Optics of Beam Transport in the NSLS UV-FEL*

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Abstract

The NSLS-FEL is designed as a single pass FEL to generate radiation 1 mJ per pulse (10 psec) in 10^{-4} bandwidth, with continuously tunable wavelength in the range 100-300 nm. A superconducting, recirculating linac provides electron beams of energy 20 MeV to 260 MeV at 4π mm mrad normalized rms emittance with less than 0.1 % momentum spread and 2 mm rms bunch length. The optics in this machine is seriously restricted by the requirement to not degrade the electron beam quality. We present a lattice design for the transport lines to be used in beam injection, linac focussing and recirculations. These beam lines are tuned to be linearly achromatic and isochronous, to avoid beam breakup in the cavities, and to minimize second order distortions of the emittance. Special transport lines are designed that allow rapid switching of the electron beam to drive two different FEL wigglers. This provides the capability for up to four simultaneous, high power, independently energy tuned laser beam.

1 INTRODUCTION

The NSLS at Brookhaven National Laboratory is proposing the construction of a UV-FEL operating in the wavelength range from visible to 750 A at near gigawatt peak power [1]. The accelerator which we propose to use is a superconducting recirculating linac designed to generate electron beam energy 20 to 260 MeV with a normalized emittance of $\epsilon_n = 4\pi$ mm-mrad and a local momentum spread 0.1%. The machine shown in Fig. 1 consists of a 20 MeV injector, a superconducting linac segment, a recirculator, and a separating/matching section. Electron beam can be recirculated to make up to three passes through linac segment. The linac segment accelerates the beam at different energy with an energy gain of 80 MeV per pass and a final energy of 260 MeV. There are two recirculation lines (100 MeV and 180 MeV) to transport beam back to linac for further acceleration. Each recirculation line consists of two arcs and a transformer. The final part of transport line is used to switch beam to different wigglers and match the beam at the entrance of each wiggler to the required FEL parameter. In this paper, we focus on the basic first order design of the transport lines in NSLS UV-FEL. The higher order effects and the error studies will be presented later. In section 2, we will discuss the lattice of the injector and the superconducting linac. The recirculation optics will be discussed in section 3. Finally, we will treat the beam switch and matching section in section 4.

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2 INJECTOR AND LINAC BEAM OPTICS

A 10 MeV, 300 A peak current, 6 ps bunch length electron beam is produced by a BNL's type laser photocathode rf gun [2]. A solenoid is placed immediately at the exit of the electron gun to provide an axial symmetric focussing force in the transverse plane. To reduce self fields due to the beam space charge, the beam is further accelerated to 20 MeV by superconducting rf cavities following the solenoid and matching quadrupoles. Injection into the linac is through the last magnet of a four bend magnet chicane section that allows launching of three beams of different energy onto a collinear path. The injection line has three 15 degree bend magnets and six quadrupole magnets tuned for an isochronous transport between the rf cavity and the first quad in the linac. The quadrupoles are powered symmetrically in order to reduce the number of power supplies required. This provides sufficient freedom of the betatron functions in this line in order to reduce the sensitivity to quad alignment and powering errors, while maintaining the isochronous condition.

The linac optics are designed using a simple FODO lattice structure with the first section having approximately a 90° phase advance. Latter section have a progressively higher phase advance for the first pass, in order to provide additional focusing for the second and the third pass. The six quadrupoles are independently powered, air cooled, iron pole magnets of quite low power. The quadrupole aperture is enlarged to 6 cm radius to provide for a large beampipe in order to reduce the wakefield effects from the transitions between superconducting cavities. Adequate space has been provided for diagnostics and vacuum system components in the quadrupole regions. Beam steering will be provided by weak air core dipole magnets at the same position as the diagnostic pickup, with additional steering provided by quadrupole alignment changes.

Subsequent passes through the linac see less focusing and therefore will show longer period betatron oscillations. The beam ellipse at the start of the next pass is the same as the output from previous pass, since the transform of recirculation line is tuned to be a unit matrix. This prevents the angular kicks from one pass from increasing the

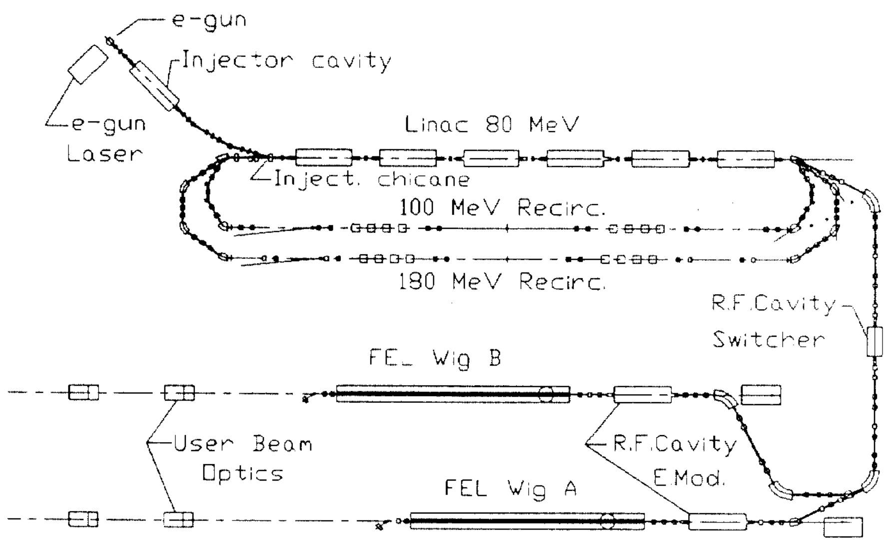

Figure 1: Schematic layout of NSLS UV-FEL.

transverse position offset of subsequent passes through the linac, therefore reducing the sensitivity to multi-pass beam break-up.

3 RECIRCULATION TRANSPORT LINES

Each of the recirculation transport lines is composed of two isochronous 180 degree bend arcs connected by a symmetric transformer. At the end of the linac, a single dipole (spreader) provides the dispersion necessary to separate the passes into the different transport lines. The bending arcs are tuned to be isochronous and are therefore achromatic to first order at both ends. This simplifies the tuning of the long transformer straight sections since the dispersion is maintained zero throughout its length and the beta functions can be tuned with considerable freedom. The quadrupoles in both the arcs and the transformers have been tuned assuming a mirror symmetry about their mid-points. The assumption that the arcs are symmetric produce a symmetric dispersion function in the arcs making the achromatic condition easily satisfied, a necessary condition for the arcs to be isochronous. A minimum of three dipoles and two-pair of quads [3] are required to achieve the isochronous condition for the arcs. Although two quads are sufficient the extra quads provides an isochronous condition independent of the drift lengths between the quadrupoles.

There are four dipoles instead of the minimum in both the 100 MeV and 180 MeV arcs. The dipoles in the 100 MeV arc are all sector magnets to reduce vertical focussing. The 180 MeV arc suffers additional vertical focussing from the beam spreader/combiner dipole and its symmetric pair, but the other two dipoles at the center of the arc are sector magnets. To compensate for the additional vertical focussing from the dipoles, the 180 MeV arc uses five quadrupole families rather then the three families in the 100 MeV arc.

The optimization of the input beam ellipse conditions for each arc has been the subject of considerable effort. With the increased number of quadrupole there are so many solutions that it was difficult to track them, while trying to reduce second order effects and error sensitivity for the arcs. One approach which has proved helpful is to tune the arcs to a periodic lattice condition with zero momentum compaction factor. Then properties of the arc could be tracked by varying the betatron tunes, ν_x and ν_y. Figure 2 shows that the maximum value of beta-functions, β_x and β_y, and the chromaticities, ξ_x and ξ_y, (for one of our better solutions in the 100 MeV arc) as the vertical betatron tune ν_y was varied. The optimum value of vertical tune was found to be $\nu_y \approx 0.272$ and the periodic lattice functions for this optimum value are shown in Fig.3. The quadrupole strength in the arc of the 100 MeV recirculation line then is set for this tune. The beam at the entrance of the 100 MeV arc needs to be matched to this periodic solution. This gives the matching conditions for setting the linac quadrupoles. However, the condition of $\alpha = 0$ required by the periodic solution for the arc, may not be achieved when the required value of the beta-functions is tuned. This phase error causes the machine function to be shifted slightly from the values of the periodic solution. The same procedure is applied for the lattice of the 180 MeV line. The optimum value of tune is found to be $\nu_y \approx 0.292$.

4 BEAM SWITCH/MATCH FEL WIGGLERS

In order to drive two FEL wigglers, the electron beam (260 MeV) is switched to different beamlines after the third pass of linac by an rf beamswitch. By introducing an rf cavity in the middle of the arc, the energy of different beam

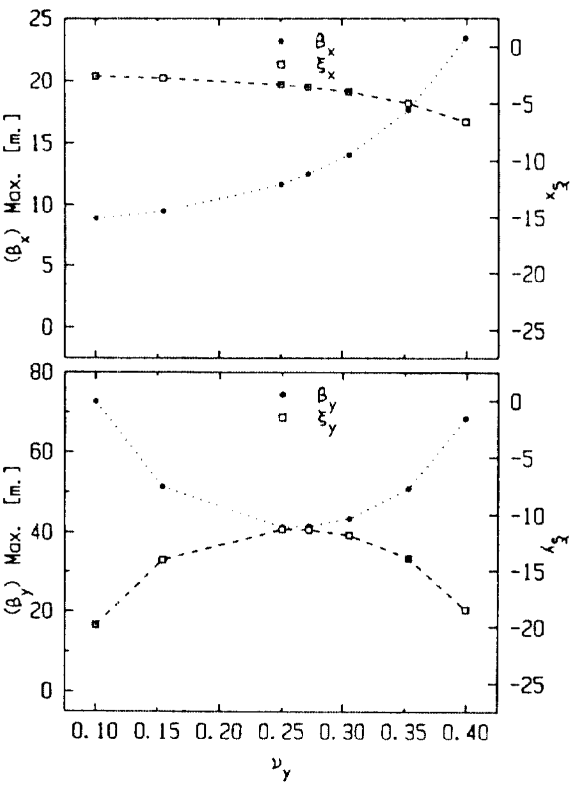

Figure 2: Maximum beta-function and chromaticity vs the vertical tune for the 100 MeV arc.

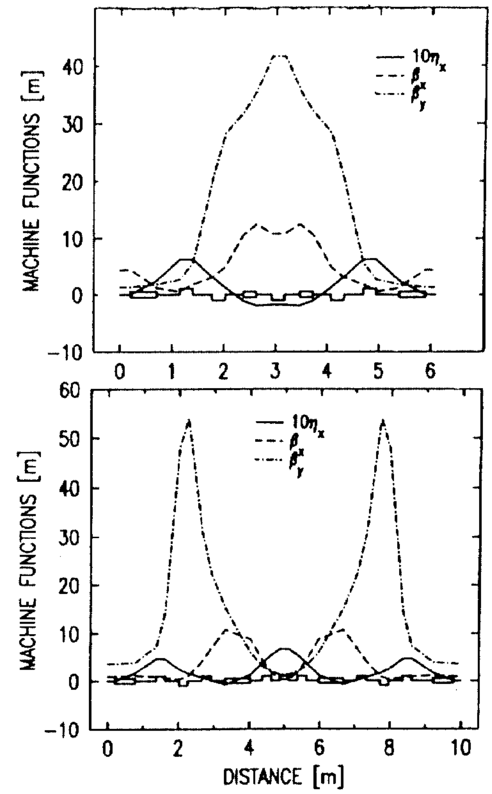

Figure 3: Machine functions for the 100 MeV (upper) and the 180 MeV (lower) arc periodic solutions with $(\nu_x,\ \nu_y) = (1.059,\ 0.272)$ and $(\nu_x,\ \nu_y) = (1.685,\ 0.292)$ respectively.

pulses is modulated ± 5 MeV on the crest of the rf wave. After the next dipole magnet the two beam pulses are separated 5.5 cm in horizontal coordinate by dispersion. A septum magnet at this point will be used to switch the beam pulses into two beamlines for wiggler A and B respectively. The FEL A is serviced by a transport line that is nearly symmetric but for 5 MeV increment provided by rf cavity. The beam passes by a septum magnet undeflected by its magnetic field. The FEL B is serviced by the beam reduced in energy by 5 MeV in the rf cavity, which passed through the septum field and is deflected into a separate beam line. Both transport lines are first order achromatic and isochronous.

The resonant wavelength tuning (±10%) is achieved by energy modulation (±5%) of the electron beam rather than by wiggler gap changes. This energy modulation will be done by special purpose accelerating cavities placed just before each of the two wigglers. In order to match beam to FEL wigglers, we use two quadrupole triplets separated by the modulated cavities. The first triplet provides the initial matching into the rf cavity and the second into the undulator. The use of triplets provides a reduced chromatic sensitivity of the matching of the beam ellipse into the wiggler betatron amplitude.

Following each undulator is a quadrupole doublet and dipole magnet that is necessary to provide a momentum spectrometer for the diagnostics of the FEL gain and for tuning efficiency. The bend angle of 40° will easily give a momentum resolution of 2×10^{-4} for a position resolution of 0.25mm. With 1 to 3 Kwatts of average beam power, these elements also provide for the efficient dumping of the remaining electron beam energy into a shielded and cooled beam dump.

5 ACKNOWLEDGEMENTS

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