DELTA , A LOW-EMITTANCE STORAGE RING AS FREE-ELECTRON-LASER RADIATION SOURCE

Niels Marquardt
DELTA Group
Institute of Physics , University of Dortmund
P.O.Box 500 500, 4600 Dortmund 50, Germany

Construction of the Dortmund 1.5 GeV ELectron Test Accelerator DELTA is expected to start early this summer. The design goals of this new high-brightness photon source are to provide test possibilities for accelerator research and development, to serve as a driver for different FEL experiments, and to represent -to a limited extent- a single-user photon source of very special beam characteristics. The facility consists of a 20-100 MeV LINAC, the booster synchrotron BODO which can also be operated independently as a ramped storage ring, and the main storage ring DELTA. With its circumference of about 115 m the most recent racetrack-shaped version of DELTA has two arcs consisting of 10 separated function triplet cells and two 20 m long straight sections for insertion devices. Three different FEL projects are under development starting with an optical klystron in the visible to FEL's from λ=100 to <20 nm. Design features and status of the dedicated accelerator project are being discussed.

1. Purpose and General Goals of DELTA

The Dortmund Electron Test Accelerator Facility[1] consists of a laboratory building and a 70 m by 40 m large shed, housing the accelerator system, i.e. a LINAC of possibly 100 MeV, the booster synchrotron BODO, and the main storage ring DELTA of maximum energy of 1.5 GeV.

The intention of DELTA is to provide a national test accelerator facility designed for an energy range between 0.5 and 1.5 GeV and optimized for FEL operation[2]. It will not serve as a typical synchrotron radiation (SR) light source for long-term users. Instead, DELTA is planned to develop storage-ring and accelerator physics and to provide SR beams for short-term measurements requiring very special beam qualities and experimental conditions. As a university laboratory it is also best suited for the training of students, technicians, and accelerator physicists.

The main storage ring has a circumference of about 115 m and is designed to have two arcs, each of which consist of 10 separate-function quadrupol triplet cells, and two 20 m long straight sections usable for various insertion devices. The lattice structure with short cells and strong magnetic fields guarantees strong damping and a very low emittance. The ultra-low vacuum pressure and the small impedance of the beam chamber are providing high-current operation.

After a construction phase of three years and commissioning during the following year, routine machine operation and first experiments will start late in 1993.

The main purpose of DELTA is threefold :

(1) Investigation of accelerator physics

(a) Development of mode-damped single- and multi-cell cavities and analysis of cavity modes and of their interaction with high-current particle beams.
(b) Development of different insertion devices and of compact and inexpensive light sources.
(c) Testing of various SR instrumentation and accelerator components.
(d) Investigating the problems related to low-energy injection from LINACs and to the reduction of beam life time caused by ions generated in the storag-ring vacuum chamber.
(e) Theoretical investigation of non-linear phenomena of beam dynamics and comparison with measurements of actual non-linear variations of the beam under the influence of radiation damping. Limitations of the dynamical aperture by sextupolar fields and of the maximum possible beam currents are being investigated by tracking calculations. It will be particularly interesting to compare the results from single-particle tracking with measurements of the time development of oscillations of bunches of many particles coherently excited by fast kicker magnets. Since this has to be done within the first few thousand turns very fast electronics for the beam-position monitors have to be developed. Several theoretical investigations of non-linear beam dynamics have been started already.
(f) Monitor development for low-emittance storage rings. In collaboration with the ESRF, Grenoble, a 4-button beam-position monitor (BPM) with an improved electronics has been designed to obtain a resolution of less than 10 μm and an absolute accuracy of better than 150 μm RMS. This BPM is ready for testing at the storage ring DORIS, DESY. Special monitors to detect fast beam oscillations and non-linear particle motion are also going to be developed. For optimum FEL operation fine adjustment to zero of the dispersion in straight sections, very accurate emittance measurements, and determination of bunch lengths with specially designed monitors and pick-up electrodes are indispensable. Such monitors are going to be developed. The same is envisaged concerning closed-loop fast feedback systems. Tests with a prototype fast kickermagnet designed as strip-line resonator have been successfully performed.

(2) FEL experiments at DELTA

There is a three-stage project planned at DELTA for the development of FEL's operating at wavelengths from the visible to the XUV, with the long-term goal of realizing wavelengths clearly below 20 nm. These very short wavelengths generated from high-brilliance FEL-radiation sources are of particular interest e.g. for the wide field of X-ray microscopy of non-biological objects and in-vivo examination of biological objects.

For a joint FEL-storage-ring operation very stringent requirements have to be fulfilled by DELTA, like small emittances, short bunches, strong SR damping, large energy acceptance, low total machine impedance, extremely low vacuum pressure, active feedback systems and mode-damped cavities, long straight sections for FEL undulators.

Theoretical studies have been performed to determine the machine parameters optimized for most effective FEL-storage-ring operation and to determine the mutual influence between FEL and accelerator.

To approach the regime of extremely short wavelengths more gradually the following strategy of three steps of FEL development at DELTA is suggested which appears to be less risky and provides various possibilities to get sufficient experience.

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(a)**Phase I** : The first rather inexpensive and flexible device, called FELICITA I, is planned to be an optical klystron (OK) of 5–10 % gain which operates in the visible around 400 nm with DELTA running at 500 MeV. It will be made of simple electromagnets with 16 identical periods (λ_u=25 cm) and a total length of 4 m which can be split by extra coils into two undulators and a dispersive section. For this high-gain device of low output power to operate savely, peak currents of 60–100 A will be sufficient, with 4–6 electron bunches, corresponding to an optical cavity of 14.4 m and 9 m lenght, respectively. To reach a higher level of output power, the OK can also be operating in the conventional FEL mode with all sections at the same field. Depending on accelerator performance, however, this mode might not easily reach the oscillator threshold due to its lower gain. On the other hand, FELICITA I in the OK mode should reach the oscillator threshold also at intermediate wavelengths of 200–300 nm or even at 100 nm by either making use of the higher harmonics of the spontaneous undulator spectrum or by running DELTA at higher energies, i.e. 1000 MeV. Gain losses ($G\sim 1/\gamma$) are easily compensated by the higher peak currents possible, due to the reduced influence of Touschek effect and intra-beam scattering at higher energies. The OK will be a very valuable tool for studying laser-beam interaction, for developing mirrors withstanding high-power short-wavelength radiation, and for accurately measuring electron-beam energy and width.

(b)**Phase II** : Using the experience from phase I the next step will be the design of FELICITA II, a high-gain FEL operating in the oscillator mode near 100 nm. To obtain coherent radiation in this regime a much longer undulator with shorter periods on one side and higher peak currents from DELTA operating at higher energies on the other side are necessary. Only in this way reflectivities of mirrors of smaller than 50 % for this wavelength regime can be compensated. The undulator envisaged consists of about 230 periods of 6 cm length each, corresponding to a total length of 14 m. It will be built as hybrid magnet with standard permanent-magnet material and should reach gain values of 3–5. By operating DELTA at energies of around 1 GeV with currents of at least 150 A , this FEL produces radiation between 100 and 25 nm if suitable multi-layer mirrors are available.

(c)**Phase III** : If the mirror problem can not be solved within a few years, one could also think of a single-pass FEL with very high again installed in a by-pass and operating in a pulsed-mode (as was suggested by the Berkeley group). By using about 750 very short periods ($\lambda_u \cong 2$ cm) and an undulator length of 15 m with a few mm gap height, there might be sufficient gain already in one pass to generate a very intense pulse. After a single shot through the by-pass, the beam is deflected again into the storage ring, where it recovers by action of the various damping mechanisms from the severe energy degradation caused by its interaction with the FEL. Due to the short damping time of DELTA frequencies of the laser pulse of 10–20 Hz seem to be realistic.

(3) SR experiments for single users

According to the design concept of DELTA with the possibility of modifying and rapidly changing its beam lines and magnet lattice to satisfy the very special demands of certain test experiments, it also provides an ideal test accelerator for short-term research work with SR in most scientific disciplines. The special diagnostic tools for measuring all beam parameters, the sophisticated accelerator-control system and the methods of accurately stabilizing the beam position with feedback loops, which will be available at DELTA in the future, allow experiments which can not be performed at normal users machines. Of particular interest are those measurements which exploit the very unique time structure of the SR from single-bunch operation for the analysis of rapidly changing dynamical processes and of structural modifications.

2. Lattice and Machine Parameters of DELTA

Since the conditions of strong radiation damping (caused by strong bending fields) and small emittance (better obtained by weak fields) have to be provided simultaneously by the DELTA lattice, a simple FODO structure has been suggested at first. It turned out, however, that the very compact and dense FODO arrangement of 64 strong but short magnets necessary to fulfil these contradictory conditions does not provide sufficient space in between to insert simply formed coil heads, valves, monitor devices, etc.. Therefore, the original FODO lattice has been aban-

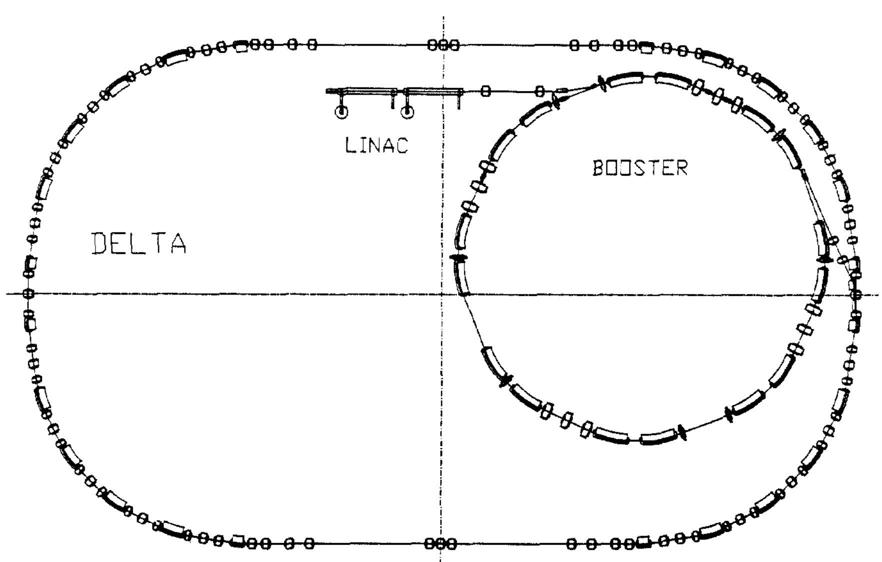

Fig. 1. General layout of DELTA with booster and LINAC

doned in favor of a triplet structure with a similar fourfold symmetry and 6 m long straight sections for insertions in each quadrant as before. The difference is that 3 short bending magnets have been combined in one with the same total strength and bending radius of 3.34 m and a length of 1.05 m, three times longer than before. Instead of alternating focussing and defocussing single quadrupoles between the dipoles, there are now three quadrupole magnets between two dipoles. As before, the most important optics parameters are determined by those of the two arcs which contain an additional straight section of 1.4 m length and extra quads and short dipoles for optical matching. Accordingly, there is more space available between the magnets and for inserting cavities and injection and extraction elements. A layout of the new lattice of the storage ring is shown in Fig. 1.

The total machine circumference has only been slightly increased to 115.2 m. The idea of maximum flexibility has been preserved by keeping the optical configuration of the arcs constant and only changing the two long straight sections according to the requirements of current experiments. With a slightly smaller emittance of 10^{-8} rad m and horizontal damping time and more or less unchanged values of energy spread and chromaticity all attractive features of the FODO lattice are preserved. Chromaticity compensation is made in the arcs where the dispersion is different from zero. As previously, sextupolar field components will be integrated in the quadrupole fields by modifying the pole faces appropriately and introducing extra coils between the upper and lower poles of the quads. A modified prototype quadrupole is under construction. Since FEL operation increases the energy spread and decreases the Touschek lifetime due to the necessary high particle densities, a sufficiently large longitudinal acceptance is important. Various tracking calculations have shown that the dynamic aperture is only slightly reduced by the nonlinear fields of sextupoles and that the energy acceptance of the DELTA triplet optics is of the order of $\Delta p/p = 5$ %. The new optics for one quadrant of DELTA is shown in Fig. 2 together with the dimensions of one triplet cell in more detail. The parameters of the linear beam optics of DELTA as well as the RF parameters are listed in Table 1.

Table 1. *The machine parameters of DELTA at E=1.0 GeV*

Circumference	$L = 115.2$ m
Bending radius	$R = 3.34$ m
Number of dipoles	$n_D = 20$
Tune	$Q_x = 10.217$
	$Q_z = 4.823$
Emittance (1 % coupling)	$\epsilon_x = 4.48 \times 10^{-9}$ m rad
	$\epsilon_z = 4.48 \times 10^{-11}$ m rad
(100 % coupling)	$\epsilon_x = \epsilon_z = 2.24 \times 10^{-9}$ m rad
Momentum compaction factor	$\alpha = 3.94 \times 10^{-3}$
Chromaticity	$\xi_x = -19.49$
	$\xi_z = -6.13$
Damping times (horizontal)	$\tau_x = 26.0$ ms
(vertical)	$\tau_z = 29.0$ ms
Synchrotron damping time	$\tau_E = 15.4$ ms
Energy spread	$\Delta E/E = 4.83 \times 10^{-4}$
Energy loss per turn	$\Delta E = 26.5$ keV
Accelerating frequency	$f_r = 500$ MHz
Harmonic number	$q = 192$
Maximum current (10 bunches)	$I = 500$ mA
(1 bunch)	$I_1 = 100$ mA
Number of cavities	$n_c = 1$
RF power (for I=500 mA)	$P_{RF} = 80$ kW

3. Injection System

The injection system of DELTA consists of a commercially available LINAC of possibly 100 MeV and a synchrotron BODO (BOoster DOrtmund) which can be ramped to the full injection energy of DELTA of maximum 1.5 GeV. Besides its normal preaccelerator mode, it is planned to operate BODO also like a storage ring with low-energy accumulation. The BODO lattice has two-fold symmetry with combined-function magnets.

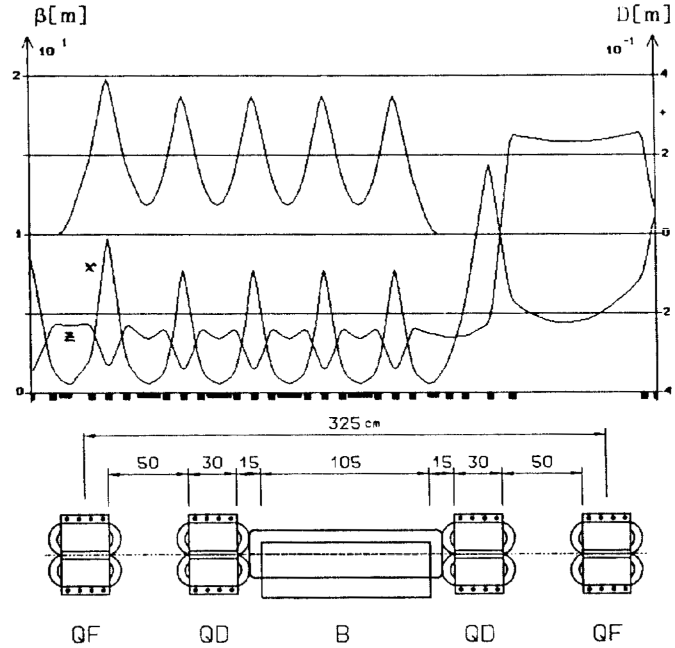

Fig. 2. Dispersion **D(s)** (upper part) and horizontal and vertical beta functions **β(s)** (middle part) for one Quadrant of DELTA and layout of a single triplet cell (lower part).

4. DELTA Magnets and Vacuum Chamber

Besides the argument of low costs, the design of the various DELTA magnets is mainly determined by the size of the vacuum chamber and the required field strengths and gradients. A conventional stainless-steel vacuum chamber will be built with one antechamber for continuously pumping with a combination of integrated DIP and NEG pumps. All dipole magnets are of C type with a gap height of 50 mm. Whereas the standard dipoles of the triplet cell have a weak quadrupole strength of $k = -0.3$ m^{-2} and a magnetic length of 1.05 m, there are a few dipoles of half the length and without such gradient which are used for dispersion matching of the straight sections. The DELTA quadrupole magnets with a weak sextupolar gradient of the pole faces and extra coils integrated between the poles to vary the sextupole strength continuously have a pole distance of 70 mm. Magnet specifications are given in Table 2.

Table 2. *Specifications of DELTA dipoles and quadrupoles*

DIPOLES :		QUADRUPOLES :	
magn. length	$l = 1.05$	*magn. length*	$l = 0.3$ m
gap height	$h = 50$ mm	*inner radius*	$r = 35$ mm
gap width	$b = 160$ mm	*max.grad.*	$dB/dx = 26.3$ T/m
field strength	$B = 1.5$ T	*max. field*	$B = 0.92$ T
current	$n \times I = 65653$ A	*current*	$n \times I = 13460$ A
cur.density	$dI/dF = 4.1$ A/mm^2	*cur.density*	$dI/dF = 2.2$ A/mm^2
power	$P = 16$ kW	*power*	$P = 2.7$ kW

References

(1) K.Wille, Nucl. Instr. & Meth. Phys. Res. A272(1988)59; K.Wille,DELTA Report (1986) and Status Report (1988), Univ. Dortmund, (1986), unpublished.

(2) D.Nölle, "Possible FEL Projects at DELTA", Contribution P40 to this Conference.