HiLumi
HL-LHC PROJECT

Progress & challenges associated with large scale laser surface treatment for SEY reduction

M. Himmerlich on behalf of CERNs TE-VSC team

ECLOUD’22 - 28.09.2022

CERN

Outline

1. Laser treatment for SEY reduction: from proof of principle to possible treatments of LHC beam screens
2. Fundamental studies and their conclusions
3. How far have we come ?

LESS (laser engineered surface structuring) = LASE

History of LESS for low SEY & E-cloud mitigation

APPLIED PHYSICS LETTERS **105**, 231605 (2014)

Low secondary electron yield engineered surface for electron cloud mitigation

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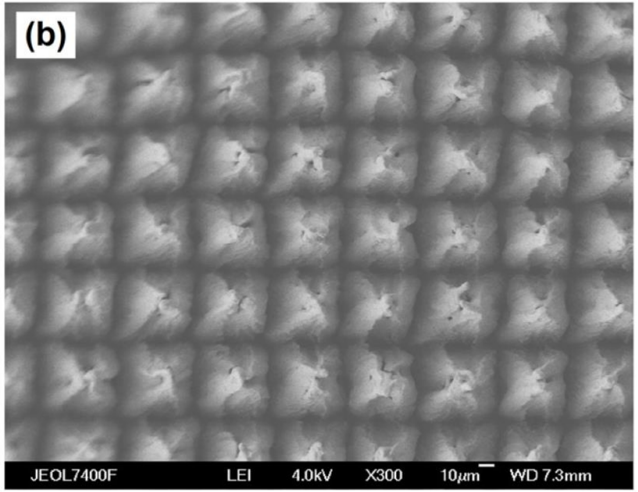


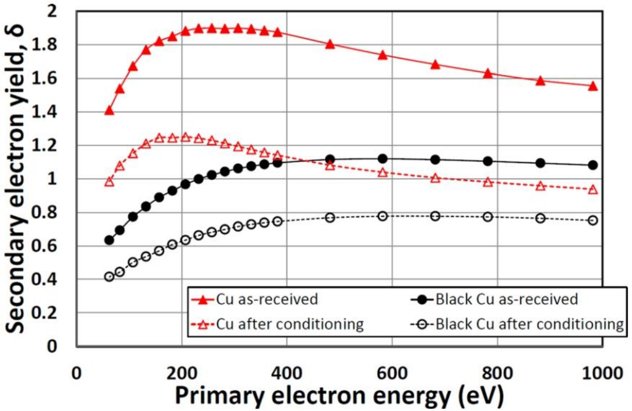
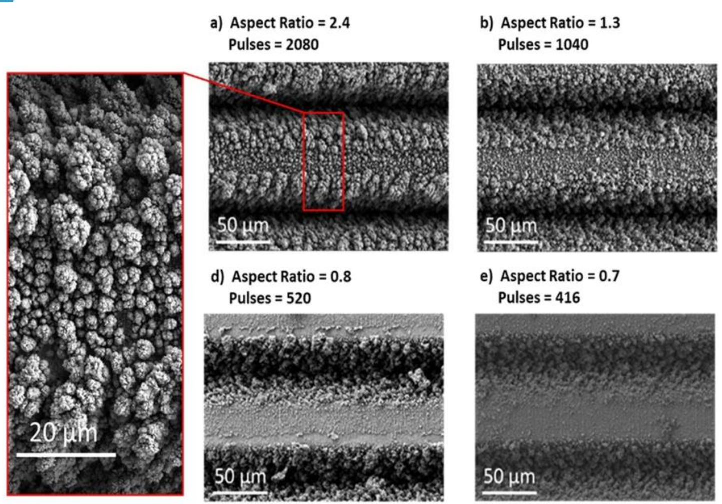


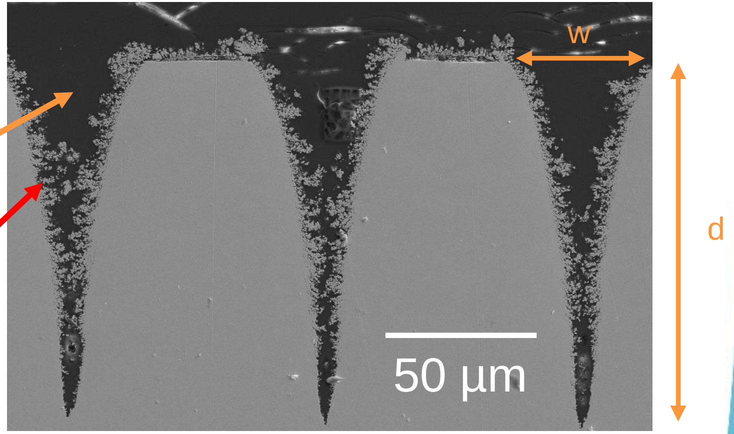
FIG. 3. SEY for Cu as a function of incident electron energy: Cu—untreated surface, black Cu—laser treated surface, and conditioning—electron bombardment with a dose of 1.0×10^{-2} C·mm^{-2} for Cu and 3.5×10^{-3} C·mm^{-2} for black Cu.

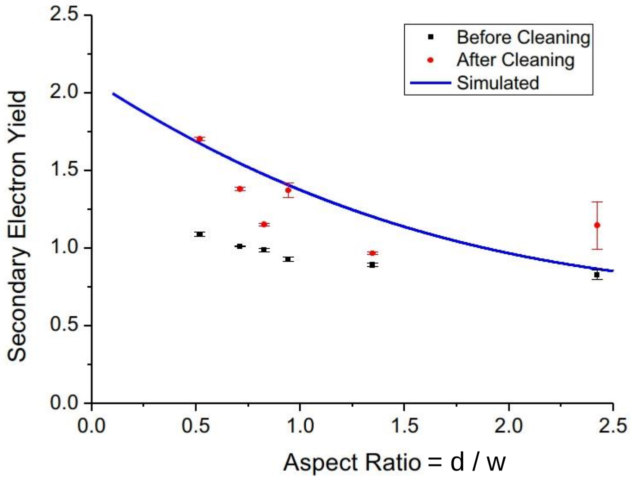
LESS studies



ablated volume

redeposited dendritic nanoparticle layer





Ablation depth, trench distance and SEY can be tuned via laser parameter adjustment

D. Bajek et al., Sci. Rep. 10 (2020), 250

E-cloud monitoring in the SPS

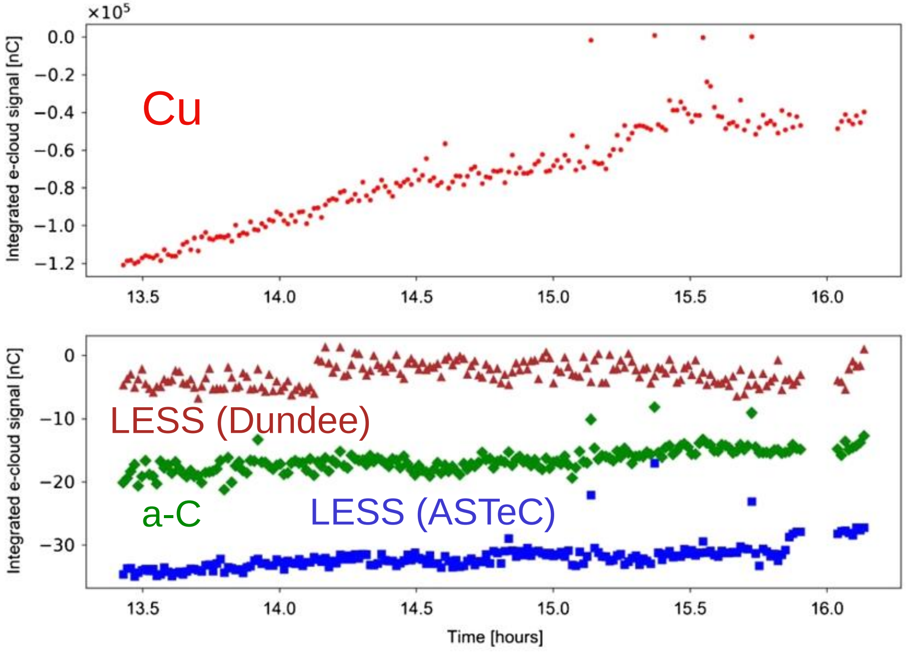
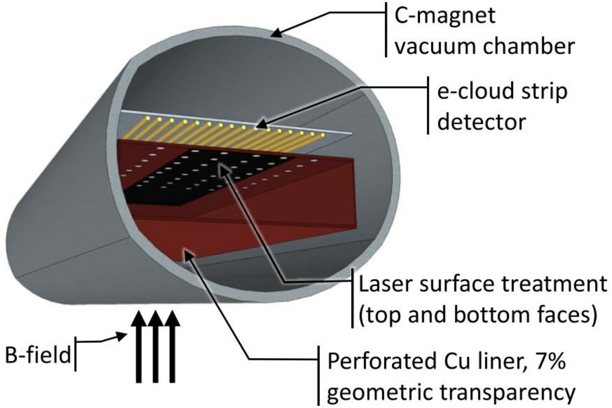


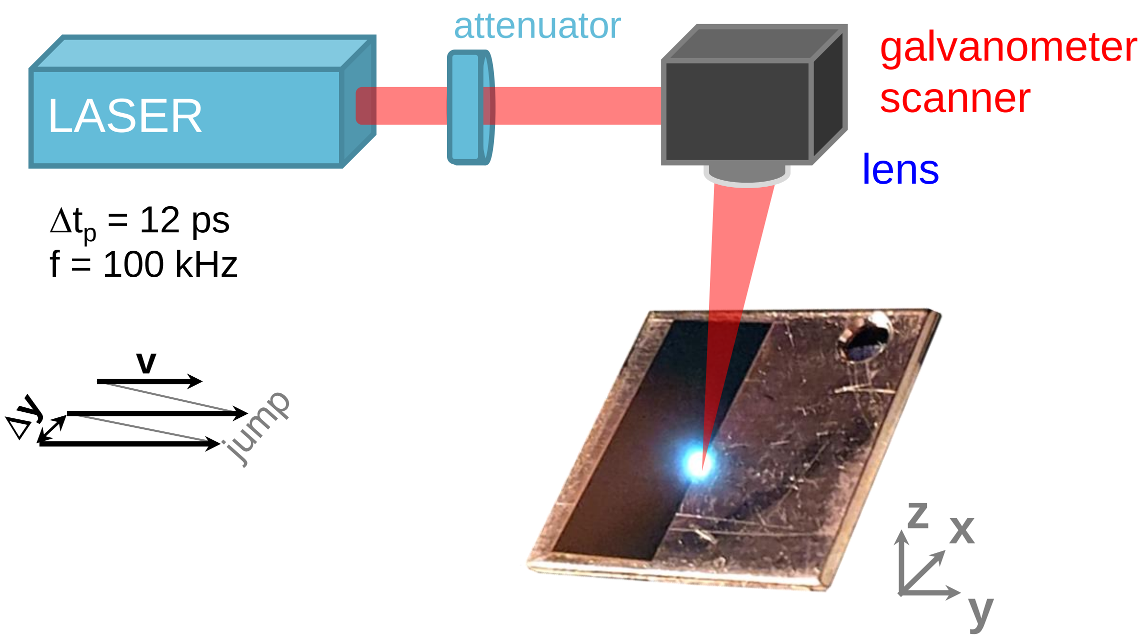
FIG. 12. Integrated signals from the ECMs during the total duration of the experiment in the SPS. (top) Reference copper liner; (bottom) liners with e-cloud mitigation: blue squares—treated by ASTeC, brown triangles—treated at the University of Dundee and green lozenges—a-C coating. Note the difference in vertical scales.



a-C coating and LESS of Cu enable electron cloud suppression

S. Calatroni Phys. Rev. Accel. Beams 20, 113201 (2017)

Laser surface processing & scale-up

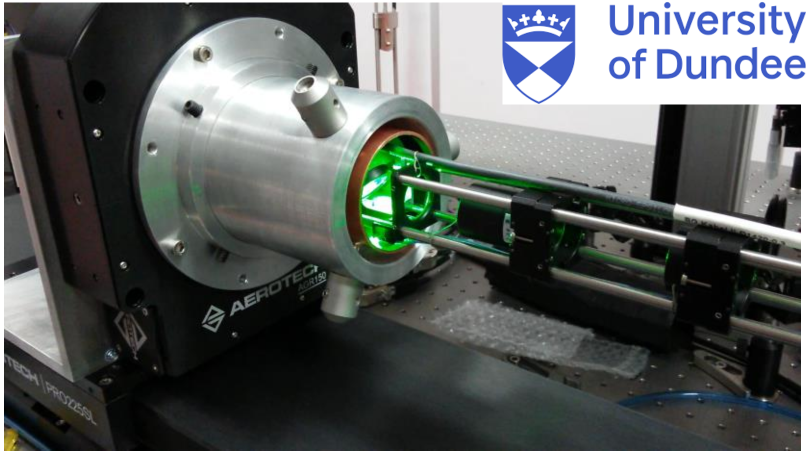


or

Motorized stage

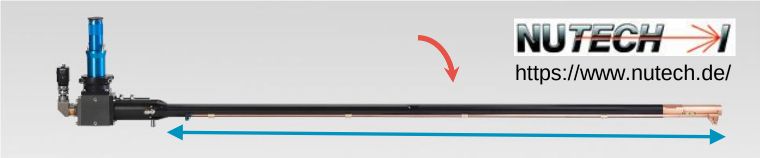
Treatment of inner surfaces ?

Courtesy of A. Abdolvand & S. Wackerow



Difficulty: guide the laser light towards the surface to be treated and define the spot size and focus

or

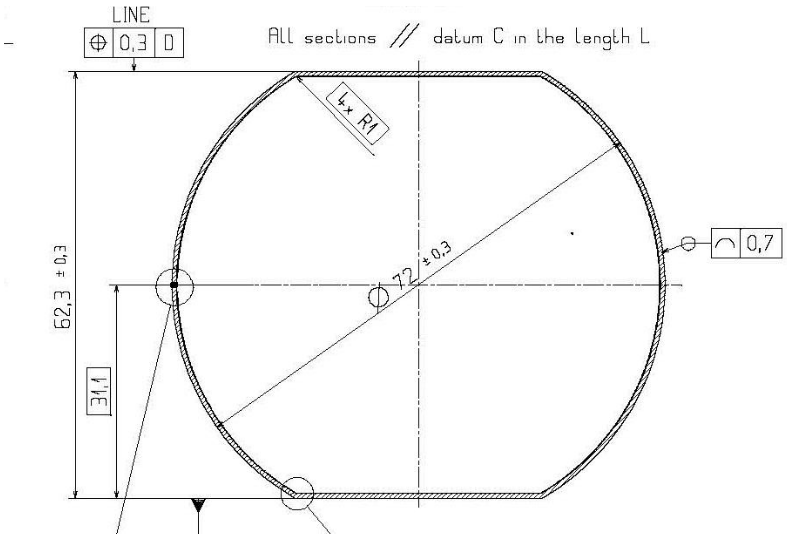


up to 2 meter insertion depth

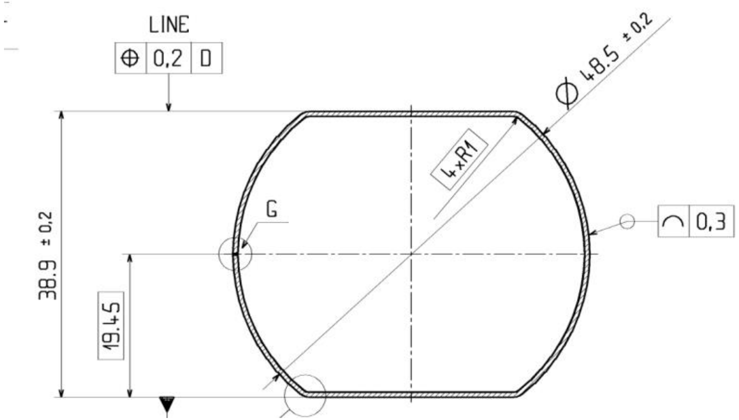
Limitations:
- → tube has to be rotated
- → minimal inner diameter
- → maximal insertion depth
- → circular cross-sections only

How about 10 m long beam screens (BS) ?

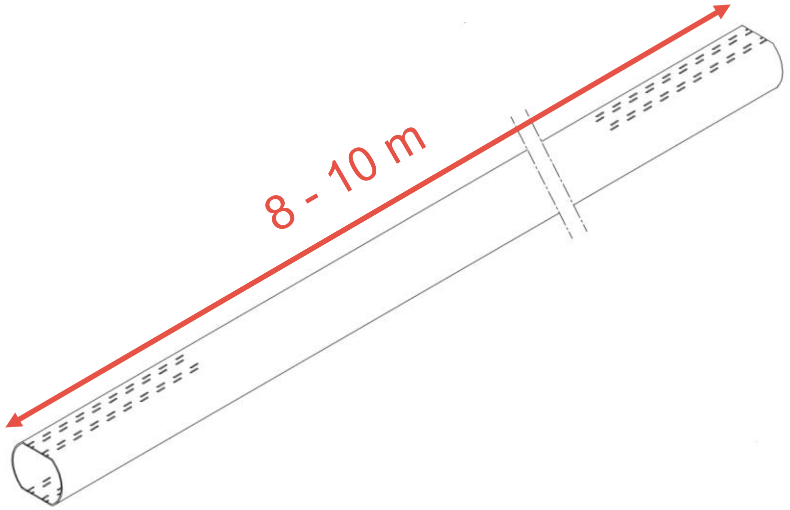
LHC Triplet magnets BS

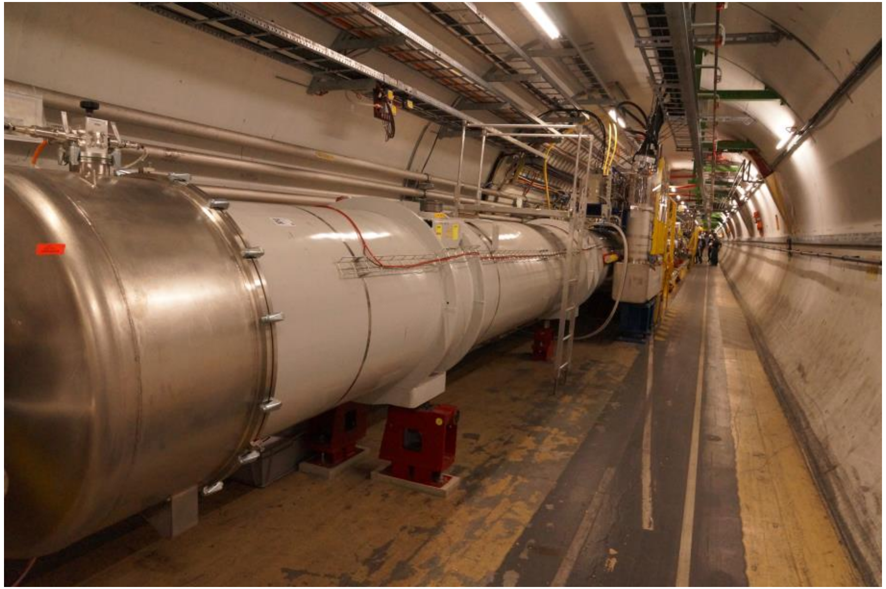


LHC Q5 standalone magnet BS

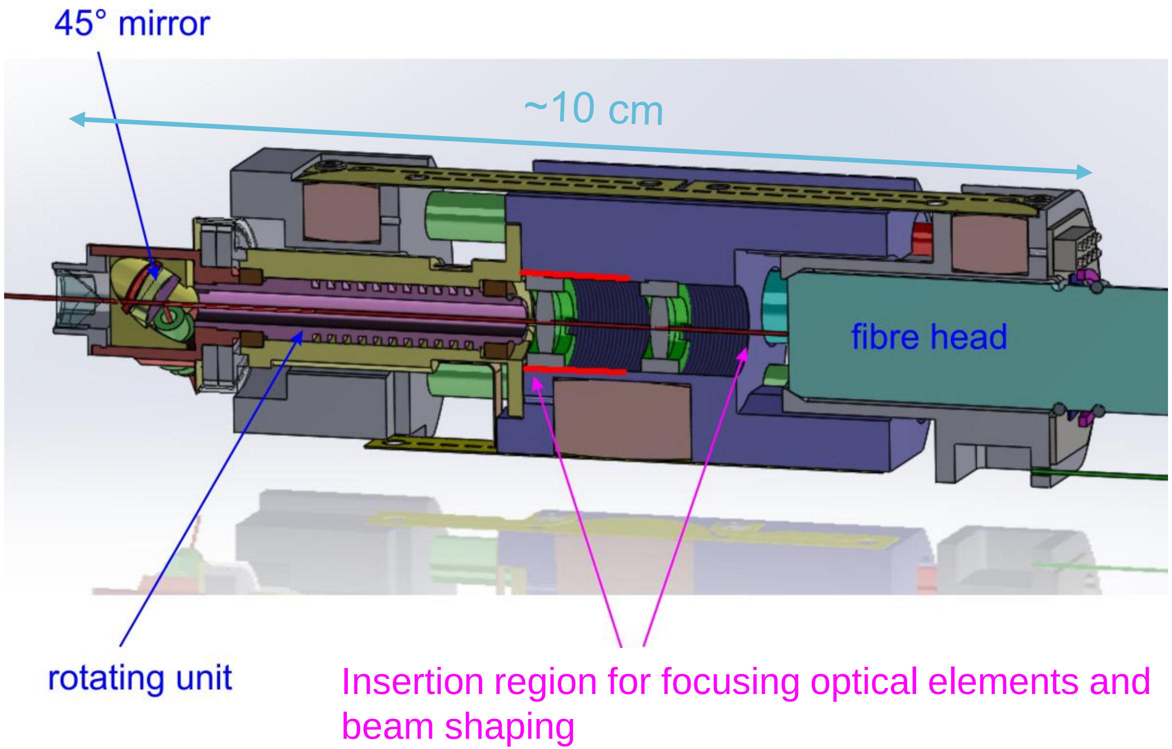


How about 10 m long beam screens (BS) ?





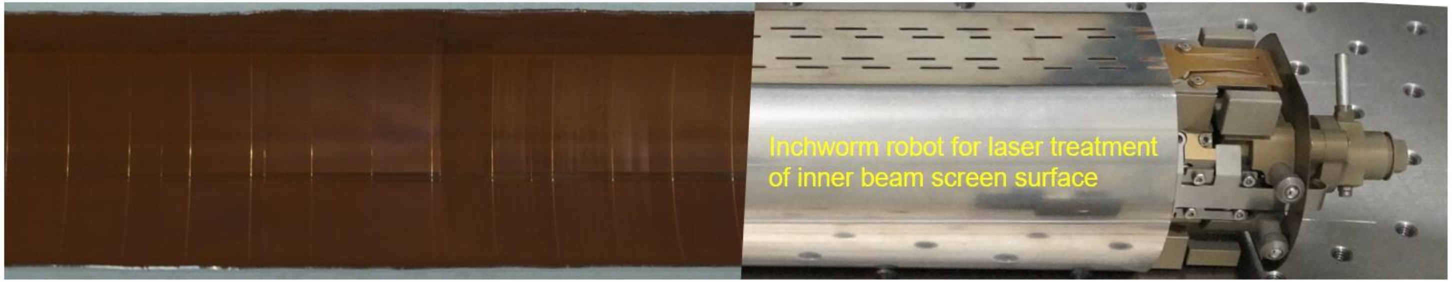
Inchworm robot for high-precission movement

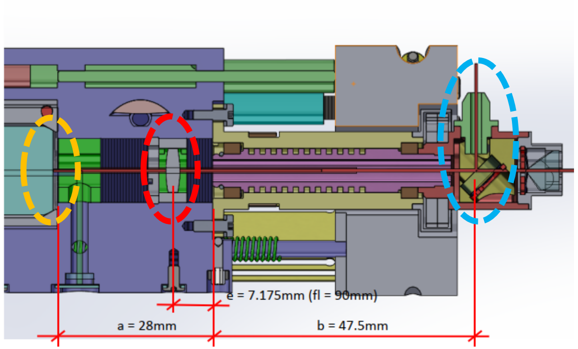


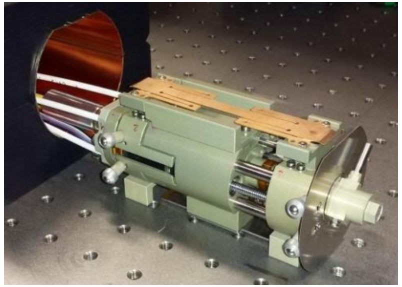
Waygate Technologies
Inspection Robotics

HiLUMI-UK collaboration

- (In-situ) treatment of Triplet magnet beam screens → now targeting standalone magnets with cryosorbers







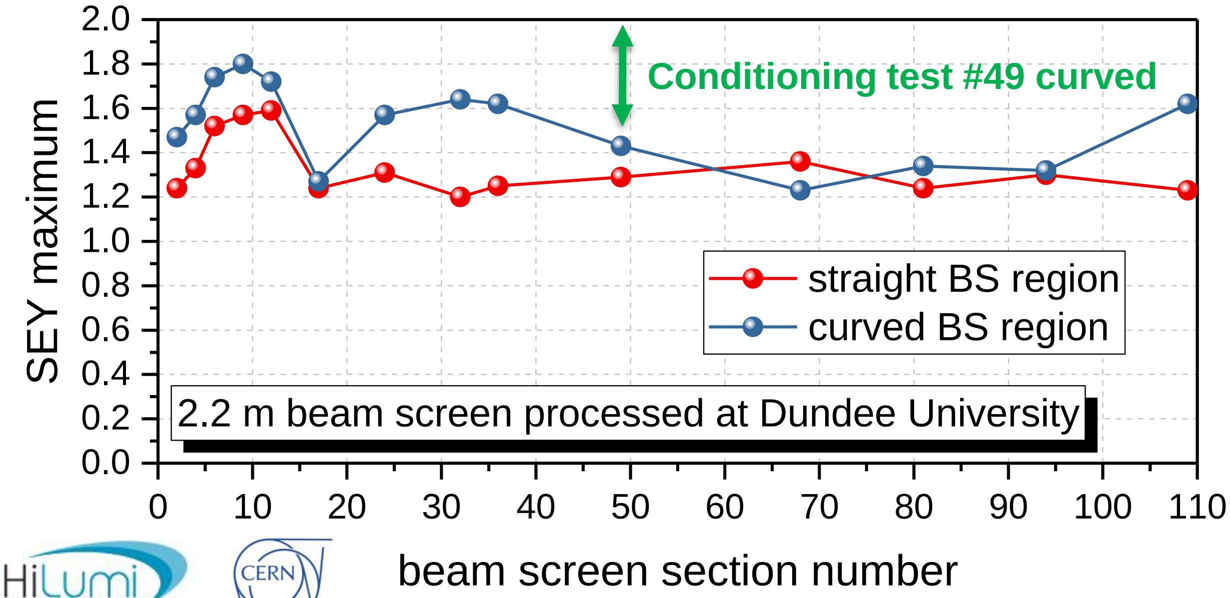
Fibre Output

45° rotating mirror

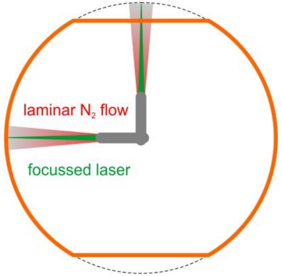
Focusing Lens

SEY analysis of laser-treated beam screen

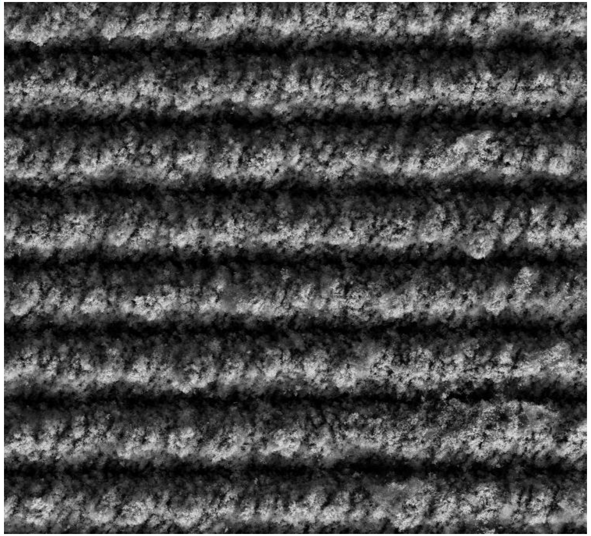
timeline of treatment including, focus & parameter optimization



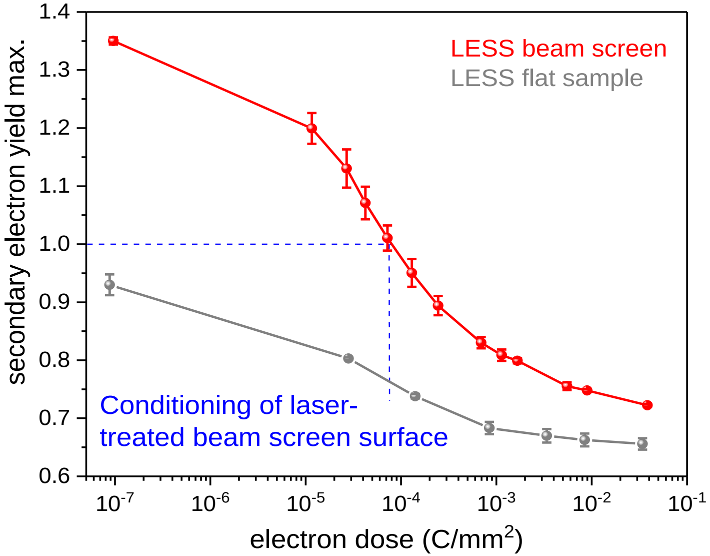
Beam screen
SEY after LESS:
1.2 – 1.6



LESS beam screen characteristics



100 µm



- ➢ homogeneous stripe pattern achieved
- ➢ inhomogeneities in curved regions
- ➢ ablation depth too high (> 25 µm)

- ➢ SEY higher compared to flat samples
- ➢ surface conditions to SEY<1 for electron doses $<10^{-4}$ C/mm² @ 250 eV

→ promising to find optimized conditions in terms of treatment speed, ablation depth and final SEY after conditioning

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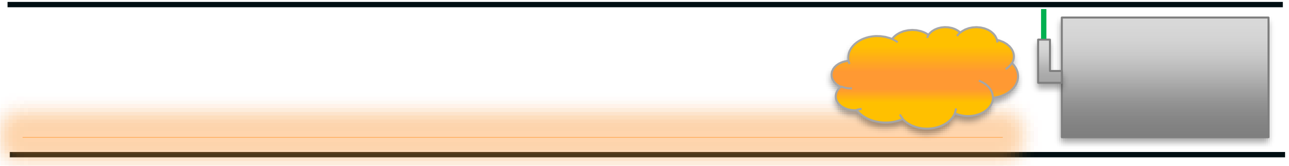
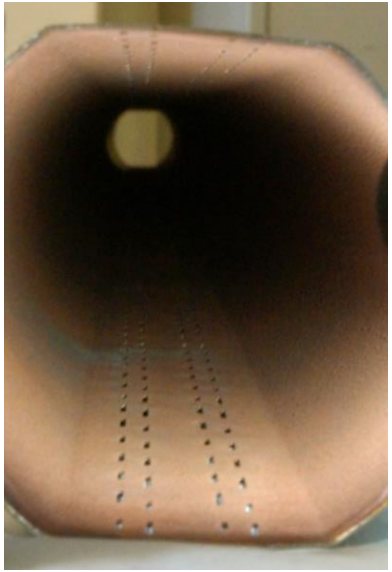
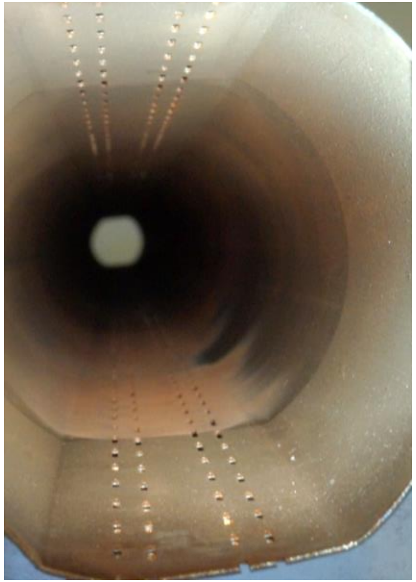
Particle generation and dust in beam screen

Vacuum
Extraction
Unit





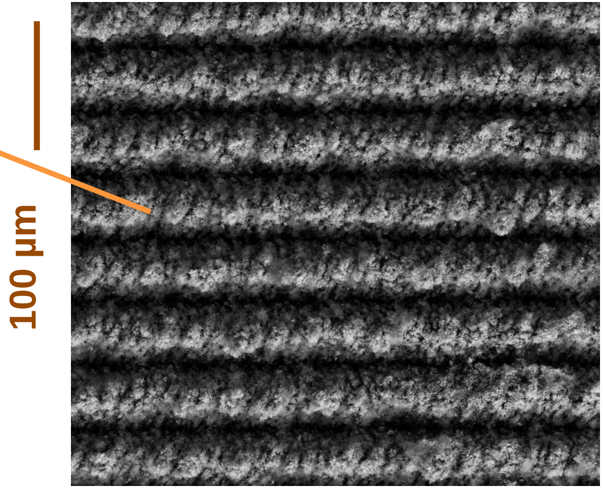


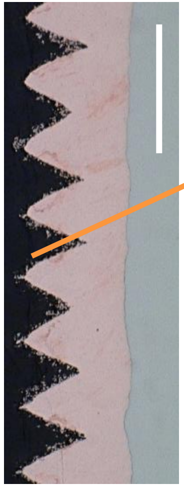
Lessons learnt and aspects to be improved

- Laser-fibre coupling was unstable and caused several damages on the fibre that required maintenance at the factory (long down-time)
- SEY of the surface was inhomogeneous due to partial treatment out of focus
- Amount of lying particles on the bottom inacceptable
- Ablation depth too large (target < 25 µm)
- Effective treatment speed quite low

LESS: Main concerns

ablated dust
&
adhering particles as risk to fall and interact
with the proton beam





ablation of material
&
influence on surface impedance
(particles & grooves)

Cryosorbers in standalone magnets

- Magnets operated at 4.2 K are equipped with cryosorbers
- In-situ a-C coating in presence of installed cryosorbers is almost impossible due to warm-up and gas release during plasma deposition
- Target: treatment of Q5 magnet from IP1 and IP5 on surface

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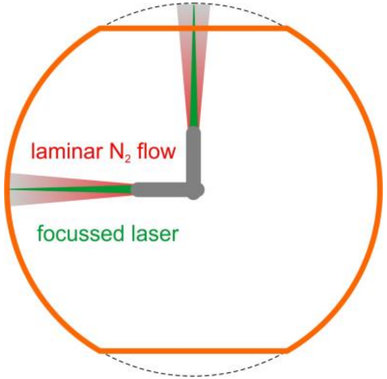
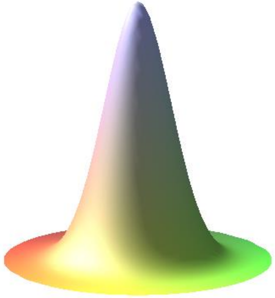
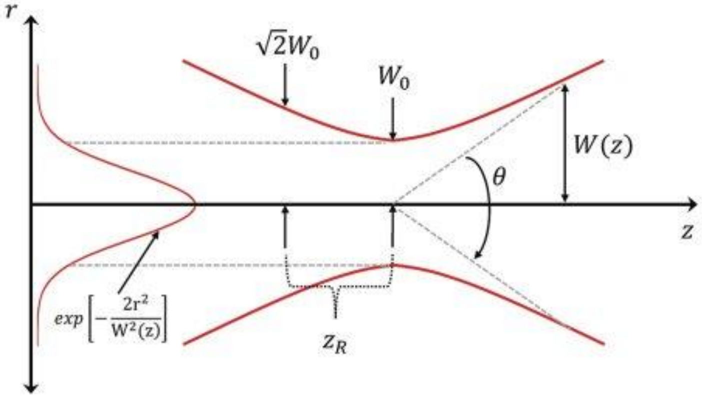
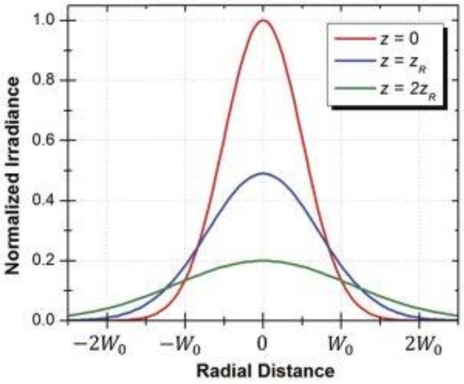
Effects of Gaussian beams of out-of-focus





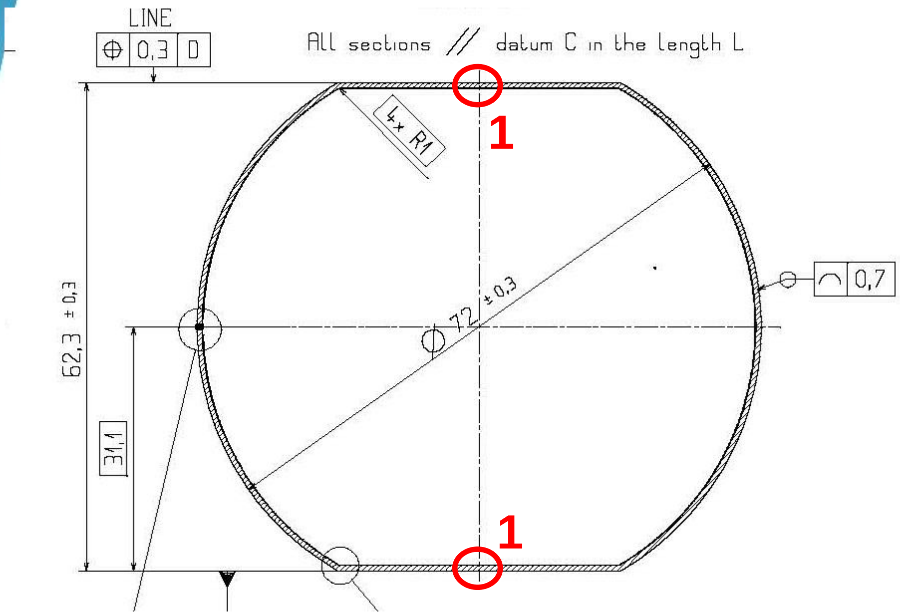




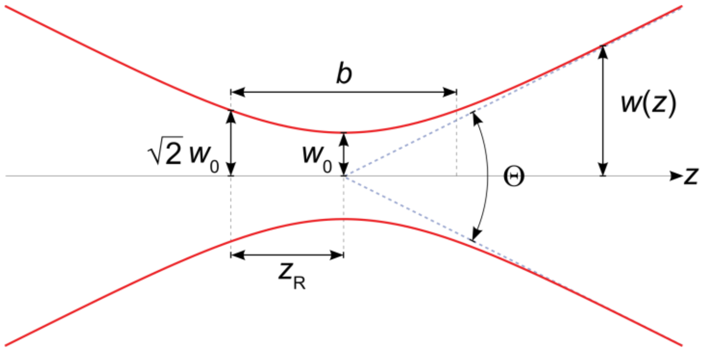
$$w_0 = \frac{\lambda \cdot f_l \cdot M^2}{\pi \cdot w_{in}} \qquad z_R = \frac{\lambda \cdot f_l^2 \cdot M^2}{\pi \cdot w_{in}^2}$$

$$z_R = \frac{\pi \cdot w_0^2}{\lambda \cdot M^2}$$

BS shape and laser focussing



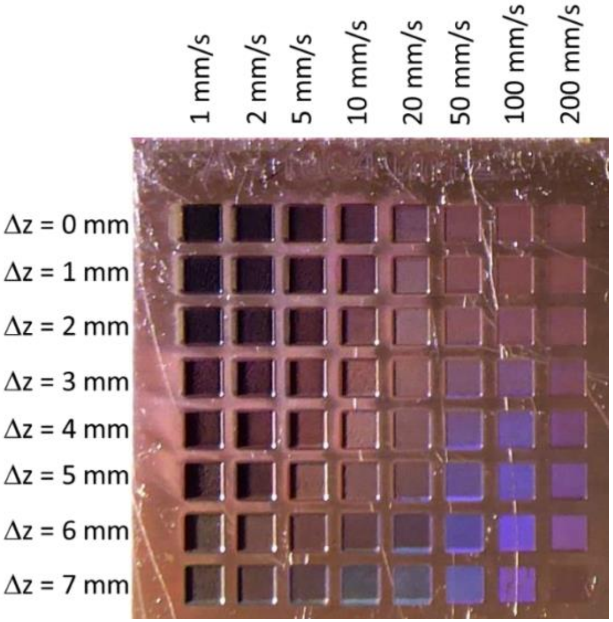
- Radius difference between curved BS part and point **1** is 4.85 mm
- If focus is set in-between, the max. focus offset would be ± 2.43 mm
- Current lens settings: f = 90 mm $2w_0$ = 52 µm, z_R = 3.2 mm
- at z_R, intensity is only 50% of that in focus



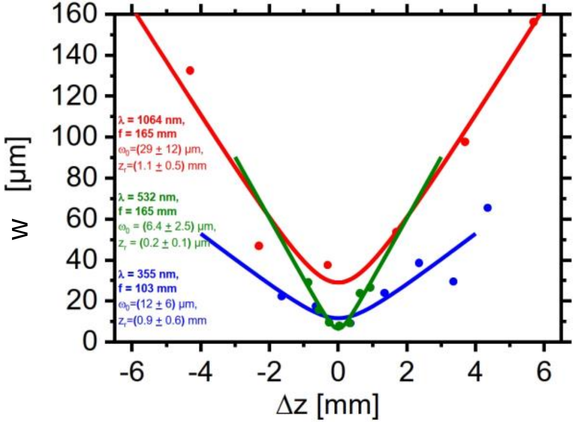
Focus size dependence of a Gaussian Beam

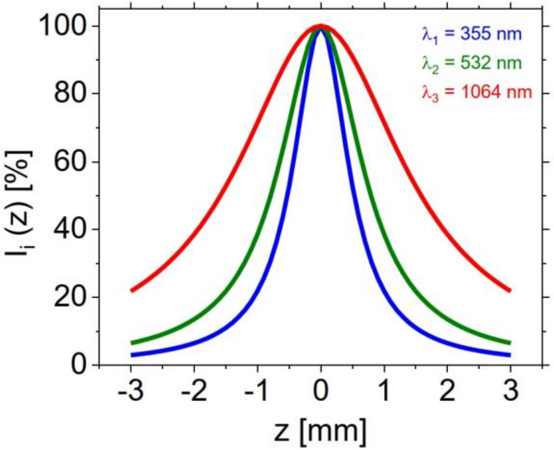
20

BS shape and laser focussing



1064 nm





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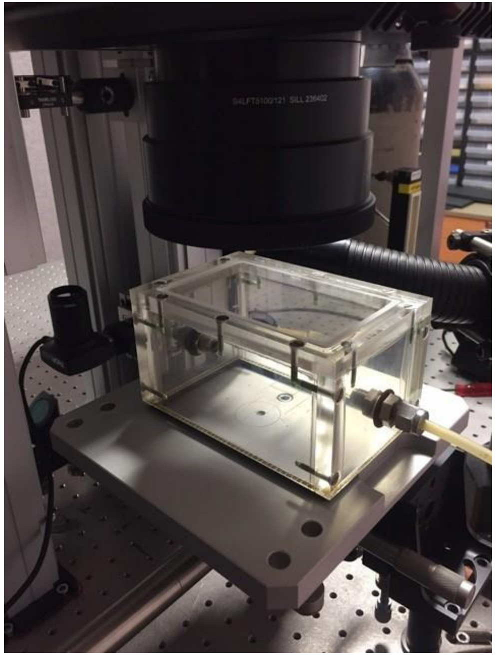
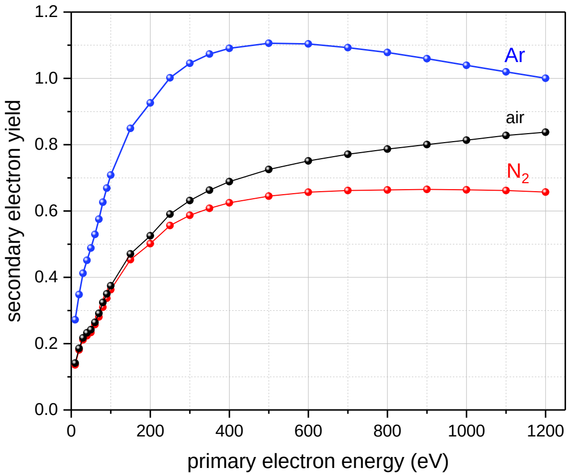
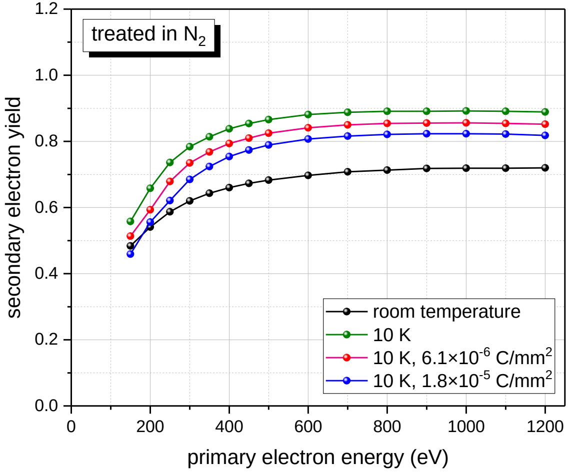
LESS: Influence of ambient gas during processing



Inert gas box for laser treatment

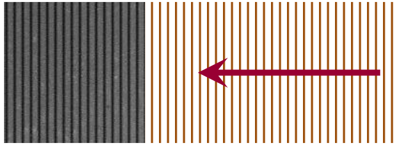




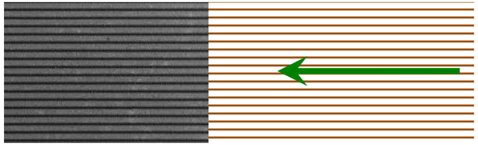
- treatment in air results in strong surface oxidation (provokes charge-up at cryogenic temperatures)
- treatment in nitrogen prevents surface oxidation

→ all setups are designed to blow N_2 into the reaction zone

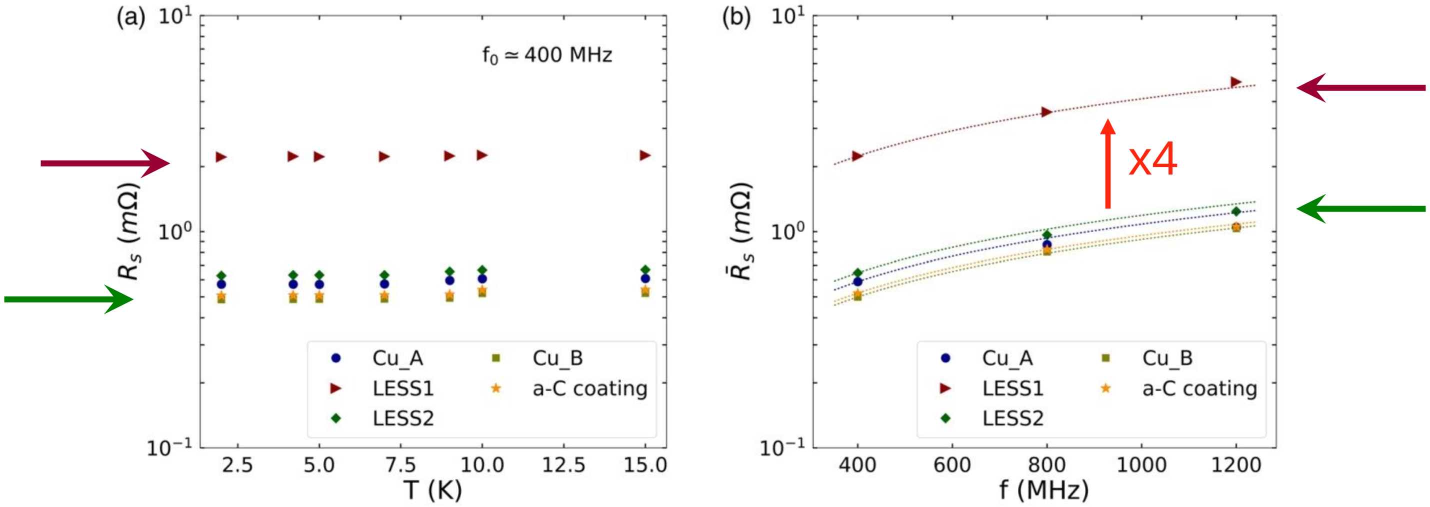
Influence of LESS on surface resistance



trenches ⊥ to beam



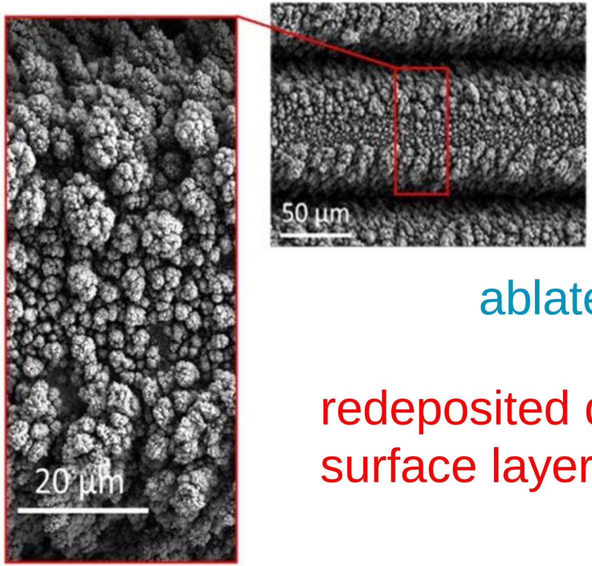
trenches ǁ to beam



- ➢ Trench depth needs to limited
- ➢ Trench alignment ideally longitudinal to beam

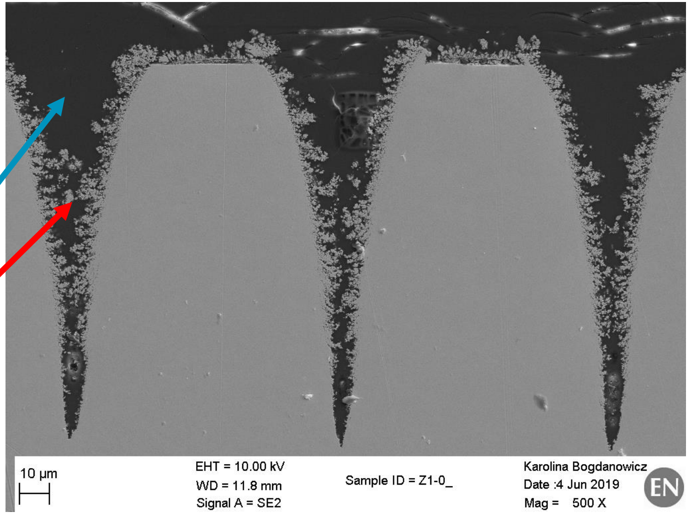
S. Calatroni et al. Phys. Rev. Accel. Beams 22, 063101 (2019)

LESS – what about the particles ?



ablated region

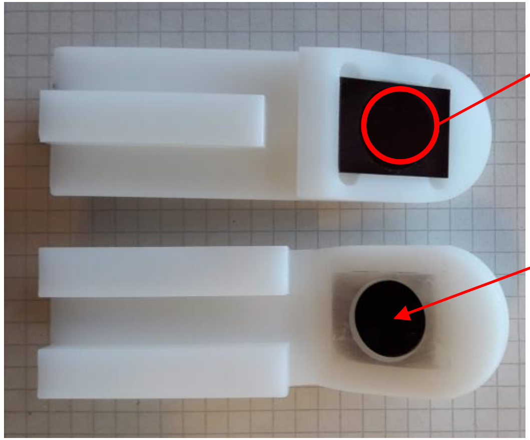
redeposited dendritic surface layer



- Particles are ablated and partially redeposited (they adhere but can be wiped off)
- Ablation depth, trench distance and SEY can be tuned via laser parameter adjustment
- Evacuation system extracts flying particles from the beam screen during processing

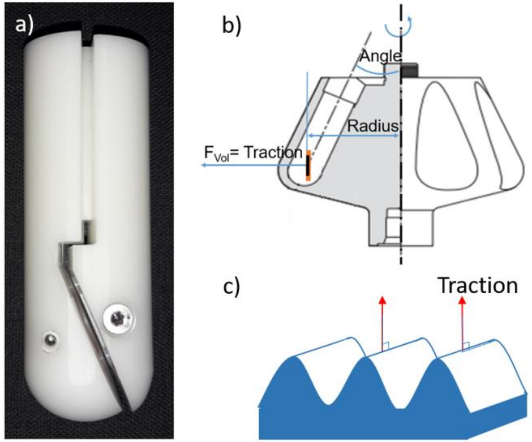
LESS – particle release during a quench

Centrifugation tests (very pessimistic scenario)



Surface submitted to centrifuge force to be analyzed

Particles collected on carbon sticker



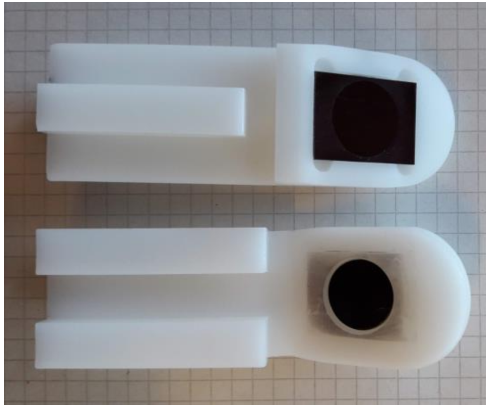
30 N/mm^2 ~ 50000 rpm

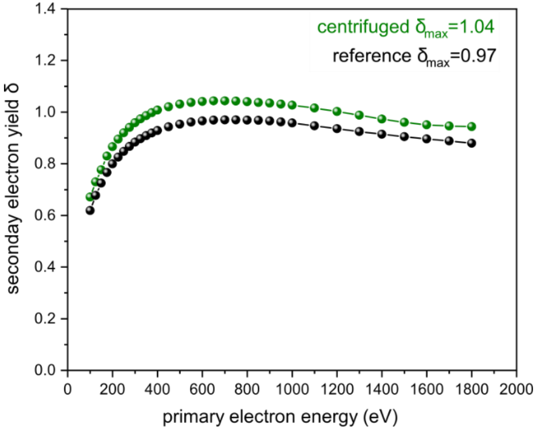
- Force active during centrifugation equivalent to situation of a magnet quench
- Material analysis after process

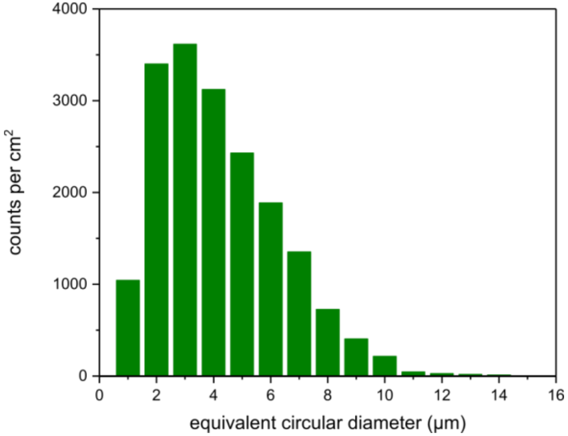
from PhD Thesis Lucie Baudin

Particle release during a magnet quench

Centrifugation tests (very pessimistic scenario)







- Number of released particles is relevant but implemented test conditions do not reflect typical operation conditions
- All particles have diameters lower than critical (<15 µm) for beam dump
- Smaller falling objects can still have influence on beam quality and intensity
- Negligible effect on SEY

from PhD Thesis Lucie Baudin

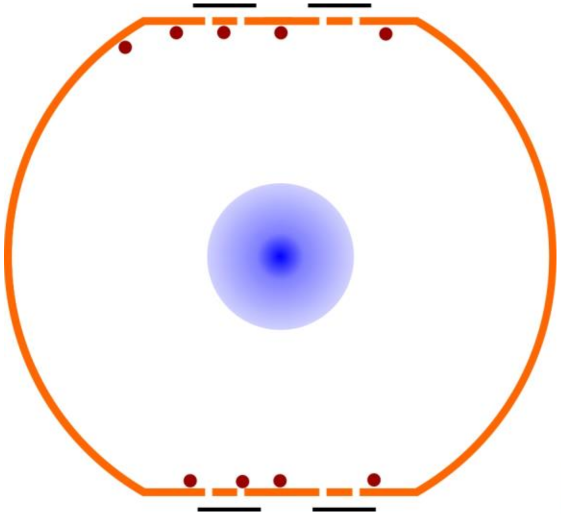
LESS – to do: test effect of lying particles

- Risk of falling particles with significant effect during operation (attraction if negatively charged)

- Metallic or oxidized particles that lie on the BS bottom due to inefficient cleaning or due to release after a quench are of concern

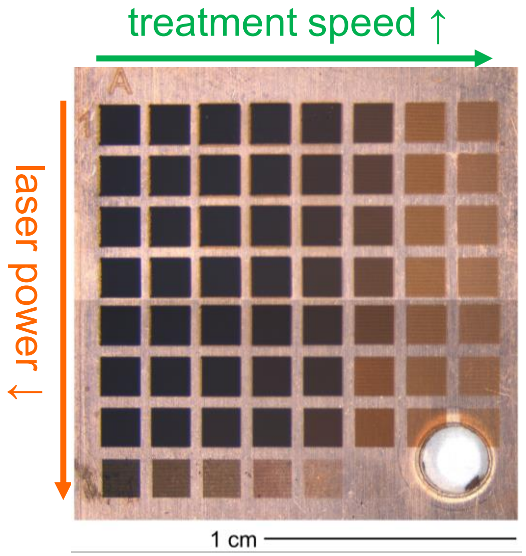
→ Removal of ablated particle by constant evacuation and gas flow during processing and post-treatment cleaning tools

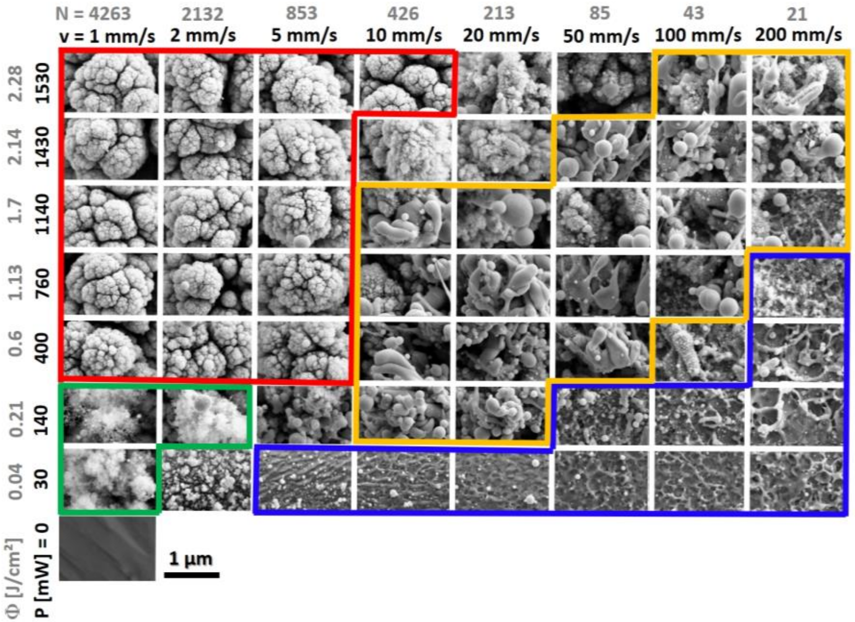
→ Measure on a test bench if such particles could get polarized or charge-up, and even get attracted by the beam



Laser treatment on Cu: recent studies

- Laser parameter screening in collaboration with IOM Leipzig





Parameters: power, wavelength, scan velocity, line distance, pulse frequency/duration, focus spot size, ambient gas

→ Surface topography depends on laser fluence

P. Lorenz et al., Lasers in Manufacturing and Materials Processing 9, (2022), 135

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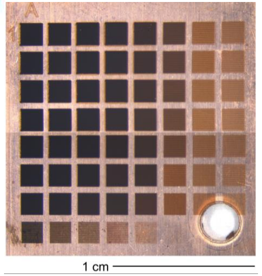

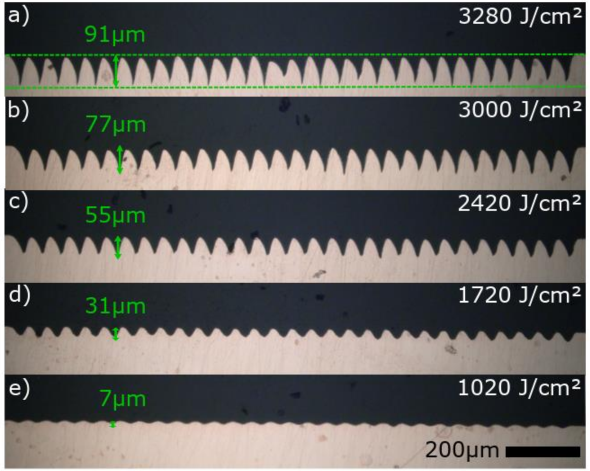

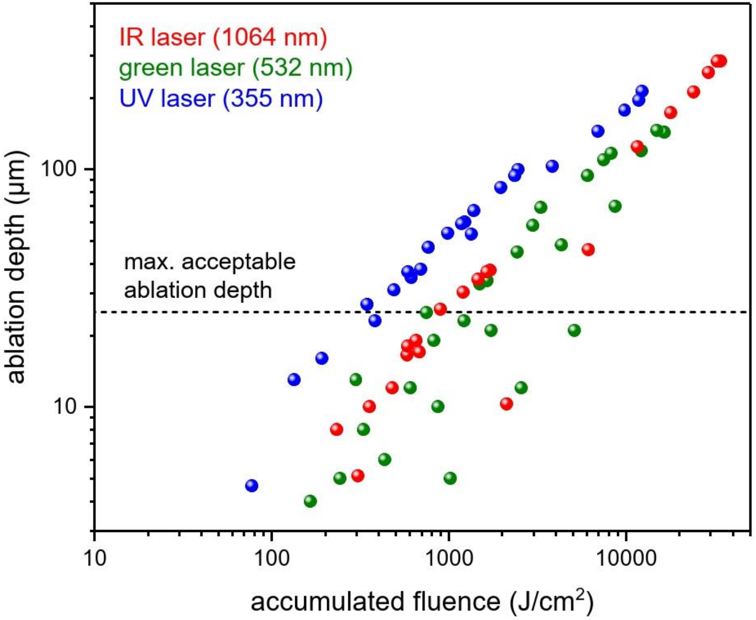

E. Bez et al., *Influence of wavelength and accumulated fluence on secondary electron yield of picosecond laser-induced surface roughening of copper*

→ Ablation depth depends on laser fluence

Laser treatment on Cu: recent studies

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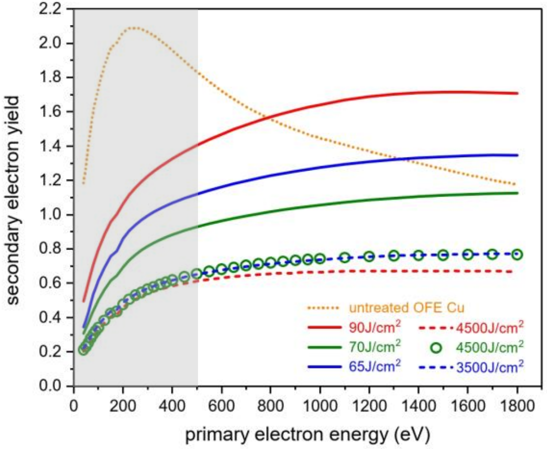
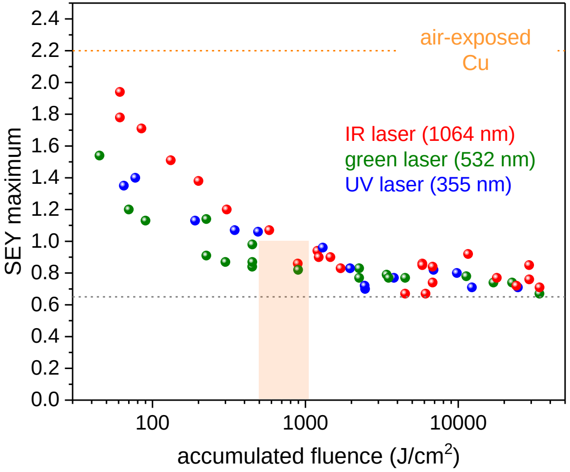
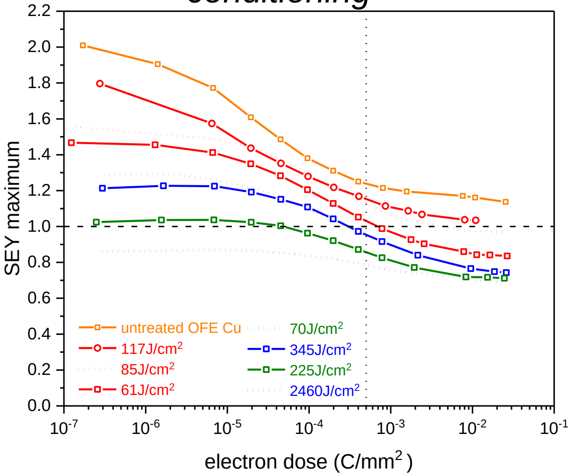
SEY



SEY maximum



conditioning

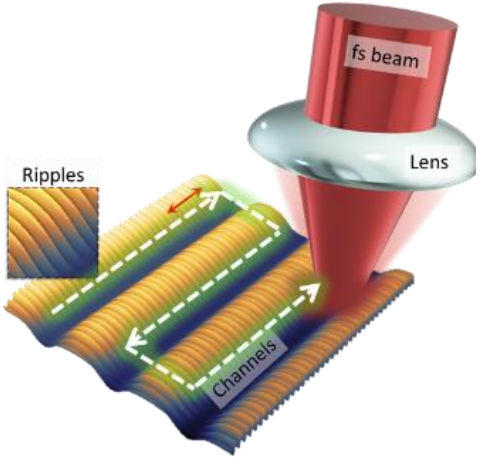


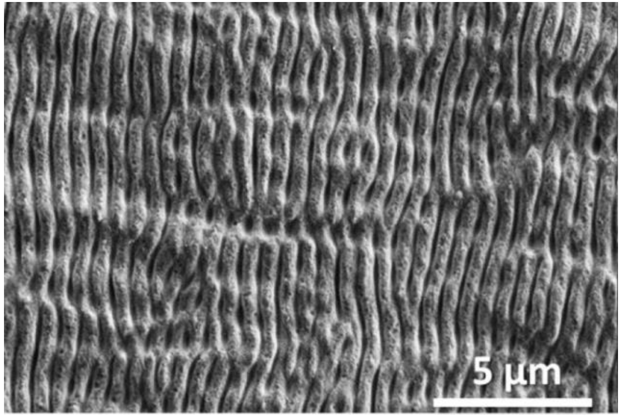
→ The parameter space for SEY engineering is large and depends on laser wavelength

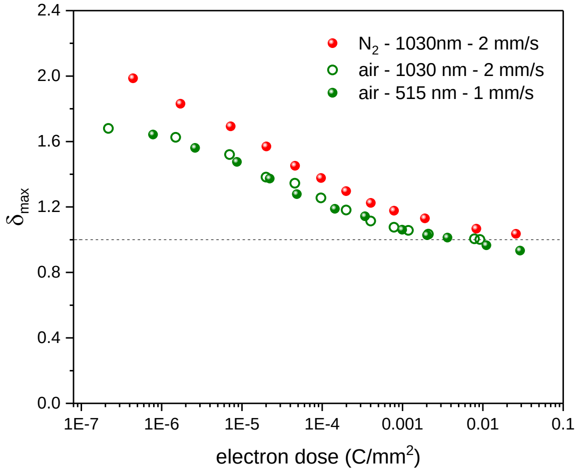
E. Bez et al., *Influence of wavelength and accumulated fluence on secondary electron yield of picosecond laser-induced surface roughening of copper*

Laser-Induced Periodic Surface Structures

- LIPSS studies in collaboration with INFN Naples



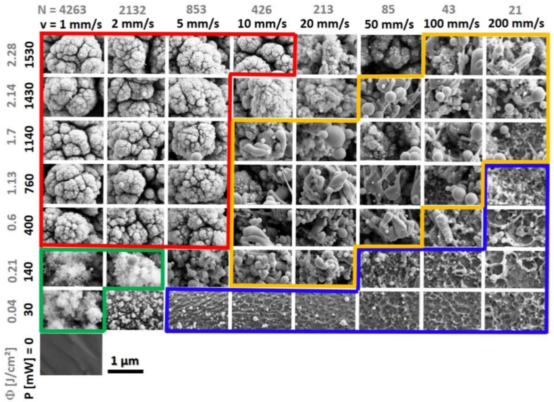


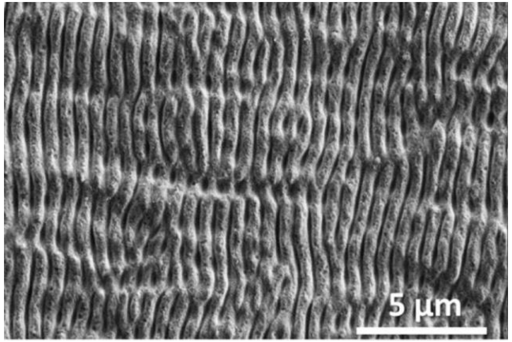


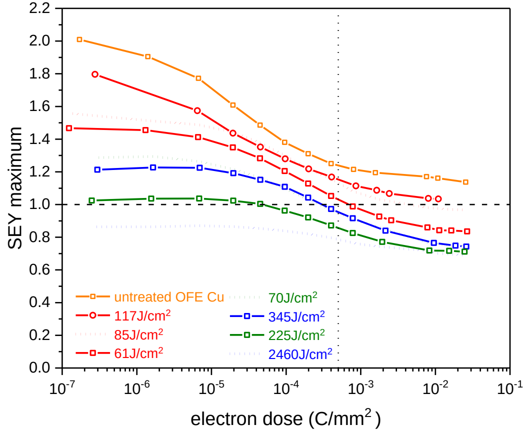
- LIPSS ideally free of particles
- Surface roughening leads to slight reduction of SEY (δ_{max} 1.6)

J.J.J. Nivas et al., Surfaces and Interfaces 25 (2021) 101179

Laser treatment on Cu: recent studies







Tuning is possible:

- ✓ limit ablation depth
- ✓ reduce particle density
- ✓ compromise on SEY compensated by conditioning

To do: transfer to CERN setup

Agreement in CERNs E-cloud working group

Optimization of laser treatment for lower particle generation and low trench depth

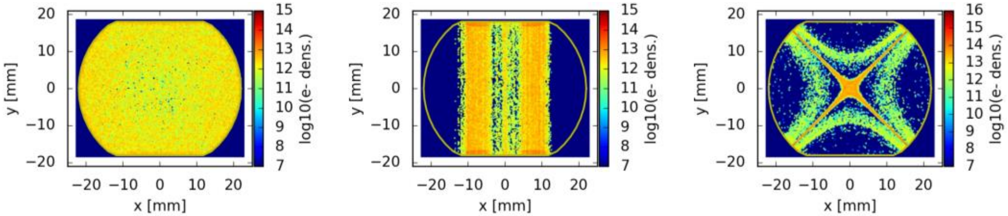
→ Initial SEY maximum of the surface will be > 1
→ Conditioning at reasonable doses will enable SEY < 1

Target for LESS performance:

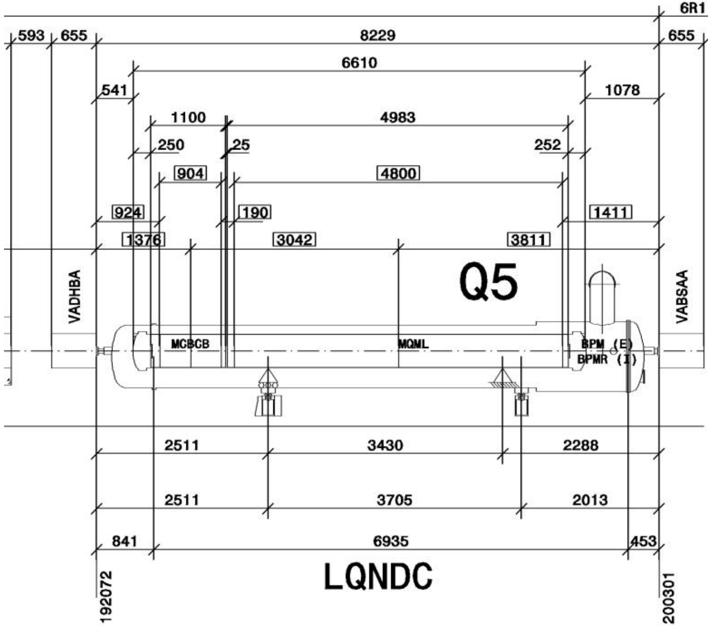
- ✓ initial SEY maximum of the processed surfaces ≤ 1.5
- ✓ Conditioning allows to reduce SEY max. to < 1 for a dose ≤ 5×10^{-4} C/mm^2

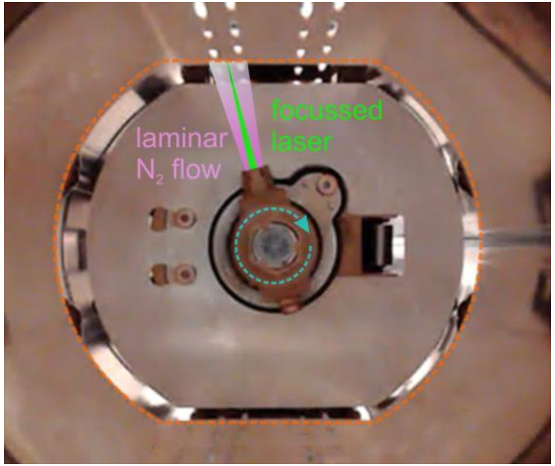
HiLumi HL-LHC PROJECT CERN

Q5 magnet LESS treatment strategy



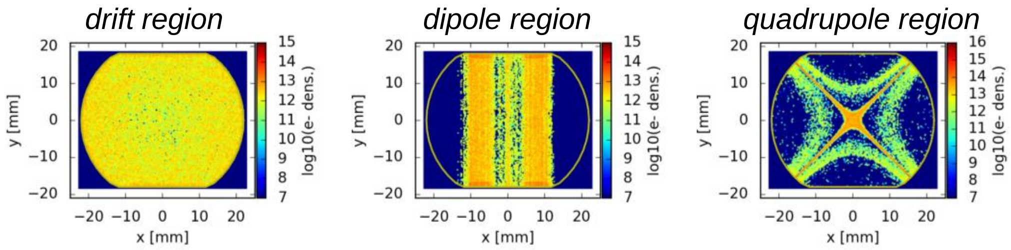
P. Dijkstal, G. Iadarola, L. Mether, and G. Rumolo, “Simulation studies on the electron cloud build-up in the elements of the LHC Arcs at 6.5 TeV,” Tech. Rep. CERN-ACC-NOTE-2017-0057, CERN, 2017.



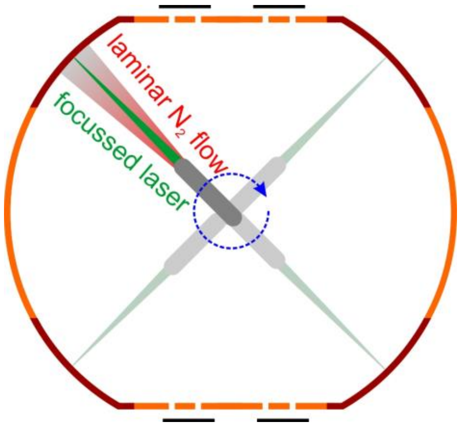


Q5 magnet LESS treatment strategy

Simulated electron distribution in LHC magnets



P. Dijkstal, G. Iadarola, L. Mether, and G. Rumolo, "Simulation studies on the electron cloud build-up in the elements of the LHC Arcs at 6.5 TeV," Tech. Rep. CERN-ACC-NOTE-2017-0057, CERN, 2017.



- Selected LESS treatment in the curved zones of the beam screens for drift region or the 4 corners to avoid burning the cryosorbers through the pumping slots

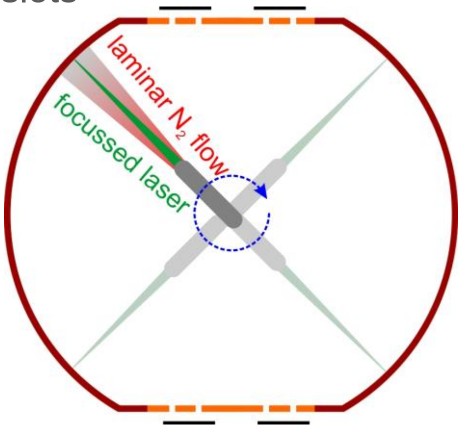
→ Reduced risk of particles falling into the beam

→ Cleaning tools can pass

→ Impedance "problems" disappear

→ Focusing "problems" disappear

→ Faster treatment possible



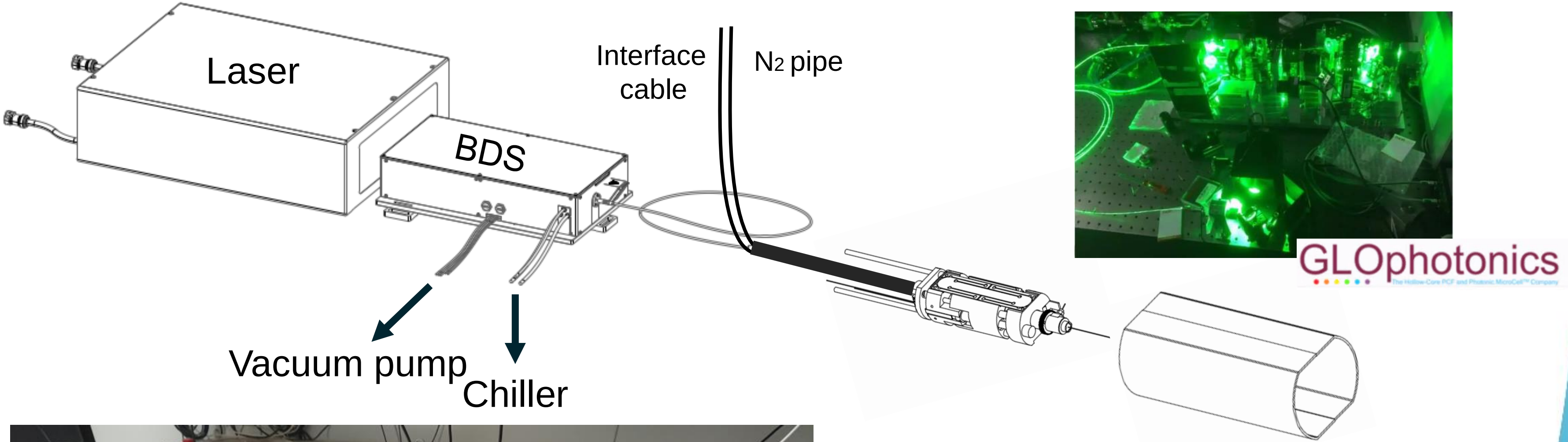
LESS – particle mitigation strategies

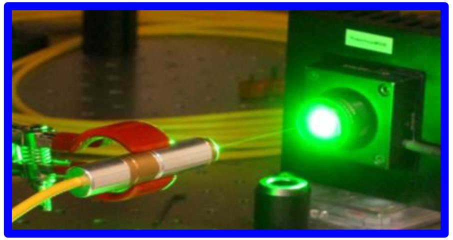
- Reduce number of released particles during processing and number of adhered particles via process optimisation (SEY < 1.5, also beneficial for lower surface impedance and limited ablation depth)
- Reduce risk of particles falling into the beam by spatially selective treatment
- Extract majority of ablated particles via a strong air flow thorough the pipe (50 l/min) via a extraction and filtering unit
- Post-processing passage with “cleaning unit/carrier” without touching the treated regions

Outline

1. Laser treatment for SEY reduction: from proof of principle to possible treatments of LHC beam screens
2. Fundamental studies and their conclusions
3. How far have we come ?

LESS @ CERN – 532 nm R&D system





Stable coupling into 15 m long fibre

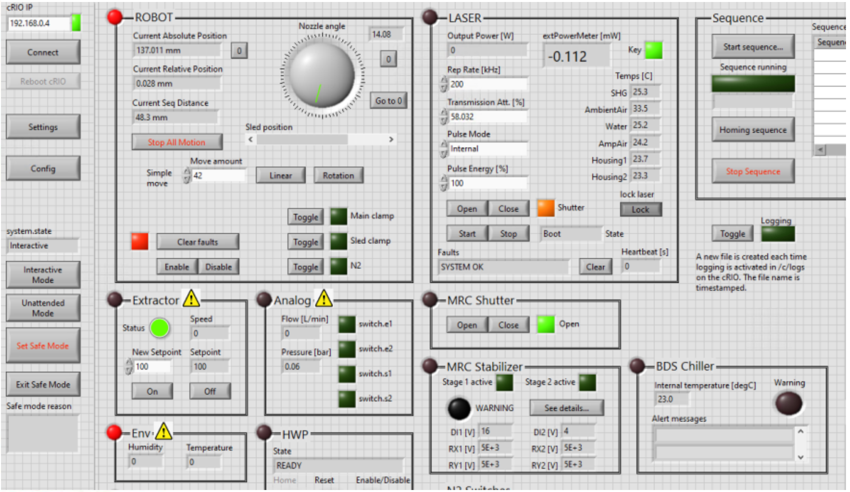
Integrated control system

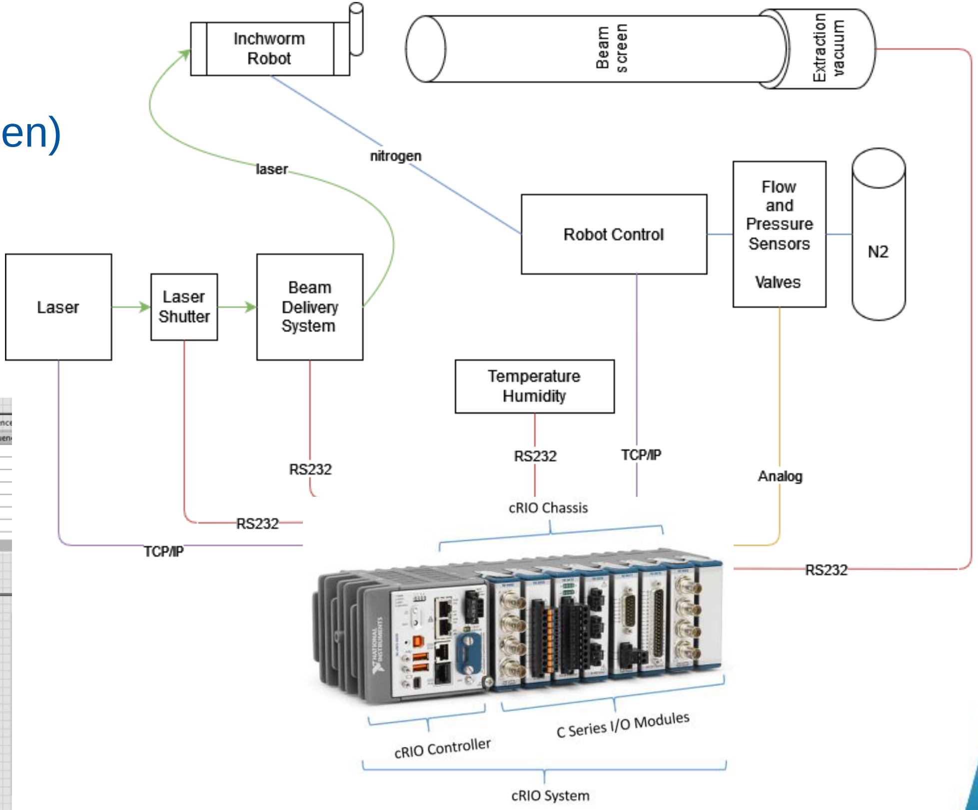
System control development

In collaboration with BE-CEM-MTA

(J. Tagg, P. J. Koziol, O. O. Andreassen)

NI compact RIO + LabVIEW

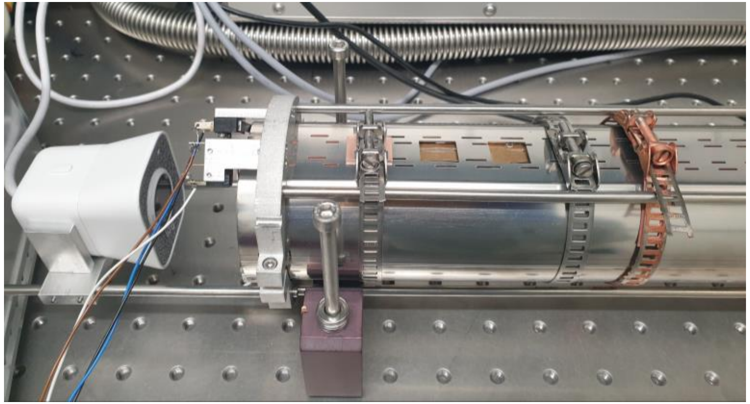


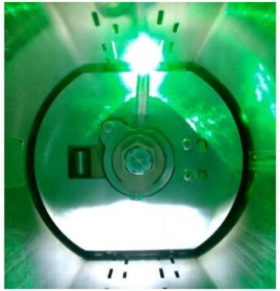


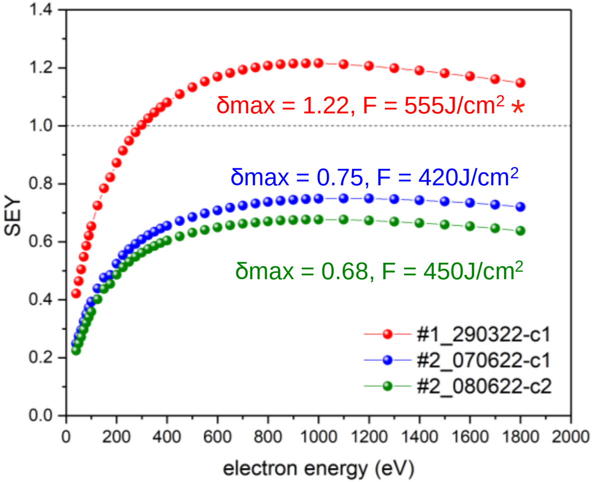
J. Tagg, JACoW ICALEPCS2021 (2022) 492-496,
DOI: 10.18429/JACoW-ICALEPCS2021-TUPV039

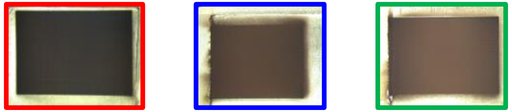
LESS @ CERN – where are we and where do we want to go

- Test bench on 74 mm BS finally operational and first optimisation on small scale ongoing
- Vacuum extraction and treatment scale-up components are available





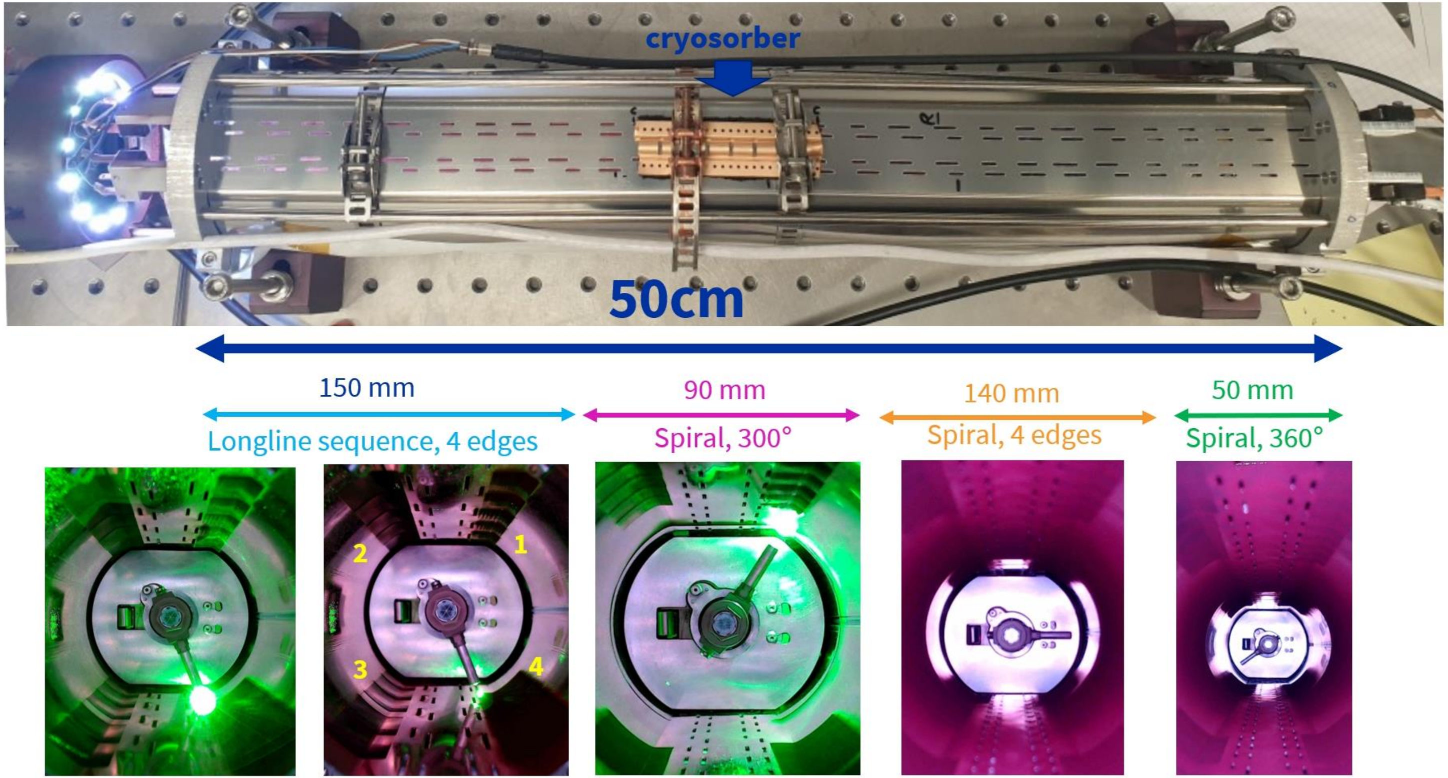




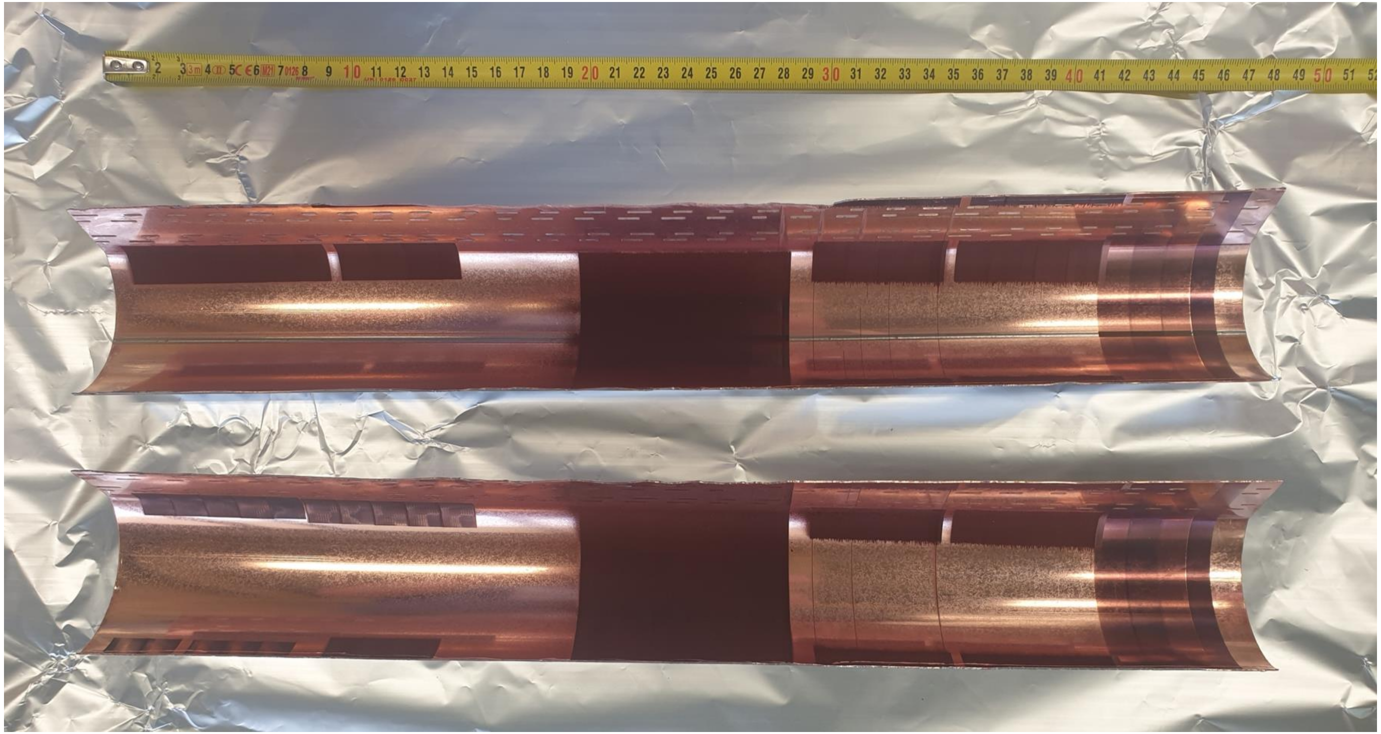
- Low SEY can be obtained with 532 nm on small scale
- First parameter optimisation, speed-up and stability tests started

* modified focus settings

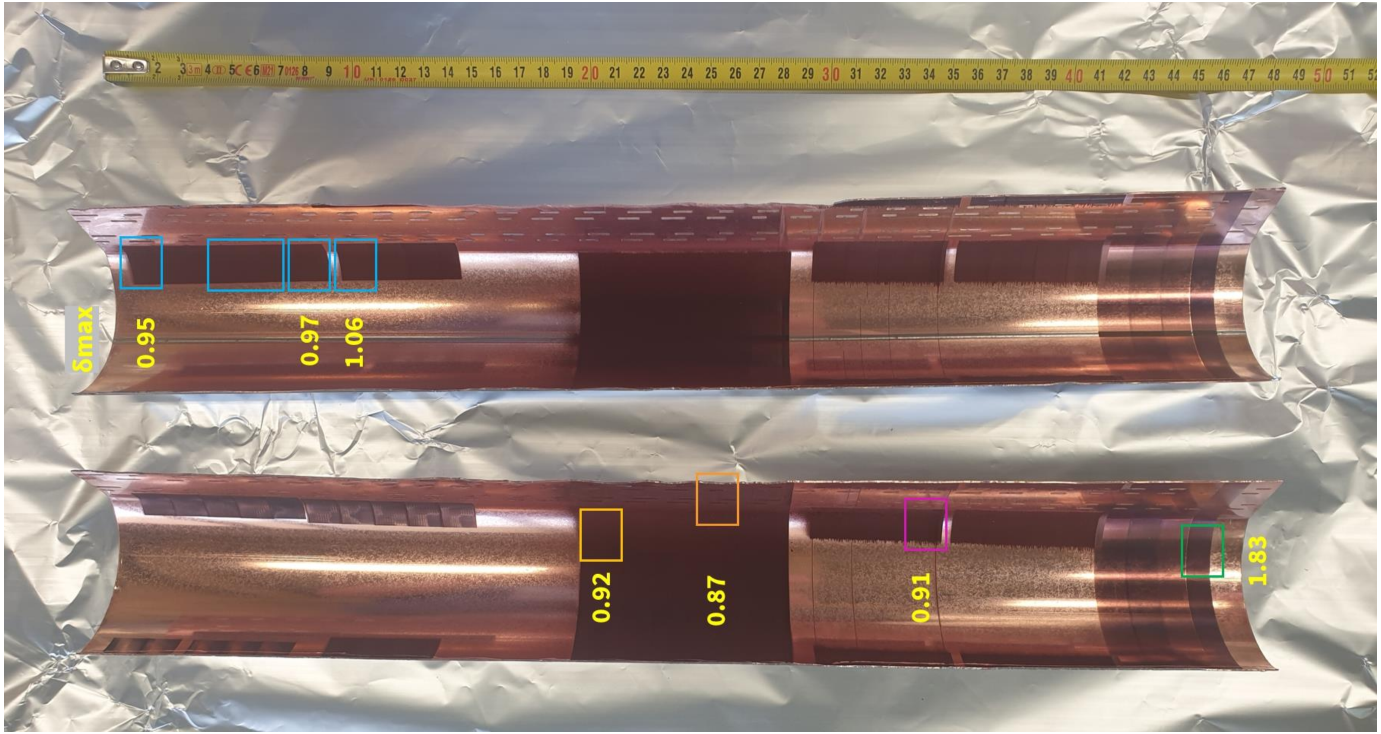
Test of patterns and adapted treatment strategy



Test of patterns and adapted treatment strategy



Test of patterns and adapted treatment strategy



Summary

- Precise robot movement and laser scanning in BS in operation (limited to BS shape)
- Delivery of laser power to BS surface stable
- Treatments are reproducible and can be selectively varied in treatment position and SEY
- Suppression of oxidation and strategies to control surface impedance developed
- Final processing considers: low SEY vs. number of particles

Upcoming Tasks & Challenges

- Transition to 50L beam screen geometry
- Scale up treatment to 8 m long beam screen
- Cable and fibre handling and synchronization with robot during processing > 2m
- Development of a post-treatment cleaning unit
- Demonstration of E-cloud mitigation and stable conditions in Vacuum Pilot Sector of the LHC

Acknowledgement

CERN:

- E. Bez, A. K. Reascos Portilla, M. Watkins, J. Tagg,
  P. J. Koziol, O. O. Andreassen, S. Calatroni, M. Taborelli

Collaborations:

- D. Bajek, S. Wackerow, R. Uren, A. Abdolvand (University Dundee)
- P. Lorenz, M. Ehrhardt, K. Zimmer, A. Anders (IOM Leipzig)
- J.J.J. Nivas, A. Passarelli, M. R. Masullo (INFN-Naples) + CNR-SPIN + Univ. Naples