The Einstein Telescope beampipe vacuum system: Exploring novel techniques and materials for a cost-effective design solution.

Carlo Scarcia (on behalf of ET vacuum team at CERN)

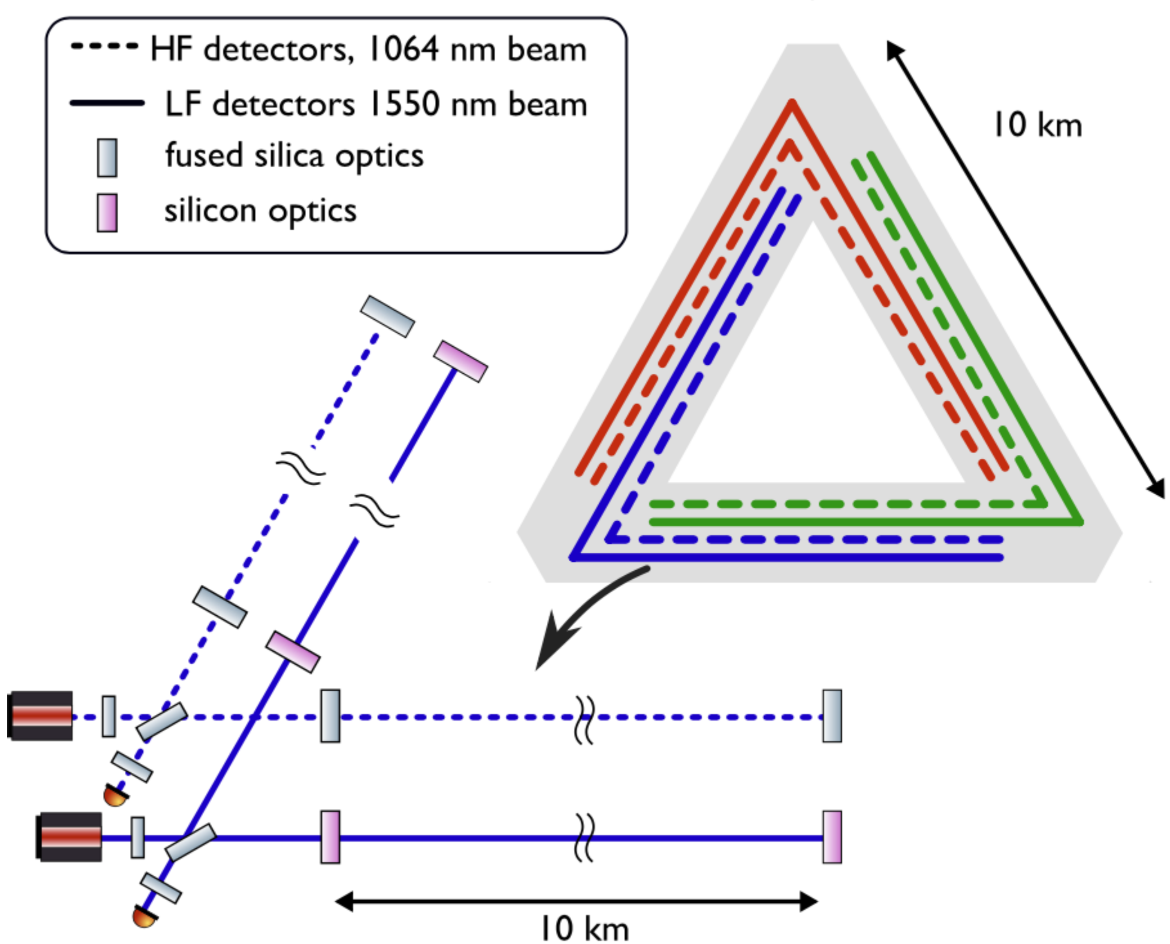
24/04/2024

The Einstein Telescope (as conceived in CDR 2020)

- **6 interferometers** nested in a **triangular shape.**
- **200-300 m underground.**
- Each vertex comprises two interferometers :
  - **ET – Low Frequency (LF) [3 Hz to 40 Hz]**:
    large cryogenic silicon test masses (10 – 20 K), new suspensions suspension system, new wavelength, etc.
  - **ET – High Frequency (HF) [30 Hz to ~10kHz]**:
    high-power laser and circulating light power, large mirrors, etc.

Goal:

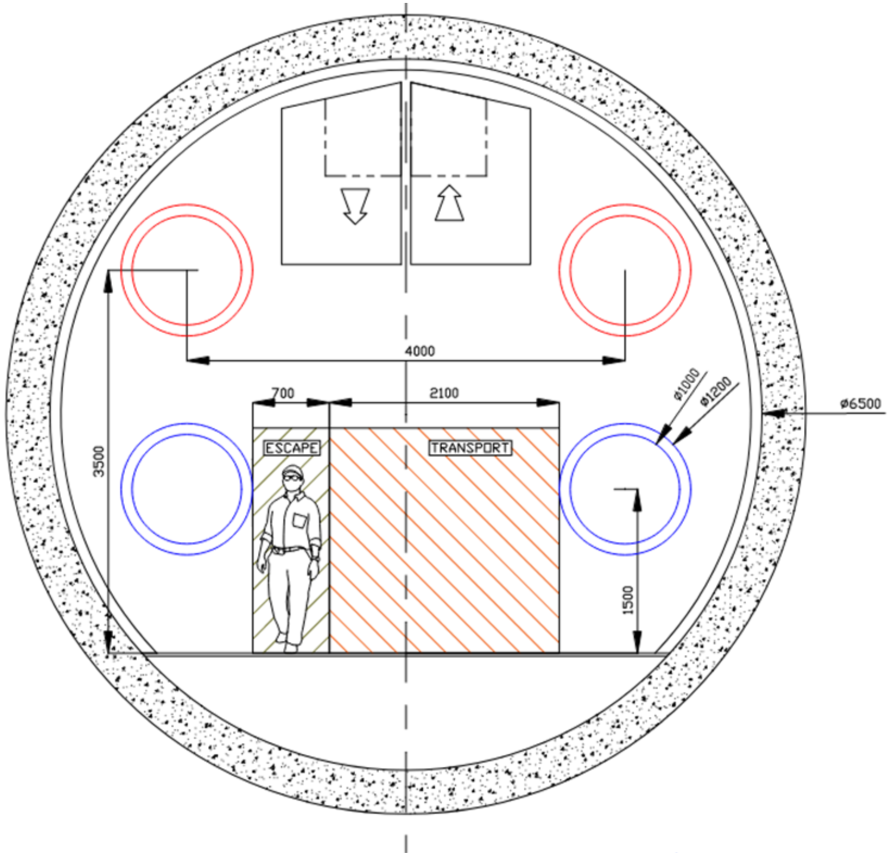
x10 better sensitivity than VIRGO



Source: Rowlinson et al., Feasibility study of beam-expanding telescopes in the interferometer arms for the Einstein Telescope.

The Einstein Telescope: beampipe vacuum system

The **10 km long** optical cavities require **ultrahigh vacuum** to reduce the noise due to gas pressure fluctuations along the laser trajectory to a level ≈10 times lower than the sum of the other noises.



Source: ET design report update 2020 and XIII ET symposium (2023)

Dimensions

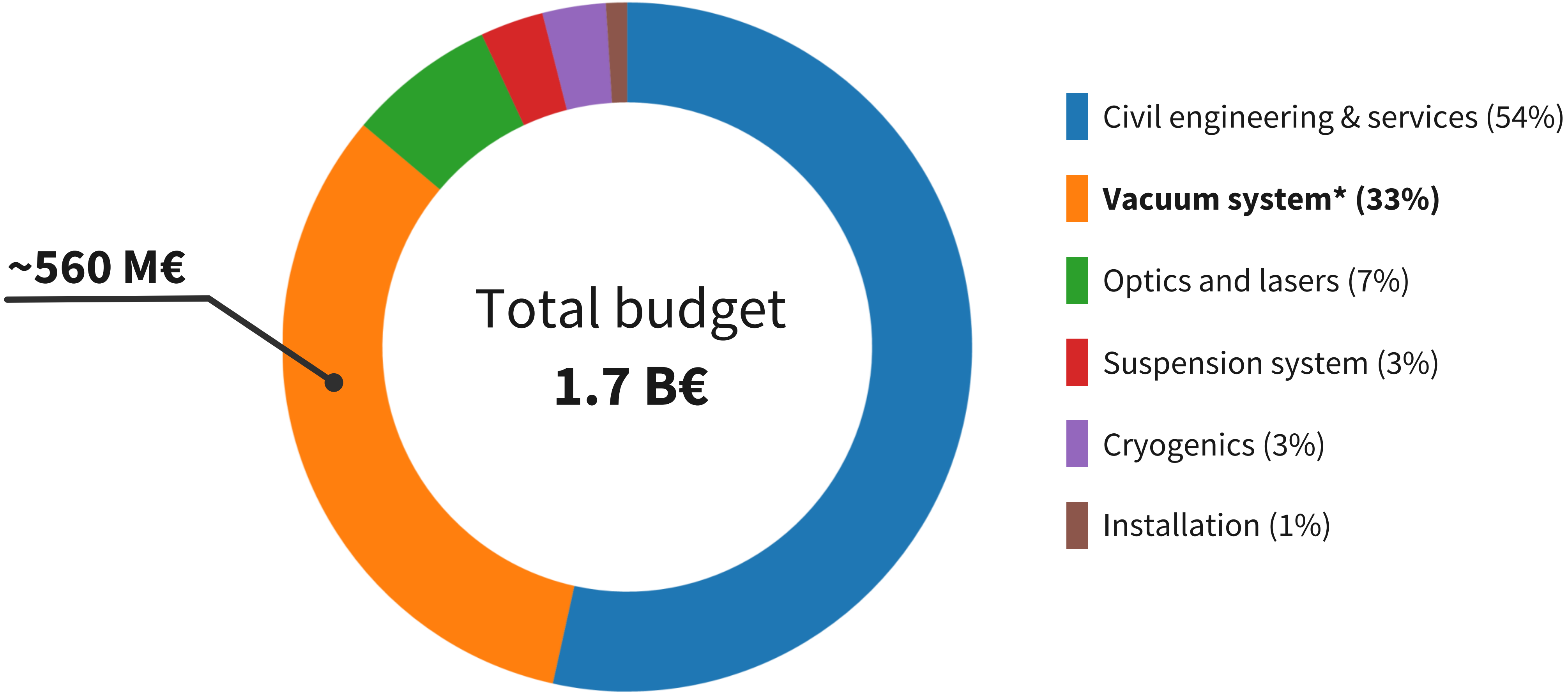
- Tunnel diameter: 6.5 m
- Four beampipes per arm
- **Beampipe internal diameter: 1 m**
- **Total beampipe length: 120 km**

Partial pressure requirements

- $H_2 \approx 10^{-10}$ mbar
- $H_2O \approx 10^{-11}$ mbar
- Heavy hydrocarbons < 10^{-14} mbar

The vacuum system impact on budget

If VIRGO vacuum system costs are scaled to ET dimensions [1] :



[1] ET collaboration, Einstein Telescope preliminary cost book, 2020
[2] ET Science Team, Einstein gravitational wave Telescope conceptual design study, 2011

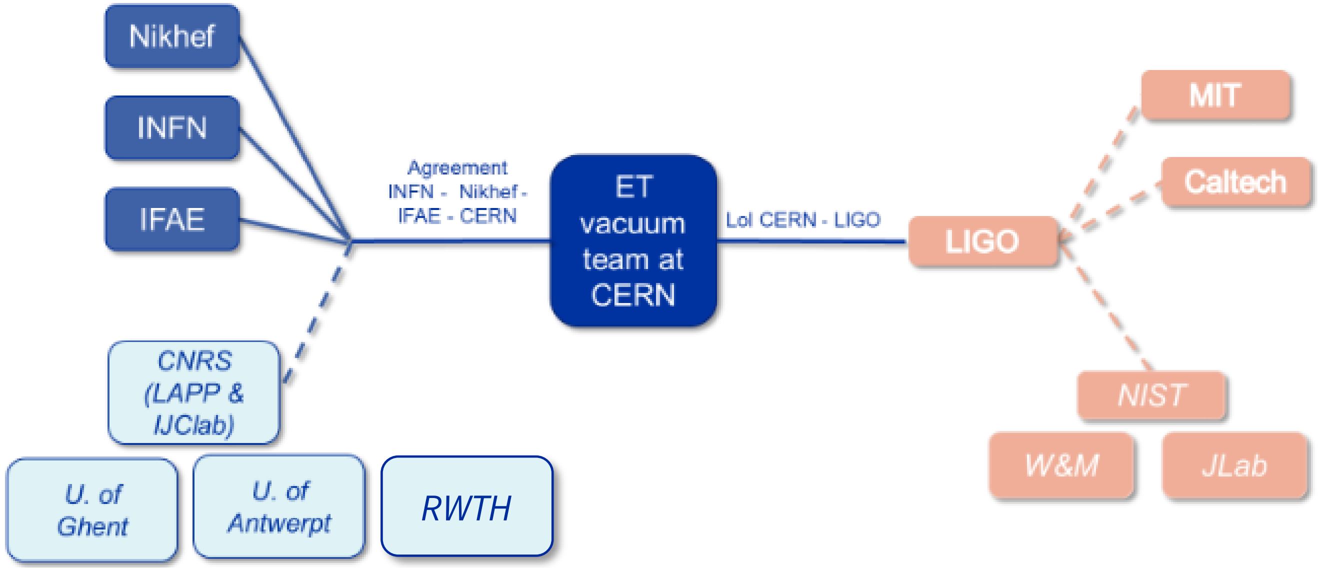
*including towers
(~<10% of the vacuum system budget [2])

GW and particle accelerators community join the forces

NSF Workshop on Large Ultrahigh-Vacuum Systems for Frontier Scientific Research (2019)

Credit: LIGO

Collaborations as of today:



Nikhef

INFN

IFAE

Agreement INFN - Nikhef - IFAE - CERN

ET vacuum team at CERN

LoI CERN - LIGO

LIGO

MIT

Caltech

NIST

W&M

JLab

CNRS (LAPP & IJClab)

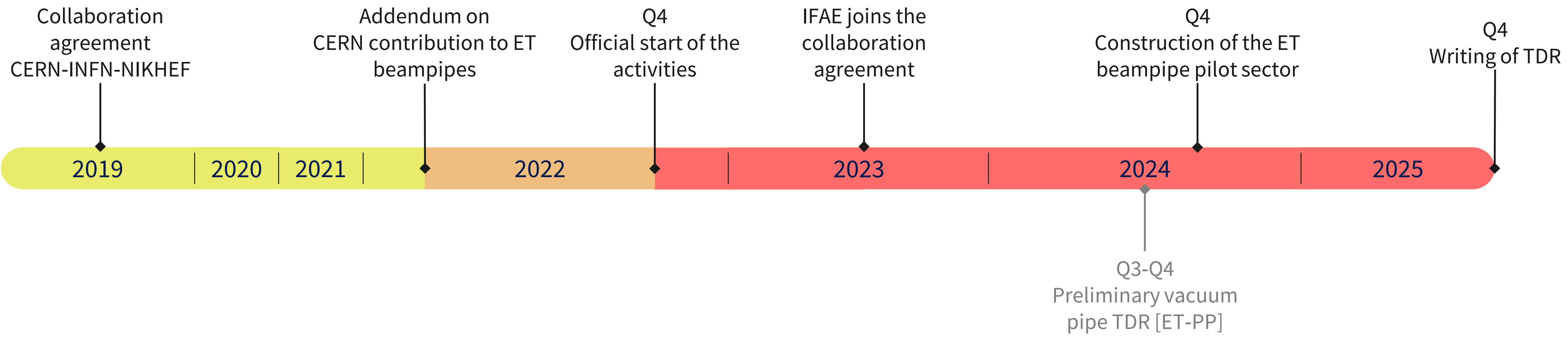
U. of Ghent

U. of Antwerpt

RWTH

The gravitational waves and particle accelerators community joined the forces toward the study of **cost-effective designs, materials, and techniques for the next generation of gravitational wave detectors.**

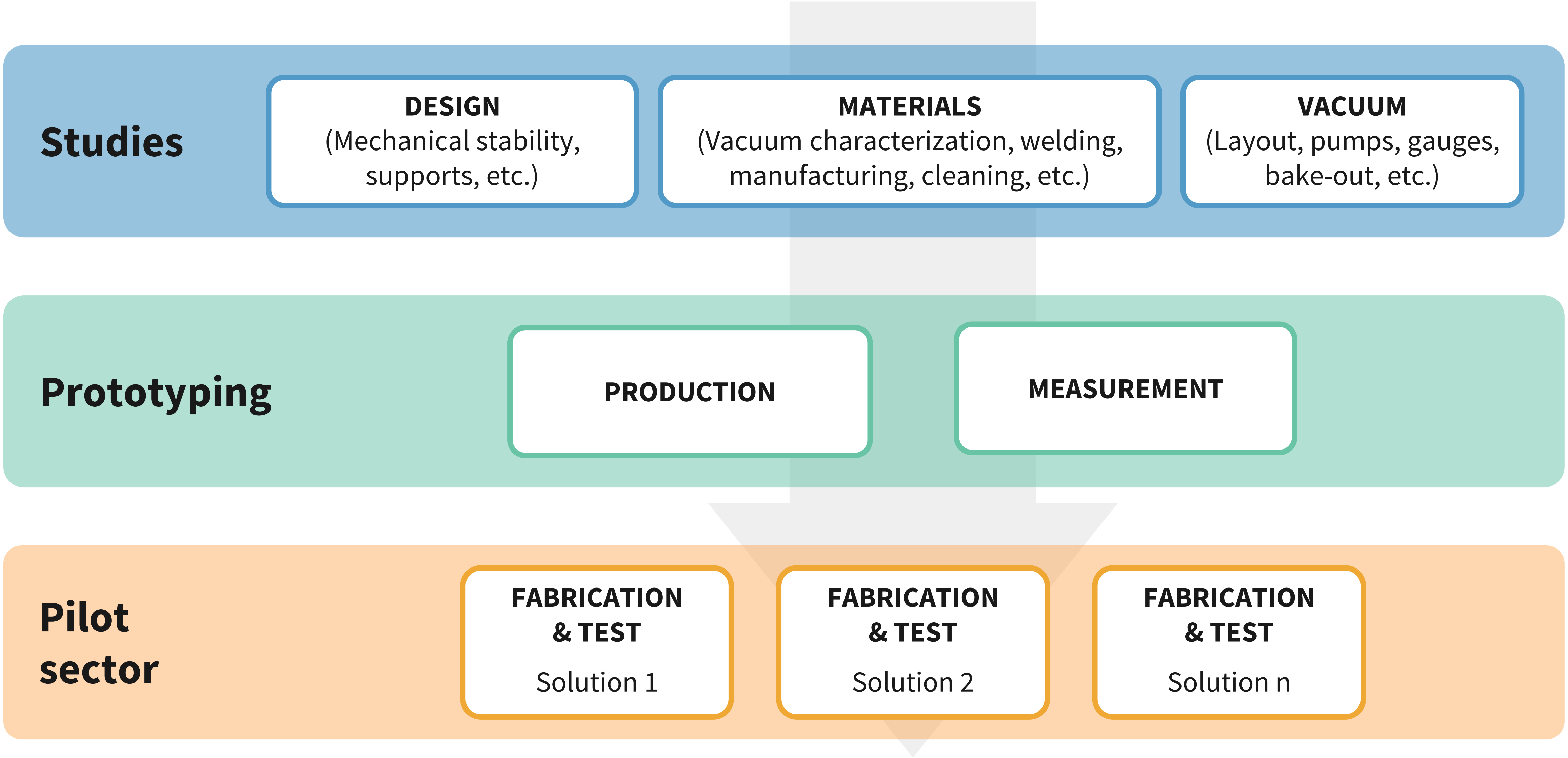
GW and particle accelerators community join the forces



The main objectives are:

- **Coordinate the contributions** of all parties involved in the study of ET beampipes.
- Design, manufacture, assemble, and test a **pilot sector** of the selected ET beampipe vacuum systems.
- Preparation and writing of the '**Technical Design Report**' for the vacuum systems of the ET's arms, including cost estimations.
- Contact and sharing of information with **Cosmic Explorer community**.

CERN technical involvement



Studies

DESIGN
(Mechanical stability, supports, etc.)

MATERIALS
(Vacuum characterization, welding, manufacturing, cleaning, etc.)

VACUUM
(Layout, pumps, gauges, bake-out, etc.)

Prototyping

PRODUCTION

MEASUREMENT

Pilot sector

FABRICATION & TEST
Solution 1

FABRICATION & TEST
Solution 2

FABRICATION & TEST
Solution n

Examples of ongoing activities: Design

Straight beampipe module
(LIGO/VIRGO like)

3-4 mm thick tube

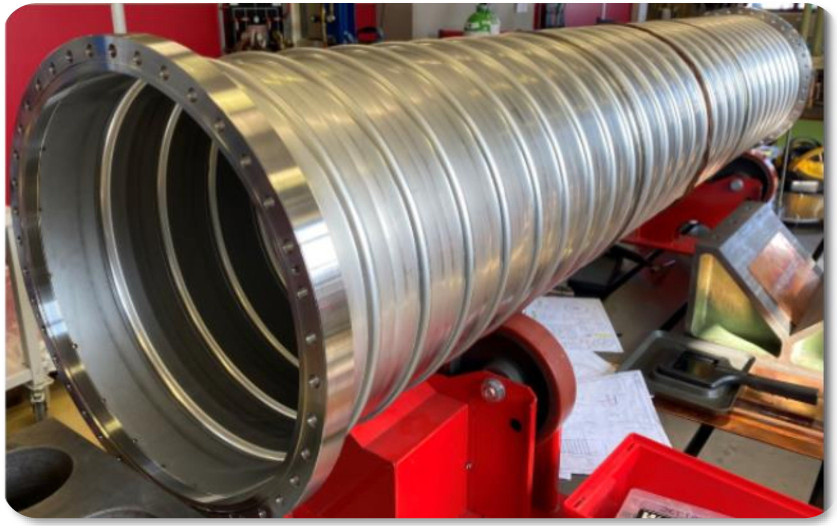
- **Requires bellows & stiffeners.**
- **Discontinuous production.**

Corrugated beampipe module

1-2 mm thick tube

- **No bellows & stiffeners.**
- **Lower kg/m** of **material.**
- **Continuous production.**
- **Less current** input if Joule effect **bakeout.**

Credit: LIGO



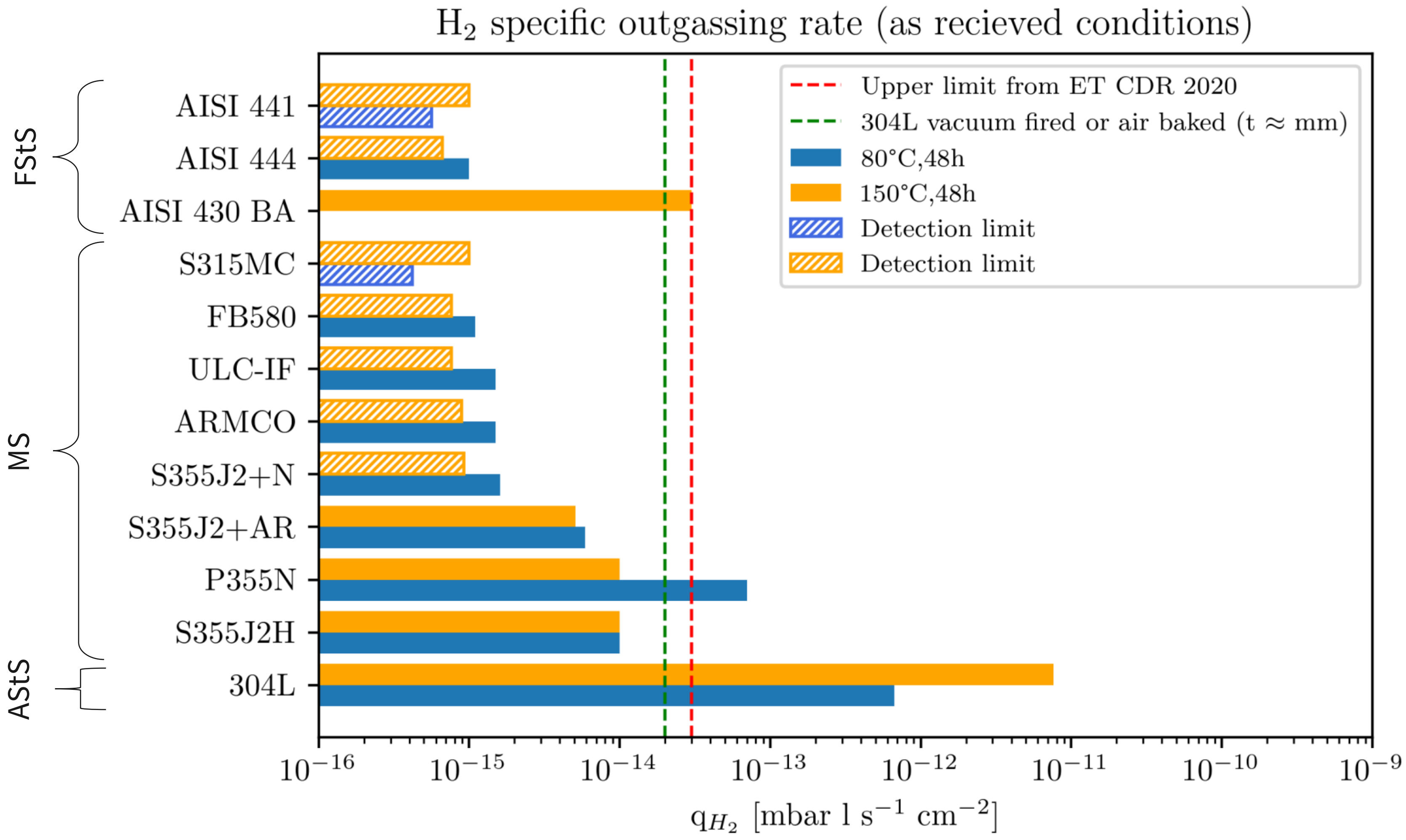
Credit: CERN

Examples of ongoing activities: Materials

Ferritic alloys

Mild steel and ferritic SS

- **Outperform austenitic SS outgassing rates without requiring HT treatment**
- **Lower (>30%)** raw **material cost**

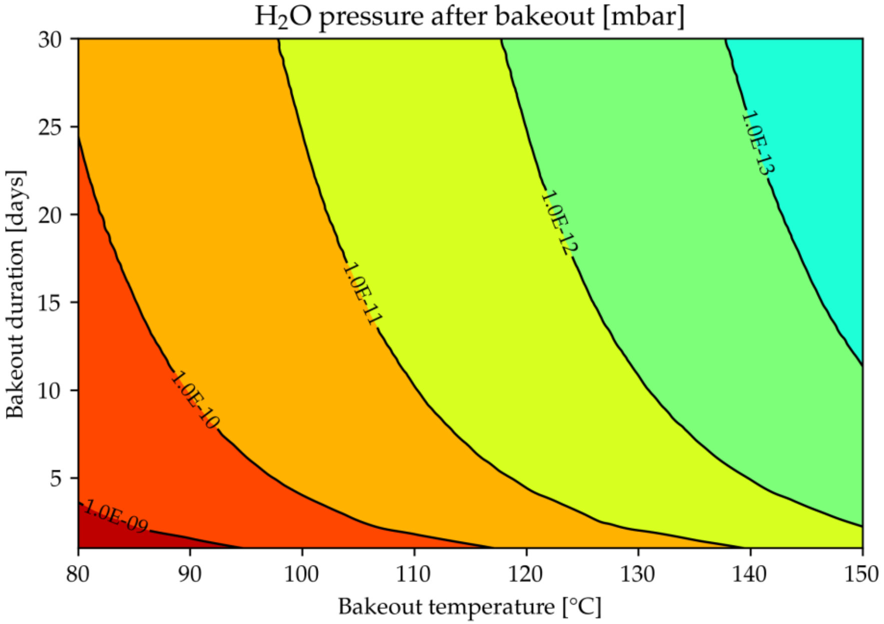


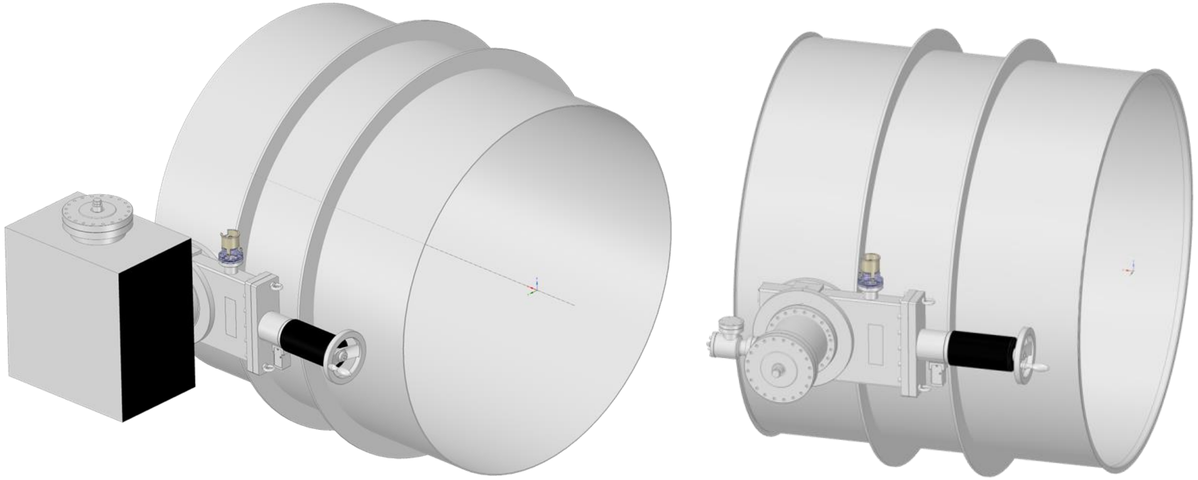
AStS: Austenitic Stainless Steel, FStS: Ferritic Stainless Steel, MS: Mild Steel. Vacuum Fired (950°C, 2h), Air baked (450 °C, 5d). Measurement error: ±40%; Detection limit: 50% of background

Examples of ongoing activities: Materials/Vacuum

Bakeout/Layout cost optimization

- **Bakeout temperature** and **duration**
- **Pumps size** and **distribution**





Pumps integration

- Vacuum **system sectorization**
- **Compact design**
- **Commercial instruments** and **pumps**

Examples of ongoing activities: Prototyping

System characteristics

DN400 – 2100 mm (t < 2 mm)

AISI 304L-VF
(AStS)

AISI 441
(FStS)

S315MC
(MS)

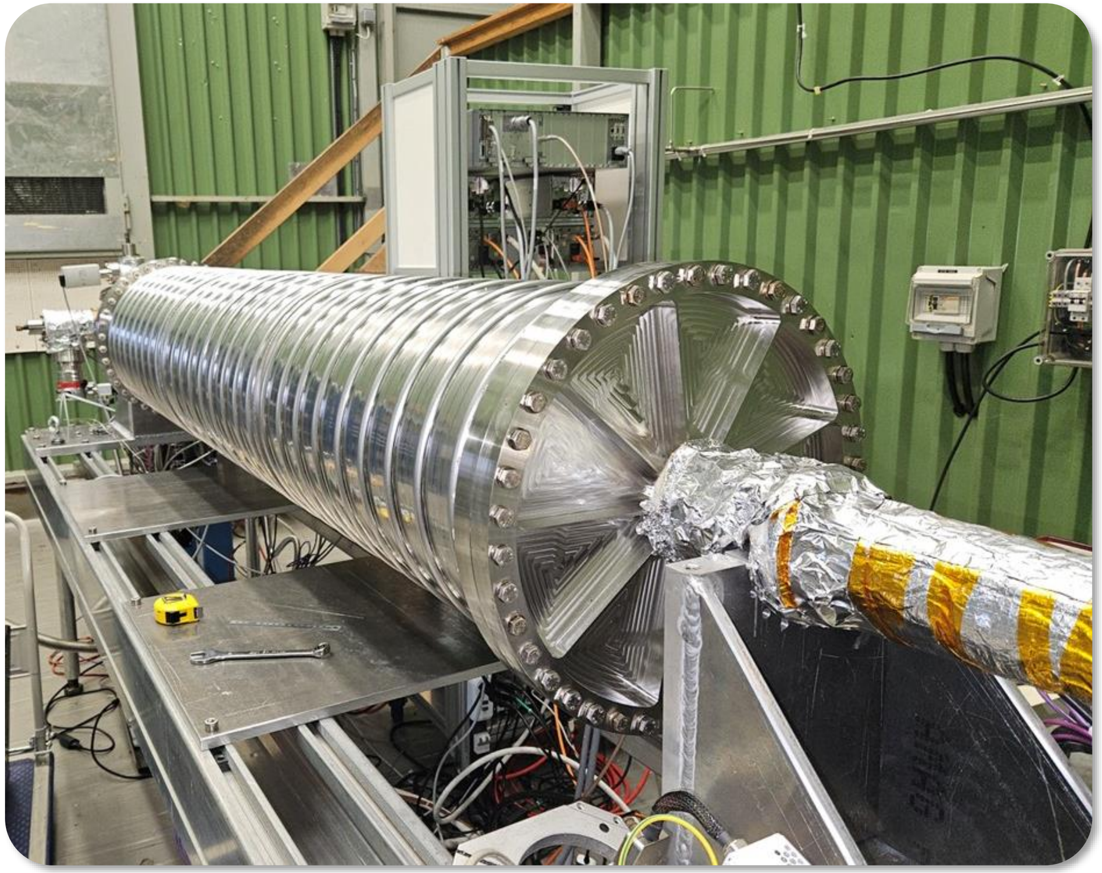
Pumping speeds scaled to ET dimensions

Objectives

Verify water outgassing **modelling**

Ultimate pressure after 80°C and 150°C bakeout

Test the **effect** of the **increasing pumping speed during bakeout** on ultimate pressure



Examples of ongoing activities: Prototyping

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✓

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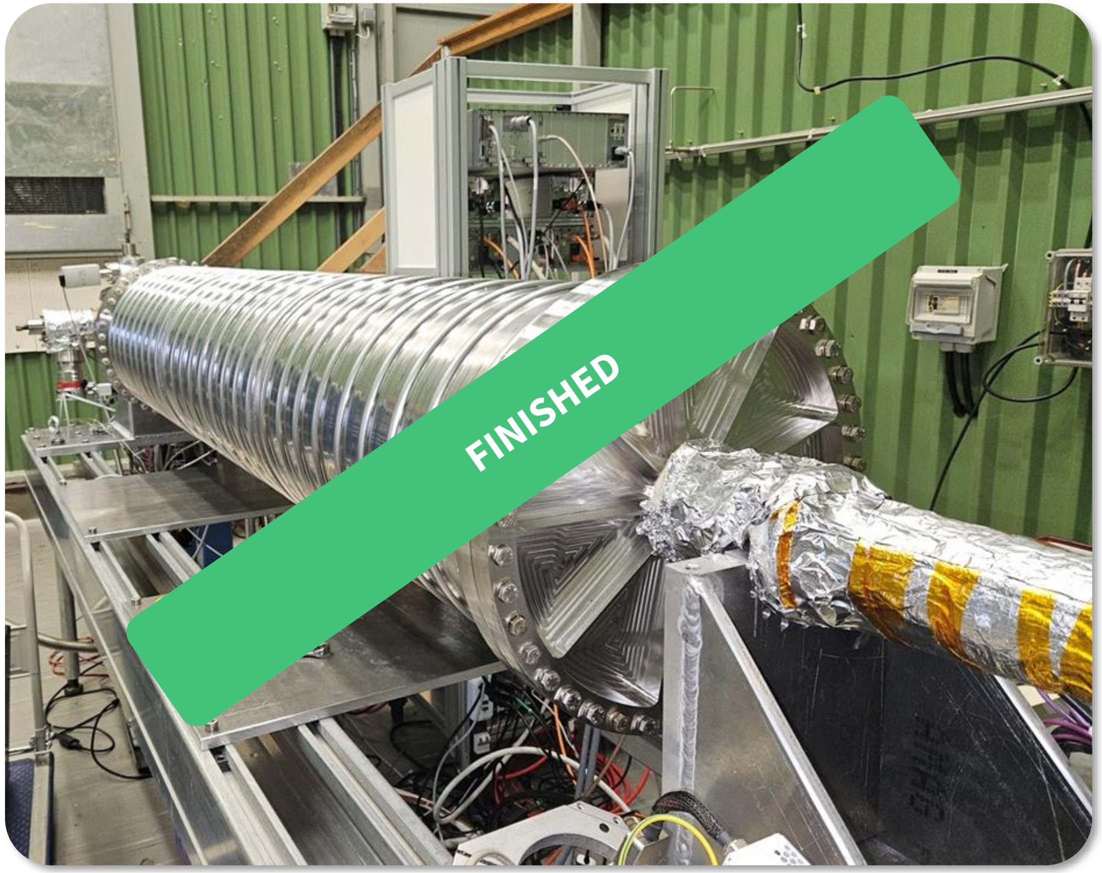
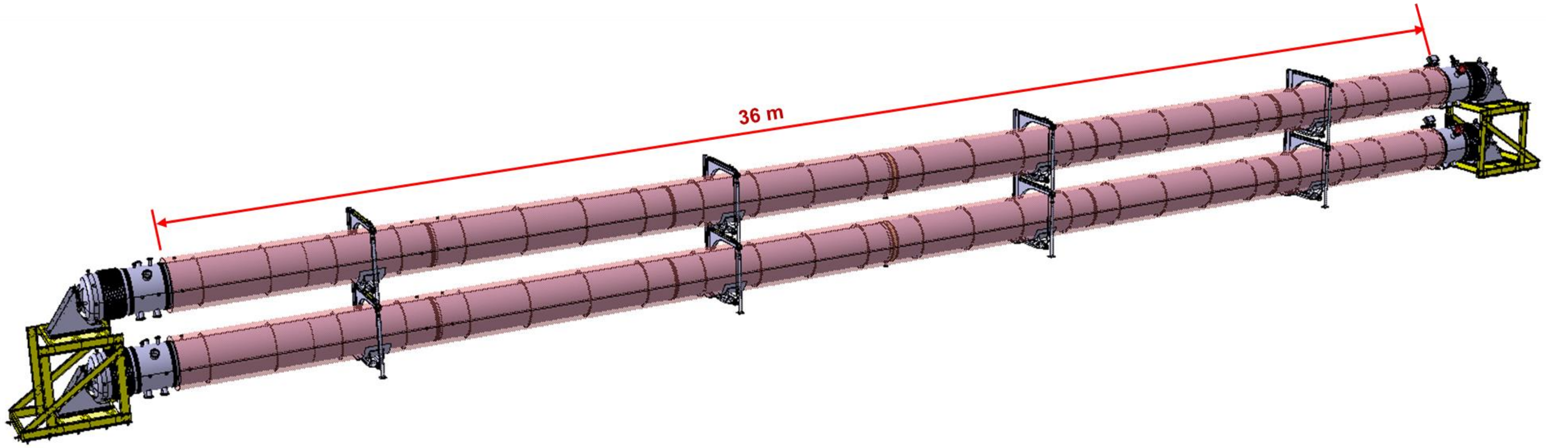


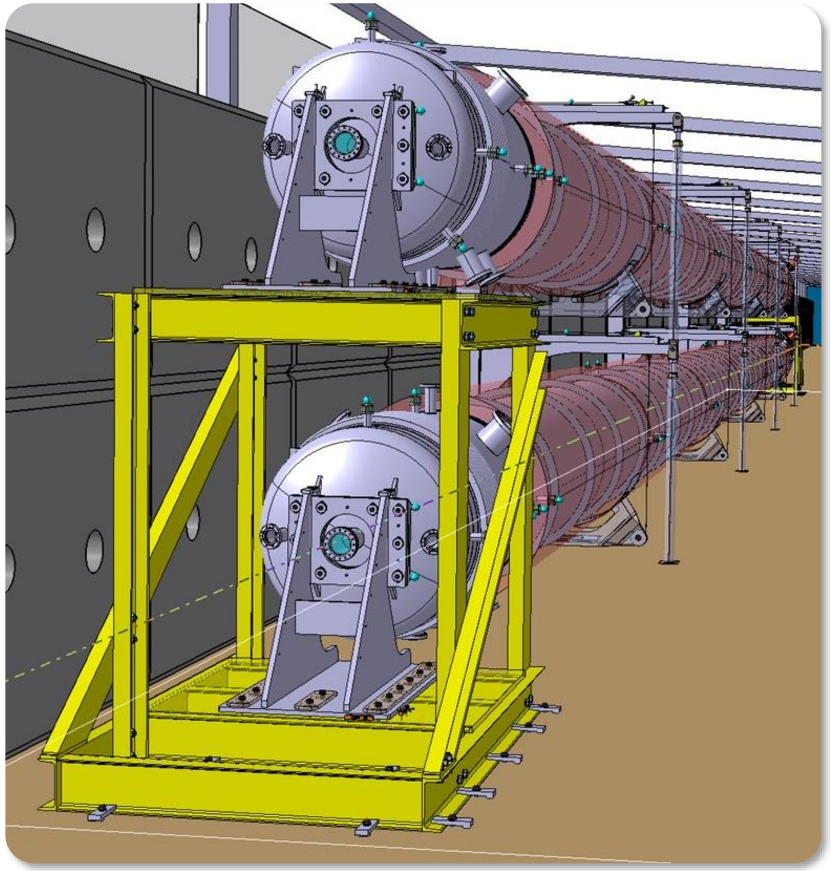
Outlook: ET beampipe pilot sector

The pilot sector aims to **test the design, fabrication, installation and commissioning** of the proposed **beampipes and support system**. It also aims to compare the feasibility of a selected number of technical choices.

From Q4 2024:

- **2 tubes Ø 1 m x 36 m**
- **AISI 441 (thickness 4 mm)**
- **VIRGO-like solution (straight tube)**

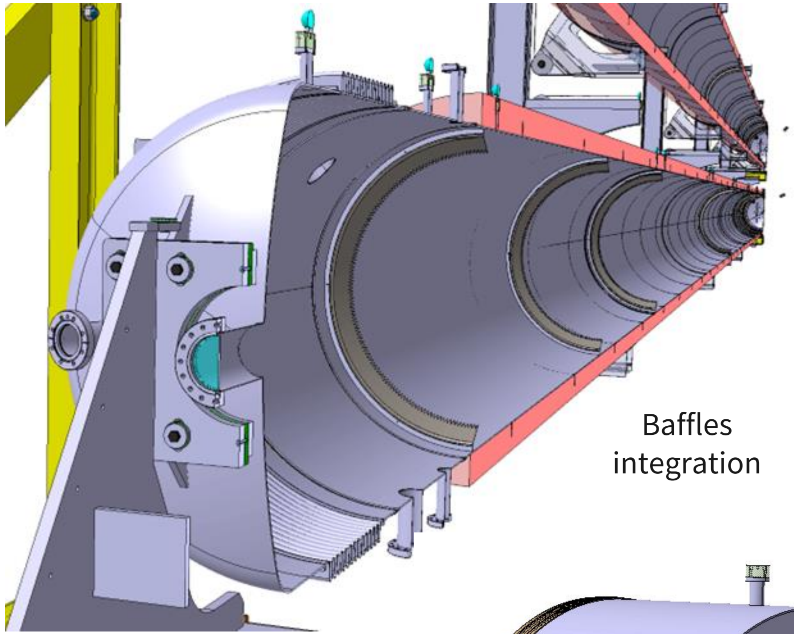


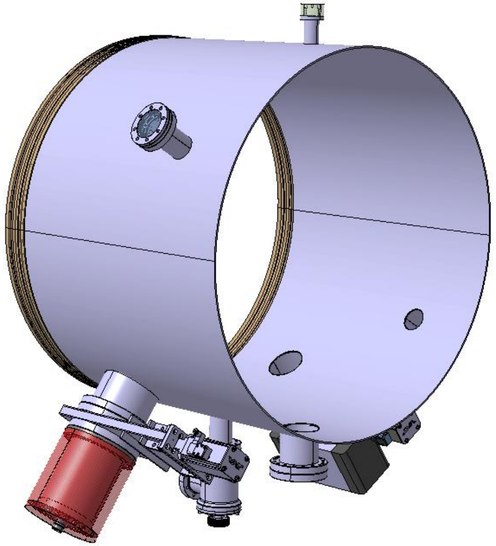


Outlook: ET beampipe pilot sector

Typical tests are:

- Installation and alignment of supports and beampipes.
- In-situ welding and assembly.
- Integration of thermal insulation, instrumentation and vacuum components.
- Leak detection procedure during fabrication and assembly.
- Pumpdown time.
- Bakeout: temperature distribution and efficiency.
- Ultimate partial pressures and outgassing rates.
- Validate the calculated vibration transmission matrix.
- Efficiency of the methods used to reduce the quantity of dust


Baffles integration


3D model of the pumping module

Further readings

[Beampipes for Gravitational Wave Telescopes 2023]

A.T. Perez Fontenla, Materials and their production processing for ET's beampipes

G. Favre, Manufacturing and welding options

G.J. Deleglise Design of beampipes for GWT

C. Scarcia, Sectorisation, pumping system, commissioning and operation of ET beampipes

I. Wevers, Vacuum measurements of materials and coatings for GWD beampipes

L. Marques Antunes Ferreira, Options for surface finishing of beampipes for gravitational wave telescopes

P. Cruikshank, Leak Detection: from component production to system installation

L. Scibile, Installation and logistics (manufacturing facility, storage, transport, timeline)

J. Hansen, The ET pilot sector at CERN

G. Pigny, Control systems

J.A. Ferreira Somoza, Cost assessment guidelines

[XIII ET Symposium]

C. Scarcia, ETO: Vacuum Pipe project

[2nd ET annual meeting]

C. Scarcia, CERN vacuum pipe results

L. Scibile, CERN vacuum pipe planning and perspective

C. Garion and P. Chiggiato, Presentation of the technical challenges for vacuum tube manufacturing [Einstein Telescope Industry Webinar]

Thank you for your attention

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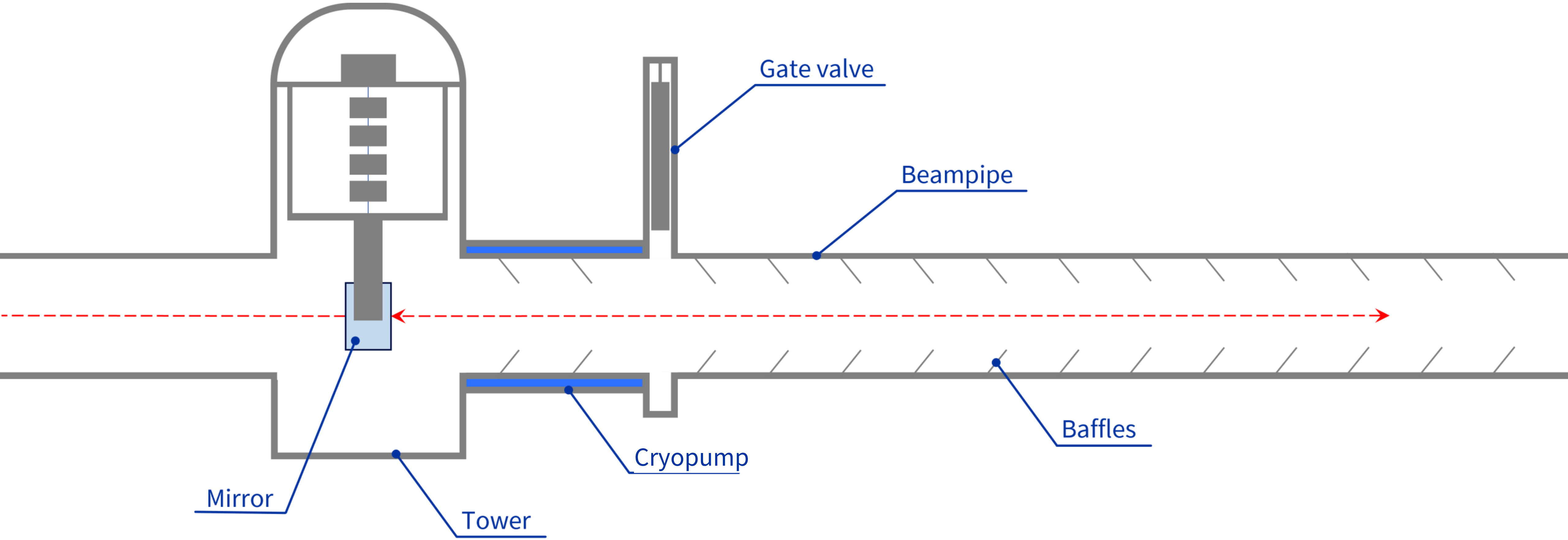
Gravitational Wave Detectors: the vacuum system



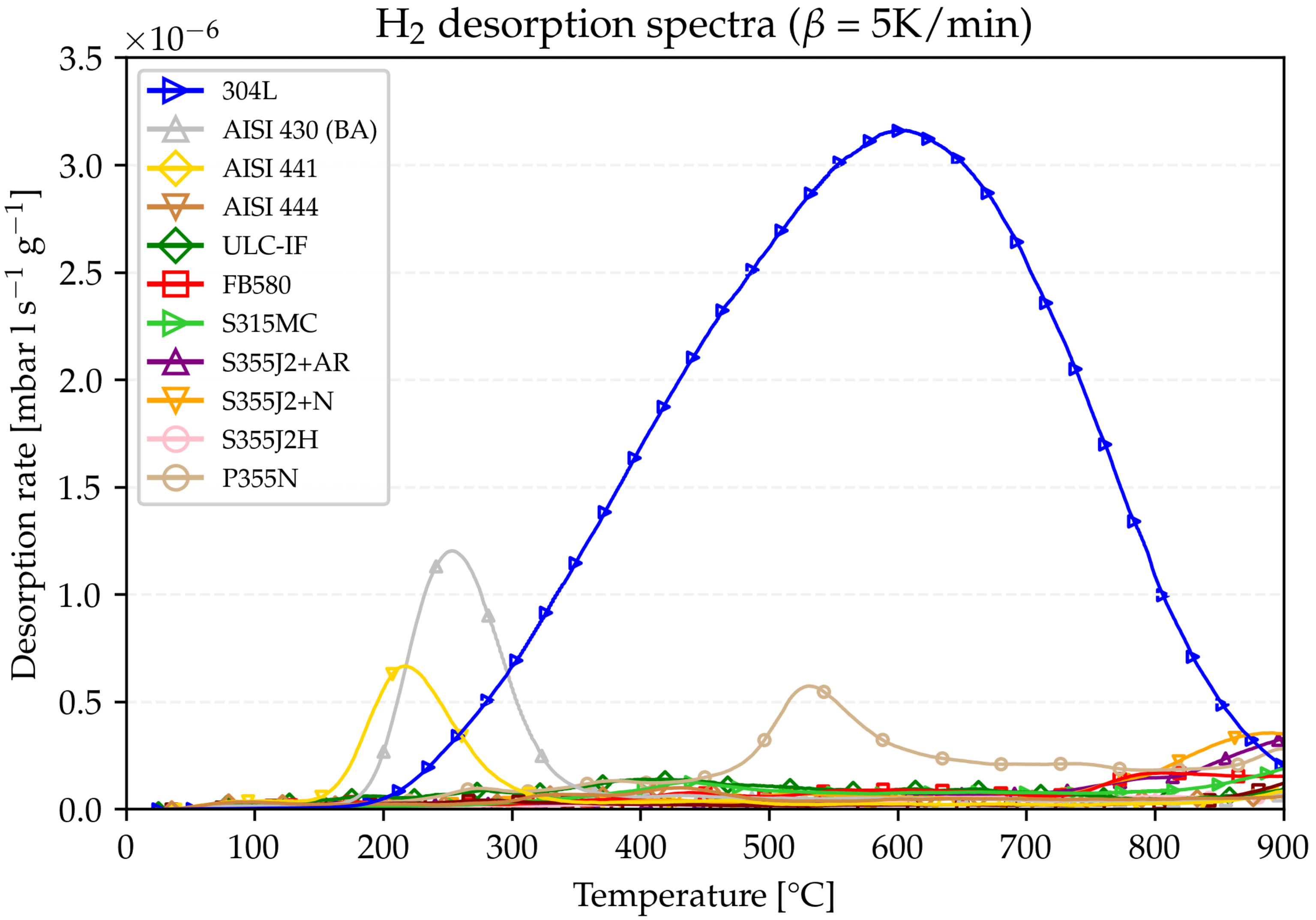
Vacuum characterization of ferritic alloys

H_2 content

	Steel grade	H_2 content [ppm at.]
	304L	**80**
Ferritic StS	**AISI 430 (BA)**	**8.3**
	AISI 441	6.8
	AISI 444	**1.5**
Mild steel	ULC-IF	3.7
	FB580	2.8
	S315MC	2.7
	S355J2+AR	2.0
	S355J2+N	1.6
	ARMCO	1.2
	S355J2H	**7.8**
	P355N	**1.0**

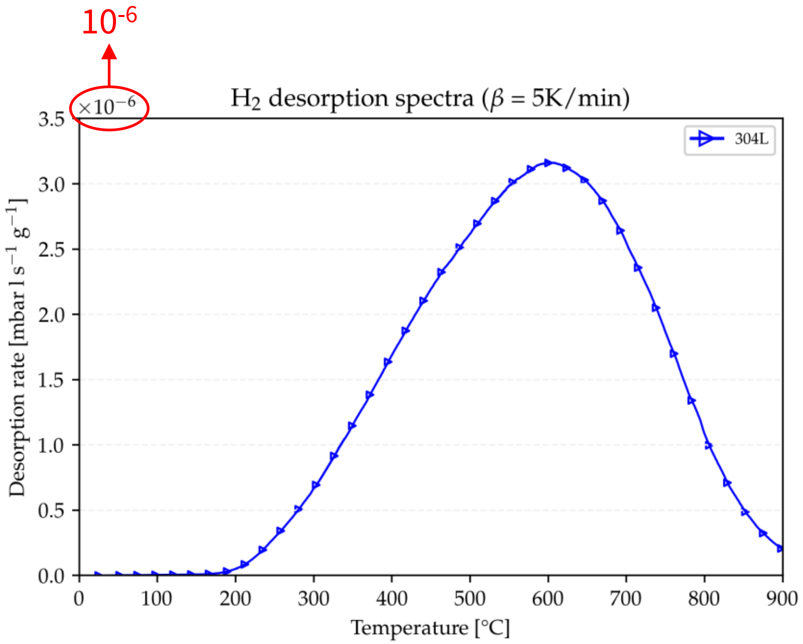
Concentration calculated from quantity of H_2 (considered to be uniformly distributed) extracted with TPD (up to 850°C)

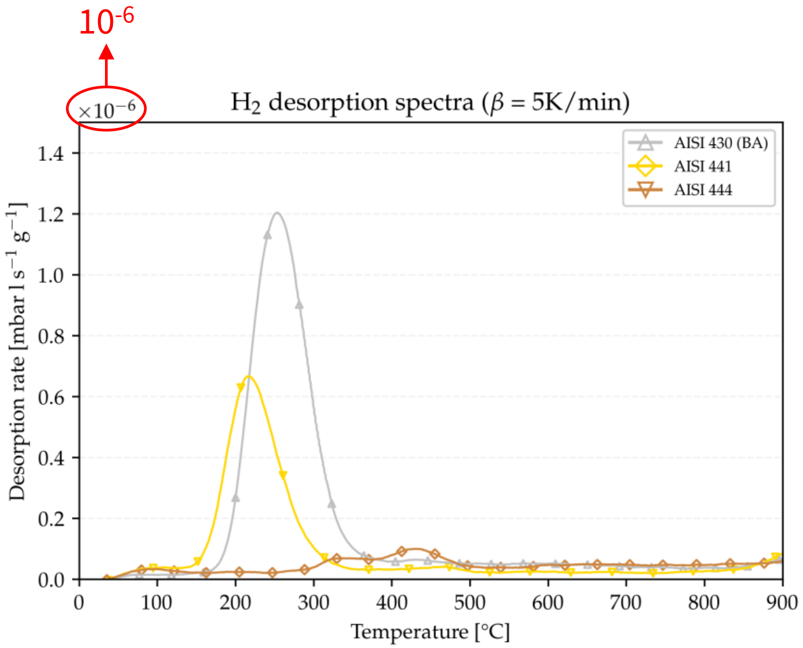
Background removed

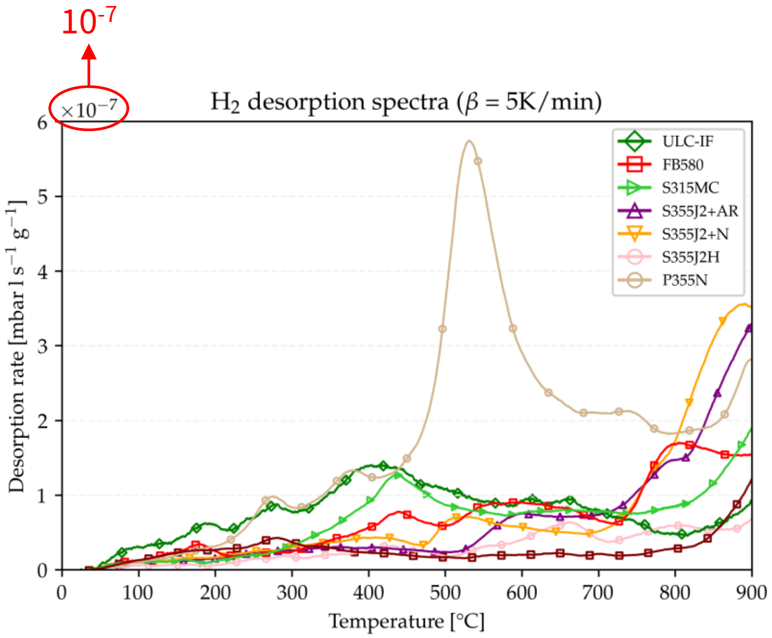


Vacuum characterization of ferritic alloys

H_2 content







Austenitic microstructure

Diffusion peak

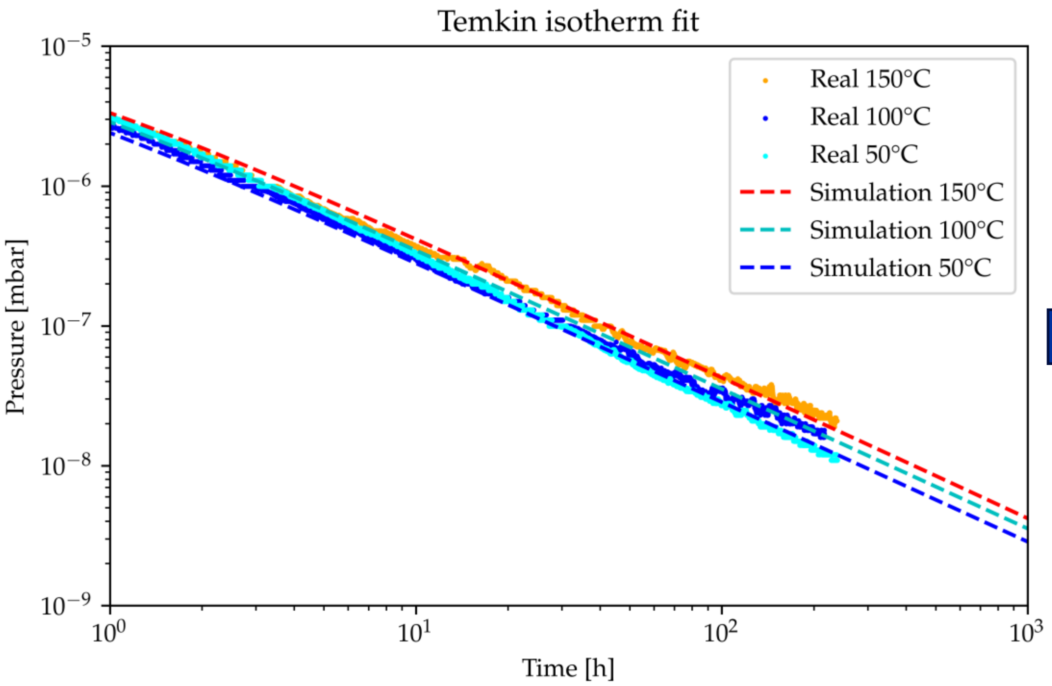
Ferritic microstructure

Ferritic/Bainitic – Ferritic/Pearlitic microstructure

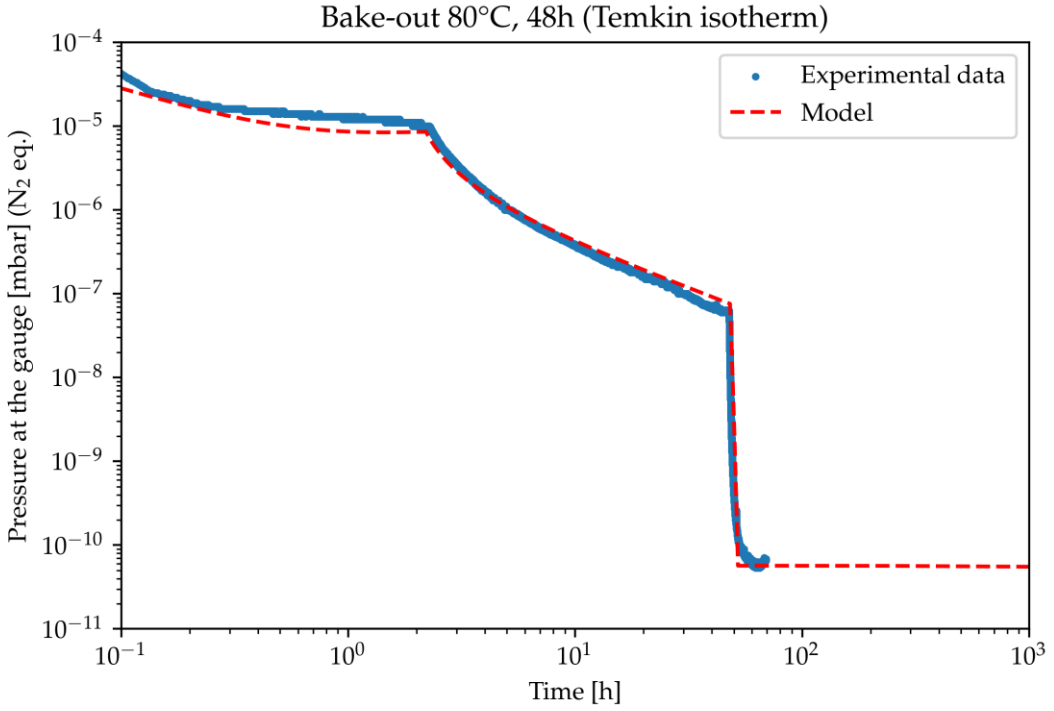
De-trapping peaks

Vacuum characterization of ferritic alloys

H_2O pressure modeling

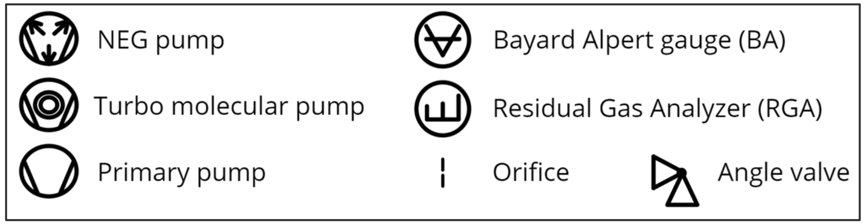


H_2O binding energy
&
coverage



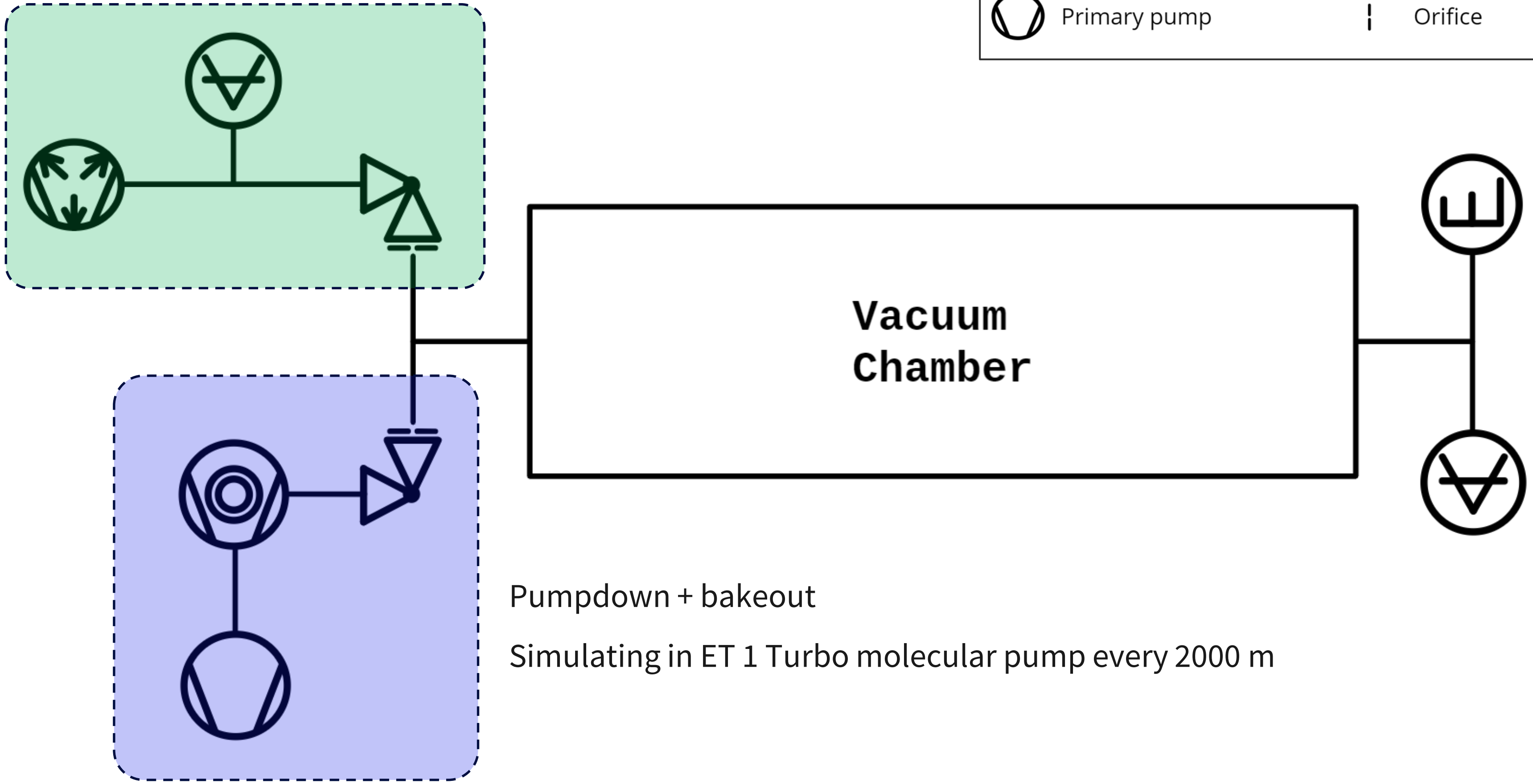
ET corrugated prototypes

Vacuum layout



Bakeout + UHV pumping

Simulating in ET
1 NEG every 50 m
(1500 ls^{-1} for H_2O)



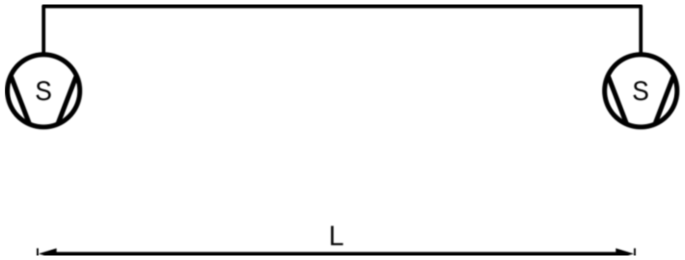
Pumpdown + bakeout

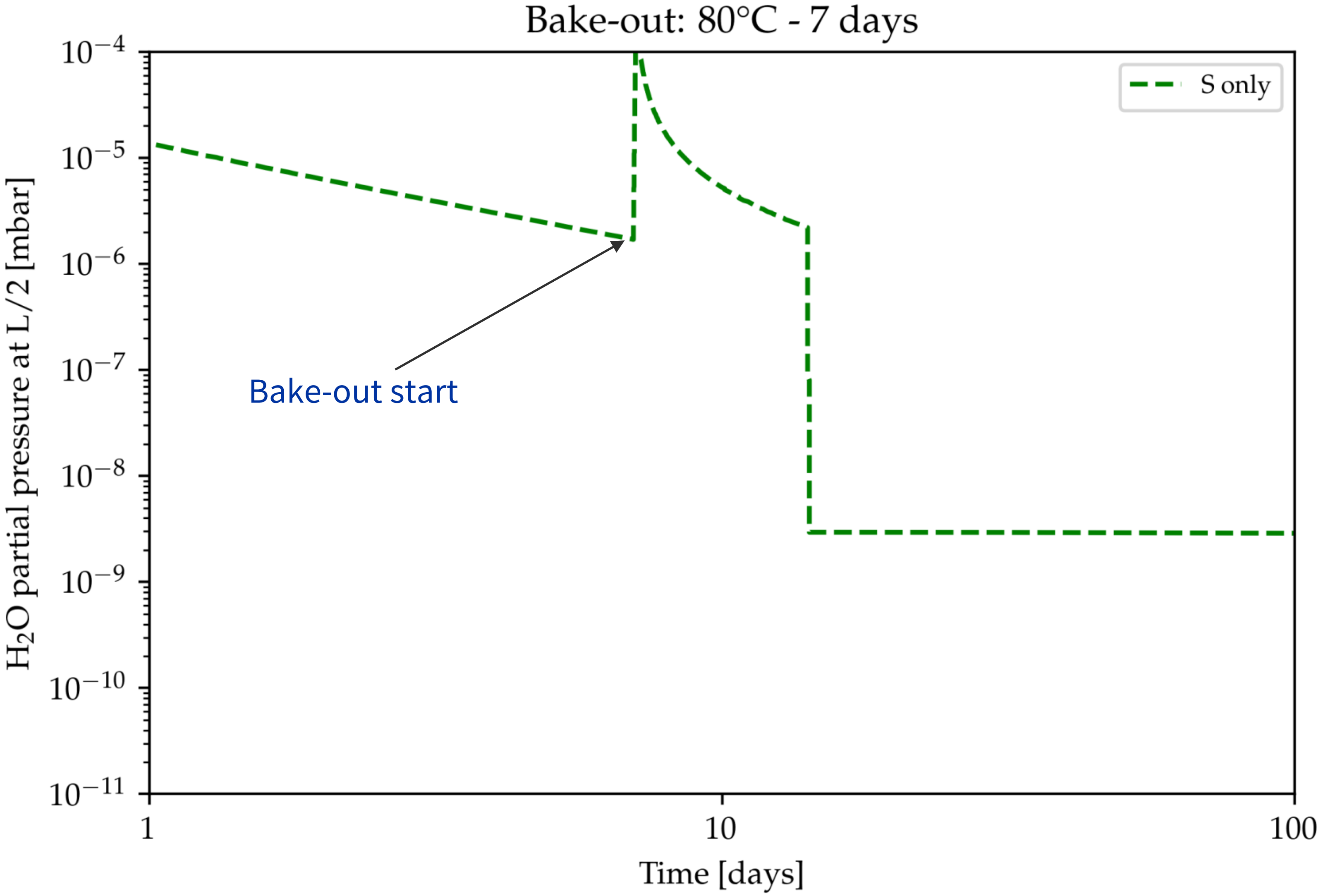
Simulating in ET 1 Turbo molecular pump every 2000 m

ET corrugated prototypes

Bakeout scheme

Experimental verification of beneficial effects of increased pumping speed during heating





ET corrugated prototypes

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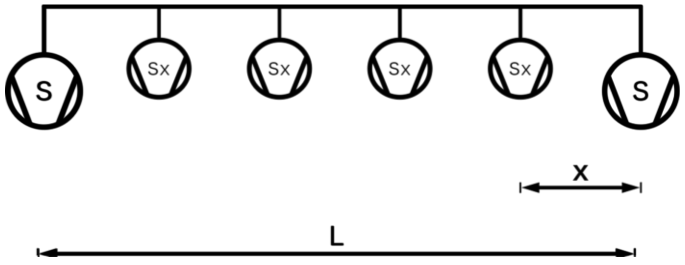
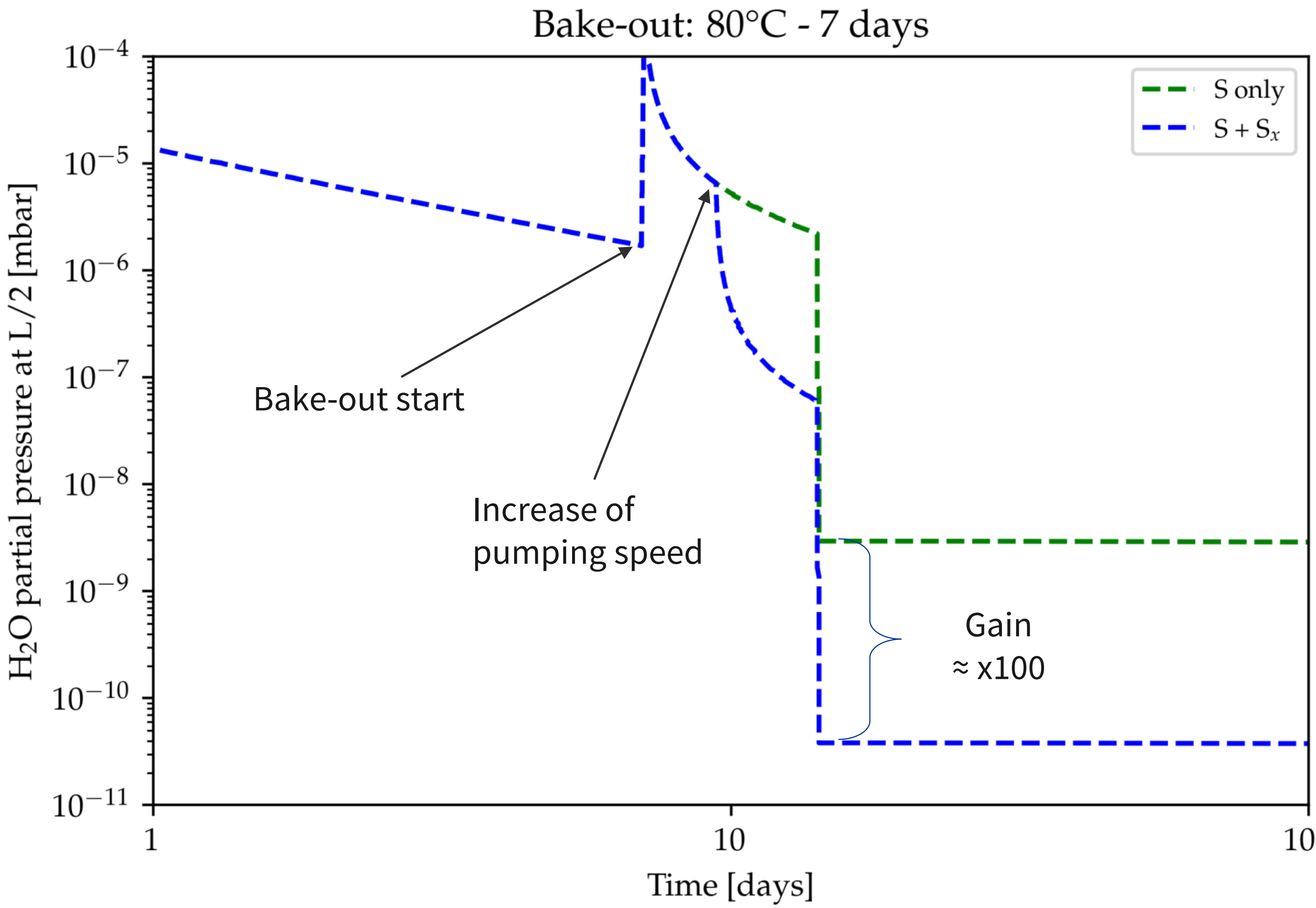


We could exploit the use of NEG pumps [SAES proposal, 2010]

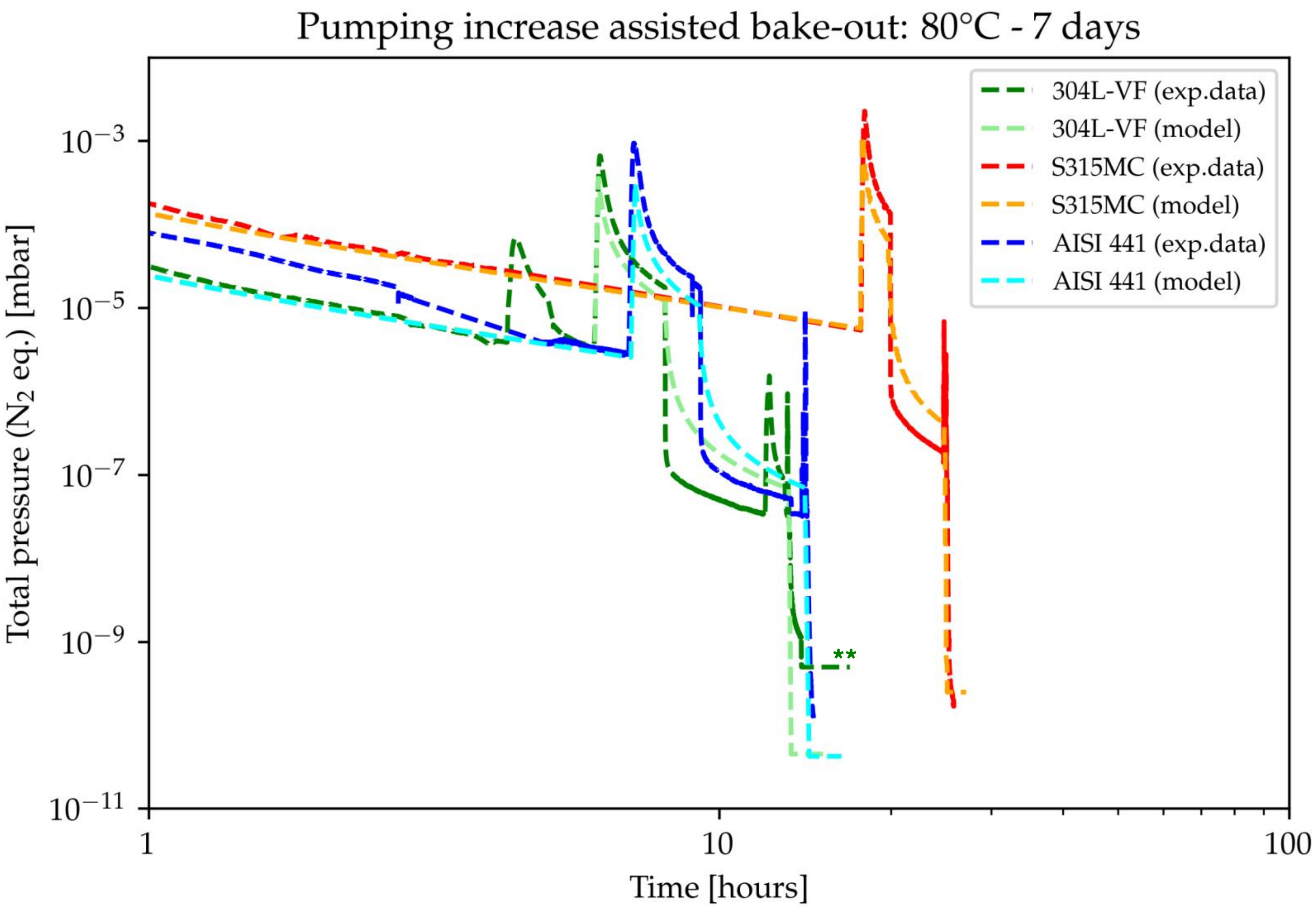

Bake-out: 80°C - 7 days

Bake-out start

Increase of pumping speed

Gain ≈ x100

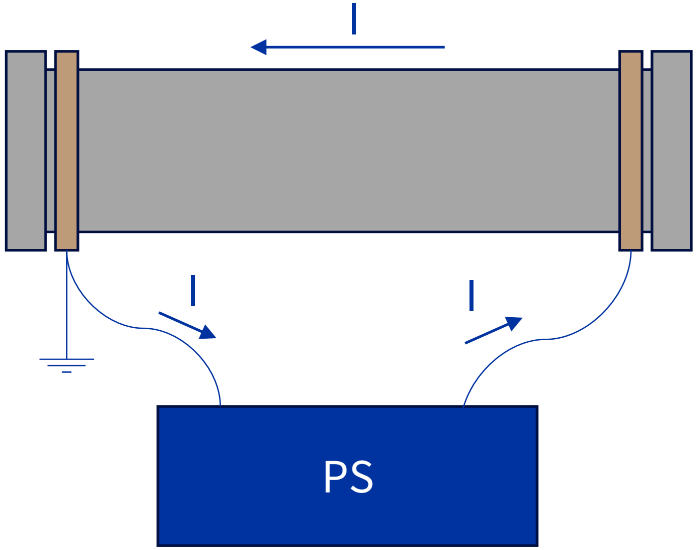
Examples of ongoing activities: Prototyping



** DN400 closing flanges erroneously fired before machining

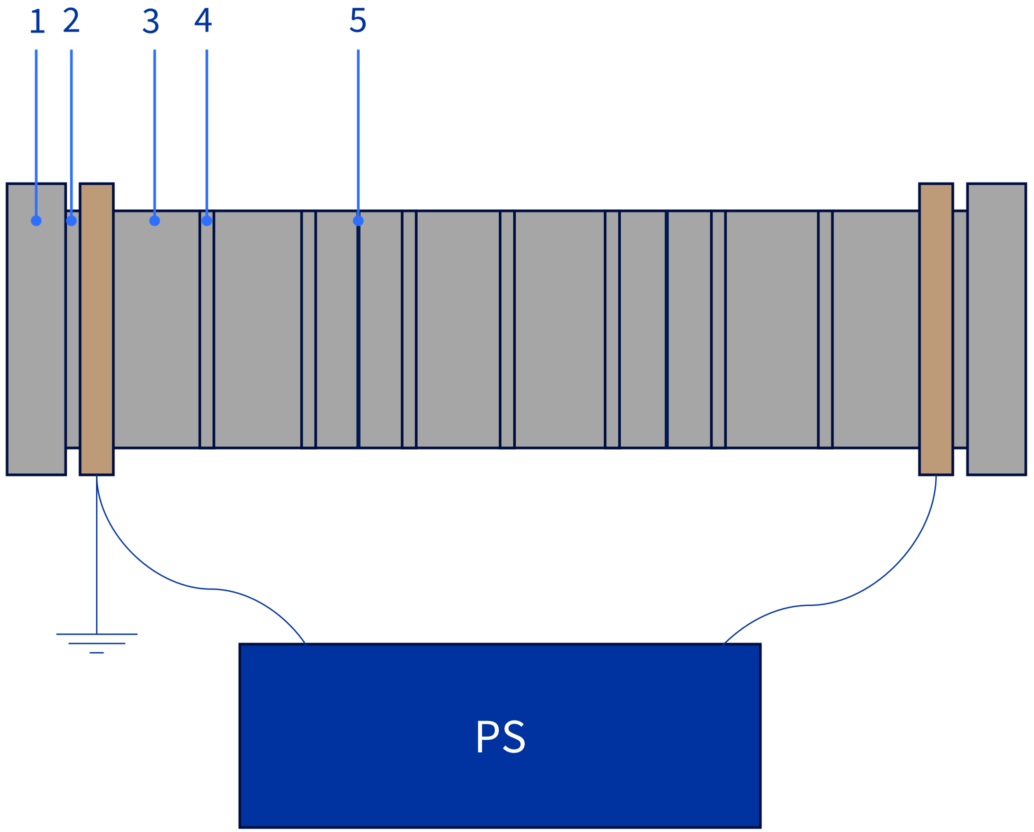
1. **Good matching between** the **model** and **experimental data**.
2. The **model**'s **predicted water partial pressure** values **generally align with** the **values** from the **mass spectrometer signal**.
3. The **increase of pumping speed during** the **bakeout** is **proven** to be a **viable solution to shorten** the **duration**.

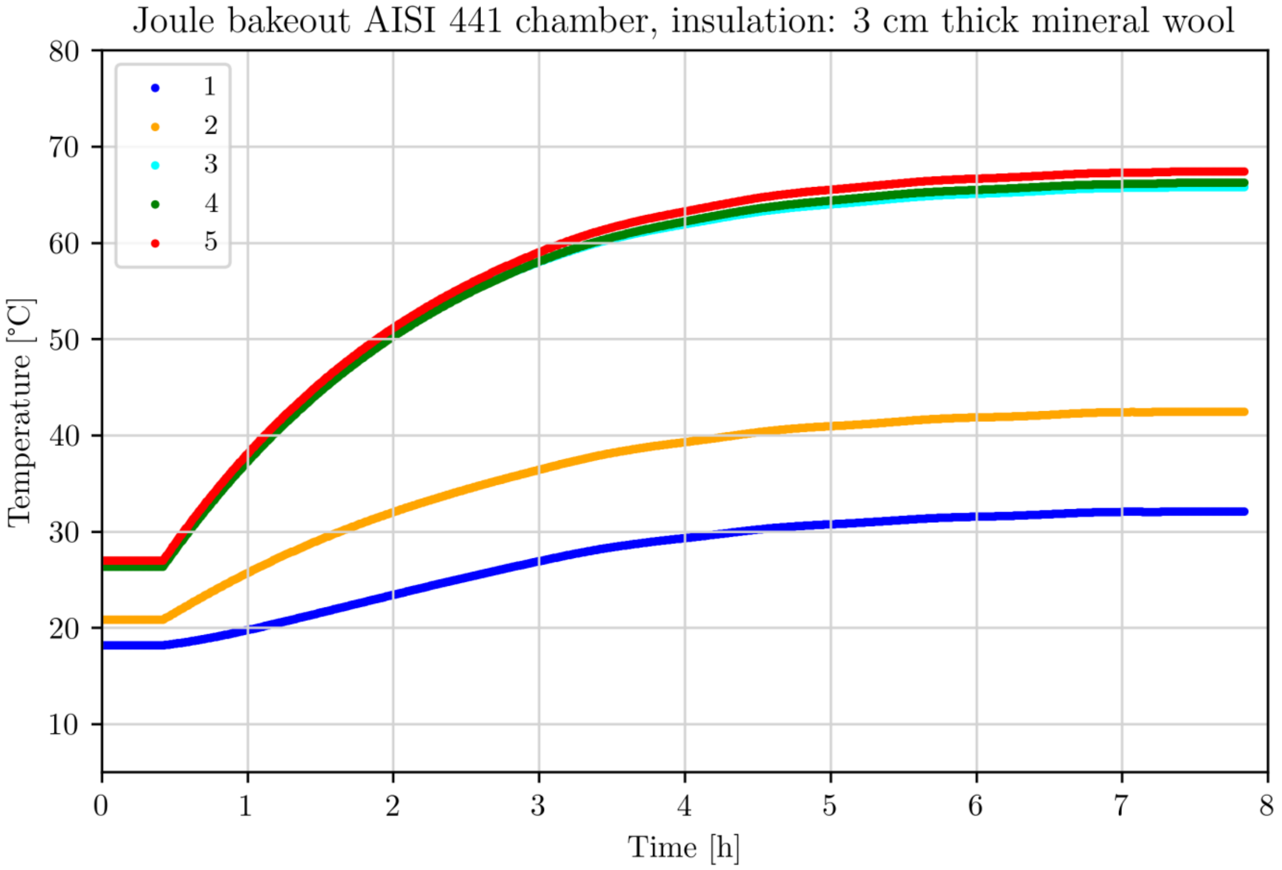
Examples of ongoing activities: Vacuum



Power supply max current: 400A

Examples of ongoing activities: Vacuum





Chamber:
AISI 441 (400 x 1.5 x 2050 mm)

Max temperature according to heat transfer model: 64°C
Max recorded temperature: 66°C