Summary Report of FEL Commissioning

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(for Axel Brachmann)

Reports

- Beam commissioning of SACLA BL1 SX FEL driven by a compact dedicated linac
  Takahiro Inagaki, SACLA

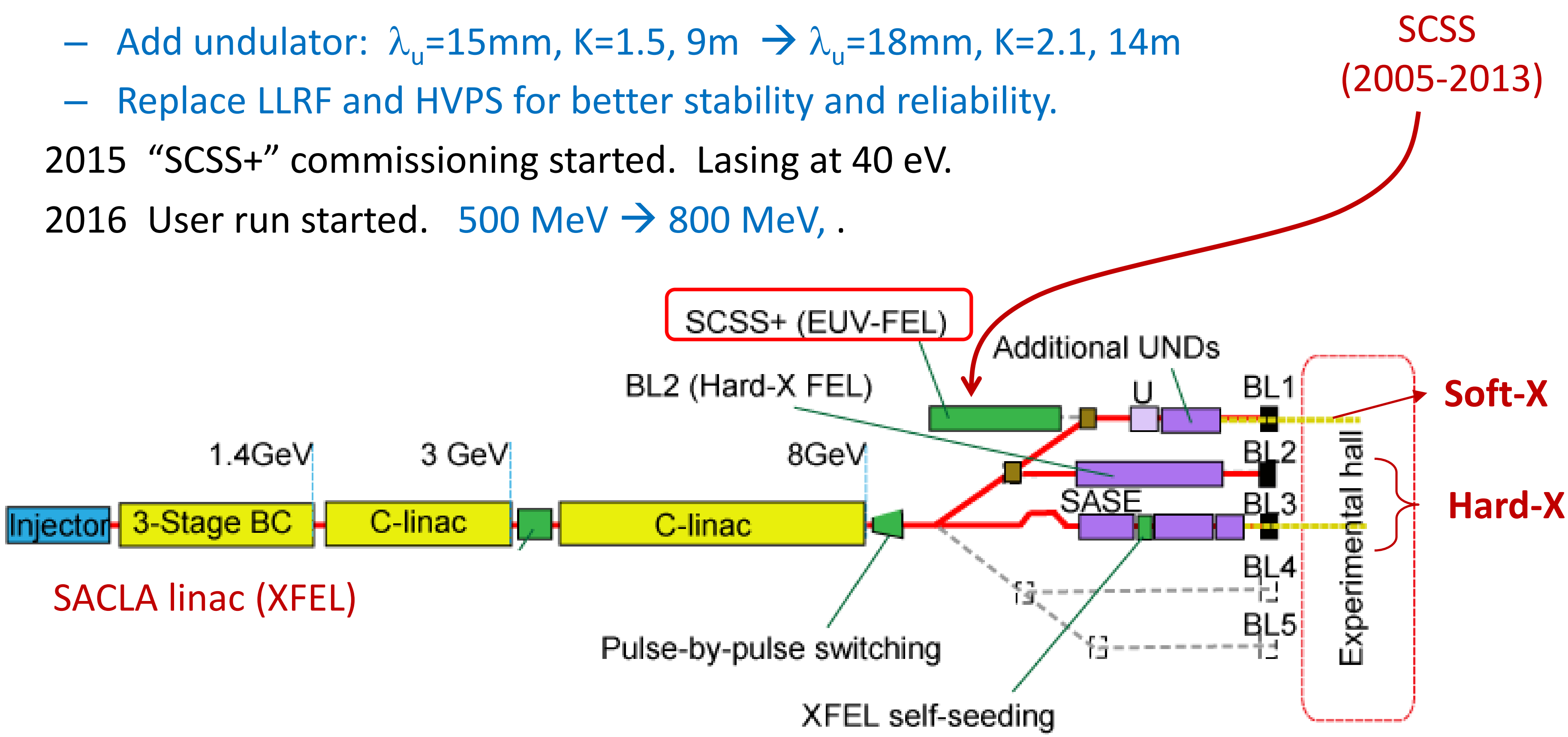
- Commissioning results from European XFEL injector
  Matthias Scholz, European XFEL

- Experience with high power RF sources and RF conditioning
  Florian Loehl, PSI

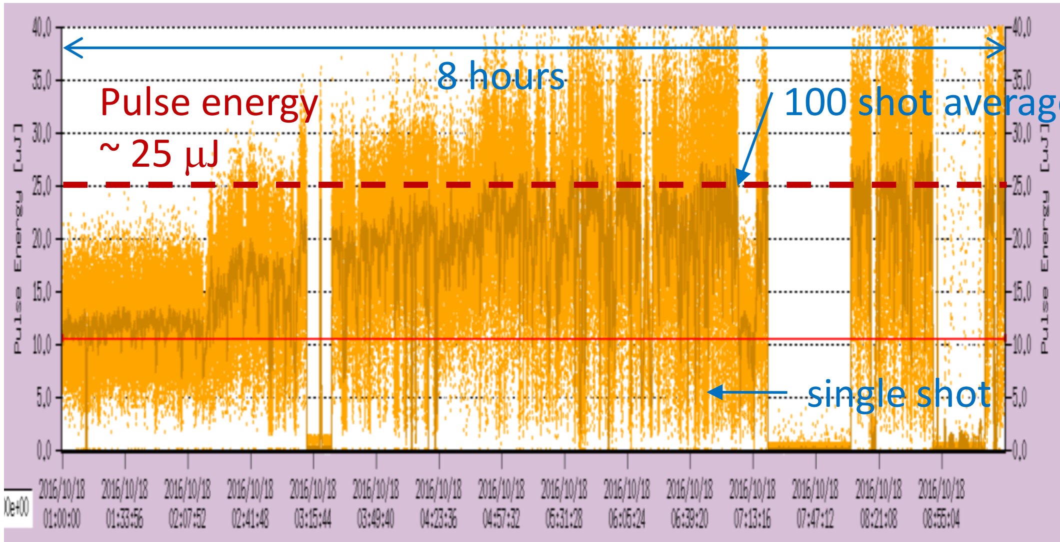
- Undulator BBA & FEL commissioning
  Heung-Sik Kang, PAL

Beam commissioning of SACLA BL1 SX FEL driven by a compact dedicated linac, Takahiro Inagaki, SACLA

- 2005-2013 Prototype accelerator "**SCSS**"
- Move to **SACLA-BL1** and rearranged as "**SCSS+**".
  - Add accelerator: 250 MeV → 500 MeV
  - Add undulator: λ_u=15mm, K=1.5, 9m → λ_u=18mm, K=2.1, 14m
  - Replace LLRF and HVPS for better stability and reliability.
- 2015 "SCSS+" commissioning started. Lasing at 40 eV.
- 2016 User run started. 500 MeV → 800 MeV, .

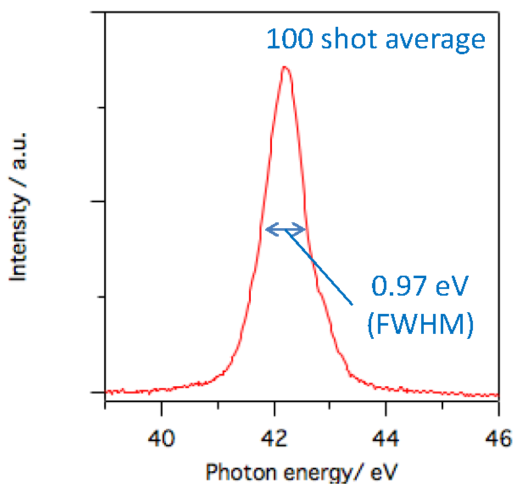


SACLA BL1 SX FEL Now and Future

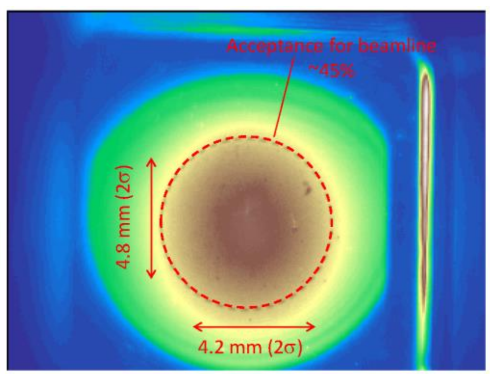


Commissioning was started 09/2015.
User run was started in July 2016.
Intense SASE radiation is obtained in wide energy range.

○ Electron beam energy 350~800 MeV
○ SASE photon energy　20～110eV
△ SASE pulse energy　～25 μJ（50 μJ at the undulator）
△ Shot-by-shot fluctuation　～30%　...not yet reach to SASE saturation.



Spatial profile after front-end slit 42 eV



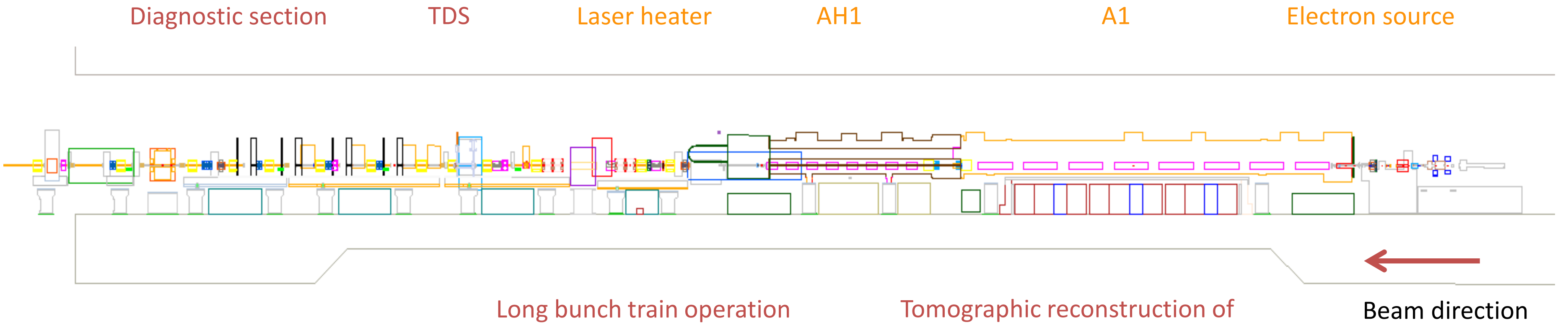
Future plans

Higher peak current, with a harmonic cavity (C-band) at BC1

Add a C-band linac for higher energy (available space up to 1.7 GeV).

Add an undulator segment for more pulse energy.
Seeded FEL, ...

Commissioning results from European XFEL injector, Matthias Scholz



Long bunch train operation

Tomographic reconstruction of horizontal phase space

Emittance measurements and optimizations (projected and slice)

Emittance measurements along bunch trains (projected and slice)

Quantity	TDR	Achieved
Macro pulse repetition rate	10 Hz	10 Hz
RF pulse length (flat top)	650 us	670 us
Bunch repetition frequency within pulse	4.5 MHz	4.5 MHz
Bunch charge	20 pC - 1 nC	20 pC – 1 nC
Slice emittance (about 50 MV/m gradient, 500 pC)	0.6 mm mrad	0.6 mm mrad*
Achieved projected emittance for 500 pC bunches and ~53 MV/m gun gradient		1.2 mm mrad

XFEL injector emittance measurements with four screen method

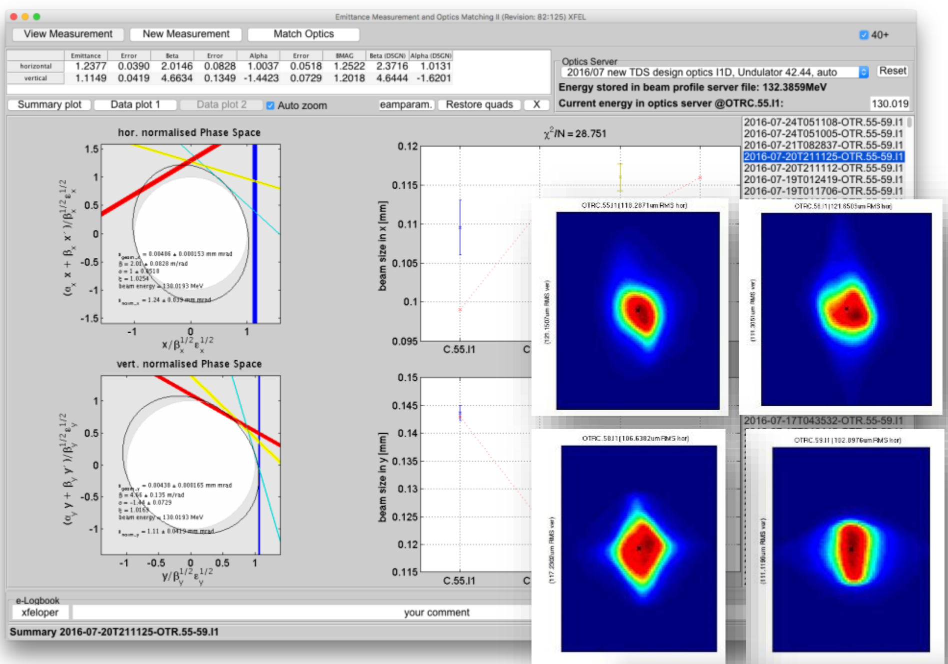
Four screens are moved into the beam trajectory and the beam sizes are measured on each screen.

Well

It is t

We have a highly developed Matlab tool for measurements and matching that is well known by the operators.

Cons: One measurement takes several minutes to move the screen in and out…

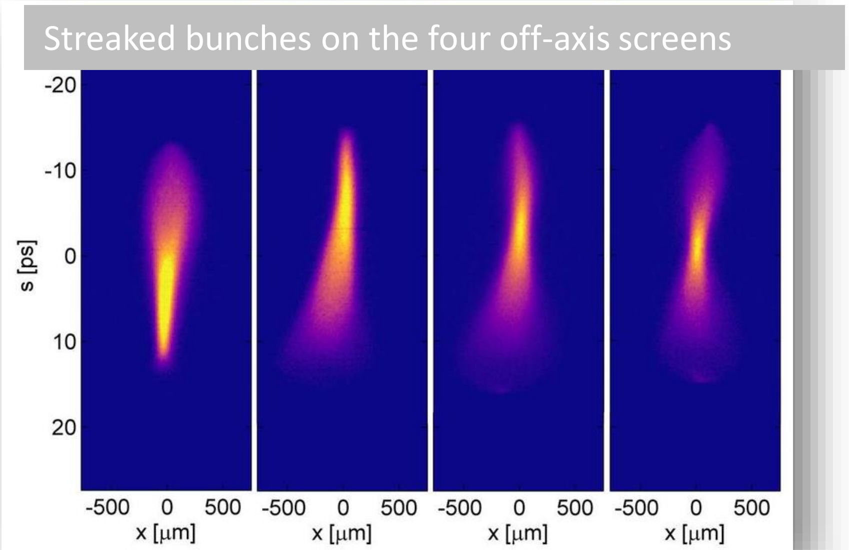


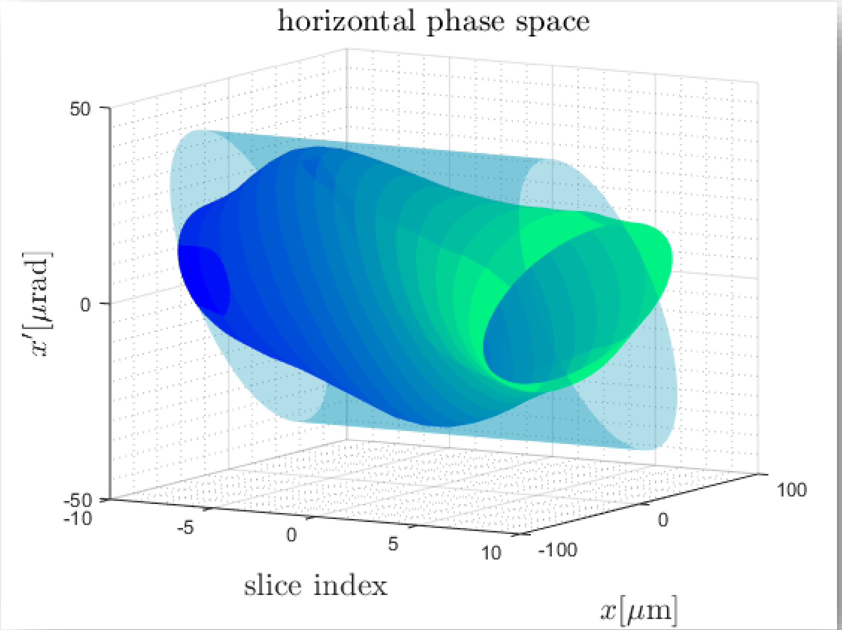
Best results from projected emittance measurements for different bunch charges. These numbers were measured with a gun gradient of 53 MV/m.

Charge	Horizontal	Vertical
50 pC	0.56 mm mrad	0.64 mm mrad
100 pC	0.77 mm mrad	0.83 mm mrad
500 pC	1.28 mm mrad	1.23 mm mrad
1000 pC	2.95 mm mrad	2.81 mm mrad

Most of the time was spend to optimize emittances of the 500 pC case. Thus it is possible that the other results can be improved further in the future.

Slice emittance measurements with four screens





The smallest slice emittances achieved so far using the four screen method (and 500 pC bunches) were:

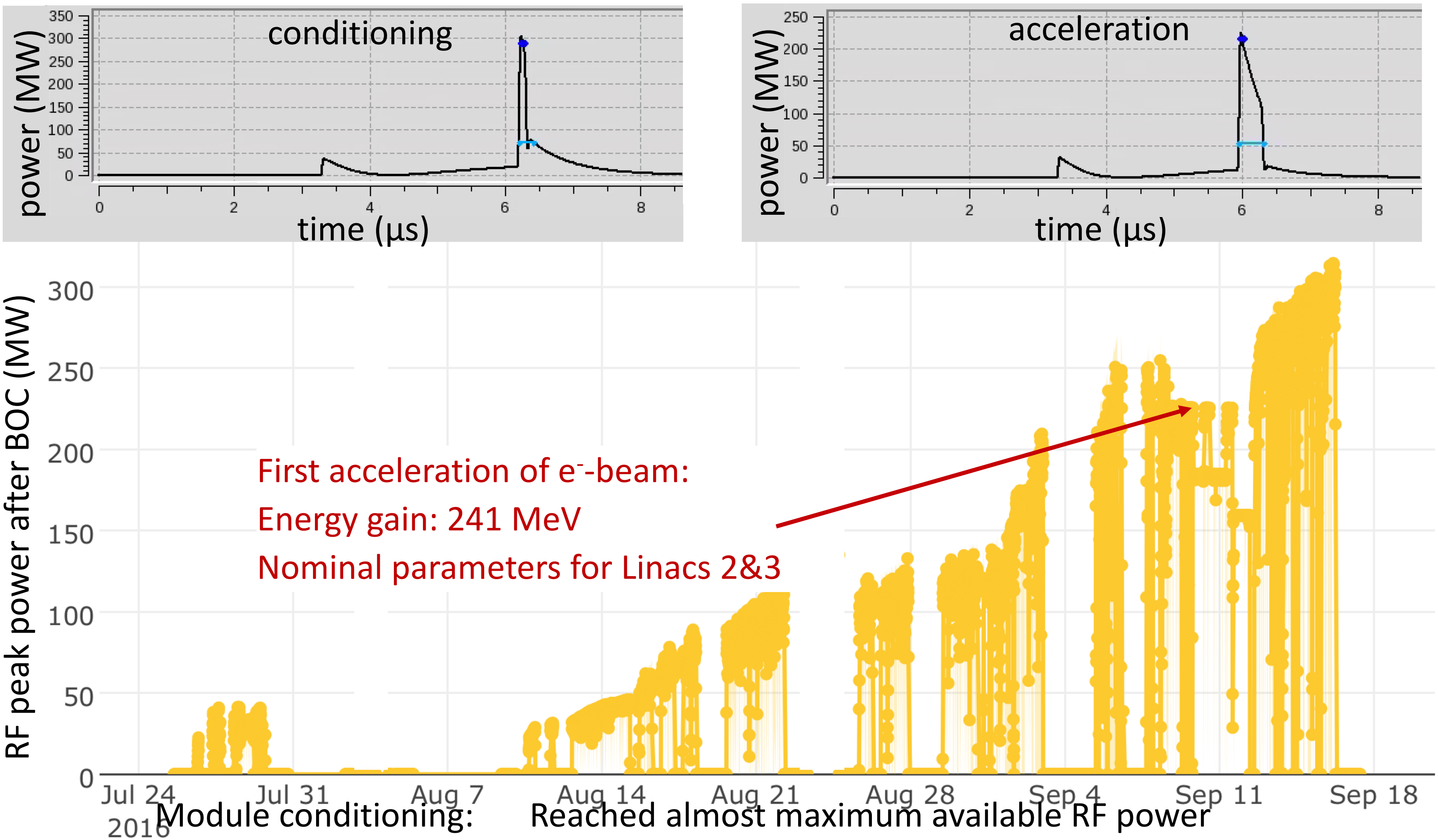
0.6 µm rad with 53 MV/m gun gradient
0.5 µm rad with 60 MV/m gun gradient

Dark blue to green: Phase space ellipses for all bunch slices.
Light blue: Phase space ellipse with design Twiss parameters and normalized emittance of 0.5 mm mrad.

Experience with high power RF sources and RF conditioning, Florian Loehl, PSI

	S-band	C-band	X-band
LLRF	Fully digital LLRF systems (presented at 2014 meeting)		
Drive amplifiers	Solid-state: Microwave Amplifiers	Solid-state: Advantech	Currently TWT amplifier, plan to upgrade to solid-state eventually
Klystrons	Thales TH2100L	Toshiba E37212	SLAC XL5
Modulators	*Solid-state* ScandiNova K2 from test facility	*Solid-state* *Linacs 1&2:* Ampegon Type-µ *Linac 3:* ScandiNova M1071	*Solid-state* ScandiNova K2 from test facility
Waveguides	*SF_6* Mixture: MEGA, PSI, …	*Vacuum* MHI-MS Loads: CML	*Vacuum* CERN, PSI, Nihon Koshuha
Structures	PSI RF gun 1-2 x RI 4m S-band	PSI BOC + 4 x PSI C-band	CERN-PSI-Elettra X-band (2x)

Conditioning of first C-band module



Module conditioning: Reached almost maximum available RF power

(50 MW, 3 µs, full compression)

Overall very good experience, but…

Humidity of transformer oil in modulators

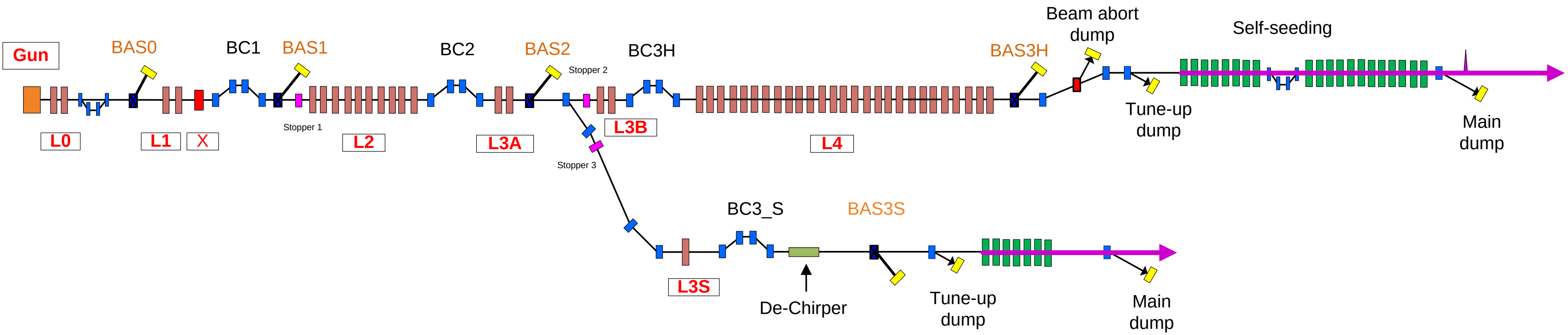
- In one of the modulator types, we saw a quick increase of the oil humidity during operation
- Rate of increase correlates with oil temperature
- Around 2-3 g of water are added into the system per day during operation

PSI evaluated possible sources. Water seems to come out of isolation paper and other plastic material in the transformer.

→ Around 500 g of water can be stored in the transformer when assembled at 50% relative humidity
→ Tested: oil could be dried using a N_2 flow over the oil surface
→ Tested: oil could be dried using a room air flow over the oil surface

Chemical equilibrium between humidity in air cover layer, oil, and plastic material in transformer
→ Need a way to dry the transformers / oil during operation

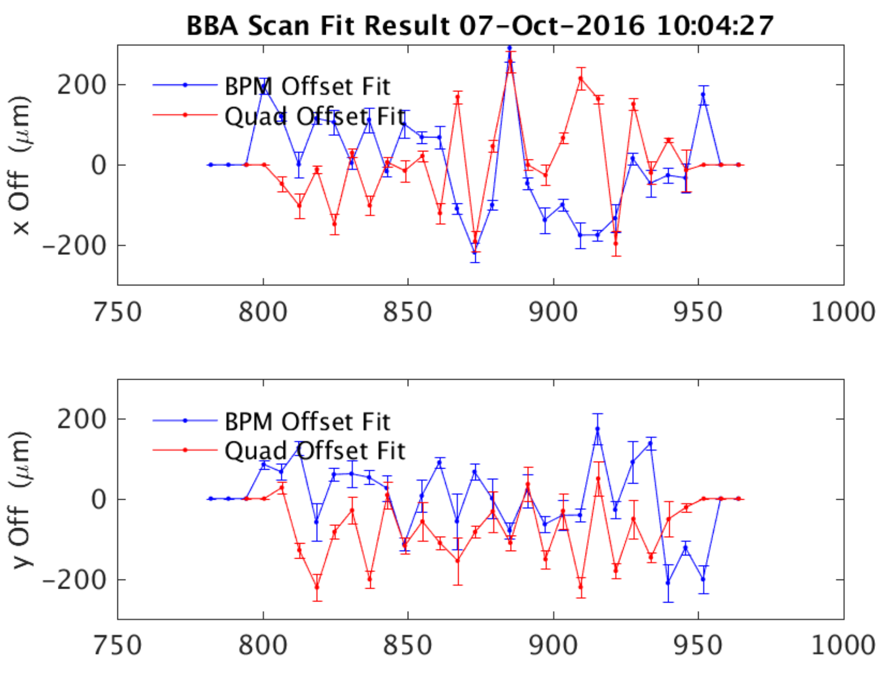
Undulator BBA & FEL commissioning Heung-Sik Kang, PAL



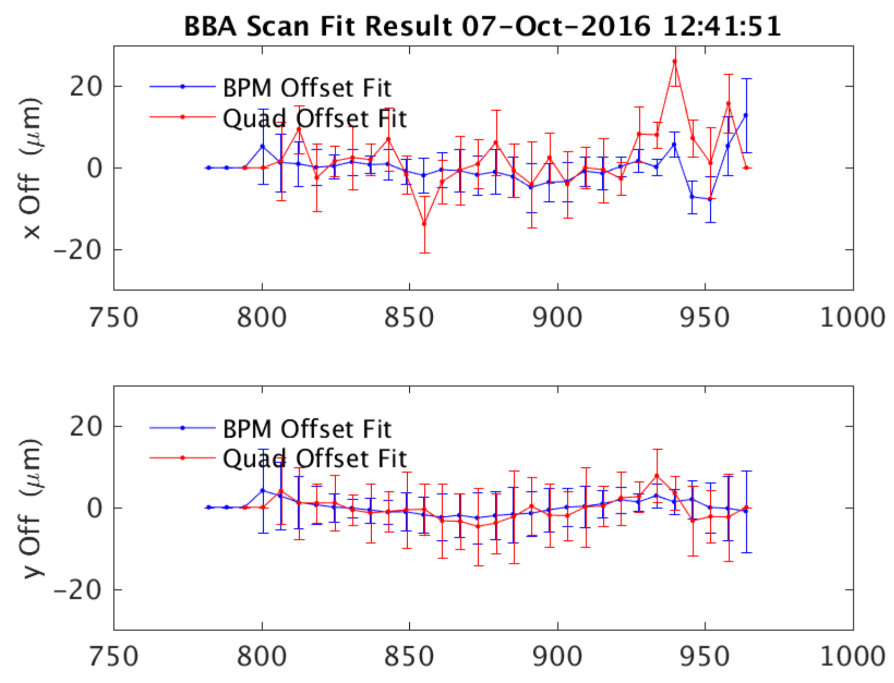
Nov 2015	RF conditioning Started
14 April 2016	Beam commissioning Started
25 April	10 GeV acceleration Achieved
03 June	Dipole edge radiation Observed
12 June	Undulator radiation Observed
14 June	First SASE lasing at 0.5 nm
July	Summer maintenance for 1 month
30 August	SASE lasing at 0.5 nm (재현)
09 September	Beamline commissioning with 0.5 nm FEL is Completed
08 October	Lasing at 0.35 nm
16 October	Lasing at 0.2 nm
?	Lasing at 0.15 nm

Beam Based Alignment for Undulators

1-st step

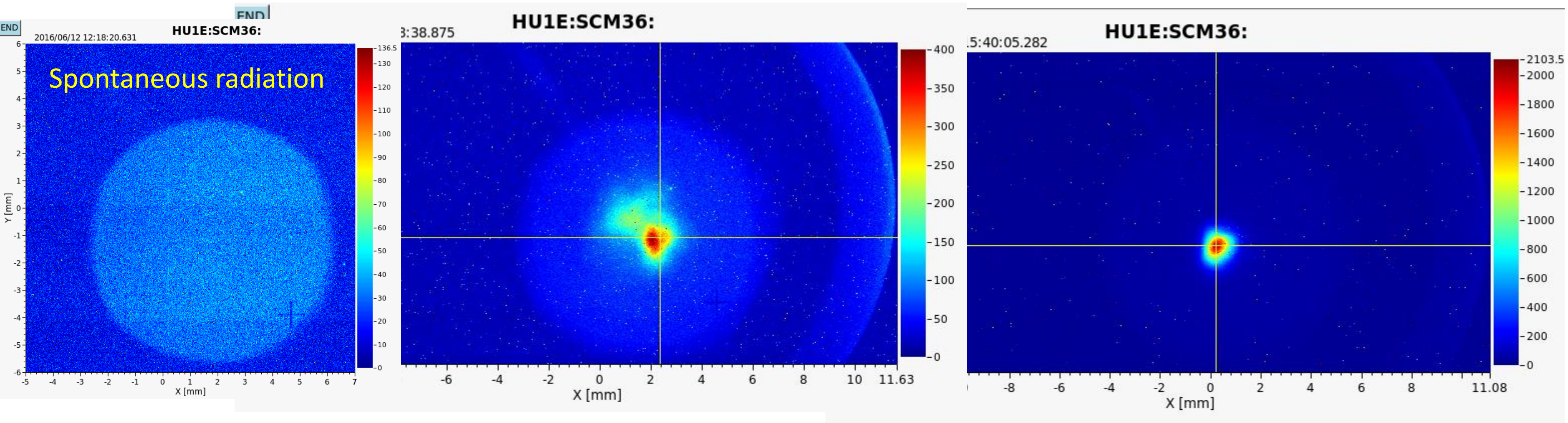


8-th step



First Lasing

0.5 nm on 14 June 2016

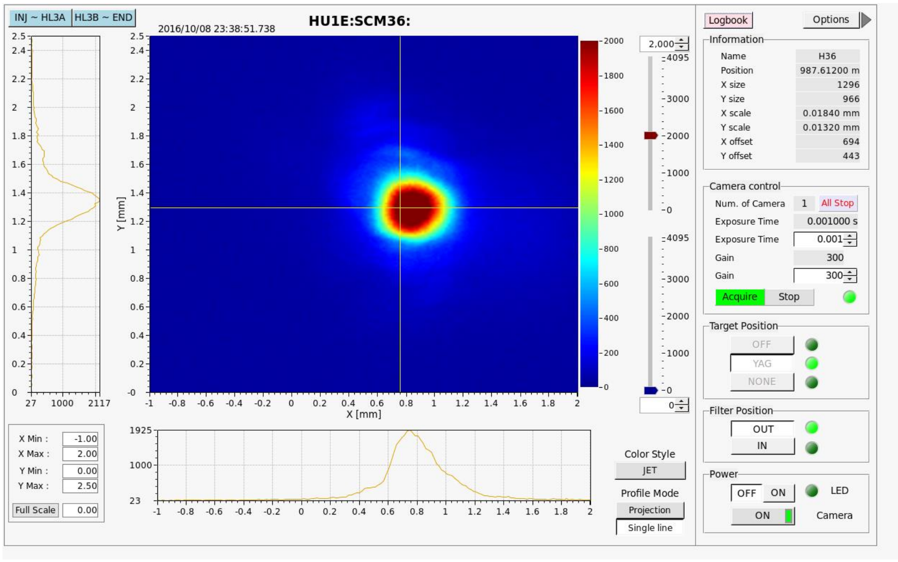


12 June 2016

05:01, 14 June 2016

16 June 2016

0.35 nm FEL (08 Oct. 2016, 2:13 pm)



A lot of work took place

Undulator Optimization

- K-value tuning
- Undulator Field Center
- Phase matching
- Undulator Tapering   (TBD)