THE MAINZ MICROTRON

OPERATION EXPERIENCE AND UPGRADE PROGRESS*)

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Abstract

The Mainz Microtron (MAMI) is a cascade of three normal conducting race track microtrons operated at 100% duty factor. The first two of it have been in operation in a preliminary setup ("MAMI A") from Feb. 1983 to Oct. 1987 at maximum energy of 187 MeV. Operating experience with this setup is communicated. The complete machine, designed for 855 MeV maximum energy, is presently under construction, first beam being expected for end of 1989. Its present status and some special observations are communicated.

Introduction

General

MAMI is the result of an attempt to realize a continuous beam electron accelerator using normal conducting structure in c.w. operation. Its design philosophy is immediately seen from the basic linac equation

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

where ΔT = energy gain, r = shunt impedance per unit length, L = linac length and P = total r.f. power. Since in normal conducting 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 beam n times, however, the above equation becomes

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

Thus, recirculating a beam 30 times saves three orders of magnitude in L*P, making a normal conducting structure a convenient and economic device of proven ruggedness and reliability also for c.w. operation [1]. 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. 1. 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 m of wavelengths (1 or 2, in practice). This condition reads in case of hard-edge magnets and v = c

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

where ΔT is 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.

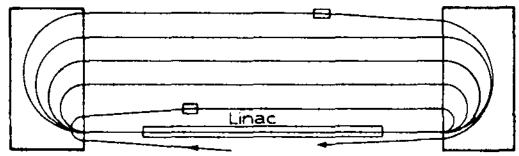

Fig. 1: Scheme of an RTM.

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 m.

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 [1]. Thus, a specific problem of normal conducting c.w. microtrons is to get a beam of sufficient energy at injection since, unlike with pulsed microtrons, the microtron linac itself cannot be used as a preaccelerator because of its low field gradient.

Layout of MAMI

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 [1]. 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. 1 gives the main parameters of this machine in its final version, Fig. 2 shows its plan view. As accelerating structure an on-axis coupled biperiodic structure [2] (modified Chalk River design, see Fig. 3)) is used, operating at 2449.6 MHz. As a countermeasure against beam blow-up (BBU) [3], in the second and third RTM the resonant frequencies of the higher order modes are multiply split by changing the orientation of the pairs of coupling slots in the accelerating cells with respect to each other along the structure (angle α in Fig. 3) [4, 5]. Because of the very high r.f. stability required, both r.f. amplitude and phase are stabilized at each klystron by feedback control from output to input. Thus the klystrons (TH 2075) have to be operated below saturation, reducing the maximum available power per klystron from 50 kW to about 40 kW. Total r.f. power required at 100 μA

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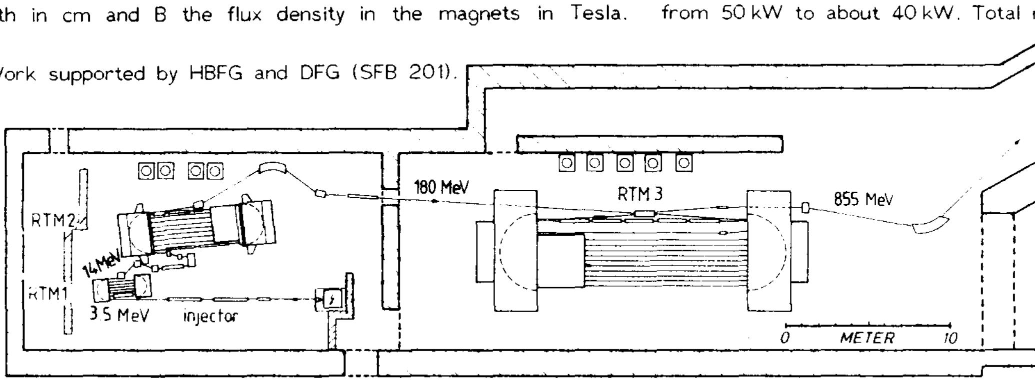


Fig. 2: Plan view of MAMI. First and second RTM stages (left hall) are essentially the ones used for "MAMI A".

klystron sockets

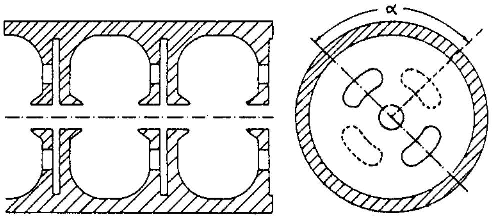


Fig. 3: The MAMI Structure

beam intensity is 275 kW, including the 3.5 MeV injector linac. Beam focusing and beam position monitoring is done on the linac axis only. For the latter, distinction between turns is achieved by short beam bursts or blackouts [1].

		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	$\leq$ 120
Beam intensity	μA	$>$100	70	100
			(achieved)	(design)
Injection	100 keV gun and three linac sections, fed by another klystron			
Extraction	from each even numbered return path of RTM3, i.e. in steps of 15 MeV each			

Tab. 1: Main parameters of MAMI.

Pre-History

First design considerations and experimental tests on basic components of MAMI started in 1974, resulting in a rather detailed proposal [1]. The first stage of MAMI, using a van de Graaff at 2,1 MeV as an injector was completed in one of the experimental halls of the original building of the institute in spring of 1979. Though the dedication of the machine was solely to serve for machine studies and as an injector for the second stage to follow, its 14 MeV, 100 μA beam was already used for several users experiments [6,7,8]. In Feb. 1983 the 2nd stage of MAMI was completed and "MAMI A", consisting of the van de Graaff and two microtron stages, was set into operation [9].

MAMI A

General

This machine, described in detail in [9], is shown schematically in Fig. 4. The 2.1 MeV electron bunches supplied by the van de Graaff preaccelerator are matched to the 14 MeV microtron by energy modulation in the first buncher section and flight time compression in the subsequent magnet system. After a phase shift of 38° during the first turns due to the relatively low injection energy, the bunches approach asymptotically the resonant value of -22°. The transverse motion is stabilized by two solenoid lenses on both ends of the accelerator axis. In order to match the beam to the 180 MeV microtron the bunch length is reduced by the second buncher and the longitudinal dispersion of the second interface system. As the longitudinal motion in the 180 MeV stage is more stable the synchronous phase was put to -16°, leading to smaller energy spread in the beam. Quadrupole duplets at each end of the accelerator axis serve here for transverse focusing. In both microtrons the decrease of focusing strength at growing energy is counteracted by pseudodamping in such a way that the beam diameter stays roughly constant during acceleration.

Since the r.f. power demand of the 2nd stage exceeds the maximum power of one klystron, the outputs of two klystrons were combined and redevided by means of a hybrid. By controlling the amplitudes of and the phase shift between the klystrons, each microtron could be supplied with its proper r.f. power.

Beam position and phase monitoring was done in the microtrons for each turn separately by means of r.f. cavities on the common linac axis [10]. Beam profile monitoring was done in the first microtron by means of a movable screen along one of the pole face edges, in the second by observing the synchrotron radiation in one of the magnets (Fig. 4). In the interfacing systems both beam position and profile could be measured by means of wire scanners (small circles in Fig. 4). All these signals could be analysed and used for beam transport and matching optimisation by computer [11, 12]. For beam extraction at fractional energy, in the second stage the beam could be bent slightly inwards on every second return path to leave the microtron a few cm off axis (as indicated for the last orbit in Fig. 4).

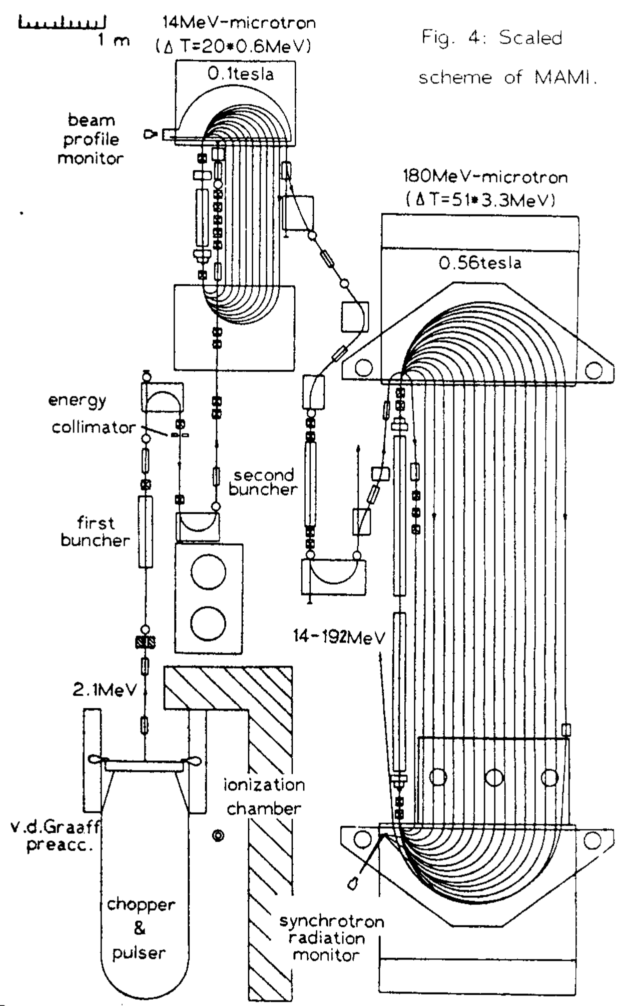


Fig. 4: Scaled scheme of MAMI.

Operating Experience

When the machine was first operated in Feb. 83, we observed at the synchrotron radiation monitor a strong distortion of the beam profile in the last orbits of the second stage, which obviously was caused by a quadrupole like field rotated by 45° with respect to the horizontal. We assigned this to a small azimutal alignment error in one of the quadrupole duplets on the linac axis and compensated it by a small rotation of one of the quadrupoles. This compensation worked very well. However, as pointed out below, the effect could have had another reason than assumed. By further improvement of the machine tuning during the following weeks, the beam diameter in the second microtron was reduced to the design value of about 2 mm for intensities up to 30 µA. At higher currents a slight increase of the phase space was produced by larger voltage fluctuations of the preaccelerator, and, eventually, by higher cathode heating. (Normally the cathode was only heated to get a maximum beam current of 30 µA in order to increase its lifetime.) Beam transmission through the machine was soon very close to 100 %.

The energy spread and energy stability of the beam were measured several times and with different electron spectrometers. The average value of about 30 keV FWHM was consistent with the design calculations, the mean energy was stable within ± 12 keV.

In general, the machine ran quite reliably and stably from the beginning over periods of typically several hours without operator action. Due to the high degree of computer control and computer aided analysis of the many monitor signals it was relatively easy to operate and trouble shooting was quick and easy in most cases [13].

MAMI A was operated from spring 83 through fall 87 by almost 19000 hours of usable beam, mostly for users experiments, the results of which are compiled in [14]. Most problems arose from the van de Graaff and the interface between van de Graaff and first RTM. So, more than 80 % of repair time were due to problems in connection with high voltage generation and faults of the electronic subsystems in the terminal. The stably achieveable beam current of MAMI A was limited to about 60 µA by the radiation sensitivity of the van de Graaff high voltage control circuit. Further, some difficulties arose from the r.f. distribution control between the RTMs which could become important at higher beam intensity. Since there was no strong demand by the users for beam currents in excess of 60 µA, no serious attempt was made to enhance the beam intensity in this preliminary setup. Occasionally, a low intensity halo was observed around the output beam, which, nevertheless, would be troublesome for experiments in which solid state detectors were used close to the target. It turned out that this halo was due to beam optical imperfections in the rather complicated, early designed interfacing system to the first RTM. Besides, the input energy of 2.1 MeV for the first RTM turned out to be somewhat too low, leading to uncomfortably small beam acceptance.

The Final Setup

General

To house the final setup of MAMI, new buildings had been constructed adjoining the original experimental halls. These buildings have been finished by late 1986. Construction of another large experimental hall will be started by early 1989. MAMI A was shut down by Oct. 1987 and RTMs 1 and 2 have been dismantled to be moved into the new accelerator hall (Fig. 2). For the reasons mentioned above, for the new setup the injection energy of RTM1 has been raised to 3.5 MeV and the interface system drastically simplified. Further, the r.f. system was simplified by adding a separate klystron for RTM1 (see Tab. 1).

The New Injector

For the reasons mentioned above and in order to allow the use of a polarized electron source [15] the van de Graaff was replaced by a 3.5 MeV linac injector. Its 100 keV electron source consists of a 12 keV triode gun, the anode of which acts as an emittance filter, followed by a 88 keV post accelerator gap [16]. To feed the linac the DC gun beam has to be chopped into bunches of ± 20° or less [17]. To achieve this without increase of the transverse emittance, a system consisting of two circular deflecting r.f. cavities, a slitcollimator with adjustable slitwidth and a solenoid pair (Fig. 5) was build up [18]. The bunchlength can be set both by variation of the r.f. amplitude and the slitwidth.

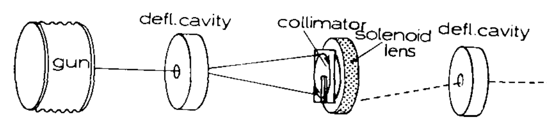


Fig. 5: Scheme of the chopper system.

The focal length of the solenoid lens (Fig. 5) is half the distance between the cavities and the slit. Hence the part of the beam, which passes through the slit is focused to the axis at the second cavity. If the second cavity has the same amplitude and phase (in the coordinate system of the bunch) as the first one, it cancels to first order the transverse momentum imparted to the beam (rigorous cancellation is not possible on principle [18]). So far, the chopper follows the NBS-LASL design philosophy [19]. The circular deflecting cavities, however, are of a novel design, using one single r.f. mode instead of two degenerate ones [18]. Thus, both the r.f. setup and operation of the chopper are considerably simplified. The linac itself was designed using the PARMELA code, a major constraint being the demand that the whole injector should be supplied by one klystron only [20, 21]. This led to a relatively long, low powered structure, derived from the ordinary MAMI - structure by increasing the shunt impedance somewhat at the expense of web thickness and beam orifice.

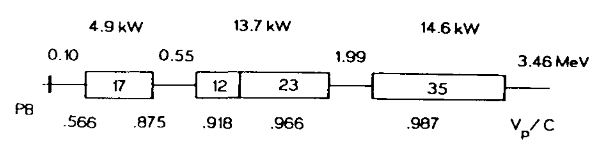


Fig. 6: Scheme of injector linac. PB = prebuncher. Numbers give r.f. power, beam energy, number of accelerating cells and phase velocity respectively.

The main data of the linac are given in Fig. 6. The phase velocity is raised from cell to cell in the first section and in three steps in the remainder. Focusing is achieved by a pair of solenoid lenses in front of each section. For more details see [17, 22]. To ensure the output beam of the injector linac to hit the inherently small longitudinal acceptance window of a microtron a high resolution device for measuring energy and longitudinal emittance of the linac beam is indispensible and, considering the many operating parameters at the linac, its display should follow the settings immediately. Such a device, with a resolution of < 0.5 deg and < 0.5 keV respectively, consisting of a deflecting magnet, an r.f. deflecting cavity and a TV display [23], was installed between injector and RTM1. When the injector was first operated in spring '88, it turned out that it was quite easy to operate and that the beam parameters, once optimized, were stable and - most important - reproducible from run to run within very narrow limits. The fast phase space analyser proved to be an extremely helpful device for optimizing the injector settings. Fig. 7 shows a photograph of its TV-display at 100 µA beam intensity. The phase space shown compares quite comfortably with the acceptance of roughly ± 10 keV and ± 5 deg respectively of the subsequent microtron.

Speaking of transverse optics, we found that our r.f. structure acts as a weak quadrupole, oriented as the coupling slots in the cavities, i.e. under 45 with respect to horizontal/vertical (Fig. 3). The above mentioned beam distortion at MAMI A was probably at least in part due to this phenomenon. It was definitively observed now in the injector linac because of absence of any other plausible source like a misaligned quadrupole duplet or so. The underlying field distortion is below the sensitivity of about 10^{-3} of our bead measurements during developement of the structure, but it is sufficient to cause a noticeable beam spot distortion on a screen about 3 m downstream the linac. We learned afterwards [24] that this phenomenon had been observed already earlier at Novosibirsk at such a structure operating at 430 MHz. In this structure the cavities were bolted together instead of being brazed, so it was possible to change the orientation of the coupling slots. It was found, that the effect practically disappeares if the slots on either end of an accelerating cell were oriented in parallel to each other ($\alpha = 0$ in Fig. 3) [25]. For MAMI this knowledge is useless since all structures are brazed already and, moreover, in the second and third stage different angles α are needed to split the higher order modes. It turned out, meanwhile, that the effect can be compensated in the injector linac by applying a weak skew quadrupole formed by air coils between first and second section and in the midst of the third section: at proper settings (which can be found easily) the projections of the normalized emittance on either horizontal or vertical plane (measured by variable lens and wire scanner) do not show any increase along the linac within reading errors. Yet it is felt, that one should not rely upon such empirical remedies. So we will turn the injector linac azimuthally by 45° so that the quadrupole axes are no more skew, and for RTM1 a section with parallel slot pairs is under construction from surplus cavities. Probably, we will turn the r.f. sections azimuthally in RTM2 and 3 too, though, after compensation as described, we did not have any inconvenience from the effect in MAMI A.

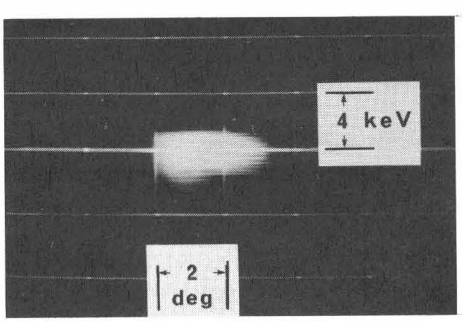


Fig. 7: TV display of the phase space analyser at 100 µA beam intensity.

The Magnets of RTM3

Three dimensional computations by the PROFI-code and measurements at a small model magnet had shown that the flux density of 1.54 Tesla of the original design [1] would result in too bad field homogeneity. Thus a new design with 1.284 Tesla was made, corresponding to an energy gain of 7.5 MeV per turn. These magnets, 450 tons each, have been mounted in place and field mapped meanwhile. Fig. 8 shows a midplane cut through a magnet, showing pole face and return yokes of the main magnet, the reverse field magnet to cancel vertical defocusing and the field clamp. Including the space required for the coils the yoke has to span a distance of 5.7 m. Thus, inevitably the pole pieces will be moved noticably by the magnetic force. Great care was taken, therefore, to make the yokes under given space and weight limitations as stiff as possible and to link the different parts in such a manner that the movement is kept strictly reproducible, i.e. avoiding possible stick-slip action at the parts.

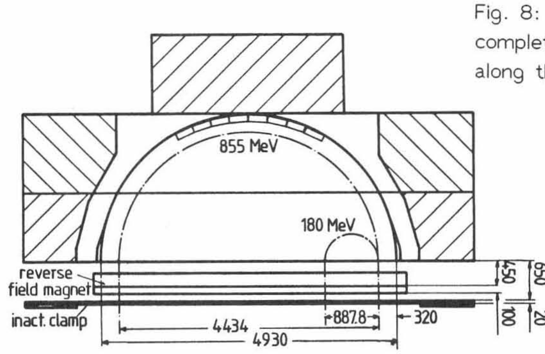
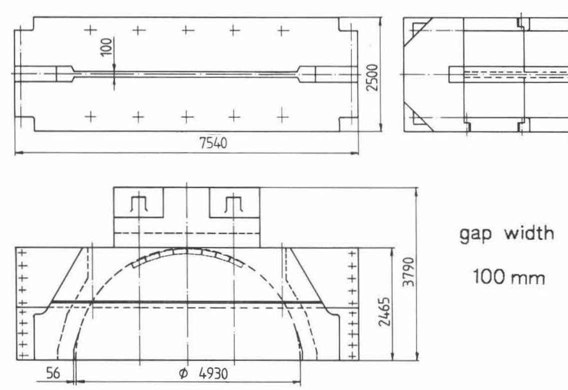


Fig. 8: Cut of the complete magnet along the midplane.

For these reasons the poles were realized as integral parts of the yokes. Since the weight of individual parts is limited to 80 tons by the crane in the accelerator hall, each pole had to be formed by two yoke bars. Therefore, a cut through the pole faces parallel to the front edge had to be accepted. Fig. 9 shows the resulting construction of the main magnet. It is supported by three hydraulically adjustable supports, one under the rear yoke and two under the opposite ends of the lower front yoke. Thus, the lower middle yoke is engaged between these two parts by steps. The upper front yoke is hooked by a corresponding step on the upper middle yoke. This assembly is sustained by the lower yoke assembly by means of spacers at the opposite ends and a spacer of unmagnetic stainless steel along the rear part of the pole face circumference. These assemblies are fixed by fitting bolts and bolted together by hydraulically biased screw bolts. All iron pieces are insulated by 25 micron Kapton foils against each other to prevent flow of possibly irreproducible eddy currents.



gap width

100 mm

Fig. 9: Construction of the main magnet (reverse field magnet and clamp omitted).

The need of weight limitation led to a relatively complicated outer shape of the pieces which would have been rather expensive to manufacture of forged steel. So all pieces were made of cast low carbon steel ("ZSH extra"), cast and machined by Thyssen A.G.

Measurements of the field distribution showed excellent reproducibility. For one of these magnets Fig. 10 shows a map of the difference between the measured flux density and the desired reference value. The field gradient of about 0.4 % over the pole face has to be reduced by at least a factor of ten for proper beam optics [26]. As was proven practice with MAMI A already [9], this will be achieved by surface correcting coils. However, due to the expectedly higher current densities required, it will no more be possible to simply use etched printed circuit board, but the coil windings are being manufactured from sheet aluminium, fixed by a special epoxy on a substrate of glass fiber and perforated sheet aluminium. A test with this technology worked out very satisfactorily [27]. At present the first of the total of four 12 m^2 correcting coils has been manufactured, the second one is under construction.

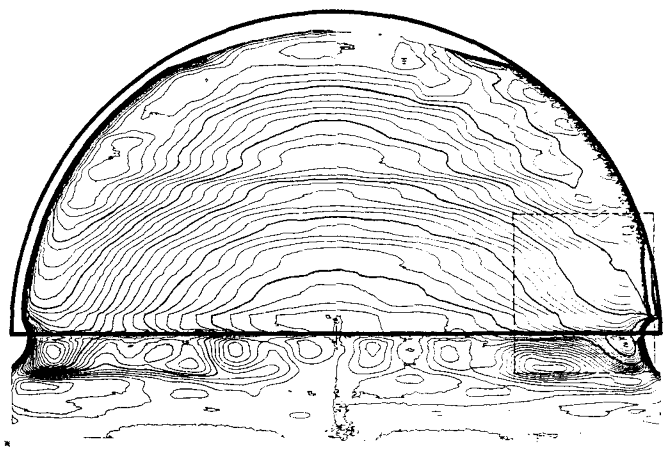


Fig. 10: Field map of the whole magnet at 1.284 T in steps of 2 Gauss each, reference fringe field being substracted.

Status of other Components (Oct. 88)

The two computers HP1000 for MAMI A [28] have been replaced by one µVax II (operating system VMS), keeping essentielly the structure of the control-software (the way of process-communication, the databank-handling and the distribution of the tasks between the processes). Also the main part of the well proven peripherie has been adapted to the new computer (CAMAC, at the desk touch panels and knobs). Up to now only a few functions are performed by intelligent microprocessor-subsystems (water- and r.f. supervision). Aside from the essential control-software for the new injector several new software components have been installed on the µVax, for example automatic emittance measurements, automatic beam-handling, a BASIC-like interpreter as operator interface for more complex tasks, and data-processing for the manufacturing of the correcting coils. The new control software seems to be as reliable as the old one and we had no serious problems in operating the injector.

RTM1 and RTM2 are presently being reconstructed (with some minor modifications) in the new hall. The magnets of the interface between RTM2 and RTM3 and the linac sections, beam monitors, most of the vacuum chambers and the 4 * 90 steerers for RTM3 are tested and ready to be put in place. The RTM3 klystron sockets are in an advanced state of construction. The klystron power supply for RTM2 and RTM3 is installed and presently under commissioning.

We hope to have the first 855 MeV beam by end of 1989.

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