MAX IV 3 GeV NEG coated storage ring status

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on behalf of the MAX IV vacuum team

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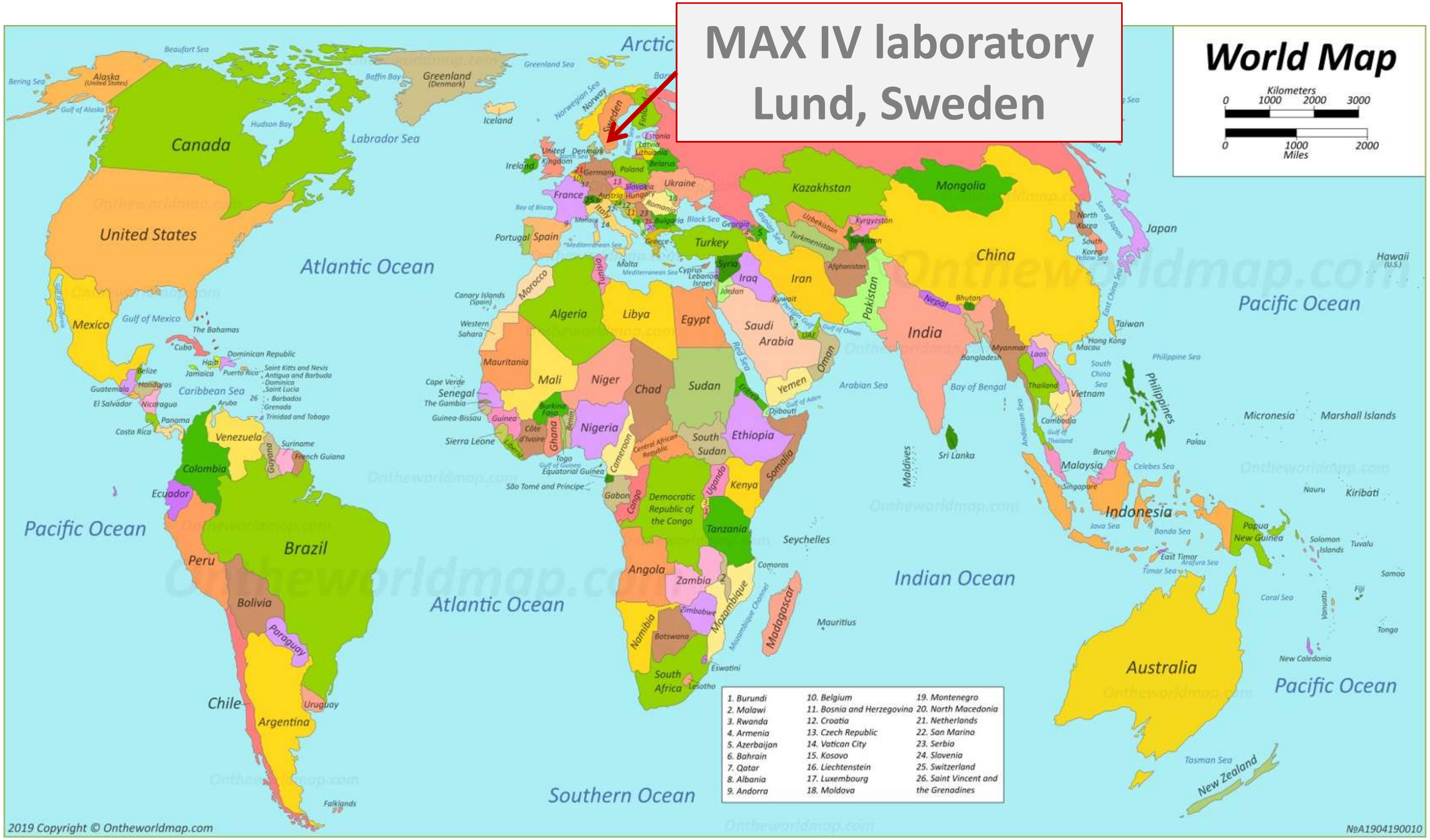
Fermi National Accelerator Laboratory, IL, USA

Contents

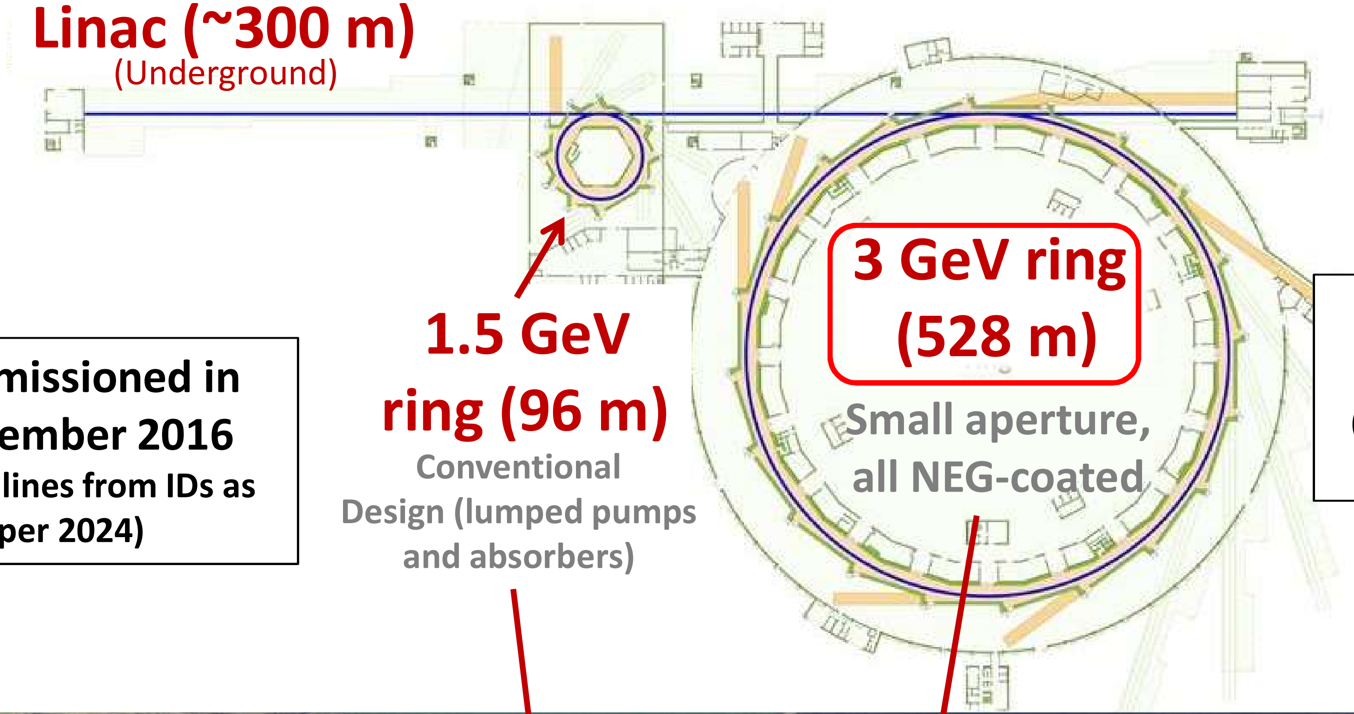
Location



MAX IV laboratory
Lund, Sweden

MAX IV facility layout

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



Linac (~300 m)
(Underground)

Short pulse facility
(1 Beamline)

Commissioned in September 2016
5 Beamlines from IDs as per 2024)

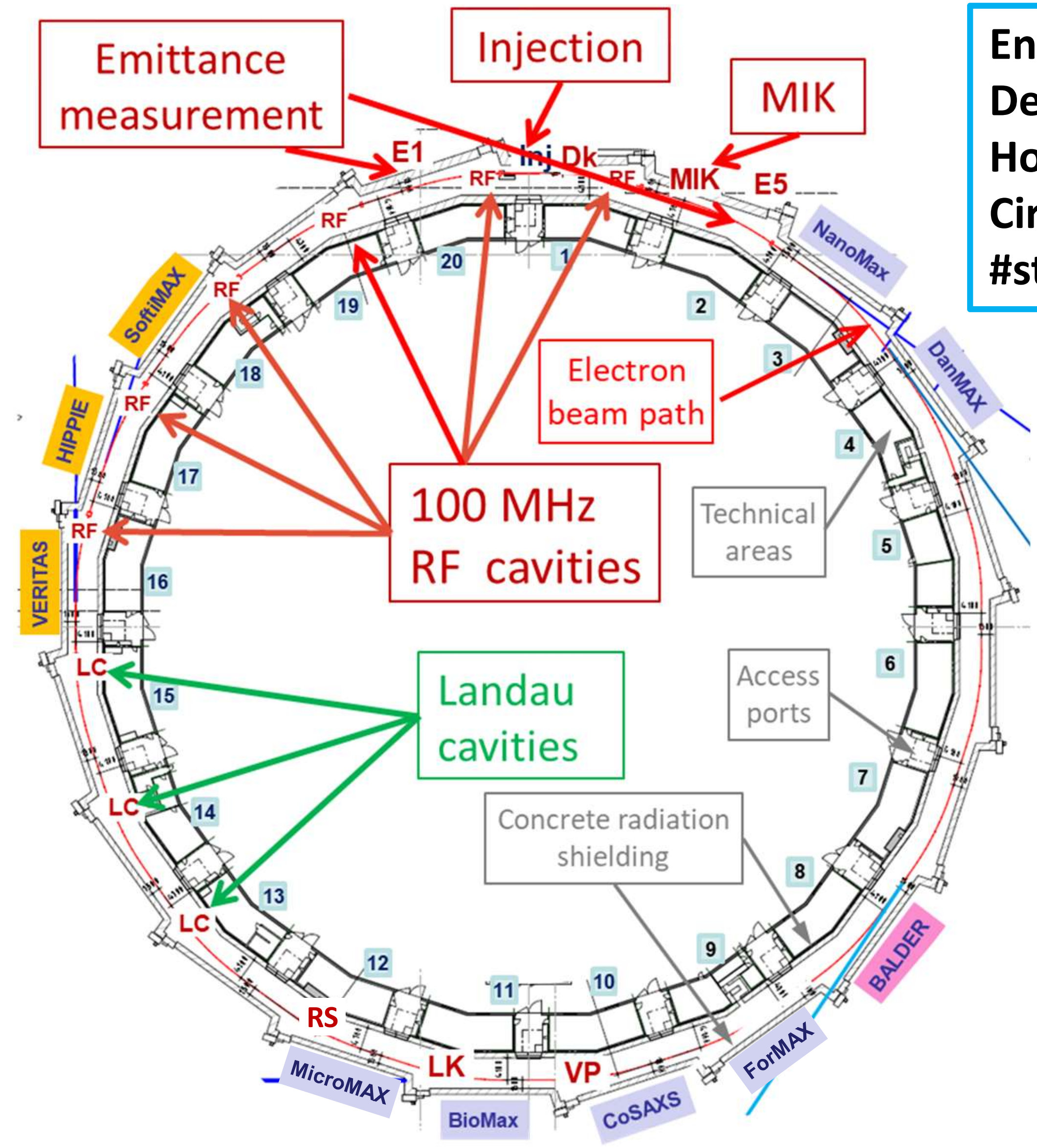
1.5 GeV ring (96 m)
Conventional Design (lumped pumps and absorbers)

3 GeV ring (528 m)
Small aperture, all NEG-coated

Commissioned in August 2015
(10 Beamlines from IDs as per 2024)

MAX IV 3 GeV storage ring layout

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:

6 In-vacuum undulators:
- NanoMax, BioMax IVU18
- Cosaxs IVU 19.3, DanMax IVU16
- ForMax IVU17, MicroMax IVU18

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

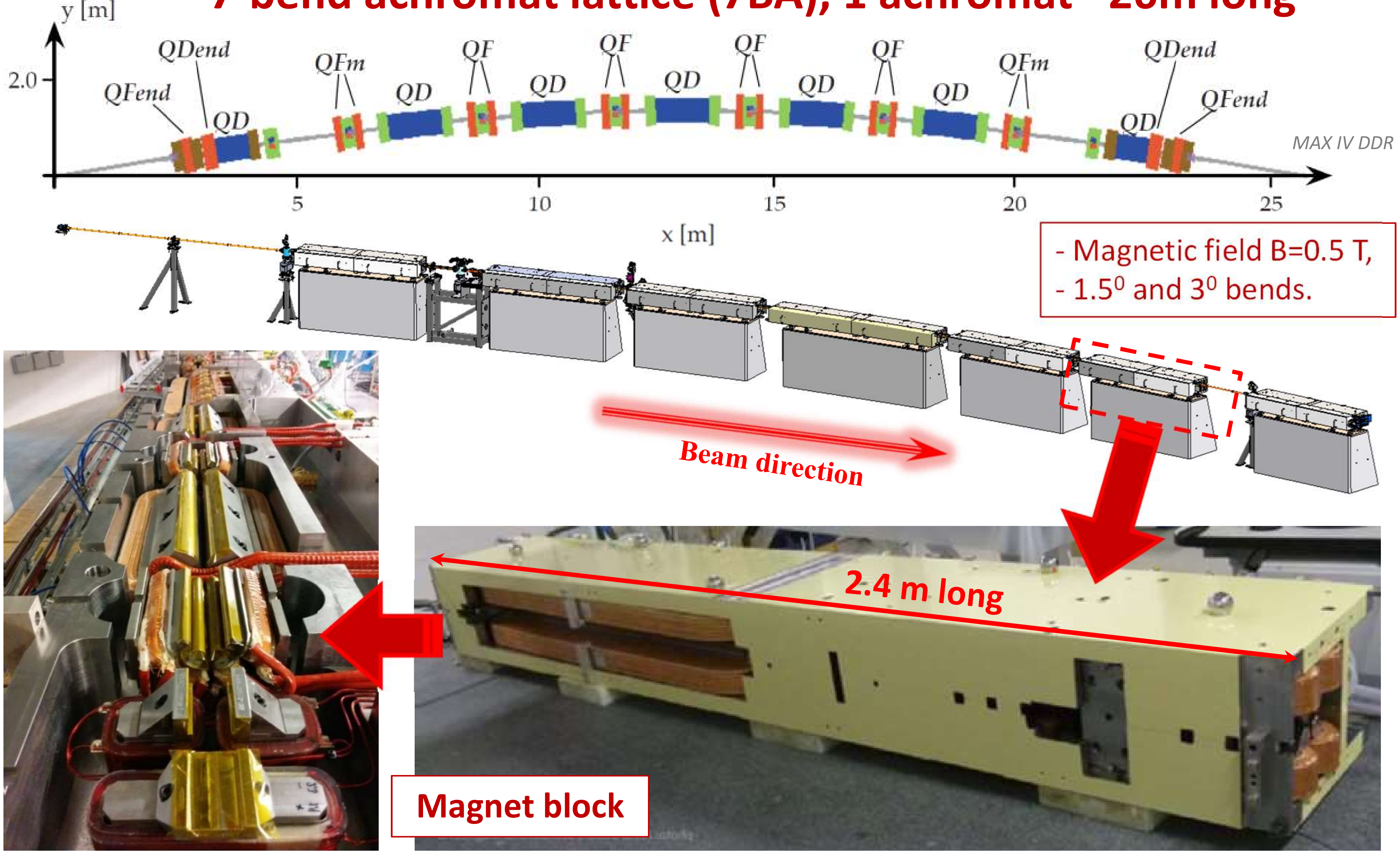
1 In vacuum Wiggler (2.4 m long)
- BALDER IVW50

Legend:
- **Dk: Dipole kicker (S1)**
- **MIK: Multipole Injection Kicker (L)**
- **LK: Longitudinal kicker (S2)**
- **VP: Vertical pinger (S2)**
- **RS: RF cavity spare position (S2)**

L=long straight, S=short straight,

3 GeV magnet lattice

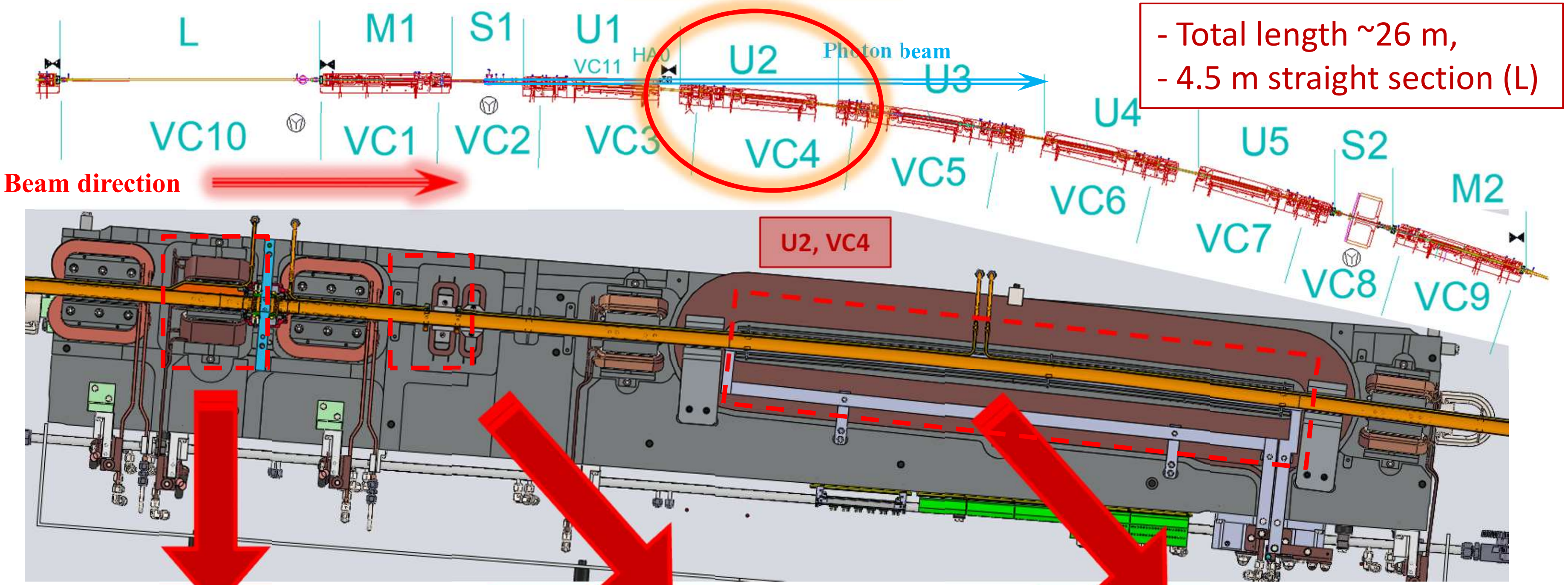
7-bend achromat lattice (7BA), 1 achromat ~26m long



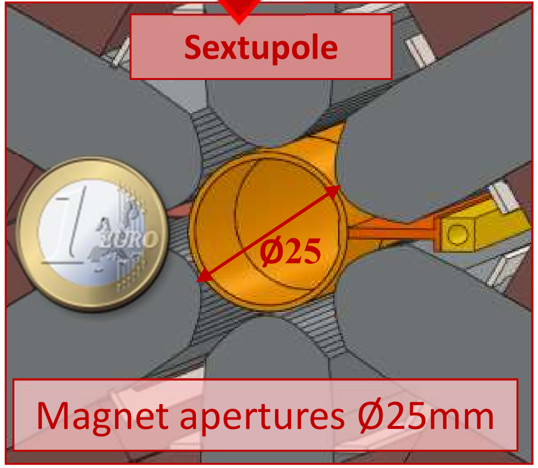
MAX IV DDR

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

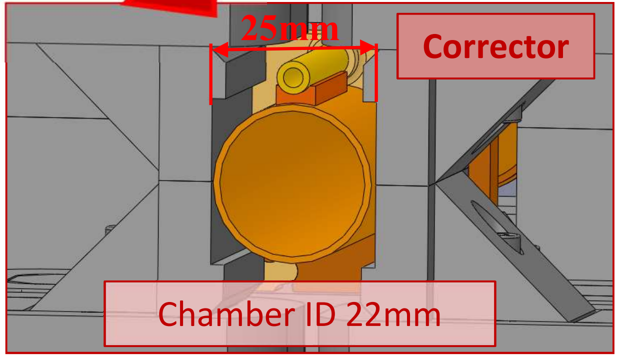
3 GeV magnet and vacuum layout



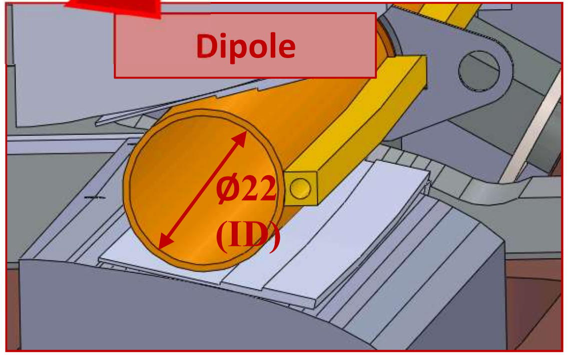
- Total length ~26 m,
- 4.5 m straight section (L)



Magnet apertures Ø25mm

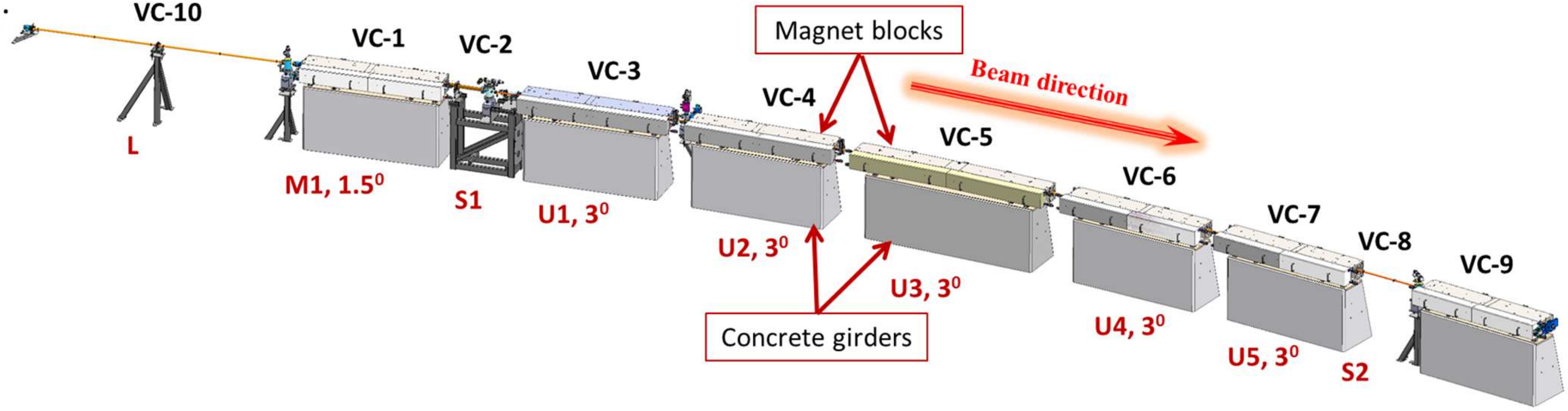


Chamber ID 22mm

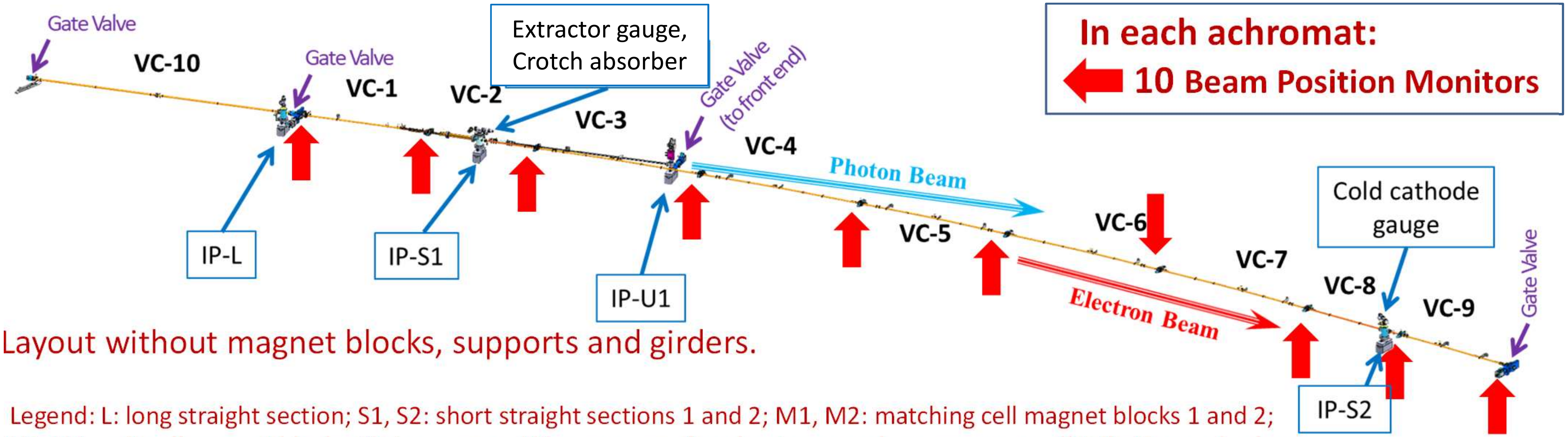


Min. clearance with the iron 0.5 mm, min. clearance with the coils 2 mm.

Vacuum achromat layout



Layout with magnet blocks, supports and concrete girders (26.4 m long)



In each achromat:

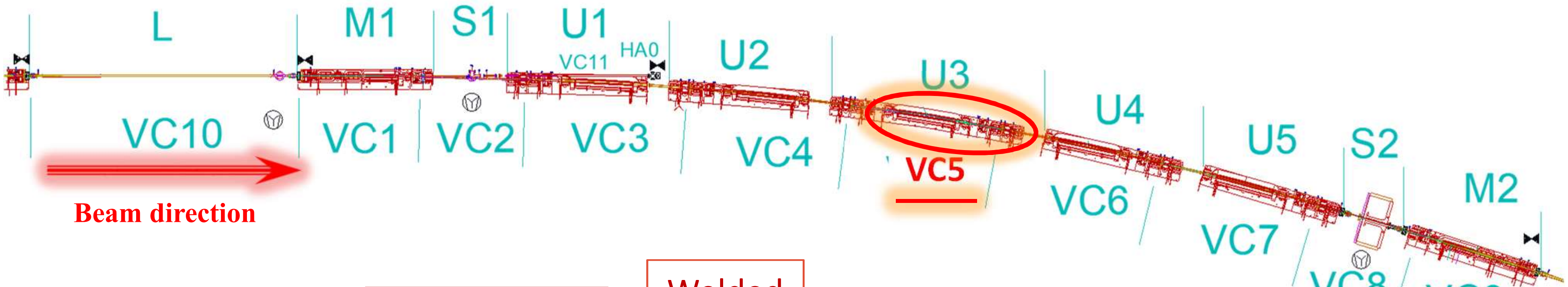
10 Beam Position Monitors

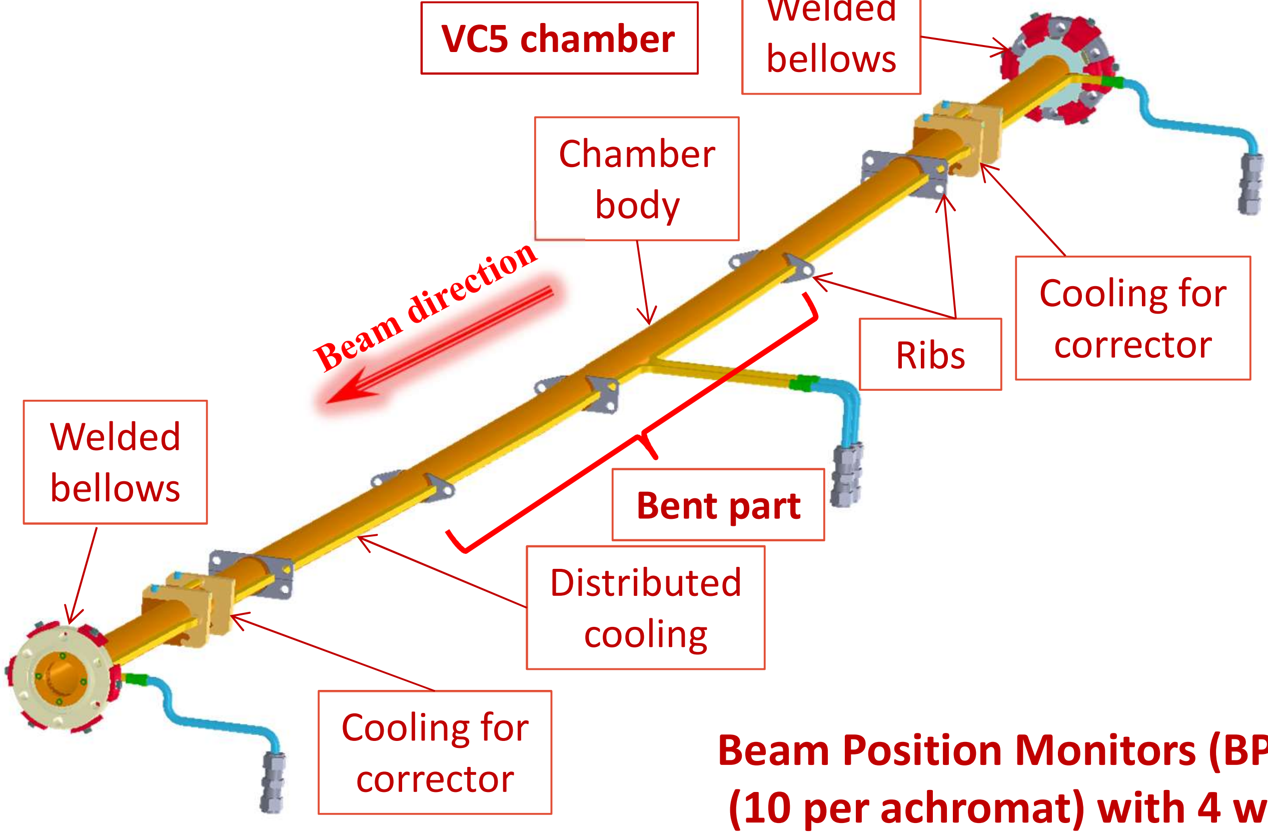
Layout without magnet blocks, supports and girders.

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




VC5 chamber

Welded bellows

Chamber body

Beam direction

Ribs

Cooling for corrector

Bent part

Distributed cooling

Welded bellows

Cooling for corrector

Material: OFS copper

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

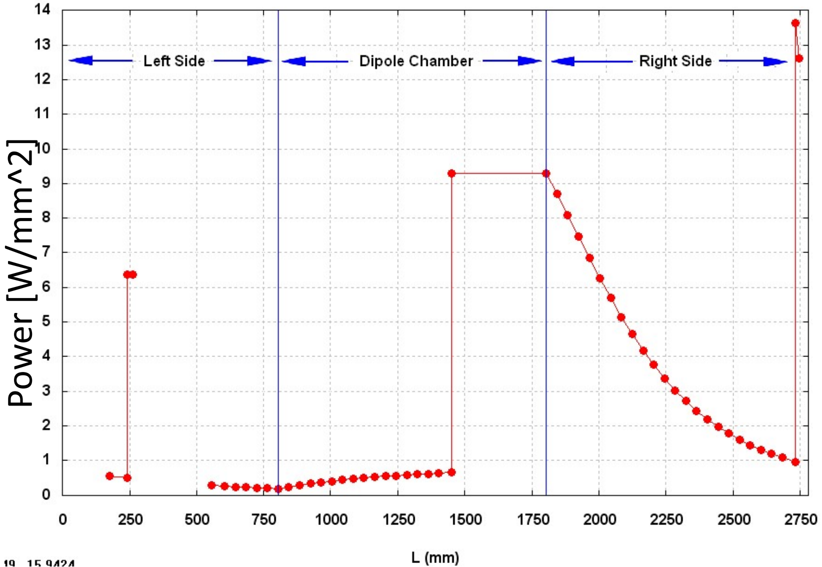
Arc length: 1 m,
Bending angle: 3^0,
Bending radius: 19 m.

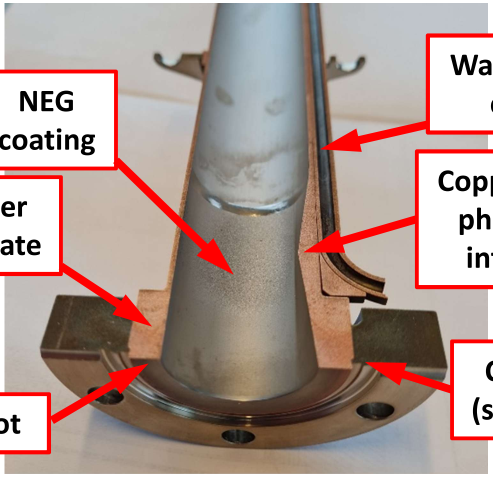
NEG-coated inside.

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

General vacuum chamber geometry

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





NEG coating

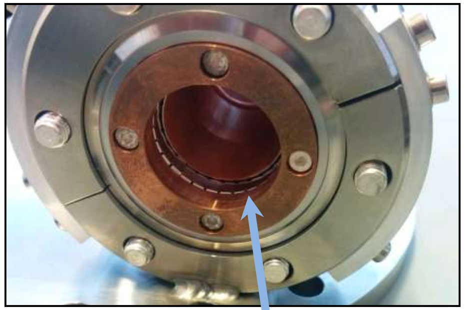
Copper substrate

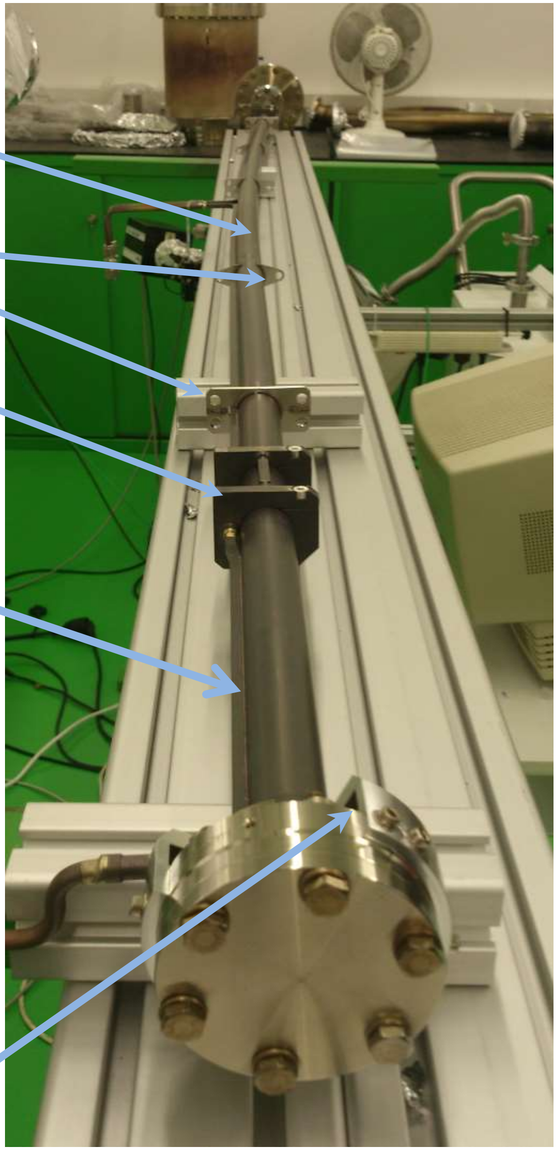
Spigot

Water cooling channel

Copper taper for photon beam interception

CF knife edge (stainless steel)





Chamber body

Ribs

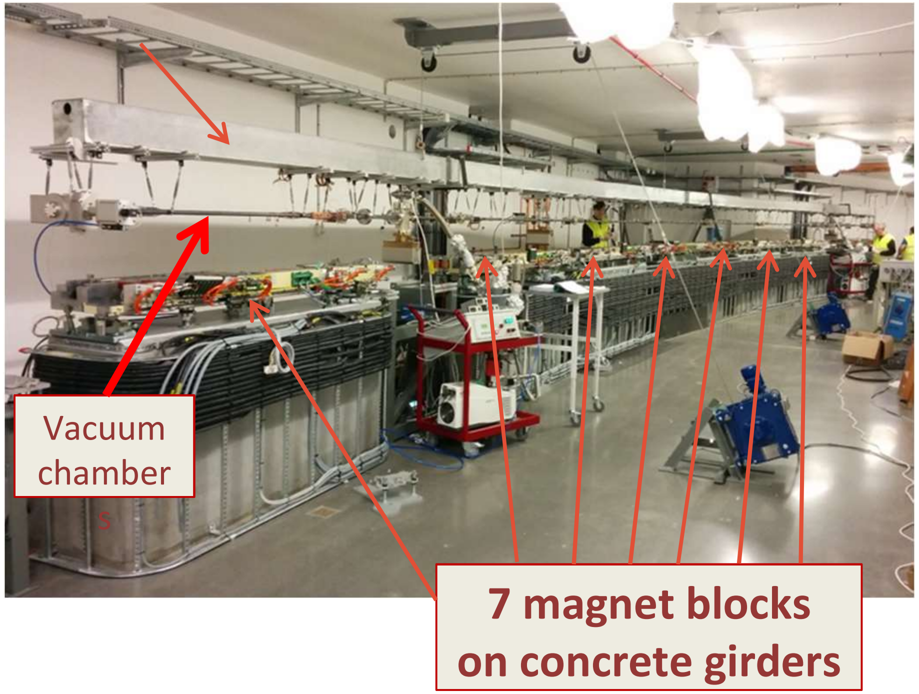
Cooling for corrector area

Distributed cooling

Welded bellows with RF shielding

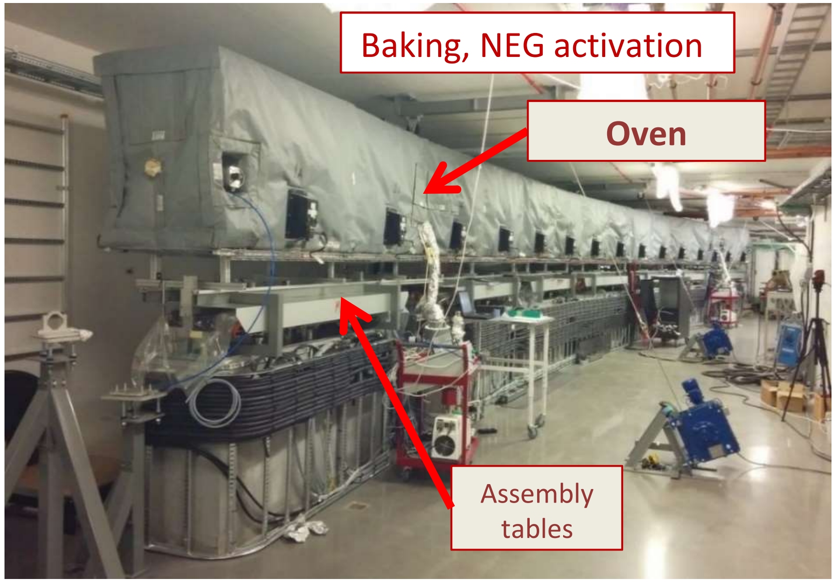
Installation procedure

Ring installation was tested and rehearsed by installing and activating 1 mockup achromat inside a separate hall.



Actual vacuum installation lasted 7 months (November 2014 – June 2015).
Main steps included:

- vacuum chambers were assembled above lower magnet haves,
- Lifted up with a strongback,
- baked and activated at 180 deg C with oven,
- lowered to the lower magnet halves,
- Magnets were closed,
- Straight sections between achromats were installed and baked in-situ,

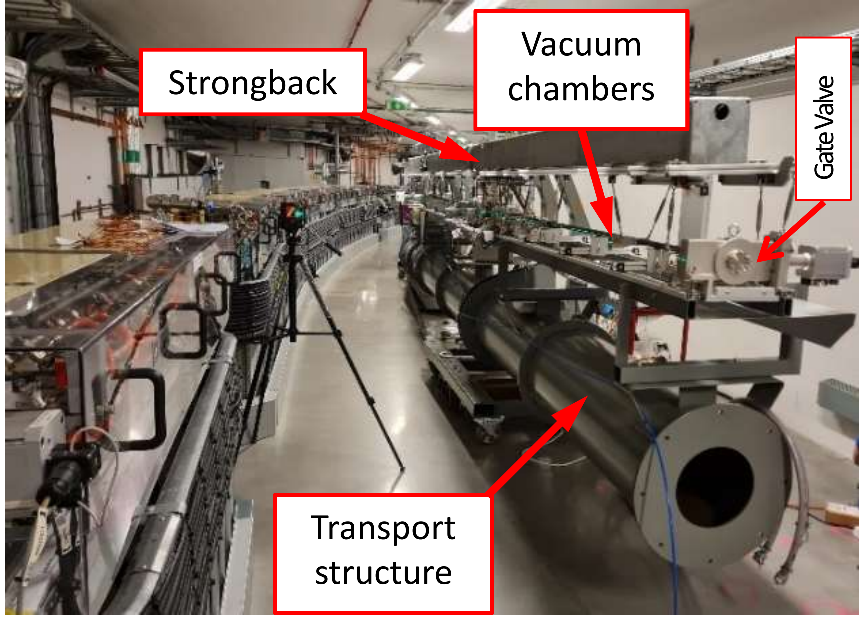


Spare vacuum achromat

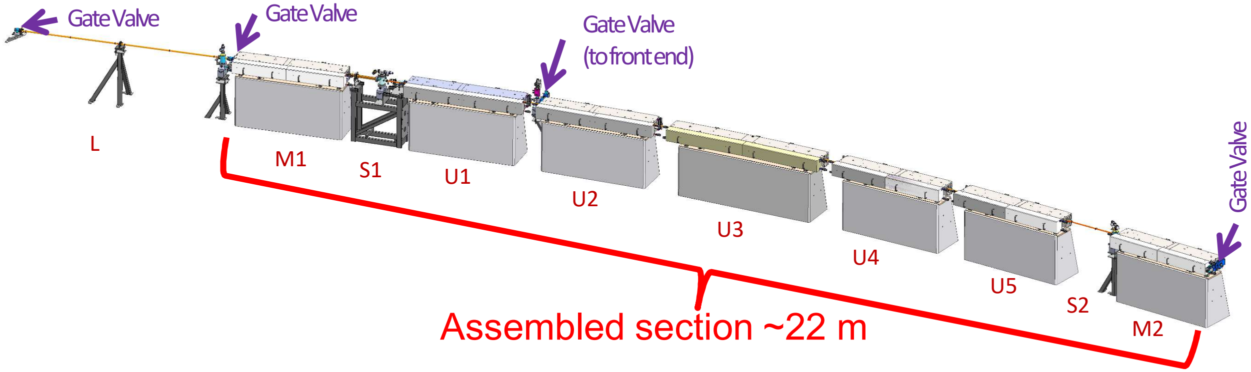
If one vacuum achromat is damaged beyond repair a spare vacuum achromat will be used as a replacement. This will reduce the downtime of the accelerator compared to the standard installation duration of an achromat.

- One standard vacuum achromat was prepared (in 2021) inside the 3 GeV storage ring tunnel and is kept as a **spare unit**, under vacuum, with the **NEG coating activated**.
- It was prepared on a **movable transport structure** which can be rolled inside the accelerator tunnel to a specific achromat that may need to be exchanged.

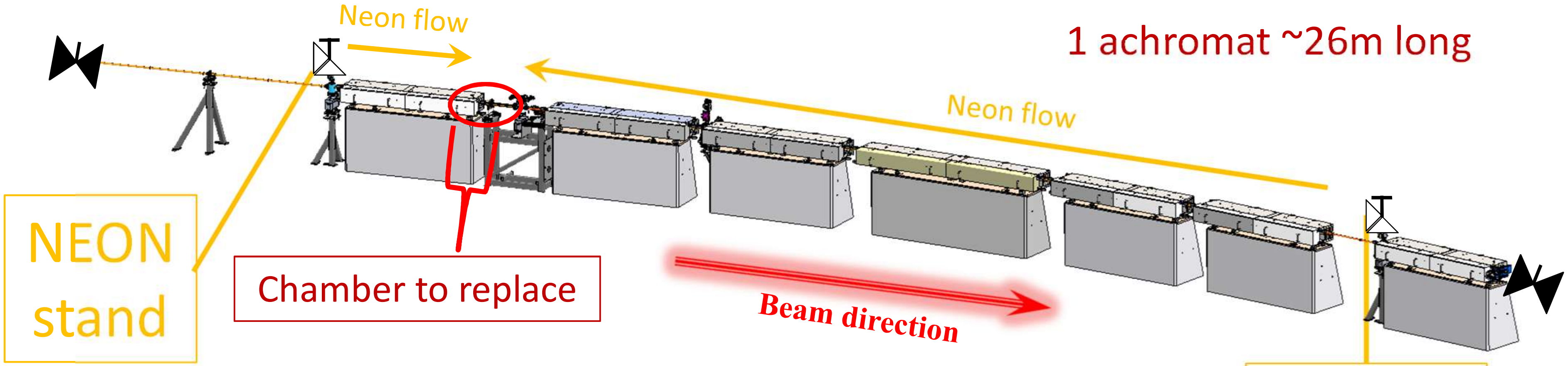
Spare achromat on the transport structure:



One achromat (~26,4 m long):



Neon venting for interventions



Neon flow

1 achromat ~26m long

Neon flow

NEON stand

Chamber to replace

Beam direction

NEON stand

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 NEG film.

Procedure using Neon gas for venting at MAX IV:

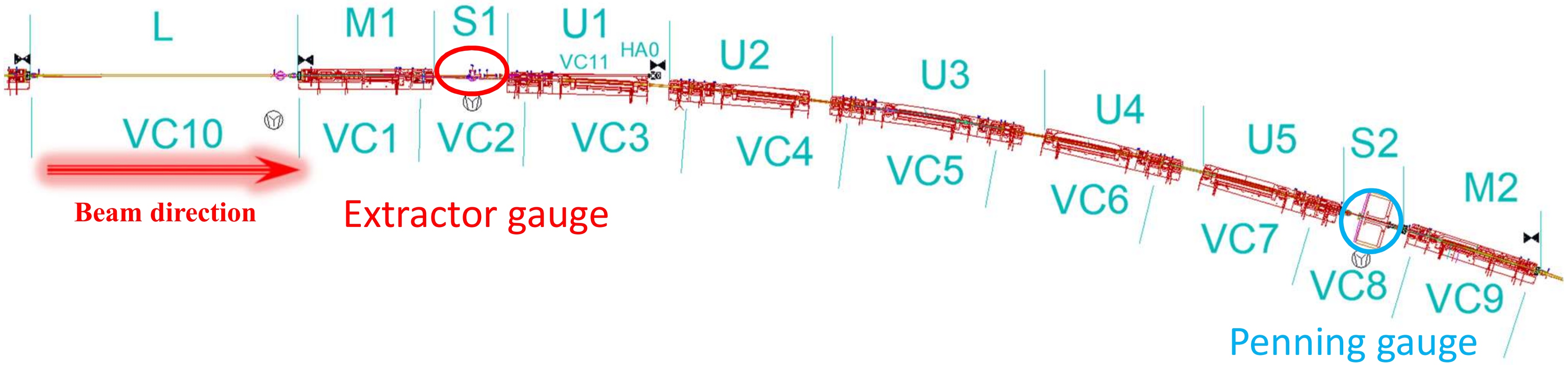
- gate valves at extremities are closed,
- section is vented with purified Neon to above atmospheric pressure,
- the component is replaced, neon flow is preserved (so that the air do not enter the system),
- after new components are installed the system is pumped down with turbo molecular pumps and then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

Such intervention takes 1 day followed by **4 days of pumping with turbo and ion pumps.**

Standard procedure without venting with neon includes NEG activation (by heating) and needs **2-4 weeks**.
Neon venting was done in 2018 in 2 achromats, and in 2020 in one achromat to add 2 new gate valves – it did not limit the operation.

Vacuum Performance of the MAX IV 3 GeV storage ring

Vacuum performance



Beam direction

Extractor gauge

Penning gauge

- Average base pressure (April 2024):

  ~1.5e-10 mbar (extractor gauges)

- Accumulated beam dose:

  9300 Ah (April 2024)

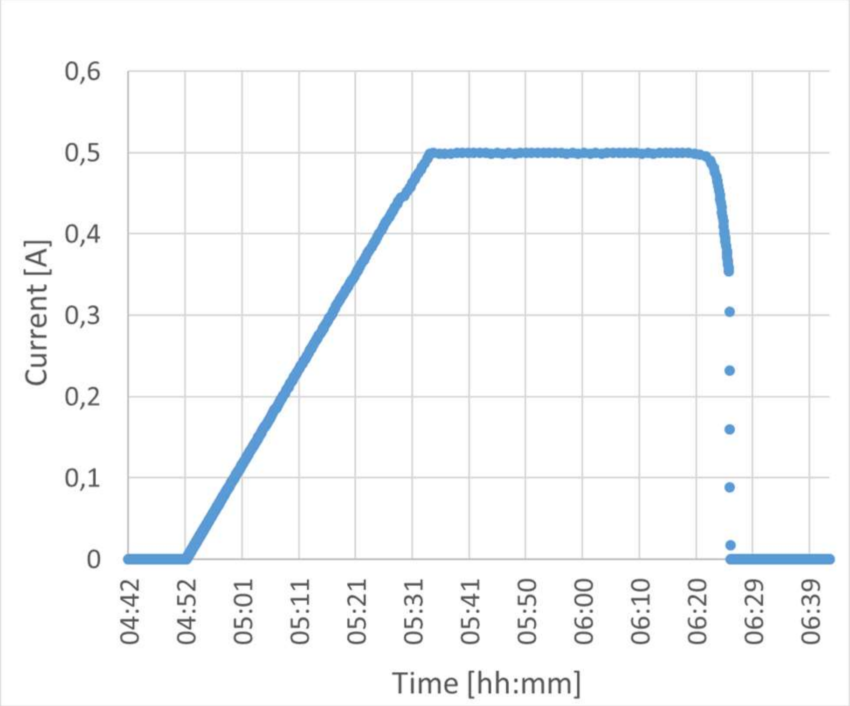
- Max. stored current:

  500 mA (November 2018)

  total lifetime was 14 h,

- Beam current for delivery to beamlines:

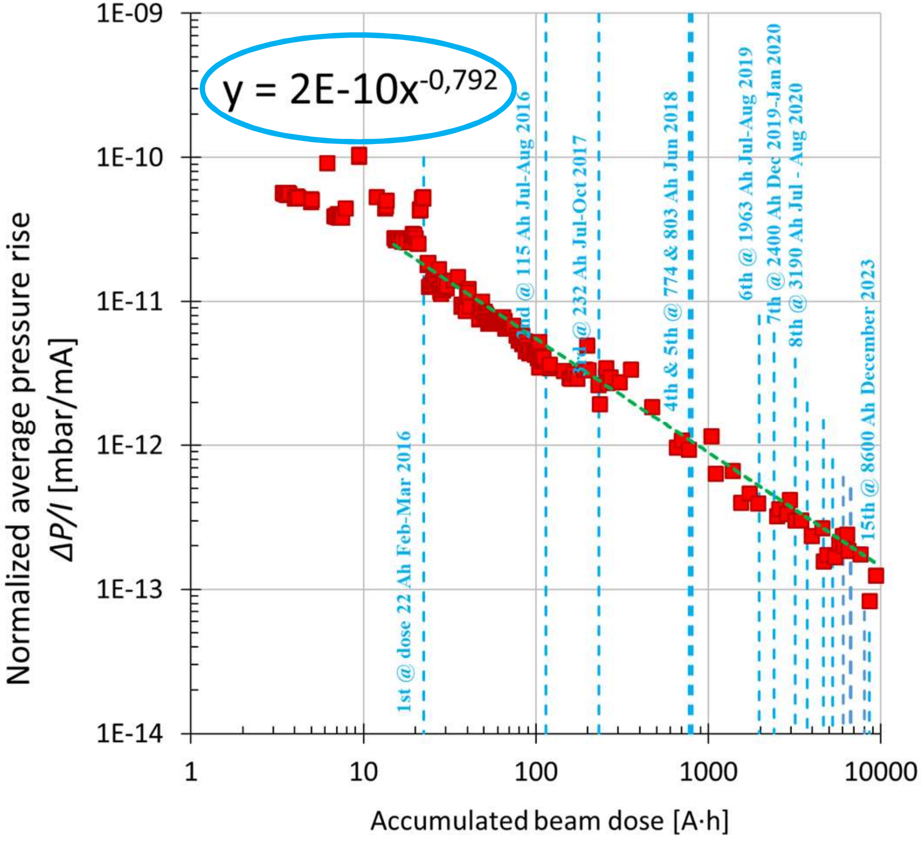
  400 mA, (total beam lifetime ~15 h)



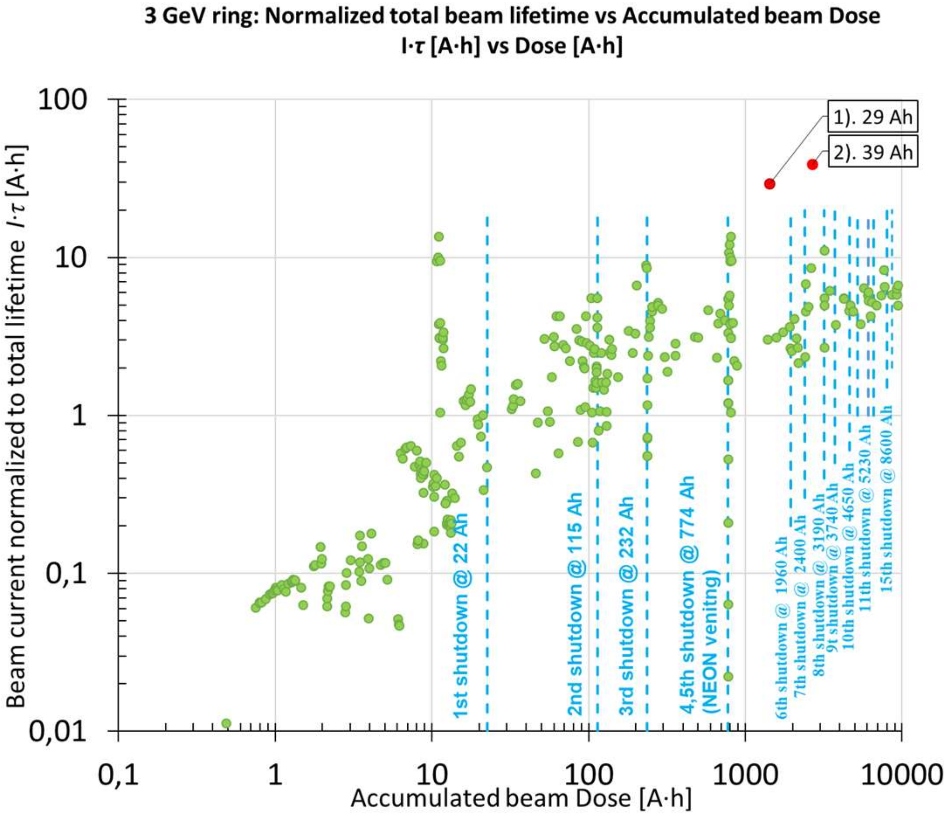
Vacuum performance: pressure

October 2015 – April 2024 (**9300 Ah** accumulated beam dose), 14 shutdowns.

Normalized average pressure rise (mbar/mA) versus the accumulated beam dose (A h):



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


3 GeV ring: Normalized total beam lifetime vs Accumulated beam Dose
I·τ [A·h] vs Dose [A·h]

Operational status

Year	Planned delivery [h]	total downtime [h]	uptime [%]	MTBF (Mean Time Between Failure) [h]	Vacuum related downtime [h]	Vacuum related downtime contribution to total downtime [%]
2019	4573	124.50	97.28	39.72	1.5	1.2
2020	4872	126.83	97.40	38.89	3.45	2.7
2021	3744*	116.90	96.88	78.85	0.55	0.5
2022	4464	80.77	98.19	72.00	0	0
2023	4776	91.58	98.08	75.81	3.68	4

*reduced due to COVID

Machine protection system logic of Front Ends and Beamlines improved

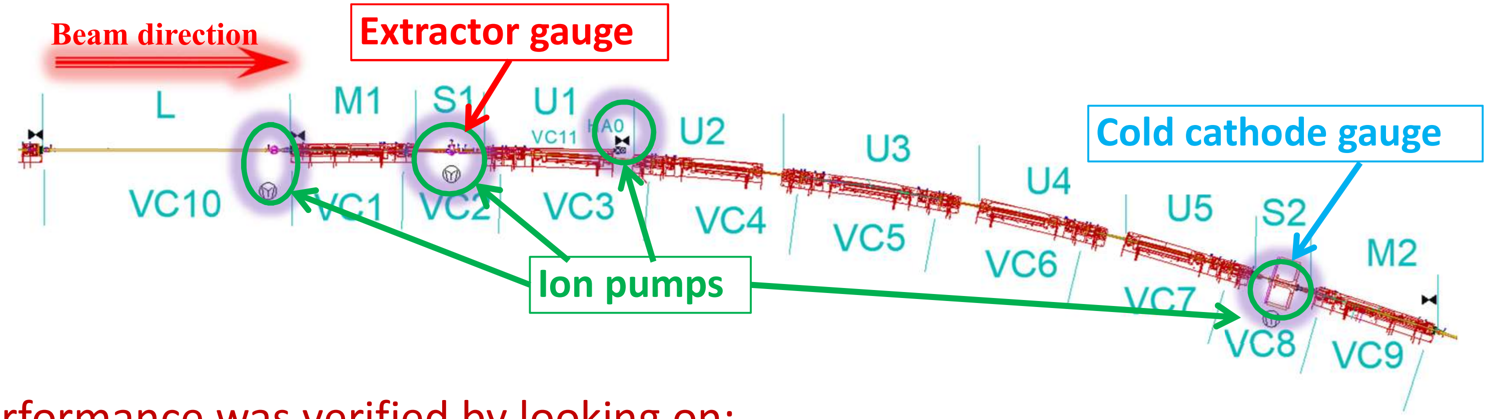
- **2019**: 2 events related to short lived vacuum spikes from penning gauges/ion pumps.
- **2020**: 6 vacuum related events caused beam dump. 4 events related to short lived vacuum spikes from penning gauges/ion pumps, 2 events related to faulty ion pump controllers.
- **2021**: glitch in ion pump controller.
- **2022**: no vacuum related beam dumps, 1 beam trip due to faulty thermocouple reading.
- **2023**: 4 short lived vacuum spikes from penning gauges/ion pumps.

Usually it takes 20 minutes to recover from a simple vacuum related beam dump. In case of complications can be up to 100-1000 min, which still is counted as vacuum beam downtime.

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>63 (out of 97) on pumps were switched OFF along the electron beam path.</u>

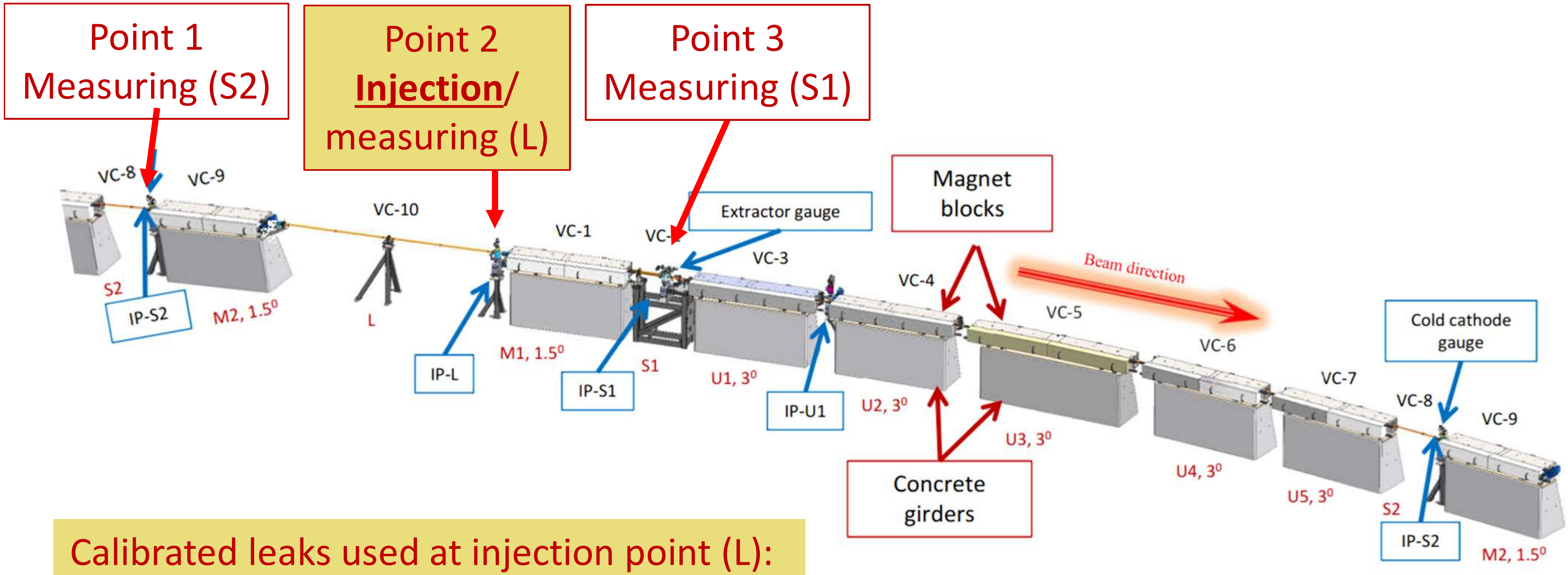


Performance was verified by looking on:

- Effect on the beam lifetime: negligible effect,
- Effect on the beam size: no significant change observed,
- Pressure: pressure measured in S1 by extractor gauges increased by factor of 3.4,
- Radiation increase: no increase outside in the experimental hall,
- Gas spectra (measured by Residual Gas Analyzers): most changes in uncoated areas of copper crotch absorber.

NEG coating studies

To evaluate the NEG coating properties injection and measurement systems were installed in an achromat.



Point 1
Measuring (S2)

Point 2
Injection/
measuring (L)

Point 3
Measuring (S1)

Calibrated leaks used at injection point (L):

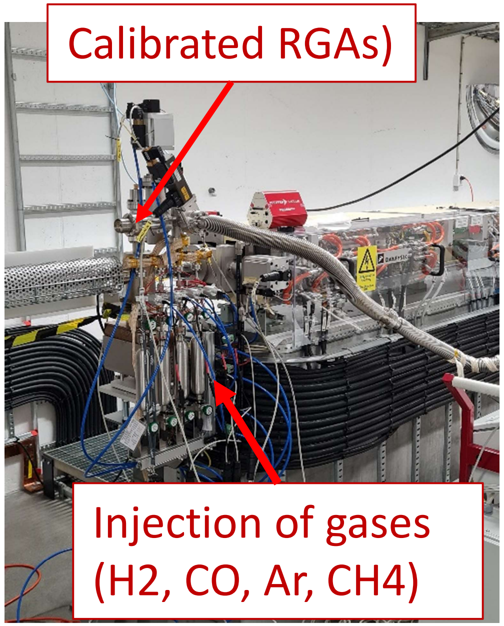
Gas	Leak rate [mbar*l/s]
Hydrogen	1E-06
Carbon monoxide	1E-06
Methane	5E-07
Argon	5E-07

The measurements were done with and without beam and with nearest ion pumps switched OFF.

Measurements done with calibrated Residual Gas Analyzers (RGAs).

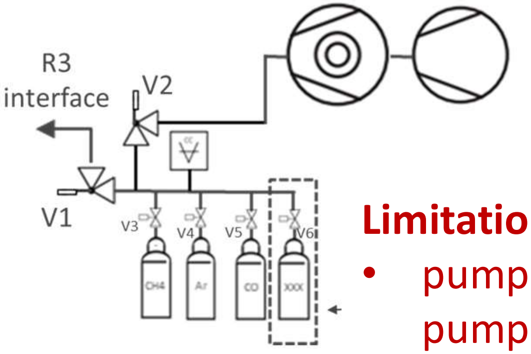
NEG coating studies

Point 2: Injection/measuring

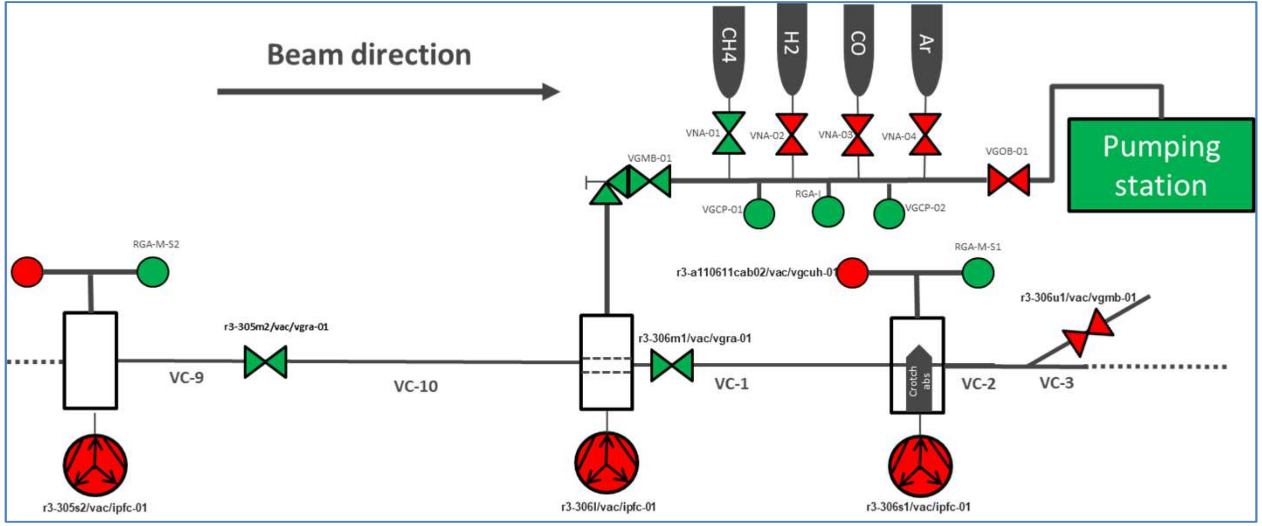


Calibrated RGAs)

Injection of gases (H2, CO, Ar, CH4)



Injection – Only storage ring connected, measurement.



- Step 1: measure beam induced pressure increase for each gas specie (@ 0, 100, 200, 300, 400 mA beam current), **done**
- Step 2: Evaluate the NEG coated vacuum chamber pumping speed in point 2, **ongoing**
- Step 3: Calculate beam induced desorption, **ongoing**

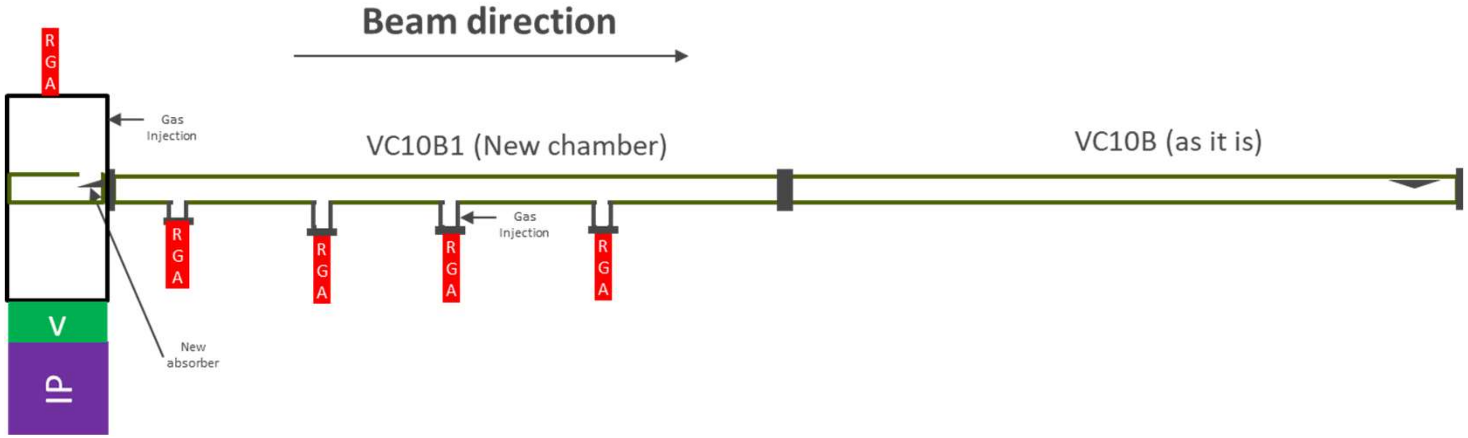
Limitations:

- pumping from ion pumps cannot be excluded even if they are OFF (residual pumping effect),
- injection of gases very close to the measurement point,
- measurement points 1 and 3 to far away to detect injected geterable gases.

NEG coating studies

Possibility of phase 2 - new vacuum chamber in long straight section (under review):

- Might allow to evaluate vacuum chamber starting from zero beam dose (observe Photon Stimulated Desorption yield, and pumping speed evolution),
- a design to improve the quality of the measurement,
- an absorber to collect as much photons as possible (to be assessed),
- a position to increase the photons flux (to be assessed),
- More pressure measuring points for pumping speed measurement along the vacuum pipe.



Future storage ring upgrade

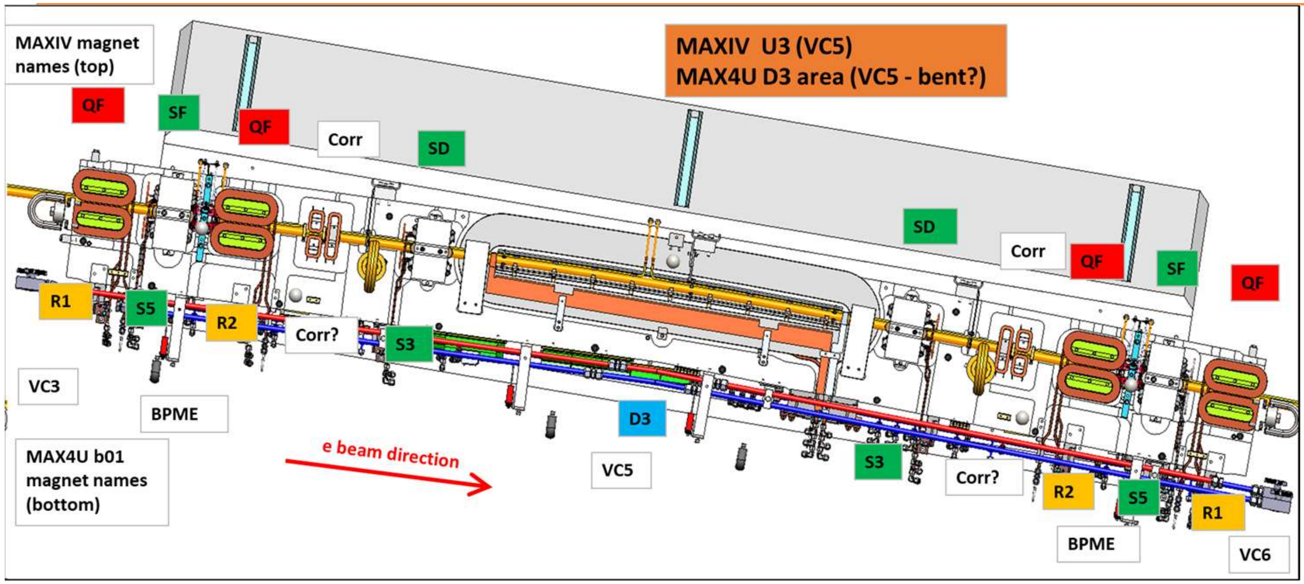
MAX IV upgrade: MAX4U

- Hard boundary conditions:
    - Emittance $\lesssim$ **100 pmrad**.
    - Keep shielding wall/existing light source positions
    - Limited dark period
    - Cost-effective
    - Realizable until the early part of the next decade
- Assumptions
    - Keep the ring periodicity
    - Keep all light source positions
    - Keep the injector: accumulation (no swap-out)
    - Keep the RF system

➢ **MAX 4$^{\underline{U}}$** is ***NOT a conventional upgrade,*** which requires replacement of most components.

➢ **MAX 4$^{\underline{U}}$** is a ***surgical intervention*** that provides an ***outstanding*** performance improvement while maintaining much of the existing hardware.

MAX IV upgrade: MAX4U



Few candidate lattices considered.

CDR to be prepared: December 2025

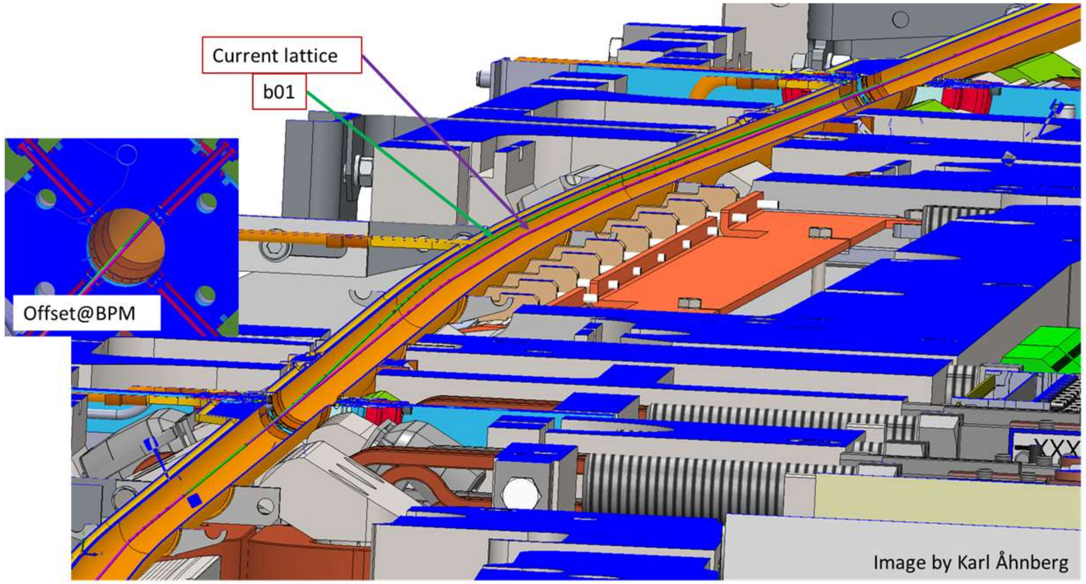


Image by Karl Åhnberg

1st lattice considered (b01):

- Longitudinal locations of magnets unchanged,
- Magnet aperture unchanged,
- Change of magnet transversal location and function limited to one block (U3),
- Max excursion of new beam orbit, comparing with existing ring, is 8 mm,
- Bending of vacuum chambers considered to fit to the new orbit.
- Other lattices to be analysed.

Conclusions

- **MAX IV 3 GeV ring is operating since the end of 2015 without major issues.**
- **The main design parameters (horizontal emittance 0,33 nm rad, total beam lifetime 5 A h, maximum beam current 500 mA) were reached.**
- **There are no operational issues related to the NEG coating (no peel-off, no saturation) that could limit the operation or machine performance in any way.**
- **The vacuum conditioning (measured by pressure reduction) progressed fast since the start of commissioning and is still observable. It is comparable with other new storage ring based light sources: Sirius (LNLS, Brazil) and ESRF-EBS (France).**
- **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.**
- **Vacuum system of MAXIV 3 GeV ring was cost effective: ~12,000 EUR/m (in 2014).**
- **Flexible design of the MAX IV vacuum chambers might allow (without purchasing new chambers) to accommodate new beam orbit of new lattice for the MAX4U upgrade project.**

Thank you for your attention

Thanks to Eshraq Al-Dmour, Åke Andersson, Pedro F. Tavares
and MAX IV Vacuum Team.

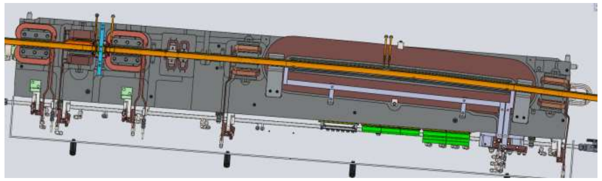
Back up

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.

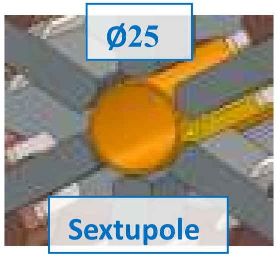
No space for lumped pumps

photo: Anna Olsson, Scanditronix Magnet AB

- **Small aperture of the magnets**

  Magnets' aperture Ø25 mm.

Low conductance of vacuum tubes



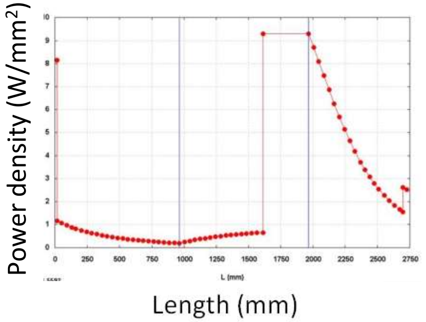
- **Low target dynamic pressure**

  Average pressure 1e-9 mbar.

Need of pumping and low PSD

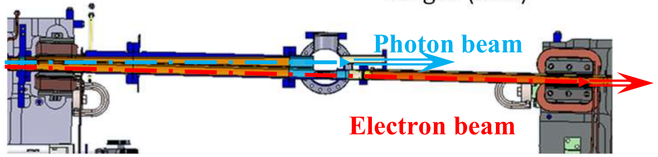
- **Removal of the SR power (BM & ID)**

  Power density along bent vacuum chamber walls and absorbers.



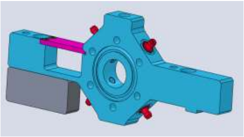
- **Extraction of synchrotron radiation**

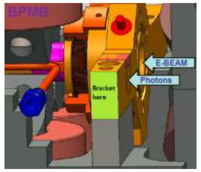
  Limited by small bending angle.



- **Stable positioning of BPM**

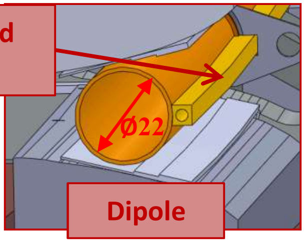
  Disentangling the BPMs from the chambers.





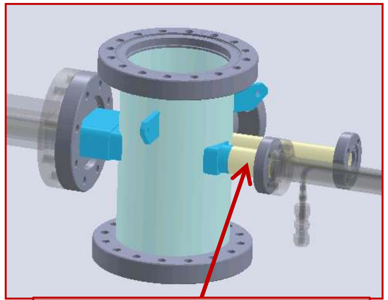
Vacuum system design approach

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

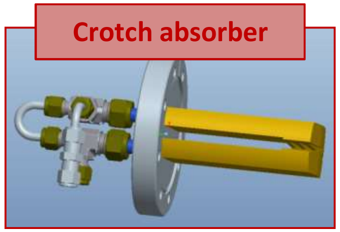


- **Substrate: Silver bearing (OFS) Copper** vacuum chambers (resistance to thermal cycling).

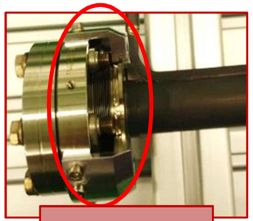
- **Distributed water cooling** to cope with SR.
- Areas made of **stainless steel** for fast corrector coils.



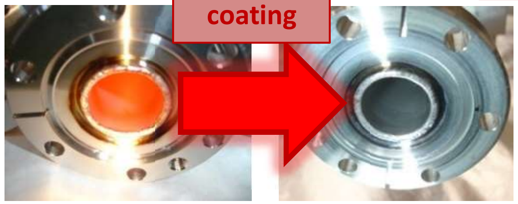
- One **Lumped absorber** per achromat needed to extract the photon beam to the front ends.



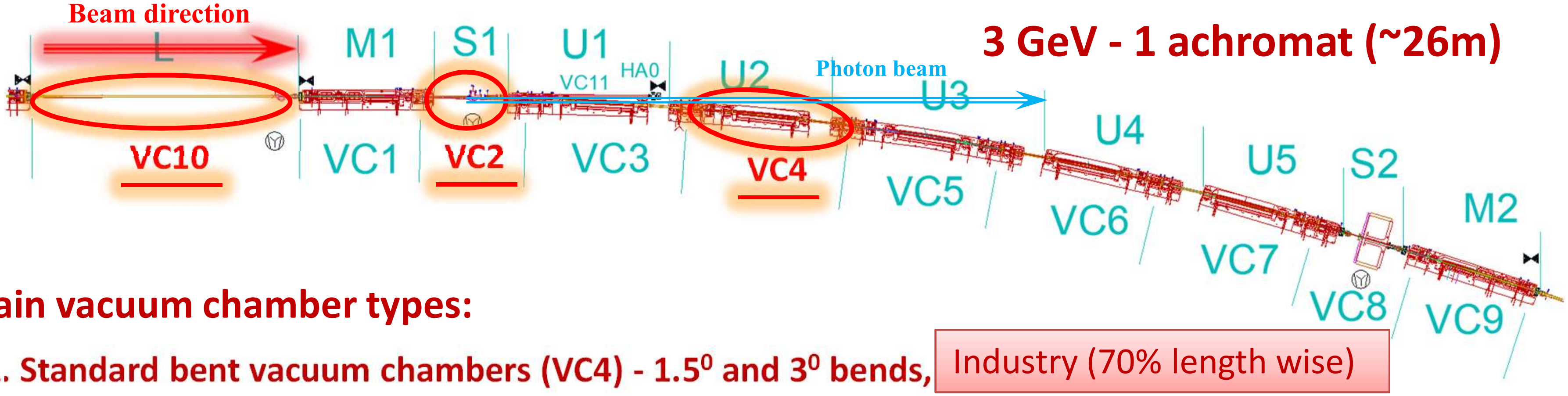
- **Welded bellows** at vacuum chamber extremities to allow expansion without affecting the BPM position and temperature.



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



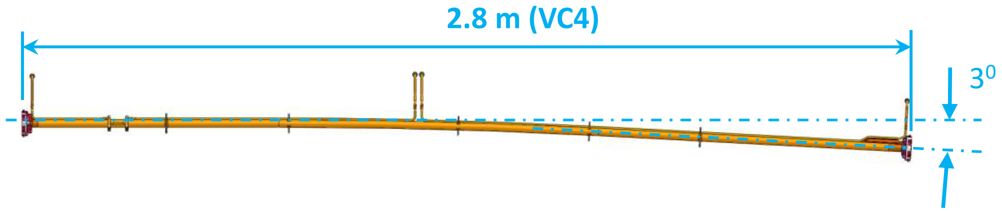
NEG coating series production

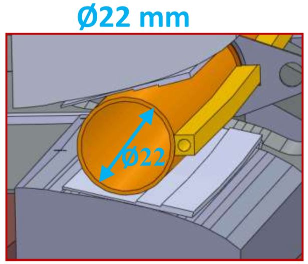


3 GeV - 1 achromat (~26m)

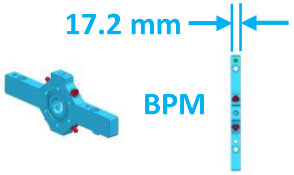
Main vacuum chamber types:

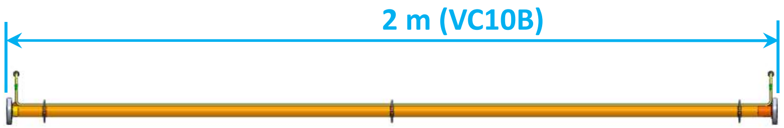
1. **Standard bent vacuum chambers (VC4) - 1.5^0 and 3^0 bends,** Industry (70% length wise)





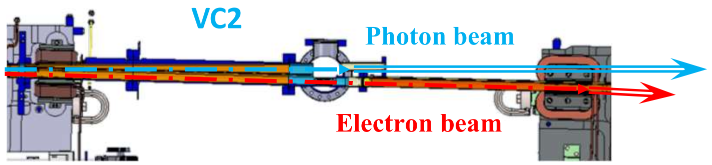
2. **Straight vacuum (VC10) chambers,** Collaboration with ESRF (15%)

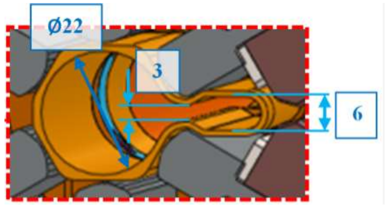




3. **Special vacuum chambers.**

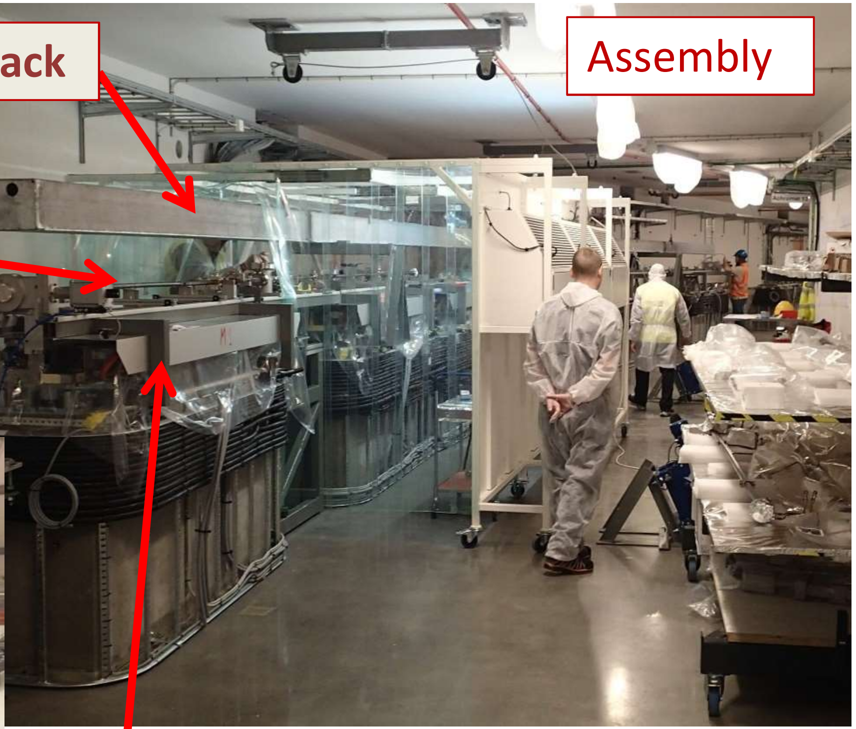
Collaboration with CERN (15%)





Installation procedure

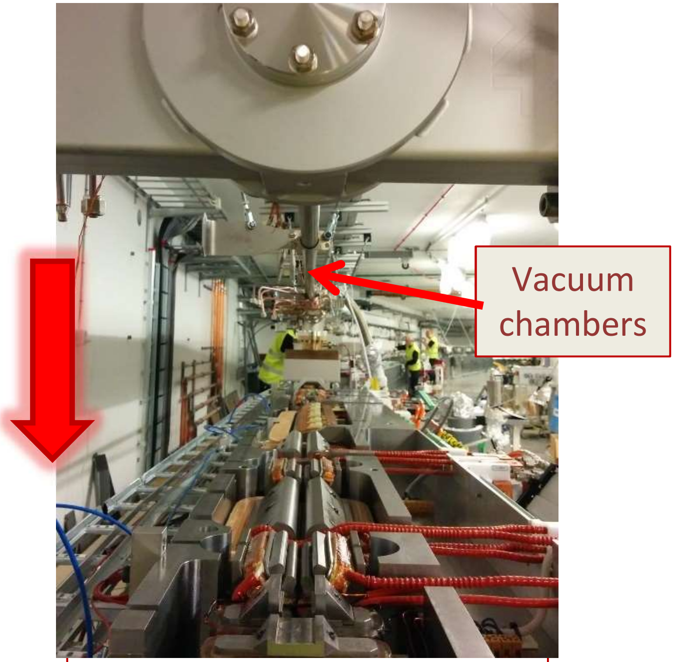
- Magnet top halves removed,
- Vacuum chambers assembled insitu (above bottom magnet halves),
- Pumpdown and testing,
- Lifting vacuum chambers with strongback
- Baking (1 day), activation (1 day),



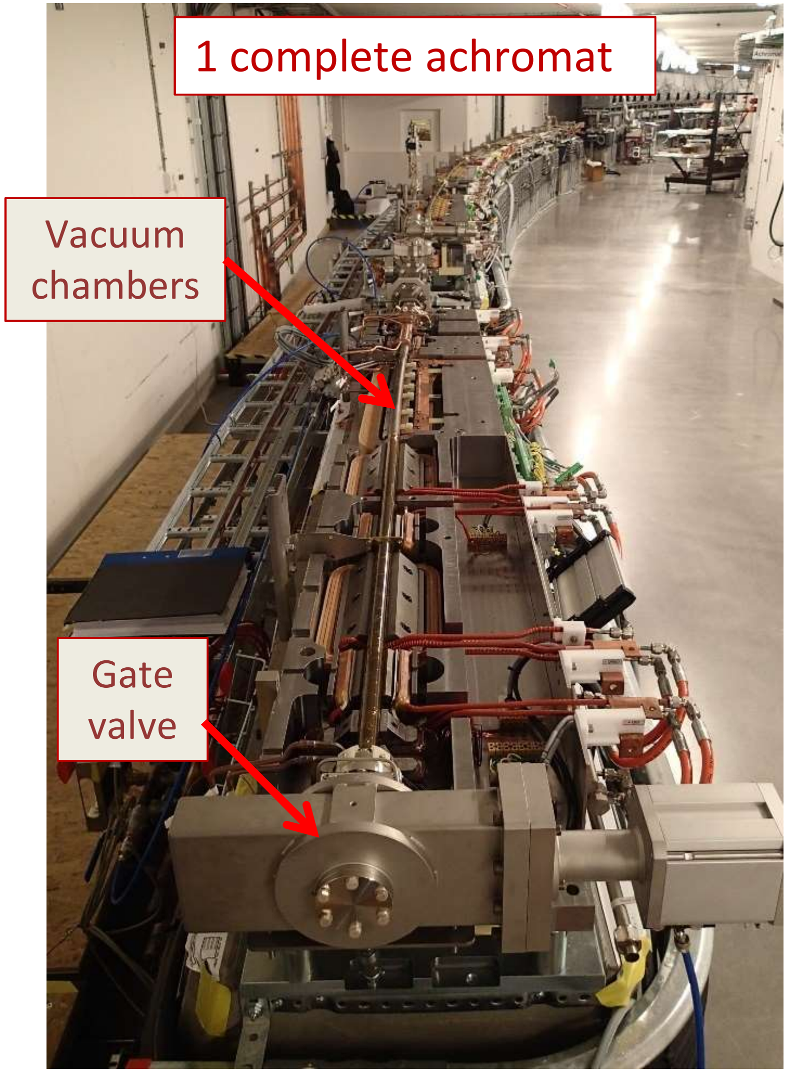
Installation procedure

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

- closing magnet blocks.
- Straight sections between achromats were installed and baked in-situ



Lowering vacuum assembly



NEG coating of vacuum chambers

All the vacuum chambers were NEG (Non-Evaporable Getter) coated with:

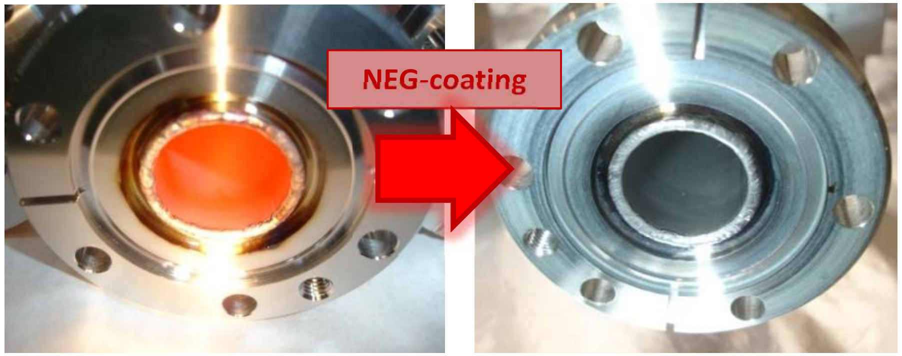
- Thin film (0.5-2 µm) of Ti-Zr-V (30%, 30%, 40% respectively) alloy deposited by magnetron sputtering.

NEG film, after activation (heating up to 180^0C under vacuum), activates and pumps active gasses (do not pump noble gasses nor methane CH_4), and has lower PSD (Photon Stimulated Desorption).

The prototyping and validation of the NEG coating on standard and most complicated geometrically chambers was done in collaboration with CERN.

The extruded copper tubes prior to the coating were cleaned and surface treated (etched, passivated), then NEG coated.

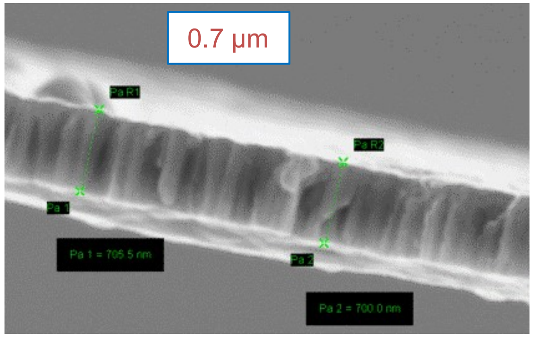
'NEG thin film coatings: from the origin to the next-generation synchrotron-light sources', *Paolo Chiggiato, CERN (presented at OLAV'14)*



Chamber before coating

Chamber after coating and thermal cycling

SEM coating thickness measurements:



Coating non-conformities

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

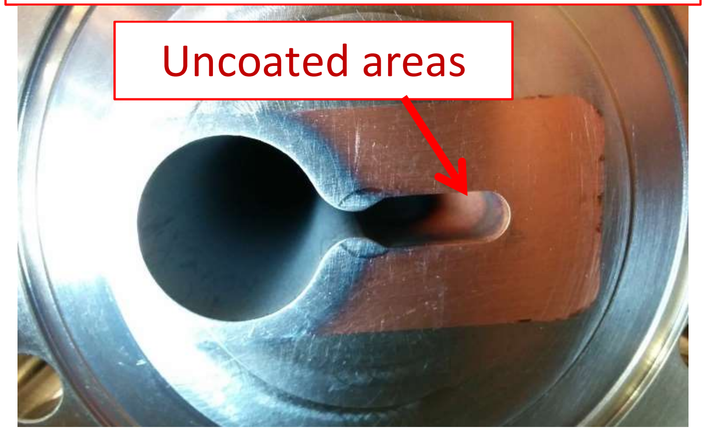

Peeling-off at RF fingers and Cu endpiece

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


Peeling-off


Severe peeling-off

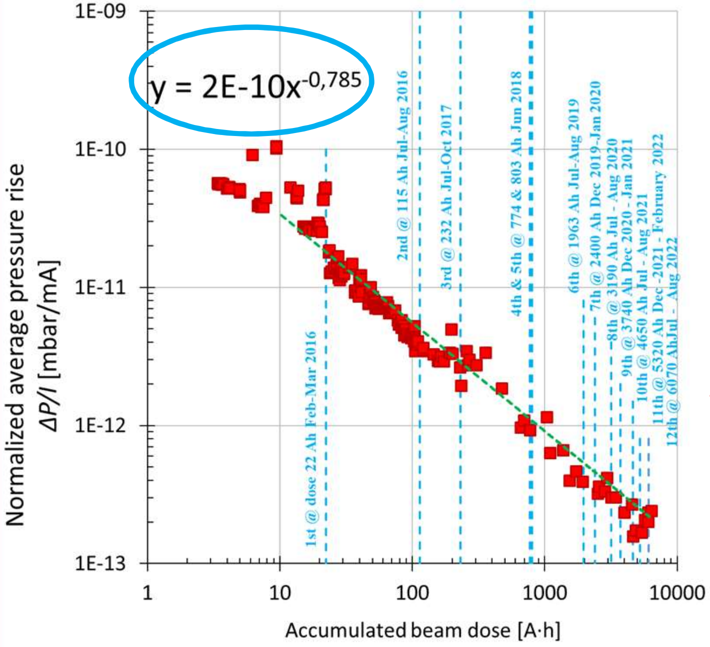
Uncoated areas:
Few cm^2 uncoated, in complex chambers.


Uncoated areas

Vacuum performance: pressure

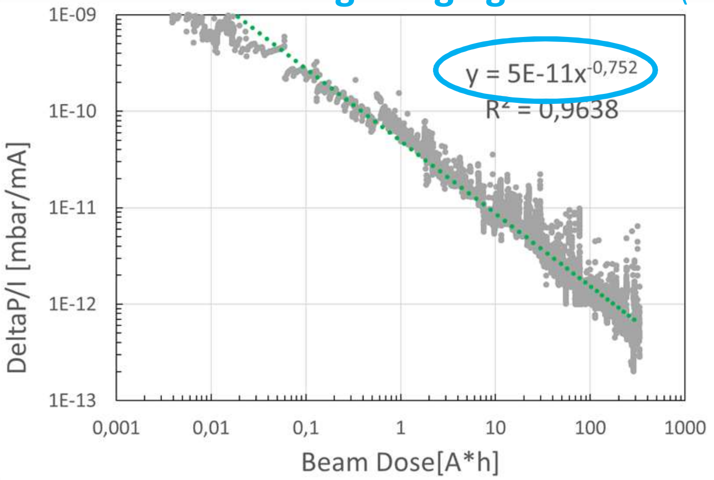
Normalized average pressure rise (mbar/mA) versus the accumulated beam dose (A h):

MAXIV 3 GeV storage ring



October 2015 – Oct 2022

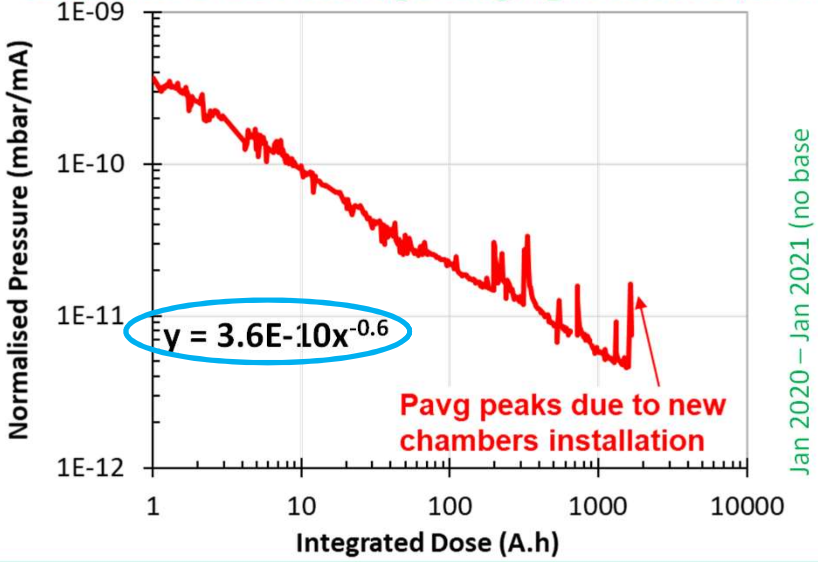
Sirius 3 GeV storage ring light source (LNLS, Campinas, Brazil) *



Jan 2020 - Dec 2021

*courtesy of Rafael Molena Seraphim (LNLS, Campinas, Sirius)

ESRF EBS 6 GeV storage ring light source (Grenoble, France) *



Pavg peaks due to new chambers installation

Jan 2020 – Jan 2021 (no base pressure subtracted)

*courtesy of Cristian Maccarrone (ESRF, Grenoble, France)

The absolute values of the slopes of the conditioning curves:

0.78 for MAXIV,

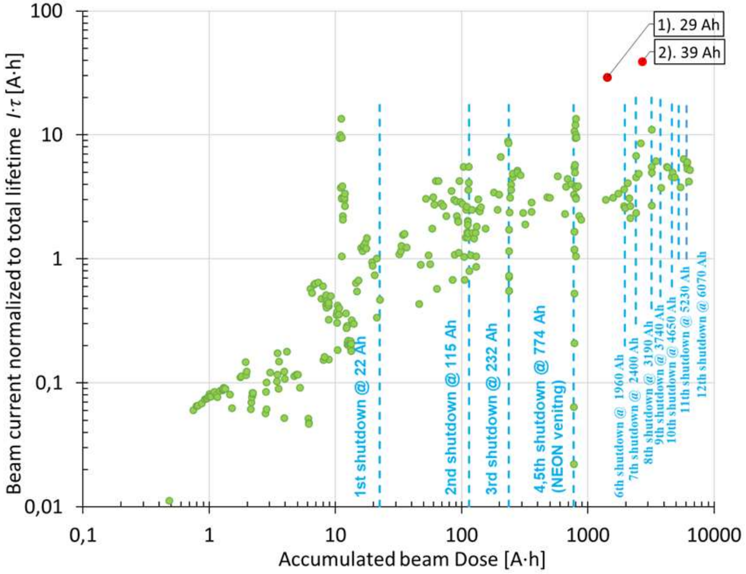
0.75 for Sirius,

0.6 for ESRF-EBS.

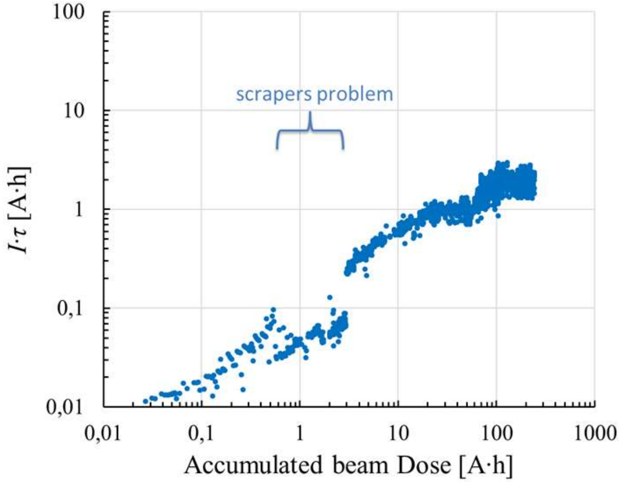
Vacuum performance: total beam lifetime

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

MAXIV 3 GeV storage ring



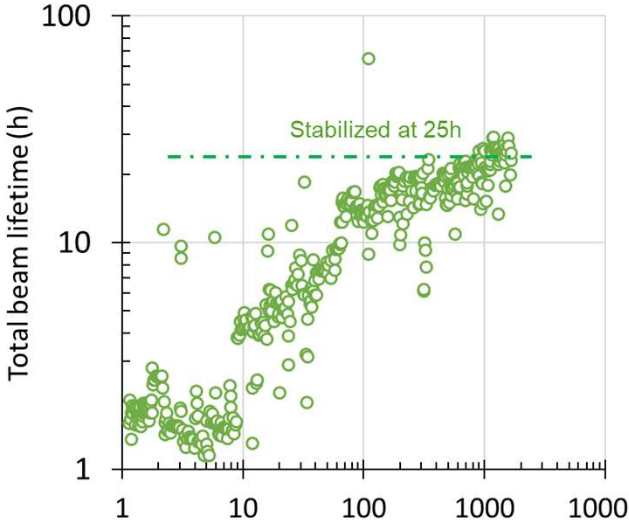
Sirius 3 GeV storage ring light source (Campinas, Brazil) *



Jan 2020 - Dec 2021

*courtesy of Rafael Molena Seraphim (LNLS, Campinas, Sirius)

ESRF EBS 6 GeV storage ring light source (Grenoble, France)*



Jan 2020 – Jan 2021
Beam current 200 mA i.e.: for total lifetime of 25 h, normalized beam lifetime is 5 Ah (as per January 2021)

*courtesy of Cristian Maccarrone (ESRF, Grenoble, France)

At higher doses the lifetime for MAXIV and ESRF-EBS is ~5 Ah.

Vacuum performance: vacuum beam lifetime

Measurement of Vacuum related beam lifetime.

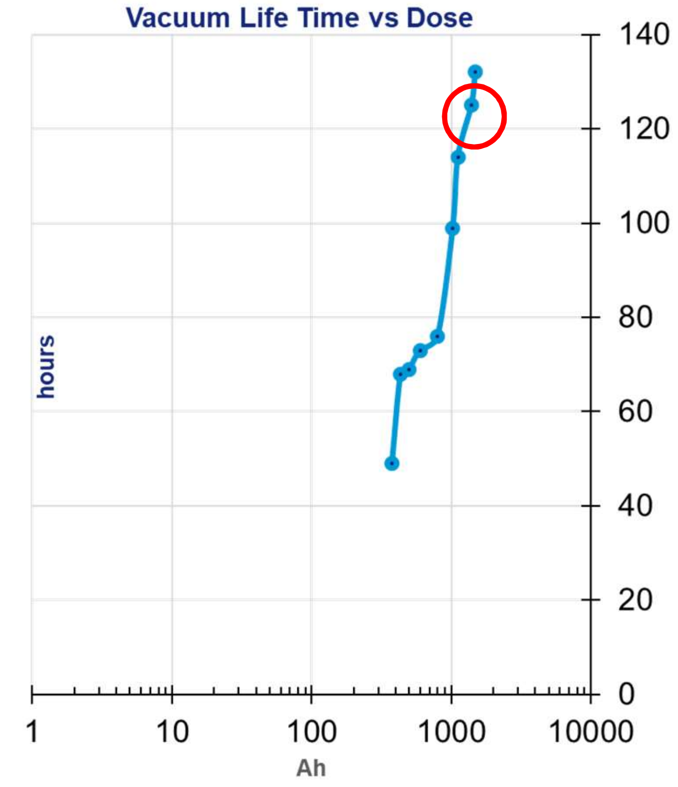
MAXIV 3 GeV storage ring

At MAXIV measurements of vacuum lifetime at 2 beam doses were taken with beam current of 350 mA. The lifetime listed below can be considered as the lower limit for the vacuum-related beam lifetime.

Accumulated beam dose	Normalized vacuum beam lifetime	Lower limit for vacuum related beam lifetime
[A h]	[A h]	[h]
1430	29,2	83,3
2690	38,8	111,1

At accumulated beam dose of ~1400 Ah vacuum beam lifetime for MAXIV was **83,3 h** and for ESRF-EBS **125 h**.

ESRF EBS 6 GeV storage ring light source (Grenoble, France)*



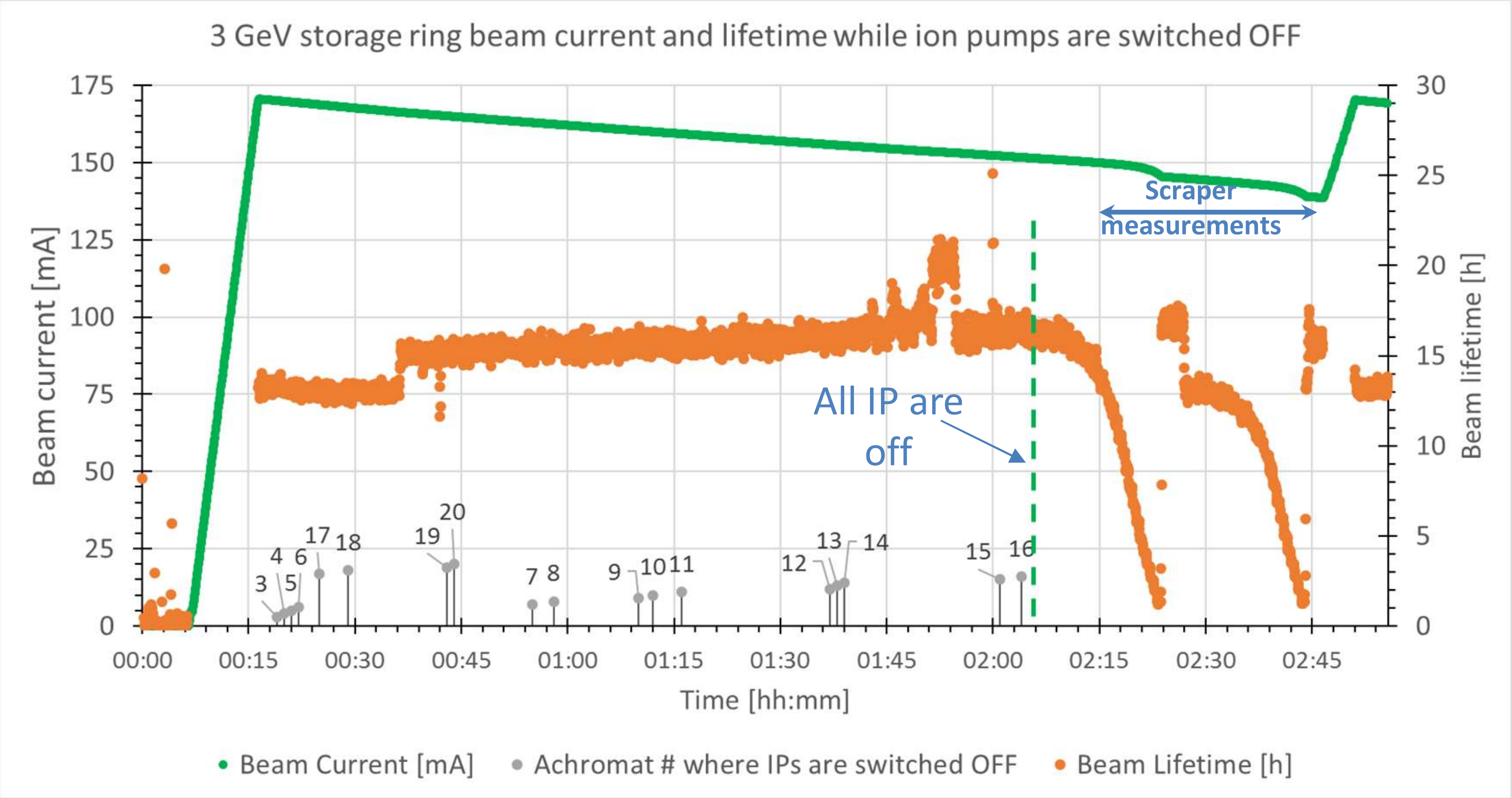
Jan 2020 – Jan 2021

*courtesy of Cristian Maccarrone (ESRF, Grenoble, France)

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

Vacuum performance

(tests with ion pumps OFF)



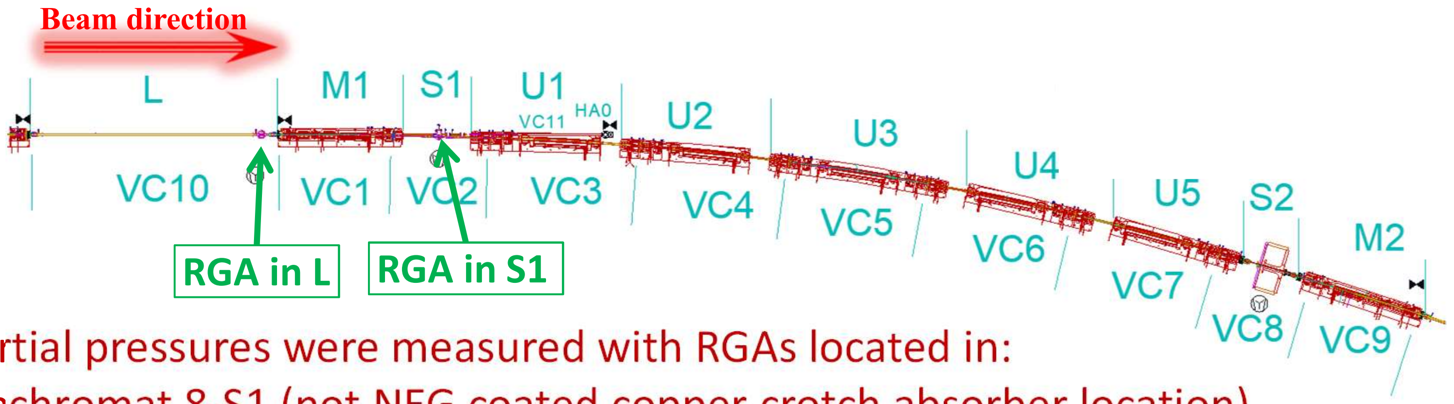
Time from injection (hh:mm)	Current (mA)	Lifetime (h)	I.tau (Ah)	comment
00:16	170	13	2.21	before the start of the test (all IP are on)
02:07	150	16	2.40	all IP are off *
02:45	139	15.5	2.15	after scraper measurement & all IP are off*
02:46	170	13	2.21	top up and all IP are off*.

Negligible effect on beam lifetime.

* except RF, inj. & ID

Vacuum performance

(tests with ion pumps OFF)



Partial pressures were measured with RGAs located in:

- achromat 8-S1 (not NEG coated 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 (ion pumps ON) and with stored beam with ion pumps OFF, summary 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%

Vacuum performance

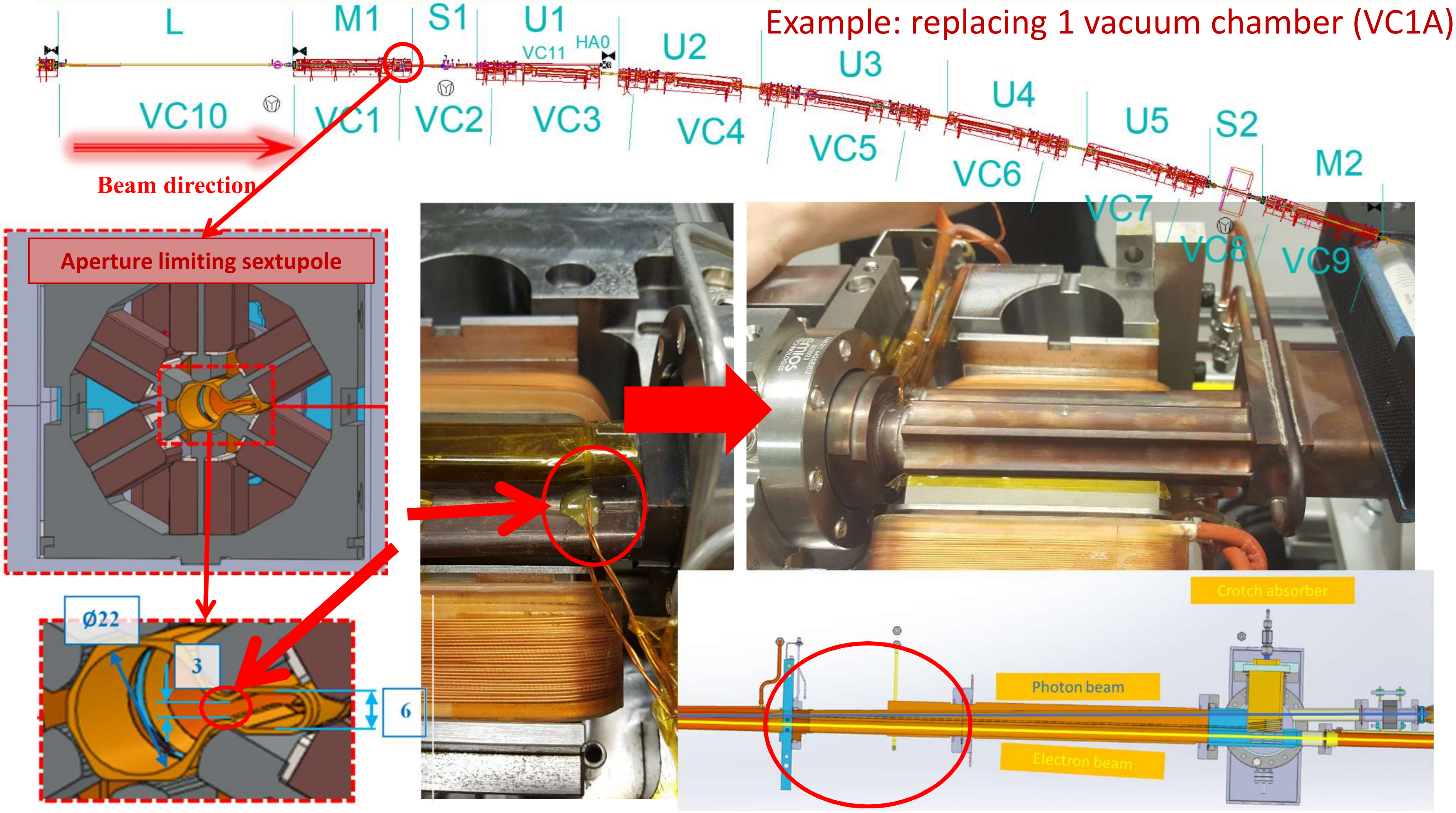
(tests with ion pumps OFF)

- 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.

Neon venting for interventions



Example: replacing 1 vacuum chamber (VC1A)

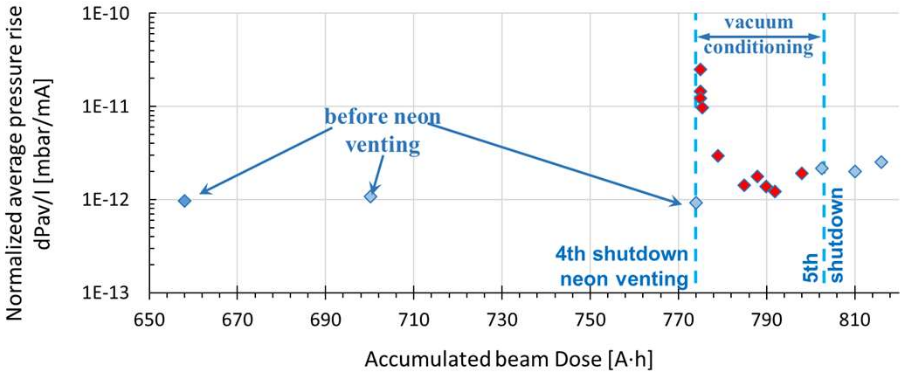
Neon venting was used at MAXIV for the first time in 2018 (as above) and did not limit machine startup nor operation.

Neon venting for interventions

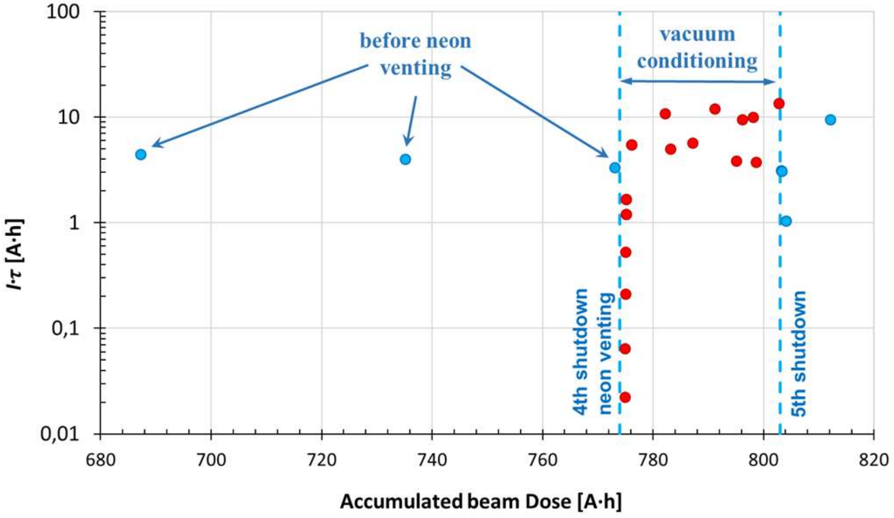
Vacuum conditioning and beam lifetime after neon venting intervention in 2018

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

Normalized average pressure rise vs accumulated beam dose before and after neon venting



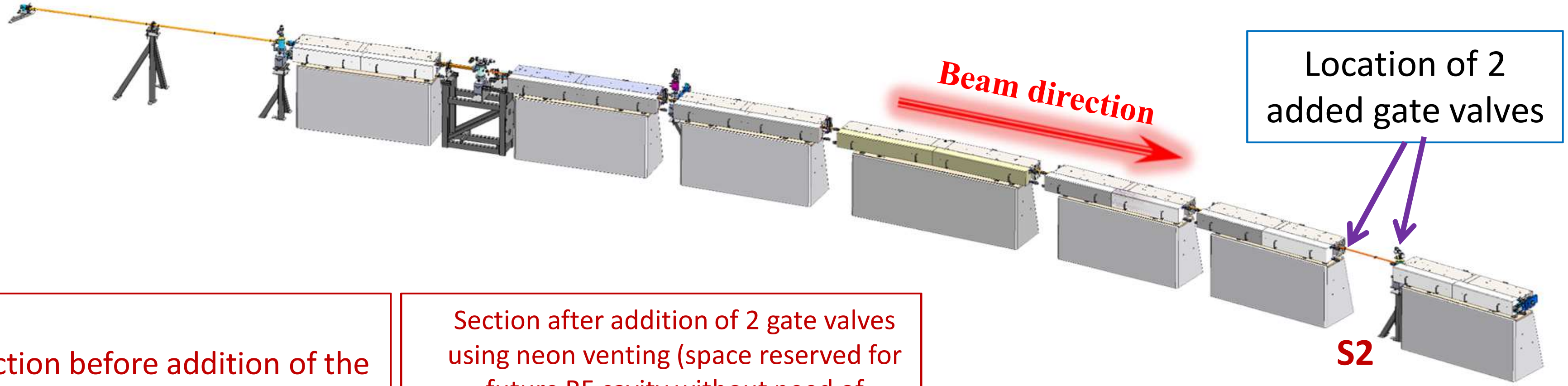
3 GeV ring: Normalized lifetime vs accumulated dose
I·τ [mA·h] vs Dose [A·h]



No limitation in storage ring performance was observed after ~10 A h beam dose.

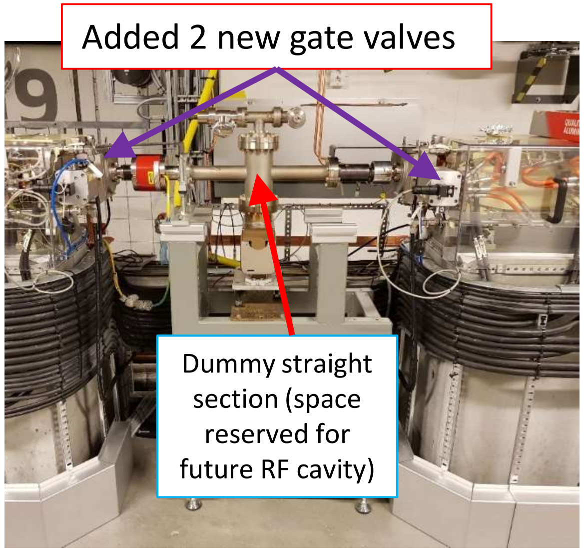
Neon venting for new installations: adding new gate valves

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 limitations.



Section before addition of the 2 gate valves

Section after addition of 2 gate valves using neon venting (space reserved for future RF cavity without need of venting the whole achromat)



Two additional gate valves were installed. This will allow future installation of a RF cavity, without the need of venting the achromat again.

- One achromat (~22 m long) was vented with high purity neon gas, therefore there was **no need of reactivating the NEG coated vacuum chambers**.
- The procedure utilizing high purity neon venting (instead of following the standard procedure: venting, baking and activation of the NEG coating) **saved significant amount of time, resources and did not jeopardize the accelerator operation**.