ISNIE 2018 Summer School: introduction to vacuum technology and engineering

Dr. Marcelo Juni Ferreira
Vacuum System Section Leader
European Spallation Source ERIC

Outline

- Introduction,
- Class "0" of vacuum: surface/material science perspective,
- Gas regimes and simulations,
- Vacuum for Neutron instruments,
- Ex: LOKI – instrument,
- Vacuum Laboratory,
- References,
- Notes,

Introduction

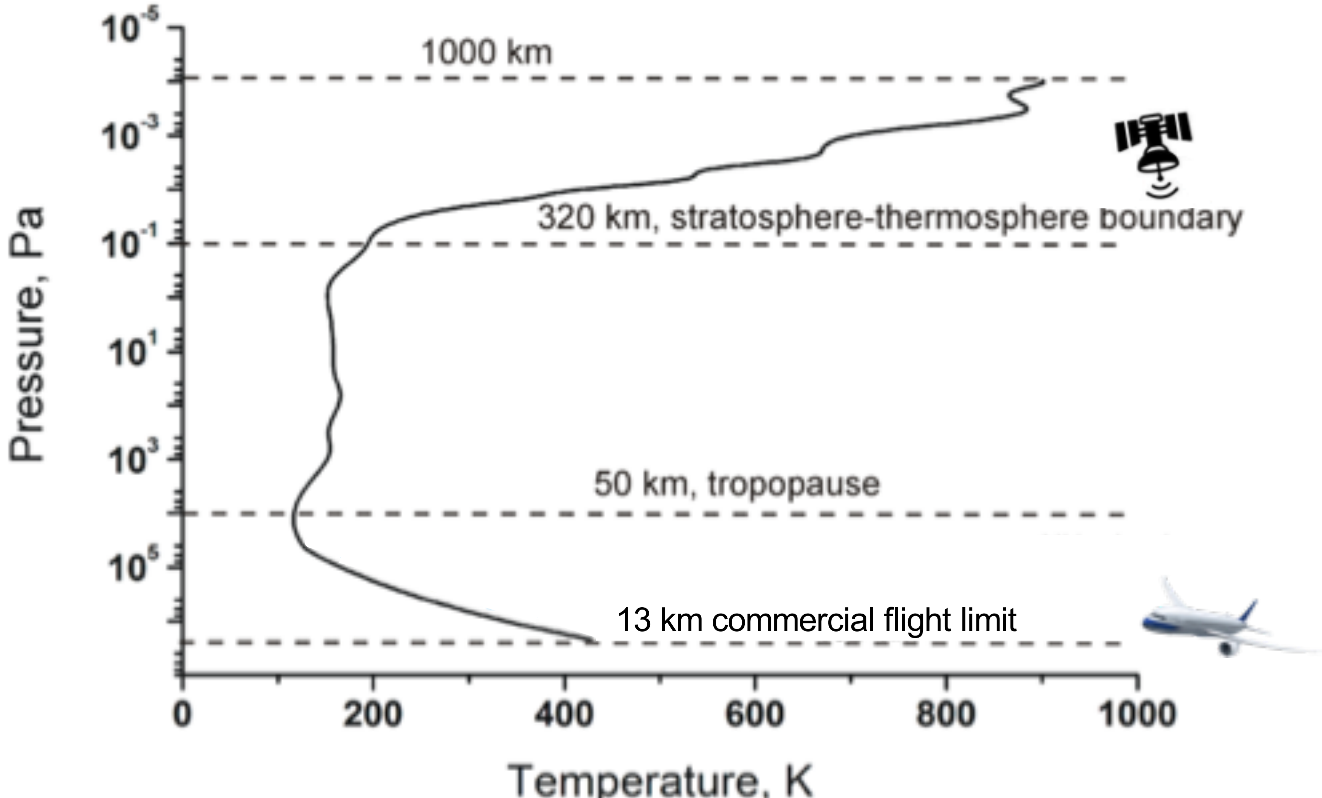
Goal: short introduction on the vacuum field (surface science, gas dynamics, simulations, vacuum instrumentation...) and the science and engineering for a larger "user facility."

Justification: why do we need vacuum?

"the **surrounding gas** can **interfere** on the **desirable process**, it means, it is a requisite part of the process or/and an integral part of a product"

Ex: heat transfer, vaporization, chemical/physical reactions or effects, protection...

Introduction:
Pressure range of earth's atmosphere



Moon's surface atmospheric pressure:
3×10^{-10} Pa

Introduction: Vacuum Terms (ISO 3529/1)

Vacuum range Pa [N/m²]	Naming
100 kPa - 100 Pa (1000 mbar - 1 mbar)	low (rought) vacuum
100 Pa - 0,1 Pa (1 mbar - 10^{-3} mbar)	medium vacuum
0,1 Pa 10 µPa (10^{-3} mbar - 10^{-7} mbar)	high vacuum (HV)
< 10 µPa (abaixo de 10^{-7} mbar)	ultra-high vacuum (UHV)
< 10^{-10} Pa (abaixo de 10^{-12} mbar)	extreme high vacuum (XHV)*

Standard references conditions for gases :

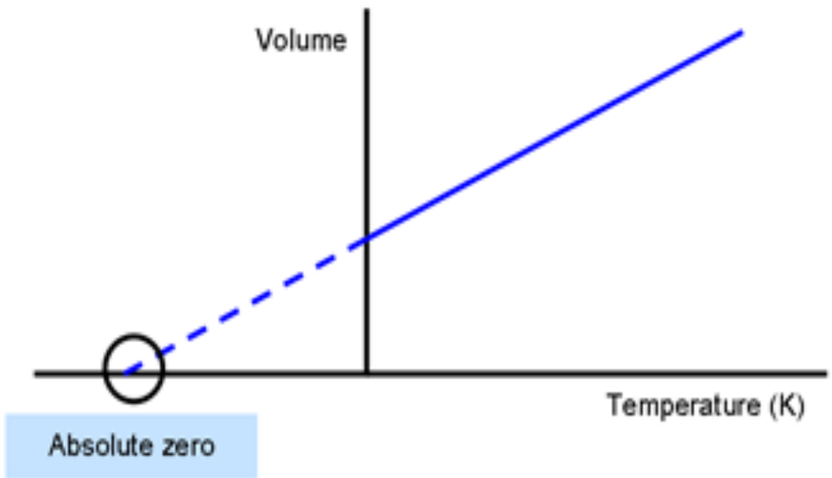
Temperature : 0 ° C

Pressure : 101,325 Pa (= 1,013.25 mbar)

ISO definition:
"A commonly used term to describe the state of a rarefied gas or the environment corresponding to such a state, associated with a pressure or a mass density below the prevailing atmospheric level"

Introduction: Ideal Gas Law

$$P \,.\, V = N.\, R.\, T$$



P = pressure [Pa]

V = vomule [m^3]

N = amount of substance [mol]

R = universal gas constant (k . N_A) [8.314 J. $K^{-1}mol^{-1}$]

T = temperature [K]

Class "0" of vacuum : monolayer

CAS CERN-94
A.G. Mathewson

How many molecules we have at the surface of a cube of 1 liter?

Place one molecule of nitrogem by side another over the cube surface (definition of monolayers).

6 side = 0.010 x 0.010 x 6 = 0.06 m^2

$$\frac{1}{3.7 \cdot 10^{-10} \times 3.7 \cdot 10^{-10}} = 7.3 \cdot 10^{18} \text{ molecule/m}^2$$

$0.06 \times 7.3 \cdot 10^{18} =$ **$4.4 \cdot 10^{17}$ molecules**

The molecular diameters are measured in Ångström (1 Å=10^{-10} m).
Diameter of nitrogen molecule : 3.7 Å

Class "0" of vacuum : pressure equivalent

What is one monolayer of gas as pressure equivalent?

Using the ideal gas law at standard conditions for temperature and pressure (STP):
10^5 Pa (1 atm) at 273.15 K (0° C)

$2.69 \cdot 10^{22}$ molecules in 1 liter.

$$\frac{4.38 \cdot 10^{17} \times 101{,}325}{2.69 \cdot 10^{22}} =$$ **1.65 Pa ($1.65 \cdot 10^{-2}$ mbar) medium vacuum!!**

Class "0" of vacuum : gas in solid solution

How much gas we have in solid solution (1 liter) on stainless steel (SS) 304?

Typical value (ASTM handbook) for nitrogen on austenitic phase is 150 ppm in weight.   SS304 density: $8 \cdot 10^3$ g/liter

$$150 \text{ ppm} = \frac{150}{10^6} \times 8 \cdot 10^3 = \mathbf{1.20\ g/liter}$$

Using the ideal gas law at STP :
$2.69 \cdot 10^{22}$ molecules in 1 liter => $4.77 \cdot 10^{-23} * 2.69 \cdot 10^{22} =$ **1.28 g**

≈ 150 ppm of nitrogen in SS304 is equivalent of 1 bar atmosphere!!

* 1 molecule of nitrogen weight = $4.77 \cdot 10^{-23}$ g

Regimes and simulations

Knudsen number (Kn): is a dimensionless number defined as the ratio of the molecular mean free path length to a representative physical length scale*

λ = mean free path   **L** = representative physical length

$$Kn = \frac{\lambda}{L}$$

Vacuum range Pa [N/m²]	Mean free path [m]	Kn for 10 m	Kn for 0.1 m
0.1 Pa - 10 μPa (10^{-3} mbar - 10^{-7} mbar)	$6.7 \cdot 10^{-2}$ – $6.7 \cdot 10^{2}$	$6.7 \cdot 10^{-3}$ – $6.7 \cdot 10^{1}$	$6.7 \cdot 10^{-1}$ – $6.7 \cdot 10^{3}$

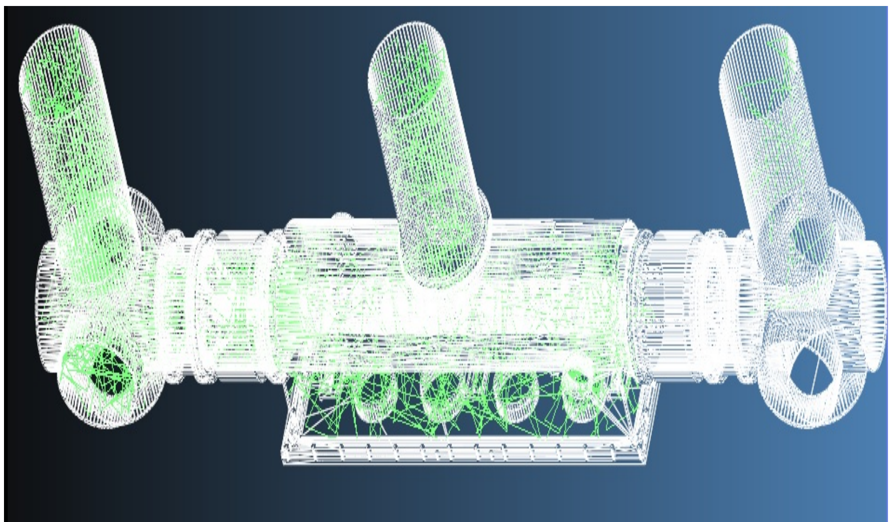
Kn >> 1 hydrodynamics regime (Navies-Stokes commercial software)

Kn << 1 free molecular regime (Monte Carlo MOLFLOW, Angular Coefficient COMSOL/Fluid Flow module, MATHCAD…)

Kn ≈ 1 transitional regime (COMSOL/Multiphysics, academic software, MATHCAD, private calculations…)

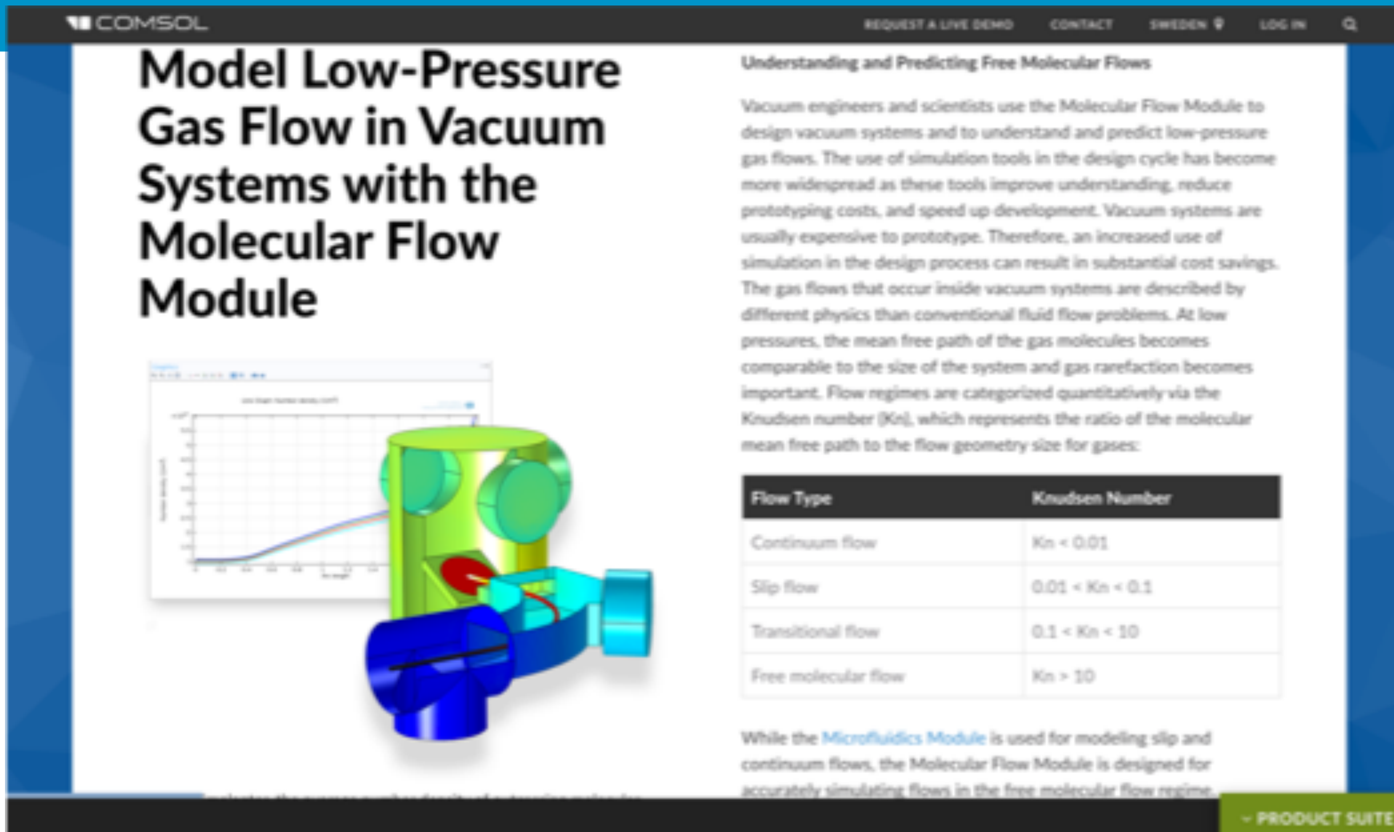
MOLFLOW +

By Roberto Kersevan (CERN), more than 20 years of development for synchrotron accelerators.



- steady state and transient,
- only molecular regime,
- temperature,
- accept external files STL,
- possible to couple synchrotron radiation,

COMSOL/Multiphysics



COMSOL REQUEST A LIVE DEMO CONTACT SWEDEN LOG IN

Model Low-Pressure Gas Flow in Vacuum Systems with the Molecular Flow Module

Understanding and Predicting Free Molecular Flows

Vacuum engineers and scientists use the Molecular Flow Module to design vacuum systems and to understand and predict low-pressure gas flows. The use of simulation tools in the design cycle has become more widespread as these tools improve understanding, reduce prototyping costs, and speed up development. Vacuum systems are usually expensive to prototype. Therefore, an increased use of simulation in the design process can result in substantial cost savings. The gas flows that occur inside vacuum systems are described by different physics than conventional fluid flow problems. At low pressures, the mean free path of the gas molecules becomes comparable to the size of the system and gas rarefaction becomes important. Flow regimes are categorized quantitatively via the Knudsen number (Kn), which represents the ratio of the molecular mean free path to the flow geometry size for gases:

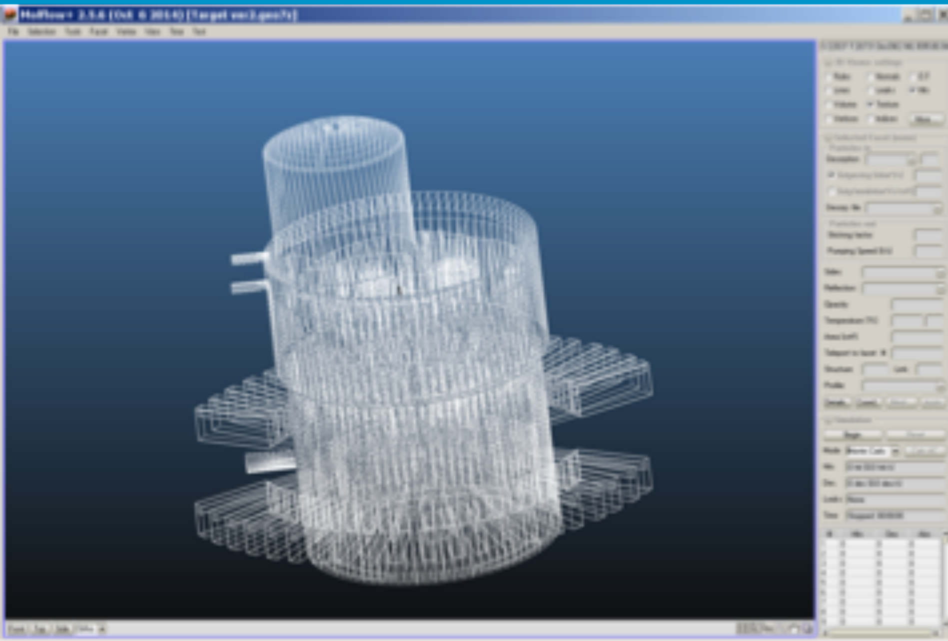
Flow Type	Knudsen Number
Continuum flow	Kn < 0.01
Slip flow	0.01 < Kn < 0.1
Transitional flow	0.1 < Kn < 10
Free molecular flow	Kn > 10

While the Microfluidics Module is used for modeling slip and continuum flows, the Molecular Flow Module is designed for accurately simulating flows in the free molecular flow regime.

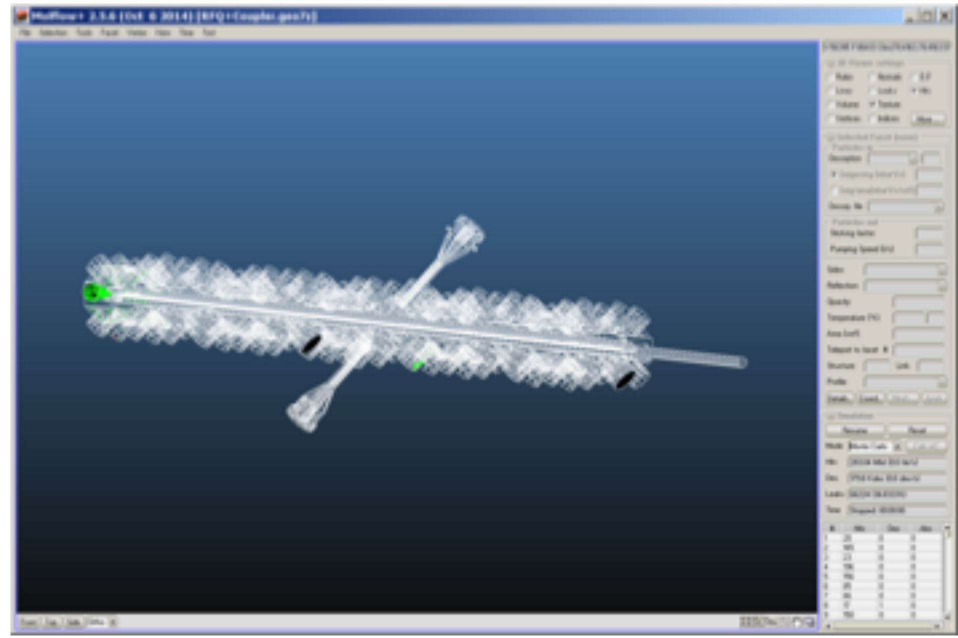
PRODUCT SUITE

Single tool allows to simulate all range of Knudsen number!!

MOLFLOW +
Ex: Target monolith vessel and RFQ

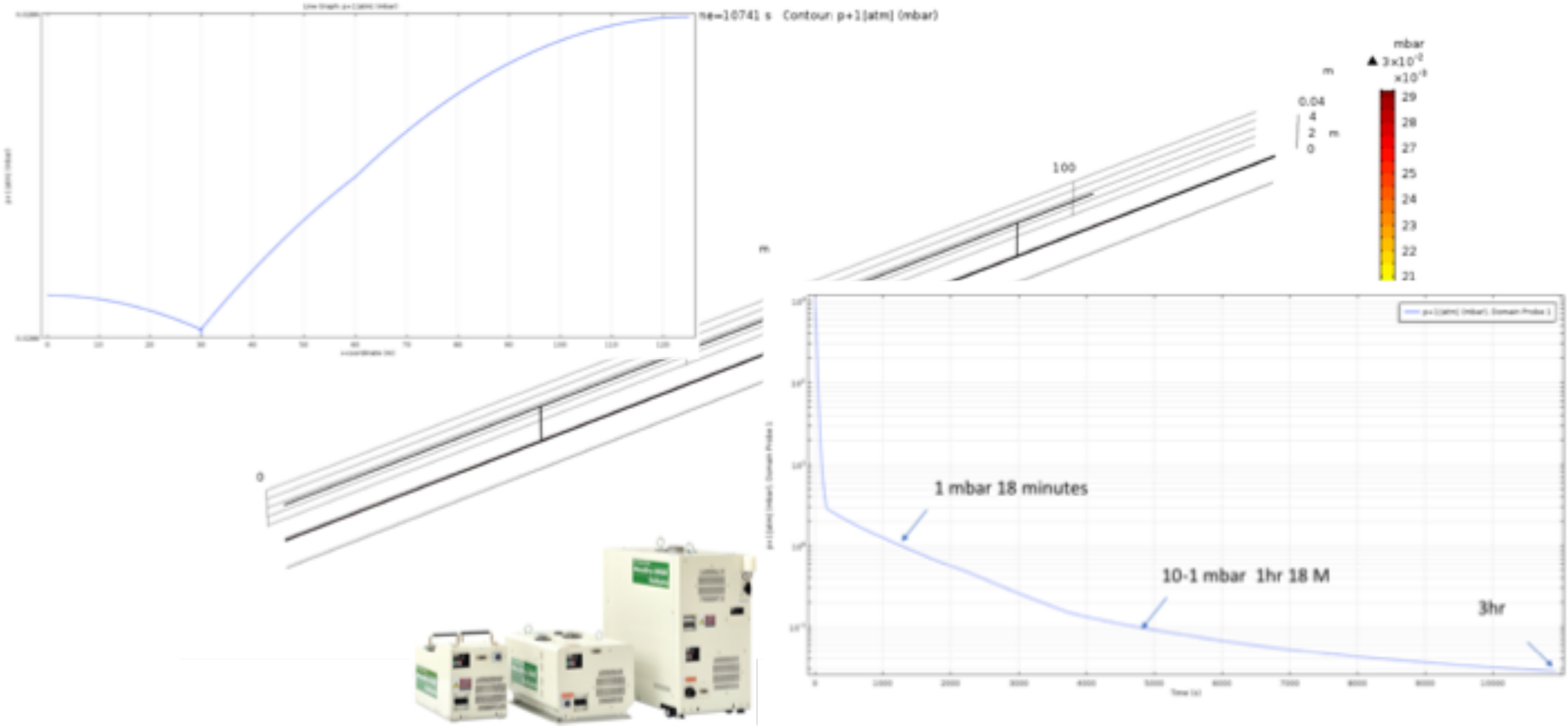


Target monolith vessel

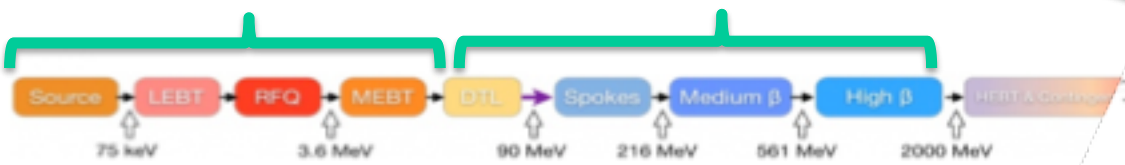


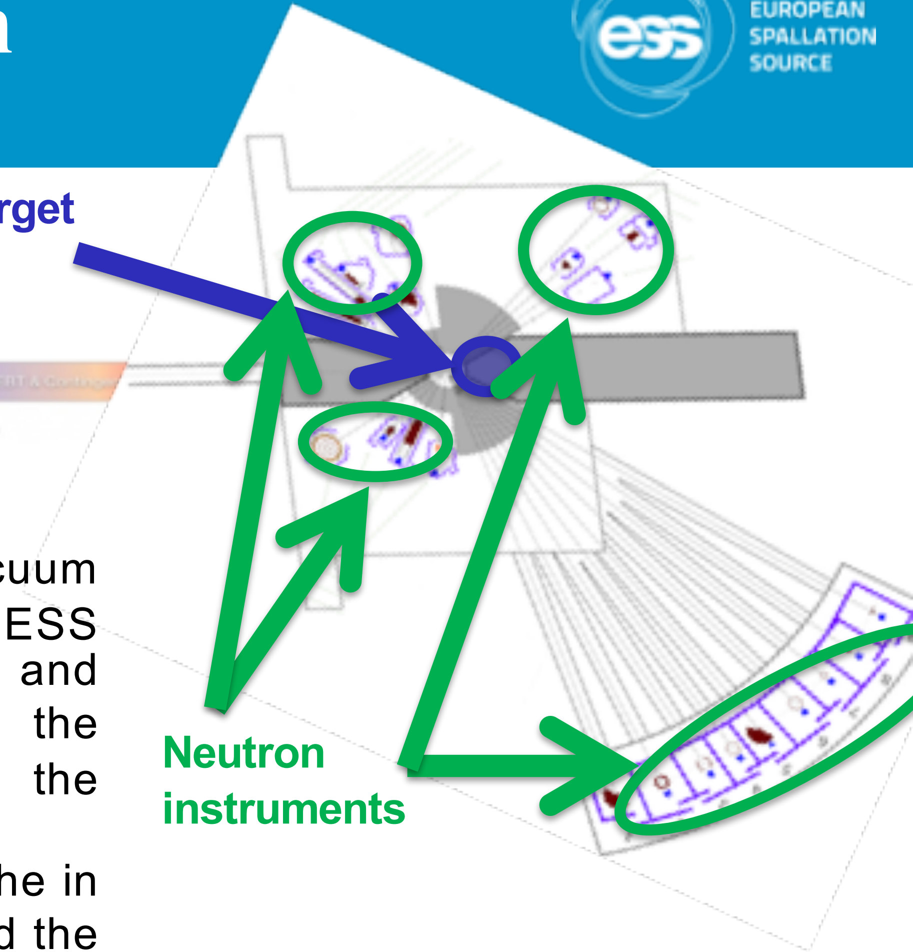
RF Quadrupole

COMSOL/Vacuum
Ex: Generic long Instrument



Ex: ESS Vacuum System



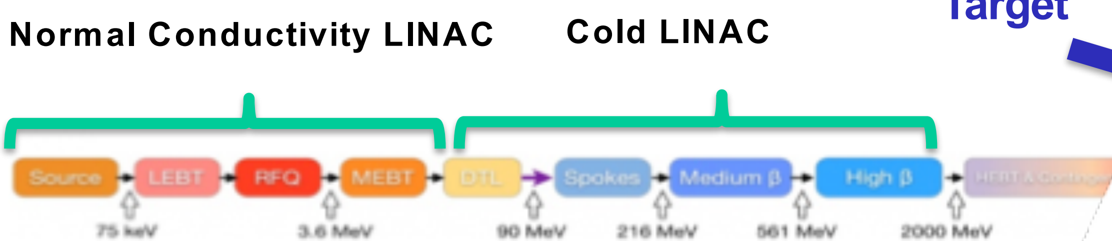


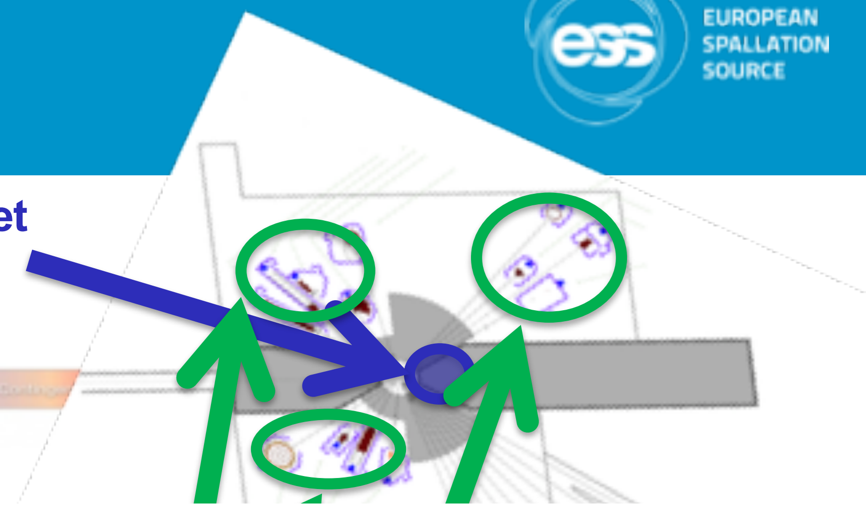
The ESS organization charges the ESS Vacuum Section (VS) with the responsibility for all ESS vacuum systems (vacuum instruments and Control System) including not only the Accelerator, but also the TARGET and the Neutron Instruments.

The main task of the ESS VG is to support the in kind contributions on the vacuum system and the **integrated vacuum design** of the ESS complex.

Ex: ESS Vacuum System

EUROPEAN SPALLATION SOURCE





Justification: ***integrated design*** of the vacuum system, simplify, ***common components***, ***reduce maintenance*** and training, ***lower number of hardware spare parts***, create ***scale to lower costs*** (Framework Agreements), *simplify interfaces with other sub-systems* (EX: ICS, MPS, PSS interface).

It means, support the collaborations on Neutron Instrument to work on their specific needs looking from the ESS long term operation in a most cost effective way.

Vacuum Standardization, an Integrated Approach

Working closely with our partners across the project one of our primary goals was to promote the use of **common vacuum equipment** and **standards**. As a result a Vacuum Standardization meeting was held in February 2014 where equipment suitable for Standardization was agreed and reflected in the ESS Vacuum Handbook.

An important element of this Standardization is the **Procurement Policy** applied for the procurement of all "major" vacuum equipment. The primary objective of the program is to develop a list of **standard vacuum equipment** for use project wide to minimize project costs, reduce spares holdings, training and achieve other benefits of standardization.

http://europeanspallationsource.se/accelerator-documents

Description: ESS Vacuum Handbook Part 1
Document No [illegible]
Date 23 May 2014

1. INTRODUCTION

The European Spallation Source (ESS) is an accelerator-driven neutron spallation source. The linear accelerator (LINAC) of which is a critical component. The role of the accelerator is to create protons at the ion source, accelerates them to an appropriate energy, and steers them onto the target to create neutrons via the spallation process for use by a suite of research instruments.

2. SCOPE

The ESS Vacuum Handbook comprises four (4) parts:

ESS Vacuum Handbook Part 1 – General Requirements for the ESS Technical Vacuum Systems,

ESS Vacuum Handbook Part 2 – Vacuum Equipment Standardization,

ESS Vacuum Handbook Part 3 – Vacuum Design & Fabrication, and

ESS Vacuum Handbook Part 4 – Vacuum Test Manual

This Vacuum Handbook (VH) part 1 provides guidelines, and imposes requirements where necessary, for the definition of equipment and processes associated with the vacuum systems of the Accelerator, Target and Neutron Instruments. The VH is applicable to all vacuum components and systems exposed to a technical vacuum environment.

This VH, a level 2 requirement, is to ensure that consistent standards are employed throughout all the accelerator, target and neutron instrument vacuum systems and hardware.

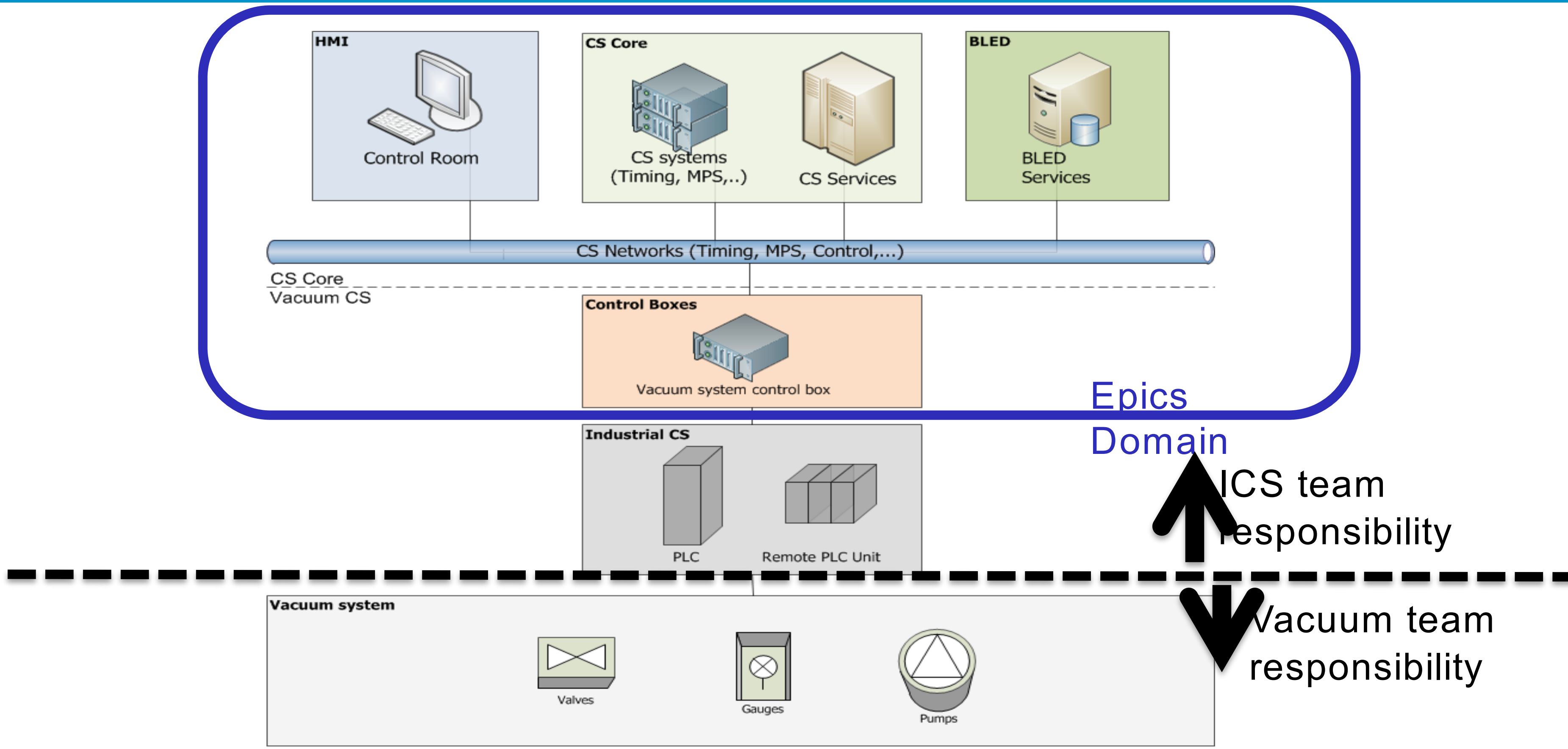
This VH will be periodically updated throughout the life of the ESS project.

All queries or additional information concerning the contents of this handbook should be addressed to the ESS Vacuum Group Section Leader (VGL).

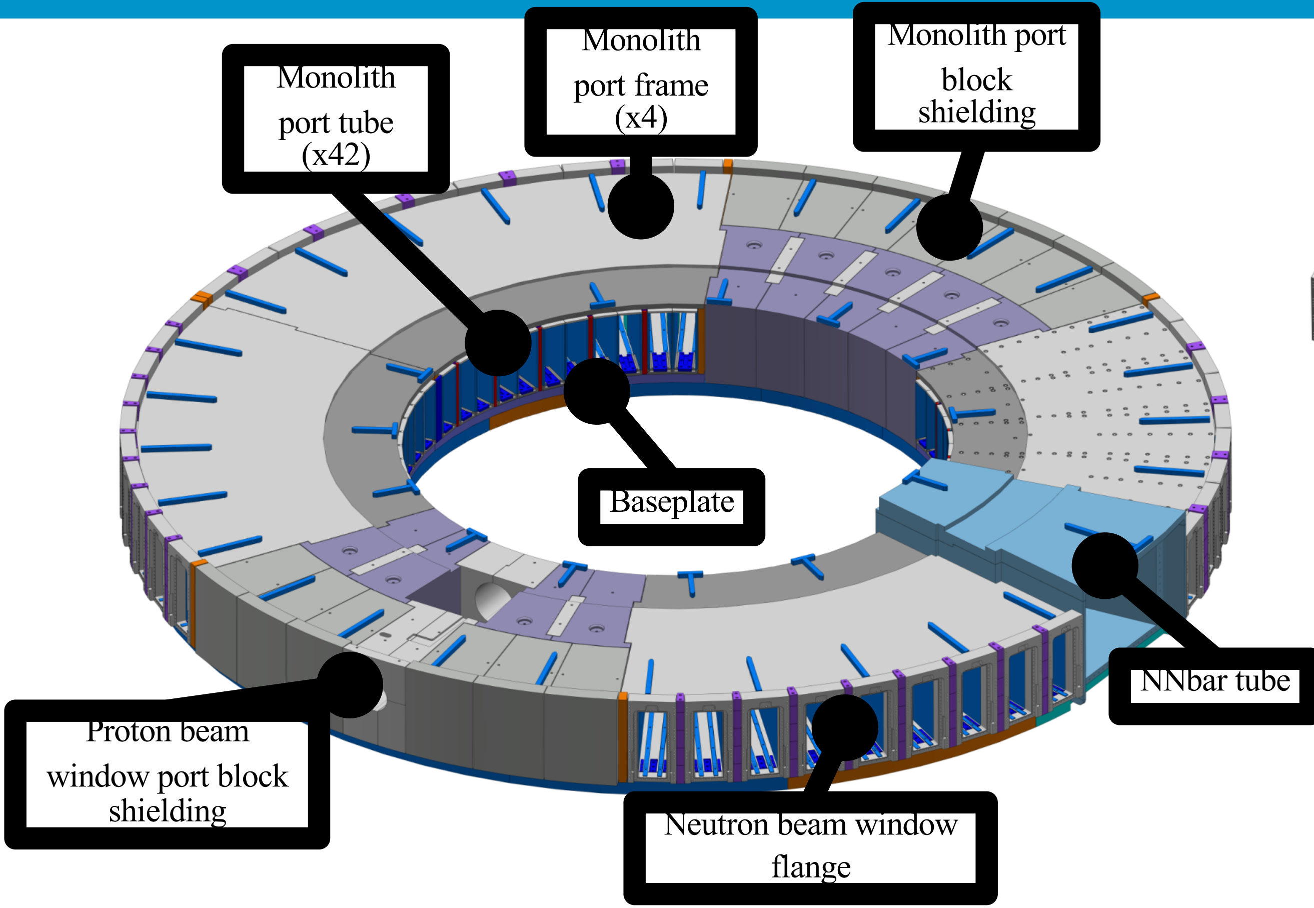
3. REPONSABILITIES

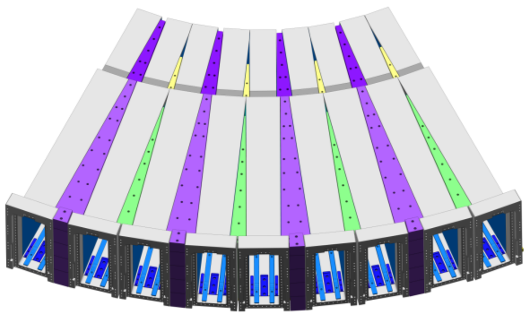
The ESS vacuum team has overall responsibility for all technical vacuum systems used on the Accelerator, Target and Neutron Scattering Instrument Systems and has

Vacuum Control System



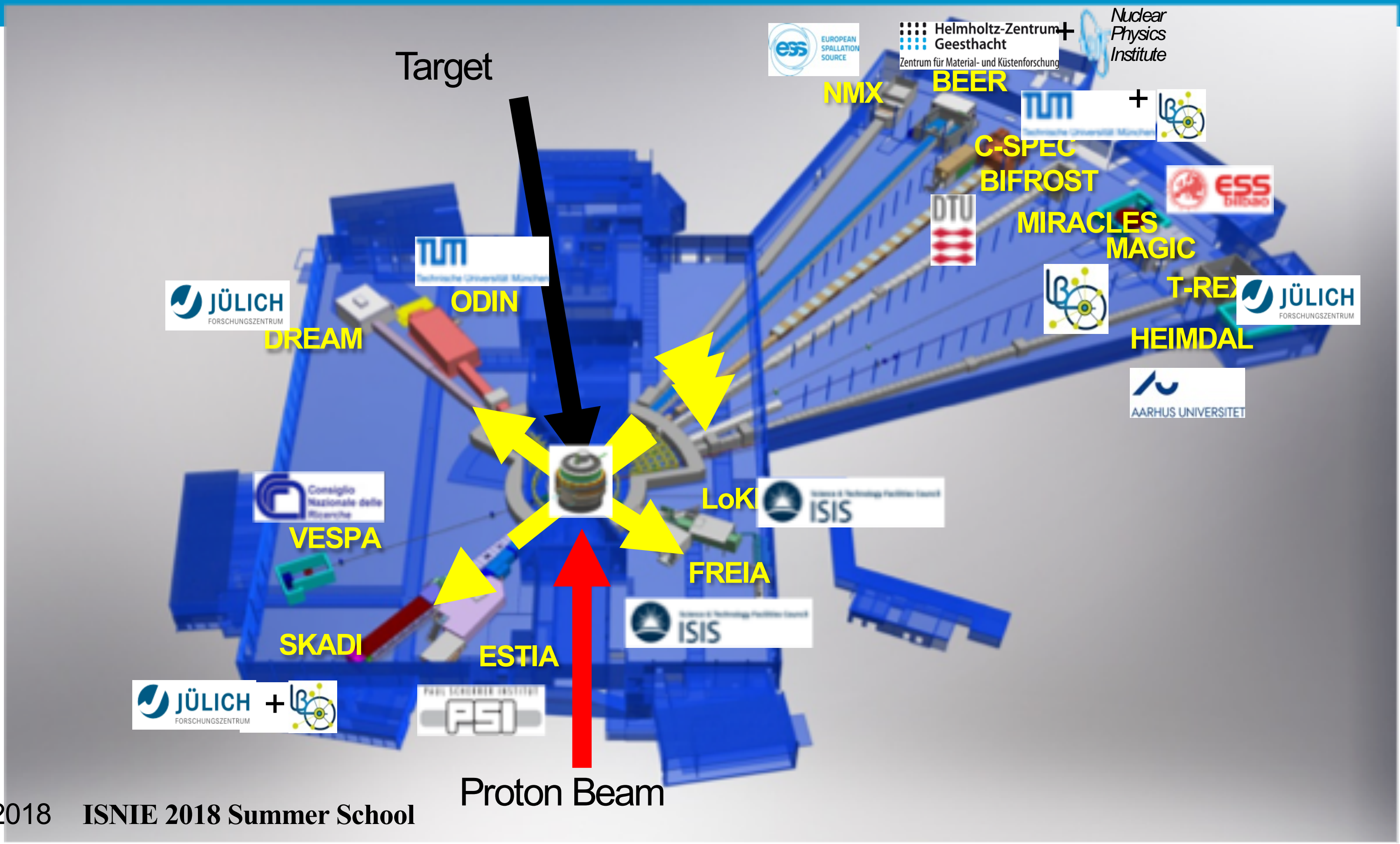
Monolith Port Block Package





Consists of vacuum chambers with radiation shielding in between. The **Inserts** and **Plugs** are placed and aligned within the chamber.

First 15 Neutron Science Instruments
ESS Lead Partners for Instrument Construction

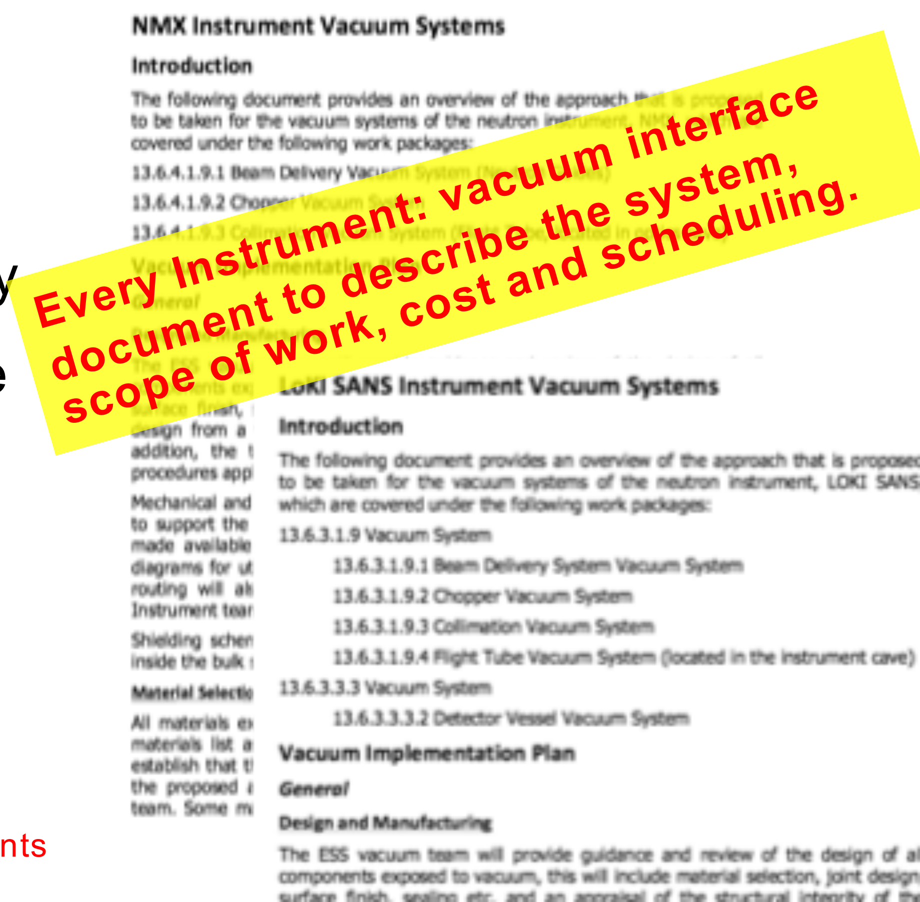


Vacuum Standardization, an Integrated Approach: Neutron Instrument

Working closely with the Neutron Instruments across the project to promote the use of **common vacuum equipment** and **standards**. Every Neutron Instrument shall have a **Vacuum interface document** to specify the details of the vacuum system following all necessary rules at ESS site (Ex: bunker requirements).

The Vacuum Team support a wiki page to simplify the communications with the in kind on the vacuum documents and support.

Ex: LOKI and NMX instruments



NMX Instrument Vacuum Systems

Introduction

The following document provides an overview of the approach that is proposed to be taken for the vacuum systems of the neutron instrument, NMX

covered under the following work packages:

13.6.4.1.9.1 Beam Delivery Vacuum System

13.6.4.1.9.2 Chopper Vacuum System

LOKI SANS Instrument Vacuum Systems

Introduction

The following document provides an overview of the approach that is proposed to be taken for the vacuum systems of the neutron instrument, LOKI SANS which are covered under the following work packages:

13.6.3.1.9 Vacuum System

13.6.3.1.9.1 Beam Delivery System Vacuum System

13.6.3.1.9.2 Chopper Vacuum System

13.6.3.1.9.3 Collimation Vacuum System

13.6.3.1.9.4 Flight Tube Vacuum System (located in the instrument cave)

13.6.3.3.3 Vacuum System

13.6.3.3.3.2 Detector Vessel Vacuum System

Vacuum Implementation Plan

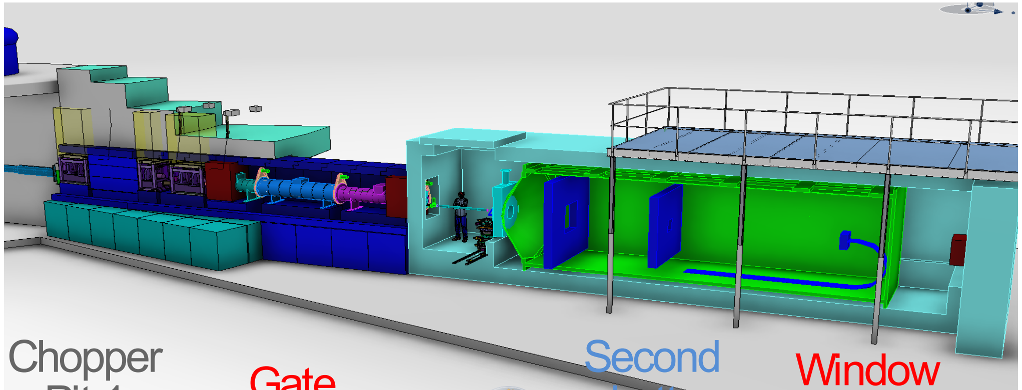
General

Design and Manufacturing

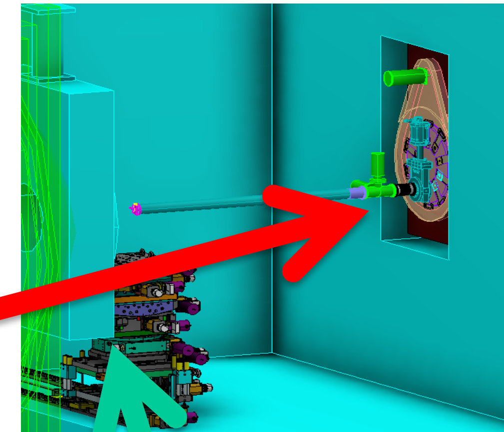
The ESS vacuum team will provide guidance and review of the design of all components exposed to vacuum, this will include material selection, joint design, surface finish, sealing etc. and an appraisal of the structural integrity of the

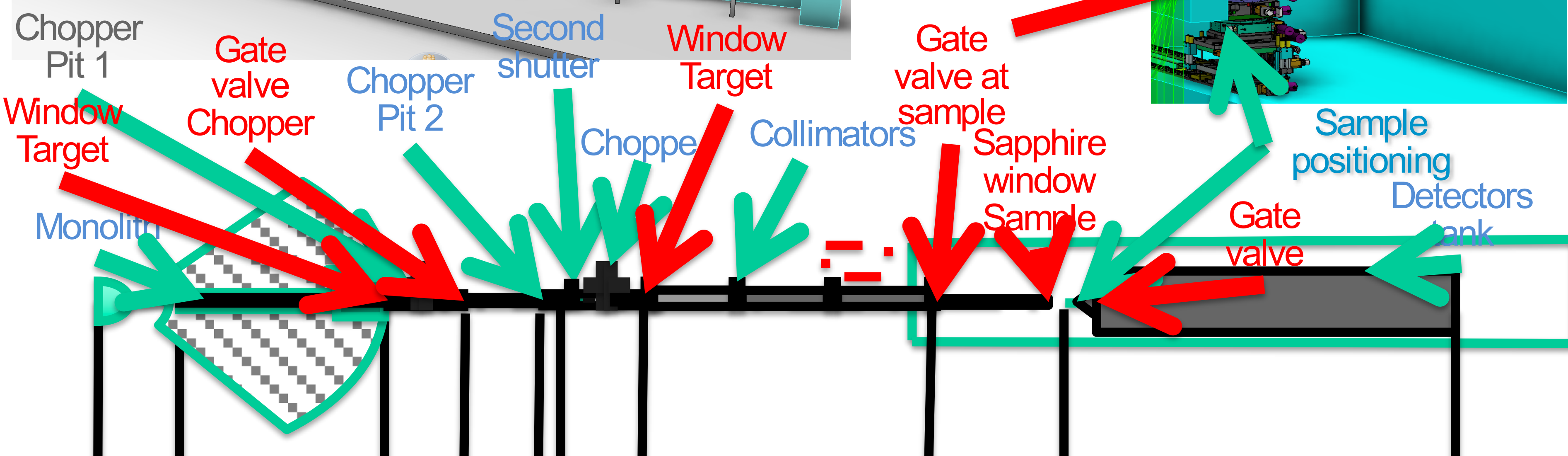
https://confluence.esss.lu.se/display/VG/Neutron+Instruments

LoKI – SANS Instrument



- Interface document for Instruments already in discussion,
- Standardization model in place.





Vacuum Specifications

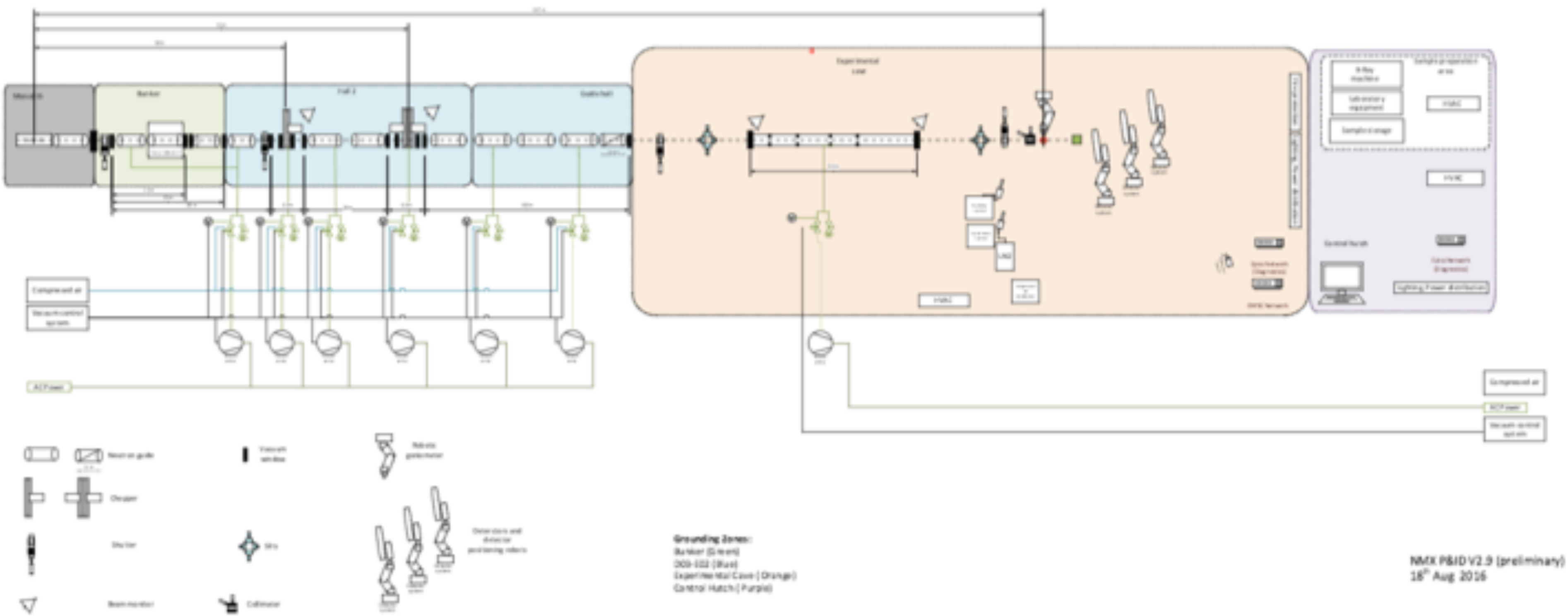
EUROPEAN SPALLATION SOURCE

ISNIE 2018
I. Sutton

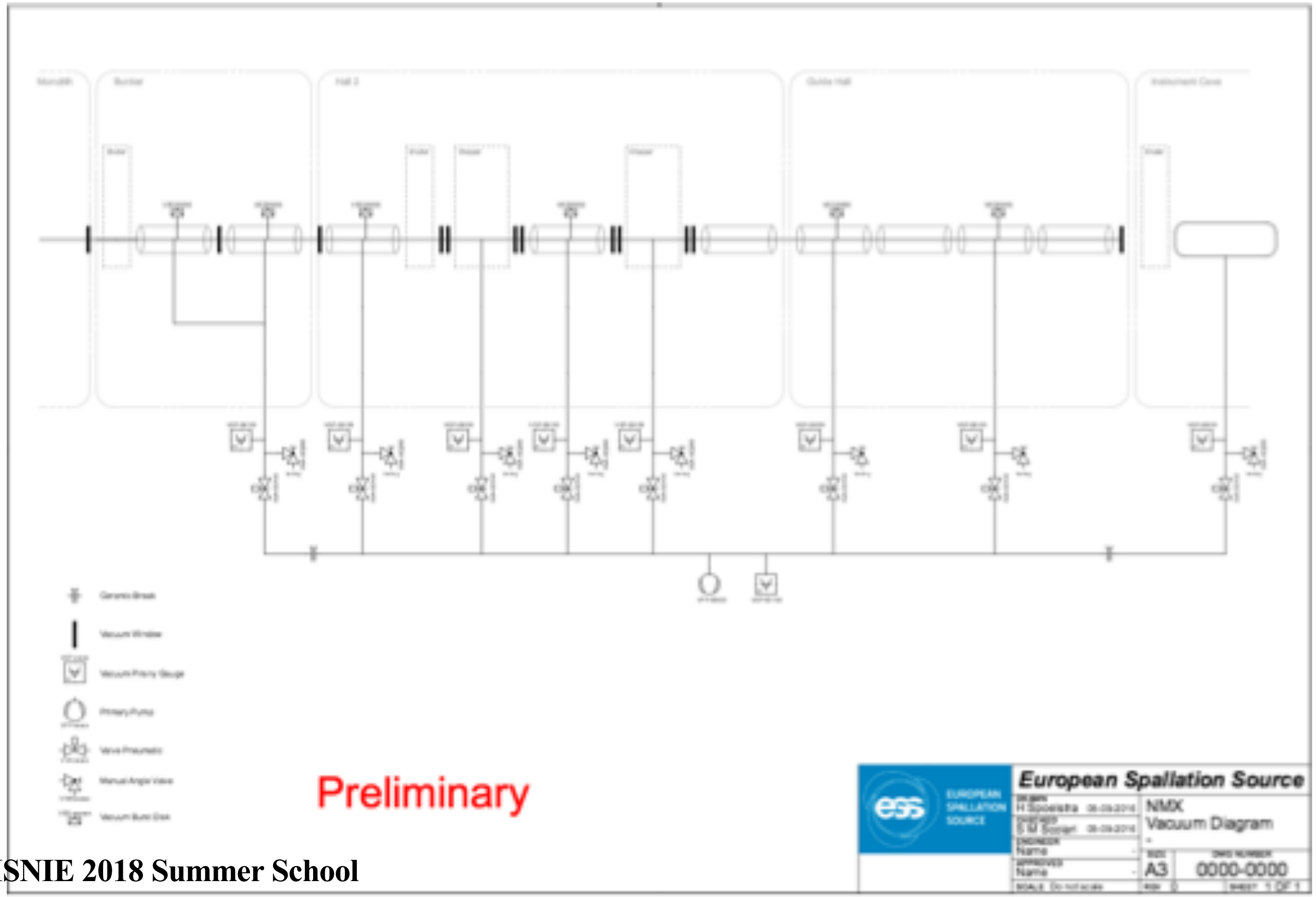
What are typical vacuum requirements for this type of

Component type	High speed neutron chopper	
Example	ILL / IN5 CRD M-Chopper	
Operating vacuum level	5e10-4	mbar
Pumped volume	0,1	m3
Cycle time	6 months	
Pump down	1 day	
Materials	Steel housing	
	Painted surfaces	
	Glass neutron guide	
	Aluminium rotor	
Radiation level	High	
Maintenance period	5 years	

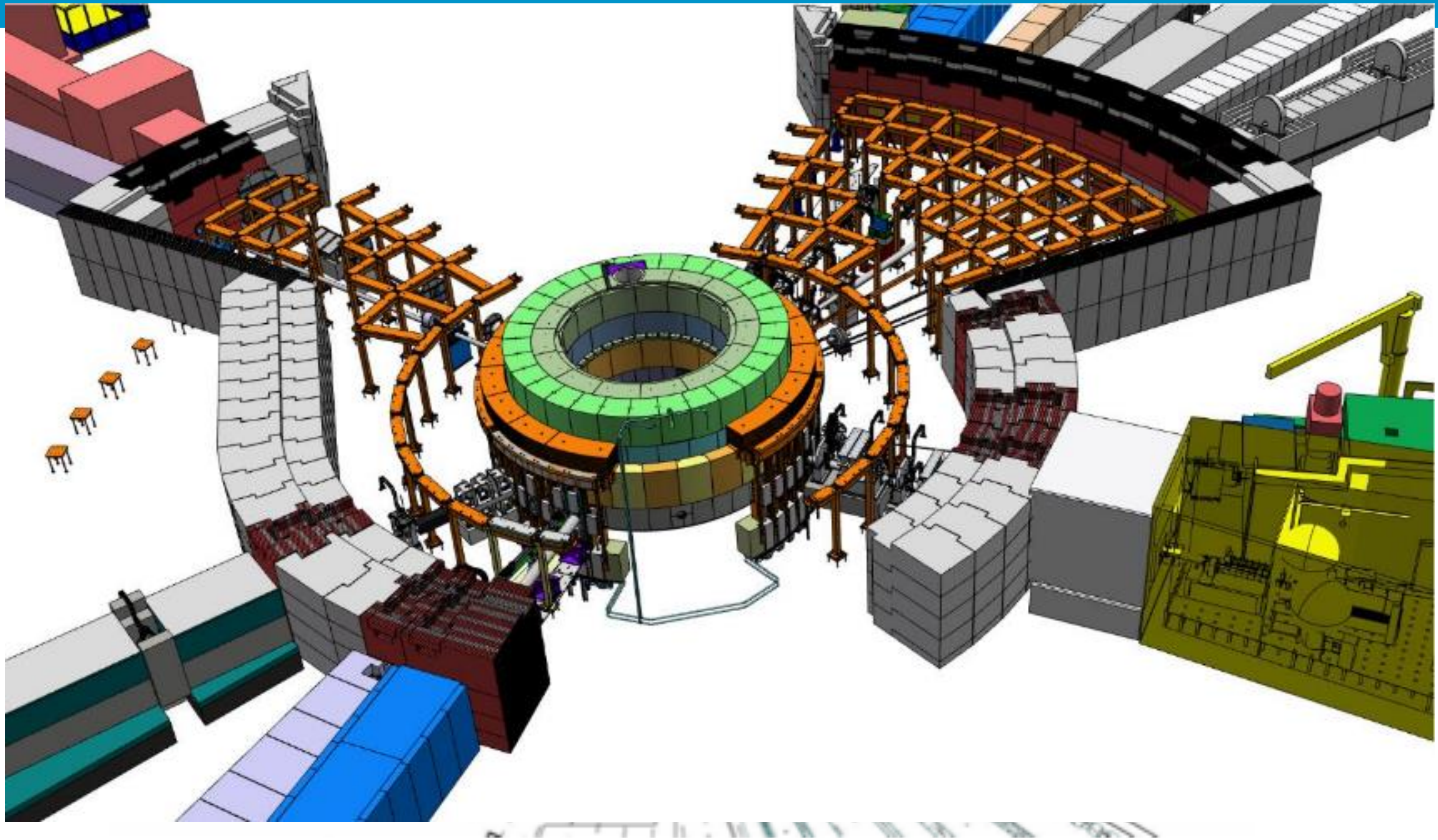
Control Diagram Instrument Ex: NMX



Vacuum Diagram: NMX

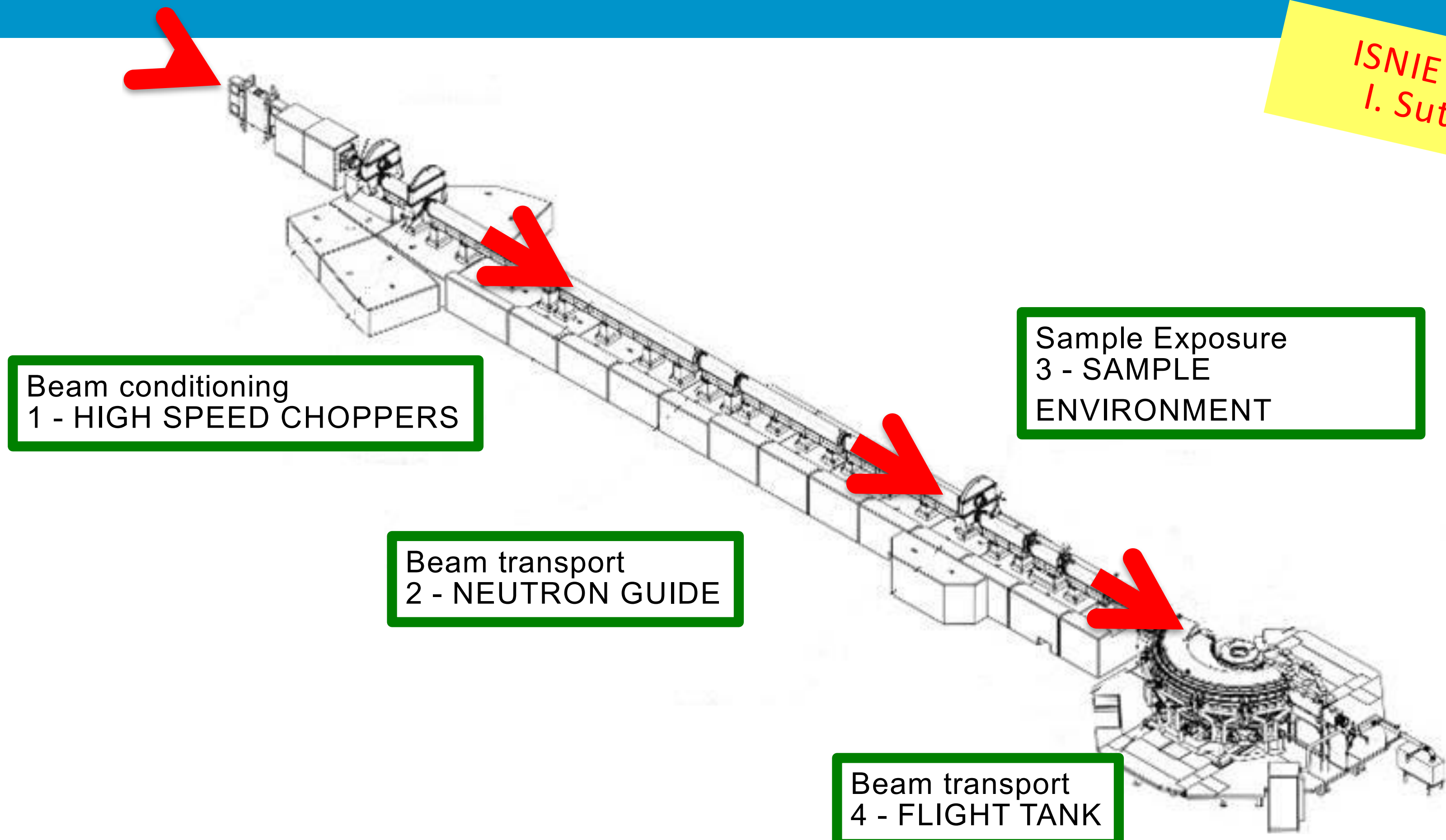


The bunker



Typical vacuum system implementations

ISNIE 2018
I. Sutton



Examples
A range of requirements and challenges

ISNIE 2018
I. Sutton

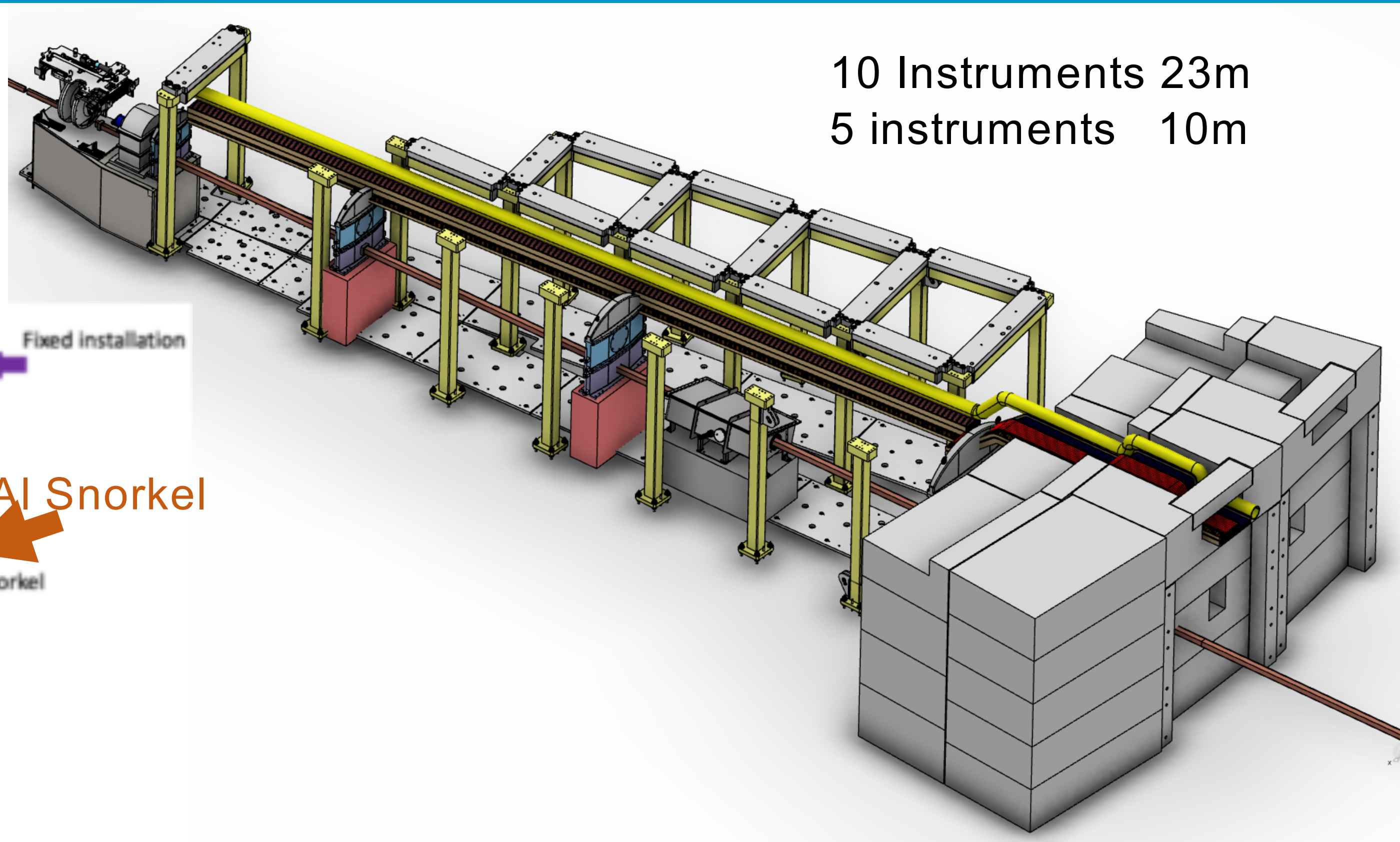
Neutron Optics: NBOA

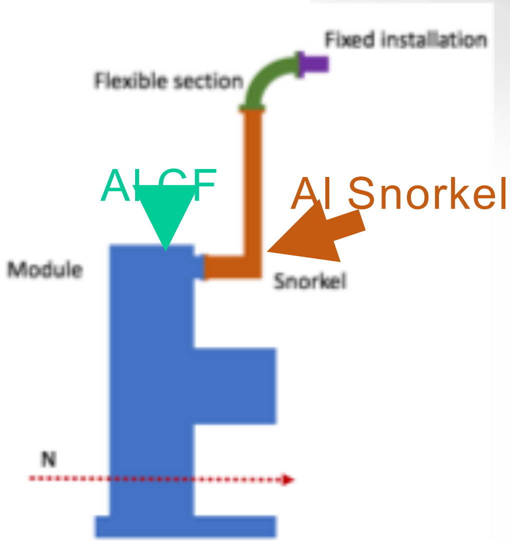
Criteria	HS Choppers	Neutron Guide	Detector vessel	Sample environment
Vacuum level	Good	Poor	Good	Very good
Pumped volume	Small	Moderate	V.Large	V.Small
Cycle time	V.Slow	V.Slow	Moderate	Fast
Radiation hardness	High	High/Mod	Low	High
Servicability	Low	V.Low	Moderate	High

Physical boundary?

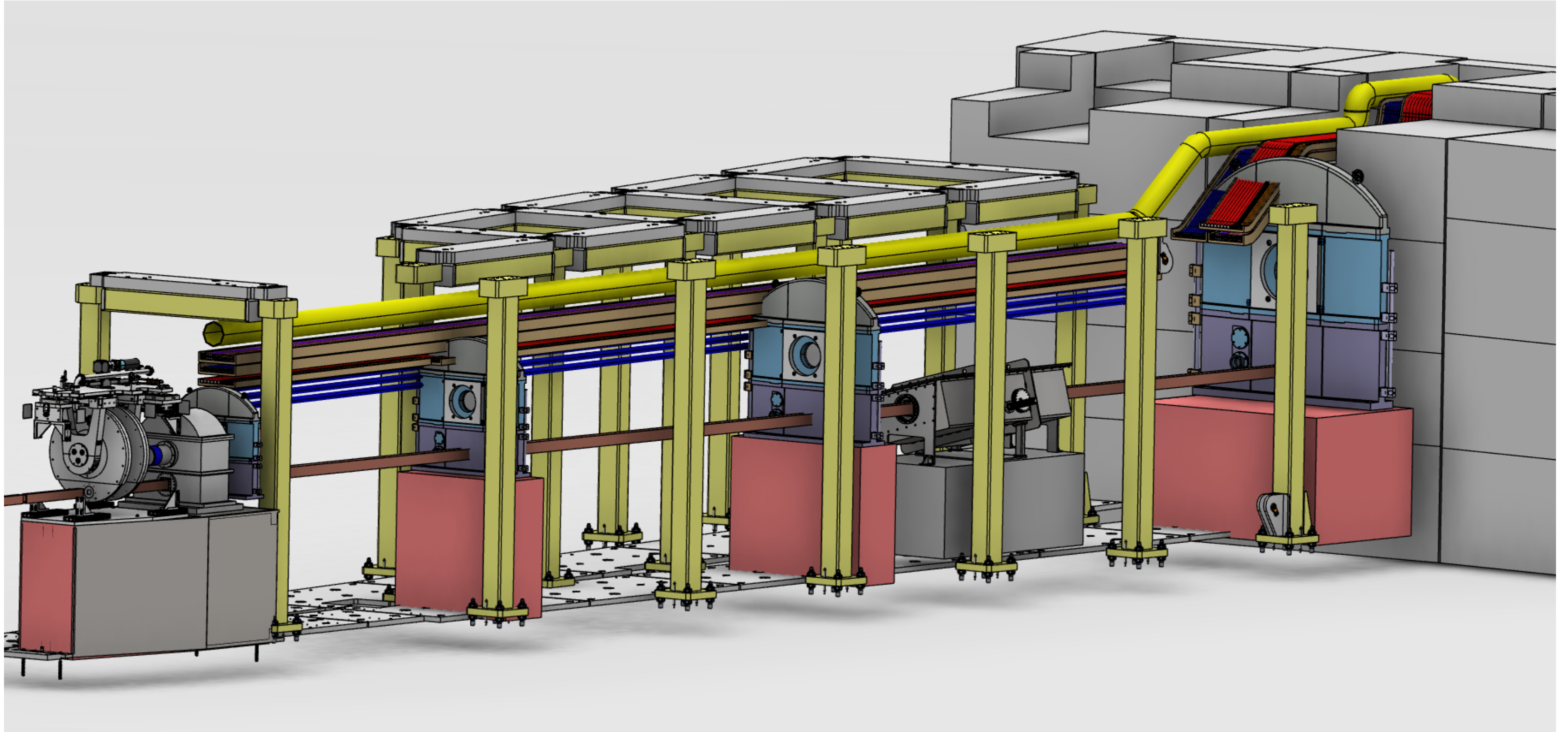
Vacuum Manifold inside Bunker

10 Instruments 23m
5 instruments 10m

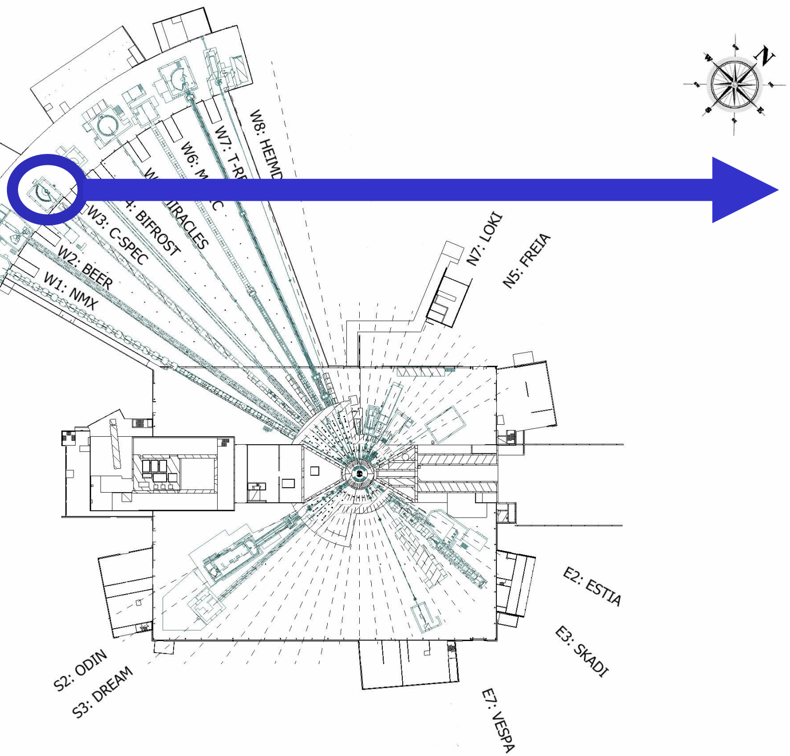


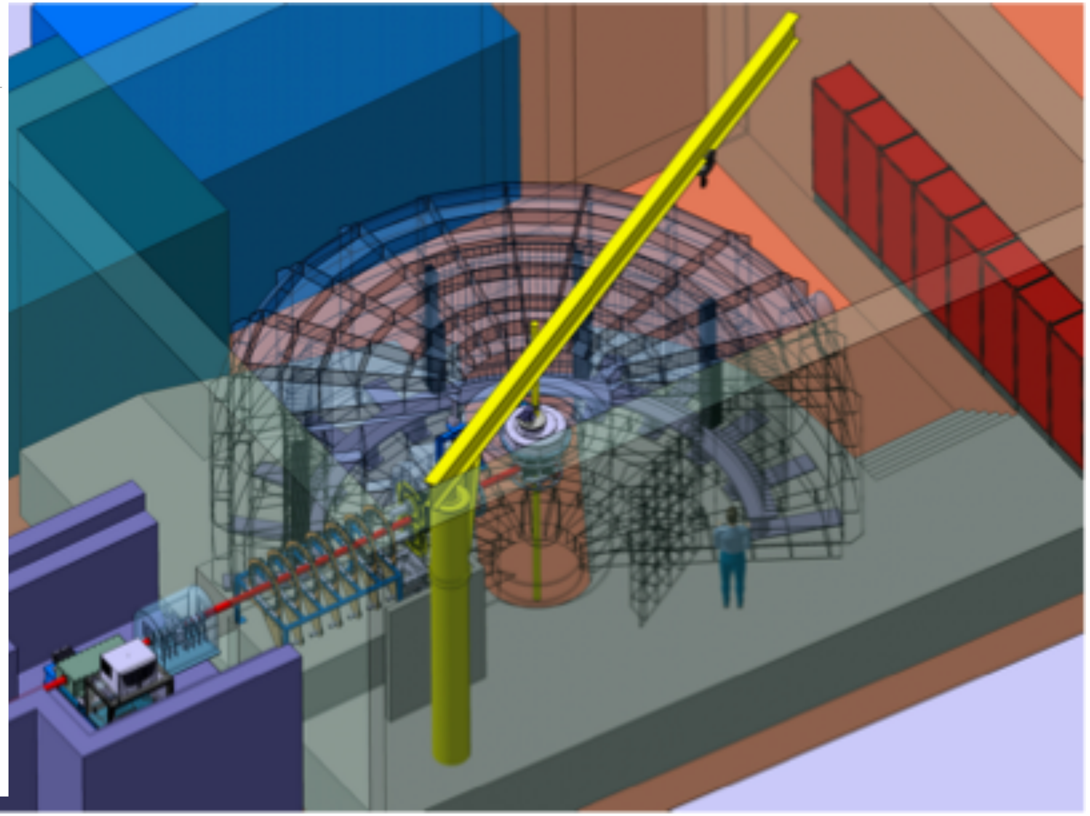


Vacuum Manifold inside Bunker



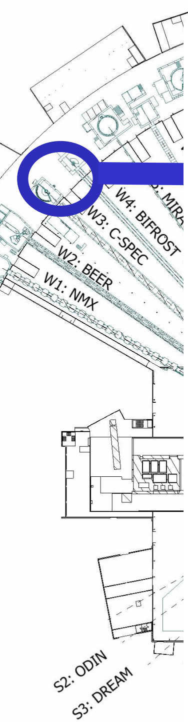
CSPEC: Cold Chopper Spectrometer





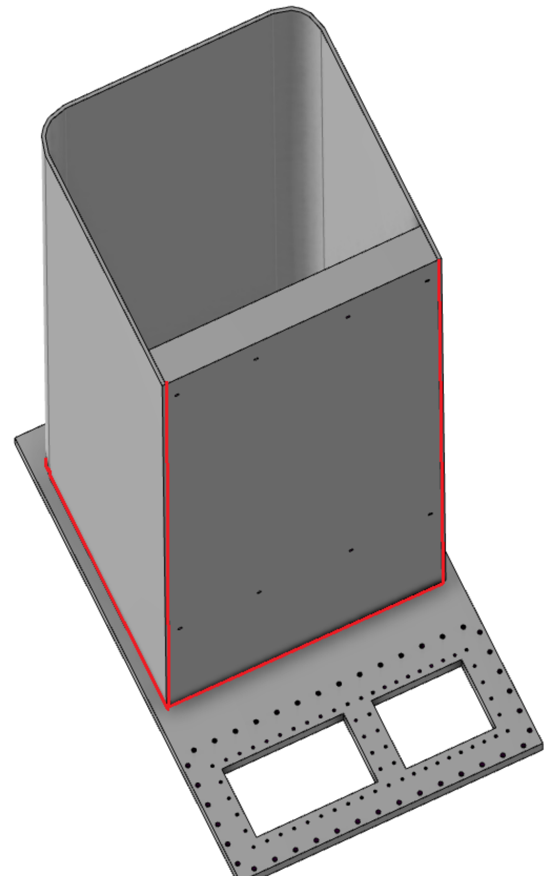
31

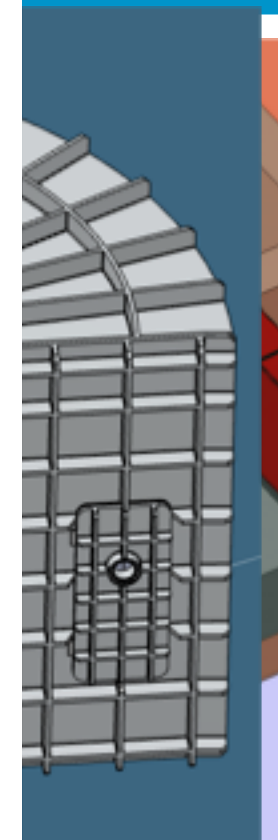
CSPEC: Cold Chopper Spectrometer



In vacuum Multi-Grid detector chamber (CSPEC and T-REX):

-Vessels made of Al 6061,
- Inside the vessel $ArCO_2$ at 1bar,
- Leak rated for high vacuum,
- Outside the vessel UHV,
- Different thickness parts, thinnest 3mm,
- Minimum heat spreading, avoid warping,
- Size ~400x400mm, length 1.3m to 3m.





Vacuum Support: Vacuum Laboratory

Vacuum Integration Test Facility (VITF)

This facility will provide the capability for seamless integration of all vacuum systems used on the accelerator, target and neutron instruments with the ICS (ESS Integrated Control System). This allows control logic to be developed and interlocks checked before implementation on the actual systems. EPICS control screens will also be developed together with data acquisition functions using this facility.

Gauge Calibration Facility (GCF)

The GCF will be used to confirm the operation and calibration of all vacuum gauges prior to installation with calibration performed against a secondary standard. All vacuum instrumentation (vacuum sensors and RGAs) installed on the accelerator, target and neutron instruments will use this facility.

Vacuum Support: Vacuum Laboratory

Outgassing Test Facility (MTF)

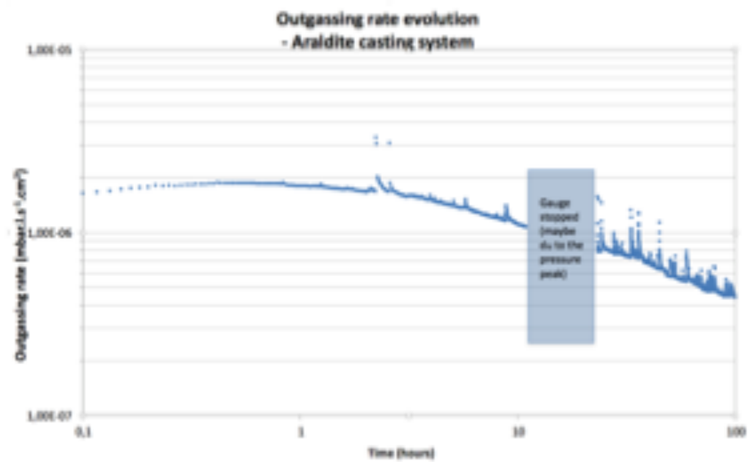
This facility is designed to support the selection and approval of materials for use in a vacuum environment in accordance with the requirements of the ESS Vacuum Handbook (VDH) and the interface document for each Neutron Instrument, where materials having vacuum compatible characteristics are listed. This facility will be in support of neutron instrument design where materials used inside the vacuum system of the Neutron Instruments. Ex: selection of vacuum compatible cabling, to minimize the contamination of vacuum spaces. The selection process will also include a quality control aspect requiring the batch-to-batch monitoring of materials.

Report for Outgassing Test

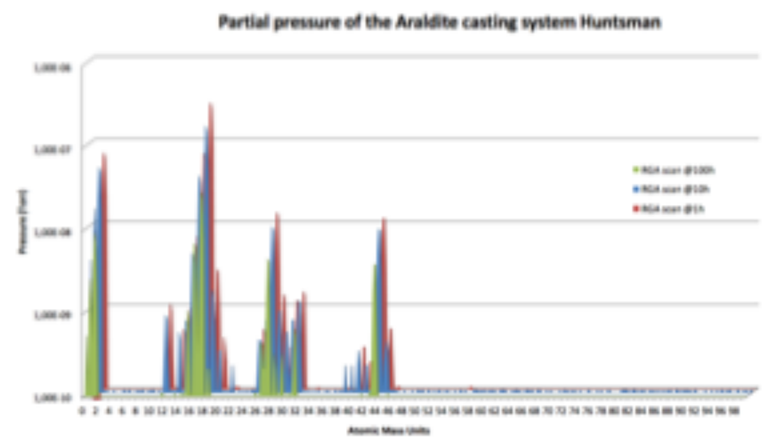
EUROPEAN SPALLATION SOURCE

ESS – Vacuum
K. Barthelemy

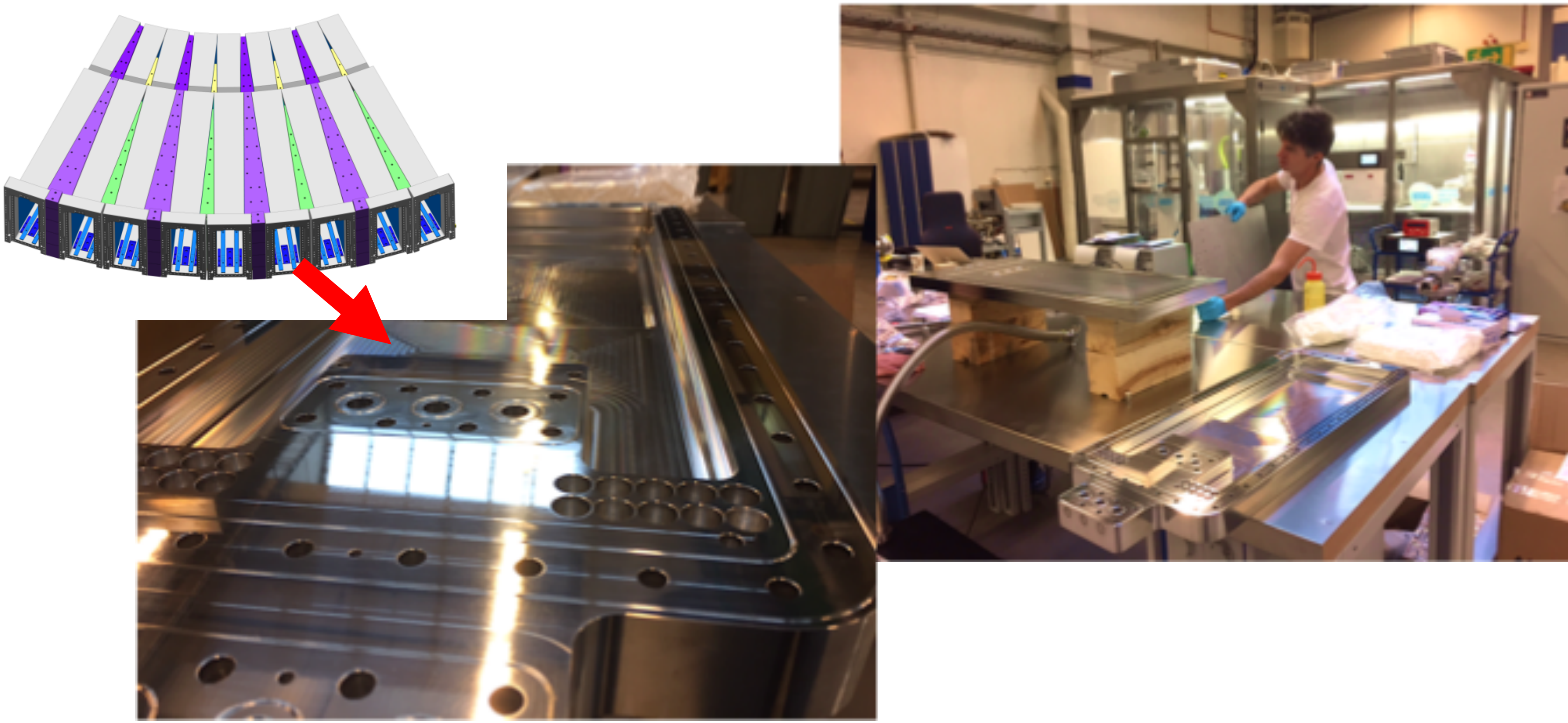
Date: 19/10/17 Ref. number: XXXXXXX	OUTGASSING TEST of Araldite® Casting System	EUROPEAN SPALLATION SOURCE
SAMPLE DESCRIPTION		
Material: Araldite® DBF (resin) and Aradur® HY 951 (hardener)	**Provider**: Huntsman	
Dimension : /	**Surface** : ≈6,5 cm²	
		
TEST FACILITY AND EQUIPMENT		
ESS outgassing test facility (See ANNEX 3). Test carried out according to Throughput Method of [REF 3].		
Gauges: IONIVAC IE514 N_2 calibrated according to [REF 1].	**RGA**: Hiden HALO 200 RC	
PRE-TEST TREATMENTS		
Cleaning: None	**Bake-out**: NO	
BLANK TEST		
Chamber Gas-Load: 1,4 E-08 mbar l/s	**RGA scan**: No anomalies (see ANNEX 4)	
PREPUMPING IN THE LOADLOCK CHAMBER		
Time to reach <10⁻⁴ mbar: 6h05	**Total time in the loadlock** : 6h35	
OUTGASSING DATA WITH BACKGROUND SUBTRACTED (mbar l/s/cm²)		
OGR @1hour: 2E-06	**OGR @10hours**: 1E-06	**OGR @ 100hours**: 4E-07
REFERENCES		
REF 1. ISO 3567:2011(E) – Vacuum gauges, Calibration by direct comparison with a reference gauge.		
REF 2. J. Vac. Sci. Technol. A 25(1) Jan/Feb 2007 – Recommended practice for process sampling for for partial pressure analysis.		
REF 3. AVS recommended practice – Recommended practices for measuring and report outgassing data.		
Test executor: K. Barthelemy	**Checker**: L.Page	**Approver**: M. J. Ferreira



ANNEX 1 - OUTGASSING EVOLUTION CURVE



Neutron Beam Extraction (NBEX): Window Flange



References

- Mathewson, A.G. Vacuum System Design. In: TURNER, S. (ed.). Proceedings, CERN Accelerator School: 5th General Accelerator Physics Course. CERN - 94. v. 2. p.717-729.
- Proceedings, CAS – CERN Accelerator School: Vacuum in Accelerators, CERN-2007-003, Geneva, 2007.
- INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. ISO 3529-1:1981 - Vacuum technology – Vocabulary – Part 1: General terms. Genebra, Suíça, 1981.
- WUTZ, M.; ADAM, H.; WALCHER, W. Theory and Practice of Vacuum Technology. Braunschweig, Germany: Friedrich Vieweg & Sohn, 1989, 686p. ISBN 3-528-08908-3
- Jousten, K (ed.). Handbook of Vacuum Technology. Weinheim, Germany: Wiley-VCH, 2008. 1002p. ISBN 3-527-40723-5.
- ESS Vacuum Handbook

https://europeanspallationsource.se/accelerator/specialized-technical-services#vacuum

Important notes

EUROPEAN SPALLATION SOURCE

- Vacuum groups are responsible for the vacuum requirements of the vacuum system (true for almost all facilities!!),
- Vacuum Group responsible to over see all related aspect of the vacuum contributions(including the interfaces with Control System and Safety, installation, services…),
- Create a vacuum description as starting point for easy conversation across interfaces (facilities, suppliers…),
- Cost x Performance: can be extremely complex decision, if no specific boundaries are clear (budge, facility environment, "from scratch", adapting old solutions, life-cost…),

It means: Open the discussion with your vacuum representative as soon you understand what the instrument needs


Thank you!
Tack!
EUROPEAN
SPALLATION
SOURCE