OVERVIEW OF FELS UNDER CONSTRUCTION INCLUDING FELs AT FERMI ELETTRA, SPRING-8 AND FRASCATI SPARC

Giuseppe Penco*, ELETTRA, Basovizza, Italy

Abstract

This talk will report the present status of the worl-wide FEL projects under construction including FELs at Fermi@Elettra, SPring-8 and Frascati SPARC.

FERMI@ELETTRA FEL STATUS

FERMI@Elettra is an S-band linac-based Free Electron Laser (FEL) implementing High Gain Harmonic Generation (HGHG) in the $4 - 100$ nm output wavelength range [1]. The FERMI accelerator (see fig. 1) is mainly composed by a 100MeV photo-injector, two magnetic chicanes to nominally compress the beam from 10ps to 1 ps(full width) and an S-band linac to accelerate the 800pC-bunch extracted up to 1.5GeV. Moreover the layout foresees an X-band cavity to linearize the longitudinal phase space [2] and a laser heater system to suppress the microbunching instabilites [3]. RF deflecting cavities installed after the first bunch compressor and at the end of the linac have been designed to measure and optimize the beam slice parameters and to characterize the RF sections wakefields effects [4]. The FERMI project is divided in two phases: FEL1 (100-20nm) that will be completed in 2010 and fully commissioned up to the mid of 2011, and FEL2 (20 - 4nm) that will be commissioned in 2011.

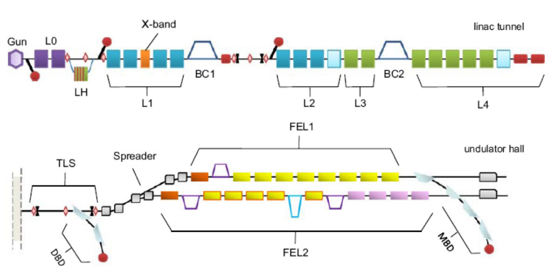

Figure 1: Split schematic of FERMI@Elettra, including the S-band linac, the X-band cavity, the bunch compressors (BC1 and BC2), transfer line (TLS, spreader), FEL lines and beam dumps (DBD,MDB).

The drive laser for the photo-injector is the third harmonic ($\sim$ 260nm) of a Ti:Sa amplifier, with a maximum energy per pulse of about 0.5 mJ. The first electron bunch was extracted in August 2009 by sending a 10ps flat-top laser pulse to the 1.6-cell RF gun cathode. The quantum efficiency (Q.E.) was initially about $3 \cdot 10^{-5}$ but progressively it has been degrading losing more than one order of magnitude after 3 months of operation. From a Q.E. map of the cathode surface it came out that the Q.E. drop is localized in the cathode center where the UV laser is more often driven. During the shut-down between November '09 and February '10 a cleaning procedure has been performed, consisting in venting the RF gun with Ozone gas for few hours and baking out for 2 days. When the beam commissioning started again in February 2010 the Q.E. came back to more than $3 \cdot 10^{-5}$. In the following operation run a Q.E. degradation was observed again but at a very slower rate.
The beam tracking optimization studies performed in the past years [1] called for a 800pC-10ps bunch at the gun exit, with a ramped longitudinal profile, necessary to linearize the strong wakefield effects in the linac section [5]. After having verified the feasibility to shape the laser pulse profile in a proper way to extract the desired ramped current bunch, the machine configuration has been simplified: since the actual linac layout does not include the X-band section and the second bunch compressor (BC2), the beam commissioning main target for the end of 2010 is the optimization of a 250pC-flat top electron bunch ("low charge option"), at an energy of 1.2GeV and compressed from $\sim$5 ps to $\sim$0.5-1ps (full width).
The injector parameters optimization was performed by measuring the Twiss function of the beam after the first two accelerating sections (L0), at about 100MeV through the well known quadrupole scan method (referred to [6] for details on the 100-MeV beam diagnostic station). After minimizing the projected emittance by tuning the RF gun phase and its solenoid, the beam optics is matched with elegant code interfaced to the Tango server through Matlab scripts. The magnets setting is read, matching is computed by the code and finally applied to the machine. The mismatch parameters measured are 1.005 ± 0.003 and 1.001 ± 0.002 respectively for the horizontal and vertical plane. The best projected emittance (100% particles) values obtained are around 0.9 mm mrad [7]. The injector performance is strongly dependent on the laser quality and the cathode surface status: the non uniformity in the extracted charge distribution affects the evolution of the beam emittance at low energy, leading to have a projected emittance in the range 1.2-1.7 mm mrad. The cleaning procedure described above is going to be implemented routinely in the future in order to keep high the photoinjector performance.
The 250pc-bunch was transported to the BC1 spectrometer and accelerated up to 350MeV, with the correct optics, also considering the BC1 dipoles vertical focusing. The mismatch parameters in x and y are respectively 1.030 ± 0.004 and 1.117 ± 0.124. The BC1 chicane angle is variable from 0 to 0.12 rad and the residual trajectory distortion measured is less than 10 μm at the two BPMs downstream of BC1

* giuseppe.penco@elettra.trieste.it

for the whole range. Bend magnets trim coils correct the trajectory to the level of 20 μm, taking into account the magnet-to-magnet differences that could in principle corrupt the achromaticity of the chicane. In June-July 2010 the first magnetic chicane was commissioned [8]: major goals have been achieved in terms of comparison of the machine model with measured quantities. The good machine modeling has translated into an online control of the accelerator as for optics matching, trajectory correction and bunch length compression. A bunch length monitor (BLM) is installed downstream of BC1 [9] . It is based on the detection of the edge radiation coming from the last dipole of BC1 and detected by a pyrodetector, and the diffraction radiation coming from a ceramic gap, that is collected by 3 electromagnetic horns and detected by 3 RF diodes (30-100-300GHz bandwidth). The comparison between the measurements with the theory for gap radiation emission has shown an excellent agreement of the signal vs. linear compression factor and good reproducibility are demonstrated. The projected emittance is degraded after passing through L1. Figure 2 shows the horizontal emittance as function of the L1 RF phase (90deg is on-crest) with BC1 off and at 0.085 rad bending angle, respectively. A large residual dispersion ($\sim$ 25mm) has been measured in the bc1 region and chromatic aberrations could explain the growth with no compression as the energy chirp increases (same in the vertical plane). Further optimization studies are going to be performed. A contribution from coherent synchrotron radiation might be identified in the fast rising of the curves for Compressor factor (CF) >3.2 (phase>20deg). Elegant simulation predict $\sim$15% emittance growth only for CF>10, but the non linearized longitudinal phase space at the entrance of BC1 leads to a 1 kA-current spike at the bunch head for CF>3, that could be the main cause for the projected emittance blow up. Moreover intense fragmented images are detected on the OTR screen (not visible with the YAG screen) downstream of BC1 for CF>3. From the LCLS experience these could be interpreted as COTR signal due by microbunching instabilities, which could be suppressed with the implementation of the Laser Heater. This is already installed and preliminary test of alignment between the laser and the electrons have been already done [7].

The beam has passed through the whole linac even if at a lower energy than the nominal value, reaching the DBD. The plan for September - December 2010 is:

1. Beam transport optimization through the linac, limiting the emittance to less than 1.5 mm mrad;

2. Very accurate trajectory correction to the $\sim$ $10\mu m$ level to transport the bunch through the vacuum chamber and define a reference trajectory for the electron-photon interaction (no undulators installed to avoid damaging the poles) [10];

3. Radiator tuned at 60nm and tuning of the phase shifter to generate SASE radiation;

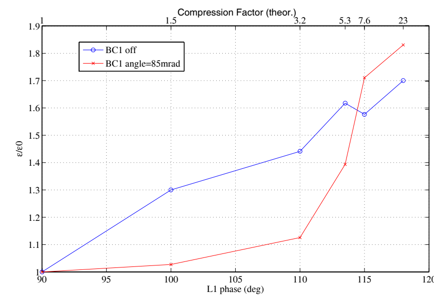

Figure 2: Relative emittance growth in BC1 area, with and without compression. The error on the central values is of the order of 10%

4. Generation and optimization of harmonic generation at 60 nm (seeded signal at 240nm).

In 2011 the second bunch compressor and the forth harmonic X-band cavity will be installed, allowing to have the linac in the nominal condition to optimize the 800pC-bunch and to lase at 20nm according to the HGHG scheme (FEL 1 stage). In parallel the installation of the beam-line and of the undulators for the second stage (FEL 2) will be carried on. In second semester of 2011, the beam is going to be sent in the FEL 2 undulators chains: the goal is to reach output fundamental wavelength at 4.2nm and third harmonic at 1.4nm, by means of the implementation of a double cascades in HGHG mode. The design is also compatible with a change to HHG-seeding at some point in the future if HHG power levels for <50 nm become sufficiently strong (see figure 3).

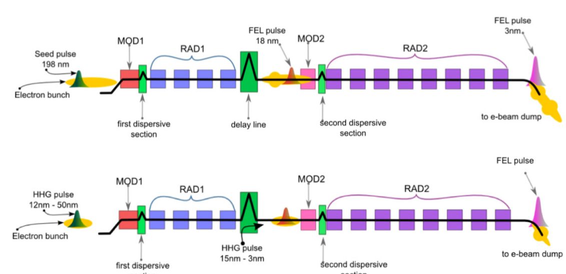

Figure 3: The HGHG scheme for FEL 2 (on the top) and the compatible HHG-seeding scheme (on the bottom) [10]

SPARC PROJECT FEL STATUS

The SPARC project aimed at the realization an FEL driven by a brightness photo-injector [11], with the main objective of studying the FEL dynamics in SASE, seeded and cascaded configurations, and exploring the FEL operation with exotic beams [12, 13]. In the framework of the DS4 EUROFEL collaboration, a research work plan aiming at the investigation of seeded and cascaded FEL configurations was implemented [14]. The main goal was to study and test the amplification and the FEL harmonic generation process of an input seed signal such as higher order harmonics generated both in crystals and in gases. The SPARC FEL can be configured to test several seeded and cascaded FEL configurations and represents the test and training facility for the SPARX FEL project [15] which foresees to provide radiation in the range 10-1 nm. The SPARC Accelerator layout is reported in figure 4.

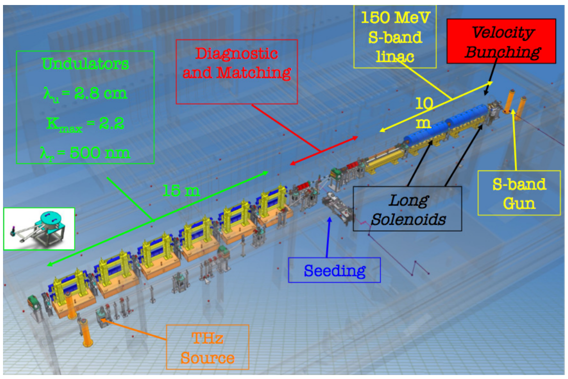

Figure 4: The SPARC Accelerator layout

The electron source consists in a 1.6 cells S-band RF gun (2.856 MHz), followed by 3 S-band traveling wave accelerating structures to boost the beam energy up to 150 MeV. One of the main goals of the SPARC photoinjector is to generate short electron bunches with the velocity bunching technique [16]. The longitudinal phase space rotation in the velocity bunching process is based on a correlated time-velocity chirp in the electron bunch, so that electrons on the tail of the bunch are faster than electrons in the bunch head. This rotation occurs inside the longitudinal potential of a traveling RF wave (longitudinal focusing), which accelerates the beam inside a long multi-cell RF structure an simultaneously applies an off-crest energy chirp to the injected beam. To keep the space charge effects under control when the bunch is compressed, the first two S-band traveling wave accelerating structures, downstream of the 1.6-cell S-band RF gun, are embedded in long solenoids. An RF deflecting cavity placed at the exit of the third accelerating structure allows bunch length and slice emittance measurements [17]. When the downstream dipole is switched on a direct measurement of the longitudinal trace space is also possible. Four beam lines have been built downstream the photo-injector for different experiments: SASE and seed FEL experiments [12, 18, 19]; a bypass line with a magnetic chicane for diagnostics and magnetic compression experiments and another two lines for ICS (Inverse Compton Scattering) and plasma acceleration by external injection experiments [20].

The SPARC commissioning initiated in autumn 2008 and the beam compression via velocity bunching with emittance compensation was demonstrated in April 2009 [16, 21]. The first SASE FEL signal was observed in February 2009 and in July 2009 a significant increase of the extracted radiation was obtained thanks to the higher bunch charge and peak current available [13]. Full saturation at the nominal wavelength of 500nm has been achieved in 2010 by combining the beam obtained in velocity bunching compression mode, with a proper undulator taper ensuring a compensation of the correlated beam energy spread residual from the compression process [18]. In this mode of operation, which was previously studied in [22], the generation of single spike SASE FEL pulses has been demonstrated. In Fig. 5 a single shot SASE spectrum where the typical spikes are not visible is shown. The horizontal axis represents a wavelength range of 45 nm centered at 540nm, the vertical axis corresponds to the vertical position at the spectrometer entrance slit. The SPARC operation in seeded mode has been tested both at high seed energy, with a seed signal constituted by the second harmonic of a Ti:Sa laser generated in a BBO crystal ([18]) and with higher order harmonics of the same laser, generated in a gas cell [19]. In the first case, the seed signal at 400nm has been doubled in frequency in a FEL cascade. Saturation in the radiator tuned at 200nm has been reached and radiation pulses at 66nm, the third harmonic of the radiator, have been detected. In Fig. 6 an example of a single shot spectrum of the third harmonic is shown. The wavelength range represented is 11.6nm centered at 66nm, the vertical axis represents the position on the vertical slit as in Fig. refsase540nm. At 66nm an average pulse energy of about 30nJ was obtained with a beam energy of 176MeV and a peak current of 50A.

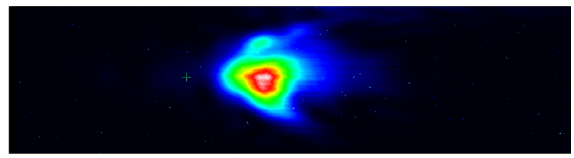

Figure 5: Single shot SASE spectrum centered at 540nm

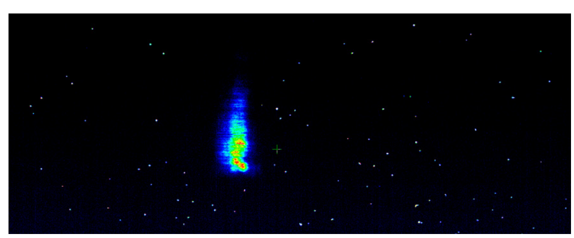

Figure 6: Single shot of the third harmonic (66nm)

X-RAY SASE-FEL AT SPRING-8

The SPring-8 Compact SASE Source (SCSS) project was started in 2001 [23]. Figure 7 shows a view of the present status of the SCCS project under construction. The total system length results "compact" thanks to the in-vacuum short period undulator (18mm), that requires a beam energy of 8GeV to obtain 0.1nm radiation. Moreover the choice of using normal conducting accelerating section at C-band frequency (5712 MHz), originally developed at KEK, allows to reach high gradient acceleration capability (35MV/m for multi-bunch operation and 40MV/m for single bunch operation) with low cost and short production time. Owing to the high peak power of the XFEL radiation and short pulse duration, the repetition rate of 60Hz is acceptable for most of the scientific cases.

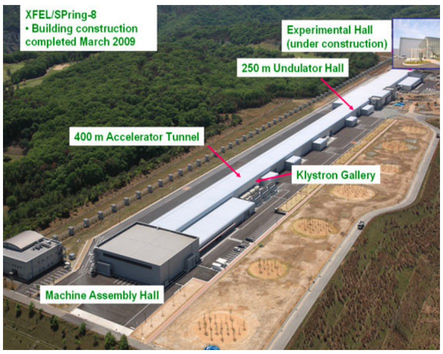

Figure 7: XFEL project at SPring-8 construction status

SCSS Test Accelerator

In order to test the performance of developed technologies, expecially the low emittance electron injector a prototype accelerator for XFEL was constructed in 2004-2005. It consists of the electron gun and injector system, four C-band sections and two in-vacuum undulators (period of 15mm). 1 Amp electron beam is generated from a CeB6 single crystal thermionic cathode [24] operating at 1500 degree C and having a diameter of 3mm. The theoretical thermal emittance at the cathode is about 0.4π mm mrad [23] and to minimize the emittance growth due to space-charge, the electron source is mounted on the 500kV pulsed-voltage gun. The emittance was measured at the gun exit by the double-slit method [25] providing 1.1 or 0.6 π mm mrad respectively including tail component or considering the net emittance core for 1A beam current. To

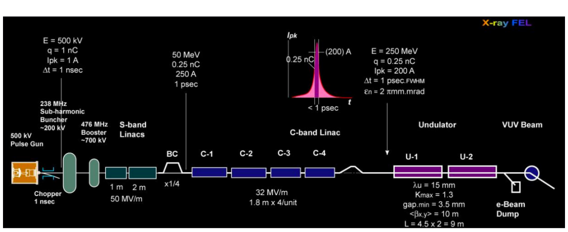

Figure 8: SCCS test accelerator schematic view

form a 1ns single-bunch from the long pulse generated by the gun, a fast-pulsed beam deflector was used. This system is consequently free from cathode-dark-current. The electron beam is compressed by means of velocity bunching system and bunch compressor to enhance the peak current up to 300A. The 250pC-bunch is then accelerated by the C-band linac up to 250MeV and transported into two undulators, which generate SASE radiation in the range of 30-60nm [26]. In 2006 there was the first lasing at 49nm, while in 2007 the XFEL/SPring-8 team succeeded in fully saturate at 60nm. Measuring the bunch temporal distribution and assuming a slice energy spread of 0.05%, the FEL gain curve has been fitted with simulation output data obtained starting from several bunch emittance values: an emittance of 0.7 π mm mrad excellently reproduces the experimental results and it satisfies the beam requirements for the XFEL SCCS injector. User operations have been carrying on since 2008. The electron source has been in operation for 20000 hours before suddenly degradation, showing a very long lifetime and very high reliability.

A beam arriving time jitter of 46 fs at the entrance of undulator was measured. This is a surprising result considering the long pulse generated from the thermionic gun and the high total compressor factor along the linac. The optical pulse length of FEL beam was experimentally determined by means of correlations measurement using multi-photon ionization of He-gas. Typical operation condition, FWHM width of 30 fs was observed.

XFEL/SPring-8 Machine Status

Figure 9 shows the machine configuration and simulated beam evolution along with multi-stage bunch-compressions.

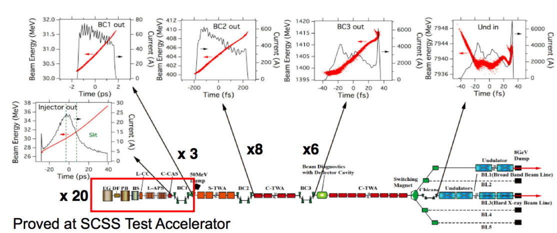

Figure 9: XFEL/SPring-8 machine configuration

The injector part of the XFEL/SPring-8 machine is similar to the test accelerator and was excellently proved. It consists in the thermionic cathode generating 1A and 3μs pulse beam at 500kV, followed by a fast-deflector to select 1ns bunch. Then the bunching system is composed by a sub-harmonic cavity at 238MHz, a buncher cavity at 476MHz to boost the beam up to 1MeV and a L-band cavity (1428MHz) to capture the bunch and accelerate it to 30MeV. At this point the bunch is compressed by a factor 20. A magnetic chicane compresses the beam by a factor 3 (I_{peak} = 60A) and then four S-band units (8 cavities at 17MV/m) push the beam energy to 415MeV. A second magnetic chicane compresses the beam by a factor 8 and through 12 C-band units (24 cavities at 35MV/m) the beam energy reaches 1450MeV. Another magnetic chicane compresses further the bunch length by a factor 6, leading the total compression factor to 3000 and the peak current at 3kA. At this point to investigate the longitudinal profile and characterize the slice beam parameters an RF deflecting cavity (C-band) is currently being developed. Then the beam is accelerated by 52 C-band units (104 cavities) to reach 8GeV. To prevent that the dark current emitted in the C-band accelerator could irradiate the undulator magnets, special magnetic chicane were prepared right before the undulator line.

The accelerator and undulator building constructions were completed in March 2009. It took three years to complete the mass production of 64 klystrons and rf pulse compressors, and 128 accelerating structures: it was finished in February 2010. The main accelerator components have been installed in the 400m-tunnel and compact modulators and control racks in the klystron gallery [27]. Precision temperature feedbacks on the accelerating sections and rf-pulse compressors have been required by the operation at such high accelerating gradients [28]. Moreover the high stability of the accelerating field, especially before the bunch compressors, have required to install the LLRF system in special racks with fine temperature control. In order to keep the peak current stability jitter lower than a few %, the voltage stability of the RF section in the injector has to be better than 0.01% and the RF phase better than 0.1 degree [29]. To guarantee this performance high-power inverter-tyoe power supply with precision of $< 0.01\%$ level of pulse-to-pulse stability have been developed.

The undulator line consists of 18 series of 5m long in-vacuum undulators with variable gap from 2mm to 40mm, while the nominal one is 4mm (K=1.9) [REF: linac conf paper]. The in-vacuum undulator design guarantees the ideal heat isolation from the environmental temperature change, allowing a good temperature stabilty of the permament magnets. Moreover opening the gap at 40mm allows sending a laser beam for alignment of the cavity BPMs.

High power processing of the accelerating structure and debugging the control system are going to start in October 2010, while the commissioning with beam is scheduled in March 2011.

REFERENCES

[1] "Conceptual Design Report" for the FERMI@Elettra project (2007).

[2] P .Emma, LCLS-TN-01-1, November 14,2001.

[3] Z. Huang et al., Phys. Rev. ST Accel. Beams 13, 020703 (2010).

[4] P. Craievich at al., Proc. of the DIPAC 2007 conference.

[5] M.Cornacchia et al., Phys. Rev. ST Accel. Beams 9, 120701 (2006).

[6] G. Penco et al., Proc. of EPAC 2008 Conf., Italy

[7] G. Penco et al., Proc. of IPAC 2010, TUOARA02, Kyoto, Japan.

[8] S. Di Mitri et al., Proc. of the FEL 2010 Conf., Malmö, Sweden.

[9] M. Veronese et al., Proc of the FEL 2010 Conf., Malmö, Sweden.

[10] E. Allaria et al., Proc of FEL 2009 conference, Liverpool, UK.

[11] D. Alesini et al., Nucl. Instrum. Methods Phys. Res., Sect. A 507, 345 (2003).

[12] L. Giannessi et al. Nuclear Instruments and Methods in Physics Research Section A, Vol. 593, Issue 1-2, p. 132-136.

[13] M. Ferrario et al., "Recent results of the SPARC FEL experiments", Proc. of the FEL 2009 conference, Liverpool, UK.

[14] L. Poletto et al., EUROFEL-Report-2005-DS4-008 (2005), https://www.eurofel.org/e693/e1009/

[15] L. Palumbo et al., "Status of SPARX Project", Proc. of the FEL 2009 conference, Gyeongju,Korea.

[16] M. Ferrario et al., Phys. Rev. Lett. 104, 054801 (2010).

[17] D. Alesini et al., Proc of DIPAC 2009, Basel, Switzerland.

[18] L. Giannessi et al.,"FEL EXPERIMENTS AT SPARC: OPERATION IN SEEDED AND CHIRPED MODE", Proc. of the FEL 2010 conference, Malmö, Sweden.

[19] L. Giannessi et al.,"FEL EXPERIMENTS AT SPARC: SEEDING WITH HARMONICS GENERATED IN GAS", Proc. of the FEL 2010 conference, Malmö, Sweden.

[20] A.Bacci et al., Nuclear Instruments and Methods in Physics Research Section A, Vol. 608, Issue 1, Supplement 1, Pages S90-S93, 2009.

[21] D. Filippetto et al., "Velocity bunching experiment at SPARC", Proc. of the FEL 2009 conference, Liverpool, UK.

[22] E. L. Saldin, E. A. Schneidmiller, and M.V. Yurkov, PRST-AB 9, 050702 (2006)

[23] T. Shintake and XFEL/SPring-8 Joint Team, "Status report on Japanese XFEL construction project at SPring-8", Proc. of the IPAC 2010, Japan.

[24] K.Togawa et al., Phys. Rev. ST Accel. Beams 10, 020703 (2007).

[25] C. Lejeune and J. Aubert, in Applied Charged Particle Optics, edited by A. Septier, Advances in Electronics and Electron Physics Supplement 13A (Academic Press, San Diego, 1980), pp. 159 259.

[26] T. Shintake et al., Nature Photonics, Vol. 2, Sept. 2008, pp. 555-559.

[27] T.Shintake et al., "Compact Klystron modulator for XFEL/SPring-8", Proc. of the IPAC 2010, Japan.

[28] T. Hasegawa et al., "Status of precision temperature regulation system for C-band accelerator in XFEL/SPring-8", Proc. of the IPAC 2010, Japan.

[29] H.Hanaki et al., "Construction of Injector System for SPring-8 X-FEL",Proc. of this conference.