Ar-Nb ion energy distribution and thin film properties in HiPIMS with a positive voltage pulse

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Outline

- Framework
- R&D simulations
- R&D experiments
- Next steps
- Conclusions
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The CRAB cavity: what for?

HL-LHC upgrade (by 2025) aim at increasing luminosity by a factor of 5. 16 CRAB cavities will be mounted around the two main experiments (CMS-ATLAS).

Why CRAB?
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Why CRAB?
The CRAB cavity R&D

1st bulk Nb CRAB cavity for HL-LHC completed and under test in SPS

0.66 m
The CRAB cavity R&D

1st **bulk Nb** CRAB cavity for HL-LHC completed and under test in SPS

R&D in the **FCC** framework for alternative **Nb/Cu** WOW CRAB cavities

1st **Cu WOW** CRAB cavity prototype to be Nb coated
The CRAB Cu cavity

CHALLENGES:

1. Superconducting cavities require high purity and defect-free coatings

2. Complex shape: avoid shadowing / uniform growth
The CRAB Cu cavity

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Total power loss ~ 60W @ $Q_0 = 4 \times 10^8 / 3$ MV deflection
CRAB cavity coating challenge
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Cylindrical sputtering source
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Coating surfaces at different:

- distances (50 – 150 mm)
CRAB cavity coating challenge

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- incident angles (0 – 90 °)
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From R&D to scale-1 cavity

1. Basic tests in a R&D experimental setup:

   • Basic plasma physics in HiPIMS
   • Optimization of HiPIMS parameters
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   - Coating of copper strips with the CRAB cavity shape
   - Parallel implementation of plasma diagnostics
   - New sputtering source development
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3. Coating of the first scale-1 cavity prototype
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Plasma simulation of 60 mm long cylindrical cathode

Experiment
P = 5.10^{-3} \text{ mbar} / \text{Ar} / 1kW / DCMS

Side view of the cylindrical cathode (permanent magnet inside)
Plasma simulation of 60 mm long cylindrical cathode

**Experiment**
P = 5.10^{-3} mbar / Ar / 1kW / DCMS

**Plasma simulation**
P = 5.10^{-3} mbar / Ar / 10W / DCMS

Output: Nb sputtering profile
Plasma simulation of 60 mm long cylindrical cathode

Experiment
P = 5.10^{-3} mbar / Ar / 1kW / DCMS

Plasma simulation
P = 5.10^{-3} mbar / Ar / 10W / DCMS

Output: Nb sputtering profile

x5 cathodes in WOW
Transport simulation and thickness profile

→ Nb thickness profile, scaled to an equivalent 15’ coating at 1kW/cathode
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→ Nb thickness profile, scaled to an equivalent 15’ coating at 1kW/cathode
→ Uniformity copes with peak power density position → layer morphology?

Could HiPIMS?
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R&D experimental setup

- 43 cm high DN150 vacuum chamber
R&D experimental setup

- 43 cm high DN150 vacuum chamber
- 2” magnetron source, 15° tilted
R&D experimental setup

- 43 cm high DN150 vacuum chamber
- 2” magnetron source, 15° tilted
- Mass and energy analyser (MEA):
  time integrated + time resolved measurements of ion fluxes
Samples and holder

View from bottom of the MEA entrance orifice
Samples and holder

View from bottom with sample holder

~ 14.5 cm

2" Nb target

0°
Samples and holder

View from bottom with sample holder

- FIB cut
- 15 mm
- 10 mm
- 5 mm
- 20 mm

- 2” Nb target
- ~ 14.5 cm
- 0°
- 90°

Sample holder
HiPIMS configurations

- Duty cycle: 1 kHz
- Main pulse (MP): 30 μs
HiPIMS configurations

- Duty cycle: 1 kHz
- Main pulse (MP): 30 μs
- Delay (D): 4 μs
HiPIMS configurations

- Duty cycle: 1 kHz
- Main pulse (MP): 30 μs
- Delay (D): 4 μs
- PP duration (PP): 20 – 250 μs
Time-integrated IEDF

By using the MEA

![Graph showing count rate vs energy for different conditions.](image-url)
Time-integrated IEDF

By using the MEA

Evidence of a dominant high energy ion population!
FIB on DCMS coatings

Experimental parameters:
- Argon pressure: $8 \times 10^{-3}$ mbar
- Niobium target
- Power: 250 W (1.5 hours)

DCMS with grounded substrate

DCMS with -50V bias on substrate
FIB on HiPIMS coatings

a) HiPIMS, no PP, grounded substrate
FIB on HiPIMS coatings

a) HiPIMS, no PP, grounded substrate

b) HiPIMS, no PP, -50 V bias on substrate
FIB on HiPIMS coatings

a) HiPIMS, no PP, grounded substrate

b) HiPIMS, no PP, -50 V bias on substrate

c) HiPIMS, +50 V PP, grounded substrate

Biased-like effect with a positive pulse!
90° sample gets densified with 200 μs positive pulse at +50V
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Validation of coating setup with **mockup** samples

- Time- and **spatially-resolved** (substrate-cathode distance) IEDF measurements
- Deposition on **samples reproducing the CRAB cavity shape**
- Assess layer uniformity and SC properties with **different coating configurations**
Validation of coating setup with mockup samples

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Conclusions

• First indication of coating uniformity with simulations in DCMS

• Measured mass-, energy-resolved ion fluxes (Ar\(^+\), Nb\(^+\))

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Conclusions

• First indication of coating uniformity with simulations in DCMS

• Measured mass-, energy-resolved ion fluxes ($\text{Ar}^+$, $\text{Nb}^+$)
  Evidence of a dominant high energy ion population with positive pulse

• Performed sample coatings in different HiPIMS configurations:
  FIB analysis indicates a biased-like effect with a positive pulse!
  90° sample gets densified with 200 μs, +50V positive pulse
Backup Slides
<table>
<thead>
<tr>
<th>Process</th>
<th>Sample</th>
<th>XRF [μm]</th>
<th>FIB [μm]</th>
<th>Dr [nm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCMS (1.5 h / 250W)</td>
<td>0°</td>
<td>1.5</td>
<td>1.6</td>
<td>17.8</td>
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<tr>
<td></td>
<td>90°</td>
<td>0.5</td>
<td>1</td>
<td>11.1</td>
</tr>
<tr>
<td>DCMS and -50V bias on samples (1.5h / 250W)</td>
<td>0°</td>
<td>1.9</td>
<td>1.93</td>
<td>21.4</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>0.6</td>
<td>1.3</td>
<td>5.4</td>
</tr>
<tr>
<td>HiPIMS 30 μs pulse (4h / 250W)</td>
<td>0°</td>
<td>2.1</td>
<td>2.1</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>0.7</td>
<td>1.3</td>
<td>5.4</td>
</tr>
<tr>
<td>HiPIMS 30 μs pulse and -50 V bias on samples (4h / 250W)</td>
<td>0°</td>
<td>2</td>
<td>2</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>0.7</td>
<td>0.8</td>
<td>3.3</td>
</tr>
<tr>
<td>HiPIMS 38 μs pulse and +50V / 200 μs reverse kick (4h / 250W)</td>
<td>0°</td>
<td>2</td>
<td>2.2</td>
<td>9.2</td>
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<tr>
<td></td>
<td>90°</td>
<td>0.67</td>
<td>0.8</td>
<td>3.3</td>
</tr>
</tbody>
</table>
FIB on HiPIMS coatings

a) HiPIMS (grounded substrate)

b) HiPIMS with -50 V bias on substrate

c) HiPIMS with +100 V positive pulse (grounded substrate)
FIB on HiPIMS coatings

a) HiPIMS (grounded substrate)

b) HiPIMS with -50 V bias on substrate

c) HiPIMS with +100 V positive pulse (grounded substrate)
Biased-like effect with a positive pulse!

90° sample gets densified with 200 μs, +100V positive pulse
30us MP – 4us D – 200us RK 100V
How to measure time-resolved ion fluxes

- CP400 Ion counter
- ECL-TTL converter
- Multi-channel Scaler MCS4

Time-resolved Measurements:
- 50ns dwell time
Time-resolved $\text{Ar}^+$ fluxes

30 $\mu$s MP

30 $\mu$s MP – 25 $\mu$s D – 35 $\mu$s RK