ACCUMULATOR RING H^- INJECTION OPTIMIZATION STUDIES

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Abstract

H^- ion injection into an accumulator ring is a limiting process for future high-intensity pulsed spallation neutron sources. To facilitate the injection design process, a method has been developed to access a tracking code, ACCSIM [1], from within an optimization package [2]. The optimization tool is a C++ interactive driver with steepest decent and genetic algorithm optimization methods and parallel computing capabilities. Some injection parameters varied in the optimization process are the H^- beam size and position, the foil configuration and thickness, and the horizontal and vertical bump time profiles. Constraints and figures-of-merit include maximum allowed foil temperature, maximum allowed space charge tune shifts, maximum allowed foil traversals, and maximum allowed beam losses. Application of this method to accumulator ring injection in the proposed National Spallation Neutron Source (NSNS) is presented.

1 BACKGROUND

In NSNS an intense H^+ beam is built up in an accumulator ring by stripping an incident 1 GeV H^- beam at injection. The H^- ions and stripping foil are necessary to overcome Liouville's Theorem in merging the injected beam into the circulating H^+ beam. Building up the circulating beam is an intricate process requiring a time-dependent bump of the reference orbit over ~1200 turns to obtain the required emittances and distributions. In addition, other considerations impact the process. Because of the high beam intensity, uncontrolled beam line losses must be kept to a minimum ($<10^{-4}$). The temperature of the carbon stripping foil must not exceed 2750° C. The tune shift induced by the space charge in the circulating beam must be small (<0.15) to avoid resonances. To minimize beam losses and satisfy these constraints, a number of parameters can be varied: the H^- beam size and position, the foil configuration, the horizontal and vertical bump time profiles, the foil thickness, and the longitudinal parameters. The problem of injection into the NSNS accumulator ring is thus one of optimization. With this in mind, a method has been developed to call a tracking code, ACCSIM[1], from within an optimization package[2]. We apply this method to minimize beam losses during accumulator ring injection into the proposed NSNS.

2 MODEL DESCRIPTION

2.1 Overall Configuration

The optimization of NSNS ring injection is accomplished by calling the particle-tracking code, ACCSIM, from the SUPERCODE driver Shell. SUPERCODE is an interactive C++ shell that incudes optimization tools. In this case we utilize a Genetic Alogrithm (GA) option to perform the optimization. The information flow between codes is shown schematiccaly in Fig. 1. The optimizer creates a population, each member consisting of a set of selected values for the indpendent variables, and passes each member to a distinct copy of ACCSIM (which is used by SUPERCODE as a "function evaluator"). These copies can reside on separate workstations, or on separate nodes of a parallel computer. Each copy of ACCSIM then performs a calculation using its input and returns the constraint and Figure-of-Merit (FOM) values. These are then used by the GA routine to create a new generation, and the procedure is iterated to convergence. The message passing is done using PVM [3] with which we have used up to 20 workstations in parallel.

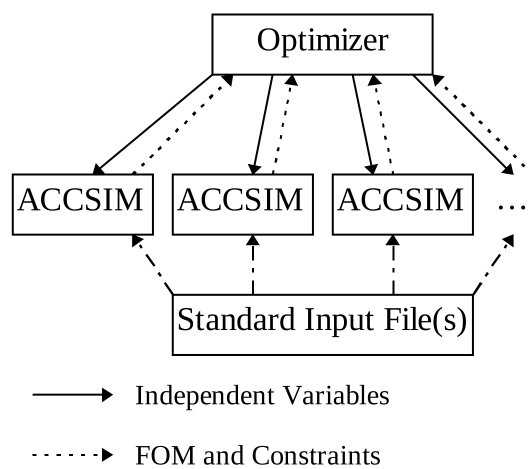

Fig. 1 Overview of information flow in the optimization setup.

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2.2 ACCSIM Modifications

To facilitate the present studies, a number of additions were made to ACCSIM: (1) exponential decay (x,y) bump profiles, (2) foil temperature calculation, (3) in-foil nuclear elastic scattering (NES) loss fraction calculation, (4) foil-induced fractional 4&5 excited state H^o production calculation, (5) injected beam coordinates and final bump location to obtain specified final painted emittances, and (6) message passing to/from the optimizer as discussed.

2.3 Problem Formulation

The constraints are listed in Table 1 and the variable parameters in Table 2. The Figure-of-Merit is minimum beam loss (NES + H^o 4&5 state losses). The tune shift depends on the longitudinal parameters through the bunching factor. This dependence will be explored in future work. Present calculations were performed with the following longitudinal parameters: first harmonic RF at 30 keV and the ring transit frequency and 65% longitudinal bunch length.

Table 1. Constraints on Calculated Quantities.

Constraint
Peak Foil Temperature $\leq$ 2750 °C
Peak x tune shift < 0.15
Peak y tune shift < 0.15

To find optimal solutions, the parameters listed in Table 2 are allowed to vary within the indicated bounds.

Table 2. Variable Input Parameters.

Bound:	Lower	Upper
Linac Beam x/y Beta (m)	1	50
Initial Bump x/y offset (mm)	0	15
Normalized bump x/y e-fold time scale	1	10
foil thickness (mg/cm^2)	50	1000

3 RESULTS

Table 3 shows the results of injection optimization studies performed to date. Due to the "fuzziness" of the GA optimizer there are occasional borderline violations of constraints. The total loss rate is the sum of the nuclear elastic scattering (NES) and the H^0 4&5 state excitation rates in the stripping foil. Small angle Coulomb scattering is ignored here, but will be considered in future studies. The bump rates are exponential decay rates in the bumped beam position. The initial bumped beam is centered at the x and y offsets relative to the injected beam center. The circulating beam center after injection is positioned to yield the desired transverse emittances. Large bump rates lead to hollow profiles in the corresponding phase space. Small bump rates lead to peaked beam profiles. Except when beam center fixed in y, all the parameters in Table 3 are varied by the optimizer to minimize total losses and to satisfy the constraints.

3.1 Presentation of Results

Most of the following studies have constant offsets in y. The resulting y-y' phase space beam profile is a hollow ring. The x bump rates are slow, leading to peaked beam profiles in x-x' phase space.

The first three cases in Table 3 examine the effect of the foil edge configuration on the loss rate. The most striking feature is the large loss rate for a single-edged foil. This results from a higher particle-foil impact rate than for the other cases. The results for the two- and three-edged cases are very similar, showing no advantage with a three-edged foil. However, a three-edged foil can be used to collimate the beam.

The second study shown in Table 3 consists of four cases differing in the fraction of the injected beam allowed to miss the foil. This portion of the beam remains H^- and goes to the beam dump. When 2% or more of the beam is allowed to miss the foil, the foil-induced beam losses decrease measurably. This is caused by fewer foil impacts per particle, which results from the placement of the injected beam closer to the foil edge when more beam is allowed to miss the foil.

In some estimates as much as two-thirds of the beam energy loss promptly leaves the foil, which implies reduced foil heating. In the third study, the energy deposition formulation for the beam in the foil was arbitrarily halved. With this reduced heating the optimizer selected a thicker foil to eliminate the excited state H^0 losses while still satisfying the foil temperature constraint.

In the next study, the nuclear elastic scattering cross section was arbitrarily tripled. The main effect on the solution was an enhancement of the NES losses. The other quantities show little effect. For foil thicknesses around 600 mg/cm^2, the H^0 loss rate is strongly decreasing, while NES losses increase linearly. Hence, the tendancy toward thinner foils from tripling the NES cross section is countered by the tendancy toward thicker foils driven by the H^0 loss rate.

The remaining studies include orbit bumps (hence phase space painting) in both x and y. Reductions occur in all losses, in foil impacts per particle, and in x space charge induced tune shifts, together with an increase in foil thickness made possible by the reduced particle hit rate. The optimal bump rates are slow in y and fast in x, so the resulting phase space distributions are peaked in y-y' and hollow in x-x'. Hence, the additional degrees of freedom provided by a variable y bump allow improved solutions compared to x bump alone.

The final study involves the selection of a different figure-of-merit, namely minimum number of foil traversals. The optimizer achieves this by selecting a very narrow injected beam that can subsequently clear the foil in the circulating beam. To satisfy the foil temperature constraint, given the intense injected beam spot, the optimizer is forced to make the foil very thin. The resulting excited H^0 losses are huge, so that the solution is technically unacceptable, but the value of 1.8 foil hits per particle is indeed small.

3.2 Summary

The coupling of optimization with accelerator physics techniques provides a systematic automated approach to the solution of complicated design problems. Applications of such an approach to injection into the NSNS ring yield sensible solutions that could otherwise be obtained only via trial and error.

4 FURTHER STUDIES

A number of enhancements to the present study will be pursued. These involve (1) the inclusion of Coulomb scattering effects of beam particles impacting the foil, (2) an enhancement of the current simple treatment of space charge effects to include orbit effects and resonances, and (3) enhanced modeling of the longitudinal beam dynamics to facilitate longitudinal phase space painting into rings with generalized RF systems including several harmonics.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] F. W. Jones, "User's Guide to ACCSIM", TRIUMF Design Note TRI-DN-90-17, (1990).

[2] S. W. Haney, et al., Fusion Technology, **21**, (1992), 1749.

[3] http://www.netlib.org/pvm3/book/pvm-book.html

Table 3. Summary of Optimization Runs

Case Studies	FOM - Fractional Loss ($x10^{-4}$)			Foil Hits / Part.	Constraint Values			Variable Parameter Values			
	Total Loss	NES Loss	H^o Loss		Max Dn_x	Max Dn_y	Foil Tmp (^oC)	Bump Rates r_x, r_y	x,y Offset (mm)	b_x Inj. (m)	b_v Inj. (m)	Foil Thick mg/cm^2
Foil Edge												
1 Edge, 1% Miss	3.90	3.21	0.68	29.8	0.16	0.15	2724	1.3, ∞	5.7, 15.1	29.2	21.9	581
2 Edge, 1% Miss	1.81	1.41	0.40	12.4	0.16	0.15	2667	1.3, ∞	6.6, 15.1	38.5	21.9	612
3 Edge, 1% Miss	1.95	1.46	0.49	13.1	0.17	0.15	2742	1.3, ∞	5.0, 15.8	42.7	15.3	600
% Miss Foil (2 Edge)												
0.5% Miss	1.64	1.45	0.20	11.9	0.17	0.15	2755	1.3, ∞	4.5, 15.1	34.6	21.6	653
1.0% Miss	1.81	1.41	0.40	12.4	0.16	0.15	2667	1.3, ∞	6.6, 15.1	38.5	21.9	612
2.0% Miss	1.38	1.26	0.12	10.0	0.16	0.15	2769	1.3, ∞	5.0, 15.1	34.6	21.6	679
4.0% Miss	1.39	0.90	0.49	8.1	0.16	0.15	2712	1.5, ∞	5.4, 15.0	30.0	22.1	600
Foil E-Dep (2-Edge)												
100% Dep. , 1% Miss	1.81	1.41	0.40	12.4	0.16	0.15	2667	1.3, ∞	6.6, 15.1	38.5	21.9	612
50% Dep. , 1% Miss	1.70	1.62	0.08	12.4	0.15	0.13	2662	1.6, ∞	3.4, 17.1	46.4	6.9	703
s_{NES} x 3												
2 Edge, 1% Miss	5.18	4.77	0.41	14.0	0.16	0.15	2747	1.2, ∞	4.5, 16.0	46.9	14.1	610
3 Edge, 1% Miss	3.98	3.30	0.68	10.2	0.16	0.16	2707	1.5, ∞	8.9, 15.0	30.	22.6	582
Y-Bump												
2 Edge, 1% Miss	1.41	1.21	0.21	10.0	0.12	0.15	2733	6.9,1.2	5.7, 6.0	35.7	22.1	650
2 Edge, 4% Miss	1.07	0.96	0.11	7.6	0.10	0.15	2742	6.2,1.3	6.3, 4.8	37.6	21.1	686
3 Edge, 1% Miss	1.43	1.27	0.16	10.3	0.11	0.15	2741	5.7,1.2	3.7, 5.9	37.8	21.1	663
3 Edge, 4% Miss	1.18	0.97	0.21	8.1	0.12	0.15	2745	4.1,1.3	6.3, 5.5	33.5	21.4	649
Min. Traversals												
3 Edge, 4% Miss	469	0.02	469	1.8	0.12	0.13	2748	3.8,1.	6.0 , 0.2	6.2	1.3	71