

LATEST RESULTS AT THE UPGRADED PITZ FACILITY*

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Abstract

The Photo Injector Test facility at DESY, Zeuthen site, (PITZ) develops and optimizes electron sources for high-power, short-wavelength FELs such as FLASH and the European XFEL. PITZ has now restarted operation after a very significant upgrade. A new laser system has been installed which, when fully commissioned, is expected to deliver 20 ps-long pulses with rise and fall times of 2 ps. Also, a new 1.5-cell L-band gun with improved cooling channel design has been installed. A new dry-ice cleaning method was employed during this gun's preparation, and conditioning results from this gun show significantly decreased dark current compared with the summer 2007 run. We describe the new stage of the facility, report the complete conditioning results from the new electron gun, give an overview of the experimental results so far from the 2008 run period, and present a description of the additional planned upgrades toward the full operating design of the facility.

THE UPGRADED PITZ FACILITY

The PITZ facility is designed for the commissioning and testing of electron sources for machines requiring

high-brightness electron beams, such as FLASH¹ and the European XFEL.² Electron beam characterization performed includes measurement of both the longitudinal and transverse phase space distribution of the electron beam. A particular goal for the facility is to demonstrate the European XFEL design value of 0.9 mm mrad rms transverse projected emittance for a beam with 1-nC bunch charge.² In August 2007, rms transverse projected emittance measurements including 100% of the detected charge yielded a value of 1.26 ± 0.13 mm mrad (geometric average of two transverse planes with statistical errors).³ The current upgrade of the facility will further improve on these promising results.

A number of important changes have been made to the experimental setup, with practically every component of the beamline replaced or moved to a new location. The current layout is shown in Figure 1. The L-band 1-1/2 cell electron gun (prototype 3.2) used in the summer 2007 measurements has been replaced with a new gun cavity. This cavity has been commissioned first at a new, dedicated conditioning test stand whose setup includes diagnostics similar to the low-energy section of the PITZ beamline. The new gun, prototype 4.2, incorporates 14 independent water channels in an improved cooling

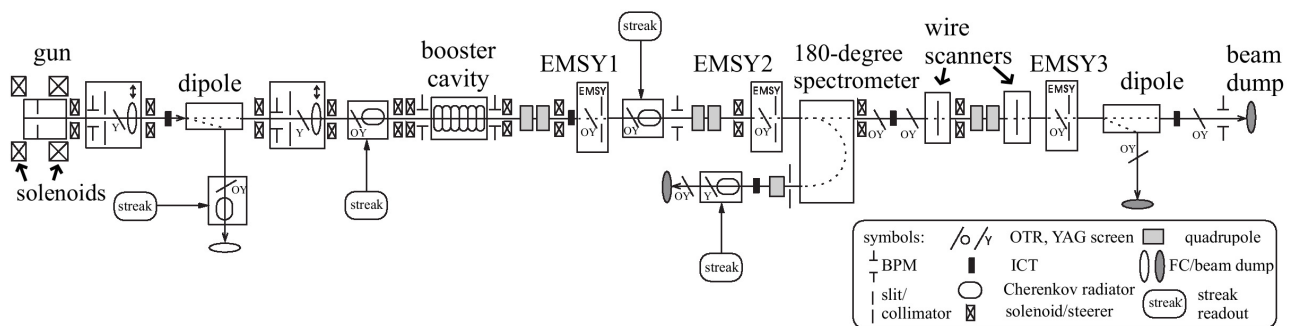


Figure 1: Facility layout of the upgraded Photo Injector Test facility in Zeuthen (PITZ).

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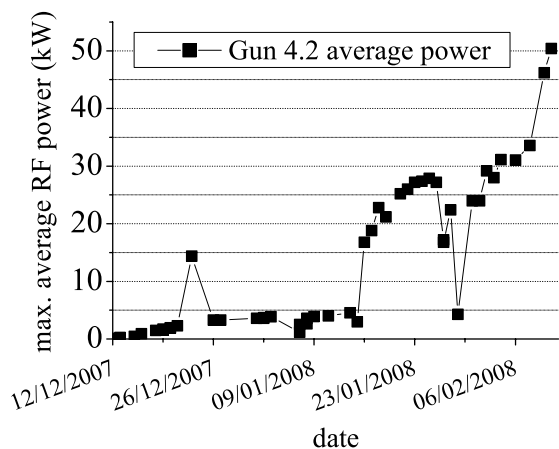


Figure 2: Progress of conditioning for gun prototype 4.2 at the CTS from December 2007 to February 2008.

design, and the cavity's interior surface was prepared using a dry-ice cleaning procedure intended to reduce the dark current.

An entirely new photocathode drive laser has also been installed in order to improve the rise and fall time of the UV pulses from 6-7 ps in the previous version to around 2 ps. Beam dynamics simulations have shown that the steeper edges of the laser pulses in time lead to a reduction of the rms projected transverse emittance of the electron bunch emitted from the photocathode.⁴

The electron beam diagnostics have also been improved during the most recent shutdown period. The dipole magnet following the gun has been redesigned with an inner chamber width of 27 mm for transmission of the electron beam under a wider range of focusing conditions. The dispersion coefficient of this dipole at the observation screen is 425 mm. First measurements of the beam momentum as a function of the RF power in the gun yielded a maximum mean momentum of ~ 7 MeV/c. A fit of these results to simulations using a measured field balance in the gun (ratio between the full- and half-cell fields) of 1.05 confirms that the peak field at the cathode is more than 60 MV/m, a European XFEL design parameter. Measurements of the longitudinal phase space using short Gaussian pulses from the new photocathode laser (discussed further below) have also been performed using this dipole in combination with a streak camera. The strongly nonlinear phase-space distribution observed has been compared with ASTRA simulations.⁵

An important addition to the electron beam diagnostics is a 180° -dipole spectrometer arm in the high energy section of the linac (after the booster cavity). This multipurpose dispersive section has been designed to operate as an electron spectrometer up to 40 MeV, to characterize the longitudinal phase space of the beam, and to measure the slice emittance, the transverse emittance of individual longitudinal slices of the bunch.⁶ The dipole magnet for the spectrometer arm, centered 7.7 m downstream the gun, has a bending radius of 300 mm, and produces a peak field of 0.46 T. The dispersion coefficient of the dispersive arm is 600 mm, independent

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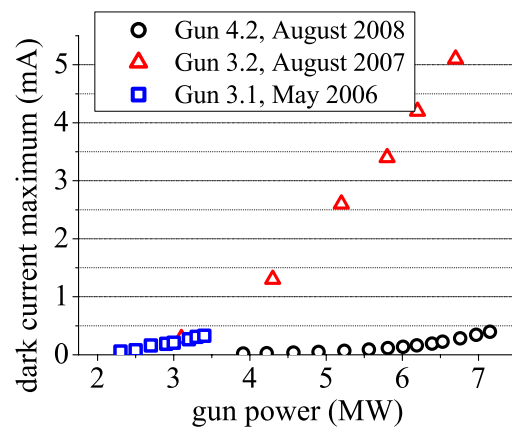


Figure 3: Dark current from three different gun cavities tested at PITZ.

of the beam drift length following the 180° bend. The beam dump in this dispersive arm can accept up to 800 micropulses per second (an average current of $0.8 \mu\text{A}$).

A new double cross for diagnostics has been installed, centered 74 cm downstream from the cathode, just after the RF gun. The new design of this diagnostics cross also provides larger cross sections for the pumping ports, and the geometry has been improved to reduce wake fields from the electron bunch.⁷ Like the old design, it includes a Faraday cup and integrated YAG screen, mounted on a movable actuator, for electron beam charge measurement and transverse profile observation. The cross also houses several mirrors, one for directing the UV laser light to the cathode and two actuator-mounted mirrors for observing the cathode and for looking downstream along the beam pipe. It also contains a slit which can be used in tandem with the first dipole magnet just downstream of the cross for high-resolution beam momentum measurements.

COMMISSIONING OF A NEW ELECTRON GUN

The new electron gun was conditioned at the Conditioning Test Stand (CTS) up to an average power of more than 50 kW. Operation at this average power was achieved with $700 \mu\text{s}$ RF pulses of 7.2 MW peak power at a 10 Hz repetition rate. High-average-power operation was reached only with careful gun tuning and was not yet stable (at the level necessary for emittance measurements, for example). The progress of the gun conditioning as marked by maximum average power achieved per 8-hour shift for the 60-day conditioning period at the CTS is shown in Figure 2. This data represents several cycles of increasing peak RF power in the gun cavity at successively higher RF pulse lengths.

After this conditioning at the CTS, the gun prototype was moved over to the PITZ main linac during the facility upgrade. In both locations, the measured dark current and the reflected power from this gun are lower than the previous cavity. The reflected RF power from the cavity is reduced to $\sim 0.3\%$ of the absorbed power, compared to

about 3% from gun prototype 3.2 (at around 7 MW peak power). Dark current measurements vs. RF power are shown in Figure 3. Each point represents the maximum dark current measured at a Faraday cup 78 cm downstream of the cathode during a full scan of the main solenoid current. As with the reflected RF power, the dark current at high gun power is an order of magnitude less than for previous gun prototypes. The gun cavity has been cleaned using a dry-ice sublimation-impulse technique. This type of cleaning involves several different thermo-mechanical and chemical processes, and is effective for particles down to ~ 100 nm in size.⁸ The reduced amount of dark current facilitates operation of the cavity with high peak electric fields at the cathode surface.

NEW PHOTOCATHODE DRIVE LASER

The new photocathode laser was developed at the Max-Born-Institute, Berlin, Germany. The system is based on an Yb:KGW oscillator, an Yb:YAG regenerative amplifier, and a two-stage Yb:YAG double pass amplifier. The laser produces pulse trains at 10 Hz, each containing up to 800 micropulses spaced at 1 μ s. During tests at MBI, micropulses with durations of ~ 20 ps (FWHM) and rise and fall times of about 2 ps were realized. The energy of each micropulse in the UV (at 257.5 nm) will be about 10 μ J in the long flat-top pulse mode. The pulse shaper for long, flat-top pulses is not yet commissioned at PITZ, but short Gaussian pulses with measured FWHM of 2.1 ps are already available.

The previous laser system produced flat-top pulses with rise times of 6-7 ps.⁹ Reducing the rise and fall times of the laser pulse to 2 ps limits the growth of the projected transverse emittance due to space charge, decreasing the contribution from the large slice emittances in the head and tail of the electron bunch.

The laser beam line images the UV pulses from the plane of a set of remotely-selectable beam shaping apertures to the cathode surface. These apertures, with diameters from 0.2 mm to 3 mm, select the central portion of the transverse Gaussian profile of the laser beam in order to produce various laser spot sizes on the photocathode. About 10% of the laser energy from the laser table is transmitted to the cathode, depending on the aperture chosen.

Unused cesium telluride photocathodes normally have a low-electric-field quantum efficiency (ratio of the number of emitted electrons to the number of photons striking the cathode surface) on the order of 5%.¹⁰ For this efficiency, UV pulse energy of 0.1 μ J would be required to yield a bunch charge of 1 nC. At the required charge density at the cathode, however, space-charge effects limit the emission. A large working overhead in the laser energy is required. Moreover, the initially high quantum efficiency degrades during operation, typically due to poor vacuum conditions and damage to the emissive film from dark current and sparks in the vacuum chamber. Lifetimes on the order of months have been demonstrated at PITZ and

FLASH for operation around 40 MV/m peak electric field at the cathode, when the vacuum pressure can be maintained below 10^{-9} mbar even during RF operation.¹¹ Much shorter lifetimes (~ 100 hours) were observed in the 2007 experimental run with higher peak fields, but current observations are more consistent with the longer lifetime observed at lower gradient. Lower dark current improves the cathode lifetime at high peak field directly by reducing damage to the cathode emissive film and indirectly by allowing lower vacuum pressures to be maintained during RF operation. Also, fluorine-containing insulators used in some of the diagnostics elements of the beamline have all been replaced, as fluorine was detected via X-ray photoelectron spectroscopy on the surface of used cathodes which exhibited rapid degradation during the previous run.¹²

OVERVIEW OF FUTURE PLANS

The recent upgrade at PITZ represents important progress toward the full planned design of the facility, but several important components remain to be installed.

One of these is the cut disk structure (CDS) booster cavity, to be installed in the fall of 2008. The performance of the current 9-cell booster cavity is strongly limited by the available cooling system. The CDS booster will replace the current one at its present distance from the gun, which was changed during the PITZ upgrade to the proper position for emittance conservation corresponding to the peak field at the cathode of 60 MV/m. The new booster cavity will provide greater acceleration of the electron beam (up to beam momenta of ~ 30 MeV/c) and greater stability.¹³

Two proposals for slice emittance measurements are being pursued. One involves imposing an energy chirp on the beam by off-crest acceleration in the booster cavity and transverse emittance analysis in the high-energy dispersive section. This approach has been studied in simulation and measurements seem possible with reasonable errors (5-10%).¹⁴ The other couples the quadrupole scan technique for emittance analysis with streak camera measurements. Measurement configurations with multiple quadrupoles have been explored to reduce the error contribution from space-charge effects near the beam waist.¹⁵

Also planned is a quadrupole-based tomography section, consisting of three identical focusing-defocusing (FODO) cells and four screen stations.¹⁶ Quadrupole magnets are also needed for matching the beam at the entrance to the tomography module, several of which are already installed in the linac beamline. The design for the tomography section provides a 45° phase advance between the screen stations, which has been shown to produce the smallest errors in emittance measurements using four screens.¹⁷ In a further upgrade following the commissioning of the tomography module, four kicker magnets will be used to extract single micropulses (up to a few) from the pulse train for analysis. Ultimately, a transverse deflecting cavity can be added to the design with which the tomography module will be able to

measure the slice transverse emittance of the electron bunches.¹⁸

Another dispersive section in the high-energy section of the linac is also planned to replace the dipole magnet now located after the third emittance measurement system (see Figure 1). The design of this new section seeks 1 keV/c momentum spread resolution but also the capability to measure the slice emittance of the electron bunch with an energy chirp obtained by off-crest acceleration in the booster cavity. In contrast to the dispersive section immediately following the booster, this section is designed to accept average current up to the 72 μ A, as planned for the European XFEL. Several designs with multiple dipole magnet configurations have been considered in detail to meet the measurement requirements and bring the deflected beam back to the main beam dump.¹⁹

SUMMARY AND CONCLUSIONS

The PITZ facility has resumed operation after an 8-month long shutdown, during which several key systems were replaced or improved. A new electron gun with an improved water cooling design has been commissioned. After being specially prepared with a dry-ice cleaning technique, this new cavity shows remarkably low dark current compared to previous versions. The measured RF reflection from the cavity is also low, about ten times less than the cavity used for emittance measurements in 2007. The photocathode drive laser has been replaced by a new system which will deliver longitudinal flat-top pulses with rise and fall times of around 2 ps, very important for the electron bunch phase space according to beam dynamics simulations. A number of developments have been realized in the electron bunch diagnostics beamline, including a new 180° dipole spectrometer after the booster cavity.

Future plans for the facility include a new booster cavity for beam acceleration up to 30 MeV and a tomography module consisting of four screens and three quadrupole FODO cells. Another dispersive section is also planned to replace the third beamline dipole and to be used for momentum, momentum spread, and slice emittance measurements.

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