Vacuum Chambers and NEG Coating Technologies

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- Dynamic gas density
- Role of surface and radiation
- Cold beam pipe. Hydrogen accumulation
- Other requirements for vacuum beam pipe
- LHC arc beam pipe
- Equations for residual dynamic gas density prediction
- Surface Conditioning
- Solutions made for LHC arc beam pipe

- NEG coating
- Example: PETRA III DWG

Very interesting but not in the presentation:
SuperKEKB solutions for EC mitigation, HF impedance
XFEL impedance budget. Technical solutions
MAX IV SR Source
NEG characterization at BINP
BINP technologies for vacuum chamber fabrication

Vacuum requirements

Residual gas density should be at level $10^5 \div 10^9$ cm^{-3} (pressure $4 \cdot 10^{-10} \div 4 \cdot 10^{-6}$ Pa at RT)

Metallic surface contains 10 ÷ 100 ML (1 ML ≈ 10^{15} cm^{-2}) of

- Chemically bound: MxOy, Mx(OH)y, Mx(HOC_3)y, carbon clusters
- Physically adsorbed: H_2O, organics

Example: Surface of a tube with D=5 cm contains on $10^7 \div 10^8$ times more molecules than ones inside the tube in gas phase at density 10^9 cm^{-3} !

Radiation can provoke dissociation of the molecules which causes desorption of:

- H_2 - most critical for cryogenic beam pipe because H_2 can re-desorb on surface with very low binding energy
- CO, CO_2
- Saturated hydrocarbons CxHy (due to catalytic reactions on surface)

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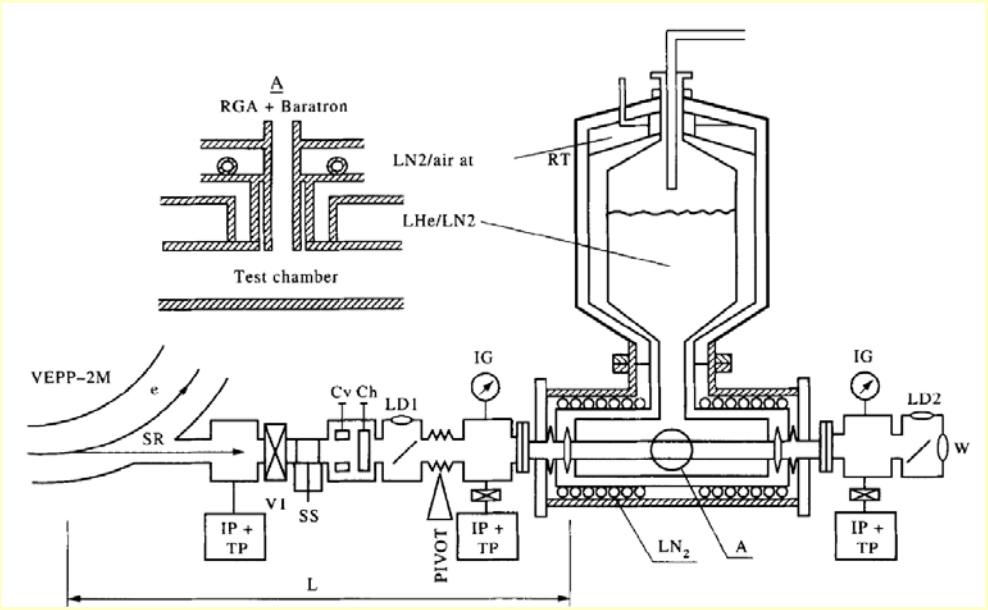
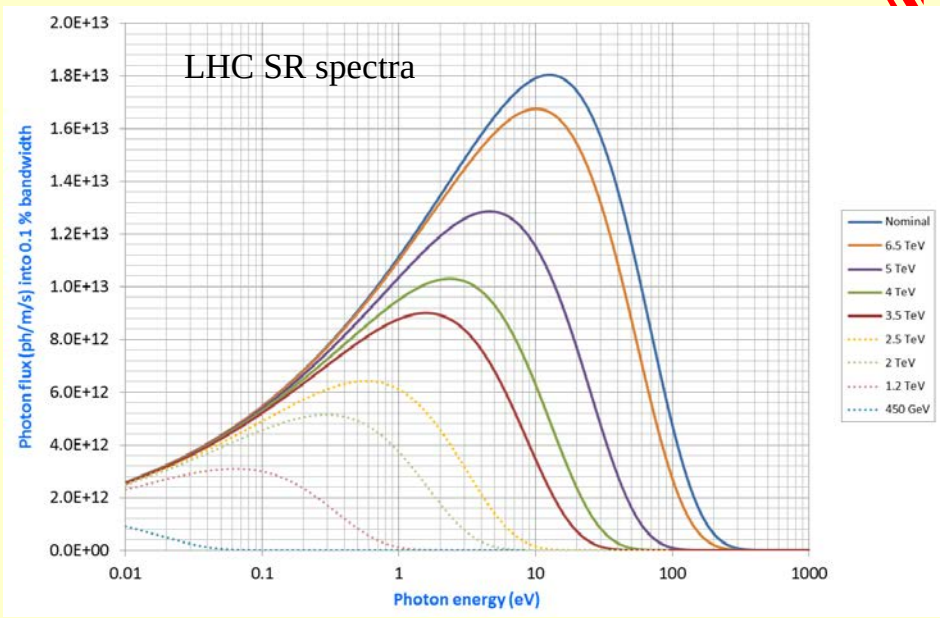
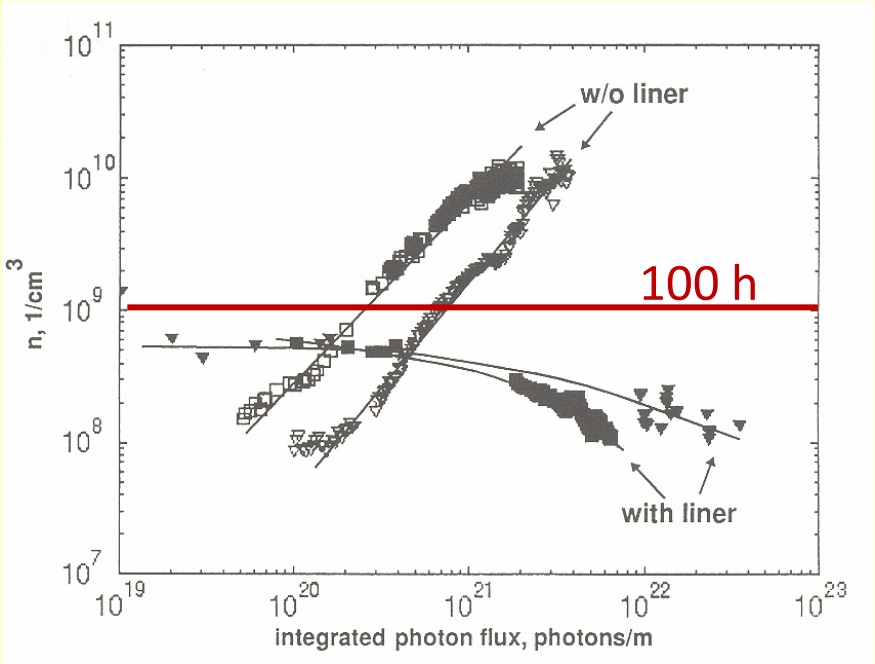
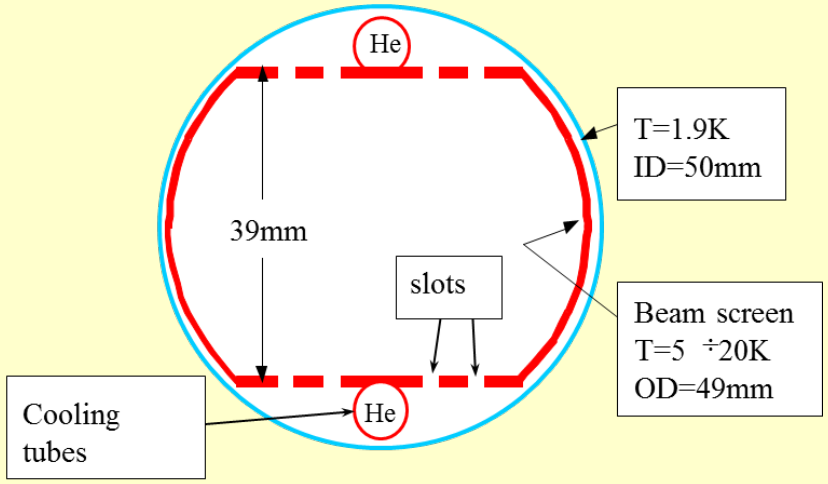
Dynamic density of hydrogen in cold pipe in presence of SR





Experiments at BINP (25 years ago!) in collaboration with SSC (20 TeV per beam) and CERN vacuum groups





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Other requirements

- **Vacuum tightness!**
- **Mechanical stability against external pressure or quenching**
- **Low SEY & PEY: Electron Clouds (EC) problems in case of high intensity positively charged beams**
- **Impedance: LF - resistive instability (LHC, FCC), HF: wake-field at connections, longitudinal non-uniformity, roughness, oxide layer (SuperKEKB at KEK, XFEL at DESY)**
- **Power absorption: SR, EC, Image Current**

Phenomena in LHC cold beam pipe

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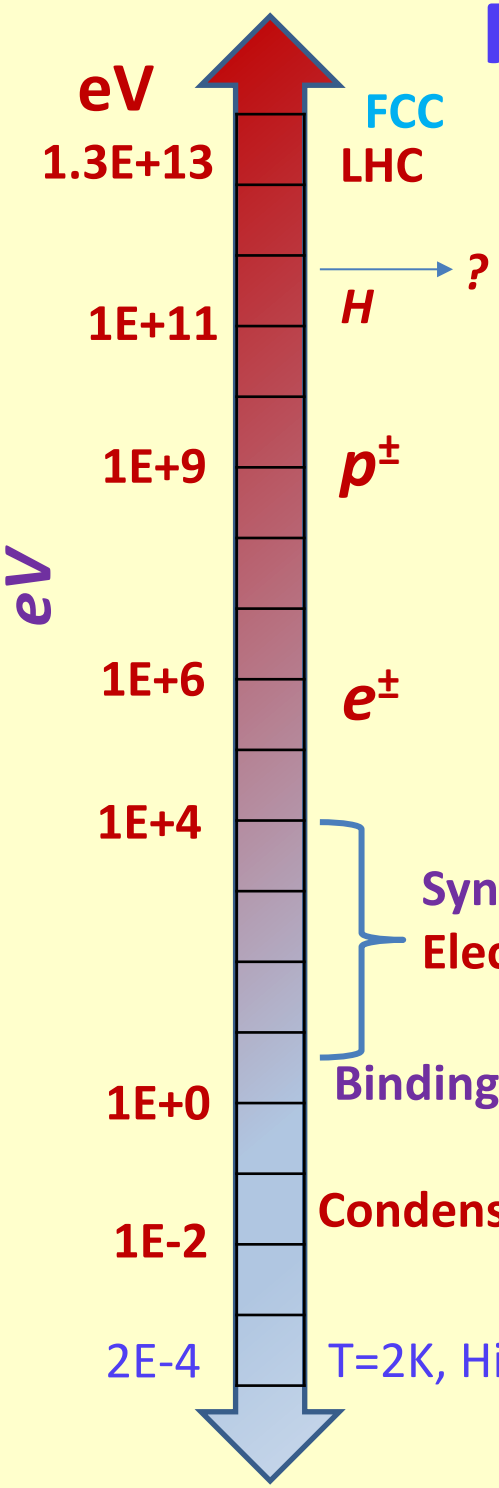

Dynamic residual gas density

$n < 1E9\ cm^{-3}$ for LHC in arcs

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Phenomena in cold beam pipe

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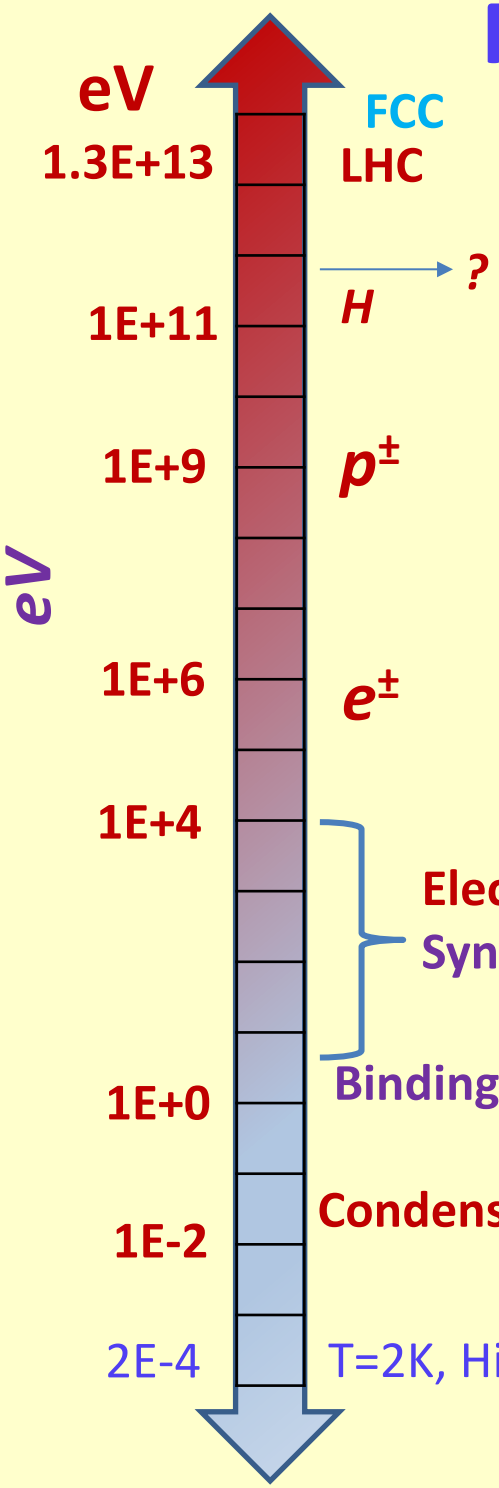
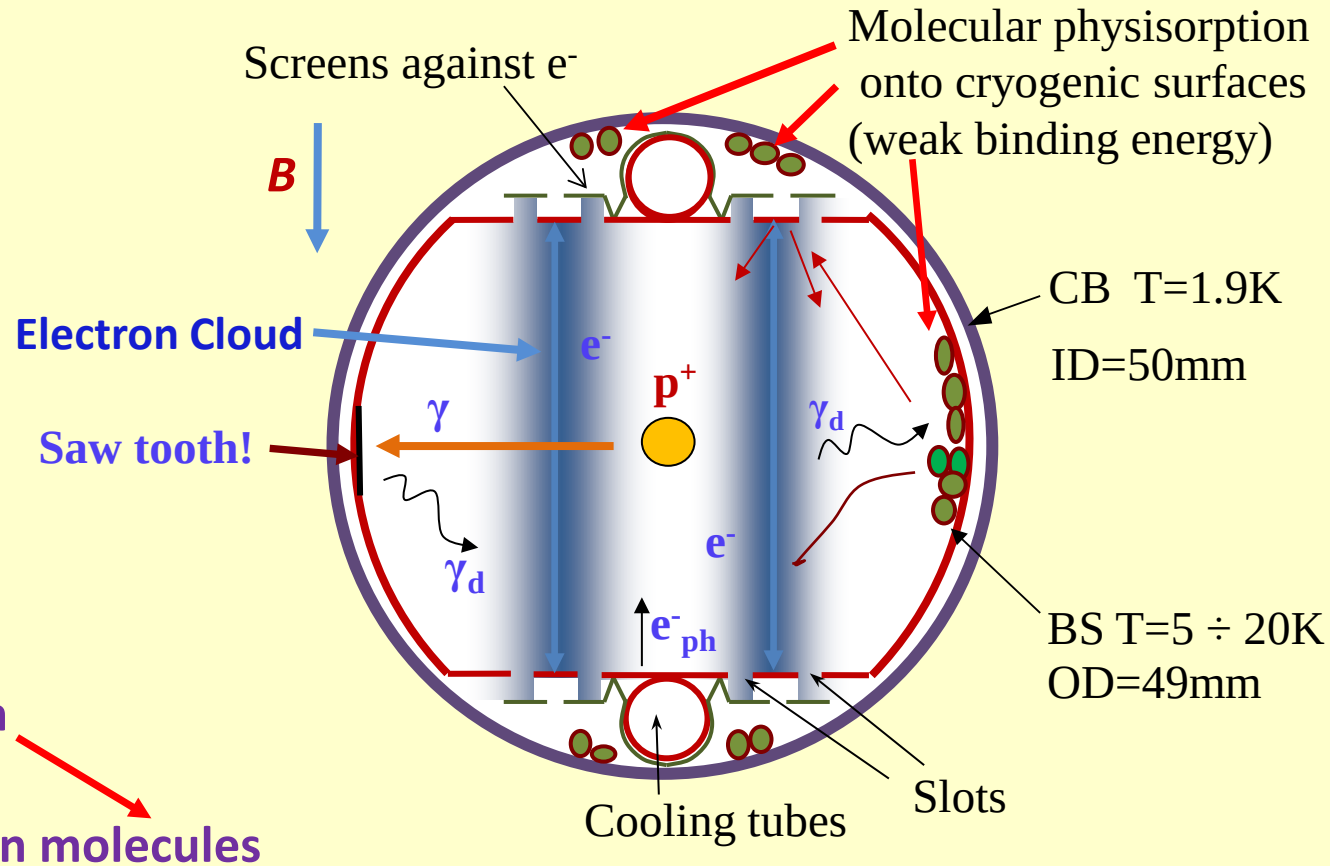


Cross-section of arc LHC beam pipe in dipoles



Dynamic residual gas density

$n < 1E9\ cm^{-3}$

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Equations for residual dynamic gas density prediction

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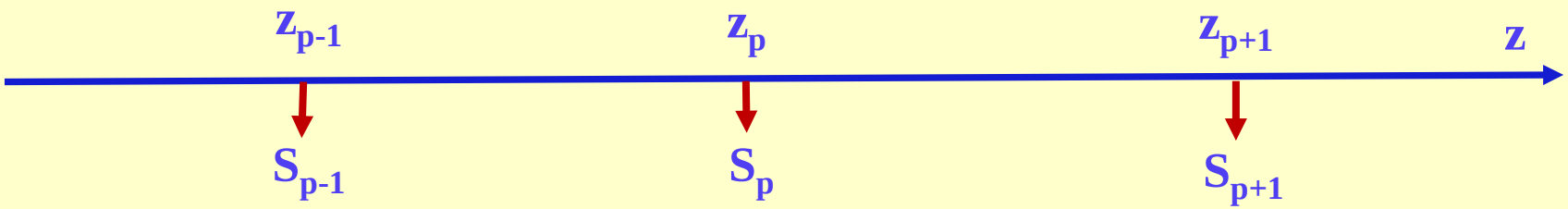

$$A\frac{\partial n_i}{\partial t} = q_i + q_i' + \frac{\partial\left(u_i \frac{\partial n_i}{\partial z}\right)}{\partial z} - \sum_p S_{pi}\delta(z - z_p)[n_i - n_{pi}] - s_i[n_i - n_{si}] - \sigma_i C_i l \cdot [n_i - n_{ei}] \approx 0$$

Limited by u_i **100 l/s** **10000 l/s**

re-cycling

$$l\frac{\partial a_i}{\partial t} = \sigma_i C_i l \cdot [n_i - n_{ei}] - q_i'$$

$C_i = \frac{1}{4}\vartheta$

a_i **- surface density of phisisorbed molecules**

l **– perimeter of the beam pipe cross-section**

$\sigma_i = f(a_1 \ldots a_i \ldots a_k, T)$ **- Sticking probability**

$n_{ei} = g(a_1 \ldots a_i \ldots a_k, T)$ **- Ultimate density**

$$q_i = \eta_i \dot{\Gamma} + \beta_i I_e + \sum_j \psi_{ij} I_j \qquad q_i' = \eta_i'(a_i)\dot{\Gamma} + \beta_i'(a_i) I_e + \sum_j \psi_{ij}'(a_i) I_j$$

$\dot{\Gamma}, I_e, I_j$ **- fluxes of photons, electrons and ions correspondingly**

$\eta_i, \beta_i, \psi_{ij}$ **- primary desorption yields at irradiation by photons, electrons and ions correspondingly**

$\eta_i', \beta_i', \psi_{ij}'$ **- secondary desorption yield (re-cycling)**

Equations for residual dynamic gas density prediction

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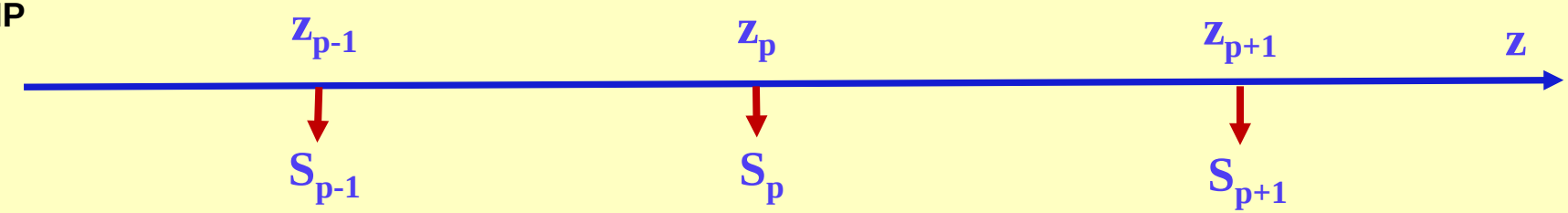
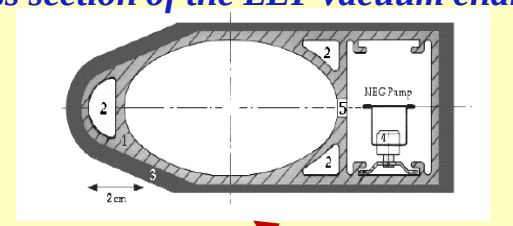
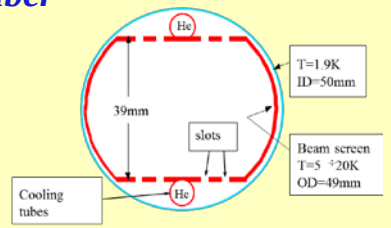


Cross section of the LEP vacuum chamber





LHC

Limited by u_i — 100 l/s — 10000 l/s

$$A\frac{\partial n_i}{\partial t} = q_i + q_i' + \frac{\partial\left(u_i \frac{\partial n_i}{\partial z}\right)}{\partial z} - \sum_p S_{pi}\delta(z - z_p)[n_i - n_{pi}] - s_i[n_i - n_{si}] - \sigma_i C_i l \cdot [n_i - n_{ei}] \approx 0$$

re-cycling

$$l\frac{\partial a_i}{\partial t} = \sigma_i C_i l \cdot [n_i - n_{ei}] - q_i'$$

a_i - surface density of phisisorbed molecules

l – perimeter of the beam pipe cross-section

$$C_i = \frac{1}{4}\vartheta$$

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$\dot{\Gamma}, I_e, I_j$ - fluxes of photons, electrons and ions correspondingly

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$\eta_i', \beta_i', \psi_{ij}'$ - secondary desorption yield (re-cycling)

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Conditioning

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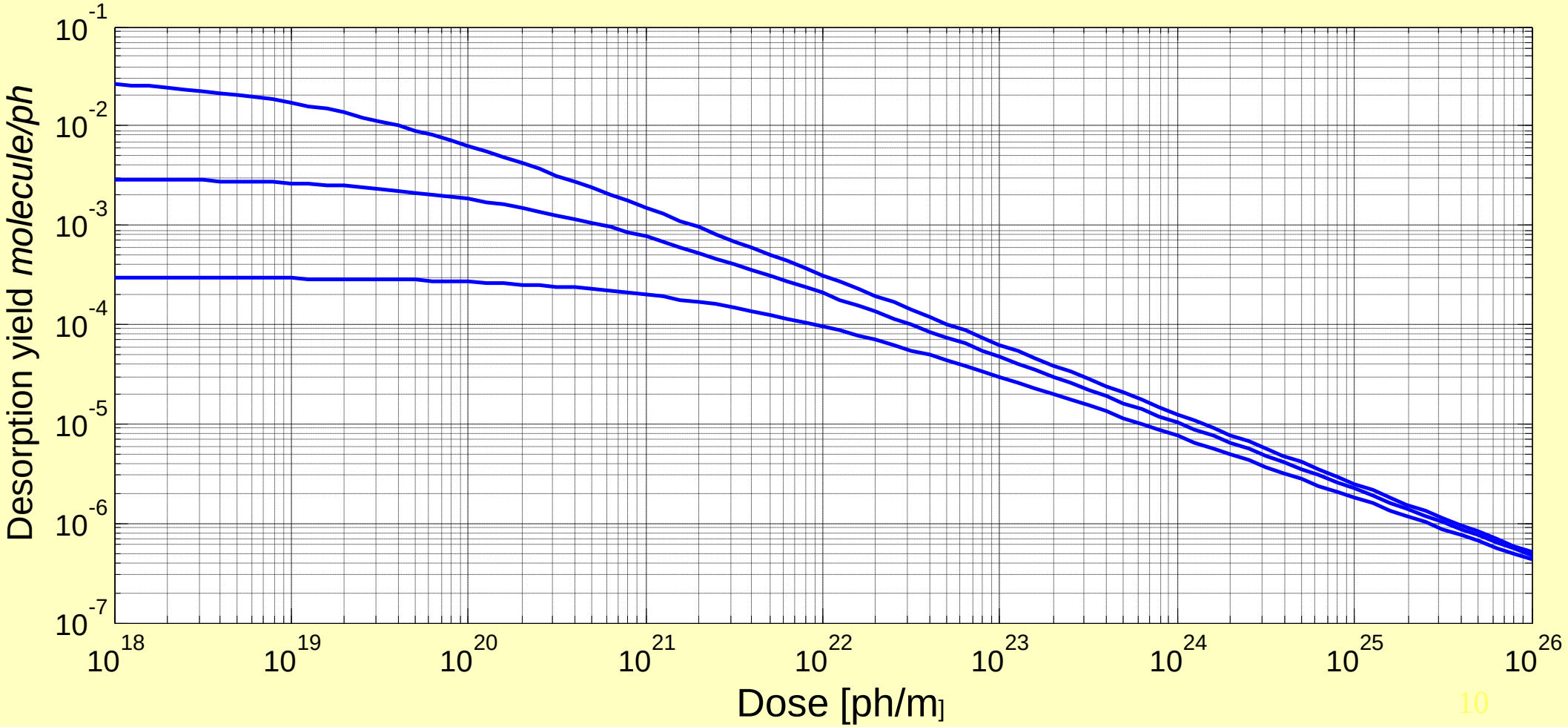
$$\eta = \eta_0 \frac{1}{1 + \left(\frac{\Gamma}{\Gamma_{1/2}} \right)^{\varepsilon}}$$

Photon stimulated desorption at RT

Electron stimulated desorption 30 – 100 times higher



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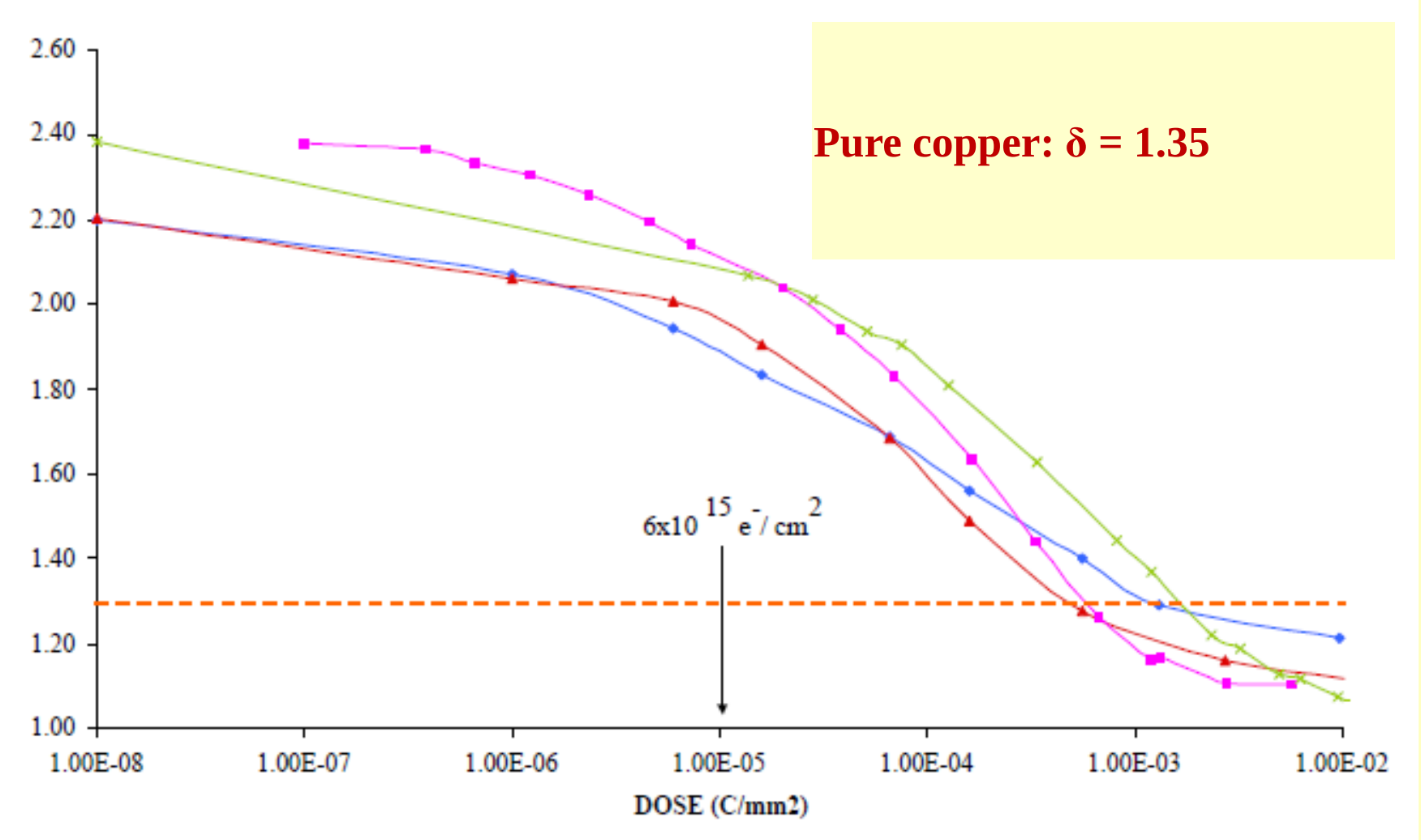
Surface conditioning (SEY must be less 1.3 for LHC arcs)

SEY measurements at CERN for copper samples:



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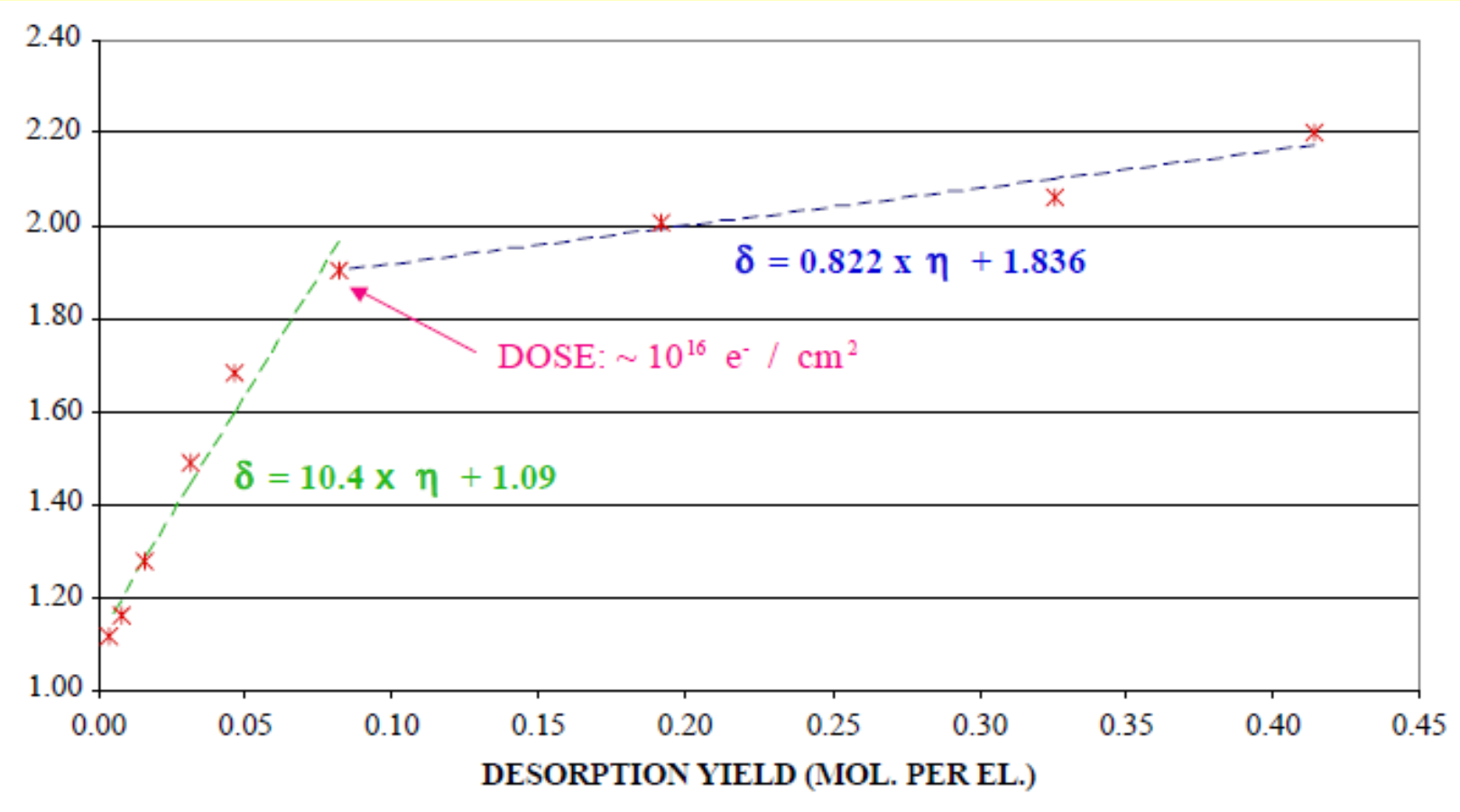
Relation between SEY and ESD during conditioning!



B.Henrist, N.Hilleret, C.Scheuerlein, M.Taborelli, G.Vorlaufer. The variation of the secondary electron yield and of the desorption yield of copper under electron bombardment: origin and impact on the conditioning of the LHC. Proceedings of EPAC 2002, pp. 2553-2555, Paris, France.

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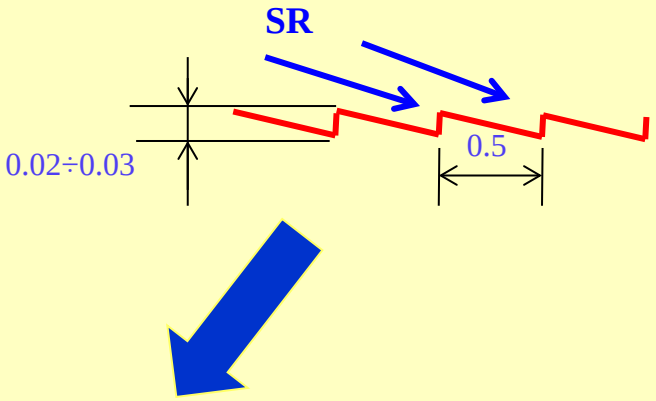
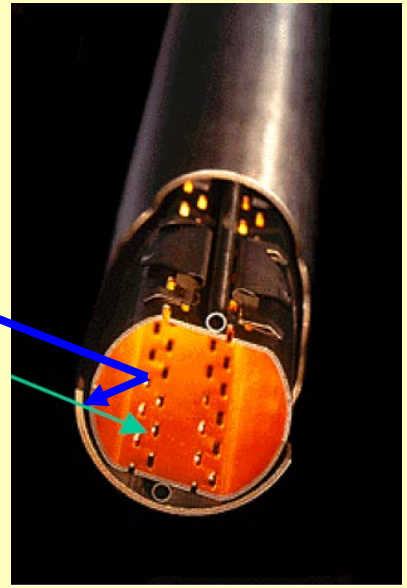
Important solutions made for LHC arc beam pipe

Beam screen: shading of CB against SR and EC, power absorption

Copper co-lamination: high electrical conductivity at cryogenic temperature

Saw tooth!





Decreasing number of diffusely scattered photons

- decreasing number of photo-electrons (3 ÷ 5 times!) and increasing of conditioning effectiveness

Open question: conditioning is slow in compare with laboratory experiments (10 times at least!)

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Future

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	LHC	HL-LHC	HE-LHC	FCC h-h	CEPC
Energy per beam, [TeV]	7	7	16,5	50	
Dipole field, [T]	8.4	8.4	20	16	
Current per beam, [A]	0.584	1.12	0.478	0.5	
Bending radius, km	2.8	2.8	2.8	10.4	
SR critical energy [keV]	0.044	0.044	0.575	4.3	
Beam pipe horizontal half aperture [cm]	2.3	2.3	~1.3	~1.3	
SR photon flax in arc [ph/m/s]	1E17	1.8E17	1.9E17	1.6E17	
SR incident angle in arc[mrad]	2.5÷5	2.5÷5	2.5÷5	~1.4	
SR max power in arc [W/m]	0.22	0.425	**5.6**	**36**	

Main problems for FCC:

- The SR power absorption
- The chose of the Beam Screen optimum temperature
- Long term prediction of the dynamic gas density

BINP is installing special SR beam line for vacuum investigations

There is experimental program for HL-LHC and preliminary program for FCC

CEPC conceptions of cold beam pipe are welcome to BINP for investigation!

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Low crass-section RT beam pipe

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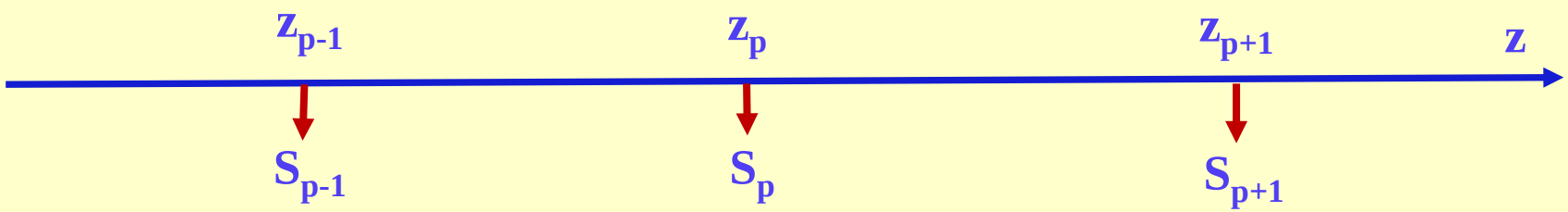
(narrow gap undulators, low emittance SR Sources)



$$A\frac{\partial n_i}{\partial t} = q_i + q_i' + \frac{\partial\left(u_i \frac{\partial n_i}{\partial z}\right)}{\partial z} - \sum_p S_{pi}\delta(z - z_p)[n_i - n_{pi}] - s_i[n_i - n_{si}] - \sigma_i C_i l \cdot [n_i - n_{ei}] \approx 0$$

Limited by u_i

~~100 l/s~~ ~~10000 l/s~~

Example: *u* **is in the range 1** ***l/s*m*****, L= 5m** $\dot{\Gamma} > 10^{18}$ *ph/m*

Even at low $\eta = 10^{-6}$ *moleculer/ph* **(about one year conditioning),**

corresponding equilibrium gas density is $n \approx \frac{\eta \dot{\Gamma} L^2}{12u} 10^{-3} \approx 2 \cdot 10^9\ cm^{-3}$

Or $P \approx 10^{-5}$ Pa **after 1 year operation!**

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Equations for residual dynamic gas density prediction

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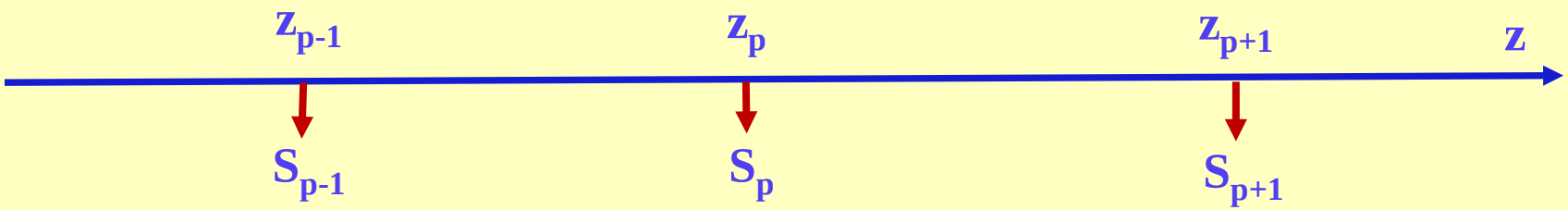

NEG coating!

Limited by u_i **100 l/s** **10000 l/s**

$$A\frac{\partial n_i}{\partial t} = q_i + q_i' + \frac{\partial\left(u_i \frac{\partial n_i}{\partial z}\right)}{\partial z} - \sum_p S_{pi}\delta(z - z_p)[n_i - n_{pi}] - s_i[n_i - n_{si}] - \sigma_i C_i l \cdot [n_i - n_{ei}] \approx 0$$

re-cycling

$$l\frac{\partial a_i}{\partial t} = \sigma_i C_i l \cdot [n_i - n_{ei}] - q_i'$$

Sorption capacity 1 ML. Lifetime ?

Most popular NEG composition is TiZrV – low activation temperature 180 °C

Advantages: low $\eta_i, \beta_i, \psi_{ij}$ and low SEY, high pumping speed

Disadvantages: Needs baking, low sorption capacity (lifetime ?)

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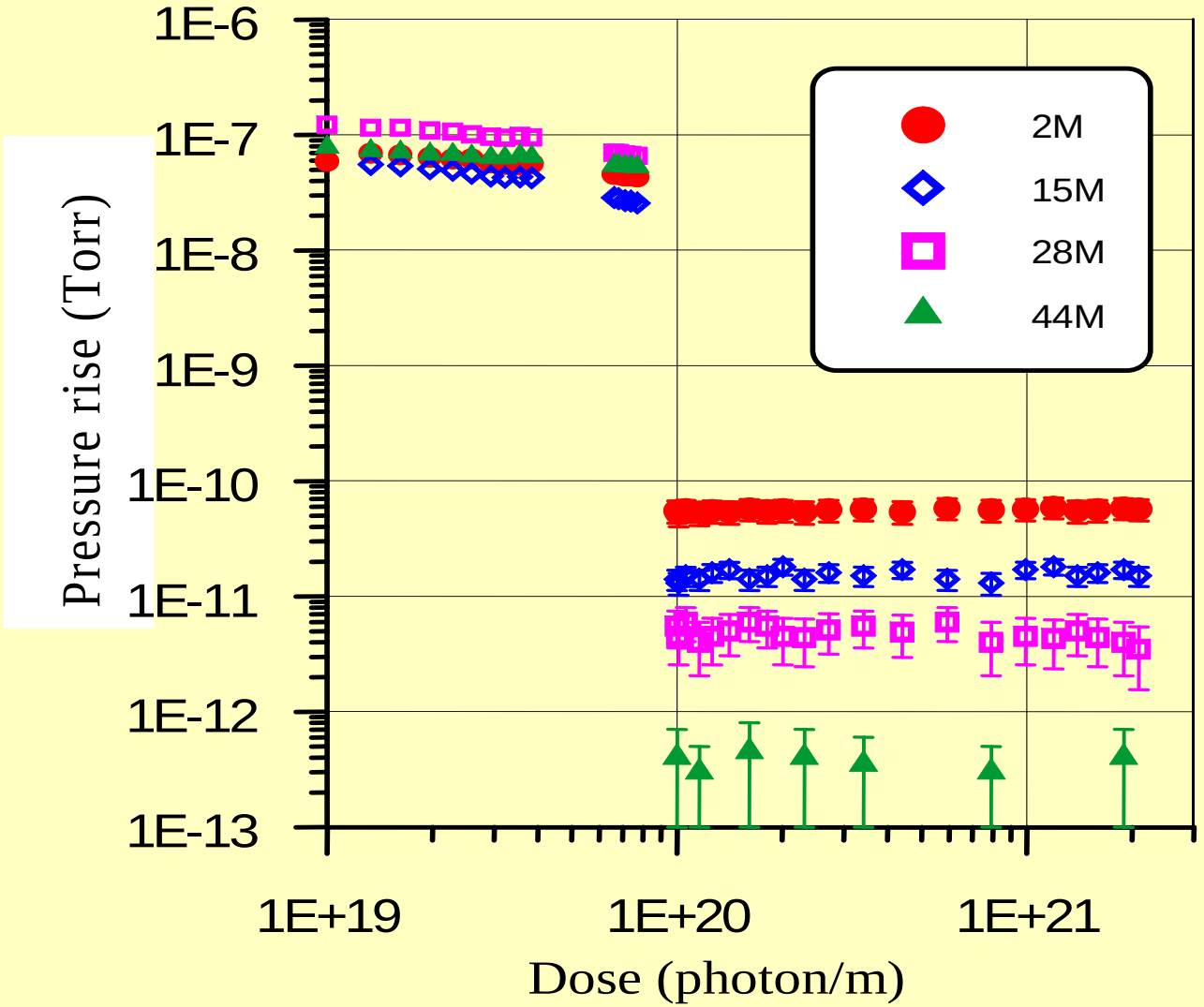
Investigation of TiZrV.



Effect of activation. Photon flax 4E16 ph/m/s

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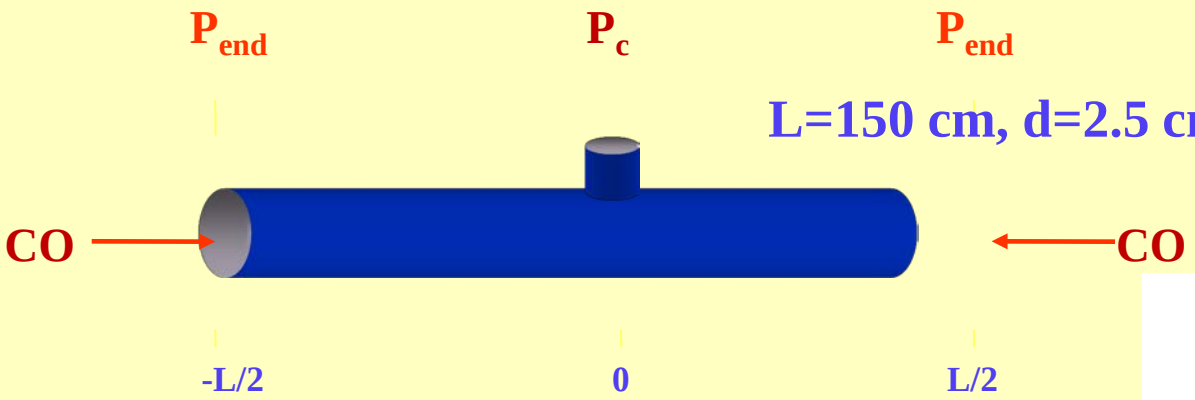
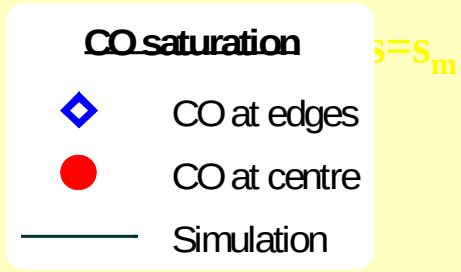
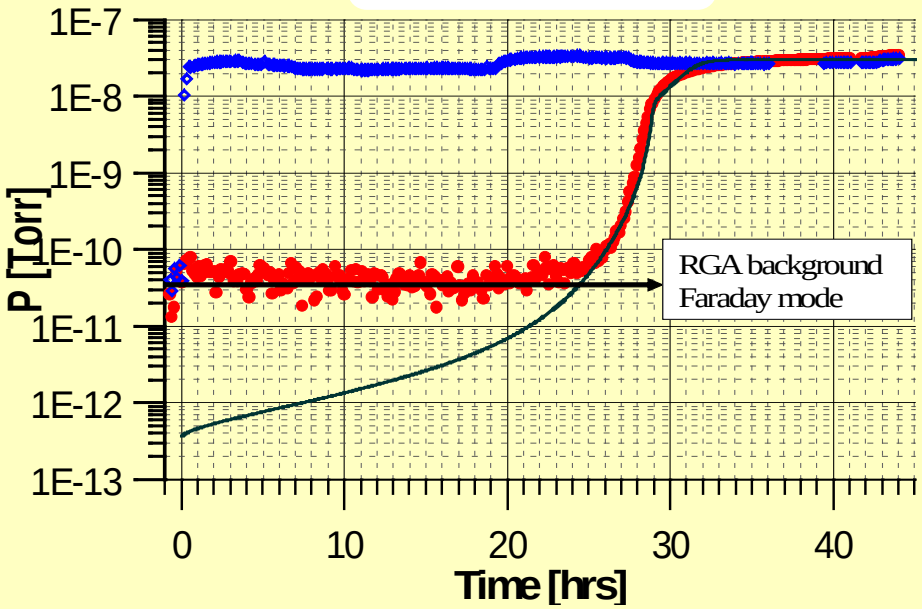
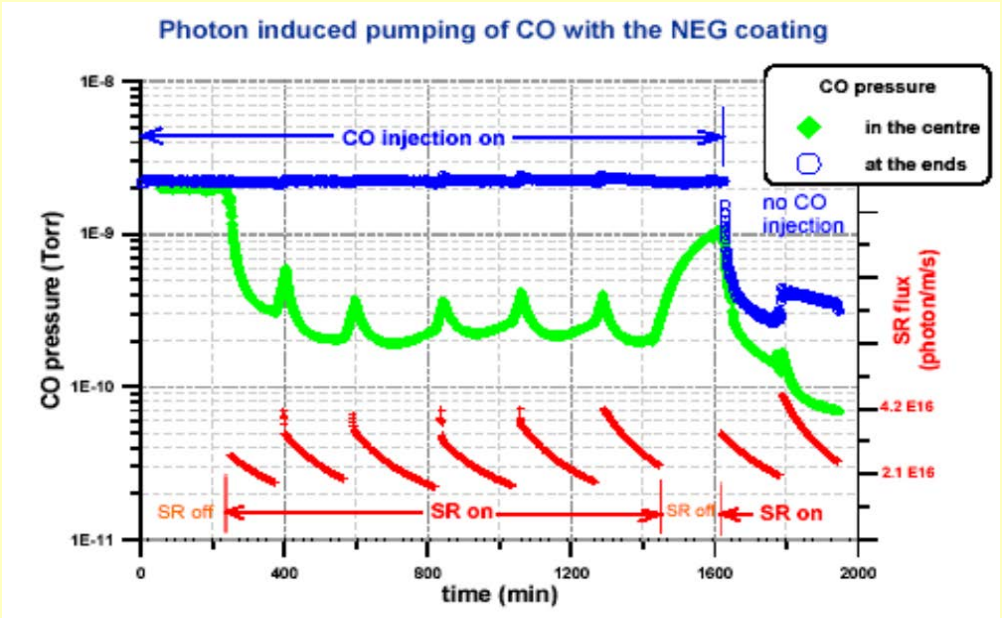
Experiment with saturated NEG









SR stimulate diffusion of molecules into NEG film!

– prolongation of lifetime!

- No re-cycling!

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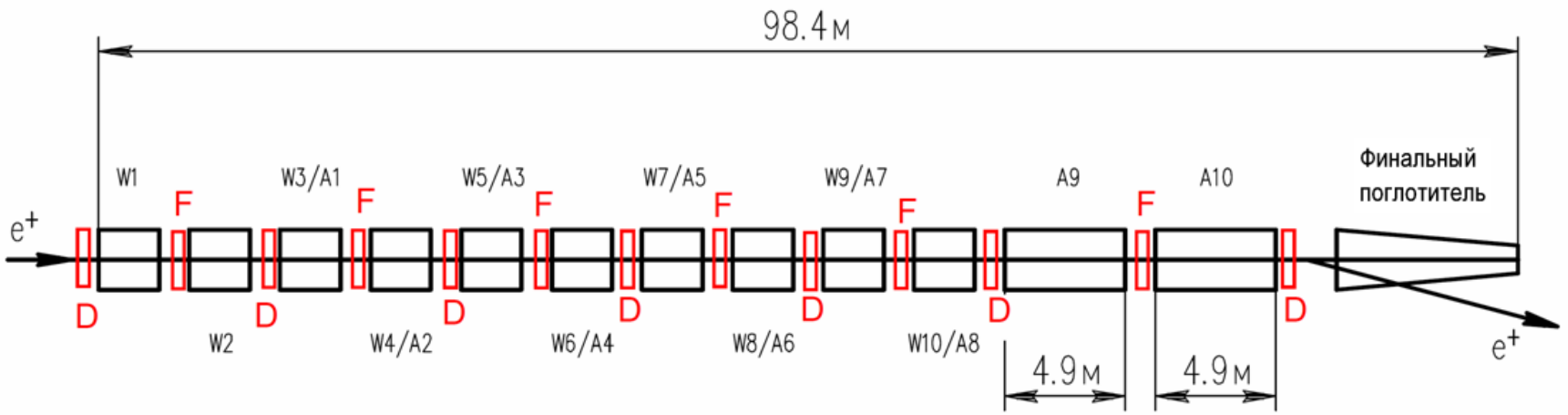
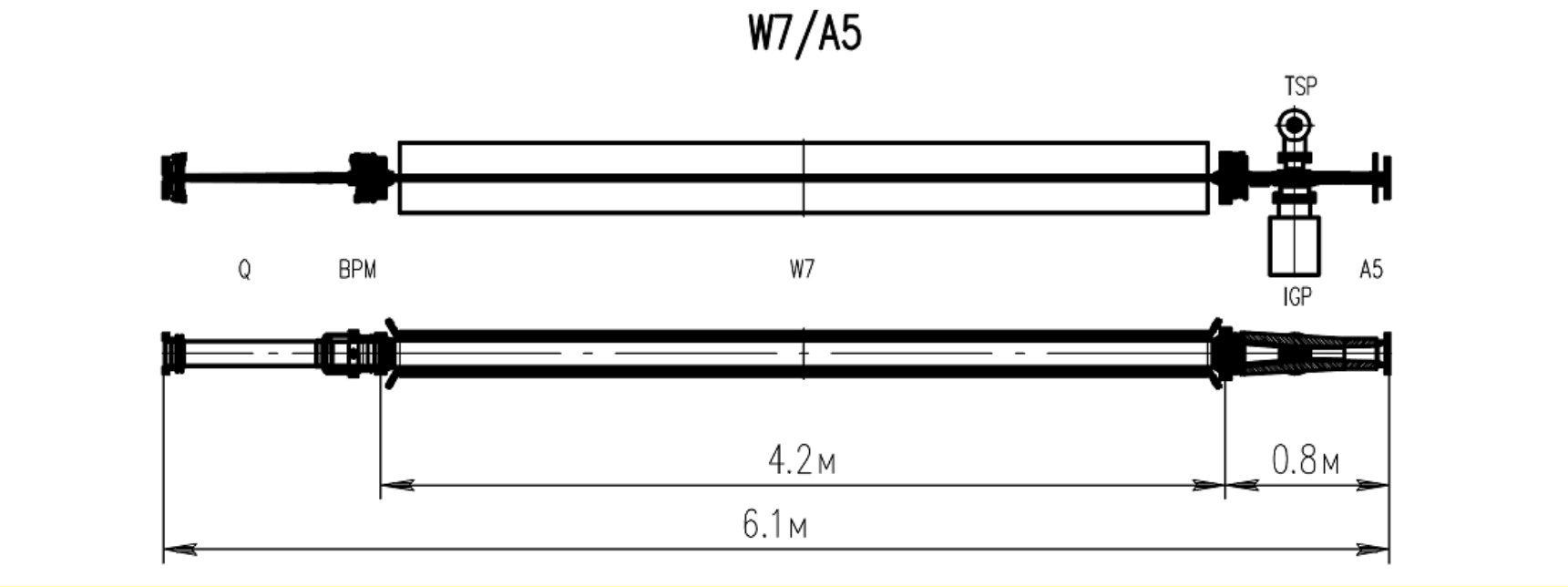
3.3 DWG PETRA III

Total SR power 2*450 kW . P < 2E-6 Pa





NEG deposition system

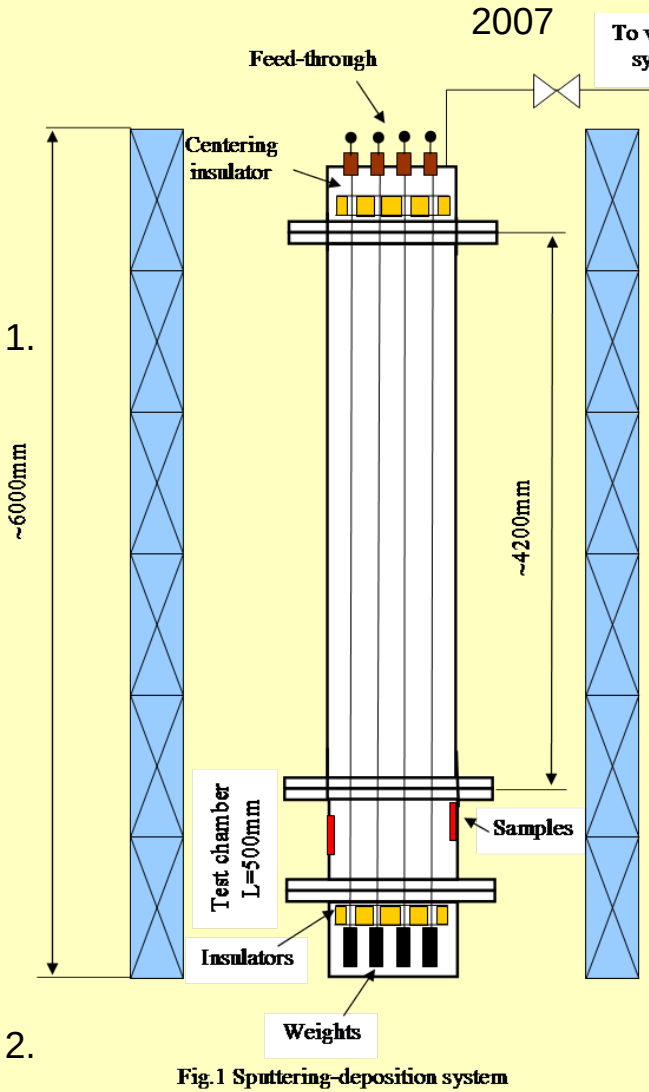


Fig.1 Sputtering-deposition system

Bmax=700G

E= 200 – 300 V

Power = 10 -15 W/m

4 PETRA III damping section wiggler chambers are deposited by TiZrV NEG film

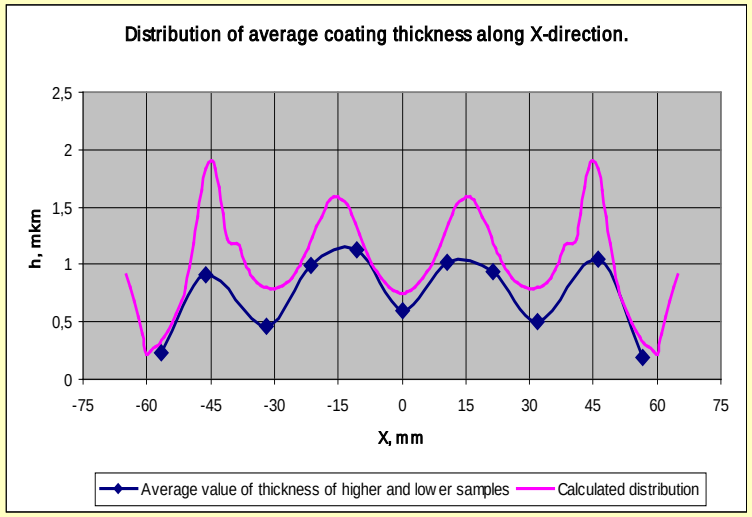


Fig.4. Distribution of average coating thickness along X–direction at Z = 2410 mm.

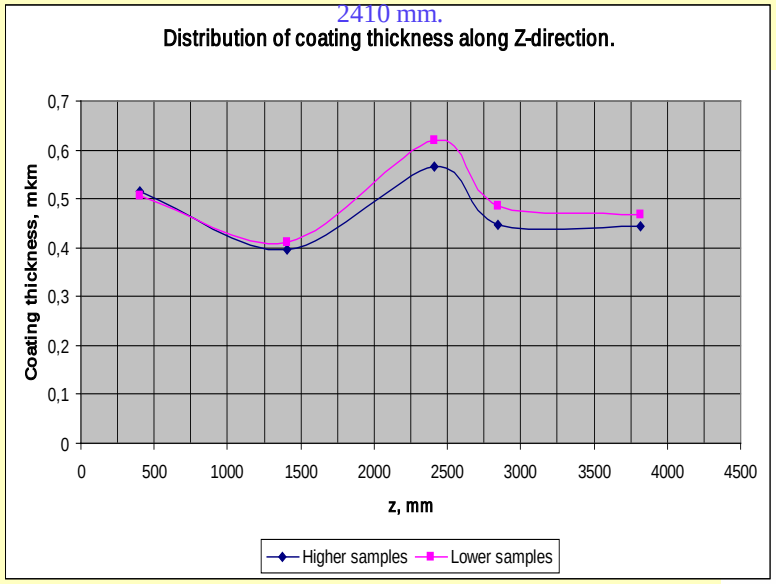


Fig.5. Distribution of coating thickness along Z–direction at X = 0 мм.

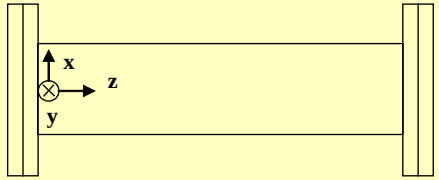


Fig.3. Sketch of the vacuum chamber.

	Weight composition, %	Atomic composition %
Ti	25	30.4
Zr	32	20.4
V	43	49.2

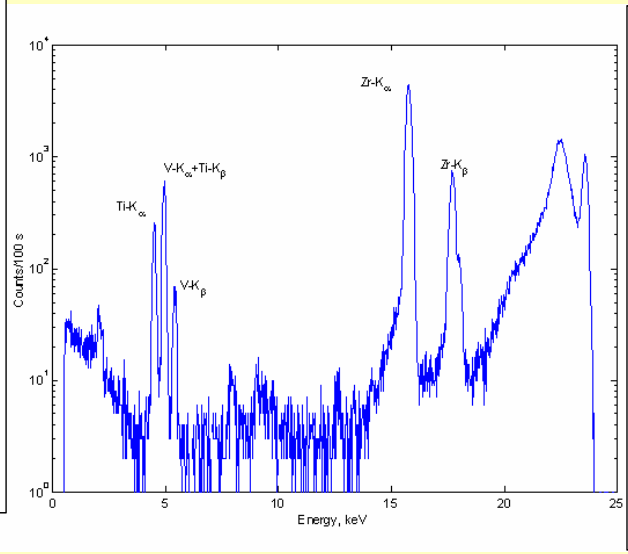


Fig.2. An example of XRF spectrum of getter sample.

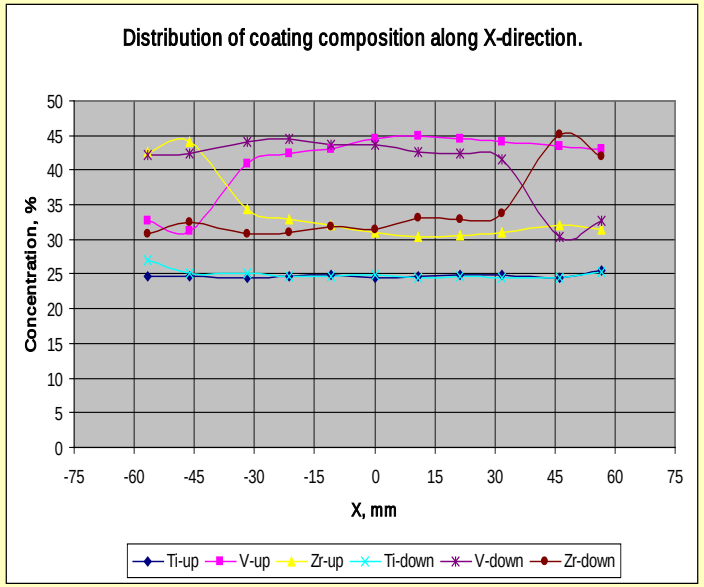


Fig.6. Distribution of coating weight composition along X-direction at Z = 2410 мм.

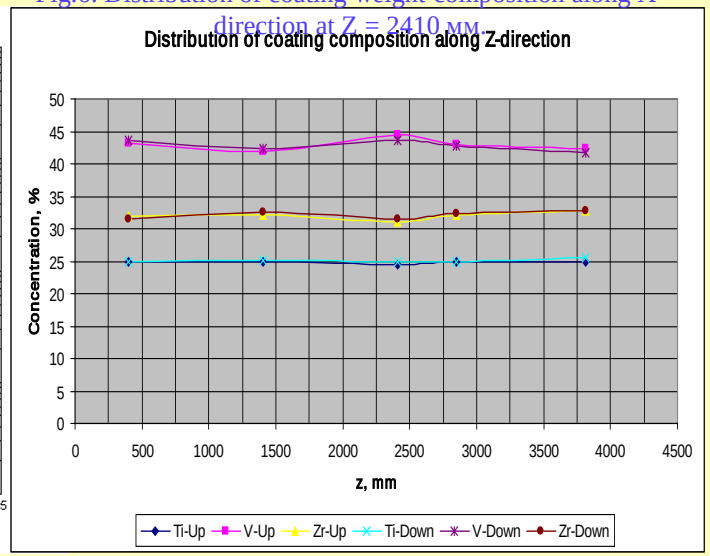
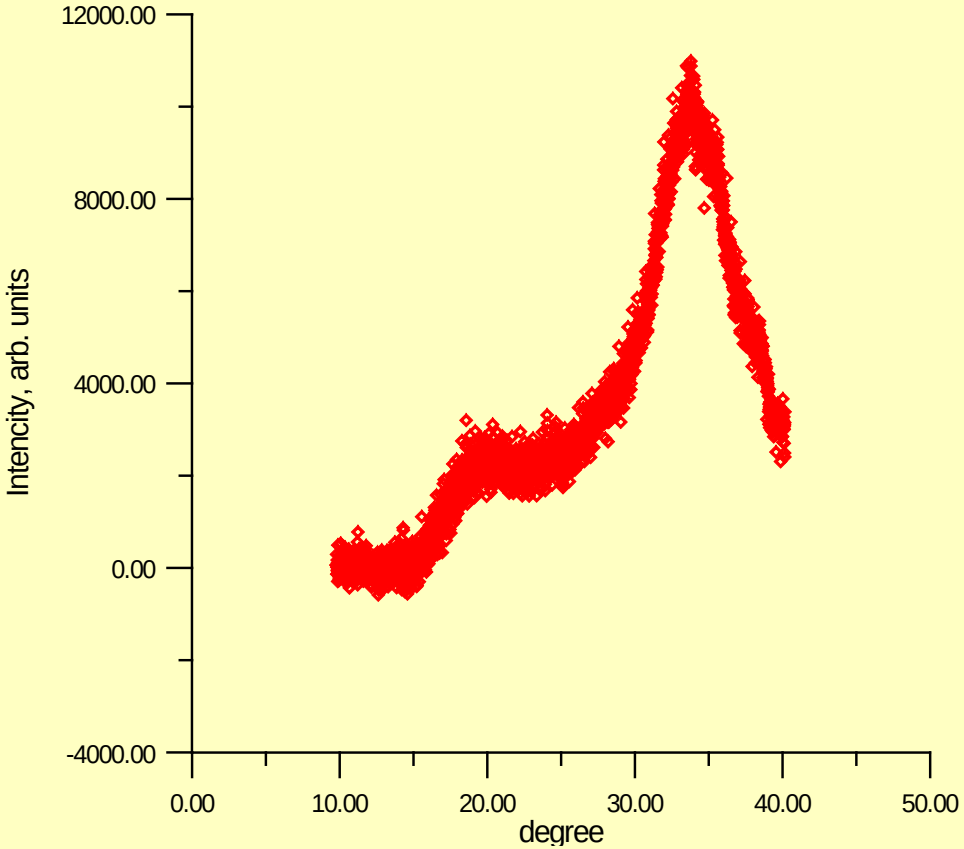


Fig.7. Distribution of coating weight composition along Z-direction at X = 0 мм.

X-Ray Diffraction (XRD) analysis

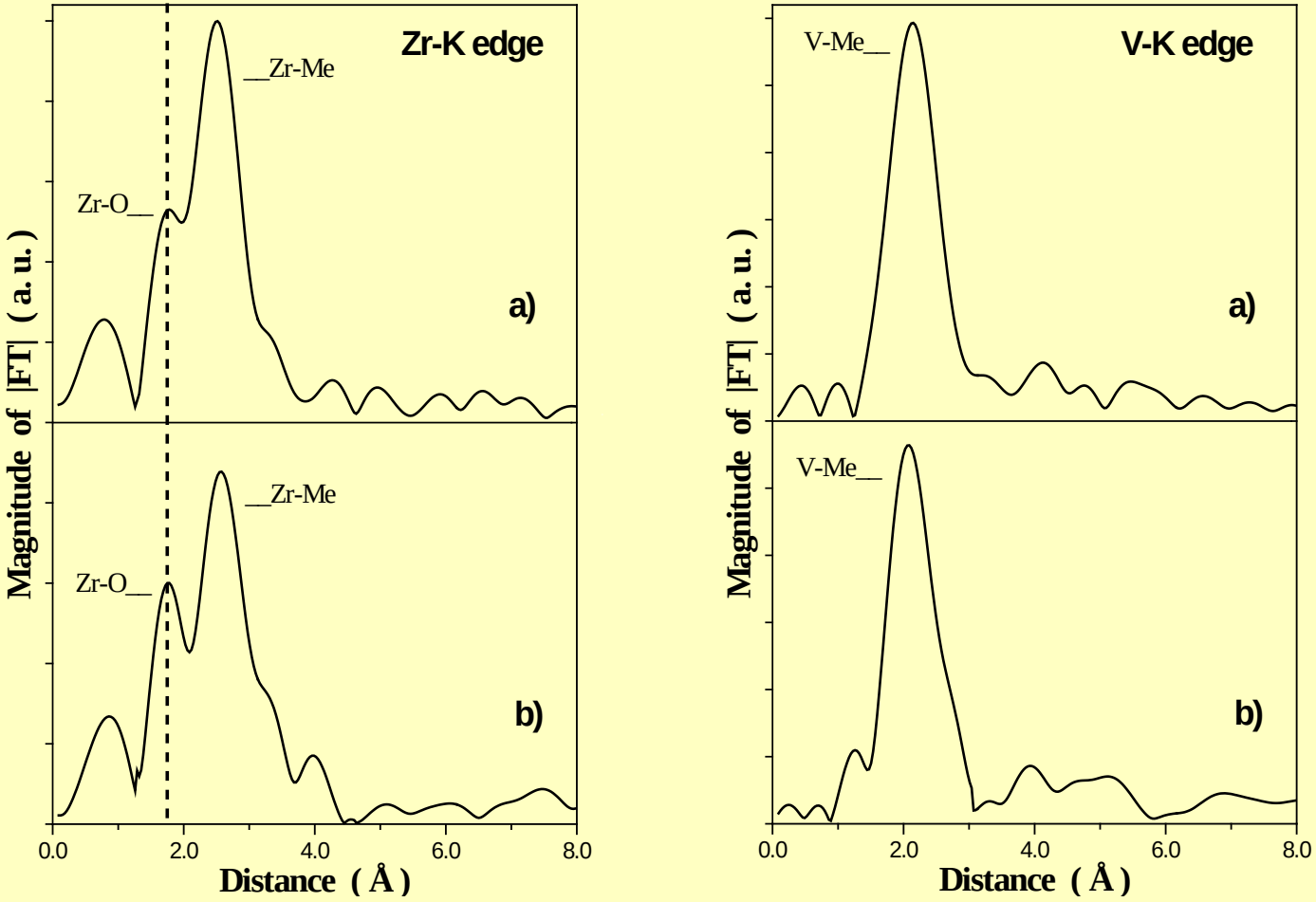


E_{ph}=8.048 keV

Substrate is amorphous pure quartz

The XRD pattern of coating seems to be typical for amorphous materials or for materials with very small particle size, not more than ~1.0-1.5 nm.

EXAFS



FT| curves describing zirconium and vanadium local arrangement: a) fresh getter; b) old getter

EXAFS preliminary layout

- Local coordination around Zr and V atoms of the fresh sample seems to be typical for that of metallic glasses. Indeed only one main peak corresponded to the first Me-Me distances is observed at |FT| curves of Zr and V spectra, around 2.5 and 2.2 angstroms, respectively. The values of Me-Me distances taken from |FT| curves are not physical ones, because they are not phase-corrected. The calculated correct values of bond length from Zr and V to the nearest neighbours correspond to 2.9 and 2.7 angstroms, respectively. Taking into account that the difference in metallic radii of Zr and V is also about 0.2 angstroms, one may conclude that the local atomic compositional coordination is uniform. It is also support the metallic glass model of the getter structure.
- Local coordination around Zr of the “old” sample considerably differs from the freshly deposited sample. A small peak at 1.6 angstroms seen at |FT| curve of fresh sample strongly increased in the case of old sample. This peak corresponds to Zr-O bond and reflects the formation of zirconium oxide at the getter surface under atmospheric conditions. As can be seen in Fig.7, the vanadium does not show any traces of oxidation in the freshly prepared sample. Even for the case of the aged sample the vanadium does not considerably oxidized. The magnitude of the peak at 1.3 angstroms, corresponding to V-O bond in |FT| curve, is very small compared to the main V-Me peak. It means that the only Zr atoms capture oxygen under atmospheric conditions.
- The potential of EXAFS spectroscopy for studying of the local atomic structure of ZrTiV NEGs is not limited by this study. In future one may to study the changes in structure of NEGs under their treatment and working cycles. In this case one may useful to increase the surface sensitivity of EXAFS method by means of the total electron yield (TEY) and (or) other well-known experimental techniques.

Thanks for your attention