

HEAVY ION STORAGE RINGS FOR ATOMIC PHYSICS

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Summary

A survey on the presently known storage and cooler ring projects for heavy ions is given. Some characteristic features of heavy ion storage and cooling are pointed out. The influence of proposed in-ring experiments using internal atomic or electron targets, laser radiation or colliding beam techniques on the ring designs is discussed in connection with a brief description of the heavy ion Experimental Storage Ring project ESR, which is part of the recently approved heavy ion synchrotron facility SIS/ESR at GSI/Darmstadt [1].

Introduction

The increasing interest in heavy ion storage rings is demonstrated by a series of corresponding projects or design studies recently elaborated in different countries. This development certainly has been stimulated by the progress in antiproton beam accumulation and cooling. The use of cold circulating heavy ion beams promise extreme angular and energy resolution in atomic and nuclear spectroscopy as well as new experimental techniques.

Besides storage, accumulation and cooling, mainly the following options for the operating modes of heavy ion storage rings are desired: energy variation, bunching, simultaneous circulation of different charge states. Interaction between circulating ions and internal target atoms, cooling electrons, and laser radiation will be studied. Even colliding beam experiments by means of crossing two beams co-circulating in the same ring on different closed orbits due to their different momentum to charge ratio are coming into consideration and feasibility studies have been started.

Among the ion species accessible to experiments, there are two especially attractive groups: beams of highly or even fully stripped heaviest ions up to uranium and beams of exotic radioactive projectile fragments produced by different reactions between 100 MeV/u and 1 GeV/u.

There is no practical experience with heavy ion beam cooling. All cooler ring designs are based on the results with electron cooling of proton beams in the range 1.4 MeV to 200 MeV at Novosibirsk [2], CERN [3], or Fermilab [4], and on the experience with stochastic cooling of proton and antiproton beams gathered mainly at CERN above 100 MeV [5].

Heavy ion storage and cooling projects

As far as design parameters were available at the end of 1984, there are 8 projects dealing with the storage and the cooling of heavy ion beams (see Fig. 1 and Table 1). The analysis of the scientific aims as well as of the design features - e.g. existing injectors (see Table 1 and Fig. 2) or storage ring parameters - suggests the division into three families of projects.

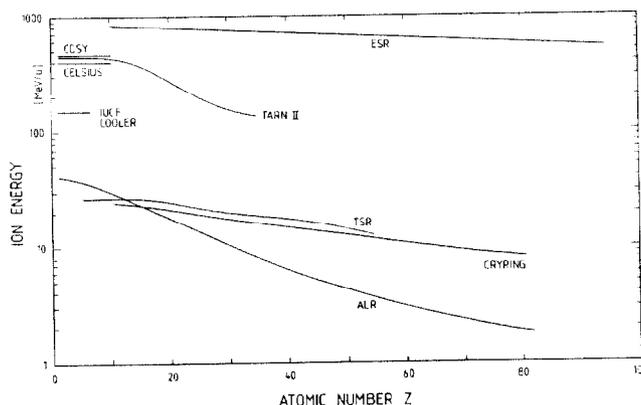


Fig. 1: Maximum energy vs. atomic number Z (without $Z/A > 0.5$) of stored ions for the various heavy ion storage and cooler projects. With the exception of the ESR, all rings require acceleration to reach the maximum energy. In the ESR design this synchrotron mode is provided for in-ring experiments with fully stripped heaviest ions below the injection energy.

1. Cooler rings for protons and light ions

The first three rings of Table 1 use existing cyclotrons as injectors and are designed mainly for storage and cooling of proton or light ion beams. Due to the expected small emittance and momentum spread of cooled beams, experiments on nuclear structure and reaction mechanisms will be performed with precision and resolution not attainable so far. The heavy ion programmes at these rings depend strongly on the development of ion sources for highly charged ions (e.g. electron cyclotron resonance ion source ECRIS) and their adaption to cyclotrons. Anyway, the range of available ion masses - with respect to comfortable beam energies and intensities - seems to be restricted to mass numbers $A \leq 50$.

The IUCF-Cooler [6], fed by a K=220 sector cyclotron, will go into operation in 1986. A K=650 injector cyclotron is planned for the future. The injector for CELSIUS [7] is a K=200 cyclotron which can be operated either in a pulsed mode with modulated frequency (for protons) or in the dc-mode. Heavy ions up to Ne(+7) will be produced by an internal PIG ion source. First experiments are scheduled for 1987. The COSY ring [8] will be supplied with protons of several hundred MeV by the linac planned for the spallation neutron source (SNQ) or at low energy by the K=45 JULIC cyclotron. Complemented with a superconducting ECRIS (called ISIS) the latter machine could serve also as injector of light ion beams up to 11 MeV/u.

Table 1: Storage rings for heavy ions with beam cooling.

| Ring | Cooler | CELSIUS | COSY | ALR | TSR | CRYRING | TARN II | ESR |
|-------------------------------------|-----------------|------------------|----------------|--------------|-------------------|---------------|--------------|------------------|
| Institution | IUCF | Univ. Bloomingt. | KfA Jülich | Univ. Aarhus | MPI Heidelberg | AFI Stockholm | INS Tokyo | GSi Darmstadt |
| Circumference C [m] | 168 | 81.8 | 163.6 | 31.8 | 35 | 30.5 | 75.6 | 103.2 |
| Max. B _p [Tm] | 3.7 | 6.3 | 7.7 | 1.85 | 1.5 | 1.4 | 6.9 | 10 |
| C/B _p [T ⁻¹] | 47 | 13 | 21 | 17 | 23 | 22 | 11 | 10 |
| Injector | cyclotron K=220 | cyclotron K=190 | cyclotron K=45 | tandem 6 MV | tandem 15 MV+lin. | RFQ --- | RFQ or cycl. | h.i.synch. 18 Tm |
| Mass range [u] | 1-20 | 1-20 | 1-20 | 4-238 | 12-130 | 20-208 | 1-100 | 20-238 |
| Injection [MeV/u] | 220-55 | 190-45 | 45-11 | 3-0.05 | 15-7 | 0.3 | 0.8 | 834-556 |
| q/A | 1-0.5 | 1-0.3 | 1-0.5 | 0.5-0.1 | 0.5-0.37 | 0.5-0.3 | 1-0.25 | 0.5-0.39 |
| Max. energy [MeV/u] | 500-150 | 1200-395 | 1500-460 | 41-2 | 27-13 | 24-9 | 1300-140 | 834-556 |
| Cool. range [MeV/u] | 50-400 | 40-550 | 10-500 | 0.1-10 | 1-30 | 0.1-10 | --- | 4-560 |
| Operation in | 1986 | 1987 | --- | --- | 1988 | --- | 1987 | 1988/89 |
| Status | construct. | construct. | proposal | study | proposal | study | t. design | t. design |

2. Low energy heavy ion rings

Low energy heavy ion ring designs of comparable circumference of around 30 m and maximum bending power B_p between 1 and 2 Tm have been worked out in Aarhus (ALR) [9], Heidelberg (TSR) [10], and Stockholm (CRYRING) [11]. Differences between these rings, with respect to the available ion mass numbers and energies, result mainly from existing or planned injector machines.

An existing 6 MV-tandem will be used as injector for the Aarhus ring. In Heidelberg, the more comfortable combination of a 15 MV-tandem with a linac for variable ion velocity $\beta=v/c$ delivers energies up to 15 MeV/u for ions with Z/A=0.5. For the CRYRING the production of highly charged heavy ions, e.g. Pb(+64), will take place in CRYISIS, a novel kind of CRYEBIS with ion beam instead of gas injection. For acceleration to energies up to 300 keV/u an RFQ-linac is being studied.

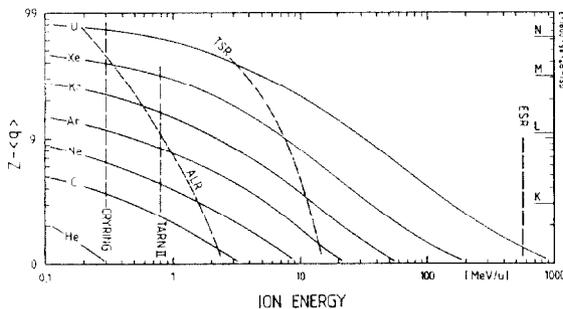


Fig. 2: The solid curves represent experimental results below 20 MeV/u [13] and above 450 MeV/u [14] on average equilibrium electron numbers $Z-\langle q \rangle$ after solid strippers vs. specific stripping energy. Crossing points with the dashed lines describe the ionic states available behind the injectors for the various h.i. storage rings.

3. High energy heavy ion rings

Beams of all kinds of fully stripped ions up to uranium will be available for the ESR in Darmstadt with the heavy ion synchrotron SIS (B_p= 18 Tm) as injector. The maximum bending power of the ESR (B_p= 10 Tm) enables to store totally stripped Uranium ions at 560 MeV/u, where more than 50 % stripping yield is expected.

The maximum energy for Z/A=0.5 is 834 MeV/u. One of the design goals for the ESR are experiments with accumulated and cooled beams of radioactive projectile fragments.

Because of its high bending power (B_p=6.9 Tm) and its compact magnet structure TARN II [12] may be classed with the ESR, though, the injection energy for heavy ions is considerably lower. Heavy ion beams of 0.8 MeV/u will be delivered by an RFQ-linac, protons and light ions by the existing K=68 cyclotron.

Characteristics of heavy ion storage and cooling

Accumulation of high beam currents

In most cases, the phase space density of beams behind heavy ion accelerators is rather low compared to proton beams. The reasons are less bright sources for highly charged ions and the beam dilution in stripper targets, where high fractions of the beam are lost to unused charge states. In most cases the latter effect is more important than multiple scattering and energy straggling in the stripper targets. Sufficiently high beam currents in h.i. storage rings have, therefore, to be accumulated by means of beam stacking in the transverse or longitudinal phase space or by combining both methods. This, however, reduces once more the average phase space density in the beam. The application of beam cooling simultaneously to stacking or in the time between to stacking steps could save ring acceptance and provide higher beam currents. Compression of particles in phase space by stripping injection is possible only with partially stripped ions at sufficiently high energy where the conversion to fully stripped ions is very close to 100 % (Fig. 2).

A special goal of the ESR design was the capability to accumulate radioactive beams produced by fragmentation or fission of fast heavy projectiles. The ring is able to accept beams with transverse emittances up to 20 π mm mrad and with momentum spreads up to 1 %. The number of ions per injected turn will strongly depend on the selected species and vary between 10⁵ and 10⁸. Accumulation to much higher ion numbers is feasible only if the available phase space of the storage ring could be repeatedly made free by sufficiently fast pre-cooling of the hot injected beam. Similar to the cooling scheme for antiprotons in the AA-ring at CERN, the application of a two stage cooling method is planned: Fast stochas-

tic pre-cooling of the injected turn - before moving it towards the stack - combined with consecutive electron (in AA-ring stochastic) cooling of the stack in order to reach excellent beam quality. With a band-width of 1 GHz for the pick-up and kicker systems 10^7 to 10^8 injected fragment ions should be pre-cooled within 1 s or less.

Beam cooling

Under identical conditions the electron cooling rates for ions are, in a good approximation, determined by the proton cooling rate multiplied by q^2/A . For instance, the following partially stripped ions will be cooled approximately as fast as protons: Ne(+5), Ar(+6), Kr(+10), Xe(+12), and U(+16). For fully ionized ions the cooling rates are increased by the following factors: 5 (Ne), 8.1 (Ar), 15.4 (Kr), 22.1 (Xe), and 35.6 (U). If the best experimental values for the cooling of protons [2] are extrapolated to U(+92) at 30 MeV/u, the cooling time estimates are in the order of 1 ms or - with upgraded electron current density - even shorter.

Stochastic heavy ion cooling works faster than proton cooling only in the amplifier noise limited range, i.e. at low beam currents and high beam temperature, where it takes profit from the larger signal power ($\sim q^2$ or $\sim Z^2$) of highly charged ions. In any case, the stochastic cooling cannot compete with electron cooling if low beam temperatures have to be reached.

Limits of cooling and beam heating

The space charge forces causing beam instabilities or shifts of the betatron tune increase $\sim q^2/A$. Incoherent shifts of betatron tunes $\Delta Q = -0.05$ due to transverse space charge forces seem to be tolerable in storage rings [18]. The longitudinal (microwave) instability limit may be considered at least as severe as the ΔQ -limit, though, for intermediate or low energies ($\beta < 1$), estimates by means of the Keil-Schnell criterion [19] are not confirmed experimentally. If comparable importance is attached to both limits, then the relation between emittance $\varepsilon = \varepsilon(h) = \varepsilon(v)$ and momentum spread $\delta p/p$ of a coasting beam is approximately

$$\varepsilon \approx 0.64 R (\delta p/p)^2 / \gamma^2$$

where R is the mean orbit radius in meters and γ the relativistic factor (the transition point of the storage ring is assumed to be $\gg \gamma$). At $\gamma = 1.6$ and $R = 100$ m (ESR at 556 MeV/u) we find $\varepsilon = 4.1 (\delta p/p)^2$ m.

The circulating beam is strongly heated by scattering in an internal target - gas jet or atomic beam of typically 1 to 10 ng/cm² thickness - and in the residual gas (at 10^{-11} mbar below pg/cm²). Energy loss, small angle scattering, and momentum scattering (energy straggling) reduces the beam quality and the efficiency for in-ring experiments. Slow beam heating may also come from intrabeam scattering ($\sim q^4/A^2$) which - at extreme phase space densities - is probably as critical as microwave instabilities are [20]. Also the presence of weak longitudinal instabilities or higher order betatron resonances can be considered as beam heating sources. Misalignment of ring magnets and cooling devices will predestinate, independently of other heating sources, lower limits for the beam temperature.

Electron cooling should generally be able to work against most of the beam heating mechanisms, - with the exception of misalignment - and increase the beam life essentially. The beam life would then be determined mainly by charge changing processes in the internal target, radiative capture of cooling electrons, large angle scattering (at low energy) or nuclear reactions (at high energy).

If the circulating beam is bunched, compensation for the mean energy loss is easily done by means of an rf-cavity. In this case, if not excluded by too high charge changing or large angle scattering rates, the application of larger target thickness up to 1 $\mu\text{g}/\text{cm}^2$ may be considered.

Beam loss

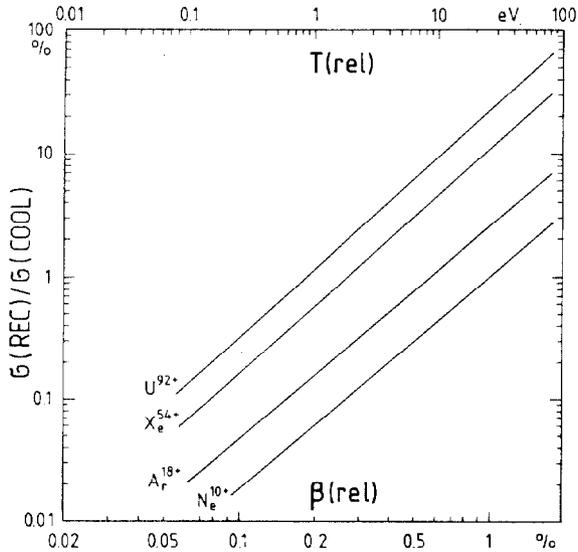
The beam loss rate due to charge changing collisions between heavy ions and residual gas molecules is determined by the total charge changing cross section and the mean gas density in the ring. For the ESR design, semi-empirical extrapolations of experimental cross sections at ion energies below 10 MeV/u were used to calculate the required vacuum [12]. Two points measured behind the Bevalac at 437 and 962 MeV/u for U(+91) and U(+92) in carbon targets [13] are below our estimate by nearly two orders of magnitude. Therefore, the charge state survival times estimated in Table 2 for a residual gas pressure of 10^{-11} mbar (90 % hydrogen and 10 % nitrogen, carbonmonoxide, etc.) are probably strongly underestimated at energies above 100 MeV/u, at least for U(+92) at 550 MeV/u. In storage rings for light ions the vacuum pressure can be raised to 10^{-10} mbar, low energy heavy ion rings require $\leq 10^{-12}$ mbar.

Table 2: Estimates of survival times of two charge states of Uranium at 10^{-11} mbar and three different energies.

| | 30 MeV/u | 200 MeV/u | 550 MeV/u |
|--------|----------|-----------|-----------|
| U(+78) | 150 s | 0.41 h | 0.75 h |
| U(+92) | 140 s | 2.2 h | 22 h |

A more critical problem is the radiative recombination (REC) of cooling electrons with the highly ionized ions [15]. The ratio of REC to cooling [2] cross sections $\sigma(\text{REC})/\sigma(\text{COOL})$ turns out to be independent of the charge state, but to increase $\sim A \beta(\text{rel})^2$, where $c\beta(\text{rel})$ is the relative velocity between ion and cooling electron (Fig. 3). During the cooling process beam losses are expected to be tolerable even for the heaviest ions, provided, the initial mean $\beta(\text{rel})$ is not too high. The recombination time of a cold uranium beam interacting continuously with the electrons of $4 \times 10^8/\text{cm}^3$ density over 2 % of the orbit length is estimated to be ≈ 11 s, i.e. not very comfortable. Hence, the duration of experiments with the circulating ion beam needing simultaneous electron cooling could be limited to several seconds, at least in the worst case of a highly ionized uranium beam. For partially stripped light ions or lower charge states of heaviest ions di-electronic capture rates could set even stronger limitations to the beam life [16]. Therefore, when the desired ion beam temperature is reached, one should reduce the current density of the cooling electrons to values which just avoid beam heating.

Higher charge changing rates could be tolerated by means of multi-charge operation. This mode of storage ring operation, which has been investigated in Darmstadt and Heidelberg, requires ring designs with large momentum acceptance and vanishing dispersion at the positions of target and electron cooling.



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Fig. 3: Ratio $\sigma(\text{REC})/\sigma(\text{COOL})$ vs. $\beta(\text{rel})$, as defined above. At the beginning of the cooling, the initial mean values for the equivalent electron energy $T(\text{rel}) \approx 2.6 \times 10^5 \beta^2(\text{rel})$ eV (upper scale) range typically from a few eV (SIS-beam) to more than 10 eV (fragment beam). The electron beam temperature is expected to be 0.1 to 0.5 eV.

Ionisation of the residual gas

The ionizing power of highly charged ions grows proportionally to q^2 . Hence, 10^9 fully stripped uranium ions circulating with 2 MHz in a ring will produce nearly as much secondary ions per meter as a 3 A-electron beam at the same velocity would do, but - on the average - the charge state of secondary ions produced by the ion beam will be much higher [17]. The increased presence of positive charge in the electron cooling section could additionally give rise to instabilities of both the electron and the ion beam.

Diagnostics of beam temperatures

Temperature measurements at both the electron and the ion beam are of essential importance to achieve high performance in the cooler ring operation. The high recombination, ionization and excitation cross sections of highly charged heavy ions will probably help to develop special methods. The photon spectra emitted during REC in the cooling section, for example, could possibly give valuable information: the width of spectral lines should be correlated with the distribution of $\beta(\text{rel})$, i.e. with the temperatures in both the electron and ion beam. If one of the temperatures is known or extremely low, the other could be deduced from the spectral line profile. Enhanced REC rates for diagnostics can probably be achieved by laser radiation.

The Experimental Storage Ring ESR

The ESR (Fig. 4) is designed for the maximum ion rigidity $B\rho=10$ Tm and is able to accept $U(+92)$ up to 556 MeV/u, $Ne(+10)$ up to 834 MeV/u and protons up to 2.2 GeV. The circumference of the ring is 103.2 m. Two 9.5 m long straight sections are provided for the installation of in-ring experiments and electron cooling equipment. The magnet structure of ESR enables to match the ion optics to special requirements for electron cooling, internal targets, crossed beams, etc. by means of variable tunes - typically between 2 and 2.5- and variable dispersion function (Fig. 5). Elements for injection, fast and slow extraction, two r.f. cavities and stochastic cooling will be placed into four 2.5 m and four 1.50 m long straight sections. Smaller gaps between the magnets will be used for higher order corrections and beam pick-ups. The vacuum system is designed for 10^{-11} mbar.

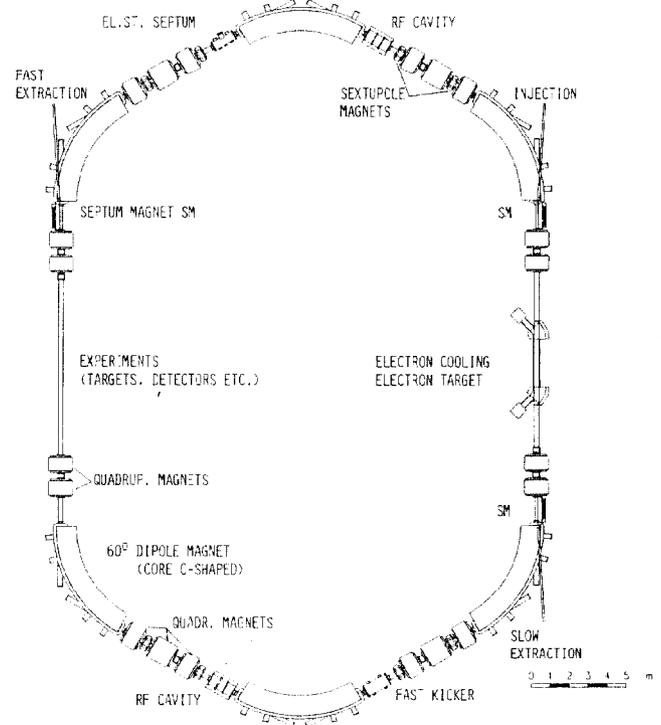


Fig. 4: The Experimental Storage Ring ESR at GSI-Darmstadt.

The motivation for the ring is to provide the following novel facilities for atomic and nuclear studies:

→ Accumulation of fully ionized ions up to uranium to the highest possible phase space density using the electron cooling technique.

→ Accumulation of radioactive ion beams produced by fragmentation or fission of fast heavy projectiles. Combination of stochastic pre-cooling and electron cooling will be applied to enable experiments with these secondary beams.

→ Experiments with circulating beams at energies variable from the Coulomb barrier up to the maximum energies.

Internal targets, electrons or laser beams as interacting media will be applied.

→If feasibility studies will end positively, experiments with two beams crossing each other while co-circulating stably in the ESR on separate closed orbits due to different rigidities [21]. Atomic collisions between two highly or fully ionized heavy systems could be studied at collision energies near the Coulomb barrier.

→Improvement of the quality and increase of the energy of the beams accelerated in the heavy ion synchrotron SIS. Fast beam transfer from SIS into ESR must be done by two steps with longitudinal stacking, because of the 1:2 ratio of the ring sizes. The stored beam can be cooled and eventually bunched to a good time structure. By slow extraction out of the ESR the macroscopic duty factor of the SIS beam could be stretched to nearly 90 % even with some gain in average beam current. Totally stripped ions can be reinjected into SIS and accelerated once more. For U(+92) the maximum energy is raised from 1.0 (without ESR) to 1.35 GeV/u.

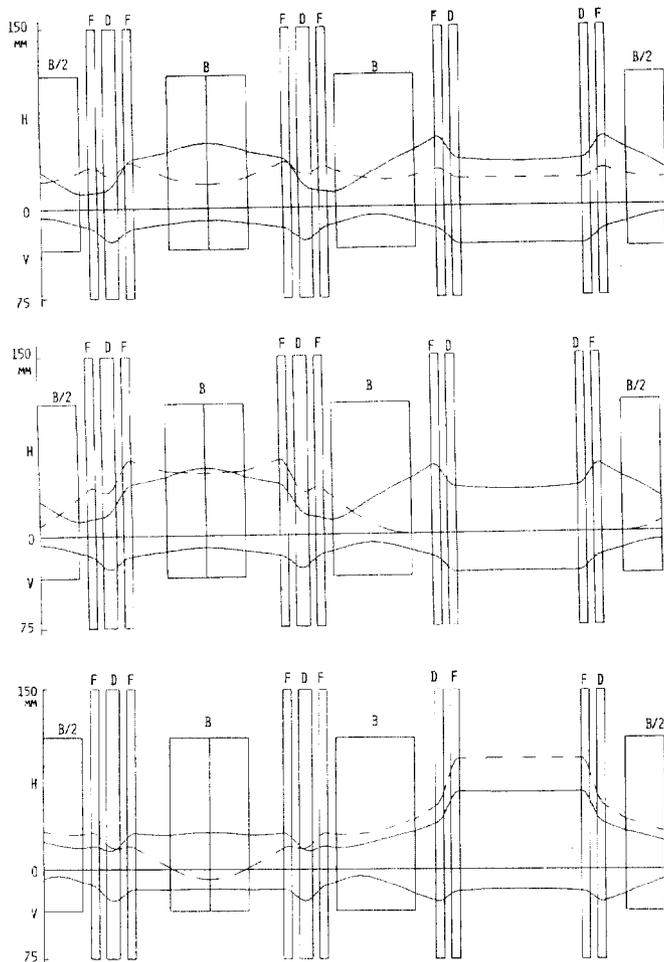


Fig. 5: Three operation modes for the ESR lattice at fixed betatron tunes ($Q(h)=2.3$, $Q(v)=2.4$): Envelope functions (solid lines) and closed orbit for $\delta p/p=+1\%$ (dashed line) are plotted. Mode I will be applied for the accumulation of high beam currents or of projectile fragment beams, mode II for in-ring experiments -e.g. with multi-charge beams from U(+87) to U(+92)- and mode III for crossed beam experiments.

The most important, preliminary parameters of the electron cooling section for the ESR in the working range 4-560 MeV/u are:

| | | | |
|-----------------|----------------------------|-----------------|--------|
| e-energy | 2-320 keV | e-current | 1-10 A |
| Current density | ≤ 1 A/cm ² | Cathode temp. | 0.1 eV |
| e-beam diameter | 2-5 cm | Horiz. aperture | 25 cm |
| Eff. length | 2.5 m | Install. length | 4.5 m |

Presently, feasibility studies on the parameter set for the electron cooling section have been started. The technical design of main components of the ESR (dipoles, quadrupoles, r.f. cavity) is underway. Simultaneously, the beam dynamics calculations are being extended to higher orders to detect problematic error resonances driven by multipole fields of the main ring magnets and, if needed, to calculate distribution and strengths of correction elements.

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