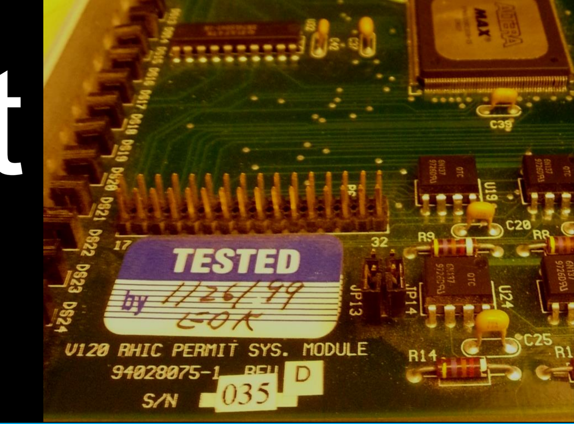
Understanding the failure characteristics of the beam permit system of RHIC at BNL



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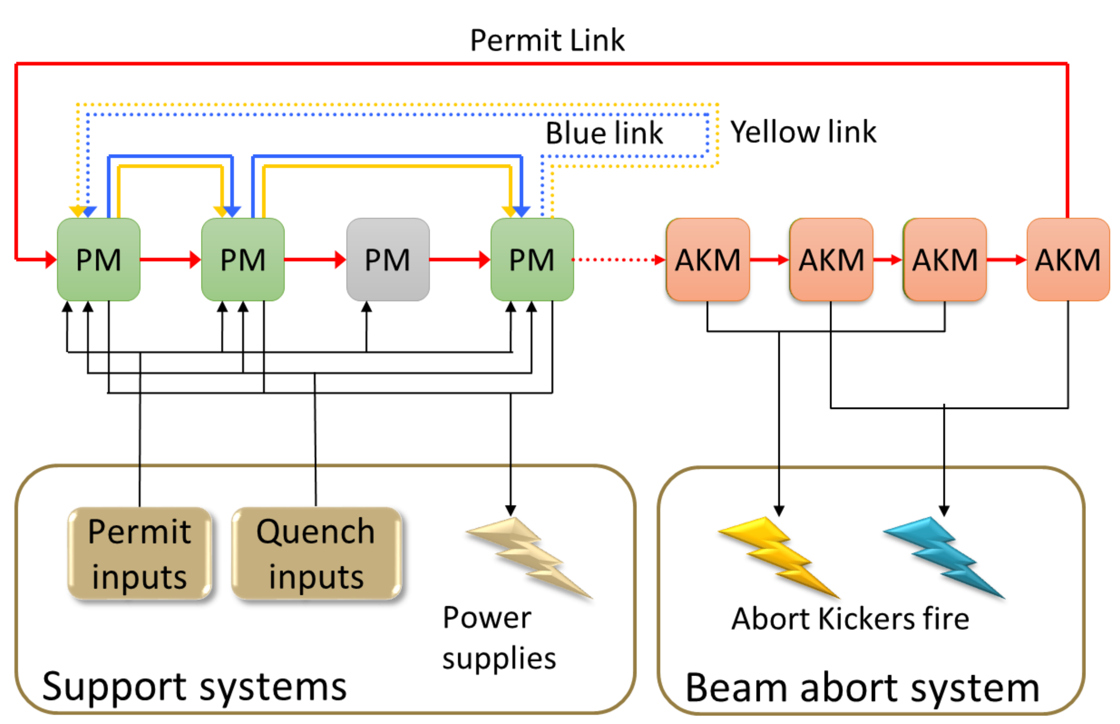
Objective

Gain profound view into the failure characteristics of BPS, by deriving probabilities of system states as a function of beam store length

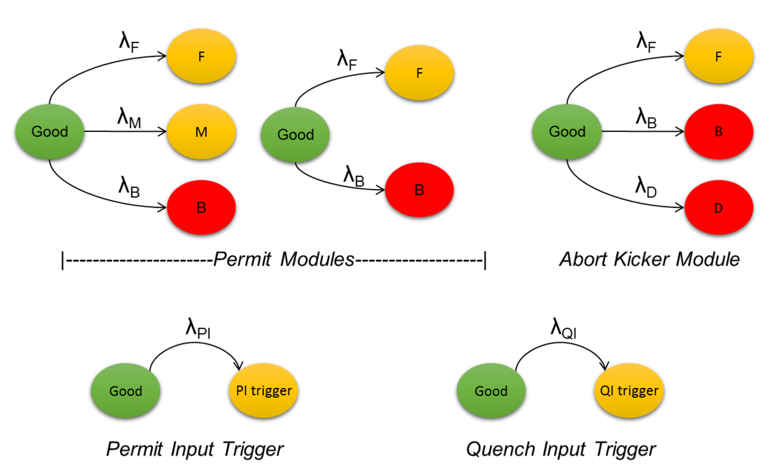
Introduction

- Peak energy stored in RHIC is about 72 MJ
- BPS takes action for the safe disposal of this energy in case of failure
- High reliability for BPS is essential
- Earlier Monte Carlo model[1] runs 17 hrs. for 1E9 iterations to produce failure probabilities[2] for a certain store length
- This work generates analytical expressions for system failure probabilities as a function of store length

Beam Permit System[3]



- 33 Permit Modules (PM) and 4 Abort Kicker Modules (AKM)
- Inputs (PI & QI) are the health inputs from the field
- Permit, B/Y link communicate the support system statuses
- PM takes decision to declare failure state, and drop link(s)
- AKM signal abort system to dump the beams



Competing Risks[4]

Risks: $j = \{1, 2...k\}$
PM: $j = \{F, M, B\}$
AKM: $j = \{F, B, D\}$

F -> False beam abort
M -> false Magnet quench
B -> Blind
D -> Dirty dump

CDF $F_j(t) = \frac{\lambda_j}{\sum_{i=1}^{k} \lambda_i}\left(1 - e^{-(\sum_{i=1}^{k} \lambda_i)t}\right); j = \{1, 2.., k\}$

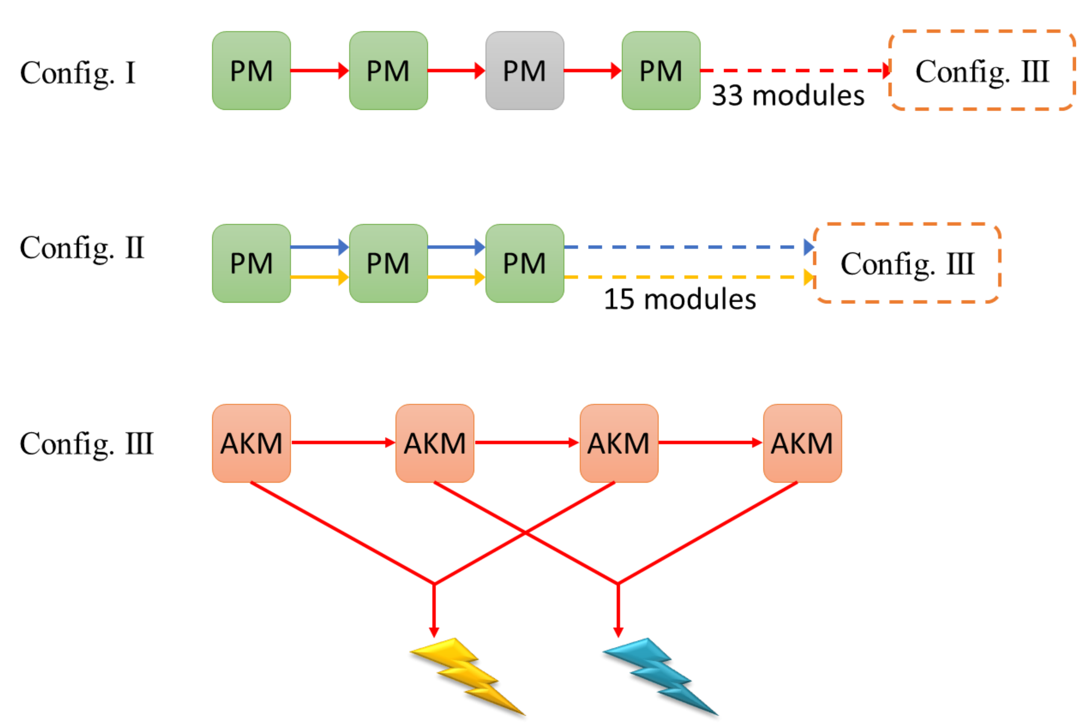
$S_T(t) = e^{-(\sum_{i=1}^{k} \lambda_i)t}$

$$S_T(t) + \sum_{j=1}^{k} F_j(t) = 1$$

Analytical Model

System States

- For reliability metrics, we are interested in system inputs and outputs.
- Linearize structure: PM is the input interface, AKM is the output interface
- Divide the system into segments relevant for system states
- Triggering states: Failure density function *p(t)*
  Passive states: Failure distribution function *P(t)*



Triggering state: for m[th] module, and j[th] state where j= {F, M, PI, QI}, failure density function and failure distribution function is given by

$$p_j^m(t) = \lambda_j e^{-(\sum_{i=1}^{k} \lambda_i)t}\ ; \ P_j^m(t) = \int_0^t p_j^m(t)$$

Passive failure state: for j[th] state where *j= {B, D}*, failure distribution function is given by

$$P_j^m(t) = \frac{\lambda_j}{\sum_{i=1}^{k} \lambda_i}\left(1 - e^{-(\sum_{i=1}^{k} \lambda_i)t}\right)$$

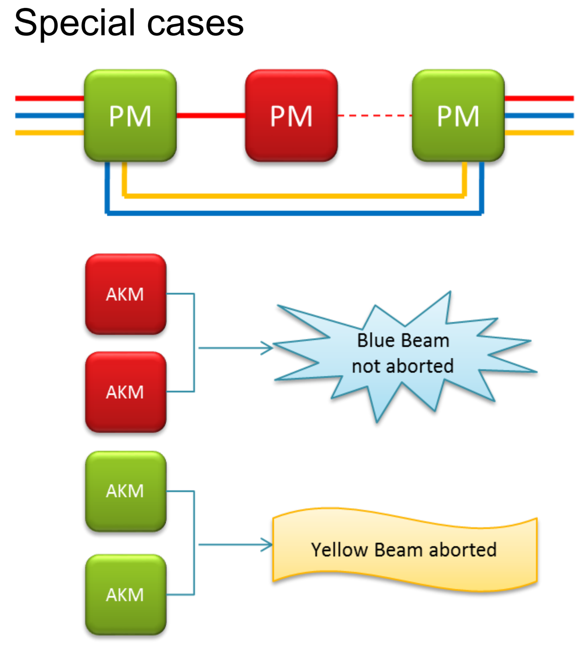
Passive good state: failure distribution function is given by

$$P_G^m(t) = e^{-(\sum_{i=1}^{k} \lambda_i)t}$$

For a module *m*, at any given instant, following is always true

$$P_G(t) + \sum_j \left(P_j^m(t)\right) = 1$$

Special cases



Blind component skipped

Both of the redundant AKMs fail

State Expressions

The probability expressions are developed[5] by observing each modules' state, starting from Master PM to last AKMs. The expressions are quite complicated, but use the following strategy:

Abbr.	System state description	Passive states	Trigger states
ND	No Dump	X	None
GD	Good Dump	all G	PI, QI
FD	False Beam Abort Failure	all G	F
MD	False Quench Failure	all G	M
BD	Blind Failure	atleast a B	PI, QI, F, M
DGD	Dirty Good Dump	atleast a D	PI, QI
DFD	Dirty False Beam Abort Failure	atleast a D	F
DMD	Dirty False Quench Failure	atleast a D	M

Verification

Due to small probabilities of dirty and blind failures, we assign hypothetical failure rates to modules, and compare the results of Monte Carlo model and Analytical model

Abbr.	Analytical	Monte Carlo
$P_{ND}(t)$	0.0149852	0.0149856
$P_{GD}(t)$	0.0621532	0.0621708
$P_{FD}(t)$	0.3105783	0.3105881
$P_{MD}(t)$	0.2494602	0.2494724
$P_{BD}(t)$	0.2754812	0.2754846
$P_{DGD}(t)$	0.0087564	0.0087507
$P_{DFD}(t)$	0.0406134	0.0406134
$P_{DMD}(t)$	0.0379719	0.0379183
Total (from model)	1.0000000	1.0000000

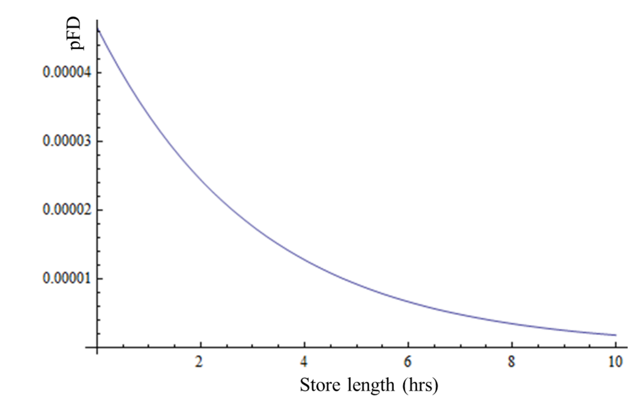
- Probability values are very close
- Sum of probabilities is 1
- Verified the analytical model

After the verification of the analytical model, we put the actual failure rates and store length in the model to get the actual probabilities of system states

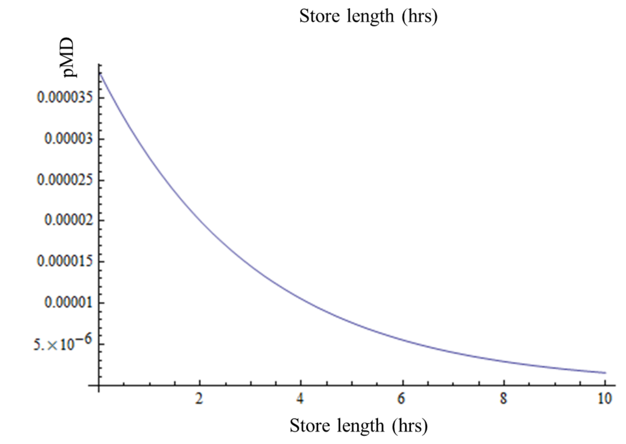
$$P_{ND}(t) = 0.143573$$
$$P_{GD}(t) = 0.856193$$
$$P_{FD}(t) = 0.000123713$$
$$P_{MD}(t) = 0.000101377$$
$$P_{BD}(t) = 7.74551\ E - 6$$
$$P_{DGD}(t) = 1.39145\ E - 6$$
$$P_{DFD}(t) = 1.99945\ E - 10$$
$$P_{DMD}(t) = 1.64755\ E - 10$$

Discussion

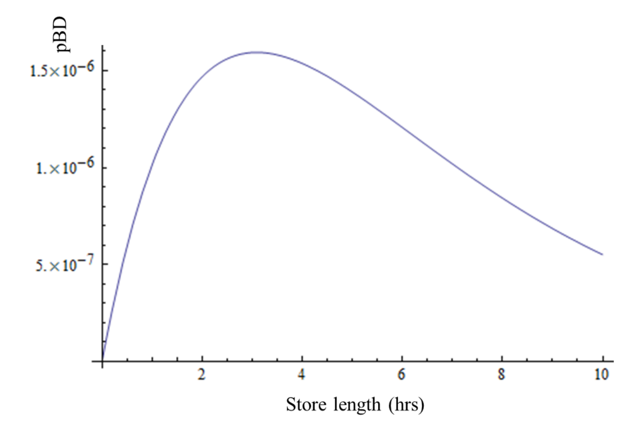
Plotted are the failure density functions of the three important system states with respect to reliability and availability of Beam Permit System, namely FD, MD and BD



System false beam abort failure



System false magnet quench failure



System blind failure

Facilitates easy analysis of change in system states with changing

- Component failure distributions
- PI/QI trigger rates

Importance of modules[6]

- Failure rate magnitude
- Structural position: in path of propagation of multiple failures, nearness to output, bypassing of modules, redundancy

Interdependency analysis[6] of modules

Step towards eRHIC[7] design

References

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Footnotes

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