INJECTION INTO A HIGH-INTENSITY SYNCHROTRON FROM A CYCLOTRON

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ABSTRACT

The first stages of the proposed 30 GeV, 100 μA TRIUMF KAON factory[1)] consist of a 0.45 GeV Accumulator ring injecting into a 3 GeV 50 Hz Booster synchrotron. The Accumulator is filled with 1.25×10^{13} protons over ~ 15 ms by charge exchange injection of H^- ions from the TRIUMF cyclotron. The manipulation of injection parameters to produce stable particle distributions and to control beam loss will be discussed together with features of the beam transport system which decouples and matches the cyclotron and ring. The recently funded $11M KAON Factory pre-construction Engineering Design and Impact Study will be described.

1. INTRODUCTION

The five major competing kaon factory proposals have similar aims and architecture. A rapid cycling booster synchroton accelerating protons to a few GeV (where $\beta \simeq 1$) is followed by a second synchroton to provide the major energy gain. All use charge exchange injection to populate phase space over many turns; all, except TRIUMF, propose to use linac injectors. The relatively low instantaneous beam current from the H^- cyclotron coupled with the high rate of acceleration necessitate a fixed energy accumulator, (A-ring), which gathers charge for one booster cycle while the previously accumulated charge is being accelerated. The TARN, Indiana and Celsius cooler/synchroton rings already operate with cyclotron injectors but with less intensity and a lower rate of acceleration. The kaon factories are more concerned about fractional beam loss.

Meson factories and synchrotron laboratories have data on radiation fields vs beam loss at accumulator and kaon factory energies. A hands-on maintenance environment, 0.1 mSv/h at 0.5 m after cool down, corresponds to 2 nA/m loss at TRIUMF. The field 14 m downstream from a heavily shielded and collimated "thin", 2 mg/cm^2, carbon target removing ~ 4.5 μA of the beam is 4 mSv/h. A and B rings share the same tunnel, circumference 214 m. Average currents would be 50 and 100 μA and hands-on maintenance limits the distributed loss to 0.8% at 0.45 GeV or 0.06% at 3 GeV or some combination. Localisation by collimation may be desirable. Losses at injection or extraction should be kept below 1 μA at 0.45 GeV, or equivalent, and the region equipped with closely packed shielding and remote handling.

Intrinsic beam loss mechanisms due to instabilities from collective effects and the proximity to resonances depend on the local beam density. Existing synchrotrons operate with circulating currents ~ 2 A. The initial rf should be a harmonic of the cyclotron frequency (23 MHz) and bucket-to-bucket transfer used between machines. These constraints converged on a reference design[1-3)] with 40 bunches at 46 MHz. Each contain 3×10^{11} protons with transverse emittance ≥ 30 π mm mrad in both planes and longitudinal emittance ≥ 0.05 eVs to yield tune shifts $\Delta Q_{x,y}$ and $\Delta Q_s/Q_s \leq 0.2$. Cost factors, e.g. beam pipe size, "good field" width, set the upper limit. A mismatch of position or shape on transfer can lead to injected beam lying outside the machine acceptance. Losses also occur via gas scattering, electron trapping, collision with septa and by proton energy loss and angular scatter in the charge exchange foil. These interception losses are of greater concern for cyclotron injectors than linacs because of the longer accumulation time at lower energy.

2. PAINTING

Typical cyclotron, and linac, emittances are 1 or 2 π mm mrad and $\sim 10^{-3}$ eVs, much smaller than the minimum stable acceptance. Septum-less charge exchange injection allows the controlled, optimal, population of an acceptance. A trapezoidal, rather than gaussian, form factor, minimises tune shift. A reformulation[3)] of the Keil-Schnell criterion gives the maximum slope of the density distribution in longitudinal phase space. Injection of a small-emittance beam displaced from the closed orbit populates an annular region of phase space, Figs. 1 a,b. The double peaked distribution may be filled by sweeping the closed orbit from a position close to the injected beam onto the axis. This also moves the stored beam toward the ring centre and off the foil. The foil and incoming beam are kept at the edge of the accumulating distribution. This process has been termed painting. The ratio of foil traversals to revolutions is termed "turn factor (TF)". A finite momentum dispersion, η, at the foil location enables synchrotron oscillations to reduce foil traversals.

The horizontal betatron amplitude of particle (x, x') may

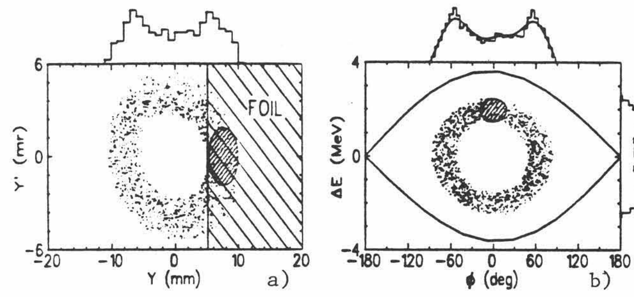

Fig. 1. Population of annular regions in phase space by charge exchange injection of a beam of small emittance displaced from the closed orbit.

be described by the Courant Snyder invariant

$$\epsilon_x = \gamma_x x^2 + \beta_x x'^2 + 2\alpha_x x x'$$

where α_x, β_x and γ_x are lattice parameters (at the foil location unless stated otherwise). Similarly ϵ_y. Consider Fig. 2; if the tunes are irrational the TF for an individual proton is the fraction of the betatron locus, in normalised phase space, overlapping the foil. Planner[4] has derived turn factors for painting in transverse and longitudinal phase space valid where $CP < F_i$. He shows that, ideally, the lattice construction should permit foil placement where $(\alpha\eta + \beta\eta') = 0$. The foil area projecting into the acceptance, hence TF, can be reduced by making the H^- spot dimensions small compared with the ring acceptance. The H^- half-width must be $\gtrsim 2\left[(\epsilon_{H^-}/\epsilon_{\rm painted})^4/2\right]^{1/6}$ to contain the divergence within the acceptance. The matched half-width is $(\epsilon_{H^-}/\epsilon_{\rm painted})^{1/2}$. The difference in TF is about a factor 2; half arising from the narrower foil, half from a shortened dwell time on the foil as the closed orbit displacement collapses. The TF is not very sensitive to change of parameters provided $\epsilon_{H^-} \leq 4\epsilon_{\rm painted}$.

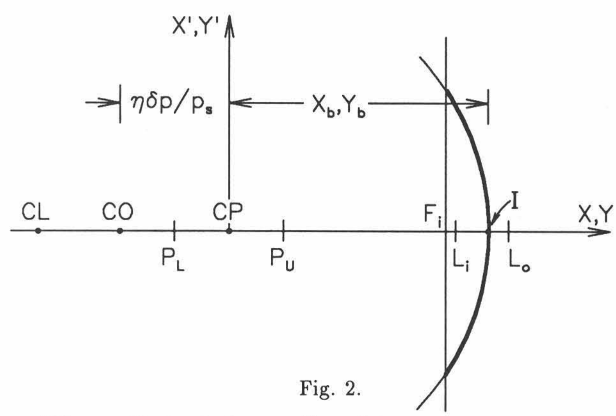

Fig. 2.

CL	Mechanical centre-line of ring
CO	Closed orbit of synchronous momentum P_s
CP	Closed orbit of particle with momentum $(P_s + \delta P)$
I	Injection point of H^- ion, momentum $(P_s + \delta P)$
$(CP - I)$	Betatron amplitude of resulting proton $(P_s + \delta P)$
$(L_i - L_o)$	Width of H^- beamlet with momentum $(P_s + \delta P)$; width of H^- spot if injection achromatic at foil
$(P_L - P_U)$	Closed orbit band for beam with momentum band $(P_s + P_L) \leq P \leq (P_s + P_U)$
F_i	Inner edge of foil; may coincide with L_i for achromatic "ideal" case.

Dispersion at the foil automatically correlates a lower momentum component with a larger betatron amplitude. Both phase spaces may be painted by varying the momentum without the necessity of a closed orbit bump; however the resulting distribution is unlikely to be ideal in both planes. There are other constraints. Consider Fig. 2 and a matched case. To fit within a horizontal acceptance A_x,

$$\left(\eta_x/\sqrt{\beta_x}\right)(\Delta p/p) < \sqrt{A_x} - \sqrt{\epsilon_{H^-}}$$

On the other hand for the proton beam to clear the foil and give a longitudinal TF≤0.5

$$\left(\eta_x/\sqrt{\beta_x}\right)(\Delta p/p) > \sqrt{\epsilon_{H^-}}.$$

Should an elliptical beam cross section be desirable small y amplitudes should correlate with large x when painting. Some authorities claim that it is difficult, in practice, to completely compensate all skew fields. Coupled motion then produces a halo with both large x and y amplitudes and retention requires a pipe with rectangular cross section. Schönauer[5] has proposed to offset the H^- beam in one plane and use a difference resonance to populate the other. This also reduces TF.

3. ACCUMULATION STUDIES

The basic geometric approach is used to devise a strategy yielding the desired average TF. The final TF will be affected by other physical processes. A general computer code, ACCSIM has been written to simulate accumulation. It incorporates, in some cases approximately, first order lattice optics, synchrotron motion, chromatic (momentum dependent) effects, imperfections or higher order terms described by thin lenses, transverse and longitudinal space charge, Coulomb scattering and energy loss and collimation. It yields the number of foil traversals, accumulated ensembles, form factors and tune shifts, loss statistics and origin, and indicates potential pathalogical behaviour. The latter require confirmation by analysis or by more accurate but less general programs. Eventually the foil traversal data will be folded with analytic descriptions of proton/foil interactions to better describe beam halo where simulation statistics are poor.

Hollow Longitudinal Distributions[6]

Space charge forces render the beam accumulated by the process illustrated in Fig. 1b unstable, (Fig. 3). Write the longitudinal potential as $V(\phi) = V_{\rm rf}\sin\phi + V_1\sin\phi + V_2\sin 2\phi \ldots$ where $V_{1,2}$ are space charge contributions. A filled acceptance with 3.2×10^{11} protons has $V_1 = -120$ kV and $\mid V_{2,3}\ldots \mid < 20$ kV compared with $V_{\rm rf} = 575$ kV. A midway stage with the outer half only filled has $V_1 = -30$ kV, $V_2 = +60$ kV. The small amplitude synchrotron tune is decreased in the first case, by $\sqrt{V_1/V_{\rm rf}}$, and increased in the second. The tune for the largest amplitudes, which average the potential, has a small decrease for the second case.

The first moment of the particle distribution in normalised phase space is termed the dipole moment. The presence of a small dipole amplitude in a hollow beam displaces the loci in a sense to enhance the dipole. Saturation is reached when the rate of growth and diffusion from tune spread balance. This occurs within a few thousand turns, hence this effect is important for cyclotron injectors and perhaps linacs. Computer simulations do not predict loss in the accumulator but do predict longitudinal emittance growth and possible loss in the following synchrotron. The amplitude ±1 deg seen for 1.6×10^{11} p/bucket is close to the borderline of acceptability and we prefer methods which fill the centre of the longitudinal bucket first. We have seen no evidence to date of instability for beams hollow in transverse phase space.

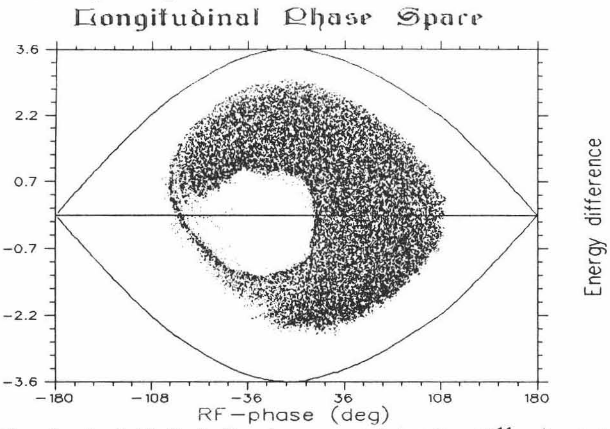

Fig. 3. An initially hollow beam containing 3×10^{11} p/bucket generates a dipole amplitude of 29 deg after ~1000 turns. V_{rf} = 566 kV.

Coulomb Scattering

Protons traversing the stripping foil are scattered by the electric field of the nucleus and atomic electrons. Consider the annular distribution of Fig. 1a. A scattering event $\pm\delta y'$, from residual gas or from a foil spanning the distribution, can increase or decrease the betatron amplitude, being most effective when y≈0. Foil scatters when "painting" occur where $y \approx y_{max}$ and, in the limit, always increase the betatron amplitude but by a small amount since the $\delta y'$ vector is almost perpendicular to the phase space vector. However at the edge of the acceptance 100 foil traversals can increase the emittance significantly; Fig. 4. A cyclotron injector should probably not paint the extreme outer edge.

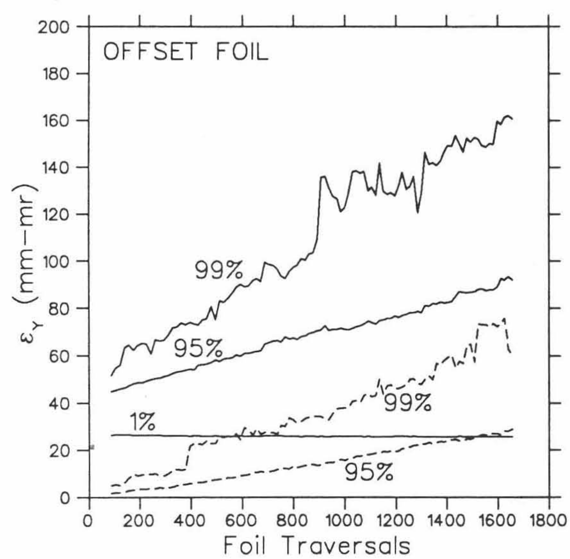

Fig. 4. Emittance growth with foil traversals. H^- injected at the edge of a 250 $\mu g/cm^2$ C foil. The closed orbit is offset to paint an annulus $25 \leq \epsilon_x \leq 43\pi$ mm mrad (solid line) and coincident with H^- beam centre (dashed line).

The importance of this process led to an investigation of the precision of the model used for calculations. The differential and total cross sections were obtained[7] for several light elements using electron and nuclear charge density distributions calculated by a Hartree Fock method. The maximum retained angle of scatter for an acceptance of 50π mm mrad and β=10 m is 20 m rad. There are ~3 events/traversal and few particles undergo more than one thousand scatters, hence the smallest scattering angle of interest is ~ 1 μrad. These give the fitting range for parametrised models. Some experimental data on nuclear elastic (and inelastic) scattering extend into ~ 20 m rad and match with the calculated value.

Foil Lifetime

The foil thickness producing the equilibrium charge distribution causes excessive scattering; 250 $\mu g/cm^2$ carbon is a compromise giving 99% conversion at 450 MeV. The foil lifetime is chiefly determined by radiation-induced alteration of the lattice, although at high temperatures this may be exacerbated by crystalline phase change. The TRIUMF cyclotron foil life corresponds to ~ 6×10^{19} protons/mm^2. Aluminum oxide or thin carbon foils folded into a double layer may have a longer life.[8] Comparisons of different materials under identical conditions are planned at the 800 MeV 100 μA Los Alamos proton storage ring.

Example

Figure 5 shows an ACCSIM simulation of a scheme in which 45π mm mrad in both planes is painted by a momentum sweep from low to high energy coupled with a simultaneous lowering of the closed orbit.[9] The H^- beam ($\epsilon_x = 3\pi$, $\epsilon_y = 2\pi$ mm mrad, ΔE=±0.6 MeV, $\Delta\phi$ = ±20 deg (46 MHz)) is converted by a foil with two free edges. The synchronous closed orbit is offset 28 mm to facilitate injection optics. Foil interactions increase the geometric TF by 17% to 0.009. The accumulated emittance (99%) is ϵ_x=47.7 π and ϵ_y = 51.3π mm mrad. The foil life is estimated >8 h at 100 μA from 4×10^{13} traversals/mm^2/20 ms cycle.

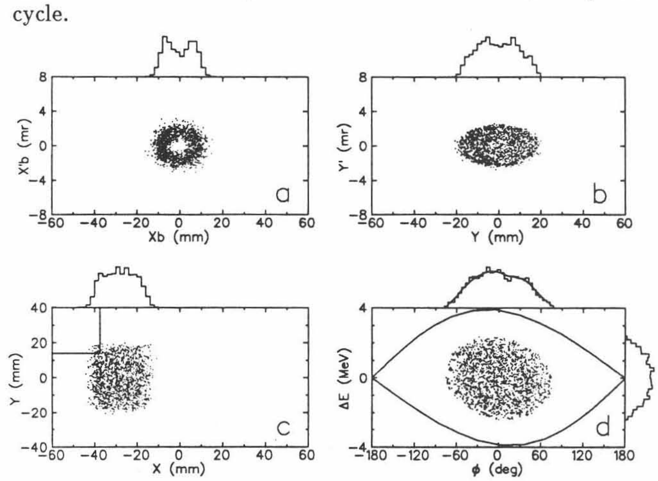

Fig. 5. Ensemble accumulated after 20,000 turns (simulation), the injected H^- and foil are in the top left hand corner.

4. CYCLOTRON AND TRANSFER LINE

The H^- extraction system is reviewed elsewhere.[10] The energy spread and transverse emittance of the extracted H^- beam are a function of the energy gain per turn in the cyclotron (Fig. 6a). Figure 6b gives the average, geometric, turn factor, as a function of horizontal acceptance. $\Delta E/\text{turn} \leq 0.5$ MeV and acceptance $\geq 40\pi$ mm mrad give a comfortable regime with TF < 0.01. 100 μA cw in the kaon factory requires cyclotron operation equivalent to 135 μA to allow for extraction efficiency, generation of empty buckets to accommodate ring kicker magnet rise and fall, and time to reset painting parameters. TRIUMF has demonstrated 425 μA equivalent, which would reduce TF by a factor 3; however the pulse width of 100 deg (46 MHz) just fits the A ring acceptance and would preclude longitudinal painting which gives a similar TF.

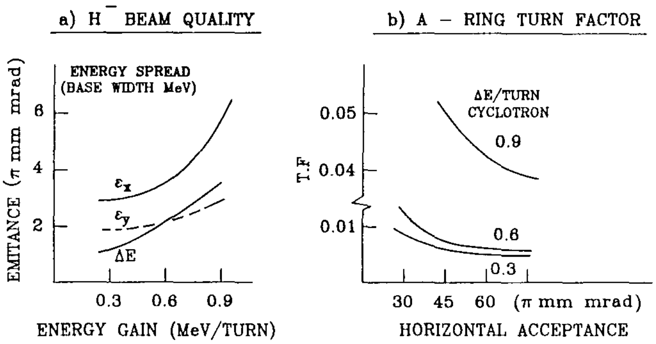

Fig. 6. a) Energy spread and transverse emittance of H^- beam extracted from TRIUMF as a function of energy gain. b) Average geometric turn factor as a function of A ring acceptance for the data of 6a.

The 150 m transfer line linking the cyclotron and accumulator rings should incorporate features to decouple the kaon factory from drifts in cyclotron conditions and to prepare the H^- beam for injection. Drifts in extraction energy must be compensated since the A-ring frequency is locked to TRIUMF and the ring energy, once constructed, is fixed. Extraction will not be single turn and empty buckets would be generated by a fast (1 MHz) chopper rather than at the ion source. An electric field of 5 kV/cm·m should rise and fall between cyclotron bunches i.e. 35 ns. The H^- beam should have no tails to extend over the acceptance boundary when painting close to the edge. Their presence may be sensed by stripping H^- into a detector at emittance measuring stations and at a dispersed focus. Energy ramping would take place just before injection. Rees[9] has suggested that, to avoid increasing the H^- energy spread, two cavities phased 180° apart should be used and the energy swept by adjusting the phase difference.

H^- will be stripped to H^+ in a single foil located inside the A- ring. Unconverted H^0 may be useful for diagnostics. Provision must be made in the ring to collect H^- ions in the event of a broken foil or a mis-steered beam.

5. Pre-construction Engineering Design and Impact Study[2]

Following favourable technical reviews and indications of international support totalling ~200 M$C the Federal and Provincial Governments have funded jointly an 11 M$C pre-construction engineering design and impact study. This will run from October 1988 to December 1989 and will lead to a revised cost-estimate, a better definition of international support, an assessment of the effect on Canada, and explore industrial interest in the design and manufacture of accelerator components.

The accelerator design package (8M$) includes the construction of prototypes of critical items in addition to funding beam dynamics studies and experiments. A second generation electrostatic deflector and prototype iron core current compensated magnetic channel will be built for the H^- extraction program together with a prototype 1 MHz chopper for the 0.45 GeV beam transfer line. Booster synchrotron equipment consisting of a prototype 3 m, 50 Hz, 0.27 to 1.05 T dipole magnet, a 50 kV, 46-61 MHz rf cavity and a section of ceramic beam pipe with rf shield will be constructed. Further details may be found in Ref. 2.

ACKNOWLEDGEMENTS

The comments of R. Baartman, M.K. Craddock and S. Koscielniak and the help of R. Laxdal, F. Jones and R. Lee in performing calculations are gratefully acknowledged.

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