THE GENERATION AND DIAGNOSIS OF PULSED RELATIVISTIC ELECTRON BEAMS ABOVE 10^{10} WATTS*

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A review of the several approaches to the generation of intense electron streams in the megavolt energy regime is presented. The techniques used in the diagnosis of the 30,000 ampere, 3 Mev beam from a gas insulated coaxial system with a characteristic pulse length of 25 nanoseconds are discussed. The general features of such a stream drifting under self-focused conditions are presented and the results compared with the theory of such an idealized beam. The results of work conducted with cathode arrays of varying geometry are discussed. In particular, the dynamics of 20,000 ampere streams at 2 Mev, from arrays with $1 \leq n \leq 4$, are presented. Based on these data, a prognosis is made for the limitations of future high peak power electron accelerators at energies in the 10 Mev range.

Introduction

The problems of the generation of relativistic electron streams at high current densities (> 10 A/cm^2) in conventional uniform field acceleration tubes are reasonably well understood.[1] The limitations imposed by space charge forces under uniformly accelerated flow restrict such systems to modest levels of performance in applications where very high electron energy flux is desired; e. g., for pulsed radiolysis, pulsed heating of matter, radiography, etc. As a result, attention has been focused, over the past decade, on systems depending upon non-uniform pulsed acceleration schemes. Such accelerators are capable of providing the fields necessary for cold cathode field emission, and the generation of relativistic streams at emitter current densities above 10^6 A/cm^2. As reported in earlier publications,[2, 3] these systems have made possible the study of well-controlled relativistic self-focused electron streams and it is the dominance of the "self-field" in these beams which has ameliorated the post-acceleration beam-handling problem. It is the intent of this paper to provide a brief review of the techniques used in the generation and handling of these streams with a discussion of recent results obtained in this laboratory on the behavior of multiple streams drifting under "field-free" conditions.

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Power Supply Techniques[4]

Since the development of very high peak power pulsed systems has not yet emerged from the single shot or low PRF mode, the basic supply serves as a form of power concentrator. As a result, present approaches have followed along rather conventional lines and generally consist of some form of impulse-voltage multiplication system to pulse charge an energy storage pulse-forming line. The main advances in supply technology have involved those characteristics affecting performance in meeting the unique requirements of this application: improvement of dielectric storage characteristics to satisfy the (pulsed or dc) geometry, increased energy density and reliability, advances in impedance matching during power delivery to optimize power transfer efficiency, and improved switch characteristics. Due to the brevity of the pulses practicable at these very high power levels, distributed lines are typically employed. Three schematics representing the currently preferred approaches to fast megavolt pulsed power systems are shown in Figure 1.

The traditional route to these supplies is outlined in the schematic of Figure 1(a) which depicts a Marx surge circuit with a stacked stripline storage system. The shaded areas indicate high dielectric constant storage media while the unshaded line interfaces contribute little to the system energy capacity through large interline separation. The system is typically dc charged with simultaneous or self-cascading triggering of the spark gaps S_2. Due to the switch complexity and reduced specific energy capacity of such parallel-series systems, a more common form of this older circuit is the stacked Blumlein circuit which has been used so successfully by J. C. Martin and Colleagues at Aldermaston, England.

A coaxial version of the folded Blumlein generator is shown in Figure 1(b), while the simple stacked stripline version would be similar

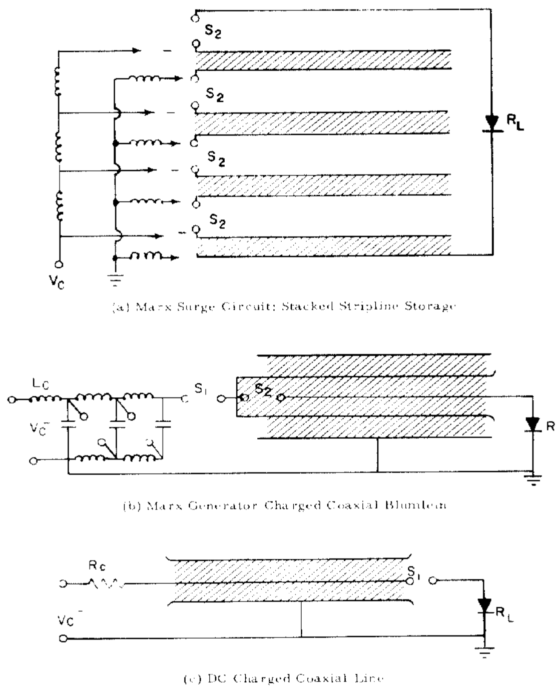

Figure 1. Pulsed Power Systems

to that shown in Figure 1(a) with high ϵ dielectric layers between the switched line interfaces. It is obvious that the Blumlein generator represents an extension of the simple single pulse-forming lines into a two stage line with a single switch located at the end opposite the load. The output of each folded section under matched conditions now equals the charging voltage with a pulse length equal to the full transit time of the equivalent unfolded strip. However, the impedance is now the sum of the impedances of each section. Due to the line-load symmetry, no voltage appears across the load until one line section is shorted, and, as a result, no switch isolation of the load is required. The increased efficiency of energy storage, increased output voltage and decreased switch requirement have made this the preferred approach to the development of large solid and liquid dielectric systems. The coaxial arrangement shown in Figure 1(b) offers the added advantages of good intrinsic shielding, decreased edge effects and improved supply-load transition geometry over the earlier (folded) stripline geometry. The reader is referred to Reference 4 for additional details of Blumlein generator theory and practical engineering considerations in larger stacked arrays.

The third schematic shown in Figure 1(c) represents the dc charged coaxial line. The system may be described as an end switched coaxial line from which the energy may be dumped directly without power supply isolation other than that offered by the high impedance of the generator itself. Neglecting end effects, the pulsewidth is, as before, twice the transit time of the wave in the line. The form of the capacitor or line will of course depend upon the stored energy requirement, system impedance, delivery time and voltage regime of interest. For the development of megavolt systems capable of performance above 10^{10} watts in this laboratory, the simple coaxial geometry has been used with gaseous dielectrics as the storage medium and a modified Van de Graaff generator as the power supply. No voltage multiplication is employed in the systems used in obtaining the results which follow, as the system pressure vessel is the outer grounded electrode, while the inner coaxial electrode constitutes an extension of the generator structure itself. The prime advantages of this direct route to the megavolt high peak power supply are: precisely controlled (dc charged) store conditions, single point low jitter switching, coaxial geometry and high intrinsic efficiency under matched load conditions. Its main disadvantage arises from the dc store requirement: the greatly enhanced short pulse dielectric characteristics of commonly used storage/insulating media cannot be exploited in the basic supply itself. The comparative operational advantages of the pulse charged and dc charged megavolt coaxial systems, represented by the schematics of Figure 1(b) and 1(c), are currently being evaluated at the 10^{12} watt level.

Tube/Diagnostic Considerations

The main features of the "conventional" field emission diode used with these systems are shown in Figure 2. Coaxial symmetry is preserved by end-switching the 3 meter long storage line onto the cap of the field emission tube, using the environment of the insulating gas as the switching medium. The trigatron switch configuration used in the system shown (FX 1) has demonstrated jitter times in closing a 3.6 Mv gap of ± 5 nanoseconds[5] with a fixed delay in command of 900 nanoseconds. The tube structure itself has been described elsewhere.[2, 6]

It is based upon a design originally described by Martin and Smith of AWRE for which flashover strengths of > 0.20 Mv/cm have been realized with laminated acrylic-aluminum structures for pulses of tens of nanoseconds using the dielectric geometry shown. Because of the higher allowable voltage gradients in the nanosecond time regime, the tube is short compared to a conventional accelerator tube. This results in a low inductance tube structure.

The operating impedance of the tube is determined mainly by the geometry of the cathode

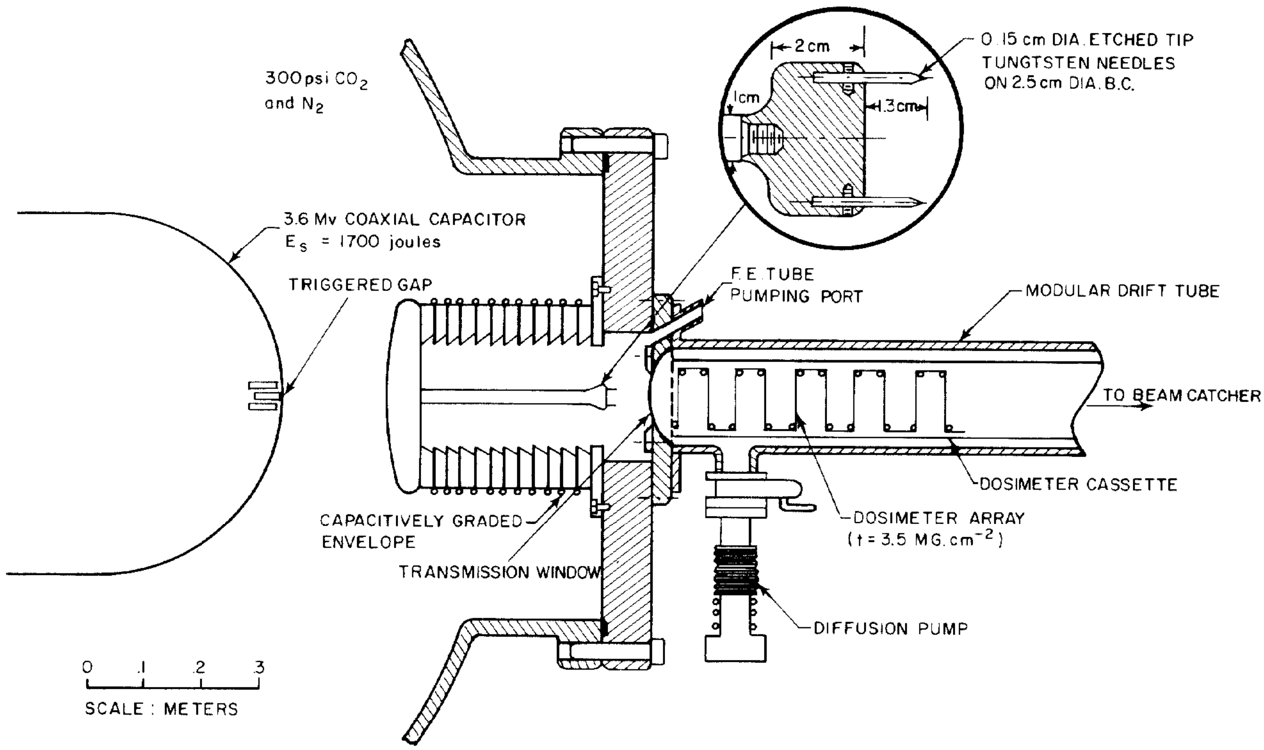

Figure 2. Field Emission Tube/Beam Diagnostics Geometry

array. Because of the high current densities at the emitters, the space charge dominates the behavior of the tube, making cathode surface considerations of secondary importance. The cathode to anode (ground plane) spacing is on the order of a few centimeters. The tube is designed so that the gap spacing is adjustable and is usually adjusted empirically to provide a suitable match to the line impedance (Z_ℓ = 40 ohms for the system shown).

As shown in the figure, the anode of the tube consists of a thin transmission window; e. g., 20 mg/cm^2 Ti, which introduces only a few percent energy degradation in the stream as it exits into the differentially pumped drift region of the accelerator. Stream behavior is then studied in detail using the thin film dosimetric technique described in Reference 3; usually with the simultaneous determination of integrated charge per pulse (Faraday cup) and current pulse profile (Rogowski coil).

The thin film (Dupont MSC-300) mapping technique[3] is capable of providing a rather complete map of stream behavior for a single pulse due to the negligible energy loss of relativistic electrons in traversing the 3.5 mg/cm^2 film; e. g., 6 kev at 3 Mev. The technique of film readout consists of optical scanning and determination of the increased transmission at 6550 Å due to radiation induced dye bleaching. Film calibration has shown the utility of the technique to ~ 5 megarads integrated dose or current densities of ~ 1500 A/cm^2 for relativistic beams with a spatial resolution of ~ 100 microns possible, limited primarily by film inhomogeneities. Readout of the film is accomplished with a two-dimensional Beckman and Whitley isodensitracer or a simple scanning densitometer where beam profiling is adequate. Intercalibration of such profiles with direct calorimetric determinations of stream current density (deduced with the use of the experimentally determined energy spectrum of the beam), has shown good (± 15%) agreement.

It should be pointed out that the current density distributions obtained with the dosimetric technique provide only time integrated information and give no insight into the dynamics of stream behavior during the interesting initial self-focusing phase.

Self-Focused Stream Considerations

The self containment of drifting relativistic electron streams has been discussed by Bennett[7] and Lawson.[8] Experimental results have been reported by the authors.[3]

For all radial positions, r, such that r is much less than the beam length, and assuming a uniform current density, j, with a beam radius of r_b, the fields acting on the stream are:

$$\left.\begin{aligned} E &= \frac{I}{2\pi\beta r}\sqrt{\frac{\mu}{\epsilon}} \\ v \times B &= \frac{\beta I}{2\pi r}\sqrt{\frac{\mu}{\epsilon}} \end{aligned}\right\} \quad r > r_b$$

$$\left.\begin{aligned} E &= \frac{j r}{2\beta}\sqrt{\frac{\mu}{\epsilon}} \\ v \times B &= \frac{\beta j r}{2}\sqrt{\frac{\mu}{\epsilon}} \end{aligned}\right\} \quad 0 < r < r_b$$

In all cases $v \times B = \beta^2 E$ so that E must always be reduced by positive space charge in order to achieve beam self-containment. $\beta^2 + f > 1$ is the requirement, where f is the ion electron ratio which is never greater than 1 in the case of the drifting beam.

It can be shown in the case of beam produced ionization that the ratio of ions to primary electrons is $f = \beta c \sigma n_a t$, where n_a is the neutral atom density, σ is the ionization cross section and t is the time measured from the passing of the beam front. In the case of a 2 Mev beam, the $\beta^2 + f > 1$ criterion is satisfied in 1 nanosecond at a pressure of 6×10^{-2} torr. This has been confirmed in studies of the 2 Mev pulsed beam on FX 1.

In the following treatment, it is assumed that the beam and its associated fields are contained in the cylindrical drift tube which provides the return current path. For drift tube sizes used in our experiments, the above relations are valid within about a nanosecond of the passing of the beam front. (A maximum radius of 7 cm and a beam length of 30 cm make the long filament assumption about 10% accurate.)

Following the development of Lawson[8] using an idealized model, one can estimate the focusing properties of the stream. The trajectory of a particle in a constant current density, constant radius stream is calculated. The radial force on an electron in such a stream is:

$$\begin{aligned} F_r &= e E_o (1 - f) - ev \times B \\ &= e E_o (1 - f - \beta^2) \end{aligned}$$

where:

$$E_o = \frac{j r}{2\beta}\sqrt{\frac{\mu}{\epsilon}}$$

Using the approximation of small angle deflection so that:

$$\frac{d}{dt}(\gamma m v_r) \approx \gamma m \ddot{r}$$

where:

$$\gamma = \left(1 - \beta^2\right)^{-1/2}$$

and assuming:

$$\dot{r}(o) = 0$$

and:

$$r(o) = r_b$$

one obtains the solution:

$$r = r_b \cos\frac{2\pi}{\lambda}\beta c t$$

where:

$$\lambda = \left(8\pi^2 c^2 \beta^3 \gamma m\right)^{1/2} \cdot \left[e\sqrt{\frac{\mu}{\epsilon}}\left(\beta^2 + f - 1\right)\right]^{-1/2} j^{-1/2}$$

It is seen that $\beta + f > 1$ is necessary for focusing and the focusing distance varies inversely with the square root of current density. This relation predicts $\lambda \approx 15$ cm for 2000 A/cm^2 and $f \approx 1$ which is in good agreement with experimental results obtained at Ion Physics Corporation. It follows that the beam can be propagated at low ion-to-electron ratios and as a result at low gas pressures. In this manner the beam can be utilized as a high current transmission line. If the beam is sufficiently neutralized to be self-confined, then the image current repulsive forces are also greater than the image charge attraction and the beam then is in stable equilibrium in the drift region. This has been observed in experiments at this laboratory.

The maximum obtainable current densities can be estimated by writing the total beam field energies for the non-neutralized beam. The E-field, although reduced by (1 - f), has added to the kinetic energy of the secondary electrons.

Again assuming a constant current density with a beam radius of r_b, the electric field energy per unit length of beam is:

$$\frac{E_e}{\ell} = \frac{I^2 \mu}{16\pi\beta^2}\left(1 + 4\ln\frac{r_c}{r_b}\right)$$

the magnetic field energy per length of beam is:

$$\frac{E_m}{\ell} = \frac{\mu I^2}{16\pi}\left(1 + 4\ln\frac{r_c}{r_b}\right)$$

$$\frac{E_{m+e}}{\ell} = \frac{I^2 \mu}{16\pi\beta^2}\left(1 + 4\ln\frac{r_c}{r_b}\right)(1+\beta^2)$$

If we now note that the maximum available energy per unit length is:

$$\frac{V_o I}{\beta c} = \frac{V_o I \sqrt{\mu\epsilon}}{\beta}$$

where V_o is the acceleration voltage, then we have an outside limit on current density:

$$\frac{I}{V_o}\sqrt{\frac{\mu}{\epsilon}}\,\frac{1}{16\pi\beta}\left(1 + 4\ln\frac{r_c}{r_b}\right)(1+\beta^2) < 1$$

It is realized, of course, that as kinetic energy is put into field energy, that β must decrease; however, for highly relativistic beams most of the energy can be taken from the electron with only a small change in β.

The logarithmic term is analogous to the normal transmission line expression and the other term depends on the form of j(r), here assumed constant.

Assuming the beam of FX 1, with which most of the self-focused stream experiments have been performed:

$$I = 2 \times 10^4 \text{ amperes}$$

$$V_o = 2 \times 10^6 \text{ volts}$$

$$\frac{1+\beta^2}{\beta} \approx 2$$

then:

$$\frac{r_c}{r_b} < 4$$

In a 10 cm diameter drift tube then, $r_b = 1.25$ cm and j = 4000 A/cm^2 which is seen on FX 1 at the optimum pressure. This leads to the possibility of controlling current density with the drift chamber dimensions. Very early work to this end has been performed on FX 1 where a current density of at least 5000 A/cm^2 has been produced 80 cm from the window using a tapered tube. Studies of beam propagation have shown that at least half the beam can be delivered at the end of a 3 meter drift length.

Multiple Stream Studies

Studies of single and multiple stream behavior have been conducted in order to assess the problems associated with stream stability and self-focusing under the conditions available with existing equipment (beam energies $\leq$ 3 Mev, total current $\leq$ 30,000 amperes, τ = 25 nanoseconds). The mapping configuration is shown in Figure 2 and consists of a film array which permits cross-sectional profiling at 1 cm longitudinal intervals in the stream. Each section is indexed so that the resulting distributions can be referenced to the drift tube and cathode(s) symmetry axes. Figure 3 shows a typical set of data taken for a single pulse at 3 Mev with an annular beam at entrance from a single point (1 cm diameter, 40 degree taper) stainless steel cathode. In this case the maximum current density is realized at the second focal point at z = 11 cm, probably due to aberrations introduced by the entrance beam geometry and divergence due to window scatter.

Figure 4 presents data recorded with a four-point array under drift tube conditions near optimum (for air) for stream self-focusing at this energy (p = 150 microns, E = 2.2 Mev). Mapping was conducted at $0 \leq z \leq 30$ cm. In this geometry, the individual annular streams entered the drift region with good uniformity at an average current density of $\sim$ 900 A/cm^2. The six o'clock cathode is obviously "weak" due to non-uniform spacing, a condition which was later corrected. The most interesting iso-current density contours are indicated in the entrance plane, 1 cm and 30 cm profiles. The results show that the four component stream was self-magnetically confined in a stable manner and the intermediate profiles showed the beam to be in stable cylindrically symmetric flow beyond the first pinch point (z = 5 cm). As shown in Figure 4, the 30 cm profile indicates current densities above 2000 A/cm^2, well above the linear region of the film. As a result, an inflection of the film response is evident at $\sim$ 1 cm radius (j_e = 1600 A/cm^2) with loss of information in the central region of the film. The information is regained by means of a routine normalization (to total current). This procedure indicates an axial power level of 4 x 10^9 w/cm^2 maintained stably over the drift region 5 < z < 30 cm.

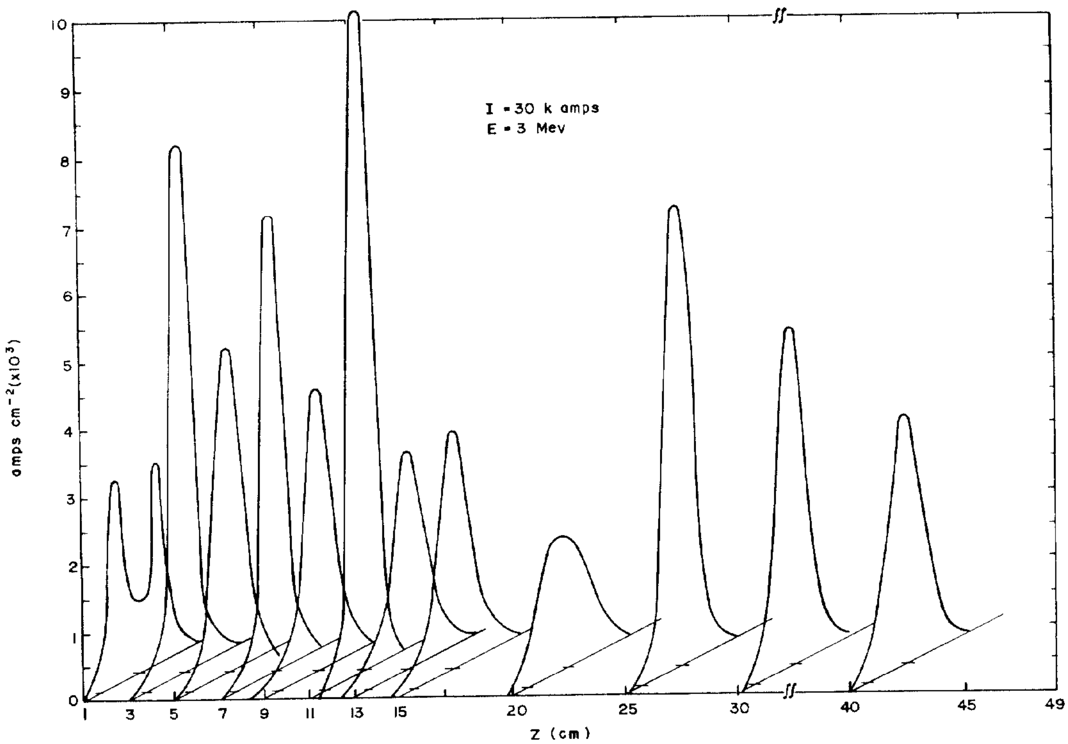

Figure 3. Profiles of Drifting 3 Mev Pulsed Electron Beam

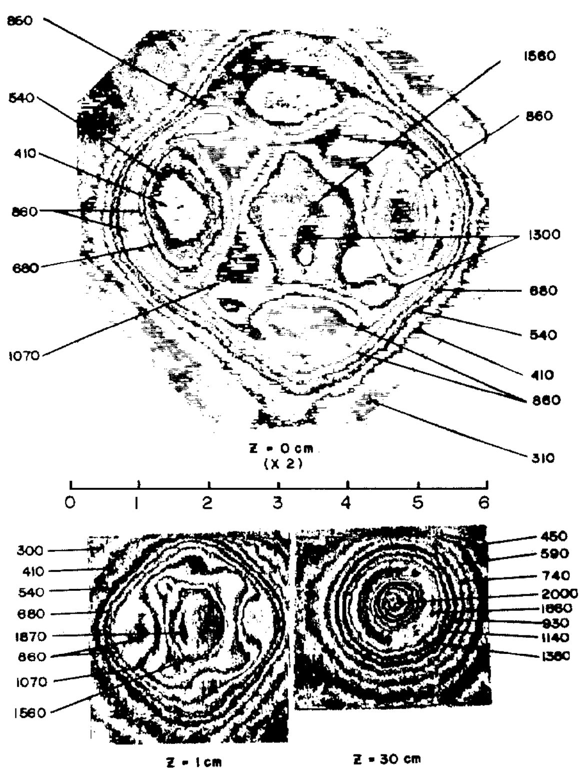

Figure 4. j_e Profiles in a 25 Kiloampere 2 Mev Stream at 0, 1 and 30 cm (Current Densities in A-cm^{-2})

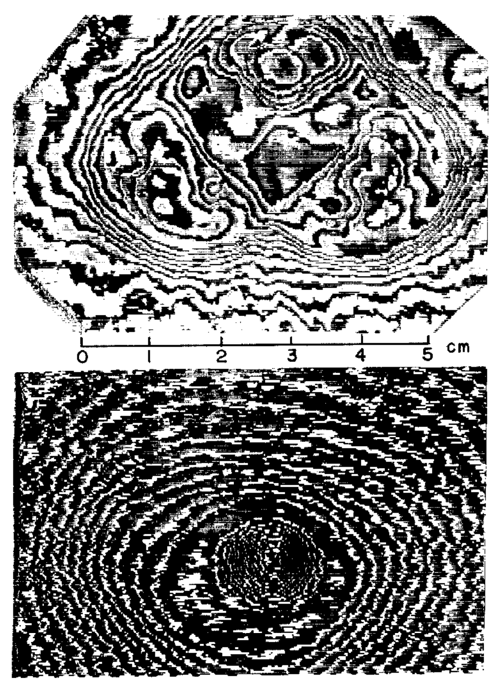

Figure 5. Three Point Emitter Profiles
p = 150 Microns (Air)
I = 20, 000 Amperes

Figure 5 shows a similar profile taken at ~ 7000 amperes/emitter under similar conditions for a three point array. The data shown provide support for the following encouraging qualitative conclusions: (a) current partition among multi-point arrays in these megavolt emitters can be precisely controlled, thereby permitting the necessary flexibility for realization of low impedance acceleration structures and (b) self-focused multiple streams behave stably in this time regime, and provide a natural means for the concentration or focusing of relativistic streams from large area, high current arrays.

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