CERN Accelerator School:
Vacuum for Particle Accelerators

seminar:

MAX IV laboratory

vacuum systems

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MAX IV vacuum team

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Lund, Sweden

Contents

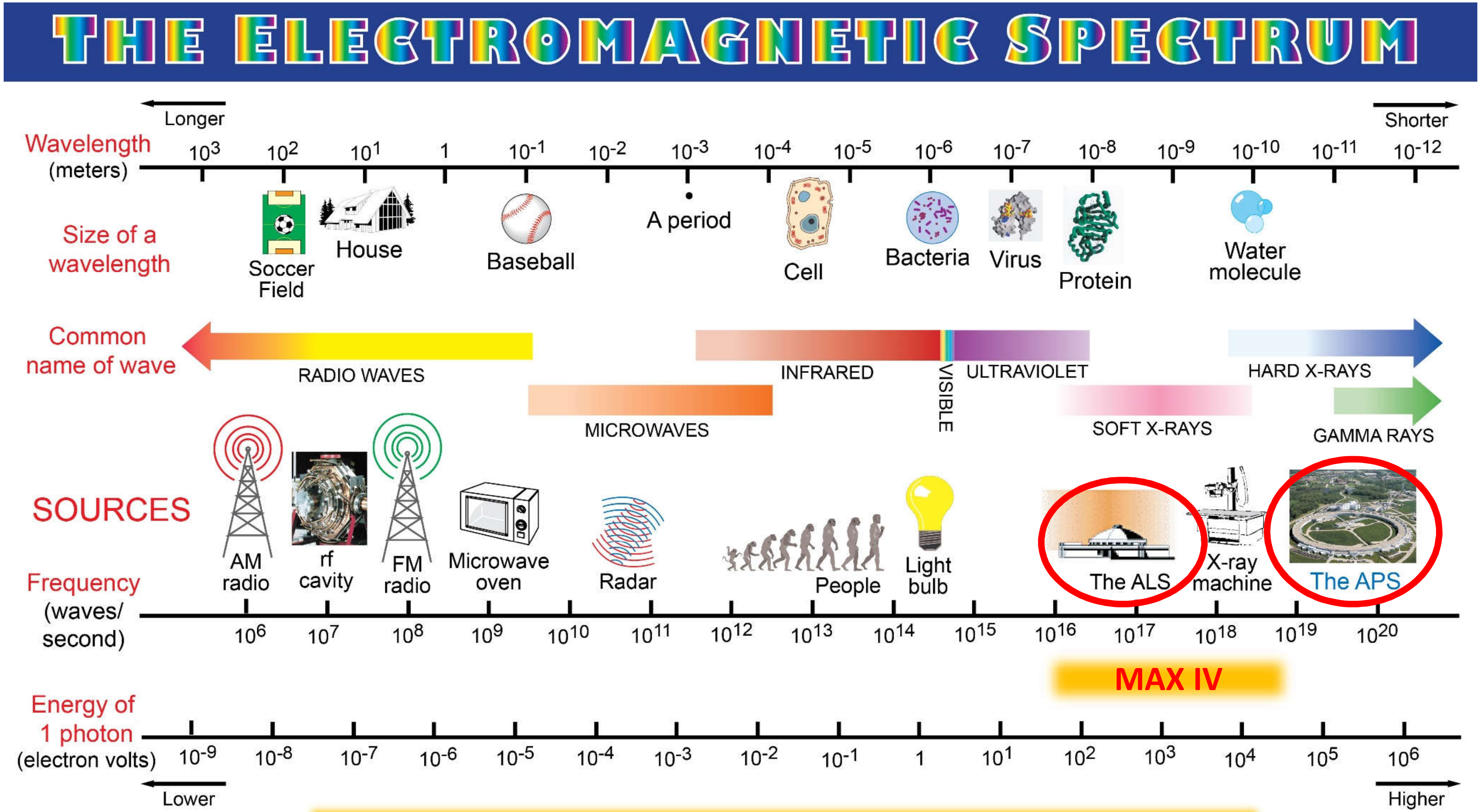
- Introduction to synchrotron radiation sources,
- MAX IV accelerator layout,

<u>3 GeV storage ring:</u>

  - vacuum system design,
  - NEG coating development,
  - installation,
  - vacuum system commissioning status,

- 1.5 GeV storage ring layout,
- Conclusions and future plans.

What MAX IV provides?

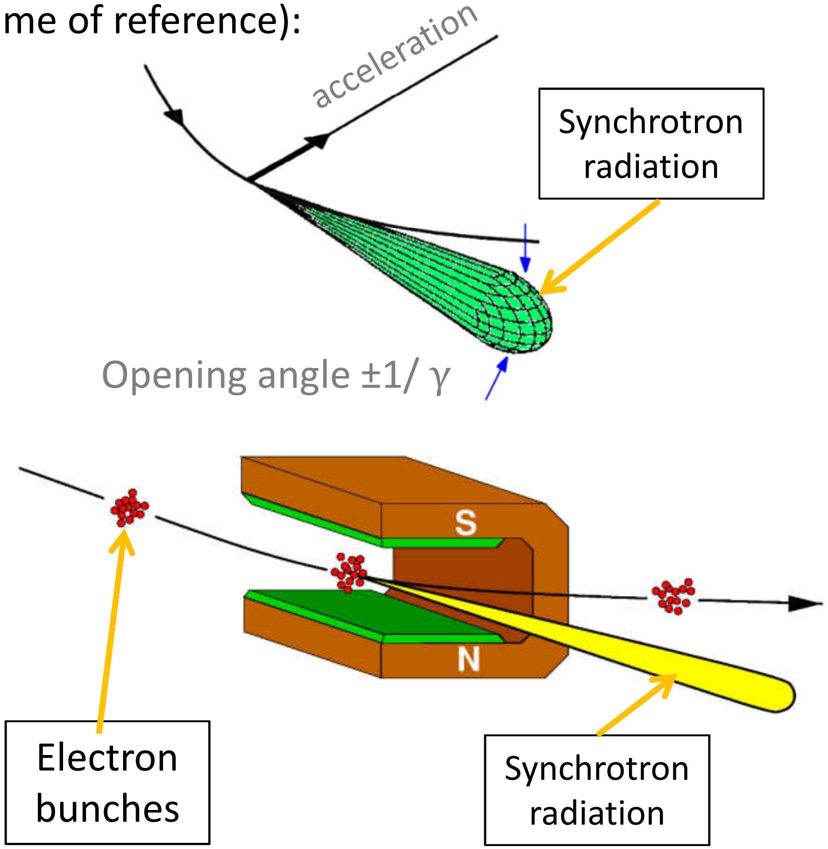


MAX IV is a synchrotron light source providing radiation from 4 eV till 40 keV to the beamlines for experiments.

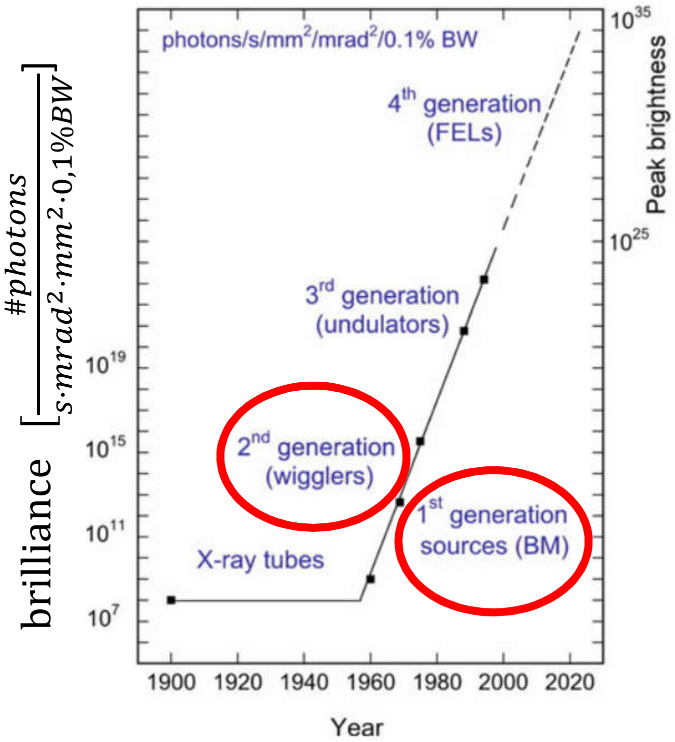
www2.lbl.gov

1st, 2nd Generation light sources

Radiation emission of a relativistic electron (stationary lab frame of reference):



X-ray source brilliance as a function if time since discovery of X-rays in 1895



$$\textbf{brilliance} = \frac{\#photons}{s \cdot mrad^2 \cdot mm^2 \cdot 0{,}1\%BW}$$

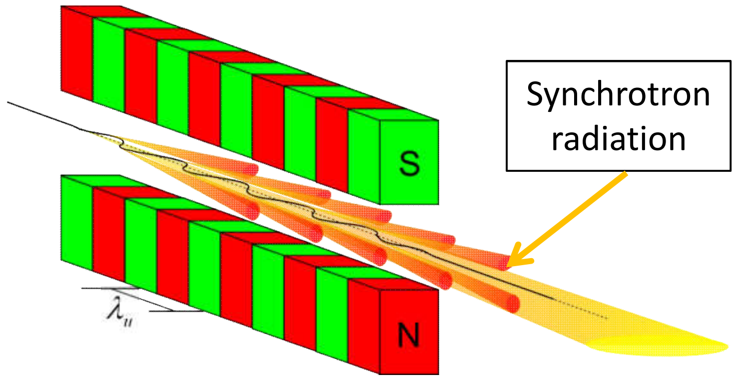
The greater the brilliance, the more photons of a given wavelength and direction are concentrated on a spot per unit of time.
Brilliance is mainly determined by the cross-section of the electron beam.

1st generation light sources at high energy physics accelerator facilities (parasitic operation)

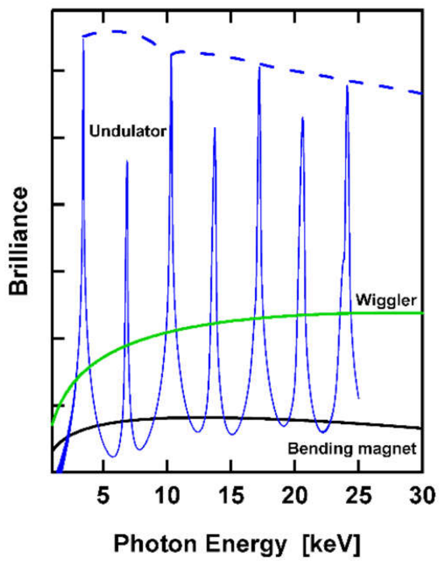
2nd generation light sources purpose built facilities: bending magnet radiation then also insertion devices (wigglers)

3^{rd} Generation light sources

Insertion device - periodic magnetic structure (wiggler, undulator):

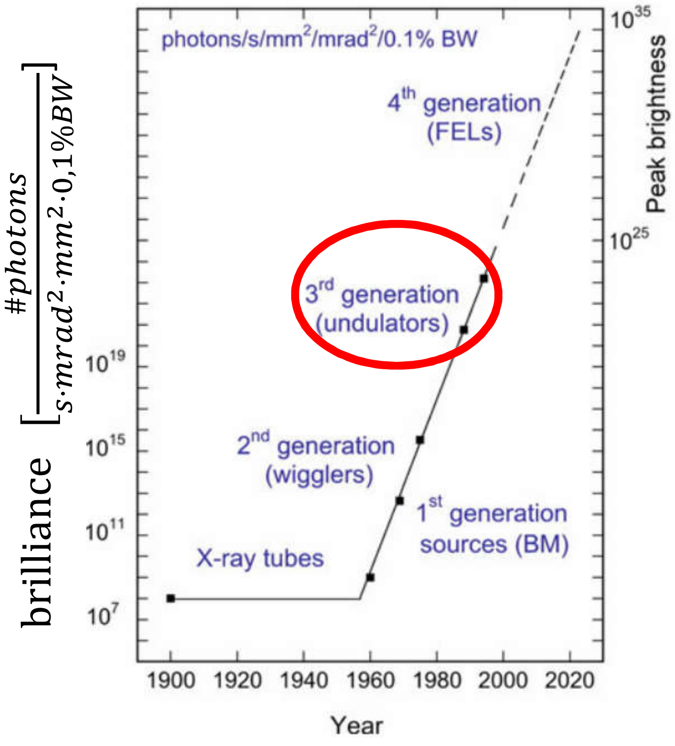


Brilliance of 3 radiation source types:



http://photon-science.desy.de/research/students__teaching/primers/synchrotron_radiation/index_eng.html

X-ray source brilliance as a function if time since discovery of X-rays in 1895



3^{rd} generation light sources: Shift to insertion devices (undulators)

4^{th} Generation light sources?

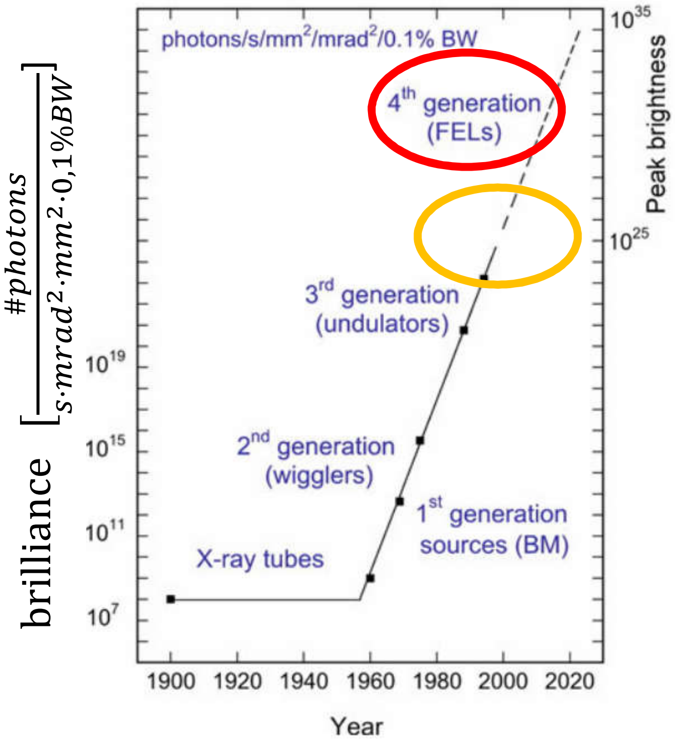
4^{th} Generation light sources, mainly Free Electron Lasers (FELs) with brilliance higher from previous generation by many orders of magnitude.

MAX IV is **<u>storage ring based</u>** 4^{th} generation light source with brilliance higher by at least one order of magnitude from 3^{rd} generation light sources.

At MAX IV:

- Higher brilliance is achieved by lowering electron beam emittance,
- Only insertion devices are used: wigglers, undulators, (no more bending magnet radiation).

X-ray source brilliance as a function of time since discovery of X-rays in 1895



4^{th} generation light sources:
at least 1 important parameter factor of 10 better than the previous generation.

http://photon-science.desy.de/research/students__teaching/primers/synchrotron_radiation/index_eng.html

MAX IV layout

Synchrotron light source facility in Lund, Sweden.

3.7 GeV Linear accelerator - Linac (300 m)

Electron gun

Short pulse facility

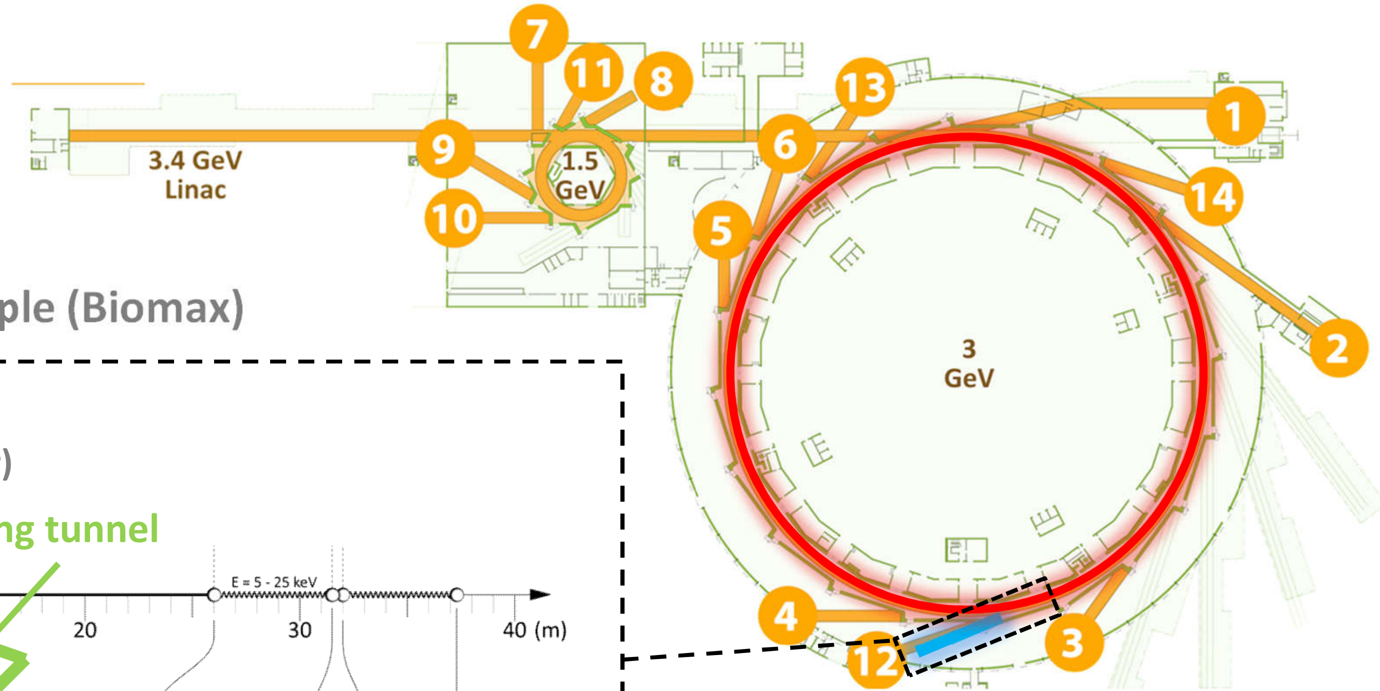
1.5 GeV storage ring for soft x-rays

3 GeV storage ring for hard x-rays

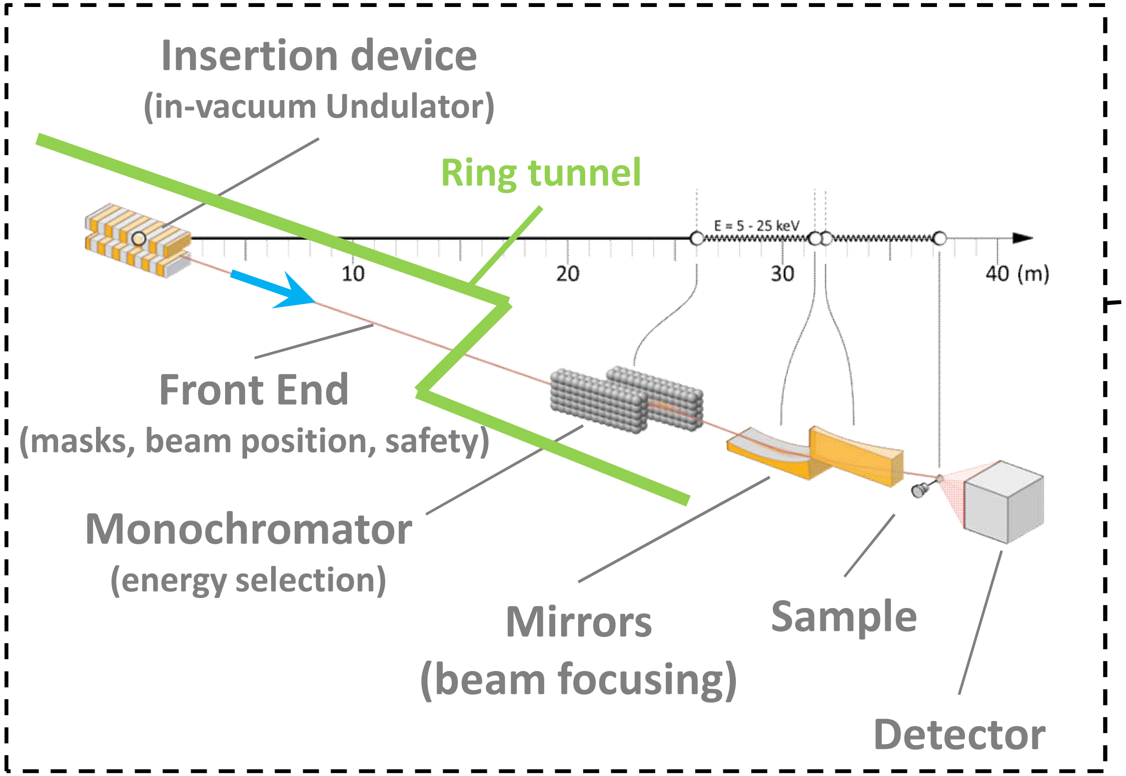
Commissioning started: September 2016

Commissioning started: August 2015

MAX IV beamline layout



Beamline layout example (Biomax)



Beamlines at MAX IV:
6 beamlines in operation/commissioning,
5 being installed,
3 under design.

Total beamline capacity: ~30 beamlines

https://www.maxiv.lu.se/

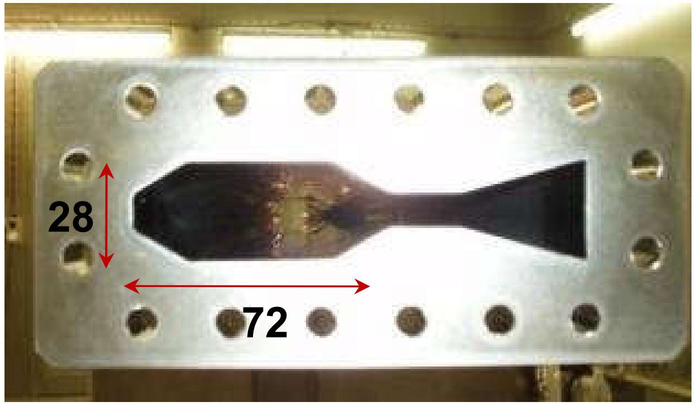
Before MAX IV

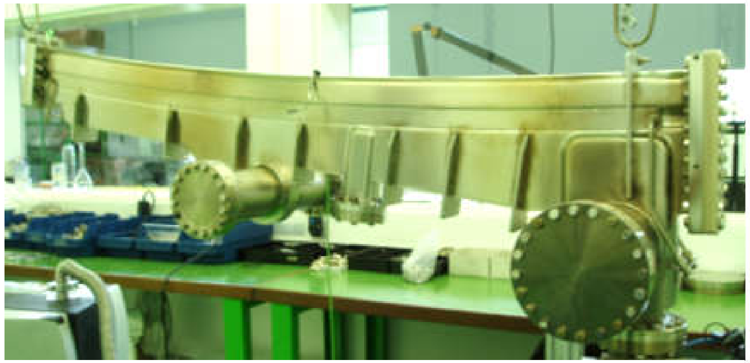
ALBA vacuum system and other 3rd generation storage rings

Also ANKA, SLS, CLS, ASP, Diamond…etc.

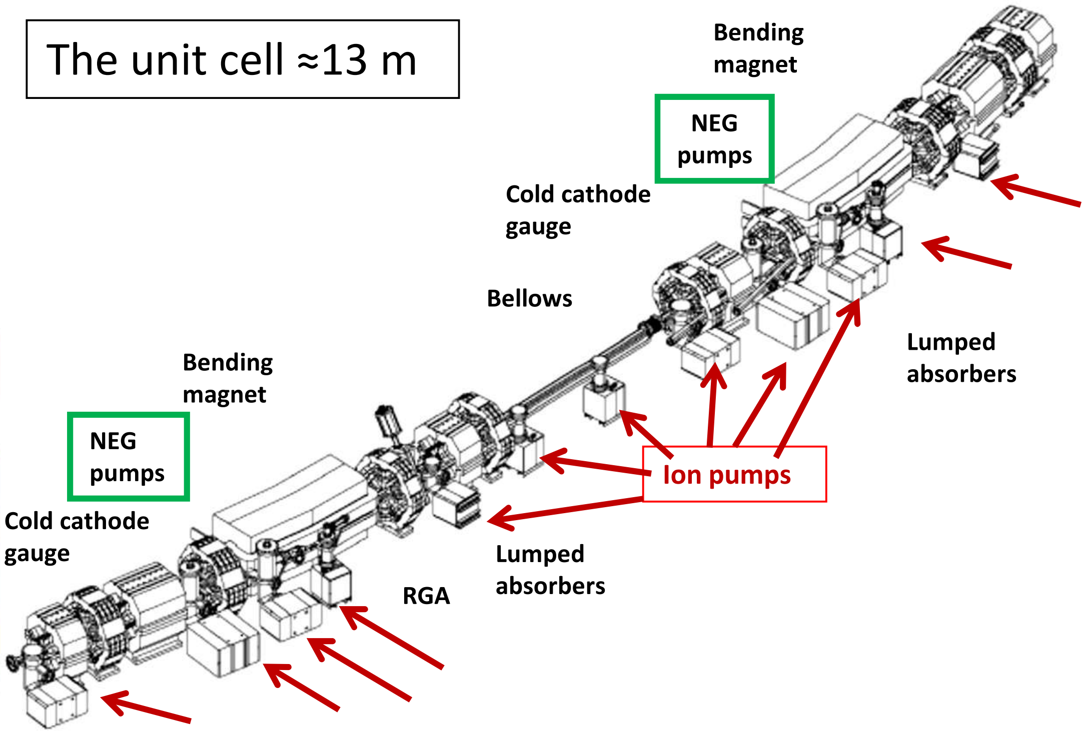
- **Antechamber design with lumped copper absorbers.**
- **Keyhole profile 28x72 mm.**
- **Stainless steel 316LN.**
- **Pumping mainly by ion and NEG pumps.**
- **Overall pump speed 60400 l/s**

Keyhole profile





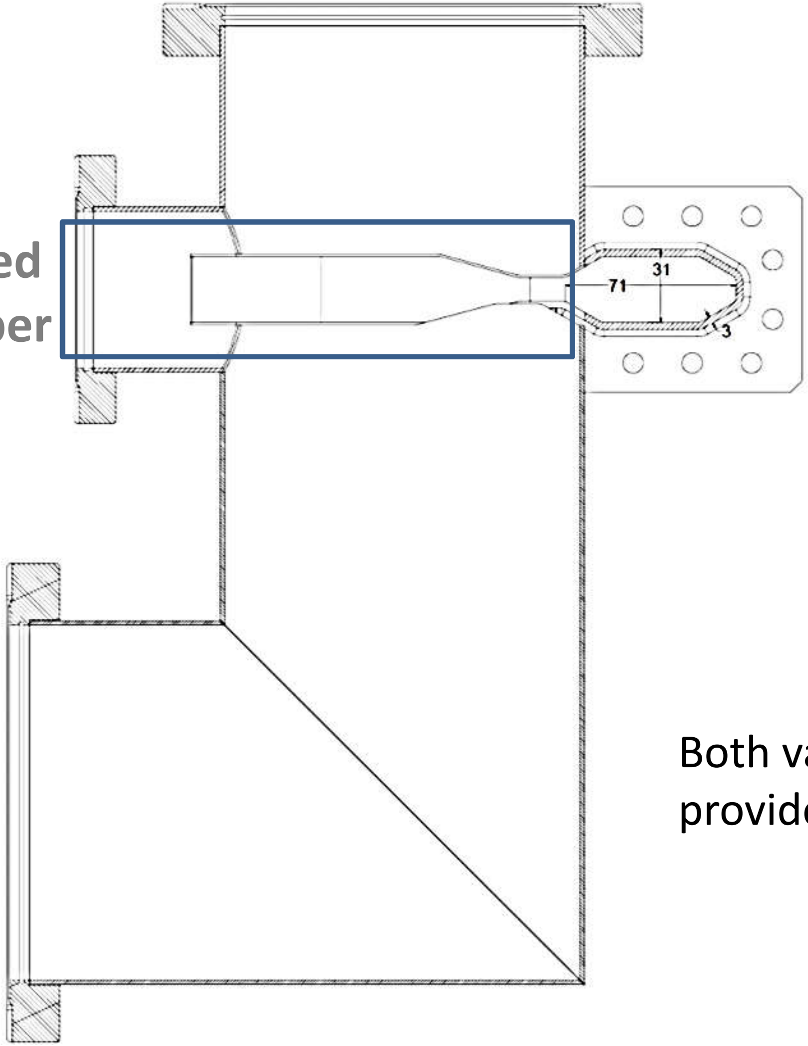
The unit cell ≈13 m



Conventional vs compact vacuum system

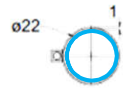
Conventional vacuum system

Lumped absorber



Ion pump

MAX IV (3 GeV storage ring) vacuum chambers



NEG-coating

Size of 1 € coin

Both vacuum systems types provide the same functions.

MAX IV as 4th gen. light source

The 3 GeV storage ring: what is special about it?

Brilliance mainly depends on the electron beam transverse size and divergence, product of which is called beam emittance ϵ.

One way to increase the brilliance is to lower the emittance of the circulating beam.

γ – Lorentz factor (E/E_0)

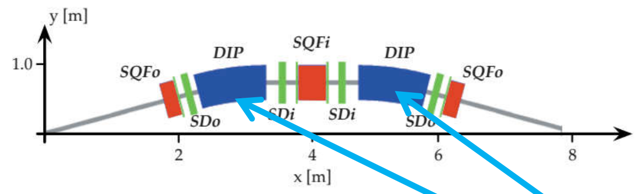
Emittance scaling: $$\epsilon_0 \propto \frac{\gamma^2}{\rho . N_B^3}$$

ρ – bending radius of bending magnets

N_B – number of bending magnets

MAX IV as 4^{th} gen. light source

1.5 GeV double-bend achromat (DBA) lattice:

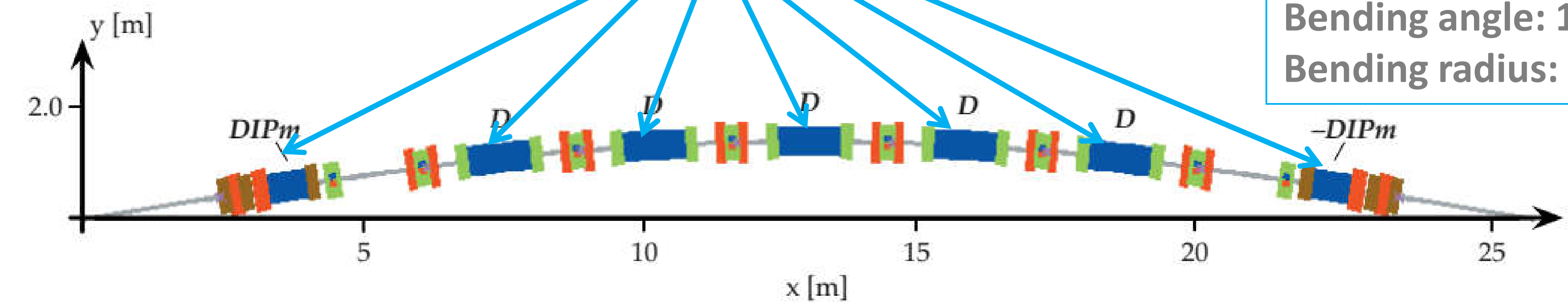


2 dipoles,
Bending angle: 30^0
Bending radius: 3.8 m

Energy:	**1.5 GeV**
Horizontal Emittance (bare lattice):	**6 nm rad**
Circumference:	**96 m**
#straight sections:	**12 x 3.3 m**

3 GeV 7-bend achromat lattice:

Dipole magnets



7 dipoles,
Bending angle: 18^0
Bending radius: 19 m

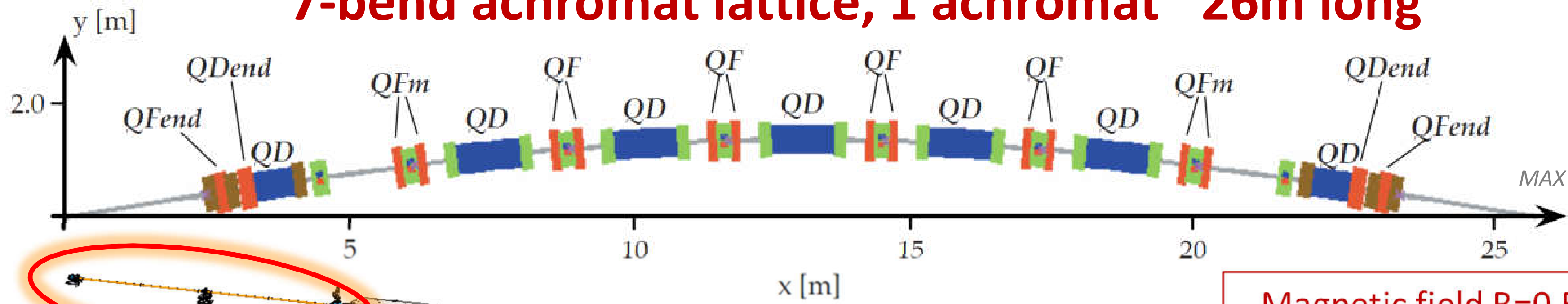
Lattice of choice for the 3 GeV ring: 7-bend achromat (multi-bend achromat). Choice of such lattice puts major constraints on the vacuum system design.

Energy:	**3 GeV**
Horizontal Emittance (bare lattice):	**0.33 nm rad**
Circumference:	**528 m**
#straight sections:	**20 x 4.5 m**

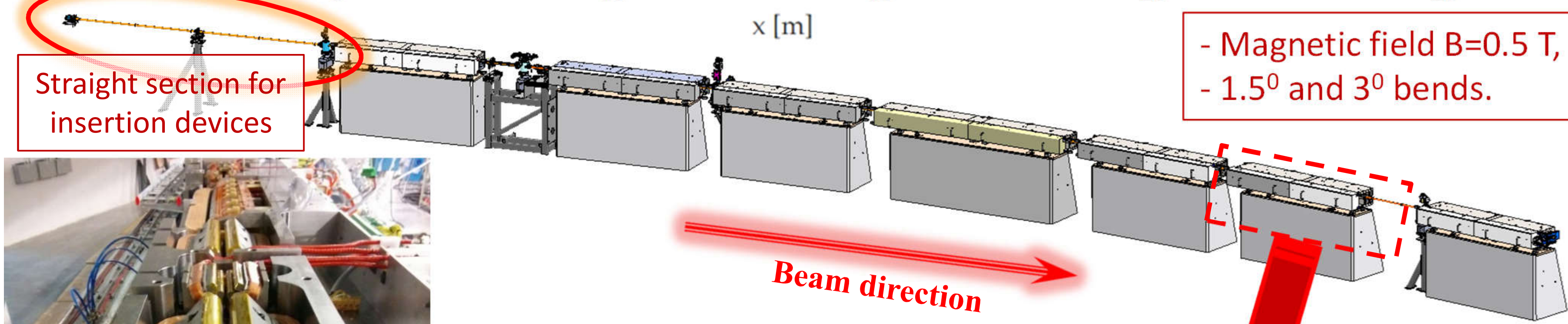
MAX IV DDR

3 GeV achromat layout

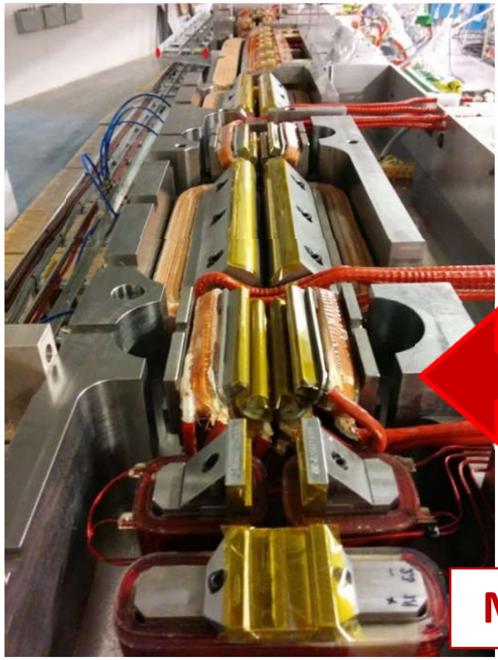
7-bend achromat lattice, 1 achromat ~26m long

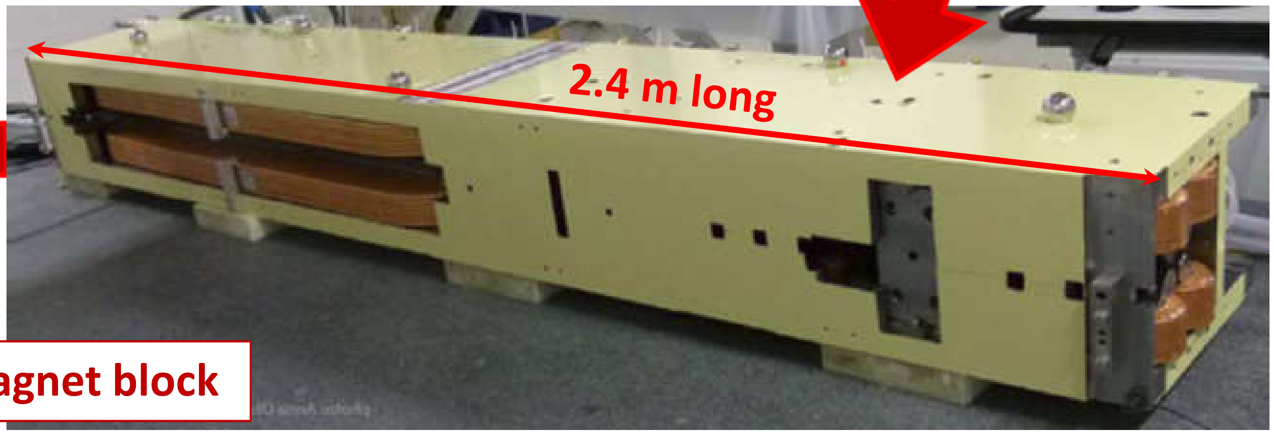


- Magnetic field B=0.5 T,
- 1.5^0 and 3^0 bends.



Straight section for insertion devices

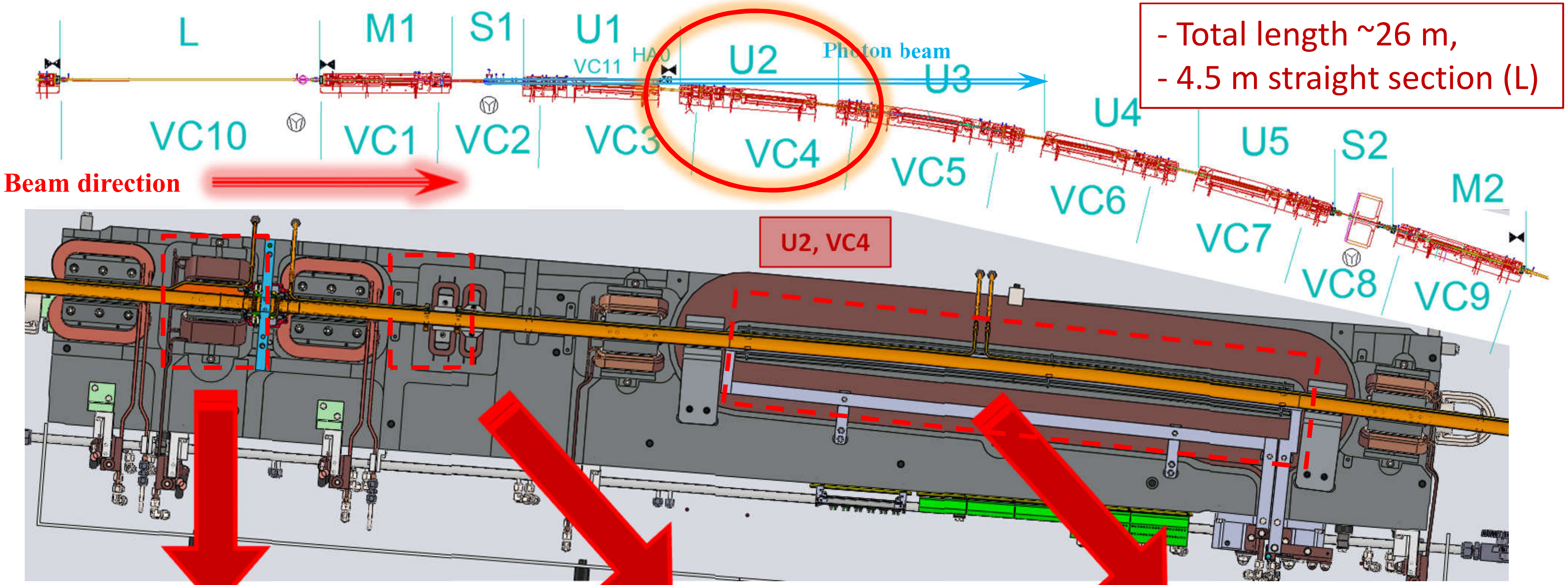


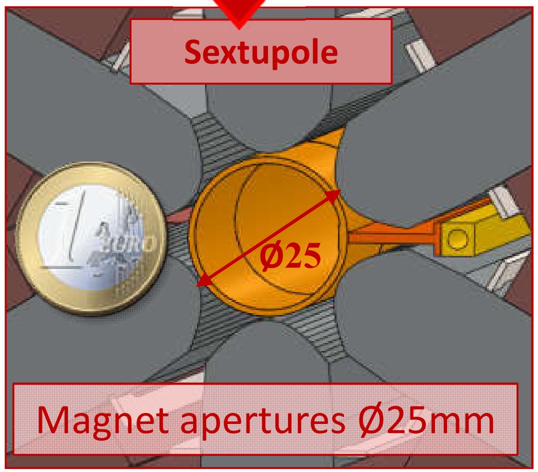


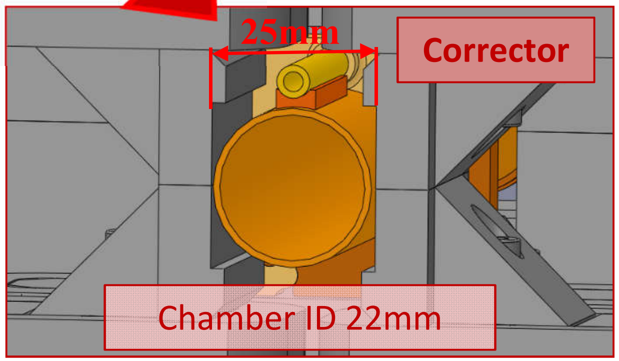
Magnet block

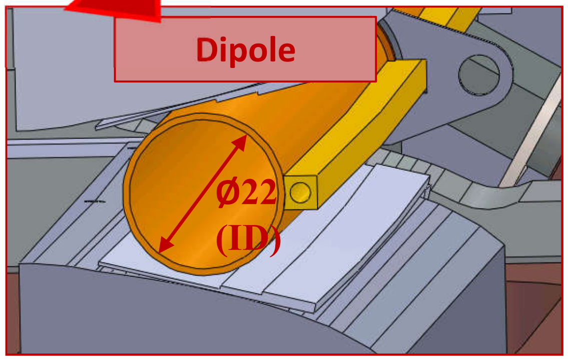
3 GeV magnet layout

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









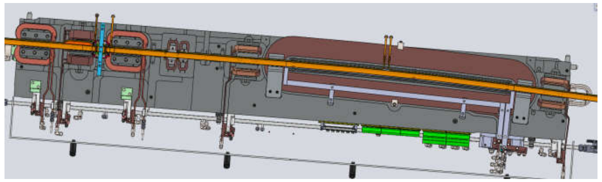
Min. clearance with the iron 0.5 mm, min. clearance with the coils 2 mm.

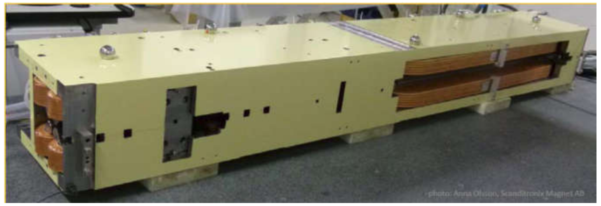
Vacuum system constraints and requirements

- **Compact lattice**

  No space for lumped absorbers

  Small longitudinal distance between magnets.





- **Closed solid magnet block**

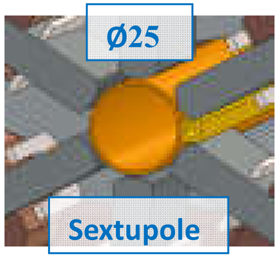
  Little place around the magnets.

  No space for lumped pumps

- **Small aperture of the magnets**

  Magnets' aperture Ø25 mm.

  Low conductance of vacuum tubes



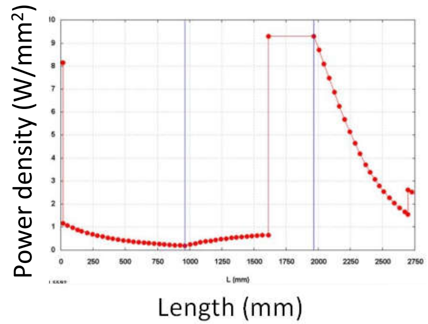
- **Low target dynamic pressure**

  Average pressure 1e-9 mbar.

  Need of pumping and low PSD

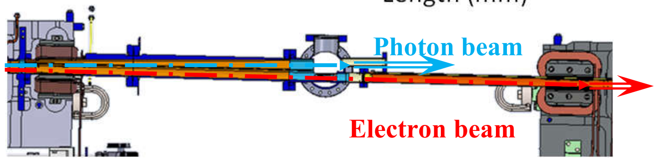
- **Removal of the SR power (BM & ID)**

  Power density along bent vacuum chamber walls and absorbers.



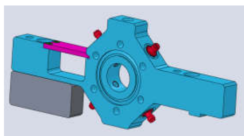
- **Extraction of synchrotron radiation**

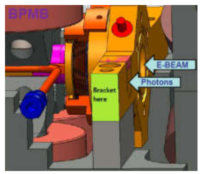
  Limited by small bending angle.



- **Stable positioning of BPM**

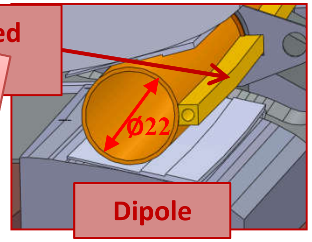
  Disentangling the BPMs from the chambers.

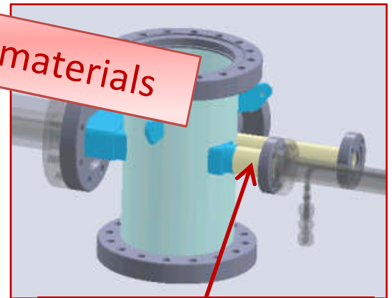


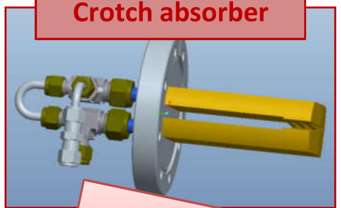


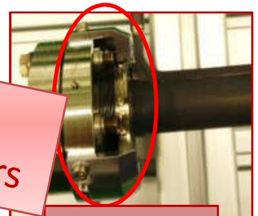
Vacuum system approach

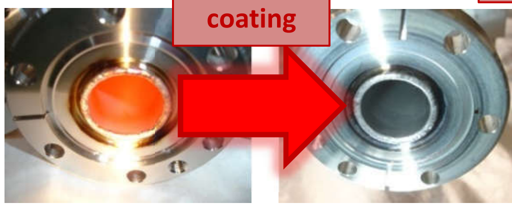
- **Geometry**: inside diameter **22 mm**, **1 mm** wall thickness, bends of 1.5^0 and 3^0 over 19 m radius.
- **Substrate: Silver bearing (OFS) Copper** vacuum chambers (resistance to thermal cycling).
- **Distributed water cooling** to cope with SR.
- Areas made of **stainless steel** for fast corrector 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**.



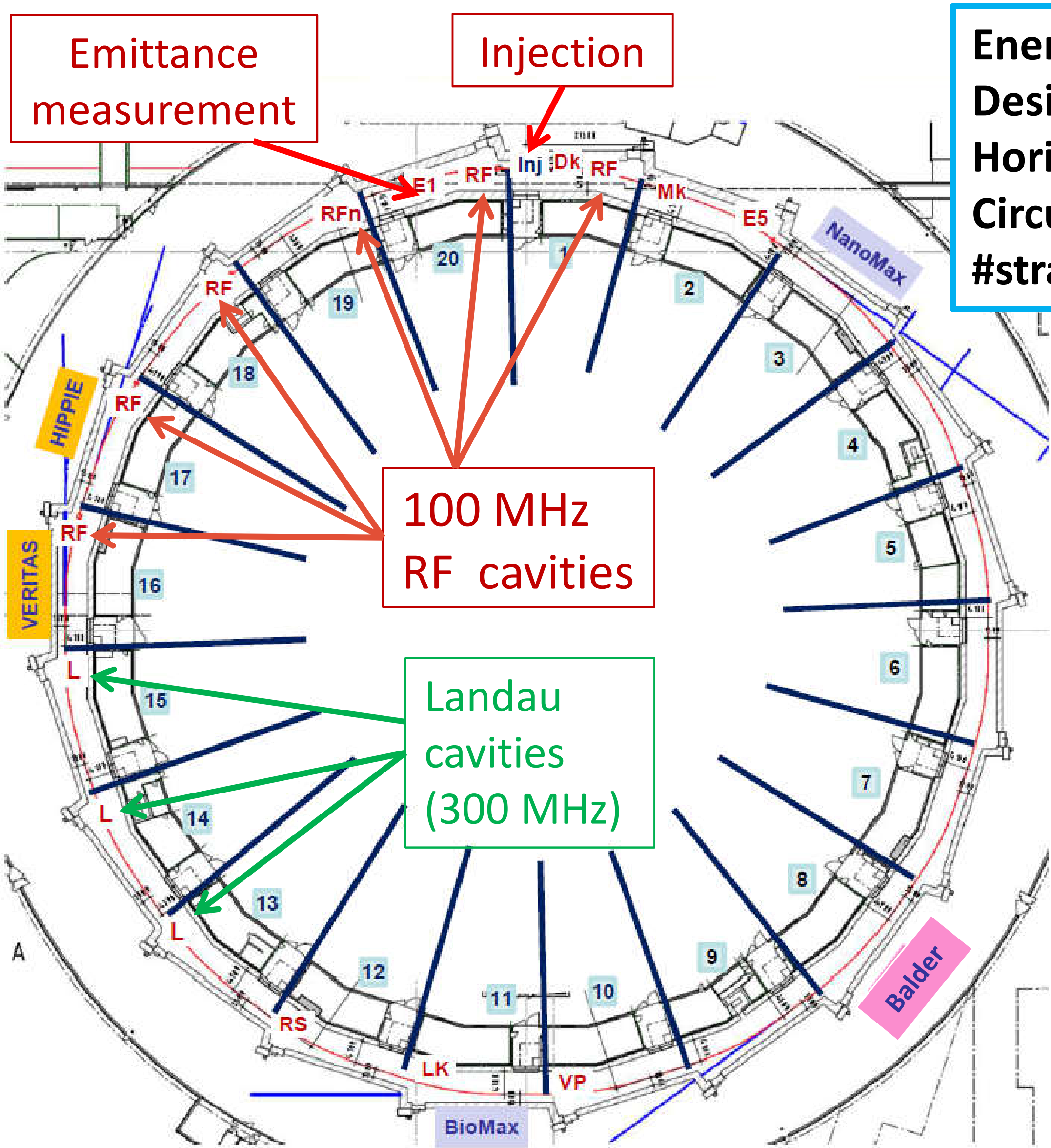








3 GeV ring layout



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

Installed Insertion Devices:

2 In vacuum undulators (2 m long)
- NanoMAX IVU18
- BioMAX IVU18

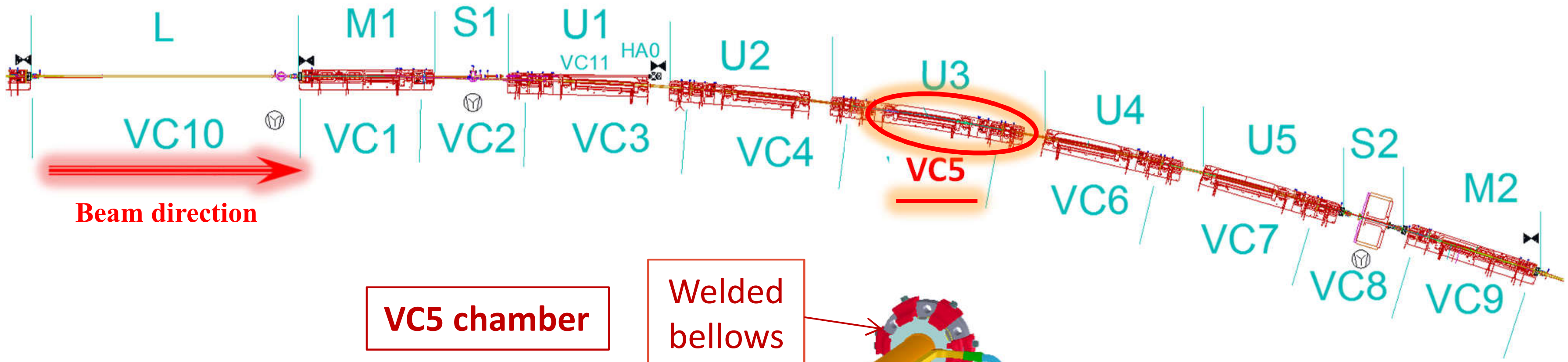
2 EPU (4 m long, min gap 11 mm)
- VERITAS EPU48
- HIPPIE EPU53

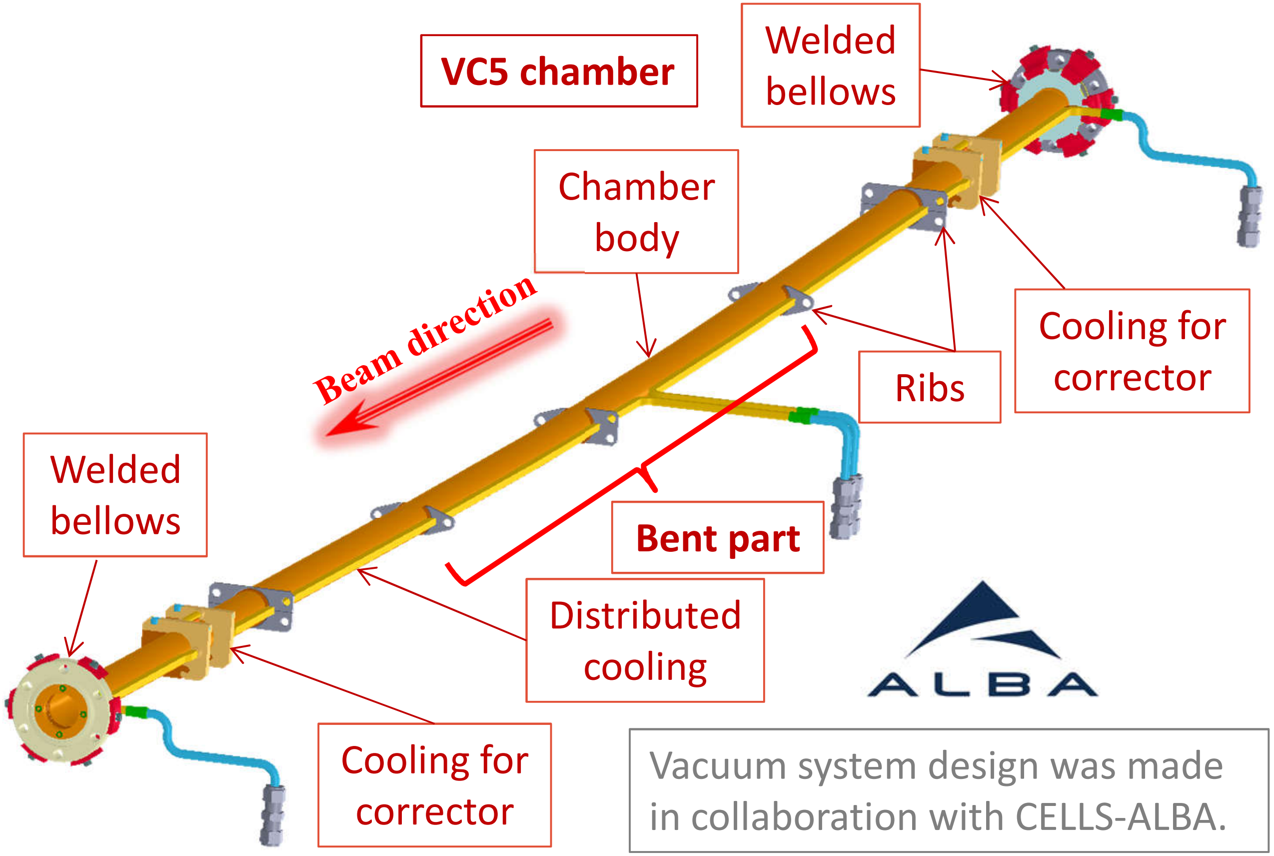
1 In vac. Wiggler (2.4 m long)
- BALDER IVW50

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

L=long straight,
S=short straight,

Standard vacuum chamber geometry





Vacuum system design was made in collaboration with CELLS-ALBA.

Material: OFS copper

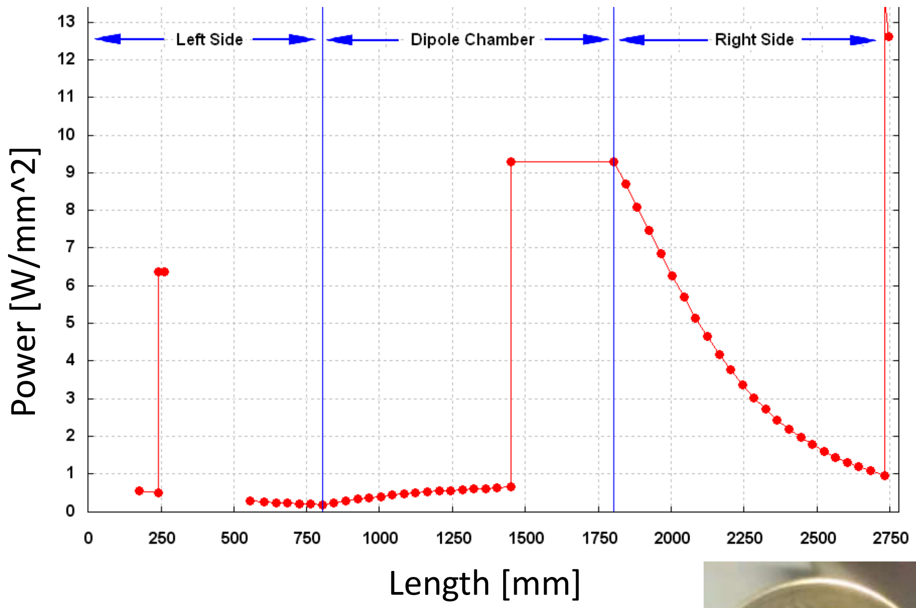
Inside diameter: 22 mm,
Total length: 2.5 m,

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

NEG-coated.

General vacuum chamber geometry

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

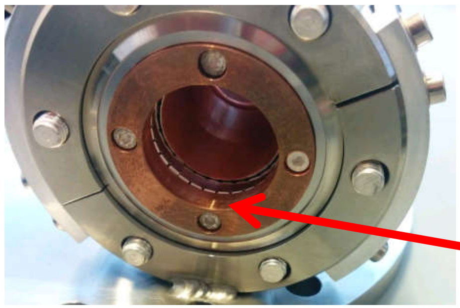


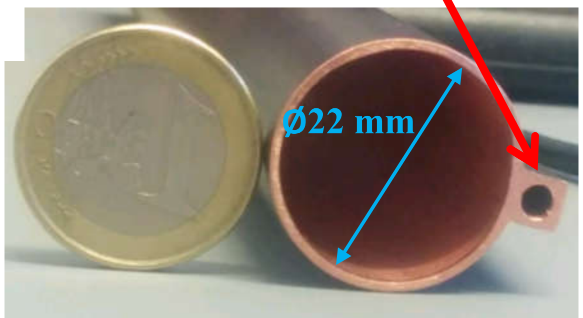
Chamber body

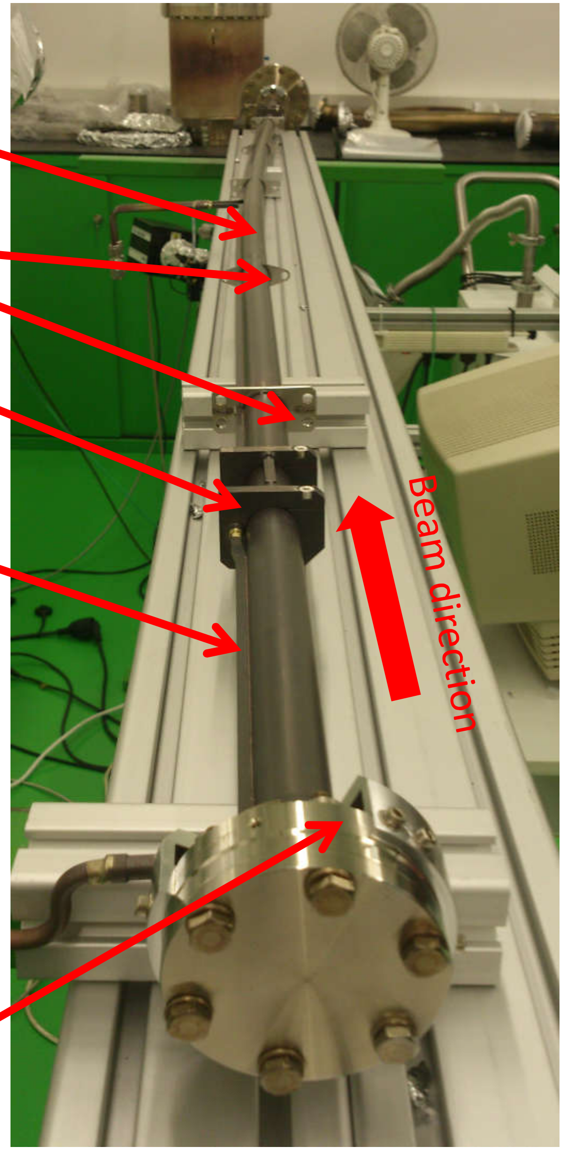
Ribs

Cooling for orrector area

Distributed cooling

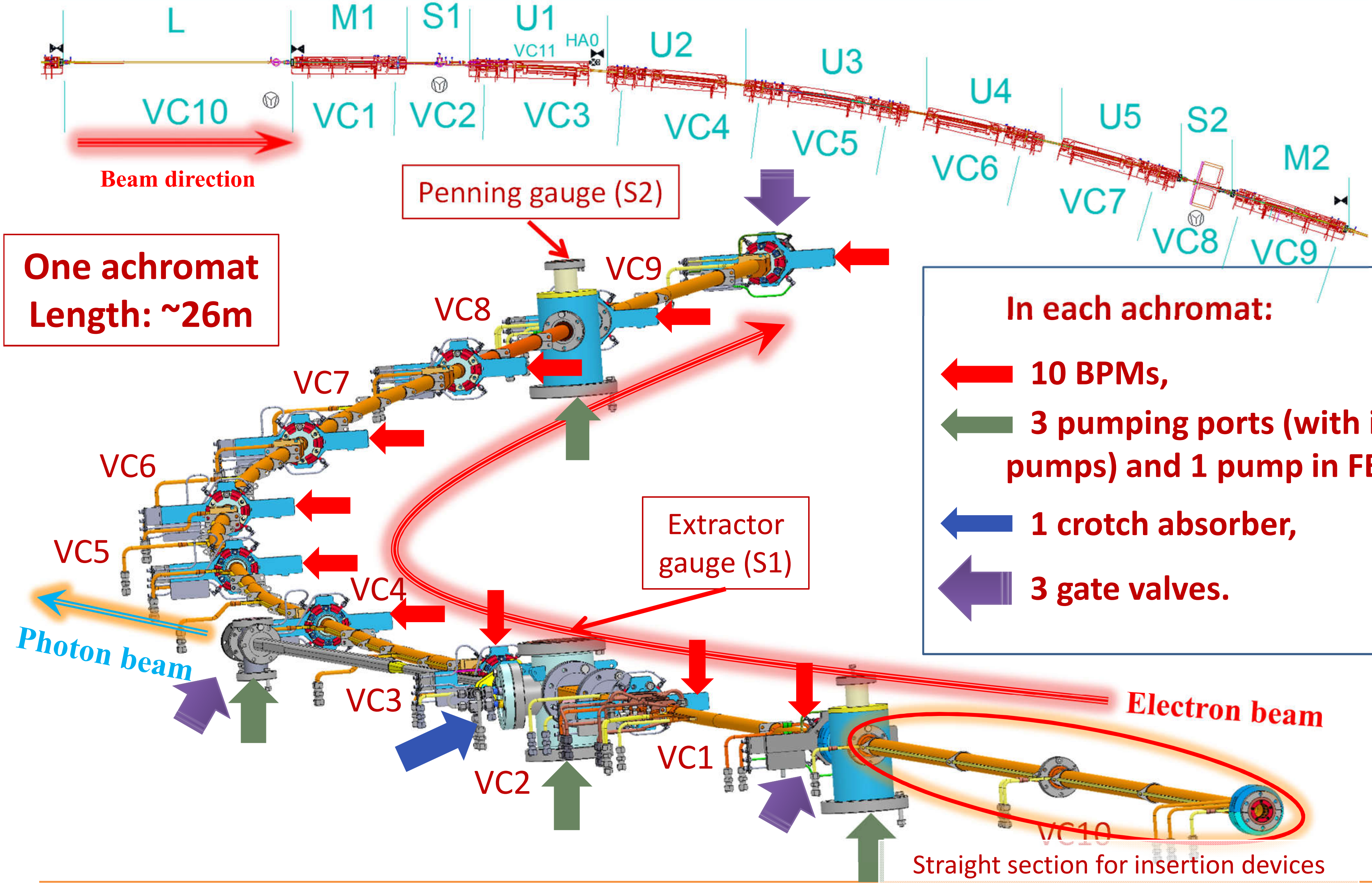






Welded bellows with RF shielding

Vacuum achromat layout

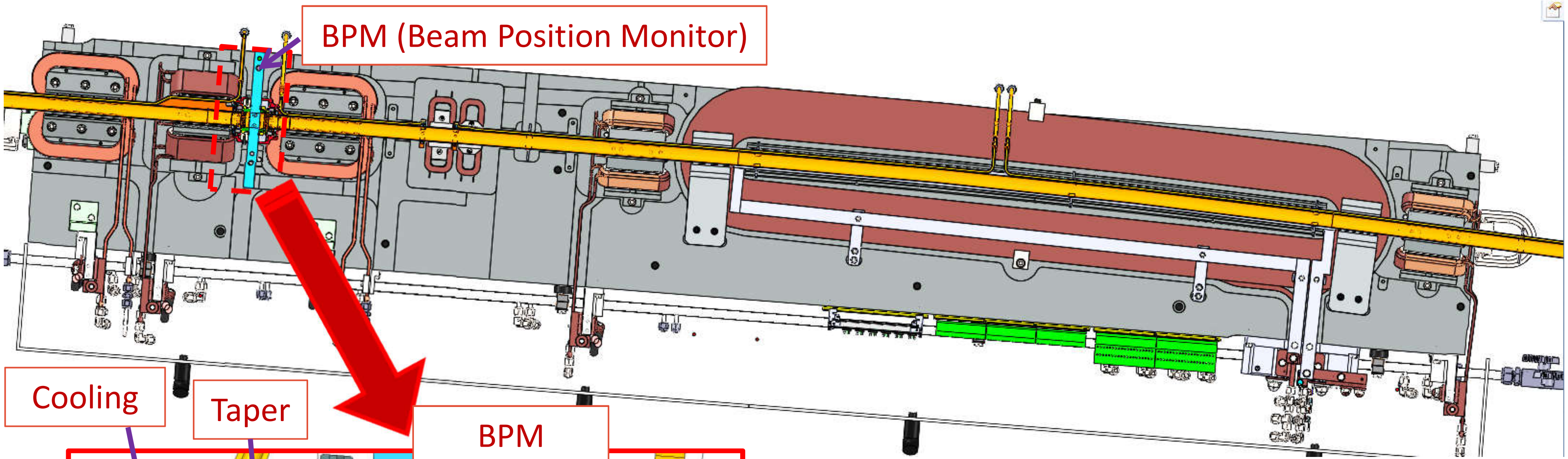


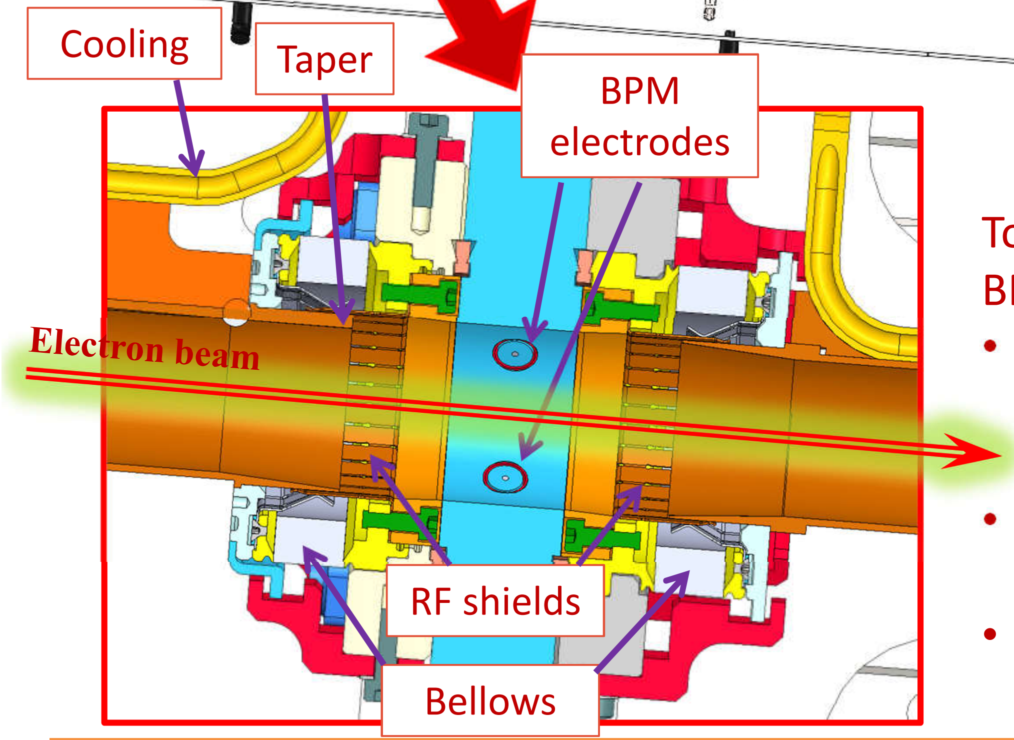
One achromat Length: ~26m

In each achromat:

- **10 BPMs,**
- **3 pumping ports (with ion pumps) and 1 pump in FE,**
- **1 crotch absorber,**
- **3 gate valves.**

BPM stability

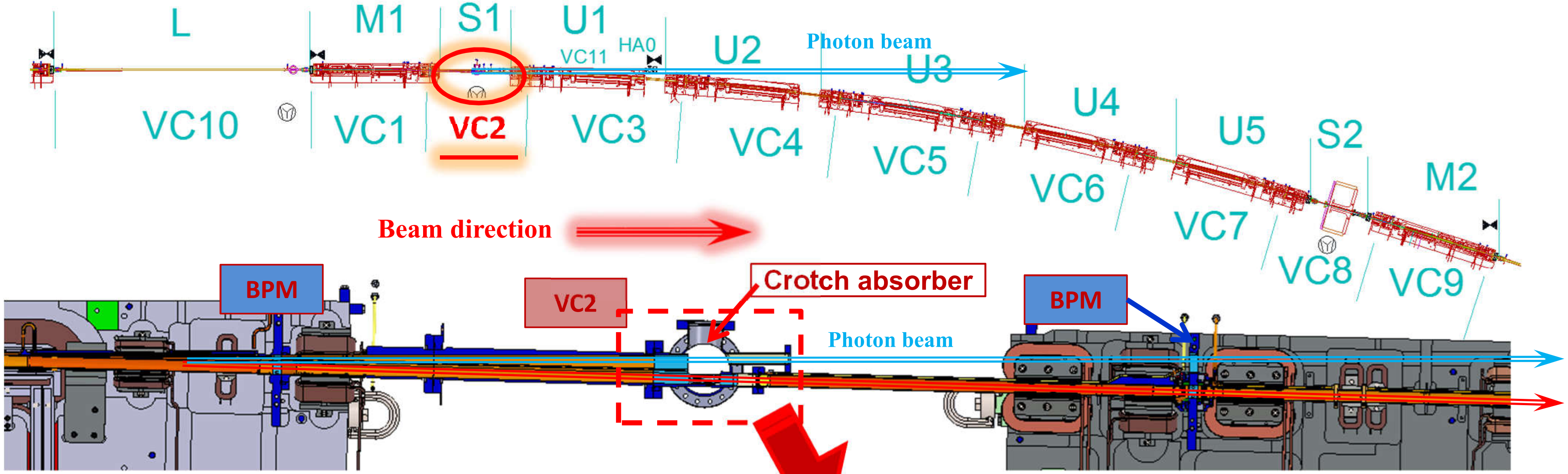




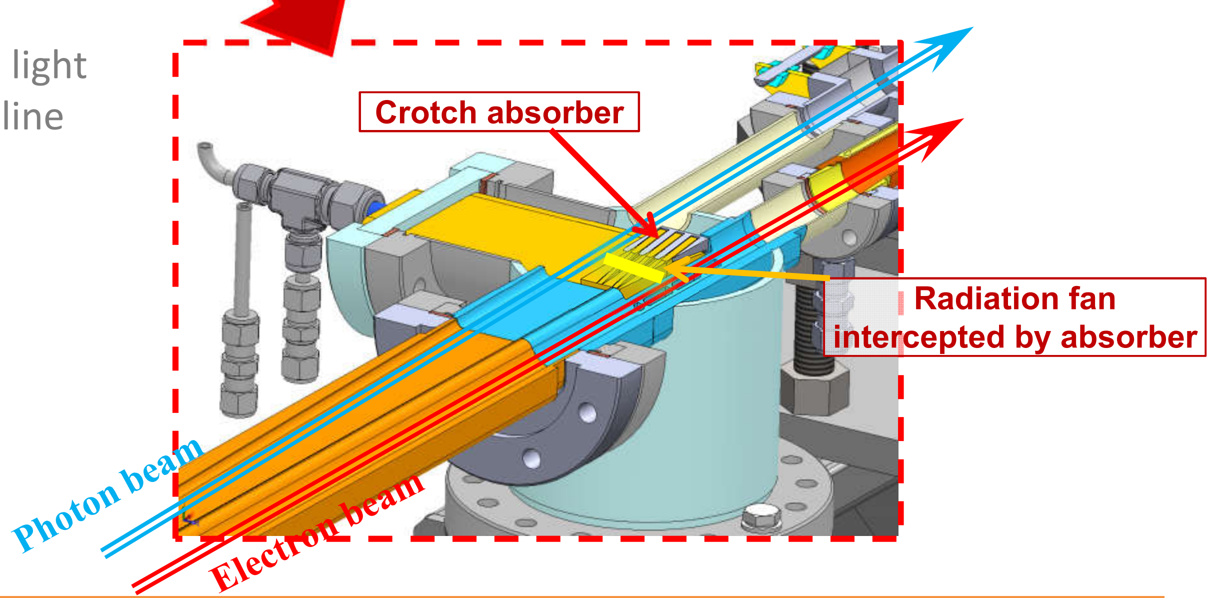
To ensure thermal and dimensional stability of BPMs (Beam Position Monitor) :

- RF shielded bellows at chamber extremities to allow pipe expansion without affecting the BPM position and temperature,
- Taper to shield BPM stainless steel body from radiation,
- Copper chamber water cooled all-along.

Synchrotron light extraction



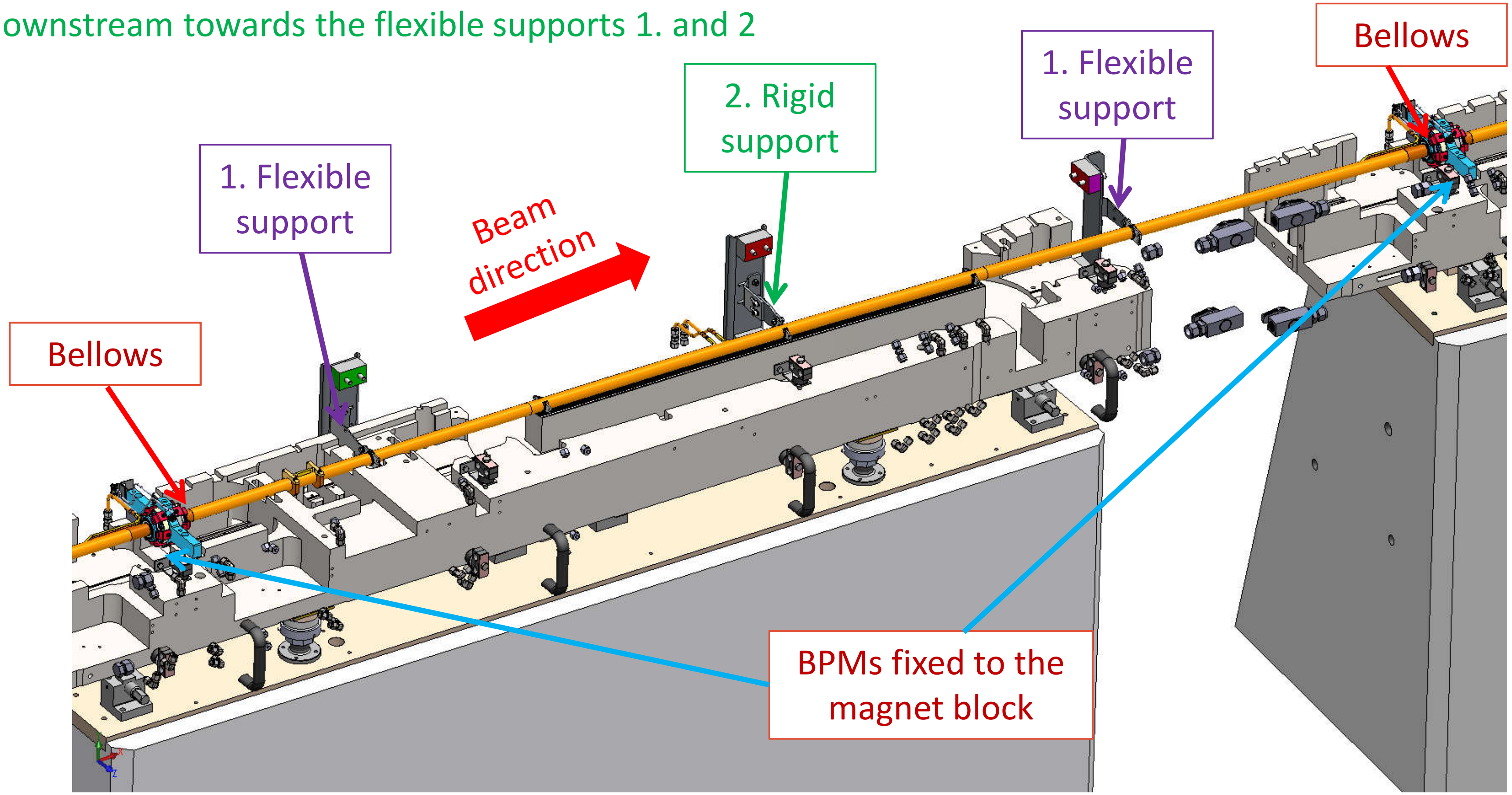
Short straight section 1 – synchrotron light extraction to the Front End and Beamline



Chamber fixation

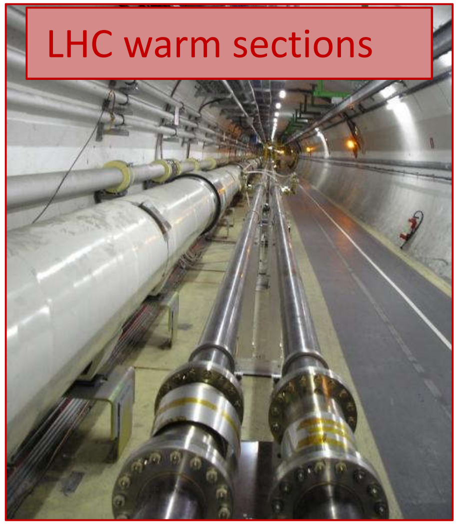
1. Flexible support: allows longitudinal movement of the chamber in order to release the stresses from the chamber and block the transversal movement.

2. Rigid support: fixes the chamber in the middle of the dipole part and keeps the chamber in its nominal position both in transversal plane and longitudinally, allowing the chamber to expand upstream and downstream towards the flexible supports 1. and 2

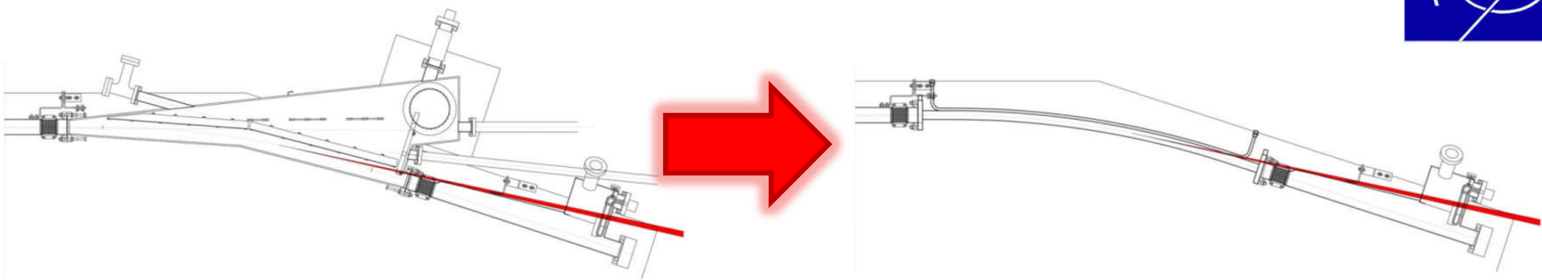


NEG coating development

- NEG-coating of vacuum chambers by magnetron sputtering 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 56% of storage ring is NEG coated.
- In MAX II since 2007 three dipole chambers were replaced by NEG-coated vacuum chambers.



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



NEG-coating R&D at CERN

To validate the coating feasibility 3 main stages of NEG (Ti, Zr, V) coating validation by magnetron sputtering in collaboration with CERN were undertaken. (R&D duration ~2 years).

1. Define and perform initial **surface treatment** of OFS copper substrate.
2. Validate compatibility of NEG-coating (adhesion, thickness, activation behavior):

   a). on etched **OFS copper**.

   b). on **wire-eroded** surfaces and used **brazing alloys**.

3. NEG-coating validation of compact vacuum chamber **geometries**:

   a). Coating and testing of **small diameter**, **bent** tubes.

   b). Establish coating procedure/technology and coat chambers of **complex geometry**.

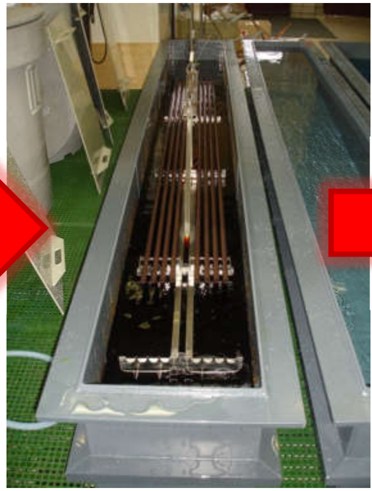
1. Surface treatment (R&D at CERN)

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.

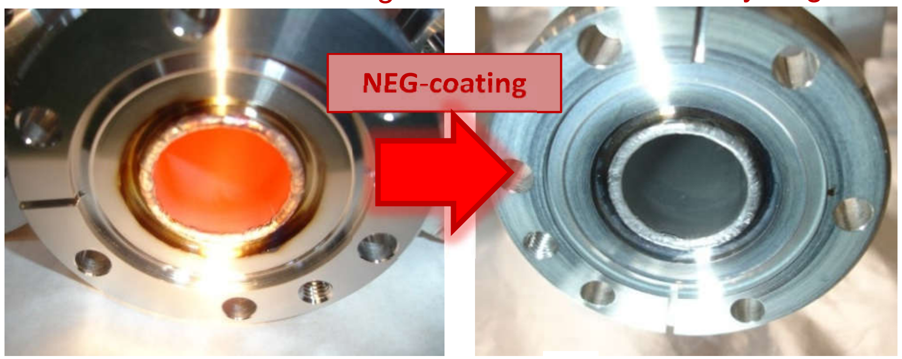
2. and 3 a). Coating compatibility

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

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

Chamber before coating

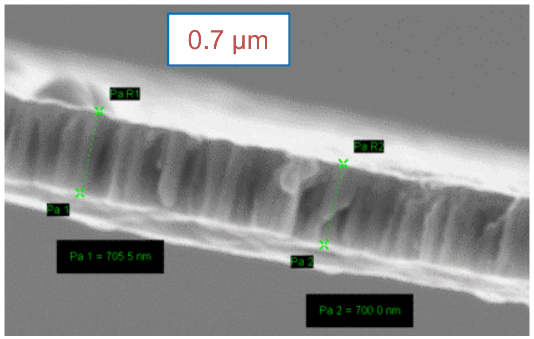
Chamber after coating and thermal cycling

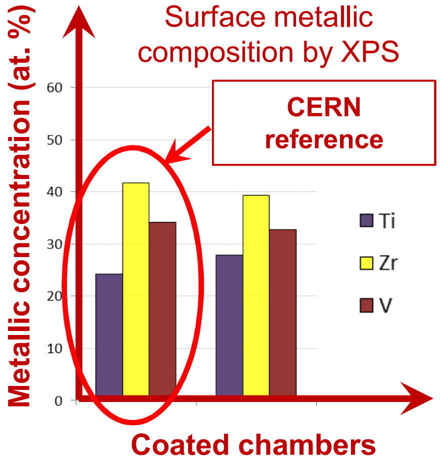


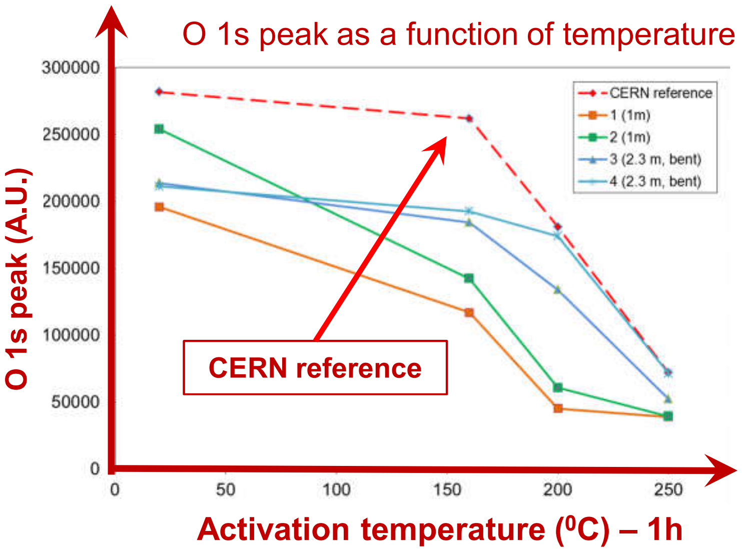
NEG coating requirements:

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

SEM thickness measurements:

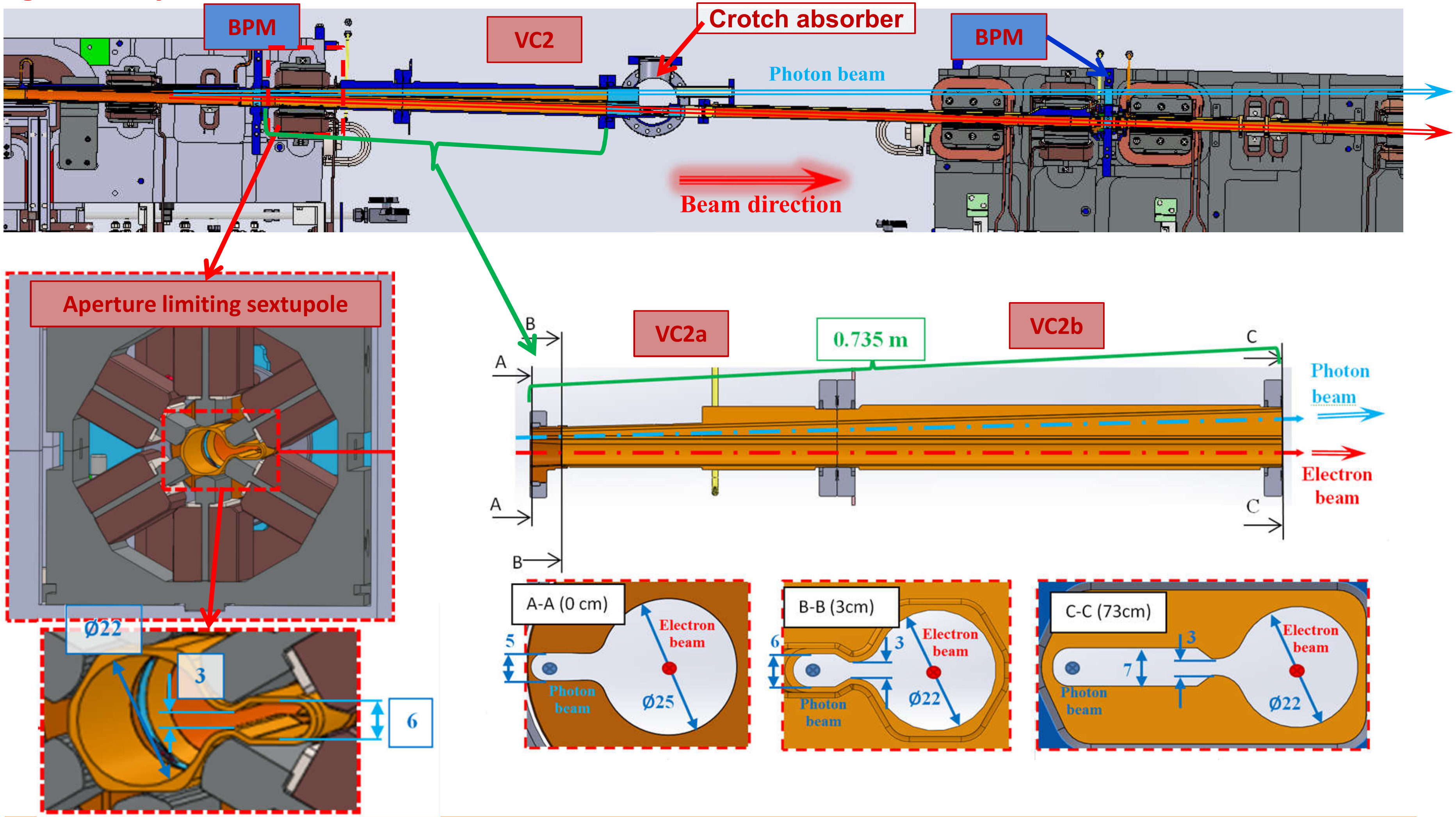






3. b) Complex vacuum chambers (R&D at CERN)

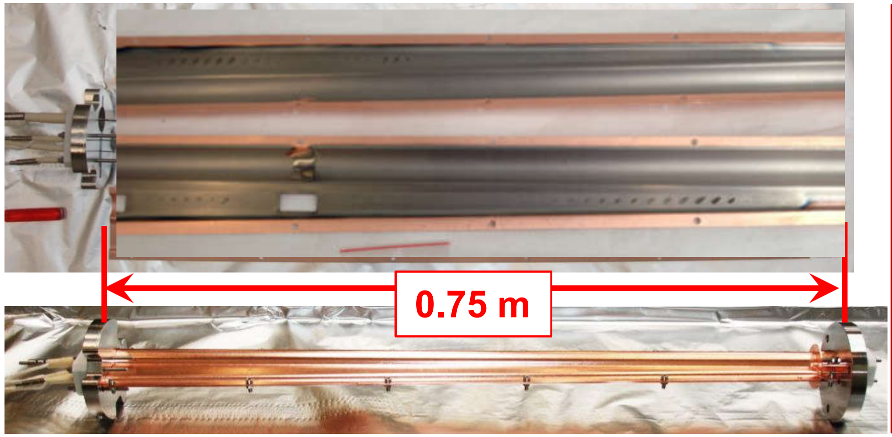
3 b). Establish coating procedure/technology and produce chambers of complex geometry: Vacuum chamber for beam extraction.



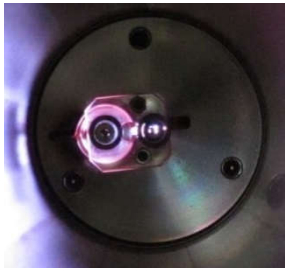
3. b) Complex vacuum chambers (R&D at CERN)

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

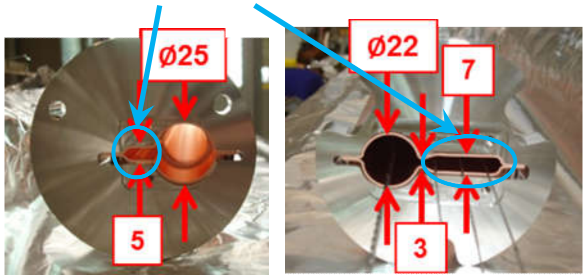
Chamber exit



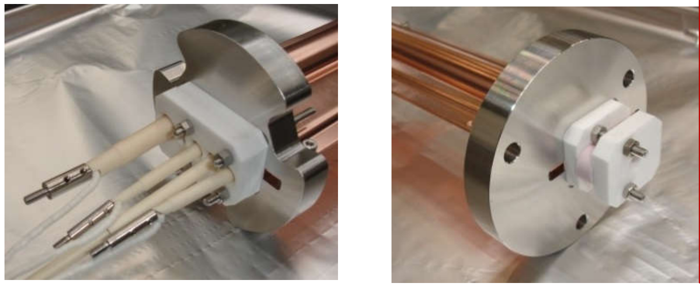
Chamber entrance



Glow discharge during coating



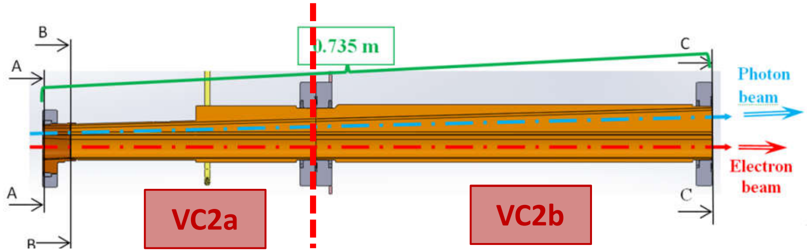
Chamber exit



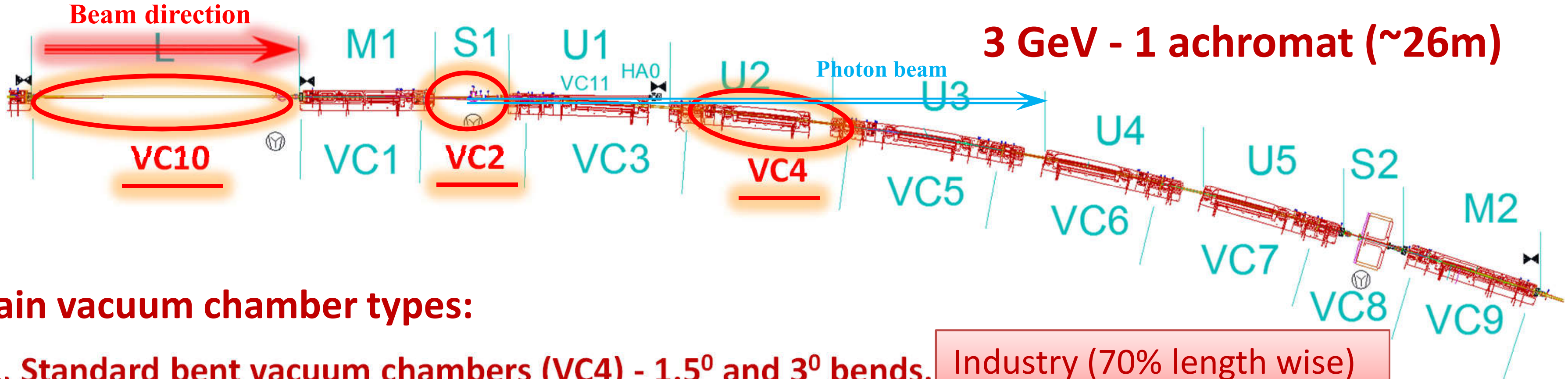
Chamber entrance

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

Due to difficulties with coating – chamber for coating was divided and coated in 2 runs.



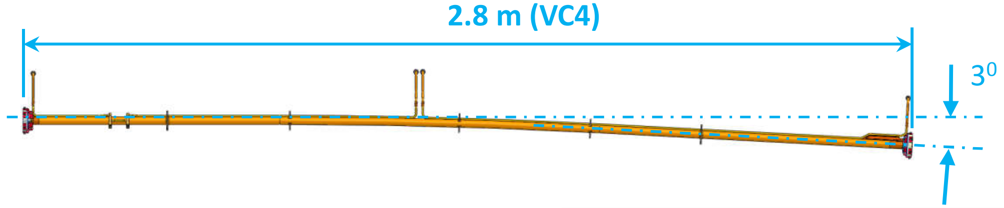
NEG-coating series production

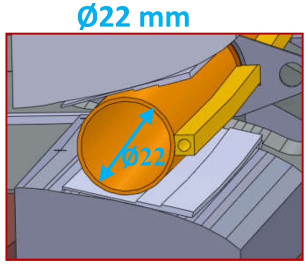


3 GeV - 1 achromat (~26m)

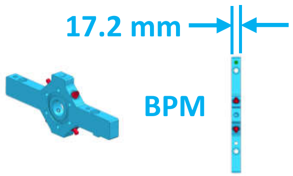
Main vacuum chamber types:

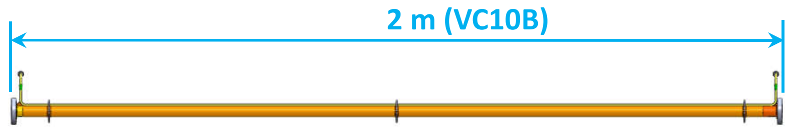
1. **Standard bent vacuum chambers (VC4) - 1.5^0 and 3^0 bends,** Industry (70% length wise)





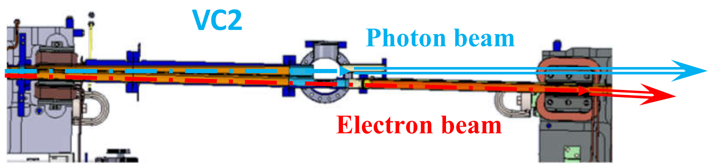
2. **Straight vacuum (VC10) chambers,** Collaboration with ESRF (15%)

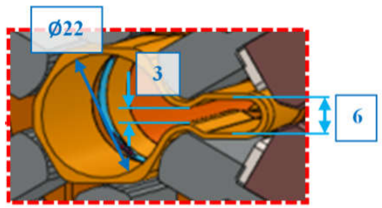




3. **Special vacuum chambers.**

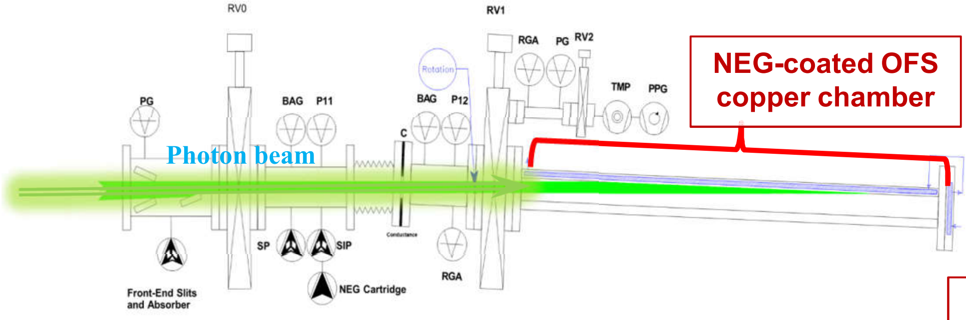
Collaboration with CERN (15%)

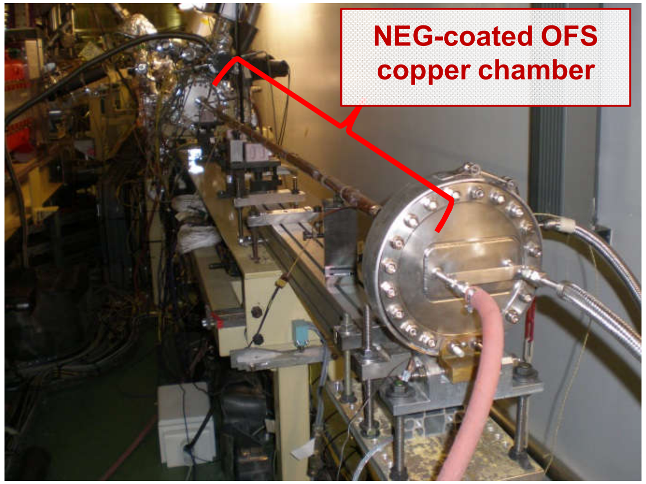




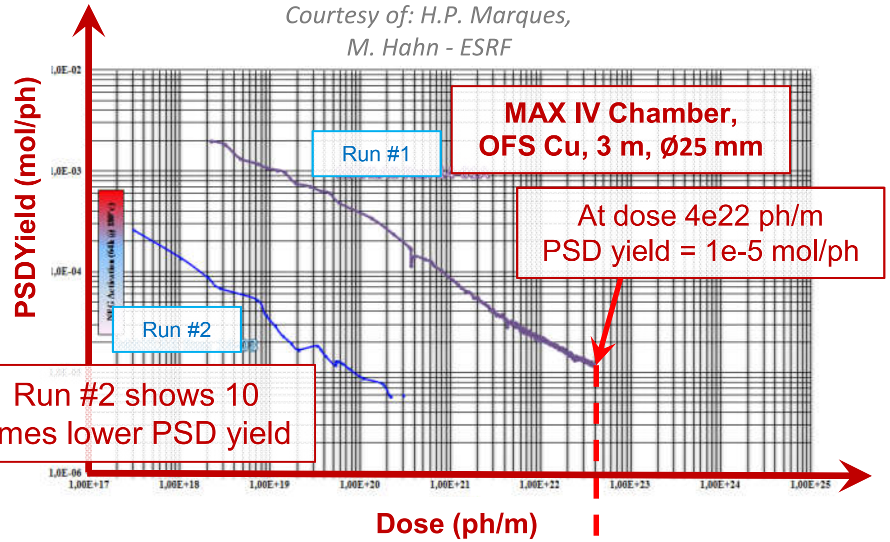
Activities at ESRF

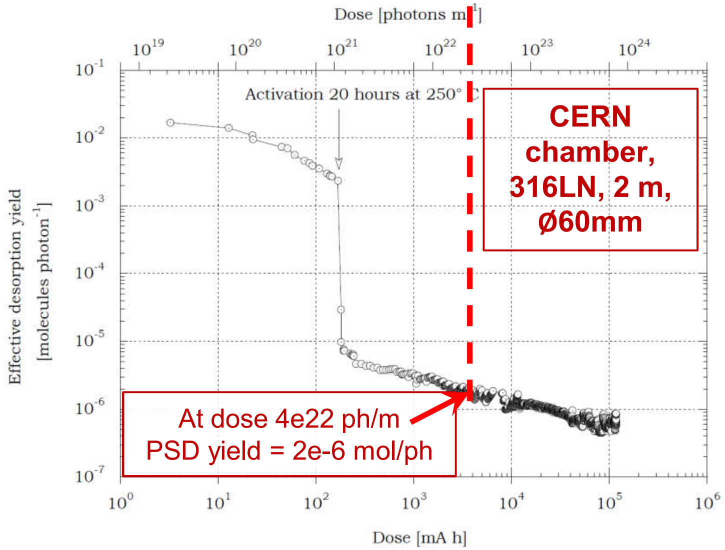
Photon stimulated desorption (PSD) measurements at ESRF (beamline D31), chamber after activation.





Courtesy of: H.P. Marques, M. Hahn - ESRF





'Synchrotron Radiation-Induced Desorption from a NEG-Coated Vacuum Chamber', P. Chiggiato, R. Kersevan

Measured PSD yield from Run #2 similar to what was measured before.

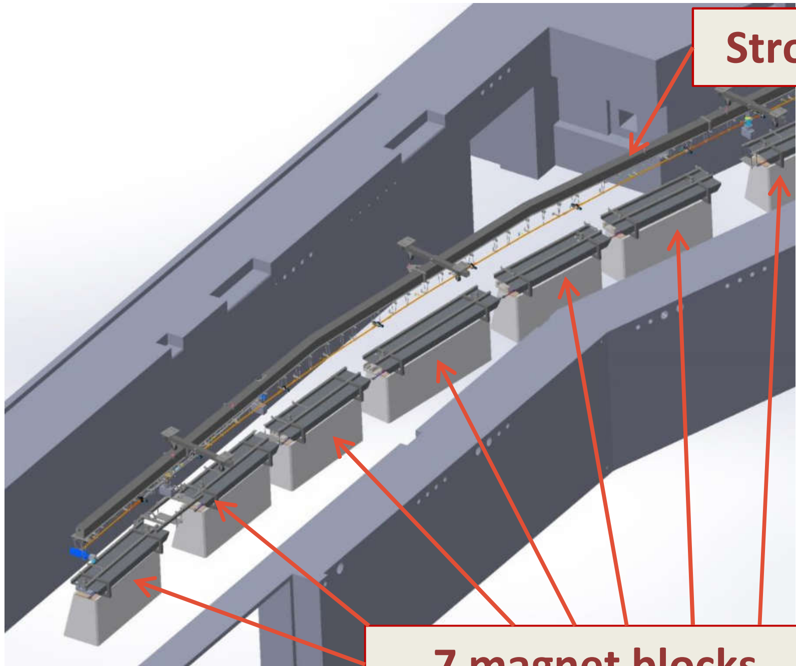
Installation procedure

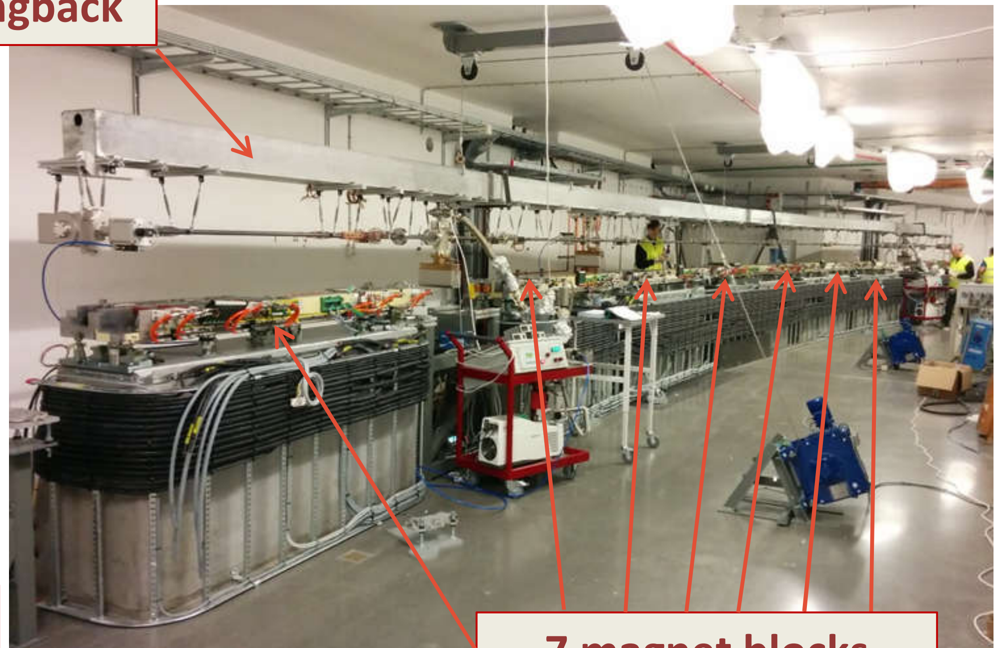
Installation of NEG-coated ring

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

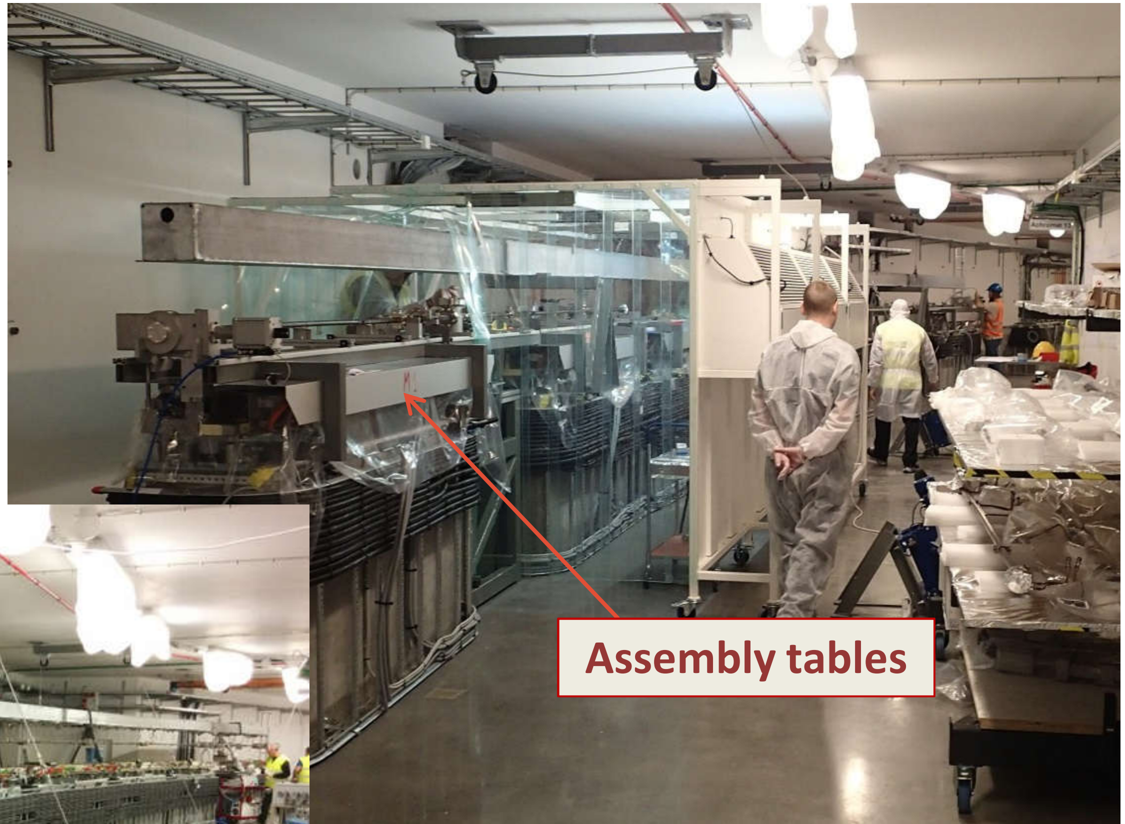
Installation done with help from Budker Institute of Nuclear Physics (BINP)

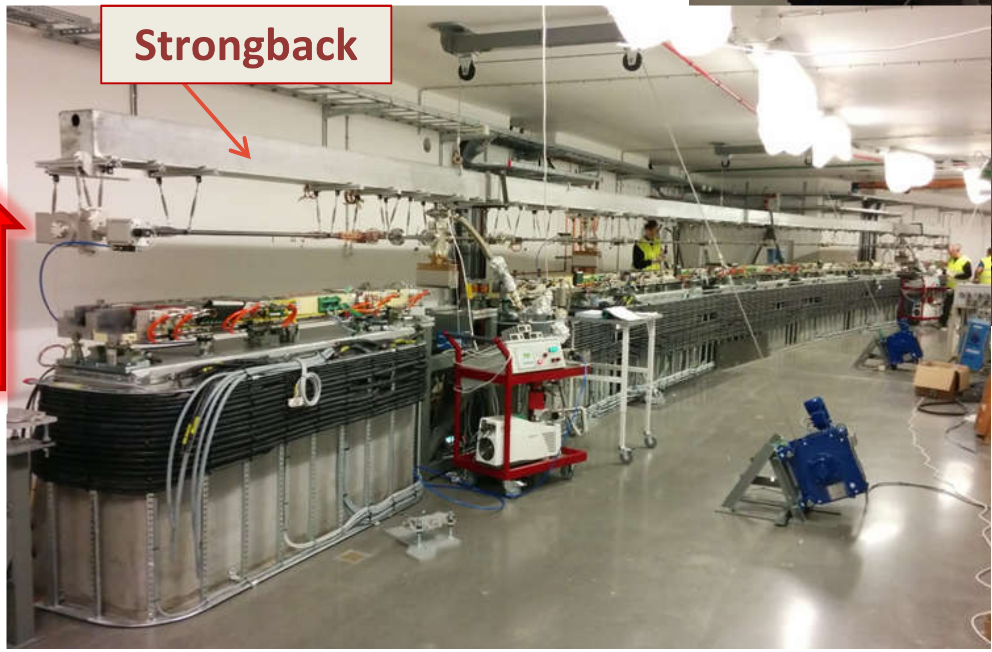




Installation procedure

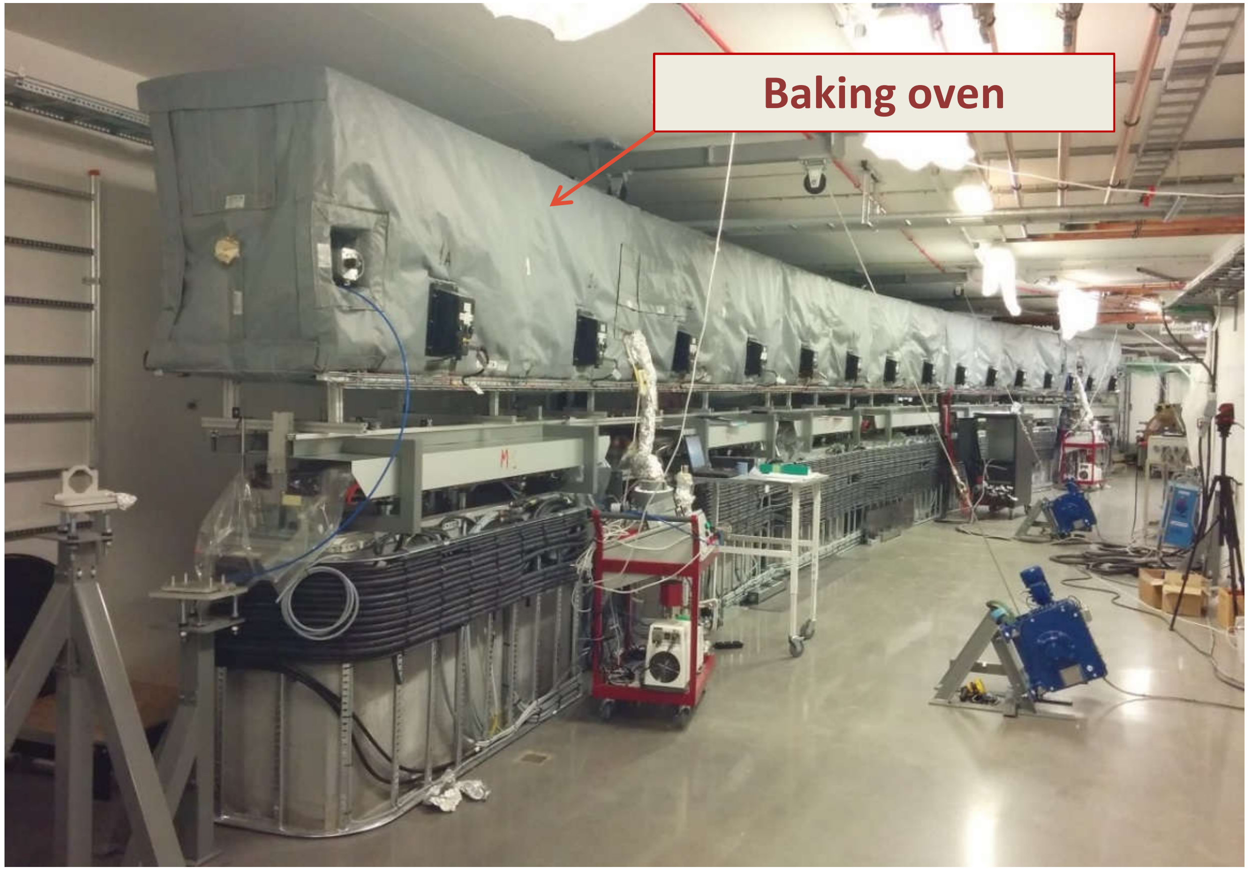
- Assembly insitu (above magnets),
- Pumpdown and testing,
- Lifting,





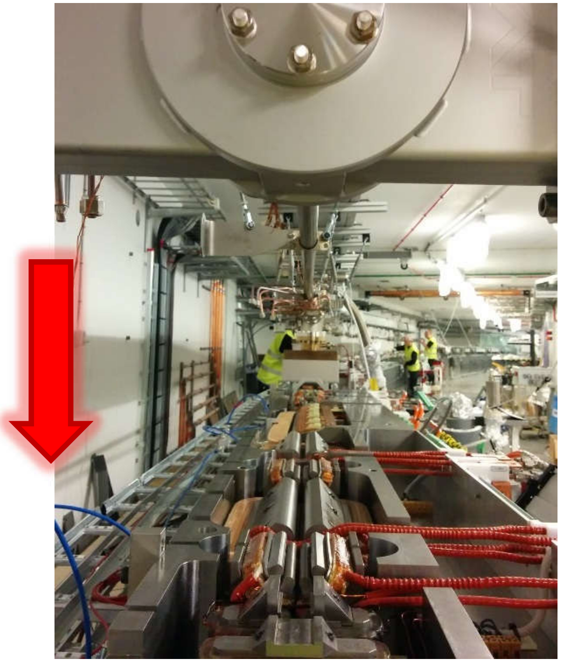
Installation procedure

- Baking (1 day), NEG activation (1 day),

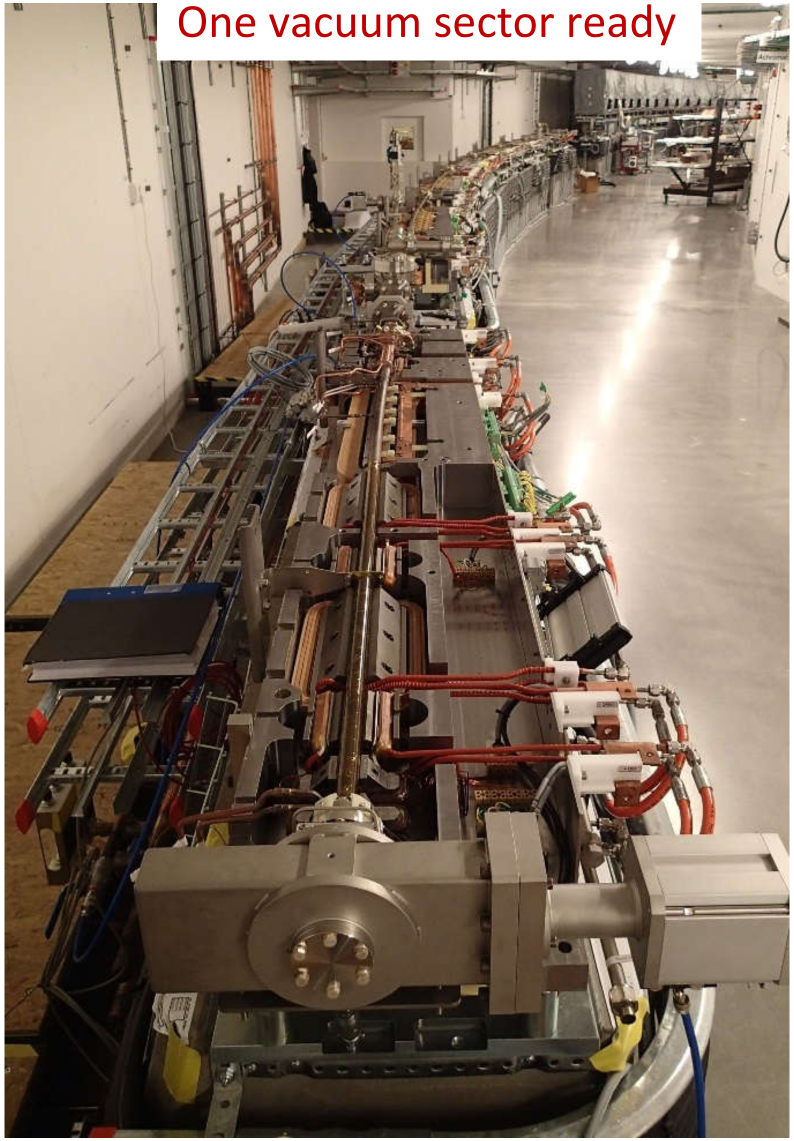


Installation procedure

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



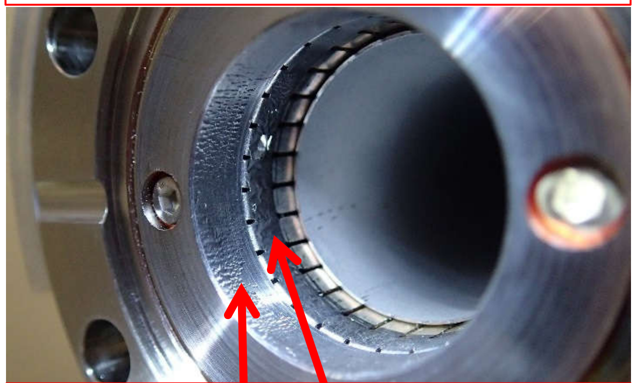
One vacuum sector ready



Coating non-conformities

All the chambers were inspected at site before installation.

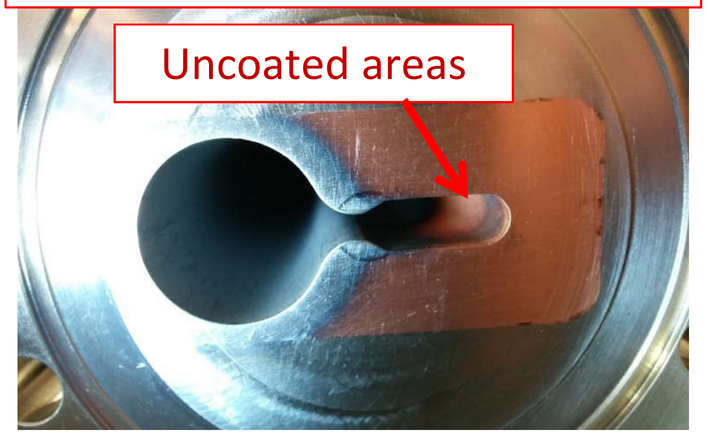
Observed peeling-off:
At RF fingers Cu-Be insert and Cu end piece. RF fingers and Cu end were not shielded properly during coating.
Solution: new pieces ordered and replaced (without coating).



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.



3 GeV commissioning progress

3 GeV storage ring commissioning started in August 2015

Average base pressure:

- Gauges 2e-10 mbar,
- Ion pumps under range.

Accumulated beam dose

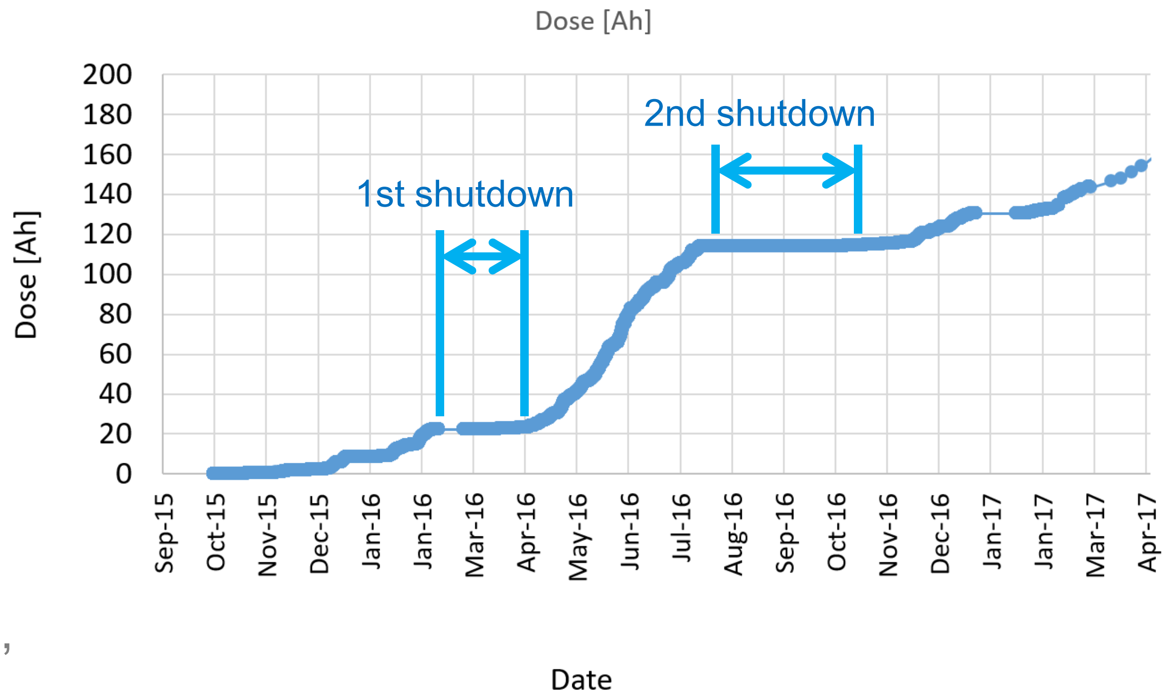
- 210 Ah (June 2017).

1st shutdown March 2016:

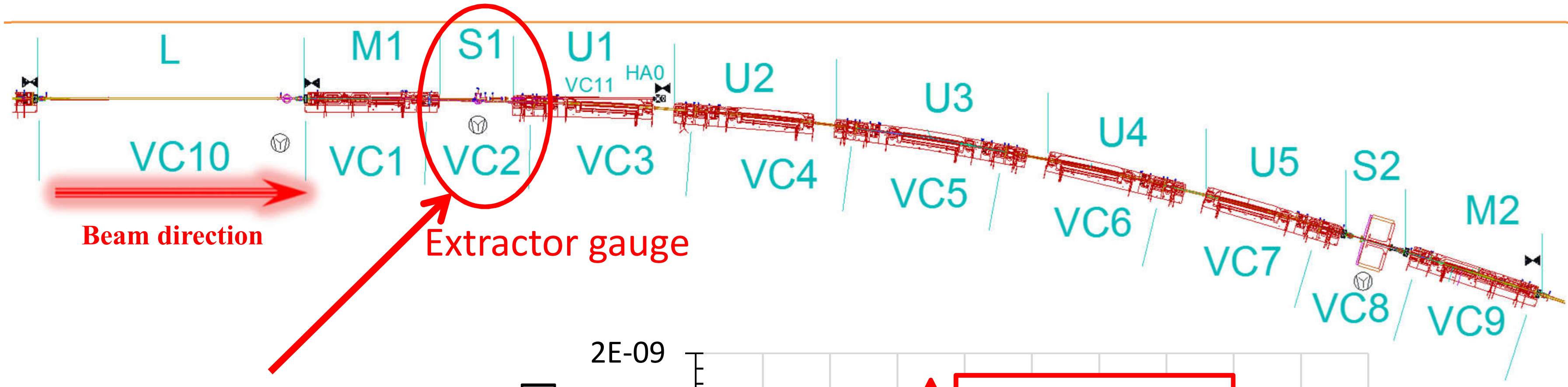
- 2 in-vacuum undulators,

2nd shutdown August 2016:

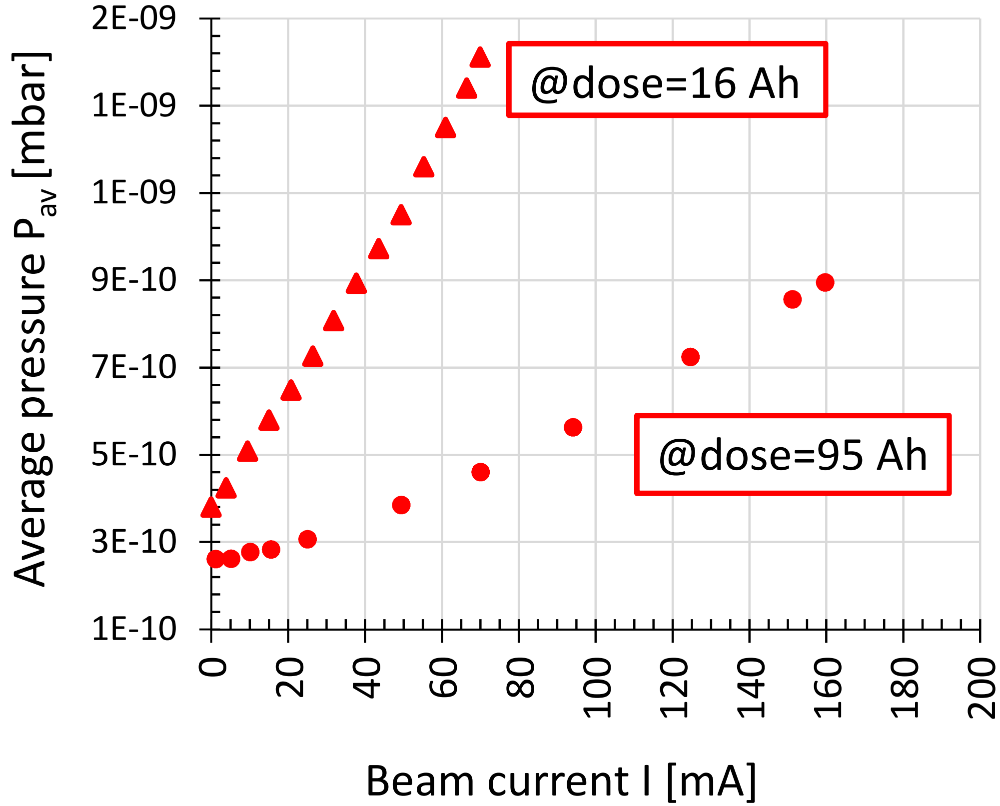
- 2 EPU chambers (8x36mm),
- In-vacum wiggler.



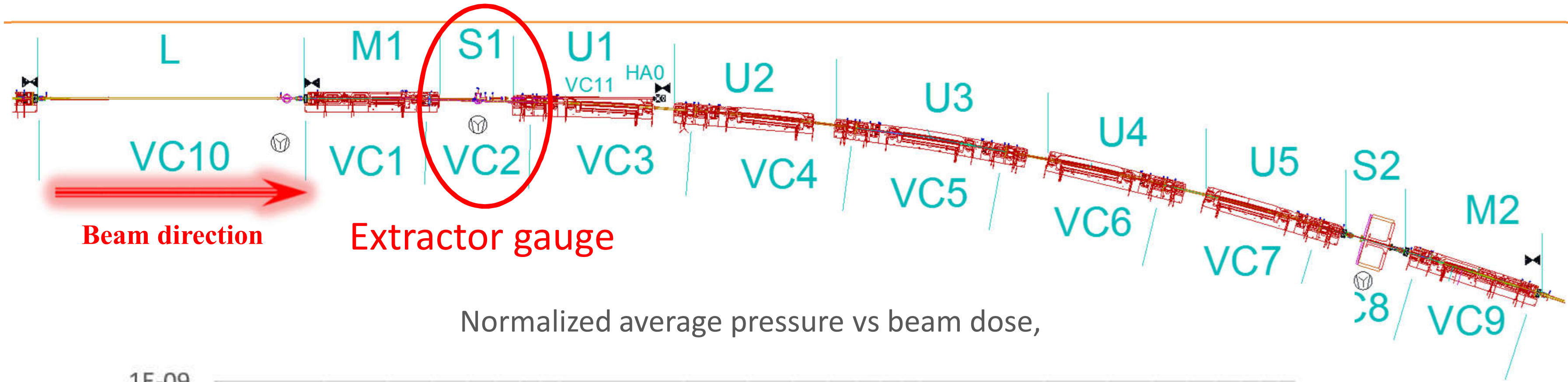
Pressure vs beam current, dose



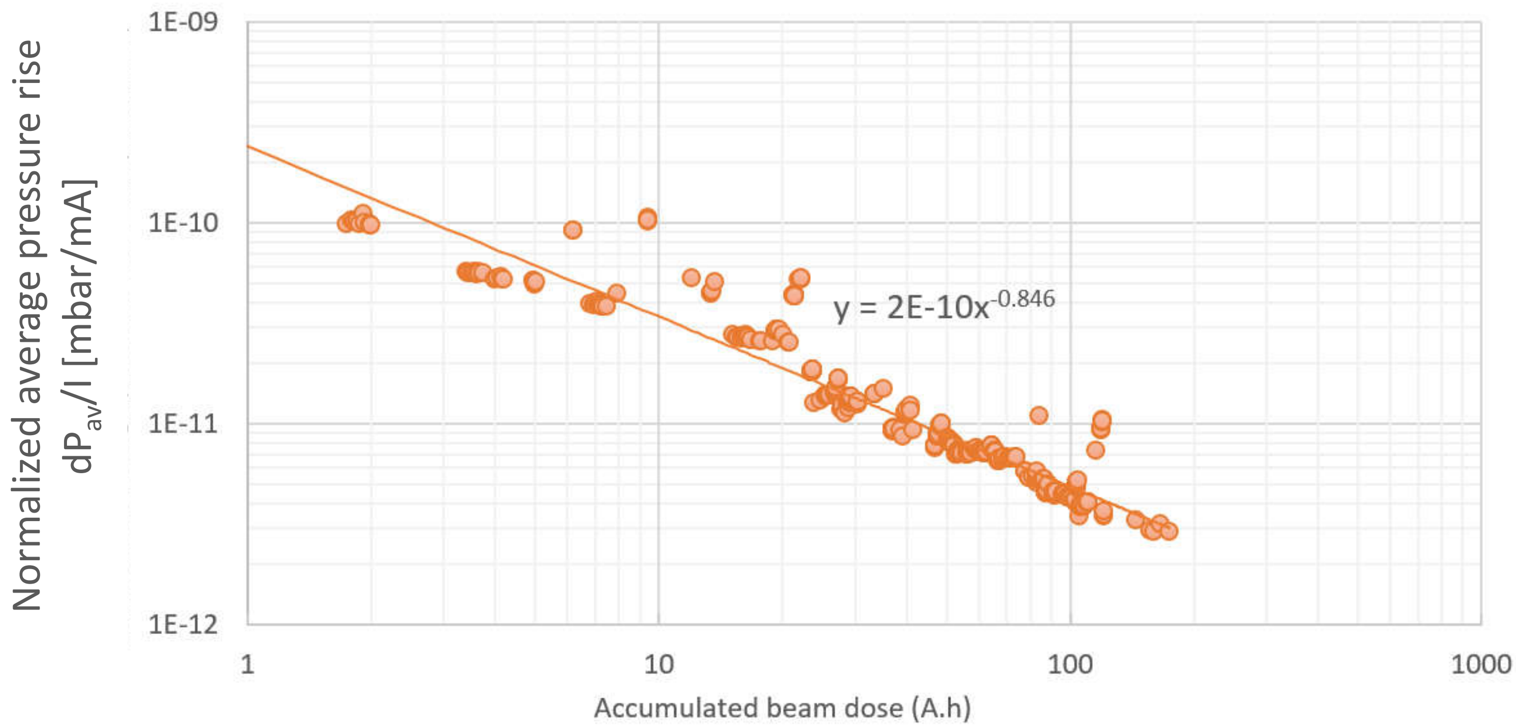
Pressures at dose 16 Ah and 95 Ah during beam ramp up. (pressure recorded by extractor gauge at **not** NEG coated **crotch absorber** in S1)



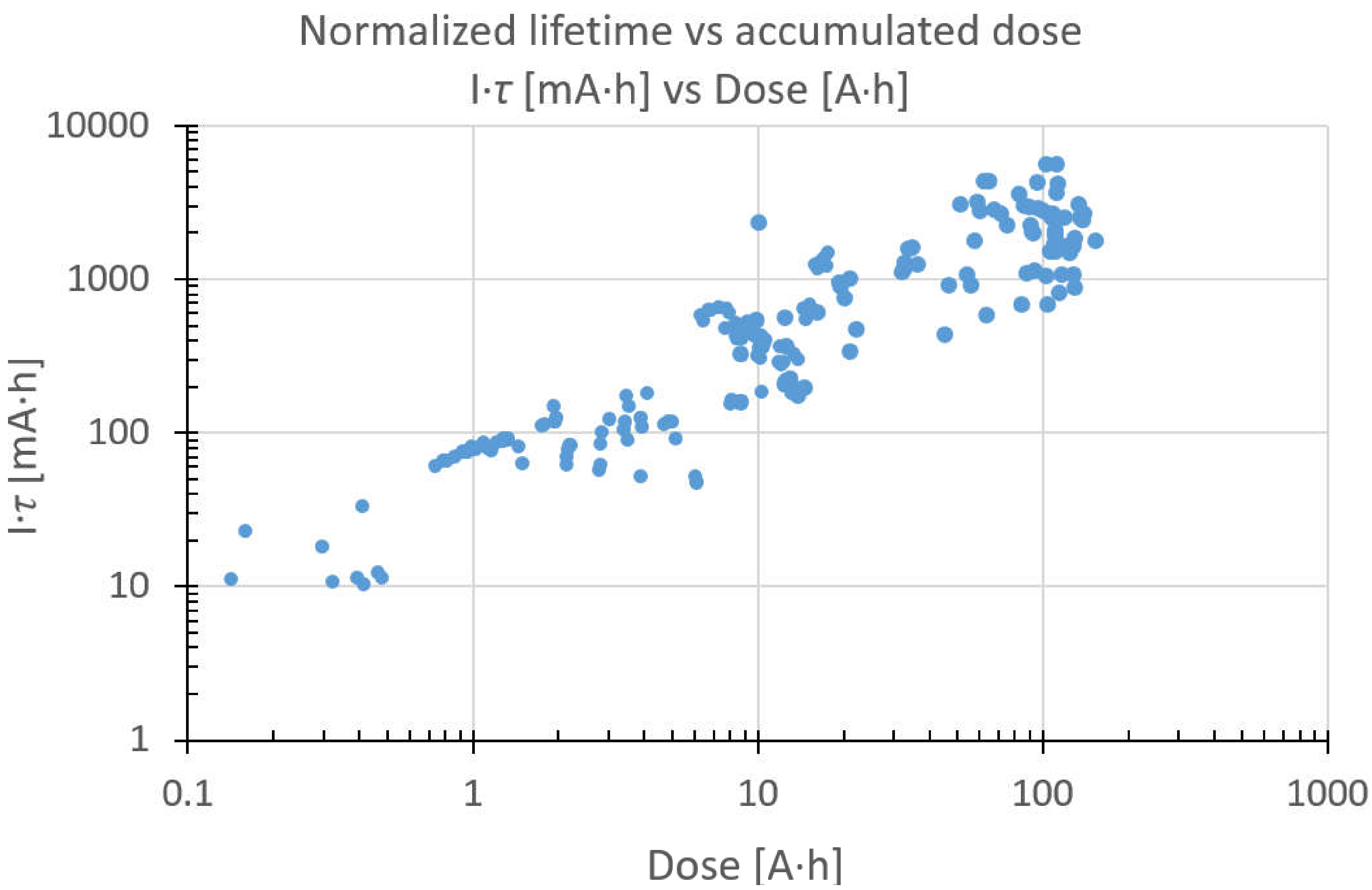
Vacuum conditioning curve



Normalized average pressure vs beam dose,

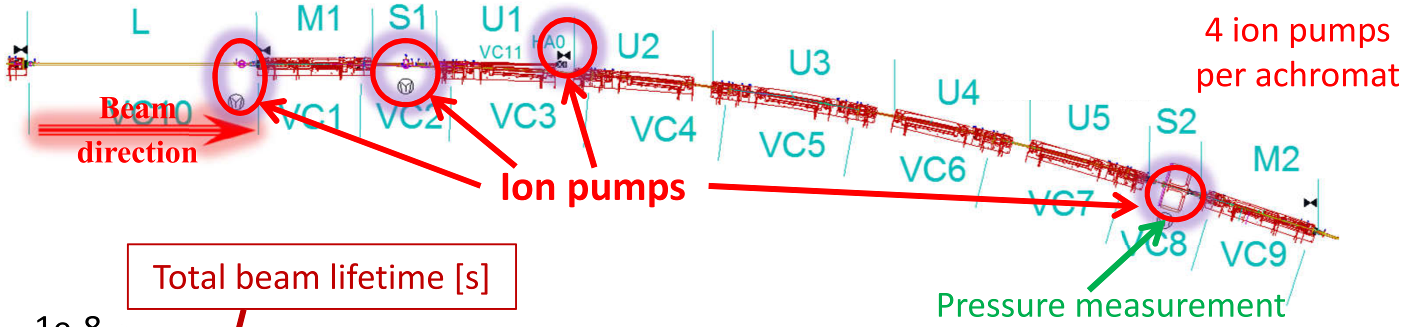


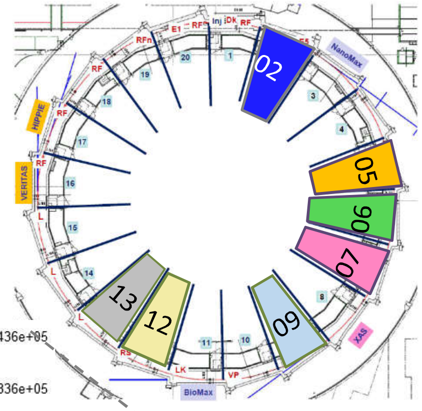
Lifetime evolution

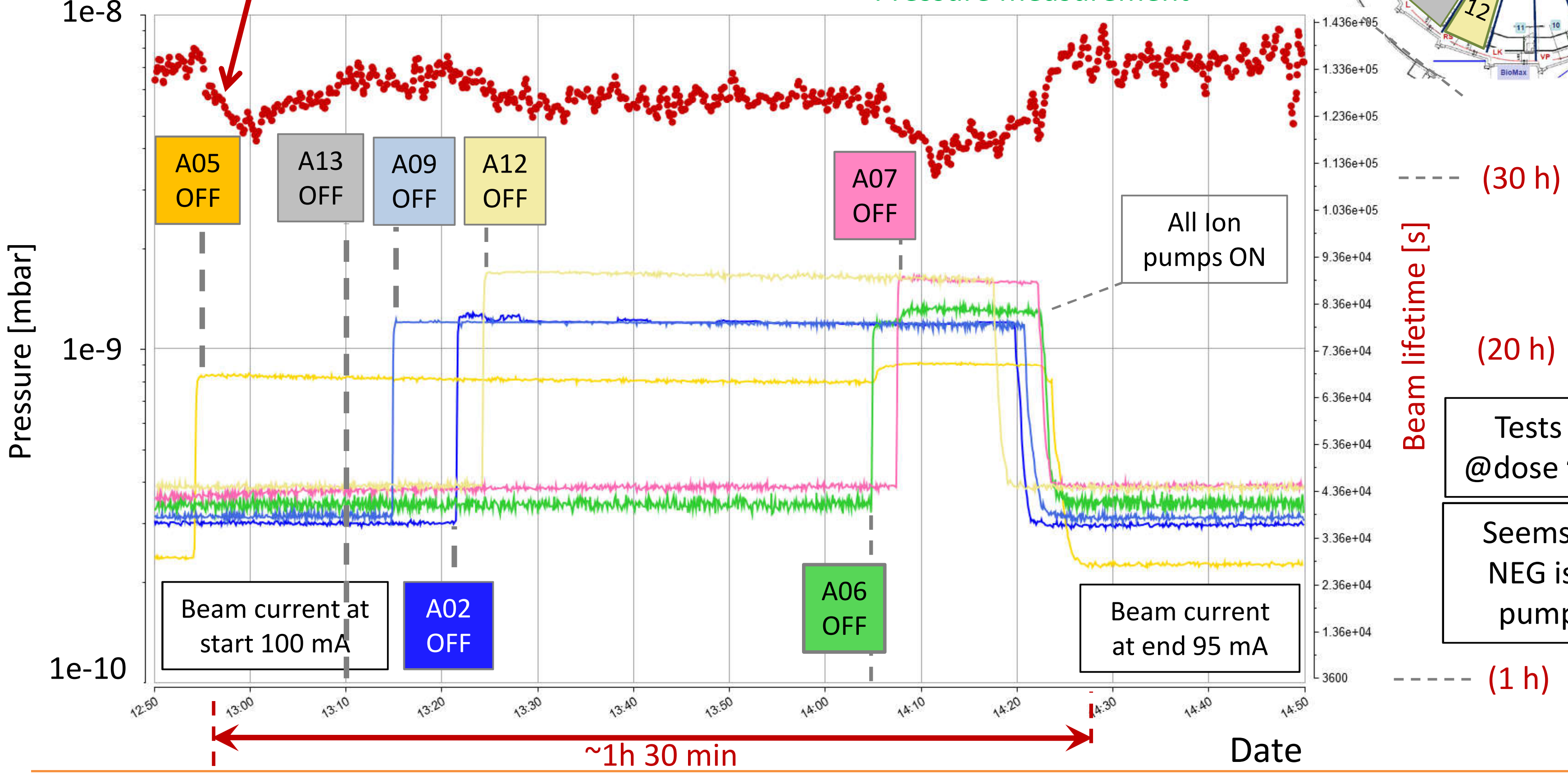


Beam lifetime up to 6 Ah,   Maximum stored beam current 198 mA

3 GeV ring Lifetime tests



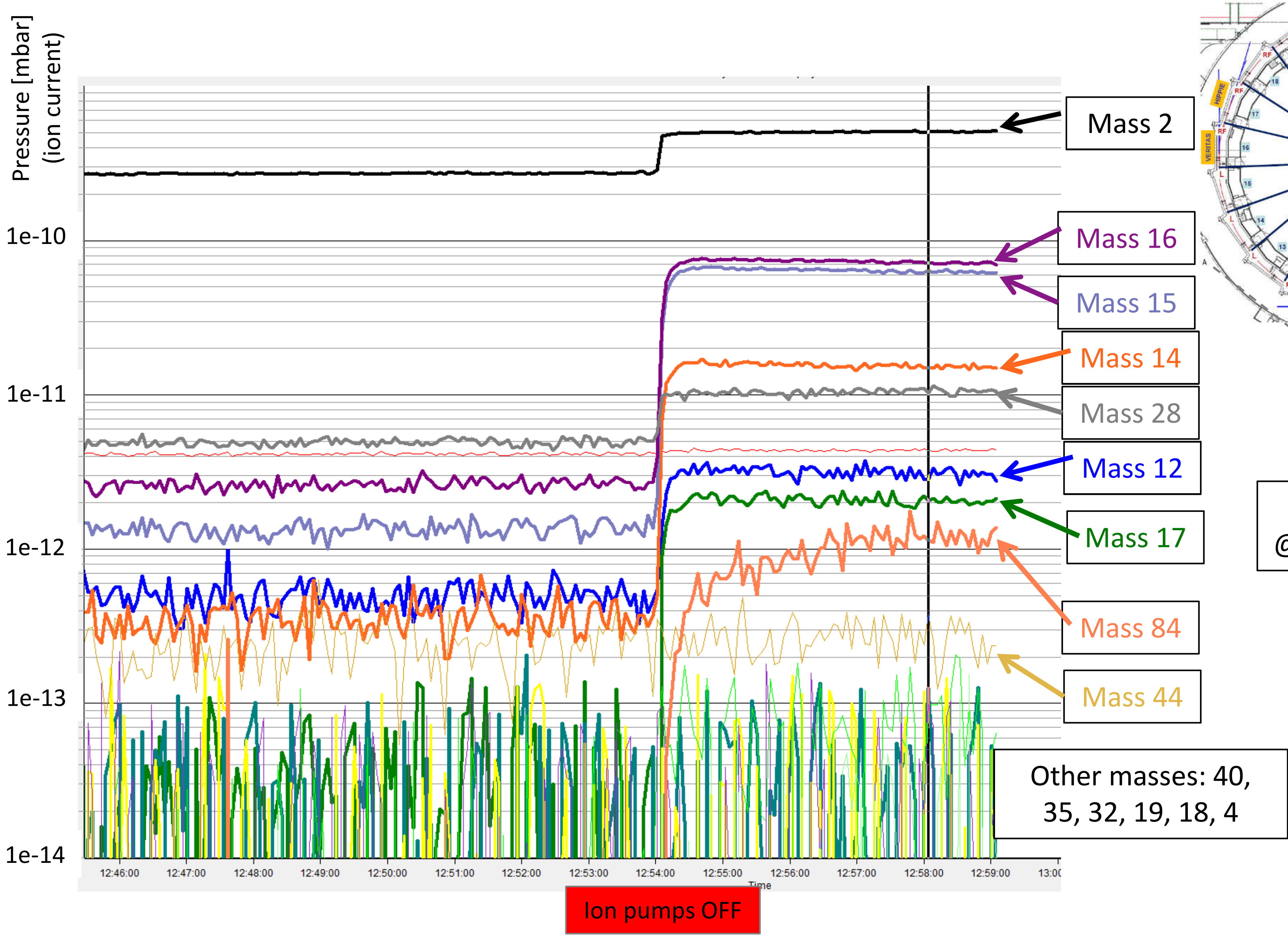


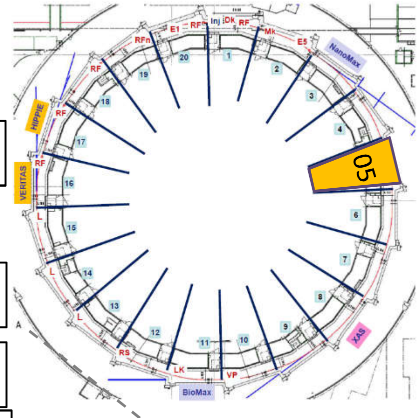


Tests done @dose ~190Ah

Seems that NEG is still pumping

3 GeV ring Lifetime tests - RGA



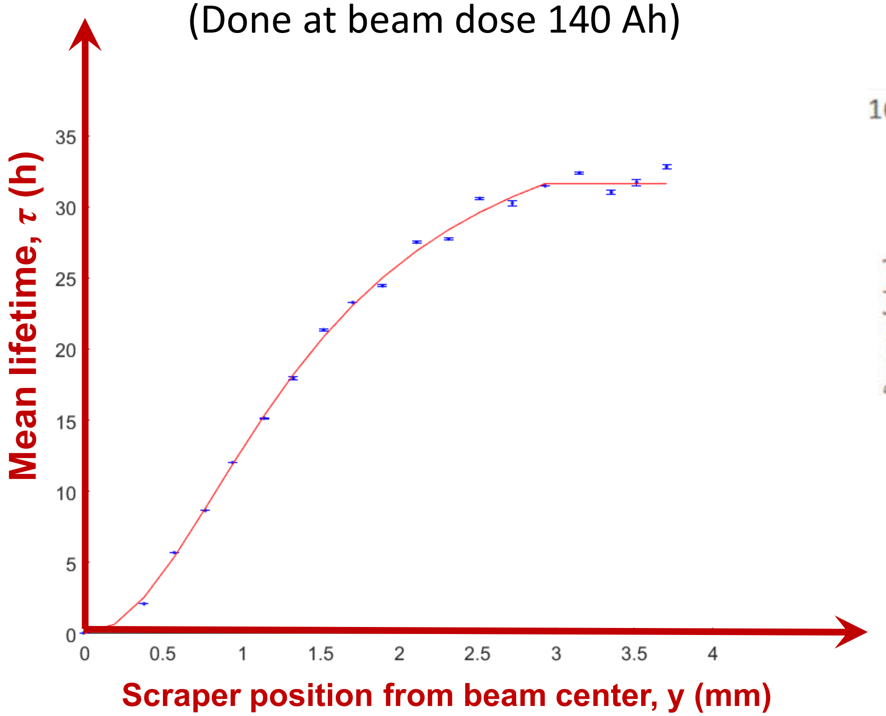


RGA in A05

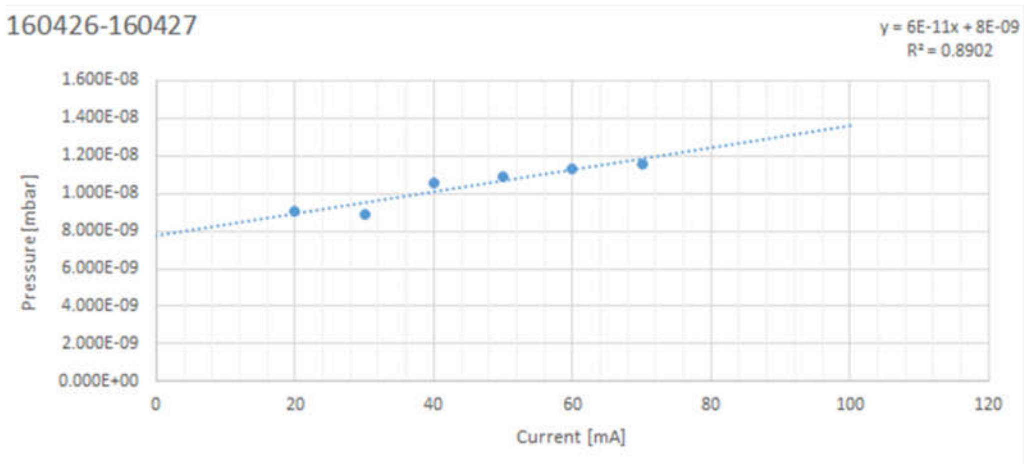
Tests done @dose ~190Ah

Scraper measurements

Mean lifetime vs vertical scraper distance from the beam center (Done at beam dose 140 Ah)



Total average pressure along the beam path (contribution from all gasses based on the RGA spectra Z^2 =5.77)

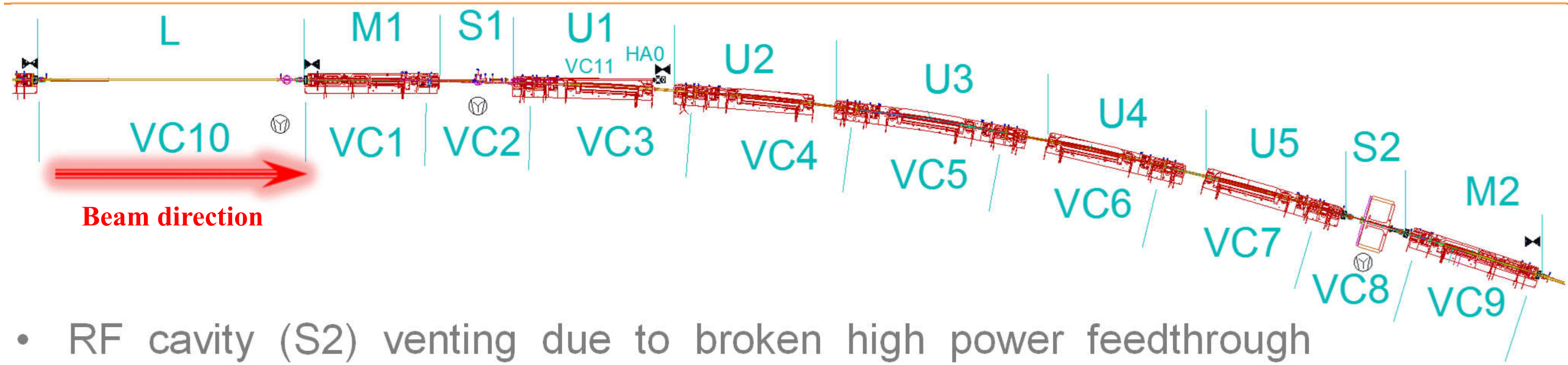


At 70 mA (dose 140 Ah):

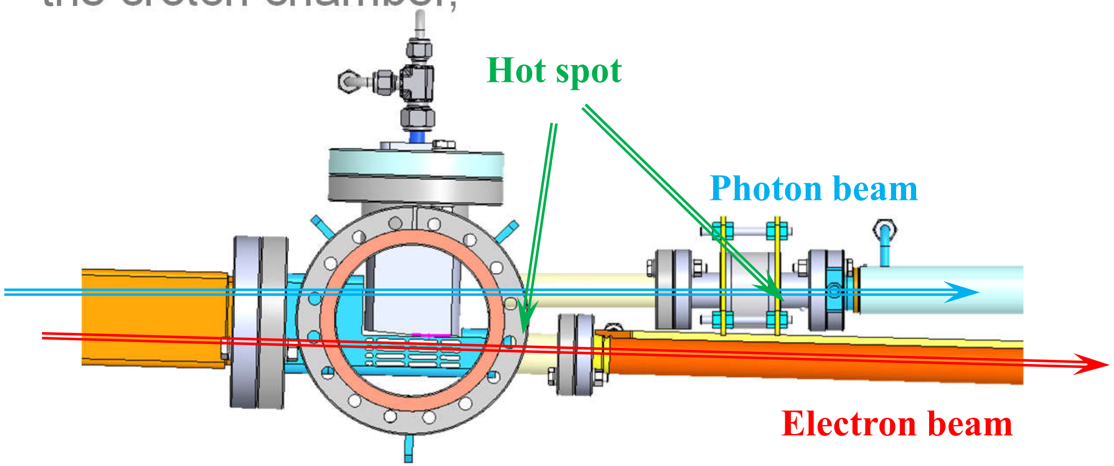
Elastic beam lifetime	$\tau_{elastic}$ = 163 h
Inelastic beam lifetime	$\tau_{inelastic}$ = 104 h
Touschek lifetime	$\tau_{Touschek}$ = 63 h

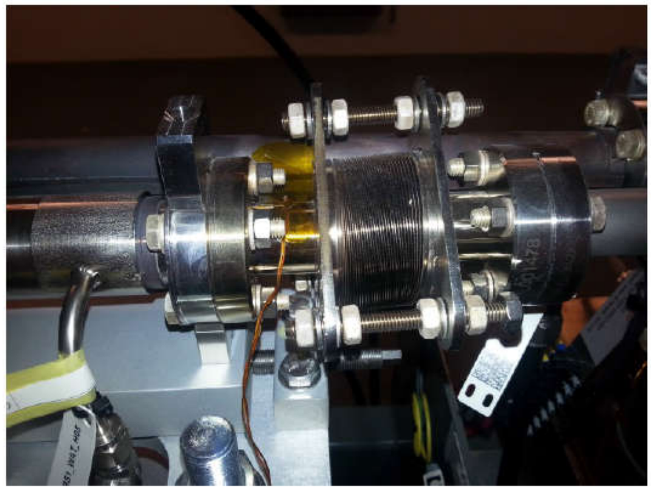
Pressure as seen by the beam 7.3e-09 mbar

Problems

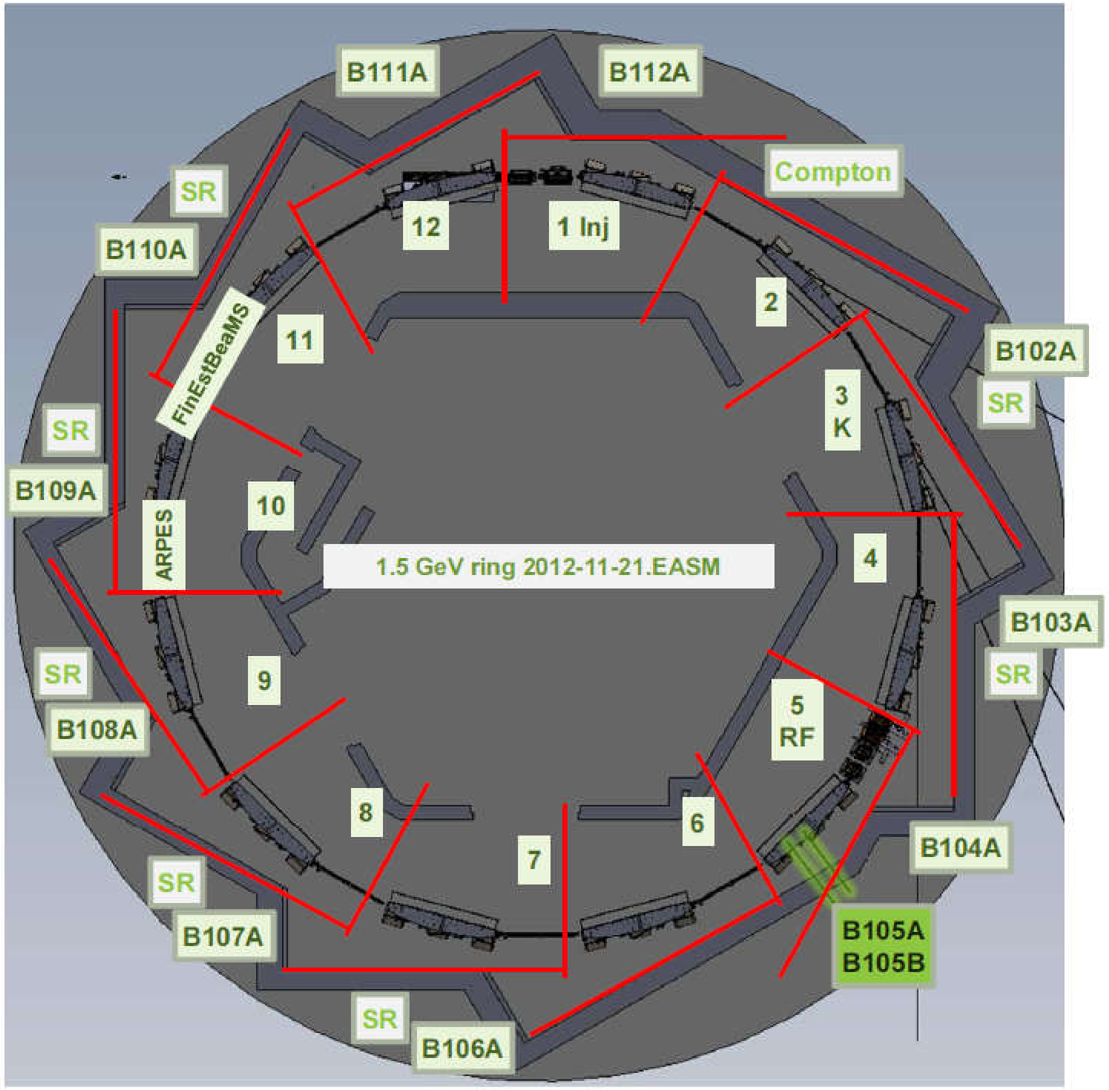


- RF cavity (S2) venting due to broken high power feedthrough during conditioining (with closed valves). Now cavity is removed from the ring and dummy chamber placed as could not be run with high power anymore. Now awaits conditioning outside the ring.
- Hot spots in proximity of crotch absorber (S1), mis-positioning of the crotch chamber,





1.5 GeV storage ring layout

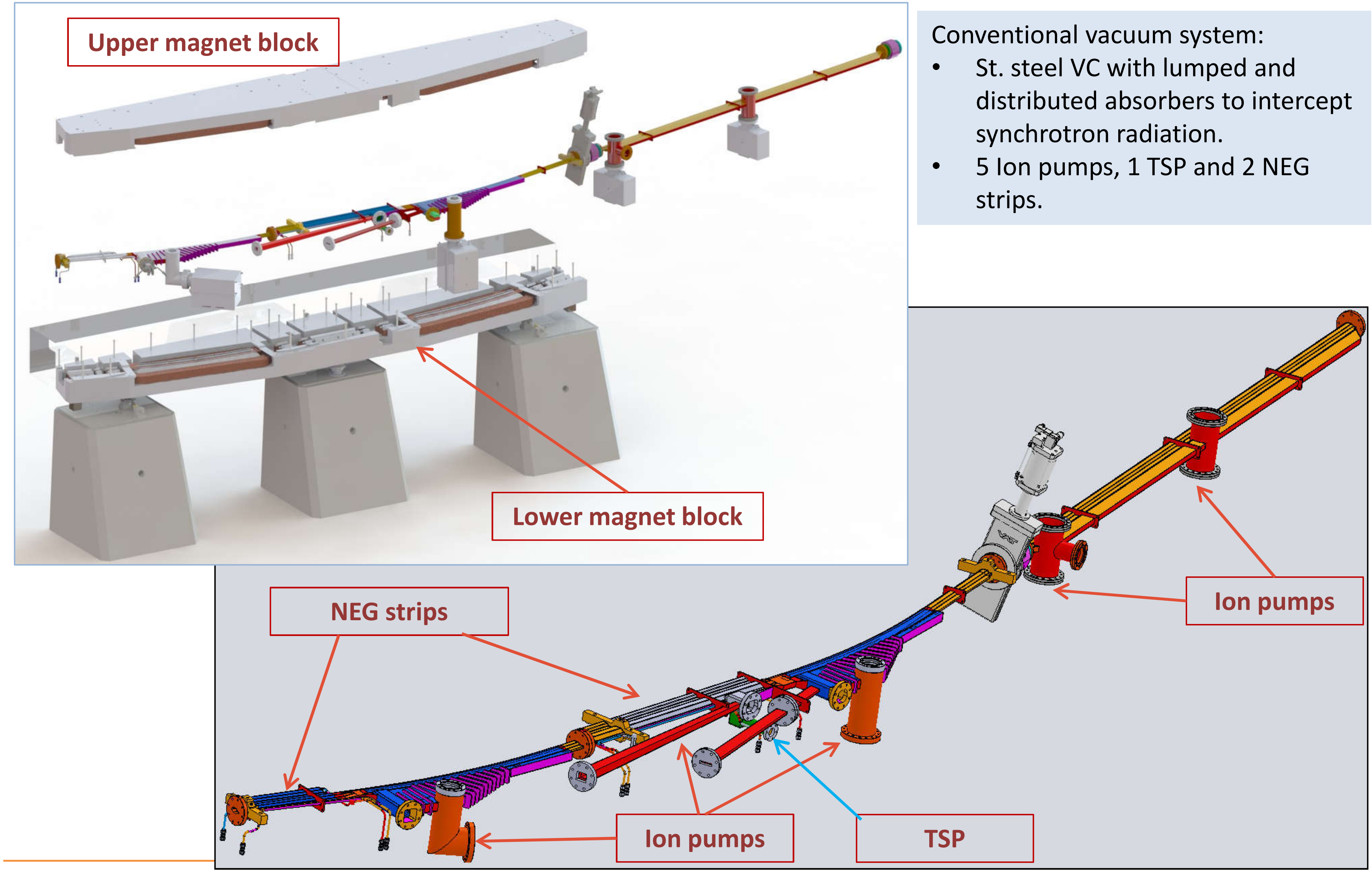


- 96m circumference
- 12 DBA.
- 12 straight sections of which, all for ID, except:
  - Ach. 1: injection
  - Ach. 5: RF straight
    Ach. 3: inj. Kicker +ID

1.5 GeV storage ring vacuum system

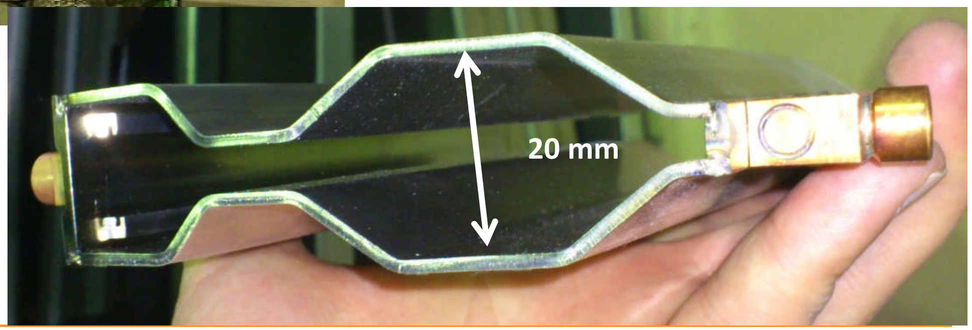
Conventional vacuum system:

- St. steel VC with lumped and distributed absorbers to intercept synchrotron radiation.
- 5 Ion pumps, 1 TSP and 2 NEG strips.



1.5 GeV storage ring vacuum system

Vacuum chamber during the testing.

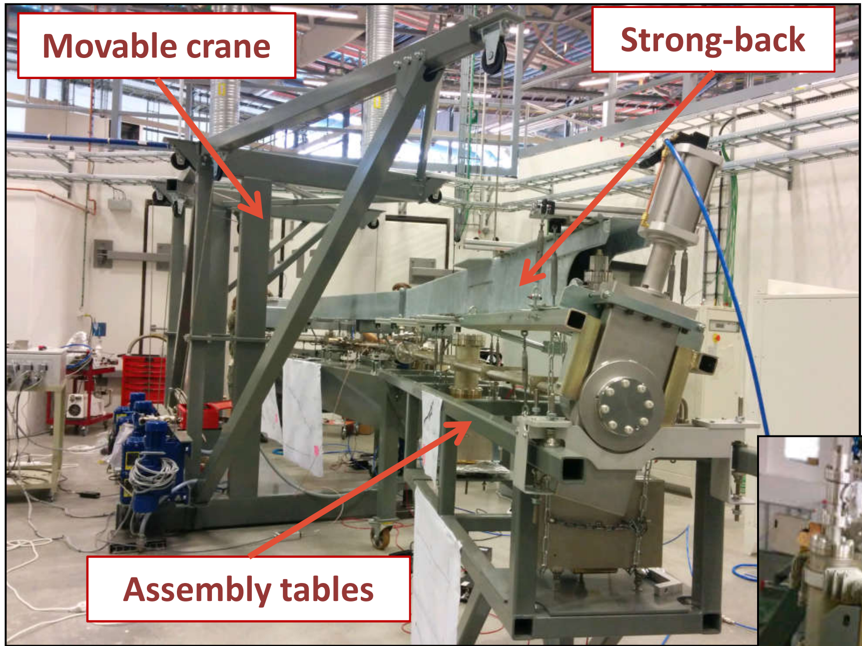


1.5 GeV storage ring installation

Assembly outside the tunnel

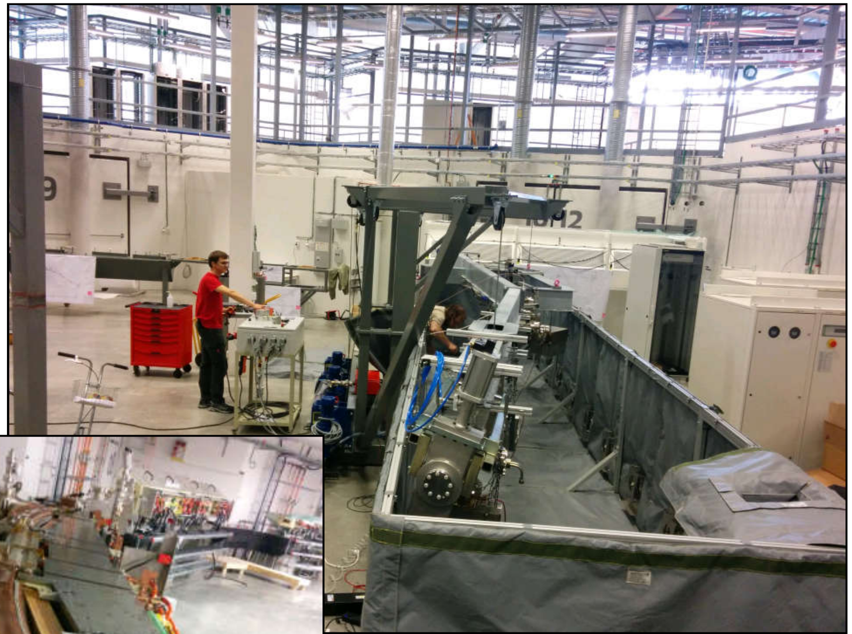
Movable crane

Strong-back



Assembly tables

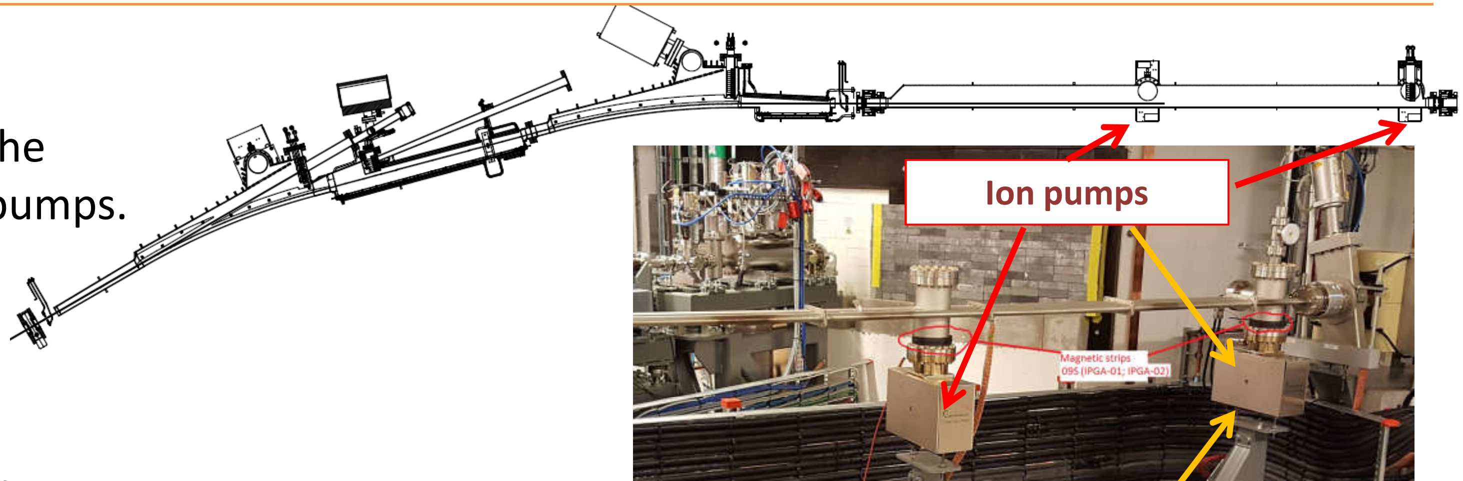
Baking in-situ



Vacuum chambers installed in side the magnet blocks

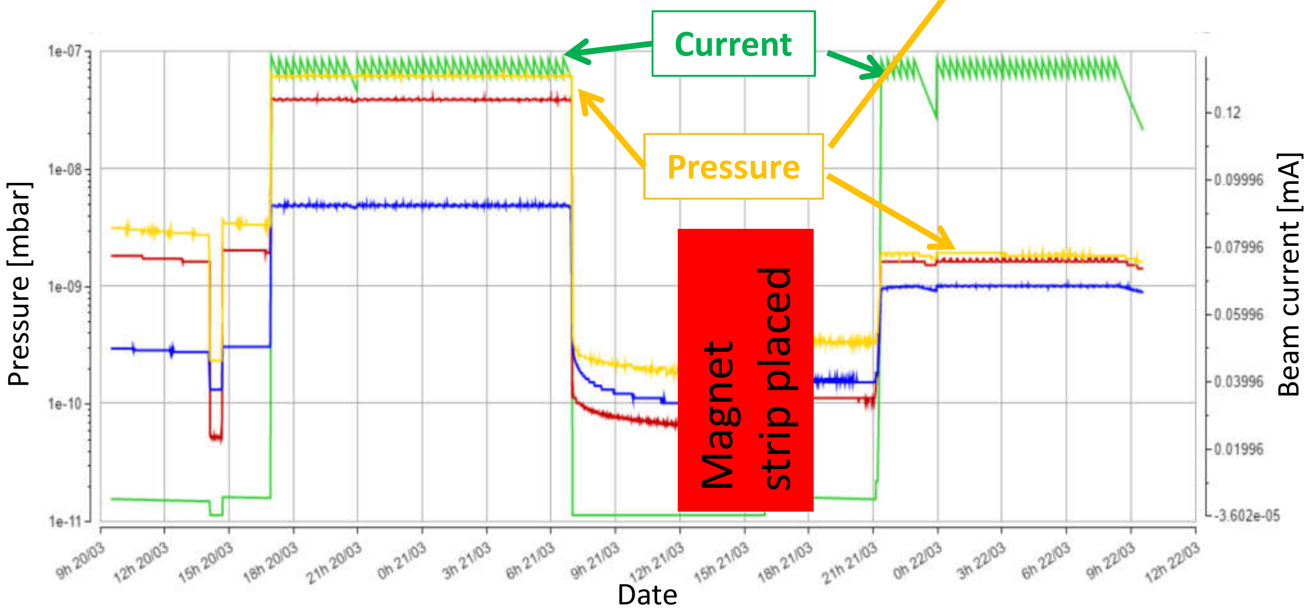
Ion pump pressure reading issues

Strong effect from photoelectrons in the reading of the ion pumps.



Magnet strip placed in some ion pumps to prevent photoelectrons entering ion pumps.

Pressure reading reduced 32 times.



Conclusions and future developments

Conclusions:

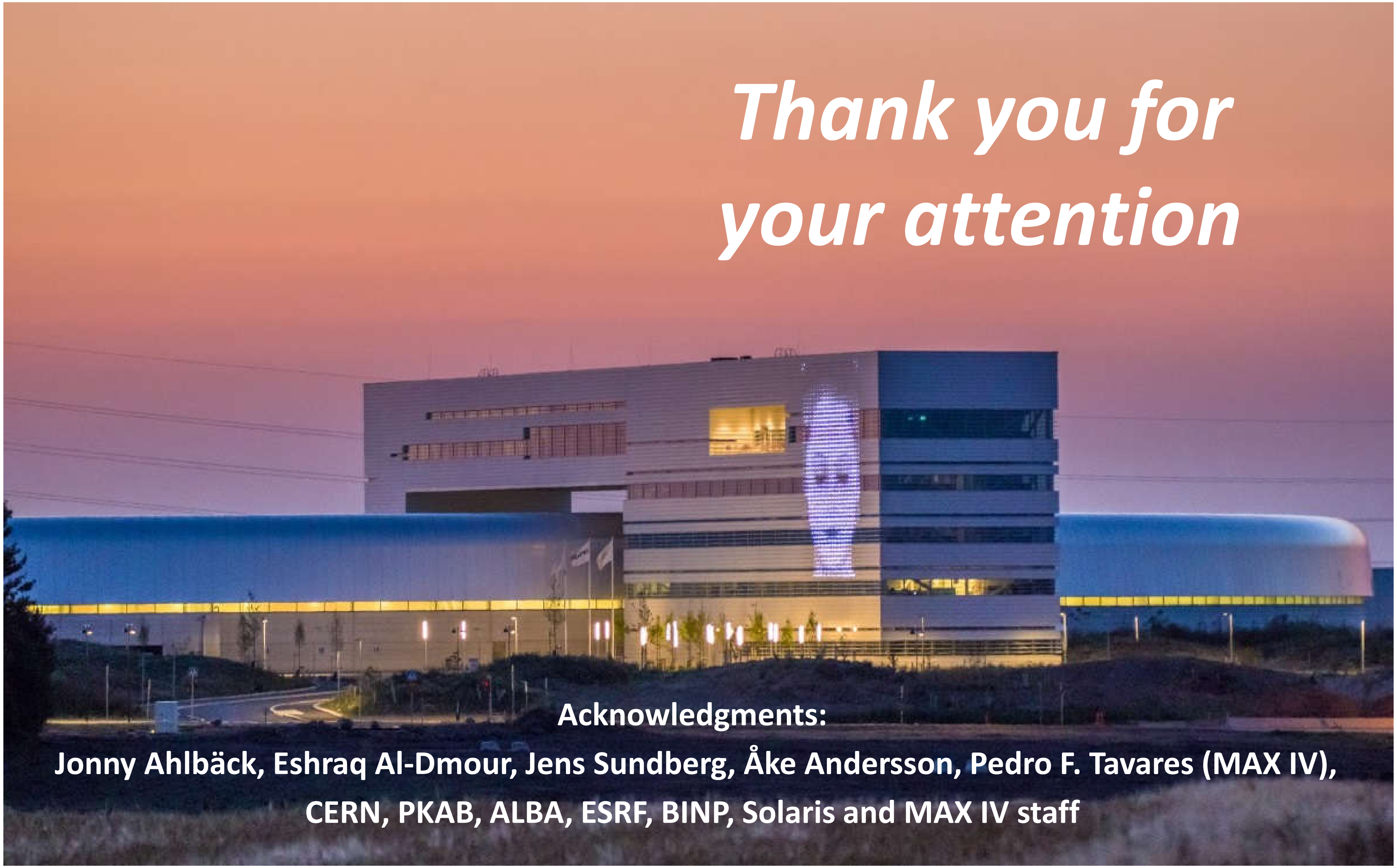
- The application of NEG coating has to be considered from the beginning of machine design as it has many implications (geometry, manufacturing, cleaning etc),
- Hot-spots from SR due to mis-positioning of some vacuum chambers,
- Ion pumps strongly influenced by photoelectrons (up to factor of 40),
- Discrepancy between pressure at the extraction/cold cathode gauges and average beamlife time pressure estimation,
- What is the behavior of NEG film at presence of synchrotron radiation?

Upgrades considered for synchrotron storage rings:

- Vacuum chamber outer diameter 10 mm,
- Compact vacuum system design,
- Very low impedance flange/bellow assemblies,
- Distributed pumping, low PSD.

Development needed for future storage rings:

- Coating of 8 mm aperture, long, bend chambers,
- Effective thin layer in-situ baking system (for robust re-activation and faster installation),
- Handling of flexible, delicate and small vacuum pipes,
- Study new materials possible for chamber manufacturing,
- New methods of coating (electroforming).



Thank you for your attention

Acknowledgments:

Jonny Ahlbäck, Eshraq Al-Dmour, Jens Sundberg, Åke Andersson, Pedro F. Tavares (MAX IV), CERN, PKAB, ALBA, ESRF, BINP, Solaris and MAX IV staff