CARBON COATING OF THE SPS DIPOLES

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Introduction
Coating techniques
Results
Conclusions
For the Large Hadron Collider to work at his design luminosity, the Super Proton Syncrotron (SPS) must be able to feed him with proton beams 25 ns spaced bunches accelerated at 450 GeV.

With the actual configuration of the machine, this beam induces Electron Multipacting (EM), causing emittance blow up and beam losses.

One way to mitigate EM is to coat the internal walls of the beampipes with a material having a maximal Secondary Electron Yield (SEY), below 1.3. ($\delta_{\text{max}} < 1.3$)

Carbon was chosen because of low SEY of graphite (~1.0) and low chemical reactivity
Almost 5 km of the SPS are filled with MBB and MBA type dipoles (>700).

The length of each dipole is 6.5 m and weighs ~18 tons.

The beampipes are embedded in the yoke.

coat new beampipes, open the dipole, insert beampipe, close the dipole.

coop the actual beampipes directly in the dipole.

Easy to coat
Too expensive (open/close dipole)

Easy to coat
cheaper
COATING TECHNIQUES

coat new beampipes, open the dipole, insert beampipe, close the dipole.

DC Cylindrical Magnetron Sputtering (DCCMS)

coat the actual beampipes directly in the dipole.

DC Planar Magnetron Sputtering (DCPMS) using the dipoles field

DC Planar Magnetron Sputtering (DCPMS) using Permanent Magnets

Plasma Enhanced Chemical Vapor Deposition (PECVD) from C$_2$H$_2$

DC Hollow Cathode Sputtering (DCHCS)

The sputtering techniques all give carbon coatings with $\delta_{\text{max}} \sim 1$. PECVD give carbon coatings with $\delta_{\text{max}} \sim 1.5$. 
Coat new beampipes by DC Cylindrical Magnetron Sputtering (DCCMS)
Coat new beampipes by DC Cylindrical Magnetron Sputtering (DCCMS)
COATING TECHNIQUES - DCCMS

Coat new beampipes by DC Cylindrical Magnetron Sputtering (DCCMS)

[Diagram showing a housing vacuum chamber with graphite targets and getter targets.]

7.4 m

Paul Luigi
Coat new beampipes by DC Cylindrical Magnetron Sputtering (DCCMS)
Coat new beampipes by DC Cylindrical Magnetron Sputtering (DCCMS)

**Pressure:** $1.2 \times 10^{-1}$ mbar (Ne)

**Power:** 1.8 kW (3A @ 600 V)

**B:** 180 Gauss

0.5 µm in 8 hours

**THE TECHNIQUE IS MATURE FOR LARGE SCALE PRODUCTION**
Coat actual beampipes by DC Hollow Cathode Sputtering (DCHCS)

Graphite targets (cells)
COATING TECHNIQUES - DCHCS

Coat actual beampipes by DC Hollow Cathode Sputtering (DCHCS)

Graphite targets (cells)

MBB dipole
COATING TECHNIQUES - DCHCS

Coat actual beampipes by DC Hollow Cathode Sputtering (DCHCS)

Graphite targets (cells)

Pressure: $2.4 \times 10^{-1} \text{ mbar (Ar)}$
Power: $1.8 \text{ kW (3A @ 600 V)}$

$0.5 \mu\text{m in 20 hours}$

THE TECHNIQUE IS ALMOST MATURE FOR LARGE SCALE PRODUCTION
Why *almost*?

Some “dark” defects appear along the central line of the chamber.
Why *almost*?

Some “dark” defects appear along the central line of the chamber

Electrons focused into the center of the cells  \[\rightarrow\] Increase ion density near the substrate  \[\rightarrow\] Low energy ion bombardment  \[\rightarrow\] Structure modification (equivalent to temperature)

*At the center of the cells* Focusing Electrons?
Why *almost*?

Some “dark” defects appear along the central line of the chamber

**Monte carlo simulation of electron’s trajectories** (with SimIon 6.0)

Counts (electrons)

**At the center of the cells** Focusing Electrons?

Electrons focused into the center of the cells  ➔  Increase ion density near the substrate  ➔  Low energy ion bombardment  ➔  Structure modification (equivalent to temperature)
Why *almost*?

Some “dark” defects appear along the central line of the chamber

Ions Energy Distribution Function
(measured with RFEA)

Electrons focused into the center of the cells
Increase ion density near the substrate
Low energy ion bombardment
Structure modification (equivalent to temperature)
Why *almost*?

Some “dark” defects appear along the central line of the chamber

**Ion flux along the cells**

![Graph showing ion flux along the cells.](image)

**At the center of the cells**

Electrons focused into the center of the cells → Increase ion density near the substrate → Low energy ion bombardment → Structure modification (equivalent to temperature)
How to solve the problem?

Use the dipole’s magnetic field to avoid the electrons to reach the center of the cell: Larmor radius $< 25$ mm (half cell)

Tests in 25cm prototype

Electrons focused into the center of the cells → Increase ion density near the substrate → Low energy ion bombardment → Structure modification (equivalent to temperature)

$B = 0$ Gauss $r_{\text{Larmor}} = \infty$
How to solve the problem?

Use the dipole’s magnetic field to avoid the electrons to reach the center of the cell: Larmor radius $<< 25$ mm (half cell)

Tests in 25cm prototype

Electrons focused into the center of the cells $\rightarrow$ Increase ion density near the substrate $\rightarrow$ Low energy ion bombardment $\rightarrow$ Structure modification (equivalent to temperature)

Next steps: check if ion flux distribution follows; apply this to coat a real dipole
SEY versus the energy of primary electrons
RESULTS – Lab - SEY

SEY versus the energy of primary electrons

Coatings obtained by sputtering are similar
PECVD coatings have high SEY
Coatings morphology

Roughness could explain the lower $\delta_{\text{max}}$ of sputtered coatings relative to HOPG.

But not the high $\delta_{\text{max}}$ of PECVD coatings.
**RESULTS – Lab - XPS**

XPS analysis

![C1s line graph](image)

- Sputtered coatings and HOPG have the maxima at 284.4 eV => typical of graphite, sp² bonds
- PECVD coatings have the maxima shifted by 0.2eV to high binding energies => the fraction of sp³ bonds start to be important => more “diamond like”

As hydrogen is inherent to the PECVD process (precursor is C₂H₂), this technique was discarded for low SEY coatings.
Max SEY ($\delta_{\text{max}}$) versus hydrogen in the plasma during the coating by sputtering

The influence of Hydrogen in sputtered coatings is confirmed by experiments where $H_2$ is deliberately injected during the coating process
Max SEY ($\delta_{\text{max}}$) versus time and storage conditions

Simple storage, (Al foil, flanges, etc.), is enough to prevent ageing in air. Ageing not yet understood… but mastered!
RESULTS – Lab - Multipactor

Tests in the “Multipactor” system
(see Fritz Caspers talk (79) this afternoon)

Uncoated dipoles present strong multipacting, dependent of the magnetic field (cyclotron resonnance)

Coated dipoles shows no multipacting
Results from Electron Cloud Monitors in the SPS

Set-up: carbon coated liners with strip detector in 1.2K Gauss field
Beam: 2-3 batches, 72 proton bunches, 25 ns spacing, 450 GeV

E-cloud signal for carbon is 4 orders of magnitude below that for stainless steel.

Negligible ageing (accuracy of SEY measurements +/- 0.03)
RESULTS – SPS – Pressure

Dynamic pressure measurements in a drift zone of the SPS

- Gauge 1
- Gauge 2
- Gauge 3

External solenoid on StSt bellow

Central solenoid on 12m coated chamber

External solenoid On StSt chamber
RESULTS – SPS – Pressure

Dynamic pressure measurements in a drift zone of the SPS

Solenoid in carbon coated chamber has no effect in pressure
=> NO E-CLOUD
Conclusions

1 – Sputtered films are better than PECVD. (very likely due to higher sp$^2$/sp$^3$ ratio)

2 – H$_2$ is the key parameter to keep $\delta_{max}$~1.0 in sputtered films.

3 – ageing in air OK: negligible if sample protected( Al foil, flanges, etc.)

4 – ageing in the SPS OK: negligible (ECMs).

5 – ECM in SPS OK: coated liners have $10^4$ less multipacting than stainless steel.

6 – Multipactor tests OK: multipacting before coating, no multipacting after coating.

7 – Dynamic pressure tests in SPS OK: effect of solenoid in stainless steel parts, no effect in coated parts.

8 – So far, the sputtered carbon coatings passed all the tests.

9 – DCCMS technique is “ready to go”: can be used to coat parts that will not require disassembling/assembling magnets (pumping port shields, quadrupoles, drift tubes, etc)

10 – DCHCS technique is almost ready: need to solve the “dark area” problem and build 6.5 m cathode for MBA. Can be used to coat dipoles (MBB and MBA)

Thank you for your attention