Candidate Beam Tube Materials Vacuum Properties

Carlo Scarcia (w/ data contribution from Aiman H. Al-Allaq and James Fedchak)

2025/09/30, BTW3 workshop

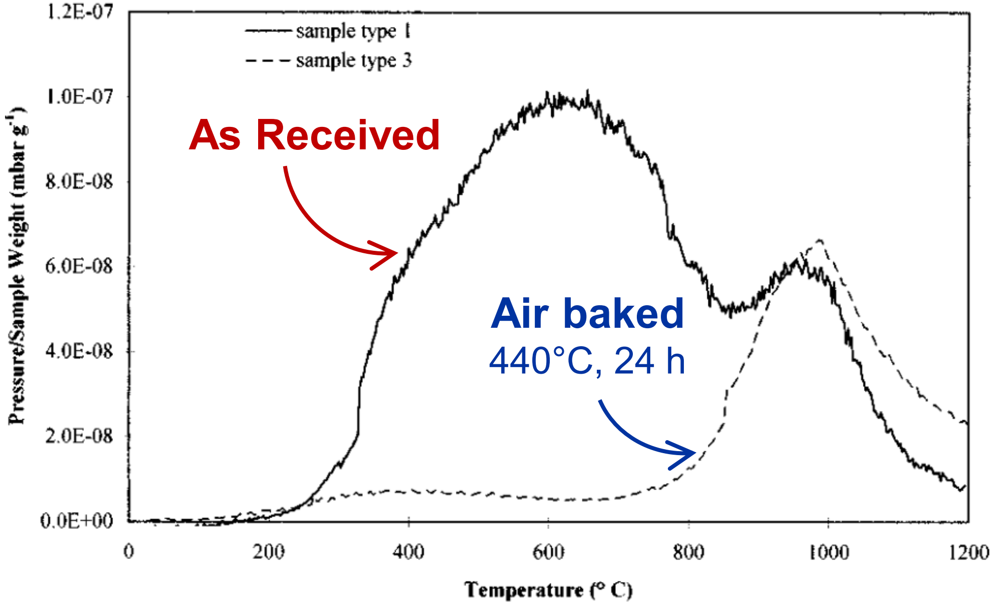
2G-GWD beam pipe material: 304L air-baked

Air bakeout (L. Petermann, 1965 FR1405264)

→ H_2 depletion + diffusion barrier w/ Fe-rich passivation layer

	LIGO[1]	Virgo[2]
Applied on	Coils	Tubes
Tube thickness [mm]	3.23	4
Air bake recipe	454°C, 36 h	410°C, 72 h
In situ bakeout	160°C, ~3 weeks	150°C, ~1 weeks
In-field specific outgassing rates [mbar l s^{-1} cm^{-2}]	**6.1 – 8.4 × 10^{-14} (@ 23°C)**	**≈ 1×10^{-14} (@ 20°C)**

Thermal desorption measurements on 304L specimens (30 x 10 x 5 mm, 5 K/min) [3]



Credit: VIRGO

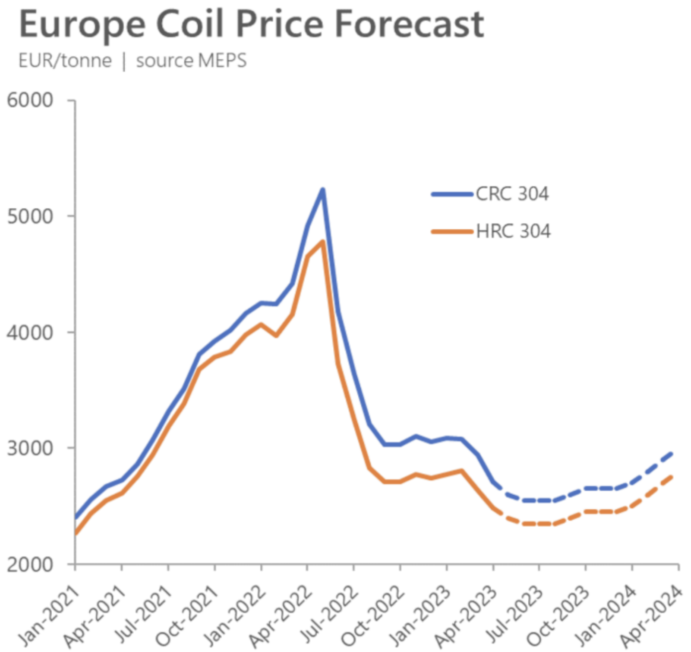
[1] Weiss R., Residual Gas in the LIGO Beam Tubes: Science, Arts and Recipes, AVS 50, 2003
[2] Pasqualetti A., Virgo Vacuum System, INFN-LASA, 13/06/2024
[3] Bernardini *et al.*, Air bake-out to reduce hydrogen outgassing from stainless steel, JVST A, 16, 188–193 (1998)

Scalability problem from 2G-GWD to 3G-GWD

Raw material
&
air-bakeout cost

Production time

New requirements
vs
vacuum system cost



VIRGO production rate
(air-bakeout limited):
20 m/day

ET (120 km) production time:
~16 years
(365 days production)

Residual gas noise contribution[6,7]:
((x~10 better than LIGO/VIRGO)

ET: $<10^{-25}$ $Hz^{-1/2}$

CE: $<5 \times 10^{-26}$ $Hz^{-1/2}$

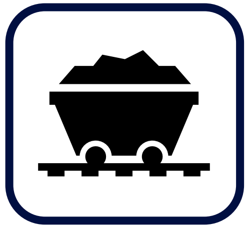
Forecasted budget for beampipe vacuum (from 2G)[6,7,8]:

ET: ~440 M€

CE: ~730 M$

[6] *Matthew Evans et al.* Cosmic Explorer Horizon Study, 2021
[7] ET Science Team, Einstein gravitational wave Telescope conceptual design study, 2011;
[8] ET collaboration, Einstein Telescope preliminary cost book, 2020

Cost reduction guidelines from previous workshops[4,5]



Less expensive beam pipe materials

Mild steels & Ferritic stainless steels

Literature review: only four articles reporting on UHV studies on mild steels and ferritic stainless steels.

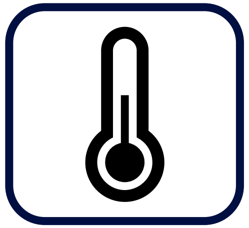
C. D. Park *et al.*, *J. Vac. Sci. Technol. A* 26, 1166 (2008).

C. D. Park *et al.*, *J. Vac. Sci. Technol. A* 34, 021601 (2015).

S. Kato *et al.*, J. Vac. Soc. J. 55, 160–163 (2012).

J. Kamiya *et al.*, Vacuum 98, 12–17 (2013).

Results limited to water outgassing at room temperature and the total outgassing rate after bakeout



Lower bakeout temperatures (<150°C)

Low binding energy coatings (Fe_3O_4, a-Si:H)

[4] NSF Workshop on Large Ultrahigh-Vacuum Systems for Frontier Scientific Research Instrumentation, LIGO-P1900072-v1, H.F Dylla, R. Weiss and M.E. Zucker, eds
[5] Beampipes for Gravitational Wave Telescopes 2023, CERN, 27-29 March 2023

The landscape of labs and measurements

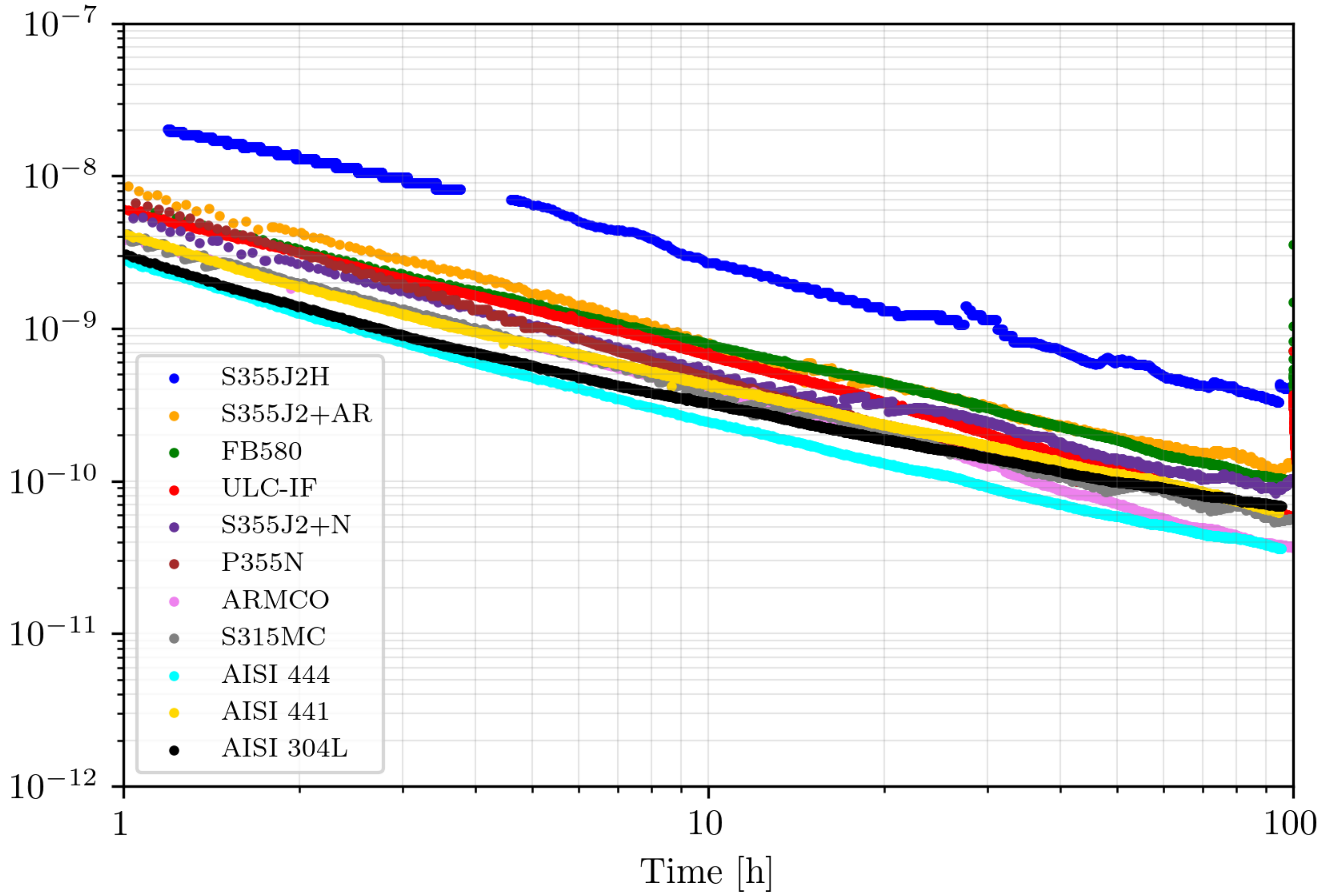
	CERN	NIST	Jefferson Lab	William & Mary
H_2O outgassing rate (Room temperature)	Throughput	Throughput	Throughput	-
Outgassing rates after bakeout	Coupled accumulation-throughput (H_2, CH_4, CO and CO_2)	Rate of rise (H_2)	Rate of rise (H_2)	Rate of rise (H_2)
Other measurements	TPD XPS Water binding energy	-	Water binding energy	XPS
Materials	Mild steel, Ferritic StS. Austenitic StS.	Mild steel Austenitic StS.	Mild steel Austenitic StS.	Mild steel
Coatings	a-Si:H	-	Fe_3O_4	Fe_3O_4

Reminder: The cleaning method/procedures were different!

Water outgassing rate at room temperature

Throughput method

	Sample	q_{10h} (x 10^{-10}) [mbar l s^{-1} cm^{-2}]
Mild steel	**S355J2H**	**27**
	S355J2+AR	8.1
	FB580	7.9
	ULC-IF	6.7
	S355J2+N	4.9
	P355N	4.7
	ARMCO	3.9
	S315MC	**3.7**
Ferritic StS	**AISI 444**	**2.4**
	AISI 441	**4.3**
	304L	**3.3**



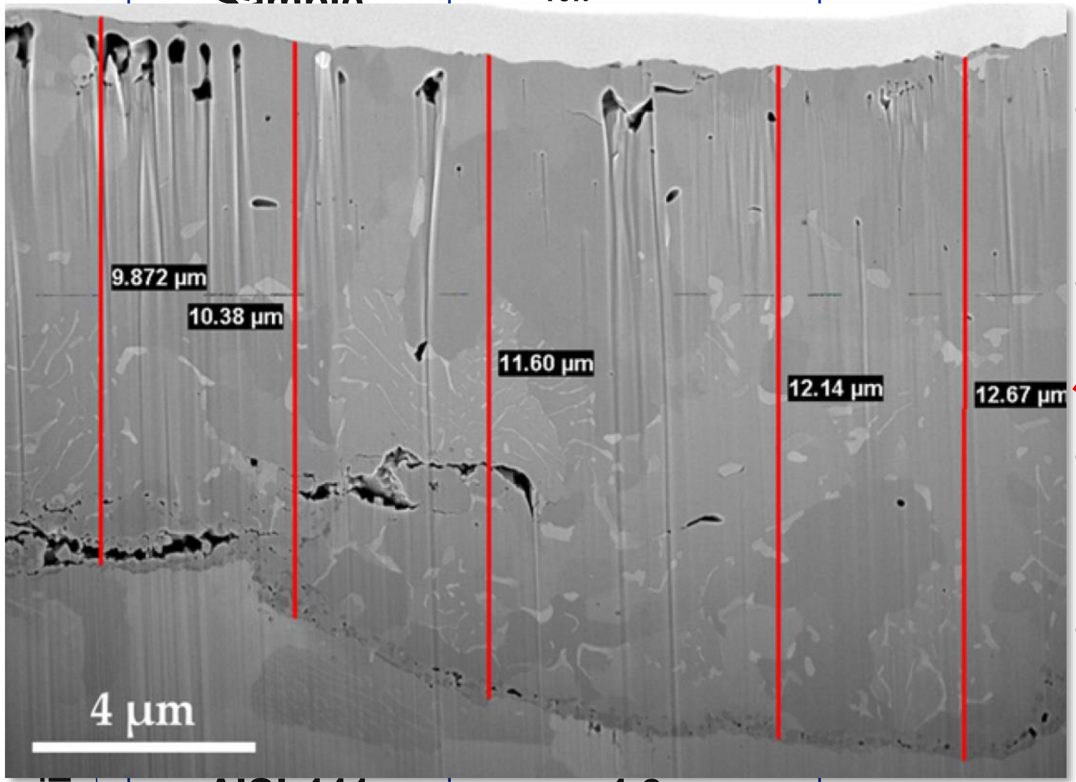
Background system removed.

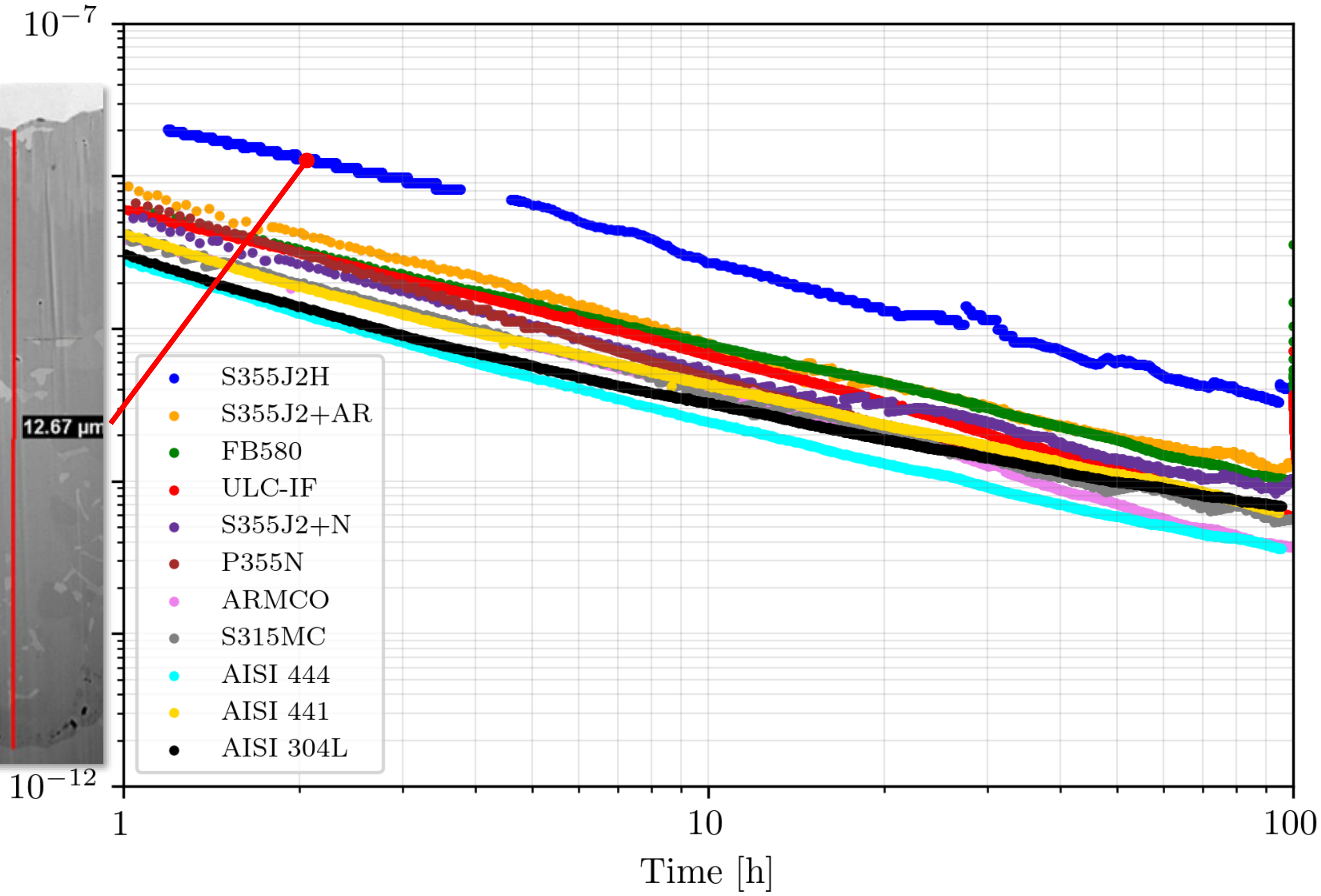
Water outgassing rate at room temperature

Throughput method

Sample	q_{10h} (x 10^{-10})
AISI 441	4.3
304L	3.3

Ferri



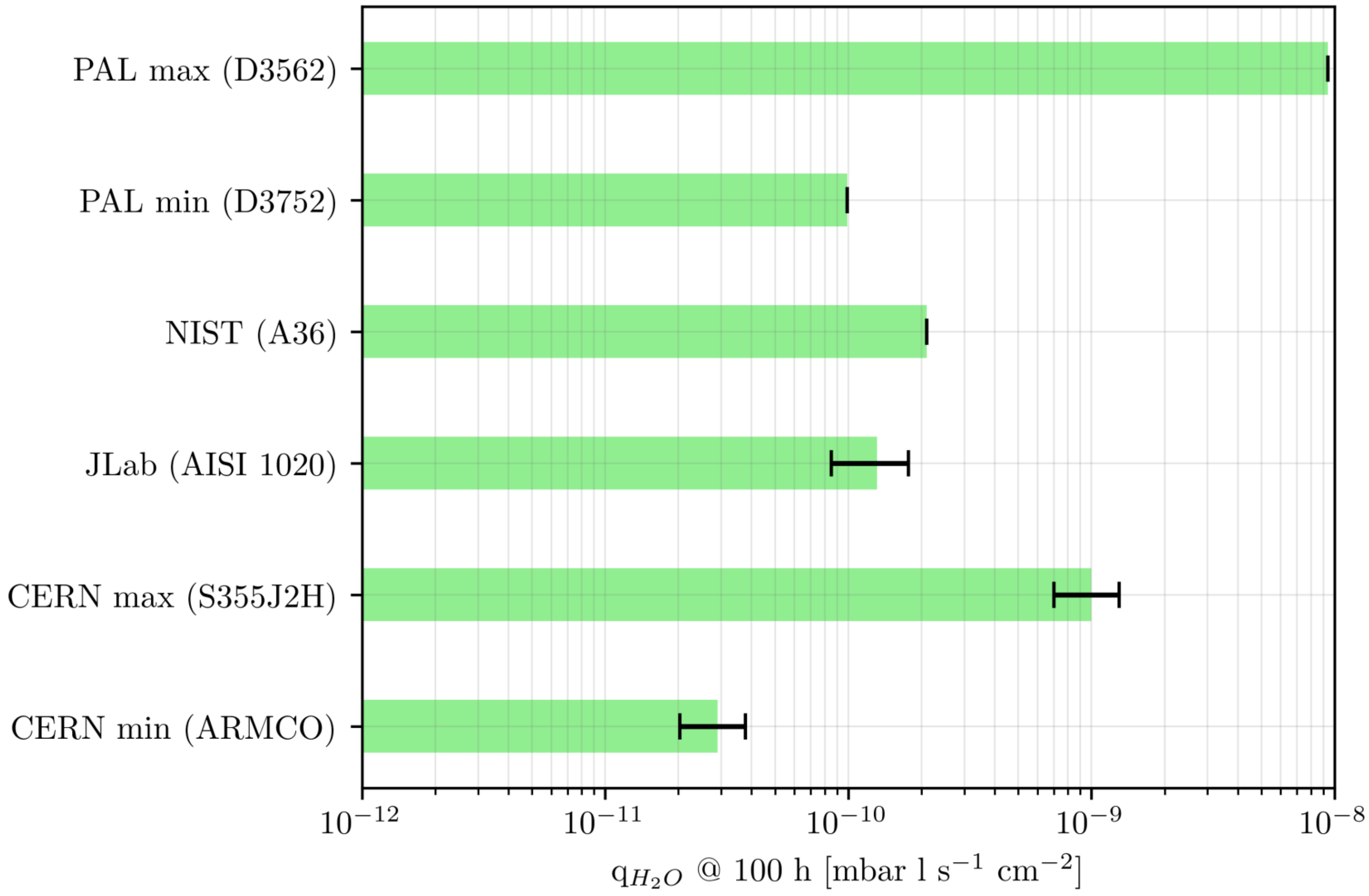


Background system removed.

Water outgassing rate at room temperature

Throughput method (100h pumping at RT)

	Tmeas. [°C]	Pre-treatment
CERN[a] (min, max)	21±2	None
Jefferson Lab [*unpublished*]	25	Acid etched
NIST[b]	24 (avg.)	(Machined?)
PAL[c] (min)	24±1	Machined + baked 150°C, 24 h + vented for 5h w/ N2
PAL[c] (max)	24±1	baked 150°C, 24 h + vented for 5h w/ N2



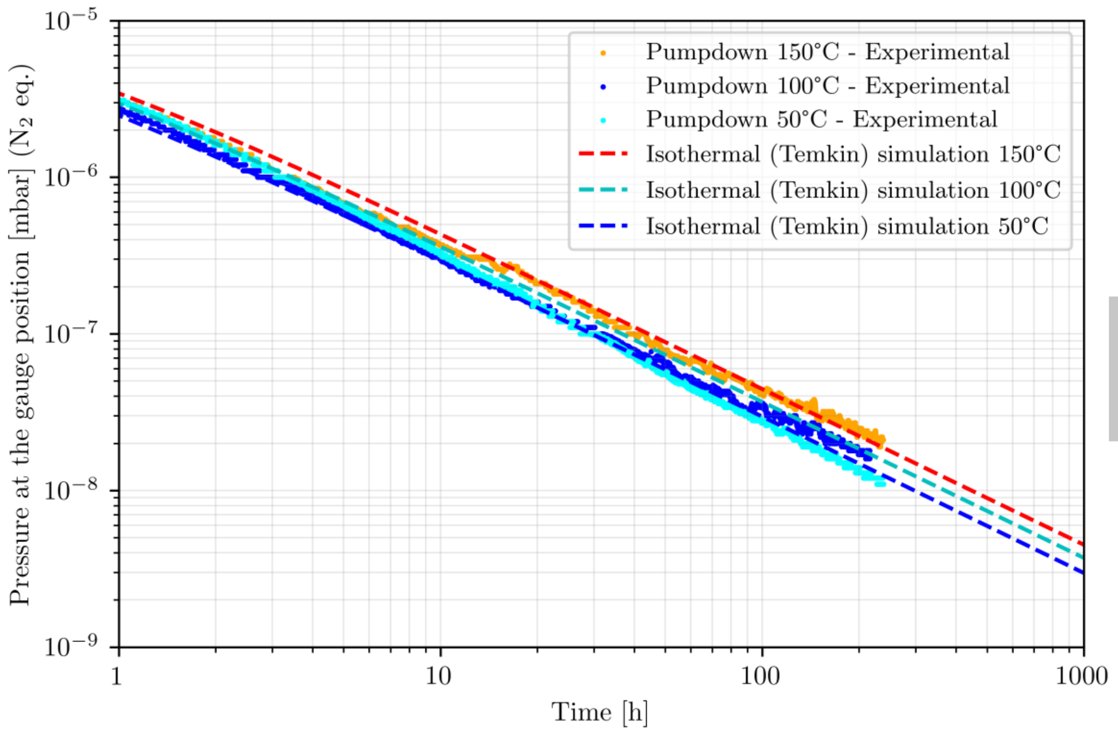
[a] Scarcia C. *et al.*, *J. Vac. Sci. Technol. B* 42, 054202 (2024)
[b] Fedchak J., Beampipes for Gravitational Wave Telescopes 2023, CERN, 27-29 March 2023
[c] *Park. C. et al.*, J. Vac. Sci. Technol. A 34, 021601 (2016)

Water vapour binding energy

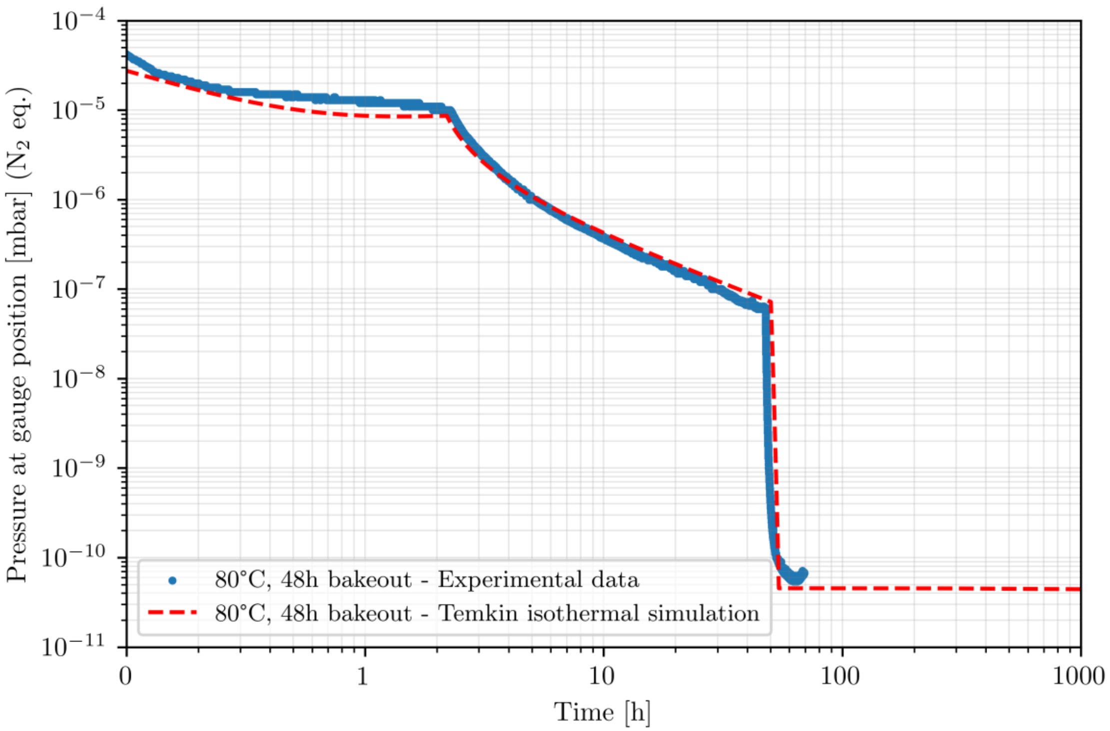
Throughput method

Objective: extraction of water vapour binding energy/ies and coverages (distribution) to simulate bakeouts.

Example from a mild steel chamber (P355N)



H_2O binding energy/ies & coverage



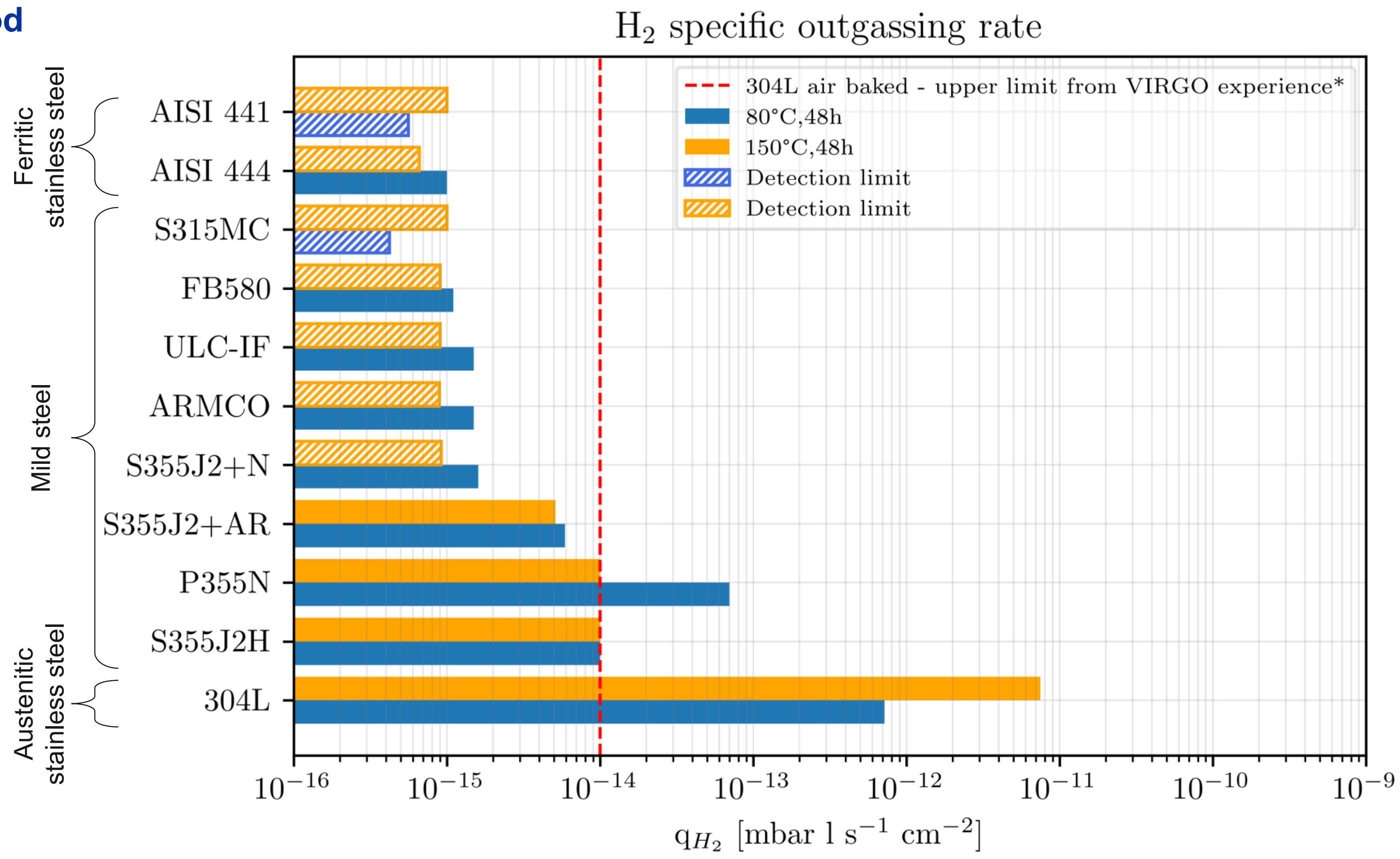
Background removed. Pumping speed corrected to gauge position.

H_2 outgassing rates after bakeout

Throughput-accumulation method

Two bakeout temperature sets:

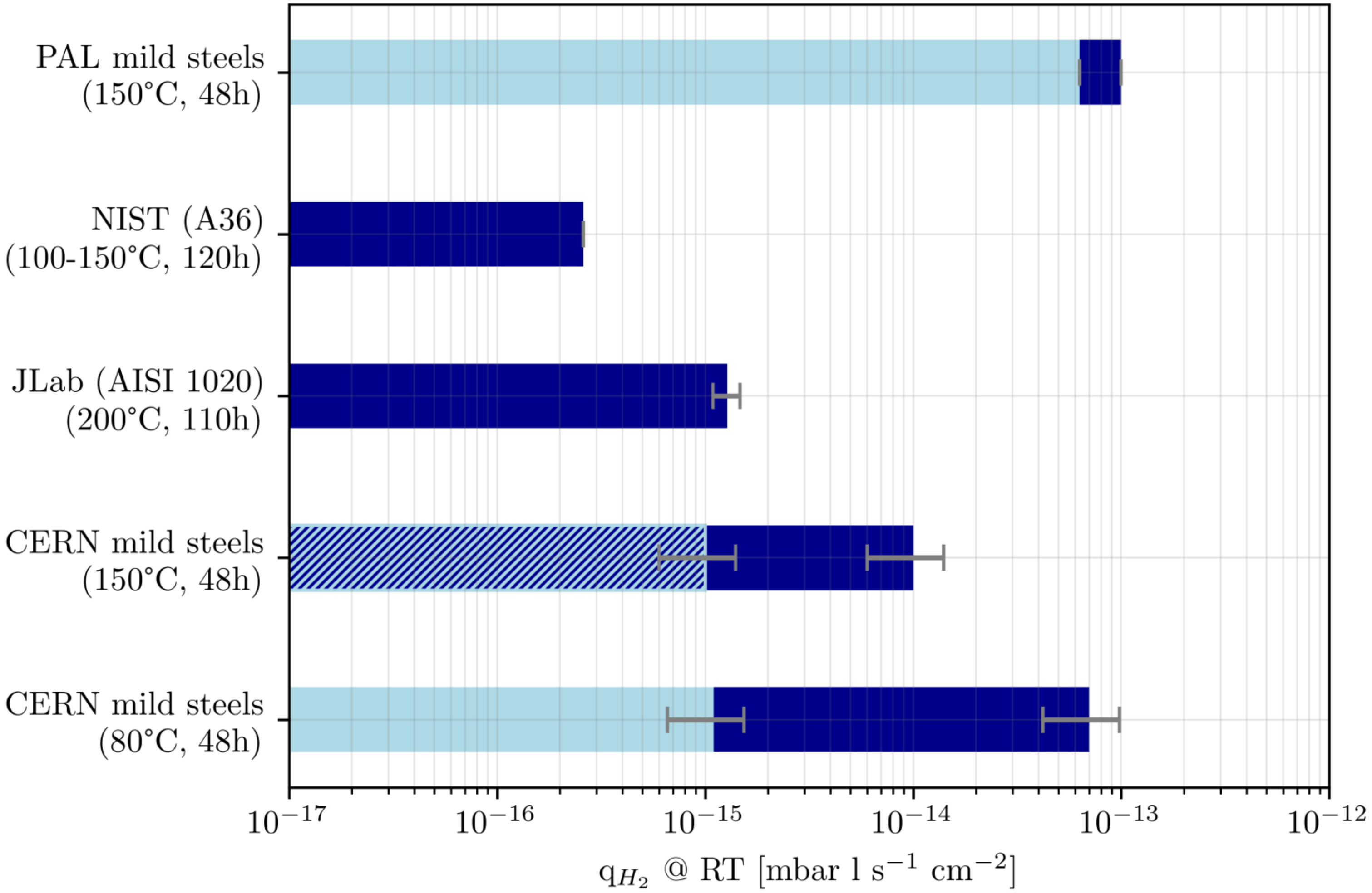
- 80°C: "Economical" alternative
- 150°C: Reference used in the current generation of GWD



Background removed. Measurement error: ±40%; Detection limit: 50% of background. *Air bakeout at ~410°C, 72h followed by a 150°C, 1 week.

H_2 outgassing rate after bakeout

	RT [°C]	Pre-treatment	Method
CERN[a]	21±2	None	Throughput - Accumulation
Jefferson Lab [*unpublished*]	-	400°C, 48 h	RoR
NIST[b]	26 (avg.)	None	RoR
PAL	24±0.1	None (max) Min (850°C, 12 h in a vacuum furnace)	RoR



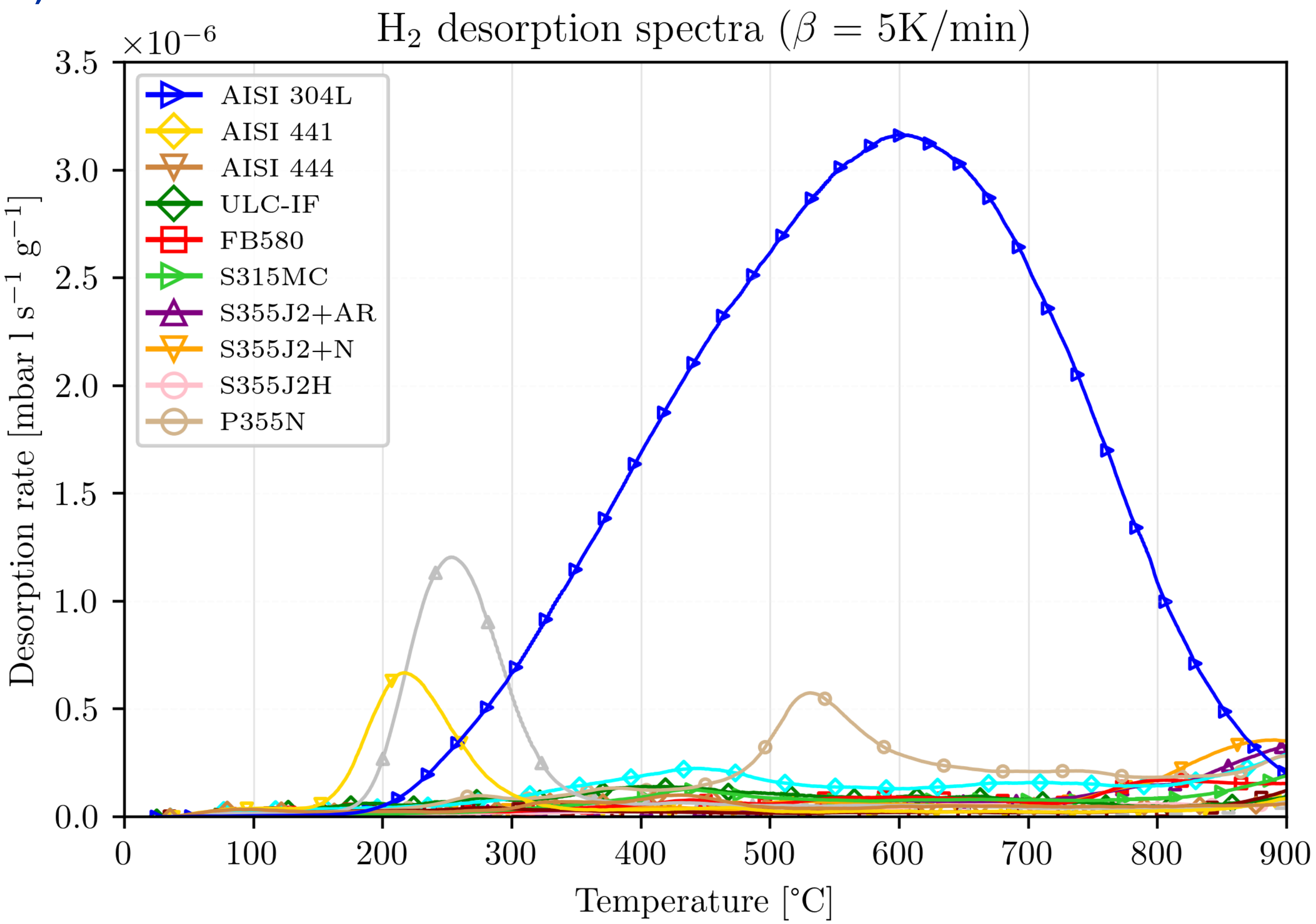
[a] Scarcia C. *et al.*, *J. Vac. Sci. Technol. B* 42, 054202 (2024)
[b] Fedchak J., Beampipes for Gravitational Wave Telescopes 2023, CERN, 27-29 March 2023
[c] *Park. C. et al.*, J. Vac. Sci. Technol. A 34, 021601 (2016)

H_2 content

Temperature Programmed Desorption (TPD)

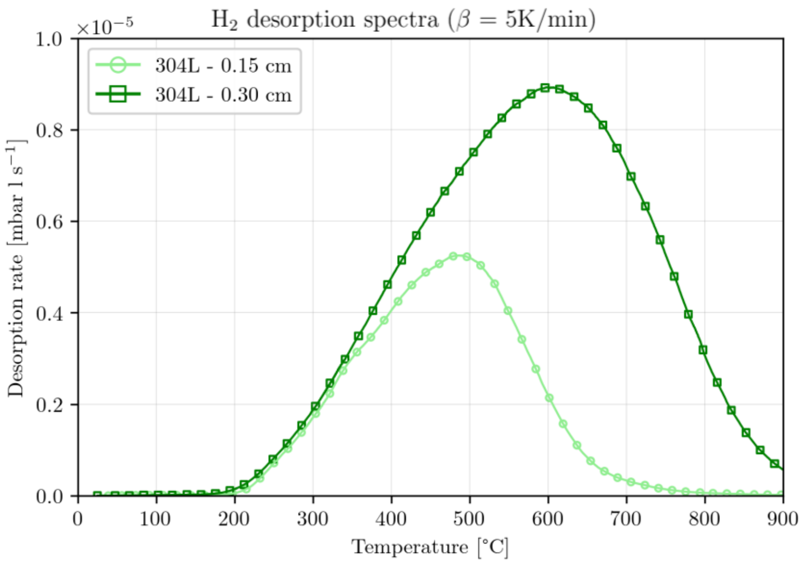
	Steel grade	H_2 content [ppm at.]	Microstructure
	304L	**80**	Austenitic
Ferritic StS	AISI 441	1.7	Ferritic
Ferritic StS	**AISI 444**	**1.3**	Ferritic
Mild steel	ULC-IF	3.7	Ferritic
Mild steel	FB580	2.8	Ferritic - Bainitic
Mild steel	S315MC	2.7	Ferritic - Pearlitic
Mild steel	S355J2+AR	2.0	-
Mild steel	S355J2+N	1.6	-
Mild steel	ARMCO	1.2	-
Mild steel	**S355J2H**	**7.8**	-
Mild steel	**P355N**	**1.0**	-

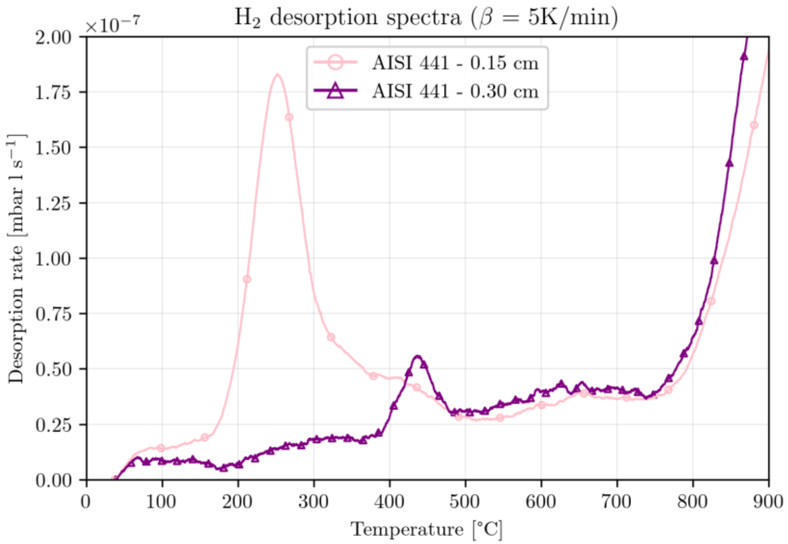
Concentration calculated from quantity of H_2 (considered to be uniformly distributed) extracted with TPD (up to 850ºC).
Graph normalized to sample weight.
Background removed.

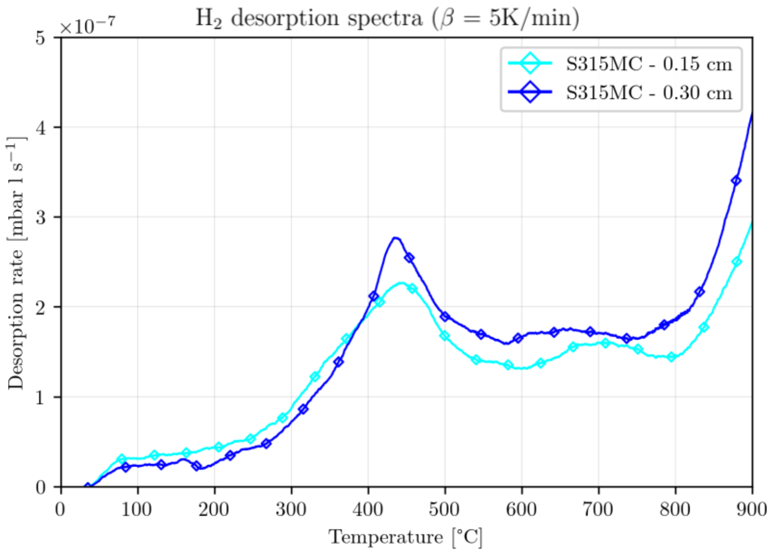


H_2 thermal desorption: peaks origin

Temperature Programmed Desorption (TPD)







Austenitic microstructure

Ferritic microstructure

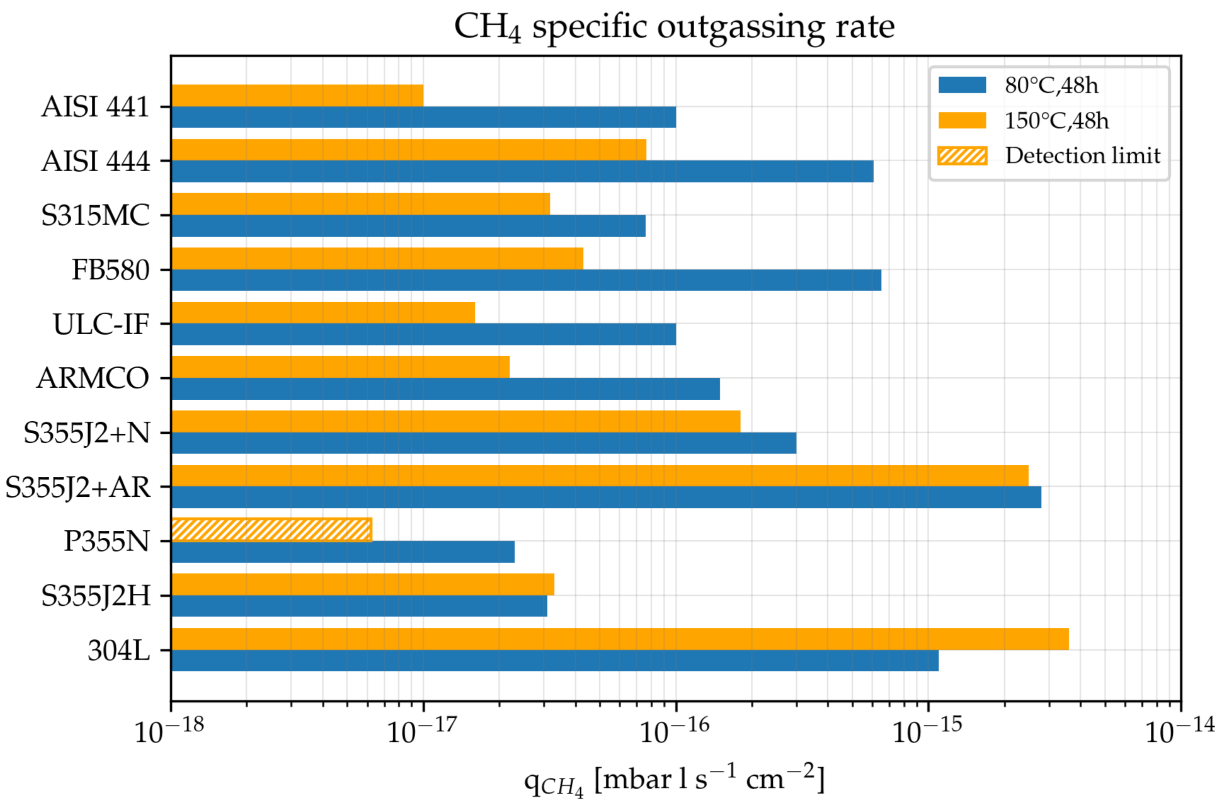
Ferritic/Bainitic – Ferritic/Pearlitic microstructure

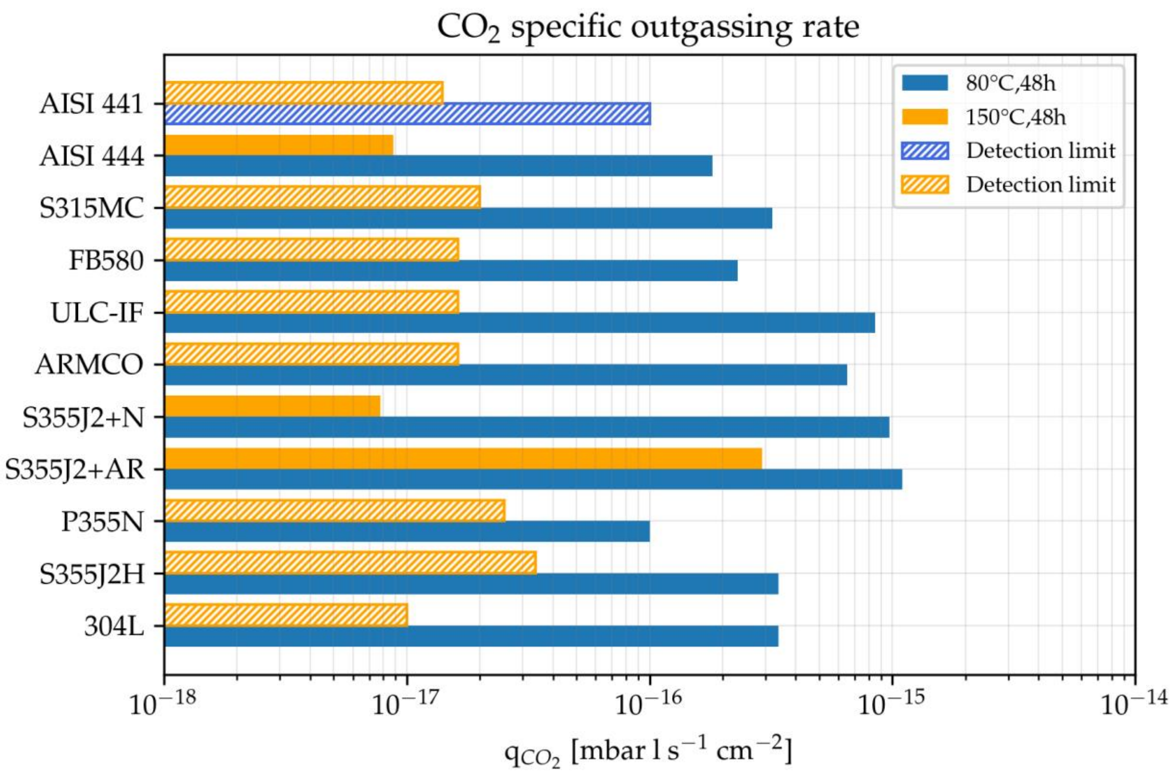
Diffusion peak

De-trapping peaks

CH_4 & CO_2 outgassing rate after bakeout

Throughput-accumulation method

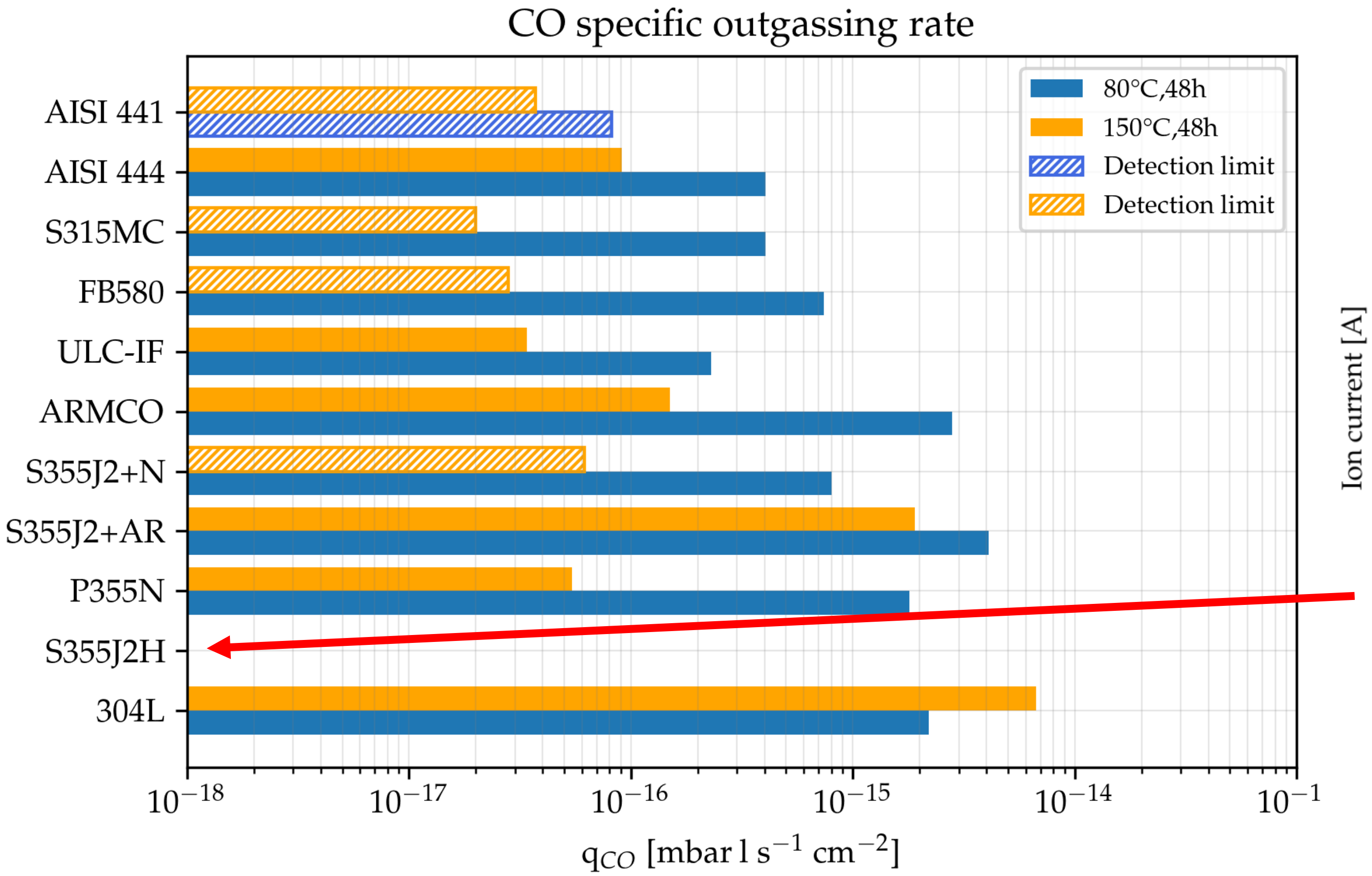


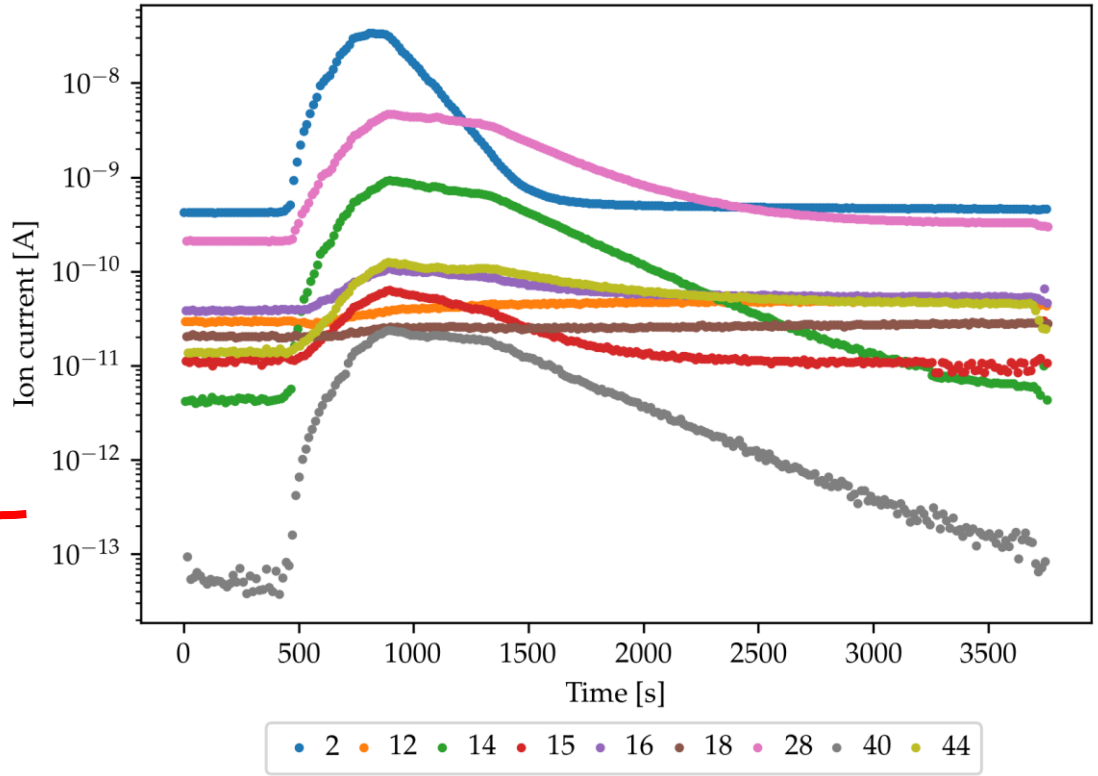


Measurement error: ±40%; Detection limit: 50% of background

CO outgassing rate after bakeout

Throughput-accumulation method





Measurement error: ±40%; Detection limit: 50% of background

ET corrugated beampipe prototypes

System characteristics

DN400 – 2100 mm (t < 2 mm)

AISI 441 (FStS)	**S315MC** (MS)	**AISI 304L-VF*** (AStS)

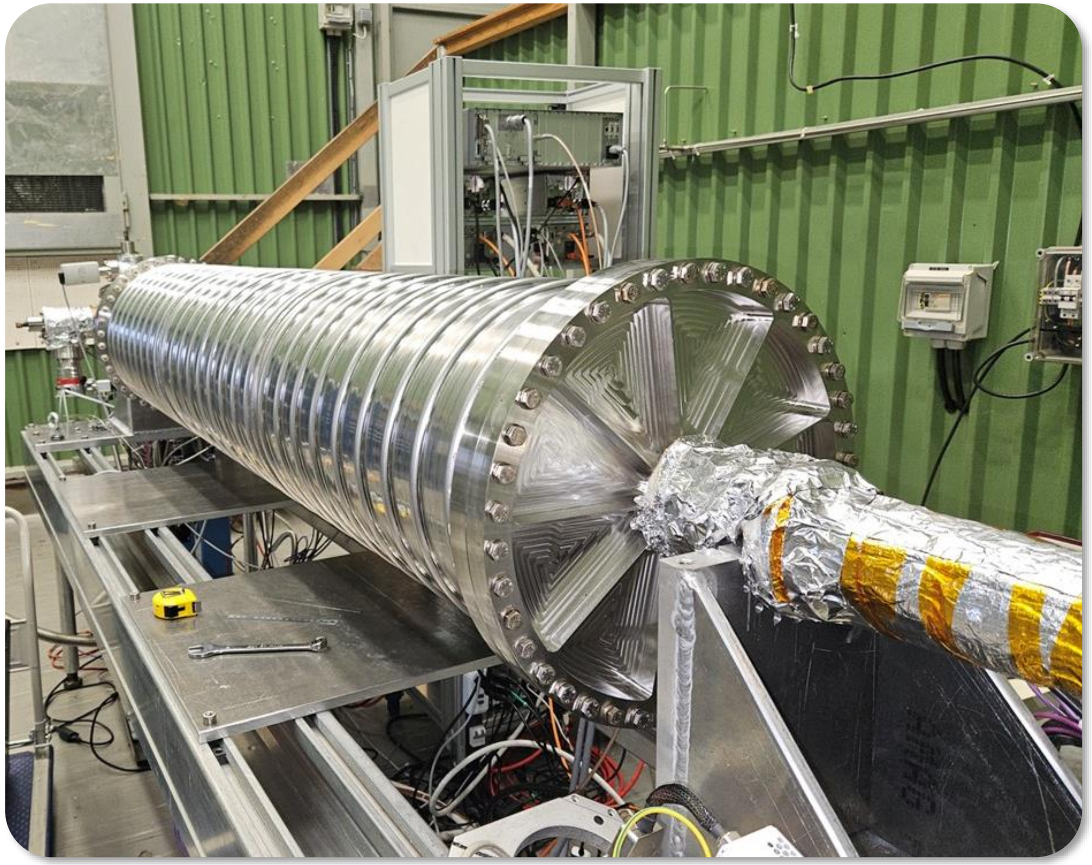
Pumping speeds scaled to ET dimensions

Objectives

Ultimate pressure after 80°C and 150°C bakeout

Verify water outgassing **modelling**

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

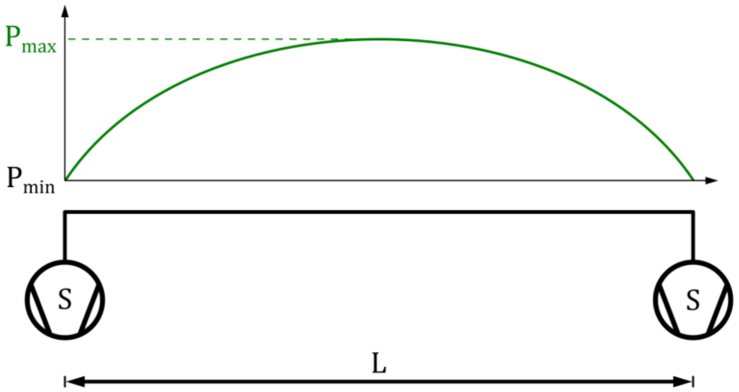


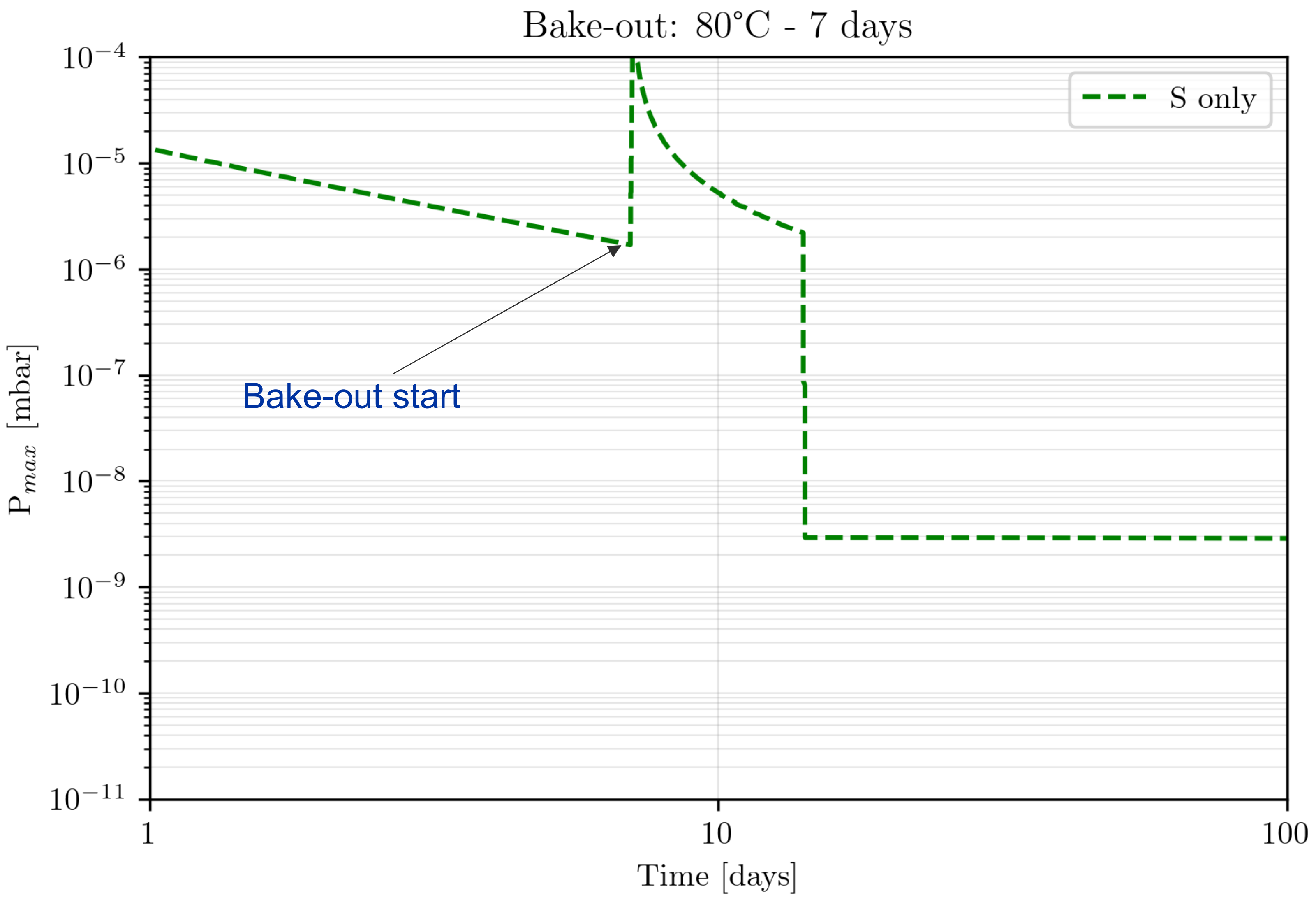
AISI 441 corrugated chamber.

AStS: Austenitic Stainless Steel, FStS: Ferritic Stainless Steel, MS: Mild Steel. *950°C, 2h. Pressure at the end of treatment:~10^{-5} mbar.

ET beampipe pre-prototypes

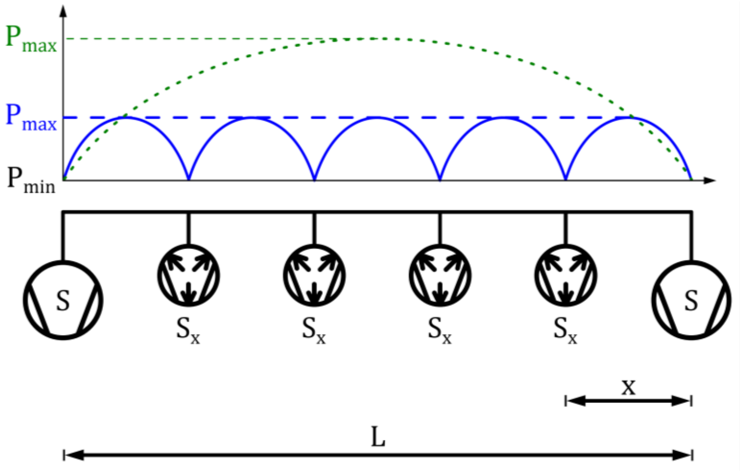
Modelling of effects of increased pumping speed during heating



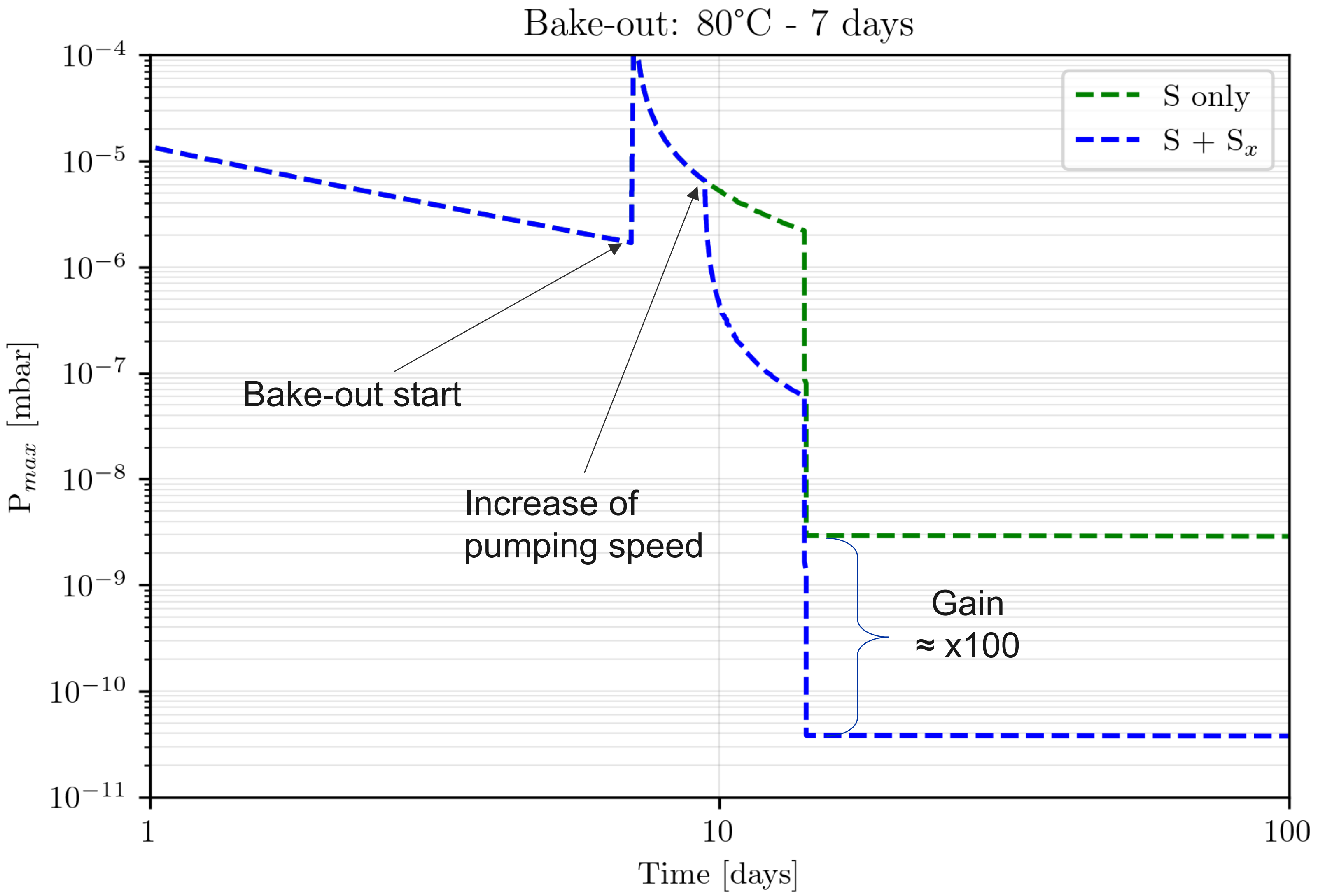


ET beampipe pre-prototypes

Modelling of effects of increased pumping speed during heating



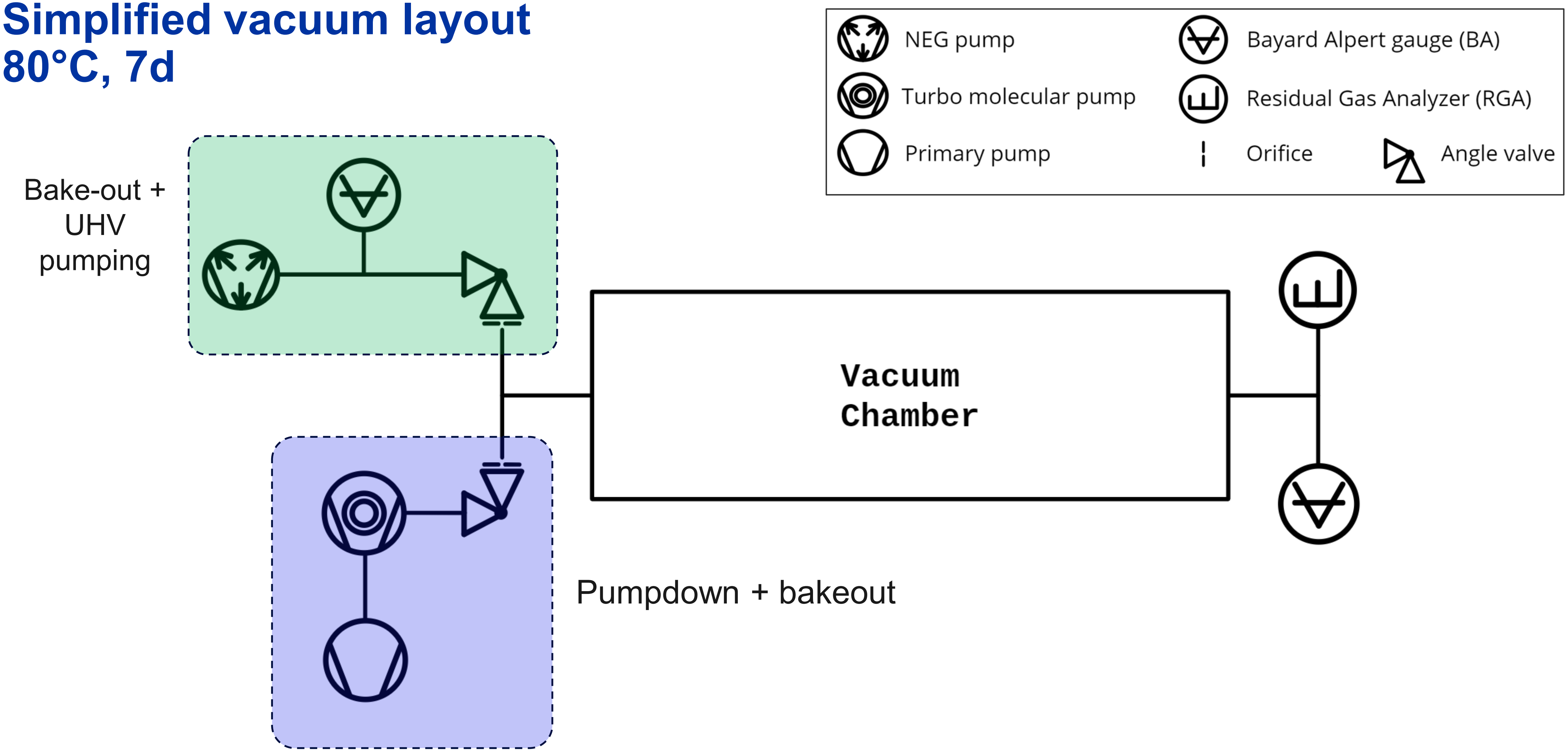
We could exploit the use of NEG pumps [SAES proposal, 2010]



Simulated layout: S = 1000 l/s, L = 2 km, S_x = 1500 l/s (H_2O), x = 50 m.

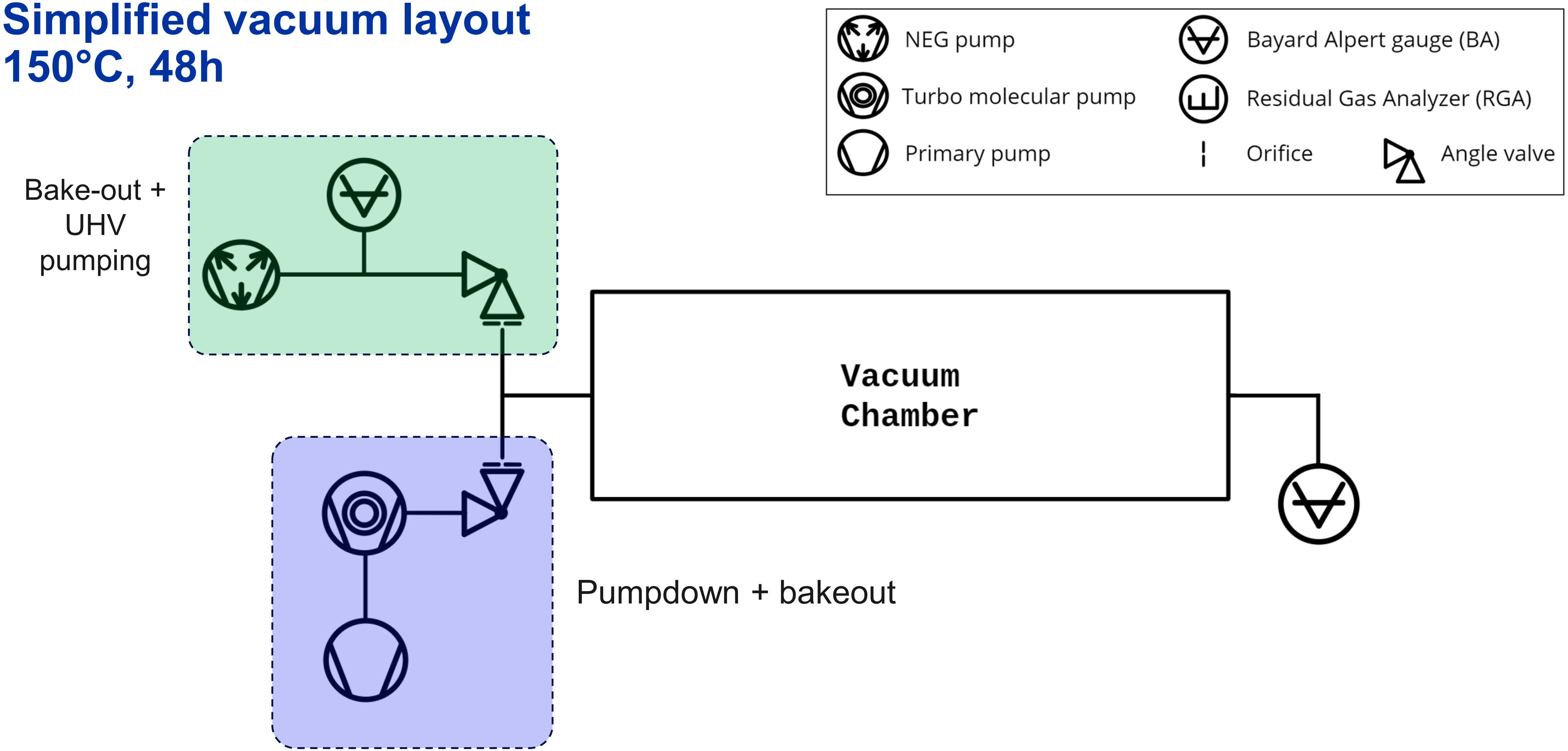
ET beampipe pre-prototypes

Simplified vacuum layout
80°C, 7d

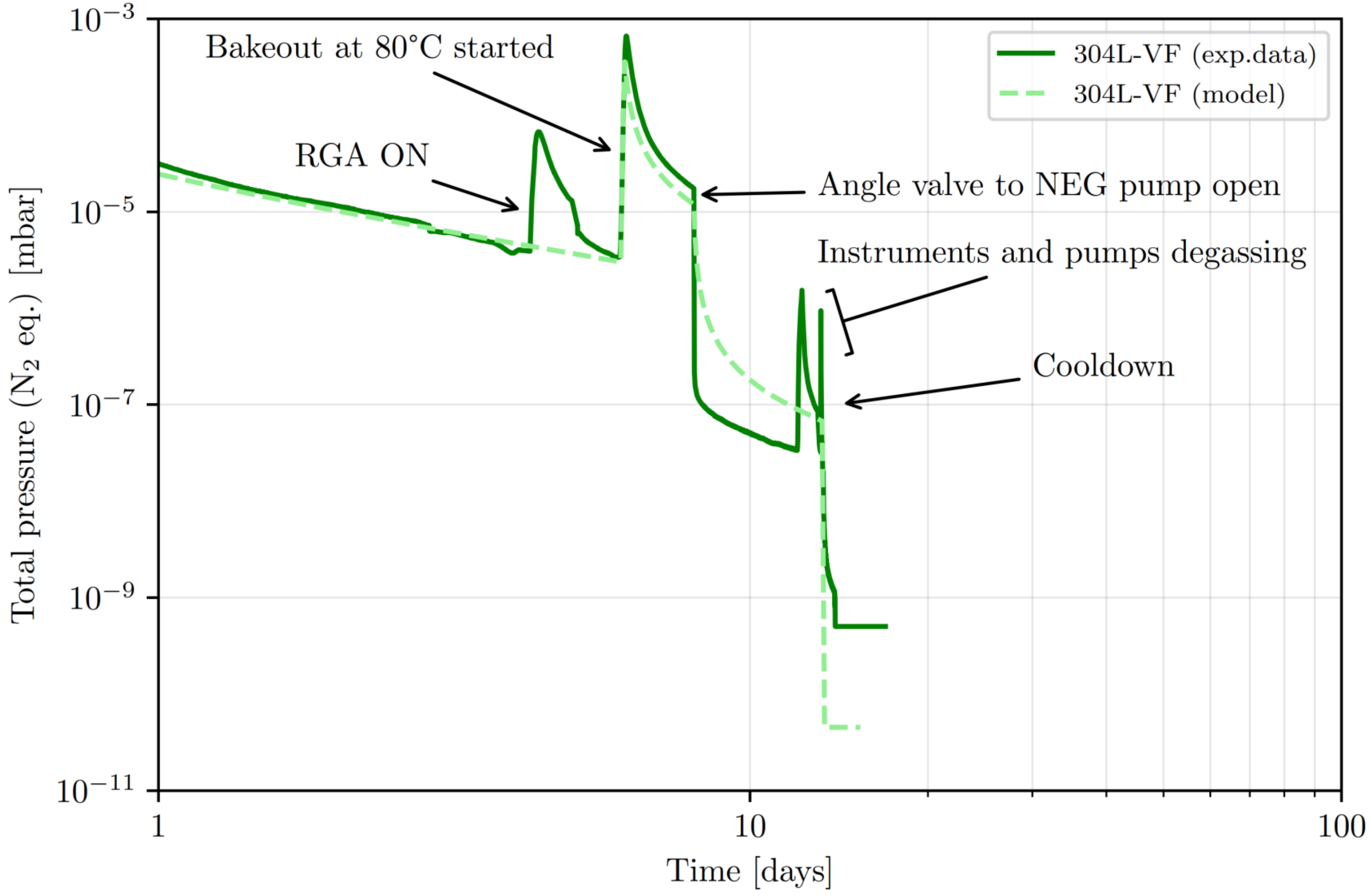


ET beampipe pre-prototypes

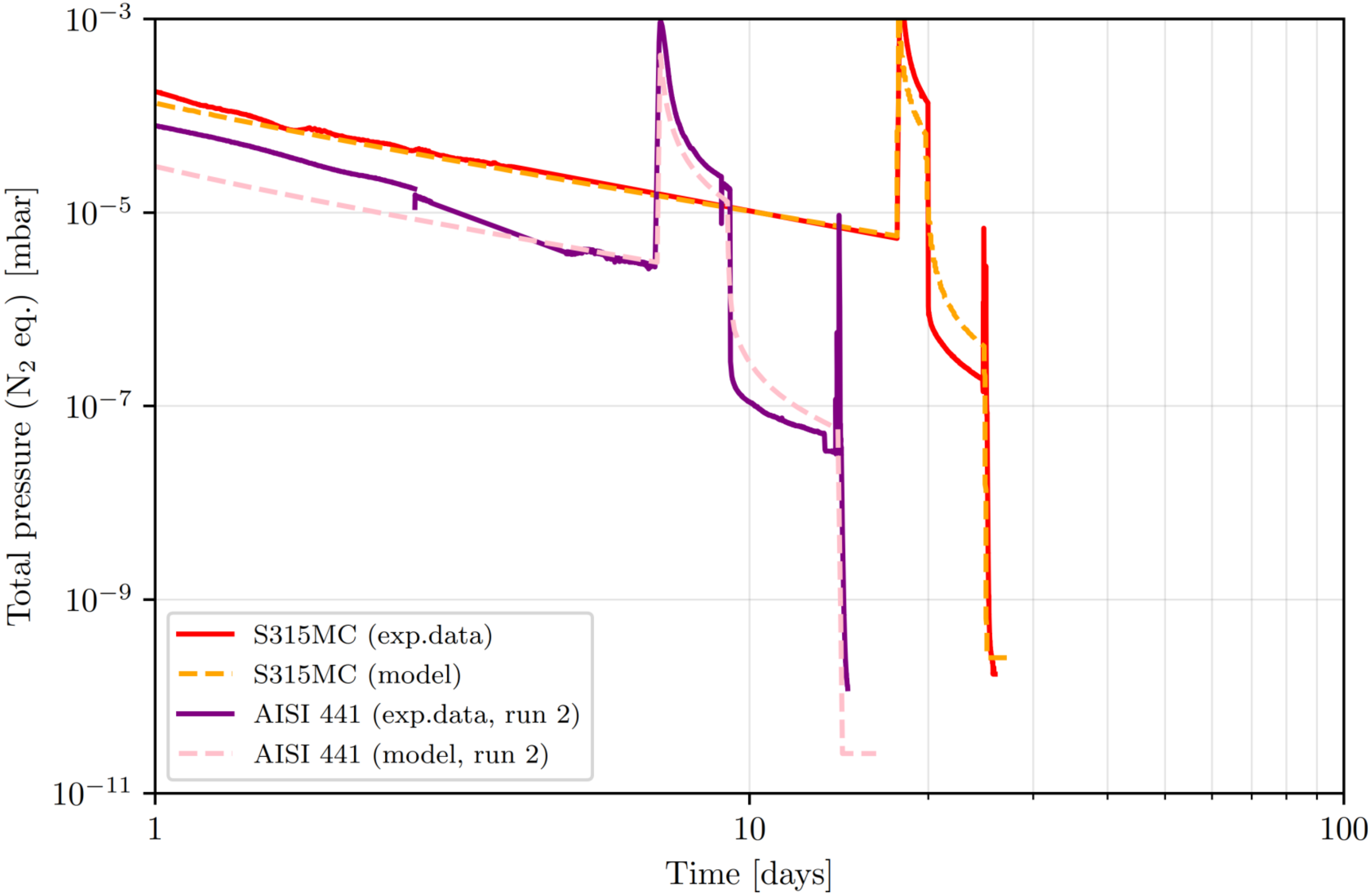
Simplified vacuum layout
150°C, 48h



ET beampipe pre-prototypes

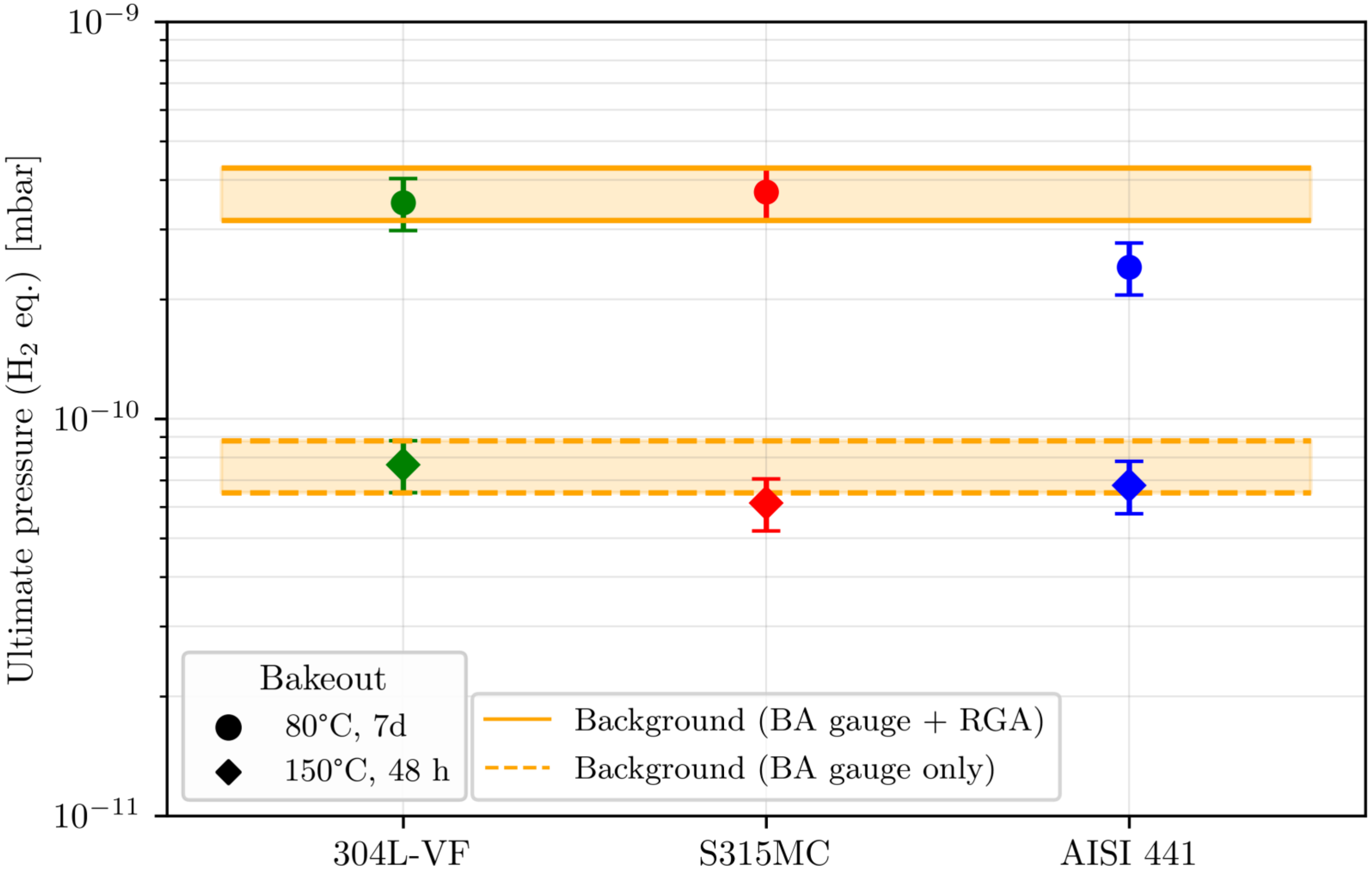


ET beampipe pre-prototypes



ET beampipe pre-prototypes

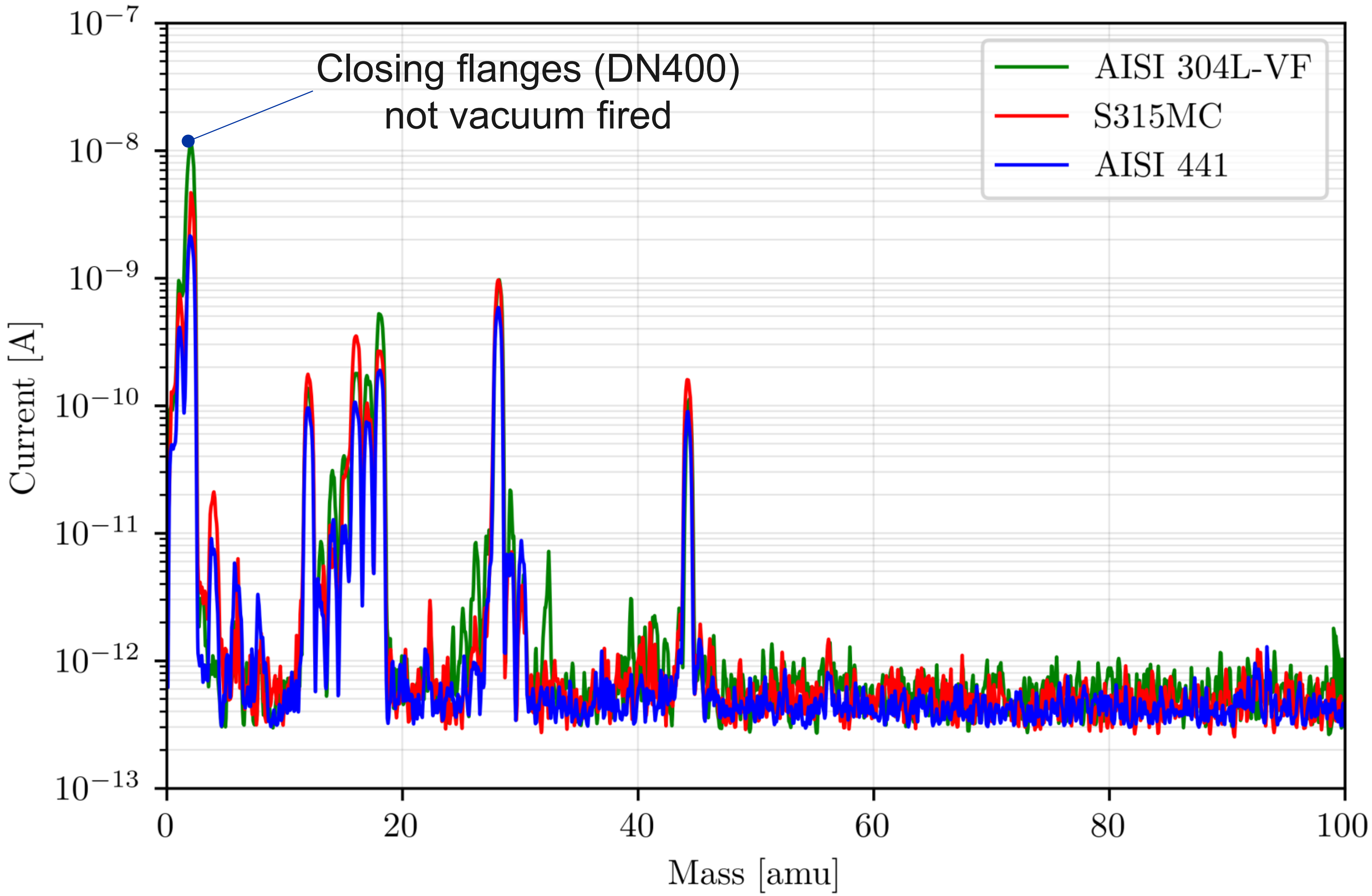
For all the chambers, **ultimate pressures are limited** by **instrumentation outgassing rates**.
(q_{H2} in line with sample measurements)



Orifice limited: 31 l s^{-1} for H_2, beampipes area: 28800 cm^2, H_2 to N_2 conversion factor: 0.46, BA gauge error: 15%. BA: Bayard-Alpert, RGA: Residual Gas Analyser.

ET beampipe pre-prototypes

Gas composition measured at 20±3°C 48 h **after** the **80°C, 7 d bakeout.**



Other prototypes

LoLA (Low outgassing Large Apparatus)
Full DN250 - 16 m vacuum system.

ET pilot sector at CERN
First AISI 441 beamline/background sys.

Implications of ferritic alloys on ET beampipe

Residual gas noise in GWD beam pipes

For a gas species, i [7]:

$$Strain(f) = \sum_i \sqrt{\frac{4\,(2\pi\boldsymbol{\alpha_i})^2}{L^2\,\boldsymbol{v_{0_i}}} \int_0^L \frac{\boldsymbol{\rho_i}\,(z)}{\omega(z)} e^{-\frac{2\pi f \omega(z)}{\boldsymbol{v_{0_i}}}} dz}$$

Where:

$\rho(z)$ = gas density ⇔ pressure distribution

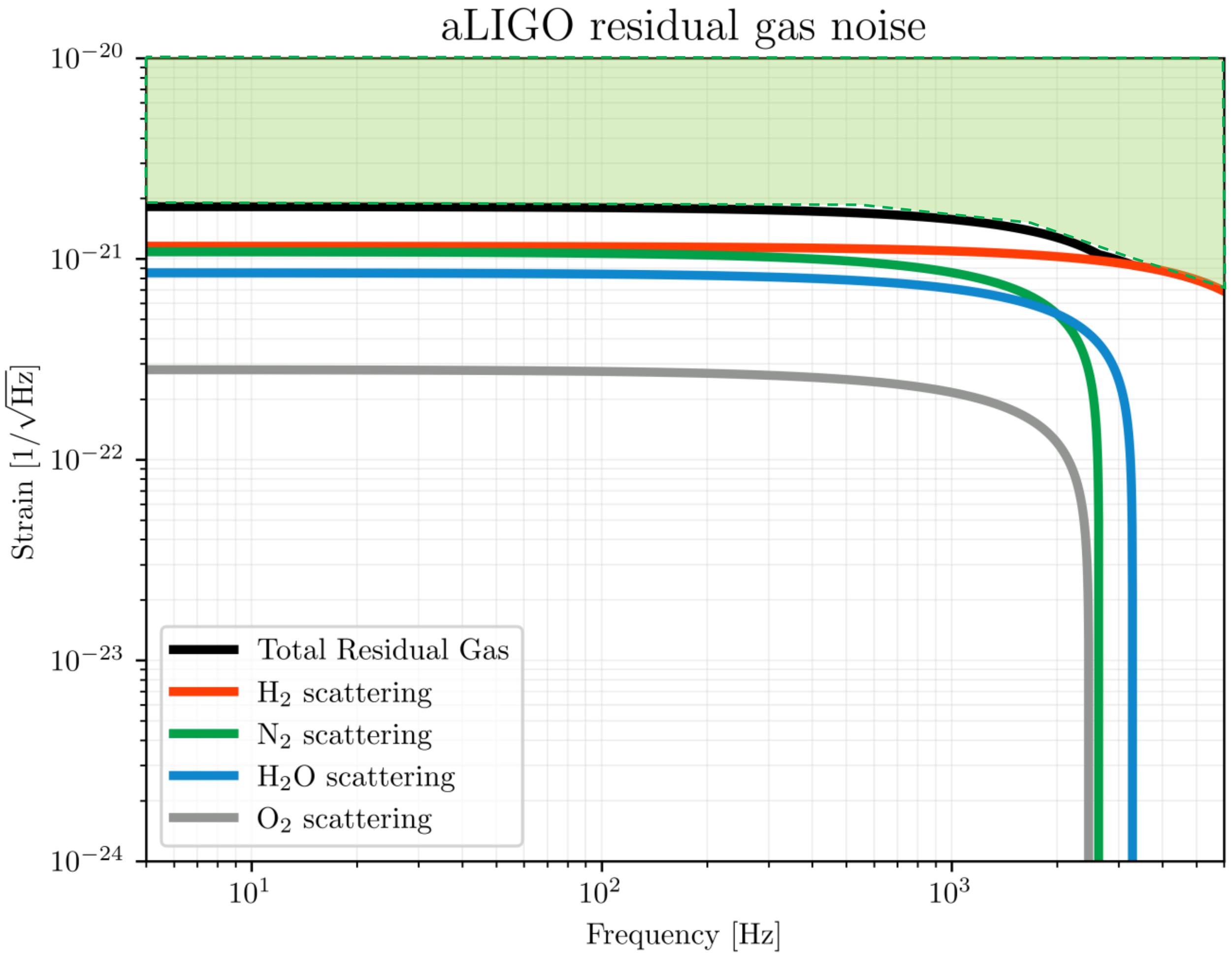
α = gas optical polarizability

v_0 = most probable thermal speed

f = frequency

$\omega(z)$ = laser beam gaussian radius

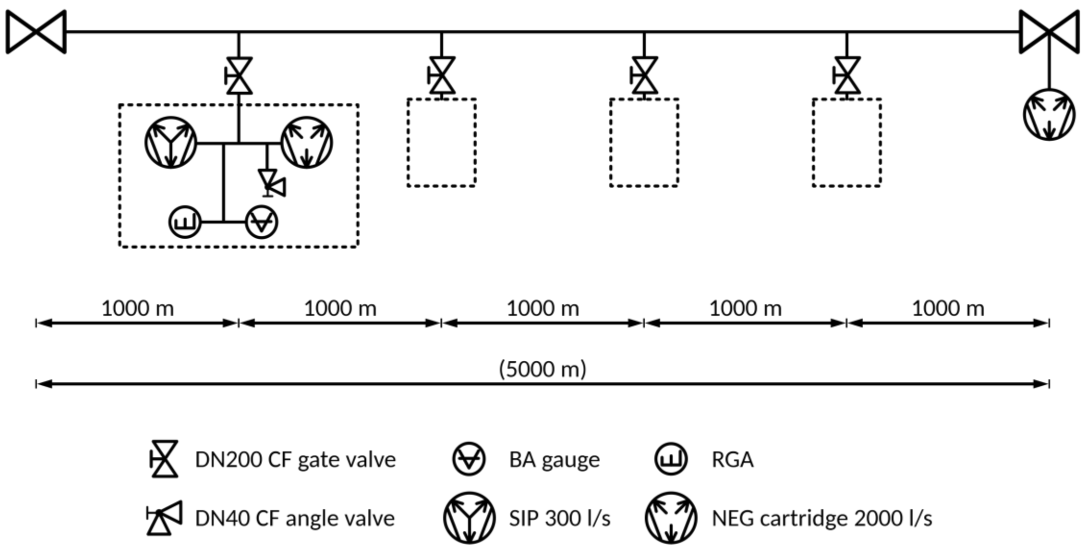
L = interferometer arm length



[7] M. E. Zucker and S. E. Whitcomb. “Measurement of optical path fluctuations due to residual gas in the LIGO 40-meter interferometer” (1994)

Implications of ferritic alloys on ET beampipe

Gas	Specific outgassing rate [mbar l s^{-1} cm^{-2}]	
	AISI 441[8] (150°C, 48 h)	AISI 304L air baked[1] [454°C, 36 h] (160°C, 504 h)
H_2	$<1\times10^{-15}$	6.1×10^{-14}
CH_4	$<1\times10^{-17}$	$<1.3\times10^{-18}$
H_2O	3×10^{-17} Simulated w/ isotherms for 150°C, 168 h[9]	$<1.1\times10^{-18}$
CO	$<3.7\times10^{-17}$	$<2.7\times10^{-18}$
CO_2	$<1.4\times10^{-17}$	$<1.13\times10^{-15}$

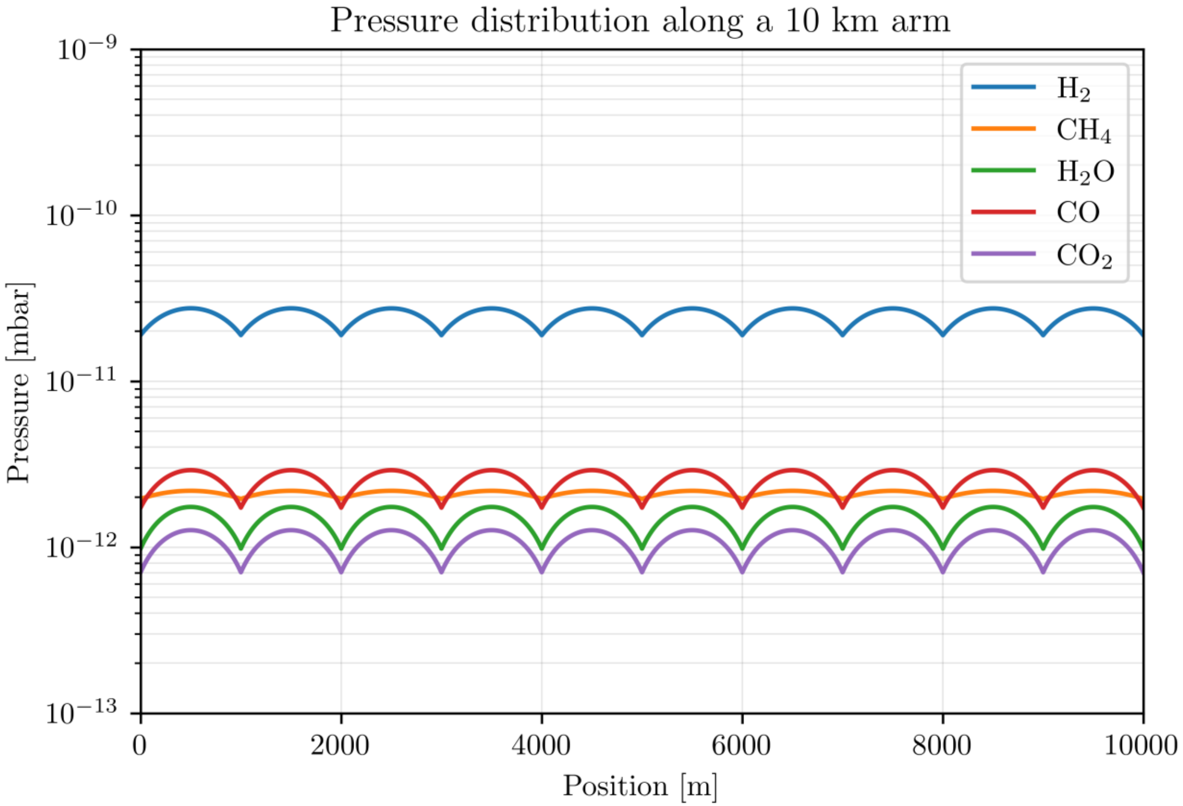


UHV layout proposed for ET[9]

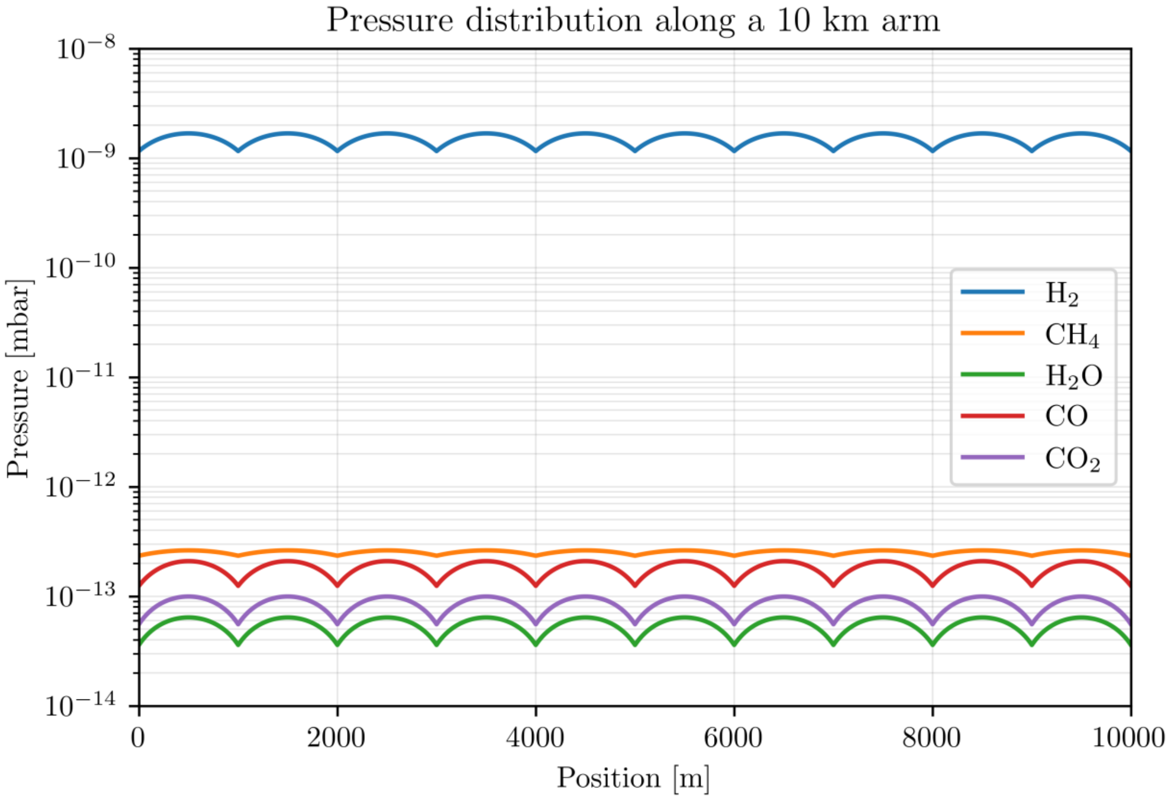
[8] Scarcia C. *et al.*, J. Vac. Sci. Technol. B 43, 044203 (2025)
[9] Scarcia C., The Einstein Telescope beam pipe vacuum system: Exploring novel techniques and materials for a cost-effective design solution, Doctoral thesis, 2025

Implications of ferritic alloys on ET beampipe

AISI 441[8]
(150°C, 48 h)
Water contribution simulated after 150°C, 168 h bakeout

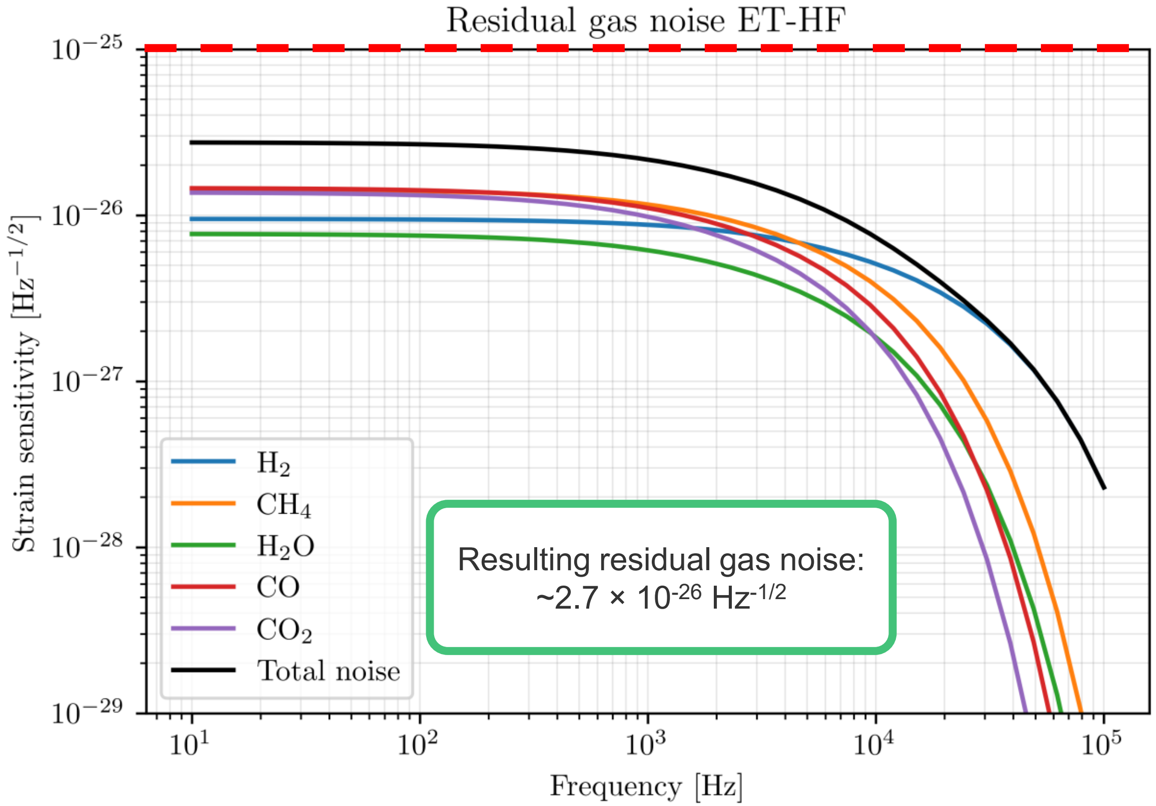


AISI 304L air baked[1]
[454°C, 36 h]
(160°C, 504 h)



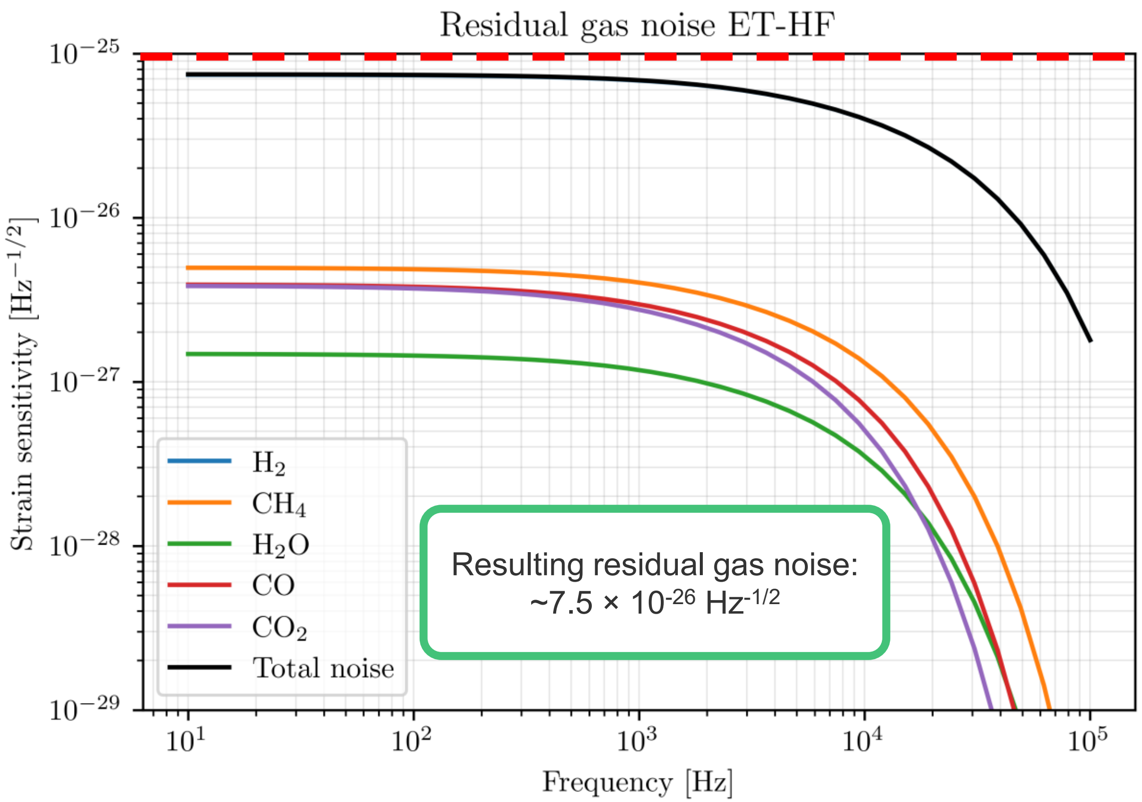
Implications of ferritic alloys on GWD beampipe

AISI 441[8]
(150°C, 48 h)
Water contribution simulated after 150°C, 168 h bakeout



Resulting residual gas noise:
~2.7 × 10^{-26} Hz$^{-1/2}$

AISI 304L air baked[1]
[454°C, 36 h]
(160°C, 504 h)



Resulting residual gas noise:
~7.5 × 10^{-26} Hz$^{-1/2}$

Upper limit from requirements: < 1 × 10^{-25} Hz$^{-1/2}$ (ET-0385A-24)

Optical parameters taken from ET-0385A-24. Gas parameters taken from [9]

Conclusions/Considerations

Studies of vacuum properties

- **Mild steels** and **ferritic stainless steels** are **compatible** with **UHV applications**.
  As received, their **bulk** **H_2 outgassing rates outperform** the **austenitic stainless steels** currently used in GWDs by **several orders of magnitude.**
  - **Outgassing rates of ferritic alloys are more susceptible to surface quality rather than bulk.**

- **Isothermal models** were developed to **predict** the **water outgassing rate after bakeout**.

- **General agreement of results across the labs**

Prototyping

- **Models** and **materials experimentally validated** with **GWD sector-scaled mockups**.

Beam pipe vacuum system impact

- The **experimental data** and **models** developed **can be applied to design** the **full** vacuum **commissioning sequence**.
- Considering strict boundary conditions and applying a rationalised set of design criteria, and the new beam pipe materials we could **potentially save up to 80%** of the forecasted **budget** for the **vacuum system's hardware** (excluding beam pipe production).

A friend once said..

"The issue is not can one make the requirement but rather can one make them at significantly reduced cost."

Rainer Weiss,
Beampipes for Gravitational Wave Telescopes 2023, CERN, 27-29 March 2023

Well Rai, we are getting there!

Thanks for your attention

home.cern