Wrocław University of Technology

Approach to modeling of the fast energy discharge in cryogenic systems in the form of an electric arc

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Cryogenic Safety- HSE seminar

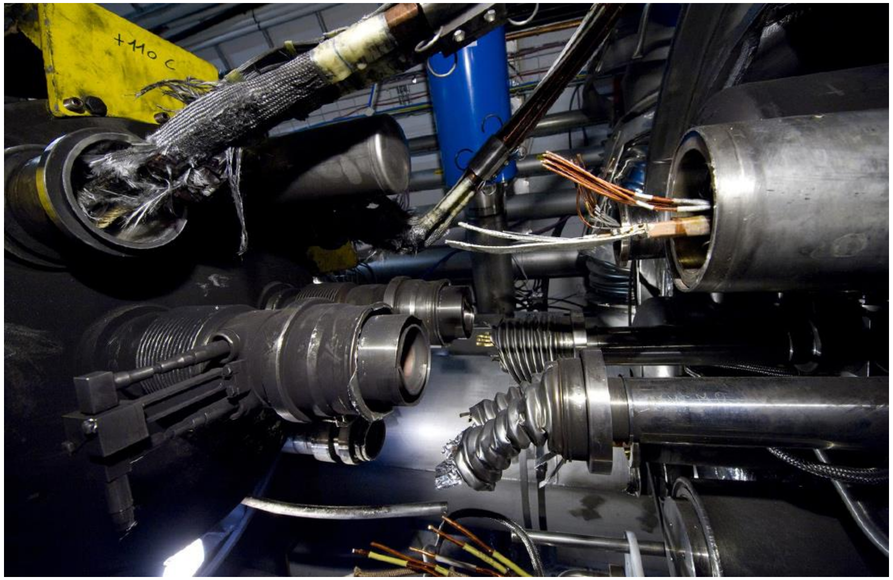
CERN, 21.09.2016

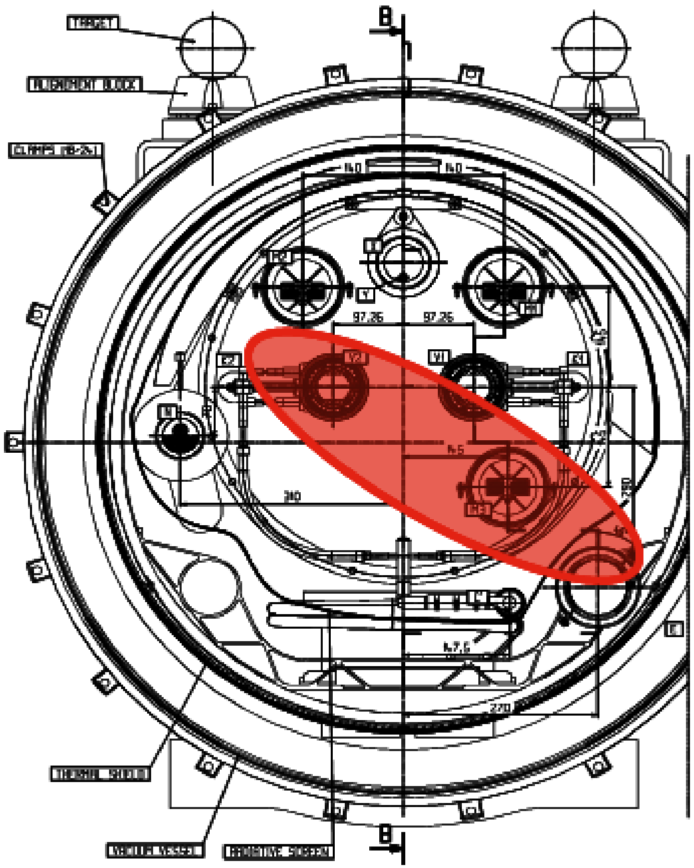
Outline

- Problem's background
- Theoretical approach for estimation of the energy discharge by electric arc
- Temperature and fluid type influance one the electric arc ignition
- WUST test setup description
- Conclusions

Problem's background

080919 incident in the LHC sector 3-4





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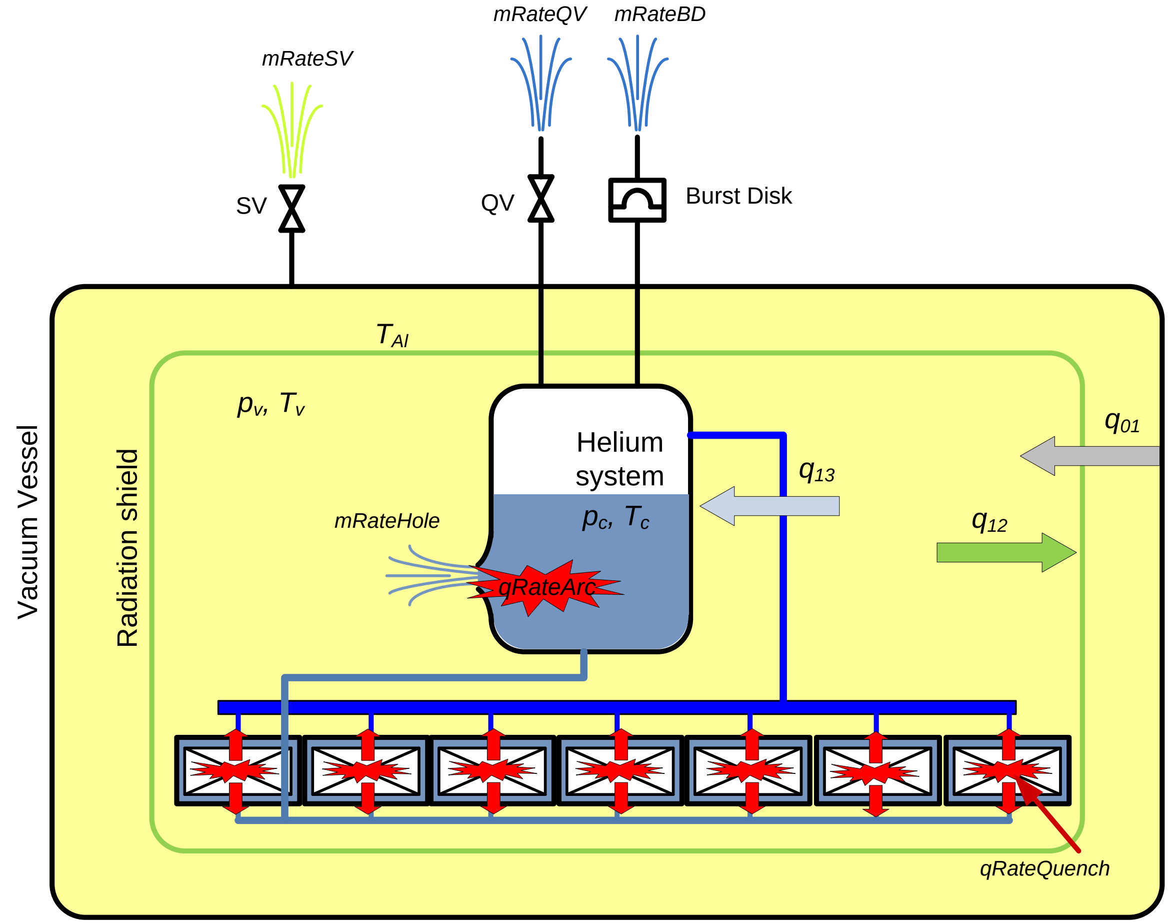


Schematic view of the electric arc consequence in the KATRIN CPS cryostat [1]

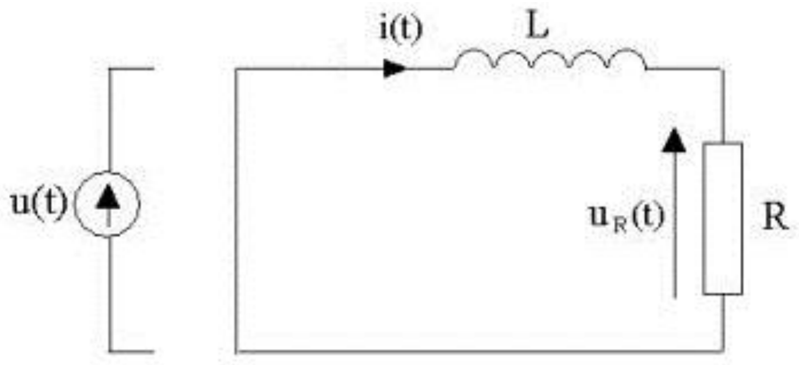
Problem’s background

Questions to be answered in the cryogenic systems with the superconducting devices:

- How much energy from electric arc can be deposited in the helium (or in other cryo fluid)
- How much energy from electric arc can be deposited in the metal (pipes/ vessels)
- If energy deposited in the metal can perforate the metal, and, if YES, how big will be the hole in the metal

Arc power evolution

RL circuit model can be used to calculate power dissipation from coils into surrounding



$$i(t)=i_0 e^{-\frac{R(t)}{L}t} \qquad u_R(t)=u_0 e^{-\frac{R(t)}{L}t}$$

$$P(t)=i(t)\cdot u_R(t)=i_0\cdot u_0\cdot e^{-\frac{R(t)}{L}t}\cdot e^{-\frac{R(t)}{L}t}$$

$$P(t)=i_0\cdot u_0\cdot e^{-2\frac{R(t)}{L}t}=i_0^2\cdot R(t)\cdot e^{-2\frac{R(t)}{L}t}$$

i(t) - current in circuit, A
i_0 – current in circuit in t_0, A
R(t) - circuit resistance, Ώ
L- coil impedance, H
$u_R(t)$ - voltage in the arc circuit in t_0, V
u_0 - ignition voltage, V
P - power on the resistor, W

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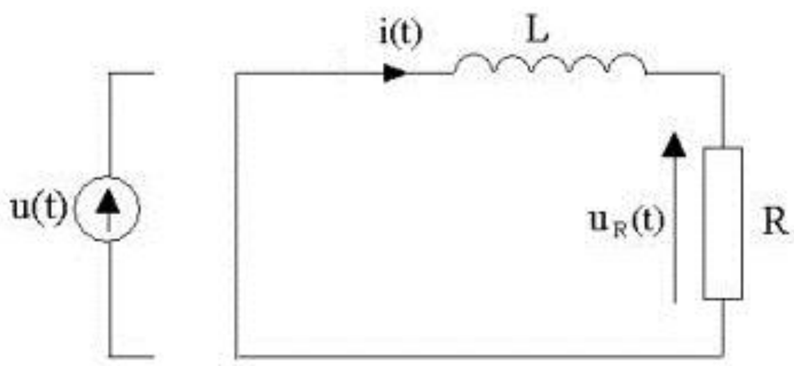

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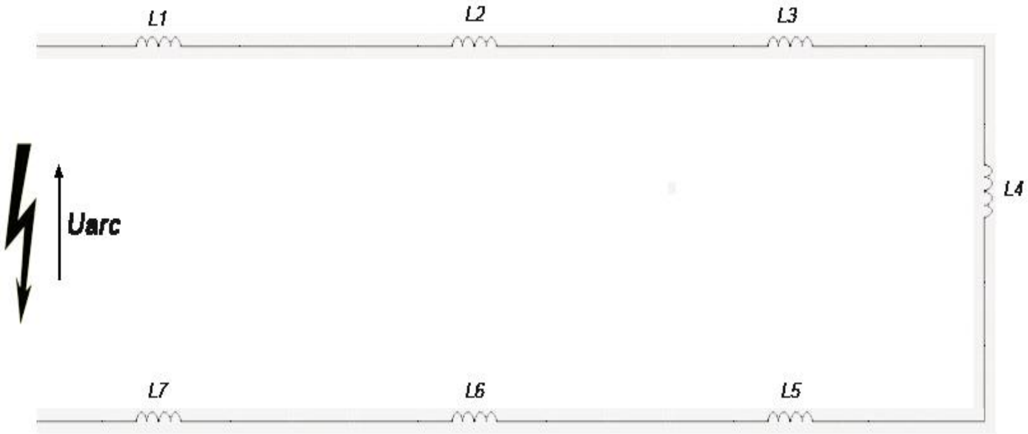
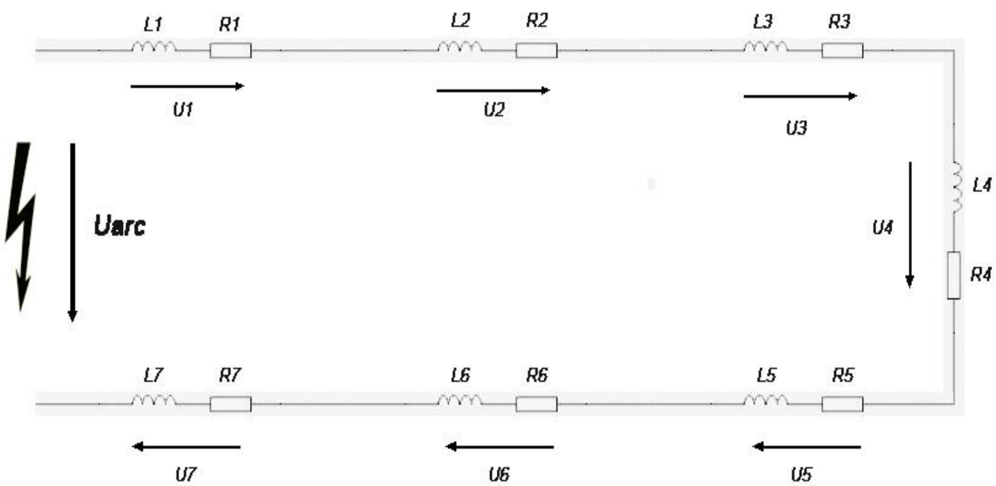
Arc voltage/resistance



Superconducting mode

$$R = R_{Arc}$$



Conducting mode

$$R = \sum_{i=1}^{7} R_i + R_{Arc}$$

Arc voltage/resistance [2]

Van C. Warrington

$$R_{Arc} = \frac{28.71 \cdot l}{i^{1.4}}$$

J. Lewis Blackburn

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

l- arc length [m]
i -circuit current [A]

Direct formulas for

$$\mathrm{R}_{\mathrm{arc}} = \frac{dU_{arc}}{di_{arc}}$$

Notthingham

$$\mathrm{U}_{\mathrm{arc}} = \mathrm{A} + \mathrm{B} \cdot l + \frac{C + D \cdot l}{i_{arc}^{\alpha}}$$

Osborne

$$\mathrm{U}_{\mathrm{arc}} = \mathrm{A} + \frac{C}{i_{arc}^{\alpha}} (l + D)$$

A-constant measured in experiment,
C-constant that depends on pressure,
D-constant that depends on temperature,

Rieder and Schneider

$$\mathrm{U}_{\mathrm{arc}} = \mathrm{A} + (l + \beta) \cdot K_{iarc}$$

A - constant measured in experiment
K_{iarc} - electric field intensity
b - constant that depends on electrodes material
l - arc length

Arc voltage/resistance

There is no universal way to calculate electrical arc resistance.
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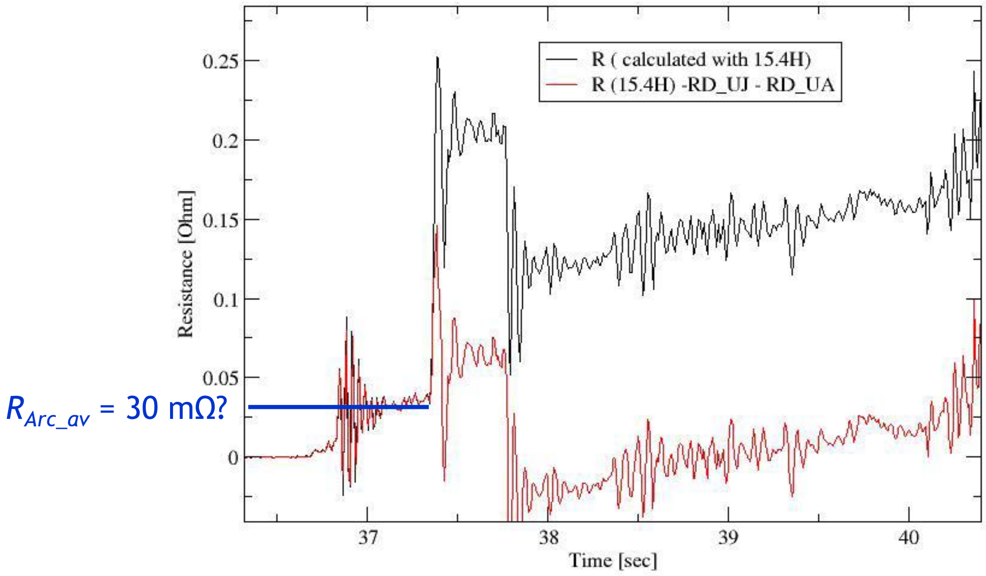

Evolution of resistance of the arc during 080919 LHC incident [3]

Arc voltage/resistance

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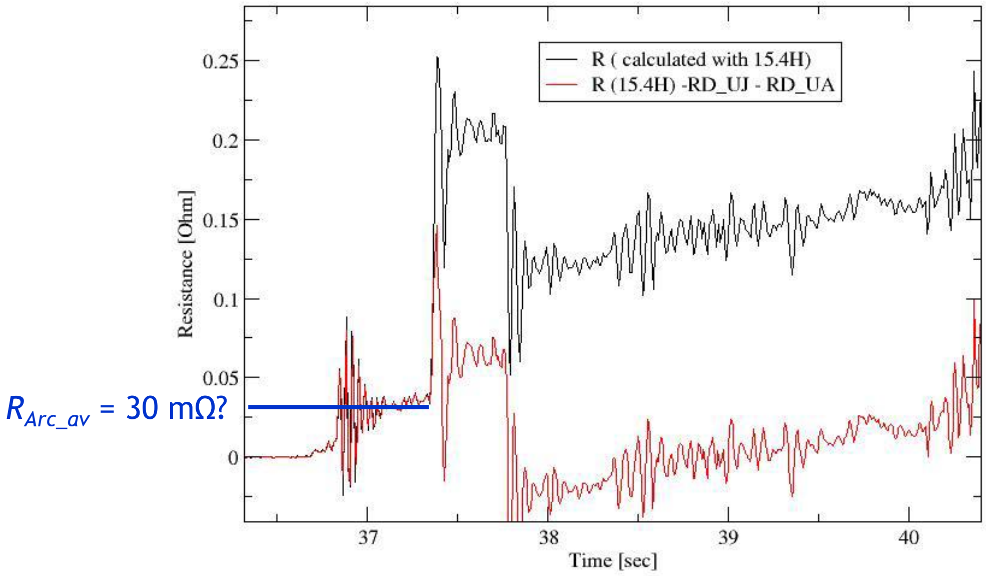


Evolution of resistance of the arc during 080919 LHC incident [3]

For:
l = 30 mm
I=8.7 kA

From Blackburn equation:
R_{Arc} = 4.96 mΩ

From Warrington equation:
$RArc$ = 2.622 μΩ

Temperature effect on the electrical breakdown [4]

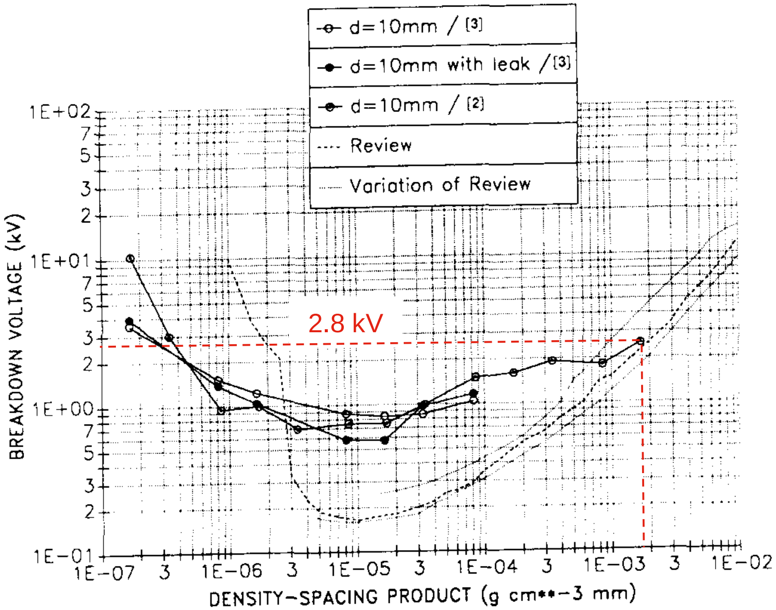


Figure 3.
Paschen curve of helium at room temperature.

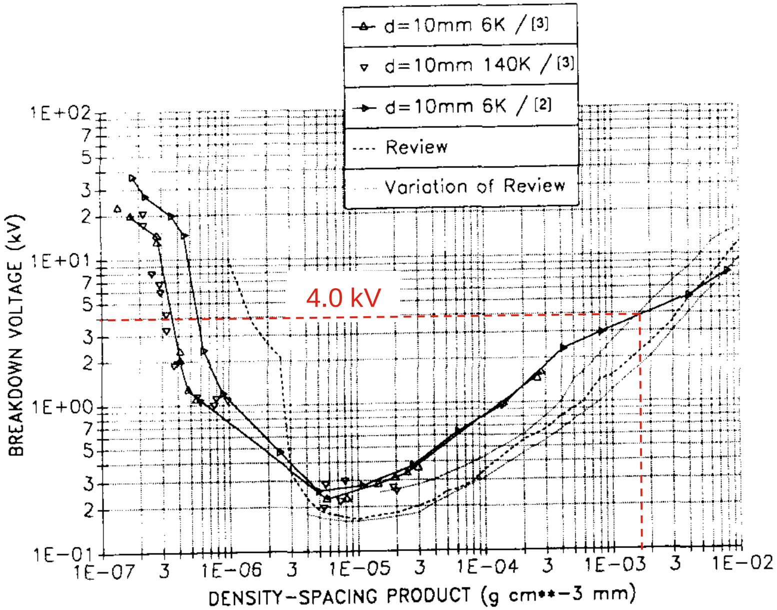


Figure 4.
Paschen curve at cryogenic temperatures.

Liquid cryogen effect on the electrical breakdown

- No data avaiable for cryogenic fluids
- In case of transformer oils the breakdown is of about 20kV/mm as for dry air is 3kV/mm

- Conclusion: most of energy desipated by electrical arc is storied in the cryogen then in the metal structure?

Vessel perforation by the electrical arc

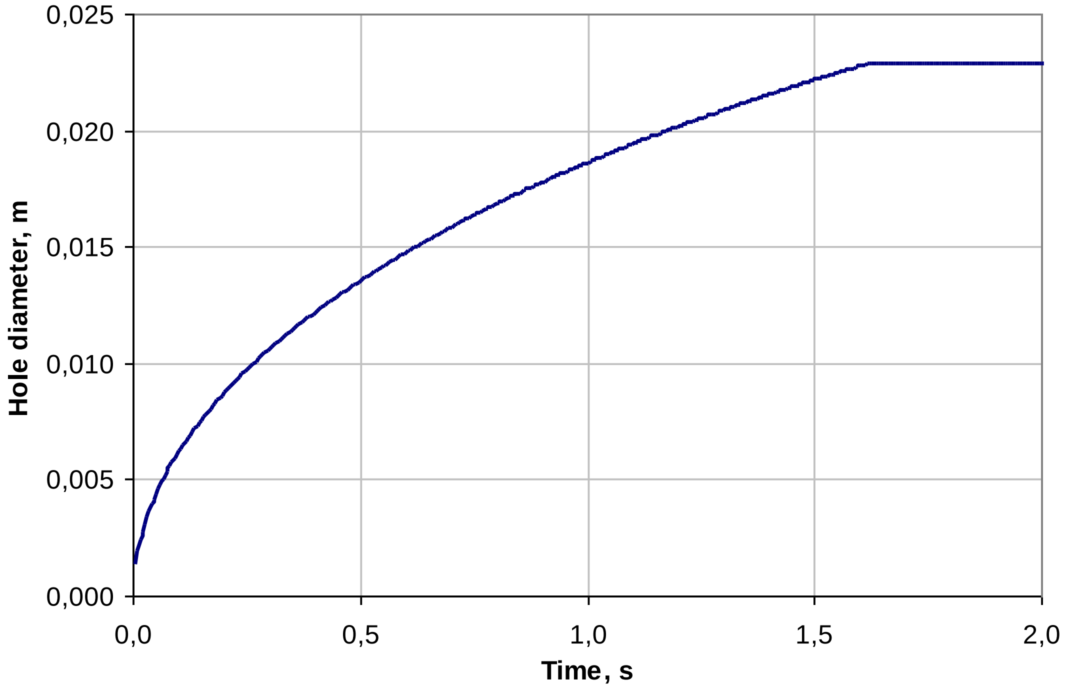
The hole size propagation in the He vessel *d(t)* can be calculated from the following equation

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

$W_w(t)$- thermal energy transferred directly into vessel wall, J
T – temperature, K
c_p – heat capacity of the wall material, J/K·kg
r – wall material melting heat – r=270 kJ/kg
z – thickness of vessel wall
ρ – density of vessel well, kg/m^3 – 7920 kg/m^3

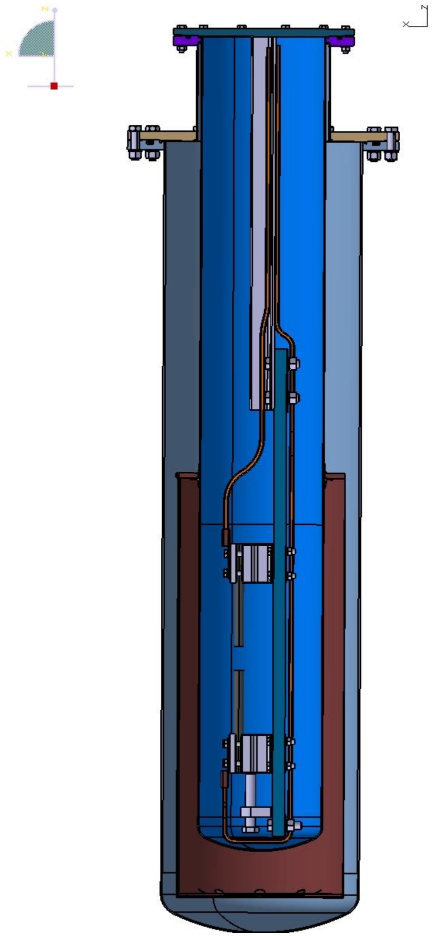
$$\int_{4.5K}^{1700K} c_p\,dT = 941\,kJ/kg$$

Vessel perforation by the electrical arc

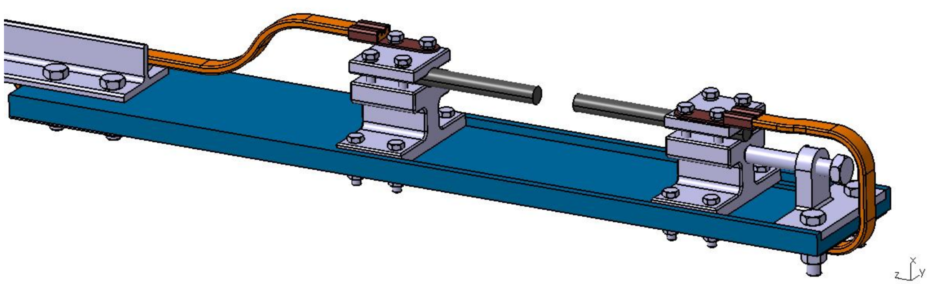


Evolution of hole diameter created by electrical arc in KATRIN CPS cryostat vessel [1].
Vessel wall thickness – 5mm, 1.5% of arc energy deposited in the vessel wall

WUST cryostat concept



Cryostat cross-section



Insert with position-controled electrodes

Conclusions

- The energy deposited in the liquid cryogens and cryostat metalic structure is a very important issue for sizeig of the SV for cryogenic systems that contain the SC magnets
- The electric arc creation and its behaviour in liquid cryogens is not or poorly investigared yet
- WUST intend to construct the dedicated cryostat for such investigations

Reference

[1] P. Bielowka, M. Chorowski, J. Polinski, *Safety analysis of CPS cryostat R3.0*, 325/20451773/ITEP-KRYO, 2011

[2] J Reece Roth, *Industrial Plasma Engineering: Volume 1: Principles*, Institute of Physics Publishing, Bristol and Philadelphia 1995

[3] *Report of the task force on the incident of 19 september 2008 at the LHC*, LHC Project Report 1168

[4] M. Irmisch at all., *Breakdown Characteristics of He Gas at Cryogenic Temperature and Low Pressure*, IEEE l'kansactions on Electrical Insulation ***Vol. 28 No. 4***, August ***1993***

Thank you for the attention!