UK Accelerator Institutes Seminar

Design and Operation of MAX-IV Vacuum System Based on NEG Coating

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MAX IV

CONTENTS

- MAX IV facility
- 3 GeV storage ring vacuum system and layout.
- The vacuum chamber design.
- NEG coating R&D.
- Installation procedure.
- Vacuum system operation and performance.
- Neon venting for interventions.
- Conclusion.

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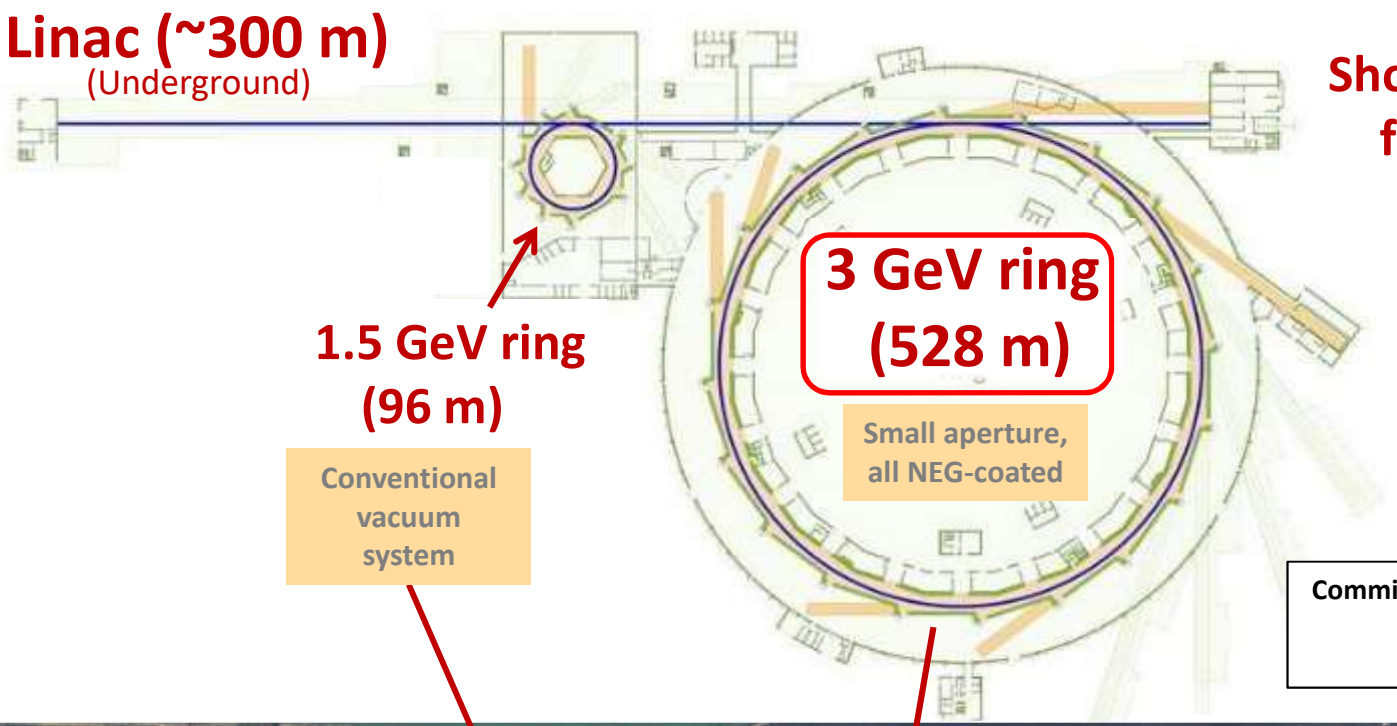
MAX IV Facility



Short pulse facility

3 GeV ring main parameters

Operating energy	3.0 GeV
Circulating current	0.5 A
Circumference	528 m
Straight section length	4.6 m
Hor emittance, naked lattice	0.33 nm rad
Hor emittance incl IDs	0.23 nm rad
Coupling	0.5-3 %
Total beam life-time	10 h
RF	100 MHz

Commissioning of the 3 GeV ring started: August 2015

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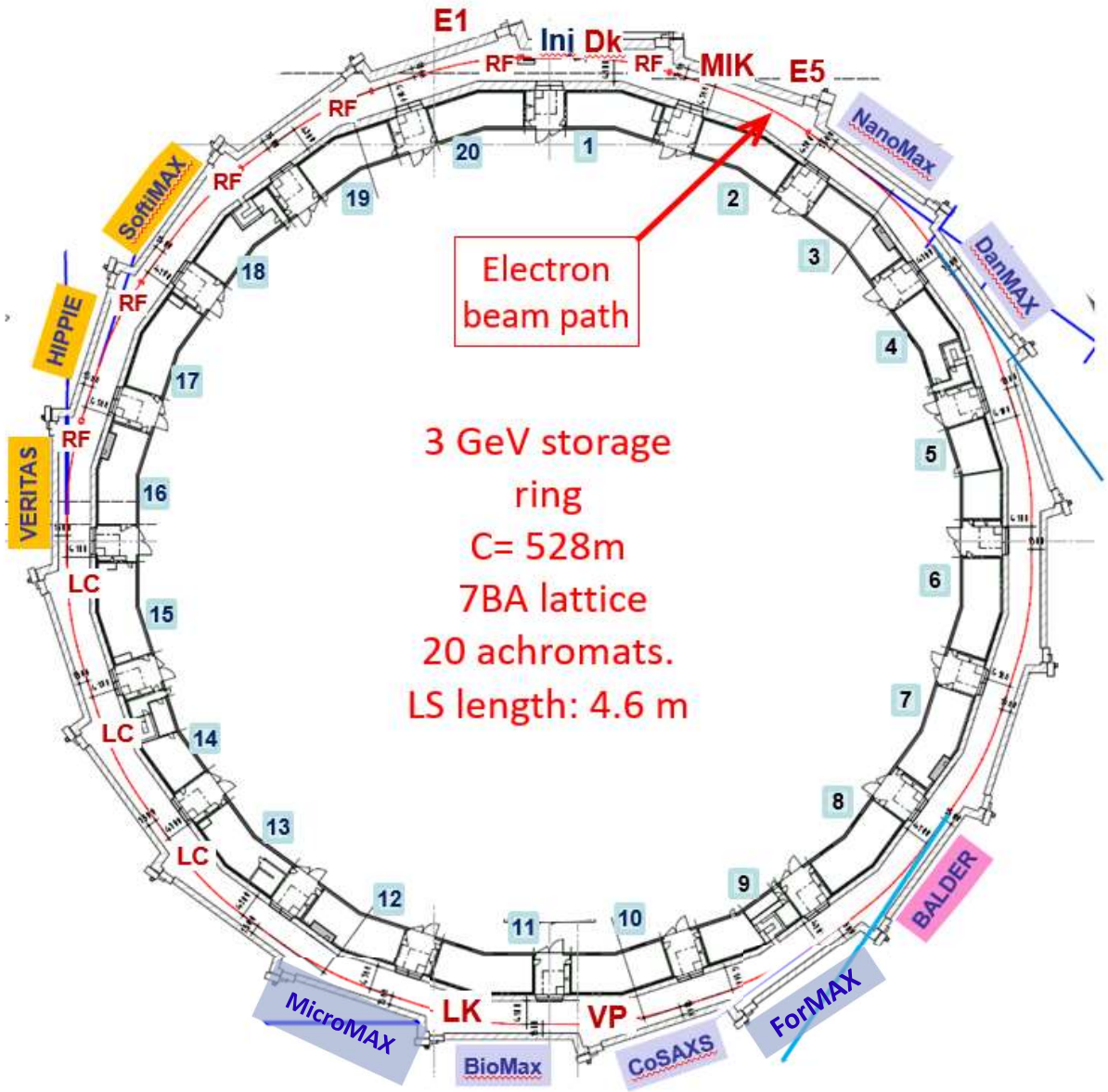
Introduction – 3 GeV Storage Ring



- Inj: injection straight
- RF: 100 MHz cavities
- LC: 300 MHz Landau cavities
- E1, 5: emittance/diagnostics beamlines.
- DK: dipole kicker.
- MIK: multipole Kicker.
- LK: longitudinal kicker.
- VP: vertical pinger.

Apple undulators

In-vacuum undulators

In-vacuum wiggler

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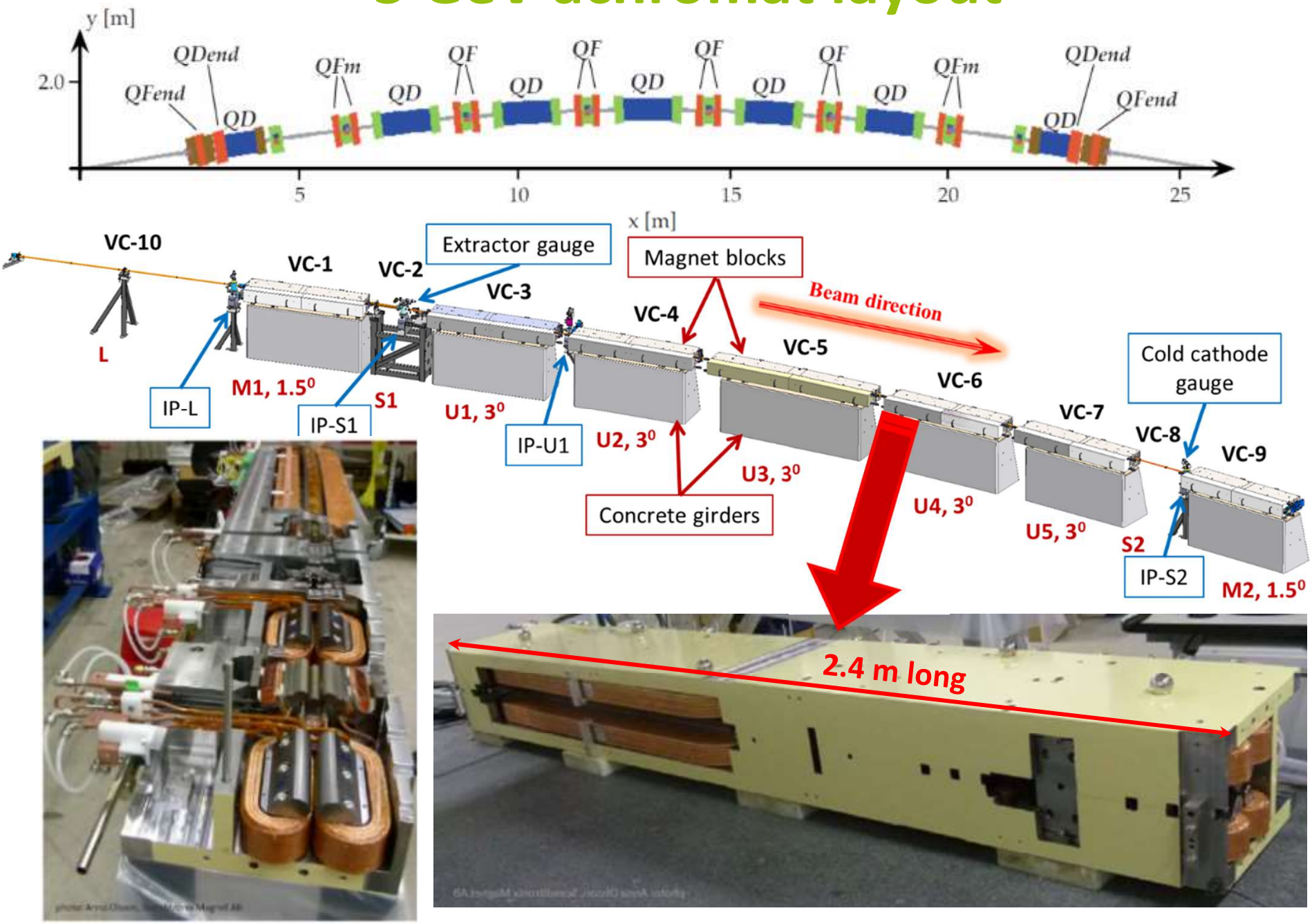
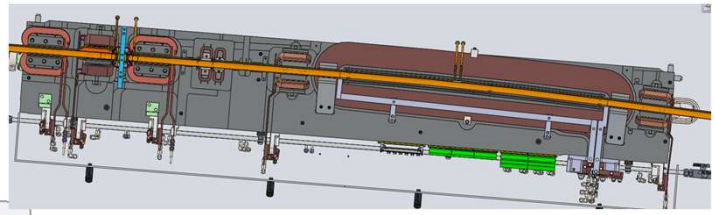
3 GeV achromat layout



3 GeV storage ring vacuum system and layout.

Vacuum system constraints

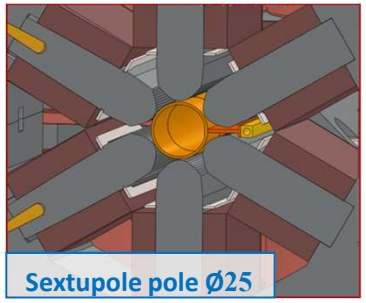


- **Compact lattice**
  Small longitudinal distance between magnets.
- **Closed solid magnet block**
  Little space around the magnets.

No space for lumped absorbers or pumps

- **Small aperture of the magnets**
  Magnets' aperture Ø25 mm.

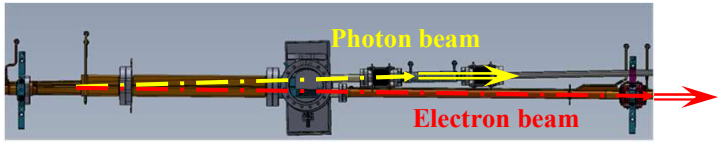
Low conductance of vacuum tubes



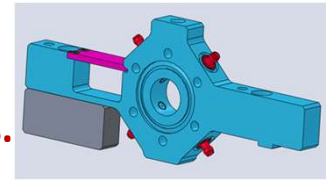
- **Low target dynamic pressure**
  Average pressure 1e-9 mbar.

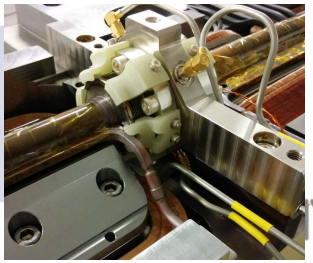
Need of pumping and low PSD

- **Removal of the SR power (BM & ID)**
  Power density along bent vacuum chamber walls and absorbers.



- **Extraction of synchrotron radiation**
  Limitations due to small bending angle.
- **Stable positioning of BPM**
  Isolating as much as possible the BPMs from the chambers.

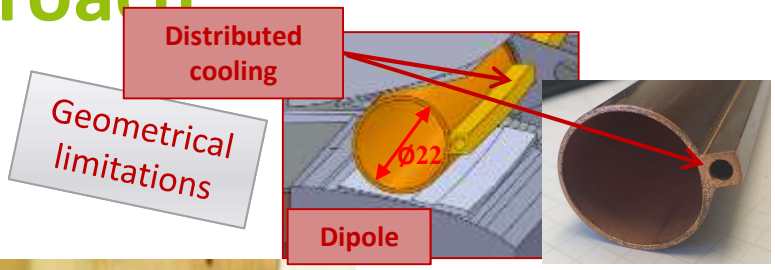


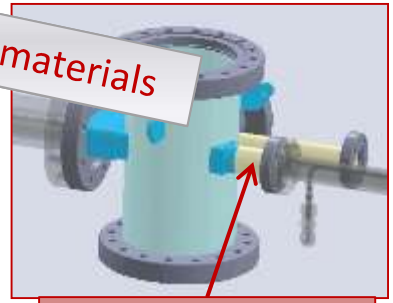


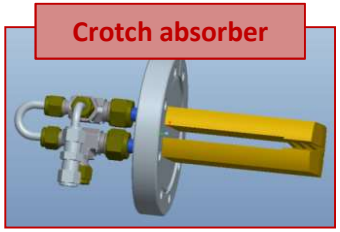
Vacuum system design approach

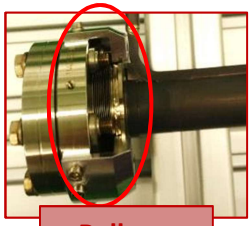
- **Geometry**: inside diameter **22 mm**, **1 mm** wall thickness, bends of 1.5˚ and 3˚ over 19 m bending radius.
- **Substrate: Silver bearing (OFS) Copper** vacuum chambers (resistance to thermal cycling)**.**
- **Distributed water cooling** to cope with SR**.**
- Areas made of **stainless steel** for fast corrector coils.
- One **Lumped absorber** per achromat is 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.

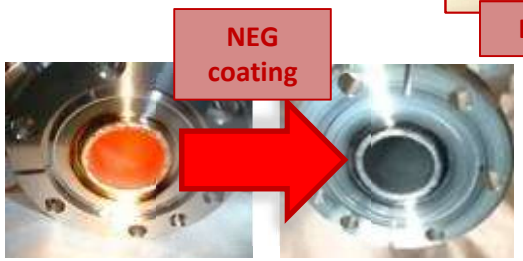
- Distributed pumping and low PSD all along the conductance limited chamber, utilizing thin film **NEG-coating**.











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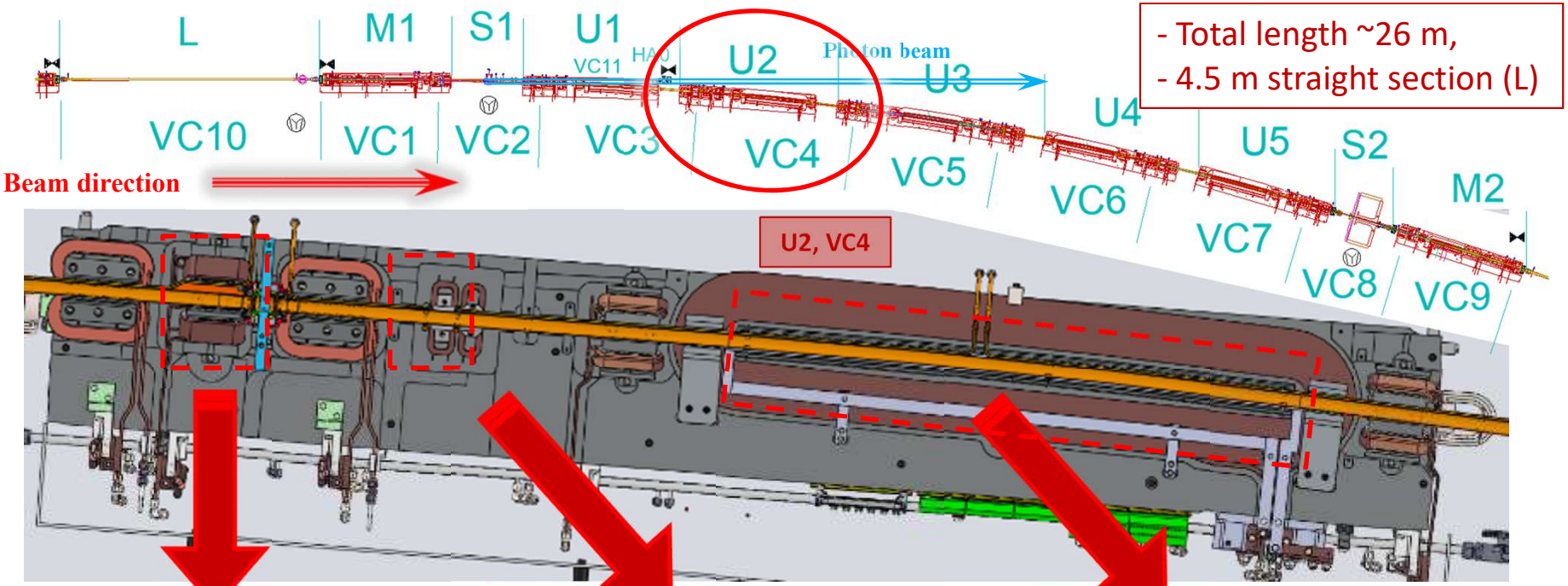
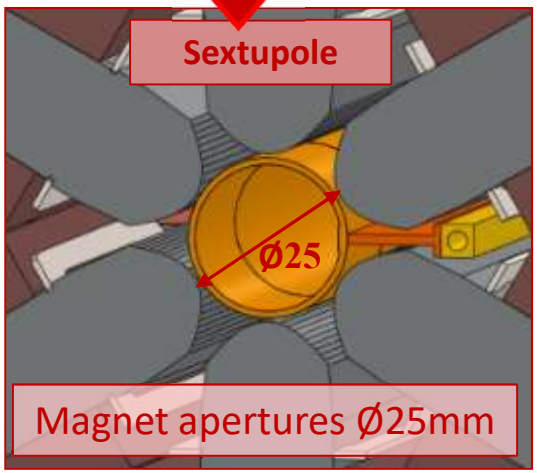
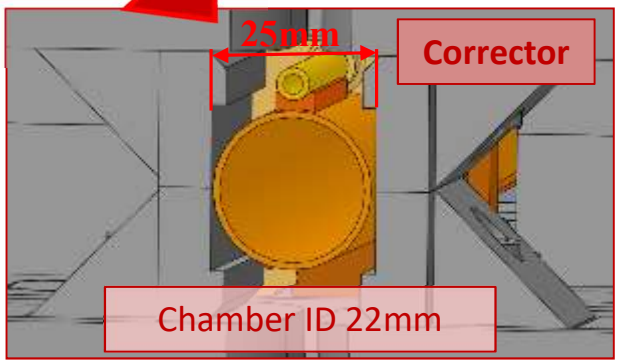
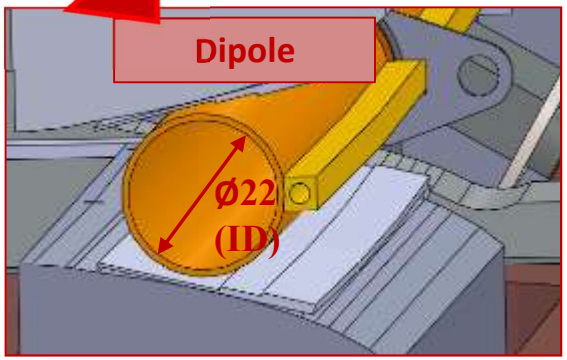
The design of the vacuum chambers

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





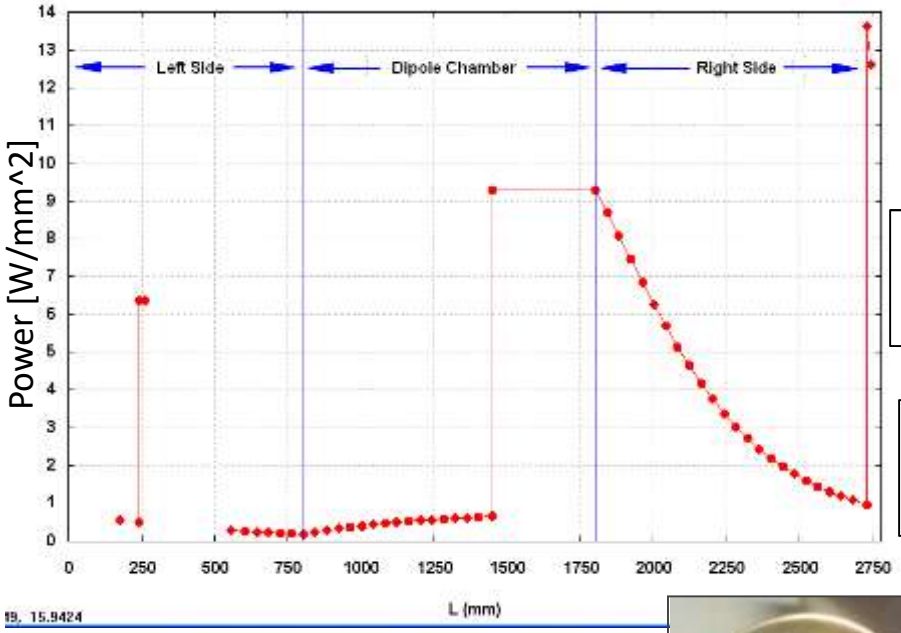




Min. clearance with the iron 0.5 mm, min. clearance with the coils 2 mm.

General vacuum chamber geometry

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

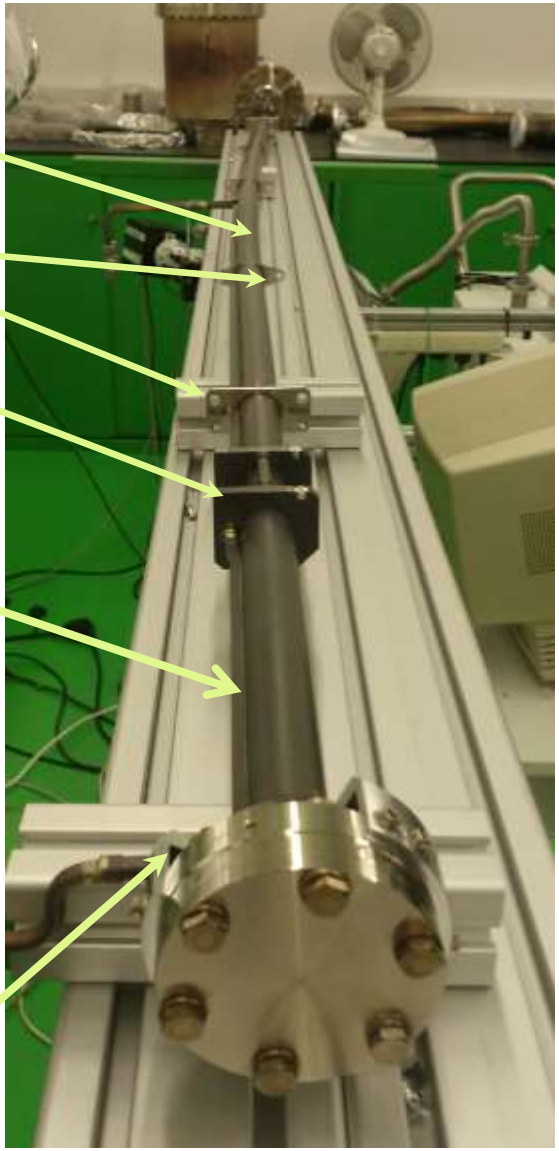


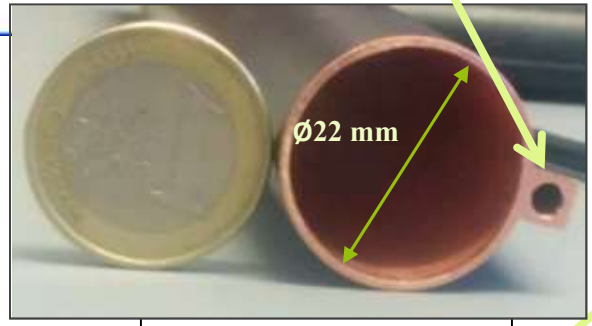
Chamber body

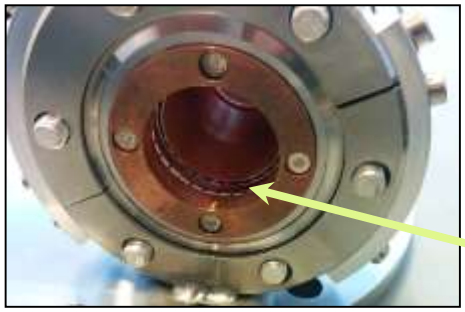
Ribs

Cooling for corrector area

Distributed cooling







Welded bellows with RF shielding

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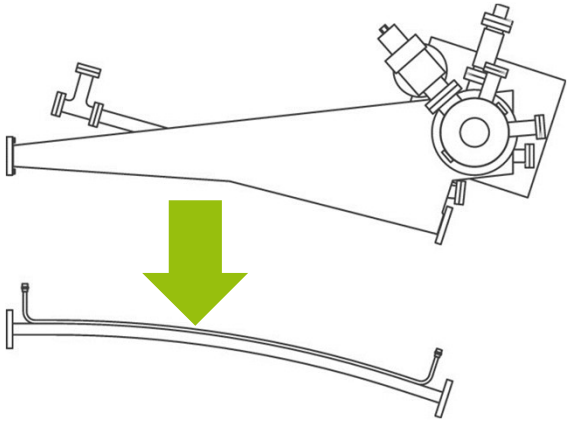
NEG coating

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

- NEG-coating of vacuum chambers was developed at CERN for warm LHC sections, 6 km of vacuum pipe was coated.
  - NEG-coating is used widely in many light sources - mainly for ID chambers.
  - At SOLEIL synchrotron 56% of storage ring is NEG coated.
  - In MAX II* (light source operated in Lund, decommissioned in 2016) three dipole chambers were replaced by NEG-coated copper vacuum chambers.

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



* 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 at CERN

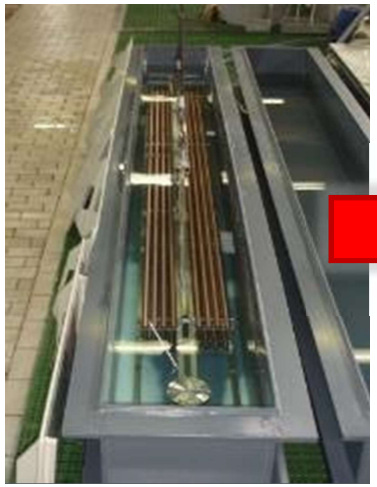
1. Define and perform initial surface treatment of OFS copper substrate.

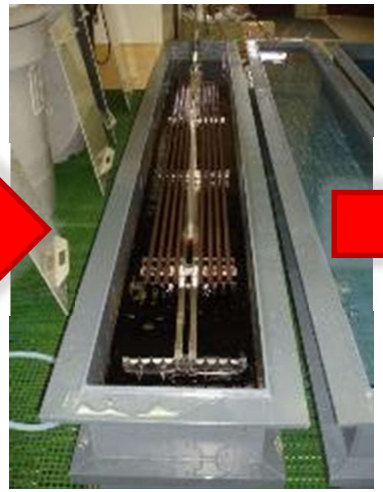
- chosen treatment (following LHC experience) was:

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.

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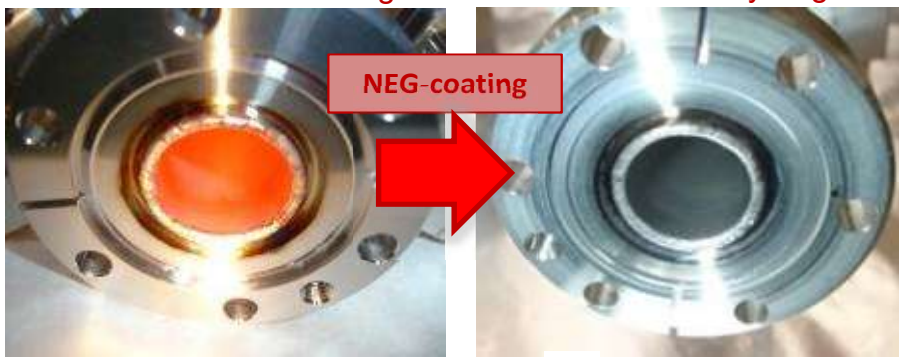
NEG coating development at CERN

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

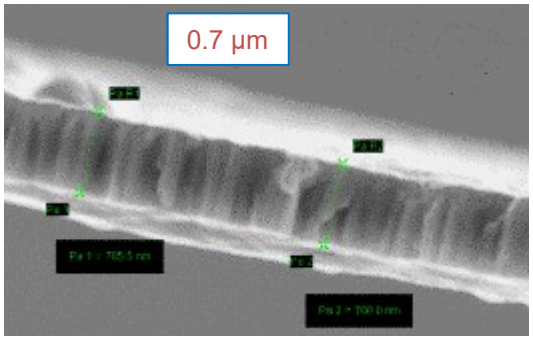
- **Etched OFS copper tubes,**
- **wire eroded surfaces**
- **brazing types (substrate),**
- **for small diameter bent tubes (geometry).**

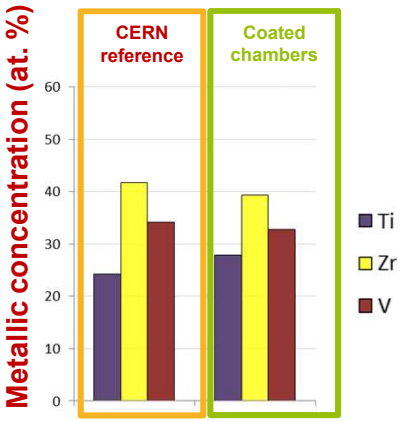
Chamber before coating

Chamber after coating and thermal cycling



SEM thickness measurements:



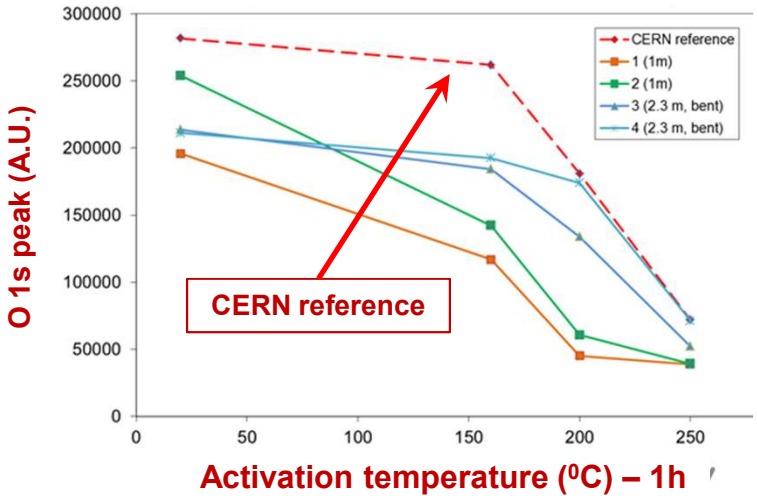


Surface metallic composition by XPS

NEG coating requirements:

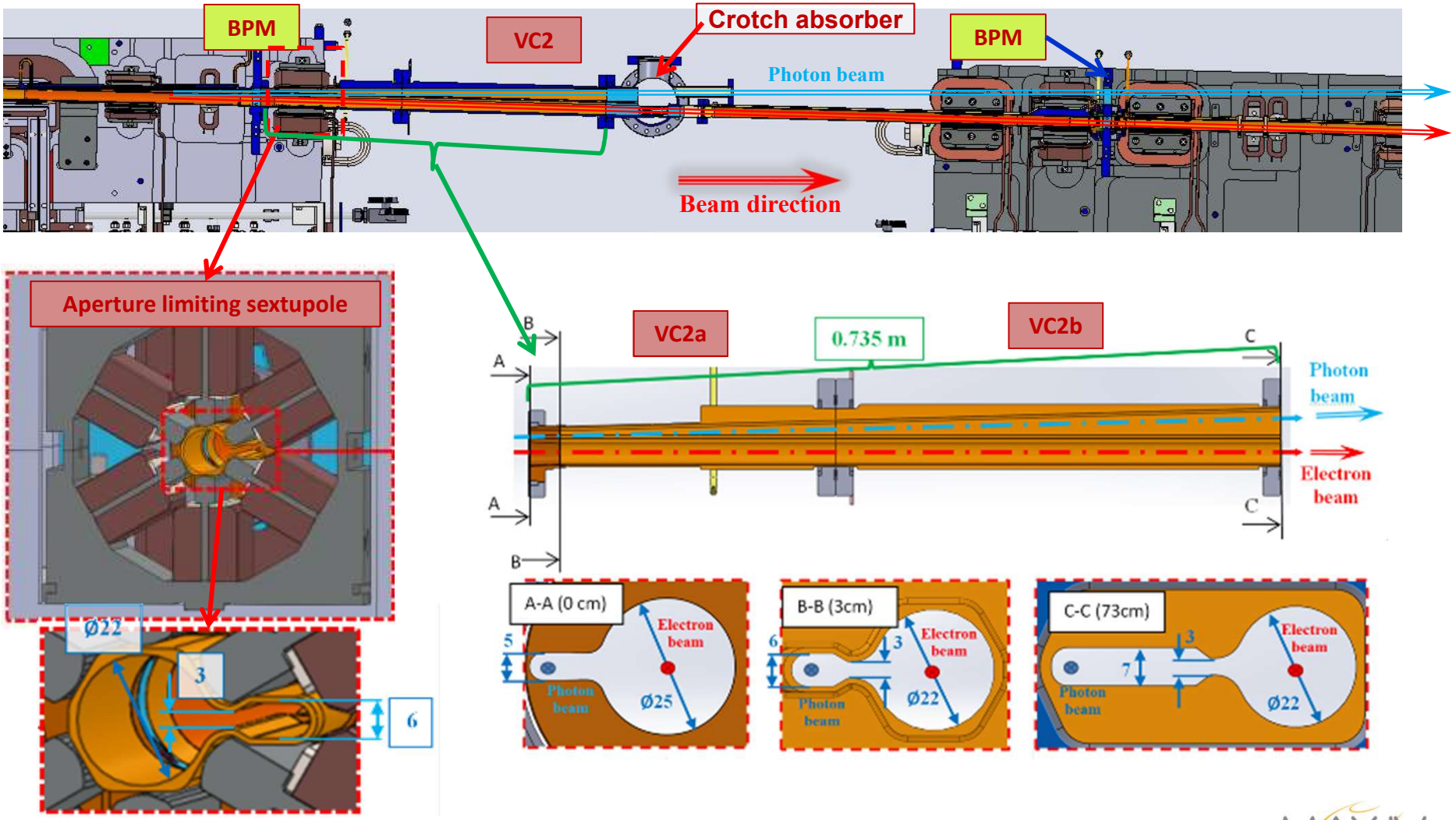
- ✓ ***No peel offs, full coverage***
- ✓ ***Coating thickness 0.5 – 2 µm,***
- ✓ ***Correct composition of Zr, Ti, V,***
- ✓ ***Good activation behavior.***

Oxygen content evolution on NEG coated copper samples recorded by XPS measurement.



NEG coating development at CERN

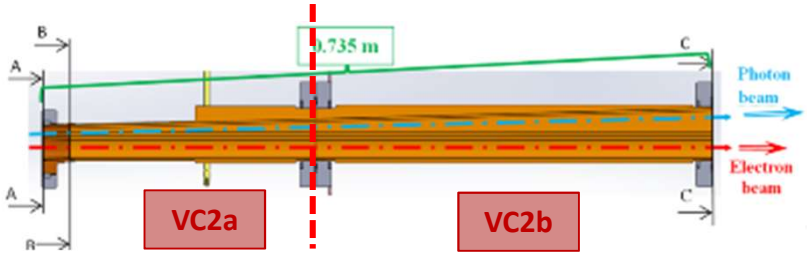
3. Establish coating procedure/technology and produce chambers of complex geometry:
Vacuum chamber for beam extraction (4 vacuum chambers / achromat).

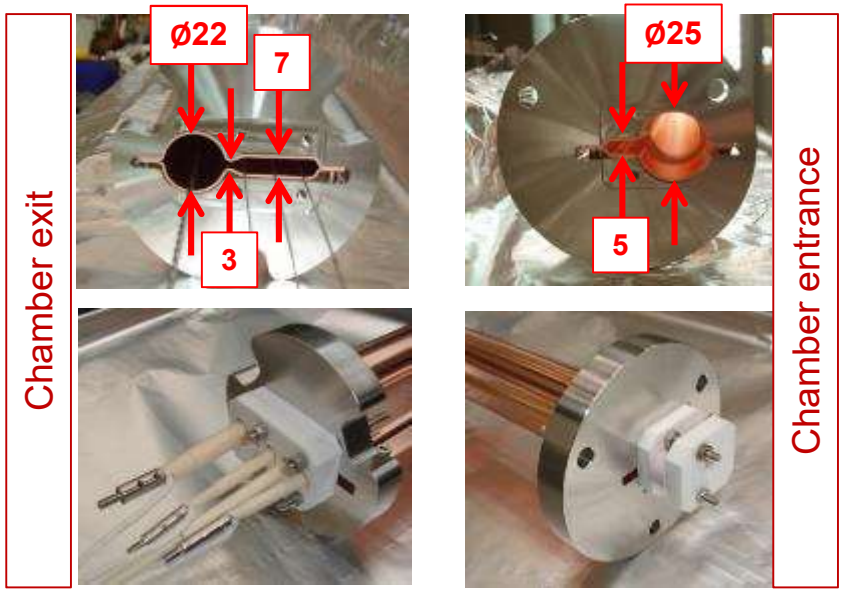


NEG coating development at CERN

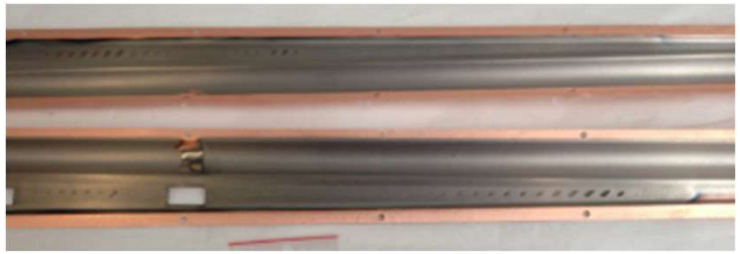
Prototype was made at CERN in two halves to allow easy inspection of the coating quality.

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,
'delayed' activation in the antechamber

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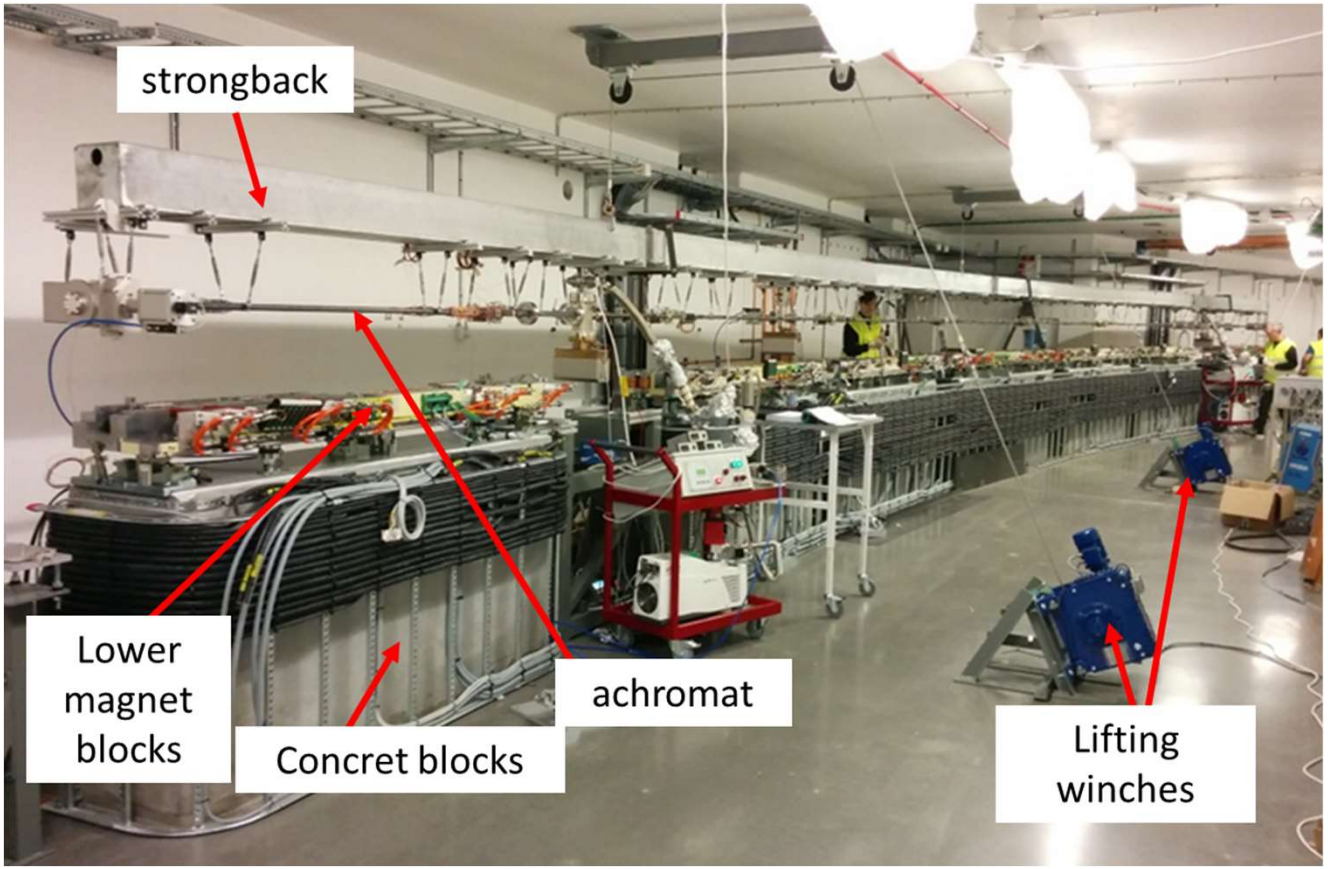
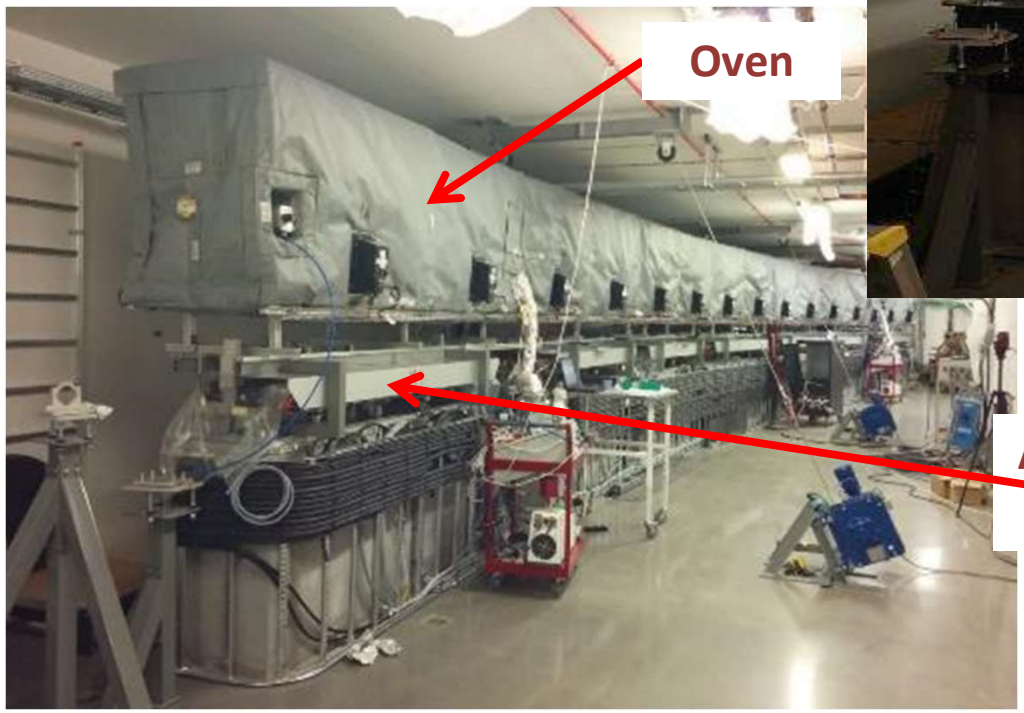
The installation procedure

- Ring installation was tested and rehearsed by installing and activating mockup achromat.
- Two teams working in parallel.
- The installation period was 6 months for the whole ring.
- Installation tools:

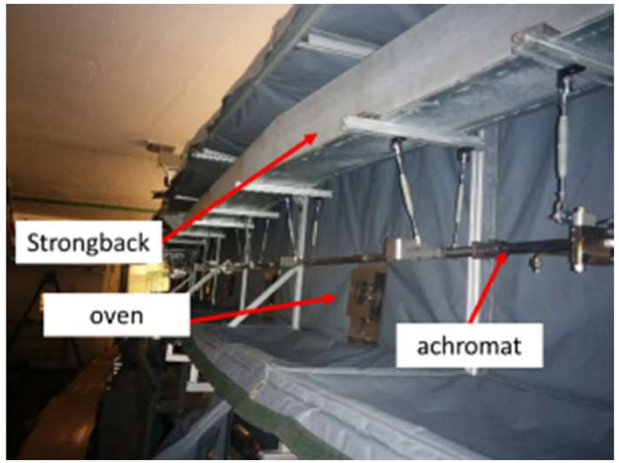


The installation procedure

- Magnet top halves removed,
- Installation of assembly tables.
- Assembly of vacuum chambers
- Pump down and testing,
- Lifting chamber up,
- Installation of bakeout oven
- Baking (1 day), activation (1 day),

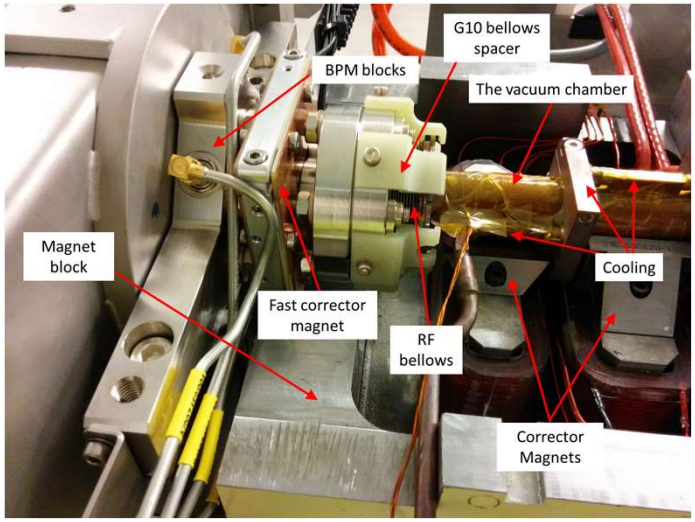


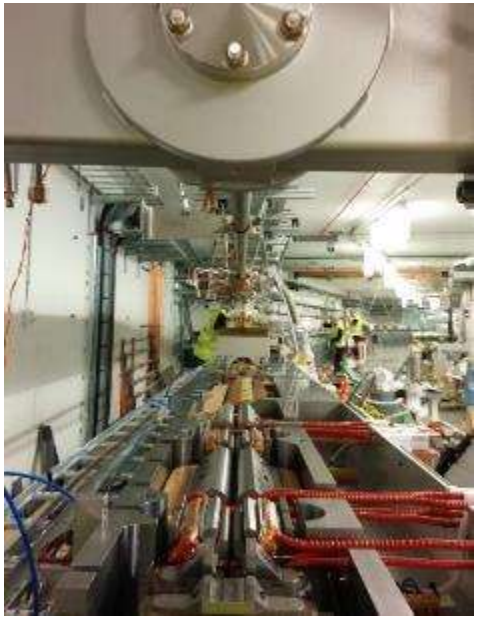
Assembly tables

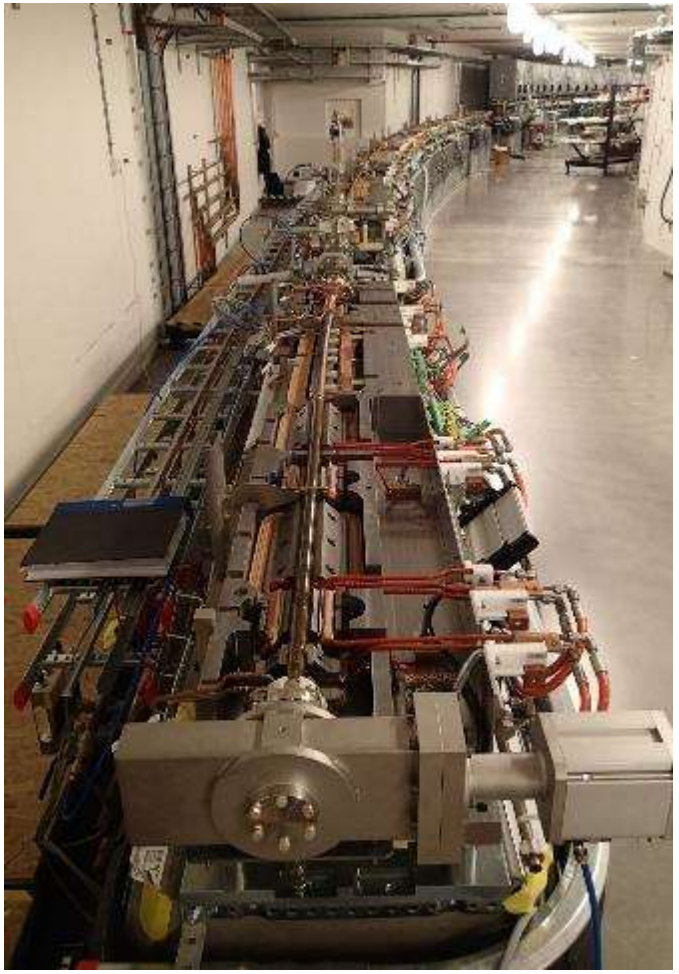


The installation procedure

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

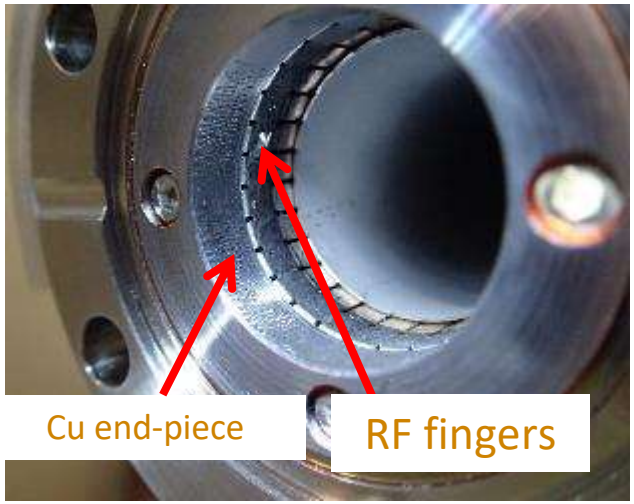






Installation issues:

Coating peeling-off



Damage of bellows
during manipulation

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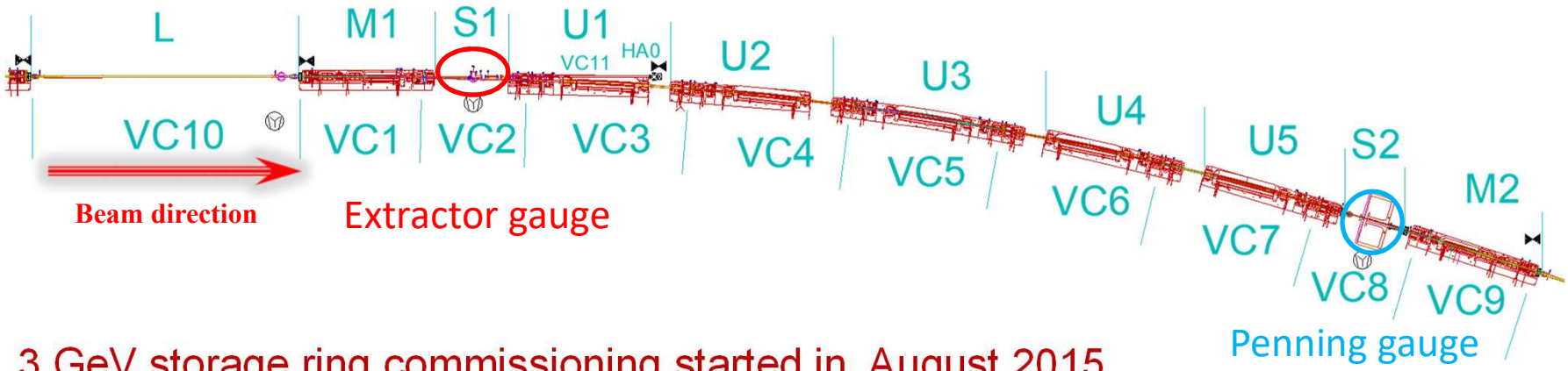
Vacuum performance



3 GeV storage ring commissioning started in August 2015

- Average base pressure (now):

  ~2e-10 mbar (extractor gauges)

- Accumulated beam dose:

  5220 Ah (Jan. 2022)

- Max. stored current:

  Design current: 500 mA (November 2018)

  total lifetime was 14 h

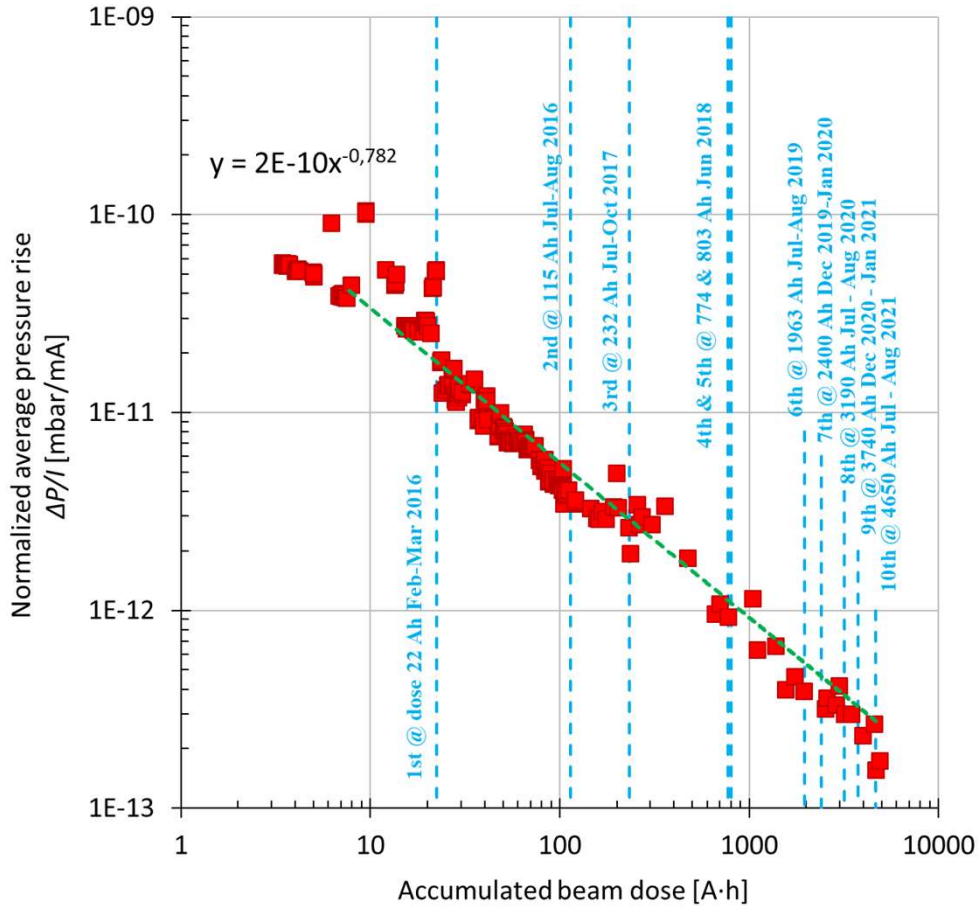
Current operation parameters for delivery to users:

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

Vacuum performance

- Vacuum performance can be measured by the average pressure reduction and the increase in the total beam lifetime as the accumulated beam dose has increased.

- 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.

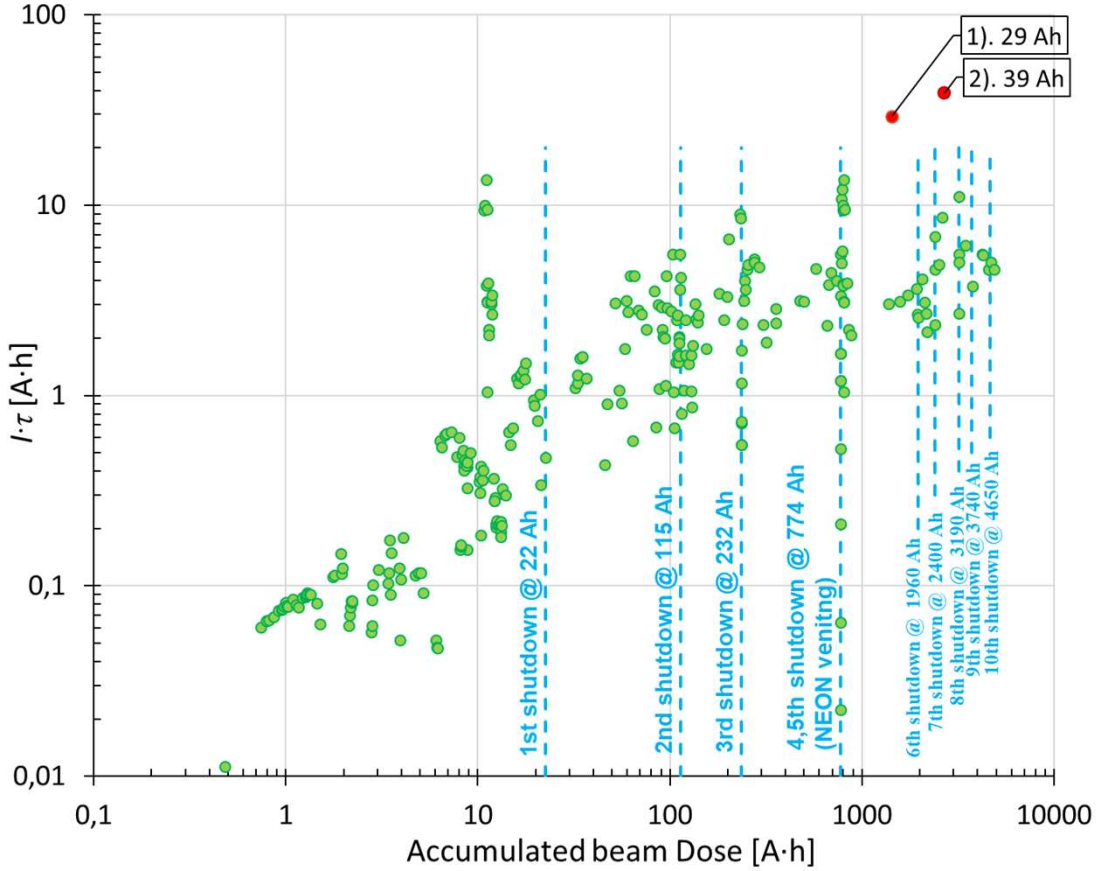


The absolute value of the slope of the conditioning curve (marked in green) is ~0.78

Vacuum performance

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

* Two points marked in red see next slide.

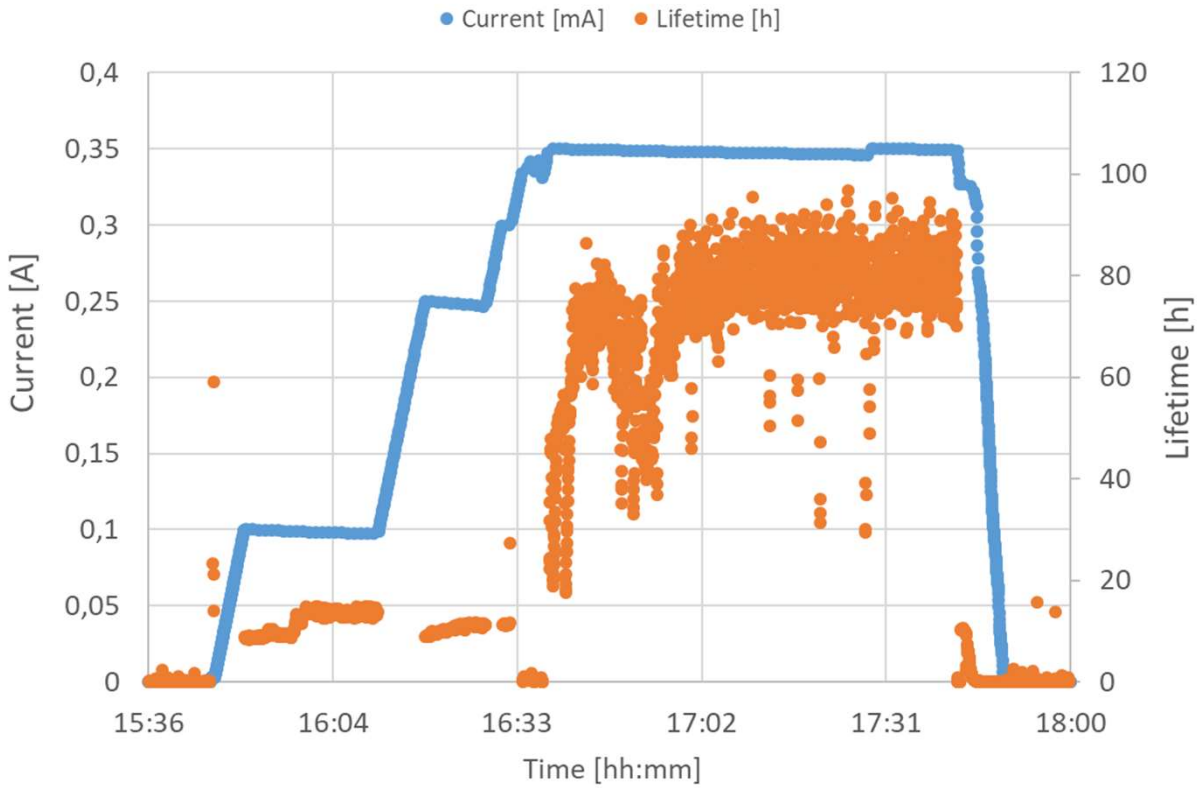


After each shutdown that involves vacuum intervention there is an increase in the average pressure and reduction in the lifetime, but recovery is fast, depending on the shutdown scope.

Vacuum performance

Tests 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 -> the total beam measured lifetime is the lower limit for the vacuum related lifetime.



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

Measurements at different doses (1430 Ah and 2690 A h) 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.

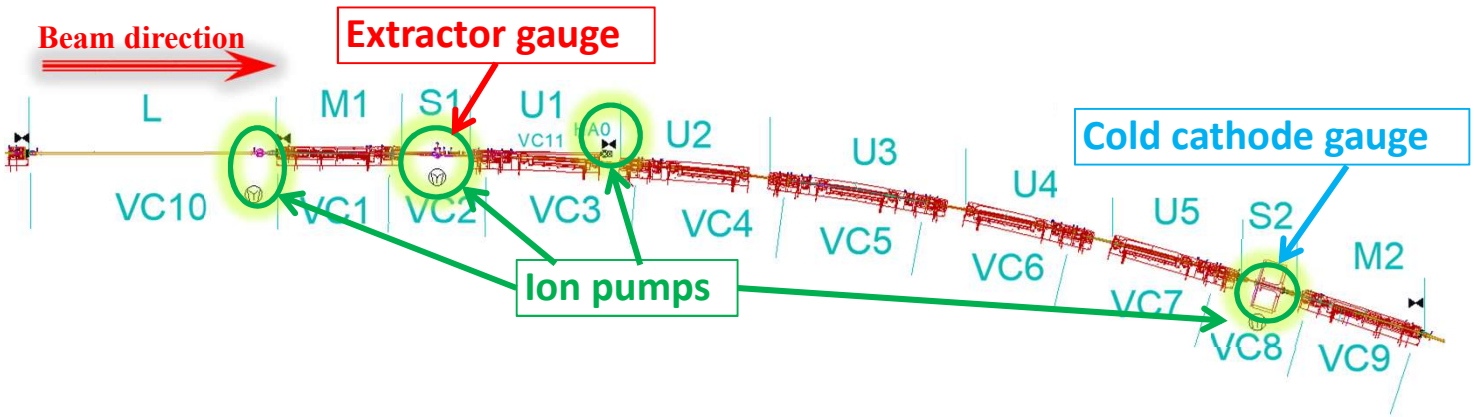
Vacuum Performance

(tests with ion pumps OFF)

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

Verify performance by looking to:

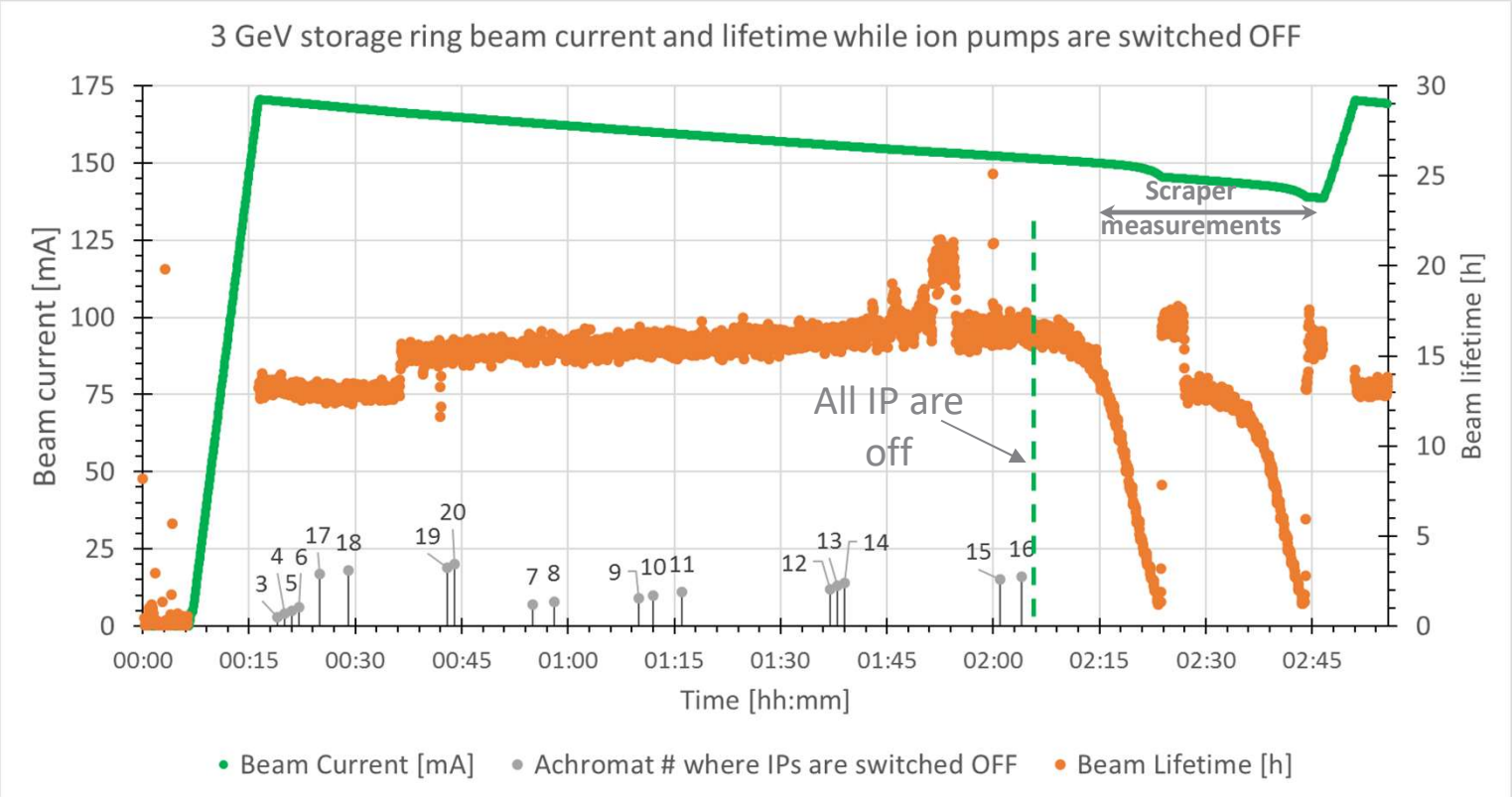
- Pressure,
- Residual Gas Analyzer scans (gas spectra),
- Effect on the beam size,
- Effect on the lifetime,
- Radiation increase outside in the experimental hall.



* 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) (uncoated areas).

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:

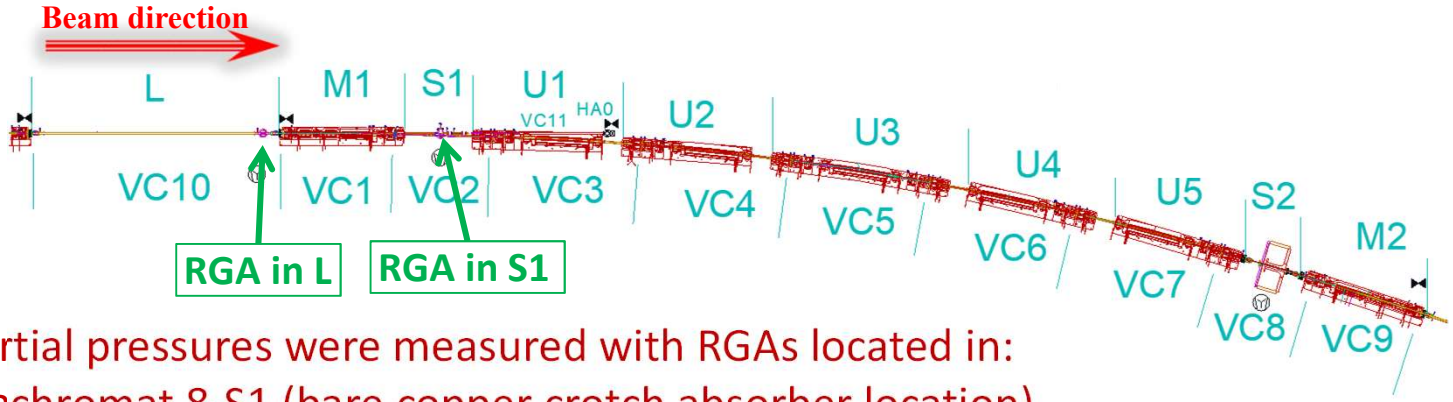
Beam current [mA]	Ion pumps status	S1 (Extractor gauges) average pressure [mbar]
0	ON	2.7E-10
140-170	ON	4.1E-10
140-170	OFF	1.4E-09
pressure ratio (with beam)		3.4

- radiation level: no increase outside ring tunnel (in the experimental hall).

MAX IV

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%

Operational status

Year	Planned delivery (h)	total downtime (h)	uptime (%)	Vacuum related downtime (h)	No. of vacuum downtime events	Vacuum related downtime contribution to total downtime (%)
2019	4573	124.50	97.28	1.5	2	1.2
2020	4872	126.83	97.40	3.45	6	2.7
2021	3744	116.95	96.88	0.5	1	0.5

- **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**: 1 vacuum related event caused beam dump.
  The event related to short lived vacuum spikes from a penning gauge.

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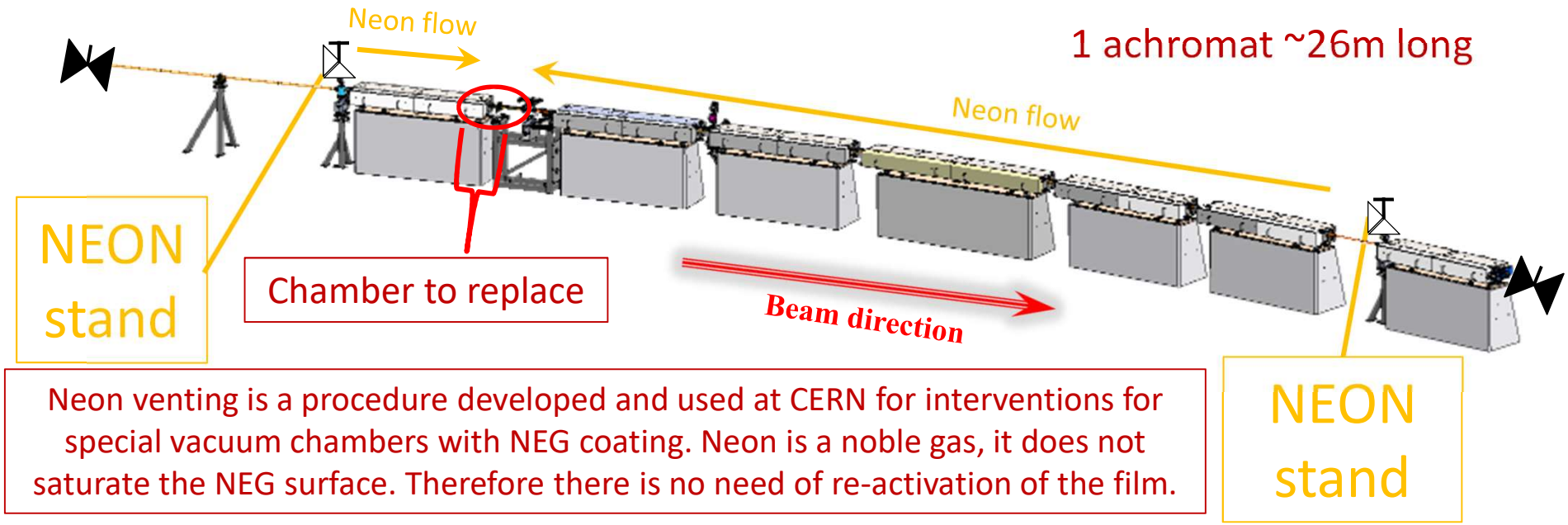
Neon venting for new installations/interventions



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).

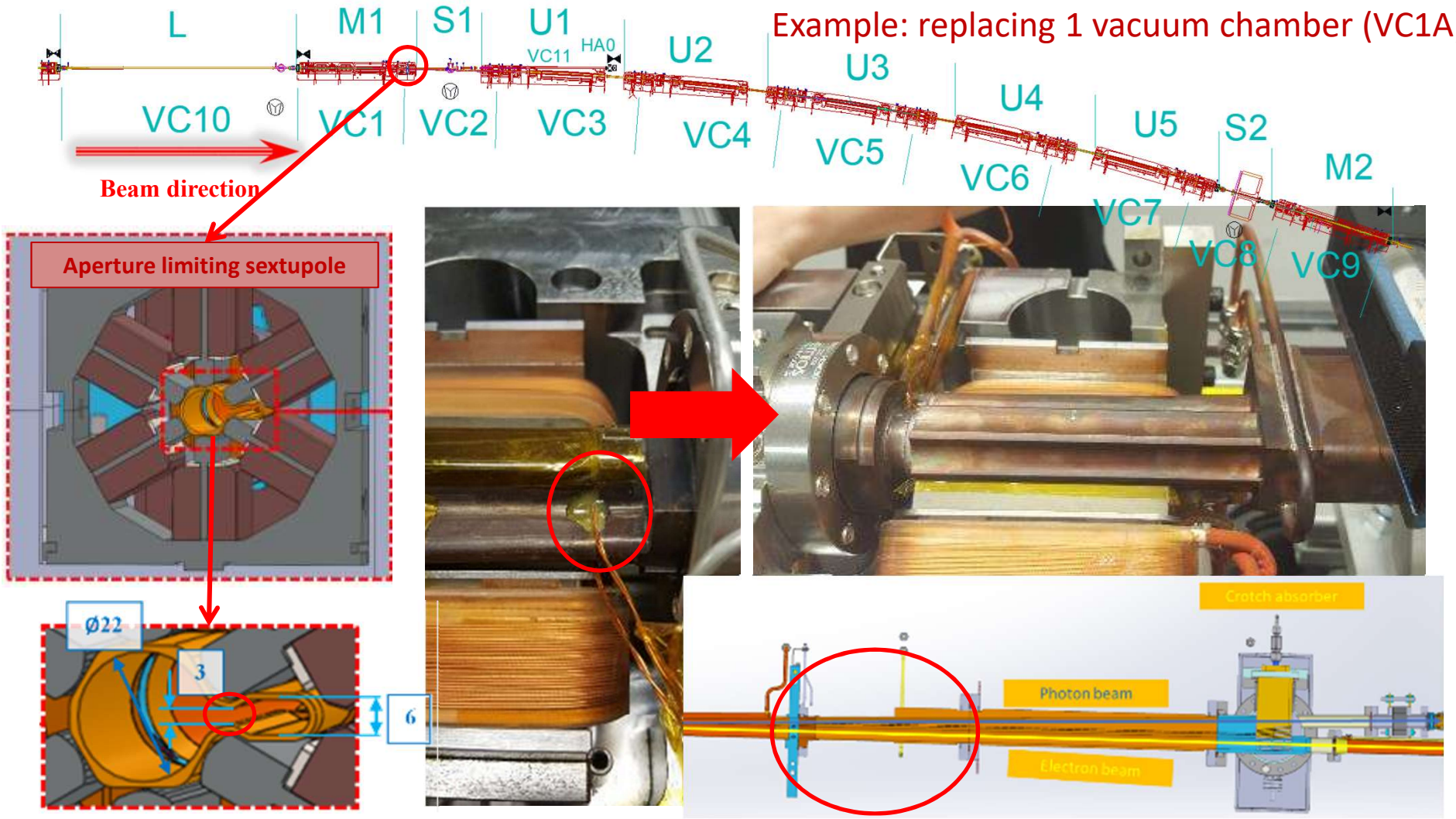
Such intervention on the accelerator itself takes around 2 hours (excluding preparations) and afterwards pumping down with turbo molecular pumps and ion pumps takes around 4 days.

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

MAX IV

Neon venting for new installations/interventions

Example: replacing 1 vacuum chamber (VC1A)

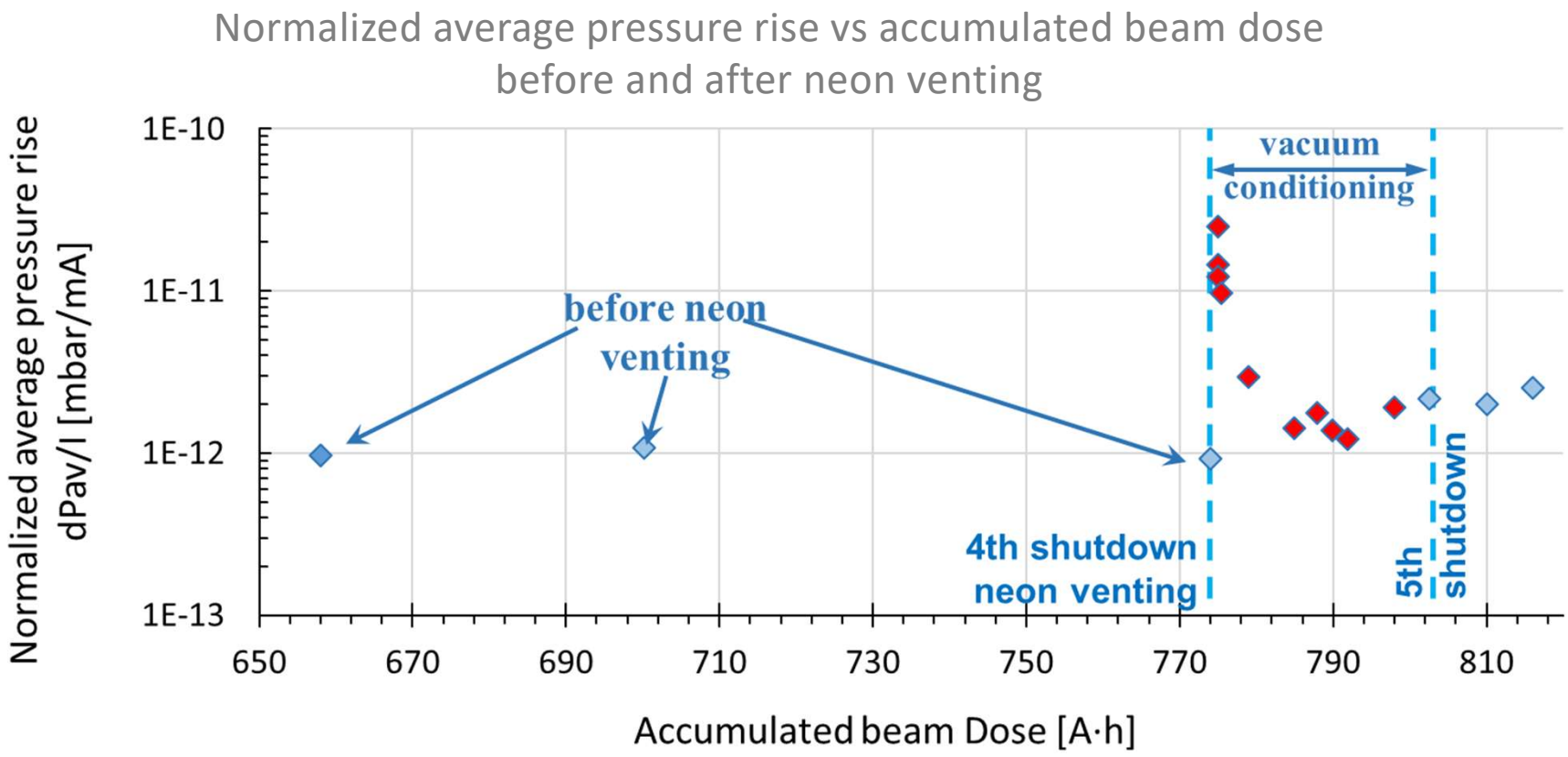


Neon venting was used during for the first time in 2018 and did not limit machine startup nor operation.

Neon venting for new installations/interventions

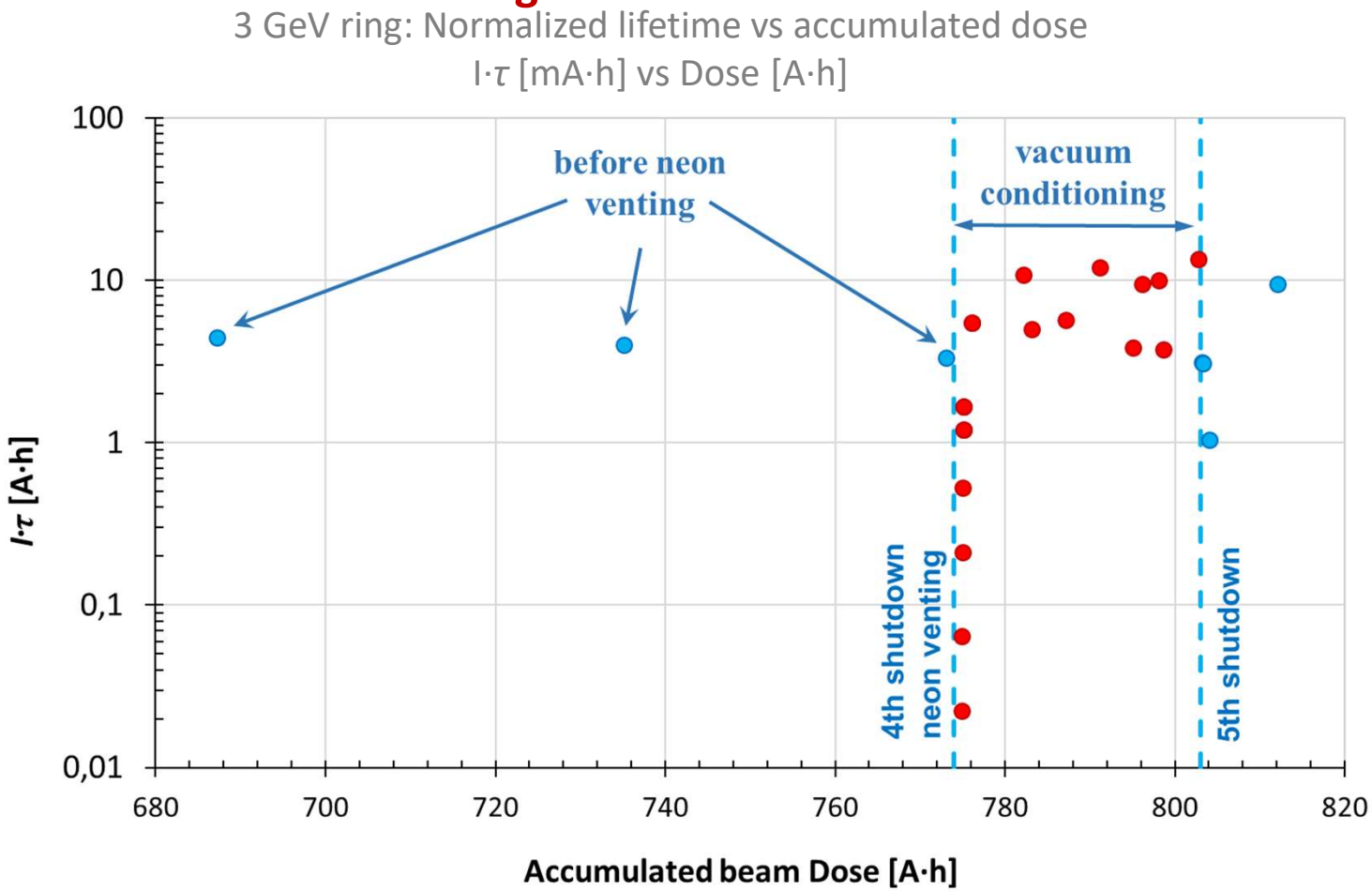
Vacuum conditioning after neon venting intervention in 2018

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



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

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Conclusions

- MAX IV 3 GeV ring is operating since the end of 2015 with no major issues.
- The design, NEG coating and installation were challenging.
- The 3 GeV storage ring NEG coating project was successful thanks to close collaboration with CERN.
- 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 confirmed that NEG coating is still performing well.
- The vacuum conditioning (measured by pressure reduction and lifetime increase) are proofs of the successful operation.
- 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.

MAX IV

Thank you for your attention

For more details:

Commissioning and operation status of the MAX IV 3 GeV storage ring vacuum system

https://doi.org/10.1107/S1600577521002599

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