250 MeV INJECTOR FACILITY FOR THE SwissFEL PROJECT

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Abstract

The X-ray FEL project at PSI, SwissFEL [1], involves the development of an injector complex that enables operation of a SASE FEL at 0.1-7 nm with permanent-magnet undulator technology and minimum beam energy, i.e., a cost-effective way to obtain laser-like radiation in the X-ray spectral region. In order to extensively study the generation, transport and time compression of high brightness beams and to support the component developments necessary for the XFEL project, PSI is presently constructing a flexible 250 MeV injector test facility.

In this paper we review the overall accelerator facility with its main components and present the expected beam performances.

INJECTOR MISSION

Generally the injector test facility must serve two main purposes. First, it provides a tool to verify experimentally the performance predicted by the simulation codes and to demonstrate the feasibility of a compact Free Electron Laser, and second it's the optimal platform to develop and test the different components/systems and optimization procedures necessary to operate the SwissFEL accelerator.

The scientific objectives of the injector facility can be generally summarized in term of beam performances, component functionality, machine stability and reliability. The primary objective of the installation is to explore the generation of high brightness beams according to the requirements of SwissFEL (Table 1). The feasibility of a compact XFEL has been analyzed via start-to-end beam dynamic simulations [2-4] including the FEL undulator lines [5, 6]. To establish a robust baseline concept the injector has been designed [7] starting from the experience cumulated with advanced RF photo cathodes similar to the LCLS photo-cathode source [8], keeping the option to integrate later the innovative Low Emittance Gun (LEG) presently under investigation at PSI [9]. Particularly challenging is the extremely low transverse emittance necessary to guarantee the electron beam transverse coherence during the lasing process at 0.1 nm.

Table 1: SwissFEL Electron Beam Parameter Range

Operating mode parameters	unit	High Charge	Low Charge
Beam Energy	GeV	5.8	5.8
Single Bunch Charge	pC	200	10
Core-Slice Emittance	mm.mrad	0.43	0.18
Slice rms E-spread	MeV	0.35	0.25
Peak Current	kA	2.7	0.7
Projected Emittance	mm.mrad	0.65	0.25
rms Bunch Length	fs	31	6.2
Compression Factor	-	125	240
Repetition Rate	Hz	100	100

ACCELERATOR LAYOUT

General Layout

The overview of the facility is shown in Figure 1. In the low energy region enough space has been reserved in the tunnel to accommodate alternative electron source configurations while at high energy a 16 m diagnostic line will be used for projected and slice parameter characterization.

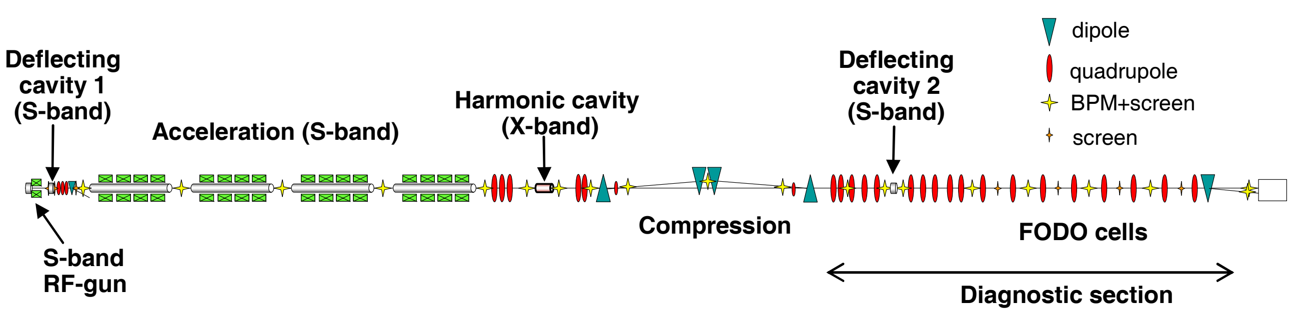

Figure 1: Schematic of the 250 MeV injector test facility.

The first installed electron source will be an S-band RF photo injector, previously developed at CERN within the CTF program [10,11]. This source should provide a projected emittance below 0.4 mm.mrad at 200 pC. The gun will be driven by an advanced Ti-Sapphire laser system specially developed for this project and presently being commissioned [12]. The main characteristics of the laser driver system are a large wavelength tunability from 253 nm up to 300 nm to control the cathode intrinsic emittance, and longitudinal laser pulse manipulation integrally in the UV with prism based stretching and a UV Dazzler.

Four S-band normal conducting travelling wave cavities will boost the energy up to maximum 350 MeV on crest and provide the necessary energy chirp for the magnetic compression, while a fourth harmonic X-band cavity will be used to linearize the longitudinal phase space distribution in front of the magnetic compression chicane.

A solenoid magnet placed at the gun exit provides the matching condition at the entrance of the first S-band travelling wave cavity satisfying the invariant envelope conditions for emittance compensation [13,14]. Further solenoids surround each S-band travelling wave structure to provide additional focusing and Twiss parameter control.

The 10.5 m long bunch compressor consists of four dipoles and two quadrupoles for dispersion correction. The designed R_{56} and bending angles are typically 46.8 mm and 4.1 deg respectively. The central dipoles are nevertheless transversally adjustable to guarantee enough flexibility for the compressor studies.

The diagnostic line following the bunch compressor chicane will be used for measuring the projected and slice emittance and energy spread. The optic, consisting of matching section plus FODO cells, has been optimized in order to allow measurements of the slice and projected parameters using the same magnet settings. A more detailed description of this section can be found in [15,16]

Accelerating Structures

To establish a robust baseline concept for SwissFEL we decided first to concentrate our investigations on an electron source concept based on state of the art RF photo injectors, benefiting from the progress accumulated over the last two decades. Particularly encouraging in this field are the recent results achieved at LCLS [18] which comply with the specification of SwissFEL. The CTF RF-gun is a 2.6 cells RF photo injector that will be used until completion of the development of a new source with better performance and suited for high repetition rates.

Table 2: Basic Cavity Characteristics (Filling Time, Gradient or Deflecting Voltage for Given RF Power)

structure	**Type**	**μs**	**MV/m**	**MW**
RF- Gun	2.6 cells	0.8	100	21
S-band Booster	TW 2π/3	955	22	44.2
X-band	TW 5π/6	0.1	40	29
	Type	**μs**	**MV**	**MW**
Deflector 1	SW-1 cell	0.8	0.150	0.025
Deflector 2	SW-5 cells	0.8	4.9	5

The booster linac is composed of 4 S-band structures, each 4 m long, designed by PSI [19] and manufactured in collaboration with the company Research Instruments (formerly ACCEL). An elliptical shape of the iris has

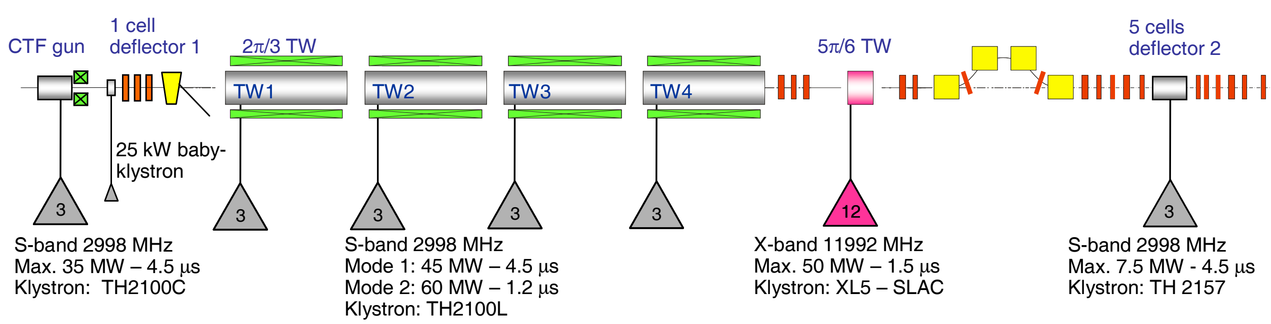

Figure 2: RF systems of the 250 MeV Injector test facility at PSI.

RF Systems

A general overview of the RF system is given in Figure 2. To avoid cross talk and increase the flexibility of the system each cavity is independently powered by a high power klystron amplifier. Each klystron will be powered by a high-voltage solid-state pulsed modulator manufactured by the company SCANDINOVA [17]. This modulator consists of a set of 1.5 kV IGBT switch modules operated in parallel on a multi core pulse transformer. This technology synthesizes reliability, flexibility and compactness. The water cooling of the modulator components ensures minimum heat dissipation in the air. In particular the pulse length can easily be remotely adjusted allowing different operation modes of the klystron amplifiers. The suppression of high voltage thyratron switches should sensibly decrease the operation costs of the machine.

been adopted to minimize the surface electric field and a two-port race track geometry of the input and output coupler will minimize the kicks due to the dipole and quadrupole components of the electric field.

The design and manufacture of the 12 GHz harmonic cavity is a joint effort between CERN and PSI. Recently ELETTRA decided to join this collaboration as the specifications meet the requirements for the harmonic system at FERMI [20]. The cavity is a modified SLAC H75 structure [21] placed in front of the compression chicane for linearization of the longitudinal phase space. Due to the stringent alignment tolerances two HOM BPMs have been integrated to allow a Beam Based Alignment of the structure [22]. In order to characterize the slice parameters of the beam two S-band deflecting cavities are implemented directly after the RF-gun at ~7 MeV and in front of the diagnostic line at 250 MeV respectively. The typical longitudinal resolutions expected for those systems are 47 fs and 11 fs respectively. Both cavities are manufactured in collaboration with LNF-INFN in Frascati. The 5 cell deflector at 250 MeV is a slightly modified version of the deflector developed for Fermi at ELETTRA [23]

RF Low Level Electronics

The Low Level RF Electronics concept is based on down converting any RF signals (3, 12 GHz) to a common intermediate frequency of 46.84 MHz which is the 64th sub-harmonic of 3 GHz. These signals are digitized by 16 bit ADCs sampling with 125 MHz (24th sub-harmonic of 3 GHz). On state-of-the-art FPGA platforms (Xilinx Virtex5) the in-phase and quadrature-phase components of the RF vectors are extracted by non-IQ sampling [24]. For the nominal operation SwissFEL requires very tight RF amplitude and phase stabilities of 0.01% and 0.01 deg (S-band), respectively [2].

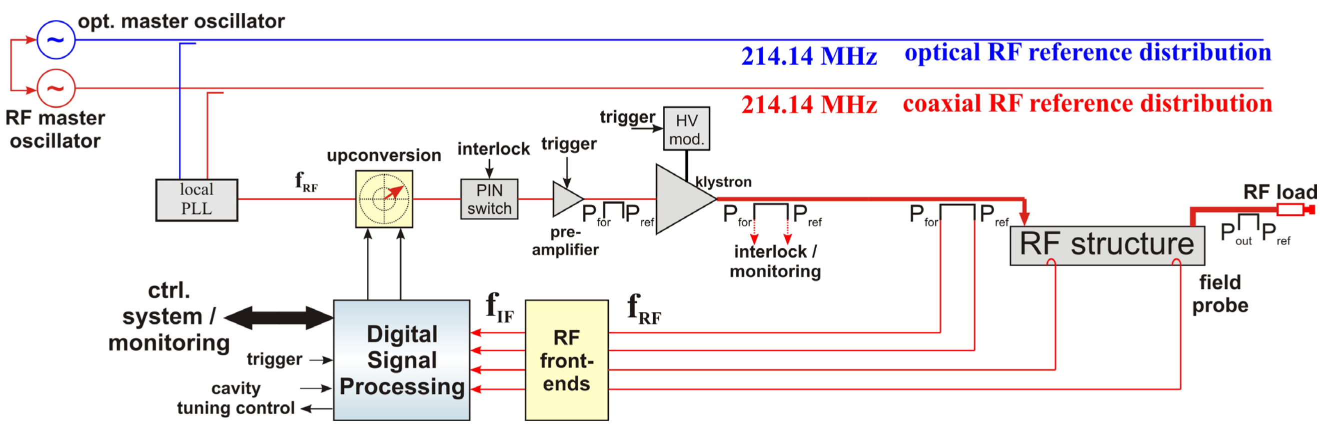

Figure 3: Generic LLRF system for all 3/12 GHz RF stations.

To fulfil these requirements, digital pulse to pulse feedbacks and adaptive feed forward systems to compensate repetitive systematic distortions will maintain the amplitude and phase stability of the individual RF cavities. Vector modulators will control the drive signal to the high power klystrons. The I/Q input signals of the vector modulators are generated by 16 bit DACs driven by the same 125 MHz clock as the ADCs. A generic schematic of the LLRF system for the 3 and 12 GHz RF stations is shown in Figure 3.

All local oscillator, ADC and DAC clock signals are derived from the 3 and 12 GHz reference signals which are generated locally at each RF station by PLL systems locked to the distributed reference signal of 214 MHz. The pulse to pulse RF stability will mainly be determined by the high voltage pulse to pulse stability of the modulators which has to be in the order of 10^{-5}. Although PFN based modulators have already reached this stability [25] the applied solid state based modulators still have to demonstrate this performance.

A temperature stabilized LLRF distribution system and an optical synchronization system will be installed in parallel. While the more robust RF-based system will guarantee machine operation with sub-50 fs peak to peak stability, the more sophisticated optical timing distribution will be developed during test injector operation aiming for sub-10 fs timing jitter [26].

Diagnostics

The injector test facility will allow the development of instrumentation, which is capable of measuring the stringent beam parameters of SwissFEL. The standard beam position monitors (BPM) use 500 MHz resonant stripline pick-ups [27], which will provide sub-10 mm resolution by applying direct sampling of the pick-up signals [28]. Cavity BPMs for the SwissFEL undulator lines are being developed at the test injector aiming for sub-micron position resolution.. Screen monitors have been combined with BPMs in monolithic stations in order to check for movements of beam line components during operation. The screen monitor stations are equipped with YAG:Ce crystals for low charge operation and 1 µm thick OTR foils for high resolution (sub-10 µm) profile measurements [29]. Following the bunch compressor at 250 MeV beam energy, a dedicated diagnostics section, consisting of a 5-cell standing wave RF deflector and 3.5 FODO cells with horizontal phase advance of 55° per cell, has been designed for the measurement of projected and sliced (horizontal) emittances using the same beam optics. THz bunch compression, bunch arrival time and electro-optical bunch length monitors [30, 31] complement the beam diagnostics in the longitudinal plane.

POSSIBLE MISSION EXTENSIONS

We are considering extending the injector with a second beam line parallel to the diagnostic section in order to test echo-enabled harmonic generation (EEHG) [32] as a possible seeding scheme for soft X-rays. For this experiment it is foreseen to use the SwissFEL type of undulator.

EXPECTED PERFORMANCES

The design concept and start to end simulations of the injector facility have been described in [7]. The assumptions on the initial thermal emittance (see Table 3) are based on the measurements performed recently with photo cathodes at PSI [33] and SLAC [18]. The exchangeable cathode will in particular allow thermal emittance studies with respect to the cathode preparation procedures. Table 4 summarizes the expected beam characteristics after compression. According to these simulations the injector should deliver a beam fulfilling the SwissFEL requirements. For the final machine we are currently studying an increase of the injector energy up to maximum of 450 MeV to alleviate space charge effects during compression.

Table 3: Beam Parameter at the Photo Cathode for High and Low Charge Operation.

Parameter	200 pC	10 pC
Thermal Emittance (mm.mrad)	0.195	0.072
Laser rms Size (μm)	270	100
Laser Rectangular Pulse FWHM (ps)	9.9	3.7
Laser Rise and fall Time (ps)	0.7	0.7
Peak Current (A)	22	3

Table 4: Beam Parameters after Compression for High and Low Charge.

Parameter	200 pC	10 pC
Energy (MeV)	255	
Rms Bunch Length (fs)	193	33.2
Rms Projected Emittance (mm.mrad)	0.38	0.1
Rms Slice Emittance (mm.mrad)	0.33	0.078
Peak Current (A)	352	104

CONCLUSIONS

PSI is building a 250 MeV accelerator test facility to demonstrate experimentally the gun concept and the first compression stage foreseen for the SwissFEL injector. The components currently under development for the final machine will be tested and optimized in this facility. The gun section will be commissioned by end of 2009 while the entire accelerator will be available in autumn of 2010. Furthermore we are considering adding a second beam line for EEHG experiments.

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