# Theoretical Studies of the Ultra Slow Extraction for the Cooler Synchrotron COSY-Jülich

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*Abstract*

The Cooler synchrotron COSY[1] will accelerate protons from 40 MeV up to 2.5 GeV. It is the goal of this machine to use the beam of maximum brightness for internal target experiments, as well as for external experiments. The tool for the extraction of a low emittance beam is the ULTRA SLOW EXTRACTION scheme developed by W. Hardt for the LEAR[2]. The 3rd order extraction resonances at $Q_X$=10/3, 11/3 resp. will be driven chromatically. A spill rate of longer than 5 seconds will be controlled by noise generators acting in the momentum phase space. The dynamic acceptance during extraction will be controlled by 11 families of sextupoles. It is expected to extract a beam with a horizontal emittance of less than 1 $\pi$ and a momentum spread of less than 0.02%.

## I. OVERVIEW OVER THE SYSTEM

The lattice of the Cooler Synchrotron COSY has been described in detail in ref. [3]. It comprises 6 DFFD cells, each of which incorporates 4 dipole magnets, 4 quadrupole magnets, and 1 or 2 sextupole magnets. Three cells form one 180 degree bending arc. The two arcs are connected by 40 m long straight sections of four quadrupole quadruplets each.

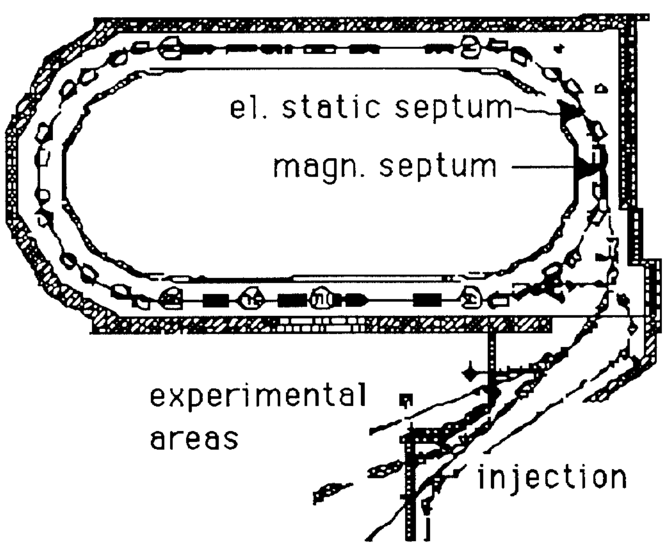


Fig. 1: Layout of the Cooler Synchrotron COSY

The straight sections normally provide an identity transformation with adjustable magnifications at their centers. Using four quadrupole families in the cell structure such that the 2nd and 5th cells are identical (two families) and the remaining four cells are identical (also two families), it is possible to make the telescopic insertions dispersion free and at the same time to meet one other condition.

The telescopes can be run in a triplet mode through most of the energy range. In this mode, there are common focal points between each quadruplet. A wide range of magnifications at the telescope centers is available. For the highest energies, the telescopes can be run in a doublet mode where the magnification at the telescope centers is unity. They can also be run in a $\pi$-$2\pi$ mode where the magnification at the center is adjustable.

The electrostatic septum is located between the 4th and 5th cells. Here there is substantial dispersion of the order of 7 m. The magnitude and orientation of the dispersion vector can be varied slightly by adjusting the fourth quadrupole parameter mentioned above.

## II. EXTRACTION WORKING POINTS

A wide range of tunes is available in the lattice. However, for efficient stochastic cooling, the phase advance between the pick-ups and the kickers should be an odd multiple of $\pi/2$. Because the pick-ups and kickers are separated by one half of the ring circumference for both the radial and the vertical planes, the preferred tunes are seen to be N+0.5 for some integer, N. For COSY, the best choices for extraction would be 10/3 or 11/3.

In order to minimize the angular spread in the extracted beam and thus minimize losses on the septa, we follow the LEAR method where the key unstable fixed point remains fixed as the momentum is varied. Going to the limiting momentum where the stable phase area vanishes completely, the equilibrium orbit must lie on top of this key unstable fixed point. Because the range in possible dispersion vectors is limited, this fixed point must lie around an angle of 70 degrees in the normalized phase space, thus fixing the outbound vertex of the triangular stability limit. There are now two choices for the outgoing separatrix; one of these is nearly vertical in the normalized phase space and thus provides no radial turn separation where the septum can be placed. This separatrix is obtained by approaching the resonance from above and clearly cannot be used. The other separatrix, obtained by approaching the resonance from below, is nearly parallel to the radial axis; it provides excellent radial separation with the resonant growth. Thus for either working point, we are constrained to approach the resonance from below.

The periodicity of the sextupoles in the dispersive cell structure is even. Using the 11/3 resonance for extraction has the advantage that only odd harmonics of the sextupole field drive the resonance. Thus the sextupoles in the arcs can be separately set to achieve the desired chromaticities, knowing

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that they will not otherwise influence the extraction. Then the sextupoles in the dispersion-free insertions can be set to obtain the desired extraction conditions, and they will not change the chromaticities.

## III. NUMERICAL DESIGN METHOD

The linear *interactive* LATTICE code [4] has been modified to calculate the amplitude dependent tune shifts using the distortion function method of Collins and Ng [5]. It was further modified to calculate the second derivatives of the tune shifts with respect to Δp/p and amplitude. The amplitudes and phases of the resultant sextupole fields with respect to the resonances $3Q_x=N$ and $Q_x+2Q_y=N$ are also calculated. All of these quantities can be fit simultaneously. The calculations are performed by the canonical method of linear transformations interspersed with nonlinear kicks at the centers of the sextupoles.

The method is to fit up to 11 sextupole families to yield the required radial chromaticity, the radial tune shift with radial amplitude and provide the correct phase of the resultant sextupole field in order that the unstable fixed point is superimposed on the dispersion vector. At the same time the coupling between the two planes, the spread in the vertical working point, and the magnitude of the driving term for the $Q_x+2Q_y=N$ resonance are minimized. Each sextupole strength is constrained to lie within limits that are both feasible and small enough that complicating higher-order fixed points do not upset the extraction procedure. This LATTICE does quite nicely within a few hours on an 80486 PC-AT computer. If the mixed derivatives are not specified, the solution speed is increased by an order of magnitude.

We show, as an example, a good solution for $Q_x=11/3-0.01$ and $Q_y=3.6$. The outgoing separatrix is nearly parallel to the x axis, and the dispersion vector is exactly superimposed upon the key unstable fixed point. Fig. 2 shows that an ion that just misses the electrostatic septum at 4.5 cm returns three turns later with an amplitude of 6 cm. The quadratic and higher order dependencies on Δp/p are not calculated.

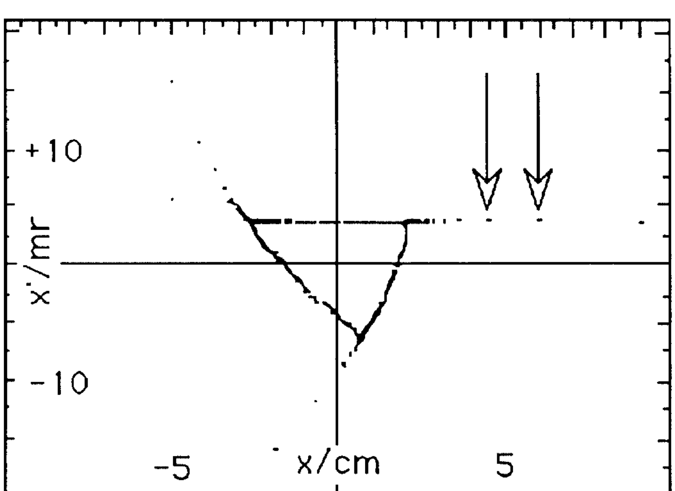

Fig. 2: Outgoing particles at the electrostatic septum

## IV. NUMERICAL VERIFICATION

The radial and vertical tunes are similar and sextupoles driving the $3Q_x=N$ resonance can also drive the $Q_x+2Q_y=N$ resonance. That would result in a blow up of the beam in the vertical plane, possibly before it can be extracted radially. Therefore it is important to verify that coupling tune shifts and the driving term for the coupling resonance have been adequately limited. Fig. 3 shows the dynamic aperture close to the extraction resonance, calculated with LATTICE. The vertical physical aperture limitation of ± 2.9 cm lies well within the dynamic aperture.

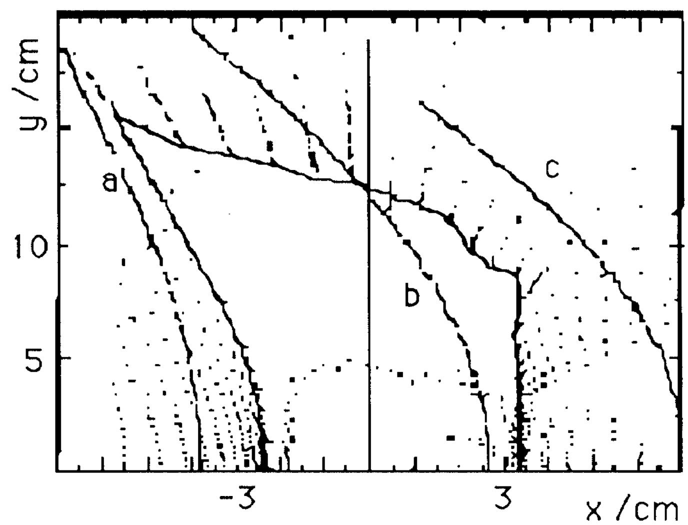

Fig. 3: Dynamic aperture near the extraction resonance (a); b) and c) correspond to coupling resonances

As a separate check on the method, the separatrices for a number of momenta were calculated with MAD, verifying that the outgoing leg was independent of momentum.

Finally DIMAD was used to gradually accelerate a representative group of 1000 ions into the resonance, increasing their relative momentum by $10^{-6}$ per turn. The initial distributions were parabolic in three phase planes with emittances of 5π mm-mr in both the radial and the vertical phase planes and an initial momentum spread of ±0.05%.

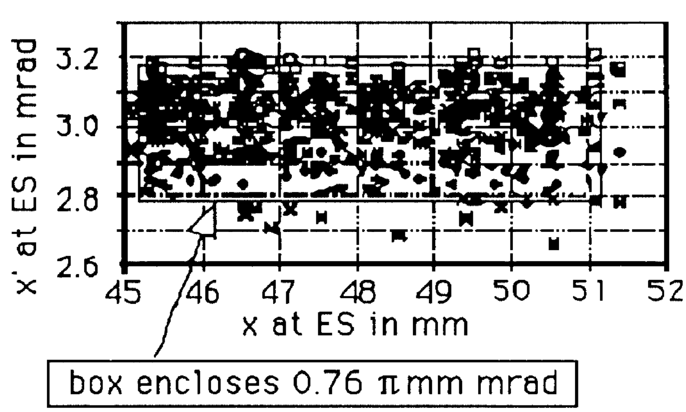

Fig. 4: Phase space of the extracted particles

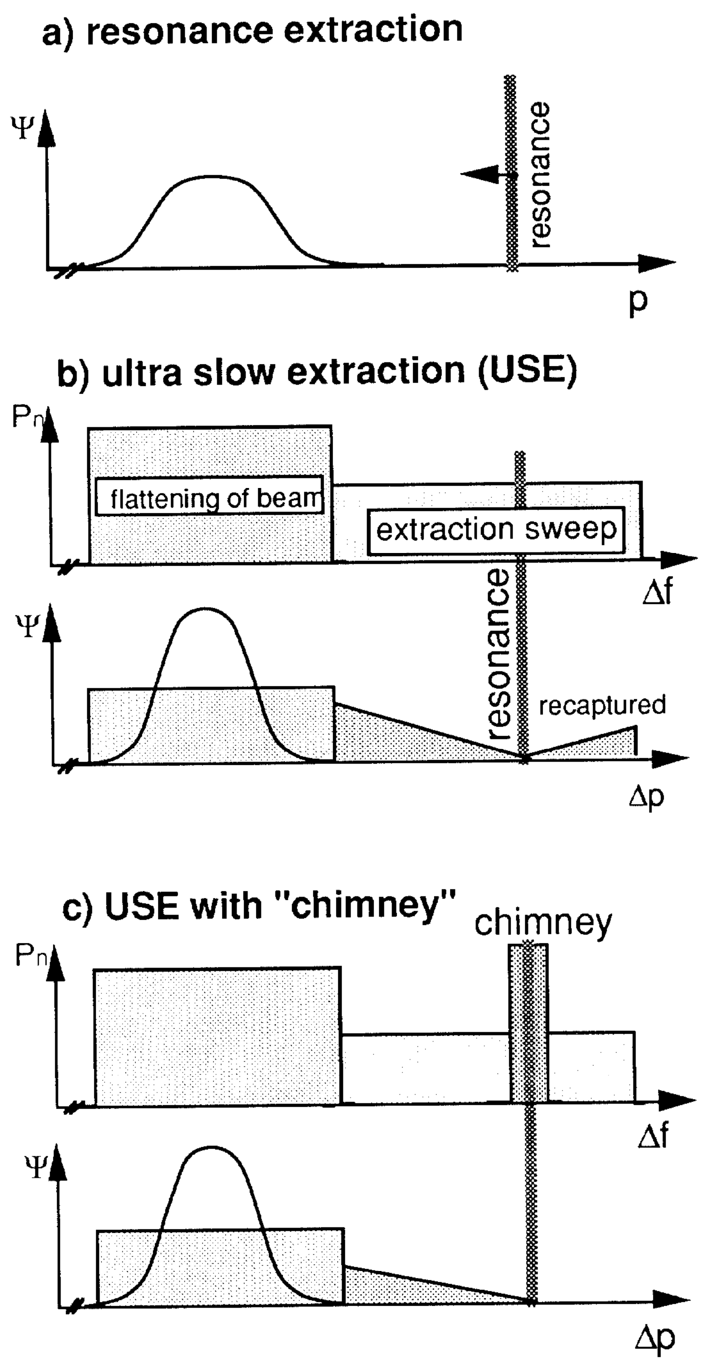


Fig. 5: Extraction schemes

About one half of these ions were extracted within a radial emittance of about 0.8π mm-mr as shown in Fig. 4. Correcting for terms in $(\Delta p/p)^2$ will reduce this emittance by an order of magnitude. The other half were recaptured as the separatrices reappeared as the momentum increased beyond the vanishing stable phase area. This is because the motion stagnates in the vicinity of the unstable fixed point, and the acceleration rate in the numerical simulation was unrealistically high. In the actual implementation, a strong noise signal, the chimney, is introduced such that ions are unable to move beyond the resonance momentum (see Fig. 5). In the simulation, these recaptured ions were accelerated intc the septum.

A similar run where the acceleration rate was increased tenfold resulted in the extraction of a small fraction of the beam.

The DIMAD runs verify the lack of coupling between the vertical and the radial plane and small coupling between the initial momentum and the radial emittance of the extracted beam.

A separate DIMAD run was used to determine the locus of the equilibrium orbit and the key unstable fixed point as functions of momentum. This run revealed that the quadratic terms cause the unstable fixed point to move slightly and also caused the motion of the equilibrium orbit to depart from a straight line by a similar amount as it passes the unstable fixed point. The curvature increases noticeably for momenta above the maximum for the extracted beam. A desirable improvement would be to zero this quadratic term which LATTICE cannot calculate.

## V. ACKNOWLEDGEMENTS

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