Vacuum Technology for Diffraction Limited Storage Rings

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ALS-U
ADVANCED LIGHT SOURCE

Outline

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- ALS-U NEG R&D Results and Further work
- Summary

Diffraction Limited Storage Ring (DLSR)

CHALLENGES IN THE DESIGN OF DIFFRACTION-LIMITED STORAGE RINGS*

R. Hettel, SLAC National Accelerator Laboratory, Menlo Park, California, USA

INTRODUCTION

The world has entered a new, fourth generation of storage ring light source design – rings having electron emittances well below the nanometer-radian-scale emittances of third generation machines. The NSLS-II, now in commissioning, will reach ~0.6 nm-rad emittance with its 792-m-circumference double-bend achromat (DBA or 2BA) lattice operating with damping wigglers. Meanwhile, lower emittance with smaller circumferences has been made possible with the advent of buildable multi-bend achromat (MBA) lattices. The first such undertaking is the 3-GeV, 528-m-circumfernce MAX-IV project [1], which will have 250-pm-rad or less emittance using a 7BA lattice. Such low-emittance MBA lattices having five or more bending magnets per achromat been envisioned for decades [2] but were never constructed due to technical challenges associated with the requisite small dimensions of the lattice magnets.

These challenges have been addressed over the past few years and many have been overcome. In short, it took the development of small aperture vacuum technology using chambers coated with non-evaporable getter (NEG) material for distributed vacuum pumping, development of precision machining and alignment methods needed for the smaller high performance magnets, and an evolution in the understanding and simulation of non-linear beam dynamics before a practical design for a low emittance MBA storage ring light source could be proposed.

- 4^{th} Gen. Light source with MBA lattice and pm emittance, electron beam emittance < ε_r
- Key feature is larger number of magnets with smaller magnet pole tip radius ~ 15mm
- Small magnet radius creates challenges for vacuum system – small vacuum chambers limits pumping conductance

DLSR Vacuum Challenges

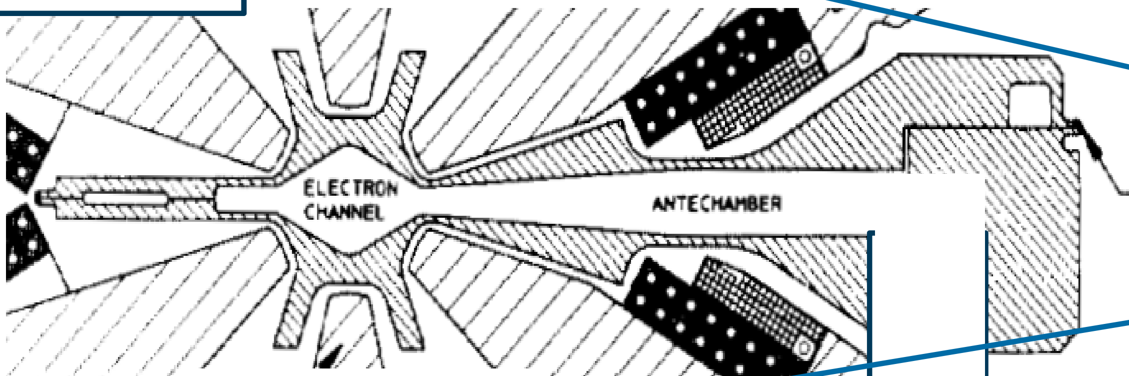
3rd DLSR Workshop SLAC 2013: Accelerator Session Close-Out Report: Vacuum

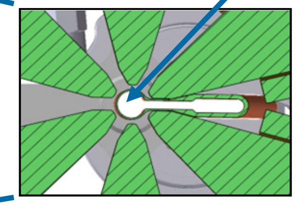
- In-situ bake out / activation procedures:
  - Minimum gap needed between chamber and magnet poles.
  - Chamber heating methods, how to apply thin radiation resistant heat films.
- NEG Coatings:
  - Coating very narrow gap and small <10 mm chambers.
  - Surface roughness
  - Photon extraction ports:
  - Coating key hole geometry is challenging.
  - Fabrication methods compatibility with coating processes.
  - Coating development in industry. Very limited industrial capability – a possible risk.
  - NEG impedance might become a problem for very short bunches.
- Photon absorbers:
  - Compact geometry with adequate cooling and minimized radiation scattering.
  - Radiation shielding with aluminum chambers.
- Impedance: More gentle transitions, round chambers improve geometric impedance; smaller cross sections, NEG coatings challenging.
- Simulations:
  - Useful tool, may be a necessity for ray tracing and multiple mis-steering cases.
- Alignment:
  - Low vibration mounts, stable chamber and BPM position, low impedance bellows.

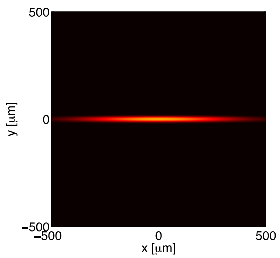
3rd Gen. to 4th Gen. Storage Ring Vacuum System

ALS / ALS-U

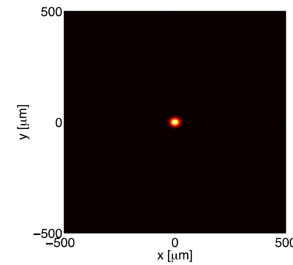
NEG Coating







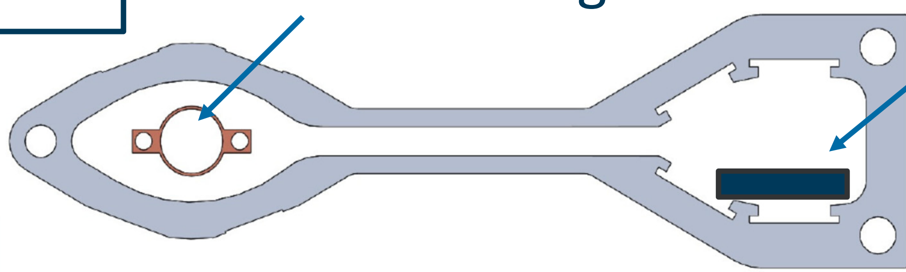
Large Ion Pump



APS / APS-U

NEG Coating

NEG Strip



TUYBB3

Cater, J., et al. MEDSI (2018)

DLSR Vacuum Technology Trend

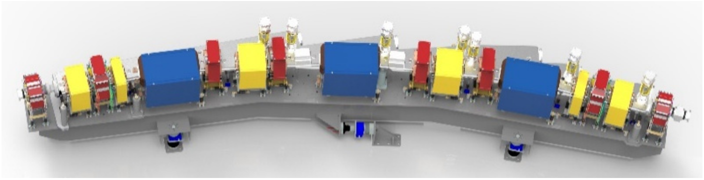
SOLEIL
100% NEG
Cu, Al, SS
Keyhole,
Antechamber
10mm ID

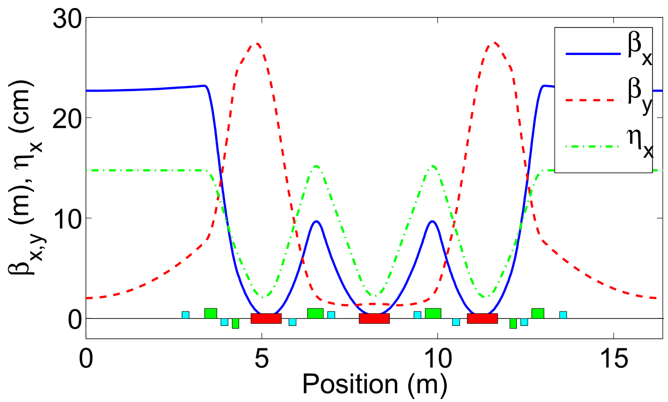
Chamber Aperture →

Circumference <250 m	Circumference 0-300 m	Circumference 300-750 m	Circumference 750-1000m	Circumference 1000-1500m	Circumference >1500m
ALS-U **70% NEG** **Cu, Al, SS** **Keyhole,** **Antechamber** **6-20mm ID**	**SLS** **100% NEG** **20mm ID**	MAX-IV, 22mm 100% NEG Coated OFS Copper SIRIUS, 26 mm 100% NEG Coated OFS Copper	ESRF-Upgrade ~26mm magnet bore Stainless Steel	APS-Upgrade ~26mm magnet bore SPring-8 Upgrade ~26mm magnet bore	
ASP 32x70mm Stainless Steel, keyhole Antechambers	ALBA 28x72 mm Stainless steel - antechambers	SOLEIL 25x70mm NEG coated Aluminum SS antechambers at dipoles	NSLS-II Aluminum ante-chamber 25x76 mm		
SPEAR III 34x84 mm OFE Copper Clamshell		DIAMOND 38x80 mm Stainless Steel, Antechambers at dipoles	ESRF 33 x74mm Stainless Steel	SPring-8 40 x70 mm Aluminum ante-chamber	PETRA III 40x80 mm At Dipoles Aluminum Ante-chamber Stainless elliptical
ALS 42mm Vertical Aluminum Clam shell	ELETTRA 60x88 mm Stainless Steel 316LN rhomboidal shape			APS 42x85 mm Aluminum ante-chamber	

ALS-U Project: Motivation – Lower Emittance & Higher Brightness

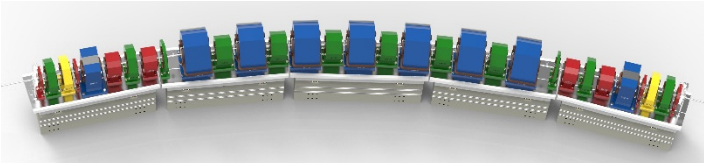
ALS today : triple-bend achromat

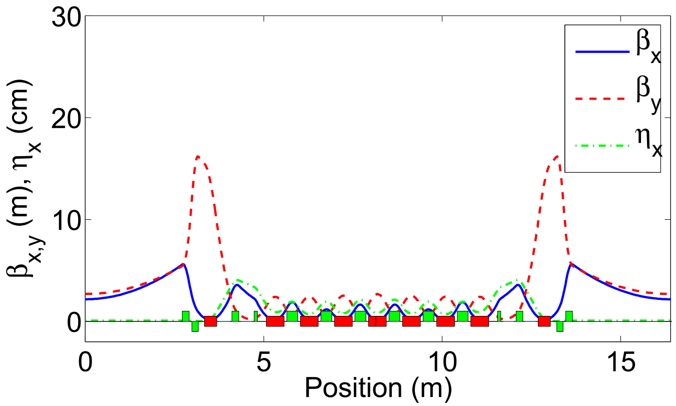




$\varepsilon_x \approx 2000$ pm rad at $1.9GeV$

ALS-U: nine-bend achromat with reverse bends



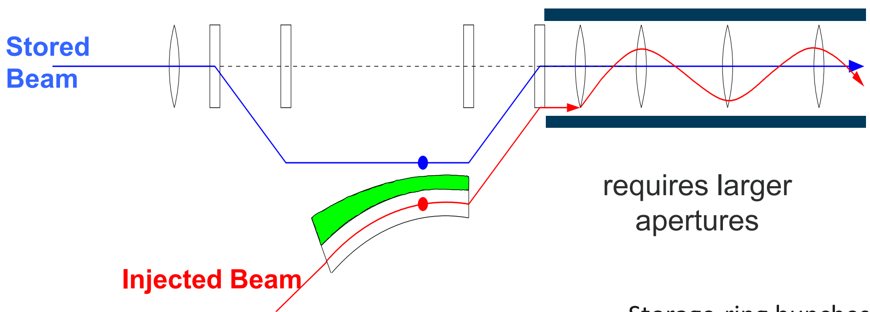


$\varepsilon_x < 75$ pm-rad at $2.0GeV$

Large increase in coherent fraction due to lower emittance and smaller β-functions

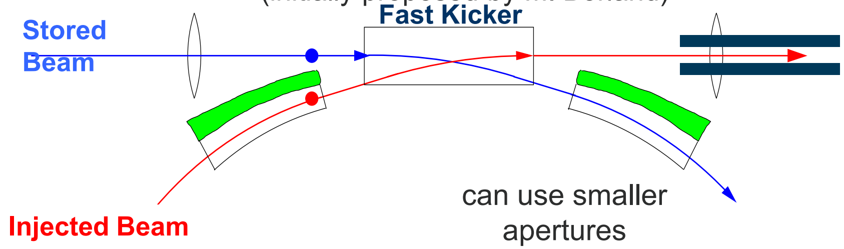
ALS-U Swap-Out Injection

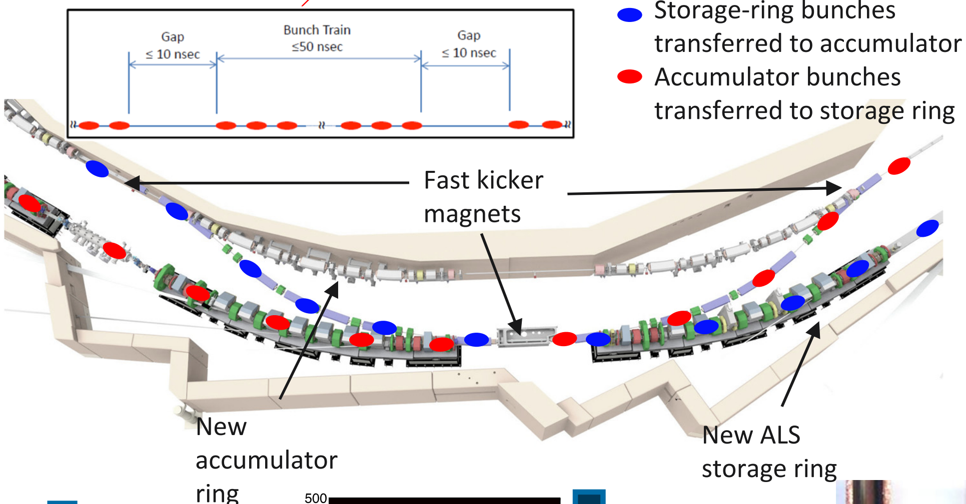
Off-axis injection + accumulation



On-axis swap-out injection

(initially proposed by M. Borland)





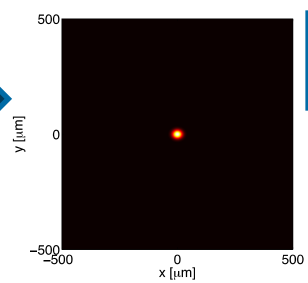
Swap-out enables:

- MBA lattices with smaller dynamic apertures → higher brightness
- Small round apertures → improved undulator performance

Bunch train swap-out with beam recovery in accumulator:

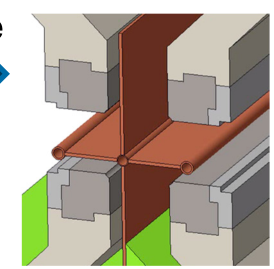
- Lower demand on the injector
- Very small (~nm) injected emittance

Allows lattices with stronger focusing + higher brightness



Allows for **small (~6mm) round** apertures

Permits higher performance polarizing undulators



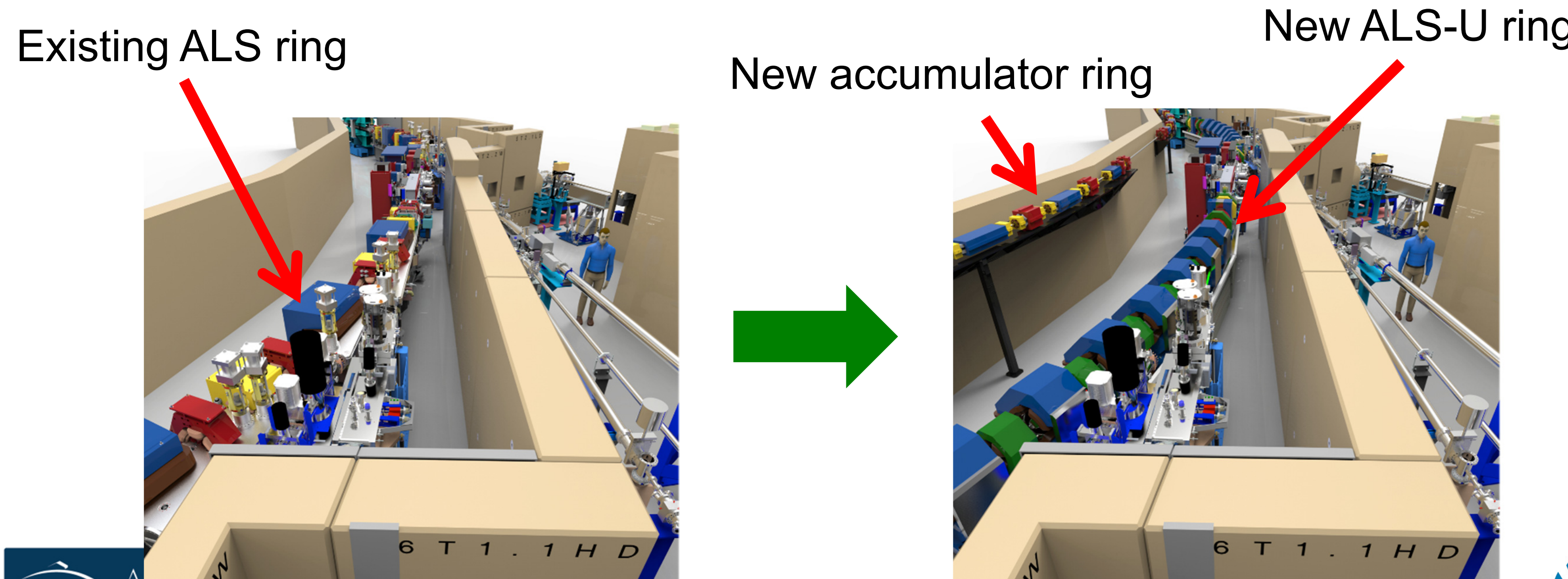
Delta/Apple-X undulator

ALS-U Accelerator Systems Scope

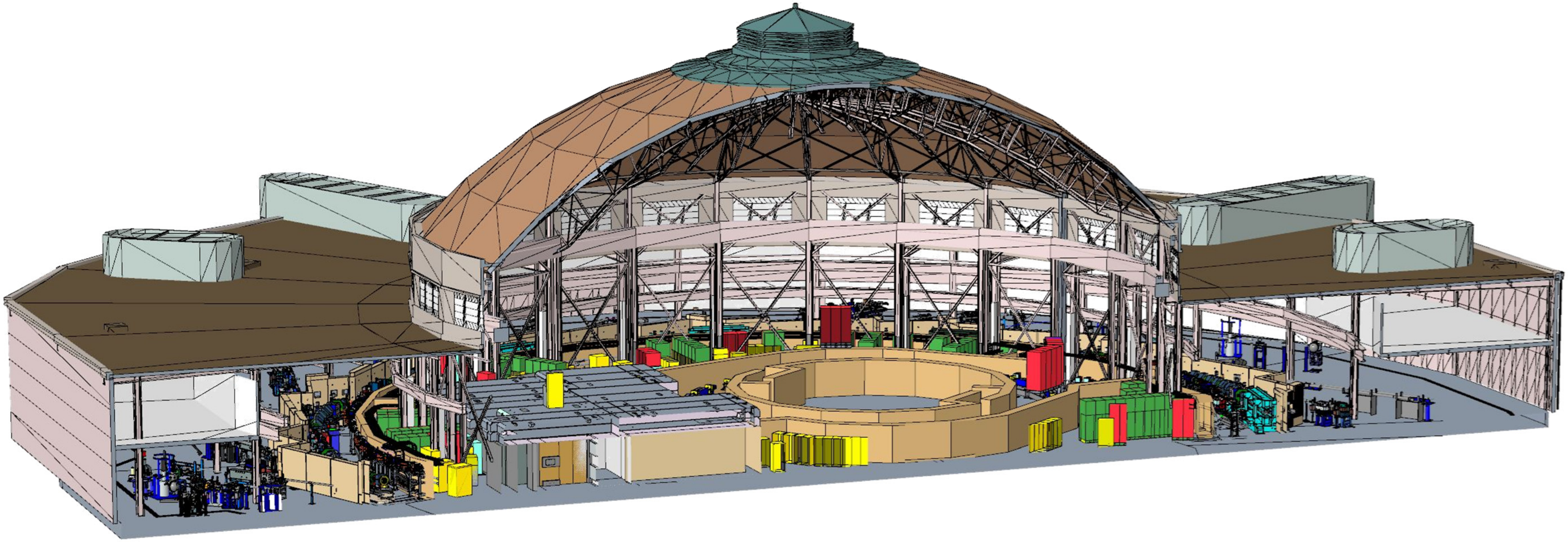
Replacement of the existing triple-bend achromat storage ring with a new, high-performance storage ring based on a multi-bend achromat.

Addition of a low-emittance, full-energy accumulator ring in the existing storage-ring tunnel to enable on-axis, swap-out injection using fast magnets.

Addition of 3 new flagship undulators and beamlines

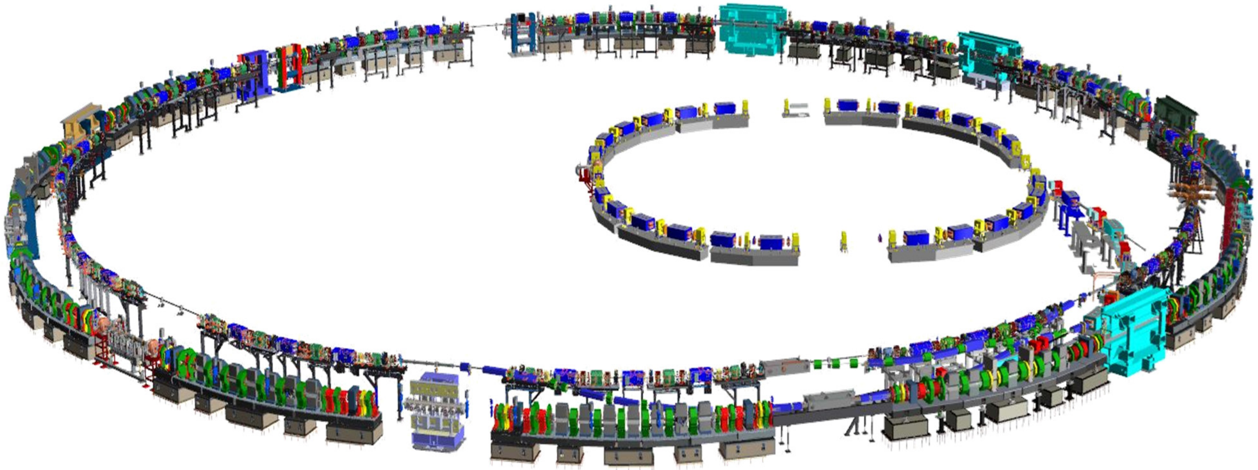


ALS-U Accelerator Systems Complex

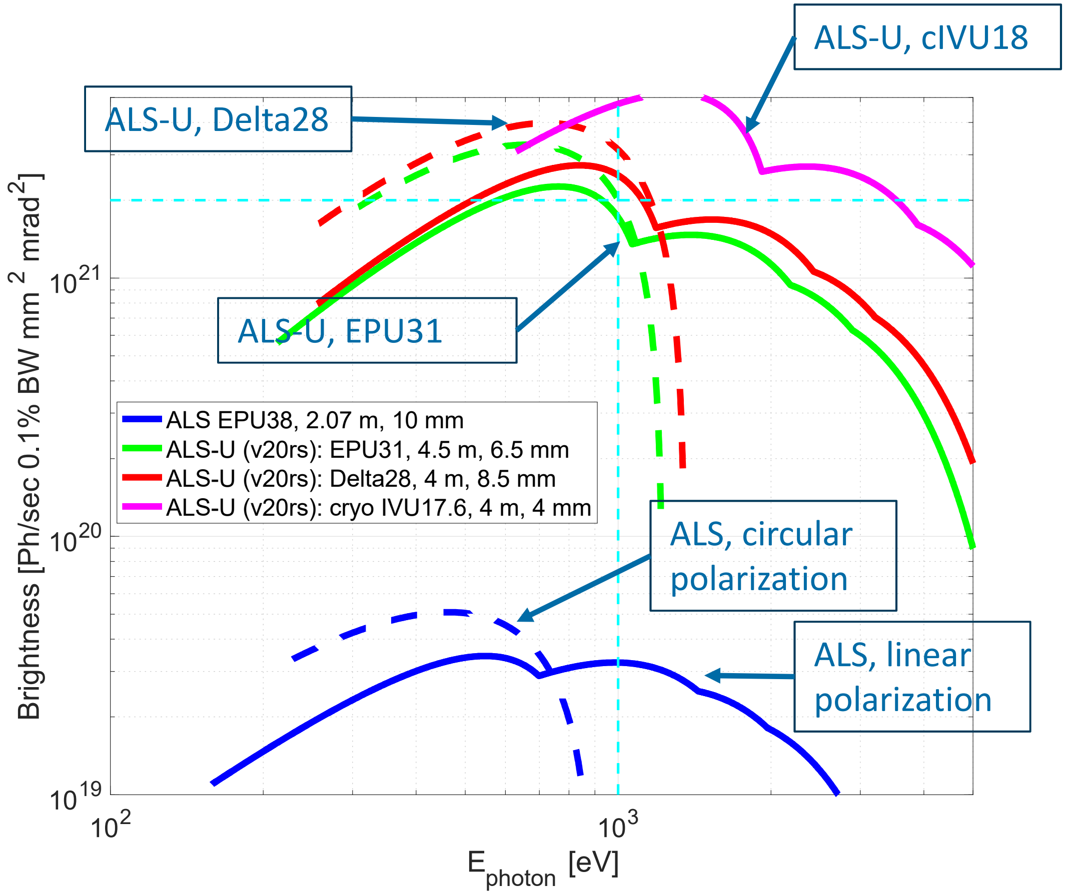


Reuse of existing infrastructure

- Building & Utility
- LINAC, Booster
- Photon Beamlines

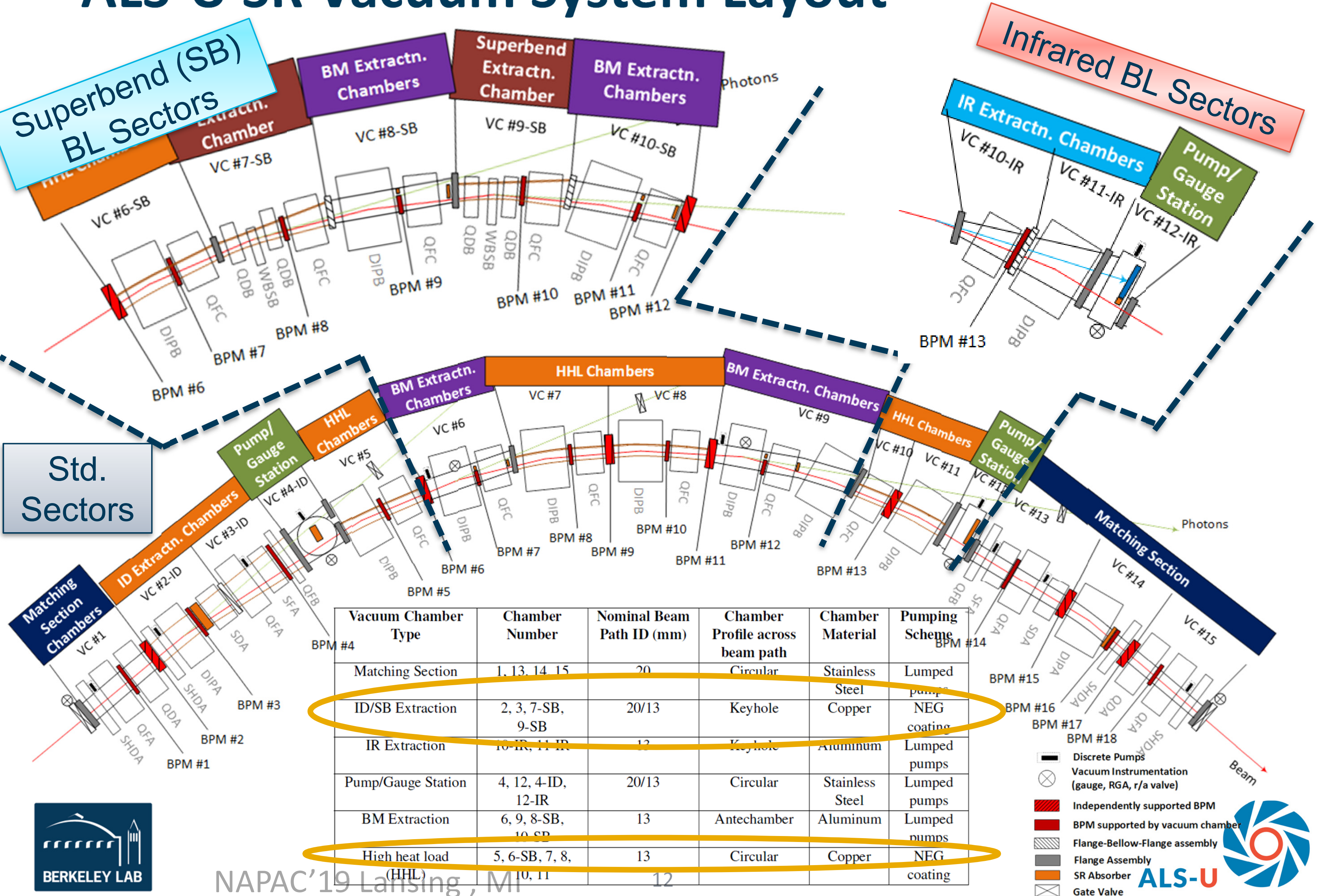


ALS-U SR Parameter and Vacuum Requirement



Storage Ring	Design actual
Energy	2.0 GeV
ε_x (full coupling)	70 pm
ε_y (full coupling)	70 pm
$\Delta p/p$	1.04×10^{-3}
$\sigma_{x/y}$ @ ID	12 μm/14 μm
$\sigma_{x/y}$ @ Bend sources	7 μm/10 μm
Bunch Length (FWHM)	110 ps
Current	500 mA
Lifetime	>1 h
Vacuum	**<1e-9Torr**
Min. Physical Aperture	**13mm**

ALS-U SR Vacuum System Layout



Vacuum Chamber Type	Chamber Number	Nominal Beam Path ID (mm)	Chamber Profile across beam path	Chamber Material	Pumping Scheme
Matching Section	1, 13, 14, 15	20	Circular	Stainless Steel	Lumped pumps
ID/SB Extraction	2, 3, 7-SB, 9-SB	20/13	Keyhole	Copper	NEG coating
IR Extraction	10-IR, 11-IR	13	Keyhole	Aluminum	Lumped pumps
Pump/Gauge Station	4, 12, 4-ID, 12-IR	20/13	Circular	Stainless Steel	Lumped pumps
BM Extraction	6, 9, 8-SB, 10-SB	13	Antechamber	Aluminum	Lumped pumps
High heat load (HHL)	5, 6-SB, 7, 8, 10, 11	13	Circular	Copper	NEG coating

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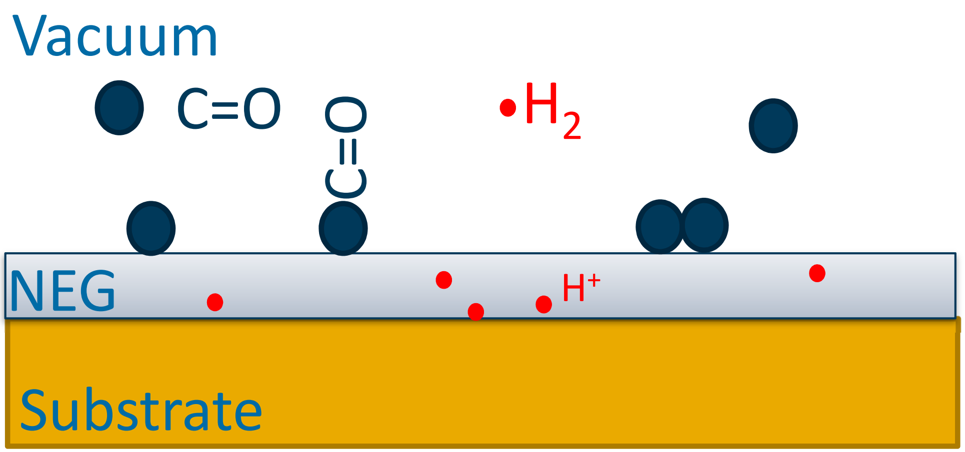
NEG Coating of Narrow Vacuum Chambers

- Non-evaporable getter (NEG) coating of vacuum chambers pioneered at CERN LHC. 6km of vacuum chamber NEG coated.
- 1 µm Ti, Zr, V alloy film applied to inner chamber wall using physical vapor deposition process



Using discharges to obtain gettering effect for residual gases, a means of pumping

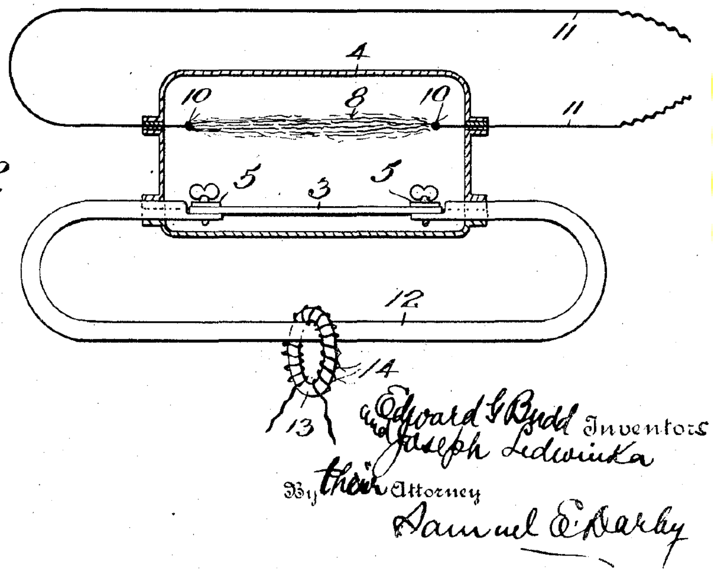
E. G. BUDD AND J. LEDWINKA.

METHOD OF ANNEALING METAL.

APPLICATION FILED SEPT. 6, 1916.

1,427,753. Patented Aug. 29, 1922.

Fig. 2.



In Fig. 2 we have shown means for producing a high tension electric spark or discharge, indicated at 8, within the chamber 4, as a means for exhausting said chamber of its oxidizing air, the spark terminals 10, 10, being included in circuit connections 11, 11, supplied with high tension current from any convenient source.

After the removal of the oxidizing agent, air or gas, or the influence thereof, from

Exploiting discharges producing gettering effects is long known

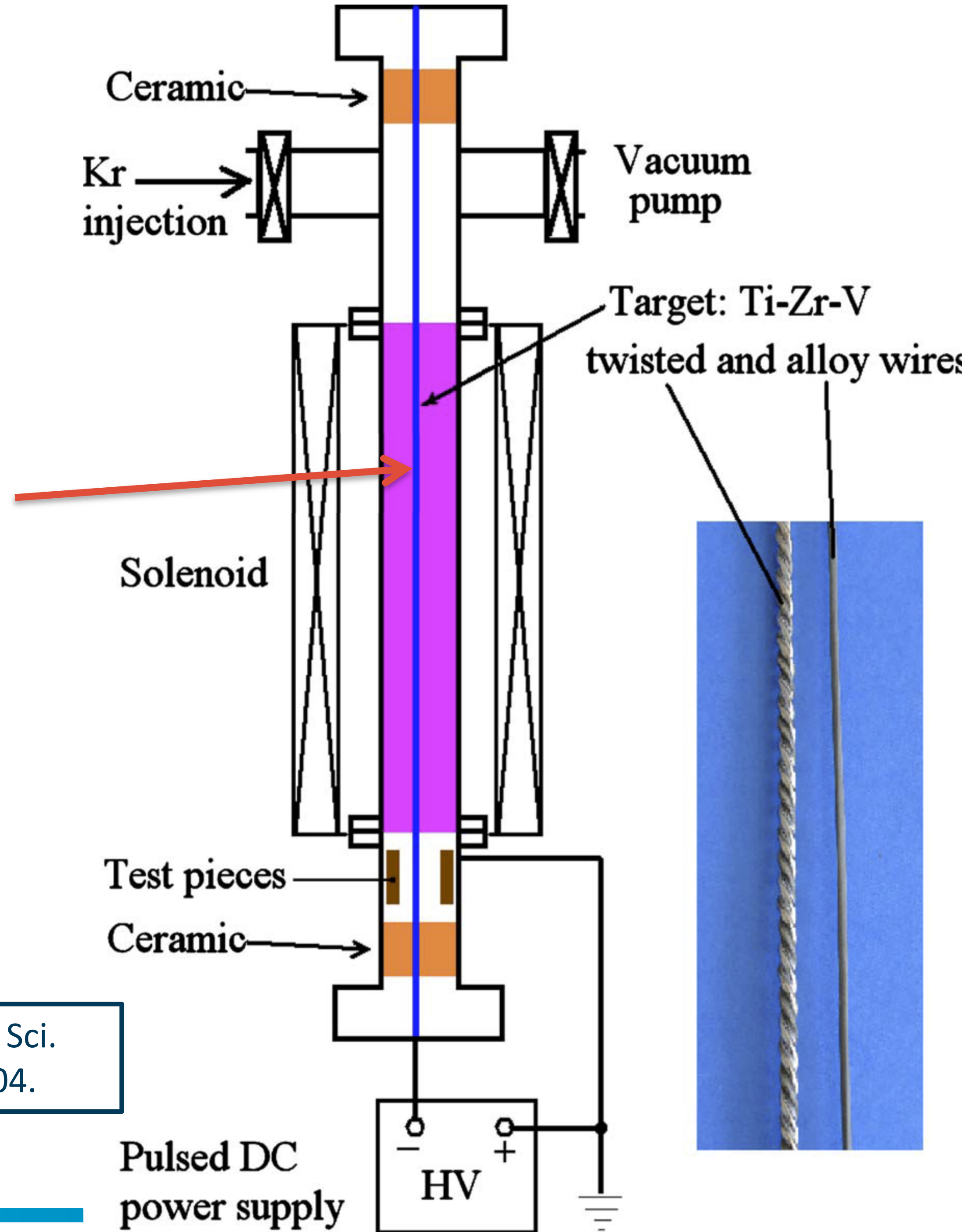
- Evaporative getters
- Non-evaporative getters

Deposition by Wire Sputtering

Space between wire and inner wall needs to accommodate:

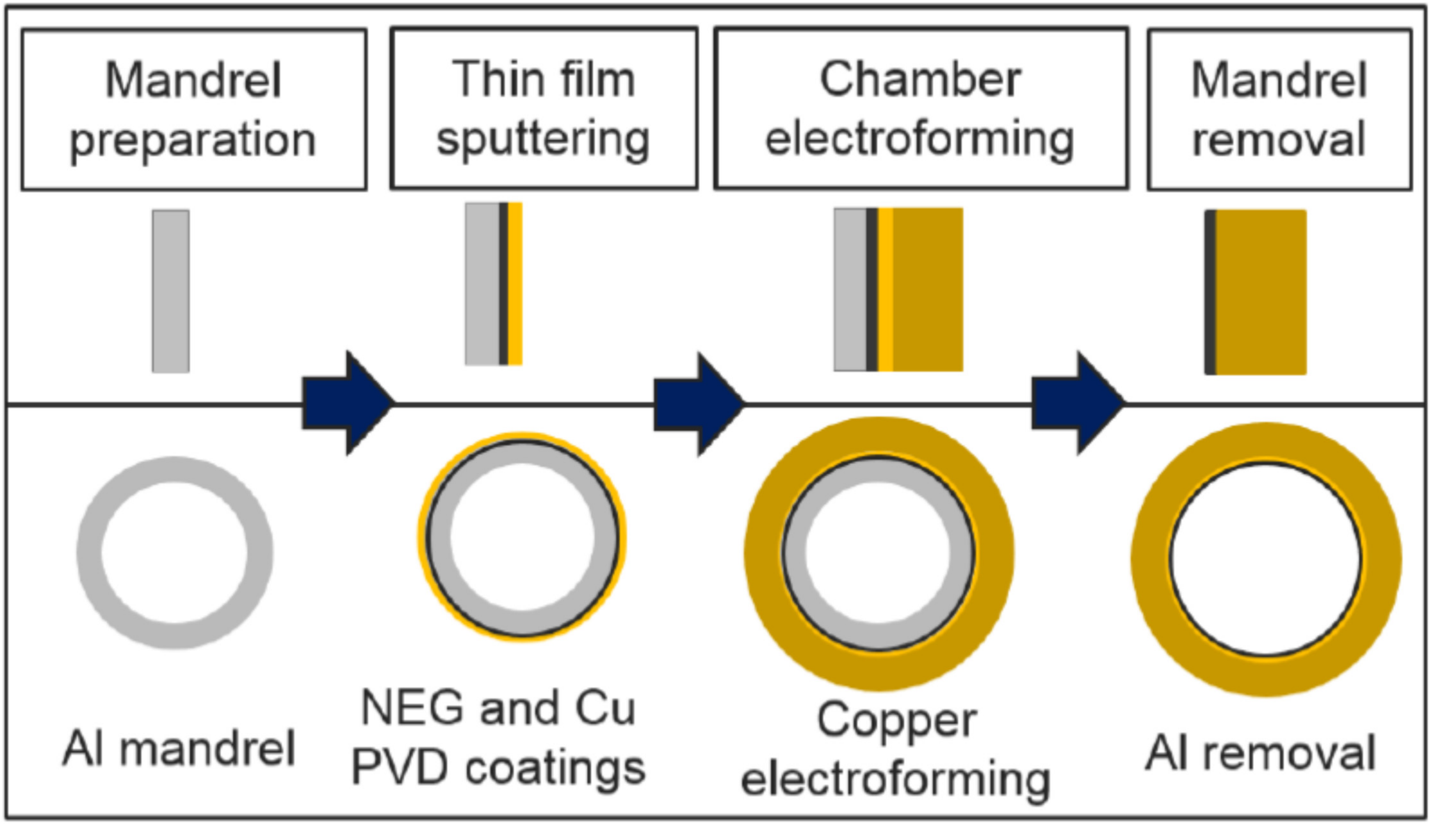
- sheath
- presheath & plasma

Challenging for narrow chambers ~15mm



R. Valizadeh, et al., J. Vac. Sci. Technol. A **28** (2010) 1404.

Alternative NEG coating method for narrow vacuum chambers

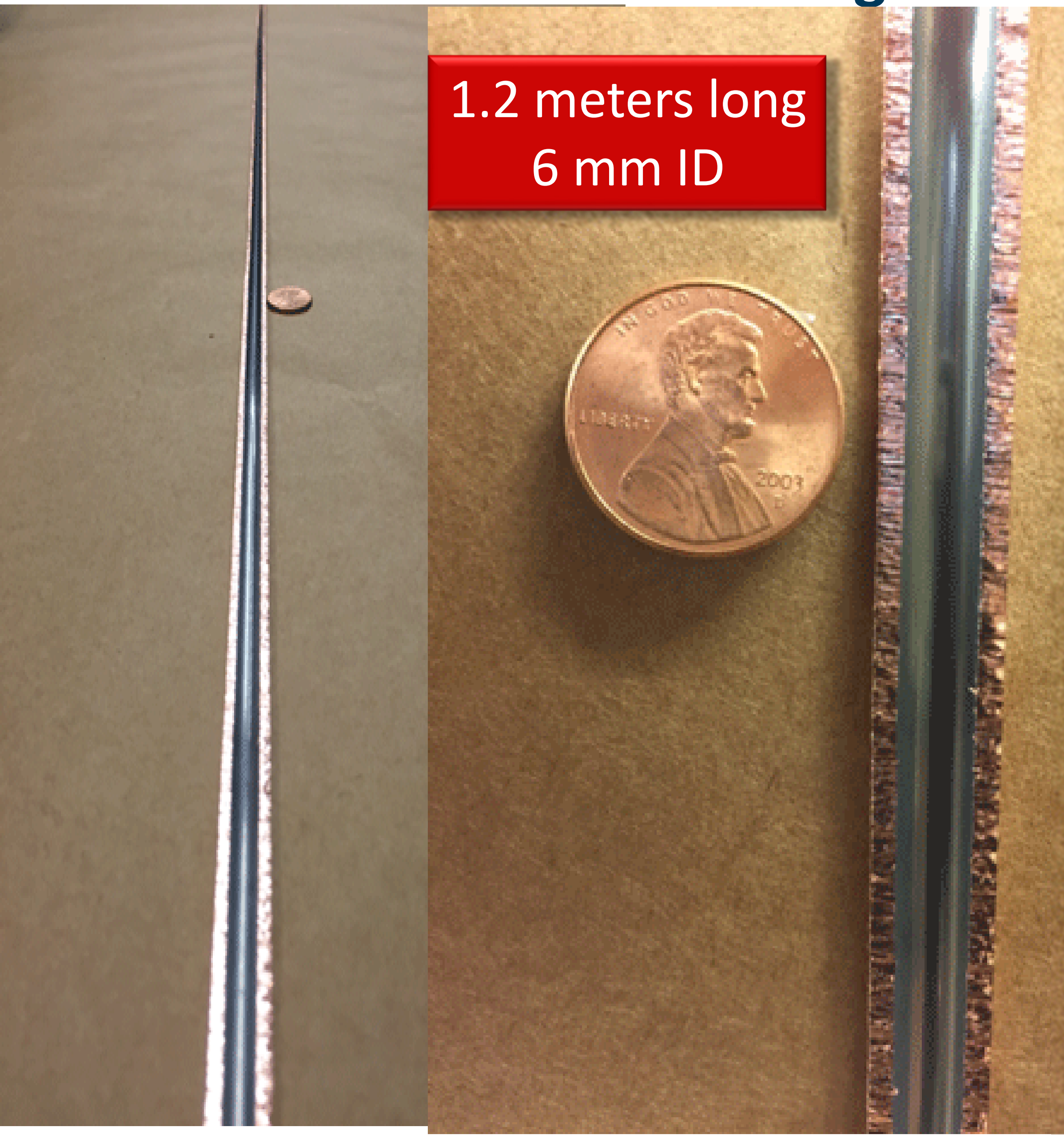


Lain Amador, L., et al. JVST (2018)

ALS-U NEG R&D Motivation

- NEG coating of small ID chambers below 15mm using classical twisted wire PVD process is possible but challenging.
- Pumping performance of these small ID NEG coating are yet to be fully characterized.
- Very few commercial vendors capable to coating small ID NEG chambers.
- Handling and operation of NEG coated chambers requires specialized knowledge. ALS's first NEG coated chamber installed in 2017.

ALS-U Pioneered NEG Coatings of Narrow Chambers using PVD



- Use twisted wires
- coating ~ 1 μm thick
- no adhesion issues on Al and Cu chambers
- we find some local composition variations

Optimal parameter set:

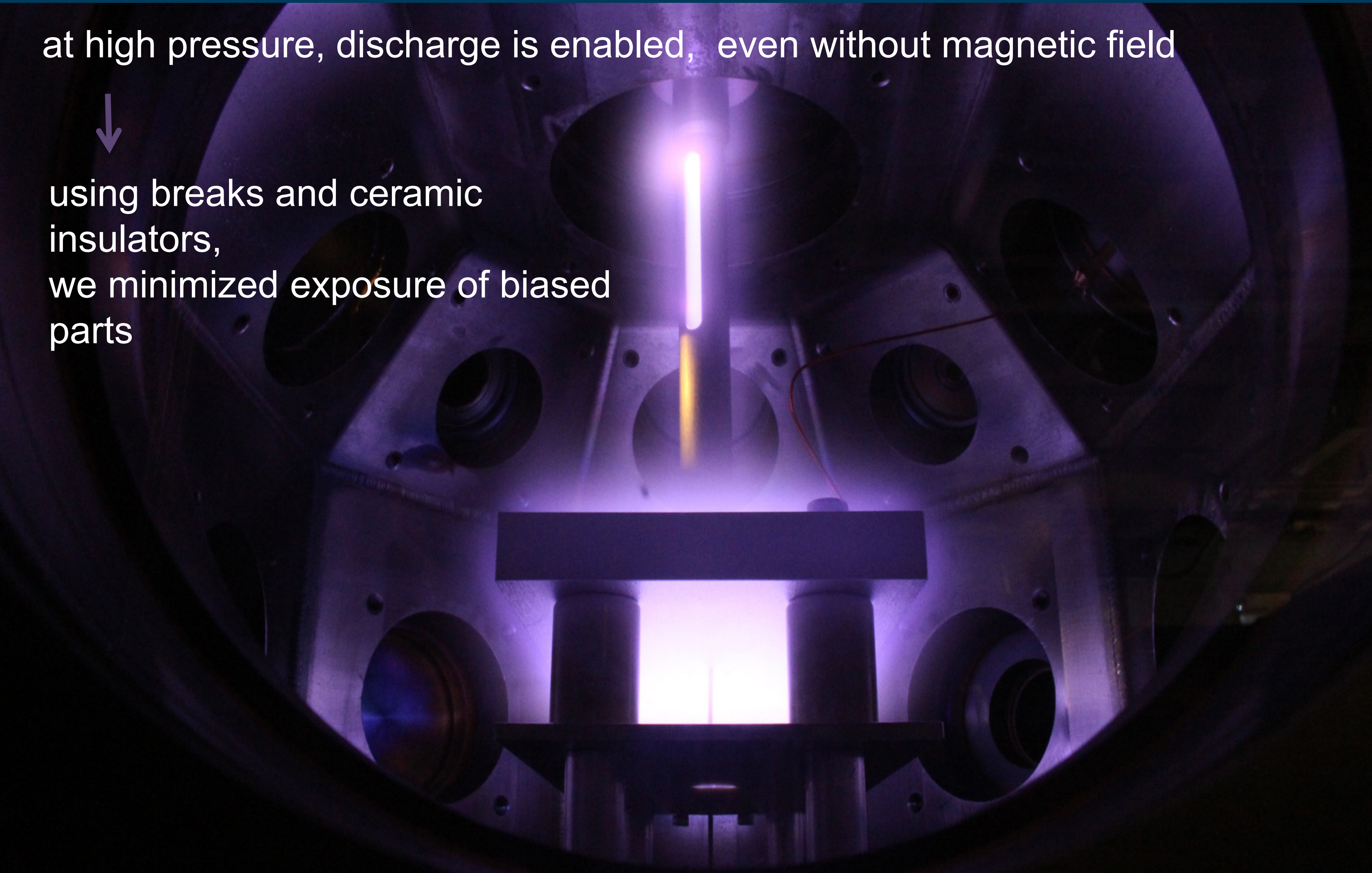
- 1000 V, 50 mA
- pulsed (10 μs on/ 50 μs off)
- mag. coil current 200 A dc
- original base pressure in low 10^{-8} Torr range
- 0.54 Torr (72 Pa) pure Ar, no flow to get uniformity

Parasitic discharge at wire ends

at high pressure, discharge is enabled, even without magnetic field

↓

using breaks and ceramic
insulators,
we minimized exposure of biased
parts



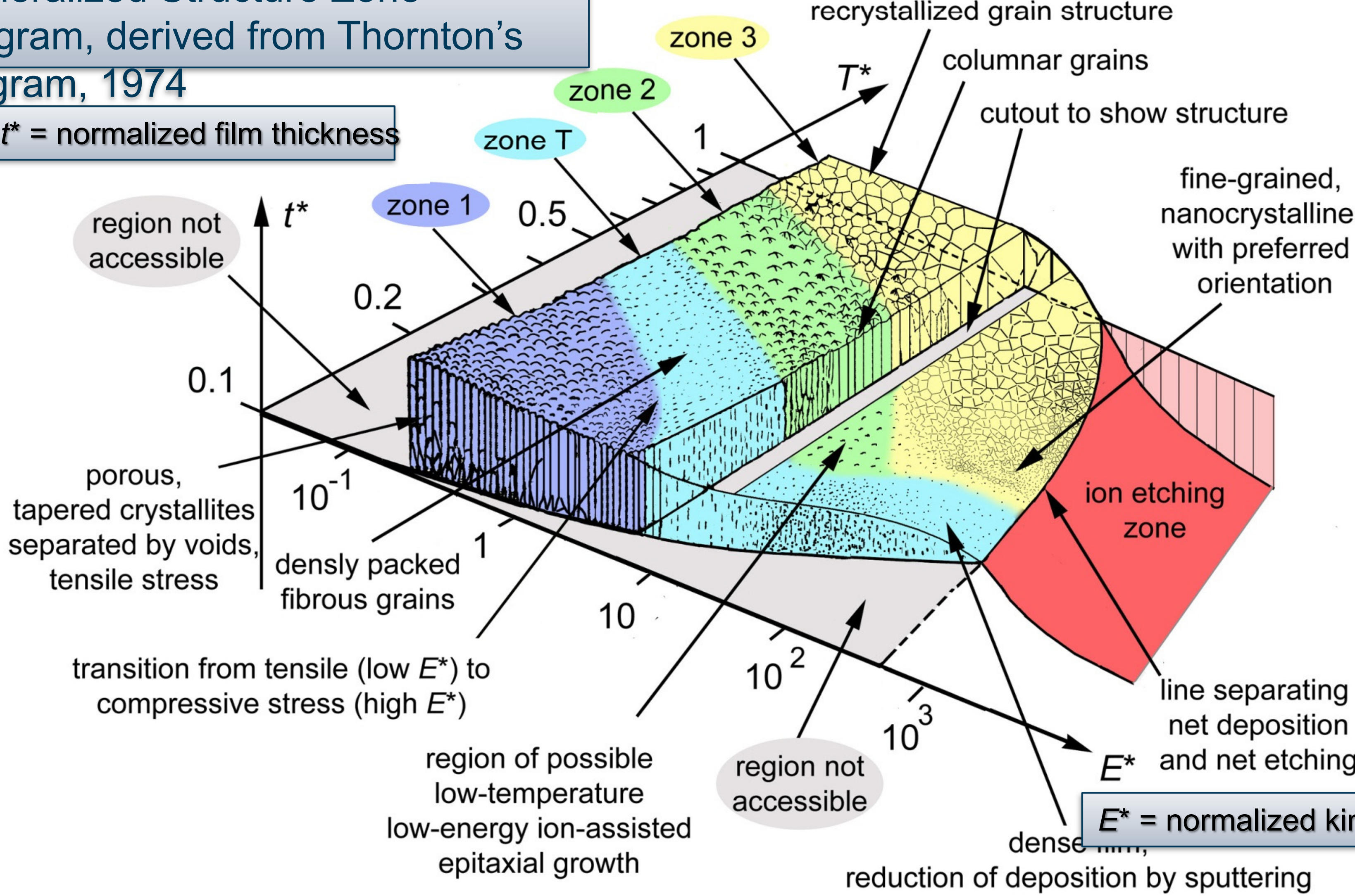
Structure Zone Diagram extended to plasma-assisted deposition

Generalized Structure Zone Diagram, derived from Thornton's diagram, 1974

*T** = normalized temperature and potential energy

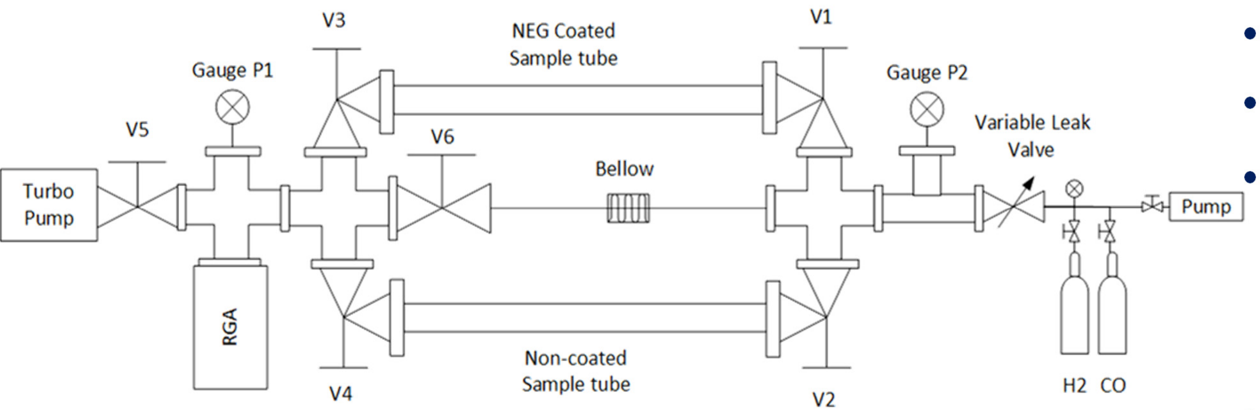
*t** = normalized film thickness

*E** = normalized kinetic energy



A. Anders, Thin Solid Films **518** (2010) 4087

ALS-U NEG Coating R&D – Pumping Measurement



- Activation: 240°C for 12 hrs
- Pumping test: Throughput
- MCTP simulations used to determine corresponding sticking coefficient to measured P_{INJ}/P_{INJ}
- Test carried out using CO & H2

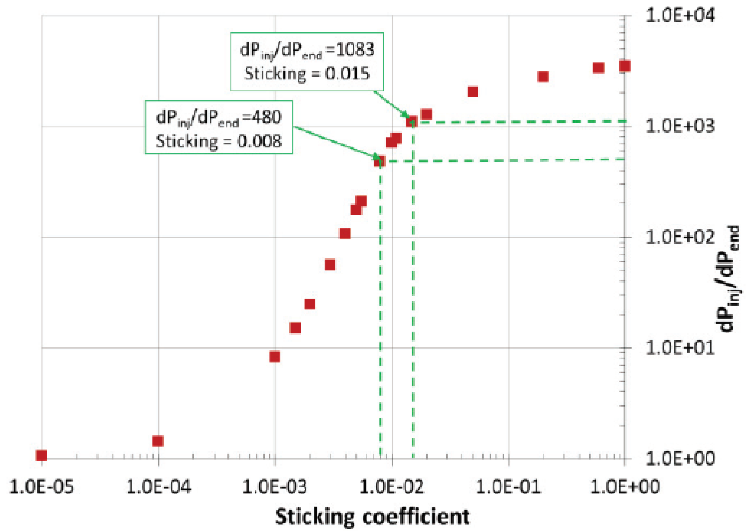


Figure 2: Monte Carlo simulations results for a 1 m long NEG-coated tube of 21 mm inside diameter.

NEG THIN FILM COATING DEVELOPMENT FOR THE MAX IV VACUUM SYSTEM

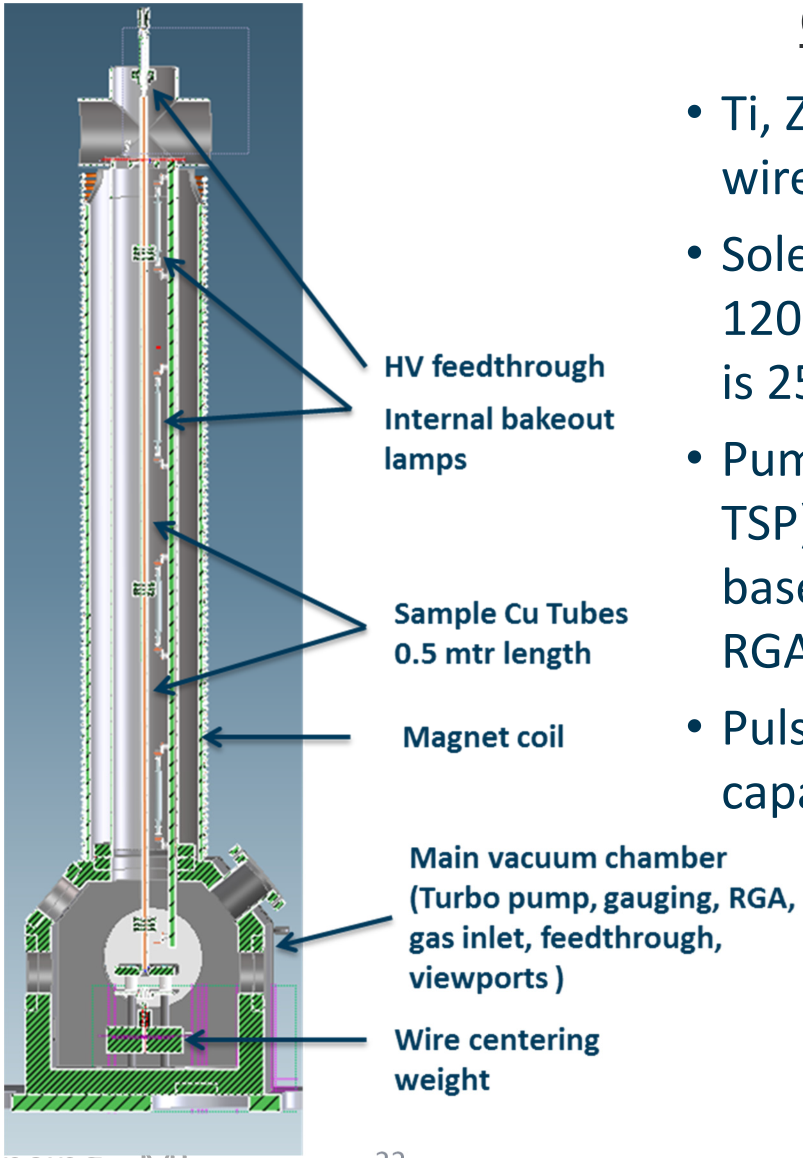
S. Calatroni, P. Chiggiato, P. Costa Pinto, M. Taborelli, CERN, Geneva, Switzerland
M. Grabski#, J. Ahlbäck, E. Al-Dmour, P. Fernandes Tavares, MAX IV Laboratory, Lund University, 22100 Lund, Sweden

CERN Data based on 60mm ID tubes,

		H_2	CO	N_2	CH_4
Maximum sticking probability	smooth	$8x10^{-3}$	0.7	$1.5x10^{-2}$	
	rough	$3x10^{-2}$	0.9	$3.0x10^{-2}$	
Surface capacity [molecules cm^{-2}]	smooth		$8x10^{14}$	$1.5x10^{14}$	
	rough		$8x10^{15}$	$1.5x10^{15}$	
Electron stimulated desorption yields [molecules per impinging electron]	electron energy = 500 eV negligible dose	$2x10^{-4}$	$1x10^{-4}$		$5x10^{-6}$
Photon stimulated desorption yields [molecules per impinging photon]	Ec=194 eV [51] negligible dose, normal incidence	$3x10^{-6}$	$<2x10^{-8}$		$<3x10^{-8}$
	Ec=4.5 KeV [41, 42] 10^{21} ph m^{-1} 10 mrad incidence	$1.5x10^{-5}$	$<10^{-5}$		$2x10^{-7}$

Tab.1: Summary of the some functional properties of Ti-Zr-V film coatings. Pumping speed and gas capacity are referred to film coated at 100°C (smooth) and 250°C (rough). Electron and photon desorption yields are reported only for smooth films. Pumping speed and gas capacity can be improved by increasing the substrate roughness.

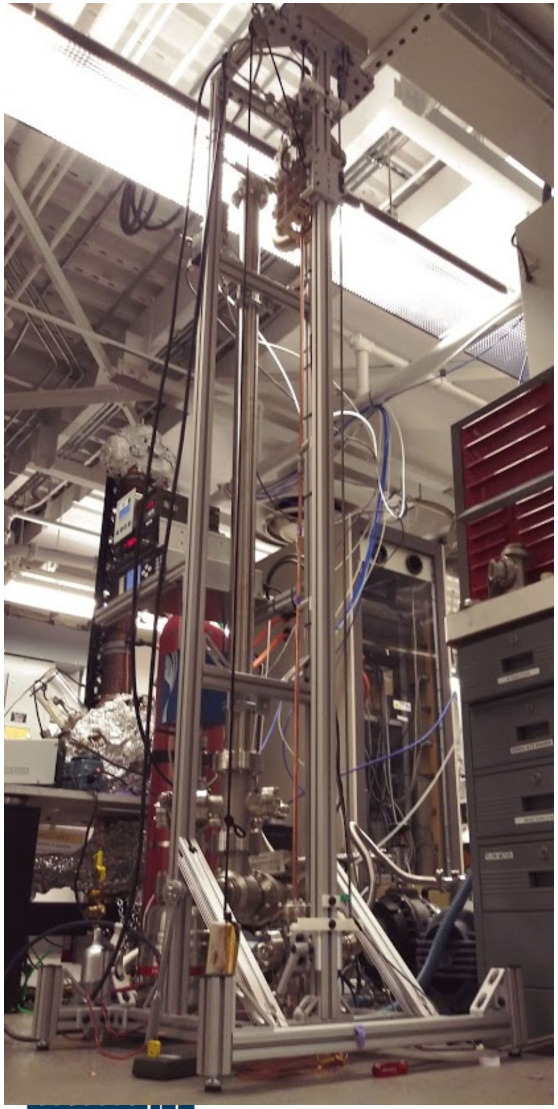
ALS-U NEG Coating R&D – Coating Setup #1

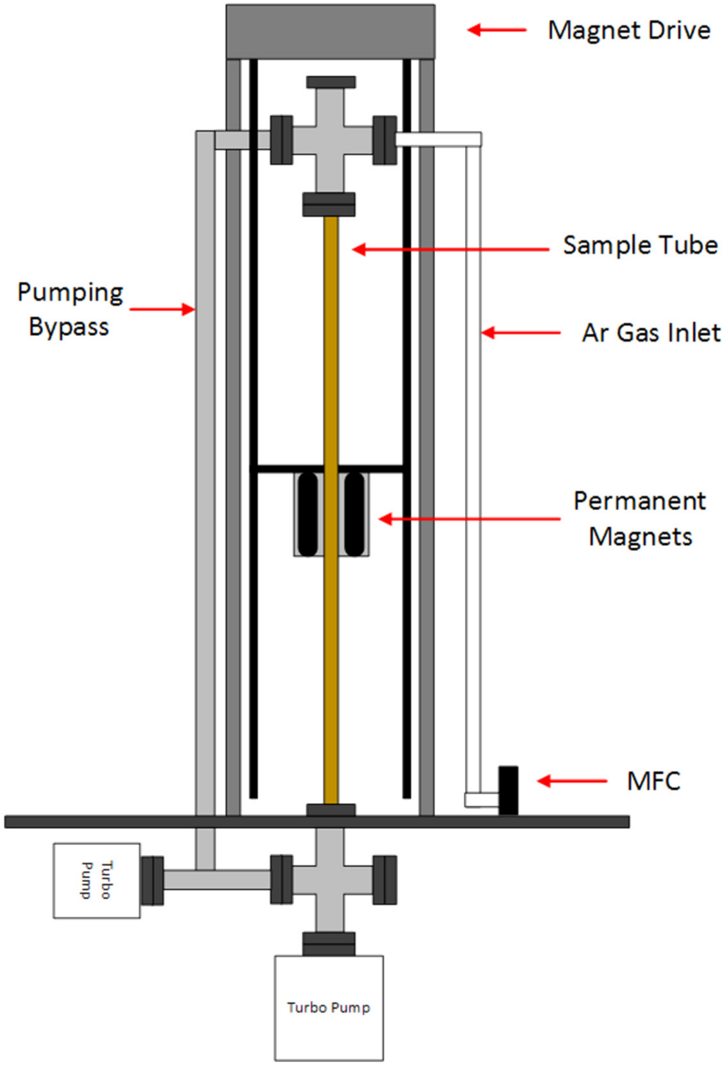


Coating Process

- Ti, Zr & V 0.02” dia. twisted wires from ESPI
- Solenoid 114mm ID, 1200mm Length, Mag. field is 250Gs
- Pumping systems (Turbo + TSP) capable of 5e-10mbar base pressure. Equipped with RGA, MFC and Baratron.
- Pulsed DC power supply capable of 1kV, 500mA

ALS-U NEG Coating R&D – 2m long setup





Coating Process

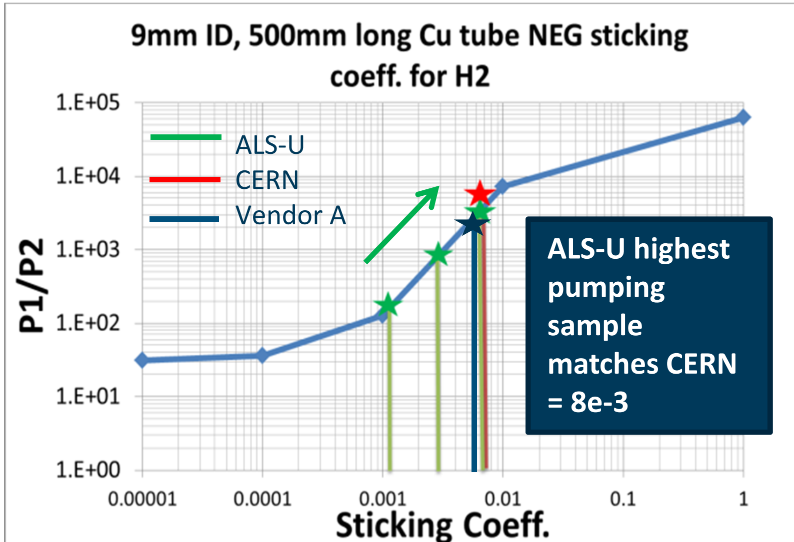
- Ti, Zr & V 0.02” dia. twisted wires
- Permanent Mag. >500Gs
- Pumping systems (Turbo + TSP) capable of 5e-10mbar base pressure. Equipped with RGA, MFC and Baratron.
- DC power supply capable of 1kV, 500mA
- Coating duration targeted for 1 micron.

ALS-U R&D NEG Samples

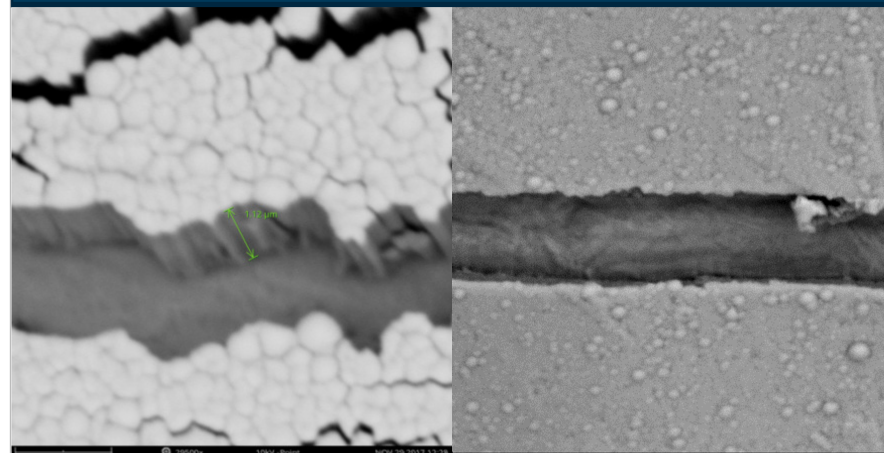
- LBL 6mm ID x 1.2m
- LBL 9mm ID x 2m
- LBL 20mm ID x 0.6m
- Vendor A 6mm ID x 0.5m
- Vendor A 9mm ID x 0.5m
- Vendor B 10mm ID x 0.5m

ALS-U NEG Coating R&D H2 Pumping

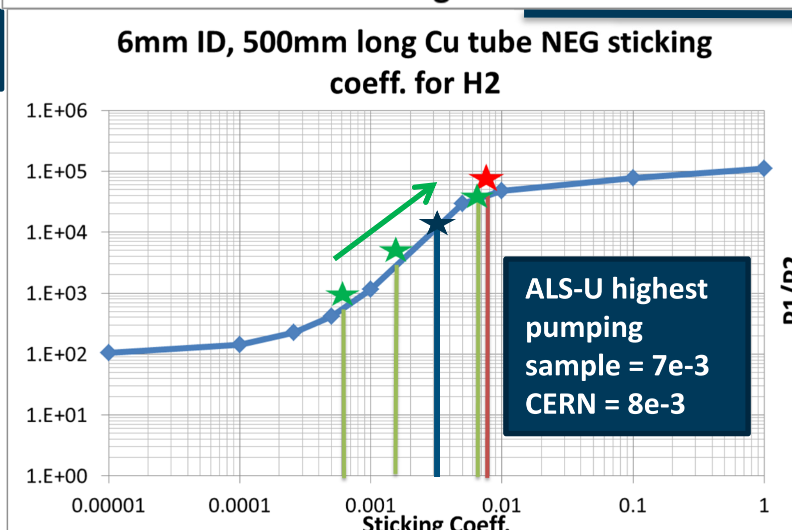
9mm ID



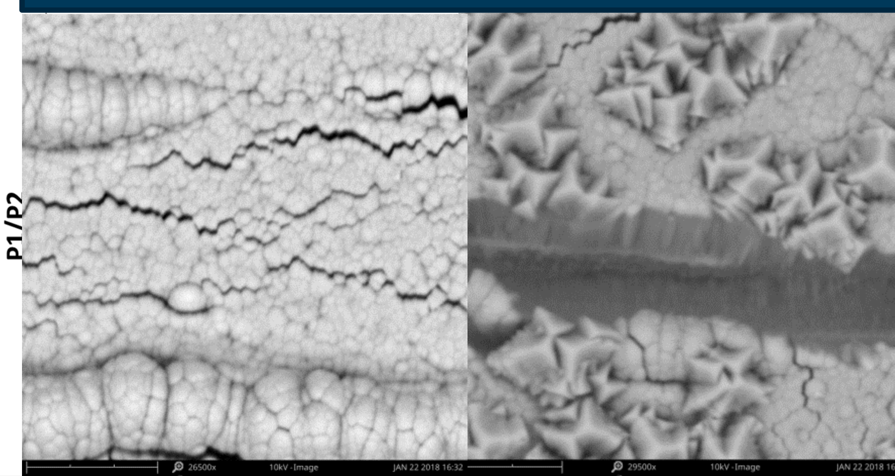
Larger columnar growth has superior pumping, dense fibrous growth structures has inferior pumping



6mm ID

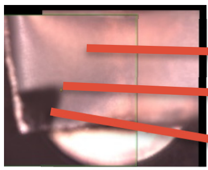


Non-uniformity structural morphology

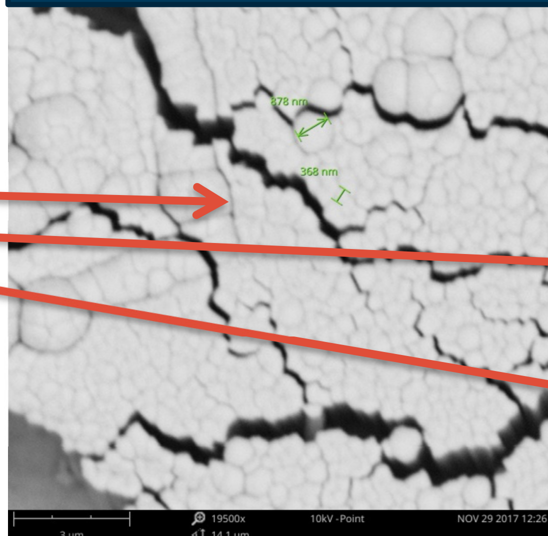


NEG Coating R&D – Best Performing H2 pumping films SEM Images

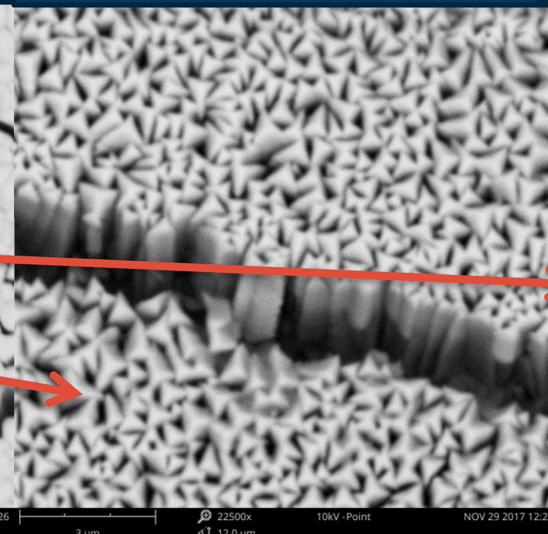
9mm ID



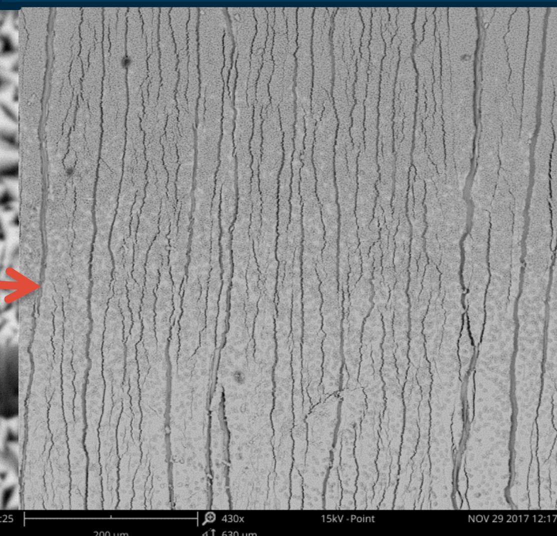
900nm to 300nm size round columns



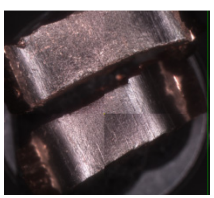
Patches of angular columns



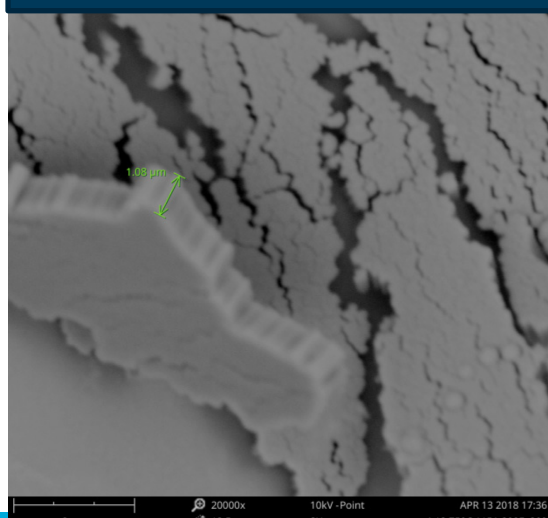
Interface between the two morphologies



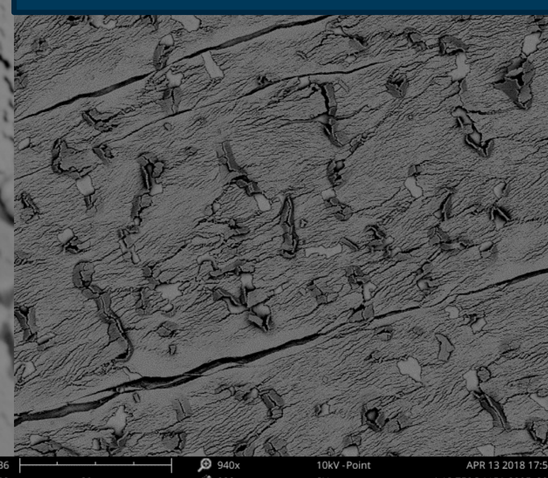
6mm ID

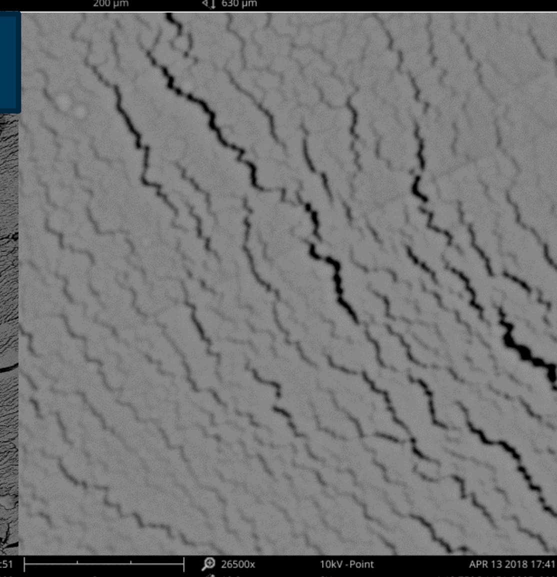


300nm size round columns



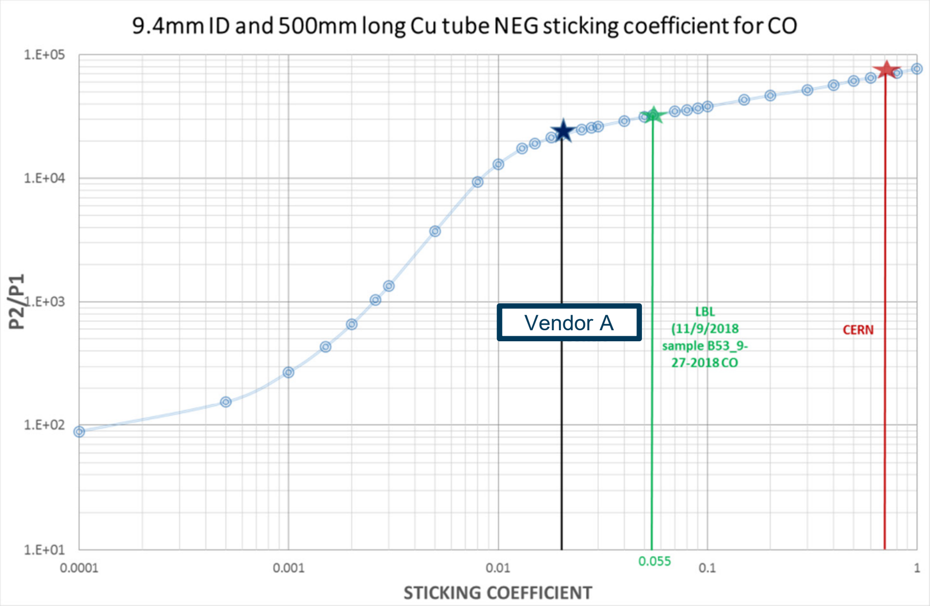
Pitting likely caused by prolonged acid etch

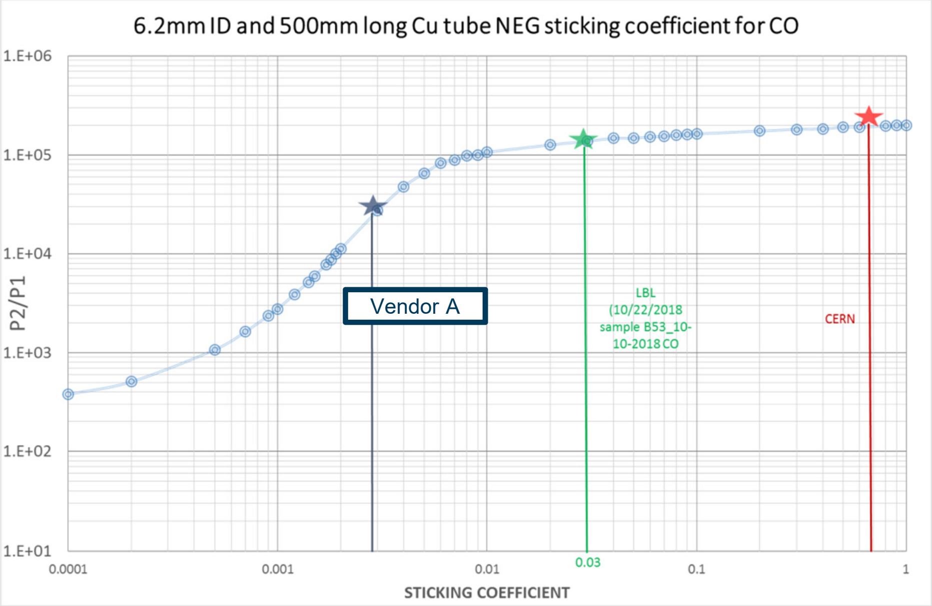




BERKELEY LAB

ALS-U NEG Coating R&D CO Pumping

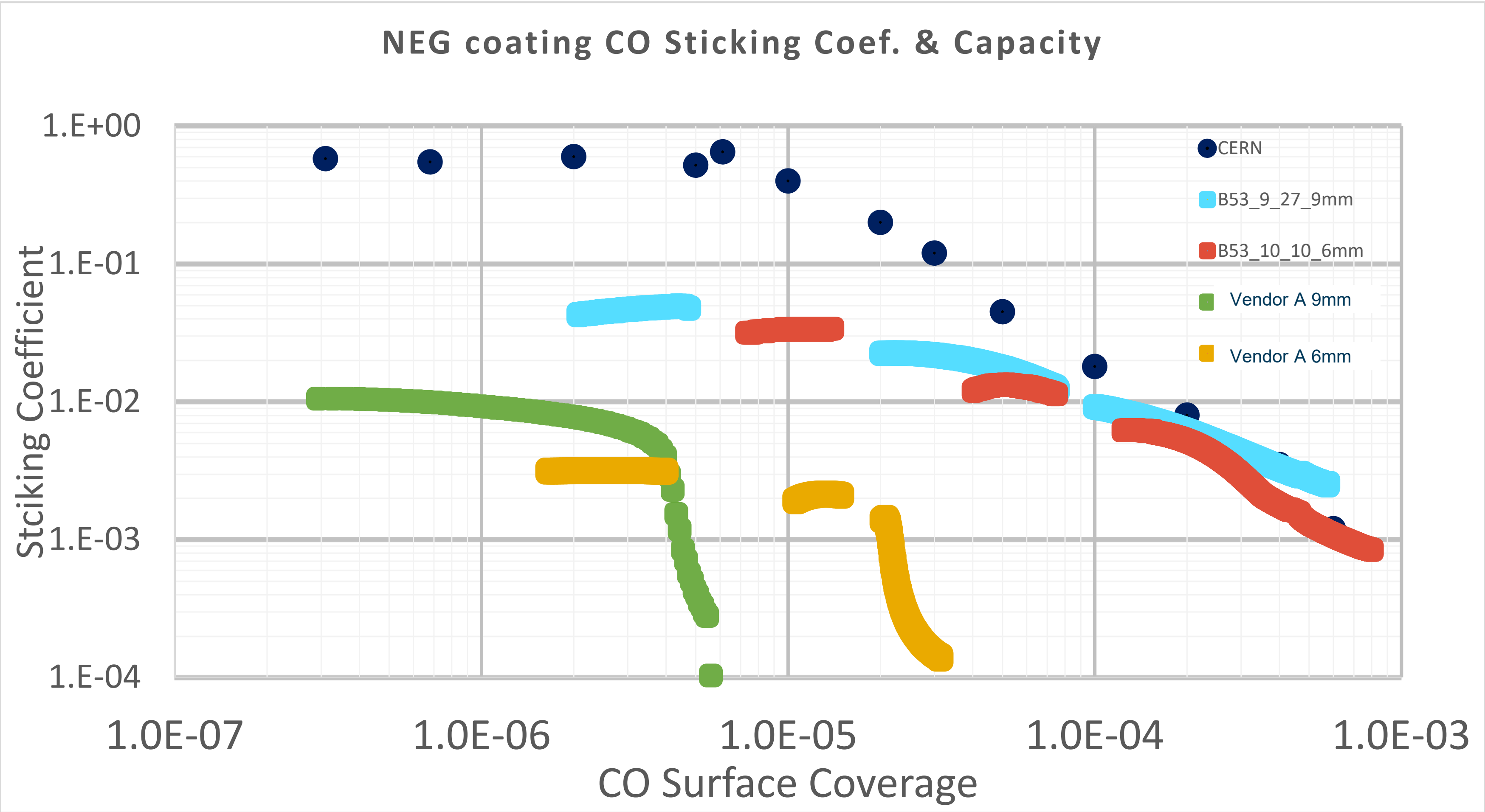




Appears to be a common issue:

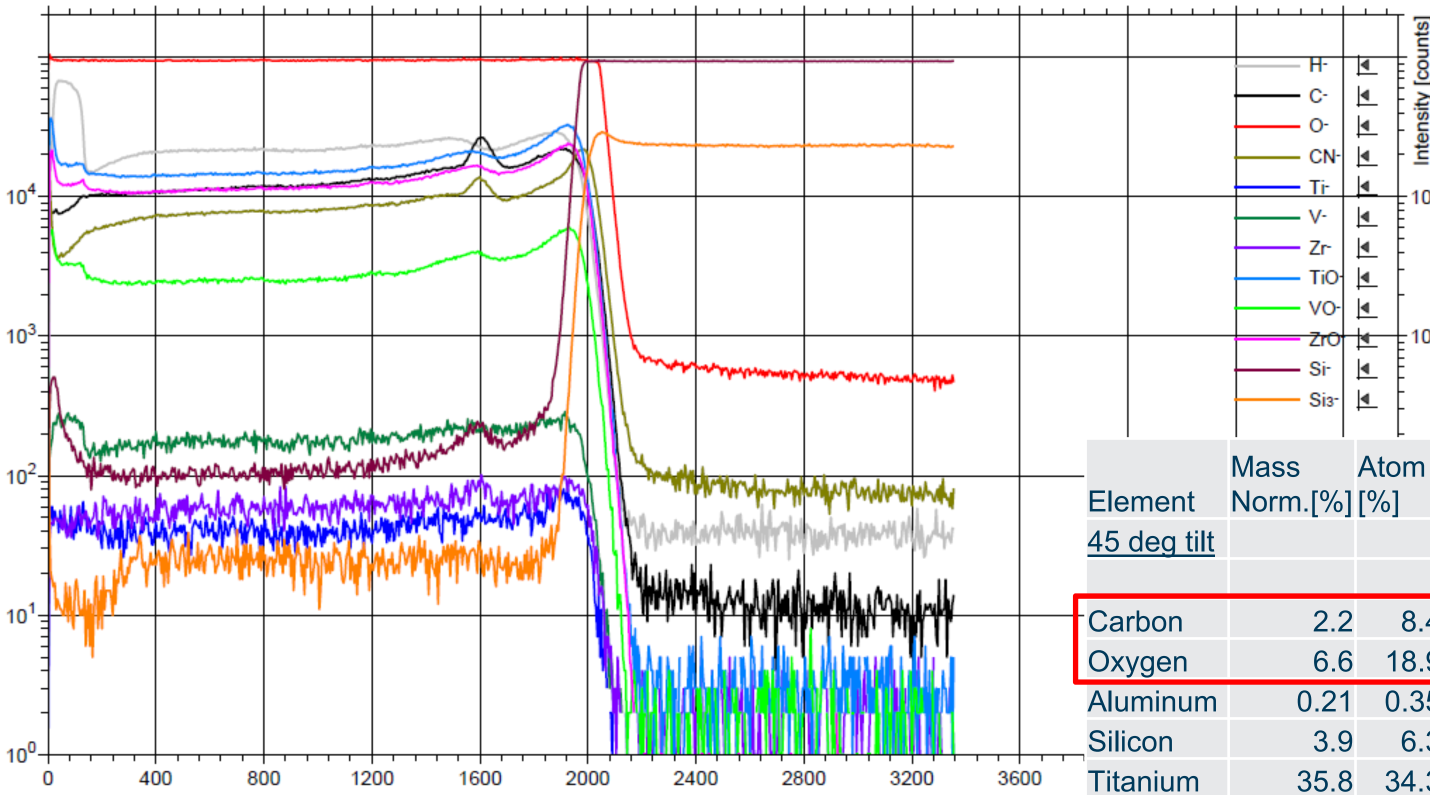
- STFC - 9mm ID– 0.01
- IHEP - 35mm ID – “promising”
- SIRUS - 24mm ID – not reported
- MAX-IV - 21mm – not reported

NEG Coating R&D CO Pumping Capacity Comparison



NEG Coating R&D: TOF-SIMS, EDX analysis of NEG samples

Sample Parameter		**Analysis Parameters:**		**Sputter Parameters:**	
Sample:	B53_10_10_18	PI:	Ga	SpI:	Cs
Comment:	B53_10_10_18	Energy:	15 keV	Energy:	2 keV
Origin:		Current:	4.000 pA	Current:	96.000 nA
File:	B53_10_10_18.itax	Area:	50 x 50 µm²	Area:	300 x 300 µm²
Polarity:	**Negative**	PIDD:	1.10E+15 Ions/cm²	SpIDD:	2.23E+18 Ions/cm²



Element	Mass Norm.[%]	Atom [%]	abs. error [%] (2 sigma)	rel. error [%] (2 sigma)
45 deg tilt				
Carbon	2.2	8.4	0.26	11.6
Oxygen	6.6	18.9	0.66	10.0
Aluminum	0.21	0.35	0.06	29.5
Silicon	3.9	6.3	0.25	6.5
Titanium	35.8	34.3	1.8	5.1
Vanadium	14.7	13.2	0.79	5.3
Zirkonium	36.6	18.4	1.9	5.2
	100	100		

NEG Coating R&D: CO performance issue

- Narrower chambers shows worse pumping performance
- Replicating CERN results for CO pumping speed is challenging
- Discussions with CERN casts doubt on validity of comparing to CERN data.
  - Flat samples may have been used.
  - Experiments show CO capacity is enhanced by regeneration by synchrotron radiation.
- Low conductance could reduce efficiency of activation process
- Vacuum simulation of ALS-U SR arc using NEG R&D CO performance shows acceptable pressure profile.
- Surface engineering
  - Long chemical etch of substrate increases roughness which leads to improved CO pumping.
  - Surface reaction post NEG coating to reduce surface carbides?

ALS-U NEG R&D Next Steps

- Short term plan for internal NEG R&D program.
  - Improving / understanding CO performance
  - New NEG coating rig
  - PSD measurement collaboration
  - Impedance characterization on ALS
  - Collaboration with vendors and institutions

Summary

- Space constraints is a major driver for the vacuum technology for ALS-U .
- NEG coating technology is essential for achieving vacuum requirements with the small apertures of the ALS-U vacuum chambers.
- The in-house NEG R&D efforts has showed promising results and pushed the boundary of the technology down to 6mm ID chambers.