BEAM LOSS COLLECTION ON THE ESS ACCUMULATOR RINGS

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Abstract

The Linac and Accumulator Rings of the European Spallation Source [1] provide a mean beam power of 5 MW, and the need to control beam loss has dominated their design. The function of the beam loss collection system in the two 1.334 GeV accumulators is to localise all loss and associated activation efficiently, in one well shielded region, thereby allowing hands-on maintenance elsewhere. Here, the rings' beam loss collection system is described, detailing the collector system layout and the main parameters optimised, and showing how effective machine protection is ensured under most foreseeable circumstances. Important aspects of the design are: optimising speed and efficiency of halo removal over the ~1000 turns the beam circulates in the ring; minimising halo and out-scatter; heat deposition and activation issues; optimising transverse and longitudinal collector geometries.

1 OUTLINE OF ESS RING COLLECTORS

1.1 Ring Parameters and Design Approach

The two 1.334 GeV rings operate in parallel at 50 Hz. $2.34\text{x}10^{14}$ protons are accumulated in each ring over the ~1000 turn charge exchange injection process; once both rings are filled, beam is extracted in a single turn. The subject of this work is the control of loss once beam has entered the ring.

The design aim has been to optimise primarily for known and likely regular 50 Hz losses, whilst maximising as far as possible protection for irregular or fault loss. The expected regular losses (0.02%) are due to the stripping foil which produces a negative momentum tail and emittance growth. There may also be regular loss due to space charge emittance growth, and irregular losses of all types due to fault conditions. The ring lattice design includes one dedicated long dispersionless straight for collimation. This contains the two main systems: the General Betatron and Momentum Tail Collectors. In addition, there is a General Momentum Collector further downstream, provided for irregular loss.

1.2 Outline Configuration

The **betatron system** is based on the standard configuration of a primary jaw defining the usable aperture, and two secondary jaws for intercepting out-scatter [2], Figure 1. Collimation and full rectangular apertures are 260 and 480 π mm mr respectively. Tolerances indicate optimal betatron phases for secondary collectors are 18° and 163°, but lattice constraints make the latter 140°. Betatron phase advances are roughly equal in the transverse planes, and so jaw assemblies for both are combined in a 'hollow box' construction. The double jawed primaries chosen demand similar secondaries. Double jawed collectors are also included at 90°. Preferred materials are graphite and steel for primaries and secondaries respectively

A special **momentum tail system** was designed into the lattice. Particles losing momentum at the high dispersion injection point undergo enhanced betatron oscillations, these are intercepted at their next maxima 180° downstream in the collector straight. This system is combined with the betatron system; one betatron primary jaw doubles as the momentum tail collector.

The double jawed **general momentum system** is placed at the first dispersion maxima after the collector straight. This will remove low momentum particles leaking from the main collectors, and longitudinal loss.

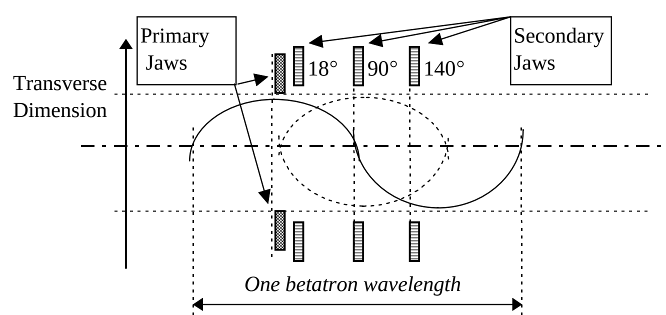


Figure 1: Schematic Of 1D Betatron System

1.3 Key Parameters & Particle Interactions

The basic configuration described leaves many important design choices open, particularly transverse and longitudinal geometry. Basic aims in optimising collector system design are: (i) to minimise out-scatter from the primary collectors, (ii) to minimise or control collection time for halo and (iii) to maximise out-scatter collection. The first two are critically dependent on geometry, the third depends on an optimised set of secondary collectors.

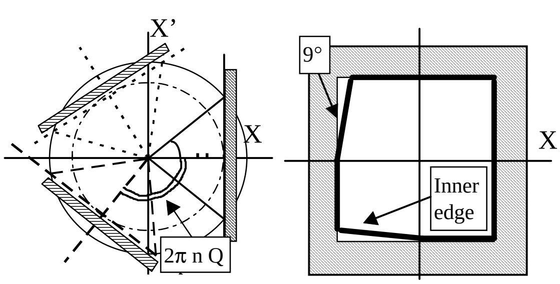
The purpose of the collector system is to localise activation; only particles escaping the shielded collector straight are of interest. These will be mainly protons near 1.334 GeV which out-scatter from the surface of the collector. Most secondary particles (low energy protons, and n, π, μ, e at various energies) will encounter the extensive collimation, which is included in addition to the collector jaws.

For detailed information of *out-scattering protons*, a Monte Carlo code is being developed. However, an approximate physical model is valuable for understanding and estimating key parameters. Three effects dominate: ionisation energy loss, ‘Gaussian’ multiple Coulomb scattering and large angle/inelastic nuclear interactions. It is assumed all protons undergoing the last receive enough angular deflection to be removed. This implies exponential attenuation, with 87% removal over 2 mean free paths (λ). Multiple scattering is estimated using a ‘Gaussian’ spatial distribution [3], calculated at an average energy to allow for energy loss. For graphite, the 1σ beam spatial width is ~5 mm at 1λ (30 cm), increasing rapidly with length. Therefore the probability of out-scatter, Figure 3, is a sensitive function of *impact depth* over ~1 mm scales.

2 TRANSVERSE GEOMETRY

2.1 Model of Collection Process & Simulation

A monochromatic circulating bunch of emittances (ε), can be represented in normalised transverse phase space (X,X’,μ) as helically rotating particles on the surface of a cylinder (a.cos(μ(s)+ϕ),a.sin(μ(s)+ϕ),μ(s)), with μ(s) the betatron phase at a point and a=$\sqrt{\varepsilon}$ the amplitude. A short, flat collector at one machine azimuth removes a sector of beam at $\mu(s)=(2\pi Q\,n)$ on the n^{th} turn, Figure 2a. The collection process, defined by parameters such as impact depth and collection time, are non-trivial functions of Q and ε. To study collection of beams with spreads in (Q, ε), in two transverse dimensions, the best approach is a Monte Carlo program.



(a) Collector Action (b) Transverse Shape

Figure 2: Collector Action and Shape

Transverse positions for 10^5 particles are calculated at the collector on successive turns with the standard formula, $z_n = A_n \cdot \cos\left[2\pi \cdot Q_z \cdot n + \varphi_z\right]$, until they hit. Uniform random distributions in ϕ [0,2π], and in Q over the expected ranges, are used. Growth rate of the beam (*GR)* is modelled with $A_n=(A_0+GR\ n)$, the betatron amplitude on the n^{th} turn. With this model, the properties of any 2D collector geometry may be assessed as a function of (*Q*,*GR*,ε*)*. Most valuable are distributions in impact depth and turns taken to hit. No attempt is made to predict the distributions on the real machine, which are dependent on many unknown parameters. These simulations do however give a detailed knowledge of collector behaviour over all expected ‘loss space’ (ε, *Q*, *GR*), thus ensuring no ‘holes’ exist.

2.2 Possible Geometries and Growth Rates

There are two extremes for transverse collector shape: (i) double jawed flat collectors and (ii) single jawed angled collectors, that cover maximum and minimum areas of phase space for a given emittance respectively. The advantage of the first is quick removal of halo. The second collects particles more slowly but generally reduces out-scatter by increasing mean impact depth.

Jaws with angles of 9° relative to the flat are chosen, which give advantages without reducing useful aperture significantly; the inner edge is at $\varepsilon_{inner}=200\,\pi$ mm mr. Growth rates from 10^1-10^{-3} mm/turn have been modelled. For the normal losses expected typical values are 0-100 μm/turn; values of $\geq$1mm/turn are relatively fast and might be expected under fault conditions.

2.3 Results and Conclusions

Simulations indicate a single angled collector, at typical 1D growth rates, removes 95% of beam in ~10^3 turns at mean impact depths of ~1 mm. Double edged flat collectors remove 95% of beam in ~60 turns, with mean impact depths of ~0.1 mm. Beam circulates in the rings for 10^2-10^3 turns, and it is desirable to remove fast growth within 100 turns. However, tenfold enhancements in impact depths will significantly reduce out-scatter.

Simulations show most desirable properties of both are achieved in a hybrid system with an angled edge at smaller emittances ($\varepsilon_{inner}<\varepsilon<\varepsilon_{coll}$) and additional double flat jaws at the collimator emittance ($\varepsilon\geq\varepsilon_{coll}$), Figure 2b. Quickly growing particles have inherently large impact depths, and are also intercepted efficiently.

3 LONGITUDINAL GEOMETRY

3.1 Length & Scattering on Inner Edge

In order to absorb 1.334 GeV protons and most products, a collector of one proton range (~2m graphite) is required. The main bulk of the collector will for these reasons be one range long. However, the optimal form of the collector edge next to the beam is non trivial.

Consideration of helically rotating particles in transverse phase space, with a collector of significant length, shows particles hit the inner collector edge as well as the front face. Most particles approach the collector at near zero angle, and so hitting the inner edge at zero impact depth enhances out-scatter. In addition, such out-scatter may not be efficiently intercepted, as secondary collectors are optimised for beam emerging near the front face. Calculations show that in a short collector, the front face shadows the inner edge which thus has negligible effect. However, at lengths of over ~4° in betatron phase, this is not the case and significant out-scatter occurs. Therefore the inner edge at such lengths should be set back with respect to the normalised beam envelope.

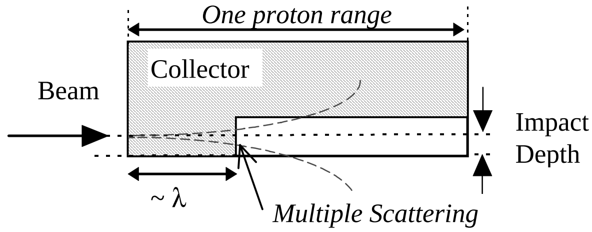


Figure 3: Longitudinal Collector Geometry

3.2 Beam Removal Process & Conclusions

The main removal process in the collector is scattering of the proton or its products into the downstream collector material. The inner face of the primary is a *deflector*. To maximise this scattering the front face should be as many λ as possible, but this increases scattering on the inner edge. Use of a higher A material shortens λ, but disadvantages in increased activation and heat deposition relative to graphite must be considered. The shape presently favoured is flat (normalised) for λ, followed by a set-back of ≈4 mm. This ensures most beam is removed in one turn with minimal interception of the inner edge. A result of the finite length of the inner face is production of protons with significant energy loss, which must be intercepted by downstream collectors.

There are a number of parameters here that need optimisation, and for this more detailed information is required. This will be provided by the 3D Monte Carlo code under development.

4 SECONDARY COLLECTORS

4.1 Essentials & Effect of Primary Shapes

Results from [2] have been applied, and the system has been outlined above. The 90° collectors prevent large emittance particles escaping the system, and allow for isotropic scattering in collector materials. The angled edges of the primary jaws are included on secondaries where practical. Secondary collectors are set at $\varepsilon_{coll+\Delta}$, the collimator limit plus the tolerance set-back, $\Delta \approx 2$ mm.

4.2 Acceptance Allocation

There are three boundaries in the machine acceptance imposed by the collector system ε_{inner}, ε_{coll}, $\varepsilon_{coll+\Delta}$, where primary angled jaws, primary double jaws, and secondary jaws become visible to the beam. At $\varepsilon \geq \varepsilon_{coll+\Delta}$ beam has to pass secondary collectors to escape the system. Projecting all downstream edges back to the primary, Figure 4, shows how effectively the system collimates. In fact few particles with $\varepsilon \geq \varepsilon_{coll+\Delta}$ will escape in one turn, whether resulting from out-scatter or fast fault loss. Therefore, significant protection is provided against very fast growth. Values of these three boundaries may benefit from further optimisation.

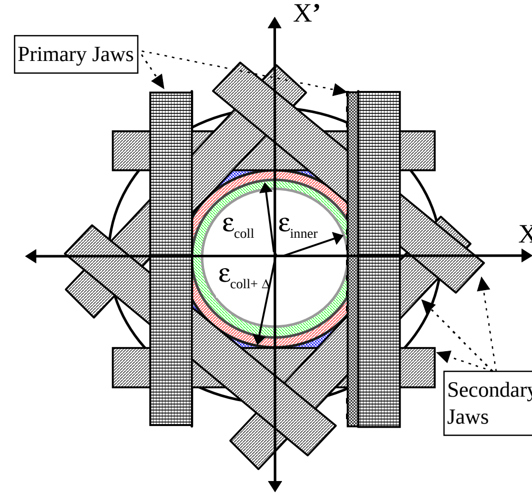


Figure 4: Normalised Phase Space Covered

5 PRACTICALITIES AND CONCLUSIONS

5.1 Construction, Heating and Activation

All collectors will be ~1 m long, modular hollow box constructions, with material extending out transversely ≥5 cm. Usual active handling procedures for quick removal will be employed. Extensive shielding is provided around the collector region. Graphite is preferred for the primary collectors because of its activation properties, and a cheaper steel construction for the secondaries. Heat is spread out over ≥1 m in the low A materials chosen, and the large heat capacity associated with the significant mass of material ensures temperature rises are moderate. Calculations show heating will not be a problem, assuming basic loss protection systems are present. Water cooling is provided for the primary collectors.

5.2 Conclusions

The main parameters of the collector system are established. Studies of the effects of collector geometry, outlined here, coupled with forthcoming Monte Carlo simulation will provide fully optimised designs.

REFERENCES

[1] ESS Feasibility Study, Vol 3, Nov 96, ESS 96-53M, *(available from KFA Julich or RAL).*

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[3] B. Rossi, “High Energy Particles”, Prentice Hall