Beam Measurements and Operating Experience at MAMI *

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Abstract

Beam measurements and operating experiences at the RTM-cascade MAMI are reported. The main beam data reached at 855 MeV are: 107 μA cw-current, a short term energy width of 30 keV (with correctable long term drifts of about 100 keV, all FWHM) and transverse emittances of $12 \cdot 10^{-9}$ / $0.7 \cdot 10^{-9} \pi \cdot$ m$\cdot$ rad horizontally resp. vertically (measured for currents up to 5 μA till now). The maximum beam energy was 881 MeV.

1 INTRODUCTION

The 855 MeV cw-race-track-microtron cascade MAMI (MAinz MIcrotron) has been in full operation for three years, serving five experimental areas (cf. [1],[2] for the main data of MAMI and an overview of the whole facility). Besides its intense, very reliable operation for nuclear physics with a beam quality as yet always exceeding the demands of the experiments, continuing investigations concerning the precise beam properties and a more and more detailed machine diagnostics are done. This is not least for that reason important, that future demands, e.g. a stable microfocus in the 10 μm-region for the coherent generation of soft x-rays by the MAMI-beam or its ultrahigh stability for a 10^{-7} parity violation experiment, go to the limits of or even exceed the present performance. The fundamental beam parameters and the methods to get reliable values for them are reported here, as well as the main operating experiences and improvements on MAMI.

2 BEAM MEASUREMENTS

The absolute value of the MAMI output energy has been determined via a precision measurement of the radii of some higher turns in the third microtron, by the rf position monitors on the linac axis and a slender quadrupole on the return paths [3]. The result was $E(90 \text{ turns}) = 855.1 \pm 0.16$ MeV, and for the extractable energy now the formula $E(n) = 180.02 + 7.504 \cdot n - 3.5 \cdot 10^{-5} \cdot n^2 \pm 0.16$ MeV is used (n even; the n^2-term is an empirically fitted correction for the deviation of the beam path from a half circle in the 18.6% reversed fringe field).

Concerning the energy width of the beam, elastic electron scattering spectra taken during about 0.5 h show a FWHM peak-width of 50 keV, which however, is just the resolution quoted for the spectrometers. From the machine side a more detailed analysis was done. By making known energy and phase deviations at the injection to the three RTM's, measuring the resulting phase oscillations and comparing them with PTRACE simulations, the theoretical phase compression factors of 0.43 and 0.66 from RTM1 $\rightarrow$ 2 $\rightarrow$ 3 were verified and the "intrinsic" longitudinal phase space at 855 MeV determined to be $F = \pi \cdot 0.4° \cdot 10$ keV. This is in good agreement with the fact ([4],[5]) that the energy stability of a nonisochronous multiturn machine like MAMI is, for an amplitude stability of the rf-field $\Delta A/A \leq 10^{-3}$, given by $\delta E = \Delta E$(per turn!)$*\Delta A/A$. (Another demonstration of this stability is that the total energy loss of 600 keV by synchrotron radiation in RTM3 is compensated down to 10 keV by an automatic phase migration of 0.6°over the 90 turns). To this intrinsic energy width of the RTM's one has to add statistically 11 keV from an rf-phase jitter of 0.2° and 21 keV from quantum fluctuations of synchrotron radiation in RTM3; so at 855 MeV, one has a short term stability of 30 keV FWHM. However, there are long term drifts of empirically about 100 keV FWHM, resulting e.g. from a drift of the rf-phase of sometimes 1° and temperature changes of the accelerator hall, which contribute with -18 keV/°C, changing the distance of the 180° dipoles by thermal expansions of the floor. However, these effects can be counteracted, and a permanent monitoring of the MAMI-energy to $< 10^{-4} - 10^{-5}$ by slender 4^{th}-harmonic rf-cavities on the return paths, measuring beam positions via a TM_{110}-mode is under way.

The transverse emittance of MAMI has been determined by varying the focal length of a lens and measuring the beam diameter downstream with a wire scanner or looking at synchrotron radiation spots. Due tu the very small size of the beam spots, the accuracy of these measurements used to be rather poor. Fig. 1a shows a more precise setup with which the emittance was measured turn by turn in RTM3: the synchrotron light spot of the beam entering the fringe field of the 180°-dipole was magnified 250 times by a telescope and a camera to a TV-screen, and with a storage oscilloscope, a cut of the video signal at maximum horizontal and vertical diameter was taken over 1 second (for the resolution of the method cf. the two dips in fig. 1a which are the image of the double cross-hairs of the telescope; the linearity of the image intensity was tested by beam current variation). By a slight excitation of the steerers on the return paths of RTM3, successive beams were separated from the background of the up to 89 other ones and their 1 σ-diameter measured; via $x_n = \sqrt{\epsilon_n \beta_n}$, the β-functions well known by the machine optics, one gets the emittances. The

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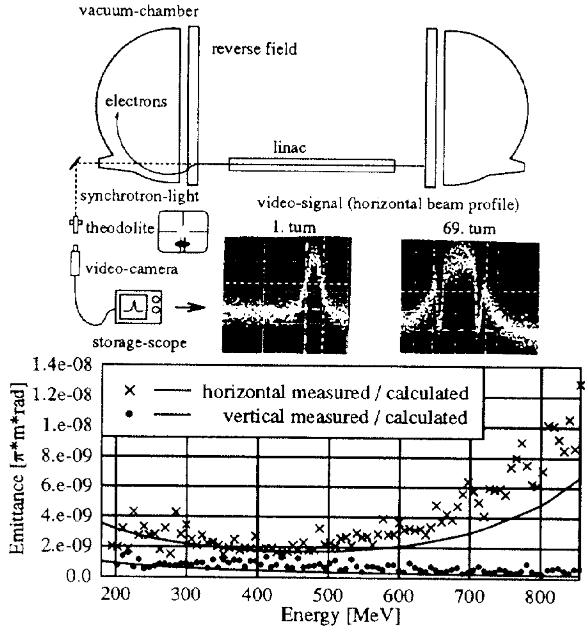

Figure 1: Experimental setup (a) and results (b) of the turn for turn transverse emittance measurement in RTM3.

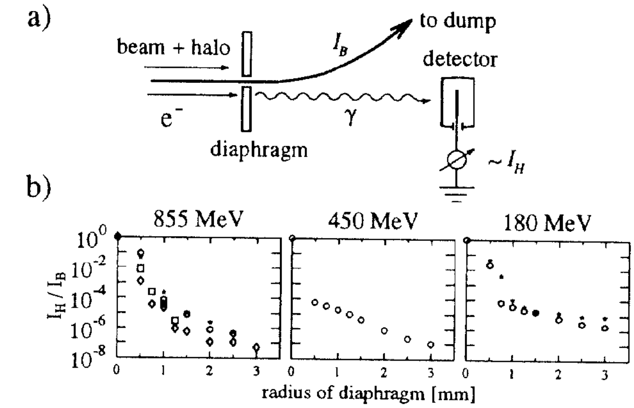

Figure 2: a) Schematic setup and b) results of beam halo measurements at different runs (different symbols).

measurement was done with currents up to 5 μ the result is shown in fig. 1b. The horizontal emittance has a minimum around 400 MeV (30th turn) and then goes up a factor of six mainly by stochastic emission of synchrotron radiation, in good agreement with a Monte-Carlo simulation [6]. The latter fact proves that other emittance worsening mechanisms in RTM3 are at least small. The vertical emittance just goes down by pseudodamping, which shows the very good decoupling of the two phase planes (tuned by two weak 45°-skew quadrupoles on the linac axis). A detailed determination of $\varepsilon_{1\sigma}$ for beam currents up to 100 μA has still to be done: as a matter of fact the level of γ-radiation at RTM3 grows quicker than the current for $i > 50\mu$A at the moment, on the other hand in a first measurement a horizontal and vertical emittance of 2/0.3 $10^{-8}\pi\cdot$ m $\cdot$ rad resp. was found for the 230 μA/12 nsec diagnostic beam pulses at 855 MeV.

Since a coincidence experiment using a BGO-ball detector with a minimum distance of only 2 cm from the 3 μA-beam was successfully done at MAMI, it was clear that only a very faint beam halo can exist. Its quantitative measurement, i.e. the percentage of beam current outside a certain multiple of the beam radius (1σ) was done by guiding the beam through diaphragms of different radii and measuring the relative intensity of forward γ-radiation, the calibration of the ionisation chamber detector being done by low beam currents hitting aluminum foils of different thickness. The result for different energies is shown in fig. 2. The energy of the halo-electrons was determined by a supplementary experiment at the tagged-photon facility [7]: moving a 40 μ-wire through the beam one clearly sees the Gaussian beam nucleus and beyond 5 σ a much broader 10^{-6} halo, but with the same energy, as an addition of the energy of the scattered electrons and the coincident γ's showed. Therefore, it was quite obvious to explain the halo by small angle scattering off residual gas atoms. Taking an appropriate scattering formula (e.g. from [8]) one gets after some manipulations, that the percentage dn/n of electrons scattered beyond a radius r is proportional to $(\beta i/\gamma i)^2 \cdot p \cdot l \cdot 1/r^2$ (p-residual gas pressure, l-path length of beam in the RTM and $\beta i, \gamma i$ its initial beta function and energy). With a pressure of 10^{-5} Pa one gets good quantitative agreement with the measurement, explaining especially the dominant contribution from RTM2 with its high $(\beta i/\gamma i)^2 \cdot l$ ($0.10^2{\cdot}758$ m, compared to $0.018^2{\cdot}3075$ m for RTM3).

3 BEAM MONITORING

A quite sophisticated beam monitor system has been built around MAMI, for details cf. [9]. The safety system for the high current beam is now complete, the main part of it being 16 ionisation chambers (air filled 46x24x5 cm^3 aluminum chambers, ionisation current 100 fA – 1 μA) which are aligned at all longer straight beam paths. They switch off the up to 86 kW beam by hardware interlocks above a certain γ-radiation threshold and their on-line display is very valuable for optimum beam guiding.

Additionally to some dozens of wire scanners, synchrotron radiation cameras and fluorescent screens 10 rf-cavities measure the beam position (down to 50 μm at 1 nA and to 10 μm at higher currents) and current (for $i \geq 40$ nA, $\pm 1\%$) along the interfaces between the RTM's. For beam guiding in the RTM's, there are low-Q rf-cavities on the linac axes to detect the up to 300 μA, 12 nsec, 0.1 – 9 kHz diagnostic pulses.

A great improvement was achieved in a simple way to measure very low cw-currents with the percentage accuracy demanded for many experiments: a careful measurement of the current on the linac axis versus the number of turns in RTM3 [10] showed that the beam losses are $\leq 2 \cdot 10^{-5}$/turn. Therefore, some redundant low-Q intensity monitors on the axis of RTM2 (51 turns) and RTM3

(90 turns at 855 MeV) measure the sum current down to 51·15 nA and 90·8 nA respectively, just by detecting their output with a sensitive 500 pW power meter (R&S, NRV-Z4). For a very high sensitivity down to 60 pA,±1% at 855 MeV, RTM3 is operated with only four by 56% over-powered rf-sections, the fifth section being used as a high impedance (30 MΩ) intensity resonator. The absolute calibration of all current measuring devices is done against a DC-current transformer, whose accuracy is limited to 300 nA because of Barkhausen noise, therefore, a beam of some ten μA has to be generated for this purpose. However, a second DCT will be inserted on the linac axis of RTM3, with a sensitivity of $300/90 = 3.3$ nA at 855 MeV.

The sensitivity of our synchrotron radiation photoeffect-current-monitors has been increased to 80 pA photo current /1 nA beam current with a linear dynamic range of 1 nA – 60 μA. However, with the long term calibration of these devices one has to be careful: depending on the vacuum conditions at their operating place, a decrease in sensitivity of up to 10% per 200 μA-beamhours occured, accompanied by the deposition of a brownish layer on the V2A-photocathodes.

The monitoring and control of MAMI has been improved and clearified very much by the completion of a graphical display and operating station [11].

4 OPERATING EXPERIENCES

MAMI hasnow been operating for 13.400 hours with one (single) MK20 barium-dispenser cathode [12] without significant deterioration of performance. The beam from the standard gun is chopped down to 36°, for the low-life-time polarized gun 90° are accelerated satisfactorily. Definite shifts of the transverse phase space at the injection showed that more than four times its area can be accelerated through MAMI totally distortion free. The weak couplings between horizontal and vertical plane were removed by 45°-skew quadrupoles at several places. The maximum operating current was 107 μA (41% beam loading in RTM3), a jump in beam current of up to 60 μA in 10 μsec (the minimum rise time because of the 3 km beam path in RTM3) was mastered by the rf-amplitude regulation. Also long beam pulses (1 ms with 100 μsec rise time) were accelerated up to 114 μA. For the experiments, beam currents between 1 pA and 60 μA were demanded till now. The reliability of the machine has always been excellent, intervalls of 12 to 40 h for retuning are standard, the most uncritical subsystems being the multiturn RTM's.

A 30% longitudinally polarized beam is now routinely accelerated through MAMI, within the error of ±2% of the Møller-polarimeter without loss of polarization [13]. According to the BMT-formula, the ratio of horizontal spin precession to beam bending angle in deflecting dipoles is given by $\varphi_s/\varphi_p = 1 + E/440.65$ MeV. Therefore in RTM3 the spin does alltogether 90 + 107 rotations and, as a complement to the existing, quite complicated, 100 keV spin rotator at the polarized gun, a fine tuning of the longitudinal spin direction (7°/85 keV) was successfully carried out by fine tuning the energy of this machine. Since 3 of the 5 experimental areas are reached by a beam bending of ±90° and with a possible beam splitter [14] in mind, the "magic"energies of 440.65 and 881.3 MeV are of special interest. We made a quick successful attempt to reach a final energy of 881 MeV by just raising all magnetic fields and rf-amplitudes by 3%, which at the same time proved that an interpolation of the 15 MeV extraction energy steps at MAMI is possible at least down to 490 MeV.

A very serious problem was a heavy clogging of the TH2075-klystron collectors by CuO after about 6.500 h of operation which caused the loss of two tubes. Our investigations showed the result that the value for the maximum conductivity of the cooling water (2 μS/cm) given by the manufacturer was much too generous. By adding mixed bed ion-exchangers to our water regeneration plant, thus diminishing our conductivity by a factor of ten to 0.2 – 0.25 μS/cm, and at the same time hindering the access of oxygen [15] as far as simply possible, the corrosion was practically stopped. The collectors, hidden in a not demountable cylinder, were successfully cleaned by an iterative procedure of mechanical scratching and chemical etching by 20% phoshoric acid + inhibitors [16].

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