CW Racetrack Microtrons*

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Introduction

High energy electron beams have been used for four decades to probe the structure of the nucleus and to gain insight into other nuclear properties. Until recently the physics of the electronuclear interaction has been inferred by the detection of only a single reaction product during the measurement. However, in order to distinguish between several possible competing processes, it is necessary to detect two or more reaction products in coincidence. Due to the finite resolving time of the detector system, accidental coincidences between uncorrelated events can result in undesirably high background at high instantaneous reaction rates. These accidental events can be minimized by making the ratio of peak to average reaction rates as close to unity as feasible, i.e., by the use of high duty factor beams.

The need for high duty factor electron beams was convincingly presented in an overview by B.E. Norum of proposals for cw electron beam facilities presented at the 1983 Particle Accelerator Conference (PAC).[1] Among the cw accelerator systems described at this conference were several[2-5] based upon Racetrack Microtrons (RTM).

Within practical limits of beam current and final beam energy, RTMs offer considerable advantage over conventional one-pass electron linacs: compact size, reduced energy spread, and cw operation at reduced rf power and reduced accelerator length (and cost). Figure 1 shows the basic configuration of the RTM. By employing multiple passes through the same accelerating structure, the structure length and rf power required to maintain the accelerating fields is considerably reduced, making cw operation more feasible. Electrons circulate in the RTM with longitudinal oscillations about the synchronous phase of the central orbit, resulting in very little increase in energy spread beyond that which occurs in one pass and, thereby, improving the energy resolution of the beam after multiple passes. By splitting the recirculating magnet into two "halves" the racetrack microtron may contain an accelerating structure of optimum length, usually with considerably higher energy gain per pass than is practical for the classical single-cavity microtron (Fig. 1). The upper limit of ~ 1 GeV on RTM beam energy is defined by the practical size of the end magnets, which are limited in field strength to not much more than 1 tesla, due in part to field uniformity requirements.

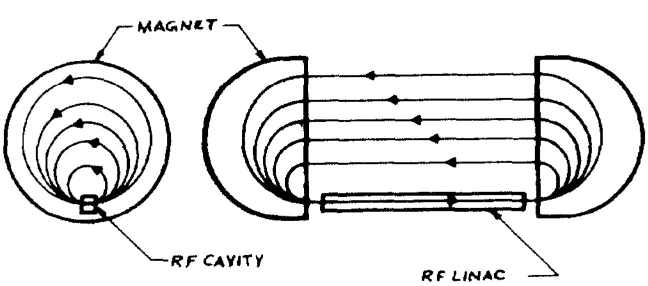

Fig. 1. Classical microtron (left) and racetrack microtron

A review of the activities in construction and operation of cw RTMs in the intervening 8 years since the 1983 PAC follows.

Table I shows the results of a survey of these activities. With the recent shut-down of MUSL-2 at the University of Illinois, there is no current activity involving cw RTMs in the western hemisphere. Very active projects are underway in West Germany and the USSR.

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Table I. Activities involving the design/construction/operation of known cw Racetrack Microtrons.

Location	# Stages 1983	Maximum Proposed Energy	Status
U. Montreal	1	50 MeV	Conceptual design completed, funding not approved.
U. Illinois	3	750 MeV	Full conceptual design of 2-stage 450 MeV RTM completed 1986. Several prototype elements built and tested. Project terminated due to funding problems.
Mainz	3	840 MeV	855 MeV 12 μA cw beam achieved, August 1990.
*Moscow	1	118 MeV (1988)	Design recently upgraded to ~ 175 MeV. Under active construction.
NIST	1	185 MeV	Over 90% complete. Injection and 1-pass tests complete. Funding withdrawn October 1990.
ANL	1	185 MeV	Planned as injector for proposed 4-GeV Hexatron Microtron project. Project not funded.

*Not presented at PAC '83.

University of Montreal

At the time of the 1983 PAC. The University of Montreal had completed a thorough conceptual design of a 50 MeV cw RTM.[5] Although the immediate goal of the proposed facility[6] was to provide a high quality electron beam of modest energy for nuclear physics research, this RTM was planned to be the first of a 3-stage RTM system for a 1 GeV Canadian electron accelerator facility. The planned first stage begins with a 100 keV dc electron gun and chopper-buncher system, based on the NIST design, followed by a 4.27 MeV rf linac of basic design similar to the edge-cooled on-axis coupled structure used at Mainz. The beam would then be achromatically injected, as shown in Fig. 2, into a 27-turn RTM with extracted beam energy continuously variable between 9 MeV and 47 MeV (nominal) and with maximum average beam current of 100 μA.

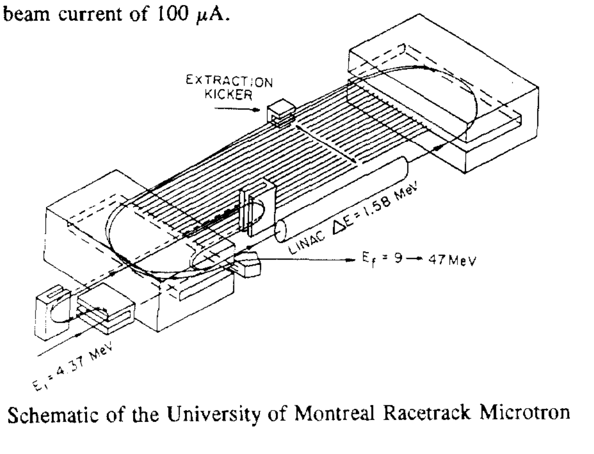

Fig. 2. Schematic of the University of Montreal Racetrack Microtron

Soon after the 1983 conference, the decision was made to fund the construction of a stretcher ring for the 300 MeV pulsed electron linac at Saskatoon, to produce a high duty factor electron beam. As a result, support for RTM facility was dropped.[7]

University of Illinois

Drawing upon years of experience in the construction and operation of the MUSL series of superconducting cw RTMs, the Nuclear Physics Laboratory at the University of Illinois developed a proposal in 1986[8] for a 2-stage 450 MeV cw room-temperature RTM facility and appropriate laboratory area for nuclear studies. This effort was guided by the recommendation of the Nuclear Science Advisory Committee (NSAC) Panel on Electron Accelerator Facilities in 1983 that the Illinois facilities be upgraded to produce a cw electron beam with energies of a "few hundred MeV."[9] Although somewhat more modest than the original plan for a 3-stage 750 MeV facility, the region of excitation attainable would be expected to provide significant advances in the understanding of nuclear dynamics, including the role of the Δ excitation. Such a facility would also serve as a complement to the 0.5-4 GeV cw electron facility of the Continuous Electron Beam Accelerator Facility (CEBAF), Newport News, Virginia. Figure 3 is a plan view of the 2-stage system. The design characteristics of the system are listed in Table II.

Table II. Principal Characteristics of the Illinois Cascade Microtron.

	RTM Stage 1	RTM Stage 2
Input Energy (MeV)	4.53	46.7
Output Energy (MeV)	46.7	455.5
Number of Recirculations	29	70
Magnetic Field (tesla)	0.247	1.000
Outer Orbit Diameter (m)	1.26	3.02
Magnet Weight (each) (tons)	32	220
Accelerator Length (m)	0.98	6.0
Energy Gain per turn (MeV)	1.45	5.84
Resonant Phase	20°	15°
RF Power: Dissipated (kW)	25.26	72.12
Beam (kW)	4.22	40.88
Total (kW)	29.48	113.0

With support from the National Science Foundation (NSF), the Nuclear Physics Laboratory staff embarked on a program of research and development of components for the 2-stage RTM system. These researches, along with close attention to the progress of RTM projects at Mainz and NBS (now NIST), resulted in a well documented, highly credible proposal for the 450 MeV accelerator system. Along with providing support for the proposal, prototypes of major components of the system were constructed and tested to shorten the time between funding and completion of the project. Among the areas of study[8] were: (1) the design and fabrication of room temperature cw linacs optimized for the University of Illinois application; (2) advances in high-power cw rf sources at 2.45 GHz; (3) development of controls for the precise regulation of rf fields in linacs; (4) construction and operation of a 100 keV electron gun for the development and testing of a subharmonic chopping and bunching system and of beam diagnostic instrumentation; (5) the design, construction and testing of low power (7-22 W) high frequency solid-state amplifiers; (6) the development of field-homogenizing and field-mapping techniques to the high accuracy needed for highly uniform field RTM end magnets; (7) design studies for large, high field RTM end magnets; (8) advances in accelerator control systems; (9) high flux, high energy radiation shielding calculations.

Following submission of the proposal for construction and operation of the 450-MeV facility to NSF, funding was initially approved by congress. Unforeseen economic events led to a reduction in the planned expansion of the NSF budget for fiscal year 1988. This prevented funding of several new projects including the Illinois RTM. Further efforts to obtain funding have been abandoned.[10]

Parallel with the efforts to develop a design and obtain support for the construction of a 450-MeV cw RTM system, the superconducting cw RTM, MUSL-2, was upgraded by replacing the original end magnets with the ones developed for the first stage of the cascade system (these were copies of the NBS RTM end magnets fabricated concurrently with the NBS components). The use of larger field area end magnets allowed for 3 additional recirculations which boosted the maximum beam energy from 67 MeV to 100 MeV at 10 μA. Experiments in nuclear physics were conducted with electron beams from this accelerator until shut-down in August, 1990.[10]

Three-Stage RTM at Mainz

The staff at the Nuclear Physics Institute at the Johannes Gutenburg University, Mainz, West Germany have, after sixteen years of steady progress, succeeded in achieving a cw electron beam of over 850 MeV from their 3-stage RTM system. A plan view of the present configuration of the system "MAMI" (MAinz MIcrotron) is shown in Fig. 4. Table III gives the system design parameters.

Initial planning and design began in 1974. The first 14-MeV stage was made operational in 1979. First beam tests of the second stage to 187 MeV maximum energy were reported at the 1983 Particle Accelerator Conference.[4]

During construction of the third stage, the first two stages were operated on a regular basis to produce cw electron beams for nuclear physics studies. The experience gained proved quite useful in optimizing the final 3-stage configuration.[11,12] In addition to the development of improved beam transport elements and advances in computer controls, the 2.1 MeV Van de Graaf injector was replaced with a 3.5 MeV rf linac for improved reliability and better energy match to the first-stage RTM.

The first two stages and new injector were moved to the new building and commissioned by June of 1990. On August 10, 1990, the electron beam was easily circulated through all 90 turns of the third stage.[13] Some of this rapid success may be attributed to careful adjustment of the correction coils in the 300 ton end magnets for optimum field uniformity.[14] By observing the synchrotron radiation emitted by the electrons on return orbits in the end magnets of the second and third stages, the transverse beam positions can be rapidly

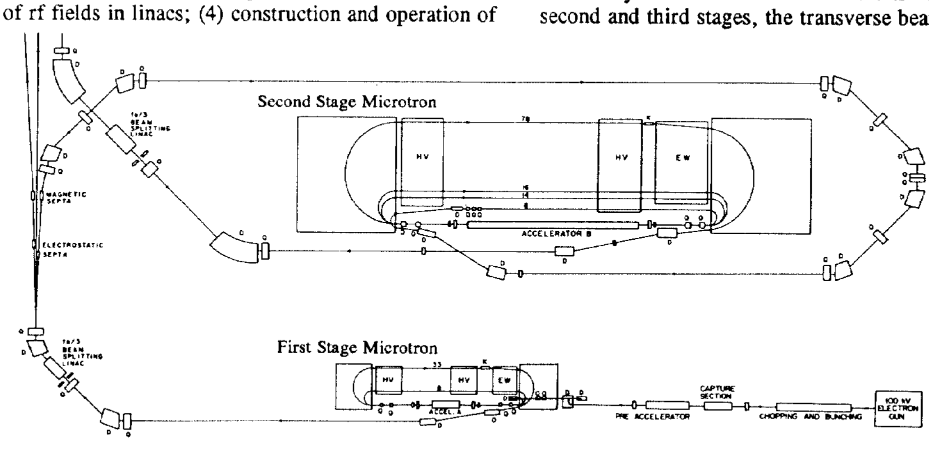

Fig. 3. Plan View of the Illinois Cascade Microtron.

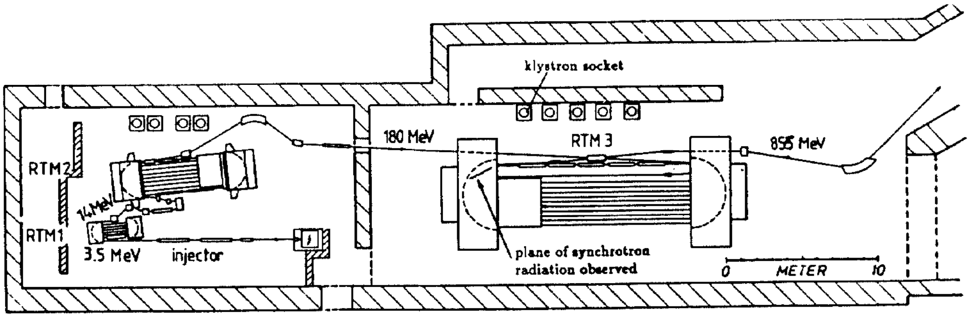

Fig. 4. Plan View of MAMI

Table III. Main Parameters of MAMI

General				
Stage No.		I	II	III
Input energy	MeV	3.46	14.39	179.8
Output energy	MeV	14.39	179.8	855
No. of recirculations		18	51	90
Magnet system				
Magnet distance	m	1.67	5.60	12.86
Flux density	T	0.1028	0.5553	1.2842
Max. orbit diam.	m	0.97	2.17	4.43
Weight per magn.	to	1.3	43	450
Gap width	cm	6	7	10
rf System				
No of klystrons		1	2	5
Linac length (el.)	m	0.80	3.55	8.87
rf power dissip.	kW	8	48	103
rf beam power	kW	1.1	17	68
Energy gain	MeV	0.6	3.24	7.5
Beam (100 μA)				
Energy width	keV	$\pm$ 9	$\pm$ 18	$\pm$ 60
Emittance vert.	μm	$< .17\,\pi$	$< .014\,\pi$	$\leq .04\,\pi$
Emittance hori.	μm	$< .17\,\pi$	$< .014\,\pi$	$\leq .14\,\pi$

adjusted without interception.[13] Figure 5 is a photo of the third stage of MAMI with one end magnet in the foreground. In later runs the cw beam current was increased to 12 μA. Although pulsed currents of 100 μA were easily achieved, higher average current will await the installation of the complete beam spill system. Meanwhile, large detection systems, including electron scattering spectrometers, are being installed[15] in newly built experimental halls in preparation for an international community of users.

Moscow State University Racetrack Microtron

In 1986 the Nuclear Physics Research Institute of Moscow State University, USSR, began construction of a cw racetrack microtron.[16] Initially, the designed maximum extracted energy was 118 MeV. Recent design changes will allow about 175 MeV. Table IV lists some of the present design parameter values.[16,17]

Table IV. Some Basic Parameters of the Moscow State University Racetrack Microtron

Injection Energy	(MeV)	6
Maximum extracted energy	(MeV)	175
Energy gain/pass	(MeV)	6
Number of passes		27
Orbit increase (wavelength)/pass	ν	1
Radio frequency	(GHz)	2.45
Resonant phase	(degree)	16
Effective shunt impedance	(MΩ/m)	80
End magnet field	(Tesla)	1.027
Average beam current	(μA)	100
Energy spread, $\Delta E/E$	(%)	10^3 - 10^4
Transverse emittance (full energy)	($\pi \cdot$mm$\cdot$mr)	0.05

At present the chopper-buncher system,[18] and capture section,[19] have been beam tested and the full injector accelerator is being commissioned. The rf system controls and 22-kW, 55% efficient klystrons are fully developed, with sufficient (12) klystrons on hand to power all accelerating sections.[17] The upgraded end magnets have been constructed and are undergoing tests for field uniformity. Construction of the full RTM is expected to be complete in 2-3 years.[17]

NIST-Los Alamos CW RTM Facility

Over the last 10 years a cw RTM facility has been under construction at the NIST site in Gaithersburg, Maryland. The original purpose was to provide a modern facility for nuclear studies using coincidence techniques and to expand the high-energy radiation dosimetry program at NIST. An additional purpose was to provide a test bed for U.S. Department of Energy-sponsored research on recirculating cw electron accelerators with room temperature rf structures to study the effects on the beam break-up (BBU) instability current threshold, in preparation for the design and construction of a high energy 2-4 GeV national cw electron beam facility.

The rf components of the NIST RTM, including controls, have been provided by Los Alamos National Laboratories. Progress on this facility has been reported in previous accelerator conferences.[20-24]

Figure 6 is a plan view of the RTM system, consisting of a 100 keV dc electron gun, chopper-buncher, and 5-MeV injector linac, followed by the RTM. Table V gives the design parameters for the RTM and the performance through 1-pass beam tests. The test results have met or exceeded design goals. Unlike most RTMs planned thus far, the NIST accelerator is designed to operate with a change in orbit length of two wavelengths per pass rather than one. This places a more restricted limit on the longitudinal phase acceptance, but the higher energy gain per pass and fewer passes permit higher beam current without crossing the BBU threshold. The higher shunt impedance of the side-coupled accelerating structure, compared to the on-axis coupled structure used in many other designs, has made the higher energy gain per pass more practical.

Following the one-pass beam tests in May 1989, the test beam line was removed to make way for the installation of the return beam lines, which is now nearly complete. Figure 7 is an overhead photograph of the RTM showing the return lines, 8-m linac and one end magnet (behind the movable extraction magnet). The design of the extraction beam line (a portion, D12 to Q18,19, is shown in Fig. 6) is complete and nearly all magnetic elements required for full RTM commissioning have been procured.

During the past year, a new high voltage power supply for the single ~500-kW cw klystron, which provides high power rf for the accelerator system, has been under procurement. A (partially installed) new control system, based upon CAMAC controlled by work stations operating with the software developed for CEBAF, was designed to replace the original multibus system for flexibility, increased reliability and future expansion.

In 1986, the funding climate forced a rethinking of priorities. Since the CEBAF design had become based upon superconducting accelerator technology, experimental studies of recirculating BBU in room temperature structures became less urgent. Therefore, the emphasis on the application of the NIST RTM, capable of much higher beam currents than other contemporary RTM designs, was directed toward its development as a driver for a cw free electron laser (FEL). This system, with output tunable over a wide range of wavelengths from less than 300 nm to 10 μ at cw power up to hundreds of watts, is described in references 25-29.

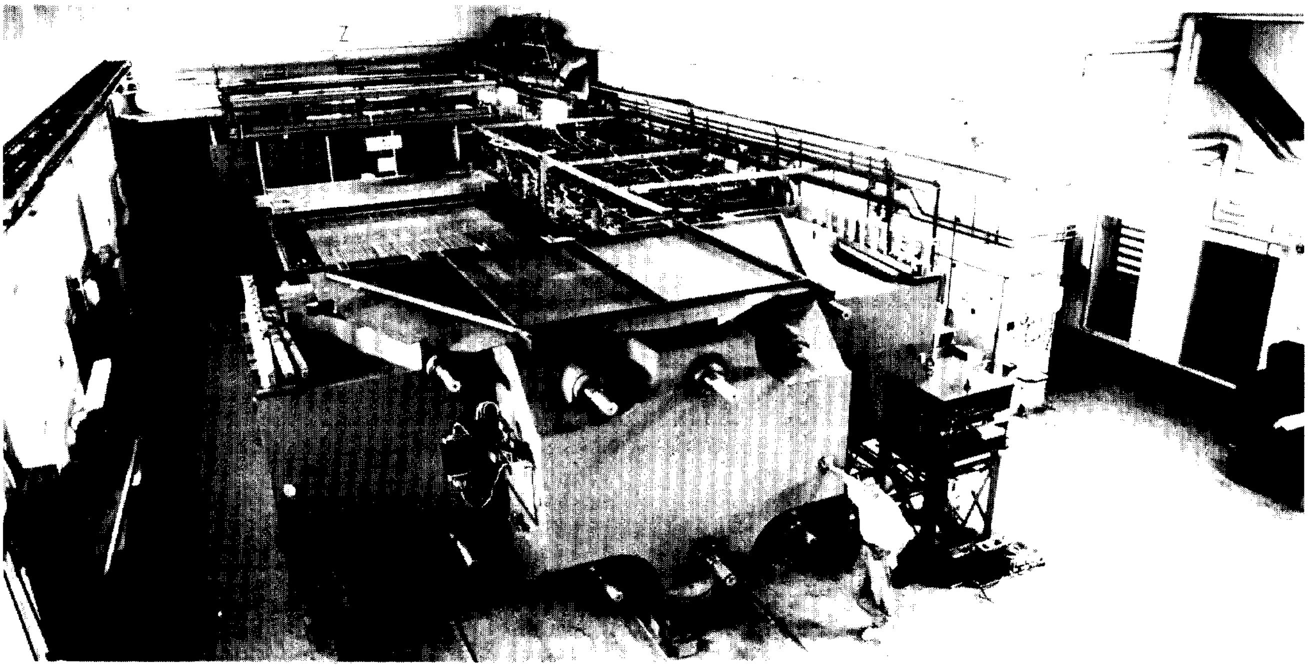

Fig. 5. Photo of 850 MeV MAMI Third Stage.

As a result of this new role for the NIST RTM, designs of the FEL system and of modifications[30] required for the RTM injector to produce a higher instantaneous current at a subharmonic of the accelerator frequency were begun in parallel with continued construction of the RTM.

In the early fall of 1990, other agency support for the FEL project was discontinued effective December 31. Subsequently NIST terminated its support of the RTM project. Efforts to obtain sufficient external support to complete and commission the RTM have been unsuccessful thus far. The nearly complete accelerator system is still available.

Conclusion

Of the half-dozen cw RTM projects reviewed, only two appear to have maintained sufficient financial support for completion. However, the technical support and cooperation demonstrated by all the laboratories involved in the design and development of RTM systems has contributed to the success of the surviving projects and is a tribute to the accelerator community and to this forum.

Table V. NIST-Los Alamos RTM Performance

	Original Design	Measured 2/87	Measured 5/89
Energy (MeV)	17-185	5.5[a]	17
Average current (μA)	550 max	630	300[b]
Average beam power (kW)	100 max	3.5	0.03
Peak current	0.07	-	-
Micropulse length (ps)	3.5	-	-
Micropulse frequency (MHz)	2380	2380	2380
Macroscopic duty factor (%)	100	100	0.5
Energy spread (keV)	40	5	18
Normalized emittance (μm)	10	0.7	2.4
Number of passes	1-15	-	1
End magnet field (T)	1.0	-	-

[a]At exit of injector accelerator.
[b]In 40 ns macropulse.

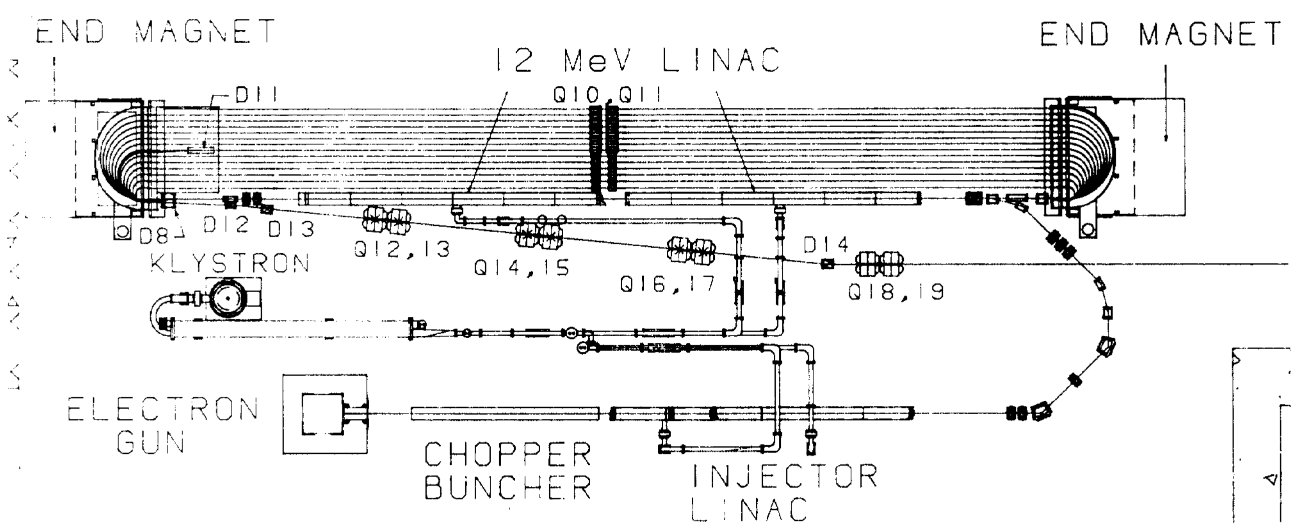

Fig. 6. Plan View of the NIST-Los Alamos RTM

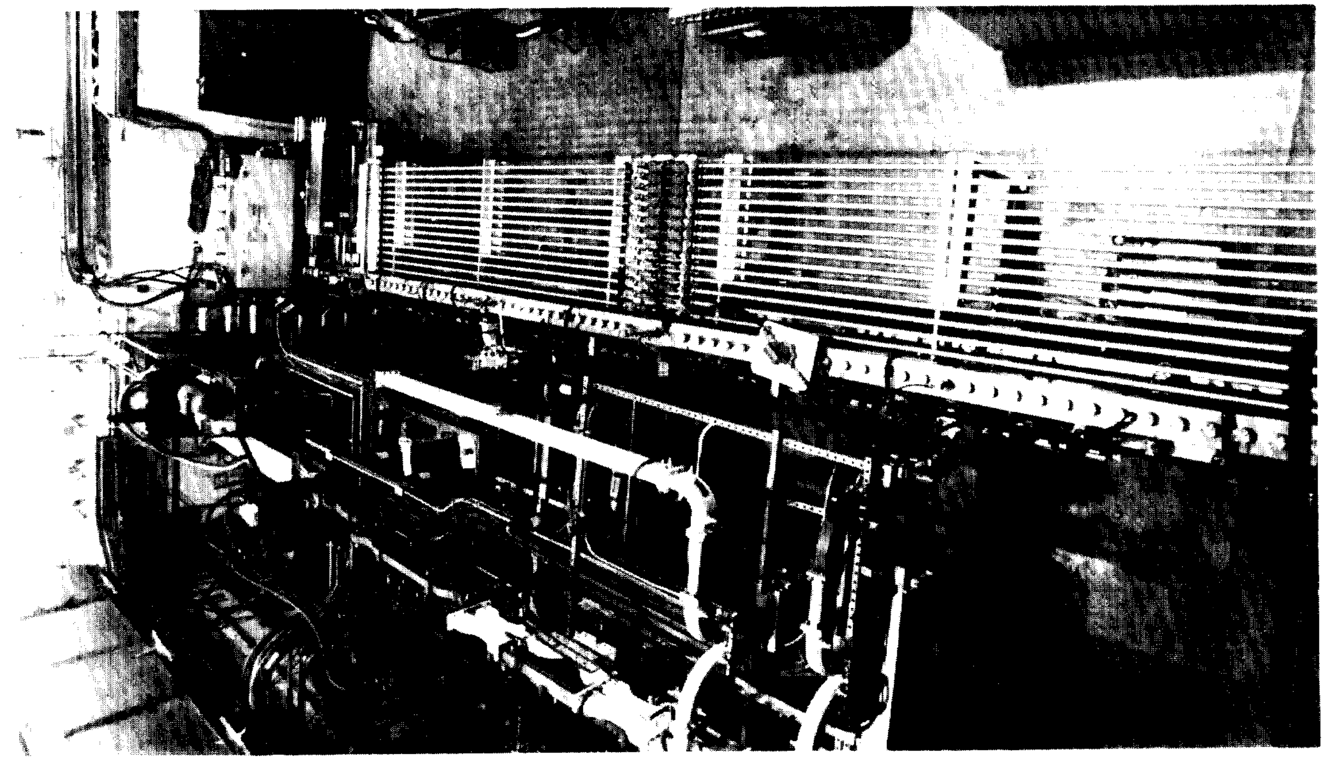

Fig. 7. Overhead View of NIST-Los Alamos RTM.

Acknowledgment

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