139
2-22-80

DR. 731

BNL 51094

MASTER

THE MEQATRON: A HIGH-POWER HIGH-FREQUENCY RF SOURCE

A. W. Maschke

September 28, 1979

ACCELERATOR DEPARTMENT
BROOKHAVEN NATIONAL LABORATORY, ASSOCIATED UNIVERSITIES, INC.
UNDER CONTRACT NO. EY-76-C-02-0016 WITH THE
UNITED STATES DEPARTMENT OF ENERGY

DISCLAIMER

DISCLAIMER

BNL- 51094
UC-28
(Particle Accelerators and
High Voltage Machines-TID 4500)

THE MEQATRON: A HIGH-POWER HIGH-FREQUENCY RF SOURCE

A. W. Maschke

September 28, 1979

ACCELERATOR DEPARTMENT

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

ABSTRACT

MEQATRON is an acronym for a multiple-beam electrostatic-quadrupole-focused array of electron beams. Conventional electron beam devices consist principally of single electron beams. In this paper the single-beam space-charge limitations are discussed, and a relationship for power flux (W/m^2) is obtained. Several features of the multiple-beam approach become clear at once. Because the multiple-beam approach removes the current limitation on performance, it is possible to design high-current low-voltage tubes. This feature is important for low-frequency (200 MHz, say) klystrons.

Another feature of the multiple-beam approach relates to the very small sizes (1 to 2 mm, say) associated with each beam. This offers the possibility of developing high-power rf sources in the millimeter wavelength region.

I. CURRENT LIMITATIONS IN ELECTROSTATIC-QUADRUPOLE TRANSPORT SYSTEMS

The space-charge limits for an electrostatic-quadrupole system were derived in a previous paper.[1] The main results can be summarized in four equations, as follows*:

$$i_{max_T} = 10.2 \left\{ \frac{k}{(1-k)^{1/3}} \; (\mu_o \; k_4)^{2/3} \right\} \left(\frac{A}{z}\right)^{1/3} \epsilon_{NT}^{2/3} \; E_{Q_{max}}^{2/3} \; \beta\gamma^{5/3} \; . \qquad (1)$$

Now both ϵ_{NT} and $E_{Q_{max}}$ can be expressed in terms of the above parameters and the length of the focusing cell, L_{cell}. Thin-lens expressions are used here for simplicity. At phase advances $\leq 90°$/cell, very little error is introduced.

$$\epsilon_{NT} = \left\{ \eta^2 k_3^2 \; \mu_o (1-k)^{1/2} \right\} \beta\gamma \; L_{cell} \quad ; \qquad (2)$$

$$E_{Q_{max}} = 6.26 \left\{ \mu_o \frac{k_3}{k_4} \right\} c \; \frac{A}{z} \; \frac{\beta^2\gamma}{L_{cell}} \quad . \qquad (3)$$

Inserting (2) and (3) into (1), we obtain an expression for the maximum transportable current which is independent of ϵ_{NT}, E_{Q_m}, and L_{cell}. We obtain

$$i_{max_T} = 1.56 \times 10^7 \left\{ k \; \mu_o^2 \; k_3^2 \; \eta^{4/3} \right\} \frac{A}{z} (\beta\gamma)^3 \; . \qquad (4)$$

*Notation is the same as in ref. 1. See Appendix I for definitions.

Now all of the variables contained within the brackets are bounded. For instance, $\mu_0 \leq \pi/2$ for stable high-current beam transport. First-order stability requires $k \leq 1$. The bound on k_3 is less precise. Clearly a linear focusing channel cannot be filled with quadrupoles having apertures much greater than their lengths. I have assumed $k_3 \leq 1/8$. A detailed analysis might allow one to push this up a bit. η clearly must be < 1. Putting in the maximum values we obtain

$$i_{max_T} \leq 5.5 \times 10^5 \frac{A}{z} (\beta\gamma)^3 .$$

Specializing to electrons, which will be the subject of this report, we obtain

$$i_{max_T} \leq 300 \; (\beta\gamma)^3 . \tag{5}$$

This corresponds to a perveance of $\sim 2 \times 10^{-6}$. A practical system might be lower by a factor of 2 or so.

When currents above the space charge limits are transported in a strong-focusing channel, the beam "blows up," i.e., its emittance increases, and then it hits the aperture and is lost. However, this "blowup" requires a few betatron oscillations. Therefore, it is possible to exceed the "stable" transport limits for a short time. Indeed, if the time is short enough (1 or 2 beam plasma oscillations) one may even violate the $k \leq 1$ condition. This is certainly an allowable condition for a klystron. Note that for propagation of a beam without blowup, Eq. (5) is probably an overestimate by at least a factor of 2.

The aperture requirement for an electron beam can be obtained from Eq. (3). We obtain the following equation for the radius of the quadrupole channel:

$$r_Q = \frac{\mu_0 \, k_3^2 \, \beta^2\gamma}{k_4 \, E_{Q_{max}}} \times 10^6 . \tag{6}$$

Putting in the maximum values for μ_0 and k_3, and putting $k_4 = 0.4$, we obtain an expression for the radius of the channel. $E_{Q_{max}}$ typically is $\sim 10^7$ V/m.

$$\therefore \; r_Q \leq 6 \times 10^{-3} \; \beta^2\gamma .$$

Note that i_{max_T} and r_Q are both proportional to $\mu_0\ k_3^2$. Therefore, the current density is inversely proportional to $\mu_0\ k_3^2$. This leads us toward more beams of smaller diameter in order to optimize the average current density. Equation (2) for the emittance puts a lower bound on the radius of the quadrupoles.

The maximum current density in a beam is given by $i_{max_T}/\pi r_Q^2$. Using Eq. (4) and (6), we obtain the following expression for the current density:

$$J = 2.7 \times 10^{-9} \frac{k\eta^{4/3}\ k_4^2\ E_{Q_{max}}^2\ \gamma}{\beta\ k_3^2}\ A/m^2 \ .$$

Similarly, by multiplying by the kinetic energy/unit charge we obtain an expression for the power density:

$$F = 1.38 \times 10^{-3} \left(\frac{k\eta^{4/3}\ k_4^2\ E_{Q_{max}}^2}{k_3^2} \right) \frac{\gamma(\gamma-1)}{\beta} \ . \qquad (7)$$

Once again inserting maximum values for k, η, k_4 and k_3, and putting $E_{Q_{max}} = 10^7$ V/m, we get

$$F \leq 1.4 \times 10^{12}\ \frac{\gamma(\gamma-1)}{\beta}\ W/m^2 \ .$$

For 250-kV electrons, $\gamma(\gamma-1)/\beta = 1$. A practical array of beams might have a power density down by a factor of 10. For example, a 10-cm x 10 cm array of beams could carry 1.4 GW.

The Child-Langmuir relation also puts a current limitation on a single beam of circular aperture. The current density is given by

$$J = 2.33 \times 10^{-6}\ \frac{V^{3/2}}{d^2} \ ,$$

where d is the spacing of the extractor electrode. The area of the source cannot be much different from d^2, so we get an effective limiting current $i_{max_{C-L}} \sim 2.33 \times 10^{-6}\ V^{3/2}$.

For a 60-kV single-beam klystron this is $\sim$34 A, which is similar to the quadrupole channel limitation [see Eq. (5)].

II. A 200 MHz MEQATRON

One can distinguish two classes of MEQATRONS. In the first class we consider a bundle of beams whose diameter is << $\lambda = c/f$. This would be the case for a 10 cm x 10-cm bundle of beams for a few hundred-megahertz system. A second class consists of a bundle of beams where the interbeam spacing is on the order of λ. It is this second class that is applicable to production of millimeter-wavelength rf.

Suppose we want a MEQATRON with 3 MW of rf power output. If the efficiency were 50%, we would require 6 MW of dc beam current. If a 50-Ω output is desired we obtain 17 kV for the peak rf voltage. Therefore it might be appropriate to choose a voltage of about 20 kV for the electron beam. We then get the following parameters:

$P_{rf} = 3$ MW

$P_{dc} = 6$ MW

$V = 20$ kV

$I_{dc} = 300$ A

$i_{max_T} = 4.5$ A

$\bar{i} = 2$ A (Perveance = 7×10^{-7})

$r_{Q_{min}} = 5 \times 10^{-4}$ for $E_{Q_{max}} = 10^7$ V/m

$V_Q = \pm 1.5$ kV

A practical array of beams will have their centers separated by about 3 r_Q. Since we require 150 beams, we could have $r_Q \sim 2.5$ mm and still fit the beams into a 10 cm x 10-cm array. $E_{Q_{max}}$ is then only 2×10^6 V/m for this case.

Since there is no magnetic field in the beam transport, and since electrostatic quadrupoles are extremely inexpensive, there is no great pressure to shorten the structure. However, if the buncher voltage is $\sim\pm 2$ kV, the drift length will be ~ 2 m.

The current of 200 A will generate a magnetic field of about 8 gauss on the outside. The current could be canceled by running current back through some of the apertures. However, the 8 gauss corresponds to an electric field of only 67 kV/m. This will result in an average displacement of the "central" orbit by $\sim$1 mm, which is easily compensated for by increasing the quadrupole aperture somewhat.

Just a word about the collector. Since the net current is divided into many beams, the total collector area will have much more surface area than a typical single-beam system. This should enable one to improve on the average power rating. Furthermore, the low voltage also reduces the x-ray hazard associated with conventional single-beam high-voltage klystrons.

III. MILLIMETER WAVELENGTHS

As an example, consider a 100-GHz MEQATRON. This is a wavelength of 3 mm. In order to make a buncher for 20-kV electrons, say, a $\beta\lambda/2$ structure is only about 1/2 mm long. This implies that the beam diameter must be in the submillimeter range in order to avoid having a vanishingly small transit-time factor for the buncher gap. A radius of 0.25 mm would be fine. This is attainable with electrostatic quads using peak electric fields of 2×10^7 V/m. (See the previous example, for instance.) If we reduce the current, i.e., let $k_3 = 0.088$ instead of 0.125, the current goes from 2 A to 1 A, and the maximum electric field would be reduced to 1×10^7 V/m. The beams are no longer "tight" packed. In order to make a buncher and collector cavity, we must run the beams at a spatial separation of $n\lambda/2$. For n = 2, the bunchers are all in phase and the beam separation would be 3 mm. Since each beam, assuming 50% efficiency, would put out 10 kW, a rather modest array could put out a few hundred kW. If the buncher voltage is kept as in the 200-MHz example, then the overall length will drop by a factor of ~ 250. This gives a transport length of about 1 cm.

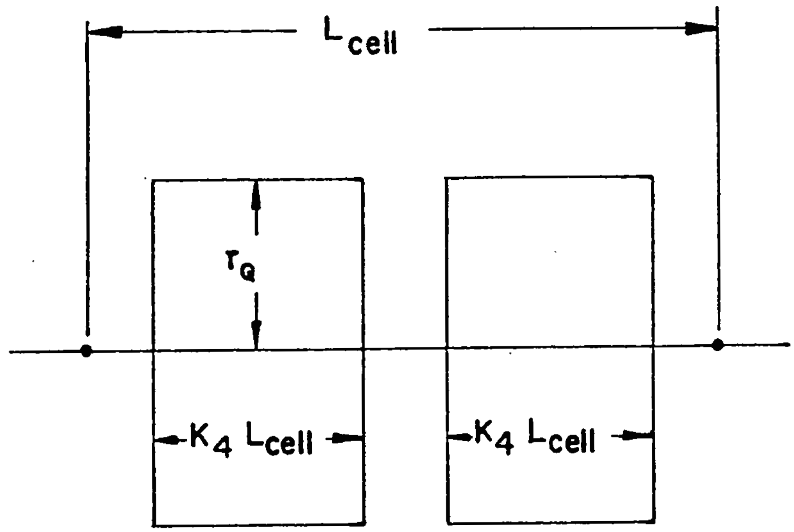
REFERENCES

1. A.W. Maschke, Space-Charge Limits for Linear Accelerators, BNL 51022, May 1979.

APPENDIX I

Mks units are used throughout. The following table lists the various symbols and their definitions. The figure illustrates the physical layout of a focusing cell.

i_{max_T}	the maximum transportable current in a quadrupole channel due to consideration of transverse space charge.
ϵ_{NT}	the normalized emittance area/π. For a beam at the space-charge limit, the beam emittance and the channel acceptance are the same.
μ_0	the betatron oscillation phase advance per cell.
k	the ratio of space-charge force to the mean restoring force of the quadrupole channel.
k_3	the radius of the quadrupoles in units of cell length, i.e., $k_3 = r_Q/L_{cell}$.
k_4	the quadrupole length in the same units.
η	the ratio of maximum to average beam size in the focusing structure. Typical values are 0.7 to 0.8. The effect of space charge is to bring η closer to unity than it would be in the same channel without space charge.



Focusing Quad

Defocusing Quad