***** DRAFT *****

[PLEASE NOTE: The final version will be published after we reach a consensus. Open issues are shown in brackets.]

INITIAL STRATEGY FOR SNS BEAM CUTOFF

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ABSTRACT

Requirements for SNS beam cut-off devices are presented. Cut-off devices for both safety and equipment protection are proposed (see tables 4-3 and 4-4).

1. INTRODUCTION

SNS will have several automatic systems for protection of personnel and property. These systems include a personnel protection system, a target protection system, and a beam permit / fast protect system. Each of these systems requires a reliable means of cutting off the accelerator beam in order to carry out its function.

The project has yet to define the critical devices[1] that will be used to cut off beam. Being named as a "beam cut-off critical device" could have a big impact on the implementation of the device (e.g. reliability requirements, cost, interfaces, etc.), so it makes sense for the project to define these critical devices as soon as possible. Thus, the intent of this paper is to document the project's consensus on what critical devices will be provided for beam cut-off. Towards that end, this paper will:

- Briefly describe SNS automatic protection systems,
- Review requirements these systems impose on beam cut-off devices, and
- Propose a set of beam cut-off devices to be used for each protection system.

Of course there are many other important aspects of providing adequate levels of protection besides the devices used for beam cut-off. These other aspects (e.g. shielding policy, personnel access control, radiation monitoring, etc.) will be addressed elsewhere. The scope of this paper is deliberately limited to the selection of critical devices to be used for beam cut-off so we can arrive at a consensus as quickly as possible.

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[1] "Critical devices are the specific accelerator or beamline components that are used to ensure that the beam is … inhibited. Common examples are … systems which operate on the injector or ion source to inhibit the beam." DOE *Draft Implementation Guide, Accelerator Safety Order* Section III.C.3.d; dated May, 1998.

2. SNS AUTOMATIC PROTECTION SYSTEMS

Following are brief descriptions of SNS automatic protection systems.

Beam Permit System. The beam permit system fulfills two functions: a "Run Permit" function, and a "Beam Pulse Enable" function. "Run Permit" is a steady-state function that ensures accelerator components are in a proper configuration to allow beam for the desired operational mode. The "Beam Pulse Enable" function prevents the timing system from triggering a macropulse before the accelerator chain is ready to accept it. The beam permit system is intended to protect equipment and is not a safety system.

Fast Protect System. The fast protect system turns off the beam rapidly (~10 μsec) when necessary, such as in the case of a beam loss. It is intended to protect equipment and is not a safety system.

Target Protection System. The target protection system turns off beam when the mercury target is not in a condition to accept beam. A primary concern addressed is cut-off of beam during a "loss-of-mercury-cooling" accident. (e.g. If the mercury target fails, the beam must be turned off or a release of radioactive material to the environment could occur). The target protection system is a safety system.

Personnel Protection System. The personnel protection system cuts off beam when it detects conditions that could result in the exposure of personnel to excess prompt radiation. Functions include personnel access control, beam containment, and radiation monitoring of inhabited areas. The personnel protection system is a safety system.

Table 2-1 lists the integrity levels expected for each system.

Table 2-1. Reliability Parameters for Automatic Protection Systems

Systems and Functions:	Integrity Level:	Frequency of challenges:
• Beam Permit System • Fast Protect System • Personnel Protection System: - Radiation monitoring for verification of compliance	Very reliable (10^{-1} to 10^{-2} PFD*)	Frequent (~ 60 / day)

• Personnel Protection System:
  - Personnel Access Control
  - Beam Containment
  - Rad monitoring for loss-of-liquid-shielding
• Target Protection System
	Highly reliable
	(10^{-3} to 10^{-4} PFD)
		Infrequent
		(~2 / year)
		
		Infrequent
		(~1 / year)

* PFD = "Probability of failure on demand"

3. REQUIRMENTS FOR BEAM CUT-OFFS

3.1 General

Prior to a discussion of requirements, it is appropriate to focus on what these requirements actually apply to. For our purposes, we can make a distinction between a “beam abort mechanism” and a “beam cut-off critical device”. A beam abort mechanism is a process that can be disrupted to abort beam. (e.g. “Kill ion source extractor voltage”). The beam cut-off critical device is the component that actually causes the disruption (e.g. an AC power breaker that interrupts AC power to the extractor power supply). This distinction is important because it narrows the boundary of the safety system. (e.g. We only have to seismically qualify the AC power breaker, not the ion source extractor power supply, electrodes, etc.). The requirements presented below apply to beam cut-off critical devices only, and not the abort mechanism as a whole.

There are a number of requirements that are universally applied to systems with high reliability requirements. These are cited below for the record:

1. Design to be fail-safe.
2. Minimize interfaces.
3. Apply conservative design features.
4. Design against single point failure: Consider redundancy; address possible common-mode failure modes (e.g. via diversity and physical separation).
5. Design to be accessible, maintainable, and testable.

3.2 Target Protection System Requirements

The quantities of radioactive products that will ultimately be generated in the target mercury will reach levels that require the target facility to comply with the regulations for nuclear facilities given in DOE O 420.1, *Facility Safety*. This order and its supporting standards, procedures, and guides prescribe a number of requirements for nuclear safety systems. Since the beam cut-off devices controlled by the TPS are of part a nuclear safety system, they must meet these requirements. The effects of nuclear facility regulations on SNS automatic protection systems are covered in detail in a separate white paper. The following paragraphs summarize these requirements as they apply to TPS beam cut-off mechanisms.

Section 4.1 of DOE O420.1 presents design criteria for nuclear safety systems. Many requirements are consistent with conventional accelerator safety system design practices and are not repeated here. Some requirements worthy of note include the following:

1. “Defense in depth” must be used to provide multiple layers of protection to prevent the “beam-during-loss-of-mercury-cooling” accident. Table 3-1 shows the current strategy for defense in depth.

Table 3-1. Defense in depth for "Beam-during-loss-of-mercury-cooling" accident

Protection System	"Safety Integrity Level" Goal	Expected Freq. of Occurrence	Net Probability Goal (per year)
Run Permit	10^{-1} < PFD* < 10^{-2}	1 / year	10^{-1} > Pr** > 10^{-2}
Personnel Protection System (Radiation monitoring for loss-of-liquid-shielding)	10^{-3} < PFD < 10^{-4}	1 / year	10^{-3} > Pr > 10^{-4}
Target Protection System	10^{-3} < PFD < 10^{-4}	1 / year	10^{-3} > Pr > 10^{-4}
Theoretical Net Probability***			10^{-7} > Pr > 10^{-10}

*PFD = "probability of failure on demand"
**Pr = "probability"
*** Actual net probability will likely be higher due to common mode considerations.

This "defense in depth" strategy requires that beam abort mechanisms be assigned to protection systems in a manner that minimizes the possibility of common-mode failures.

2. Environmental qualification must be applied to ensure that each TPS beam cut-off critical device can perform its function under any foreseeable environmental conditions. Environmental conditions should be relatively benign for beam cut-off devices at SNS, so meeting this requirement should not be too difficult. Selecting commercial equipment with specifications meeting the required environmental conditions generally satisfies this requirement.

3. Nuclear safety systems must be designed, constructed, and maintained under a quality assurance program that satisfies 10 CFR 830.120 *Nuclear Safety Management*. Items of note include:
   a) Design documents for the TPS, including beam cut-off critical devices, have to be placed under configuration control.
   b) Beam cut-off critical devices have to be inspected, tested, and controlled to make sure the wrong part doesn't get used.
   c) The design of the TPS has to be verified by persons other than those who performed the design work. This includes any TPS beam cut-off critical devices that are designed by the SNS project. (Beam cut-off critical devices that are purchased from other sources can go through a qualification process and avoid this requirement). Design changes must be verified as well.

Section 4.4 of DOE O420.1 presents requirements for mitigation of natural phenomena hazards (NPH). It states that nuclear safety systems must " be designed, constructed, and operated to withstand the effects of natural phenomena as necessary to ensure the confinement of hazardous material …" The primary implications are:

1. TPS beam cut-off critical devices will have to be qualified to withstand seismic events (levels to be determined).

2. TPS beam cut-off critical devices should be placed in separate locations within the Front End Building. This will reduce the possibility of a common mode failure due to interactions with building components during an NPH event.

A time response on the order of one second (from TPS initiating event to actual beam cut-off) is considered to be acceptable. If the beam is turned off within this time frame there should be no damage to the target and no significant release for any foreseeable accident scenario.

3.3 Personnel Protection System Requirements

The authors have not been able to find any regulatory requirements that directly specify requirements for beam cut-off critical devices for the Personnel Protection System. (Of course there are many general requirements, but none were found that say "do it this way…").

One source of guidance is the DOE "Draft Implementation Guide, Accelerator Safety Order" (Section III.C.3.d; dated May, 1998), which states the following:

> "Critical devices are specific accelerator or beam line components that are used to ensure that the accelerator beam is either inhibited or cannot be steered into areas where people are present. Common examples are steering magnets, beam stops or collimators. Other examples are systems which operate on the injector or ion source to inhibit the beam.
>
> (1) Two critical devices should be used in an interlock system if a whole-body very-high-radiation area, as defined in 10 CFR 835, can be produced.
>
> (2) The status of each critical device should be monitored to ensure that the devices are in the "safe" condition when personnel access is permitted. If only one device is used, two separate indication systems should be provided. If the "safe" condition is lost, the beam should be inhibited by operation of other critical devices upstream. Critical device command systems should be independent of the monitoring systems."

A time response on the order of 1 second (from PPS initiating event to actual beam cut-off) is considered to be acceptable. (e.g. If a person tries to enter a tunnel during operations, in one second he will not be able to go far enough into the area to receive an unacceptable radiation dose).

3.4 Equipment Protection System Requirements

There are no regulatory requirements directly affecting equipment protection beam cut-off devices.

A time response on the order of 10 μsec (from initiating event to actual beam cut-off) is needed for some equipment protection functions. A primary driver for this time response is shutting off beam when a beam loss occurs. The faster beam is cut off, the less the equipment gets activated.

It is likely that there will be frequent beam aborts due to equipment protection functions. Therefore, impact on operations is an important consideration in the selection of beam cut-off devices for equipment protection.

3.5 Selection Criteria

To set the stage for selection of beam abort mechanisms and corresponding critical devices, the following selection criteria are presented. Most of these are derived from the requirements presented above.

The Personnel Protection System should drive 3 abort mechanisms. (Two would probably be adequate, but since it's early in the project and the third comes at minimum expense, say three required). For each mechanism:

- The time response from initiating event to actual beam cut-off should be on the order of 1 second.
- Must be fail-safe.
- Reliability must be easily established.
- Must be able to periodically test its effectiveness.

The Target Protection System should drive at least 2 beam abort mechanisms. (Since the TPS has additional requirements such as seismic qualification, we may to limit the number of mechanisms used). For each mechanism:

- The time response from initiating event to actual beam cut-off should be on the order of 1 second.
- Must be fail-safe.
- Reliability must be easily established.
- Environmental qualification must be easily established.
- Natural phenomena hazard (e.g. seismic) qualification must be easily established.
- Must be able to periodically test its effectiveness.

The equipment protection systems should drive 2 beam cut-off mechanisms. For each mechanism:

- Must have minimum impact on operations.
- Must be reliable.
- Time response in microseconds.

4. PROPOSAL FOR BEAM CUT-OFF MECHANISMS

4.1 Candidate Beam Abort Mechanisms

Table 4-1 shows a comprehensive list of potential beam abort mechanisms. (John Staples of LBNL generated this list for a presentation at the January 23, 1998 SNS collaboration meeting at LBNL). This table indicates key features of each abort mechanism and in some cases comments on the feasibility of its use.

Table 4-2 presents the list of beam abort mechanisms proposed for use by SNS automatic protection systems. These mechanisms represent the best choices in terms of the requirements and selection criteria presented in previous sections.

4.2 Proposed Beam Cut-off Devices

Table 4-3 lists the proposed set of beam cut-off critical devices for use by safety systems.

It is expected that there will be on the order of 2 safety system trips per year, so impact on operations is not a primary consideration. However we are fortunate that the beam cut-off critical devices proposed do have a low impact.

Of the three sets of devices proposed, two consist of AC power breakers. Breakers are a good choice for this service due to qualification requirements discussed in earlier sections. Breakers meeting our qualification requirements should be commercially available.

Figure 4-1 shows a rough schematic of how safety system beam cut-off circuits might be implemented. The schematic shows only one breaker for each cut-off channel, but there would really be several breakers per channel due to redundancy and separation requirements. This figure shows how the critical devices could be grouped to provide some protection against common mode failures, while limiting the total number of cut-off mechanisms to three.

Table 4-4 lists the proposed set of beam cut-off devices for equipment protection service.

While some beam abort mechanisms are shared between the safety systems and equipment protection systems, the critical devices used will probably not be shared. Equipment protection systems will use faster and more complicated power supply interlock circuits rather than AC breakers.

Two of the beam abort mechanisms listed have less-than-ideal features. Ion source RF must not be left off for too long or operations will be affected. Ion source extractor voltage has a negligible impact on operations, but has a slow response time. These two mechanisms will be used in tandem to mitigate these problems. For an equipment protection trip, both mechanisms will be turned off at the same time. Beam will be inhibited in microseconds by the loss of source RF. Once the extractor voltage is off (a second or so later), the source RF will be turned back on.

Figure 4-2 shows a rough schematic of how beam cut-offs for equipment protection might be implemented. A bypass of the ion source RF interlock is shown; this interlock is bypassed when extractor voltage is off.

Table 4-1. Candidate Beam Abort Mechanisms

Item	Abort Mechanism	Impact on Operations	Time Response	Fail Safe?	Other Comments
1.	**Ion Source**				
1.1	Kill extractor power supply	Very low	seconds	Yes	Has minimum impact on operations. Too slow for fast protection, but good for relatively-long-duration shut-offs.
1.2	Change r.f. excitation pulse timing	Low	μsecs	No	Complicated; not necessarily fail-safe.
1.3	Stop r.f. excitation temporarily	Low (if short duration)	μsecs	Yes	Good for fast equipment protection, but need to resume r.f. within 30 seconds or operations is impacted. There are additional problems if source uses cesium.
1.4	Latching source chopper				The source chopper is not included in the current base-line design. If the source chopper described in the CDR were restored to the base-line design, it would still not be a good candidate since (a) it would be difficult to design this chopper to sustain the high power level required for beam cut-off service, and (b) it would not be fail-safe.
2.	**LEBT**				
2.1	Latching LEBT chopper				Not considered feasible since (a) not DC coupled, and (b) it would be difficult to design this chopper to sustain the high power level required for beam cut-off service.
2.2	Change lens voltages to defocus beam				Beam will hit electrodes. Incomplete extinction. Slow.
2.3	Close LEBT gate valve	Low	seconds	No	Would have to design to sustain the high power density. Current design is not fail-safe.
3.	**RFQ**				

Item	Abort Mechanism	Impact on Operations	Time Response	Fail Safe?	Other Comments
3.1	Kill RFQ r.f.	Low	~ 4 μsec	Yes	2 μsec to 85% gradient with Q = 5000. RF continues to transport partially accelerated beam down to 50% gradient. Some impact on operations, since RFQ tuning will change as RFQ cools. Time required to bring back on-line estimated at ~ 2 min. if RF power left off for relatively-long-duration.
3.2	Change RFQ r.f. pulse timing	Low		No	65 keV beam will be lost on vanes. Long-term effects unknown.
4.	**MEBT**				
4.1	Latch MEBT chopper				Not feasible since (a) power supplies a.c.-coupled, (b) extreme chopper stopper power density, (c) don't need nanosecond response time.
4.2	Insert beam stop	Very low	~ 1 sec	Yes	Can take full power.
4.3	Change phase on buncher cavities	Low		No	(De)accelerate beam 180 keV = 7%. Lose 2.3/2.7 MeV beam in linac. Long-term effects unknown.
4.4	Change MEBT quad currents to defocus beam	Low		Yes	Incomplete extinction. Long-term effects unknown.

Table 4-2. Proposed Set of Beam Abort Mechanisms

Item	Abort Mechanism	Impact on Operations	Time Response	Fail Safe?	Mechanism used by: PPS	TPS	Equip. Protect.
1	Kill ion source extractor power supply	Very low	seconds	Yes	X	X	X
2	Stop ion source r.f. excitation temporarily	Low (if short duration)	μsecs	Yes			X
3	Kill RFQ r.f.	Low	~ 4 μsec	Yes	X	X	X
4	Insert beam stop	Very low	~ 1 sec	Yes	X		

Table 4-3. Proposed Beam Cut-off Devices for Safety Systems

Item	Beam Cut-off Device:	Impact on Operations	Time Response	Fail Safe?	Rationale:
1	Breaker to cut off AC power to ion source extractor power supply	Low	seconds	Yes	Minimum impact on operations. Simple and reliable. Qualified breakers are commercially available.
2	Breaker to cut AC power to RFQ r.f. power supply	Low	seconds	Yes	Minimum impact on operations. Simple and reliable. Qualified breakers are commercially available.
3	End-of-MEBT beam stop	Very low	~ 1 sec	Yes	Minimum impact on operations. Simple and reliable. (A good fit for PPS. Probably not suitable for TPS cut-off since difficult to qualify).

Table 4-4. Proposed Beam Cut-off Devices for Equipment Protection

Item	Beam Cut-off Device:	Impact on Operations	Time Response	Rationale:
1	Inhibit ion source extractor HV power supply	Low	~ 1 sec.	Minimum impact on operations. Simple and reliable.
2	Inhibit RFQ r.f. power supply	Low	~ 4 μsec	Minimum impact on operations. Simple and reliable.
3	Inhibit RF to ion source	Low (if short duration)	~ 1 μsec	Minimum impact on operations. Simple and reliable.

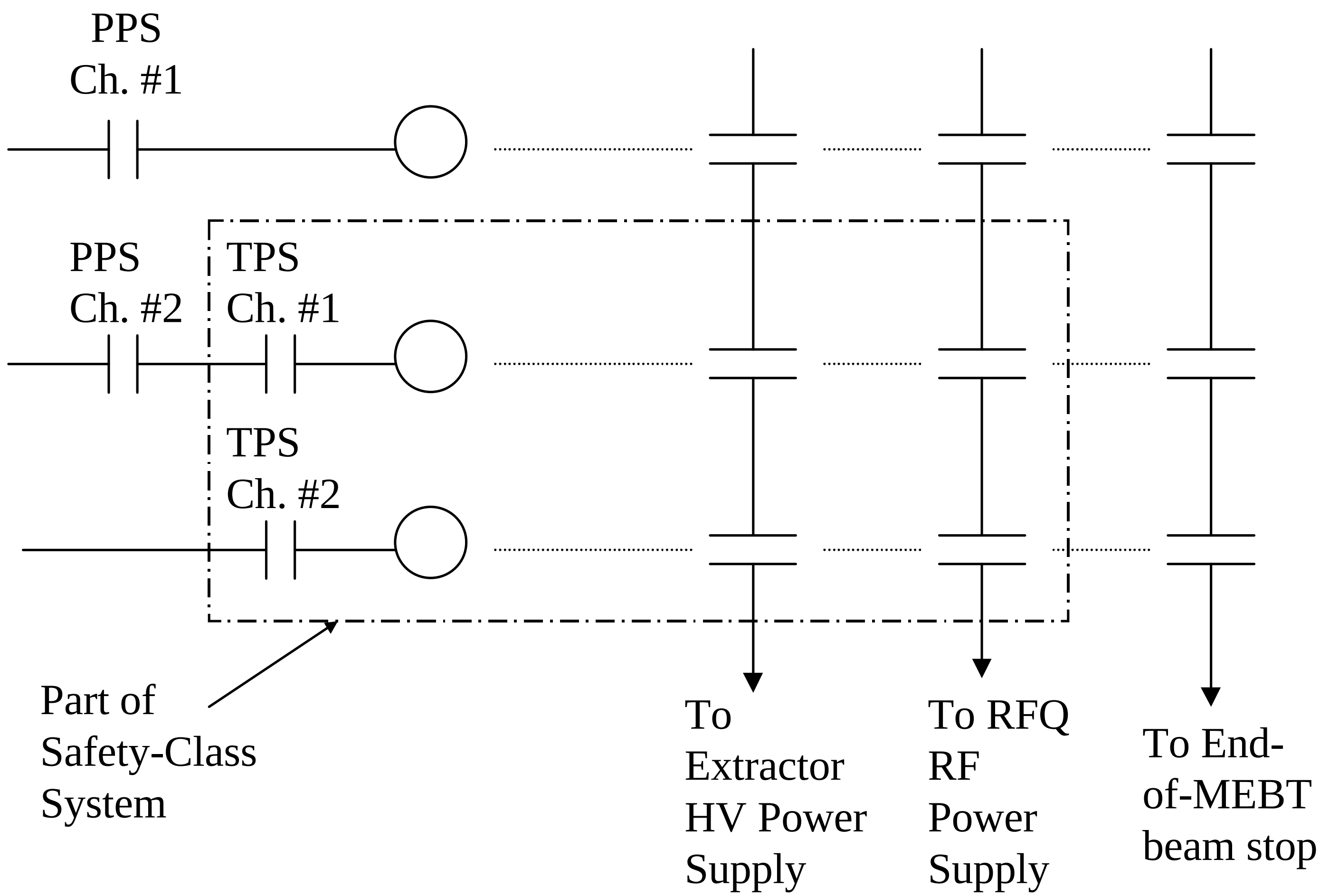

Fig. 4-1. One Option for Implementing Beam Cut-offs for Safety Systems

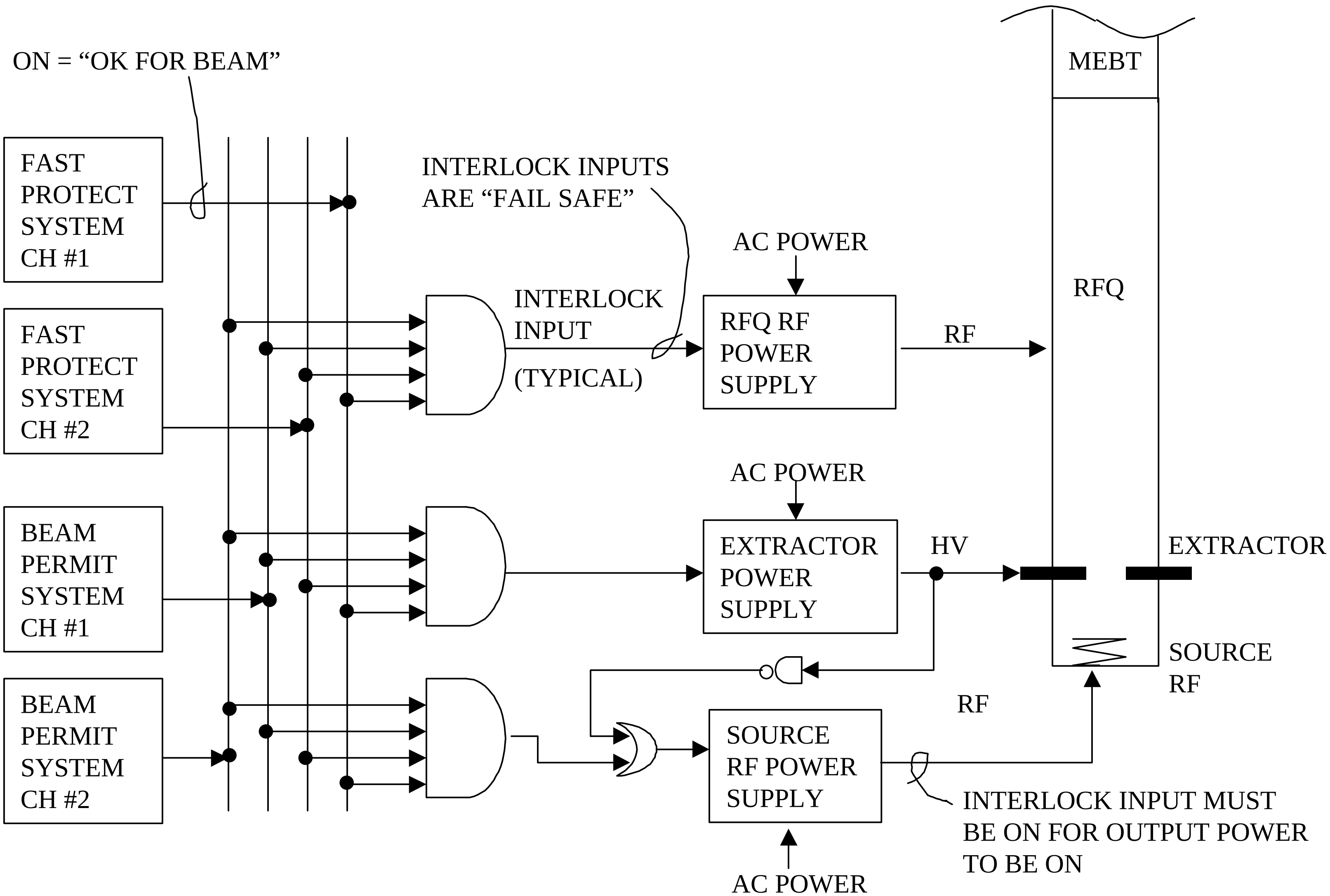

Fig. 4-2. One Option for Implementing Beam Cut-offs for Equipment Protection

5. REFERENCES:

1. *Some Effects of Nuclear Facility Regulations on SNS Automatic Protection Systems*, DeVan et al, SNS [Rough draft available on request.]
2. DOE O 420.2, *Safety of Accelerator Facilities*
3. DOE *Draft Implementation Guide, Accelerator Safety Order* (dated May, 1998)
4. DOE O 420.1, *Facility Safety*. (This order invokes several other standards and guidelines. See reference 1 for further discussion of this order and additional references).