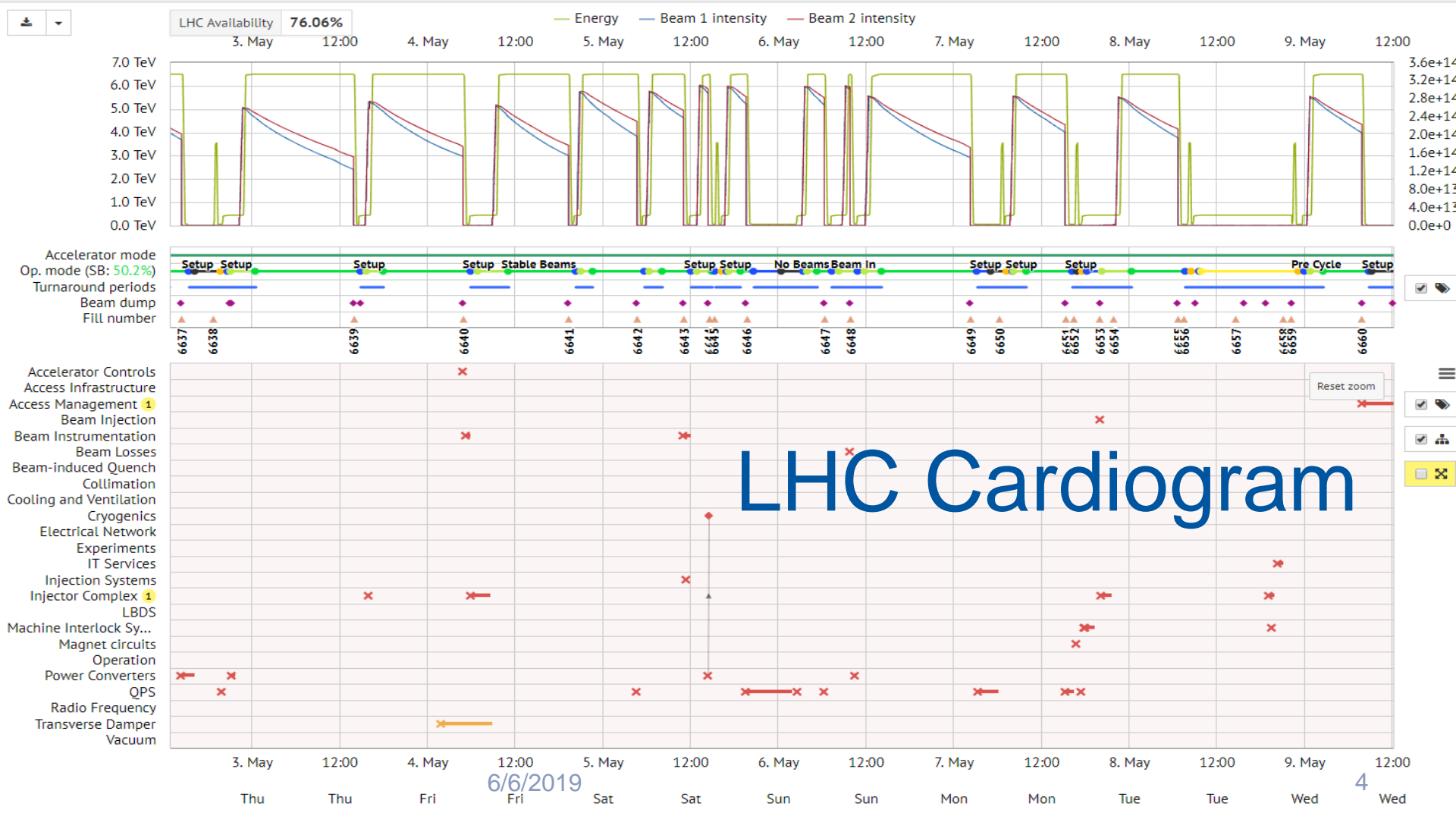# From LHC statistics to AvailSim modelling

M.Vekaria, A.Apollonio, T.Cartier-Michaud

6/06/2019

# Introduction
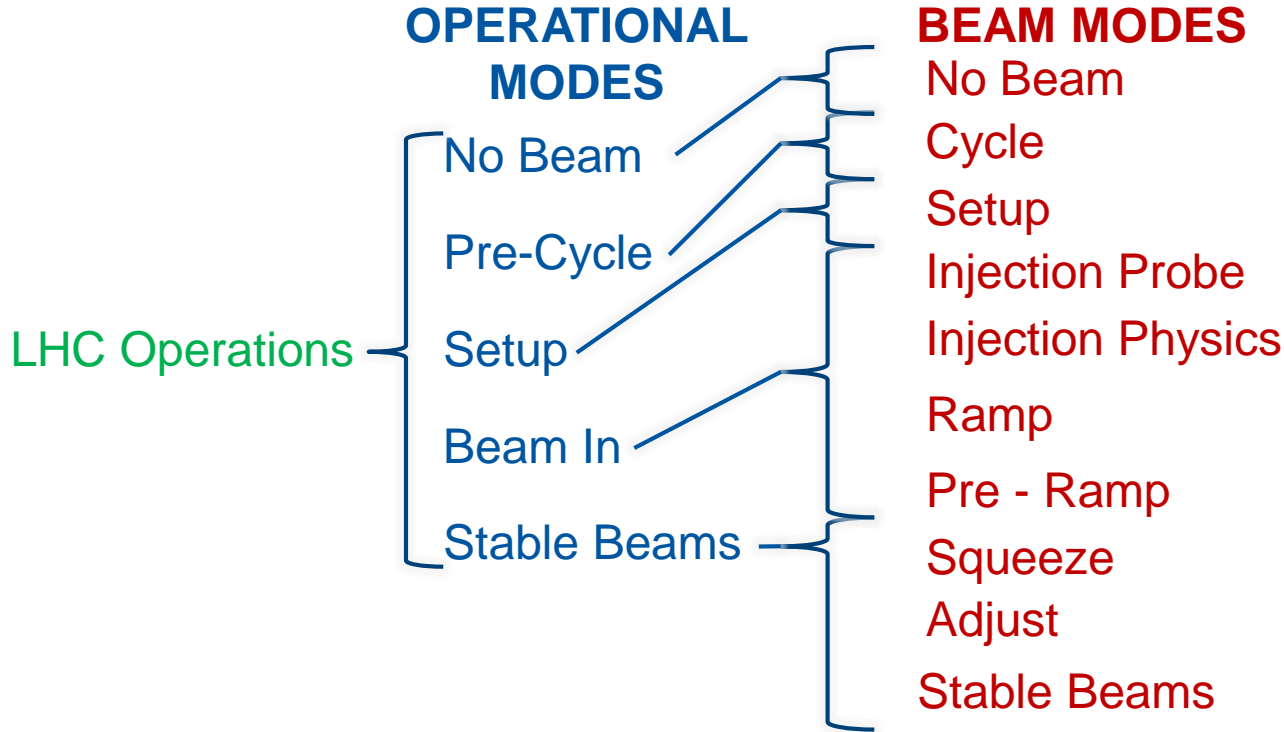
- Data sources
- Introduction to LHC Operations
  - Fault statistics in BModes
- Injection Investigation
  - Physics and Probe
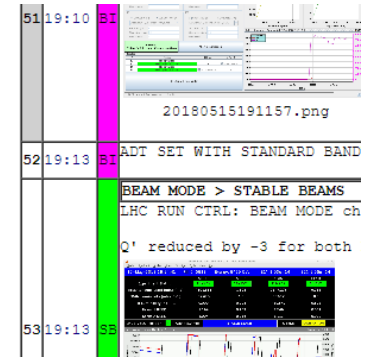- AvailSim inputs

LHC Cardiogram

6/6/2019

4

# Availsim

- Monte-Carlo simulation tool
  - Simulate the operation of accelerators eg. LHC
- Inputs based on observed performance
  - Works using different reliability measures (Mean Time To Repair, Mean Time To Fail) from faults
  - These change depending on the beam mode they occur in.
- Also requires Beam Mode durations as an input

# LHC Operation Breakdown

Aim is to calculate Beam Mode durations and calculate failure rates and repair times based on beam mode

**OPERATIONAL MODES**

**BEAM MODES**

LHC Operations
- No Beam
- Pre-Cycle
- Setup
- Beam In
- Stable Beams

Beam Modes:
- No Beam
- Cycle
- Setup
- Injection Probe
- Injection Physics
- Ramp
- Pre - Ramp
- Squeeze
- Adjust
- Stable Beams
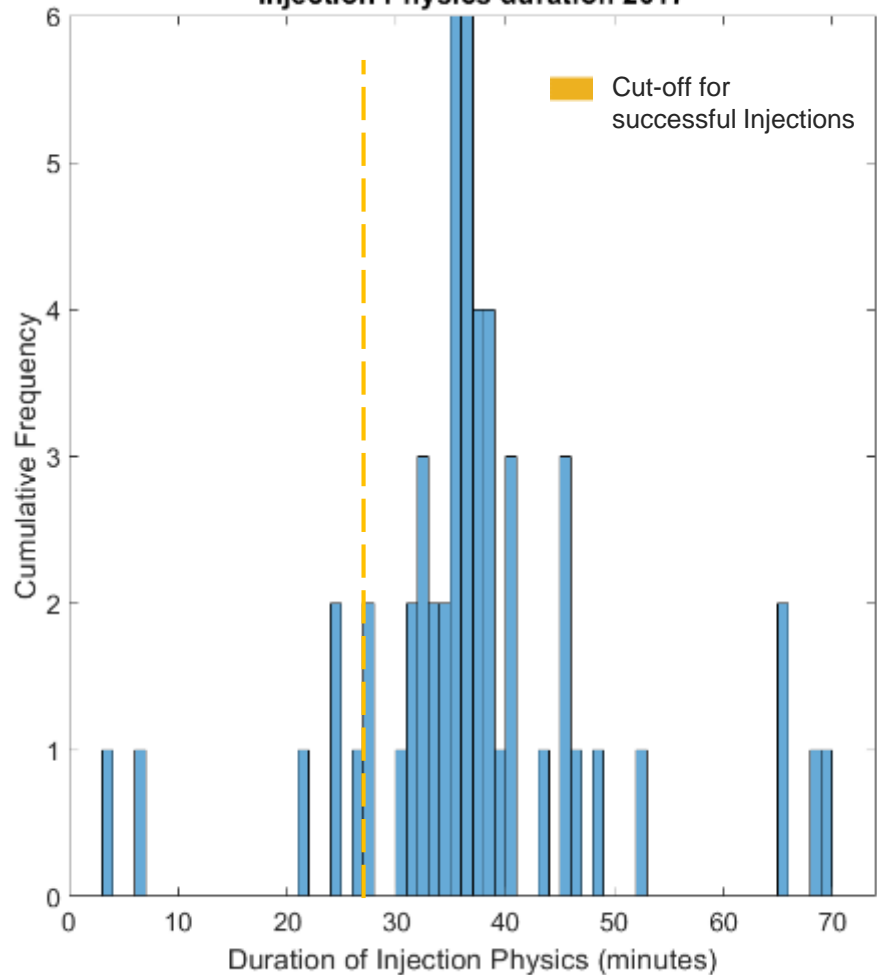


E-Logbook

# Data Sources

- Timber
  - Fill number timings
  - Beam modes
  - Beam Intensity
- AFT
  - Fault data
- Post Mortem
  - Injection scheme

# Injection Statistics

- Tasked with looking into Injection inefficiencies.
  - Looked at "injection physics" and "injection probe" for year 17-18 for AvailSim
  - One of the least reproducible modes in LHC operation
    - Why isn't theoretical minima (28mins) reached?
      - 42*20*2/60 = 28
      - Variety of discrepancies between injections that cannot be explained by faults
  - Failures should be expected to correlate to beam intensity
    - Looked at 25ns spaced 2556b
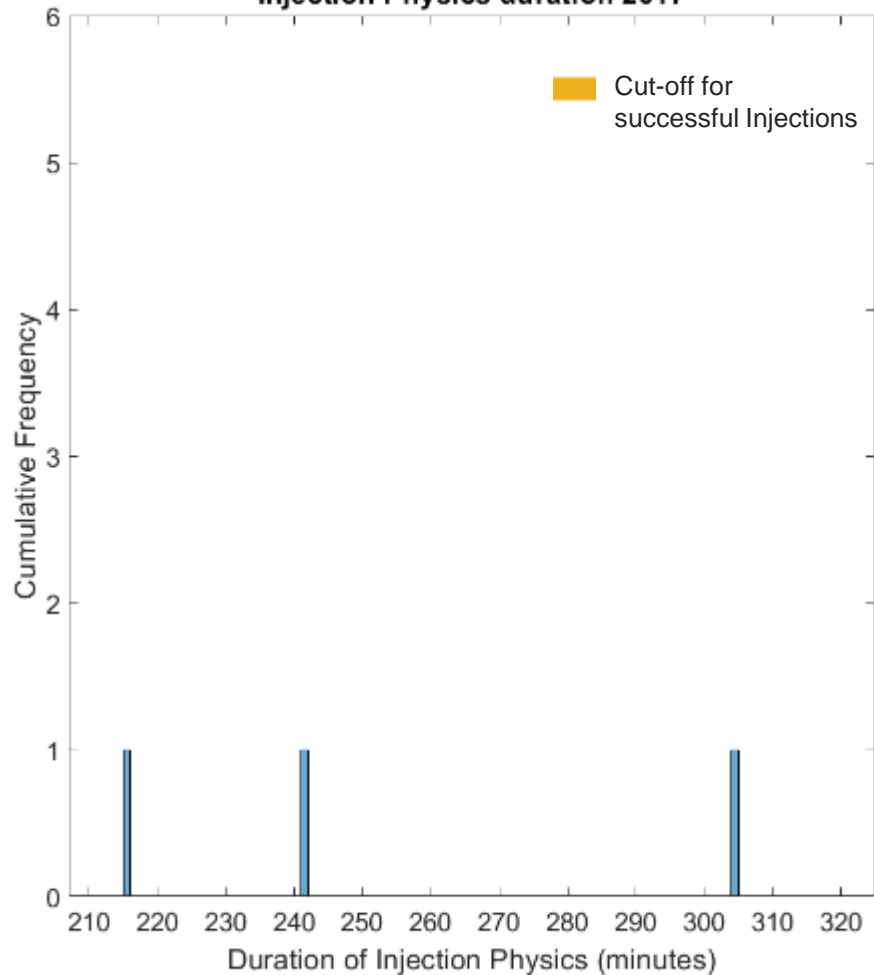
# Why Categorise?

- When looking through E-Logbook, these
  - are the most common
- What is "no explanation"?
  - There is no clear explanation in the logbook
- All of this takes into account registered blocking faults, unregistered are noted as "minor hardware error" e.g.. Faulty QPS circuit board
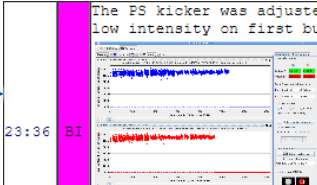
( ╯°□°）╯︵ ┻━┻

| fill# | injphy start | injph end | nominal dur | net dur | reason |
|---|---|---|---|---|---|
| 6643 | 05/05/2018 10:15 | 05/05/2018 11:13 | 00:57:15 | 00:57:15 | ATLAS restart |
| 6645 | 05/05/2018 14:33 | 05/05/2018 15:04 | 00:30:23 | 00:30:23 | no explanation |
| 6646 | 06/05/2018 01:04 | 06/05/2018 01:35 | 00:31:12 | 00:31:12 | no explanation |
| 6647 | 06/05/2018 06:13 | 06/05/2018 07:11 | 00:58:33 | 00:58:33 | no explanation |
| 6648 | 06/05/2018 09:44 | 06/05/2018 10:23 | 00:38:48 | 00:38:48 | minor hardware error |
| 6650 | 07/05/2018 05:32 | 07/05/2018 06:07 | 00:35:10 | 00:35:10 | no explanation |
| 6654 | 07/05/2018 20:04 | 07/05/2018 20:33 | 00:29:22 | 00:29:22 | no explanation |
| 6659 | 08/05/2018 22:09 | 08/05/2018 22:42 | 00:32:40 | 00:32:40 | no explanation |
| 6662 | 09/05/2018 19:31 | 09/05/2018 20:01 | 00:29:53 | 00:29:53 | losses |
| 6663 | 10/05/2018 11:25 | 10/05/2018 11:58 | 00:33:23 | 00:33:23 | minor hardware error |
| 6666 | 10/05/2018 19:39 | 10/05/2018 20:25 | 00:45:26 | 00:45:26 | injection tuning |
| 6671 | 11/05/2018 14:37 | 11/05/2018 15:28 | 00:51:02 | 00:51:02 | measurements |
| 6672 | 11/05/2018 15:36 | 11/05/2018 16:07 | 00:30:27 | 00:30:27 | no explanation |
| 6674 | 12/05/2018 01:41 | 12/05/2018 02:12 | 00:30:45 | 00:30:45 | losses |
| 6677 | 13/05/2018 10:46 | 13/05/2018 11:16 | 00:29:46 | 00:29:46 | losses,  scraping |
| 6680 | 14/05/2018 03:46 | 14/05/2018 04:16 | 00:29:24 | 00:29:24 | injection tuning |
| 6681 | 14/05/2018 04:21 | 14/05/2018 04:54 | 00:32:20 | 00:32:20 | losses |
| 6684 | 15/05/2018 03:58 | 15/05/2018 04:38 | 00:40:10 | 00:40:10 | PS cavity pulse |
| 6685 | 15/05/2018 06:04 | 15/05/2018 07:10 | 01:06:09 | 01:06:09 | injection tuning |
| 6685 | 15/05/2018 07:16 | 15/05/2018 08:35 | 01:18:39 | 01:18:39 | losses, orbit correction |
| 6687 | 15/05/2018 13:37 | 15/05/2018 14:35 | 00:58:06 | 00:58:05 | losses |
| 6696 | 17/05/2018 23:01 | 17/05/2018 23:35 | 00:33:40 | 00:33:40 | BSRT reset |
| 6700 | 19/05/2018 00:52 | 19/05/2018 01:28 | 00:35:20 | 00:35:20 | correction |
| 6702 | 19/05/2018 19:40 | 19/05/2018 20:12 | 00:32:01 | 00:32:01 | no explanation |
| 6703 | 20/05/2018 01:31 | 20/05/2018 02:00 | 00:29:08 | 00:29:08 | BSRT blocked |
| 6705 | 20/05/2018 04:56 | 20/05/2018 05:25 | 00:29:43 | 00:29:43 | no explanation |
| 6709 | 20/05/2018 18:46 | 20/05/2018 19:18 | 00:32:04 | 00:32:04 | no explanation |
| 6710 | 21/05/2018 10:20 | 21/05/2018 10:52 | 00:32:21 | 00:32:21 | SPS BQM |
| 6711 | 21/05/2018 23:23 | 22/05/2018 00:27 | 01:03:54 | 00:45:09 | SPS BQM |
| 6712 | 22/05/2018 15:21 | 22/05/2018 15:52 | 00:30:21 | 00:30:21 | no explanation |
| 6724 | 25/05/2018 15:33 | 25/05/2018 16:41 | 01:07:28 | 01:07:28 | no explanation |
| 6729 | 26/05/2018 13:07 | 26/05/2018 13:38 | 00:30:54 | 00:30:54 | losses |

# Some examples

- <u>Upstream</u>

- <u>No explanation</u>

- <u>Losses</u>

- <u>Hardware</u>

- <u>Intervention</u>

The PS kicker was adjusted for a longer pulse width which resulted in less BQM rejected bunches due to low intensity on first bunch and overall smaller spread of bunch intensity.
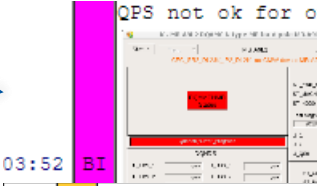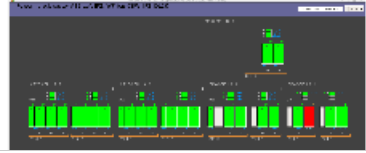
23:36  BI

Beam dump. Losses:

16:27:44 - Alarm on: BLMTI.04L6.B1E10_TCDSA.4L6.B1, integration time: 82 ms, losses = 1.278255E-01,
16:27:44 - Alarm on: BLMTI.06R7.B2I10_TCP.B6R7.B2, integration time: 80 us, losses = 9.354351E00, t
16:27:44 - Alarm on: BLMTI.06R7.B2I10_TCP.B6R7.B2, integration time: 40 us, losses = 9.498337E00, t
16:27:44 - Alarm on: BLMTI.04L6.B1E10_TCDSA.4L6.B1, integration time: 10 ms, losses = 5.333119E-01,
16:27:44 - Alarm on: BLMTI.04R6.B2I10.4R6.B2, integration time: 10 ms, losses = 5.578611E-01

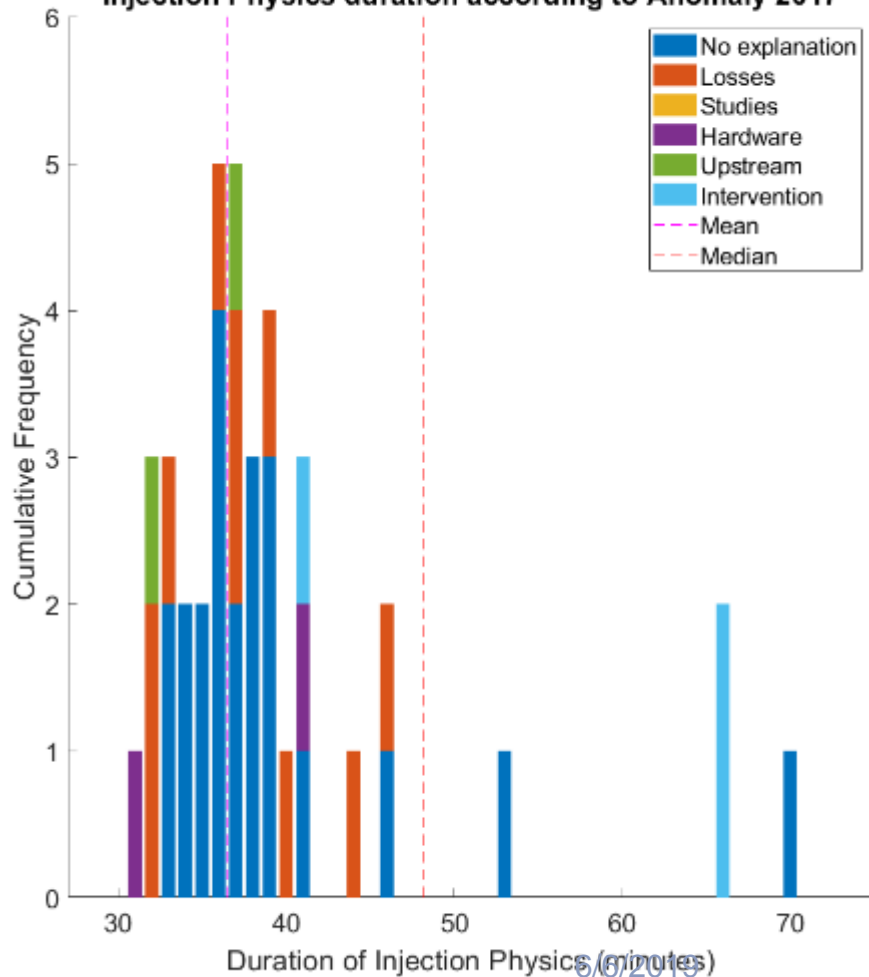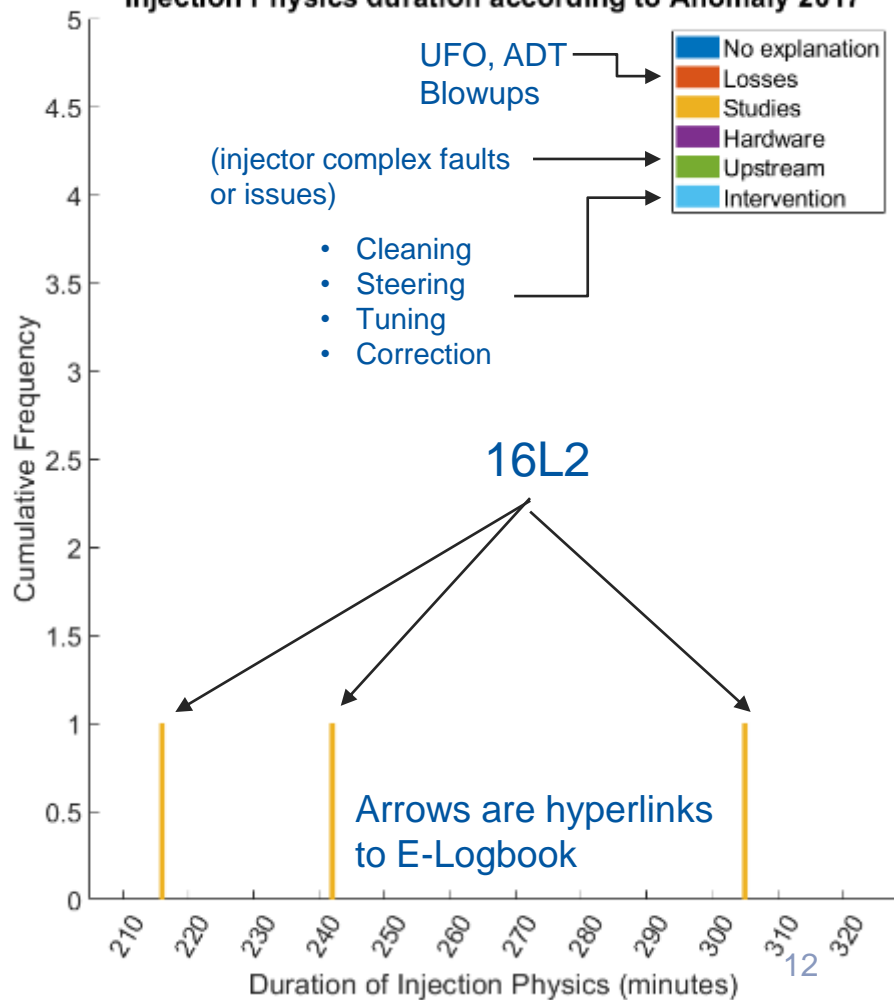QPS not ok for one board (MB.A9L2). We mask it and wait until it recovers.

03:52  BI

08:17  INJT  During the access on the 10/05, the solenoids were switched off and then switched back on again to 55A. the 16L2 issues

Injection Physics duration according to Anomaly 2017

UFO, ADT Blowups

(injector complex faults or issues)

- Cleaning
- Steering
- Tuning
- Correction

16L2

Arrows are hyperlinks to E-Logbook

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12

Injection Probe duration according to Anomaly 17

- Correction
- Calibrations

- SPS
- LINAC 2
- PSB
- PS

Corrections
No Explanation
Upstream

Chroma correction

Hyperlinked arrows again

Cumulative Frequency

Duration of Injection Probe mins
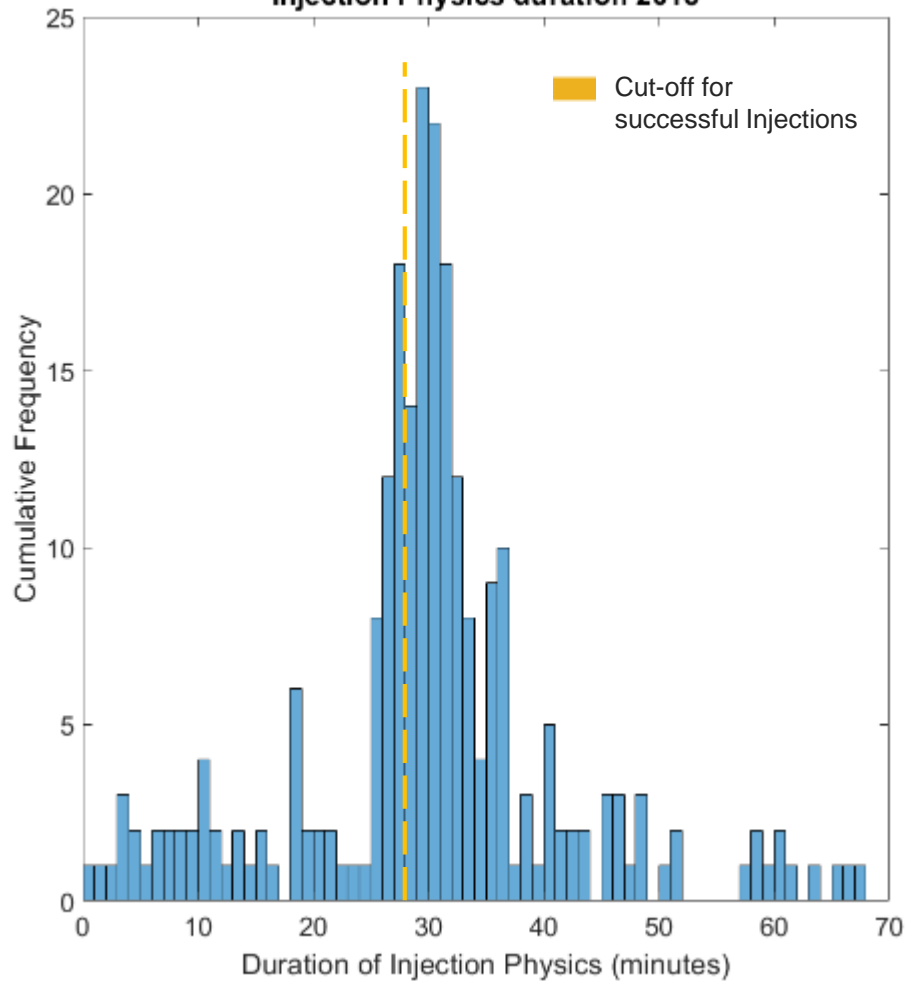
Injection Probe duration 2018

Injection Probe duration according to Anomaly 18

No explanation

Hyperlinked arrows again
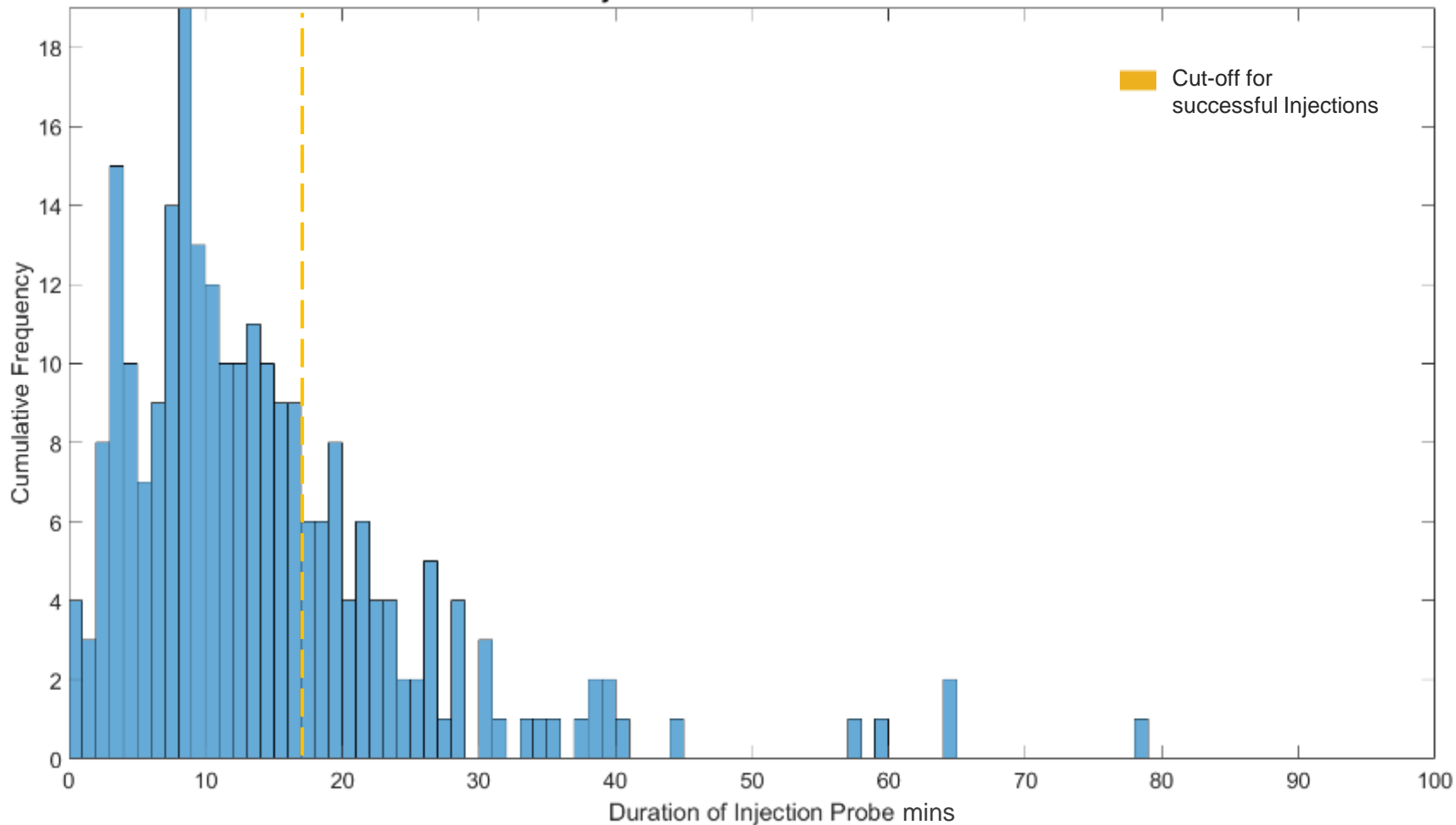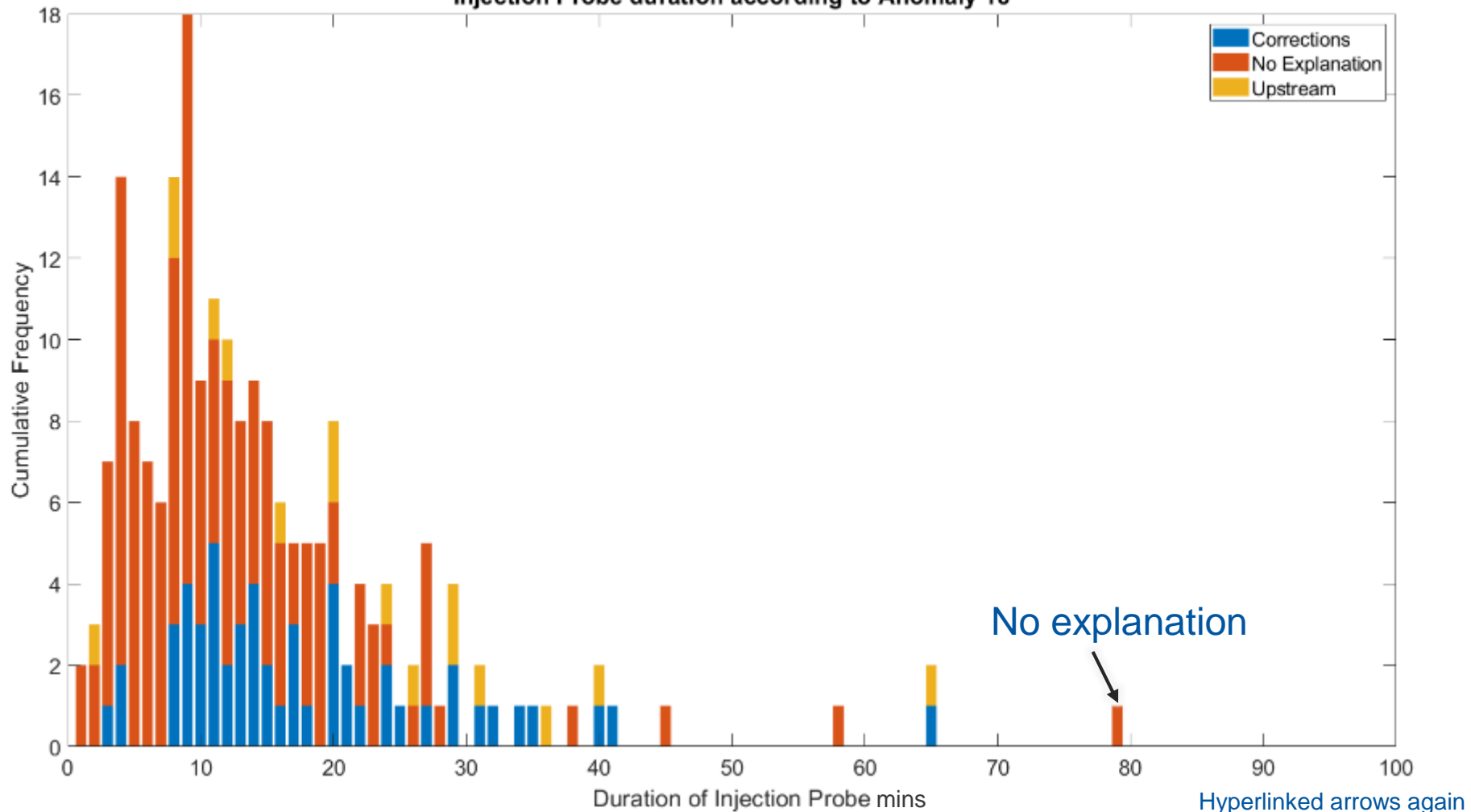
# Review

- There's a lot of "no explanation"
  - This isn't necessarily a bad thing!
  - This introduced a new task that would follow up from this (recommended by Bartosik and Rumolo), which is the first 12 bunch train.
  - Expect largest variance because of the required synchronisations and corrections between injectors and LHC
- Could not apply filter to such a large dataset, but 12b injection should be consistent across beam parameters.

**First 12 Bunches 2017**

| str Name | Mean | Median | StDev | Skew |
|---|---|---|---|---|
| "Beam 1" | 8.8386 | 2.7000 | 33.2361 | 10.4226 |
| "Beam 2" | 9.8453 | 2.7000 | 34.3954 | 9.8919 |

**First 12 Bunches 2018**

| str Name | Mean | Median | StDev | Skew |
|---|---|---|---|---|
| "Beam 1" | 8.6776 | 2.4500 | 41.7971 | 12.0328 |
| "Beam 2" | 8.6086 | 2.4500 | 40.5282 | 12.7119 |

This doesn't show the variance we expected to see, next steps would be to plot the variance of the whole of the injection process
More analysis to come

06/06/2019
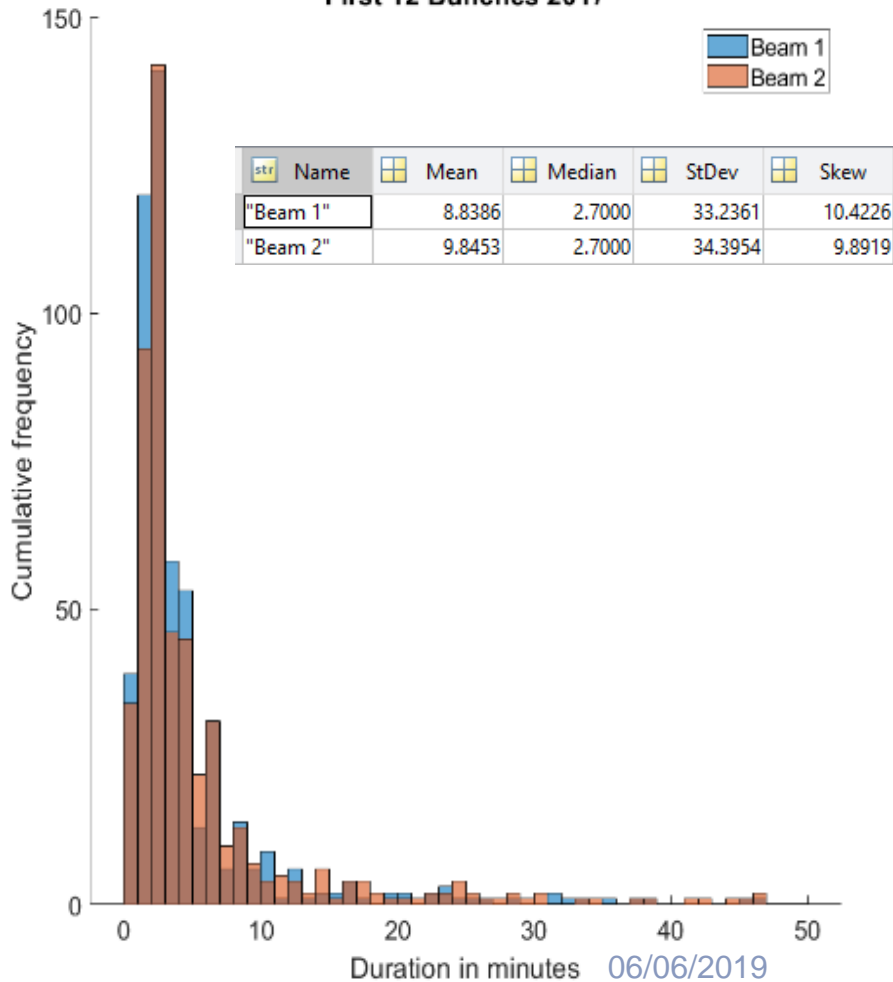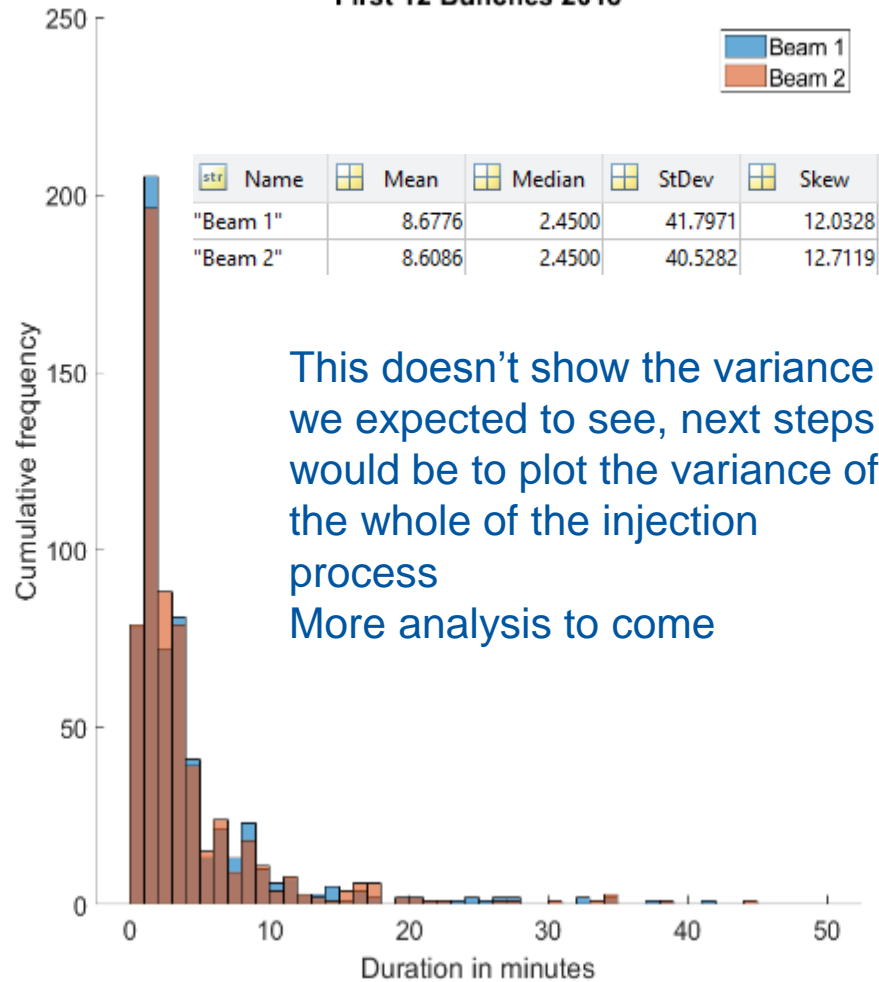
# AvailSim

- Fault and beam mode statistics calculated and output into the 'common input format'.



Beam mode B experiences 2 faults, while A experiences 0.
MTTF given by Mode duration, ergo:

$$\text{MTTF in A} \equiv \sum A/0 = \text{inf}$$
$$\text{MTTF in B} \equiv \sum B/2 = \text{val}$$

MTTR

# Process

Beam Mode Index

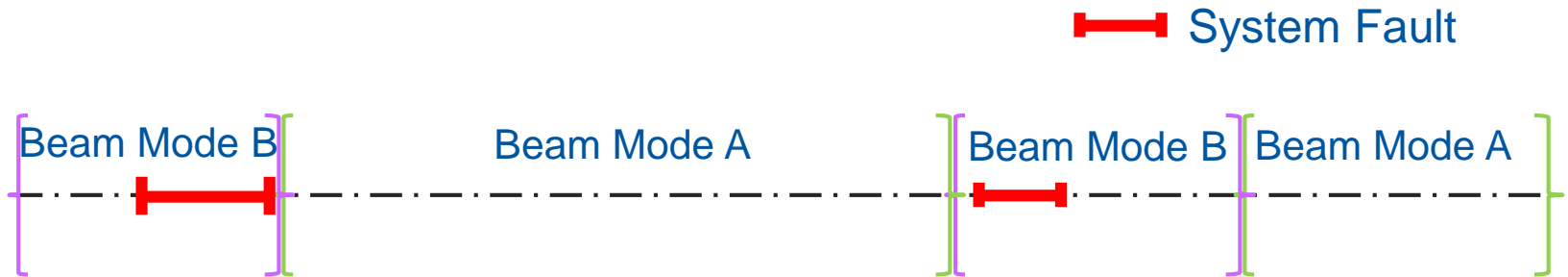| | | | |
|---|---|---|---|
| 'LHC' | 'Magnetcirc...' | '03/04/2015... | '03/04/2015... |
| 'LHC' | 'Cryogenics...' | '03/04/2015... | '04/04/2015... |
| 'LHC' | 'Cryogenics...' | '03/04/2015... | '04/04/2015... |
| 'LHC' | 'Cryogenics...' | '04/04/2015... | '04/04/2015... |
| 'LHC' | 'Experiment...' | '05/04/2015... | '05/04/2015... |
| 'LHC' | 'InjectorCo...' | '06/04/2015... | '06/04/2015... |
| 'LHC' | 'VacuumHa...' | '06/04/2015... | '07/04/2015... |
| 'LHC' | 'PowerCon...' | '07/04/2015... | '07/04/2015... |
| 'LHC' | 'PowerCon...' | '07/04/2015... | '07/04/2015... |
| 'LHC' | 'PowerCon...' | '07/04/2015... | '07/04/2015... |

- Attribute beam mode and Index location of beam mode using data from AFT and Timber

| | |
|---|---|
| '2012-02-07 13:40:52.304' | 0 |
| '2012-02-07 17:31:27.254' | 0 |
| '2012-02-09 13:36:06.550' | 21 |
| '2012-02-09 13:36:11.300' | 1 |
| '2012-02-27 15:37:33.857' | 0 |
| '2012-03-02 07:53:33.566' | 2 |
| '2012-03-02 07:53:59.670' | 21 |

Mode durations must discount fault time for MTTF

| | Name | Count | MTTF tavg | Failure Rate | STDev | Skewness | MTTR | STDev |
|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | |
| 2 | Operation | 3 | 894.4952 | 0.0011179 | 5798.049 | 0.68852 | 0.059907 | 0.034635 |
| 3 | Orbit | 0 | 1E+12 | 0 | 0 | 0 | 0 | 0 |
| 4 | Other | 5 | 596.6971 | 0.0016632 | 1506.985 | 1.2655 | 0.25622 | 0.22558 |
| 5 | PowerConverters | 62 | 43.282 | 0.023104 | 643.2234 | 4.9242 | 1.8513 | 2.8988 |
| 6 | | | | | | | | |
| 7 | QPS | 49 | 54.765 | 0.01826 | 778.3988 | 4.0663 | 1.659 | 1.8931 |
| 8 | RadioFrequency | 14 | 191.6775 | 0.0052171 | 1354.057 | 1.3064 | 1.4619 | 1.3999 |
| 9 | SIS | 1 | 2683.4855 | 0.00037265 | 0 | 0 | 0.023611 | 0 |
| 10 | TransverseDamper | 1 | 2683.4855 | 0.00037265 | 0 | 0 | 0.023056 | 0 |

◄ ► ... **Stable** | Unstable | Beam Dump ... ⊕

## Output

| | | |
|---|---|---|
| PowerConverters Inj Dump | exponential | 3.4511 |
| PowerConverters Inj Physics | exponential | 0.76964 |
| PowerConverters Inj Probe | exponential | 0.44701 |
| PowerConverters No Beam | exponential | 1.5052 |
| PowerConverters Pre Ramp | exponential | 0.01 |
| PowerConverters Ramp | exponential | 0.85618 |
| PowerConverters Setup | exponential | 0.63669 |
| PowerConverters Squeeze | exponential | 1.8548 |
| PowerConverters Stable | exponential | 1.8513 |

# Moving Statistics



Stable
Failure Rate for All systems
Systems unaffected by beam in dashed

QPS CRISIS

16L2

Legend:
- AcceleratorControls
- AccessInfrastructure
- AccessManagement
- AccessSystems
- BeamExciters
- BeamInjection
- BeamInstrumentation
- BeamLosses
- Beam-inducedQuench
- Collimators
- CoolingandVentilation
- Cryogenics
- ElectricalNetwork
- Experiments
- ITServices
- InjectionSystems
- InjectorComplex
- LBDS
- MachineInterlockSystems
- MagnetCircuits
- Operation
- Orbit
- Other
- PowerConverters
- QPS
- RadioFrequency
- SIS
- TransverseDamper
- Vacuum
- VentilationDoors

| | Failure Mode Name | Distribution | Parameters | Ref. | Description | StandbyState | Failure effects ParamAffected | AffectType | Degradation | Corrective Maintenance | Ref. | ManpowerType | No.Of Manpower | On-Off Site maintenance | RepairStrategy | Reference System | Si re |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 326 | Orbit Pre Ramp | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 327 | Orbit Ramp | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 328 | Orbit Setup | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 329 | Orbit Squeeze | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 330 | Orbit Stable | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 331 | Orbit Unstable | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 332 | Other Adjust | exponential | 514.6972 | 1 | | COLD | | | | 0.0025 | 1 | | | on | repairable | 1 | y |
| 333 | Other Beam Dump | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 334 | Other Cycling | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 335 | Other Down | exponential | 118.8893 | 1 | | COLD | | | | 0.38021 | 1 | | | on | repairable | 1 | y |
| 336 | Other Flat Top | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 337 | Other Inj Dump | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 338 | Other Inj Physics | exponential | 299.6204 | 1 | | COLD | | | | 0.088519 | 1 | | | on | repairable | 1 | y |
| 339 | Other Inj Probe | exponential | 196.4782 | 1 | | COLD | | | | 0.32535 | 1 | | | on | repairable | 1 | y |
| 340 | Other No Beam | exponential | 1175.4804 | 1 | | COLD | | | | 5.3553 | 1 | | | on | repairable | 1 | y |
| 341 | Other Pre Ramp | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 342 | Other Ramp | exponential | 55.3966 | 1 | | COLD | | | | 0.062944 | 1 | | | on | repairable | 1 | y |
| 343 | Other Setup | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 344 | Other Squeeze | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 345 | Other Stable | exponential | 536.6971 | 1 | | COLD | | | | 0.25622 | 1 | | | on | repairable | 1 | y |
| 346 | Other Unstable | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 347 | PowerConverters Adjust | exponential | 85.7829 | 1 | | COLD | | | | 0.84315 | 1 | | | on | repairable | 1 | y |
| 348 | PowerConverters Beam Dump | exponential | 7.6455 | 1 | | COLD | | | | 0.91231 | 1 | | | on | repairable | 1 | y |
| 349 | PowerConverters Cycling | exponential | 3.2301 | 1 | | COLD | | | | 0.83491 | 1 | | | on | repairable | 1 | y |
| 350 | PowerConverters Down | exponential | 11.3228 | 1 | | COLD | | | | 0.19735 | 1 | | | on | repairable | 1 | y |
| 351 | PowerConverters Flat Top | exponential | 155.7925 | 1 | | COLD | | | | 0.10292 | 1 | | | on | repairable | 1 | y |
| 352 | PowerConverters Inj Dump | exponential | 30.3978 | 1 | | COLD | | | | 3.4511 | 1 | | | on | repairable | 1 | y |
| 353 | PowerConverters Inj Physics | exponential | 64.2044 | 1 | | COLD | | | | 0.76964 | 1 | | | on | repairable | 1 | y |
| 354 | PowerConverters Inj Probe | exponential | 98.2391 | 1 | | COLD | | | | 0.44701 | 1 | | | on | repairable | 1 | y |
| 355 | PowerConverters No Beam | exponential | 130.6089 | 1 | | COLD | | | | 1.5052 | 1 | | | on | repairable | 1 | y |
| 356 | PowerConverters Pre Ramp | exponential | 80.9561 | 1 | | COLD | | | | 0.01 | 1 | | | on | repairable | 1 | y |
| 357 | PowerConverters Ramp | exponential | 34.6229 | 1 | | COLD | | | | 0.85618 | 1 | | | on | repairable | 1 | y |
| 358 | PowerConverters Setup | exponential | 17.3766 | 1 | | COLD | | | | 0.63669 | 1 | | | on | repairable | 1 | y |
| 359 | PowerConverters Squeeze | exponential | 33.2263 | 1 | | COLD | | | | 1.8548 | 1 | | | on | repairable | 1 | y |
| 360 | PowerConverters Stable | exponential | 43.282 | 1 | | COLD | | | | 1.8513 | 1 | | | on | repairable | 1 | y |
| 361 | PowerConverters Unstable | exponential | 1E+12 | 1 | | COLD | | | | 0 | 1 | | | on | repairable | 1 | y |
| 362 | QPS Adjust | exponential | 257.3486 | 1 | | COLD | | | | 2.1014 | 1 | | | on | repairable | 1 | y |
| 363 | QPS Beam Dump | exponential | 5.7341 | 1 | | COLD | | | | 2.0264 | 1 | | | on | repairable | 1 | y |
| 364 | QPS Cycling | exponential | 71.0623 | 1 | | COLD | | | | 2.5847 | 1 | | | on | repairable | 1 | y |

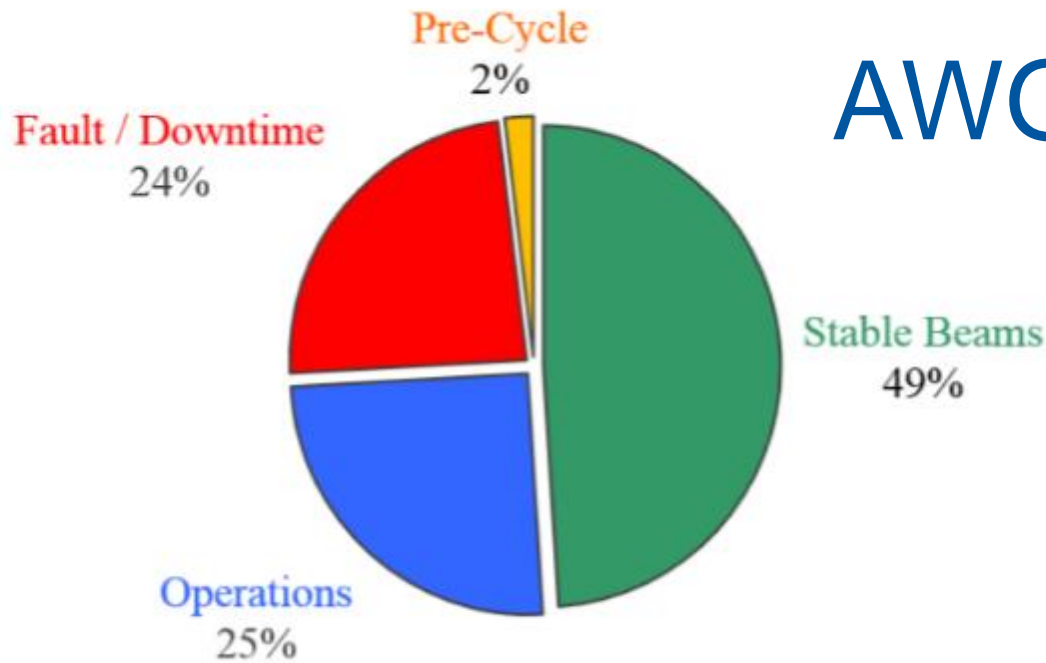| | Facility | Phase | Duration | Phase Type | Phase Group | Parent OP Phase | Next Default phase | DownRepairPolicy | Can run parallel to donwtime? | Description |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | LHC | Operation | 4956 | Operation | | | | 1 | | |
| 3 | LHC | Setup | 0.24723 | CycleStart | | Operation | Injection Probe | 1 | n | |
| 4 | LHC | Injection Probe | 0.24625 | Cycle | | Operation | Injection Physics | 1 | n | |
| 5 | LHC | Injection Physics | 0.50865 | Cycle | | Operation | Pre-Ramp | 1 | n | |
| 6 | LHC | Pre-Ramp | 0.063956 | Cycle | | Operation | Ramp | 1 | n | |
| 7 | LHC | Ramp | 0.33951 | Cycle | | Operation | Flat Top | 1 | n | |
| 8 | LHC | Flat Top | 0.068008 | Cycle | | Operation | Squeeze | 1 | n | |
| 9 | LHC | Squeeze | 0.18184 | Cycle | | Operation | Adjust | 1 | n | |
| 10 | LHC | Adjust | 0.05 | Cycle | | Operation | Stable | 1 | n | |
| 11 | LHC | Stable | 10.7314 | Cycle | | Operation | Beam Dump | 1 | n | |
| 12 | LHC | Beam Dump | 0.0081066 | Cycle | | Operation | Down | 1 | n | |
| 13 | LHC | Down | 0.56228 | Cycle | | Operation | Setup | 1 | y | |
| 14 | LHC | No Beam | 1.4931 | Cycle | | Operation | Setup | 1 | n | |

Figure 4 : Machine Mode Breakdown during Physics

- *Operations* encompasses all regular machine phases carried out between fills, including planned access. This is *all* phases when the machine is not in stable beams, not in fault, and not pre-cycle.
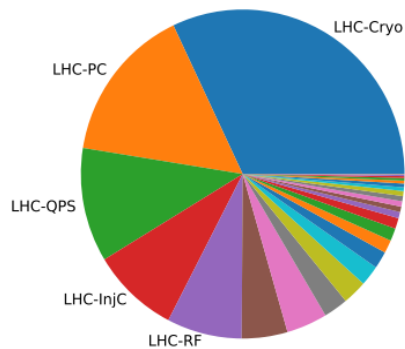- All *pre-cycles* were approximated as having a fixed length of 45 minutes.
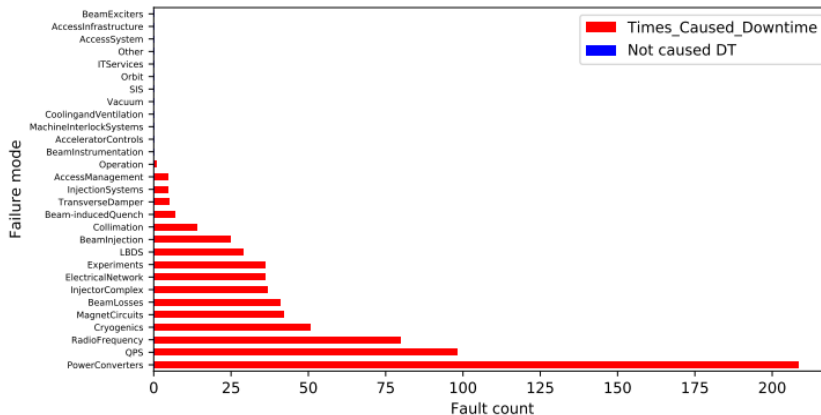
# Results
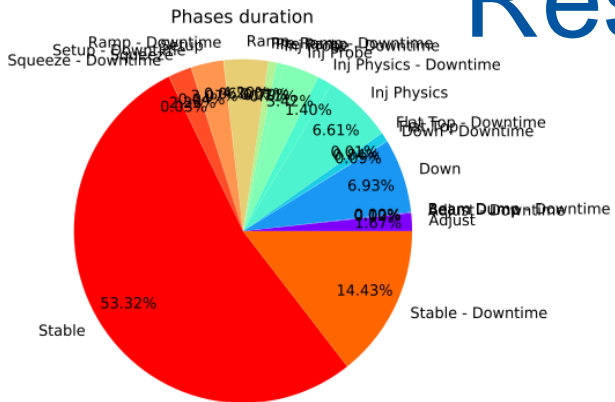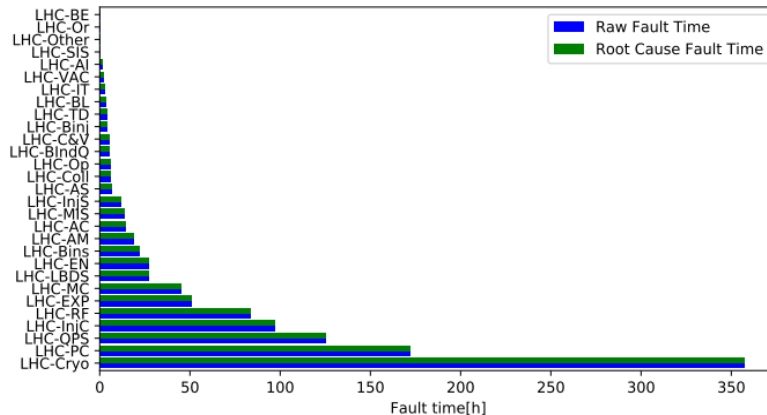
# Conclusion

- Continued work on data for AvailSim

  - Currently refining both Fault and Beam Mode statistics

  - Ideally matching AWG reports

  - Extend to other Accelerators (statistics started)

  - Predictive tool for unknown scenarios (HiLumi)

  - GAN Network as a pose to regular Neural Network

  - Translate for SWAN package?
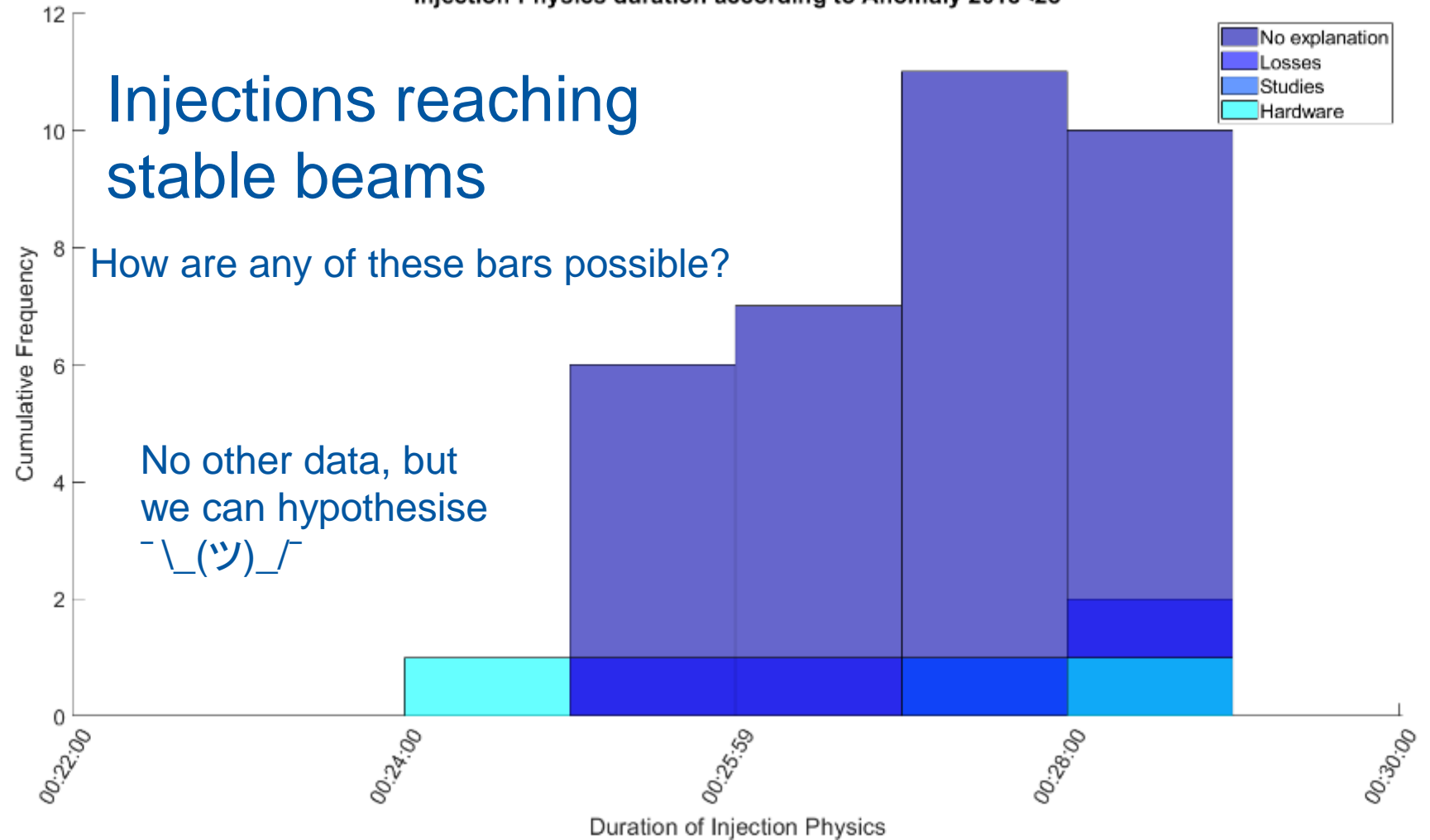
Goal - Complete model of CERN accelerator complex

# Extra Slides

Injection Physics duration according to Anomaly 2018<28

Injections reaching stable beams

How are any of these bars possible?

No other data, but we can hypothesise
¯\_(ツ)_/¯

Legend:
- No explanation
- Losses
- Studies
- Hardware

Y-axis: Cumulative Frequency (0, 2, 4, 6, 8, 10, 12)
X-axis: Duration of Injection Physics (00:22:00, 00:24:00, 00:25:59, 00:28:00, 00:30:00)

Failure distributions