Appendix B

ELFE@DESY: An Electron Laboratory For Europe at DESY

The ELFE@DESY machine study group:

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Contents

B.1 Using TESLA and HERA to produce a 15-25 GeV continuous electron beam

ELFE, an Electron Laboratory For Europe, is a project to develop a 15 to 30 GeV, high luminosity, continuous beam electron accelerator for scattering experiments from fixed nuclear targets. The goal of this project is to explore the quark and gluon structure of matter by exclusive and semi-inclusive electron scattering from nuclei. The idea of integrating ELFE into the TESLA facility is based on the fact that the superconducting linac is operated at a low duty cycle, about 0.4%, for the e^+e^- collider mode and the machine is available for other tasks during the time between collider pulses. A fraction of the beam pulses produced by TESLA could be injected into the HERA ring until the ring is filled. We show in this report that it is possible to extract the electrons from HERA used as a stretcher ring and produce a high luminosity quasi continuous beam suitable for nuclear physics experiments.

Proposals using ELFE have been discussed and collaborations have been formed at the Mainz workshop in 1992 [1]. These proposals form an extensive research program on exclusive and semi-inclusive reactions. Such experiments are at the heart of the ELFE project. To avoid a prohibitively large number of accidental coincident events a high duty cycle is imperative. The experimental program requires a high luminosity because of the low probability of exclusive processes. Finally, a good energy resolution is necessary to identify specific reaction channels.

ELFE will be the first high energy electron beam beyond 10 GeV
with both high intensity and high duty factor.

In order to develop a concrete proposal, NuPECC, the Nuclear Physics European Collaboration Committee, has made the following recommendations:

1. "NuPECC has examined the case for a European CW electron accelerator in the 15 to 30 GeV region (ELFE) which was presented to NuPECC at the Vienna meeting in April 1994.

2. NuPECC finds the physics case compelling. The investigation of strongly interacting systems with the elementary probe of the strong interaction - the quark, produced in electron-quark scattering- is essential. Studies of hadron structure by exclusive experiments are indispensable for a better understanding of QCD in the confinement regime. New windows for the investigation of hadronic matter are opened by the use of probes with strangeness and charm.

3. NuPECC considers the potential application of highest brilliance ultrarelativistic beams in the production of coherent short wavelength radiation of high intensity to be very promising.

4. NuPECC recommends that appropriate action be taken in order to proceed towards the construction of a European facility providing electron beams of high

Energy	$15 \leq E \leq 30$ GeV
Intensity	$\leq 50\ \mu$A at 15 GeV
Duty Cycle	100 %
$\Delta E/E$ (FWHM)	3×10^{-4} at 15 GeV
$\Delta E/E$ (FWHM)	1×10^{-3} at 30 GeV
ε_x/π (95 % of particles)	≤ 10 mm·μrad at 15 GeV
ε_x/π (95 % of particles)	≤ 300 mm·μrad at 30 GeV
Number of beams	3
Polarization	$\succeq 80\%$

Table B.1: *Parameters of the original ELFE project.*

duty cycle and brilliance in the 15-30 GeV energy range. It should serve scientists from universities and research laboratories as a central users facility.

In order to reach this goal, the following steps need to be taken.

a) Substantial advancement of the state of the art of superconducting RF and cryotechnology is necessary to construct such an accelerator in a cost effective way. NuPECC recognizes that significant progress has already been made. It sees important synergies with the development needed for linear colliders under consideration by particle physicists. During the next few years, an intense joint effort by the European laboratories involved is required to develop the technology further. The technical feasibility of the crucial accelerator components should be established at a testbed facility.

b) An ELFE coordinating group should be formed by the scientific community from the field of interest, with the help of NuPECC if required. This group should coordinate the technical developments needed, and integrate the present experimental programs in electromagnetic physics in order to create an enlarged and coherent community in preparation for the long range future with ELFE. An important aspect of this is the R&D work for the experimental equipment required for the physics proposed.

c) It is important to develop further potential applications, and, in particular those based on coherent radiation produced by the high-brilliance beams."

The requirements of the ELFE experimental program presented at Mainz are given in Table B.1.

A complete project was developped in 1993 using a recirculating superconducting linac of 5 GeV with three passes of the beam through the accelerator. The cost of this facility was estimated to 1759 MFF in 1993 [1]. A new proposal combining TESLA and the HERA ring used as a stretcher (ELFE@DESY) was proposed in 1995 [2]. The principle of ELFE@DESY is the following:

- Short pulses are produced at low frequency (10 Hz) by TESLA and accumulated in the HERA ring until they fill the ring.
- The stored beam is then slowly extracted from the ring over the time period between the accelerator pulses by switching on nonlinear lenses in the ring that induce a controlled beam instability (resonant growing of particle oscillation amplitudes).
- When the ring is empty, new pulses from the accelerator are stored and the extraction process starts again.

Several pulse stretcher rings are in operation: Amsterdam (AmPS), Bonn (ELSA), Kharkov (PSR-2000), MIT-Bates (South Hall Ring) and Saskatoon (EROS). Such rings have been developped to increase the duty cycle of an existing pulsed accelerator. At DESY, the problem is completely different: a ring (HERA) already exists, but it has been designed for *ep* collisions. Furthermore, the superconducting linear accelerator to be built for the TESLA project is designed for e^+e^- collisions. Thus, combining TESLA and HERA is a challenge with many technical constraints. At the beginning of 1996, a group of accelerator physicists from Bonn, DESY, Frascati, Grenoble, NIKHEF and Saclay has explored the possibility of combining TESLA and HERA to produce a beam for the ELFE physics program. The results of this feasibility study are presented in the following sections.

B.2 TESLA as an Injector for ELFE

In principle, TESLA could be operated at low gradient with high duty cycle during this time, yielding an almost continuous electron beam as required for the Nuclear Physics experiments. However, this option is excluded since neither the rf-system nor the beam optics of the TESLA linac are suited for this operation mode.

In order to obtain a beam for ELFE, only a fraction of the TESLA linac is needed, even if the accelerating gradient chosen is somewhat below the design value of 25 MV/m, thus reducing the additional cryogenic load. For the repetition rate to fill HERA a compromise must be chosen between a high peak current in the ring and the stronger requirements for the linac rf-system to accommodate more frequent pulses. We assume here a repetition rate of 10 Hz for the ELFE mode, twice the TESLA design value. Since the same linac section is also used to generate the drive beam for the Free Electron Laser facility at a rate of 5 Hz, this means that the part of the TESLA linac used as the injector for the stretcher ring will be pulsed at a rate of 20 Hz, which seems feasible with moderate modifications of the pulsed rf-power sources. For an extracted beam intensity of 30 μA, the current stored in the HERA ring is 150 mA, which appears possible both from the point of view of rf-system requirements and instabilities in the stretcher ring (see section 4).

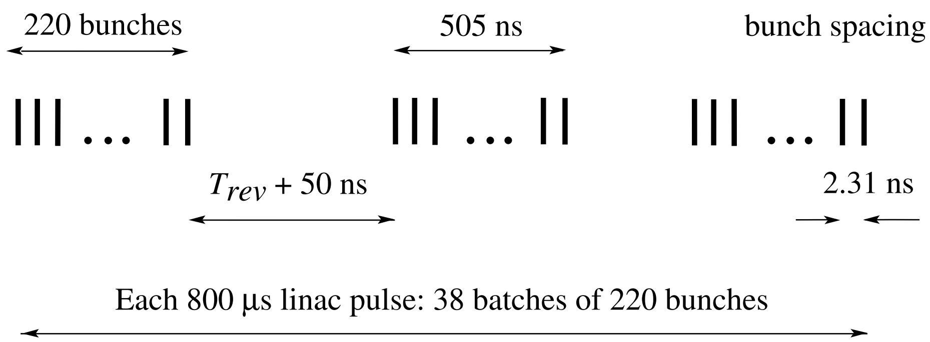


Figure B.1: *Beam pulse structure in the TESLA injector linac.*

The design linac beam pulse length of 800 μs is matched by using a multiturn injection scheme in the ring. The bunchtrain consists of 38 batches of bunches, spaced by the HERA revolution time, $T_{rev} = 21.1$ μs, plus 50 ns to account for the kicker gap (Fig. B.1).

The bunch spacing is chosen as three times the linac bucket spacing, consistent with a 433 MHz rf-system in the ring. A summary of the main parameters for the injector linac is given in Table B.2.

accelerating gradient	13 to 20 MV/m
beam energy	15 to 25 GeV
linac length	2 km
av. beam power	0.47...0.79 MW
beam pulse length	820 μs
bunch spacing	2.31 ns
bunch charge	$2.37\ 10^9 \cdot e^-$
pulse current	3.86 mA
average current	31.6 μA
repetition rate	10 Hz

Table B.2: *Main parameters of the TESLA injector linac for ELFE.*

Concerning the geometrical arrangement of the linac with respect to the HERA ring, the boundary conditions of the DESY site have to be taken into account. The present concept has one end of the roughly 32 km long linear collider close to the experimental hall west of HERA, with the linac being approximately tangential to the HERA straight section. This means that the injector linac for ELFE points away from the DESY site so that the beam has to be extracted approximately 2 km downstream and transported back to HERA (see section B.5). The beam for ELFE can be extracted from the linac beamline by extraction devices which switch the beams between e+e- and ELFE pulses.

B.3 HERA as a Stretcher for ELFE

B.3.1 Transverse optics

Motivation for modification of straight section lattice and optics

The actual layout and optics of the straight sections of the HERA electron ring have been optimized for satisfying the constraints imposed by head on electron-proton collisions:

- Bending magnets are installed in the interaction region in order to direct the beam towards the interaction point (I.P.).
- Strong quadrupoles are employed for obtaining low beta values at the I.P.
- Spin rotators are incorporated into the lattice for producing longitudinal polarization.
- A complex system of collimators is used to reduce the synchrotron radiation from the beam separation magnets to an acceptable level at the detectors.

This complex layout has to be simplified and optimized for the needs of resonant extraction if HERA is to be used as a stretcher ring: all the elements for e-p collisions have to be removed, sextupoles have to be inserted into the lattice at suitable positions with respect to the extraction septum, optical functions have to be properly defined because of their influence on extraction parameters and the horizontal tune must be close to a third-order resonance.

General Description of the Modified Ring

The basic modifications of the straight sections layout have been made after discussions with experts of DESY. All insertions have been replaced by a simple FODO array and two dipole doublets have been installed at each arc extremity in order to preserve the existing tunnel geometry (Fig.3).

The ring has now a fourfold symmetry in order to reduce the number of systematic resonances and the straight section optics is optimized for meeting the constraints imposed by injection, extraction and eventual utilization of existing experimental halls. The FODO array is composed of matched optical modules which provide a great flexibility for machine tuning and performing specific tasks:

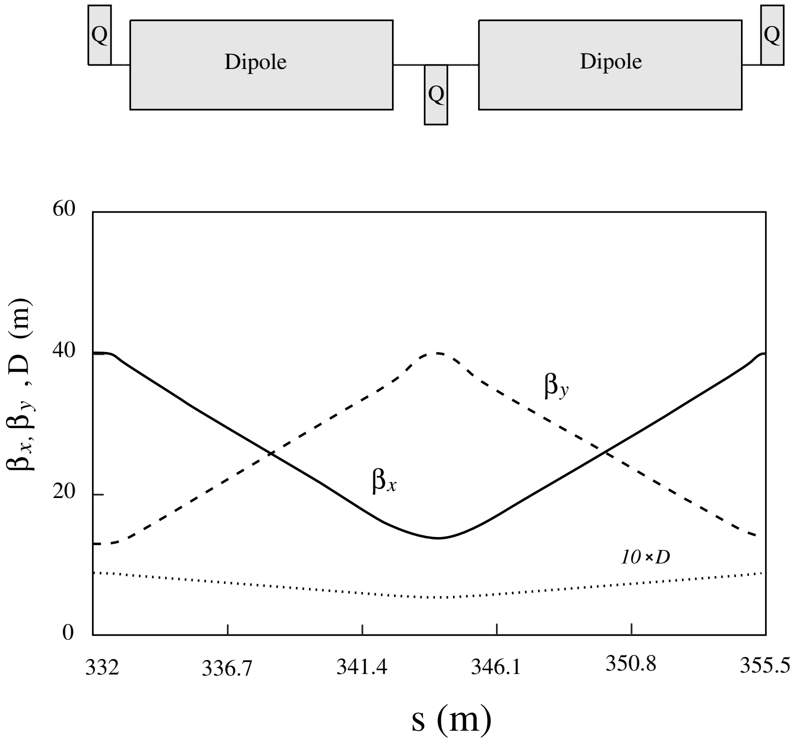


Figure B.2: *Optical functions for one FODO cell of the arcs.*

- Dispersion suppressors ensure the transition between the arcs and the straight sections where the dispersion is zero.
- A high beta insertion produces large and constant beta function in the horizontal plane at the sextupoles driving the resonance and at the extraction septum.
- A sequence of identical FODO cells with adjustable betatron phase advances provides the means of controlling the machine tunes.

In the arcs, the original optics has been maintained because the phase advance of about 60^0 per FODO cell has the desirable effect of minimizing the non linear perturbations induced by sextupoles dedicated to chromaticity correction. Sixteen independent quadrupole families are required to adjust the optical functions in the different subsystems of the ring.

Lattice parameters

The general parameters of the modified HERA electron ring are listed in Table 1 and the optical functions for one FODO cell of the arcs are shown in Fig. B.2.

The value of the horizontal tune has been chosen near the non systematic resonance $3Q_x = 127$, which will be excited for slow beam extraction by dedicated sextupoles placed in the high beta insertions.

Machine length	$L = 6335.768$ m	
Number of periods	$N = 4$	
Tunes	$Q_x = 42.335$	
	$Q_y = 47.402$	
Optical functions	At extraction septum	Maximum
	$\alpha_x = 0 \quad \beta_x = 100.3$ m	$\beta_x = 100.5$ m
	$\alpha_y = 0 \quad \beta_y = 15.1$ m	$\beta_y = 58.5$ m
	$D' = 0.0 \quad D = 0.0$ m	$D = 1.1$ m
Momentum compaction	$\alpha = 6.775 \times 10^{-4}$	
Natural chromacities	$\xi_x = -49.697$	
	$\xi_y = -53.341$	
	15 GeV	25 GeV
Energy loss per turn	$U_0 = 7.4$ MeV	$U_0 = 57$ MeV
Natural emittance	$\varepsilon_x/\pi = 12$ mm·μrad	$\varepsilon_x/\pi = 32$ mm·μrad
Natural energy spread	$\sigma_p/p = 5.1 \times 10^{-4}$	$\sigma_p/p = 8.6 \times 10^{-4}$
Damping times	$\tau_x = 93.3$ ms	$\tau_x = 20$ ms
	$\tau_y = 86$ ms	$\tau_y = 19$ ms
	$\tau_s = 41$ ms	$\tau_s = 9$ ms

Table B.3: *Main ring parameters.*

In the absence of specific constraints, the vertical tune has been kept in the vicinity of its original value. Other tunes can be achieved. For $Q_x = 46.335$ and $Q_z = 47.4$ for instance, the ring characteristics are not very different from those presented in Table B.3.

The design considerations discussed in the previous paragraph are illustrated by Figs. B.3 and B.4 which give a top view of the simplified straight section layout and the β functions in this region respectively.

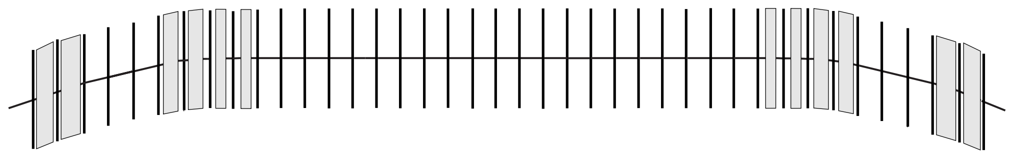


Figure B.3: *Layout for one straight section.*

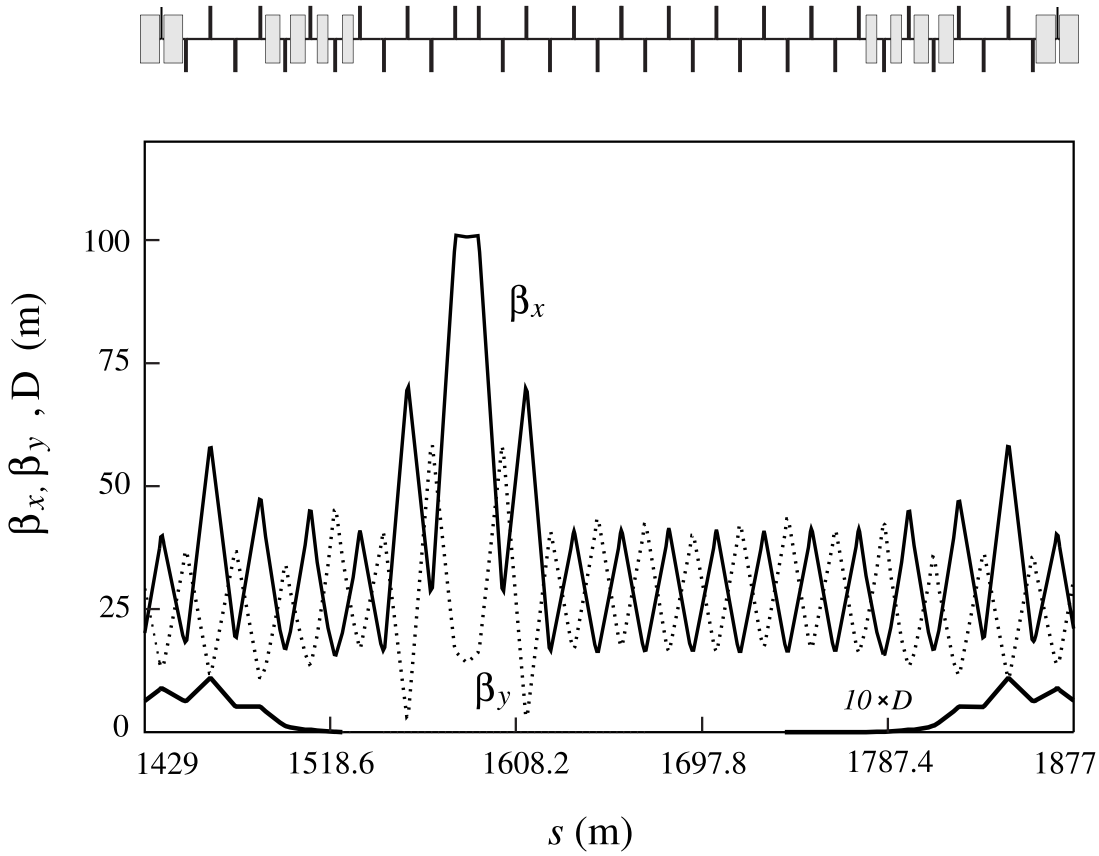


Figure B.4: *Details of the optical functions for one straight section.*

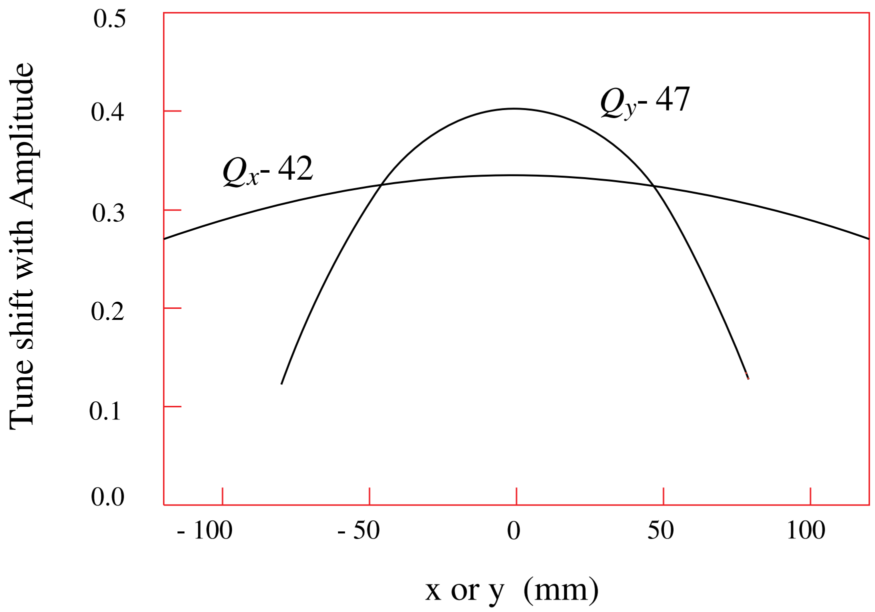


Figure B.5: *Horizontal and vertical tune shifts with amplitude.*

The high β insertion where the beam is extracted by a thin electrostatic septum is placed just downstream the dispersion suppressor. With this configuration, a free length of about 50 m is available for accommodating the extraction channel required for directing the beam towards the existing experimental hall located in the center of the straight section. It has to be noticed that the vertical beta function is only 15 m at the center of the horizontal high β insertion in order to reduce non linear coupling due to extraction sextupoles which will be installed in two opposite straight sections at 90° in angle from the extraction septum.

Issues related to non linear beam dynamics have been investigated with the simulation codes BETA and MAD. The results presented hereafter do not apply to the case where the resonance $3Q_x = 127$ is excited because the extraction sextupoles are supposed to be switched-off. The only source of non linear fields results from sextupoles located in the arcs which are used for cancelling the natural chromaticity of the ring.

Under these conditions, the non linear lattice performances can be summarized by Figs. B.5 to B.8 which display the following results calculated at the center of the high beta insertion:

- Horizontal and vertical tune shifts with amplitude (Fig. B.5).
- Dynamic aperture (Fig. B.6).
- Variation of tunes with momentum deviation (Fig. B.7).
- Variation of beta functions with momentum deviation (Fig. B.8).

As can be observed, the lattice presents excellent properties from the point of view of beam dynamics. The machine parameters are almost not affected by the presence of

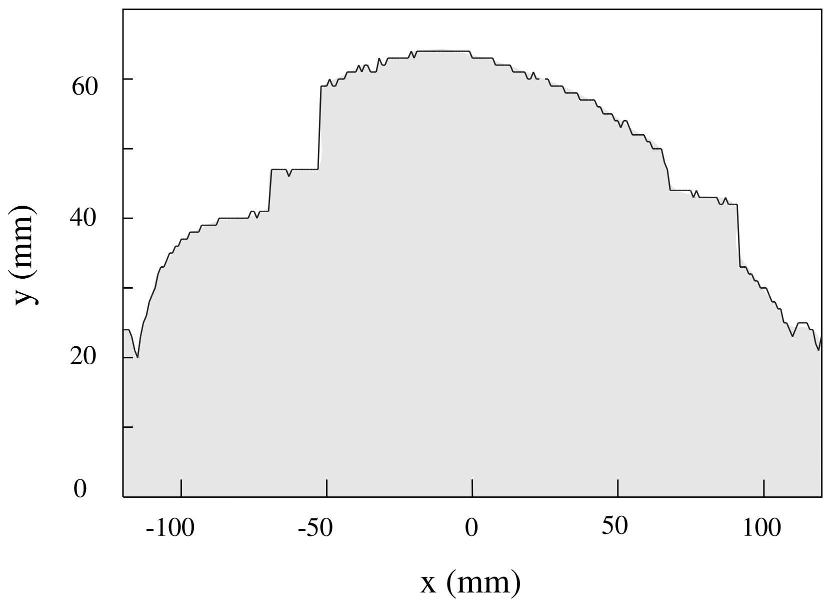


Figure B.6: *Dynamic aperture.*

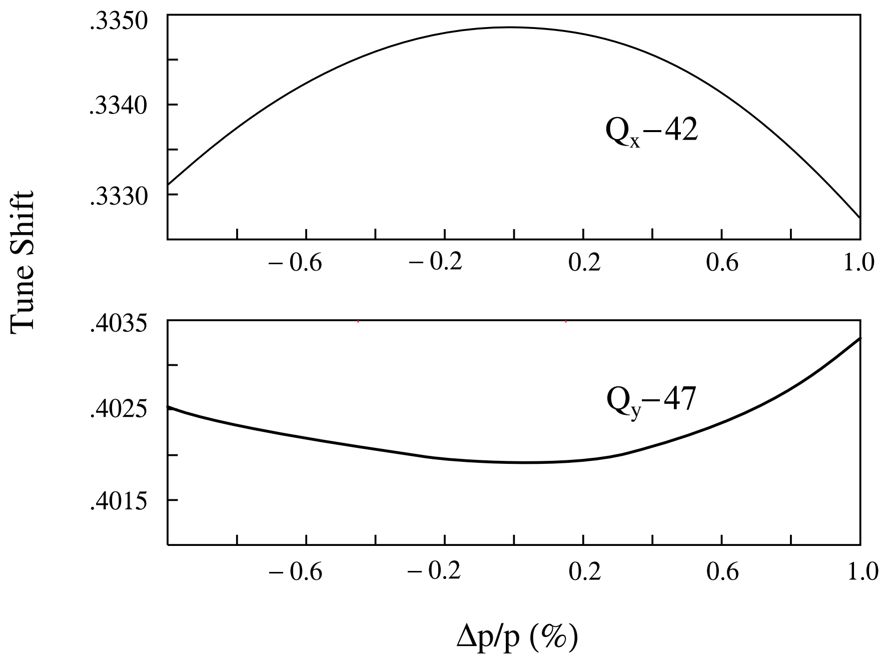


Figure B.7: *Variation of tunes with momentum deviation.*

chromaticity correcting sextupoles even in the case of very large oscillation amplitudes and momentum deviations.

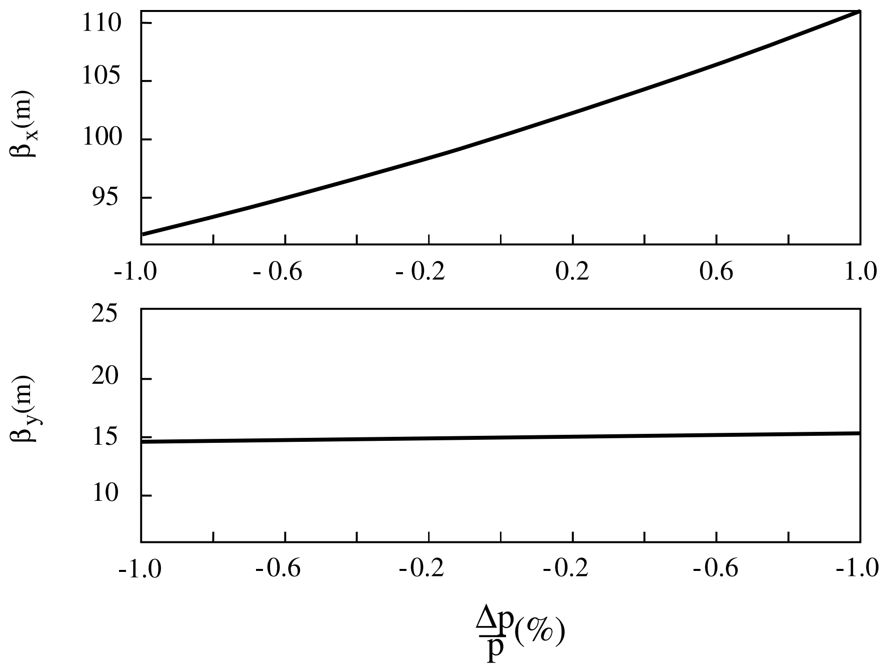


Figure B.8: *Variation of beta functions with momentum deviation.*

B.3.2 Transverse Beam Polarization

The production of a polarized electron beam is one of the requests formulated in the specifications of the ELFE project. Therefore, the effect of depolarizing resonances in the HERA ring has to be considered. The beam depolarization occurs in circular accelerators when the spin tune $\nu = \gamma a$ (a being the gyromagnetic anomaly and γ the Lorentz factor) is such that the following resonance conditions are approached:

$$\nu = mQ_x + nQ_y + pQ_s. \tag{B.1}$$

There are in fact two main categories of depolarizing resonances:

- Imperfection resonances which are induced by field errors generating vertical closed orbit distortions and which are encountered whenever ν is an integer.
- Intrinsic resonances which are driven by vertical betatron oscillations in quadrupole focusing field and which occur when $\nu = n \pm Q_y$ (n being a multiple of the number of periods of the ring).

In synchrotrons where electrons are accelerated, depolarizing resonances cannot be avoided because γ increases with time. For instance, imperfection resonances are crossed whenever the total electron energy is a multiple of 440.65 MeV. It is thus absolutely necessary to develop corrections methods in order to preserve the initial beam polarization.

In a storage ring, the energy of the beam is constant. Therefore, the polarization of the beam is preserved if one chooses a beam energy that avoids the vicinity of resonances in the ring. It follows that some energies are forbidden, because they correspond to imperfection resonances. Under these conditions and provided that resonance strengths have been minimized, one expects good transverse polarization for the ELFE beam.

In the case of the present HERA e-ring, transverse polarization is of the order of 70% [3]. The beam polarization is created by the polarization properties of the emitted synchrotron radiation over long storage times (Sokolov-Ternov effect). The theoretical maximum polarization by this effect without the influence of depolarizing resonances is 92.4%, achieved in several hours.

This process takes a long time to build up a high value of the polarization. Thus, for extracting a highly polarized electron beam from HERA, it is imperative to inject a beam already polarized and avoid the vicinity of resonances in the ring. In this case, the beam polarization will be mainly determined by the source performance because there are no depolarizing effects in the linac. Polarized electron sources deliver beams with up to 90% polarization by utilizing strained GaAs crystals. Intense activity to improve the efficiency and the life time of these sources is being pursued in several laboratories.

B.4 RF System

At 25 GeV the cavities have to supply 90 MV and 8.5 MW continuously to a beam of 150 mA. The choice of the frequency is a compromise between the physics request for a high duty cycle and the possibility of adapting existing klystrons to the required power level per unit in CW operation. The chosen frequency is 433.33 MHz, i.e. the third subharmonic of the TESLA 1300 MHz. A frequency close to 500 MHz offers moreover the advantage of exploiting already developed bunch to bunch feedback systems, which are, as it will be shown, absolutely necessary to counteract multibunch instabilities.

Various types of cavities have been considered, single cell or multicell, normal conducting (NC) or superconducting (SC). In order to make a comparison we have to set a limit of $\simeq$ 200 kW for the power that can be carried by each fundamental mode coupler. Both coaxial and waveguide couplers have been tested up to 300 kW in matched conditions, but in our case there will be relevant reflected power during part of the cycle. Because of this limit, multicell cavities have to be operated at much lower voltage than their capability and therefore are not competitive with single cells. Moreover, NC single cells supply about one third of the voltage that can be given by SC ones, and dissipate on their walls more power than is given to the beam. In Table B.4 we show a comparison between the various solutions.

The choice falls therefore naturally on SC single cells, which are also advantageous for HOM damping.

Table B.5 summarizes the characteristics of the chosen RF system. Figure B.9 shows the shape of a section of the cell. One klystron supplies power to a group of

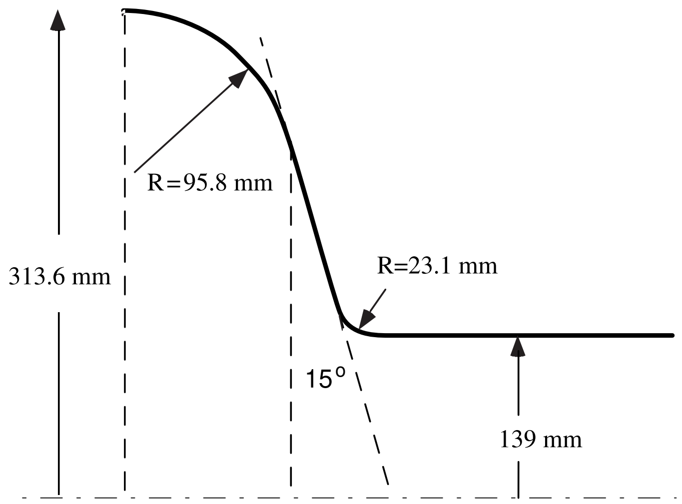


Figure B.9: *Cavity shape.*

	NC multicell	SC multicell	SC -1 cell
Voltage/cavity	2.25 MV	2.25 MV	2.25 MV
Number of cavities	40	40	40
Power dissipated	4.2 MW	320 W@ $Q = 10^9$	2500 W

Table B.4: *Comparison of various solutions for the RF system.*

four cavities. Each klystron will be separated from the load by a circulator capable of absorbing 400 kW reflected power when beam loading is absent. The power will be distributed to the cavities by magic tees or directional couplers in cascade.

The coupling factor in matched condition is $Q_{ex} = 3.5 \cdot 10^5$. It is known that, in order to avoid Robinson instability, one must either decrease the Q_{ex} below the matched value, at the expense of extra power, or implement a feedback that stabilizes the cavity voltage. As cavities are powered in groups of four, only the vector sum of the

Beam current	150 mA
Voltage / cavity	2.25 MV
Number of cavities	40
Power / cavity	210 kW
Cavities / klystron	4
Power / klystron	1 MW
Fundamental R/Q	100 Ω
Fundamental Qex	$3.5 \cdot 10^5$

Table B.5: *RF system parameters.*

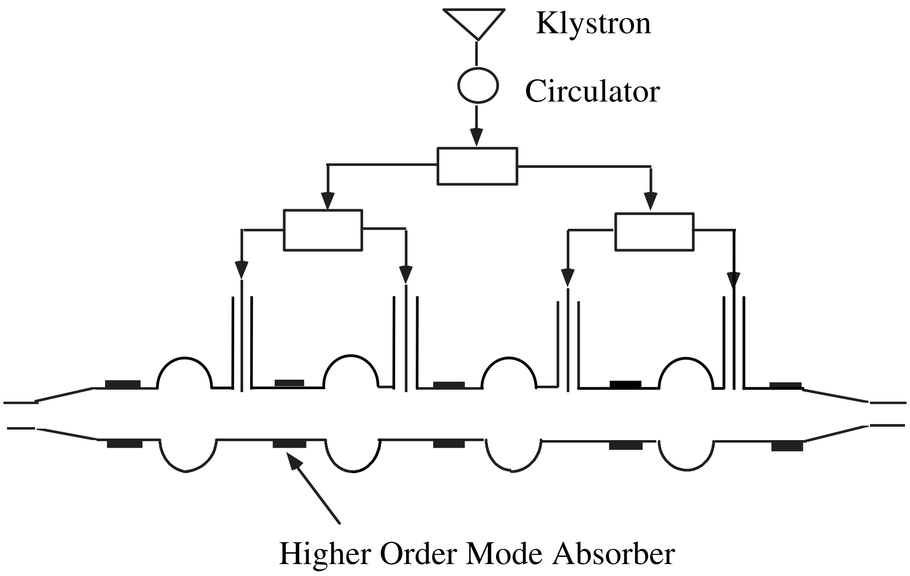


Figure B.10: *RF system module.*

voltages can be stabilized. This, however, together with a slightly lower Q_{ex} than the matched one, should be sufficient to avoid the instability, which anyhow would regard only the initial current peak during the extraction cycle.

At injection, when beam current and power are maximum, the cavities should be detuned so as to compensate the beam loading, in order to minimize the reflected power. This detuning will be constant during the cycle, because the 100 ms cycle period is too short for a mechanical system to respond. This causes an enhancement of the reflected power with respect to the compensated value. As the cavities could have different voltages, this detuning should be optimized for each cavity by minimizing the reflected power at injection. The tuning system of each cavity will be designed so as to respond only to slow average variations of the cavity tune. For this purpose, after reaching the maximum value of its current, the beam should be stored for about 1 ms before the beginning of extraction to allow sampling of phase difference between incident wave and cavity voltage after transients have died out.

Operation at lower energies would be performed by reducing the number of active cavities (at 15 GeV a group of four would be sufficient). The other ones would be strongly detuned so as not to have beam interaction with the fundamental mode.

The loss factor is very low, of the order of 0.1 V/pC, which means that the beam loses about 5 W per cavity to HOMs. This makes it easier to absorb the power for mode damping. Figure B.10 shows a possible cavity grouping used to lower losses from tapers.

B.4.1 Coupled-bunch Collective Effects.

The high current and the large number of bunches in the ring make collective coupled-bunch effects important, such as to constitute a limiting factor to the attainable current value. For longitudinal bunch oscillations, the higher order modes (HOM) of the RF cavities are the main sources of driving impedances. For the transverse bunch oscillations, both the RF cavities and the resistive wall (RW) of the vacuum chamber are important.

Tables B.6 and B.7 give the limiting HOM impedance values which cause a rise time equal to the radiation damping one, for the various types of instabilities. To interpret this table and to have a feeling of where we stand with our proposed RF system for HERA, we need a rough idea of the order of magnitude of the impedances.

For longitudinal instabilities we can assume for one HOM an impedance of 2 kΩ for each cavity. In the worst assumption, that the effects of all cavities add linearly, this makes 80 kΩ for 40 cavities. For transverse impedances we can assume similarly an impedance value of 20 kΩ/m per cavity. This makes 800 kΩ/m for 40 cavities.

As for RW effects, for a copper vacuum chamber of 4 cm lower dimension and 6.3 km length, the resulting impedance gives, at 15 GeV, a rise time which is about an order of magnitude lower than the radiation damping one. The consequence is that transverse bunch to bunch feedback is absolutely necessary. In any case, it is advisable to foresee also a longitudinal bunch to bunch feedback, as parasitic impedances of other devices on the beam trajectory may cause the overall impedance to rise above the limit.

From Tables B.6 and B.7 and taking into account an increase of a factor 3 in damping rate due to "overshoot"phenomena [4, 5], one finds that a damping time of 3 ms is sufficient. The realization of the feedback system is challenging due to the high number of bunches ($\simeq$ 9000) and low interbunch time (2.3 ns) which imposes a bandwidth larger than 250 MHz to the electronics. One can however profit by the recent developments of similar systems for the SLAC and KEK B-factories.

The system developed for PEP-II with 1700 bunches [6] and for DAΦNE with 120 bunches, has been tested successfully with 350 bunches and 400 mA on the ALS. This system is modular, so an extension to 9000 bunches seems only a matter of cost. The use of the "down-sampling" technique, which is also applicable in ELFE (at 15 GeV the synchrotron wave number is 0.03), reduces the number of parallel processors.

The system under development at KEK-B [7] is designed for 5000 bunches. The electronics have already been tested on the Accumulator Ring.

It must also be considered that in ELFE the maximum current would be kept only for about 1 msec and then would drop linearly to zero within 100 ms.

From these considerations we can conclude that a goal of 150 mA, with the above assumptions, is challenging but not unreasonable, eventually limiting the number of bunches to about 4500 in a first phase. A suitable feedback system must be developed with an adequate R&D effort, starting from the experience of the above mentioned

developments.

Energy	15 GeV
LONGITUDINAL	
τ radiation	41.4 ms
$Re[Z(\omega)] \rightarrow \tau$ antidamping	120 k$\Omega \rightarrow$ 43.5 ms
TRANSVERSE	
τ radiation	92.4 ms(x) 85.9 ms(y)
Re[Z(ω)] $\rightarrow \tau$ antidamping	2 MΩ/m $\rightarrow$ 97 ms(x) 99 ms(y)
RESISTIVE WALL	
τ antidamping	10 ms(x) 10.3 ms (y)

Table B.6: *Limit values of impedance for stability.*

Energy	25 GeV
LONGITUDINAL	
τ radiation	8.9 ms
$Re[Z(\omega)] \rightarrow \tau$ antidamping	1.5 M$\Omega \rightarrow$ 9 ms
TRANSVERSE	
τ radiation	20.1 ms 18.6 ms
Re[Z(ω)] $\rightarrow \tau$ antidamping	16 MΩ/m $\rightarrow$ 20.2 ms 20.7 ms
RESISTIVE WALL	
τ antidamping	16.7 ms 17.2 ms

Table B.7: *Limit values of impedance for stability.*

B.4.2 Bunchtrain Energy Spread Compensation

One has to compensate for beam loading in the injection linac, which causes an energy sag varying exponentially up to 0.5%, with a long time constant $\backsimeq$ 1 ms, so that on the 500 ns time scale of the injection batch it can be considered linear.

This compensation can be done either by a normal conducting overcoupled linac structure with 1 μs filling time or [2] using the method successfully tested at KEK linac, by making the beam "see" a beat wave on μs time scale by interaction with an RF structure powered at a slightly different frequency (e.g. 0.25 MHz) from that of the main TESLA linac.

The SC solution looks simpler, as it requires a standard TESLA module. The frequency difference of 0.25 MHz is within the tuning range of the TESLA 1.3 GHz cavities, so that no new structure has to be developed.

The sag voltage is 0.005×25 GeV = 125 MeV, but as the beat waveform is sinusoidal, one needs at least 1.4$\times$ 125 MV to keep the error in compensation with respect to the linear sag below 10^{-3}. This can be achieved with a standard TESLA module (8 cavities at 20 MV/m).

The effect of beam loading is negligible, as it causes a percent variation of the percent sag (i.e. an effect of the order of 10^{-4}).

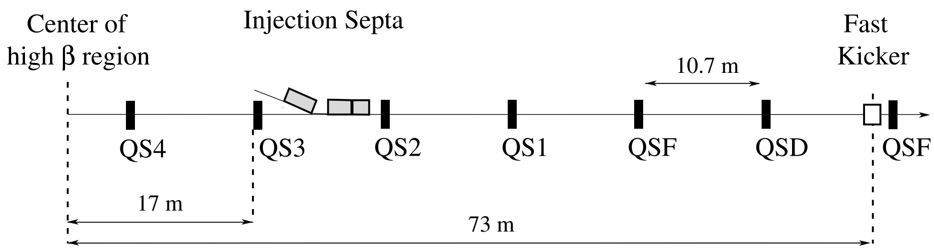


Figure B.11: *Layout of the injection system.*

B.5 Injection System

This section describes the injection scheme of the TESLA beam into the HERA electron ring. A second part is devoted to some considerations about the transfer line itself.

B.5.1 Injection Scheme

The electron beam delivered by TESLA has to be stored for a time of the same magnitude than the damping time of the HERA machine. Consequently, the injection has been studied by making some realistic hypotheses:

- The beam emittances (transverse and longitudinal) are the ring equilibrium emittances. Considering that TESLA emittances are negligible, one may get these emittances by means of synchrotron radiation in the transfer line between TESLA and HERA (see paragraph 5.2), as proposed in [2].
- The maximum beam energy is 25 GeV.
- The beam is injected on-axis. An off-axis injection, giving a hollow beam, is much more difficult to do and does not lead to any advantage. It will not be considered here.
- The beam is injected in a straight section and just downstream of the high β region.

The layout of the injection is shown in Figs. B.11 and B.12. The origin is the middle of the high β region. A first magnetic dipole MD1 and two magnetic septa (MS1 and MS2) are installed one meter upstream of the third quadrupole. The beam is injected there at a distance x_0 from the reference orbit of HERA and makes some oscillations down to a fast kicker which puts the beam on axis. This kicker is located one meter upstream of the fifth quadrupole. If M is the transfer matrix between the injection point and the kicker, the classical relations have to be fulfilled:

Injection angle (exit of MS2):

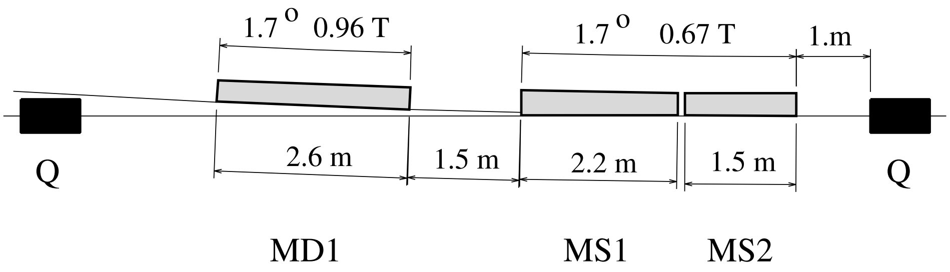


Figure B.12: *Details of the injection system.*

$$\Psi = -\frac{M_{11}}{M_{12}}x_0, \tag{B.2}$$

Kick:

$$\Delta x' = \frac{x_0}{M_{12}}. \tag{B.3}$$

The following technological assumptions are made:

- Working energy: up to 25 GeV.
- The septum thickness is supposed to be 15 mm and the beam is injected at $x_0 = 30$ mm from the HERA axis.
- The beam separation (HERA beam, injected beam) is 400 mm at QS3.

This scenario leads to the injection characteristics:

- Injection angle: $\Psi = 1.16$ mrad.
- Kick: $\Delta x' = 0.6$ mrad.
- The characteristics of the static elements of the proposed injection system are summarized in Table 8.
- The magnetic kicker is specified in Table 9. It will be powered by a kicker power supply.

The kicker power supply will be complex and large. Although the required energy in the kicker is modest (Table 10), the requirements for the switching element are indicated in Table 11. It cannot be handled by a single thyratron. A comparison with the requirements for klystron modulators indicates that a modular solution with a number of switchers will lead to a feasible design. The size and complexity of the kicker power supply will be comparable to the klystron modulators used in the NIKHEF linear electron accelerator (MEA).

Element	Field	Angle	Length
Magnetic dipole MD1	0.96 T	1.7 deg	2.6 m
Magnetic septum MS1	0.67 T	1.1 deg	2.2 m
Magnetic septum MS2	0.67 T	0.7 deg	1.5 m

Table B.8: *Summary of the injection dipole parameters.*

Energy	25 GeV
Magnetic field	0.05 T
Length	1 m
Kicker aperture	2 cm $\times$ 5 cm
Coil current (for a single turn magnet)	1600 A
Coil voltage (for a single turn magnet)	20 kV

Table B.9: *Kicker specification.*

B.5.2 Transfer Line

In this paragraph, we will make some comments about the beam transport from the TESLA linac to the HERA ring. Obviously, the scheme will depend on the layout possibilities for TESLA and is not yet well known. A possible scheme is illustrated in Fig. B.13, and its main features are the following:

- The TESLA source is not far from the HERA ring.
- The beam is extracted from the TESLA linac somewhere downstream.
- A "return loop" is used to send the beam back to HERA by using the TESLA tunnel. This return loop could be installed in the tunnel planned for the damping ring.
- The beam is injected into HERA.

We have assumed that the TESLA emittances are negligible in comparison to those of HERA. The optics of the return loop will be designed in order to generate the equilibrium values of the HERA emittances by synchrotron radiation.

Energy in pulse	1.6 J
Pulse width	500 ns
Rise and fall time	50 ns
Repetition rate	380 Hz (10 bursts, 380 pulses/s)
Burst duration	0.8 ms
Burst macro period	60 ms

Table B.10: *Kicker power supply specifications.*

Peak power	32 MW
Heating factor	12×10^9 J/s
Switching time	50 ns
Pulse duration	500 ns
Pulse recurrence (timing scheme)	21.07 s
Jitter over the 800 s beam pulse	< 5 ns

Table B.11: *Switching system.*

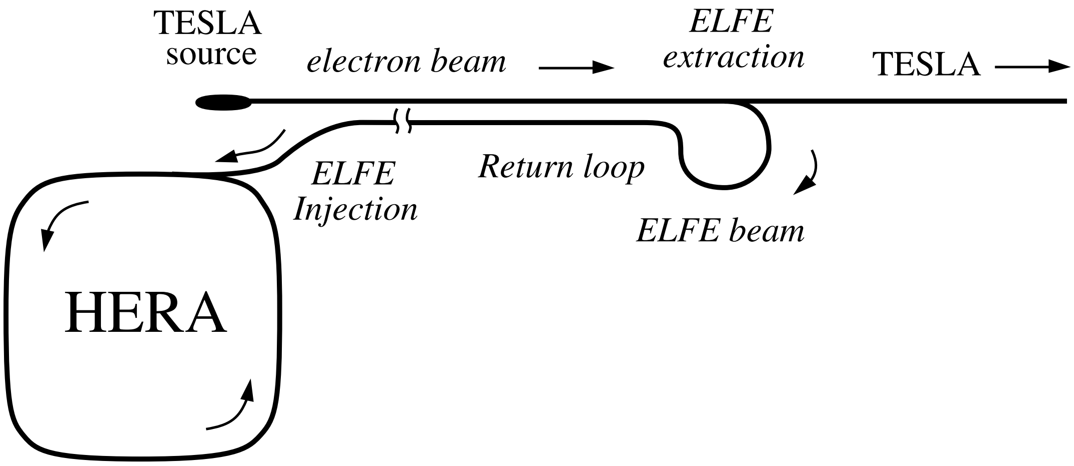


Figure B.13: *Possible scheme of the beam transport.*

The energy spread created by synchrotron radiation depends on the bending radius and angle, and thus is fixed by the geometrical layout of the return loop, whereas the created emittance also depends on the optics of the loop (characterized by the lattice invariant $< H >$).

The bending radius of the transfer line is set to 80 m to fit into the damping ring tunnel. The emittance can then be matched by using the periodic FODO cells with a distance of 8.5 m between the quadrupole centers. This structure will have to be tuned at 110° phase advance per cell at 25 GeV and 55° per cell at 15 GeV, which is possible and will give the required value for $< H >$. The maximum gradient then will be around 17 T/m for 1 m long quadrupoles. The energy spread and emittance created by the return loop are given in Table B.12.

Since the energy spread cannot be matched in this way, a wiggler has to be put into the straight section of the transfer line to give the needed flexibility to match both emittance and energy spread.

Energy E	15 GeV	25 GeV
Bending radius ρ	80 m	80 m
Dipole Field Strength B	0.625 T	1.04 T
Resulting Energy Spread $\sigma(\frac{\Delta E}{E})$	$1.7 \cdot 10^{-4}$	$6.3 \cdot 10^{-4}$
Energy Spread of HERA $\sigma(\frac{\Delta E}{E})$	$5.1 \cdot 10^{-4}$	$8.6 \cdot 10^{-4}$
Lattice invariant $\langle H \rangle$	0.79 m	0.17 m
Resulting Emittance ϵ_x/π (mm$\cdot\mu$rad)	12	32
Equilibrium Emittance of HERA ϵ_x/π (mm$\cdot\mu$rad)	12	32

Table B.12: *Characteristics of the return loop at 15 and 25 GeV.*

We can see that no fundamental problem arises and that the achievement of injection emittances close to the equilibrium values seems to be possible.

B.6 Extraction

B.6.1 Extraction Methods

One of the most crucial problems of a stretcher ring is the beam extraction. There are some choices to be made in order to define the optimal scheme from the point of view of the extracted beam performances, in terms of emittance, energy spread and duty factor. The method usually applied is resonance extraction which consists in switching-on nonlinear fields in the ring in order to excite a betatron resonance. Particle motion thus becomes unstable and there is a resonant growth of oscillation amplitudes.

The betatron instability may be a half integer or a third integer resonance. In our case, the third order resonance has been chosen, because it is weaker than the half integer resonance and in principle, allows a better control of the spill over the foreseen extraction time of about 100 ms. This choice implies that the working point is chosen to be near a non systematic third order resonance driven by dedicated sextupoles.

The transverse phase space is thus divided into two parts: a stable region having a triangular shape enclosed by the so-called separatrices, and an unstable region located outside the separatrices. Particles having initial conditions in the unstable region move along separatrices with larger and larger amplitudes until they are deflected by the extraction septum and guided into the extraction channel (Fig. B.14).

The distance between two adjacent points on the separatrix is called the pitch. Its value depends on the size of the stable region and on the optical functions of the machine. It increases rapidly turn after turn. The area of the stable region is determined by the distance between the actual machine tune and the resonant tune, the strength of the sextupoles and the beta function at the sextupoles. One way to extract all particles is to move slowly the tunes of the individual particles towards the resonance. The stable area thus shrinks to zero and unstable motion results for all particles. In the case of HERA, we must also consider the effect of synchrotron

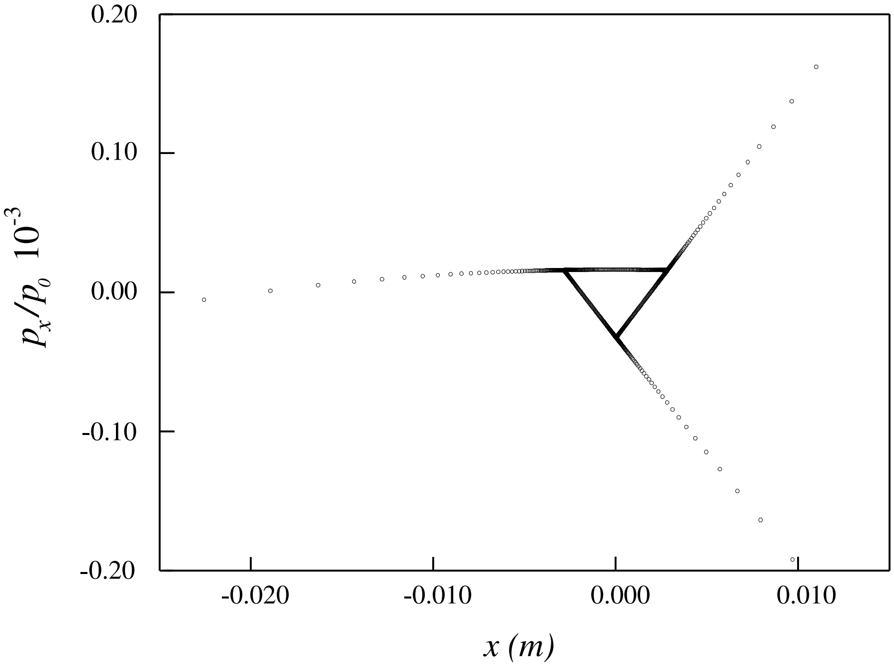


Figure B.14: *Particle trajectory just outside of stable region.*

radiation which produces a noise and ejects particles from the stable area.

However, it is sometimes difficult to empty completely the ring with these methods. Therefore, when the extraction time is considerably shorter than the radiative damping time, the linac beam can be injected off-axis in order to create an "hollow beam" in phase space. In this case, the triangle does not need to be shrunk to zero to make all particles unstable. This method cannot be used in HERA, because the extraction time is too long as compared to the horizontal damping time.

The emittance of the extracted beam is determined by the pitch at the septum and by the angular spread of particles. A high extraction efficiency can be achieved by using a septum as thin as possible. Extraction can be accomplished chromatically or achromatically. In the first case the tune depends on particle energy. Therefore phase space triangles associated with particles having different energies have different sizes. The advantage of this method is that the energy spread of the extracted beam can be made significantly smaller than that of the stored beam in the absence of strong synchrotron radiation, but the emittance is roughly equal to that of the stored beam.

With achromatic extraction, the tune is made independent of electron energy and the size of the stable region is the same for all particles. The extracted beam has a smaller emittance, but its energy spread is that of the stored beam.

B.6.2 Parameter Choice

The extraction channel has to direct the extracted beam towards the inner side of the ring, because existing experimental halls have more space in this direction.

As proposed in [2], the septum has been placed at a distance of 2 cm from the axis and the pitch has been fixed to 4 mm. This choice takes into account the geometry of the existing vacuum chamber of HERA and corresponds to a good balance of the extracted emittance and extraction efficiency (99 % for a septum thickness of 50 μm).

In order to minimize the beam envelope during extraction and to reduce the separatrix curvature, extraction sextupoles have been placed in two opposite straight subsections at 90^0 in angle from the extraction septum (or 30° modulo 360° in betatron phase from the septum).

The beta function at the septum and at the sextupoles has been fixed to 100 m in order to minimize the sextupole strength and to obtain the maximum beam envelope at the septum.

Finally, the distance to the resonant tune and the sextupole strengths have been determined to obtain the right pitch and to fit the area of the stable region equal to four times the equilibrium emittance of the stored beam (Figure B.15 and Table B.13).

Since the values of the chosen tunes are relatively close to the third integer resonance, tune oscillations induced by the ripple of the quadrupole power supplies may produce intensity modulations of the extracted current. Indeed, the measured full width of the tune ripple of HERA is about 0.002 with a dominating frequency of 50 Hz. A correction system is necessary to minimize the ripple to less than 10% of this value. A feedback system, which measures the tune, compares it with the wanted one, and corrects it with small extra quadrupoles, should be able to do this with little expenditure.

Energy	15 GeV	20 GeV	25 GeV
Horizontal tune Q_x	42.334857	42.335390	42.336006
Sextupole strength $H \times l$ [m^{-2}]	0.0569	0.0576	0.0587
Emittance of stored beam ϵ_x/π [mm·μrad]	11.70	20.80	32.48
Energy spread of stored beam $(\Delta p/p)_{rms} \times 10^{-4}$	5.136	6.848	8.559

Table B.13: *Parameters for extraction.*

B.6.3 Tracking Simulations

For an estimation of the performance of the extraction from HERA various particle tracking simulations, using the MAD [10] and BETA programs, have been performed. From these simulations can be derived the emittance and the energy spread of the

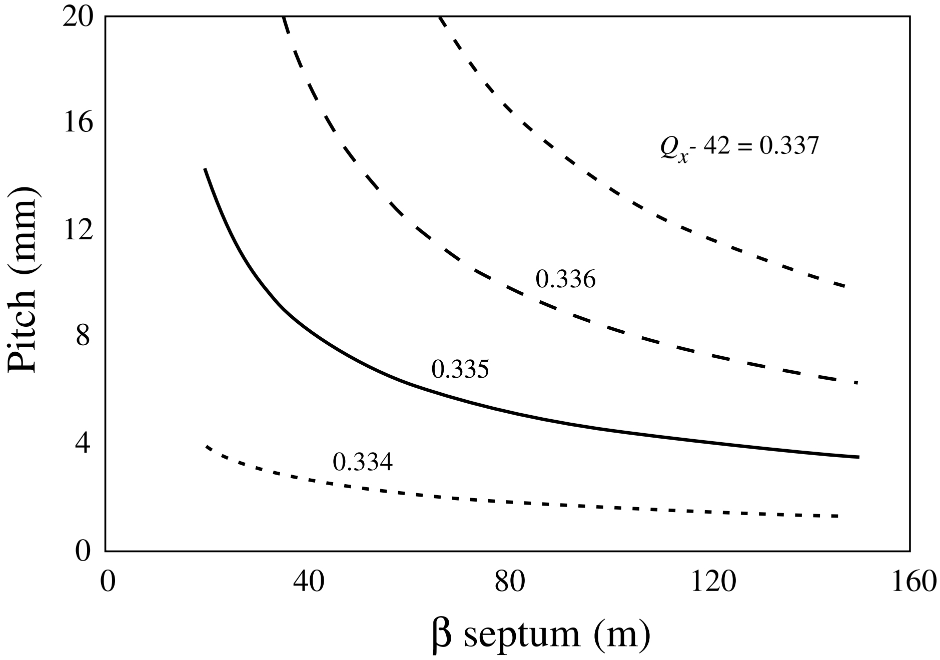


Figure B.15: *Pitch as function of β at septum and tune.*

extracted beam, as well as the intensity of extracted particles during an extraction cycle.

Since the damping times are smaller than the extraction time, the performance of the beam extraction at the end of the extraction cycle is influenced by the equilibrium emittance and energy spread of a stored beam in HERA, whereas at the beginning it is defined by the injection parameters. To avoid a transition between the two states, which would affect the duty cycle, it is preferable to inject the beam with emittances equal to the equilibrium values.

Therefore, in the simulations sets of 1000 particles were injected with gaussian distributions with equilibrium emittances along the axis and tracked for about 4700 turns, corresponding to the extraction time of 99.2 ms. Tune ramps induced by pulsed quadrupoles and ramps of the RF phase could be applied. The model used in these simulations included the effects of synchrotron radiation, which proved to be very important.

The results are shown in table B.14. In contrast to the values given in the preeceding tables for $\simeq$ 39% of the particles, *the emittances given here correspond to 90% of the extracted beam.* The energy spreads are FWHM values. The statistical uncertainties quoted are determined by the number of particles used in the simulations. The column marked "efficiency" is the number of particles extracted during the tracking simulation.

Of these particles one to two percent are lost on the septum, as might be expected from the ratio of septum thickness to pitch.

The horizontal tunes are chosen so that the spill shapes become almost constant without detailed optimization: $Q_x = 42.33486$ for 15 GeV, $E_x = 42.33565$ for 20 GeV, $Q_x = 42.33667$ for 25 GeV.

In Fig. B.16 (a) one can see the resulting spill signal of the tracking run of the 15 GeV, achromatic static case. The x, p_x and $\Delta p/p$ values of the extracted particles are shown in Figs. B.16 (b) to B.16 (d). In Figs. B.16 (e) and B.16 (f) a linear tune ramp towards the resonance is applied, and it can be seen that the p_x coordinates move corresponding to the tune change.

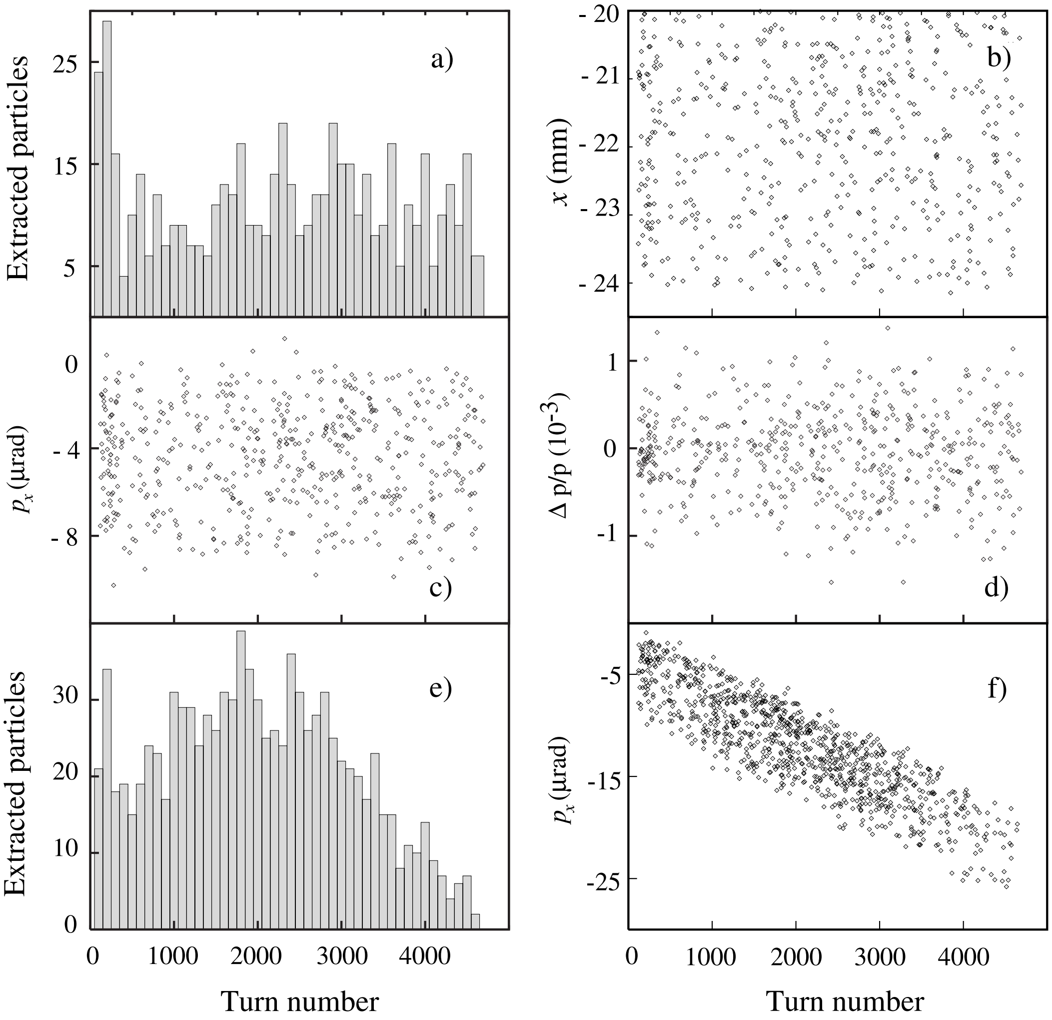
As the vertical natural emittance of the machine without coupling elements and alignment errors is zero, the simulation results do not include the influence of vertical motion. Compared to other effects, the influence of vertical motion is rather small. To check this, a simulation has been performed with a vertical emittance of one percent of the horizontal emittance, induced by linear coupling. There is no significant change in the emittance of the extracted beam.

Energy	Chromaticity	Mode	Efficiency	ϵ_x/π (90% of beam)	$(\Delta p/p)_{FWHM}$
GeV				mm$\cdot\mu$rad	$\times 10^{-3}$
15	zero	static	53.3 %	3.75 ± 0.16	1.19 ± 0.05
15	zero	coupling	57.1 %	4.07 ± 0.17	1.21 ± 0.05
15	zero	tuneramp	98.4 %	3.94 ± 0.13	1.14 ± 0.04
15	+10	static	43.0 %	90.81 ± 4.38	0.96 ± 0.04
15	+20	static	30.1 %	128.0 ± 7.38	0.69 ± 0.04
15	+30	static	21.2 %	133.8 ± 9.19	0.53 ± 0.04
15	-10	static	37.3 %	85.49 ± 4.43	0.88 ± 0.04
15	-20	static	20.6 %	106.5 ± 7.42	0.68 ± 0.05
15	-30	static	11.4 %	115.1 ± 10.8	0.42 ± 0.04
20	zero	static	69.9 %	6.76 ± 0.26	1.64 ± 0.06
20	zero	tuneramp	99.6 %	6.83 ± 0.22	1.55 ± 0.05
25	zero	static	73.3 %	10.06 ± 0.37	2.01 ± 0.07
25	zero	tuneramp	99.6 %	11.83 ± 0.37	2.08 ± 0.06

Table B.14: *Results of tracking simulations.*

With a static machine, meaning that no ramps during extraction are applied, and the chromaticity set to zero, the lowest emittance of the extracted beam can be achieved. It can be observed that the emittance grows quadratically with beam energy, due to the properties of synchrotron radiation emission. The emittance is fully within the specifications of the original ELFE proposal: about a factor of two at 15 GeV and a factor of ten at 25 GeV below the projected values.

Figure B.16: *Tracking simulations at 15 GeV, achromatic machine:*



The energy spread of the extracted particles equals the equilibrium energy spread of the stored beam, and thus grows linearly with beam energy. It should be noted that at 15 GeV the energy spread is larger than the foreseen values of the original ELFE proposal by a factor of about four, and at 25 GeV it is larger by a factor of two.

As it is impossible to empty the ring completely with a constant extracted current in the static case, tune ramps moving the tune onto the resonance and thus shrinking the stable area to zero can be used to control the extraction process. In the simulations a pair of additional quadrupoles was used to generate the tune ramps. The optical mismatching caused by the tune change is negligible.

Emittance and energy spread are not affected by a tune ramp, but the pitch and the mean angle of the extracted particles change slightly during extraction. The simulations and analytic calculations show that the pitch changes by less than 5%, and the angle changes less than 32 μrad. The change of the pitch causes a change of the extracted emittance, but the value is rather small. The angle change could cause a movement of the beam at the experiment, depending on the optics of the extraction beam line, but can be easily compensated with a pulsed dipole which counteracts the angle change.

By adapting the ramp it is possible to control the extracted current so that it is constant during extraction time. This system would measure the extracted current within one extraction cycle and adjust the ramp to optimize the performance accordingly. Such a system would compensate for slow machine drifts.

It is also possible to think of a faster feedback system, which would control the ramp directly within the cycle (for example described in [8]). But in our case it takes more than one hundred turns for a particle to get extracted from the moment it becomes unstable, so the delay between tune change and effect on extracted current is more than 2 ms. Compared to the duration of the extraction cycle of 100 ms, the achievable bandwidth of the feedback system would probably not be high enough for good performance.

Using non-zero chromaticity reduces the energy spread of the extracted beam, because particles within a certain tune spread are preferred for extraction, but also with the induced tune spread the emittance of the extracted beam is increased. The simulations show that due to synchrotron oscillations and synchrotron radiation the effective decrease in energy spread is rather small, but the accompanying emittance growth is intolerable.

An alternative extraction method depending on chromaticity, successfully applied in AmPS, is to use an RF phase ramp to push a constant rate of particles out of the RF buckets [12]. Subsequently these particles lose energy by synchrotron radiation which by chromaticity is converted into a tune change towards the resonance. This method cannot be applied successfully here, because the particles which have left the buckets lose energy too fast (at 15 GeV around 5×10^{-4} per turn). They cross the third integer resonance without getting extracted and will be lost at a later time.

B.6.4 Extraction Channel

At the extraction point a septum as thin as possible has to separate the particles to be extracted from the circulating ones. So an electrostatic septum is desired, which can be built with a reasonable thickness of 50 μm, as done for example at AmPS [11]. With a pitch of 4 mm the losses on such a thin septum are 1.3 %, meaning that an average current of 0.38 μA interacts with the septum. Because this creates a substantial heating, electrostatic septa are usually built as a wire array, since this geometry offers the best cooling by radiation.

During the interaction of the electron beam and the synchrotron radiation with the septum material secondary particles are created by electromagnetic showers, and most of these particles leave the hit wires. This could cause problems with the high voltage stability of the septum. No estimations have been done on this point so far, so it is not clear what field strength actually can be achieved. A field strength of 5 MV/m has been achieved in existing electron accelerators, for example in PSR-2000 [9]. With this strength, a 2.5 m long septum can provide an angular kick of 0.5 mrad at 25 GeV to the particles to be extracted.

Figure B.17 (a) shows the separation between the fraction of the beam which is extracted by the septum and that which remains. It can be seen that there is a high separation of 11 mm at 20 m downstream, and it can even be increased to 21 mm by inserting a 3 mm thick septum at 11 m downstream which provides a deflection of 2 mrad. A set of two septa each producing a 14 mrad kick will finally push the beam out of the machine, clear from the next quadrupole.

The trajectory created by this extraction channel can be seen in Fig.B.17 (b). The elements of the extraction channel are summarized in table B.15.

The remaining distance to the center of the experimental hall is about 40 m, which should be sufficient for designing a beamline to match the beam to the requirements of the experiment.

	Position	Length	Thickness	Strength	Deflection angle
Electr. septum	0 m	2.5 m	50 μm	5 MV/m	0.5 mrad
Magn. septum 1	11.0 m	1.0 m	3 mm	0.166 T	2 mrad
Magn. septum 2	19.2 m	1.5 m	16 mm	0.77 T	14 mrad
Magn. septum 3	21.8 m	1.5 m	16 mm	0.77 T	14 mrad

Table B.15: *Elements of the extraction channel (strengths for 25 GeV).*

To summarize, various extraction mechanisms have been studied, and the use of a tune ramp onto a third integer resonance induced by pulsed quadrupoles seems to be the most promising configuration. With zero chromaticity the emittance specified in the original ELFE proposal can be achieved, but the energy spread will be larger to some extent. An extraction channel to guide the extracted beam out of the HERA machine poses no obvious difficulties.

B.7 S-Band Linac as Injector for ELFE

Instead of using TESLA as injector for HERA as stretcher ring, it may be possible to use an S-Band Linac as injector. Most subsystems of the stretcher ring facility are independent of the injector, like the transfer line or the extraction system. Differences arise essentially from the RF and the pulse structure.

One would use the sixth subharmonic of the S-Band frequency for the HERA RF system, namely 500 MHz. This is a standard frequency for storage rings and thus no additional R&D would be necessary in this case.

The pulse structure is a more difficult problem. The S-Band Linac pulse length for collider mode is 2 μs, the repetition rate 50 Hz (table B.16). Since the HERA revolution time is 21.13 μs, the ring has to be filled with ten linac pulses, and the remaining time is available for the necessary kicker gaps. So each kicker gap is 110 ns

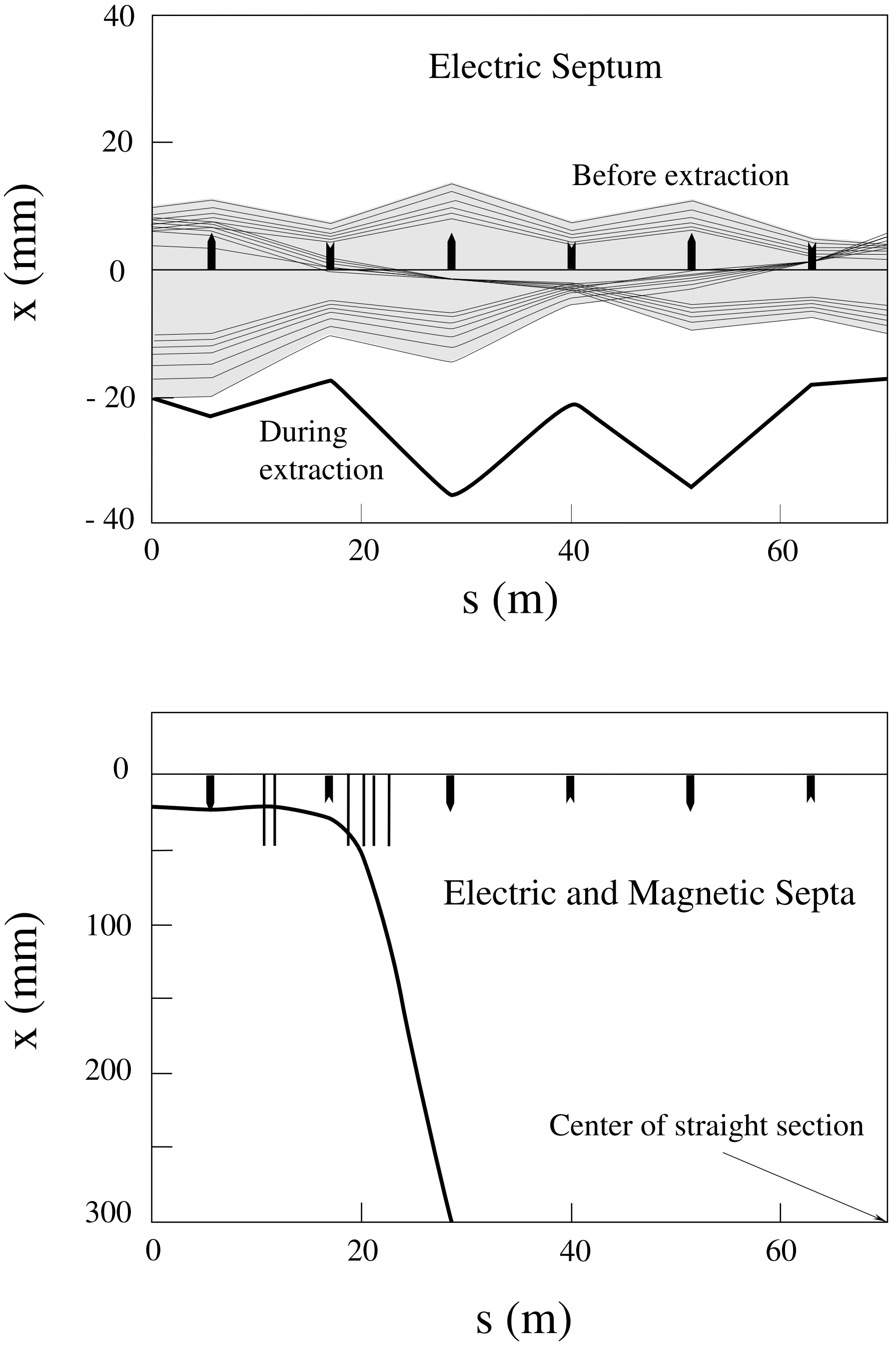


Figure B.17: *Beam separation by septa.*

long, and the ring filling factor is about 95%. The construction of the injection kicker is relatively simple.

Based on this pulse structure one can think of three scenarios for the stretcher ring operation.

	TESLA	SBL
Pulse length	800 μs	2 μs
Repetition rate	5 Hz	50 Hz
Bunches per pulse	1130	333
Charge per bunch	3.63×10^{10} e^-	1.1×10^{10} e^-
Charge per pulse	4.10×10^{13} e^-	3.66×10^{12} e^-

Table B.16: *Pulse structures of TESLA and SBL (collider modes).*

B.7.1 Injection and extraction in sequence

The "classical" stretcher ring operation cycle is composed of two main subcycles: first the ring is filled, then it is emptied. Filling the empty ring with a linac repetition rate of 50 Hz takes 200 ms. If 150 mA can be injected into HERA, and aiming for 30 μA extracted current, the ring has to be emptied within 100 ms. So, with this solution, the macroscopic duty factor of the extracted beam is only 33% . If the repetition rate is increased to 100 Hz, HERA could be filled within 100 ms and the macroscopic duty factor would be increased to 50%.

B.7.2 Injection and extraction in parallel: dynamic machine

An alternative idea is to continuously extract, and not to distinguish between injection and extraction subcycles. This means that the ring circumference is divided into ten slices with different currents. The injector delivers pulses with a constant rate, and each slice is refilled every ten pulses. The 150 mA is also a limit for the "instant" currents in each slice. For an extracted current of 30 μA, each slice has to be refilled every 100 ms and the repetition rate of the injector has also to be 100 Hz.

The extracted current has to be the same for all slices, otherwise the current at the experiment is modulated with 470 kHz. Without additional control, the extracted current depends linearly on the stored current ($I_{extracted} \sim I_{stored}$). To avoid such modulation one has to ramp the tune and to apply a different tune for each slice.

The tune has to be kept constant for two microseconds, and then has to be switched to another value within 110 ns. After ten values (for the ten slices), begins a new cycle, but with slightly different tunes, so that the tune for each slice moves towards the resonant tune individually. This control is illustrated in Figs. B.18 and B.19 for linear ramps. Fig. B.18 depicts the tune control during one revolution time (micro time structure). Fig. B.19 depicts one fifth of a complete cycle tune control, between two injections (macro time structure).

The tune shifts are created by pulsed quadrupoles. It is thinkable to generate the quadrupole currents with ten pulse generators for each quadrupole which fire one after the other. Hence each generator has 18 μs to load and 2 μs to fire, running continuously. The technical feasibility of such a pulsed device is under study, but it is clear that it will be difficult to construct and to operate.

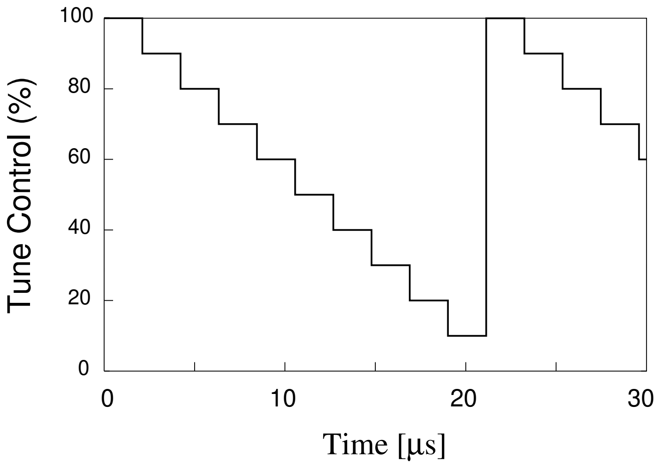


Figure B.18: *Tune modulation in scenario 2 (revolution time scale).*

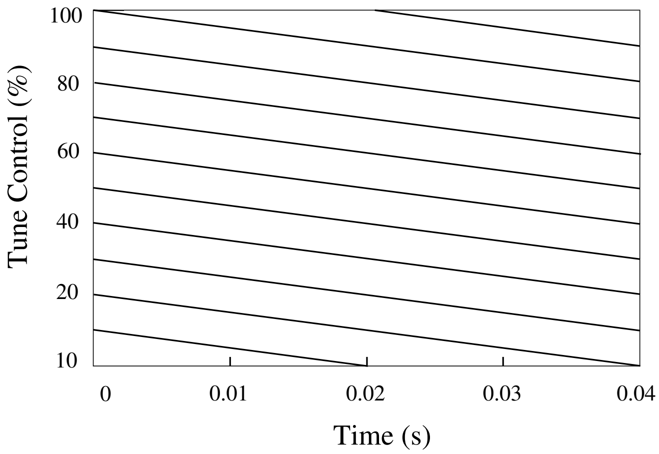


Figure B.19: *Tune modulation in scenario 2 (pulse to pulse with linear ramps).*

B.7.3 Injection and extraction in parallel: static machine

If it is technically not reasonable to construct such a tune modulation system, one still can try to use a static machine by omitting the tune ramps completely. The simulations show that by synchrotron radiation some beam is extracted, and if this extracted current is not too high, the current is nearly constant except for one peak at the beginning of the cycle (see Fig. 16 a). This peak comes from particles with high amplitudes at injection and could be removed by collimating the beam directly before injection.

The integrated extracted current could be 50-60% of the injected one, before the extracted current drops significantly. The remaining current has to be discarded by controlled dumping; the dumping device has to be able to absorb about 50% of the beam intensity continuously. So this scenario would still give almost 100% macroscopic duty factor, but only about half the extracted current.

B.7.4 Comparison of the different options

Three different scenarios have been briefly discussed. All scenarios demand an injector repetition rate of 100 Hz to be competitive. Two of them (sequential injection and extraction, and parallel injection and extraction with static conditions) do not imply technical problems, but yield either half the duty factor or half the projected extracted current. To get 100% duty factor with full extracted current a tune shift modulation system has to be installed, which probably is technically difficult.

B.8 Photon beam for ELFE

The laser backscattering technique offers the possibility of producing photon beams at electron accelerator facilities. Such photon beams are characterized by high polarization (circular or linear), very low background and high energy resolution. The principle of this technique is backward Compton scattering off the electron. If a laser photon strikes a relativistic electron at a relative angle equal to 180°, it is scattered in the backward direction, inside a narrow cone with the axis coinciding with the direction of the incoming photon. Using for example, a 2660 Å laser in combination with a 25 GeV electron beam available at DESY, a maximum laser backscattering photon energy of 16 GeV can be obtained.

The main advantage of the laser back scattering beam is the low background of low energy photons. If we compare with a classical Bremsstrahlung photon beam with the well known $1/E_\gamma$ behaviour, the photon energy spectrum is approximatively flat for laser backscattering, and thus the rate of accidental hadronic events originating from the low energy part of the spectrum is strongly reduced. Collimation of the scattered photons offers a simple way to get rid of the low energy part of the photon spectrum at low incident electron energies. Nevertheless for high incident electron energies, the electron beam divergence spoils the correlation between the energy and the angle of the scattered photon, and the cut in the energy spectrum is not well defined but the low energy photon spectrum is considerably reduced.

B.8.1 Photon flux

The total photon flux for laser backscattering is proportional to the electron beam intensity, to the laser power and the electron-laser interaction length. For a given laser power P and an electron-laser interaction length L, the laser backscattering photon beam produced with electrons inside a storage ring, where the electron current is $I \simeq$ 150 mA, will have a photon flux of three orders of magnitude larger than the one produced with an extracted electron beam ($I \simeq 50\ \mu$A). This constrains the photon-electron collision to occur inside the internal HERA ring.

A possible solution consists in a standard continuous laser with a power $P = 8W$ coupled to an amplification optical cavity. The laser is trapped in a cavity made of 2 highly reflective mirrors. Amplification factors of 1000 seem quite possible. To protect the cavity mirrors from the electron beam synchrotron radiation, a small crossing angle between incident electron beam and laser line is necessary; consequently the e^--laser interaction lenght is rather small, about 2.5 cm. With an amplification by optical cavity, one would expect typically 10^9 photons per second in the total photon energy range, so in the useful range (10% of the total photon spectrum, representing the high energy region) we can assume to get 10^8 photons per second.

Considering the total number of electrons circulating in the HERA ring:

$N_e = 150$ mA $\times$ 20 μs / 1.6×10^{-19} C = 1.9×10^{13} e^-/s

With a flux of 10^9 γ/s, the life time of the electron beam would be about 5 hours, and so a possible solution would be to refill the internal ring every 30 minutes, when 10 % of the stored electrons have been lost.

One has to pay attention to the special conditions (i.e. spatial extension) of the electron beam which impinges upon the laser beam at a very precise position of the HERA ring. The ougoing photon beam could be collimated at a position as far as possible from the impact point.

B.8.2 Tagging system

The residual electrons, after the Compton interaction, can possibly be deflected in a HERA ring dipole. Only the 10% highest energies in the photon spectrum are selected by the tagging system. They correspond to smaller energies of the residual electrons. After the magnetic deflection, the localisation of these electrons should not be too close to the incident beam, in order to avoid all the synchrotron radiation problems and to install about 100 electron counters. Typically 10^6 events per second are collected by each counter.

The advantage of the tagging system is to give a high photon energy resolution of 10^{-3} and to measure precisely the photon flux.

B.9 Conclusions

The goal of our study group was to determine the feasibility of using TESLA as an injector into the HERA ring used as a stretcher, and to evaluate the performances of the extracted beam in terms of emittance, energy spread and duty factor. We have concentrated our efforts on the following problems.

- Modification of the HERA e-ring lattice for the needs of slow extraction.
- Beam extraction: analysis of possible extraction methods, simulation of the extraction process, definition of the extraction channel.
- Beam injection: optics and hardware.
- New RF system in HERA and multibunch instabilities.
- Time structure of the injected beam, compensation of beamloading in the injection linac.

Solutions have been found for these problems, although the control of beam instabilities will probably not be easy. The achievable performances of the extracted beam have been calculated assuming that the effects of machine imperfections could be corrected. The performances that can be expected from our results are given in Table B.17:

Energy range	From 15 to 25 GeV
Maximum current	30 μA
Macroscopic duty factor	88 %
Bunch spacing (433.33 MHz)	2.3 ns
Minimum horizontal emittance (90 % of particles)	4 mm·μrad @ 15 GeV
	12 mm·μrad @ 25 GeV
Associated energy spread (FWHM)	1.2×10^{-3} @ 15 GeV
	2.2×10^{-3} @ 25 GeV

Table B.17: *Expected performances of ELFE@DESY.*

Therefore, we conclude that HERA can be used in association with TESLA to produce a high duty cycle electron beam for fixed nuclear target experiments.

ELFE@DESY appears to be feasible.

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