PULSED BEAM CAPABILITIES OF THE LIVERMORE CYCLOGRAAFF*

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Summary

The Livermore cyclograaff facility has been operational for experimental use since October 1971. Accelerator development has concentrated upon production of proton beams with burst length and repetition rates suitable for fast neutron time-of-flight work. Average target currents exceeding 1 μA are now available in pulsed beam mode over the nominal 1-27 MeV range of the combined machines.

Introduction

The Livermore Cyclograaff was acquired as a replacement accelerator for the 90" variable energy cyclotron built at Livermore during 1952-54 for use in basic and applied research. The principal attractiveness of the cyclograaff concept[1] was the prospect of easy and inexpensive production of high quality proton beams over the 1-30 MeV energy range for neutron time-of-flight or high resolution charged particle spectroscopy. Secondary considerations in the selection of this accelerator system were its versatility with respect to particle species, intensity, and energy. Operation and maintenance of the accelerators promised to be simple. The cost advantage over alternative accelerators, an MP tandem or a scaled-down version of the LBL 88" isochronous cyclotron, was considerable: the negative ion cyclotron, an EN tandem, and all required beam transport equipment could be purchased for two million dollars.

Physical arrangement of the cyclograaff laboratory is shown in Fig. 1. The two components of the cyclograaff are a Cyclotron Corporation Model CNI-15 cyclotron and a High Voltage Engineering Corporation Model EN tandem Van de Graaff. During installation of the new machines, the 90" cyclotron remained in operation. In February 1971, the 90" was dismantled and removed so the room containing it could be converted to a target room for the cyclograaff. In October 1971, charged particle experiments with the cyclograaff were begun. Neutron time-of-flight work was resumed in November 1971.

Details of the beam lines have been omitted in the target pits so the permanent experimental stations can be seen more clearly. The first pit contains a 24" scattering chamber for study of charged reaction products with solid state detectors and a spectrometer for measurement of gamma ray production cross sections. The spectrometer consists of a 10" x 10" NaI scintillator surrounded by plastic scintillators for suppression of Compton scattering events. Outer layers of lead and ^{6}LiH provide gamma and neutron shielding for the scintillators.

The second pit contains a broad range split-pole magnetic spectrograph for high resolution charged particle experiments and the target position for the multiple neutron detector array. Sixteen detectors on 11 m flight paths provide angular coverage from 3.5° to 69° in steps of approximately 7.5° and from 69° to 159° in steps of 15°. The magnetic spectrograph had not been installed when the cyclograaff became operational so the first development effort was directed to pulsed beams rather than to high resolution beams.

Cyclotron

The CNI-15 cyclotron is an 80 cm, three sector isochronous machine with two 120° dees. Details of the basic structure, negative ion source, axial injection canal, and the rf and precessional extraction systems have been described previously.[2,3] The cyclotron operates in the fundamental mode producing beam bursts at the rf frequency, 25 MHz for proton beams and 12.5 MHz for deuteron beams. Burst length is normally between two and three nanoseconds and is not readily adjustable. The performance specification for the accelerator required production of a 10 μA external beam of negative hydrogen at 15 MeV with an average spread of 60 keV. Vertical and horizontal emittance of the beam were not to exceed 50 mm-mr.

After acceptance from the manufacturer, modifications were made to increase the external beam current to compensate for the losses expected in reduction of the duty cycle for time-of-flight operation. The electrostatic quadrupoles in the axial canal were altered so each element could be separately adjusted, providing steering as well as focussing. Individual supplies were installed on the harmonic coils at large radii to provide remote adjustment of the azimuth as well as the magnitude of the field bump used to increase extraction efficiency. With these changes, external beams of 25 μA of negative hydrogen and 5 μA of negative deuterium have been obtained, although the energy spread and emittance are not necessarily within the nominal specifications.

The first attempt to increase the interval between pulses for time-of-flight operation was made by chopping the low energy beam before inflection into the cyclotron median plane. Such a procedure produces complete suppression of undesired beam bursts only if the cyclotron is operating in single turn extraction mode. However, it was hoped that useful modulation of the beam current could be produced which would reduce both the circulating current in the cyclotron and the amount of full energy beam to be dumped by a post-acceleration sweeper. Both a simple pair of deflection plates placed after the ion source extraction electrode and a Lissajous sweeper installed in the axial canal failed to modulate the beam adequately. When a current pulse less than 40 ns long was injected at 400 ns intervals, only 20% of the total current extracted from the machine appeared in the principal burst. The remaining current came out on the subsequent seven or eight rf cycles showing time microstructure characteristic of multiturn extraction. For the initial time-of-flight operation it was decided to use only a post-acceleration sweeper.

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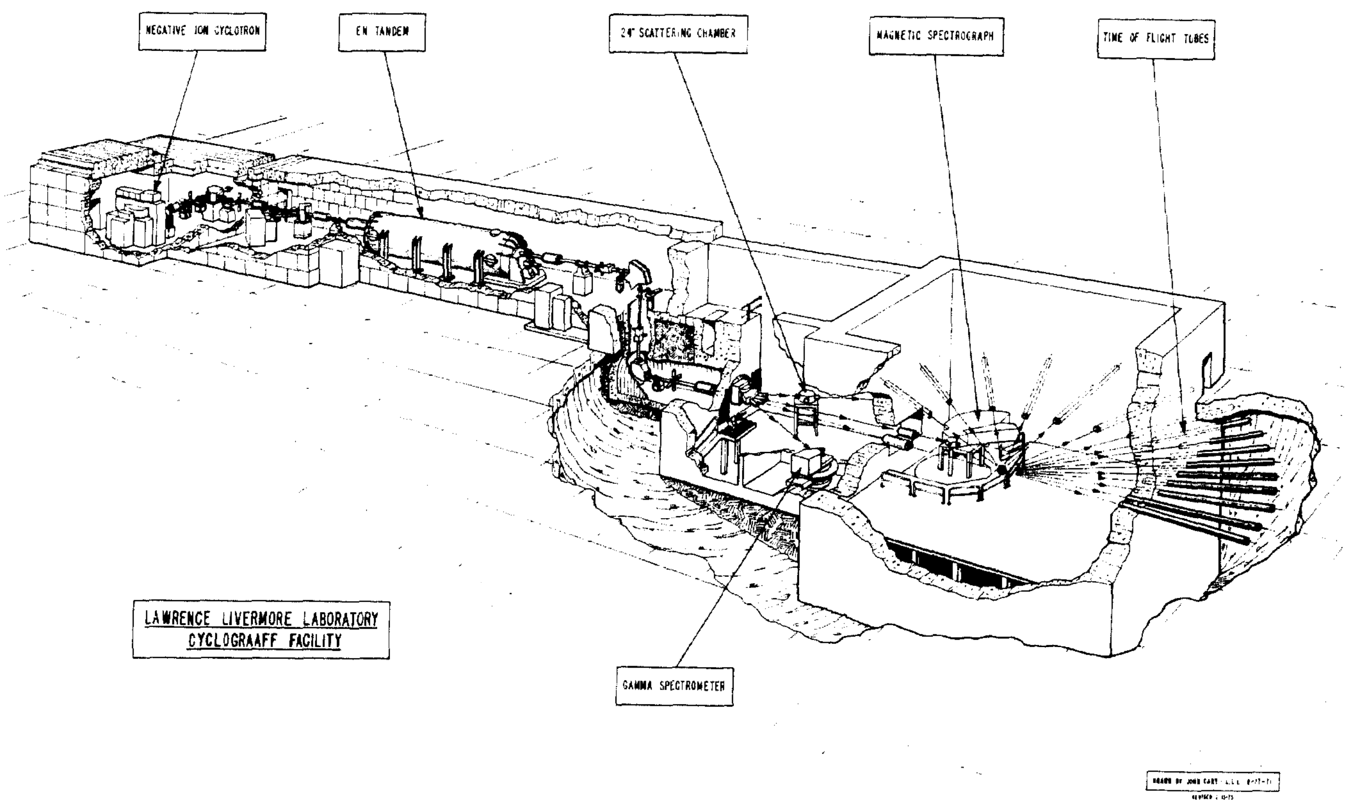

Fig. 1 Layout of Livermore cyclograaff facility

Tandem

Performance specifications for the EN tandem required production of 15 µA of analyzed proton beam at 4 MeV and 12 MeV and 25 µA at 8 MeV. The direct extraction ion source can produce hydrogen and deuterium beam currents greater than 50 µA. Alterations to provide beam handling equipment suitable for use with the cyclotron beam were made after acceptance of the machine from High Voltage. The direct extraction ion source, inflection magnet, and low energy vacuum extension were moved back 2 m to allow installation of a 10 cm quadrupole triplet on the low energy baseplate. A 10 cm aperture quadrupole doublet was installed on the high energy vacuum extension in place of the 7.5 cm doublet supplied with the machine.

Acceptance of the tandem was increased by enlarging the collimating aperture at the entrance of the stripper box to 10 mm and removing the gas stripper canal. These changes have significantly improved the transmission of the tandem when the direct extraction source is used. Beam transmission is routinely 90% - 100% over the 1 MeV - 12 MeV range for proton and deuteron beams. The quadrupole triplet, intended for use with the cyclotron beam only, is used with the low energy beams as well to obtain better transmission than is possible using only the single einzel lens provided in the low energy extension.

The foil stripper chain is loaded with a mixture of 5, 10, and 20 mg/cm^2 carbon foils on 12.5 mm apertures. Foil lifetime has been quite long even for heavy ion operation or for proton operation at low voltages. This good performance probably results from the large spot size available on the foils.

Cyclograaff

Beam Transport The components of the beam handling equipment between the two accelerators are shown in Fig. 2. The 90° magnet is operated either as an analysis magnet with 1 - 2 mm slit openings for experiments requiring good energy resolution (<30 keV) or with the slits wide open and the beam crossed over in the center of the magnet to provide high beam transmission for time-of-flight. A 7.5 mm sweeping aperture after the second quadrupole doublet is the object point for the triplet which focusses the beam on the foil stripper in the tandem terminal. After acceleration to the desired energy by the tandem, the beam is bent 90° in a single analyzing magnet whose slit settings determine the final energy resolution. The beam energy is controlled by varying the tandem terminal voltage with a standard corona triode circuit.

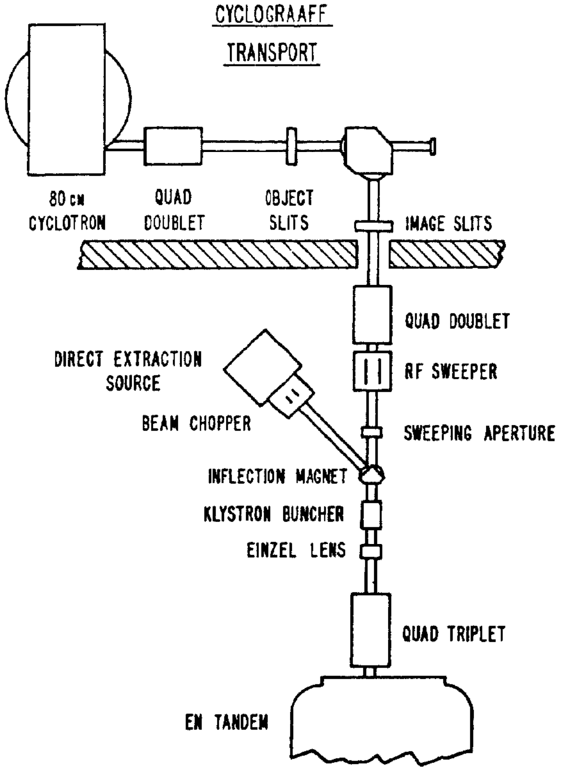

Fig. 2 Beam transport and pulsing equipment between accelerators. The drawing is not to scale.

Typical proton currents throughout the transport system for various modes of operation are listed in Table 1. Transmission of the tandem for cyclotron beam is normally 100%. The low energy quad triplet is preset before removing the low energy faraday cup and only small adjustments of that lens and the steerers are then required to obtain all of the beam on the high energy cup. The high transmission obtained when injecting unanalyzed beam in the time-of-flight mode implies that the tandem could probably transmit the full cyclotron output if necessary. However, until further experience with beam tube lifetime has been obtained or until there is experimental justification, the cyclotron beam current injected into the tandem has been arbitrarily limited to 3 μA.

Table 1: Cyclograaff Proton Beams

Beam Character	ΔE ∿ 30keV	Δt ∿ 2.5ns 5MHz Rate	Δt ∿ 1ns 5MHz Rate
Beam Extracted From Cyclotron	18.5μA	15.0μA	1.2 μA
Analyzed or Swept Beam Delivered to EN	1.8	2.5	0.15
Analyzed Beam	1.5	1.5	0.13
Target Current	1.0	1.0	0.10

Pulsed Beams Over the 1 - 12 MeV tandem range, pulsed proton or deuteron beams are produced with a low voltage chopper and a klystron buncher. The position of these elements is shown in Fig. 2. Current pulses 30 ns long are formed at frequencies of 0.625, 1.25, 2.5, or 5 MHz when the 50 keV beam is chopped on a aperture in the tank of the inflection magnet. These pulses are compressed to 1 ns fwhm by the 5 MHz klystron buncher. An average current of over 2 μA has been obtained on target at the 2.5 MHz rate.

When operating in cyclograaff mode, unwanted beam bursts are deflected by the rf sweeper between the two machines. The sweeper can be tuned over a 2 MHz to 5 MHz range and will operate at peak-to-peak voltages up to 30 kV. A digital countdown from the cyclotron rf drives the sweeper. For proton operation, the sweeper is run in a zero pass mode at $f_o/10$ or $f_o/7$, producing beam bursts at rates $f_o/5$ and $f_o/7$ respectively. At the 5 MHz rate ($f_o/5$), average proton target currents of 1 μA have been obtained regularly with burst lengths of 2.5 ns. In deuteron operation at $f_o/5$ (2.5 MHz) target currents of more than 100 nA have been obtained with similar burst lengths. The usual difficulty with post-acceleration sweeping, background from the stopped beam, is not encountered in this case because of the many meters of concrete and earth separating the detectors from the sweeping aperture.

An internal slit system similar to that of the TUNL cyclograaff[4] was installed in the cyclotron to allow adjustment of phase acceptance and the amplitude of radial oscillations. An adjustable slit is placed at 180° on the third turn and a single post is positioned between two turns further out. By adjusting slit aperture and post position, the burst width may be reduced to 1 ns. A plot of extracted current versus burst width obtained during initial use of the slits is shown in Fig. 3. Extraction efficiency increases from 25% to over 60% when the slits are used. Larger currents than indicated in Fig. 3 have been obtained in recent work.

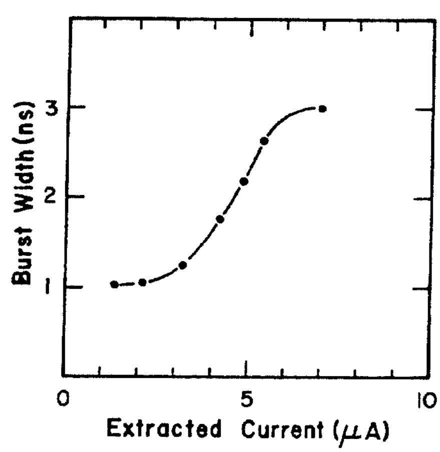

Fig. 3 Pulse width (fwhm) vs current extracted when median plan collimation is used.

Use of the internal slit system results in good time stability of the beam. An average target current of 100 nA has been obtained at the 5 MHz rate with 1 ns burst width. The envelope of the prompt gamma ray burst from the target after a one-hour run is shown in Fig. 4. During this run the cyclotron was freely tuned to maintain maximum beam. Despite this tuning, the envelope has expanded to only 1.5 ns fwhm. All the results presented here have been obtained using 5 cm x 5 cm NE 213 scintillators and stop pulses for the time-of-flight electronics derived from the cyclotron rf. Improved time resolution could be obtained with faster scintillators and better stability is expected when a beam pickoff timing system is used.

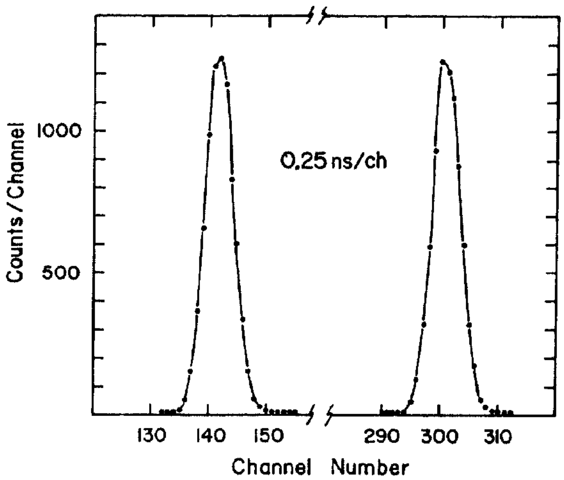

Fig. 4 Prompt gamma ray peaks from two successive beam bursts after a one-hour run. The peaks are separated by 40 ns.

No direct measurements of the energy spread of the beam obtained when the internal slits are used have been made. If one assumes that half the 1 ns burst width at the target results from debunching of the beam over the 60 m flight path from the cyclotron, then the energy spread in the beam is 15 keV or less.

Accelerator Development Further work on the two accelerators will be done to increase the versatility and ease of operation of the facility. Addition of improved diagnostic equipment for the cyclotron including a differential beam probe and digital monitoring of the magnetic field and rf voltage are planned. An inner set of harmonic coils will be installed to allow better centering of beam orbits. A slow square wave pre-injection chopper will be installed on the cyclotron to reduce by 50% the amount of full energy beam that must be dumped during time-of-flight experiments.

Upgrading the tandem to operate at 7.5 MV by installing stainless steel electrode tubes and converting to SF_6 insulating gas is desirable. This step would close the gap between 12 MeV and 15 MeV in the proton energies available, extend the upper limit to 30 MeV, and significantly improve the heavy ion capabilities of the accelerator. A Li vapor canal charge exchange source is under construction for the tandem to replace the ^{3}He and ^{4}He beam capability lost when the 90" cyclotron was shut down.

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