Commissioning of the European XFEL Injector

Frank Brinker, DESY for the commissioning team
Commissioning of the European XFEL Injector

The European XFEL Facility

Experimental Hall

Beam Dumps

Photon Beam Lines

Undulators

Electron Beam Distribution

Collimation

Linear Accelerator

Bunch Compressors

Injector
Commissioning of the European XFEL Injector

View into the injector tunnel

1.3GHz gun

1.3GHz cryo module A1

3.9GHz cryo module AH1

Beam dump

Spectrometer dipole

Fast kickers and screen stations

Transverse deflec. structure

Diagnostic section

Laser heater

Beam dump

Spectrometer dipole

Fast kickers and screen stations

Transverse deflec. structure

Diagnostic section

Laser heater
Stepwise commissioning during installation

In order to gain valuable experiences with the different systems at an early stage the commissioning started already end of 2013 with the gun.
After RF operation of the gun in Dec 2013 and Sept. 2014 the UV-laser installation was finished beginning 2015:

**February 10th 2015** First photo electrons from the XFEL Gun!

- 1.3 GHz, 1.5 cells
- $Q_0 \approx 20000$
- Gradient on cathode: 50 – 60 MV/m
- 650 µs pulse length, 10 Hz rep. rate
- Max. average RF Power: 42 kW
- Emittance (1nC): < 0.9 mm mrad
- Cs$_2$Te Cathode

Screen picture of the first photo electrons at XFEL – 3mm Aperture, 20 Bunche, 10 Hz, ca. 2nC
Commissioning of the European XFEL Injector

Operations panel of the laser system (MBI, Berlin)

Here: 30 Laser pulses

Pulse energy

Laser profile before the aperture

and on the virtual cathode
Commissioning of the European XFEL Injector

November 2015: complete Installation is finished with the 3rd harmonic module (INFN)

September 23 2015

November 11 2015
Installation of the XFEL cryo plant finished:

Cold compressor box (Linde)

Distribution box (BINP)
After technical commissioning of the modules: Injector cooldown

- **December 9**
  - Starting cooldown of the injector for the first time.
  - First cooldown of AH1 module at all!

- **December 14**
  - Injector is at 2K

- **December 15**
  - Stable 2 K in the injector with cold compressors.

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**Plotting Data**

- 4.5 K
- 2 K
Cavities were tuned to resonance between December 16. - 18.

- December 18.
  - Rough calibration of all cavity signals
  - All loaded Q were adjusted to 4.6e6 using the automatic Ql adjustment tool.
  - All feedback loops were closed and module was running with nominal amplitude.

Cavity phasing of A1 was achieved January 9, 2016.
≈ 1% of accelerator length
≈ 1% of final energy
≈ 1% of electrons/second
but all accelerator sub-systems needed and functional
Third harmonic module AH1 (INFN, Milano)

18 December 2015:
- First rough calibration
- Nominal pulse structure Fill Time: 750 us
- Flat Top: 650 us
- Gradient well above nominal 30 MV of VS voltage
- First quench > 45 MV

10 February 2016:
- QL aligned well within the 10% requirement
- Phases within 15°

16 February 2016:
- Back on beam
- Moved to -180° (wrt on-crest), calibration with beam energy

For details on SC modules see D.Reschke’s talk on Thursday THYB01 on ‘Performance of Superconducting Cavities for the European XFEL’.
Reduced energy spread

Beam in the dump line with large dispersion

3rd harmonic off 3rd harmonic at -16 MV

1.3 GHz

-0.2 0 0.2 [ns]

1.3 GHz + 3.9 GHz

-0.2 0 0.2 [ns]
Trajectory response measurements show good matching with theoretical predictions.

- The optics model used in the optics server is correct.
- The magnetic fields of the quadrupole magnets are well known.
**Beam Position Monitor Performance (PSI, CEA/IRFU)**

- Newly developed BPM system (DESY/PSI/CEA)
- Performs smoothly and beyond specs
- Single shot resolution:
  - 1-5 µm at 500 pC
  - 10 – 50 µm at 20 pC

### Resolution of the diagnostics

<table>
<thead>
<tr>
<th>Diagnostic Type</th>
<th>Resolution at 20 pC</th>
<th>Resolution at 500 pC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Button BPM</td>
<td>10 µm</td>
<td>5 µm</td>
</tr>
<tr>
<td>Cavity BPM</td>
<td>10 µm</td>
<td>&lt;2 µm</td>
</tr>
<tr>
<td>Re-entrant BPM</td>
<td>50 µm</td>
<td>5 µm</td>
</tr>
<tr>
<td>Toroid</td>
<td>0.3 pC</td>
<td>0.3 pC</td>
</tr>
</tbody>
</table>

### Graphs

**Graph 1**

- Position resolution [µm] for different BPMs at 500 pC.
- Key BPMs: BPMG-24/11, BPMG-25/11.

**Graph 2**

- Position resolution [µm] for different BPMs at 20 pC.
Long Bunch Trains

- 1 to 2700 bunches per train at a 10Hz repetition rate
- 2 W to 3.5 kW beam power at 130MeV and 1nC (10-472kW at 17.5GeV)
- Expected dark current of up to about 30 W at 130MeV and 600 μs

Many bunches make European XFEL unique
Should be established as soon as possible

The machine protection system MPS sets the bunch numbers depending on:
- Status of magnets, screens, valves
- Status of cryogenics and modules
- Losses along the machine (measured with scintillators)
March 19th: Operation of full bunch train at 250 pC!

- Low losses
- Low activation
- Fine tuning of low-level RF Feedback and Feedforward systems to control RF flat top with beam loading
- Adjustment of laser parameters to avoid charge and trajectory variations

Variation of orbit after gun and in dispersive section
Charge stability much better after laser adjustment

See also the talk from K.P.Przygoda on Thursday THOAA03 on “MTCA based cavity regulation”
- Transmission through the injector beamline.

- Charge distribution over the pulse train – corrected with the injector laser power.
The operation of the injector with 2700 bunches did not increase the losses.

- The losses are dark current dominated.

Integrated charge so far is ~1.5 C.
Projected emittances of ~1.2 mm mrad could be achieved with a 500 pC bunch charge.

e.g.

<table>
<thead>
<tr>
<th>Plane</th>
<th>Emittance</th>
<th>BMAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal</td>
<td>1.3 mm mrad</td>
<td>1.16</td>
</tr>
<tr>
<td>vertical</td>
<td>1.1 mm mrad</td>
<td>1.04</td>
</tr>
</tbody>
</table>

The BMAG parameter is a measure for the beta function error.

- A link to the optics server allows the automatic matching of the optic with a chosen set of quads.
- The deformations of the bunch shapes indicate distortions which need further investigations.
Off-axis screens and fast kickers in the diagnostic section allow to measure emittances of single bunches during operation with long bunch trains.

These measurements are fast and allow also to measure the emittance and mismatch evolution over the bunch train.
Evolution of the projected emittance, the mismatch and the beam shape over the bunch train.

Courtesy of B. Beutner
Further automated procedures in operation and development

- Phase scans of Gun and modules
- Charge feedback
- Generic scan tool (QE-Map, dipole scans, gun alignment, …)
- Orbit stabilization
- Dispersion correction
Investigate influence and operation of flat top laser pulses.

- The laser pulse stacker can be used since April 15.
- Max. Pulse length is 26 ps (FWHM) at the moment.
- The reduced space charge effects should lead to a smaller emittance as shown at the test facility PITZ.
- This effect could not be seen yet. We need more time for further studies.

Gain material: Yb:YAG
Intra burst repetition rate: 4.5 MHz, 3 MHz, 1MHz, 100 kHz
Pulse width (FWHM):
  - Phase 1 (MBI): Short pulse: < 3 ps, Long pulse: ~12 ps
  - Phase 2 (DESY): Shaped 26 ps with 2 ps rising edges
Energy per pulse in burst:
  - > 0.7 µJ pP @ 3 ps
  - > 3 µJ pP @ 10 ps

Courtesy of L. Winkelmann, I Hartl
Preliminary results: Bunch length measurements with EOD

A laser passes through a crystal which is placed near to the beam. The electrical bunch field influence the outcoming laser pulse.

Better suited for measurements after the first bunch compressors – in the injector the bunches are too long for a clear signal.

Signal of one bunch

courtesy of C.Gerth, P.Peier, B.Steffen
Next Steps: TDS System (INR, Moscow)

- 3.0 GHz, 3 MW, < 3 µs pulse length
- RF-station is operational
- Structure will be connected these days
- Technical commissioning planned for this month

Beam commissioning:

- Establish procedures for automated measurement of slice parameters within bunch train
To avoid micro bunch instabilities a moderate increase of the energy spread is foreseen by means of a laser heater.

A part of the IR laser which drives the Gun laser is coupled out and will be brought to overlap with the electrons in a wiggler magnet.

- The IR laser is successfully aligned through the laser beamline (~40m) and wiggler vacuum chamber.
- Next steps:
  - Find transverse and longitudinal overlap
  - Investigate laser-beam interaction, find optimal working points
Conclusion & Outlook

Injector commissioning goals:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro pulse repetition rate</td>
<td>10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>RF pulse length (flat top)</td>
<td>600 μs</td>
<td>&gt;600 μs</td>
</tr>
<tr>
<td>Bunch repetition frequency within pulse</td>
<td>4.5 MHz</td>
<td>4.5 MHz</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>20 pC – 1 nC</td>
<td>20 pC – 1 nC</td>
</tr>
<tr>
<td>Slice emittance</td>
<td>0.4 - 1.0 mm mrad</td>
<td>TDS by May</td>
</tr>
</tbody>
</table>

- Full injector commissioning started Dec. 2015 and will continue until end of July ‘16
- Sub-systems operate reliably, often beyond specs
- Minimum goal for emittance reached, sufficient for first lasing at XFEL
- Extensive emittance studies needed to investigate the full potential
- TDS and Laser Heater to be commissioned in May
- “Frequency ramping” of the gun in preparation
Acknowledgements

The started operation of the injector is the result of the tremendous effort of all partners of this project from design, fabrication and testing of the components to installation and commissioning over the last years.

Many thanks to all the colleagues who contributed to this success.
Thank you for your attention!