

FEL DISTURBANCE BY AMBIENT MAGNETIC FIELD CHANGES

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Abstract

The VUV-FEL FLASH at DESY in Hamburg (Germany) is mostly located inside the circular accelerator PETRA which serves as an injector for the electron proton collider HERA. SASE was regularly lost in FLASH when protons were ramped to the injection energy in PETRA. This effect was mediated by magnetic field changes in the order of $1 \mu\text{T}$, caused by time-dependent uncompensated magnet currents of more than 800 A which made PETRA act like a large current loop. The resulting beam displacements of several hundred μm in the undulators proved to be enough to make SASE fail. This serious disturbance of user runs was eliminated by introducing an improved compensation scheme which further limits residual currents in PETRA during proton injection. The consequences of this observation for the design of the XFEL are briefly discussed.

PROBLEM DESCRIPTION

Accelerators at DESY

The DESY laboratory in Hamburg, Germany, operates several accelerators for high energy physics (HEP) and synchrotron radiation (SR) research:

- The prime HEP machine is the electron proton collider HERA. Electrons and protons are created and accelerated in separate linacs, ramped to 7 GeV in the synchrotron DESY, and further ramped to 12 and 40 GeV, respectively, in PETRA from where they are injected into HERA.
- When not used as an injector for HERA, electrons in PETRA are used to create SR for experiments. The accelerator DORIS is fully dedicated to this purpose.
- The VUV-FEL (Vacuum-UltraViolet Free Electron Laser) FLASH (Free electron LASer at Hamburg) is a totally self-contained machine, not depending on any of the other accelerators. Earlier this year lasing was achieved at a wavelength of 13.1 nm. The components of FLASH are schematically shown in Fig. 1. FLASH is about 300 m long and almost all of it is located inside the PETRA ring.

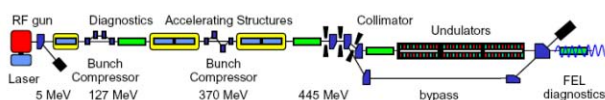


Figure 1: Schematic of the VUV-FEL FLASH at DESY.

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FLASH Disturbances Caused by Proton Ramping in PETRA

During proton ramping in PETRA severe disturbances of FEL operation were observed. Beam position measurements showed an increasing orbit displacement with increasing linac length (Fig. 2). At PETRA energy settings

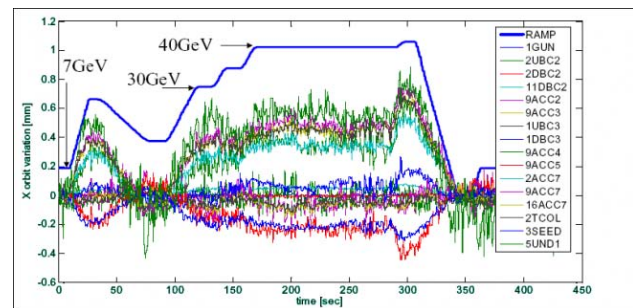


Figure 2: PETRA proton energy ramp and orbit displacement at various locations along the linac as a function of time. From top to bottom the position labels in the table correspond to increasing linac length. The largest displacement occurs in the undulator.

larger than 10 GeV the orbit displacement in the undulators was large enough to cause the breakdown of SASE (self-amplified spontaneous emission).

At least two mechanisms are conceivable which could mediate the observed disturbance:

- Unintentional electrical coupling through the DESY mains which is heavily loaded during proton ramping in PETRA.
- The changing magnetic field of PETRA acting as a current loop, powered by the not fully compensating sum of dipole and quadrupole magnet currents.

The measurement of the magnetic field in various places and as a function of several variables can clarify the picture.

MAGNETIC FIELD MEASUREMENTS

Measuring Equipment

Two types of device were used for measuring ambient magnetic fields on the DESY site:

1. A Hall probe connected to a multimeter for measuring one field component with a resolution of 10 nT. This instrument was used for quick surveys.
2. A Smart Digital Magnetometer (Honeywell HMR-2300) for measuring all three field components simultaneously. It delivers digital data on an RS-232 serial

port. Connected to a laptop running an Agilent Vee readout program, this formed a mobile monitor station. The observed accuracy was 100 nT full width.

Both devices were operated in ranges appropriate for measuring the earth's magnetic field (about $50 \mu\text{T} = 0.5 \text{ G}$).

B Field Changes During PETRA Proton Ramps

Already the first measurements using the Hall probe showed that during proton ramps PETRA was acting as a current loop. Fig. 3 shows the measured vertical component of the magnetic field as a function of the energy setting of PETRA. At $E = 40 \text{ GeV}$ PETRA adds about $1 \mu\text{T}$ to the

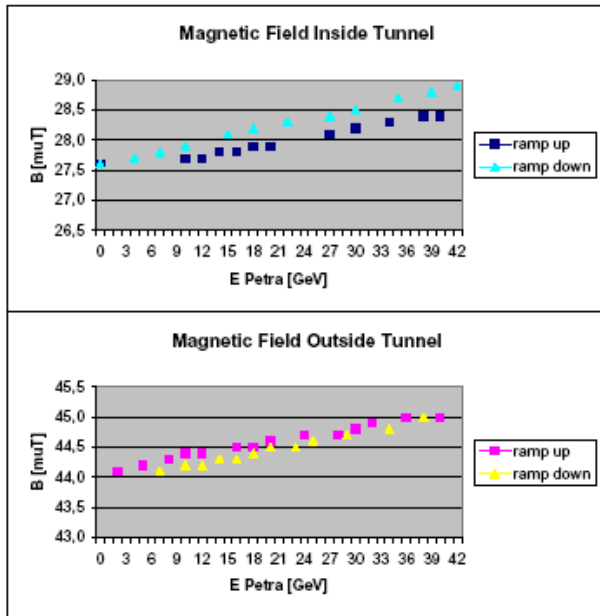


Figure 3: Vertical component of the magnetic field as a function of the PETRA energy setting, measured at the same linac position inside and outside the FLASH tunnel.

vertical component of the ambient magnetic field. This is enough to cause beam deflections in the unshielded warm low energy parts of the linac which lead to SASE breakdown in the undulators.

Using the 3D-device it was possible to record magnetic field data over the full time span of proton ramps in PETRA. Fig. 4 shows the data for two ramps during 20 minutes. Only the vertical field component changes during ramping and the field variations accurately follow the energy variations in PETRA. The energy ramp from 7 to 40 GeV is accompanied by a field change $B_y \approx 0.8 \mu\text{T}$.

Given the location of the measurement, $r = 126 \text{ m}$ and $y < 10 \text{ m}$, Biot-Savart's Law can be used to calculate the loop current. The radial and axial components of the magnetic field created by a circular current loop at an arbitrary point (r, y) w.r.t. the center of the loop are given by

$$B_r(r, y) = \frac{\mu_0 I}{2\pi} \frac{y}{r\zeta} \left[\frac{a^2 + r^2 + y^2}{(a-r)^2 + y^2} E(k) - K(k) \right]$$

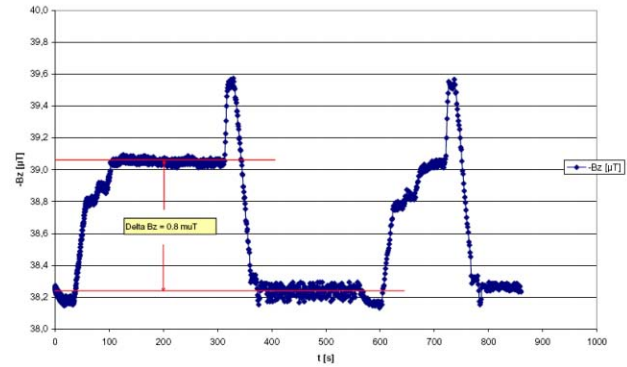
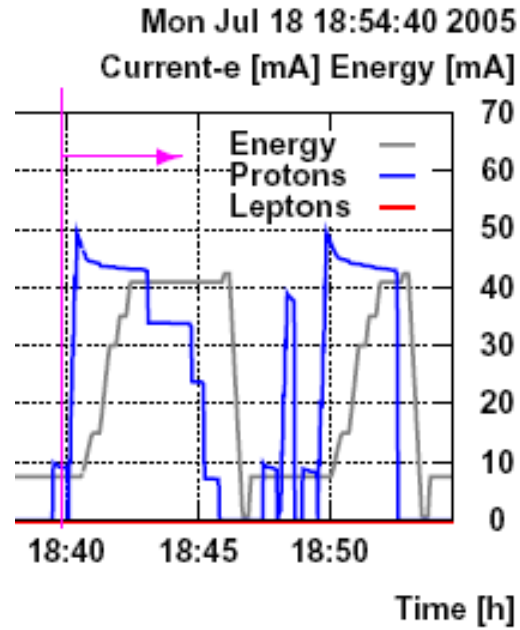


Figure 4: Top: Proton energy (grey) in PETRA. Bottom: Vertical component of the magnetic field at $r = 126 \text{ m}$ and $y < 10 \text{ m}$ w.r.t. the centre of the PETRA ring, measured during the same time interval.

$$B_y(r, y) = \frac{\mu_0 I}{2\pi} \frac{1}{\zeta} \left[\frac{a^2 - r^2 - y^2}{(a-r)^2 + y^2} E(k) + K(k) \right]$$

with

$$k = \sqrt{\frac{4ar}{(a+r)^2 + y^2}} \quad \text{and} \quad \zeta = \sqrt{(a+r)^2 + y^2}$$

$K(k)$ and $E(k)$ are the complete elliptic integrals of the first and second kind. Using a WWW field calculator [1] one finds that at $r = 126 \text{ m}$ a field $B_y = 0.8 \mu\text{T}$ is created by a current $I = 425 \text{ A}$.

B Field Variations along FLASH

On two access days the vertical magnetic field component B_y was measured at various z positions along FLASH with PETRA at energy settings of 0 and 40 GeV. The field difference as a function of z is shown in Fig. 5. Within the

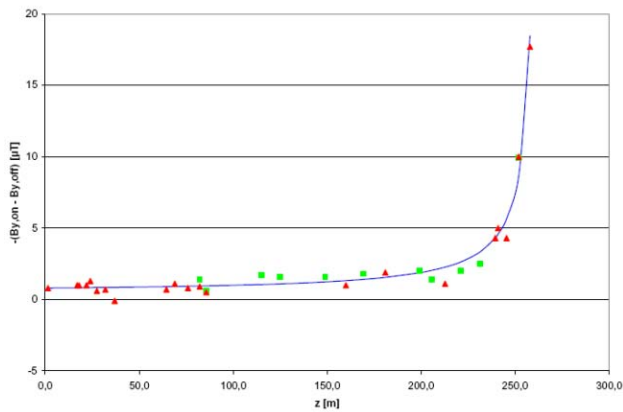


Figure 5: Difference of the vertical magnetic field component B_y for PETRA energy settings of 0 and 40 GeV, measured along the FLASH linac on two different days. The line is the field calculated for $I = 425$ A.

measurement accuracy the PETRA induced field component at all positions is compatible with being created by a current $I = 425$ A. The line in Fig. 5 is not a fit, but an absolute calculation. Using this result for beam simulations one finds that for maximum beam deflections in the order of the beam size the uncompensated current in PETRA needs to be a factor 10 smaller.

PETRA COMPENSATION

PETRA Compensation Experiment

In order to provide further conclusive evidence, a PETRA compensation experiment was performed while FLASH was running in user mode. At an energy of 40 GeV the dipole current was lowered until the magnetic field in the control room was back at its 0 GeV value. The field change $\Delta B_y = 0.9 \mu\text{T}$ required a current change $\Delta I = 422$ A, in good agreement with the measurement described above. In addition, SASE, which was lost while ramping up, immediately reappeared after the dipole compensation.

An Improved Compensation Scheme

The usual technique to prevent residual magnetic fields from a ring accelerator is intelligent cabling of all magnets. The best solution is to power the magnets in two separate symmetric half circles as is practiced at HERA, but this needs a full extra accelerator circumference of cable which has its cost. At PETRA the dipole and quadrupole magnets are cabled such that of the maximum dipole current of 6600 A at 40 GeV 580 A remain uncompensated. During magnet massage immediately after injection this rises to 860 A. This is now compensated by sending an energy-dependent current through a still unused current rail in the PETRA tunnel.

OTHER FIELD SOURCES

The strong disturbance of FLASH by PETRA acting as a current loop arose suspicions about the other ring accelerators at DESY.

- The effect of energy changes in the DESY synchrotron is negligible in the FLASH tunnel, totally outside it and 142.5 m away from the center.
- The effect of DORIS is as strong as that of PETRA but DORIS ramps very seldom, sometimes less than once per week.
- The FLASH modulators and klystrons cause magnetic field changes of about $\Delta B_y = 0.4 \mu\text{T}$ at the FLASH beam line.
- There are still unidentified sources of relevant magnetic field changes.

In order to better diagnose FLASH behaviour, a magnetic field monitoring system will be installed. Using Hall probes it will record quasi-static field changes in several critical positions, while coil sensors will be used to monitor oscillating fields up to 300 Hz.

CONCLUSIONS AND OUTLOOK

XFEL, DESY's approved future project, will extend the FEL principle to the X-ray regime. Its injector section will also be located inside the PETRA ring which will then be operated top-up at an energy of 6 GeV for SR experiments (PETRA III). This mode of operation will cause much smaller ambient magnetic field changes and no active compensation scheme is foreseen so far. Since the largest part of XFEL is outside the DESY site, a magnetic field monitoring system is indispensable in order to diagnose effects which are not under DESY control.

REFERENCES

- [1] E. Dennison, Magnet Formulas Web Site, <http://www.netdenizen.com/emagnet/offaxis/iloopcalculator.htm>.