NEG coating deposition of small-gap chambers: an industrial point of view

E. MACCALLINI
T. PORCELLI
M. MURA
P. MANINI

making innovation happen, together

SAES Getters S.p.A., viale Italia 77, 20045 Lainate, Italy

Contents

- NEG coating: critical aspects in Low Emittance Rings
- NEG coating in
  - Small gap and small diameter chambers
  - Curved chambers
  - Complex geometries
- Industrial challenges
- Conclusions

NEG coating multiple features

- NEG coating as a vacuum pump for particle accelerators was developed and patented at **CERN** for LHC (Large Hadron Collider).
- Typical NEG coatings are **~1 µm TiZrV**, deposited by **magnetron sputtering**.
- NEG coating can be activated at low temperature (e.g., **180 °C x 24 hours**) during machine bake-out.
- Several machines worldwide have already implemented this technology to boost machine performance & design (Soleil, MAX IV, Solaris, Sirius).
- Extensive work has been made by many groups through the years to study the properties of NEG coating (cf. literature from CERN, ESRF, LBNL, KEK, Daresbury, ...).

NEG coating: driving technological aspects

- In Synchrotron Radiation Sources, **NEG coating**
  - Provides a **distributed pumping** solution.
  - **Mitigates** the effect of **small conductance** on pumping speed.
  - Transforms the **pipe wall**, from a source of gas to a **pumping surface**.
  - Can effectively **pump** most gases (**H_2, H_2O, CO, N_2, O_2, CO_2**), except for noble gases and hydrocarbons.
  - Has a **low SEY**, **mitigates PSD** and **ESD**.
- In order to optimize the NEG coating characteristics, the following physical and chemical properties must be tuned
  - Thickness (capacity, impedance, PSD, SEY)
  - Morphology (pumping speed)
  - Compactness vs columnar
- It is complex to contemporary optimize all NEG coating characteristics
- An additional complexity is added by new Low Emittance Ring requirements…

Low emittance synchrotron light sources

- Low Emittance Rings require a step forward to many technologies
- **Low emittance** is needed to achieve **high brilliance** (e.g, the two parameters are inversely proportional)
- The **beam size** is in the µm scale
- In order to get these conditions, the **vacuum chambers diameter** is reduced down to **(10÷20) mm**

Vacuum implications of the low emittance requirement

- From the vacuum point of view, low emittance is challenging and it has a strong impact on the design of a storage ring:
  - Several **compact magnet lattices** are needed for strong focusing (quadrupoles), chromaticity correction (sextupoles) and SR generation (IDs).
  - Beam lifetime is threatened by **beam-beam** (Touschek effect) and **beam-gas** interactions.
  - Beam-on pressure should be in the **UHV** range (at least 10^{-9}–10^{-10} mbar).
  - The management of **SR power** deposited on the chamber walls is not straightforward, from both the **thermal** and **PSD outgassing** points of view.

- **Small-aperture** beam pipes and **narrow-gap** chambers for IDs are needed.
- **Antechambers** for pumping and **heat-load handling** (beam absorbers) are not always feasible.
- Space for traditional **large vacuum pumps** close to the beamline is reduced.
- Chambers made of a material with a **good thermal conductivity** are envisaged, as well as **distributed cooling**.

Low emittance machines

- In recent years, new machines have been built (Sirius, MAX IV) and many existing facilities have started to plan major upgrades, which are already underway or will start in the next few years (APS-U, ALS-U, ESRF II, HEPS, Soleil Upgrade, Elettra 2.0, SLS II, Diamond II, Petra IV, Spring-8 II, …).
- All these projects aim at a high brilliance, thus at the lowest possible emittances.
- The ideal goal are **Diffraction-Limited Storage Rings** (DLSR), where the beam emittance should approach the diffraction limit.
- For most of these projects, **NEG coating** is one of the enabling technologies to achieve the target dynamic pressure and beam parameters.

NEG coating for narrow-gap beam pipes

Strengths	Weaknesses
-Distributed pumping of main gases -Mitigation of PSD, ESD and SEY -Reduce outgassing	Difficult deposition in not cylindrical geometries
Opportunities	**Threats**
To be explored the NEG coating with reverse technique developed at CERN	Given higher complexities, reproducible deposition for large productions must be explored

NEG coating for narrow-gap beam pipes

Threats
Given higher complexities, reproducible deposition for large productions must be explored

- NEG coating of complex narrow chambers needs optimization of industrial process

NEG coating properties on standard large chambers

		H_2	CO	N_2	CH_4
Maximum sticking probability	smooth	$8x10^{-3}$	0.7	$1.5x10^{-2}$	
	rough	$3x10^{-2}$	0.9	$3.0x10^{-2}$	
Surface capacity [molecules cm^{-2}]	smooth		$8x10^{14}$	$1.5x10^{14}$	
	rough		$8x10^{15}$	$1.5x10^{15}$	
Electron stimulated desorption yields [molecules per impinging electron]	electron energy = 500 eV negligible dose	$2x10^{-4}$	$1x10^{-4}$		$5x10^{-6}$
Photon stimulated desorption yields [molecules per impinging photon]	Ec=194 eV [51] negligible dose, normal incidence	$3x10^{-6}$	$<2x10^{-8}$		$<3x10^{-8}$
	Ec=4.5 KeV [41, 42] 10^{21} ph m^{-1} 10 mrad incidence	$1.5x10^{-5}$	$<10^{-5}$		$2x10^{-7}$

Tab.1: Summary of the some functional properties of Ti-Zr-V film coatings. Pumping speed and gas capacity are referred to film coated at 100°C (smooth) and 250°C (rough). Electron and photon desorption yields are reported only for smooth films. Pumping speed and gas capacity can be improved by increasing the substrate roughness.

P. Chiggiato and P. Costa Pinto, Thin Solid Films 515 (2006) 382–388.

STICKING PROBABILITY α

$$S = \frac{1}{4} \cdot \langle v \rangle \cdot \alpha \cdot A$$

NEG coating properties on standard large chambers

How these properties change in narrow chambers for Low Emittance Ring?

Tab.1: Summary of the some functional properties of Ti-Zr-V film coatings. Pumping speed and gas capacity are referred to film coated at 100°C (smooth) and 250°C (rough). Electron and photon desorption yields are reported only for smooth films. Pumping speed and gas capacity can be improved by increasing the substrate roughness.

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The road from prototypes to industrialisation

- Being an industrial player, SAES is involved in both **R&D activities** and **industrialisation** of the NEG coating process.

R&D: feasibility study on new chamber designs

- Proposal of "NEG coating-oriented" geometry modifications
- Design and fabrication of specific tooling (holders, spacers, extensions, …)
- Theoretical calculation of deposited thickness profile
- MolFlow+ simulations
- Deposition trials
- Film characterisation (SEM/EDX, XRF, profilometer, transmission factor)

Industrialization: coating several chambers of the same type for big upgrade projects

- Make the deposition process robust (UHV cleaning, plasma stability)
- Ensure reproducibility
- Production plan (time and cost effectiveness)
- QA & QC (PFMEA, control plan, CoT) from raw materials (cathodes) to final product

Ongoing NEG coating activities at SAES

- Several activities—also in collaboration with synchrotrons and research facilities throughout the world—are currently ongoing to assess NEG coating deposition in

Small gap and small diameter chambers

  - R&D activities in collaboration with **Soleil** (transmission factor and PSD measurements) in view of their future machine upgrade;
  - NEG deposition in small tubes (ID down to 6 mm) and pumping characterisation (transmission factor measurements).
  - NEG deposition in long and narrow insertion devices (down to 5 mm vertical gap, 4 m long);

Curved chambers and complex geometries

  - NEG deposition in complex-shape chambers for **ALS-U** (strong curvature, small gaps, variable keyhole sections).

Additional activities

  - R&D on **copper** coating deposited by magnetron sputtering (same technique as for NEG coating).

- In 2021-2022, NEG coating of several hundred chambers for Low Emittance Ring

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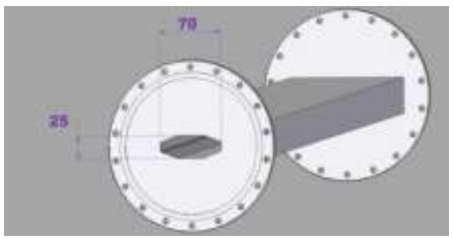
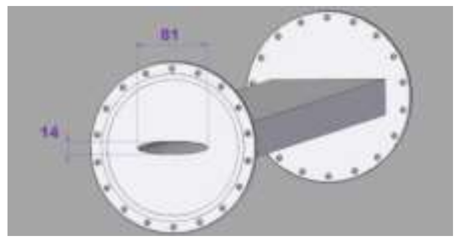
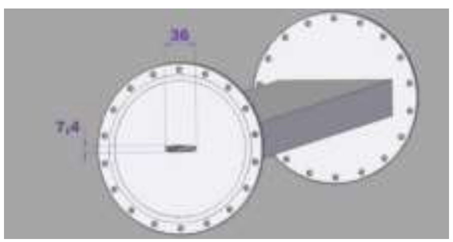
- NEG coating of **500+** Inconel and aluminium chambers (ID 22 mm) to be for **APS-U** will start in the following months.

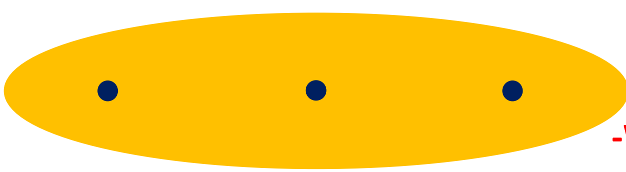
NEG coating of high aspect ratio chambers

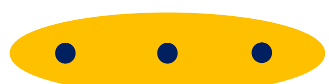
- NEG coating of high aspect ratio chambers is often necessary to meet the working parameter of new machines.
- Insertion devices: vertical gap down to 7 mm or even 5 mm.
- Circular beam pipes: ID>20 mm, down to 6 mm, is often requested.





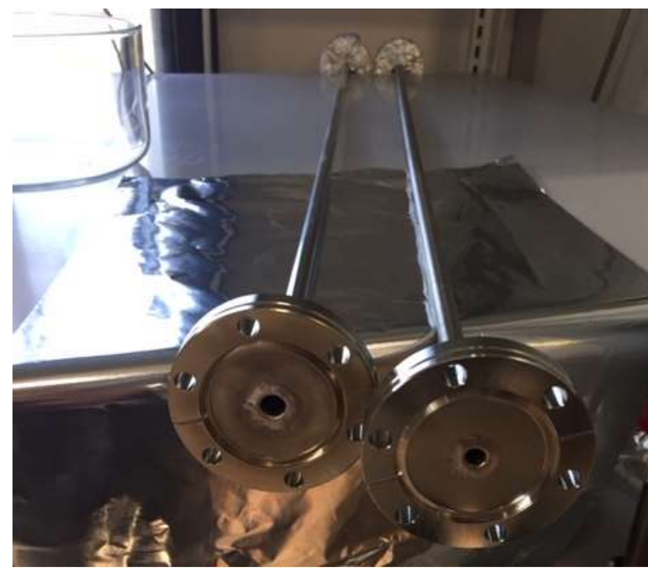






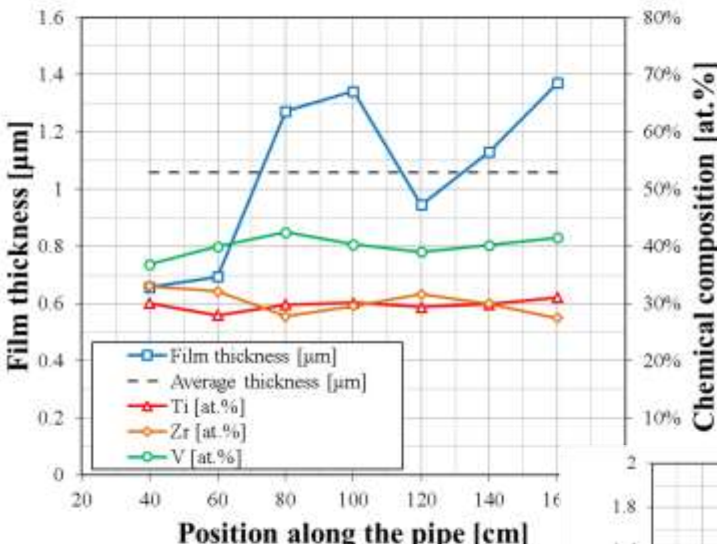
Many challanges

-Working pressure
-Cleaning
-Cathode misalignment

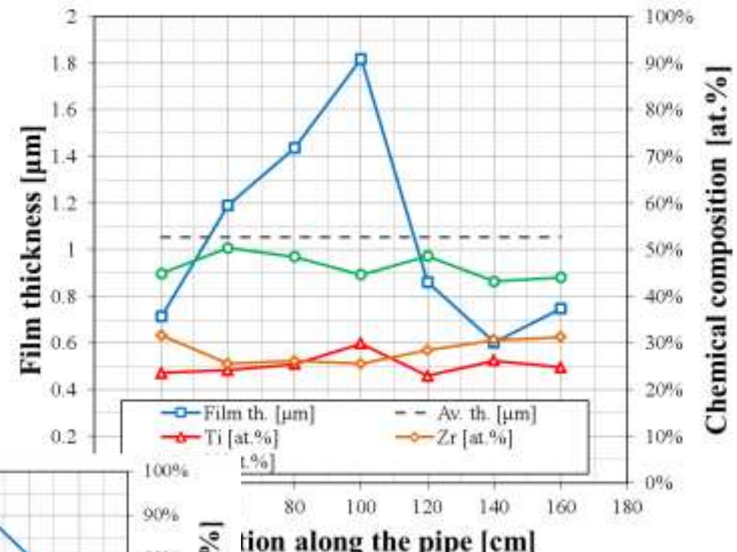


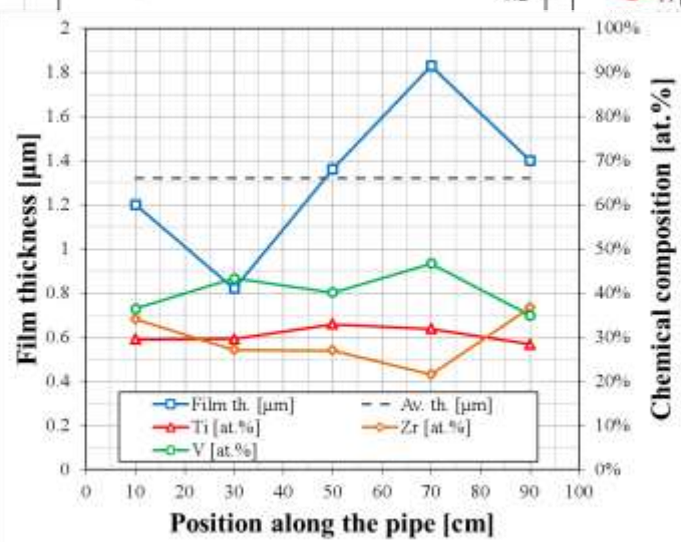
Thickness and chemical-composition profiles

ID=10 mm
Average thickness: ~1 µm (±38%)



ID=8 mm
Average thickness: ~1 µm (±43%)





ID=6 mm
Average thickness: ~1.3 µm (±38%)

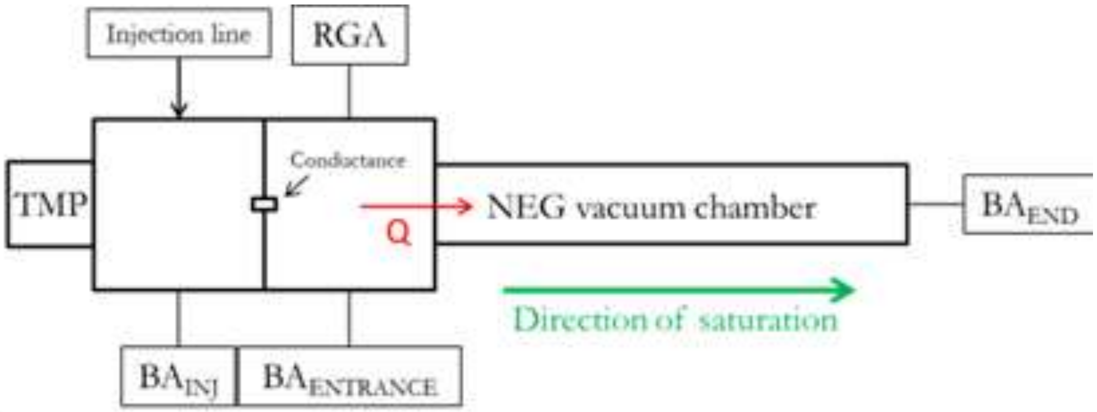
Thickness and chemical composition measurements were made by **EDS** at different positions along the pipe.

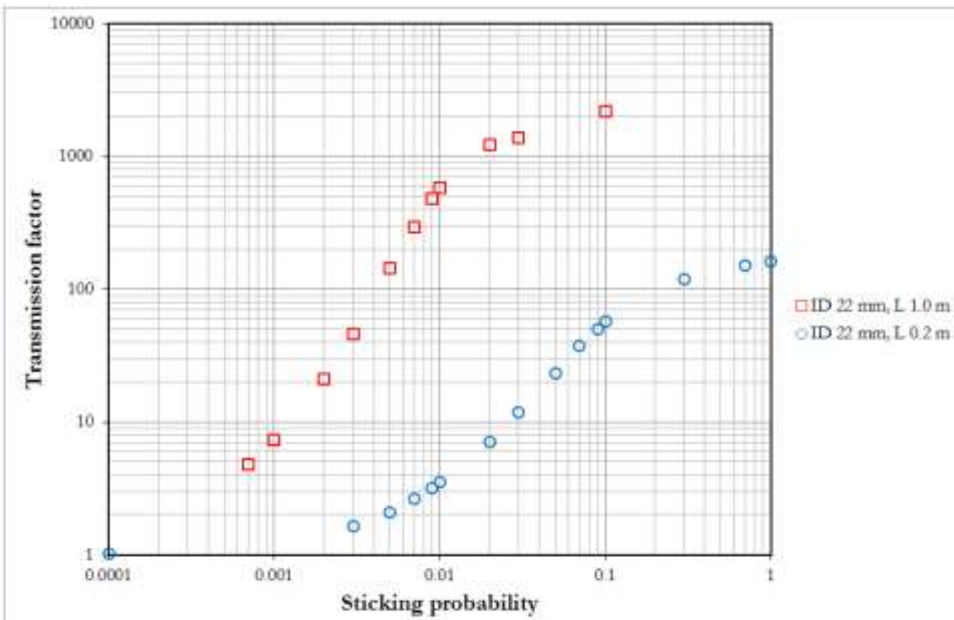
T. Porcelli et al., NEG coating deposition and characterisation of narrow-gap insertion devices and small-diameter chambers for light sources and particle accelerators, Vacuum, 138 (2018), 157-164

Transmission factor test-bench

- Fischer-Mommsen dome equipped with three extractor gauges and LN_2 cold fingers, to deal with transmission factor measurement of chambers with a high aspect ratio.

From Tr factor to sticking probability





$$Tr = \frac{\Delta P_{ENTRANCE}}{\Delta P_{END}}$$

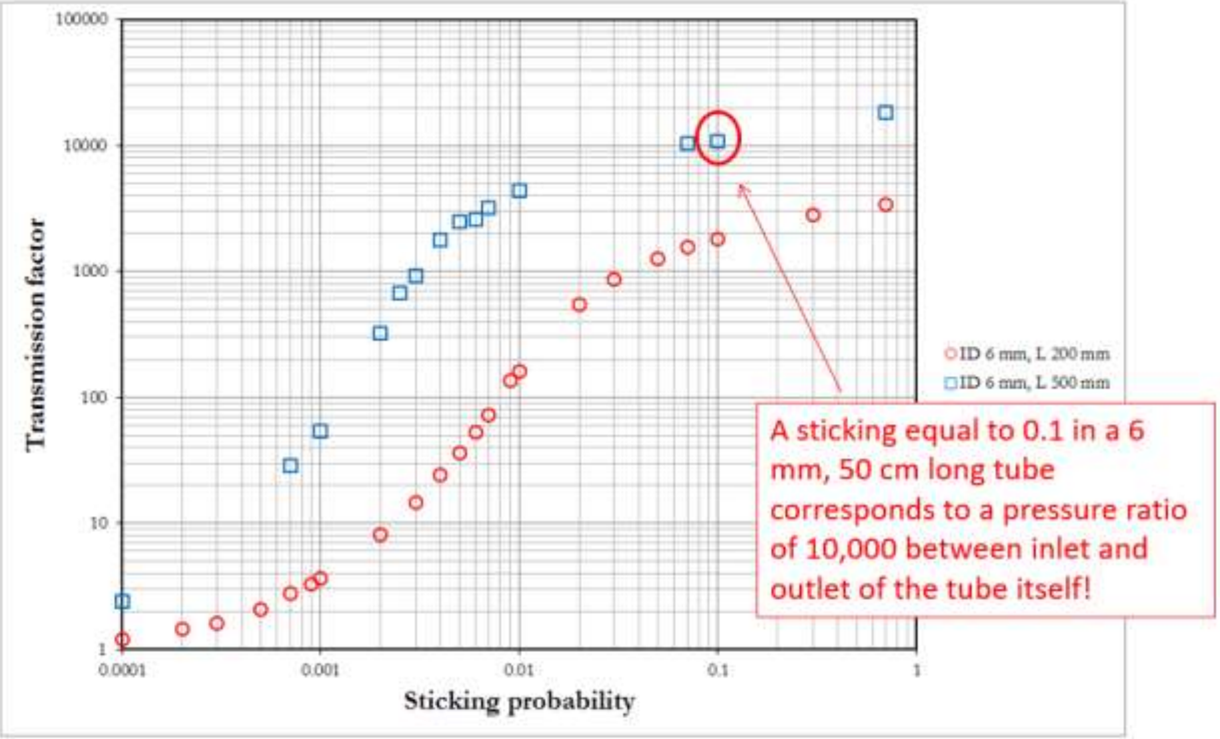
From experiments

Through **MolFlow+** simulations

Sticking probability α

Tr factor on high aspect ratio chambers

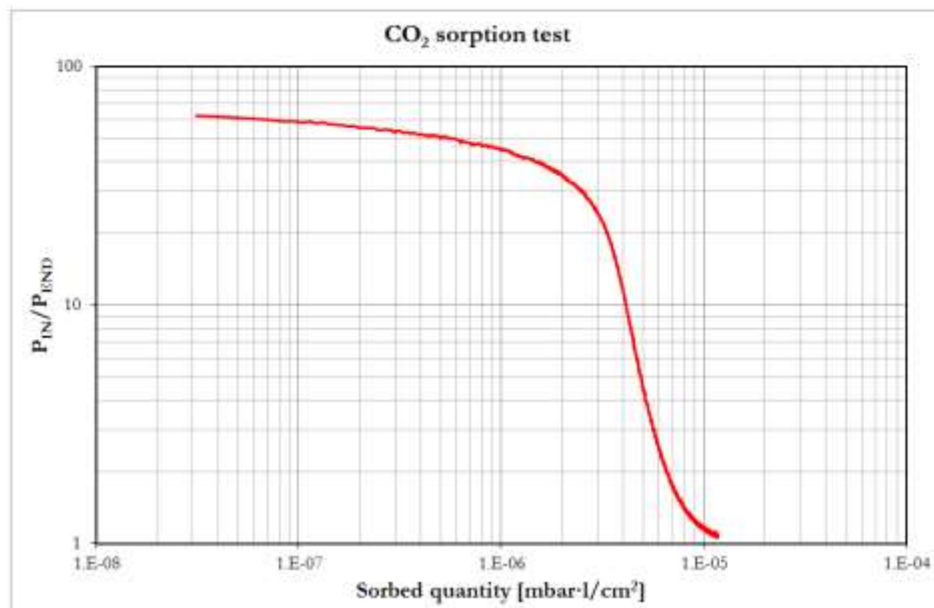
- When testing high aspect ratio beam pipes, the measurement of their sticking probability becomes very challenging:
  - Simulations can be very time-consuming;
  - H2 Tr measurements are influenced by CH4 (not pumped by NEG and generated by gauge filaments) → need for RGAs instead of BA/EXT gauges and possibly LN_2 trap.
  - A high sticking factor (typically α>0.1 for CO) means a difference of several orders of magnitude between the two gauges!
  - The injected gas is likely prevalent at the entrance of the coated tube but not at the end → RGAs are needed.



Soleil-SAES joint R&D activities

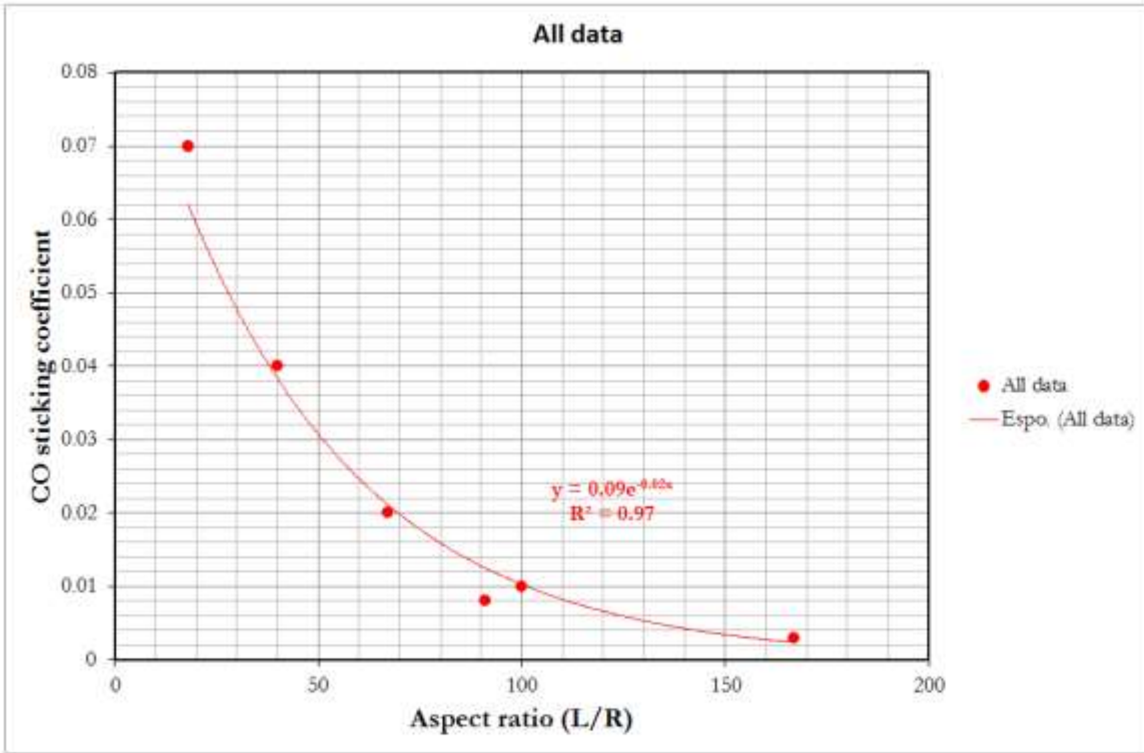
- Soleil is working on the CDR and TDR for the future **Soleil Upgrade**.
- A collaboration project is ongoing between Soleil and SAES to study the properties of small-gap NEG-coated tubes in terms of:
  - Pumping properties (sticking probability and sorption capacity);
  - NEG film behaviour in dynamic conditions (PSD measurements).
- ID20 and ID10 mm tubes are the subject of this study.
- Preliminary sorption results are available.
- PSD results made at Soleil will be available soon.

ID38, 20 cm long tube
Initial CO_2 sticking probability: **0.7**
(calculated through MolFlow+ simulations)



For more results, do not miss Vincent Le Roux presentation later this afternoon.

Initial characterization CO-SC vs aspect ratio



- Initial investigation showed the reported trend of sticking coefficient in narrower NEG coated tubes (diameter between 6mm, 10mm and 20 mm)
- PSD measurments will give strong fact about the NEG pumping characteristics (see Vincent Le Roux presentation)

Ongoing NEG coating activities at SAES

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<u>Small gap and small diameter chambers</u>

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<u>Additional activities</u>

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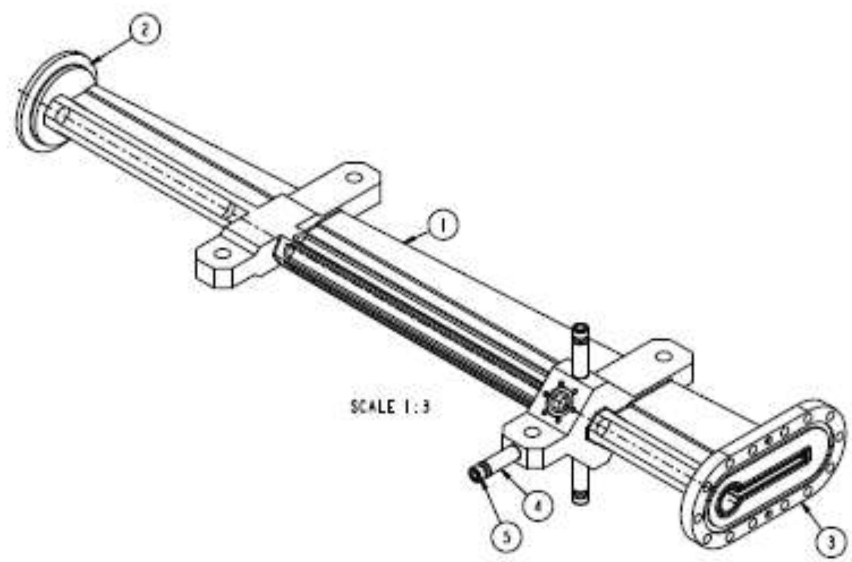
R&D on complex shapes: VC03 chamber for ALS-U

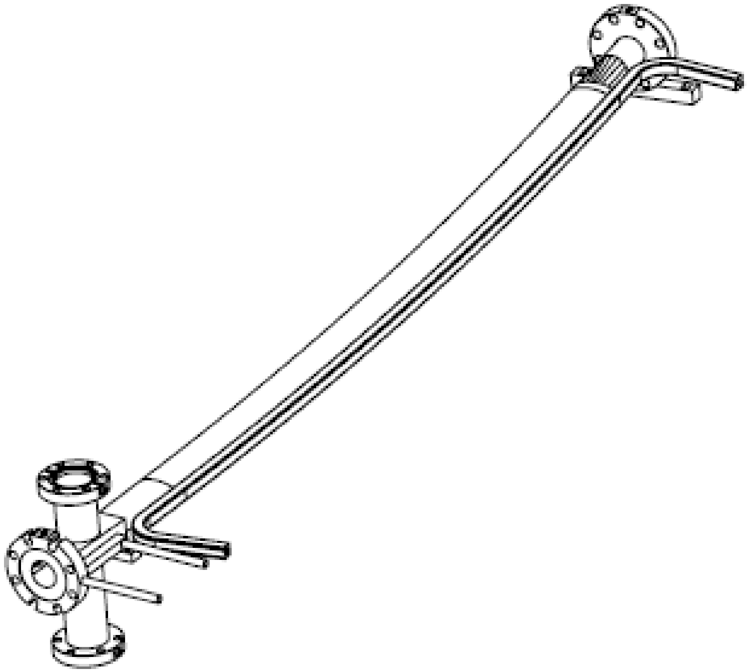
- Many critical aspects:
  - 5 mm gap keyhole;
  - 20 mm ID beam line;
  - Variable horizontal section;
  - Need to use 2-3 cathodes;
  - Plasma ignition everywhere;
  - Spacing between cathodes is very important to achieve a uniform deposited thickness.



Courtesy of Sol Omolayo, Lawrence Berkeley National Lab. – ALS-U project

R&D on complex shapes: AR dipole for ALS-U

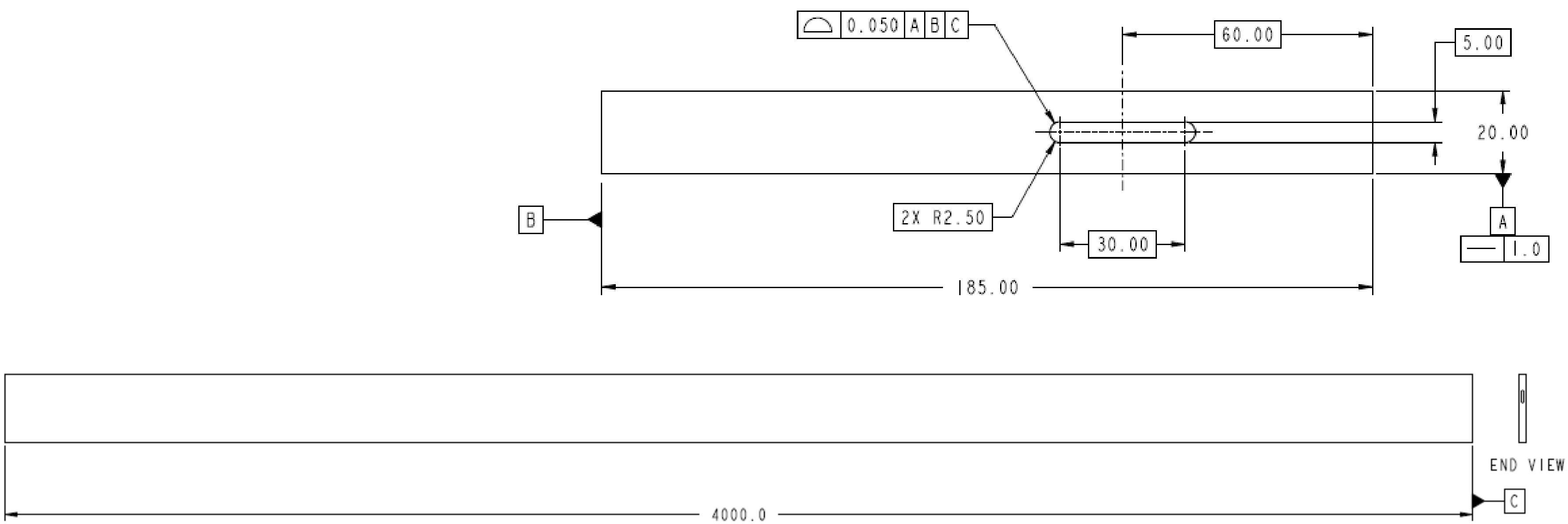
- Critical aspects:
  - Strong curvature;
  - Non constant section (circular-elliptical-circular);
  - No direct visual through the end;
  - Need for special cathode holders.



Courtesy of Sol Omolayo, Lawrence Berkeley National Lab. – ALS-U project

R&D on complex shapes: ID for ALS-U

- Critical aspects:
  - 4 m long aluminium chamber;
  - 30x5 mm cross section;
  - Cathode alignment is very challenging;
  - Deposited film must be uniform all along the chamber.



Courtesy of Sol Omolayo, Lawrence Berkeley National Lab. – ALS-U project

From prototypes to series production

- Soleil was the first machine which extensively adopted NEG coating (>55% of the ring circumference).
- 2005-2006: SAES successfully coated more than 100 chambers (quadrupoles, sextupoles, IDs).
- Since then, SAES expanded its NEG coating facility to be able to deal with big orders of NEG coated chambers for other machine upgrades.

Proceedings of EPAC08, Genoa, Italy THPP147

NEG COATED CHAMBERS AT SOLEIL: TECHNOLOGICAL ISSUES AND EXPERIMENTAL RESULTS

C. Herbeaux, N. Béchu, Synchrotron SOLEIL, Gif-sur-Yvette, France.
A. Conte, P. Manini, A. Bonucci, S. Raimondi, SAES Getters SpA, Lainate, Italy

Abstract

The SOLEIL accelerator complex includes a 100 MeV LINAC pre-injector, a full energy booster synchrotron and a 2.75 GeV electron storage ring with a 354m circumference, which provides synchrotron light to 24 photon beam lines.

SOLEIL is the first synchrotron facility specifically designed to make extensive use of Non Evaporable Getter (NEG) coating technology to improve the vacuum, reduce bremsstrahlung radiation and boost beam performances. In fact, NEG coating of the straight parts of the vacuum system covers more than 50% of the overall storage ring surface and includes 100 q-pole and sextupole chambers as well as several conductance limited narrow insertion devices vacuum vessels. Use of such a large amount of NEG coated chambers has posed several challenges in term of coating technology, chamber testing, installation and machine commissioning.

We report in the present paper main technological issues related to the chambers preparation, film deposition, quality control and characterization. Chambers installation in the main ring, conditioning and activation procedures as well as preliminary vacuum performances will be also discussed.

New NEG coating deposition lab.

Two deposition facilities

ISO-6 clean room

- 24 m^2 ISO-6 clean room, employed for chambers' handling before and after NEG deposition.

Quality assurance and quality control

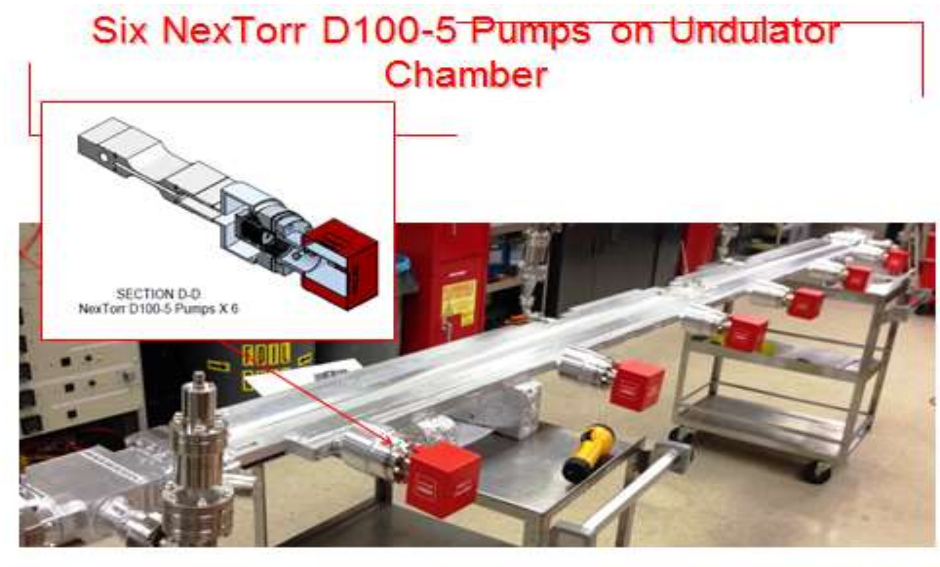
- SAES plant in Lainate is **ISO 9001:2015**, **ISO 14001:2015** and **IATF 16949:2016** certified.
- NEG coating deposition is regulated by a dedicated *Manufacturing and Inspection Flow Chart*.
- *Process Failure Mode & Effects Analysis* (PFMEA) allows to identify and correct every potential critical step, through the adoption of a specific *Control Plan* which covers all the production phases, from cathodes preparation to UHV cleaning, NEG deposition and final shipping to the customer.
- Each chamber is shipped with a Certificate of Testing (CoT) reporting all the tests results required by the customer (e.g., film thickness and chemical composition, RGA scans before/after activation, sticking probability measurements).

Conclusions

- NEG coating is an enabling technology for Low Emittance Ring
- Given the chambers complexity of LER, NEG coating presents many challenges in terms of
  - uniform thickness and composition
  - Stability of the plasma
  - Deposition in not-cylindrical geometries
- SAES is ready to deposit large batches of chambers with diameters down to 6 mm
- The NEG deposition process of complex chambers are under refinement

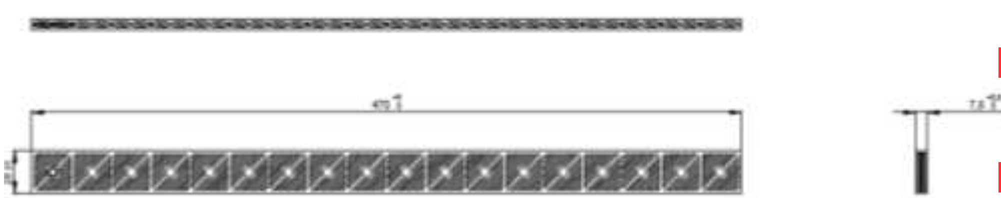
Other NEG distributed ideas

NEXTorr pump distribution



Courtesy of Wilson Lab., Cornell – Vacuum level 1e-10 Torr

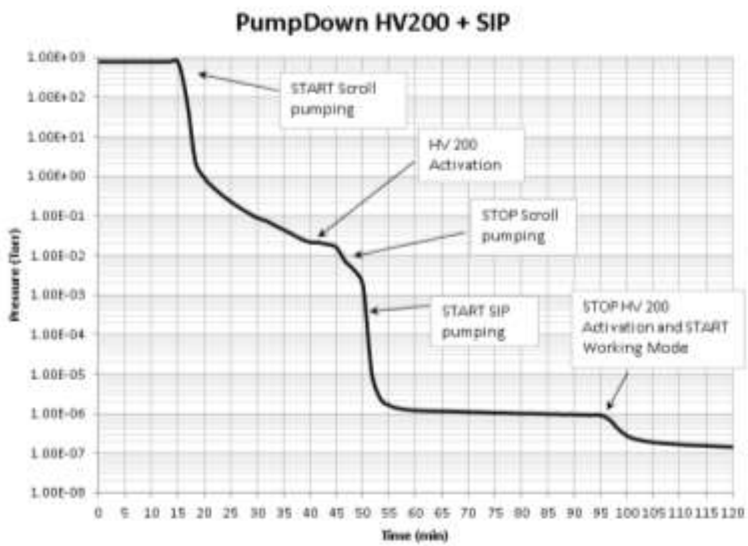
Courtesy of PSI (SWISSFel) – Vacuum level 1e-10 Torr



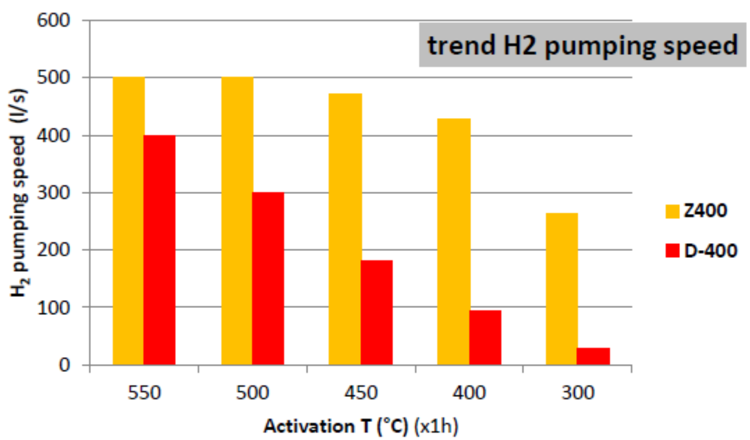
- LINEAR ZAO ELEMENT 47x8x3 cm
- If fully activated, it can deliver 500 l/s for H_2 and 230 l/s for CO
- Activated by bake out or through passage of current in the cage

Other NEG distributed ideas

ZAO can be activated in high vacuum



- ZAO activation can start at 1e-2 Torr
- By combining NEG pump with compact ion pump or TMP, the system can be pumpdown at 1e-7 Torr in 1.5 hours



- ZAO based pump can achieve the 80% of the nominal pumping speed if activated at 400°C instead of 550°C standard activation temperature

Thank you for your attention

w.: www.saesgroup.com
e.: enrico_maccallini@saes-group.com