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THE RELEVANCE OF ISIS EXPERIENCE TO THE DESIGN OF FUTURE HIGH INTENSITY SYNCHROTRONS

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Abstract The relevance of the experience obtained in the design and operation of the high intensity synchrotron ISIS is discussed in relation to the design of future high intensity machines.

1. INTRODUCTION

The ISIS 50 Hz, 800 MeV proton synchrotron (1) now operates at an average output current of 100 μA, a level markedly above that of other operating synchrotrons. Experience gained in the design and operation of the ring is relevant to many design areas of future high intensity machines. Of most relevance are the civil and mechanical engineering design details, the interlock and beam loss protection systems, the level of beam losses and damage, the performance of the ceramic vacuum chambers with their associated radio frequency shields, the H– injection system performance, and the observations and studies of beam instabilities. These topics are discussed in sequence in this report.

2. CIVIL AND MECHANICAL ENGINEERING

The ISIS synchrotron has been constructed in the magnet hall that previously housed the weak focusing, 7 GeV proton synchrotron, Nimrod. Many advantages have accrued from the use of this large magnet hall. The large space available, both inside and outside the magnet ring, see Figure 1, has eased the procedures adopted for hands–on–maintenance and simple remote–handling.

Nowadays the cost of such a magnet hall would be prohibitive. Instead a tunnel is suggested, but one with enlarged by–pass regions for one or two areas of the ring designated for beam loss collection. Such a beam loss concentration system has worked well at ISIS. The by–passes would be equipped with movable shielding and a working area for the repair of active, damaged components. For access into and around the ring, shielding would be moved to lie adjacent to the components of high activation. Maintenance in the low radiation regions is then conventional and only that in the highly active regions requires special procedures.

The important civil engineering features are the sizes of the tunnel and by–pass regions. The tunnels may be required to house more than one magnet ring and the ease of removal and installation of components should be a major consideration.

3. PROTECTION AGAINST LOST BEAM

The beam power in ISIS is such that protection against lost beam must be provided to prevent damage to the accelerator components. The protection takes two forms.

Firstly, most of the lost beam is picked up on water cooled graphite collectors, appropriately placed in the ring. Separate collectors are provided for horizontal and vertical loss, the former being the more important for ISIS. Most of the collectors are remotely adjustable and are positioned in long straight 1 of the synchrotron, see Figure 1. This serves to concentrate the loss in one area. The important feature of the primary horizontal collector is its location at a high dispersion point in the ring at an inside machine radius, so that it intercepts non–accelerated beam that spirals inwards. Separate collectors are provided to gather the partially stripped H° beam produced during injection and also to shield the septum of the extraction magnet.

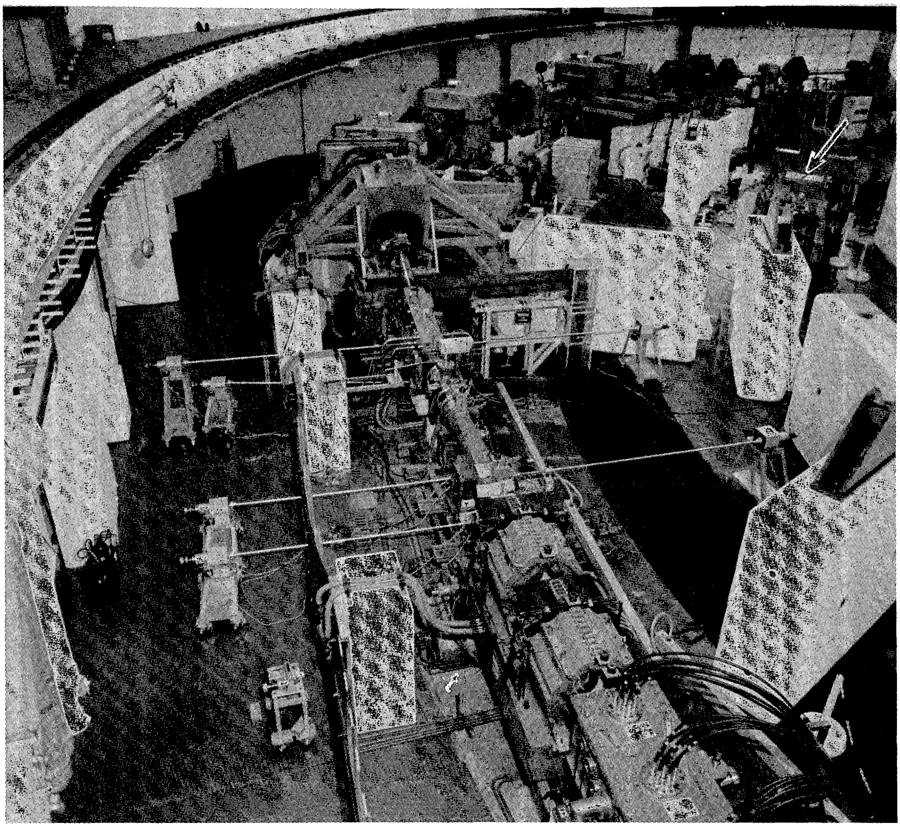

Figure 1 ISIS synchrotron superperiod 1 showing the beam collector straight and a dipole in the maintenance area (arrowed)

Secondly, action is taken dependent on the magnitude and frequency of occurence of the beam loss. This is measured in all areas of the machine every pulse by means of beam intensity and beam loss monitors. The action varies from turning the beam off to writing warning messages on the display at the main control desk.

TABLE 1 Intensity Monitor Operated Protection

a) 3 PULSE TRIP

Interlock broken only if excessive beam loss occurs on three consecutive beam pulses

LEVELS	Injection	4.9×10^{12}	(per pulse)
	Trapping	4.9×10^{12}	
	Acceleration	2.0×10^{12}	
	Extraction	1.0×10^{12}	
	EPB Line	1.0×10^{12}	
	Total Loss	4.9×10^{12}	

b) AVERAGING TRIP

Interlock broken when excessive beam loss occurs for an averaged loss during the previous 25 machine pulses (updated each machine pulse)

LEVELS	Injection	1.1×10^{12}	(per pulse)
	Trapping	4.0×10^{12}	
	Acceleration	5.0×10^{11}	
	Extraction	5.0×10^{11}	
	EPB Line	5.0×10^{11}	
	Total Loss	4.8×10^{12}	

c) WARNINGS

No beam trip produced. A visual warning is displayed on the control desk if the average beam loss during the previous 30 seconds or 20 minutes exceed pre-set values

		30 sec	20 min	
LEVELS	Injection	1.0×10^{12}	8.5×10^{11}	(per pulse)
	Trapping	3.3×10^{12}	2.8×10^{12}	
	Acceleration	1.5×10^{11}	1.0×10^{11}	
	Extraction	2.0×10^{11}	1.0×10^{11}	
	EPB Line	3.5×10^{11}	3.5×10^{11}	
	Total Loss	4.0×10^{12}	3.8×10^{12}	

Toroids are used as intensity monitors, and long ionisation chambers filled with Argon as beam loss monitors, for linac, synchrotron and extracted proton beamline (EPB). The beam intensities of all three are continuously displayed along with the injection, acceleration and extraction efficiencies. Also on continuous display are the outputs of the beam loss monitors. Tables 1 and 2 show the levels of beam loss which are used in the protection algorithms. Where the cause of loss is uncertain, the repetition rate of the accelerator is reduced by a factor of 32 and a high intensity beam is then re-established. In the case of loss of a high percentage of the 70 MeV injector beam, the intensity of the pre-injector is reduced by means of a beam diluter.

One special consideration for ISIS is that the spallation target, which runs at high temperature, suffers a severe thermal shock if the beam is turned on or off suddenly. This shortens the target life-time and so the protection system has been developed to allow some intermittent beam loss conditions to exist, for example the occasional extraction kicker mis-fire.

Even with all the protection provided, there have been a few operational mishaps. In the beamlines, vacuum leaks have developed due to the distortion of joints by beam heat deposition. In the synchrotron there has been some vacuum chamber component damage, and this is described in section 4. High levels of induced activity have sometimes been found away from the beam loss collector region. However, in general the protection has worked well and has been an indispensible feature of the machine. It has allowed the machine to continue operating at times with some systems working non-optimally. The general level of induced activity has been acceptable and maintenance has proceeded with no member of staff receiving an annual dose higher than one tenth of the permitted maximum level. Figure 2 shows the output of the 40 synchrotron beam loss monitors and Figure 3 shows the induced activity levels after shut down.

TABLE 2 - Beam Loss Monitor Operated Protection

Injector

Beam trip occurs if any 1 of 19 beam loss monitor outputs exceeds its pre-set level or if the summed output of the 19 monitors exceeds a pre-set level on 2 machine pulses out of 4. Typical levels are below 4×10^{10} ppp.

Extraction

Beam trip occurs if the output of the ring beam loss monitor closest to the extraction septum magnet exceeds a pre-set level on 2 machine pulses out of 4. Typical level is less than 4×10^{9} ppp.

EPB

Warnings only are provided. The warning is displayed when the output of any 1 of 10 monitors exceeds its pre-set limit. Typical levels are less than 1×10^{9} ppp.

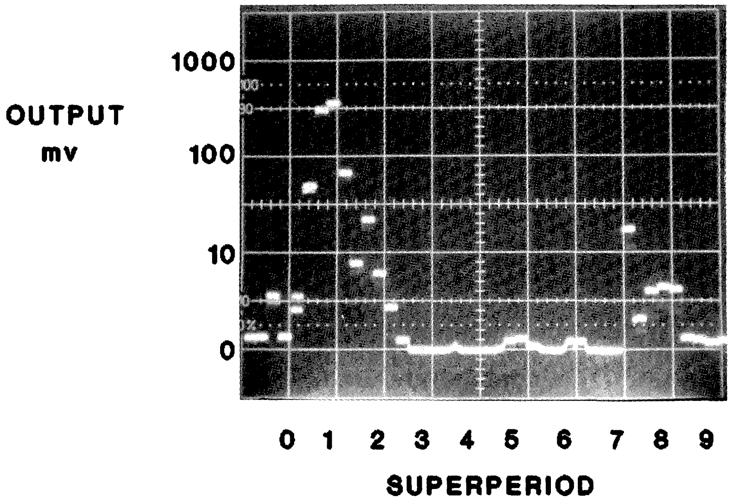

FIGURE 2 - Output of synchrotron beam loss monitors.

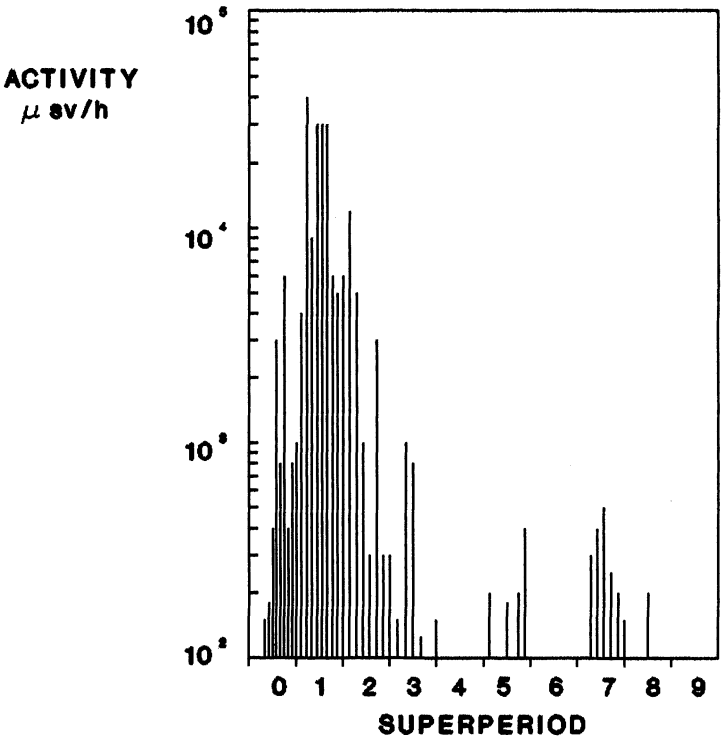

FIGURE 3 - Induced activity in synchrotron.

The importance of a protection system for any future high intensity machine cannot be stressed too highly. As at ISIS, the magnet lattices should be designed from the outset with appropriate straight section spaces available for beam loss collectors. A finite dispersion straight is important for longitudinal beam loss collection.

4. OPERATIONAL PERFORMANCE OF VACUUM CHAMBER COMPONENTS.

The alumina vacuum chambers with glazed joints developed for ISIS have proved to be extremely robust and reliable in operation. To date only one small leak has occured at a glazed joint and this was easily cured. Accidental beam spill has not damaged any ceramic chamber although it has caused discolouration which gradually fades. Radio frequency shields are required inside such chambers to improve beam stability by providing a low impedance for beam induced r.f. currents. The shields in ISIS are stainless steel wire cage structures, as illustrated in Figure 4, which are contoured to follow the beam profiles to minimise the space-charge reactance. The shields are coupled by capacitors presenting a low impedance at r.f. but a high impedance to the synchrotron cycling frequency.

There are developments at other laboratories to integrate the rf shield and coupling capacitors with the ceramic chamber using printed circuit techniques. It would be difficult to follow the profiles with such a shield, but this is of less importance in higher energy machines. However, damage of such a shield by the beam would mean the replacment of the ceramic chamber.

In two separate incidents on ISIS, r.f. shields have been hit by the beam resulting in melting of the stainless steel. With the non-integral construction it proved possible to remove these damaged shields from their ceramic chambers without difficulty and replace them with new ones. This was done without the need to re-survey components, which would not be the case if a vacuum chamber had to be replaced.

The only other incident involving beam damage to components, apart from damage to vacuum seals, was to one of the three extraction kicker magnets. Extraction from ISIS is vertically upwards and the kicker magnets are relatively simple, low impedance, single turn, lumped element, ferrite magnets. When trying to compensate for a reduced kick in an upstream kicker magnet by increasing a slow orbit bump, about one third of the area of the upper half of the single turn coil of the downstream kicker was melted away by the beam. However, the extraction system continues to work at very high efficiency with the magnet in this state.

The operational performance of the ISIS vacuum chamber components thus leads to the following main recommendations for future high intensity machines.

i) Glaze-jointed ceramic vacuum chambers with integral or separate shields merit serious consideration.

ii) Simplicity in design is important to provide rugged components and to allow ease of maintenance of radio-active items.

5. CHARGE EXCHANGE INJECTION

Direct multiturn charge-exchange injection of H- ions through a stripping foil has proved to be the most effective way of injecting into a high intensity proton synchrotron. At the present operating intensity of 100 μA on ISIS, the injection

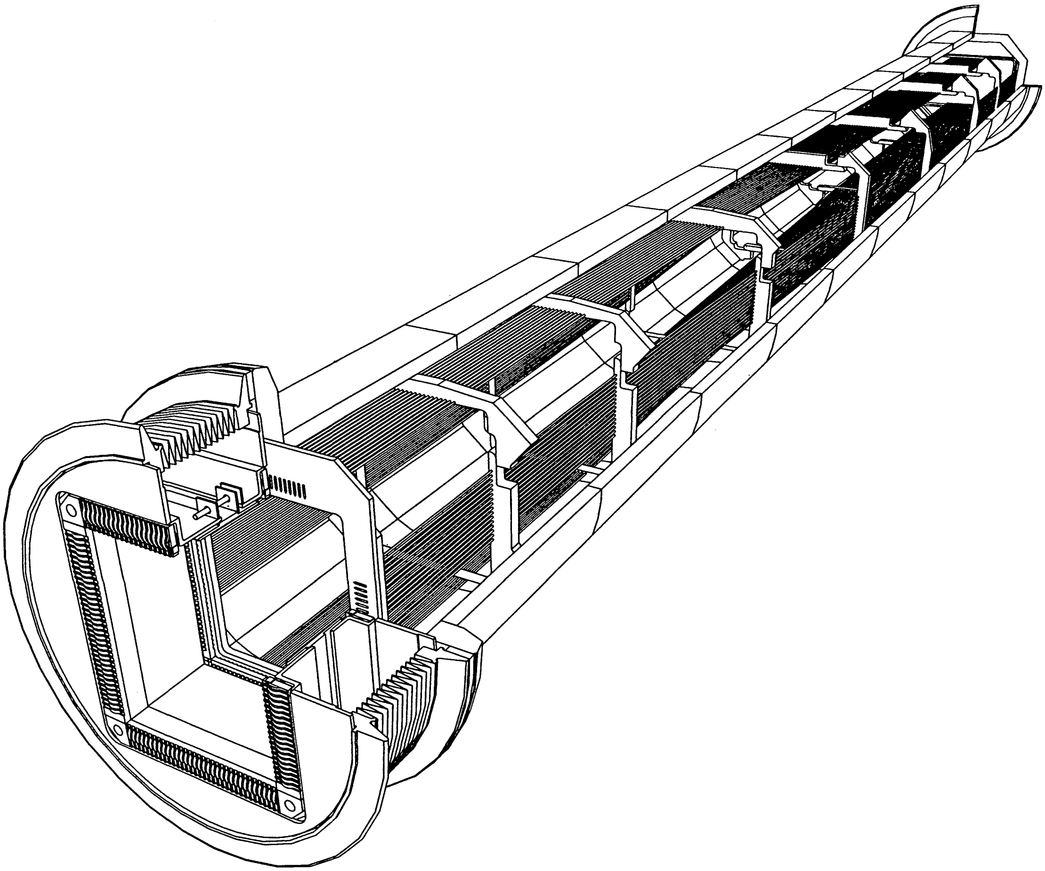

Figure 4 – Ceramic Doublet Quadrupole Vacuum Chamber Fitted with capacitively coupled r.f. shield and bellows unit

efficiency is 98%, with 2% of ions being only partially stripped to H° and collected on a beam dump. Higher intensitites have been injected without showing any sign of saturation, but injection efficiency does fall slightly and at 200 μA injected, the efficiency is down to 92–94%.

The aluminium oxide stripping foils used in the ISIS injection system have been extremely successful, achieving irradiation lifetimes of around 180,000 μAh injected current (~ 4 Ah total irradiation). Because the injection energy for ISIS is 70 MeV, these foils are only 50 μg/sq cm thick and the long lifetimes are obtained by having initially stress–free foils, which are now separated from the support frame on three sides.

In a suitably designed charge–exchange injection system it is possible to have considerable control over beam brightness, emittance, phase–space density and line density distributions. In the ISIS system there is some control over these parameters in the two transverse phase–planes but for future machines control of all three phase–plane parameters should be possible. Minimising the number of foil traversals by the circulating proton beam, to reduce beam loss from momentum growth and angular scattering, is of great importance in the design of such injection systems. This requires a lattice designed to optimise injection, and longlife stripping foils with at least two free edges which are stable in operation.

Experience on ISIS indicates that manufacture of such foils is possible. The maximum thickness of aluminium oxide foils is limited to around 150 μg/sq cm, but it has been demonstrated that thicker foils can be obtained by folding to produce multilayers. The KEK Laboratory in Japan is also experimenting with irradiation of such folded foils (2), but made of carbon. Thick foils could readily be made in carbon but multilayer foils may have the advantage that radiation induced stresses may be partially cancelled between the foil layers, particularly at the unsupported corner.

6. OBSERVATIONS AND STUDIES OF BEAM INSTABILITIES

Five instabilities have been observed on the ISIS synchrotron: coasting beam vertical resistive wall, coasting beam longitudinal microwave (3), bunched beam vertical head tail resistive wall, bunched beam longitudinal quadrupole mode and, during the transition from coasting to bunched beam, a high frequency vertical instability. The second, third and fourth of these do not conform to theory and the fifth is not understood. That three sets of observations should be mis–interpreted appears unlikely and so doubt is cast on the underlying theories.

Longitudinal coasting and bunched beam theories have therefore been re–examined and a number of doubtful features have been identified. In particular, for the coasting beam case, it appears that both the form assumed for the initial perturbation and the calculation of the beam–environment interaction are not strictly valid and that as a consequence, the related Keil-Schnell criterion (4) is incorrect. Similar invalid features have been identified for the bunched beam case and have been reported in the literature (5). It is planned to publish the coasting beam findings shortly. It is believed that estimates for instability thresholds in future high intensity machines should thus be treated with some caution.

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