SLAC-PUB-1217
(A)
March 1973

# THE RACETRACK MICROTRON AS A NEGATIVE PION SOURCE FOR RADIOTHERAPY*

Perry B. Wilson
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

Craig S. Nunan
Varian Associates, Palo Alto, California 94303

Should clinical trials indicate that negative pion therapy is an improvement over present radiotherapy techniques, reliable pion sources of acceptable cost and size will be required at a number of major medical centers. A 300 KW, 500 MeV electron racetrack microtron is proposed which employs conventional accelerator guides and which can meet hospital requirements on cost, space and operational reliability. Coupling this machine to multi-channel pion applicators, a dose of 100 rads can be delivered in 5 to 10 minutes to a tumor treatment volume of 1000 cc, permitting treatment of 1000 cancer patients per year per machine.

## Radiotherapy Requirements

The primary reasons for interest in pion radiotherapy are the feasibility of a relatively precise restriction of the intense porition of the radiation dose to the selected treatment region and the possibility that the lower oxygen enhancement ratio of negative pions relative to x-rays may result in fewer recurrences of primary tumors. The ultimate test of pion therapy would be a clinical trial. To obtain statistical significance, a large number of patients should be treated by each trial procedure and followed up for a number of years. For example, Boag[1] shows that 700 patients are required in order to have a 75% chance of detecting a 10% difference in the success of two different treatment methods. Ideally, such a clinical trial should take place in major hospitals where full and close support of other medical specialties is readily available, and where it is possible to obtain full comparability with the best techniques of x-ray therapy.[2] The need for machine reliability is especially important. Serious difficulties can occur in patient care and even in the probability of patient cure if unplanned interruptions of more than several days occur in the patient's treatment schedule. The largest machines now routinely used in hospitals are the 30 to 50 MeV betatrons and linear accelerators for cancer therapy with electrons and high energy x-rays. These machines cost between a half and one million dollars and require about 2000 square feet of space. One would not want to increase these cost and space figures by more than perhaps a factor of two or three for a pion facility.

In x-ray cancer therapy a typical procedure is to deliver 6000 rads total tumor dose, fractionated into 30 treatments of 200 rads each, given 5 days per week for 6 weeks, treating perhaps 500 new patients per year per x-ray machine. Karzmark[3] shows the average time per patient treatment with x-rays as 5 minutes for patient setup, 3 minutes for miscellaneous tasks and 2 minutes for x-ray exposure. Assuming a relative biological effectiveness of 2.5, a possible patient treatment schedule with pions might be 100 rads per day for 24 days. Based on a survey of radiotherapists, Brennan[4, 5] states that 10 minutes exposure time is an acceptable mode. This is the basis for the generally accepted design goal of $4 \times 10^{12}$ neutrons/s for neutron therapy machines. Assuming 10 minutes for pion exposure, 10 minutes total for patient setup and miscellaneous tasks, and two treatment rooms used sequentially, 96 patients could be exposed per 16 hour day and 1000 new patients could be treated per year per pion machine.

## Pion Applicators for Proton and Electron Accelerators

The local dose produced per stopping pion is about 40 MeV, or $0.64 \times 10^{6}$ rad-cm$^3$. To deliver a dose of 100 rads to 1000 cm$^3$ treatment volume in 10 minutes, the required yield at the patient is $2.6 \times 10^8$ $\pi^-$/s. Harrison[6] estimates $1.5 \times 10^7$ $\pi^-$/s per MeV-sr per $\mu$A of 500 MeV protons on a 10 cm carbon target after 50% decay in flight. For the TRIUMF 100 $\mu$A, 500 MeV cyclotron, Harrison describes a 7-meter long beam transport system design with 0.01 sr and ± 10% momentum acceptance to deliver $3.4 \times 10^8$ $\pi^-$/s in a beam size variable from 3 × 3 to 10 × 10 cm at the patient, with ± 5% uniformity of pion flux across the beam.

Boyd[7] gives the yield of 68 MeV pions out of a 6-meter channel from a 2.5 cm titanium target or 5 cm carbon target as $1.15 \times 10^5$ $\pi^-$/s per MeV sr per $\mu$A of 500 MeV electrons. Boyd describes a 60-channel superconducting magnet beam transport system which with 1/60 sr and a conservative ± 2% momentum acceptance per channel, would deliver $2.6 \times 10^8$ $\pi^-$/s for a 500 $\mu$A electron beam on a 2.5 cm titanium target. It may be interesting to study an alternative approach, using only 4 channels of more conventional water-cooled beam transport system with design goals of 0.02 sr and ± 10% momentum acceptance per channel and a 600 $\mu$A 500 MeV electron beam on a 5 cm titanium target, in order to deliver a 100 rad dose in 10 minutes to a 1000 cm$^3$ tumor treatment volume. This smaller number of channels might provide easier access for patient setup and easier independent control of the spectral energy distribution of pion beams directed at different angles to the patient.

## Calculation of Microtron Design Parameters

A choice of parameters for a particular microtron design inevitably involves compromises between conflicting requirements. The following general criteria were used here: the final energy and average beam power should be about 500 MeV and 300 kW; the length of the accelerating structure should not exceed 20 m; the diameter of the end magnet pole faces should not exceed 3m; the maximum field in the end magnets should not exceed about 15 kG; the diameter of the first orbit should be at least several centimeters larger than the outer radius of the accelerating structure; the orbit separation should be sufficient (> 10 cm) to allow the installation of beam focusing elements on individual orbits; the overall conversion efficiency of rf power into beam power should not be less than about 50%.

The principal equations used in calculating the microtron parameters are listed in Table I. Equation (1) for the synchronous energy gain applies to the case of uniform field end magnets. Using a magnet system of the type proposed by Rand,[8] more design flexibility is possible since the field is adjustable individually for each orbit. In the energy gain expressions given in Eq. (2) for the standing wave (SW) case, it is assumed that the structure is detuned off resonance so as to maximize the energy gain for a given synchronous phase angle. In the traveling wave (TW) case, synchronous operation is assumed for simplicity, although asynchronous operation would also produce a somewhat greater voltage gain.

The design of Table I, column 1, employs an orbit length increment of two wavelengths per turn ($\nu = 2$). Four klystrons are used, with one of them reserved for the injector. The advantages are very few turns (9), low pulse accelerator current (180 mA), wide orbit spacing (24 cm), and low coupling coefficient ($\beta = 2.0$), which is also the VSWR seen by the klystrons with the beam off. The chief disadvantage is the lower available phase space associated with the $\nu = 2$ mode.. From Bathow,[9] the phase space that can be accelerated for 10 to 20 turns without particle loss can be estimated for the two modes

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

(To appear in the Proceedings of the 1973 Particle Accelerator Conference, San Francisco, Calif., March 5-7, 1973)

as $(\Delta\phi)(\Delta U/U_s) = (24^o) \cdot (12\%)$ for $\nu = 1$ and $(12^o) \cdot (3\%)$ for $\nu = 2$. Operation in the $\nu = 2$ mode may be acceptable, but more careful attention must be paid to tolerances on the magnetic field and transient beam loading for the accelerator structure. There should be no problem in achieving energy and phase spreads from the injector which are well within the limits set even for $\nu = 2$. For example, the MIT injector[10] provides 85% of a 10 mA pulse beam current at 23 MeV in less than $2^o$ phase spread and 0.3% energy spread, with 8% beam loading.

A potentially more serious problem is the variation in energy gain and synchronous phase angle that can occur during the transient beam loading period. By properly programming the amplitude of the input rf to the accelerator as a function of time, it should be possible to keep the energy gain per turn constant well within the 3 percent maximum range allowed for $\nu = 2$, taking into account both the beam loading and orbit filling transients. As a simple example, the variation in energy gain can be held to less than a 2% range for the design of column 1 by starting the injection current 3.1 $\mu$s after rf power starts, and by modulating the klystron drive to drop the rf power to 56% during the first 0.8$\mu$s of injection.

The second column in Table I gives a design with 18 turns for the $\nu = 1$ mode. Three klystrons are used, with one-half the power of one klystron driving the injector. This arrangement results in good overall conversion efficiency (68%) but with a fairly heavy accelerator beam loading droop (79% relative to the loaded beam energy). Although a high value of $\beta$ (5.0) is required, by using 3 dB couplers to split the load seen by each klystron, any reflected power can be dissipated in terminations attached to the couplers. Addition of a fourth klystron, as shown in column 3, reduces the beam loading droop, decreases the size of the machine, and makes possible independent operation of the injector. For injector and accelerator lengths of 5.5 m at $\beta = 2.0$ and 5.0, the final energy is 528 MeV, the (uncompensated) beam loading droop is 43%, and the net conversion efficiency is 53%.

The design of column 4, Table I, uses three 6 m constant gradient traveling wave structures at 425 MHz, with half the power of one of the two klystrons split off for the injector. The advantages of this design are a small number of turns (12), wide orbit spacing (22 cm) with $\nu = 1$ operation, and low accelerator beam loading droop (32%). The chief disadvantage arises from the short pulse length available from the VA-812E klystron. Taking into account both the structure filling time and the orbit filling time, the maximum beam pulse length is estimated to be about 21 $\mu$s for a 25 $\mu$s klystron pulse. This reduces the average beam power to about 250 kW.

The possibility of beam breakup must be considered for each of the preceding machine designs. Taking into account the feedback loop provided by the recirculating beam a simple expression for the current threshold for beam breakup in the long pulse limit is given by Eq. (9), Table I. Assuming representative parameters for the design given in column 3 ($\overline{V} = 250$ MV, $\lambda_t = 0.5$ m, $L_a = 5.5$ m, $L_0 = 18$ m, $r_t = 2.0$ M$\Omega$/m), a current threshold of 400 mA is calculated. The effect of focusing, and the possibility of tuning the accelerator substructures to different breakup frequencies should increase the starting current threshold by an order of magnitude above this value.

Because of the high average power of the recirculating beam in these machines, beam interception must take place only on water cooled collimators, located on each orbit near the magnets. The beam interception will be minimal in normal operation. In the case of mistuning, excessive beam interception at any collimator will trigger the klystron mod-anode modulators to drop the pulse length and pulse repetition rate.

## Concluding Comments

Electron microtrons or recirculated beam linear accelerators have been suggested previously.[11-15] The intent of the present effort is to suggest a design which is optimized for hospital application, based to some degree on LASL experience. The VA-862D, a modified version of the LAMPF[16] 805 MHz klystron, is rated at 5 MW peak power, 150 kW average power and 45% efficiency. Knapp[17] has reported on acceleration of long pulse electron beams in an 805 MHz structure. There are a number of advantages in using relatively low operating frequencies such as 805 or 425 MHz. Klystron beam apertures, cathodes, collectors and output windows can be large, resulting in long klystron life at high average rf power and long pulse length. Beam breakup current thresholds are higher. For a chosen number of incremental wavelengths per turn, the number of orbits is less, resulting in greater phase space for electrons actually reaching the target, reduced defocusing effects due to end magnet fringe fields, lower beam current loading of the accelerator guide, and fewer quadrupoles.

Further analysis would be required to select and define an optimum microtron design. The final design should include sufficient flexibility to allow operation over a range of parameters. For example, the choice between $\nu = 1$ or $\nu = 2$ operation can be determined experimentally be designing the machine to permit operation in both modes. The specific design examples shown in Table I, however, illustrate the feasibility of achieving the beam energy and power required for pion radiotherapy in a compact accelerator using a water-cooled accelerating structure and a recirculated beam.

In order to illustrate space requirements, a 9 orbit, 805 MHz, 4 klystron microtron design is shown in Fig. 1. Two $180^o$ magnets are shown, each of which would weigh 45 tons based on the yoke shape proposed by Peterson,[18] or 11 tons based on the stepped field design of Rand.[8] The total area is 6000 square feet for machine, shielding and treatment rooms.


## Acknowledgements

The authors wish to thank the following for information and comments: P. J. Tallerico of LASL, O. C. Lundstrom of Varian, C. J. Karzmark of Stanford Medical Center, and D. Boyd and R. Rand of Stanford University.


## References


1. J. W. Boag, J. L. Haybittle, J. F. Fowler and E. W. Emergy, Brit, J. Radiol 44, 122-125 (1971).
2. M. Catterall, "The treatment of patients with fast neutrons from the medical research council's cyclotron at Hammersmith Hospital, London." To be published in Proceedings on Particle Accelerators in Radiation Therapy, Los Alamos Scientific Laboratory, Oct. 2-4, 1972.
3. C. J. Karzmark and D. C. Rust, Brit. J. Radiol. 45, 276-278 (1972).
4. J. T. Brennan, Europ. J. Cancer 7, 245-248 (1971).
5. J. T. Brennan, Letter to Editor (Jan. 24). To be published in Brit. J. Radiol. (1973).
6. R. W. Harrison, "A beam transport system for the medical facility at TRIUMF," Report TRI-72-1, Univ. of Victoria Physics Dept. (1968).
7. D. Boyd, H. A. Schwettman and J. Simpson, "A large acceptance pion channel for cancer therapy." To be published in Nucl. Instr. Methods (1973). Also, Report HEPL 697, Stanford University (1972).

8. R. E. Rand, "A multiorbit recirculation system for a superconducting linear accelerator — the recyclotron," Proceedings of the 1973 Particle Accelerator Conference. To be published in IEEE Trans. Nucl. Sci. (1973).

9. G. Bathow and E. Freytag, "Discontinuous phase oscillations in particle accelerators," DESY Report 69/29.

10. J. Haimson, "Initial operation of the MIT electron linac," Proceedings of the 1973 Particle Accelerator Conference. To be published in IEEE Trans. Nucl. Sci. (1973).

11. B. H. Wiik, H. A. Schwettman and P. B. Wilson, "A 200 MeV superconducting racetrack microtron," Report HEPL-396, Stanford University (1965).

12. B. H. Wiik and P. B. Wilson, Nucl. Instr. Methods 56, 197-208 (1967).

13. C. S. Robinson, "The design of high energy microtrons," Tech. Report No. 156, University of Illinois Physics Research Laboratory (1967).

14. D. Barbero, L. Gonella, V. Pasino, S. Rebola and A. Stringazzi, "Intensity limits and beam quality in the linatron (recycled electron linac)." Proceedings of the 8th International Accelerator Conference (CERN Scientific Information Service, Geneva, 1971).

15. H. S. Kaplan, H. A. Schwettman, W. M. Fairbank, D. Boyd and M. A. Bagshaw, "A hospital-based superconducting accelerator facility for negative pi-meson beam radiotherapy." To be published in Radiology (1973).

16. D. C. Hagerman, "Operating results on the 800 MeV proton linac at LASL," Proceedings of the 1973 Particle Accelerator Conference. To be published in IEEE Trans. Nucl. Sci. (1973).

17. E. A. Knapp, IEEE Trans. Nucl. Sci. NS-16, No. 3, 329-337 (1969).

18. G. A. Peterson, Nucl. Instr. Methods 61, 347-348 (1968).

19. W. B. Herrmannsfeldt, R. H. Helm and R. R. Cochran, "Electromagnetic and mechanical properties of niobium cavities for a superconducting linear accelerator." Proceedings of the 1970 Proton Linear Accelerator Conference, NAL, Batavia, Illinois (1970).

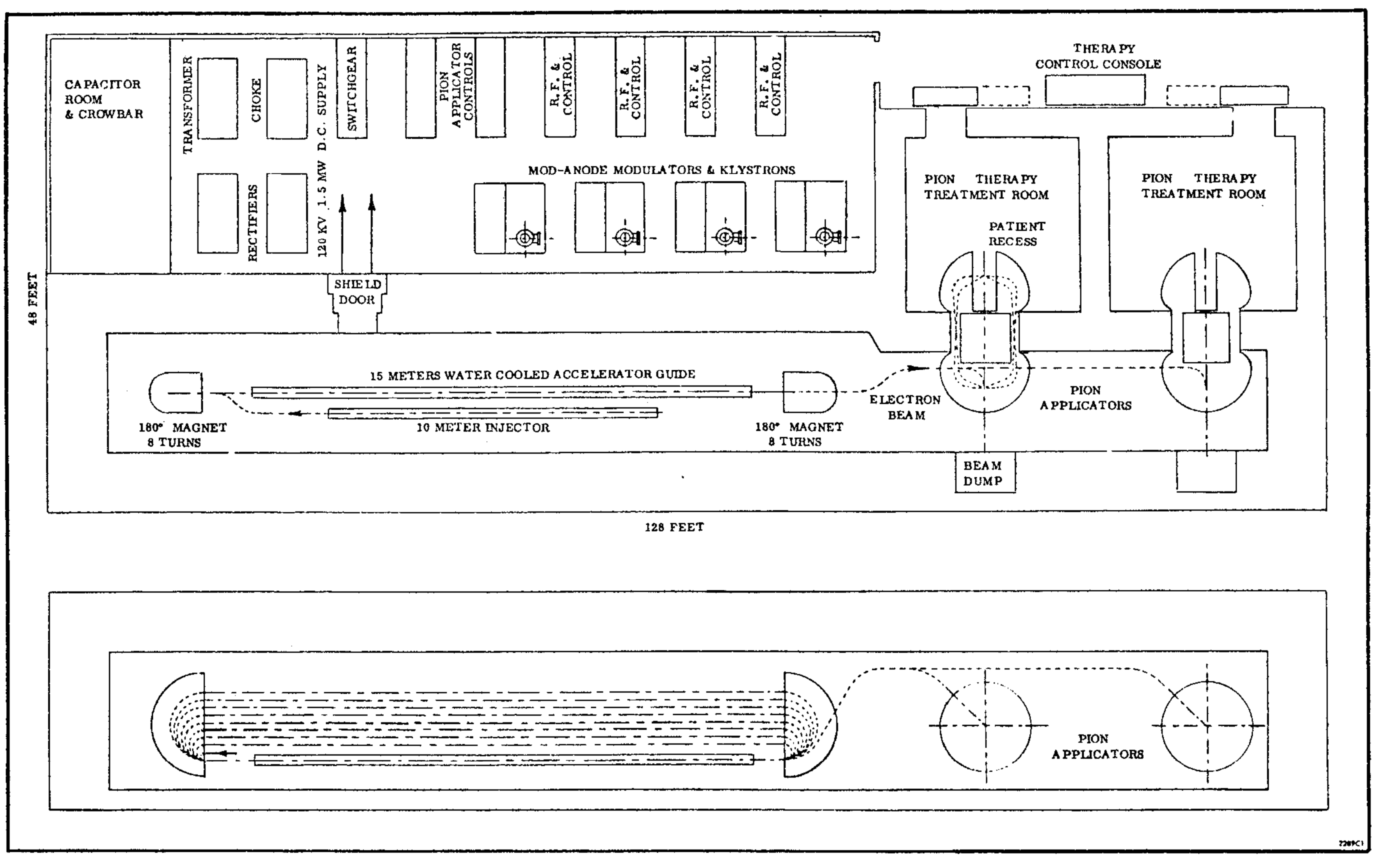


FIG. 1--Pion therapy accelerator.

## MICROTRON DESIGN PARAMETERS

| Parameter | Units | SW $\nu = 2$ | SW $\nu = 1$ | SW $\nu = 1$ | TW $\nu = 1$ | Notes and Equations |
|---|---|---|---|---|---|---|
| Final energy, $U_f$ | (MeV) | 497 | 513 | 528 | 507 | (a) |
| Average beam power | (kW) | 298 | 308 | 317 | 305 | |
| Number/type of klystrons | | 4/VA-862 | 3/VA-862 | 4/VA-862 | 2/VA-812E | |
| Frequency | (MHz) | 805 | 805 | 805 | 425 | |
| Peak/average power per klystron | MW/(kW) | 5/150 | 5/150 | 5/150 | 20/300 | |
| Duty cycle, D | (%) | 3 | 3 | 3 | 1.5 | |
| Pulse length/rep rate | ($\mu$s/pps) | 250/120 | 250/120 | 250/120 | 25/600 | |
| Number of orbits, n | | 9 | 18 | 18 | 12 | |
| Magnetic field, B | (kG) | 14.3 | 15.3 | 15.6 | 12.0 | (1) |
| Synchronous energy gain per turn, $U_s$ | (MeV) | 51.0 | 27.15 | 27.75 | 40.5 | (2) |
| Pulse output current | (mA) | 20 | 20 | 20 | 40 | (b) |
| Accelerator pulse current, $i_0$ | (mA) | 180 | 360 | 360 | 480 | |
| Accelerator pulse input power, $P_0$ | (MW) | 14.25 | 11.88 | 14.25 | 30.4 | (c) |
| Coupling coef. $\beta$(SW), attenuation $\tau$(TW) | | 2.0 | 5.0 | 5.0 | 0.125 | (d), (j) |
| Shunt impedance per unit length, r | (M$\Omega$/m) | 40 | 40 | 40 | 25 | (e) |
| Synchronous phase angle, $\phi$ | (deg) | 9 | 18 | 18 | 18 | (f) |
| Accelerator effective length, $L_a$ | (m) | 15 | 10 | 5.5 | 18 | |
| Accelerator beam loading | (%) | 67 | 79 | 43 | 24 | (g) |
| Accelerator reflected power, beam on/off | (%) | 5/11 | 1/44 | 3/44 | --- | (h), (3) |
| Injection energy, $U_i$ | (MeV) | 38.4 | 23.9 | 29.0 | 21.7 | (2) |
| Injector pulse input power | (MW) | 4.75 | 2.38 | 4.75 | 7.6 | (c) |
| Injector effective length | (m) | 10 | 8 | 5.5 | 12 | |
| Injector reflected power, beam on/off | (%) | 6/11 | 5 11 | 7/11 | --- | (h), (3) |
| Injector beam loading | (%) | 7 | 9 | 5 | 5 | (g) |
| Filling time, $T_F$, accelerator/injector | ($\mu$s) | 3.6/3.6 | 1.8/3.6 | 1.8/3.6 | 3.6/3.6 | (i), (4) |
| Diameter of final oribt, $d_n$ | (cm) | 231 | 224 | 226 | 281 | (5) |
| Diameter of first orbit, $d_1$ | (cm) | 42 | 22.3 | 24.2 | 34.5 | (5) |
| Structure radius, $r_s$ | (cm) | 16 | 16 | 16 | 29.5 | (6) |
| Orbit separation, $\Delta d$ | (cm) | 23.7 | 11.9 | 11.9 | 22.5 | (7) |
| Orbit filling time, $T_0$ | ($\mu$s) | 1.2 | 1.6 | 1.0 | 1.9 | (8) |

Notes: (a) Final energy, $U_f = nU_s + U_i$. (b) Taken as (300 kW/500 MeV)/D. (c) Includes a waveguide loss of 5%. (d) For SW designs the injector coupling coefficient is 2.0. (e) Los Alamos side-coupled structure[17] assumed for standing wave case, "bulgy-disk" structure[19] for traveling wave case. (f) Optimum synchronous phase is $\phi \approx \tan^{-1}(1/\pi\nu)$.[9] (g) Defined as $[V(i_0 = 0) - V(i_0)]/V(i_0)$. (h) Ratio of reflected to input power measured at the structure. (i) Assumes $Q_0 = 27,000$ (SW) and $Q_0 = 39,000$ (TW), based on Refs. 17 and 19. (j) For the TW case, the group velocity varies over the range $v_g/c = .0048 - .0062$ assuming three structures each 6 m long.

Equations:

(1) Magnetic field, $B(\text{kG}) = [U_s(\text{MeV}) \cdot f(\text{GHz})]/(1.432\,\nu)$.

(2) Voltage gain (SW); $V = (rLP_0)^{1/2}\,[2\sqrt{\beta}/(1+\beta)]\cos\phi\,[1 - (K\sqrt{\beta})\cos\phi]$, where $K = (i_0/2)\sqrt{rL/P_0}$. Voltage gain (TW); $V = (rLP_0)^{1/2}(1-e^{-2\tau})^{1/2}\,[\cos\theta - K(1-e^{-2\tau} - 2\tau e^{-2\tau})/(1-e^{-2\tau})^{3/2}]$, where $\theta \approx \phi\,[1 - K(1-e^{-2\tau})^{3/2}(1-e^{-2\tau} - 2\tau e^{-2\tau})]$ is the phase angle between the negative of the beam induced wave and the klystron produced wave.

(3) Reflected power; $P_r/P_0 = 1 - (i_0V/P_0) - [4\beta/(1+\beta)^2][1 - K/\sqrt{\beta})\cos\phi]^2$.

(4) Filling time (SW); $T_F = (2Q_0/\omega)\,[1/(1+\beta)]$. Filling time (TW); $T_F = (2Q_0/\omega)\tau$.

(5) Orbit diameter; $d(\text{cm}) = 6.67\,U(\text{MeV})/B(\text{kG})$.

(6) Structure radius; $r_s(\text{cm}) \approx 1 + 12.1/f(\text{GHz})$.

(7) Orbit separation; $\Delta D(\text{cm}) = 9.55\nu/f(\text{GHz})$.

(8) Orbit filling time (assuming total length between magnets = $1.18\,L_a$); $T_0 \approx (\pi n/2c)(1.5\,L_a + d_n + d_1)$.

(9) Beam breakup current threshold; $i_0(\text{BBU}) \approx (2\bar{V}\lambda_t)/(\pi\, r_t L_a \bar{L}_0)$, where $\bar{V}$ is the average recirculation energy, $r_t$ and $\lambda_t$ are the shunt impedance per unit length and wavelength of the breakup mode, and $\bar{L}_0$ is the average orbit length.