INFN LNF

Brookhaven National Laboratory

Electron Cloud Mitigation Strategies for the EIC: INFN’s Research on Coated Surfaces

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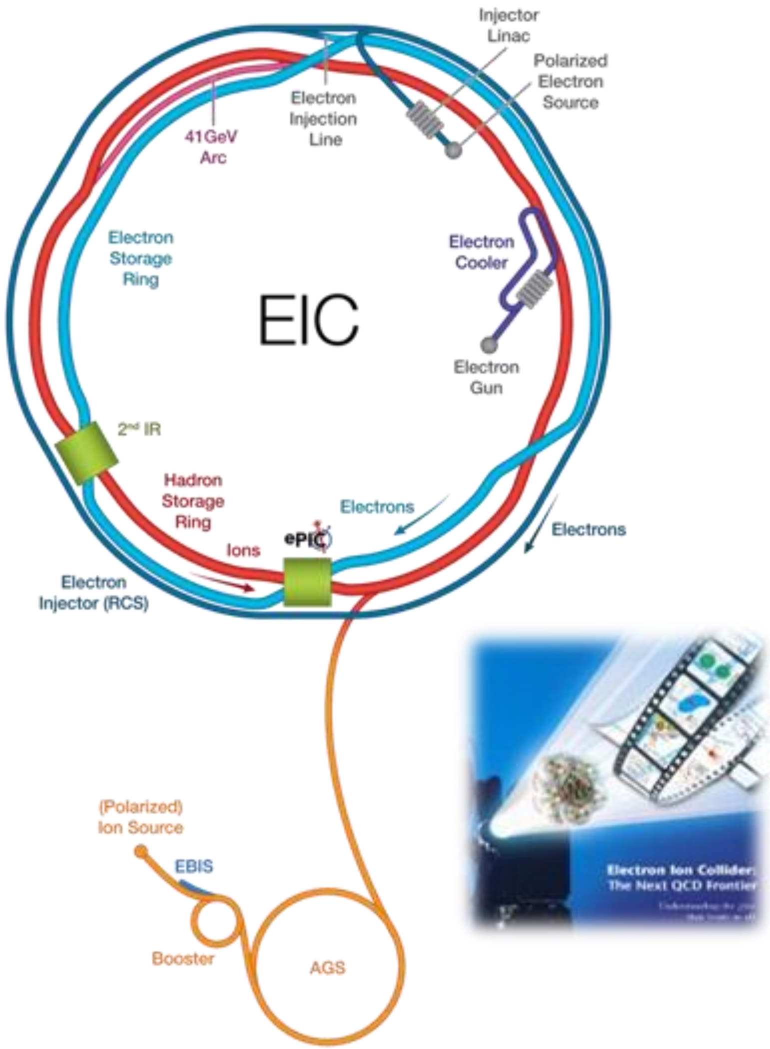
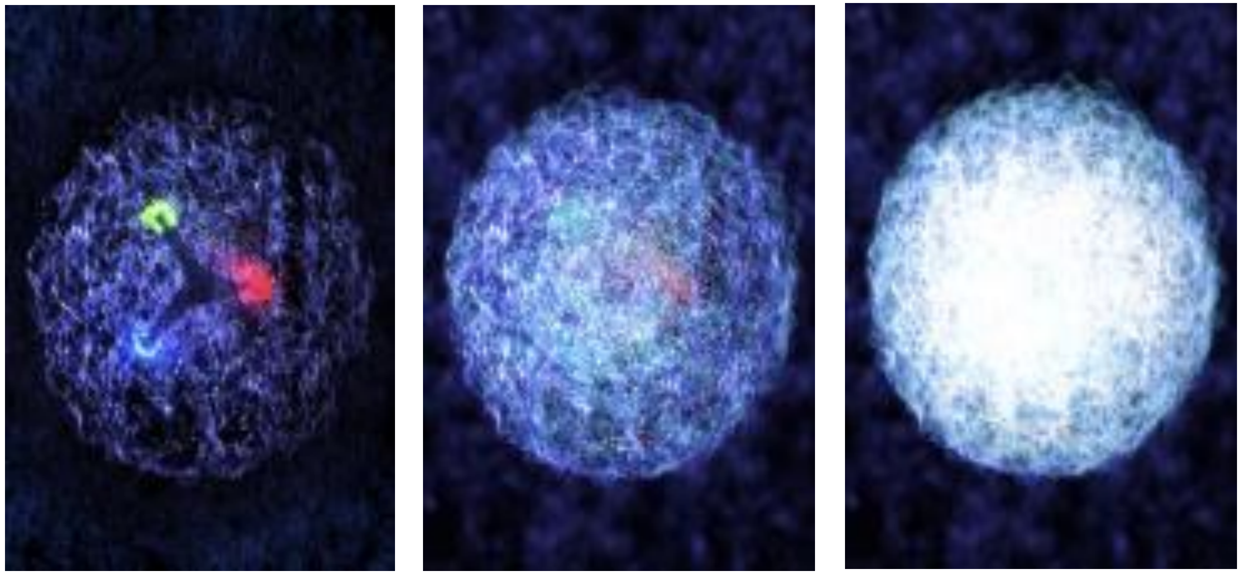
Giornate Nazionali ePIC Italia
Padova June 18th, 2025

EIC = Decades of Discovery Potential



Polarized electrons colliding with polarized protons, polarized light ions, and heavy ions will allow to study sea-quarks and gluons to understand:

- Mass and spin of the proton
- Spatial and momentum distribution
- Possible gluon saturation
- Hadron formation



EIC – CDR 2021

EIC Requirements

- High Luminosity: L= $10^{33} – 10^{34}$ cm^{-2} sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
- Large Ion Species Range: Protons – Uranium
- Large Detector Acceptance
- Accommodate a Second Interaction Region (IR)

EIC – CDR 2021

Table 1.1: Maximum luminosity parameters.

Parameter	hadron	electron
Center-of-mass energy [GeV]	104.9	
Energy [GeV]	275	10
Number of bunches	1160	
Particles per bunch [10^{10}]	6.9	17.2
Beam current [A]	1.0	2.5
Horizontal emittance [nm]	11.3	20.0
Vertical emittance [nm]	1.0	1.3
Horizontal β-function at IP β^*_x [cm]	80	45
Vertical β-function at IP β^*_y [cm]	7.2	5.6
Horizontal/Vertical fractional betatron tunes	0.228/0.210	0.08/0.06
Horizontal divergence at IP $\sigma^*_{x'}$ [mrad]	0.119	0.211
Vertical divergence at IP $\sigma^*_{y'}$ [mrad]	0.119	0.152
Horizontal beam-beam parameter ξ_x	0.012	0.072
Vertical beam-beam parameter ξ_y	0.012	0.1
IBS growth time longitudinal/horizontal [hr]	2.9/2.0	-
Synchrotron radiation power [MW]	-	9.0
Bunch length [cm]	6	0.7
Hourglass and crab reduction factor [17]	0.94	
Luminosity [10^{34} cm^{-2} s^{-1}]	1.0	

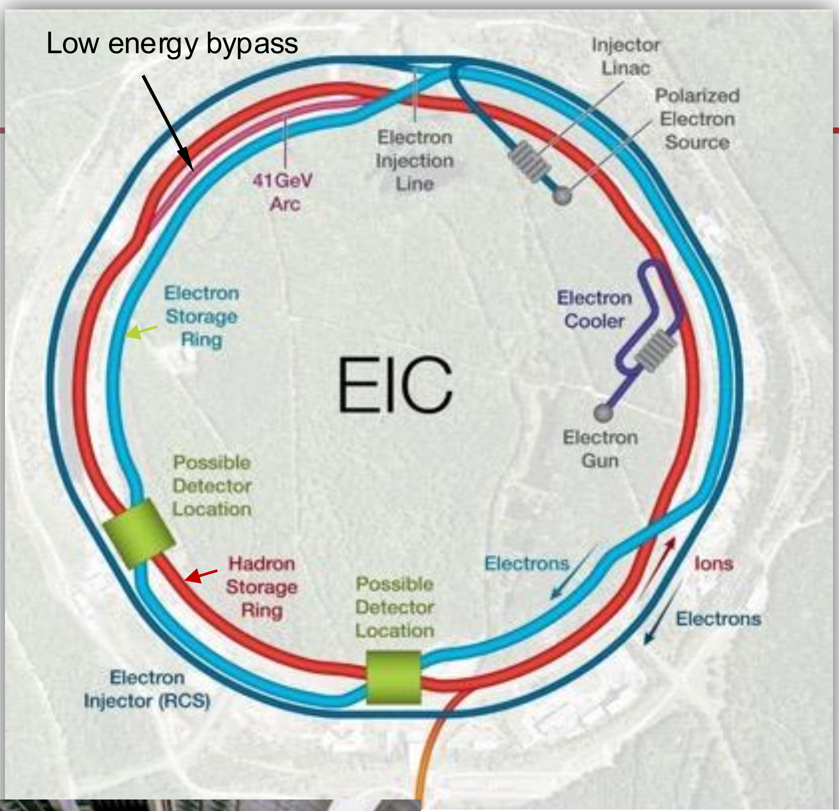
Facility Overview

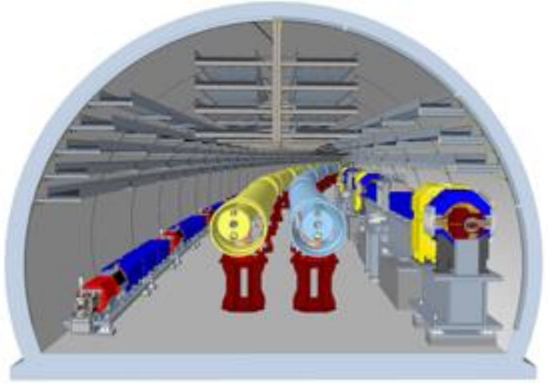
UPGRADE

- **Most existing RHIC infrastructure to be reused but…**
  - Additional 142,000 ft^2 in support buildings
  - New substations (65MW) and overhead 13.8kV power line
- **Upgrade RHIC** -> Hadron Storage Ring (HSR)
  - Major modification to vacuum system
  - Low energy bypass for synchronization with electrons
- **Strong hadron cooling to control emittance growth**

NEW

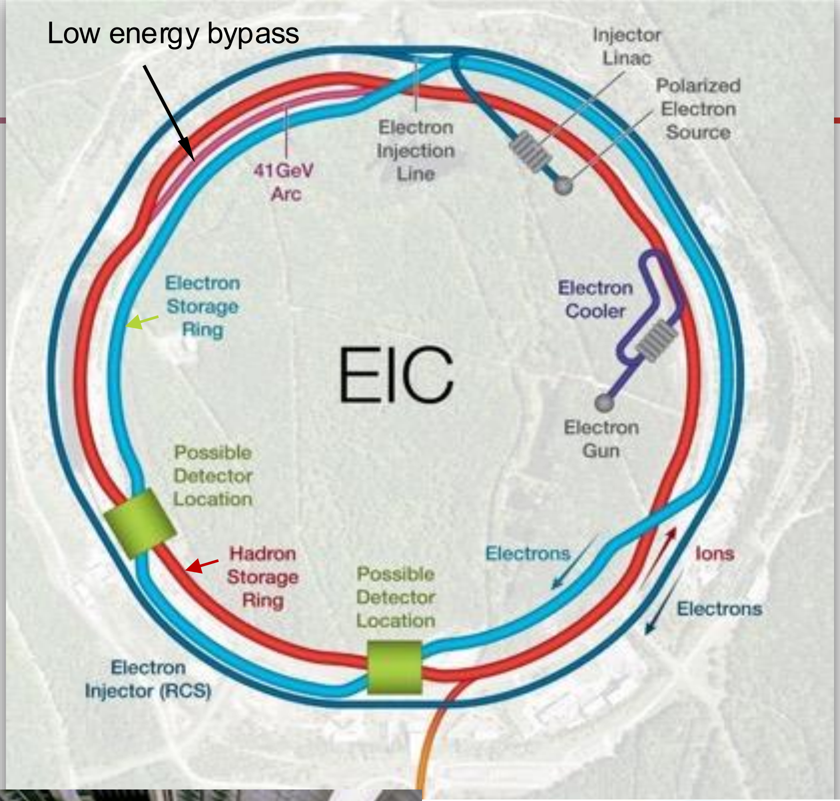
- **New electron accelerator system**
  - Polarized electron source
  - 400 MeV LINAC
  - Rapid Cycling Synchrotron - RCS (400MeV -> 18GeV)
  - Electron Storage Ring – ESR (up to 2.5A)
- **New central detector**
  - High luminosity ($10^{34}/cm^2/s$)
  - 25mrad crossing angle with crab cavities

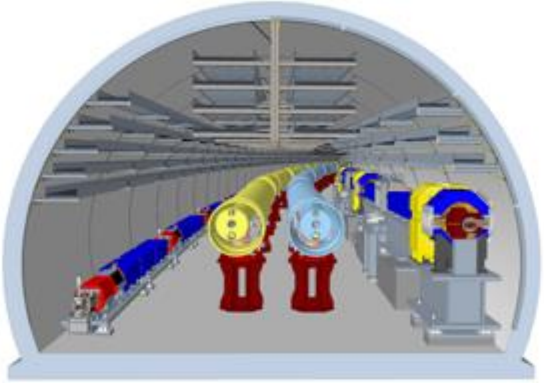




Existing Vacuum System

- Two existing <u>super conducting rings</u>
  - Warm sections between arcs
- A total of **8 arcs** from RHIC will be reused
- Arc length ~480m
  - Seven arcs require beam screens
- Each arc consists of ~72 magnets
  - **>500 beam screens** (72 magnets x 7 arc)
- Majority of arcs are dipoles and CQS (67%)
  - 30 dipoles
  - 35 CQS (Corrector, quad, sext)



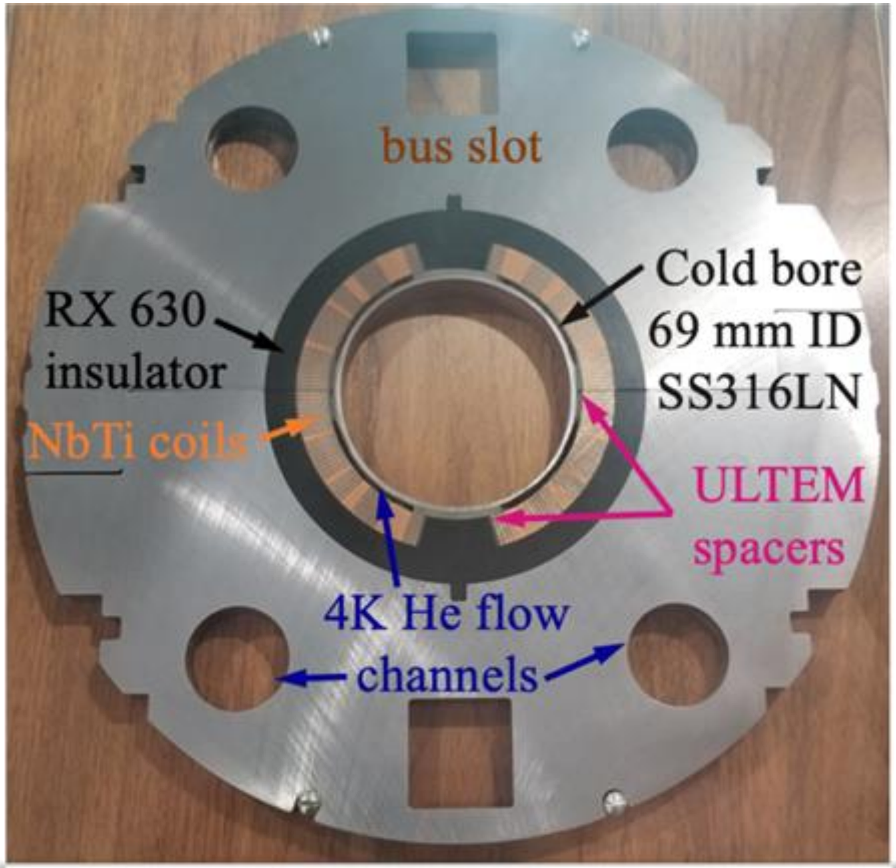


Challenges

- Aggressive new parameters required for EIC
  - High stored current (0.72 A vs 0.27 A)
  - Reduced bunch length (60 cm vs 600 cm)
  - Short bunch spacing (10 ns vs 108 ns)
  - High bunch charge (1.2×10^{11} ppb)

- Existing cold bore beam pipes are stainless steel
  - High surface resistance → **Excessive resistive wall heating**
  - High secondary electron yield (SEY) → **Electron cloud formation**

- Electron cloud formation can lead to:
  - heat load;
  - vacuum degradation;
  - beam instabilities;
  - emittance growth;
  - etc.



RHIC arc dipole cross section

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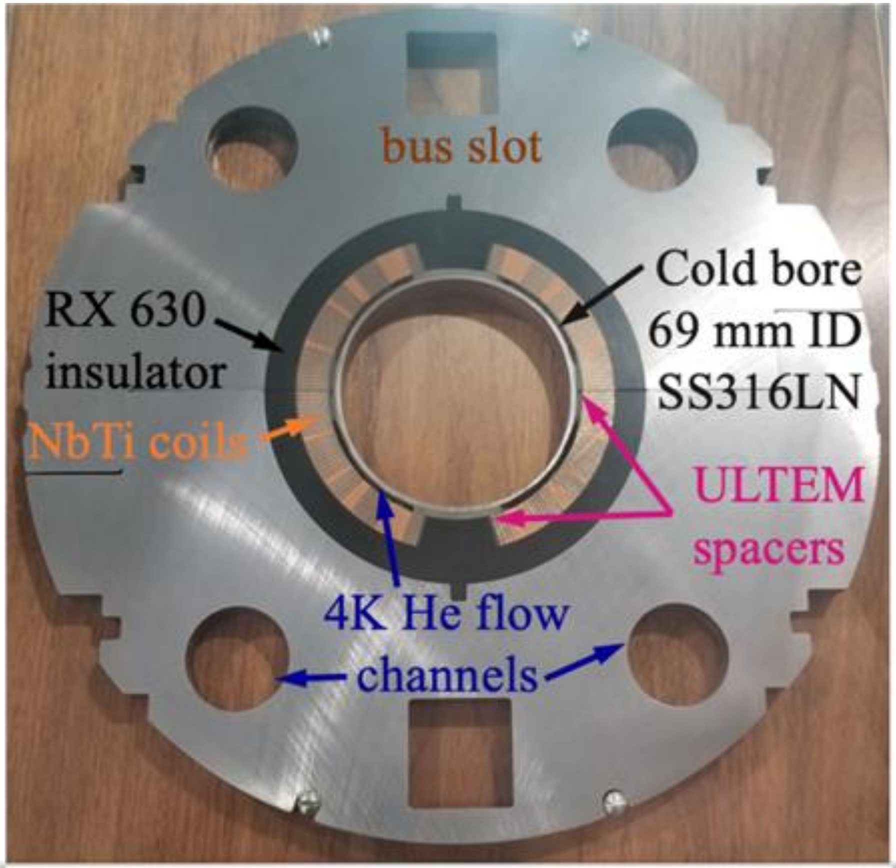
→ *e-cloud* mitigation is crucial



RHIC arc dipole cross section

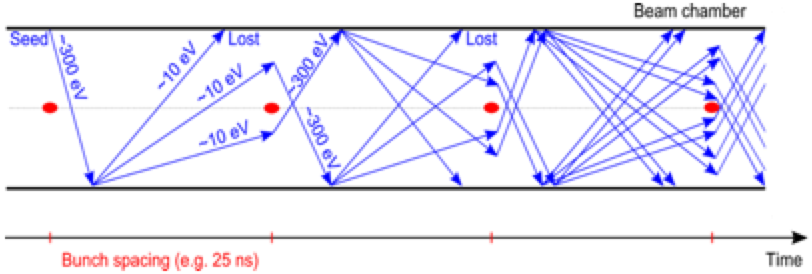
e-cloud

Residual Gas ionization

Phoelectrons from synchrotron radiation

Desorption from losses on the wall

Generation of electrons inside vacuum chamber



1. Interaction of primary electrons with the beam
2. Acceleration of primary electrons
3. Production of Secondary electrons when hit the wall

Electrons multiplication

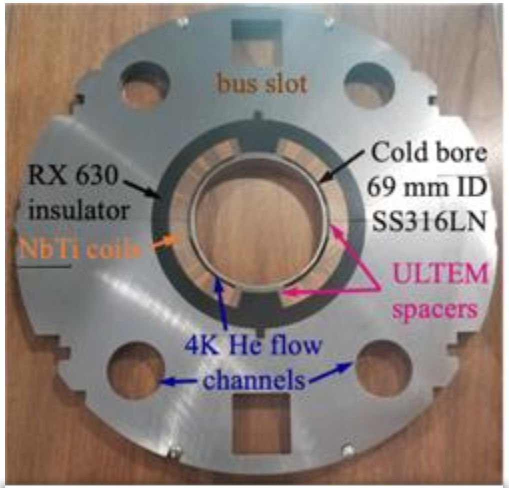
Electron Cloud

R. Cimino, T. Demma; Electron cloud in accelerators
International Journal of Modern Physics A Vol. 29, No. 17 (2014) 1430023

HSR Beam Screen

- In the non-cryogenic (warm) sections, the electron cloud can be mitigated by using non-evaporable getter (NEG) coating.

- To avoid high RW heating and electron cloud, a <u>beam screen</u> (BS) will be installed in the beampipe of the RHIC superconducting magnets.



RHIC arc dipole cross section

EIC HSR beam screen

<u>must ensure</u>:

- Adequate Vacuum level and stability.

- Low impedance to limit dynamic heat load and to avoid impedance-driven instabilities.

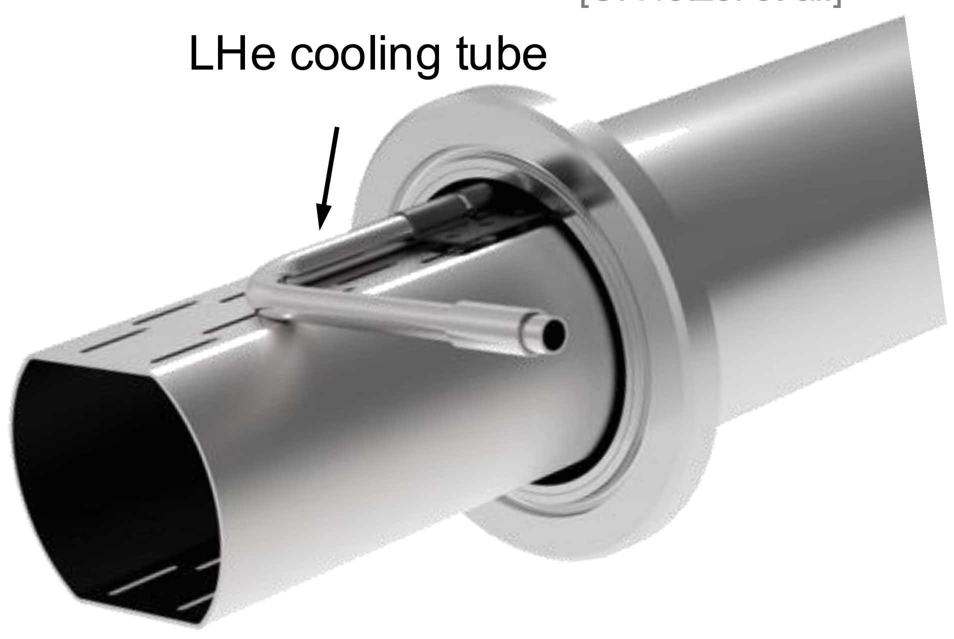
- The control of e-cloud build up.

HSR Beam Screen

EIC HSR beam screen

will be made of:

- Non-magnetic 316LN stainless steel.
- Oxygen-free high-conductivity (OFHC) copper.
- Low Secondary Electron Yield coating.



HSR Beam Screen

EIC HSR beam screen

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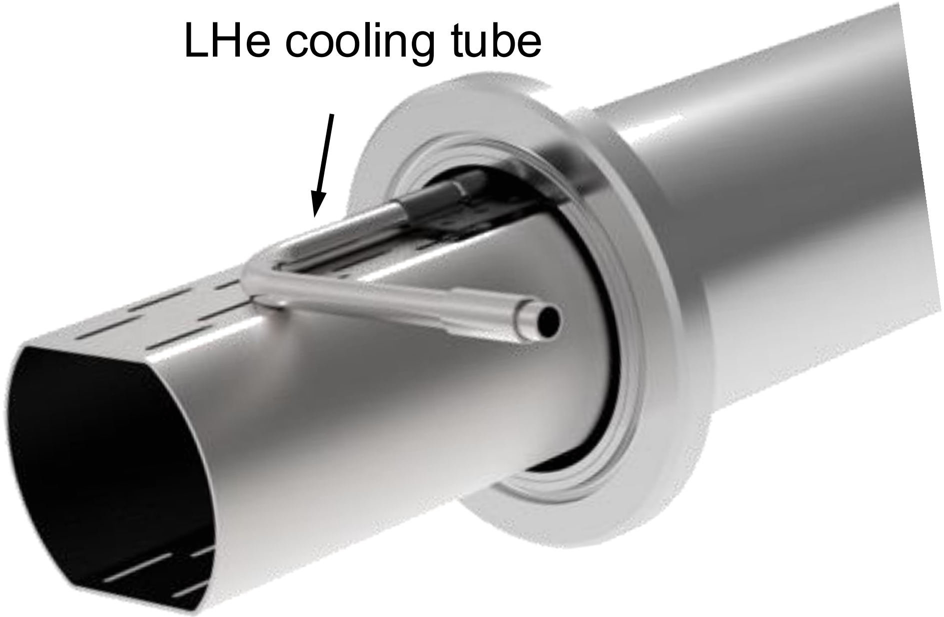
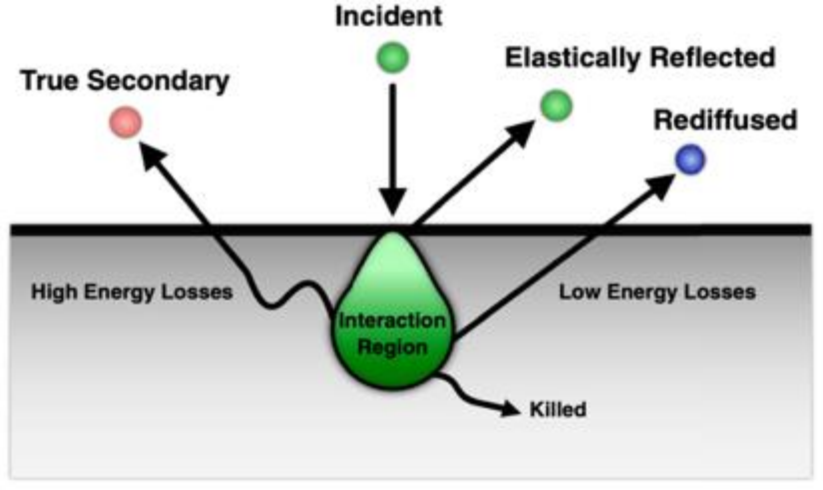
- Non-magnetic 316LN stainless steel.
- Oxygen-free high-conductivity (OFHC) copper.
- Low Secondary Electron Yield coating. (SEY < 1.1)

[C. Hetzel et al.]



Secondary Electron Yield of Materials

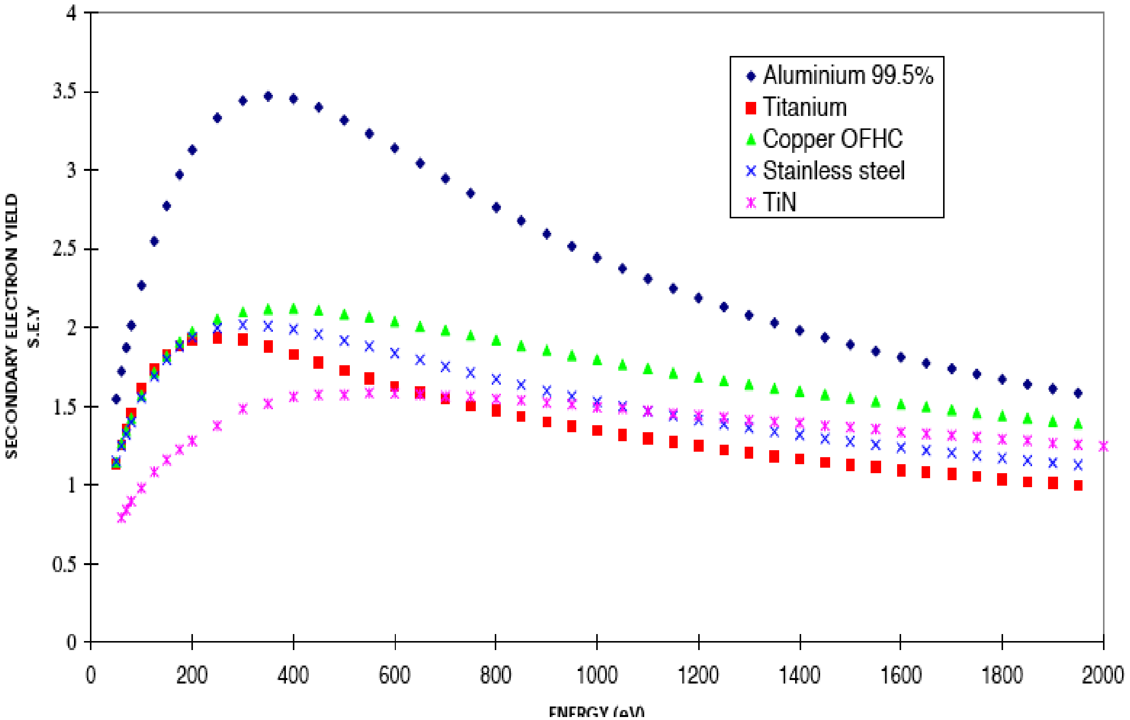
Secondary Electron Emission



Three-step process:

- **Production of SE at a depth *z***
- **Transport of the SE toward the surface**
- **Emission of SE across the surface barrier**

$$SEY = \frac{I_{out}}{I_{in}}$$

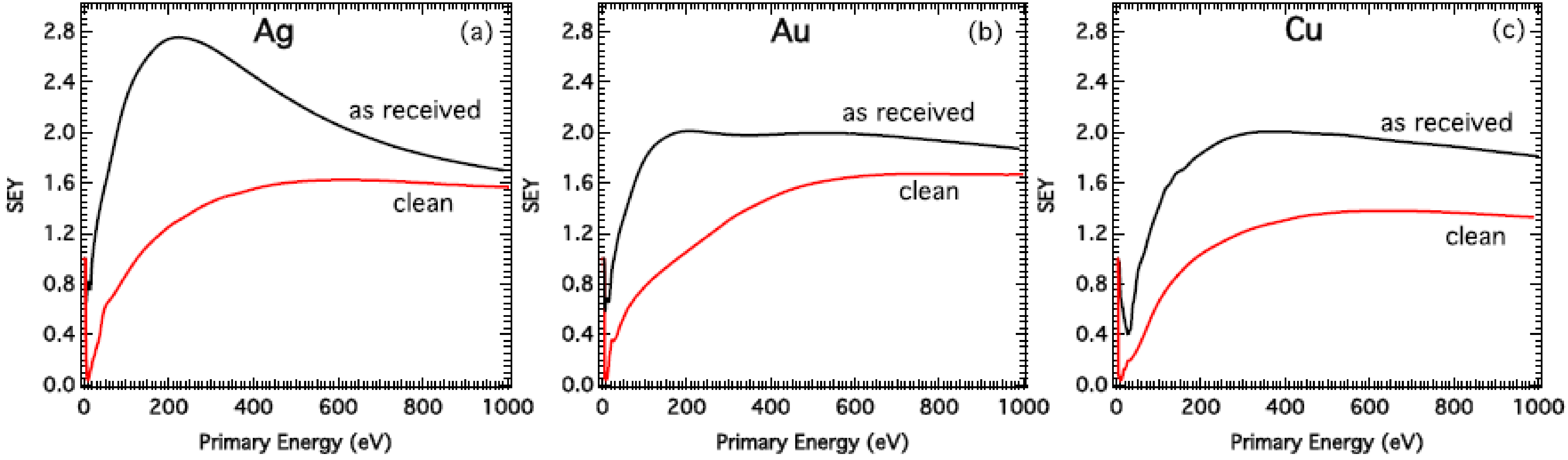


Intrinsic property of materials, strongly dependent on the surface characteristics:

- chemistry
- adsorbates, even at sub-monolayer coverage
- morphology

SEY of Materials

L. A. Gonzalez et al., AIP Adv. (2017)

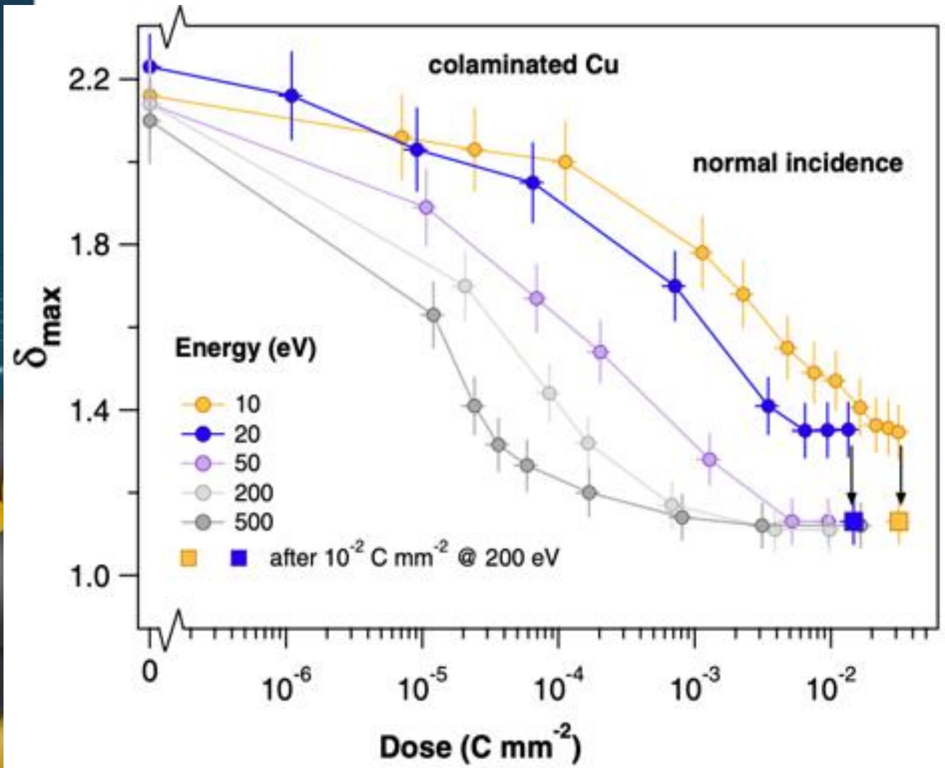


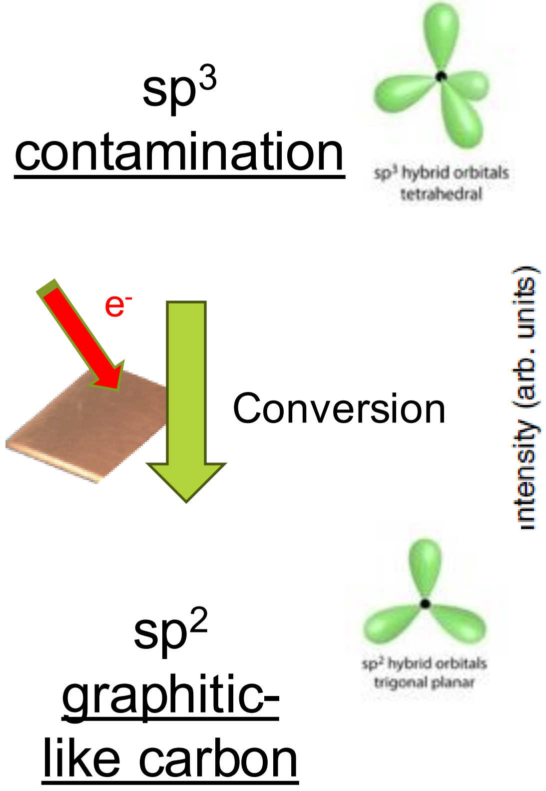
- **<u>Chemisorbed</u> compounds modify the chemical bonds at the metal surface**

SEY variation induced by surface modifications

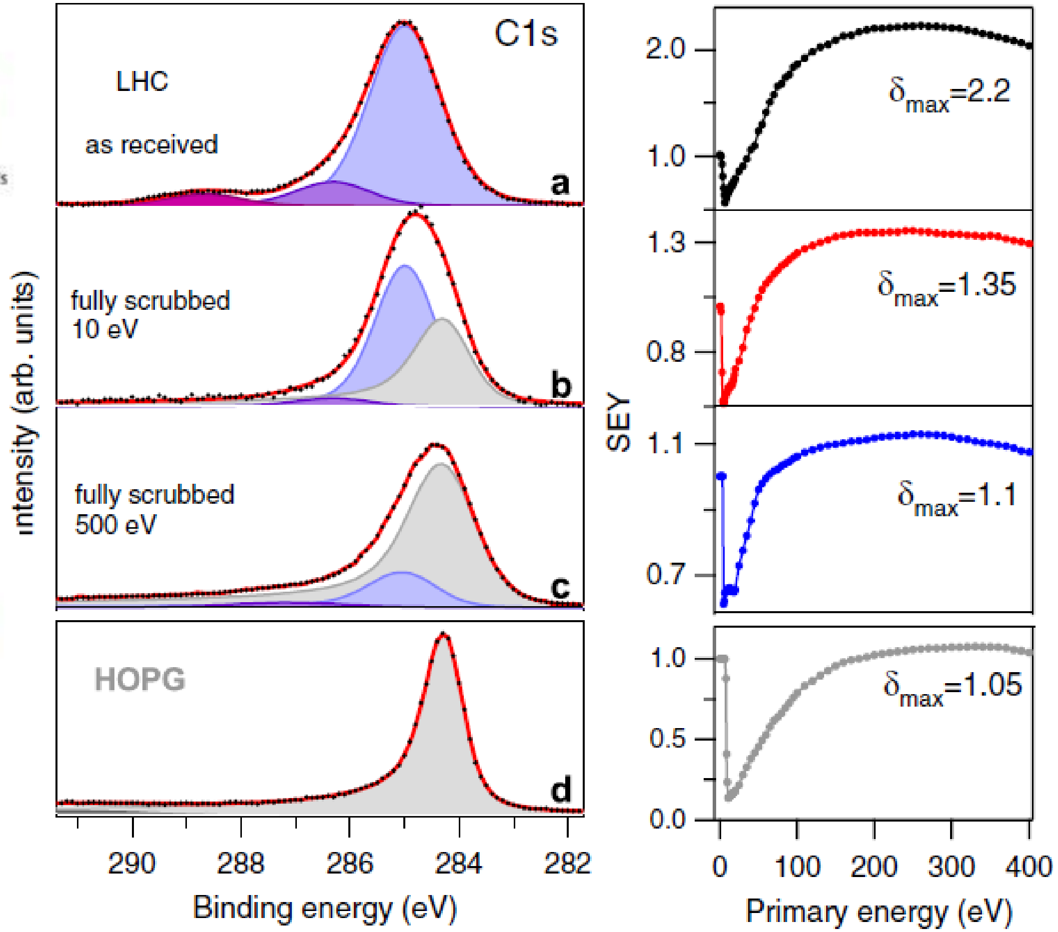
Chemical variation induced by electron irradiation

- **SEY depends on the surface chemical state**





Copper

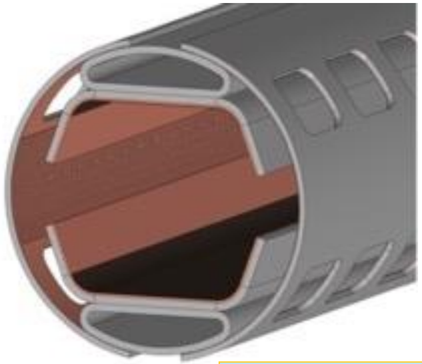


R. Cimino et al., Phys. Rev. Lett. (2012)

Low SEY mitigation Strategies

Surface Treatments

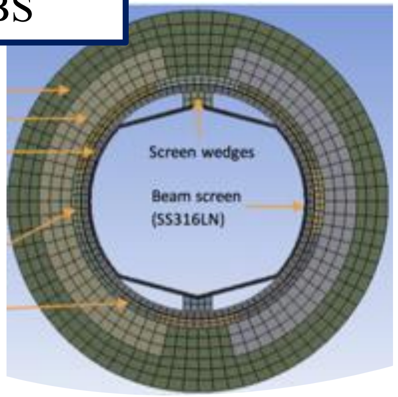
FCC-hh BS



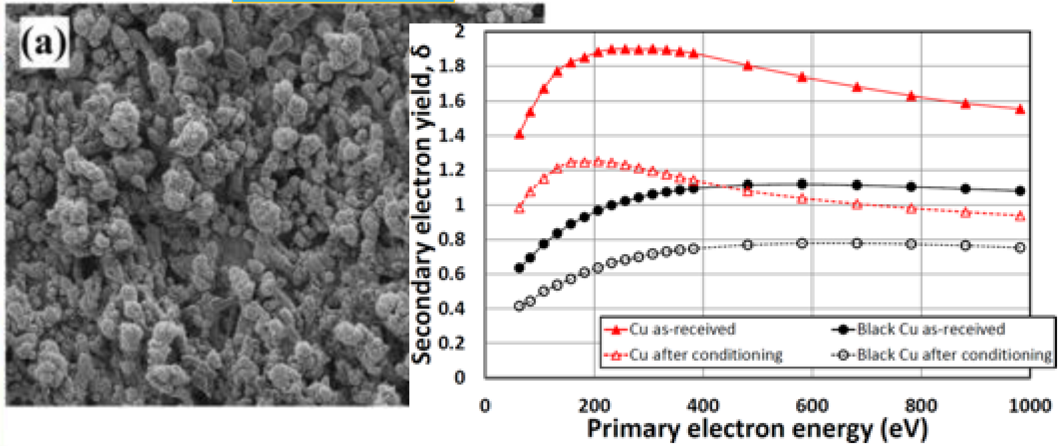
Morphology

Coatings

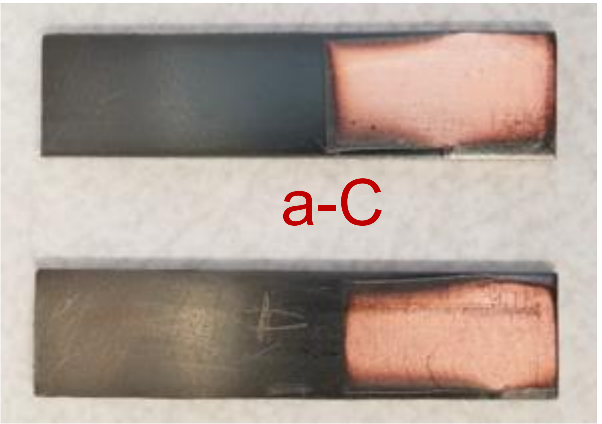
EIC BS

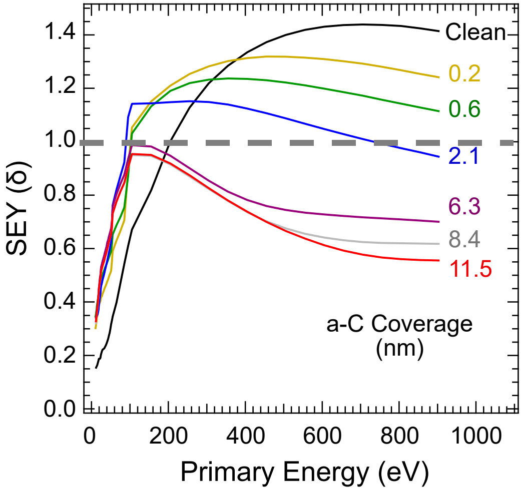


LASE-Cu



R. Valizadeh et al. , Appl. Surf. Sci. (2017)



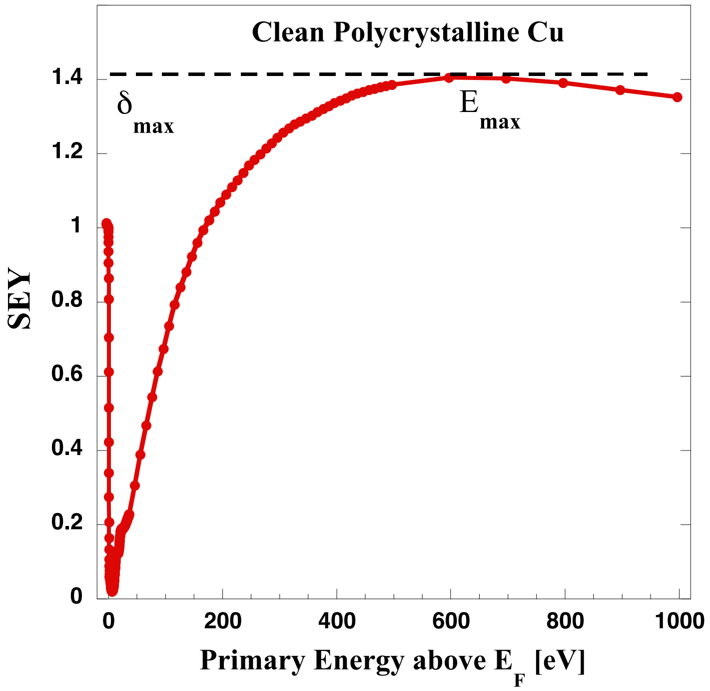


M. Angelucci et. al; Phys. Rev. Research Rapid comm. 2, 032030(R) (2020)

SEY variation induced by surface modifications

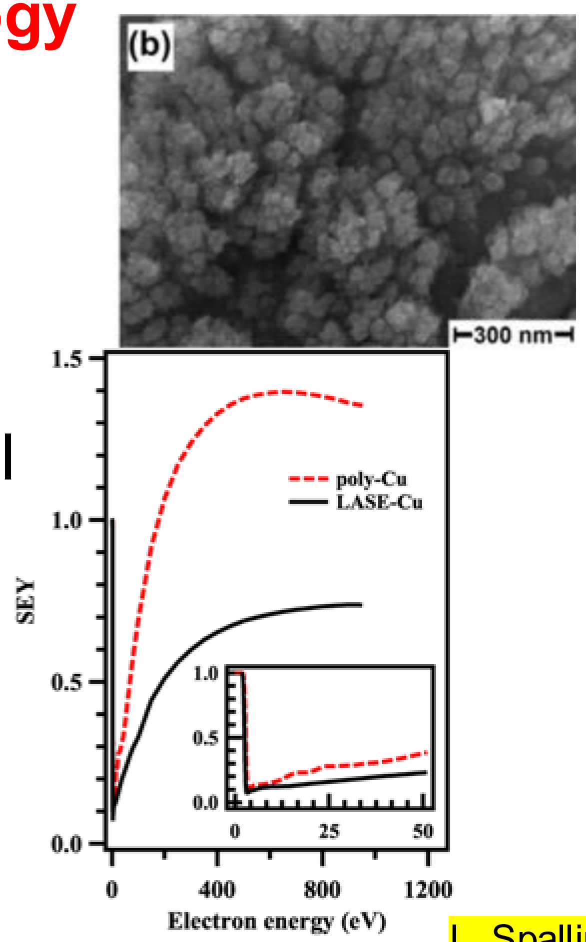
Morphology

Engineering the surface morphology



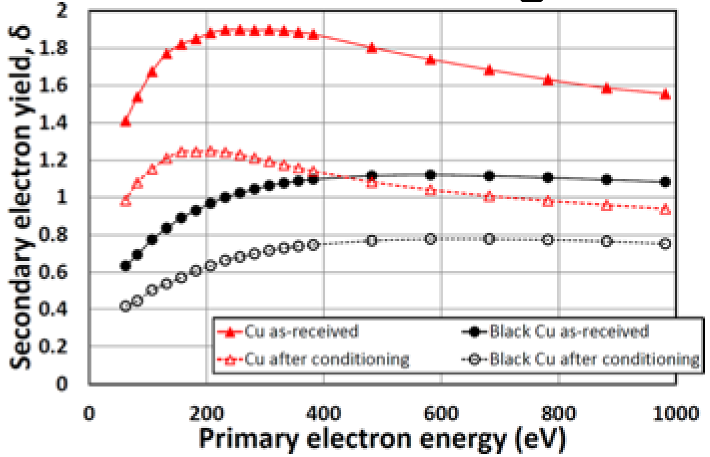
R. Cimino et al. PR ST (2015)

Morphological Changes



L. Spallino, J. Vac. Sci. Technol. B (2020)

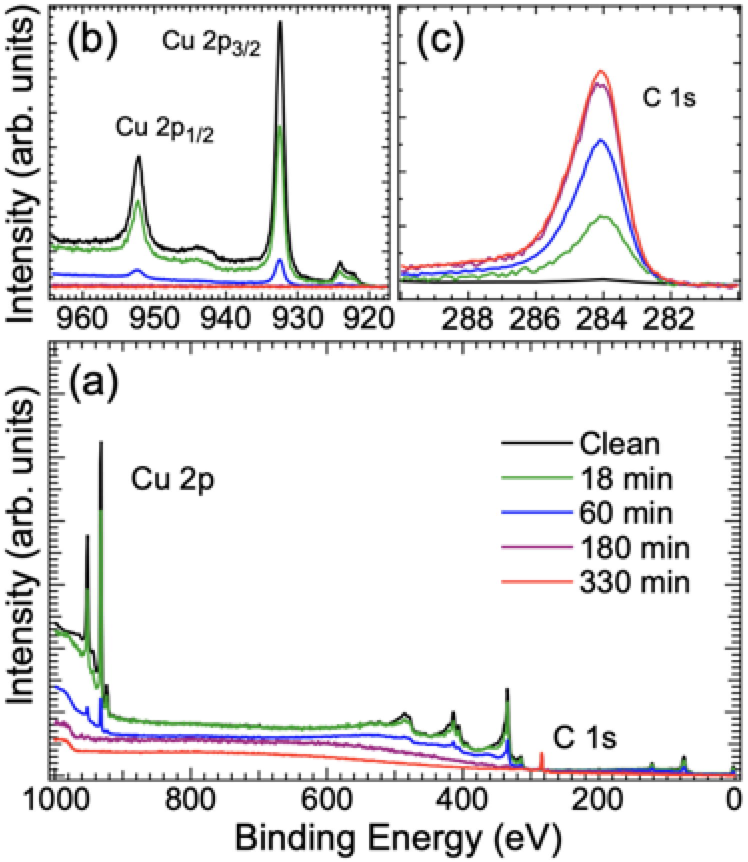
Laser ablation and conditioning



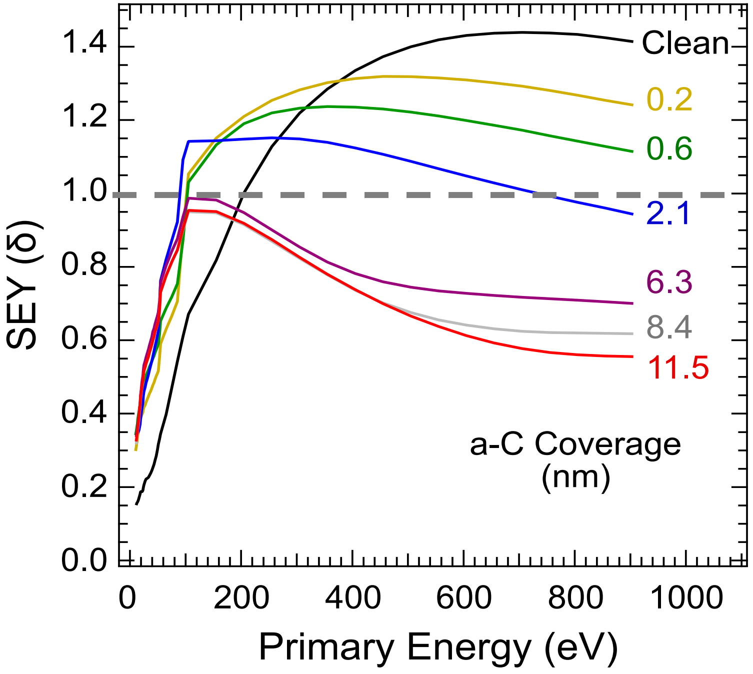
R. Valizadeh et al. , Appl. Phys. Lett. (2014)

SEY variation induced by surface modifications

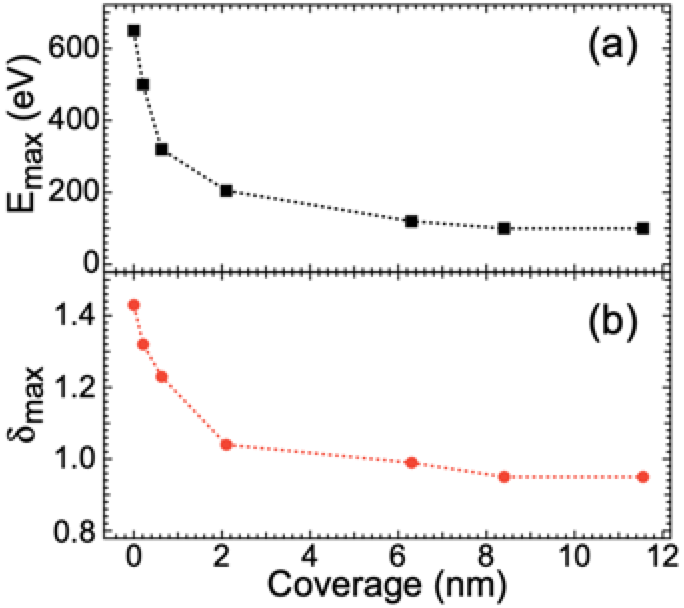
Coatings



M. Angelucci et al., Phys. Rev. Res. (Rapid Comm.) (2021)



- **SEY depends on the coverage thickness, even at sub-monolayer coverage**

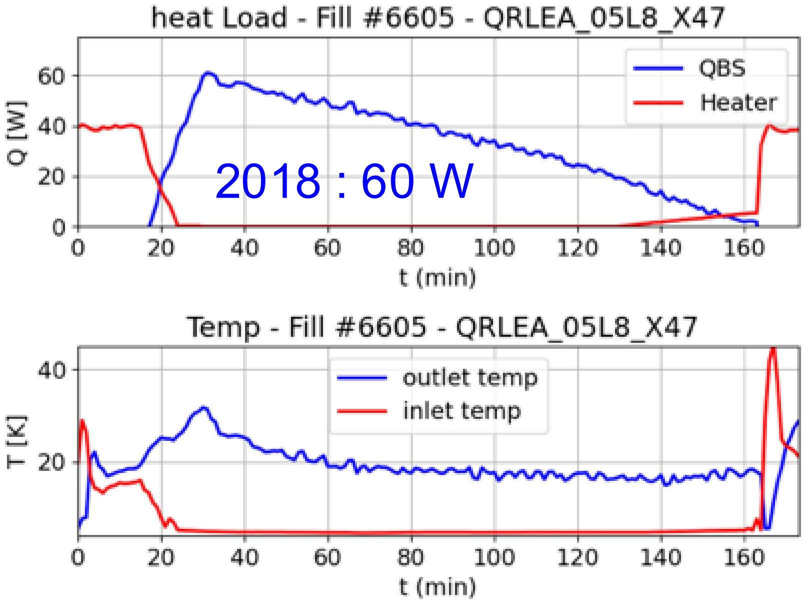


Consequences of this observation are relevant to determine the minimal layer thickness that defines the SEY of the system

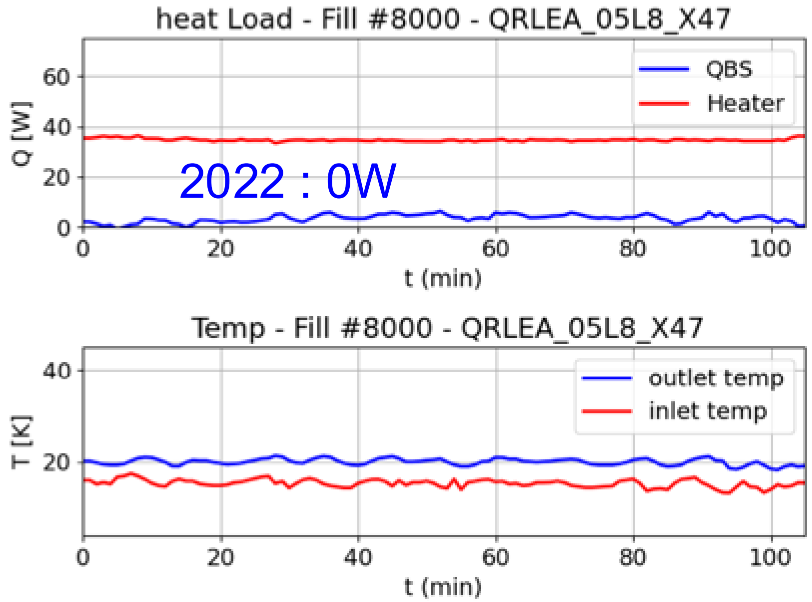
Validation at CERN of a-C coatings

Courtesy of
B. Bradu (CERN)

- One quadrupole was coated with amorphous carbon during 2020: Q5L8
- About 60 W was observed during scrubbing in 2018 in this magnet
- No heat load observation in 2022 *(sync . rad. + image cur < 2 W, not observable)*



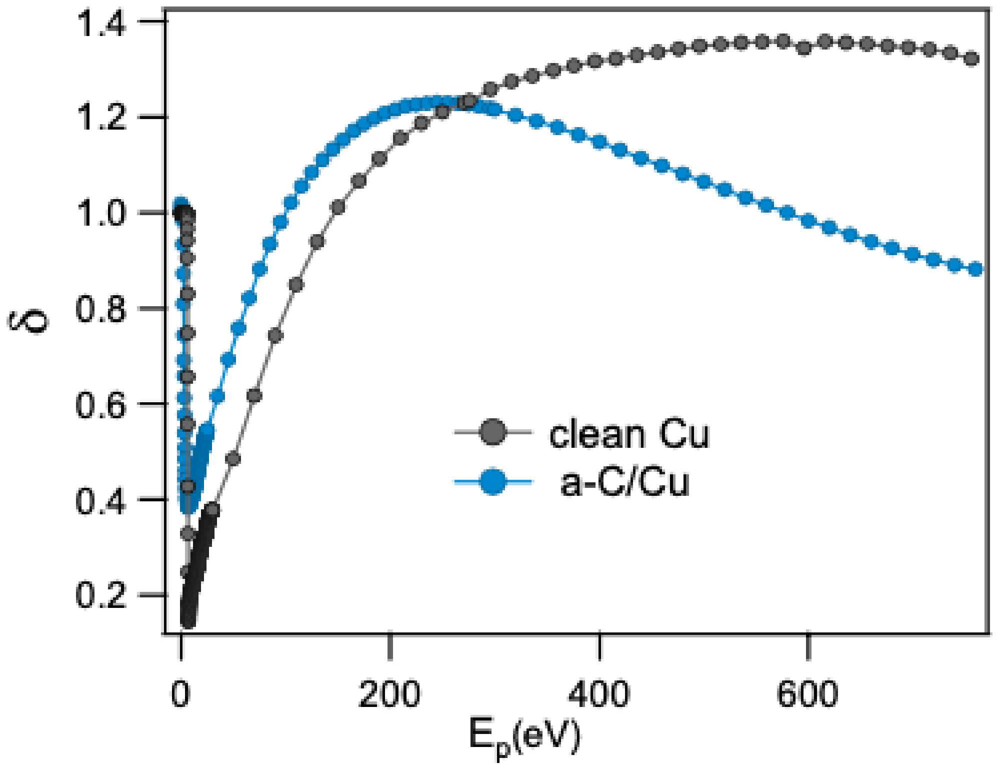
After coating



➔ e-cloud heat loads have been removed after a-C coating as expected ☺

SEY variation induced by surface modifications

Modification of surface



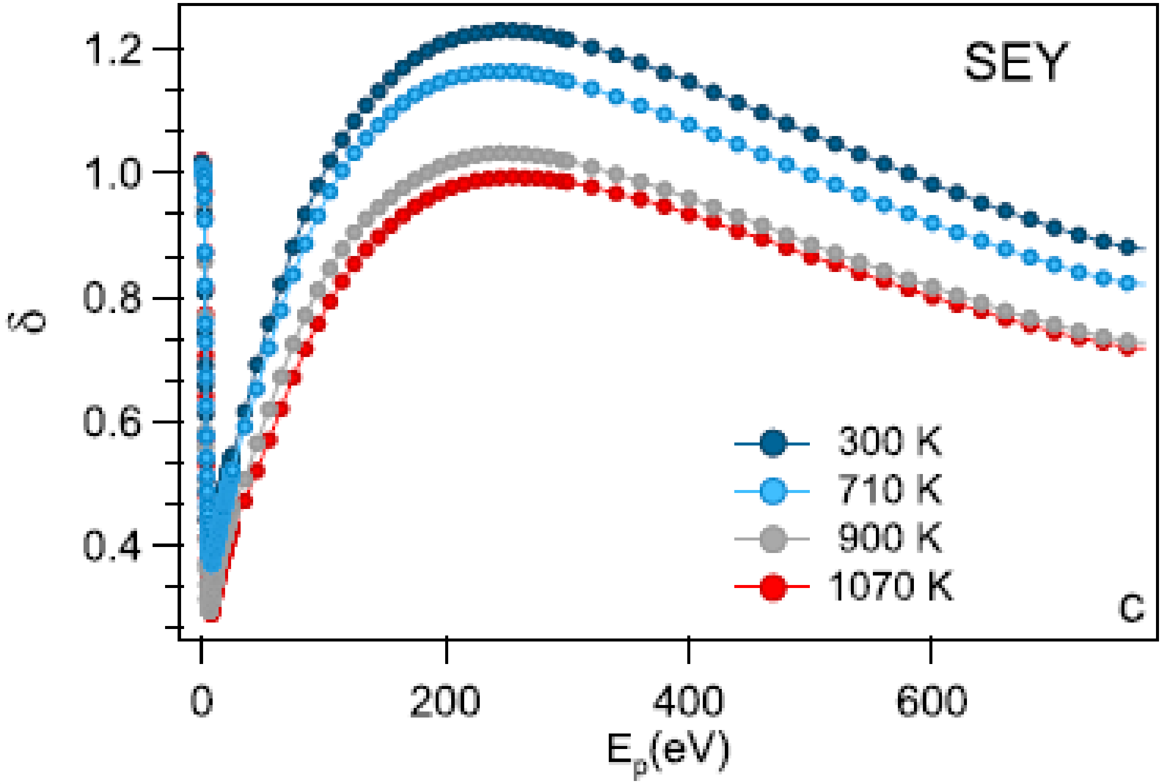
R. Larciprete et al., Appl. Surf. Sci. (2015)

Amorphous C coating

ultra high vacuum
RF magnetron sputtering 50W
p(Ar) 6x10^{-2} mbar
a-C (~ 20 nm)/poly Cu

SEY variation induced by surface modifications

Modification of surface



R. Larciprete et al., Appl. Surf. Sci. (2015)

Amorphous C-coating

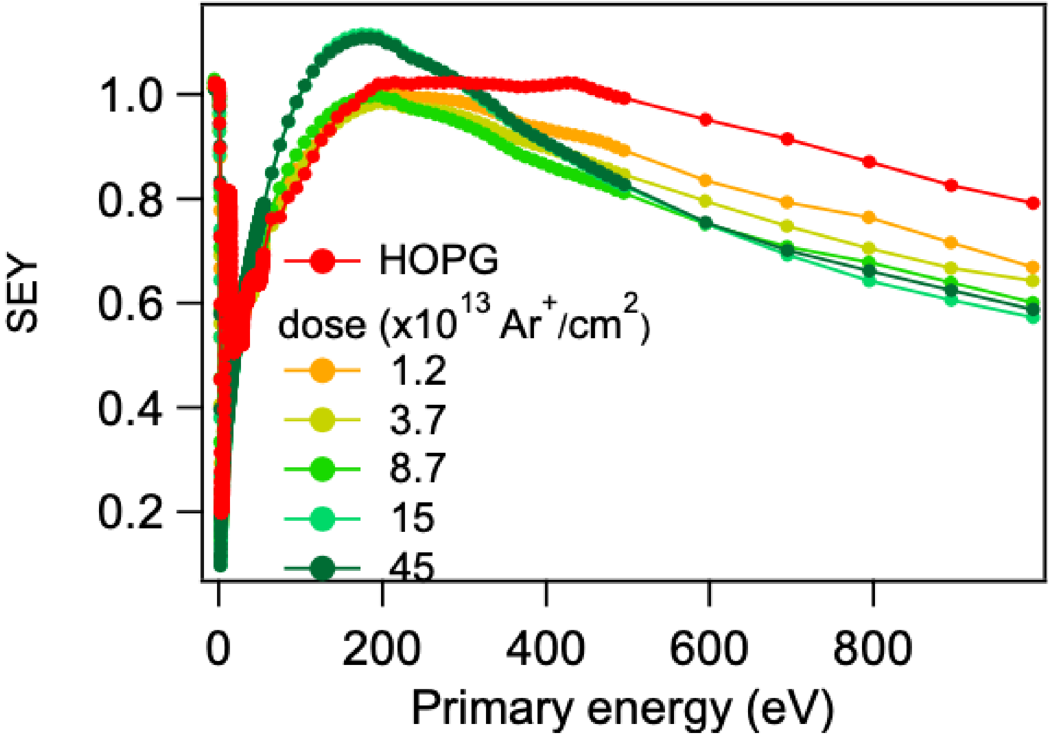
Thermal graphitization of thin amorphous C layers deposited by magnetron sputtering on Cu substrates

SEY variation induced by surface modifications

Defects

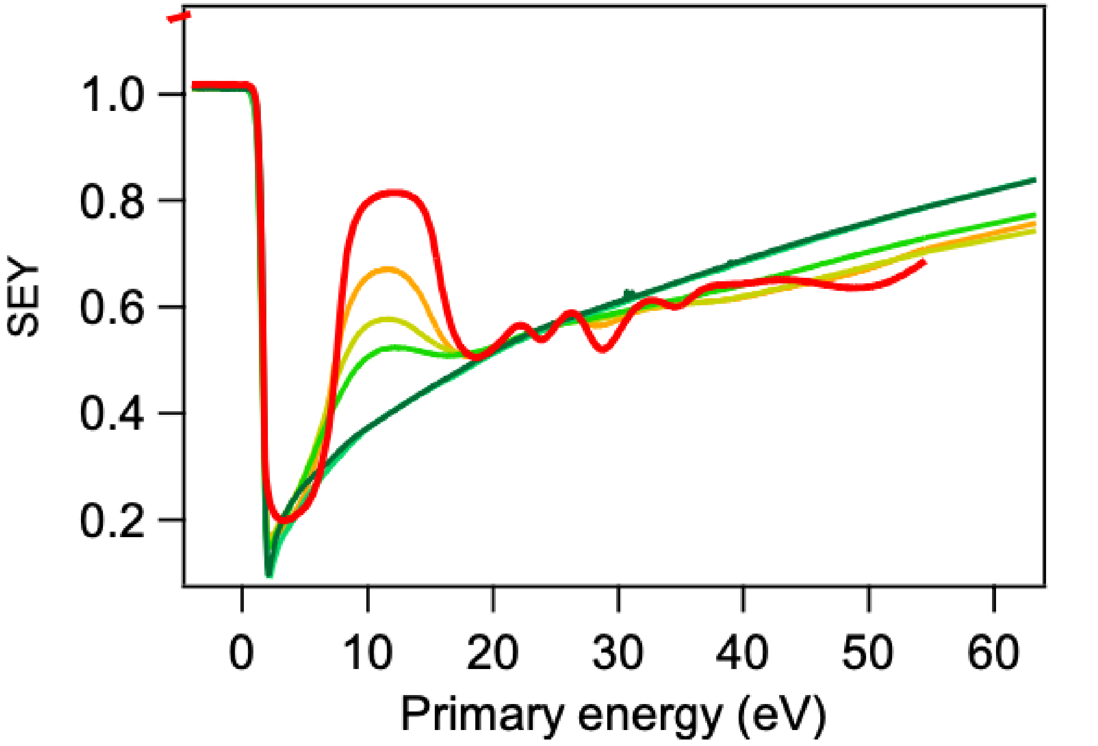
Modification of surface

Structural modification



L.A. Gonzalez et al., AIP Adv. 6 (2016) 095117

Ar$^+$ Sputtering



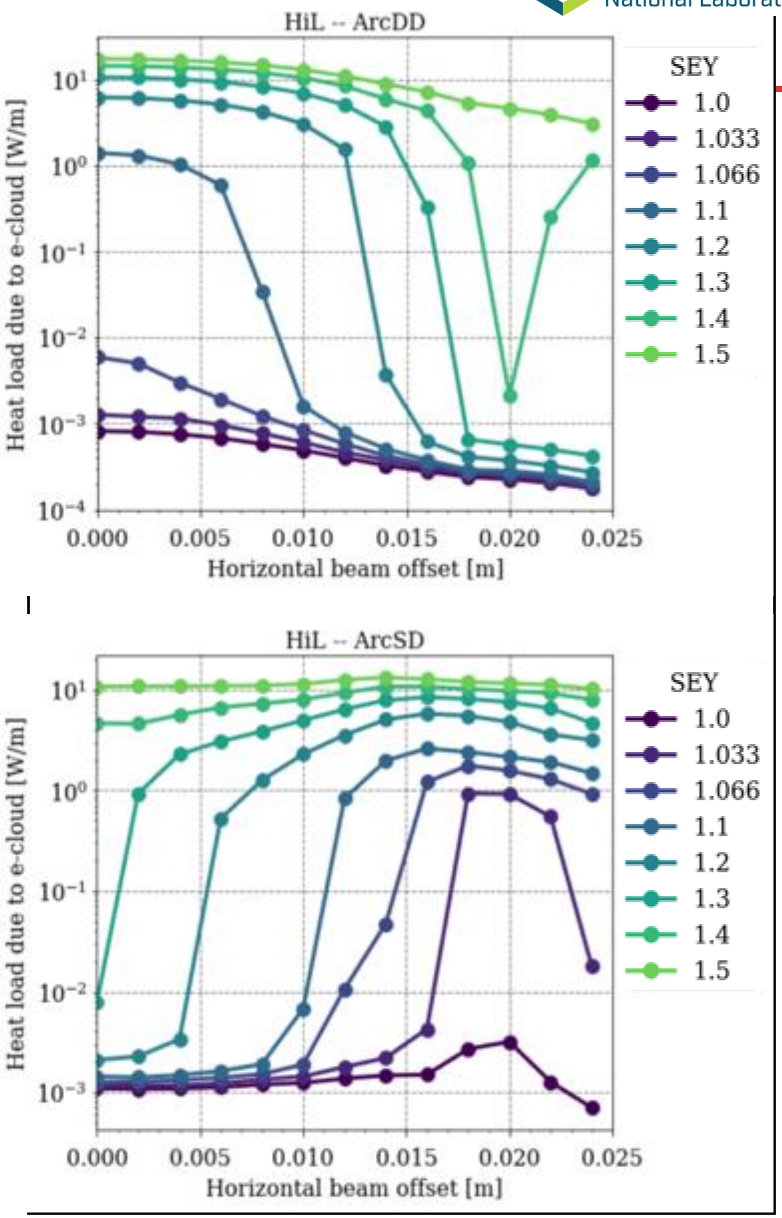
Requirements on a-C SEY

[Courtesy of C. Hetzel et al.]

PyECLOUD Calculation for EIC

- Dipoles <= **1.08**
- Quadrupoles <=**1.08**
- Sextupoles <=**1.02**
- No magnetic regions <**1.1**
- Quadrupoles and Sextupoles occupy the same beam screen
  - More stringent requirement to be followed
- SEY limits apply after adequate scrubbing
  - Requirement needs to be established
  - Cryogenic design budget can support an SEY 1.1 in all beam screens

Qualification and SEY experimental characterization of coatings SEY are mandatory for the new BS!



INFN (LNF) – EIC Collaboration

This Collaboration aims to:

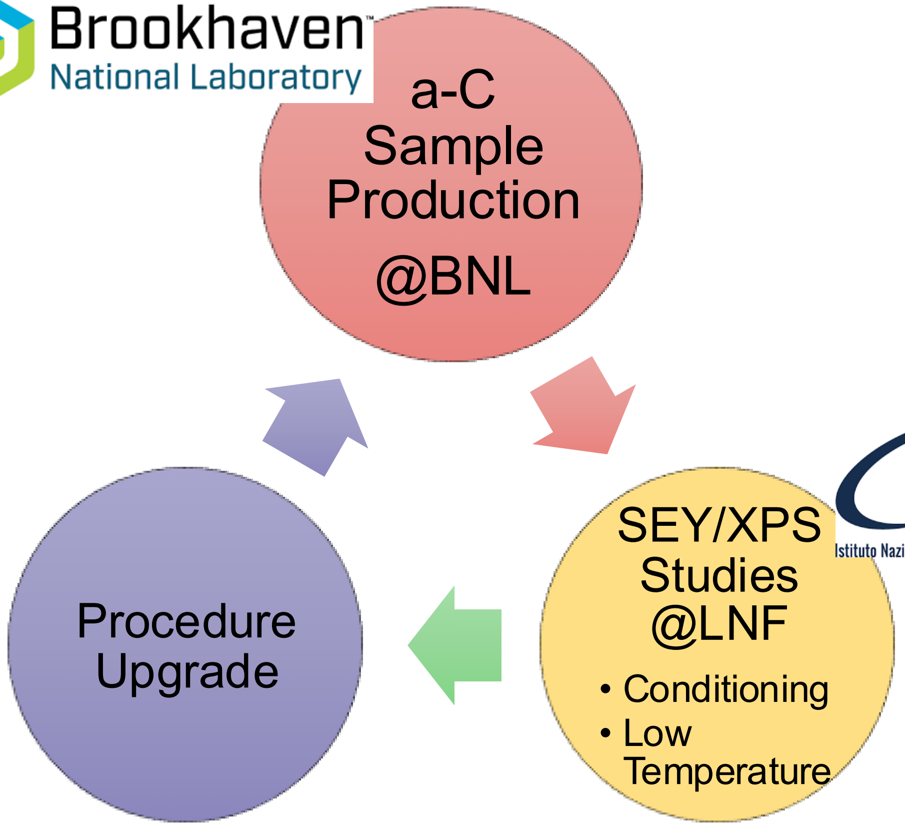
1) Perform, at LNF, surface studies for qualifying the Beam Screen (BS) prototypes of the hadron ring vacuum chamber of EIC.

2) Provide a complete, turn-key SEY measurement system to be delivered to EIC to 'in-house' qualify the BS mass production.

The **mitigation of collective effects** (e-cloud, etc.) and impedance driven instabilities in circular accelerators are also based on the definition of new constructive materials and on their Secondary Electron Yield (SEY) characterization.

LNF-INFN will perform the necessary studies to validate prototype materials and coatings to define the best practices for final production.

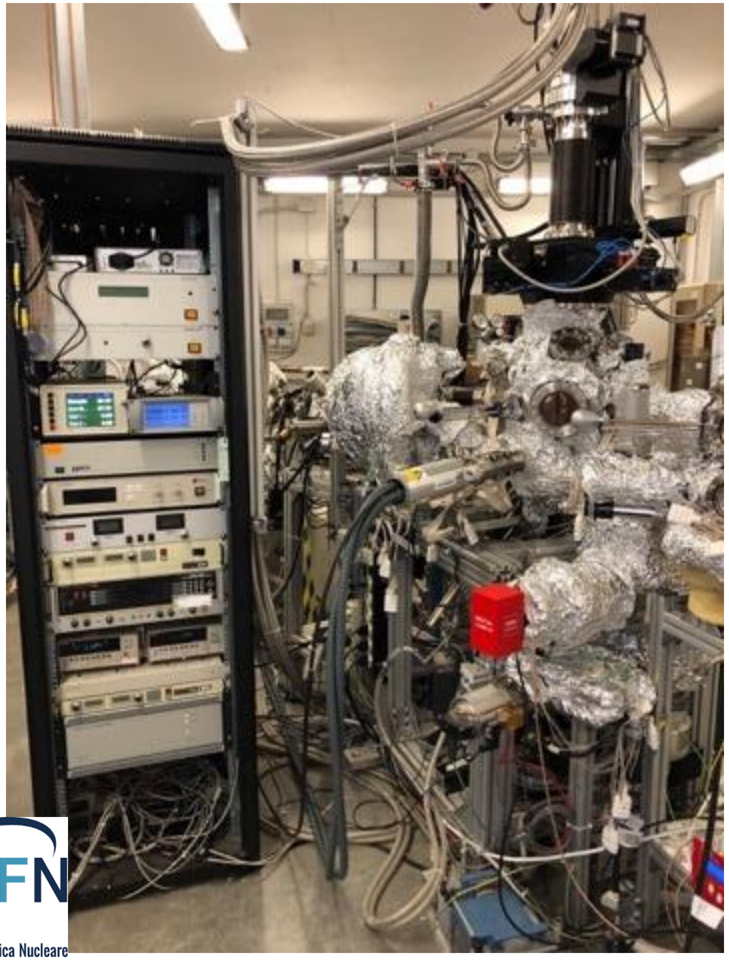
Third Party Contract



Experimental stations at XUV MaSSLab - INFN

SEY/XPS Studies @LNF

State of the art apparata for Surface Science Studies



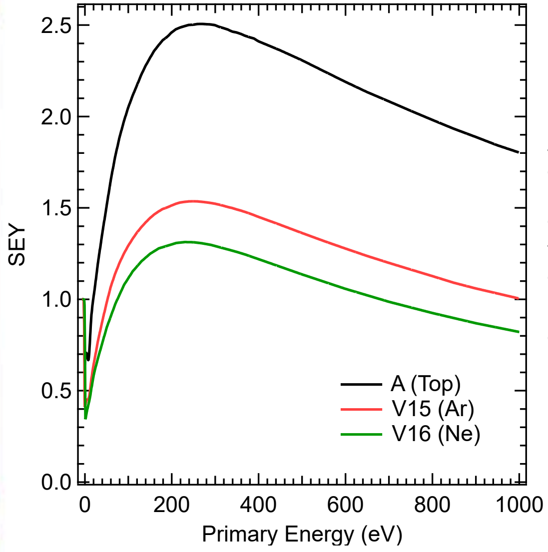
UHV µ-metal Chamber:

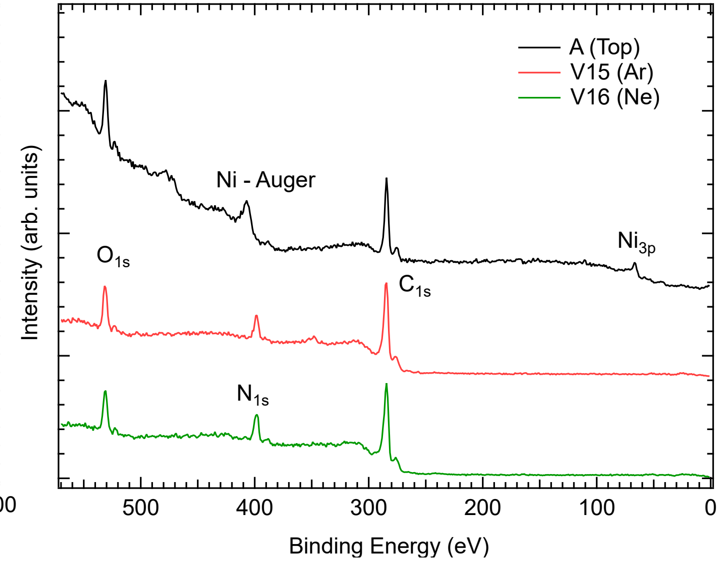
- $1\text{x}10^{-10}$ mbar base pressure
- XPS set-up (Al and Ag monocromatic and Al and Mg nonmonocromatic sources)
- Electron gun (5-1000 eV, 1nA-1µA)
- Flood gun (5-1000 eV, 100nA – 500mA)
- Quadrupole Mass Spectrometer (100 amu)
- Low temperature Manip. (T range: 10 – 300 K)

EIC a-C coatings on copper substrates (preliminary results @ RT)

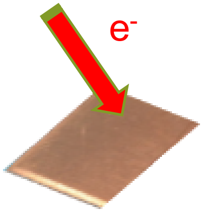
SEY/XPS Studies @LNF

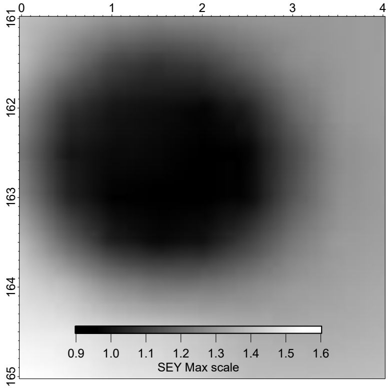
Characterization

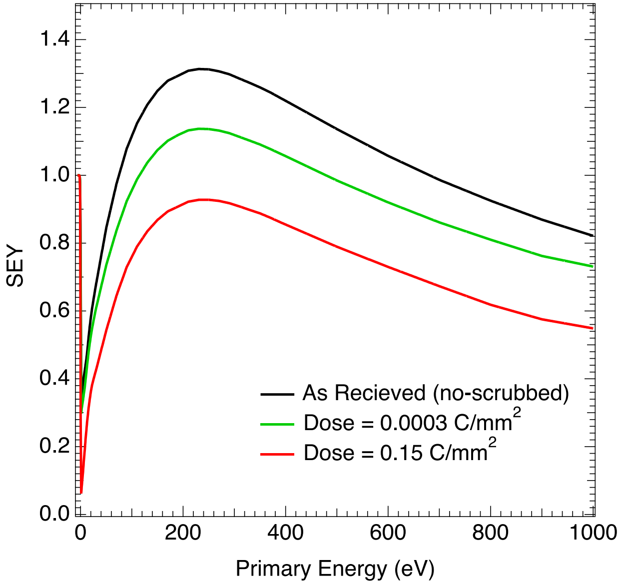


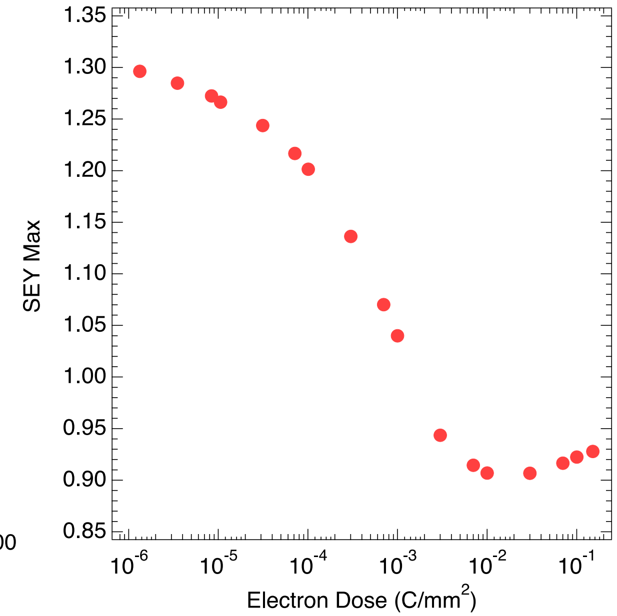


Conditioning









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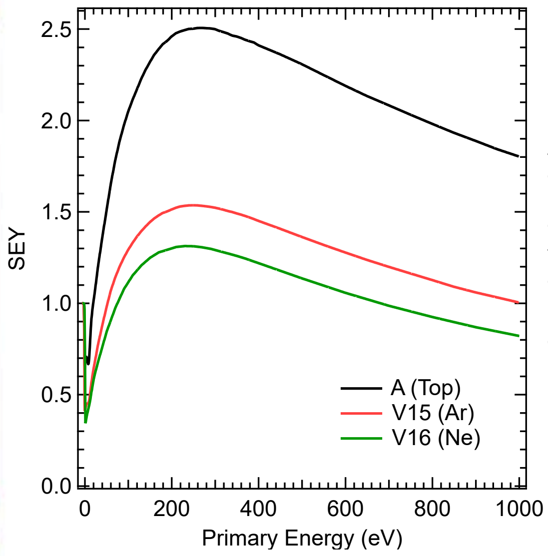
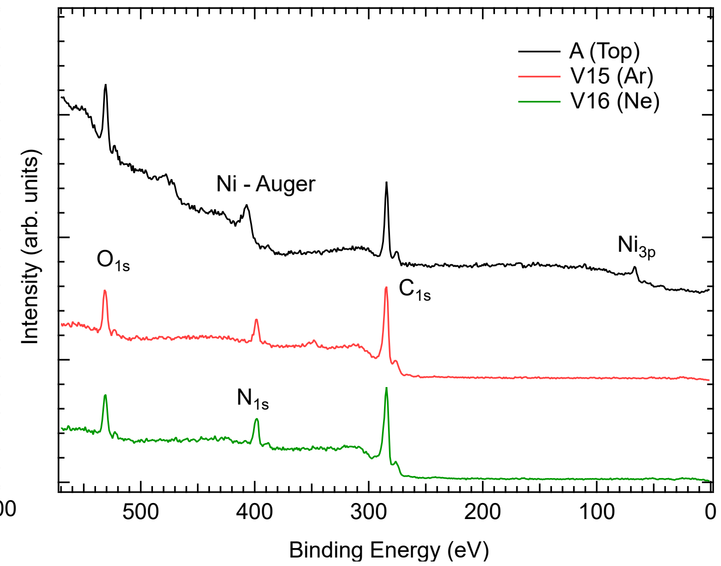
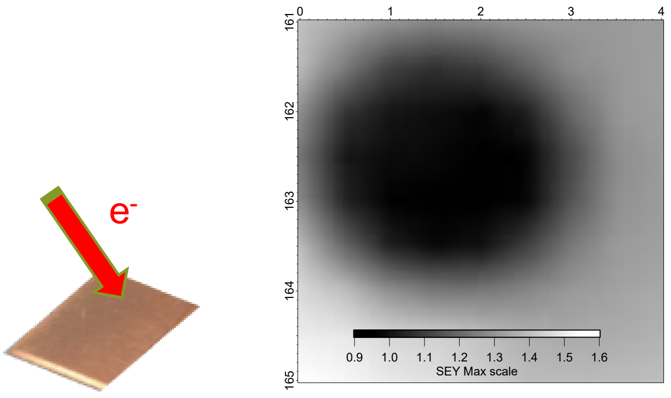
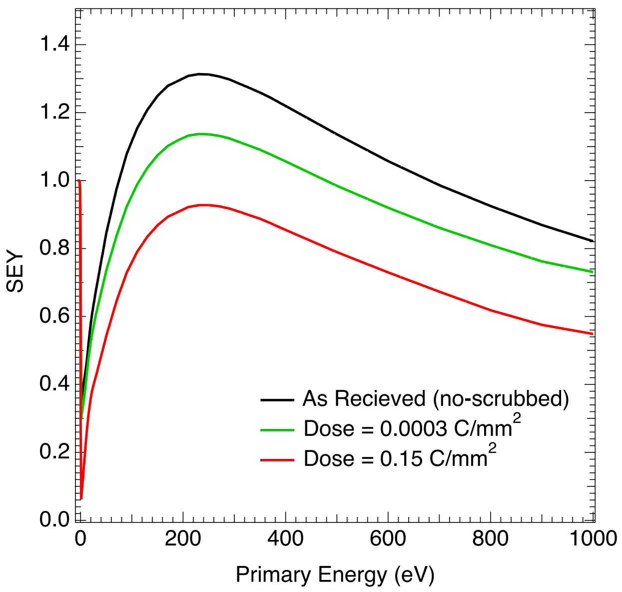


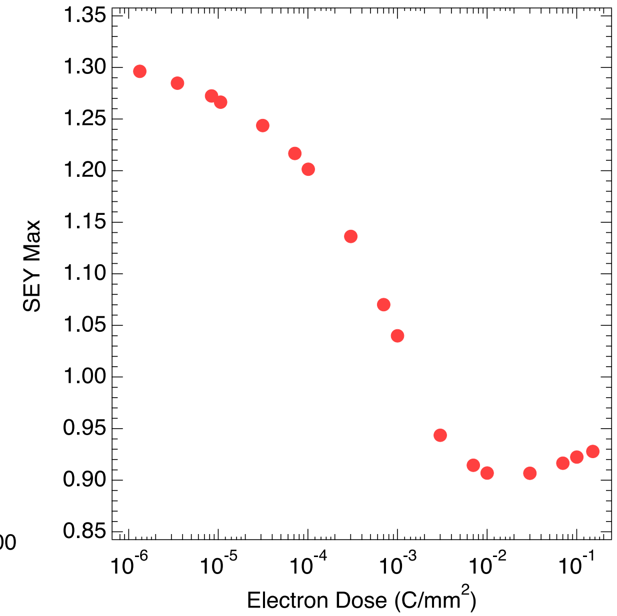


To be studied at cryogenic temperature!

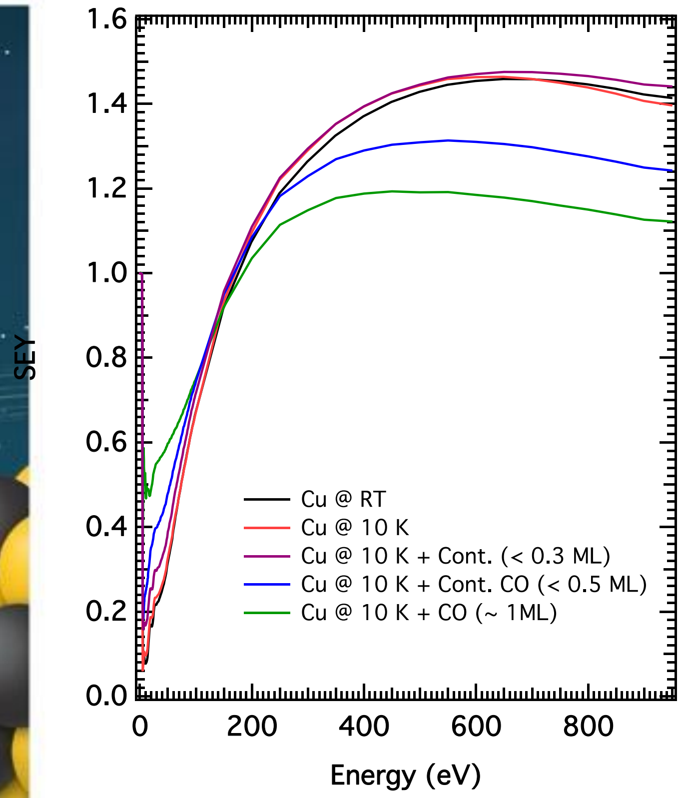
Conditioning

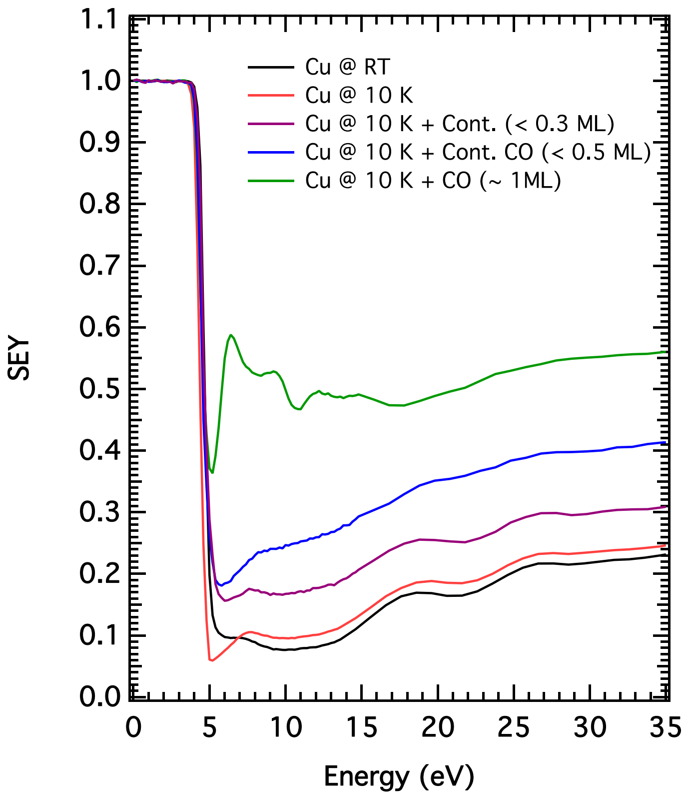






SEY of Materials

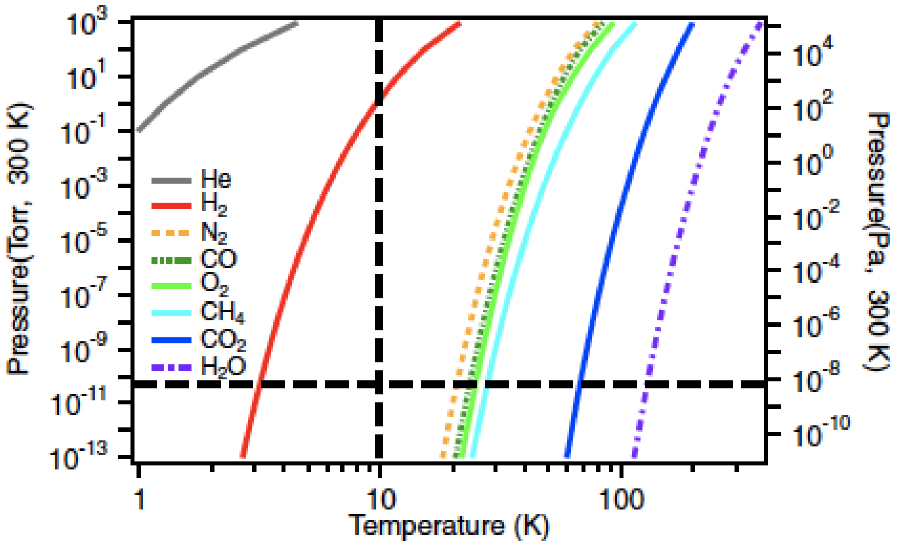




L. A. Gonzalez et al., AIP Adv. (2017)

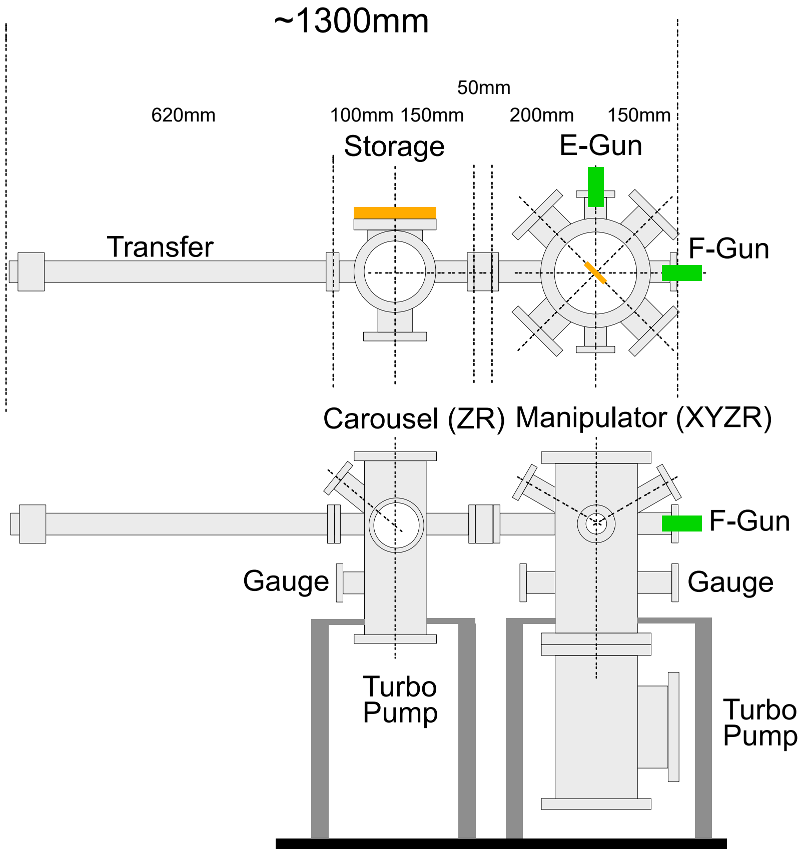
Residual gas in a vacuum at cryogenic temperature

SEY of cold surfaces influenced by gas <u>physisorption</u>



INFN (LNF) – EIC Collaboration

This Collaboration aims to:
1) Perform, at LNF, surface studies for qualifying the Beam Screen (BS) prototypes of the hadron ring vacuum chamber of EIC.
2) Provide a complete, turn-key SEY measurement system to be delivered to EIC to 'in-house' qualify the BS mass production.



The **qualification of materials during their mass-production** is a necessary end step of the manufactory chain. The possibility to have a measurement mock-up system to qualify materials in situ, is therefore essential to avoid expensive and time-consuming materials' validation from external laboratories.

LNF-INFN will design, set-up, test and deliver a full-working turn-key SEY measurement system to be available in-house, for BS large scale production validation.

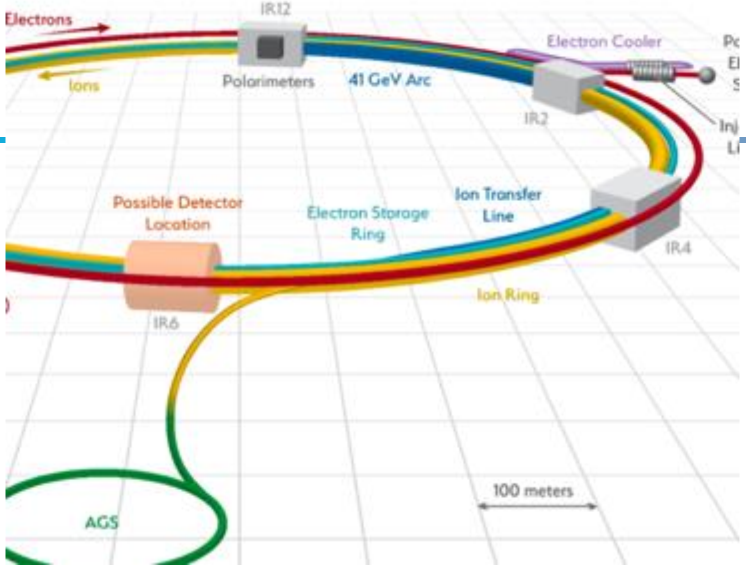
INFN (LNF) in-kind contribution to EIC

Conclusions

LNF - INFN can significantly contribute having a "state of the art" laboratory, competences and experienced people to perform such studies and design the measurement system to be delivered.

International fundings

INFN - CSN5 fundings



Thank you for your kind attention

Thanks to the MaSSLab team at LNF

L. Spallino

R. Cimino

R. Larciprete

EIC Brookhaven National Laboratory

Thanks to the BNL – EIC vacuum group team

C. Hetzel

S. Verdu Andres

INFN Istituto Nazionale di Fisica Nucleare

Tanks to the technical support of:
M. Pietropaoli, V. Sciarra and G. Viviani

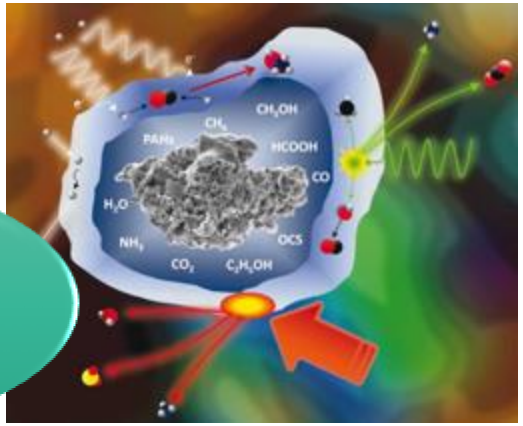
Multidisciplinary activities

R&D for accelerators

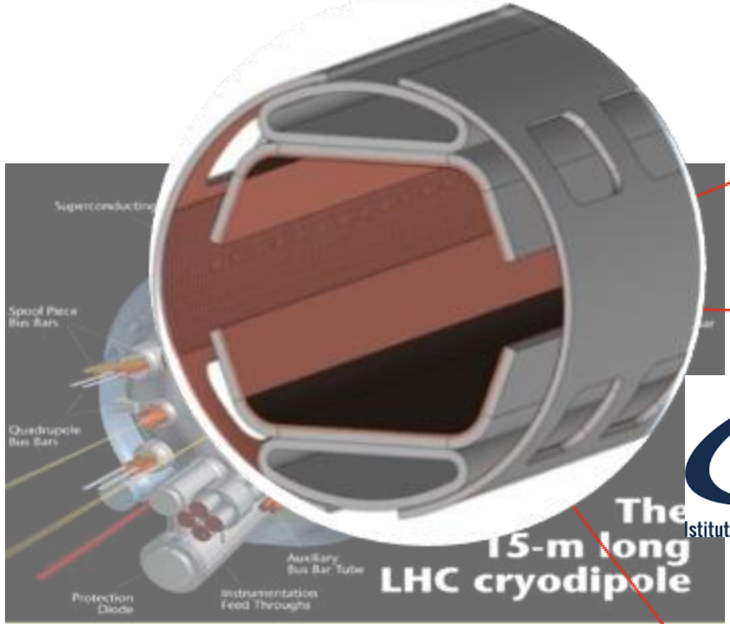
Multipacting

Space

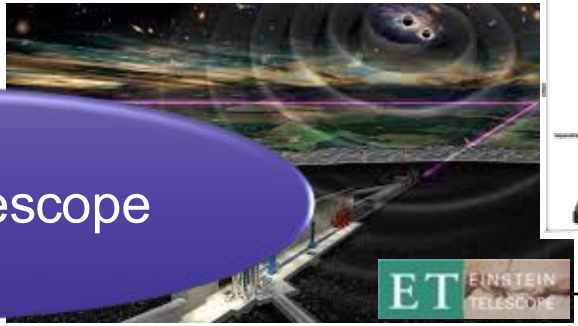
Thermal and non-thermal desorption in interstellar medium



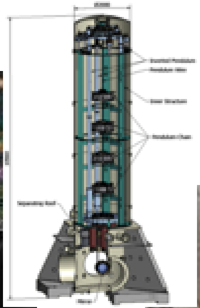
Astrochemistry



INFN
Istituto Nazionale di Fisica Nucleare



Einstein Telescope

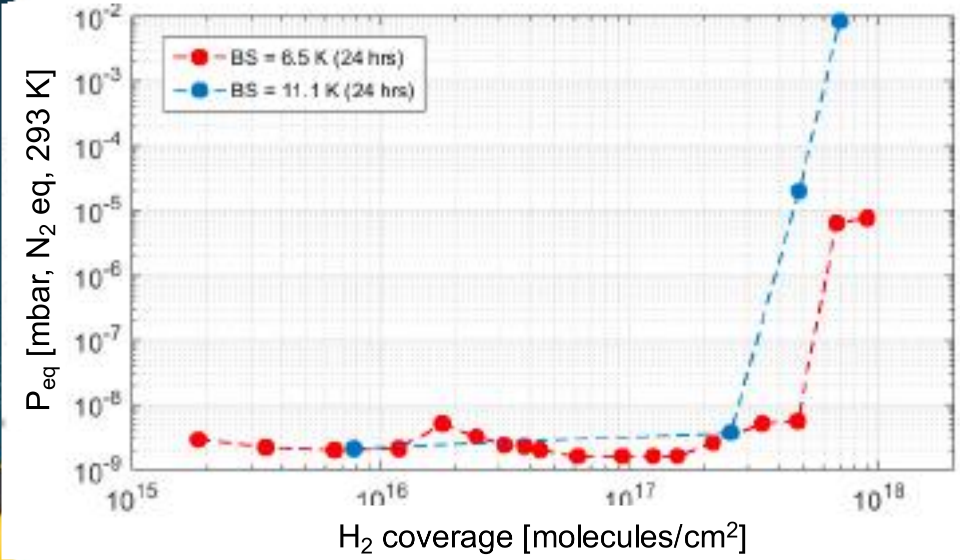


Cryogenic tower vacuum, mirror surface properties

CERN (2016) a-C coating at cryogenic temperature

Improvement of the cryogenic vacuum performance

a-C H_2 adsorption isotherms at 6.5 K and

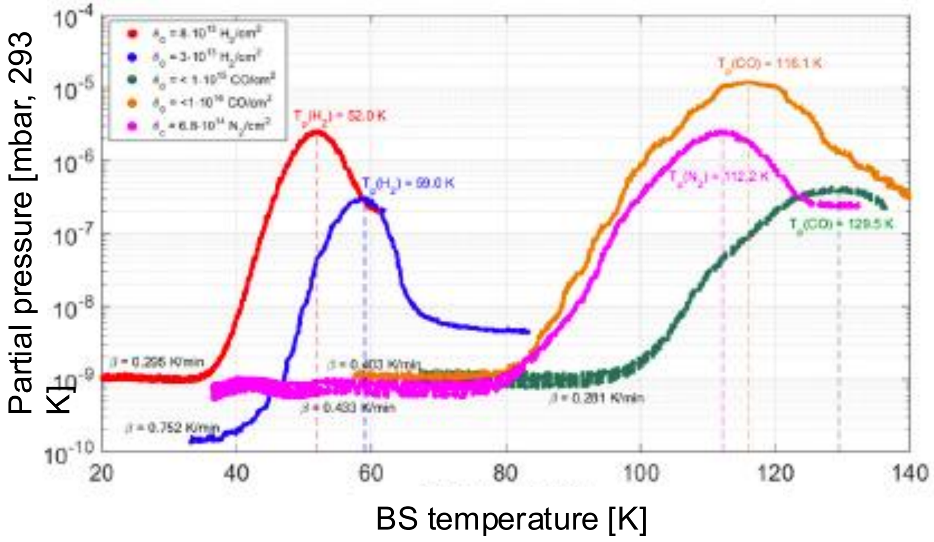


R. Salemme et al., Proceedings of IPAC2016, Busan, Korea

The CERN a-C film increases the adsorption capacity by a factor 100 (~10^{17} H_2/cm^2) compared to flat SS and Cu

Those results depend on surface morphology

TDS for H_2, N_2 and CO measured for a-C coating as function of θ_0 and β

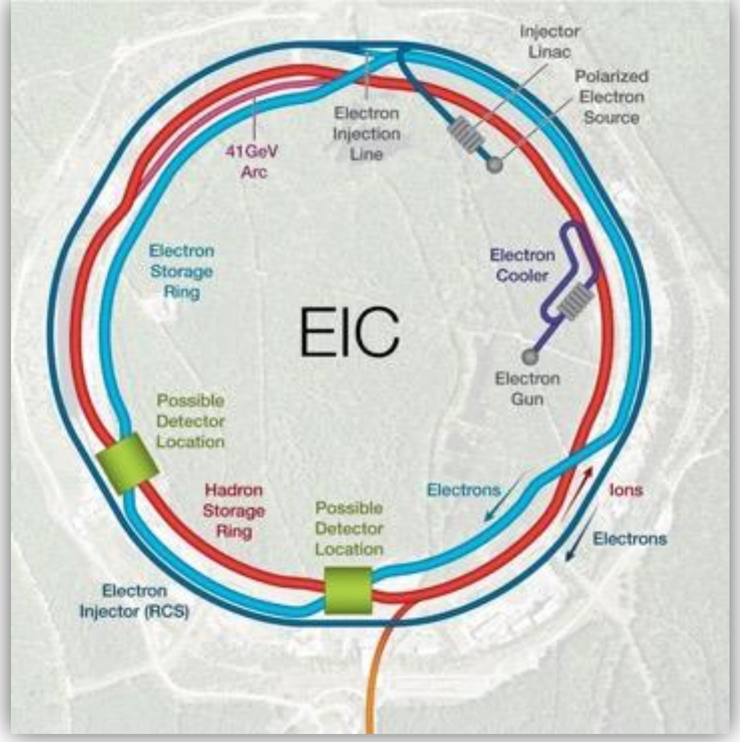


R. Salemme et al., Proceedings of IPAC2016, Busan, Korea

The CERN a-C film presents higher desorption temperatures for H_2 and CO, respectively, 30 and 60 K.

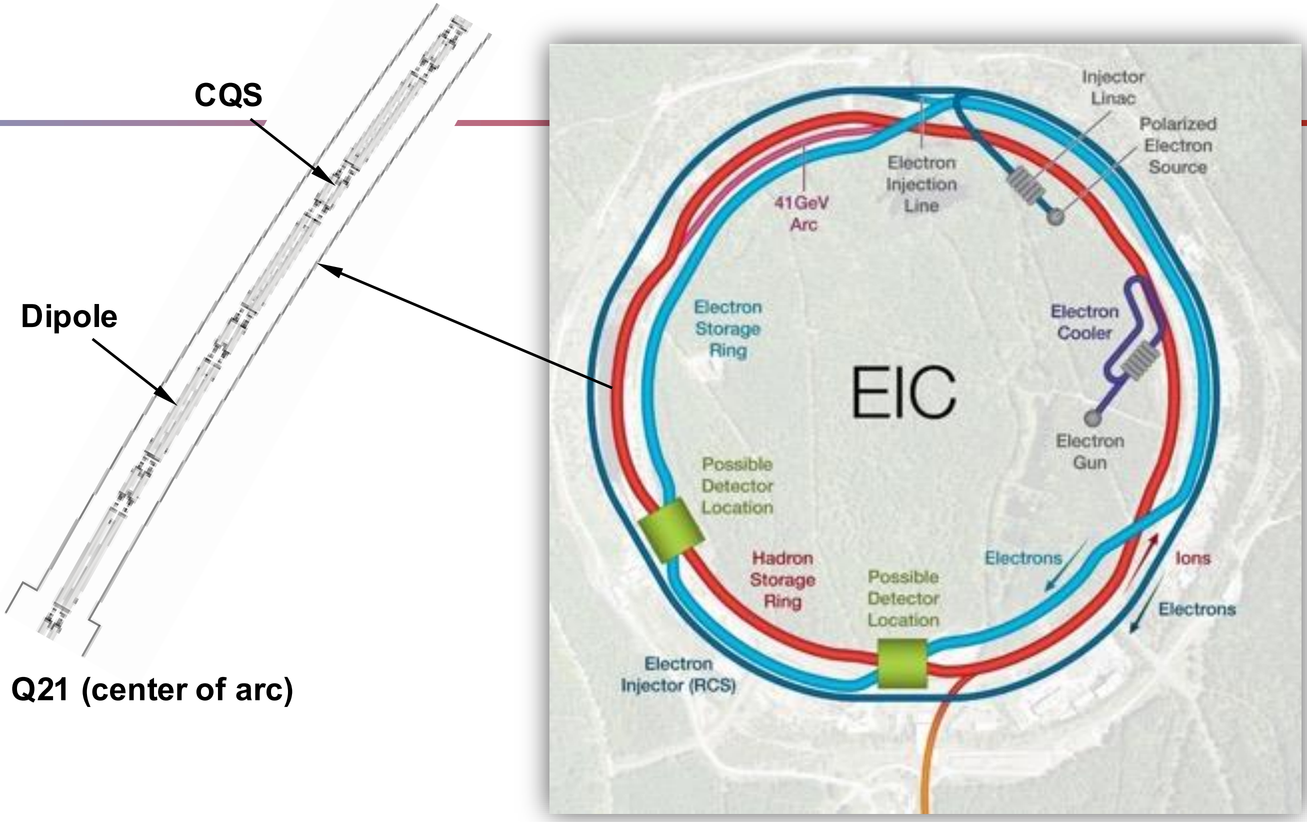
Existing Vacuum System

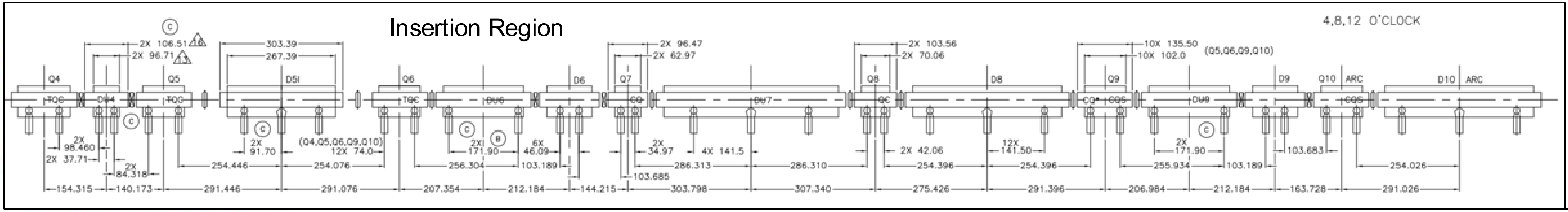
- Two existing <u>super conducting rings</u>
  - Warm sections between arcs
- A total of **8 arcs** from RHIC will be reused
  - Inner ring used as a low energy bypass at 1 o’clock
  - Inner ring used as a transport to injection at 4 o’clock – **NOT UPGRADED**



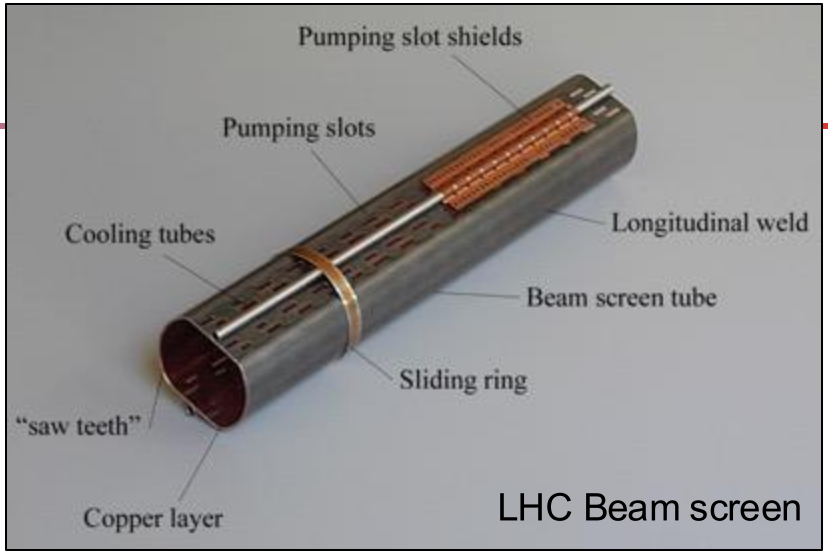
Arc Layout

- Arc length ~480m
  - Seven arcs require beam screens
- Each arc consists of ~72 magnets
  - **>500 beam screens** (72 magnets x 7 arc)
- Majority of arcs are dipoles and CQS (67%)
  - 30 dipoles
  - 35 CQS (Corrector, quad, sext)

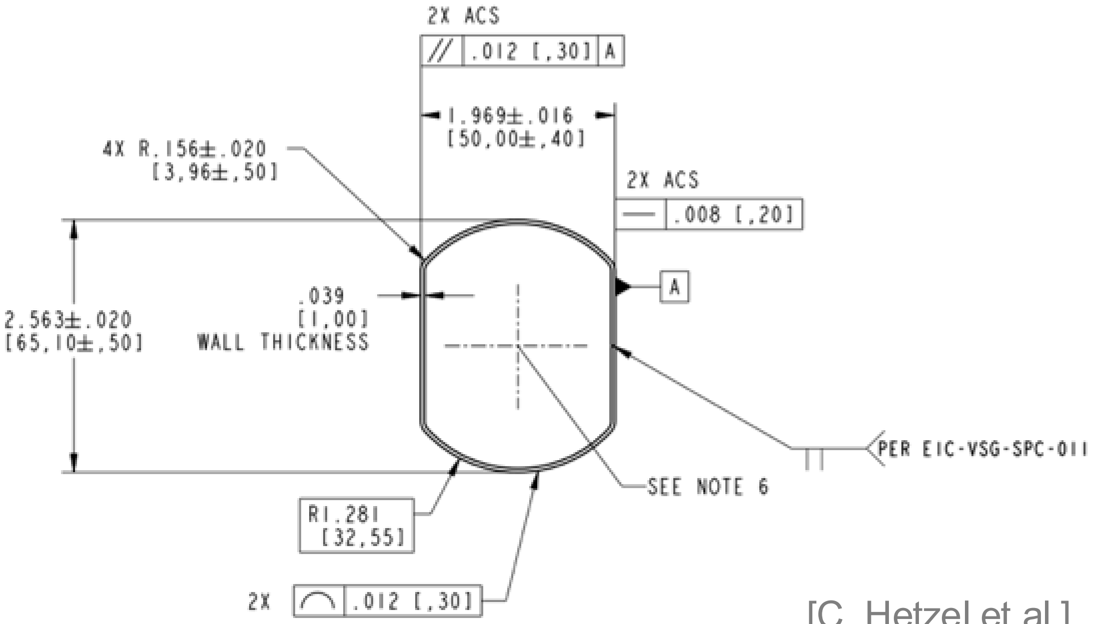




HSR Beam Screen



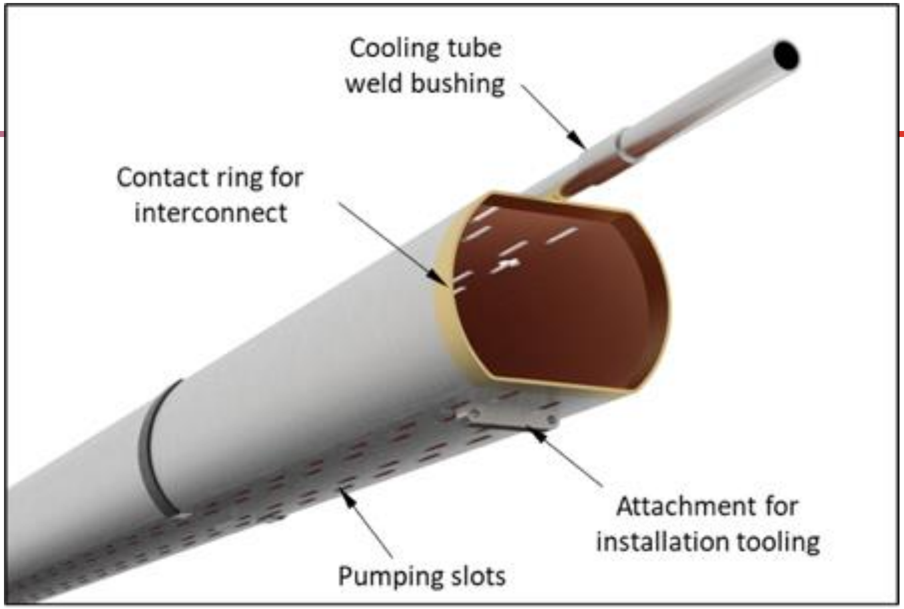
- Design based on LHC screen
- Copper cladded stainless steel
  - P506 stainless steel
  - C10100 OFE copper
- Baseline design wall thickness: 1.0mm
  - Investigated 0.8mm to reduce installation forces
- Profile will be roll formed with a single weld
  - Fabricator is confident welding on flat



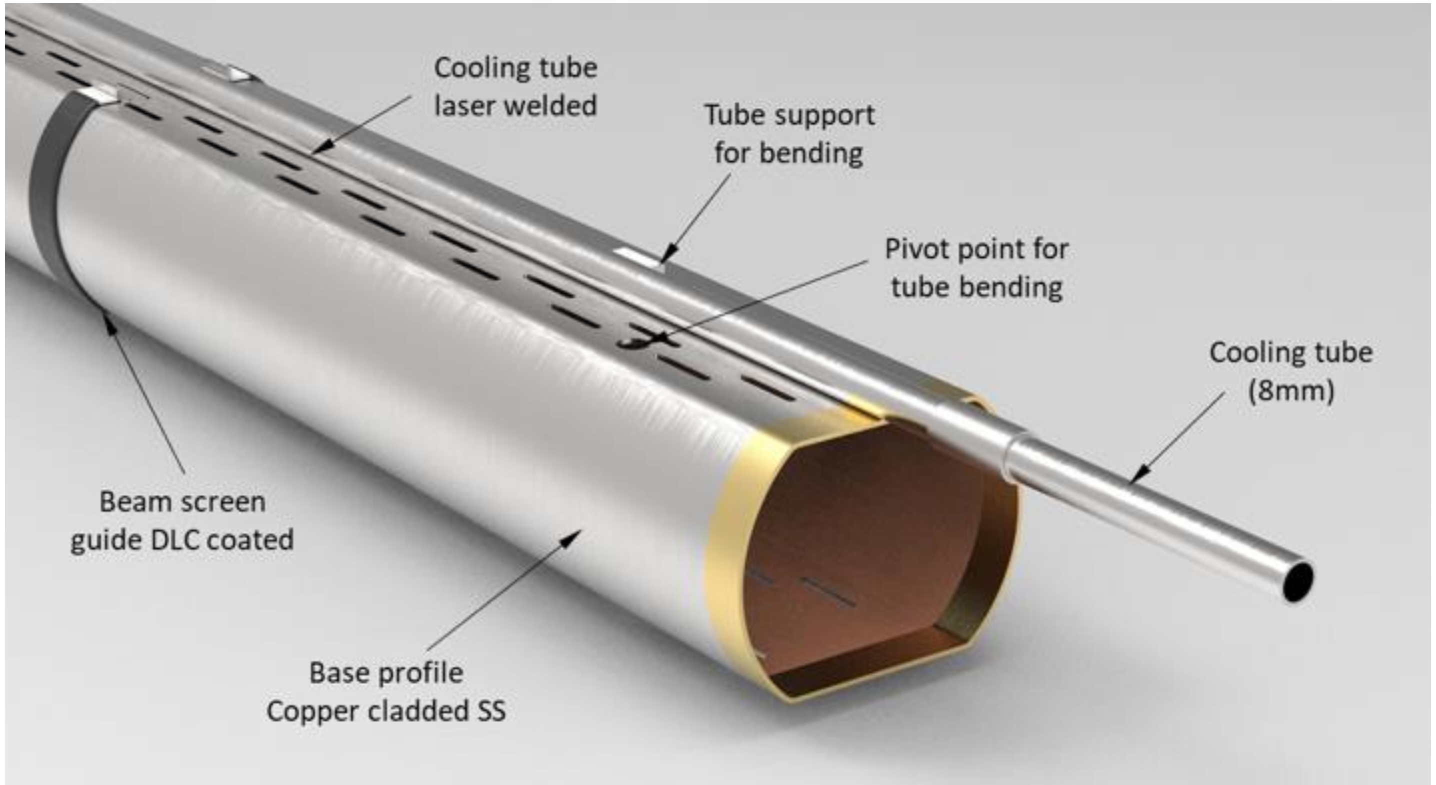
[C. Hetzel et al.]

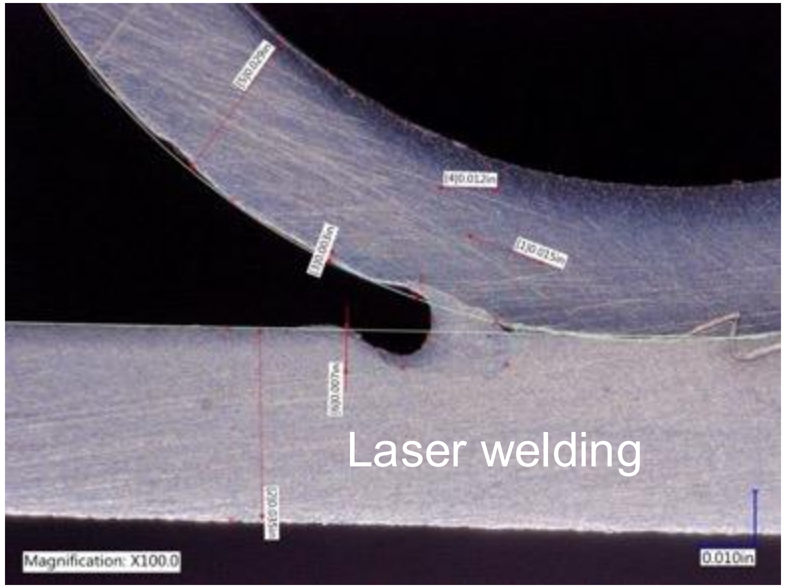
HSR Beam Screen

- Operating temperature: 4.5 – 10K
- Single cooling tube
  - No synchrotron radiation
  - ~0.5W/m heat load



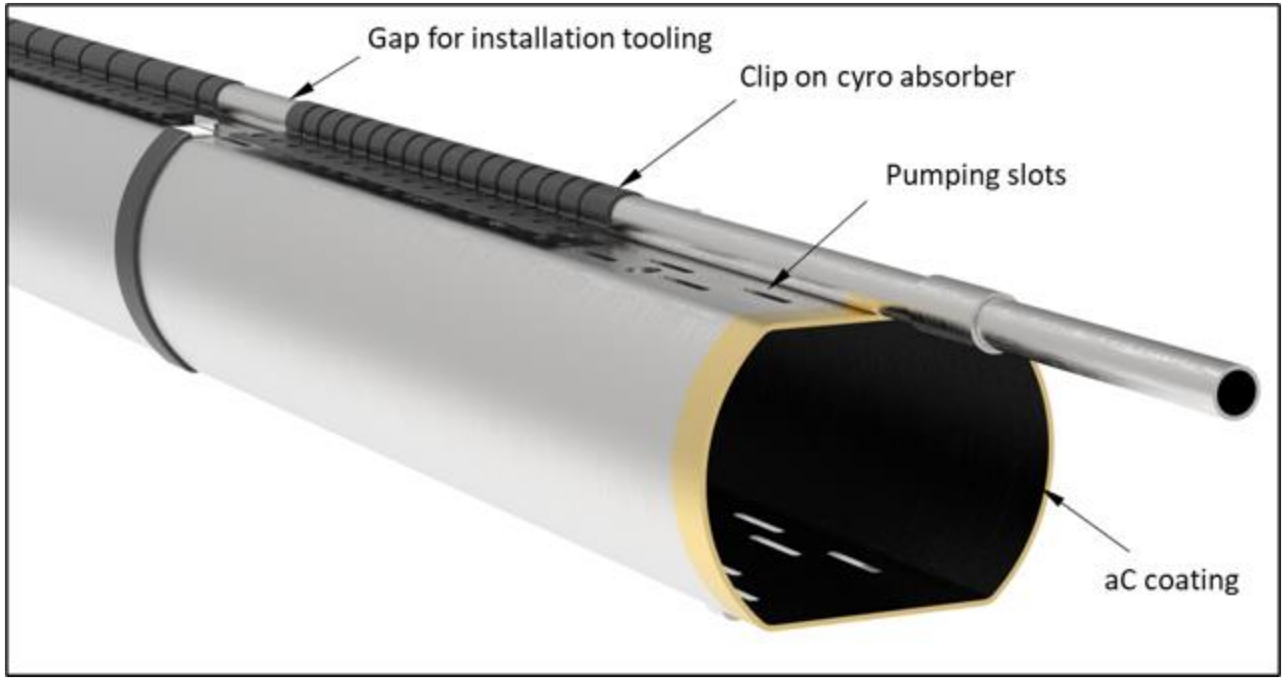
[C. Hetzel et al.]





HSR Beam Screen

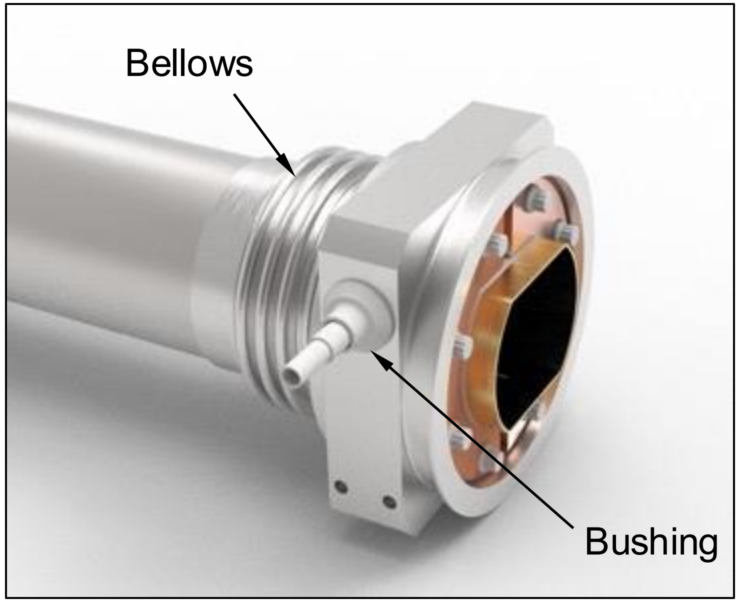
- Beam facing surfaces will be coated with amorphous carbon
  - Keep SEY values below requirement
- Slots in screen for pumping
  - Working with vendor on randomizing slot pattern
  - Controls gas density
  - Equilibrium pressure defined by slot conduction
- Cryo absorber outside of beam channel
  - Only on one side of beam screen
  - Additional pumping capacity for $H2$
  - Considering a-C carbon coating

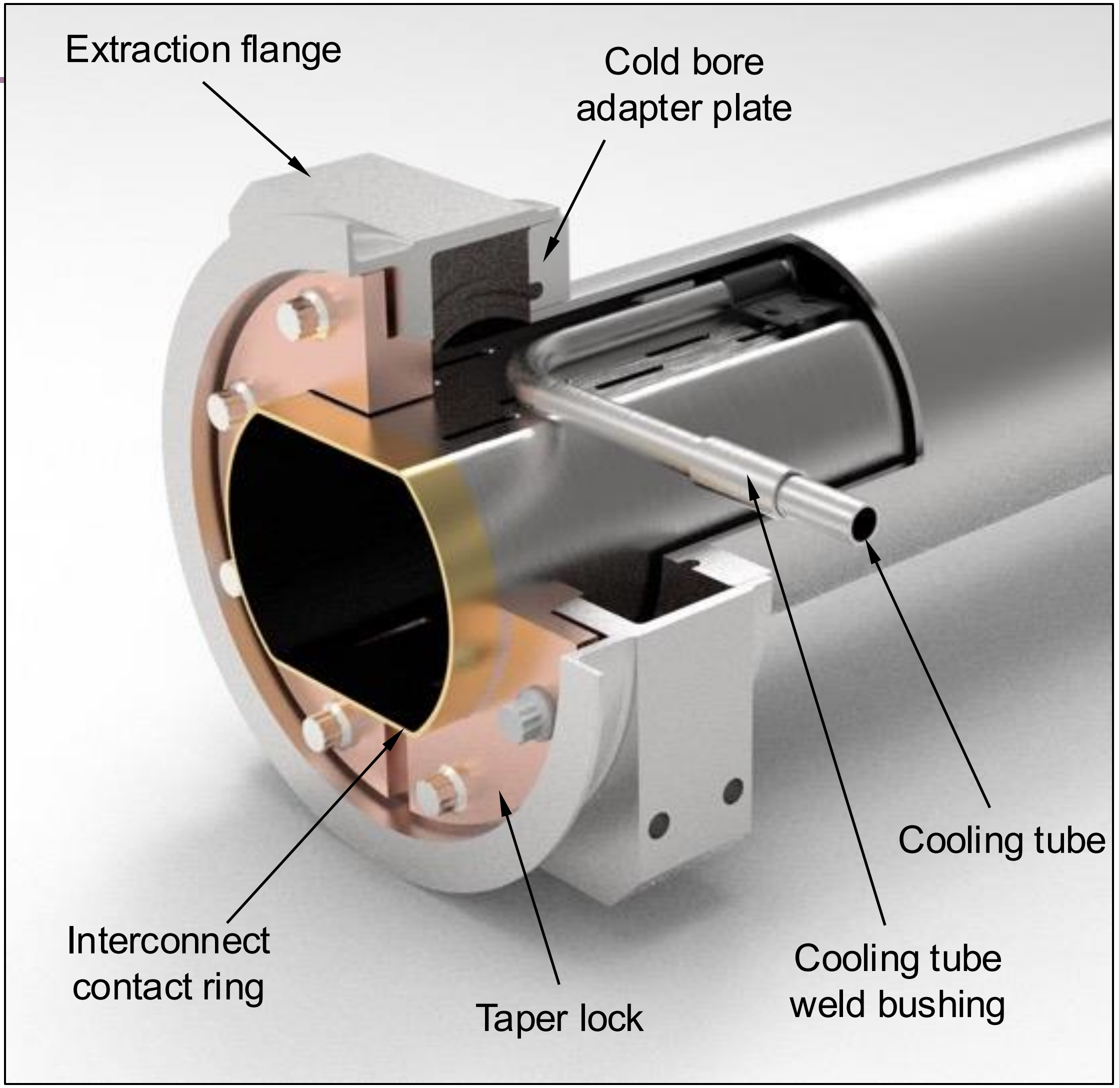


[C. Hetzel et al.]

Cooling Pipe Extraction

- Extraction of cooling line from UHV required
  - Needed to bypass interconnect bellows
  - Requires modification to existing cold bore
  - Work to be done in situ
- Taper lock fixes beam screen to cold bore
- One fixed side and one movable side
  - Provides compliance between cold bore and beam screen

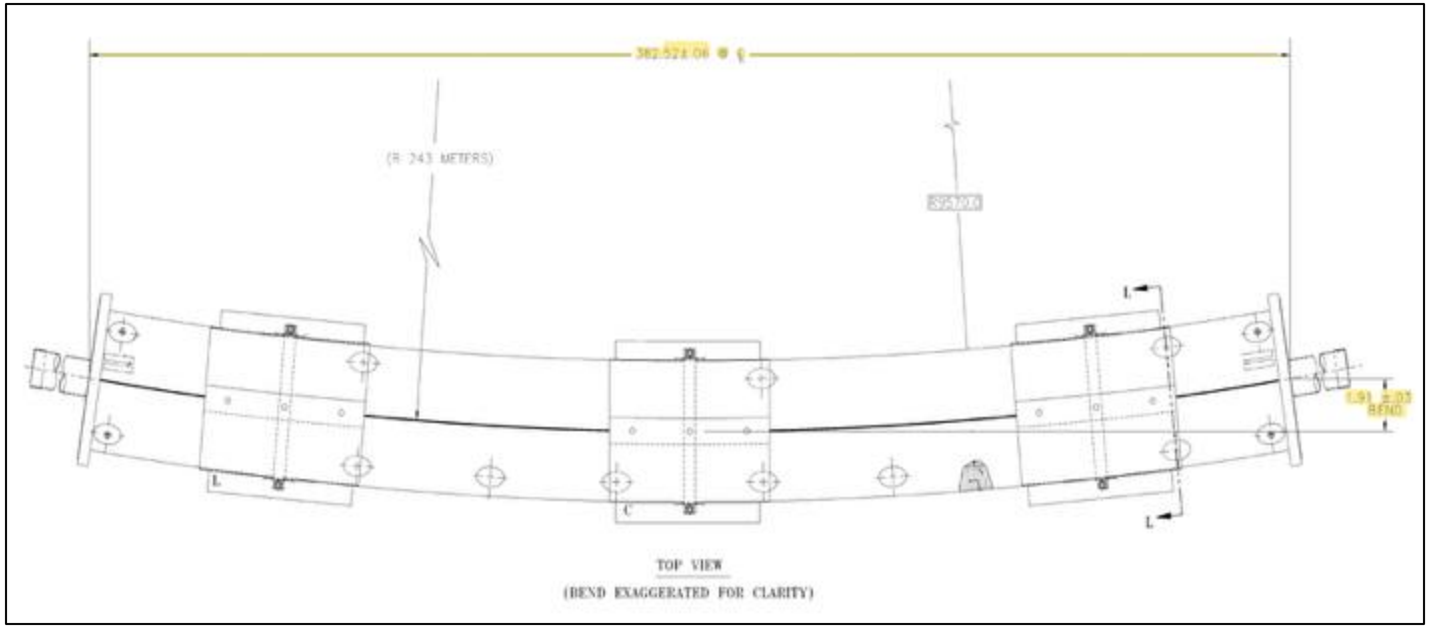




[C. Hetzel et al.]

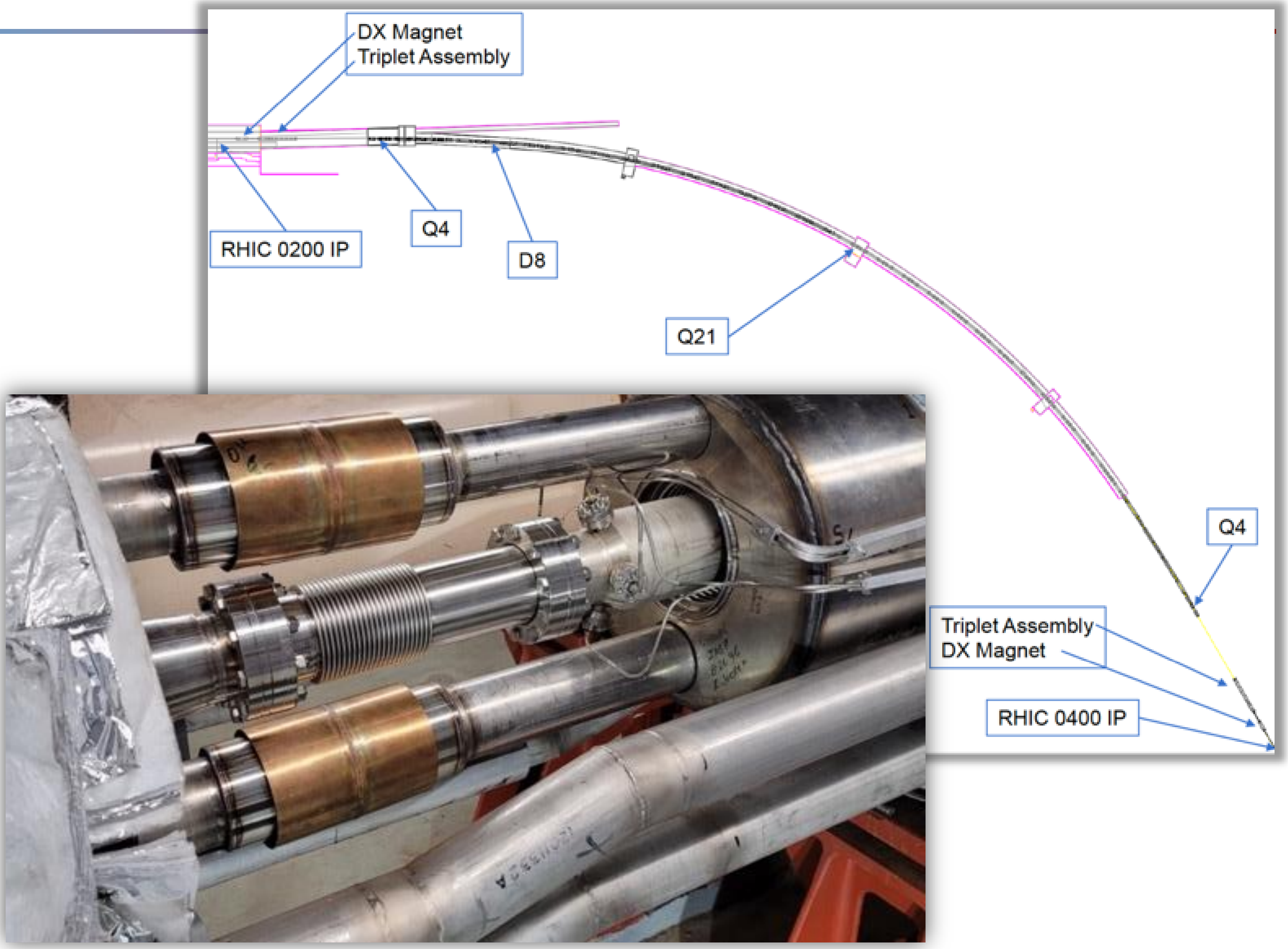
Installation Challenges

- In situ installation
- Dipoles have sagitta (40mm)
- Access only through interconnect (35cm)
- Shield existing stripline BPMs
- UHV work



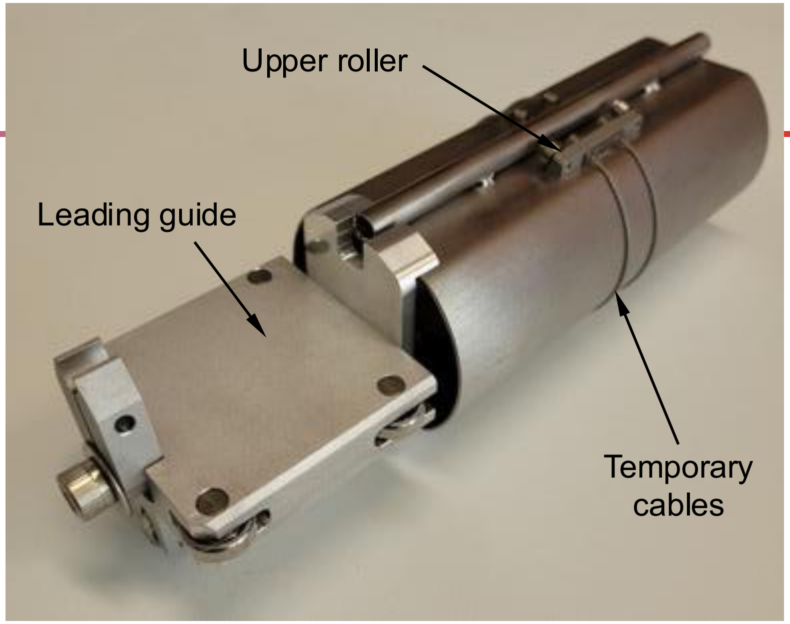
Installation Approach

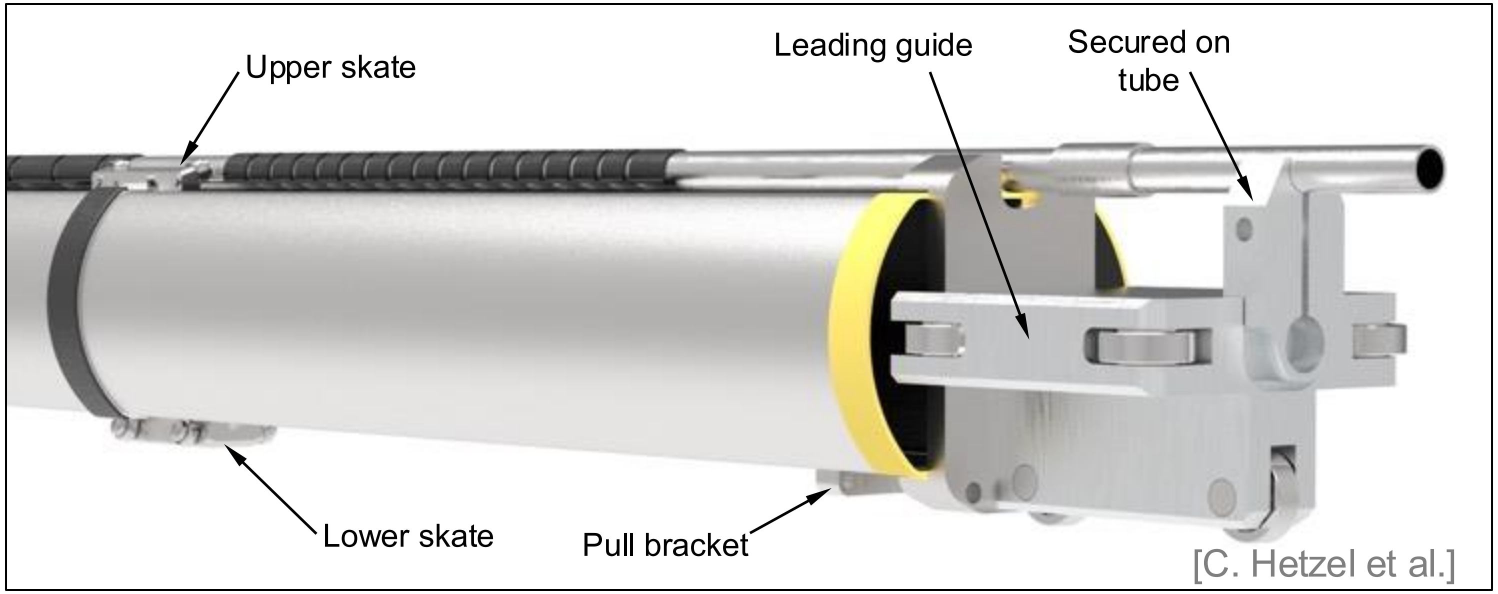
- In situ installation
  - Limited access between magnets
  - Additional obstacles (process lines, etc)
  - Screen sequence must be in order
- Each arc is ~480m long
  - Max pull ~240m (38 magnets)
- Start from warm sections
- Possible access at D8
  - Reduces max pull ~50m (29 magnets)



Installation Approach

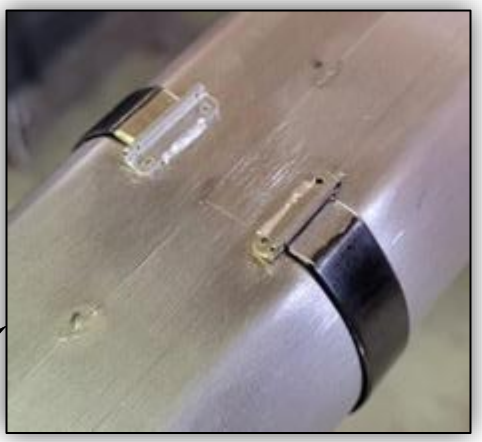
- Existing cold bore beam pipes will be cleaned
- Each cold bore will be measured prior to installation
  - Undersized bores will be removed from the line
- Transit through magnets
  - Leading guide (both ends of screen)
  - Temporary rolling elements (skates)
  - Removed before entering final magnet
- Last magnet
  - Final cleaning
  - Leading guide
  - Beam screen guides
- Evaluating if screens can be pushed

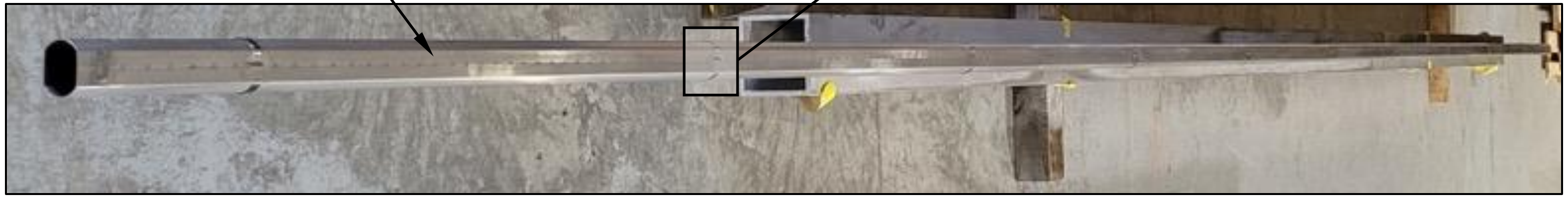


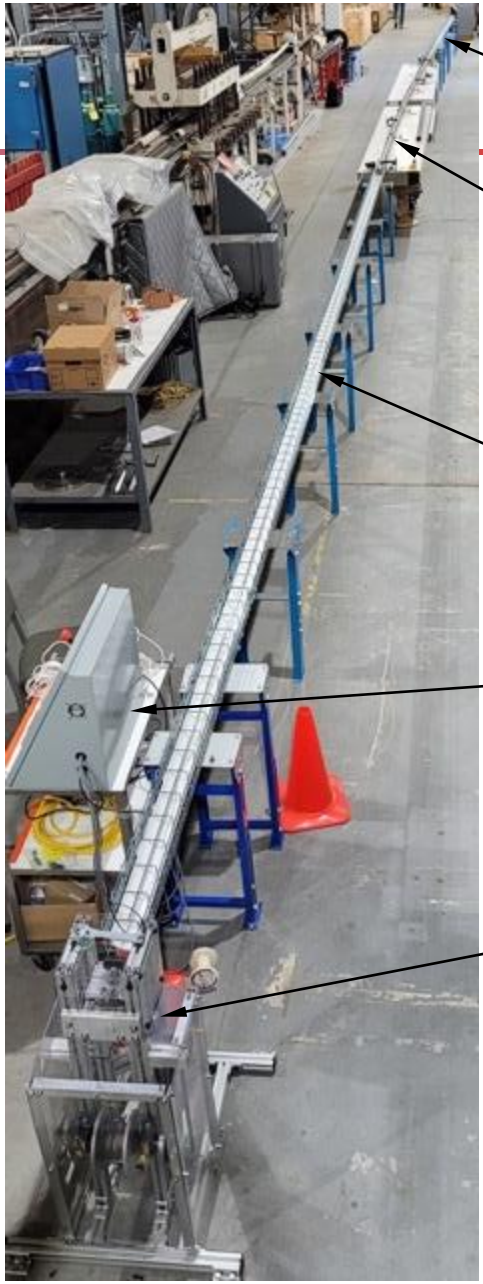


Full Length Pull Test

- Full length screen test performed
  - 1mm thick profile with all features
  - Fabricated in segments
- ~20 pulls completed
  - Force required ~60#
- Future work
  - Add CQS equivalent tube inline
  - Particulate generation





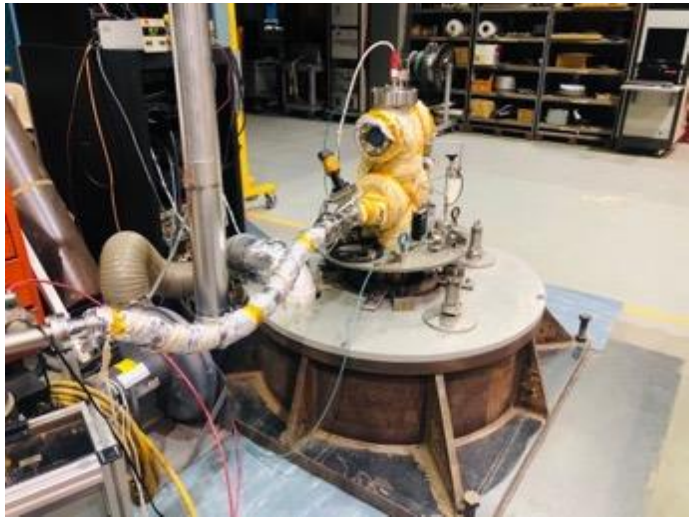


[C. Hetzel et al.]

Coating System - Vertical

a-C
Sample
Production
@BNL

- Capabilities
  - Max length: 6.1m [20 ft]
  - Max field: 300G
  - Coil ID: 25cm [10”]
- Previously used for NEG coatings
- Bipolar plasma supply
- Currently producing samples using argon and neon



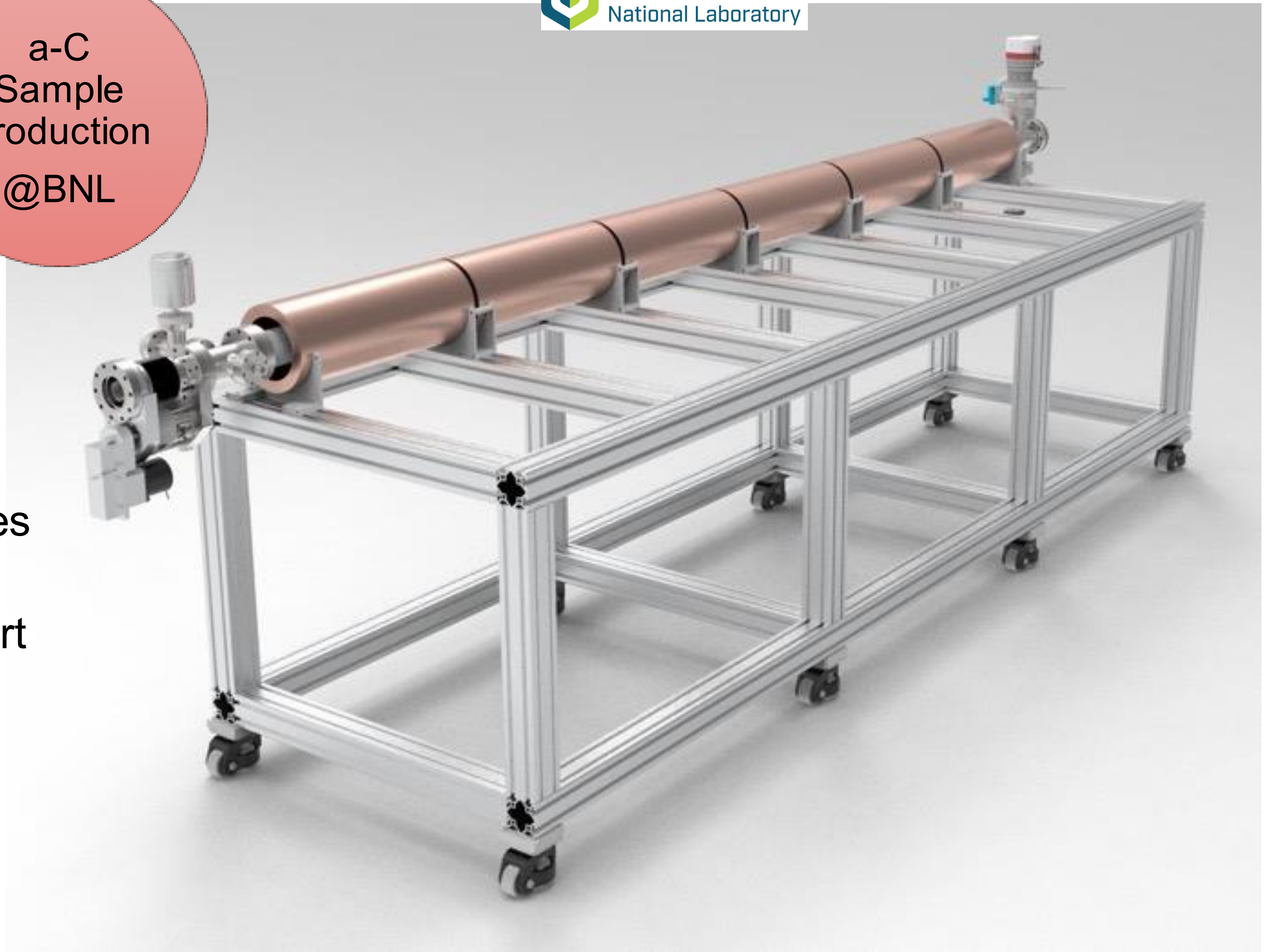
Brookhaven National Laboratory

Coating System - Horizontal

- External solenoids
  - Self supporting coils
  - OD x ID 7.2” [183mm] x 5.2” [132mm]
  - 250G @ 10.2A
- Frame 80-20
  - Purchase as a kit (pre-cut)
- Coating/transport pipe
  - 3” tubing with 4.63” CF
- Beam screen installed with removable skates
  - Also used for transit through cold bore
- Graphite rod support by intermediate support
  - Moved back and forth to minimize uncoated areas

a-C Sample Production @BNL

Brookhaven National Laboratory

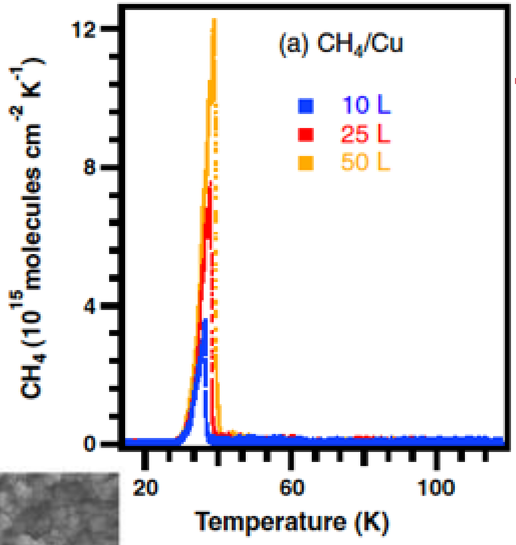


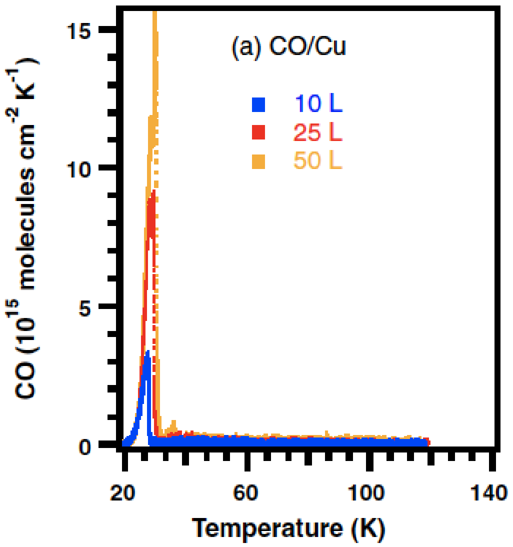
Desorption studies

SEY/XPS Studies @LNF

Thermal Programmed Desorption investigation

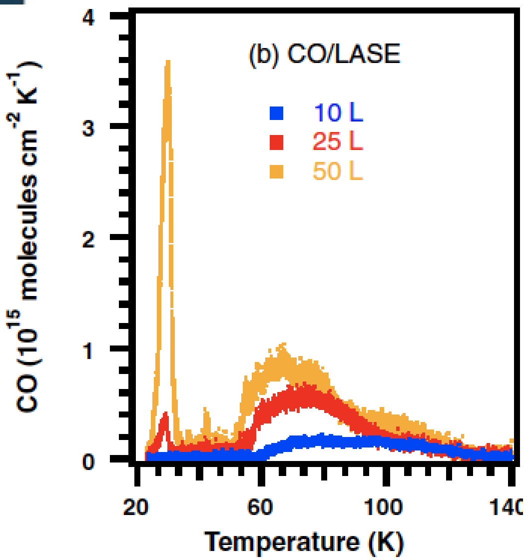
Poly-crystalline Cu

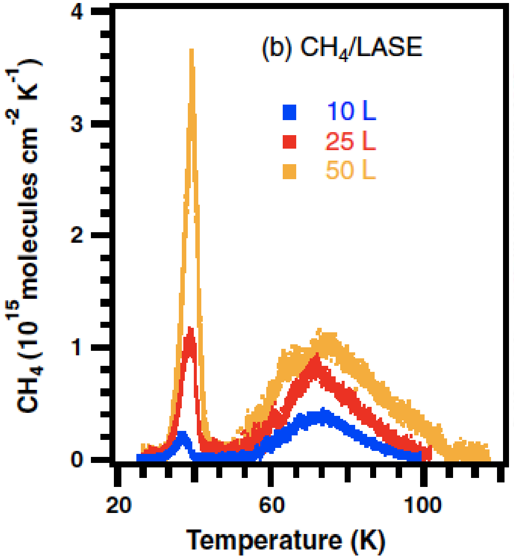


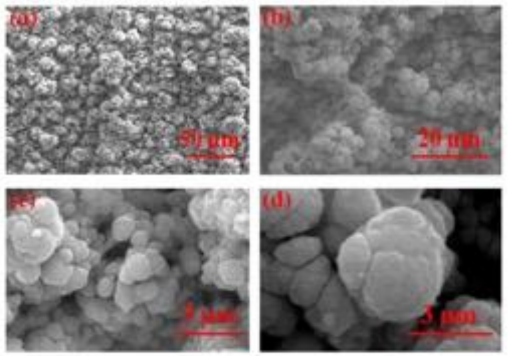


LASE-Cu substrate

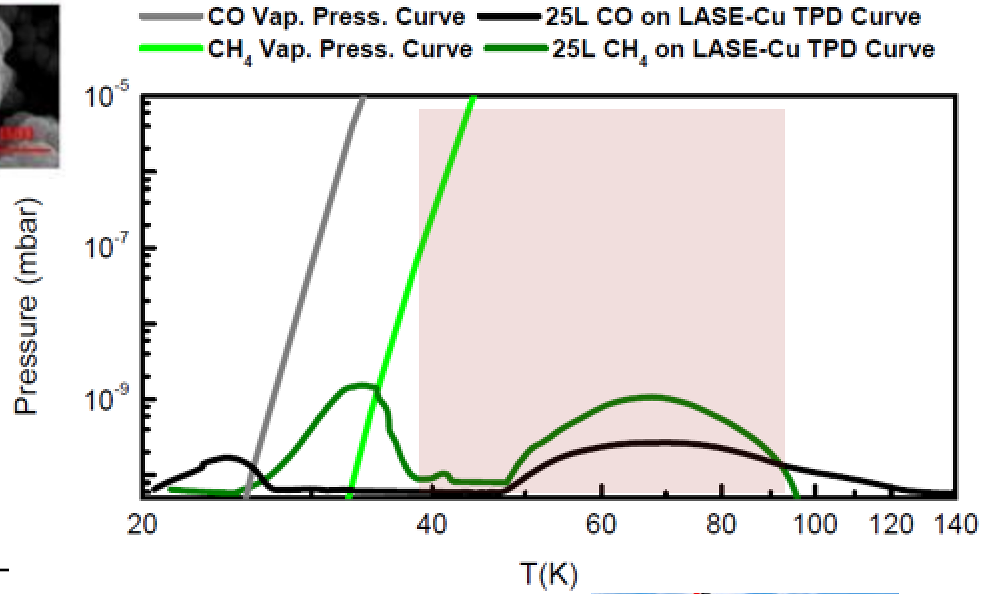
L. Spallino et al., Phys. Rev. Accel. Beams (2020)







L. Spallino et al. , Appl. Phys. Lett. (2019)



Consequences of this observation are relevant for the choice of the working temperature range in cold parts of accelerators (FCC)