Surface Resistance and Impedance Effects of LESS (laser engineered) Processing for Q5 Magnets

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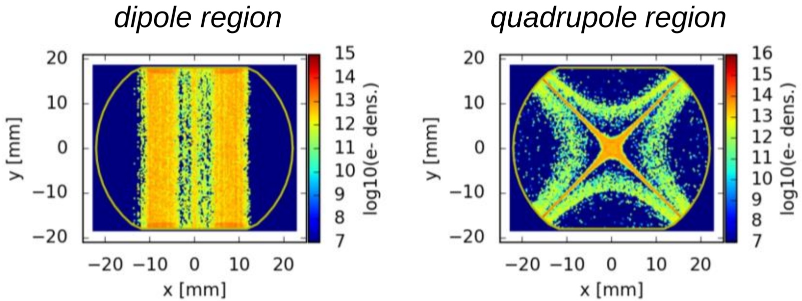
97th Impedance Working Group meeting - 04.03.2025

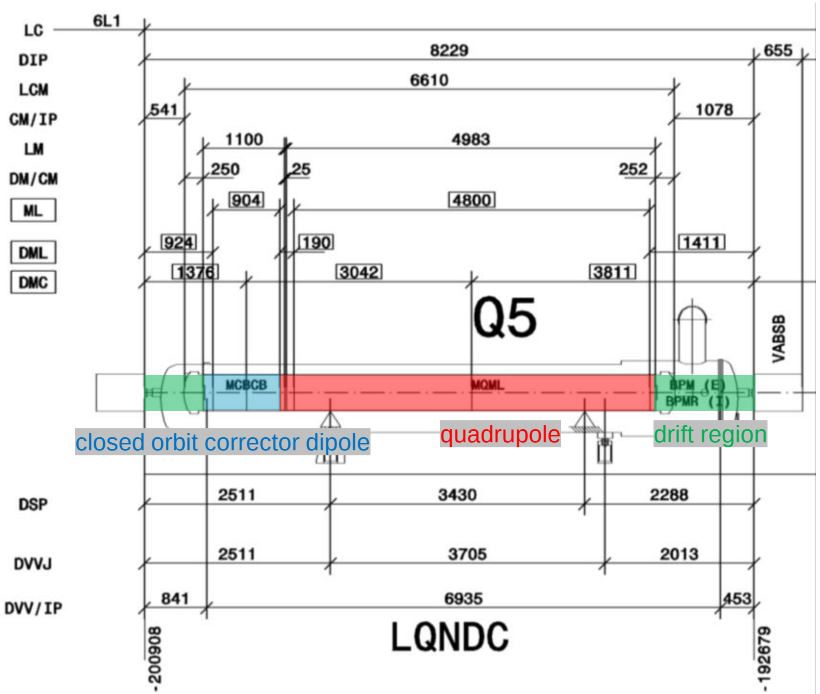
LESS project for Q5 magnets with Cryosorbers

Simulated electron distribution in LHC magnets



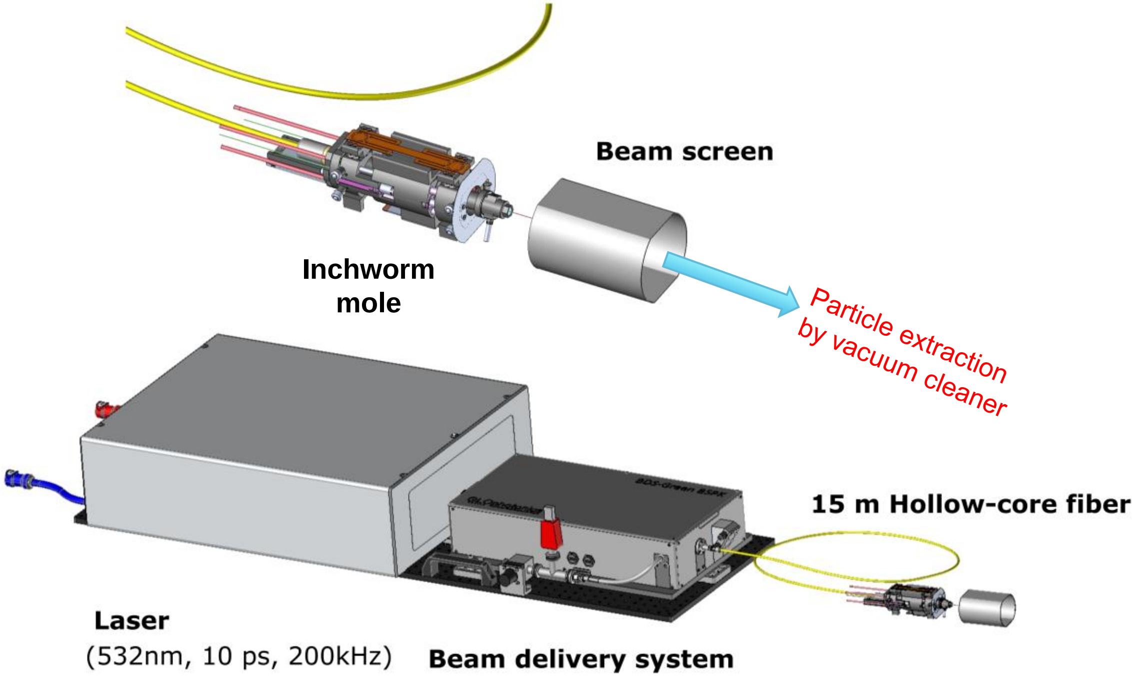
P. Dijkstal et al., Tech. Rep. CERN-ACC-NOTE-2017-0057, CERN, 2017.

- SEY reduction & E-cloud mitigation for improvement of beam quality for Hi-Lumi operation required*
- a-C coating is baseline for LHC, but not applicable in presence of cryosorbers
- Project for development of laser treatment solution of 4 Q5 magnets of IP 1 & 5 on surface

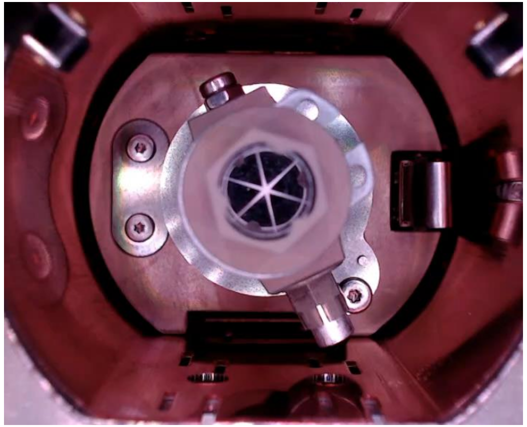


*see predictions for HL-LHC by G. Iadarola:
https://indico.cern.ch/event/1154258/#43-need-for-coating-in-q4-and
https://indico.cern.ch/event/1191314/#3-specification-of-sey-require

Laser treatment of beam screens



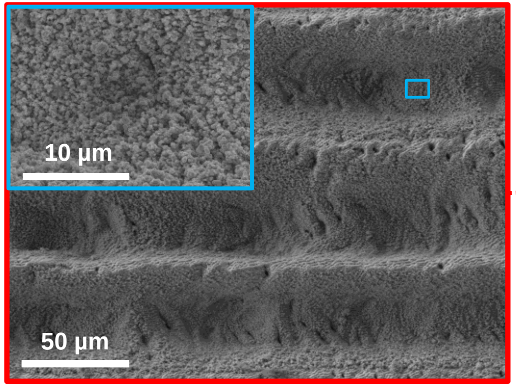
(1030 nm, 1 ps, 500 kHz)

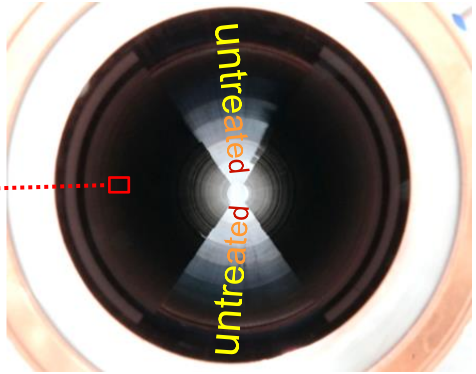


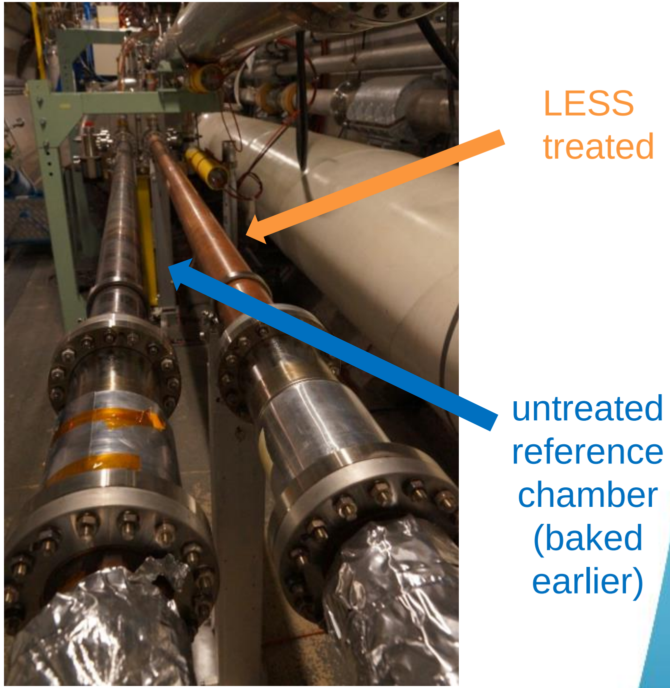
Laser-treated chamber for LHC validation

3.113 m test chambers were installed in the LHC in a LSS (Vacsec.C5R6.B) in 11/2023

- Goal: verify that the activity seen by the surrounding BLMs is compatible with LHC operation
- The test is a prerequisite for the treatment of Q5 beam-screens for HL-LHC to mitigate e-cloud
- The chamber is treated in a similar configuration as for a quadrupole magnet with top and bottom areas untreated

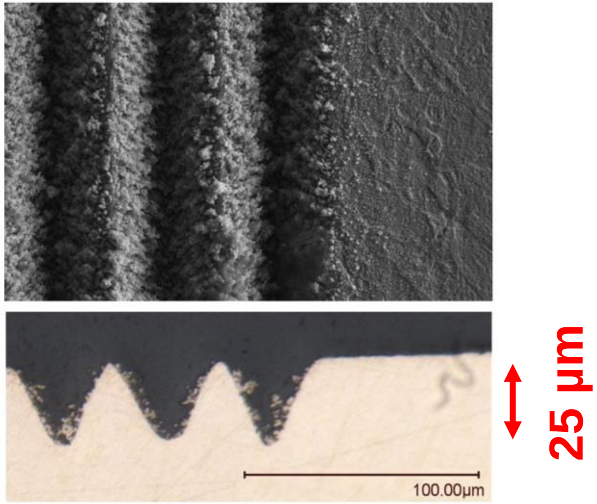






LHC-VC-EC-0003, https://edms.cern.ch/document/2914342/1.0

Considerations for BS surface resistance



Topography:

- 0 - 50 µm deep and wide trenches formed
- Microstructure covered with adherent nanoparticles

Impedance:

- 75 um Cu OFE layer on stainless steel

→ Limit trench depth to 25 µm to not risk influence of underlying steel especially after a possible second laser passage

What is the influence of the surface roughening on resistance and impedance for the LHC operation conditions ?

Surface Resistance of Cu LESS – QPR study

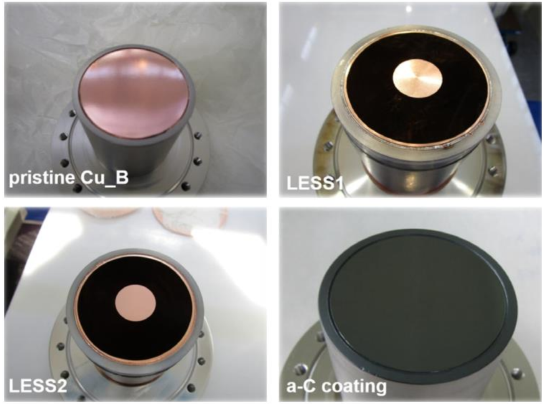
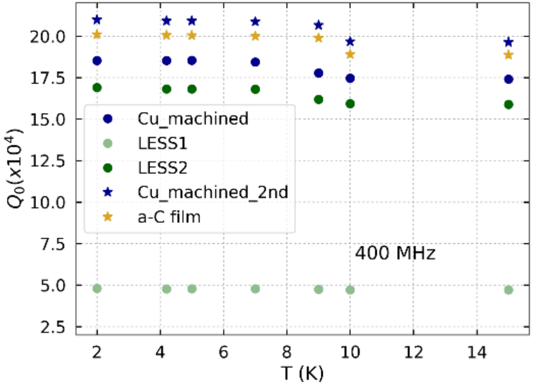


FIG. 2. The four characterized sample surfaces. Cu_A or Cu_B, pristine OFE copper; LESS1, copper with a radial laser pattern; LESS2, copper with a circular laser pattern; a-C coating, copper with an amorphous carbon coating.



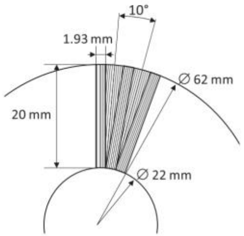
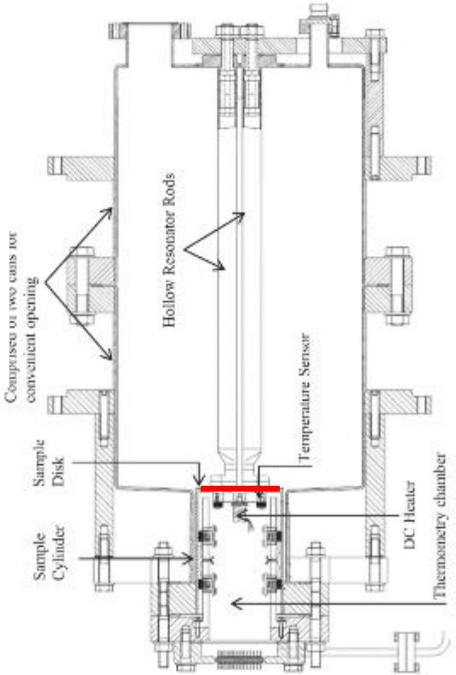


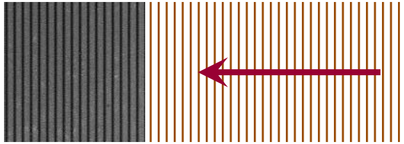
FIG. 4. Schematic pattern for the laser treatment of the QPR sample LESS1, repeated along the entire annular surface.



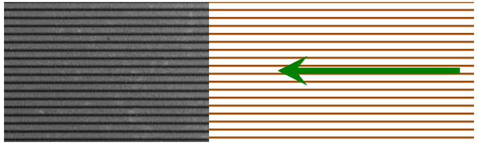
Courtesy M. Arzeo, S.Calatroni

S. Calatroni et al. Phys. Rev. Accel. Beams 22, 063101 (2019)

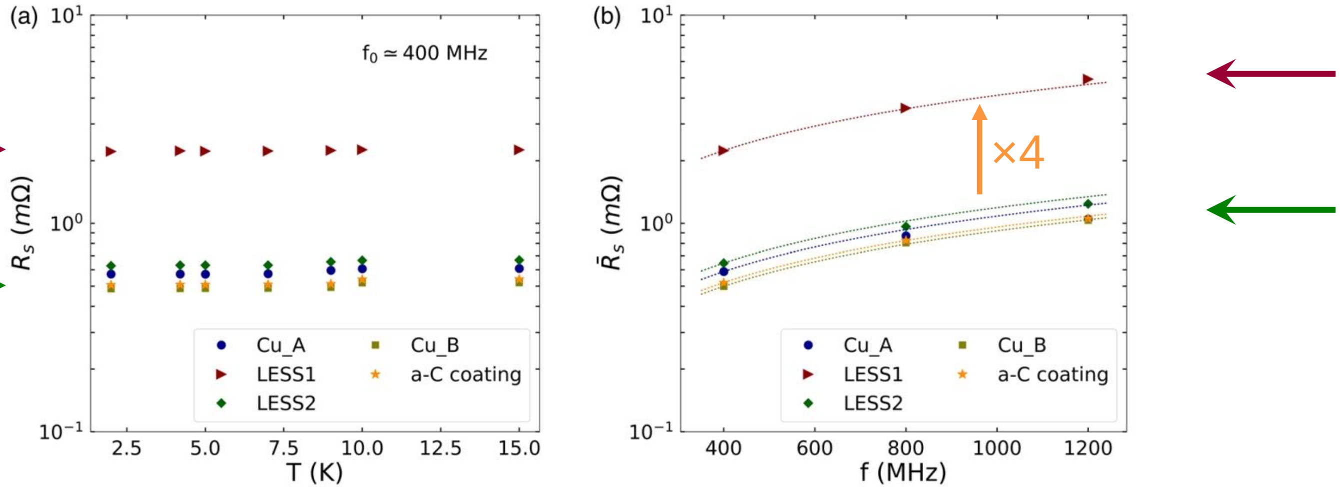
Surface Resistance of Cu LESS – QPR study



trenches ⊥ to beam



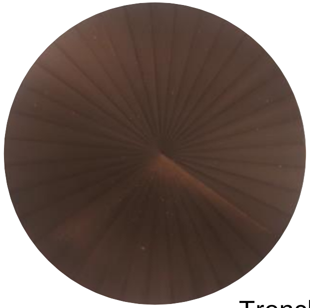
trenches ∥ to beam



S. Calatroni et al. Phys. Rev. Accel. Beams 22, 063101 (2019)

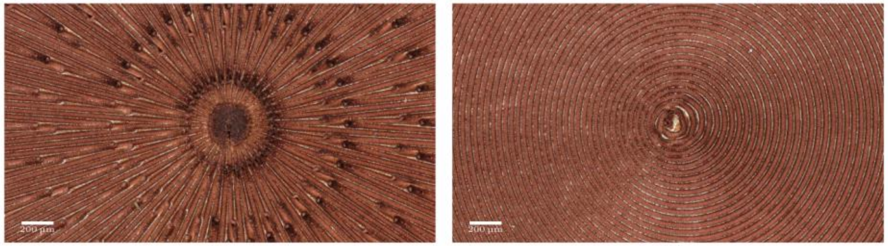
FIG. 5. (a) Surface resistance as a function of the sample temperature for pristine copper and for the different surface treatments. (b) Surface resistance averaged over the temperature as a function of the QPR mode frequency for pristine copper and for the different surface treatments. The curves show the functional dependence $f^{2/3}$, having the data points at 400 MHz as a reference. Error bars are not shown for a better visualization of the different data points (measurement uncertainty $\delta R_s/R_s \approx 10\%$).

Surface Resistance of Cu LESS – CHCDR study




Trench depth 25-30 µm

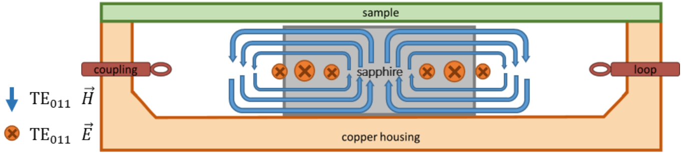
perpendicular ⊥ longitudinal ∥



(a) (b)

FIG. 1. Optical micrographs of the center of the laser-engineered surface structured copper discs. (a) Radial LESS-I structure and (b) Azimuthal LESS-II structure.

closed Hakki-Coleman dielectric resonator (CHCDR)



3.4 GHz

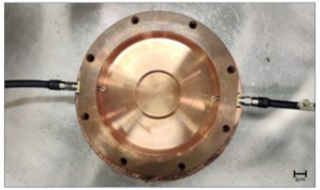


Figure 1: Photograph of the sapphire loaded CHCDR.

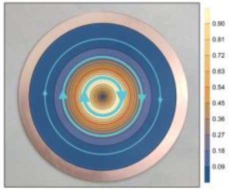
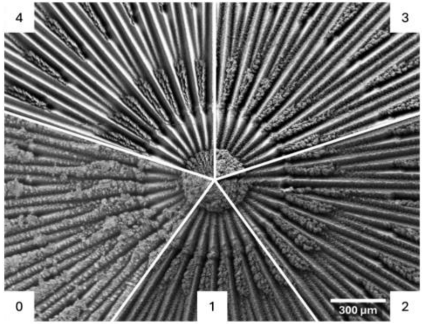


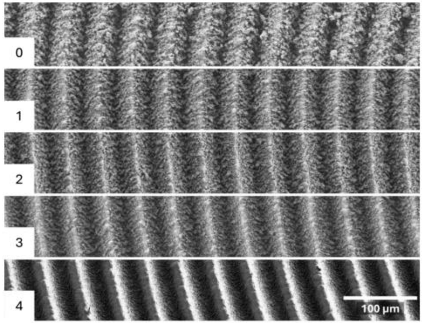
Figure 2: Induced azimuthal surface current density distribution on the sample surface for the TE_{011} mode. The red circle indicates the edge of the dielectric puck.

P. Krkotić et al., Phys. Rev. Accel. Beams 27, 113101 (2024)

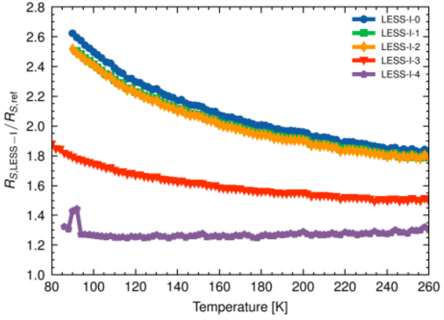
Surface Resistance of Cu LESS – CHCDR study

Stepwise cleaning and nanoparticle removal

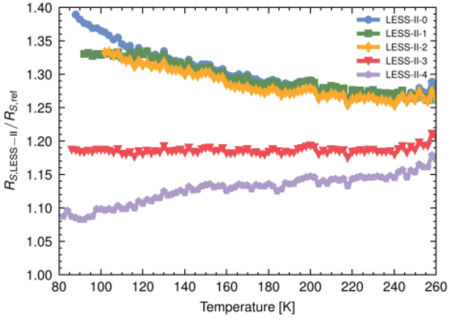




perpendicular ⊥   Trench depth 25-30 µm   longitudinal ∥

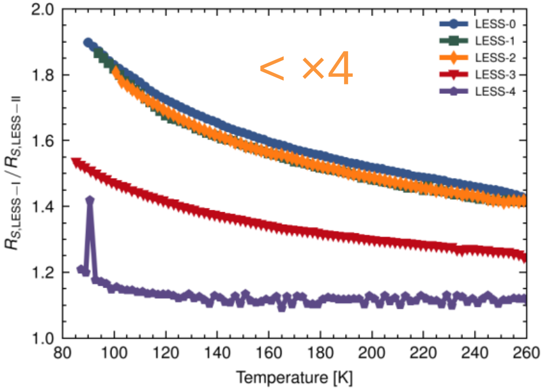


(a)



(b)

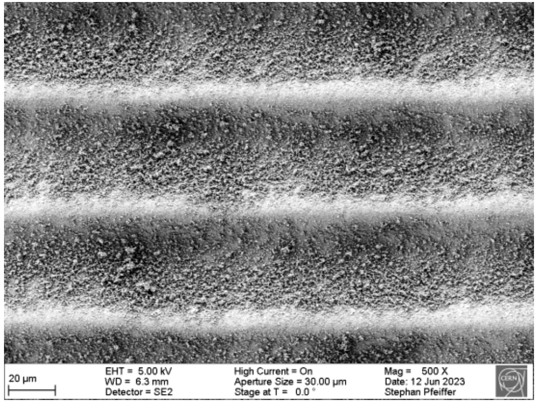
Ratio ⊥ / ∥   3.4 GHz

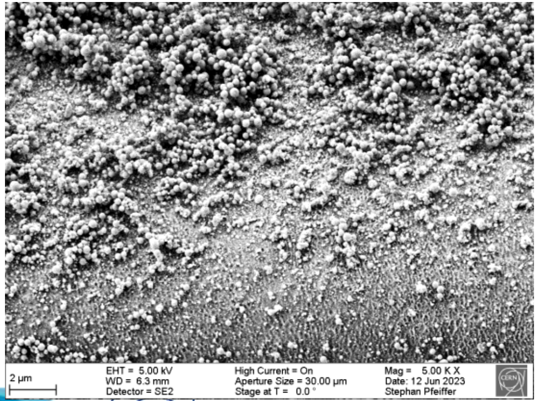


(c)

P. Krkotić et al., Phys. Rev. Accel. Beams 27, 113101 (2024)

Compromises for laser process optimisation





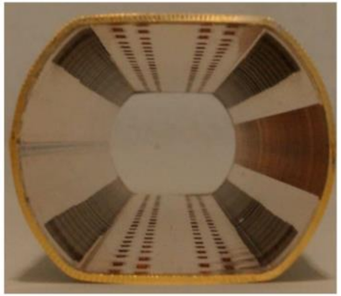
- Longitudinal grooves with depth < 20 um
  → δ_{max} = 1.4 - 1.5, fewer particles at the surface,
  → lower increment of surface resistance
  → particle diameter < 1 µm, no particulate detachment

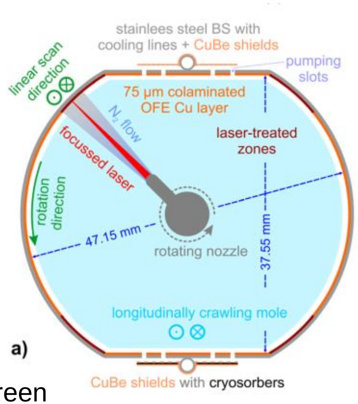
- Treatment of only 22% of the full circumference in the corners of the BS
  → minimisation of particulate risks
  → less influence on beam impedance

- estimated treatment time: 3-4 weeks per Q5 magnet

Q5 magnets with Cryosorbers – optimised LESS

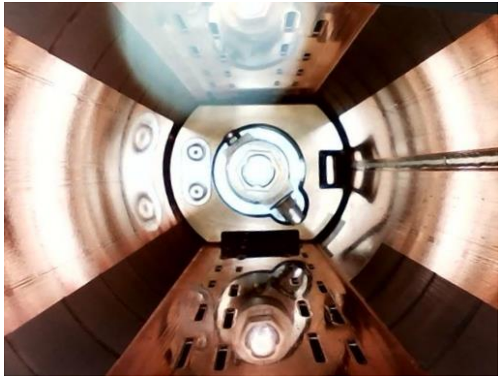
- Solution for quadrupole magnet region: 4 corners LESS treated to mitigate electron multipacting in the central region



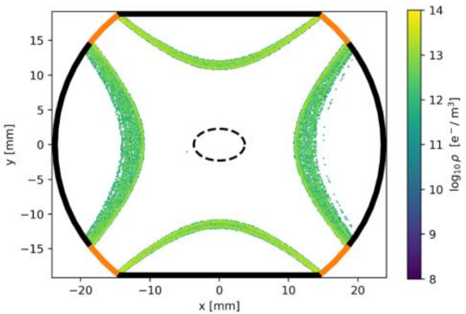


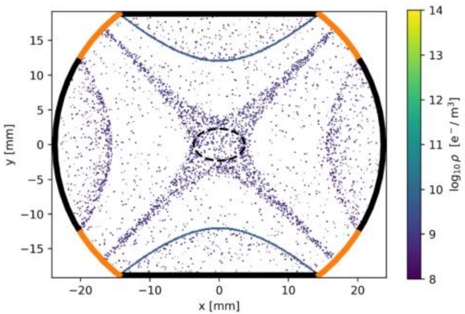
Selectively processed beam screen

Camera Inspection of 4×20º treated beam screen

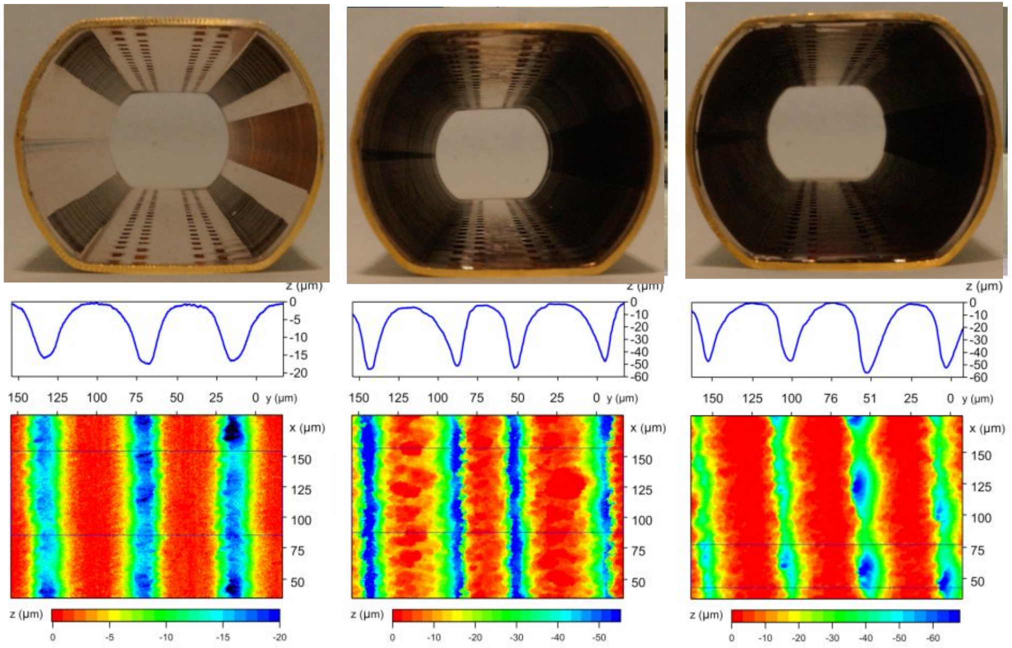


E'cloud simulation by K. Paraschou





Surface resistance of processed beam screens



(a) 4 × 20° longline — longitudinal ∥

(b) 360° longline — longitudinal ∥

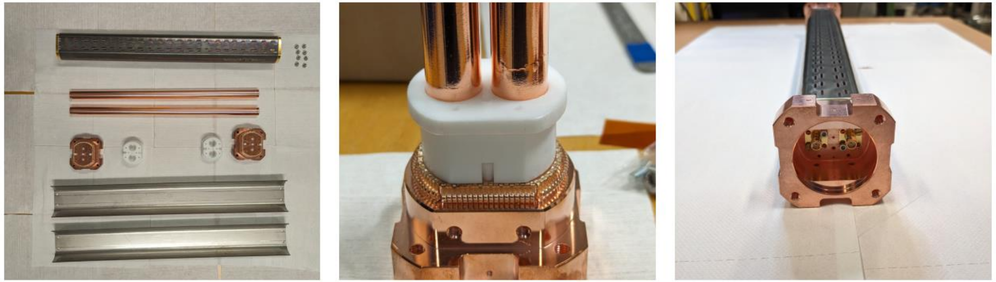
(c) 360° spiral — perpendicular ⊥

Aim:

- Test performance of final laser processing strategy
- Confirm orientational dependence of resistance

Patrick Krkotić et al., arXiv:2502.01392v1, https://doi.org/10.48550/arXiv.2502.01392

Surface resistance of processed beam screens



(a) shielded pair assembly pieces (b) end cap assembly (c) view on probes

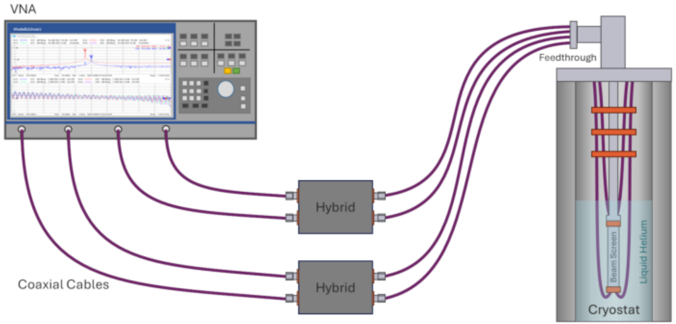
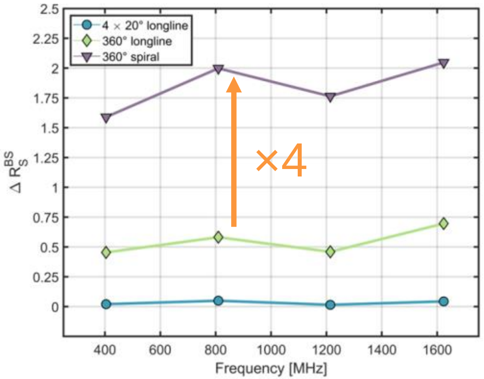


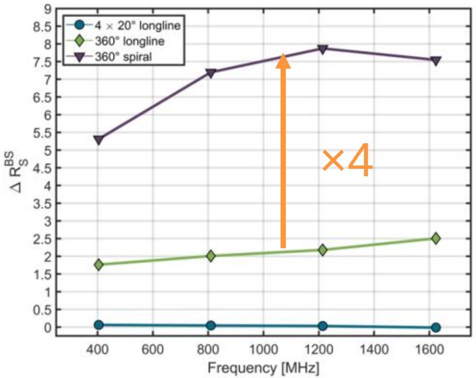
FIG. 4: Assembly of the LHC beam screen for measureme

Measurement procedure

- Five measurements at RT
- Five measurements at RT
- Cool-down – (1m liquid helium)
- Five measurements at 4.2 K
- Natural warm-up – (measurements)



(a) direct comparison @ RT



(b) direct comparison @ 4.2 K

FIG. 10: Measurement results presented as relative change of BS surface resistance for the laser treated samples compared to the standard LHC BS.

Patrick Krkotić et al., arXiv:2502.01392v1, https://doi.org/10.48550/arXiv.2502.01392

Surface resistance of processed beam screens

Increment of surface resistance compared to Cu OFE

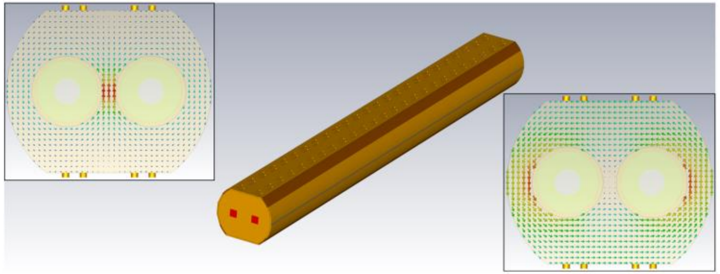


FIG. 6: CST version of the reconstructed LHC beam screen with the 4 × 20° longline treatmen Orange areas represent pure copper, brown areas refer to the laser treated copper and the grey area represents the welding line of stainless steel. Insets indicate the magnetic fields for the even mode (down right) and odd mode (up left) mode configuration.

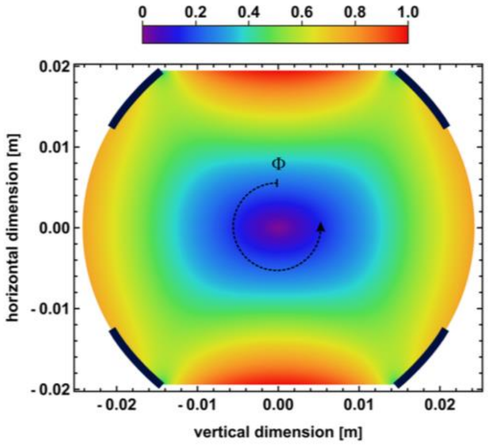
TABLE I: Summary of the surface resistance increase factor for the laser-treated areas, relative to pure copper, averaged across all resonances. The error is defined as the maximum deviation from the average to the highest or lowest value.

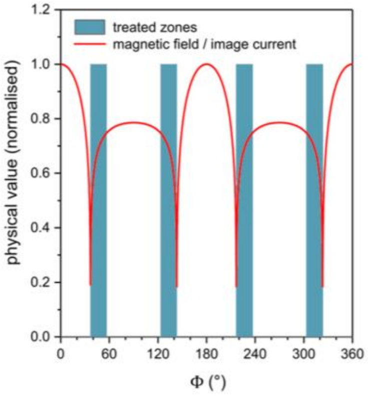
	4 × 20° longline	**360° longline**	**360° spiral**
$R_{S,\mathrm{RT}}^{\mathrm{LESS}}$	$1.29^{+0.16}_{-0.16}$	$1.55^{+0.14}_{-0.09}$	$2.85^{+0.19}_{-0.26}$
$R_{S,4.2\,\mathrm{K}}^{\mathrm{LESS}}$	$1.41^{+0.15}_{-0.13}$	$3.11^{+0.39}_{-0.35}$	$7.98^{+0.89}_{-1.67}$

Trench depth	15-20 µm	50-60 µm	50-60 µm
Orientation	longitudinal ∥	longitudinal ∥	perpendicular ⊥

Patrick Krkotić et al., arXiv:2502.01392v1, https://doi.org/10.48550/arXiv.2502.01392

Longitudinal Beam Impedance





Time-domain simulations using
CST's 2024 Wakefield Solver

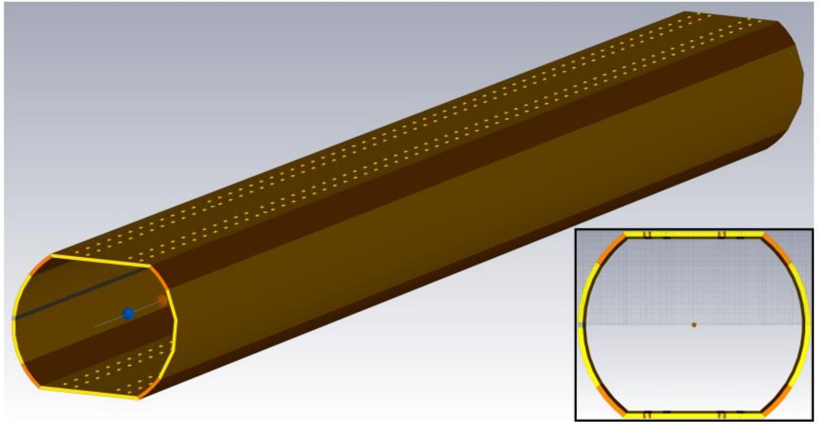


FIG. 13: CST wakefield simulation model for the LHC beam screen with 4 × 20° longline laser treatment configuration. The inset shows the cross-sectional mesh view.

Patrick Krkotić et al., arXiv:2502.01392v1, https://doi.org/10.48550/arXiv.2502.01392

Longitudinal Beam Impedance

Q5 LESS treatment parameters

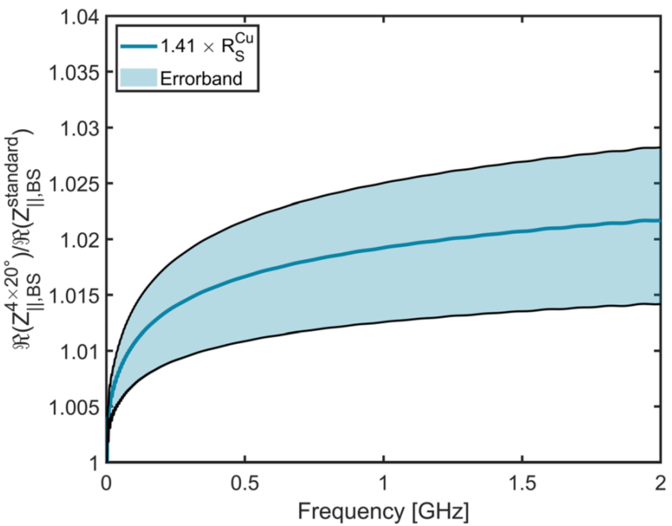


Fig. 10 Comparison of real part of the longitudinal beam impedance: ratio between selective laser treated LHC beam screen and standard LHC beam screen including error bands.

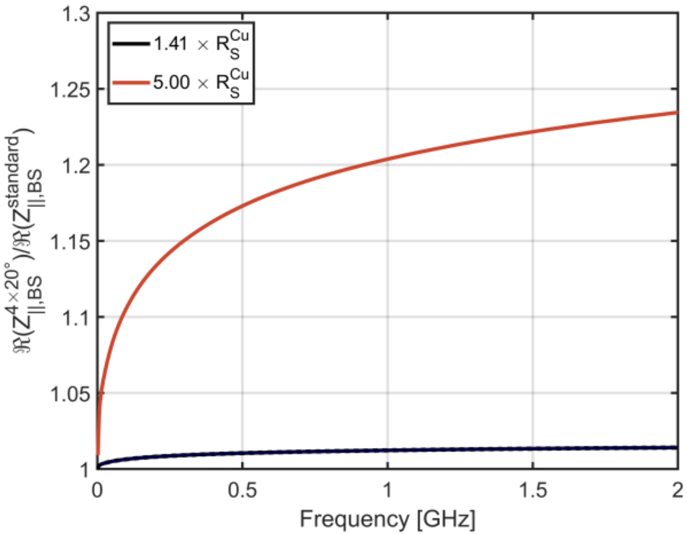


FIG. 14: Comparison of the real part of the longitudinal beam impedance: ratio between the 4 × 20° longline laser-treated LHC beam screen and the standard LHC beam screen.

Patrick Krkotić et al., arXiv:2502.01392v1, https://doi.org/10.48550/arXiv.2502.01392

Conclusions

- Laser processing leads to increment of Cu surface resistance with clear anisotropy caused by the formed trenches

- Longitudinal trench alignment with current direction is preferred

- Selecting a partial treatment for LESS of the Q5 magnets in the important zones for E'cloud mitigation in quadrupole magnets (4 corners) leads to an increment of the longitudinal beam impedance of < 3 % on a length of 5 m beam screen to be treated

- Does the Impedance Working Group rate the LESS treatment positive for a potential ECR to come for the Q5 magnet treatment ?