MODIFICATION OF THE KARLSRUHE ISOCHRONOUS CYCLOTRON TO AN ENERGY VARIABLE MACHINE

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Introduction

The Karlsruhe Isochronous Cyclotron [1] was designed in 1962 as a very simple fixed frequency (FFAG) machine to accelerate d, α-particles up to a fixed energy of 26 MeV per Nucleon. In 1972 the machine was made more attractive for nuclear physics by adding an axial injection system [2] and a number of external ion sources (LASKA - a Lambshift-source for polarized deuterons, a special Penning-source for completely stripped Lithium ions, HISKA- an ECR-Type source for completely stripped light ions from Nitrogen up to Neon and recently a powerful atomic beam source for polarized deuterons was ordered from SENTEC [3] in order to increase the extracted current for these particles from the present 50 nA to a few μA).

Nevertheless, for the future use of the machine, either in basic nuclear physics as an injector for a cooler-ring or a SULEICKA-type post accelerator [4], or as a stand alone machine for application-oriented research we think that it is important to make the machine more flexible. In the following the actual status of such a modification project is briefly described.

Design goals for the modification

There are two main drawbacks of the existing machine. First of all it can only accelerate protons as H_2^+-molecules (26 MeV/N). The potential of our external ion sources to produce polarized protons cannot be used. Secondly the boundary condition that only fully stripped light ions can be accelerated gives an external current for these ions which is at least one order of magnitude lower than from other comparable machines. These considerations give us the following main design goals:

- ability to accelerate protons up to an attractive energy E_p > 70 MeV
- acceleration of partly stripped light ions to an energy E_{LI} > 20 MeV/N.

In addition for all particles an energy variation of a factor of two would be desirable.

Another boundary condition for the modification was that we would like to maintain the nice feature of our three fold symmetry machine, which having 3 DEES gives us a high energy gain per turn and therefore a good extraction efficiency. Last but not least the modification should be cheap which requires the use of existing hardware as intensively as possible.

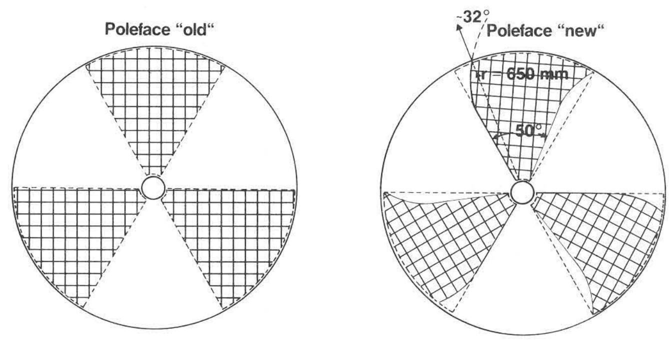


Fig. 1: Modification of the straight sectors to spiraled ones.

Basic ideas for the modification

In order to implement the necessary axial focusing for the protons the original straight sectors have to be replaced by new sectors with a spiral (figure 1). The necessary HF-frequency variation of 24-40 MHz has to be achieved by replacing the actual self-excited system coupling the 3 DEES in the center of the machine by a driven system, where an external amplifier is coupled separately to each of the DEES (figure 2).

Magnet fields

Compared to the actual configuration the sector angle in the center of the machine has to be reduced from 60^o to 50^o. Above R = 50 cm a spiral (figure 3), which is optimized via beam dynamics calculations, is introduced. In order to leave space for the acceleration system the whole sector is rotated by 10^o. Field calculations show that the demountable pole plate (installation plate for the sectors) have to be reduced by 2 cm on each side (which increases the flutter). The iron-field will be isochronized for the highest proton energy. Field calculations show [5], that then the correction coils have to compensate for less than 300 Gauss for the whole range of energies and particles. These correction coils can be taken over by the new set of harmonic coils built in 1978 [6].

The actual main coils and cooling power as well as the existing power supply allow the increase of the current from the present 340 A to 520 A giving a maximum of 745 000 AW needed for the acceleration of the light ions up to K = 140.

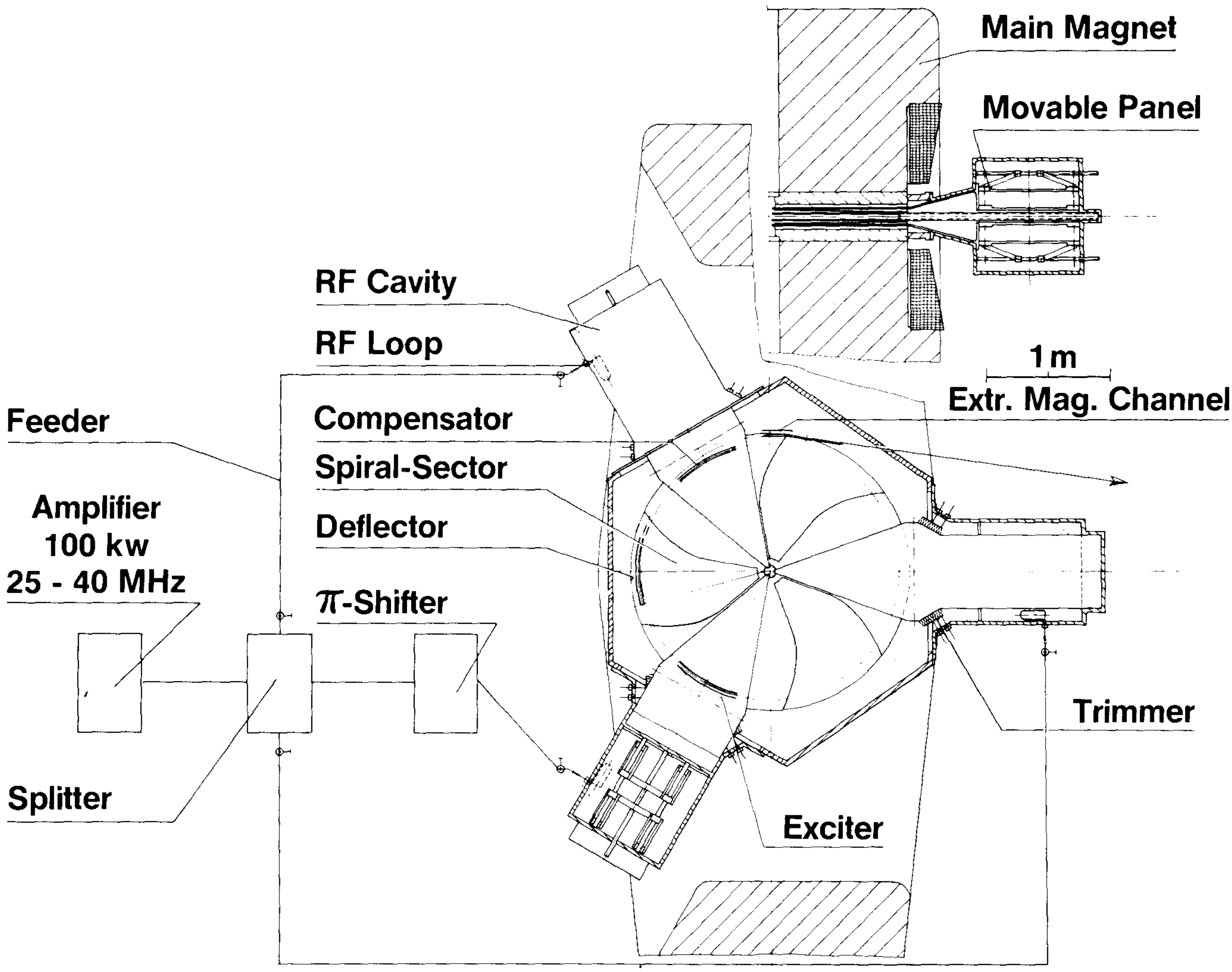


Fig. 2: Schematic of the modified Karlsruhe Isochronous Cyclotron

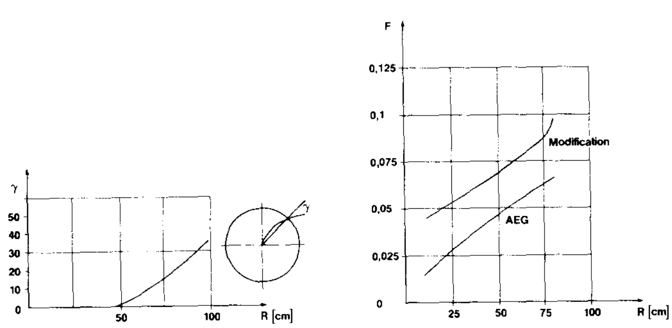


Fig. 3: Optimized spiral and improvement of flutter

RF-System

The rf-system consists of 3 separate resonators (figure 2) each one of which is excited by an induction loop. The matching to the 50 Ω coaxial transmission line coming from one common power amplifier (100 kW, 24-40 MHz) via a high power splitter is achieved by rotating the coupling loop. The coupling loop will be horizontal for 40 MHz and has to be rotated by 68^0 to match the 24 MHz. The geometry of the resonators inside the magnetic field is taken over from the existing machine.

The final part of the outer conductor including the surrounding vacuum chamber has to be changed (figure 4). The tuning of the resonators is achieved by two vertical moving panels. To cover the frequency range of 24-40 MHz the calculated panel distance, Δd = 1 - 20 cm has to be realized. In a 1:3 model the calculations could be justified (figure 4). The power consumption of the 3 resonators for the maximum frequency of 40 MHz will be:

losses in the resonator	70 kW
losses in the feeders	6 kW
losses in the power splitter	5 kW
losses in the 180^0 phase shifter	3 kW
for 2nd harmonic operation	
	84 kW

As protons have to be accelerated on the 2nd harmonics, DEE 2 has to be excited with a phase of 180^0 (figure 5). The rf-amplifier built by ZARAT was installed in Karlsruhe in Jan. 1984 and is know working with a special matching unit together with the existing DEE-system. The amplifier is built up outside the cyclotron vault and the power is transmitted via a 35 m long 50 Ω coaxial line.

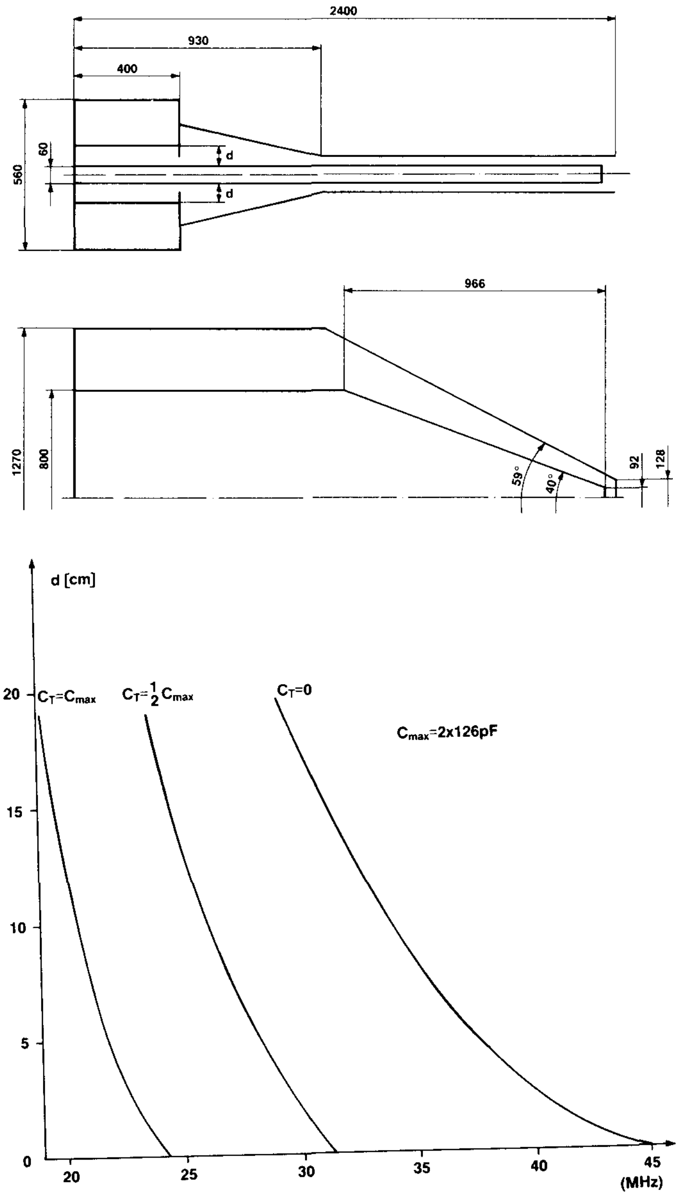


Fig. 4: Principle of the modified D-System. The tuning of the resonators is achieved by two vertical moving panels. For fine tuning an additional adjustable capacity is foreseen. The shown tuning diagrams are measured values from the 3:1 model

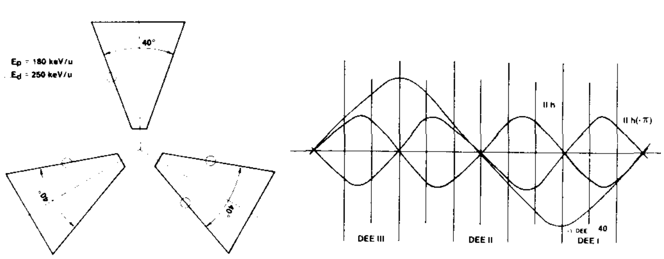


Fig. 5: Principle of the second harmonic operation with a three Dee-System

Beam dynamics

The beam dynamics was calculated on the IBM computer in Karlsruhe using a dynamic programme of a mathematical analog model from IFN-Krakau [7]. The code calculates on the basis of nonlinear differential equations in cylindrical coordinates. A third differential equation calculates at the same time the phase shift of the beam relative to the accelerating voltage. Figure 6 gives the optimal working lines in the Q_Z versus Q_R diagram. Figure 7 shows more detailed results for the acceleration of protons up to an energy of 84 MeV. By a property machined magnetic field where the first harmonic is lower than $\pm$ 10 Gs (tolerances in the iron profile vertical $\leq$ 100 μ and spiral positioning horizontally better than 0.1 mm) the resulting beam quality should be:

Emittance:	15 mm mrad
$\frac{\Delta E}{E}$:	$2\text{-}5 \cdot 10^{-3}$
$\Delta\pi$:	1 nsec

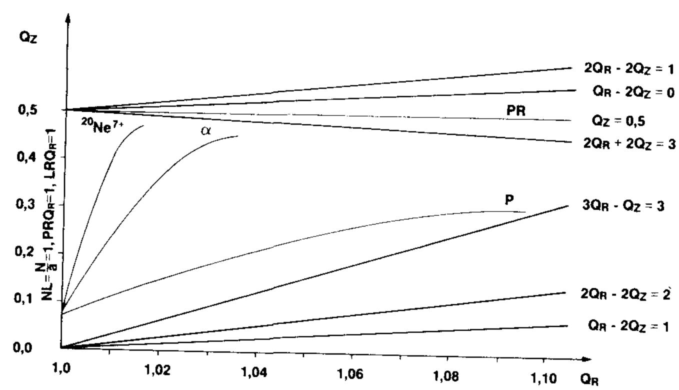


Fig. 6: Working diagram in the Q_Z versus Q_R plane for the modified Karlsruhe Isochronous Cyclotron

Extraction

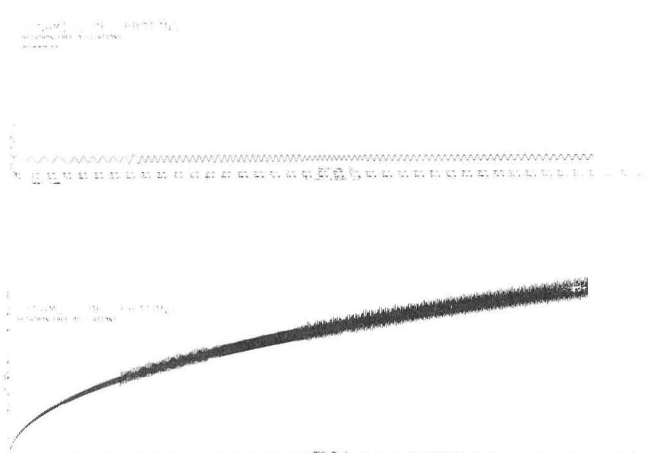
The main extraction problem is the low turn separation of 0.6 mm for the highest proton energy. Therefore a turn expansion via an electrostatic first harmonic is foreseen (figure 2). It consists of a radial exciter system (peeler) of a length of 35° in a radial range of 101 cm - 104 cm and a second system (compensator) of the same kind 110° away. The reason for the second system is to suppress the second harmonic, which might cause a radial emittance growth. Such a system has been successfully tested at the electron model in Dubna [9] and at the W 120 M cyclotron in REZ (Czechoslovakia). We expect, by using a field strength of about 35 kV/cm an increase of the turn separation up to 8 mm at the septum. Detailed calculations using the calculated emittances from the beam dynamic program at the entrance of the system will be done in the near future.

Parameter set for the modified Karlsruhe Cyclotron

Machine parameters		
$\Delta(K)_{HI}$	MeV/N	80-140
$\Delta(K)_p$	MeV/N	40-84
Z/A		1 - 0.35
T_{max} } p	MeV	83.94
T_{min} } p	MeV	40
T_{max} } d	MeV/N	35
T_{min} } d		20
$(B_p)_{ext}$	kGs	9 - 13
$(B_d)_{ext}$	kGs	12 - 16.5
$\Delta f_p(k=2)$	MHz	27 - 40.57
$\Delta f_p(k=2)$	MHz	27 - 37.8
$(Q_Z)_p$		0.1 - 0.358
$(Q_R)_p$		1 -1.085
F_{eff}		0.48 - 0.15
N_{magn}		3
α_{sec}	Grad	50
$\gamma_{sec\ max}$	Grad	32
$(\Delta R)\ \gamma_{sec}$	cm	50 - 104
h_{min} (hill)	cm	8 - 11
h_{max} (valley)	cm	24 - 24
N_{dee}		3
α_{dee}	Grad	40
ΔT/turn	MeV	0.135 for h = 2; 0.24 for h = 3
V_{dee}	kv	40

Main particles to be accelerated		
Particles	Energy in MeV/Nucleon	
p,p↑	40 - 84	h = 2
d,d↑, Z/A = 1/2	18 - 35	h = 3
$^3H^+$	10 - 15	h = 3
$^3He^{2+}$	32 - 60	h = 2; 3
$^6Li^{2+}$	11 - 15	h = 4
$^{12}C^{5+}$	18 - 24	h = 3
$^{14}N^{6+}$	18 - 25	h = 3
$^{16}O^{7+}$	19 - 26	h = 3
$^{20}Ne^{9+}$	19 - 28	h = 3

Extracted currents		
Particle	I(μA)	Ion Source
p, d	80 - 100	Internal PIG
α, $^3He^{2+}$	30 - 50	
Z/A = 1/2	0.01 - 0.5	External HISKA
Z/A < 1/2	0.2 - 2	External LISKA
d↑, p↑	1 - 3	Atomic Beam Source



Summary

The modification of the Karlsruhe Isochronous Cyclotron seems technically feasible by mainly exchanging magnetic structure of the pole plates and adding a new acceleration system. Cost estimates for this procedure are in the range of 2-3 Million DM. After the modification of the Karlsruhe Cyclotron installation, which includes a number of unique measurement apparati (Magnetic Spectrometer "Little John", special arrangement for the measurement with polarized neutrons "Polka" and the large neutron-time-of-flight spectrometer i.E.) will be a very competitive machine in a still interesting energy range. In addition the machine would be a powerful injector for any post accelerator project in the future.

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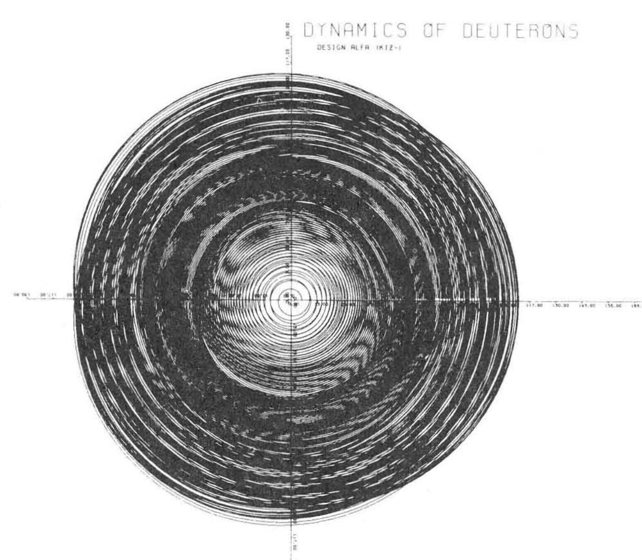

Fig. 7: Axial and radial Betatron Oscillations