Preliminary design of the pressure relief system for the EDIPO 2 He vessel

R. Guarino*
X. Sarasola
E. Solodko
P. Bruzzone
K. Sedlak

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Outline

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- Safety pressure relief device

- Pressure relief & He recovery
  - Quench energy deposition
  - Two/three-volume model

- Conclusions
The European DIPOle (EDIPO) is a test facility for fusion and high-energy physics superconducting samples. It is located in Villigen, Switzerland. An unprotected quench in 2016 led to an irreversible damage of the magnet assembly. EDIPO 2 is the upgraded design\(^1\) with a target field of 15 T (~1 m uniform field length).

Instead of supercritical He cooling of the old EDIPO facility, a He bath cooling (~4.2 K, 1 atm) is the preferred choice for EDIPO 2.

A He vessel has been designed and is currently under manufacturing (delivery by Q4 2021).

A preliminary design of the pressure relief system is necessary.

Two scenarios considered:
- safety pressure relief after an accidental scenario (worst-case event)
- pressure relief and He recovery during normal operation
The He inlet is regulated through a Joule-Thomson valve.
A burst disc is chosen as safety pressure relief device.
The total He volume and filling level can be chosen in a wide range.
A He recovery pipe connects the He vessel to a recovery volume (e.g. balloon at 1 atm pressure).
Staged pressure protection

- It is considered a good engineering practice in the design of cryogenic pressure systems\(^2\).
- We fix the operating pressure and the maximum allowable working pressure.

\[ p_{\text{op}} = 1.01 \text{ bar} \]
\[ p_0 = 2.00 \text{ bar} \]
\[ p_s = 3.00 \text{ bar} \]
\[ p_t = 5.72 \text{ bar} \]

191% minimum test pressure (mechanical design)
100% (ref.) maximum allowable working pressure (burst disc)
67% relieving pressure
34% operating pressure

Safety pressure relief device

- The burst disc has been sized according to EN 13648-3.
- Two credible accidental events are considered:
  - unprotected quench ($I_{op}$ in the range 14-18 kA and power supply with $V_{PS} \approx 5$ V)
    \[
    \dot{Q} = I_{op}V_{PS}
    \]
  - loss of vacuum (specific heat power deposition of 0.6 W/cm$^2$ on the vessel external surface\(^3\) $A_{vessel} \approx 14.2$ m$^2$)
    \[
    \dot{Q} = Q'A_{vessel}
    \]
- For $I_{op} < 17.1$ kA, the loss of vacuum represents the worst case scenario.

Safety pressure relief device

- The He flow through the burst disc is in subcritical conditions.
- The minimum flow area (i.e. burst disc diameter) can be computed.
- A conservative design is pursued by adding a safety factor on the maximum mass flow rate.

<table>
<thead>
<tr>
<th></th>
<th>Unprotected quench</th>
<th>Loss of vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum heat power</td>
<td>90.0 kW</td>
<td>85.4 kW</td>
</tr>
<tr>
<td>Maximum mass flow rate</td>
<td>5.03 kg/s</td>
<td>4.77 kg/s</td>
</tr>
<tr>
<td>Safety factor on mass flow rate</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Minimum burst disc diameter</td>
<td>55.0 mm</td>
<td>53.6 mm</td>
</tr>
</tbody>
</table>

- The closest standard (commercial) burst disc size is DN65.
In normal operation one must relieve the rising pressure, e.g. after a protected quench, and it is desirable to recover the outflowing He.

Through a thermodynamic analysis of the system, it is possible to:
- simulate the He pressure rise following a quench
- simulate the time evolution of the pressure (and temperature) after opening the relieving valve
- provide an engineering tool to support the sizing of the recovery pipe

We have developed a two/three-volume model, based on a simplified description of the system.
Overview of existing models

- Two-volume model developed at CERN\(^4\), for studying quench in magnet strings.
- Two volume model developed at CEA\(^5\), for simulating the He pressure rise following a quench.
- Both models deal with superfluid He and simulate short time spans; no recovery pipes are included.

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\(^4\) Chorowski et al., Towards a better understanding of the physics of the two-volume model of accelerator magnet quench thermohydraulics, *Cryogenics* 46 (2006) 581.

Two/three-volume model overview

- **Main features:**
  - small volume A directly heated by the heat source (i.e. quench energy)
  - isentropic volume B (in the short time frame considered)
  - volume C ‘active’ only after valve opening
  - ‘virtual pistons’ that separate the two or three volumes

- **Novelty:**
  - pressure drop along the recovery pipe
  - “recirculation” (i.e. internal) mass flow rate
Quench energy deposition

Quench energy

\[ E_{\text{coil}}(t) = \int_0^t R_{\text{coil}}(t)I(t)^2\,dt \]

Diffusion through conduction + convection

\[ \frac{T(t) - T_\infty}{T(0) - T_\infty} \approx r(\xi, \beta) \]

\( \xi, \beta \) functions of material properties and heat transfer coefficient (natural convection)

‘delayed’ quench energy to include diffusion

\[ E_{\text{coil}}(t) \rightarrow E'_{\text{coil}}(t) \]

Energy fraction transferred to the He bath

\[ E_{\text{He}}(t) \approx E'_{\text{coil}}(t) - m_{\text{coil}} \int_{T_0}^{T(t)} c_{\text{coil}}(T)\,dT - m_{\text{ins}} \int_{T_0}^{T(t)} c_{\text{ins}}(T)\,dT \]

Heat power

\[ \dot{Q}(t) = \frac{dE_{\text{He}}(t)}{dt} \]
Two-volume model

- **Effect of energy deposition**
  \[
  \dot{m}_{vap}(t) = \frac{\dot{Q}(t)}{L_{vap}}
  \]

- **Volume change**
  \[
  \frac{dV_A(t)}{dt} = \frac{\dot{m}_{vap}(t)}{\rho_{vap}} + \frac{\dot{m}_{cold}(t)}{\rho(0)}
  \]
  \[
  \frac{dV_B(t)}{dt} = -\frac{dV_A(t)}{dt}
  \]

- **Assumption**
  \( \dot{m}_{cold} \approx \dot{m}_{vap} \)
Three-volume model

\[ \dot{m}_{vap}(t) = \frac{\dot{Q}(t)}{L_{vap}} \]

\[ m_{vap}(t) = \int_0^t \dot{m}_{vap}(t) \, dt \]

assumption \( \dot{m}_{cold} \approx \dot{m}_{vap} \)

mass flow rate through the valve

\[ \rho(t) \frac{p_b^2 - p(t)^2}{2p(t)} + \frac{\dot{m}_{out}^2}{A^2} \left[ \ln \frac{p(t)}{p_b} + \frac{2L}{D} f(t) \right] = 0 \]
Two/three-volume model results

- Time variation of pressure and temperature (average values in the volume B), before and after valve opening.

\[ D = 70 \text{ mm} \]
\[ L = 10 \text{ m} \]
\[ p_0 = 2.00 \text{ bar} \]
\[ V_0 = 0.100 \text{ m}^3 \]
Two/three-volume model sensitivity analysis

- Varying diameter and length of the recovery pipe.

\[ D = 70 \text{ mm} \quad p_0 = 2.00 \text{ bar} \quad V_0 = 0.100 \text{ m}^3 \]

\[ L = 10 \text{ m} \quad p_0 = 2.00 \text{ bar} \quad V_0 = 0.100 \text{ m}^3 \]

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Two/three-volume model sensitivity analysis

- Varying relieving pressure and He total volume.

\[ D = 70 \text{ mm} \]
\[ L = 10 \text{ m} \]
\[ V_0 = 0.100 \text{ m}^3 \]

\[ p_0 = 2.00 \text{ bar} \]
Conclusions

- The EDIPO 2 He vessel has been designed and is under manufacturing.

- A preliminary design of the pressure relief system has been presented:
  - staged pressure protection concept with 1 atm operating pressure and 3.0 bar maximum allowable pressure
  - DN65 burst disc as safety pressure relief device

- A novel two/three-volume model has been developed:
  - study of quench energy deposition into the He bath
  - He pressure rise and pressure relief through a recovery pipe
  - sensitivity analyses based on 4 parameters: recovery pipe diameter \( D \) and length \( L \), relieving pressure \( p_0 \) and total He volume \( V_0 \)
  - potential design tool to support engineering choices (e.g. recovery pipe sizing)
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