Operational Status of PLS-II and PAL-XFEL

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PAL, POSTECH

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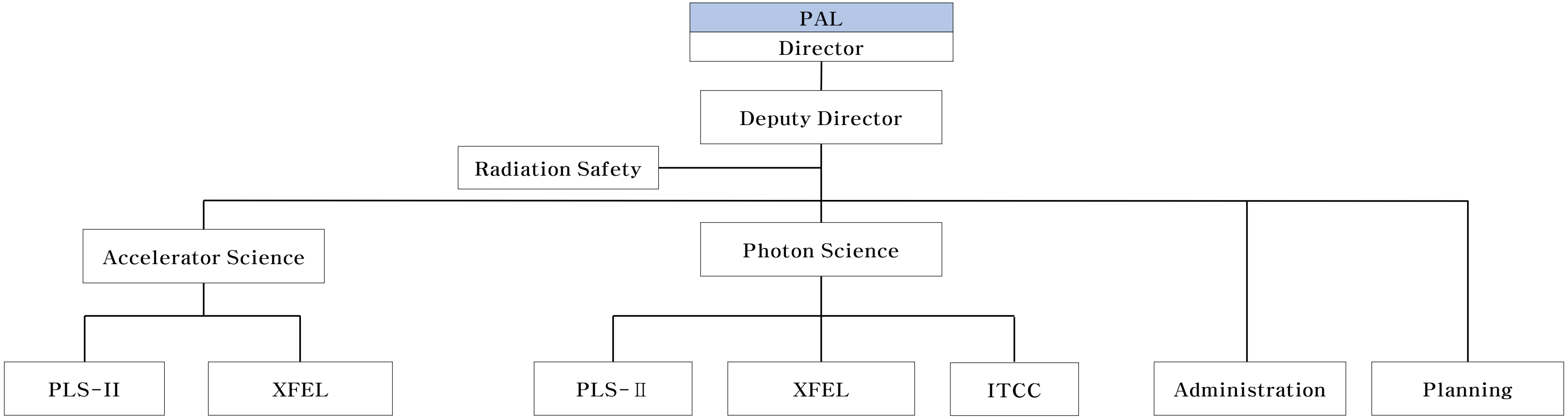
Brief History of PLS-II, PAL-XFEL

- 1988: PAL established to construct PLS
- 1991: PLS construction started
- -2.5 GeV, 282 m, 18.9 nm, 200 mA,12 straight sections
- 1995: PLS user service started with 2 beamlines.
- 2009: PLS upgrade (PLS-II) project started
- (3.0 GeV, 282 m, 5.6 nm, 400 mA, 24 straight sections)
- 2012: PLS-II started user service.

- 2011: PAL-XFEL project started
- -10 GeV S-band, 0.5 urad, 0.1 nm HX, 3 nm SX, 1100 m long
- 2015: PAL-XFEL assembly completed.
- 2016: PAL-XFEL commissioning, demo-experiment
- 2017: PAL-XFEL started user service

Organization, Budget

◇ PAL Organization



Number of PAL Staff

Total : 185

- **PLS-II : 130, XFEL: 55**
- Scientists : **96,** Engineers : **70, Administrative : 19**
- Additional contracted termed staffs.

◇ Budget FY 2017 (FY 2018)

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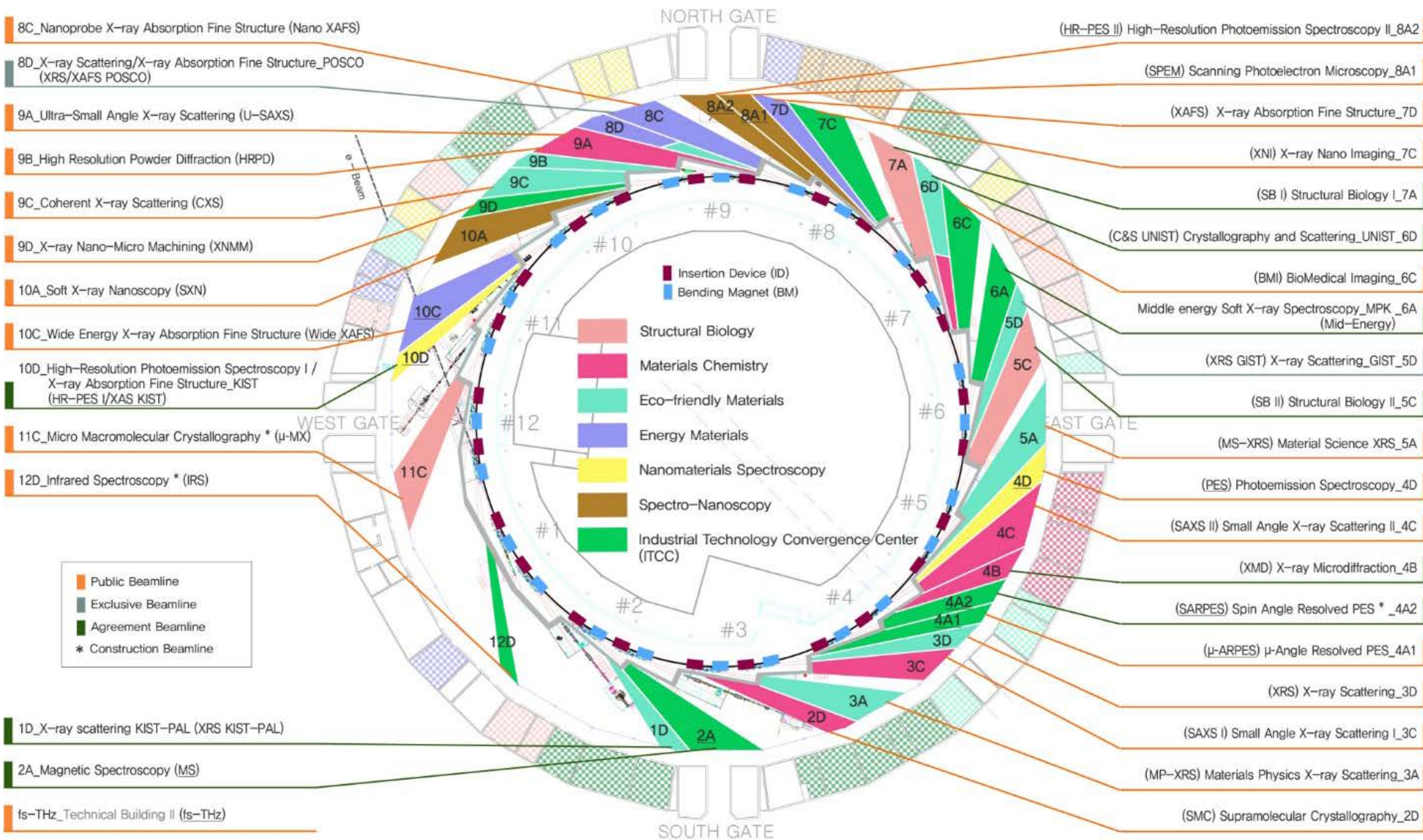
Total : 55.5M$ (58.2M$)

PLS-II : 34.3M$(36.1M$), XFEL : 21.2M$(22.1M$)

PLS-II and PAL-XFEL Facilities

구 분	PLS-II	PAL-XFEL
Area/Bulidin g	126,800 m² / 18개동 연면적 45,358.17 m²	120,620m² / 9개동 36,868.37m²
Key Components	▪ **Linac**: length 170m, energy 3GeV, ▪ **SR :** 둘레 281.8m, 12 Cells, DBA current 400 mA, emittance 5.6 nm ▪ **BeamLine :** 34 operation, 2 construction	▪ **가속장치 :** 길이 1,030m, 빔에너지 10GeV, 삽입장치 (경X선20, 연X선7) ▪ **빔 라 인 :** 길이 80m, 경X선 2기, 연X선 1기 ▪ **실험장치 :** 경X선 4기, 연X선 3기
Construction period (Operation period)	▪ **PLS** : 1988년 ~ 1994년 (1995년 ~2010년) ▪ **PLS-II :** 2012년 ~ (2009년~2011년)	2011년 ~ 2015년 (2016년(시운전), 2017년 ~ (실험개시))

PLS-II Beamline map



34 beamlines in operation, 2 beamlines under construction

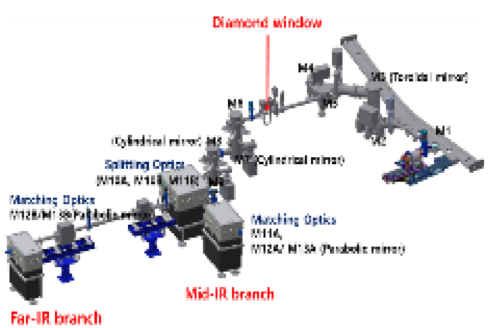
POHANG ACCELERATOR LABORATORY 浦項加速器研究所

Two additional beamlines

Two new beamlines completed in 2016

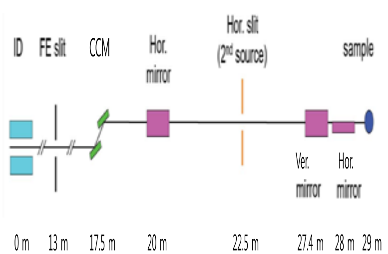
Infrared Spectroscopy

- 목 적 : Infrared spectroscopy beam line to study various phonon modes of various chemicals.
- 사업비 / 사업기간 : 35억원 / '13~'16(4년)



Micro Macromolecular Crystallography

- 목 적 : Cam analyze smaller proten crytals (50→10μm)
- 사업비 / 사업기간 : 70억원 / '13~'16(4년)



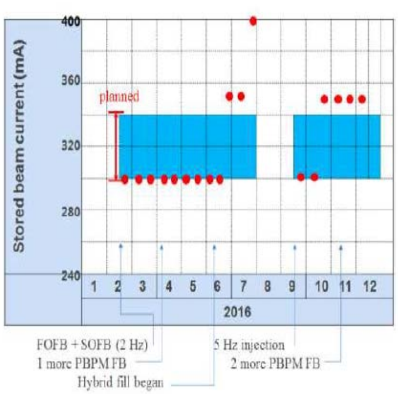
Adding the existing 32 beamlines, operating beamlines reached 34.

PLS-II Beam Operation and Availability

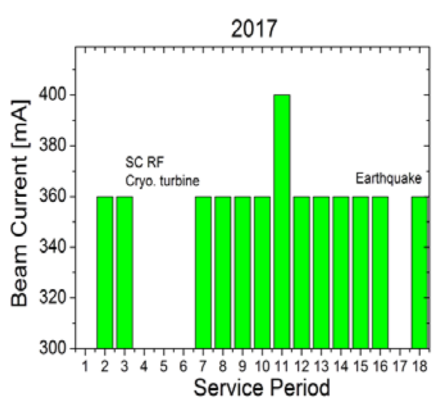
Target :

- Top-up operation in peak current 350-400 mA.
- Annual 190 days scheduled user service operation.
- Availability better than 97%.
- In 2017, there were 40 days shutdown due to cryo turbine failure, 21 days failure due to earthquake.
- Tried to compensate minimizing machine study, and maintenance, finally achieving 87% availability.

2016~2017 Beam Current in Shifts

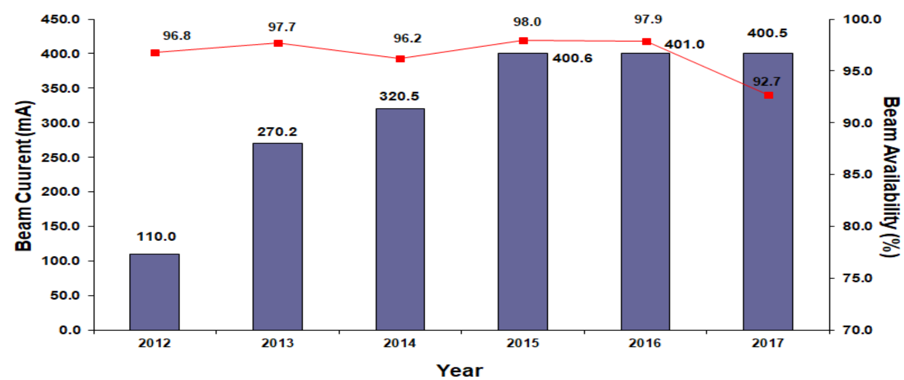


2016



2017

Availability

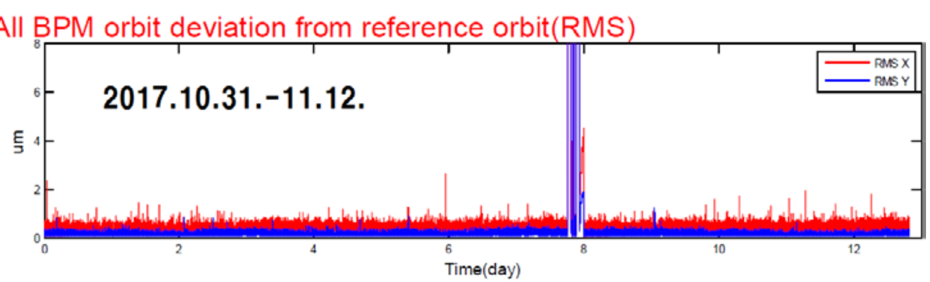


Beam Stability of the e-beams

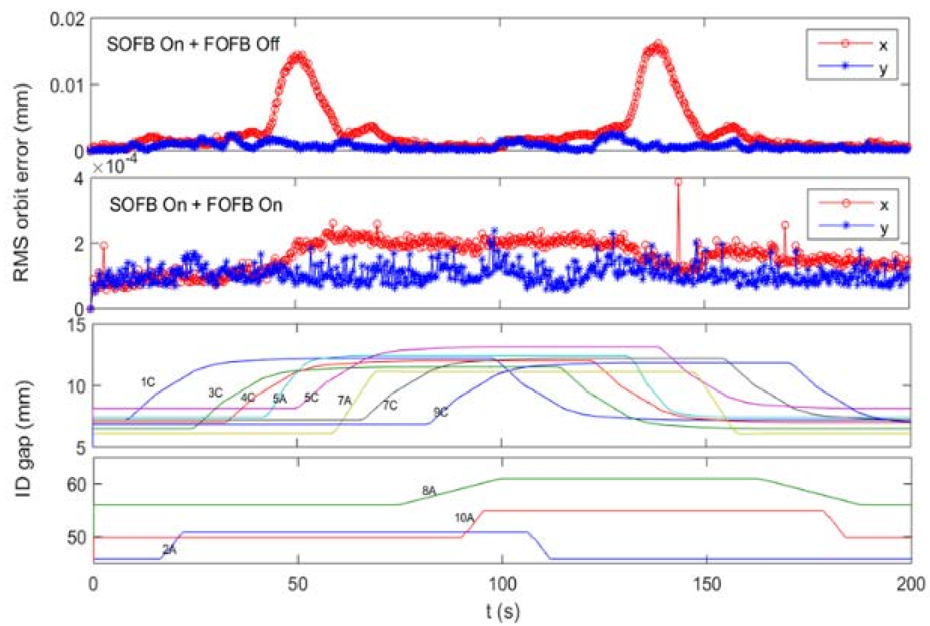
Target :

- rms deviation less than 1 um from the reference orbit.
- orbit deviation due to the ID gap movement less than 7 um rms

ebeam stability <1μm-rms



Impact of ID gap movement when FOFB on/off

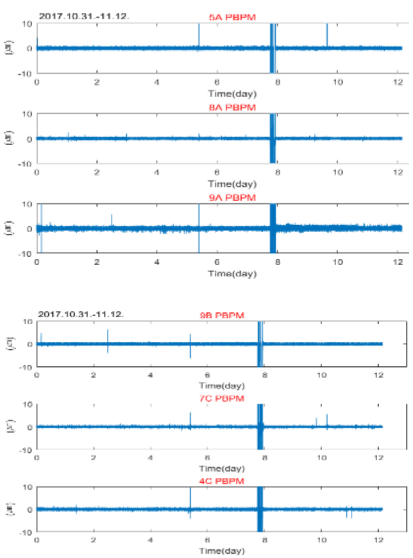


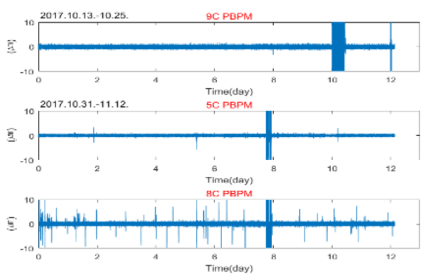
Photon Beam Stability measured using PBPM

Target :

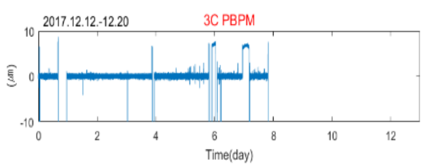
- rms deviation less than 2 um at the PBPM positions.
- 10 PBPMs are in operation and included in the feedback loop.

Measured Photon Beam Stability



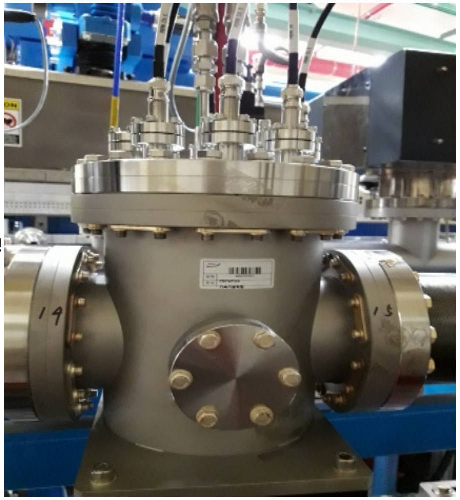


* 8C의 경우 잦은 ID gap 변경이 측정에 반영
(ID FF 효과로 다른 빔라인에는 영향 없음)



* 3C의 경우 12.12 부터 운전에 적용

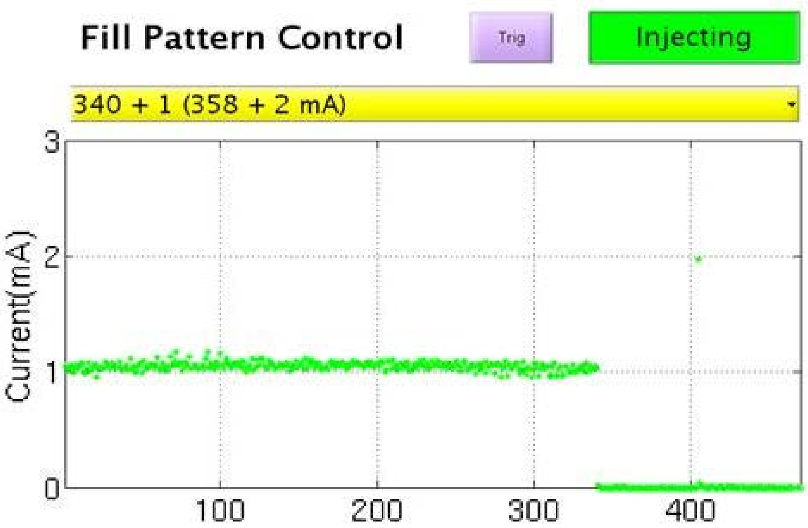
Photos of PBPMs



Hybrid mode operation

- For time resolved experiment, hybrid mode is developed and applied in the user service.
- Possible modes are 400, 400+1, 330+1, 340+1, 350+1 depending on the user request.
- Single bunch current reaches 2.0 mA. Recent machine study achieved 6.0 mA single bunch current.

Hybrid Mode Fill Pattern



2016~2017 Hybrid Mode Fill Pattern 운전 내역

차 수	I (mA)	Operation mode	
		Multi-bunch	Hybrid
2016-1차	300	400	
2016-2차	300	400	
2016-3차	300		400+1 (0.8 mA)
2016-4차	300		400+1 (0.8 mA)
2016-5차	300	400	
2016-6차	300	400	
2016-7차	300		350+1 (0.9 mA)
2016-8차	300		350+1 (0.9 mA)
2016-9차	300		350+1 (1.7 mA)
2016-10차	350	400	
2016-11차	350	400	
2016-12차	400	400	
2016-13차	300	400	
2016-14차	300		350+1 (0.9 mA)
2016-15차	350	400	
2016-16차	350	400	
2016-17차	350		350+1 (1.5 mA)
2016-18차	350		
2016-19차	350		350+1 (1.5 mA)

2016

차 수	I (mA)	Operation mode	
		Multi-bunch	Hybrid
2017-1차	0		
2017-2차	360	350	
2017-3차	360	350	
2017-4차	0		
2017-5차	0		
2017-6차	0		
2017-7차	360		350+1 (1.03 mA)
2017-8차	360		340+1 (1.06 mA)
2017-9차	360		340+1 (1.06 mA)
2017-10차	360		340+1 (1.06 mA)
2017-11차	400	400	
2017-12차	360		340+1 (1.06 mA)
2017-13차	360	350	
2017-14차	360		330+1 (2 mA)
2017-15차	360		330+1 (2 mA)
2017-16차	360		330+1 (2 mA)
2017-17차	0		
2017-18차	360		330+1 (2 mA)

2017

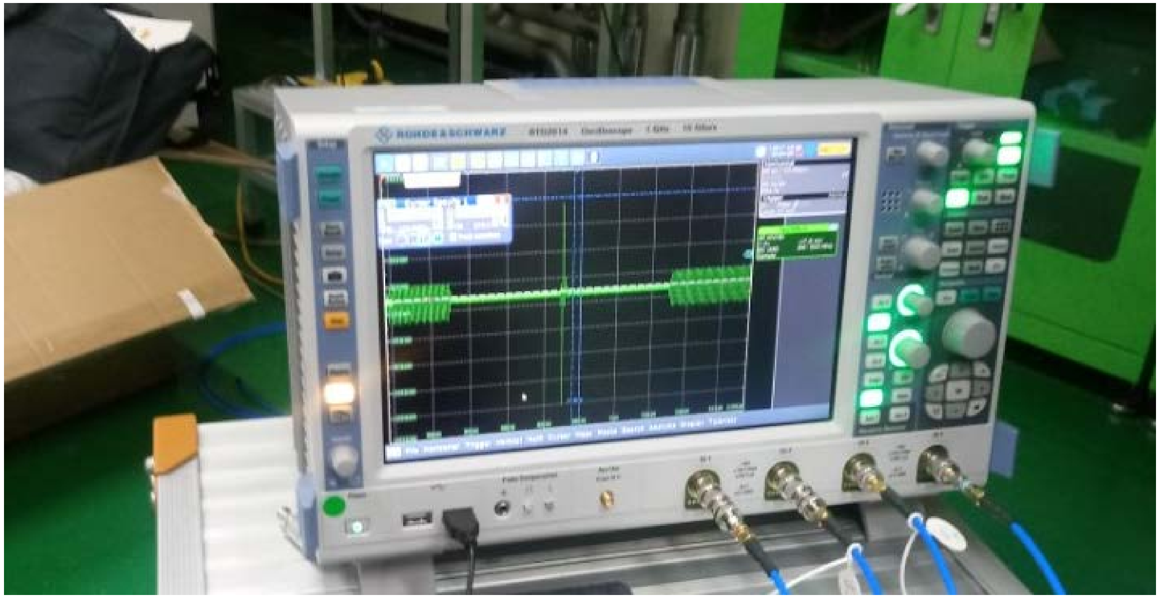
Hybrid Fill Pattern

Harmonic number 470

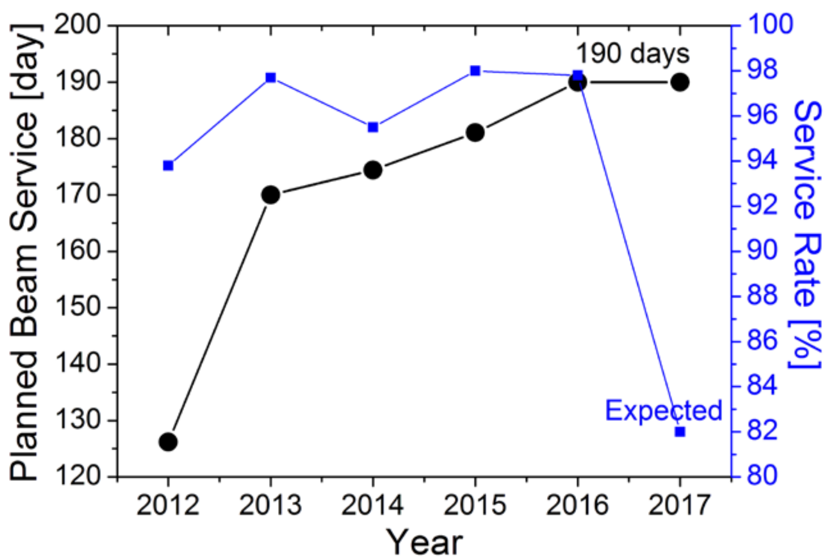
Request: wider gap + higher single current (10mA?)

2017: 400, 350+1, 340+1, 330+1(2mA)

Recently 330 + 1 (6mA) and will increase more !



User Service, Availability



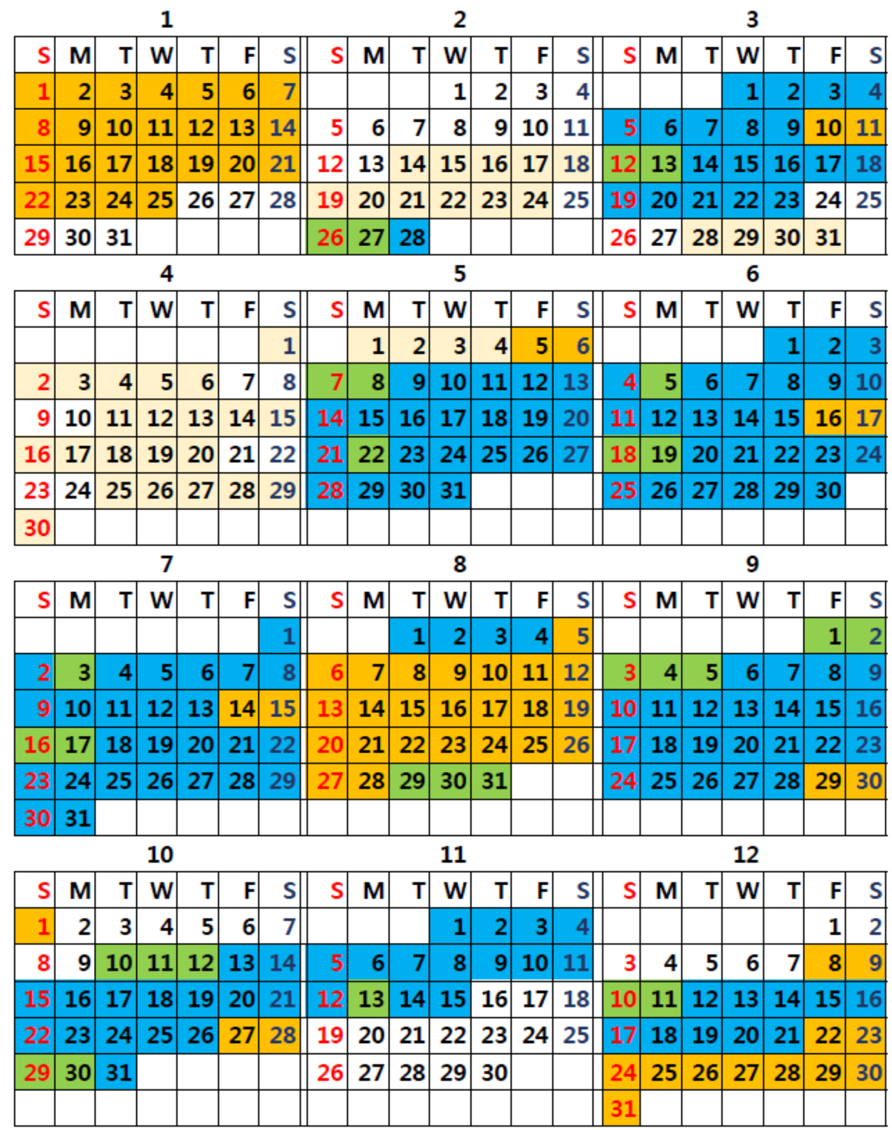
Service goal: 97 % of 190 days

Superconducting RF
- turbine : 40 days
- earthquake-UPS : 21 days

Expected: 87 % of 190 days

2017 Operation

Beam service
Turn-on, Machine study
Maintenance



Statistics of Top 29 Journal Papers

구분	논문명	`17	'16	'15	'14	'13	2016 IF
1	Nature	-	1	1	-	-	40.137
2	Nature Materials	-	1	-	-	2	39.737
3	Nature Nanotechnology	-	-	3	-	-	38.986
4	Nature Photonics	1	-	-	-	-	37.852
5	Science	2	-	3	-	1	37.205
6	Cell	-	1	-	-	-	30.410
7	Energy & Environmental Science	4	6	4	3	3	29.518
8	Nature Chemistry	-	-	-	1	-	25.870
9	Nature Physics	2	1	-	-	-	22.806
10	Advanced Materials	4	11	6	8	6	19.791
11	Advanced Energy Materials	4	-	5	2	-	16.721
12	Molecular Cell	1	-	1	-	-	14.714
13	Neuron	1	-	-	-	-	14.024
14	ACS Nano	4	3	14	11	8	13.942
15	Journal of The American Chemical Society	6	8	4	6	3	13.858
16	Nanoletters	3	1	8	3	1	12.712
17	Nature Structural & Biology Molecular	1	-	-	-	1	12.595
18	Nano Energy	5	7	5	-	-	12.343
19	Nature Communications	5	8	8	8	3	12.124
20	Advanced Functional Materials	7	14	15	2	6	12.124
21	Angewandte Chemie-international Edition	6	8	9	10	-	11.994
22	Materials Horizons	1	-	-	-	-	10.706
23	ACS Catalysis	6	-	-	-	-	10.614
24	The EMBO Journal	-	-	-	2	-	9.792
25	Proceedings of the National Academy of Sciences	-	5	1	4	1	9.661
26	Chemistry of Materials	9	-	-	-	-	9.466
27	Applied Catalysis B: Environmantal	11	-	-	-	-	9.446
28	Autophagy	1	-	1	-	-	8.593
29	Physical Review Letters	1	2	2	2	2	8.462
Total		85	79	90	62	37	-

Papers produced by using PLS-II

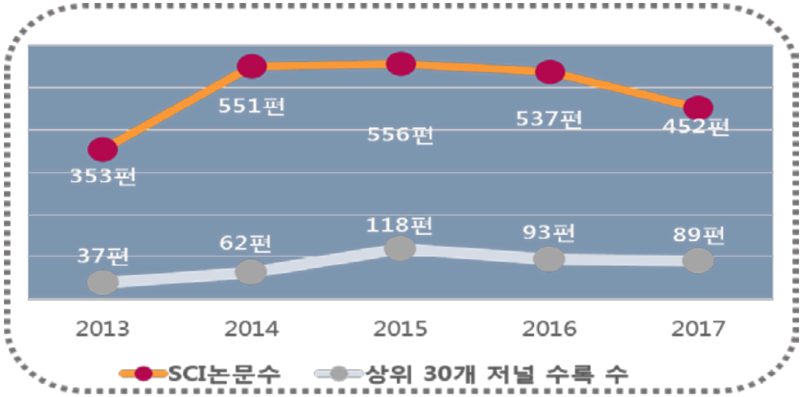
2016~2017 SCI papers

2016
papers
537건
I.F
5.82

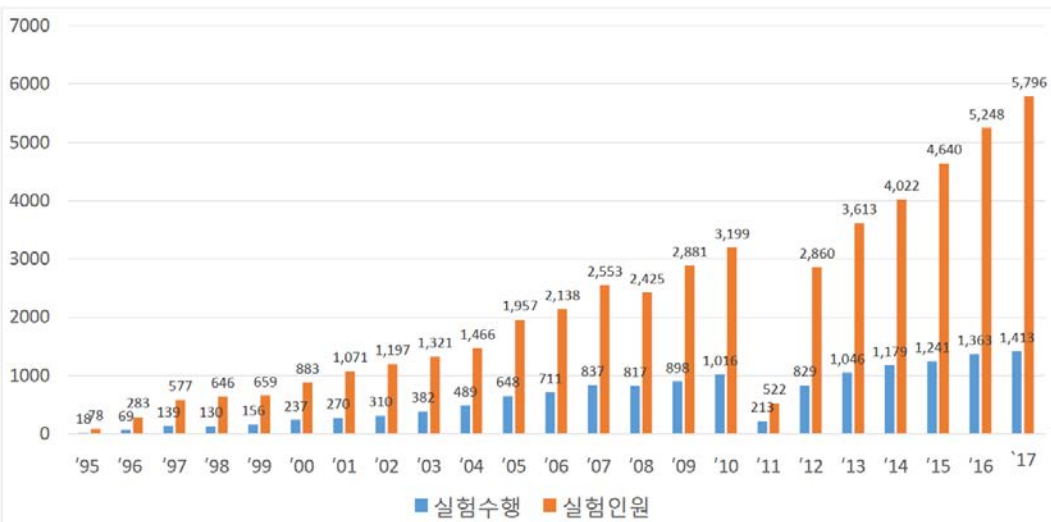
2017
papers
452건
I.F
6.41

*2016년 : 이용자 제출('15년~'17년) 2016년 발간 SCI 논문
*2017년 : '17.12월 말 기준

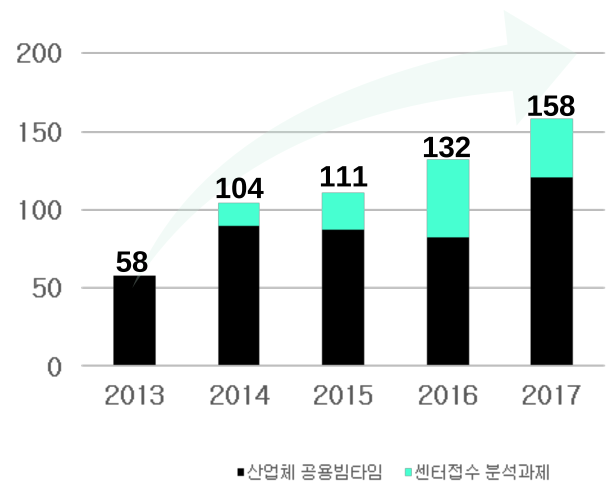
5 year trend of SCI papers



Number of Experiments and User visits



Industrial BL service in last 5 years



PLS-II Summary

- PLS started user service in 1995 with 2 beamlines and small number of user groups.
- In 2017, the community increased more than 5000 user visits, ~1500 user experiments, ~500 high impact SCI papers using 34 beamlines. This is an excellent achievements.

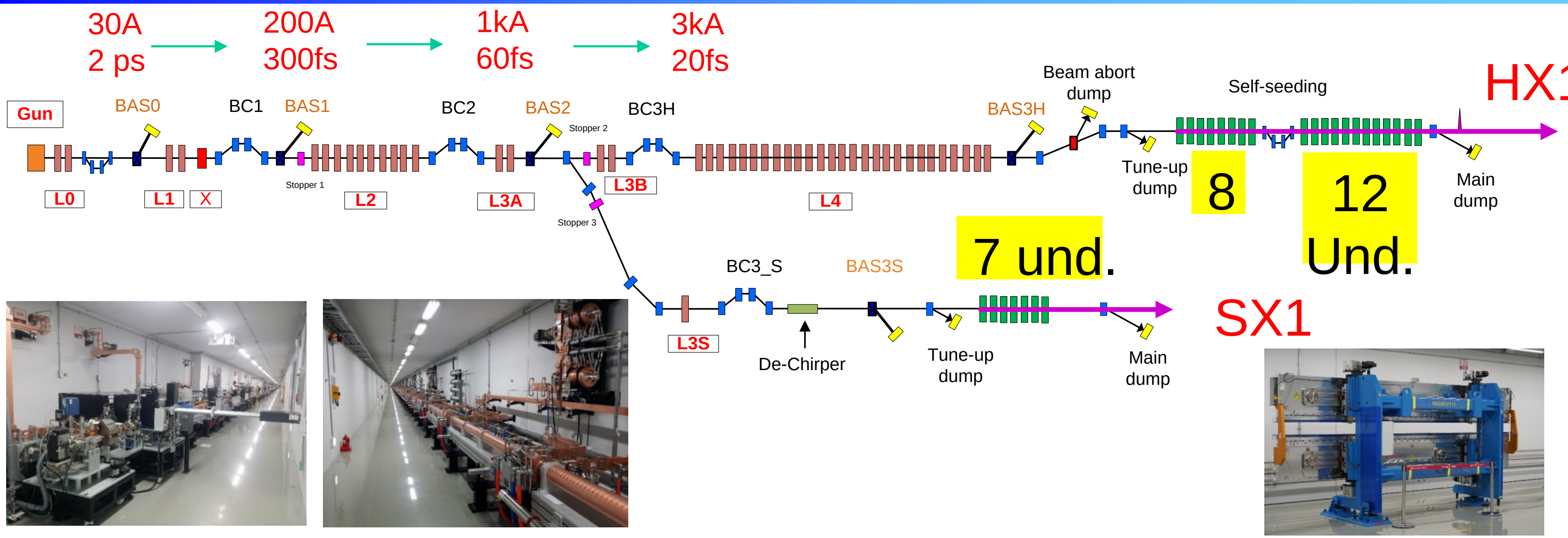
- But, many new advanced SR sources are becoming online, and maintaining competence is a big challenge for PLS-II.

- In 2017, 40 days shutdown due to cryocooler turbine failure, and 21 days shutdown due to cryocooler failure due to power outage caused by earthquake.
- Replacing outdated equipment, and maintaining state of art beamline is also another challenge.

PAL-XFEL (X-ray Free Electron Laser) Project

Apr. 2011	PAL-XFEL Project (400M USD) started
Sep. 2012 – Dec. 2014	Building construction
Jan. 2015 – Dec. 2015	Installation of linac, undulators & beamlines
14, Apr. 2016	Electron beam 1st commissioning started
25, Apr. 2016	Electron beam acceleration up to 10 GeV achieved
12, Jun. 2016	Undulator spontaneous radiation observed
14, Jun. 2016	First XFEL beam (λ=0.50 nm) observed
16, Aug. 2016	2nd commissioning (machines & diagnostics) started
Sep. 2016 – Dec. 2016	~ 0.15 nm XFEL Lasing & Saturation
Nov. 2016 – Jan. 2017	3rd commissioning (Experimental instruments & Demo Experiments) : Feasibility C
Feb. 2017	Call for the Early User Proposal
Mar. 2017 – May. 2017	Pilot & Pre Experiments
Jun. 2017	Early User Experiments (1st Half Year 2017)
Oct. 2017	Regular User Experiments (2nd Half Year 2017)

PAL-XFEL Parameters



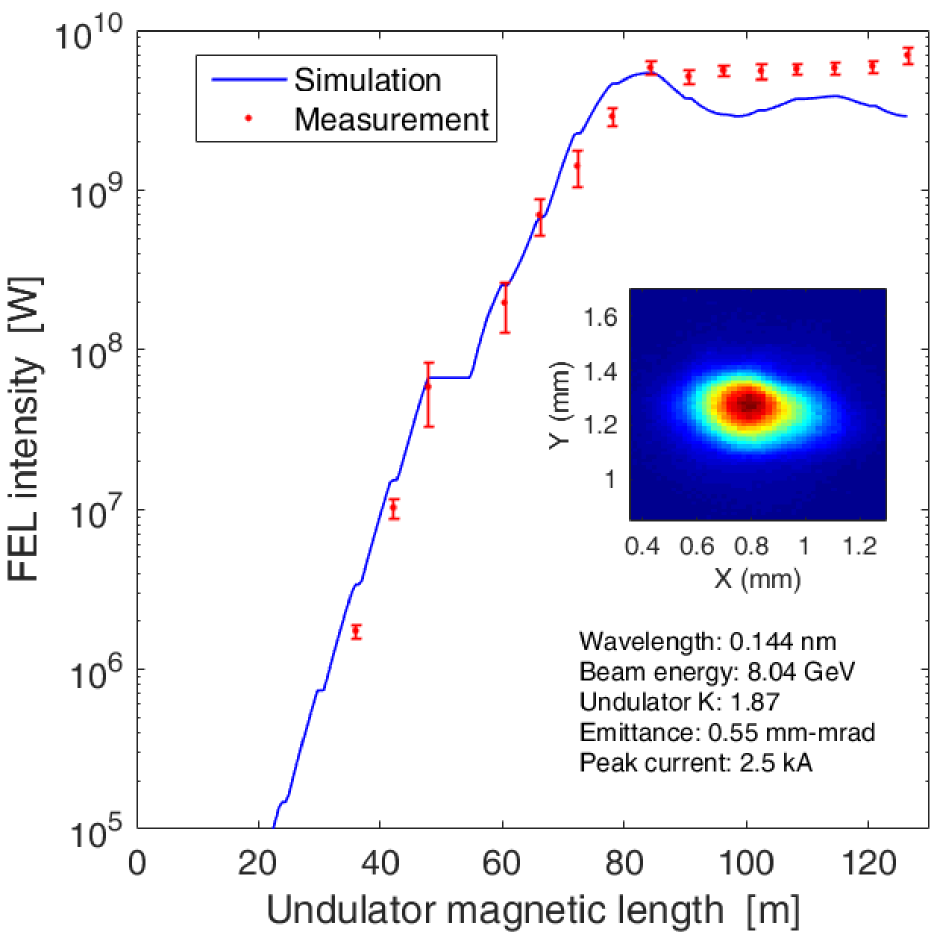
Main parameters

e⁻ Energy	10 GeV
e⁻ Bunch charge	20-200 pC
Slice emittance	< 0.5 mm mrad
Repetition rate	30 Hz (60 Hz)
Pulse duration	10 fs – 100 fs
Peak current	3 kA
SX line switching	DC (Phase-1) Kicker (Phase-2)

Undulator Line	HX1	SX1
Photon energy [keV]	2.5 ~ 12.8	0.3 ~ 1.2
Beam energy [GeV]	4 ~ 10	3.15
Wavelength tuning	energy	gap
Undulator type	Planar, out-vac.	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0

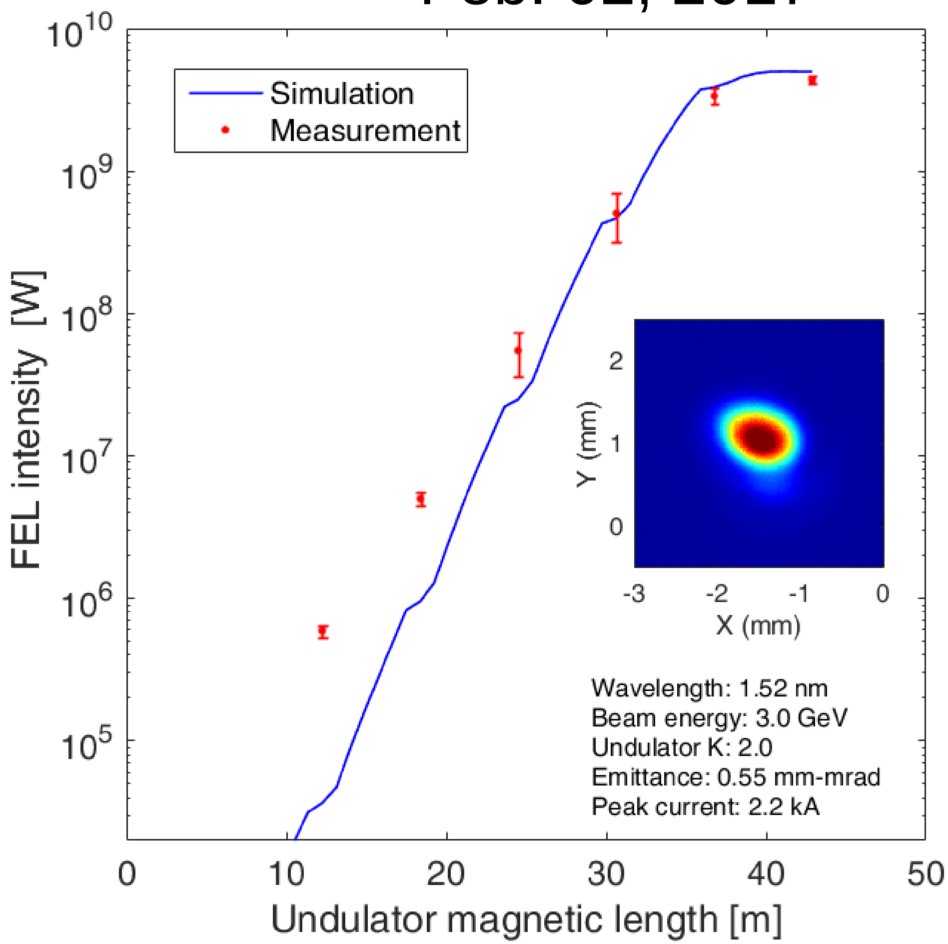
Saturation of 0.144 nm (HX) & 1.52 nm (SX)

Nov. 27, 2016



Simulation:
emittance: 0.55 mm-mrad
peak current: 2.5 kA

Feb. 02, 2017

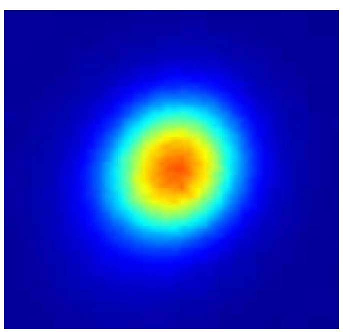


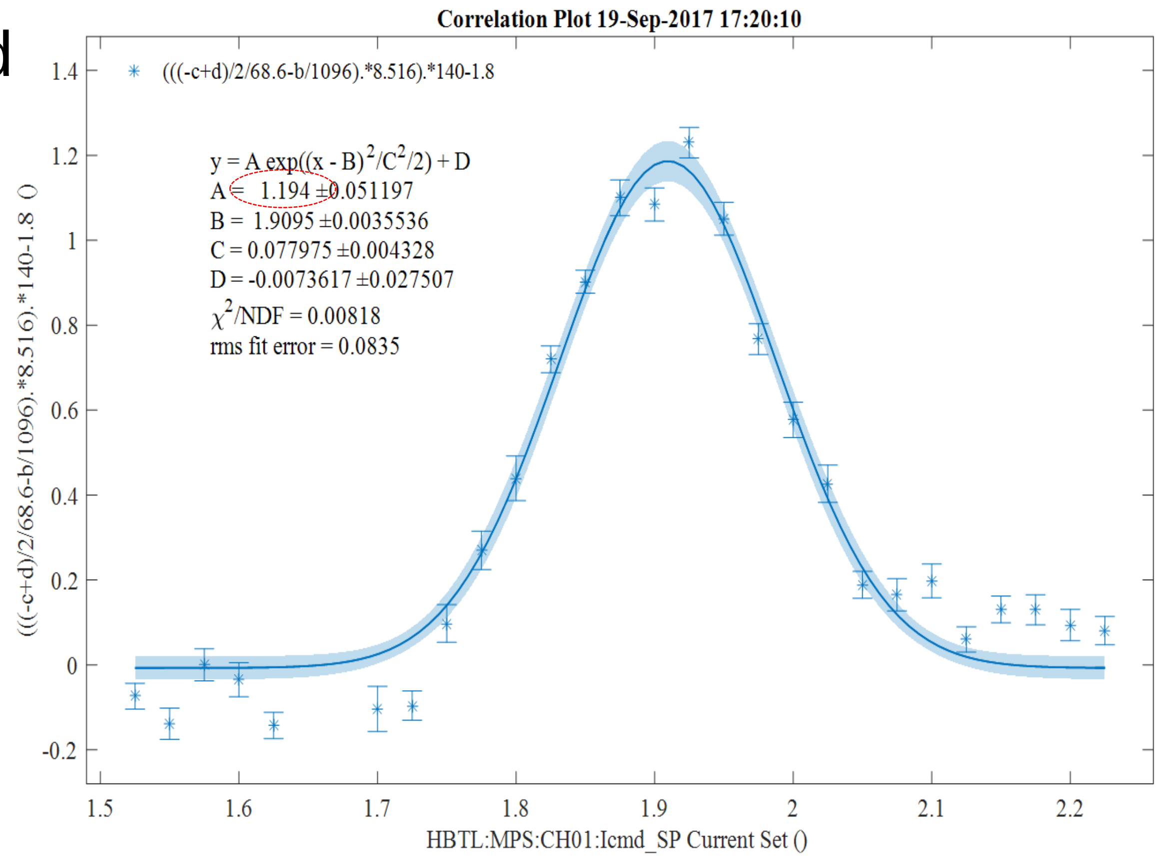
Simulation:
emittance: 0.55 mm-mrad
peak current: 2.2 kA

FEL Intensity

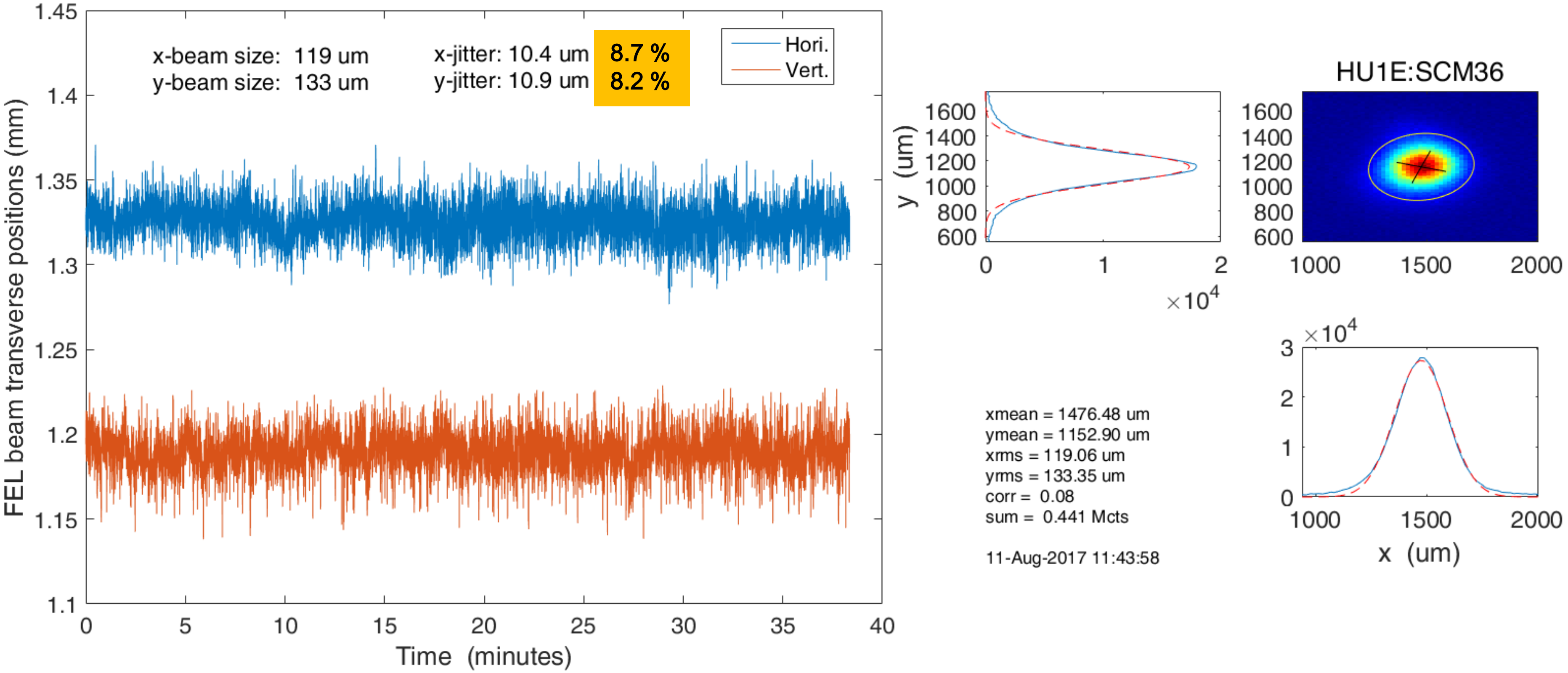
FEL intensity measured by e-loss scanning

→ over 1 mJ/pulse at 9.7 keV FEL

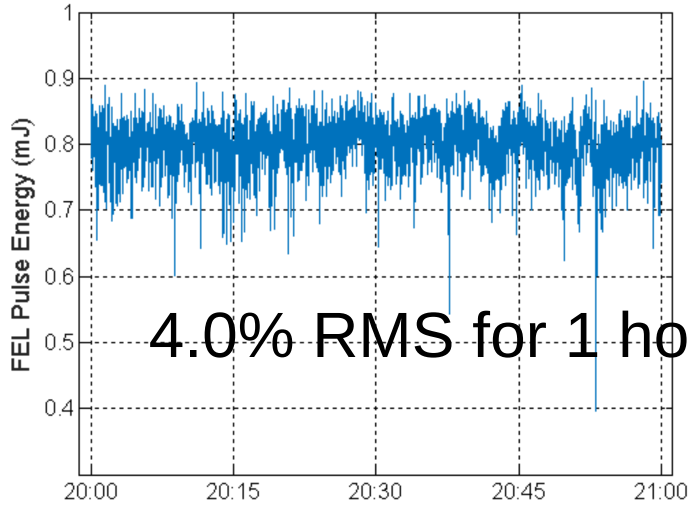




FEL beam position jitter (3-BC operation)
(measured at a 40-m downstream YAG-screen from last undulator)



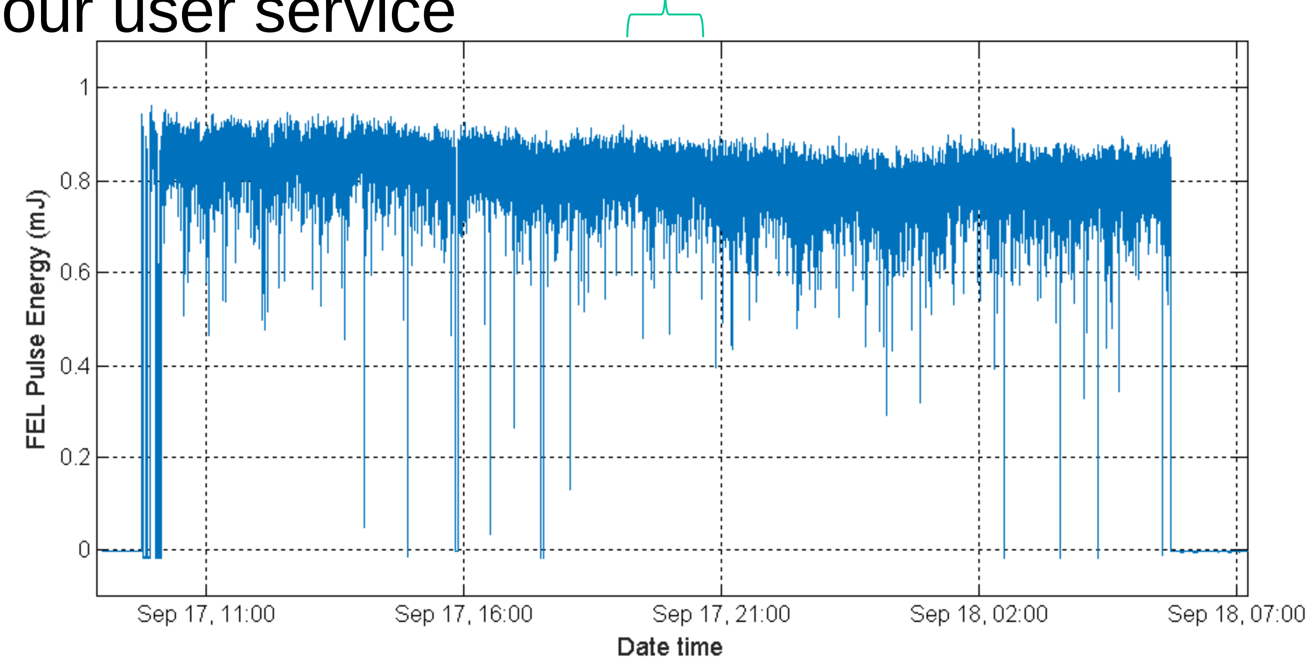
FEL intensity stability



QBPM sum data
Calibrated by e-loss

4.0% RMS for 1 hour

15 hour user service



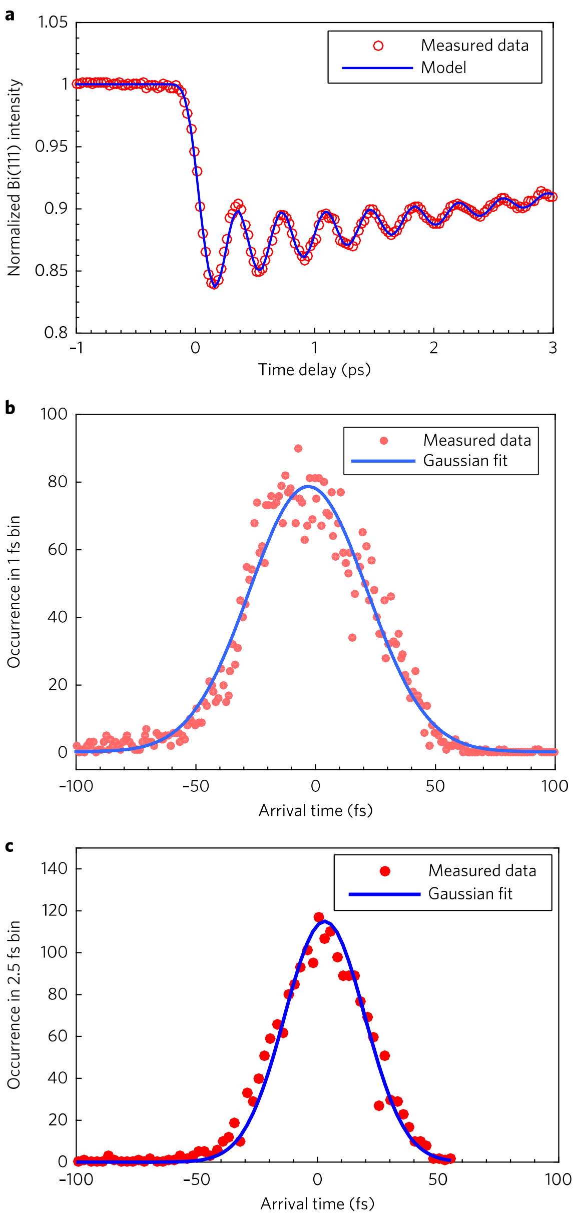
Commissioning Results of PAL-XFEL

ARTICLES
https://doi.org/10.1038/s41566-017-0029-8
nature photonics

Hard X-ray free-electron laser with femtosecond-scale timing jitter

Heung-Sik Kang[1]*, Chang-Ki Min[1], Hoon Heo[1], Changbum Kim[1], Haeryong Yang[1], Gyujin Kim[1], Inhyuk Nam[1], Soung Youl Baek[1], Hyo-Jin Choi[1], Geonyeong Mun[1], Byoung Ryul Park[1], Young Jin Suh[1], Dong Cheol Shin[1], Jinyul Hu[1], Juho Hong[1], Seonghoon Jung[1], Sang-Hee Kim[1], KwangHoon Kim[1], Donghyun Na[1], Soung Soo Park[1], Yong Jung Park[1], Jang-Hui Han[1], Young Gyu Jung[1], Seong Hun Jeong[1], Hong Gi Lee[1], Sangbong Lee[1], Sojeong Lee[1], Woul-Woo Lee[1], Bonggi Oh[1], Hyung Suck Suh[1], Yong Woon Parc[1], Sung-Ju Park[1], Min Ho Kim[1], Nam-Suk Jung[1], Young-Chan Kim[1], Mong-Soo Lee[1], Bong-Ho Lee[1], Chi-Won Sung[1], Ik-Su Mok[1], Jung-Moo Yang[1], Chae-Soon Lee[1], Hocheol Shin[1], Ji Hwa Kim[1], Yongsam Kim[1], Jae Hyuk Lee[1], Sang-Youn Park[1], Jangwoo Kim[1], Jaeku Park[1], Intae Eom[1], Seungyu Rah[1], Sunam Kim[1], Ki Hyun Nam[1], Jaehyun Park[1], Jaehun Park[1], Sangsoo Kim[1], Soonam Kwon[1], Sang Han Park[1], Kyung Sook Kim[1], Hyojung Hyun[1], Seung Nam Kim[1], Seonghan Kim[1], Sun-min Hwang[1], Myong Jin Kim[1], Chae-yong Lim[1], Chung-Jong Yu[1], Bong-Soo Kim[1], Tai-Hee Kang[1], Kwang-Woo Kim[1], Seung-Hwan Kim[1], Hee-Seock Lee[1], Heung-Soo Lee[1], Ki-Hyeon Park[1], Tae-Yeong Koo[1], Dong-Eon Kim[1] and In Soo Ko[2]

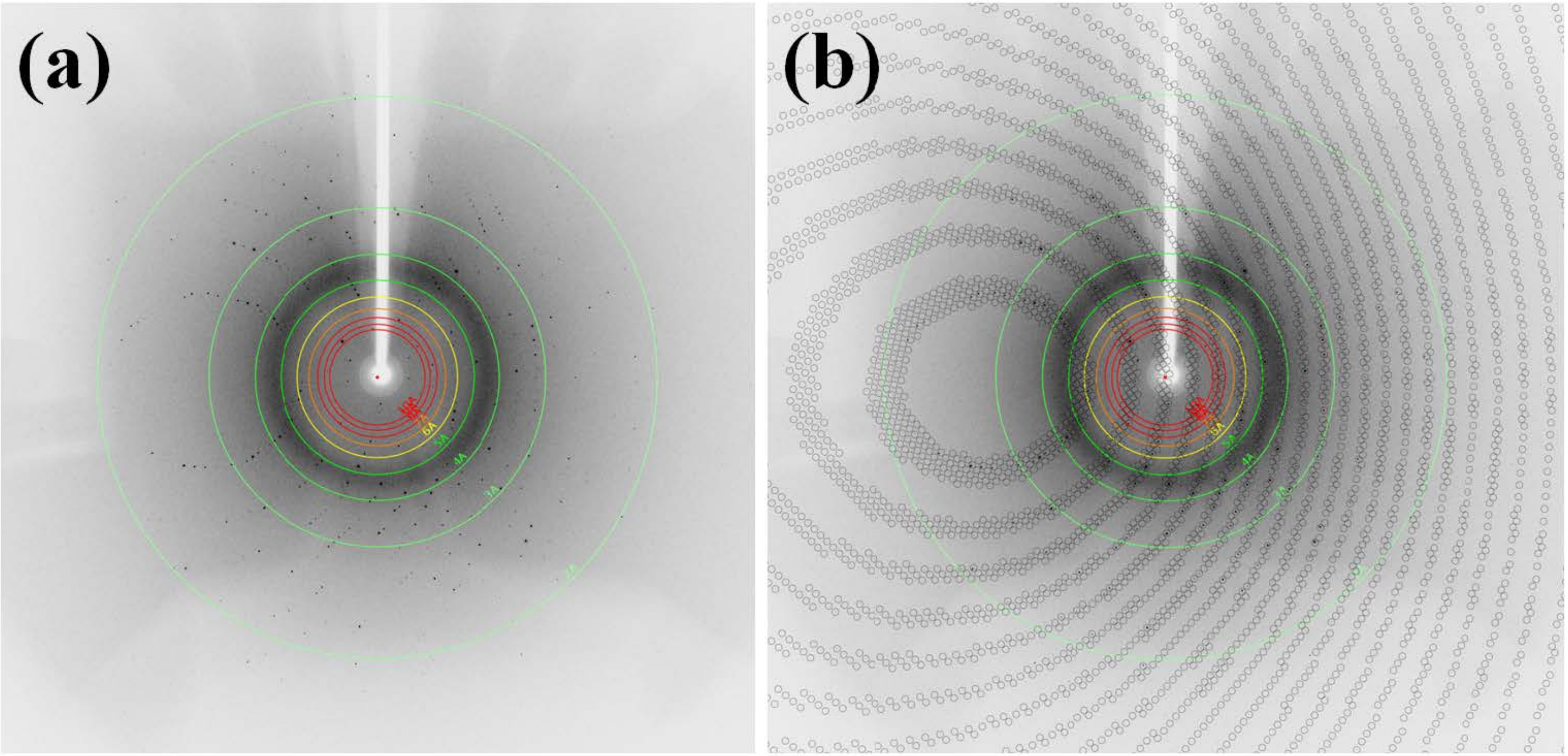
The hard X-ray free-electron laser at the Pohang Accelerator Laboratory (PAL-XFEL) in the Republic of Korea achieved saturation of a 0.144 nm free-electron laser beam on 27 November 2016, making it the third hard X-ray free-electron laser in the world, following the demonstrations of the Linac Coherent Light Source (LCLS) and the SPring-8 Angstrom Compact Free Electron Laser (SACLA). The use of electron-beam-based alignment incorporating undulator radiation spectrum analysis has allowed reliable operation of PAL-XFEL with unprecedented temporal stability and dispersion-free orbits. In particular, a timing jitter of just 20 fs for the free-electron laser photon beam is consistently achieved due to the use of a state-of-the-art design of the electron linear accelerator and electron-beam-based alignment. The low timing jitter of the electron beam makes it possible to observe Bi(111) phonon dynamics without the need for timing-jitter correction, indicating that PAL-XFEL will be an extremely useful tool for hard X-ray time-resolved experiments.



Pump laser-xfel jitter : 57 fs (FWHM)

PAL-XFEL Demo Experiments

Diffraction patterns from Lysozyme crystals



Filtered with *NanoPeakCell* Resolution: ~ 1.8 angstrom

Analyzed with *CrystFEL*

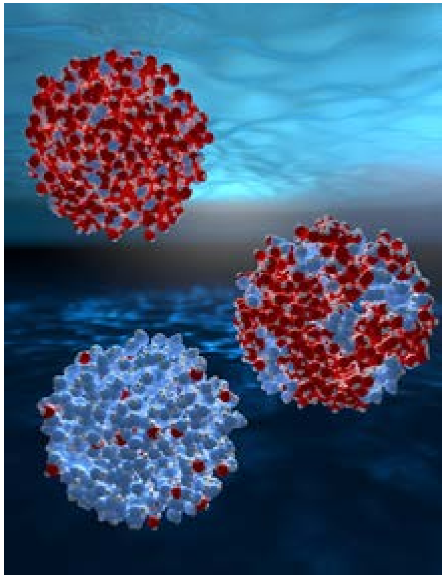
PAL-XFEL User service

PAL-XFEL User service start ('17.6.~)

- 1st Half ('17.6~'17.9) : 8 Experiments
- 2nd Half ('17.10~'18.1) : 18 Experiments

1st PAL-XFEL User Sweden-Korean collaboration team

Studied supercooled water molecule structures and published the results in Science.



* PI : **Prof. Anders Nilsson (Sweden Stockholm Univ.)**

PAL-XFEL Operation Schedule

		Y2017 (12 H OM)		Y2018 (12/24 H OM)		Y2019 (24 H OM)	
		1/2	2/2	1/2	2/2	1/2	2/2
XSS	FXS	OPER	OPER	OPER	OPER	OPER	OPER
	FXL	OPER	OPER	OPER	OPER	OPER	OPER
NCI	SFX	COMS	OPER	OPER	OPER	OPER	OPER
	CXI	OPER	OPER	OPER	OPER	OPER	OPER
SSS	XAS	COMS	OPER	OPER	OPER	OPER	OPER
	XES	COMS	OPER	OPER	OPER	OPER	OPER
	FTH	COMS	OPER	OPER	OPER	OPER	OPER
	RXS	INST	INST	COMS	COMS	OPER	OPER

OM: Operation Mode; INST : Installation; COMS : Commission; OPER : Operation;
XSS (X-ray Scattering & Spectroscopy); FXL (Femtosecond X-ray Liquidography); FXS (Femtosecond X-ray Scattering)
NCI (Nano Crystallography & Coherent Imaging); SFX (Serial Femtosecond Xtallography); CXI (Coherent X-ray Imaging)
SSS (Soft X-ray Scattering & Spectroscopy); XES (X-ray Emission Spectroscopy); XAS (X-ray Absorption Spectroscopy)
FTH (Fourier Transform Holography); RXS (Resonant X-ray Scattering)

PAL-XFEL Near Future Instrumentation Operation Schedule

PAL-XFEL Summary

PAL-XFEL was successfully commissioned and achieved all the target specifications.

Beamlines are also commissioned and carried out demo experiments using Lysozyme crystals confirming all instrumentations (including detector, DAQ) are working as expected.

PAL-XFEL has a strength in (1) world best timing jitter between pump and probe (2) excellent beam position stability (3) lazing capability in tender x-ray region (around 1-2 keV)

In 2017, operated 120 days for user service for 30 experiments, and expect 140 days operation for 38 experiments in 2018.

Thank you for your attention !