# DESIGN OF A DISPERSIVE BEAM TRANSPORT LINE FOR THE JETI LASER WAKEFIELD ACCELERATOR*

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## *Abstract*

Laser wakefield accelerators (LWFAs) emit electrons with energies of a few 100 MeV at very short bunch lengths while having a compact design. However, electron bunches from LWFAs show a larger energy spread than those of conventional accelerators. This is a challenge when using these bunches e.g. to generate radiation in an undulator. A possible strategy to cope with that is to spectrally disperse the bunch and match the resulting spatial distribution with an undulator field amplitude varying in the dispersion plane.

For realizing the dispersion a pair of dipole magnets is used. The electrons leaving this dipole chicane have to meet certain requirements imposed by the undulator: In the deflection plane the beam has to be collimated and its energy distribution must match the undulator field. In the other transversal plane the beam has to be focused to the center of the undulator, keeping the value of the beta function small. To include this in the compact design of the whole setup, a combination of specially designed quadrupole and sextupole magnets is employed. In this contribution the design of the setup of this chicane is presented.

## INTRODUCTION

Synchrotron and undulator radiation can be used to characterize the electron bunches of an accelerator. This is planned to be applied to bunches of the JETI-LWFA at the university of Jena, Germany. The undulator radiation will be employed to determine the transverse electron bunch size and divergence. Coherent and incoherent synchrotron radiation of a bending magnet will be used for the analysis of the temporal structure of the bunch.

A sketch of the whole diagnostic setup planned is shown in fig. 1. Leaving the LWFA, the beam can travel two alternative paths: Either it is sent through a dogleg chicane to an undulator or, with the two dipoles of the chicane turned off, in forward direction to an electron spectrometer consisting of a permanent dipole magnet in a yoke. The synchrotron radiation will be extracted at the second dipole of the chicane.

Earlier experiments already have demonstrated the generation of undulator radiation with LWFAs [1]. One of the major challenges to be faced is the large energy spread of the LWFA as it deteriorates the quality, increases the bandwidth and reduces the spectral brilliance of the undulator radiation. Particularly the increased bandwidth of the undulator radiation results in an increase of its divergence and thereby in a decreased resolution of the electron bunch diagnostics based thereon. One approach to compensate for the energy spread is to spatially disperse the electron beam in one transversal plane and to match the resulting spacial energy distribution with the magnetic field amplitude of the undulator [2]. The goal of the work presented here and in [3] was to optimally match the undulator design (described in detail in [3]) and the beam optics of the transport line such that the bandwidth of the undulator radiation is reduced to the natural bandwidth $\Delta\lambda/\lambda \approx 1/N_u \approx 1\,\%$ with $N_u = 100$ undulator periods despite of an energy spread of the electron beam of the order of 10 %.

In order to achieve this goal a set of requirements in terms of dispersion and betatron function matching as well as geometric boundary conditions have to be met. These parameters in detail will be explained in the next section.

## REQUIREMENTS OF THE CHICANE

*Geometrical requirements* For the whole transport line a geometrical aperture of five times the rms beam radius is foreseen. As the electron spectrometer will be included in the setup the beam to the undulator has to pass the spectrometer above the yoke. Additionally sufficient space for shielding the magnetic fields of the spectrometer magnets has to be foreseen. Altogether a parallel offset of 60 mm has to be generated by the chicane.

The chicane is designed for an energy of the reference particle $E_0$ =120 MeV. Two edged dipoles are used, therefore only the variation of the distance between the two dipoles determines the required beam offset. The requirements mentioned above and the properties of the magnets result in a fixed distance of 1.1 m between the dipoles.

At the second dipole there must be enough space left in tangential direction to the beam path to create an offset between the electron beam and the synchrotron radiation large enough to extract the synchrotron radiation. As the aperture of the synchrotron radiation beam pipe can limit the bandwidth there should be no quadrupoles placed closely behind the second dipole.

*Dispersion matching* The electron energy band for which the undulator is optimized is 120 MeV ± 10 %. In the de-

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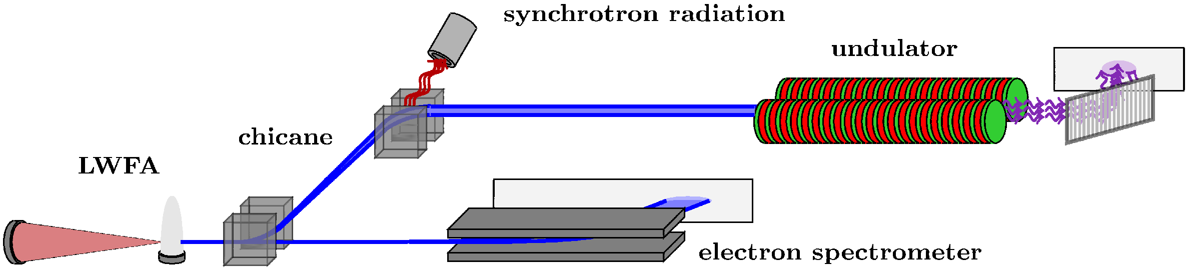


Figure 1: Sketch of the setup of the chicane: Two dipoles disperse the beam and produce a sufficient offset to pass the spectrometer, seven quadrupoles (not shown here) collimate the beam, control the dispersion and match the required beam parameters at the entrance and center of the undulator.

flection plane $x$ the dispersion $d\Delta x$ of the beam has to be adjusted to the varying field of the undulator. Furthermore the dispersion must be constant over the length of the undulator, i.e. the derivative $D'$ of the dispersion function of the transport line has to be zero at the entrance of the undulator.

*Matching of the betatron function* The electron beam can be considered as a set of monoenergetic beamlets with different energies covering the energy range of the beam. The propagation of each of these beamlets through the chicane can be treated separately. In the ideal case a beamlet is transversing only a field in the undulator which is adjusted to its energy. As the beamlet has a finite transversal extension $\sigma_x$, however, parts of the beamlet transverse a non ideally matched field and the radiation emitted will be of a slightly different wavelength. To keep the bandwidth of the undulator radiation narrow $\sigma_x$ has to be small enough that the difference in the wavelength is smaller than the natural bandwidth of the emitted undulator radiation. To achieve a homogeneous beam in the undulator the beamlets should be slightly focused to the center of the undulator.

In the plane $y$ perpendicular to the deflection plane the waist of each monoenergetic beamlet should be in the center of the undulator and the beta function should be $L/2$ with a total length $L$ of the undulator.

The target values for the different parameters are listed in table 1.

Table 1: List of requirements of the chicane for dispersion and beam parameters from [3].

| **parameters of the bunch** | |
|---|---|
| Energy | 120 MeV |
| Energy range | ± 10 % |
| **target beam parameters in the center of the undulator** | |
| Dispersion $d\Delta x$ | 4.0 mm |
| $D'$ | 0 |
| Beam size $\sigma_x$ | 0.09 mm |
| $\alpha_x$ | 0 |
| $\beta_y$ | 0.5 m |
| $\alpha_y$ | 0 |

## SPECIFICATIONS OF MAGNETS

*Dipoles* The two dipoles of the chicane are commercially available electromagnets. The square pole is assumed to have an edge length of 50 mm and a maximum field of 0.46 T at a gap of 20 mm as offered e.g. by GMW. This causes an angle of deflection of approximately 60 mrad for electrons with $E$ = 120 MeV.

*Combined function magnets* The combined function magnets are specially designed and fabricated for this experiment. Due to the rather small deflection angle in the dipoles both beam pipes, the one for the deflected and the one for the undeflected beam, have to pass the combined function magnets. This defines a lower limit for the gap of 40 mm. To reach the necessary quadrupole strength a gradient of 80 T/m is required at a pole length of 50 mm. As an additionally requirement from the beam optics the length of the magnet must not exceed 140 mm. Simulations have shown that matching these parameters is technically feasible.

## POSSIBLE DESIGNS FOR THE CHICANE

Possible designs for the chicane were studied using linear beam dynamics model. The quadrupoles were approximated as thin lenses and an energy of 120 MeV with an energy spread of ±10 % was assumed. Solutions were found by minimizing a figure of merit containing the deviation from the target values by varying the strengths of the quadrupoles and the distances between the quadrupoles.

The half divergence angle of the incoming electron beam was measured in an experiment using the JETI facility to be 1 mrad. As there are no measurements of the emittance of the beam the source size was estimated to be 20 $\mu$m, which is approximately the transversal extension of the accelerating region of the plasma wave. Assuming that $\alpha$ equals zero at the source the resulting geometrical emittance is 20 $\mu$m mrad which is in good agreement with other measurements [4].

Two possible arrangements are shown in fig. 3. To achieve the requirements at least seven quadrupoles are necessary in order to keep the beam small. Due to the strong divergence it is favorable to place the first set of

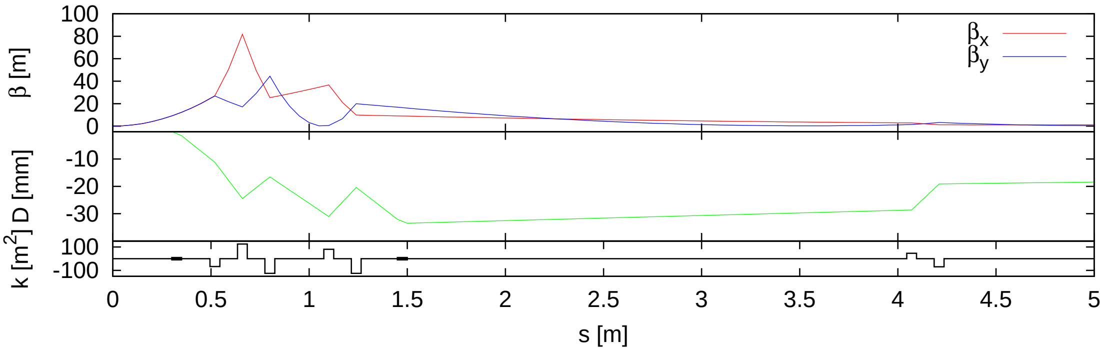
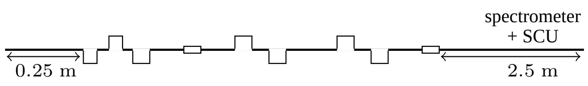
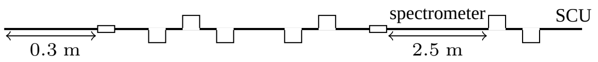


Figure 2: Results of the linear beam propagation using setup 3b.

quadrupoles as close to the source as possible. As the plasma accelerator, however, is in a large, evacuated target chamber it is not possible to place the first electromagnet closer than 0.3 m to it. In case permanent magnets inside the vacuum chamber are used, the distance to the accelerator could be reduced to approximately 0.25 m distance as shown in fig. 3a.



(a) Triplet of permanent magnets in target chamber



(b) Last doublet after electron spectrometer

Figure 3: Possible options for the quadrupole lattice.

The solution with the permanent magnets inside the vacuum chamber, however, was dismissed because the chromatic error of the quadrupoles cannot be corrected in the non dispersed beam, i.e. before the first dipole. Therefore particularly the beam to the spectrometer would be disturbed by such an arrangement to a non-tolerable extent.

A slight variation of setup fig. 3b with the last quadrupole doublet before the spectrometer would be an alternative arrangement but is less favorable in this setup as this doublet would have to be removed for the extraction of the synchrotron radiation. Consequently setup fig. 3b was chosen as the baseline design for the chicane optics. The results achieved are shown in fig. 2. The beta function is getting quite large due to the small emittance and large divergence of the LWFA. The beam parameters achieved compared to the target parameters are listed in table 2.

The crucial beam parameters determining the undulator radiation bandwidth can essentially be achieved by this solution, the deviation in $\alpha_x$, $\beta_y$ and $\alpha_y$ appears to be tolerable. Subsequent calculations have to prove that radiation generated by this beam in the undulator fulfills the requirements, especially the monochromaticity necessary for the use as diagnostics.

Table 2: List of beam parameters in the center of the undulator achieved with setup fig 3b.

| **beam parameters** | achieved | target parameters |
|---|---|---|
| Dispersion $d\Delta x$ | 3.8 mm | 4.0 mm |
| $D'$ | 0 | 0 |
| Beam size $\sigma_x$ | 0.15 mm | 0.09 mm |
| $\alpha_x$ | -0.39 | 0 |
| $\beta_y$ | 0.08 m | 0.5 m |
| $\alpha_y$ | 0.39 | 0 |

Further analysis of the system has shown that the chromatic error of the focusing optics has a significant effect. Therefore a correction by sextupole magnets is required for the setup, which is planned to be included in the quadrupole magnets. Design simulations for these combined-function magnets are under way.

## CONCLUSIONS

In this contribution a design for a dogleg chicane as transport line between the JETI laser wakefield accelerator and an undulator with transversally varying magnetic field amplitude is presented. The beam entering the undulator matches the required conditions, especially the nonzero dispersion, zero dispersion derivative and beamlet size restriction. Though this beam transport line including the quadrupole design is technically challenging the solution found seems to be realizable in the experiment. A next step will be the measurement of the emittance at the JETI-LWFA. Further analysis with particle tracking programs has to be done as well as the tracking of the beam in the undulator and simulation of the emitted radiation.

## REFERENCES

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