Accelerator Vacuum Technology Challenges for Next-Generation Synchrotron-Light Sources

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Content

- **1. Introduction: Goals and Performance of Ring-Based LSs (Light Sources)**
- **2. Future trends in DLSR (Diffraction Limited Storage Rings)**
- **3. Associated Vacuum Issues and Special Hardware Development**
- **4. Conclusions**

Introduction

Goals and the target performance of LS (Light Source) storage rings:

Constant delivery of a high quality, intense and stable photon beam to a large number of beamlines

High quality and intense photon beams: Often characterized in terms of

$$Brilliance = \frac{Photons}{Second \cdot mrad^2 \cdot mm^2 \cdot 0.1\%BW} \propto \frac{I}{\varepsilon_x \varepsilon_y}$$

I : Beam current, ε_u : Transverse emittance

Presently a big global wave for 3GLS → DLSR (Diffraction Limited Storage Rings or 4GLS)

Lowering of transverse beam emittance

Optimal ring structure from DBA, TBA lattice → MBA lattice

Ring-Based LS Future Trends

- A global wave today to construct (or *re-construct*) ring-based LSs having the horizontal emittance ε_H by **tens of factors** below the “nm·rad” range

Basic principle used:

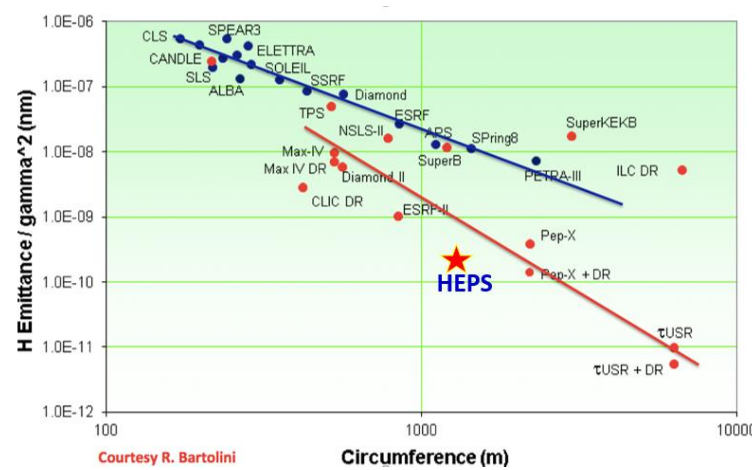
$$\left(\varepsilon_H\right)_{Minimum}^{Theoretical} \propto E^2 \cdot \theta^3$$

E: Beam energy, θ: Bending angle

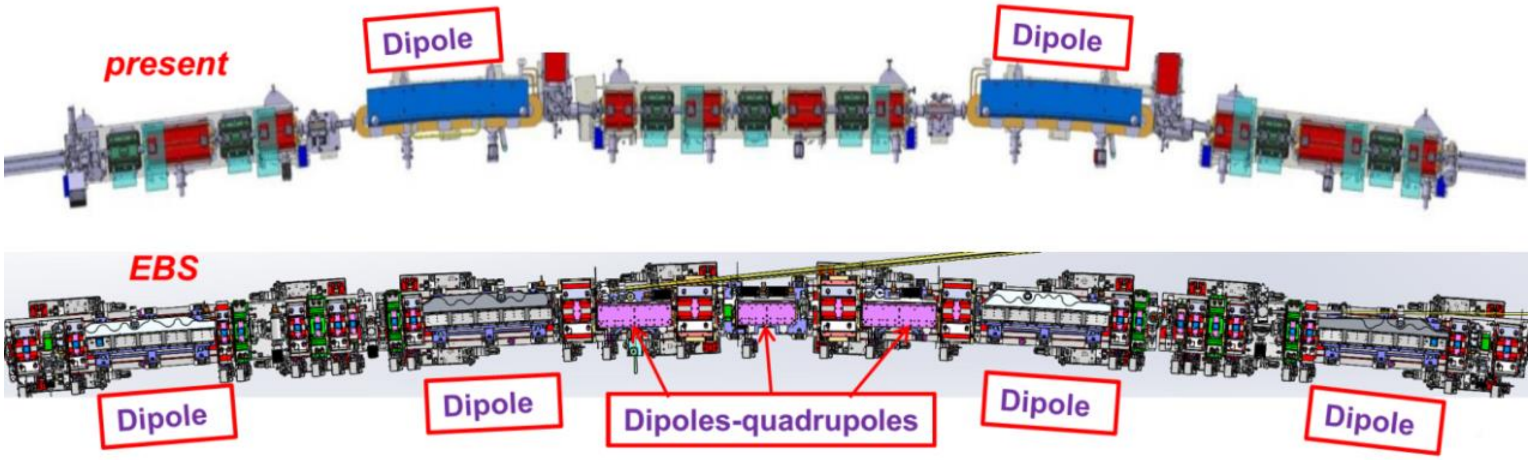
Beam energy

$$\epsilon_0 \sim \frac{E^2}{(N_s M)^3}$$

Number of sectors Dipoles per sector



MBA (Multiple Bend Achromat) instead of DBA, TBA



Comparison between ESRF and ESRF-EBS

Especially for machine "upgrades", the resultant ring configuration tends to be extremely *dense*

APS →APS_U, Spring_8 →Spring_8 II, ESRF →EBS

Low emittance → Strong focusing → Smaller bore radii → Narrower VC aperture → Higher impedance (Resistive-Wall & Broadband) → Lower vacuum conductivity → Special vacuum technology (NEG, …)

Challenges on vacuum systems for Low Emittance/DLSRs

Main Purpose of DLSRs_Vacuum System Design:
Have low dynamic pressure which gives good beam lifetime,
and to handle the power deposited by SR.

- High gradient quadruple → Small magnet bore aperture
  Vacuum Chamber designs compatible with magnet poles, photon extraction and beam stay clear conditions(space limitation)
- Handle the power deposited by SR →
  Integration of pumping ports, photon absorbers, collimators and crotches(high SR power)
- Small magnet bore aperture → Low profile vacuum chamber(Lumped pumping would not be as efficient in reducing the pressure)
  Detailed evaluation of vacuum profiles along the ring(conductance limitation)

→ NEG coating must be a very helpful method for DLSRs to provide distributed pumping

- Some specific hardware development in future DLSRs
  "Zero-impedance" flange, RF_shield Bellow, BPM etc…
- In-situ baking materials development
  thin Polyimide foil heater + Al coating polyimide foil

New LS's Parameters

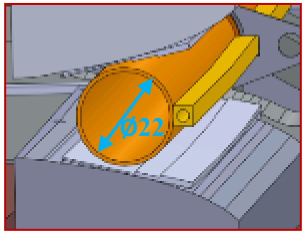
Table 1: New Ring-Based LS's Parameters

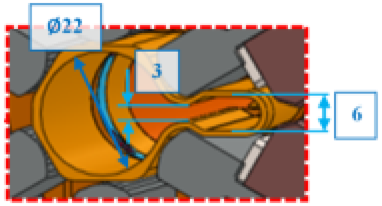
Facility	C(m).	E(GeV)/I(A) εx(pm.rad)	Mag. Bore(mm)	Chamber Material	Baking Method
MAX-IV (Sweden)	528 (20cell-7BA)	3/0.5 330	25	OFS Cu (100% NEG Coating)	Ex-situ
SIRIUS (Brazil)	518.4 (20cell-5BA)	3/0.5 250	28	OFS Cu (100% NEG Coating)	In-situ
EBS (France)	844 (32cell-7BA)	6/0.2 135	26	SST/Al (Partial NEG Coating)	In-situ
SPring-8_U (Japan)	1436 (48cell-5BA	6/0.1 140	26	SST (No NEG Coating)	Ex-situ
APS_U (USA)	1100 (40cell-7BA)	6/0.2 60	26	OFS Cu/Al (Partial NEG Coating)	Ex-situ

Vacuum Chamber Design(1)

The clearance between the chambers and the magnets poles is 0.5~1.0 mm; the chambers are produced with tight mechanical tolerances to avoid any interference with the magnet poles and coils (for example, all tolerances of the chambers should be less than 0.3 mm).

Ø22 mm





Aperture limiting sextupole

MAX-IV Dipole Chamber

Technologies applied:

- Wire erosion.
- TIG welding.
- E-beam welding
- Bending.
- Brazing.

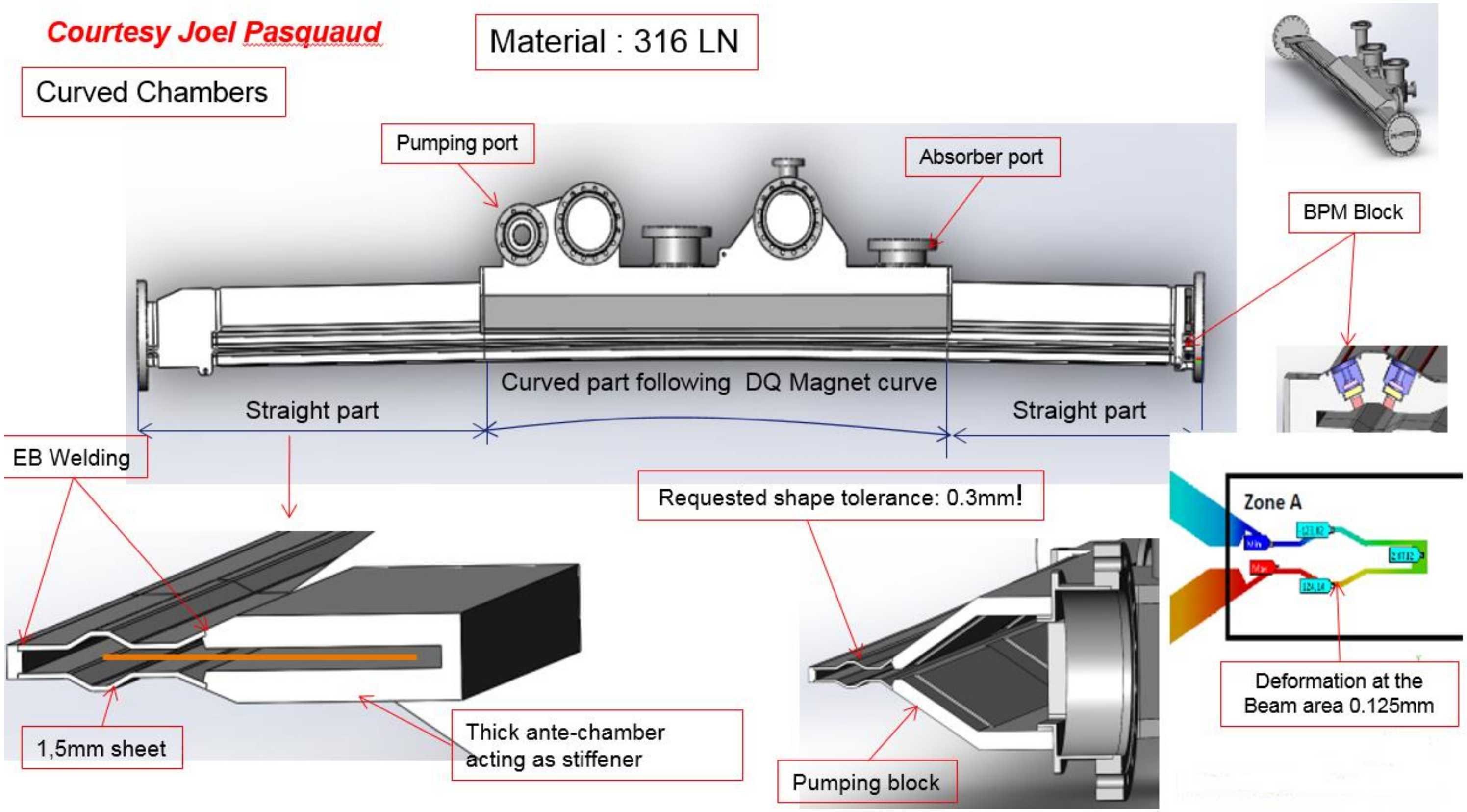
MAX-IV Sextupole Chamber with Key-Hole

Technologies applied:

- Milling.
- Etching.
- Turning.
- NEG-coating
- Etc..

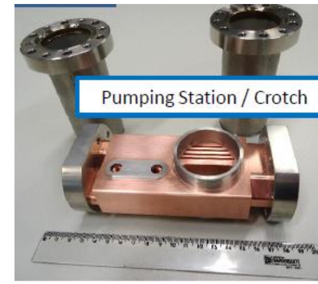
Vacuum Chamber Design(2)

EBS chambers(low profile) are going to be installed in the central DQ (Dipole Quadrupole) magnets



Handle higher SR Power(1)

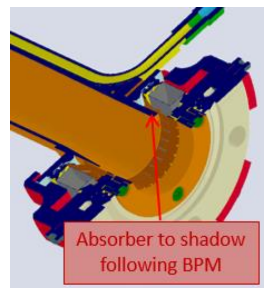
Integration of pumping port and photon absorber

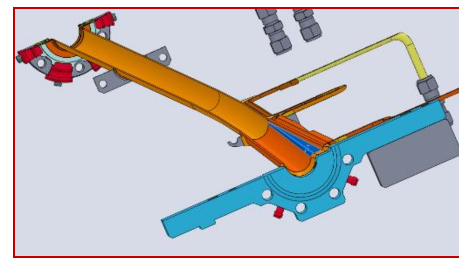


SIRIUS

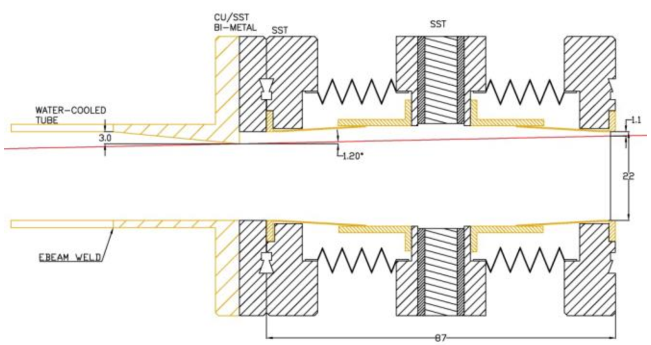
Compact geometry with adequate cooling and minimized radiation scattering

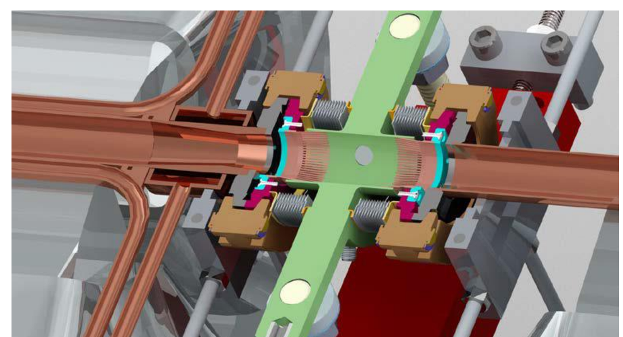
In-line absorber was used for shadow following BPM





MAX-IV

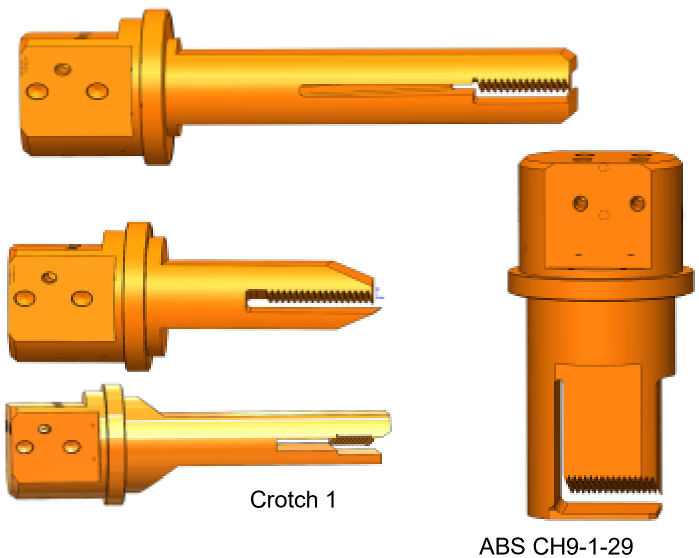




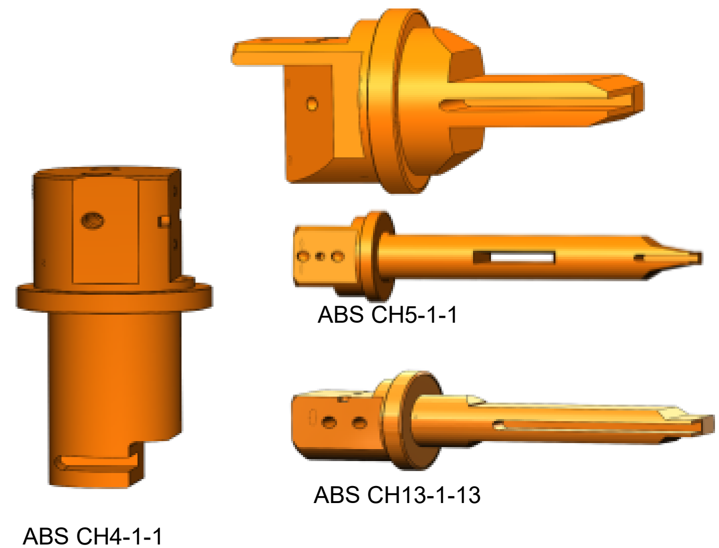
APS-U

Handle higher SR Power(2)

Family Toothed (up to 110 W/mm²)



Family Frontal (up to 50 W/mm²)



EBS

- 12 lumped removable photon absorbers (on flanges) per cell
- These absorbers will be machined from a block CuCrZr, including the CF knife edge

Single piece construction without brazing or welding.

Handle higher SR Power(3)

Material Selection "Glidcop AL-15 Vs Copper Chromium Zirconium (C18150)"

Material Properties

- *Thermal Conductivity (RT):*
  Glidcop Al25, Al15: 344 - 365 W/(m.K)
  Cu-Cr-Zr: 314 - 335 W/(m.K)
- *Elastic Modulus:*
  Glidcop Al15, Al25: 130 GPa
  Cu-Cr-Zr: 123 GPa
- *0.2 % Yield Strength, (RT, Cold Worked):*
  Glidcop Al15, Al25: 470 - 580 MPa
  Cu-Cr-Zr: 350 - 550 Mpa
- *Coefficient of Thermal Expansion:*
  Glidcop Al15, Al25: 16.6 µm/K
  Cu-Cr-Zr: 17.0 µm/K

- *Cu-Cr-Zr (C18150) is 1/4th the price of Glidcop AL-15.*
- *Cu-Cr-Zr is readily available in different forms and sizes from many suppliers.*
- *Cu-Cr-Zr loses its strength rapidly if exposed to sustained temperatures > 500°C*
- *Glidcop is the choice if brazing is required.*

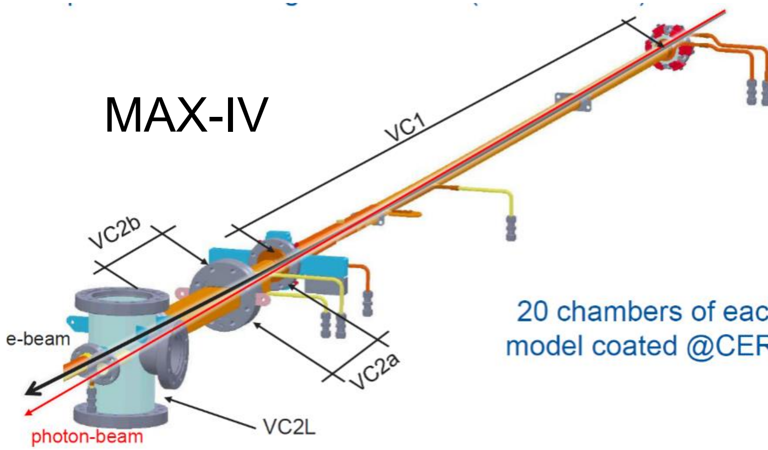
Ref: Li M. and Zinkle S. J. (2012) Physical and Mechanical Properties of Copper and Copper alloys, Comprehensive Nuclear Materials, Vol. 4, pp 667-690

Distribution Pumping_NEG coating(1)

High brightness At affordable cost → Magnetic poles close to the beam → Smaller aperture beam pipes → Distributed pumping

NEG coating, which turned out to be very effective in pumping the residual gases without pumping ports, is more and more used in ring-based LSs.

MAX-IV



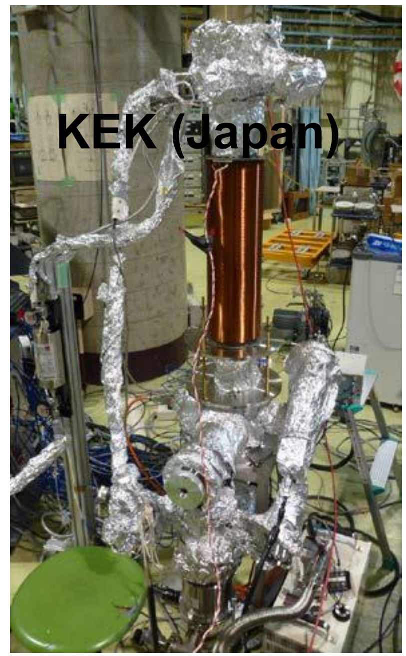
20 chambers of each model coated @CERN

MAX-IV and SIRRUS NEG coating for whole ring
EBS and APS-U NEG coating for partial ring

NEG coating issues

- Coating very small aperture even <10mm chambers
- Surface roughness
- Coating photon extraction key hole(~6mm gap) is challenging
- Fabrication methods compatibility with coating processes
- Coating development in industry. Very limited vendor capability-a possible risk
- NEG impedance might become a problem for very short bunches

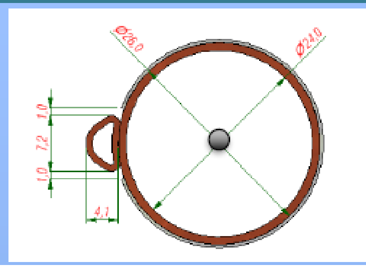
NEG Coating Facility around the world



NEG Coating Procedure

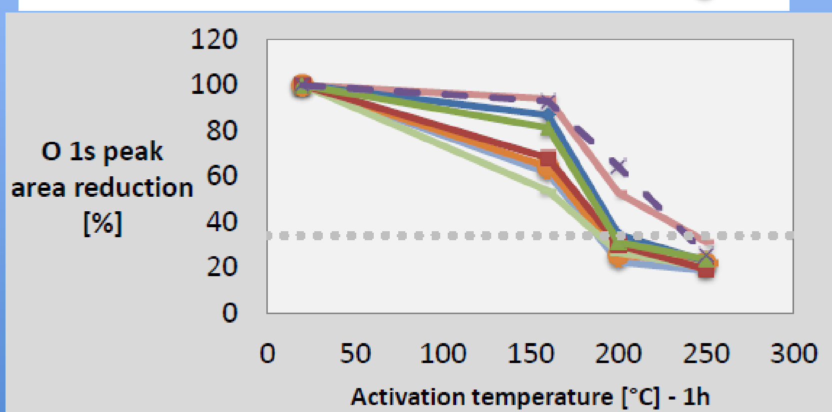
LNLS/SIRIUS

XPS analysis –circular profile

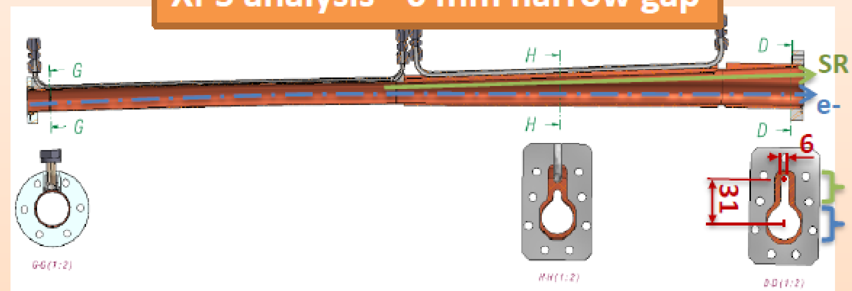


Coating procedure (1 steps):

1. Coating of the circular profile (1 cathode: 1 mm) - > ●

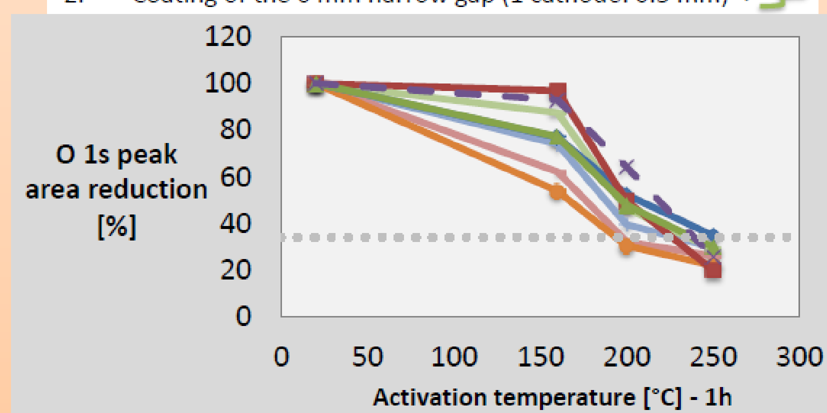


XPS analysis - 6 mm narrow gap



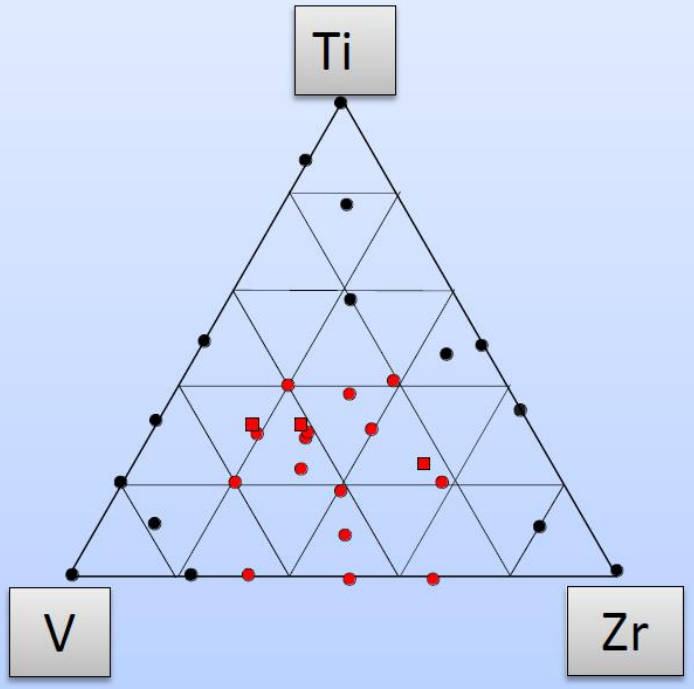
Coating procedure (2 steps):

1. Coating of the circular profile (1 cathode: 1 mm) - >
2. Coating of the 6 mm narrow gap (1 cathode: 0.5 mm) ->



Coating Parameters Optimizations

Daresbury/UK

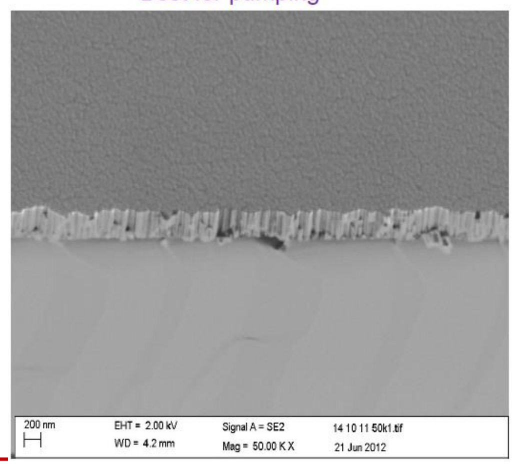


composition and microstructure affects activation energy and pumping performance

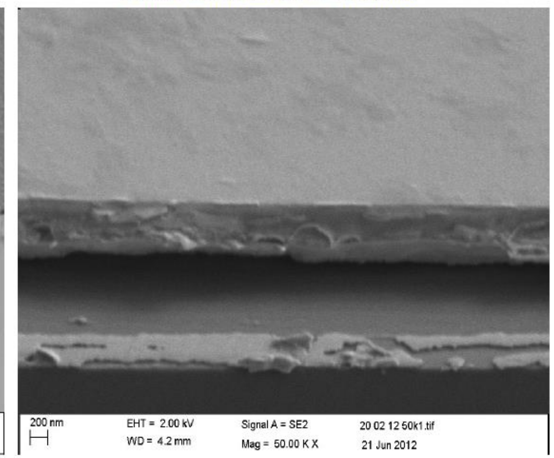
Table 1
Sticking probabilities for different gases and CO sorption capacity for the columnar and dense samples activated at different temperatures T_a.

T_a	Dense				Columnar			
	Sticking probability			CO sorption capacity	Sticking probability			CO sorption capacity [ML]
	H_2	CO	CO_2		H_2	CO	CO_2	
150 °C	0.002	0.04	0.075	0.004	0.004	0.2	0.13	3.5
180 °C	0.0013	0.025	0.012	0.13	0.014	0.2	0.13	3.5
250 °C	0.004	0.085	0.02	0.12	0.02	0.2	0.13	–

columnar
Best for pumping

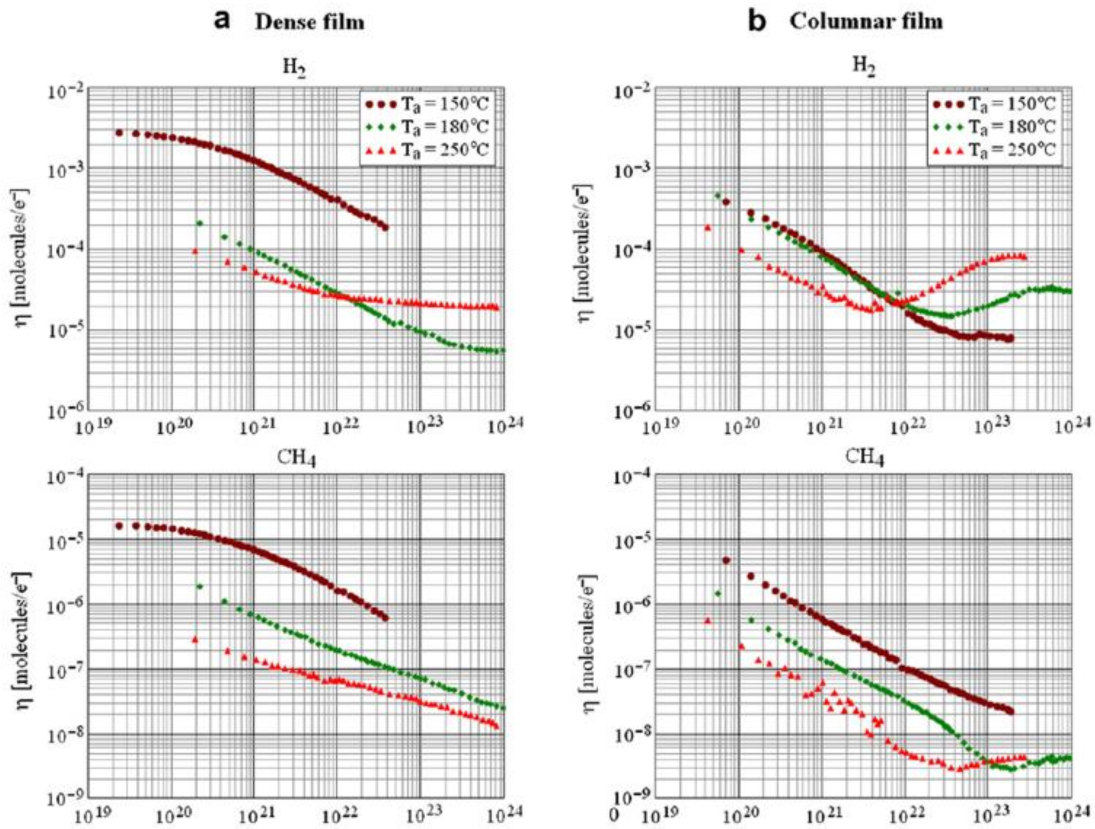


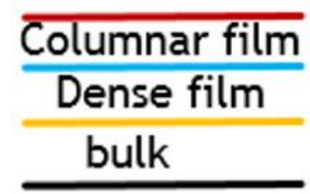
dense
A first candidate for a barrier



NEG Coating/Double Layer Coating

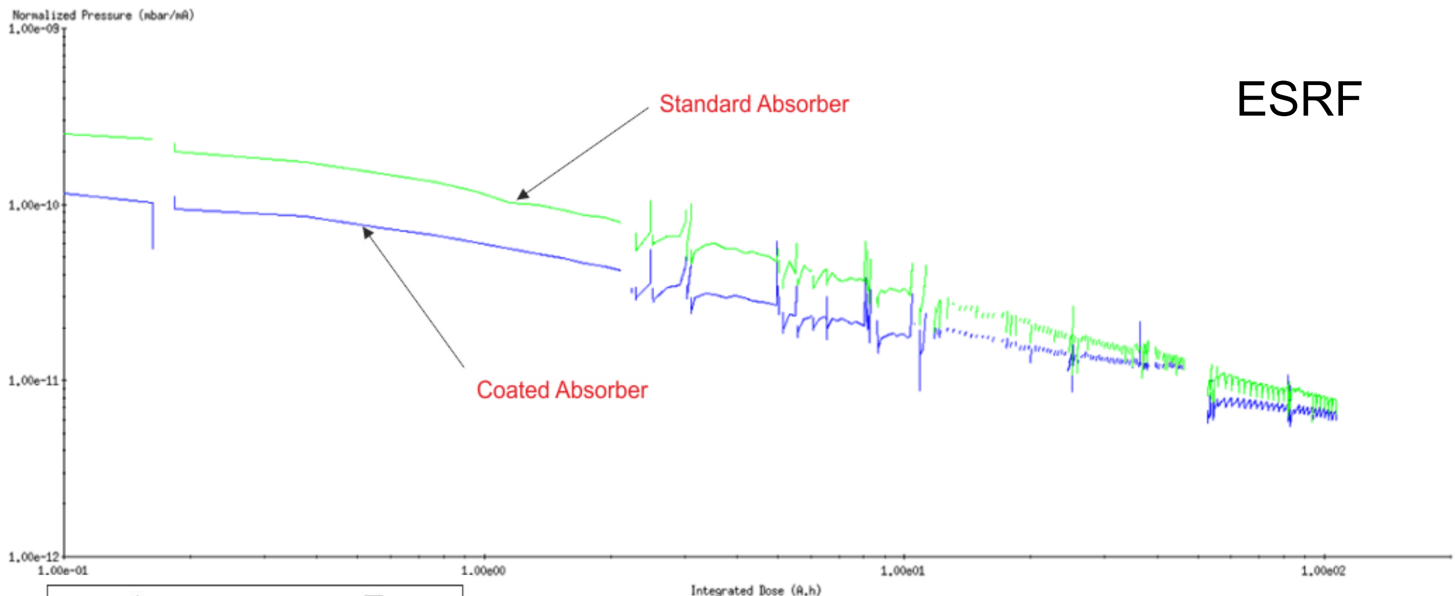
Daresbury/UK

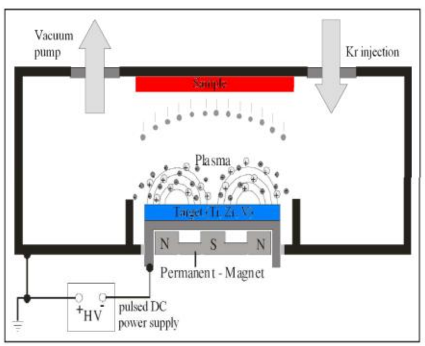




There are two solutions to benefit from the low desorption yields and the high pumping speed and capacity:
(1)vacuum firing of the vacuum chamber before NEG deposition,
(2) a protective layer between the vacuum chamber material and a columnar NEG (for example, TiN or dense NEG coating).

NEG Coating Benefit for Other Components



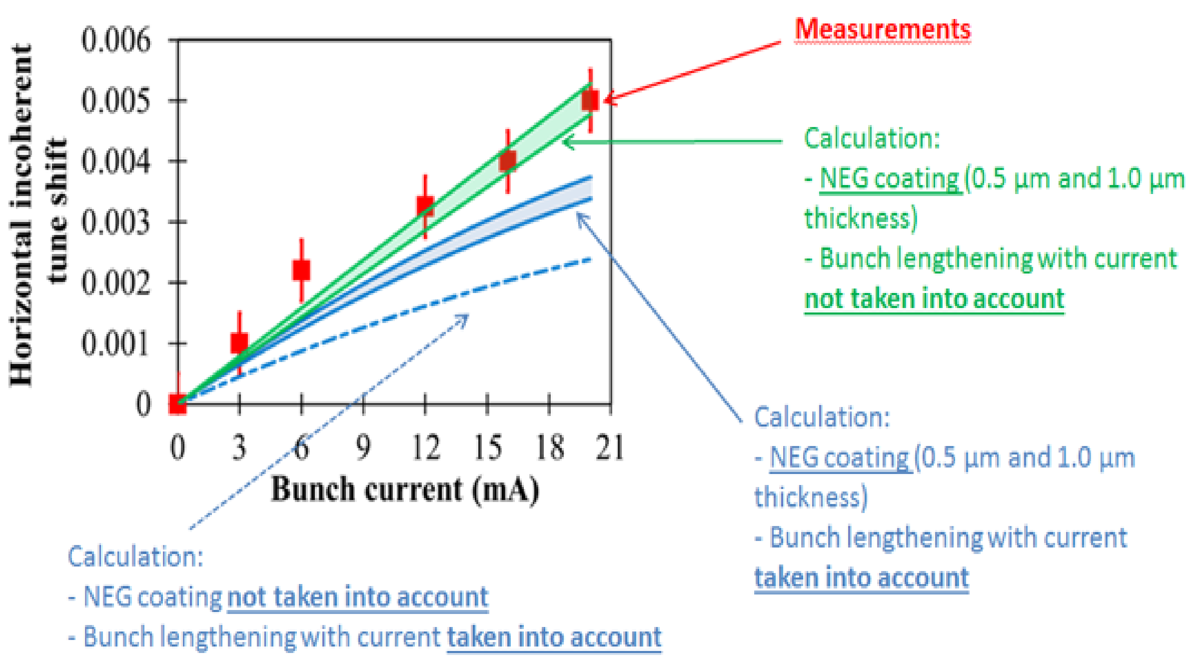


NEG coating

- R&D is continuing with the objective to explore if it is advantageous to coat the photon absorbers of the new machine.

NEG Coating Cons(impedance issue)

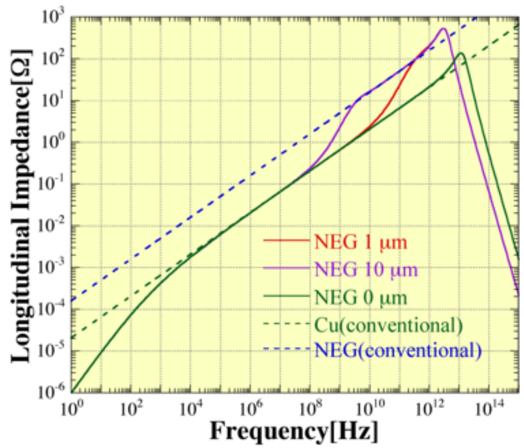
- At SOLEIL, the effect of NEG coating was also confirmed to contribute non-negligibly in the incoherent tune shifts arising from VC cross section asymmetry:



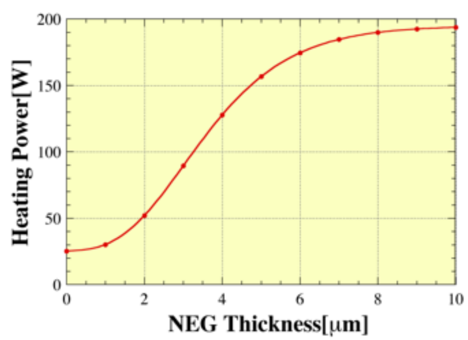
(P. Brunelle et al., PRAB ***19****,044401 (2016))*

NEG Coating Cons(impedance issue)

- Resistive wall impedance of the NEG coating
  - An example of calculation in a case of NEG coated Cu sheet for the in-vacuum undulator.
  - Electric conductivity of NEG coating : $10^6\ \Omega^{-1}\mathrm{m}^{-1}$
  - cf. SUS : $1.4\mathrm{X}10^6\ \Omega^{-1}\mathrm{m}^{-1}$
  - Cylindrical approximation
    - $k_{loss} = \frac{6.38\times10^{12}}{g_u[\mathrm{mm}](\sigma_t[\mathrm{ps}])^{1.5}}$
    - $P_{RW} = \frac{k_{loss} I^2 L}{f_b}$
  - For $g_u = 4$ mm
    - 1 μm coating little affect the impedance.
- Cylindrical duct of Ø24 mm I. D.,
  - Power loss will be 1/6 of 4 mm duct, 200 W.
  - 23 W/m heat load is predicted for SUS pipe without Cu plating.
  - Heat load for the Cu pipe will be 4 W/m.
  - Suitable candidate of the duct material is OFHC Cu or Cu alloy.
  - Aluminum-alloy tube is considered a candidate where a deformed cross section is required.
  - SUS duct needs thick Cu plating.



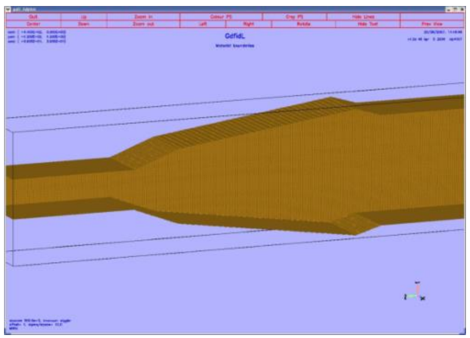
KEK_LS

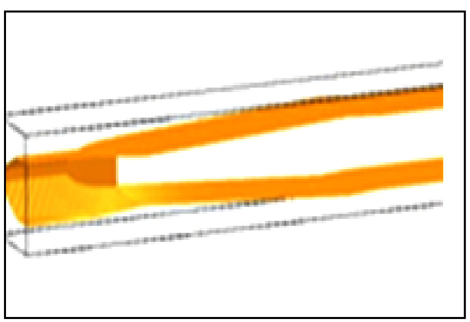


Some Specific Hardware Development

- Impedance: More gentle transition, no gap between flanges, RF shielded bellows… round chambers improve geometric impedance, smaller cross section…

• SOLEIL in-vacuum ID tapers





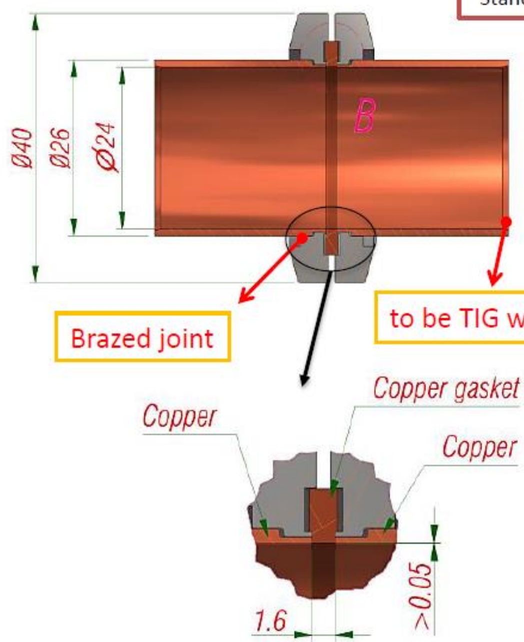
In-vacuum taper structure: Initial (above). Improved (below)

- Initial tapers creating a cavity structure when the ID gap was opened had a serious problem of beam-induced heating.
- New tapers greatly improved the heating issues.

Some Specific Hardware Development

Modified KEK MO-type flange (circular and non-circular):

- No gap
- No step
- Smooth inner surface
- Beam only see copper

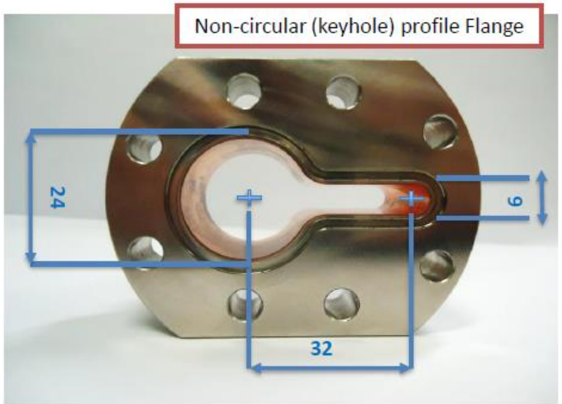


Tightening Results
Torque of 2 N.m sealing to < 1.10^{-10} mbar.L/s

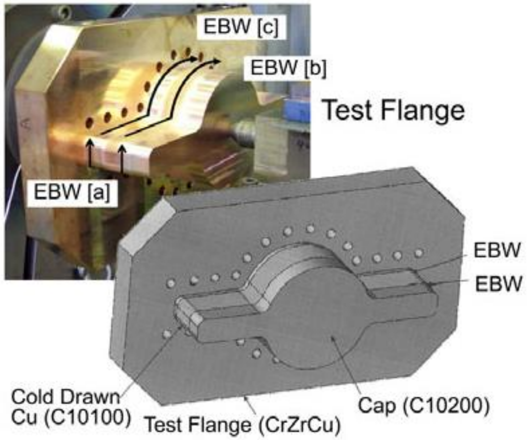
Standard circular profile Flange

SIRIUS

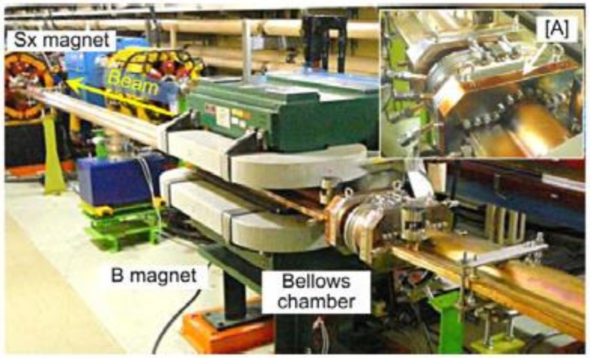
Non-circular (keyhole) profile Flange

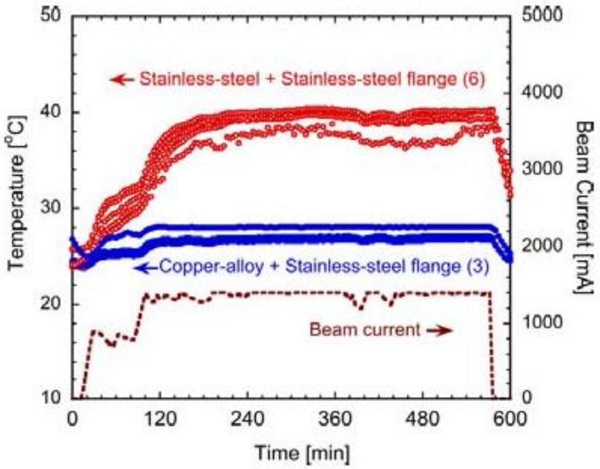


Some Specific Hardware Development



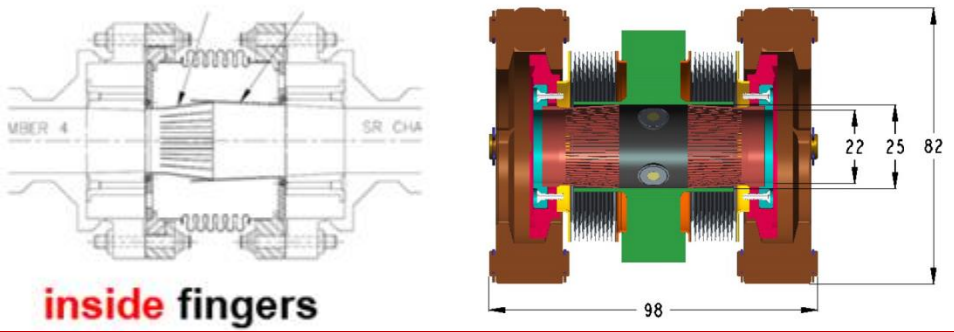
- GlidCop or CrZrCu flanges

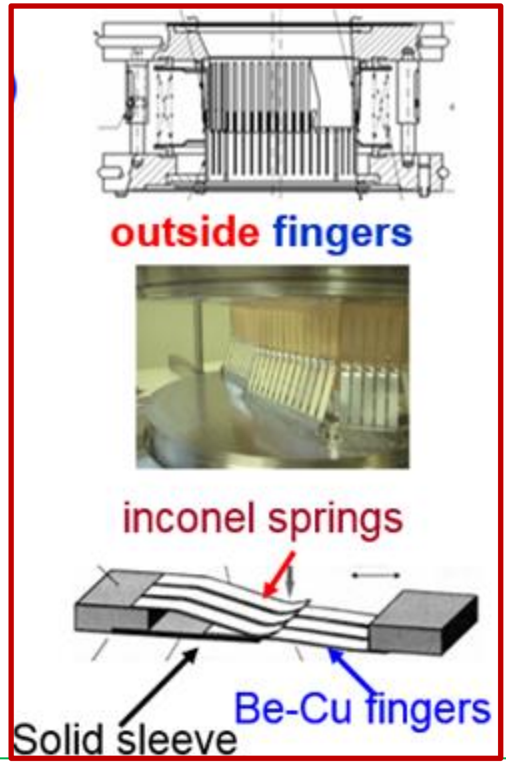




KEK_B

Some Specific Hardware Development





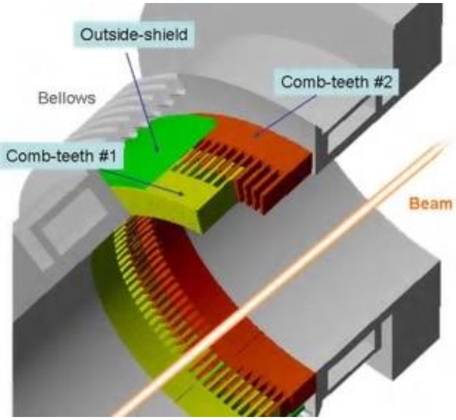
Inside fingers	Outside fingers
(APS, LNLS)	(PEP II, Soleil, DLS, …)
Simple, reliable	Lower impedance
$$	$$$

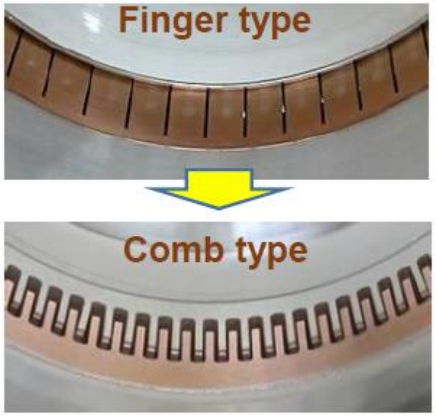
Simulations of narrow finger bellows:

Inside fingers : K_{loss} ≈ **1.9 x10^{-2} V/pC** ± 2 mm offset ≈ **21.4 x10^{-2} V/pC**

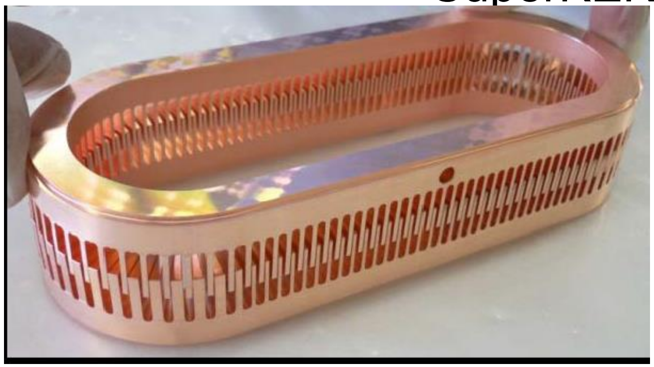
Outside fingers : K_{loss} ≈**2.1 x10^{-2} V/pC** ± 2 mm offset ≈ **8.7 x10^{-2} V/pC**

Some Specific Hardware Development





SuperKEK_B



The comb-type RF shield has a structure of nested comb teeth, and has higher thermal strength and lower impedance than the conventional finger-type one.

Advantages of the comb-type RF-shield are as follows:

(1)The RF shield, i.e. the copper teeth, has a high thermal strength compared to thin fingers.

(2)There is no transverse step at inside surface in principle, and the shield has low impedance.

(3)The TE-mode like HOM, which can easily couple with the finger-type RF shield, hardly goes through due to the large radial thickness of teeth.

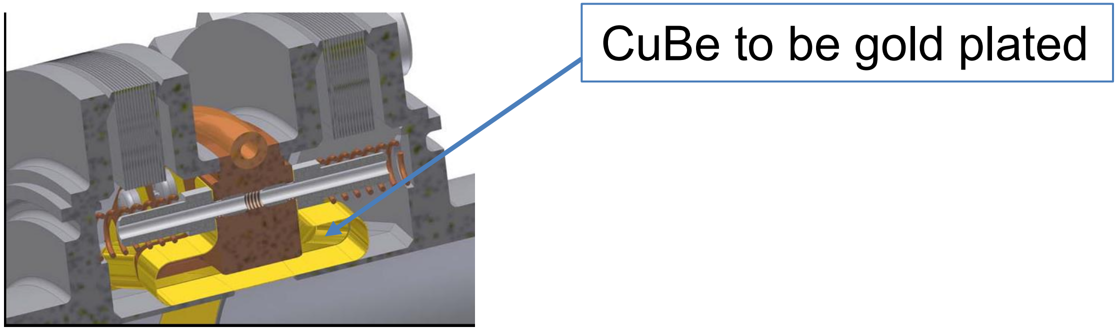
(4)There is no sliding point on the inner surface of beam duct, which otherwise could be a source of arcing.

(5) The RF shield can fit for beam ducts with various cross sections.

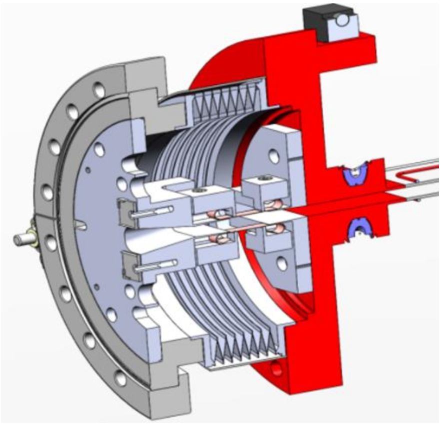
The potential disadvantages compared to the finger-type RF shield, on the other hand, are the limited stroke of expansion/contraction, typically ±4 mm, and the small bending angle, ±30 mrad at most.

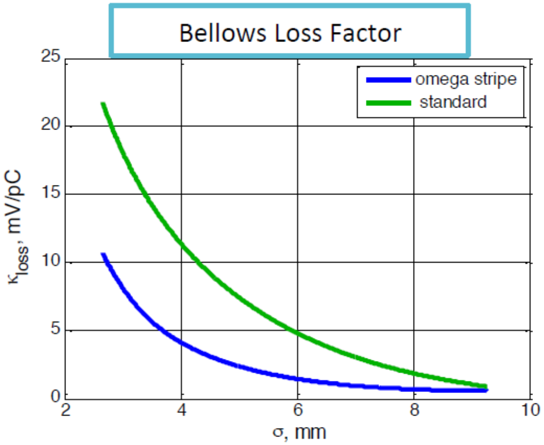
Some Specific Hardware Development

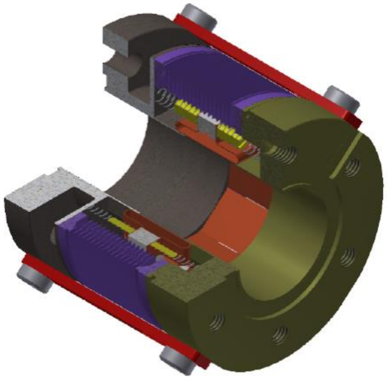
Omega Stripe RF shield



EBS



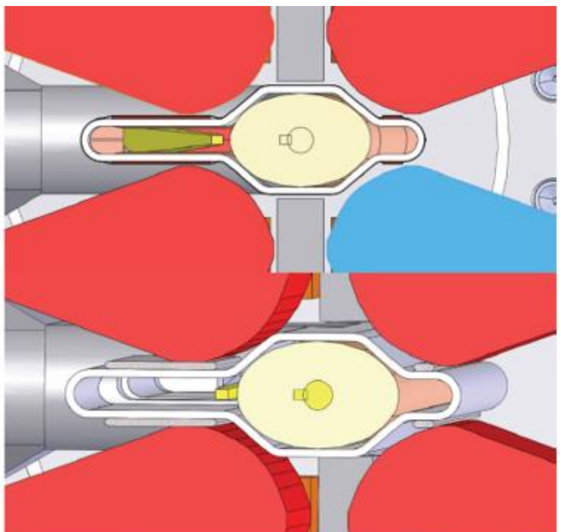




SIRIUS

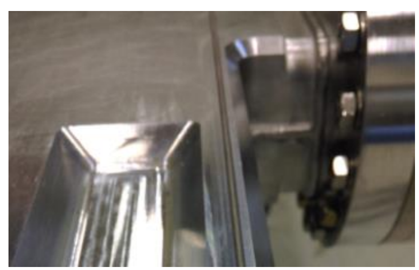
In-situ bake out/NEG coating activation

- Minimum gap needed between chamber and magnet poles(0.5~1.0mm)
- Chamber heating methods, how to apply thin radiation resistant heat films



- **Different configurations of heating element arrangement have been developed**
- **Thermal simulation is being carried out by means of FE module of Solid Works**

EBS



316L Sheathed heaters

Test shaping insulation coats (aluminum coated PI)

In-situ bake out/NEG coating activation

The vacuum system for Sirius is being designed to be baked in-situ for NEG coating activation!

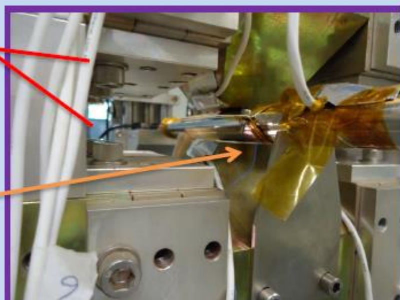
Main specifications for the required heaters:

- Thickness <= 0.4 mm
- Voltage < 50V
- Max. tested temperature 220 °C

Heater developed along with a Brazilian company

T_{poles}= 35.2 °C

0.5 mm gap



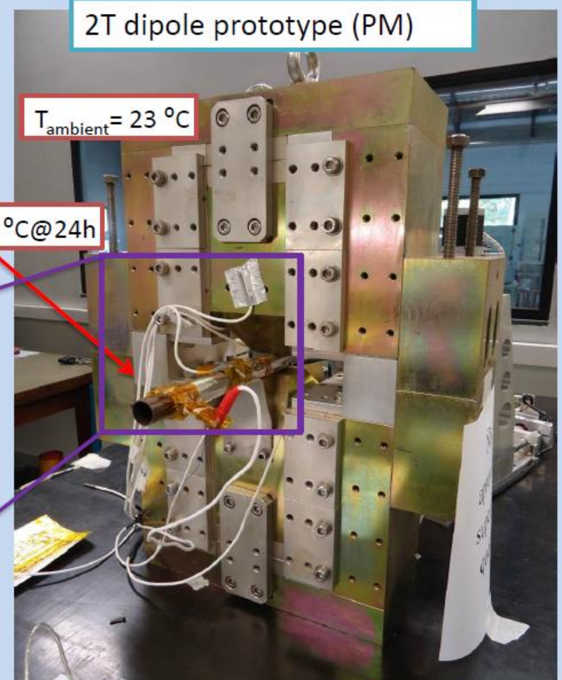
max. ΔT_{poles}= 12.2 °C ; max. ΔT_{PM}= 8.8 °C

Test of impact of an in-situ bake-out for NEG activation on permanent magnets

2T dipole prototype (PM)

$T_{ambient}$= 23 °C

T_{tube}= 200 °C@24h



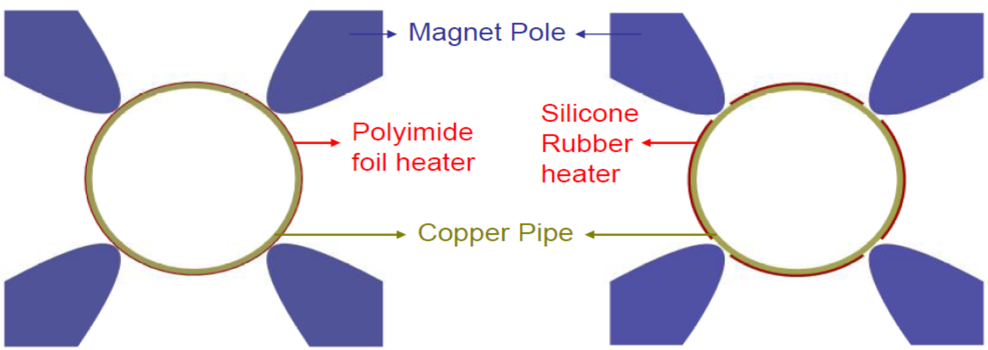
Still need to check the radiation resistance of the heating tapes!

SIRIUS

In-situ bake out/NEG coating activation

Polyimide foil heater

Silicone rubber heater



Thickness 0.3mm

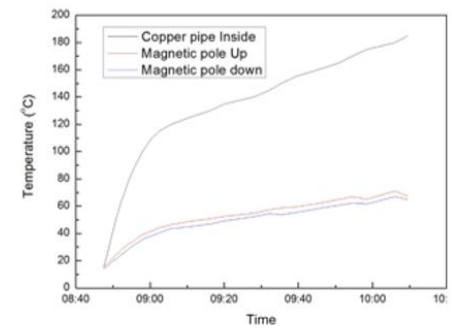
Thickness 1.0mm

Coper Pipe Outside Diameter: 104mm
Magnet Pole Distance:105mm

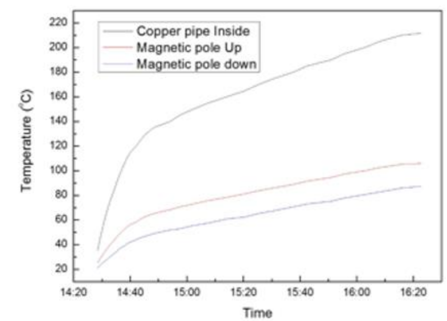
IHEP

Temperature Rise Curve

Polyimide foil heater



Silicone rubber heater



Summary

- The vacuum system for the next-generation ring-based LSs has to cope with high synchrotron radiation, high photon flux, intense HOM excitation, strong collective effect, and so on.

- The low emittance lattice is making the vacuum chambers and components more and more miniature, both transversely and longitudinally, making their designs and vacuum pumping difficult with classical pumps.

- Vacuum pumping with NEG coating on the other hand is becoming increasingly attractive for the future machines. The use of NEG coated chambers must be considered right on the beginning of the design phase since it has a huge impact on infrastructure, fabrication strategy, cleaning procedures, baking strategy, etc.

We have experienced various problems during the operation 3rd generation LSs, and learned lots of things. These experiences should be some of help for the future design of next-generation LSs.

Thank you for your attention