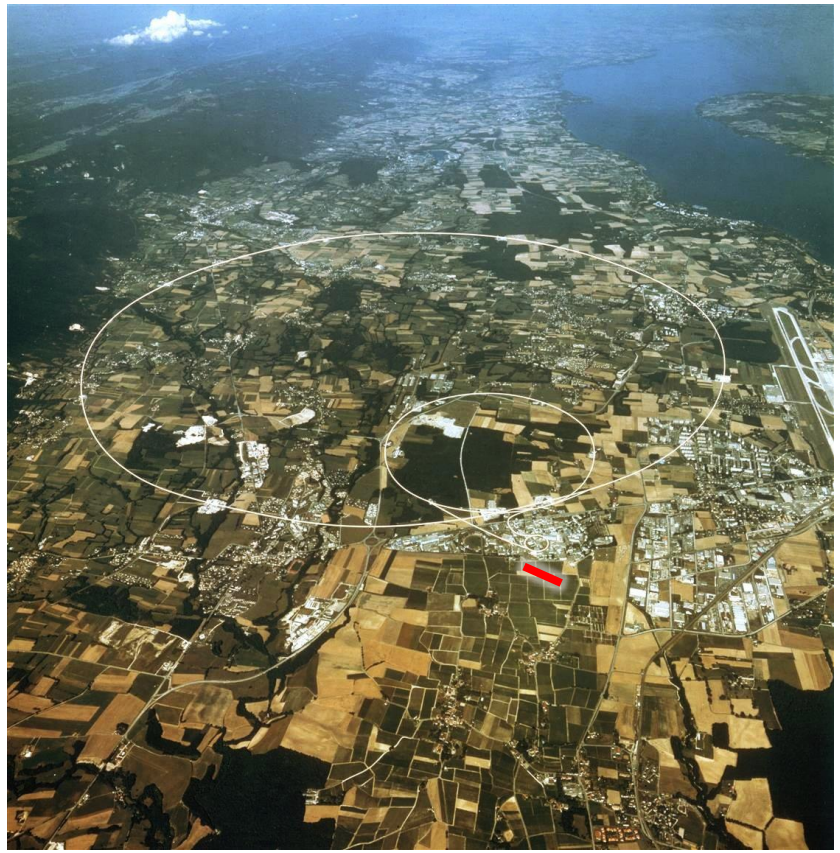
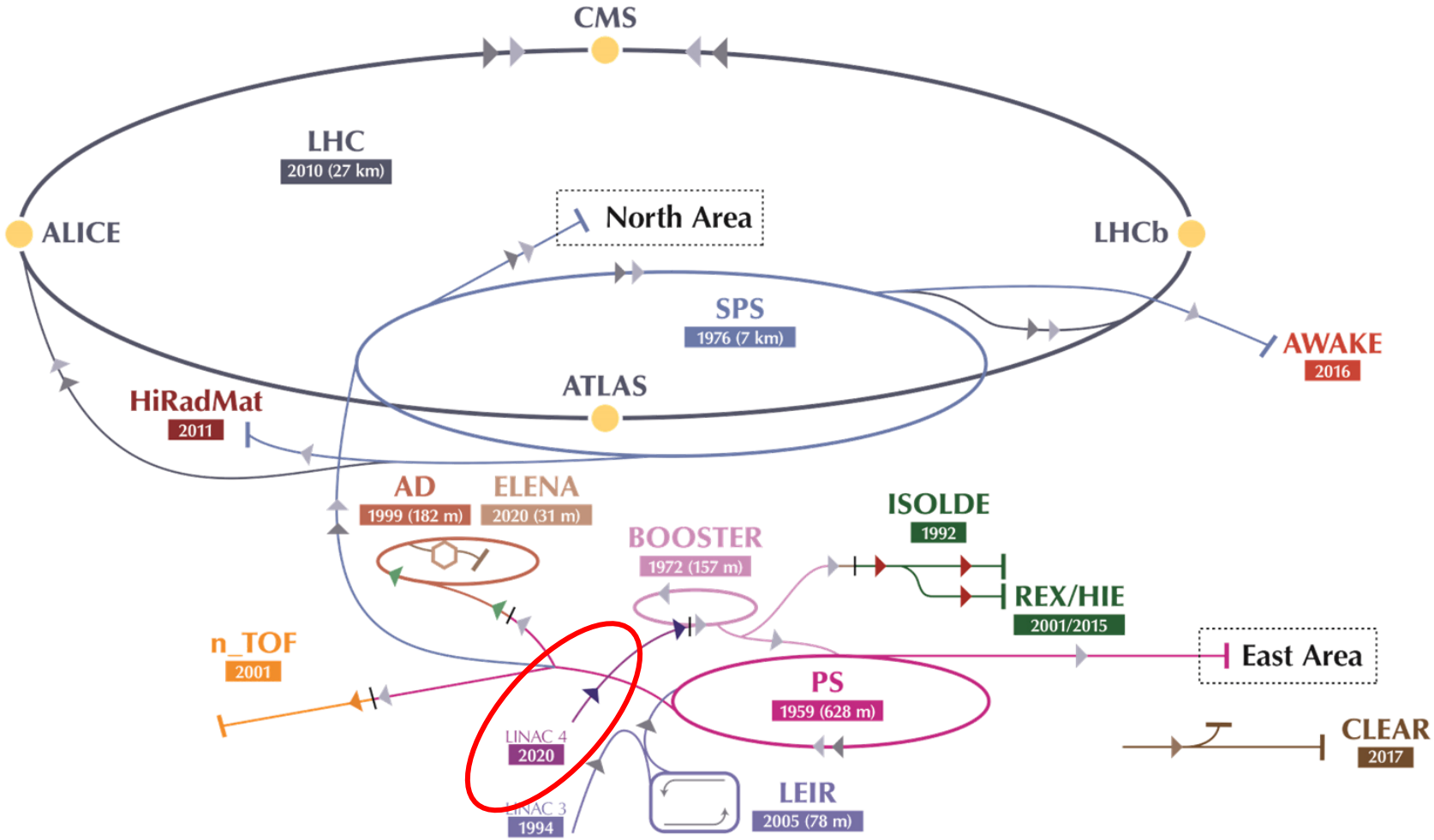
CERN

Low-energy H- irradiation of accelerators components: influence of material and material properties on the breakdown resistance at high electric fields

Sergio Calatroni on behalf of the spare RFQ Project team

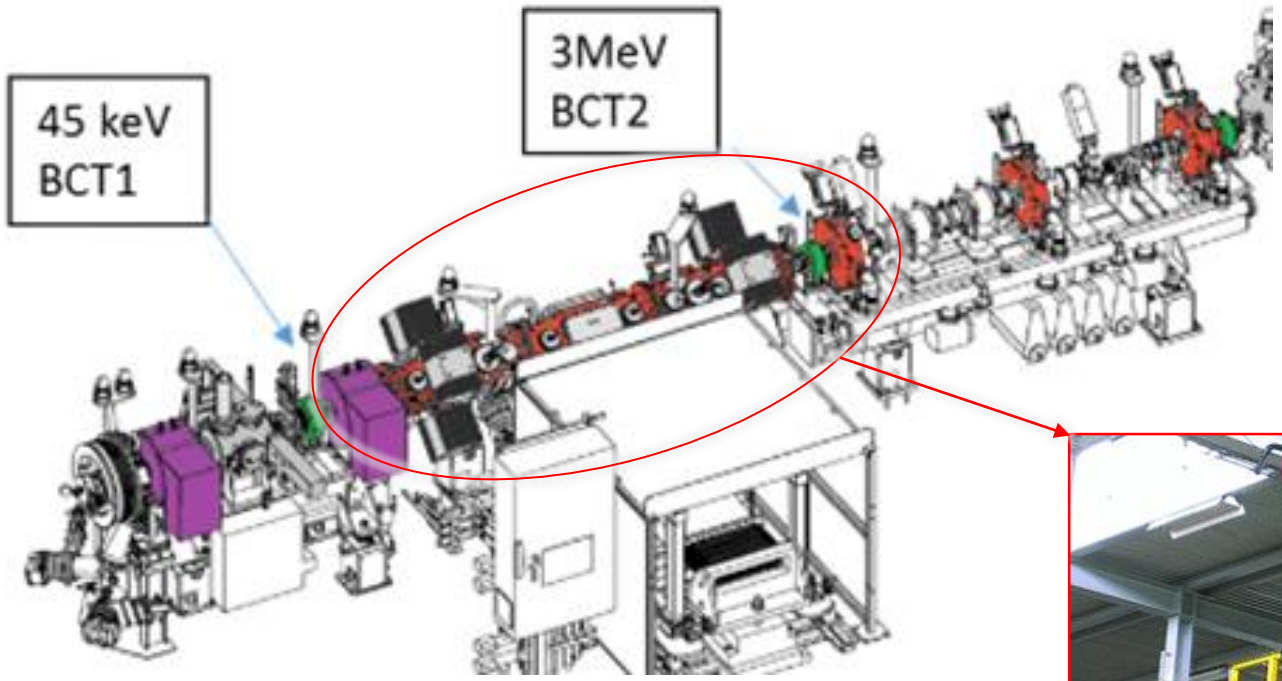
CERN Accelerator complex





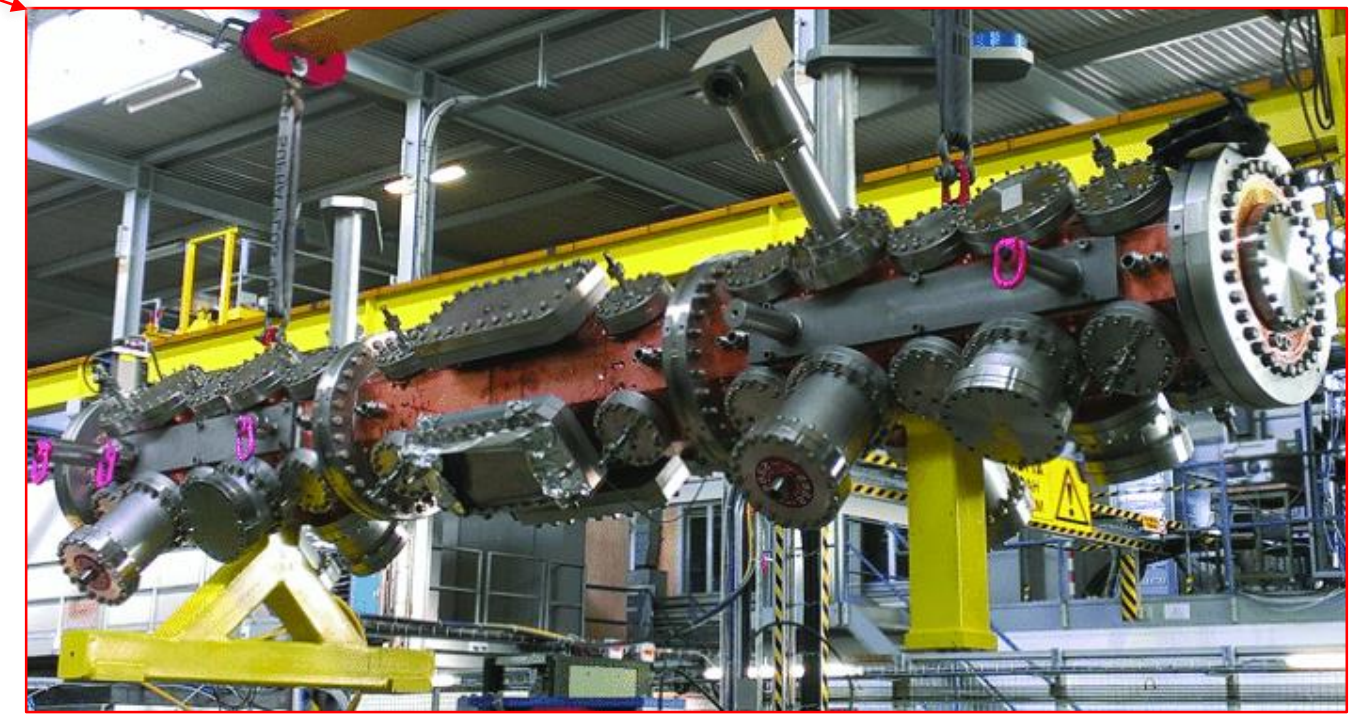
LINAC4, a new linear accelerator as injector for the HL-LHC

The radiofrequency quadrupole (RFQ) of LINAC4



Richard Scrivens

- RFQ properties
- 0.6 ms pulses
- 1 Hz rep rate
- 30 mA pulse current

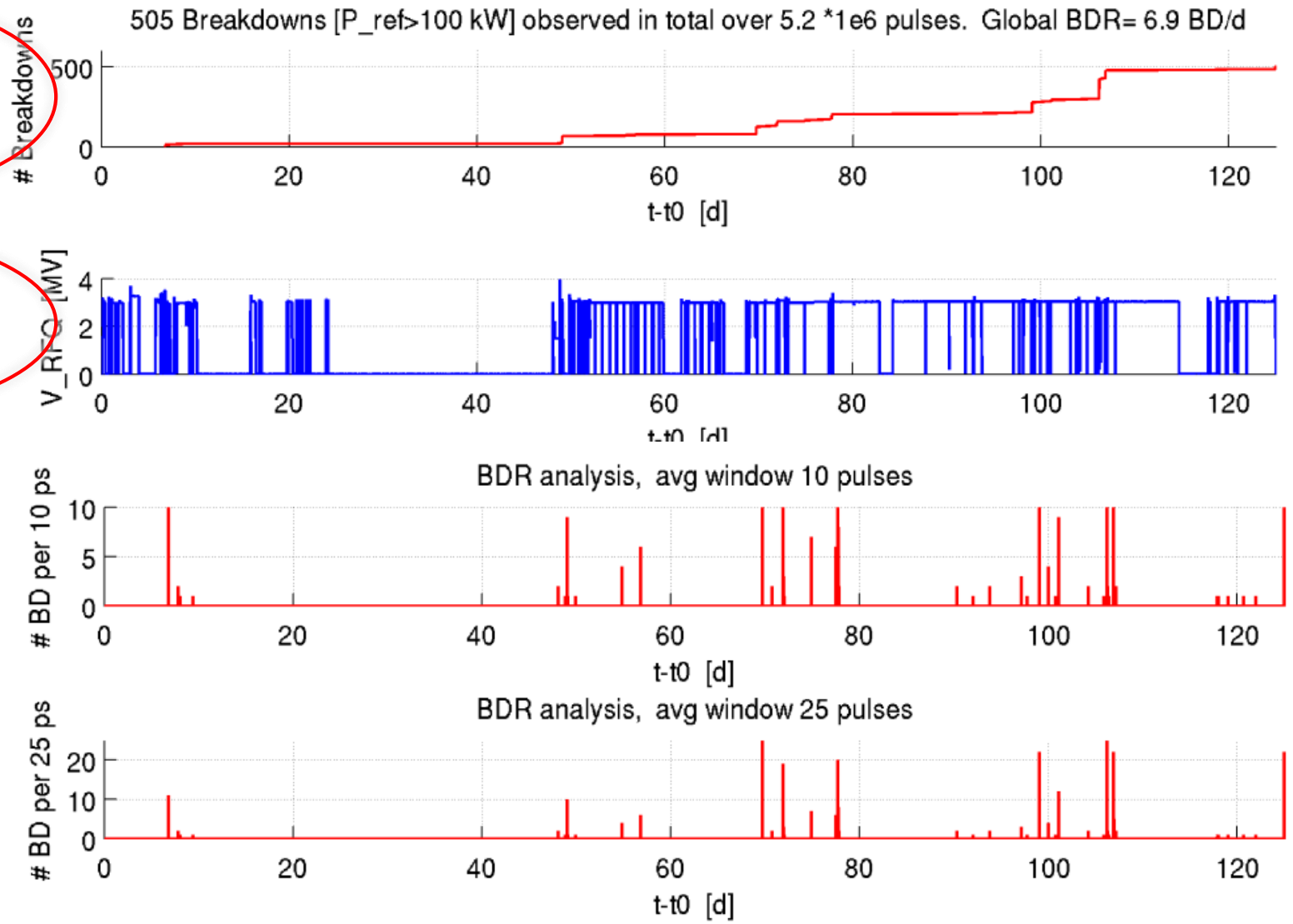


- Increased brightness
- Increased energy (160 MeV for LINAC 4)
- H^- beam
- RFQ as first-stage accelerator

Breakdown rate (BDR) in RFQ

BDR: ~10^{-4}

Surface field: ~35 MV/m

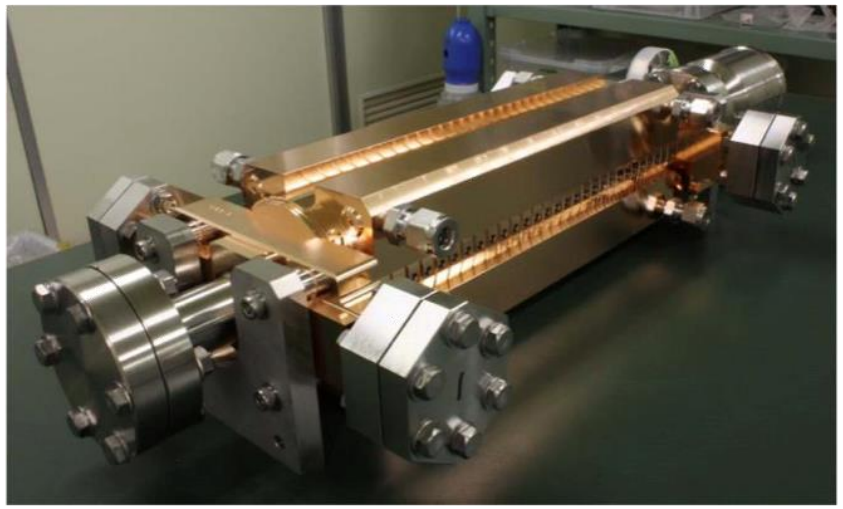


RF pulse 1 ms
Rep rate 1 Hz

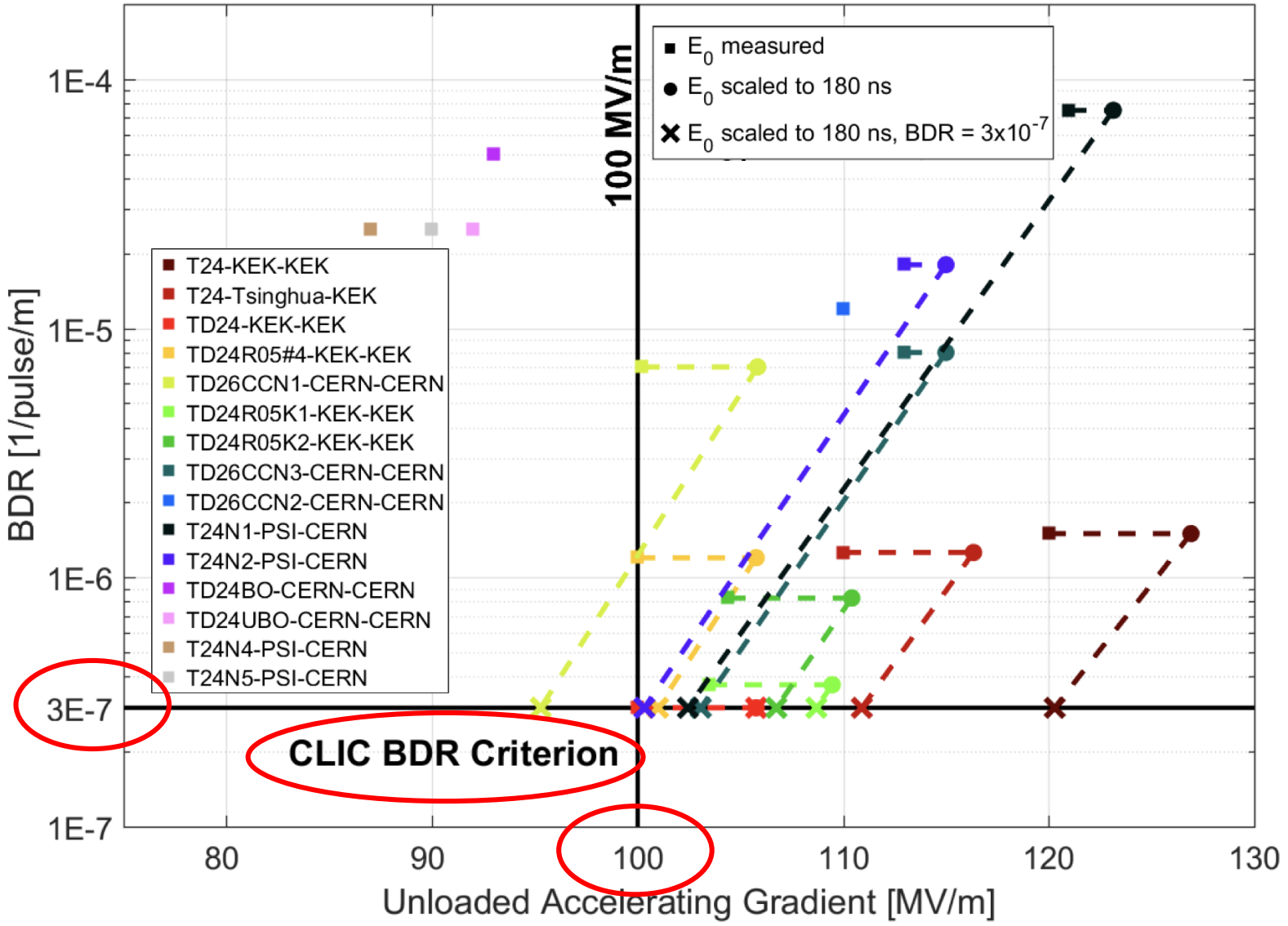
Rolf Wegner

BDR in CLIC accelerating structures, a comparison

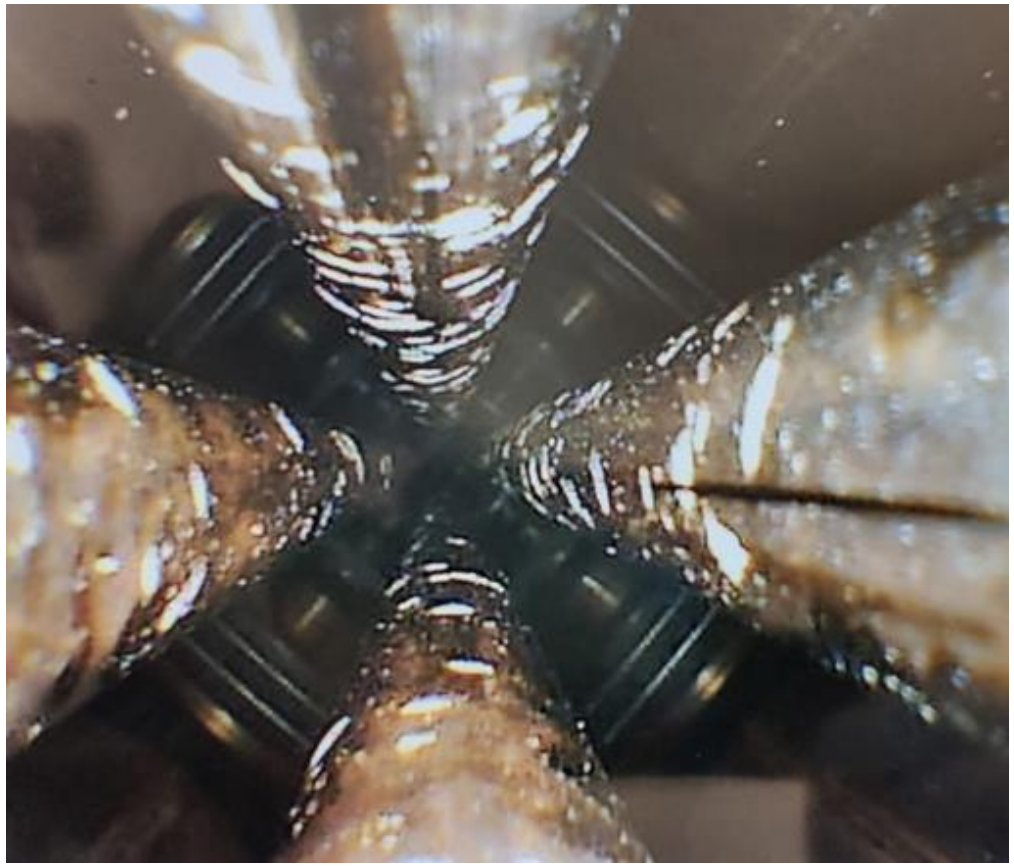
RF pulse 230 ns
Rep rate 50 Hz



W. Wuensch, S. Stapnes



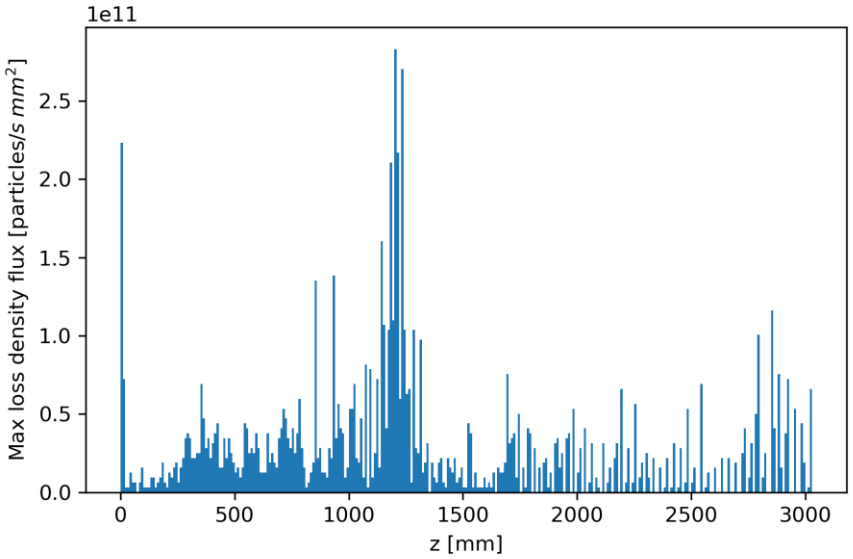
Damage from breakdowns

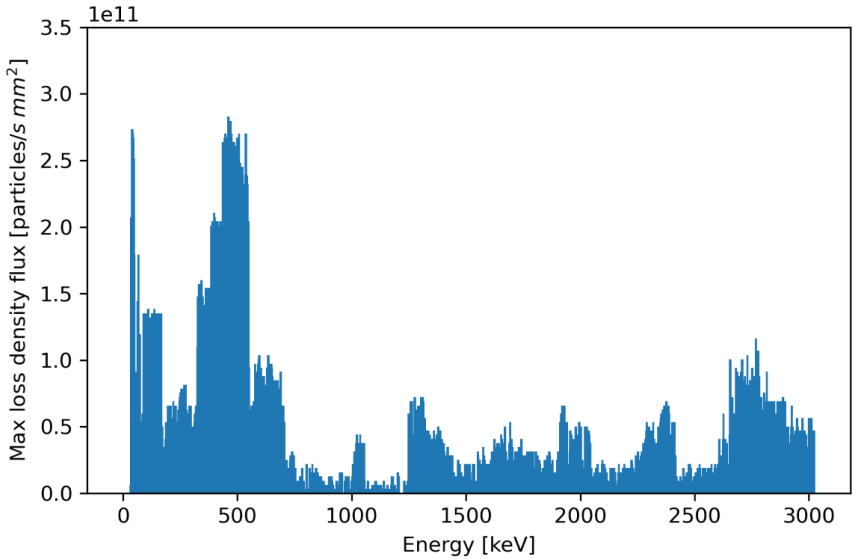


- A replacement RFQ is being manufactured
- Need to understand origin of enhanced breakdown rate, and find a mitigation
- Could breakdowns be correlated with beam losses ?

Density calculations per second

The maximum value of particles/mm2*s and the resulting power loss can be calculated along the RFQ

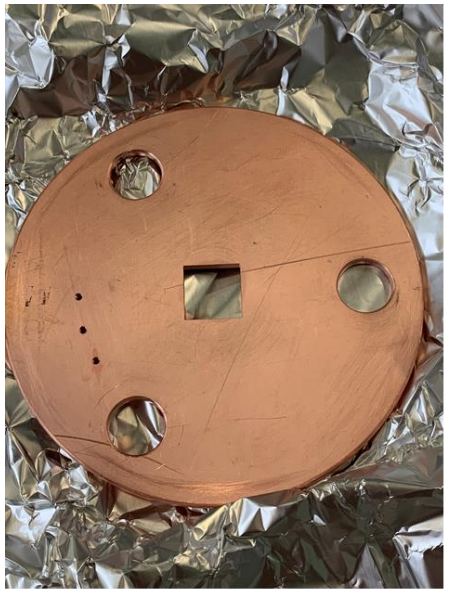


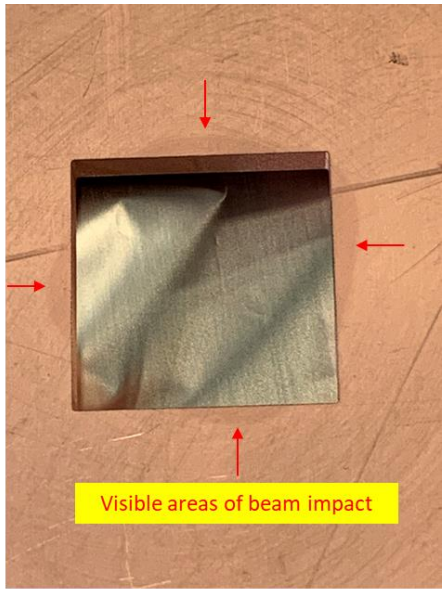


Assuming that this picture doesn't evolve in time, in one year (100 days) of RFQ operation the maximum dose locally deposited would be:

~2E11 p/s/mm^2 x 1E7s = 2E18p/mm^2

Preliminary test: sample irradiation





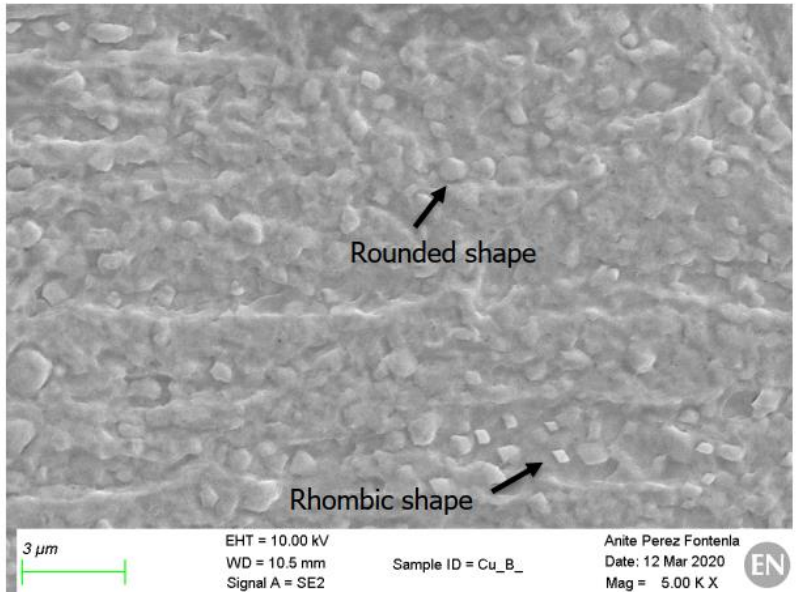
Evidence for blistering on copper upon H^- irradiation at 45 keV (penetration 300 nm)

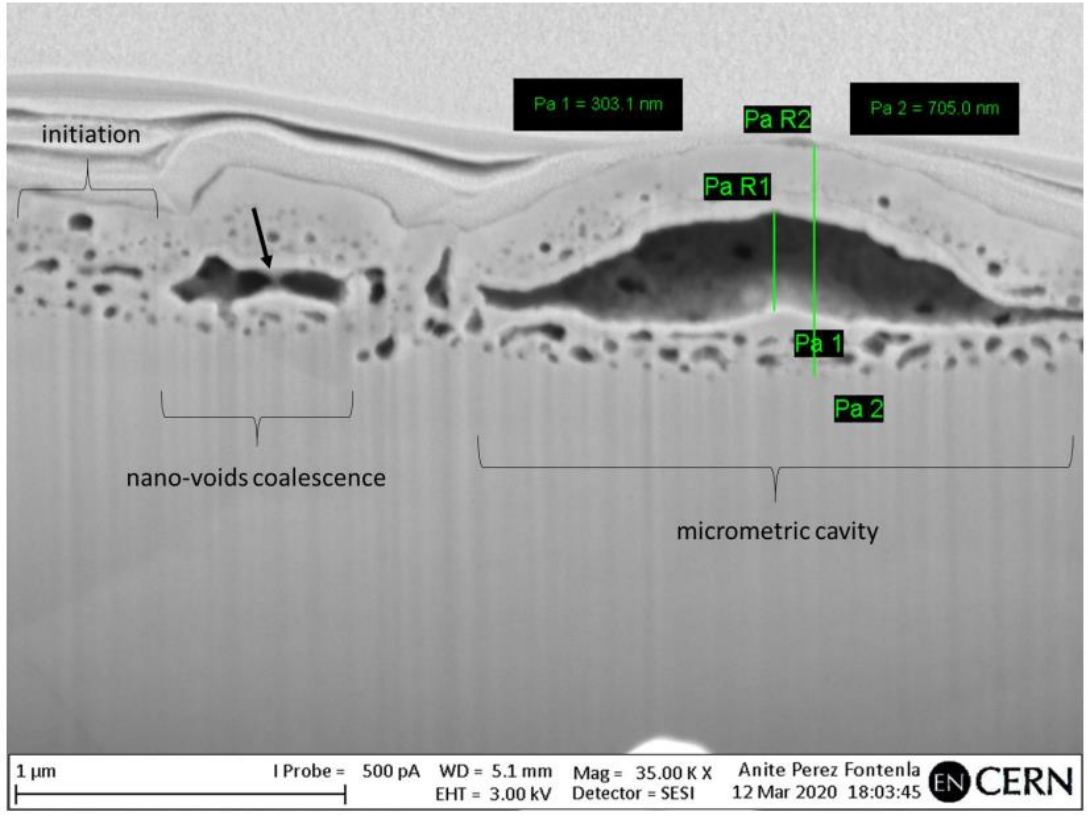
Preliminary tests at LINAC4 test source (collimator 1) and confirmed in literature

Edgar Mahner,
Anité Perez Fontenla

3 mm thick Cu-OFE
Aperture 15 x 15 mm^2

Beam time≈ 12 days
E= 45 keV H^-
I≈ 35 mA
Ions Impacting Total= 1.7 $x10^{19}$
Dose: ~7$x10^{18}$ H^-/cm^2





Working hypothesis & highlights of work plan

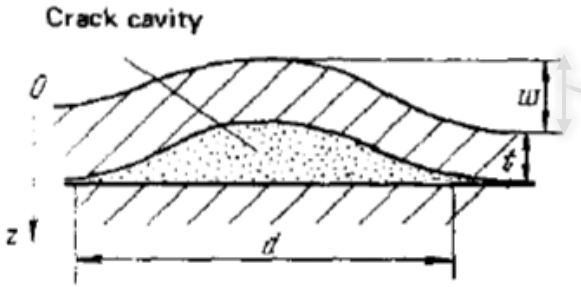
- Study goal: design a new RFQ with better expected performance in terms of beam acceptance and breakdown resistance and beam loss resilience than the present RFQ.

- Hypothesis: blistering from beam losses as triggers for breakdowns

  - Finding a new material for RFQ fabrication with better performance than annealed Cu-OFE in terms of high electric field strength and beam loss resilience
  - Design of an RFQ based on such a new material (if found) with higher surface E-field limit and/or high acceptable beam loss limit

Mechanics of blistering I

- Blistering (and exfoliation) driven by the penetration of relatively insoluble gases depends ceteris paribus on:
  - Radiation dose (minimum dose required for appearance of blisters), ion energy, temperature of the “target”, angle of incidence



Displacement at the center of the blister *w*

FIG. 23. Buckling of a surface layer of the target.

1003 Sov. Phys. Usp. 24(12), Dec. 1981

$$(\sigma_r)_{max} = 3qa^2/4h^2 \quad [1]$$

where $(\sigma_r)_{max}$ is the maximum radial stress, q is the uniformly distributed load over the entire surface of the plate, a is the blister radius, and h is the thickness of the circular surface film or, in our case, the blister skin thickness. The internal pressure of the gas near the surface p is equal to the uniform load q. To achieve blistering, the stresses on the skin plate (blister cap) must rise above the yield stress of the metal.

Adapted from: https://indico.cern.ch/event/933868/ by Stefano Sgobba

Mechanics of blistering II

D. Moreno and D. Eliezer, On the Blister Formation in Copper Alloys due to the Helium Ion Implantation, Metallurgical and Materials Transactions A Vol. 28a, March 1997—755

Table II. Average Blister Size Yield Stress and the Constants *K* for Different Treated CuBe

	Yield Stress (MPa)	Blister Radius (Average) a (μm)	K (Atoms/cm^3 · Å)
CuBe annealed	190	0.445	1.57×10^{17}
CuBe rolled	240	0.375	2.78×10^{17}
CuBe aged	650	0.475	4.70×10^{17}

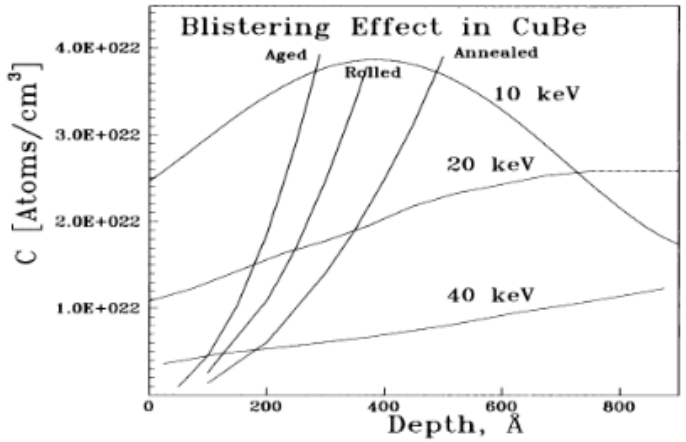


Fig. 7—The implanted helium concentration profiles near the surface at 10, 20, and 40 keV ion energies of implantation for a total dose of 4×10^{17} He/cm^2. In the same graph, the He-critical concentration for blister formation, calculated by Eq. [6] for annealed, rolled, and aged CuBe alloy, is presented.

- "Blister diameter size depends strongly on the crystallographic direction of implantation"
- This behaviour may be related to the difference in the stopping power attributed to the crystallographic orientation of the surface in relation to the ion beam

C. Quiros et al., Blistering and hydrogen retention in poly- and single- crystals of aluminium by a joint experimental-modelling approach, Nuclear Materials and Energy, Volume 20, August 2019, 100675)

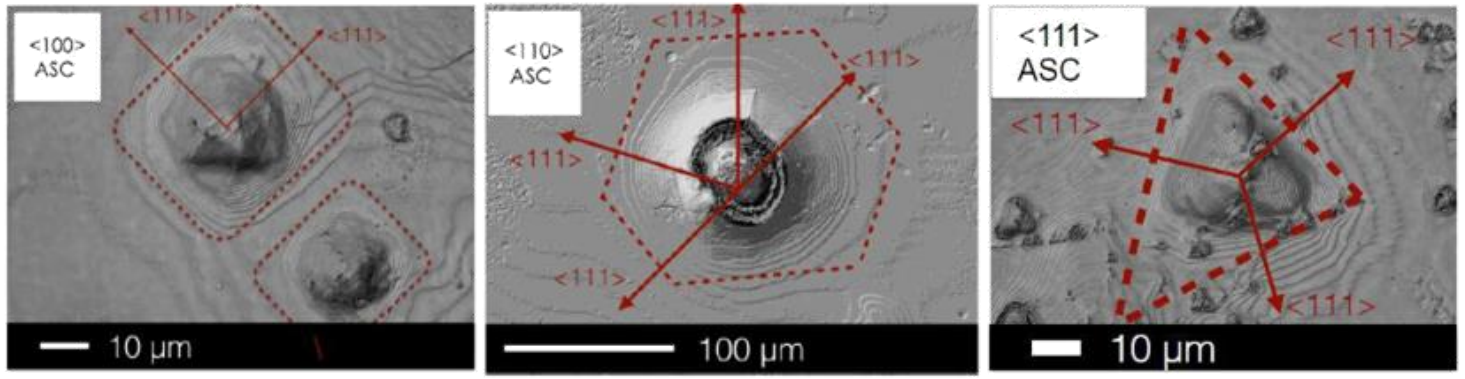


Fig. 4. Confocal images of the ⟨100⟩ (left), ⟨110⟩ (center) and ⟨111⟩ (right) ASC samples exposed to H_2 plasma with an incident ion flux of 1.6×10^{20} ions/m^{2}s, sample temperature of 618 K, incident ion energy of 320 eV and fluence of 2×10^{23} ions/m^2. The scale is not the same in every image.

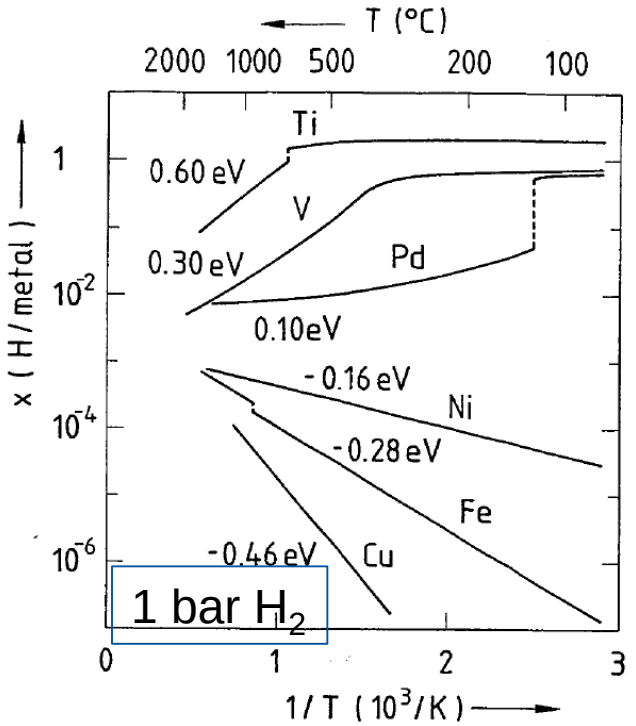
Adapted from: https://indico.cern.ch/event/933868/ by Stefano Sgobba

Hydrogen solubility I

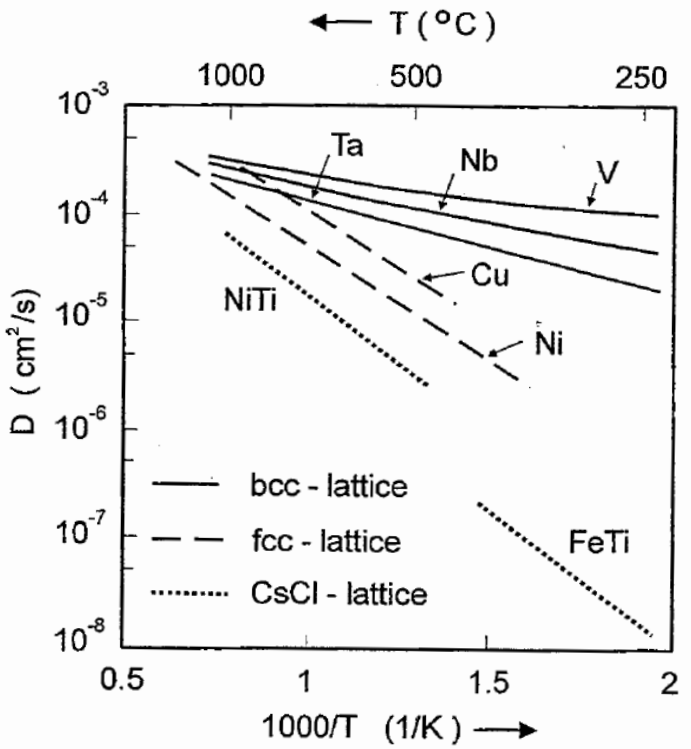
- Hydrogen solution must be energetically favorable
- Hydrogen must have high diffusivity at room temperature
- Hydrogen solubility limit must be high

H. Wipf, Phys. Scr. T94 (2001) 43

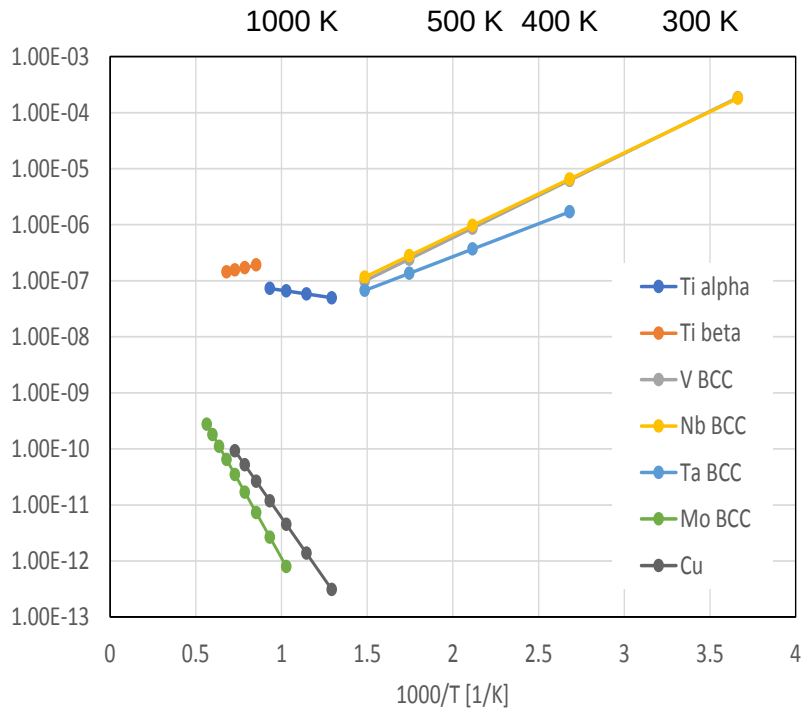
Solubility K_S [mol m^{-3} Pa$^{-0.5}$]



Diffusivity D [m^2 s^{-1}]



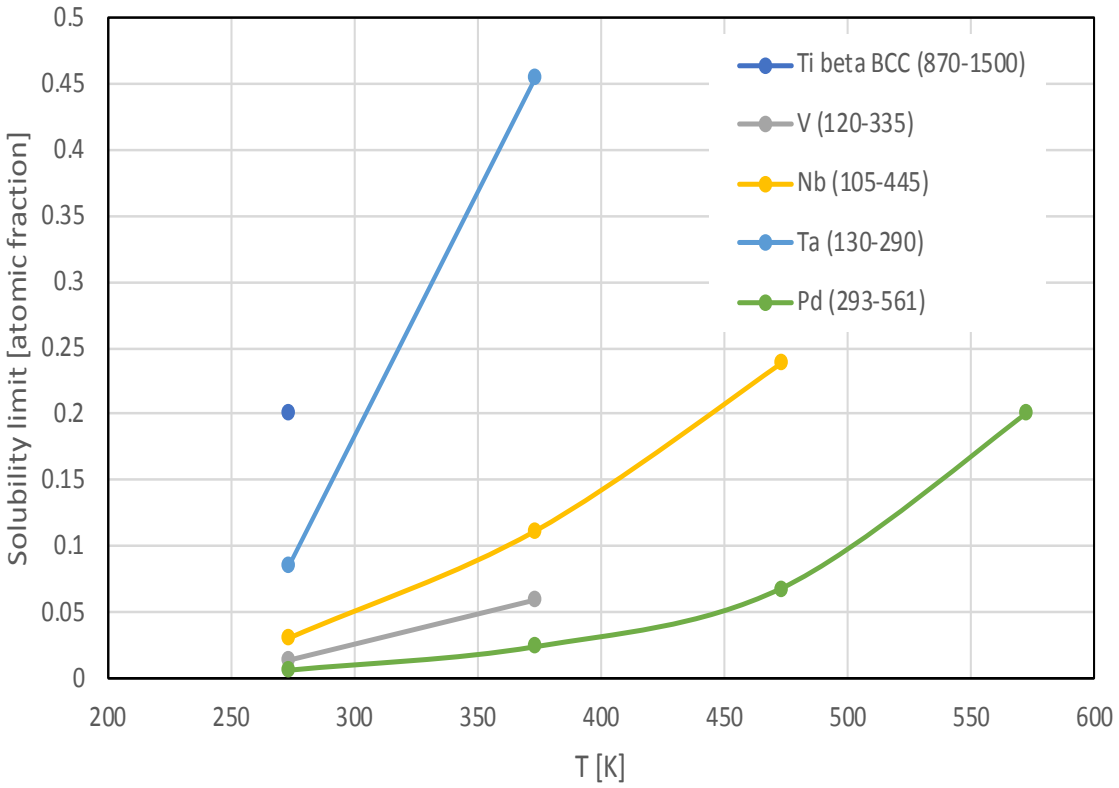
Permeability $\phi = K_S D$ [mol m^{-1} Pa$^{-0.5}$ s^{-1}]



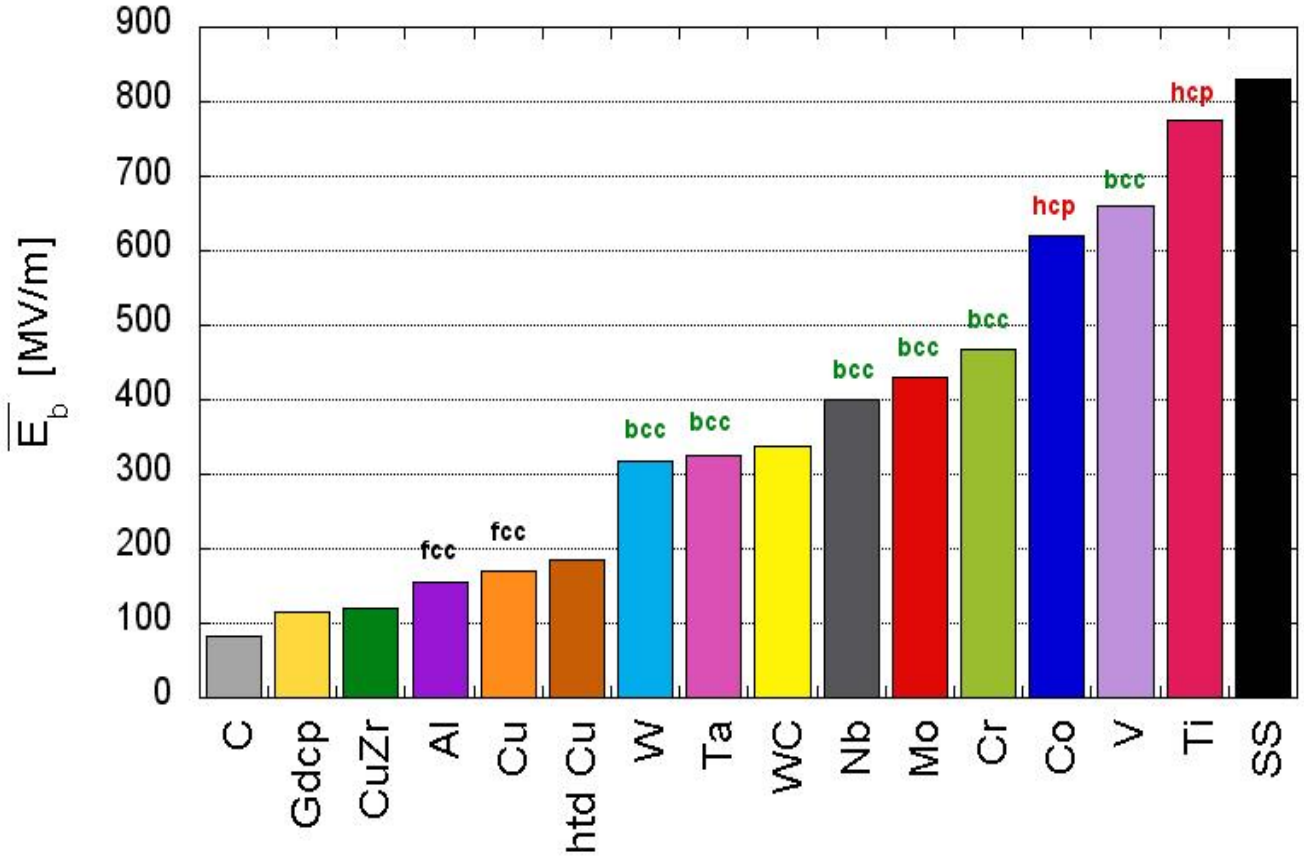
Adapted from: https://indico.cern.ch/event/933868/ by Sergio Calatroni

Hydrogen solubility II

Gases and Carbon in Metals, FIZ Karlsruhe



A. Descoeudres, F. Djurabekova, K. Nordlund, CLIC Note 875



Adapted from: https://indico.cern.ch/event/933868/ by Sergio Calatroni

How to limit hydrogen bubble formation

- Criteria for material choice I:
  - Material strength larger than copper
  - Reduced dislocation movement
  - Presence of trapping centers for hydrogen to prevent coalescence
- Criteria for material choice II:
  - Hydrogen solution must be energetically favorable
  - Hydrogen must have high diffusivity at room temperature
  - Hydrogen solubility limit must be high

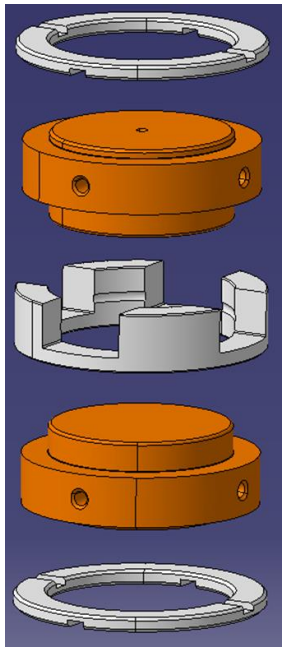
- Selected material candidates:
  - Cu-OFE (reference), $CuCr_1Zr$, CuBe, Nb, β-Ti-6Al-4V, Ta
  - (electrical conductivity is not a primary concern for RFQ vanes)

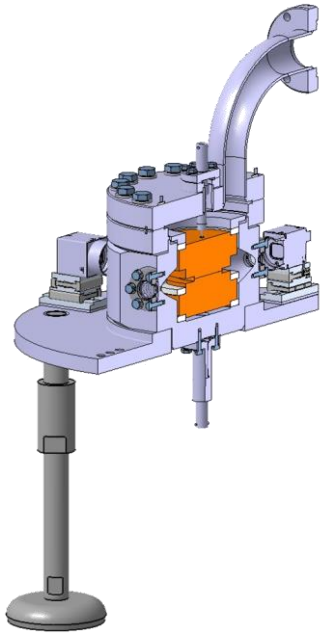
Experimental studies

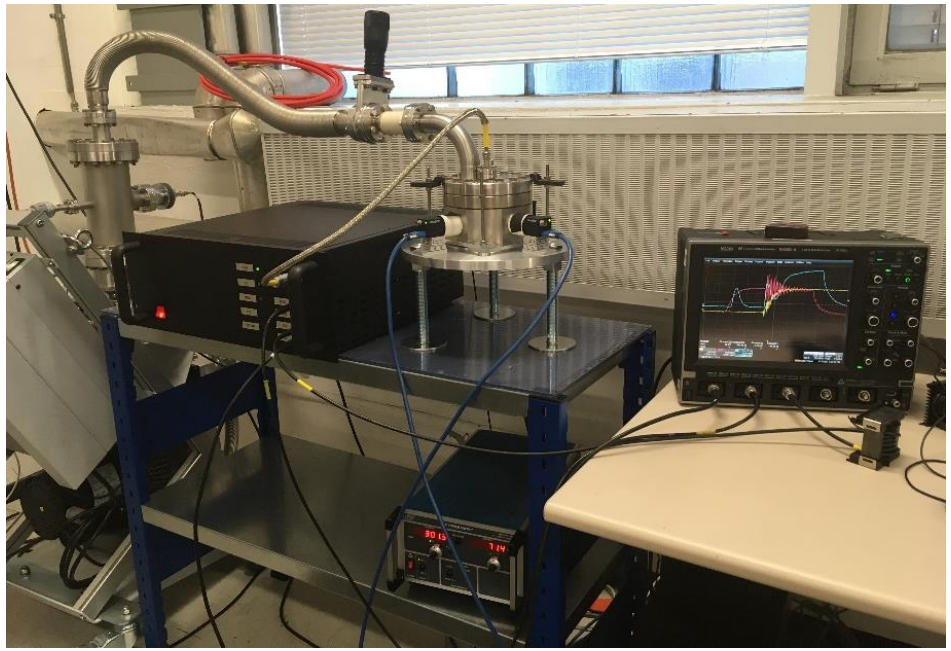
- Measure BDR as a function of H irradiation with LES system
- Material analyses with SEM and FIB on LES electrodes and other irradiated samples.
  - Benefit from know-how developed with CLIC and with conditioning of RF structures (Xboxes, etc.)
- Be open to new evidence…!

- Leverage expertise developed within CLIC high gradient studies & collaboration with Helsinki University
  - Material irradiation with ion implanter (500 keV) and Tandem (5 MeV)
  - Expertise of materials for nuclear fusion
  - Simulation of H bubbles formation and coalescence

LES = Large Electrodes System, pulsed DC system

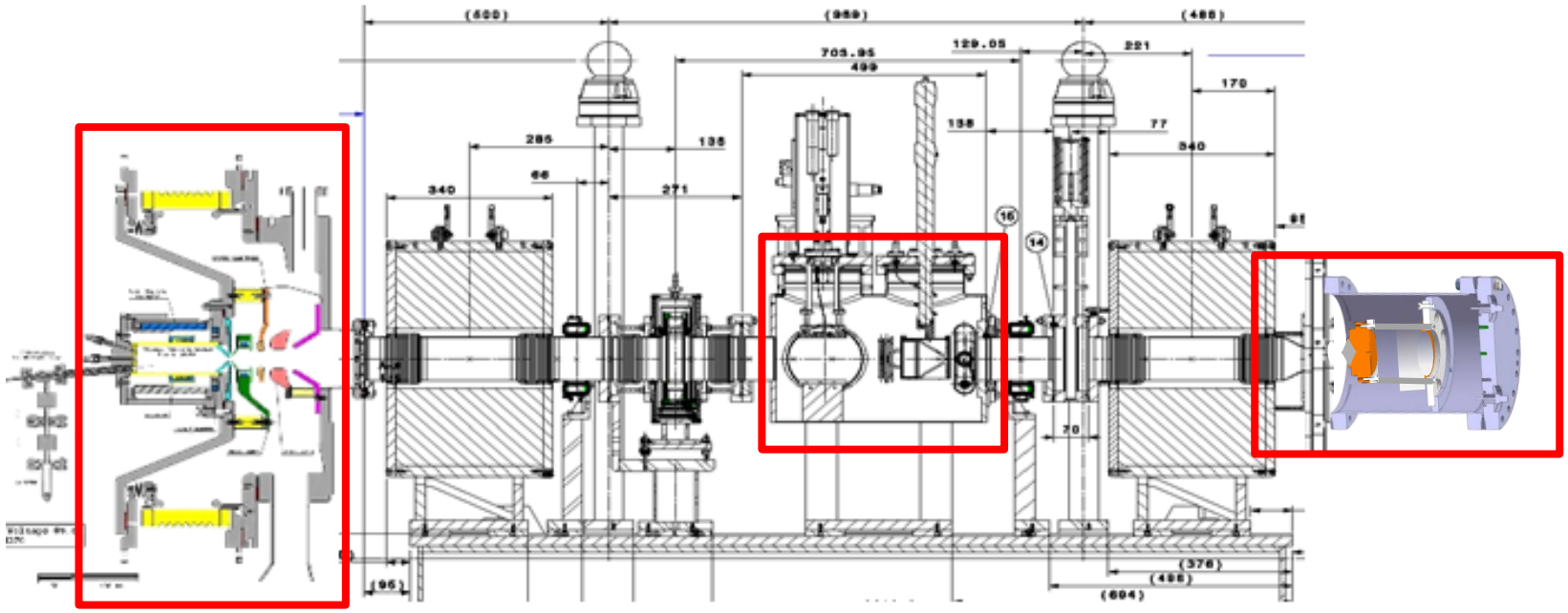


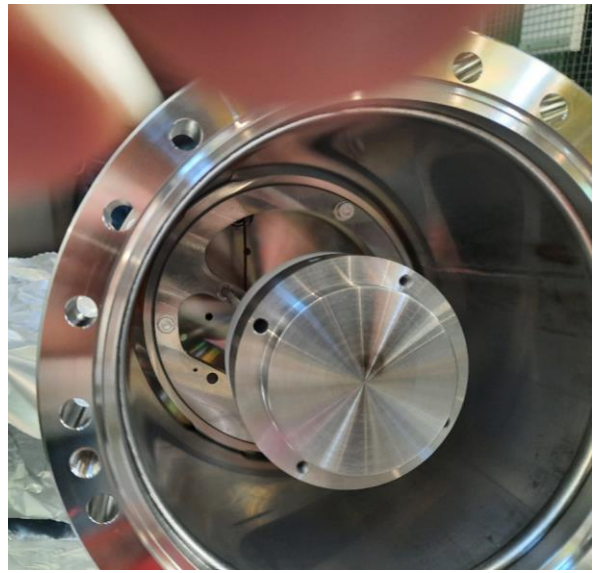




Ruth Peacock

Irradiation setup – LINAC4 source test stand





H^- Source 45 keV

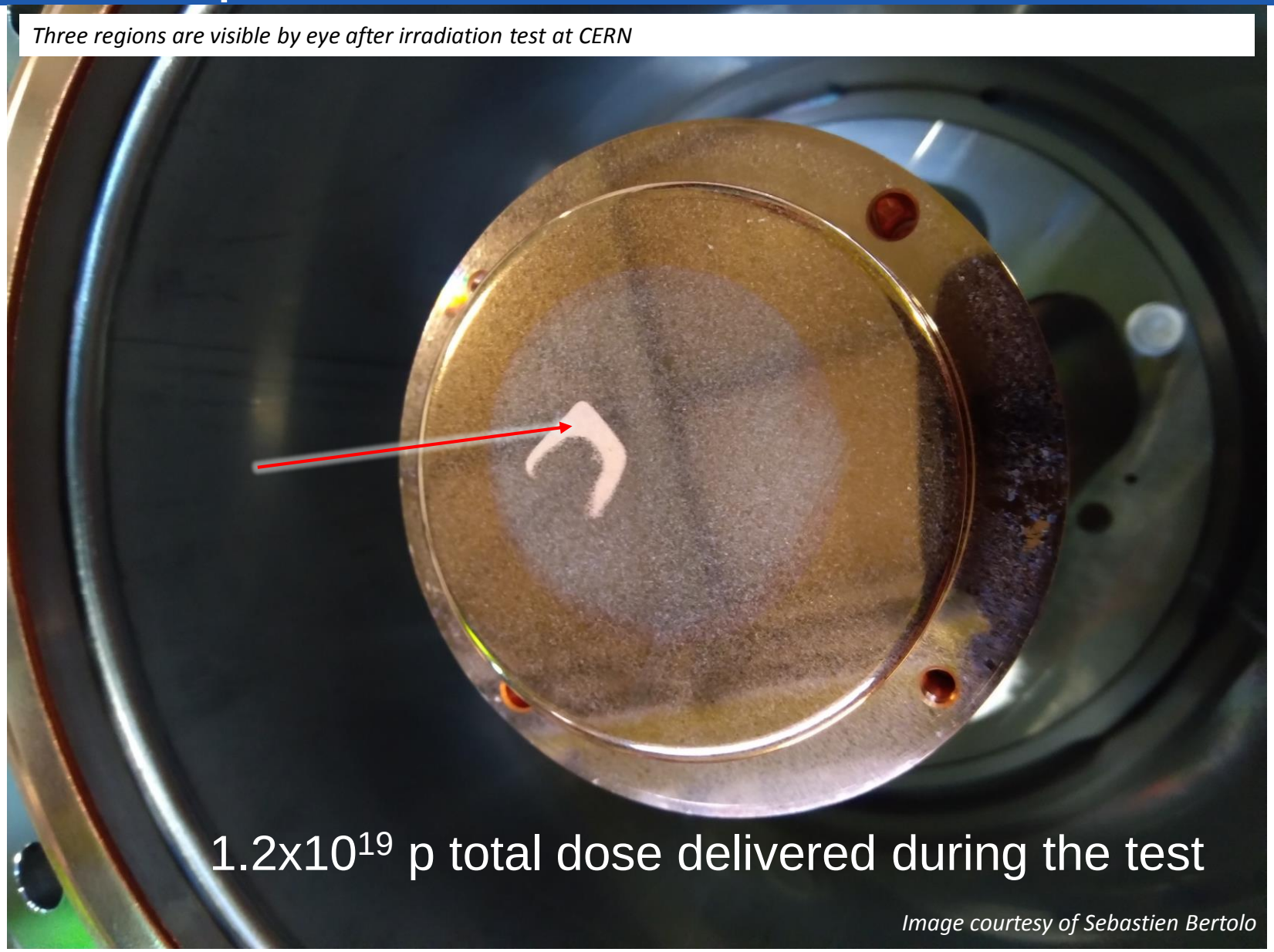
Low-energy beam transport

2 Steerers, 2 Solenoids

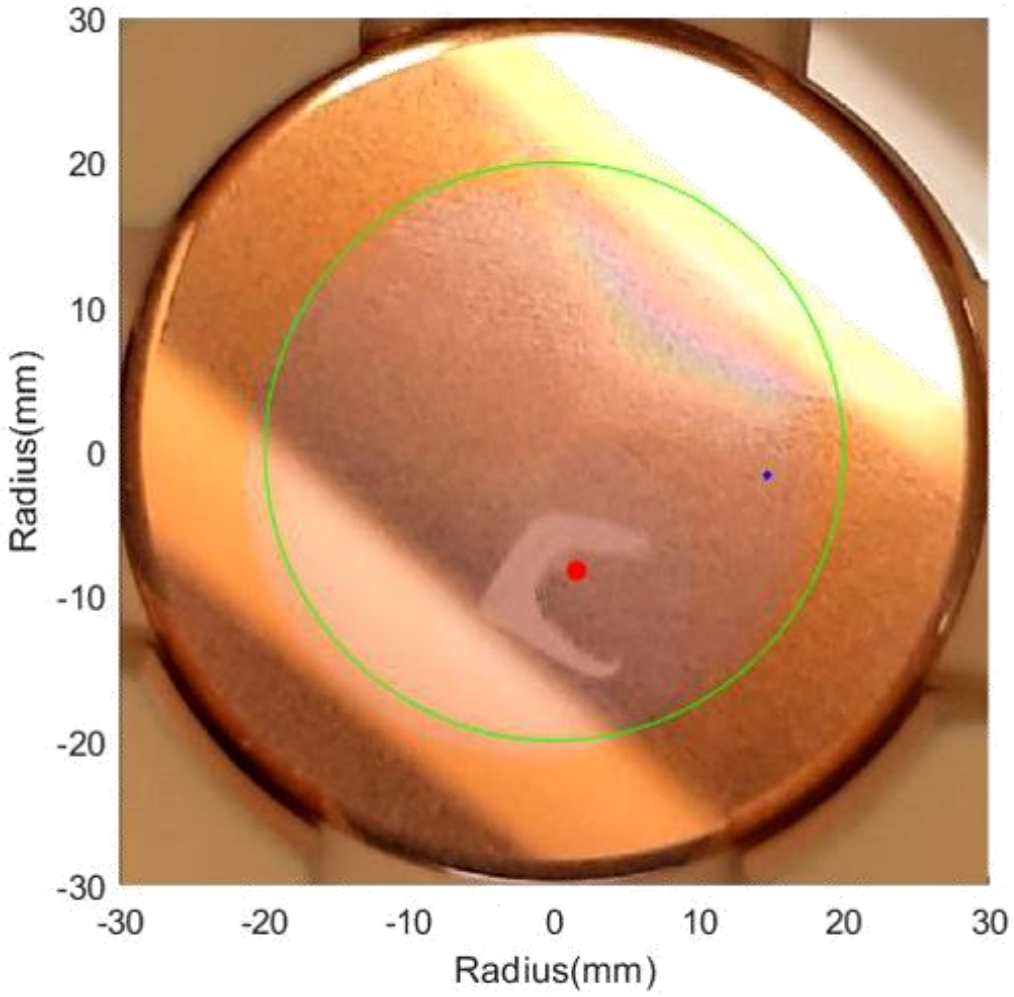
Sample holder

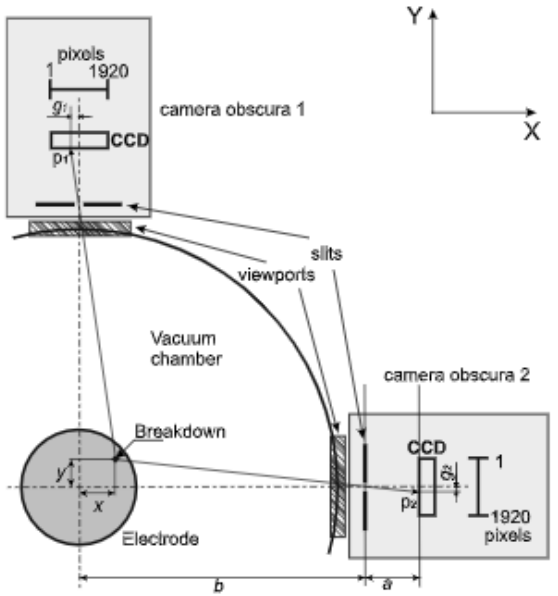
Alessandra Lonbardi

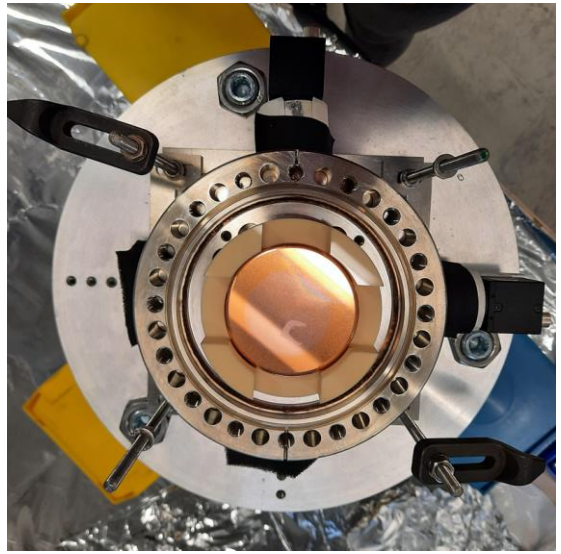
First irradiated sample – LINAC 4 source at 45 keV



First tests with LES on irradiated electrode

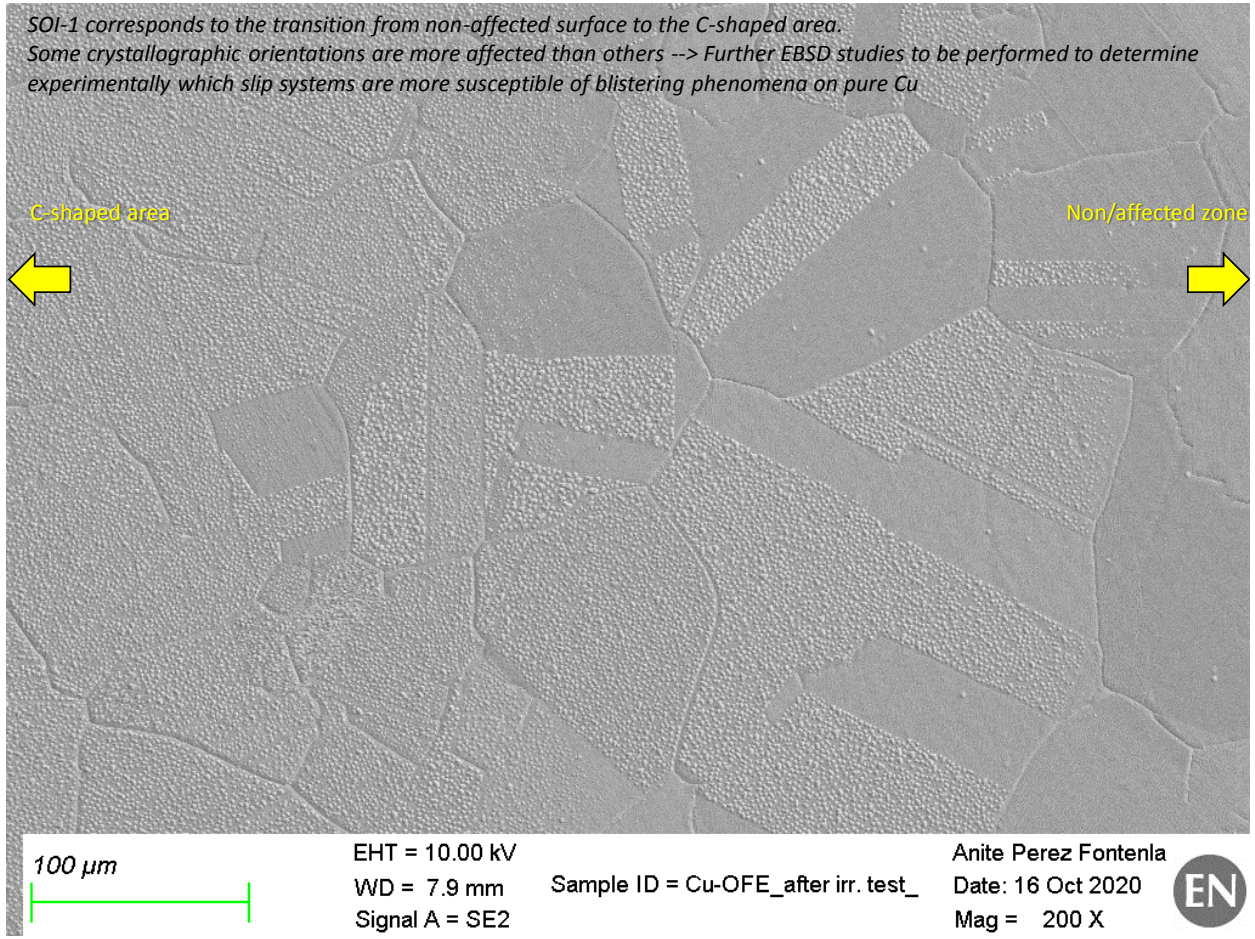


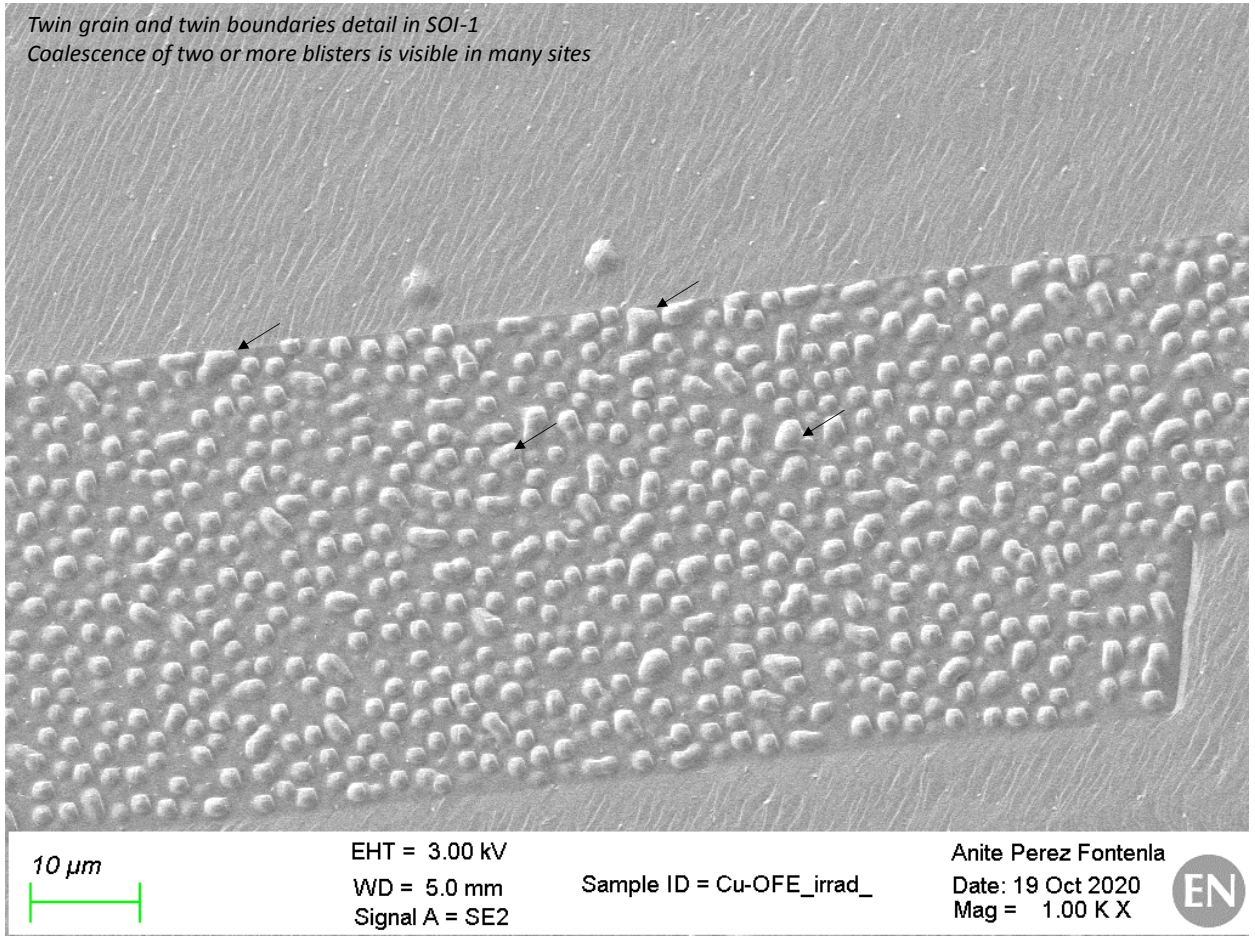




See next talk by Ruth Peacock

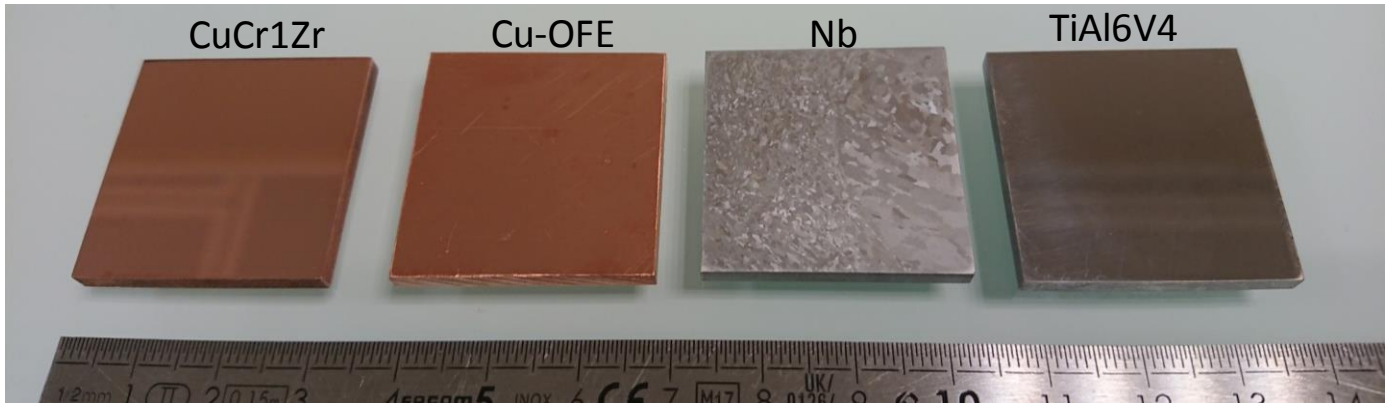
SEM results: a teaser

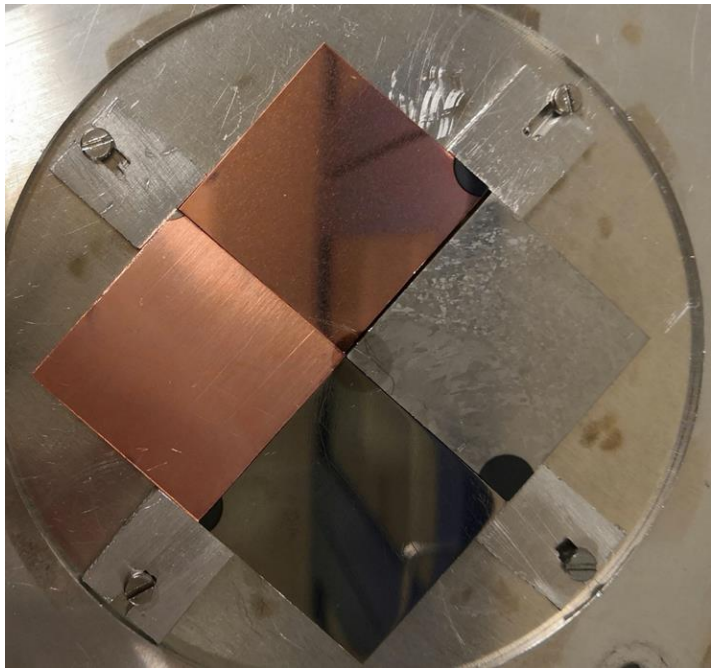




See next talk by Anité Perez Fontenla

Irradiation in Helsinki





Helsinki's system:

- Particle type H2+, 90 keV
- Normal incidence angle
- Maximum diameter of the sample holder: Ø100 mm → 4 samples of 30 mm x 30 mm can be tested simultaneously

Main goal of this preliminary test was to confirm that is comparable with irradiation test performed at CERN (Cu-OFE collimators EDMS 2356205***)*** → **Cu-OFE** sample (as rolled) equivalent to Collimator's was sent

Three additional samples were sent → **$CuCr_1Zr$**, Nb and TiAl6V4 (manually polished)

	Energy [keV/H]	Dose [1E18p/cm^2]	Beam Current [µA]	Time [h]
First Test	45	4	5	18
Second Test		1		4.5

Anité Perez Fontenla, Mizohata Kenichiro (Helsinki)

Bubbles and voids, Helsinki

JOURNAL OF APPLIED PHYSICS **110**, 023509 (2011)

Dislocation nucleation from near surface void under static tensile stress in Cu

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[1]*Helsinki Institute of Physics and the Department of Physics, Accelerator Laboratory, P. O. Box 43, FIN-00014 University of Helsinki, Helsinki, Finland*
[2]*EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon OX14 3DB, United Kingdom*

(Received 14 December 2010; accepted 4 June 2011; published online 21 July 2011)

We examine a possible mechanism for the formation of protrusions on a metallic surface held in a sufficiently high electric field in the presence of a near-surface void. By means of molecular dynamics simulations we show that the high tensile stress exerted on a Cu {110} surface with a near-surface void can promote the nucleation of dislocations on the void surface. These dislocations cause slip along {111} crystallographic planes leading to mass transport in the volume above the void. We find a linear correlation between the radius of the void and the maximum depth for the growth to occur. © *2011 American Institute of Physics*. [doi:10.1063/1.3606582]

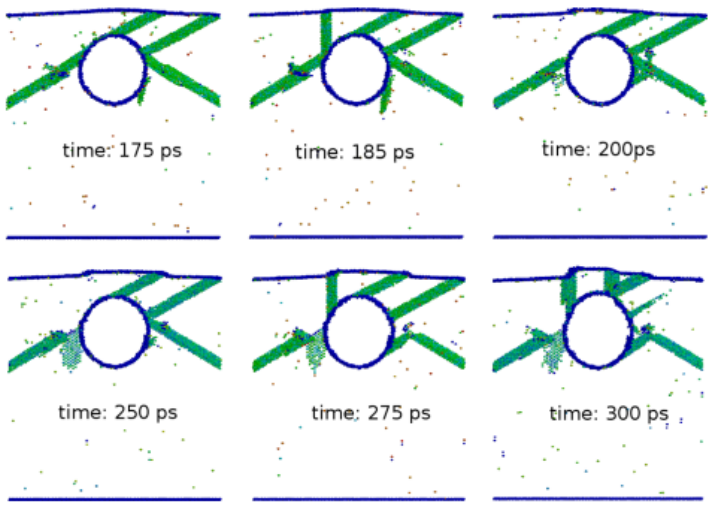
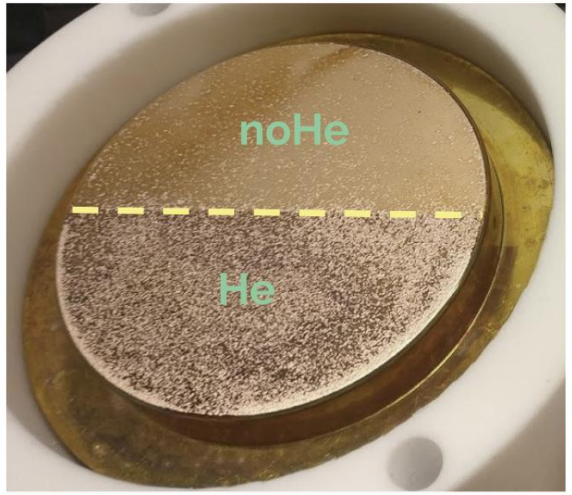
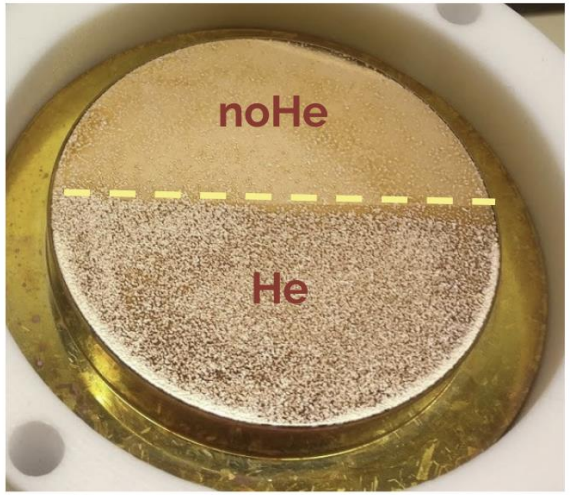


FIG. 2. (Color online) Snapshots of the simulation of the void with radius $r = 28$ Å; temperature of the cell 600 K; applied stress 4.58 GPa. The forces were exerted on atoms on the two top layers. Atoms on the stacking faults and surfaces are shown.

Electrodes half He irradiated, then high-field pulsed (Helsinki).



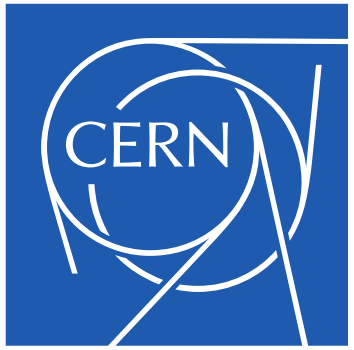
Cathode



Anode

Final remarks

- Material selection for new RFQ, more robust to beam losses
- Work in synergy with CLIC, leveraging expertise of the Collaboration
- Irradiation of samples in Helsinki for physics understanding
- Irradiation experiments at CERN with LINAC 4 source test stand (limited availability)
- BD testing in LES system on electrodes of different materials
- SEM + FIB + EBSD + … material analyses to understand origin of enhanced BDR
- PhD student partly funded from RFQ and CLIC to work on this study, supervised from Helsinki University (Flyura Djurabekova)
- Information gathered could be useful for CLIC and high-gradient technologies in general (effect of beam losses)

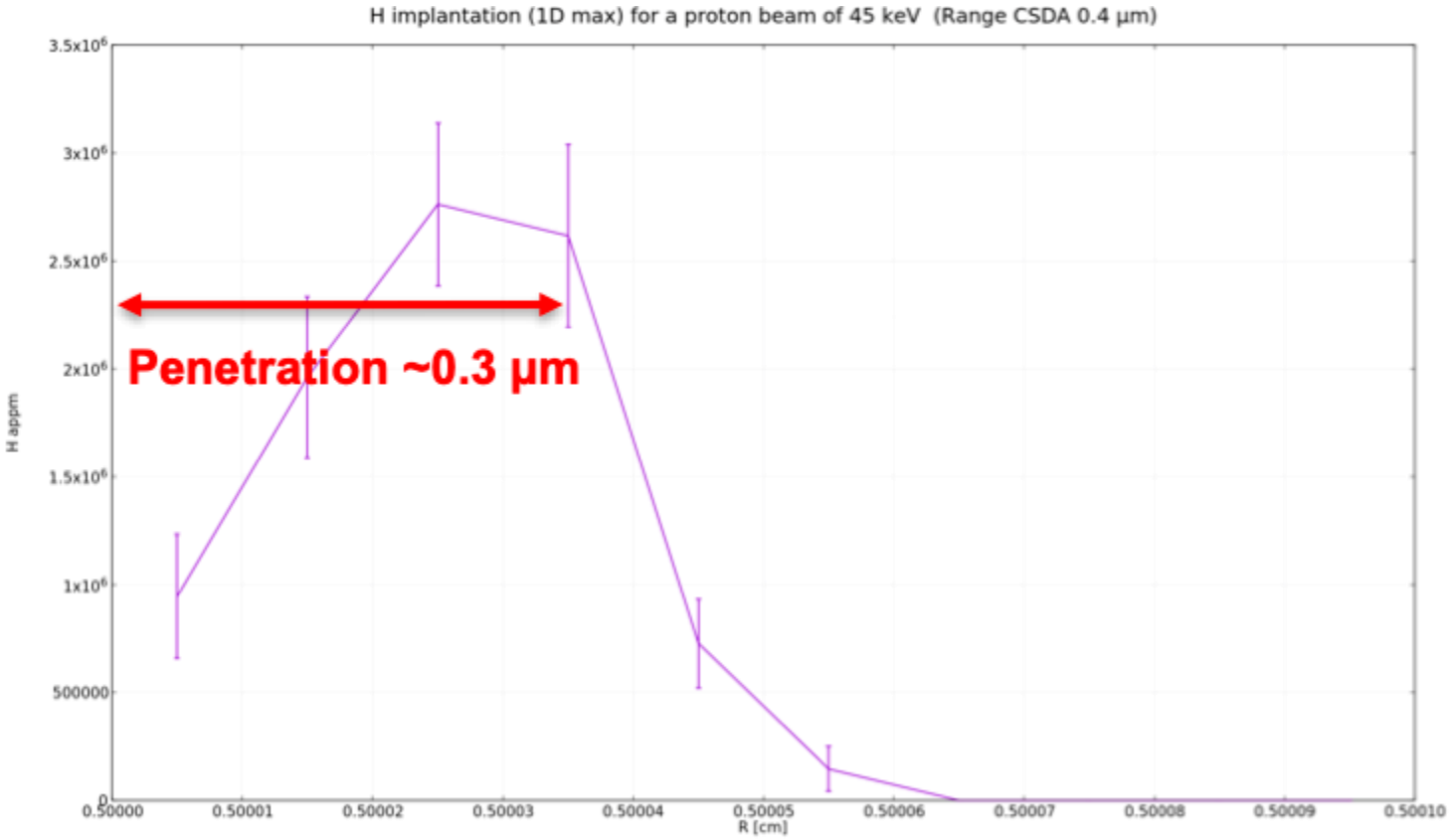

CERN

Range of implantation

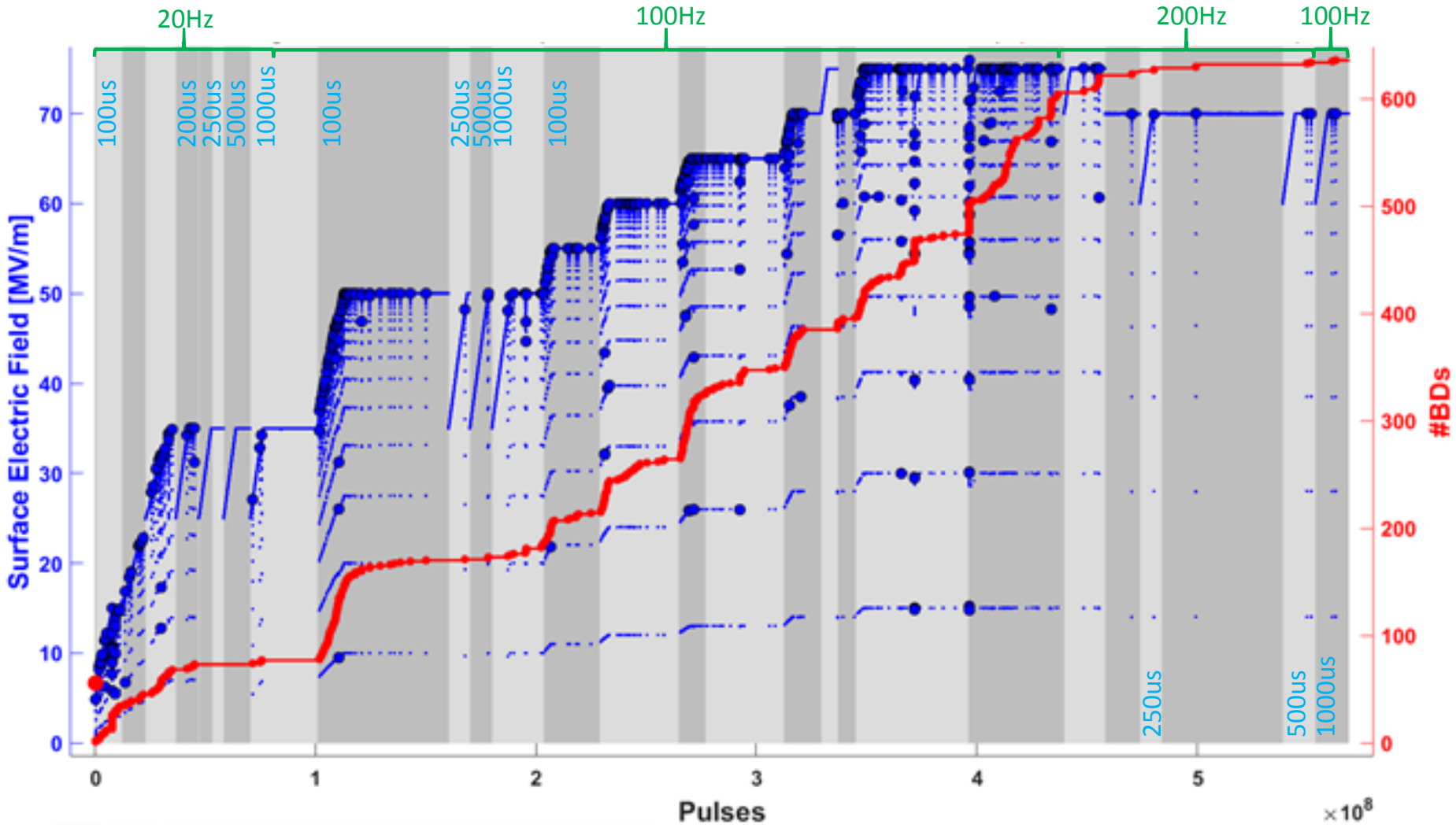
From Luigi Salvatore Esposito, Francesco Cerutti, Marco Calviani.

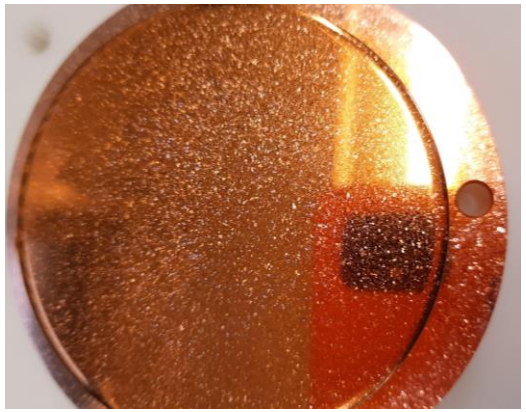
At 90 keV, an H_2^+ impinging the copper surface dissociates into H^0 and H^- in << 1 nm. H^0 then gets ionized in an even shorter length.

Thus, the penetration of an H_2^+ beam at 90 keV is essentially equivalent to that of an H^- beam at 45 keV



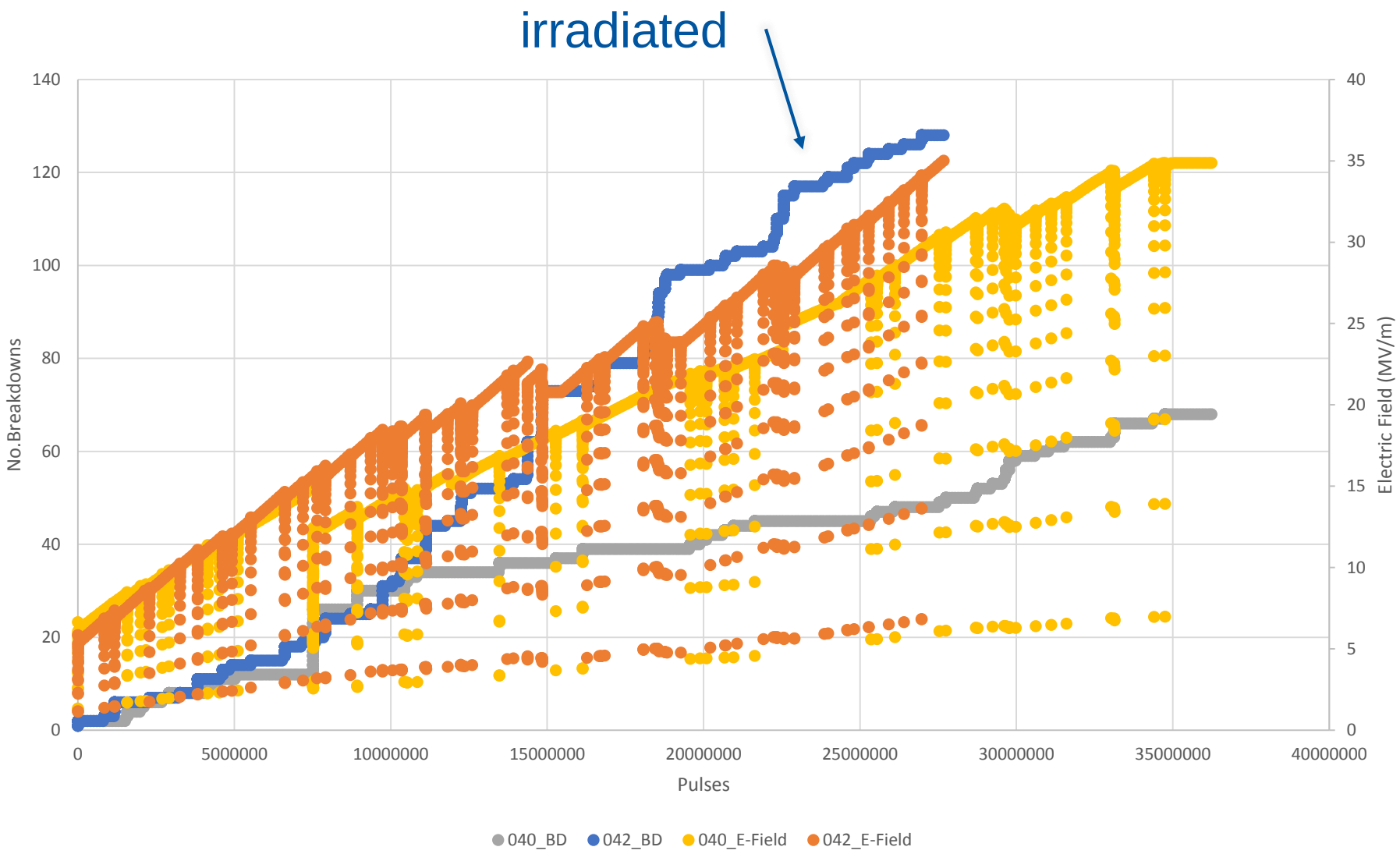
First tests, reference electrodes: HT 815 °C, up to 1 ms pulse

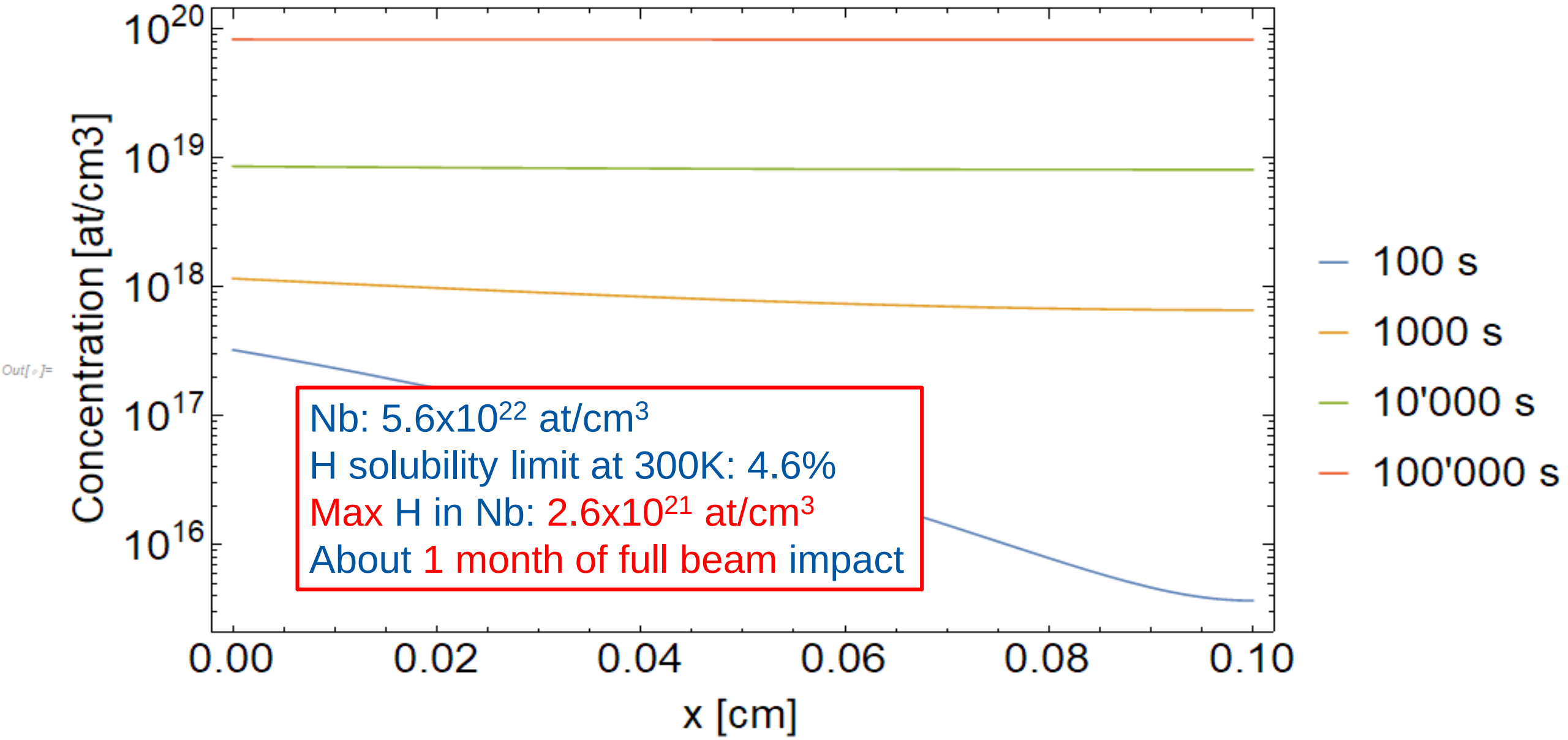




Ruth Peacock

Comparison of first conditioning



Ruth Peacock

Concentration of H in Nb at 300 K