FIRST RESULTS ON ENERGY RECOVERY IN THE JEFFERSON LAB IRFEL *

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Abstract

A recirculating, energy-recovering linac is used as driver accelerator for Jefferson Lab's high average power FEL. CW beam of 5 mA design current is transported from the superconducting RF (SRF) linac to the wiggler for lasing, and then recirculated back to the linac for deceleration and energy recovery. About 75% of the beam power is extracted before the beam is transported to the beam dump. Energy recovery reduces power consumption, RF equipment capital costs, and beam dump shielding requirements. It is arguably essential as FEL technology is scaled to higher average power levels.

To date, 4 mA of CW beam has been energy recovered successfully. There is no evidence of RF instabilities due to the energy aperture of the transport system, momentum compaction or the phase of the decelerating beam. HOM power from the beam has interfered with the operation of the IR interlock detectors, designed to protect the warm waveguide window from thermal runaway. Installation of copper screens appears to have solved the problem. More detailed studies of the HOM spectra and their correlation to the beam properties are planned.

1 INTRODUCTION

Jefferson Lab's IRFEL is presently being commissioned to produce CW, kW-level light at 3 to 6 μm wavelength. Output power of 710 W at 4.8 μm has been achieved to date [1], [2] with energy recovery. The IRFEL driver accelerator consists of a 10 MeV injector, which includes a 350 kV photocathode gun, followed by a copper buncher cavity and a CEBAF-type 1497 MHz superconducting RF (SRF) cryounit to generate an accelerating gradient of 10 MV/m. The linac uses a full CEBAF cryomodule to generate an average accelerating gradient of 8 MV/m, for a resulting beam energy of 42 MeV. The beam is transported from the linac to the wiggler where the lasing process takes place. A transport lattice recirculates the spent beam back to the linac for deceleration and energy recovery where about 75% of the beam power is converted into RF power. The 10 MeV beam is then transported to a dump.

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In Section 2 we present our operational experience with energy recovery of 4 mA of CW beam in an SRF accelerator. In Section 3 we describe the problem we encountered with the IR detectors and link it to higher-order modes (HOM's) excited by the sub-micron long bunches.

2 OPERATIONAL EXPERIENCE WITH ENERGY RECOVERY

In the energy recovery mode of operation, the beam is accelerated by the SRF linac to a final energy of 38.5 MeV (as measured by the bending magnets), is then transported around the recirculation path, enters the same SRF linac approximately 180° out of the crest of the RF wave for energy recovery—thereby being decelerated to 10 MeV—and is finally transported to the dump. Therefore, at any time there are two beams in the linac cavities (one accelerating and one decelerating). Longitudinal dynamics imposes off-crest operation for the two beams. When the FEL is turned on, the accelerating beam is at a phase of 8° from the RF crest and the decelerating beam is at 180° from the accelerating beam. With 6 kW (unsaturated) klystron power, in the energy recovery mode, we have optimized the external Q's to 4×10^6, which allows operation at 8 MV/m in the presence of microphonics of 370 Hz peak-to-peak for 5 mA of average current.

2.1 Power Requirements

To date we have accelerated and stably energy recovered up to 4 mA of continuous wave beam. We have demonstrated that energy recovery works equally reliably in the pulsed mode where 200 μsec beam pulses enter the SRF cavities at several Hz rate (from 2 Hz to 60 Hz). Figure 1 demonstrates the difference between non-recirculated operation and energy recovery, in pulsed mode. The signal plotted is GASK, the signal used to control the amplitude of the RF drive. When the 200 μsec beam pulse enters the cavity, there is a beam-induced gradient fluctuation due to transient beam loading. In response, the gradient modulator drive tries to compensate by demanding more klystron power, resulting in the waveforms depicted in Figure 1, with signal levels around 1.5 to 2 V. With energy recovery, however, the same GASK signals are very close to zero as the two signals cancel each other thereby making the decelerating beam act as the power source.

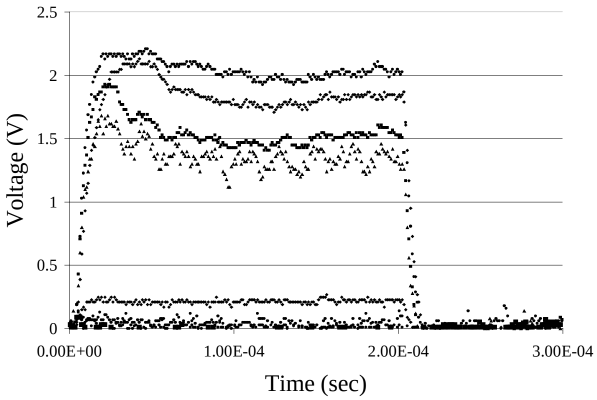

Figure 1: Gradient modulator drive signals in four different linac cavities, measured without energy recovery (signal level approx. 2 V), and with energy recovery (signal level approx. 0 V).

The power requirements for acceleration of 1 mA, 2.4 mA, 3 mA and 3.5 mA with energy recovery are shown in Table 1 and compared to those without beam. To enhance the contrast, power requirements for acceleration of 1.1 mA without energy recovery are also shown.

Table 1: Forward power to the cryomodule cavities under different beam conditions. The last four columns are for energy recovery.

Cav.	Beam off	1.1 mA	1 mA	2.4 mA	3 mA	3.5 mA
1	2.47	5.11	2.17	2.23	2.37	2.20
2	2.02	5.05	1.95	1.95	1.84	1.90
3	1.14	3.46	1.18	1.33	1.27	1.32
4	2.11	4.63	2.29	2.33	2.57	2.36
5	1.53	3.99	1.68	1.83	1.71	1.83
6	1.91	4.81	2.01	2.00	2.27	2.06
7	1.87	4.37	2.15	1.94	2.07	1.87
8	1.73	4.23	1.84	1.79	1.73	1.63

2.2 RF Stability

Fluctuations of the cavity fields in the linac can cause beam loss on apertures, phase oscillations and optical cavity detuning [3]. All three effects change the beam-induced voltage in the cavities through the recirculating beam. Depending on the RF feedback characteristics, this can lead to instabilities both of the accelerating field and the laser output power. To date we have accelerated, energy-recovered and lased stably up to 3.6 mA of CW beam current with no evidence of any type of instability.

3 HIGHER-ORDER MODES AND IR DETECTORS

3.1 IR Interlock Detectors

Each cavity in the cryomodule is kept under vacuum by two waveguide windows, a ceramic one at 2 K and a polyethylene one at room temperature. The waveguide section between the windows is protected against arcing by an interlocked photomultiplier tube and against thermal runaway (mostly of the warm window) by a thermopile infrared detector. The IR detector is aimed at the cold waveguide's parts through a 16 mm diameter tube departing from the narrow sidewall of the high aspect ratio waveguide. During the first operation of the FEL with sizable CW beam (~1 mA), it was noticed that the signal from the IR detector (normally negative, since it detects a temperature lower than that of the detector's body) was increasing towards zero. This observation was ascribed to possible HOM emission, with consequent additional heating of the waveguide area, but no further action was taken. As the current was raised in recent weeks, the signal from the IR detectors in all cavities was observed to rise, until, at about 1.5 mA, it reached the set trip point of the IR interlocks, shutting off the beam and the RF power and virtually preventing operation of the machine. The observed anomalous response from the IR detector possesses the following characteristics: a) it appears only when the beam is on, and b) the response time with beam on/off is of the order of one second, a couple of orders of magnitude faster than the normal thermal response time of the waveguide subjected to a few kilowatts of incident power.

Based on these observations, it was thought that the IR detector was producing a spurious signal, not due to real temperature changes in the waveguide assembly. Bench tests of an IR detector assembly revealed that the detector is sensitive to direct exposure to RF, producing a positive signal with a response time of one second. Measurements performed around 20 GHz showed a sensitivity of the detector of about .4-.6 mV/mW. The 16 mm diameter tube in which the detector is assembled has a cut-off frequency of about 11 GHz in the TE_{11} mode and about 14.4 GHz for the TM_{01} mode. The installation of an RF screen with mm-sized holes removes most of the signal associated with the beam's suspected HOM's, while still providing reasonable response from the fundamental RF power heating of the waveguide. The observation of the RF response of the IR detector provides us with a bolometric tool for the detection and analysis of the HOM's generated by the beam. An assembly of three detectors with different screens has been placed on one of the cavities' waveguides. The assembly is mounted at 90º from the direct line of sight of the interlocking IR detector on a 16 mm pipe "tee". The detectors in this assembly show no response under the zero power condition, since they are not looking at the waveguide's cold surfaces, but at a room temperature part of the "tee". They also show no response to RF power on, indicating that the IR radiation is not coupled to it via the 90º "tee". When the beam is turned on, however, the IR detector responds with a positive signal with a one-second time constant (Figure 2). Only microwave energy between 11 GHz and a few tens of GHz can couple efficiently through the bend and propagate to the detector. This additional confirmation of the correlation of the IR response with RF, and not with heating, strongly supports the hypothesis that no additional heat is being generated which could endanger the safe operation of the superconducting cavities.

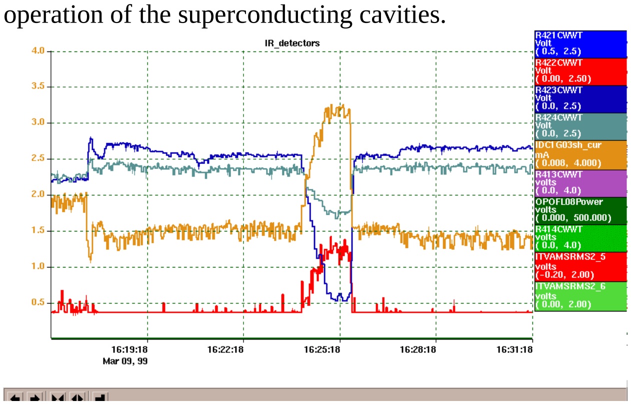

Figure 2. Traces of standard IR interlock detectors (changing from high to low, polarity reversed) and of 90º offset detectors (changing from low to high) as the beam is turned on.

The typical signal detected by the IR sensors indicated that the amount of HOM power reaching the detector is of the order of several milliwatts. At present, the coupling factor from total HOM power generated to that detected is unknown, although it should be very small, probably less than 10^{-2}.

3.2 *Higher-Order Modes*

Power emitted by the beam in the form of Higher-Order Modes has been estimated to be of the order of a few watts per cavity. A fraction of that power (at frequencies between 1.9 GHz and several GHz) should propagate into the HOM extraction waveguides and be absorbed by specially designed loads kept at the cryomodule thermal shield's temperature, 50 K. Other modes will propagate down the beam pipe and be absorbed anywhere in the cavities at 2 K or in the warm sections of the line. Thermal measurements of potential losses due to longitudinal modes have so far failed to detect additional heat loads due to HOM's, but the sensitivity of these measurements is of the order of a few watts per cavity. Additionally, modes' power will propagate into the fundamental power coupler and will be absorbed by waveguide filters in the guide's warm sections. Lightly-coupled electric field probes, coupling mostly to TE_{0n} modes in the high aspect ratio rectangular waveguide, have provided qualitative insight into the spectrum of the emitted RF (Figure 3).

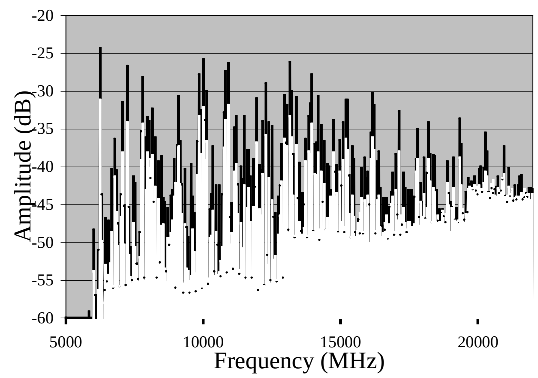

Figure 1. RF spectra sampled from the input waveguide of a cryomodule cavity. Black trace: 3.5 mA beam. White trace: 1.3 mA beam.

Preliminary results show a highly populated spectrum of lines spaced by 37.425 or 74.850 MHz (the bunch repetition frequency). The spectra start at about 6 GHz, the cut-off frequency of the TE_{01} mode in the guide. The spectra are detected up to 22 GHz, the upper frequency of the analyzer.

4 OUTLOOK AND CONCLUSIONS

We have successfully operated Jefferson Lab's IRFEL in energy recovery mode with up to 4 mA of CW recirculating current. No evidence of RF instabilities has been observed. The presence of HOM's from the short bunches in the SRF cavities has been confirmed by different methods. Detection of HOM power by the IR interlocks has interfered with operations, but the installation of copper screens appears to have solved the problem. The response of the detectors themselves to the HOM's is planned to be used to gain information about their dependence on beam properties such as bunch length, bunch repetition frequency and charge per bunch.

5 ACKNOWLEDGMENTS

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6 REFERENCES

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