Recent Experimental Results on Amorphous Carbon Coatings for Electron Cloud Mitigation

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Outline

1. Motivation
    - SPS-U: Super Proton Synchrotron Upgrade
    - New solution $\rightarrow$ Amorphous Carbon Coating
2. Experiments
    - Coating Configurations
    - Experiments in the lab
    - Implementation in the SPS: E-cloud experiments
    - Ageing (increase of SEY) observation of a-C coating
3. Conclusions and outlook
    - Conclusions
    - Outlook

Outline

The goal of this work

SPS-U: make the SPS able to deliver the above nominal beams to LHC and reach maximum luminosity.

Find a solution to eliminate e-cloud in the SPS, which

- can be implemented in the present SPS-dipoles without aperture reduction
- does not require bake-out
- is robust against air venting (maintenance, installation...)
- has a long life time

The condition for the secondary electron yield to avoid e-cloud in SPS dipoles with nominal LHC beam is (G.Rumolo et al.)

$$\delta_{max} < 1.3$$

Possible remedies for the electron cloud in the beam pipe:

- Low Secondary Electron Yield (SEY) thin-film coatings
- surface conditioning
- clearing electrodes
- chamber with grooves or slots

Ti-Zr-V film coating (implemented in straight sections of LHC) have $\delta_{max} = \mathbf{1.1}$ after **activation** at temperature higher than **180°C** (24h). But they cannot be applied to the **SPS** because the SPS magnet vacuum chambers are **not bakeable**.

TiN works well under the effect of photon conditioning in situ. But **no photons** in the **SPS**.

Which material to start with:

Known facts

- For air exposed stainless steel, Cu and Al $\delta_{max} > 2$.
- In the periodic system, elements with fewer electrons (on the left side) $=>$ lower SEY.
- 'Beam scrubbed' surfaces are covered by more carbon (at least Cu and StSt).

Try Carbon, which has few electrons

- SEY of graphite is much lower than diamond, so try to make graphite-like coatings.
- Graphite is not very reactive, should be less affected by air exposure.
- Graphite-like Amorphous Carbon (a-C) Thin Film Coating.

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Coating Configurations - DC magnetron sputtering

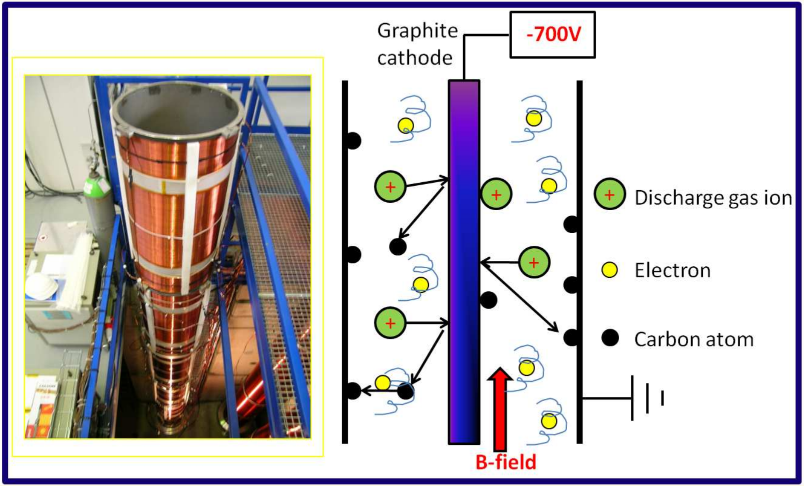
Different coating configurations were used:

- Cylindrical **tube** with one graphite rod cathode (for lab samples for SEY investigation and vacuum characterization)
- **Liner** in tube with 4 graphite rods (Lab samples, liner for e-cloud monitors)
- MBB magnet chamber **in-situ** (chamber in the dipole) with Multi-electrode geometry (Version I: coating in-situ in SPS dipoles)
- MBB magnet chamber **stand-alone** with liner configuration (Version II: coating outside SPS dipoles)

Different discharge gases (Ne, Kr, Ar) and different coating parameters (Temperature of substrate, discharge gas pressure, power) can be used.

Cylindrical tube configuration

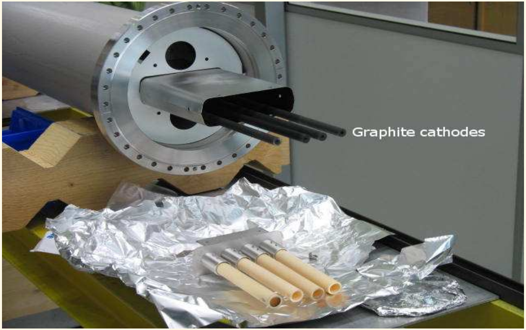
Lab samples for SEY and vacuum characterizations



Liner in tube with 4 graphite rods

Lab samples, liner for e-cloud monitors

- The coating chambers were inserted in a solenoid and the magnetic field is parallel to the cathodes and chamber axis.
- The surface temperature can rise to 250°C.
- Four graphite rods were used to avoid coating in-homogeneity.



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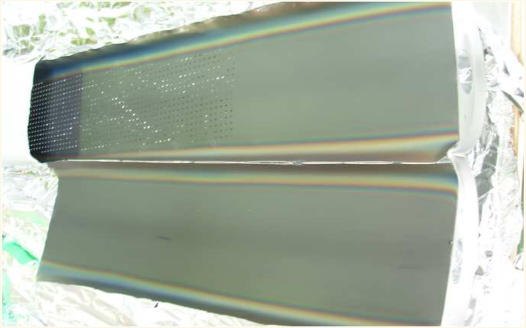
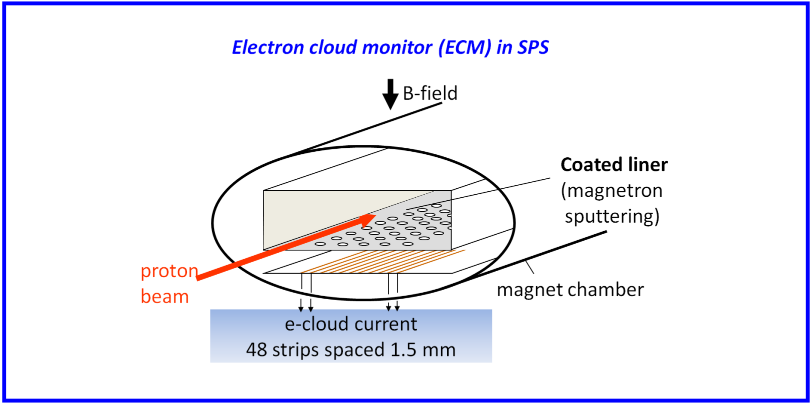
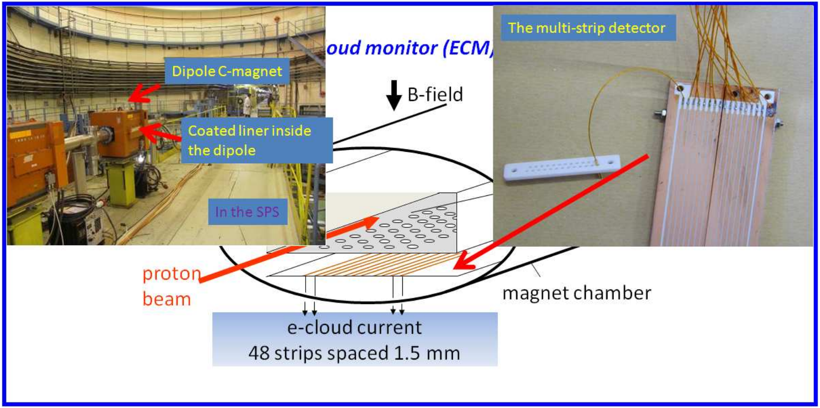


Coating for the Electron Cloud Monitor in the SPS



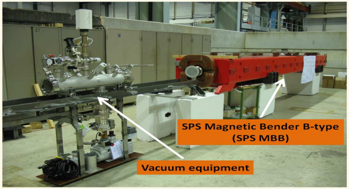
Coating for the Electron Cloud Monitor in the SPS



MBB magnet in-situ with Multi-electrode geometry

Version I: coating in-situ in SPS dipoles

- The magnetic field of the dipole was used and was **perpendicular** to the cathodes and chamber axis.
- The power during coating was kept limited in order to avoid overheating and damaging of the coil of the dipole.
- Three MBBs have been coated.
- Disadvantage: in-homogeneity.



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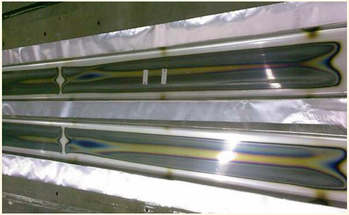

MBB magnet stand-alone with liner configuration

Version II: coating outside SPS dipoles

- Use the same technique as for liner coating to coat the vacuum chamber outside the SPS magnet.
- Three new MBBs have been coated.
- Disadvantage: Cut-open SPS dipole magnet and reassembly. (Expensive process!)
- Advantage: Perfectly homogeneous coating for large scale production can be done in advance.

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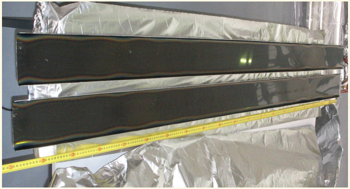
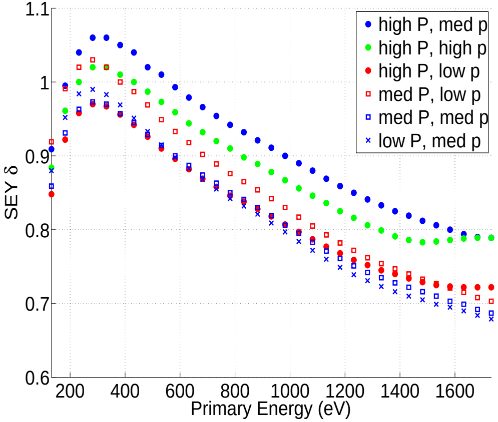


The SEY as a function of PE

P: power, p: pressure



- Measured directly after extraction from the deposition chamber and transfer to the SEY apparatus through air.
- The precision of the presented SEY values is estimated to ± 0.03.
- δ_{max} is between 0.9 and 1.1 and E_{max} = 300 eV. (not sensitive to coating parameters as pressure, power.)

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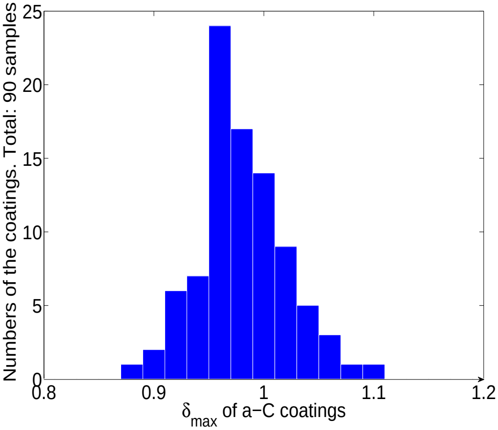

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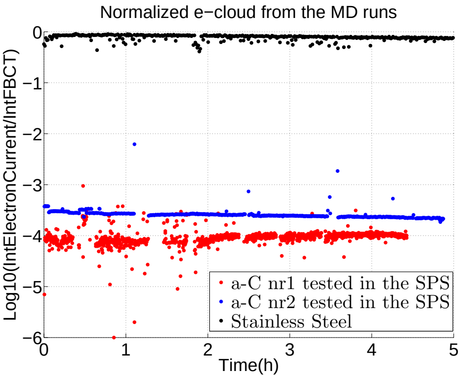
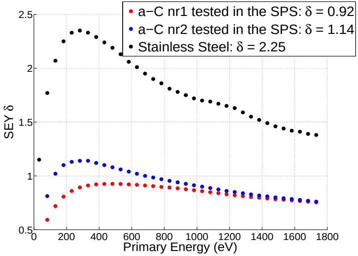
Electron Cloud Monitor (ECM)

- Electron cloud current normalized with beam intensity v.s time, measured by ECM in the SPS.
- 3-4 batches of nominal LHC beam. $(1.15 \cdot 10^{11}$ protons/bunch)



- SEY measurements in the lab.



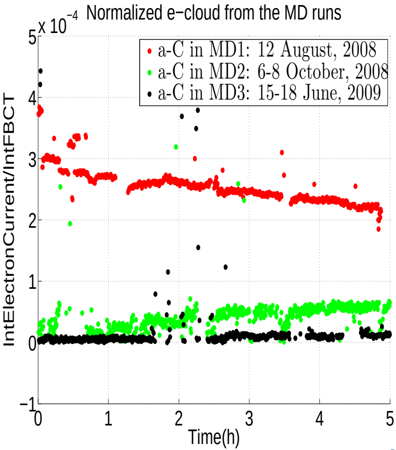
Observe!

- EC signal is 10^4 higher on StSt than a-C.
- Low SEY $\Rightarrow$ Low electron current signal.

Ageing observation of a-C **in the SPS**

One a-C coated liner has been tested during 3 Machine Development (MD) Runs with 3-4 batches of nominal LHC beam accelerated to 450 GeV/c.

- Vertical unit: nC/10^{10} protons per bunch
- The a-C coated liner was kept in the SPS for more than one year operation. (more than 2 months of venting, maintenance, installation...)
- **No sign of ageing in the SPS**.



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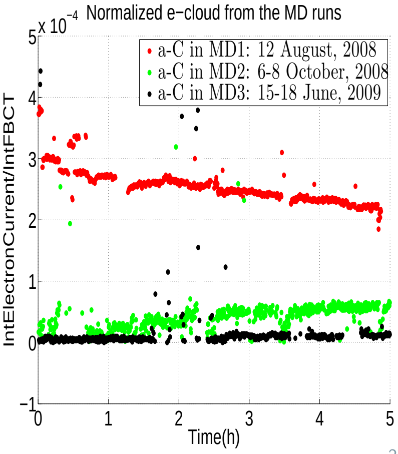

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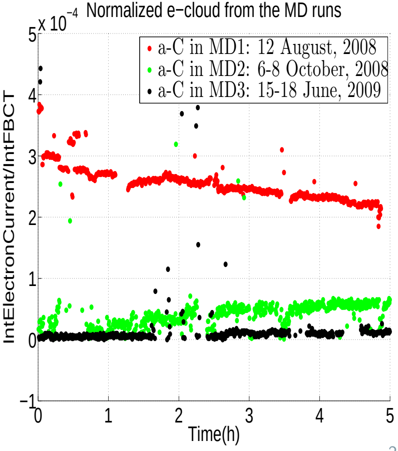

Inspection of **FIVE** liners extracted from **SPS**

One Stainless Steel liner and four a-C coated liners

Liner	SPS operation	$\delta_{initial}$
StSt (Reference)	1 year (5 MD runs)	2.25
C-strip (a-C coating of 40mm width)	1 year (5 MD runs)	0.92
C-Zr (a-C on rough Zr coating)	1.5 years (9 MD runs)	0.95
CNe64 (a-C coating)	2 months (2 MD runs)	0.95
CNe65 (a-C coating)	2 months (2 MD runs)	0.95

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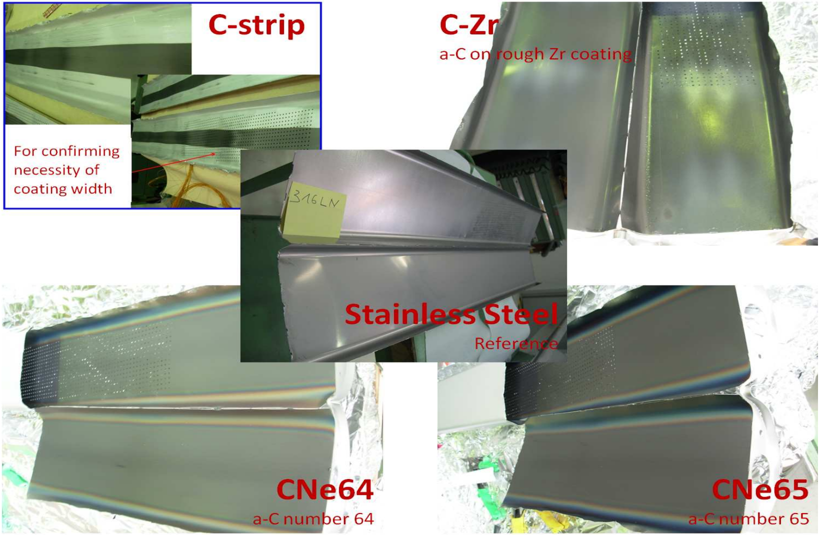

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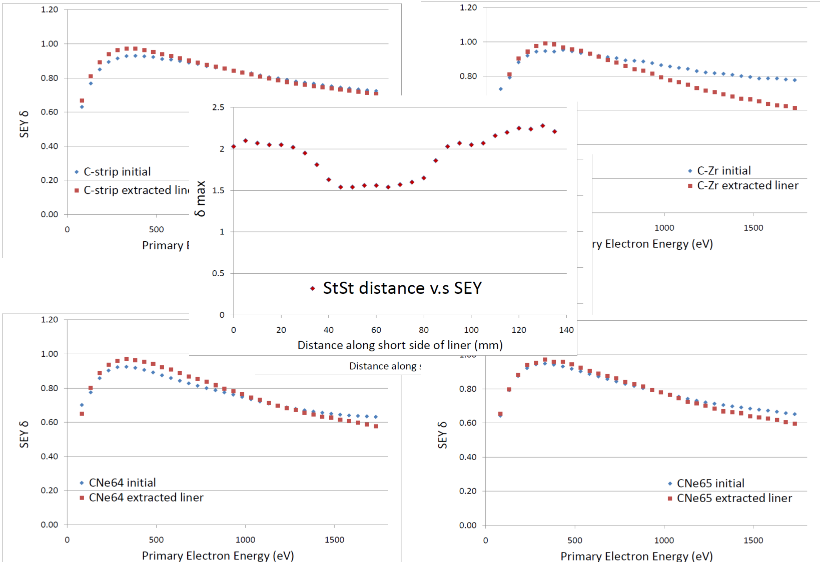
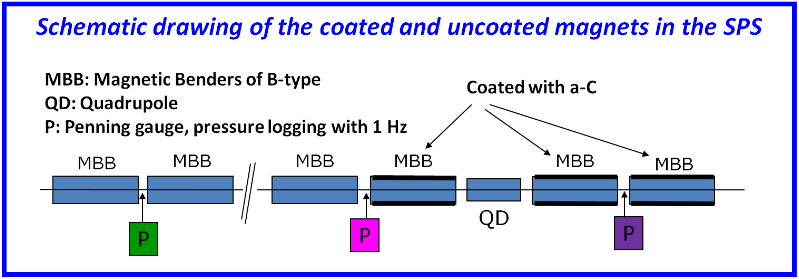


Three MBB dipoles have been coated with a-C coating in-situ dipole (Version I)



- Microwave transmission measurements detected e-cloud related signal in the coated and uncoated magnets.
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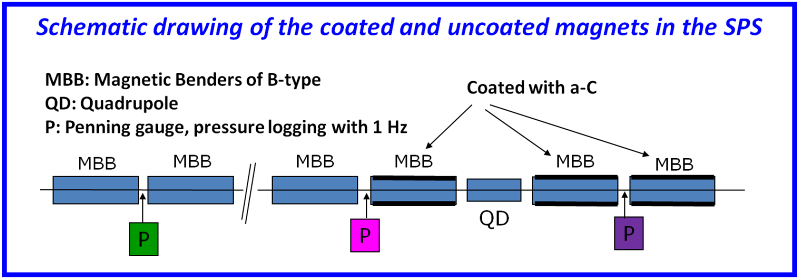

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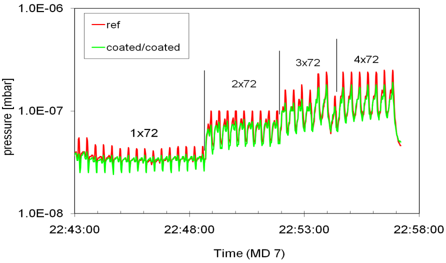
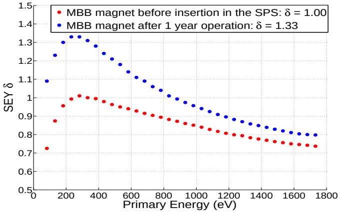
E-cloud related measurements/SEY measurements in the lab

- Dynamic pressure rise between the coated and uncoated magnets.
- The nominal LHC beam: 1,2,3 and 4 batches with 72 bunches at 25 ns spacing.



- SEY measurements before/after insertion in the SPS.



- No significant different in pressure rise.
- Big increase of SEY after extraction.

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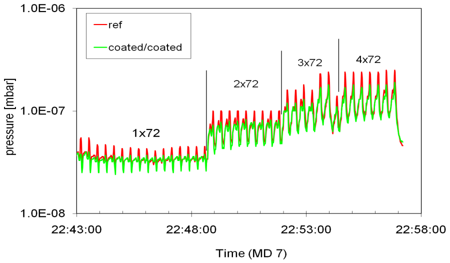
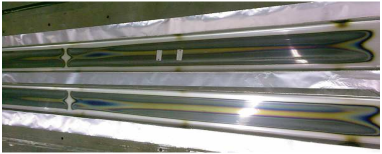


- Non-uniform coating color indicates differences in thickness and possibly composition.



- Bad SEY is mostly due to the in-homogeneous coating.
- Coat MBB vacuum chamber stand-alone outside dipole!!! (Version II)

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Conclusions

- A-C thin films produced by d.c magnetron sputtering show a reliable low initial SEY (well below $\delta_{threshold} = 1.3$).
- A complete suppression of e-cloud can be achieved by coating of liners with a-C.
- The coating of liners does not show ageing (increase of SEY) after more than 1 year of exposure in the SPS.
- Magnetron sputtered a-C film is a potential solution to eliminate e-cloud.

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Outlook

- The future activities will be focused on:
  - modifying the coating system in order to find an efficient and economical solution to coat beam pipes in a large scale with the same quality of coating as in the ECMs.
  - following the ageing development of the liners and getting a deeper understanding of a-C thin film both in the lab and in the SPS.
  - following the ageing development of the new version of MBB coating and getting a deeper understanding of the relationship between dynamic pressure rise and e-cloud effect.
- The first implementation in a large scale with this type of a-C coating is now planned to be performed in the SPS magnet of total 200 m during the shutdown 2012.

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