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THE SIS - ESR PROJECT OF GSI

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During the last years GSI developed plans for future accelerators and experimental facilities with the intention to extend heavy ion research in a wide scope to higher energies and into new fields of research using novel techniques for acceleration, accumulation, storage and phase space density increase of heavy ion beams up to ^{238}U.1) The prime goals of this development plan using as a first step a synchrotron acceleration ring connected with an accumulator-, storage-, cooling- and experimental ring are the following:

1. Provide completely stripped heavy ion beams up to U^{92+} with the highest phase space densities using various cooling techniques in a storage ring.

2. Provide radioactive heavy ion beams by accumulation, storage and cooling of fragmentation or fission products from beams of the synchrotron.

3. Provide facilities for internal target experiments using simultaneously cooled circulating beams.

4. Provide two merging beams in the storage ring with well defineable collision energies up to the Coulomb barrier of the heaviest ions like U^{92+} in order to study atomic collision processes in high Coulomb fields with both nuclei highly ionized.

5. Provide a beam of heavy ions up to U^{92+} with best phase space density for further acceleration and collisions in superconducting collider rings at very high c.m. energies (>20 GeV/u) and as high as possible luminosities.

I. Heavy ion synchrotron SIS 18 and the experimental storage ring ESR

Fig. 1 shows a layout plan of the heavy ion synchrotron SIS 18 2) to be built at GSI for acceleration of heavy ions up to an energy of 2 GeV/u connected with the experimental storage ring ESR, which can be used for accumulation, storage and phase space density increase of heavy ions up to uranium with energies between 834 MeV/u (Ne^{10+}) and 556 MeV/u (U^{92+}).

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The synchrotron with a circumference of 206.4 m and a maximum bending power B_ρ= 18 Tm accelerates heavy ions up to uranium with a cycling rate of 3 Hz (up to 1.2 T) and 1 Hz to the highest energies. The ESR has exactly half the circumference (for preservation of the bunch structure) of SIS 18 and B_ρ= 10 Tm.

A heavy ion beam accelerated in the UNILAC up to 20 MeV/u, and stripped to an adequate high charge state for the desired energy

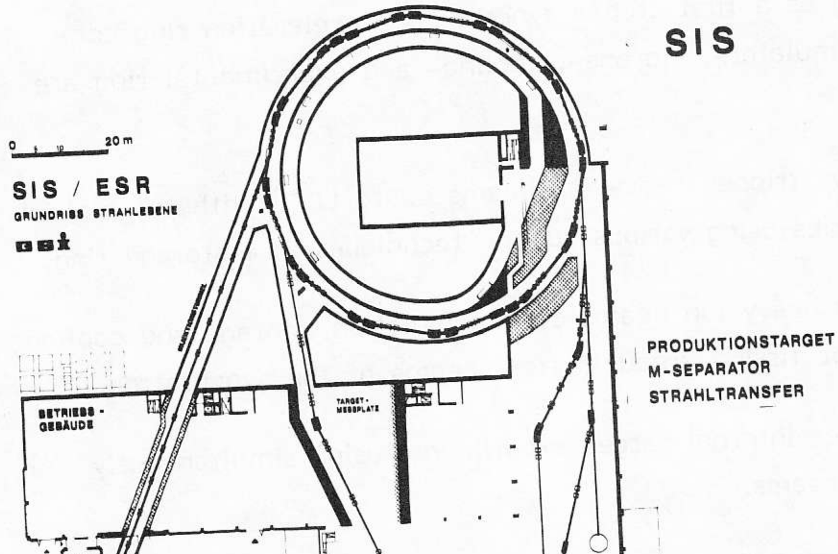

Figure 1.
Layout plan of the heavy ion synchrotron SIS 18 and the experimental storage ring ESR.

and intensity, is injected into SIS 18 during 10 to 30 turns and accelerated to maximum energies, depending on the charge states of the ions as shown in Fig. 2.

For uranium ions with a charge state of $q = 78^+$, after stripping behind the UNILAC with a foil target, 1 GeV/u is achieved as maximum energy. Two systems will be installed for beam extraction. A slow extraction over a period of 100 ms and a fast extraction during a single turn for a transfer of the bunch structure into the ESR. Between SIS 18 and ESR the beam may be stripped once more to the highest desired charge state. The ESR with a bending power of $B\rho = 10$ Tm allows to store ions up to U^{92+} with the following maximum energies: Ne^{10+} (834 MeV/u), Ar^{18+} (709 MeV/u), Kr^{36+} (650 MeV/u, Xe^{54+} (609 MeV/u) and U^{92+} (556 MeV/u). The uranium ions can be fully stripped at this energy with an efficiency of 60 % in a Cu-target of several g/cm^2 thickness. The stripping yield increases strongly with decreasing charge, thus one expects a yield of 70 % for Pb^{82+}-ions (574 MeV/u) and already 100 % for Xe^{54}-ions (609 MeV/u). Alternatively one can install a reaction target for Coulomb break up, fragmentation or fission of the beam. The favourable kinematic focussing of the products around the beam direction and velocity allows effective accumulation of radioactive beams with the ESR, which can be operated at $\Delta p/p = \pm 2$ % and a radial acceptance of about 140 x πmm mrad. Fig. 3 shows the layout plan of the ESR, with two 9.5 m long straight experimental sections, in one of which an electron cooling device will be installed.

The other 4 straight sections will be used for the installation of rf cavities, slow and fast extraction elements. The rf cavities are used for acceleration, deceleration and especially also bunching of the beam together with the electron cooling for reduction of the longitudinal phase space. With the fast extraction system one can transfer a highly ionized and cooled beam back to SIS 18 for further acceleration or specially also deceleration. The optics of the ring allows three modes of operation, one specially suited for accumu-

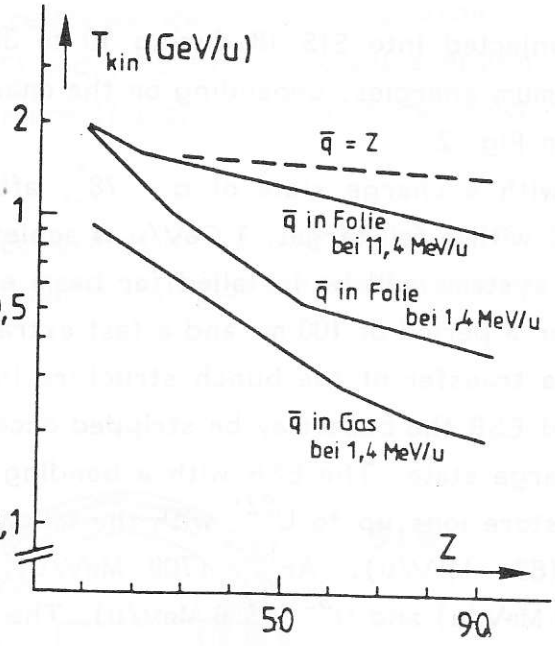

Figure 2. Maximum achieveable energies at SIS 18 as a function of nuclear charge. The energies are given for a gas- or a foil-stripper at an energy of 1.4 Mev/u, resulting in relatively low degrees of ionization. If a second stripper at 11.4 MeV/U is added or if completely ionized particles from the experimental storage ring ESR are reinjected into the synchrotron higher energies can be achieved.

lation, one with no dispersion in the straight sections, which allows multi-charge operation. For a cooled uranium beam, charge states from 89^+ to 92^+ may circulate without any further losses. In a third mode one can inject ions of slightly different momenta, which then may be brought to merge with a well defined angle of about 100 mrad. This may be used to study collisions of two highly ionized beams at fixed target equivalent energies of up to 7.2 MeV/u.

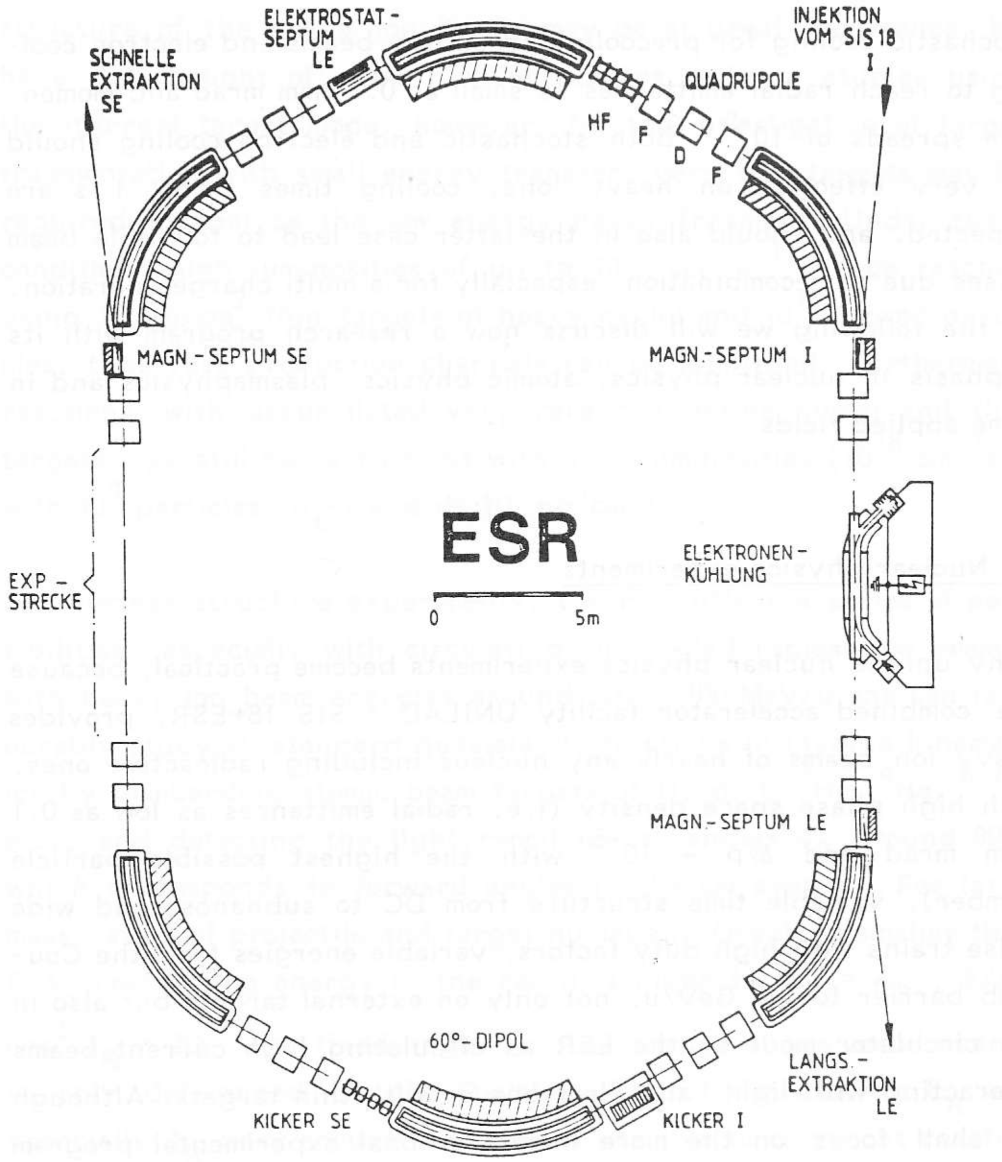

Figure 3. Layout plan of the experimental storage ring ESR with a circumference of 103.2 meters. In two straight sections each with a length of 9.5 m experiments and the facility for cooling can be mounted.

The most important facilities of the ring are various complementary cooling devices which can be operated simultaneously. We consider stochastic cooling for precooling secondary beams and electron cooling to reach radial emittances as small as 0.1 πmm mrad and momentum spreads of 10^{-5}. Both stochastic and electron cooling should be very effective on heavy ions, cooling times below 1 s are expected, and should also in the latter case lead to tolerable beam losses due to recombination, especially for a multi charge operation. In the following we will discuss now a research program with its emphasis in nuclear physics, atomic physics, plasmaphysics and in some applied fields.

II. Nuclear physics experiments

Many unique nuclear physics experiments become practical, because the combined accelerator facility UNILAC + SIS 18+ESR, provides heavy ion beams of nearly any nucleus including radioactive ones, with high phase space density (i.e. radial emittances as low as 0.1 πmm mrad and $\Delta/p \sim 10^{-5}$ with the highest possible particle number), variable time structure from DC to subnanosecond wide pulse trains with high duty factors, variable energies from the Coulomb barrier to 1-2 GeV/u, not only on external targets but also in the circulator mode of the ESR as circulating high current beams interacting with light and electrons or with thin targets. Although we shall focus on the more unconventional experimental program with the circulating beams in the ring, we shall also mention some external target experiments, which need beam tailoring using both rings.

For nuclear reaction studies, at the highest energies, which can be only carried out using external targets, the high beam intensity, low emittance and subnanosecond pulse structure will be specially useful for detection of rare events like subthreshold production of K^+ and $\bar{p}$, which provide interesting signals for cooperative production effects in hot compressed nuclear matter. But also for experiments using combined magnetic and time of flight methods for particle identification the low emittance and subnanosecond pulse structure of the heavy ion beams may be of great importance. We have not thought of many nucleus-nucleus collision studies using the internal target mode, however, for the investigation of target fragmentation with small energy transfer, very thin targets may be required to analyse the low energy heavy fragment. Under these conditions high luminosities of up to 10^{30} $cm^{-2}s^{-1}$ can be reached using 10 ng/cm^2 thin targets of heavy nuclei and 10^{10} stored particles, thus rare production channels can be identified. Furthermore reactions with accumulated very rare radioactive nuclei and thin targets may still be carried out with good luminosities (10^{28} $cm^{-2}s^{-1}$ with 10^4 particles, A_t=1 and d= 10 ng/cm^2).

For nuclear structure experiments, the ESR offers a series of possibilities, especially with circulating and cooled radioactive beams. With heavy ion beam energies around 300 - 400 MeV/u one can favourably study all standard quasielastic reactions in inverse kinematics by bombarding atomic beam targets of H, d, t, ^{3}He, ^{4}He, ^{6,7}Li etc., and detecting the light recoil ion at angles ϑ_R around 90°, which corresponds to forward angles in the c.m. system. For large mass ratios of projectile and target nuclei and Q-values smaller than $E/A_p \cos^2\vartheta_R$ the energy of the recoil is given by $E_R = A_R \,.\, E/A_p \cos^2 \vartheta_R + 2Q$. For fixed angle ϑ_R, the change of the recoil energy is only determined by the Q-value. Thus by measuring E_R and especially ϑ_R very accurately it seems possible to carry out reaction spectroscopy with a Q-value resolution in the order of 70 keV.

For this a combination of position sensitive ΔE and high-resolution E-detectors should be sufficient. Thus inverse kinematics allows reaction spectroscopy with medium resolution determined mainly by the emittance of the beam. All improvements of the beam emittance due to better cooling allows more accurate Q-value measurements. This new method is uniquely suited for reaction spectroscopy on exotic nuclei, accumulated as medium energy cooled beams in the accumulator cooler ring. As target one can also use atomic beams with polarized p, d etc. thus gain the full power of this interesting reaction spectroscopy method also for radioactive nuclei.

Accumulated medium energy radioactive beams may be slowed down after cooling and implanted into semiconductor-detectors for high resolution and high efficiency β-γ-spectroscopy on exotic nuclei. If in addition the beam of radioactive nuclei could be polarized - several schemes are in discussion - nmr experiments with the resonance being detected by the destruction of the anisotropy of the nuclear radiation can be performed for determination of magnetic and in favourable cases also quadrupole moments of nuclei far off stability.

In a proposal by Otten and his collaborators [4)] collinear laser spectroscopy on Rydberg-states, which may be prepared by laser induced radiative capture, dielectronic recombination or charge transfer, is suggested to investigate Lambshift and the isotope shift also on radioactive nuclei. Using similar techniques, it should be possible to induce M1-transitions between hyperfine levels of few electronsystems of heavy nuclei, the splitting of which becomes in the energy range of optical transitions.

A unique field of nuclear structure physics may come from in beam α- and γ-spectroscopy using neutron deficient or neutron rich ion beams, like ^{56}Ni or ^{8}He, ^{50}Ca etc. to produce nuclei far off stability. Such experiments could be performed externally but also using internal targets for increased luminosity in case of rare beams.

Weak decays of completely ionized radioactive nuclei may be investigated for the first time. There is a particular astrophysics interest in the study of a yet undiscovered decay mode, the β^- decay to bound states of highly ionized nuclei, which leads to relatively fast decays of normally stable atoms in a highly ionized plasma. Examples of such nuclei are ^{187}Re or ^{163}Dy, the life times of which may be reduced by many orders of magnitude in a high ionization state [5]. The measurements of endpoints of β-spectra in context with an antineutrino mass determination may be also taken up on completely ionized nuclei to avoid all perturbing atomic effects and at the same time making use of the special kinematic conditions offered by a moving beam of radioactive nuclei with precisely known velocities. More favourable candidates than ^{3}T may be chosen.

Atomic physics experiments

The ESR offers probably the prime attraction to precision atomic spectroscopy, the study of atomic processes with highly ionized atoms and some fundamental experiments for QED. This program has an extremely wide scope so that we can sketch it only in the present context.

First let me mention a few interesting processes which can favourably be studied with stored, cooled and highly ionized atoms. The only recombination process for completely stripped ions interacting with free electrons is radiative electron capture. It is of utmost importance for the ion losses in an electron cooling device. This process can be studied for the first time systematically as function of the relative velocity, atomic number and atomic state. There is an interesting proposal by Winnacker et al.[6], to induce radiative electron capture with intense laser light directed along the electron-ion beams in the cooling device, to populate selectively Rydberg states in highly ionized atoms. With a consecutive laser transition precision spectroscopy seems possible. Polarized light may be used to produce polarized atomic as well as nuclear states. Laser induced radiative capture may pave also a road to laser cooling of highly ionized beams. The analysis of the spectral distribution of radiative capture radiation may be used as a diagnostic for the temperature of the cooling electrons [3]. Due to its partial monochromaticity it may become a powerful source of electromagnetic radiation of variable energy up to several 100 keV. It would be circularly polarized in case of the use of polarized cooling electrons.

Another very interesting process is resonant dielectronic recombination [7]. The captured electron excites simultaneously a bound electron in the ion to an excited state. This process may be also used to excite selected states in few electron systems.

Interesting suggestions for investigation of the quasi molecular X-radiation were put forward [8]. In collisions of bare nuclei with atoms or few electron systems at energies with adiabatic collision conditions (close to the Coulomb barrier), the vacancy can be filled with an electron in the initial and final phase of the transition leading to photon emission of the same energy. Thus the transition amplitudes of the ingoing and outgoing channel interfere. From an analysis of the resulting modulation of the MO-X-spectrum as function of the impact-parameter one hopes to measure the binding energies as function of the internuclear distance of quasi molecules up to Z=184. It is also suggested to use this method in nucleus-nucleus collisions to measure the lifetime of short lived nuclear molecules or intermediate systems formed in collisions with nuclear contact; which may lead to longer time delays between the MO-X-transitions in the initial and final channel. These experiments may be performed either with the merging beam technique or by slowing down completely stripped and cooled ions from medium energies to the adiabatic velocity regime.

The merging beam technique using completely stripped uranium-ions may be most favourably applied to the study of spontaneous positron production in the overcritical Coulomb field of longlived nuclear molecules with Z up to 184 formed with cross section of about 100 mb in collisions close to the Coulomb barrier, according to recent experimental indications [9]. The study of this process with bare nuclei would increase the pair creation probability by a factor of 40 and would also allow an unique signature for the formation of the charged vacuum. In this process the electron of a pair created in the high field will be bound in the 1s-state of the Z=184 atom (the positron is emitted and will be detected) and will appear again with high probability in one of the outgoing U-ions as U^{91+} charge state. Thus we suggest positron spectroscopy in coincidence with U^{91+} ions as unique signature for the formation of the charged vacuum in $U^{92+}+U^{92+}$ collisions.

Very interesting suggestions have been made by Deslattes and collaborators [10] to perform high precision X-ray measurements on one, two and three electron systems as function of Z up to uranium. The wavelengths of the X-rays emitted from stored, cooled and slowed down heavy ion beams in the ESR are measured with special focussing X-ray diffraction devices. By measuring the energies as function of the velocity of the circulating beam, the undesired Dopplershifts may be determined and eliminated. Systematic measurements as function of Z and for different isotopes are necessary to extract the various contributions to QED corrections like selfenergy and vacuum polarization but also the undesired nuclear finite size effects.

There are also series of experiments suggested to test fundamental symmetries in electromagnetic interaction [11]. It looks like that T-invariance may be favourable studied with the radiative capture of polarized electrons in completely stripped ions with high precision. Another proposal is concerned with detection of parity violating effects in forbidden transitions (2s-1s) of high Z hydrogen- or heliumlike ions. Again the production of polarized atomic states from which the X-ray emission anisotropy should be measured, would be required.

A very interesting question was asked recently by Schiffer [12] in context with our proposal: Could there be an ordered condensed state in beams of heavy ions? Indeed, one expects as consequence of the large long range Coulomb interaction between the ions at low beam "temperatures" a short range order to be produced leading possibly to a "liquid" or "solid" frozen Coulomb lattice in the beam. The relevant order parameter is the ratio of the Coulomb energy between a pair of particles and the random kinetic energy of the beam particles. This order parameter $\Gamma = [Z^2e^2/a]/kT$, where a is the distance between two particles, may reach values of up to 100 if a ~ 1 micron and kT ~ 0.5 eV, values which may be reached using electron cooling. This is close to order parameters needed for a phase transition[13]. Very recently Pestrikov [14] claims to have observed ordering effects in a "Coulomb string" of proton beams cooled by electrons.

IV. Applications

Many interesting applications of the medium energy heavy ion beams have been suggested [1]. Some of those, which use the specific capability of the ESR to store and bunch high currents of medium energy heavy ions will be mentioned.

A bunched well focussed beam from the ESR stopped in a cylindrical volume of matter (0.3 mm dia, ~ 3 mm long) produces power densities of up to 0.03 TW/mg during 20 ns which may lead to temperatures of 20-50 eV and pressures of 20-100 Mbar in the material depending on the equation of state. Thus it should be possible to study the equation of state at high temperatures (> 10 eV) and dynamic effects like the energy transport by conductivity and thermal radiation and hydrodynamic flow [15].

Intense heavy ion beams are also well suited for pumping sources of lasers as has been shown recently [16]. A rough estimate 17) shows that using a Xe-beam of 1 GeV/u with 10^{11} ions/pulse, bunched to a pulse duration of 5 ns, the pumping of laser transitions in the region of some ten Å should be possible.

It was also suggested 18) to use an **uranium** beam of 500 MeV/u stored in the ESR traversing a thin gas target for the production of highly charged recoil ions with averaged kinetic energy of a few eV. With a beam of 10^{11} circulating uranium ions at 500 MeV/u one hopes to extract from an argon target with a thickness of 10^{14} atoms/cm^2 a beam of 10^{12} Ar^{18+} ions per sec.

The cooled beams from the ESR are also very well suited for injection into a high energy superconducting colliderring. Due to the small momentum spread, stacking in the longitudinal phase space needs only relatively small aperture of the magnets, which may lead to costsaving magnet designs.

I should like to thank all the many discussion partners which helped us to work out our plans in a very short time.

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