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THE OSAKA UNIVERSITY LINAC

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Abstract

During November, 1978 a new, high current electron linear accelerator became operational at the Institute for Scientific and Industrial Research (ISIR), Osaka University, Japan. The linac is intended for studies in radiation chemistry, radiation effects and nuclear physics. The machine was designed and constructed by Systems, Science and Software, Hayward, California. This report describes the linac and its initial performance.

General Description

A diagram of the major components of the system is shown in Fig. 1. To some extent the beam line describes the linac; all other systems are peripheral, but, the overall system is synergistic; hence the system stability and useability (ratio of time available for use to time machine is on-line) depends upon the specification and achievement of the tolerances of the peripheral system (as well as the beam line). Stability tolerances are set by the beam line design, that is, they are operating tolerances, whereas useability (or reliability) depends primarily upon de-rating components.

The desision was influenced by the short pulse mode of operation, where it was also proposed to transmit 7 nC charge bursts in pulses of about 30 psec to be accelerated to 30 MeV. The fraction of stored energy removed by the beam must be negligible to prevent serious energy drop during the transient regime. Thus, the final design is a compromise based on the judgment of the designer on the acceptability of the theoretical performances. The following paragraphs are brief comments on each of the major subsystems of the machine.

Injector Design

The choice of L-band was principally dictated by the short pulse mode requirement. Clearly, the 30 MeV long pulse specification could easily be met in S-band whereas in L-band there is a waveguide length problem. But the decisive factor was the injection system.

The plan decided upon is subharmonic pre-bunching (SHPB). A beam modulated by a single gap cavity bunches, at the end of its drift distance, about one-half the injected charge of one cycle into one radian. If the beam were modulated at the sixth subharmonic about one-half the injected beam charge of that cyclic period would be bunched into one cycle of the basic machine frequency. This charge bunch can then be re-modulated at the basic machine frequency to produce a one radian bunch at the basic machine frequency. The only serious necessity to produce a single RF bunch is that the gun pulse does not last longer than one RF cycle of the subharmonic frequency.

It may superficially appear that the purpose of subharmonically bunching the beam is to produce more charge in the bunch, yet it will, on computation be evident that the bunched fundamental charge is $q \approx 3I_0/2f$; but without the SHPB the 3 nsec injected pulse would remain a 3 nsec pulse with a microstructure of 6 pulses of about 30 psec extent. In the present state of modulator design the gun pulse cannot be made shorter than about 2-3 nsec; thus, the SHPB solves the problem of getting one RF cycle into the linac.

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Basic Accelerating Structure

The choice of parameters for the constant gradient accelerating waveguide were, of course, dictated by the particle energy level to be achieved at the specified beam power conversion efficiency. Thus, for a no load energy of 35 MeV and a beam current of 700 ma at about 20 MeV with 18 MW input power (efficiency 0.78) the accelerating waveguide will have the properties listed in Table I (1).

Table I

Shunt impedance, r	40 Mohms/m
Figure of merit, Q	19,000 ($2\pi/3$ mode)
Attenuation length, $2I_0L$	0.834 nep (3.62 db)
Length, L	3.0 meters (40 cavities)
Initial atten. coeff., I_0	0.0944 nep/m
Initial norm. group vel., v_g	0.0075
Electric field intensity, E	11.63 MV/m (18 MW)
Fill time, τ	1.96 μs
Stored energy, J	24 joules (18 MW)
Operating frequency, f	1300 mcs (λ = 23.06 cm)

RF Power Supply

The principal RF power is supplied by a TV-2022A klystron, rated 22 MW, pulsed by a conventional 18-section line-type PFN with de-Qing video-pulse amplitude stabilization. (The waveguide requirement of 20 MW allows 2 MW for operation of a tapered phase velocity buncher.) In spite of no guarantee of supply main stability it was decided not to use induction regulators (in the interests of economy); the resulting klystron pulse does not suffer by more than $\pm$ 1% current variations.

Solenoidal Containment System

The beam line system consists of numerous components with interspaces so that it appeared a practical magnetic beam containment system would be to immerse the linac in a Helmholtz solenoid.

The relativistic Brillouin Flow condition can be shown to be given by (see appendix)

$$B_z = \sqrt{\frac{2}{\pi}\,\frac{m_0 I\eta}{e\,b^2}\,\frac{1}{\sqrt{\gamma^2-1}}} = \frac{.3693}{b}\sqrt{\frac{I}{\sqrt{\gamma^2-1}}}$$

where I is the dc beam current
η is the impedance of free space
b is radius of the beam
γ is the normalized energy of the beam
and all units are MKS except magnetic flux. This may be compared with the conventional non-relativistic solution

$$B_z = \frac{8.30}{b}\sqrt{\frac{I}{\sqrt{V_0}}} \quad \text{GAUSS}$$

where V_0 is the beam voltage. Thus relativistic motion only causes a slight change from the "classical" case. Previous experience has shown that beam scalloping due to not providing precisely the Brillouin conditions is negligible in linacs. Therefore the power supply to the coils was divided into four groups, to provide some variability. Field ripple due to finite coils is about four percent with 25 cm coil spacing. The basic electron-optical plan was to focus the beam by means of a Glaser lens, the focus or waist coinciding with entry into the Helmholtz solenoidal field.

The disadvantage of the scheme is the long drift

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space required and the likelihood of satellite pulses owing to the fact that the velocity modulated current is never zero in the RF cycle.

It is doubtless evident that it is essential to maintain phase coherence between the fundamental and subharmonic frequencies; this is accomplished by multiplying the subharmonic to produce the fundamental. Pulse-to-pulse stability also requires that the gun trigger pulse be given at a specified phase; this is achieved by forming the trigger pulse from the subharmonic signal.

The electron optics of the ISIR linac were largely based upon that of its predecessor, the ANL high current linac (2); the design was based upon focussing the gun beam into the Helmholtz solenoidal field to achieve near-Brillouin flow conditions.

Initial Performance

The initial steady-state performance ($1\mu s$) of the linac is illustrated on Fig. (2). The machine will put out 5 nC in about 60 ns during single burst operation, as measured by means of a streak camera. Time-elongated pulses (compared to the pulse out the linac) are often owing to different transit times through magnet systems (non-isochronous systems); that is not the case in the present system and the cause of the implied wide phase spread is still being investigated, although the wide phase spread is inconsistent with good energy spectrum, Fig.(3).

Acknowledgements

In a project of this size the cooperation of many engineers is required. The authors, therefore, wish to acknowledge the contributions of Mssrs. R. Reutz, D. Ferguson, S. White, E. Ferrer and R. Medonza.

References.

(1) The choice of parameters is discussed in The Design of Travelling Wave Electron Linear Accelerators, W. J. Gallagher IEEE Trans. Nuc. Sci. NS-14, 282 (1967)

(2) A High Current Electron Linac, IEEE Trans. Nuc. Sci. NS-18, 584 (1971)

Appendix

The analysis for relativistic Brillouin flow supposes the beam immersed in a solenoidal magnetic field, both axes being coincident. The equations of motion of a beam particle in cylindrical coordinates are:

$$\frac{d(\gamma\dot{z})}{dt} = \frac{e}{m_0}\left(E_z + \dot{r}B_\varphi - r\dot{\varphi}B_r\right)$$

$$\frac{d(\gamma\dot{r})}{dt} = \frac{e}{m_0}\left(E_r + r\dot{\varphi}B_z - \dot{z}B_\varphi\right) + \gamma r\dot{\varphi}^2$$

$$\frac{1}{r}\frac{d(\gamma r^2\dot{\varphi})}{dt} = \frac{e}{m_0}\left(E_\varphi + \dot{z}B_r - \dot{r}B_z\right)$$

The radial electric field at the beam boundary ($r = r_0$)

$$E_r = \frac{e\rho}{2\pi r_0\epsilon_0}$$

Where ρ is the linear charge density, and therefore the beam current

$$I = \rho\dot{z}$$

The circumferential magnetic field associated with the beam

$$B_\varphi = \frac{\mu_0 I}{2\pi r_0}$$

The applied solenoidal field is B_z. Thus the equations of motion become:

$$\frac{d\gamma\dot{z}}{dt} = \frac{e}{m_0}\frac{\dot{r}}{r}\frac{\mu I}{2\pi}$$

$$\frac{d\gamma\dot{r}}{dt} = \frac{e}{m_0}\left(\frac{I}{2\pi\epsilon_0 r\dot{z}} + r\dot{\varphi}B_z - \dot{z}\frac{\mu I}{2\pi r}\right) + \gamma r\dot{\varphi}^2$$

$$\frac{1}{r}\frac{d\gamma r^2\dot{\varphi}}{dt} = -\frac{e}{m_0}\dot{r}B_z$$

Solving the latter equation

$$\frac{d(\gamma r^2\dot{\varphi})}{dt} = -\frac{e}{m_0}r\dot{r}B_\varphi$$

or

$$\gamma\dot{\varphi} = -\frac{e}{m_0}\frac{B_z}{2}$$

Where the boundary condition is $\dot{\varphi} = 0$, $B_z = 0$. This is the conventional Larmor frequency for the orbiting of a charged particle in a magnetic frequency.
The first equation may be integrated directly

$$\gamma\dot{z} - \gamma_0\dot{z}_0 = \frac{e}{m_0}\frac{\mu_0 I}{2\pi}\ln\frac{r}{r_0}$$

Where the boundary conditions are $\gamma\dot{z} = \gamma_0\dot{z}_0$ at $r = r_0$.
The radial equation becomes, substituting from the above

$$\frac{d(\gamma\dot{r})}{dt} = \frac{e}{m_0}\frac{I}{2\pi r}\left(\frac{1}{\epsilon_0\dot{z}} - \mu_0\dot{z}\right) - \frac{r}{4\gamma}\left(\frac{eB_z}{m_0}\right)^2$$

We will now choose B_z so that $d(\gamma\dot{r})dt = 0$,

$$\frac{r}{2\gamma}\left(\frac{eB_z}{m_0}\right)^2 = \frac{e}{m_0}\frac{I}{2\pi r}\frac{\eta}{\gamma\sqrt{\gamma^2-1}}$$

where we note that $\left(\frac{1}{\epsilon_0\dot{z}} - \mu_0\dot{z}\right) = \eta\left(\frac{1}{\beta} - \beta\right)$
$\eta = \sqrt{\mu_0/\epsilon_0}$
is the impedance of free space; $c = 1/\sqrt{\mu_0\epsilon_0}$ is the velocity of light in free space). Hence,

$$B_z = \sqrt{\frac{2}{\pi}\frac{m_0}{e}\frac{I\eta}{r_0^2\sqrt{\gamma^2-1}}}$$

$$= \frac{0.369346}{r_0}\frac{I}{\sqrt{\gamma^2-1}} \quad \text{GAUSS}$$

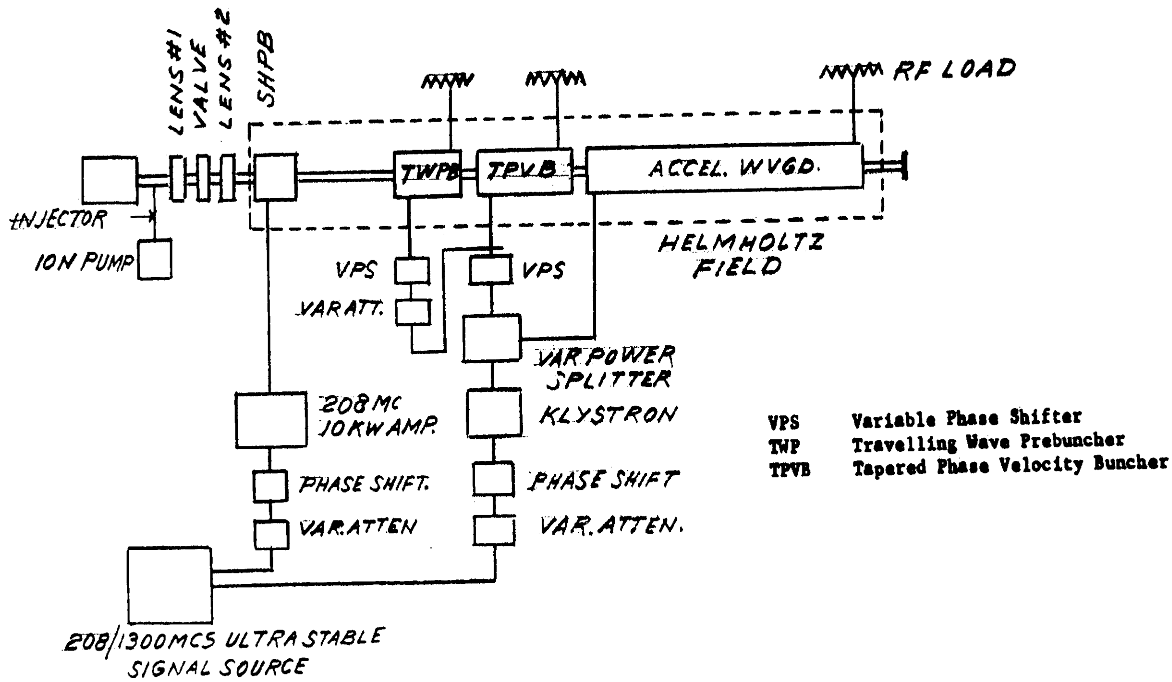


Fig. (1) Diagram of Major Components of ISIR Linac

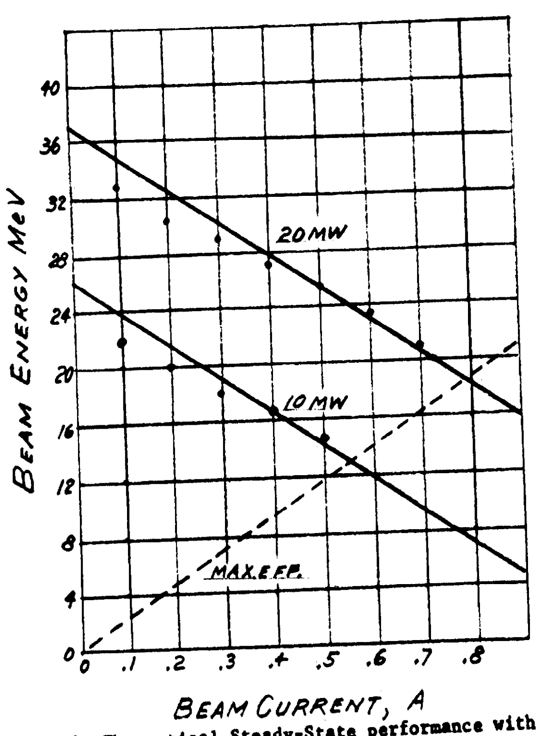
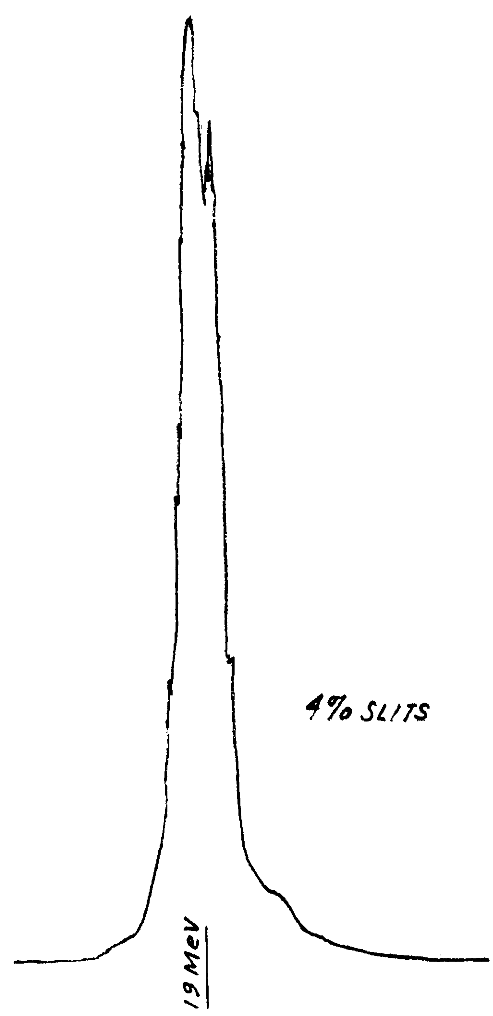


Fig. (2) Theoretical Steady-State performance with experimental data indicated.



To the right, Fig. (3) Output spectrum, 750 ma 19 MeV, FWHM .052 (traced from spectrometer print-out)