R a PY from Candidate Materials for the FCC-hh Vacuum System.

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outline:

- The problem
- The experimental approach
- Selected results
- Conclusion

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Schematic of an 80 – 100 km long tunnel

FCC-hh Key Parameters

Version 1.0 (2014-02-11)	LHC	HL-LHC	FHC-hh
c.m. Energy [TeV]	14		100
Circumference *C* [km]	26.7		100 (83)
Dipole field [T]	8.33		16 (20)
Injection energy [TeV]	0.45		3.3
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0	5.0
Stored beam energy [GJ]	0.392	0.694	8.4 (7.0)
SR power per ring [MW]	0.0036	0.0073	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	0.33	28.4 (44.3)
Critical photon energy [keV]	0.044		4.3 (5.5)

The case of FCC-hh

FCC-hh Key Parameters

Schematic of an 80 – 100 km long tunnel

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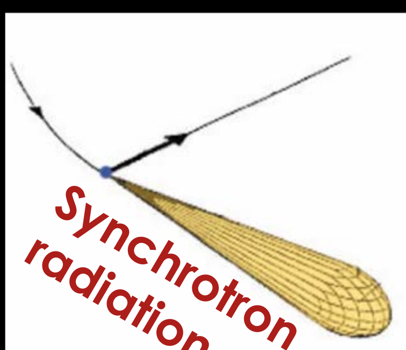
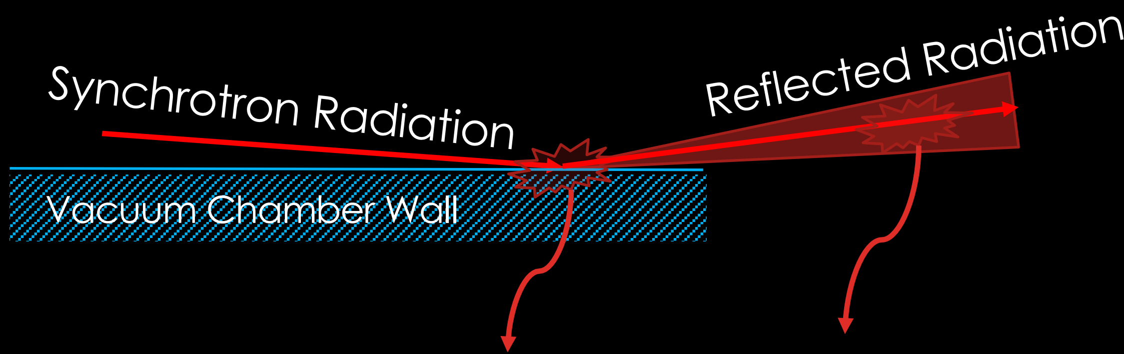
Cryogenic Operating Temperature (1.9 K at the dipole walls)



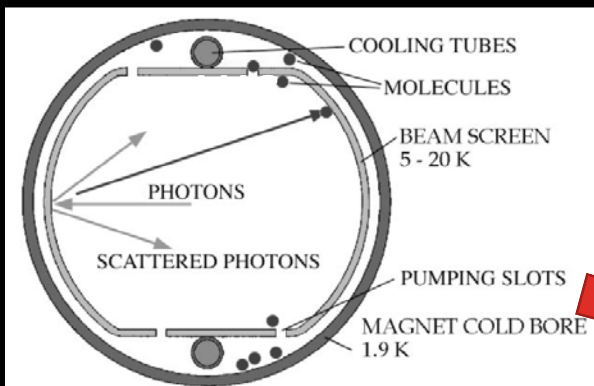
Incident Radiation = ~~Transmitted~~ + Reflected + Absorbed



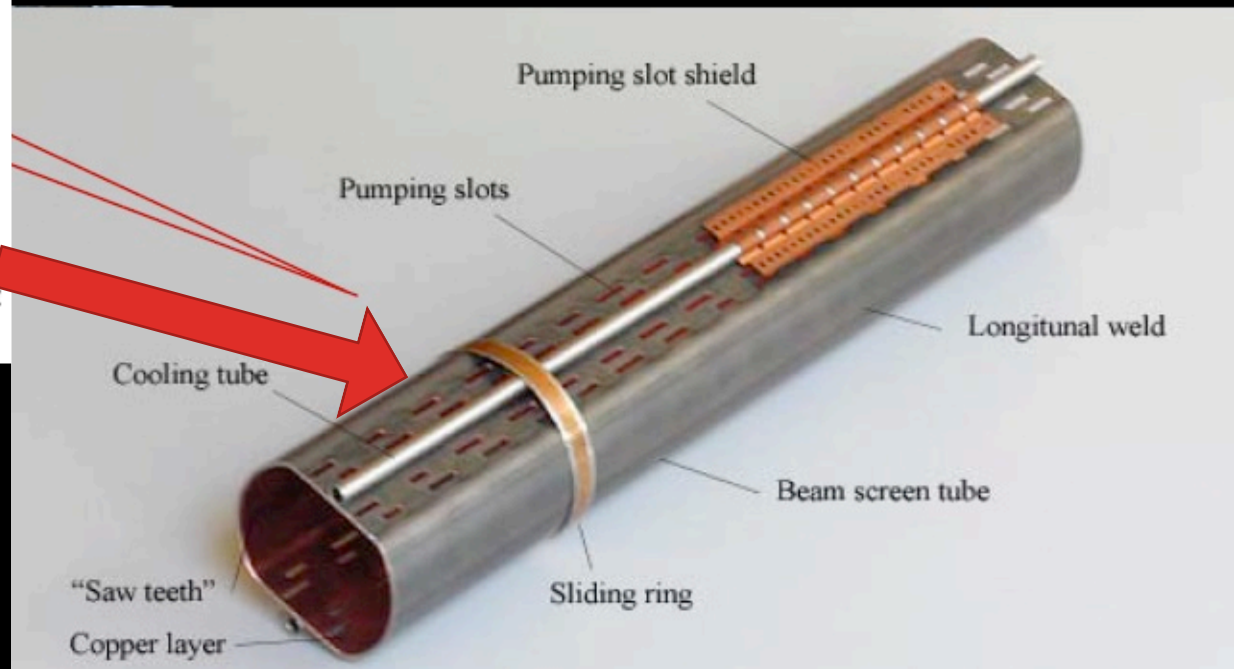
Absorbed Radiation	Reflected Radiation
• Heat Load • Photo Electrons • Photo Stimulated Desorption	• Heat Load • Photo Electrons • Photo Stimulated Desorption
On the orbit plane	ALL THIS IN OTHER PARTS OF THE MACHINE

From LHC Beam screen concept (5 K < T < 20 K)

F. Zimmermann et al., HF2014, Bejing, China (THP3H1)



43.6 mm

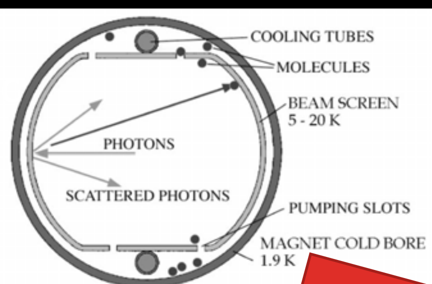


O. Gröbner, Vacuum 60 (2001) 25-34

SR = 0.17 W/m/ap
Tot. Power =0.007 MW

LHC Beam screen concept (5 K < T < 20 K)

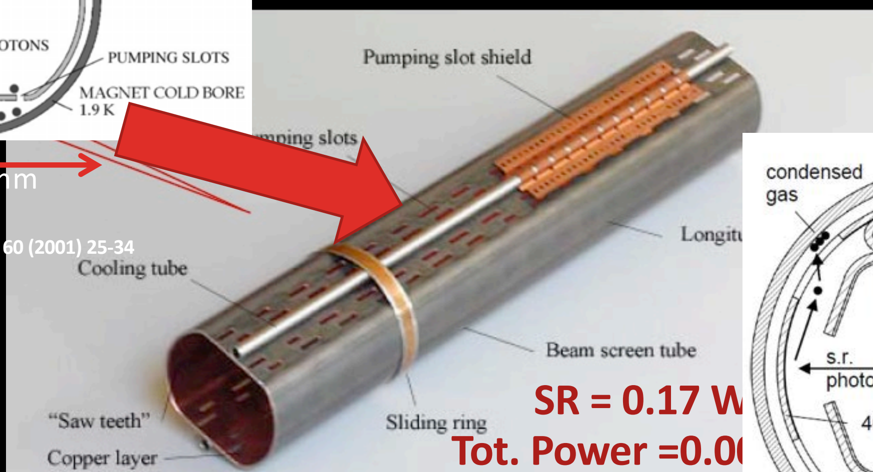
To FCC-hh Beam screen optimization (40 K < T < 60 K)

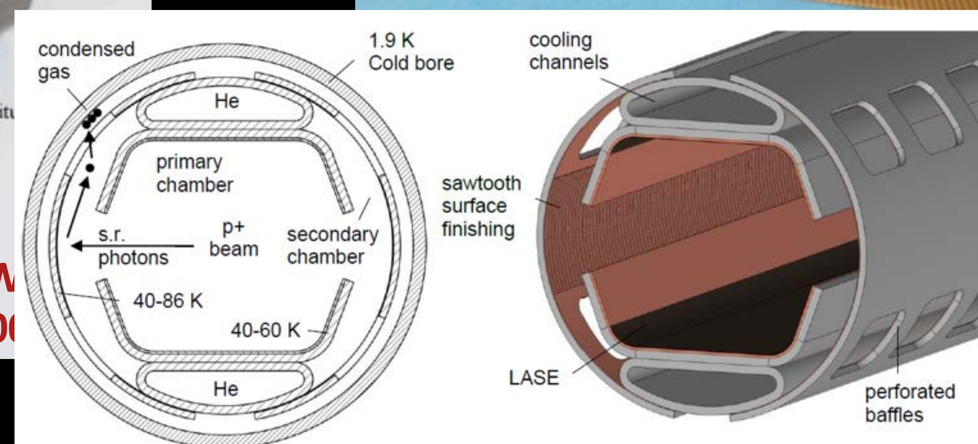


43.6 mm

O. Gröbner, Vacuum 60 (2001) 25-34

F. Zimmermann et al., HF2014, Bejing, China (THP3H1)





See: EuroCirCol-P2-WP4-D4.4_Analysis of beam-induced vacuum effects

Two main properties of material needs to be carefully investigated:

Reflectivity (R)

The part of incident radiation which is reflected by the wall chambers

Photo Yield (PY)

How many electrons are produced per incident photon

These properties depend on:

- Incident Angle: θ_i
- Energy of Radiation
- Chemical Composition of the Surface
- Surface Treatment
- Coating

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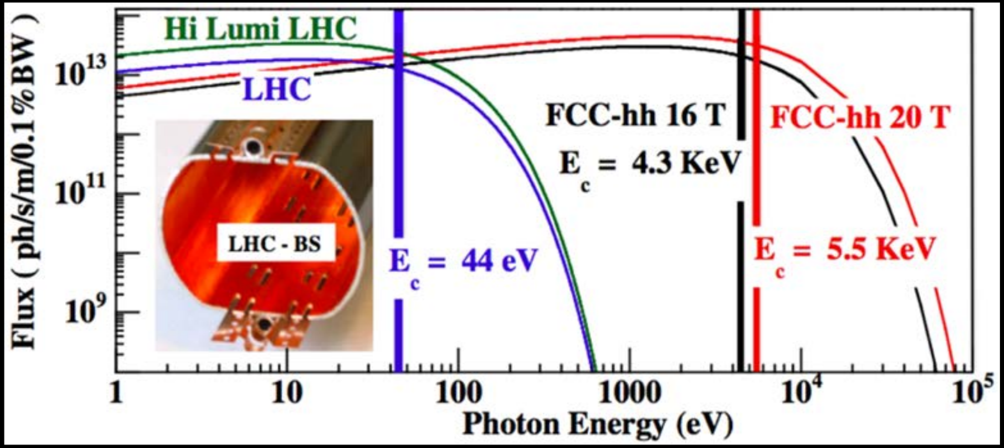
Very Grazing angles:

LHC ~ 0.28°

FCC-hh ~ 0.08°

Radiation Energy Spectrum: from eV to several keV



R. Cimino, V. Baglin and F. Schäfers, PRL. 115 (2015) 264804

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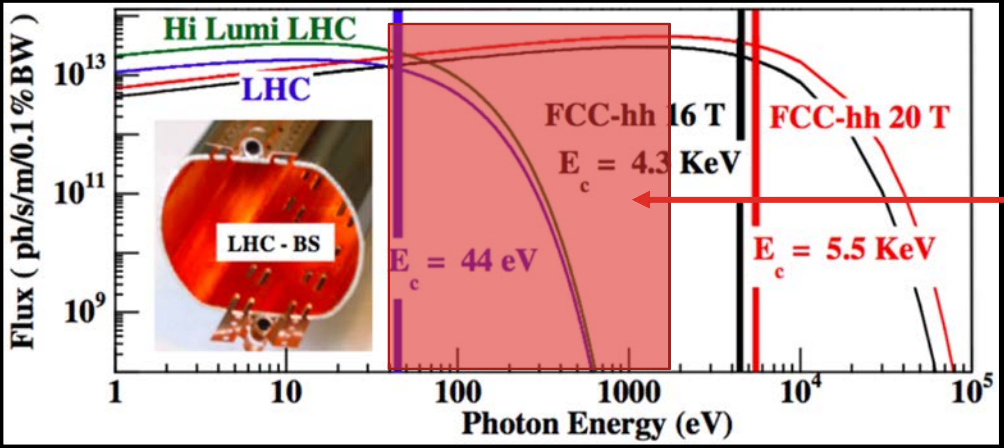
There are indications suggesting that R, and Photo induced desorption are more significant in the lower energy part of the spectrum.
PY should slowly increase with photon energy.

Radiation Energy Spectrum: from eV to several keV



R. Cimino, V. Baglin and F. Schäfers, PRL. 115 (2015) 264804

We first investigate the 35-1850 eV region

These properties depend on:

- Incident Angle: θ_i
- Energy of Radiation
- Chemical Composition of the Surface
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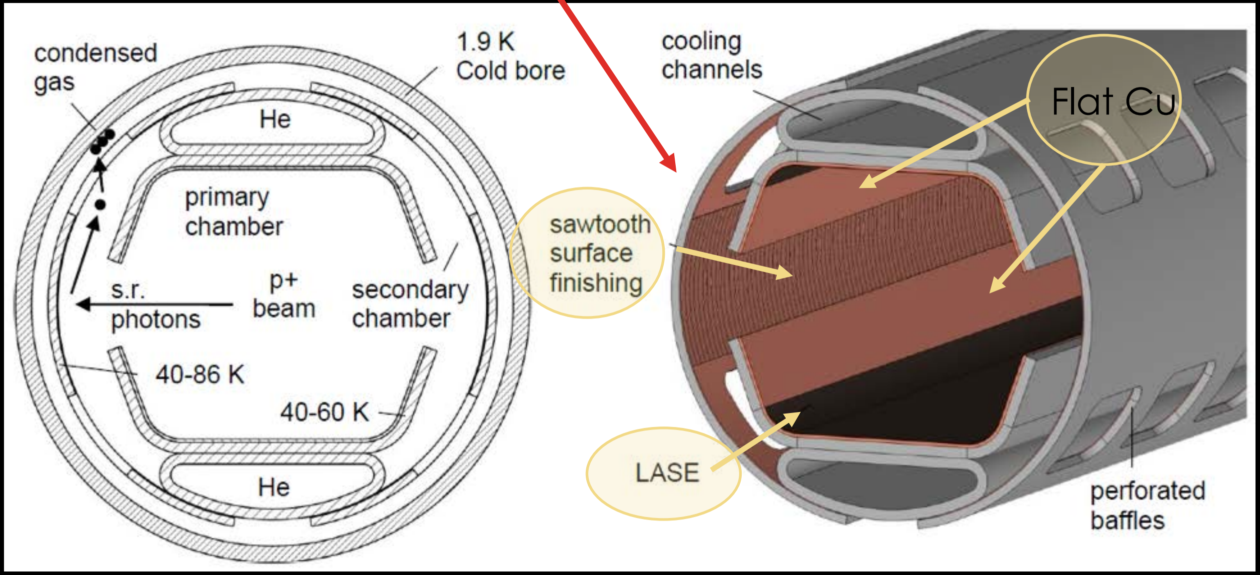


"Ray tracing" programs are at the base of the design phase and generally use R simulated values (from Reflectivity programs)

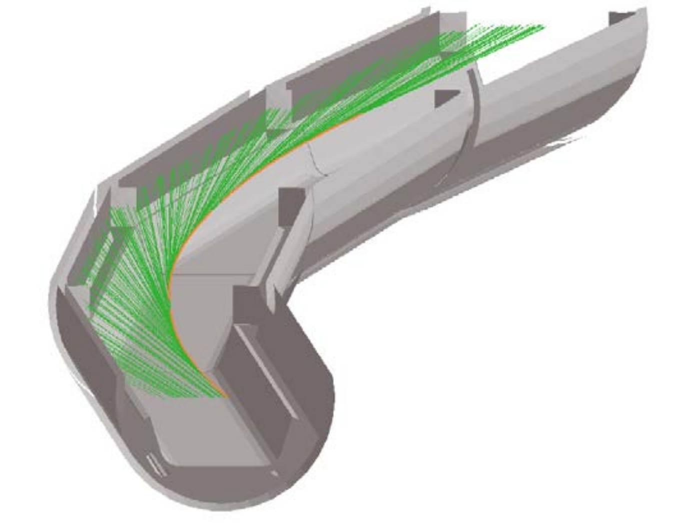


Figure 12. Ray tracing simulation of the SR flux generated by a 50 TeV, 500 mA beam, 15.78 T in the vacuum chamber of three consecutive MQ and a SSS, highlighting in green the photon trajectories

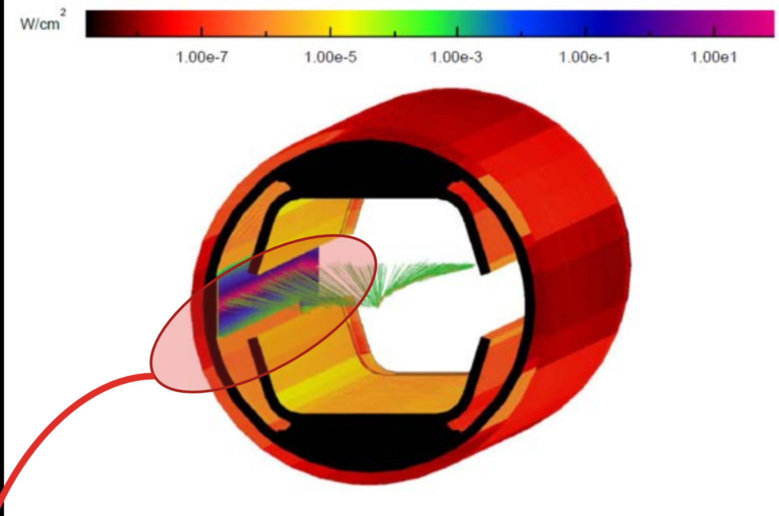


Figure 11. Ray tracing results of the SR power generated by a 50 TeV, 500 mA beam, 15.78 T in a standard arc dipole chamber, as obtained with Synrad+ [14]. The beam sagitta and photon trajectories can be clearly appreciated

Thanks to:
I. Bellafont

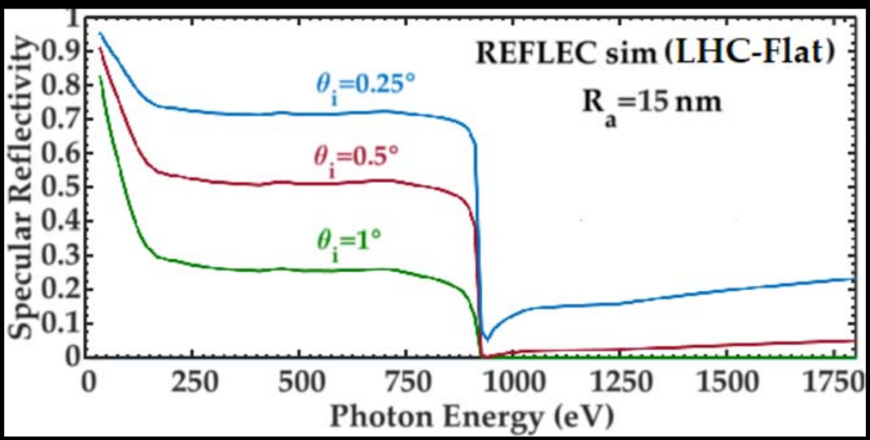
- Are simulated R data good enough?
- Or should we measure R and PY for all proposed materials in realistic geometrical conditions to validate all simulations?

Usually, analytical programs are used for optical calculation
To calculate **SPECULAR REFLECTIVITY**

R (specular reflectivity) is the normalized number of photons emerging from the sample with the same divergence of the incoming beam and at the geometrical reflection

R_t (total reflectivity) is the normalized (to the incoming flux) number of photons emerging from the sample in all directions.

In machine simulations both R and R_t are important.



REFLEC simulations of Specular reflectivity VS Photon Energy at three incidence angle for a LHC-Flat Cu sample vs. photon energy

In optical simulation codes R_a is a considered as a (Debye-Waller) perturbation. It does not work for:

- high roughness technical surfaces.
- high photon energies
- grazing angles
- also, at very grazing angles -> contaminants should play a major role (difficult to predict)
- Different Surface Geometry-> Saw Tooth profile (ST)
- Treated Surface -> Laser Treated Samples (LASE)

Experimental data are needed!

outline:

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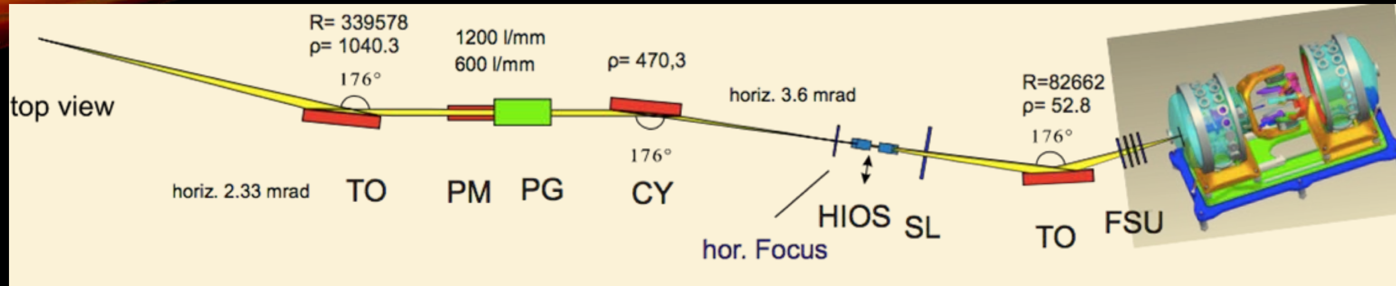
Strategy:

- Identified a close to optimal experimental set-up to perform Reflectivity and Photo Yield studies on technical materials of interest to FCC-hh at very grazing angle and in the wider energy range available.
- LNF launched a long term proposal (MICA) and received support by INFN and beamtime by the project CALIPSOplus. (under the Grant Agreement 730872 from the EU Framework Programme for Research and Innovation HORIZON 2020)
- In 2015 – 2018 an intense experimental campaign at the Synchrotron radiation Facility BESSY-2 using the Optics beamline and reflectometer (with guest experimentalists).

Experimental Layout



A. Sokolov, et al., Journal of Synchrotron Radiation 25, 100 (2018).

Experimental Parameters

- Phot. Energy range 35÷1800 eV
- Beam height h=0.3 mm
- Incident Beam measurement
- GaAsP Photodiodes (4x4mm) (0.1*4mm)
- Low Incident angles down to 0.25°
- High second order suppression

The Beamline

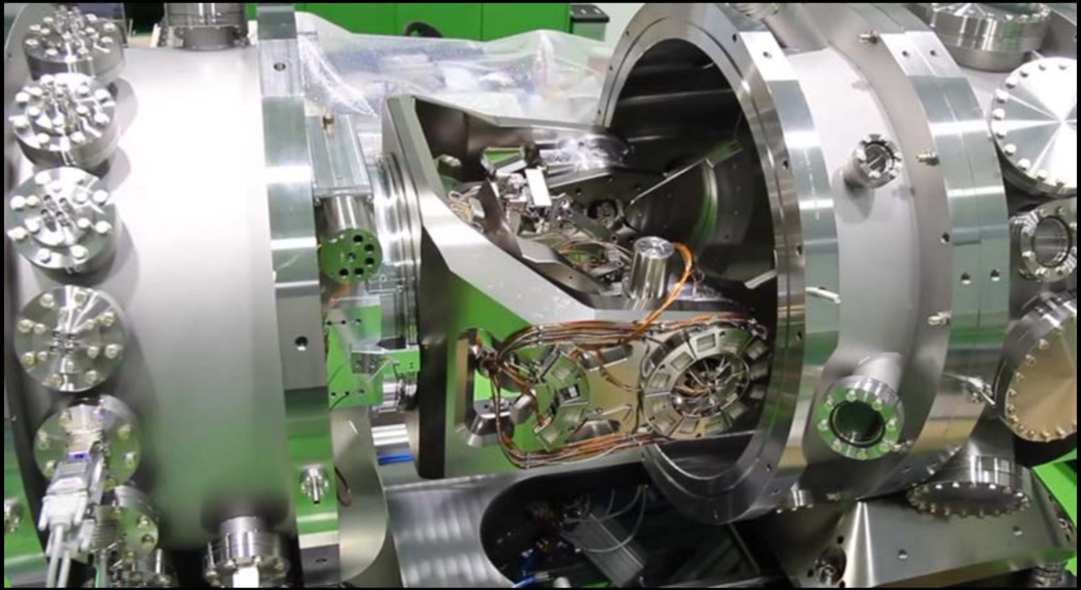
The Reflectometer

Axis	Hardware	Range	Pos. accuracy
Azimuth angle β	HUBER 430	-180° - 180°	3.6“
Sample angle θ	HUBER 411	-90° - 270°	3.6“
Detector angle 2θ	HUBER 411	-180° - 180°	3.6“
Detector off-plane (2 axes)	Ceramic motors	-25 mm – 25 mm (-4° - 4°)	50 nm
Sample Adjustment Tx, Ty, Tz	Ceramic motors	-20 mm – 20 mm (not simul.)	500 nm
Sample Adjustment Rx, Ry, Rz	Ceramic motors	-10° - 10° (not simul.)	1“

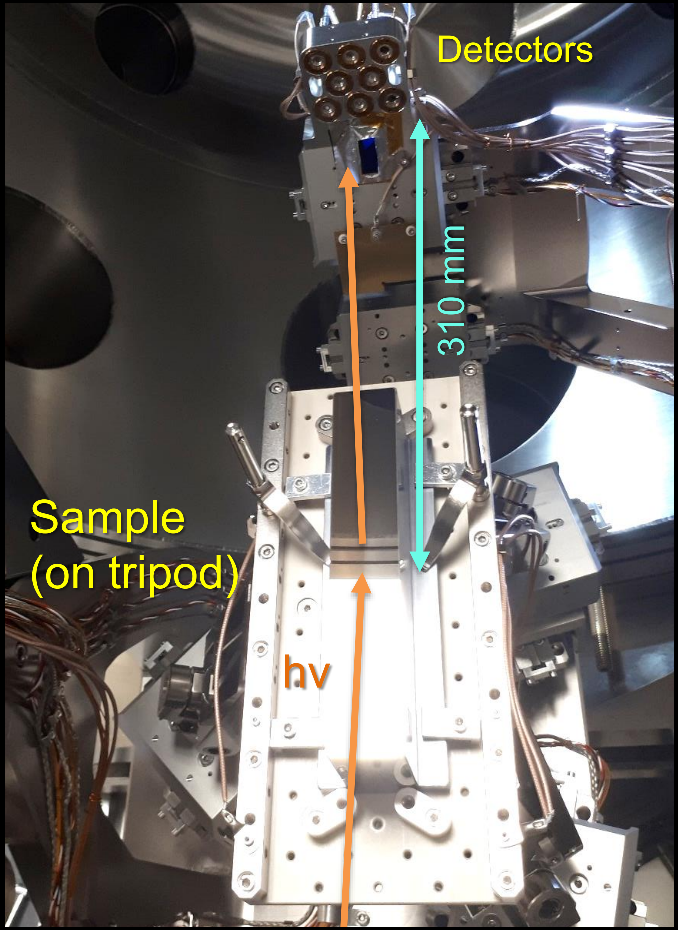
A.A.Sokolov,et al,Proc.of SPIE92060J-1-13(2014)

BESSYII – OPTICS Beamline end station

See movie at: https://www.helmholtz-berlin.de/pubbin/igama_output?modus=datei&did=887

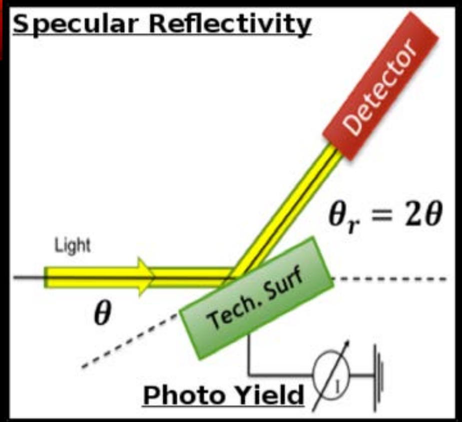


REFLECTOMETER



Station dedicated to the at wavelength characterization of precision gratings and nano-optical devices

EXPERIMENTAL LAYOUT



θ/2θ geometry allows to detect the specular reflected signal.
Two possible way

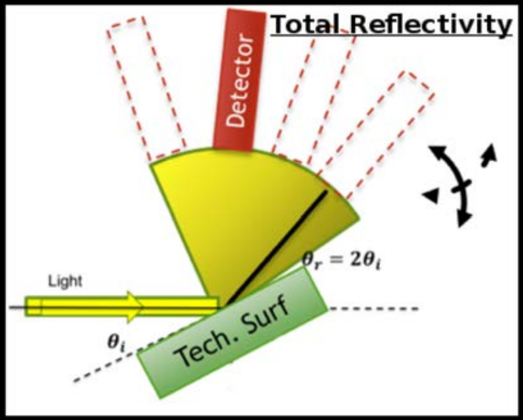
Fixed θ/2θ Beam Energy Scan

Fixed Beam Energy θ/2θ Scan

$$R = \frac{I}{I_0}$$

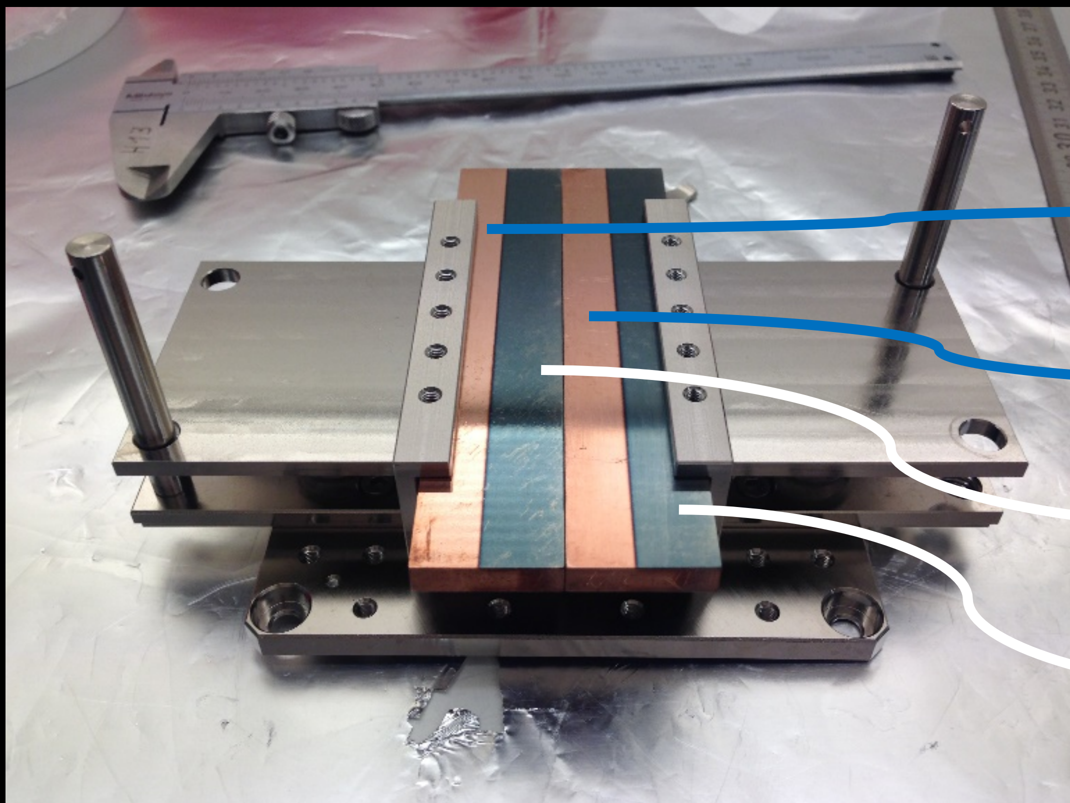
Simultaneously measure the current generated on the sample is detected for **PY**

$$PY = \frac{N_e}{N_\gamma}$$



Fixed photon energy and incident angle Moving the detector in θ_r and Φ, the **angular distribution** of the Reflected signal is mapped.

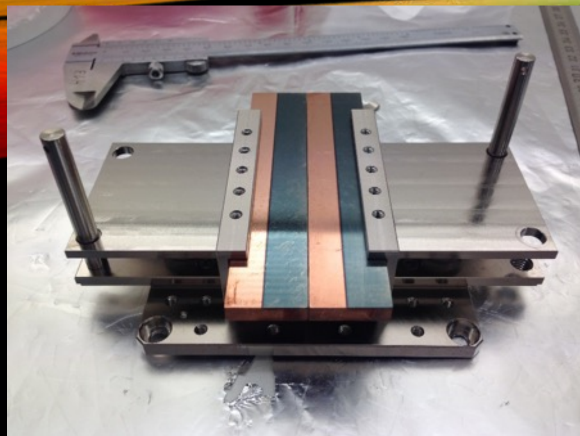
To study the impact of Ra on reflectivity



AFM data

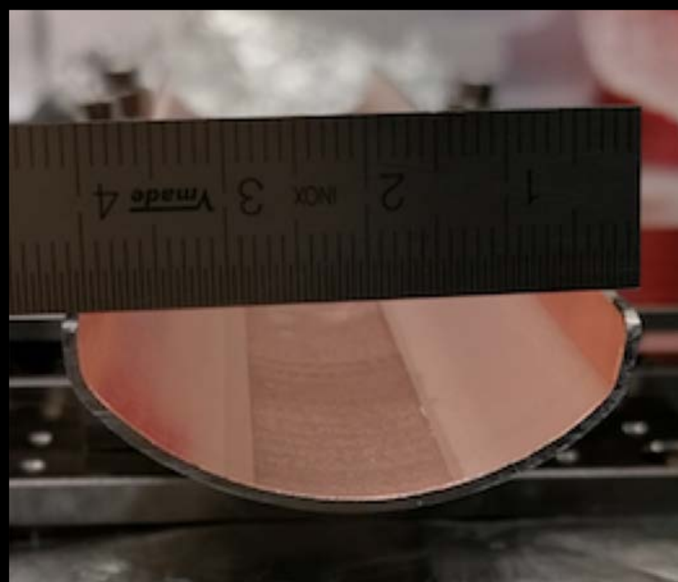
Sample	RMS Roughness (R_a)
Cu 1A	10 nm
Cu 2A	27 nm
Cu 1B	25 nm
Cu - LHC	15 nm
Cu 1A CC	13 nm
Cu 2A CC	28 nm
Cu 1B CC	32 nm
Cu – LHC CC	20 nm

Cu (different Roughness)
Cu+ a-Carbon Thin Film (50 nm)

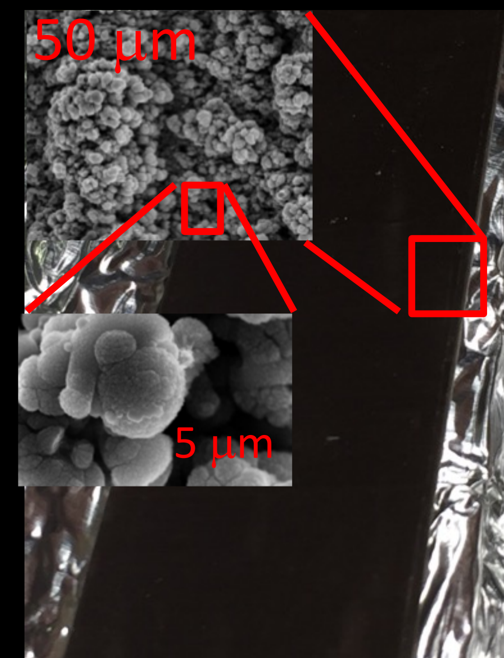


The sample studied:
Cu (different Roughness)
LHC - Saw Tooth
LASE
Cu+ amorphous Carbon Thin Film
and: NEG, Stainless Steel, ...

Cu LHC



LHC Saw Tooth



LASE Cu

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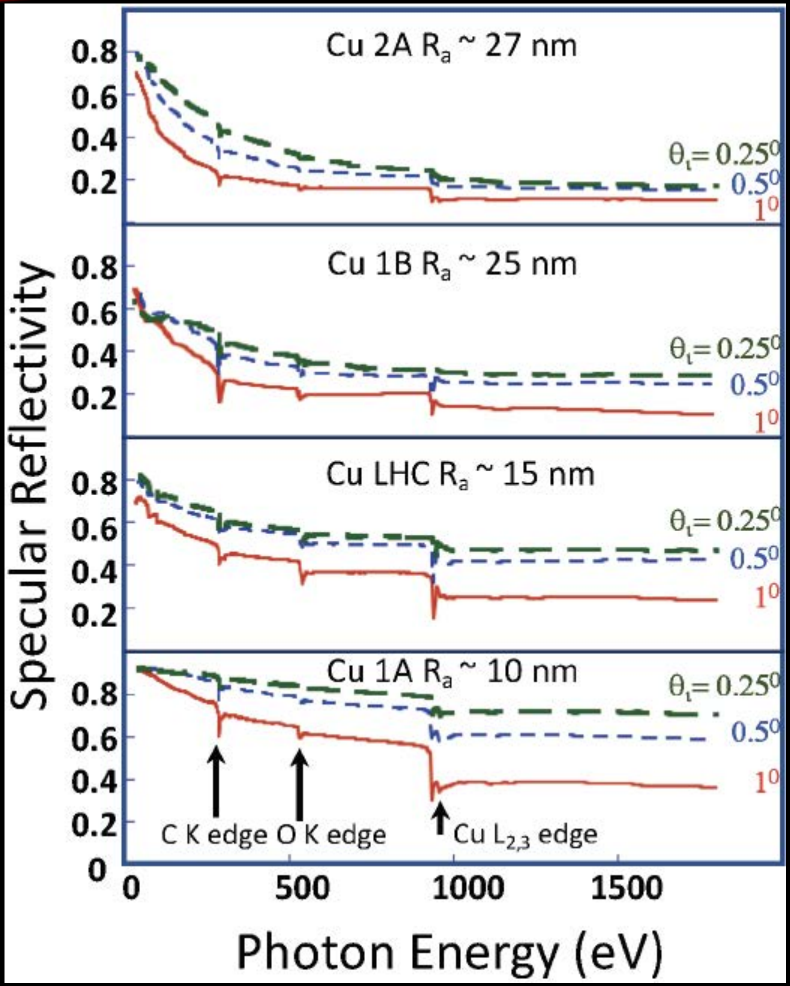
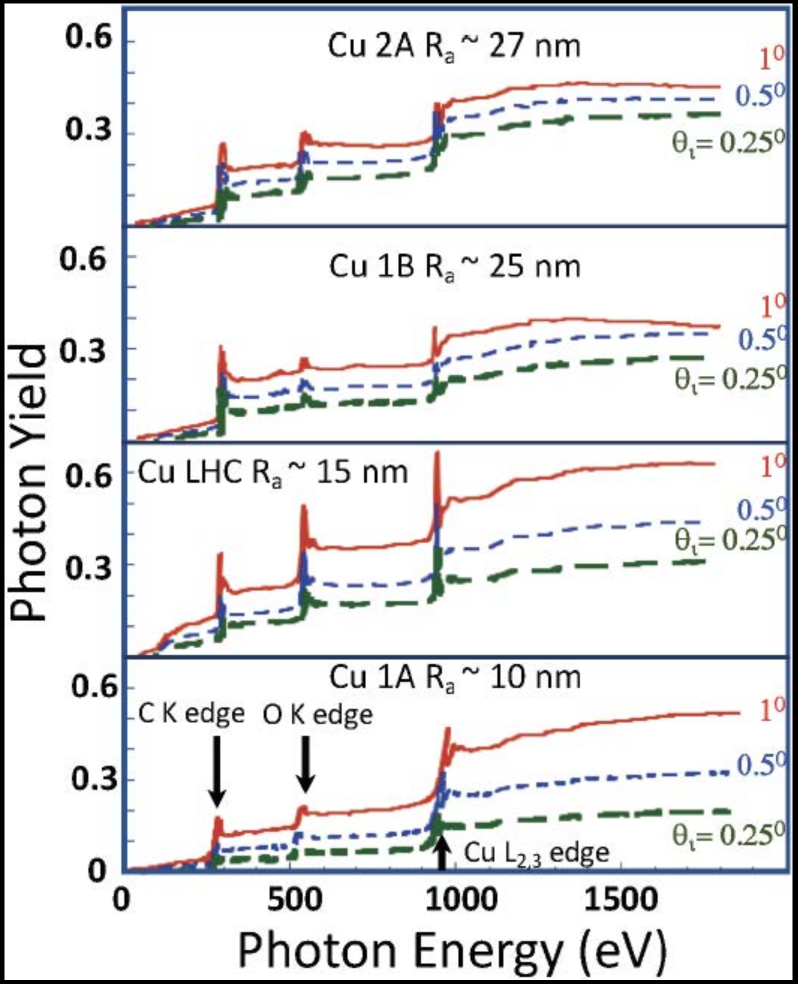
Specular Reflectivity and Photo Yield





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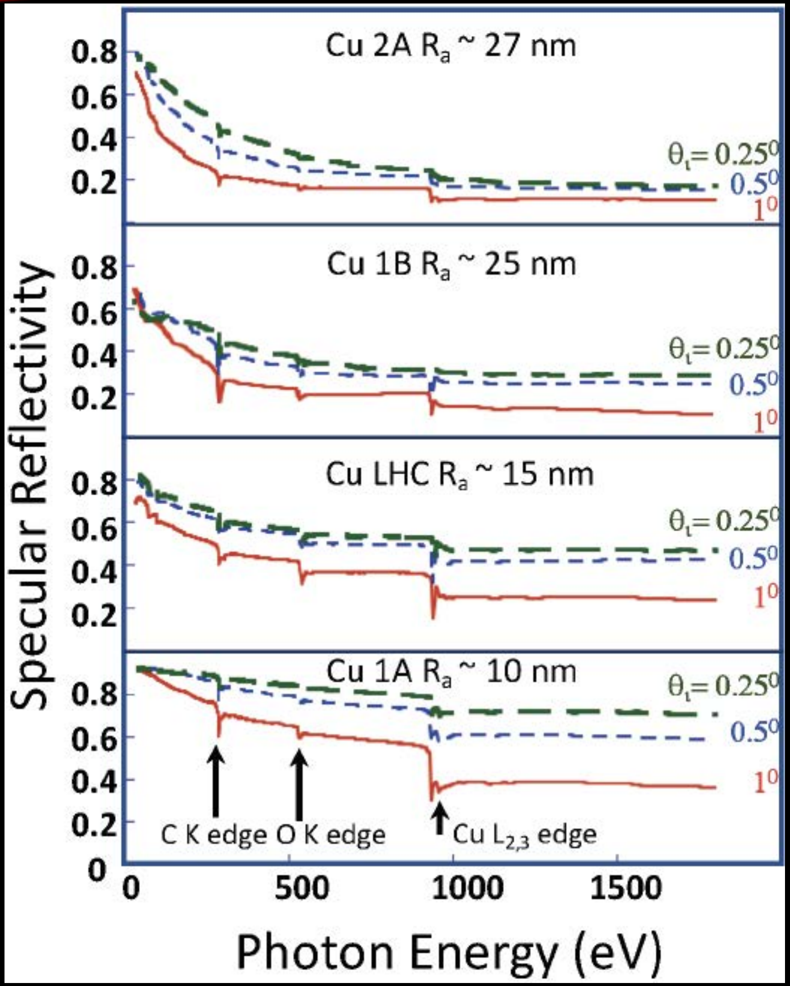
Specular Reflectivity and Photo Yield



- In all cases, R is higher at lower photon energies.
- In all cases, R is higher at lower angle of incidence θ_i.
- Reflectivity, after the observed Cu-$L_{2\text{-}3}$ absorption edge at 930-950 eV is much higher than in simulation.
- In all spectra we measure a significant effect due to the absorption edges of C K-edge at 280 eV and O Kedge at 530 eV (surf. cont.)
- C and O K absorption edges are more effective at lower incidence angles.
- Roughness, as expected, plays a major role in determining the ability of a surface to specularly reflect impinging photons.

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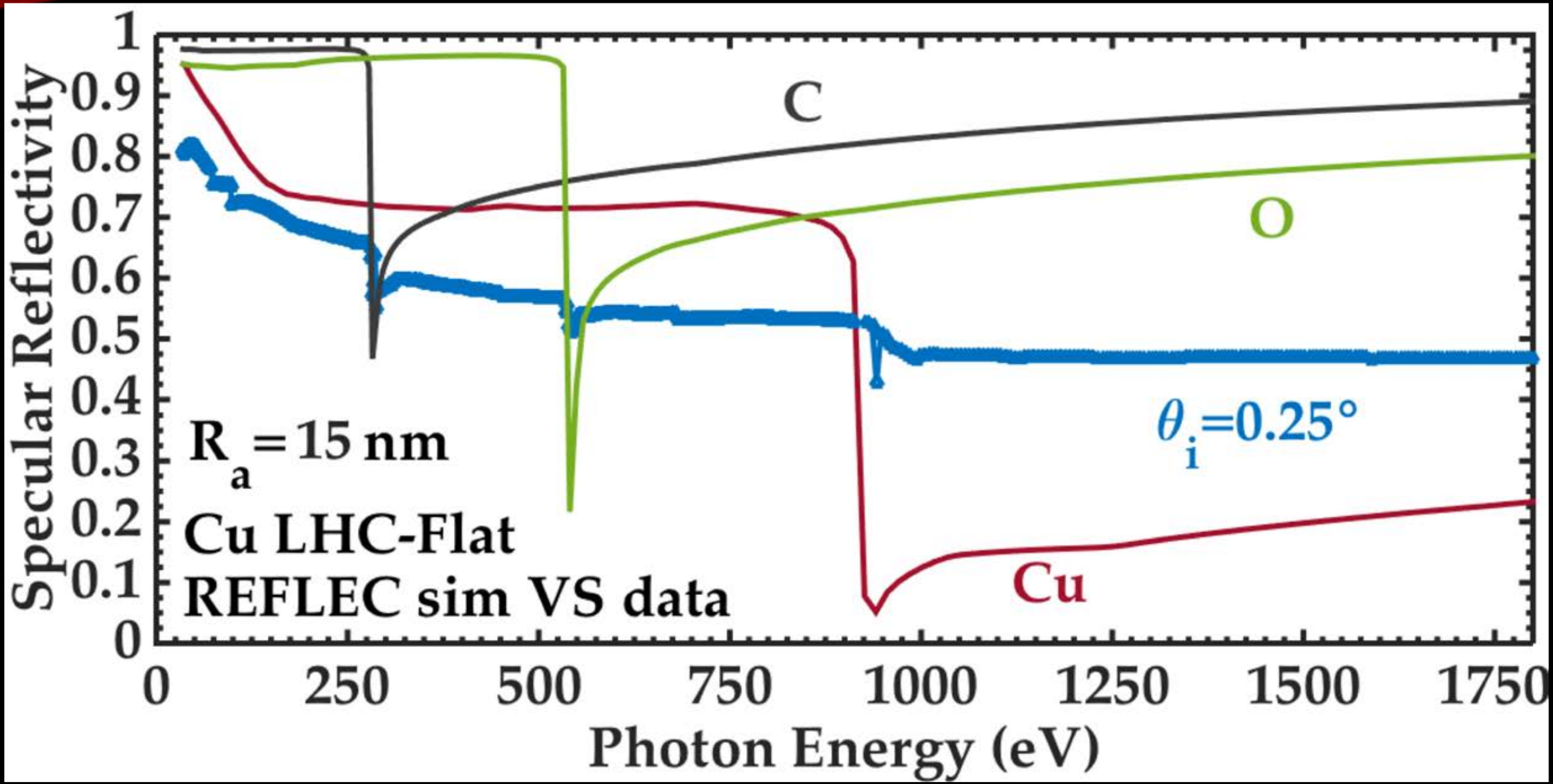
Specular Reflectivity and Photo Yield



Comparison of REFLEC simulations and experimental data of Specular Reflectivity VS Photon Energy of Cu LHC sample (θ_i = 0:25). To understand the role of air contaminants simulations for Carbon and Oxygen are also reported.

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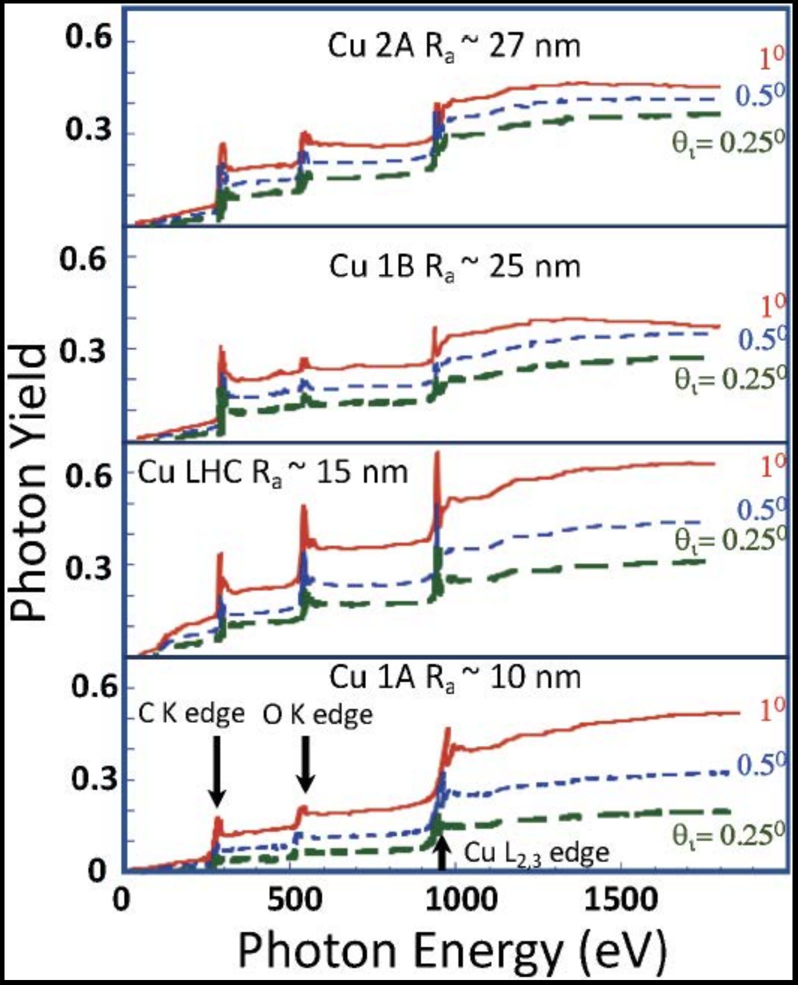
Specular Reflectivity and **Photo Yield**

- In all cases, PY is higher at higher photon energies.
- The PY dependence on θ_i is consistently dimmed and finally washed out when surface Ra is increasing.
- In all cases, the Cu-L2-3 absorption edge at 930-950 eV is visible and cause an increase in the measured PY.
- In all spectra we measure a significant effect due to the C K-edge at 280 eV and O K-edge at 530 eV (surf. Contaminants)
- Roughness does influence the PY. The lower is Ra, the highest is the measured PY. Also because Reflected photons do not produce photoelectrons!



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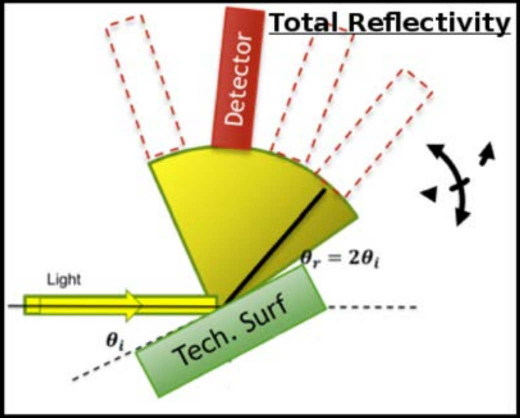
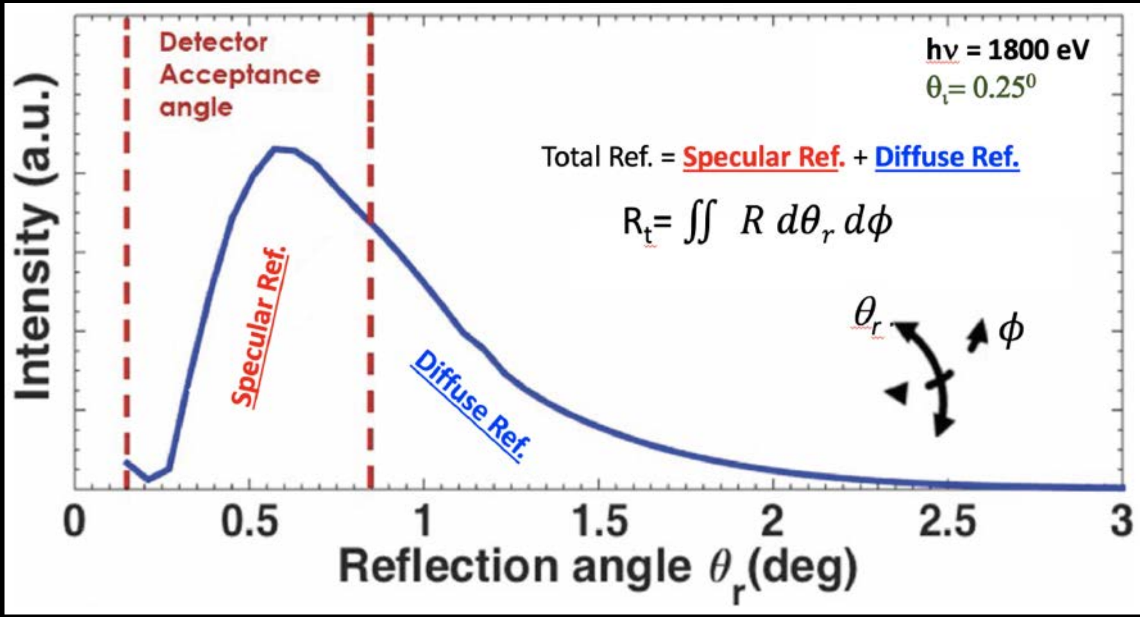
Angular Distribution of Reflectivity

Incident angle
photon Energy } Fixed
The detector moves over the reachable Solid Angle[Φ θ]





Total Reflectivity is calculated integrating the angular distribution in θ_r **and Φ**

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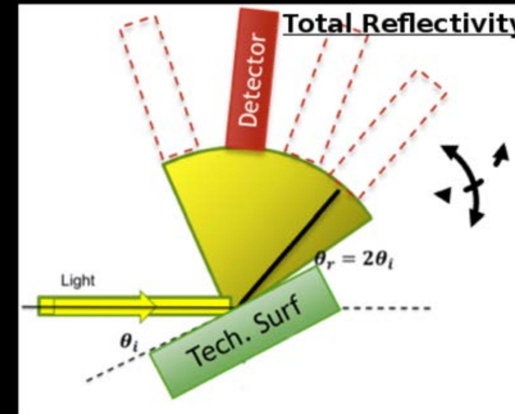
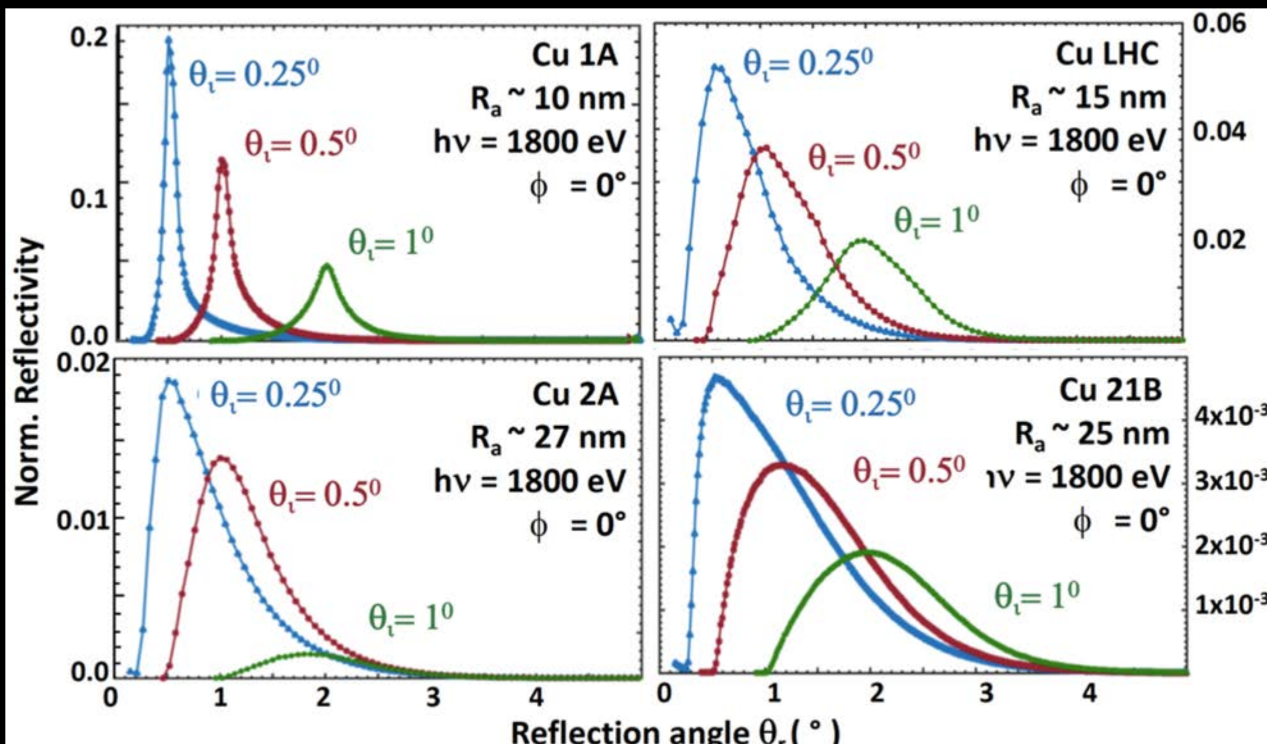
Angular Distribution of Reflectivity



Reflectivity Angular Distribution of Samples
With different Roughness



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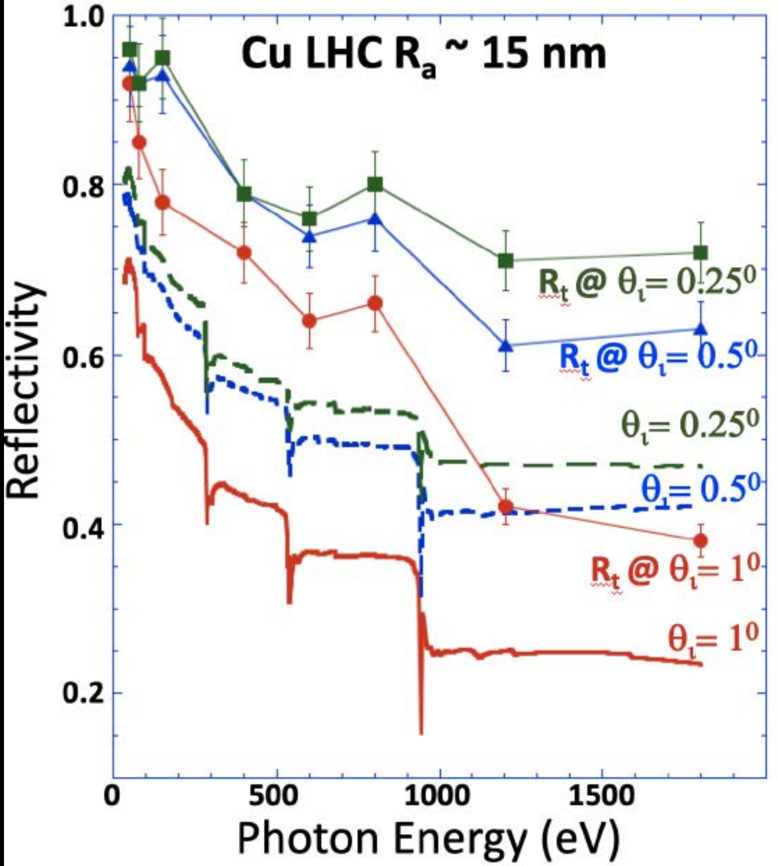
Specular Reflectivity VS Total Reflectivity



Photon energy $h\nu$(eV)	Specular Reflec. $\theta_i = 0.25°$ ($\Delta R/R=\pm$ 2%)	Total Reflec. $\theta_i = 0.25°$ ($\Delta R_t/R_t=\pm 5\%$)
1800	0.47	0.72
1200	0.47	0.71
800	0.53	0.80
600	0.54	0.76
400	0.59	0.79
150	0.71	0.95
80	0.75	0.92
50	0.81	0.96

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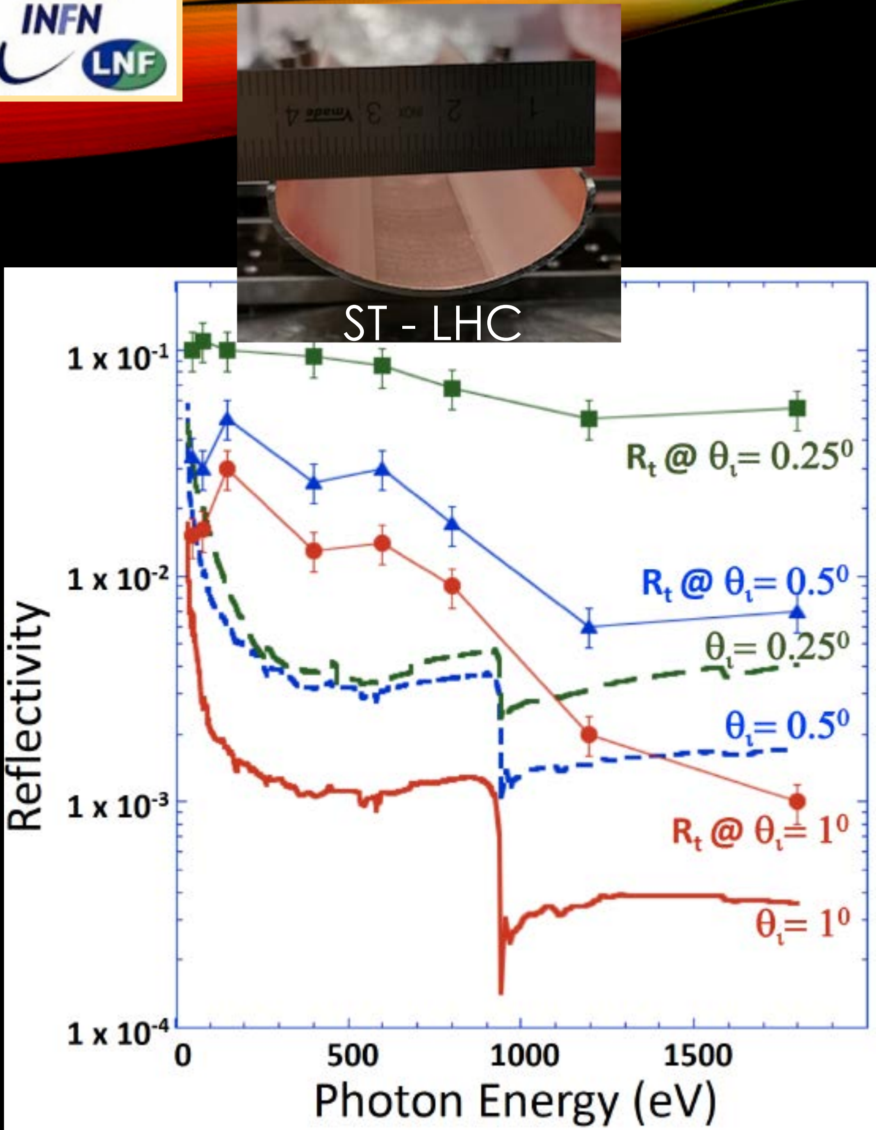
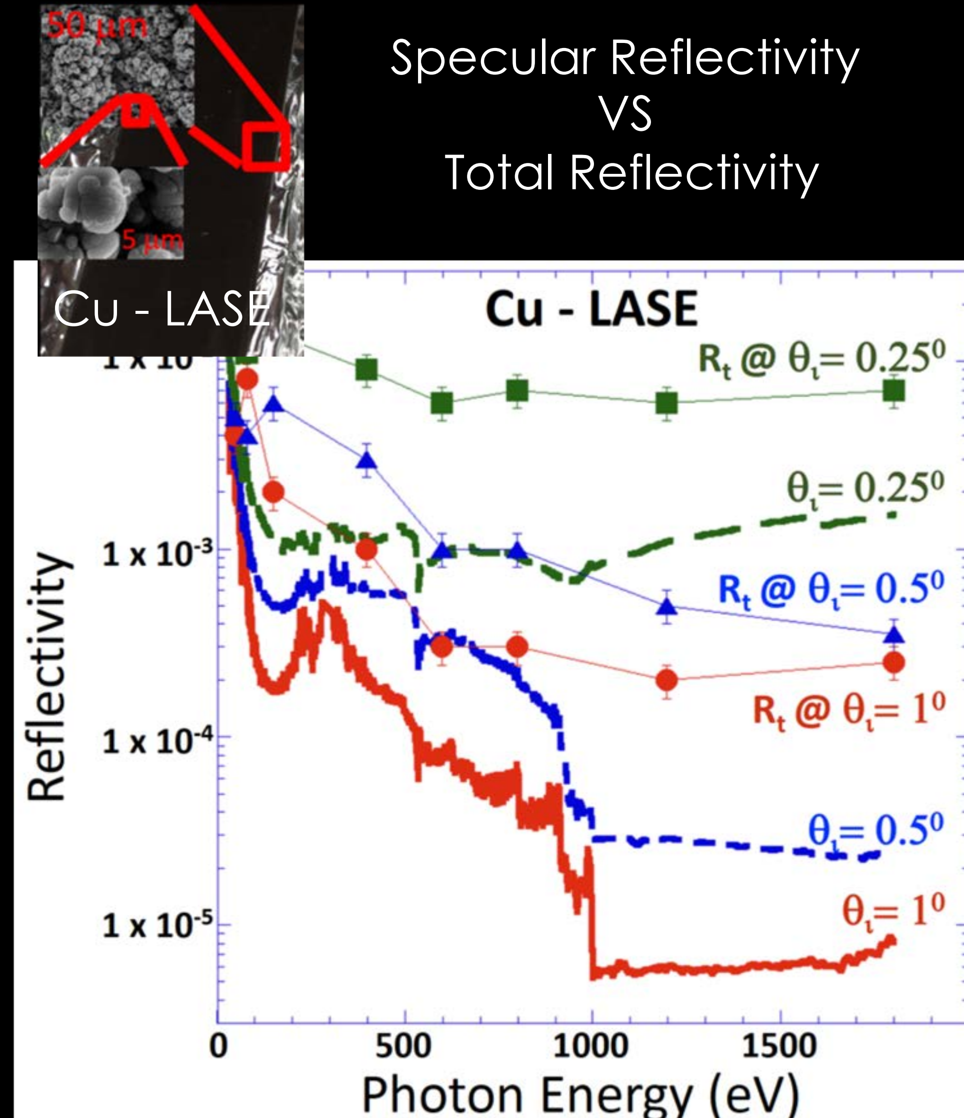
Specular Reflectivity
VS
Total Reflectivity





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Specular Reflectivity
VS
Total Reflectivity

Photon energy $h\nu$(eV)	Specular Reflec. $\theta_i = 0.25°$ ($\Delta R/R = \pm$ 2%)	Total Reflec. $\theta_i = 0.25°$ ($\Delta R_t/R_t = \pm$ 10%)
1800	0.004	0.05
1200	0.003	0.05
800	0.0045	0.07
600	0.0035	0.08
400	0.004	0.1
150	0.01	0.10
80	0.02	0.11
50	0.03	0.10

Photon energy $h\nu$(eV)	Specular Reflec. $\theta_i = 0.25°$ ($\Delta R/R = \pm$ 2%)	Total Reflec. $\theta_i = 0.25°$ ($\Delta R_t/R_t = \pm$ 20%)
1800	0.0015	0.007
1200	0.0011	0.006
800	0.0009	0.007
600	0.0009	0.006
400	0.001	0.009
150	0.001	0.014
80	0.003	0.011
50	0.006	0.012

We can generate experimental values that can be mediated and used in realistic simulations.

E. La Francesca et al: submitted to PR ST

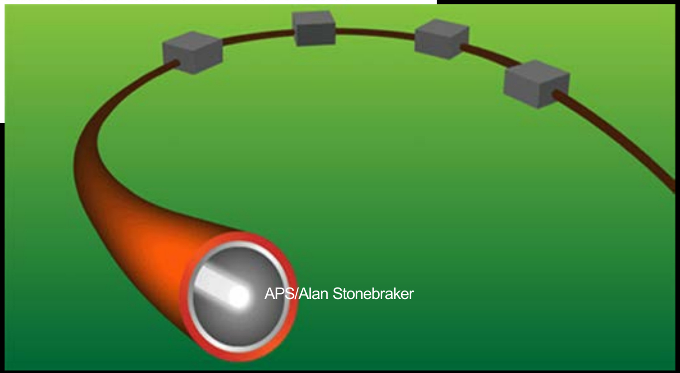
Presented at: FCC-2015 Washington

Do alternatives to optimization of HL removal from BM cold masses exists?

PRL **115,** 264804 (2015) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2015

Potential Remedies for the High Synchrotron-Radiation-Induced Heat Load for Future Highest-Energy-Proton Circular Colliders

R. Cimino,[1,2,*] V. Baglin,[2] and F. Schäfers[3]



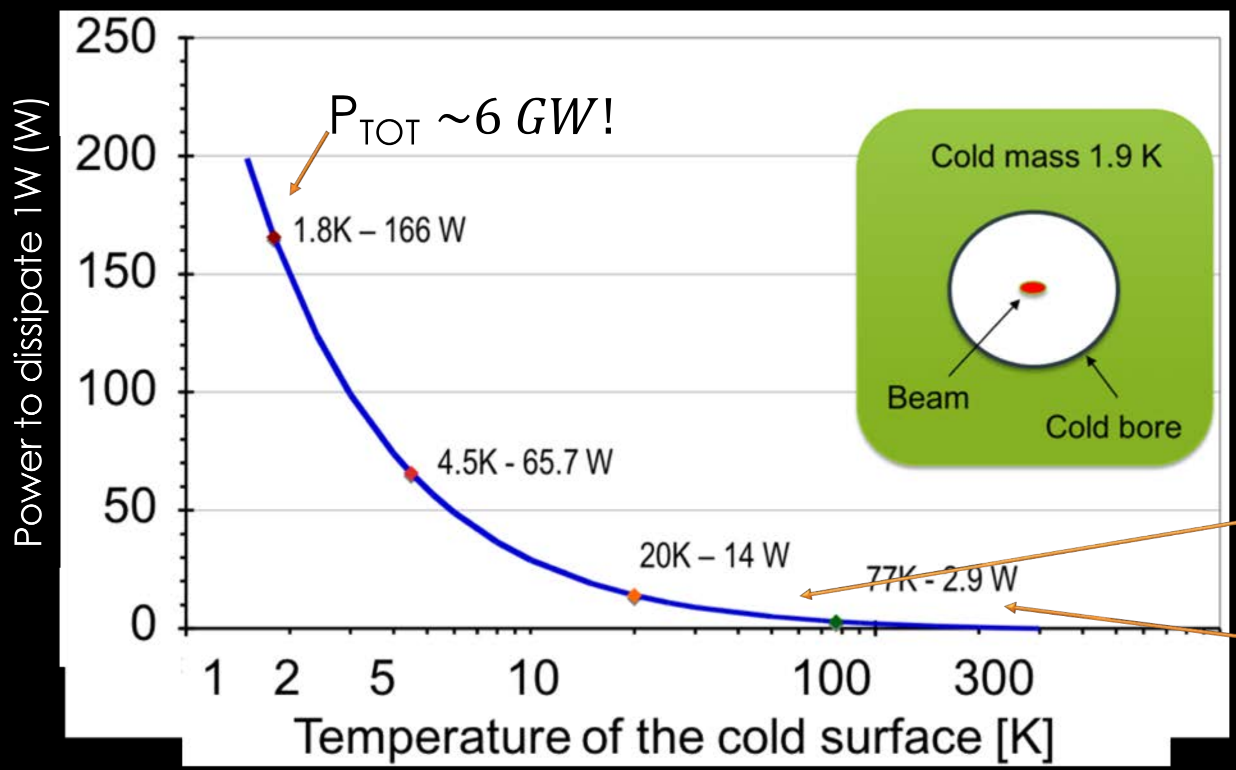
From: APS physics Physics

Synopsis: Cooler Colliders

...... The proposal is to coat the interior of the copper tube with a thin layer of carbon that reflects all the incident radiation. ...... the radiation, and the heat it carries, is transported away from colder regions towards periodically placed room-temperature absorbers, which are easier and cheaper to cool than the tube itself. **The authors claim that this design would reduce the power consumption potentially cutting the associated costs in half**.
(– Katherine Wright, APS, Physics)

Heat Load Dissipation VS Temperature

Some Numbers:
(Power → Feasibility → Sustainability!)



@ 60K $P_{TOT} \sim 100\ MW$

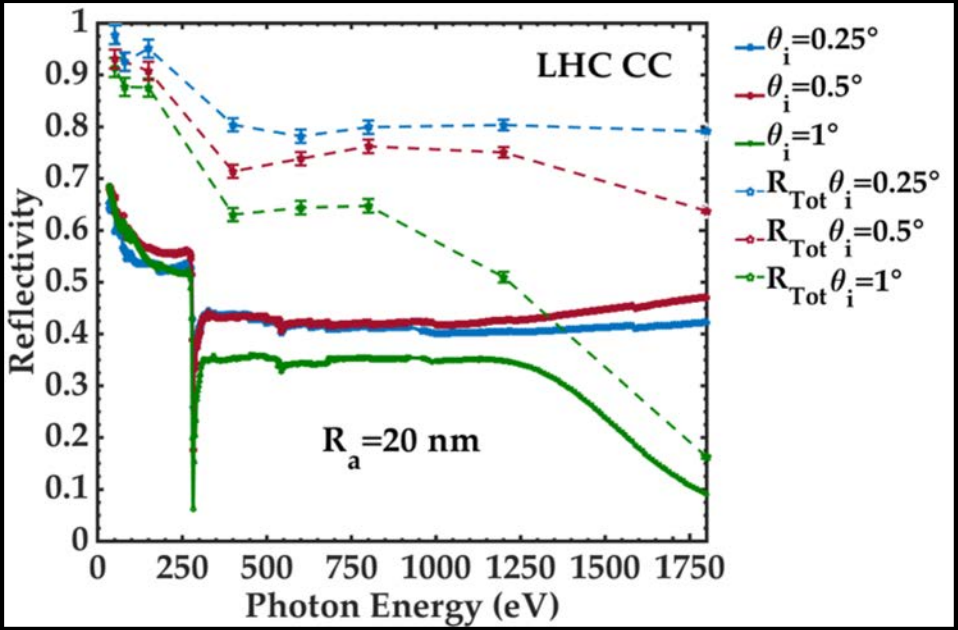
@ RT $P_{TOT} \sim 20\ MW$

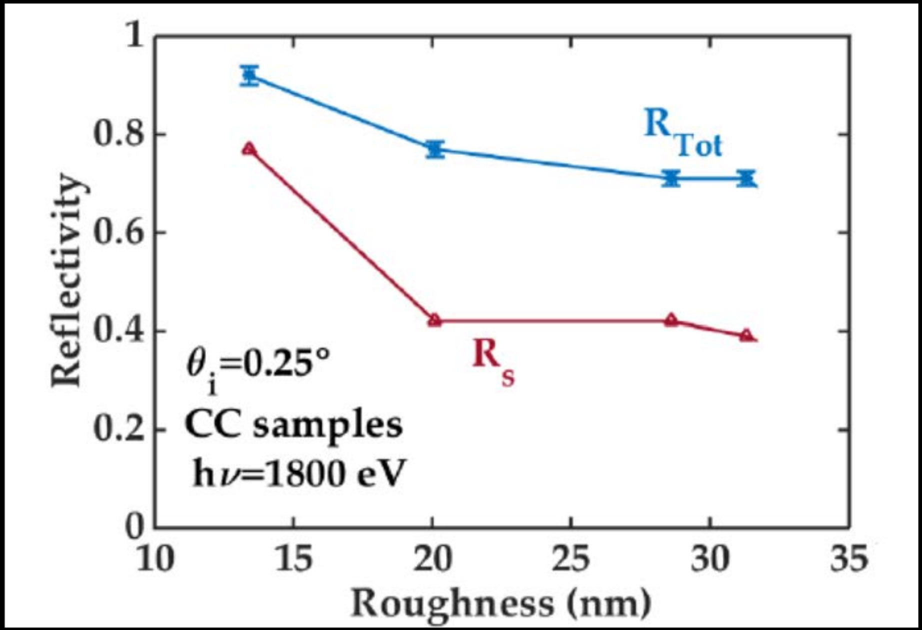
Credits: R. Kersevan - 2017

R. Cimino, V. Baglin and F. Schäfers, PRL. 115 (2015) 264804

Specular and Total Reflectivity VS Photon Energy of LHC-Flat Carbon Coted (CC) sample.

Comparison between Specular and Total Reflectivity VS R_a for Carbon coated samples: at 1800 eV and incidence angle θ_i = 0.25°





Increases with decreasing θ_i
It stays above 80 %

Does not significantly decreases with R_a!!

R. Cimino, et al to be published

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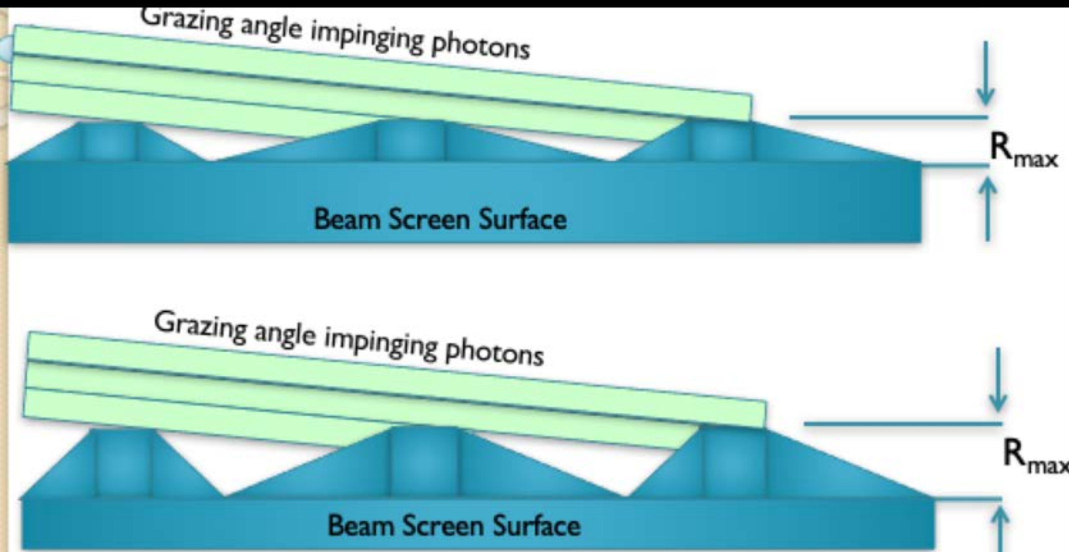
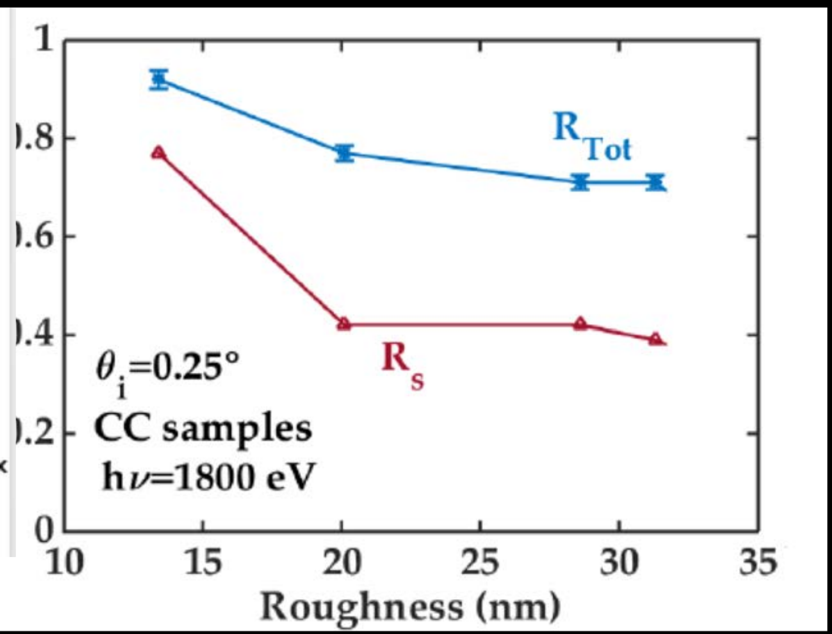
R. Cimino, V. Baglin and F. Schäfers, PRL. 115 (2015) 264804





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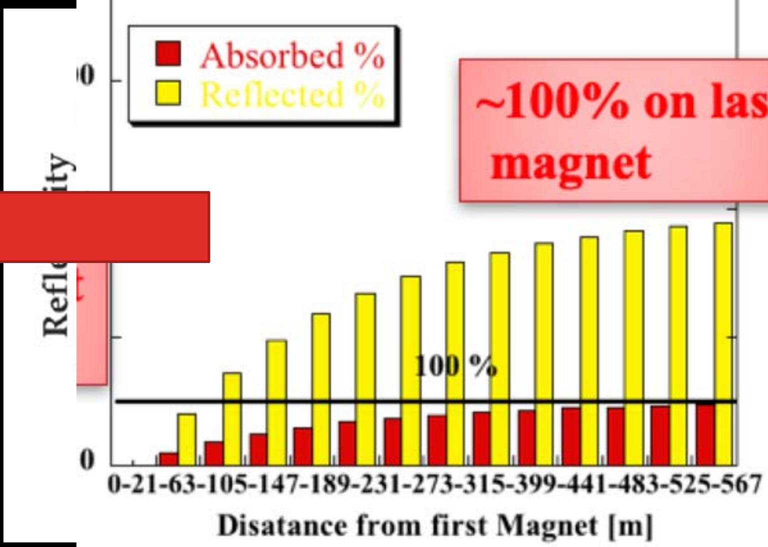
PRL **115**, 264804 (2015) PHYSICAL REVIEW LETTERS

Potential Remedies for the High Synchrotron-Radiation-Induced Heat Lo... Highest-Energy-Proton Circular Colliders

Heat Load Propagation Vs Reflectivity of BS

LHC standard surface finish

Depending on the distance between RT absorbers, one can foresee a significant reduction in the HL to be dissipated at COLD, and reduce constructive and machine running costs.



~100% on last magnet

Within 500m ~ 70% of expected HL adsorbed @ LT

R. Cimino, V. Baglin and F. Schäfers, PRL. 115 (2015) 264804

outline:

- The problem
- The experimental approach
- Selected results
- Conclusion

Conclusion

- R and PY on technically relevant samples can be experimentally measured!
  - We showed: - the importance of contaminants (LT studies?)
    - the importance of total R
- Simulation for Machine Design study must be supported by:
  - Experimental data of each individual Material Property
  - Dedicated experiments are the only way to produce the necessary inputs close to realistic conditions.
- We experimentally add a positive piece of information to validate the use of low SEY, high Reflectivity Carbon coatings to extract the HL from the cold BS to RT absorbers with a net reduction in building and running costs.

Acknoledgments

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