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Improving electron beam quality of the Boeing free electron laser

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The successful operation of any free electron laser (FEL) is critically dependent upon electron beam quality. In a radiofrequency (rf) accelerator the micropulse or instantaneous beam emittance and peak current is established by the injector, however, it is important to maintain this beam's quality as it is accelerated and transported to the wiggler. In the past year, work has continued to enhance the electron beam of the Boeing FEL. The previous year's improvements in levelling the gun charge during the macropulse and rf power flatness were reported in the 1989 FEL conference. More recent work has concentrated upon the rf master oscillator and electron beam transport, which have lead to reduced macropulse energy spread, as well as decreased position and angle jitter. Also some electron beam diagnostics have been upgraded The result has been lower macropulse emittance at the entrance to the wiggler

1. Introduction and description of the FEL

During the past year the Boeing free electron laser optical cavity was changed from a simple concentric cavity to a much large grazing incidence ring resonator. Since the single pass losses in the ring resonator are much larger (approximately 35%) than they were for the concentric cavity (5 to 7%), it was clear the electron beam needed improving if the ring experiment was to succeed. This article describes the work done to achieve better beam quality. The discussion briefly covers the three general areas of rf power, beam transport and beam diagnostics.

Fig. 1 shows the layout of the Boeing FEL facility. The electron beam beginning at the thermionic gun is bunched by three stages of rf bunching to approximately 12 ps. Six traveling wave rf sections accelerate each micropulse to 110–120 MeV. The rf power is pulsed at 2 Hz repetition rate with 120 μs long macropulses. A doubly achromatic 180° beamline consisting

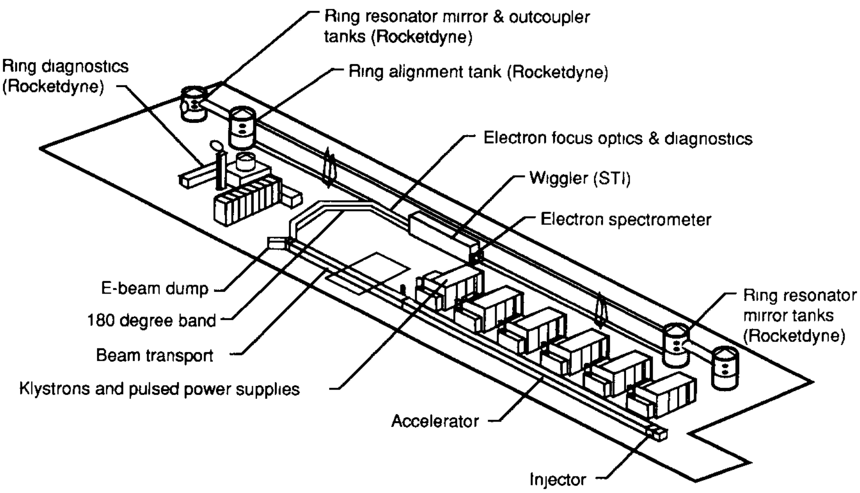

Fig. 1. Laboratory layout of FEL ring resonator experiment.

of four dipoles and fourteen quadrupoles transports the electrons to the wiggler.

The next section of this article discusses the effect the master oscillator's spectral purity has on the beam energy. Section 3 outlines changes to the electron beam optics, and in particular shows how the emittance at the wiggler was reduced by removing the focus–defocus (FODO) quadrupole array. Some of the new e-beam diagnostics installed and planned are investigated in section 4. The major change was the wide-spread use of optical transition radiation (OTR) view screens throughout the machine and in the wiggler.

2. Rf master oscillator

The argument for stable rf power is shown in fig. 2. Data taken two years ago compared FEL output with electron beam energy and position variations during the macropulse. The fig. illustrates the effect of slow, but significant slewing in the rf power with a period of approximately 20 μs. A major contributor to the operation of the FEL with a concentric cavity at 0.75% extraction efficiency was due to reducing this energy slew [1].

Fast energy jitter (changes in less than 5 μs) also has a detrimental effect on FEL performance, as illustrated in fig. 3. Shown is a calculation for the small signal gain as a function of pass number [2]. The calculation on the left assumes no energy jitter or slew, the one on the right used the observed jitter as measured by the energy stripline (see fig. 2). Such jitter slows startup and severely limits the FEL's saturated output.

It was discovered that the main source of energy jitter was the master oscillator for the rf. The master oscillator is used as the frequency and phase reference

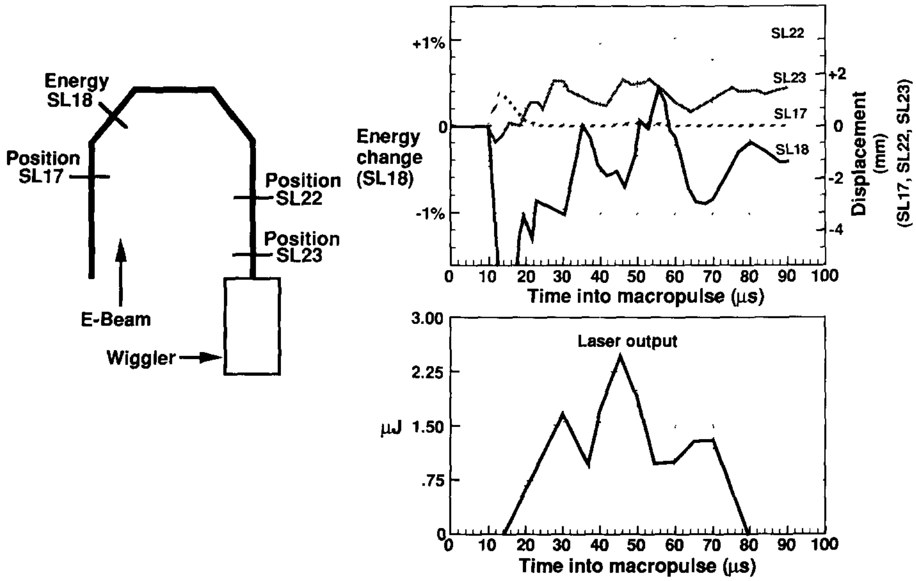

Fig. 2. Measurements taken in 1988 correlating FEL output with electron beam energy slew.

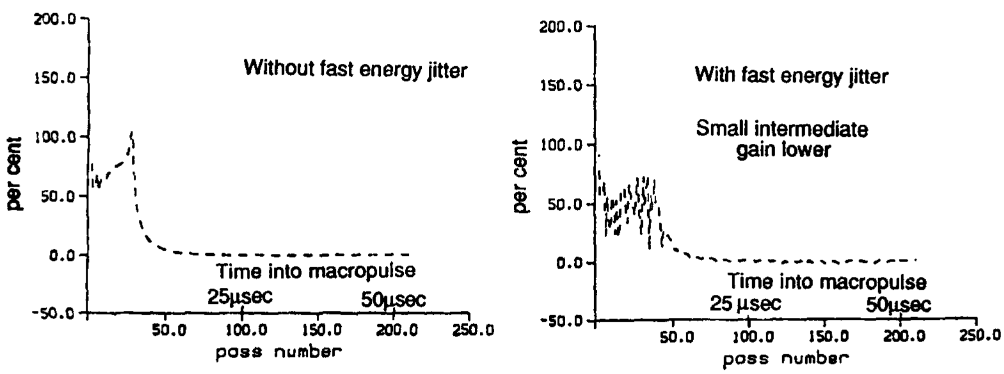

Fig. 3. Gain vs pass number, without and with fast energy jitter.

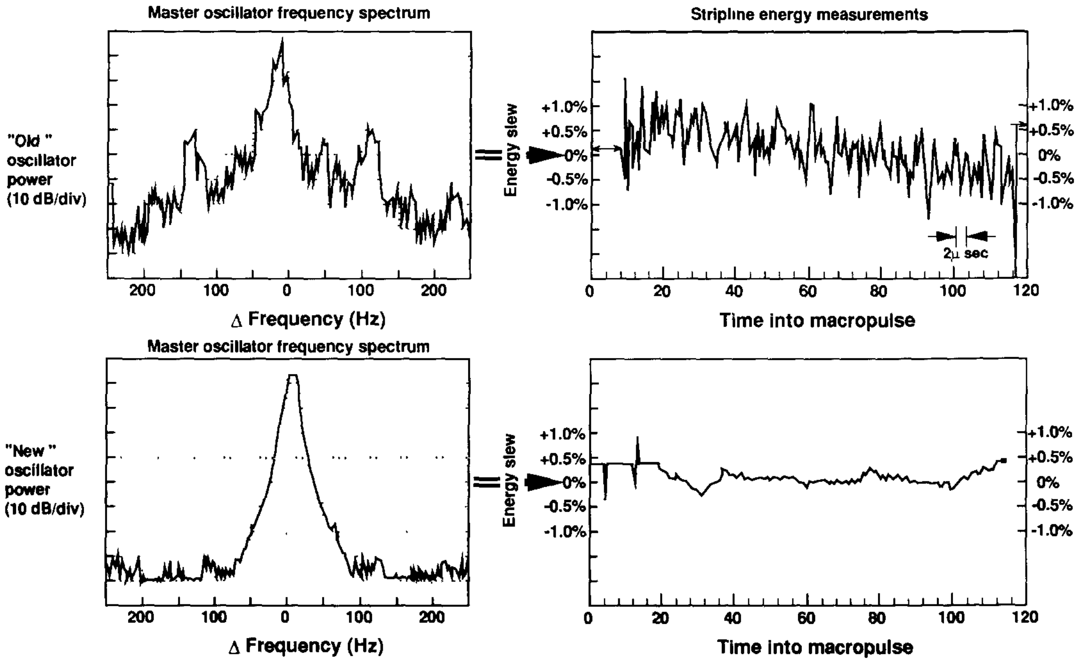

Fig. 4. The phase noise in the master oscillator frequency spectrum (left) was correlated/observed to impress a fast energy jitter on the electron beam (right) The frequency spectrum of the original and new master oscillators are compared on the left and the corresponding energy jitter from the striplines are shown at the right. Frequencies within ±200 Hz. introduce a ±5% peak to peak jitter with a 2–10 μs period

for all the accelerator rf. The effect master oscillator spectral purity has on beam energy jitter is strikingly illustrated in fig. 4. At the left are the frequency spectra for two different oscillators and the effect these spectra have on the beam energy as measured with the energy striplines (see fig. 2). The "old" oscillator was the one used during the concentric cavity tests, while "new" denotes the one currently operating for the ring resonator experiment.

3. Electron beam transport

Emittance growth caused by transporting the electron beam to the wiggler can be significant in low emittance accelerators. And FEL gain and extraction efficiency is strongly dependent upon beam emittance [3]. The magnitude of growth possible in going around the 180° bend is given in fig. 5 for the three major sources, transport aberrations, space charge and wakefields. This calculation [4] illustrates how simply making the beam too large at the bend's entrance can increase the emittance. This calculation ignores any contribution from misaligned beamline elements.

The control of the bend's emittance growth has been done by removing the FODO array of ten quadrupoles between the sixth accelerator section and the bend, and replacing them with two quadrupole triplets and a couple of OTR view screens. The old and new versions of the beamline are given in fig. 6.

4. Electron beam diagnostics

A better electron beam also requires upgrading the diagnostics used for sizing and alignment. Optical tran-

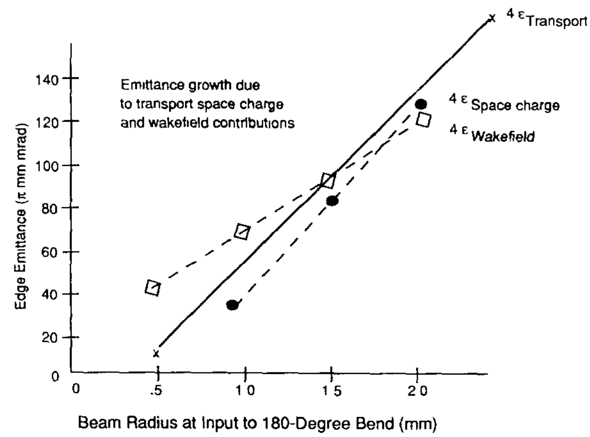

Fig. 5. The calculated emittance growth as a function of beam radius at the entrance to the 180° bend. The contributions from beam transport, space charge and wakefield effects are approximately equal.

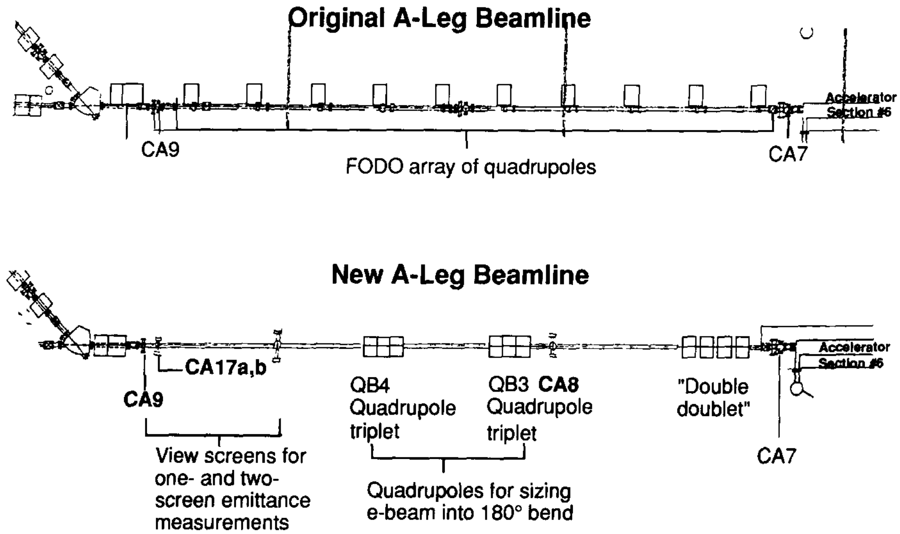

Fig. 6. Drawings of the beamline between the end of the accelerator and the start of the 180° bend. The top shows the original FODO array of ten quadrupole magnets. The current beamline configuration is drawn below.

sition radiation (OTR) view screens are now extensively used around the beamline. OTR was first installed in front of and inside the wiggler because beam size matching and alignment are especially important here.

Figs. 7 and 8 illustrate how OTR was implemented and lead to better screen resolution. Fig. 7 gives the schematic layout of a typical wiggler OTR station. The OTR screen itself is a 300 μm thick aluminum, diamond-turned mirror. A movable blocking foil of 50 μm thick stainless steel can be inserted in front of the OTR mirror to shadow the intense spontaneous emission from the screen and allows the OTR light to be seen. The shadow shield is removed to view the alignment laser, which defines the ring resonator optical axis, or to view the spontaneous emission itself. Since OTR light is emitted at the specular angle, the light intensity

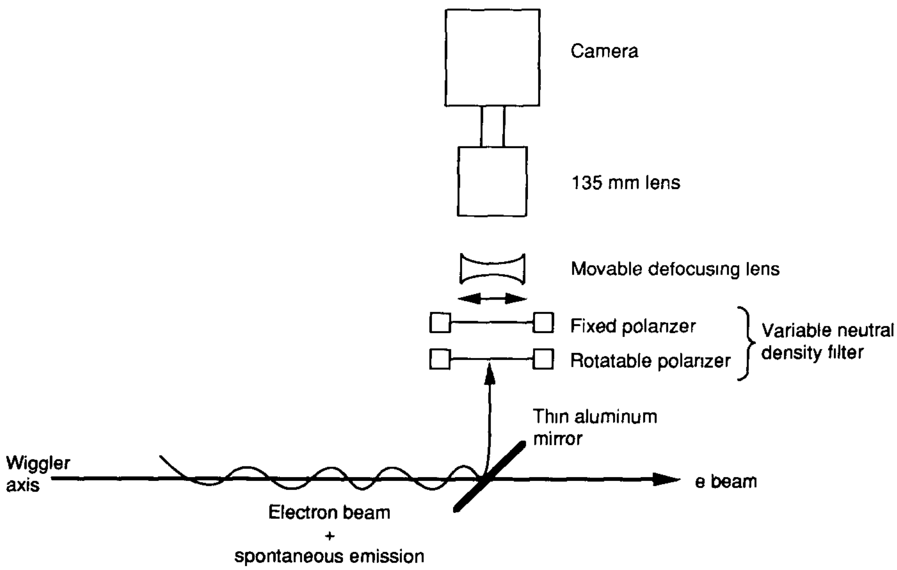

Fig. 7. Drawing of a typical wiggler optical transition radiation (OTR) view screen station. The blocking foil can be removed to observe the spontaneous emission position, size and angle relative to the alignment laser.

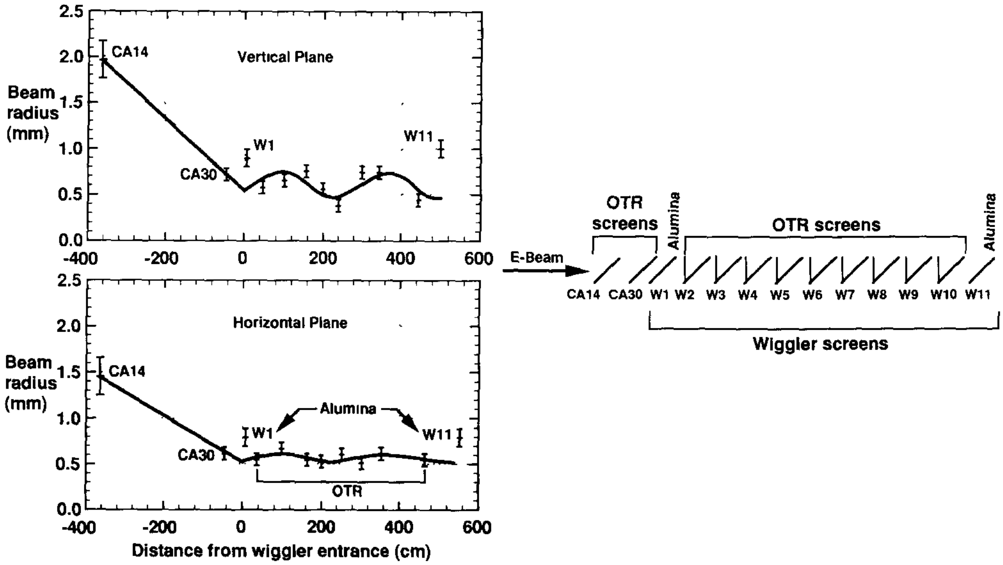

Fig. 8 The electron beam's radius through the wiggler as measured with OTR screens. Measurements made at the wiggler's entrance and exit with the alumina screens are plotted as W1 and W11.

going into the camera cannot be controlled with an iris. Instead a pair of crossed linear sheet polarizers are used to attenuate the light. One polarizer can be rotated remotely relative to the other to form a variable neutral density filter. A vidicon camera focuses on fiducials scribed onto the aluminum mirror. A defocusing lens on a pneumatic slide can be inserted to shift the camera's focus to infinity. With this lens in place, the angular distribution pattern of either the OTR or spontaneous emissions can be measured.

The better resolution given by the OTR screens can be seen in fig. 8. The drawing on the right schematically shows the screen positions in front of and inside the wiggler. Wiggler screens WI and W11 are alumina, all the others are OTR. Measurements are presented at the left and are discussed in more detail in ref. [5].

The electron spectrometer located after the wiggler (see fig. 1) is used to measure the energy of the electron beam. Data from this spectrometer was a valuable measure of the optical extraction efficiency during the concentric cavity tests [1]. However, its poor energy resolution limited its value as a beam diagnostic. Therefore this spectrometer's focal plane readout was changed from a quartz Cherenkov view screen to an OTR screen. This OTR screen also has a movable blocking foil. Behind this screen is a water cooled Faraday cup beam stop. Two fused-silica relay lenses bring the OTR light out to a shielded gated intensified CID camera. The gate on this camera can be adjusted to view the energy and energy spread for either the entire macropulse or groups of micropulses down to a single micropulse. The energy spreads of individual micropulses for different times into the macropulse are shown in fig. 9. The

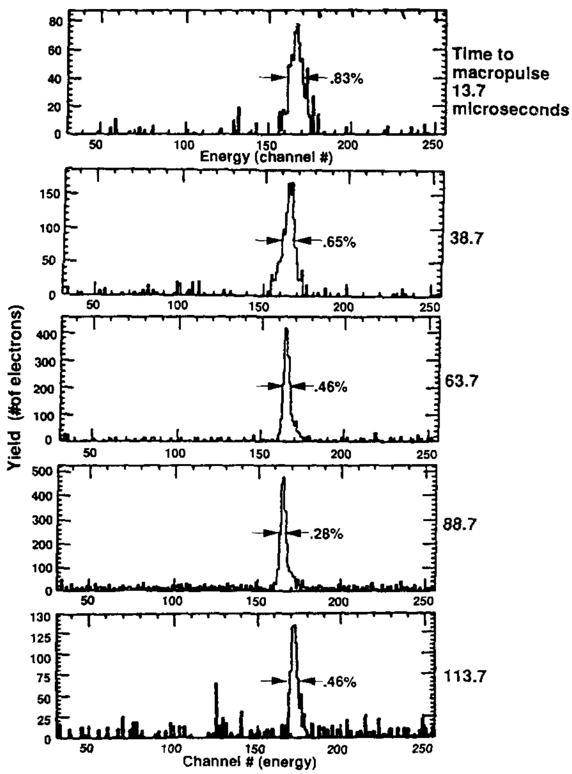

Fig. 9. The micropulse energy spread of the electron beam for micropulses 13.7, 38.7, 63.7, 88.7 and 113.7 μs into the macropulse. Higher electron energy is to the right.

micropulse energy spread is over 0.5% FWHM early in the macropulse, but as the rf control system begins to stabilize the energy spread falls to between 0.25% and 0.5%. Plans are in progress to instrument another spectrometer earlier in the beamline to use this type of information as an accelerator tuning aid.

5. Summary and conclusions

Work during the past year has improved both the accelerator's rf system and beamline transport. Measurements have correlated phase noise in the rf master oscillator with a fast energy jitter of the electron beam. Reduction of this phase noise eliminated this fast energy jitter resulting in reduced macropulse energy spread, and spatial and angular jitter at the wiggler. Simplifying the transport between the accelerator and the 180° bend allowed more flexibility in sizing and aligning the beam into the bend. This reduced the emittance growth in the bend and increased charge transport.

Also the extensive use of optical transition gave more accurate beam size measurements and better alignment through the wiggler. An OTR screen at a spectrometer's focal plane allowed the single micropulse energy spread to be measured.

This work has lead to much better beam quality at the wiggler, but more needs to be done. In particular, much of the beamline components should be more accurately aligned, this is true for both the 180° bend magnets and the accelerator sections and optics. Also it is necessary to make the daily setup and operation of the injector and accelerator more reproducible. Plans are in progress to do this.

Acknowledgement

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