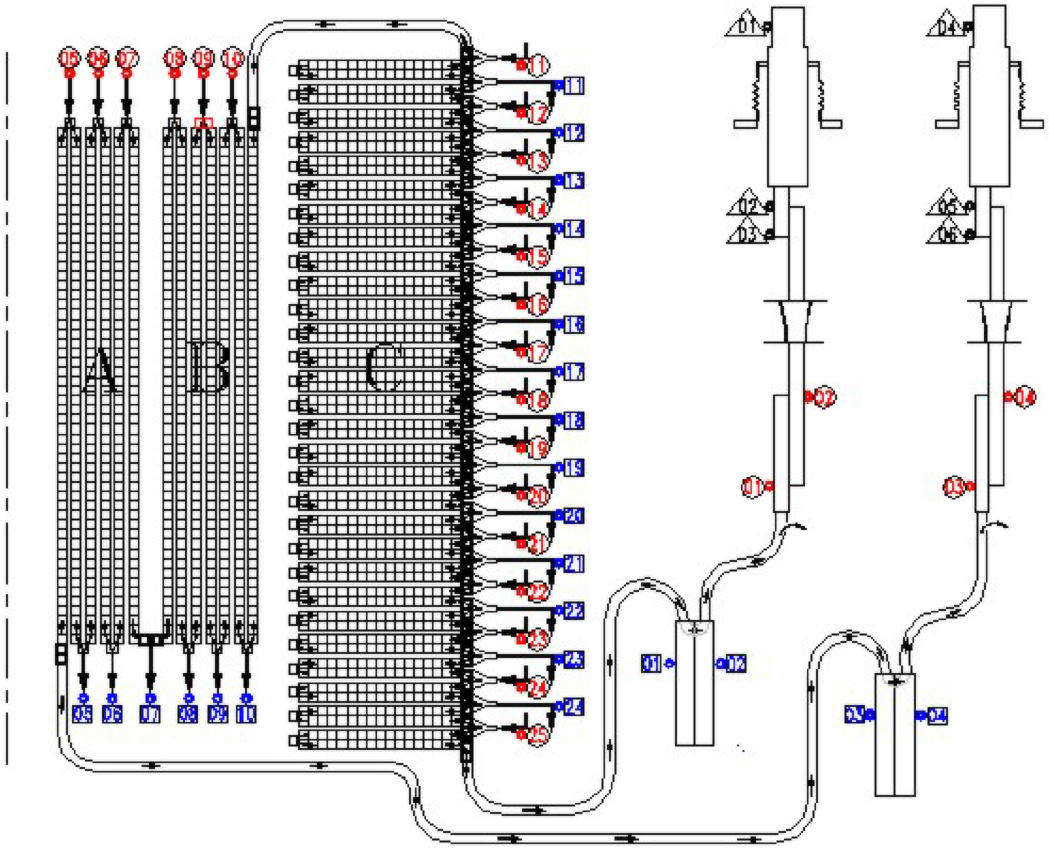
R_{joint} ~ 0.45 nΩ at B = 0

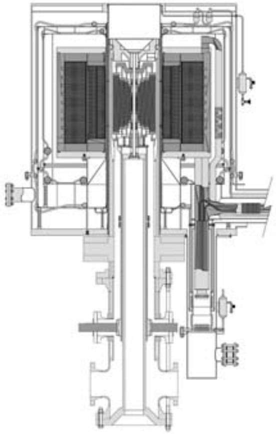
Corrected energy deposition for 0-5-0 kA outsert-current ramps



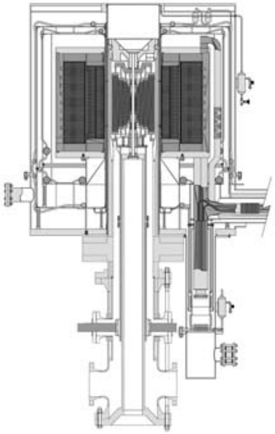


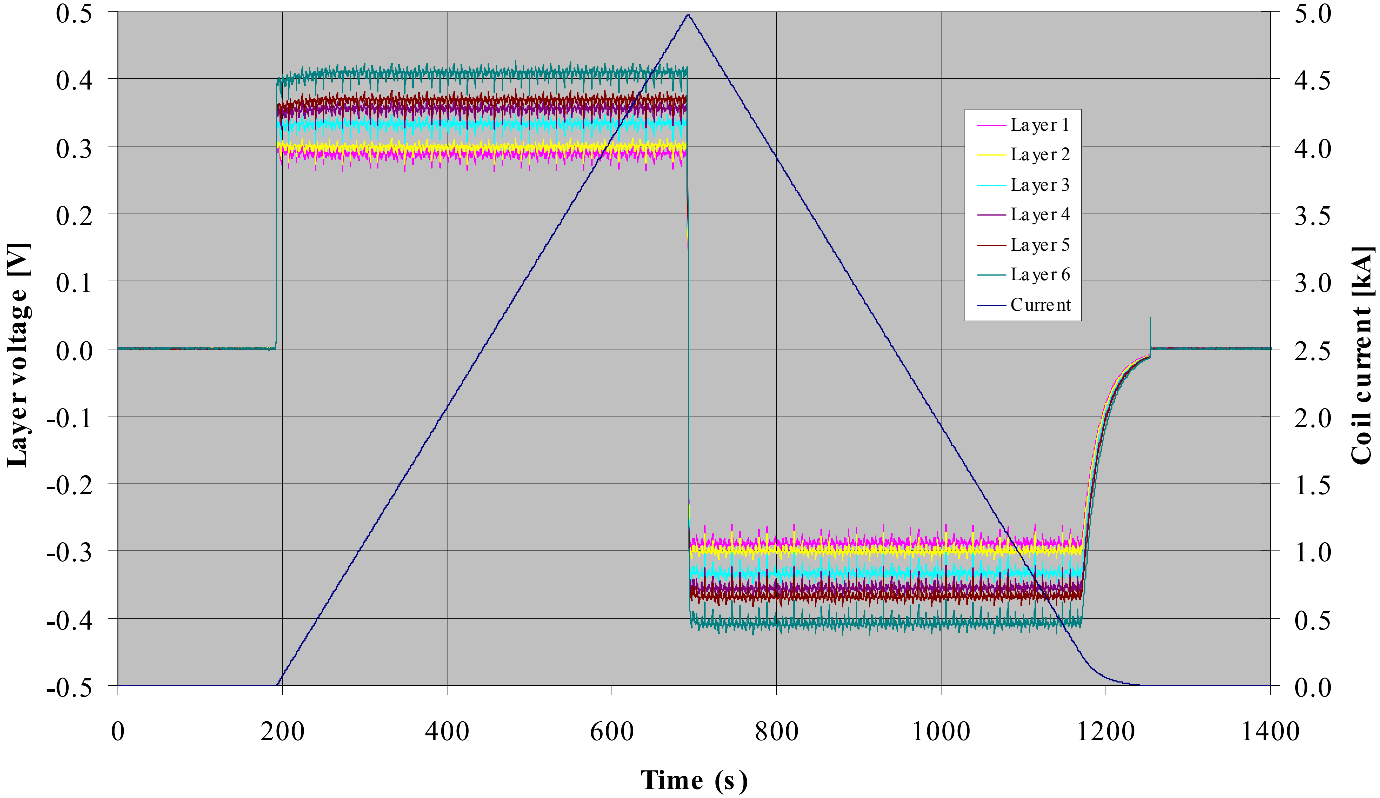
Joints, flow connections, and voltage taps on the outsert



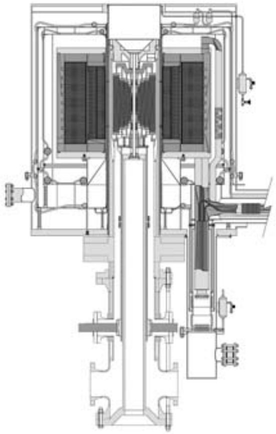


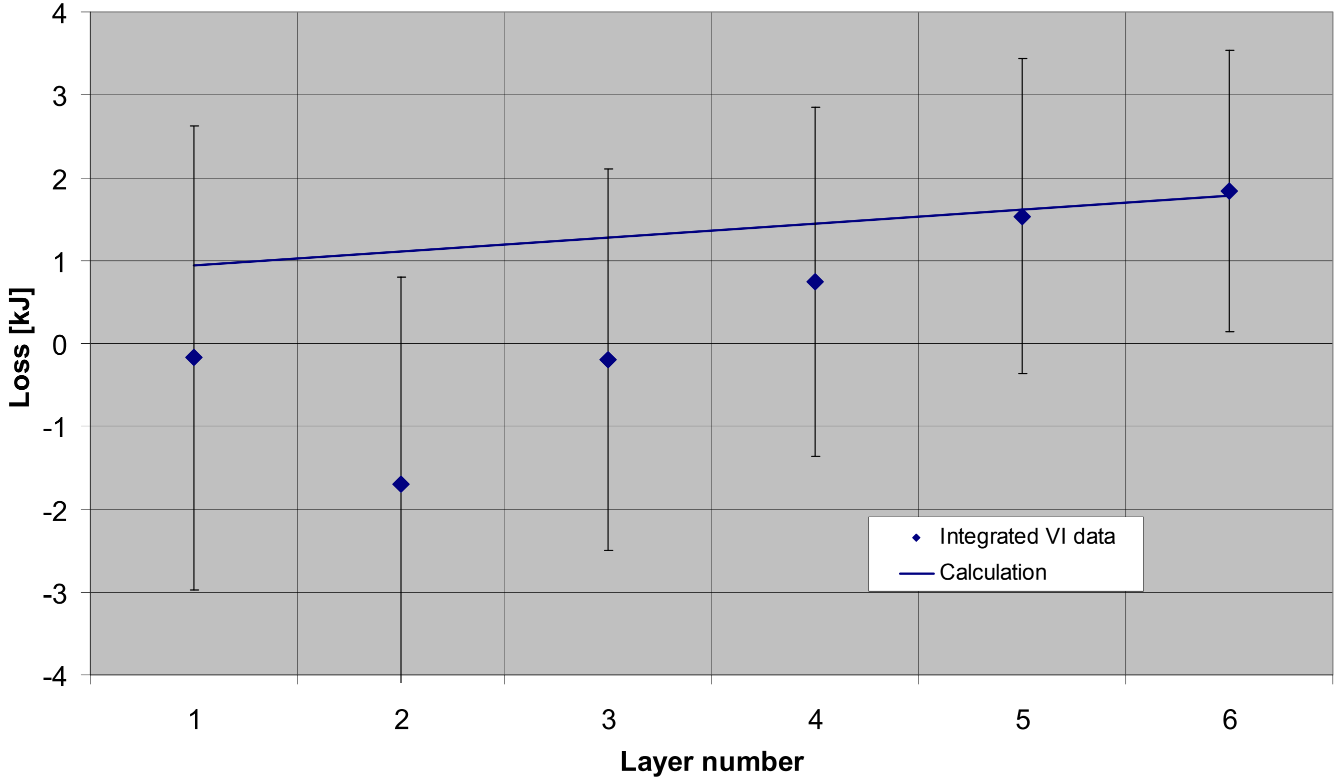
Layer voltages for Coil A during 0-5kA-0 ramp at 10 A/s



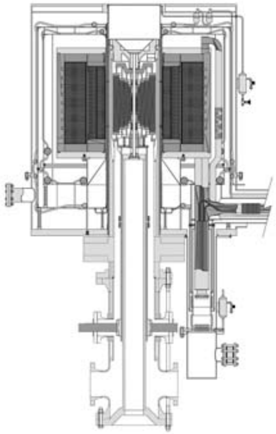


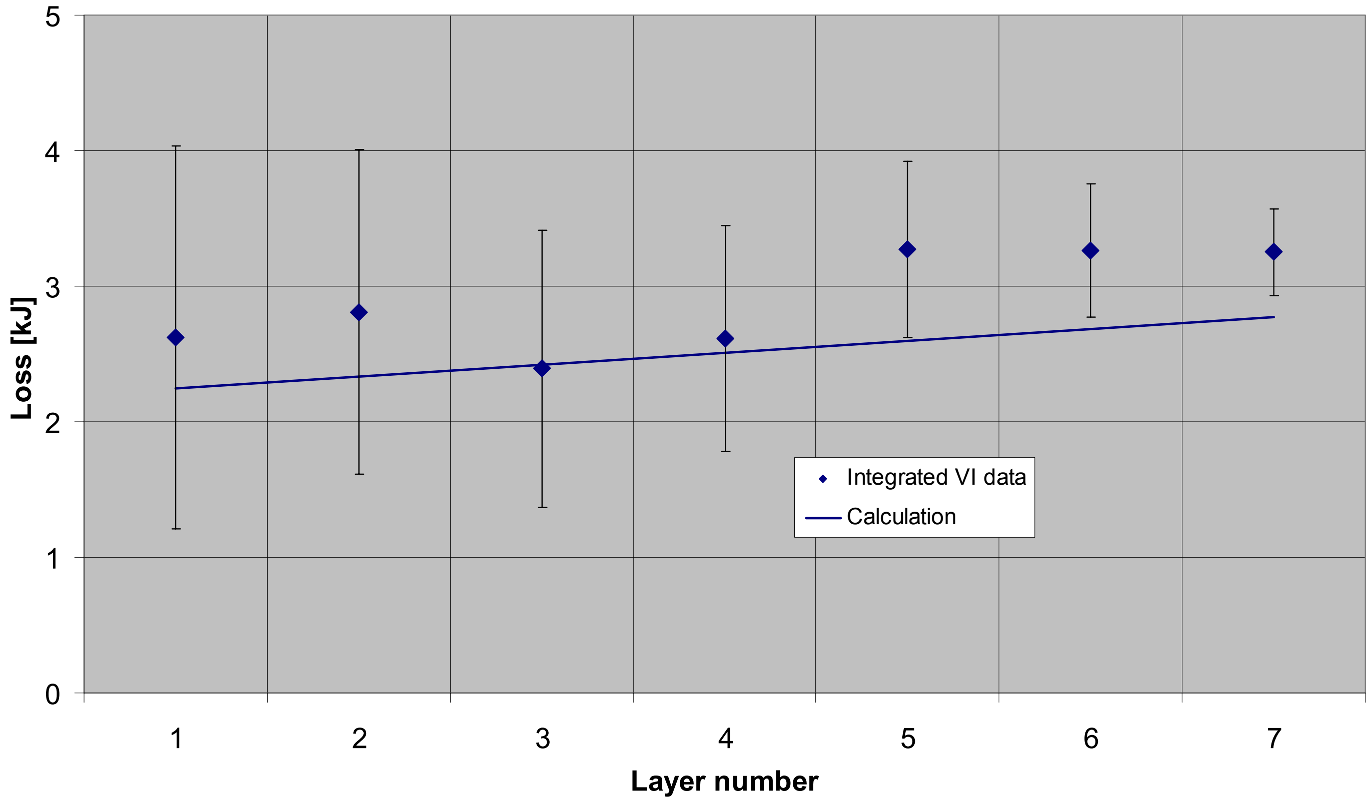
Losses due to current in Coil-A layers



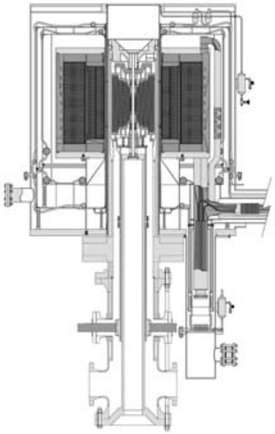


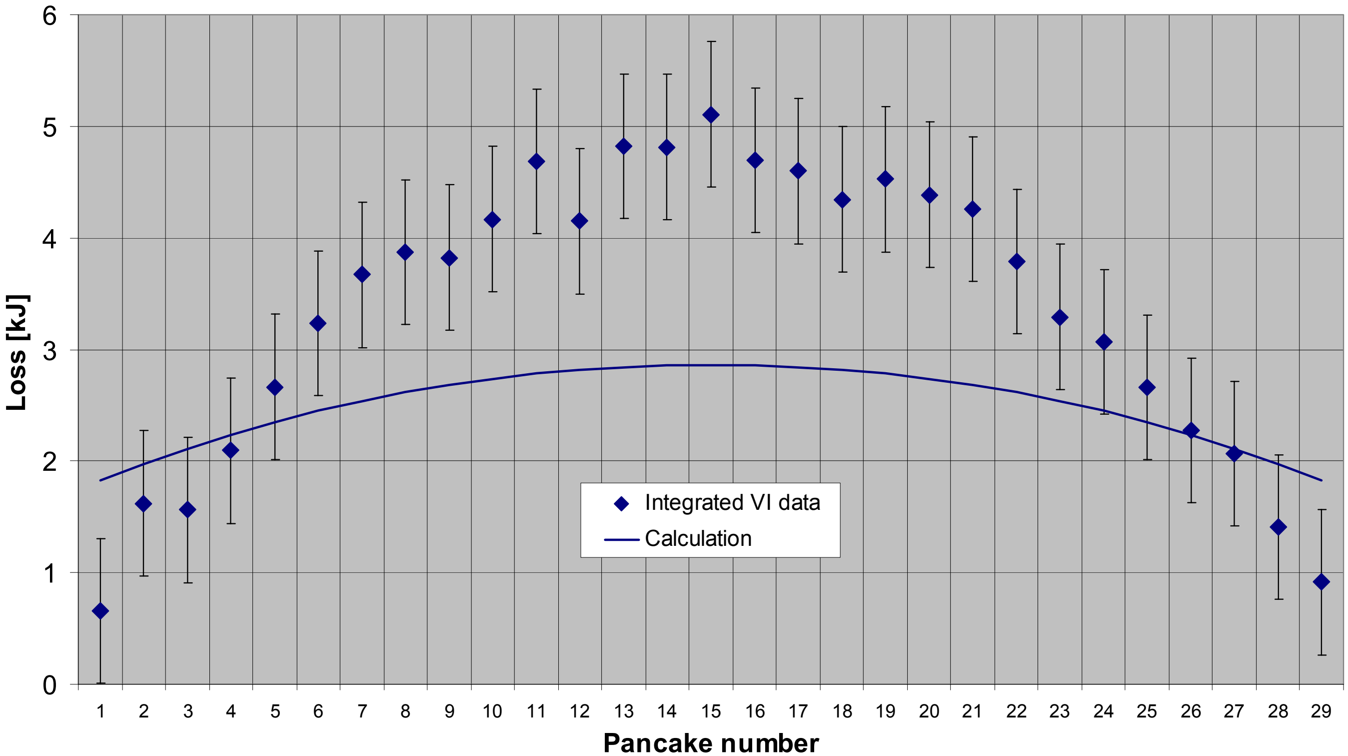
Losses due to current in Coil-B layers

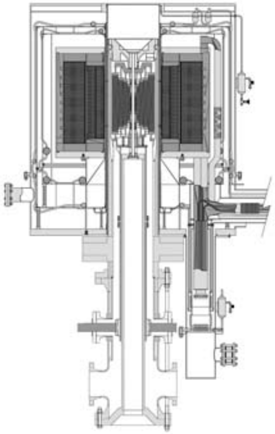




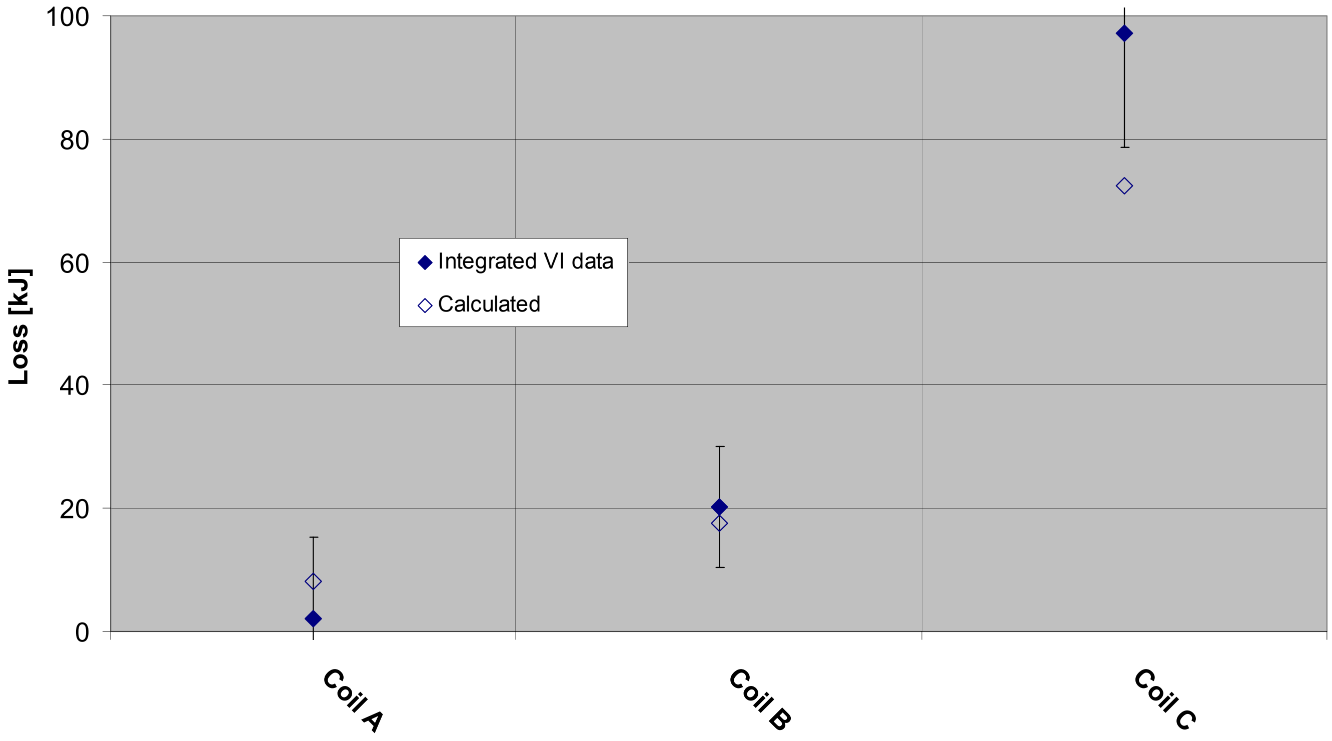
Losses due to current in Coil-C pancakes



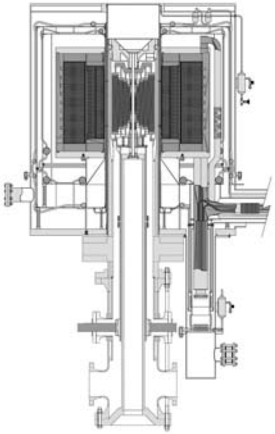




Distribution of losses generated by individual coils



Calculated hysteresis and coupling losses for typical Hybrid operations

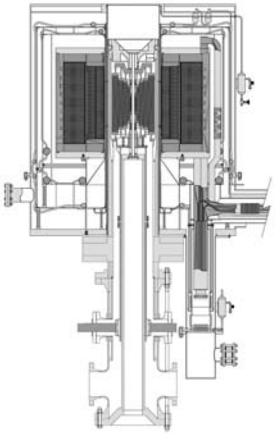


Linear ramp up or down in current at various rates

$I_{out,max}$ [kA]	Q_{hyst} [kJ]	Q_{coup} [kJ] Ramp rate [A/s]: 2	3	5	10
0	0.00	0.00	0.00	0.00	0.00
0.5	5.60	0.10	0.15	0.25	0.49
5	44.20	0.98	1.48	2.46	4.92
8	58.10	1.57	2.36	3.94	7.87
10	62.10	1.97	2.95	4.92	9.84

Exponential dis-charge for typical time constants (dump and crowbar)

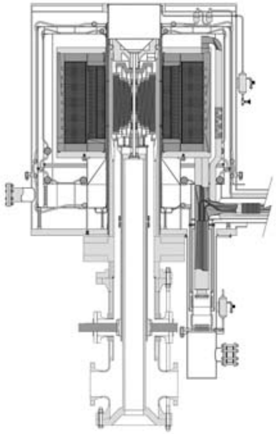
$I_{out,max}$ [kA]	Q_{hyst} [kJ]	Q_{coup} [kJ] τ_{disch} [s]: 4.4	700
0	0.00	0.00	0.00
0.5	5.60	2.78	0.02
5	44.20	277.65	1.76
8	58.10	710.79	4.50
10	62.10	1110.61	7.03

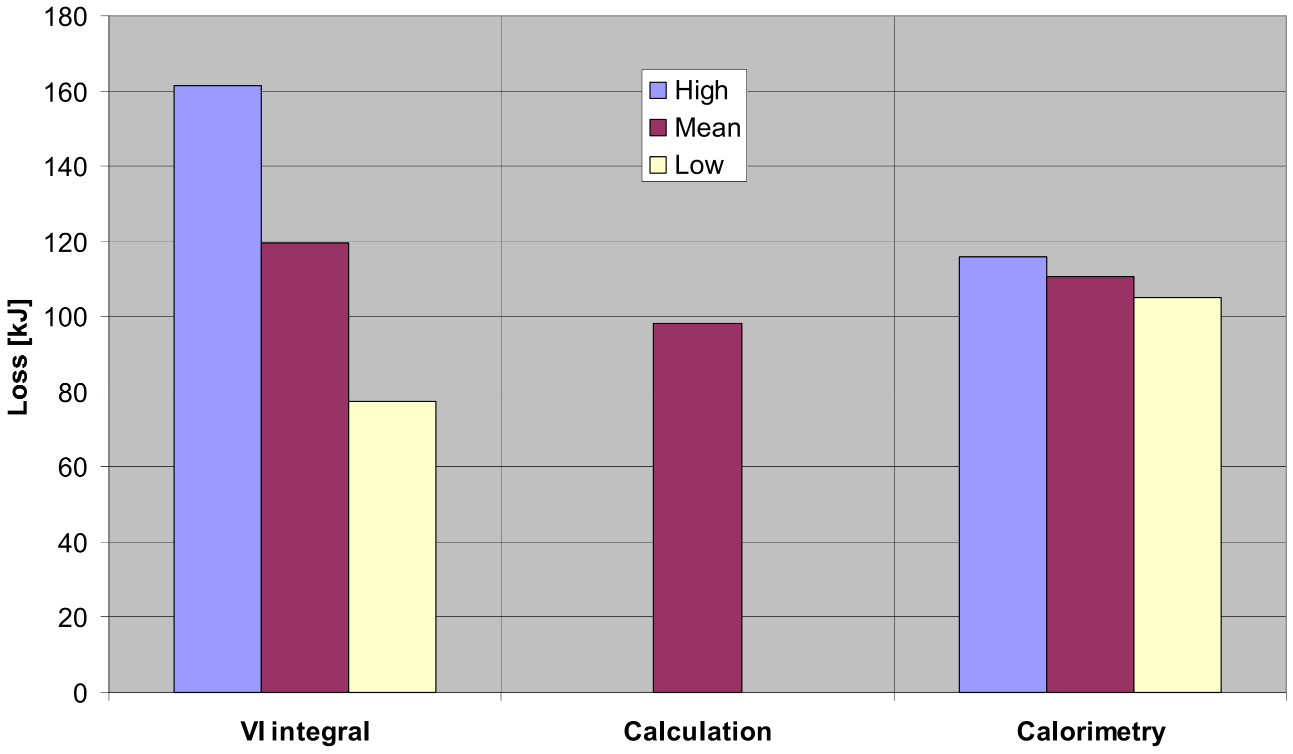


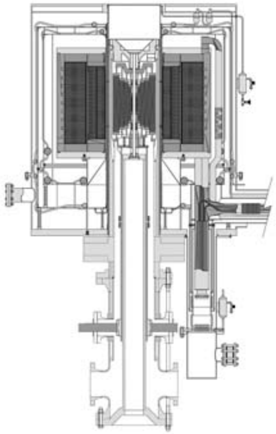
Basis of loss calculations

- $J_C(B,T)$ as given in “Outsert conductor parameters” table
- d_{eff} of 42, 49, and 50 μm (Coils A, B, and C, resp.)
- τ_{cable} of 30,30, and 160 ms (Coils A, B, and C, resp.)

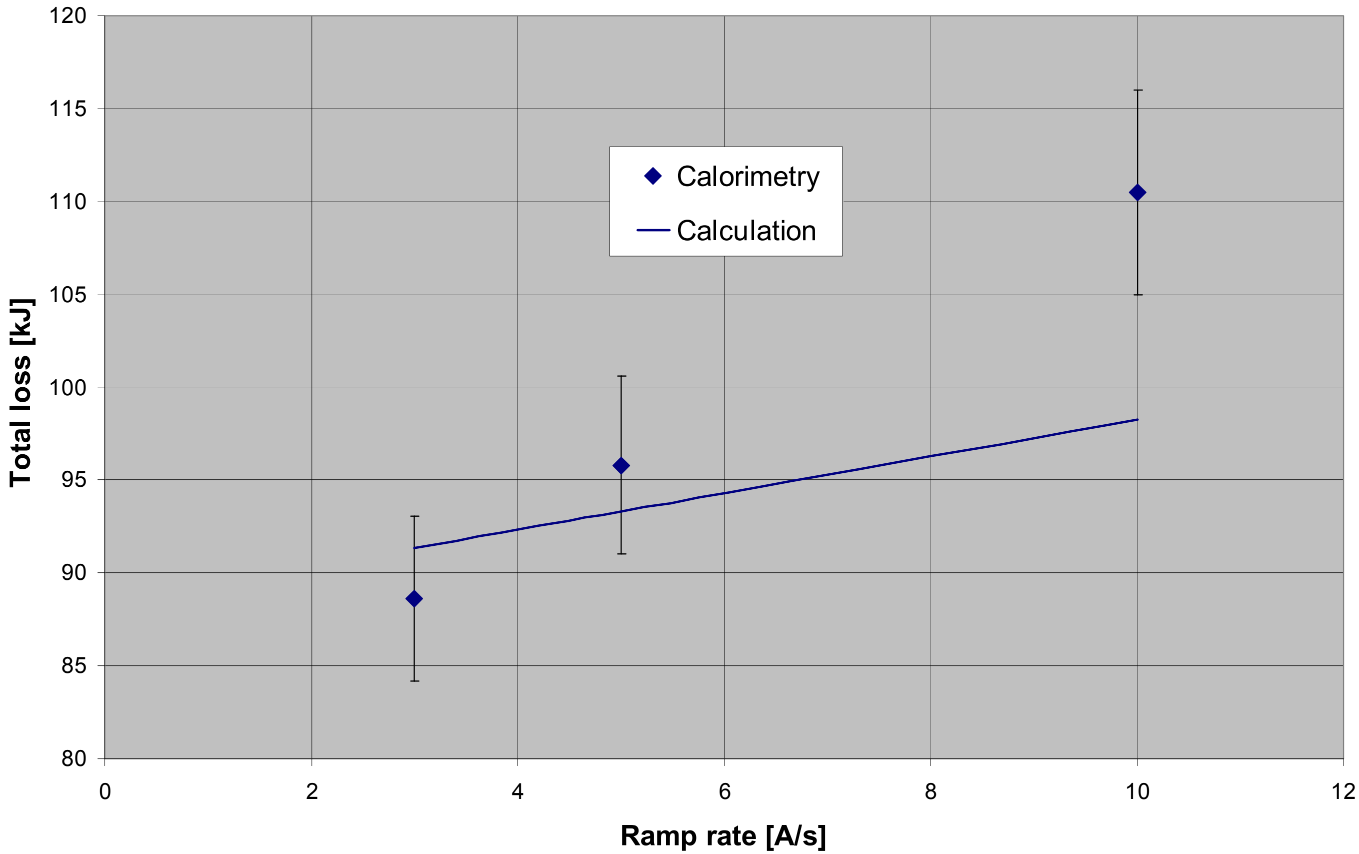
Alternate determinations of the total loss for 0-5kA-0 ramp at 10 A/s

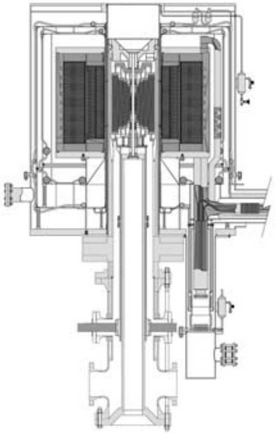




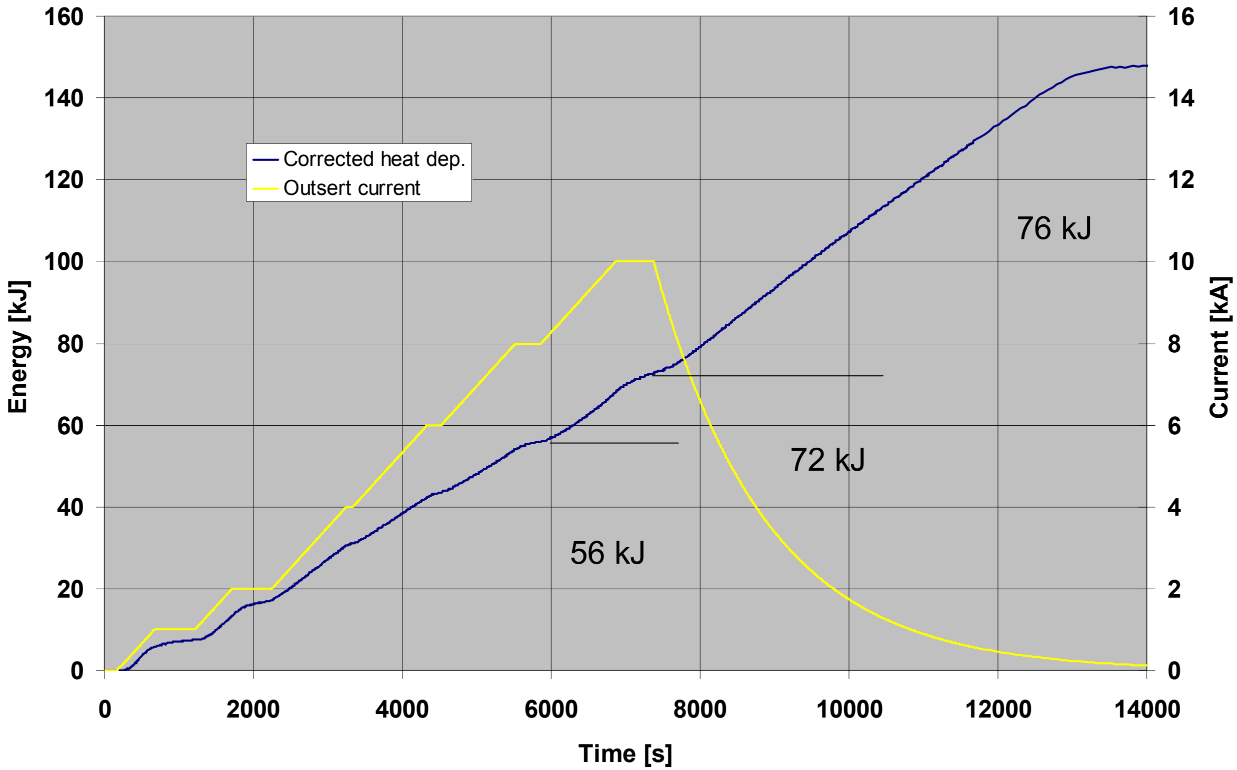


Losses for 0-5kA-0 ramps at different ramp rates

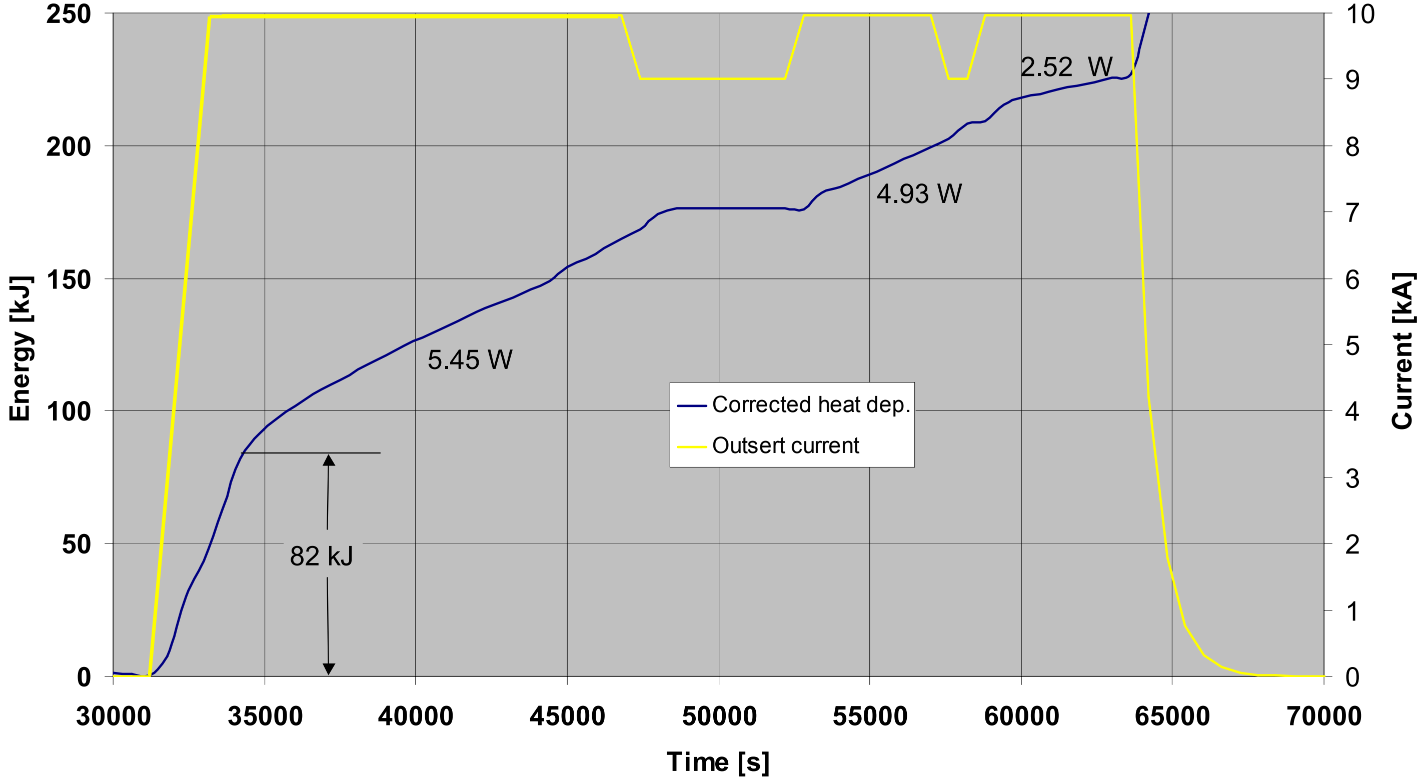


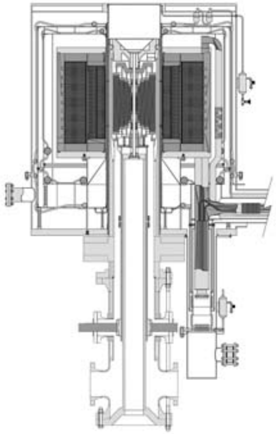


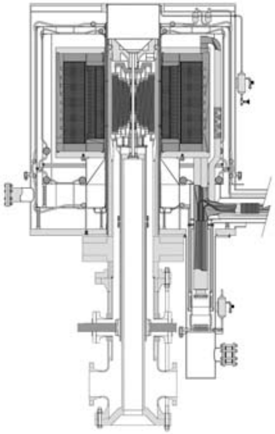
Corrected energy deposition for 0-10kA ramp at 2 A/s followed by crowbar with 700s time constant



Corrected energy deposition during a 0-10kA ramp and 8h hold







Index losses

Index heating occurs near the critical current I_0 according to

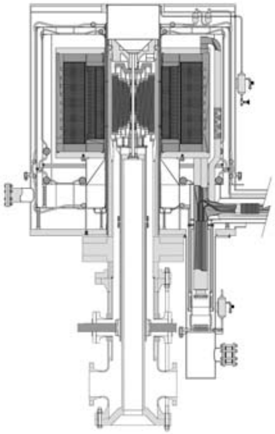
$$\dot{Q}_{index} = I^{n+1} E_0 \int \frac{dl}{I_0^n(B,T)}$$

where E_0 is the criterion for establishing I_0 and the index n characterizes the rate of rise of voltage with increasing current. $I_0 = I_0(B,T)$ and the integration is over a length of conductor in the windings with local variations of both.

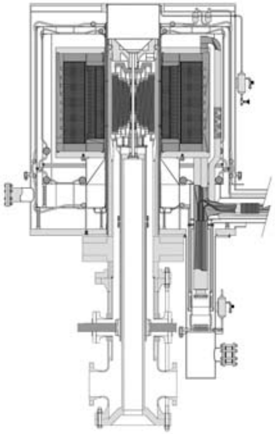
In tests of the Hybrid CICCs, $E_0 = 50\ \mu\text{V/m}$ and $n = 15$.

Appreciable index heating can be expected in the Hybrid outsert for elevated temperatures (e.g, ~ 4 K in Coil A).

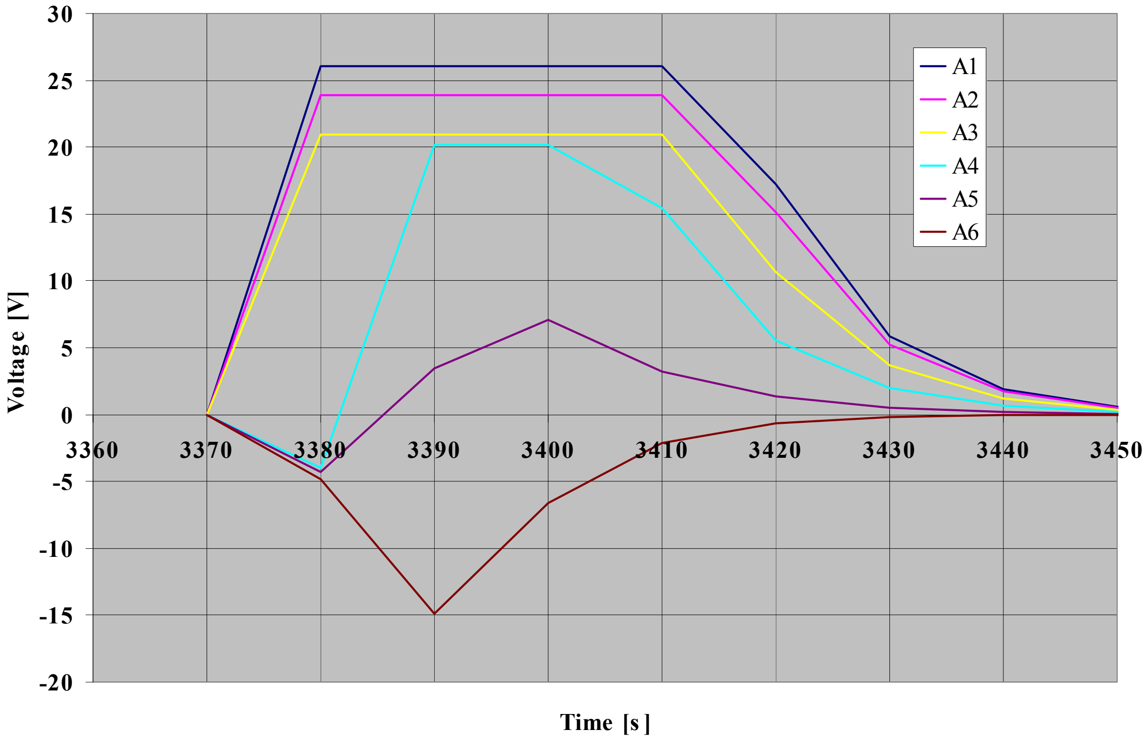
Index heating: key in the process leading to quenches during early phases of operation



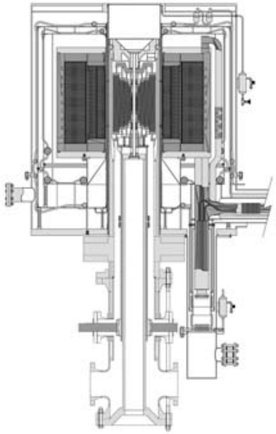
- Limited cooling afforded by static HeII in long channels locally exceeded by transient losses
- Local temperature elevation into HeI range
- Locally reduced critical current and low-level heating by index losses
- Slow runaway toward quench due to drastically reduced heat transport of HeI
- This is a delicate balance affected by:
  - field from insert,
  - prior operations, or
  - starting temperature of HeII reservoir



Unprotected quench, 10 July 2000



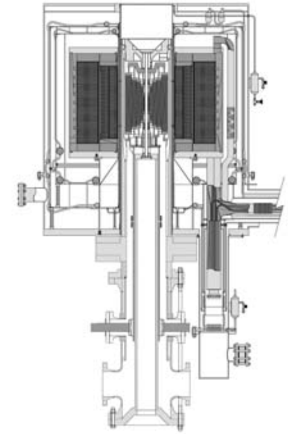
Coincidence with a malfunction of the quench-detection computer resulted in sparse data

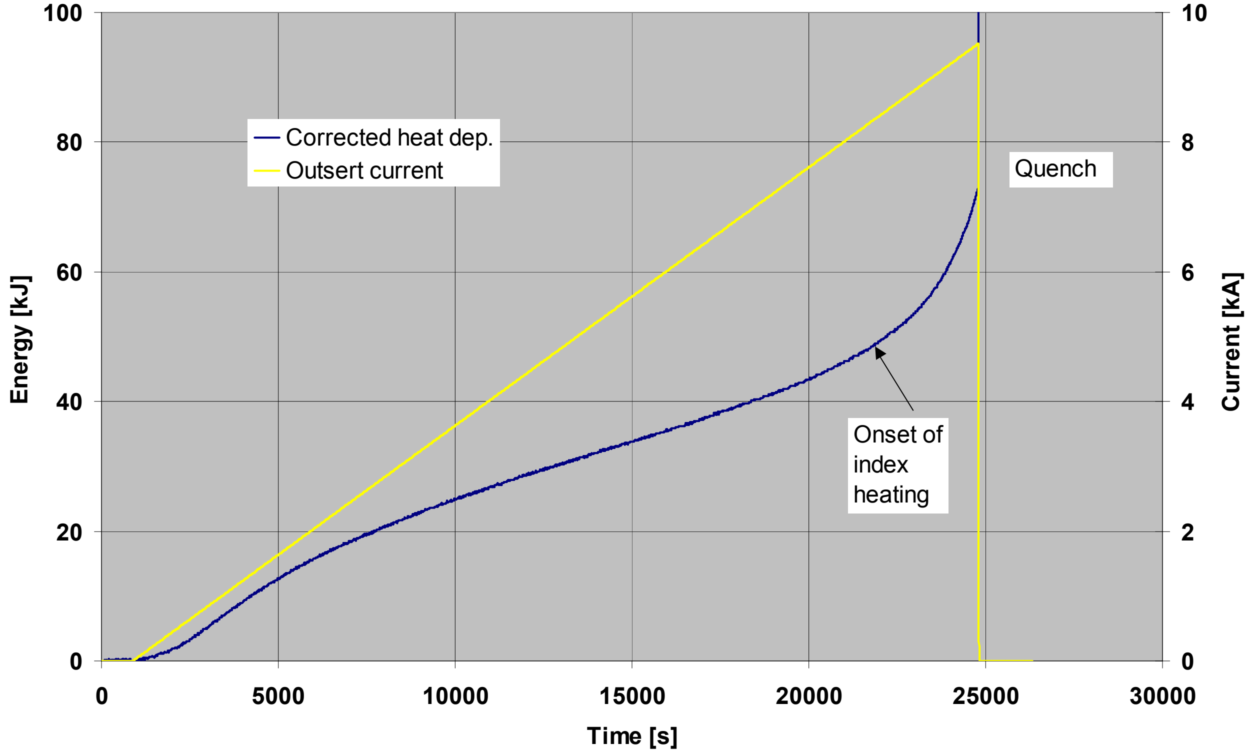


Unprotected quench: what we know

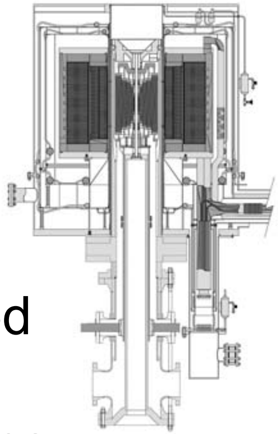
- The quench occurred after being at full current (10 kA) for about 4 minutes.
- Only Coil A developed resistance.
- Resistance in Coil A developed most quickly in the first 3 layers.
- A clear indication of resistance in the 4th and 5th layers was not evident until 10 s or more after the quench was fully developed.
- Resistance was never clearly evident in the 6th layer.
- The development of resistance was such that the discharge quickly became exponential in character with a time constant of about 10 s.
- Analysis indicates the “hot-spot” temperature was 500K or greater.

Outsert performance following unprotected quench





- The apparent net result is essentially a reduction of the index from around 15 to about 5.
- Index heating at 8 kA or below is negligible.
- On-axis contribution 11.4 T, max field 12.5 T



Summary

- Measurements of total ac losses are comparable to calculated values
- Electrical measurements during triangular ramps provide some confidence in the spatial distribution of calculated losses
- AC losses do not appear to be substantially different than assumed during the design phase
- Calorimetric data from high-current ramps suggest that limited cooling during fast charges and the onset of index heating results in a delicate balance between stable operation and slow, thermal runaway.
- This may explain the quenches observed in the early phases of operation
- A better assessment of this possibility requires more detailed thermal analysis, which is the subject of a companion paper at this workshop