Modeling accelerator reliability

Miha Reščič, Rebecca Seviour
University of Huddersfield, UK

Overview

- ADS & Accelerator reliability
- How to approach reliability
- Modeling reliability
- Results
- Next steps

Accelerator Driven Sub-critical Reactor

University of HUDDERSFIELD
International Institute for Accelerator Applications

- Aim to provide a service to the national grid
  - Beam trips significant neutron flux driver in a ADS reactor
  - Beam trips have two major consequences for the target:
    - thermal shock
    - for commercial operation of an ADS to be viable high machine availability is required. In energy production every second the reactor is not producing electricity at the contracted level the operator is fined
- Also prediction of beam trips needed for
  - Maintenance scheduling
  - Spare parts procurement

ADS Technology Readiness Assessment

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance	Green	Green	Green
	Reliability	Yellow	Yellow	Red
Accelerating System	RF Structure Development and Performance	Green	Green	Green
	Linac Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
RF Plant	Performance	Green	Green	Green
	Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Red
Beam Delivery	Performance	Green	Green	Green
Target Systems	Performance	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
Instrumentation and Control	Performance	Green	Yellow	Yellow
Beam Dynamics	Emittance/halo growth/ beamloss	Green	Yellow	Yellow
	Lattice design	Green	Yellow	Yellow
Reliability	Rapid SCL Fault Recovery	Yellow	Red	Red
	System Reliability Engineering Analysis	Yellow	Red	Red

*Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production. 2010. DOE sponsored White Paper on Technology for Accelerator Driven Systems.

Green: “ready”, Yellow: “may be ready, but demonstration or further analysis is required”, Red: “more development is required”

ADS & Accelerator Reliability Requirements

- Downtime requirements*:

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam trips ($t < 1$ sec)	N / A	< 25000/year	< 25000/year	< 25000/year
Beam trips ($1 < t < 10$ sec)	< 2500/year	< 2500/year	< 2500/year	< 2500/year
Beam trips (10 s $< t < 5$ min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips ($t > 5$ min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	$> 50\%$	$> 70\%$	$> 80\%$	$> 85\%$

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ADS & Accelerator Reliability Numbers

- SINQ (PSI):
  - 2000: the number of short beam trips at roughly 50 per day ($t < 3$ min)
  - 2006 (August 14 to December 21):
    - 5500 trips of ($t < 1$ minute) and
    - 570 interrupts of ($t < 8$ hours)
- SNS (ORNL):
  - 2010:
    - Daily about 100 trips per day of duration (1 s $< t < 1$ minute) and
    - Daily 10 trips of duration (1 min $< t < 1$ hour)
  - 2013:
    - a daily average of about 40 trips of duration ($t < 1$ minute)

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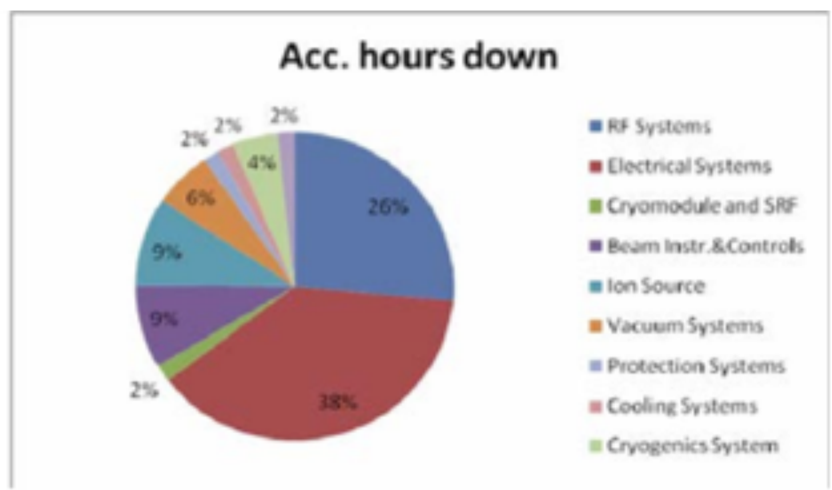
Predictive methodologies

- Top-Down / Deductive
  - Need detailed info about components and connections
  - Need “solid” database of components
  - Most common: Reliability Block Diagram (RBD)
    - Layout of RBD usually depends on system state!
  - Fault Tree Analysis (FTA)
    - Determine all component faults that lead to given system fault

- Bottom-Up / Inductive
  - Failure Mode and Effects (Criticality) Analysis (FMEA/FMECA)
    - Can be performed with expert judgment on relative criticality of components
    - Can be performed also with less detail in design

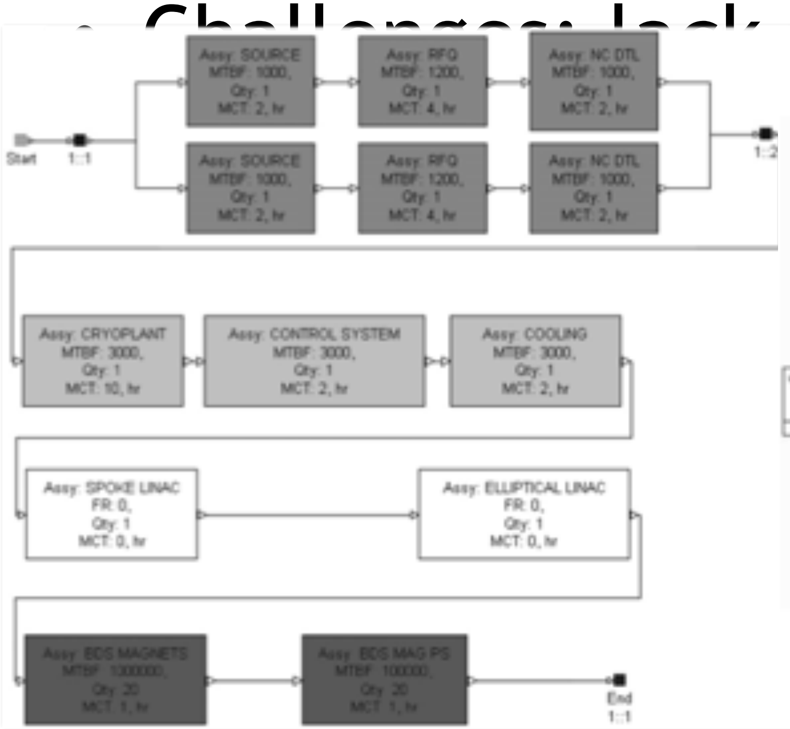
Addressing Accelerator Reliability

- During design stage
  - Predictive methods, design change
- After finished construction
  - Statistical analysis or performance, parts replacement



During design phase

- Reliability Block Diagrams, Fault Tree Analysis, Failure Mode and Effects Analysis,
- Challenges: lack of data



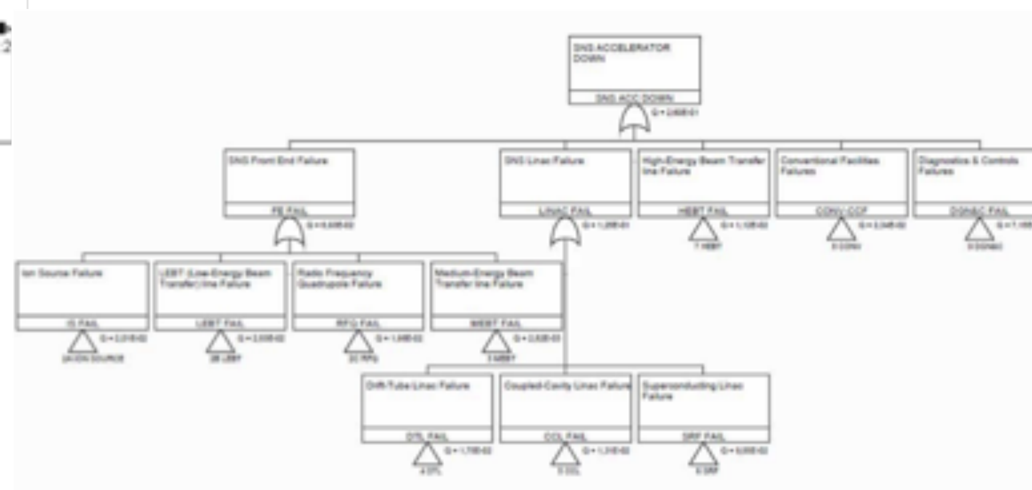


Figure 2: First level of the SNS RS Model – SNS Main Fault Tree structure

Why different approach

- Accelerator reliability is not yet fully defined, understood nor addressed, but there is data that is retrievable from modern operating accelerators that contains detailed information about the accelerator behavior.
- Analyzing this data could provide insight and yield results that classical approaches (e.g. RBDs) struggle with due to the lack of good quality data.
- Accelerators are very complex, too complex to be able to model every detail
  - Data-centric approach
  - Use system-agnostic data (e.g. beam current)
- Instead of *"more precision, less accuracy"* in modeling reliability – "*more observation, more predictability*"?

Recent developments

- AvailSim, Monte Carlo simulations
- Markov chains sensitivity analysis
- Predictive data-centric models

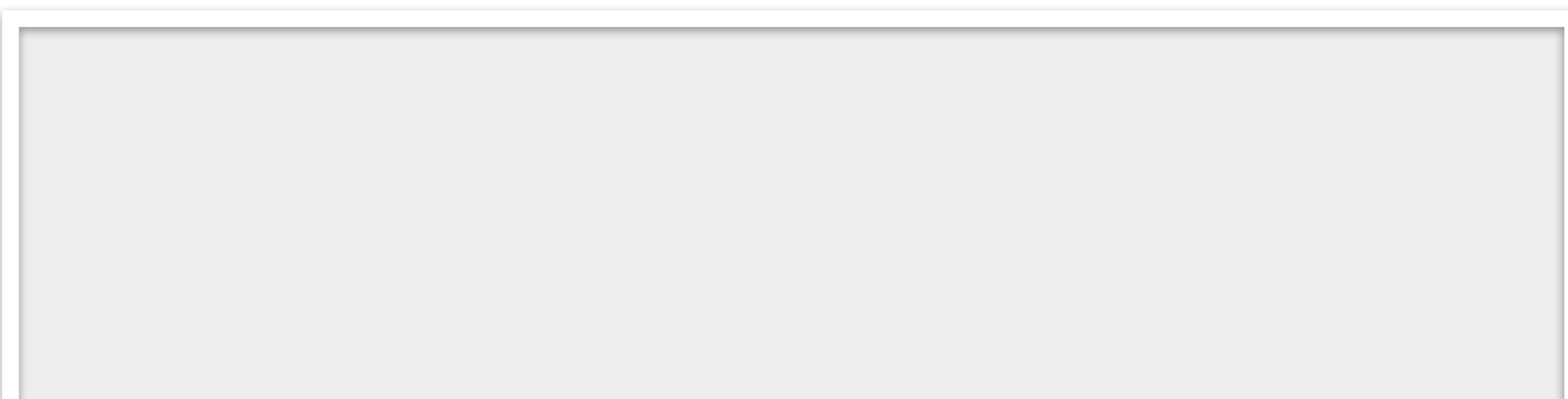
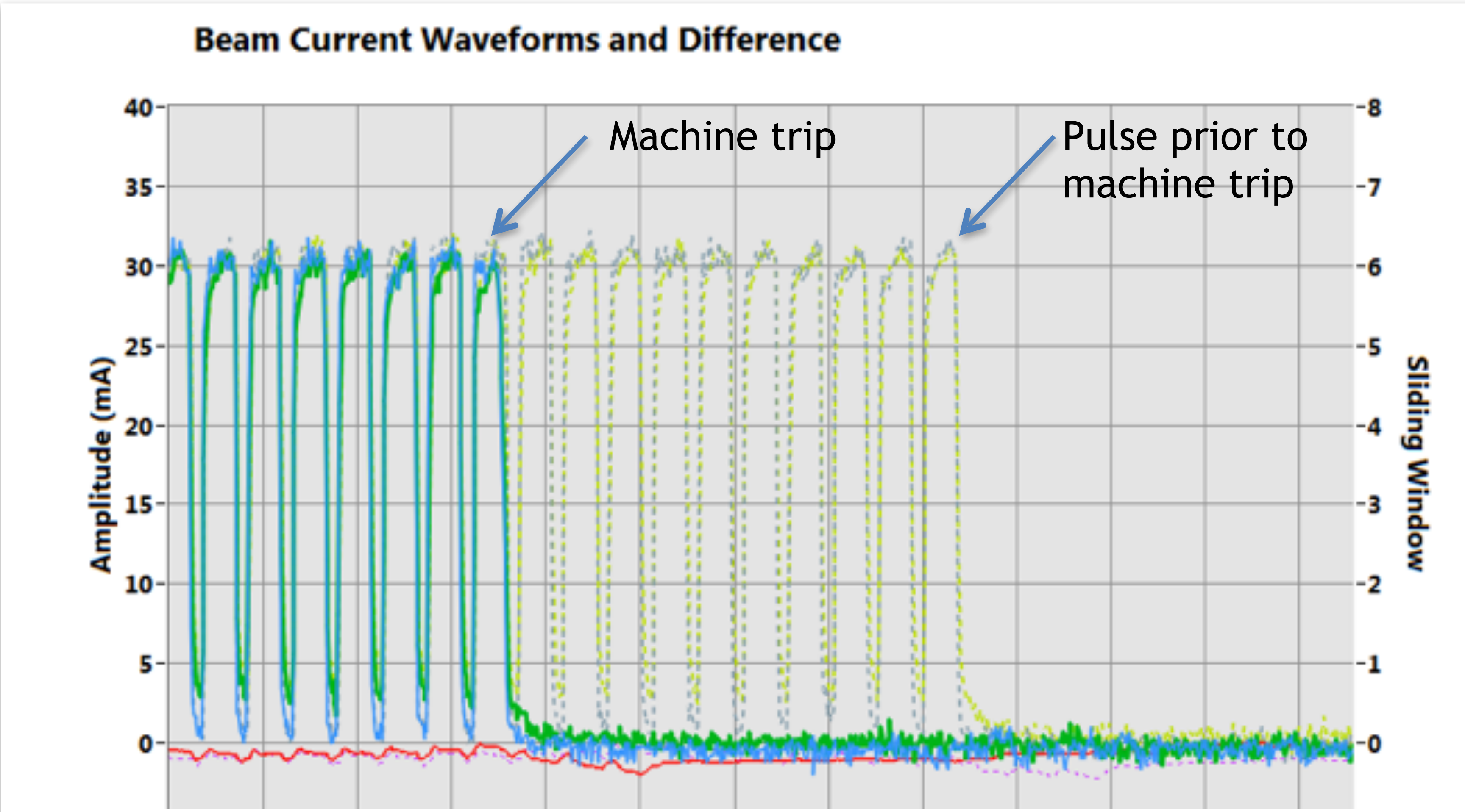


Figure 3: Example of prognostics output.

SNS Beam Current Signal

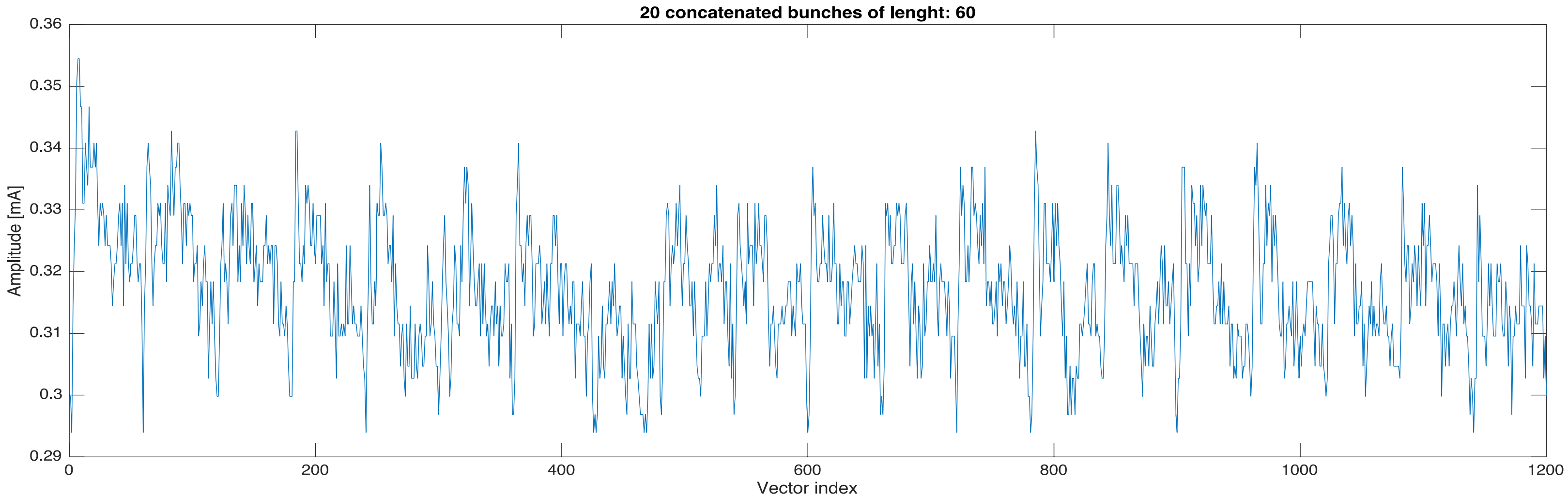


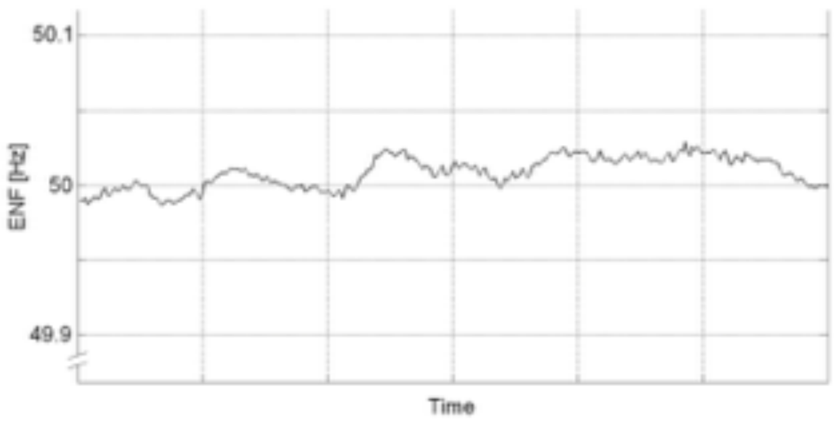
Pulse time

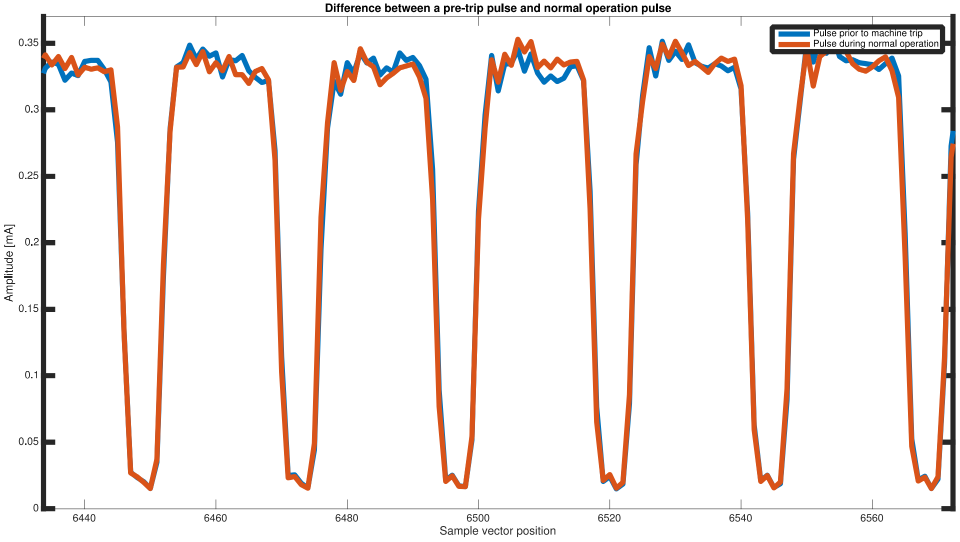
Emergent behavior

- Complex accelerator system has 1000’s of interconnected devices
- These devices connected and running together generate an unique signature (e.g. beam current)
- Changes in operation of the accelerator is caused by one (or more) devices changing behavior (e.g. sub-optimal performance or malfunction)
- Question: Can this change be detected in the unique signature?
- Answer: Most probably yes
- Example:
  - The national power grid is a large system of 1000’s of interconnected devices (producers, consumers, distribution grid, transformers etc.)
  - The unique signature of the current distributed by national power grids is used in acoustic forensics to identify and verify when recordings are made

Electric Network Frequency Criterion







ENF Criterion

- Create databases of certain pulse types:
  - Pre-trip: dataset of last successful pulses before the machine tripped
  - Normal operation: dataset of pulses from normal operation
- Matching algorithms:
  - Minimum Root Mean Squared (RMS)
  - Maximum Correlation coefficient (CC)

$$RMS(x,y) = E_{rms} = \sqrt{\frac{\sum_{i=1}^{L}(x[i]-y[i])^2}{L}}$$

$$CC(x,y) = \frac{\sum_{i=1}^{L}(x[i]-\bar{x})(y[i]-\bar{y})}{(L-1)\sigma_x\sigma_y}$$

- Procedure
  - Calculate RMS, CC values for sample and databases
  - If threshold is reached, match is detected
  - Depending on match type:
    - Pulse is pre-trip = high probability the machine will trip the next pulse
    - Pulse is normal operation = next pulse will not trip the machine

Initial results

- The setup
  - 2 databases: Pre-trip, normal operation
  - 5 days of SNS trip data:
    - 1200 pulses
    - 18M datapoints
- Matching samples
  - 100 pre-trip pulses
  - 100 normal operation pulses

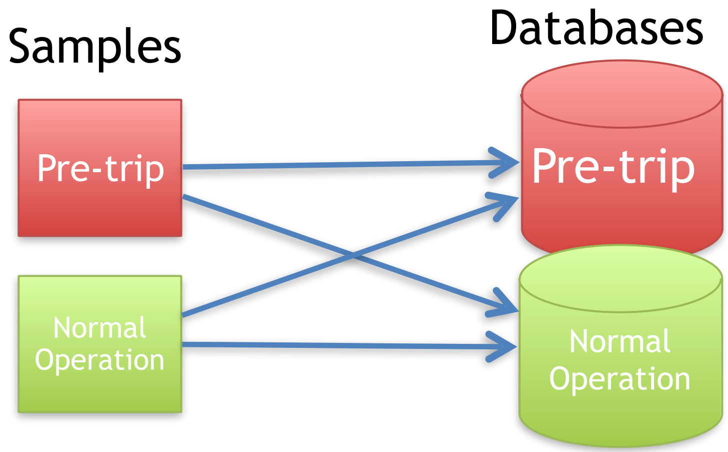
Percentage of successful matches per pulse type

Method	Correct	False	As both	Not identified
RMS	11.1%	8.1%	8.1%	72.7%
MCC	6.1%	21.2%	17.2%	55.5%

TABLE 6. *Previous* sample matching results, percentage of all samples

Method	Correct	False	As both	Not identified
RMS	28.0%	7.0%	39.0%	26.0%
MCC	50.0%	0.0%	33.0%	17.0%

TABLE 7. *Next* sample matching results, percentage of all samples



Next steps

- Refine ENF matching algorithms
  - Use higher fidelity data, bunch-by-bunch matching
- Stochastic – Hidden Markov Models (HMM)
  - Models are trained on sets of data to be able to recognize patterns
  - Example: speech recognition
  - Leverage knowledge base from speech and pattern recognition
  - Test on datasets we have, compare results ENF results

Summary

- The drive of research is the future **industrial application** of accelerators
- Adopt a data-centric, system-agnostic approach
- Reliability can be improved by predicting failures, not only by designing them away
- Reliability as a discipline is well advanced in industry, but not in accelerator field
- Looking at predicting behavior using analytical and stochastic methods to evaluate if this can give vital needed seconds for accelerators to be used in an industrial setting

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Thank you!