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DESIGN STATUS OF THE MUNICH CYCLOTRON SUSE

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Abstract

At the Munich Accelerator Laboratory the design study for the superconducting sector cyclotron SuSe with the existing 13MV-tandem as injector is in a final state. SuSe will accelerate protons and heavy ions to maximum energies of 500MeV respectively 300MeV/u (for Q/A=0.5) with excellent beam properties. Some new technical developments were needed. A prototype of a superconducting sector coil is under test. Several models for the RF-cavities were built. At present a 1:1 prototype power model is under construction. A superconducting channelmagnet without stray fields for injection is developed.

The Heavy Ion Accelerator System SuSe

At the Munich Accelerator Laboratory the project study on an accelerator system for heavy ions is under way to make accessible the medium energy range up to 300 MeV/u corresponding to the pion production threshold. Some topics of an experimental program are:
- nuclear structure at high energy/momentum transfers
- nuclear matter at high density (pion condensation)
- exotic proton/neutron-rich nuclei (fragmentation)
- biological/medical applications (tracerimplantation)

Excellent beam qualities are essential for an appropriate exploration of this field with precise experiments. Therefore the starting point of the Munich concept is the requirement for intense beams (~10^{13}p/sec) in a broad mass range with a phase space volume of the ion bunches, which is matched to the best experimental equipments available at present: energy spread $\Delta T/T = 10^{-4}$, bunch length Δt=20psec and emittances $\varepsilon_{x,y} = 0.1$ π mm mrad. To reach this one has to start with a small phase space already in front of the preaccelerator. Any enlargement in all succeeding parts of the system including the beam preparation system between the postaccelerator and the experimental setup has to be avoided.

In this respect the 13MV-tandem in Munich is an ideal injector. Typically for ^{12}C at T_{max}=5.6MeV/u the intensity is I>10μA, the area of the longitudinal phase ellipse is $\pi \cdot \Delta T \cdot \Delta t = \pi \cdot (0.8\text{keV/u}) \cdot (150\text{psec})$ and the emittances are $\varepsilon_{x,y} = 1$ π mm mrad.

As postaccelerator a superconducting separated sector cyclotron (SuSe) is best suited for conservation of the phase space volume. In a synchrotron the intensity is reduced drastically and usually the phase space volume is enlarged. A superconducting compact cyclotron is not feasible due to the lack of axial focusing power. Furthermore this type of cyclotron needs injection by stripping the ions at the beginning of the first orbit. In order to minimize the phase space enlargement due to energy and angular straggling the bunches have to be focused in longitudinal as well as in both transversal directions at the stripper. On the other hand a careful dispersion matching must be obtained at the start of the ion path in the cyclotron.

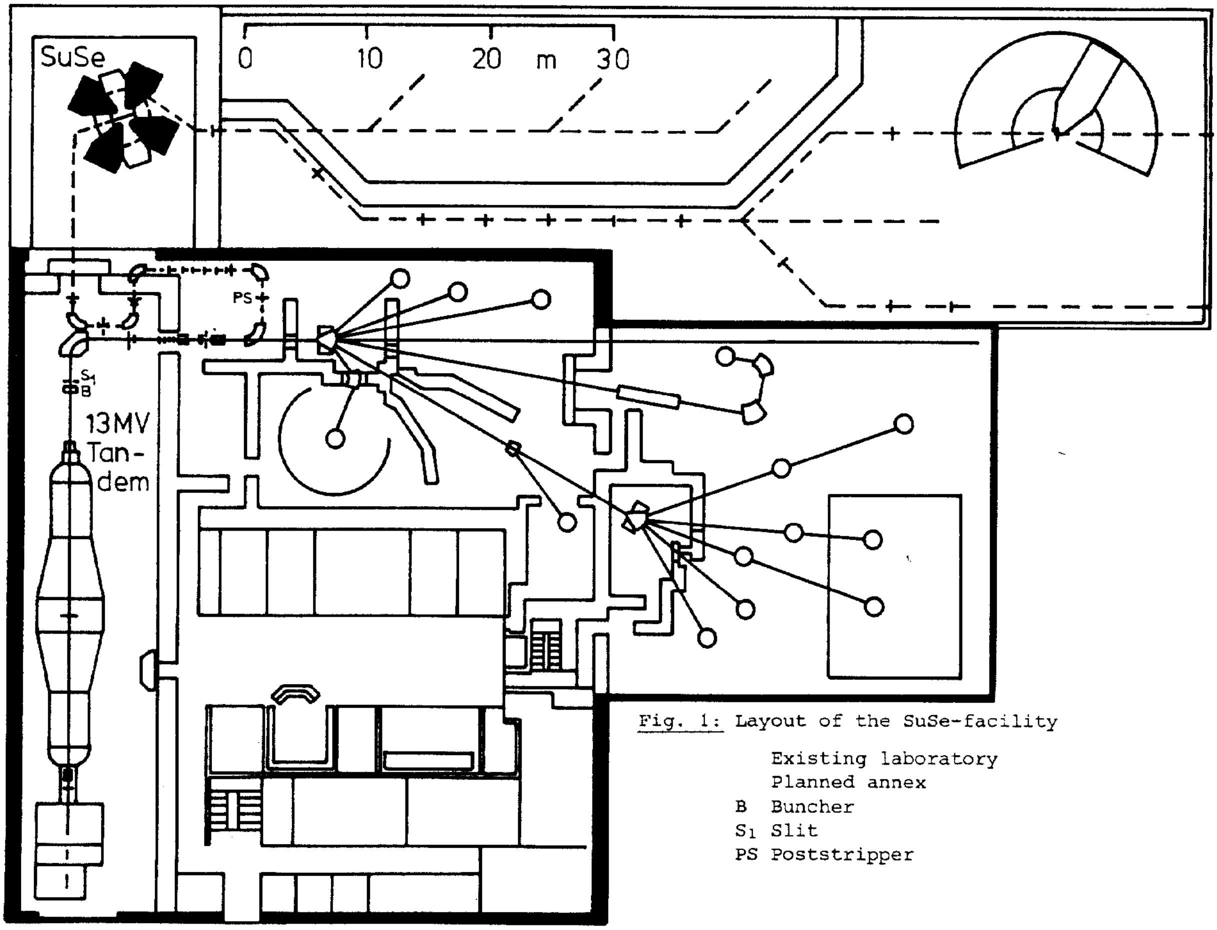

Fig. 1: Layout of the SuSe-facility

Existing laboratory
Planned annex
B Buncher
S1 Slit
PS Poststripper

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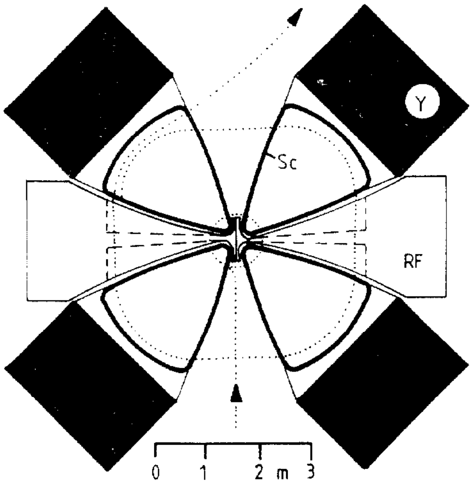

Fig. 2: Top view of the cyclotron
Sc: superconducting sector coil
Y : iron yoke
RF: accelerating cavity

Both conditions cannot be fulfilled at the same time in a compact cyclotron. In the case of SuSe the post-stripper PS is positioned outside the sector cyclotron (fig.1). The buncher B produces a time focus of $\Delta t \approx 65$ psec (for ^{12}C) at the stripper, and an achromatic magnetic system provides an image of the slit S_1 (total width: 2 mm) at PS. Then the disturbing influence of the straggling in the stripper foil is insignificant. The beam transfer line and matching system between the tandem and the cyclotron is described in more detail in [1].

The separated sector cyclotron SuSe (fig.2) consists of four sector magnets and two accelerating cavities positioned in opposing sector gaps. Some significant features are summarized in tab.1. The injection radius is $\bar{r}_1$=0.40m, the extraction radius is $\bar{r}_2$=2.40m. Thus the energy gain factor is 36 for non-relativistic particles and 54 for ions with $Q/A=0.5$ and T_2= 300MeV/u. Each sector magnet consists of two superconducting main coils, two sets of nested superconducting trim coil layers, a warm iron yoke and two cold iron pole tips inside the main coils. At the extraction radius the highest induction is 4.8T.

The acceleration cavities (TE101mode) operate at 59 to 74MHz and harmonic numbers 5 to 16. The accelerating voltage in each cavity increases with radius from $U(\bar{r}_1)=0.25$MV to $U(\bar{r}_2)=1$MV. As shown by W. Joho[2] the longitudinal phase space is governed by a Hamiltonian $\Delta E \cdot \sin\phi = \text{const}$, where $\Delta E \cdot \cos\phi$ is the energy gain per turn and ϕ the phase deviation of a particle with respect to the accelerating frequency. Thus a radially increasing acceleration voltage yields a radially decreasing phase width. The benefit of this phase compression is that the $\cos\phi$-dependence of the energy gain of particles with different phase deviations does not cause a significant distortion of the longitudinal phase space.

The transversal emittances are reduced according to the momentum gain - that is a factor 7.8 decrease for the fastest ions and a factor 6 for the slowest. Thus at the extraction radius the transversal emittances are expected to be $\varepsilon_{x,y} \approx 0.15\ \pi$ mm mrad and the radial beam width about 0.5 mm (in the valley). Thus the turn separation at extraction of $\Delta r(\bar{r}_2) \geq 2.5$ mm for $U(\bar{r}_2)$ = 1 MV per cavity is sufficient for single turn extraction. The turn separation at injection will be $\Delta r(\bar{r}_1) \geq 9$ mm.

The properties of some typical beams at the exit of SuSe are given in tab.2. In fig.1 the beam transport and preparation system between SuSe and experimental equipments is indicated. This system consists of several ion optical modules with separated functions allowing the adjustment of the beam properties to various experimental requirements in a flexible way. As an example for measurements with high resolution spectrometers a variable spatial dispersion at vanishing angular dispersion can be obtained without change of any other optical properties.

Table 1: Main features of SuSe

Injection radius $\bar{r}_1$	0.4 m
Extraction radius $\bar{r}_2$	2.4 m
Maximumfield at $\bar{r}_2$	4.8 T
Average field at $\bar{r}_2$	2.25 T
Sector angle per magnet	≈ 50°
2 accelerating cavities	TE 101 mode
Resonant frequency range	59....74 MHz
Harmonic operation modes	5.,6.,...16.
Max.accel.Vol.per turn at $\bar{r}_1$	500 KV
Max.accel.Vol.per turn at $\bar{r}_2$	2 MV
Beam separation at $\bar{r}_1$	9 mm
Beam separation at $\bar{r}_2$	2.5 mm

Table 2: Some properties of typical beams

Ion	$^{1}_{1}H^{1}$	$^{3}_{2}He^{2}$	$^{12}_{6}C^{6}$	$^{32}_{16}S^{15}$	$^{58}_{28}Ni^{21}$	$^{197}_{79}Au^{34}$
T [MeV/u]	500	450	300	246	126	25
$\varepsilon_{x,y}$ [πmm mrad]	0.11	0.11	0.13	0.16	0.17	0.41
$\Delta T/T$ [10^{-4}]	2.0	1.0	1.0	1.7	2.3	3.1
bunch [psec]	33	22	16	17	19	46
intensity [pnA]	5000	1000	3700	18	10	1

The Present State of the Project Study

In first order approximation all essential problems of the total SuSe-system are solved on the design level. As an example the injection and extraction system is described in another contribution to this conference[3]. At present for some parts of the system alternative solutions are investigated to improve the technical feasibility at lower costs if possible. This concerns especially the superconducting trim coils, which originally were planned with a pear like shape. Recently calculations of fields and beam dynamics with trim coils of more conventional form yield promising results[4].

In parallel to the design considerations a feasibility study concerning new technical developments is in progress. We work on prototypes of three essential elements: a main coil of the superconducting sector magnets, an accelerating cavity and a superconducting channel magnet without stray fields.

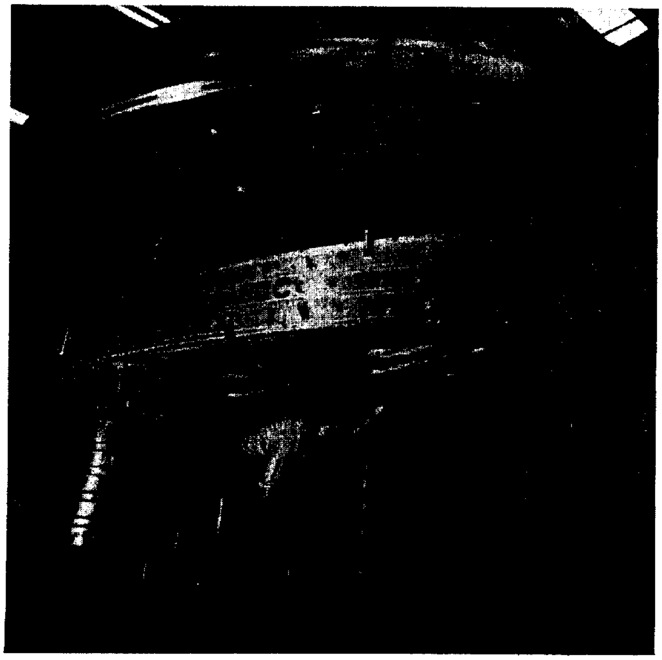

Fig. 3: View of the superconducting prototype coil

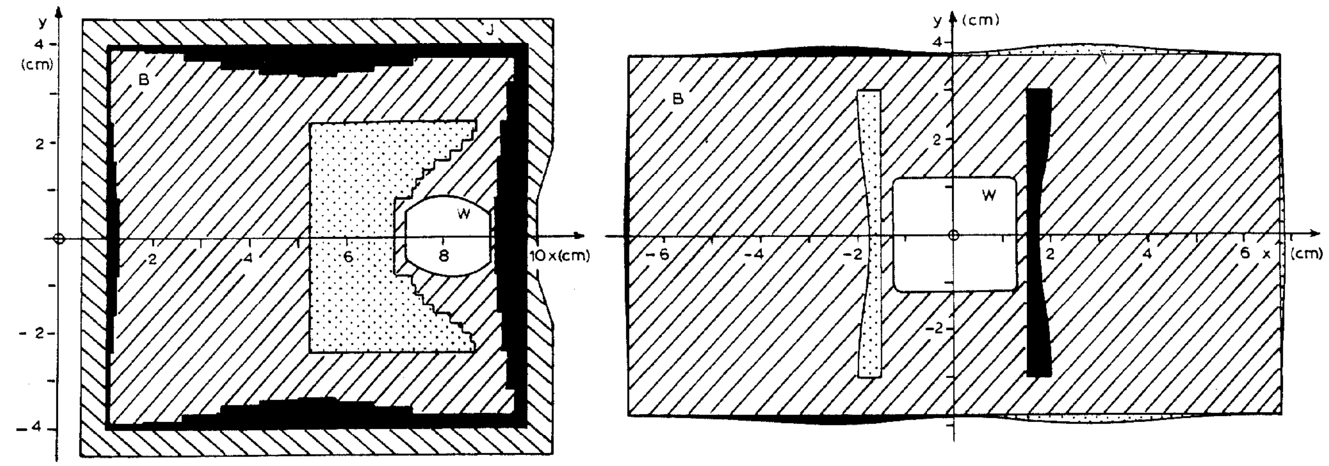

Fig. 4: a) ■ j = ±220 A/mm^2, I_{tot} = 257 kA turns, for $7 \le x \le 9$ cm: $B_y(x,0)$ = 2T.
b) ■ j = ±300 A/mm^2, I_{tot} = 107 kA turns, for $|x| \le 1.5$ cm: $B_y(x,0)$ = 0.6T.

Cross sections of two channel magnets. B: magnet body, J: jacket, W: beam window

The superconducting sector coil is described in some detail in^1. After having been designed in Munich it was ordered at BrownBoveri/Mannheim in August 1980 and has been delivered in December 1982. At present we are installing numerous probes (fig.3). This includes voltage measurements across all 23 double pancakes of the coil, 12 Hall-probes, 6 inductive and 6 ohmic heaters to trigger quenches at known positions, 40 temperature probes of different types and about 20 probes for strain measurements.

The accelerating cavities have been investigated by means of measurements on several models (scaled by the factor 1:8 to 1:2.5) as well as computer calculations with the code CAV3D^5 recently developed for arbitrarily shaped three dimensional cavities. All essential problems are solved at this stage of the investigations: the frequency variation method, the radial increase of the voltage distribution and a power consumption which is expected to be quite moderate (~170 kW per cavity at U_{max}=1 MV). Now a model in the scale 1:1 for power tests in a vacuum tank is under construction^6.

The superconducting channel magnets without stray field are essential for the injection and extraction system of SuSe. These magnets have to produce inductions of up to 2T in a background field of ~2T inside a narrow channel with a cross section of 1x1cm^2 along the ion path. Because they are located in the vicinity of the circulating particles they must not produce significant stray fields in a distance of a few cm.

A simple coaxial line with a cylindrical inner conductor and a coaxial outer conductor is a well known special case of such a channel magnet. Between the inner and outer conductor the magnetic field decreases as 1/r. Outside the cable the magnetic field produced by the inner current is just compensated by that of the opposite outer current. Even at the front and the end faces the outside field vanishes, if the connections between the central and the outer cylinder are directed radially (with constant azimuthal current distribution). This easily can be seen from symmetry arguments and $\oint \vec{H}\cdot d\vec{s}=0$. Only at the entrance and exit windows of the beam at the faces the azimuthal current distribution is disturbed, causing small stray fields.

The field of applications of coaxial magnets is limited by the large field gradient $\partial H/\partial r$. Nearly any gradient is attainable, e.g. $\partial H/\partial x=0$, if the cross sections of the inner and outer conductors are chosen in a proper manner. The inner conductor consists preferably of a bundle of parallel wires, which return on the outer conductor thus forming loops. There always exists a current distribution on the outer conductor which makes the field outside vanishing. This can be seen, if one thinks for a moment the outer conductor being a superconducting surrounding foil. Switching on the inner current there are surface currents induced in the foil, which hinder the magnetic flux from penetrating through it. The current distribution can be calculated by a fitting program with the wire positions as variables (within given limits) and the fields as goal of the fit (outside zero, inside the useful channel certain values). The cross sections of two channel magnets useable for different parts of the injection system of SuSe are shown in fig.4. In case b) the outer conductor may consist completely of superconducting foils (Nb_3Sn). In case a) an additional superconducting foil outside the outer conductor can suppress stray fields caused by imperfect positioning of the wires. The foils must be normal conducting during the adjustment of the background field. A bended channel magnet of type a) is under construction, which could be used as injection element M4 (see^3).

The SuSe project study including the final design and the experimental feasibility study will be finished at the end of this year. The project has already been recommended by two different Advisory Committees though with some reservations. It is not yet funded.

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