COMMISSIONING AND OPERATION OF THE 1.5 GeV HARMONIC DOUBLE SIDED MICROTRON AT MAINZ UNIVERSITY[#]

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Abstract

In December 2006 the 4th stage of the Mainz Microtron MAMI was successfully set into operation, accelerating the 855MeV beam of the existing three racetrack microtron cascade (MAMI B) to 1508MeV. This new recirculating cw electron accelerator is realised as a worldwide unique Harmonic Double Sided Microtron (HDSM). Since February 2006, after only 14 days of commissioning with beam, the HDSM serves as part of the MAMI C accelerator cascade in routine 24h a day operation for nuclear physics experiments. We give a brief overview of the design and construction of the HDSM and describe the experiences gained during commissioning and the first 18 months of operation.

INTRODUCTION

Already in the 1970´s the Institut für Kernphysik (IKPH) was one of the protagonists in the course of developing cw electron accelerators. The chosen machine type was the racetrack microtron (RTM, [1]) with a normal conducting linac. This scheme makes efficient use of rf-power and its inherent strong phase focussing guarantees excellent beam quality and stability. The three-RTM cascade MAMI B [2] delivered since 1990 a low emittance beam up to 883MeV and 100µA for nuclear and particle physics as well as for proof of principle X-ray generation experiments [4]. The annual operation time is on average well above 6000h. In the meantime more than 60% of the beam time is with polarised electrons up to 85% polarisation and 40µA current.

In the late 1990´s within the framework of a new Collaborative Research Centre (CRC443) the physics case for an energy upgrade of MAMI to 1.5GeV was defined. Main boundary conditions were, that existing experimental halls must be used for installation and that the excellent beam quality and operational stability are maintained. To make best use of the Institutes expertise in accelerator technology, it was decided to build the new stage as a Harmonic Double Sided Microtron (HDSM) with moderate gradient (~1MeV/m) normal conducting linacs. A fourth RTM stage was not possible to realise. The magnet weight scales with the max. output energy ~E^3 (for const. magnetic field), therefore its 180°-bending magnets would have weighed 2200t each. A superconducting recirculator would have been distinctly more expensive compared to the 12.5Mio EUR investment costs for the HDSM.

HDSM DESIGN

A detailed description of the HDSM principle and design can be found in [3]. Here only some main features are repeated. The setup realized at IKPH is shown in Fig. 1 and its main parameters are given in Table 1.

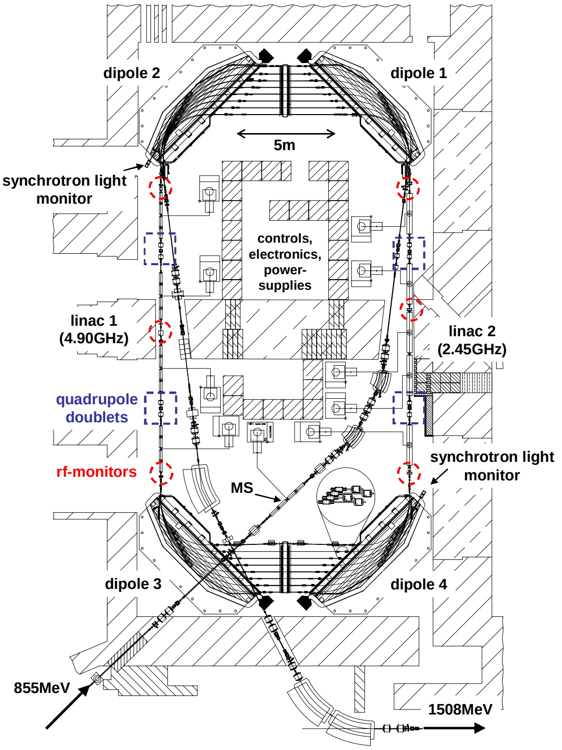

Fig. 1: Layout of the HDSM (linac sections in doubled width / only every 6th recirculation path is plotted).

Taking into account, that in a DSM the minimum phase advance per turn for coherent acceleration is 2×2π, the synchronous energy gain per turn as a function of magnetic field B and rf-wavelength λ reads (for homogeneous bending dipoles):

$$\Delta E = \frac{ecB}{2(\pi - 2)} \cdot 2\lambda$$

(e: elementary charge; c: speed of light)

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For B=1.5T and λ=0.1224m (the MAMI B rf-wavelength) one calculates ΔE=48.2MeV. With the available space for the linac installation one would have needed the huge amount of 1.7MW rf-power to feed 2×5 linac sections. This exceeds the MAMI standard for the dissipated rf-power per linac length by more than a factor of 6. To reduce this power consumption and to avoid severe cooling problems, we designed the DSM for a basic frequency of 4.90GHz, twice the MAMI B frequency. This leads to one halve of the necessary synchronous energy gain and to only one fourth of the power requirement.

The strong vertical defocussing due to the 45°-pole face rotation at beam entrance and exit of each dipole is compensated by an appropriate field decay perpendicular to the pole face (Fig. 2). With this field configuration, the 180°-bending systems act as simple drift spaces. In the vertical direction the drift length is ca. constant at 12.5m, whereas in the horizontal plane it drops from +1.5m to -13.5m with increasing energy. Thus transverse focussing can be obtained by only two pairs of quadrupole doublets on each linac straight, balancing the optical lengths between their primary planes as far as possible [5]. This avoids placing any focussing elements in the dispersive regions.

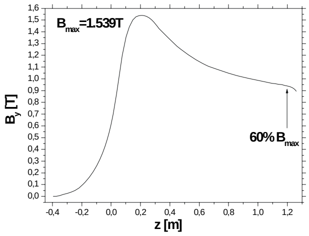

Fig. 2: DSM Field gradient. perpendicular to pole face.

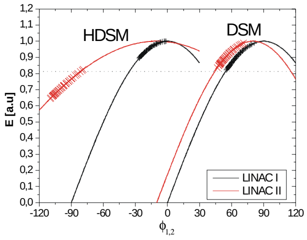

Fig. 3: Development of synchronous phases.

However, as a consequence of the field decay the synchronous energy gain per turn decreases with increasing turn number. This is, due to the strong longitudinal focussing, automatically realised by a smooth phase slip down on the accelerating waves (Fig. 3, DSM), a proper set of injection energy and linac phases given. During this phase slip the longitudinal Q-value crosses several resonances and for the last turns approaches the ½-resonance, thus reaching the boundary of longitudinal stability. In case of a small asymmetry (e.g. a phase deviation of only 2° between the two linacs), from ca. turn 30 on longitudinal stability gets lost and phase space distortions occur. This is due to the strong longitudinal focussing on the steep 4.90GHz rf-waves. Therefore we searched for a design with higher inherent stability.

If the geometry of the DSM is chosen such, that the first full turn with respect to linac 1 is equal to an uneven number of rf-wavelengths, in linac 2 only every second bucket is populated by the recirculated bunches [3]. This allows to operate this linac at the standard MAMI B frequency of 2.45GHz. By an appropriate setting of the two linac amplitudes and phases one can arrange, that most of the necessary reduction of energy gain takes place in linac 2 with its less steep gradient (Fig. 3, HDSM).

Table 1: Main parameters of HDSM and for comparison of RTM3, the last stage of MAMI B.

		RTM 3	**HDSM**
General			
$E_{Inj.}$	MeV	180.2	855.3
$E_{Extr.}$	MeV	855.3	1508.4
turns	#	90	43
power consumption	kW	650	1400
RF system			**Linac 1 | Linac 2**
linac amplitude	MV	7.80	9.05 | 9.30
energy gain / turn	MeV	7.50	16.7 – 14.0
frequency	GHz	2.4495	4.8990 | 2.4495
sections/klystrons	#	5/5	8/4 $^{(*)}$ | 5/5
electrical linac length	m	5×1.77	8×1.07 | 5×2.02
shunt-impedance	MΩ/m	72	80 | 72
dissipated power	kW/m	10.8	14.0 | 11.8
beam load@100µA	kW	67.5	37.0 | 28.4
Magnet system			
min. / max. field	T	1.2842	0.939 – 1.539
min. / max. gap	mm	100	85 – 140
min. / max. radius	m	0.47 – 2.22	2.23 – 4.60
weight	t	2×450	4×250
Beam parameters			
Energy width	keV	13	110$^{(**)}$
hor. emittance	nm rad	8	9$^{(**)}$
vert. emittance	nm rad	0.5	0.4$^{(**)}$

$^{(*)}$ A fifth unit is placed in the injection beam line for longitudinal matching purposes (MS). $^{(**)}$ Calculated with SYTRACE.

This avoids the over focussing and therefore the instability in the last turns, even in the case of phase deviations between the two linacs of 5° (related to 4.90GHz). This rf-scheme gave rise to the name Harmonic Double Sided Microtron. Tracking calculations taking into account the effects of stochastic emission of synchrotron radiation showed, that the normalised longitudinal and horizontal emittances grow only moderate [5]. In fact the absolute transverse emittance stays nearly constant during acceleration, and with beta functions well below 20m the beam size is in the order of some tenths of a millimetre.

CONSTRUCTION

The most important milestones of the HDSM-construction after approval of the project in 1999 and start of the purchasing phase are given here in short form:

General: Adaptation of two existing neighbouring experimental halls to the accelerator setup (e.g. cutting openings for the linacs in the 3m concrete walls between them). Installation of a new cooling system and a 2MVA transformer station till 2002.

180°-bending systems: Magnetic and mechanical design of the four 90°-dipoles at IKPH ([6], [7]). 2000 – 2002 fabrication of the magnets (each consisting symmetrically of only one upper and lower piece), delivery and alignment at their final positions. Careful field mapping of them for symmetrical and anti-symmetrical field components. The latter turned out to be negligible. Manufacturing of an individual symmetric pair of surface correction coils for each magnet ([8], [9]). Based on tracking calculations with the measured fields design and precise positioning of the spacer bars in the huge (7m×2m) vacuum chambers. From March till September 2006 final installation of the two 43-pipe recirculation vacuum “harps” together with the individual horizontal and vertical corrector magnets pairs on each pipe (total number 2×4×43).

2.45GHz linac: Largely a copy of the well proven linac of RTM3 (Table 1), therefore the first main component ready for operation in August 2005 [10]. Problems in manufacturing the five accelerating sections overcome by a change of manufacturer. Amplitude/phase regulation and the interlock systems redesigned in modern technology.

4.90GHz linac: At start of the HDSM-project no high power source and waveguide components for ~50kW cw available. Severe delay in klystron development (27 instead of 12 months projected), therefore delayed power test of the 4.90GHz prototype section (fully developed and built at IKPH) and other components (circulators, couplers, loads) till end of 2003. Then smooth industrial manufacturing and series tests at IKPH. Consequently 4.90GHz linac as last system ready for operation in December 2006. Details on design and manufacturing of both types of accelerating sections in [11].

BEAM DIAGNOSTICS

A reliable and adequate beam diagnostic is essential for a smooth machine commissioning and later on for stable operation, fast beam tuning and analysis of beam dynamic properties. The general arrangement of the beam monitors in the HDSM is shown in Fig. 1. Position, phase and intensity of the beam can be detected at both ends and in the middle of the linacs. Low-Q (~90) rf-monitors in TM_{010}- and TM_{110}-Mode [12] are excited by short beam pulses (diagnostic pulse mode: 12ns pulses with 100μA peak current and 1Hz - 10kHz rep. rate, i.e. max. average beam current 12nA) to identify individual turns by time of flight. By a multiplexing system the signals are digitised for automatic beam steering and also displayed on oscilloscopes ([13], [14]). Similar non destructive but high-Q rf-monitors are abundantly installed in the injection and extraction beam lines for permanent control of the cw beam position and phase. Synchrotron radiation monitors at dipole 2 and 4 allow to see the whole fan of 43 recirculations simultaneously, which is a powerful tool for transversal beam matching. By a zoom lens higher magnification of individual turns for beam size measurements is possible. As a very simple and reliable monitor, especially during the commissioning phase, when electronic beam monitors typically suffer from timing problems, we used a bunch of luminescent view-screens (LUMO). They consist of a thin Al-plate, covered with ZnS, which is mounted on a see-saw like arrangement with a small iron yoke as counterpart inside the vacuum. By a small external magnetic field the screen is flipped into the beam (of course only at low beam currents in the order of nA) and viewed with a low cost CCD camera. These monitors are very inexpensive and compact. In the injection and extraction beam lines a total number of 20 was installed. Also on the linac axes, in the middle of the quadrupole doublets, we use this kind of monitor. There the screens have holes of 3mm (linac 1) and 5mm (linac 2) (adapted to the resp. linac aperture), which allows to flip the screen into the beam without disturbing it. The desired turn can be observed by displacing the beam with the correctors on the associated upstream dispersion line.

COMMISSIONING

Commissioning of the HDSM with beam followed the sequence of final installation work. Four meaningful milestones were defined: initiation of the injection beam line with a first 90°-deflection through dipole 1 (Fig. 1), establishing a first full turn, acceleration through all 43 turns to the end energy, and finally guiding a high power cw-beam to the experimental areas. The first three steps were performed in low power diagnostic pulse mode or with cw-currents less than 10nA. Prior to each step a detailed checking procedure for all components involved was done: their correct description in the data base representing the machine status, their allocation by the control system, and their functioning (e.g. polarity and pre-calculated current values of magnetic elements). Because the control of the HDSM is an extension of the existing reliable control system of MAMI [14], right from beginning all routines for efficient operation were available. Other prerequisites were naturally a carefully checked hardware interlock system and the proved functioning of the radiation protection safety system.

End of September 2006 within 2h the 855MeV beam of MAMI B was guided through the injection beam line and HDSM dipole 1 to a luminescent screen just in front of dipole 2. Proper focussing was achieved with quadrupole settings within a few percent to the design values, and the excitation of all correctors was well below 1mrad. The beam enters the HDSM hall via a 2.8m long 40mm diameter bore through dipole 3 (Fig. 1), 40cm above the accelerator plane. As expected by field measurements, no deterioration of the beam spot was observed when fully scanning this aperture.

End of November 2006 both linacs were installed and the HDSM was vacuum pumped. However, due to problems with the klystron high voltage power supplies, the 4.90GHz linac was still not internally phased and both linacs not operational. Therefore a first full turn without acceleration was scheduled. Because the beam thus enters dipole 3 and 4 with 9MeV too low energy (no acceleration in linac 1), the fields of these dipoles had to be reduced by 9MeV/(855+9)MeV=1.04% from their 1.539T standard value. Greatly assisted by the LUMOS on the two linac axes and in the first dispersive recirculation paths this full turn recirculation was easily achieved. It allowed to commission the low-Q position, phase and intensity rf-monitors in both linacs. From now on their signals were available on oscilloscopes in the control room and digitised for automatic beam steering.

On 19th of December the HDSM was ready for full operation. For both linacs and the 4.90GHz module in the injection line the internal phasing had been done by network analyzer measurements. The linac design amplitudes were set by input power, using the shunt impedances of their sections known by low power rf-measurements. After again a full turn was established, the crest phases of all three rf-systems were determined within a few degrees via the transverse beam position on LUMOS respectively downstream at high dispersion locations (MS: first recirculation path between dipole 1&2 / 4.90GHz linac: first recirculation path between dipole 3&4 / 2.45GHz linac: second recirculation path between dipole 1&2). Then by calibrated phase shifters in the reference lines of each rf-system the design start phases could be set.

Now by using the pairs of horizontal and vertical correctors on each successive recirculation path, the beam intensity and position rf-monitor signals from the subsequent linac were optimised. This was done “by hand”, turn after turn. Because, as expected, the appropriate corrector strengths varied only slowly, as a good starting point to reach the next turn the previous setting could be used. Every 5 to 10 turns the linac phases and amplitudes were slightly adjusted for a smooth phase advance in both linacs. So within altogether 9 hours of operation the beam could be accelerated through all 43 turns to the end energy of 1.508GeV. Because the installation work of the extraction path was still not finished, the beam was stopped at a collimator at the entrance of linac 1. The optimisation of transverse matching was easily achieved by observing the fan of 43 synchrotron radiation spots from dipole 2. By adjusting appropriate quadrupoles in the injection beam line the beta-beat could be drastically reduced (Fig. 4), increasing the overall transmission to better than 99%. Right from the beginning the HDSM behaved very good natured. There exists a rather broad range of linac amplitudes and starting phase combinations for smooth phase advance per turn. A once defined setting allows stable operation for many hours.

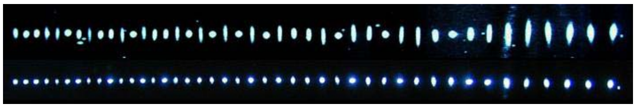

Fig. 4: Synchrotron radiation fan with 43 beam spots from dipole 2. Upper row: before matching / Lower row: after optimisation of matching

After the annual Christmas shutdown a fully automated control system routine for transverse beam optimisation was available [13]. In February 2007, after completion of the extraction beam line, the beam was guided to the high power dump in the spectrometer hall. Therefore the beam loss monitor system, consisting of 10 flat ionisation chambers (8litre volume, 58cm×28cm×5cm) was set into operation. This system is a copy of the one installed at MAMI B and switches off the beam within ms when appropriate set levels are exceeded. It is able to detect beam transmission losses in the 10^{-6} region at several 10µA cw current. Besides machine protection this system is a valuable tool for beam optimisation, because it was always a reliable indicator for a good overall beam quality. First tests with cw currents of several µA showed, that there were still beam losses in the high 10^{-4} level. Further careful optimisation of transverse matching and longitudinal beam dynamics did not improve this situation significantly. However, from the excitation pattern of the horizontal correctors between dipole 1&2 it was possible to deduce, that the beam was perturbed by stray fields from the injection magnet very close to the end of linac 2 and the corresponding extraction magnet near the entrance of linac 1. These magnets are rather compact and excited to field levels of 0.8 and 1.3T. By applying some magnetic shielding on the beam tubes near them and by appropriate excitation of horizontal and vertical correctors at both ends of the linacs the beam losses were reduced by one order of magnitude. Moreover the excitation strength of the recirculation path correctors could be reduced by up to a factor of 10 to below ±0.5mrad (Fig. 5). During commissioning also a few misalignments of components were cured, having reduced the free aperture e.g. at the entrance of linac 1 down to $3\times3\text{mm}^2$.

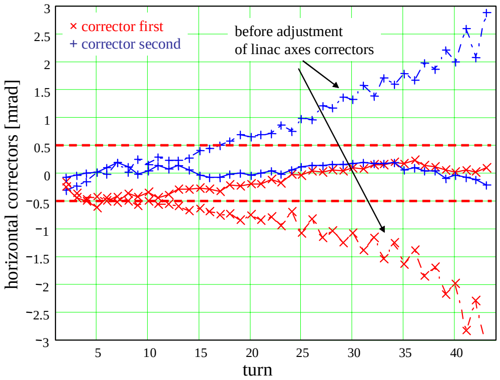

Fig. 5: Horizontal corrector strengths between dipole 1&2 before and after optimisation of linac correctors and stray field shielding of injection and extraction dipoles.

The first user run was performed beginning on 23rd of Februar 2007 for the A1-collaboration in the three spectrometer hall [15], delivering a polarised beam of 10µA for 10 days of continuous operation. We already achieved 80% beam on target for data taking. Over night and on weekend the machine was, as familiar from MAMI B, operated by student operators with only one accelerator expert on-call duty. The successful completion of this beam time marked the end of the commissioning phase.

OPERATION AND BEAM MEASUREMENTS

In the following weeks the other two experimental halls (Tagged-Photon-Beam facility of the A2-collaboration and the Parity Violation Scattering Experiment of the A4-collaboration) were commissioned with beam. End of 2007 we had a record of 7180h of MAMI beam time with already 3300h HDSM operation. After a maintenance shutdown the four-staged microtron cascade MAMI C is normally set into operation within three hours. During start-up and beam tuning the operator is supported very effectively by interactive routines and automatic optimisation routines ([13], [14]). Periods of 24h of undisturbed operation without any operator intervention are common practice after accelerator halls and machine reached thermal equilibrium (cooling water stability ±0.05°C, room temperature stability ±0.4°C).

By a moveable extraction magnet in front of dipole 2 beam extraction from turn 2 – 29 between 872MeV and 1308MeV is possible. This feature was used for calibration measurements at the Tagged-Photon facility. During two days of beam tests, in connection with measurements done to obtain the final HDSM operating license from the radiation protection authority, we ran with beam currents between 60μA and the max. design current of 100μA. The very low radiation background in the HDSM halls indicated that beam losses are well below 10^{-5}. After one year of operation the base pressure of the HDSM is in the order of 10^{-8}mbar. It increases by synchrotron radiation induced gas desorption by ca. $2\cdot10^{-9}$mbar/μA, in good agreement with calculations done during the layout of the vacuum system.

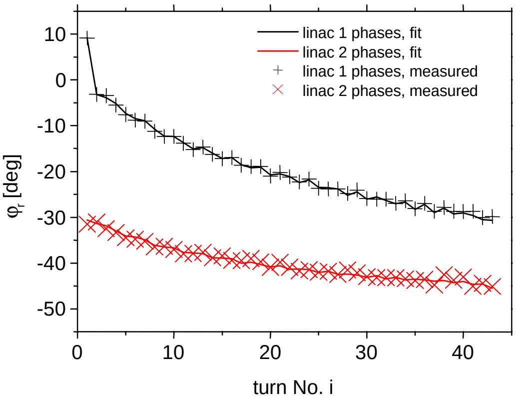

Fig. 6: Measured and fitted synchronous phases in linac1&2 after optimisation.

Measuring the beam size in turn 42 at dipole 2 with a high magnification CCD camera allows to estimate the emittances. From the measured values σ_h=0.30mm and σ_v=0.28mm (resolution: 0.15mm) and the known beta-functions at this SR-spot (β_h=8m and β_v=40m) the emittances can be calculated to be 11nm rad and 2nm rad. This agrees quite well with the calculated values given in Table 1.

To define and reproduce the longitudinal beam dynamic we introduced an automatic procedure, which determines precisely the crest phases of the three rf-systems: By varying the phase of the rf-system under test the beam energy is changed. Due to the strong longitudinal dispersion this changes the beam phase in the next rf-cavity monitor on the axis of the subsequent linac. The extremum measured there defines the phase of maximum acceleration (accuracy: ~0.5°). Then the start phase for both linacs can be easily set. By small phase adjustments of the matching section the injection energy can be shifted by a few 100keV. Comparison of measured phases with simulations reveals an excellent agreement. Fig. 6 shows the measured phases in linac 1&2 after optimisation, and the theoretical curves fitted by variation of the phases and amplitudes of both linacs and the injection energy. The parameters obtained by this fit match very well to the design values. The large jump between the first two turns in linac 1 is due to the phase displacement of +13° for longitudinal matching purposes in the injection turn, which is then cancelled by the chicane in the first recirculation path between dipole 3&4. The half axes of the measured longitudinal acceptance ellipses in the middle of linac 1 are 10°@4.90GHz and 400keV. As predicted, operation with phase deviations down to -3.5° and up to +2.5° of linac 2 (2.45GHz) are possible.

The settings of the quadrupole doublets on the linac axes are within some percent to the design values. Exiting betatron oscillations by corrector kicks and comparing with the simulations showed good agreement. The coupling between the planes is less than 10%. This effect, also observable at RTM2 and RTM3 of MAMI B, is presumably caused by small azimuthal misalignments of quadrupoles, in the order of few tenths of a degree. The transverse acceptance of the HDSM was measured by exciting betatron oscillations with orthogonal phases up to the point, where beam losses on the 10% level occur. Transforming the estimated acceptance ellipses to the middle of linac 1 results in 0.4 mm rad horizontal and 0.6 mm rad vertical.

CONCLUSION

With the Harmonic Double Sided Microtron the limitations of an RTM in the GeV region can be overcome. With the same magnet weight as an RTM it delivers nearly twice the output energy. The price one has to pay is a distinctly more complicated beam dynamic. On the basis of our experiences with the MAMI RTM-cascade and with the aid of modern simulation tools all obstacles were mastered. The successful and very fast commissioning process and the reliable operational behaviour clearly demonstrate, that the HDSM is the best continuation of the outstanding RTM principle.

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