PAL Accelerator/Vacuum Technology and EIC

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POHANG ACCELERATOR LABORATORY

Outline

- **Status of PLS-II and PAL-XFEL**
- **Vacuum R&D in PAL**
  - ✓ Vacuum System for a 4th Generation Storage Ring Studied in PAL
  - ✓ 3D Printing Techniques to the Vacuum System
  - ✓ Improvement of Vacuum Property of materials
- **Summary**

PLS-II Overview: Chronology

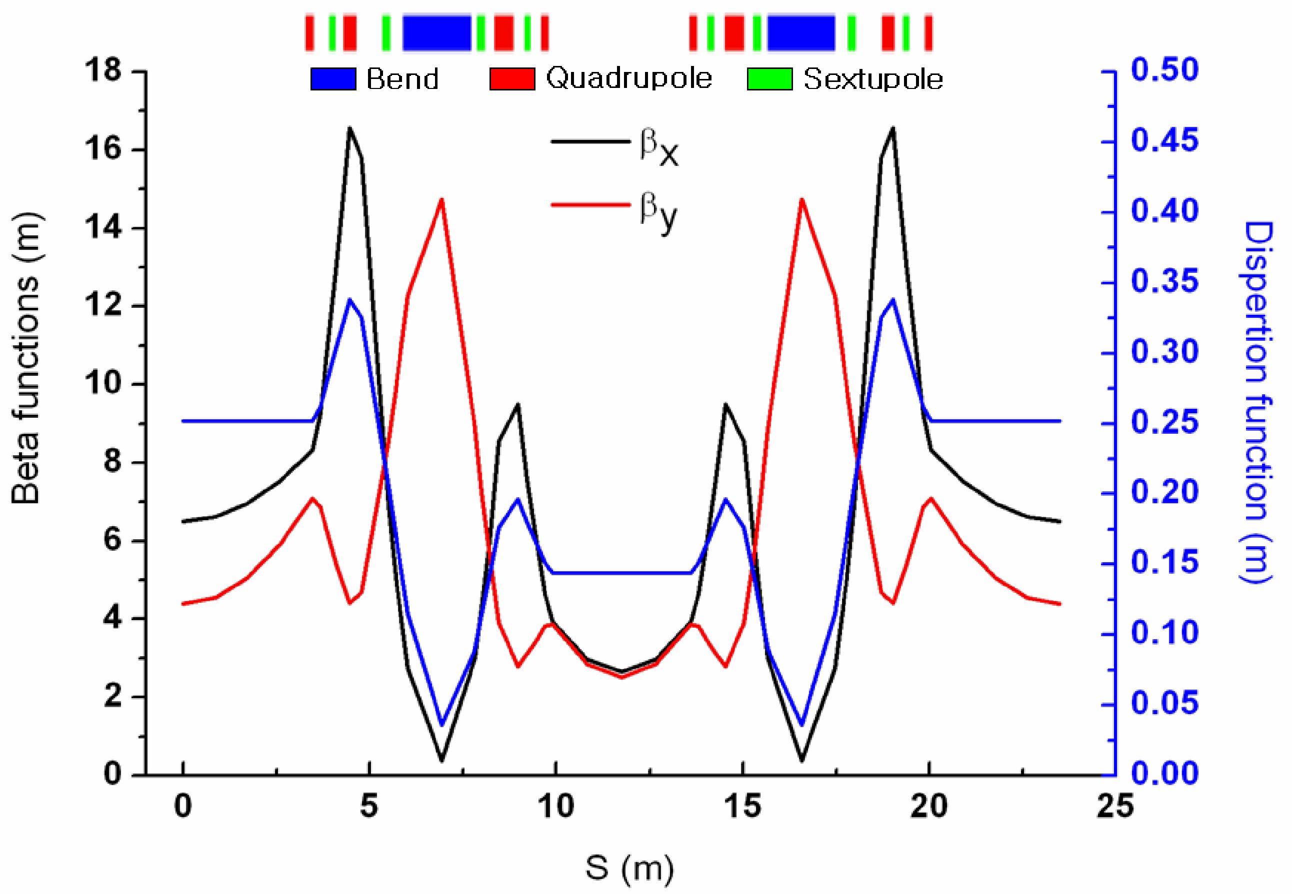
I. PLS

▪ Project started	Apr.	1988
▪ User service started	Sep.	1995

II. Major Upgrade of the PLS (PLS-II)

▪ 3.0 GeV PLS-II Upgrade begin	Jan.	2009
▪ 3.0 GeV PLS-II Upgrade Complete	Dec.	2011
▪ User service started	Mar.	2012
▪ 3.0 GeV 400 mA Top-up operation	July	2015

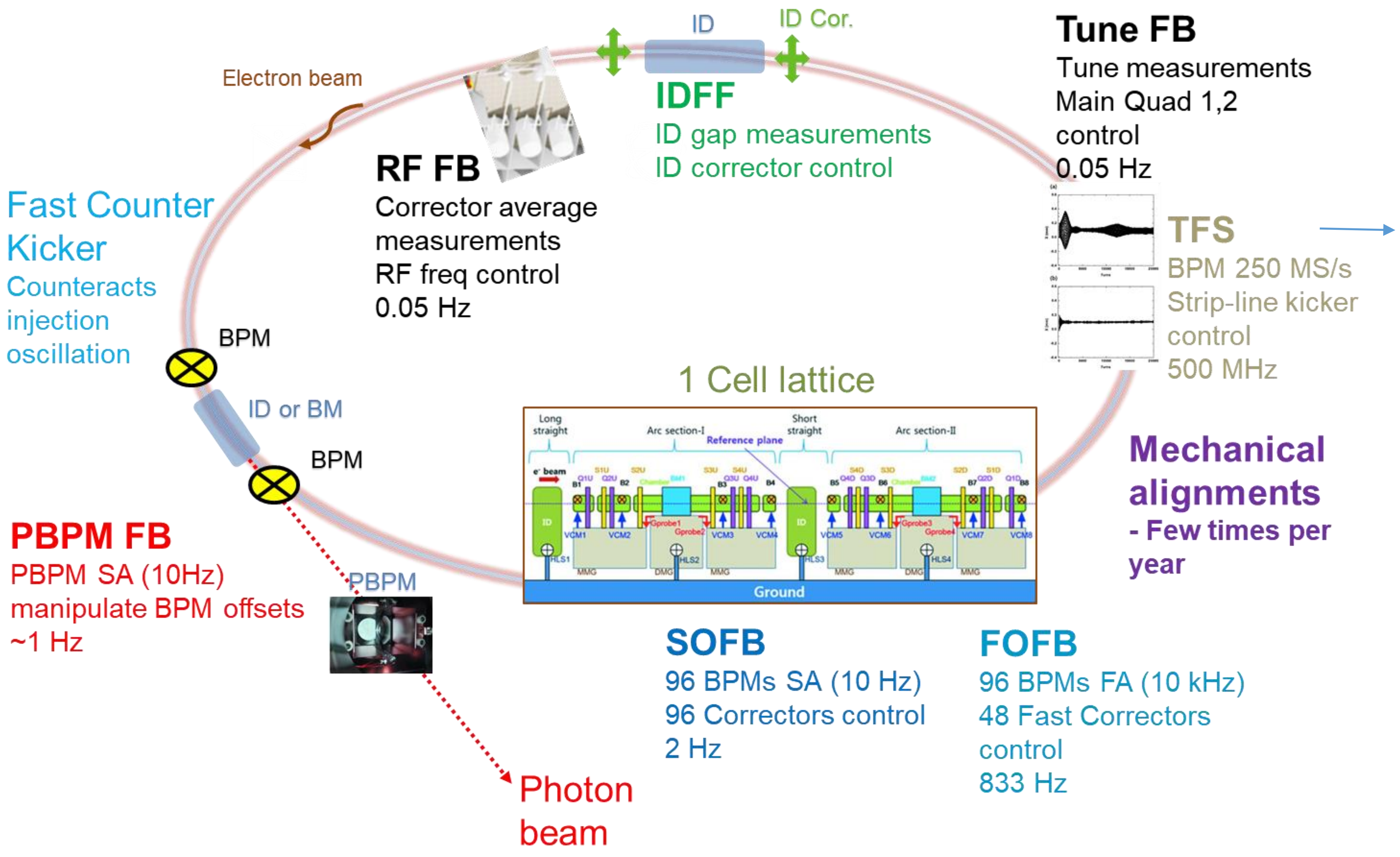
PLS-II Overview: Storage ring

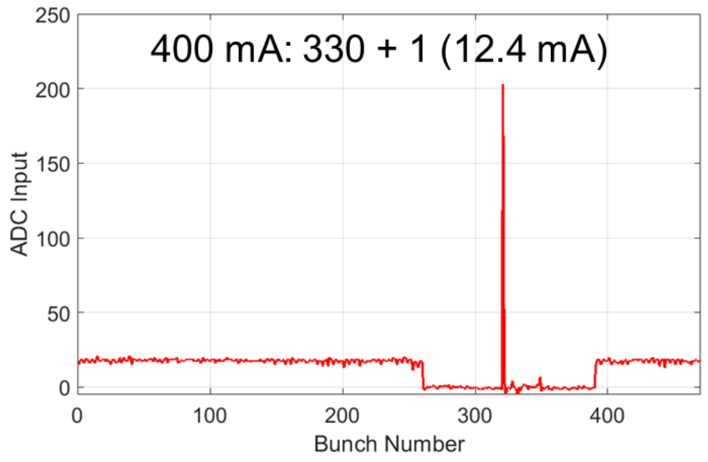


✓ 42 % of the circumference available for straight sections

- Beam Energy 3.0GeV
- Beam Current 400mA
- Lattice DBA
- Superperiods 12
- Emittance 5.8 nm·rad
- Tune 15.37 / 9.15
- RF Frequency 499.97 MHz
- Circumference 280 m

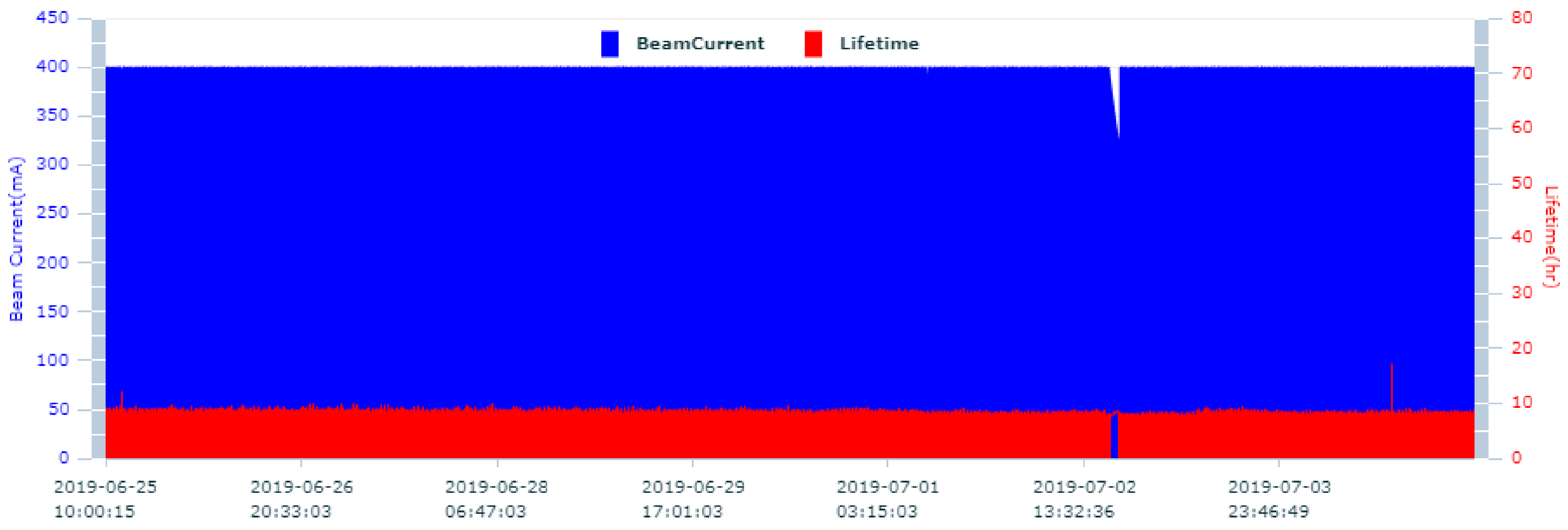
PLS-II Overview: Instrumentations for high performance operation

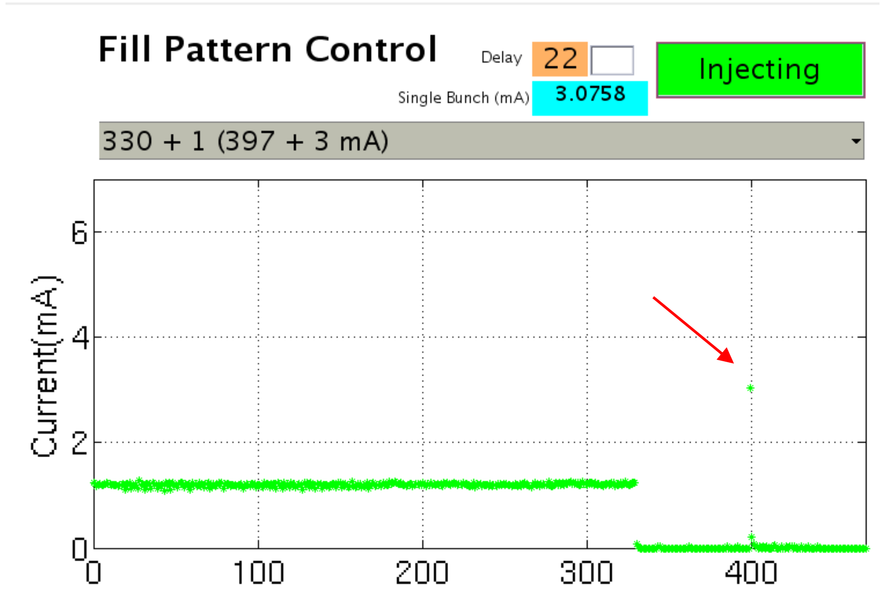




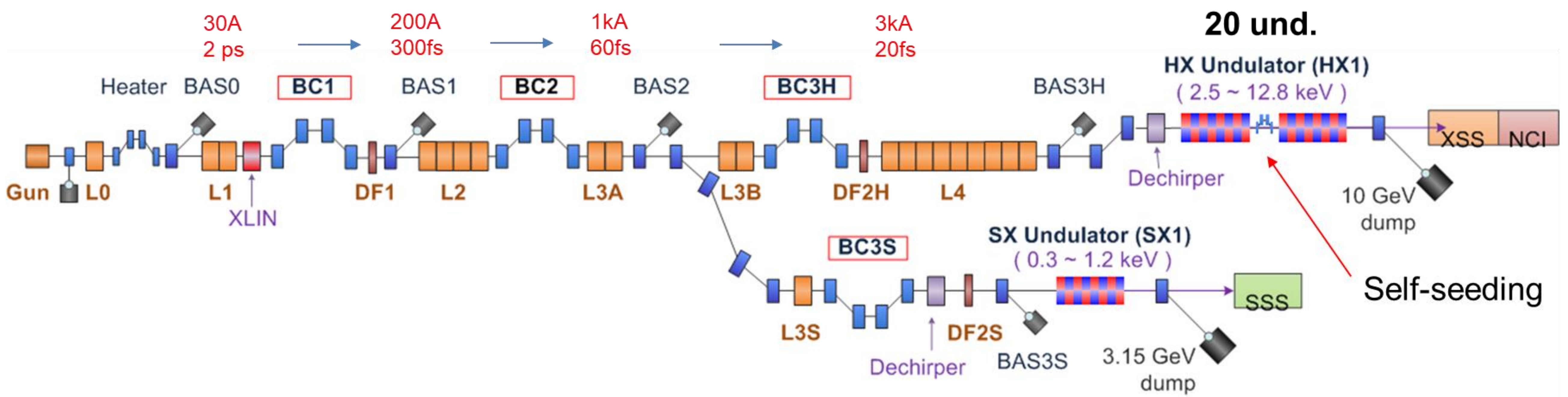
PLS-II Overview: Operation

- 4 user runs (No dump) in the 1st half of 2019
- Routinely 400 mA Top-up (Hybrid mode)
- SRF CM3 leak (Recovery until 2020) → Currently 250 mA Top-up operation





PAL-XFEL Overview



Main parameters

e^- Energy	11 GeV
e^- Bunch charge	20-200 pC
Slice emittance	< 0.4 mm mrad
Repetition rate	60 Hz
Pulse duration	5 fs – 50 fs
Peak current	3 kA
SX line switching	DC magnet (to be changed to Kicker by 2020)

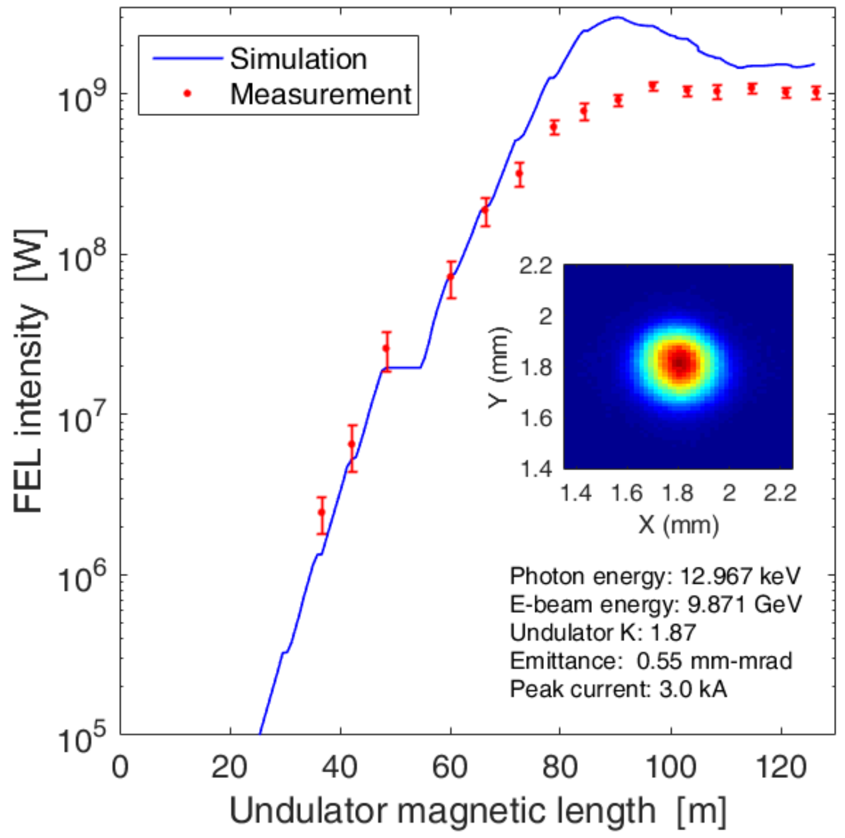
Undulator Line	HX1	SX1
Photon energy [keV]	2.0 ~ 14.5	0.25 ~ 1.25
Beam Energy [GeV]	4 ~ 11	3.0
Wavelength Tuning	energy	gap
Undulator Type	Planar, out-vac.	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0

PAL-XFEL Overview: Brief Time Line

- April 2011 — PAL-XFEL project started
- Sep. 2012 — Construction started
- Jan. 2015 — Building completed
- Dec. 2016 — Installation completed

- April 12, 2016 — Commissioning started
- June 14, 2016 — First SASE lasing at 0.5 nm
- Oct. 28, 2016 — Lasing at 0.15 nm
- Nov. 27, 2016 — Saturation of 0.15 nm (project completed)
- March 16, 2017 — Saturation of 0.1 nm (design goal achieved)

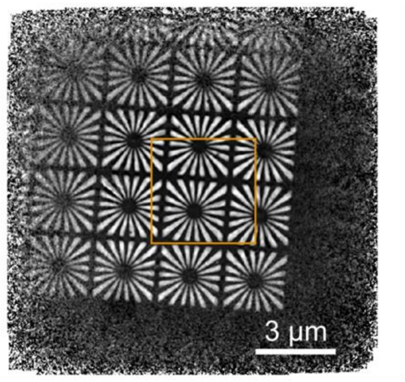
- June 7, 2017 — First User Service
- May 30, 2018 — Self-Seeding Test
- Nov. 2018 — Permission granted to operate up to 11 GeV
- Mar. 2019 — 60 Hz operation started



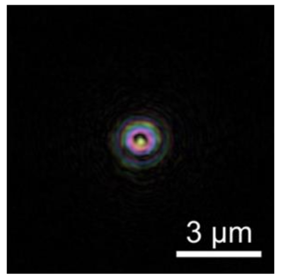
PAL-XFEL Overview: FEL Performance

▪ FEL power stability	< 5% RMS
▪ FEL position stability	< 10% of beam size
▪ FEL central wavelength jitter	0.024 % (1/5 of SASE BW)
▪ FEL beam availability	> 96%
▪ **Timing stability** between X-ray pulses and optical pulses	**18 fs (rms)**
▪ **Relative electron beam energy jitter**	**1.2 x 10-4**
▪ Electron beam arrival time jitter	12 fs

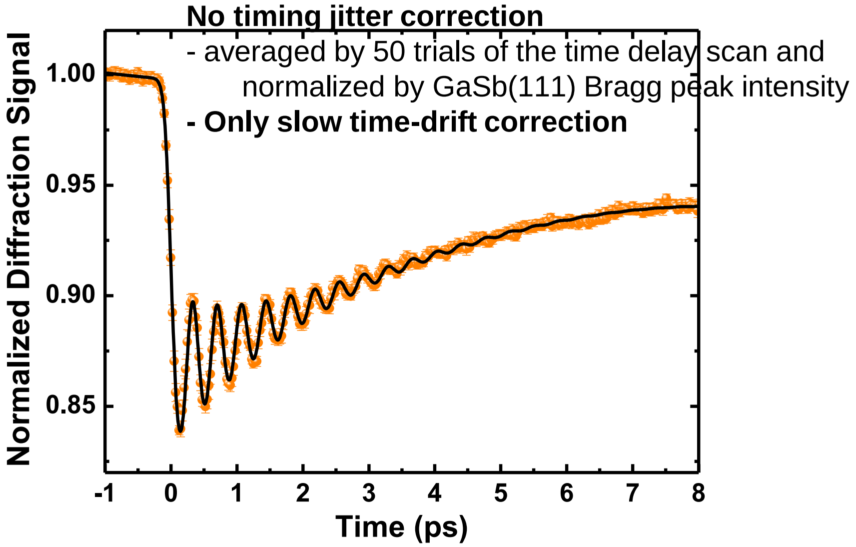
Ptychography (J. Hasting)

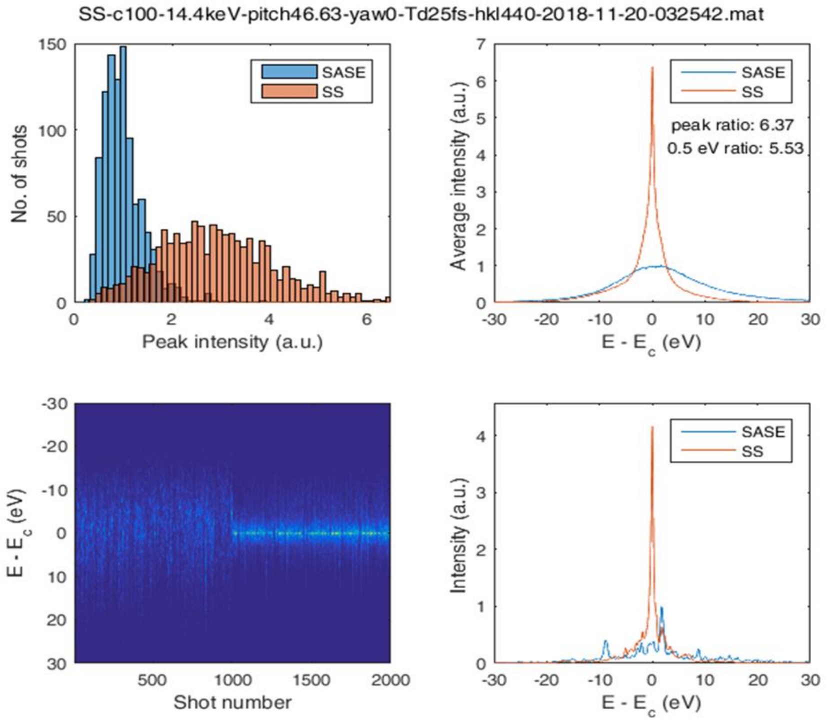


Reconstructed object (scan area in orange)



Reconstructed complex illumination at object plane





Machine components developed in Korea

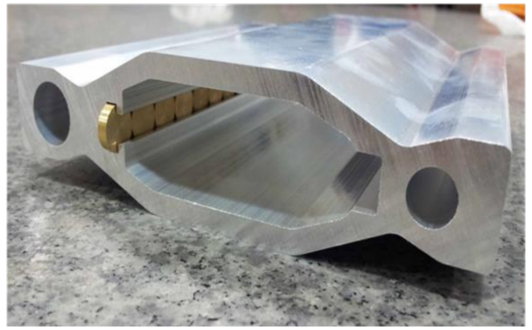
○ **Developed in the PLS-II project**
- In-vacuum undulator
- MPS
- Many vacuum components
- RF window

○ **Developed in the PAL-XFEL project**
- SLED
- CCPS
- Accelerator column
- RF window
- Magnet
- Undulator
- Klystron

○ **In the future**
- Thyratron
- E-gun
- Capacitor

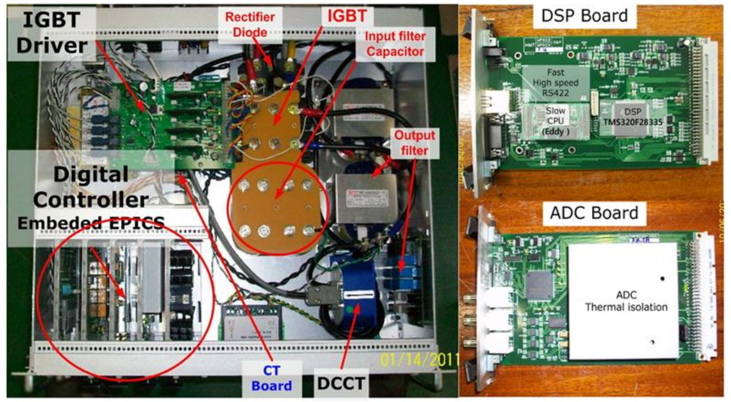
❖ **Photon absorber**
- Cold forged OFHC
- High thermal conductivity
- High yield stress

❖ **Pill type getter**
- Distributed pumping for straight section



❖ **Modulator, CCPS**

❖ **MPS**



❖ **In-vacuum undulator**

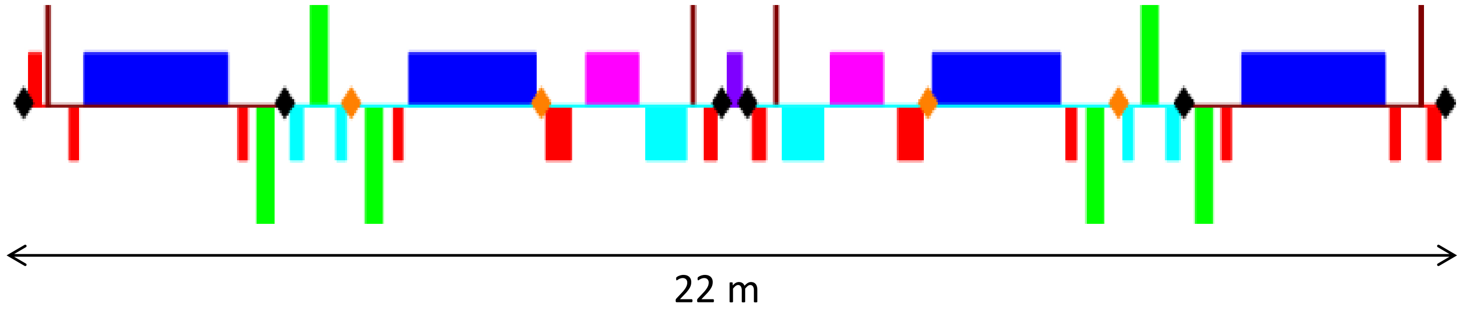
❖ **Accelerating column, SLED, RF window**

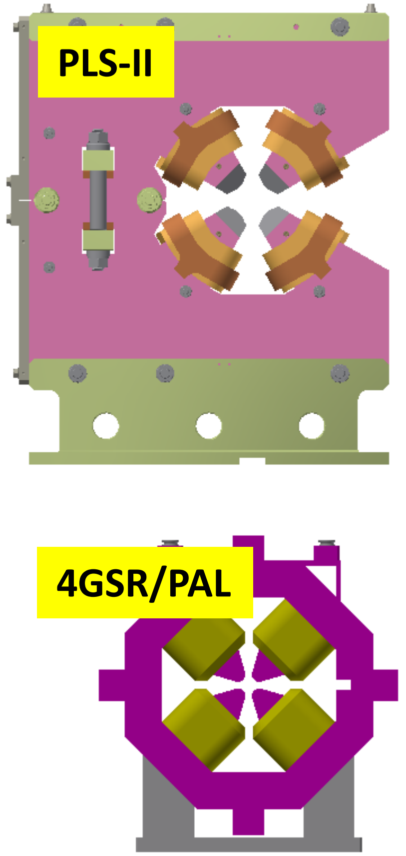
Vacuum System for a 4th Generation Storage Ring Studied in PAL

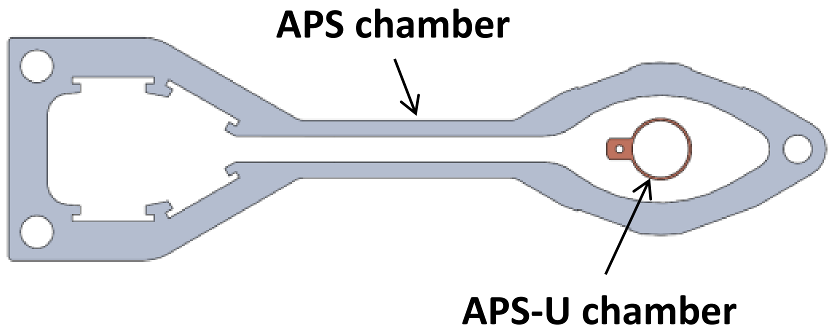
Modern Low Emittance Storage Ring

- The 3rd Generation Storage Ring Lattice:

- The 4th Generation Storage Ring Lattice:







❖ Main features of recent vacuum systems for 4GSR:

Small aperture

Tight space

→

- Low gas conductance
- Hard to install discrete vacuum components

→

"Distributed" pumping and "distributed" photon absorption

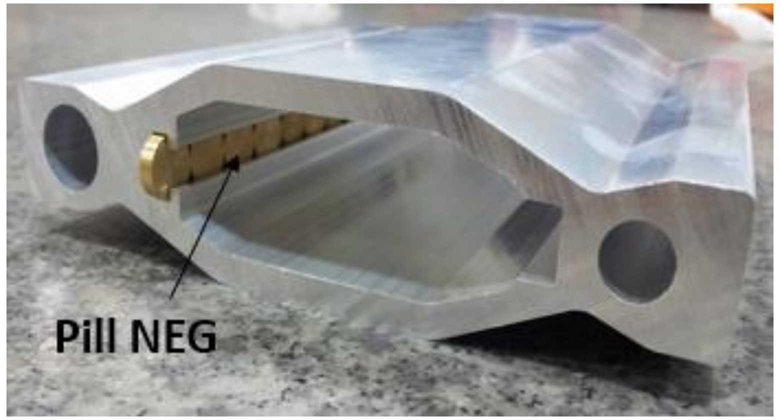
Vacuum System for a 4th Generation Storage Ring Studied in PAL

Limitations of the current vacuum techniques for the 4GSR

- ❖ Conventional vacuum chamber with the large antechamber, where the discrete pumps and photon absorbers are installed, will not be suitable to the future advanced lattice as the number of magnets is increasing and as the bore size is decreasing further.

- ❖ NEG coated chamber is the best option at the present time but it still needs a lot of time and effort to optimize the coating process for each chamber of different shape.
- ❖ The impedance effect on the beam due to the NEG coated layer has not been fully understood yet.

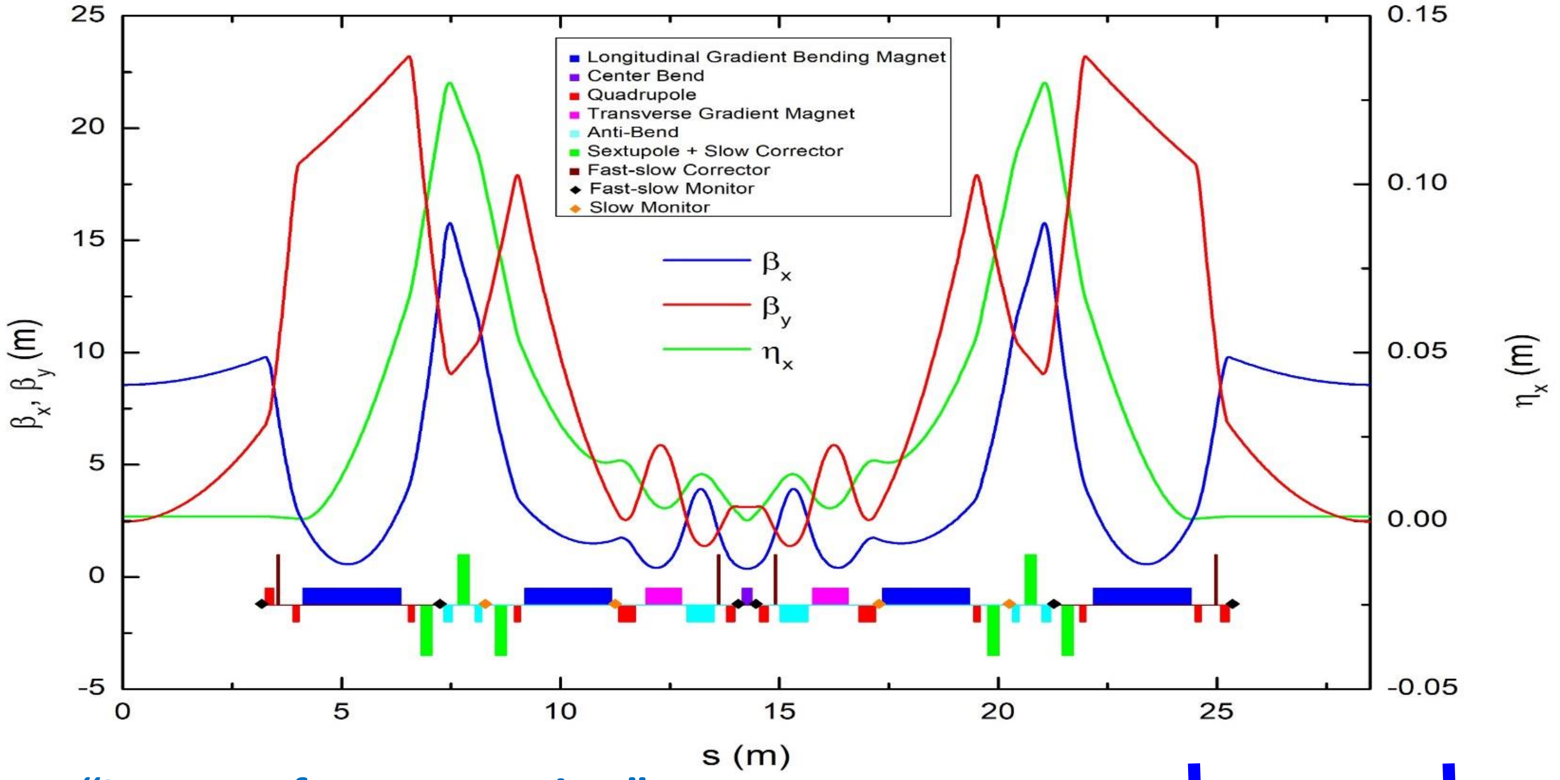
➔ A vacuum chamber using **"pill-type" getters** with **3D printing techniques** is a practical alternative to the conventional vacuum chamber or the NEG coated chamber for the 4GSR.



"Straight section chamber with pill-type getters being in use at PLS-II storage ring"

Vacuum System for a 4th Generation Storage Ring Studied in PAL

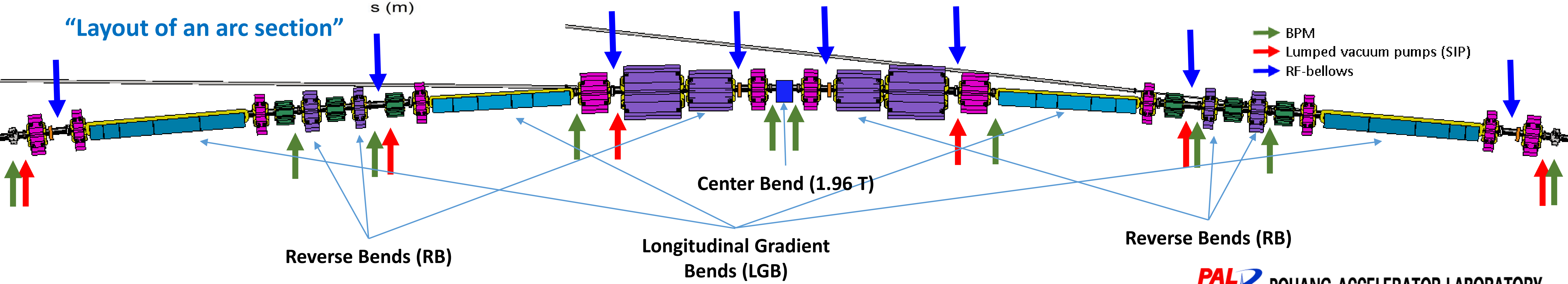
"Linear lattice design"



"Main parameters"

4GSR Ring		Value	Unit
Design Parameters	Cell Number	28	-
	Circumference	798.843	[m]
	Electron Energy	4	[GeV]
	Natural Emittance	58	[pm rad]
Tune and Chromaticity	Horizontal Tune	67.441	-
	Vertical Tune	23.168	-
	Natural Horizontal Chromaticity	-115	-
	Natural Vertical Chromaticity	-78	-
	Horizontal Chromaticity	3.5	(target)
	Vertical Chromaticity	3.5	(target)
Radiation related quantities	Energy Loss per Turn	1009	[keV]
	Energy Spread	0.1197	[%]
	Horizontal Damping Time	11.1	[ms]
	Vertical Damping Time	21.1	[ms]
	Longitudinal Damping Time	19.3	[ms]
Twiss functions at the ID	Horizontal beta function at the ID center	8.42	[m]
	Vertical beta function at the ID center	3.28	[m]
	Dispersion function at the ID center	0.00	[m]

"Layout of an arc section"



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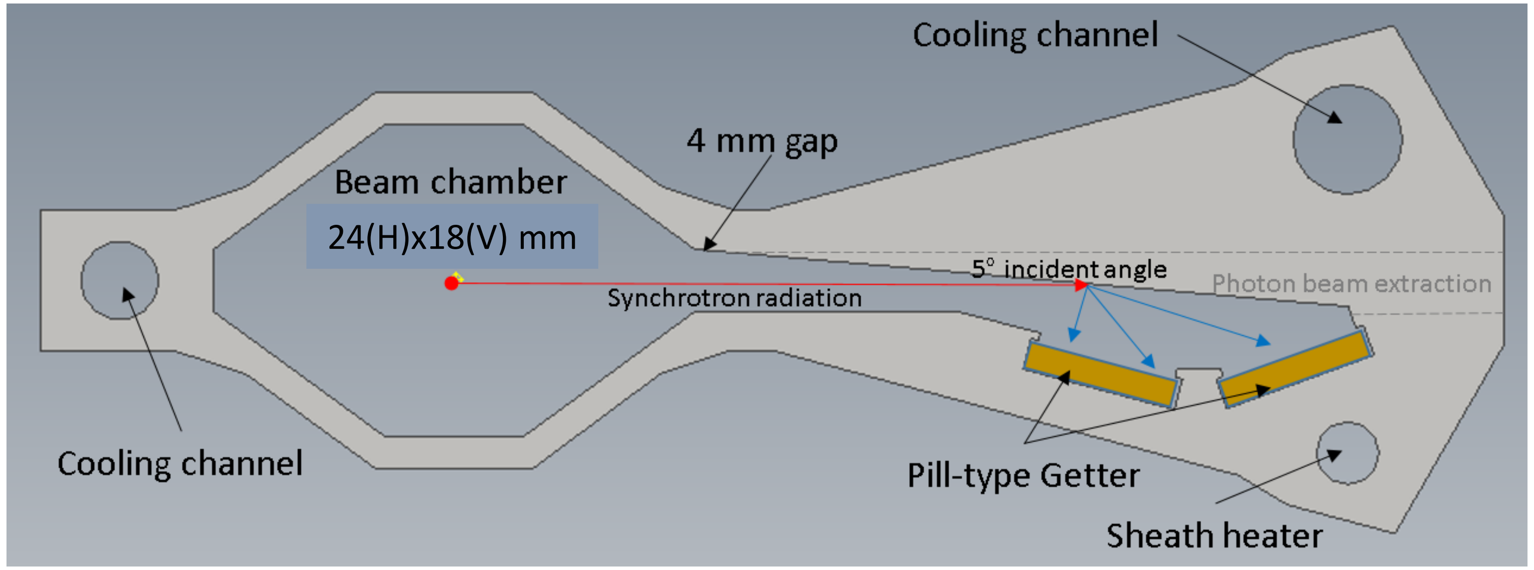
Vacuum System for a 4th Generation Storage Ring Studied in PAL

Conceptual design of the vacuum chamber

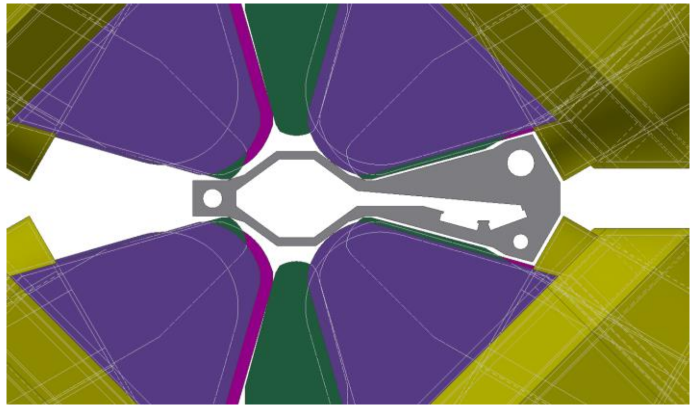
❖ **Handling of PSD gases and SR heat loads**

1. Aperture of the beam chamber is 24 mm (H) x 18 mm (V).
2. 5°-Inclined side chamber wall absorbs most of the photon beams.
3. PSD gas is mostly pumped by distributed pill-type getters.
4. Cross sections of the vacuum chambers in an arc-section are the same, except for the center-bend chamber which aperture is only 10 mm (V).

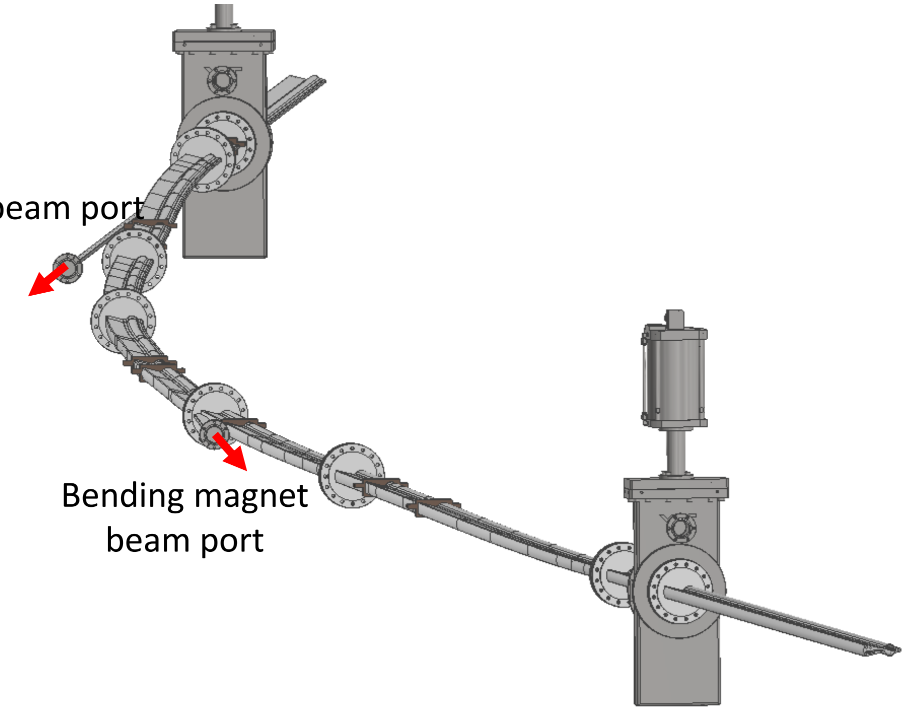
"Cross section of the vacuum chamber"



"Vacuum chamber and magnets"



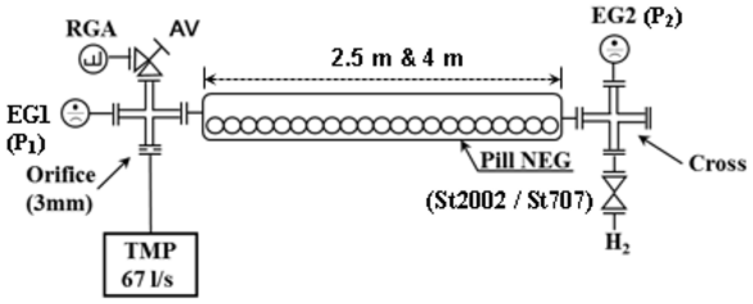
"Vacuum chambers of an arc-section"



Vacuum System for a 4th Generation Storage Ring Studied in PAL

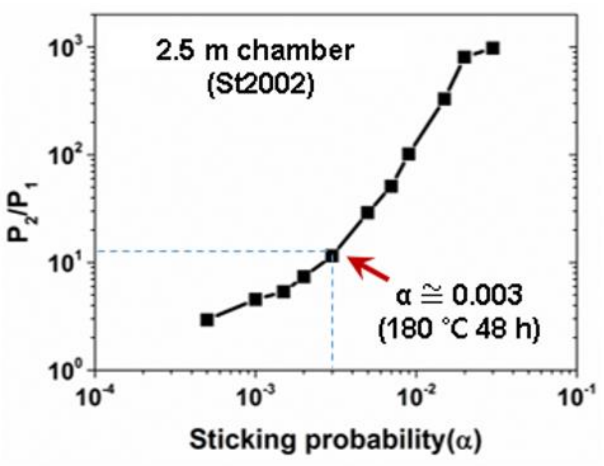
Sticking coefficient of the commercial pill-type getters

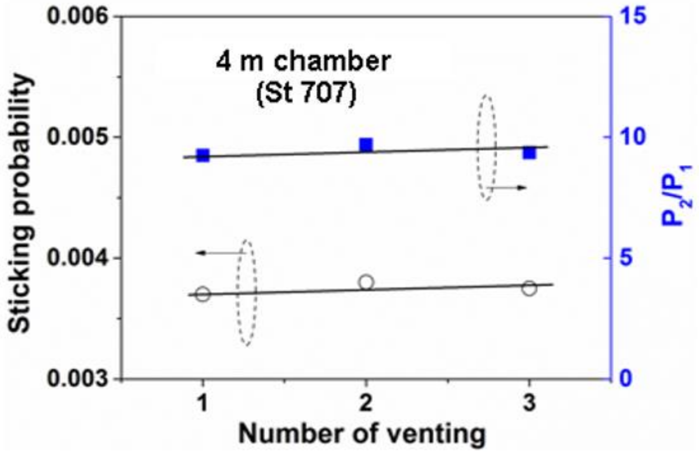
Set up



- The pressure(P_2) is kept constant (1×10^{-6} mbar) by injecting the H_2 gas
- TMP evacuate the gases that can't be pumped by pill NEG slowly.
- Molflow+ was used for calculation of sticking probability from ratio of pressure.
- Sticking probability: $\alpha \propto P_2/P_1$

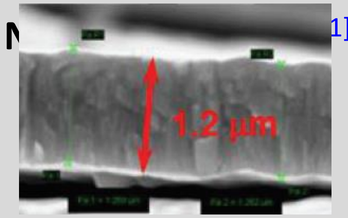
Results of H_2 sorption





- Pill NEG have a value of sticking probability about 0.003 → 1/5 of a NEG coated chamber roughly.
- Sticking probability is substantially constant after three additional venting.

"NEG film vs. Pill-type getter"

Type			Note
Facture	Sintering	Compressing	
Activation	200℃, 1 d	180℃, 1 ~ 2 d	
Pumping speed per length	-	Low (< 1/10)	Surf. Area ↓
Sticking probability (α)	**0.015** (200°C, 24 h)	**0.003 ~ 0.0037** (180°C, 48 h)	
α (after two additional venting)	0.015 → 0.008	Substantially constant	
Capacity (H_2)	-	1000×	Thickness↑
Disadvantages	Aging after venting	Particle	

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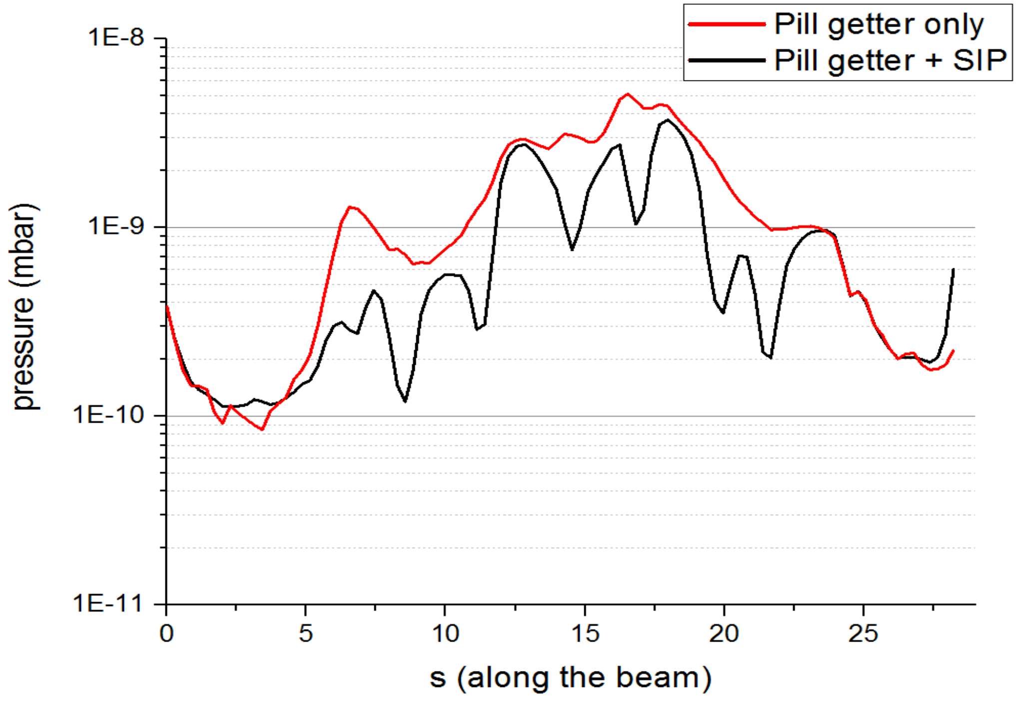
Vacuum System for a 4th Generation Storage Ring Studied in PAL

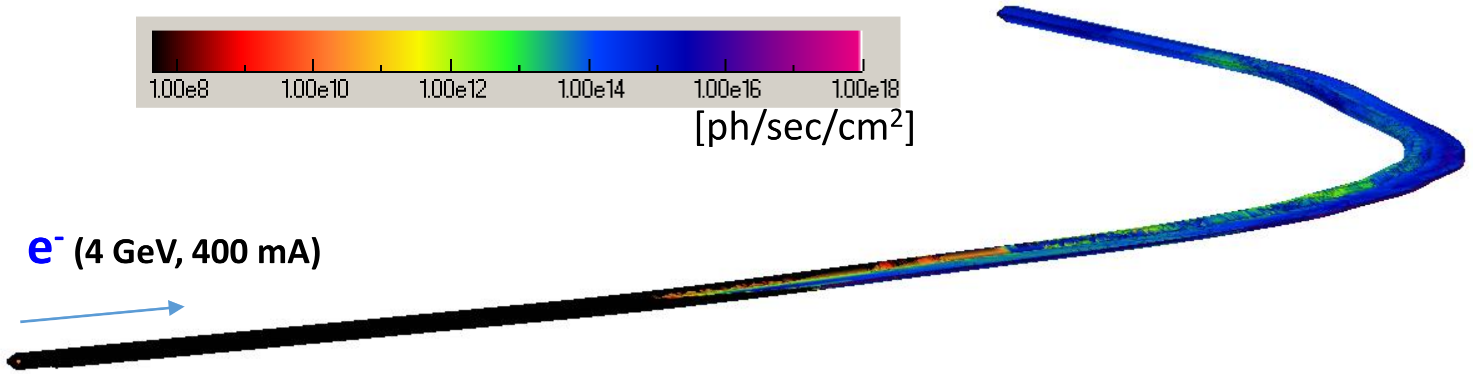
Pressure profile

- Total photon stimulated desorption calculated by Synrad is 1.74×10^{-6} mbar l/s with PSD coefficient of 1×10^{-6} /ph.
- Average pressure with only pill getter pumps of sticking coefficient 0.004 is 1.4×10^{-9} mbar and 8×10^{-10} mbar with additional 8 sputter ion pumps.
- Wire heater is inserted into the side channel of the vacuum chamber for 180℃ bake-out and NEG activation.

"H_2 pressure profile of an arc-section after beam dose of more than 1000 Ah ($\eta=1\times10^{-6}$/ph)"



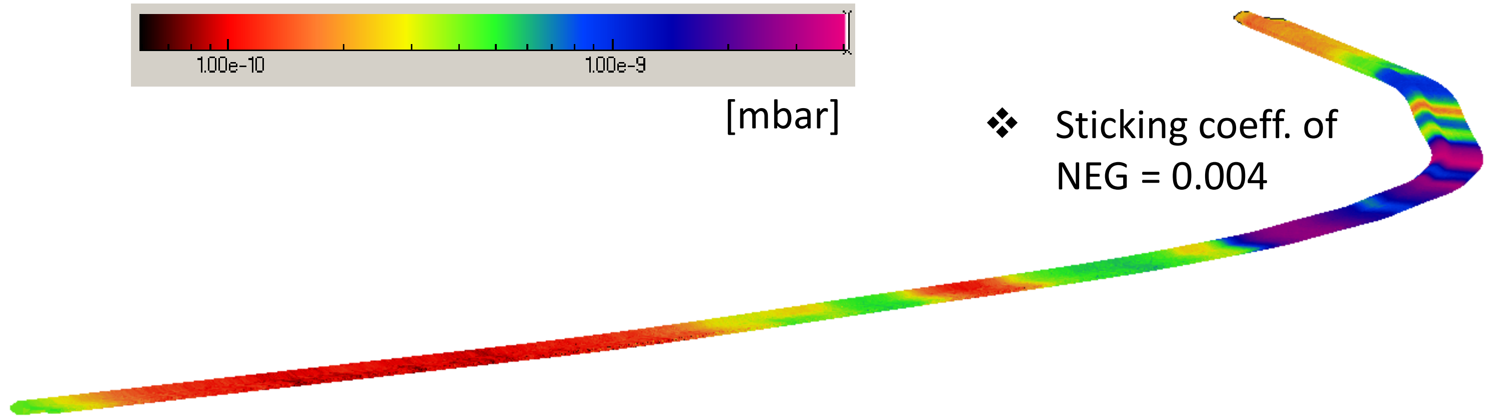
"Synrad simulation (PSD calculation)"



η = 1E-6/ph

Q_{tot} = 1.74E-6 mbar l/s

"Molflow simulation (pressure calculation)"

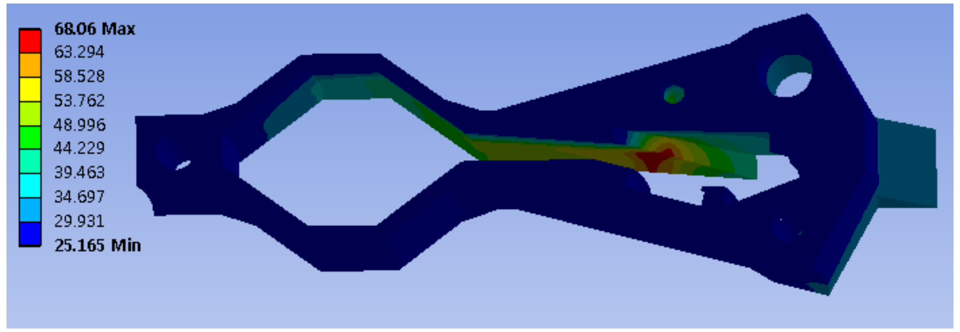


❖ Sticking coeff. of NEG = 0.004

Vacuum System for a 4th Generation Storage Ring Studied in PAL

Thermal analysis with the SR heat loads

- Most intense thermal load is 0.77 W/mm^2 from the center bend.
- Thermal analysis results show that both aluminum and Cu alloy can be used for the vacuum chamber material.
- Aluminum chamber can be fabricated by extrusion, bending and welding.
- Cu alloy chamber can be fabricated by machining of two pieces (top and bottom) and welding.
- Temperature of the sharp edge at a beam exit branch is 68℃ (endurable).

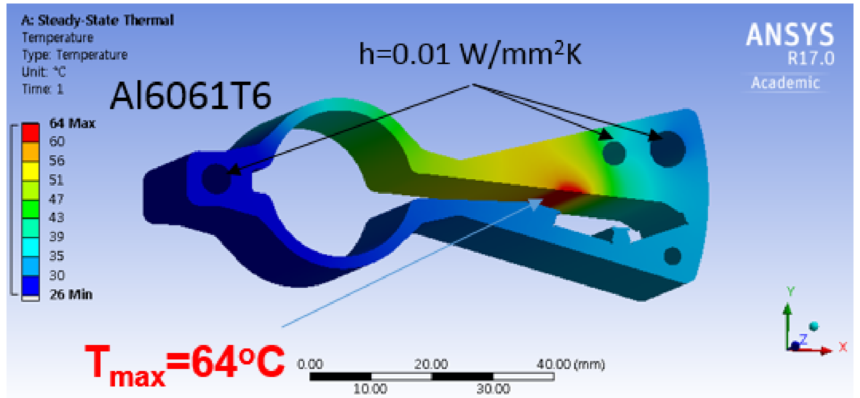


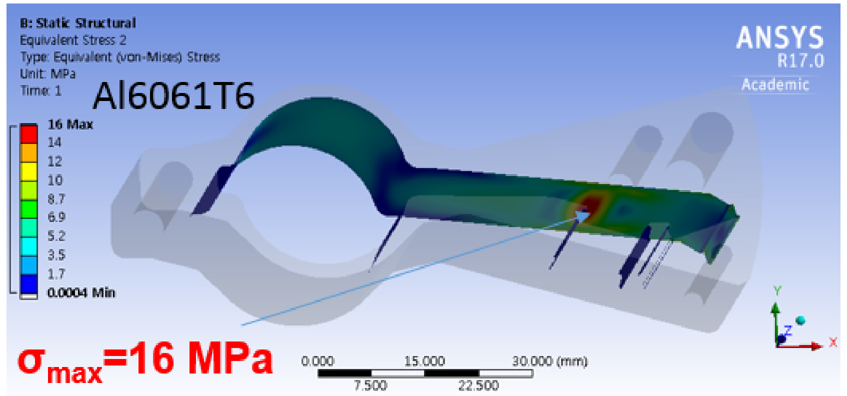
❖ Heat load from Center Bends

	B	Bend angle	Total power	Source distance	Inc_angle (H)	Inc_angle (V)	Foot print V-height	Thermal load
Center bend	1.96 T	1.6°	6 kW	2.25 m	2.35°	5°	0.44 mm	**0.77 W/mm^2**

❖ Results

Material	T_{max} (chamber)	T_{max} (Water channel)	σ_{max}	σ_{yield} (Cold worked)
Al6061T6	**54°C**	**46°C**	**16 MPa**	214 MPa
OFC Cu (C10100)	**48°C**	**40°C**	**9 MPa**	120 MPa
CuCrZr (C18150)	**50°C**	**41°C**	**11 MPa**	210 MPa





Vacuum System for a 4th Generation Storage Ring Studied in PAL

Strengths and weaknesses of the current design

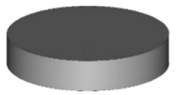
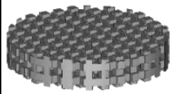
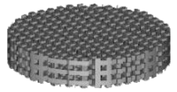
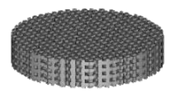
- Easy to fabricate by extrusion where Aluminum alloy can be used
- Extensive R&D to customize NEG coating is not needed
- Moderate activation temperature (180℃) limits the pumping ability of the commercial getter pumps
- Sticking coefficient of the commercial pill-type getter is not high enough

3D Printing Techniques to the Vacuum System

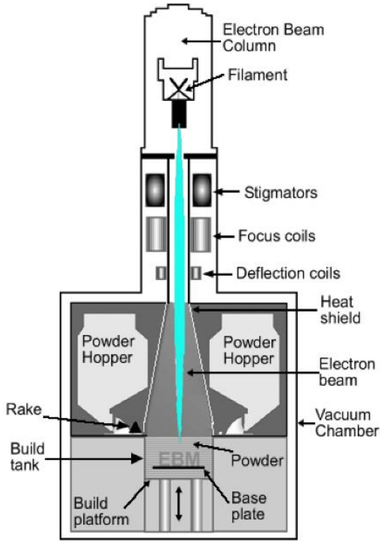
Prototype of a 3D printed getter

- Mesh structure design for maximum specific surface area
- Fabrication of Ti getter using 3D printer with titanium powder in vacuum environment (Electron Beam Melting in vacuum → high purity Ti)
- Pumping speed of one 3D printed Ti getter is measured to be 0.6 l/s, which is as much as 60% that of the conventional NEG
- <u>Alloy (Ti, Zr, V, Al,…) powders are necessary to increase the pumping speed and to lower the activation temperature</u>

"Design of 3D printed getters"

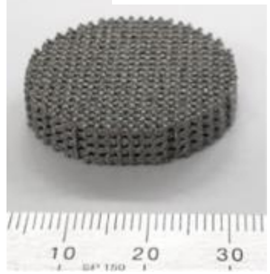
Sampl e	3D CAD design	Diamete r (mm)	Height (mm)	Area (mm²)	Relative Area (%)
Bulk		30	6	1978	100
C2		30	6	4859	246
C3		30	6	6974	353
C4		30	6	9094	460

"3D printing *via* EBM"



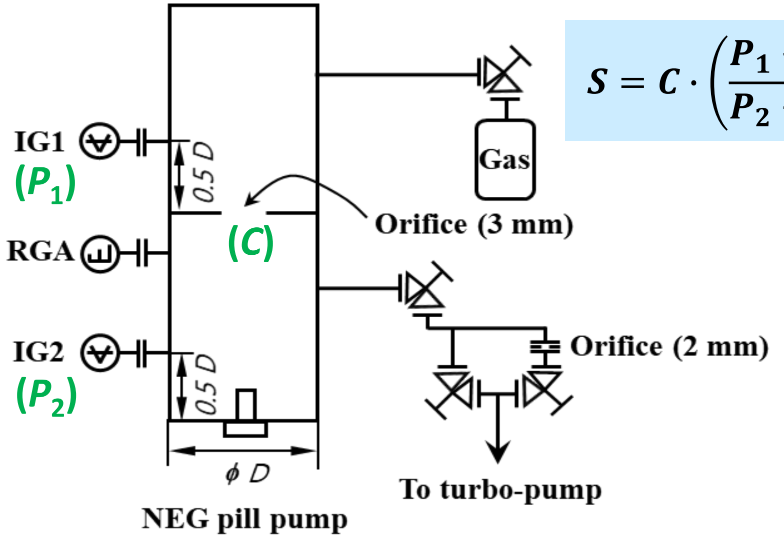
Electron Beam Melting

[image from MPI.com]

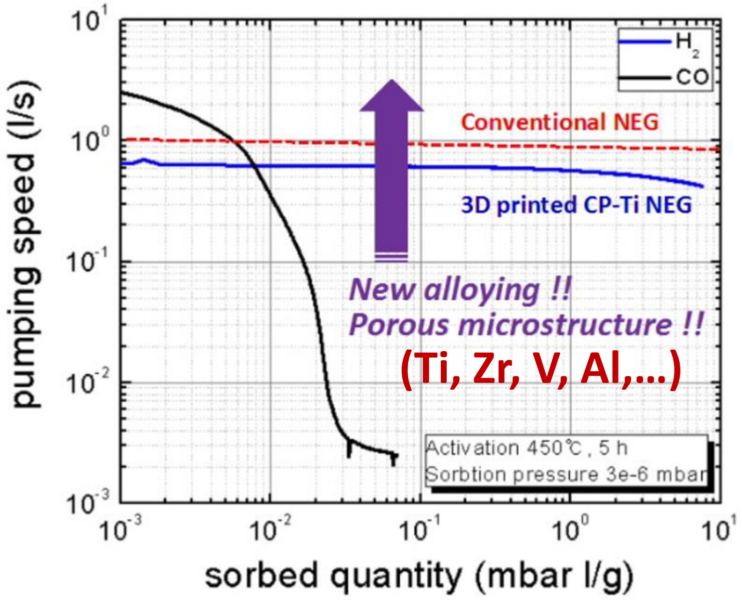


3D printed Ti NEG

"Pumping speed (S) measurement"



$$S = C \cdot \left(\frac{P_1 - P_{01}}{P_2 - P_{02}} - 1 \right)$$

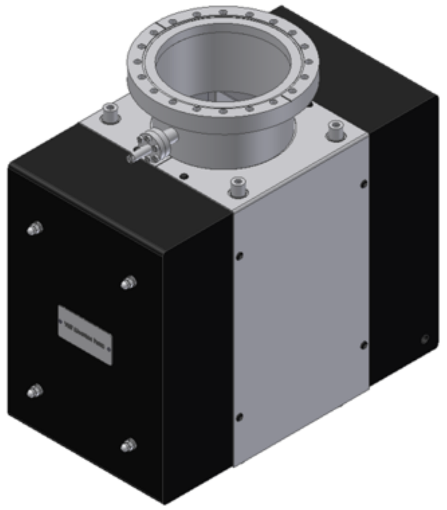


3D Printing Techniques to the Vacuum System

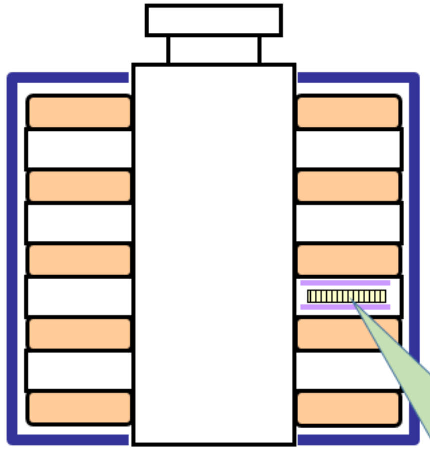
Prototype of a compact 3D printed sputter-ion pump with mesh anode structures

"Pumping mechanism of the sputter-ion pump (SIP)"

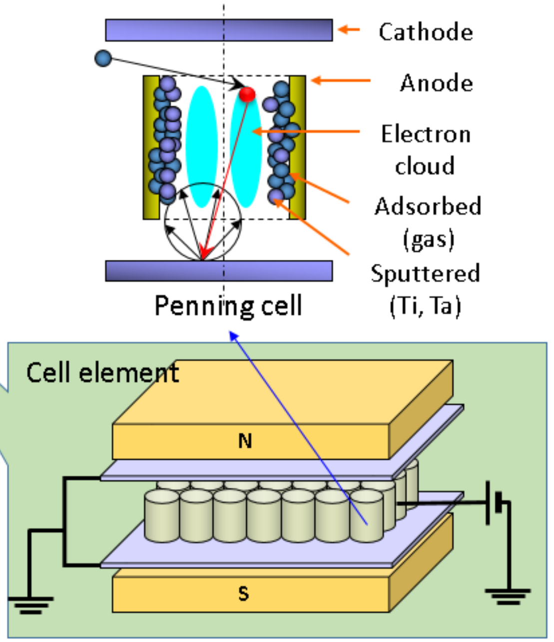
- Step 1: Gases enter into electron cloud of a Penning cell by chance
- Step 2: Gases are ionized and incident on the cathodes
- Step 3: Cathode materials (Ti) are sputtered and deposited on the anode surface
- Step 4: Gases incident on the anode combine chemically with the deposited Ti



[External view]

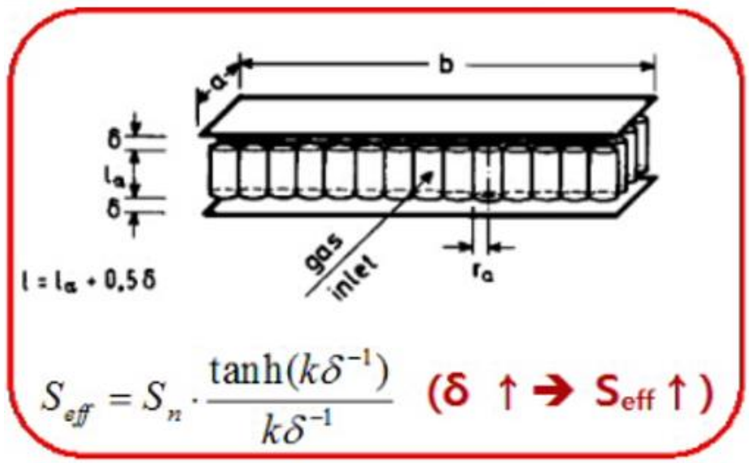


[Internal view]

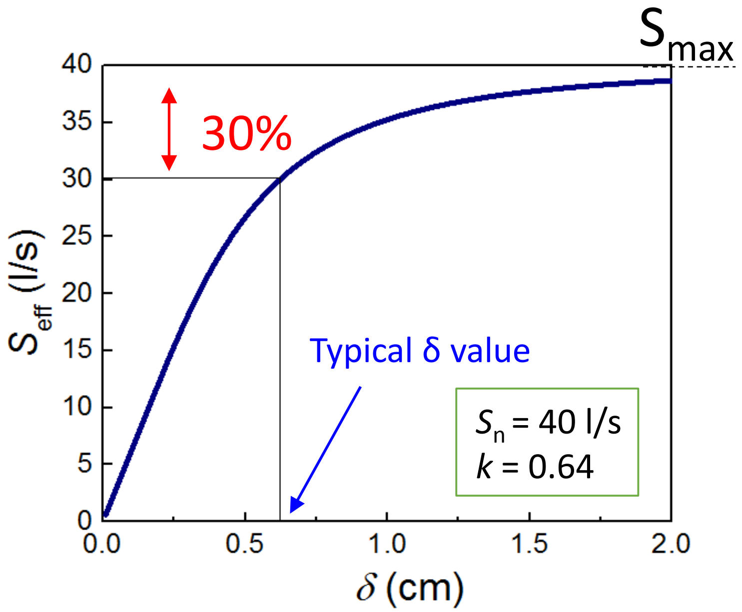


"Performance gain by optimization of the cell structures"

- Effective pumping speed is limited by the inlet conductance of the cell structure
- Performance optimization of the SIP is a compromise between the gap(δ) and the anode length(*l*), and the sum of them is constrained by a required magnetic field
- **Transparent anode cell to the gas flow** could maximize the inlet conductance if the anode cell could maintain the electron discharge
- Theoretically **30%** improvement is possible → 30% more compact SIP



"JVSTA 11, 1154 (1974)" [12]



3D Printing Techniques to the Vacuum System

Prototype of a compact 3D printed sputter-ion pump with mesh anode structures

"3D printed anode structure for the SIP"

- Mesh anode is proposed for the transparent anode cell structure
- Mesh anode cell by 3D printing *via* Selective Laser Melting (SLM)
  - ✓ First attempt
  - ✓ Stainless steel powder material
  - ✓ Thickness of 1 mm
  - ✓ Opening area of 50% (not optimized)
  - ✓ Geometric surface of 2,189 cm^2
  - ✓ Some manufacturing defects
- Normal anode cell structure fabricated by the same way for reference
  - ✓ Geometrical surface of 1,768 cm^2
- Surface area of the mesh anode is 20% higher than the conventional anode

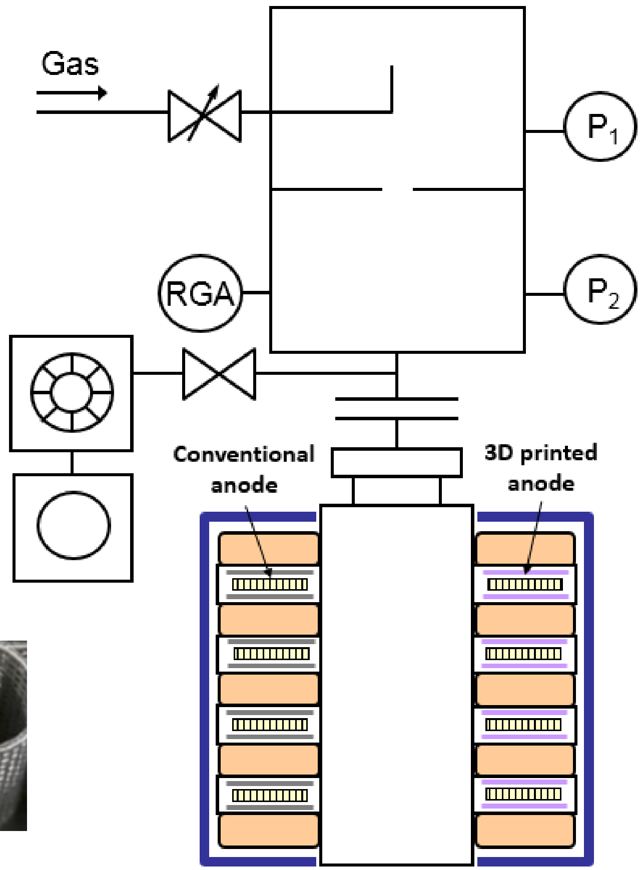
3D Printing Techniques to the Vacuum System

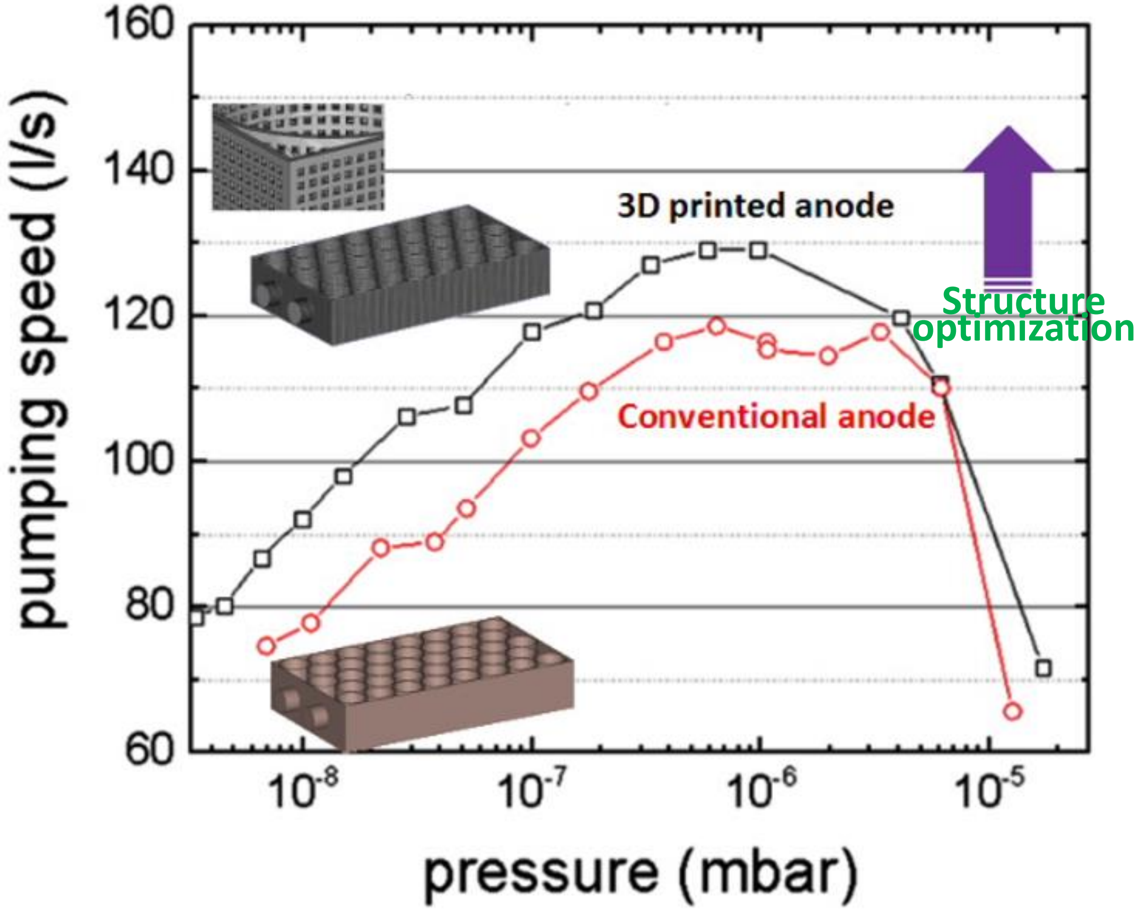
Prototype of a compact 3D printed sputter-ion pump with mesh anode structures

"Pumping speed test (Mesh anode vs. Conventional anode)"

- Prepared a SIP with the mesh anode cell and the conventional anode cell together
- Measured the pumping speed (*S*) of each type after the same procedure (roughing down, bake-out, saturation, …)
- Nitrogen gas

$$S = C \cdot \left(\frac{P_1 - P_{01}}{P_2 - P_{02}} - 1 \right)$$





"Results"

- 10% higher N_2 pumping speed
  - ✓ Opening area (conductance) is not optimized
  - ✓ Some defects
- → Quantitative analysis of the conductance effect is needed
- → Geometric area effect need to be evaluated

Vacuum Materials

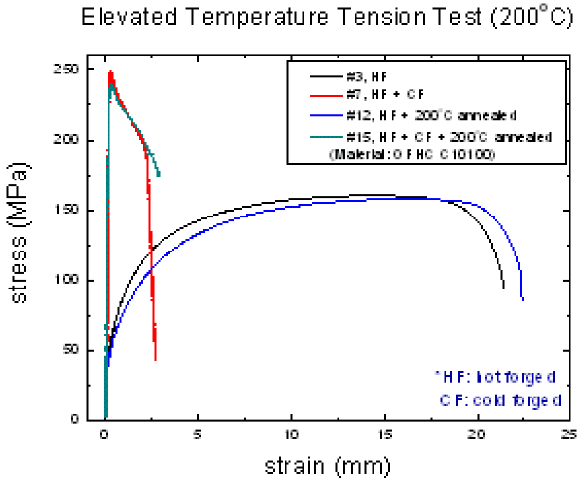
High heat load photon absorber (Cold forged OFHC)

Cold forging vs. Hot forging

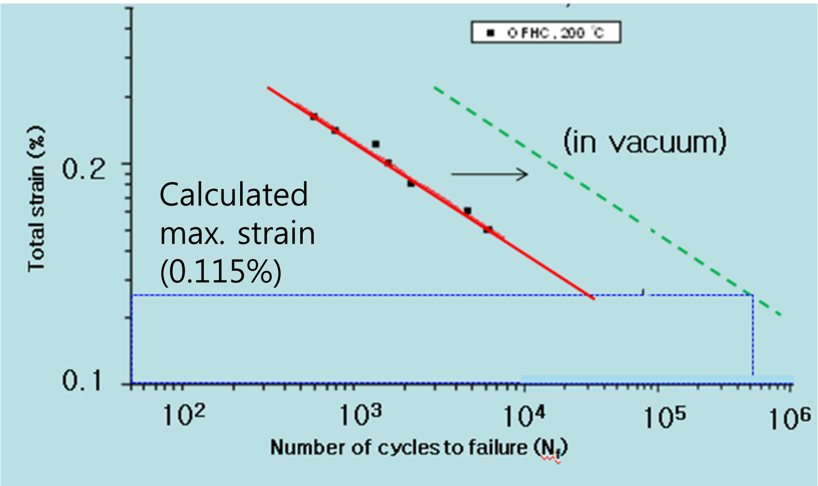
- OFHC
  - ✓High thermal conductivity
  - ✓E-beam welding
  - ✓Easily available than Glidcop

- Elevated temperature (200℃) tension test

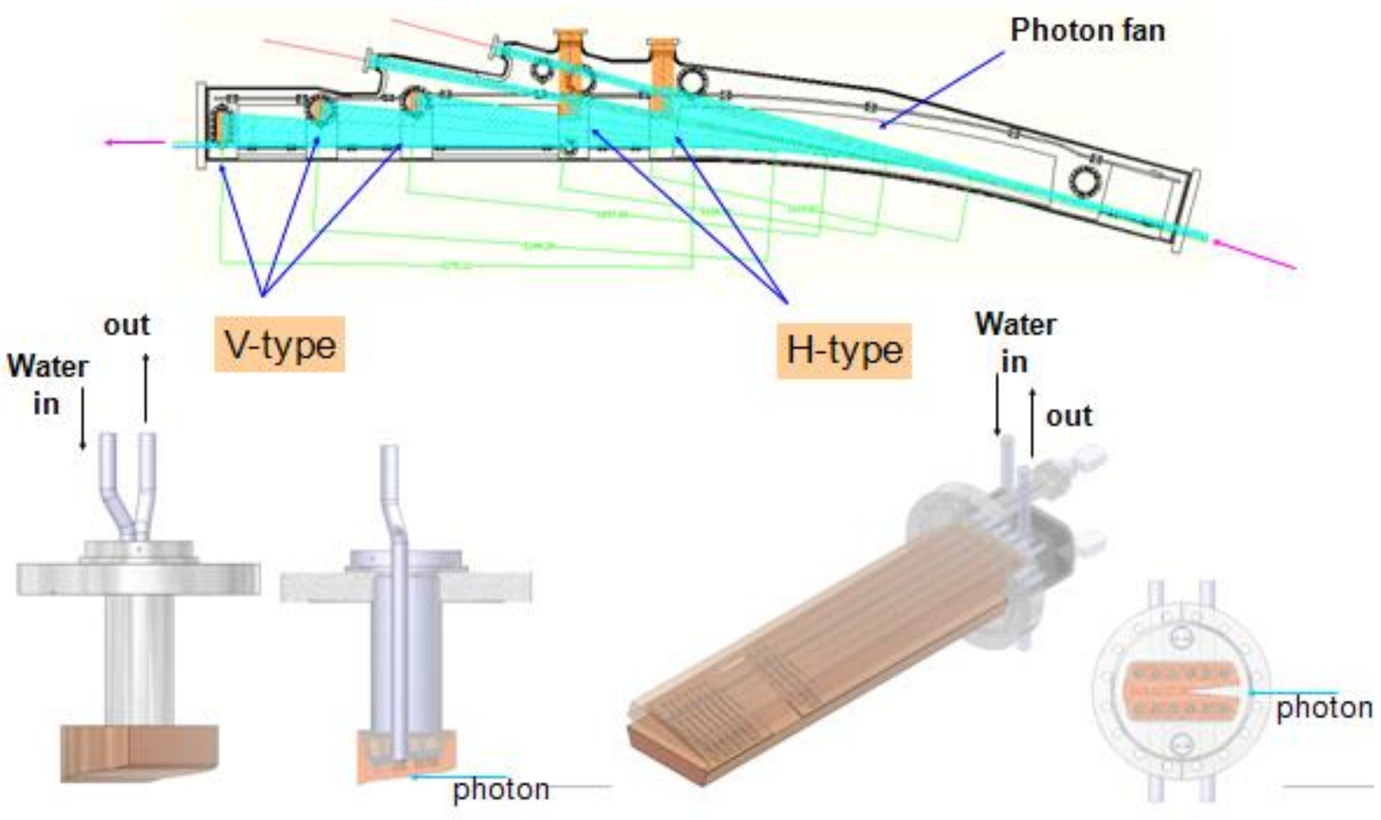
Material process	YS(0.2%) / MPa	TS / MPa	EL / %
Hot forged (OFHC)	48.3	160.3	42.4
Hot + Cold forged	244.4	249.1	5.2
HF + 200℃ Annealed	48.9	157.7	43.9
HF + CF + 200℃ Annealed	240.0	240.3	5.8



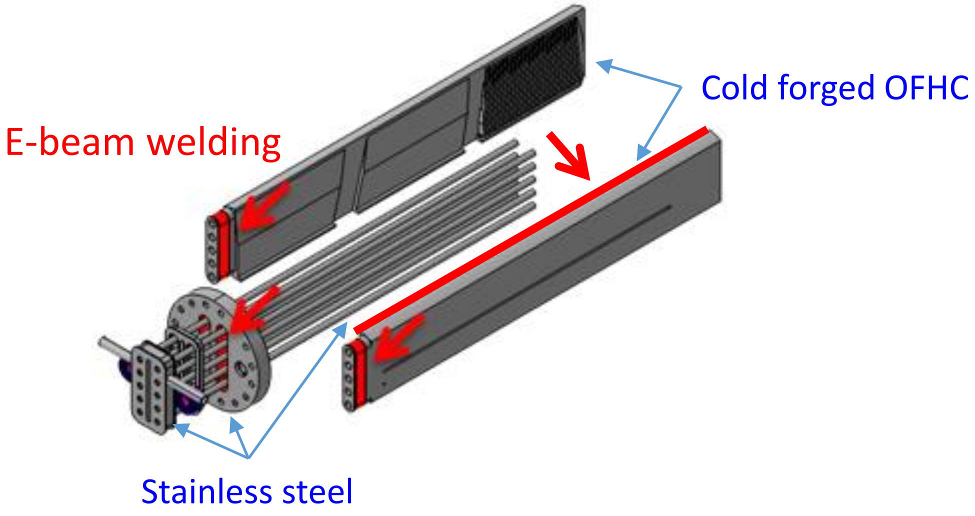
Fatigue lifetime measurement



- Number of cycles to failure for total strain of 0.115 % (most severe point) in air is measured to be larger than 10,000 cycles
- Fatigue lifetime in vacuum is 10 times longer than that in air, typically.
- The lifetime of the PLS-II photon absorber is expected to be longer than 100,000 cycles



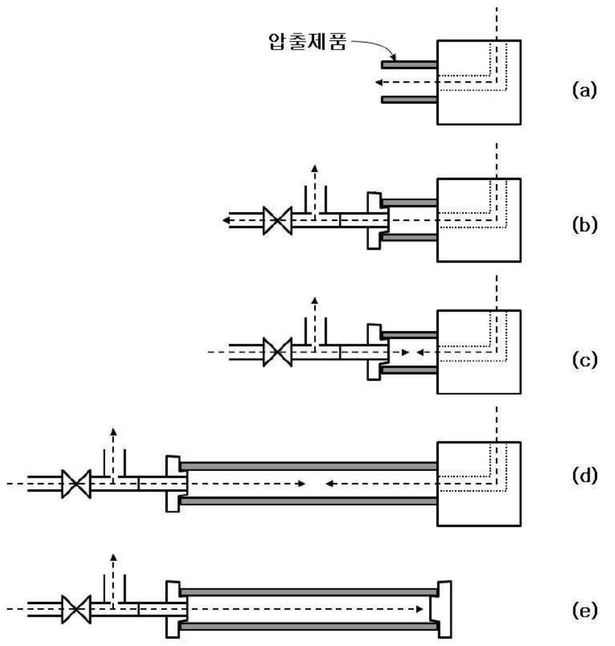
❖ **Photon absorbers for PLS-II storage ring**

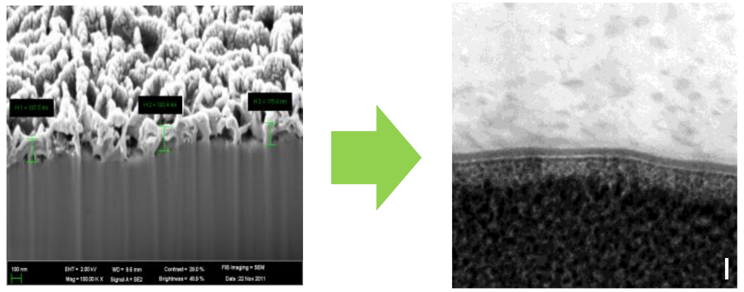


Vacuum Materials

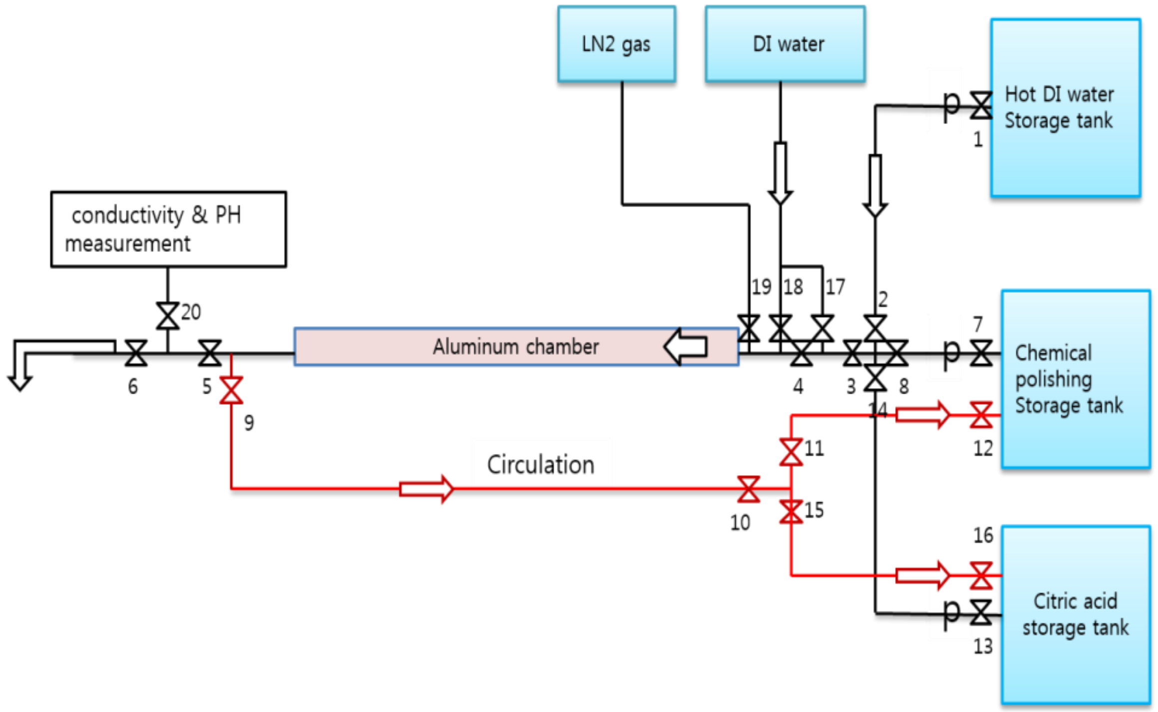
High surface quality aluminum (extruded/polished) undulator chamber

Controlled gas
(N_2 or Ar + O_2)



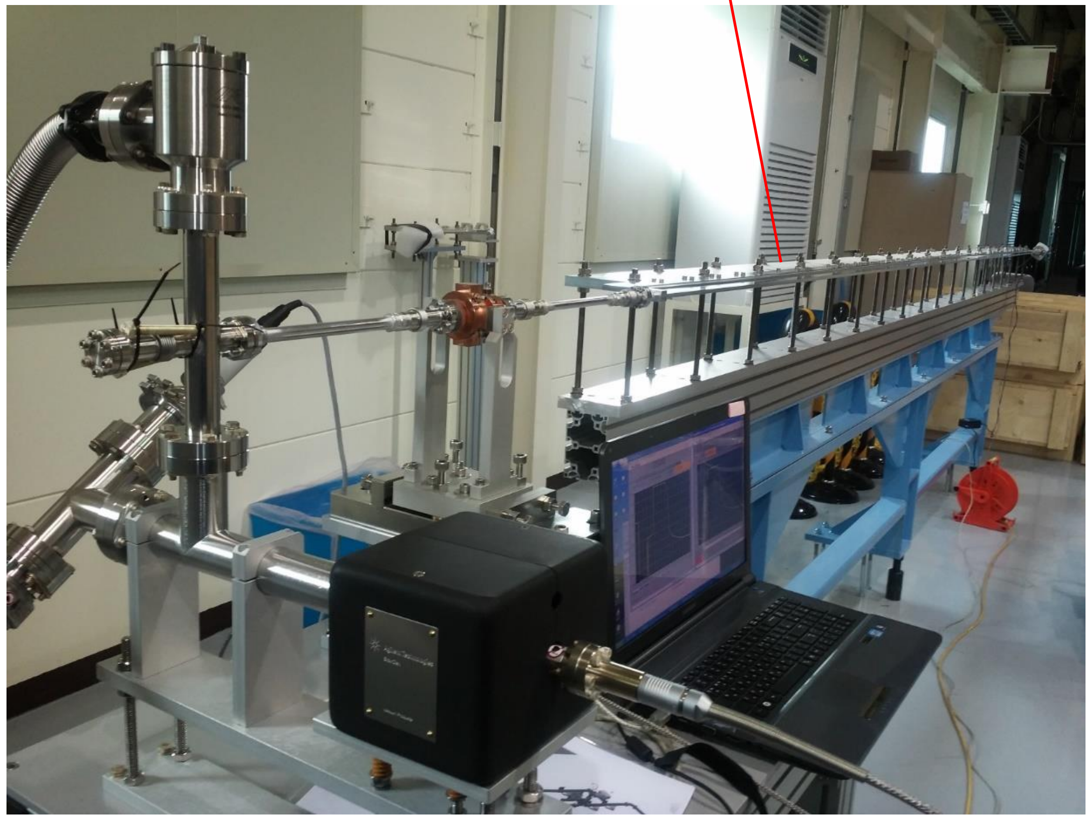


❖ Extrusion with controlled gas environment



❖ High throughput chemical polishing

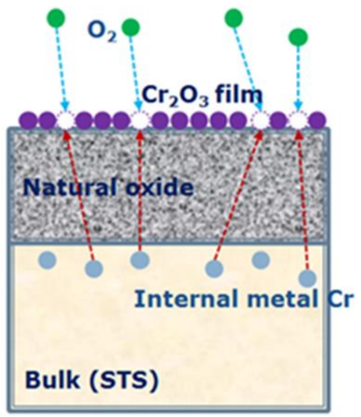
R_a < 200 nm, Oxide layer < 7 nm



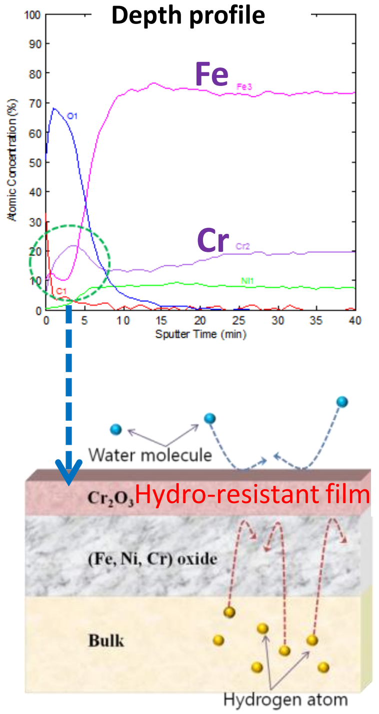
❖ Undulator vacuum chamber for PAL-XFEL

Vacuum Materials

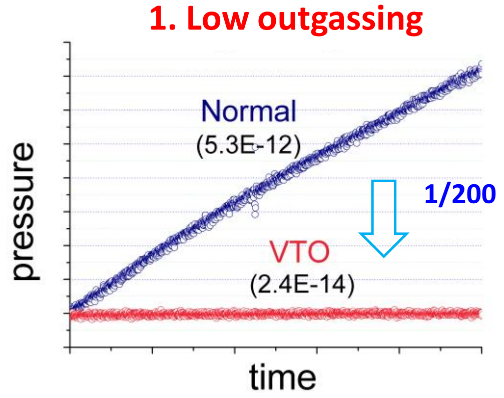
Stainless steel extreme-high vacuum (XHV) chamber

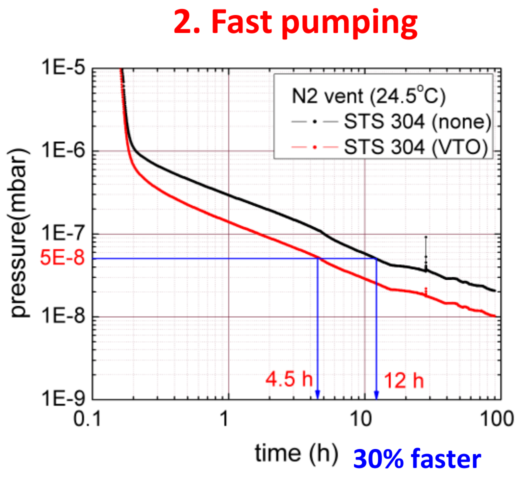


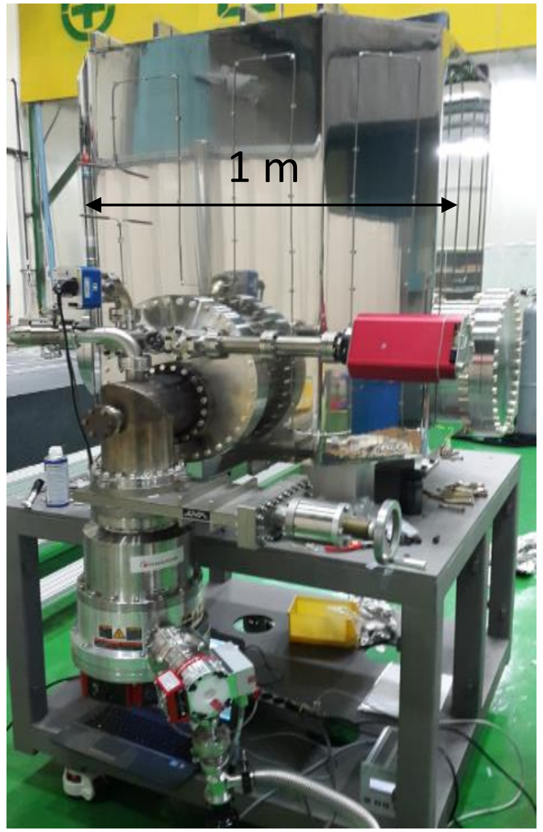
Vacuum Thermal Oxidation (VTO)
($P(O_2)$=1E-9 torr @ 450℃)

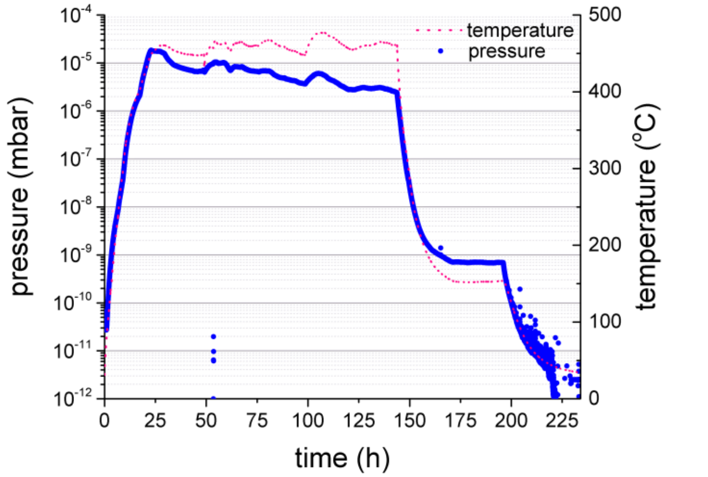


Hydrogen barrier by the Cr_2O_3 layer









❖ Ultimate pressure < 1.4E-13 mbar!

Summary

- ❖ **Various acclerator components are developed in PAL**
  - Magnets, IVU, modulator, MPS, CCPS, RF window, SLED, accelerating column, klystron, long undulator,…
- ❖ **Vacuum R&D activities in PAL**
  - 4GSR vacuum chamber with function of distributed pumping and photon absorption
  - 3D printed getters and sputter ion pumps → Need optimization and more study
  - Material treatments to improve vacuum/mechanical properties
    - ✓ Cold forged oxygen free copper → High heat load vacuum components
    - ✓ High surface quality aluminum → High quality surface but easy to fabricate
    - ✓ Stainless steel for XHV → Photo-cathode gun vacuum system
- ❖ **Future collaboration in various fields will be beneficial to both PAL and EIC**

Thank you for your attention!