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

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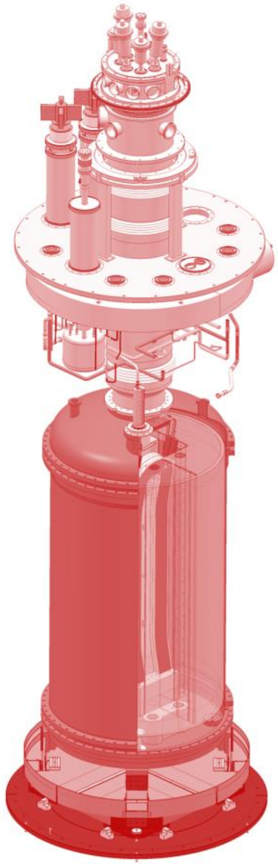

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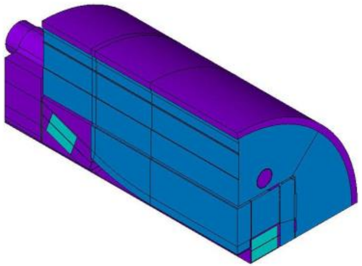
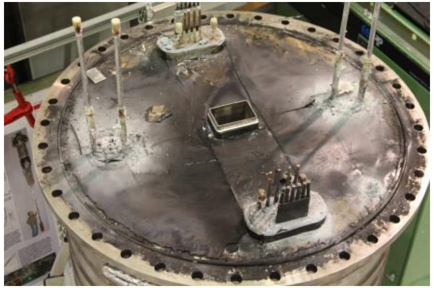
Introduction

- 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).





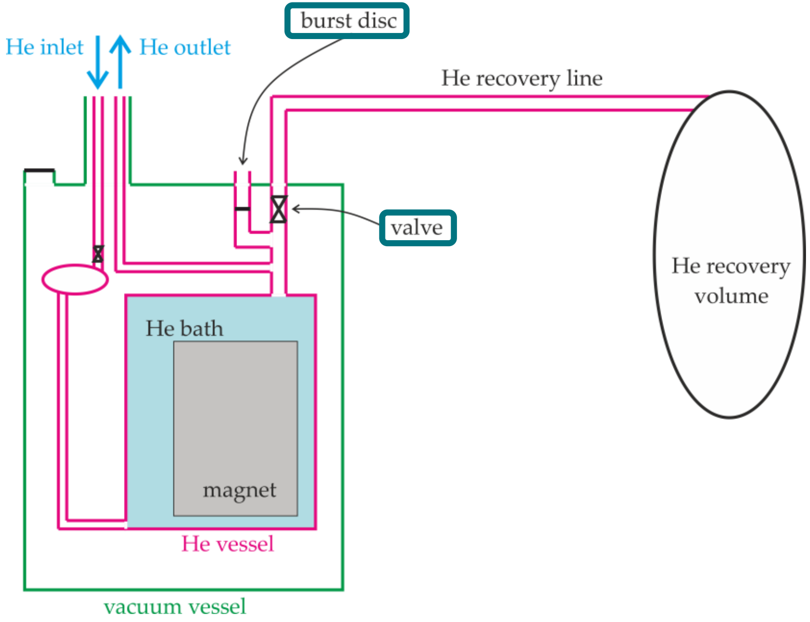
[1] Araujo et al., Progress on the update of EDIPO, a 15 T large aperture dipole, *IEEE Transactions on Applied Superconductivity* **31** (2021) 9500205.

Objectives

- 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

He vessel schematic

- 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.

191%	p_t = 5.72 bar	minimum test pressure (mechanical design)
100% (ref.)	p_s = 3.00 bar	maximum allowable working pressure (burst disc)
67%	p_0 = 2.00 bar	relieving pressure
34%	p_{op} = 1.01 bar	operating pressure

[2] Grohmann & Süßer, Conceptual design of pressure relief systems for cryogenic applications, *Advances in Cryogenic Engineering* **1573** (2014) 1581.

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} ≈ 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} ≈ 14.2 m^2)

$$\dot{Q} = Q' A_{vessel}$$

- For I_{op} < 17.1 kA, the loss of vacuum represents the worst case scenario.

[3] Lehmann & Zahn, Safety aspects for LHe cryostats and LHe transport containers, *Proceedings of the 7th International Engineering Conference*, London, 4-7 Jul 1978.

Safety pressure relief device

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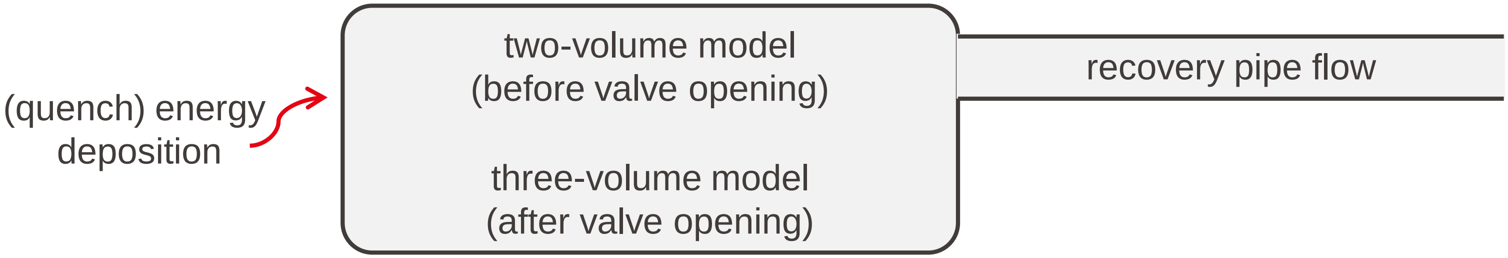
- The He flow through the burst disc is in subcritical conditions.
- The minimum flow area (i.e. burst disc diameter) can be computed.
- A conservative design is pursued by adding a safety factor on the maximum mass flow rate.

	Unprotected quench	Loss of vacuum
Maximum heat power	90.0 kW	85.4 kW
Maximum mass flow rate	5.03 kg/s	4.77 kg/s
Safety factor on mass flow rate	1.25	1.25
Minimum burst disc diameter	55.0 mm	53.6 mm

- The closest standard (commercial) burst disc size is DN65.

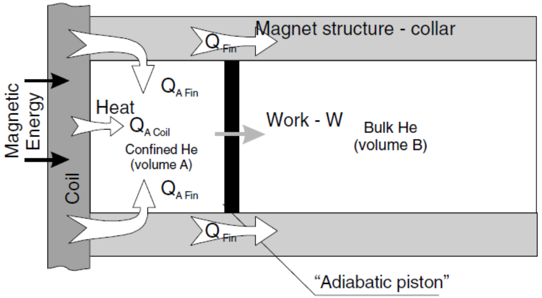
Pressure relief & He recovery

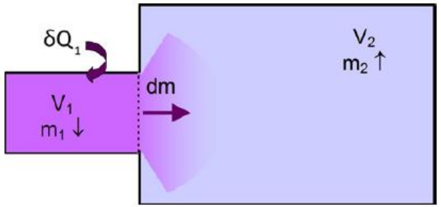
- In normal operation one must relieve the rising pressure, e.g. after a protected quench, and it is desirable to recover the outflowing He.
- Through a thermodynamic analysis of the system, it is possible to:
  - simulate the He pressure rise following a quench
  - simulate the time evolution of the 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.



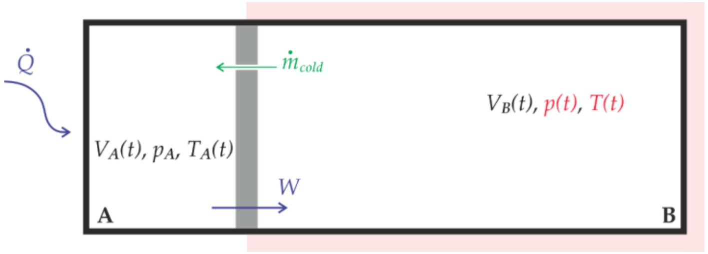


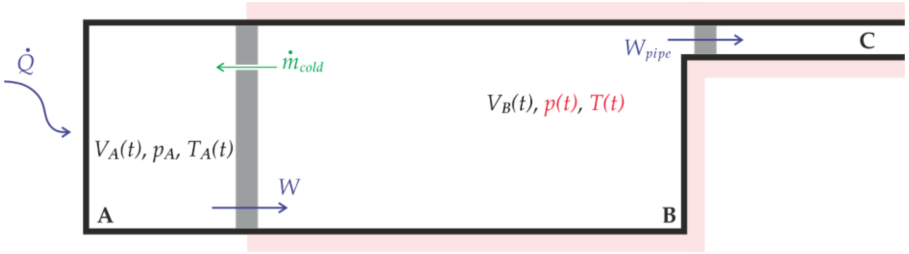
[4] Chorowski *et al.*, Towards a better understanding of the physics of the two-volume model of accelerator magnet quench thermohydraulics, *Cryogenics* **46** (2006) 581.

[5] Meuris, Experimental simulation of helium pressure rise during a quench of a superconducting coil cooled by a superfluid helium bath, *Cryogenics* **53** (2013) 17.

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

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quench energy $E_{coil}(t) = \int_0^t R_{coil}(t) I(t)^2 \mathrm{d}t$

diffusion through conduction+convection $\frac{T(t) - T_\infty}{T(0) - T_\infty} \approx r(\xi, \beta)$

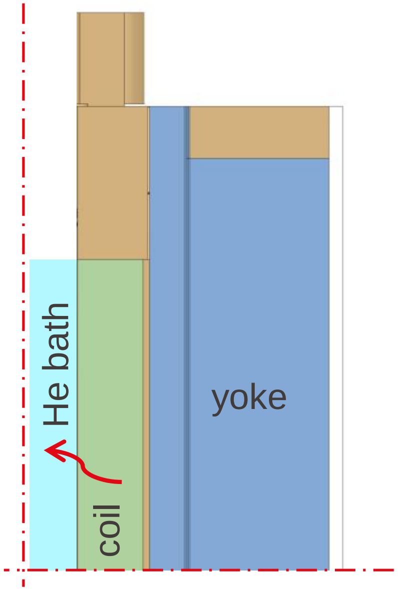
ξ,β functions of material properties and heat transfer coefficient (natural convection)

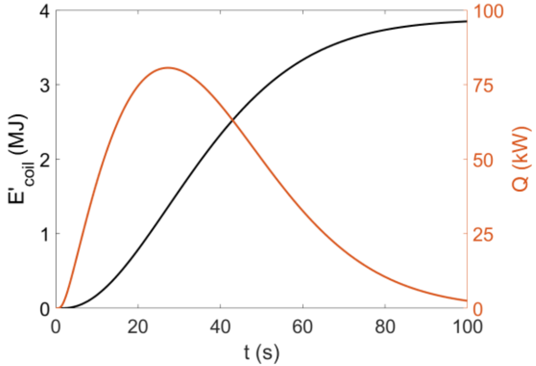
'delayed' quench energy to include diffusion $E_{coil}(t) \rightarrow E'_{coil}(t)$

energy fraction transferred to the He bath

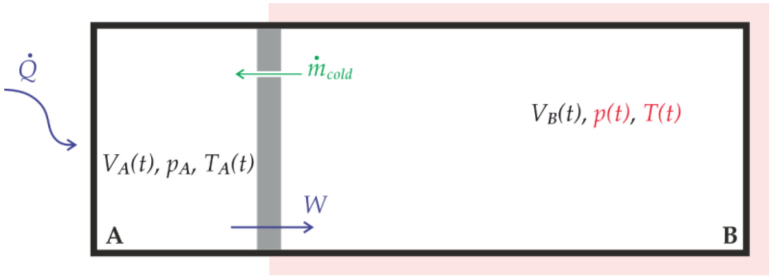
$$E_{He}(t) \approx E'_{coil}(t) - m_{coil} \int_{T_0}^{T(t)} c_{coil}(T) \mathrm{d}T - m_{ins} \int_{T_0}^{T(t)} c_{ins}(T) \mathrm{d}T$$

heat power $\dot{Q}(t) = \frac{\mathrm{d}E_{He}(t)}{\mathrm{d}t}$





Two-volume model



effect of energy deposition

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

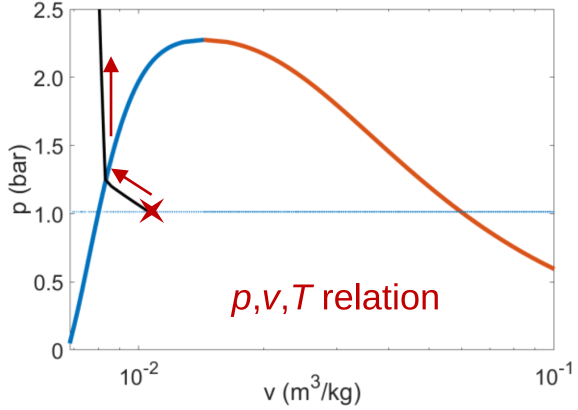
$$m_{vap}(t) = \int_0^t \dot{m}_{vap}(t)\mathrm{d}t$$

assumption $\dot{m}_{cold} \approx \dot{m}_{vap}$

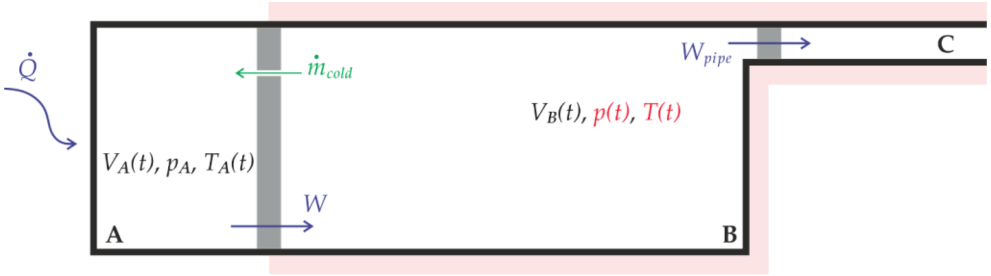
volume change

$$\frac{\mathrm{d}V_A(t)}{\mathrm{d}t} = \frac{\dot{m}_{vap}(t)}{\rho_{vap}} + \frac{\dot{m}_{cold}(t)}{\rho(0)}$$

$$\frac{\mathrm{d}V_B(t)}{\mathrm{d}t} = -\frac{\mathrm{d}V_A(t)}{\mathrm{d}t}$$



Three-volume model



effect of energy deposition

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

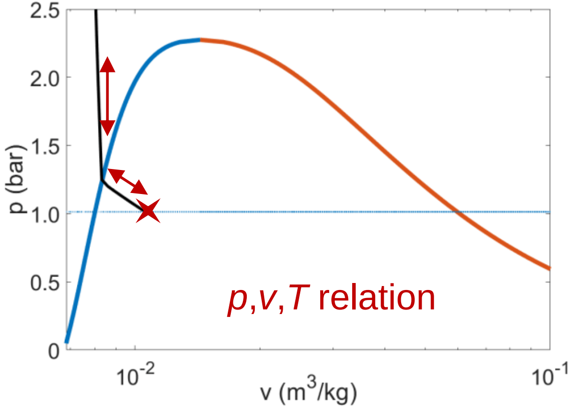
$$m_{vap}(t) = \int_0^t \dot{m}_{vap}(t)\mathrm{d}t$$

assumption $\dot{m}_{cold} \approx \dot{m}_{vap}$

volume change

$$\frac{\mathrm{d}V_A(t)}{\mathrm{d}t} = \frac{\dot{m}_{vap}(t)}{\rho_{vap}} + \frac{\dot{m}_{cold}(t)}{\rho(0)}$$

$$\frac{\mathrm{d}V_B(t)}{\mathrm{d}t} = -\frac{\mathrm{d}V_A(t)}{\mathrm{d}t} + \frac{\dot{m}_{out}(t)}{\rho(t)}$$



mass flow rate through the valve

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

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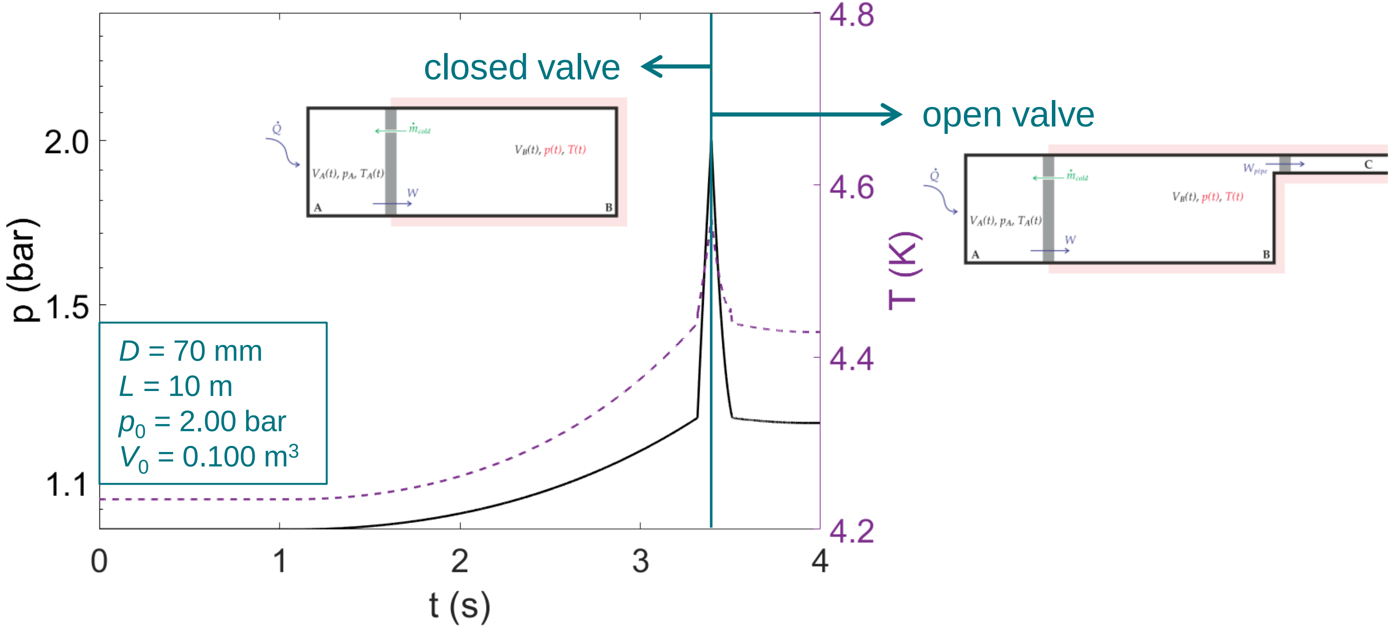
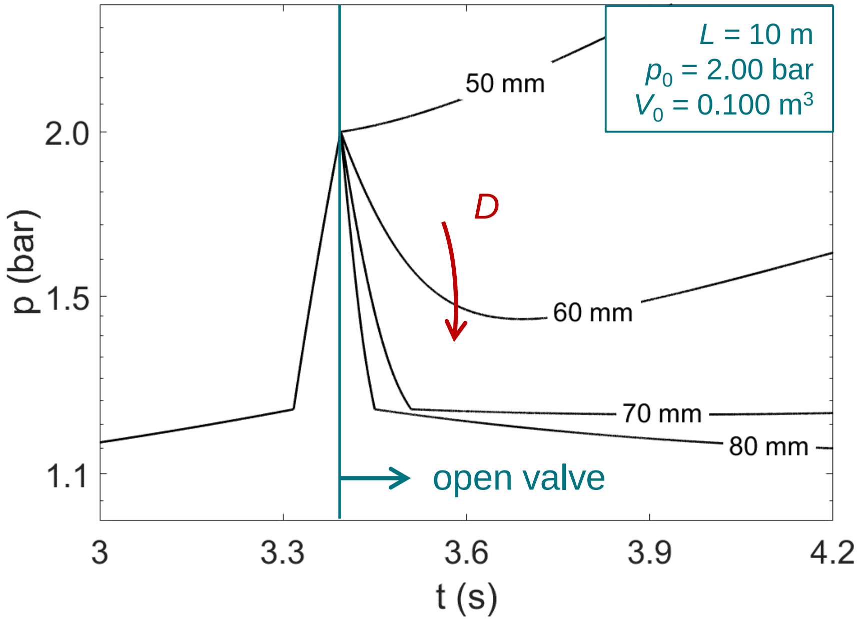
Two/three-volume model results

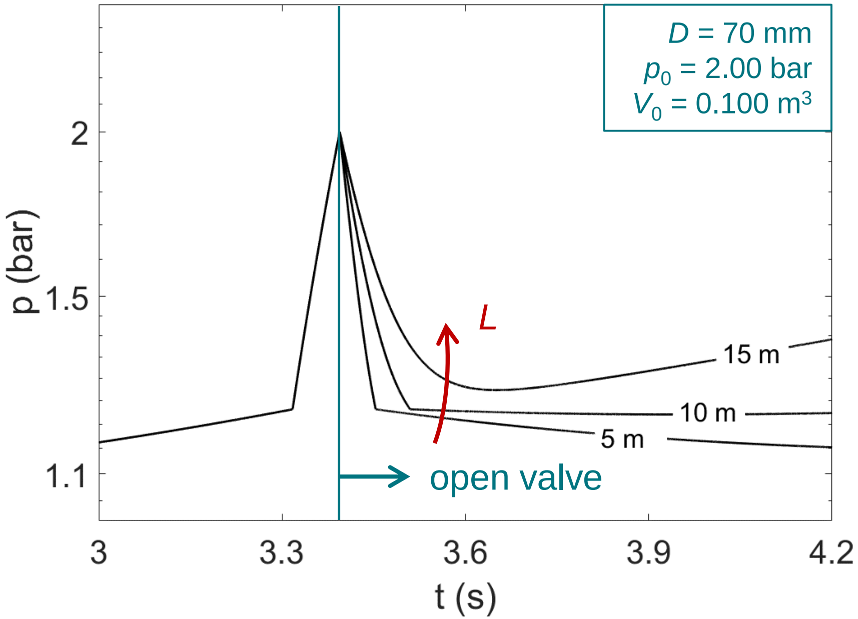
- Time variation of pressure and temperature (average values in the volume B), before and after valve opening.



Two/three-volume model sensitivity analysis

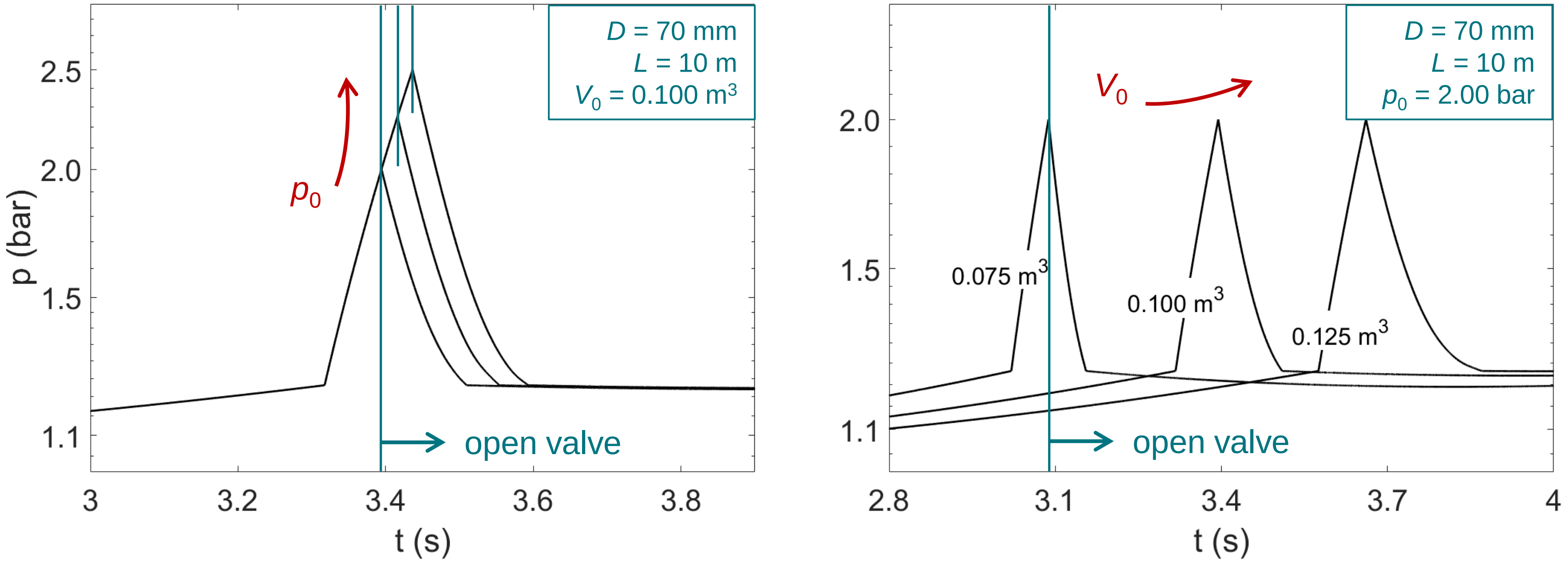
- Varying diameter and length of the recovery pipe.





Two/three-volume model sensitivity analysis

- Varying relieving pressure and He total volume.



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)

EPFL

EUROfusion

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