Vacuum System of the 3 GeV Storage Ring at MAX IV Laboratory

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on behalf of the MAX IV vacuum team

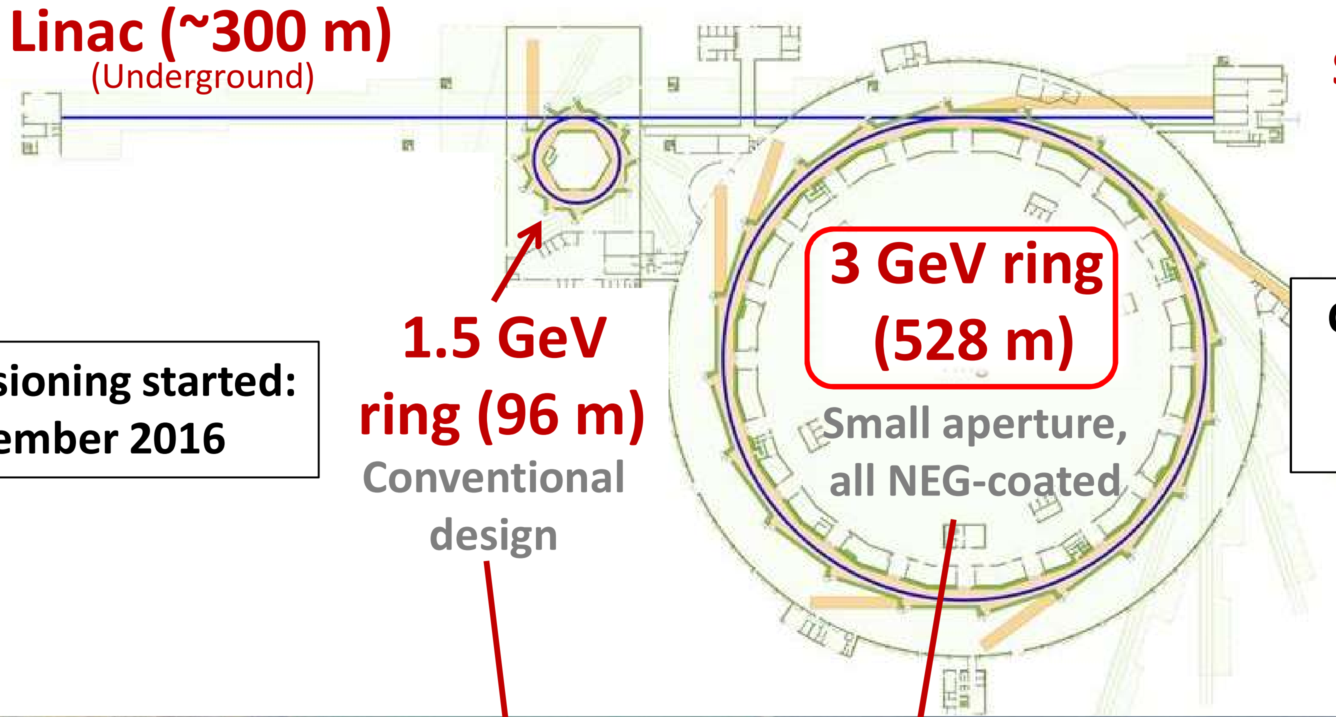
Electron-Ion Collider Accelerator Partnership Workshop 2021
(EIC2021), October 26-29, 2021

Location

MAX IV laboratory in Lund, Sweden

MAX IV facility layout

Max IV - Synchrotron light source facility in Lund, Sweden.



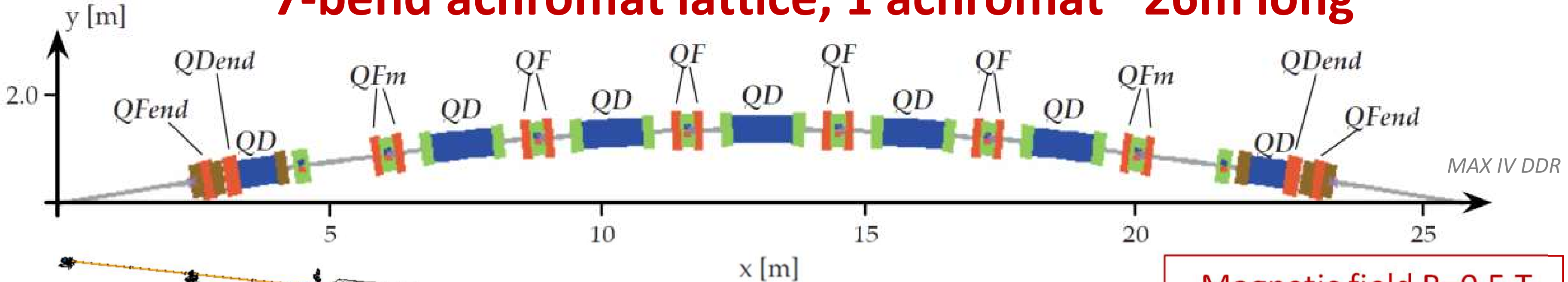
Commissioning started: September 2016

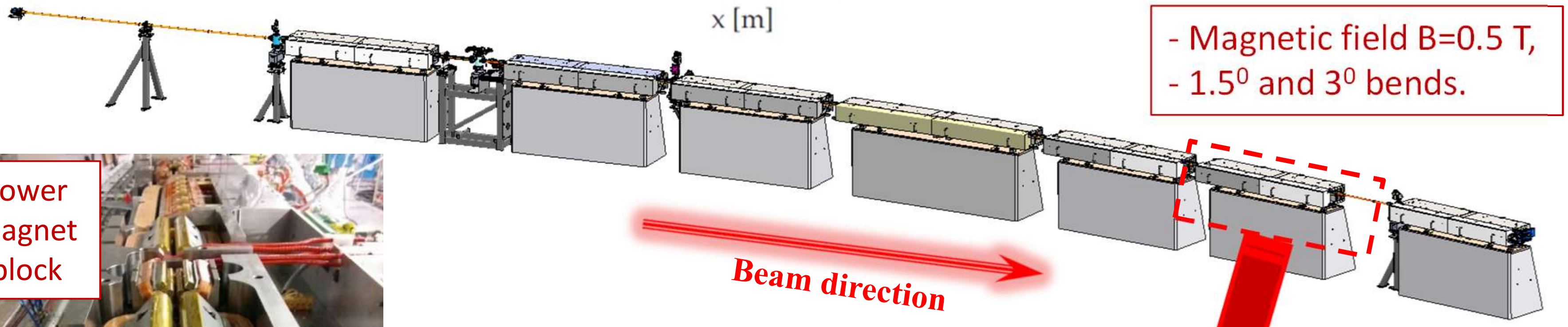
Commissioning started: August 2015

MAX IV 3 GeV storage ring vacuum system design and layout

3 GeV magnet lattice

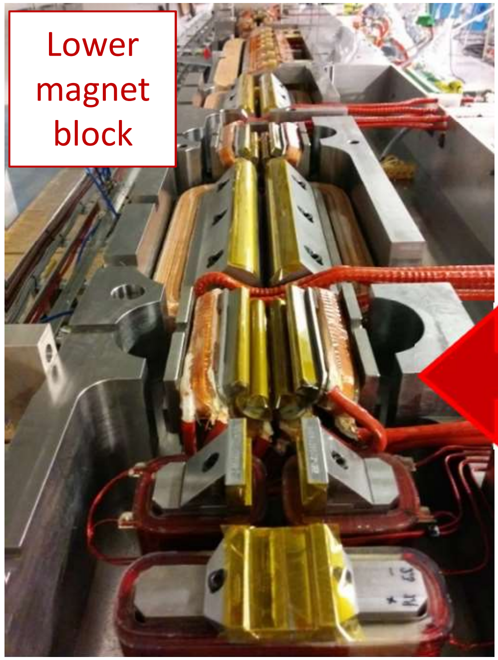
7-bend achromat lattice, 1 achromat ~26m long

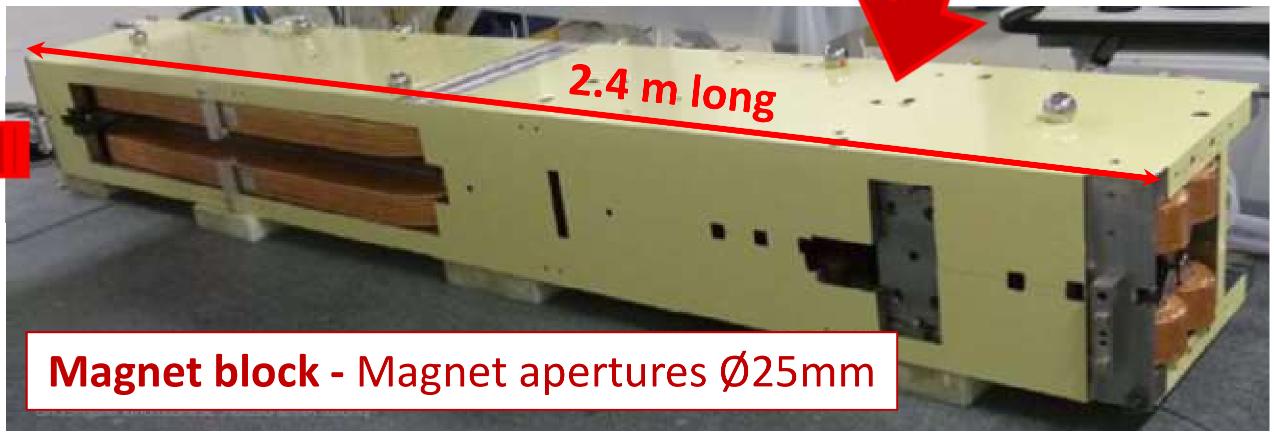




- Magnetic field B=0.5 T,
- 1.5^0 and 3^0 bends.

Lower magnet block





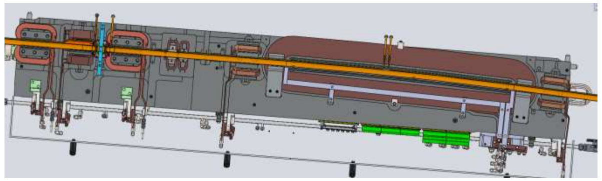
Magnet block - Magnet apertures Ø25mm

Vacuum system constraints and requirements

- **Compact lattice**

  Small longitudinal distance between magnets.

No space for lumped absorbers



- **Closed solid magnet block**

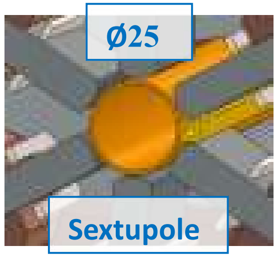
  Little place around the magnets.

No space for lumped pumps

- **Small aperture of the magnets**

  Magnets' aperture Ø25 mm.

Low conductance of vacuum tubes



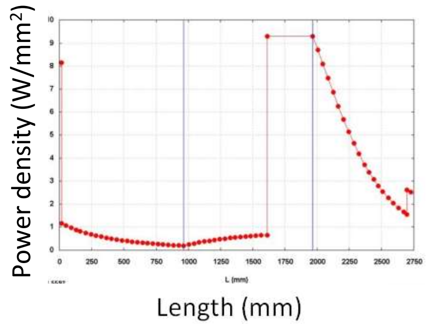
- **Low target dynamic pressure**

  Average pressure 1e-9 mbar.

Need of pumping and low PSD

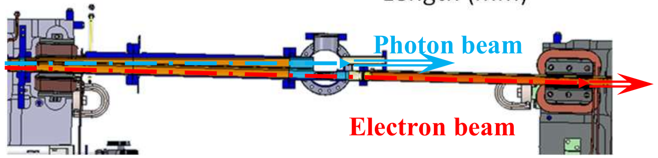
- **Removal of the SR power (BM & ID)**

  Power density along bent vacuum chamber walls and absorbers.



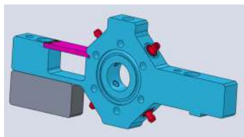
- **Extraction of synchrotron radiation**

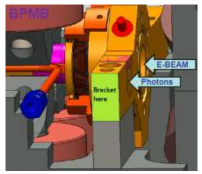
  Limited by small bending angle.



- **Stable positioning of BPM**

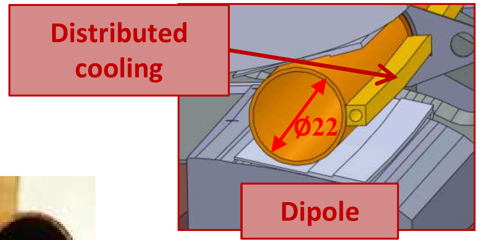
  Disentangling the BPMs from the chambers.





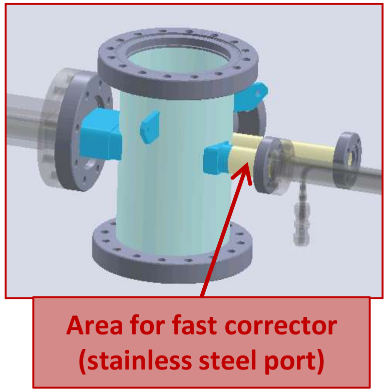
Vacuum system design approach

- **Geometry**: inside diameter **22 mm**, **1 mm** wall thickness, bends of 1.5^0 and 3^0 over 19 m radius.

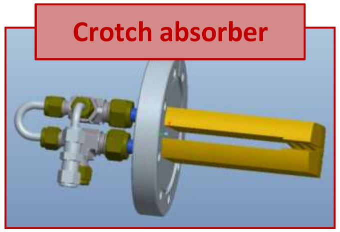


- **Substrate: Silver bearing (OFS) Copper** vacuum chambers (resistance to thermal cycling).

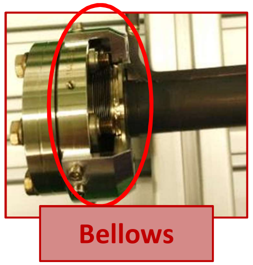
- **Distributed water cooling** to cope with SR.
- Areas made of **stainless steel** for fast corrector coils.



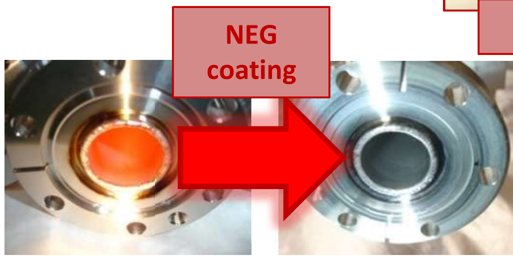
- One **Lumped absorber** per achromat needed to extract the photon beam to the front ends.



- **Welded bellows** at vacuum chamber extremities to allow expansion without affecting the BPM position and temperature.

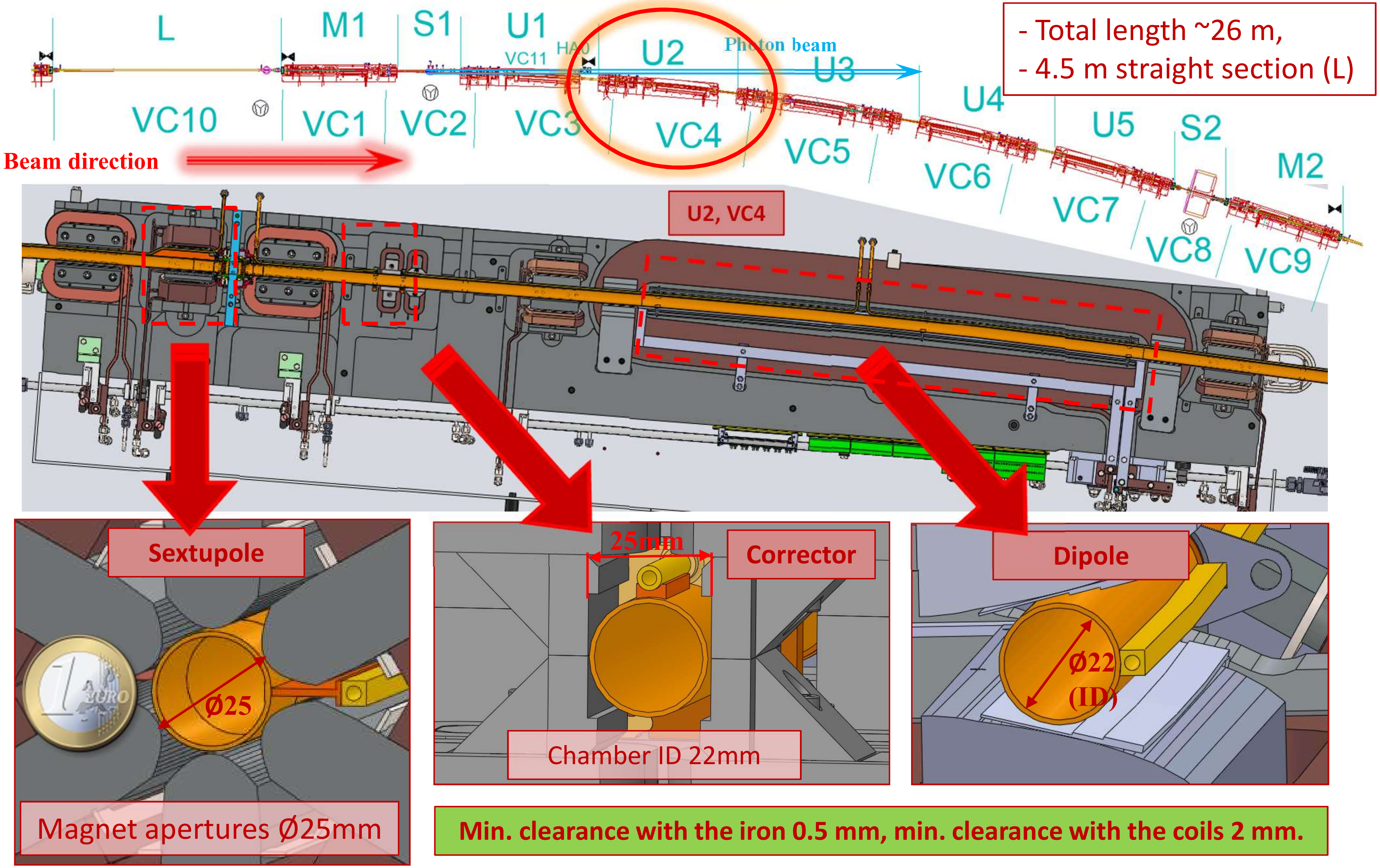


- Distributed pumping and low PSD all along the conductance limited chamber, utilizing thin film **NEG-coating**.



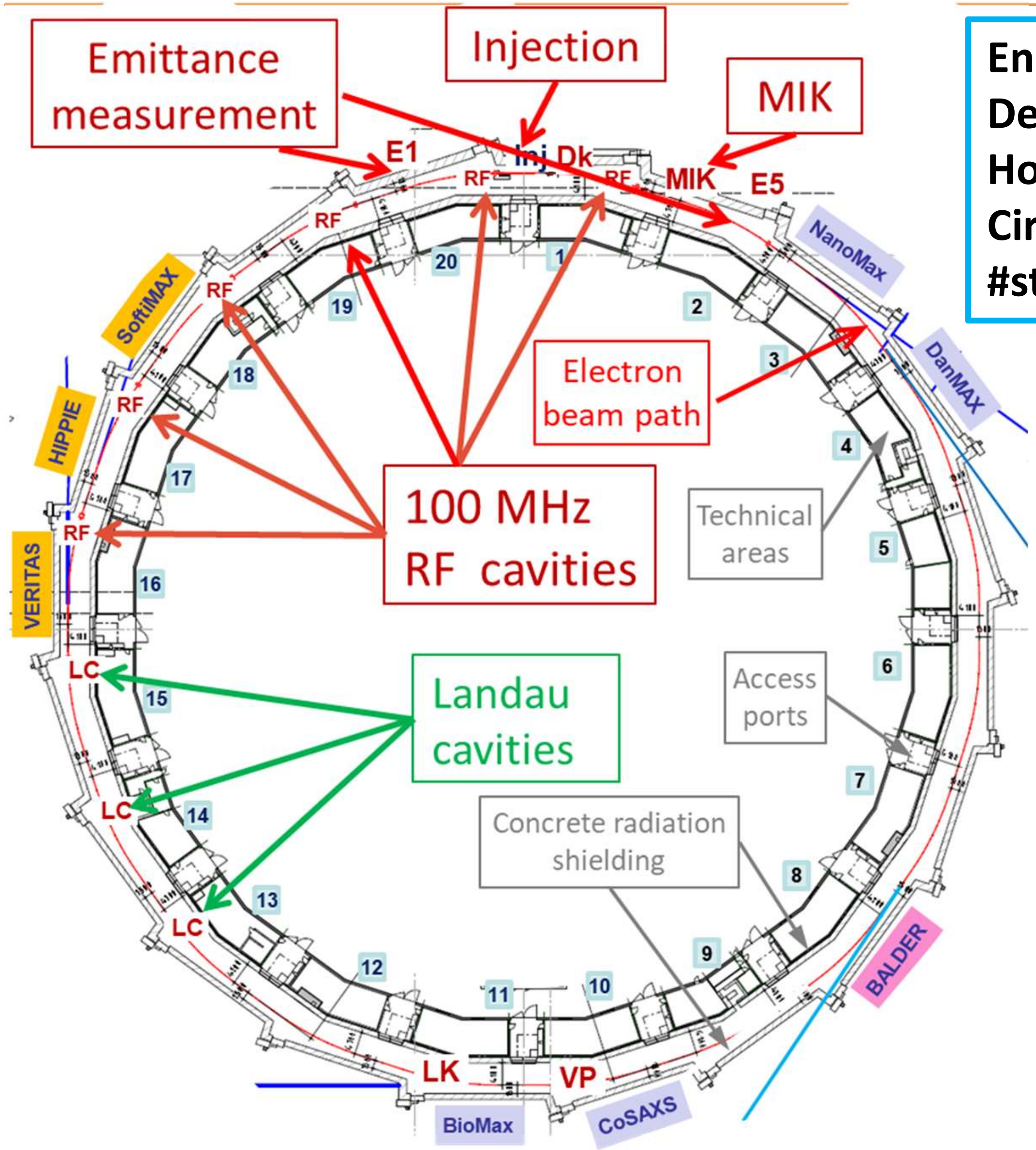
3 GeV magnet and vacuum layout

- Total length ~26 m,
- 4.5 m straight section (L)



Min. clearance with the iron 0.5 mm, min. clearance with the coils 2 mm.

3 GeV storage ring layout



Energy:	**3 GeV**
Design current:	**500 mA**
Horizontal Emittance:	**0.2-0.33 nm rad**
Circumference:	**528 m**
#straight sections:	**20 x 4.5 m**

Installed Insertion Devices:

3 In vacuum undulators (2 m long)
- NanoMAX IVU18
- BioMAX IVU18
- COSAXS IVU 19.3

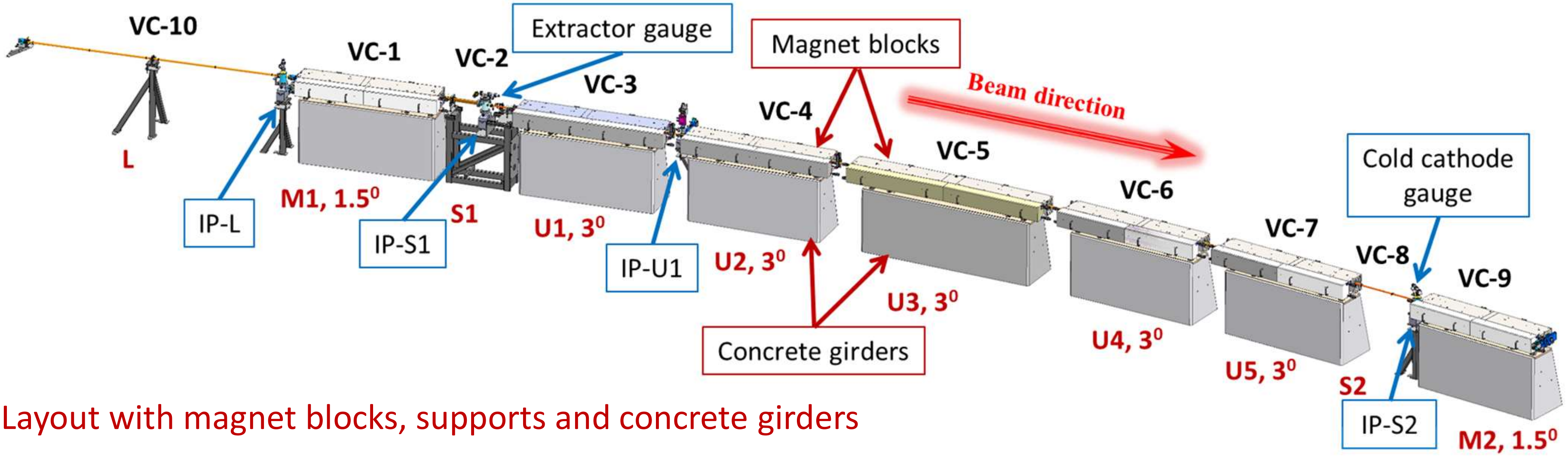
3 EPUs (4 m long, min gap 11 mm)
- VERITAS, SOFTIMAX - EPU48
- HIPPIE - EPU53

1 In vac. Wiggler (2.4 m long)
- BALDER IVW50

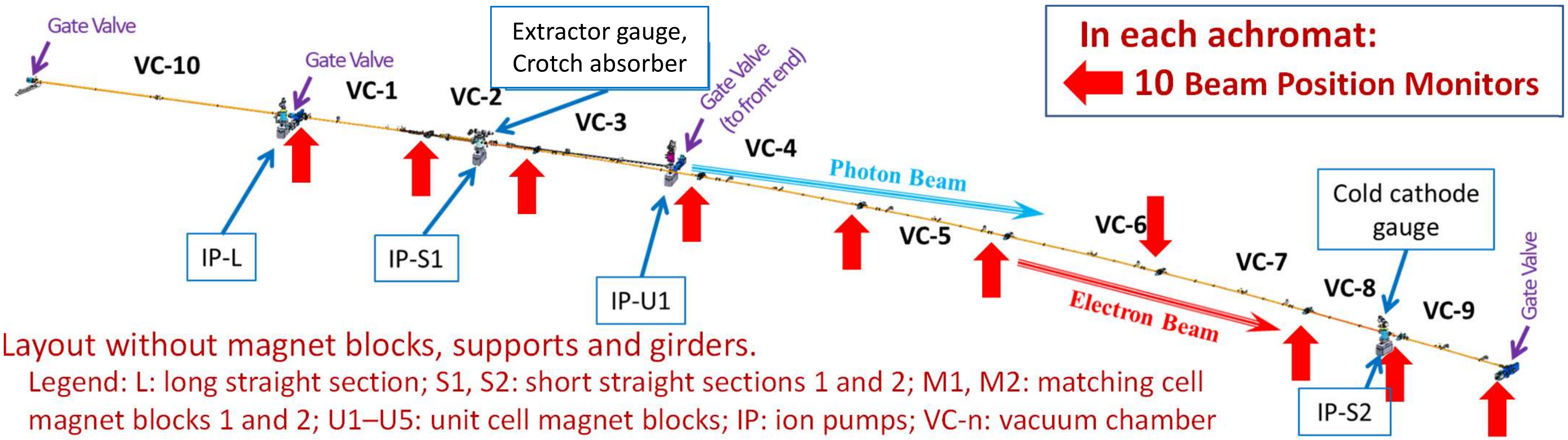
Legend:
- **Dk: Dipole kicker (S1)**
- **Mk: Multipole Injection kicker (L)**
- **LK: Longitudinal kicker (S2)**
- **VP: Vertical pinger (S2)**

L=long straight, S=short straight,

Vacuum achromat layout



Layout with magnet blocks, supports and concrete girders

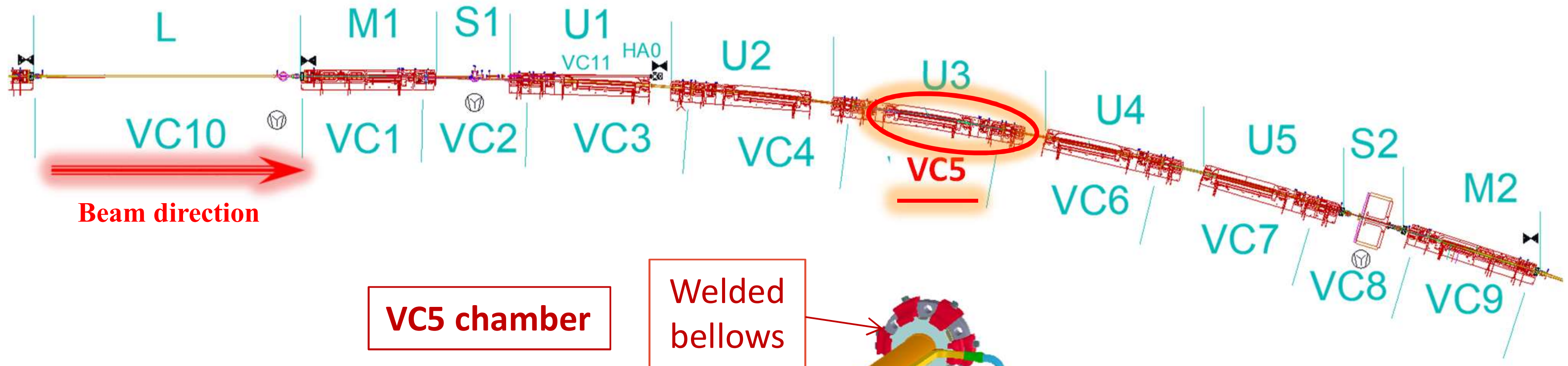


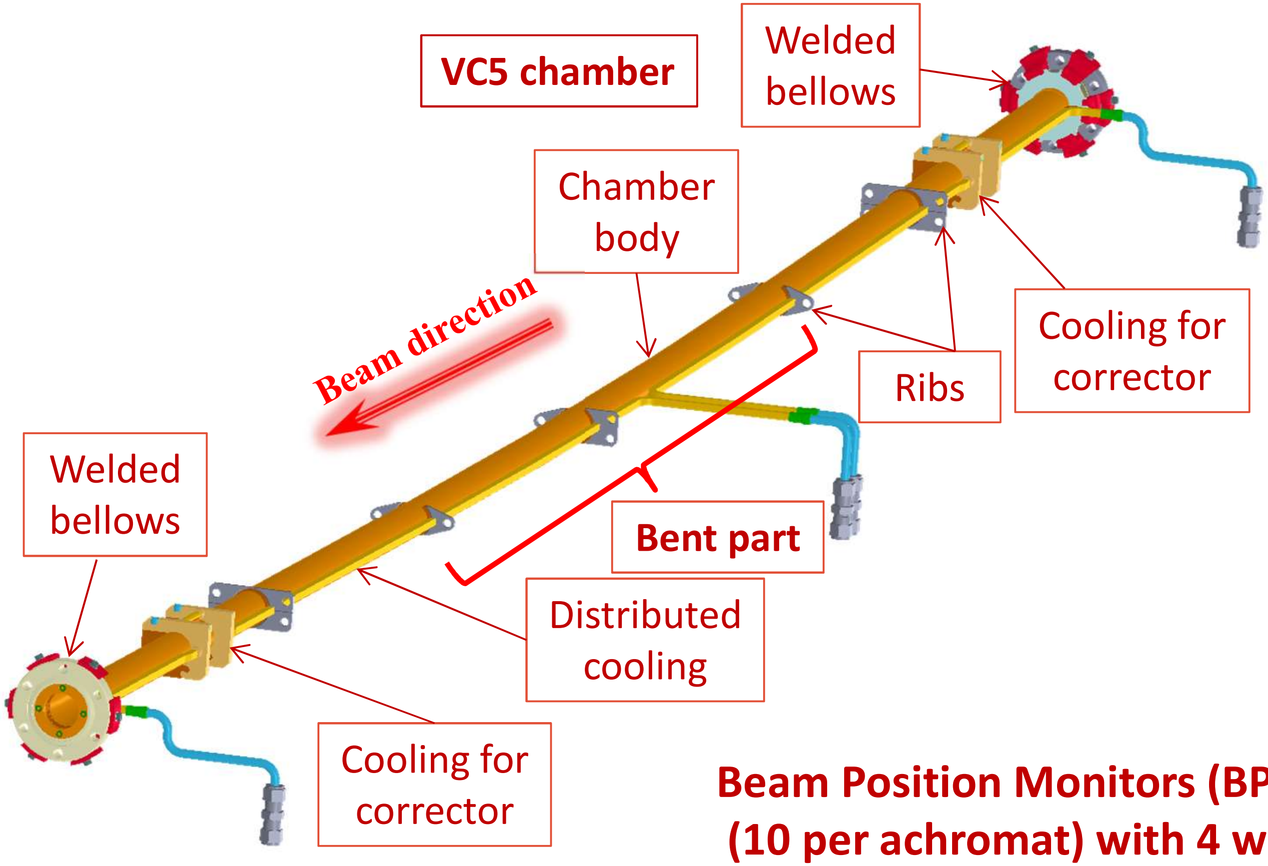
Layout without magnet blocks, supports and girders.

Legend: L: long straight section; S1, S2: short straight sections 1 and 2; M1, M2: matching cell magnet blocks 1 and 2; U1–U5: unit cell magnet blocks; IP: ion pumps; VC-n: vacuum chamber types and vacuum gauge distribution and valves.

Vacuum chamber design

Standard vacuum chamber geometry





Material: OFS copper

Inside diameter: 22 mm,
Total length: 2.5 m,

Arc length: 1 m,
Bending angle: 3^0,
Bending radius: 19 m.

NEG-coated.

Beam Position Monitors (BPMs) are mostly stand alone (10 per achromat) with 4 welded buttons.

NEG coating development

NEG coating development

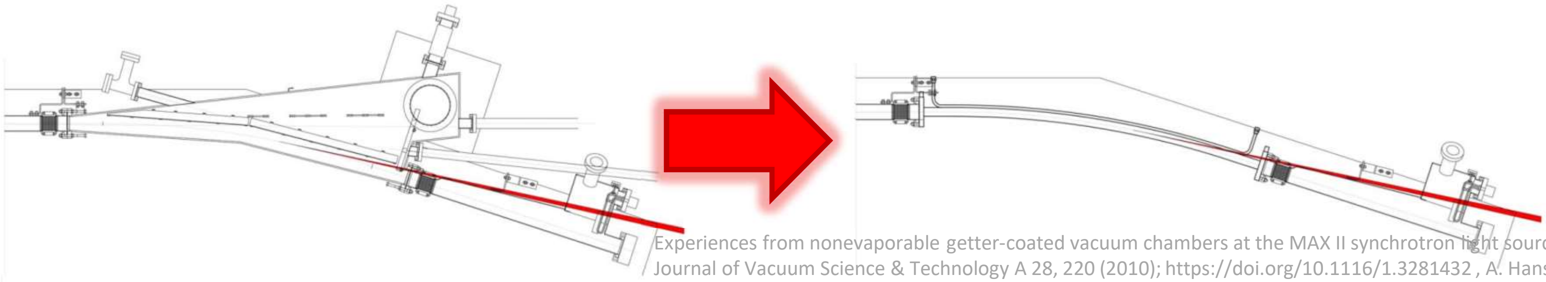
NEG (Non-Evaporable Getter) coating:

- Thin film (0.5-2 µm) of Ti-Zr-V alloy deposited by magnetron sputtering,
- After activation (heating up to 180^{0}C under vacuum) it becomes active and pumps active gasses (do not pump noble gasses nor methane CH_4), and has lower PSD (Photon Stimulated Desorption).

'NEG thin film coatings: from the origin to the next-generation synchrotron-light sources', *Paolo Chiggiato, CERN (presented at OLAV'14)*

NEG-coating of vacuum chambers by magnetron sputtering developed at CERN for warm LHC sections.

- NEG-coating is used widely in many light sources - mainly for insertion device chamber.
- At SOLEIL 56% of storage ring is NEG coated.
- In MAX II (light in Lund, decommissioned in 2016) three copper dipole chambers were replaced by NEG-coated vacuum chambers.
- Sirius (LNLS) storage ring is coated with NEG, operating since 2019.



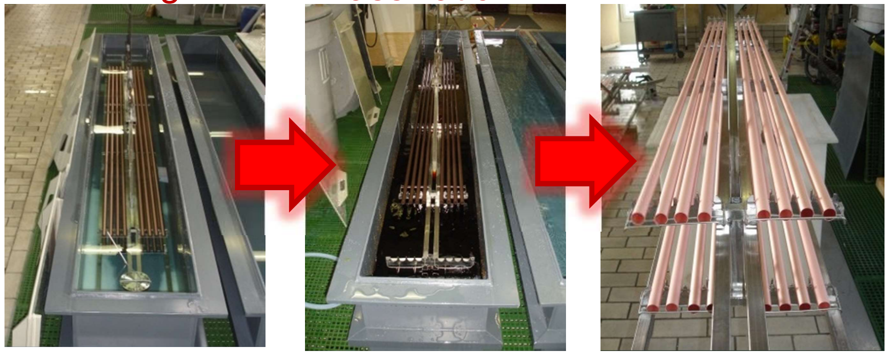
Experiences from nonevaporable getter-coated vacuum chambers at the MAX II synchrotron light source
Journal of Vacuum Science & Technology A 28, 220 (2010); https://doi.org/10.1116/1.3281432 , A. Hansson, E. Wallén, M. Berglund

NEG coating development

1. **Define and perform initial surface treatment of OFS copper substrate.**

Basing on experience with LHC warm section vacuum chambers, chosen treatment was: Degreasing -> Etching -> Passivation.

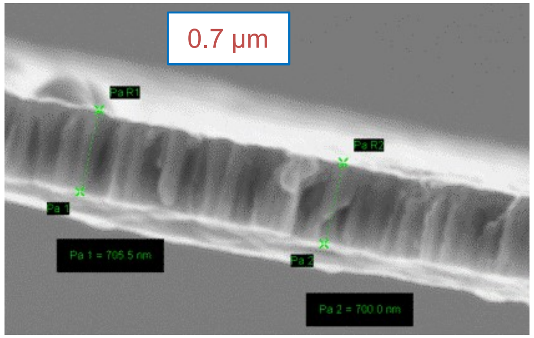
Etching: Passivation:



2. Confirm compatibility of NEG-coating (adhesion, thickness, composition, activation behavior):

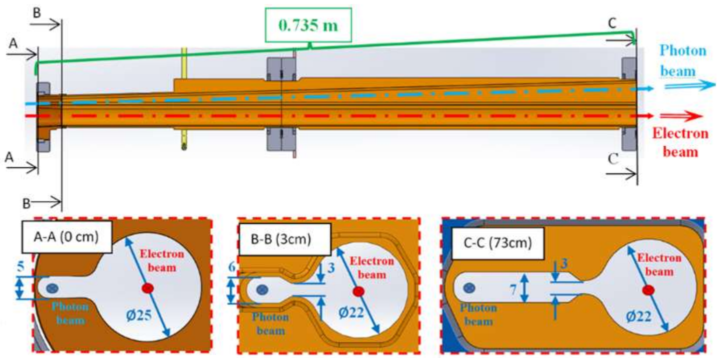
a. on used substrates (etched OFS copper tubes, wire eroded surfaces and brazing types),
b. for vacuum chamber geometry (small chamber diameter, long and bent tubes).

SEM thickness measurements:



3. Establish coating procedure/technology and produce chambers of complex geometry:

Vacuum chamber for photon beam extraction.



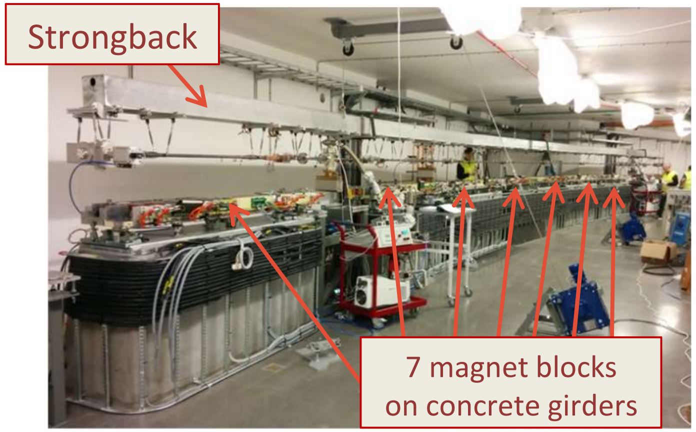
Installation procedure

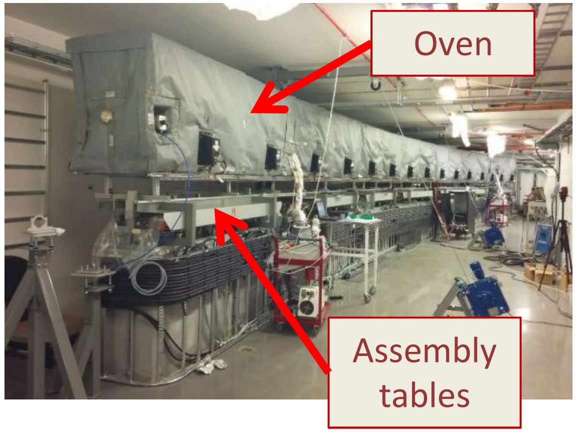
Installation procedure

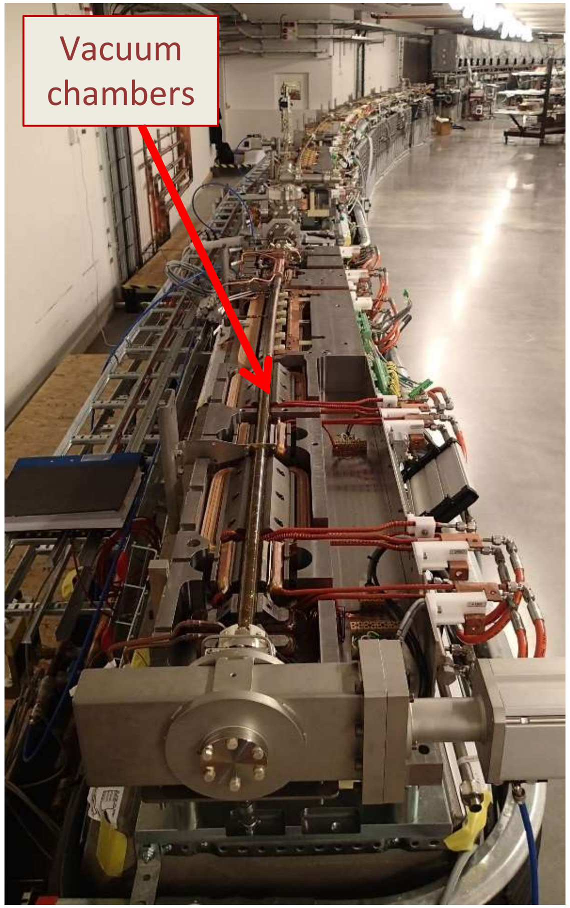
Ring installation was tested and rehearsed by installing and activating 1 mockup achromat in summer 2014.

Actual installation started in November 2014, ended June 2015

- Assembly of vacuum chambers insitu (above bottom magnet halves),
- Baking (1 day) and NEG activation (1 day) of vacuum chambers hanging freely above lower magnet halves with an baking oven,
- Installation of final equipment (supports, BPM cables),
- Lowering to the bottom magnet half and closing magnets,



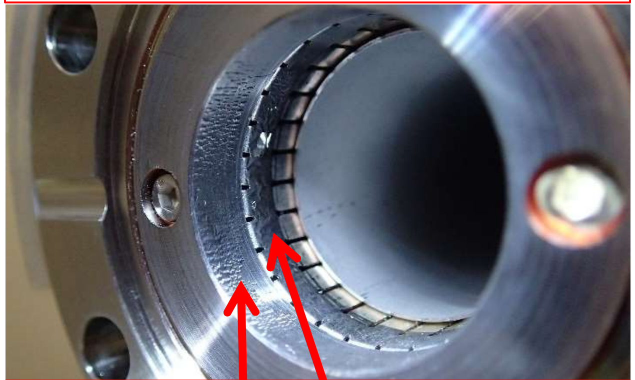




Coating non-conformities

70 % of the chambers were NEG coated by industry.
All the chambers were inspected at site before installation, few non-conformities were found:

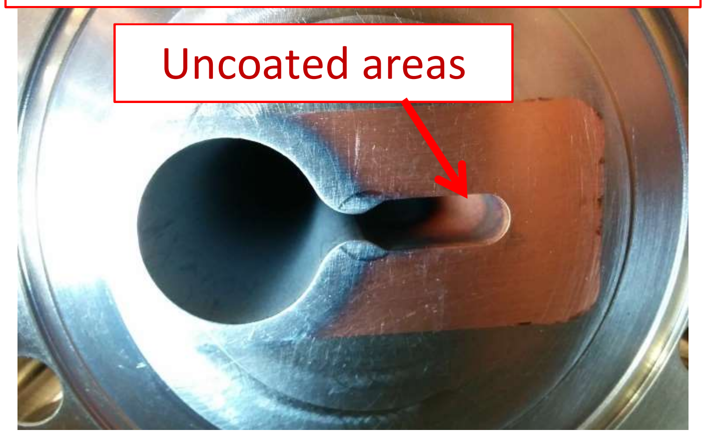
Observed peeling-off:
At RF fingers Cu-Be insert and Cu end piece. RF fingers and Cu end were not shielded properly during coating.
Solution: new pieces ordered and replaced (without coating).



Peeling-off at RF fingers and Cu endpiece

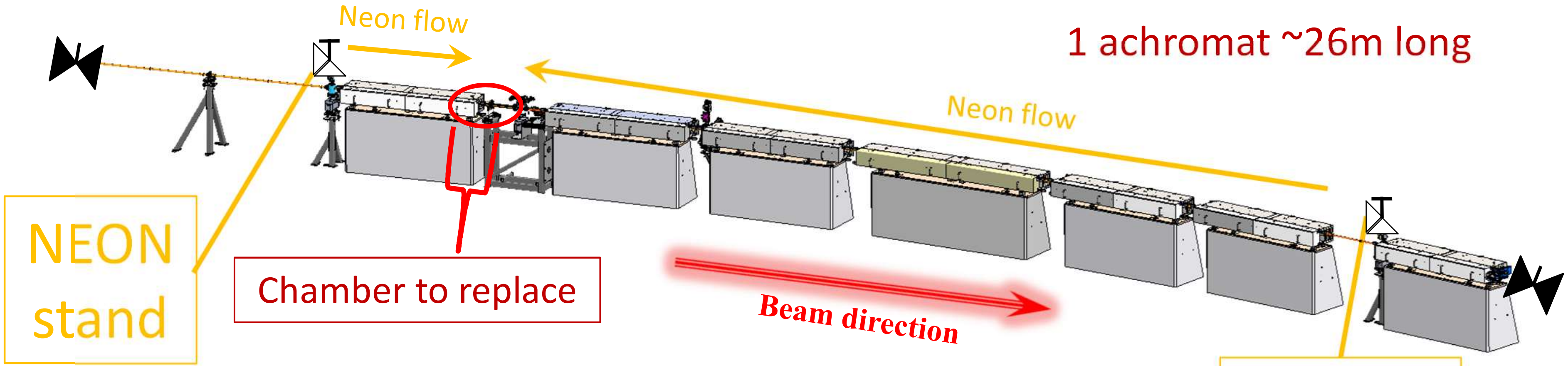
Peeling-off at the edge of stainless VC. Chamber not aproved for installation.

Uncoated areas:
Few cm^2 uncoated, in complex chambers.



Neon venting for new installations/interventions

Neon venting for new installations/interventions



Neon venting is a procedure developed and used at CERN for interventions for special vacuum chambers with NEG coating. Neon is a noble gas, it does not saturate the NEG surface. Therefore there is no need of re-activation of the film.

Procedure using Neon gas for venting at MAX IV:

- gate valves at extremities are closed,
- section is vented with purified Neon to above atmospheric pressure,
- the component is replaced, neon flow is preserved (so that the air do not enter the system),
- after new components are installed the system is pumped down with turbo molecular pumps and then ion pumps are switched on (no activation of the NEG coating is performed).

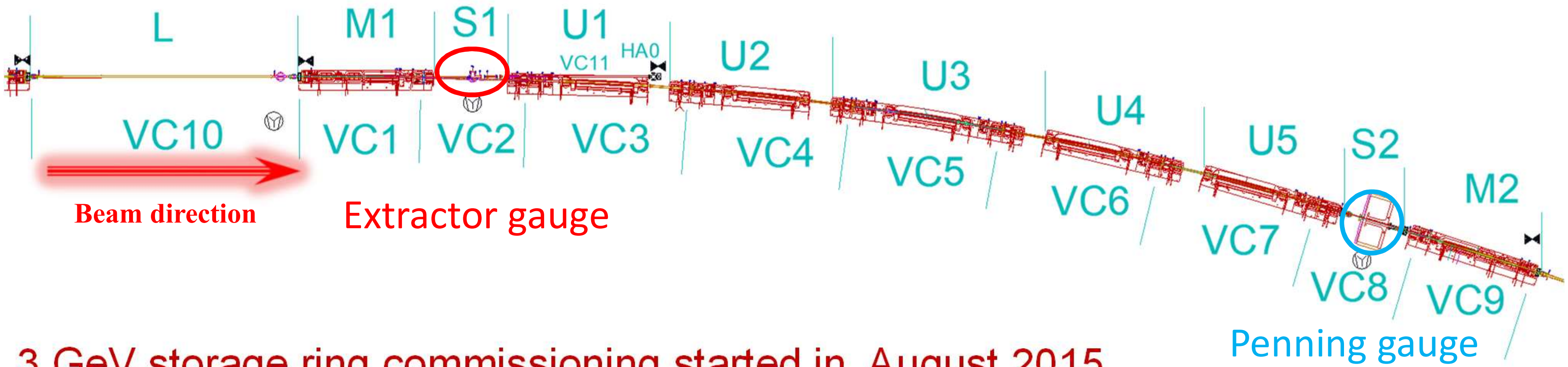
Such intervention on the accelerator takes around 2 hours (excluding preparations) and afterwards pumping down with turbo molecular pumps and ion pumps takes ~4 days which yields in total up to 5 days.

Standard procedure without venting with neon includes baking and NEG activation (and needs 2-4 weeks.

Neon venting was used in 2018 then in 2020 - it did not limit machine startup nor operation.

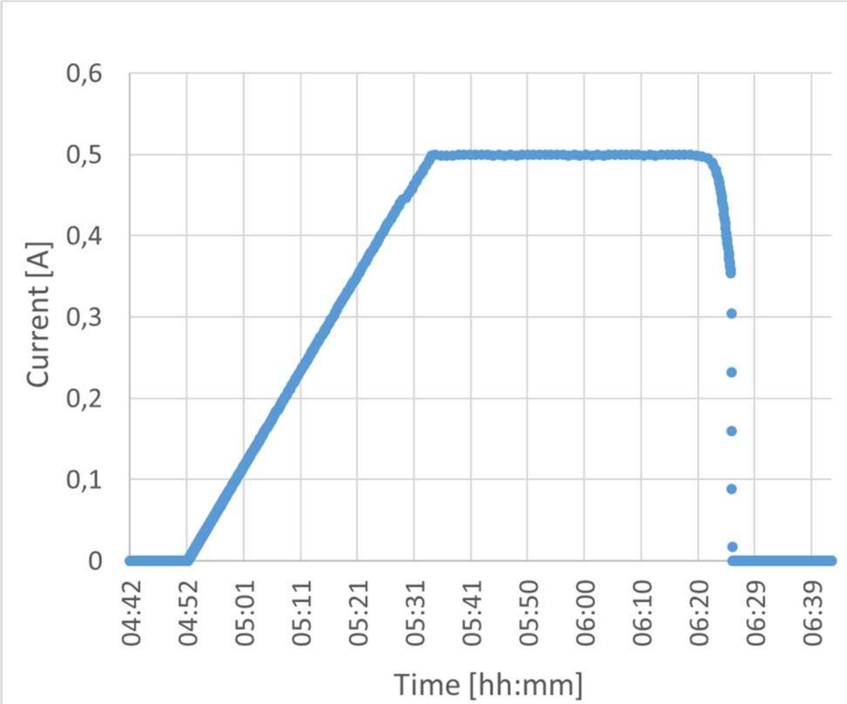
Vacuum Performance of the MAX IV 3 GeV storage ring

Vacuum performance



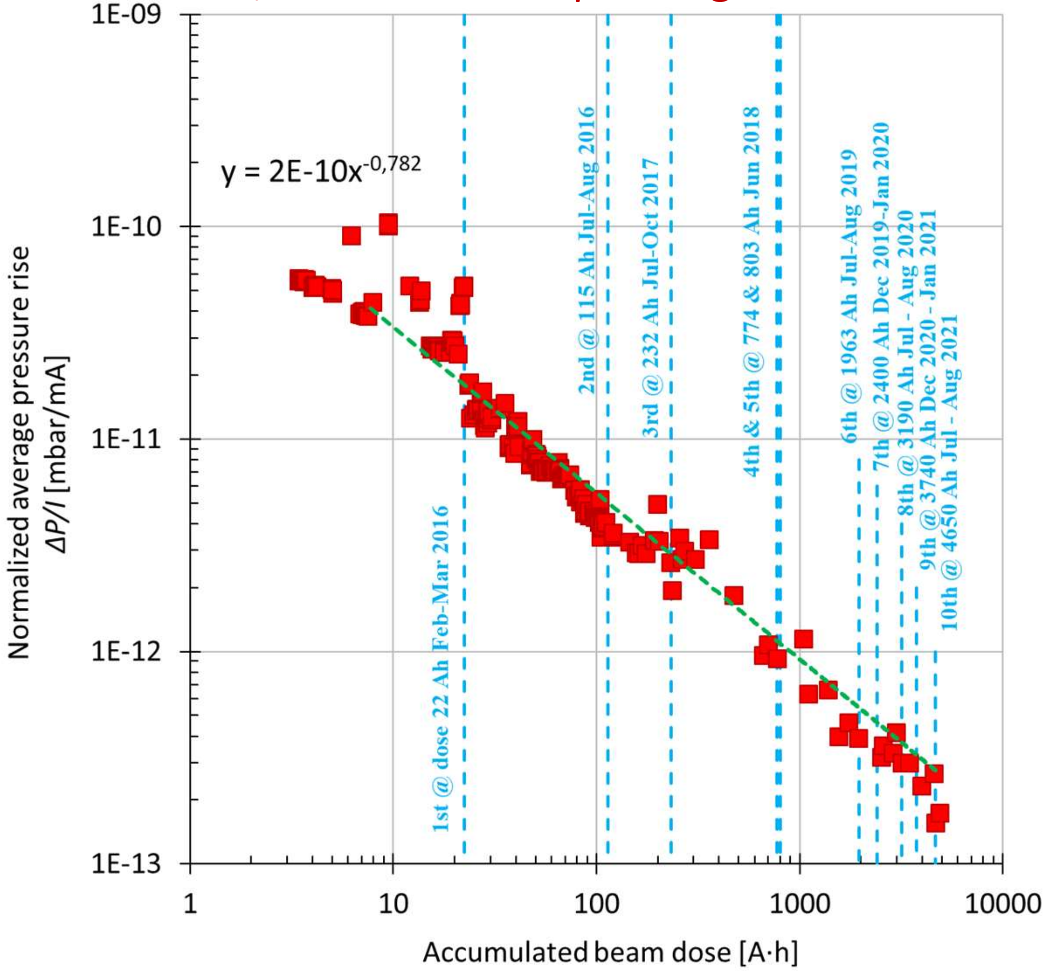
3 GeV storage ring commissioning started in August 2015

- Average base pressure:
  ~2e-10 mbar (extractor gauges)
- Accumulated beam dose:
  4890 Ah (10th October 2021)
- Max. stored current:
  500 mA (November 2018)
  total lifetime was 14 h



Vacuum performance

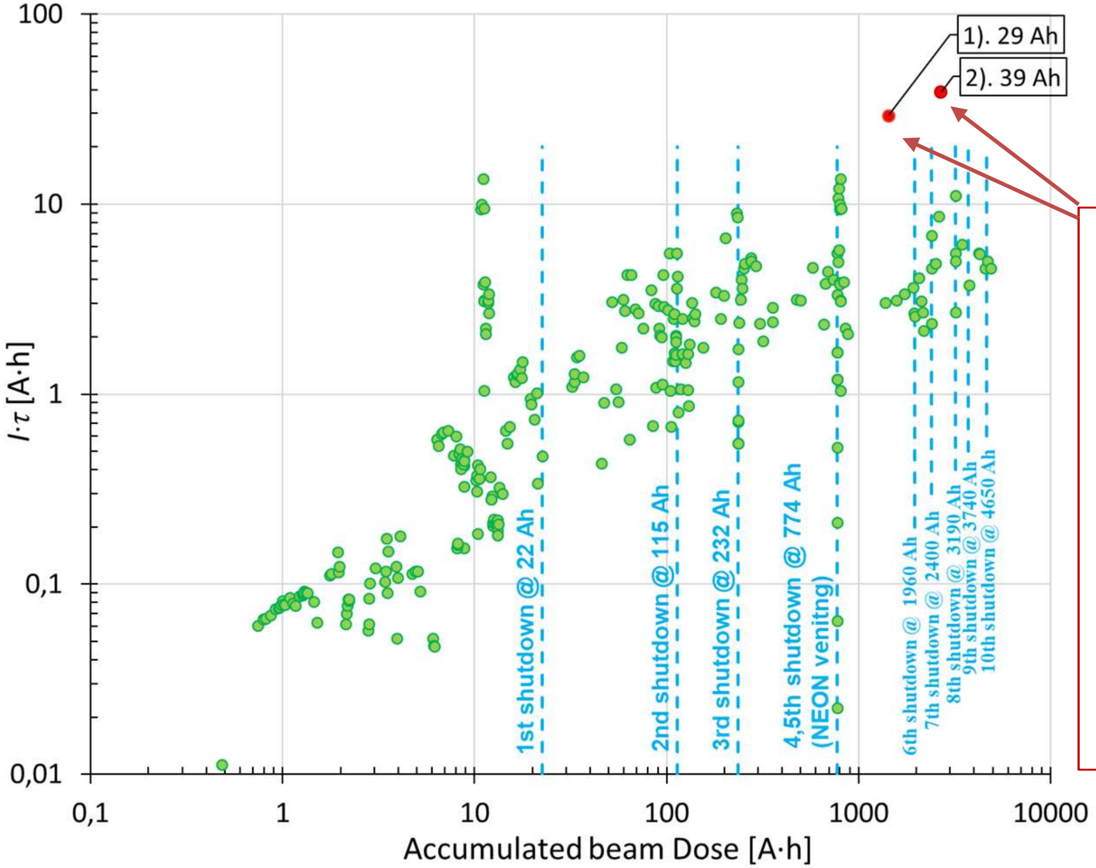
Normalized average pressure rise (mbar/mA) versus the accumulated beam dose (A h).
Blue vertical lines mark shutdowns, with the corresponding beam dose and date.



The absolute value of the slope of the conditioning curve (marked in green) is ~0.78

Vacuum performance

Normalized total beam lifetime I (A h) versus accumulated beam dose (A h).



Current operation parameters for delivery to users:

- Current 300 mA,
- Total beam lifetime ~15 h

Tests were done where the effective bunch length was intentionally enlarged (beam longitudinally unstable, landau cavities detuned).

Beam enlarged longitudinally -> bunch particle density reduced -> Touschek lifetime negligible

Measurements at different does were taken with a beam current of 350 mA, and total beam lifetimes of 83 and 111 h were measured (29 and 39 A h respectively). Those can be considered lower limits for the vacuum-related beam lifetime.

After each shutdown that involves vacuum intervention there is an increase in the average pressure and reduction in the lifetime, but recovery is fast, depending on the shutdown scope.

Vacuum Performance

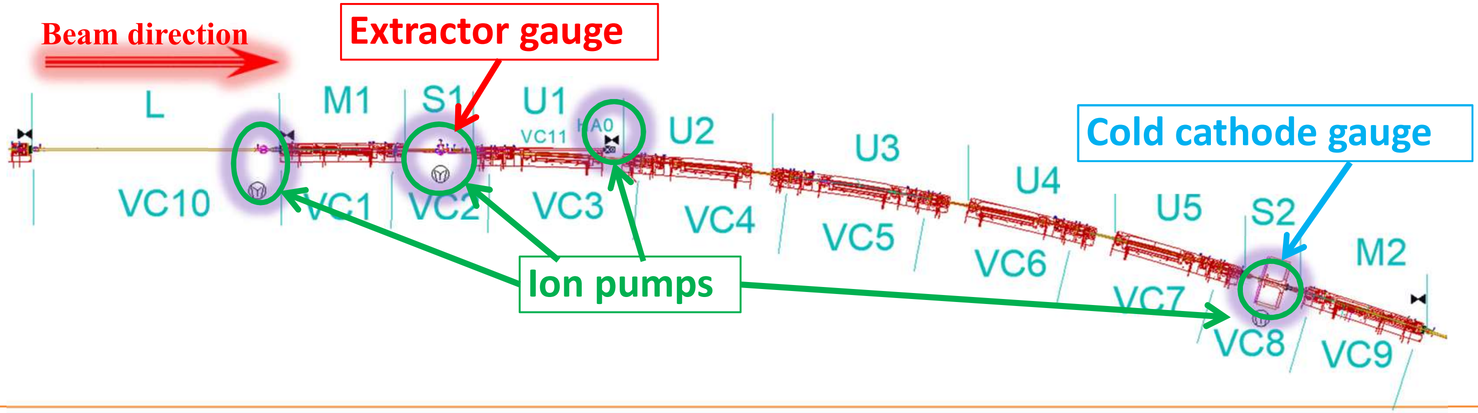
(tests with ion pumps OFF)

Test to investigate NEG performance at accumulated dose 367 Ah (13 march 2018)
Beam was stored @ 170 mA, then almost all ion pumps along the electron path were turned off.

Verify performance by looking to:

- Effect on the lifetime, — No effect on lifetime.
- Effect on the beam size, — No effect on beam size.
- Pressure, — Average pressure increased by factor of 3.4.
- Radiation increase outside in the experimental hall, — No increased radiation.
- Residual Gas Analyzer scans (gas spectra). — Gas spectra slightly changed.

Out of 97 Ion pumps installed in 3 GeV ring 63 were switched OFF.
Leaving ion pumps ON in RF cavities (12), Insertion devices (9), Diagnostic beamlines (13).



Operational status

Year	uptime (%)	Vacuum related downtime (h)	Vacuum related downtime contribution to total downtime (%)
2019	97.28	1.5	1.2
2020	97.40	3.45	2.7
2021 (until 10 Oct. 2021)	96.33	0	0

- **2019**: 2 vacuum related events caused beam dump.
  2 events related to short lived vacuum spikes from penning gauges/ion pumps.
- **2020**: 6 vacuum related events caused beam dump.
  4 events related to short lived vacuum spikes from penning gauges/ion pumps, 2 events related to faulty ion pump controllers.
- **2021**: no vacuum related beam dumps

Conclusions

- MAX IV 3 GeV ring is operating since the end of 2015 without major, unresolved issues.
- The main design parameters of the storage ring (horizontal emittance 0,33 nm rad, beam lifetime 5 A h, maximum beam current 500 mA) were reached.
- There are no operational issues related to the NEG coating that could limit the operation or machine performance in any way.
- There is no sign of NEG coating peel off or saturation and tests done assure that NEG is still performing well.
- The vacuum conditioning (measured by pressure reduction) progressed fast since the start of commissioning and is still observable.
- Neon venting technique was used for vacuum interventions, significantly reducing the intervention time.
- All the above demonstrates that NEG technology is reliable and effective in ensuring low dynamic pressure in such accelerators.
- The 3 GeV storage ring NEG coating project was successful thanks to close collaboration with CERN.

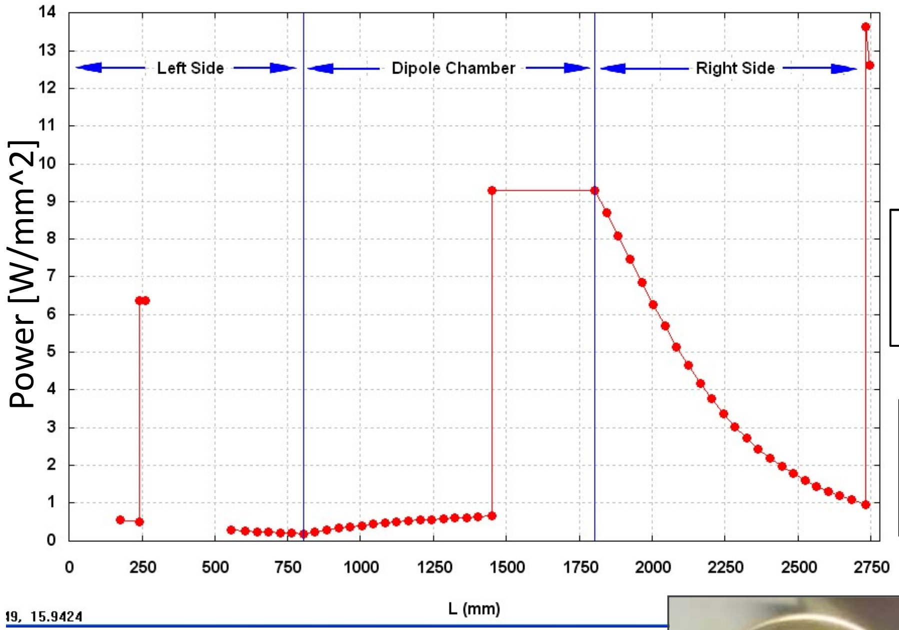
Thanks to Eshraq Al-Dmour, Åke Andersson, David K. Olsson,
and MAX IV Vacuum Team.

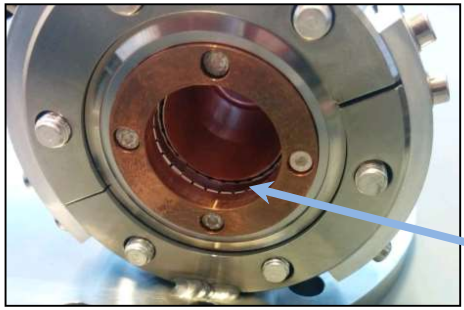
Contact: marek.grabski@maxiv.lu.se

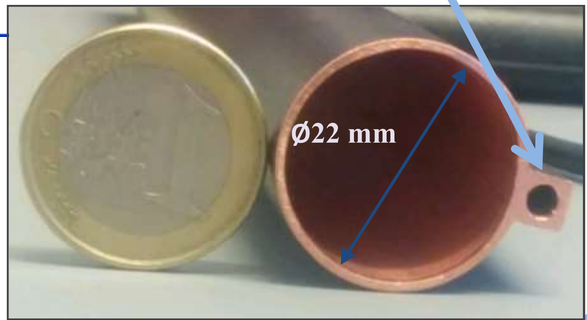
Backup slides

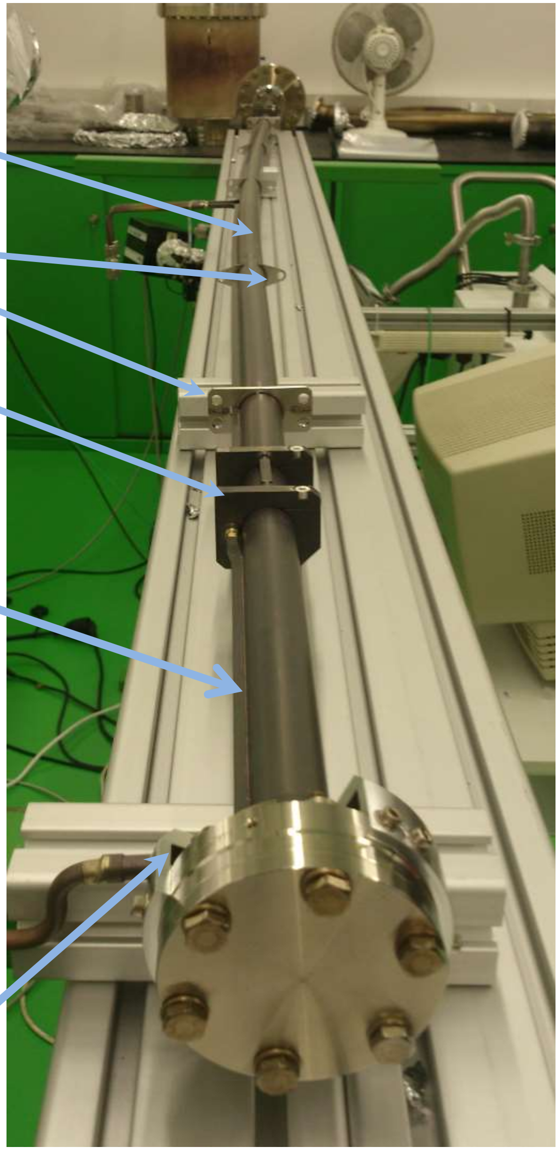
General vacuum chamber geometry

Power density deposited by synchrotron radiation on the wall of vacuum chamber vs. length









NEG coating development at CERN

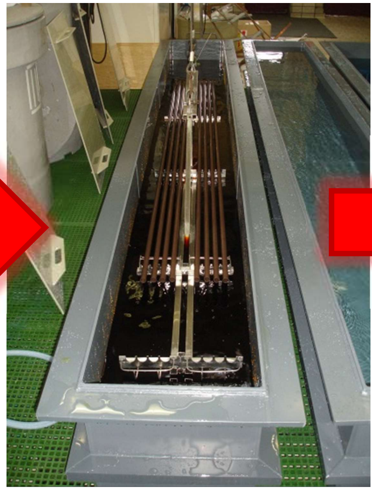
1. **Define and perform initial surface treatment of OFS copper substrate.**

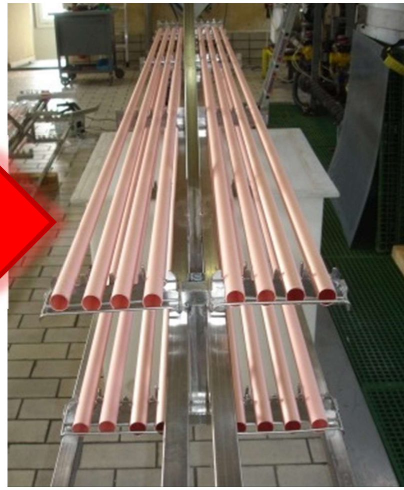
Basing on experience with LHC warm section vacuum chambers, chosen treatment was:

Degreasing -> Etching -> Passivation.

Etching was needed to remove about 50 µm of the material to ensure that the extruded copper tubes are free from contamination that could be trapped in the cortical layer of the substrate.

Etching: **Passivation:**





NEG coating compatible

Ready for manufacturing

Observed defects:

100% of tubes were visually inspected at each step of the cleaning process.

About **10%** of the tubes were discarded by visual inspection at various stages of the cleaning process due to strong contamination.

NEG coating development at CERN

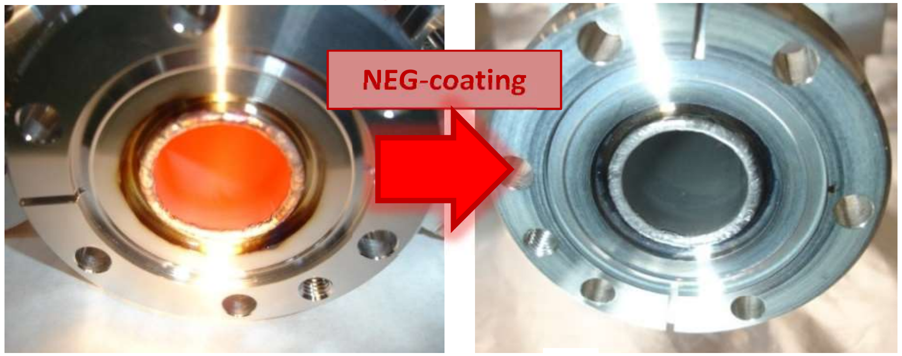
2. Confirm compatibility of NEG-coating (Ti, Zr, V):

a. on used substrates (etched OFS copper tubes, wire eroded surfaces and brazing types),

b. for vacuum chamber geometry (small chamber diameter, long and bent tubes).

Chamber before coating

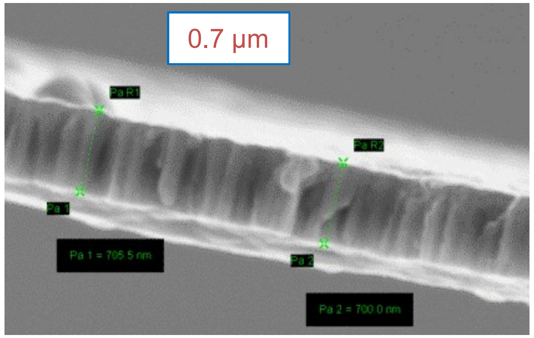
Chamber after coating and thermal cycling

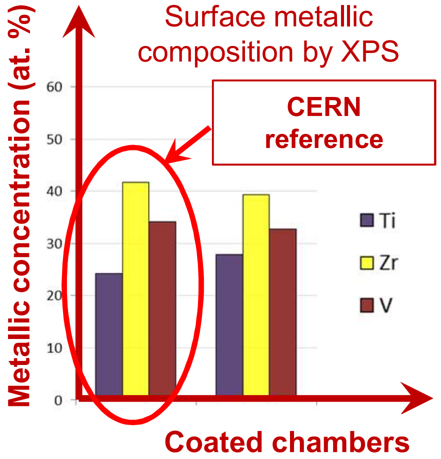


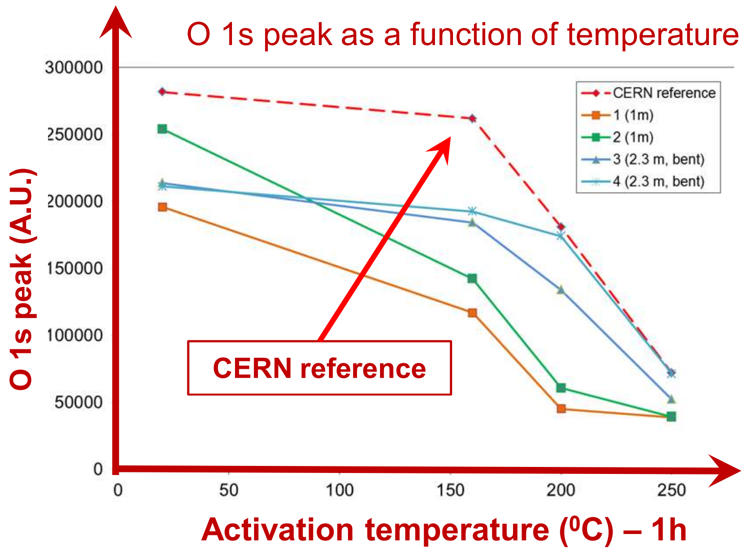
NEG coating requirements:

- **No peel offs,**
- **Coating thickness 0.5 – 2 μm,**
- **Correct composition of Zr, Ti, V,**
- **Good activation behavior.**

SEM thickness measurements:

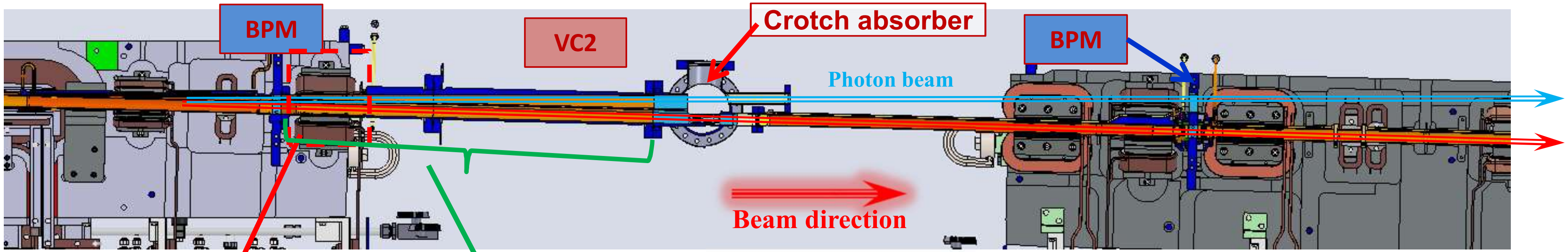


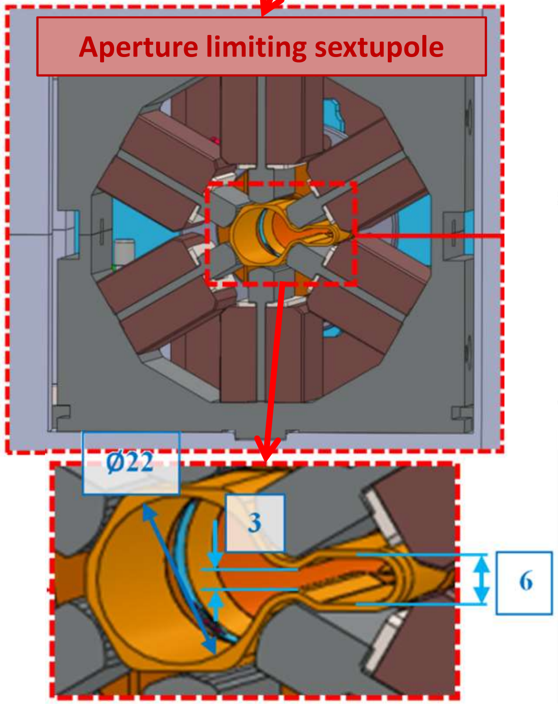


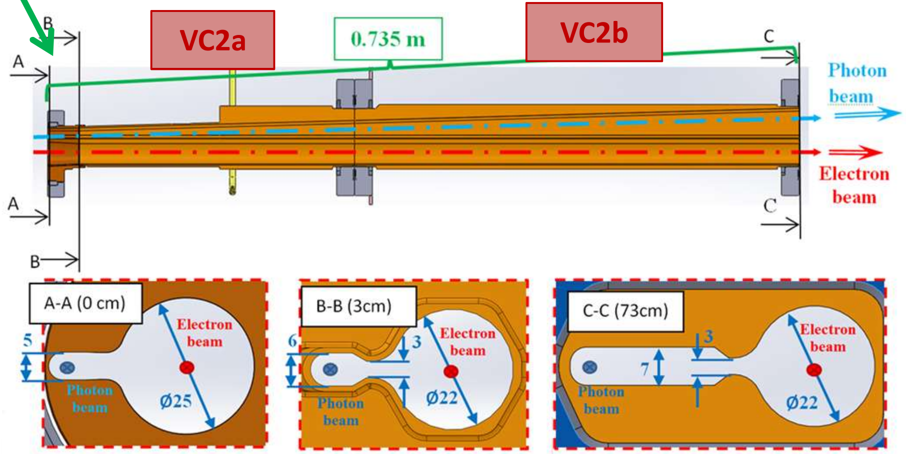


NEG coating development at CERN

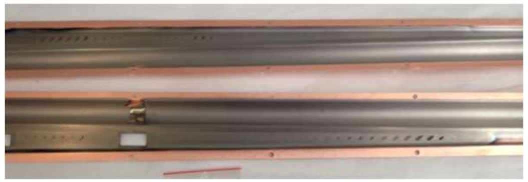
3. Establish coating procedure/technology and produce chambers of complex geometry: Vacuum chamber for beam extraction.







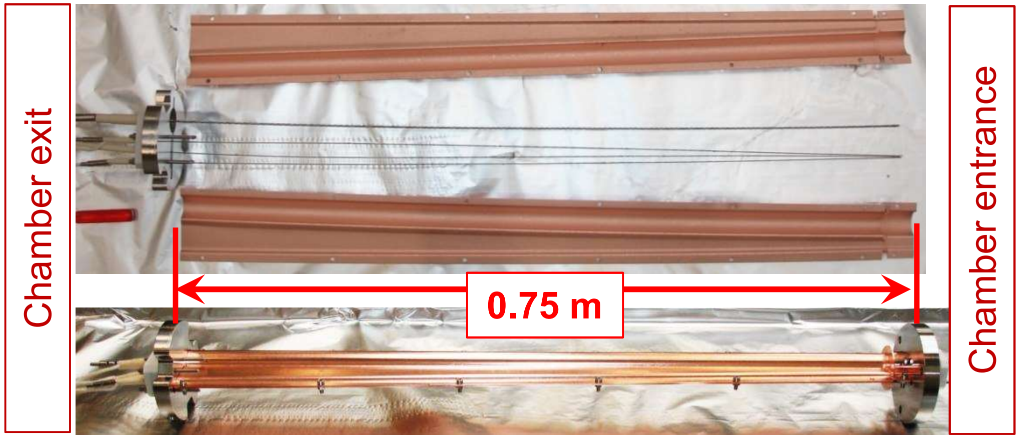
Prototype chamber after coating:



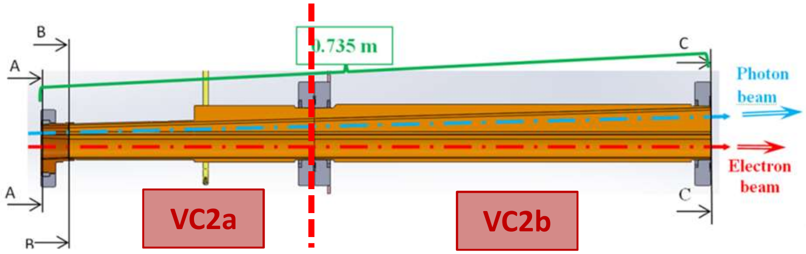
- ✓ **Thickness – OK,**
- ✓ **Composition OK,**
- *X* - **'delayed' activation in the antechamber**

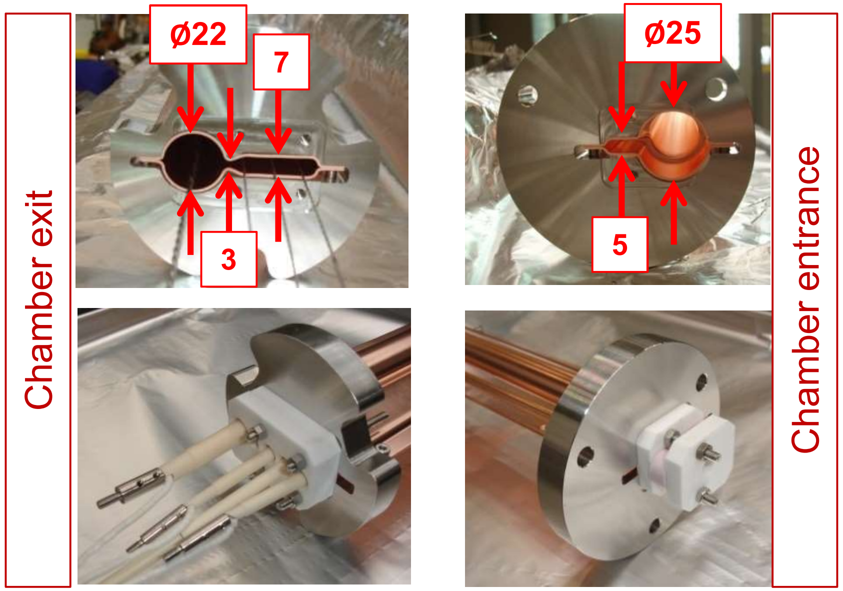
NEG coating development at CERN

Prototype was made at CERN in two halves to allow easy inspection of the coating quality.

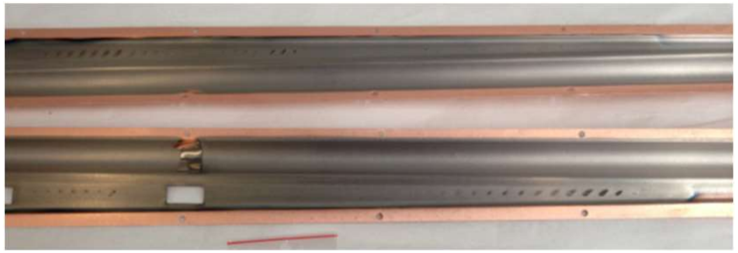


Due to coating difficulties – chamber divided in 2 and coated in 2 runs (circular main tube, antechamber).





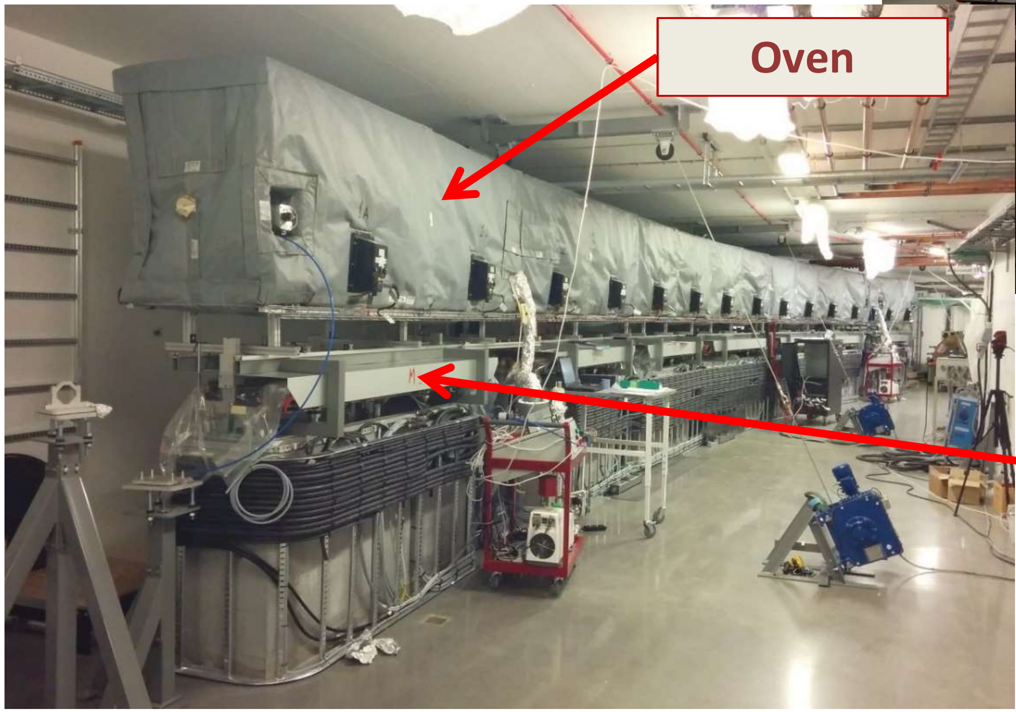
Prototype chamber after coating:



- ✓ **Thickness – OK,**
- ✓ **Composition OK,**
- *X* - **'delayed' activation in the antechamber**

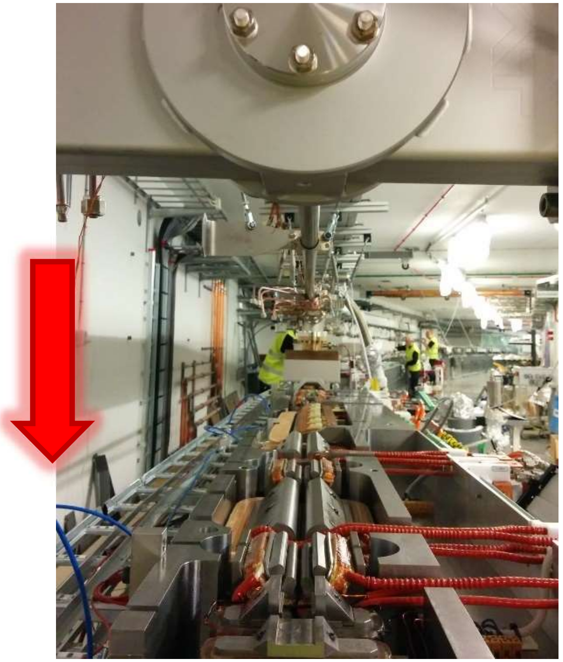
Installation procedure

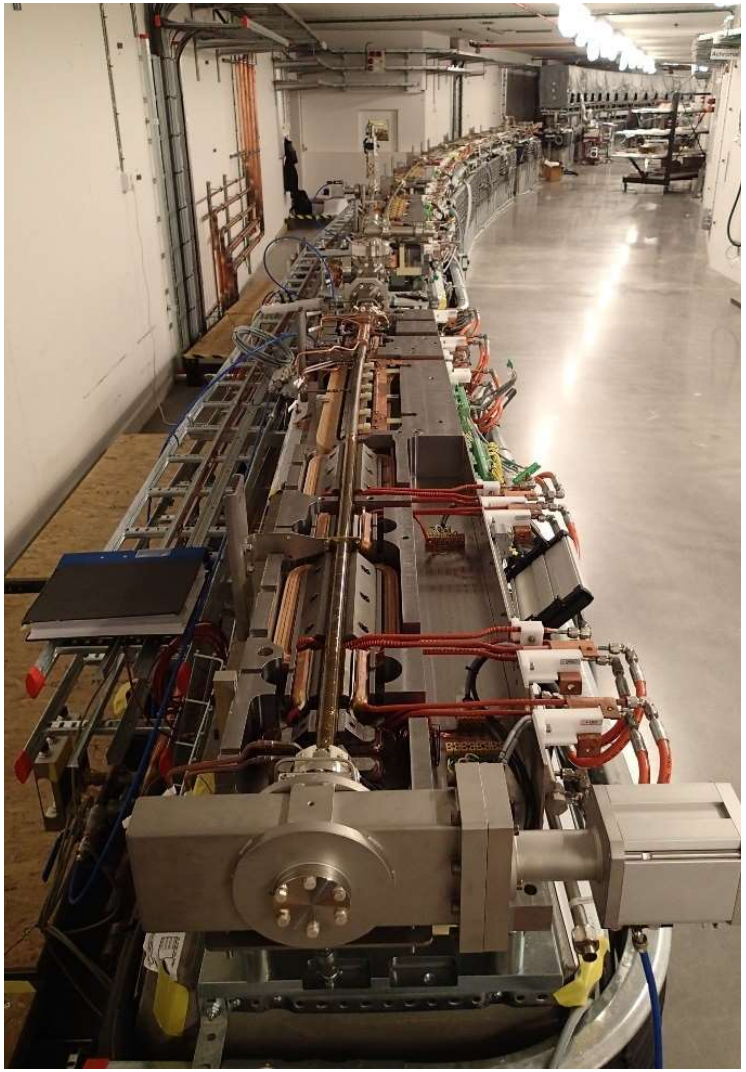
- Magnet top halves removed,
- Assembly of vaccum chambers insitu (above bottom magnet halves),
- Pumpdown and testing,
- Lifting chamber up,
- Baking (1 day), activation (1 day),



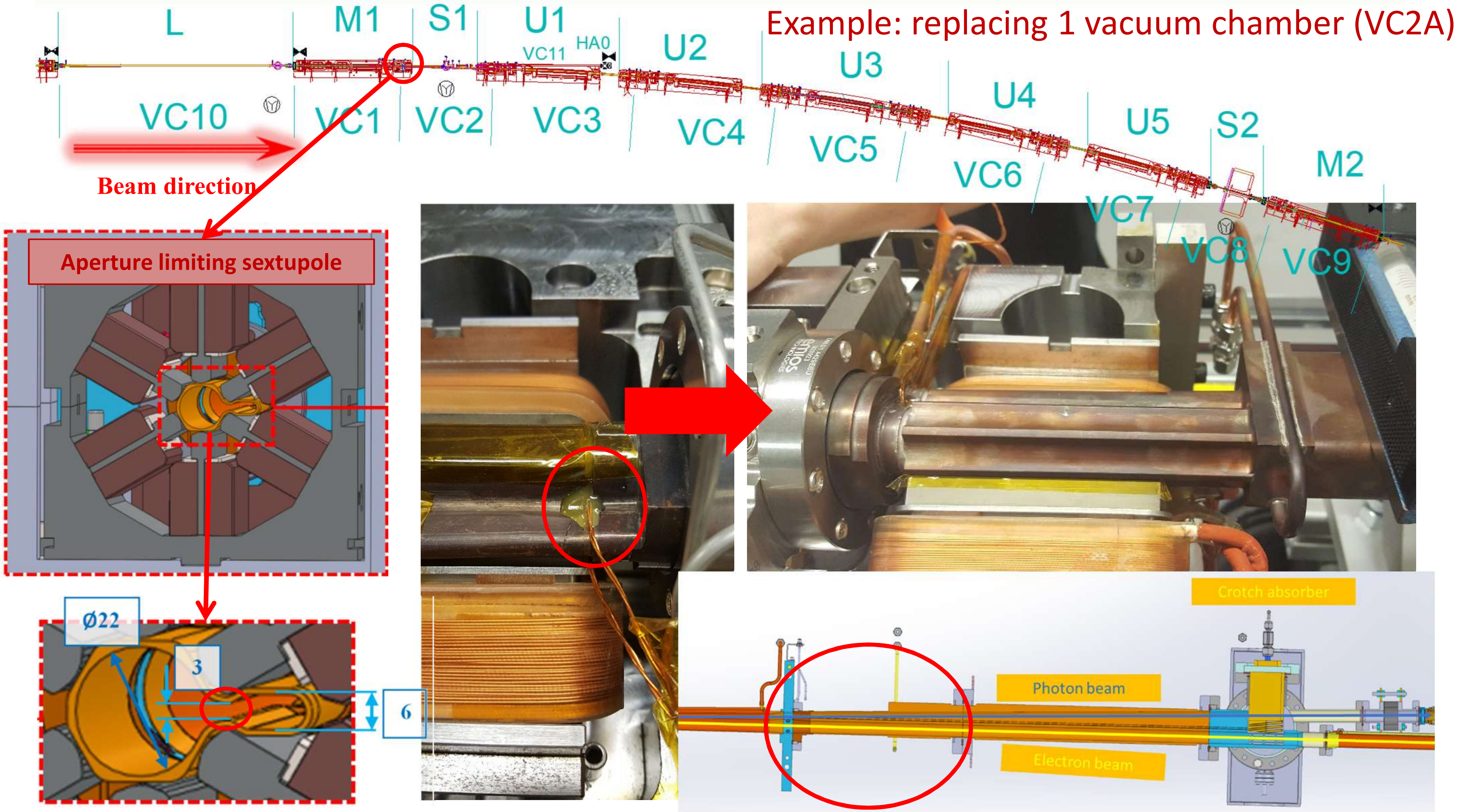
Installation procedure

- Installation of final equipment (supports, BPM cables),
- Lowering to the bottom magnet half,
- closing magnet blocks.





Neon venting for new installations/interventions

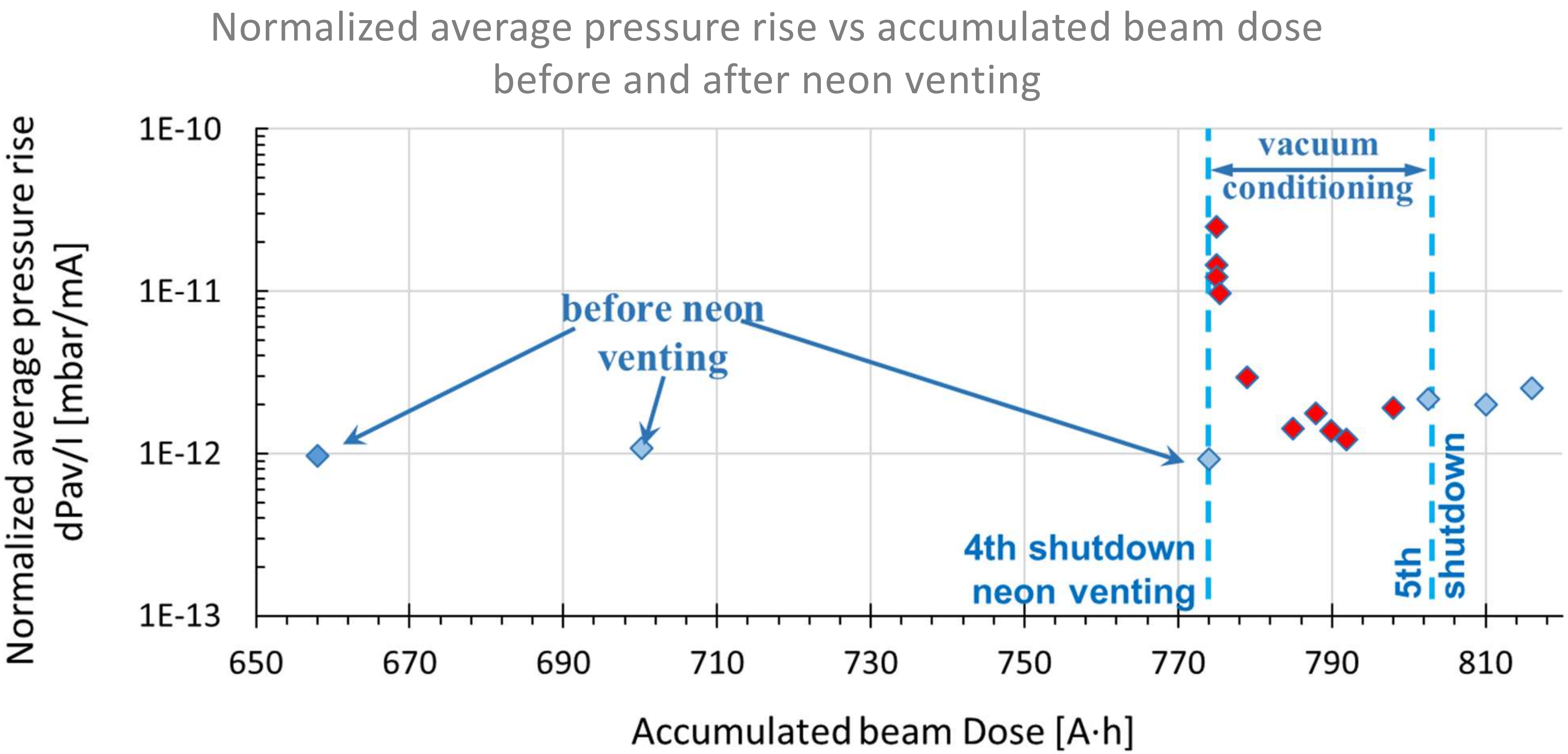


Neon venting was used for the first time in 2018 (as above) and did not limit machine startup nor operation.
It was used again in 2020 for installation of components with no dedicated machine studies, but going directly to startup, then operation. The storage ring was back to operation without any limitations.

Neon venting for new installations/interventions

Vacuum conditioning after neon venting intervention in 2018

After the first Neon venting intervention in 2018 dedicated beam time (1 week) for vacuum conditioning and machine performance studies was scheduled.

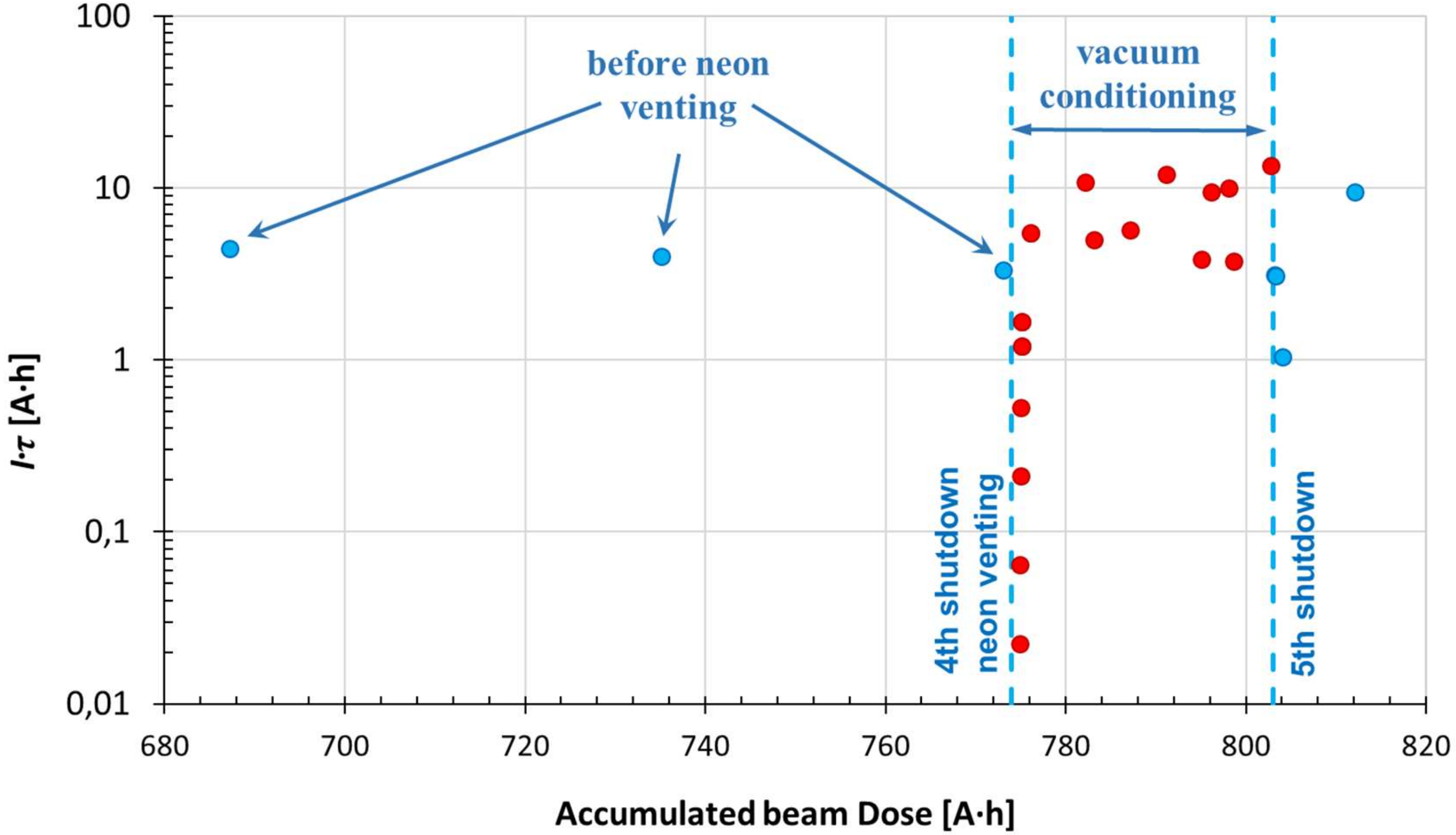


Neon venting for new installations/interventions

Beam lifetime after neon venting intervention in 2018

3 GeV ring: Normalized lifetime vs accumulated dose

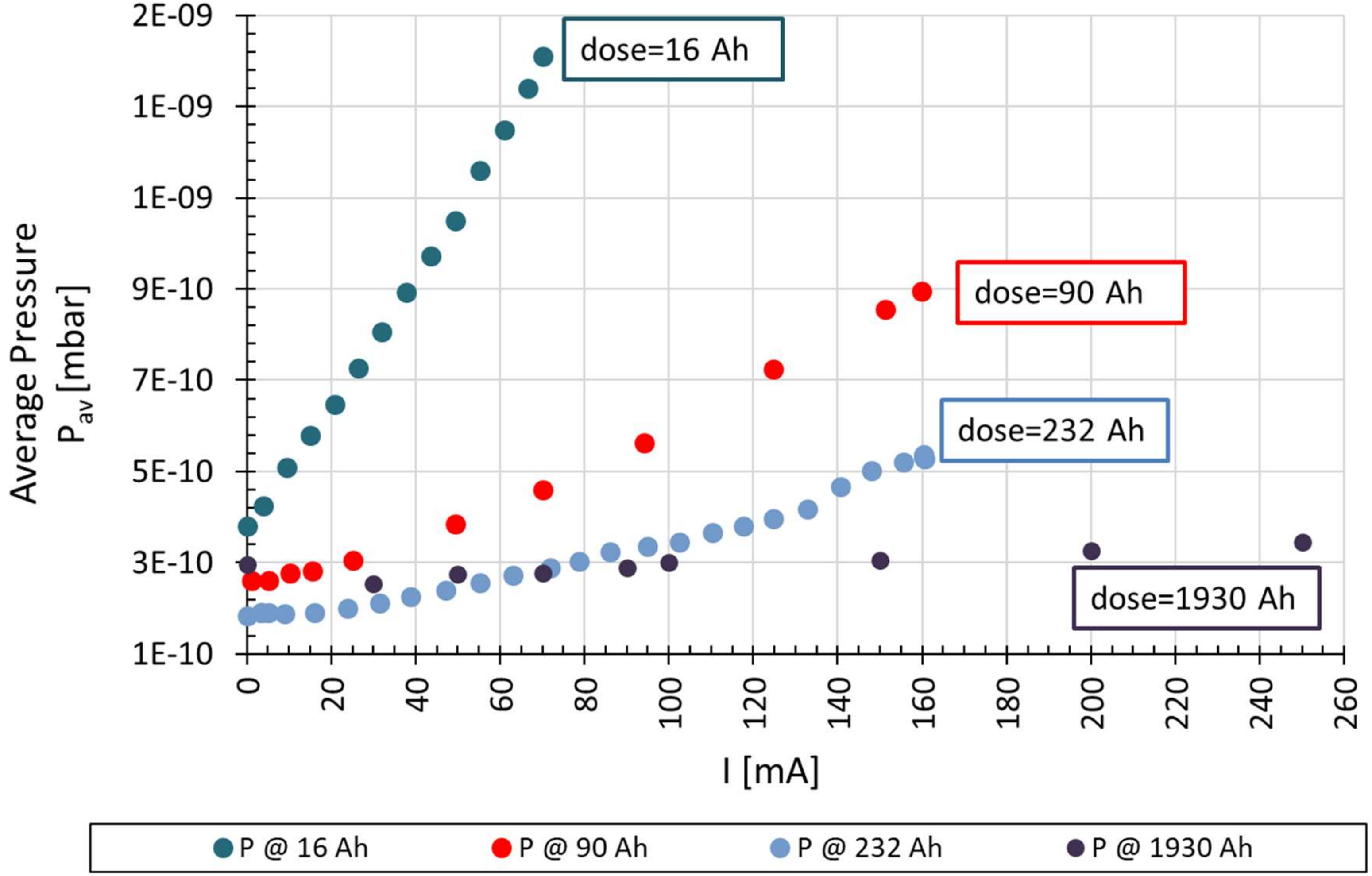
I·τ [mA·h] vs Dose [A·h]



Neon venting was used again in 2020 for installation of components with no dedicated machine studies, but going directly to startup, then operation. The storage ring was back to operation without any limitations.

Vacuum performance

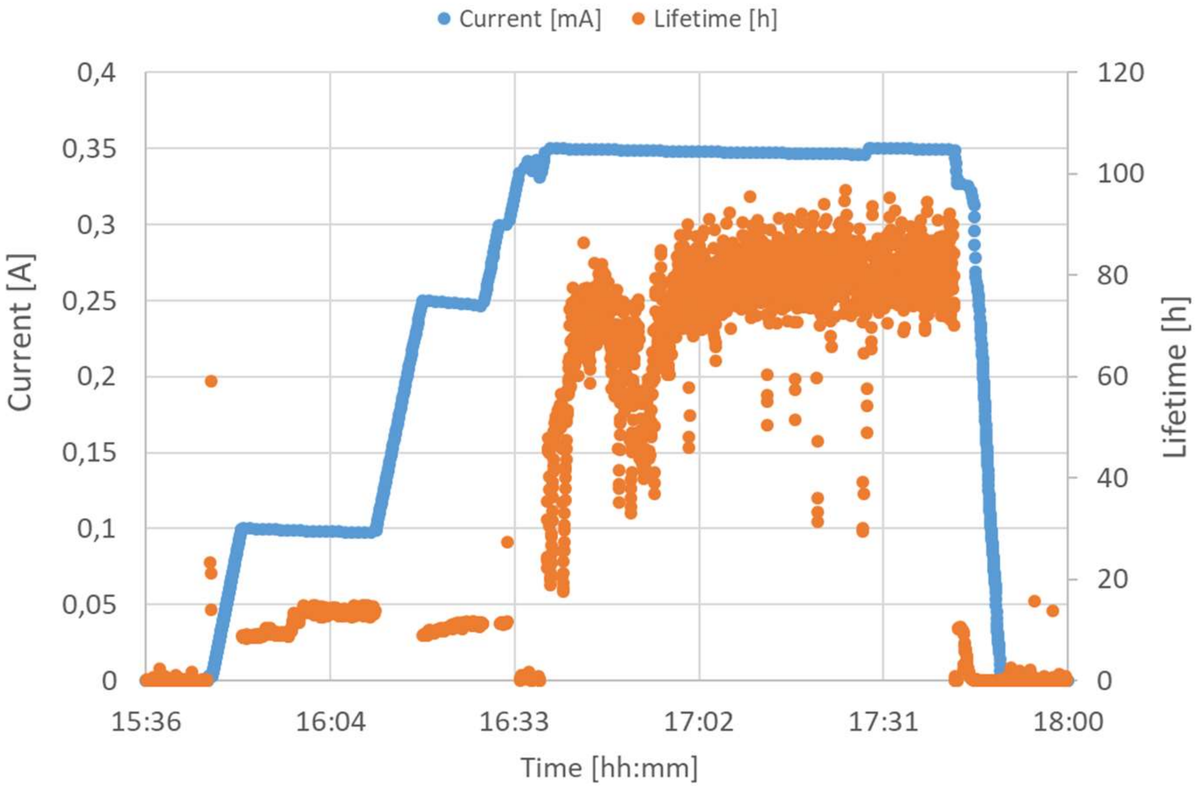
Average pressure vs. current at various beam doses (measured with extractor gauges)



Vacuum performance

Tests were done where the effective bunch length was intentionally enlarged (beam longitudinally unstable, landau cavities detuned).

Beam enlarged longitudinally -> bunch particle density reduced -> Touschek lifetime negligible

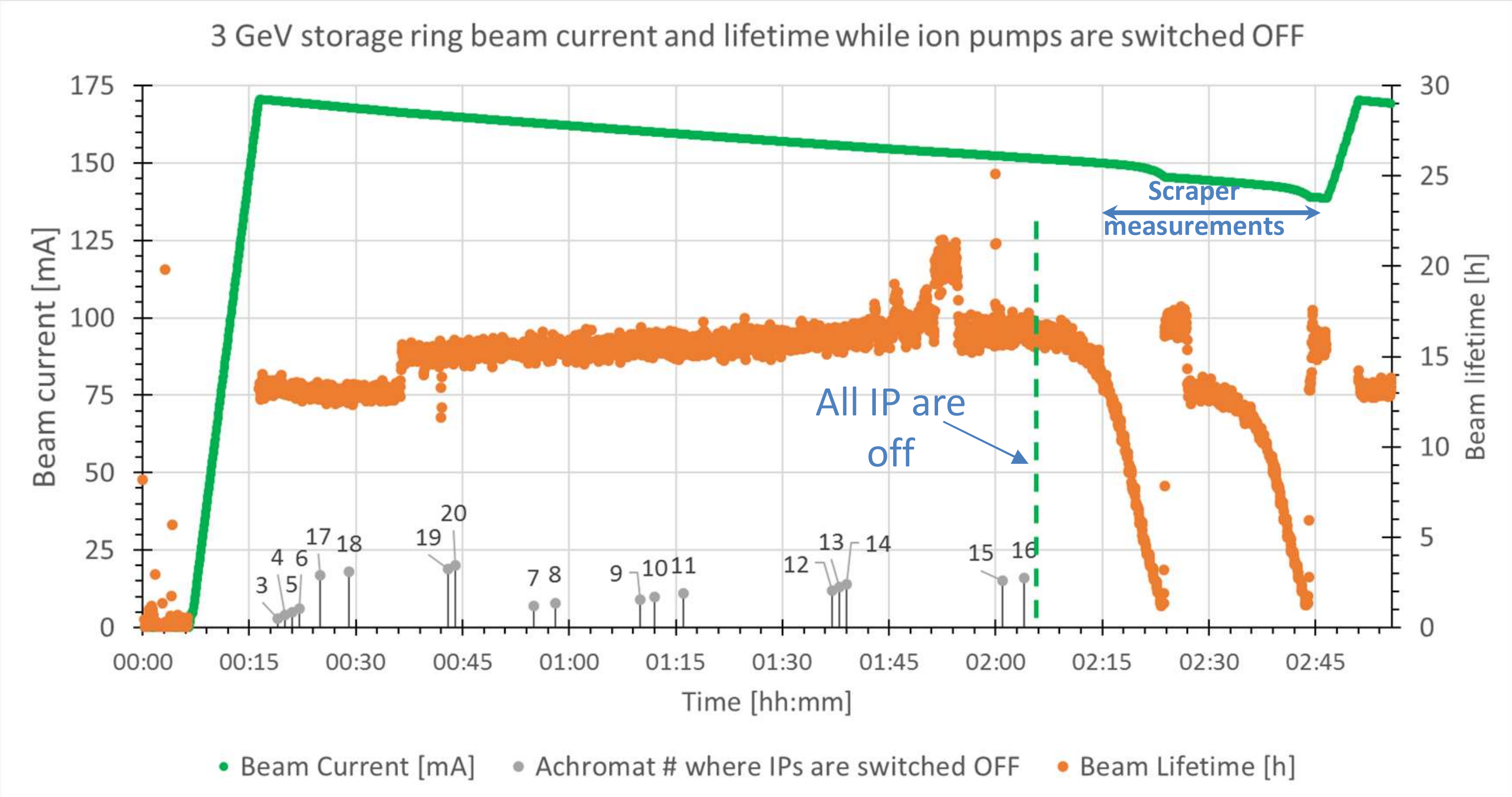


(11th March 2018, at beam dose 1430 Ah, measured lifetime 83 h)

Measurements at different does were taken with a beam current of 350 mA, and total beam lifetimes of 83 and 111 h were measured (29 and 39 A h respectively). Those can be considered lower limits for the vacuum-related beam lifetime.

6th DLSR workshop: Oct. 2018. Experience with NEG coated chambers as absorbers and pumps E. Al-Dmour

Vacuum performance
(tests with ion pumps OFF)



Time from injection (hh:mm)	Current (mA)	Lifetime (h)	I.tau (Ah)	comment
00:16	170	13	2.21	before the start of the test (all IP are on)
02:07	150	16	2.40	all IP are off*
02:45	139	15.5	2.15	after scraper measurement & all IP are off*
02:46	170	13	2.21	top up and all IP are off*.

Negligible effect on lifetime.

* except RF, inj. & ID

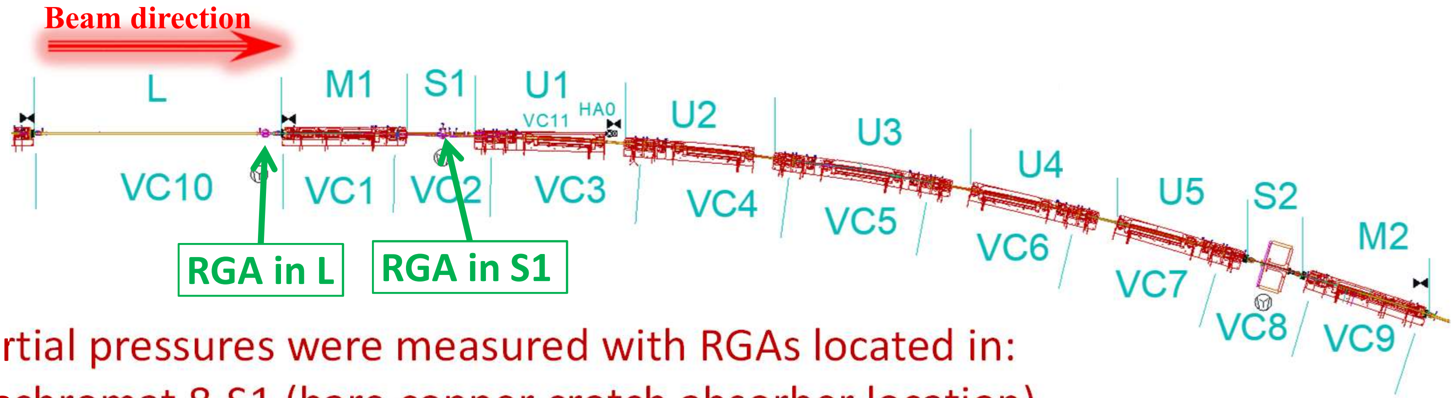
Vacuum performance
(tests with ion pumps OFF)

- Effect on the beam size: a slight change in the beam size, not clear if related to vacuum level,
- Pressure:

Beam current [mA]	Ion pumps status	S1 (Extractor gauges) average pressure [mbar]
0	ON	2.7E-10
140-170	ON	4.1E-10
140-170	OFF	1.4E-09
pressure ratio (with beam)		3.4

- radiation level: no increase outside in the experimental hall.

Vacuum performance
(tests with ion pumps OFF)



Partial pressures were measured with RGAs located in:
- achromat 8-S1 (bare copper crotch absorber location)
- achromat 17-L (long straight section fully NEG coated, can be considered as the most representative spectrum of the 3 GeV storage ring)

Spectrums were recorded with no stored beam, with stored beam at standard operation (ion pumps ON) and with stored beam with ion pumps OFF, summarized below:

				Mass (gas species)				
RGA location	Current [mA]	Ion pump status	beam dose [Ah]	2 (H_2)	16 (CH_4)	18 (H_2O)	28 (CO)	44 (CO_2)
8-S1 (location of crotch absorber)	0	ON	450	97.9%	0.4%	0.1%	1.3%	<0.1%
	163	ON		90.2%	0.8%	<0.1%	7.7%	0.2%
	146	OFF		73.4%	6.3%	0.1%	16.1%	0.1%
17-L (straight section)	0	ON		98.7%	0.2%	0.1%	0.8%	0.1%
	170	ON		94.7%	0.4%	<0.1%	4.2%	0.3%
	140	OFF		95.7%	1.2%	<0.1%	2.8%	0.1%