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TITLE: PHERMEX STANDING-WAVE LINEAR ELECTRON ACCELERATOR

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PHERMEX STANDING-WAVE LINEAR ELECTRON ACCELERATOR

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Summary

The PHERMEX standing-wave rf electron linac is a high-current pulsed electron beam generator that is used for flash x-radiography. This accelerator is being upgraded to 1000-A peak current and 50-MeV peak energy over a 150-ns pulse or over three 40-ns pulses. This upgrade is a result of increasing the rf power in the cavities and installing a new (Physics International) injector pulser.

Introduction

PHERMEX is a three-cavity, standing-wave rf electron linac. PHERMEX began operation in 1963 at 21 MeV and 300 A; was upgraded in 1967 to 27 MeV, and will be upgraded to 50 MeV and 1000 A in 1983.[1,2] PHERMEX is an acronym for Pulsed High-Energy Radiographic Machine Emitting X-Rays. The primary application of the PHERMEX beam is to generate a short x-ray burst for flash x-radiographic measurements. A flash radiograph is an areal density distribution image of a rapidly moving object. This image is generated when a short duration point x-ray source is directed at an object and x-ray film. PHERMEX differs from most radiographic source machines in that the PHERMEX x-ray system can resolve very small density variations in extremely thick high-atomic number objects. To generate such a high-quality flash x-ray beam, the accelerated electron beam must be of short duration (≤200 ns) to minimize object motion blur, high energy and high current to maximize x-ray flux in the 2- 7-MeV x-ray energy range, and focusable to a small spot (~1- 5-mm diam). A standing-wave linac is well suited for generating this type of electron beam.

Accelerator Configuration

Figure 1 shows a schematic of the accelerator. In a typical pulse, first, rf energy flows into the accelerator cavities for 1 μs, building up the accelerating electric field strength until the resistive cavity power loss equals the input power. A 200-ns, 300-A electron pulse is injected into the first cavity that focuses, chops, and accelerates the electron beam. The other cavities further focus the beam that is then magnetically focused to a minimum spot size on an x-ray converter.

The original rf amplifiers are RCA 6949 models, which develop 1.13 MW pulsed at 50 MHz. As part of the 1983 upgrade, these will be replaced with Eimac X2159 tetrode amplifiers that deliver 5 MW pulsed at 50 MHz. This amplifier was developed by the Los Alamos Hydrodynamic Group. It has an 80% plate efficiency and a 16 dB gain for a 3-ms pulse operated once every 10 s. Figure 2 shows a circuit schematic for the tetrode amplifier with the bias inputs and the bias isolation circuitry omitted. The X2159 is a cylindrical tube with the cathode, the control grid, and the screen grid constructed of tensioned rods appropriately aligned so that the control grid intercepts a minimum of cathode emission, and the screen grid provides maximum capacitive shielding between the control grid and the plate. The primary difficulty operating this tube at 50 MHz is that the active cathode length is approximately 0.1 λ (λ = 6 m at 50 MHz), and the tube is almost resonant at 50 MHz. The control grid/cathode input is series resonant at 52 MHz, the shorted plate-screen circuit is self-resonant at 76 MHz with the corona shields in place. A secondary difficulty is the propensity of the control grid-screen grid-circuit for supporting a 900-MHz parasitic. The operating line gives a 120-Ω plate resistance with a 35-kV plate bias, a 1500-V screen bias, a 1000-V control-grid bias, and a grounded cathode. The rf drive for the X2159 final amplifier originates at the shorted resonant line-plate circuit of an Eimac 4CX1500 driver amplifier. The 120-kW driver power is coupled through six 25-Ω RG 14-17 (Scyllac) cables, 3/4 wavelength long. As the X2159 control grid is near series resonant, the grid input impedance is very small (< 0.1 Ω). The six cable network transforms this 0.1 Ω to 60 Ω, which is a convenient output impedance for the driver. The six cables connect symmetrically around the X2159 control grid; a 4.16 Ω impedance was chosen to match the control grid-transmission line impedance inside the tube. The RG 14-17 has a resistive sheath grading the potential at the conductor-dielectric interface; the cables are slightly attenuating at 50 MHz (3 dB/100 ft). At 900 MHz, RG 14-17 is so strongly attenuating that the six cable network is totally absorbing; consequently,

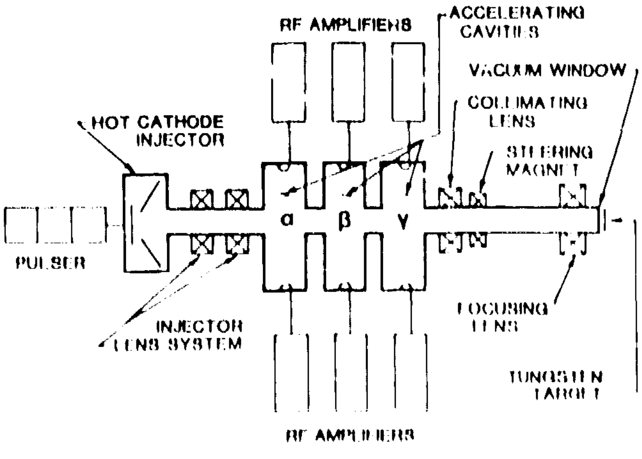

Figure 1. PHERMEX accelerator schematic.

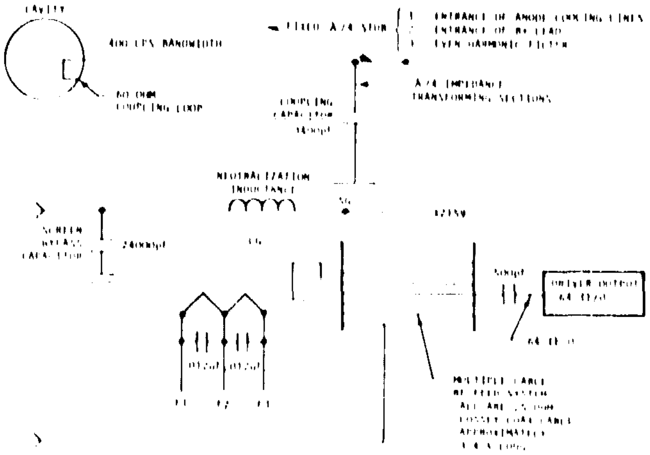

Figure 2. Rf amplifier schematic.

the 900-MHz parasitic is stabilized. The screen grid is rf biased by a small neutralization inductor to ground. This inductor is adjusted to null capacitive feedback from the plate to the control grid at 50 MHz. The plate is matched to the 60-Ω output transmission line by an adjustable near-quarter wave, 9-Ω transmission line. The loop that couples the amplifier to the cavity TM_{010} mode is adjusted to present a 60-Ω pure resistive load. Typically, two X2159 amplifiers are coupled to a single cavity. This load impedance looking into the loop is

$$Z(\omega) = X_L \left\{ \frac{nQK^2}{\alpha^2 + 1} - j \frac{nQK^2\alpha}{\alpha^2 + 1} + j \right\} ,$$

where X_L is the loop reactance,
Q is the unloaded cavity Q,
K^2 is the loop coupling constant,
n is the number of loops,
α is $\frac{\omega - \omega_0}{\omega_0} Q$,
ω_0 is the cavity resonant frequency, and
ω is the improved frequency.

The coupling K^2 is set by adjusting the coupling angle of the loop; X_L is typically 30 Ω, and α is tuned to the frequency where $Z(\omega)$ is 60 Ω resistive.

The cavities are copper walled, 2.6-m-long, 2.5-m-radius cylindrical structures with 0.05-m radius apertures for beam transport. The unloaded Q is 125,000; the resonant frequency is 50 MHz. The cavity-electric field strength on axis is related to the total input power

$$E(MV/m) = 3.48 \ P(MW) \ .$$

Two 5-MW amplifiers will develop 11 MV/m, which is 0.7 of the W. D. Kilpatrick limit.[3] With three cavities, this gives a 50-MeV-electron beam peak energy.

The PHERMEX electron gun is biased by a 500-kV Femcor pulser generating a 200-ns, 300-A electron beam. This pulser will be replaced with a 1.25-MV Physics International pulser that will deliver three 40-ns pulses or a single 150-ns pulse generating a 1000-A gun current. Figure 3 shows a diagram of the PI pulser. The behavior of the triggered gas switches is critical to making the triple-pulse concept work. The switches remain conducting several hundred microseconds after they are triggered, even though no voltage is applied across the switch electrodes. Three Marx generators, three ethylene glycol 40-ns pulselines, and three triggered SF_6 switches are used. In three pulse operations, Marx #1 is erected, charging Pulseline #1; this pulseline is switched out through a transfer line to the electron gun. The triggered SF_6 switch is synchronized with the phase of the rf in the cavities and has a subnanosecond jitter. Marx #2/Pulseline #2 operates the same as System I; the Pulseline #2 voltage is switched through Pulseline #1, Switch #1, and the transfer line. Marx #3/Pulseline #3 operates in the same manner. The shunt load isolates the pulser from the electron gun. One-hundred-fifty-nanosecond pulse lengths are achieved by replacing Switches #2 and #3 with a 15-ns section of ethylene-glycol pulse line, erecting all three Marx's together, and switching the pulseline voltage out through Switch #1. The pulse output is connected through a 50-Ω series resistor to a 45-ns long, 60-Ω-oil pulseline and then to the electron gun. The gun load is 1000-Ω; the 50-Ω resistor matches the gun reflections preventing the 45-ns line from ringing.

The electron gun is a Pierce geometry diode with a thermionic 10-cm-diam barium-oxide-impregnated cathode. Two solenoidal focusing lenses transport the beam to the first accelerating cavity. The beam is 2-cm radius and slightly diverging at the cavity entrance. The divergence is necessary to compensate for the rf focusing of the entrance aperture.

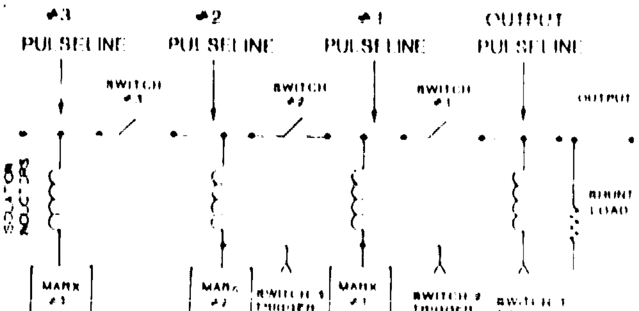

Figure 3. Three pulser schematic.

Electron Beam Characteristics

The first cavity chops and accelerates the electron beam. Because the electron mass increases six to seven times in the first cavity, the exit aperture defocusing forces are small. The second and third cavities accelerate the chopped beam to 21 MeV at 300-A peak current. The beam emittance after acceleration is 1 π cm-mrad (unnormalized) at 21 MeV. The beam pulse-train current profile is shown in Fig. 4. The pulses are 3.3 ns (FWHM) long with 1 ns rise time. This pulse length gives a 60° beam fill of the rf period. As a result of the beam fill, the 8.6-ns electron transit time of a single cavity and the 20-ns period of the rf accelerating field, the beam energy varies 30% during the pulse (see Fig. 5). In addition, the beam energy varies 10% during the pulse train due to the rf energy that each pulse extracts from the cavities as each pulse is accelerated.

A solenoidal lens at the exit of the third cavity refocuses the beam to a 0.5 cm radius 2 m beyond the cavity exit. Two further lenses focus the beam to a 0.05-cm radius at the x-ray converter. Steering

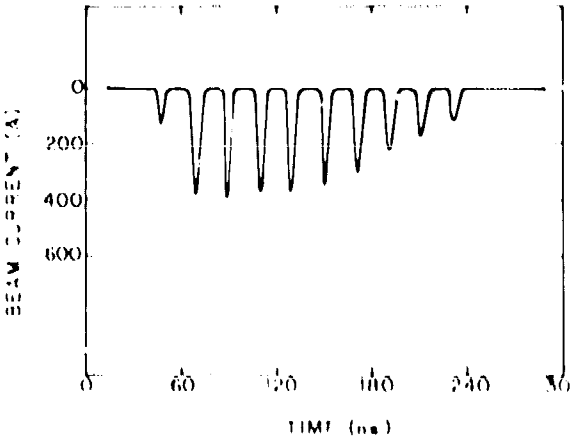

Figure 4. Beam current pulse train.

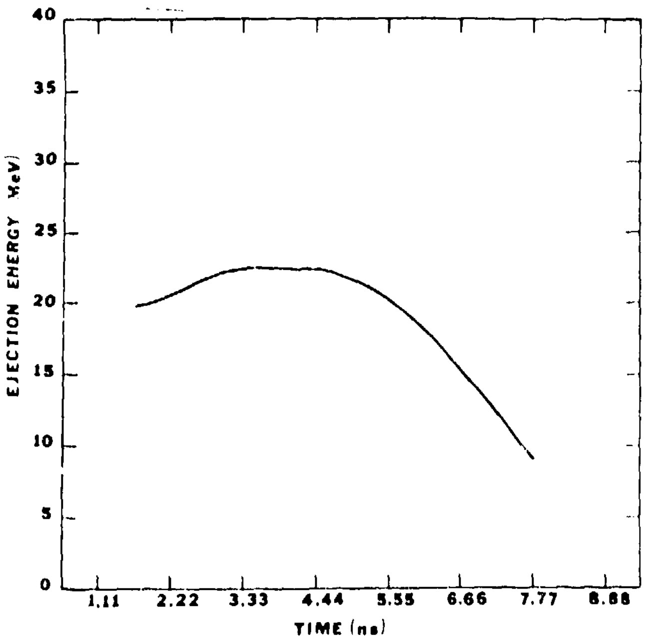

Figure 5. Beam energy variation.

magnets correct for small misalignments in the beam pipe. The minimum spot size achievable is primarily determined by the beam energy variation, rather than the beam emittance. For the last 10 cm of beam travel during focusing, the beam transits a beryllium collimator with a 0.5-cm entrance radius and a 0.15-cm exit radius. The presence of this collimator increases the beam focusing, although the exact mechanism is not well understood. The focused beam then passes through a 0.04-cm-thick-beryllium vacuum window and a 0.175-cm-thick-tungsten x-ray converter (~1/2 range) to a 10-cm-thick-beryllium beam stop. The 10-kA/cm^2 focused beam-current density is sufficient to cause a damaging thermomechanical shock in the tungsten, so the target is rotated for each 200-ns pulse train. The beryllium window survives several thousand pulses before requiring replacement. An aluminum Compton diode is used to monitor the flux density of the x-rays generated by the converter.

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