CONTINUOUS BEAM ELECTRON ACCELERATORS

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Abstract

After a short discussion on the currently used methods to achieve continuous electron beams a few projects of the currently persued ones are described in some detail, short status reports of others are given.

Introduction

After a generation of low duty cycle machines, allowing essentially single arm experiments in nuclear and medium energy physics only, an increasing demand for the possibility to perform coincidence experiments led to a large number of proposals for suitable machines. Starting in the late 1960's, an evolution began from which by now three general schemes evolved which have demonstrated successful operation: the stretcher ring, the recirculated superconducting (s.c.) linac and the race track microtron. In the following the general design philosophy of each of these schemes is given and a major project of each kind is presented in some detail as an example. Short status reports are given on the other projects currently pursued.

Stretcher Rings

General

Obviously, a stretcher ring is a quite natural upgrade of a given conventional pulsed accelerator to convert it into a c.w. electron source. The basic idea is to inject each beam pulse into a storage ring and to extract it from the ring smoothly during the time interval to the next pulse. Since some time is needed for injection and for the onset of extraction, the beam will not really be c.w., but appreciably close to. To fill the ring completely, the beam pulse duration has to be equal to the revolution time of the ring (single turn injection) or a not too large multiple of it (multiturn injection). Usually, multiturn injection is required to match the pulse length of the linac of a few microseconds to the stretcher circumference. This technique is well known from injection into synchrotrons except that it takes place at higher energy (which, in doubt, makes it easier). The usual extraction procedure is to provide some nonlinearity in the ring to obtain a finite bucket size and to slowly tune the ring towards an instability (usually 3rd integer), thus squeezing the beam slowly out of the shrinking bucket. The particles emerging from the neighbourhood of the unstable fixpoints at the corners of the triangular bucket are then peeled off by a septum (Fig. 1). To improve the energy spectrum of the extracted beam, the chromaticity of the ring may be used to preferably extract particles of a certain energy.

If the energy of the stored beam exceeds a few 100 MeV, r.f. accelerating cavities are necessary in the ring in order to compensate synchrotron radiation loss. If the operating frequency is chosen equal to the linac frequency (which is usually S-band) one may have problems with the beam aperture and in finding a suitable r.f. source for c.w. operation at the given frequency. If a subharmonic is chosen, one has to accept the disadvantage common to synchrotron injectors that only a fraction of the r.f. buckets in the linac can be used for acceleration. At the expense of duty factor the r.f. in the ring may also be used to ramp up the energy of the stored beam prior to extraction.

The further possibilties to use the ring with internal targets or as a synchrotron radiation source make it a really versatile device. A specific problem of stretchers, however, is to achieve a smooth time structure in the extracted beam.

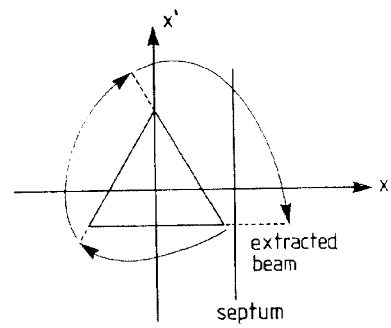

Fig. 1:
Phase space scheme of 3^{rd} integer extraction

ELSA of Bonn University

General: This stretcher ring was constructed to improve the duty factor of the Bonn 2.5 GeV synchrotron. Besides it may be used in "ramping mode" as a postaccelerator or as a synchrotron radiation source up to 3.5 GeV [1]. Its plan view is shown in Fig. 2. The lattice of the ring consists of sixteen separated function FODO cells containing a deflecting magnet in each drift space. Two straight sections are formed by omitting the magnets in two adjacent cells in which the dispersion function is made to zero by omitting one magnet in each of the four neighbouring cells. Thus a somewhat elliptical ring is formed by 24 identical 15 deg bending magnets with rectangular pole faces. Bending radius is chosen to 10.88 m. The circumference of the ring is 164.4 m, more than twice the circumference of the feeding synchrotron. Thus, to fill the ring completely, the beam has to be spilled out of the synchrotron over about 3 turns.

Operation Modes: Besides of the pure stretcher mode, in which a maximum beam current of 200 nA (limited by the synchrotron) can be extracted, ELSA may also be operated in ramping mode, of which Fig. 3 shows schematically some possible operation cycles. Since ramping generally takes several synchrotron cycles, the average beam intensity of the extracted beam is drastically reduced. One may, however, enhance the average intensity at further expense of the duty factor by injecting several synchrotron pulses prior to ramping. Tab. 1 gives some typical numbers [1].

R.F.System: Operation frequency is 500 MHz, same as in the feeding synchrotron. ELSA has two r.f. systems. For use in stretcher mode, a five cell DORIS cavity is used, driven by a 50 kW source. For use in ramping mode, two seven cell PETRA cavities are installed, driven by a common 250 kW source.

Status: ELSA has demonstrated first successful operation in 1987 and is currently in the commissioning phase [2].

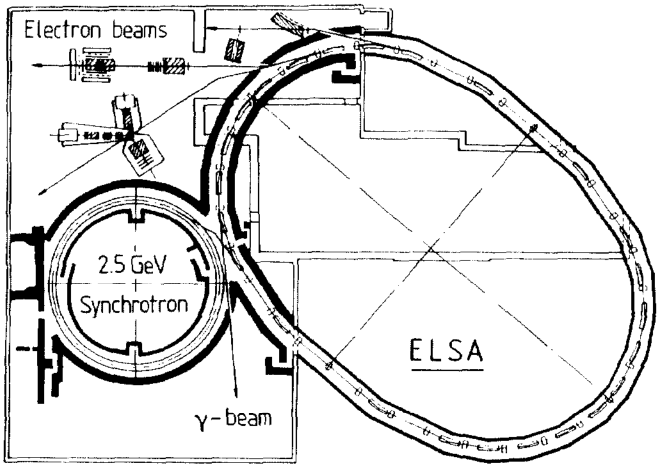

Fig. 2: Plan view of ELSA

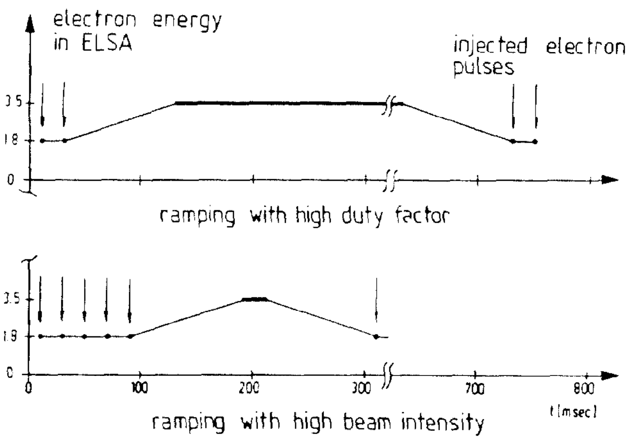

Fig. 3: Ramping schemes

	operation mode			no. of injected pulses
	stretcher	postaccelerator (ramping)		
duty factor	95%	60%	6%	
internal current	12 mA	12 mA	12 mA	1
		24 mA	24 mA	2
			60 mA	5
average external current	200 nA	5 nA	10 nA	1
		10 nA	20 nA	2
			50 nA	5

Tab. 1: Beam currents in different operation modes

Tohoko 150 MeV Stretcher Ring ("SSTR")

The 150 MeV pulse stretcher of Tohoku University was the first stretcher ring to be constructed. It was completed by the end of 1981 and is used since then for both machine studies and nuclear physics experiments. The ring contains 8 magnets forming a regular octogon of 15.5 m circumference. It uses the synchrotron radiation loss for extraction in that, by virtue of the chromaticity of the ring, a 3rd integer resonance is set at a fixed energy level, into which the electrons slowly sink down. An appreciably smooth spill out has been demonstrated. An extracted beam of 1 µA with an energy spread of 0.2% at a duty factor of 80% is achieved [3, 4].

MAX of Lund University

The MAX facility consists of a pulsed 100 MeV S-band micrc tron, followed by a ring which is used both as a synchrotron ligh source and as a stretcher. In light source mode a circulatin beam of routinely 200 mA is injected successively, being rebunche by the 500 MHz system of the ring and subsequently ramped t 550 MeV. As insertion devices an ondulator is operating, a 8 wiggler is under construction. There are three beam lines i operation, three under construction and two more projected. Th system became operative during 1986.

First stretcher operation was achieved in early 1987, sinc June 87 the extracted beam is used for nuclear physics experiments The beam energy is 60...95 MeV, its intensity 200 nA at a dut factor of 80...90%. Emittance is about 1 mm mrad, energy spreac 100 keV [5].

EROS, University of Saskatchevan

EROS is the earliest proposed stretcher ring which has finally come to realization [6]. After several modifications it consists in its final version of two long straight sections, connected by two bends of 4 magnets each with 1 m bending radius. Thus, the ring of 108 m circumference surrounds very closely the feeding 300 MeV linac (1µsec pulse length with 360 Hz p.r.f. max.) and energy compressing system.

The r.f. system consists of a 11 cell, 2856 MHz structure with a beam aperture of 4 cm. At 300 MeV, the circulating beam current is limited to about 250 mA by the fact that no sufficiently powerful c.w. klystron (10kW at 500 mA) is available at that frequency.

First extraction of the stored beam by a third integer resonance was reported for summer 1987 [7]. EROS is currently in the commissioning phase. So far, EROS was operated at 165 MeV without r.f. (similar to the Tohoku SSTR).

The NIKHEF "UPDATE"

Besides of an energy upgrade of the existing linac to 900 MeV (max.,unloaded), an energy compressing system and a stretcher ring of 215 m circumference with three turn injection will be installed. An extracted beam of at least 90% duty factor is expected with maximum intenstiy of 40 µA average in the range of 150 to 700 MeV (up to 900 MeV at lower current). For use with internal targets the option of a 200 mA stored beam is provided.

This project has recently been funded, beam commissioning is expected by early 1992, cost estimate is 12 M$ (assuming 1$ = 1.9 FL) [8].

The MIT Stretcher

A new pulse stretcher ring proposal has just been funded to convert the present recirculated pulsed linac into a 1 GeV c.w. facility. 16 magnets, originally from the Princeton-Penn accelerator with bending radius of 9.1 m form an essentially rectangular ring of 75*40 m in size with 190 m circumference. Thus, the 1.3 µsec, 40 mA beam pulse of the head to tail recirculated 500 MeV linac needs two turn injection. An energy compressing system is provided between linac and stretcher to stabilize the beam energy and improve its spectral width to ± 0.02%. The r.f. system operates at the linac frequency of 2856 MHz and consists of a single cavity with 4 cm beam aperture. There will be an internal target area using the 80 mA circulating beam optionally. Extraction is done by exciting a half integer resonance. Expected beam properties are: 300 to 1000 MeV, 50 µA, 85% duty factor, emittance of 0.01 π*mm*mrad, energy width of ±0.02% [9]. Construction time schedule is 4 years, price estimate 14 M$(1987) [10].

Tohoku 1 GeV Stretcher Ring, Sendai

A new proposal has been worked out for a 1 GeV stretcher ring [11,12]. It is now planned to upgrade the present 300 MeV linac to 500 MeV by adding two more klystrons and replacing the accelerator sections by new ones, and to double its energy by head-to-tail recirculating the 1 µsec beam pulse. After passing an energy compressing system the beam is injected by two turn injection into the race-track shaped ring of 165 m circumference, formed by 12 bending magnets.

In stretcher mode, at a repetition rate of 300 pps and a peak current of 100 mA an average extracted beam of 30 µA is expected with an energy spread of 0.1% at 90% duty factor. For this mode a 6 kW r.f. system at 2856 MHz is to be used.

For use as a synchrotron radiation source, the ring may be ramped up to 1.5 GeV. A separate 100 kW r.f.system at the 6th subharmonic will be installed for this mode.

Recirculated Superconducting Linacs

General

The use of s.c. linac structures was the first attempt pursued to achieve c.w. electron beams [13]. It became clear relatively soon, however, that the energy gradients safely achievable in s.c. structures would be smaller than those in a pulsed conventional linac, so it became important to cut the otherwise excessive length by multiple passage of the beam through one and the same linac. Obviously, this is possible with an electron beam because $v \approx c$ from a few MeV on, and it is much easier to do with a c.w. linac than with a pulsed one because the difficulties with transient beam loading are omitted. On the other hand, it turned out that counter-measures against "multipass beam blowup" are indispensible.

For a simplified, but essentially realistic, model of this instability consider a single cavity with a certain amplitude of a resonant deflecting mode in it [14]. A beam (unbunched for simplicity) passing through will undergo a periodic deflection, which, depending on the optics of the recirculation system, will result in a position oscillation at the next passage. Depending on the phase of the oscillation, energy transfer between mode and beam may take place. Further, the beam will undergo another deflection, the resulting beam movement being transferred by the next recirculation into the cavity again and so on over all passes. If under the condition of phase closure the net energy exchange over all passes results in an energy transfer into the mode larger than ohmic loss, an exponential growth of beam oscillation will occur. Without counter-measures, this occurs rather likely at threshold currents of a few µA, considerably lower than for the "classical" one-pass-blowup mechanisms.

Considerable amount of new insight has been gained during the past decade in the nature of the difficulties experienced with s.c. structures of the first generation and ways to avoid them have been found. Details on recent technology of s.c. structures are given in the paper of D. Proch [15].

Referring to the recirculating system, generally both isochronous and nonisochronous systems could be used. If, however, only a few linac passages are involved, it is reasonable to chose an isochronous system and to accelerate the (relativistically frozen) bunches on the crest of the wave.

CEBAF, Newport News: The "Continuous Electron Beam Facility" presently under construction will provide c.w. beams with energies up to 4 GeV and currents up to 200 µA. Originally, it was proposed as a combination of a normal conducting pulsed linac with head-to-tail recirculation and a strecher ring [16]. In 1985, however, it was felt that r.f. superconductivity had reached a maturity that would allow large-scale application, as demonstrated by research progress in Europe, the US and Japan [15,17].

The general layout of this machine is shown in Fig. 4 [17]. It consists roughly of two s.c. linacs of 0.5 GeV energy gain each, connected by recirculation systems which allow for up to 8 linac passages.

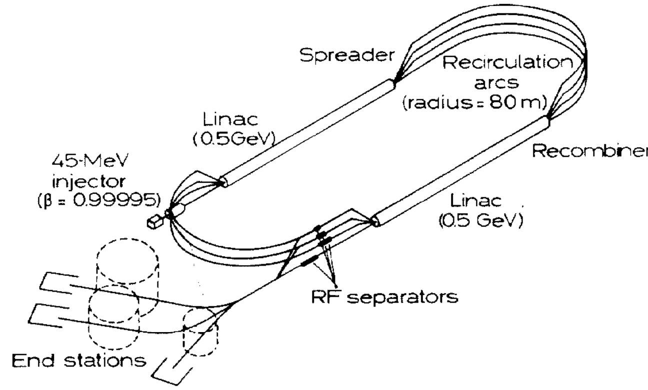

Fig. 4: General layout of CEBAF

For the linacs the Cornell cavity design [18] has been adopted. In this design each cavity consists of 5 cells in π-mode, operated at 1500 MHz. Four pairs of these cavities (see Fig. 5) are housed in one common cryostat. Thus each cryostat represents 4 m of electrical length. The accelerating gradient being chosen to 5 MeV/m, each linac will consist of 25 cryostats.

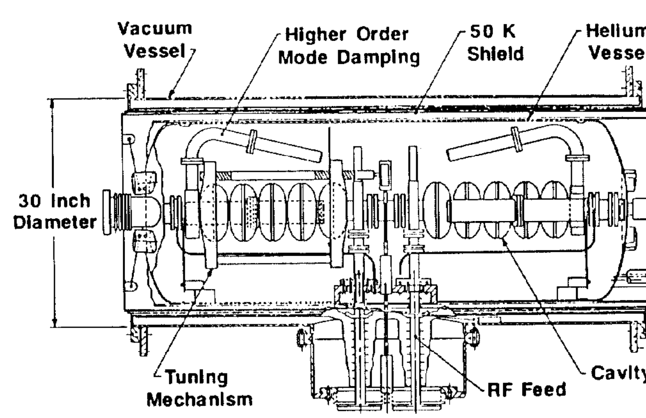

Fig. 5: CEBAF accelerating module

The operating temperature was chosen on the basis of cost optimisation to be 2.0 K. The total cooling power of the central refrigerator is 5 kW(2K), about half of which is due to r.f. load.

The isochronous recirculation arcs are separated vertically by means of vertically deflecting "spreader" and "recombiner" systems, each consisting of two pairs of oppositely excited magnets separated by a reversing quadrupole triplet. Thus a vertical beam shift is achieved in two steps with zero net dispersion. Generally, the recirculation system is only loosely packed with dipoles in order to have the opportunity to raise the beam energy in case future development of s.c. cavities would allow higher accelerating gradients.

HEPL-Recyclotron, Stanford University

This machine is the result of a project which began in the mid 1960's and which was the first, pioneering attempt towards c.w. electron accelerators [19]. In its present form it consists of a s.c. linac, operating at 1.8 K at 1.3 GHz, and a recirculating system . The linac operates c.w. up to an energy of about 40 MeV, from there on at decreasing duty cycle (e.g. about 10% at 70 MeV). Its maximum beam current is 500 μA. However, if used for FEL operation (which is its present destination) only one bucket in 110 is filled and the average current drops to 100 ... 200 μA, peak current being several Amperes. The energy may be doubled by the recirculating system. In this case, however, the beam intensity is limited to 100 μA by multipass beam blowup. Typical energy spread under all conditions is 20 keV. A program is under way to build a new high brightness injector that could allow charges of 1 nC/bunch at emittances of 10π*mm*mrad transversely and 200 π*keV*ps longitudinally [20].

MUSL, University of Illinois:

The "Microtron Using Superconducting Linac" also belongs to the early, pioneering c.w. machines. An upgraded version, "MUSL2", built in 1975 to 78, produced a c.w. beam with a maximum energy of 67 MeV. Its beam intensity, however, was severely limited by multipass beam blowup. After a major upgrade in 1986 the machine now performs as follows [21]: Due to new end magnets (identical to those used in the NBS machine), allowing a maximum of 9 recirculations , its maximum energy is enhanced to 100 MeV and by installation of a new linac, equipped with loading probes to suppress the blowup modes, the maximum beam current was increased to 10 μA c.w. at all energies. The machine is routinely operated for three major experimental areas: an electron scattering coincidence facility, a tagged photon facility and a bremsstrahlung irradiation facility.

The 130 MeV Recyclotron of TH Darmstadt

The superconducting recirculator presently under construction at "Technische Hochschule Darmstadt" is a machine of the new generation, based upon the initial work of H. Piel and coworkers at "Gesamthochschule Wuppertal" [22], then persued further by the Darmstadt staff. It is shown schematically in Fig. 6. The structure is operated at 3 GHz at a gradient of 5 MeV/m. The injector linac consists of a 5 cell capture section and two 20 cell standard sections (π-mode, thus 1m electrical length each). The main linac consists of four cryostat modules, containing two 20 cell structures each.

At present the injector is being operated routinely at an output energy of 8.5 MeV. One of the cryostats of the main linac, equipped with two 1m structures, has recently been set into operation successfully with injector beam [23].

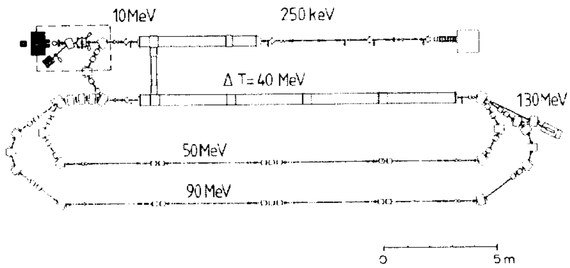

Fig. 6: Plan view of the Darmstadt Recyclotron

LISA at INFN, Frascati

In the frame of feasibility studies on a high energy facility [24] using s.c. structures the project LISA has recently been funded to gain experience with s.c. technology and recirculators. The linac of LISA will consist of four cavities with four cells of DESY-HERA design (500 MHz) each. It will be recirculated by an isochronous system. As an injector, for simplicity a 1 MeV normal conducting linac of MAMI design is to be used at a harmonic S-band frequency. At the design gradient of 5 MeV/m, output energy will be 49 MeV after recirculation. The recirculating system will allow for up to 73 MeV, in case the cavities would perform better than design. LISA will be used subsequently to drive a FEL in the infrared region. Therefore, besides of c.w. operation also pulsed operation will be possible providing a peak current of 6 A in the bunches [25].

Microtrons

General

The definition of the shunt impedance r of a linac structure may be written as

$$\Delta T^2 = r*L*P$$

where ΔT = energy gain, L = linac length and P = total r.f. power. Since in normal conducting (n.c.) structures r is of the order of 50 MΩ/m, a ΔT of the order of several 100 MeV requires such a large product L*P, that only pulsed operation is technically feasible. By recirculating the linac n times, however, the above equation becomes

$$T^2 = (n*\Delta T)^2 = r*L*P*n^2$$

Thus, recirculating a linac 30 times saves three orders of magnitude in L*P, making a n.c. structure a convenient and economic device of proven ruggedness and reliability also for c.w. operation [26]. Clearly, such a large number of recirculations requires a simple and economic recirculation scheme, as given by the race track microtron (RTM), shown in Fig. 7. This scheme is nonisochronous, implying that a resonance condition has to be fulfilled between energy gain per pass and magnetic flux density in the reversing magnets such that the path length has to increase from one linac passage to the next by an integer number ν of wavelength (1 or 2, in practice). This condition reads in case of hard-edge magnets and v = c

$$2.096\ \Delta T = \nu * \lambda * B$$

where ΔT in the energy gain in the linac in MeV, λ the r.f. wavelength in cm and B the flux density in the magnets in Tesla.

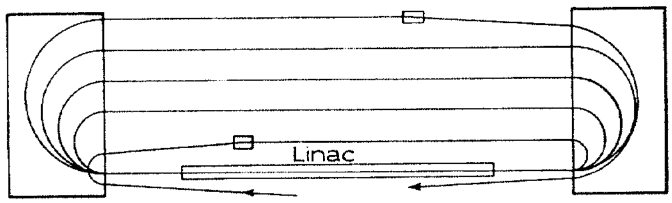

Fig. 7: Scheme of an RTM.

Acceleration occurs off the crest of the r.f. wave and the particles oscillate about a certain stable phase angle at which the energy gain is equal to its resonant value ΔT. The longitudinal bucket size is strongly dependent on this phase angle and is drastically reduced with increasing ν.

Multipass BBU is less dangerous in n.c. RTM's than in s.c. recycling machines because of the much lower Q value of the linac structure. It is, however, still of concern if many turns and/or high beam intensity are involved [14].

By a rule of thumb in any microtron the energy at the first magnet passage should not be essentially smaller than one tenth of the output energy [26]. Thus, a specific problem of normal conducting c.w. microtrons is to get a beam of sufficient energy for injection since, unlike with pulsed microtrons, the microtron linac itself can not be used as a preaccelerator because of its low field gradient.

The output energy of an RTM is limited to about 1 GeV because of emittance growth due to synchrotron radiation and because of rapidly increasing magnet weight. "Higher order microtrons" [27, 28, 29] have been proposed requiring less cumbersome magnets at the expense of more complicated beam optics. However, emittance growth, too, limits their energy to a few GeV anyway.

MAMI of Mainz University

General: In the "Mainz Microtron" the injection problem has been solved by cascading three RTM's, magnetic flux density (and, thus, resonant energy gain per turn and orbit circumference) being increased from stage to stage [26]. By these means, the range from a few MeV at injection to 855 MeV output energy is bridged in a beam dynamically safe and yet economic way. Tab. 3 gives the main parameters of this machine in its final version, Fig. 8 shows its plan view. As accelerating structure an on-axis coupled biperiodic structure [30] (modified Chalk River design) is used, operating at 2449.6 MHz. Total r.f. power required at 100 μA beam intensity is 275 kW, including the 3.5 MeV injector linac. Extraction at the last stage is done by slightly inward deflection of the beam on the appropriate return path (Fig. 7), thus shifting the beam off the linac axis by several cm into the extraction beam line. This can be done on every second path, so output energy is variable in steps of 15 MeV each.

Status: In a preliminary version ("MAMI A") [31], the two first stages of MAMI, using a van de Graaff at 2.1 MeV as an injector have been operated routinely for users experiments from spring 1983 through fall 1987. During this period about 19000 hours of usable beam have been delivered at a maximum energy of 187 MeV and at a maximum current of 70 μA (limited by some trivial control problems which will be eliminated in the final version). MAMI A ran very reliably and stably, occasional malfunction in most cases caused by the van de Graaff [32]. In fact, the 2.1 MeV input energy of RTM 1 turned out to be chosen somewhat low and was now raised to 3.5 MeV for the sake of less critical beam dynamics.

MAMI A is being dismantled now to be moved into the new accelerator hall. The new injector [33, 34, 35] has been completed and is currently in an advanced, so far successful commissioning phase. The reversing magnets of RTM 3 [36] are mounted in place and are currently being homogenized by means of pole face correcting coils to meet the required homogeniety of a few 10^{-4}. A 100 keV polarized electron source for optional use with MAMI is presently under construction [37]. First 855 MeV beam is expected for the second half of 1989.

		RTM1	RTM2	RTM3
Flux density	Tesla	0.10	0.56	1.28
Energy gain/turn	MeV	0.60	3.24	7.50
No. of Klystrons	TH 2075	1	2	5
r.f. power at 100 μA	kW	9	65	168
No. of turns		18	51	90
Magnet distance	m	1.7	5.6	12.8
Input energy	MeV	3.5	14	180
Output energy	MeV	14	180	855
Emittance at output:				
horizontal	mm*mrad	$\leq 0.17\pi$	$\leq 0.014\pi$	$\leq 0.14\pi$
vertical	mm*mrad	$\leq 0.17\pi$	$\leq 0.014\pi$	$\leq 0.04\pi$
Energy width	keV	18	36	≤ 120
Beam intensity	μA	>100	70	100
		(achieved)		(design)
Injection	100 keV gun and three linac sections, fed by another klystron			

Tab. 3: Main parameters of MAMI.

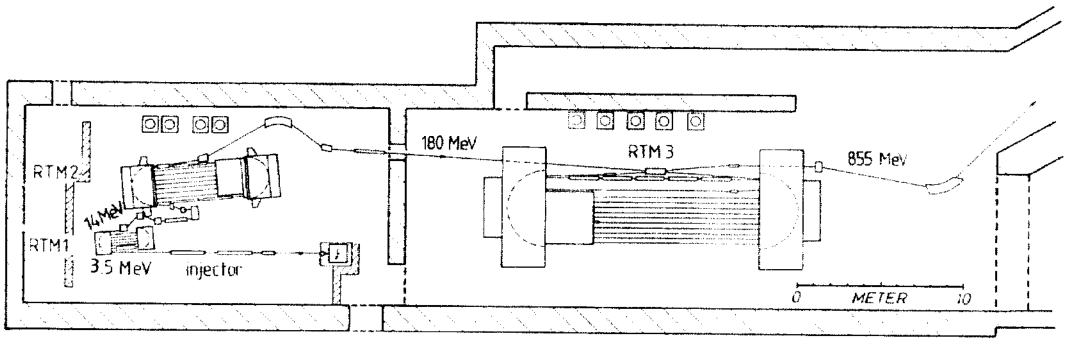

Fig. 8:
Plan view of MAMI.
First and second RTM stages (left hall) are essentially the ones used for "MAMI A".

The NBS-LANL-Microtron (Gaithersburg, Maryland)

This 185 MeV c.w. microtron design [38] solves the injection problem by using a more powerful injector linac (5 MeV) and a special beam reversing scheme after the first linac traversal by which the beam is reflected into the linac, being accelerateed once again in opposite direction (Fig. 9). So far, this scheme has been used successfully in pulsed microtrons [39] . Since the energy gain in the linac (side coupled structure at 2.38 GHz) is 12 MeV, the beam energy at the first regular magnet passage is 29 MeV. Because of the high field gradient of 1.5 MeV/m to be used, the high energy gain per turn and the high maximum beam current of 550 μA, the total r.f. power required comes close to 400 kW. Flux density in the end magnets being 1T, an increase of orbit circumference of 2 wavelengths per turn (ν=2) had to be accepted.

The machine is in an advanced state of construction. The 5 MeV injector has demonstrated successful operation exceeding design goals, first beam test of the main linac is expected in spring '88. Originally planned for machine studies and nuclear research, the machine has recently been dedicated to operate a FEL. A suitable gun to provide higher peak current is in preparation [40,41].

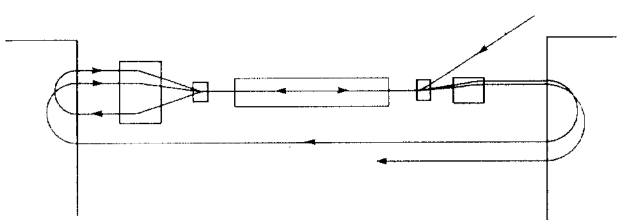

Fig. 9: Reflected-beam-injection.

University of Sao Paulo, Brazil

A 21 MeV, 100 μA c.w. microtron for nuclear physics research at the Physics Institute has partly been funded and construction has been started.

After preacceleration to 3 MeV by a linac the beam will be injected using the scheme of Fig. 7. The microtron is designed for 25 linac traversals at ν = 1. The flux density in the reversing magnets being chosen to 0.123 T, the resonant energy gain per turn will be approximately 0.72 MeV at 2450 MHz. The r.f. power required is 40 kW, of which 30 kW are used for the injector. One common 50 kW klystron TH 2075 will serve as a r.f. source.

Price estimate is 0.7 M$, first beam is expected for the middle of 1990. It is planned to add a second microtron stage with an output energy of 200 MeV later on [42].

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