Availability, Efficiency and Integrated Luminosity:

Rising to the challenge in the FCC-ee

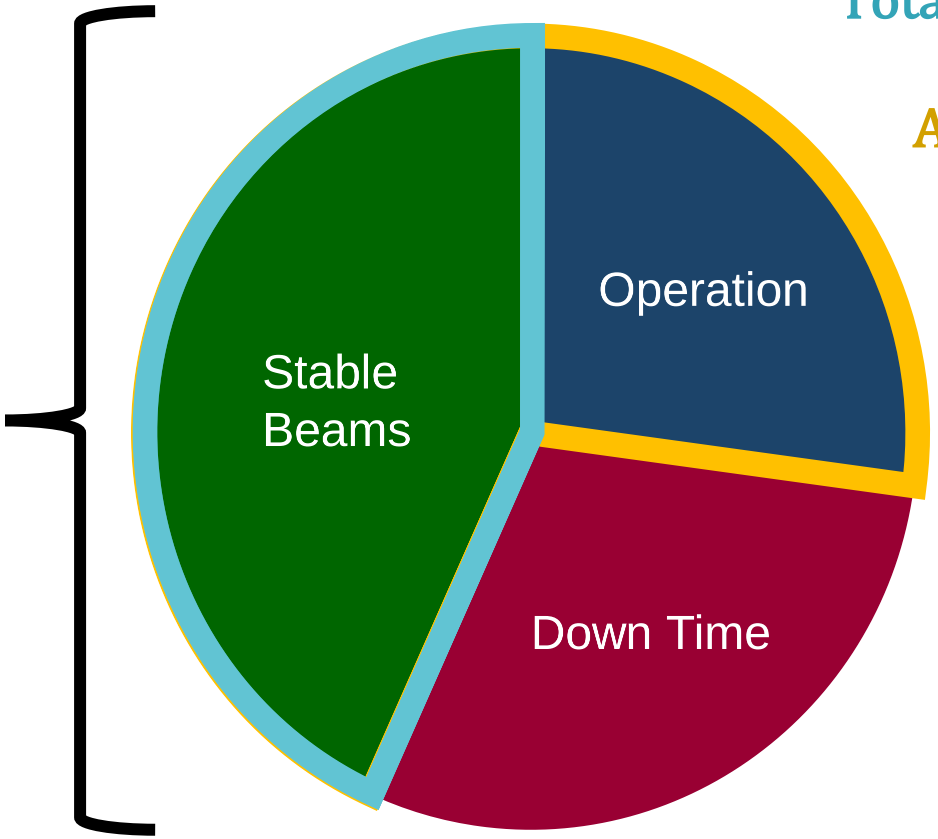
Jack Heron, Hannah Dostmann, Lukas Felsberger, Daniel Wollmann, Jan Uythoven

22nd May 2025

Availability and Luminosity

FCC-ee:

365	days
−120	(extended shutdowns)
− 30	(annual commissioning)
− 20	(machine development)
− 10	(technical stops)
185	**days for physics**



$$\text{Efficiency } E = \frac{\text{Stable Beams time}}{\text{Total physics time}}$$

$$\text{Availability } A = \frac{\text{Up time}}{\text{Total physics time}}$$

Breakdown into Systems and Subsystems

Extrapolate from reliability performance of existing accelerator systems

1) System failure rate

FCC-ee

	Both Rings
1	Accelerator Controls
2	Elevators & Handling Equipment
3	Access System
4	Electrical Networks
5	Alarm System
	Main Rings
6	Beam Instrumentation
7	Collimation
8	Cooling + Ventilation
9	Cryogenics
10	Extraction Systems & Beam Dump
11	Beamstrahlung Absorber
12	Injection Systems
13	Beam Losses
14	Machine Protection/Interlocks
15	Magnets
16	Power Converters
17	RF
18	Transverse Damper
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	Injector Complex
35	HE Linac
36	Pre-Linacs

Failure Rate

Repair Duration

Availability

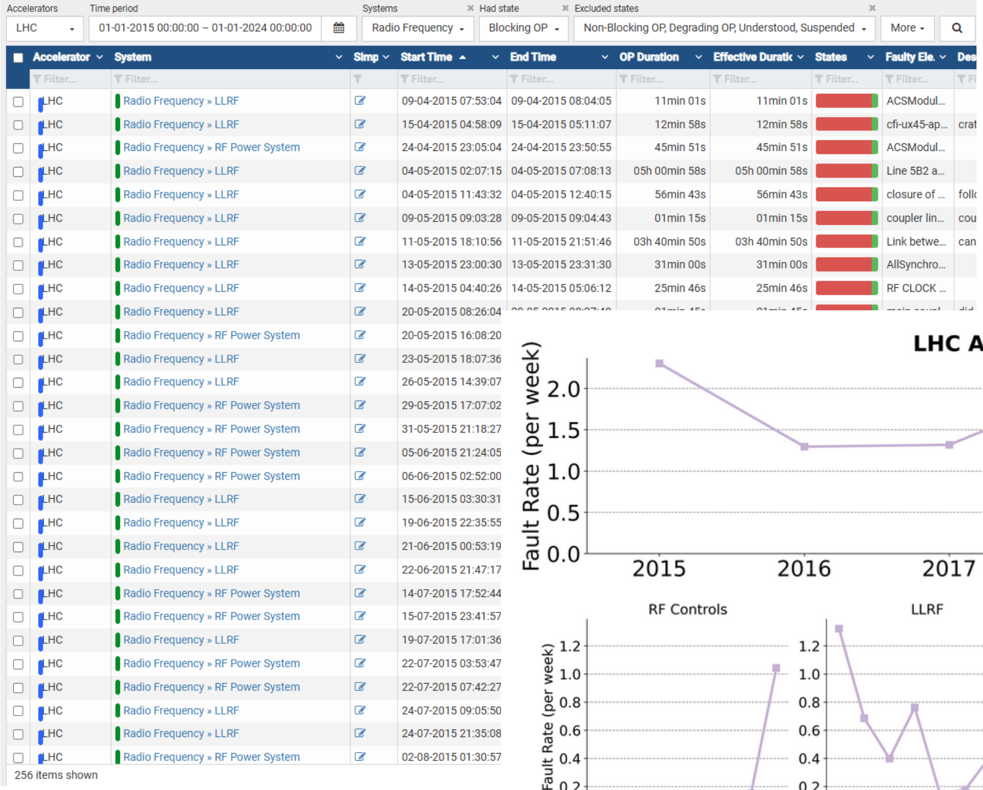
Integrated Luminosity

AvailSim4
https://gitlab.cern.ch/availsim4/

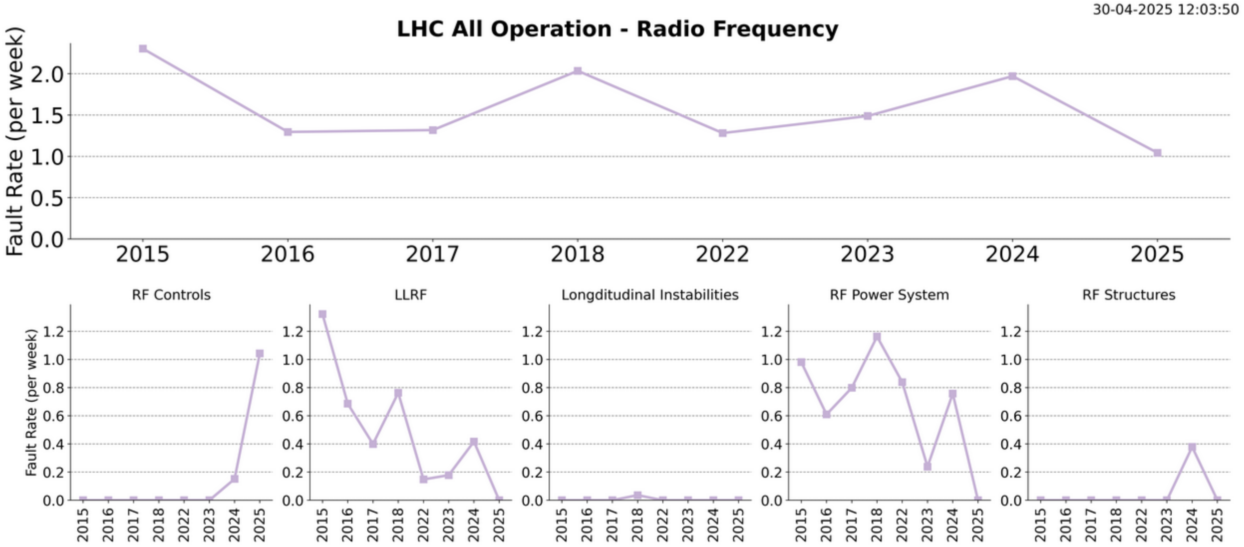
RF System

Accelerator Fault Tracking

aft.cern.ch
aft-stats.web.cern.ch



- **Using AFT fault data 2015-2024**
- **LHC:**
  - 16 SRF cavities



- **FCCee:**

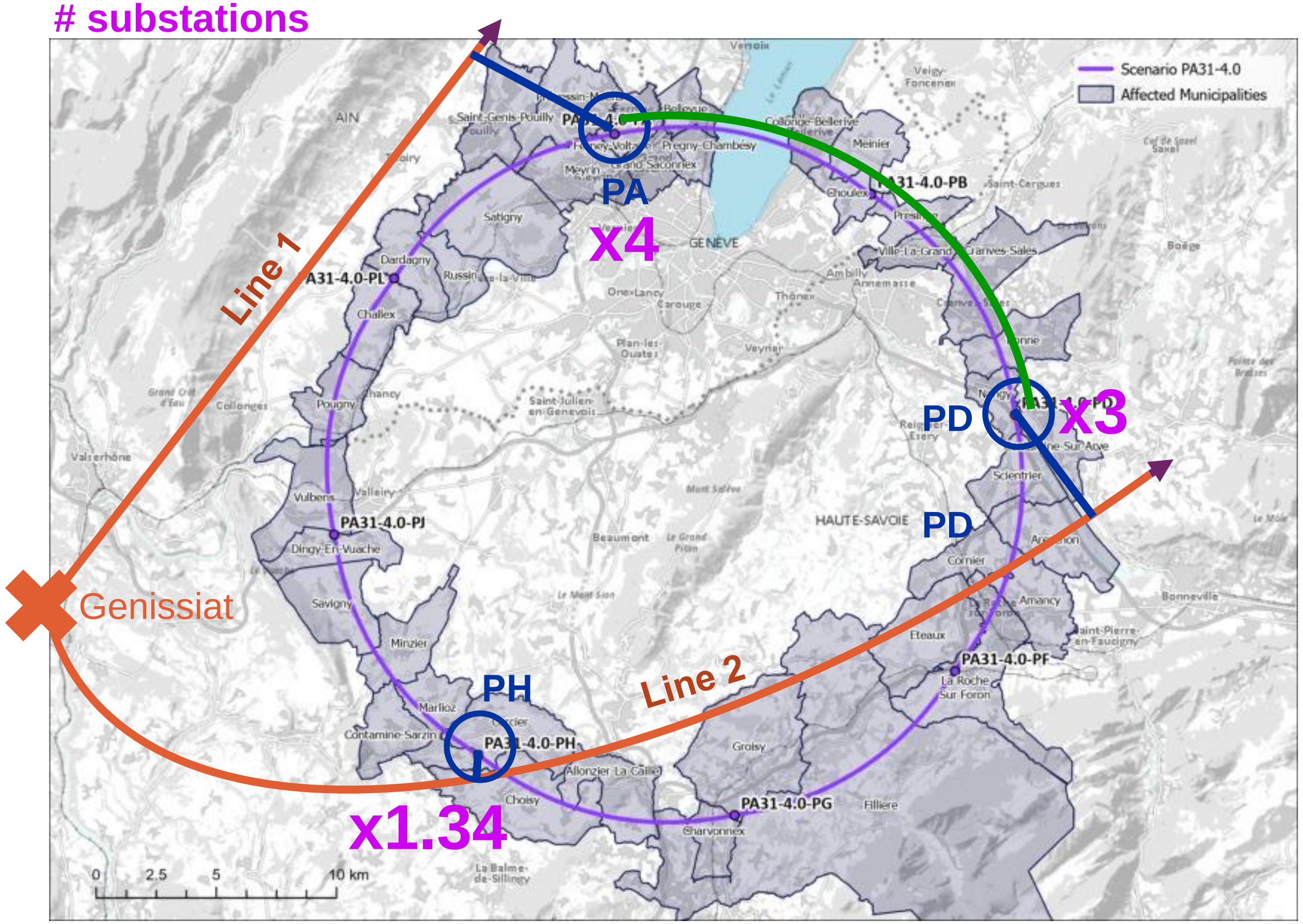
	Z		W		ZH		tt̄	
	collider*	**booster**	**collider***	**booster**	**collider****	**booster**	**collider****	**booster**
Cavities [#]	132	112	132	112	264	112	672	448
Redundancy [cavities]	1	0	6	0	26	11	67	44
Redundancy [%]	0.75	0	4.5	0	10	10	10	10

* Per beam ** Both beams

Acknowledgement: Olivier Brunner, Andy Butterworth, Franck Peauger, Ivan Karpov

Electrical Network

- **External Network Perturbations:**
  - Independent at PA and PH-PD
- **Internal Equipment Faults:**
  - Scaled by number of Substations
- **Redundant link PA-PD:**
  - Only for non-child down time
  - Changeover ~1 h
  - Not applicable to PH



See presentation:
Hannah Dostmann
Technical Infrastructure Availability
Technical Infrastructure: Electricity & Energy Management
Tuesday 20th May

Acknowledgement: Charline Marcel, Mario Parodi

Power Converters

- **LHC fault data**
- **Same level of redundancy as LHC**

FCC - Power Converters						Comparison : FCC - LHC		
		n_FCC [-]	Current [A]	Voltage [V]	Power [W]	LHC Cat. [-]	MTBF of single converter [h]	Group MTBF with FCC n° [d]
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Grand Total		18,007						**0.6 days**

One dump every 3 days

5 days

9 days

Acknowledgement: Byamba Wicki, Serge Pittet

Breakdown into Systems and Subsystems

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Extrapolate from reliability performance of existing accelerator systems

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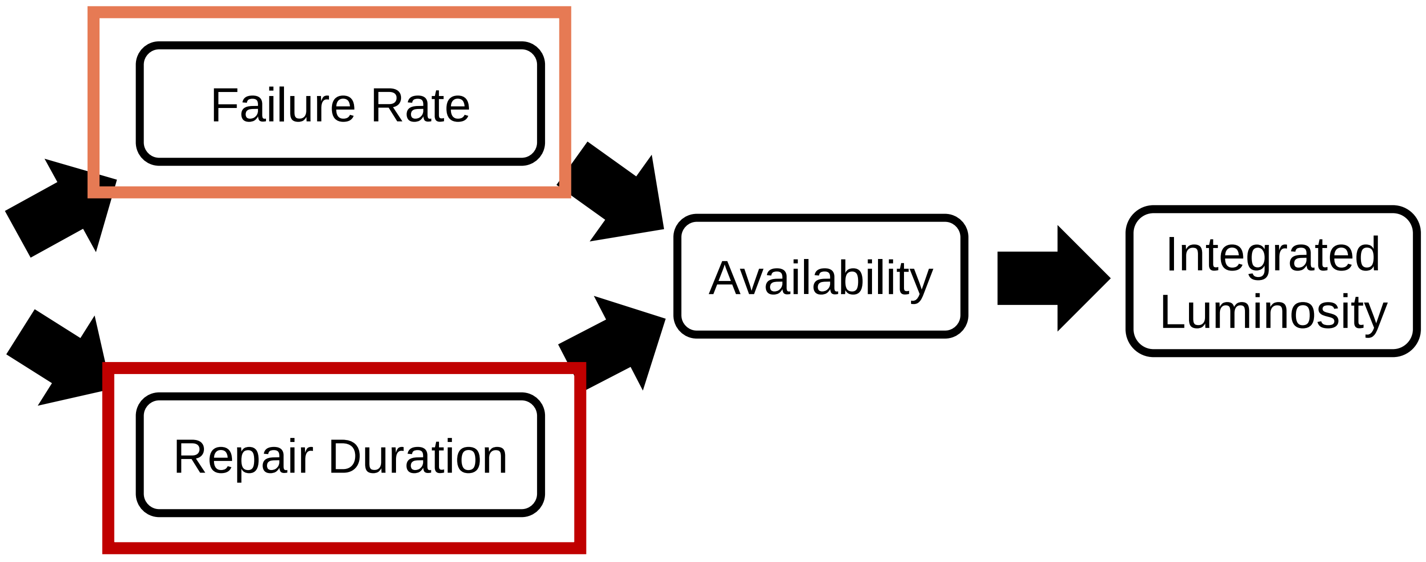

2) System repair duration

Two fault types:

Remote Repair Faults

- Repair achieved from the control room
- E.g. by resetting components

Human Repair Faults

- Requires human intervention
- Approach time and/or cool down time

https://www.istockphoto.com/vector/isometric-control-center-gm164401684-15526568
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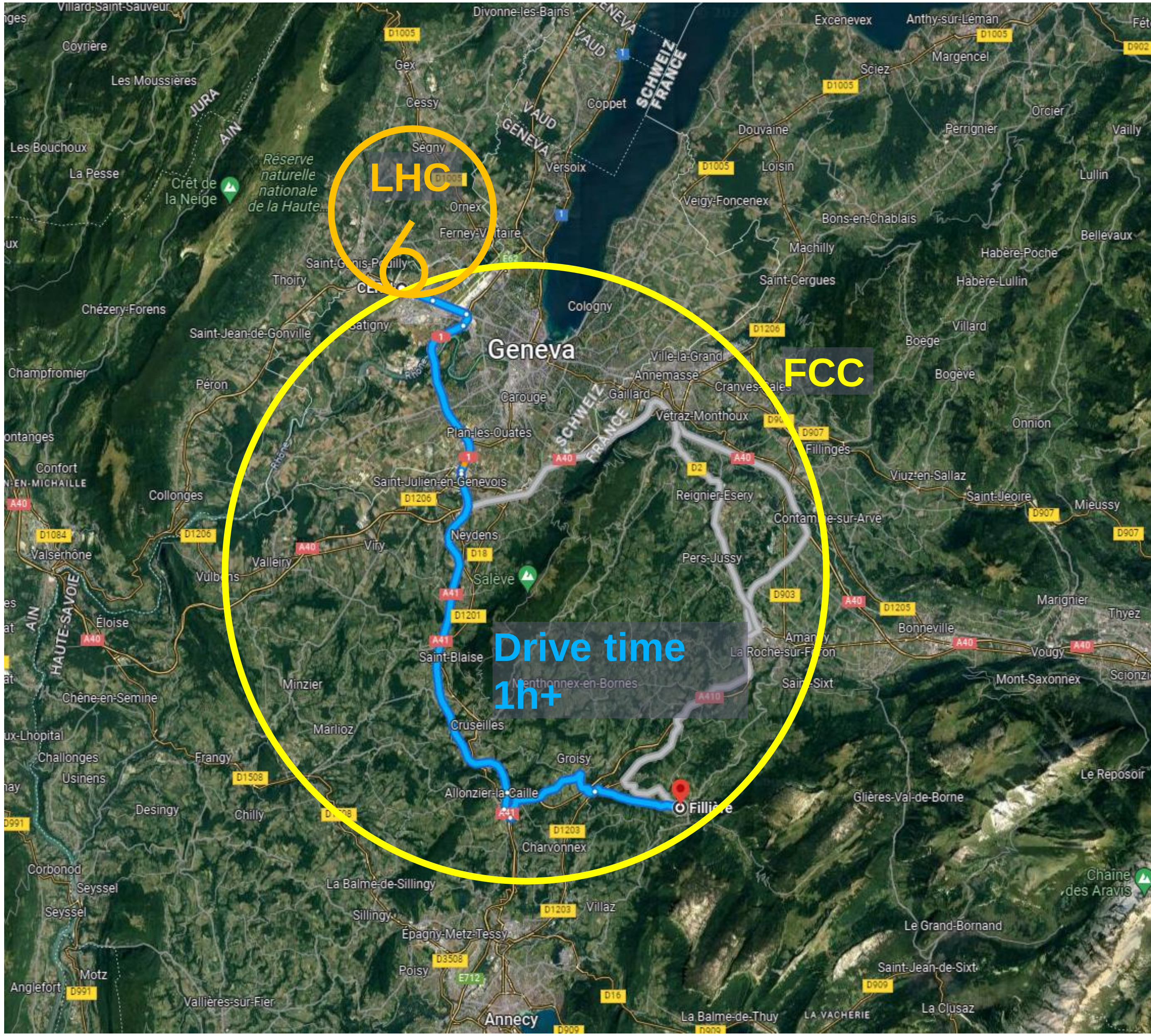
Human Repair Faults

- Requires human intervention
- Approach time 0.3-1.5 h
- Cool down time 1-24 h



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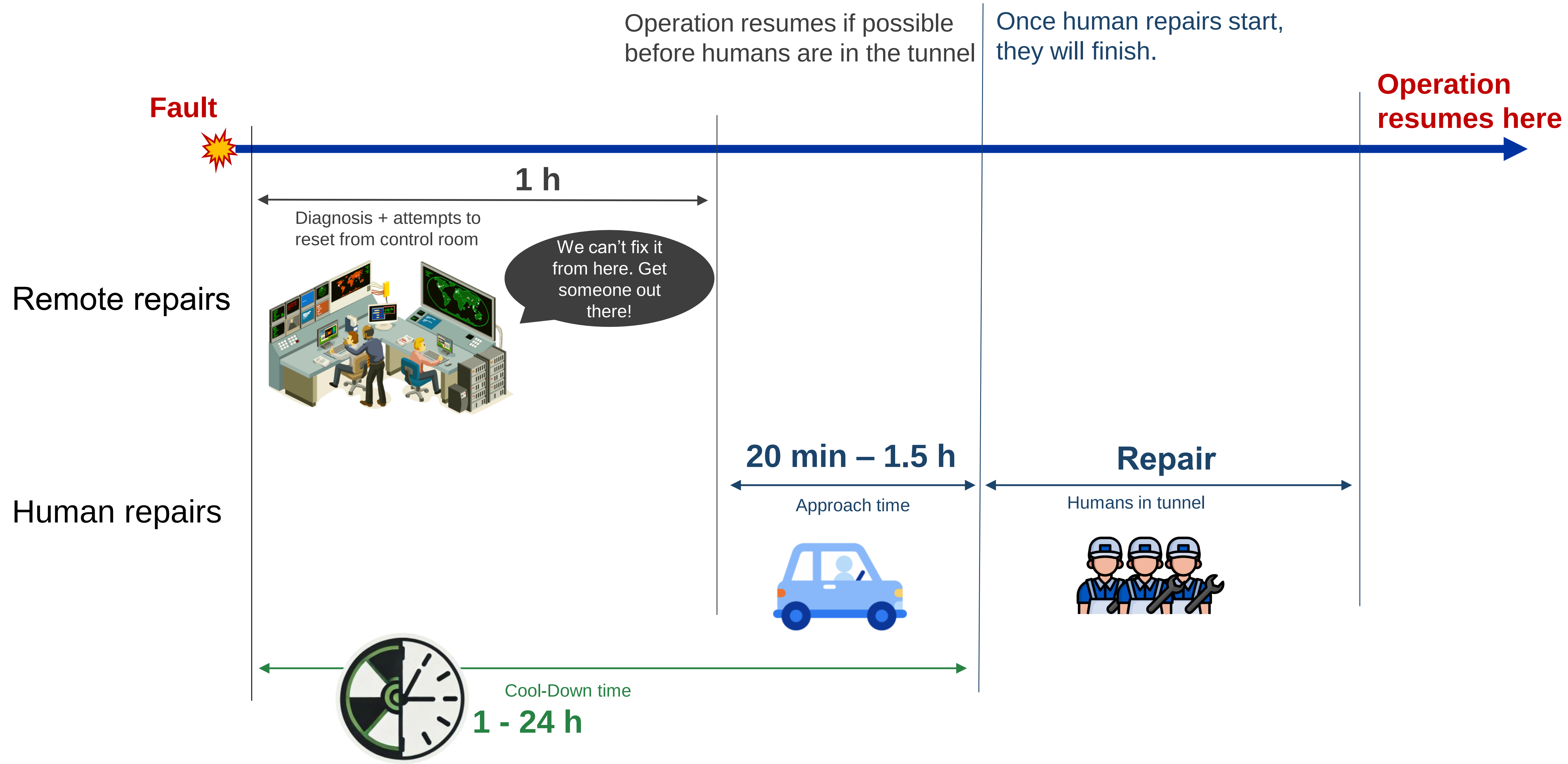
“Realistic” Repair Timeline:



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Extrapolate from reliability performance of existing accelerator systems

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Failure Rate

Repair Duration

AvailSim4
https://gitlab.cern.ch/availsim4/

Availability

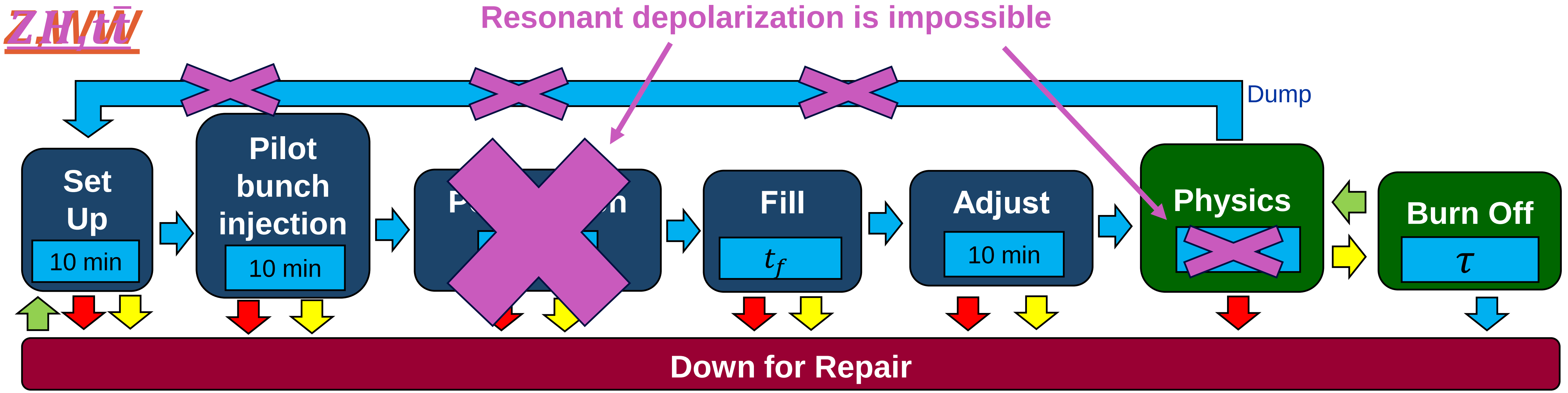
Integrated Luminosity

3) Accelerator Performance

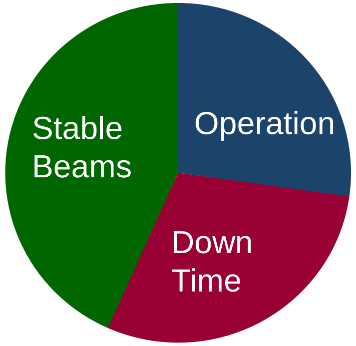
2) System repair duration

- Remote repairs
- Human repairs
  - Approach time
  - Cool down time

FCC-ee Operation Cycle



- Default
- Repair completed
- Collider failure
- Injector Complex failure



	Z	WW	ZH	tt
Fill time t_f (min)	7.7	2.5	1.52	1.45
Lifetime τ (min)	15	12	12	11

Acknowledgement: Jacqueline Keintzel

Acknowledgements

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- William Corocho (SLAC)
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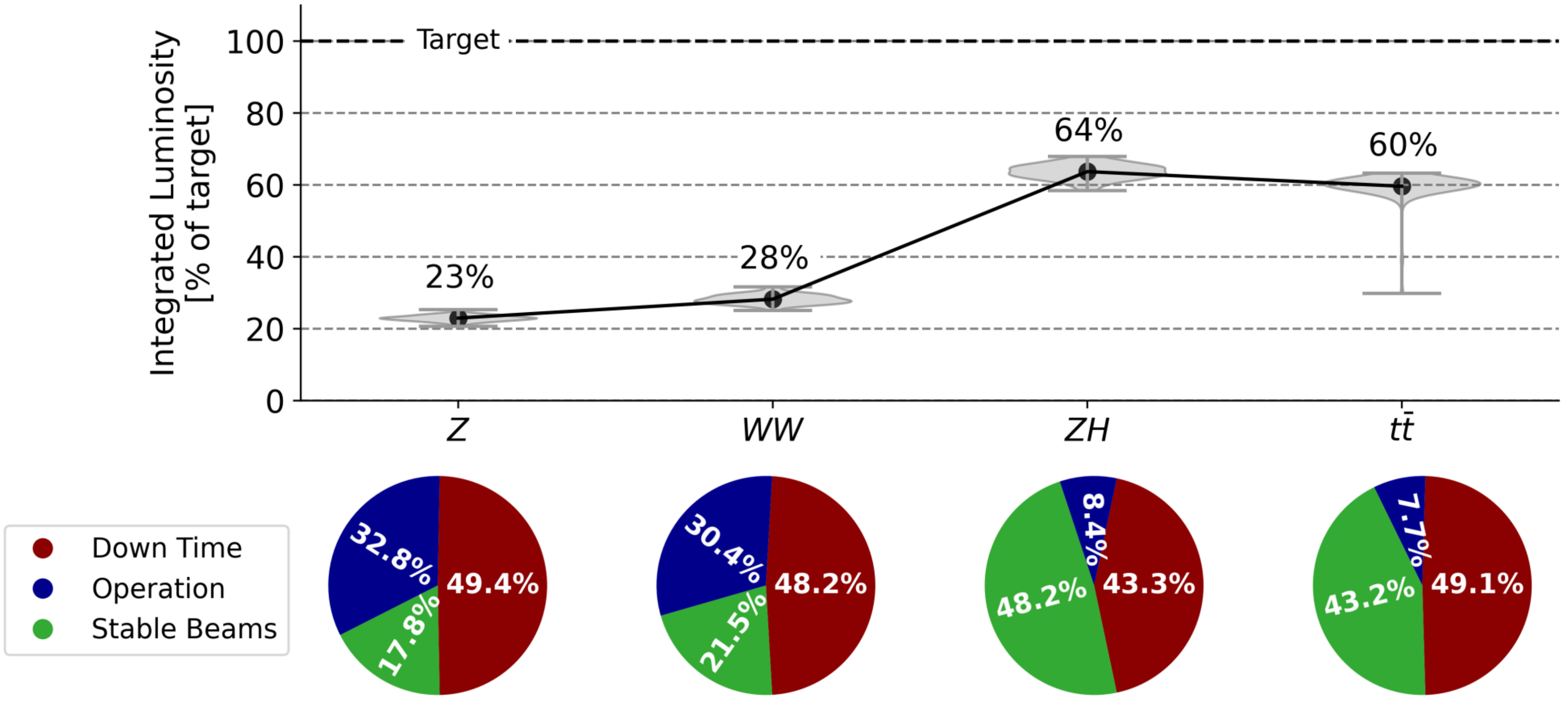
- Giacomo Lavezzari
- Manuel Colmenero Moratalla
- Milosz Blaszkiewicz
- Markus Widorski
- Andrew Coleman

Results

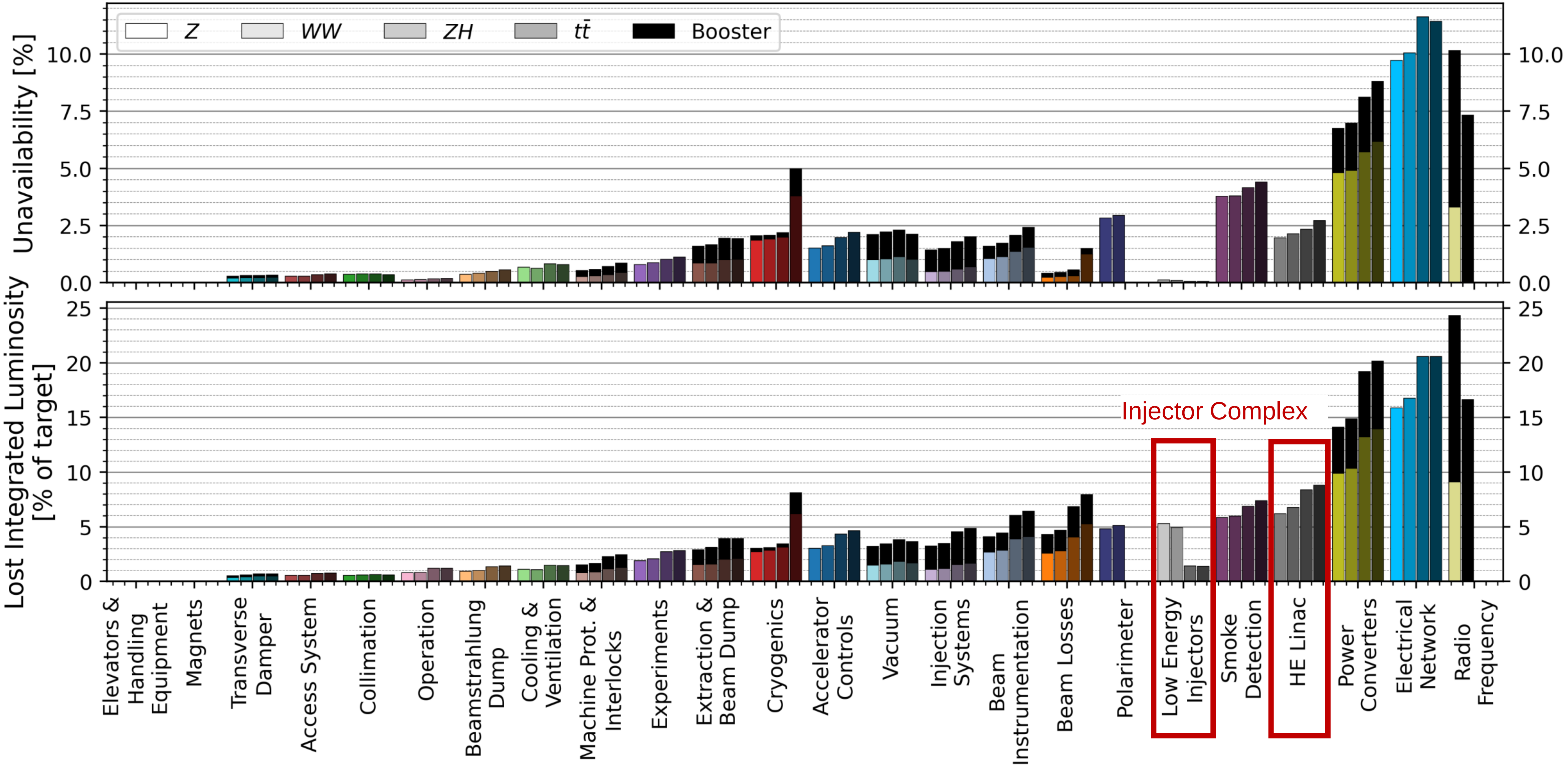
Overall Performance



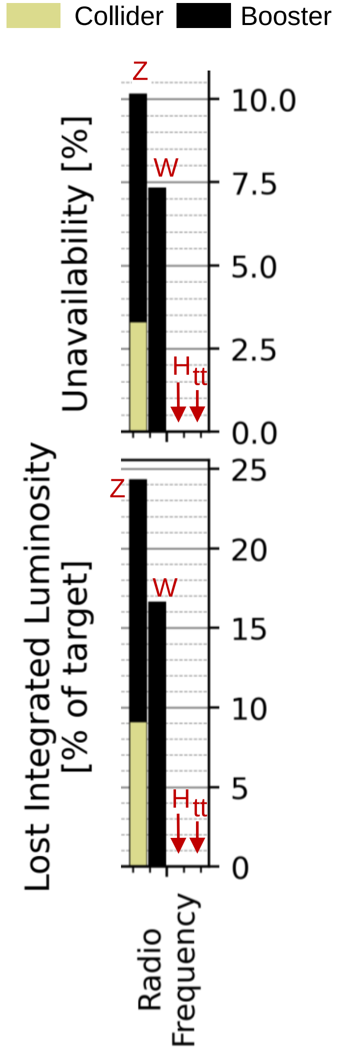
- Delivered integrated luminosity below design in all energy modes
- Due to low availability <u>and</u> low efficiency
- Particularly in Z and W modes due to long turnaround time following dump

	Z	W	H	tt
Integrated luminosity target [ab-1]	205	19.2	10.8	3.12

Unavailability & Lost Luminosity



RF System



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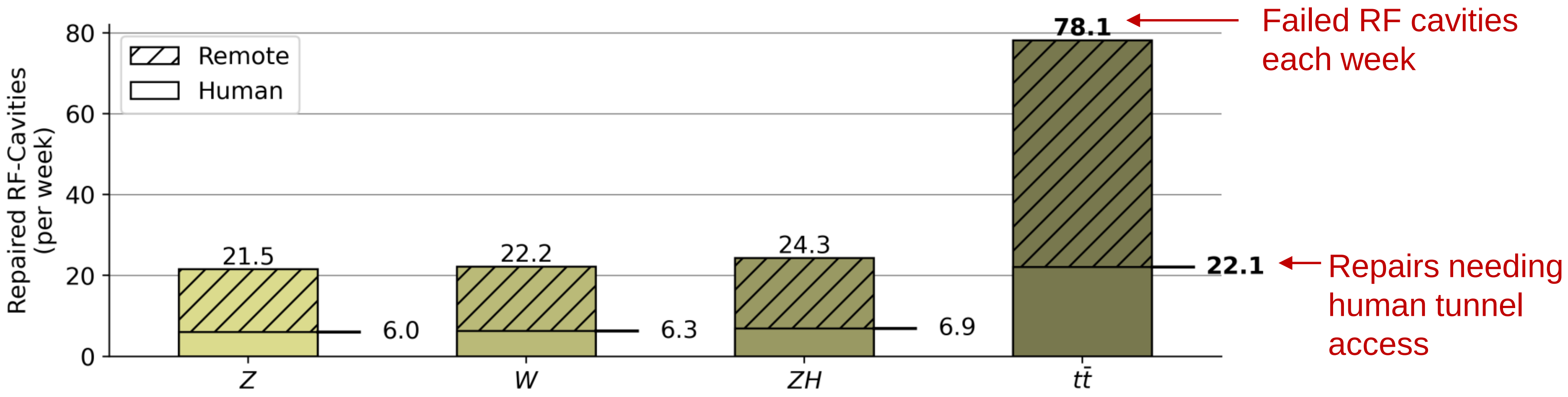
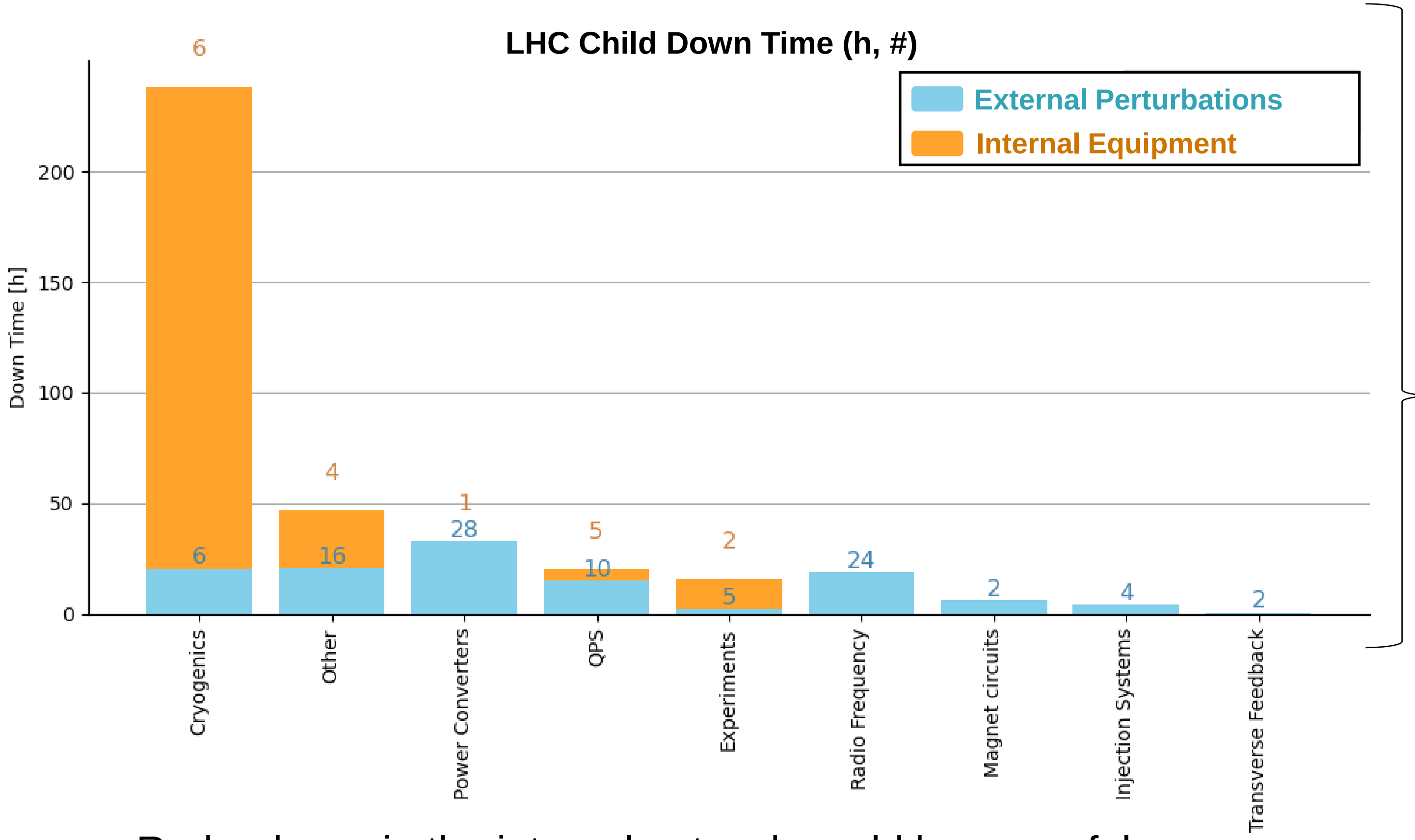
Redundancy eliminates down time completely

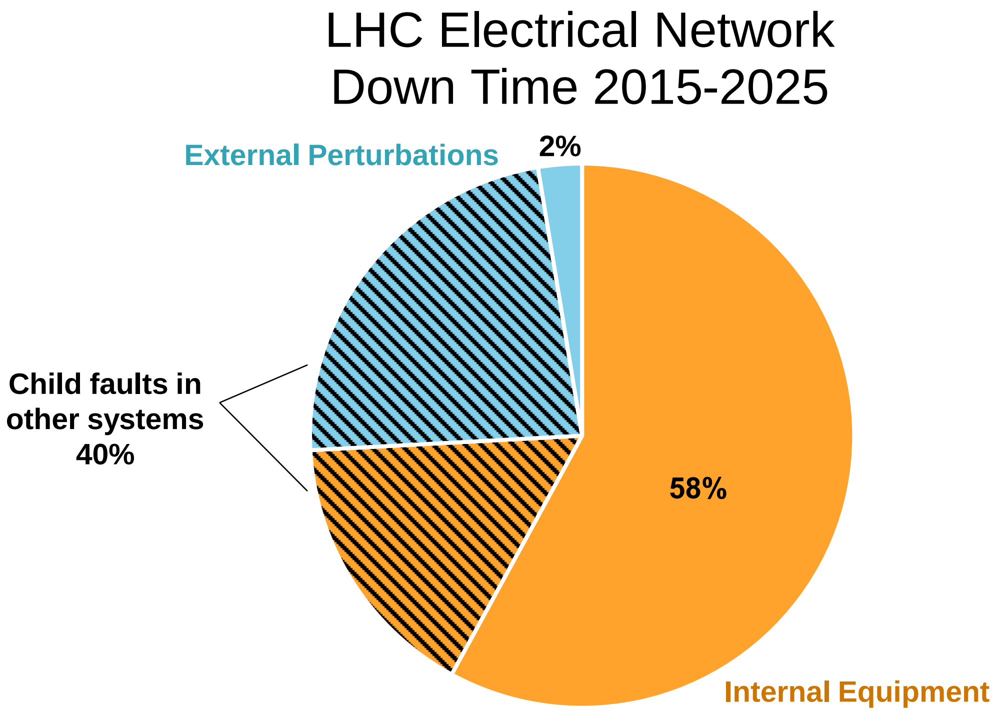
Redundancy
- Results assume perfect redundancy (invisible to operation, no common mode failures)
- We need to look closer at subsystems + auxiliaries

Operational Cost Factors:
- High failure rate of cavities, esp. in tt (1120 cavities) - hard-working maintenance service



Electrical Network





- Redundancy in the internal network could be powerful
- However – we need a solution for child faults!
    - ➢ Rigorous design requirements for resilience to power disturbance
    - ➢ How to dampen voltage deviations (internal + external) ?

<u>See presentation:</u>
Hannah Dostmann
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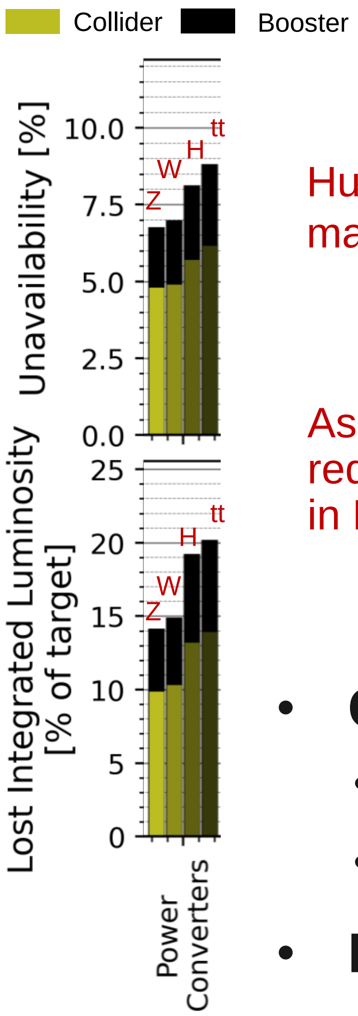
Power Converters



Huge number of converters due to many sextupole & corrector magnets

Assumes the same degree of redundancy as exists currently in LHC

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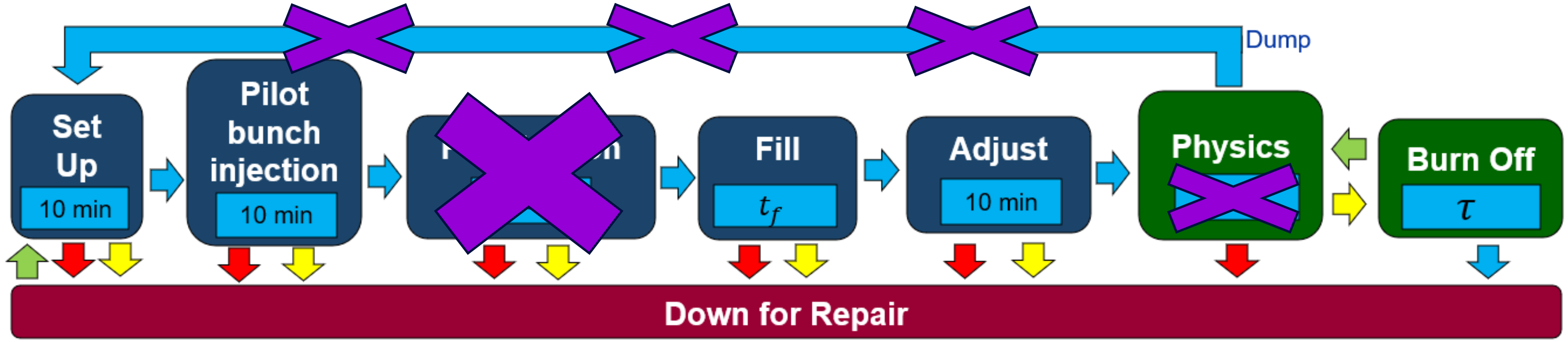
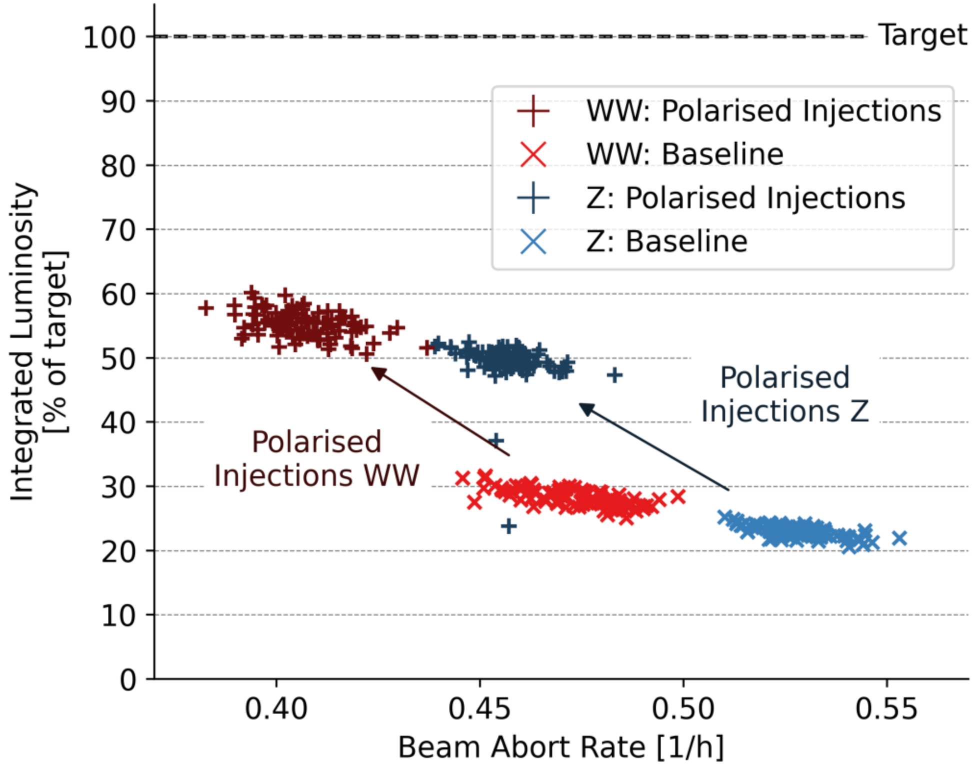
Grand Total		18,007						

- **Current optics configuration:**
  - Sextupoles powered in groups of four
  - Correctors powered individually
- **How many power converters can we lose without dumping the beam?**
  - Needs a detailed study from optics and machine protection

Solution: Injection of Polarised Bunches

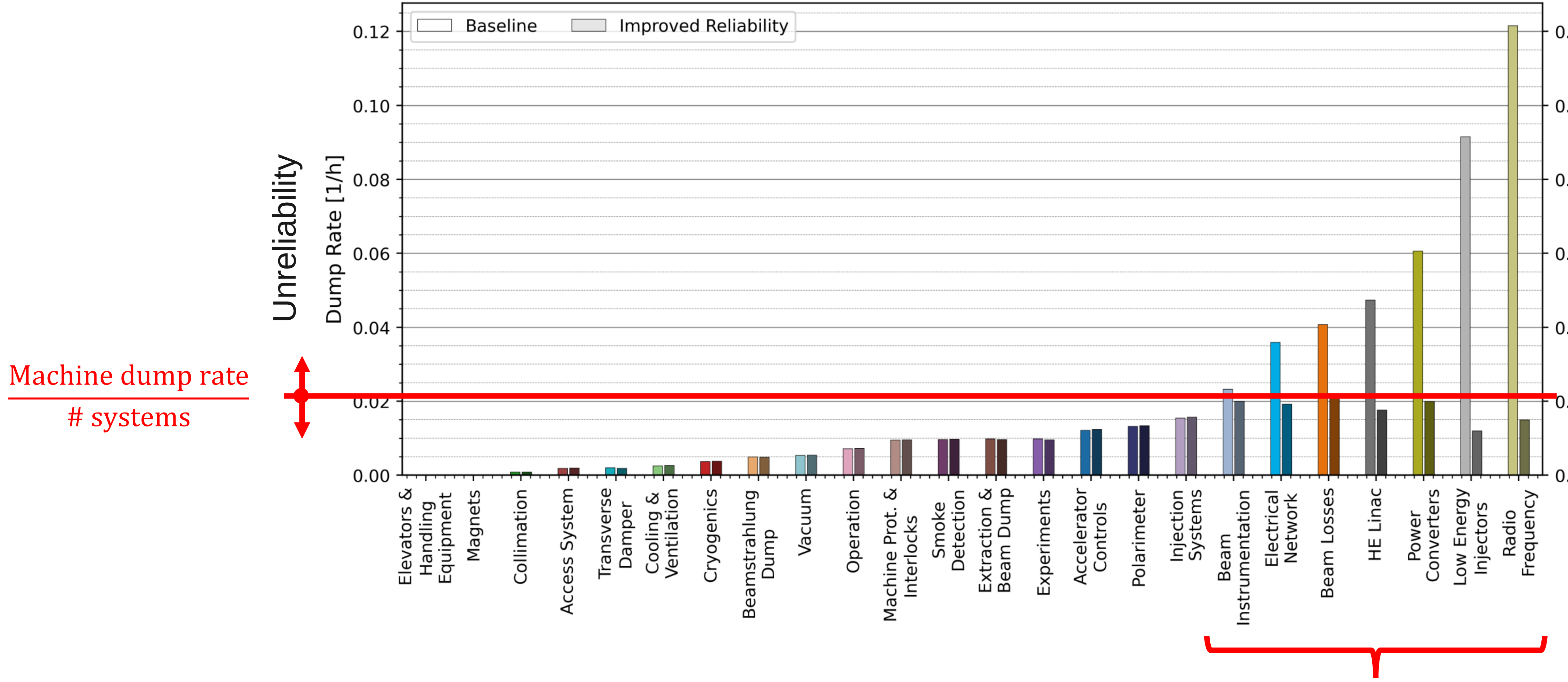
Z,W





More than doubles delivered integrated luminosity

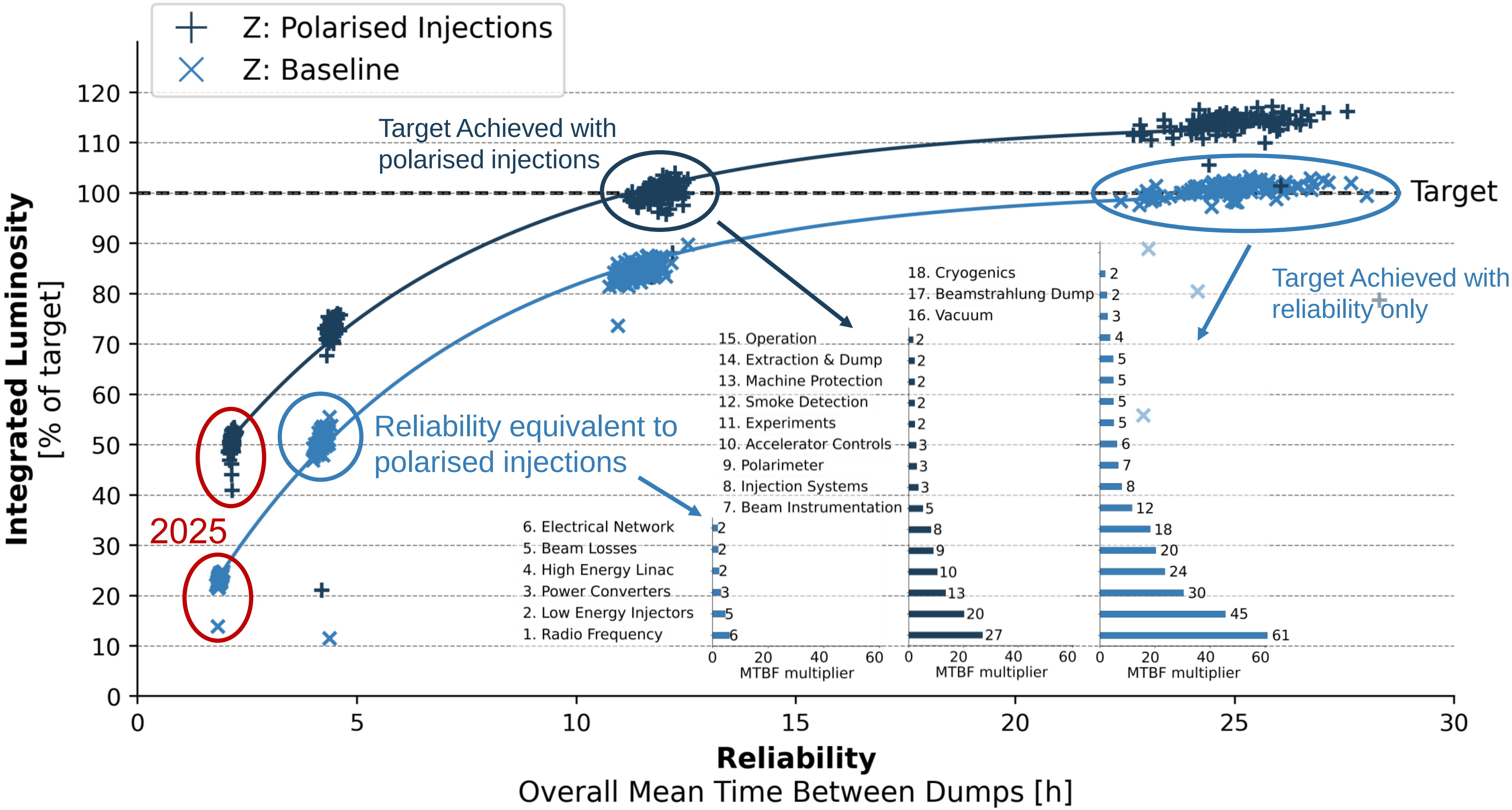
Parameter Scan: Reliability



Most efficient way to allocate resources for reliability consolidation:

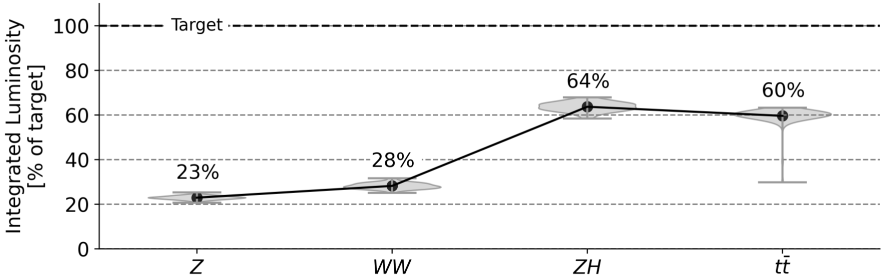
Only systems above the required dump rate need to improve

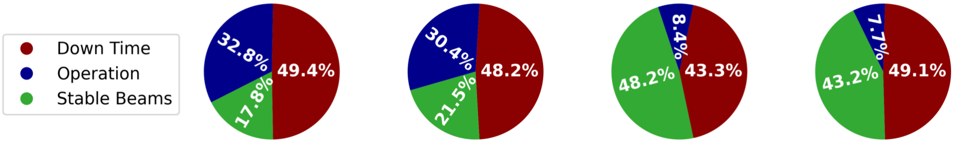
Parameter Scan: Reliability



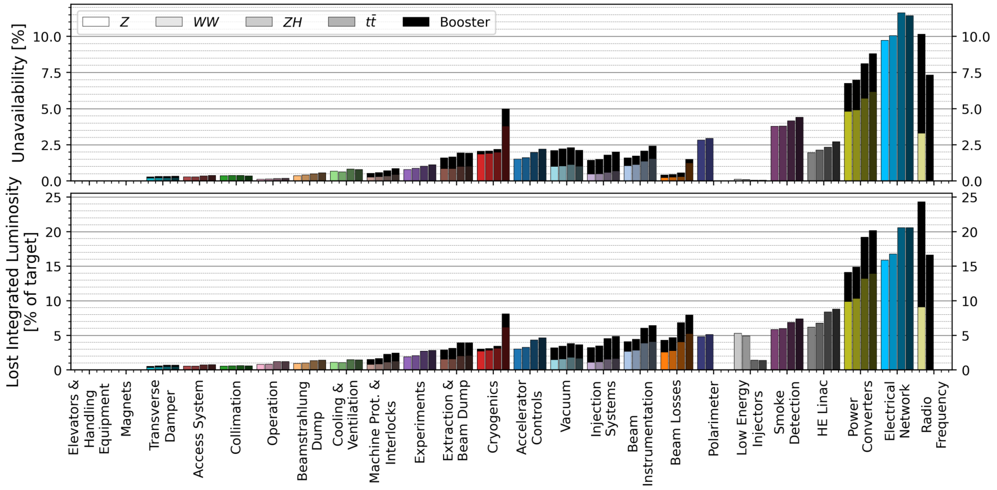
Conclusions

- **Forecasted integrated luminosity is below design in all energy modes**
  - Low availability <u>and</u> low efficiency

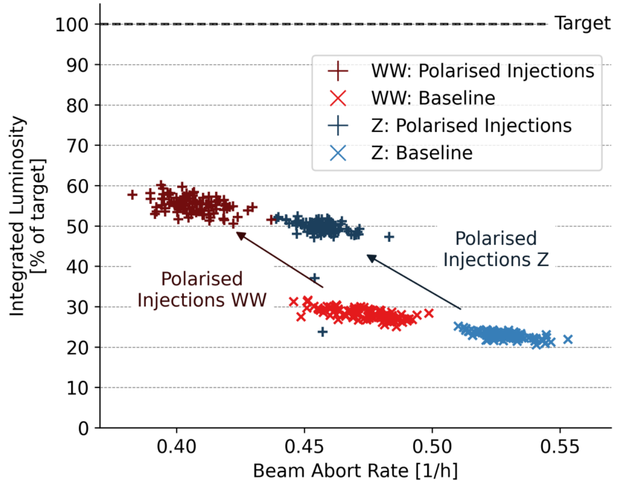




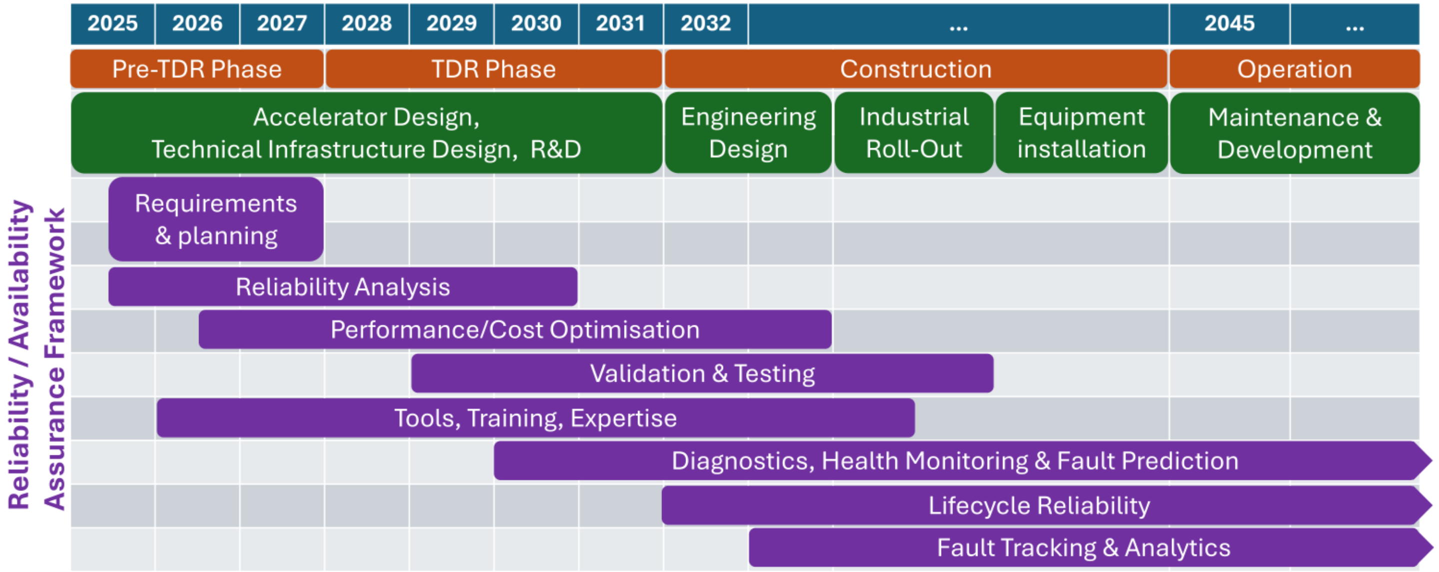
- **Systems of highest concern:**
  - RF
  - Power Converters
  - Injector Complex
  - Technical Infrastructure
  - Beam Losses



- **R&D Opportunity:**
  - Injection of polarised bunches



Outlook



Success in FCC requires machine-wide improvement in reliability

<u>Systematic Reliability / Availability Support Framework</u>

<u>Short Term</u>:

- Requirements and milestones, performance benchmarking
- More nuanced reliability models in parallel with design process
- “Low-hanging fruit” – R&D opportunities evaluation
- Performance/Cost optimisation over the whole machine

- Develop a coherent support framework for all system designs

<u>TDR & Beyond:</u>

- Design for reliability:
  - Detailed modelling
  - Redundant / modular / hot-swappable paradigm
  - Interfacing between systems
- Tools, training, expertise
- Extensive hardware testing & validation

- Diagnostics & Health Monitoring
- Fault prediction
- Fault tracking & Analytics
- Lifecycle Reliability

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