Vacuum Technology

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$$p \cdot V = N \cdot k_B \cdot T$$

1. **Basics of vacuum physics**

2. **Vacuum chambers**

3. **Vacuum pumps**

4. **Vacuum measurement**

5. **Example: KATRIN main spectrometer**

6. **Literature, downloads**

1. Basics of vacuum physics

Karlsruhe Institute of Technology

- What is vacuum?
- Short history of vacuum
- Equation of state for an ideal gas
- Gas flow and conductance
- Pumping speed
- Vapour pressure
- Outgassing, desorption, adsorption, ...
- Leakrate
- Some units

What is vacuum (DIN 28400)?

Vacuum denotes the condition of a gas where

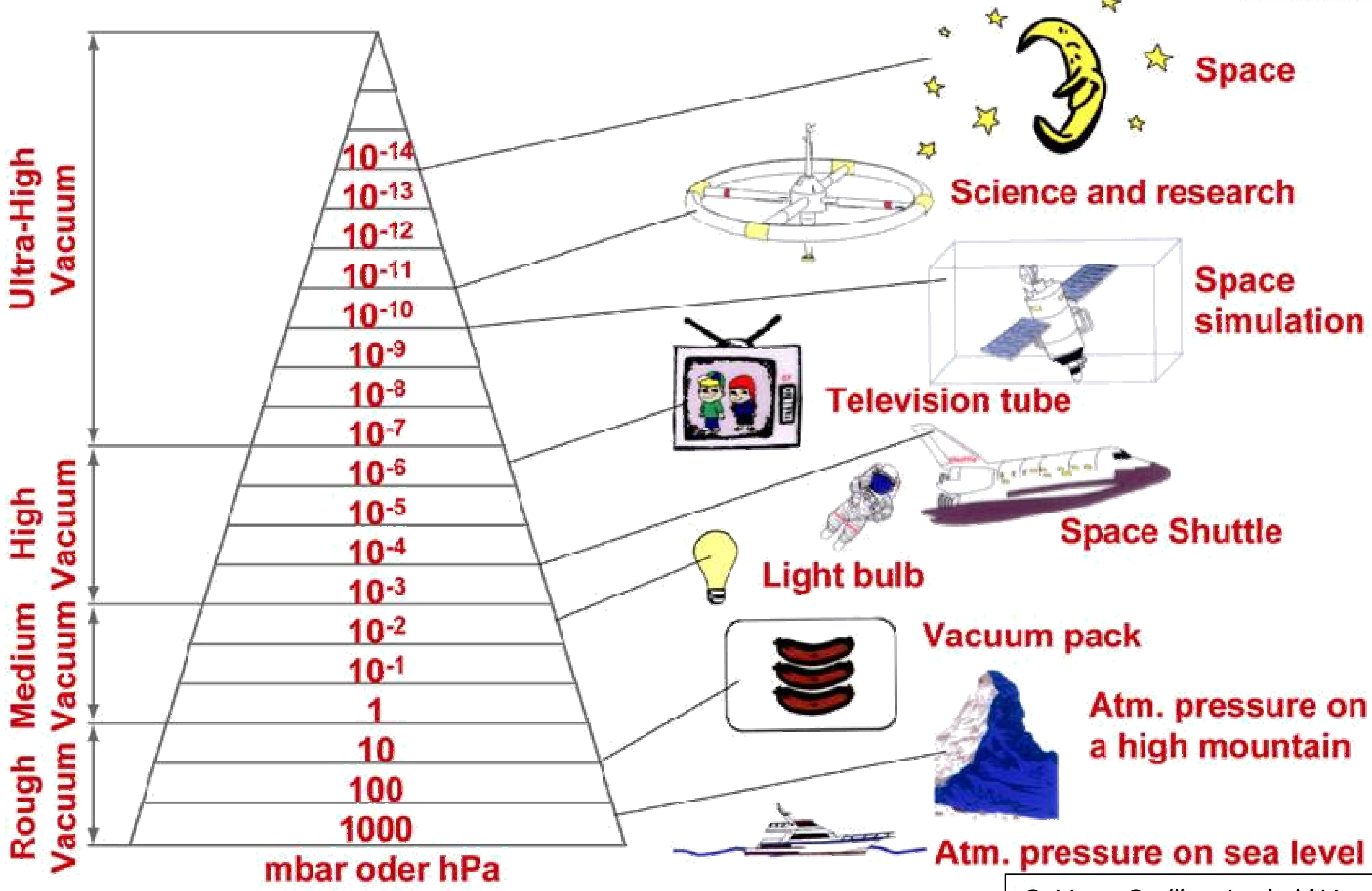
- the pressure inside a recipient (vacuum chamber) is smaller than outside.
- the pressure of the gas is smaller than 300 mbar, i.e. smaller than the lowest atmospheric pressure on the surface of the earth.

Ranges of vacuum

– **rough (low) vacuum:**	**10^3 – 1 mbar**
– **medium vacuum:**	**1 –10^{-3} mbar**
– **high vacuum (HV):**	**10^{-3} –10^{-7} mbar**
– **ultra-high vacuum (UHV):**	**< 10^{-7} mbar**
– **extreme high vacuum (XHV):**	**< 10^{-12} mbar**

different definitions in Europe and the US

Ranges of vacuum and applications

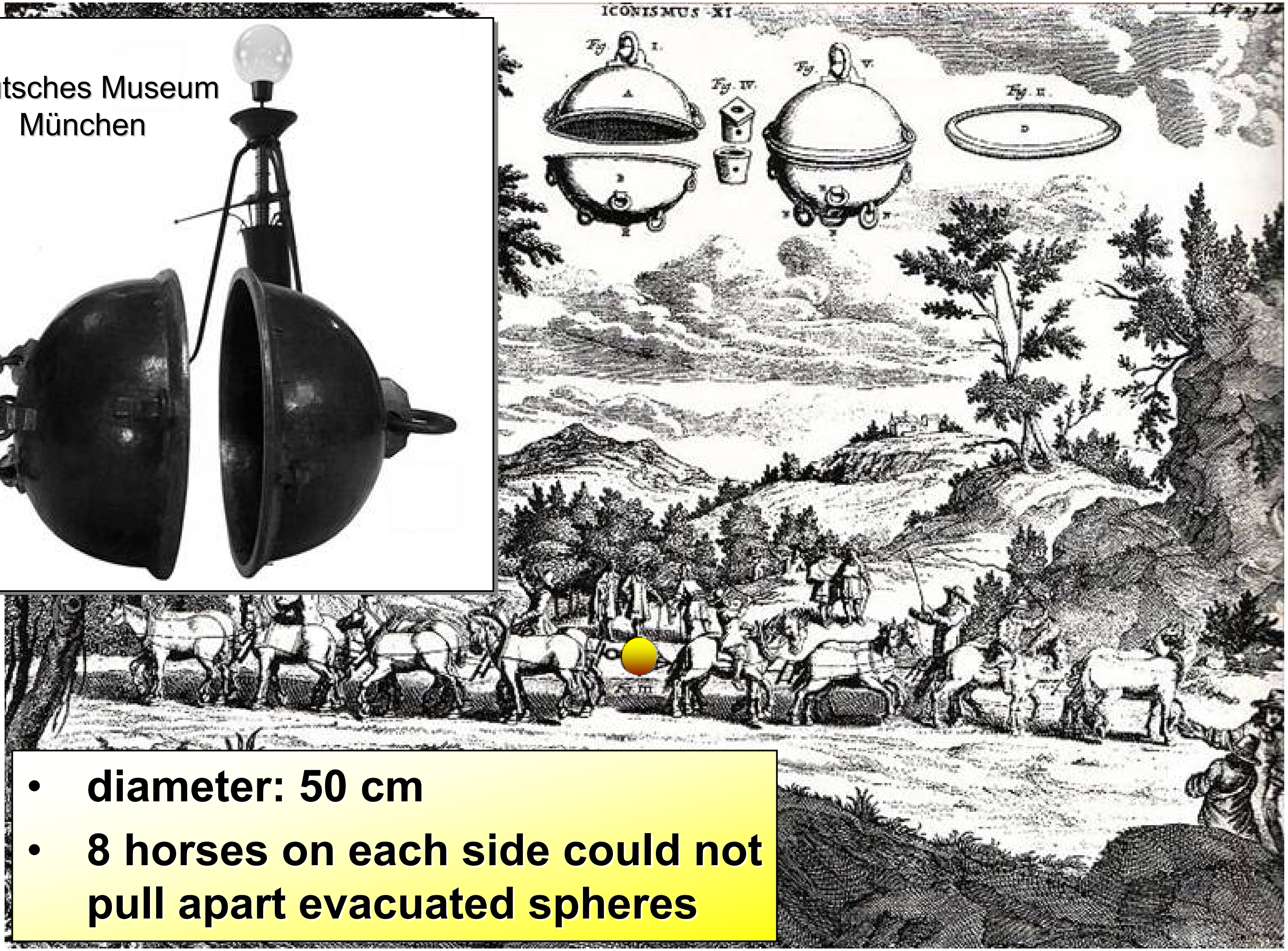


G. Voss, Oerlikon Leybold Vacuum

Short history of vacuum

- **~400 BC:**
  - **Democritus** proposed atoms and empty space in between.
  - **Aristotle** denied the existence of empty space.
- **1613 – 1650 AD:**
  - **Galileo Galilei** measures the density of air
  - **Torricelli** performs vacuum experiments with a mercury filled glass tube
  - **Pascal** discovers that the hight of the liquid depends on its density
  - **Pascal and Descartes** develope the idea of air pressure measurements at different altitudes
- **~1650 AD:**
  - **Otto von Guericke** (Magdeburg) starts vacuum experiments
  - developement of air pumps from a water pump of the fire brigade
  - Magdeburg hemispheres

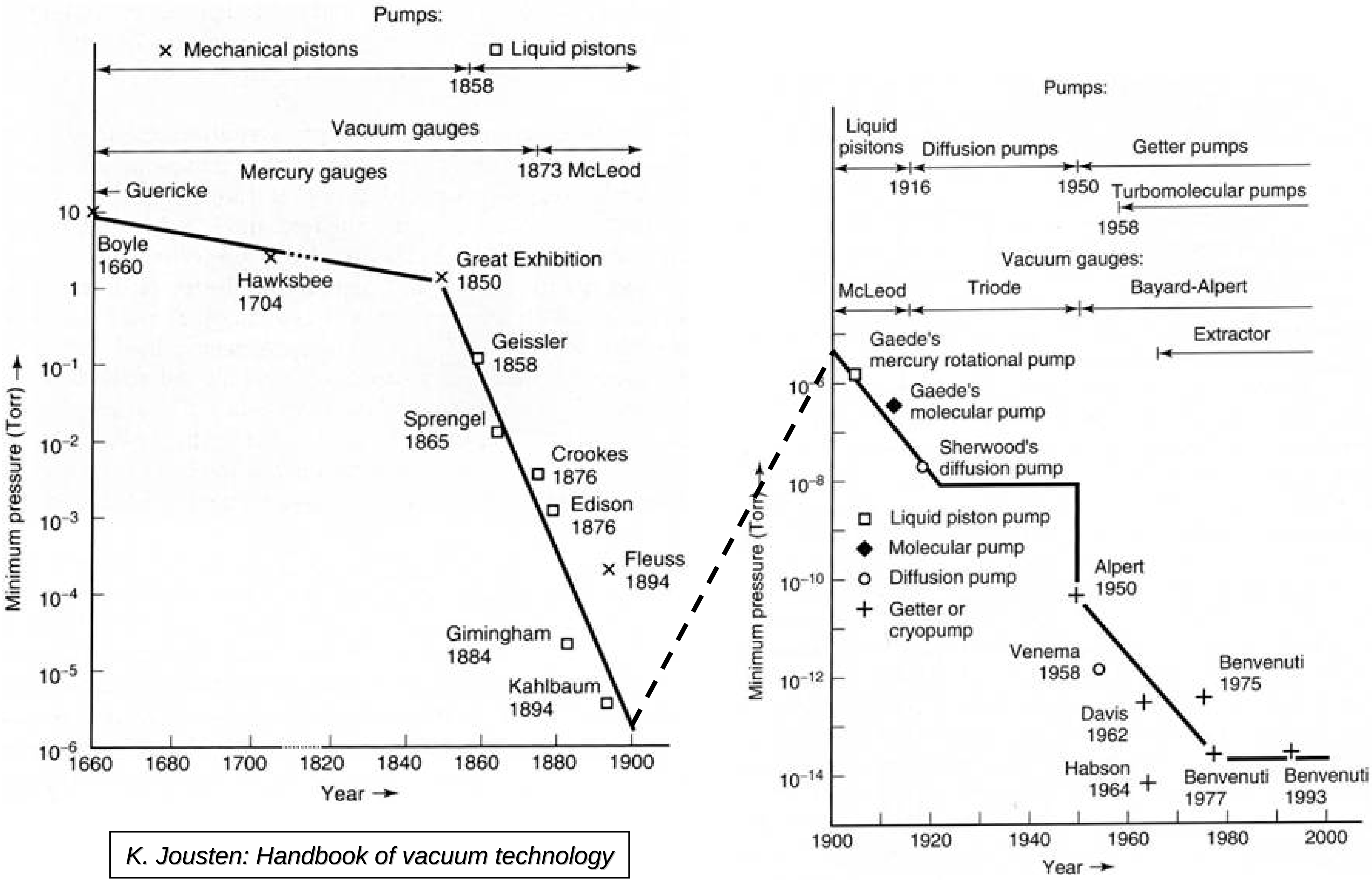
Guericke: Magdeburg Hemispheres



Deutsches Museum
München

- **diameter: 50 cm**
- **8 horses on each side could not pull apart evacuated spheres**

Short history of vacuum



K. Jousten: Handbook of vacuum technology

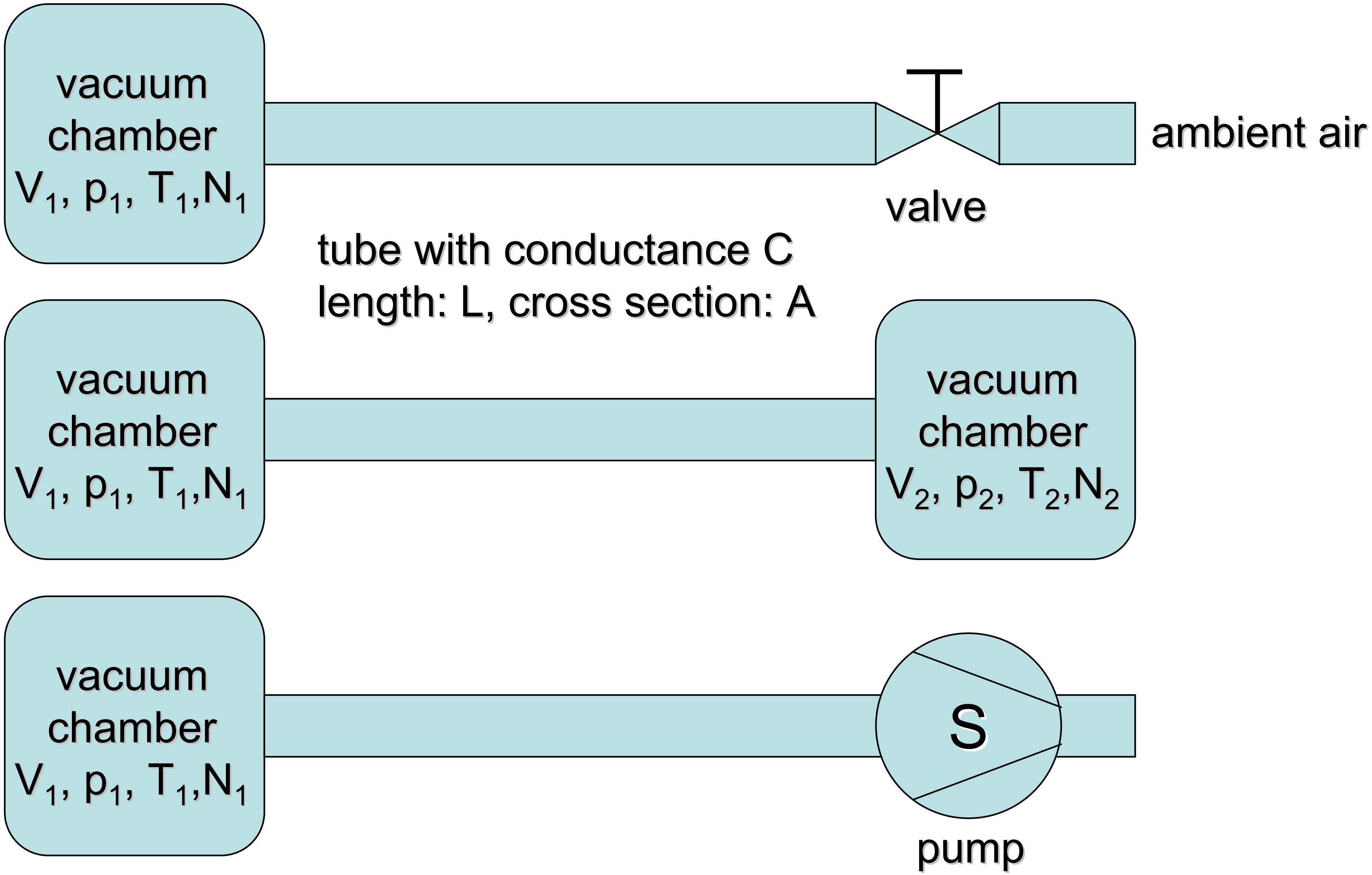
Equation of state for an ideal gas

$$p \cdot V = N \cdot k_B \cdot T = \nu \cdot R \cdot T$$

- p = pressure of the gas [mbar]
- V = volume of the gas [l]
- N = number of gas molecules in volume V
- *ν* = number of mols [mol]
- T = absolute temperature [K]
- k_B = Boltzmann constant = $13.807 \cdot 10^{-23}$ mbar · l/K
- R = molar gas constant = 83.145 mbar · l/mol · K

- p · V is often used instead of the mass of a gas
- standard conditions: p_0 = 1013.25 mbar, T_0 = 273.15 K

Gas flow and conductance



Gas flow (throughput)

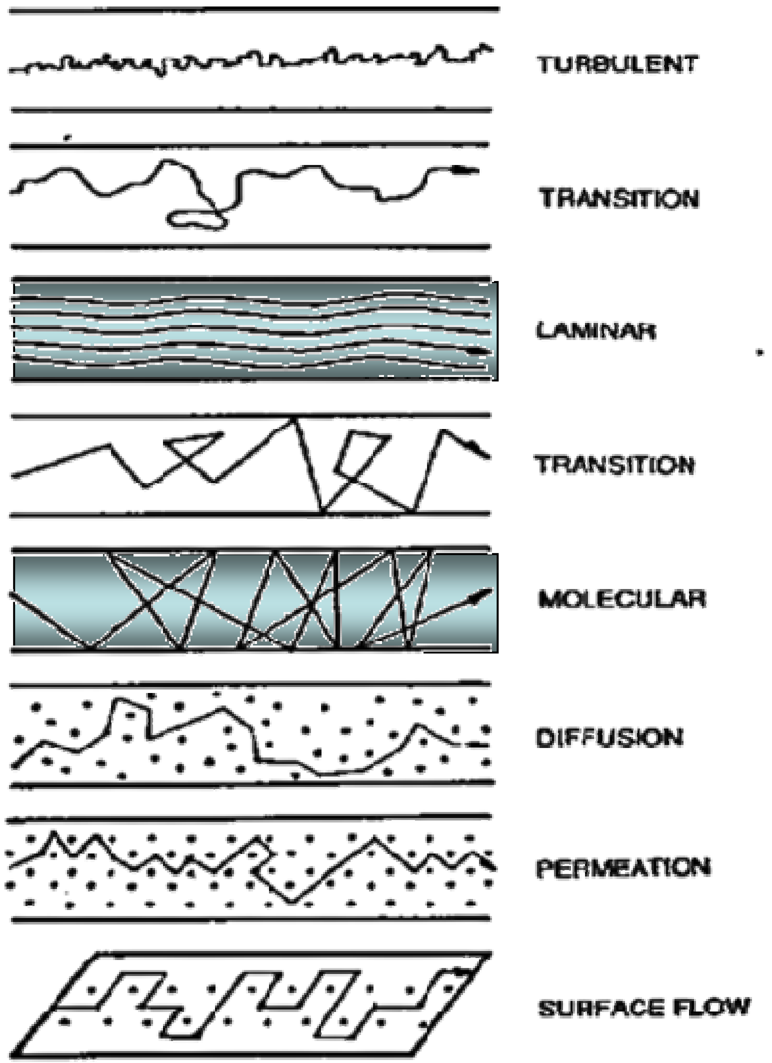
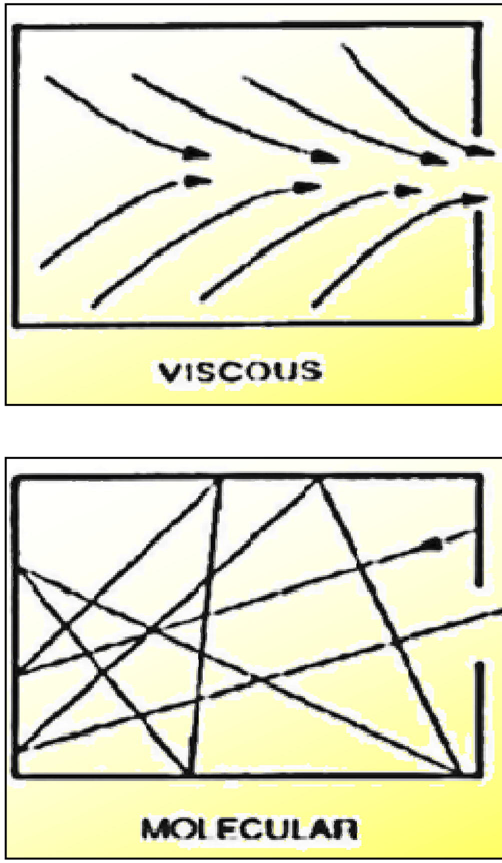


Figure 3.4 Molecular trajectories at various types of flow.



gas molecules follow the pressure gradient

gas molecules interacte only with the walls

Figure 3.8 Viscous and molecular flow patterns.

Marsbed H. Hablanian
High-Vacuum Technology
A Practical Guide

Velocity and mean free path

- **mean thermal velocity (Maxwell – Boltzmann)**

$$\bar{c} = \sqrt{\frac{8 \cdot k_B \cdot T}{\pi \cdot m_P}} = \sqrt{\frac{8 \cdot R \cdot T}{\pi \cdot M}} = 145.5 \sqrt{\frac{T[K]}{M[g/mol]}} \text{ in } [m/s]$$

$$(\text{examples: } \bar{c}(N_2, 20°C) = 471\, m/s \;;\; \bar{c}(H_2, 20°C) = 1762\, m/s)$$

- **mean free path**

$$\bar{l} = \frac{k_B}{\sqrt{2} \cdot \pi \cdot d^2} \cdot \frac{T}{p} \quad (d: \text{diameter of the particle})$$

$\bar{l} \cdot p$ is constant for stable temperatures

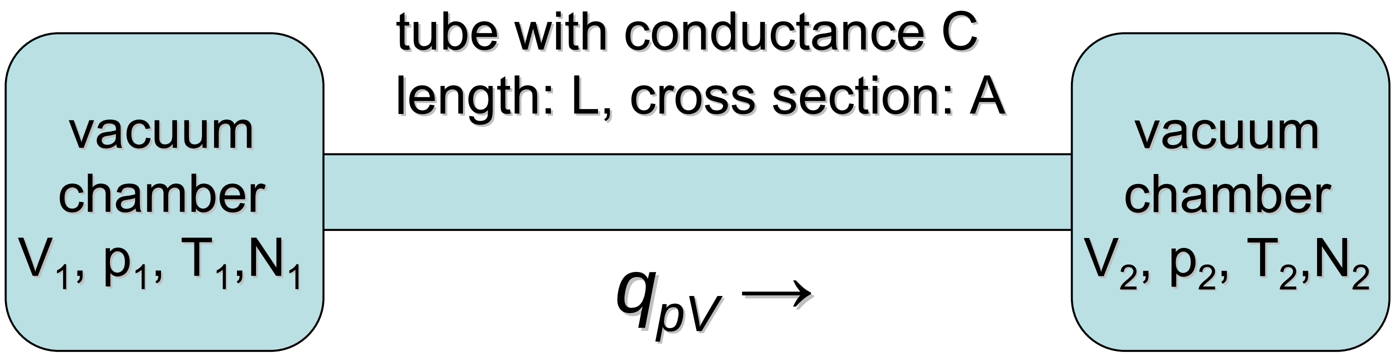
$$(\text{example: } \bar{l}(N_2, 10^{-3}\, mbar, 20°C) = 6.5\, cm)$$

- **Knudsen number (D = caracteristic geometrical dimension)**

$$Kn = \frac{\bar{l}}{D}$$

$Kn \leq 0.1$	viscous flow
$0.01 < Kn < 0.5$	transitional flow
$Kn > 0.5$	molecular flow

Conductance



- **gas flow or throughput (pump) is described by**

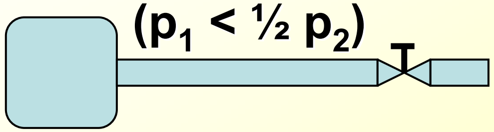
$$q_{pV} = \frac{d(p \cdot V)}{dt} = q_m \cdot \frac{R}{M} \cdot T$$

- **Conductance *C* quantifies the gas flow between a vacuum chamber and another volume or pump for a given pressure difference Δp.**

$$C = \frac{q_{pV}}{\Delta p}; \qquad \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots$$

Conductance

- **Viscous flow**
  - conductance depends on the pressure *and* mean thermal velocity
  - example: long tube
  - choked gas flow at large pressure difference ($p_1 < ½\, p_2$)



$$C_{tube}^{laminar} = \frac{\pi \cdot D^4 \cdot (p_1 + p_2)}{256 \cdot \eta_v \cdot L}$$

$$\eta_v = \frac{4 \cdot (\bar{l} \cdot p)}{\pi \cdot \bar{c}} = \text{viscosity}$$

$$D = \text{diameter of tube}$$

$$L = \text{length of tube}$$

- **Molecular flow**
  - conductance depends on mean thermal velocity
  - example: circular aperture

$$C_{ap}^{mol} = \frac{\bar{c}}{4} \cdot A = \frac{\bar{c}}{4} \cdot \frac{\pi}{4} \cdot D^2$$

  - example: long tube

$$C_{tube}^{mol} = C_{ap}^{mol} \cdot \frac{4 \cdot D}{3 \cdot L} = \frac{\pi}{12} \cdot \bar{c} \cdot \frac{D^3}{L}$$

  - example: nitrogen at RT

$$C_{tube}^{mol}(N_2, 20°C) = 12.1 \cdot D^3 / L \;\; (D, L \text{ in cm})$$

Conductance

- **conductance is proportional to the mean thermal velocity and therefore depends on the temperature and mass of gas molecules**

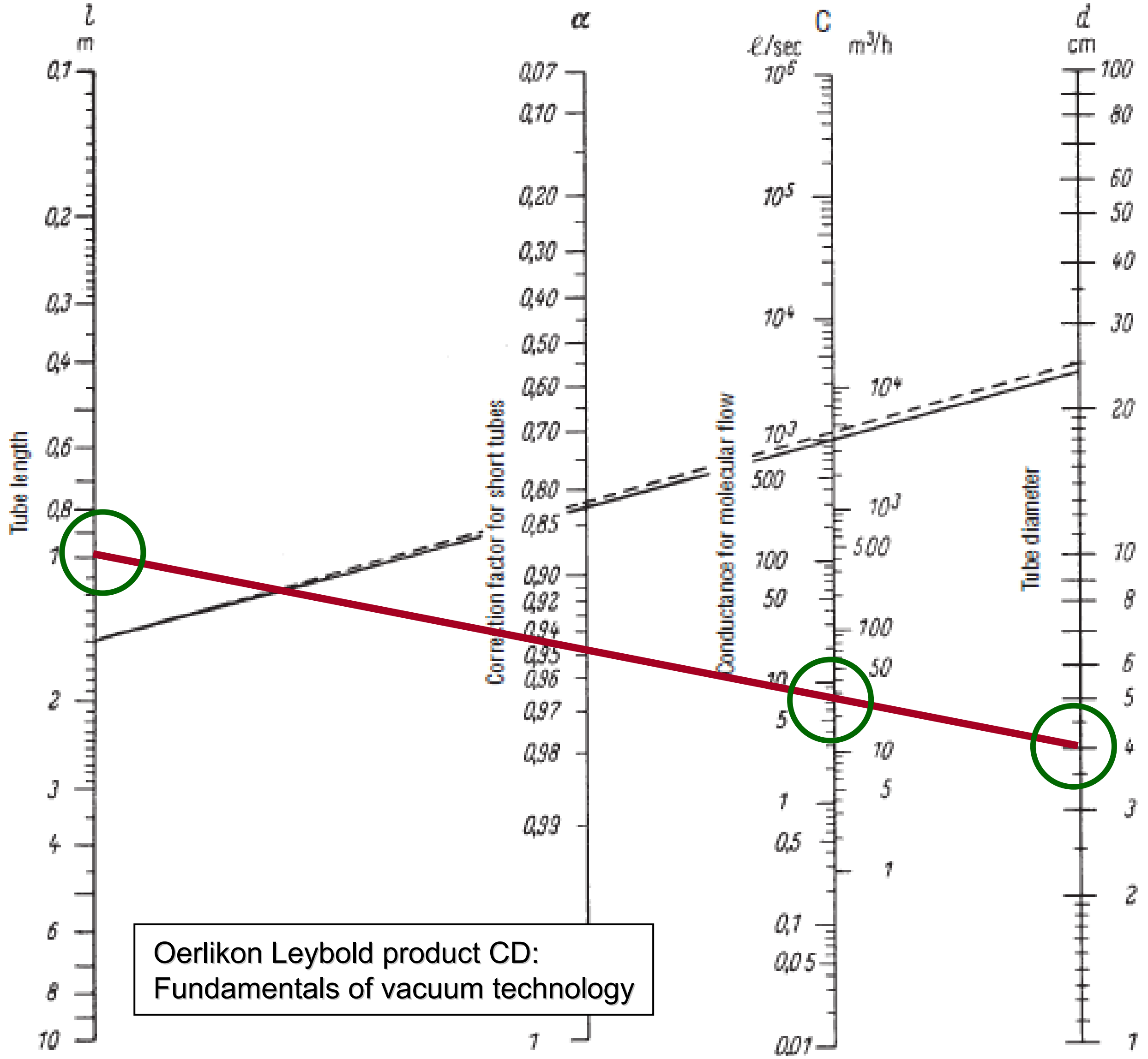
$$\bar{c} = 145.5\sqrt{\frac{T[K]}{M[g/mol]}} \text{ in } [m/s]$$

- **conductance for another gas type at the same temperature is:**

$$C(gas) = C(N_2)\sqrt{\frac{M(N_2)}{M(gas)}}$$

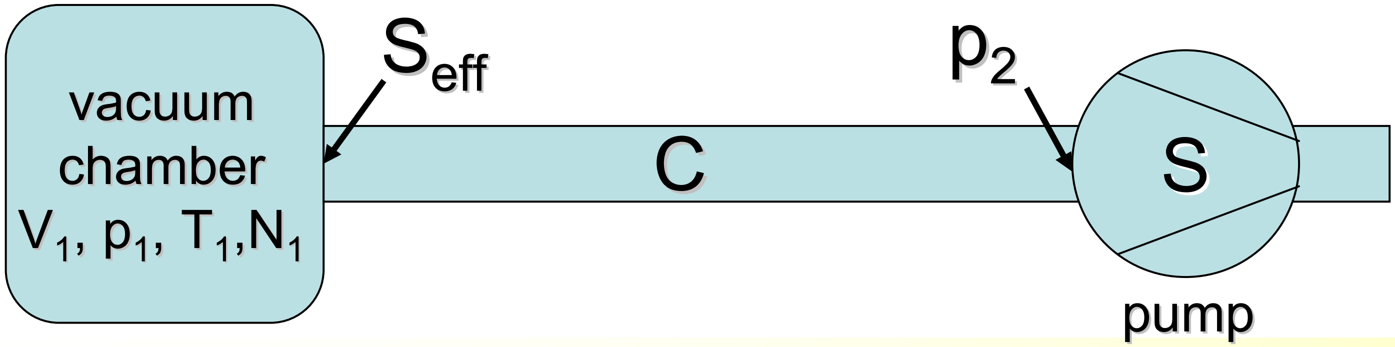
- **examples (molecular flow, 20°C, long tube, D = 4 cm, L = 100 cm)**
  - **nitrogen (M = 28 g/mol): C = 7.74 l/s**
  - **hydrogen (M = 2 g/mol): C = 29.0 l/s**
  - **argon (M = 40 g/mol): C = 6.48 l/s**
- **conductance of tubes can be determined graphically with a nomogram for nitrogen at 20°C**

Nomogram for molecular flow



Oerlikon Leybold product CD:
Fundamentals of vacuum technology

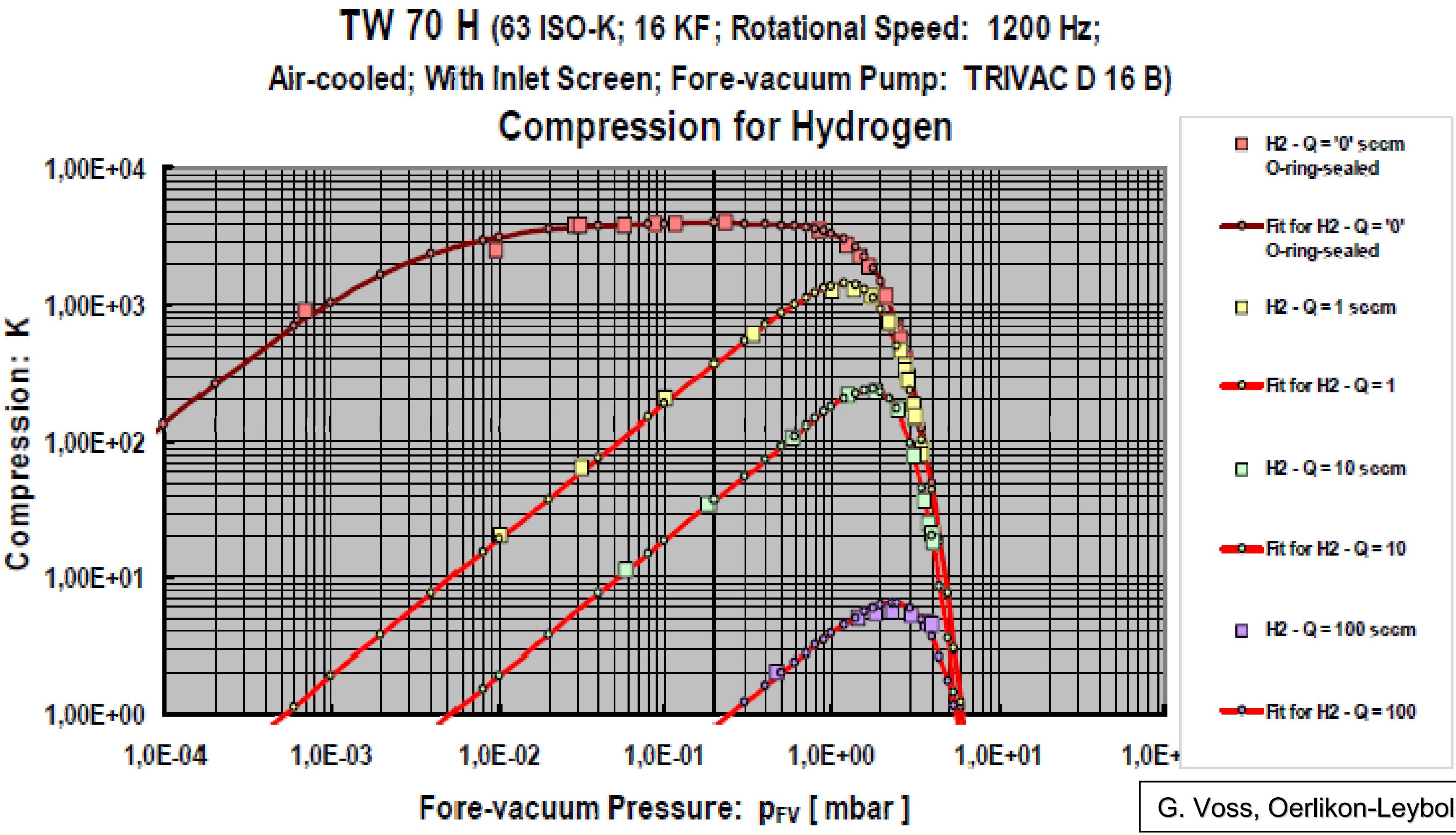
Pumping speed



- **pumping speed S in l/s or in m³/h (roughing pumps)**
- **throughput of the pump is** $q_{pV} = S \cdot p_2$
- **pressure drop across tube maintains gas flow:** $p_1 > p_2$
- **equation of continuity:** $q_{pV} = S \cdot p_2 = S_{eff} \cdot p_1 = C \cdot (p_1 - p_2)$
- **effective pumping speed:** $$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C}$$
- **example:** $$L = 100\,\text{cm},\ D = 4\,\text{cm} \rightarrow \quad C_{tube}^{mol} = 7.7\,\text{l/s}$$ $$S = 100\,\text{l/s} \qquad S_{eff} = 7.15\,\text{l/s}$$ $$S = 1000\,\text{l/s} \qquad S_{eff} = 7.64\,\text{l/s}$$

Compression factor $K = p_{hv} / p_{fv}$

- maximum compression for H_2 at $q_{pV} = 0$
- back diffusion limits high vacuum pressure



G. Voss, Oerlikon-Leybold

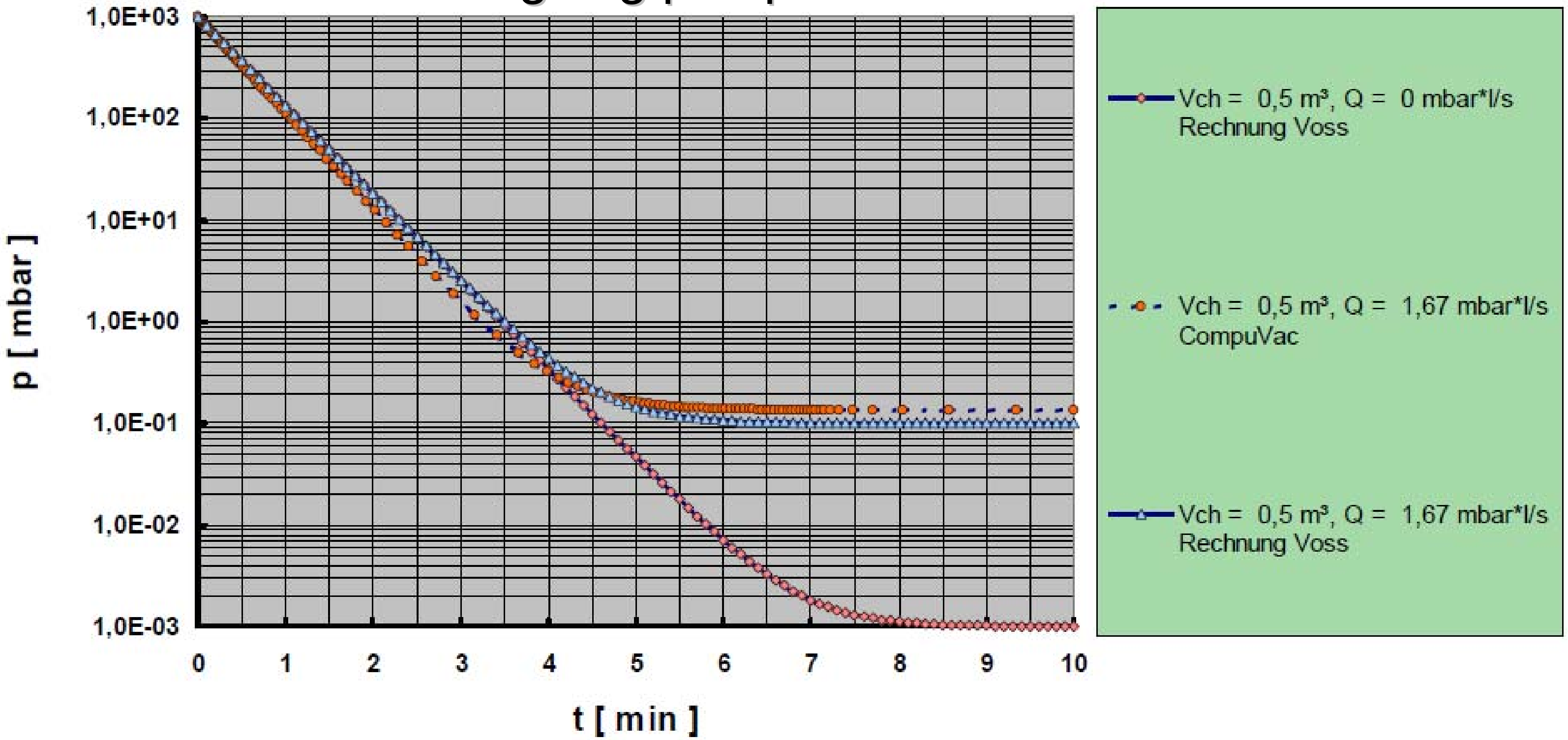
Pump-down time

$$q_{pV} = V \cdot \frac{dp}{dt} = S_{eff} \cdot (p - p_{\min})$$

$$p(t) = p_0 \cdot e^{-t/\tau} + p_{\min} \quad \text{with} \quad \tau = \frac{V}{S_{eff}}$$

- **minimum pressure *p_{min}***
  - back diffusion (pump)
  - outgassing, leaks,...
- **time dependent for UHV**
  (e.g. Hobson model, surface layers)

roughing pump



Final pressure (equilibrium)

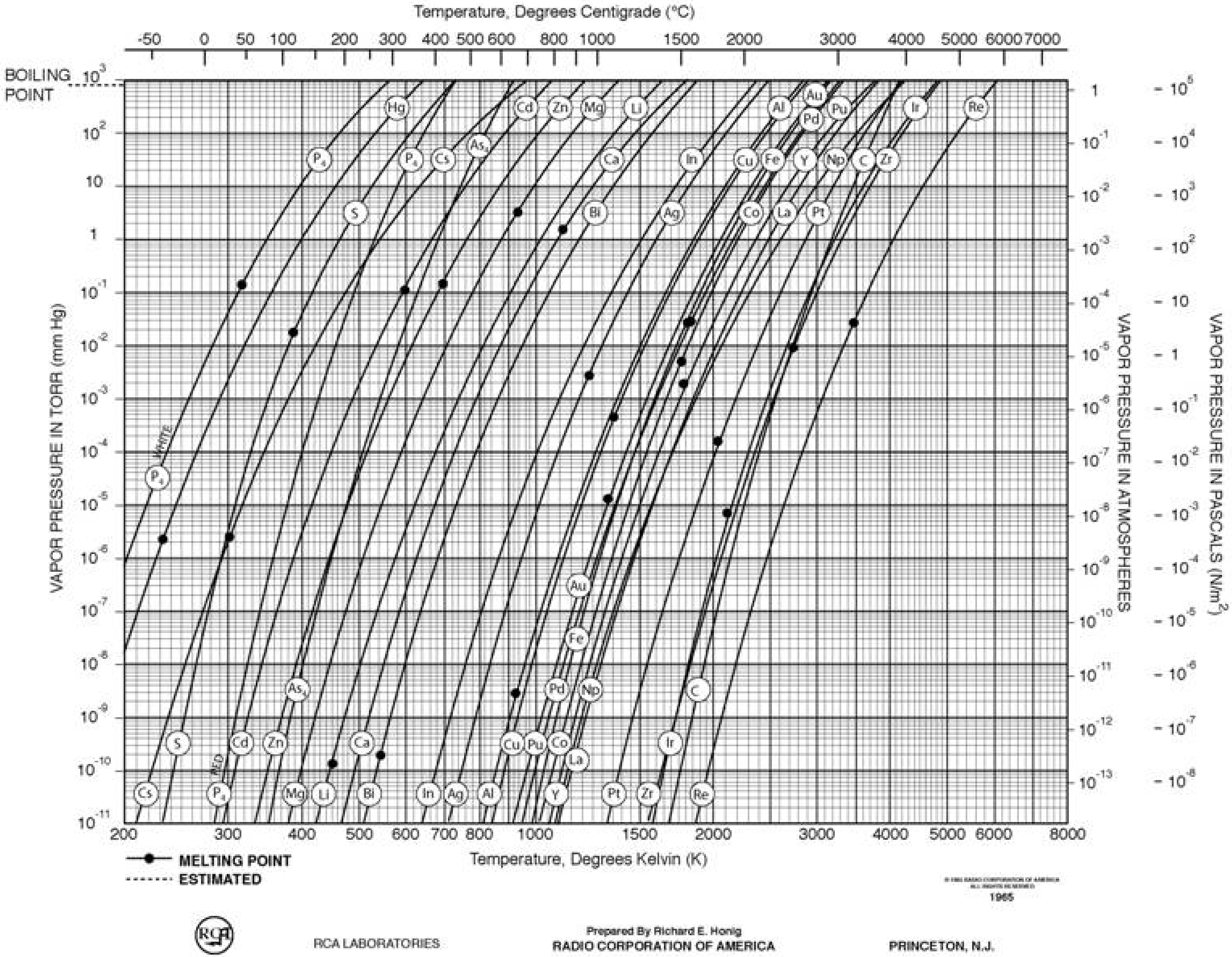
- the final pressure p_0 in a vacuum system depends on
  - the incoming gas flow q_{pV}
    - evaporation (vapour pressure) of liquid and solid materials
    - outgassing from surfaces and bulk material of the walls (desorption)
    - permeation through walls and sealing materials (e.g. Viton gaskets)
    - air leaks and virtual leaks
    - back-diffusion through mechanical pumps
  - the effective pumping speed S_{eff}
    - vacuum pumps (dominant)
    - adsorption on the surfaces inside the recipient
    - condensation
    - absorption

$$p_0 = \frac{q_{pV}}{S_{eff}}$$

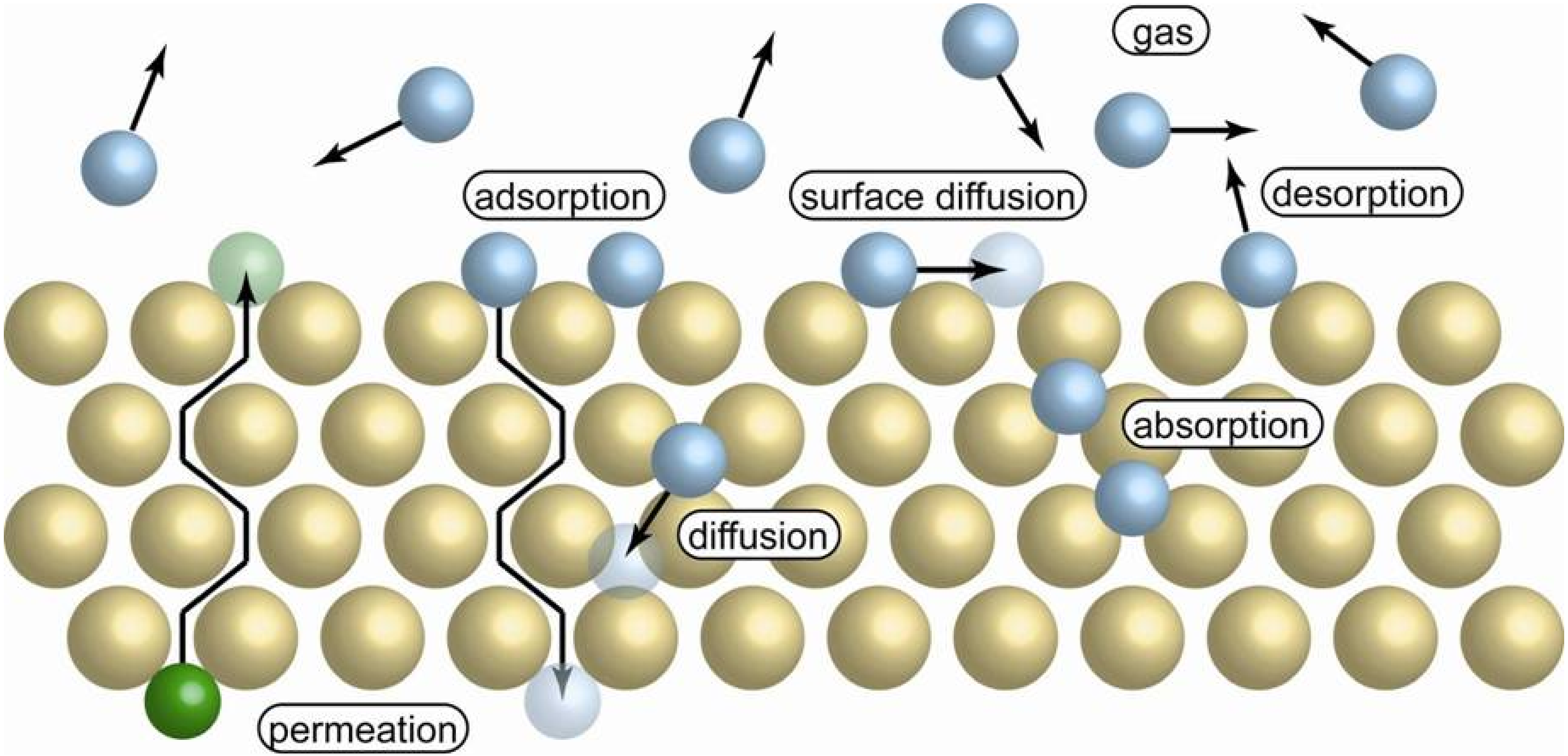
Vapour pressure

- at the ***equilibrium vapour pressure*** ***(EVP) condensation of gas and evaporation from the liquid or solid phase are equal***
- ***the EVP strongly depends on the temperature***
- ***materials inside a vacuum system should have a very low vapour pressure***
- ***lower pressures can only be reached after all material has evaporated and the gas has been pumped out***
- ***danger: high concentration can condensate in pump***
- ***example: freeze-drying***

Vapour pressure of metals



Adsorption, desorption & Co.



Outgassing = diffusion & desorption

- **outgassing is**
  - reduced by vakuum baking at high temperatures
  - reduced by long pumping times (but not as efficiently as baking)
  - the main limiting factor in UHV for the final pressure (hydrogen)
  - given in units of: mbar·l/s·cm^2
- **water**
  - after venting a thin layer of water remains on surfaces (humidity)
  - baking under vacuum above 185°C removes water
- **hydrogen**
  - hydrogen atoms are embedded in metal lattice
  - diffusion to and on surface, recombination to H_2, desorption
- **other materials**
  - e.g. hydrocarbons (oil, grease) from manufacturing on surfaces
  - thorough cleaning of the vacuum chamber necessary

Leakrate

- **normal leaks**
  - leak in gasket of a flange connection
  - leak in welding
  - leak in bulk material
  - permeation through solid materials
    - e.g. helium gas through Viton gasket
- **virtual leaks**
  - hidden, gas-filled cavity in bulk material with small channel into the vacuum chamber
  - very hard to find
  - caused by welding, manufacturing of steel, design errors, ...
- **detection of leaks**
  - helium leak-detector
  - mass spectrometer

Some units

- **Pressure (p):**

  1 mbar = 1 hPa = 100 Pa = 0.750 torr = 0.0145 psi
- **Conductance (C):**

  1 l/s = 3.6 m^3/h
- **Pumping speed (S):**

  1 l/s = 3.6 m^3/h
- **Gas flow, throughput at 0°C (q_{pV}):**

  1 mbar·l/s = 0.1 Pa·m^3/s = 1.333 Torr·l/s = 0.0181 sccm (at 20°C !)
- **Leakrate at 20°C (q_L):**

  1 mbar·l/s = 100 Pa·l/s = 0.1 W = 1.333 Torr·l/s = 0.0169 sccm
- **Outgassing, desorption (j):**

  1 mbar·l/s·cm^2 = 100 Pa·l/s·cm^2 = 1000 Pa·m/s = 1000 W/m^2

Always check the temperature when measuring a value

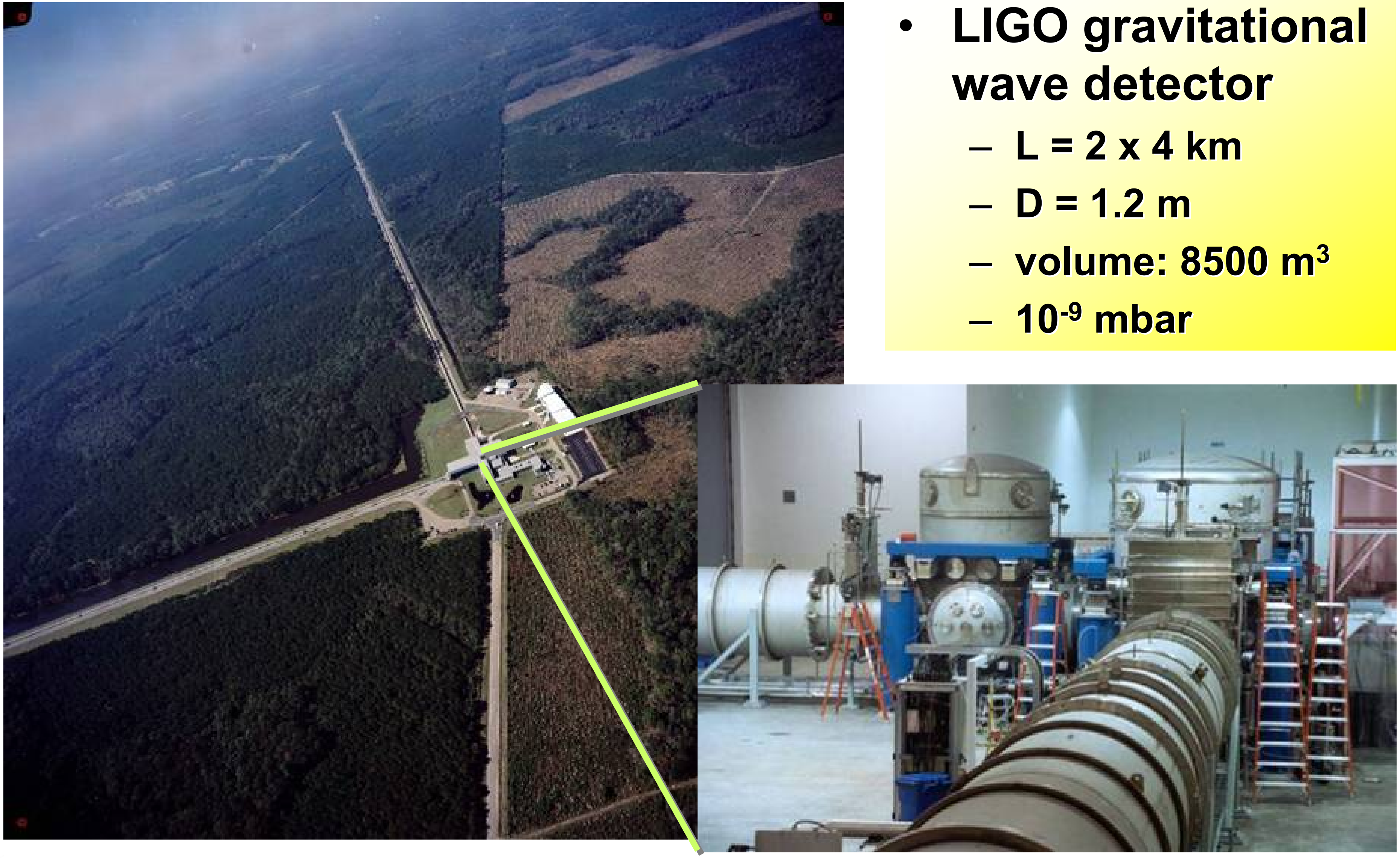
2. Vacuum chambers

- Examples of vacuum chambers
- Material selection
- Flanges and gaskets

Vacuum chambers

- **NASA Space Power Facility**
  - satellite tests
  - mars lander tests
  - tests for ISS ...
- **largest vacuum chamber**
  - diameter: 30.5 m (100 ft)
  - height: 37.2 m (122 ft)
- **vacuum system**
  - ultimate pressure: ~10^{-6} mbar
  - 48 oil diffusion pumps 700000 l/s
  - 10 cryopumps 600000 l/s
  - pump down: 8 – 12 h

Vacuum chambers



- **LIGO gravitational wave detector**
  - **L = 2 x 4 km**
  - **D = 1.2 m**
  - **volume: 8500 m^3**
  - **10^{-9} mbar**

Vacuum chambers

- **KATRIN main spectrometer**
  - **L = 24 m, D = 10 m, volume = 1240 m^3**
  - **ultimate pressure: ~ 10^{-11} mbar**
  - **pumping speed: ~ 1 000 000 l/s**

Materials for vacuum systems

- **main reqiurements:**
  - sufficient mechanical strength (10 t per 1 m^2 for Δp = 1000 mbar)
  - high gas tightness (low gas permeability, no leaks)
  - low intrinsic vapour pressure
  - low foreign gas content (outgassing)
  - good degassing properties (baking reduces outgassing)
  - high melting and boiling points (bake-out of a vacuum system)
  - clean surface
  - adopted thermal expansion behaviour between used materials
  - high thermal fatigue resistance
  - corrosion resistance

Some materials for vacuum systems

- metals
  - **stainless steel** (e.g. 304, 316 Ti, 316 L, 316 LN)
  - **aluminium** (no anodized coating !)
  - **copper** (OFHC: oxigen free, high conductivity)
  - **tungsten, titanium**, ...
  - **gold and silver** for seals and coating
  - **indium** for seals (melting point 156°C !)
- glass
  - borosilicate glass (Pyrex, Duran, ...)
  - quartz glass
- ceramics
  - Al_2O_3 ceramics (insulaters, el. feedthroughs)
- plastics (mainly for sealing purposes)
  - Viton
  - PTFE (Teflon)

Tab. 16.1 Overview of commonly used materials for vessels and seals as well as corresponding vacuum ranges.

Pressure and vacuum ranges		Application examples	Materials
10^2 mbar (10^4 Pa) 1 mbar (10^2 Pa)	Rough or low vacuum	Drying Degassing Distillation	Structural steel Stainless steel Ceramics Aluminum Elastomer seals
1 mbar (10^2 Pa) 10^{-3} mbar (10^{-1} Pa)	Medium or fine vacuum	Vacuum process technology	Aluminum Stainless steel Ceramics Elastomer seals
10^{-3} mbar (10^{-1} Pa) 10^{-7} mbar (10^{-5} Pa)	High vacuum	Coating technology Molecular beam epitaxy	Stainless steel Aluminum Al_2O_3 ceramic Elastomer seals Tantalum, molybdenum
10^{-8} mbar (10^{-6} Pa) 10^{-12} mbar (10^{-10} Pa)	Ultrahigh vacuum	Deposition of high-purity coatings Materials analysis Accelerator technology	Stainless steel Aluminum Al_2O_3 ceramic Copper seals Special seals Gold, silver, tantalum, molybdenum

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Welding of vacuum components

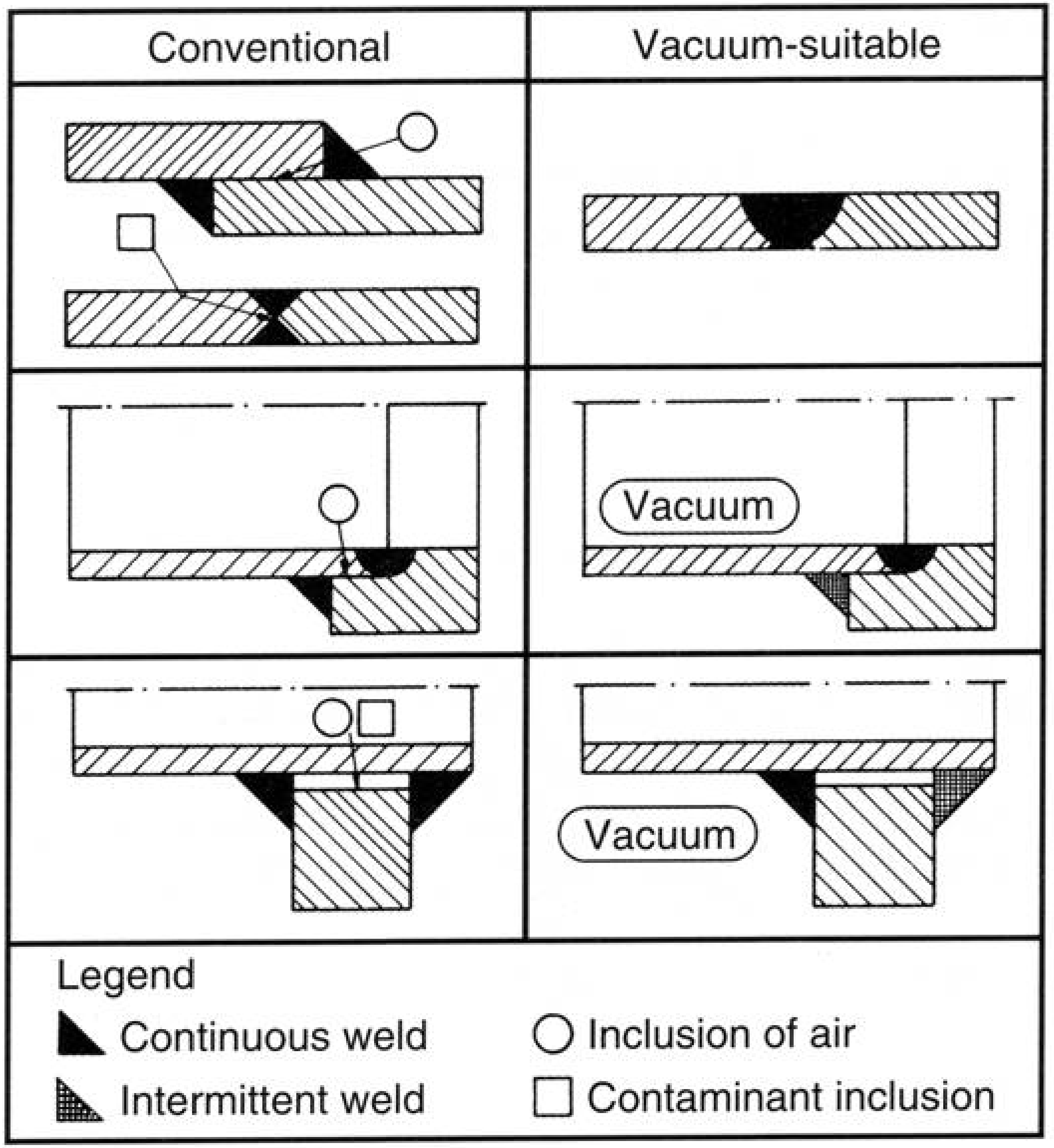

Fig. 17.1 Comparison of conventional welded assemblies and joints suitable for vacuum applications [1].

avoid cavities with trapped air

sealing weld is on the inside

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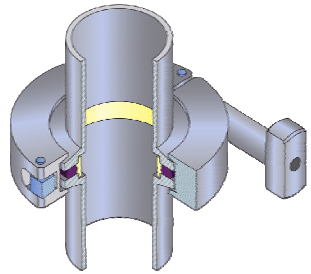
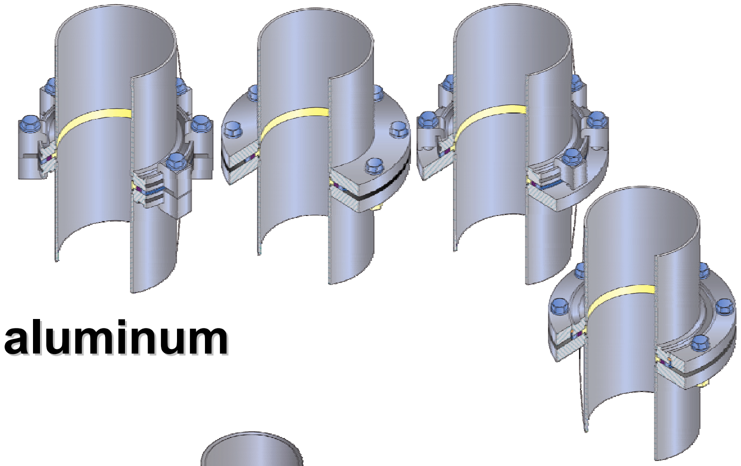
Standard flange connections

- **KF flange**
  - high vacuum (p > 10^{-7} mbar)
  - temperature range: 0°C ... 120/180°C
  - gaskets: elastomeric o-rings (Viton, ...), aluminum
  - inner diameter: 10mm ... 50 mm

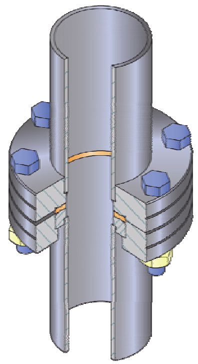


- **ISO flange (ISO-K and ISO-F)**
  - high vacuum (p > 10^{-7} mbar)
  - temperature range: 0°C ... 120/180°C
  - gaskets: elastomeric o-rings (Viton, ...), aluminum
  - inner diameter: 63 mm ... 630 mm



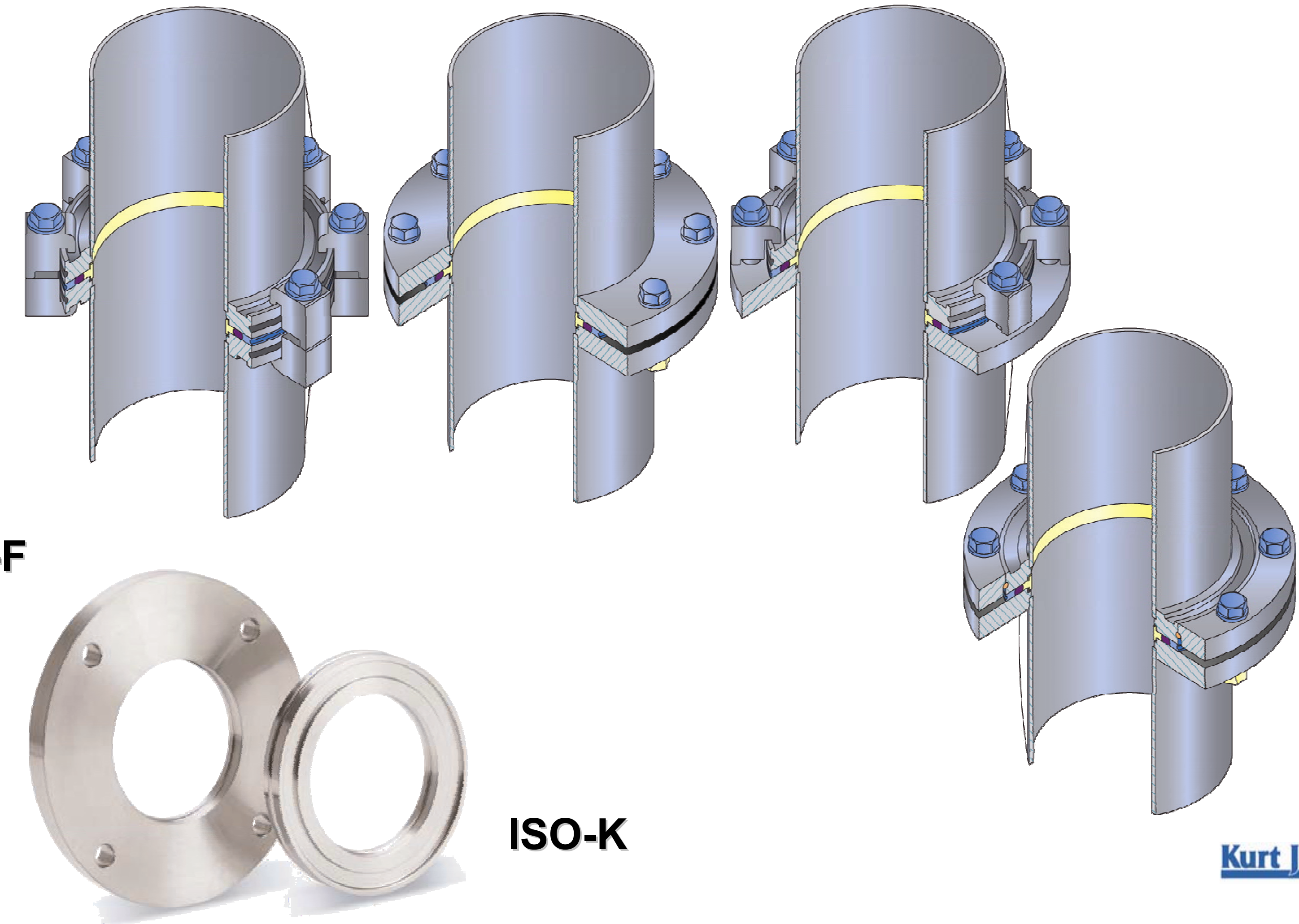
Kurt J. Lesker Company

- **CF-(ConFlat™)-Flansch**
  - UHV (p < 10^{-7} mbar)
  - Temperatur: -196°C ... 450°C
  - gaskets: OHFC copper rings
  - inner diameter: 16 mm ... 320 mm



KF-flange

ISO-flange



ISO-F

ISO-K

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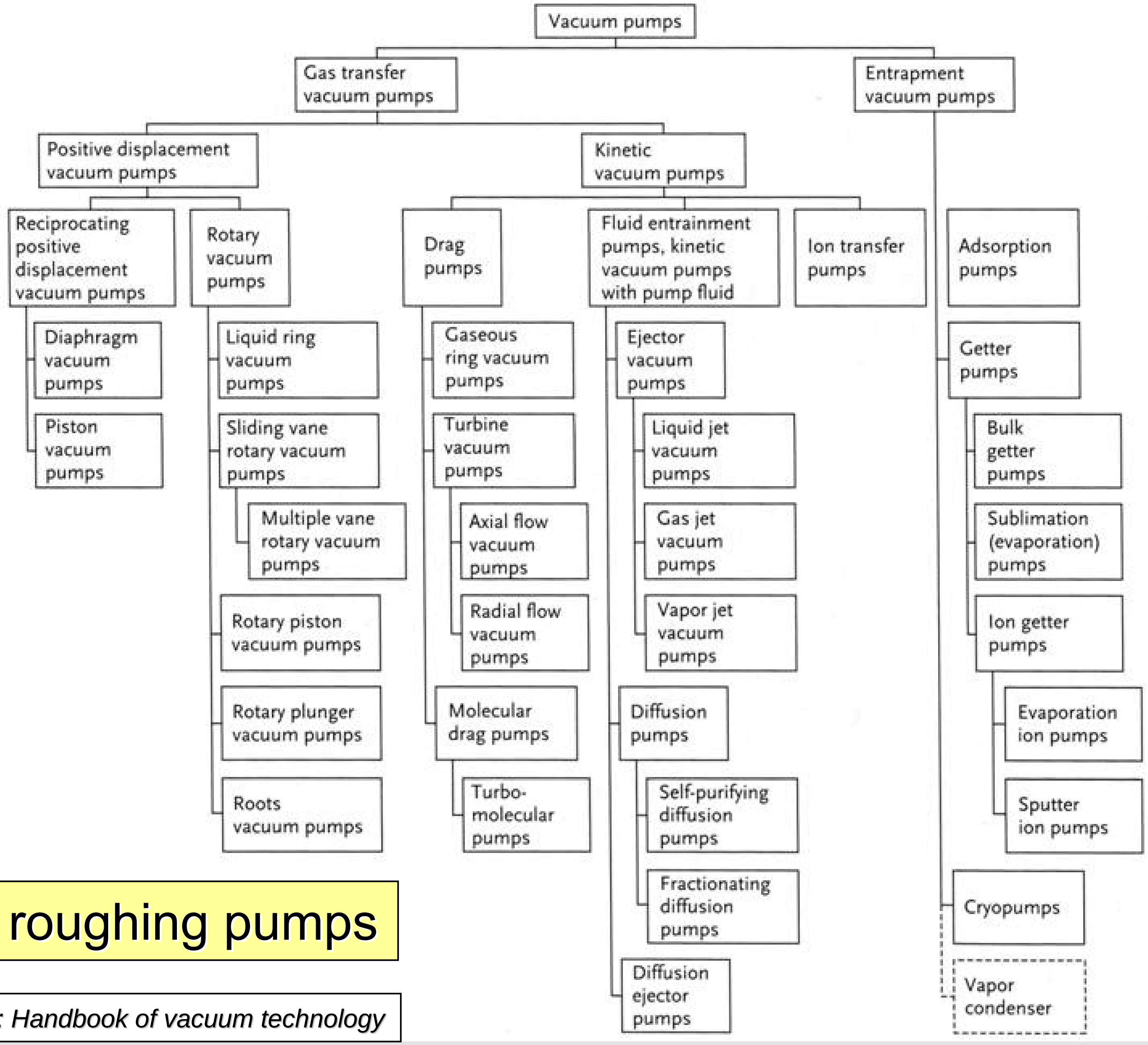
CF-(ConFlat^{TM}) flange

3. Vacuum pumps

- **Pump types**
- **Roughing pumps**
- **High and ultra-high vacuum pumps**
  - **turbo-molecular pumps**
  - **getter pumps**
  - **oil diffusion pumps**
  - **cryo pumps**



roughing pumps

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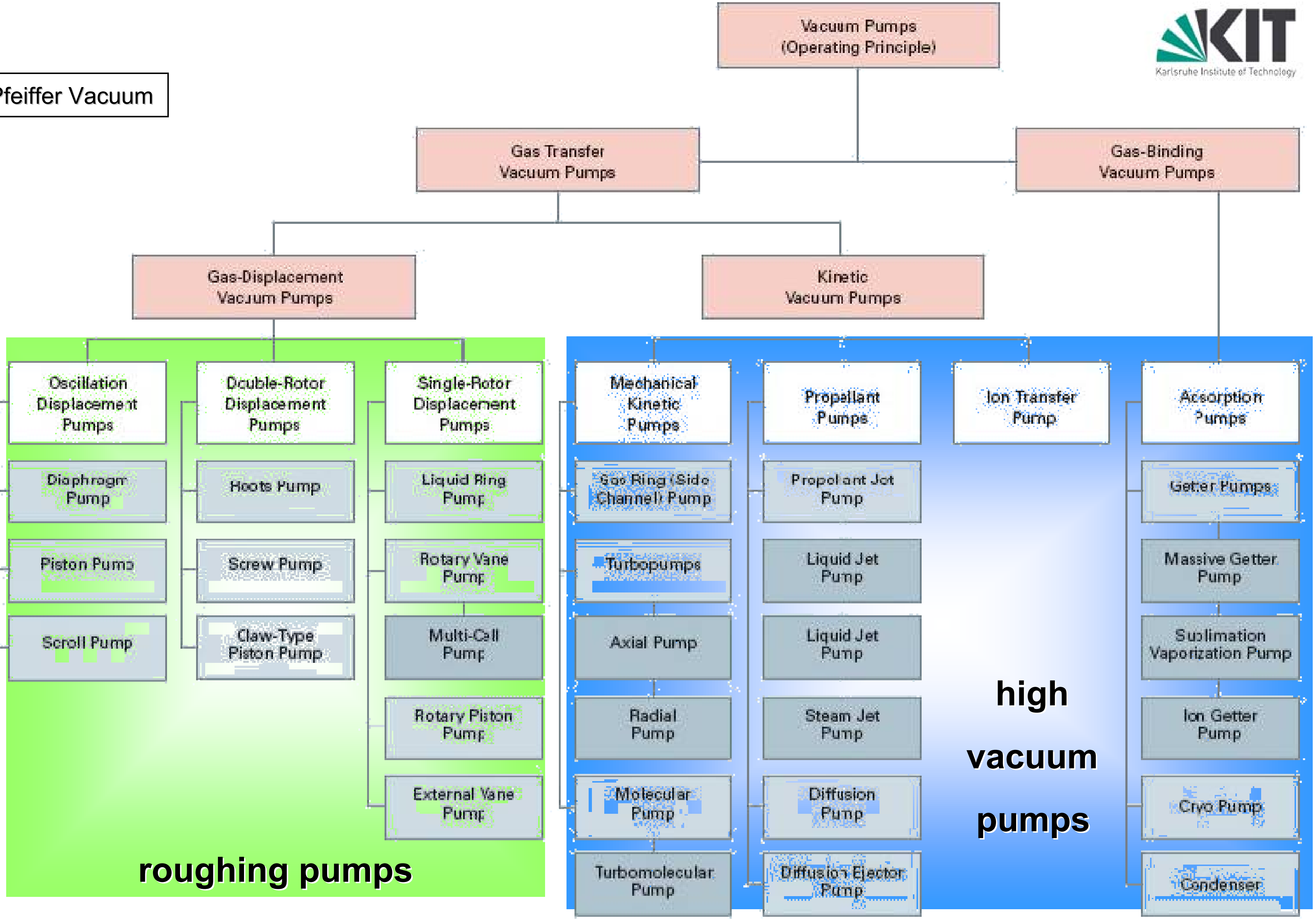
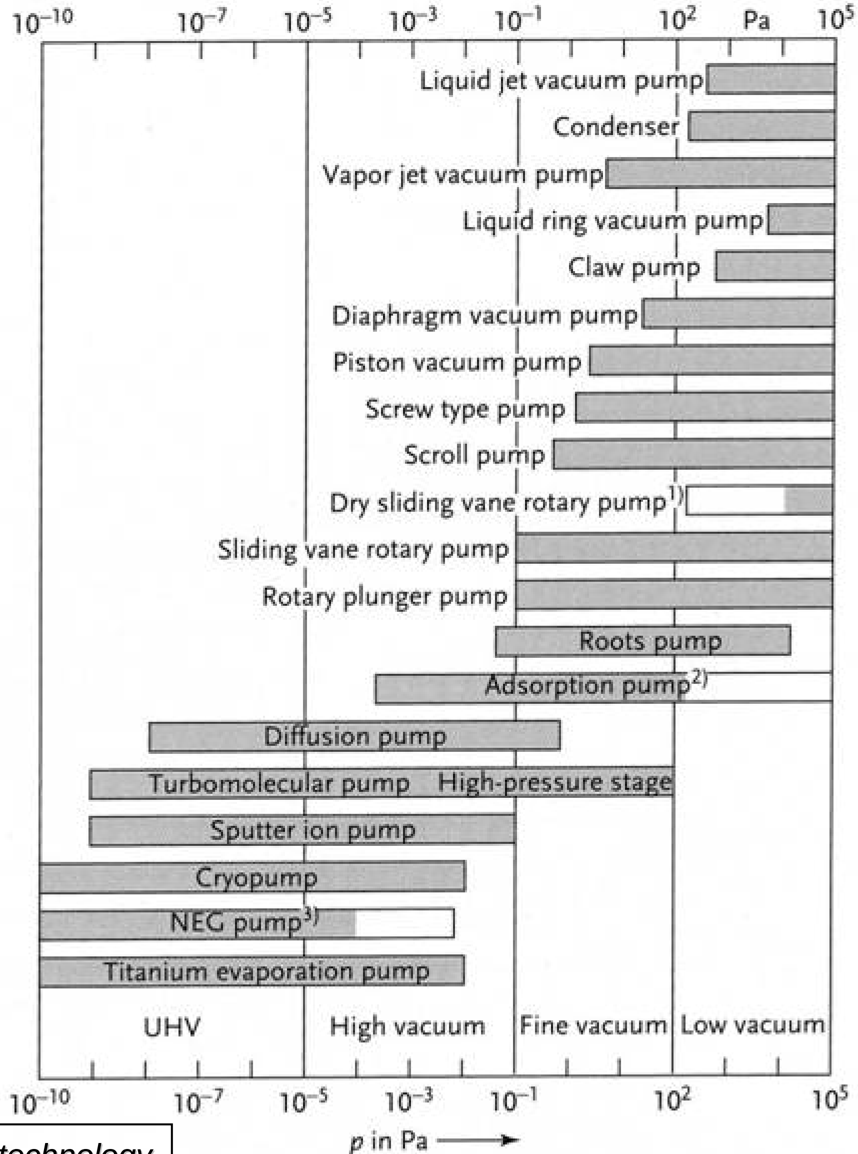
Pfeiffer Vacuum



Pressure range for different pumps



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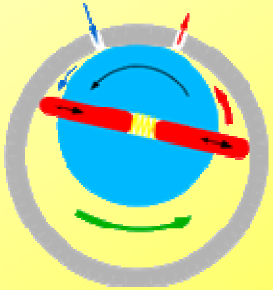
Roughing pumps

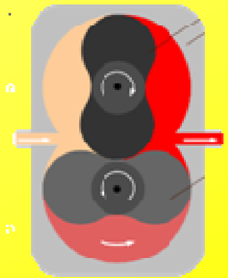
- **roughing pumps remove most of the gas**
  - pmin >10^{-3} mbar (depends on pump type)
  - needed as fore-line pump for HV and UHV pumps
- **compressed vapours (e.g. water) can condensate in the pump**
  - can damage the pump
  - condensation avoided by gas ballast valve
    which adds air to last pumping stage
- **most common pumps: rotary vane pump (oil sealed)**



- **dry pumps are used for UHV to avoid back streaming oil vapours**
  - sroll pump
  - screw pump
  - diaphragm pump
  - piston pump
  - multi-roots pump

Wikipedia.org

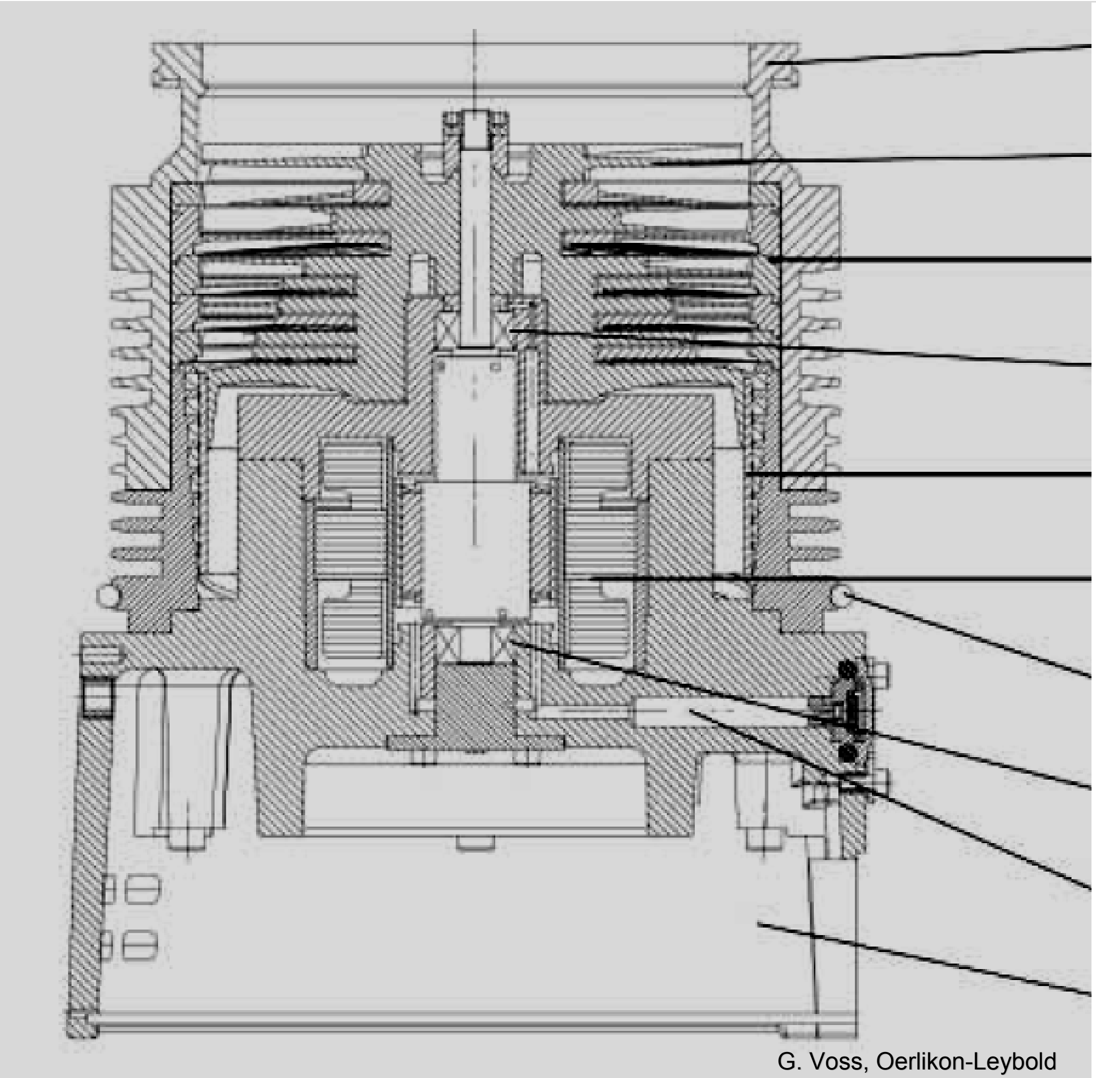
- **roots blower: additianal stage on top of roughing pump**
  - increas pumping speed and compression ratio



Turbo-molecular pumps

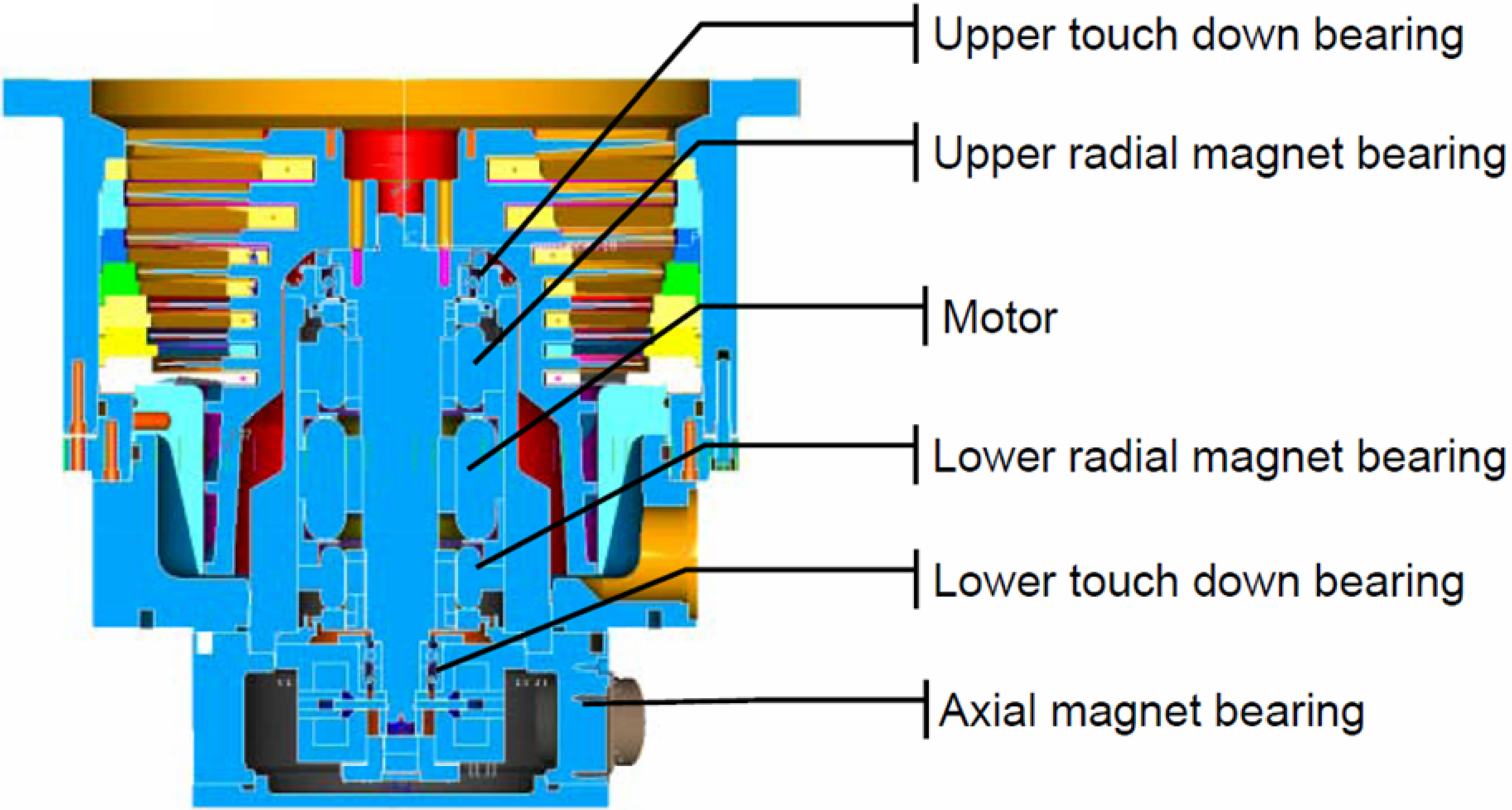
- **Turbo-molecular pumps (TMP) are designed for HV and UHV**
  - research (accelerators, electron-microscopes, fusion reactors,...)
  - manufacturing (semi-conductors, coating, ...)
- **minimum pressure: ~10^{-10} mbar**
  - depends on fore pressure (back-diffusion ↔ compression ratio)
  - compression ratio depends on gas type and throughput
  - cascaded TMPs can reach lower pressure (larger H_2 compression)
  - cleanliness: outgassing from rotor can limit pressure
- **maximum fore pressure**
  - standard TMP: < 10-1 mbar
  - widerange TMP: < few mbar (Holweck stage or similar stage)
- **operation of TMPs**
  - rotor blade tips move with speed of sound
  - large torque on housing in case of rotor crash
  - TMP has to be connected to heavy recipient or fixed to the ground

Turbo-molecular pumps



- high vacuum flange
- rotor: turbo-molecular stage
- stator
- ceramic ball bearing
- rotor: Holweck stage
- motor
- water cooling
- ceramic ball bearing
- purge gas chanel
- space for frequency converter (pump controller)

„Dry“ TMP with magnetic bearings



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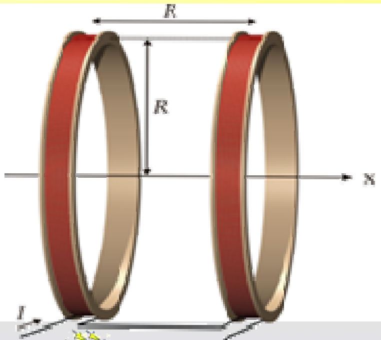
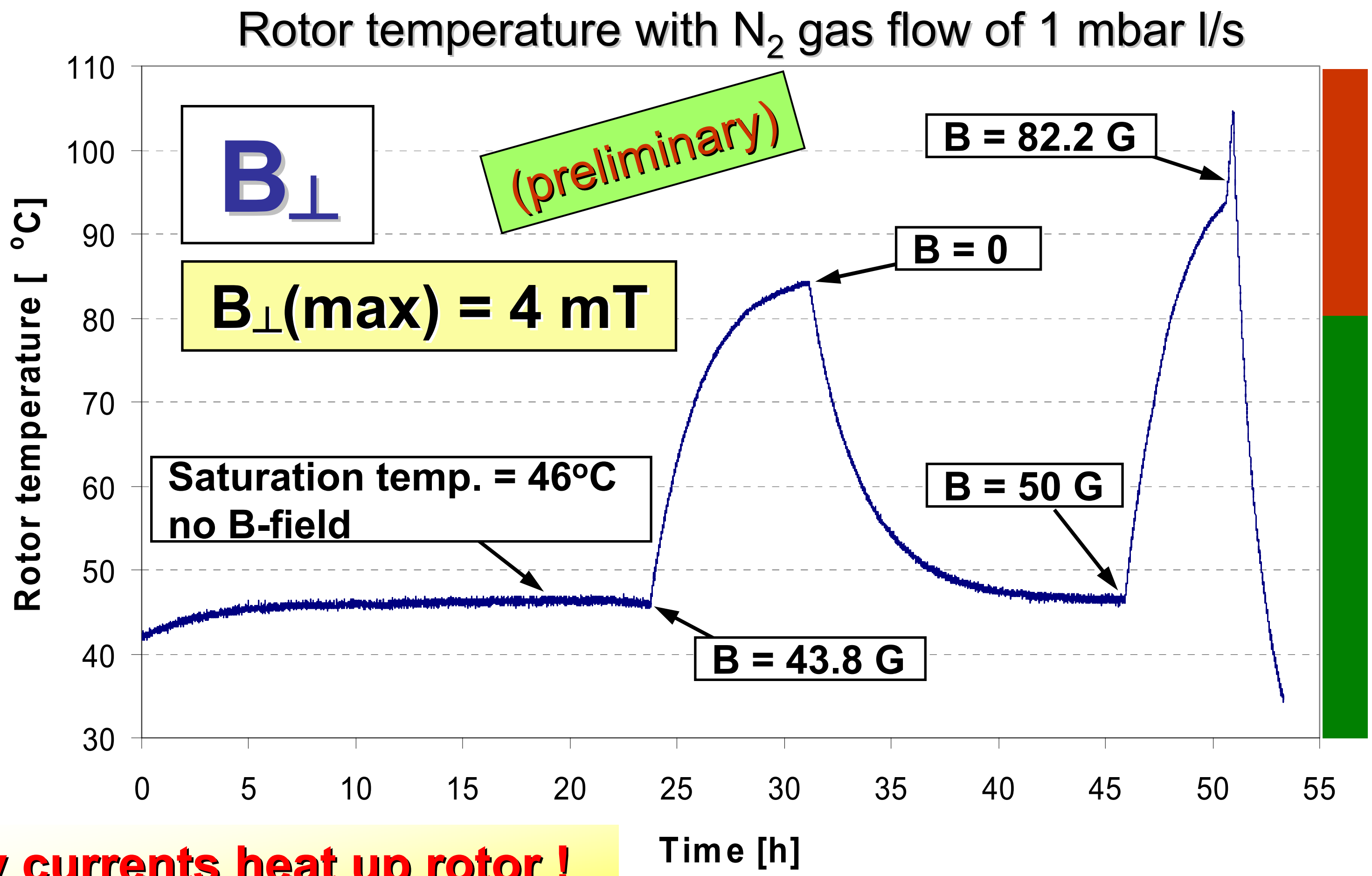
Magnetic fields and turbo-pumps

- **strong magnetic fields in source and transport section**
  - super-conducting solenoids: B_{max} = 5.6 T
- **main pumps: 16 turbo-molecular pumps (MAG W 2800)**
  - eddy currents heat rotor (T_{max} < 80°C for long term operation)
  - pumps close to beam-line to reduce loss of conductance
- **test programme**
  - measure rotor temperature of running pump with IR camera
  - different orientations of B-field relative to rotor axis ($B_{\parallel}$, $B_{\perp}$)
  - temperature vs. B-field ($0 < B_{\parallel} < 25$ mT ; $0 < B_{\perp} < 11$ mT)
  - influence of different gas loads



B-field: Helmholtz coils
Temperature: pyrometer

TMP in a magnetic field
(rotor axis perpendicular to field)



- Eddy currents heat up rotor !
- Rotor crash at ~ 120°C

Getter pumps (NEG)

- **NEG = Non Evaporable Getter**
  - sintered fine metal powder
  - properties depend on composition of alloy
  - metals: titanium, vanadium, zirconium, iron,...
  - St707: 70% Zr, 25% V, 5% Fe
  - activation by heating to appropriate temperature (St707: 400°C)

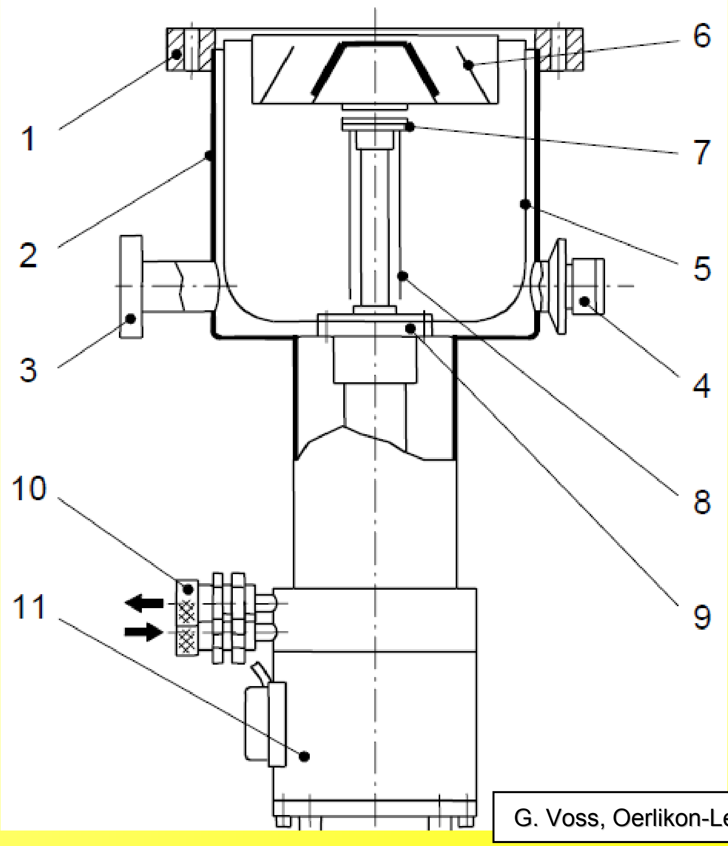
SAES St707 strips

- **getter pumps bind gas molecules on surface**
  - physisorption: reversible by heating of the getter
  - chemsorption: irreversible
  - gas can diffuse into the getter material (bulk getter pump)
  - pumping speed depends strongly on gas type (no noble gas)
- **NEG products**
  - getter strips: NEG powder on 30mm wide constantan carrier strips
  - getter pallets, getter rings, sintered bulk getters, ...
  - NEG pumps with heating, housing and CF flange (SAES)

Cryo-pumps

- pumping process: condensation, cryosorption
- ultimate pressure depends on gas and temperature (UHV)
- regular re-generation of pump (heating)

1. high vacuum flange
2. pump housing
3. fore-vacuum flange
4. safety valve
5. radiation shield
6. baffle
7. second stage of cold head
8. pumping surface
9. first stage of the cold head
10. helium gas connection
11. cold head motor



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Cryo-pumps

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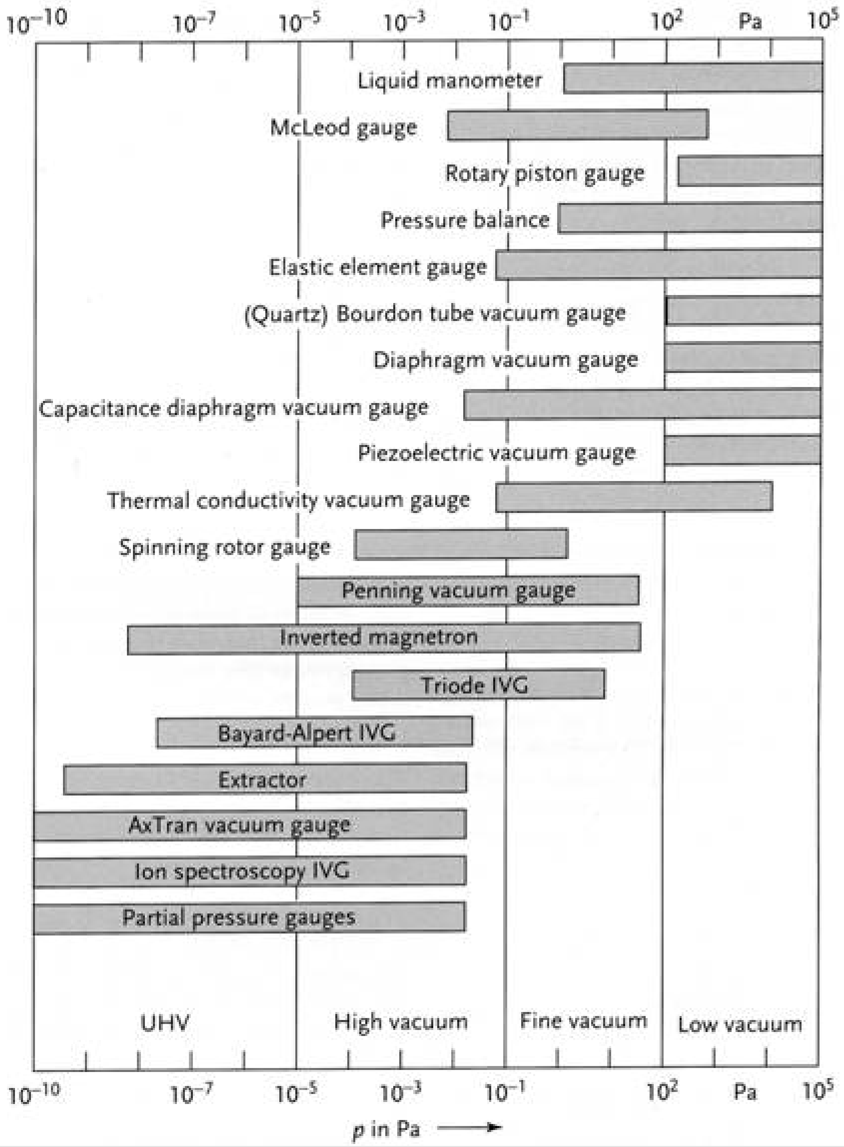
4. Vacuum measurement

- **Pressure gauges**
  - **fore vacuum**
  - **high and ultra-high vacuum**
  - **wide range gauges**
- **RGA (residual gas analyzer)**
- **Leak detection**

Pressure gauges



- **direct measurement**
  - mechanical gauges
  - low and medium vacuum
  - gas independent signal
- **indirect measurement**
  - thermal conductivity
  - ionization (<10^{-2} mbar)
  - gas dependent signal
- **wide-range gauge**
  - 1000 mbar ... UHV
  - 2 gauges in one housing
  - automatic switching
- **RGA (residual gas analyzer)**
  - partial pressure

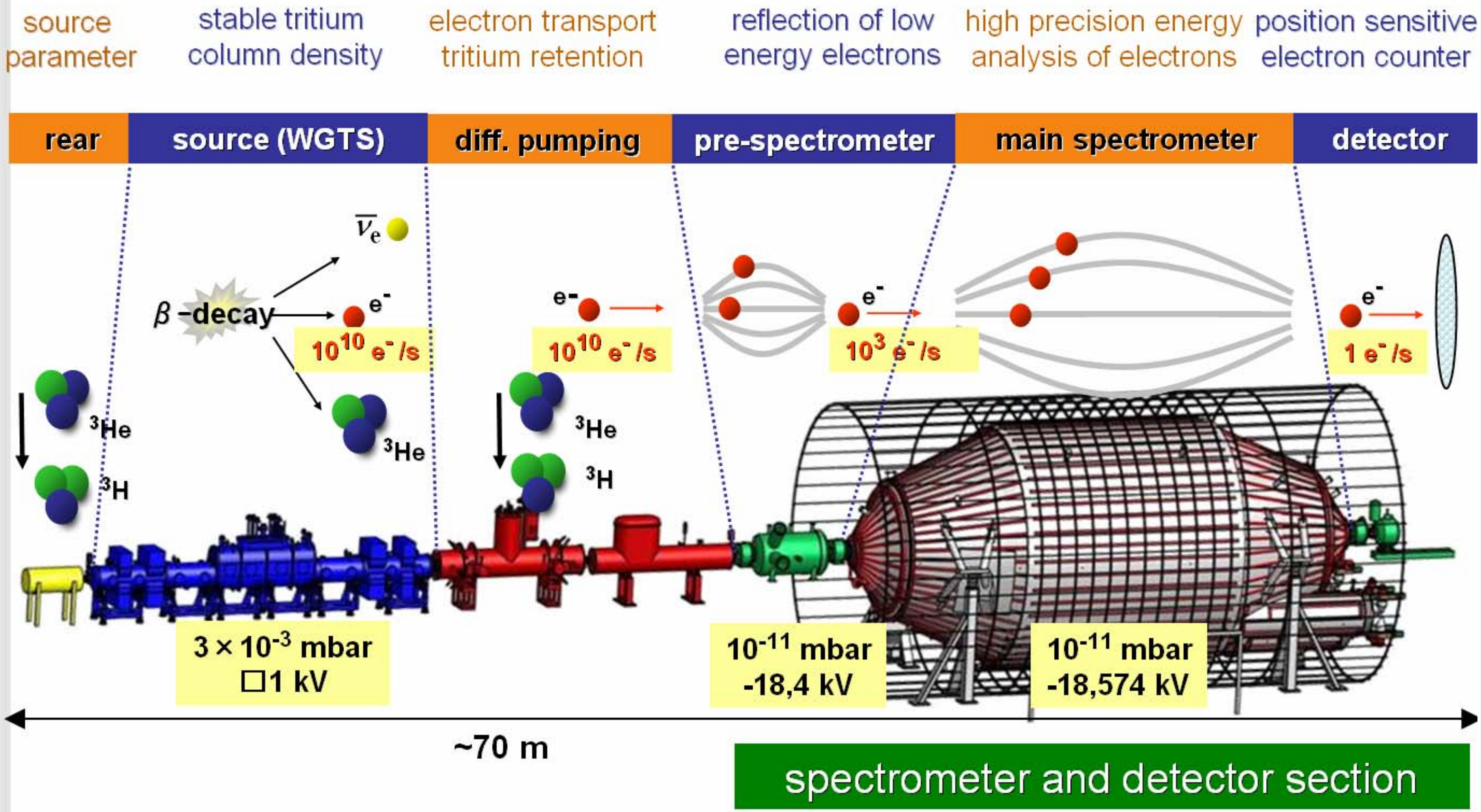
Ionization gauges

- **measured signal (10^{-2} ... 10^{-12} mbar)**
  - ionization of gas molecules by electrons (~ 100 eV)
  - signal (ion current) proportional to **number density**, not pressure **!!!**
  - standard gauge calibration for N_2 at 20°C
  - pressure reading depends on temperature and gas species (different ionization cross sections)
- **crossed electric and magnetic fields**
  - magnetic field extends path of electrons, more ionization
  - permanent gas discharge
  - penning gauge
  - inverted magnetron gauge
- **electron emitting cathode (hot cathode gauge)**
  - hot filament emits electrons
  - Bayert-Alpert gauge →
  - Extractor gauge (10^{-5} - 10^{-12} mbar)

5. Example: KATRIN spectrometer

- Prototype measurements
- Design of the vacuum chamber
- Vacuum system
- Manufacturing and surface preparation
- Bake-out
- Outgassing rates

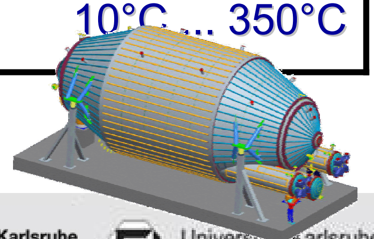
KATRIN main components



The electro-static tandem-spectrometer

KIT Karlsruhe Institute of Technology

general properties	pre-spec.	main spec.
length:	3.4 m	23.4 m
diameter (defines energy resolution):	1.7 m	9.8 m
weight:	4 to.	200 to
surface:	25 m^2	690 m^2
volume:	8.5 m^3	1240 m^3
material (stainless steel):	316LN	316LN
high voltage (vessel on insulators):	18.3 kV	18.4 – 18.6 kV
magnetic field (s.c. solenoids): earth field correction:	both ends no	both ends 12.6 m alu. coils
vacuum (TMP + NEG pumps):	10^{-11} mbar	10^{-11} mbar
temperature	-20°C ... 350°C	10°C ... 350°C



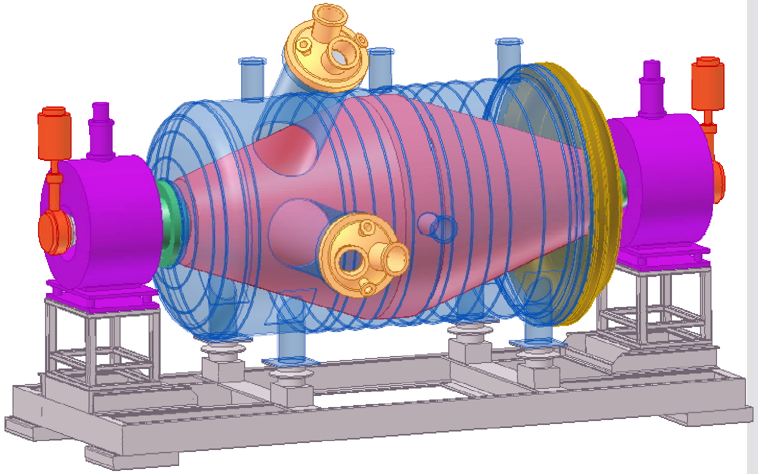
Vacuum prototype programme

- **surface preparation of 316LN recipients**
  - grinding, cleaning, electro-polishing
  - vakuum baking at up to 350°C
  - outgassing as function of temperature
- **flange design (DN 500 and DN1700)**
  - differentially pumped double sealing
  - spring loaded metal gaskets
  - handling of the gaskets
  - temperature cycles (-20°C...+350°C)
- **pumping scheme**
  - NEG pump (SEAS ST707 NEG strips)
  - cascaded TMPs
  - dry fore-pump

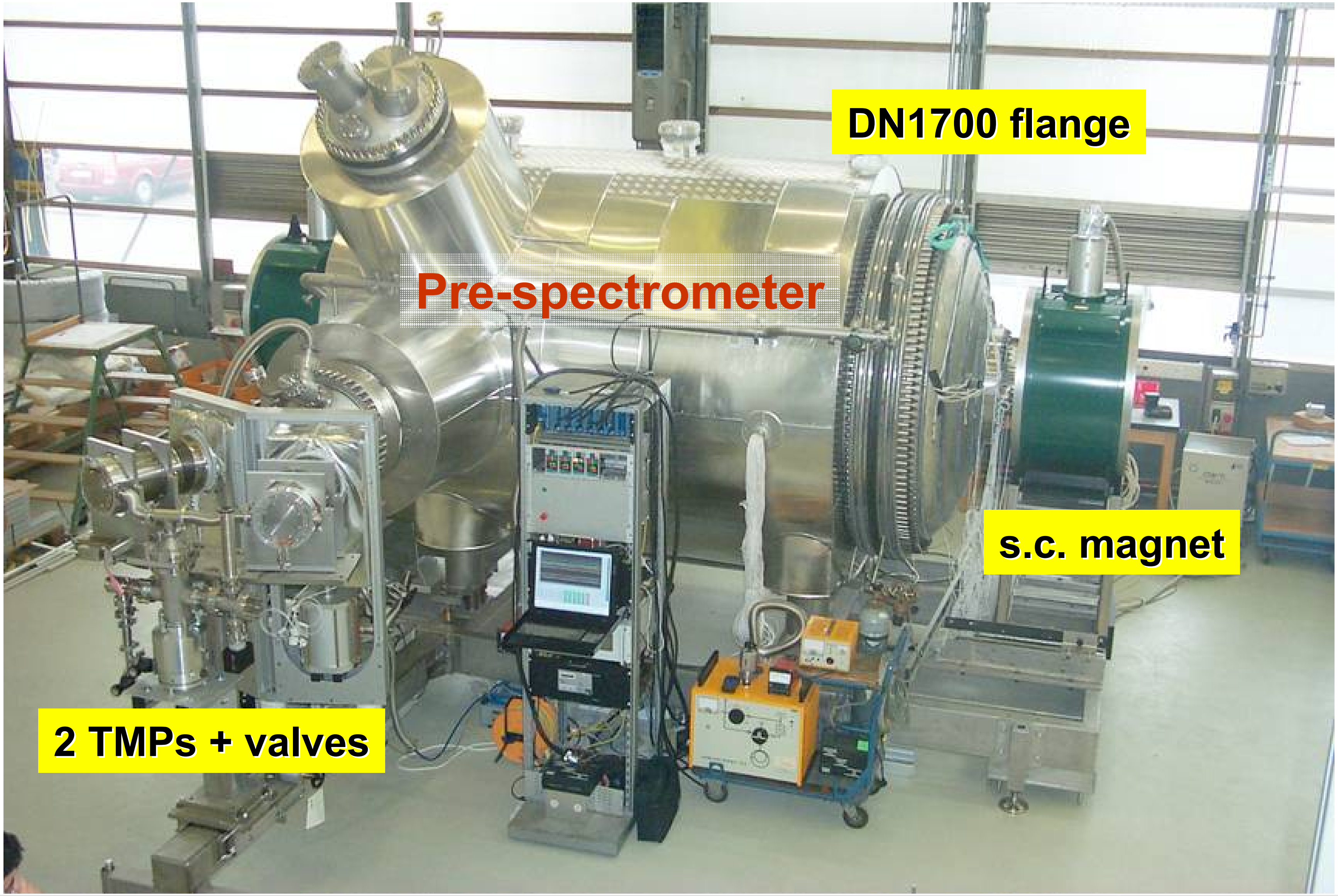
Prototypes for the vacuum system of the main spectrometer

- **Test Recipient (2002/3)**
  - Volume: 0.3 m³, surface: 2.5 m²
  - Material 316LN
  - Cascaded TMPs: 800l/s + 70l/s
  - 10m NEG (SAES ST707 strips)
  - final pressure ≈ 10^{-11} mbar

- **Pre-Spectrometer (2003/4)**
  - Volume: 8.5 m³, surface: 25 m²
  - Material: 316LN
  - Cascaded TMPs: 2x 800l/s + 500l/s
  - 90m NEG (SAES ST707 strips)

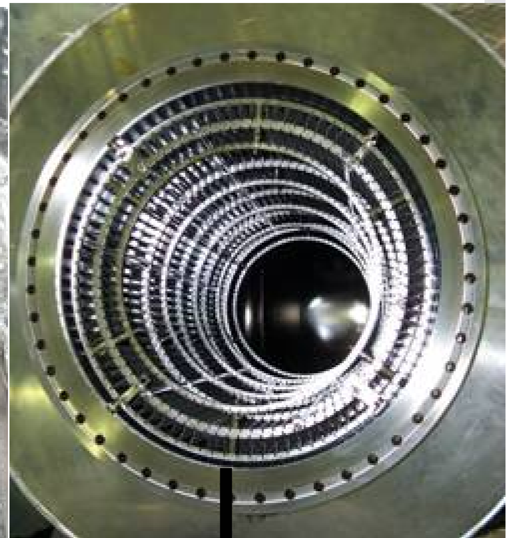


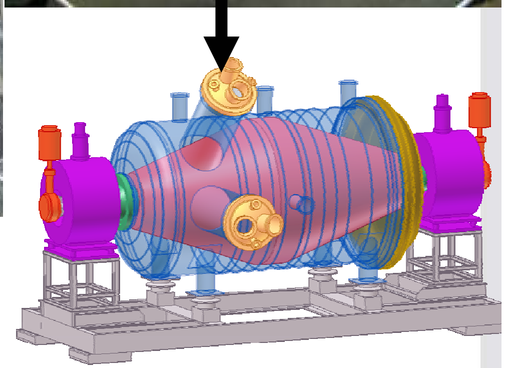
Pre-Spectrometer UHV Measurements



Installation of the NEG pump in the pre-spectrometer

(90 m of ST707 strips)





final pressure at 20°C: ≈ 10^{-11} mbar

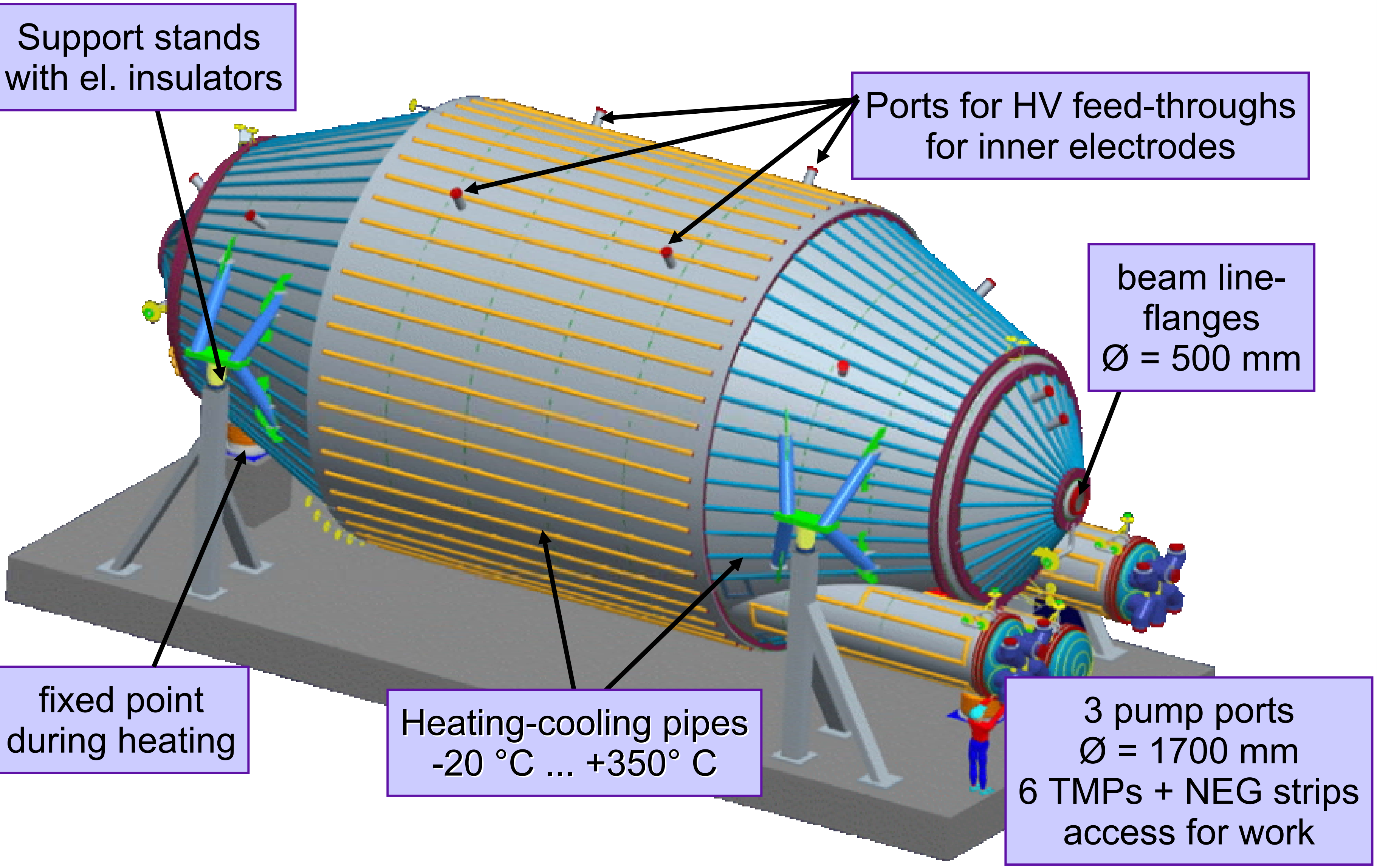
Conclusions from the pre-spectrometer

- TMPs + NEG can reach 10^{-11} mbar
- 25000 l/s pumping speed for 90 m of getter:
  - pumping speed ≈ 280 l/s m(NEG)
  - comparison with simulation: sticking coeff. ≈ 2%
- Acceptable outgassing at 20°C: ≈ 10^{-12} mbar l/s cm²
- Cooling to -20°C reduced outgassing by a factor of 8
  (but final pressure limited by TMPs and gauges)

(since 2005: electro-magnetic tests with the pre-spectrometer)

- Bornschein, Day, Habermehl, Luo, Wolf, *Hydrogen in matter 2005*, AIP conf. proc. 837 (2006) 200-209
- Luo, Bornschein, Day, Wolf, Vacuum 81 (2007) 777-781
- Day, Luo, Conte, Bonucci, Manini , J. Vac. Sci. Technol. A25(4), (2007) 824-830

Design of the main spectrometer

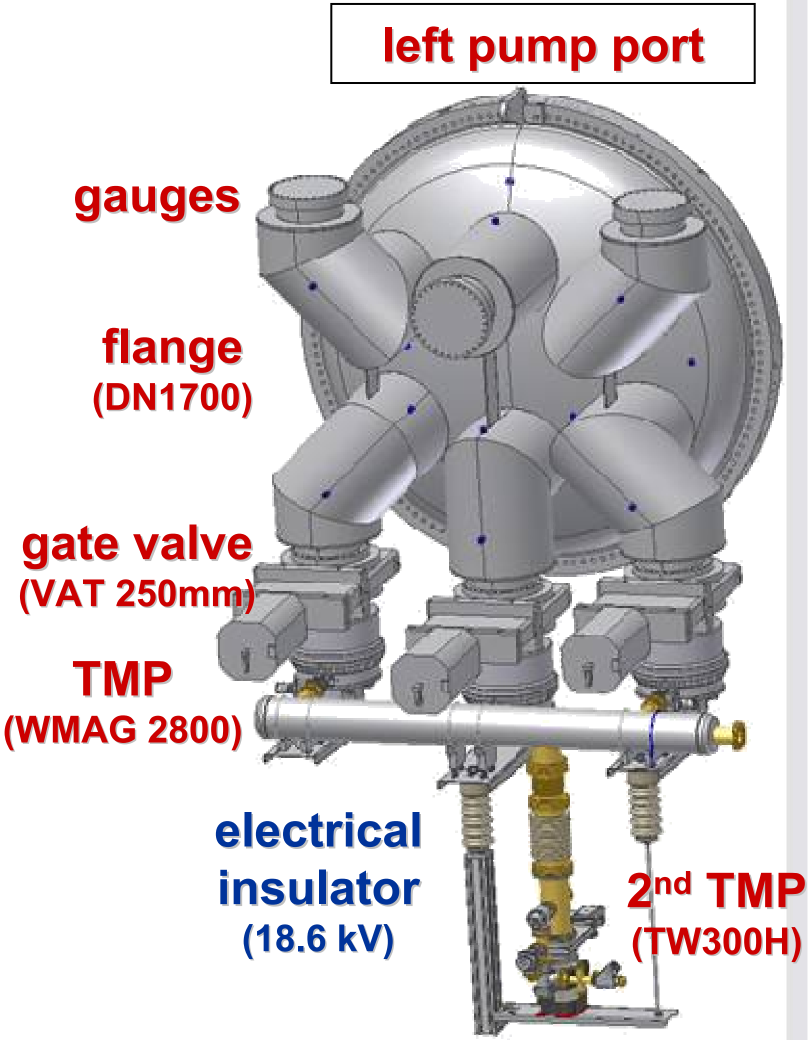


Requirements for the vacuum system

- **final pressure:** < 10^{-11} mbar
- **outgassing:** < 10^{-12} mbar l/s cm²   (innere surface: *690 m²*)
- **effective pumping speed**
  - **3000m getter strips: 1 000 000 l/s (H_2 and other active gases)**
  - **6 turbo-molecular pumps: 8 400 l/s (all gases)**
- **max. allowed gasload**
  - **H_2 < 10^{-5} mbar l/s**
    - **outgassing vessel: <6 x 10^{-6} mbar l/s**
    - **outgassing electrodes: <3 x 10^{-6} mbar l/s**
    - **6 TMPs, beamline, gauges: < 10^{-6} mbar l/s**
  - **non-getterable gases < 10^{-7} mbar l/s (hydrocarbons, noble gases,...)**

Cascaded TMPs and getter pumps

- **6 MAG W 2800 on 2 pump ports**
  - **effektive pumping speed:**
    - N_2: 1400 l/s * 6 = 8400 l/s
    - H_2: 1700 l/s * 6 = 10200 l/s
- **2 TW300H in intermediate vacuum**
    - N_2: 240 l/s
    - H_2: 150 l/s
- **2 ACP28 dry fore-pumps**
    - 28 m³/h
- **Getter:**
    - 3000 m St707 NEG strips (10^6 l/s)
- **Roughing pump: SP630**
    - 630 m³/h

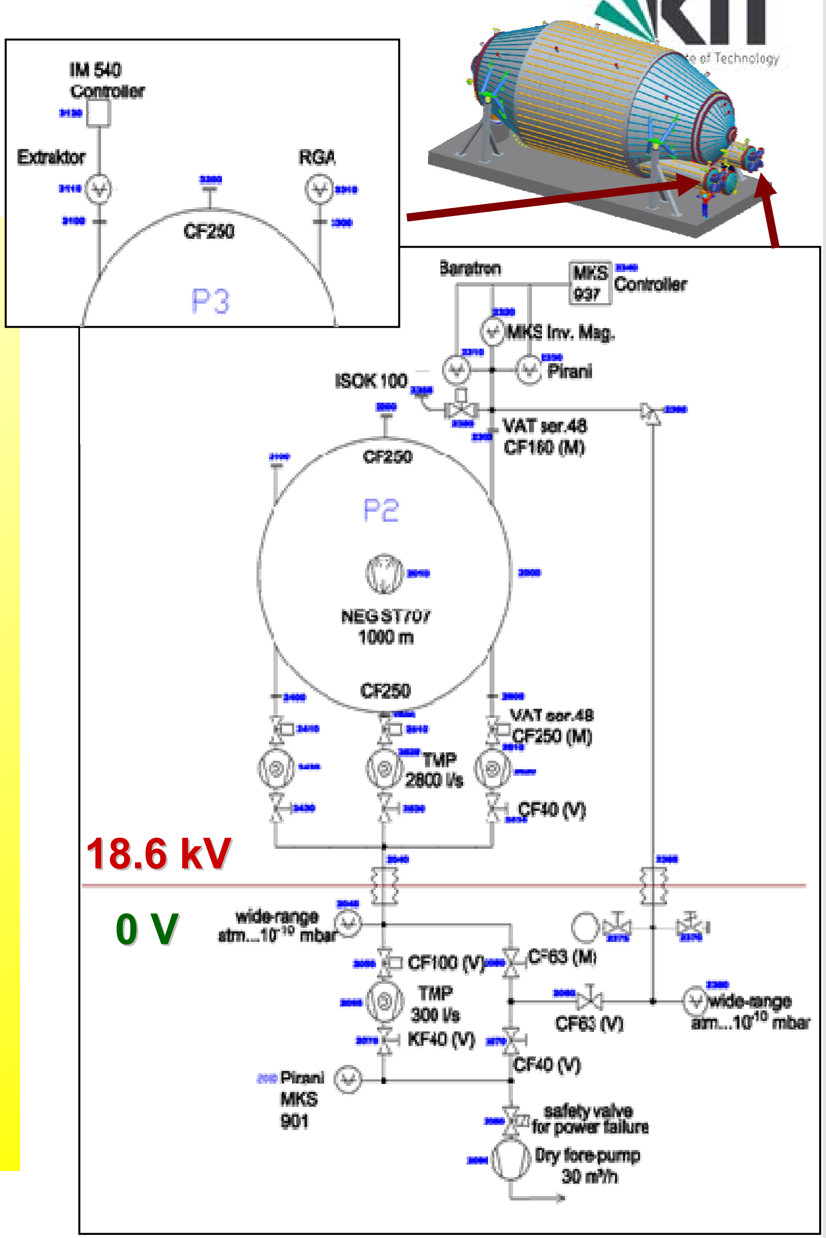


Vacuum gauges

- **UHV:**
  - MKS Pirani (pump-down and venting)
  - MKS Baratron
  - MKS inv. Magnetron (1 x 10^{-11} mbar)
  - Leybold Extraktor (1 x 10^{-12} mbar)
  - MKS mass spectrometer

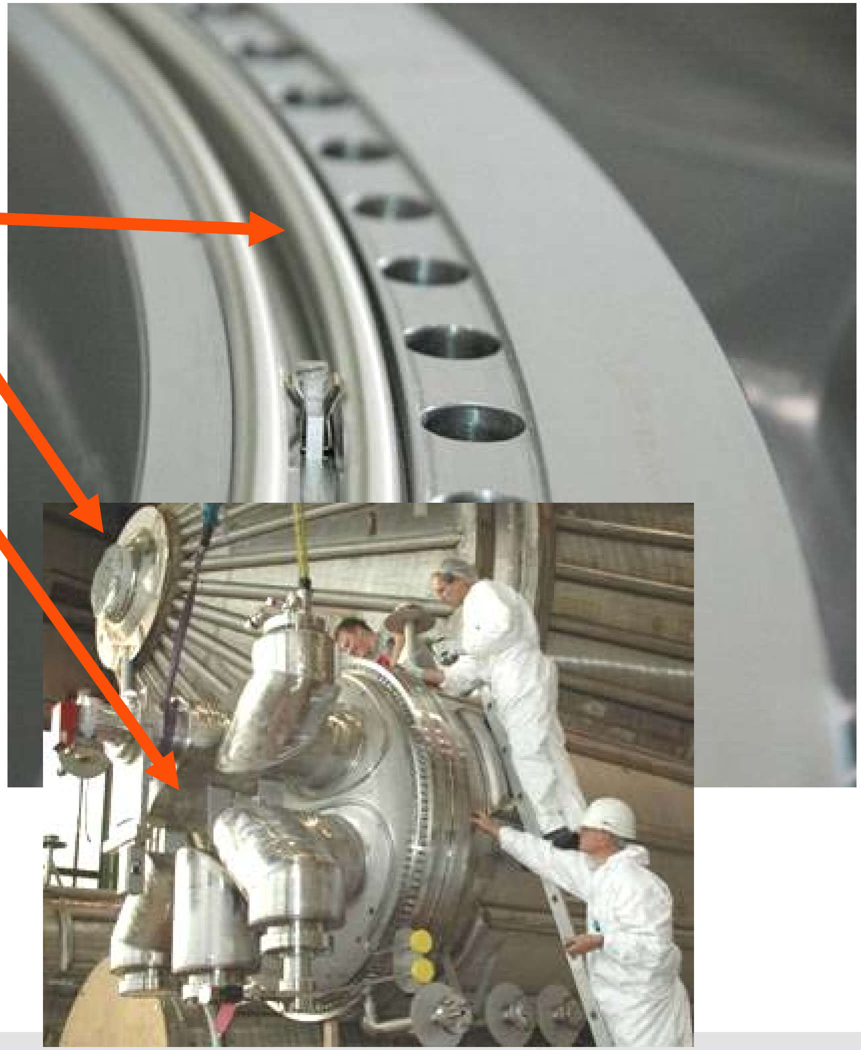
- **intermediate vacuum:**
  - MKS 999 (atm. – 5 x 10^{-10} mbar)
  - Atmion (atm. – 1 x 10^{-10} mbar)

- **fore-vacuum:**
  - MKS 901 (atm. – 1 x 10^{-5} mbar)



Flanges and Gaskets

- **UHV:**
  - CF gaskets up to 250 mm
  - HTMS double gaskets:
    - 500 mm ground-electrodes
    - 1700 mm pump ports
  - all gaskets bakable at 350°C
- **intermediate vacuum:**
  - CF gaskets
- **fore-vacuum:**
  - KF O-rings (Viton)
  - ISO K for pump-down and venting



Manufacturing of the main spectrometer

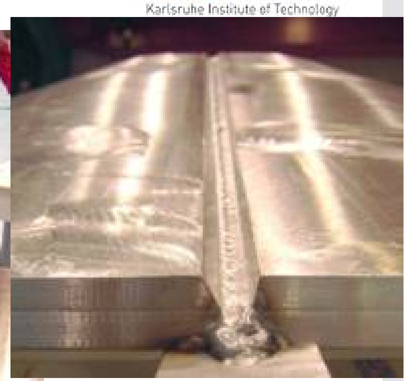
- 07/2004 start of tender action
- 12/2004 order placed (MAN-DWE)
- 02/2005 material ordered (316LN)
- 07/2005 material delivered, start of manufacturing
- 08/2006 first vacuum tests
- 25.11.2006 arrival at FZK

the beginning: 316LN ingots

Rolling of the cylindrical section

- **before rolling everything was cleaned**
- **edges had to be protected**

Manufacturing of the main spectrometer



Leaktests of the first welds

complete production hall cleaned and reserved for KATRIN

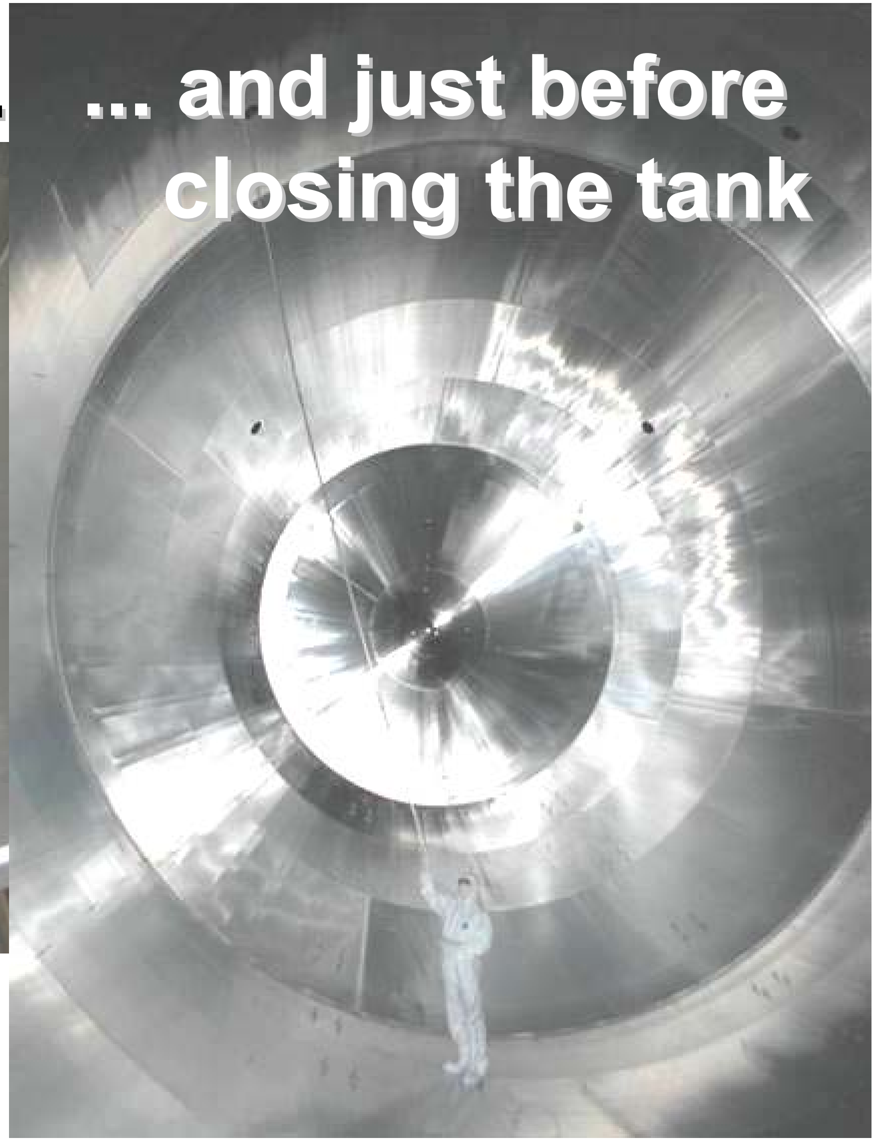
Cleaning and electro-polishing

Final assembly of the main spectrometer

KIT Karlsruhe Institute of Technology

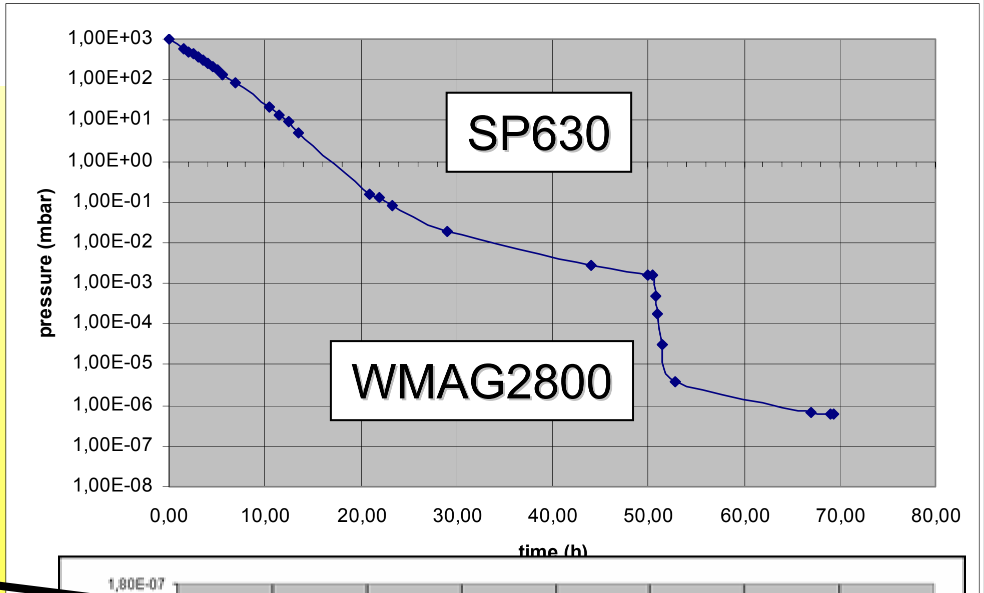
Leak-tests of flanges during manufacturing ...

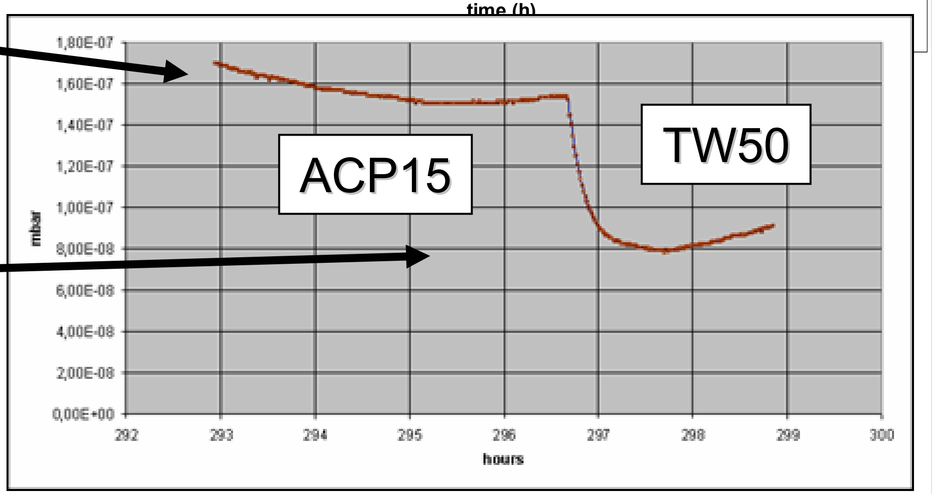
... and just before closing the tank



Pump-down of the main spectrometer

- **SP630 (630 m³/h)**
  - 2 days pump-down time
  - final pressure: 10^{-3} mbar
- **1 WMAG 2800 TMP**
  - after 1h in 10^{-6} mbar region
  - after 1 day in 10^{-7} mbar region
- **fore-pump ACP15:**
  - final pressure: 2 x 10^{-7} mbar
  - min. pressure limited by hydrogen back-diffusion
- **cascaded TMP (TW50):**
  - pressure after 1h: 8 x10^{-8}mbar

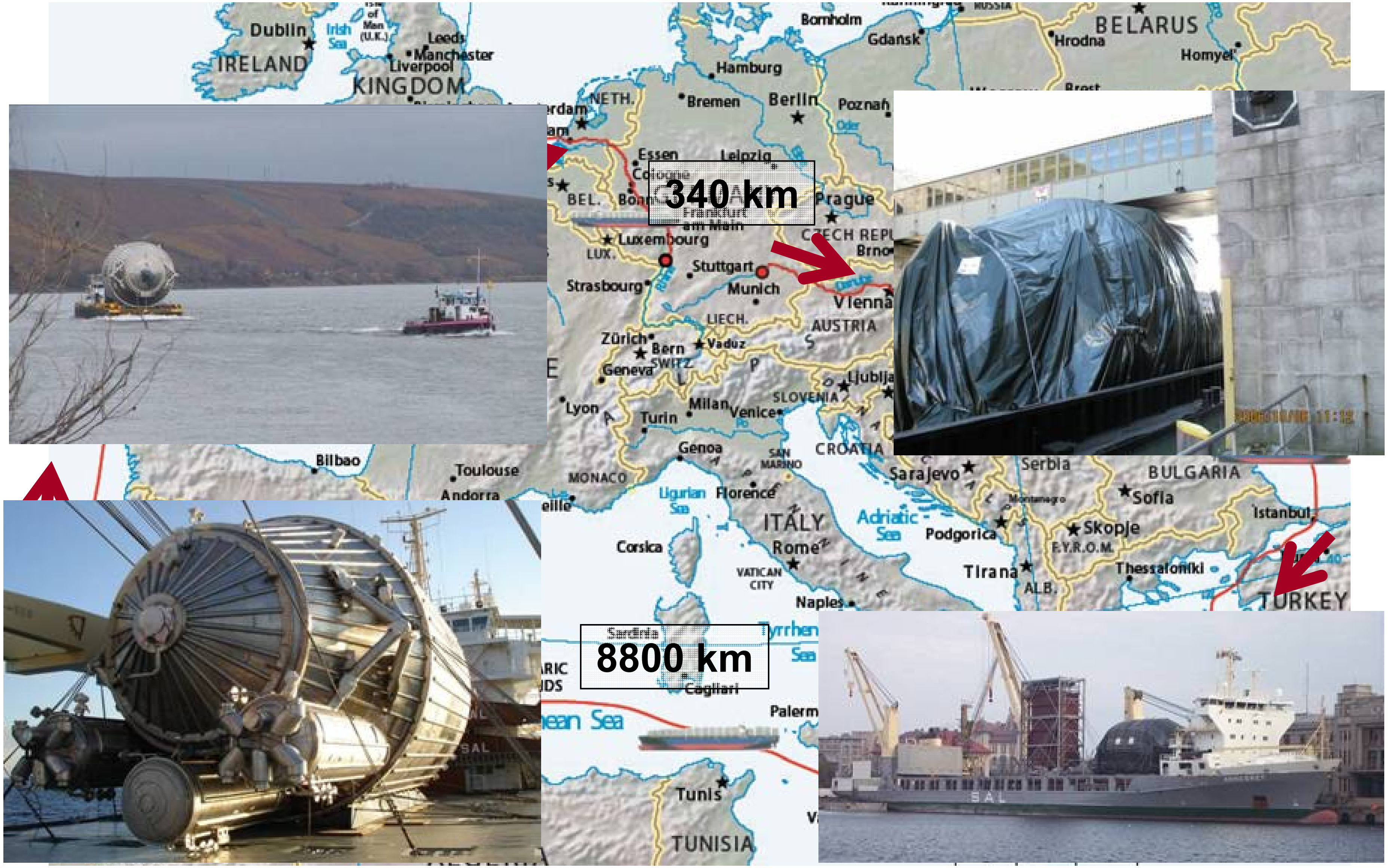




Integral He leak-test before shipping

- local leak-tests of flanges before pump down
- pump-down time: 2 – 3 days
- integral leak-test < 5 x 10^{-9} mbar l/s
- one TMP MAG W 2800 conected to leak-detector
- best pressure during leak test: 6 x 10-8 mbar

Voyage of the main spectrometer

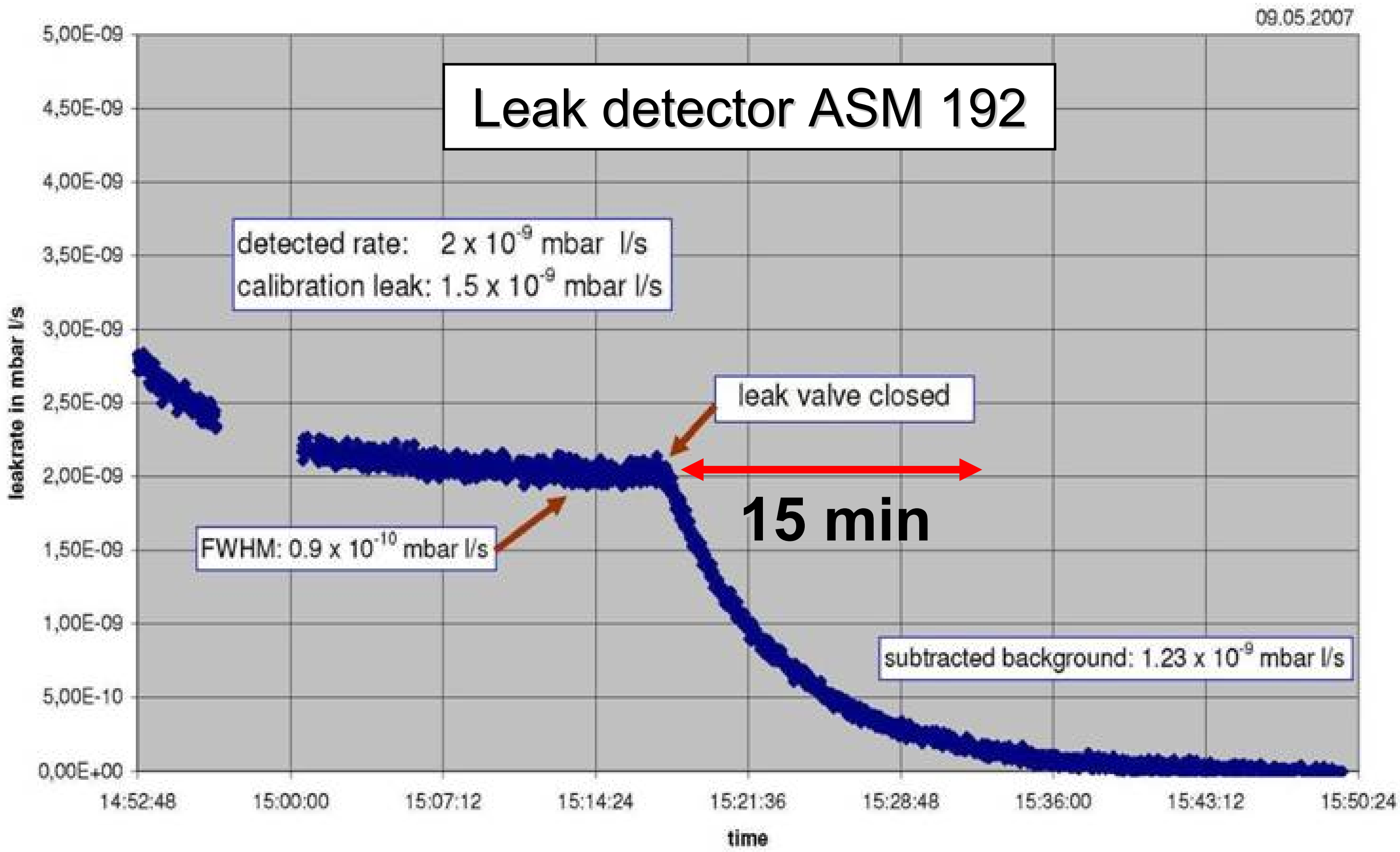


Arrival of the main spectrometer after 8800 km

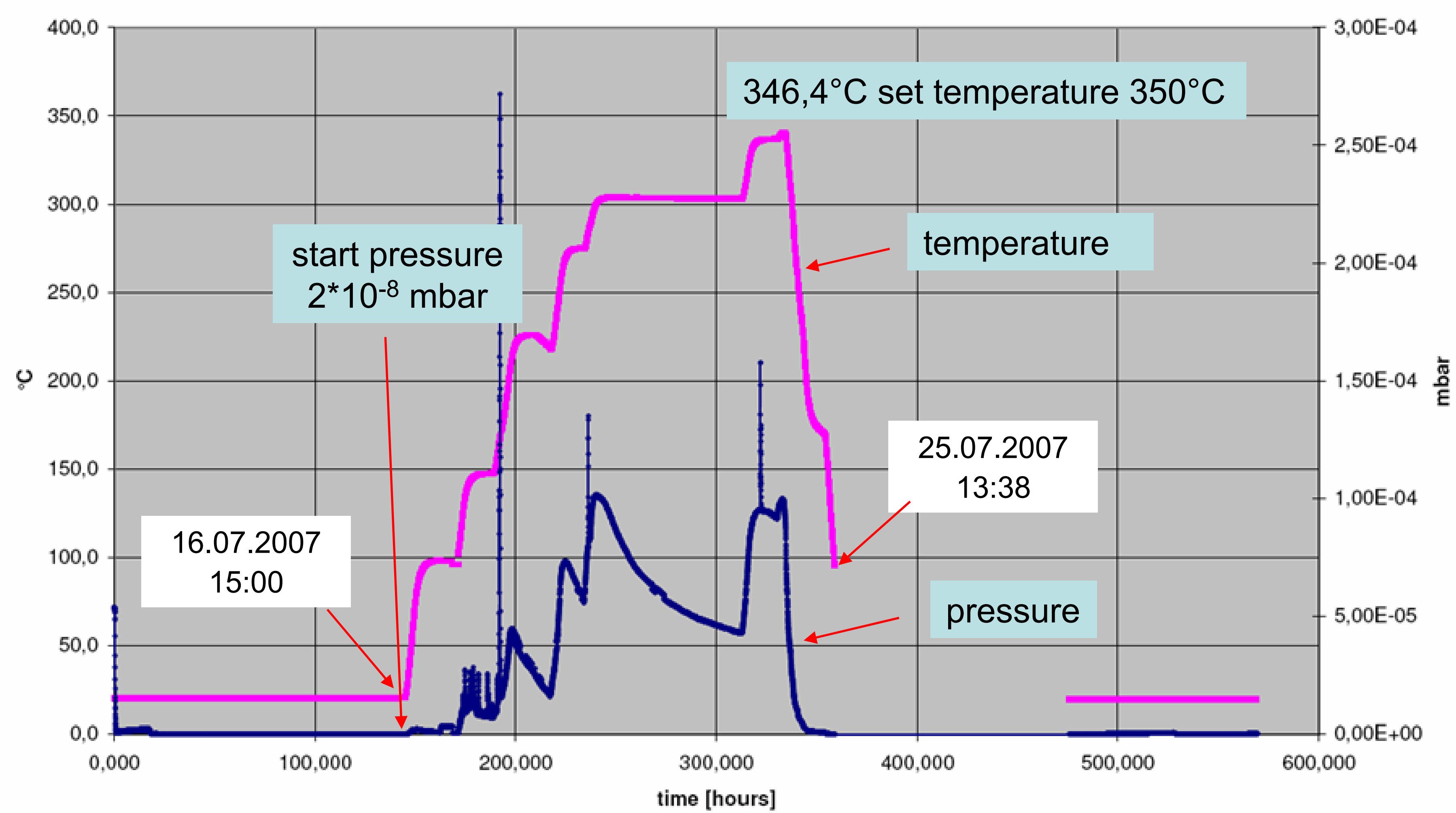
25.11.2006

Helium Leak Test

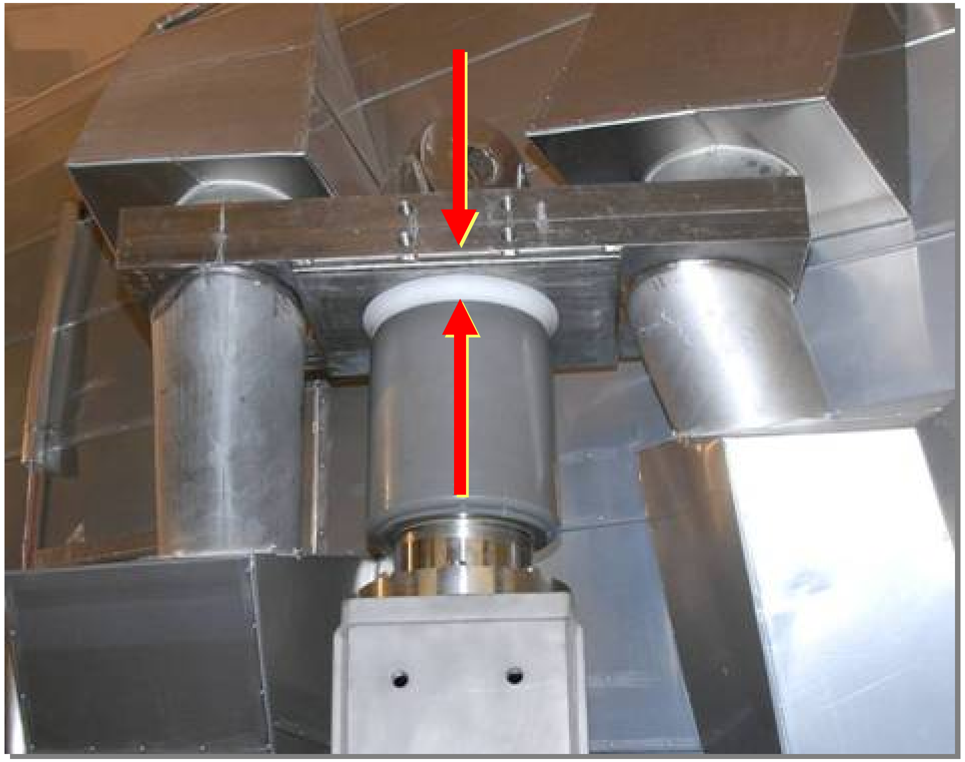
Helium test leak on vessel: 10^{-10} mbar l/s sensitivity



Bake-out of the KATRIN spectrometer



Expansion during heating of the spectrometer



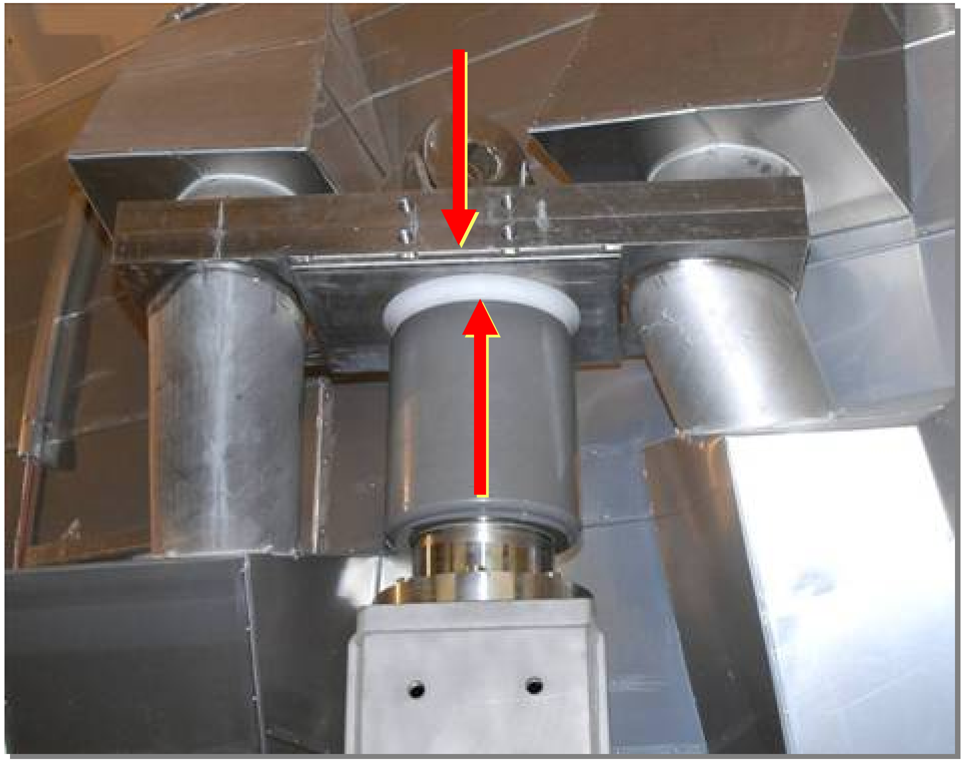
temperature

20°C

expansion

0 cm

Expansion during heating of the spectrometer



temperature

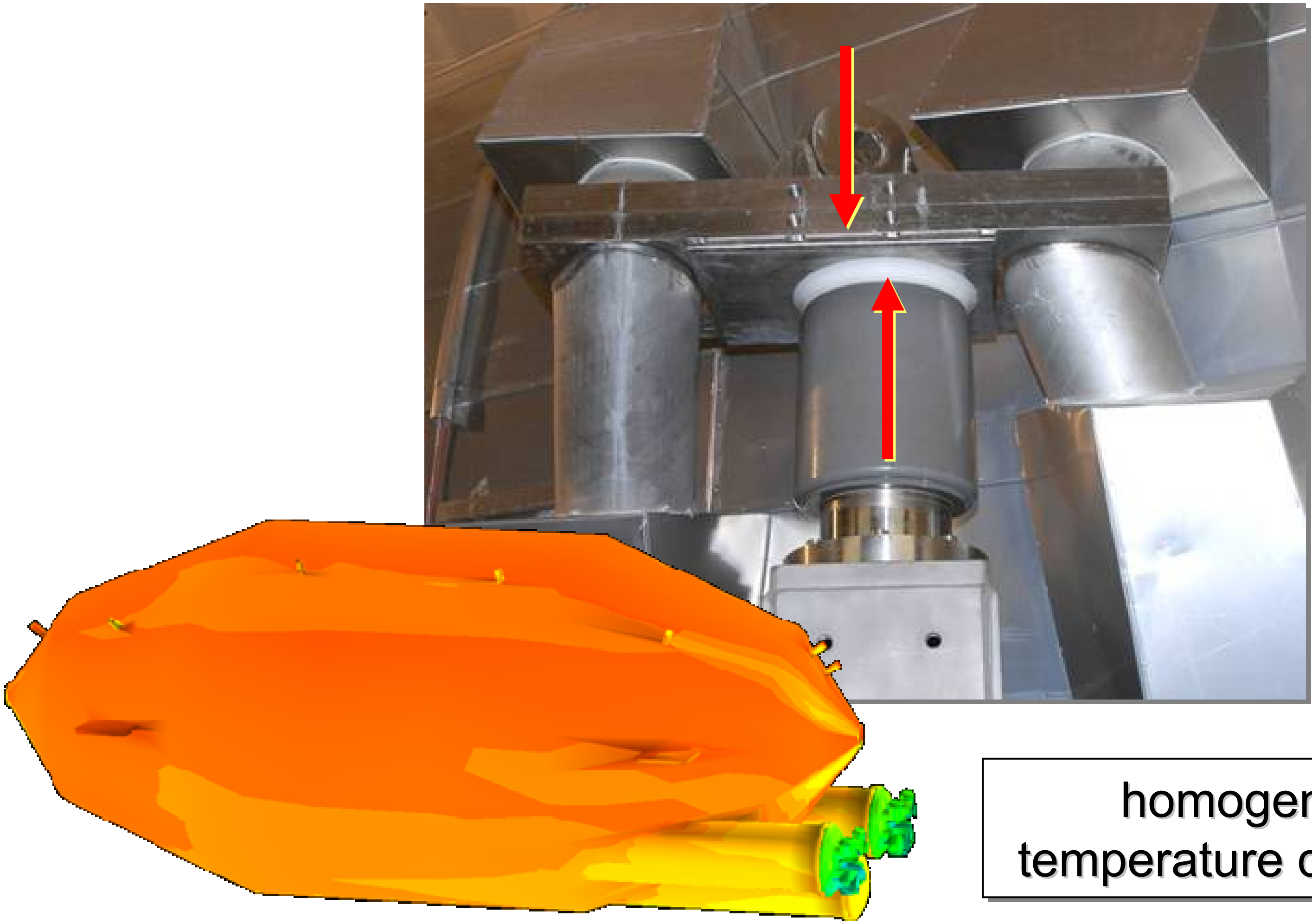
174°C

expansion

5 cm

ISAPP International School on Astroparticle Physics
Karlsruhe, 05.Aug.2009
J. Wolf, *Vacuum technology*

Expansion during heating of the spectrometer



temperature

337°C

expansion

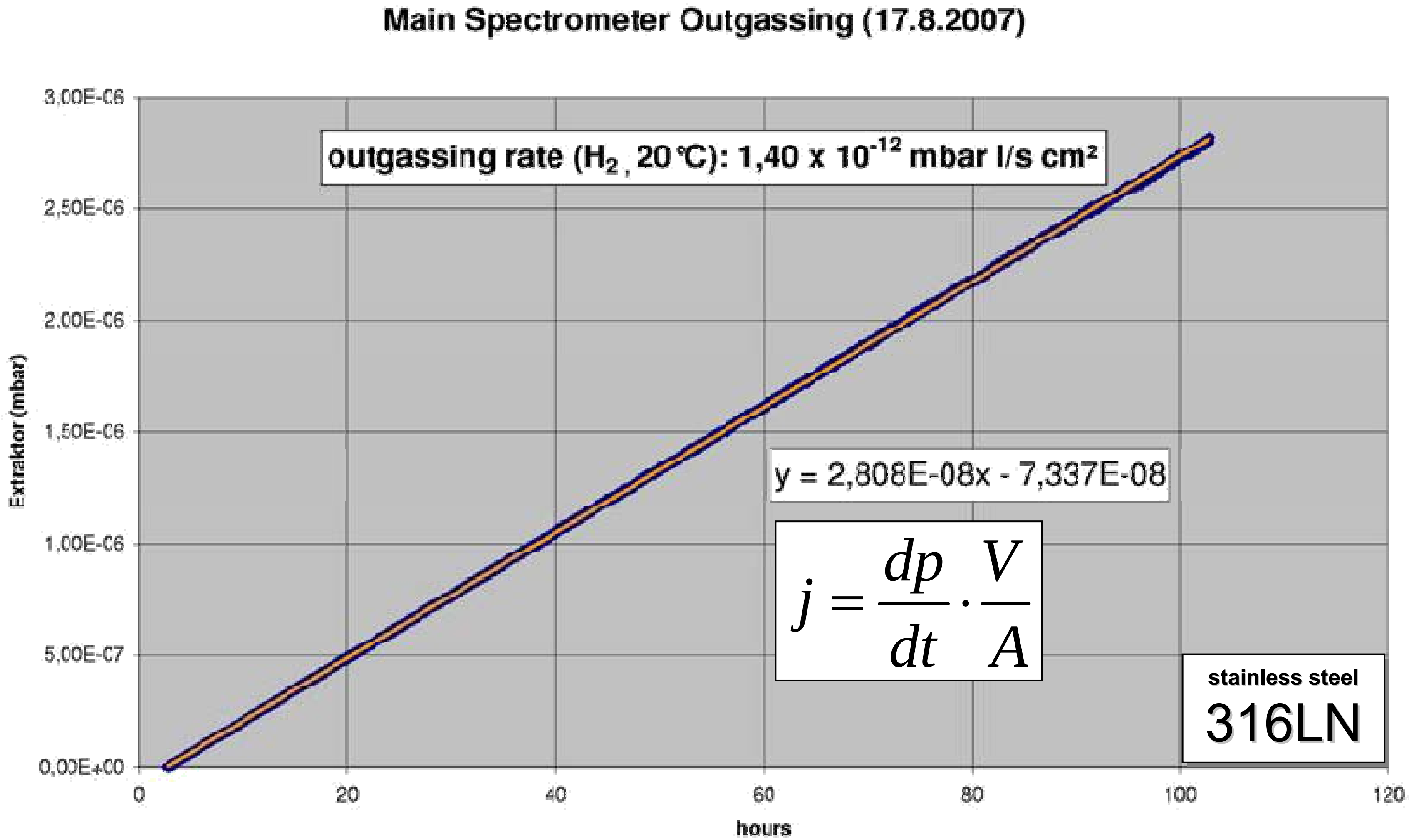
10 cm

homogeneous temperature distribution

Outgassing Rates and Final Pressure

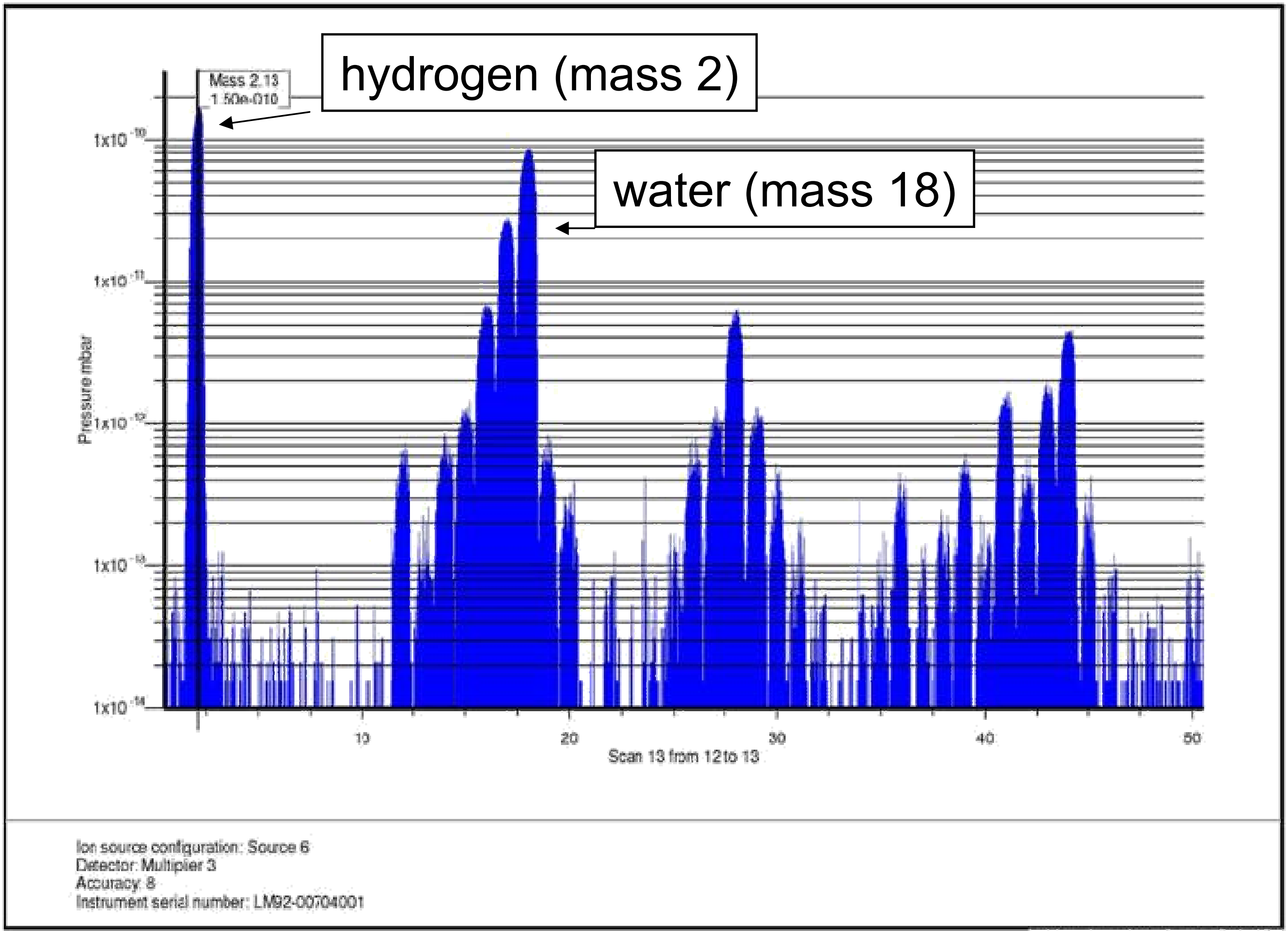
- outgassing rates measured with the rise of pressure methode
- pressure measured with extraktor gauge (± 40%)
  - gas correction for hydrogen: 2.4
- before bake-out: water dominated RGA spectrum
- after bake-out: hydrogen dominated RGA spectrum
- after bake-out: 7 pressure rise measurements
  - long-term effect of pumping (50 days)
  - temperature oft the vessel: 20°C, 15°C, 11°C
- properties of TMPs
  - effective pumping speed for hydrogen
  - gas load due to back-diffusion and/or outgassing of rotors

Outgassing rate after bake-out



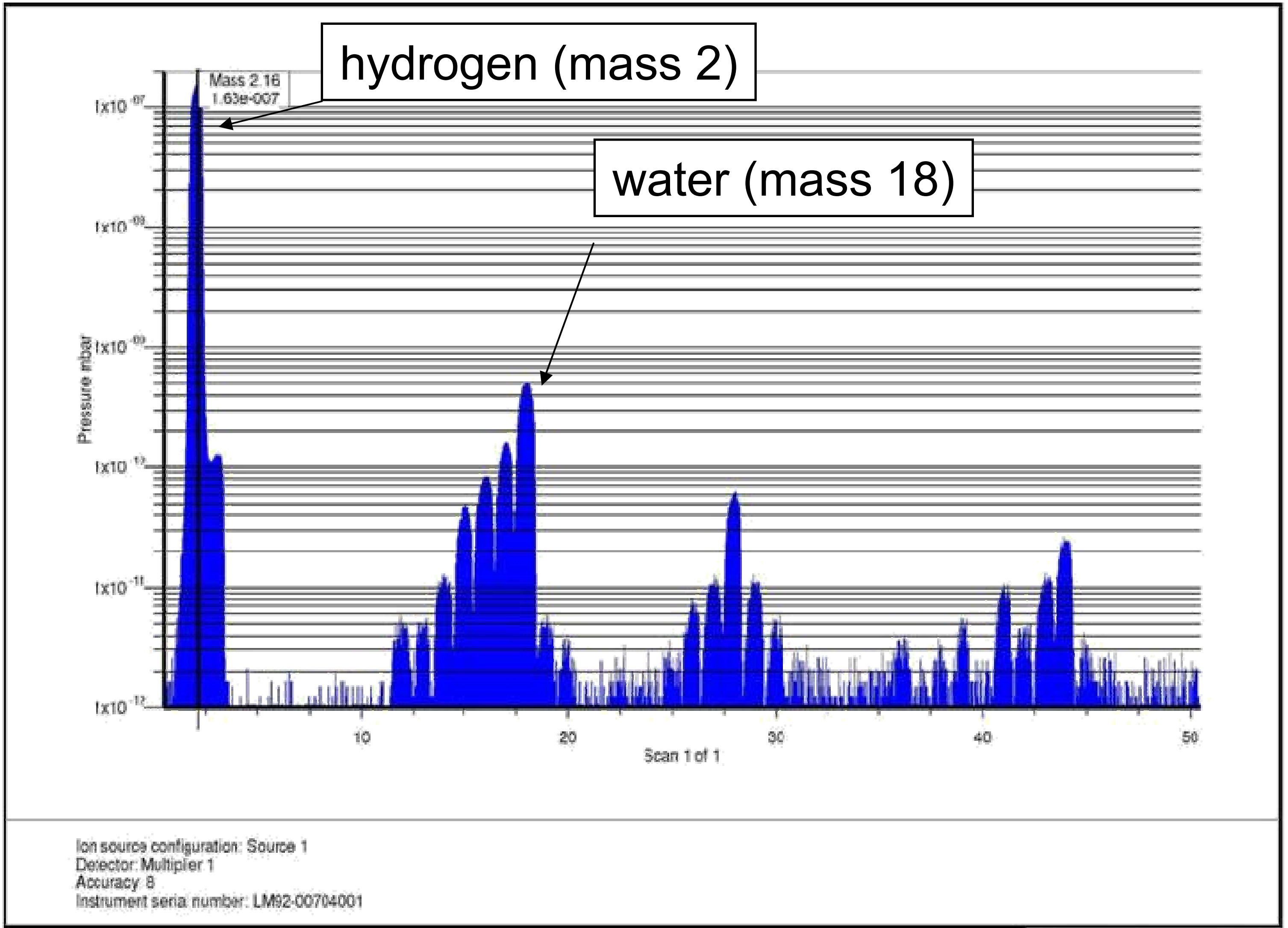
$$j = \frac{dp}{dt} \cdot \frac{V}{A}$$

RGA-spectrum after bake-out



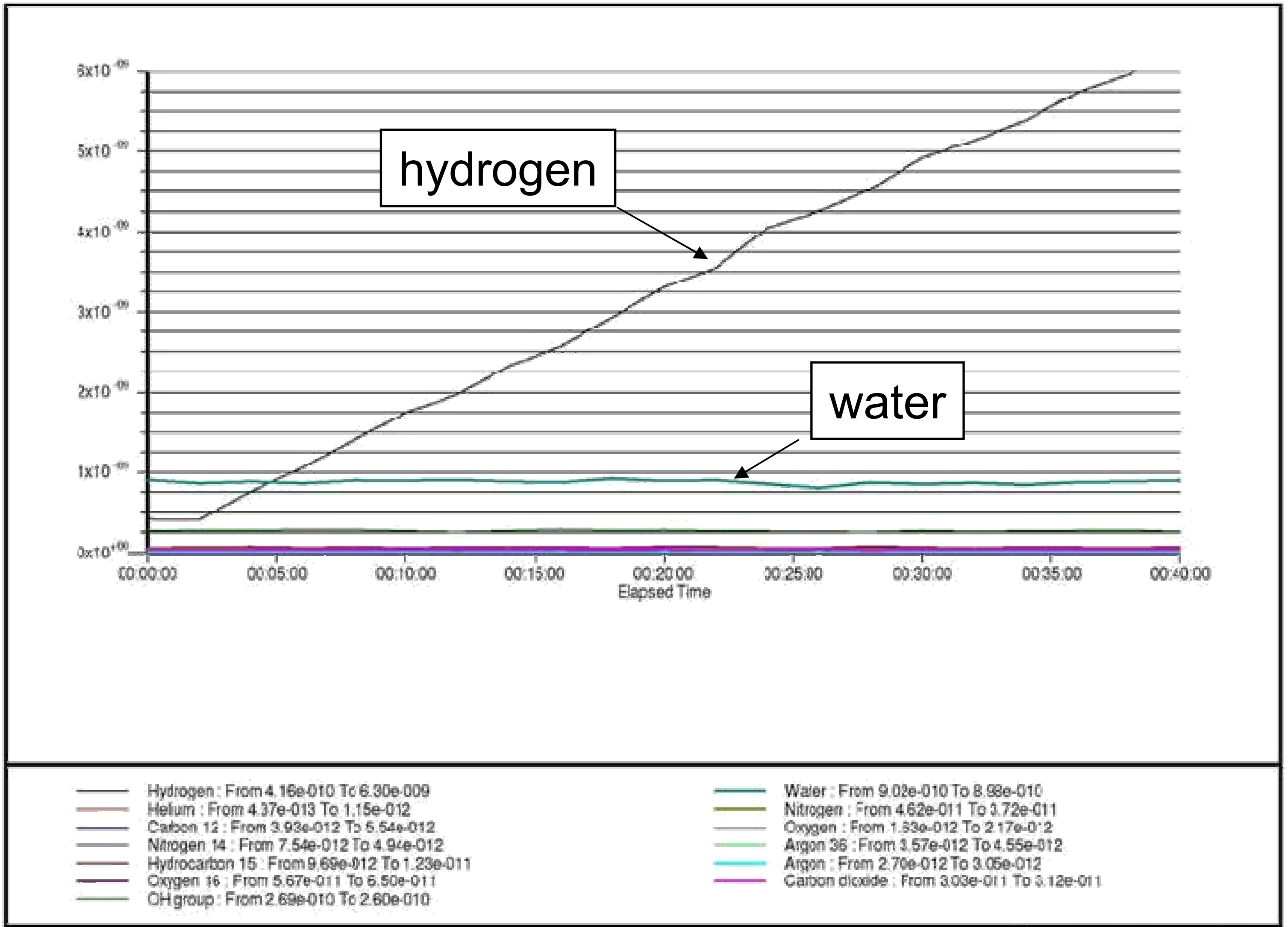
MKS Instruments, Spectra Products - Process Eye

RGA-spectrum during pressure rise



MKS Instruments, Spectra Products - Process Eye

Partial pressure over time during pressure rise measurement



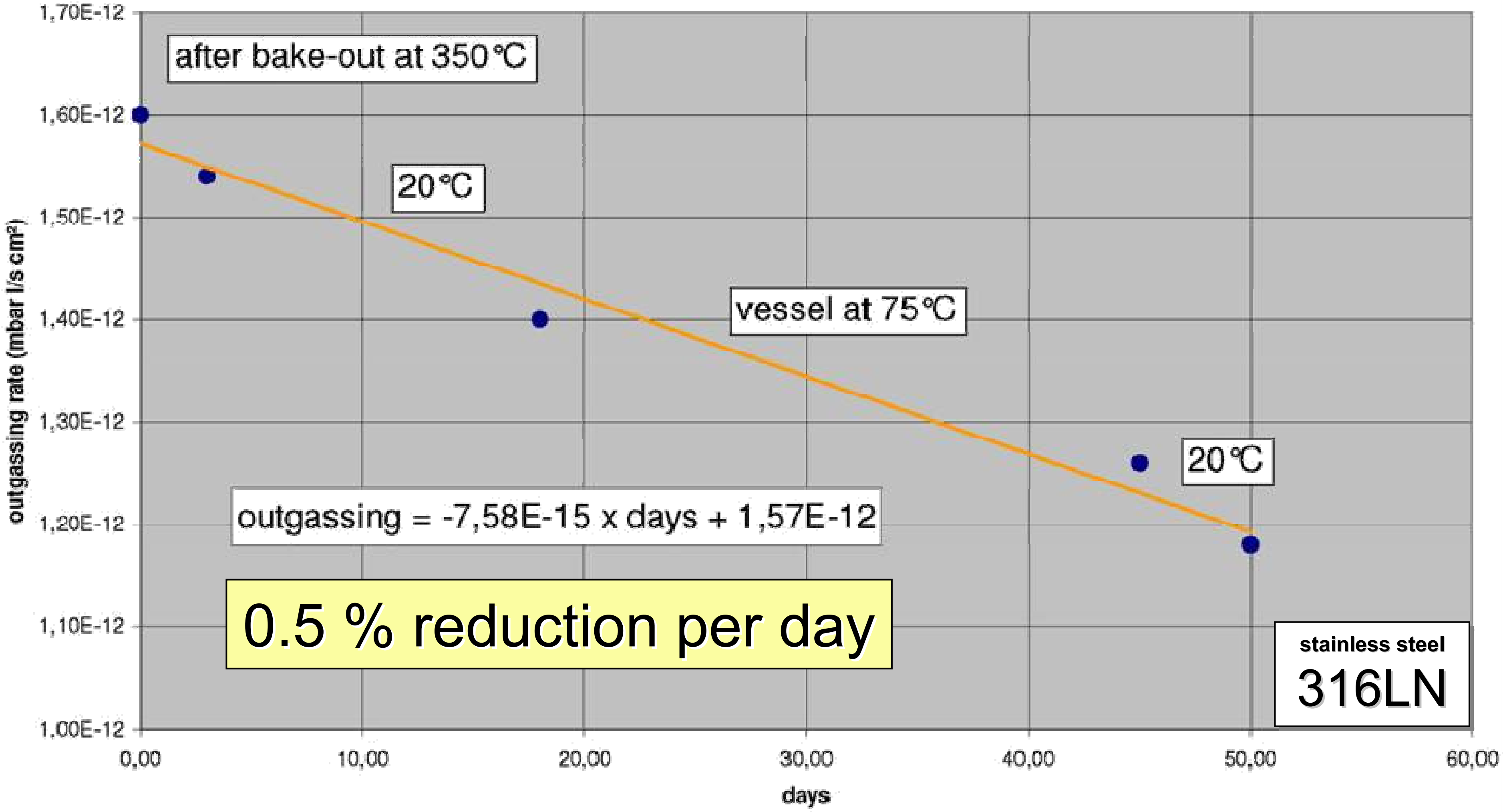
MKS Instruments, Spectra Products - Process Eye

Outgassing rates of the main spectrometer (316LN)

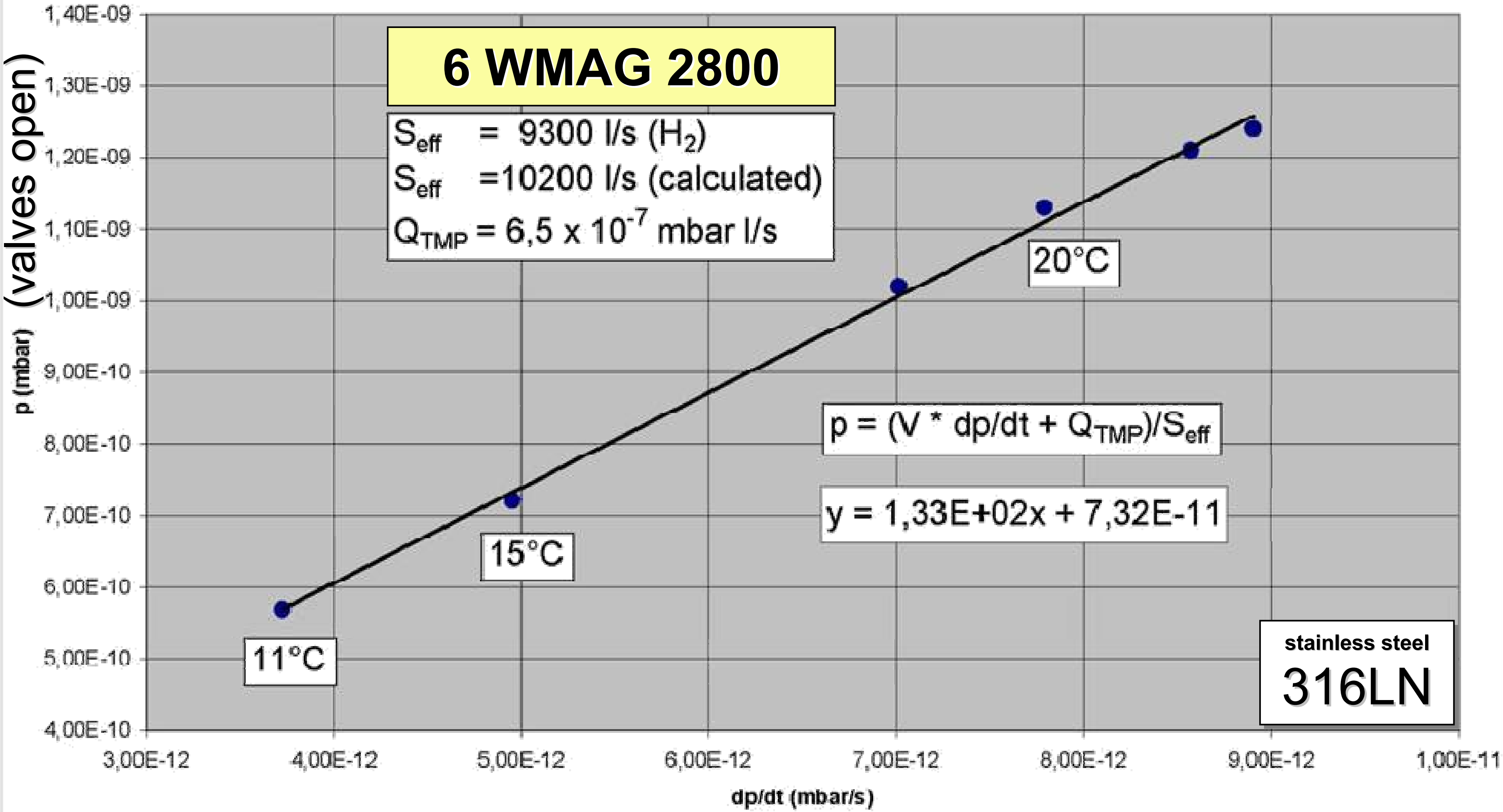
date	temp.	outgassing *mbar l/s cm²*	final pressure *mbar*	dominant gas
09.05.2007	20°C	1.05×10^{-12}	6.60×10^{-8} (2 TMP)	H_2O
30.07.2007	20°C	1.60×10^{-12}	1.24×10^{-9}	H_2
02.08.2007	20°C	1.54×10^{-12}	1.21×10^{-9}	H_2
17.08.2007	20°C	1.40×10^{-12}	1.13×10^{-9}	H_2
29.8.2007	15°C	0.89×10^{-12}	0.72×10^{-9}	H_2
31.8.2007	11°C	0.67×10^{-12}	0.57×10^{-9}	H_2
13.9.2007	20°C	1.26×10^{-12}	1.02×10^{-9}	H_2
18.9.2007	20°C	1.18×10^{-12}	0.90×10^{-9}	H_2

gas correction hydrogen: 2.4 *(D. Li, K. Jousten: J. Vac. Sci. Technol. A21(4) 2003)*

Decreasing outgassing rate over time



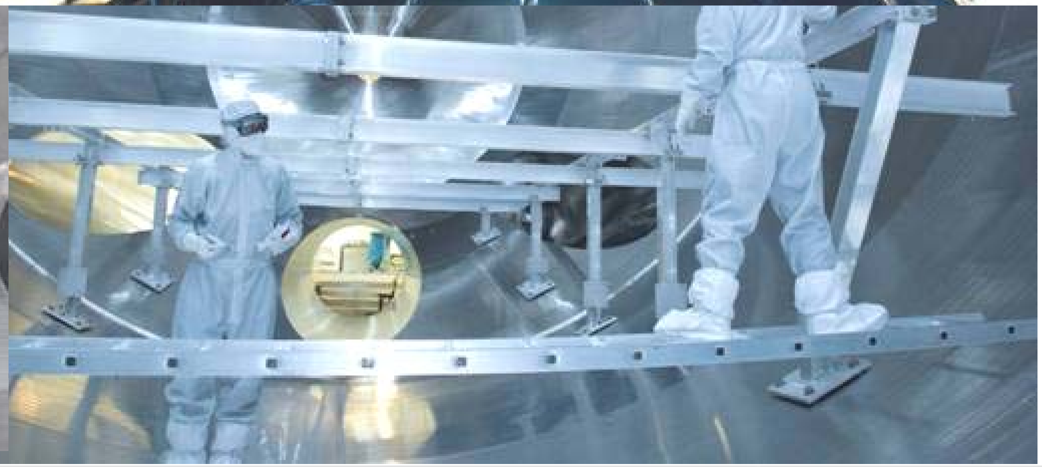
TMP properties from outgassing meas.



Conclusions main spectrometer tests

- **Leak tests:**
  - the sensitivity of the leak detector can reach 10^{-10} mbar l/s
- **Outgassing measurements:**
  - 316LN: 10^{-12} mbar l/s cm^2 achievable at room temperature
  - long term pumping reduces the outgassing rate by 0.5%/day
  - lowering the temperature from 20°C to 11°C reduces the outgassing rate by a factor of 2.
- **TMP performance**
  - the measured effective pumping speed is in good agreement with calculations (10200 l/s for H_2)
  - back diffusion contributes over 10% of the gas load at 20°C
- **Final pressure with 3000m of getter strips: 10^{-11} mbar**

Present status of the main spectrometer



6. Literature and downloads

- **K. Jousten: Handbook of Vacuum Technology (Wiley-VCH)**
- **http://www.oerlikon.com/leyboldvacuum/**
  - „Fundamentals of Vacuum Technology“ (order Leybold CD)
- **http://www.pfeiffer-vacuum.net/**
  - „Know How“: HTML chapters on various vacuum topics
  - „Products/Downloads“: PDF downloads
- **http://www.adixen.com/**
  - „Publications“: HTML and PDF articles