INITIAL EXPERIENCE WITH DELTA *

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ABSTRACT

The 3rd-generation synchrotron light source DELTA of the University of Dortmund consists of a 100 MeV linac, a full-energy booster, and a 1.5 GeV storage ring. Commissioning of the linac has been started in October 1994. In March 1995 the first beam was stored in the booster ring. On completion of the vacuum system in May 1996, commissioning of the main storage ring has begun. The first FEL experiment FELICITA will be ready as soon as sufficient beam is available. In addition, a superconducting, asymmetric multipole wiggler is presently under construction in industry.

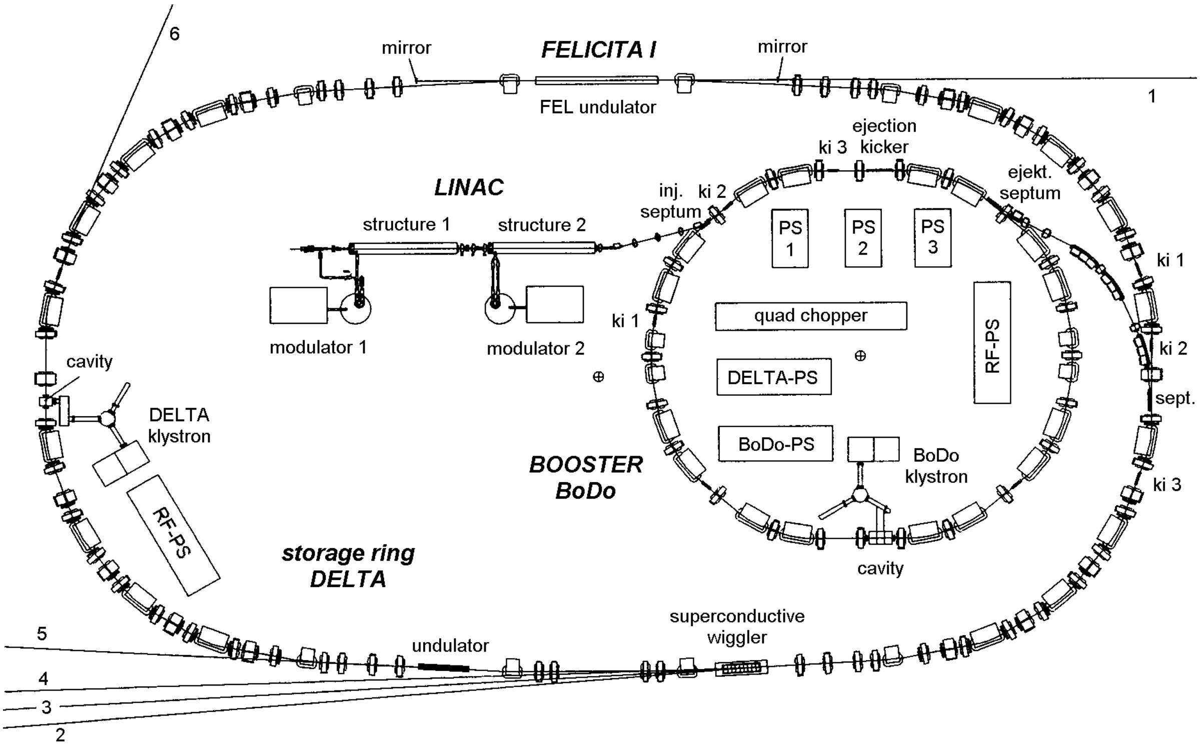

Figure 1: The electron storage ring facility DELTA with the assembled and planned experiments and beamlines. The electrons are provided by a 100 MeV linac and accelerated in a booster to the maximum operation energy of the storage ring of 1.5 GeV.

1 THE FACILITY

The Dortmund storage ring facility DELTA [1] is optimized to run FEL experiments in the visible and XUV range and to provide synchrotron radiation experiments. The FEL gain [2] is

$$G \propto K^2 N_u^3 \lambda_u^2 \frac{n_b}{\gamma^3}$$

with the undulator parameter K, the period λ_u, the number of periods N_u, the electron density n_b, and $\gamma = E/m_0c^2$. From this relation one can easily derive the general design requirements for the FEL storage ring:

- long straight sections (i.e. large N_u)
- high single bunch current I_b
- small beam dimensions $\sigma_{x,z}$ and σ_s

For FEL experiments beam energies below 1 GeV are required, but some synchrotron radiation users need higher photon energies up to $E_p \approx 10$ keV. The maximum design energy of the storage ring is therefore set to E_{max} = 1.5 GeV which is acceptable for the FEL and allows by means of superconducting wigglers the production of radiation in the 10 keV range.

The entire storage ring facility is shown in figure 1. It consists of three stages: a 100 MeV linac, the full energy booster BoDo („**Bo**oster **Do**rtmund“) and the 1.5 GeV storage ring DELTA (**D**ortmund **El**ectron **T**est

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Accelerator). The two 15 m long straight sections between the arcs allow very flexible installation of different experiments. During the first experimental period both straight sections are equipped with additional two 3° bending magnets. This setup provides suitable geometric conditions for the first FEL experiment FELICITA I, located in the upper straight section, especially to allow a short optical cavity with only 14.4 m distance between the mirrors. In the lower straight section two insertion devices are foreseen: a superconducting wiggler currently under construction and a planned permanent magnet undulator. In the future it is possible to remove the 3° magnets and to install long undulators up to 14 m length.

2 THE 100 MEV LINAC

The electron linac [3] is reconstructed using mainly parts of the old linac of the University of Mainz, which was shut down some years ago. The two 4.2 m long $\beta = 1$ constant gradient S-band structures powered with 20 MW each provide a total energy of 100 MeV. The triode gun with 50 kV extraction voltage allows either short 2 ns pulses of 1.5 A for single bunch production or with different pulser electronics longer bunch trains for multibunch operation. It follows a 6 cell $2\pi/3$-mode standing wave buncher with a design gradient of 16 MeV/m, originally designed from LAL for CERN.

Several parameters of the old linac parts had to be measured during commissioning. The results made a modification of the solenoid focusing in the buncher region necessary as well as an additional quadrupole focusing in front of the first structure. With these modifications the transmission grew from 2% to 20%.

Along the linac one gap monitor and 3 cavity monitors are installed to measure the beam current. Following values have been achieved so far:

Table 1: achieved parameters of the linac

parameters	values
particles from the gun	$N_{gun} = 1.5\ 10^{10}$
pulslength	$\tau = 2$ ns (single bunch) 15 ns (commissioning)
particles at linac exit	$N_{out} = 7.5\ 10^{9}$
emittance at linac exit	$\varepsilon \approx 1\ 10^{-6}$ m rad
transmission	$T \approx 20$ %
repetition rate	$f_{rep} = 1$ - 50 Hz
energy	$E_{out} = 78.1$ GeV

The energy is presently smaller than designed because of limitations caused by the use of the old klystrons. The system of the first structure and the buncher is only powered with 10 MW. Twice the power is required according to the design. This problem will be solved during this summer after installation of a new klystron. One consequence of the low rf power is an energy spread of about ±10%, which is larger than the acceptance of the booster. Nevertheless, with a longer beam pulse of 15 ns from the gun the present linac performance is sufficient for commissioning the booster and the storage ring.

3 THE BOOSTER BODO

The booster is designed as a storage ring operating in an energy range between 50 MeV and 1.5 GeV. All magnet circuits are powered by current controlled power supplies. This allows free choice of the ramping curve generated by a computer program. The resulting ramping cycle of at least 3 seconds (design value), however, is significantly longer than that of a White circuit. This disadvantage is compensated by an injection scheme with three kickers providing a current accumulation over many injections from the linac before the ramping starts. With this layout the booster can also be used as a storage ring for various tests.

3.1 Booster optics and injection

The booster optics is based on a standard FODO structure as shown in figure 2. It uses the same magnet types as designed for the storage ring. The magnet lattice consists of one dipole and five independent quadrupole families.

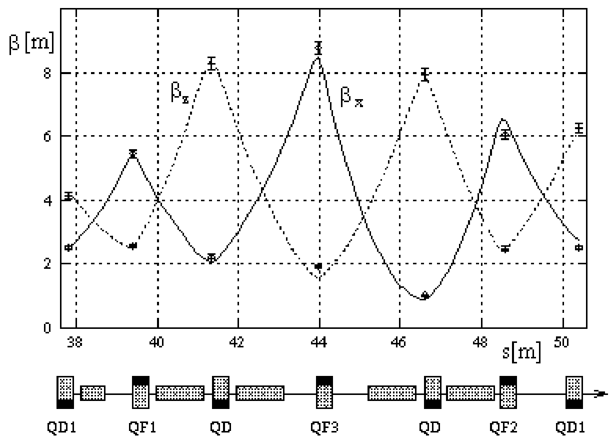

Figure 2: Optics of one quadrant of the booster. The lines are the calculated functions and the points are measured.

As already shown in optics calculations the lattice provides a large range of stable tunes. Even after tune change of one integer in vertical plane, stored beam was possible without any corrections. Nevertheless, at injection energy of presently around 70 MeV optical resonances are sometimes critical because of the long radiation damping time of $\tau_d = 40$ - 50 seconds. After several tune scans the best working point was found to be $Q_x = 2.83$ and $Q_z = 2.28$.

14 beam position monitors (BPM) are installed in the booster based on the standard technique with 4 pickup electrodes. Orbit correction is possible with 12 horizontal and 12 vertical steering coils. It was found

that without any corrections the vertical orbit distortions are within an uncritical range of some mm. Only in the horizontal plane positive displacements around +5 mm have been measured. In order to avoid time consuming realignment of all magnets, the rf frequency was changed from 499.654 MHz to 499.800 MHz. The booster runs now stable without any orbit correction.

Table 2: optical parameters of the booster @ E = 1 GeV

parameter	value
circumference	L = 50.4 m
Maximum energy	E_{max} = 1.5 GeV
tune	Q_x = 2.83, Q_z = 2.28
emittance (theory) (measured)	$\varepsilon_x = 1.60\ 10^{-7}$ m rad $\varepsilon_x = 3\ 10^{-7}$ m rad
momentum comp. factor	α = 0.117
chromaticity	ξ_x = -3.26, ξ_z = -1.91
synchr. damping time	τ_s = 5.6 ms
rf frequency	f_{rf} = 499.654 MHz
harmonic number	q = 84
cavity shunt impedance	R_s = 9.0 MΩ
rf power	P_{max} = 30 kW

Most of the quadrupoles are equipped with additional coils producing superimposed sextupole fields for chromaticity correction. During a test it was demonstrated that these fields can be switched on almost without any change of beam position. Normally the sextupole fields are off, the chromaticity is rather low and its compensation not necessary so far.

Normally the booster runs with one shot on-axis injection using only the two kickers ki2 and ki3 (fig. 1) behind the septum. The machine is then filled with 5 to 6 bunches (15 ns beam pulse from the linac). The kicker strength at injection energy is high enough to operate without dc-steering coils. Because of the low inductance of the kickers it was no problem to get rise and fall times of <100 ns with a maximum voltage of 20 kV. A test with a closed kicker beam bump for accumulation has proved the principal, but the best achieved intensity was only a factor of 2 to 3 higher than with the simple on axis injection.

The reason is the large energy spread of the linac beam, which fills the whole stable phase volume of the booster. In addition, there is a lack of damping at injection energy. Therefore, the stacking does not work properly. But also with on axis injection only 10% of the incoming particles are stored. Most of them disappear after several hundred ore even thousand revolutions. At single bunch operation the energy spread is much smaller and the injection efficiency goes up to more than 30 %. With the new LINAC klystron these problems will be solved soon.

The lifetime of an injected 70 MeV beam is presently τ_{beam} = 7 min. for currents of A_{beam} = 1 mA or less. It is much longer than required. It is determined by vacuum and shows the high quality of the vacuum chambers and the NEG-pumping system (see *5.2*). The average pressure is $p \approx 1\ 10^{-7}$ Pa. It is an interesting fact that no ion related effects have been observed so far. The installed clearing electrodes have no significant influence on the beam lifetime.

3.3 Acceleration procedure

The acceleration in the booster follows presently a computer generated curve $I_{bend}(t)$ for the bending magnets as shown in fig. 3. The current of I_{bend} = 600 A corresponds to the beam energy of E = 0.96 GeV. The cycle time of 15 s is chosen because of safety reasons. It will be reduced to 3 - 5 s later. The five quadrupole circuits are driven by similar curves $I_{quad}(t)$ including empirical corrections $f_{corr}(t)$:

$$I_{quad}(t) = a\, I_{bend}(t) + f_{corr}(t) \qquad (a = \text{const.})$$

With this technique one can keep the tune almost constant during acceleration. Beam loss occurs only at the very beginning of the ramp and can be avoided by careful adjustment of the tune.

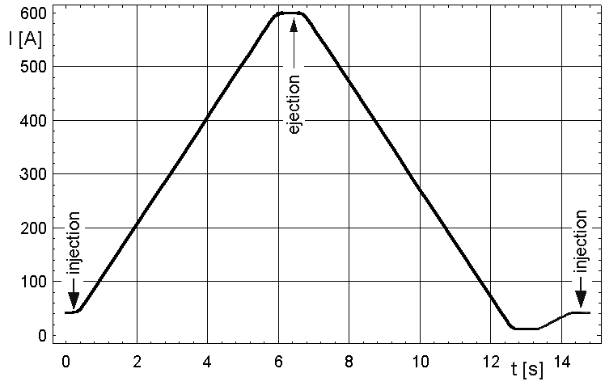

Figure 3: Ramping curve of the booster.

The quadrupoles are powered by 60 A choppers identical to the types designed at DESY for HERA. Originally they don't allow negative voltages at the output. During the falling ramp after ejection the magnet circuits have a time constant of $\tau = L/R \approx 1$ s. Below 10 A the magnet current is therefore delayed and the control loop runs into saturation. After some seconds the loop locks again. This happens in the phase without beam and seemed to be harmless. The experiences, however, have shown a drastic change of the conditions from one injection to the next. The tune at injection energy jumped up and down by several 100 kHz. Obviously due to strong hysteresis effects at low field excitations the initial conditions are undefined for this kind of operation. Therefore, the choppers have been modified in a way that during down ramping automatically a 7.5 Ω resistance is added to the circuit. The time constant reduces to τ = 0.2 s and the control loop always locks. After this modification the injection conditions are very stable.

The maximum energy achieved in the booster so far is $E \approx 1.3$ GeV with constant rf-power of $P_{rf} = 5$ kW at a frequency of 500 MHz. In order to avoid problems with cavity windows and the vacuum in this region the klystron power is presently limited to this uncritical value. It is sufficient during the first commissioning of the storage ring at the chosen beam energy of $E = 0.96$ GeV. During energy ramping the rf-power is simply kept constant.

4 BEAM TRANSFER LINE BETWEEN BOOSTER AND STORAGE RING

At the flat top of the ramping curve the beam is ejected by a fast tandem kicker and an eddy current septum. It is transferred to the storage ring by a short, compact transfer line. Because of the very limited space all magnets had to be built as small as possible. Consequences are the small 30 mm diameter of the stainless steel pipe and magnet apertures of 26 mm (bends) and 40 mm (quads). Because of the low booster repetition rate it was decided to utilize only pulsed bending magnets in the transfer line. The full wave current pulse has a period of 0.1 s. The required average power is in spite of the high field of $B_{max} = 1.4$ T only some hundred watts and water cooling is not necessary. Only the air cooled quads are powered with dc-current. The eddy currents in the 1.5 mm thick vacuum pipe have only week influence on the beam. This was found in calculations and meanwhile proved by tests.

The optics of the transfer line is critical since only 4 quads could be installed with proper betatron phase advance. Therefore, full matching of all optical parameters is not available. In addition, behind the ejection septum as well as in front of the injection septum into the storage ring the beam passes the strong stray field of the ring quadrupoles. It was not possible to implement these nonlinear fields into the optics. In the quads between the coils the vacuum pipe is surrounded by 5 mm thick iron shielding. It reduces the undesirable fields to negligible amounts. Even though the iron shielding is rather close to the poles, the influence on the main quad field is of the order of $\Delta B/B < 1\ 10^{-3}$. With these measures it was possible to find proper transfer optics for all storage ring lattices investigated so far. The recent experiments with the pulsed transport line have demonstrated its stable operation.

5 THE STORAGE RING DELTA

Various layouts of the long straight sections have been worked out during the last years. In the present layout both sections are devided into three shorter sections of 5 to 6 m each separated by small 3° bending magnets. This allows a proper installation of the first FEL experiment on one side and of two different undulator and wiggler magnets on the other side.

5.1 Storage ring optics

It was necessary to combine the required strong focusing in the arcs with the variable design of the long mostly different straight sections. At least 5 independent quadrupole families on both sides provide sufficient optics matching. The optical functions of one quadrant are shown in figure 4.

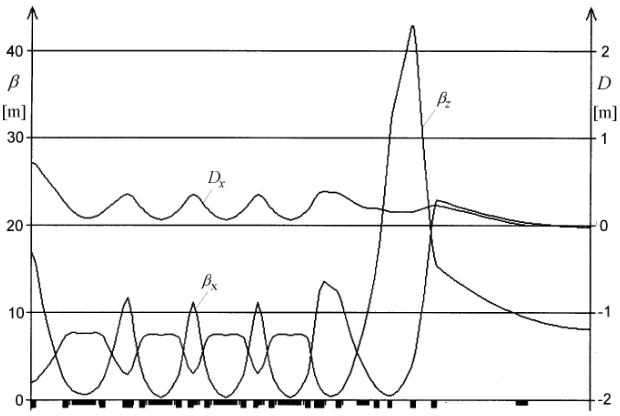

Figure 4: Optical functions of one quadrant of the DELTA low emittance optics.

The low emittance of the DELTA beam is provided by triplet focusing (DFD) between the dipoles. For commissioning less critical optics with larger emittance have been (table 3).

Table 3: parameters of the storage ring optics @ 1 GeV

parameter	low emitt.	commiss.
circumference [m]	*115*.2	*115*.2
max. energy [GeV]	1.5	1.5
tune	$Q_x = 8.76$ $Q_z = 3.81$	$Q_x = 4.82$ $Q_z = 2.73$
emittance [m rad]	$5.2\ 10^{-9}$	$5.26\ 10^{-8}$
mom. comp. factor	$\alpha = 0.005$	$\alpha = 0.024$
chromaticity	$\xi_x = -22.0$ $\xi_z = -9.9$	$\xi_x = -7.4$ $\xi_z = -4.7$
damping time [ms]	5.6	5.6
rf frequency [MHz]	499.654	499.654
harmonic number	$q = 192$	$q = 192$
cavity impedance [MΩ]	3.0	3.0
rf power [kW]	65	65

Because of the very limited space in the lattice, the required strong sextupole fields for the low emittance optics are produced by 5 cm long sextupoles mounted at the yoke of the quads and by additional integrated coils in the pole region similar as used for the booster. These hybrid sextupoles are arranged in only two families which gives sufficient dynamic aperture.

5.2 Vacuum system and injection kickers

In particular for FEL experiments, high single bunch currents are required and bunch lengthening should be suppressed. For the storage ring a low impedance chamber with keyhole cross section has been developed [4]. Two types of integrated pumps, both NEG and ion-sputter pumps, are mounted in an antechamber next to the beam. Exactly the same chamber design is also used for the booster. Because of the slow energy ramping, eddy currents don't cause significant field distortions. In both rings an average pressure in the 10^{-7} Pa range has been obtained after short pump-down time of only some few days. The beam lifetime in the booster is presently $\tau > 3$ h @ 1 GeV. Another positive experience concerns the high reliability of the special flange technique developed for DELTA. In spite of the complicated keyhole shape of the flanges and gaskets, almost no leak was found.

According to computer simulations, the main contribution to the microwave impedance of the chamber came from the original standard kicker design. A coated ceramic chamber could not be applied because of the direct synchrotron radiation and the complicated chamber cross section. A completely new kicker was developed, using the slotted metal chamber as conductor [5]. With this design the kicker impedance could be reduced by at least one order of magnitude. The resulting chamber impedance of the storage ring is $|Z/n| \approx 0.4\ \Omega$.

All kickers in both, the booster and the storage ring, are based on this technique. Careful investigations of the injection into both rings and the ejection out of the booster have shown good agreement between the design parameters and the actual values used during operation.

5.3 Status of commissioning

End of 1994 the commissioning was started with the linac. On March 24. 1995 the first beam was stored in the booster at 70 MeV. During the summer shut down the linac was modified to get much higher transmission. In November 1995 the first time beam could accelerated to 1.17 GeV. Parallel to the beam tests the hardware of the storage ring was completed (construction work in the daytime and beam operation in the evening and night). On May 20. a 1 GeV beam was ejected from the booster. Since beginning of June 1996 beam is injected into the storage ring. On June 5. one full revolution was achieved.

6 EXPERIMENTS AT DELTA

6.1 The FEL experiment FELICITA I

Parallel with the construction of the machines the first FEL experiment FELICITA I has been manufactured and installed in the straight section (figure 1). It consists of one 4.875 m long electromagnetic undulator with a period length of $\lambda_u = 0.25$ m [1]. The mirrors of the optical resonator are designed to produce visible light of $\lambda = 485$ nm. The undulator can be operated as optical klystron as well as a standard FEL.

All elements of the FEL are built and tested in the laboratory. The undulator magnet is measured by means of hall probes and a pulsed wire arrangement. After the magnet was moved to its final position in the machine the field measurement was repeated in situ. Several experimental investigations have been made to control and stabilize the mirror position within a fraction of 1 μm using a laser beam for alignment. As soon as sufficient single bunch current is stored in DELTA the first FEL experiments can start.

6.2 The superconducting multipole wiggler

In order to reach photons in the 10 keV range with beam energies around 1.5 GeV wiggler fields of $B > 5$ T are required. For DELTA an asymmetric superconducting multipol wiggler is designed [6], [7] and presently under construction in industry. It consists of two integrated sets of coils providing sine shaped fields with periods of $\lambda_u = 14.4$ cm and $\lambda_u = 28.8$ cm. Superimposing these fields produces a large asymmetry and allows circular polarized synchrotron radiation. According to the strong magnetic fields the photons are radiated into a wide fan with an opening angle of $\pm$ 25 mrad. It is possible to split the fan into tree beamlines (beamline 2 - 4 in figure 1).

The design work is now finished. Recently a module of this magnet has been successfully tested and peak fields of 5.39 T have been achieved after short training. The magnet will be delivered by end of 1996 and installed during spring 1997.

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