Conf.-650923-34

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Design Study of a 500 MeV FFAG Injector*

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ABSTRACT

A design study is presented for a 500 MeV FFAG accelerator capable of delivering 1.6×10^{14} protons per second. The output beam has an energy spread of $\pm$ 0.68 MeV with transverse emittances of 6.74 milliard-cm (horizontal) and 1.61 π milliard-cm (vertical). The output beam contains 8.4×10^{12} protons in 71 nanosecond long pulses repeated 20 times per second.

* Work supported by the U. S. Atomic Energy Commission.

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DISCLAIMER

I. INTRODUCTION

In connection with improvement programs of existing accelerators, it is of interest to consider the performance of a high intensity FFAG with a view to its possible use as an injector. Similar but less detailed considerations have been reported previously for 720 MeV.[1]

The proposed accelerator, shown in plan view in Fig. 1, has an outer diameter of 45 feet (13.7 m). The 72 magnet blocks have a total weight of approximately 450 tons and require a total power of approximately 3.4 MW for excitation. An additional 1.5 MW of radio-frequency power are required for acceleration.

II. ACCELERATOR

General Description

A plan view of the accelerator is shown in Fig. 1. Protons are formed in an ion source and accelerated to an energy of 750 keV in a Cockcroft-Walton preinjector. At this energy they are transported by a series of bending and matching lenses through a prebuncher into the injector, an Alvarez standing wave linear accelerator of one tank. In the injector, protons are accelerated to an energy of 30 MeV. The beam emerging from the linear accelerator system passes through a drift space, and then undergoes a parallel displacement down five feet (1.5 m) to the elevation of the median plane of the accelerator and enters the FFAG accelerator through a series of bending and matching magnets. The beam is then bent onto the desired orbit by an electrostatic inflector located inside the main vacuum chamber.

Parameters of the accelerator are given in Table I. The radial straight sections split the magnet into 72 blocks, of weight varying between 5.4 and 7.4 tons. The magnetic field repeats after a period of two spiral sectors, or nine radial straight sections. Thus there are eight superperiods per revolution, each containing nine different magnet blocks.

The manner in which the charge is handled in the FFAG depends upon the nature of the accelerator into which it is delivering charge. In particular, the method chosen is for matching into the Argonne ZGS with its radio-frequency accelerating system modified to operate on the fourth harmonic. A 30 mA beam from a 20 MeV linac is used to inject 10 turns into the FFAG to give 1.4×10^{12} protons per injected pulse. Six such pulses are accelerated to 500 MeV and stacked. The stacked beam is bunched with the radio-frequency accelerating system and extracted with a fast extraction system[2] to yield a 71 nanosecond beam pulse.

Acceptance of this beam by the ZGS is to be accomplished using both synchronous injection into the radio-frequency buckets and a variable magnetic field bump to distort the equilibrium orbit. With conditions set for maximum distortion of the equilibrium orbit, four stacked pulses are synchronously injected into stationary buckets in the ZGS. The equilibrium orbit distortion is then relaxed sufficiently to allow the circulating beam to miss the fringe field of the synchronous inflector. Another four stacked pulses are then place synchronously into the ZGS. This cycle is repeated once more to give a total of 10^{14} protons. The net time to deliver this charge is 0.8 seconds since the linac repetition rate is chosen to be 180 cycles per second.

Orbit Calculations

The general effects on orbit dynamics of the introduction of radial straight sections were discussed in the 12.5 BeV proposal.[3] The principal effect is the variation of the betatron oscillation frequencies with radius. This effect, calculated from the three-dimensional magnetic fields, yields the acceptably small values:

$$\Delta \nu_x \leq 0.0006 \qquad \Delta \nu_y \leq 0.010 .$$

Although, as yet, no detailed digital computor orbit calculations have been made for the present accelerator, the scaling laws of Parzen[4] have been applied to the proposal design to yield the parameters shown in Table II. The stability limits given include all the effects of radial straight sections as well as the effects of the scaling nonlinearities.

Integral resonances give rise to the tightest tolerances on field errors. Field errors which disturb the median plane symmetry and give rise to resonances involving the vertical motion have the most serious effects because of the smaller vertical aperture and because of the change in ν_y with amplitude. Analytical and digital studies in connection with the 12.5 BeV accelerator[3] show, after scaling to the present design, that the error harmonics of the field close to ν_y must be kept to less than 0.033 percent in order to keep forced vertical equilibrium orbit displacements to less than 0.49 cm at injection or 0.50 cm at 500 MeV. These harmonics arise from the random errors in the fields of individual magnets; harmonics of 0.033 percent correspond to rms field errors of 0.33 percent of the average field. These tolerances arise from

Twisted Magnet Block (0.03 cm/150 cm)	0.028%
Relative Radial Displacement of Poles (0.025 cm)	0.007%
Radial Displacement of Single Pole (0.025 cm)	0.013%
Fluctuation in Radial Gap Between Magnet Blocks (0.084 cm)	0.003%
Fluctuation in Excitation from Block to Block (0.05%)	0.004%
Net RMS	0.031%

These tolerances can be achieved quite easily.

Table II indicates that the stability limits provide adequate phase area to accommodate the contemplated injected and accelerated beams. The beam sizes shown are determined by the emittance of the linac and the multiturn method of injection. If the emittance (1.65 π milliradian-cm) of the linac beam is perfectly matched into the FFAG accelerator, a single turn will have a radial amplitude of 0.860 cm and a vertical amplitude of 0.865 cm.

The multiturn injection system requires that the radial stepover per turn of the perturbed equilibrium orbit must be large enough to move a beam width plus septum width in four turns. In the present case, with a total beam width of 1.08 cm and a septum width of 0.1 cm, the beam must move 2.92 cm in 10 turns. In the vertical direction the beam may be injected off the median plane by 1.055 cm and still be within the stability limits. This reduces the charge density and permits the largest total charge to be accepted. Adding 0.645 cm to 1.055 cm gives for the vertical betatron amplitude 1.70, thereby leaving 0.43 cm for vertical displacement of the equilibrium orbit before reaching the stability limit. A detailed study of multiturn injection has been given by Curtis.[5]

Magnet System

The nine magnets of a superperiod are shown in Fig. 2. A typical magnet block is shown in Fig. 3. Each half is constructed around a yoke that is six inches thick in the scaling pole region, increasing in thicknesses ranging from 14 inches to 18 inches in the nonscaling pole region in order to carry the magnetic flux. On the back of each slab an I-beam is welded to stiffen the slab. The other cross members of the I-beam are welded to plates which, on the bottom half, are the supporting pads for the magnet assembly.

The spiral poles are to be machined separately and bolted to the yoke surfaces. With the exception of the nonscaling poles, all machined surfaces are flat and lend themselves to routine production and machining. Machining of the nonscaling poles will be accomplished by a

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an electrostatic inflector. In designing the FFAG accelerator the following performance parameters of the linac system are utilized. Output current, 50 mA; output energy spread after debuncher, 0.05 percent; output emittance for each transverse mode, 1.65 π millirad-cm; repetition rate, 120 cycles per second.

RF Accelerating System

Four ferrite loaded cavities are used to apply the radio-frequency accelerating voltages to the protons. Figure 4 shows one accelerating cavity located in relation to the surrounding magnets. Special consideration must be given to the mounts for these magnets since cantilevering is required. Table III lists the performance parameters for the rf acceleration system.

Space-Charge Limitations

The space-charge limitations for this accelerator have been calculated from criteria developed by Laslett[9] for the individual particle transverse motion stability and for the transverse coherent beam stability. In addition, the criterion developed by Laslett, Neil and Sessler[10] for the onset of coherent instability in the transverse motion of the beam due to resistive wall effects is used. A similar criterion with respect to the longitudinal motion of the beam developed by Neil and Sessler[11] is also used.

Table IV lists the information necessary for the calculation of the space-charge limits according to the various criteria. The results of the calculations are also listed at injection and at the final energy. At injection the required number of protons, 1.4×10^{12}, is easily within the transverse incoherent and coherent limits. No difficulty from the longitudinal resistive wall instability is indicated. The transverse resistive wall instability must be circumvented, however, in order to contain the beam. In fact 17 times more charge must be contained at injection and 46 times more charge contained at 500 MeV than is given by the threshold for transverse resistive wall instability. This assumes that the threshold calculations which were carried out for an azimuthally uniform beam give a reasonable estimate for the bunched beam actually present in the accelerator. Various groups[10, 12, 13] - Brookhaven, Cornell, MURA, and Stanford - have indicated that the transverse resistive wall instability can be stabilized using either feedback techniques or external octupole fields.

Conclusion

Further study of the specific accelerator (the ZGS in the example chosen) is required to determine the feasibility of using the FFAG accelerator as an injector. However, apart from the beam instabilities for which remedies have been indicated, the FFAG is technically sound and should be considered as a possible injector. Beam stacking provides a degree of flexibility not available in some accelerators. In fact, the entire 10^{14} particles can be stacked in the FFAG and brought out using radio-frequency phase displacement and resonant extraction. If the problem of injecting many turns (10^4 - 10^5) into the final accelerator were solved, the entire beam could be transferred in 0.05 seconds. Furthermore, because of the high energy spread in the stacked beam for this mode, none of the beam instabilities would be present.

TABLE 1

ACCELERATOR PARAMETERS

MAGNET

R_o = 685.3 cm (radius of 500 MeV equilibrium orbit)

R_{max} = 693.4 cm (maximum good field radius)

R_{inj} = 568.7 cm (radius of 20 MeV equilibrium orbit)

R_{min} = 558.8 cm (minimum good field radius)

ΔR = 134.6 cm (radial aperture)

L_R = 23.0 cm (radial straight section length at R_o)

L_M = 36.8 cm (azimuthal width of magnet at R_o)

G_{inj} = 12.0 cm (vertical magnet aperture at injection)

G_{min} = 7.62 cm (vertical magnet aperture at R_{max})

B_{av} (R_o) = 5302 gauss

B_{av} (R_{max}) = 5785 gauss

B_{av} (R_{inj}) = 1142 gauss

Total Magnet Weight = 450 tons

Total Coil Weight = 27 tons

Total Magnet Power = 3.4 MW (including power in shunts)

N = 16 (number of spiral sectors)

M = 72 (number of radial straight sections)

N' = 8 (number of superperiods per revolution)

RF SYSTEM

Injection Frequency	1.705 Mc
Transition Energy	1903 MeV (outside range of interest)
Final Frequency	6.273 Mc
Total RF Power	1500 kW

TABLE II

ORBIT PARAMETERS

GENERAL

ν_x = 3.311 (radial betatron oscillation frequency)

ν_y = 2.356 (vertical betatron oscillation frequency)

A_x = 0.01094 x radius (average amplitude for radial stability limit)

A_y = 0.00375 x radius (average amplitude for vertical stability limit)

k = 8.2 (field index)

$\frac{1}{w}$ = 75 (spiral parameter - angle of spiral with circle = 13.0369°)

Beat Factor = 1.5 (ratio of maximum to minimum betatron amplitude)

Adiabatic Damping Factor = 2.431, Flutter = 0.75

Amplitude of Equilibrium Orbit Scallop at 500 MeV = 2.00 cm

AT INJECTION

T = 20 MeV

R = 568.7 cm (average equilibrium orbit radius)

a = 2.92 cm (average amplitude of largest radial betatron oscillation)*

b = 1.70 cm (average amplitude of largest vertical betatron oscillation)*

β = 0.20325, γ = 1.0213

$A_{Lim(x)}$ = 219 π millirad-cm (radial betatron phase area from stability limit)

$A_{beam(x)}$ = 16.5 π millirad-cm (radial betatron phase area of beam)

$A_{Lim(y)}$ = 18.1 π millirad-cm (vertical betatron phase area from stability limit)

$A_{beam(y)}$ = 1.65 π millirad-cm (vertical betatron phase area of beam)

*a_{inj} = 6.223 cm, b_{inj} = 2.134 cm from stability limits. Magnitudes shown result from method of injection. Spread in betatron amplitude from one injected turn gives a = 0.540 cm, b = 0.645 cm.

TABLE III

RF ACCELERATION PARAMETERS

GENERAL

V = 85.0 kV (peak volts per turn)

Γ = 0.7 (sine of stable phase angle)

h = 1 (harmonic number)

Repetition Rate = 120 per second

Acceleration Time = 6.83 milliseconds

Total RF Power = 1.5 MW

AT INJECTION

f = 1.703 Mc (particle revolution frequency)

K = 20.56 (percentage frequency shift per percentage total energy change)

$A_{Lim(s)}$ = 1.346 electron volt-sec (available bucket area)

$A_{beam(s)}$ = 0.074 electron volt-sec (area occupied by beam)

ν_s = 14.68 kc (synchrotron frequency near stable phase angle)

AT FINAL ENERGY

f = 5.373 Mc (particle revolution frequency)

K = 0.6516 (percentage frequency shift per percentage total energy change)

$A_{Lim(s)}$ = 1.634 electron volt-sec (available bucket area)

$A_{beam(s)}$ = 0.074 electron volt-sec (area occupied by single beam stack)*

= 0.60 electron volt-sec (area occupied by stacked beam)*

ν_s = 5.19 kc (synchrotron frequency near stable phase angle)

*Assumes adiabatic capture but includes factor for stacking efficiency due to small number of stacked pulses.

TABLE IV

SPACE-CHARGE PARAMETERS

GENERAL

r_o = 1.535×10^{-16} cm (classical radius of proton)

σ = 10^{16} sec^{-1} (conductivity of stainless steel)

w = 155 cm (radial aperture of vacuum tank)

n = 3 (mode number just greater than ν_y)

AT INJECTION

h = 6.34 cm (vertical aperture of vacuum tank)

Δ = 5.84 cm (radial width of beam)

τ = 3.40 cm (vertical height of beam)

g = 11.98 cm (vertical aperture of magnet)

B = 0.375 (bunching factor, B = 1 is unbunched)

ΔT = $\pm$ 26.6 keV (energy spread at injection after adiabatic bunching)

$N_{incoh(trans)}$ = 5.77×10^{12} protons (free space, unbunched, transverse, incoherent, space-charge limit)

= 2.32×10^{12} protons (bunching and image effects included)

$N_{coher(trans)}$ = 8.67×10^{12} protons (bunching and image effects included)

$N_{resis(trans)}$ = 6.43×10^{10} protons (unbunched, transverse, resistive wall space-charge limit)

$N_{resis(long)} \sim 4 \times 10^{12}$ protons (unbunched, longitudinal resistive wall space-charge limit)

N_{beam} = 1.40×10^{12} (design limit for injected beam - requires 36 milliamps from linac)

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FIGURE CAPTIONS

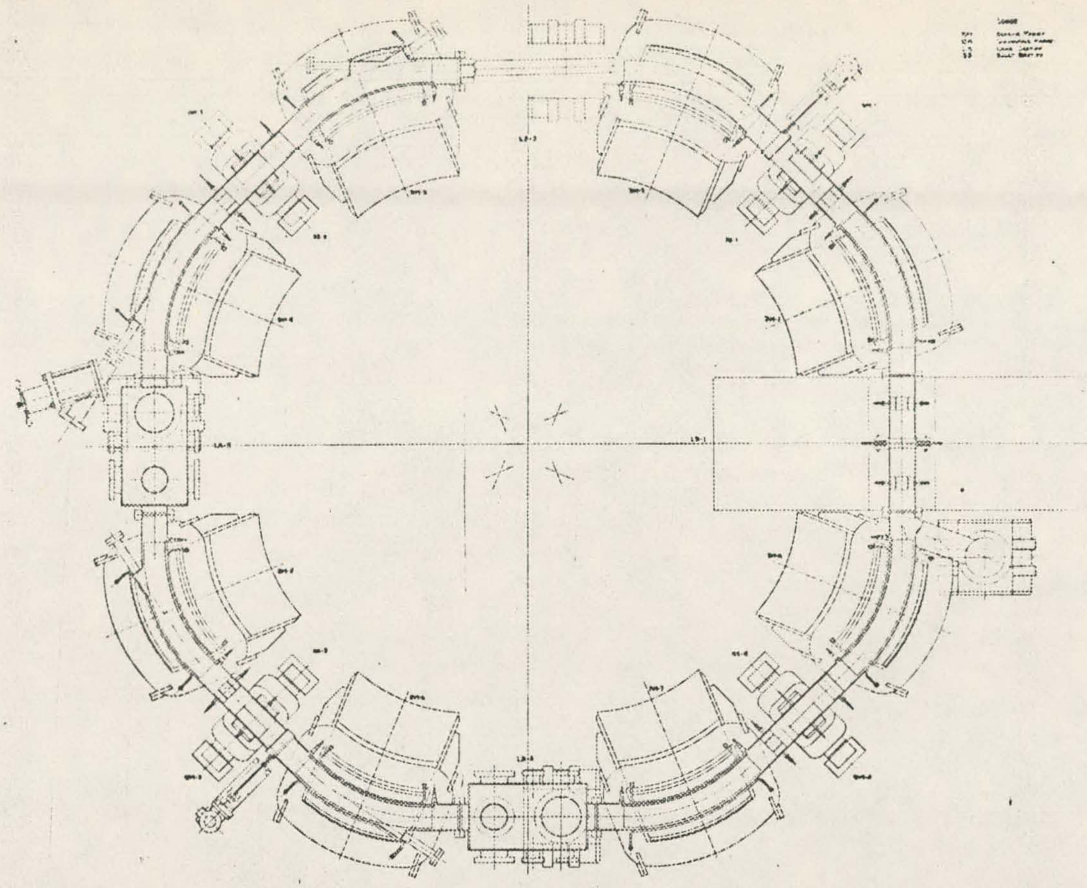
Fig. 1. Plan View of Accelerator

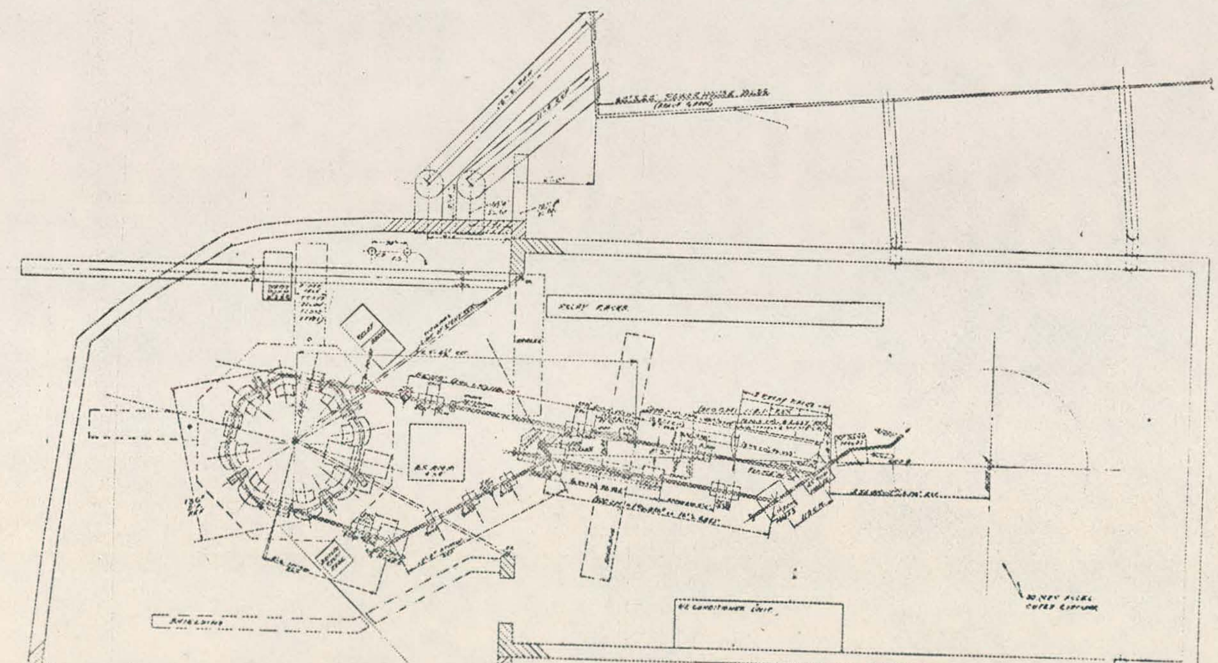
Fig. 2. Magnet Superperiod

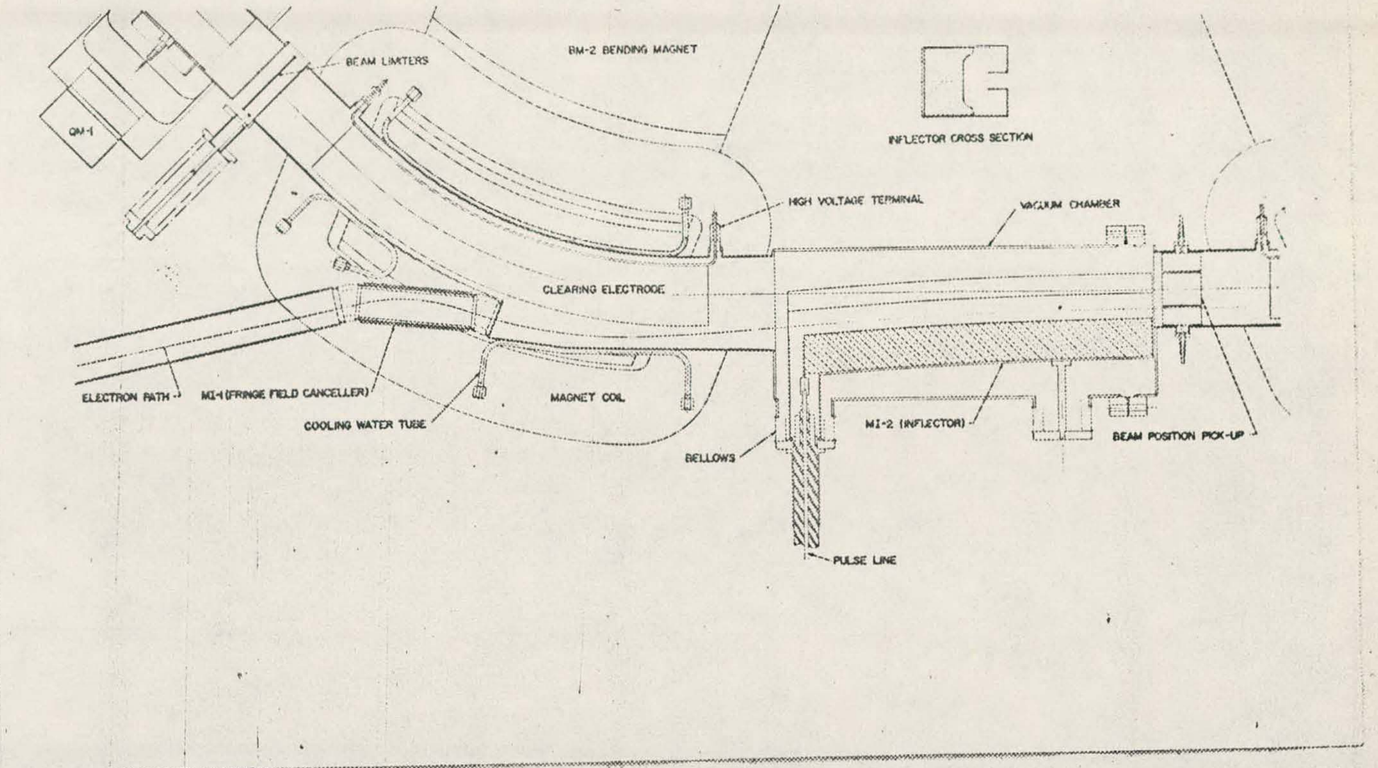
Fig. 3. Typical Magnet Block

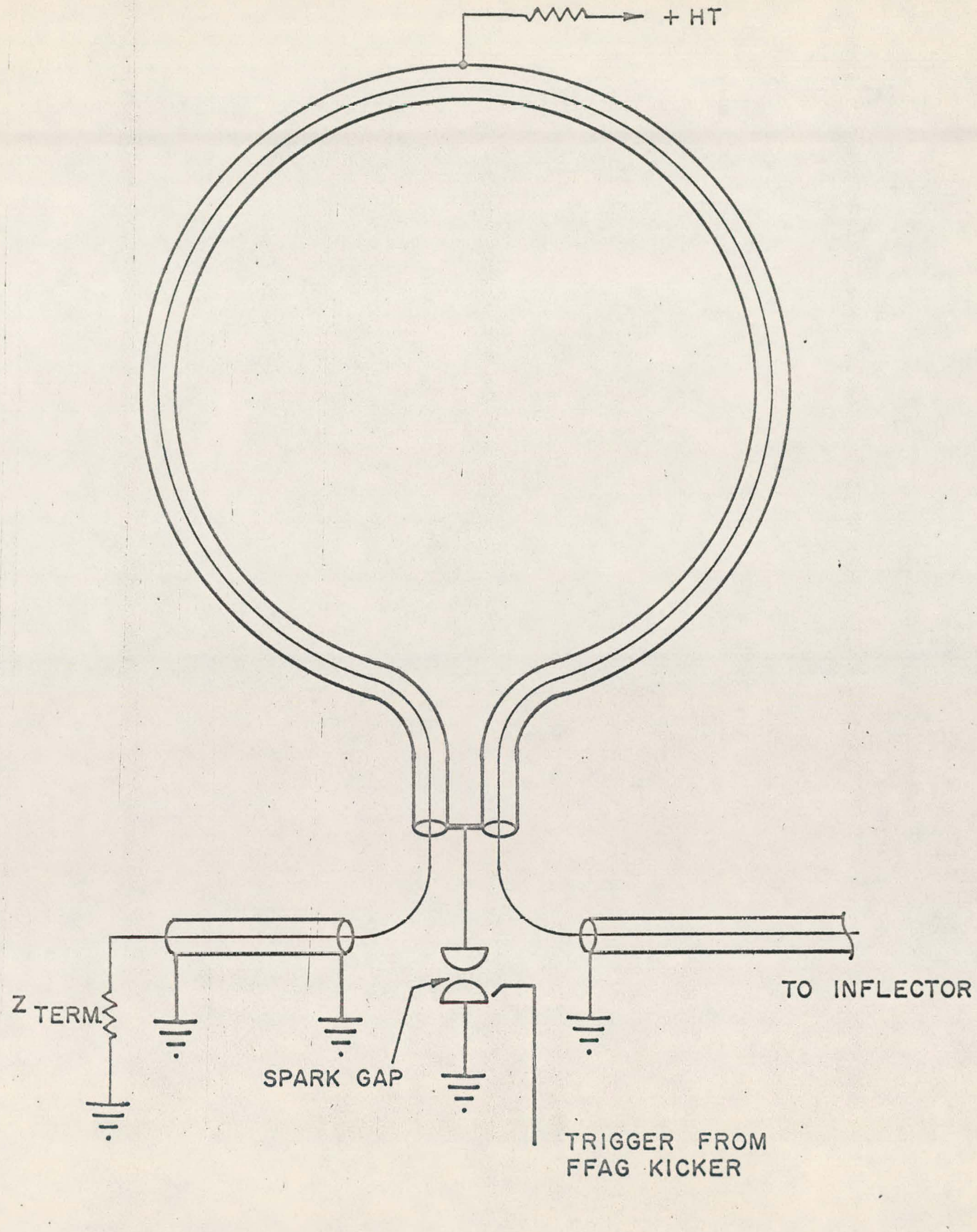
Fig. 4. RF Accelerating Cavity

TABLES






BEAM LIMITERS
BM-2 BENDING MAGNET
QM-1
INFLECTOR CROSS SECTION
HIGH VOLTAGE TERMINAL
VACUUM CHAMBER
CLEARING ELECTRODE
ELECTRON PATH
MI-1 (FRINGE FIELD CANCELLER)
COOLING WATER TUBE
MAGNET COIL
MI-2 (INFLECTOR)
BEAM POSITION PICK-UP
BELLOWS
PULSE LINE



"Ω" SWITCH