DESIGN AND STATUS OF THE 1.5 GeV-HARMONIC DOUBLE SIDED MICROTRON FOR MAMI[#]

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Abstract

A **H**armonic **D**ouble **S**ided **M**icrotron (HDSM) is presently under construction to increase the end energy of the three staged cw **R**ace-**T**rack **M**icrotron (RTM) cascade MAMI from 0.855 to 1.5GeV. This new accelerator, scheduled to come into operation in 2004, consists mainly of two pairs of 90° bending magnets and two linear accelerators (see Fig. 1). Special features of the HDSM are the operation of the two linacs at different frequencies, 2.45GHz and 4.90GHz, for higher longitudinal stability, and a relatively strong field gradient in the bending magnets for the compensation of vertical edge defocu sing.

In this paper we will present the main design considerations and report the status of construction.

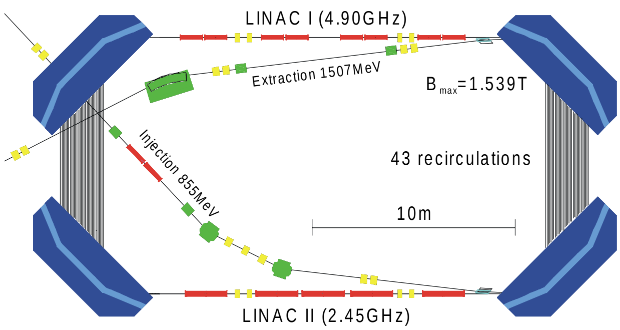

Fig. 1: General layout of HDSM

1 INTRODUCTION

In order to extend the experimental possibilities at the Institute of Nuclear Physics at the University of Mainz the end energy of MAMI will be increased by a fourth stage to 1.5GeV. The main prerequisites were that there should be no substantial degradation of the excellent beam quality and operational reliability of the RTM cascade (see Tab. 1), and that an existing experimental hall (29x15m^2) should be used for the installation of the accelerator. At the beginning two different solutions were studied: a) a superconducting isochronous recirculator with only a few turns and b) a double sided microtron (DSM) with smaller energy gain and greater number of turns. Detailed calculations for solution b) showed that the emittance increase by quantum fluctuations from synchrotron radiation was only about a factor of 1.5 in both horizontal and longitudinal directions [1]. Therefore, and because of higher investment costs of solution a) it was decided to build a DSM.

2 FROM RTM TO HDSM

For the acceleration to electron energies in the 1-2GeV range the RTM scheme becomes unpractical because of the high weight (increasing ~ E^3) of its end magnets. Extrapolating from the RTM3 dipoles (1.28T, 855MeV end energy and 450to weight) a 180° dipole for 1.5GeV would require about 2000to (1to=1000kg) of iron which would be very difficult to handle. By replacing one 180° bending dipole by two segment shaped 90° dipoles the weight per magnet is reduced by a factor of about 8. In other words, the DSM delivers, compared to a standard RTM, double the end energy for the same iron mass. Another advantage is given by the fact that a second dispersion free line exists allowing for the installation of another linac. The coherence conditions for the DSM are a little more complicated than for the RTM. The path length of the first turn and the increase of path length from turn to turn have to be counted now from the beginning of each of the two linacs individually. This results in the following set of equations:

$$\text{LINAC I:}\quad L_i + R_i = l_1 \cdot \lambda_1 + (i-1) \cdot n_1 \cdot \lambda_1$$

$$\text{LINAC II:}\quad R_i + L_{i+1} = l_2 \cdot \lambda_2 + (i-1) \cdot n_2 \cdot \lambda_2$$

$i \in 1,\ldots,43$, L_i/R_i: left/right half turns through the DSM, l_1/l_2: length of first full turn counted from linac 1/linac 2 (in units of wavelength λ_1/λ_2), n_1/n_2: path length increase per turn of linac 1/linac 2 (in units of wavelength λ_1/λ_2). For coherent acceleration l_1,l_2,n_1,n_2 must be natural numbers.

From this the following relations can be deduced:

$$n_1 \cdot \lambda_1 = n_2 \cdot \lambda_2$$
$$n_1 > l_2 \frac{n_1}{n_2} - l_1 > 0 \qquad (1)$$

For linac 1 and linac 2 operating at the same wavelength $\lambda=\lambda_1=\lambda_2$ (standard DSM) we get $n_1=n_2$ and from relation (1) it follows that the smallest path length increase per turn is $n_1=n_2=2$ and that each half turn increases by λ. This leads to an equation for the energy gain per turn ΔE as a function of the field strength B:

$$\Delta E = e \cdot c \cdot B \frac{\lambda}{\pi - 2} \qquad (2)$$

(e: electron charge, c: velocity of light). Inserting the RTM3 parameters B=1.28T and λ=0.1223m (the MAMI standard frequency is 2.45GHz) leads to an energy gain

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per turn of 41.1MeV. With our standard room temperature linac sections at 2.45GHz a energy gain of 1MeV/m in cw operation is achievable without problems, resulting in a linac length of more than 40m, which does not fit into the existing accelerator hall. Therefore, the operating frequency was changed to 4.90GHz, the double of MAMI frequency, leading to a reduction of energy gain by a factor of two.

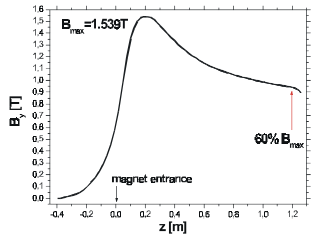

Fig. 2: DSM Field gradient

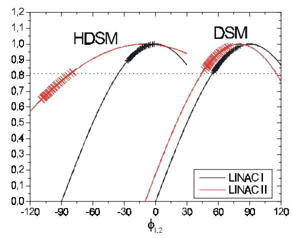

Fig. 3: Development of ϕ_0

To overcome the problem of the strong vertical edge defocusing by the segment magnets the installation of quadrupoles in the dispersion lines was considered at first. Detailed simulations have shown, however, that small systematic sextupole errors in these quadrupoles, which would have to be very compact because of the small spacing of only 54mm between the lines, would lead to unstable particle motion. Furthermore, the large number of elements which have to be tuned and in which the beam has to be centred would certainly create difficulties for the machine operation. Therefore, we decided to compensate for the defocusing by an appropriate field decay normal to the front edge of the 90° magnets. The distribution shown in Fig. 2 compensates the vertical defocusing for all energies from 855MeV to 1.5GeV so that each 180° system corresponds optically to a simple drift space, nearly constant in the vertical direction (~12.6m) and changing from 0.8m to –12.6m horizontally. The transverse focusing is done by two quadrupole doublets placed on appropriate locations on the linac axes [2].

As a consequence of the field gradient the mean bending field decreases with increasing energy. Therefore, the energy gain per turn has to decrease too in order to fulfil the coherence condition. This is, due to the strong longitudinal focusing, automatically realised by a corresponding phase slide down on the accelerating wave in case of correct energy and phase of the injected electron bunches (see Fig. 3).

The longitudinal transfer matrix $M_{long,1/2}$ of one half turn starting in front of one DSM linac for the coordinates ($\delta E,\delta\phi$) is :

$$M_{long,1/2} = \begin{pmatrix} 1 & -\dfrac{\lambda}{2E_{\max}}\cos(\phi_0) \\ -E_{\max}\dfrac{2\pi}{\lambda}\sin(\phi_0) & 1+\pi\tan(\phi_0) \end{pmatrix} \qquad (3)$$

ϕ_0: synchronous phase, E_{max}: energy gain of one linac at ϕ_0=0°.

Completing the calculation for a whole turn and assuming global phase errors δ,ε in the two linacs the range of synchronous phases ϕ_0 for stable motion is given by :

$$-2 < TRACE(M^{linac1}_{long,1/2}\cdot M^{linac2}_{long,1/2}) < 2 \Leftrightarrow$$

$$-2<\left(2+\pi\frac{\sin(\phi_0+\delta)}{\cos(\phi_0)}\right)\cdot\left(2+\pi\frac{\sin(\phi_0+\varepsilon)}{\cos(\phi_0)}\right)-2<2 \quad (4)$$

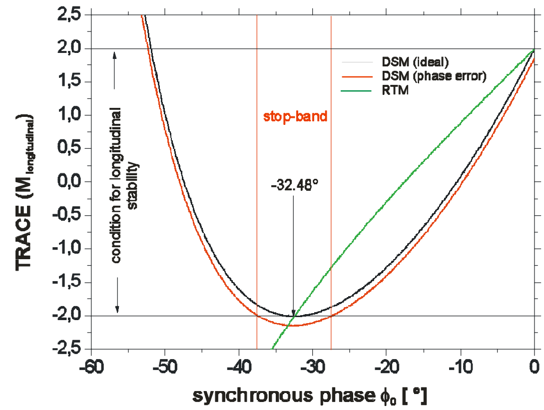

Fig. 4: Region of stable longitudinal motion.

As can be seen from Fig. 4 stable motion down to -51.85° is only possible in the ideal DSM. In case of some bunch phase deviations δ=–ε=10° , for simplification, a stop-band occurs around –32.48° due to longitudinal over focusing. On the upper left side of Fig. 5 the phase motion in case of a rf phase shift of 3° in the second linac is depicted for the demonstration of the instability. The phase space volume at 1.5GeV shown below would not be acceptable! To improve the situation, we introduced the concept of the Harmonic Double Sided Microtron [2].

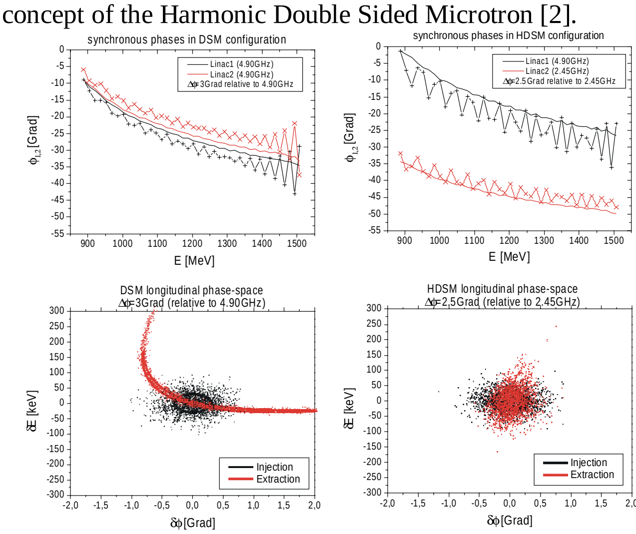

Fig. 5: Influence of phase error between linacs on longitudinal beam dynamics for DSM and HDSM.

Because of the subharmonic frequency of 2.45GHz of the bunches delivered by the existing MAMI RTM cascade, one of the DSM linacs can be operated at twice the wavelength. By choosing the l_1 to be equal an odd number of $\lambda_{4.90_{GHz}}$ only every second bucked would be occupied in linac 2. Therefore, it can be replaced by a 2.45GHz linac without destroying the coherence conditions [2]. By adjusting the starting phases and energy gains in both linacs in that way, that the 2.45GHz take over most of the necessary decrease of energy gain per turn, the critical gradient of the 4.90GHz wave at -32.5° could be avoided (see Fig. 3). In the 2.45GHz linac this gradient could never be reached.

The influence of the HDSM scheme on the stability can be seen on the right side of Fig. 5. For a phase error of 2.5° in the 2.45GHz linac (eq. 5° in 4.90GHz) the phase oscillations starts from beginning with a relatively high amplitude, the particle motion, however, remains stable and the longitudinal phase space is not distorted.

3 STATUS OF CONSTRUCTION

The DSM hall is ready for the installation of the HDSM. All necessary modifications of the existing buildings are done. A new 2MW transformer station is installed and the cooling capabilities are upgraded correspondingly.

The existing beam transport system for 855MeV electrons to the experimental areas is already rearranged to allow for beam injection to the HDSM and for the extraction of the 1.5GeV beam. All magnetic elements are modified to handle the higher electron energy. To do so, in some of the bending dipoles the field was raised to 2.2T by inserting special designed pole plates [3].

Each of the four magnets is essentially build from two 125to pieces made of high permeable cast iron. The procedure to realise the high quality and precise surface of the partly concave pole faces was worked out in close collaboration with the manufacturer [4]. The first two magnets are already delivered and one of them is installed at its final position in the underground accelerator hall. The last two magnets will follow in the next months. First field measurements show a good agreement to TOSCA calculations. The next months are dedicated to high resolution field mapping, which are the basis for the construction of surface correction coils to reach the desired field accuracy of 10^{-4} [5].

The 2.45GHz linac consists of five $\pi/2$-mode standing wave sections with 33 accelerating cells (l=2.02m) each fed by one 50kW klystron. All sections will be delivered until middle of 2003. A shunt impedance of 68MΩ/m requires an rf-power of 125kW to produce the desired maximum energy gain of 9.3MeV. The 4.90GHz linac sections were optimized starting from the 2.45GHz design in turns of field and phase stability and with respect to a high aperture of the beam hole (10mm) sacrificing some shunt impedance [6]. One section will consist of 35 accelerating cells (l=1.08mm, 78MΩ/m). Eight of these sections will be installed in linac 1, fed in pairs by one 60kW klystron (TH2166, a new development from THALES/France). The design value of 9.0MeV maximum accelerating gradient is reached at a total RF power of 120kW. At maximum beam current of 100µA additional 65kW have to be delivered. The first prototype section is under construction in house, first high power tests will be done until end of 2002.

4 SUMMARY

A 1.5GeV Harmonic Double Sided Microtron is being constructed as a fourth stage of the cw electron accelerator MAMI. In spite of strong vertical edge defocusing at the bending magnets there are no focusing elements on the dispersion lines. Instead of this, a special field decay in the magnets is used for compensation. As a consequence, the energy gain per turn decreases during the acceleration. In order to improve the longitudinal stability of this process, one of the two linacs operates at the first subharmonic of the HDSM frequency of 4.90GHz. This is possible because of the subharmonic bunch injection. We believe that our HDSM will be the best approximation to the MAMI RTM's, with respect to their very stable behaviour and excellent beam quality. First operation of this new accelerator is planned for 2004.

Tab. 1: Main parameters of RTM3 and HDSM

		RTM3	HDSM
General			
$E_{Inj.}$	MeV	180.2	855.5
$E_{Extr.}$	MeV	854.5	1507
turns	#	90	43
power consumption	kW	650	1500
RF system			**Linac 1 / Linac 2**
total energy gain	MeV	7.49	16.63 – 13.93
frequency	GHz	2.449532	4.899 / 2.449
sections/klystrons	#	5/5	8/4 / 5/5
linac length	m	8.870	8.59 / 10.10
shunt-impedance	MΩ/m	67	78 / 68
dissipated power	kW/m	11.5	14.2 / 12.4
beam power	kW	67.4	65,2
Magnet system			
min. / max. field	T	1.2842	0.95 – 1.53
min. / max. gap	mm	100	85 – 138
min. / max. radius	m	0.47 – 2.22	2.23 – 4.60
weight	to	900	1000
Beam parameters			
energy width	keV	13	110
hor. emittance	nm rad	7.8	9.2
vert. emittance	nm rad	0.5	0.4

5 REFERENCES

[1] K.-H. Kaiser et al., Proc. PAC'99, p.2915
[2] S. Ratschow, Ph.D. thesis, University of Mainz, 2000
[3] U. Ludwig-Mertin, "Beam Transport Magnets with 2.2Tesla", this conference
[4] A. Thomas et al., "Design and Construction of the 250t-Bending Magnets for the 1.5 GeV-Harmonic Double Sided Microtron for MAMI", this conference
[5] F. Hagenbuck et al., "Measurement and Correction of Asymmetric Magnet Fields in Bending Magnets", this conference
[6] H. Euteneuer et al., Proc. EPAC'00, p.1954