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Thermal and flow processes in cryogenic systems following failure modes combined with superconducting magnets resistive transitions.

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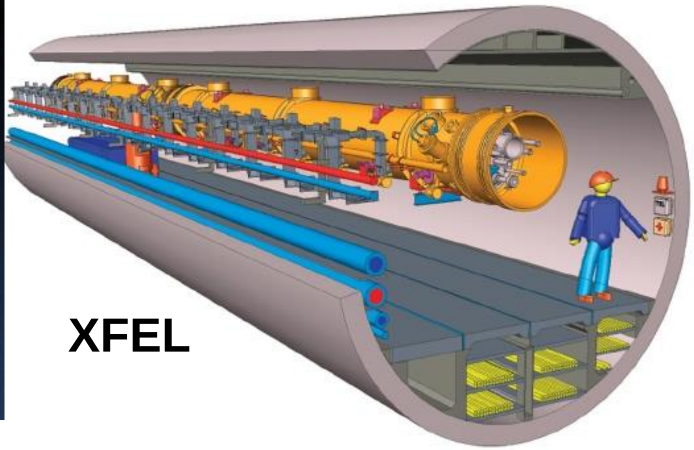
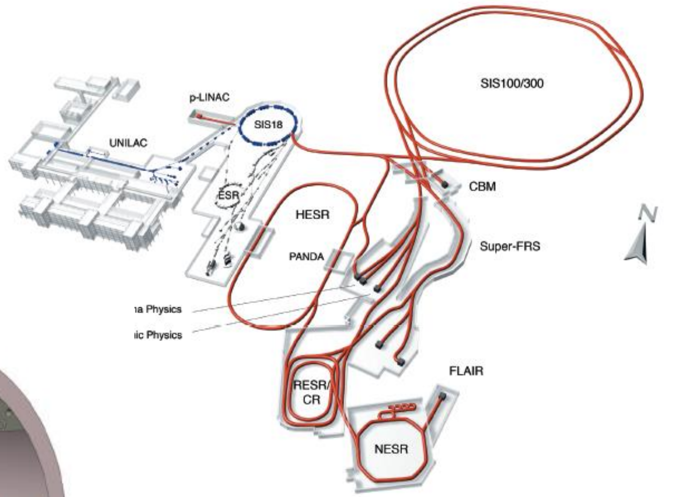
    - **Electrical arc**
    - **Magnet quench**
5. **Conclusions**

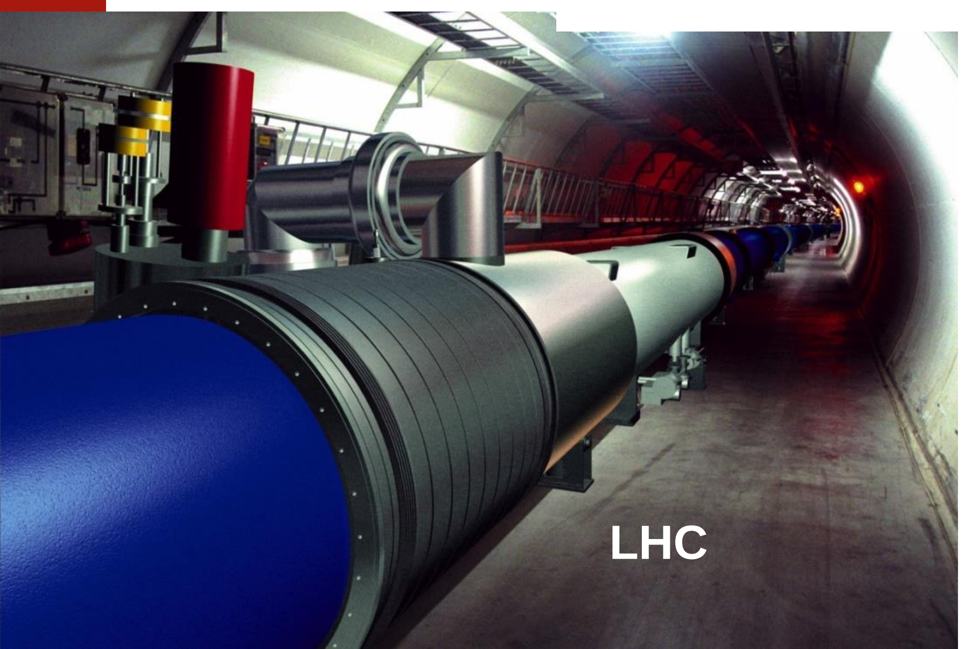
Cryogenics in „Big Science”



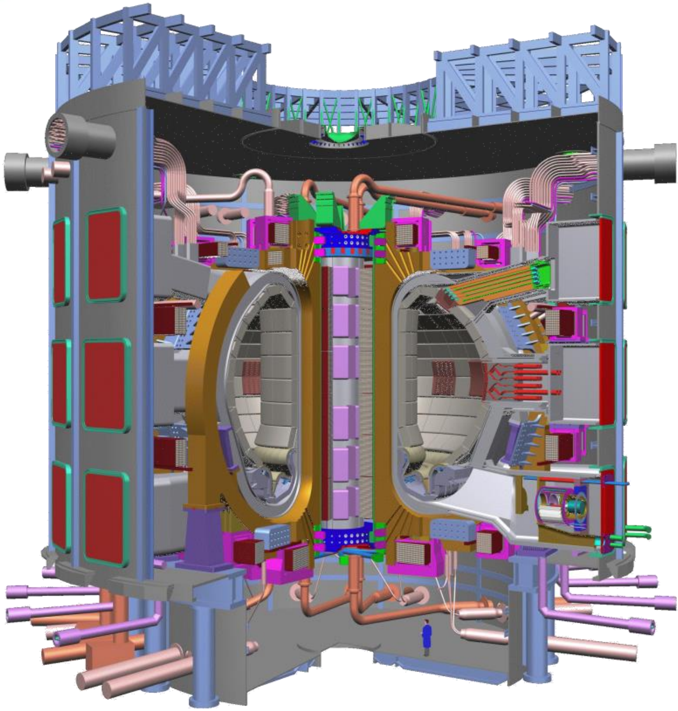
XFEL



FAIR



ITER

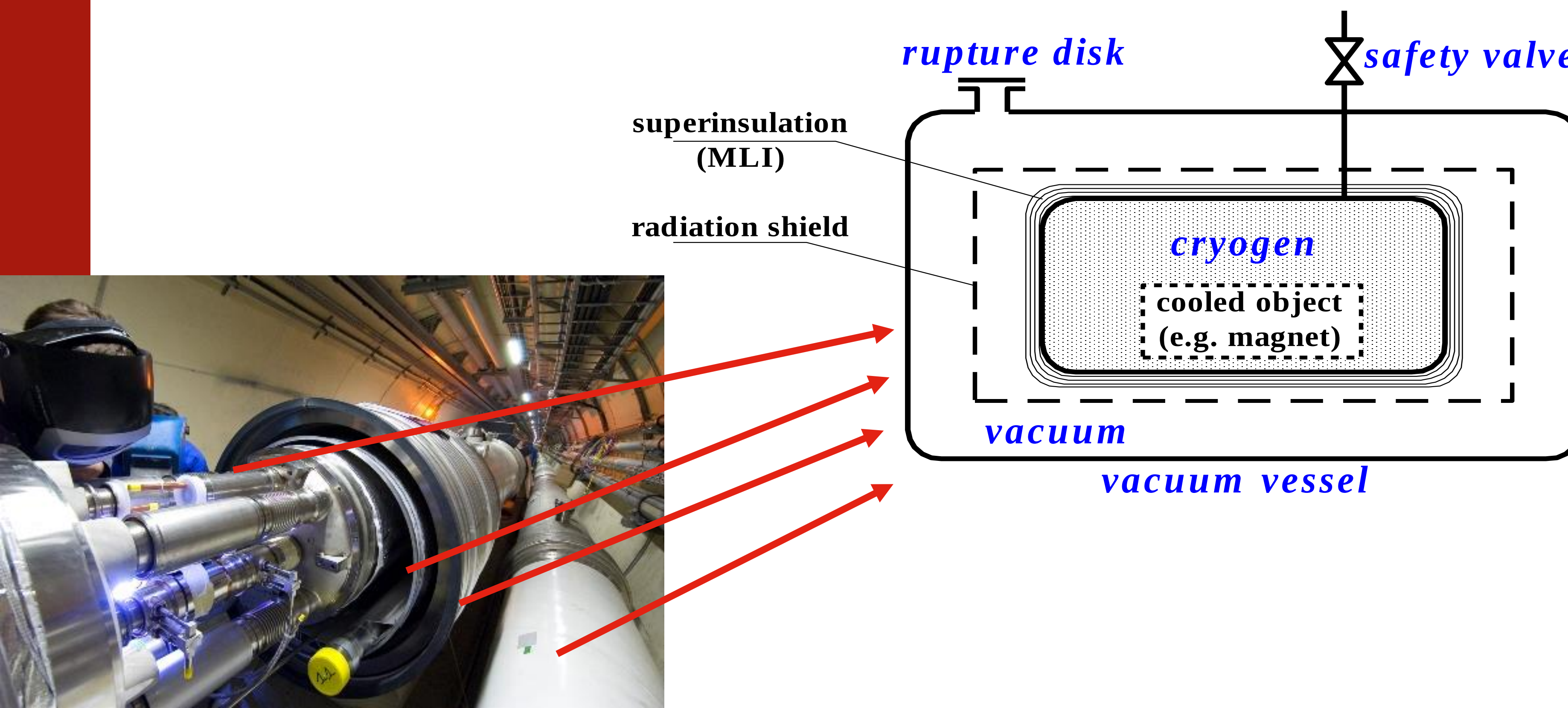


Helium cryogenics in chosen projects

Installation, location	Type	Cooling power	Helium inventory
LHC, CERN, Geneva	pp collider	144 kW	136 ton
FAIR, GSI, Darmstadt	ions accelerator	42 kW @ 4.4	11 ton
XFEL, DESY, Hamburg	free electron laser	12 kW	5 ton
W7-X, Max Planck Greifswald	fusion stellarator	5 kW	2 ton
ITER, ITER IO, Cadarache	fusion tokamak	60 kW @ 4.5 K 950 kW @ 80 K	24 ton
ILC, no decision	e+ e- lin. collider	211 @ 4.5 K	100 ton

Cryogenic node - simplest element of the cryogenic system - basis for the risk analysis

Each component of the machine like pipe, vessel, heat exchanger, and cryostat can been treated as separate helium enclosure, characterized by the amount and thermodynamic parameters of helium.



Potential failure modes of cryogenic systems

1. **Mechanical break of warm vacuum vessel followed by air flow to insulation vacuum space.**
2. **Mechanical break of cold vessel or process pipe followed by helium flow to insulation vacuum space.**
3. **Electrical arc caused by faulty joint of superconducting cables leading to the consequences similar like in failure 2, but on a much more extensive scale**
4. **Extensive resistive transition of superconducting magnets and quench propagation – non foreseen as operational mode**

Potential failure modes of cryogenic systems

1. Mechanical break of warm vacuum vessel followed by air flow to insulation vacuum space.
2. Mechanical break of cold vessel or process pipe followed by helium flow to insulation vacuum space.
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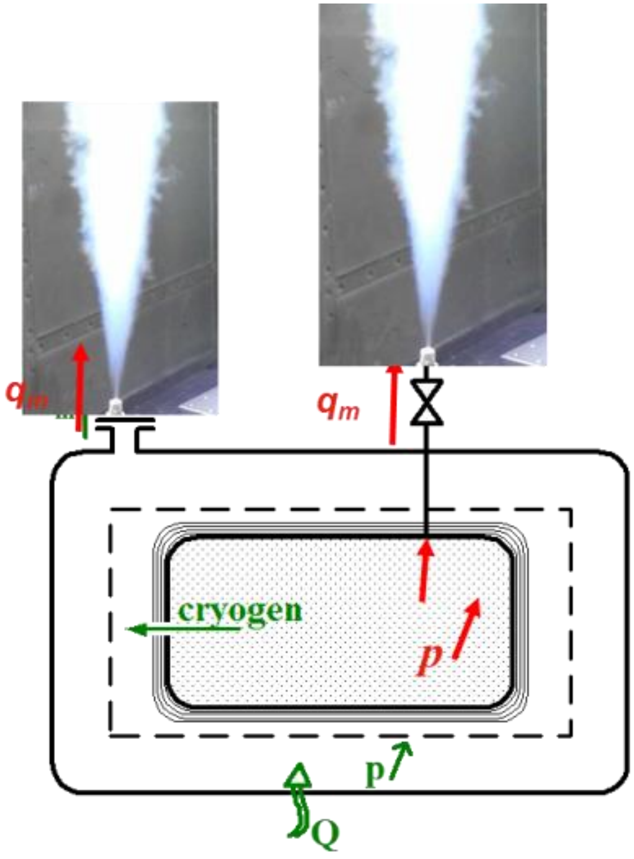
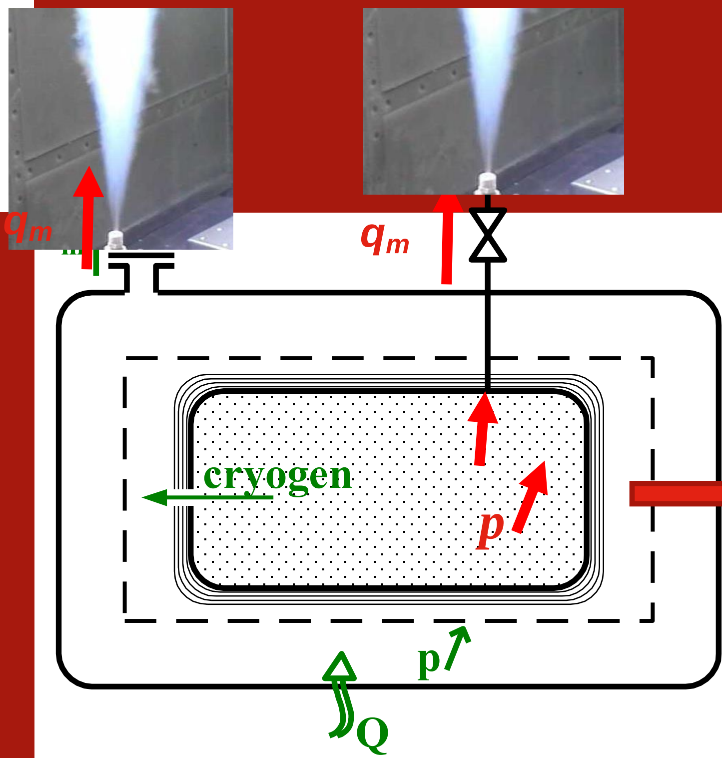
4. Extensive resistive transition of superconducting magnets and quench propagation – non foreseen as operational mode

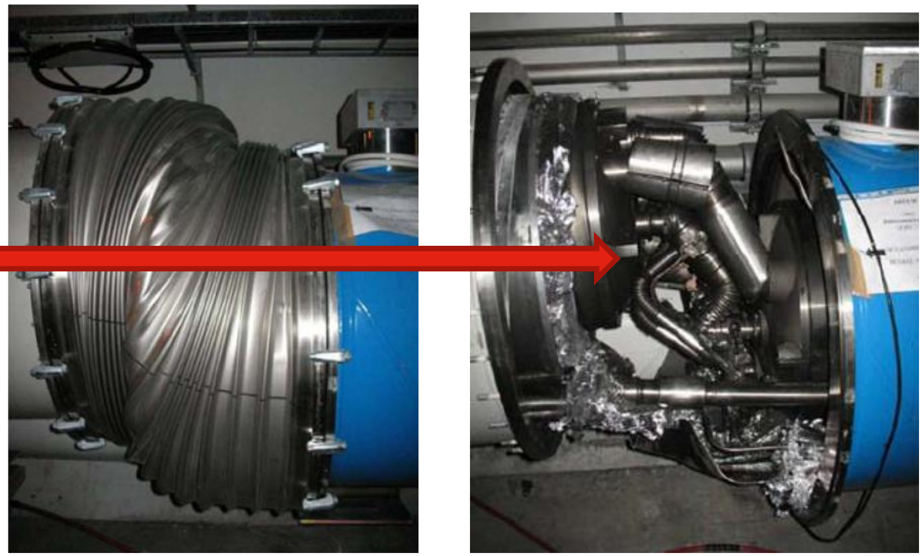
Flow consequences of mechanical break of cold vessel, including el. arc



1. Mechanical and/or arc induced break of the cold vessel
2. Fast degradation of the vacuum insulation with cryogen.
3. Intensive heat flow to the cryogen.
4. Energy release to the helium, e.g., due to a magnet quench (optionally) or eddy current heating.
5. Pressure increase of the cryogen and in the vacuum space.
6. Opening of the rupture disk and/or safety valve.
7. Cryogen discharges through the rupture disk and/or safety valve.

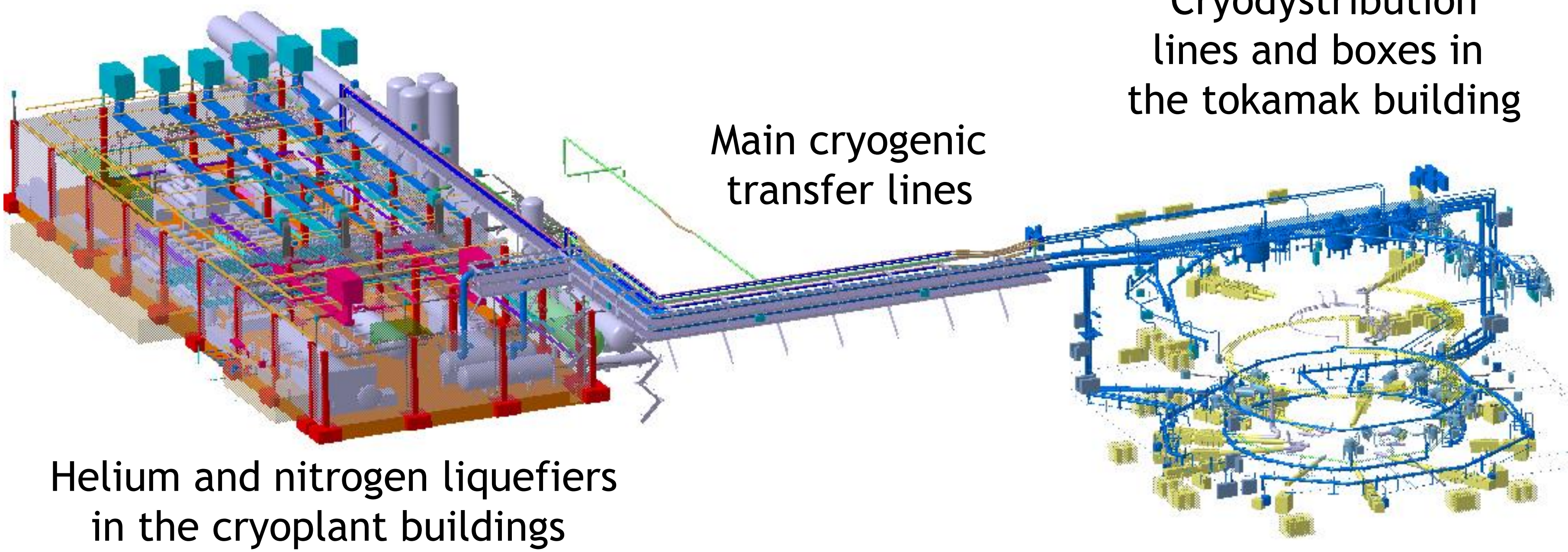
Safe operation of cryogenic systems



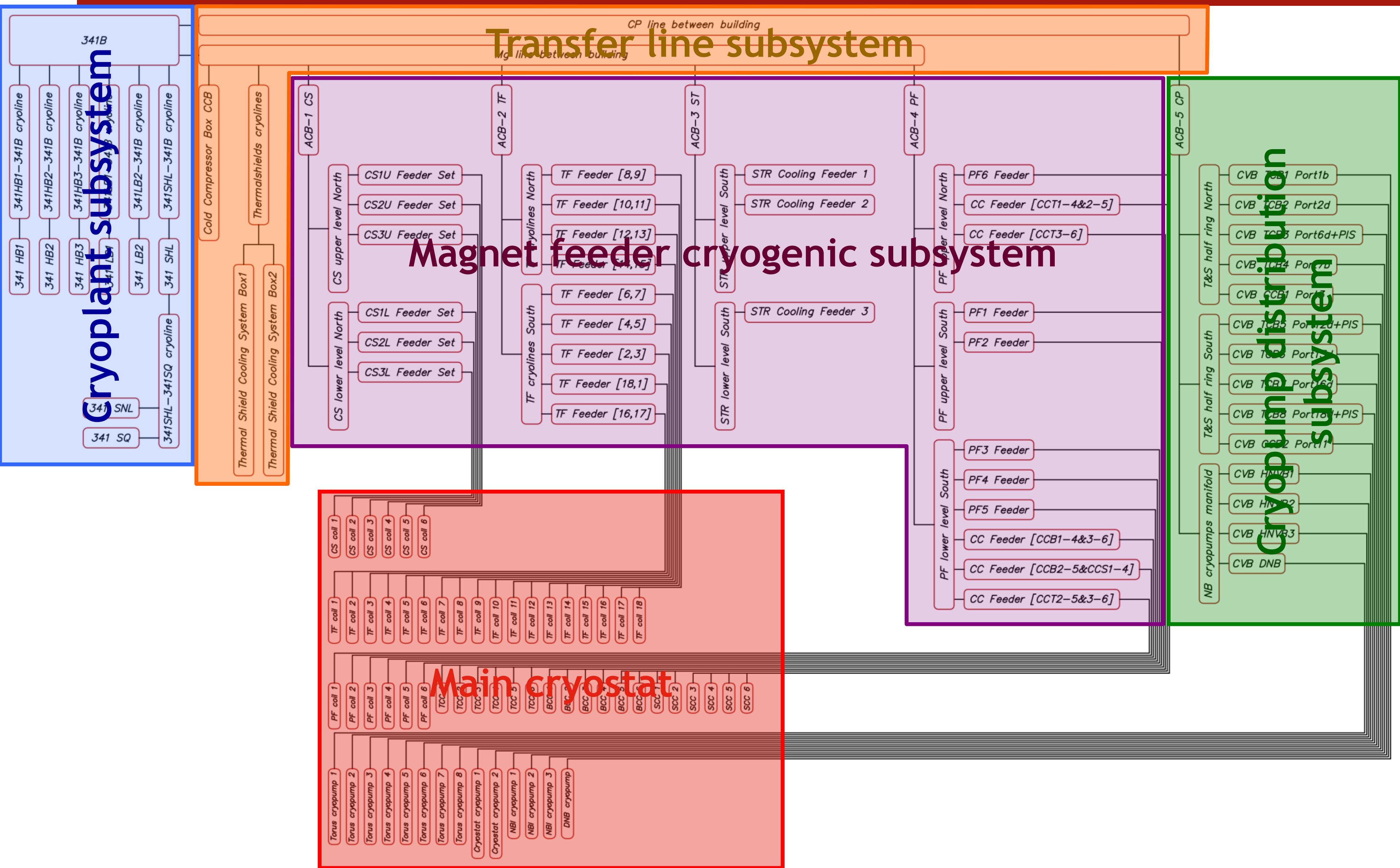


Pressurization of the vacuum space caused serious damage of the LHC accelerator in 2008

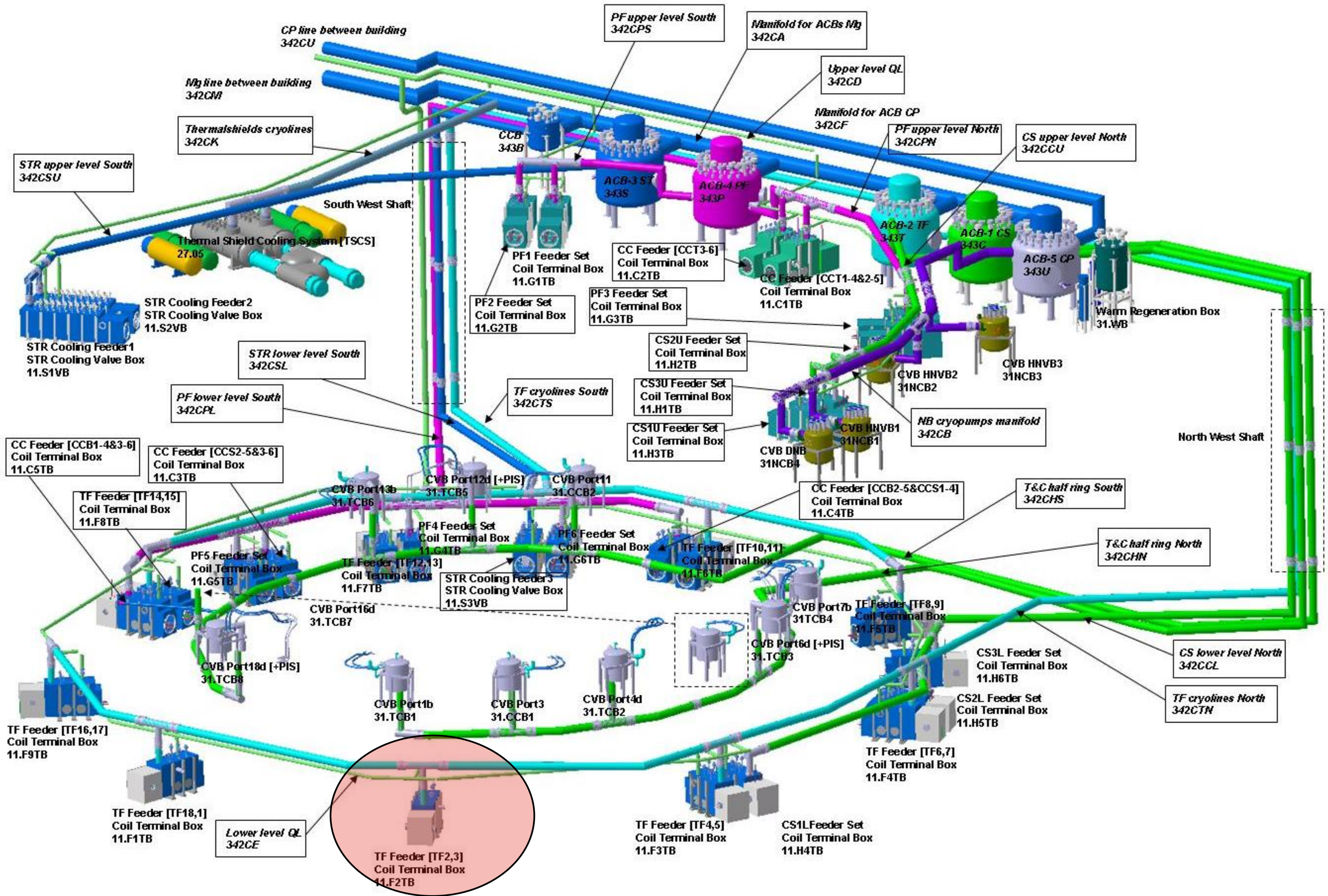
ITER Cryogenic System



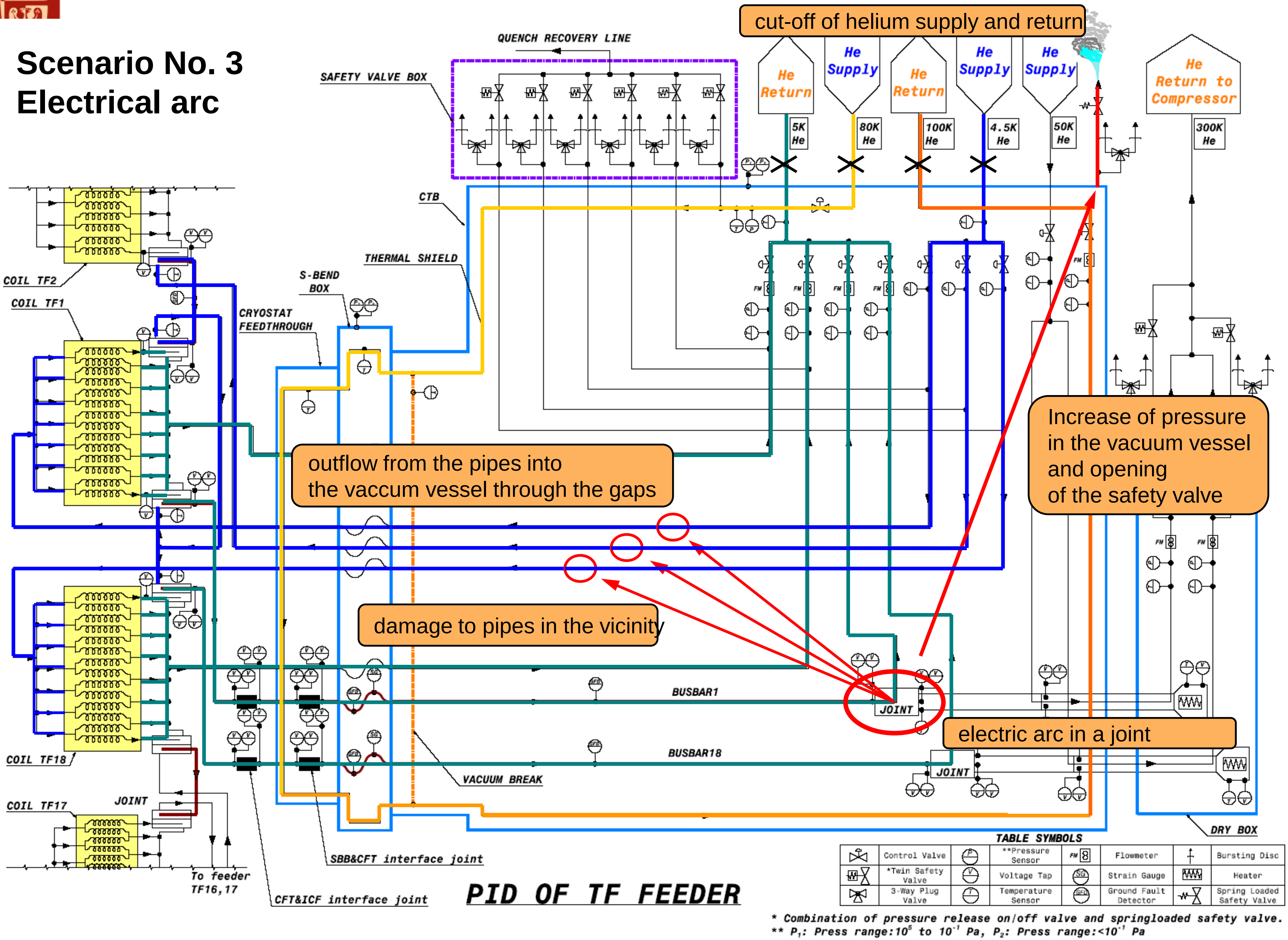
Scheme of the ITER cryogenic nodes



ITER Cryodistribution System in the tokamak building



Scenario No. 3
Electrical arc



Steps in Risk Analysis of cryogenic systems

1. **Identification of the cryogenic system nodes, their design and operation features,**
2. **Identification of the locations of the nodes in the site facilities,**
3. **Analysis of the potential failures and the determination of credible incidents (risk factors, frequency of occurrence, level of detestability, importance of defects),**
4. **Identification of credible scenarios for chosen components and the analysis of their potential causes and consequences,**
5. **Specification of the most credible incident and most credible scenario,**
6. **Dynamics simulations of the most credible and severe helium leakages to the vacuum insulation and to the environment (including oxygen deficiency hazard and the influence of cold helium impact on mechanical structures),**
7. **Proposal for the mitigation of the most credible incident consequences,**
8. **Formulation of remedial actions.**

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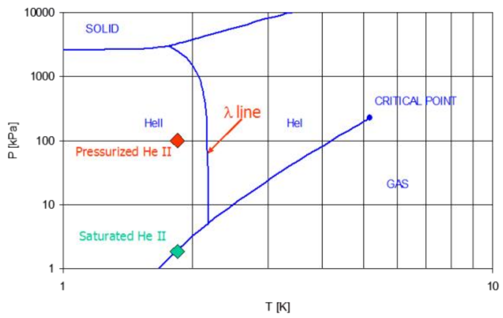
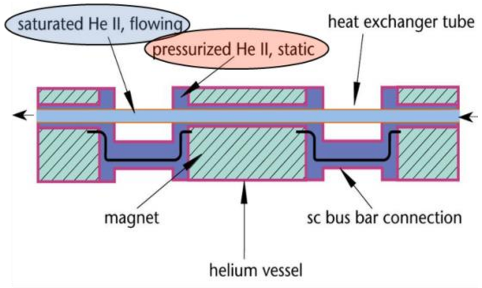
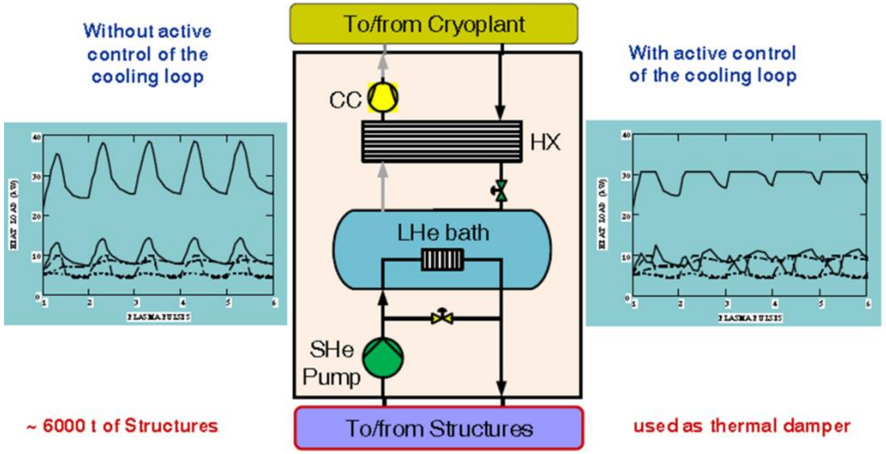
Modelling of helium flows to vacuum insulation space - two cases

CASE 1 – magnets immersed in static helium – e.g. LHC

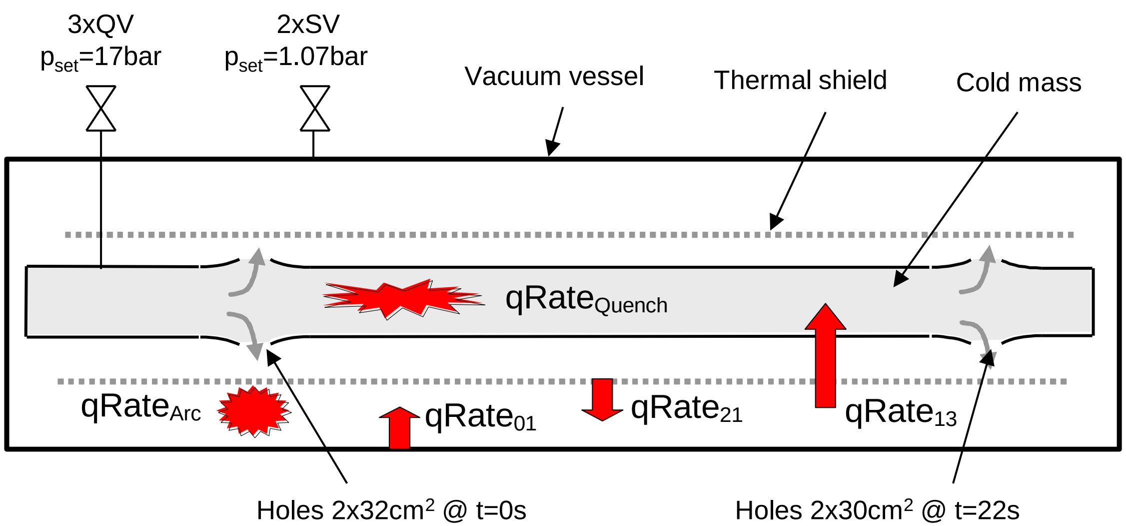




CASE 2 – coils cooled by helium flow (supercritical) –e.g. ITER



Development of mathematical model of the processes in static helium (e.g. LHC)



$$\frac{d(M \cdot u)}{dt} = \sum dq + \sum d(m \cdot h)$$

Lumped parameter approach, thermodynamic model input:

$qRate_{Quecnch}$ – heat transfer to Cold Mass helium from quenched magnets

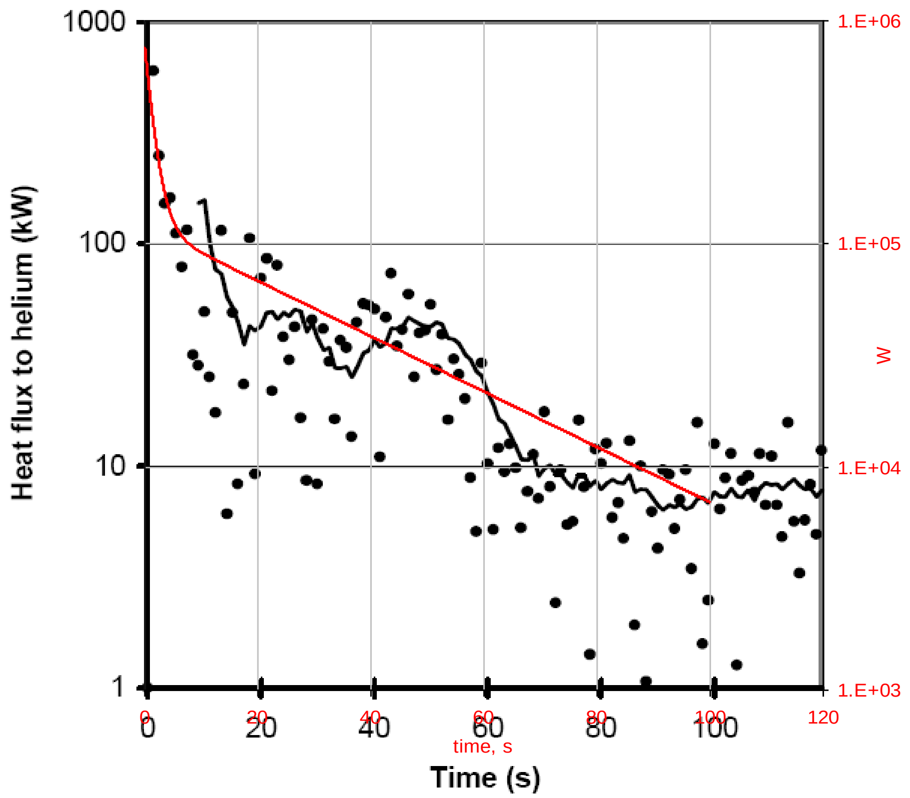
$qRate_{Arc}$ – heat transfer to helium from electrical arc

$qRate_{01}$ – heat transfer to Vacuum helium form Vacuum Vessel

$qRate_{21}$ – heat transfer to Vacuum helium form Aluminum Shield

$qRate_{13}$ – heat transfer to Cold Mass helium from Vacuum helium

Magnet quench heat transfer to cold mass helium - data from String experiments

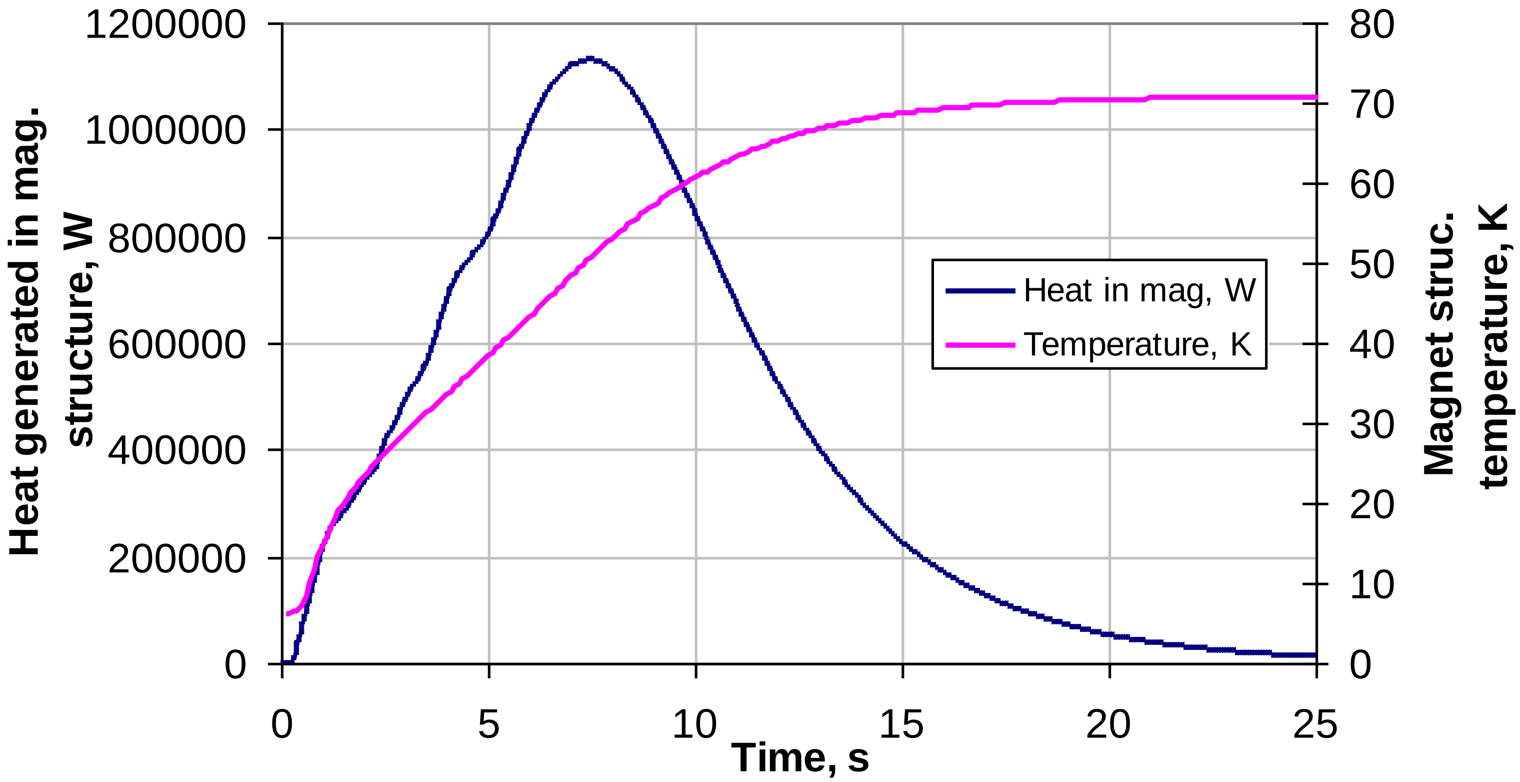


Data can be scaled according to the equation

$$E_{mag} = \frac{1}{2} L \cdot I^2$$

M. Chorowski, P. Lebrun, L. Serio, R. van Weelderen - *Thermohydraulics of Quenches and Helium Recovery in the LHC Magnet Strings* - LHC Project Report 154

Exemplary calculation of magnet structure temperature for 10 MJ coil

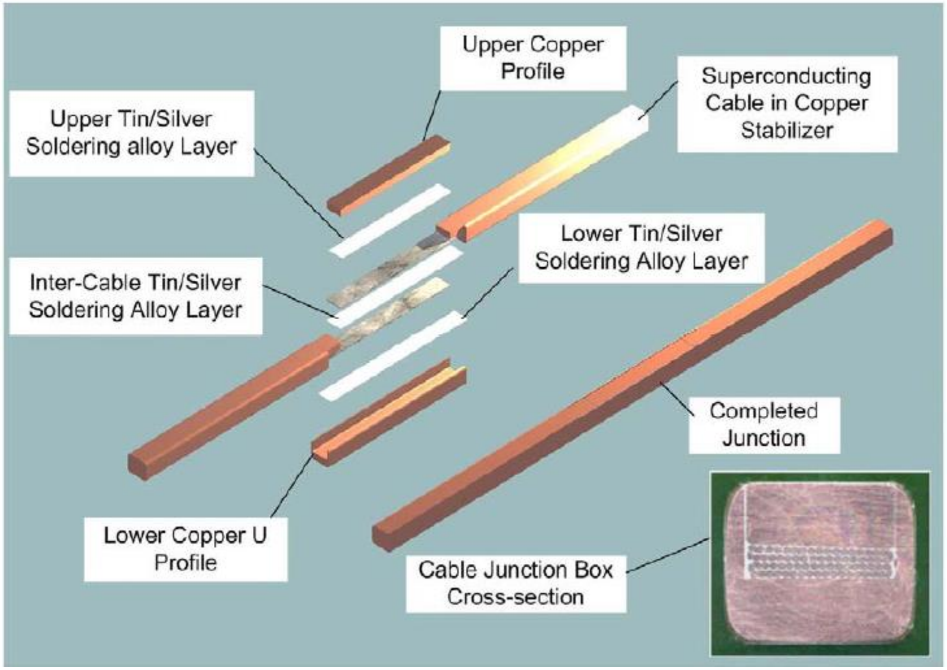


$$E = L\int_0^I i\,di \quad \Rightarrow \quad Q_{mag} = \frac{dE}{dt}$$

Magnet current decay characteristics must be known

Electrical arc

An electrical arc can origin at faulty joint of superconducting cables. The phenomenon leads to rapid and uncontrolled energy transfer from the magnet to helium and metal structure forming the second electrode.



Bajko M., et.al., Report of the task force on the incident of 19 September 2008 at the LHC, LHC Project Report 1168, Geneva, 31/03/2009

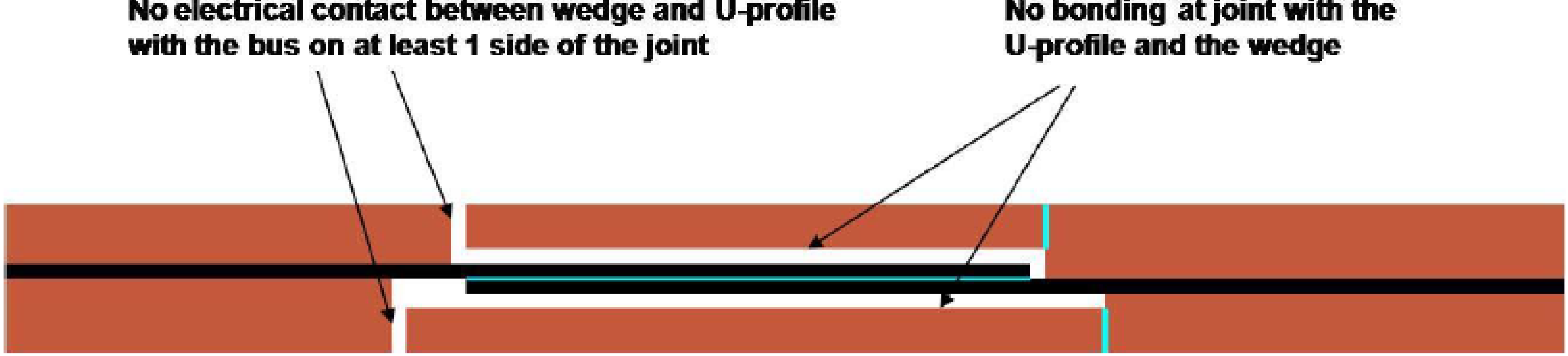
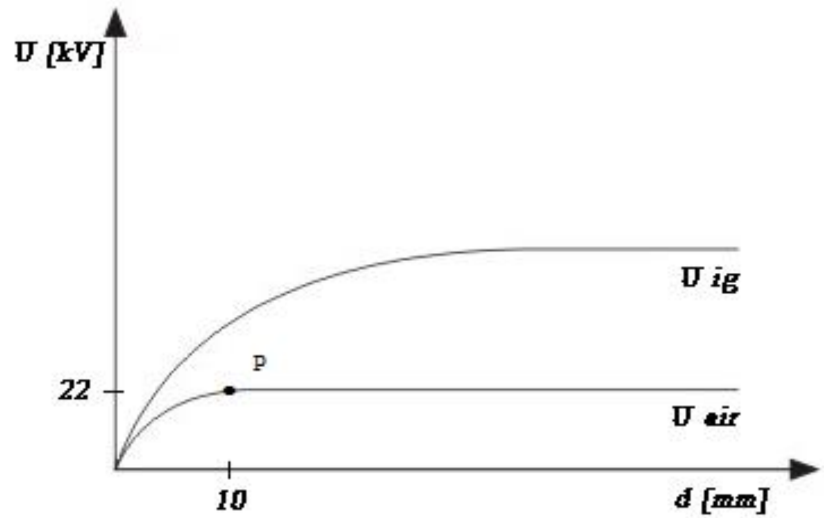


Figure 7: Model of resistive joint in bus bar
with bad electrical and thermal contact with the stabilizer

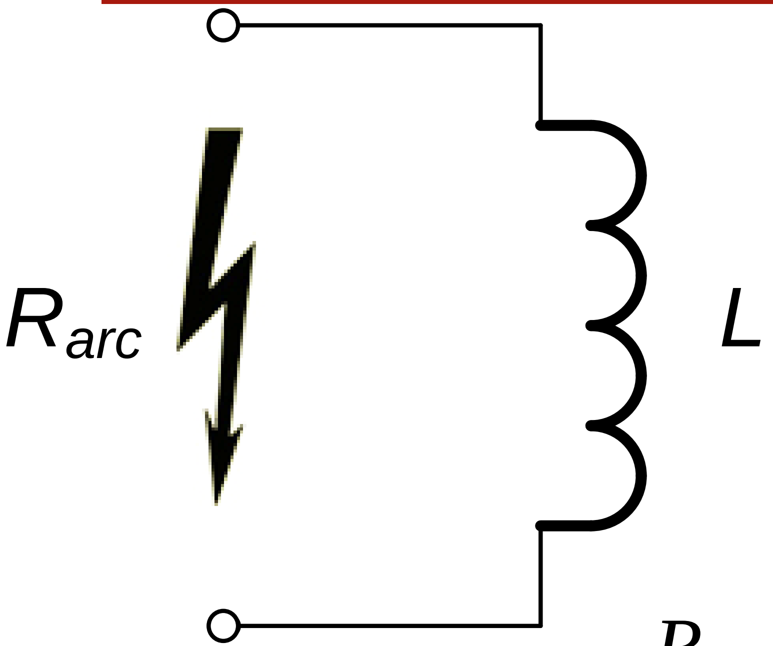
LHC interconnection



Evolution of ignition voltages with respect to distances between electrodes

Bajko M., et.al., Report of the task force on the incident of 19 September 2008 at the LHC, LHC Project Report 1168, Geneva, 31/03/2009

Electrical arc modelling



$$iR + L\frac{di}{dt} = 0$$

$$R_{arc} = \frac{dU_{arc}}{di_{arc}}$$

$$R_{arc} = \frac{1443.57 \cdot l}{i}$$

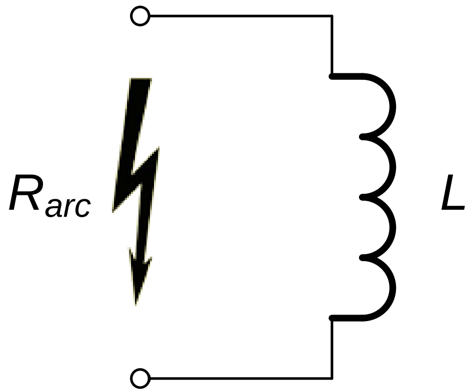
Warrington formula

l **is the arc length**

$$i(t) = i_0 e^{-\frac{R}{L}t}$$

$$u(t) = u_s \cdot e^{-k\frac{R}{L}t}$$

Electrical arc modelling



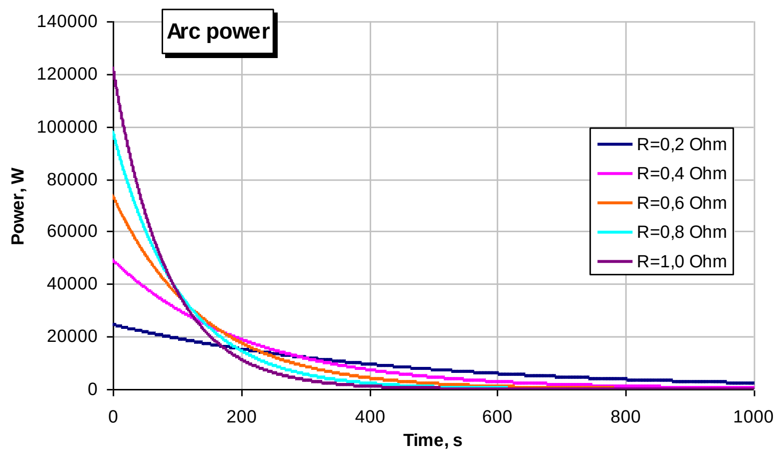
$$P(t) = u(t) \cdot i(t) \quad P(t) = P(0) e^{\frac{R}{L}t} e^{-k\frac{R}{L}t}$$

Arc power

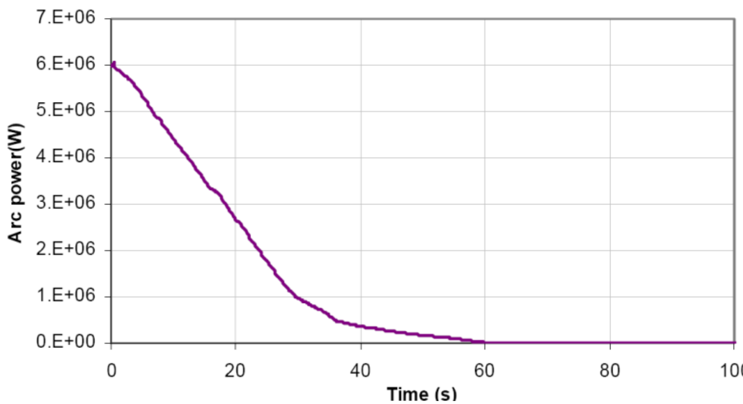
$$W = P(t)dt$$

The energy relieved by the arc

Evolution of the arc power - examples



Low current, 10 MJ magnet, calculated



Heat flux resulting from electrical arc during the 19th September 2008 incident for the initial arc current 8.7 kA

Arc energy distribution

1. **Heating and melting resulting in perforation of the cold vessel or cryostat tube,**
2. **Arc atmosphere (helium) ionization, heating and pressurization,**

The ratio IONIZATION / ELECTRODE in helium is estimated as: 50 : 1

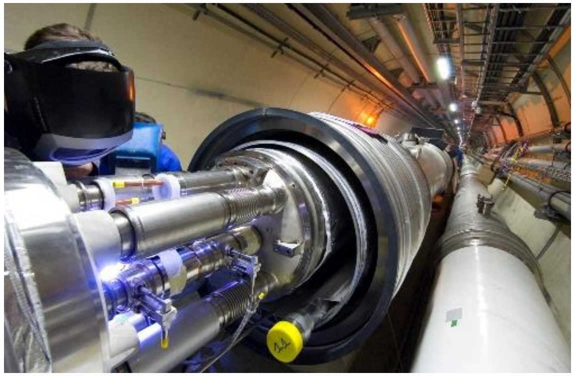
Cold vessel rupture by electrical arc

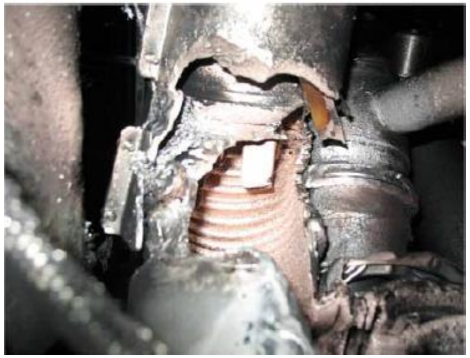
$$d(t) = \sqrt{\frac{4W_w(t)}{\left(\int_{4.5K}^{1700K} c_p \, dT + r\right)\pi \cdot \rho \cdot z}}$$

The diameter *d* of the melted breach

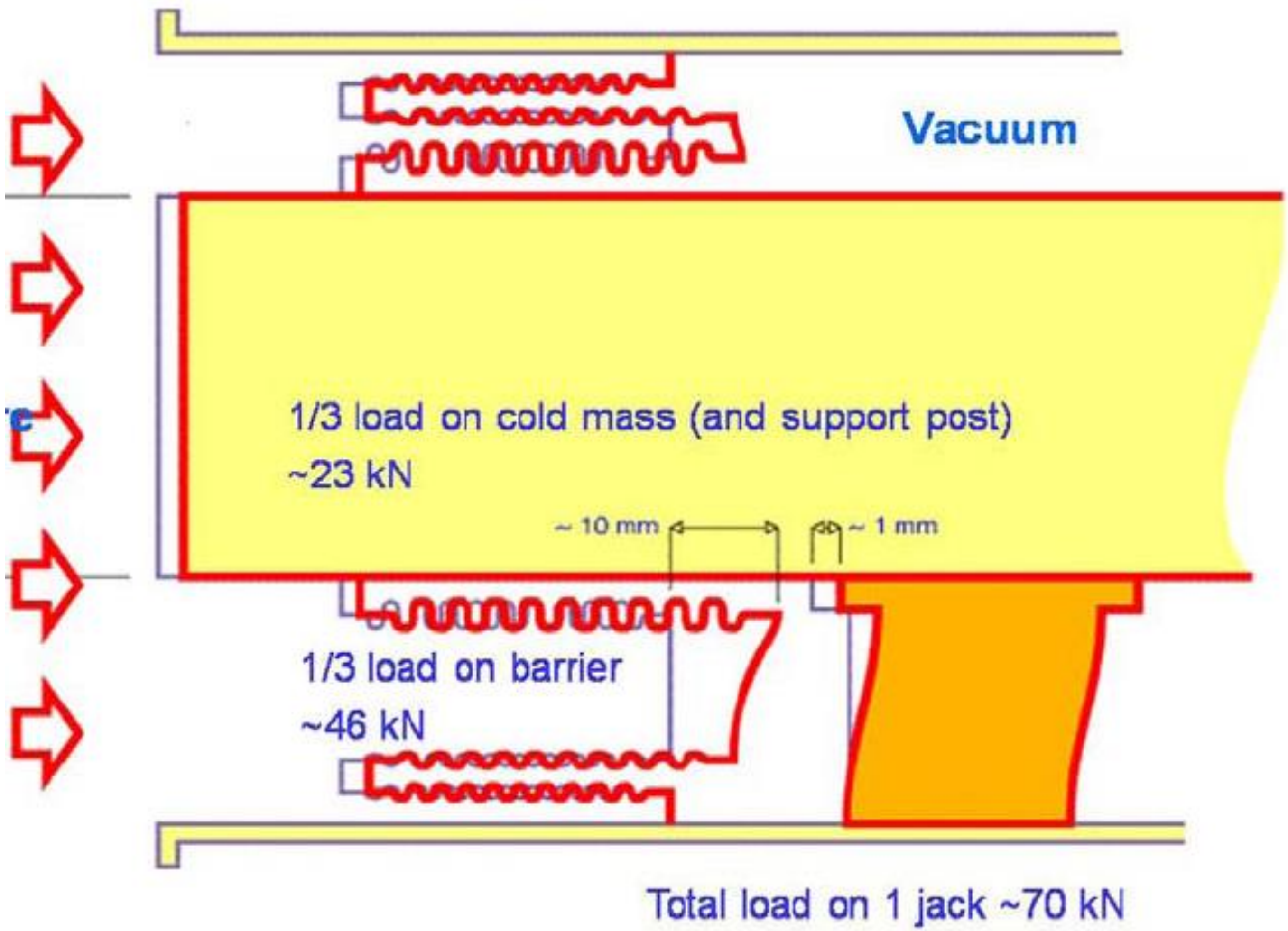
For 10 MJ of a stored inductive energy and a wall thickness of 6 mm, the expected hole diameter is 57 mm

During the 19. September incident 273 MJ of energy have been dissipated by arcs. At least 5 kg of stainless steel could have been melted, what justifies the observed breaches in helium and vacuum tubes.





Above 90% of the arc energy is transferred to pressurization of the vacuum space



Damage caused by the pressurization of the vacuum space

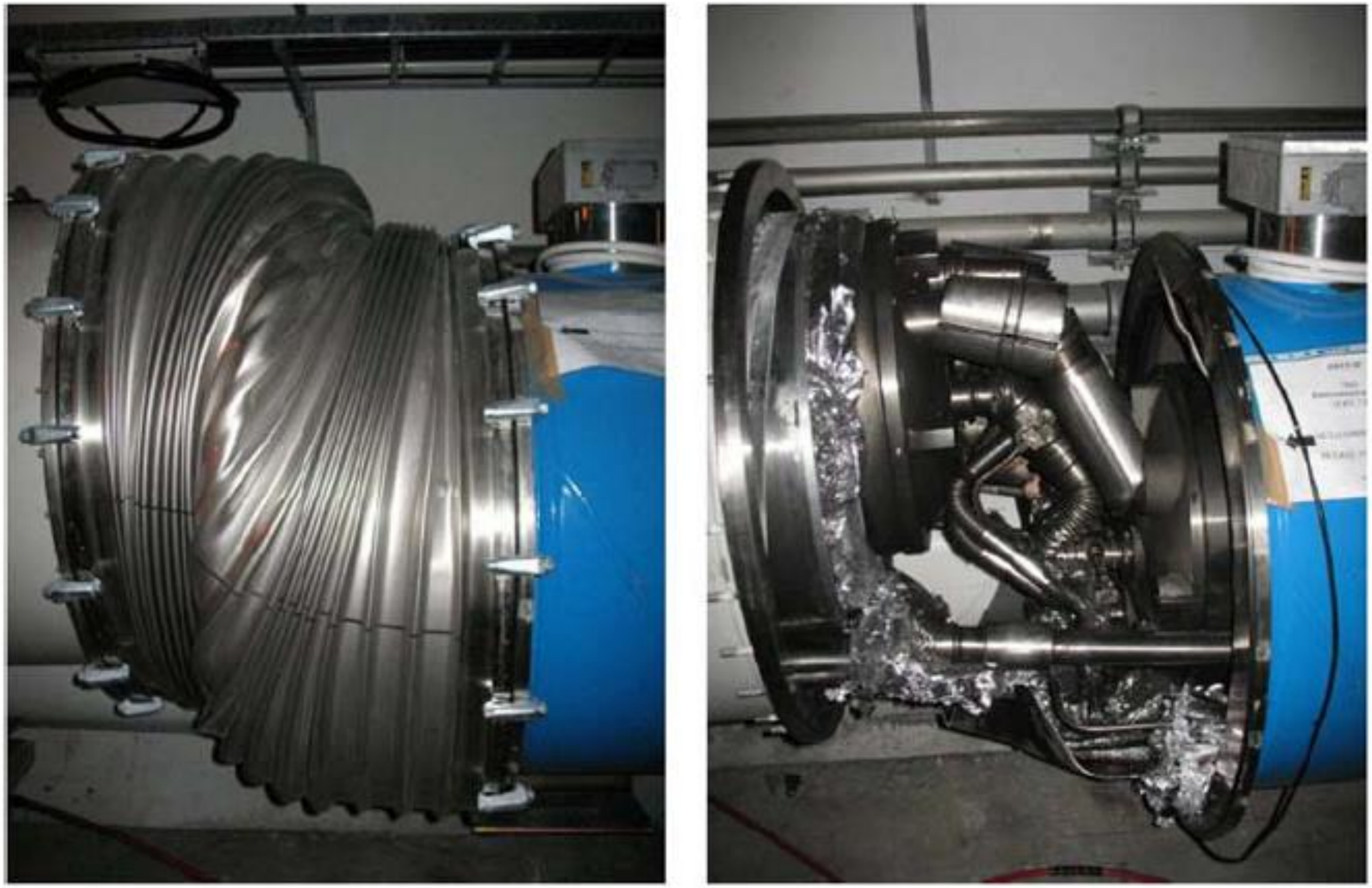


Figure 14: Damage to interconnection QQBI.27R3 by excess compression

Convective heat transfer in relieved helium filled space

Heat transfer from Vacuum Vessel to Vacuum helium – Q_{Rate01}

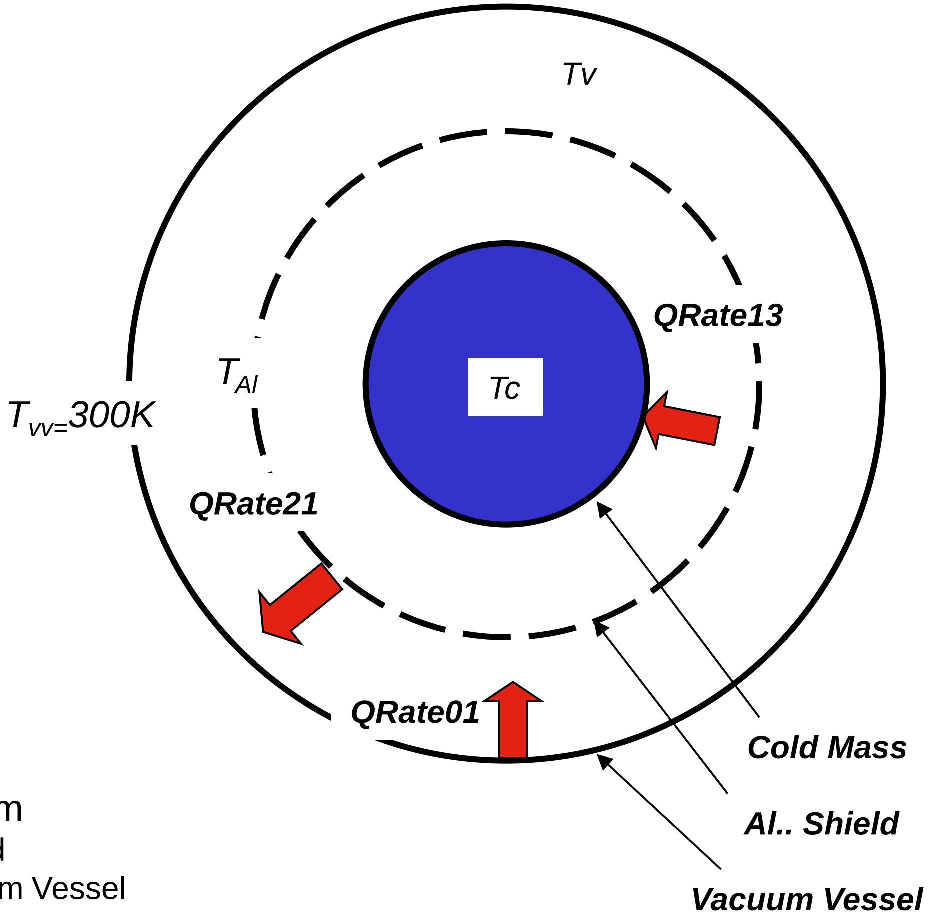
$$Q_{Rate01} = A_{vv} \cdot h_{01} \cdot (T_{vv} - T_v)$$

Heat transfer from Aluminum Shield to Vacuum helium – Q_{Rate21}

$$Q_{Rate21} = 2 \cdot A_{Al} \cdot h_{01} \cdot (T_{Al} - T_v)$$

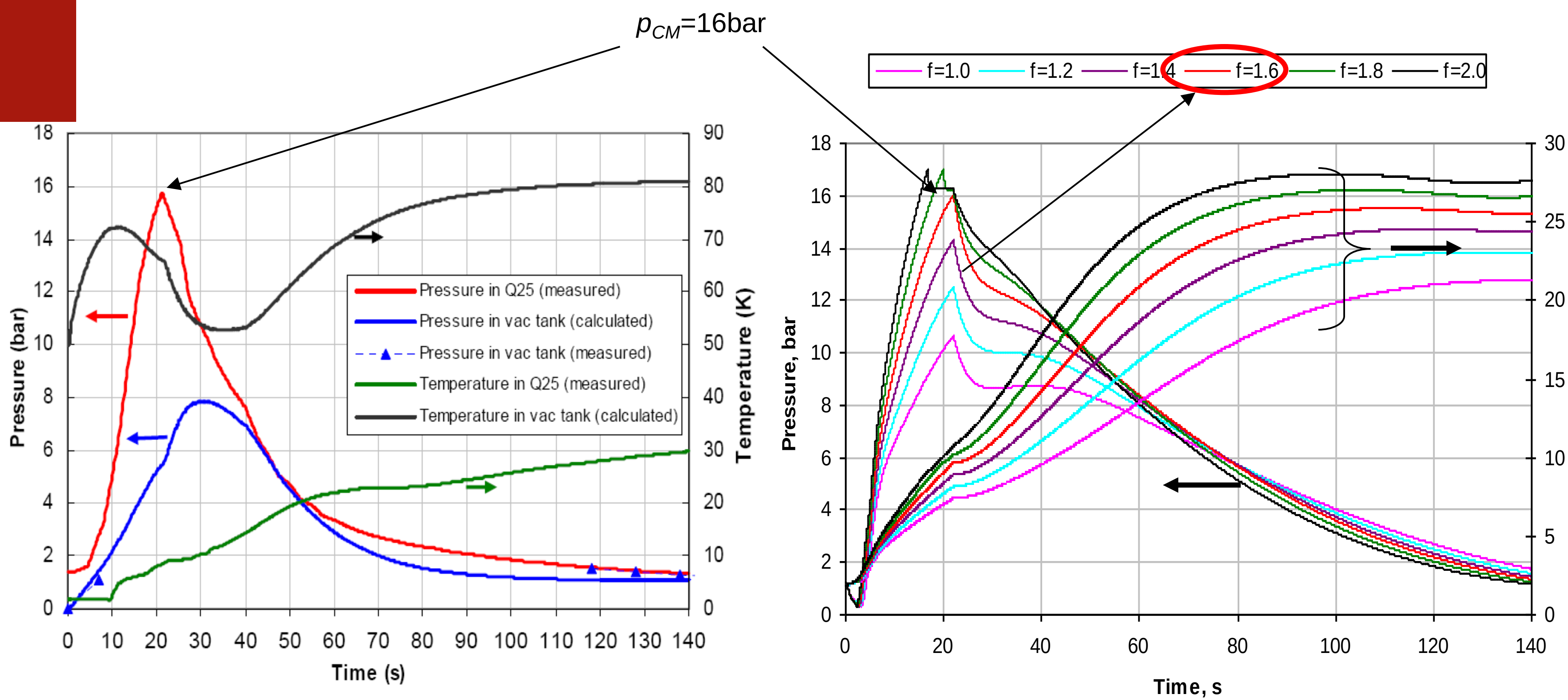
Heat transfer from Vacuum helium to Cold Mass helium – Q_{Rate13}

$$Q_{Rate13} = A_{Al} \cdot h_{13} \cdot (T_v - T_c)$$



T_c, T_v – helium temperature in Cold Mass, Vacuum
T_{Al}, T_{vv} –temperature of Vacuum Vessel, Aluminum Shield
A_c, A_{Al}, A_{vv} – area of Cold Mass, Aluminum Shield, Vacuum Vessel

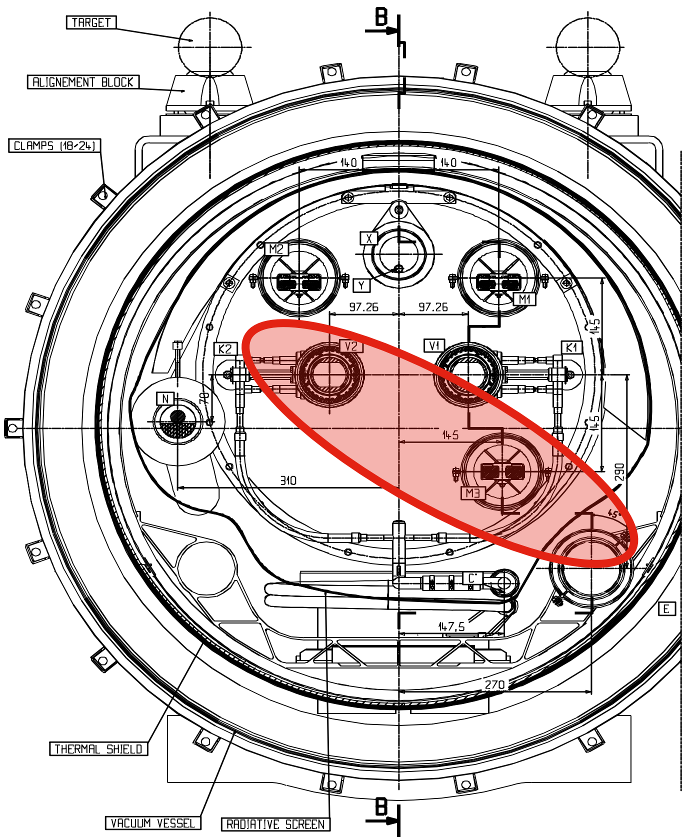
Model tuning - the only parameter to tune the model was the natural convection heat transfer coefficient



Measured and calculated data for 080919 LHC failure

Evolution of the helium temperature and pressure in Cold Mass

Modelling of 19. Sept. 08 incident



Sequence of events

19. Sept. 08 Incident

Time	Event
t=0	M3 pipe break, hole area: 2x32 cm^2 caused by Electrical arc at I=8.7kA
t=5s	Quench of 4 magnets for I=8.7kA
t=22s	pipe break, hole area: 2x30 cm^2

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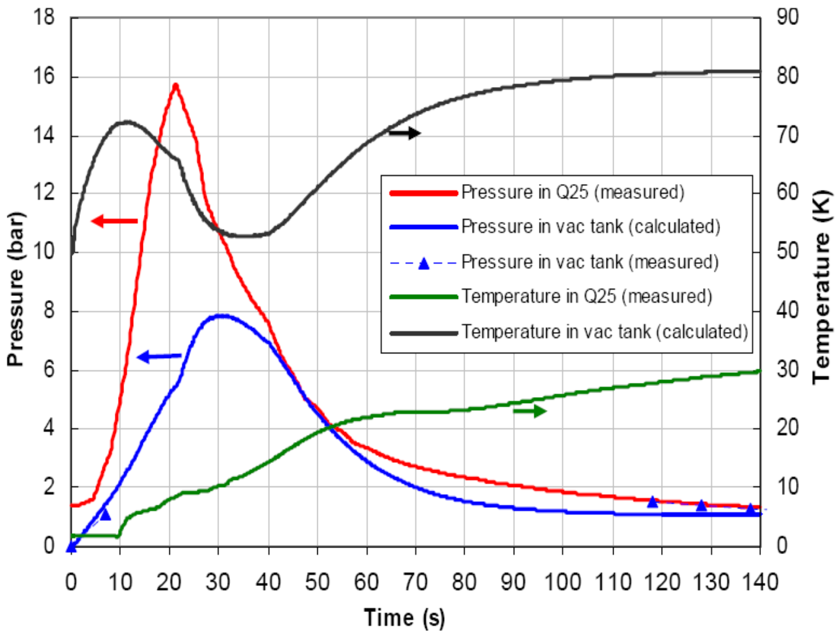
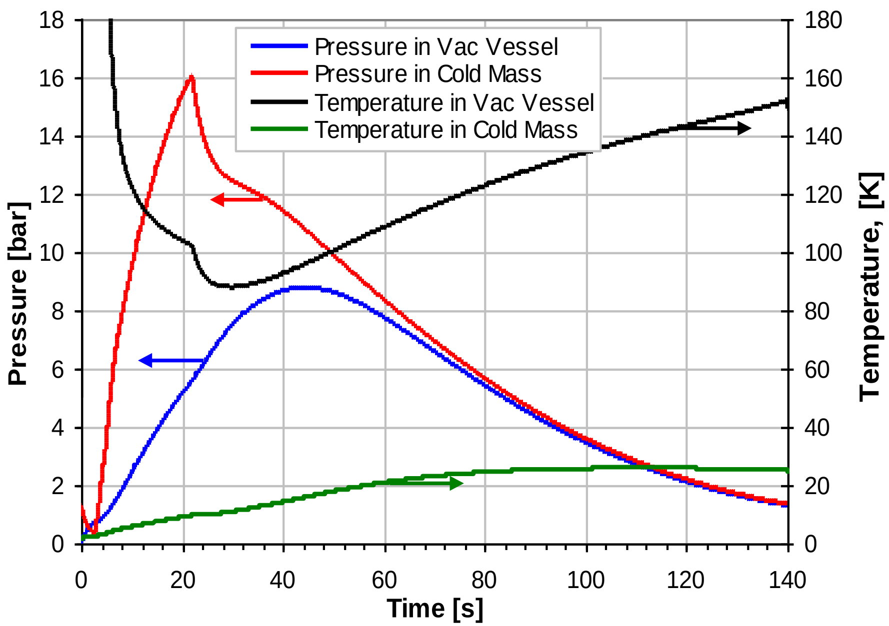
Model validation: 19. Sept. 08 incident modeling results vs. measured data

CERN data



Measured and calculated data for the 19. Sept. 08 incident (*LHC Project Report 1168*)

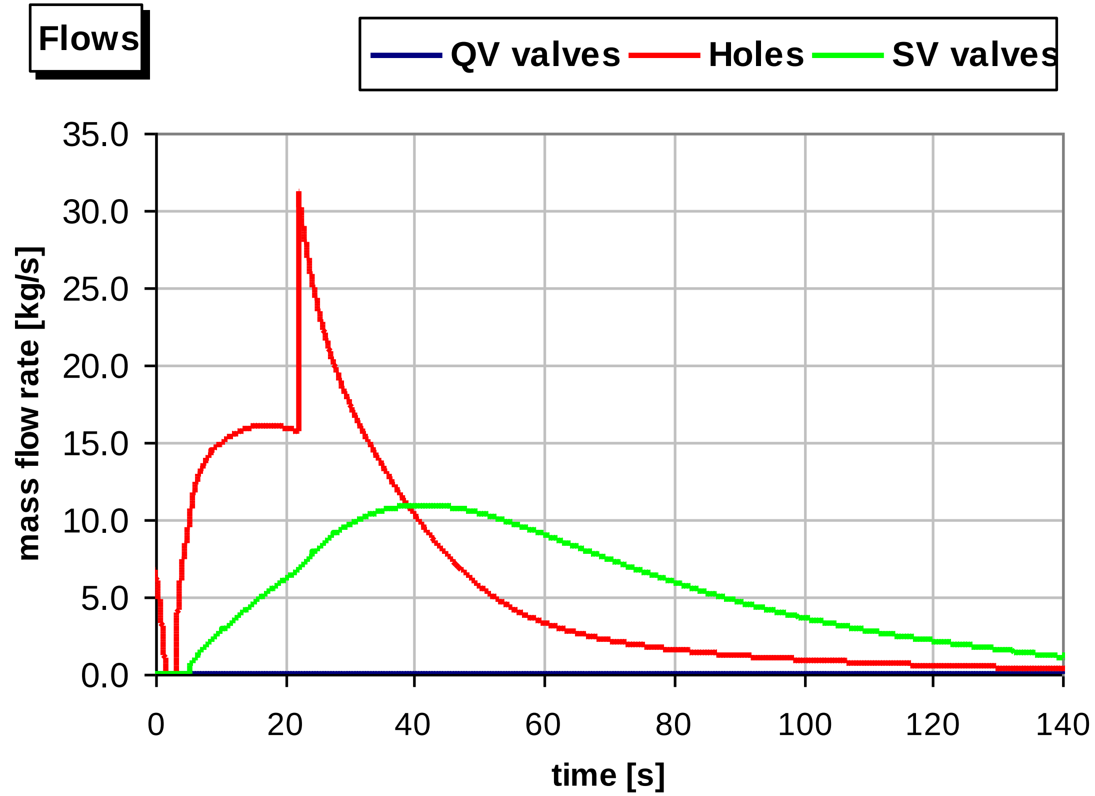
WUT calculations



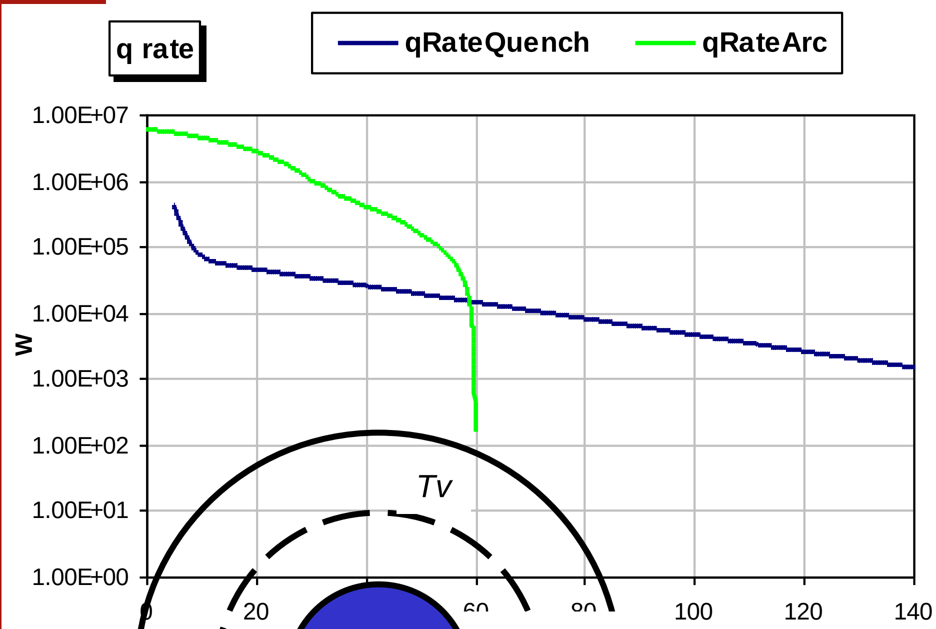
Modeling results

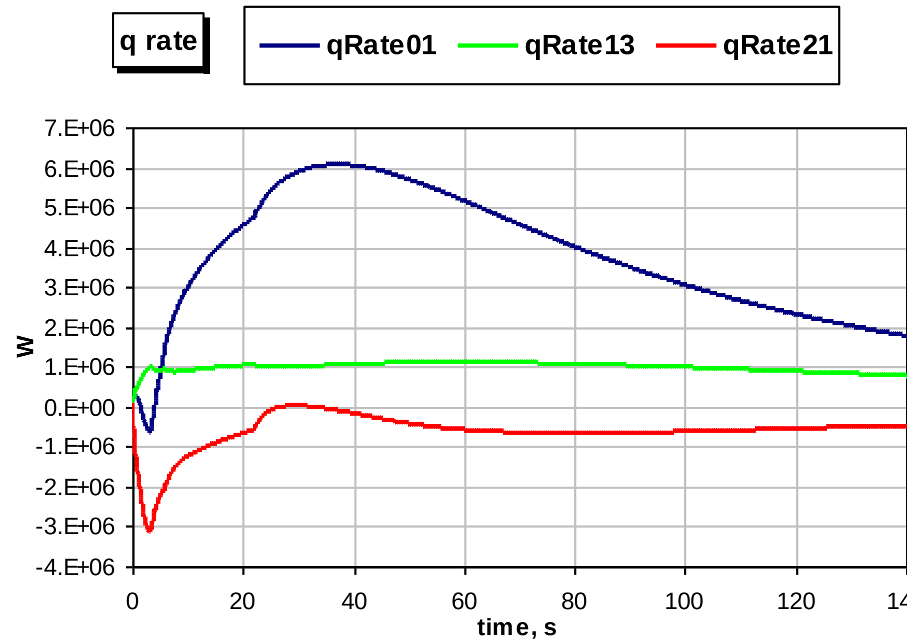
19. Sept. 08 incident - He mass flows through the holes and SV: modeling results

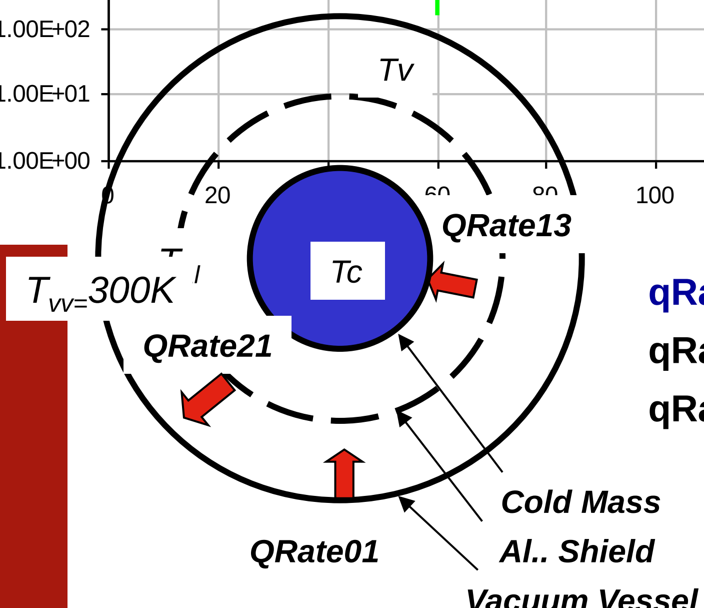
19. Sept.08 incident	
Time	**Event**
t=0	M3 pipe break, hole area: 2x32 cm^2 Electrical arc at I=8.7kA
t=5s	Quench of 4 magnets for I=8.7kA
t=22s	pipe break, hole area: 2x30 cm^2



19. Sept. 08 incident - heat transfer modeling results







$qRate_{01}$ – heat transfer to Vacuum helium form Vacuum Vessel

$qRate_{21}$ – heat transfer to Vacuum helium form Aluminum Shield

$qRate_{13}$ – heat transfer to Cold Mass helium from Vacuum helium

Vacuum vessel safety valves (SV) schemes

Prior to 19.Sept. 08 incident SV scheme

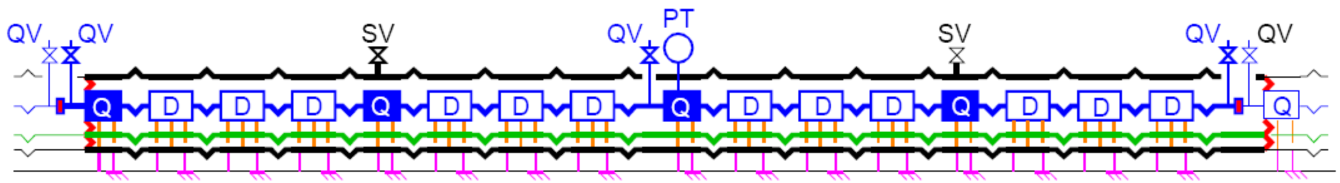
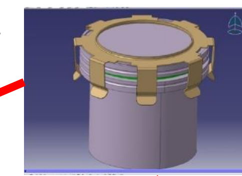


Figure L2: Present SV scheme: 2 DN90 SV. Discharge cross section: 127 cm^2



Final SV scheme

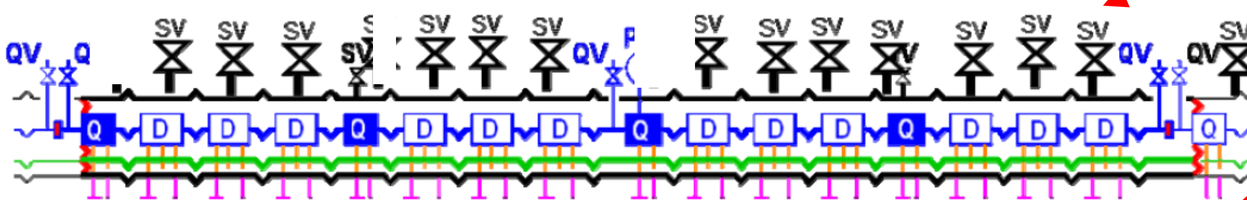


Figure L3: Final SV scheme: 1 added DN200 SV on each dipole, PRS. Discharge cross section: 4190 cm^2

Temporary SV scheme

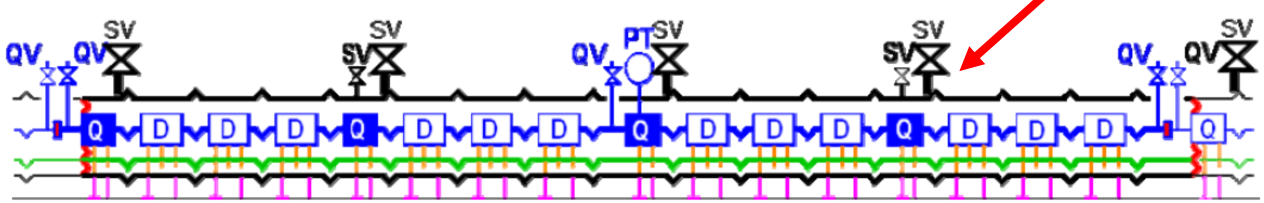
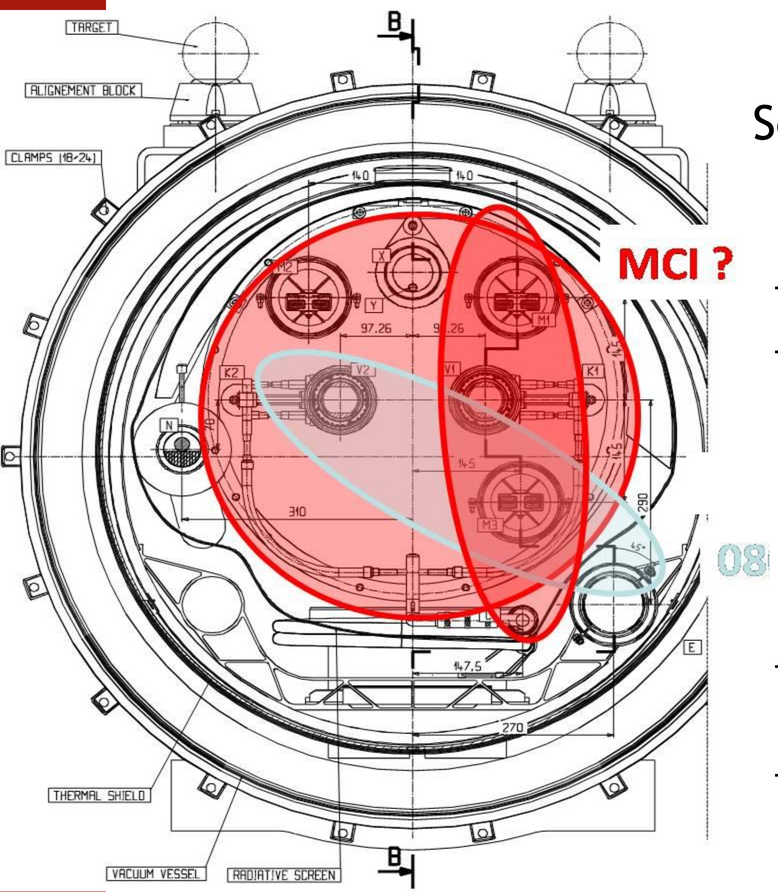


Figure L4: Temporary SV scheme for cold sectors, using PRS: 2 DN90 SV, 13 DN100 SV, . Discharge cross section: 1270 cm^2

Maximum Credible Incident analysis



Sequence of events – comparison with 19. Sept. inc.

19 Sept. 08 incident

Time	Event
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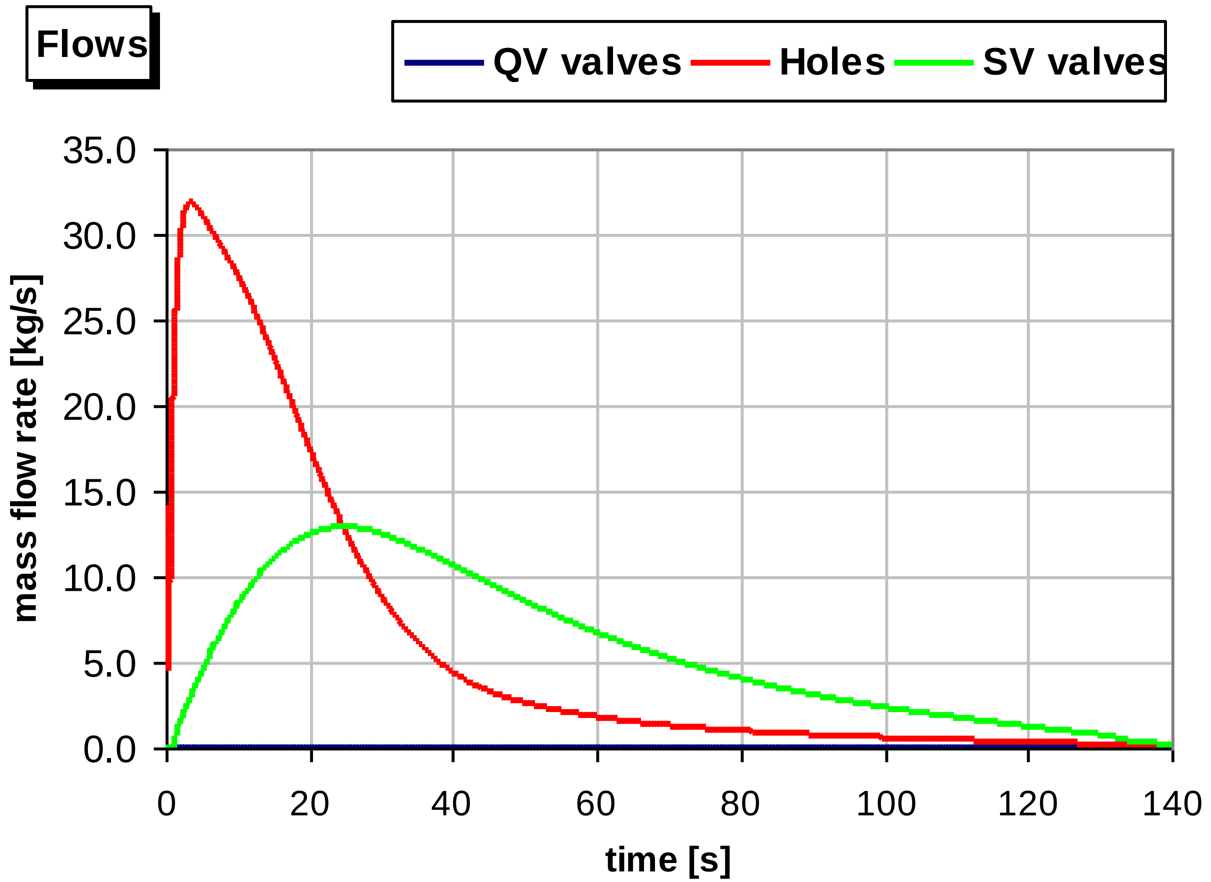
t=5s	Quench of 4 magnets for I=8.7kA
t=22s	pipe break, hole area: 2x30 cm^2

MCI

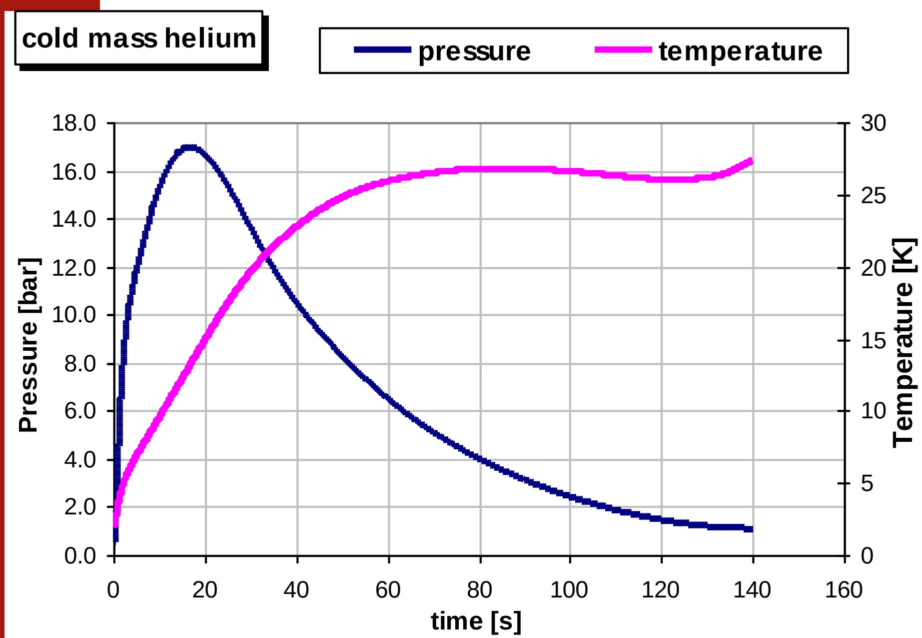
Time	Event
t=0	Pipe break with total area of the holes: 6x32 cm^2 = 192 cm^2 but Cold Mass free flow area is 60cm^2 and Quench of all (16) magnets at I=13.1kA caused by Electrical arc at I=13.1kA

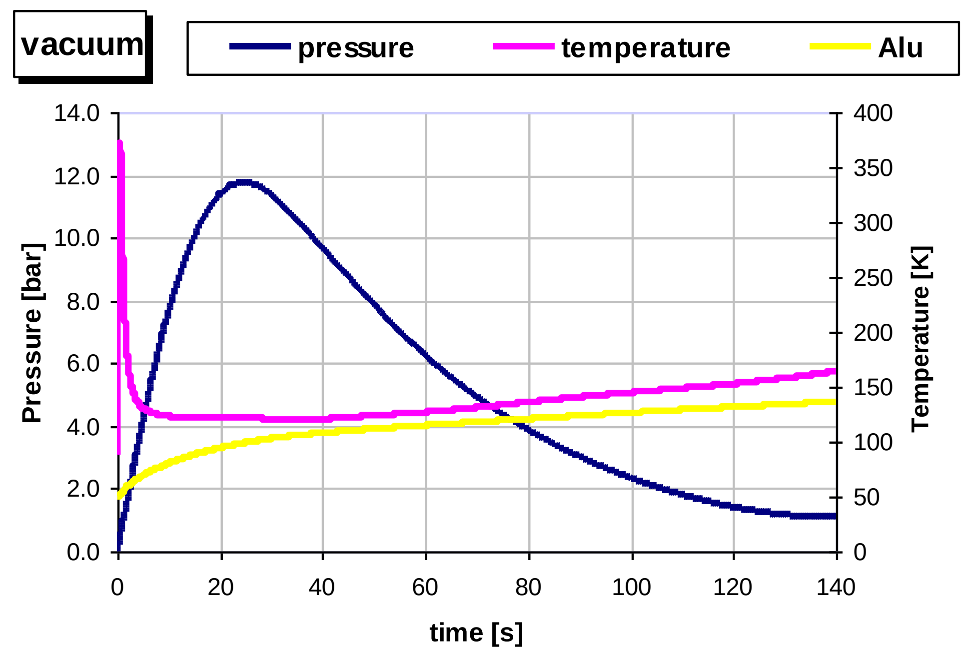
Modeling results for MCI with SV scheme prior to 19. Sept. 08 incident



Helium mass flow thought holes, SV and QV valves

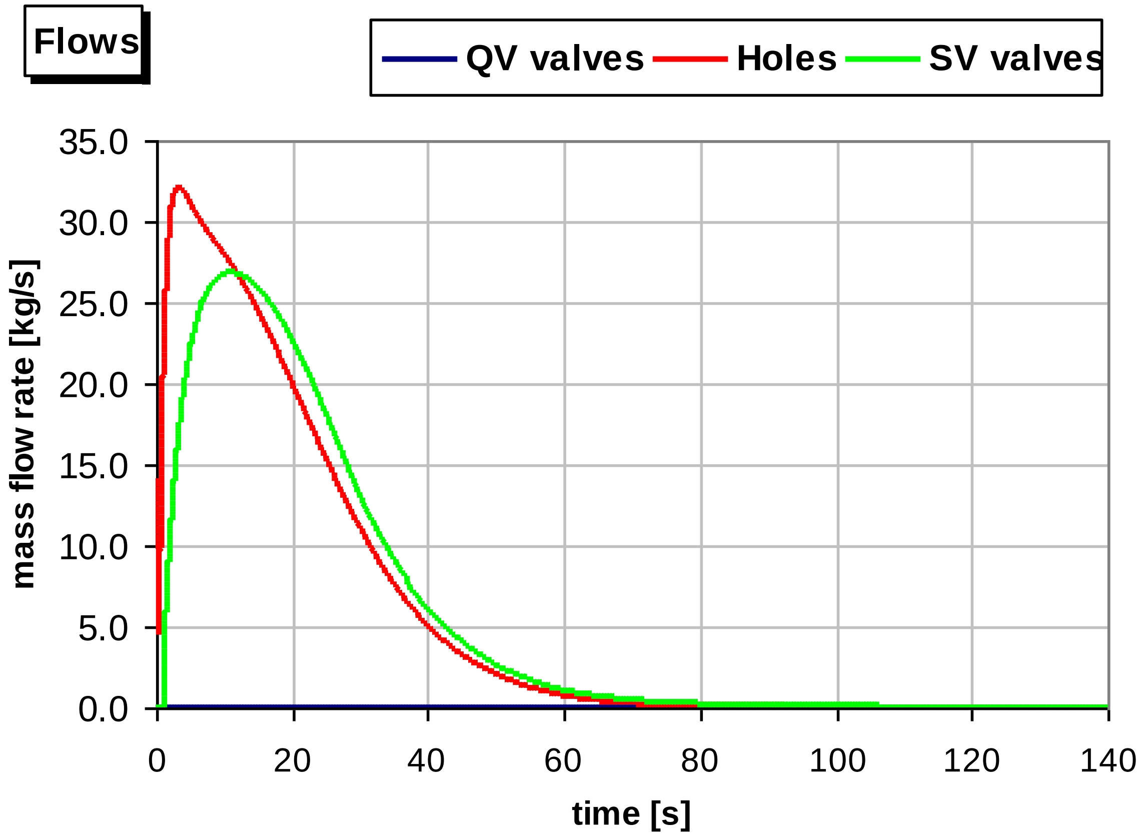
Modeling results for MCI with SV scheme prior to 19. Sept. 08 incident





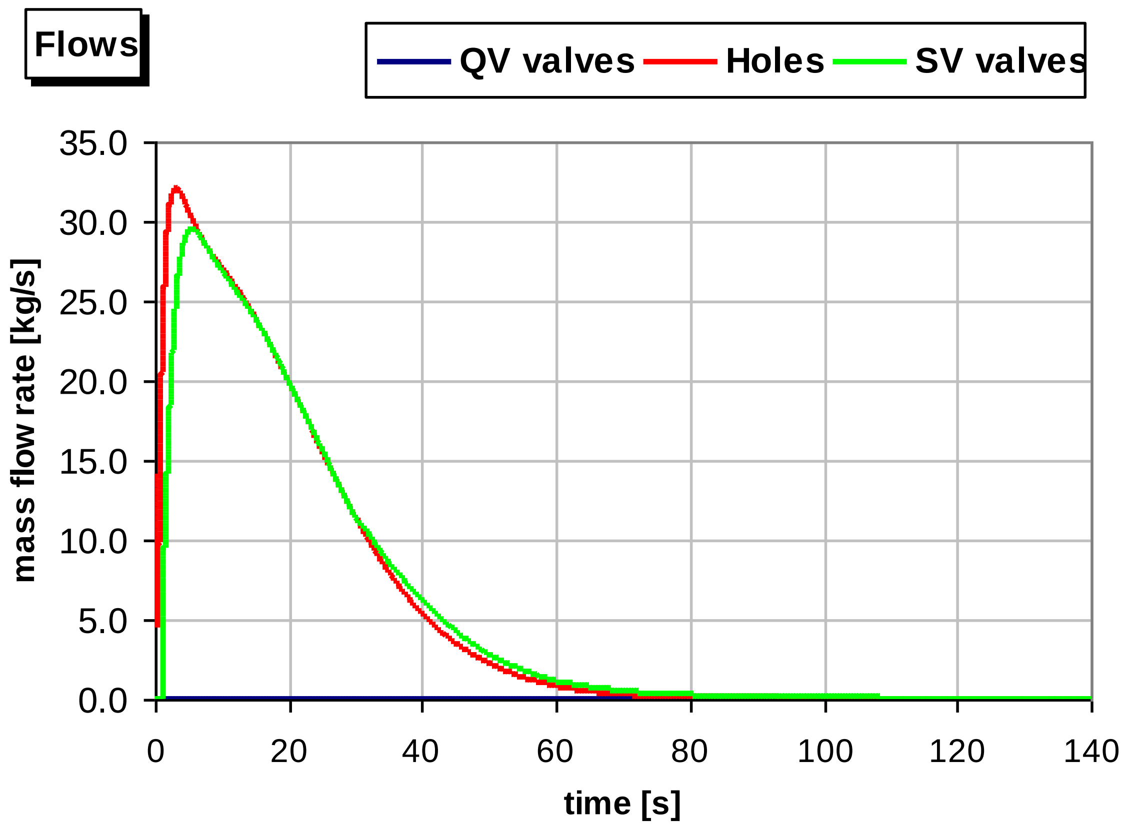
Evolution of helium pressure and temperature in Cold Mass (left) and Vacuum Vessel (right) + evolution Al. Shield temperature (right)

Modeling results for MCI with temporary SV scheme



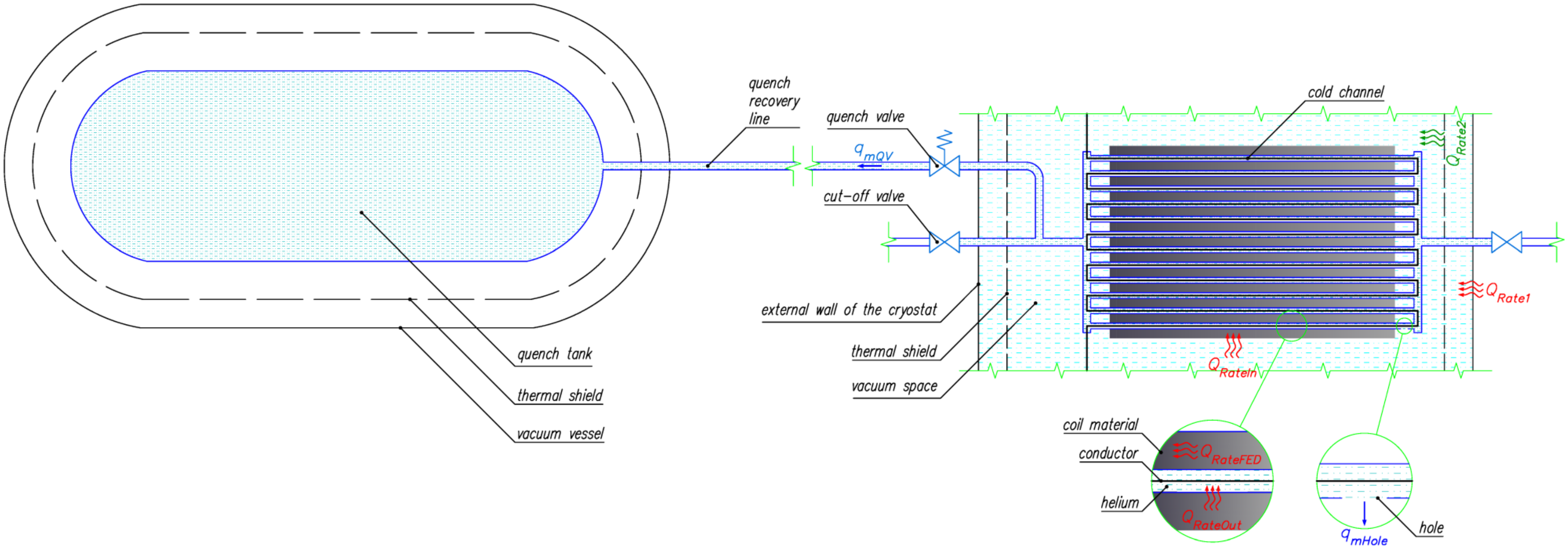
Helium mass flow thought holes, SV and QV valves

Modeling results for MCI with final SV scheme



Helium mass flow thought holes, SV and QV valves

Simplified scheme of cryostated cable-in-conduit coil - ITER

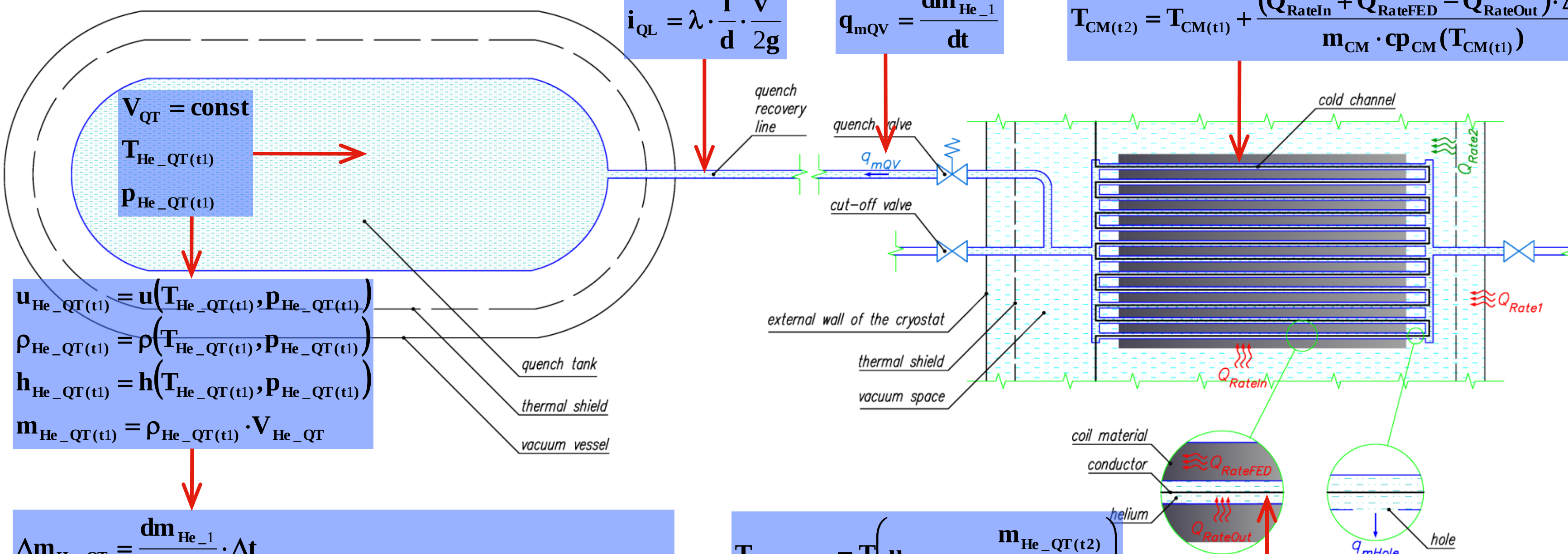


Simplified scheme of cryostated cable-in-conduit coil - ITER

$$i_{QL} = \lambda \cdot \frac{l}{d} \cdot \frac{v^2}{2g}$$

$$q_{mQV} = \frac{dm_{He\_1}}{dt}$$

$$T_{CM(t2)} = T_{CM(t1)} + \frac{\left(Q_{RateIn} + Q_{RateFED} - Q_{RateOut}\right)\cdot \Delta t}{m_{CM} \cdot cp_{CM}\left(T_{CM(t1)}\right)}$$



$$V_{QT} = const$$
$$T_{He\_QT(t1)}$$
$$p_{He\_QT(t1)}$$

$$u_{He\_QT(t1)} = u\left(T_{He\_QT(t1)}, p_{He\_QT(t1)}\right)$$
$$\rho_{He\_QT(t1)} = \rho\left(T_{He\_QT(t1)}, p_{He\_QT(t1)}\right)$$
$$h_{He\_QT(t1)} = h\left(T_{He\_QT(t1)}, p_{He\_QT(t1)}\right)$$
$$m_{He\_QT(t1)} = \rho_{He\_QT(t1)} \cdot V_{He\_QT}$$

$$\Delta m_{He\_QT} = \frac{dm_{He\_1}}{dt} \cdot \Delta t$$
$$m_{He\_QT(t2)} = m_{He\_QT(t1)} + \Delta m_{He\_QT}$$
$$u_{He\_QT(t2)} = \frac{m_{He\_QT(t1)} \cdot u_{He\_QT(t1)} + Q_{Rate1} + \Delta m_{He\_QT} \cdot h_{He\_QT(t1)}}{m_{He\_QT(t1)}}$$

$$T_{He\_QT(t2)} = T\left(u_{He\_QT(t2)}, \frac{m_{He\_QT(t2)}}{V_{QT}}\right)$$
$$p_{He\_QT(t2)} = p\left(u_{He\_QT(t2)}, \frac{m_{He\_QT(t2)}}{V_{QT}}\right)$$

$$q_{mHole} = \frac{dm_{He\_2}}{dt}$$

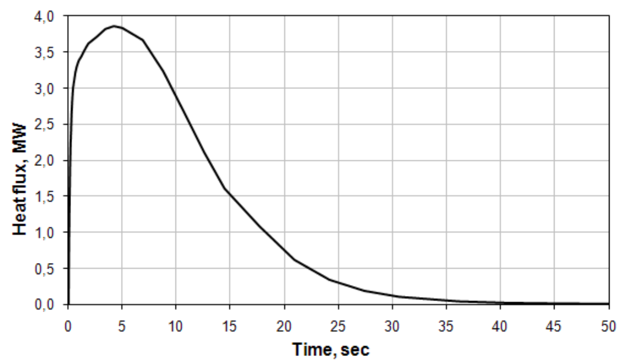
$$V_{He} = const$$
$$T_{He(t1)}$$
$$p_{He(t1)}$$

$$u_{He(t1)} = u\left(T_{He(t1)}, p_{He(t1)}\right)$$
$$\rho_{He(t1)} = \rho\left(T_{He(t1)}, p_{He(t1)}\right)$$
$$h_{He(t1)} = h\left(T_{He(t1)}, p_{He(t1)}\right)$$
$$m_{He(t1)} = \rho_{He(t1)} \cdot V_{He}$$

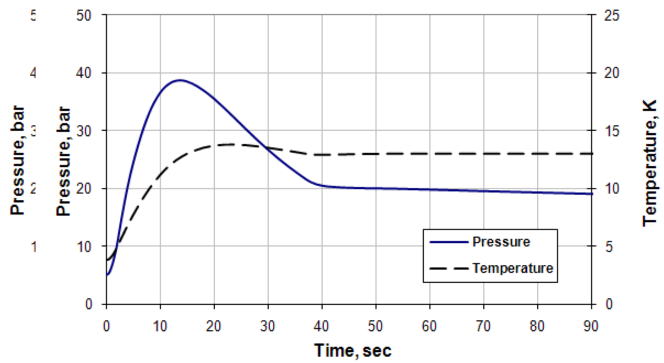
$$\Delta m_{He} = -\frac{dm_{He\_1} + dm_{He\_2}}{dt} \cdot \Delta t$$
$$m_{He(t2)} = m_{He(t1)} + \Delta m_{He}$$
$$u_{He(t2)} = \frac{m_{He(t1)} \cdot u_{He(t1)} + Q_{RateIn} + \Delta m_{He} \cdot h_{He(t1)}}{m_{He(t1)}}$$

$$T_{He(t2)} = T\left(u_{He(t2)}, \frac{m_{He(t2)}}{V_{He}}\right)$$
$$p_{He(t2)} = p\left(u_{He(t2)}, \frac{m_{He(t2)}}{V_{He}}\right)$$

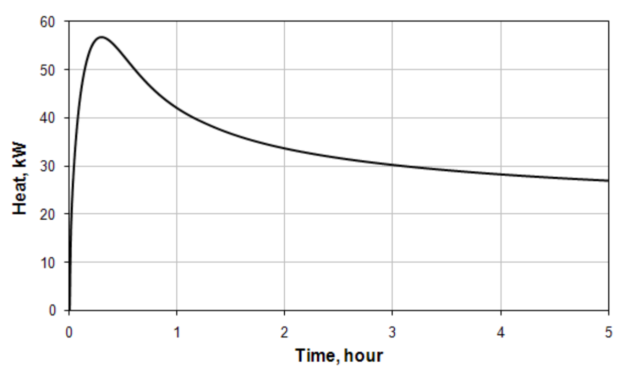
Results of the numerical simulaction



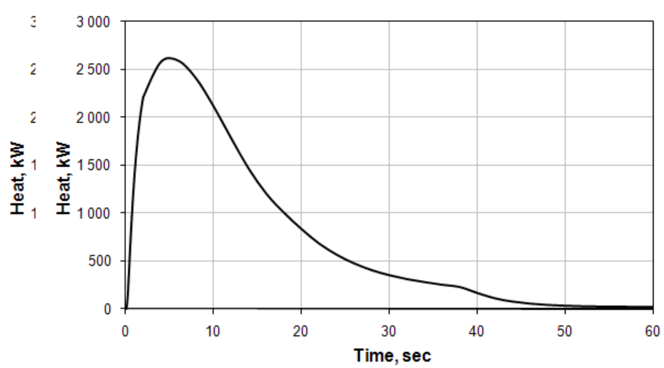
Evolution of deposited feat flux to the coil during fast energy discharge



Evolution of the temperature and pressure of the helium in the cold channel of the coil after unsealing of the coil housing during the fast energy discharge

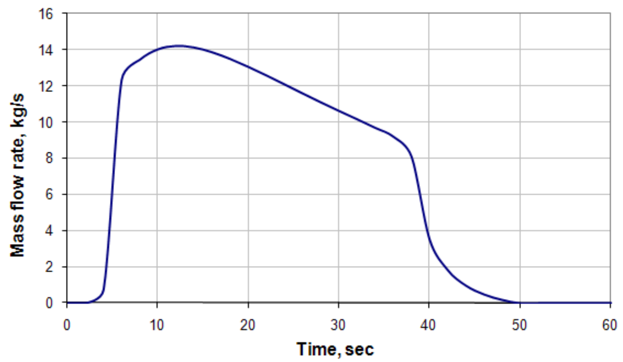


Evolution of the heat flux penetrating the metal structure of the magnet after unsealing of the coil housing during the fast energy discharge

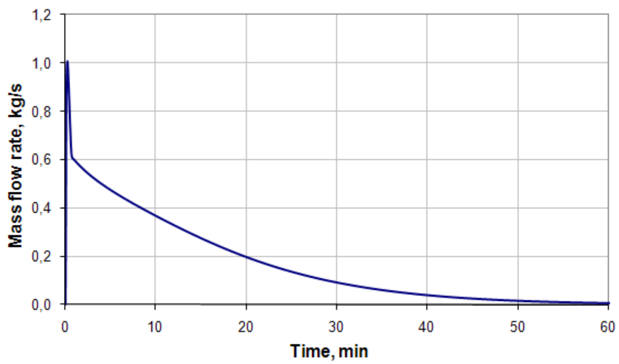


Evolution of the heat flux heating the helium inside the cold channel after unsealing of the coil housing during the fast energy discharge

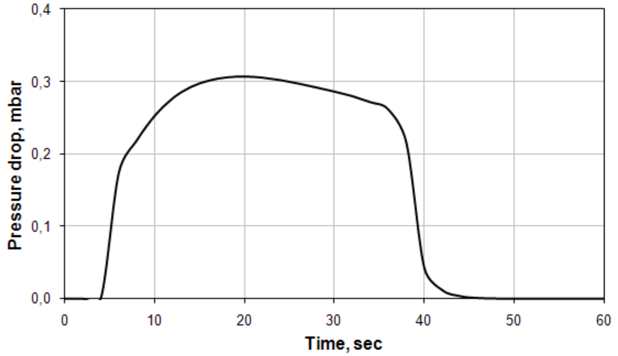
Results of the numerical simulaction



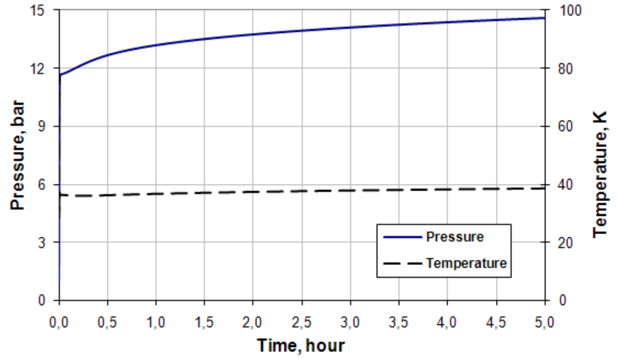
Evolution of the helium mass flow rate through the safety valve of the coil to the external gasbag after unsealing of the coil housing during the fast energy discharge



Evolution of the helium mass flow rate through the hole in one cold channel to the vacuum space of the cryostat



Evolution of the helium pressure drop inside the quench recovery line after unsealing of the coil housing during the fast energy discharge



Evolution of the temperature and pressure of the helium in the quench tank for the helium outflow from the magnet after unsealing of the coil housing during the fast energy discharge

Test rig of a cryogenic system failure

Electo
coor

He

Nitr

ety valve

/acuum vessel

Relief valve

Thermal shield

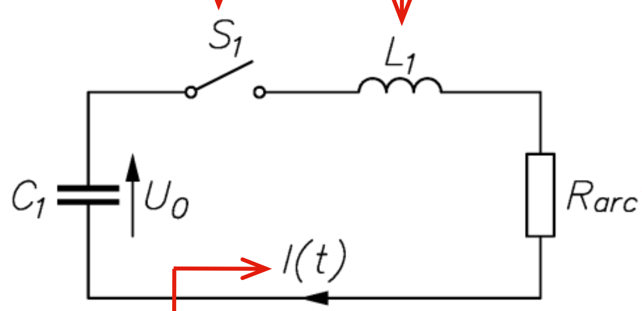
RLC circuit generating electric arc

Switching element, which is initiating generation of the electric arc

Inductor slowing down the dI/dt ratio of current pulses

Capacitors battery charged by a high voltage supply to a nominal voltage U_0, amount of the stored energy

$$E_{C1} = \frac{1}{2} \cdot U_0^2 \cdot C_1$$



$$L_1 \frac{d^2 I}{dt^2} + Rarc \frac{dI}{dt} + \frac{I}{C_1} = 0$$

Resistance of electric arc which depends on the value of the current flowing in the circuit

$$Rarc(I) = \frac{a \cdot L}{I^n}$$

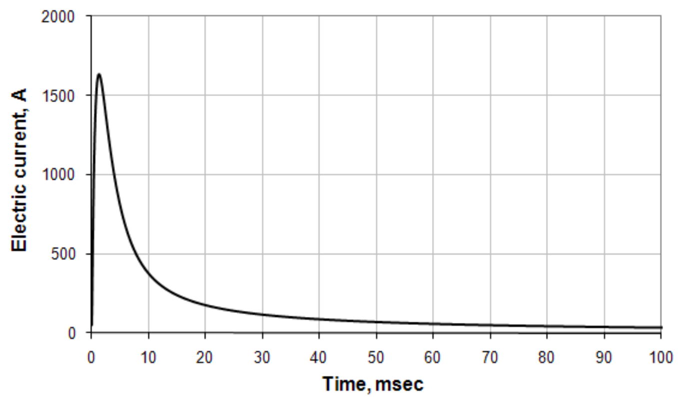
Warrlington formula
a,n – constants,
I – electric current,
L – arc length

Energy from the electric arc to the environment

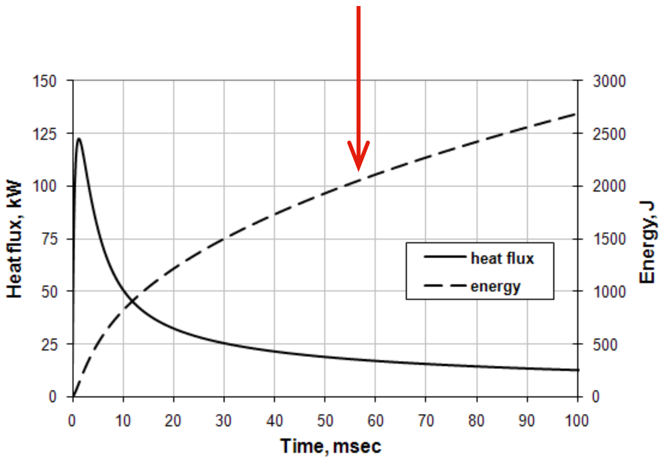
$$E_{arc} = R_{arc}(J) \cdot J(t)^2 * dt$$

Results of numerical modelling of RLC circuit generating electric arc

The curve of dispersed energy is approaching to 5kJ



Waveform of the current pulse in the RLC circuit model



Changes of energy and heat flux from the electric arc to the environment

Values of passive elements:
C_1 = 10mF
L_1 = 300uH
R_L = 500 mΩ
Nominal initial value voltage of C_1:
U_0 = 1kV

Conclusions

1. To perform risk analysis of cryogenic systemit is necessary to model heat and flow processes in the cold mass helium and vacuum space.
2. A 0D with elements of 1D model enabled the reproduction of the 19. September 2008 incident.
3. The model has been used to scale helium relief system in a number of cases, including LHC and ITER.
4. Electrical arc has been modelled with RL circuit analogy.
5. A dedicated test rig enabling validation of heat transfer from different sources including electrical arc is under construction.