Vacuum Technology for Synchrotron Radiation Sources

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I About Vacuum

Vacuum = Empty

AVS definition: “Vacuum refers to a given space filled with gas at pressures below atmospheric. Molecular density less than about $2.5\text{x}10^{19}$ molecules/cm^3

$$P = nkT \quad \text{[mbar)}$$

n … number of molecules per unit volume
k … Boltzman’s constant
T … temperature in Kelvin

I About Vacuum

- Vacuum ranges

Low (and medium): from atmospheric to about 10^{-2} mbar
Piston pumps, water ring, rotary, sorption (nitrogen)

High vacuum: from 10^{-3} mbar to 10^{-7} mbar
Roots, ejector, diffusion, molecular (water vapour)

Ultra-high vacuum: from 10^{-8} mbar to 10^{-16} mbar
Ion, cryogenic, sorption (hydrogen)

- Vacuum processes are selective:
  - Depend on the type of gas: H_2, N_2, CO, Ar, etc.

I About Vacuum

Pumping

- Main parameters:
  - - the lowest pressure (ultimate pressure)
  - - the pressure range
  - - the pumping speed
      - $S = V/t$ [l/s]
    - S is pumping speed, V is the volume, t is time
  - - the exhaust pressure (additional pump)
  - - the selectivity and residual gas composition (UHV)

I About Vacuum

Conductance

Conductance C [l/s]

$$N = C(n_1 - n_2)$$

N … number of molecules

n_1, n_2 … concentrations on both part of the conductance

C depends on the shape and geometry of the components and on the type of gas

(analytical or numerical calculations)

I About Vacuum

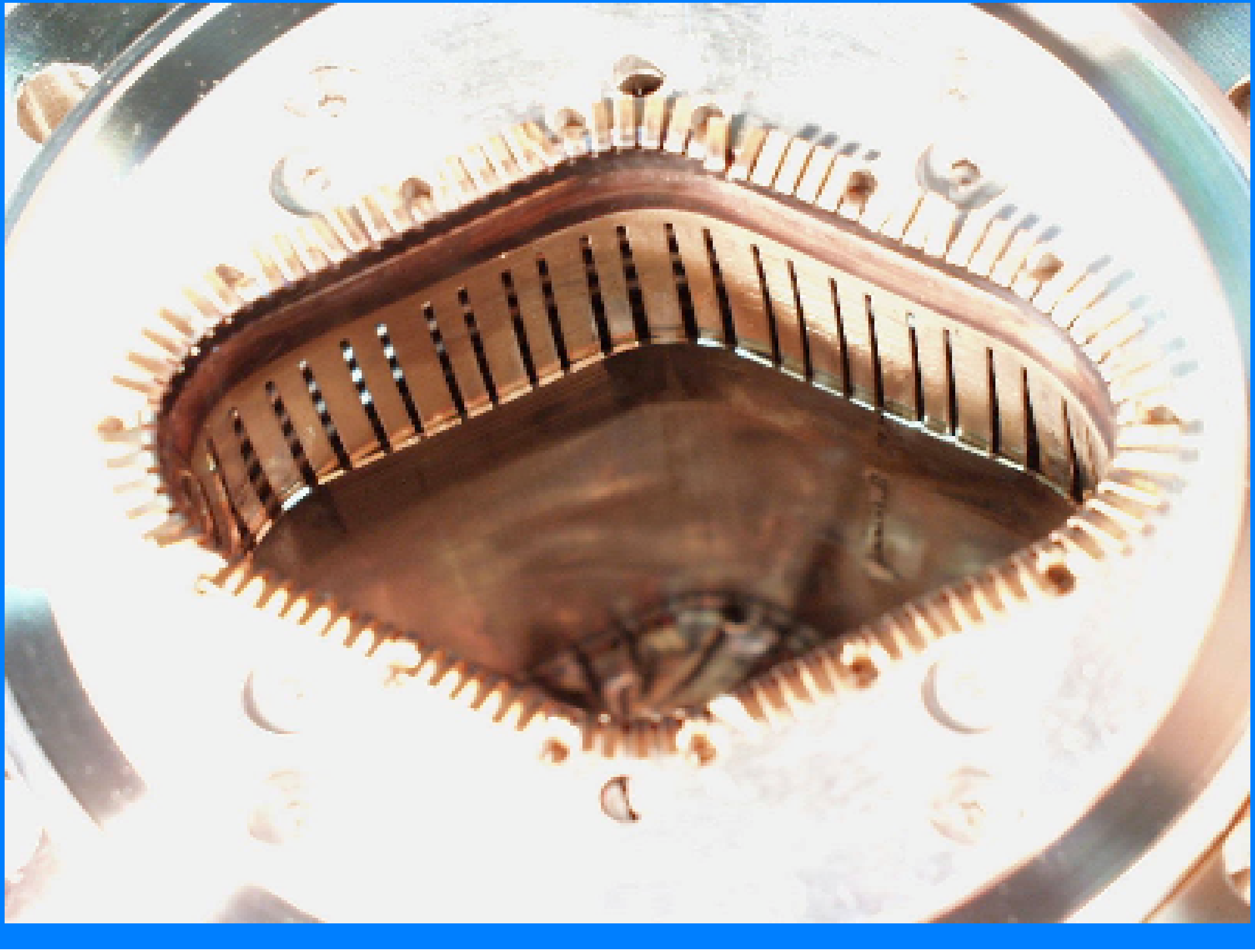
Outgassing

- Desorption rate from materials -
- Arrhenius’ equation
  - dN/dT = - const. N [exp (-E/kT)]
- E … binding energy of the molecules
- on the surface [kJ/mol]
- dN/dT = Q … thermal outgassing rate
- At the equilibrium (UHV systems)
  - P = Q/S

II Vacuum requirements for synchrotron radiation sources

- Beam lifetime due to gas density must be > 10 h
    - $1/\tau = 1/\tau_{el} + 1/\tau_{br} + 1/\tau_{tousch}$
- Short “conditioning time”
- Quick recovery after venting
- Simplicity in modification for new installations
- Smooth chamber wall design
- ELETTRA - operating pressure $< 10^{-8}$ mbar
- (dynamic pressure $< 10^{-10}$ mbar/mA)

RF shielding - "fingers"



III The choice of material

- **Sufficient mechanical strength**
  - $L_c = 1.11\ D(D/h)^{1/2}$
- L_c … critical length for cylindrical parts
- D … mean diameter
- h … wall thickness
- **Impermeable enough to gases**
- **Low vapour pressure (Cd, Zn - no!!!)**

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III The choice of material

- Good resistance to special working conditions (temperature, humidity)
- Low specific outgassing rate
- Low desorption yield
- Low magnetic permeability
- Good weldability and machining
- Good thermal conductivity
- Required electrical parameters

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III The choice of material

❑ **The mostly used materials:**

❑ - stainless steel (bad thermal conductivity)
❑ - aluminum (porous material, high desorption yield coef.)
❑ - copper (soft)
❑ - titanium - very promising material (expensive)

❑ Coated chambers(Cu, TiN, NEG - Non Evaporable Getter)

❑ Getter: a material which is included in a vacuum device
❑ (tube) for removing gas by sorption

❑ NEG: Ti-Zr-V alloys, activation at 150-180 °C for 24 h
❑ do not pump methane and inert gases!

IV Cleaning procedures

- Necessity to remove impurities and hydrocarbons
- Specific outgassing rate:
  - $q_D < 1.5 \times 10^{-12}$ mbar l/s cm^2

prior to assembly	after assembly
physical cleaning (abrasives)	plasma cleaning (O_3, N_2)
chemical cleaning (solvents)	glow discharge cleaning
firing at ambient or inert (???)	in-situ bake-out atmosphere

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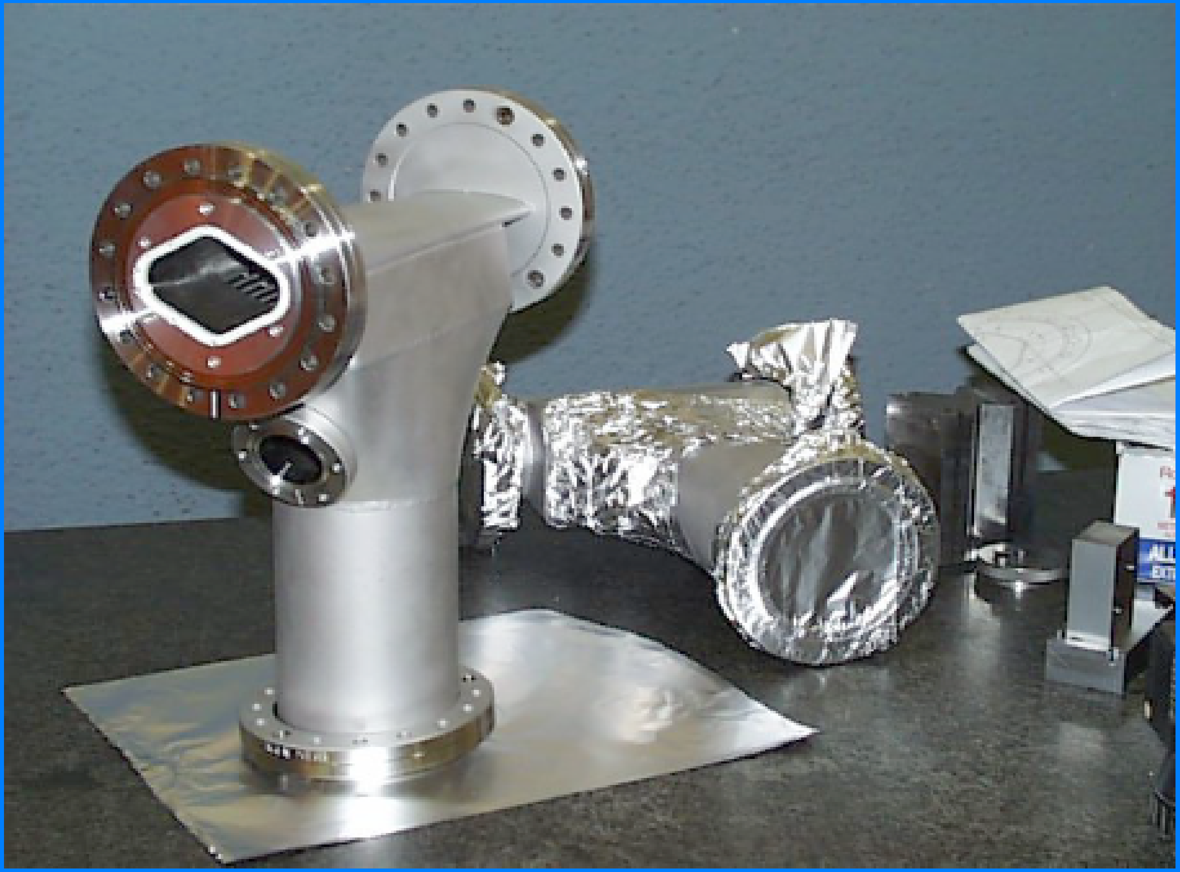
V Vacuum Chamber Design

- Main parts of the ring vacuum chamber:
- - electron chamber (elliptical, cylindrical, rhomboidal)

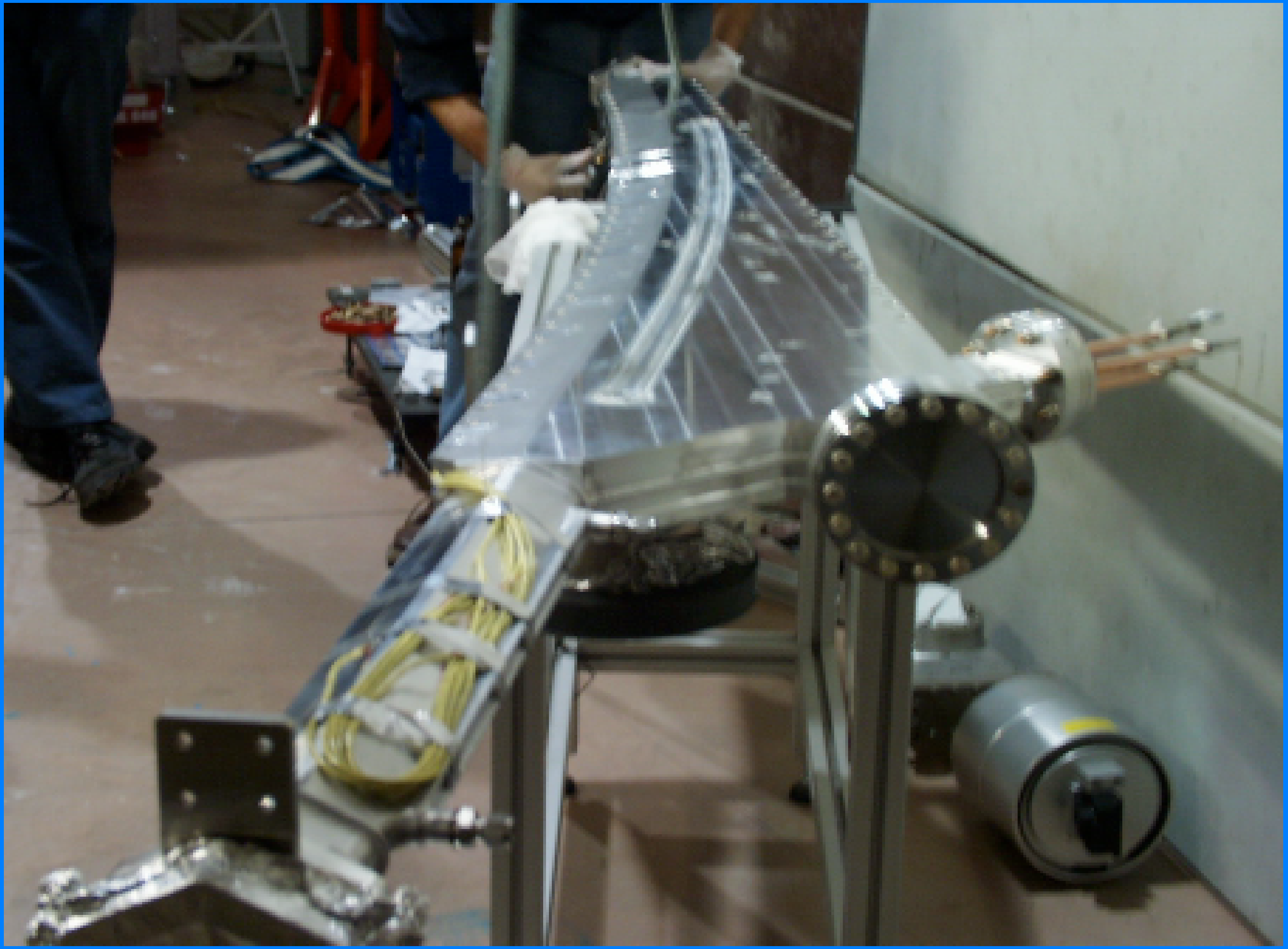
- - bending magnet chamber: antechamber solution
- efficient removal of desorbed gases far away from the
- electron trajectories through the slots

- - insertion device vacuum chamber - long (6m) tube
- with or without central pumping
- (NEG coated chambers - lower conditioning time)

Pumping spot for the electron rhomboidal chamber



Aluminum Bending Magnet Vacuum Chamber



Insertion device vacuum chamber with central pumping

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VI Pumping Requirements

- UHV conditions:
- - static pressure (without beam) $< 10^{-10}$ mbar
- - operating pressure (with beam) $< 10^{-8}$ mbar
- Total gas load
  - $Q_t = Q_{des} + Q_{ind}$
- The total photon flux (Souchet at all, 1983)
  - $dN_{ph}/dt = 8.08 \times 10^{17}\ I\ E$ [photons/s]
- I … beam current in mA
- E …machine energy in GeV

VI Pumping Requirements

- ELETTRA: 400 mA at 2 GeV, $\rho = 5.5$m
- Total number of photons = 6.4×10^{20} ph/s
- Molecules extracted from the walls
  - $N_{mol} = \eta N_{ph}$
- η … desorption yield coefficient
- Characteristic of materials - has to be measured
- The η decrease causes the pressure decrease, so called
  - "conditioning"
- Measured against Amperhour (integrated current)

VI Pumping Requirements

- **Beam induced desorption gas load in turn**
  - **$Q_{ind} = 17.8\ \eta\ N_{ph}$ [mbar l/s]**
- ELETTRA: stainless steel chamber
- $\eta = 10^{-6}$ mol/ph after 50 Ah of conditioning
- η is different for different gases
  - $\eta_{H_2} = 10 \text{ x } \eta_{CH_4}$
- **Total pumping speed:**
  - **S = Q/P = 10 000 l/s**

VI Pumping Requirements

- Pumps must be uniformly distributed along the vacuum chamber
- Pressure profile calculated at steady state
  - $dQ = C\,L\,d^2P/dx^2\,dx$
- L … half distance between two pumps
- C … pipe conductance of the perimeter B
- **Maximum pressure**
  - $P_L = q_D\,B\,L\,[1/S_P + 1/2C]$
- **Minimum pressure**
  - $P_0 = q_D\,B\,L/\,S_P$

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VI Pumping Requirements

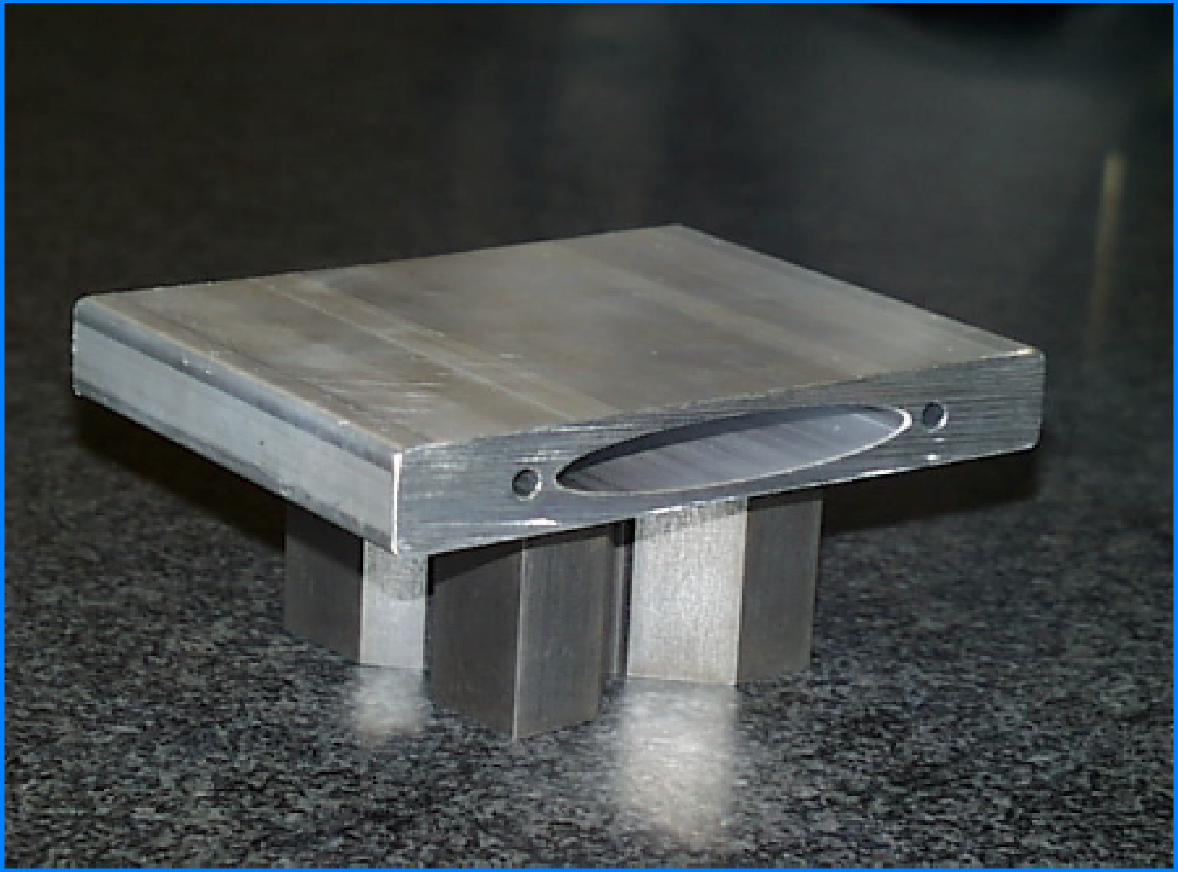
- Very important - the pressure drop
  - $P_L - P_0 = q_D B L/2C$
- Vacuum system is conductance limited
- Pumping speed is a dynamic parameter
  - $S = - V(dP/dt)/(P - P_0)$
- Real or “effective” pumping speed
  - $S_{ef} = S[1-(P_0/P)]$
- S_{ef} is falling down to 0 !

VI Pumping Requirements

- The equilibrium pressure in the ring
  - $P = (17.8\ \eta + q_D\ A)\ S_{ef}$
- A … the internal surface of the volume V
- Compromise between C and A (experience)

- η of Aluminum = 15 - 150 x η of st. steel
- η of copper < η of stainless steel
- η of titanium - no reliable data
- η of NEG seems to be < than of Al

Cross Section of the Extruded Aluminium Insertion Device Vacuum Chamber with Cooling Chanels



Aluminium Insertion Device Vacuum Chamber without central pumping

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VII Beam cleaning efficiency

- The third generation synchrotron light sources
  - 1 Ah of conditioning = 1.7×10^{23} ph/m (R.P.Walker)
- η in the range of 10^{-7} mol/ph can be reached after about 5 Ah of conditioning
- After about 10 Ah of conditioning the specific outgassing rate is $< 1 \times 10^{-13}$ mbar l/s cm^2
    - **Beam is the best cleaning agent !**

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VII Beam Cleaning Efficiency

- In situ bake-out - described as flash desorption
  - $E_D/RT_m^2 = \text{const. } \exp[- E_D/RT_m]$
- E_D… activation energy of desorption
- T_m… surface temperature at the maximum desorption rate
  - $E_D = 300 \times T_m$ [kJ/mol]
- Energy of photons $E = h\,\nu = h\,c/\lambda$
- h, c … Planck’s constant, velocity of light, resp.
- ν, λ … frequency and vawelength of photons

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VII Beam cleaning efficiency

- In-situ baking and firing

T_m [°C]	150	300	900
E_D [eV/mol]	8×10^{23}	1×10^{24}	2×10^{24}

- Photon “cleaning”

λ [nm]	500	200	1
E [eV/mol]	4×10^{26}	8×10^{26}	2×10^{27}

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VII Beam cleaning efficiency

- ELETTRA experience:
- 1) no complete bake-out before start up (1993)
- 2) enormous thermal stress - leaks found
- 3) residual mass spectra: 2(H_2), 16(CH_4), 18(H_2O),
- 28(CO, N_2), 44(CO_2)
- 4) no difference in conditioning time between baked
- and unbaked vacuum sectors
- Bake-out is time consuming, non negligible cost

VIII Pumping system

- Sputter ion pump: used crossed electric and magnetic field
- Consists of: stainless steel vessel
  - anode of honeycomb construction
  - titanium cathode
  - magnets

Advantages	Disadvantages
Gas captured inside	Start to work at 10^{-5} mbar
High S for active gases	Low S for inert gases (He)
Clean vacuum	Argon instability (triode)
No vibrations	Need refreshing (at 220 °C)

Pressure measurements according to the SIP's current reading

Current absorbed by the pump

$$I = K\,P^{n}$$

Calibration equations

$I = 1850\,P^{1.65}$	SIP 45 l/s
$I = 1740\,P^{1.18}$	SIP 60 l/s
$I = 1590\,P^{1.06}$	SIP 120 l/s
$I = 1260\,P^{1.1}$	SIP 230 l/s
$I = 1200\,P^{0.99}$	SIP 400 l/s
$I = 1050\,P^{1.03}$	SIP 900 l/s

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VIII Pumping system

- Ti sublimation pump
- Main parts: water (or LN$_2$) cooled SST vessel
- wire feed spool driven from outside
- Ti wire
- heated post
- filaments (cathode)
- Do not pump helium!

IX Pressure measurements

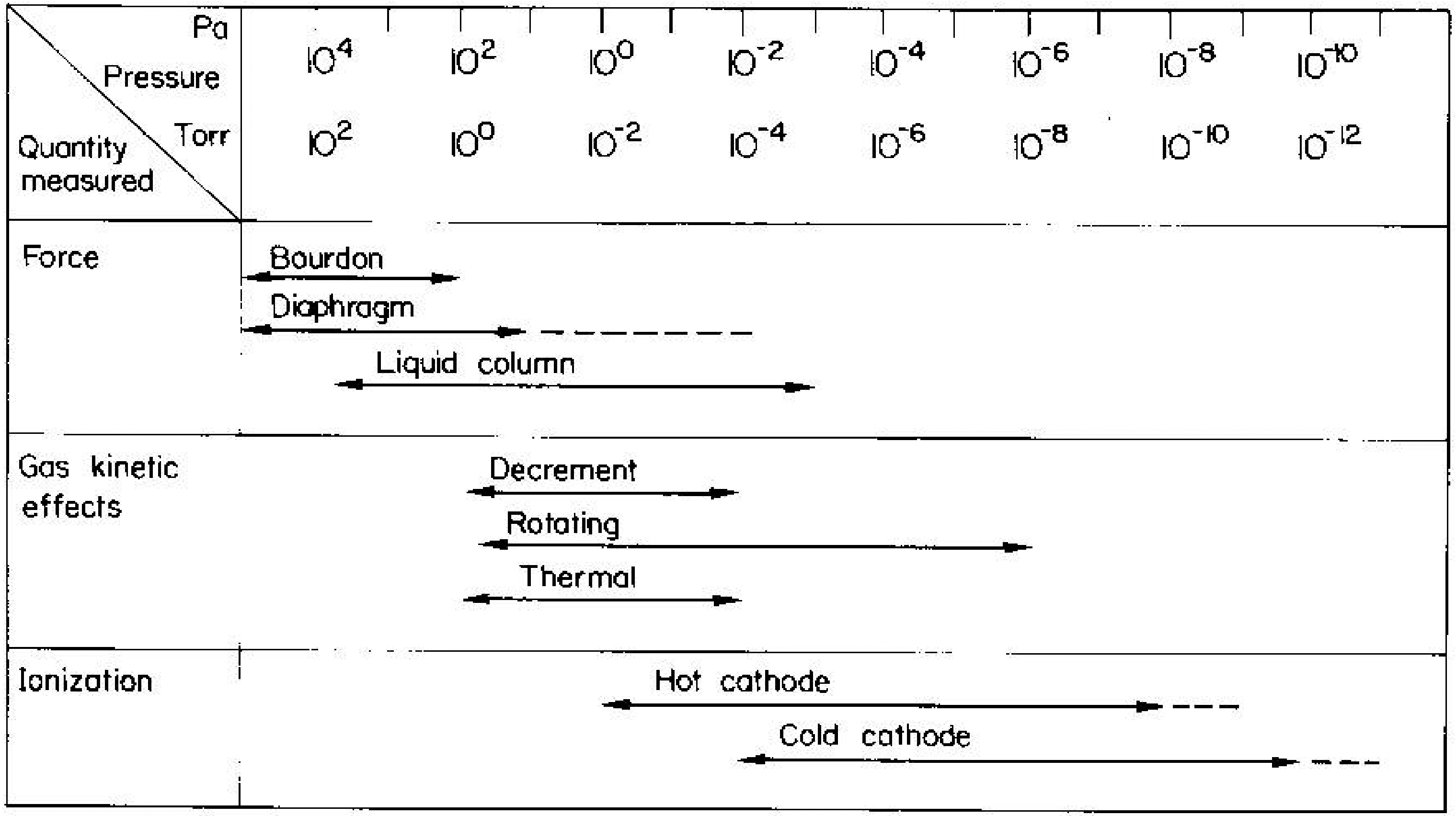
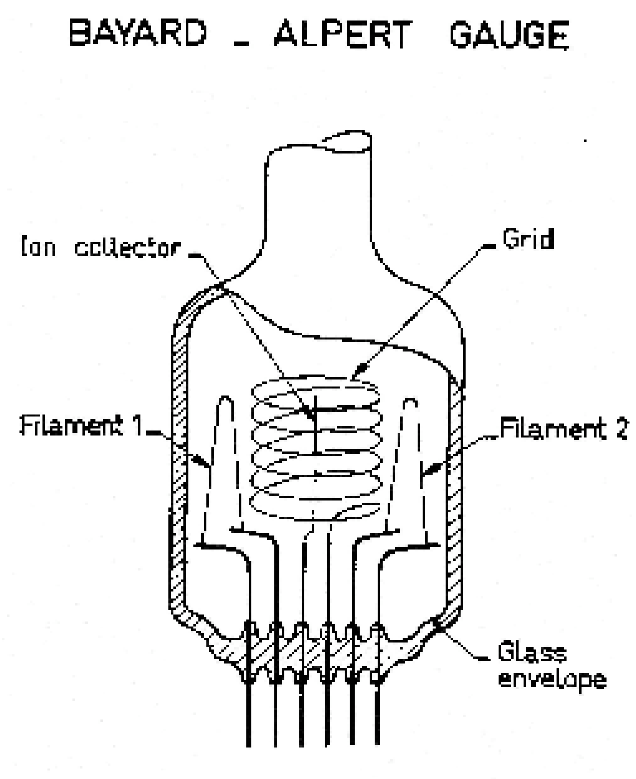


Fig. 4.64 Range of pressures covered by vacuum gauges.

IX Pressure measurements

Ionisation gauges - “hot cathode”

❑ Bayard-Alpert hot cathode gauge



$I^{+} = I^{-} s P$

from 10^{-3} to 10^{-11} mbar

Need calibration for each gas species

Linear calibration curve

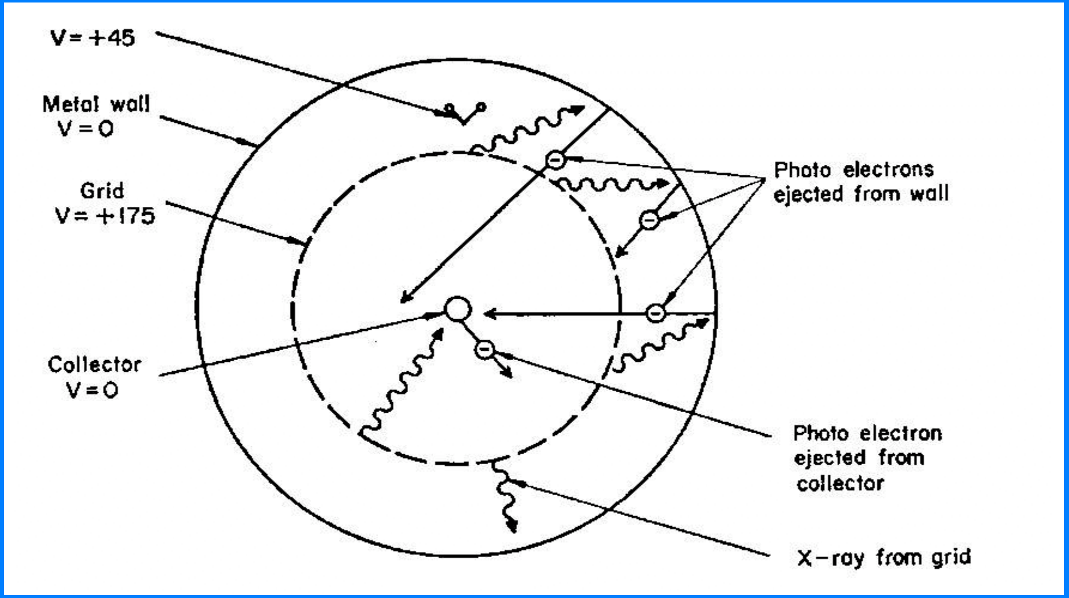
Sensitivity variation

Outgassing

VIII Pressure measurements

Ionisation gauges - “cold” cathode

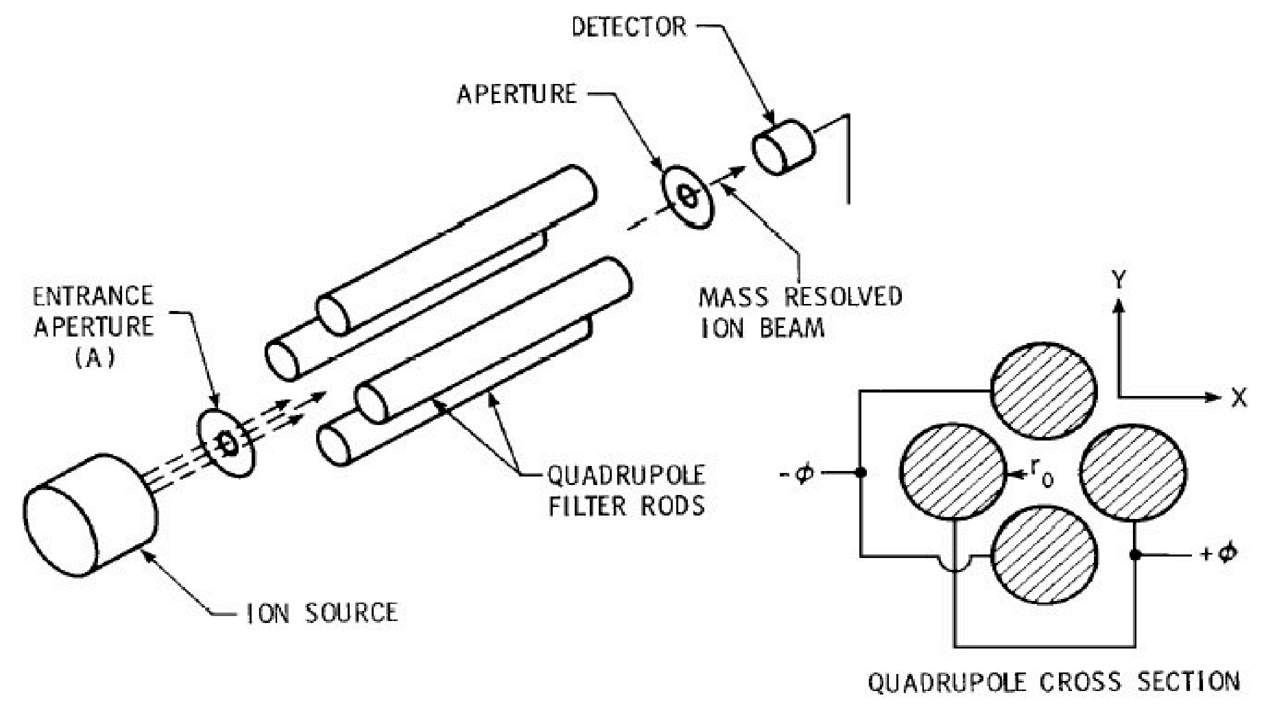
Some “Spurious” Effects



Crossed electric and magnetic field
Self sustaining magnetic discharge
Wide range - IMG
Inverted magnetron gauge
10^{-3} - 10^{-11} mbar

Need calibration for each species
Striking at low pressures

IX Residual gas analyzer



Applied d.c.+a.c.
for given frequency
e/m
is detected

Leak detector
only mass 4 (He)
registered

IX Residual Gas Analyses

QMA characteristics:

1) high pressure performance ($< 1\times10^{-5}$ mbar)

2) detection of small signals - fragment ions detection

3) dependence of sensitivity on gas species

4) hysteresis - less pronounced at $P > 10^{-8}$ mbar

5) formation of fragment ion

6) degassing of vacuum heads

7) total pressure measurement

8) last but not least - COSTS

X Reliability under real experimental conditions

What is special:

- very big facility
- must operate reliably
- radiation
- electric field
- external magnetic field
- RF structures
- overheated parts of the vacuum chamber

There is no space for vacuum instrument installation!

X Reliability under real experimental conditions

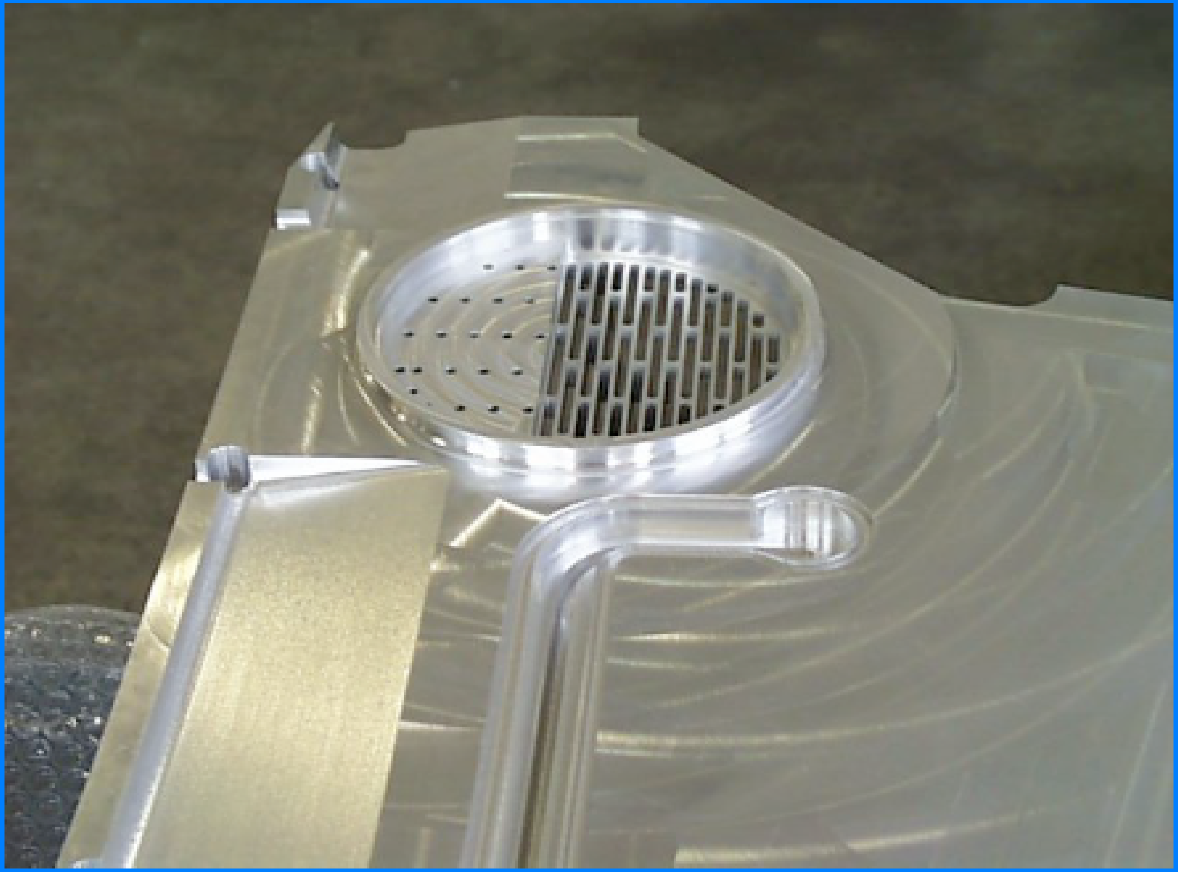
How to cure effect of:

1) radiation: developed a metal structure installed with the PEG

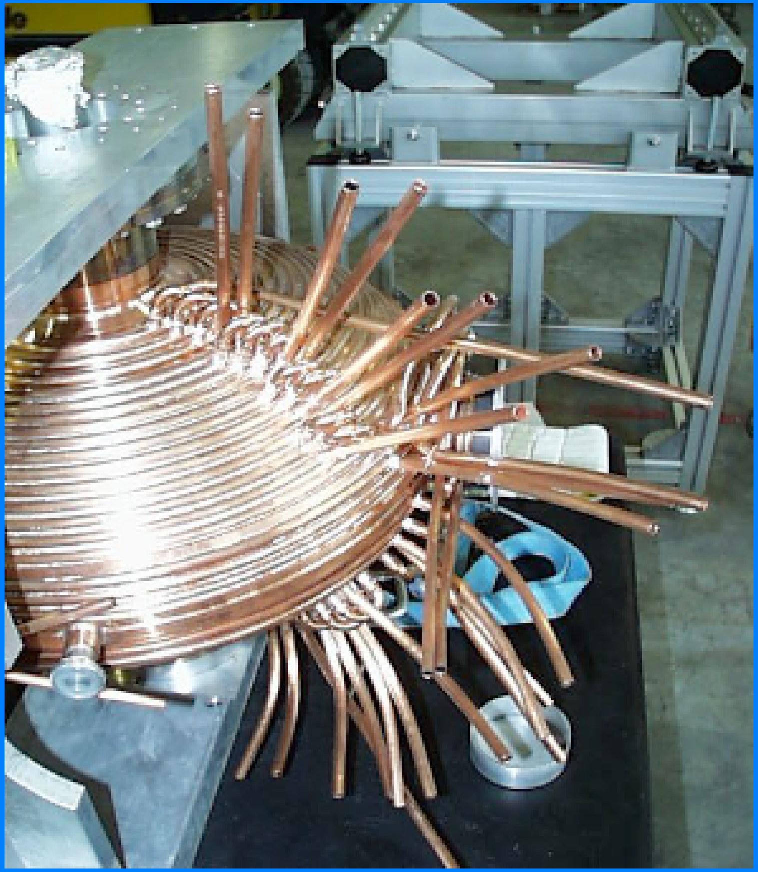
2) magnetic field: special shielding for PEG
μ metal saturates over 300 Gauss
double ARMCO sheets for RGA

3) RF structure: inside the RF cavities
frequency shifter installed

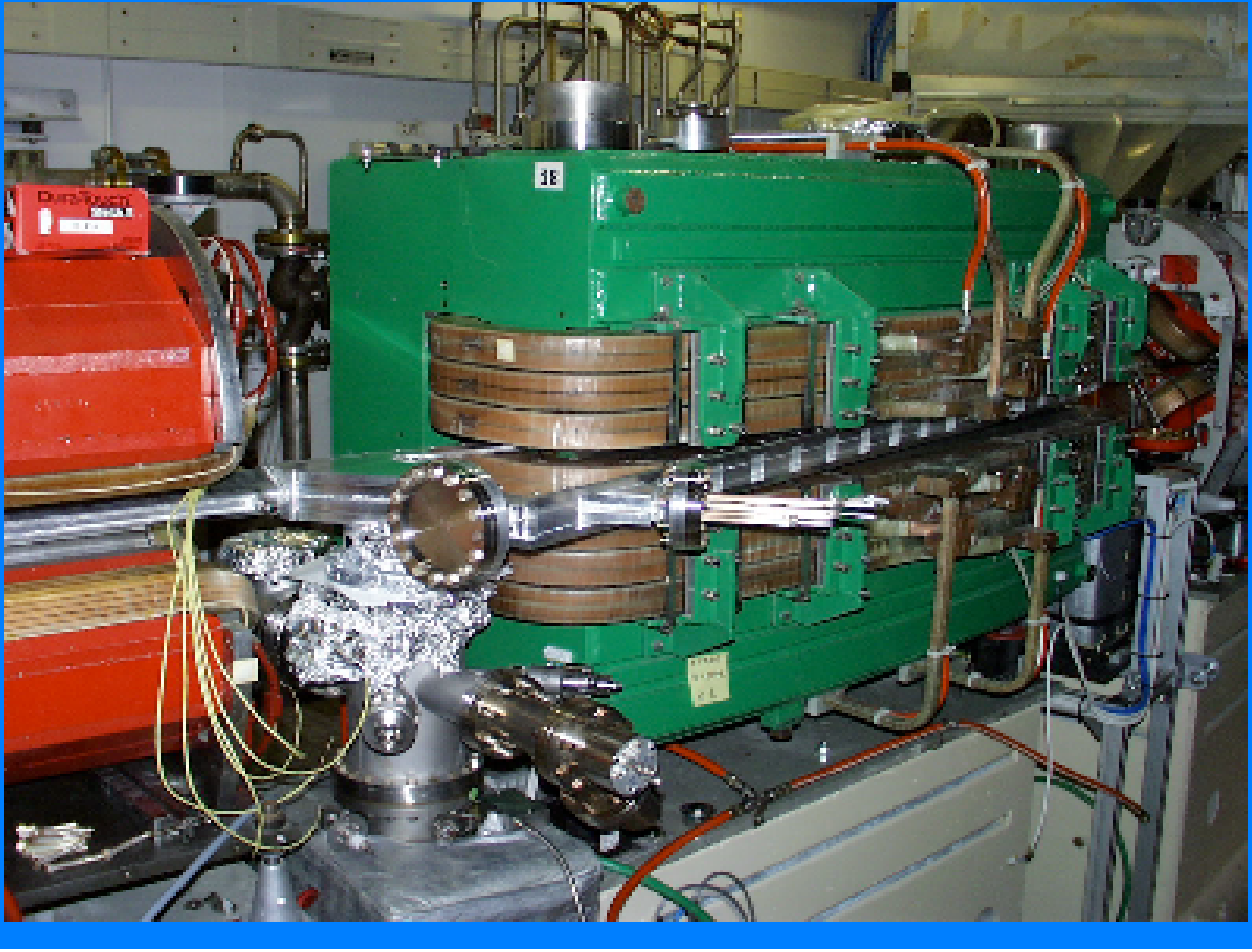
Detail of the pump attachment on the bending magnet vacuum chamber



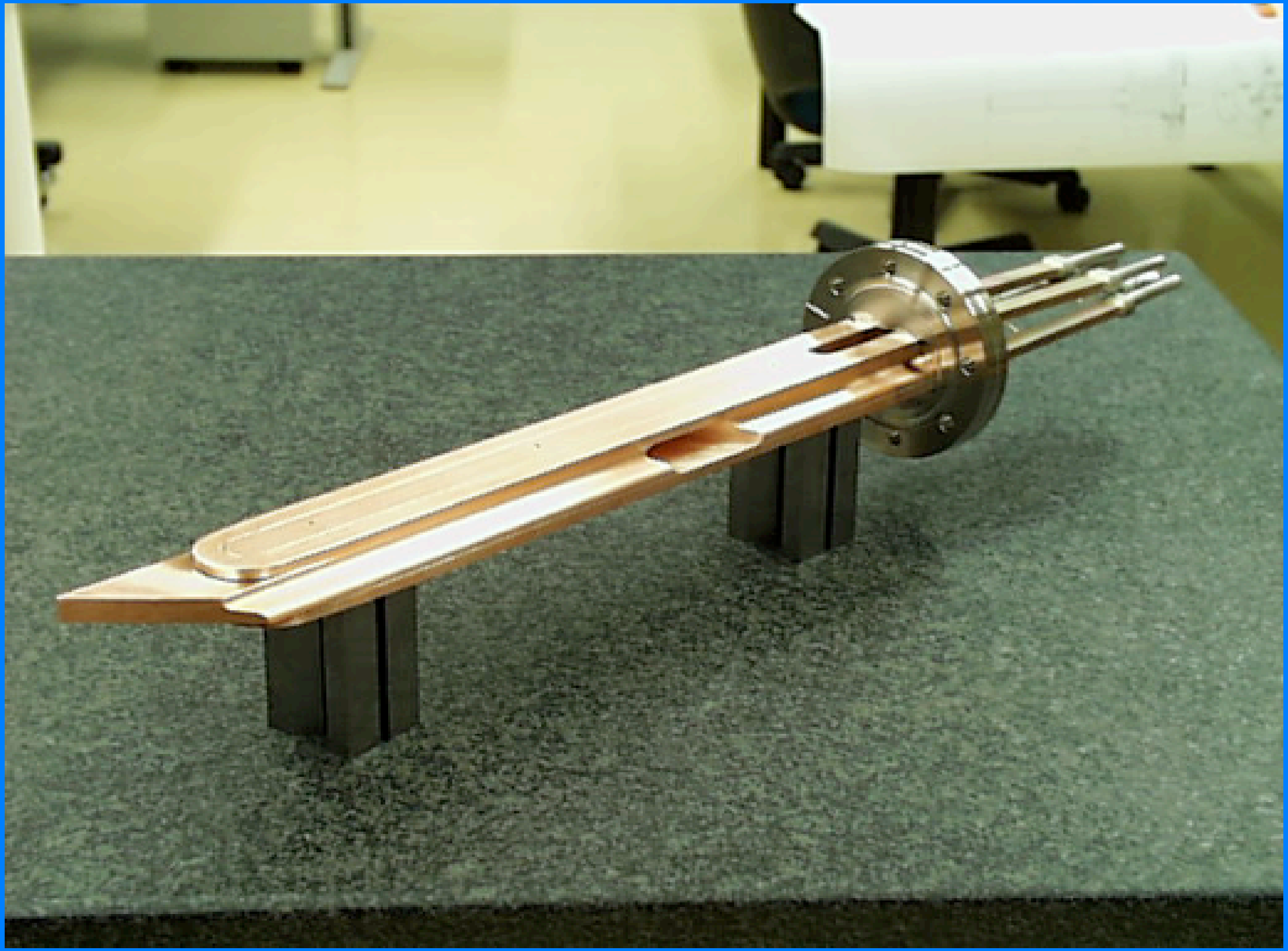
Radio Frequency Cavity from Cu with cooling channels



Bending magnet with the vacuum chamber



Photon absorber



Ron REID

Design of the accelerator vacuum system is not only the science

It is an art