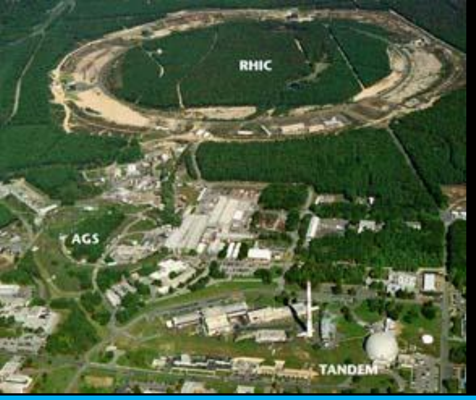
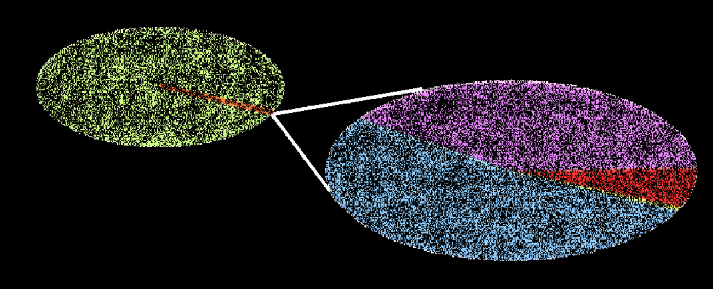


A Monte Carlo simulation approach to the reliability modeling of the beam permit system of RHIC at BNL



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Objective

To find probability of critical failures in BPS which lead to significant downtime.

Introduction

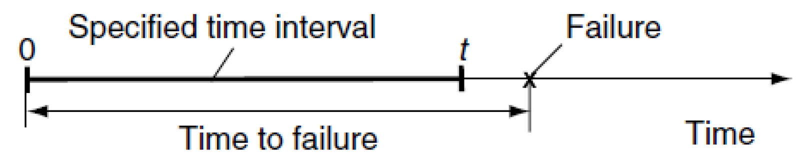
- Peak energy stored in RHIC is about 72 MJ[1] in the form of beams and magnet currents
- BPS observes the health of RHIC support systems and is responsible for taking action for the safe disposal of this energy
- Reliability of BPS directly impacts the reliability of RHIC as it protects equipment and personnel
- High reliability for safety critical system like BPS is essential

Reliability

Definition: Probability that a system will perform a required function under stated conditions for a specified period of time.

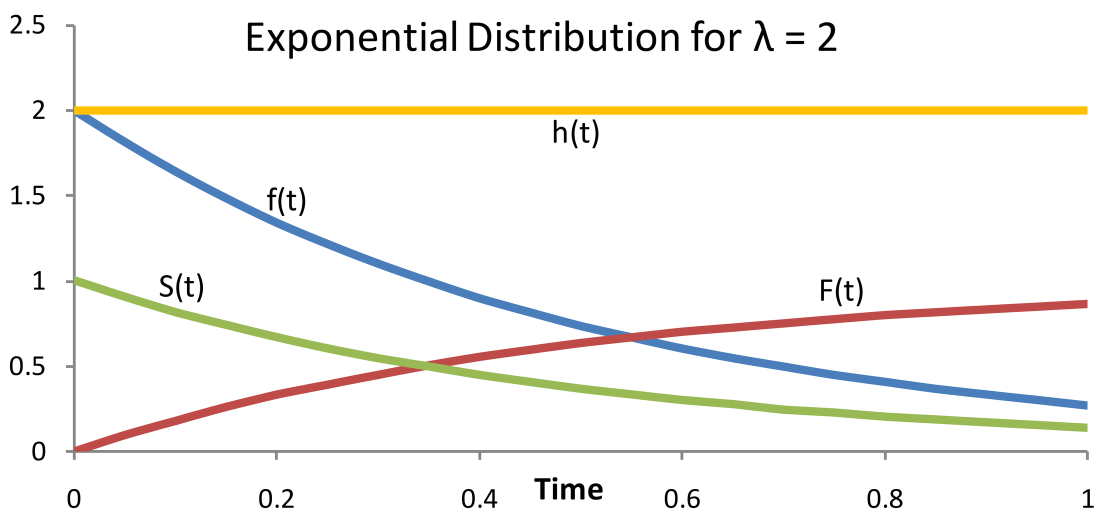
Mathematically :

$$R(t) = P(T > t)$$



Exponential distribution

- Variable of interest is "Time to failure" or "Lifetime"
- System lifetime depends on its components' lifetimes
- Intrinsic failure portion of the Bathtub Curve has a constant failure rate
- Has a exponential probability distribution function and is used to model lifetime of electronic components[2]
- Memory-less property: A used item that is functioning has the same failure distribution as a new item.



$f(t) = \lambda e^{-\lambda t}$ Failure probability density function

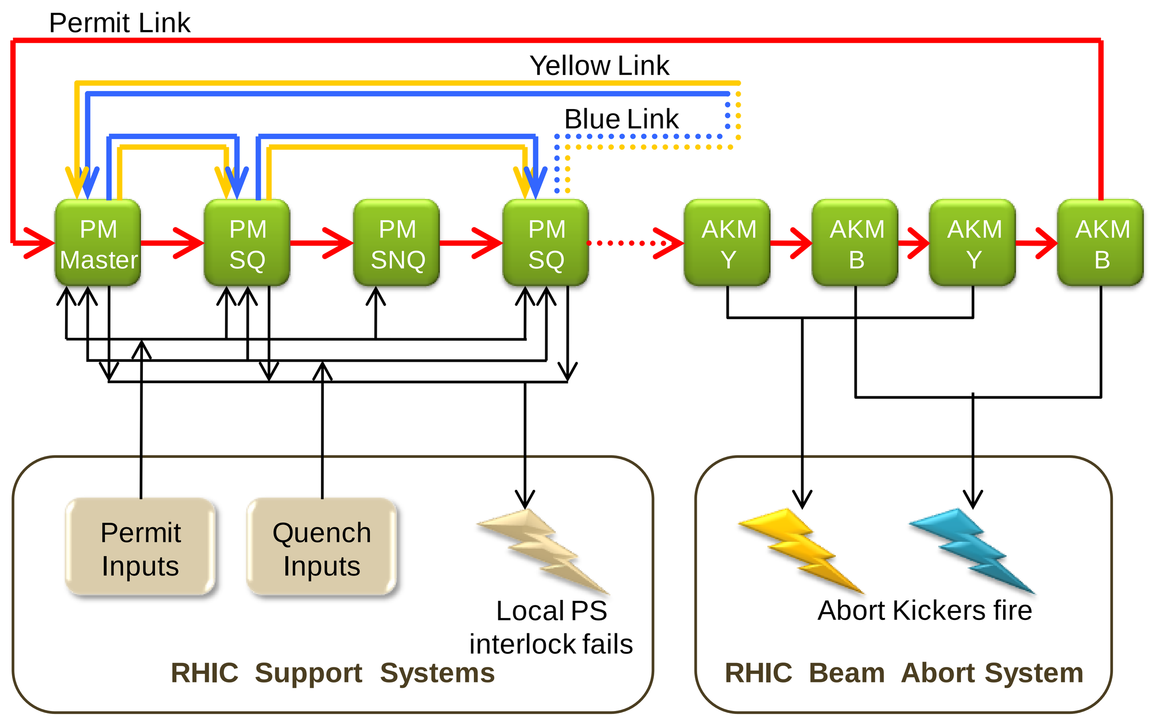
$h(t) = \lambda$ Failure rate function

$F(t) = 1 - e^{-\lambda t}$ Failure distribution function

$S(t) = e^{-\lambda t}$ Survival / reliability function

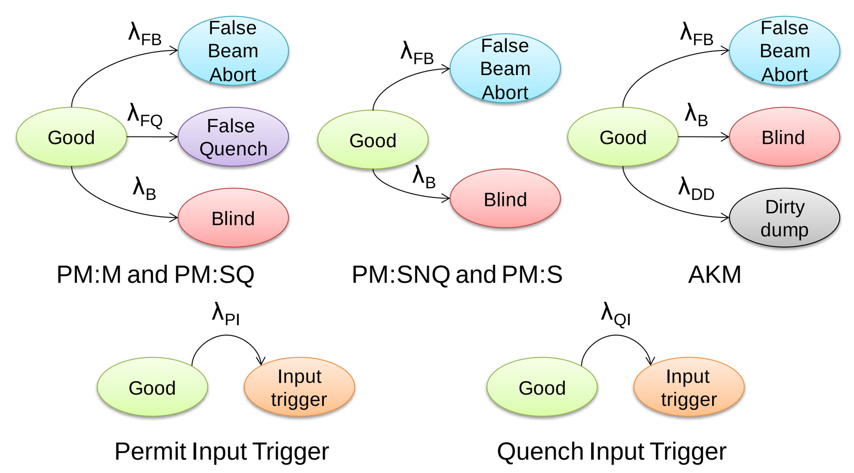
Beam permit system

- 33 permit modules & 4 abort kicker modules
- Health of the support systems as permit inputs and quench inputs
- Three carriers – permit, blue and yellow link communicate the support system statuses
- Beam abort: beam dumped by abort kickers
- Quench abort: beam dumped and magnets ramped down
- Variants of modules as PM:M, PM:SQ, PM:SNQ, PM:S and AKM



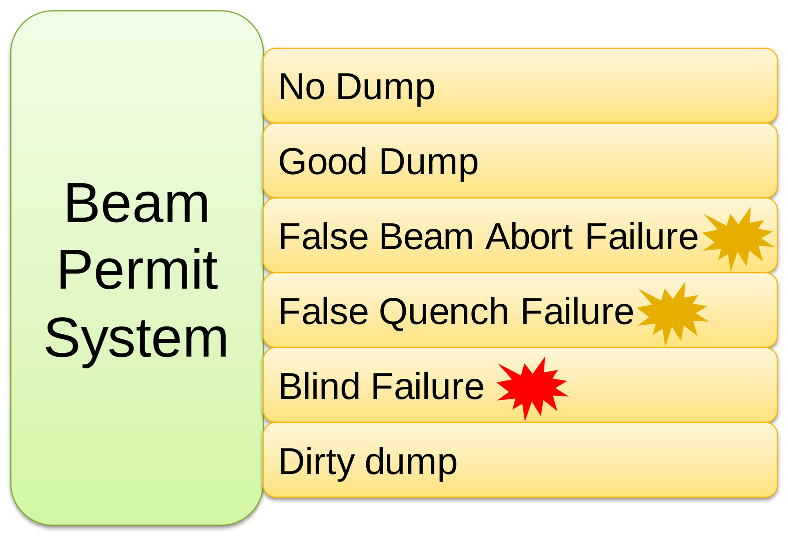
Failure modes

Failure modes of BPS modules



Above are the Markov diagrams[3] for the allowed states of BPS modules. The values of λ for different modules are calculated by Fault Tree Analysis[4]. The input trigger rates are calculated from the RHIC operational data.

Failure modes of BPS



Competing risks theory

- Multiple risks compete for the lifetime of a component to cause a final failure
- While considering crude lifetimes, each risk is viewed in the presence of all other risks
- Basic probability framework is a bivariate distribution with

Time of failure : T = [0, ∞) = continuous variate

Mode of failure : C = {1, 2... k} = discrete variate

The BPS modules are subjected to $j = \{1, 2 \ldots k\}$ risks with hazard rate as λ_j. The crude failure probability distribution function of j^{th} risk is:

$$F_j(t) = P[0 < Tj < t, Tj < Ti \ \forall i \neq j | T > 0] \ ; j = \{1, 2 \ldots k\}$$

For exponentially distributed T:

$$F_j(t) = \frac{\lambda_j}{\sum_i^k \lambda_i}\left(1 - e^{-\left(\sum_i^k \lambda_i\right)t}\right)$$

Probability of failure from risk j:

$$\pi_j = \lim_{t \to \infty} F_j(t) = \frac{\lambda_j}{\sum_i^k \lambda_i} \ ; \qquad \sum_j^k \pi_j = 1$$

Probability of survival (survival function) from all the k risks:

$$S_T(t) = e^{-\left(\sum_i^k \lambda_i\right)t}$$

Allowed values of j for module variants:

Variants	PM:M, PM:SQ	PM:SNQ, PM:S	AKM	Input triggers
j values	j = {FB, FQ, B}	j = {FB, B}	j = {FB, B, DD}	j = {PI} or {QI}

Smirnov transform[5]

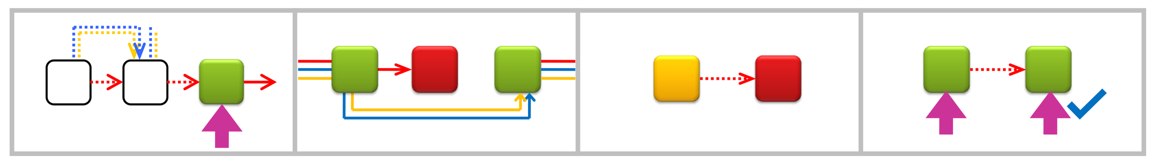
Bivariate distribution of lifetime:

$$T = \frac{-1}{\sum_j^k \lambda_j} \ln U_1 \qquad C = \begin{cases} 1, & 0 \le U_2 \le \pi_1 \\ 2, & \pi_1 < U_2 \le \pi_1 + \pi_2 \\ \ldots & \\ k, & \pi_1 + .. \pi_{k-1} < U_2 \le 1 \end{cases}$$

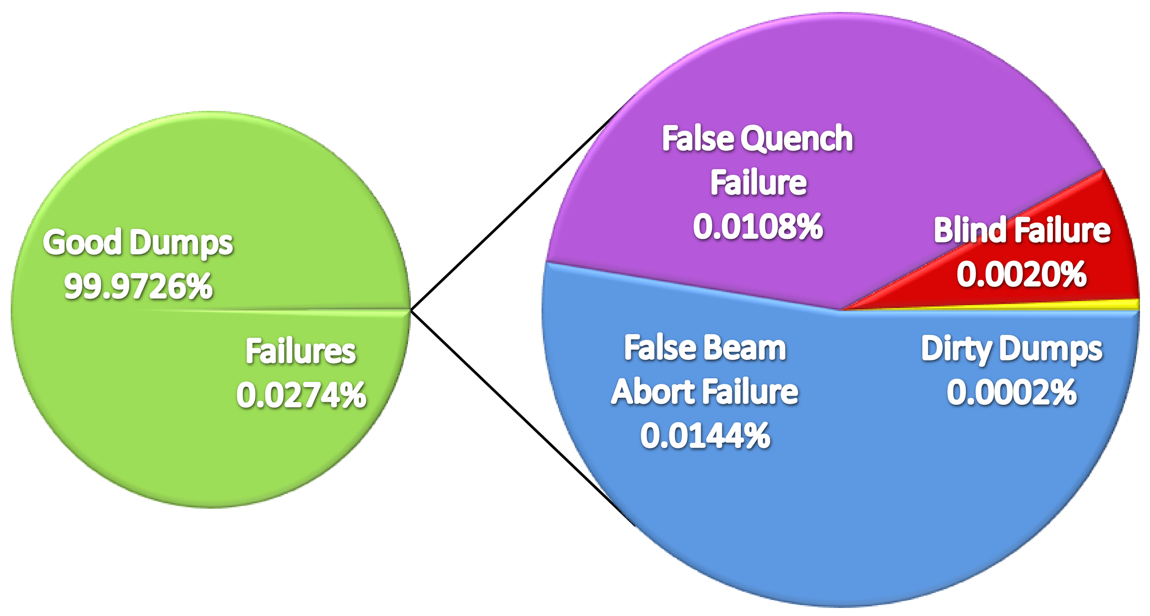
where U_1 and U_2 are pseudo-random numbers

Simulation

- Individual competing risks model for each module
- Random lifetimes are generated from Smirnov equations
- Maximum observation time : 6 hrs (avg. store length of RHIC)
- Trigger arrival freezes the system state and BPS operation is emulated
- Initial conditions: BPS is fully initialized and beam is established
- Dynamic model: no of components vary with trigger location
- PM:SNQ bypassed if blind: reduced structural importance
- False trigger blocked by a blind component
- Priority assignment to multiple triggers



Results



Above are the BPS system failure scenarios. Total failures are only a tiny fraction of the total dump events. Considering 1135 average no. of runs per year, MTTF of false beam abort failure, false quench failure, blind failure and dirty dump are 7.2, 9.5, 51.2 and 672 years respectively. The 20-year operational life of RHIC is quite lower than the blind failure MTTF, and so is the risk of a fatal failure. The false failure numbers here are acceptable, as they impose downtime to only restart the machine.

Size of the sectors depends on:

- magnitude of failure rates $\lambda_{FQ} > \lambda_{FB}$
- number of modules generating that failure $n(\lambda_{FQ}) > n(\lambda_{FB})$

Conclusion

The probabilities of dangerous failures existing in the system that can cause significant downtime are evaluated here. The upcoming eRHIC will be an extension of RHIC, housing a part of RHIC's MPS, and design of new MPS for electron ring.

The analysis also illustrates the impact of BPS design aspects and will help rendering intelligent decision support towards recommendation for eRHIC BPS design.

Acknowledgement

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Footnotes

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