Overview and Challenges of the Vacuum Systems of Diffraction Limited Storage Rings

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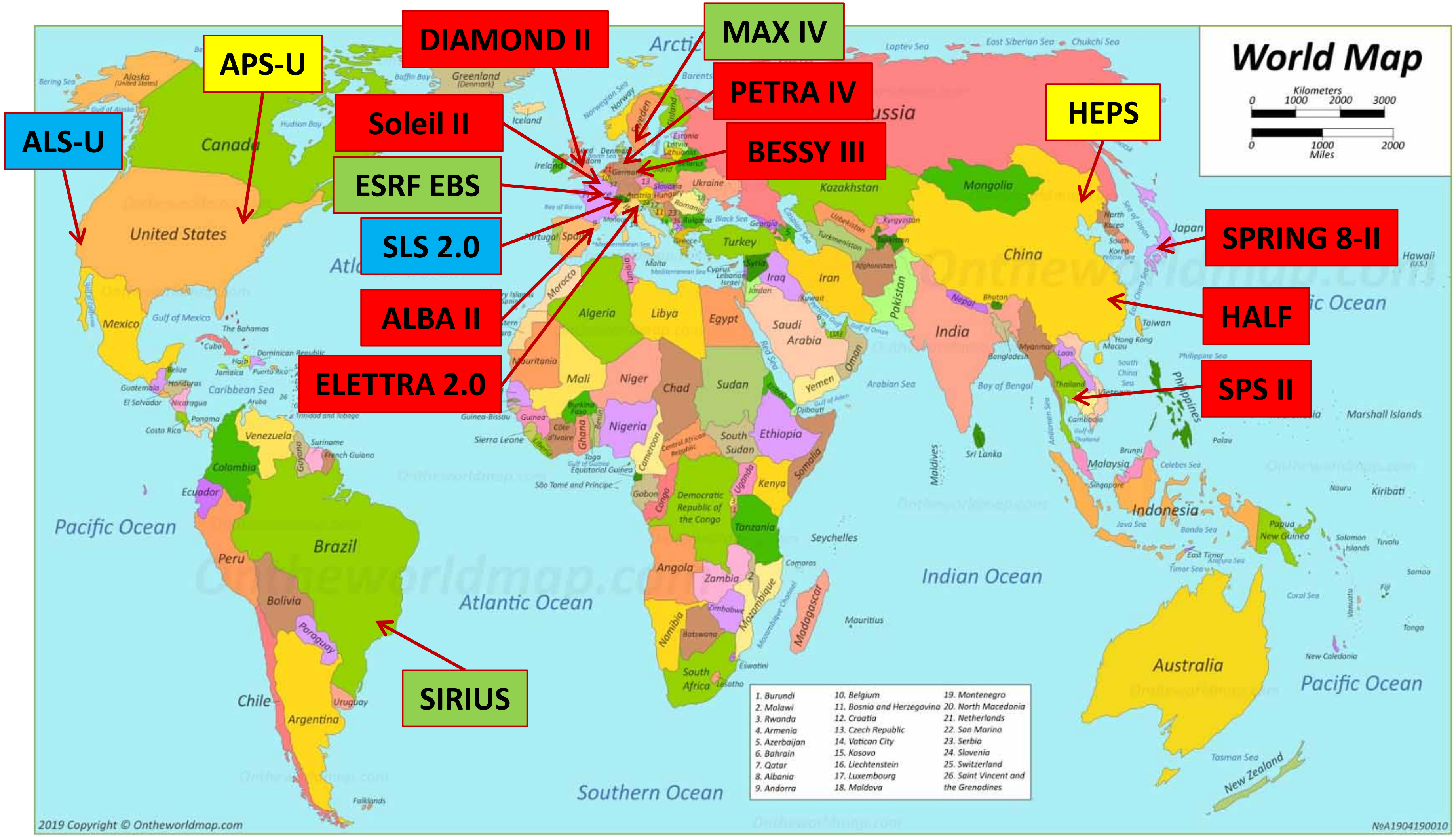
Contents

- Introduction,
- Vacuum system requirements for Diffraction Limited Storage rings (DLS),
- Design approaches,
- Chosen vacuum system design aspects of DLS,
- DLS summary
- Conclusion

Locations of Diffraction Limited Storage rings



Operation | Installation on going | commissioning in <3 years | commissioning in >3 years

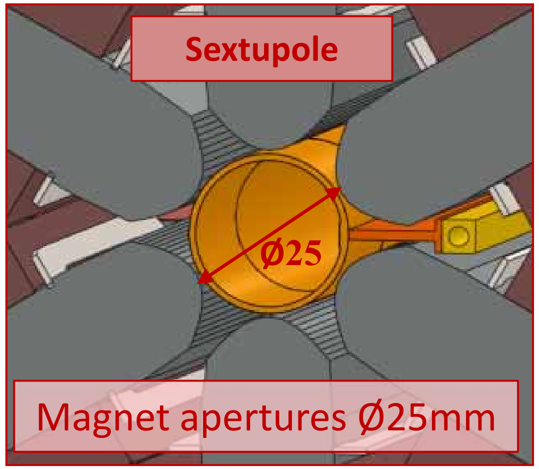
Introduction

Reduction in beam emittance → Large number of magnets (high field) → Reduce the circumference/cost → Compact lattice/magnets (small magnet aperture, limited space between magnets) → Small aperture vacuum chambers

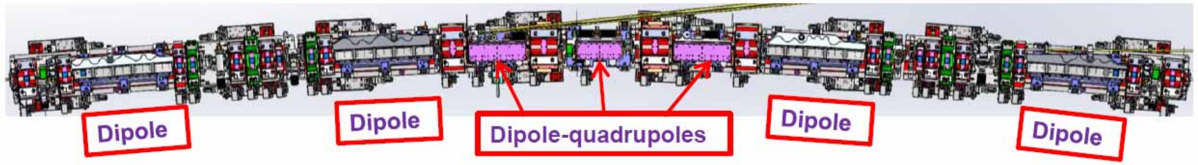
→ Limited space for absorbers
→ Limited space for pumps
→ impedance

MAX IV 3 GeV: top view of a magnet block

MAX IV 3 GeV: sextupole magnet aperture



ESRF-EBS: Top view of one cell (31 magnets per cell, 32 cells)



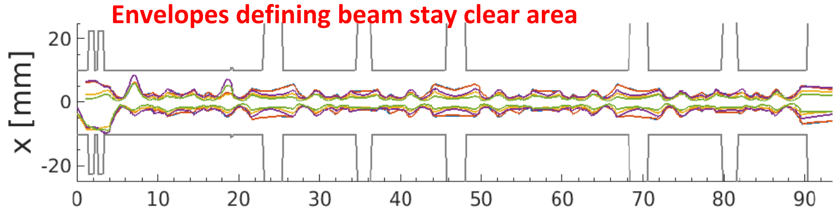
Status report of vacuum system of ESRF, C. Maccarrone, eeFACT September 2022

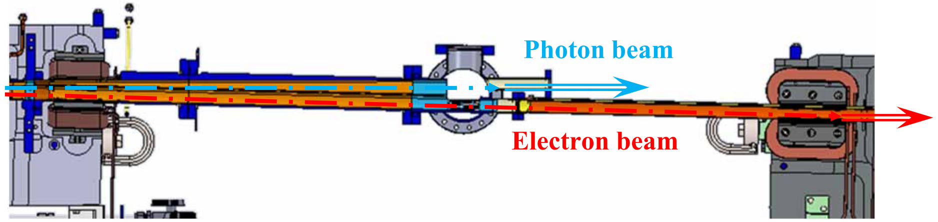
Requirements and constraints of vacuum system

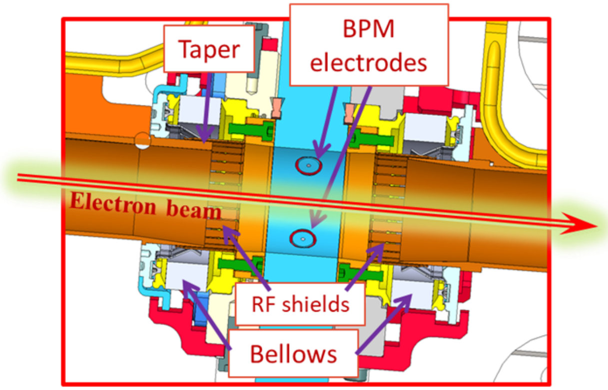
- **Vacuum related beam lifetime >5 Ah ---> average total pressure ~1e-9 mbar at dose 100 Ah.**
- **beam stay clear area (size of vacuum chambers, absorbers),**
- **allow photon beam extraction,**
- **ensure stability of BPMs (thermal and mechanical),**
- **must fit magnetic lattice (magnet apertures, distances between the magnets),**
- **beam impedance (material, shape, coating thickness, connecting flange type, shielding of bellows),**
- **compatible with stability requirements (mechanical design, supports system, water cooling),**
- **handle high power loads from synchrotron radiation from dipoles and IDs,**
- must not distort magnetic fields (material, support system),
- Integration of RF, injection, diagnostics, ID systems
- resistant to radiation (materials used),
- Installation compatible with the infrastructure (tunnel size, availability of handling cranes, time plan),
- serviceability,
- Cost, energy consumption, standardization,

Lifetime related tor residual gas density (Pressure level)

$$\frac{1}{\tau} = \frac{1}{\tau_{elastic}} + \frac{1}{\tau_{inelastic}} + \frac{1}{\tau_{Touschek}} + \frac{1}{\tau_{quantum}}$$







Design approach 1: NEG coating, distributed absorbers

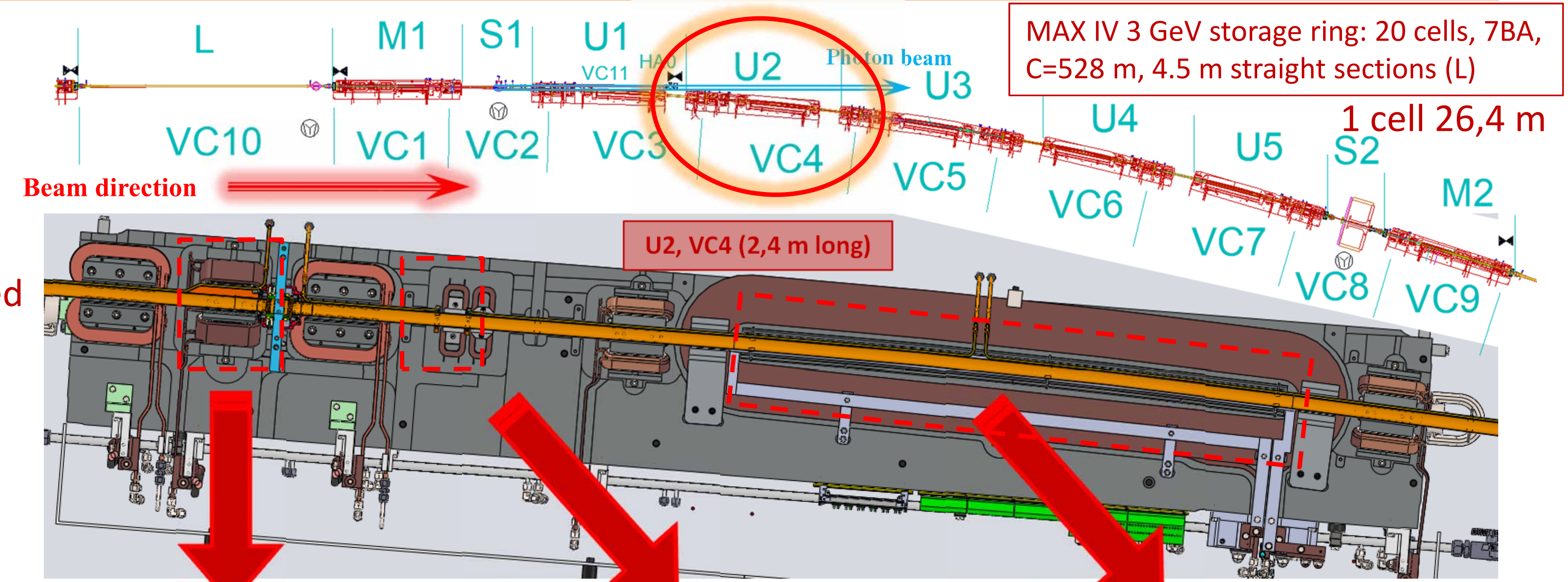
NEG coated copper tubes, with distributed absorbers at MAXIV (similar at Sirius).

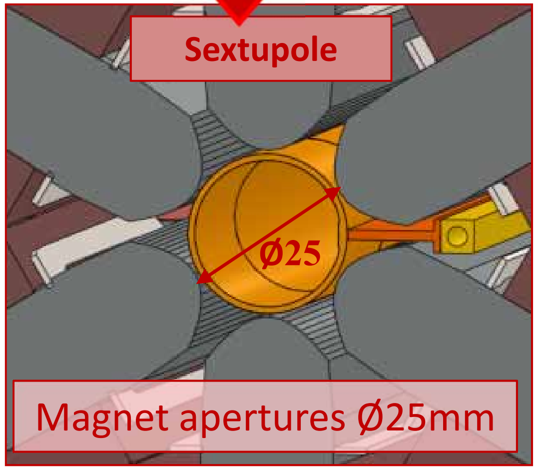
At MAX IV magnets are embedded in a closed magnet block.

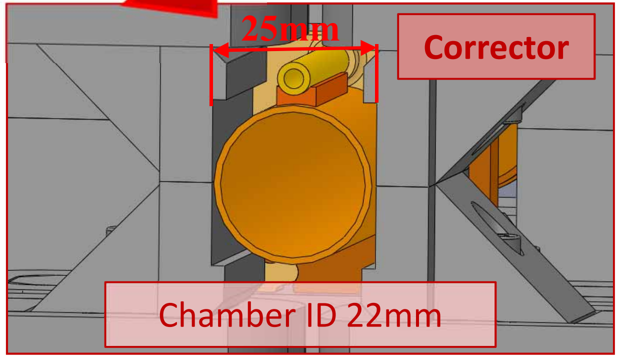
Limited lumped pumping in standard cell:

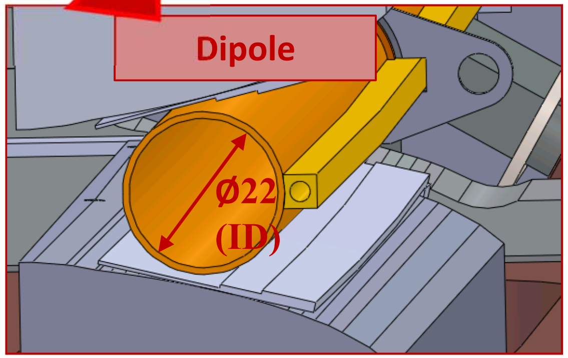
- MAX IV - 3 pumping ports with ion pumps (75 l/s), 1 crotch absorber,
- Sirius – 5 pumping ports with ion pumps (20 l/s) and NEG cartridges (200 l/s), 3 crotch absorbers,

MAX IV 3 GeV storage ring: 20 cells, 7BA, C=528 m, 4.5 m straight sections (L)









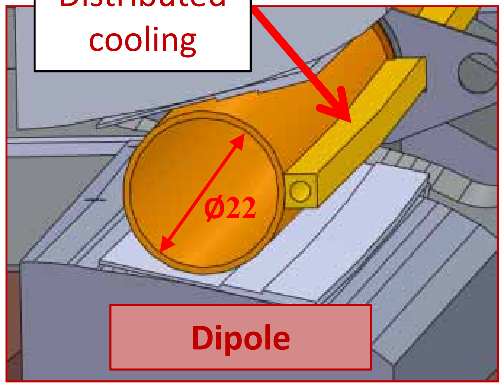
Min. clearance with the iron 0.5 mm, min. clearance with the coils 2 mm.

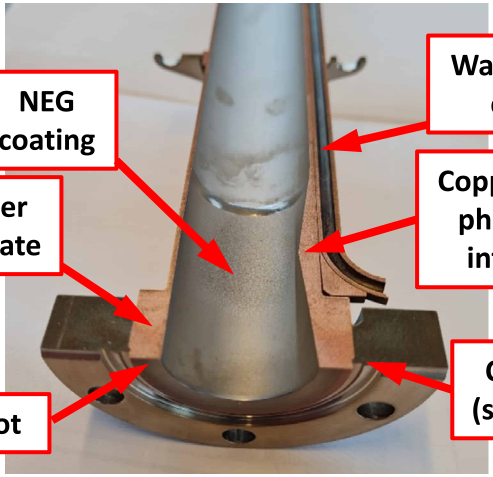
Design approach 1: NEG coating, distributed absorbers

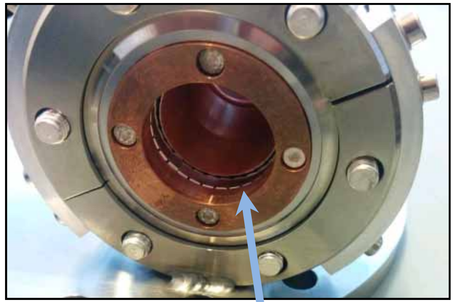
NEG coated copper tubes, distributed absorbers at MAXIV (similar at Sirius):

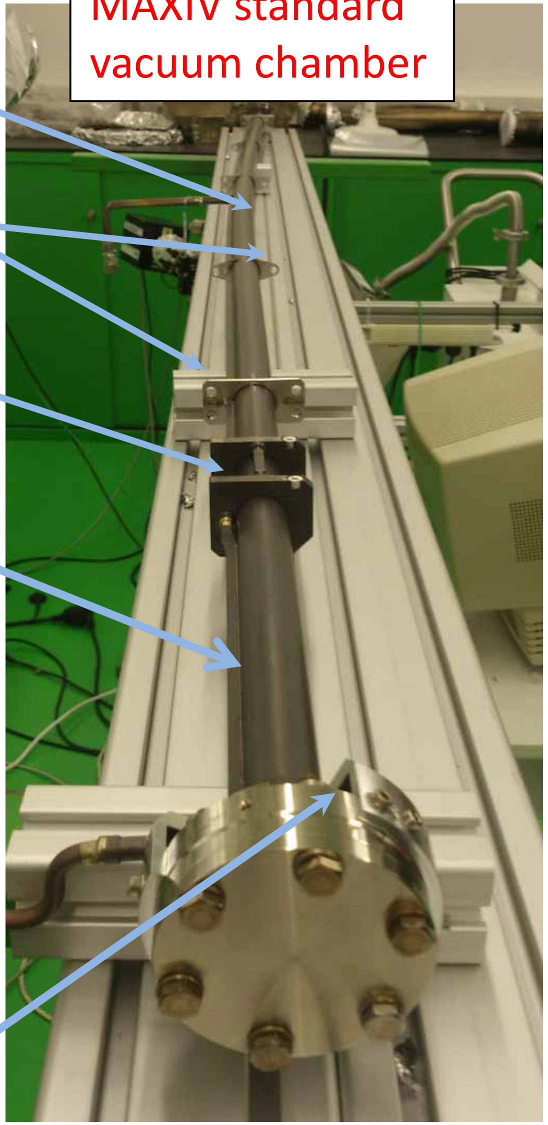
- Extruded OFS (oxygen-free silver bearing) copper tubes - high thermal conductivity (stainless steel sections for fast correctors),
- Water cooling to dissipate synchrotron radiation power,
- Absorber features (tapers) embedded in the vacuum chambers,
- NEG coating to lower Photon Stimulated Desorption (PSD) and provide distributed pumping after activation (@ ~180 deg C),

Cost effective, MAX IV 3 GeV ring vacuum system total cost: 6,336,000 €; ~12,000 EUR/m (in 2014).



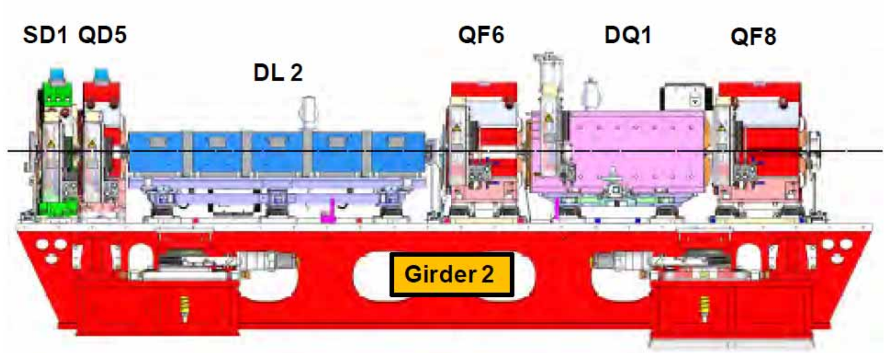






Design approach 2: Lumped absorbers and pumps

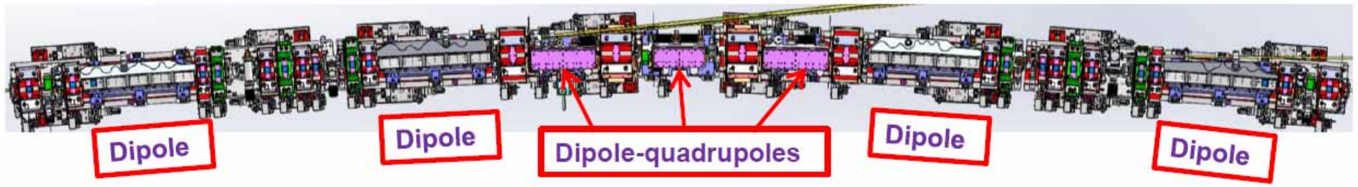
Conventional: Stainless steel and aluminium vacuum chambers with antechambers, lumped vacuum pumps and photon absorbers, NEG coating only in ID chambers (ESRF-EBS)



ESRF-EBS: Side view of one girder with magnets (4 girders per cell)

ESRF – EBS Design Report, September 2018

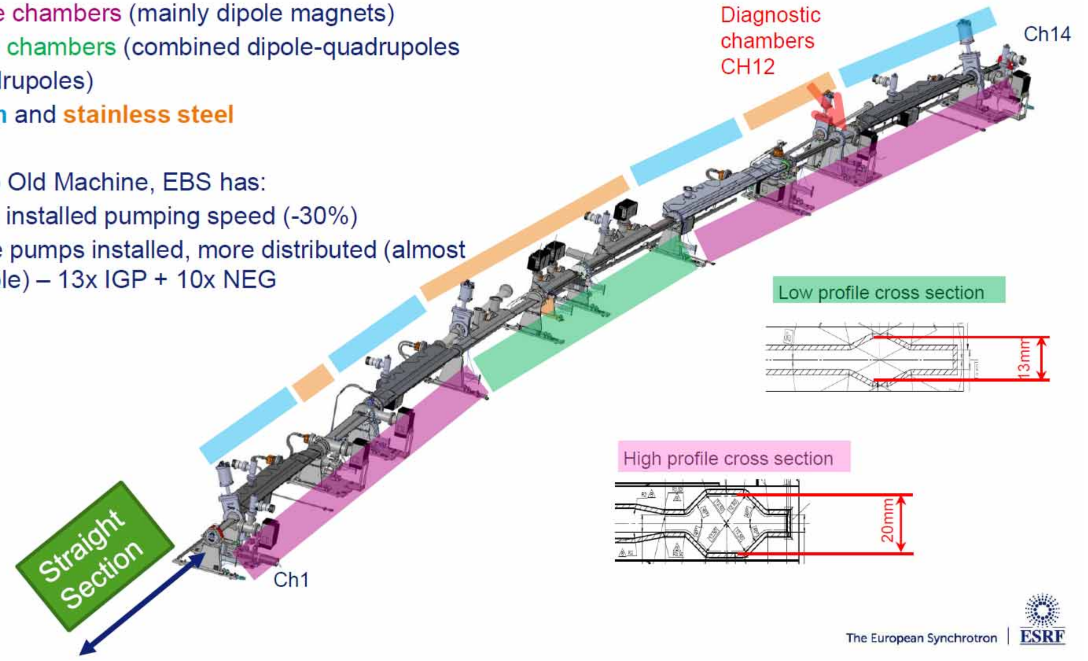
ESRF-EBS: Top view of one cell: 4 girders (31 magnets per cell, 32 cells)



Status report of vacuum system of ESRF, C. Maccarrone, eeFACT September 2022

12 Chambers per arc
High profile chambers (mainly dipole magnets)
Low profile chambers (combined dipole-quadrupoles & HG quadrupoles)
Aluminium and **stainless steel**

Respect to Old Machine, EBS has:
- Less installed pumping speed (-30%)
- More pumps installed, more distributed (almost double) – 13x IGP + 10x NEG

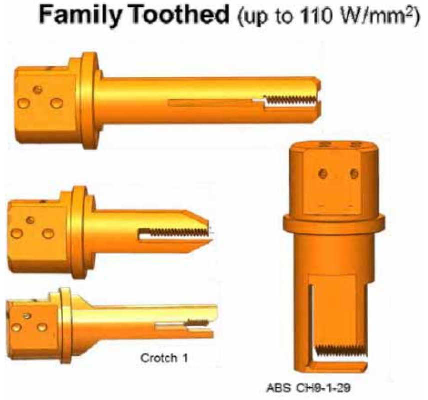


Status report of vacuum system of ESRF, C. Maccarrone, eeFACT September 2022

In each cell:

- 2 photon extraction ports.
- Lumped photon absorbers: 13 units (made of CuCrZr alloy).
- 24 lumped pumps: IP 55-75 l/s (14), NEG cartridge 100 l/s (10),
- NEG coating in ID straight sections only.

ESRF-EBS CuCrZr photon absorbers



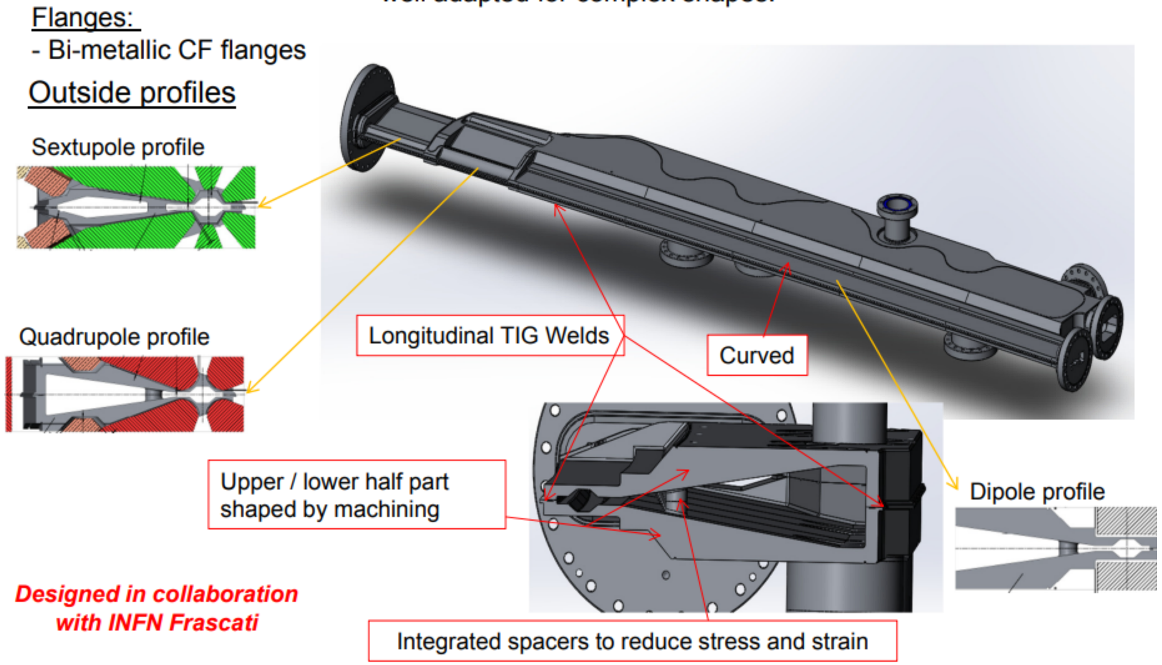
ESRF – EBS Design Report, September 2018

Design approach 2: Lumped absorbers and pumps

Conventional: Stainless steel and aluminium vacuum chambers with antechambers, lumped vacuum pumps and photon absorbers, NEG coating only in ID chambers (ESRF-EBS)

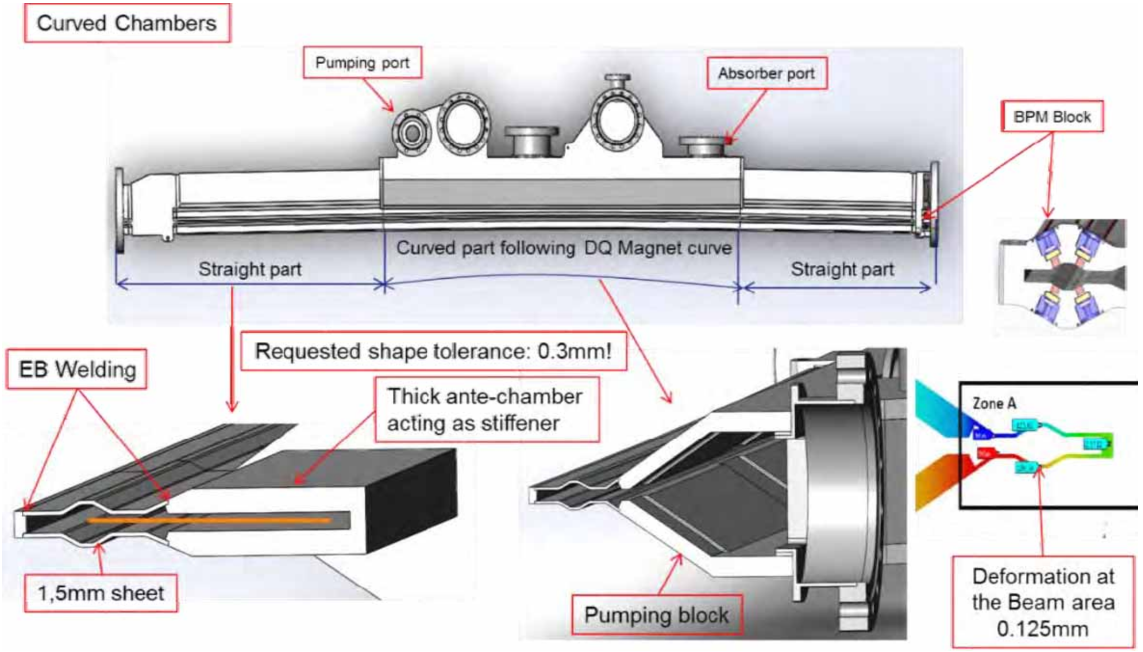
Aluminum vacuum chambers

Aluminium cheaper and easier to machine than stainless steel
=> well adapted for complex shapes.



Courtesy: ESRF EBS Vacuum Chambers & RF fingers- L.Goirand- MEDSI 2016 - 11-16 September

Stainless steel Vacuum chambers: 316 LN, 316 L



ESRF – EBS Design Report, September 2018

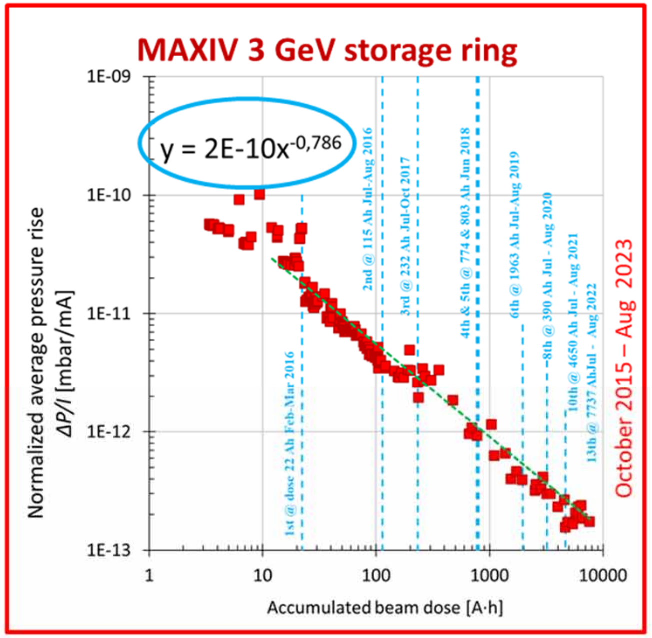
Design approach: Vacuum performance of DLS in operation

Vacuum systems based on NEG coating and distributed copper absorbers (MAX IV and Sirius) work well and conditioned fast.

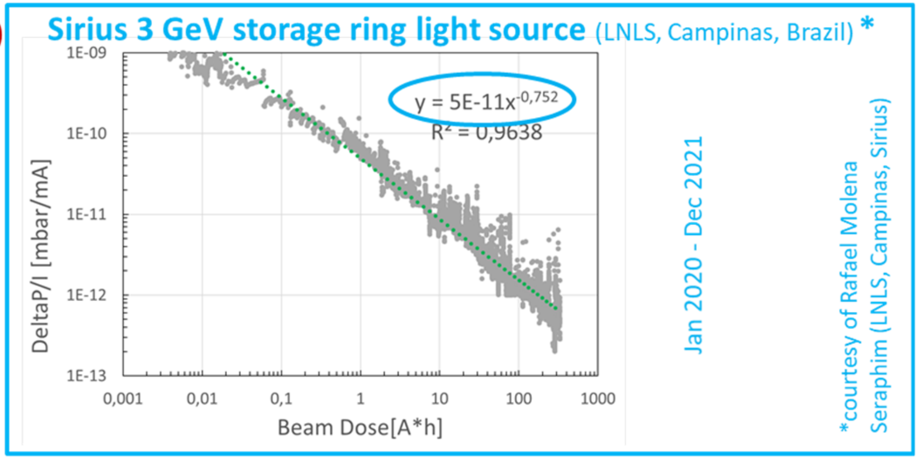
- There are no operational issues related to the NEG coating that limit the operation or machine performance in any way (no peel off, saturation not observed),
- Neon venting technique was used for vacuum interventions (MAX IV, Sirius), significantly reducing the intervention time.

Conventional vacuum system (as in ESRF-EBS) works good as well.

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



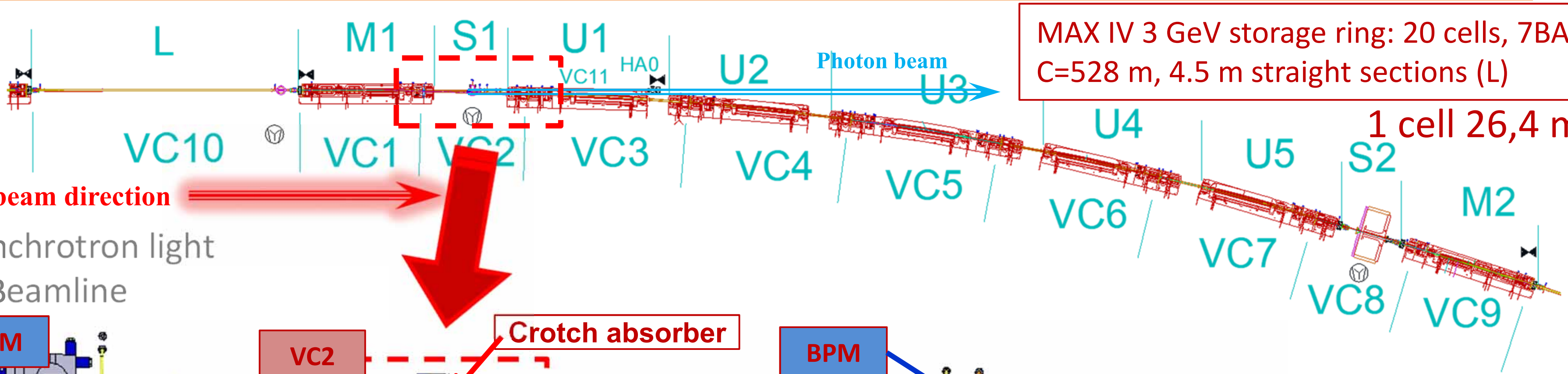
The absolute values of the slopes of the conditioning curves:
0.78 for MAXIV,
0.75 for Sirius,



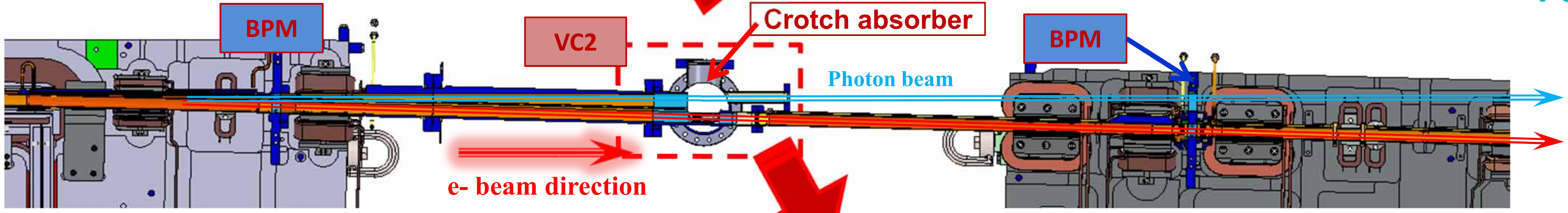
Design aspect: light extraction

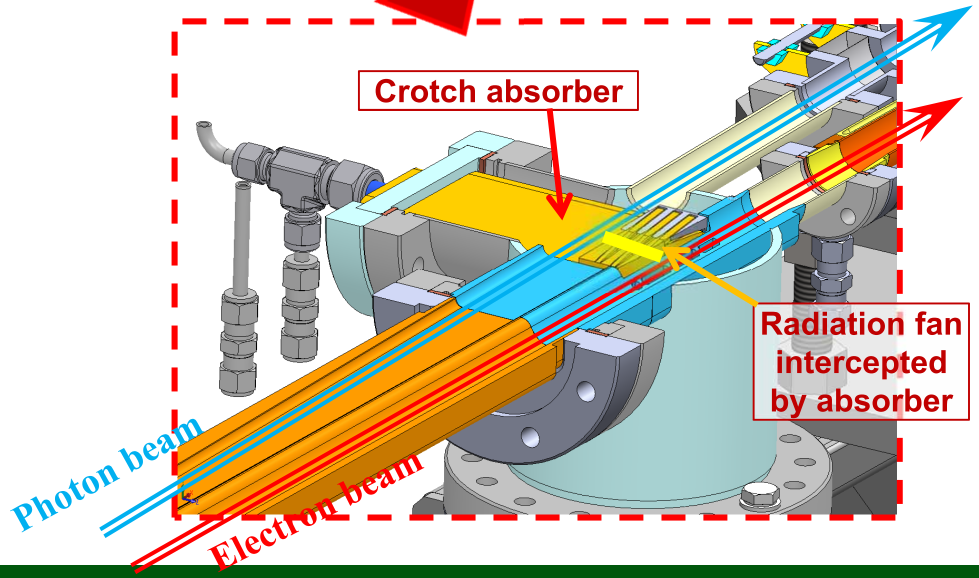
MAX IV: 1 photon extraction port per cell (1 copper photon absorber)

MAX IV 3 GeV storage ring: 20 cells, 7BA, C=528 m, 4.5 m straight sections (L)



Short straight section 1 (S1) – synchrotron light extraction to the Front End and Beamline

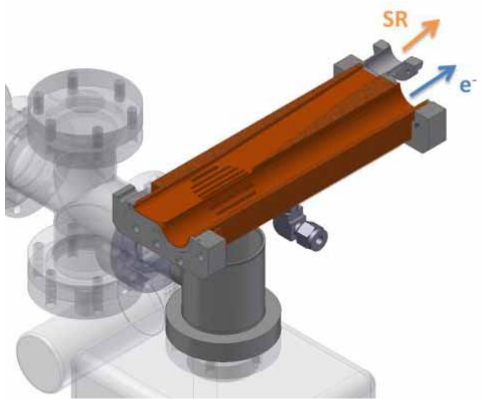




Challenges:

- Lack of space through the magnets for the photon beam chamber,
- Photon beam high power handling,

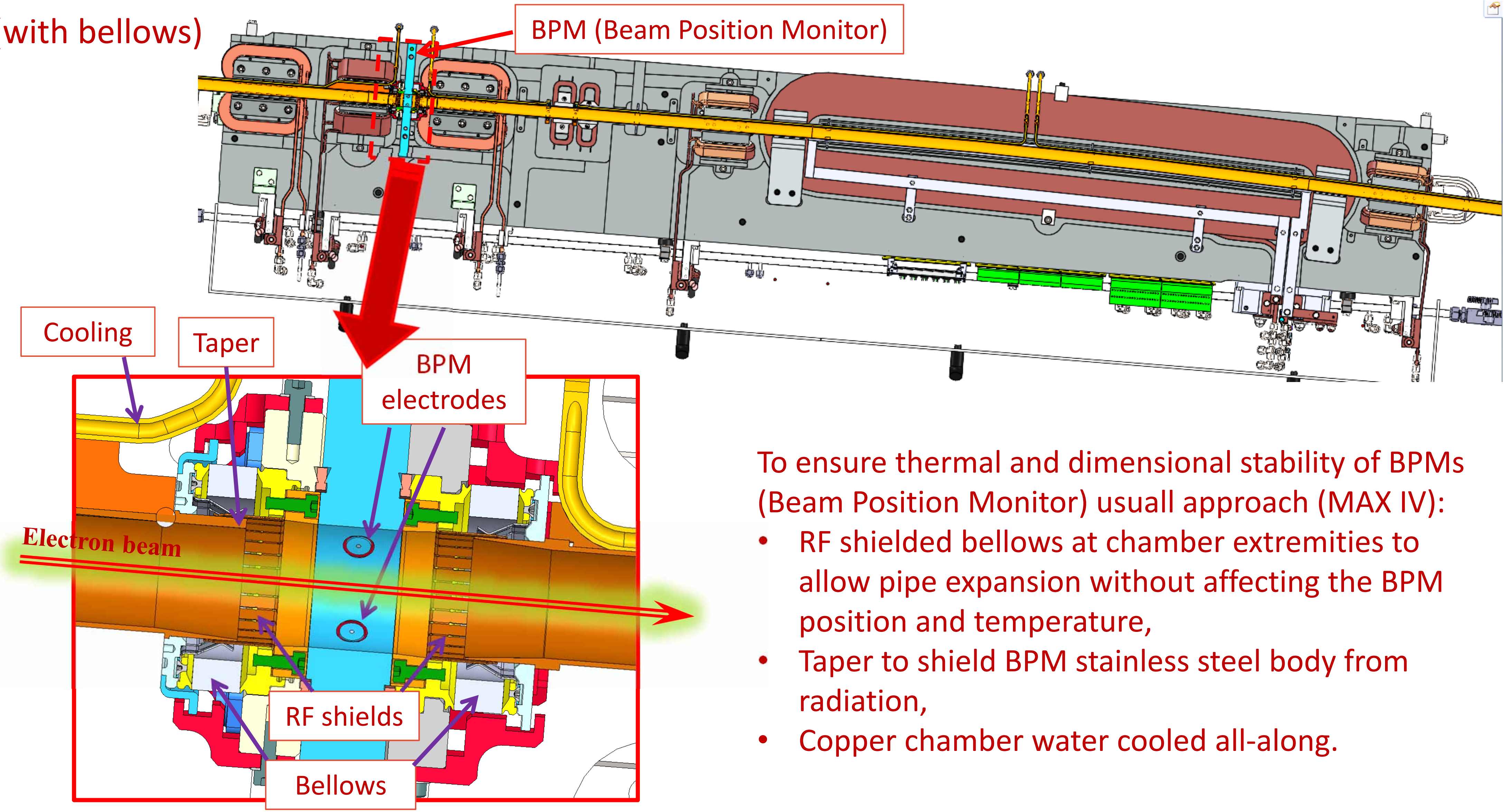
Sirius: absorbers have different design and are NEG coated, 2 photon ports per cell



VACUUM SYSTEM DESIGN FOR THE SIRIUS STORAGE RING, R.M. Seraphim, IPAC 2015

Design aspect: BPM, bellows

BPM stability (with bellows) (MAXIV),

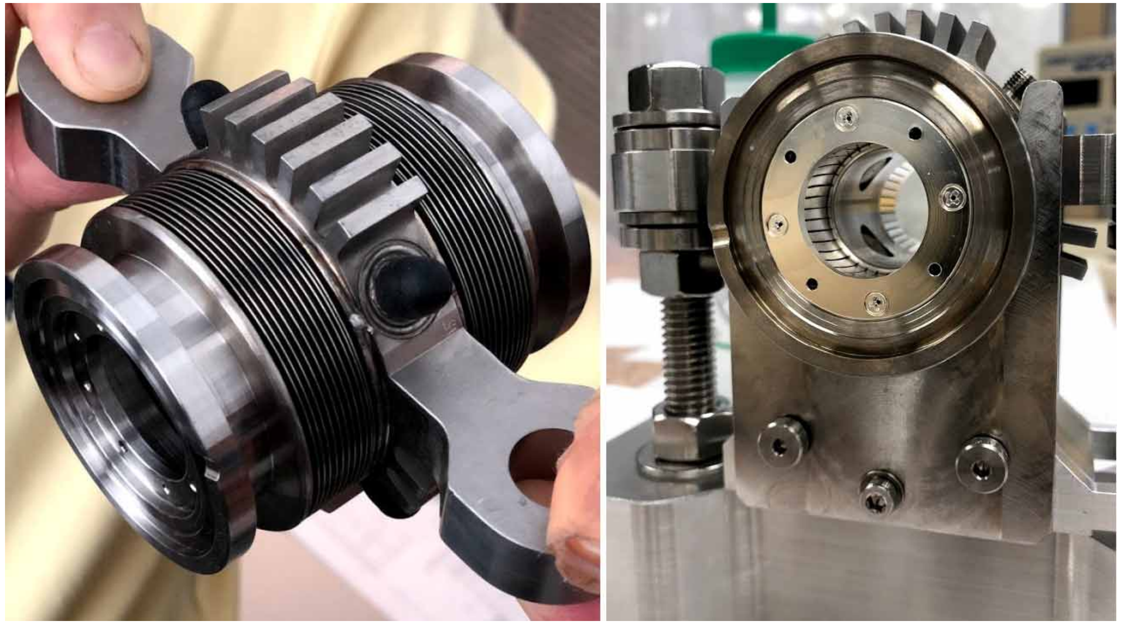


To ensure thermal and dimensional stability of BPMs (Beam Position Monitor) usuall approach (MAX IV):

- 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.

Design aspect: BPM, bellows

Bellows integrated on the BPM block for possible service (APS-U)



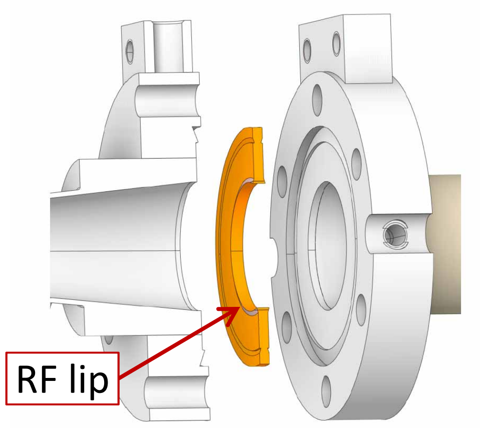
Final Design of the APS-Upgrade Storage Ring Vacuum System, J. Carter, NAPAC 2019

RF shielded bellow types (Sirius)

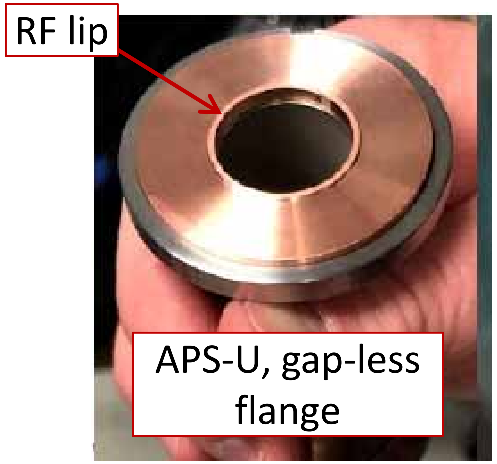
An Overview for the Sirius Vacuum System, T. Rocha, EIC 2021,

Design aspect: connection flange

Gap-less flange assembly with copper gasket (CF based) Diamond II, based on APS-U design

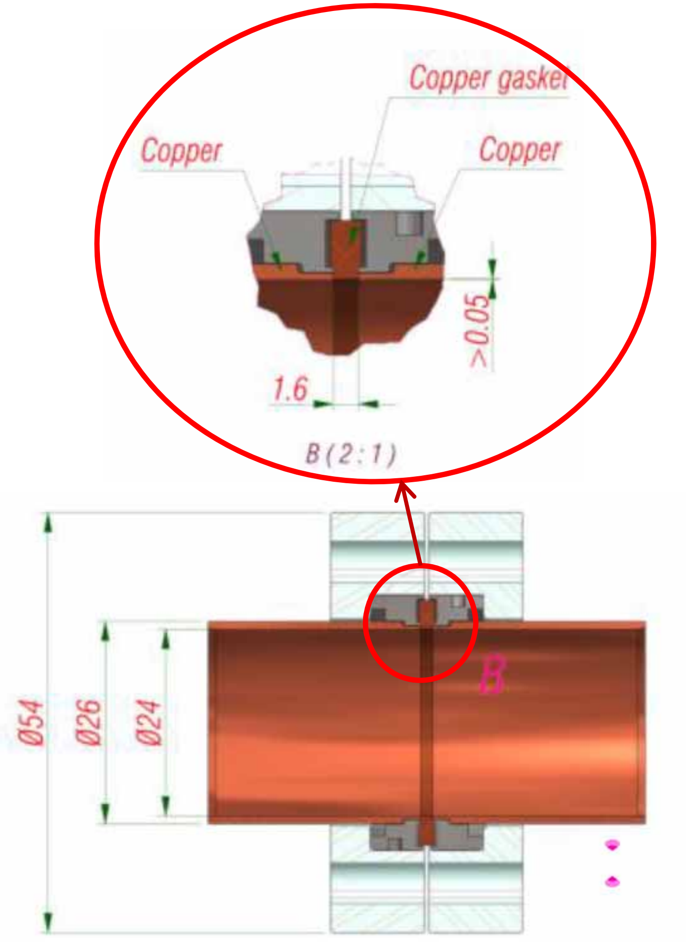


Diamond-II Technical Design Report (August 2022)



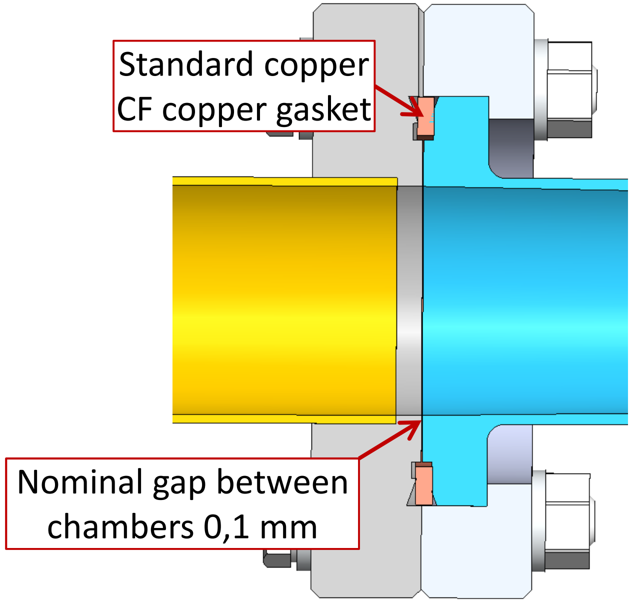
Final Design of the APS-Upgrade Storage Ring Vacuum System, J. Carter, NAPAC 2019

Gap-less flange assembly, modified KEK MO-type used at Sirius



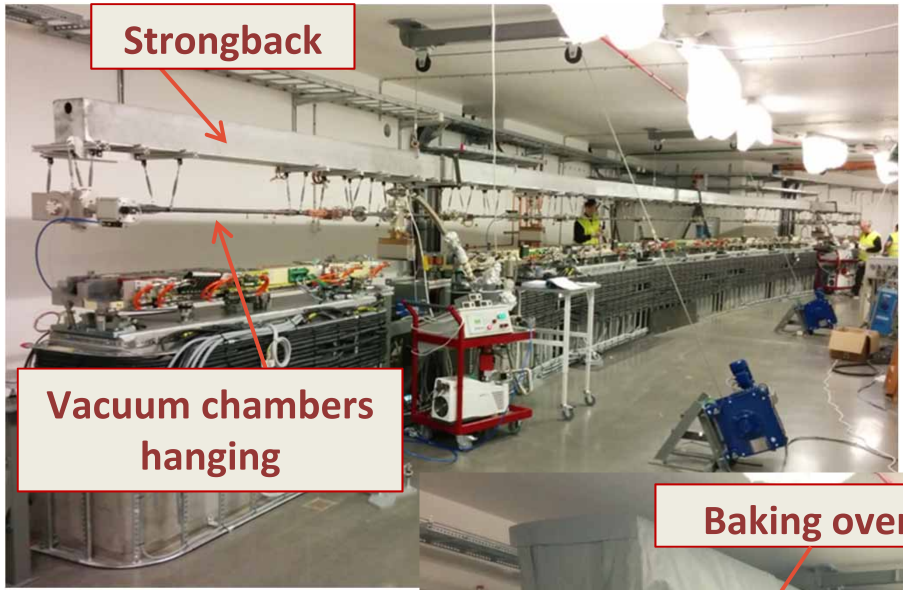
VACUUM SYSTEM DESIGN FOR THE SIRIUS STORAGE RING, R.M. Seraphim, IPAC 2015

Gap of 0,1 mm flange, CF based (spigot type) used at MAX IV 3 GeV



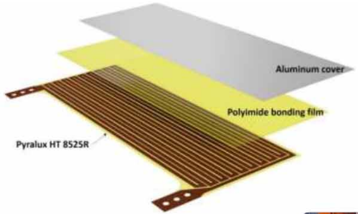
Design aspect: Installation (baking: Ex-Situ, in-situ)

Ex-situ installation and baking with an oven (MAX IV).



Installation and In-situ baking with thin heater system (Sirius, ESRF-EBS).

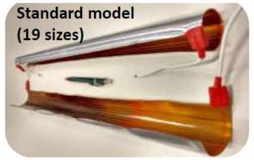
An Overview for the Sirius Vacuum System, T. Rocha, EIC 2021

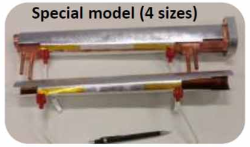


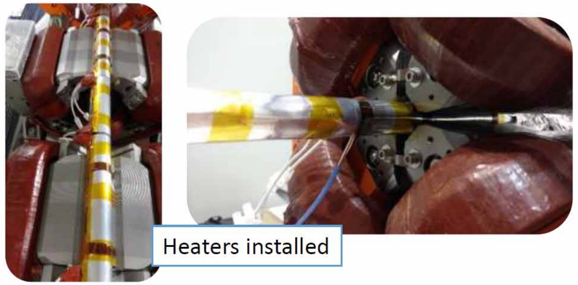
Thin heater system at **Sirius**:

- 0,4 mm thickness,
- Max operating temperature 230 deg C.

Space needed inside magnets for longer bellows to compensate thermal expansion







Total of 1635 heaters are installed in the storate ring

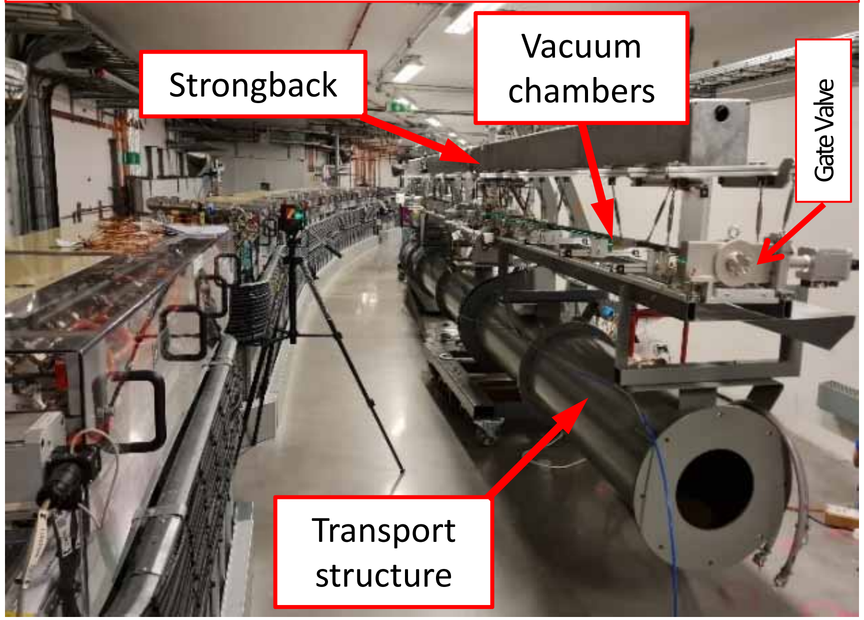
Design aspect: Serviceability

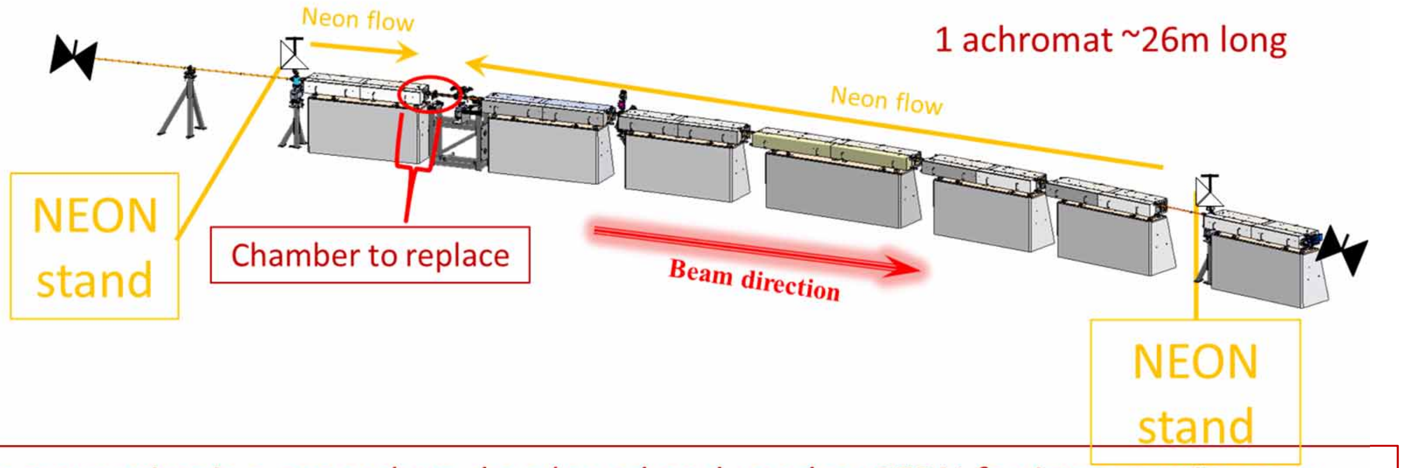
The more compact the lattice the more difficult is to do maintenance/exchange vacuum system components (limited access)

Options for service/exchange:

- Have one complete cell of vacuum chambers (spare achromat) assembled under vacuum with NEG activated (need to open all magnets),
- Make use of in-situ baking system if available to bake/activate NEG (no need to open all the magnets),
- If no in-situ baking system available need to bake/activate NEG outside the magnets with an oven (need to open all magnets),
- Use of Neon venting (to avoid need of NEG reactivation and no need to open all the magnets) (confirmed at MAXIV, Sirius, CERN),

MAX IV: One spare vacuum cell inside accelerator tunnel on a transport structure (~22 m long without straight section)





Neon venting is a procedure developed and used at CERN for interventions on 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.

At MAX IV Neon venting used in 2018 and 2020 for interventions. No limitation in storage ring performance was observed after ~10 A h beam dose.

DLS summary

Chosen Diffraction Limited Storage rings in operation, installation and design:

Facility	New/ Retrofitted; commissioning year	Circumference [m]; (# of cells - Lattice)	Energy [GeV]; current [A]; emittance [pm.rad]	Magnet bore [mm]; chamber aperture [mm]	Vacuum system design approach	Vacuum chamber material	% of chambers NEG coated (lengthwise)	# of lumped pumps per cell	Baking/ activation method
ALS-U, USA	Retro; 2026	196; (12 cell - 9BA)	2; 0,5; 70	24; 13-20	Hybrid*	St. steel, copper,	60	3-4	In-situ
APS-U, USA	Retro; 2024	1104; (40 cell - 7BA)	6; 0,2; 60	26; 22	Hybrid*	St. steel, copper, Aluminum	40	9+4 NEG strips	In-situ
Diamond II, UK	Retro; 2027	560; (24 cell - MH6BA)	3,5; 0,3; 161	24; 20	Hybrid*	St. steel, copper, Aluminum	>90	8	Ex-situ
ESRF EBS, France	Retro; 2020	843; (32 cell - H7BA)	6; 0,2; 133	~28; 13-20	Conventional (lumped pumps and absorbers	St. steel, Aluminum,	(only ID chambers in straights)	24	In-situ
HEPS, China	New; 2024	1360; (48 cell - H7BA)	6; 0,2; 34	24; 22	Hybrid*	St. steel, CrCrZr, and Inconel	70	14	In-situ
MAX IV, Sweden	New; 2016	528; (20 cell - 7BA)	3; 0,5; 300	25; 22	Distributed absorbers, NEG coating	Copper, (St. steel for ports and flanges)	>95 (fully)	3	Ex-situ
SLS 2.0, Switzerland	Retro; 2024	288; (12 cell - 7BA)	2.7; 0,4; 159	22; 18	Distributed absorbers, NEG coating	Copper, (St. steel for BPMs)	>95 (fully)	14	Ex-situ
Soleil II, France	Retro; 2028	354; (20 cell - 12 x 7BA + 8 x 4BA)	2,75; 0,5; 80	16; 12	Distributed absorbers, NEG coating	CuCrZr (full chambers), copper	>95 (fully)	4 / 7 (1 per dipole)	Ex-situ

Not in the table: Sirius, Alba II, Elettra 2.0, Petra IV, BESSY III, Spring-8 II, HALF, SPS II.

* Hybrid: Distributed absorbers and NEG coating, also lumped pumping and lumped absorbers.

Conclusion

Vacuum systems based on NEG coating and distributed copper absorbers (MAX IV and Sirius) work very well and condition fast. Conventional vacuum systems perform good as well.

Choice of good solution depends on many factors:

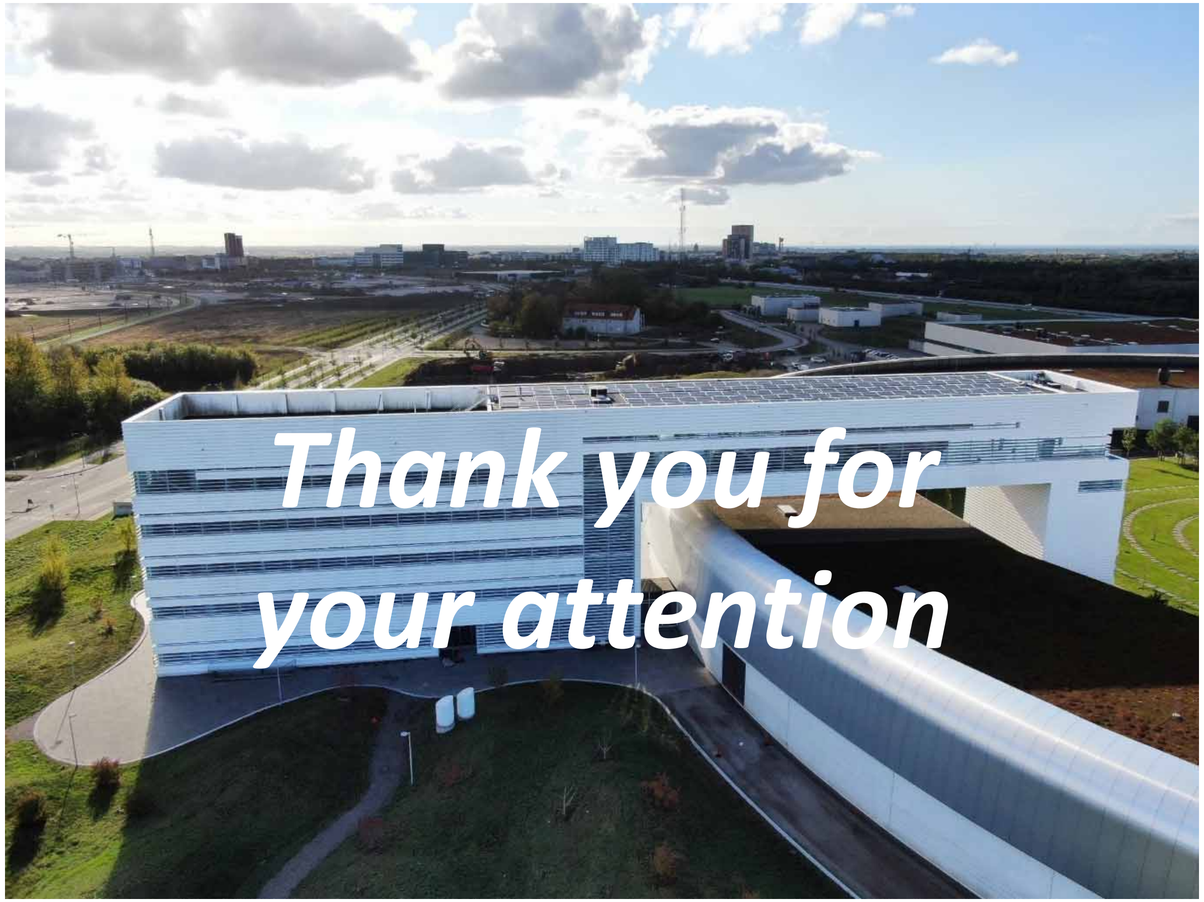
- accelerator layout (arc and straight section lengths),
- space inside and between magnets,
- number and location of photon ports,
- synchrotron radiation power to be dissipated,
- manufacturing capabilities,
- surface treatment (etching before NEG coating, NEG coating, copper coating),
- knowledge and previous experience at the facility,
- tunnel size and access (openable roof),
- available facilities (crane),
- Time constraints on the installation,

Challenges:

- Small chamber sizes, in antechamber down to 5 mm,
- Tight tolerances - difficult to manufacture,
- Ceramic chambers with high tolerances for injection chambers,
- Positioning of small, flexible chambers inside magnet apertures (spacers between poles).

New technologies:

- Broader use of CuCrZr alloy,
- Use of Neon venting,
- Chamber size down to ~6-7 mm in IDs or antechamber (NEG coating difficult and limited by chamber length),
- Raytracing and extensive use of software: Synrad software (used to generate and export synchrotron radiation power maps for Finite Elements Analyses),
- Software for vacuum simulations: Molfow+,
- Reverse coating technique (CERN).



Special thanks to Eshraq Al-Dmour and MAX IV Vacuum Team.

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