PAL-XFEL S-band Linac

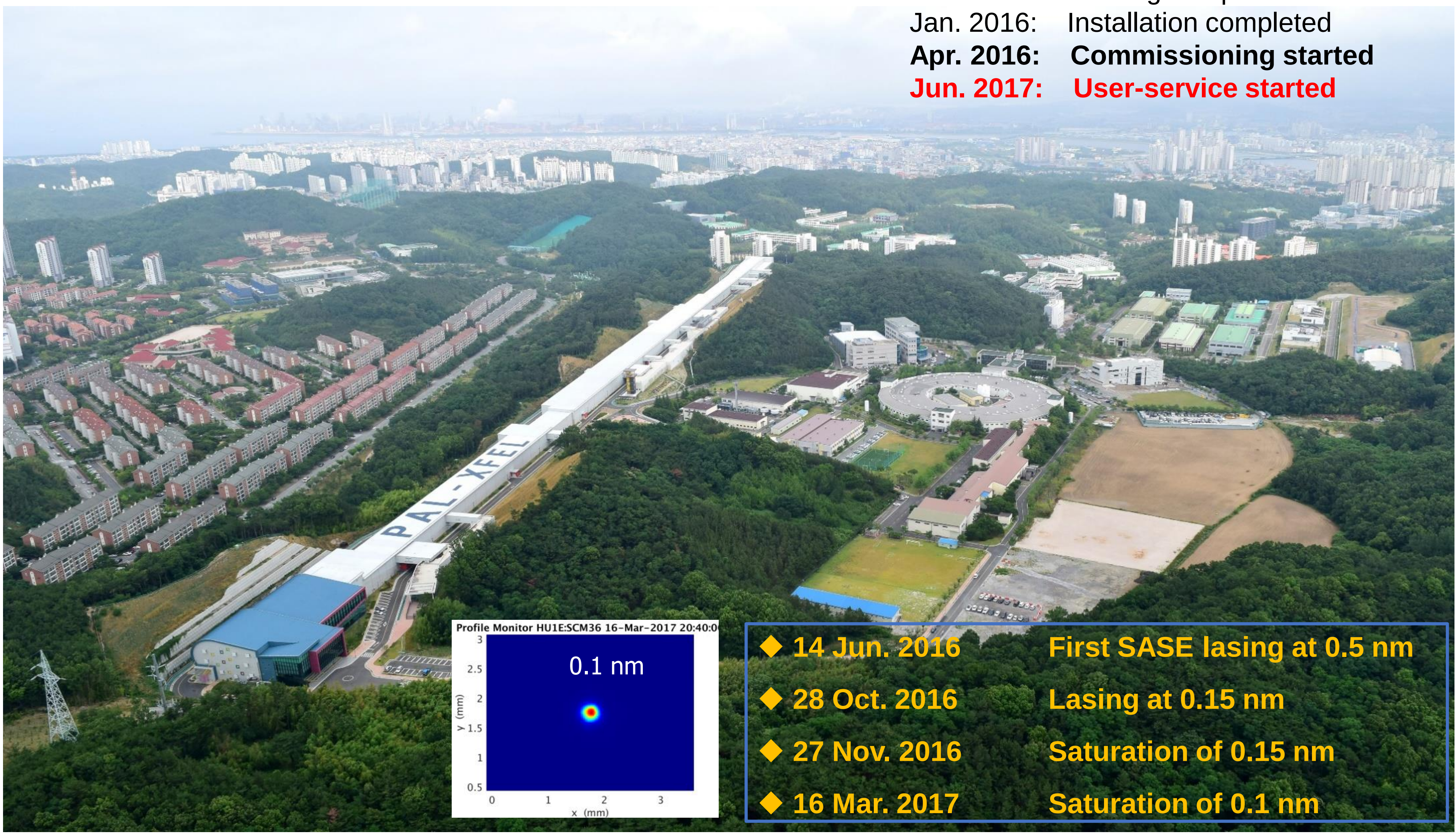
Heung-Sik Kang

포항가속기연구소
POHANG ACCELERATOR LABORATORY

PAL-XFEL

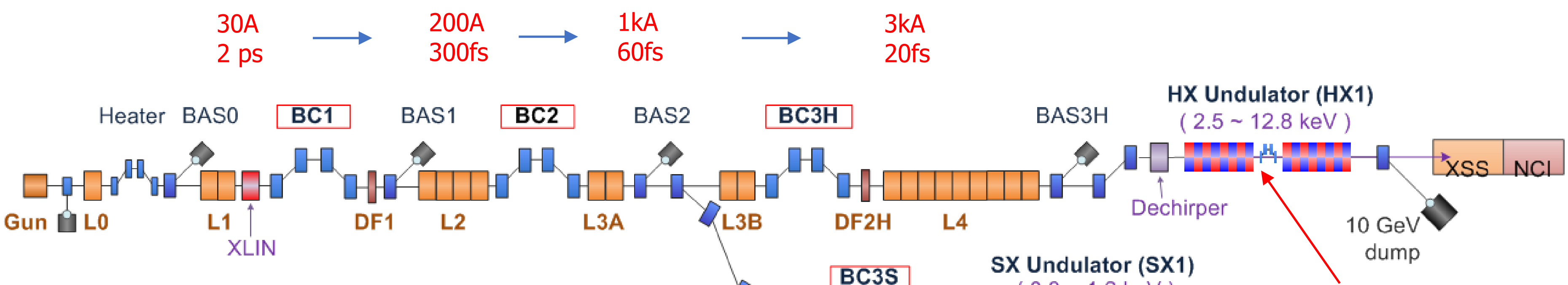
0.1 nm hard X-ray FEL using a 10 GeV normal conducting linac

Apr. 2011: PAL-XFEL project started
Jun. 2012: Ground-breaking
Dec. 2014: Building completed
Jan. 2016: Installation completed
Apr. 2016: Commissioning started
Jun. 2017: User-service started



- **14 Jun. 2016** **First SASE lasing at 0.5 nm**
- **28 Oct. 2016** **Lasing at 0.15 nm**
- **27 Nov. 2016** **Saturation of 0.15 nm**
- **16 Mar. 2017** **Saturation of 0.1 nm**

PAL-XFEL Parameters



Photocathode RF-gun

Main parameters

e^- Energy	11 GeV
e^- Bunch charge	20-200 pC
Peak current	> 3 kA
Slice emittance	< 0.4 mm mrad
Repetition rate	60 Hz
FEL pulse duration	5 fs – 50 fs
SX line switching	DC magnet

(to be changed to Kicker by 2020)

RF system

- **50 S-band RF stations**
  - 50 klystrons (80 MW, 4 us, 60 Hz, Thoshiba)
  - 50 klystron modulators
  - 42 energy doublers
  - 50 LLRF systems
  - 174 S-band accelerating structures
- **1 X-band RF**

Operation RF phase

• Gun	-33.7
• L1	-10.5
• X-linearizer	-180.0
• L2	-19.6
• L3	-3.0
• L4	-2.0

Klystron gallery

Linac tunnel

Undulator hall

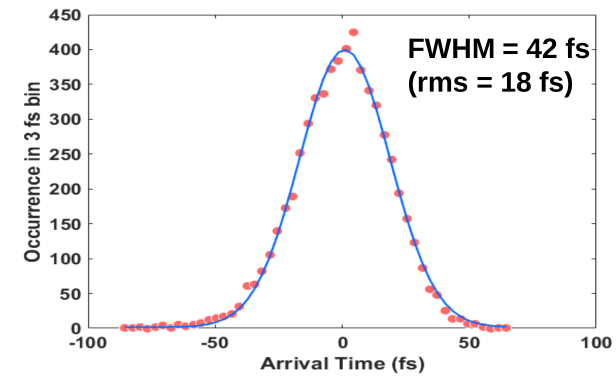
Hard X-ray experimental hall

PAL-XFEL Machine Performance

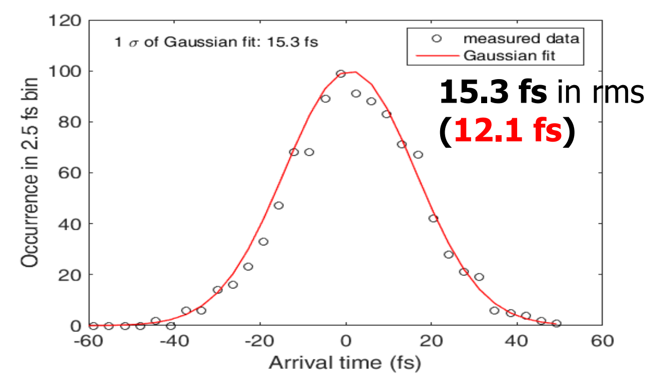
◆ **A highly stable FEL performance is achieved through a reliable & stable operation of the S-band electron linac**

- Based on a **matured S-band technology** established in Industry
- **Temporal stability: ~18 fs (rms)** between XFEL pulses and optical pulses from a synchronized laser system
- **Relative electron beam energy jitter**: < 1.5 x 10-4
  - → on crest acceleration: < 5 x 10-5
- **Electron beam arrival time jitter**: < 15 fs
- **Projected emittance**
  - Injector : 0.42 / 0.43 mm-mrad @250 pC
  - Linac end : 0.60 / 0.55 mm-mrad @220 pC
- **RF stability (rms)**
  - L1 (w/o SLED) : **0.01 degrees / 0.01%**
  - L2, L3, & L4 (w/ SLED) : **0.015 degrees / 0.02%**

Arrival time Jitter Histogram (between Laser and XFEL at sample)



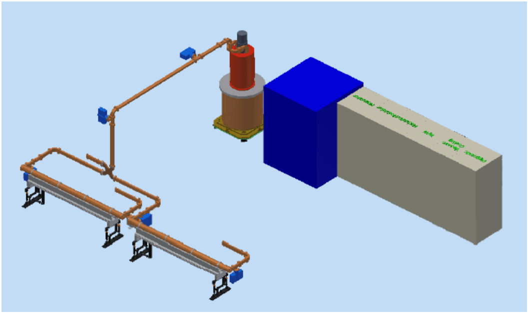
Electron beam arrival time jitter Histogram



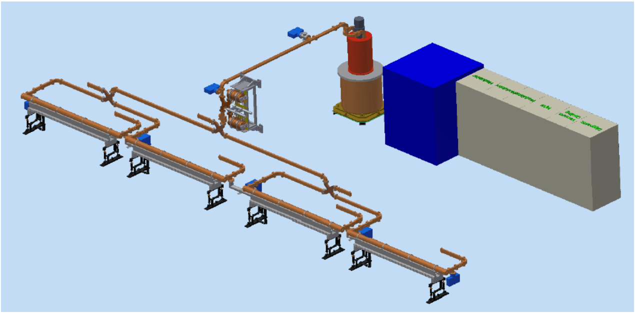
Linac System

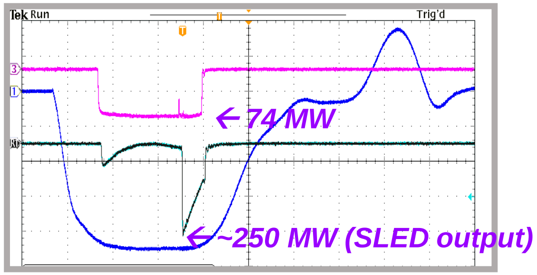
- **Klystron modulator voltage stability : < 30 ppm**

L1 (w/o SLED)

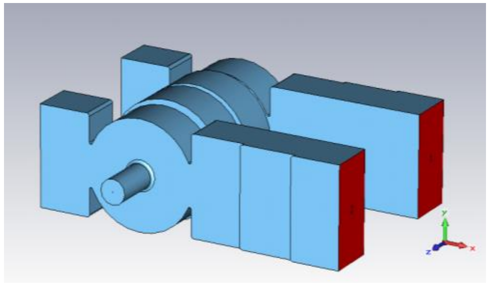


L2, L3, and L4 (w/ SLED)

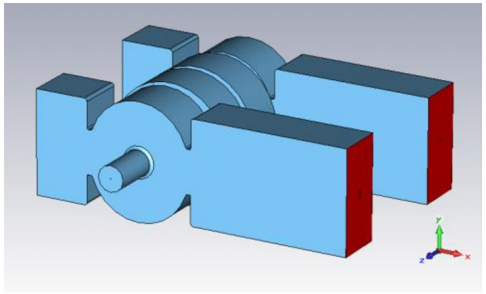




Round geometry



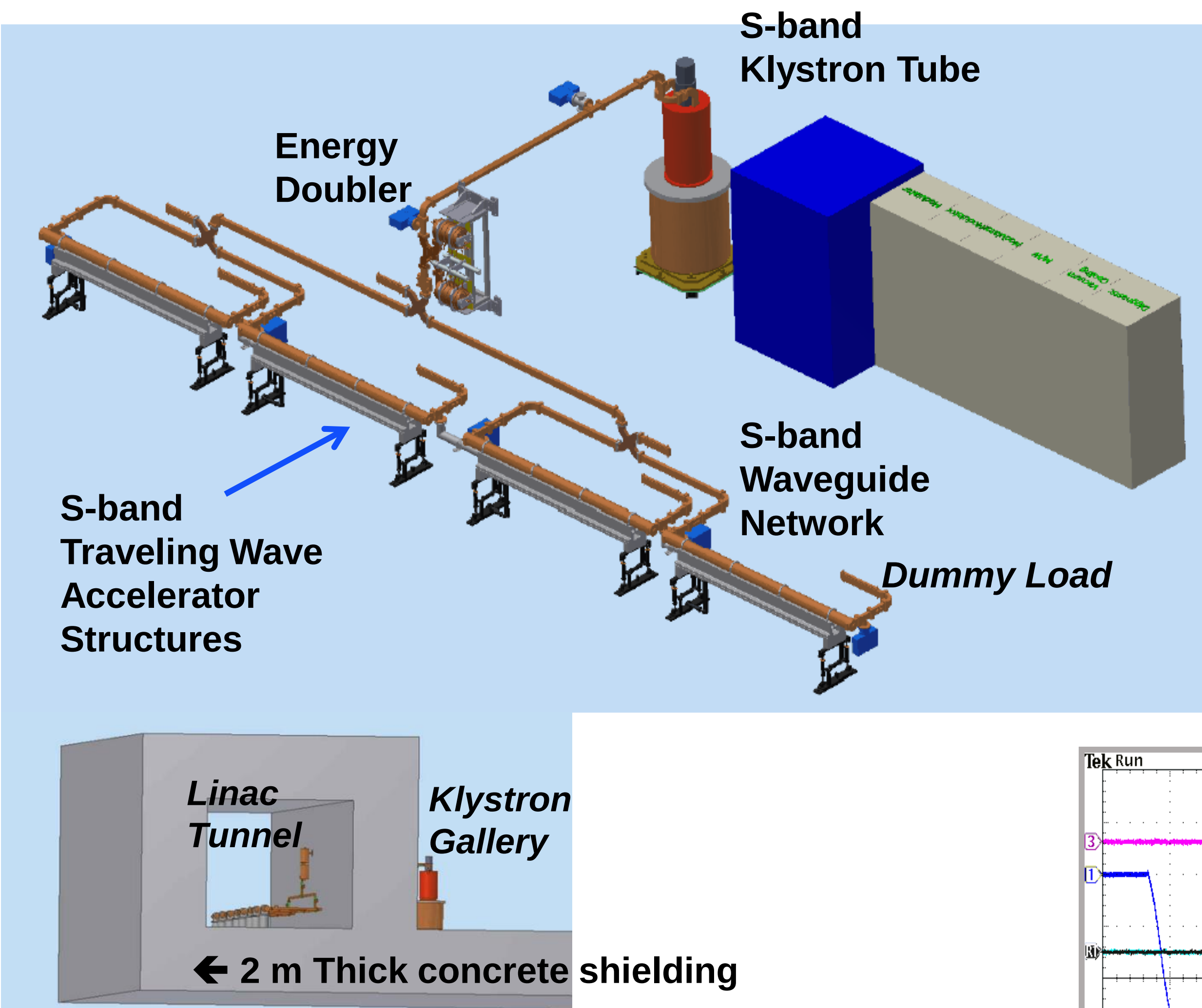
Racetrack geometry

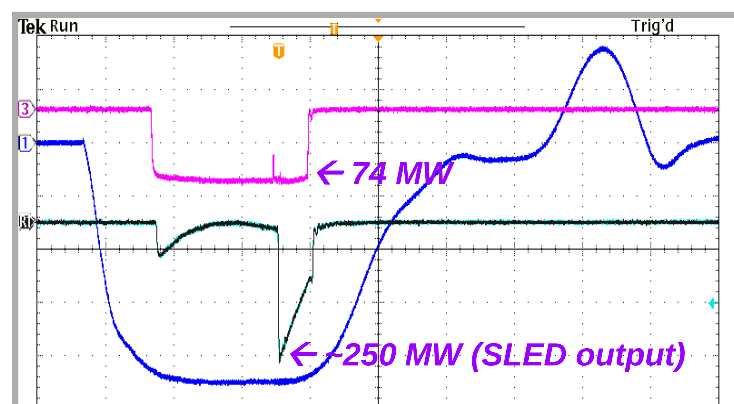


- Height of beam center: 80 cm
- Cooling temperature of accelerating structure: 30 +/- 0.01 ºC
- Quasi symmetric feed (single arm coupling) to reduce the dipole kick

  - coupler cavity with round geometry: 120 structures by Mitsubishi
  - **coupler cavity with racetrack geometry: 54 structures by Vitzro-Tech**

Basic Unit Module of XFEL Linac

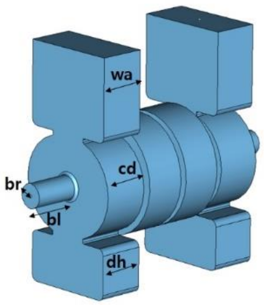




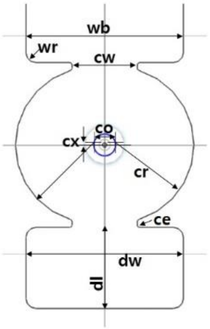
Linac Tunnel

S-band Structure (Qausi-symmetric coupler with racetrack shape)

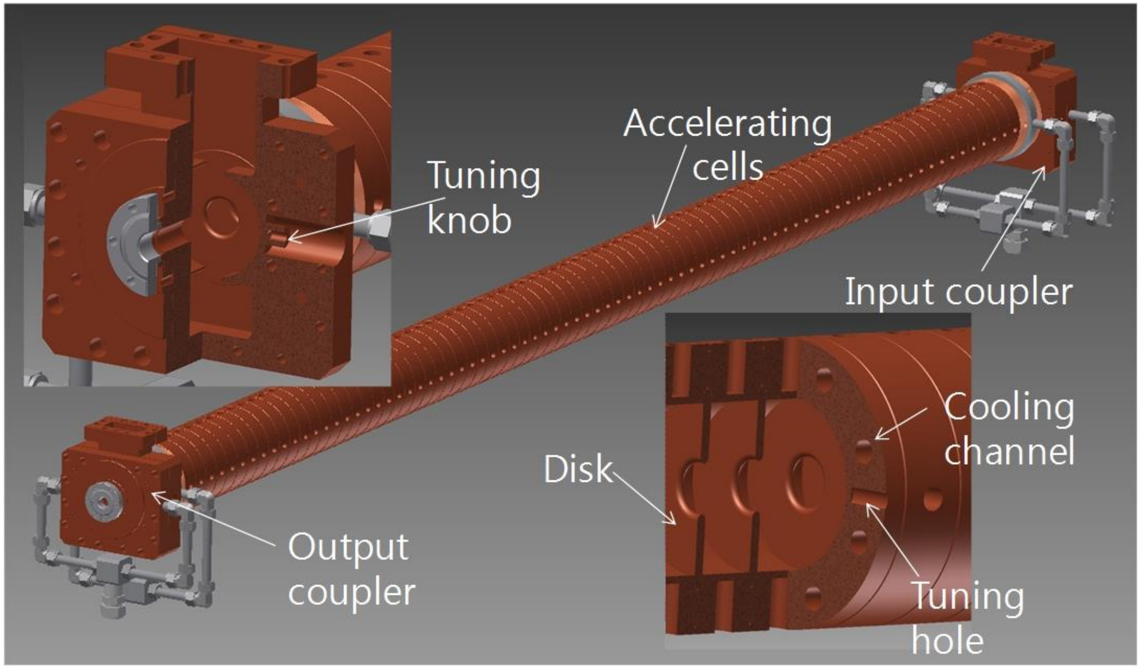
- **Quasi symmetric feed (single arm coupling) to reduce the dipole kick**
  - The same direction of coupler cavity makes the waveguide network simple
  - Racetrack type coupler cavity to reduce the quadrupole kick
- **Max. accelerating gradient: 27 MV/m**



(a)



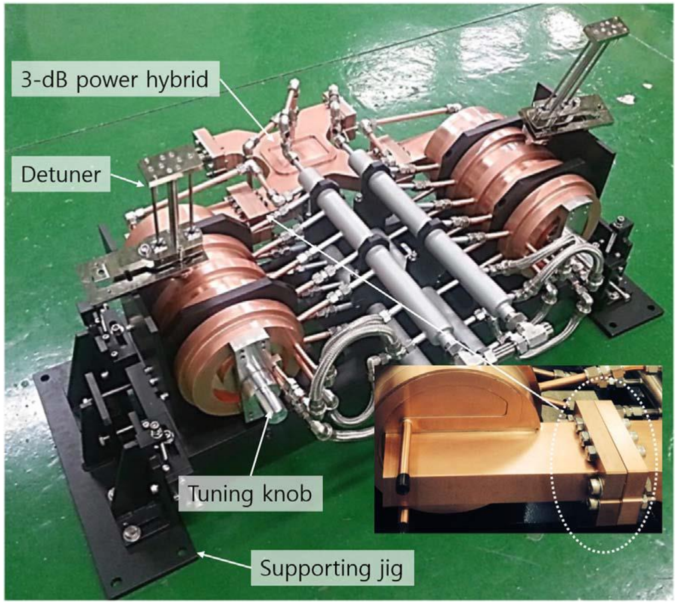
(b)

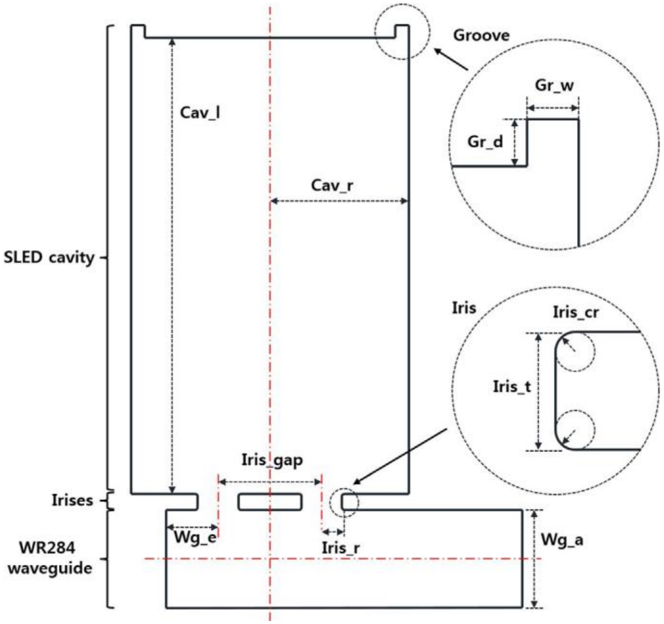


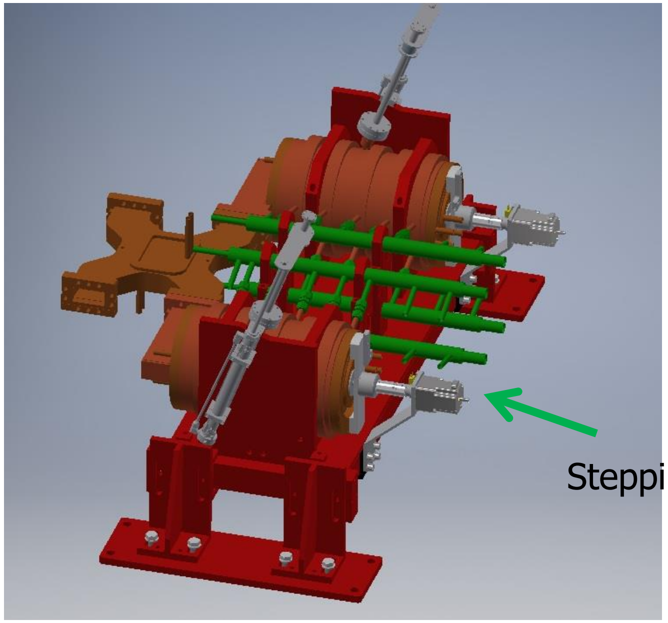
Description	S-band
Operating Frequency(GHz)	2856 ±0.5
Mode	2p/3
Q	13,000
Shunt Impedance(Mohms)	53
Attenuation constant	0.57(4.9dB)
Filling Time(us)	0.83
Water Temperature(°C)	30±0.01
Type	Quasi-Symmetry
Total Length(mm)	3138

S-band Energy Doubler

- Two-hole coupling structure to withstand 380 MW peak RF power
- Energy gain: ~1.6
- Remote control of the tuning frequency by a stepping motor
- Collaborated with a Korean company
  : Vitzro-Tech





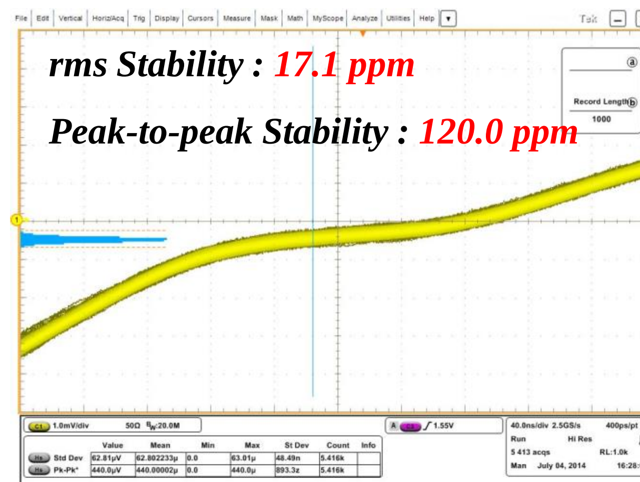


20-ppm Stability Inverter PS-type Modulator

	Unit	Value
Max. peak power	MW	200
Beam voltage	kV	400
Beam current	A	500
Beam pulse width	μs	8
Repetition rate max.	Hz	60
RF pulse width(flattop)	μs	4
Load impedance	Ω	800
Pulse transformer turn ratio		17
PFN impedance	Ω	2.7
PFN voltage	kV	46

Inverter PS

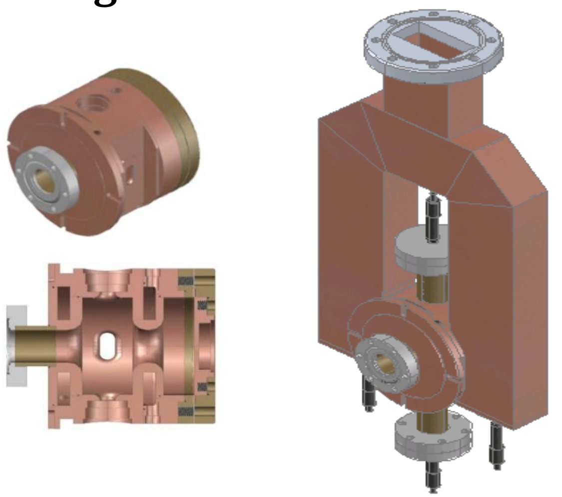
Parameter	Value	Unit
Avg. Output Power	125	kW
Max. Output Voltage	50	kV
Pulse width	7.5	us
Avg. Output Current	8.5	A
AC Input Voltage	480	VRMS
Efficiency	90	%
Cooling water	40	L/Min

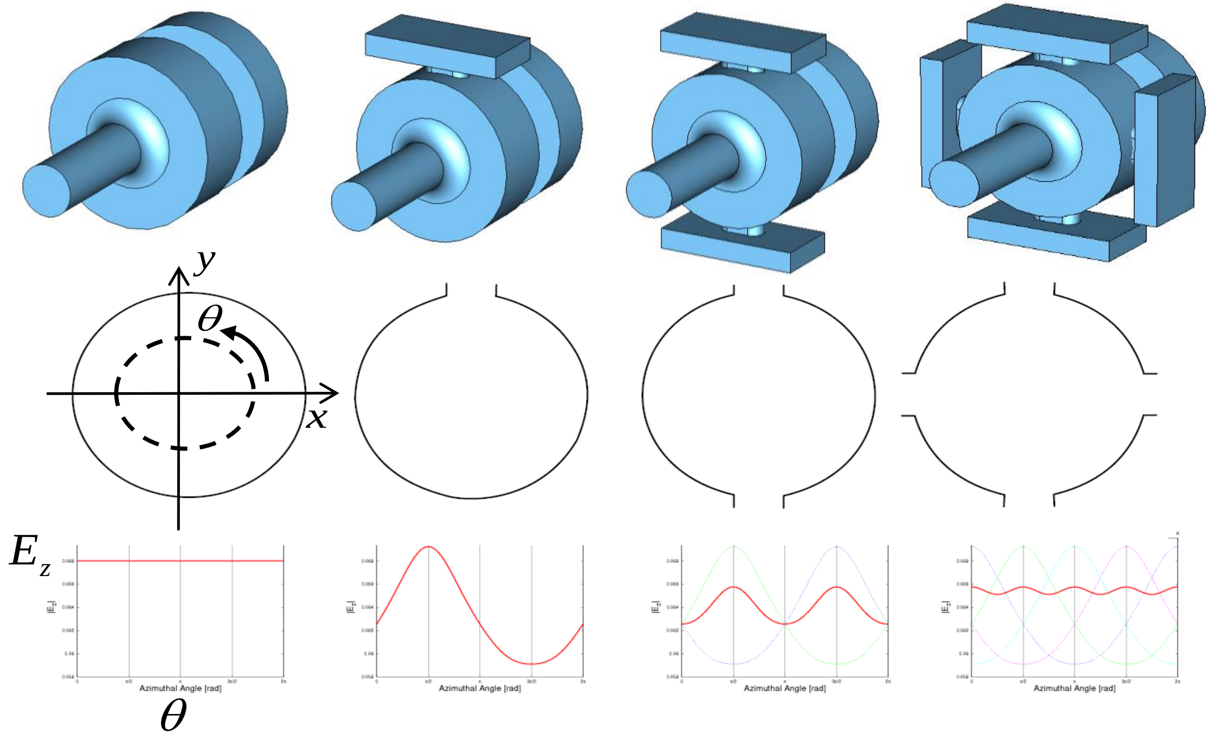


- Collaborated with two Korean companies: Posco-ICT(Vitzro-Tech) & Dawon-Sys

Photocathode RF gun in PAL-XFEL

RF gun





PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 104203 (2011)

Emittance growth due to multipole transverse magnetic modes in an rf gun

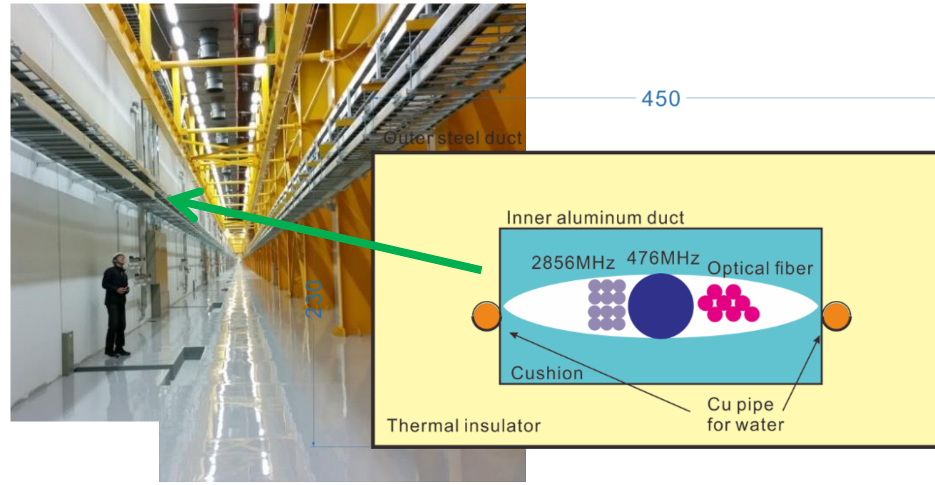
M. S. Chae,[1] J. H. Hong,[1] Y. W. Parc,[1,*] In Soo Ko,[1] S. J. Park,[2] H. J. Qian,[3] W. H. Huang,[3] and C. X. Tang[3]
[1]*Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Korea*
[2]*Pohang Accelerator Laboratory, Pohang University of Science and Technology, Pohang 790-784, Korea*
[3]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
(Received 25 March 2011; published 28 October 2011)

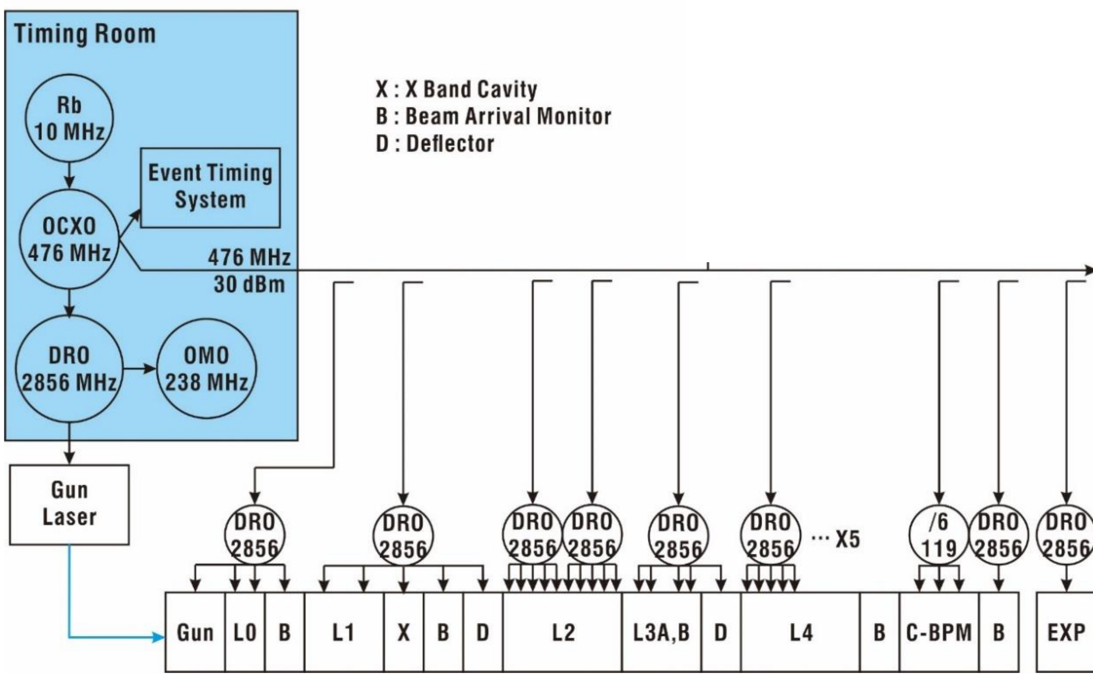
- **With 4 ports, we can make almost uniform electric field distribution.**
- **This model is easy to fabricate.**
- **Four ports is helpful to maintain the vacuum level.**

RF timing distribution system

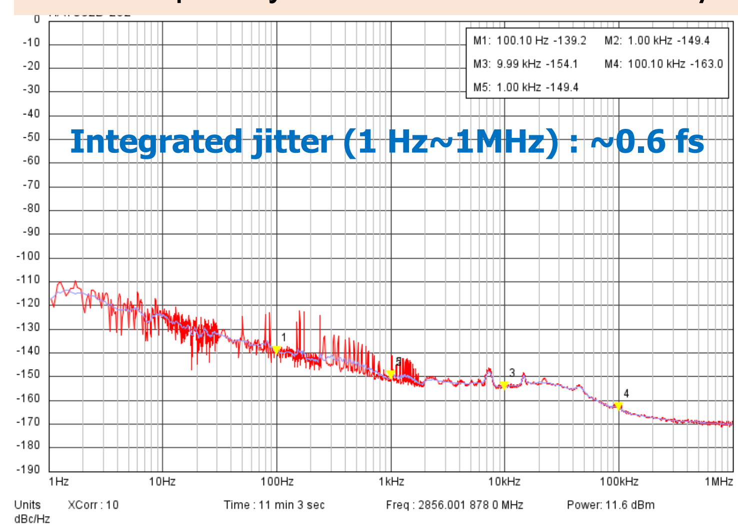
- based on low phase noise oscillator and coaxial cable (476 MHz) with passive stabilization
- Balanced optical & microwave phase detector (BOM-PD) for synchronization between RF and optical laser

Temperature stabilized duct for reference RF





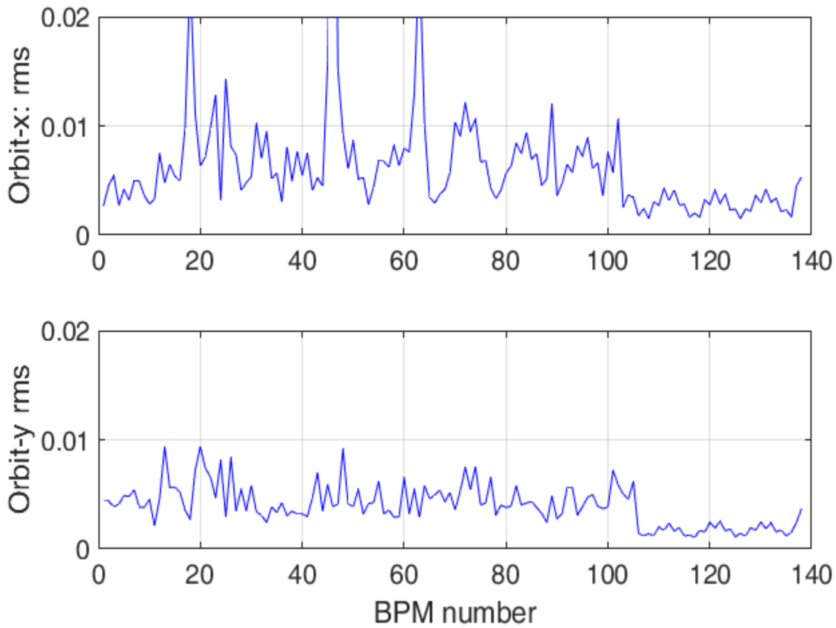
DRO : Dielectric resonator oscillator
developed by **RUPPtronik** in Germany



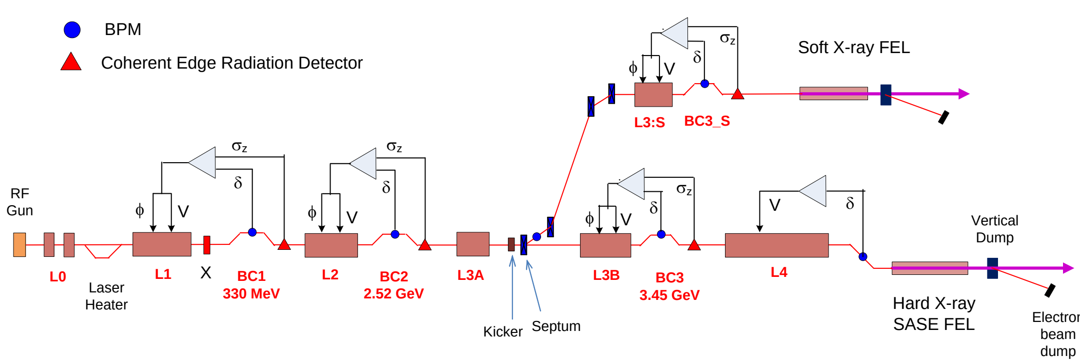
Beam-based Feedback

- Orbit feedback
  - range: Linac to undulator
  - use all correctors and BPMs except dispersive BPMS
  - runs at 1 Hz
  - The rms of the orbit variation along the undulator line

    x-plane: < 4.2 μm, y-plane : < 2.5 μm



- Energy feedback
  - dispersive BPM
  - runs at 1 Hz
- Bunch length feedback
  - CRM (coherent radiation monitor) at bunch compressors

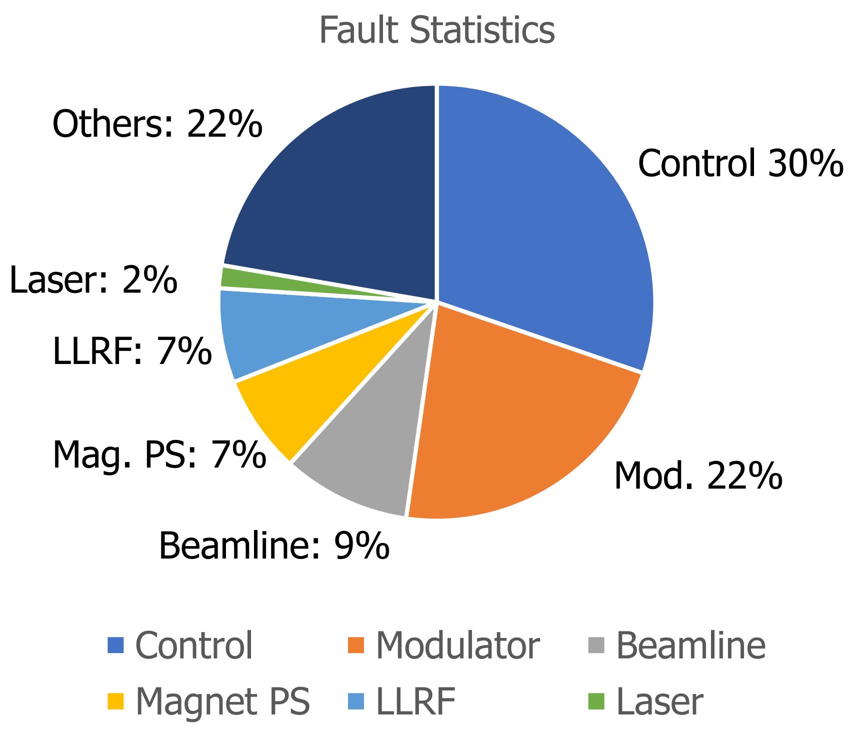



Thank you for your attention

Back-up slide

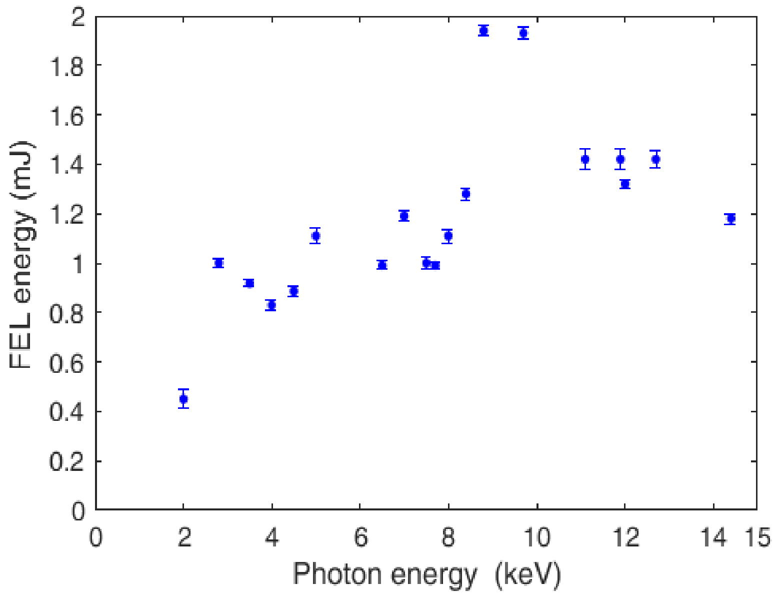
2018 User service operation statistics

- 2018 operation statistics
  - Planned beam time: 2057 h
  - Fault time: 101 h
  - Beam availability: 95%



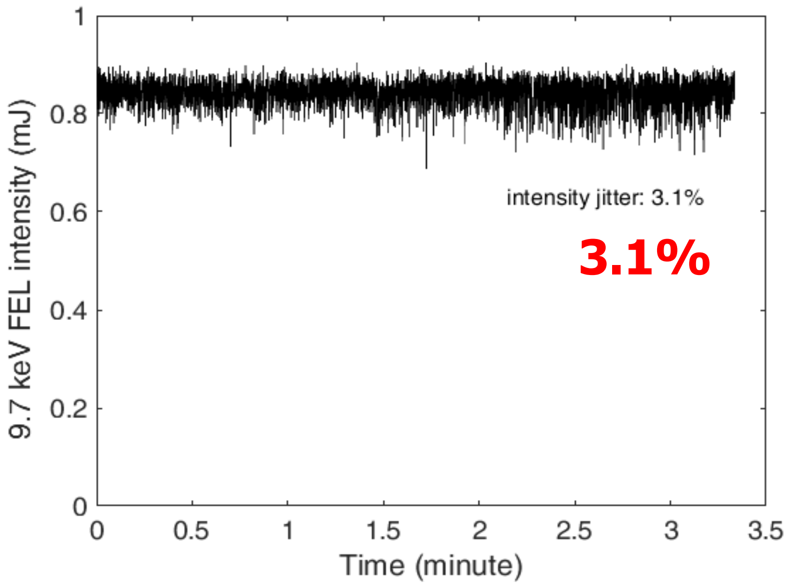
Machine Performances

◆ Photon energy	2.0 ~ 14.5 keV
◆ FEL pulse energy	2.0 mJ at 9.7 KeV
◆ FEL beam pulse duration	10 ~ 35 fs (fwhm)
◆ FEL power stability	< 5% RMS
◆ FEL position stability	< 10% of beam size
◆ FEL central wavelength jitter	0.024 %
◆ E-beam energy jitter	< 0.015 %
◆ E-beam arrival time jitter	< 15 fs
◆ FEL beam availability	~ 95%

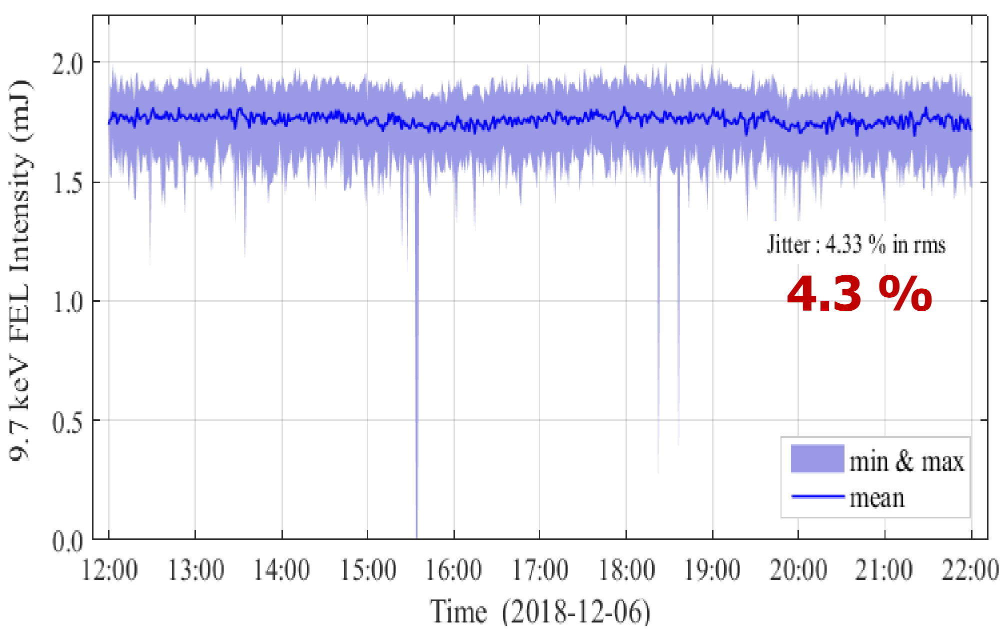


FEL intensity stability (9.7 keV FEL)

Short-term (3 min.)



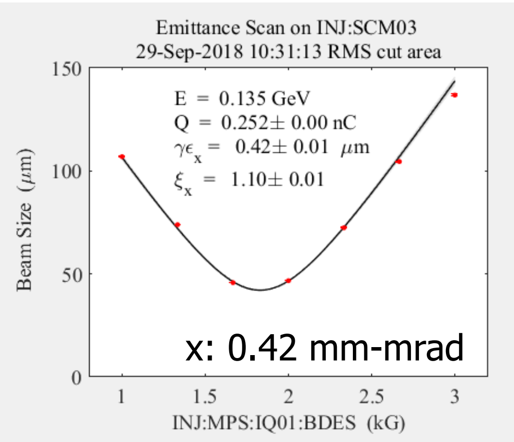
Long-term (10 hour)

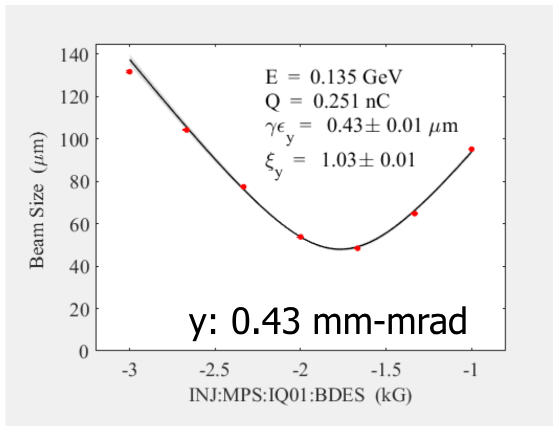


Injector Emittance

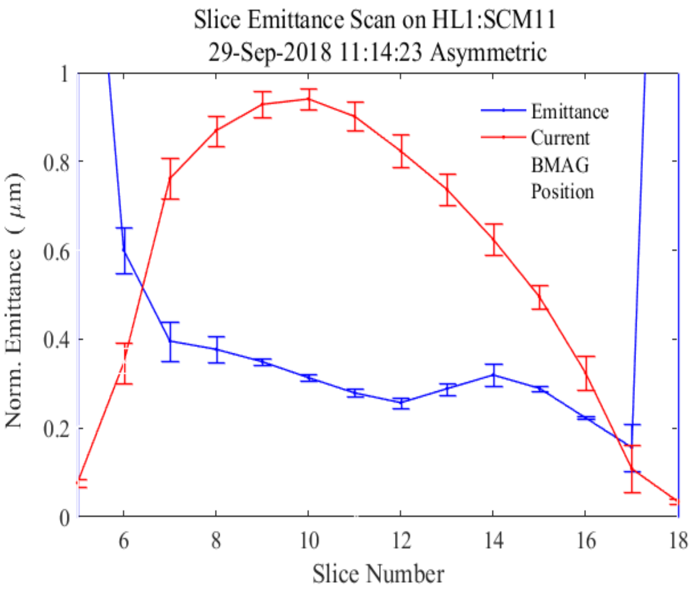
Projected emittance

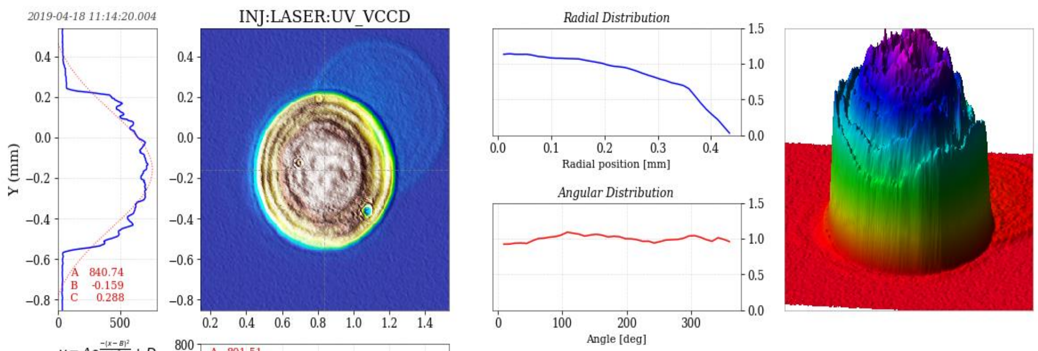
- Beam energy: 135 MeV
- Beam charge: 250 pC

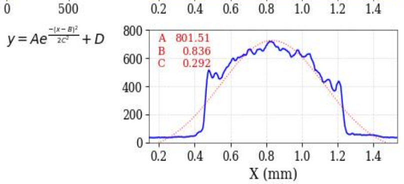




Slice emittance



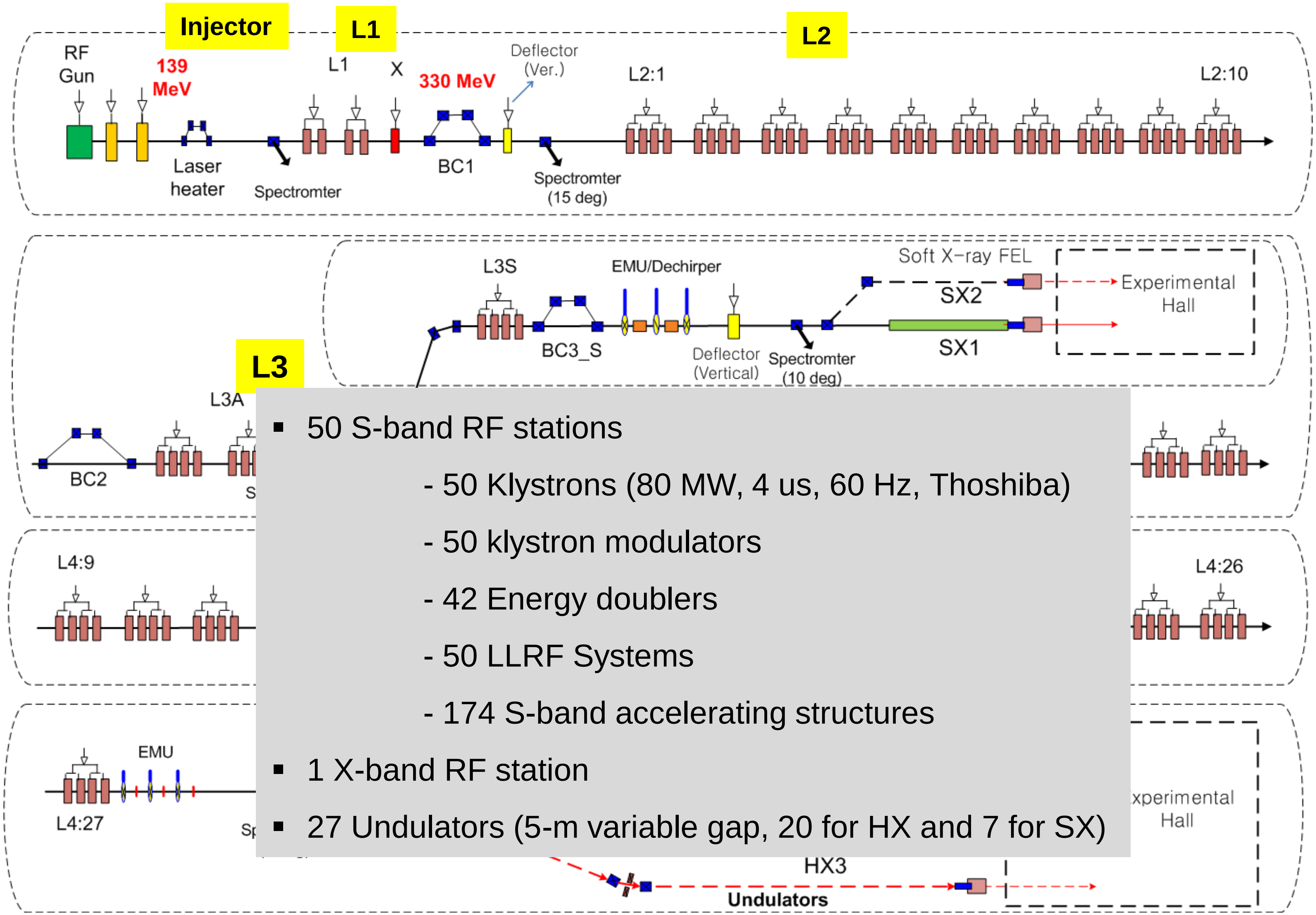




Center Position	mm	0.849, -0.198
Center of Mass	mm	0.839, -0.162
Size (w x h)	mm	0.804 x 0.870
Size (w x h)	pixel	173 x 187
Total Sum		1.1647e+07
Radial RMS	%	12.04
Angular RMS	%	4.33

Cut-gaussian laser beam profile

PAL-XFEL Layout



- 50 S-band RF stations
  - 50 Klystrons (80 MW, 4 us, 60 Hz, Thoshiba)
  - 50 klystron modulators
  - 42 Energy doublers
  - 50 LLRF Systems
  - 174 S-band accelerating structures
- 1 X-band RF station
- 27 Undulators (5-m variable gap, 20 for HX and 7 for SX)

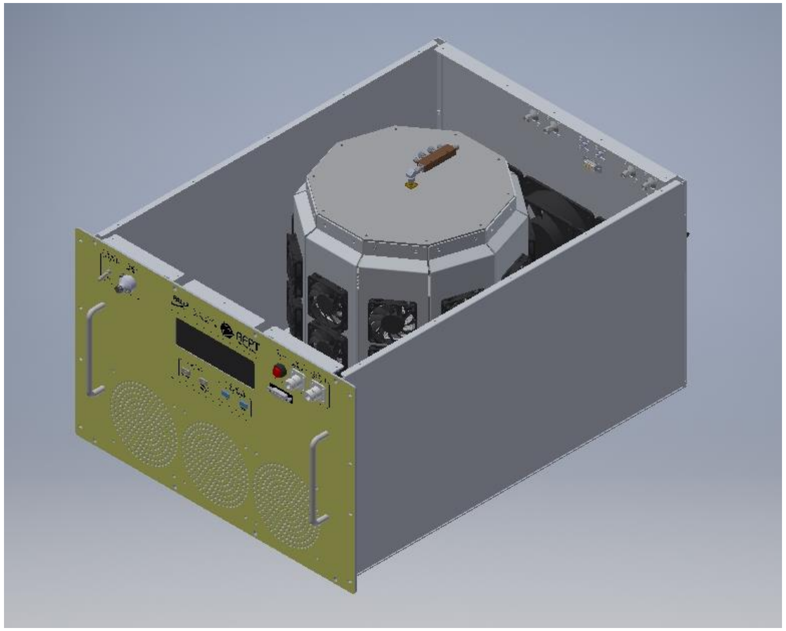
Number of Major RF Components

Classification	Section	K&M	A/S	Energy Doubler	Energy (GeV)
Injector linac		3	2	0	0.139
Hard X-ray main linac	L1	2	4	0	0.33
	L2	10	40	10	2.52
	L3A	2	8	2	3.0
	L3B	2	8	2	3.45
	L4	27	108	27	10
Soft X-ray linac		1	4	1	3~3.5
Deflector (S-band)	L1, L3	3	4	0	
Linearizer (X-band)	L1	1	1	0	
Total No.		**51**	**180**	**42**	

Main System Supplier for PAL-XFEL

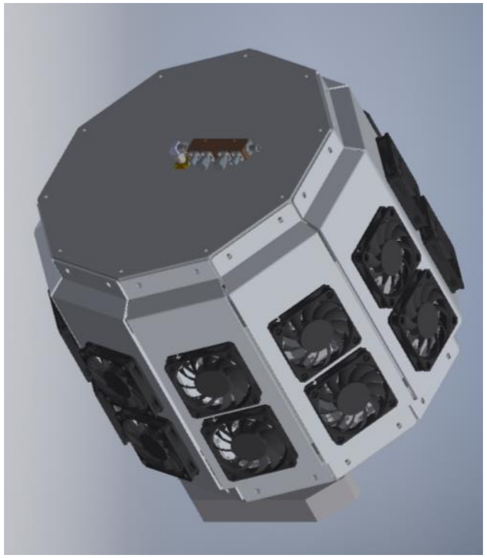
Item	No. of components	Supplier
S-band Accelerating Column	175	120: Mitsubishi 55: Vitzrotech
S-band Energy Doubler	42	Vitzrotech
200-MW Modulator	50	Vitzrotech Dawon-Sys
80 MW S-band Klystron	50	Toshiba
S-band LLRF / SSA	50	Mobiis
Magnet	251	KR Tech T. H. Elema
Undulator	37 (20 for HX, 7 for SX)	SFA Seong-Ho High tech.
BPM electronics	Stripline, cavity BPM	SLAC

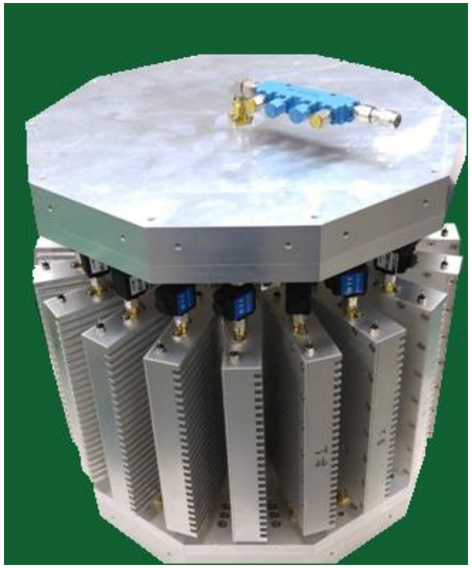
X-band SSA



Specifications

• 20-way combiner + Dual direc. coupler I.L	< 0.8dB
• Pout of Unit SSPA	> 49.0dBm (80W)
• 20ea * Unit SSPA	> 62.0dBm (1.6KW)
• Final Coaxial Cable I.L	< 0.5dB
• Final Flange Adapter I.L	< 0.2dB
• Final Pout	60.5dBm (1.1KW)

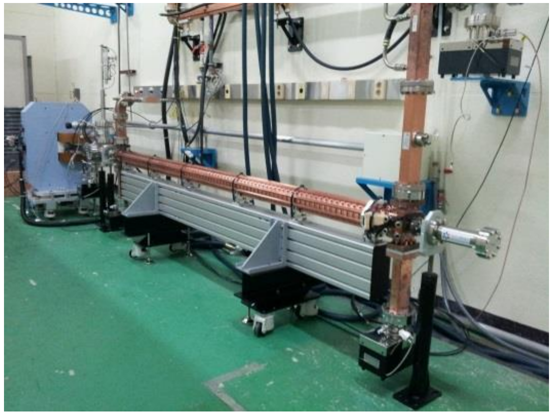




High Power Test of Accelerating Structures

MHI

VITZRO

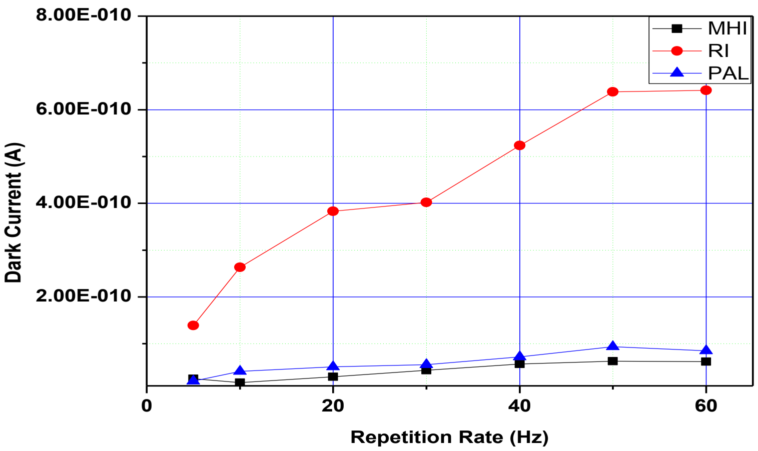


RI

RF Conditioning time (60Hz, 27MV/m)

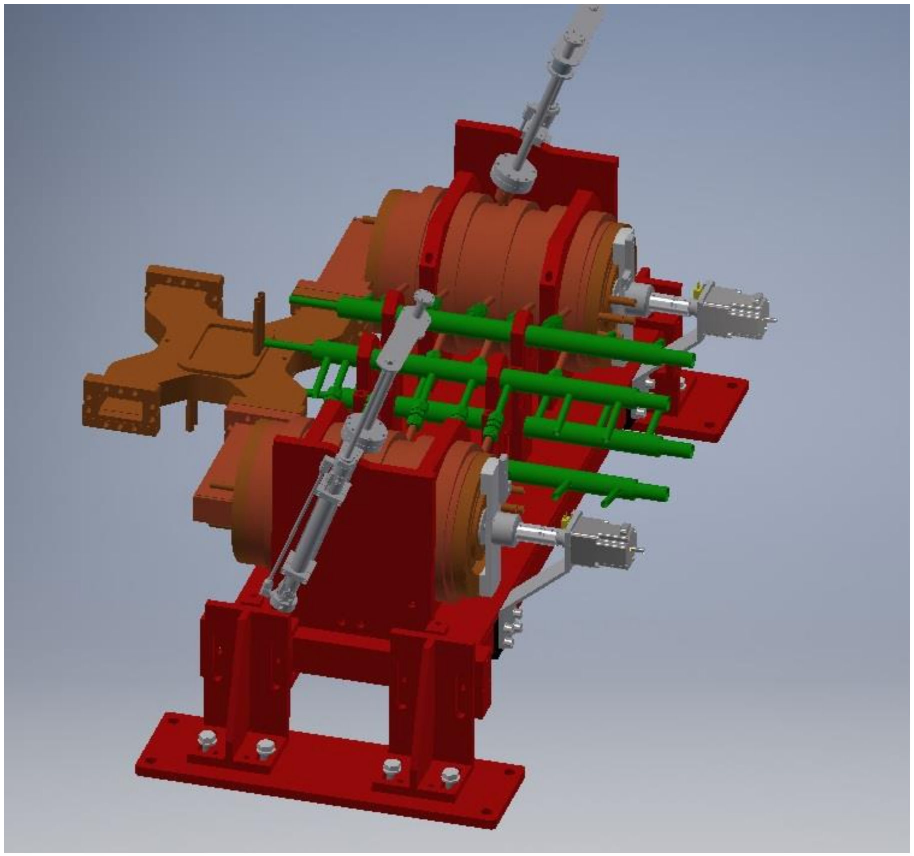
Maker	Conditioning Time (day)
RI	94.69
MHI	31.36
VITZRO	29.81

Dark Current vs. Rep. Rate

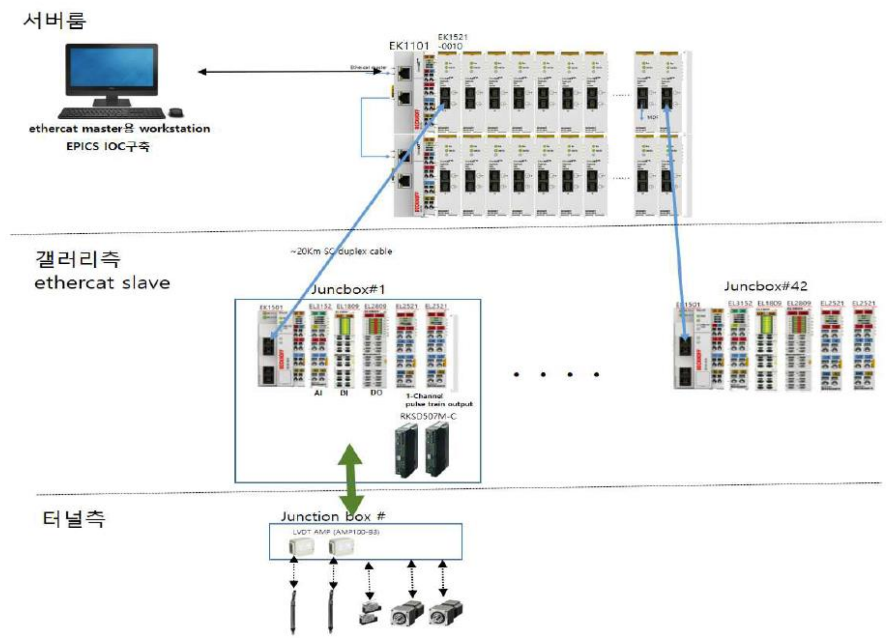


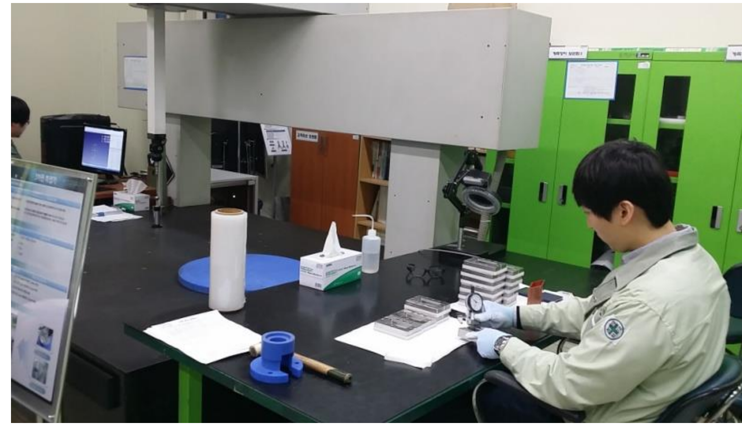
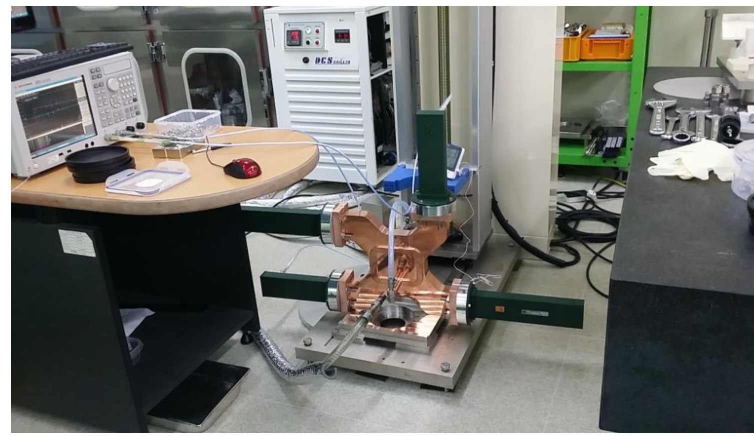
SLED frequency tuning system

SLED



SLED frequency tuning system layout



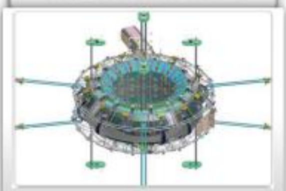

Vitzro-Tech




VITZRO TECH

Current Business Scope

Accelerator

Nuclear Fusion Biz

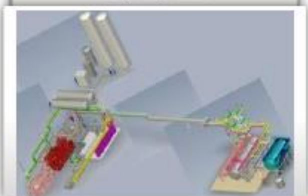


Photon Accelerator

Heavy Ion Accelerator

Cryogenic

Cryo-plant



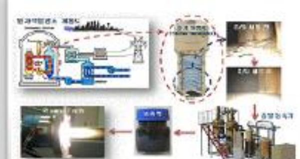
Cryomodule

Cooling system

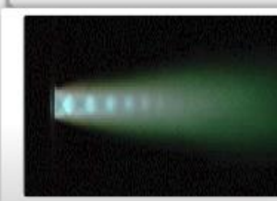
Plasma Application

KSTAR Power Supply

Radioactive Treatment



Plasma Torch



Aerospace

Rocket Engine

Test Facility

H.P Oxidizer Piping

Vacuum System

Vacuum System

Semiconductor

Vacuum Gate valve

Electric Power

High Power Breaker

Power Distribution

VI

Insulation

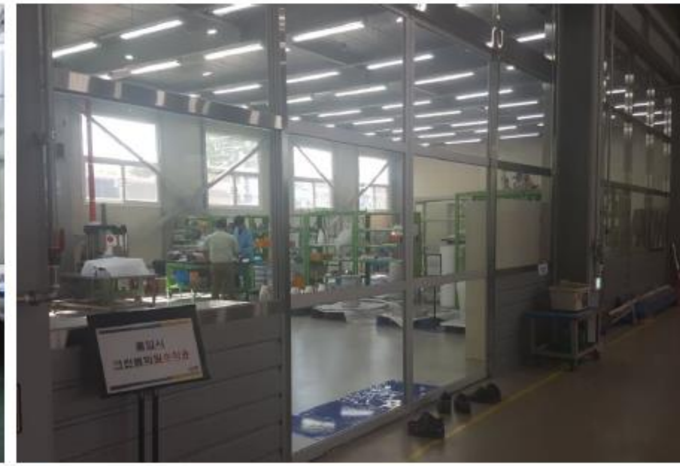
5. Facility & Certification

VITZRO TECH

Manufacturing Facility

Brazing Furnace

E-beam Welder(150kV)



Cleanroom for Storage

Machining(5 axis)

Clean Room(10000 class)

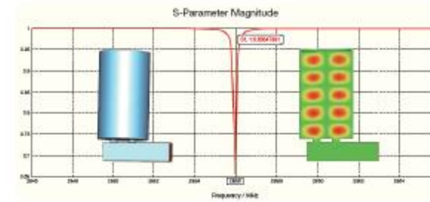
Clean Room(10 class)

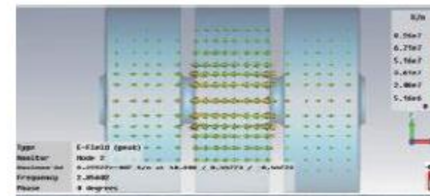
Chemical Treatment (18MΩ)

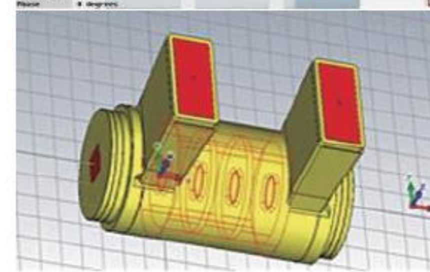
3. Main Business Participation (Project Experience)

PAL 4th Generation XFEL - Accelerating Column & Waveguide Components

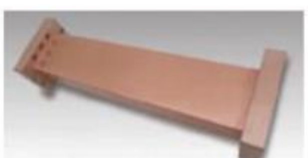
- Vitzrotech had participated in 4th Generation PAL XFEL
- Designed, Analyzed, Fabricated, Supplied, Installed **Accelerator Columns** **[From Engineering to Installation]**
- Fabricated, Supplied, Installed whole quantities of **Waveguide components** and **SLED Cavity**
- Fabricated, Supplied, Installed **Beam Line Systems**







Waveguide Component


Straight

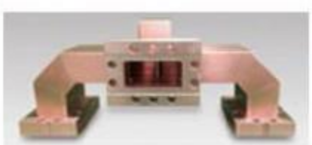

H-Bend


E-Bend


Single Type D.C


Dual Type D.C


Pumping Port


Power Combiner


Power Combiner


Rounded Type

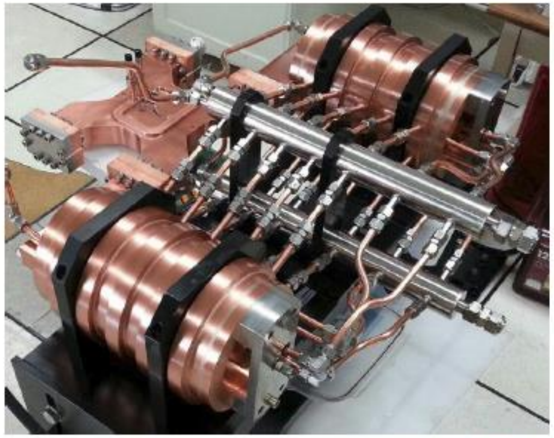

Twisted Type

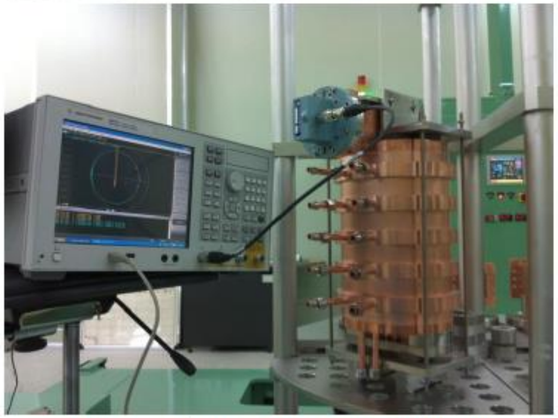

Rounded Type (Cooling)


Straight (Cooling)

3. Main Business Participation (Project Experience)

PAL 4th Generation XFEL – SLED Cavity





RF Inspection by Network Analyzer

- Mechanical Specification

Parameter	Value
Power Divider Length[mm]	380
Vacuum Leak Rate [Pa.m³/sec]	≤1.3E-11

- Electrical Specification

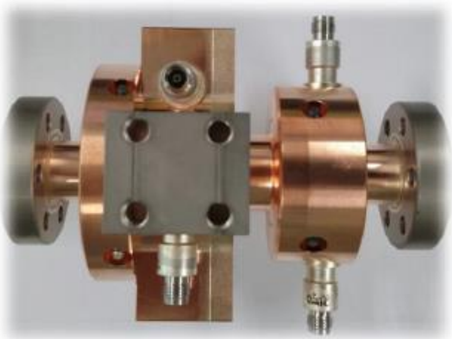
Parameter	Value
Unloaded Q	>95,000
Coupling Coefficient	5.0±0.1
Cavity mode	TE 0,1,5
Operating Freq.[MHz]	2,856
Operating Temp.[°C]	30±0.1
Maximum Peak RF Power[MW]	320
Maximum average RF power[kW]	≤23
Detune	Enable

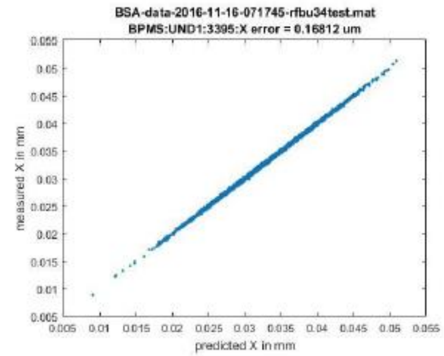
3. Main Business Participation (Project Experience)

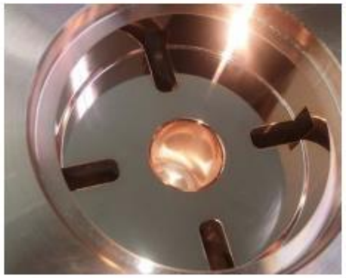
VITZRO TECH

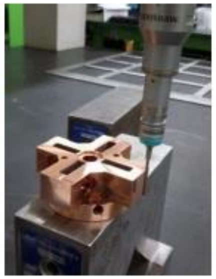
SLAC LCLS-II Project - X-Band Cavity RF BPM

➢ **Vitzrotech manufactured and supplied X-Band RF BPM (Beam Position Monitor) for SLAC LCLS-II with core technologies such as precision machining, precision joining (Brazing), precision assembly and Tuning**









Core Technology

1. RF Analysis, Design (CST)
2. Precision Machining (Mirror surface)
3. Surface Treatment for Ultra High Vacuum Component
4. Ultra Precision Assembly & Brazing (Feedthrough + Cavity Body)
5. RF Test & Tuning

● **Dipole Cavity**

Parameter	Value
Nominal Frequency TM_{110}	11.424 GHz
Tolerance TM_{110}	+- 10 MHz
Q_L or Qtotal	2000~3000
Cavity Coupling [β]	1.9-2.1
Q_0	5800-9300
Q_{ext}	2762-4894
X/Y Cross Talk	< -20 dB

● **Reference Cavity**

Parameter	Value
Nominal Frequency TM_{110}	11.424 GHz
Tolerance TM_{110}	+- 10 MHz
Q_L	2000~3000
Cavity Coupling [β]	1.9-2.1
Q_0	5800-9300
Q_{ext}	2762-4894