Electron cloud mitigation with LASE technology

O.B. Malyshev and R. Valizadeh,
on behalf of working team

ASTeC Vacuum Science Group,
STFC Daresbury Laboratory, UK

ICFA mini-Workshop on "Mitigation of Coherent Beam Instabilities in particle accelerators" MCBI 2019, 22-27 September 2019, Zermatt, Switzerland

Outline

- Introduction
- LASE as low SEY solution for e-cloud mitigation SEY measurements
- Surface resistance
- Vacuum properties
- Advantages over other passive mitigation methods
- Conclusions

Main mission of vacuum solution teams

- Develop solutions and technologies which should simultaneously meet specified parameters on
  - Vacuum (thermal outgassing, particle induced desorption and pumping)
    - Beam lifetime
    - Fast ion instability in negatively charged machines
    - Pressure instability in positively charged machines
    - E-cloud and BIEM
  - Photoelectron emission and secondary electron emission
    - E-cloud and BIEM
  - Surface resistance
    - Beam impedance and energy spread
- Implementing these technologies and solutions in real machines
  - These solutions should be compatible with mechanical, cryogenics, magnets design and other specifications.

LASE as low SEY solution for e-cloud mitigation

Existing e-cloud mitigation methods

By *active means*:

- Weak solenoid field (10-20 G) along the vacuum chamber
- Biased clearing electrodes
- Charged particle beam train parameters
  - Bunch charge and sizes, distance between bunches
- **Advantages:**
- Solenoids can be installed on existing facilities (if there is a space for them)
- Beam parameters have some flexibility
- **Disadvantages:**
  - Requires:
    - Controllers, Power supplies, Cables
    - Vacuum compatible electric feedthroughs
  - Reduced flexibility with beam parameters
  - Initial and operation cost should be considered

➢ **I.e. should be avoided, if possible**

By *passive means*:

- Low SEY material
- Low SEY coating (TiN, NEG, a-C, …)
- Mechanically grooved surface
- Rough surface (etching, anodasing, LASE)
- Permanent magnets (in KEK-B)
- Special shape of vacuum chamber
  - An antechamber allows reducing PEY)
- **Advantages:**
  - No controllers, No power supplies, No cables
  - Permanent magnets can be installed on existing facilities
- **Disadvantages:**
  - In-vacuum deposition or wet chemistry
  - Difficult to apply on existing facilities
  - Durations of surface treatments
  - Initial cost should be considered

➢ **I.e. preferable solution(s)**

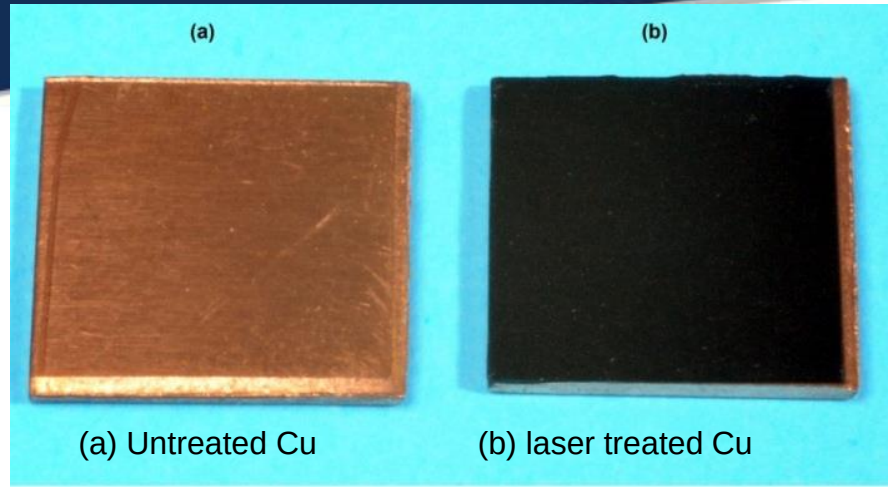
What is LASE?

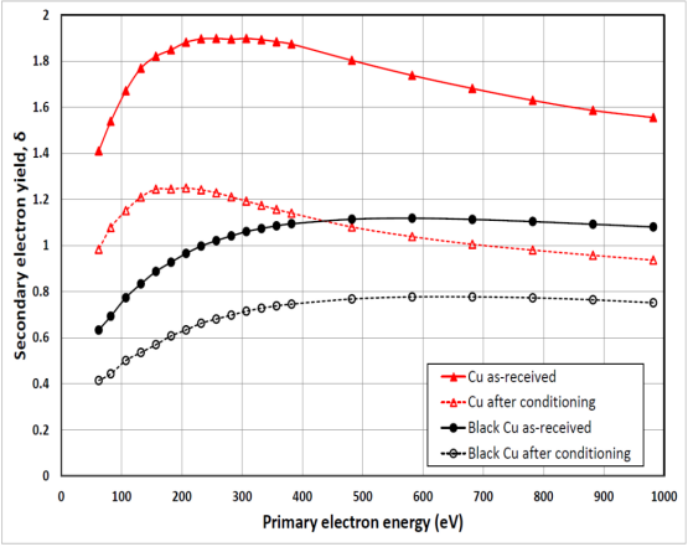
- LASE – Laser Ablated Surface Engineering

- Nanostructuring of Material Surfaces by Laser Ablation is well established science and manufacturing (> 25 years of experience), see review papers:

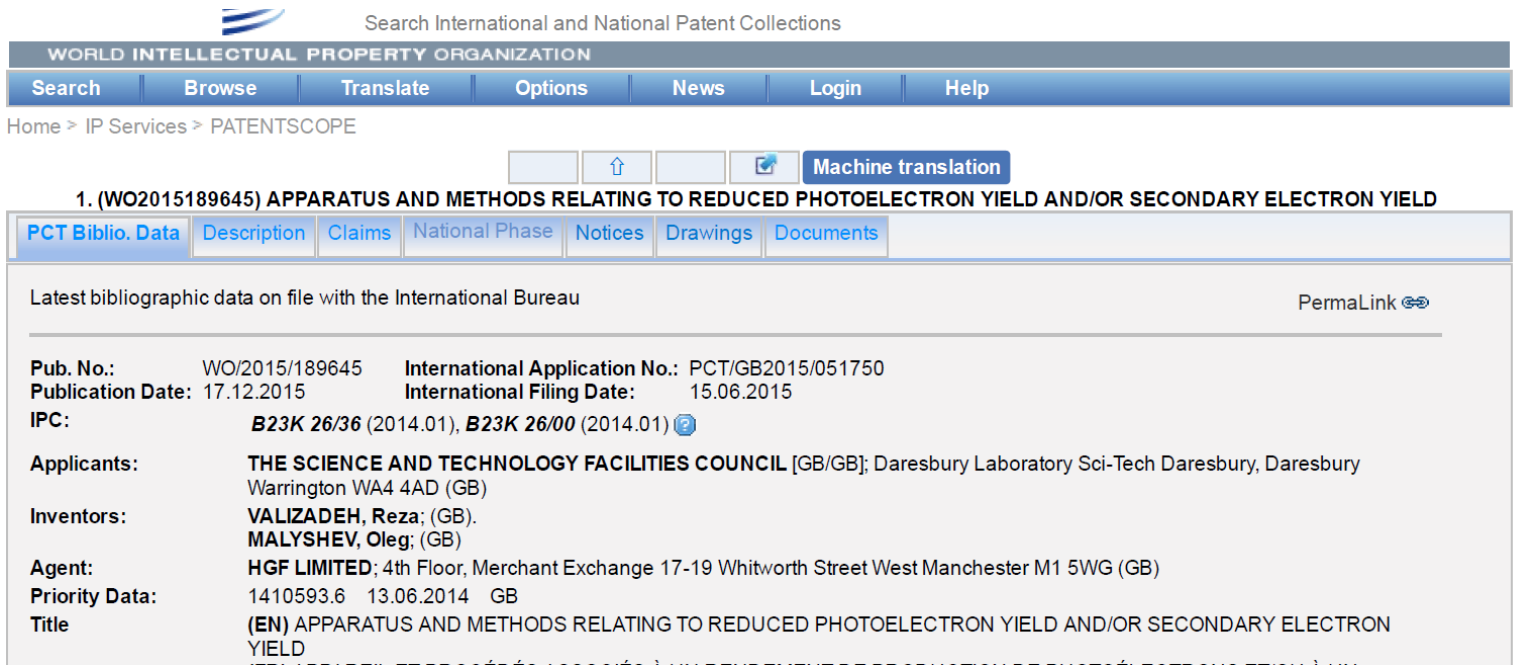
  - K.-H. Leitz, B. Redlingshöfer, Y. Reg, A. Otto, M. Schmidt, Metal ablation withshort and ultrashort laser pulses, Physics Procedia 12B (2011) 230–238.
  - A. Shih, J. Yater, C. Hor, R. Abrous, Secondary electron emission studies, Appl. Surf. Sci. **111** (1997) 251.
  - K.M. Tanvir Ahmmed, C. Grambow, A.-M. Kietzig, Fabrication of Micro/Nanostructures on metals by femtosecond laser micromachining, Micromachines **5** (2014) 1219–1253.
  - J. Byskov-Nielsen, J.-M. Savolainen, M.S. Christensen, P. Balling, Ultra-short pulse laser ablation of metals: threshold fluence, incubation coefficient and ablation rates, Appl. Phys. A **101** (2010) 97–101.

Discovery of LASE for SEY mitigation





R. Valizadeh, et al. Appl. Phys. Lett. 105, 231605 (2014); doi: 10.1063/1.4902993



Search International and National Patent Collections

WORLD INTELLECTUAL PROPERTY ORGANIZATION

Search | Browse | Translate | Options | News | Login | Help

Home > IP Services > PATENTSCOPE

Machine translation

1. (WO2015189645) APPARATUS AND METHODS RELATING TO REDUCED PHOTOELECTRON YIELD AND/OR SECONDARY ELECTRON YIELD

PCT Biblio. Data | Description | Claims | National Phase | Notices | Drawings | Documents

Latest bibliographic data on file with the International Bureau

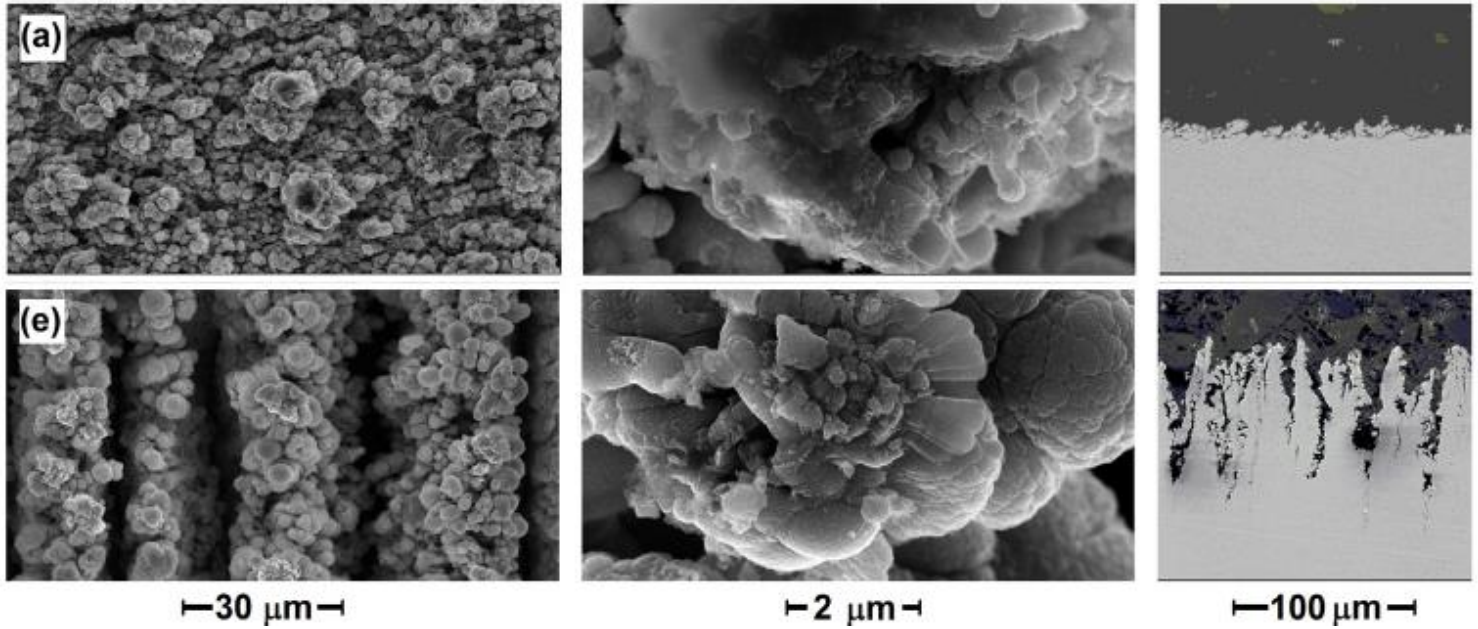
PermaLink

Pub. No.: WO/2015/189645 **International Application No.:** PCT/GB2015/051750
Publication Date: 17.12.2015 **International Filing Date:** 15.06.2015
IPC: ***B23K 26/36*** (2014.01), ***B23K 26/00*** (2014.01)
Applicants: **THE SCIENCE AND TECHNOLOGY FACILITIES COUNCIL** [GB/GB]; Daresbury Laboratory Sci-Tech Daresbury, Daresbury Warrington WA4 4AD (GB)
Inventors: **VALIZADEH, Reza**; (GB). **MALYSHEV, Oleg**; (GB)
Agent: **HGF LIMITED**; 4th Floor, Merchant Exchange 17-19 Whitworth Street West Manchester M1 5WG (GB)
Priority Data: 1410593.6 13.06.2014 GB
Title **(EN)** APPARATUS AND METHODS RELATING TO REDUCED PHOTOELECTRON YIELD AND/OR SECONDARY ELECTRON YIELD

- The new was applying LASE surfaces to suppress PEY/SEY and to solve the e-cloud problem
- Main result: SEY < 1 can be achieved on Cu, Al and stainless steel

Main results

- SEY reduction due to a superposition of
  - microstructure (groves)
  - sub-micron and nano-structures



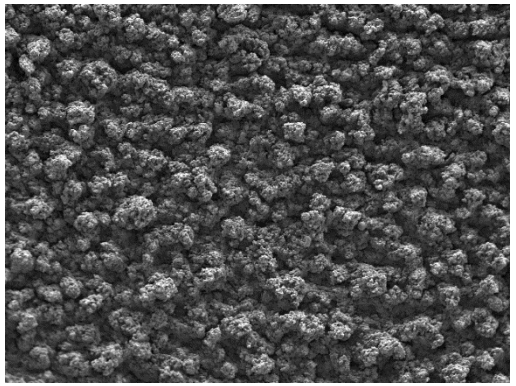
- Low SEY surfaces can be produced using various lasers with different wavelength, such as λ=355 nm and λ=1064 nm, different power, with a variety of other parameters.

Groves are main source of surface resistance.

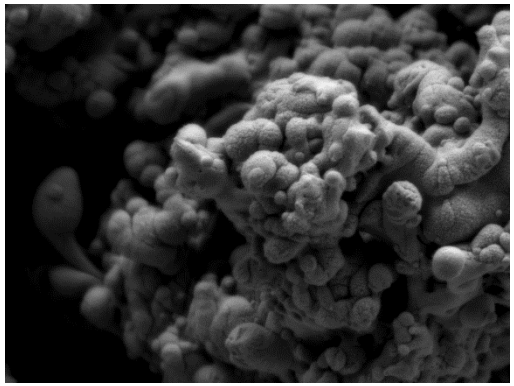
R. Valizadeh, et al.
Appl. Appl. Surf. Sci. 404 (2017) 370–379;
doi: /10.1016/j.apsusc.2017.02.013.

LASE: further development

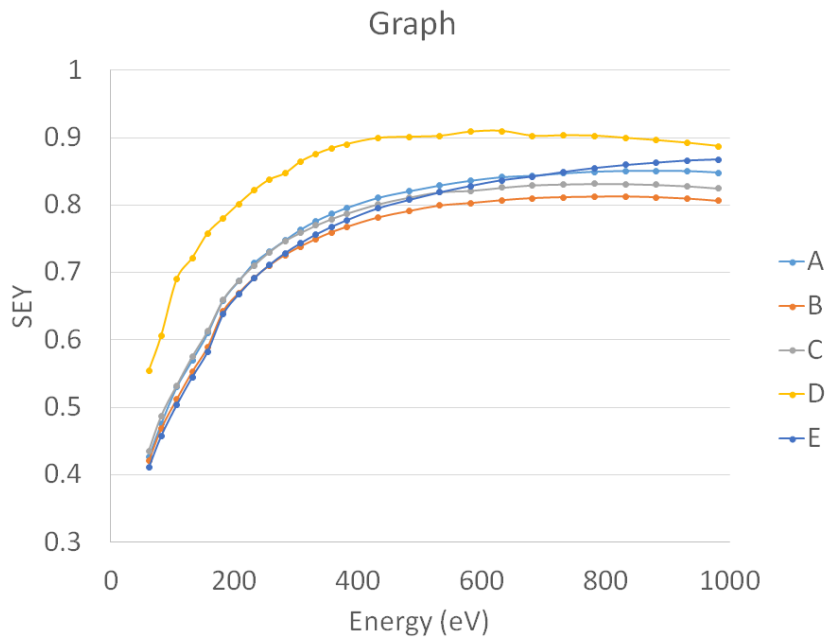
- Produced and tested more than 120 different LASE samples
  - With different laser parameters treated with the following lasers:
    - Nanosecond 355 nm
    - Nanosecond 1064 nm
    - Picosecond 355 nm
    - Picosecond 1064 nm
  - In different atmospheres:
    - Air, vacuum, Ar, CH_4
- More than **60 samples** have **SEY_{max}<1**



400 µm



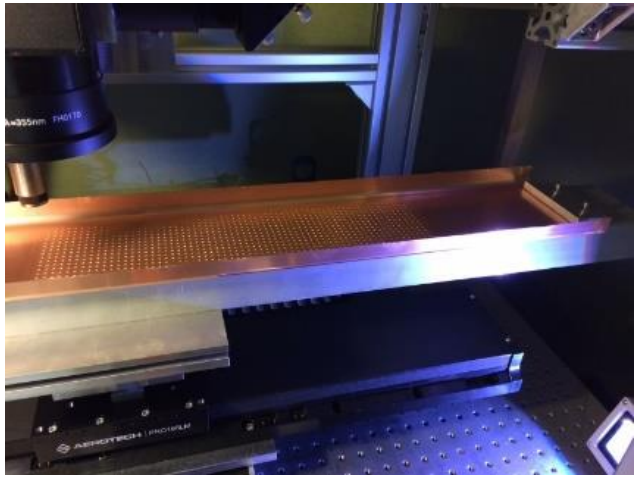
10 µm

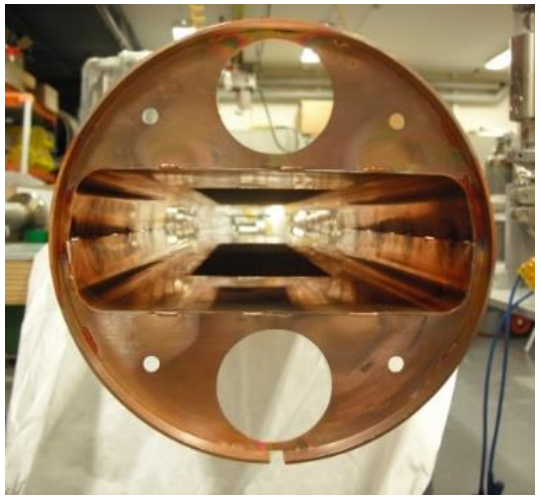


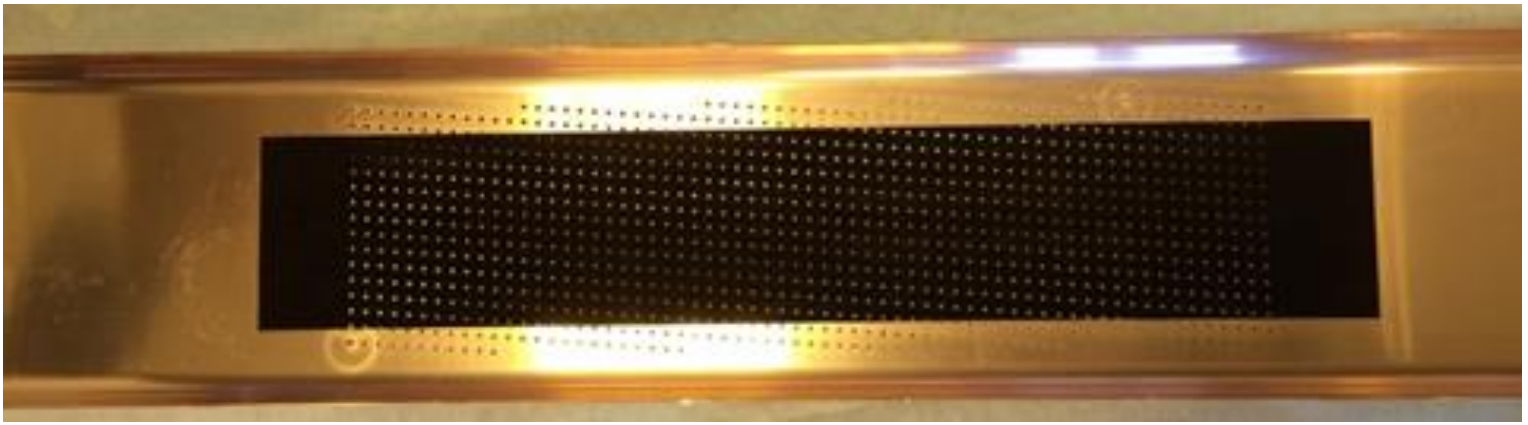
LASE treatment of the sample for SPS test

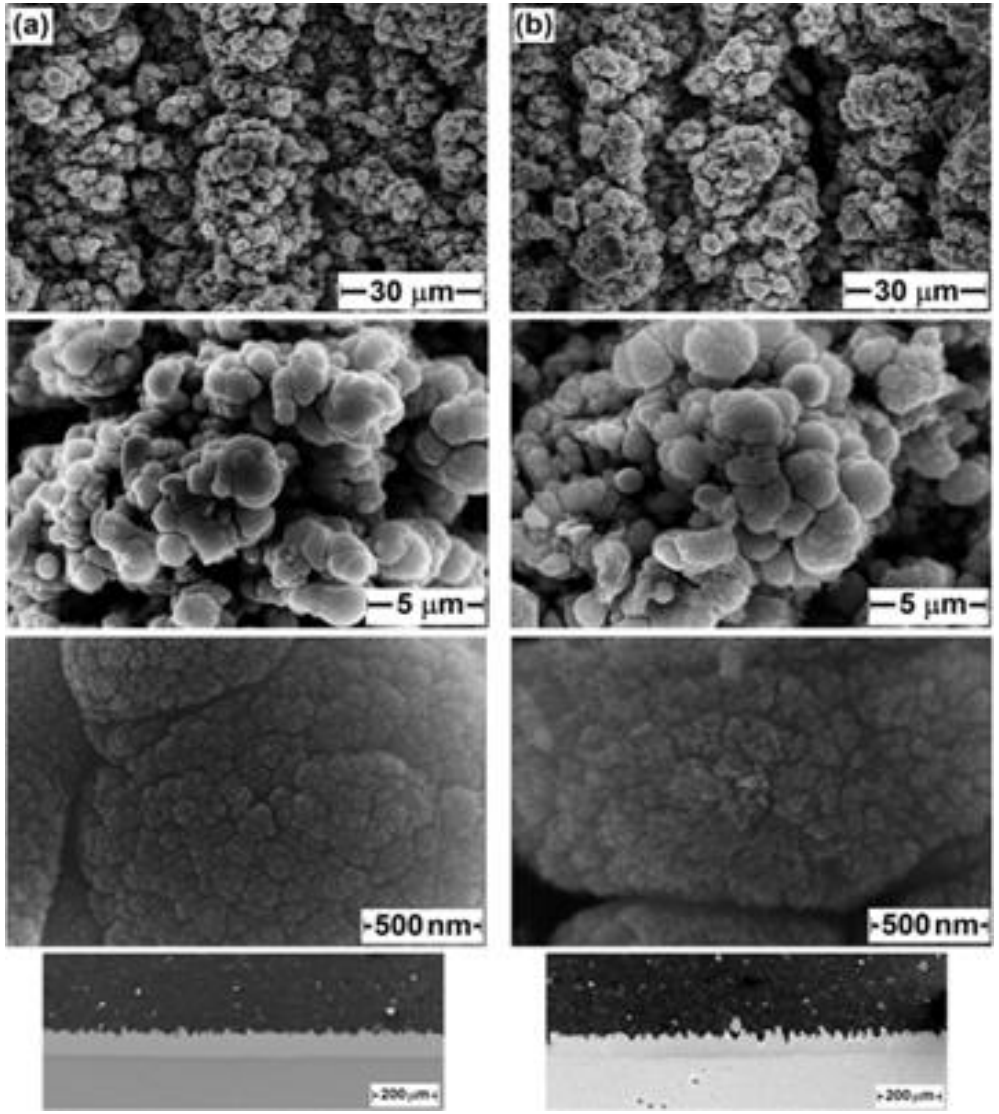
SPS liner as test sample has been laser treated:

- Two areas of 40 x 490 mm^2 with different LASE parameters

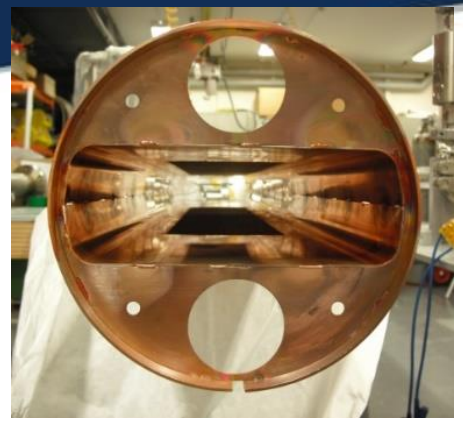


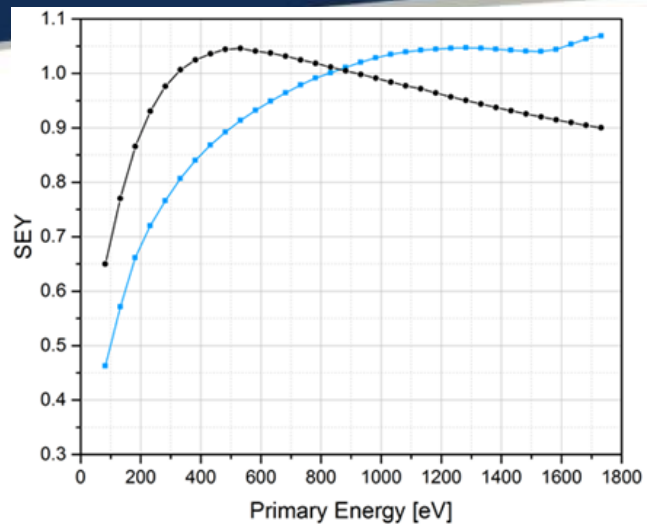


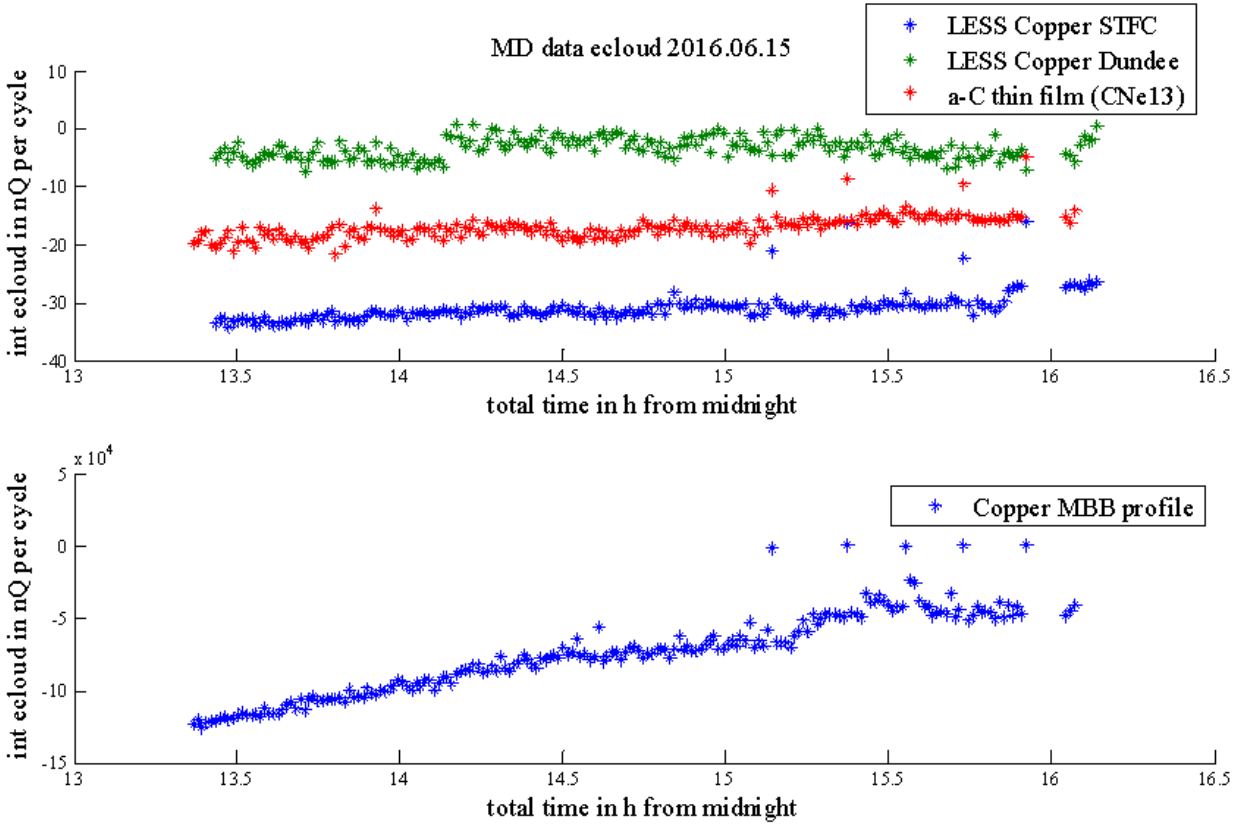




LASE test in SPS



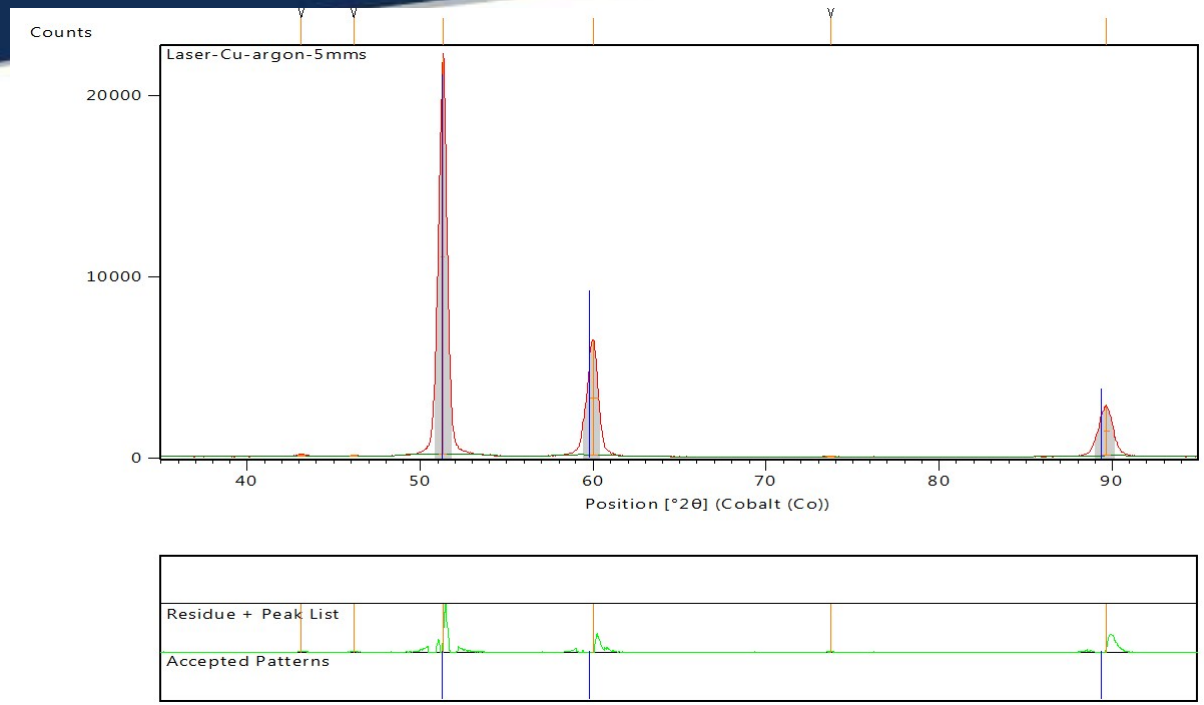


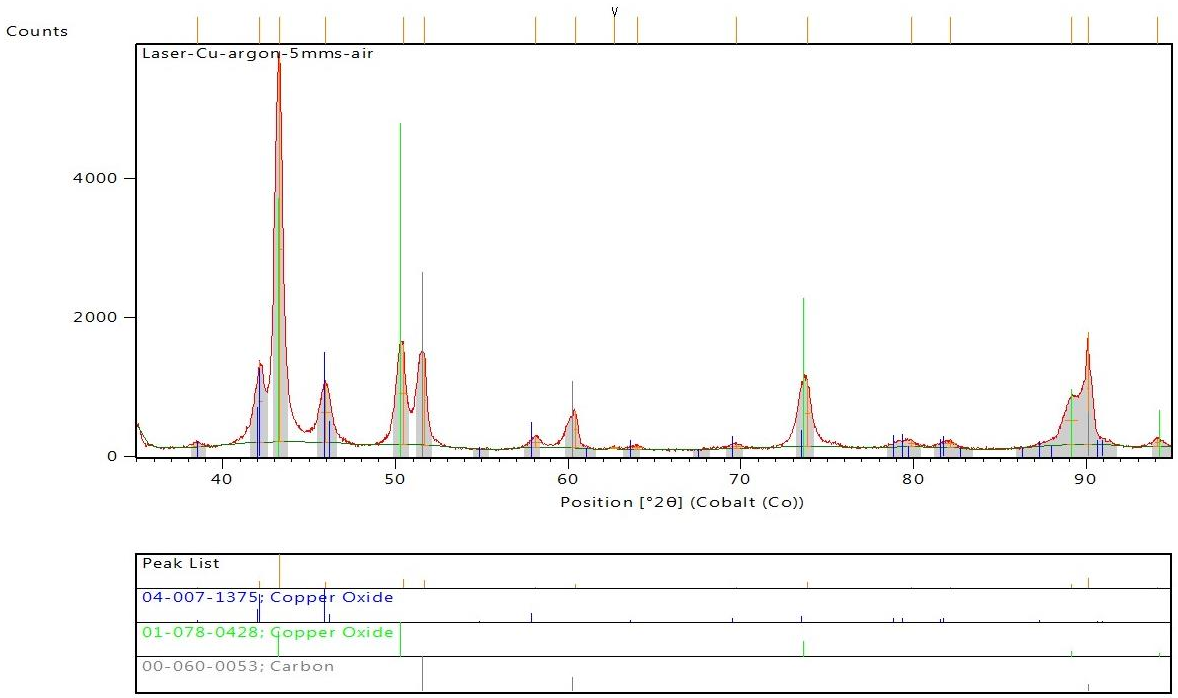


- **Electron cloud mitigation has based on LASE has been successfully demonstrated in particle accelerator for the first time**
- **SEY < 1 can be consistently achieved for practical implementations on technical surfaces.**
- **The e-cloud induced by the SPS proton beam was suppressed as efficiently as by the a-C coating**
- **The results also show that the LASE induced structure are robust, highly reproducible and scalable**

S. Calatroni, et al. First accelerator test of vacuum components with laser-engineered surfaces for e-cloud mitigation. Phys. Rev. Acc. and Beams 20, 113201 (2017)

Effect of Process Atmosphere





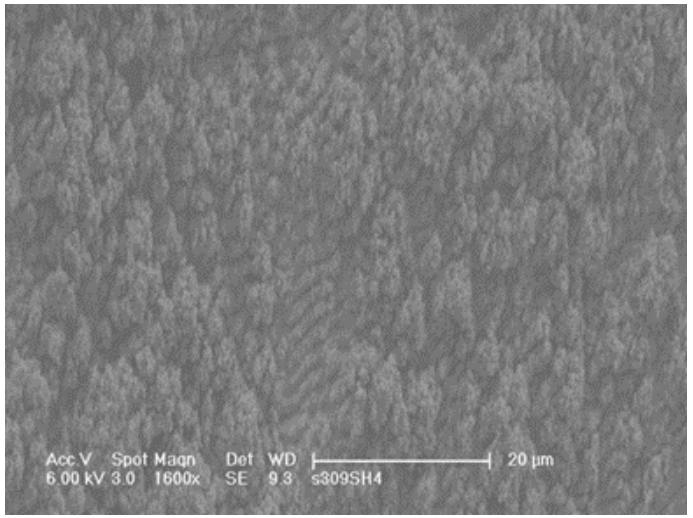
•XRD of Cu laser ablated in Ar atmosphere

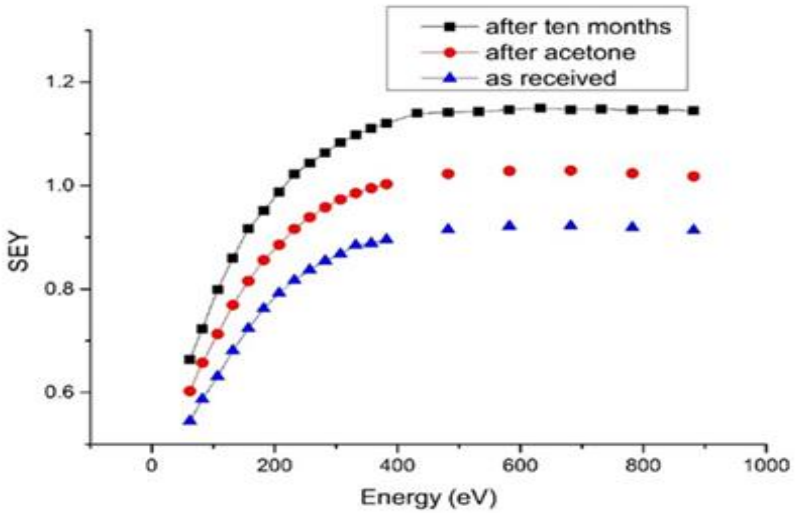
•XRD of Cu ablated in Air

- LASE in Ar atmosphere inhibit the formation of oxide layer
- LASE I air atmosphere results in a stable detectable by XRD oxide layer

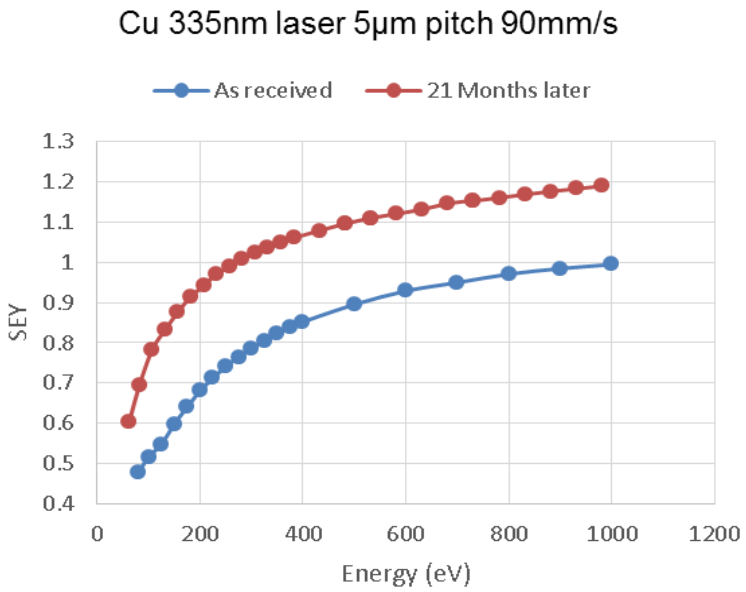
Effect of Aging on SEY

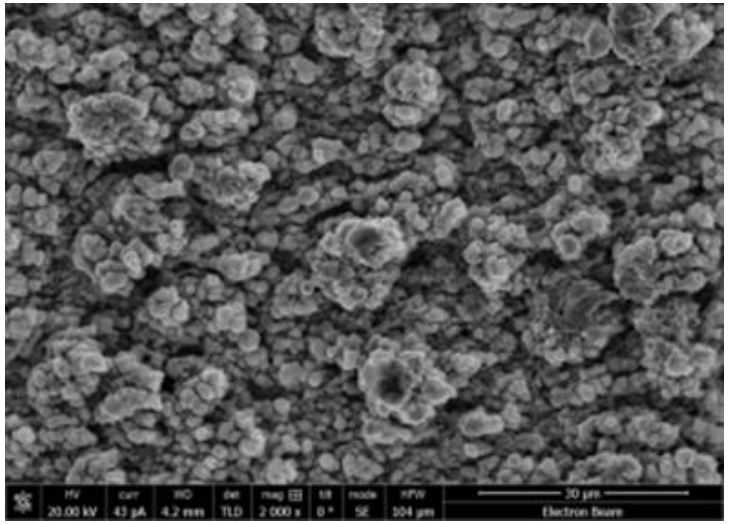
Sample	Date	pulse duration/ ps	Spot/ μ m	Scan speed/ mms^{-1}	wave length/ nm	Pitch spacing/ μ m	Repetition/ kHz	Power/ W
#1	2016.02.24	5	15	30	1064	5	1.25	5





Conditions	as reveived	after acetone	ten months later
δ_{max}	0.92	1.03	1.15
E_{max} (eV)	682	682	632

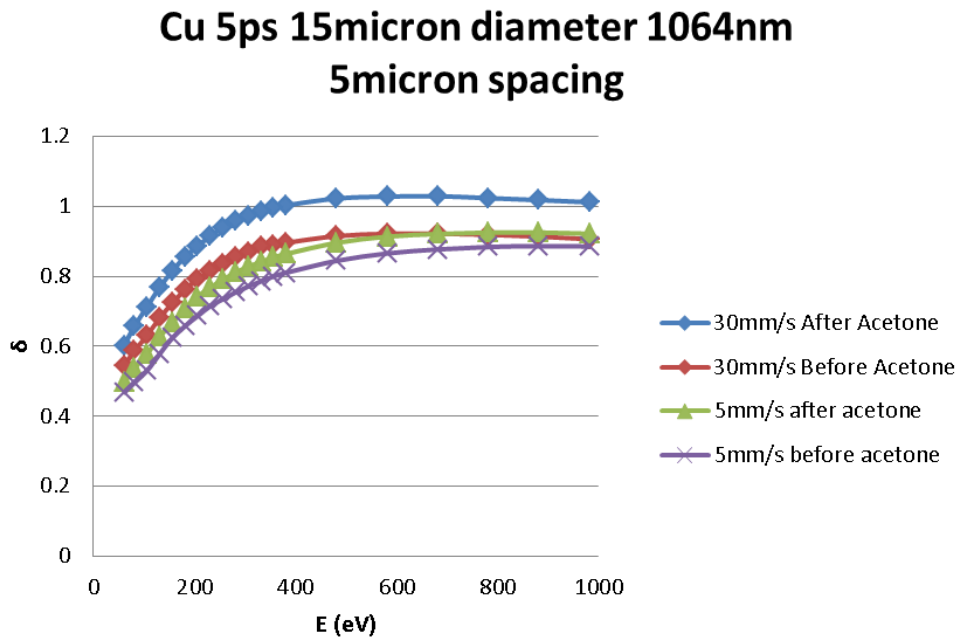




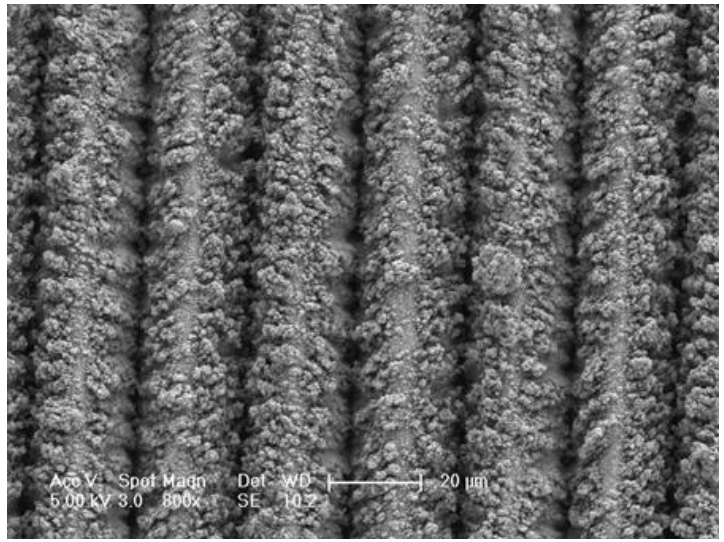
The increase in SEY is attributed to the growth of hydrocarbon on the surface which also contribute to super hydrophobicity of laser ablated surfaces

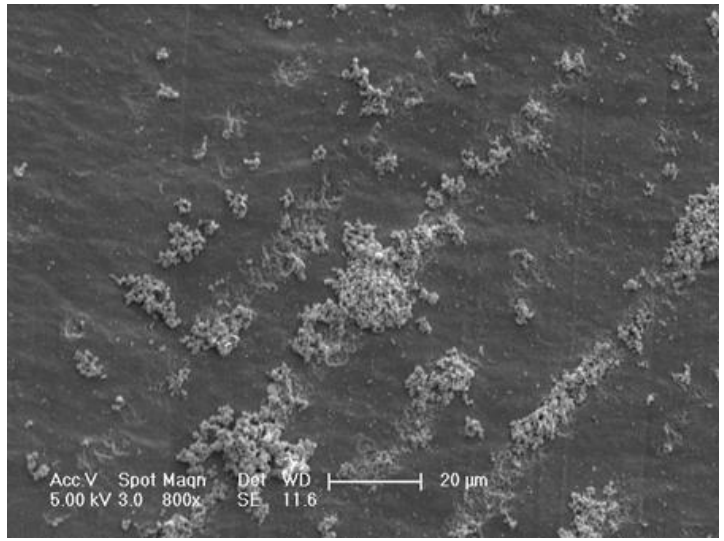
Effect of acetone and ultrasonic bath on SEY

- LASE surface is clean (no vacuum cleaning required)
- but in case of contamination after treatment they may require cleaning



	Cu 2p	O 1s	C 1s	N 1s
30 mm/s before acetone	20.7	41.9	0	37.5
30 mm/s after acetone	28.8	55.5	15.7	0
5 mm/s before acetone	45.9	54.4	0	0
5 mm/s after acetone	40.7	49.9	9.4	0





The increase in SEY can be attributed to two factors:

- ❖ Loss of particulate as can be seen on the foil left behind after ultrasonic bath cleaning
- ❖ Built up of hydrocarbon on the surface afer solvent cleaning

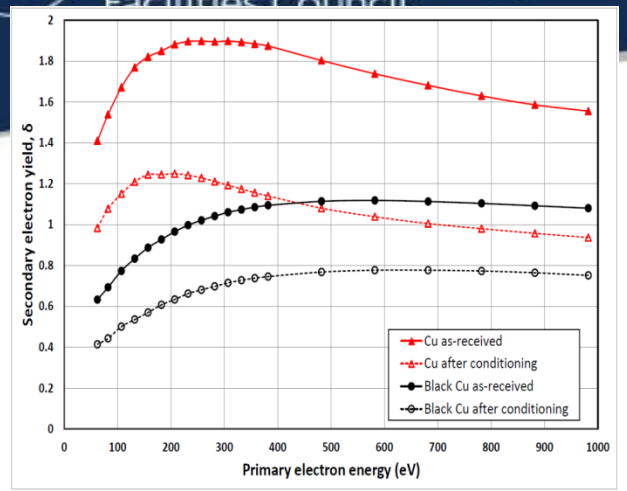
Impact of LASE e-cloud mitigation on other systems

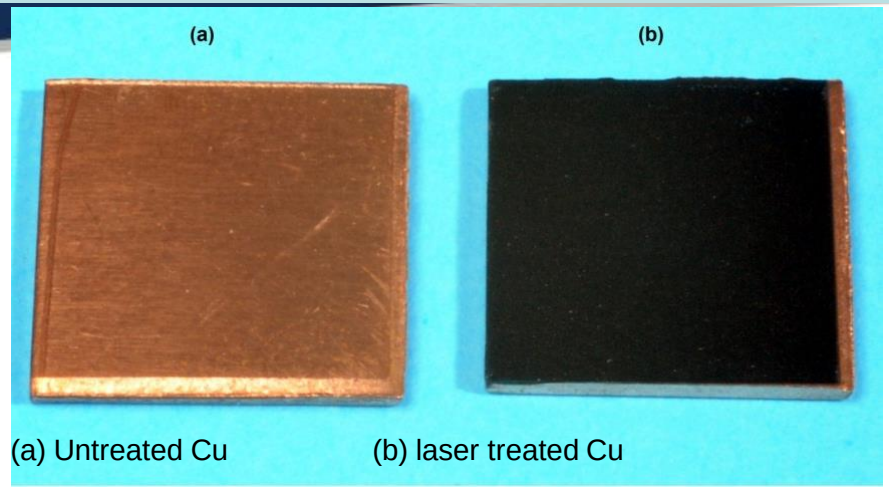
- LASE
  - **SEY: $\delta_{max} < 0.6$**

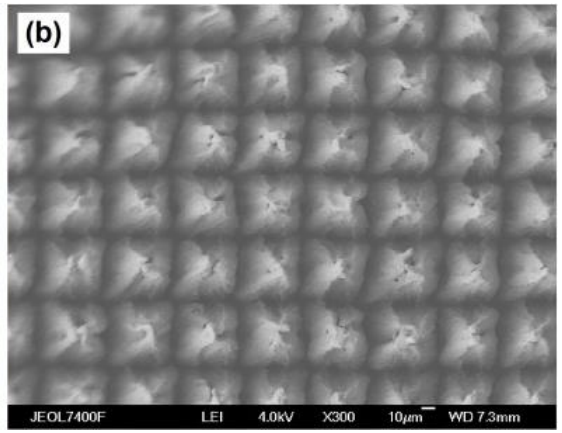
- PEY ? (scaled with SEY?)
- Vacuum
  - Bakeout
  - Thermal outgassing
  - PSD, ESD and ISD
- Beam wakefield impedance
  - Surface resistance
- UFO
  - Particle generation
- Cryogenic vacuum system
  - Effect of cryosorbed gas on PEY, SEY, PSD, ESD, ISD

Surface resistance

Low SEY studies: First LASE results in 2014

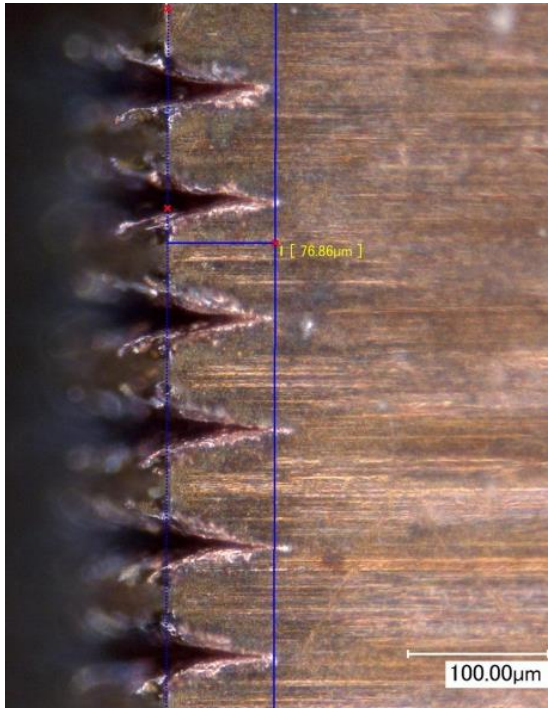






R. Valizadeh, O.B. Malyshev, S. Wang, et al. Low secondary electron yield engineered surface for electron cloud mitigation.

Appl. Phys. Lett. 105, 231605 (2014); doi: 10.1063/1.4902993



In our earlier results:

- δ_{max} **< 1** can has been achieved on Cu, Al and stainless steel
- However, main question we had to ourselves and being asked by other colleagues:
  - *How **100-μm deep groves** affect surface resistance?*

Surface resistance measurements: method

- The cavity geometry consists of two parts:
  - a body of the cavity
  - a planar sample,
  - separated by an air gap.
- Contactless

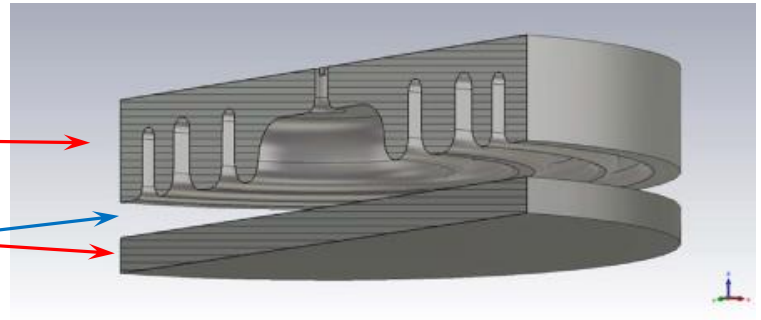
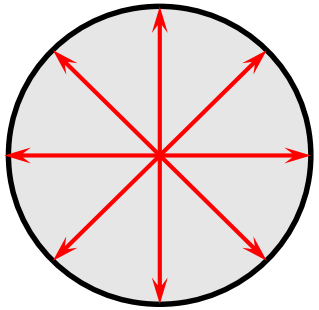
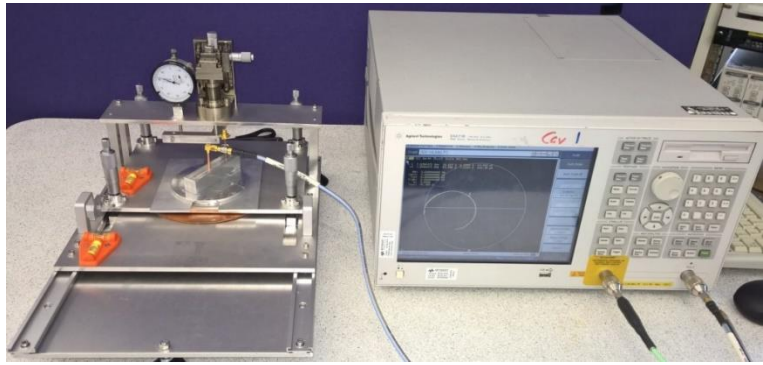


Fig. 1. A schematic of the triple choke RF cavity above a sample.



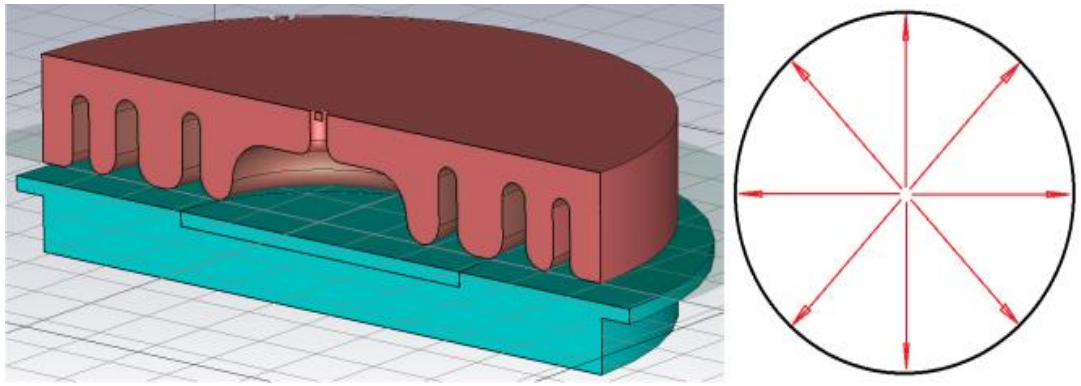
- RF chokes in order to keep the RF power within the cavity
- Operating in TM_{010} mode, has circular H field distribution hence Induces radial current.
- The surface resistance of the sample R_S^{sam} can be calculated for known
  - test cavity surface resistances R_S^{cav} and
  - measured Q_0,
- The magnetic field distribution in the cavity was calculated using CST Microwave Studio.
  - For our cavity, G = 235 Ω,
  - for a case using perfect electric conductor (PEC) boundary conditions, the field ratios are p_c = 0.625 and p_s = 0.375.

$$R_S^{sam} = \frac{G\,Q_0^{-1} - R_S^{cav}\,p_c}{p_s}$$

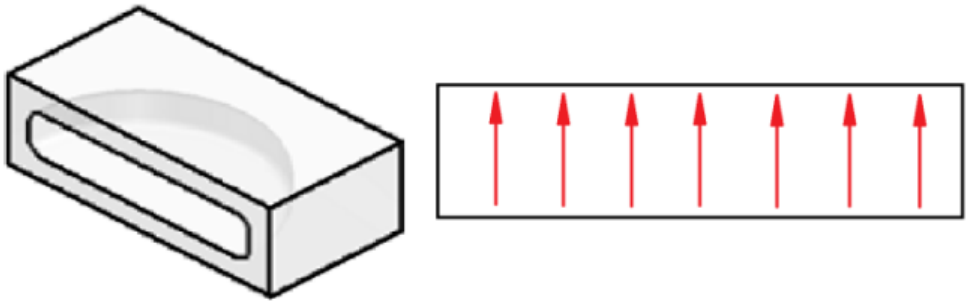


Surface resistance measurements

1st cavity – directionally averaged R_s



2nd cavity – R_s measurements along a selected direction



Test cavities (3.9 and 7.8 GHz):

- The simulation results obtained with Microwave Studio
- Fabricated from Al.
- 3 choke cavity operating in TM_{010} mode, has circular H field distribution hence Induces radial current.
- Half pill box cavity operating in TM_{110} mode, has strong transverse H field hence induces axial electric current

Samples:

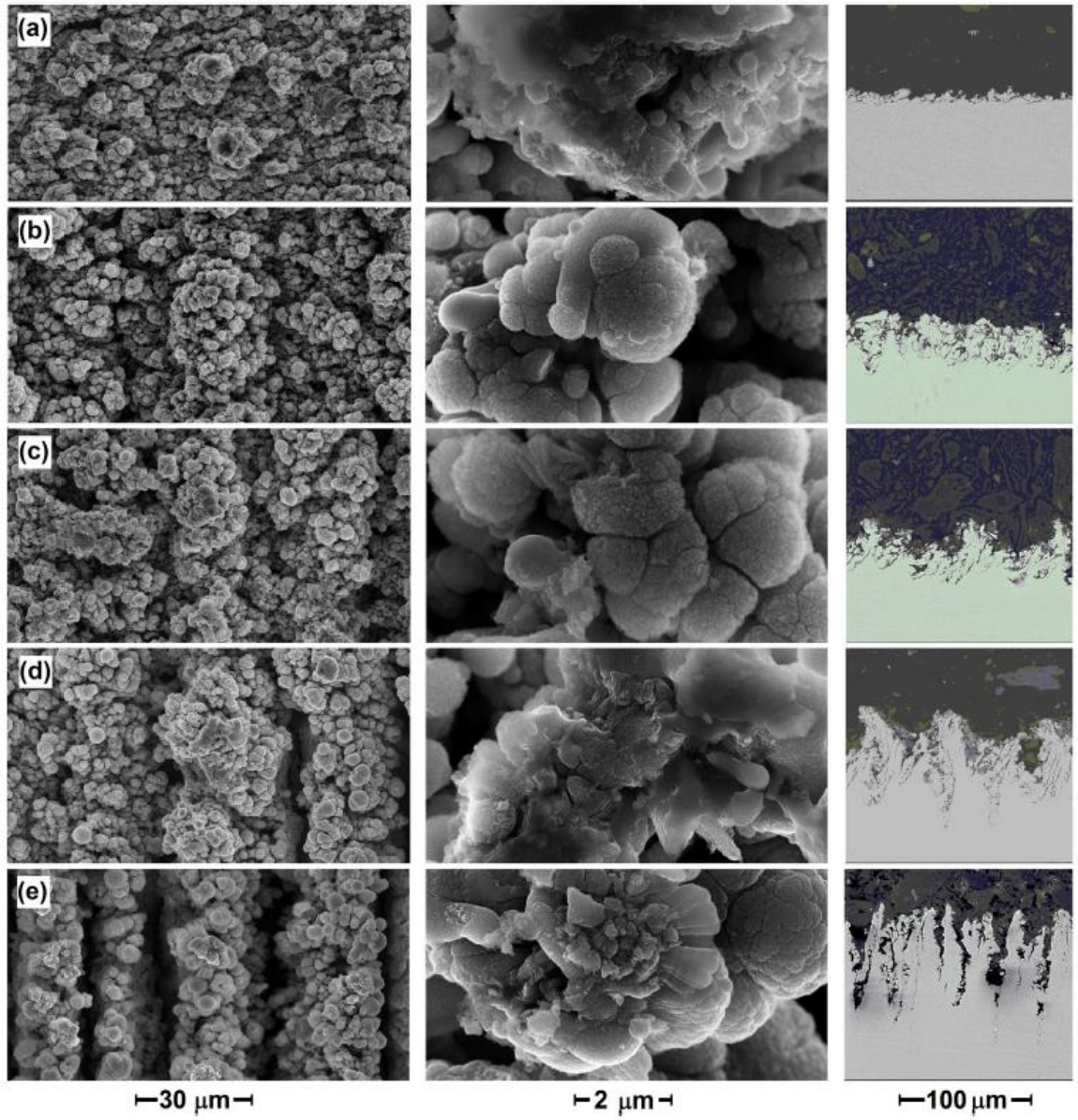
- 100 mm × 100 mm laser treated copper surface

Following low SEY studies

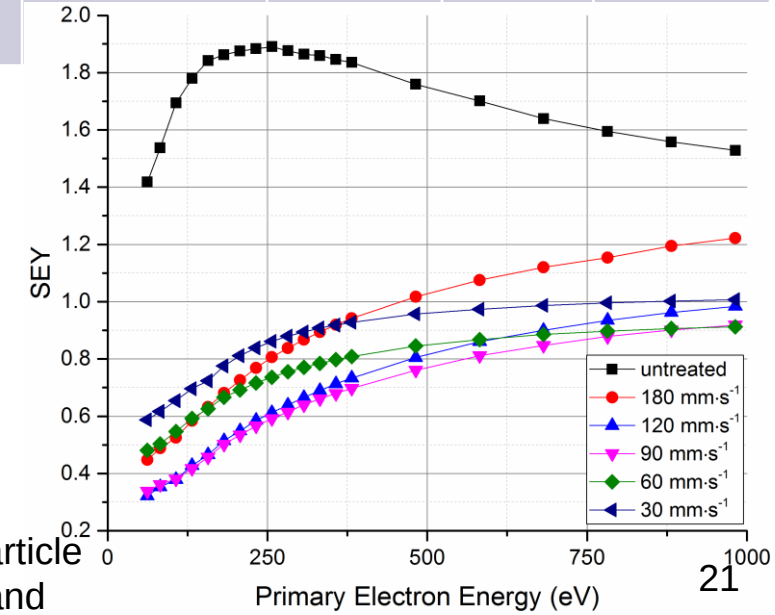
- Emphasis on physics:
  - How and why SEY is reduced on LASE surfaces
  - Further reduce SEY
  - Reduce surface resistance
  - Reduce particulate generation
  - Measure vacuum properties

- R. Valizadeh, O.B. Malyshev, S. Wang, T. Sian, L. Gurran, P. Goudket, M.D. Cropper, N. Sykes. Low secondary electron yield of laser treated surfaces of copper, aluminium and stainless steel. In Proc. of IPAC'16, 8-13 May 2016, Busan, Korea (2016), p. 1089.
- R.Valizadeh, O.B.Malyshev, S.Wang, T.Sian, M.D.Cropper, N.Sykes. Reduction of Secondary Electron Yield for E-cloud Mitigation by Laser Ablation Surface Engineering, Applied Surface Science 404 (2017) 370-379. http://dx.doi.org/10.1016/j.apsusc.2017.02.013

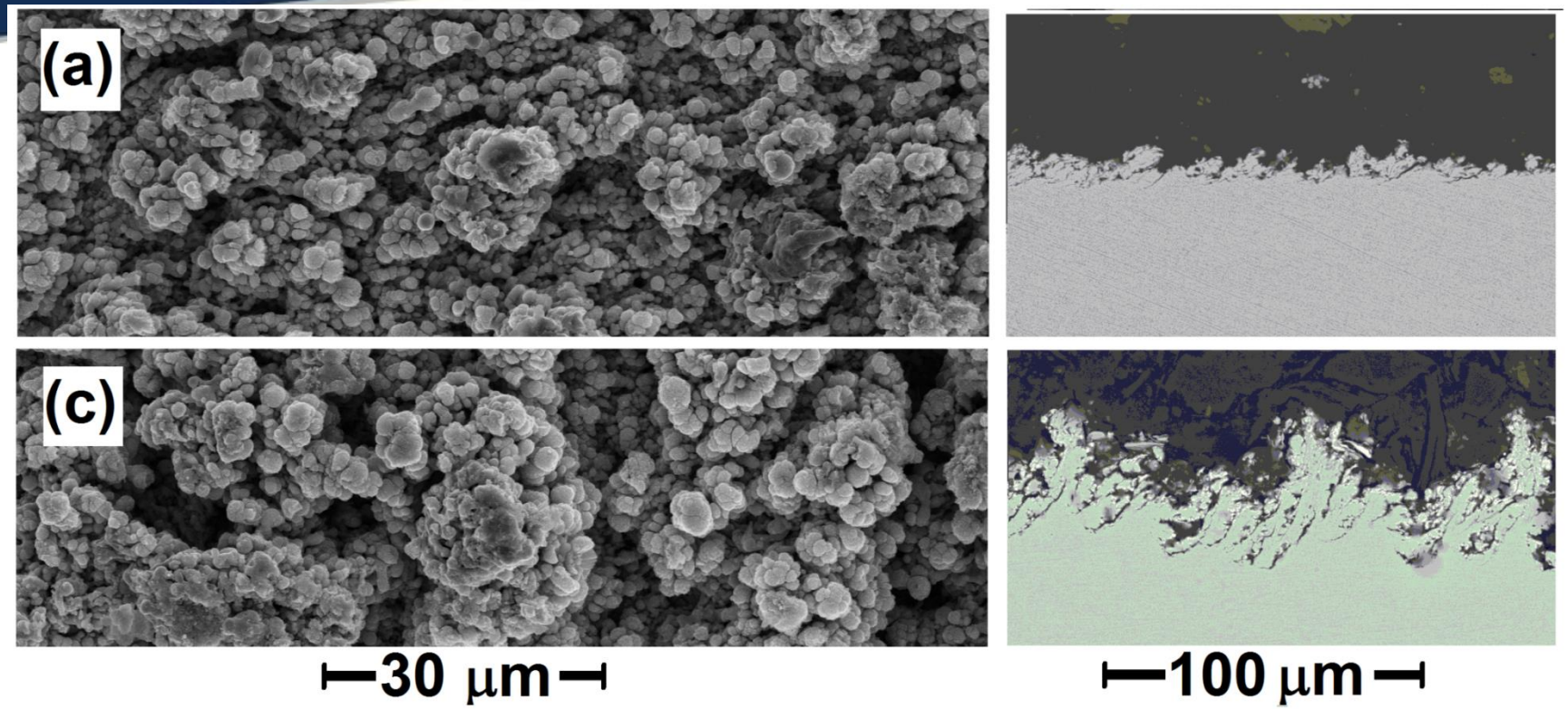
LASE: A role of laser scan speed on copper samples



Sample	Scan speed [mm/s]	Groove depth [μm]	R_s [Ω]	R_s [Ω]		
			average	0°	45°	90°
Cu	untreated	-	0.033			
(a)	180	8	0.078	0.11	0.11	0.095
(b)	120	20	0.13			
(c)	90	35	0.14	0.15	0.19	0.20
(d)	60	60	–			
(e)	30	100				



Surface in more details



Treatment of copper using a λ = 355 nm laser resulted in creation of three different scales structures as presented:

- microstructure grooves ranging from 8 to 100 μm deep,
- coral-like submicron particles superimposed on the grooves which is made of agglomeration of
- nano-spheres

Calculated and measured R_S at frequency f=7.8 GHz

Sample	Scan speed [mm/s]	Groove depth for LASE (Roughness for untreated metals) [μm]	Rs [Ω] measured with a 7.8-GHz cavity	Rs [Ω] calc with formula
Cu	untreated	0.4	0.028	0.029
(a)	180	8	0.078	~~0.046~~
(b)	120	20	0.13	~~0.046~~
(c)	90	35	0.14	~~0.046~~
(d)	60	60	–	~~0.046~~
(e)	30	100	–	~~0.046~~
Al	untreated	0.4	0.034	0.034
Nb	untreated	1.0	0.071	0.080
SS	untreated	1.4	0.17	0.16

Hammerstad and Bekkadal formula: $$R_s = \sqrt{\frac{\mu\omega}{2\sigma}}\left(1+\frac{2}{\pi}\arctan\left(0.7\mu\omega\sigma R_Q{}^2\right)\right);$$

Dielectric Resonator – Surface Resistance Measurement in ALBA (Barcelona)

- Brass cylinder
- Samples replace upper and lower plates
- Operating in the TE_{011} mode
  - Insensitive to electrical contacts to the metallic enclosure
  - Rutile
  - Resonance frequency at 77 K is 8.0 GHz
- The unloaded Q-factor is given by

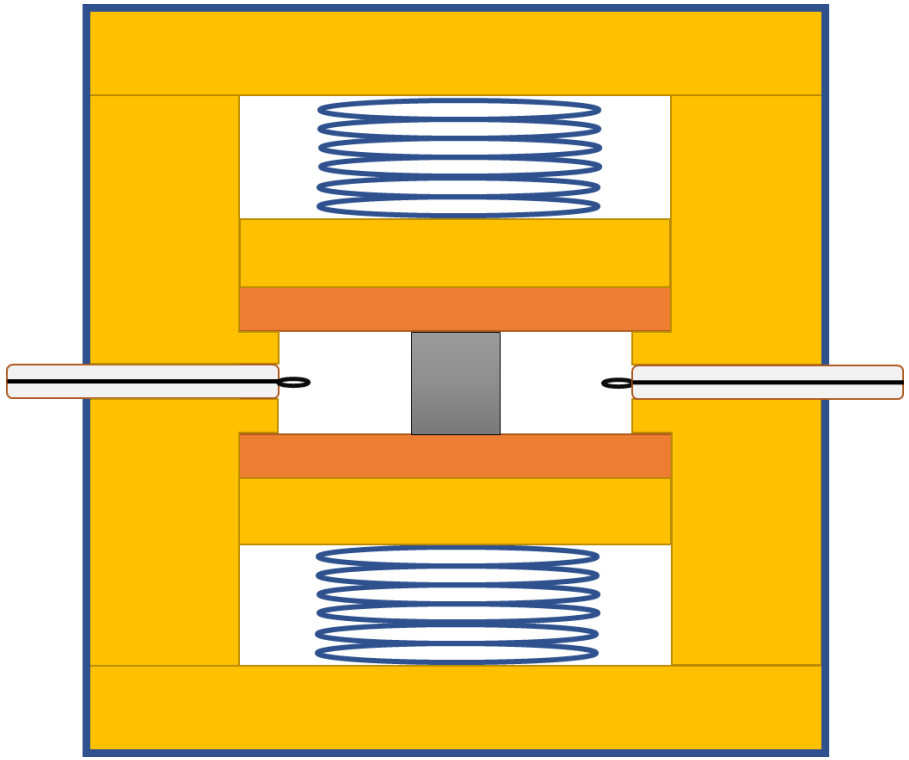
$$\frac{1}{Q_0} = \sum_i \frac{R_{S_i}}{G_i} + p \cdot \tan(\delta)$$

$R_{S_i} = Surface\ resistance$

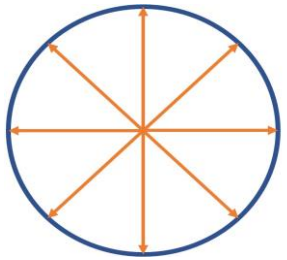
$G_i = Geometrical\ factor$

$p = Filling\ factor$

$\tan(\delta) = Loss\ factor$



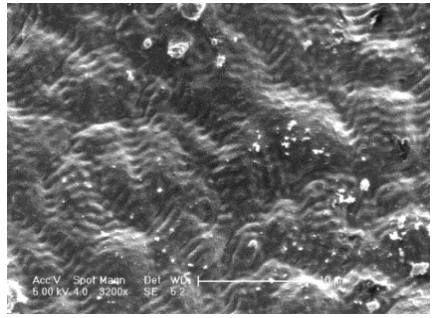
TE_{010} mode

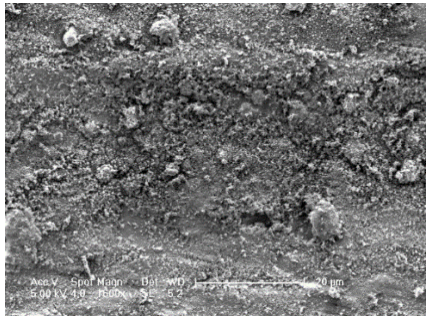


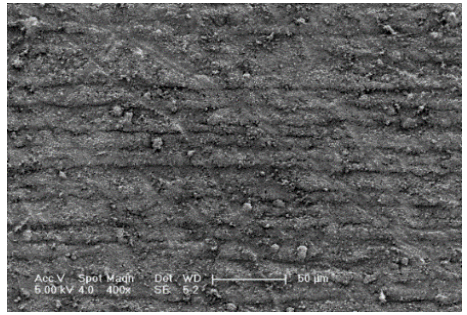
TE_{011} mode

SEY and surface resistance of LASE treated copper

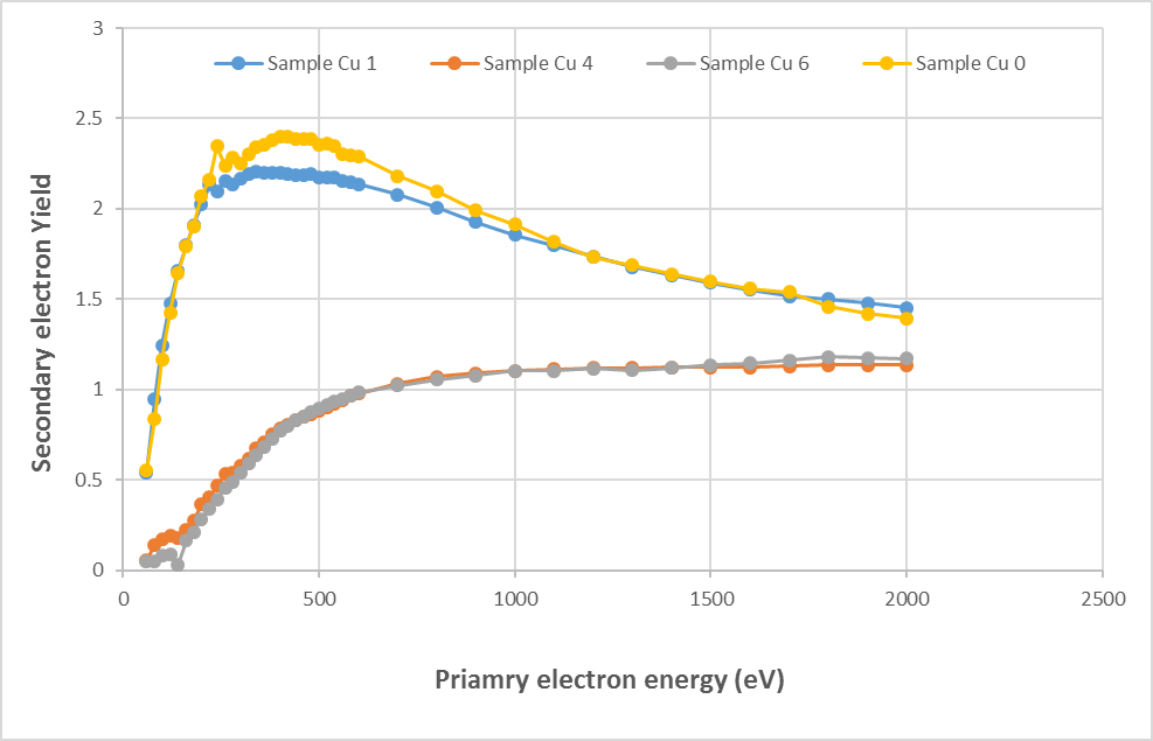
Sample	Material	λ (nm)	Average Power (W)	Pulse length (ns)	Frequency (KHz)	Pitch (μm)	Beam size (μm)	Power per pulse (μJ)	Fluence per pulse (Jcm^{-2})	Speed (mms-1)
1	Cu	1063	30	0.15	600	10	15	50	28	40
4	Cu	1063	20	2	40	50	15	500	280	40
6	Cu	1063	20	2	40	10	15	500	280	40
7	Cu	0	0	0	0	0	0	0	0	0





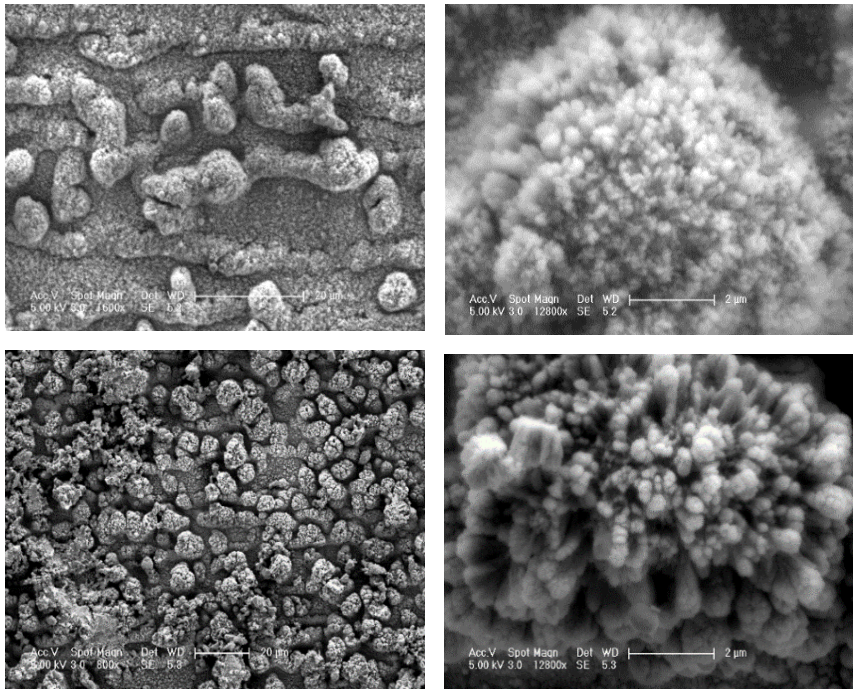


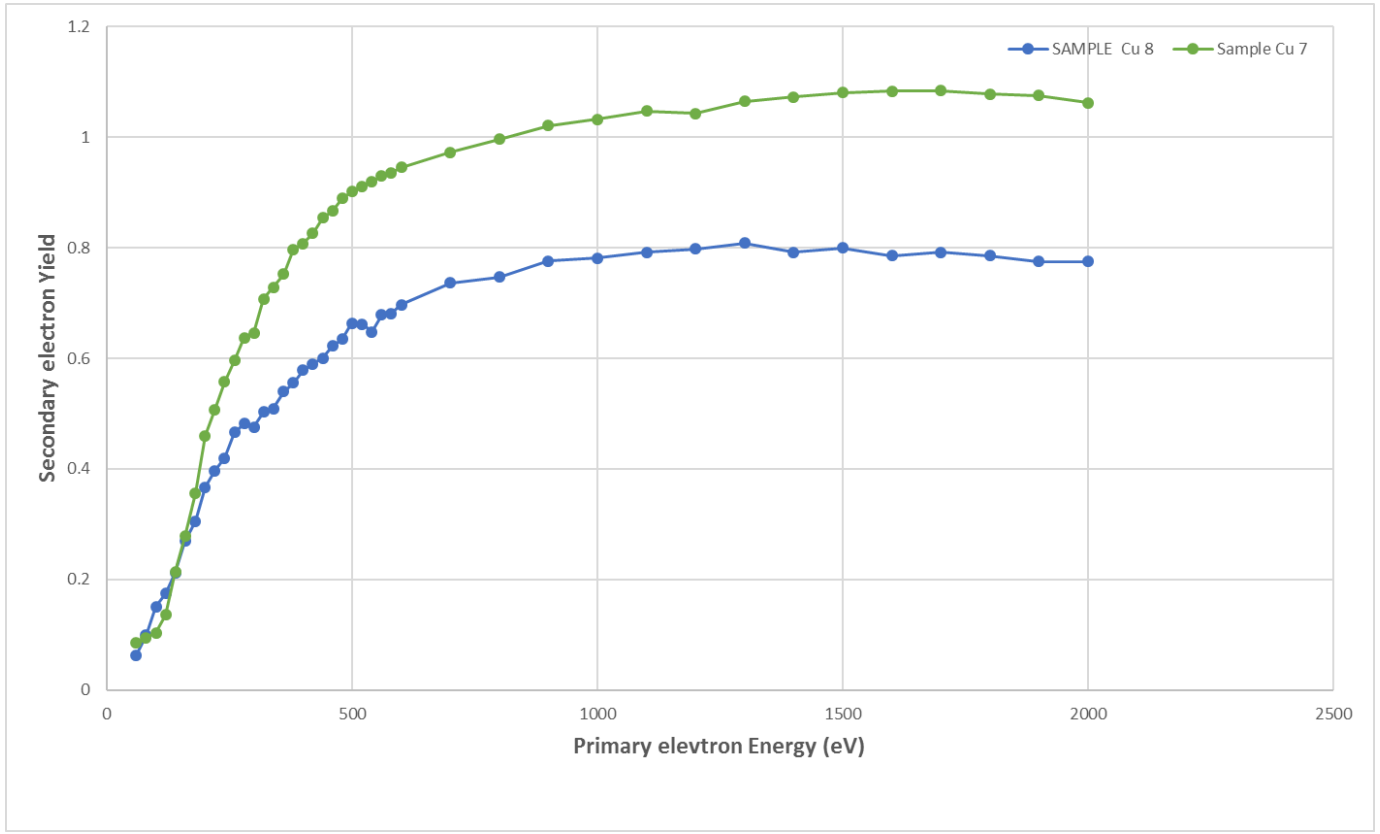
	Sample 1	Sample 4	Sample 6	Untreated
R_{SRT} [mΩ]	25.527	24.940	25.100	26.035
R_{S77K} [mΩ]	10.792	9.814	9.697	10.709



SEY and surface resistance of LASE treated copper

Sample	Material	λ (nm)	Average Power (W)	Pulse length (ns)	Frequency (KHz)	Pitch (μm)	Beam size (μm)	Power per pulse (μJ)	Fluence per pulse (Jcm^{-2})	Speed (mms-1)
7	Cu	1063	30	0.15	600	10	15	50	28	40
8	Cu	1063	30	0.15	600	5	15	50	28	40





	Condition 1	Condition 2	Untreated
R_{SRT} [mΩ]	28.516	39.431	25.175
R_{S77K} [mΩ]	14.091	25.335	10.913

An R_s increase of 14% for SEY of 1.1 and 60% for SEY of 0.8

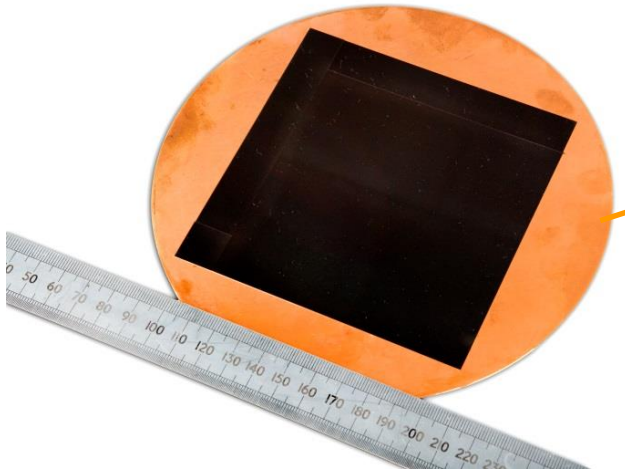
Surface resistance

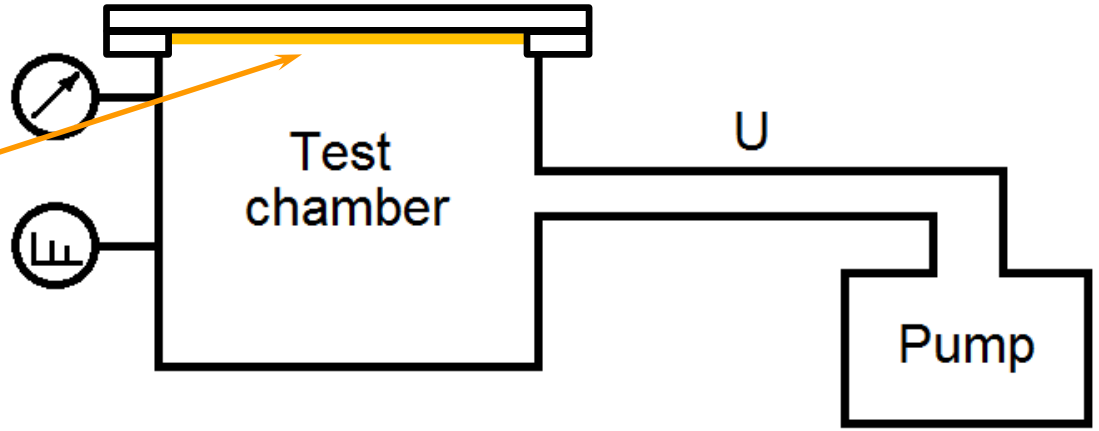
- An open question:
  - R_s as a function of temperature down to 4 K
    - To be addressed in future
    - A dedicated facility in ASTeC is under development
      - Planar samples could be studied in a few months
      - Tubular sample can be considered later

LASE vacuum properties

LASE: thermal outgassing

- Sample:
  - a 100-mm diam. disk (copper gasket)
  - After LASE
- No difference in outgassing detected in a vacuum chamber without and with a sample

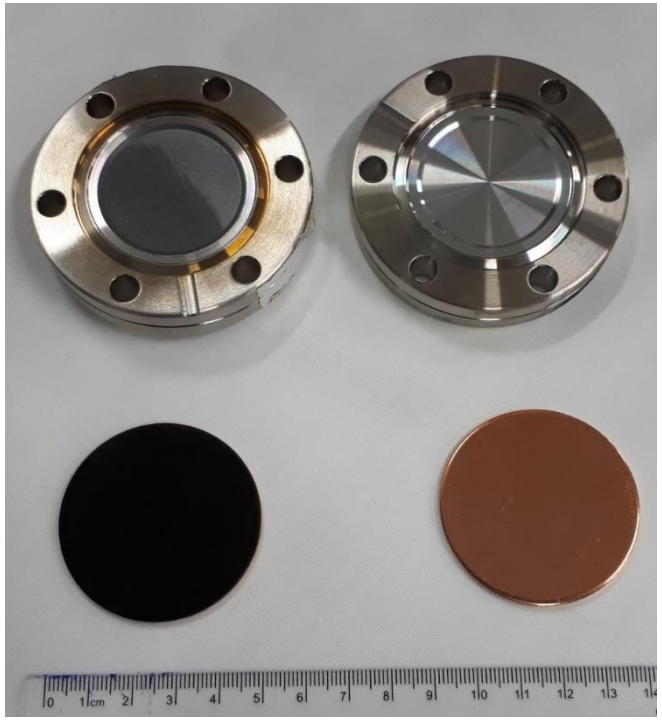


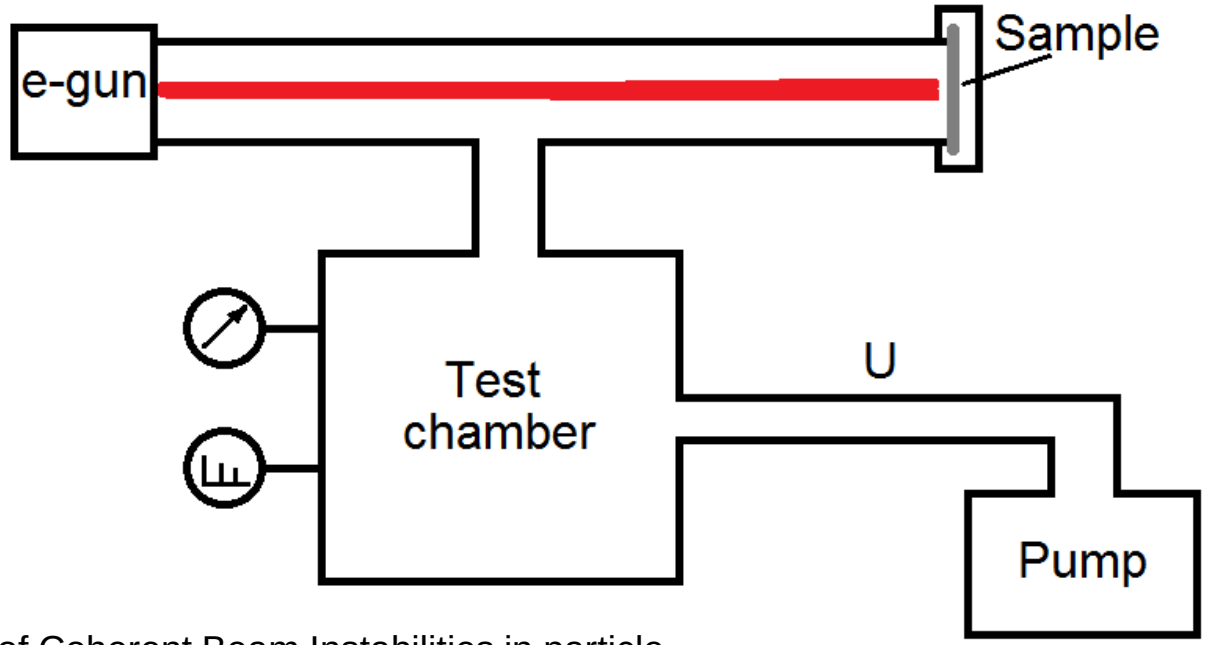


LASE: Electron Stimulated Desorption (ESD)

Samples were tested after a bakeout to 200°C for 24 h:

- 316LN stainless steel flanges DN40:
  - LASE treated in: 30 W, 600 KHz, 0.1 ns, 40 mm/s , 10 µm
  - Untreated
- Cu blank gaskets ∅48 mm:
  - LASE-1 treated in: 20 W, 60 KHz, 2 ns, 40 mm/s , 10 µm
  - LASE-2 treated in: 30 W, 40 KHz, 2 ns, 40 mm/s , 10 µm
  - Untreated (2 samples)
- E_{e-} = 500 eV

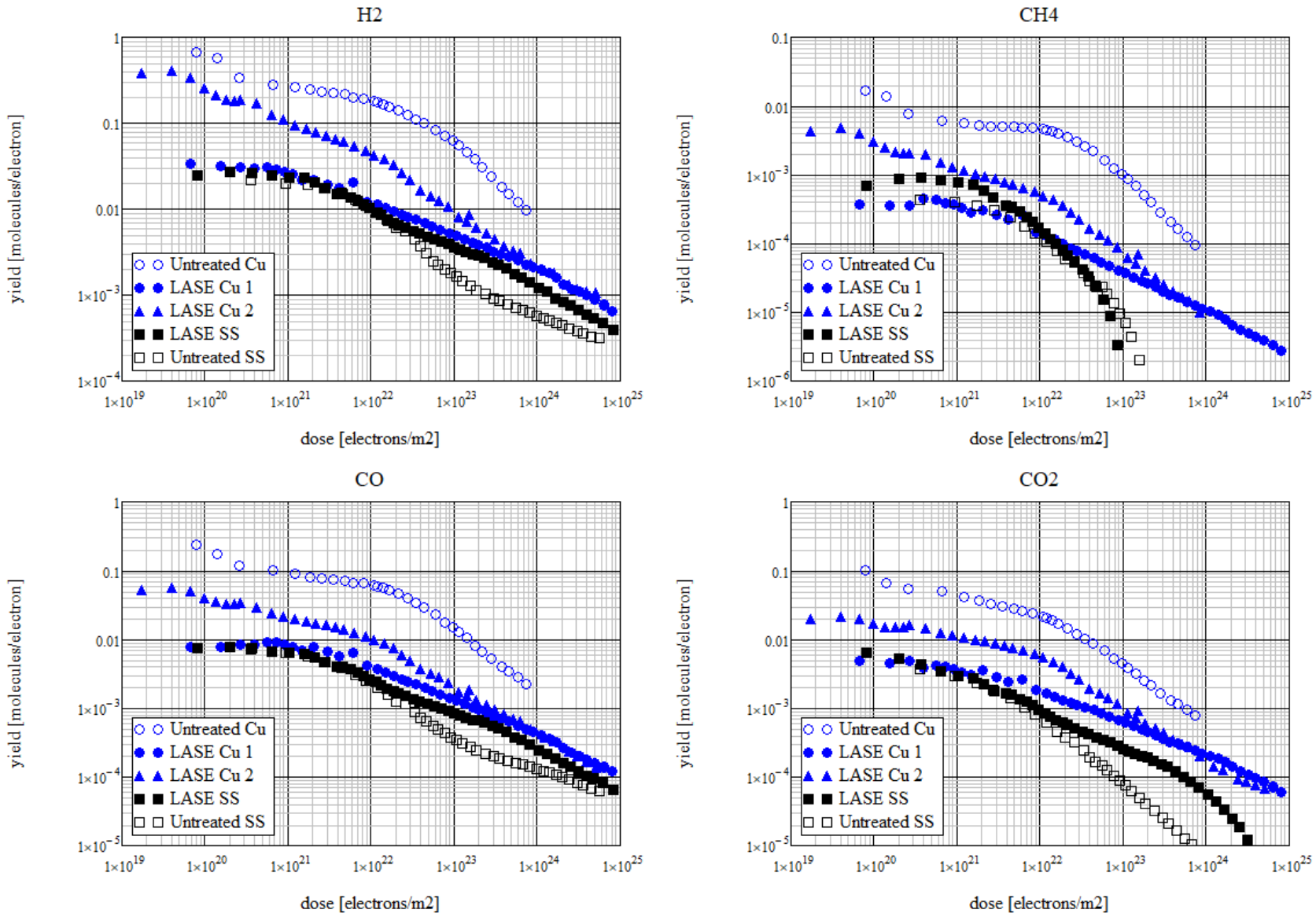




Electron Stimulated Desorption (ESD) from LASE

Main results:

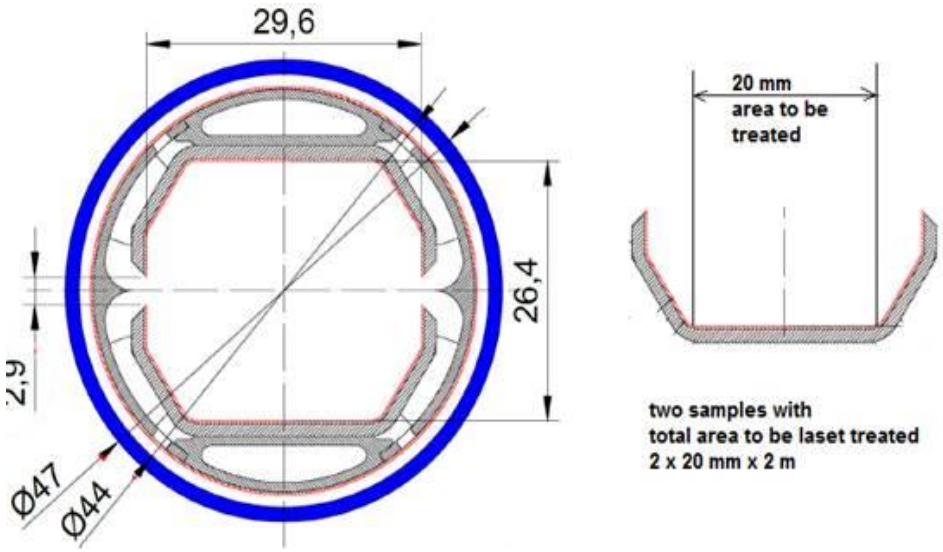
- Copper sample with LASE demonstrated lower ESD yields than untreated sample
- ESD for 316LN stainless steel with LASE is comparable with an untreated sample.

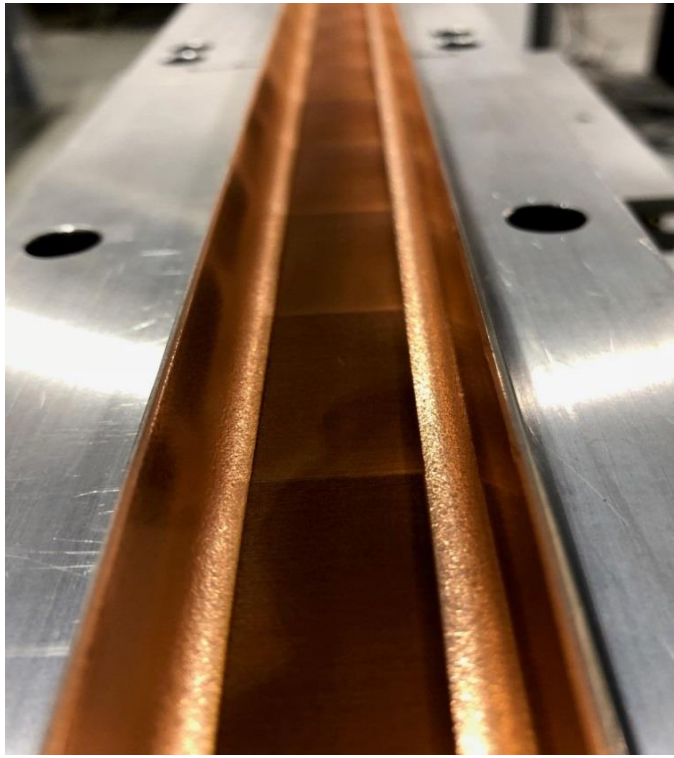


Photon Stimulated Desorption (PSD)

PSD experiment in KARA as a part of EuroCirCol WP4:

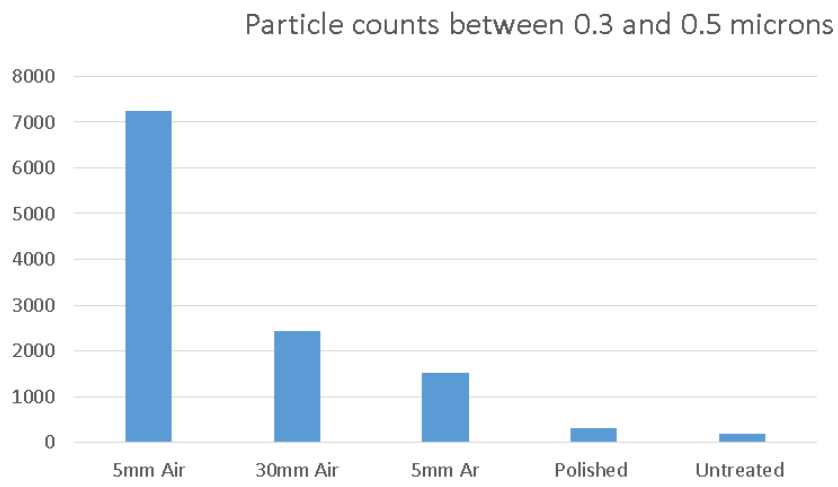
- 2 m long porotype of the FCC-hh vacuum chamber
- a tube in two halves, treated area of each half is 2 m x 20 mm.
- Laser 1064 nm.
- PSD measurements at room temperature

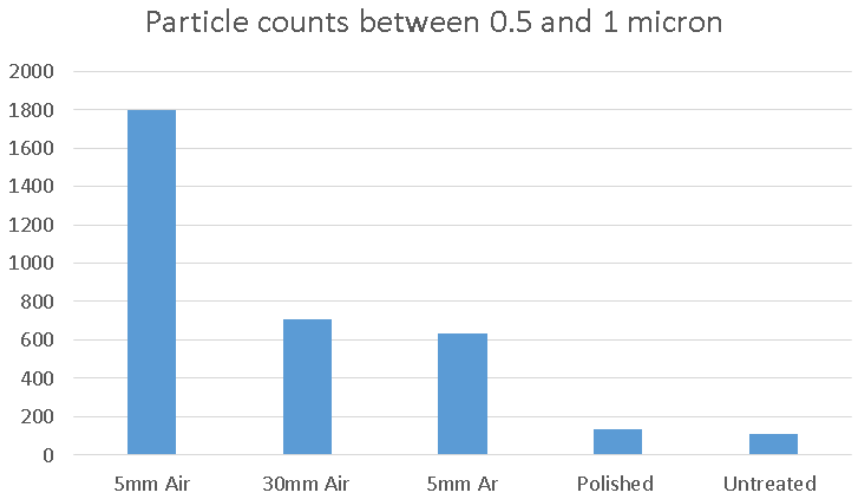




Microparticles

- Particle counts
  - Measurements taken with 0.5 bar of filtered N_2 onto a sample 50 mm away from the sample
  - The measurements taken for 1 min, the counts were averaged over 3 measurements
  - The detector could measure particles up to 25 microns
  - Largest particle size measured was 1 micron
  - Polished and untreated samples were used as reference





➢ Clear specification required on tolerable number and size of microparticles (per 1 m of beam pipe)

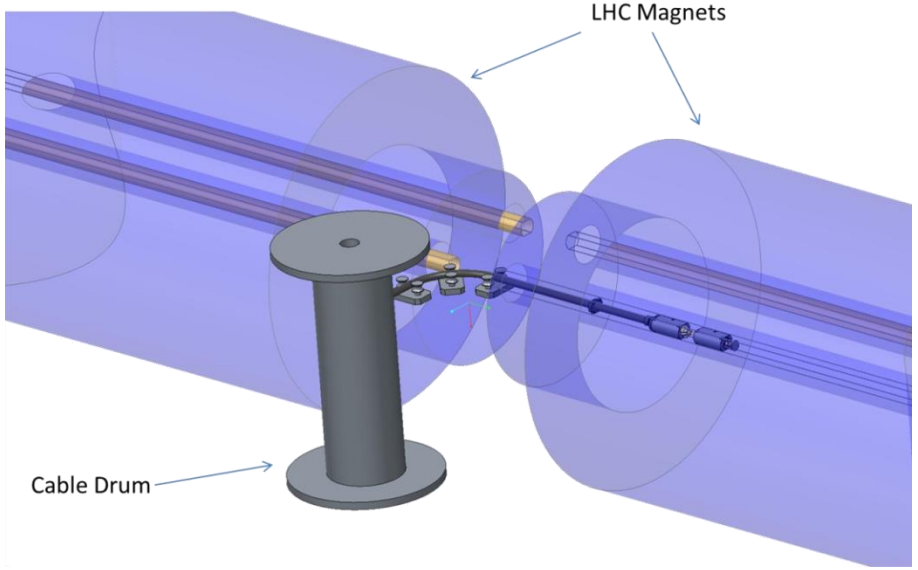
Summary: Impact of LASE e-cloud mitigation on other systems

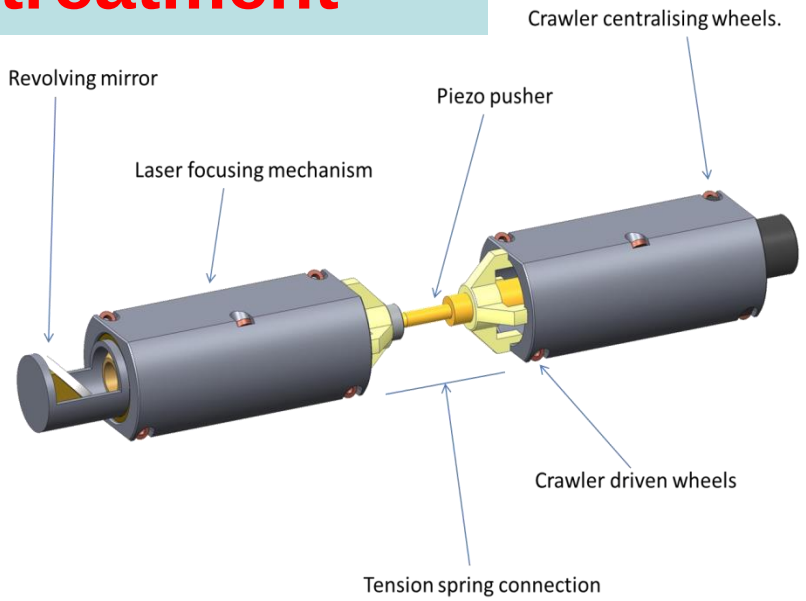
	LASE
SEY	$\delta_{max} < 0.6$
PEY	PEY? (scaled with SEY?) (R. Cimino's team - INFN)
Vacuum	
Thermal outgassing	Low
PSD	To be studied (KARA experiment)
ESD	Much lower than for untreated Cu, comparable to untreated stainless steel
Bakeout/activation temperature	Can be baked to 150 – 300 °C
Cryogenic vacuum system	Ongoing studies in INFN (R. Cimino's team) Ongoing studies in ASTeC
Beam wakefield impedance	No visible difference from Cu at 8 GHz Low R_s LASE surface development in ASTeC
UFO	Particulate generation measurements and control (LASE parameters, gas flow, cleaning, etc.)

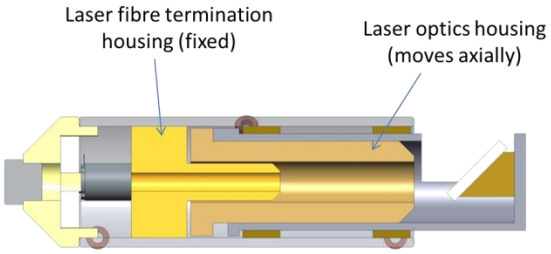
Advantages over other passive mitigation methods

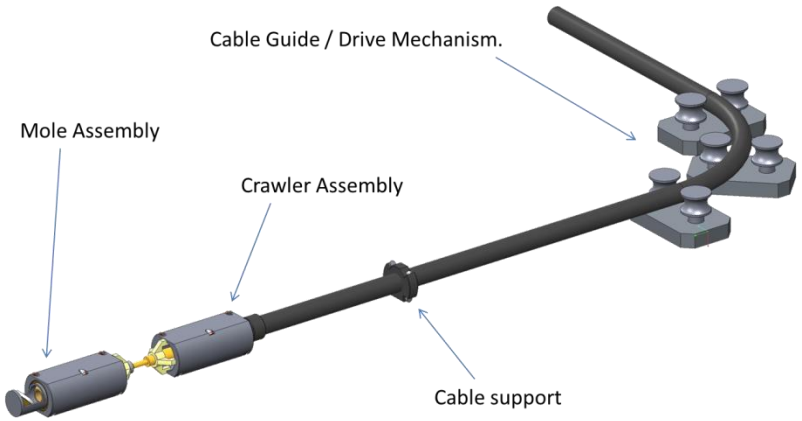
- There is no need for vacuum or clean room facilities
  - Reduced cost
- The laser is capable of fabricating the desired micro/nanostructure in a single step process.
  - Processing time
- Surface engineering is performed through a beam of light and, thus, contactless
  - No contamination from the tools or the process materials
- The process is applicable to the surfaces of any 3D object
  - i.e. inner walls of vacuum chambers
- It is possible to lase in many different environments, such as gases, liquids, or in a vacuum
  - i.e. controlling surface composition (oxides, nitrides, carbonises…) and surface formation

Technology for in-situ LASE treatment

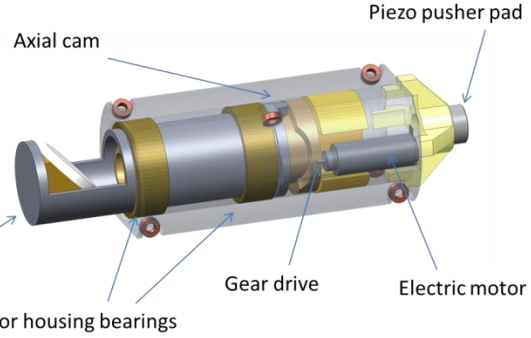








The mirror optics housing moves axially as the mirror rotates to maintain laser focus on the flat sections of beam pipe.



Conclusions

- There is a large number of LASE treatment parameters
  - Some of them lead to reducing down to $\delta < 0.6$
  - Some of above has no impact (or small increase in) the RF surface resistance at 8 GHz
    - δ_{max} and R_s specifications (tolerable level) required
  - No vacuum problems at room temperature
    - Cryogenic studies are ongoing
- The LASE technique can be applied to existing vacuum surfaces where the improvement has to be done *in-situ* with minimum disturbance to the beam line.
- **LASE can be done** in air (or selected gas) at atmospheric pressure; therefore the actual cost of the mitigation is considerably lower, a fraction of the existing mitigation processes.
- The process is also readily scalable to large areas.

Collaboration Team

- Dr Oleg Malyshev
- Dr Reza Valizadeh
- Adrian Hannah
- James Conlon
- Taaj Sian
- Patrick Krkotic
- Prof M. Pont
- Dr Phillippe Goudket
- Dr J.M O'Callaghan
- Jennifer Much

- Neil Sykes (Micronanics)
- Dr Walter Perrie (Liverpool)
- Dr Mike Cropper (Loughborough)
- Dr David Whitehead (Manchester)
- Dr Jonthan Smith (Tech X)
- Dr Paul Apte (Rideo)