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BEAM MEASUREMENTS ON ARGONNE LINAC FOR COLLIDER INJECTOR DESIGN *

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ABSTRACT

The 20 MeV electron linac at Argonne produces 5×10^{10} electrons in a single bunch. This amount of charge per bunch is required for the proposed single pass collider at SLAC. For this reason the characteristics of the beam from this machine are of interest. The longitudinal charge distribution has been measured by a new technique. The technique is a variation on the deduction of bunch shape from a spectrum measurement. Under favorable conditions a resolution of about 1° of phase is possible, which is considerably better than can be achieved with streak cameras. The bunch length at $4.5 \times 10^{10} e^-$ per bunch was measured to be 15° FWHM. The transverse emittance has also been measured using standard techniques. The emittance is 16 mm-mrad at 17.2 MeV.

CHARGE DISTRIBUTION MEASUREMENT

We measured the longitudinal charge density of the Argonne linac beam using the technique described here.

The Argonne linac is a two-section 'L' band travelling wave (TW) electron linear accelerator. The bunching system consists of a single cavity subharmonic prebuncher, a TW prebuncher, and a tapered TW buncher ($\beta_w = 0.6$ to 1). The linac produces a pulse as short as 40 ps with a charge of 7 nC. Pulses ranging from 4 to 20 MeV can be produced with total energy spread of 300 keV.[1,2]

For the purpose of this discussion, the accelerator is divided into two parts; the first part includes the bunching system and the first accelerator section. The second part consists of the second accelerator section. As the beam emerges from the first accelerator section, it is accelerated by the RF fields from the second section whose phase is varied over the course of the measurement. In the case of a monochromatic beam emerging from the first accelerator section, the energy of the beam after acceleration by the second section is

$$\gamma(\theta) = \gamma_1 \cos(\theta - \phi) + \gamma_i \tag{1}$$

where γ_1 is the peak energy contribution of the second accelerator section, γ_i is the energy of the beam emerging from the first accelerator section, θ is the phase of the portion of the beam being considered, measured from the leading edge of the bunch, and ϕ is the phase of the second klystron RF wave. The charge density, ρ, is given by $dq/d\theta$, the amount of charge in a small band of phase.

$$\rho = \frac{dq}{d\theta} = \frac{dq}{d\gamma}\frac{d\gamma}{d\theta} = -\frac{dq}{d\gamma}\gamma_1 \sin(\theta - \phi) \tag{2}$$

We use a momentum spectrometer to measure $dq/d\gamma$ for various values of θ and ϕ. We choose to fix the energy which the spectrometer will detect at a constant value γ_s. See Fig. 1. Equation (1) becomes

$$\gamma(\theta) = \gamma_1 \cos(\theta - \phi) + \gamma_i = \gamma_s = \text{constant}.$$

Thus, we determine

$$\cos(\theta - \phi) = \text{constant},$$

which implies

$$\sin(\theta - \phi) = \text{constant} = C_1.$$

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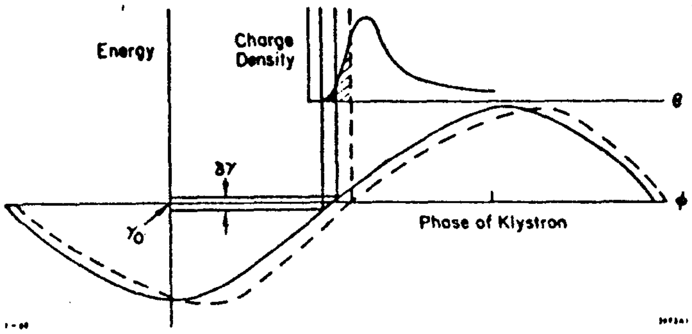

Fig. 1: For a monochromatic beam, one can reproduce the longitudinal beam profile by sweeping the phase of a klystron and measuring the charge density at a fixed energy slit.

Equation (2) becomes

$$\frac{dq}{d\theta} = -\gamma_1 C_1 \frac{dq}{d\gamma} \qquad (3)$$

So, for a monochromatic initial beam, $dq/d\theta$ is directly proportional to $dq/d\gamma$, and the beam profile measurement is straightforward.

The measurement becomes somewhat more complicated if the initial energy of the beam, γ_i, is a function of phase. Now the energy of the beam is

$$\gamma(\theta) = \gamma_1 \cos(\theta - \phi) + \gamma_i(\theta) \qquad (4)$$

and the charge density is

$$\frac{dq}{d\theta} = -\frac{dq}{d\gamma}\left[\gamma_1 \sin(\theta - \phi) - \gamma_i'(\theta)\right] \qquad (5)$$

Since $\gamma_o(\theta)$ is an unknown function, we make two measurements of $dn/d\gamma$, for the <u>same</u> θ, but two different phases, ϕ. Thus we have, for phases ϕ_a and ϕ_b

$$\frac{dq}{d\theta} = -\frac{dq_a}{d\gamma}\left[\gamma_1 \sin(\theta - \phi_a) - \gamma_1'(\theta)\right] \qquad (6)$$

$$\frac{dq}{d\theta} = -\frac{dq_b}{d\gamma}\left[\gamma_1 \sin(\theta - \phi_b) - \gamma_1'(\theta)\right] \qquad (7)$$

The unknown $\gamma_1(\theta)$ term is subtracted out giving,

$$\frac{dq}{d\theta} = \frac{\frac{dq_a}{d\gamma}\frac{dq_b}{d\gamma}\gamma_1\left[\sin(\theta - \phi_a) - \sin(\theta - \phi_b)\right]}{\frac{dq_a}{d\gamma} - \frac{dq_b}{d\gamma}} \qquad (8)$$

Again, we choose to make all energy readings through the slit γ_s. Thus $\gamma_a = \gamma_b = \gamma_s$ and, from Equation (4)

$$\gamma_s = \gamma_1 \cos(\theta - \phi_a) + \gamma_o(\theta) = \gamma_1 \cos(\theta - \phi_b) + \gamma(\theta) \qquad (9)$$

which implies,

$$\cos(\theta - \phi_a) = \cos(\theta - \phi_b)$$

and hence

$$\theta - \phi_a = \pm(\theta - \phi_b).$$

Since the + sign is unhelpful, we choose

$$\theta - \phi_a = -\theta + \phi_b$$

therefore,

$$\theta = 1/2(\phi_a + \phi_b) \qquad (10)$$

Substituting into Dquation (8),

$$\frac{dq}{d\theta} = \frac{\frac{dq_a}{d\gamma}\frac{dq_b}{d\gamma}\gamma_1\, 2\sin\frac{1}{2}(\phi_b - \phi_a)}{\frac{dq_a}{d\gamma} - \frac{dq_b}{d\gamma}} \qquad (11)$$

Equation (11) gives us an expression for the longitudinal charge density in terms of the measurable quantities ϕ_a, ϕ_b, $dq_a/d\gamma$, $dq_b/d\gamma$ provided we can successfully determine which ϕ_a and ϕ_b correspond to the same θ. It should be noted that $dq_a/d\gamma$ and $dq_b/d\gamma$ are usually of opposite sign.

To make the beam profile measurements, we set both klystrons to the same power, corresponding to energy γ_o. Also, we chose to set the spectrometer to detect electrons with energy γ_o. Assuming the beam has small variations in the incident energy, $\gamma_i(\theta) \approx \gamma_o$. Equation (4) gives

$$\gamma_o \cong \gamma_o \cos(\theta - \phi) + \gamma_o \tag{12}$$

which implies

$$\theta - \phi \approx \pm 90° \quad .$$

The horizontal axis of a chart recorder recorded a continuous sweep through the klystron phase ϕ while the vertical axis recorded the current in the spectrometer. See Fig. 2.

If $\gamma_i(\theta)$ is a fairly smooth function, it is reasonable to assume that the peaks in the unreduced data correspond to the same θ. Since $|\theta - \phi| \cong 90°$, the peaks are close to 180° apart. We then assumed that points at 90%, 80%...10% of the peak value on each curve represented nearly the same θ. Eq. (11) was used to reduce the data to charge density vs phase angle θ. We made measurements for three different currents corresponding to 7 nC/bunch, 3 nC/bunch, and 1 nC/bunch. The three beam profiles are shown in Figs. 3, 4, and 5 respectively. While the FWHM of the three beams varied from 12 to 15 degrees, almost half of the charge is in the tail of the bunch, which extends nearly 90° behind the head of the bunch. The length of the tail decreases slightly for the lower charge bunches, but the effect is not large.

The resolution of the measurement can be determined as follows. From Eq. (4) we find,

$$\frac{d\gamma}{d\theta} = -\gamma_1 \sin(\theta - \phi) + \gamma_i'(\theta)$$

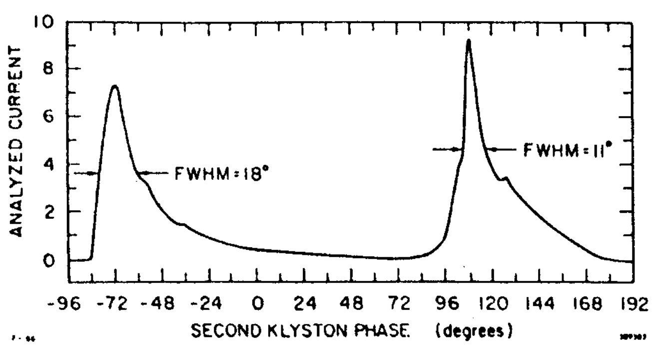

Fig. 2: Spectrometer current vs second klystron phase

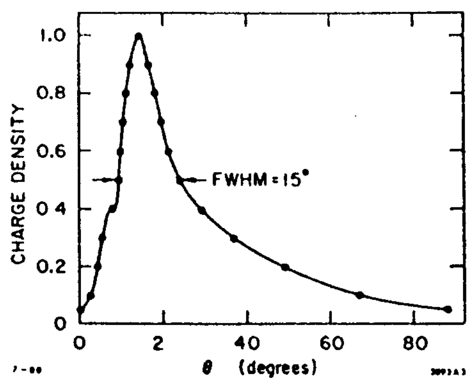

Fig. 3: Longitudinal charge density vs phase; 7 nC/bunch

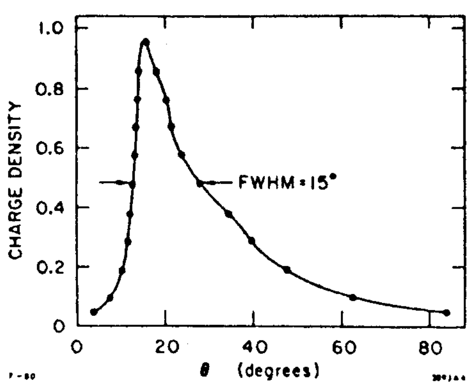

Fig. 4: Longitudinal charge density vs phase; 3 nC/bunch

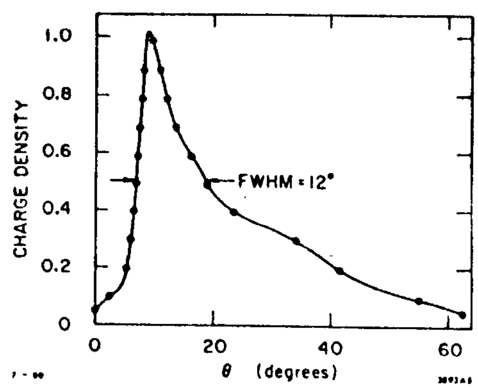

Fig. 5: Longitudinal charge density vs phase; 1 nC/bunch

Thus we have,

$$\Delta\theta = \frac{\gamma}{-\gamma_1 \sin(\theta - \phi) + \gamma_1'(\theta)} \frac{\Delta\gamma}{\gamma} \tag{13}$$

For the case at hand we have chosen $\gamma = \gamma_1 = \gamma_o$ which implies $|\theta - \phi| \cong 90°$. Eq.(13) becomes

$$\Delta\theta \cong \frac{1}{\pm 1 + \frac{\gamma_1'(\theta)}{\gamma}} \quad \frac{\Delta\gamma}{\gamma} \tag{14}$$

The uncertainty in energy consists of two parts, $\Delta\gamma$ of the spectrometer and $\Delta\gamma$ of the beam at a given θ. $\Delta\gamma$ of the spectrometer is .13% while $\Delta\gamma$ of the beam is estimated to be 50 to 100 keV or approximately 1% of 8.6 MeV. From Fig. 2 we find that for a given θ,

$$\left|\frac{dq_b}{d\gamma}\right| \cong 1.3 \left|\frac{dq_a}{d\gamma}\right|$$

From Eqs. (6) and (7) we determined

$$\gamma_1'(\theta) \lesssim \frac{1}{4} \gamma_1 \tag{15}$$

Thus

$$\Delta\theta \leq 1.2 \frac{\Delta\gamma}{\gamma} \cong 1.2\%$$

converting to degrees, the resolution is

$$\Delta\theta \leq 0.7° \tag{16}$$

For comparison, the resolution of a streak camera is

$$\Delta\theta_{STREAK} = 3.3° \tag{17}$$

EMITTANCE MEASUREMENT

We measured the emittance of the beam from the Argonne linear accelerator by two methods. In the first we used a single adjustable collimator with a Faraday cup behind it to measure the beam diameter. A quadrupole was adjusted to vary the beam size at the collimator. If we assume that the beam distribution in phase space is elliptical, then the radius of the beam at the collimator can be written

$$r = [(\theta_o L)^2 + r_o^2 L^2 (\frac{1}{f} - \frac{1}{f_o})^2]^{1/2} \tag{18}$$

where

r_o = radius of the beam at the quadrupole,

θ_o = angular divergence of the particles on the axis of the beam at the quadrupole,

L = distance from the quad to the collimator,

f = focal length of the quad, and

f_o = focal length which minimizes beam spot at the collimator.

We adjusted the quadrupole to minimize the beam size at the collimator (i.e., maximized the transmission through the slit which was iteratively adjusted to transmit about 80% of the beam). From this minimum beam radius one can find the angular divergence θ_o:

$$\theta_o = \frac{r_{min}}{L} . \tag{19}$$

The quad was then adjusted to increase the beam size more than a factor of 2. Inserting Eq. (19) in Eq. (18) we find the emittance.

$$E = r_o \theta_o = \frac{r_{min}(r^2 - r_{min}^2)^{1/2}}{L^2(\frac{1}{f} - \frac{1}{f_o})}$$

The emittance measured by this technique was $E = 16.1$ mm-mrad.

We confirmed this measurement by using the slit plus a glass slide exposure. The beam radius was measured with the slit, the angular divergence at the slit was measured by closing the slit down to about 0.15 r_o and exposing a slide 2 meters downstream of the slit. The emittance measured by this technique was $E = 15$ mm-mrad. The invariant emittance area is $E = 6 \times 10^{-2}\, \pi m_o C$ - cm. This is a factor of 20 larger than what is required at the collision point of the collider. However, the proposed 1.2 GeV cooling ring could damp this emittance down to the required emittance in one interpulse period of the collider.

CONCLUSION

The beam from the Argonne linac comes close to meeting the requirements for the proposed collider at Stanford. The bunch length is rather long for injection into SLAC's S-band linac. The full width at half maximum of the charge distribution would fit within 33° of the SLAC accelerating frequency. This would end up in a 4% energy bin which can comfortably be accepted into the cooling ring. However, about half the charge falls outside this region.

The emittance is too large to be used for the collider without a cooling ring but should be easily damped down to the required emittance in the 5.6 msec interpulse period.

Primarily on the basis of cost, we decided to design an S-band injector using a subharmonic buncher similar to the Argonne one. We believe the higher field gradients achievable at S-band should result is a shorter bunch length. Our design calculations indicate that we should obtain an emittance equal to approximately one-half that of the Argonne emittance. This factor is not critical since a cooling ring would be required in either case.

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REFERENCES

1) W. Gallagher et al., "A High Current Electron Linac," IEEE Trans. Nuc. Sci. NS-18, 584 (1971).

2) G. Mavrogenes et al., "Subnanosecond High-Intensity Beam Pulse," IEEE Trans. Nuc. Sci. NS-20, 919 (1973).