Thin Films for Particle Accelerators

Pedro Costa Pinto
Thin Films for Particle Accelerators

1. Introduction
2. Sputtering (principles)
3. Sputtering technology
4. Basics of film growth & adhesion
5. Non Evaporable Getter thin films
1. Introduction: What’s a thin film?

**Thin film**

From Wikipedia, the free encyclopedia

A **thin film** is a layer of material ranging from fractions of a **nanometer** (monolayer) to several **micrometers** in thickness.
1. Introduction: What’s a thin film?

Thin film

From Wikipedia, the free encyclopedia

A **thin film** is a layer of material ranging from fractions of a **nanometer** (monolayer) to several **micrometers** in thickness.
1. Introduction: for what purposes?

To change the surface properties of an object or a device.
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Flexible solid state batteries
1. Introduction: for what purposes?

To change the surface properties of an object or a device.
1. Introduction: for what purposes?

And for Particle accelerators?

- Ti to reduce electron multipacting and surface impedance and to evacuate electrical charges from ceramic vacuum chambers (RF windows)
- Nb for superconducting RF accelerating cavities
- Cu to reduce surface impedance (absorbers for collimators, RF couplers, etc)
- NEG (Ti-Zr-V) for distributed pumping speed;
- TiN, NEG and a-C to mitigate e-cloud.
1. Introduction: how to produce thin films?

Chemical deposition

- **Liquid**
  - Plating
  - Electroplating
  - Sol-gel

- **Vapour**
  - Chemical Vapour Deposition (CVD) (Assisted by plasma or laser)
  - Atomic Layer Deposition (ALD)

Used for accelerators technology but not discussed here
1. Introduction: how to produce thin films?

Physical (Vapour) deposition

- Thermal Evaporation
  - Joule effect
  - Electron beam
- Laser ablation
- Sputtering
  - Ion beam
  - Cathodic arc
  - Glow discharge
2. Sputtering: what is it?

to sputter originates from the Latin word sputare, meaning “to emit saliva with noise”.

![Cartoon of two men with arrows indicating saliva]

(credit: Joseph Farris, CartoonStock.com)
2. Sputtering: what is it?

In physics, it means to remove atoms from a target by bombarding it with an energetic particle.
2. Sputtering: sputtering yield $Y$

$$Y = \frac{\text{sputtered atoms}}{\text{incident ion}}$$

Depends on the chemical bonding of the target atoms & on the energy transferred by collision (ion specie and energy).

- **Threshold regime** (no cascades)
- **Linear cascade regime**
  - Recoil cascade occurs, but collisions between moving atoms are rare
- **Spike regime**
  - For high energy, most of the atoms in the “spike volume” are in motion
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Online simple sputter yield calculator (Technical University of Wien)
2. Sputtering: sputtering yield \( Y \)

\[ Y = \frac{\text{sputtered atoms}}{\text{incident ion}} \]

Depends on the chemical bonding of the target atoms & on the energy transferred by collision (ion specie and energy).

- **Niobium**
  - \( \text{Kr}^+ \)
  - \( \text{Ar}^+ \)
  - \( \text{Ne}^+ \)
  - \( \text{He}^+ \)

- **For Ar\(^+\) incident ions**
  - \( C \)
  - \( Ti \)
  - \( V \)
  - \( Zr \)
  - \( Cu \)
2. Sputtering: sputtering yield $Y$

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$$Y = \frac{\text{sputtered atoms}}{\text{incident ion}}$$

Yamamura, Y.; Itikawa, Y.; Itoh, N.; Angular dependence of sputtering yields of monatomic solids

Fig. 4.20 The normalized yield $Y(\theta)/Y(0)$ for 1.05 Ar$^+$ on Si and Ge as a function of $\theta$. Ref. [72] ACAT (Ref. [31])
2. Sputtering: Energy of sputtered atoms


\[
F(E) \propto \frac{E}{(E + U_{sb})^3} \left( 1 - \frac{E + U_{sb}}{\gamma E_{ion}} \sqrt{\frac{E + U_{sb}}{\gamma E_{ion}}} \right) \]

\[
\gamma = \frac{4M_{\text{target}}M_{\text{ion}}}{(M_{\text{target}} + M_{\text{ion}})^2}
\]

2. Sputtering: Energy of sputtered atoms


\[
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\[
\gamma = \frac{4M_{target}M_{ion}}{(M_{target} + M_{ion})^2}
\]

Stuart & Wehner, Energy "Distribution of Sputtered Cu Atoms", J. Appl. Physics, 35 (1964)
2. Sputtering: Angular distribution of atoms

Close to Knudsen’s cosine law for $E_{\text{ion}} > 1$ keV … but slightly distorted for lower energies.


Fig. 3. Polar diagram of material sputtered from Pt by normally incident Hg$^+$ ions of 100 to 1000 ev energy.

Fig. 9. Polar diagram of material sputtered from Mo strip by obliquely incident Hg$^+$ ions of 250 ev.
2. Sputtering: Transport of atoms to substrate

\[ Y(\theta) = Y_0 \cos \theta_{\text{emission}} \]

![Diagram showing cosine distribution of vapor from a point source.](image)

Fig. 4. Cosine distribution of vapor from a point source.

**PHYSICAL VAPOR DEPOSITION (PVD) PROCESSES**

by Donald M. Mattox

Society of Vacuum Coaters, Albuquerque, N.M.
2. Sputtering: Transport of atoms to substrate

\[ \text{Thickness} \propto \frac{Y_0}{d} \]
2. Sputtering: Transport of atoms to substrate

130 mm

55 mm

Relative thickness
Coordinate along major axis [mm]

Relative thickness
Coordinate along chamber mm

Calculated thickness profile for 100 mm slab

Coordinate along chamber [mm]

Transport of atoms to substrate

Vacuum, Surfaces & Coatings Group
Technology Department

P. Costa Pinto, CAS Vacuum for Particle Accelerators,
Glumslov, Sweden, 2017
2. Sputtering: Transport of atoms to substrate

Collision with the residual gas:
Low pressure (density): ~100% transmission.
2. Sputtering: Transport of atoms to substrate

Collision with the residual gas:

High pressure: low transmission & low energy
2. Sputtering: Transport of atoms to substrate

Thermalization and transmission can be simulated by Monte Carlo using the Hard Spheres model.

Loss of energy by collision (thermalizing)

Backscattering of atoms (return to target)

Loss of energy by collision (thermalizing)

Backscattering of atoms (return to target)
3. Sputtering technology

“The plasma phase is far and away the most common – stars are plasmas – but it is also by far the most difficult to discuss quantitatively.”

“For this reason we exclude it from further discussion.”

3. Sputtering technology: IBD

Ion Beam Deposition

Not convenient to coat tubes or large area substrates!
3. Sputtering technology: arc-PVD

Cathodic arc Vapor Deposition

![Diagram showing voltage and current density with regions for Dark discharge, Glow discharge, and Arc discharge.]
3. Sputtering technology: arc-PVD

Cathodic arc Vapor Deposition

Aksenov's quater-torus macroparticle filter
3. Sputtering technology: arc-PVD

Cathodic arc Vapor Deposition

Coating defects

Droplets

Hard coatings (TiN, AlTiN)

The sputtered material is ionized and can be deposited with high energy

Very good adhesion

Very dense films
3. **Sputtering technology: arc-PVD**

**Cathodic arc Vapor Deposition**

3. Sputtering technology: GDS

Glow Discharge Sputtering

![Diagram showing the relationship between voltage and current density in glow discharge sputtering, with phases labeled as dark discharge, glow discharge, and arc discharge.]

- Dark discharge: Self-maintained
- Glow discharge: Normal glow
- Arc discharge: Abnormal glow
3. Sputtering technology: GDS

Glow Discharge Sputtering
3. Sputtering technology: GDS

Example: Nb on Cu for the HIE-ISOLDE RF cavities
3. Sputtering technology: GDS

Example: Nb on Cu for the HIE-ISOLDE RF cavities
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Example: Nb on Cu for the HIE-ISOLDE RF cavities

![Diagram showing a vacuum tank, cavity, sputtering target (Nb), and Nb coating.](image)
3. Sputtering technology: reduce pressure?

**mean free path for electrons \( \gg \text{mfp} \) for atoms**

![Graph showing mean free paths for different types of particles as a function of pressure.](image)

**Fig. 2.** Mean free paths for atoms, \( l_a \), electrons, \( l_e \), and ions, \( l_i \), as a function of pressure in the argon glow discharge, calculated from kinetic gas theory.

3. Sputtering technology: RF

Glow discharge RF

\[ M_{\text{ions}} \gg M_{\text{electrons}} \]

At low frequencies (<50 kHz): both ions and electrons can follow the variations in electric fields.

At high frequency (> 3000 kHz): Ions are unable to follow the variations.
3. Sputtering technology: RF

Glow discharge RF
3. Sputtering technology: GDMS

Glow Discharge Magnetron Sputtering

A magnetron uses a static magnetic field parallel to the cathode (target) surface.

\[ \vec{E} \times \vec{B} \text{ drift} \]

The secondary electrons emitted from the target by the ion bombardment move in a direction perpendicular to the \( \vec{E} \) and \( \vec{B} \).
3. Sputtering technology: GDMS

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Glow Discharge Magnetron Sputtering

A magnetron uses a static magnetic field parallel to the cathode (target) surface.

- B field lines
- Electron
- $\vec{E}$
- Cathode (target)

N | S | S | S | N
3. Sputtering technology: GDMS

Glow Discharge Magnetron Sputtering

A magnetron uses a static magnetic field parallel to the cathode (target) surface.

\[ \text{B field lines} \quad \vec{E} \quad \vec{B} \]

\[ \text{Cathode (target)} \quad \text{N} \quad \text{S} \quad \text{S} \quad \text{S} \quad \text{N} \]

\[ \text{electron} \]
3. Sputtering technology: GDMS

Glow Discharge Magnetron Sputtering

A magnetron uses a static magnetic field parallel to the cathode (target) surface.
3. Sputtering technology: GDMS

Example: absorber blocks for collimators (CERN)

Material of the blocks: Graphite, CfC, BN, Mo-Graphite. Coatings: Ti(200 nm) + Cu(~ 5 µm), Mo (~ µm).
Up to 10 blocks / coating run
3. Sputtering technology: GDMS

Glow Discharge Magnetron Sputtering (Cylindrical)

Natural configuration to coat in tubes.

Tube (substrate)

Cylindrical magnet

Target (cathode)
3. Sputtering technology: GDMS

Glow Discharge Magnetron Sputtering (Cylindrical)

Natural configuration to coat in tubes.

External Solenoid

Target (cathode)

Long tube (substrate)
3. Sputtering technology: GDMS

Example: anti e-cloud TiN coatings for SuperKEKB
KEK - Japan
3. Sputtering technology: GDMS

Example: anti e-cloud TiN coatings for SuperKEKB
KEK - Japan
3. Sputtering technology: GDMS

Example: anti e-cloud TiN coatings for SuperKEKB

KEK - Japan
3. Sputtering technology: GDHC

Glow Discharge Hollow Cathode

Pendel electrons $\rightarrow$ increase ionization efficiency

\[ e^- \]

\[ \text{anode} \]

\[ \text{cathode} \]

\[ \text{plasma} \]

\[ a \]

\[ \text{distance between plates} \]

\[ P. F. \ Little \ & \ A. \ Von \ Engel, \ Proceedings \ of \ the \ Royal \ Society \ of \ London. \ Series \ A, \ Mathematical \ and \ Physical \ Sciences, \ Vol. \ 224, \ No. \ 1157 \ (1954) \]
3. Sputtering technology: GDHC

Example: anti e-cloud a-C coatings for the SPS (CERN)
3. Sputtering technology: GDHC

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3. Sputtering technology: GDHC

Example: anti e-cloud a-C coatings for the SPS (CERN)

Jan & Feb 2017: first SPS “in-situ” coating campaign (~130 meters coated)
4. On growth & adhesion

Phases of film growth:

Condensation & nucleation

Interface formation

Film growth
4. On growth & adhesion

Phases of film growth: Condensation & nucleation

Nucleation density:
- Deposition rate
- Mobility of adatoms on the surface ($T_s$, binding energies, contaminations, surface defects)
- Concurrent bombardment (ions, neutrals, electrons)

Preferential sites:
- Cleavage steps
- Grain boundary
- Surface atom
- Adsorbed atom
4. On growth & adhesion

Phases of film growth: Interface formation
The depositing film material may diffuse and react with the substrate to form a “interfacial region”.

- ** Abrupt**
  - Weak chemical reaction between atoms and substrate;
  - Low deposition temperature;
  - Surface contamination;
  - Low nucleation density;

- **Graded**
  - By diffusion (solubility, temperature, time, contaminations);
  - Chemical reaction (oxygen-active metals on oxide substrates);
  - By co-deposition or implantation of energetic ions of the material.

Impact on adhesion
4. On growth & adhesion

Phases of film growth: Film growth

Is the evolution of the nucleation, where arriving atoms are deposited on the previously deposited material.

Usually exhibits a columnar morphology.

TiN on glass from Macleod’s book

Nb on Cu (A. Sublet, CERN)
4. On growth & adhesion

Structure Zone Model (SZM)

Based on the compilation of the experimental results, is a guideline for “predicting” the structure of deposited thin films

1st proposed in 1969 by Movchan & Demchishin for films deposited by thermal evaporation.

\[ T_s \rightarrow \text{temperature of the substrate} \]
\[ T_m \rightarrow \text{melting point of the film material} \]

4. On growth & adhesion

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Thornton (1974) extended the model for sputtering. (included the pressure)

\[ T_s \rightarrow \text{temperature of the substrate} \]
\[ T_m \rightarrow \text{melting point of the film material} \]

4. On growth & adhesion

Structure Zone Model (SZM)


4. On growth & adhesion

Adhesion: bonding forces vs internal stresses
4. On growth & adhesion

Adhesion: bonding forces vs internal stresses
4. On growth & adhesion

Adhesion: internal stresses

\[
\text{total stress} = \text{intrinsic stress} + \text{thermal stress}
\]

determined by film deposition process

determined by difference in thermal expansion (contraction)
4. On growth & adhesion

Adhesion: internal stresses

\[
\text{total stress} = \text{intrinsic stress} + \text{thermal stress}
\]

determined by film deposition process

Ion bombardment can be used to influence stress

- film has voids, typical for evaporation
- atom inserted in surface, typical for sputtering at low pressure
- volume growth and stress relaxation, though some residual stress remains from strained bonds
- increased quench time allows for bond rearrangement, volume growth, and stress relaxation

subplantation, densification, quench time too short to allow for relaxation, typical for cathodic arcs with low or no bias
4. On growth & adhesion

Adhesion: the different types of bonding

**Mechanical adhesion:** Roughness, interlocking of substrate and layer. Used for paints etc. Sandblasting of surfaces.

**Wetting or Van der Waals adhesion:** Two surfaces in close contact experience short range forces, (not due to chemical actions but rather to adsorption-like phenomena). Typical of oxides on oxides, or of polymer films

**Chemical adhesion:** The film and the substrate make a chemical bond. This can be of two natures: covalent or ionic:

- **Covalent:** usually the case of a metal film on top of an oxidised metal
- **Ionic:** it is usually the case between two metals without oxide in between
4. On growth & adhesion

Adhesion: the different types of bonding

**Van der Waals is poor** => requires to remove organic contamination from substrate (degreasing, UV-Ozone).

**Covalent bonding can be good** => requires to choose the right combination of metal/oxide.

**Ionic bonding is better** => requires to remove oxide by ion etching before coating: metal/metal.

**Surface preparation prior to coat is CRUCIAL**
4. On growth & adhesion

Adhesion: optimise covalent bonding

The free heat of formation of the metal-oxide of the deposited atoms must be lower (more negative) than that of the oxide at the surface of the substrate.
4. On growth & adhesion

Adhesion: optimise covalent bonding

$\text{Nb}$ and $\text{Cu}$: $\text{Nb}_2\text{O}_5 = -1899.54 \text{ kJ/mol} << \text{CuO}_2 = -156.06 \text{ kJ/mol}$

Deposition of $\text{Cu}$ on oxidised $\text{Nb}$

Deposition of $\text{Nb}$ on oxidised $\text{Cu}$
4. On growth & adhesion

Adhesion: optimise covalent bonding

Good pairs metal-oxide: Nb/Cu, Ti/S.Steel, NEG\textsubscript{(TiZrV)}/Cu, Ti/Al\textsubscript{2}O\textsubscript{3}, Al/glass.

Bad pairs metal-oxide: Cu/Nb, Cu/S.Steel, Cu/glass.
4. On growth & adhesion

Film Properties
Microstructure
Adhesion

- Diffusion coefficients
- Deposition rate
- Energy of Arrival atoms
- Substrate defects
- Substrate lattice
- Substrate temperature
- Impurities
- Stresses in the film
- Ion bombardment
- Ion bombardment

Motivation: improve dynamic vacuum on the warm sections of the LHC.

- Distributed pumping speed
- Low secondary electron yield (mitigation of electron multipacting)

Motivation: improve dynamic vacuum on the warm sections of the LHC.

Cross section of the LEP dipole vacuum chamber

NEG strip

Motivation: improve dynamic vacuum on the warm sections of the LHC.

The vacuum chamber becomes a pump.

The NEG behavior of some elements were already known, but activation temperatures > 350°C

Mixing these elements to decrease the activation temperature.

(compatible with the materials used in the construction of beam pipes for accelerators)

Mixing these elements to decrease the activation temperature. (compatible with the materials used in the construction of beam pipes for accelerators)

![Diagram showing the mixing of elements to decrease activation temperature](image-url)

In 2002, Ti-Zr-V was retained for large scale production for the LHC. Activation: 24 hours at 180°C

Vacuum properties 1: pumping speed versus coverage.

Smooth (coated at 100°C)

Rough (coated at 300°C)

Vacuum properties 1: pumping speed versus coverage.

Smooth (coated at 100°C)

Rough (coated at 300°C)

Vacuum properties 2: ageing (recovery after successive air venting).

- Heating duration: 24 hours unless otherwise indicated.
- Beam pipe diameter: 80 mm.
- TiZrV/St. Steel 5 μm thick.

Graph showing the relationship between the number of heating/venting cycles and hydrogen sticking probability at different temperatures (200°C, 250°C, 300°C, 350°C). The graph includes data points for 48 h and 24 h durations.

Vacuum properties 3: photon induced desorption.


Fig. 2. Total molecular desorption yield $\eta$ (N$_2$ equivalent) of the Ti–Zr–V coated stainless-steel chamber as a function of the accumulated dose before and after activation.

Secondary Electron Yield:

B. Henrist, N. Hilleret, C. Scheuerlein, M. Taborelli,

General procedure for activation

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Time</th>
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<td>150°C</td>
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<tr>
<td>200°C</td>
<td>24h@200°C-300°C</td>
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<td>24h@200°C</td>
<td>~300°C</td>
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<tr>
<td>24h@200°C</td>
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</tr>
</tbody>
</table>

Degas filaments and ion pumps

Degas filaments

Bakeout

activation
5. Non Evaporable Getter Coatings. Production for the LHC

More than 1300 beam pipes, with different shapes and lengths.

Other machines at CERN

LEIR - Low Energy Ion Ring $P_{\text{average}} \approx 10^{-12}$ mbar

Other machines at CERN

Other machines at CERN

Extra Low ENergy Antipton storage ring

Collaboration with MAX IV

Collaboration with MAX IV

20 chambers of each model coated @CERN

Collaboration with MAX IV

Collaboration with MAX IV

Collaboration with MAX IV

Collaboration with MAX IV

Collaboration with MAX IV

Collaboration with MAX IV

Collaboration with MAX IV

Between July 2014 and April 2015

- 20 VC2a
- 21 VC2b
- 20 VC2L
- 21 VC1
- 1 VC2K1
- 1 VC2K2

Collaboration with MAX IV

Surface preparation prior to coat is CRUCIAL

Mechanical removal of most of the Cu particles (Clothing and 100 bar water rinsing).

Chemical etching of the internal surface with NH$_4$S$_2$O$_3$ (about 60μm) + passivation

Collaboration with MAX IV

Surface preparation prior to coat is CRUCIAL

Careful inspection before acceptance for mechanical assembling

Worldwide users of NEG coatings

in design/study

Worldwide NEG coating producers

ESRF (France)  LNLS (Brazil)  FMB Berlin (Germany)  KEK (Japan)  GSI (Germany)  SAES getters (Italy)
Final remarks

Thin films are part of the Particle Accelerators technology. (Km’s of beam pipes are coated and in use)

Surface preparation is crucial.

The coating must be take into account since de design phase of new components.

To follow the demand from the accelerators community, the coating technology needs to be able to develop new materials and coating configurations.

Sputtering is very “plastic” but the future may ask upside down solutions!
Summary

Inverse NEG?

- Thick Cu coating by electroplating
- Thin Cu coating by sputtering
- NEG coating

Al mandrel
Summary

Inverse NEG?

- Thick Cu coating by electroplating
- Thin Cu coating by sputtering
- NEG coating
- Etching bath (NaOH)
- Al mandrel
Thanks for your attention 😊
2. Carbon Coatings to mitigate e-cloud

Low Secondary Electron Yield Carbon coatings

![Graph showing the relationship between secondary electron yield (SEY) and energy (eV) for stainless steel and a-C carbon coating.]

Stainless steel (UHV cleaned)
Threshold for e-cloud
a-C carbon coating

P. Costa Pinto, CAS Vacuum for Particle Accelerators, Glumslöv, Sweden, 2017
2. Carbon Coatings to mitigate e-cloud

Electron cloud current in the SPS with an electron cloud detector

Beam
Cross section

Time [s]

<table>
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<tr>
<th>Time [s]</th>
<th>Beam pipe coating</th>
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Proton beam

Coating
3. Application to accelerators

The CERN accelerators complex

LHC:
• Perimeter of 27 km.
• > 3 km coated with NEG (in bakeable parts)

SPS:
• Perimeter of 7 km.
• Non bakeable.

For now e-cloud is under control but…
3. Application to accelerators

More physics ➔ Higher intensity beams ➔ More problems

Increase the luminosity of the LHC by **4x**
by 2025
3. Application to accelerators

SPS: beam instabilities.

LHC: heat load to some superconductive magnets.
3. Application to accelerators: SPS

Built in the 70’s
3. Application to accelerators: SPS

Risk & cost optimisation:

- Ranking components by “e-cloud”
3. Application to accelerators: SPS

Risk & cost optimisation:

- Ranking components by “e-cloud”
- Coat chambers in the magnets
3. Application to accelerators: SPS

Risk & cost optimisation:

- Ranking components by “e-cloud”
- Coat chambers in the magnets
- Minimize transport/removal of magnets from the tunnel
3. Application to accelerators: SPS

Layout

1 cell = 63995 mm

Risk & cost optimisation:

- Ranking components by “e-cloud”
- Coat chambers in the magnets
- Minimize transport/removal of magnets from the tunnel
3. Application to accelerators: SPS

Risk & cost optimisation:
- Ranking components by “e-cloud”
- Coat chambers in the magnets
- Minimize transport/removal of magnets from the tunnel

Efforts:
- Simulations
- Coating technology
- Logistics

1 cell = 63995 mm
3. Application to accelerators: SPS

Coating technology: Hollow Cathode Sputtering

Cathode: graphite targets (cells)

6.5 meter
3. Application to accelerators: SPS

Coating technology: Hollow Cathode Sputtering

Cathode: graphite targets (cells)

MBB type dipole
3. Application to accelerators: SPS

Coating technology: Hollow Cathode Sputtering

Cathode: graphite targets (cells)
3. Application to accelerators: SPS

Logistics

1 cell = 63995 mm

Coating lab 1

+ new long drift tubes

Coating lab 2 (radioactive)
3. Application to accelerators: SPS

Jan & Feb 2017: first SPS “in-situ” coating campaign

Goal: Check feasibility of logistics & identify problems.

Coating lab 1:
- 2 QD’s
- 7 LSS runs (9 chambers)
- 3 crab cavity chambers
- 1 LOD chamber
3. Application to accelerators: SPS

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- 3 crab cavity chambers
- 1 LOD chamber

Coating lab 2 (radioactive):
- 7 SSS’s
- (9 magnets + 4 drifts)
3. Application to accelerators: SPS

Jan & Feb 2017: first SPS “in-situ” coating campaign

Goal: Check feasibility of logistics & identify problems.

Coating lab 1:
- 2 QD’s
- 7 LSS runs (9 chambers)
- 3 crab cavity chambers
- 1 LOD chamber

Coating lab 2 (radioactive):
- 7 SSS’s
  (9 magnets + 4 drifts)

SPS tunnel:
- 9 QF’s
- 4x2 MBB’s
3. Application to accelerators: SPS

Jan & Feb 2017: first SPS “in-situ” coating campaign

Goal: Check feasibility of logistics & identify problems.

It’s feasible 😊 (small problems identified/solved)

33 coating runs; ~140 meters in 2 months
3. Application to accelerators: LHC

Heat load to the superconductive magnets that do the final focusing before the collisions

Cold bore 1.9 K

Beam screen ~20 K

protons
3. Application to accelerators: LHC

How it looks like?

~ 45 meter

150 mm
3. Application to accelerators: LHC

How to do it?

**Modular** sputtering source to be inserted in a 150 mm slot and pulled by cables all along the magnets.
3. Application to accelerators: LHC

How to do it?

**Modular** sputtering source to be inserted in a 150 mm slot and pulled by cables all along the magnets.
3. Application to accelerators: LHC

Strategy

- **2015**: Develop coating source
  - 20 cm
  - 50 cm
  - 4 m
  - 10 m

- **2016**: Optimize adhesion

- **2017**: Develop displacement of the coating source

- **2015-2017**: Develop Hot air bake (using the He capillaries)

Coat magnets in a string
3. Application to accelerators: LHC

Development of the coating source

Mitigate hydrogen outgassing by: Ti gettering + molecular drag

DC diode sputtering
3. Application to accelerators: LHC

Development of the coating source

Mitigate hydrogen outgassing by: Ti gettering + molecular drag + increase the deposition rate.

Magnetron using the Quadrupole magnet

Graphite target

field gradient 1 T/m

Beam screen
3. Application to accelerators: LHC

Development of the coating source

Mitigate hydrogen outgassing by: **Ti gettering + molecular drag** + increase the deposition rate.

![Graph showing coating source development](image)

- **Maximal SEY acceptable**
- **Coating run#**
- **SEY max.**

2015: 20cm

Magnetron using permanent magnets
3. Application to accelerators: LHC

Development of the coating source

Mitigate hydrogen outgassing by: Ti gettering + molecular drag + increase the deposition rate.

![Magnetron sputtering](image)

Maximal SEY acceptable:
- 2015: 20 cm
- 2016: 50 cm + 4 m
3. Application to accelerators: LHC

Development of the coating source

Displacement of the sputtering source.

Magnetron sputtering
3. **Application to accelerators: LHC**

![Graph showing maximal SEY acceptable for a 10 m prototype.](image)

*Maximal SEY acceptable*

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**10 m prototype**

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**10 meters**

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P. Costa Pinto, CAS Vacuum for Particle Accelerators, Glumslov, Sweden, 2017
3. Application to accelerators: LHC

Still to be done:

- Demonstrate flawless adhesion (independent of the surface state of the substrate)
- Implement hot air bakeout through capillaries.
- Test radiation resistance of the coating (1GGy)
- Prototypes for larger diameter beam screens.
- Coat a string of magnets.
- How do we assess the coating quality in the real magnets?
4. Summary

- In-situ coating technology can minimize risks and costs on the upgrade of components already installed.

- The first coating campaign in the SPS was a success and allowed to optimise the process.

- Developments for the LHC are in good track, but still a hard way to pave!
Accept the risk, find the way, execute.
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- 9 QF’s
- 4x2 MBB’s
2. The SPS case

Developments started end of 2007
2. The SPS case

Developments started end of 2007

1st step: coat beam pipes and install in the magnets
2. The SPS case

Developments started end of 2007

1\textsuperscript{st} step: coat beam pipes and install in the magnets
2. The SPS case

Developments started end of 2007

1st step: coat beam pipes and install in the magnets => very expensive! (~20 MCHF)

- Dismount from tunnel
- Open the yoke
- remove the chamber
- install coated chamber
- close the yoke
- pumping port and bellow
- check magnetic length
- mount in the tunnel
- align
3. Application to accelerators: SPS

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4x2 MBB’s

All done in due time 😊
(minor problems identified)
3. Application to accelerators: SPS

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P. Costa Pinto, CAS Vacuum for Particle Accelerators, Glumslöv, Sweeden, 2017
3. Application to accelerators: SPS

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MBB coating system

QF coating system
3. Application to accelerators: LHC

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Cold bore 1.9 K

Beam screen ~20 K

P. Costa Pinto, CAS Vacuum for Particle Accelerators, Glumslov, Sweden, 2017
3. Application to accelerators: LHC

1 spool for mechanical cable
+ 2 spools for electrical cables

10 m prototype

Turbo molecular pump

Cold bore + beam screen

1st step: Ti pre-coating ~800 nm

Ar injection

1 spool for mechanical cable

10 meters

P. Costa Pinto, CAS Vacuum for Particle Accelerators, Glumslov, Sweeden, 2017
3. Application to accelerators: LHC

10 m prototype

1 spool for mechanical cable
+ 2 spools for electrical cables

Cold bore + beam screen

1st step: Ti pre-coating ~800 nm

2nd step: carbon coating ~90 nm (with Ti flashes)

1 spool for mechanical cable

Argon injection
3. Application to accelerators: LHC

10 m prototype

1 spool for mechanical cable + 2 spools for electrical cables

Cold bore + beam screen

1 spool for mechanical cable

1st step: Ti pre-coating ~800 nm

2nd step: carbon coating ~90 nm (with Ti flashes)

Turbo molecular pump

Maximal SEY acceptable

P. Costa Pinto, CAS Vacuum for Particle Accelerators, Glumslov, Sweeden, 2017
2. Sputtering: Coating technology

Glow discharge Cylindrical Magnetron

Natural configuration to coat in tubes.

Target (cathode)
Tube (substrate)
2. Sputtering: Coating technology

Glow discharge Cylindrical Magnetron

Natural configuration to coat in tubes.
2. Sputtering: Coating technology

Glow discharge Cylindrical Magnetron

Natural configuration to coat in tubes.
2. Sputtering: Coating technology

Glow discharge Cylindrical Magnetron

Natural configuration to coat in tubes.
2. Sputtering: Coating technology

Glow discharge Cylindrical Magnetron

Natural configuration to coat in tubes.
2. Sputtering: Coating technology

Glow discharge Magnetron

Cylindrical configuration.
2. Sputtering: Coating technology

Glow discharge Magnetron