The Availability Challenge:
Targets, shortfalls and game-changing opportunities

Jack Heron

Acknowledgements: Lukas Felsberger, Jan Uythoven, Daniel Wollmann, Felix Rodriguez Mateos

8th June 2023

FCCWEEK2023

Availability and Integrated Luminosity

- **Integrated Luminosity:**

Goals:

	L $(10^{34}/cm^2 s)$	Run time (years)	L_{int} (ab^{-1})
Z	200	4	150
W	25	2	10
H	7	3	5
$t\bar{t}_2$	1.4	4	1.5

$$L_{int} = ATL$$

L = Nominal luminosity

T = Time for physics →

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

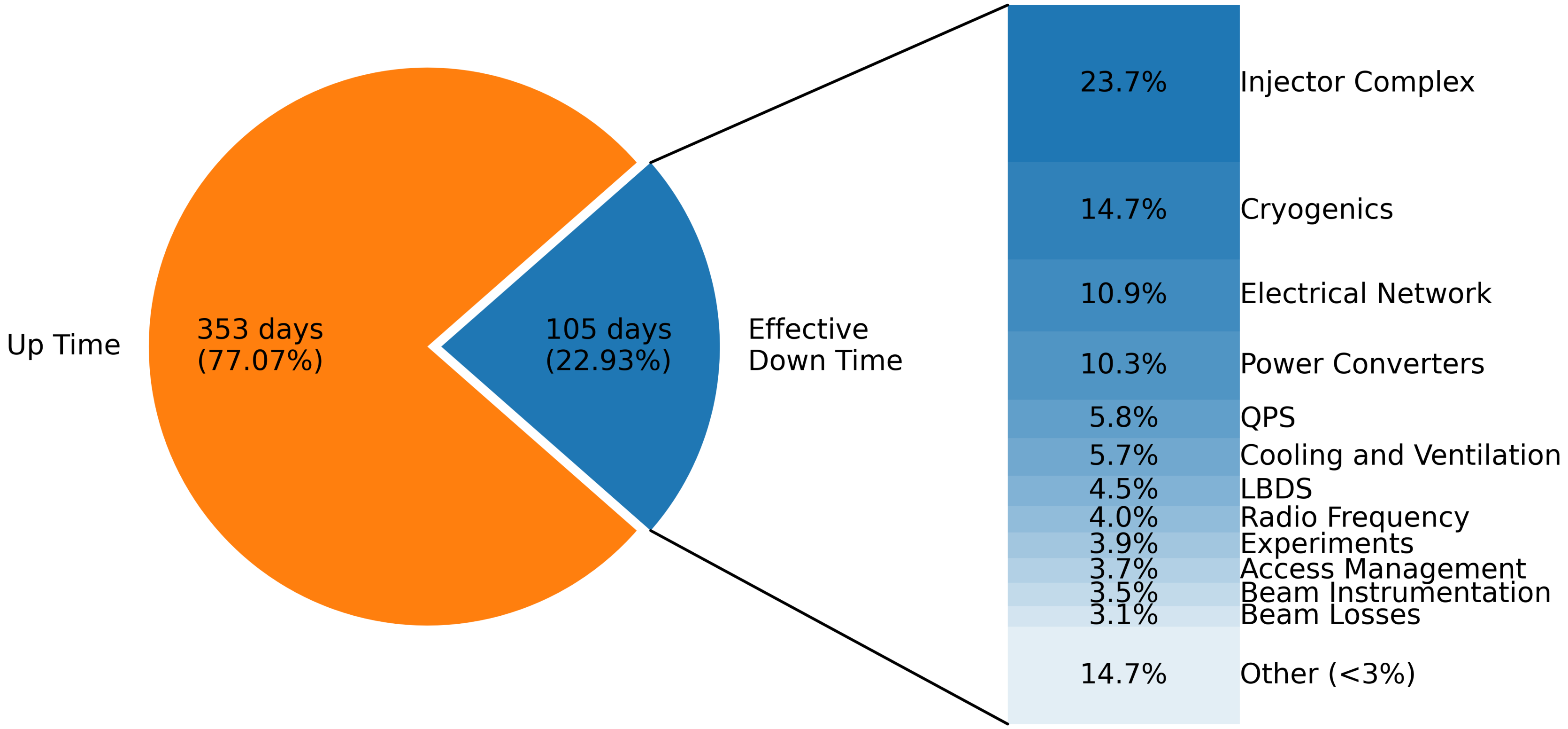
A = Availability = $\frac{\text{up time}}{\text{total time}}$

- **FCC-ee Availability Requirement:**

$$A_{FCC} \geq 80\%$$

A. Abada et al. "FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2", *European Physical Journal: Special Topics*, Vol. 228, No. 2, June 2019, pp. 377

LHC Availability in Run 2 (2016-2018)



$$A_{LHC} = 77\%$$

- **Down time scales with number of components:**

For example:

	LHC	FCC-ee
Dipoles	1232	2900 – 11600
RF cavities (accelerating)	16	140 – 1232

- **FCC-ee has orders of magnitude more components!**

"Accelerator Fault Tracker", https://aft.cern.ch/
J. Bauche, et al., "FCC-ee Main Dipole Length Considerations (from the Magnet Point of View)", FCC Week 2021, 26th March 2021.

Three-step approach

1. Targets

To reach overall 80% availability:

- "RF availability <u>must be above</u>…"
- "Top-up booster <u>must be above</u>…"
- …

2. Shortfalls

Based on current designs & similar systems:

- "RF Availability <u>will likely be</u>…"
- "Top-up booster <u>will likely be</u>…"
- …

3. Opportunities

Where do we fall short?

What can we do about this?

- Solution 1…
- Solution 2…

1. Targets $\hat{A}_i$

Allocate availability according to the "complexity" of assuring it.

i	System i	Complexity (%)	Availability Target $\hat{A}_i$
1	Top-Up Booster Ring	c_1	$\hat{A}_1$
2	Radio Frequency	c_2	$\hat{A}_2$
3	Power Converters	c_3	$\hat{A}_3$
4	Vacuum	c_4	$\hat{A}_4$
5	Cryogenics	c_5	$\hat{A}_5$
6	Extraction & Beam Dump	c_6	$\hat{A}_6$
7	Machine Protection & Interlocks	c_7	$\hat{A}_7$
8	Collimation	c_8	$\hat{A}_8$
9	Beam Instrumentation	c_9	$\hat{A}_9$
10	Cooling & Ventilation	c_{10}	$\hat{A}_{10}$
11	Electrical Networks	c_{11}	$\hat{A}_{11}$
12	Experiments	c_{12}	$\hat{A}_{12}$
⋮	etc., etc…	⋮	⋮

$$\hat{A}_{FCC} \geq 80\%$$

$$\prod \hat{A}_i = \hat{A}_{FCC} = 0.8$$

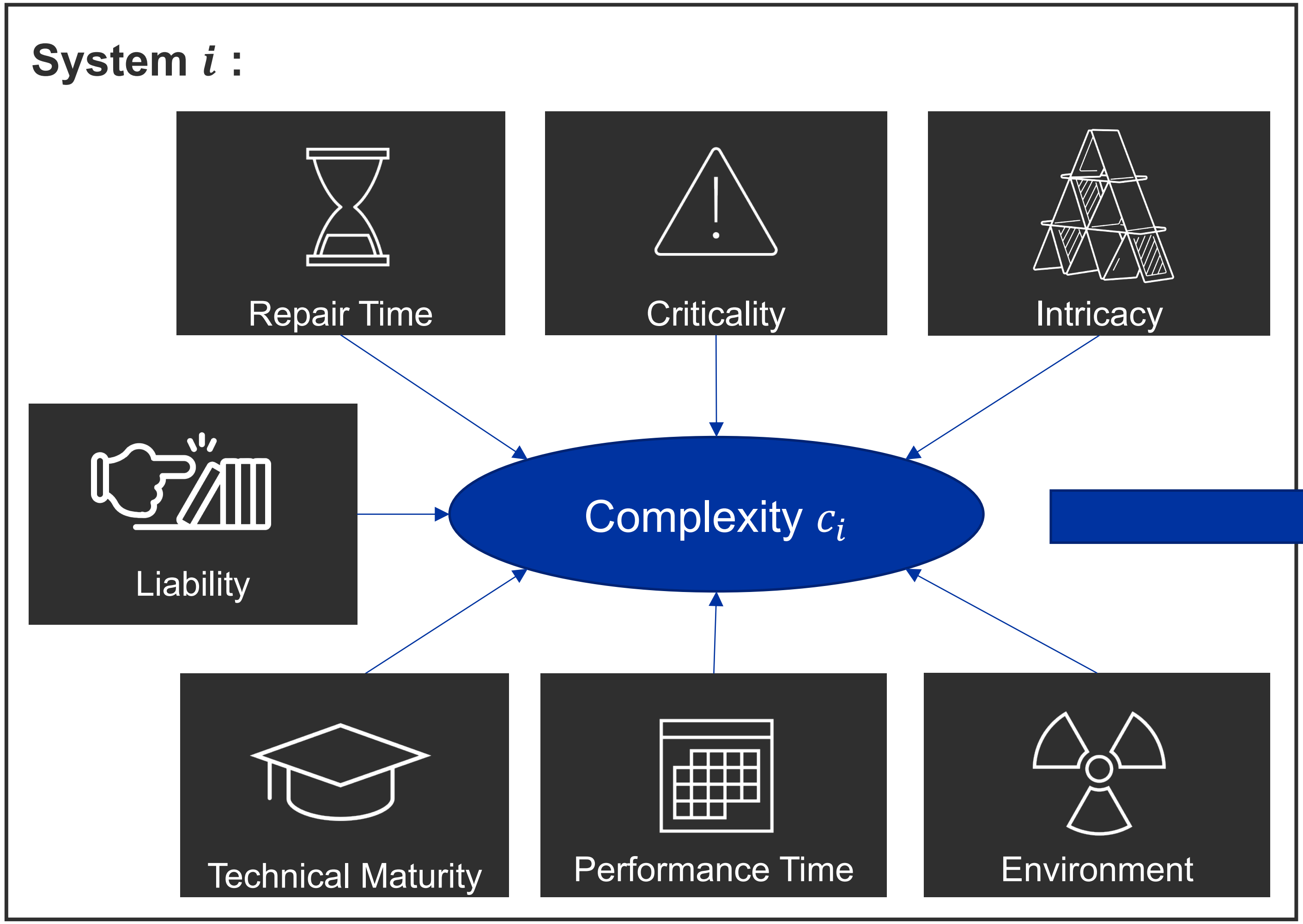
$$\boxed{\hat{A}_i = 0.8^{c_i}}$$

Higher complexity $\Longrightarrow$ *Lower target*

$$c_1 > c_2 > \cdots > c_N \quad \Longrightarrow \quad \hat{A}_1 < \hat{A}_2 < \cdots < \hat{A}_N$$

1. Targets $\hat{A}_i$

Seven scores define complexity c_i



Input from 20 accelerator experts:

- “Generalist” profile
- Diverse backgrounds

$$\hat{A}_i = 0.8^{c_i}$$

O. Rey Orozco et al. “Availability Estimation Methods based on System Complexity”, CERN, Geneva, Switzerland, July 2017.

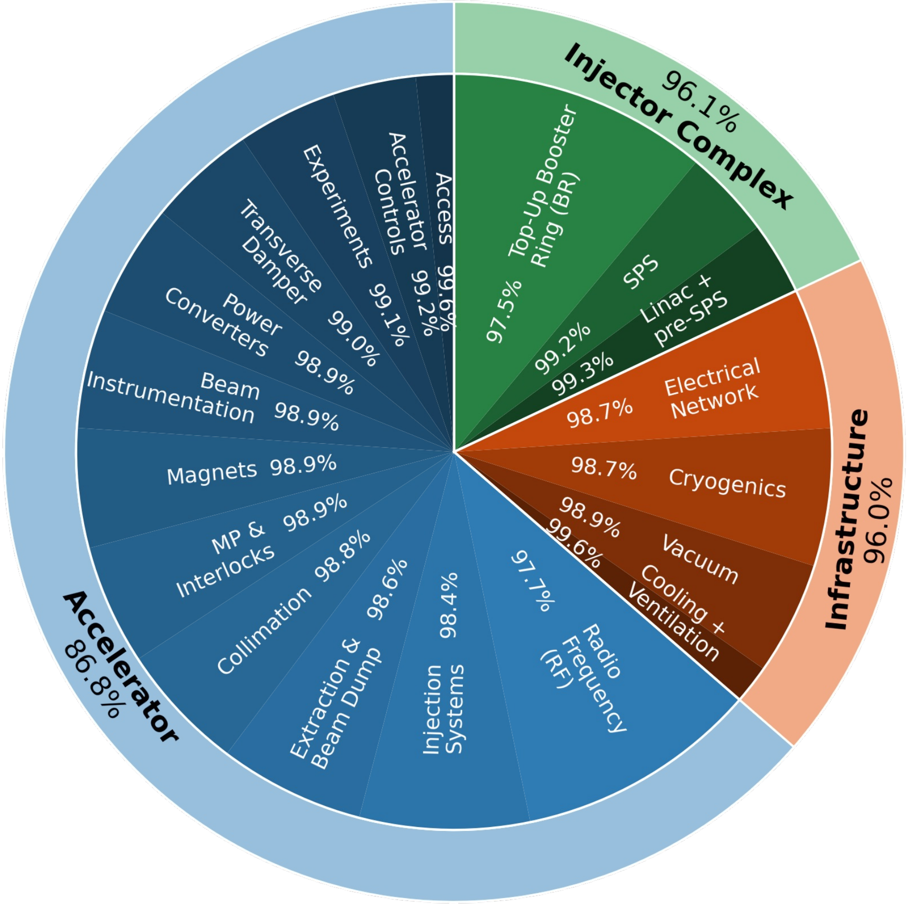
A. Apollonio et al. “Conclusions on FCC Availability Studies”, FCC Week 2018, Amsterdam, Netherlands.

A. Silvestri et al. “A new method for reliability allocation: Critical Flow Method”, *Lecture Notes in Mechanical Engineering*, Vol. 20, pp. 249-261, Jan 2015.

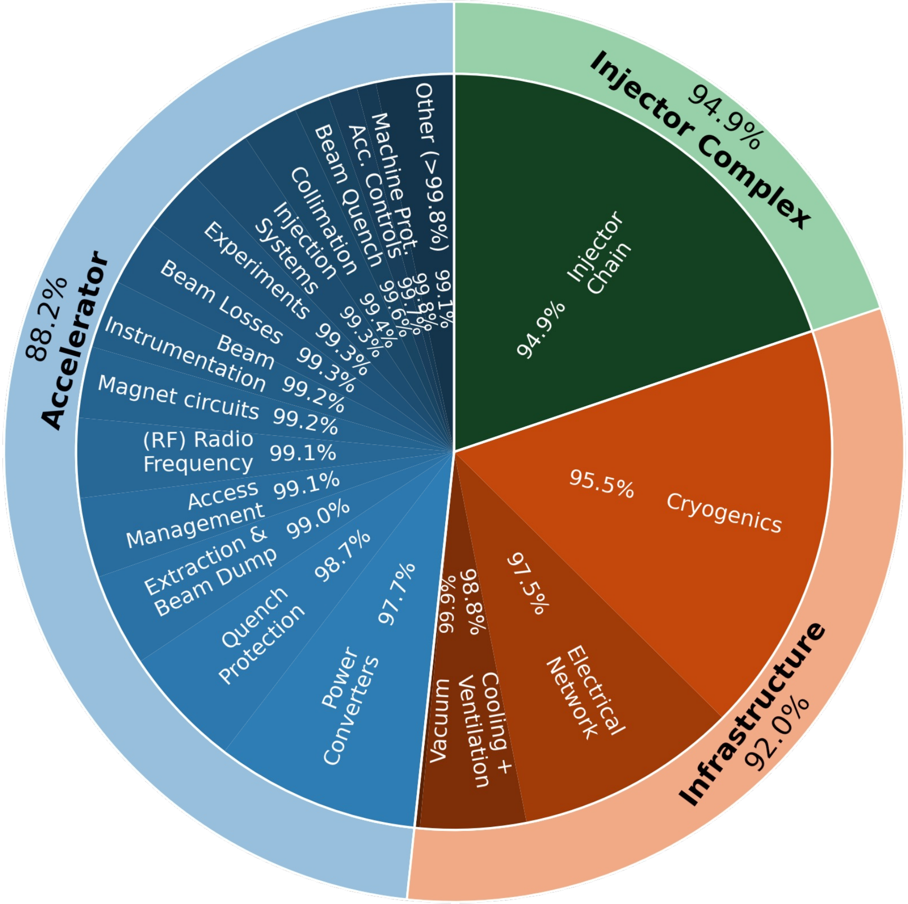
S. M. Seyed-Hosseini et al. “Reprioritization of failures in a system failure mode and effects analysis by decision making trial and evaluation laboratory technique”, *Reliability Engineering and System Safety*, Vol. 91, No. 8, pp. 872-881, 2006.

1. Targets $\hat{A}_i$

FCC-ee (targets)



LHC (achieved)



Three-step approach

1. Targets

To reach overall 80% availability:

- "RF availability must be above 97.7%"
- "Top-up booster must be above 97.5%"
- …

2. Shortfalls

Based on current designs & similar systems:

- "RF Availability will likely be…"
- "Top-up booster will likely be..."
- …

3. Opportunities

Where do we fall short?

What can we do about this?

- Solution 1…
- Solution 2…

2. Shortfalls

Radio Frequency (RF)

Energy Mode	Z 45.6 GeV main*	Z 45.6 GeV booster	W 80 GeV main*	W 80 GeV booster	H 120 GeV main†	H 120 GeV booster	$t\bar{t}$ 182.5 GeV main†	$t\bar{t}$ 182.5 GeV booster
Voltage (MV)	120	140	1050	1050	2100	2100	10300‡	11300
Gradient (MV/m)	5.72	5.34	10.95	21.55	10.78	22.42	22.52	22.42
Cavity voltage (MV)	2.14	5.00	8.20	20.19	8.08	21.00	21.10	21.08
Beam current (mA)	1400	140	135	13.5	53.4	5.3	10	1
# Cells / cavity	1	5	2	5	2	5	5	5
# Cavities	56	28	128	52	260	100	696‡	536

Table 1: RF configurations in FCC-ee [12]

*Per beam; †Both beams; ‡Includes cavities from H mode

Z, W

- High current, low voltage
- 140-308 cavities
- RF trip = beam loss

$H, t\bar{t}$

- Low current, high voltage
- 360-1232 cavities
- 10% voltage redundancy

2. Shortfalls

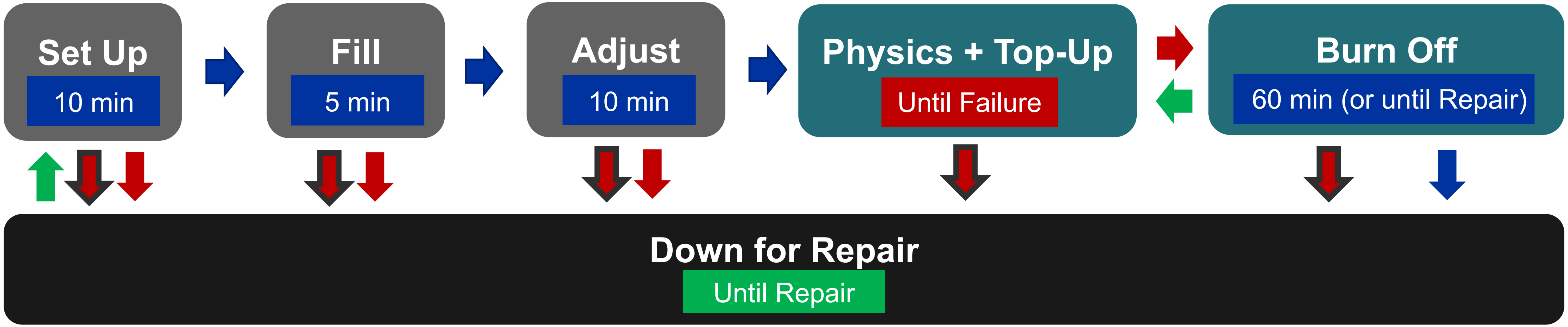
Technology Department
Machine Protection
Controls & Beam Studies
TE-MPE-CB

AvailSim4
Project ID: 131878
https://gitlab.cern.ch/availsim4/

Monte Carlo Simulation:

Phase Transitions:
- Default
- Main RF failure
- Repair complete
- Booster RF failure

States:
- Available, no luminosity
- Unavailable
- Available, luminosity



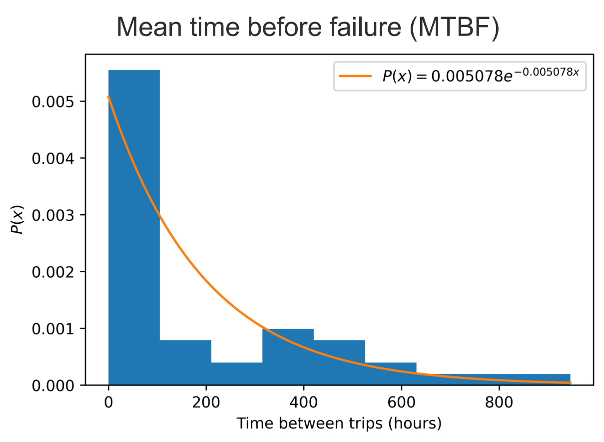
2. Shortfalls

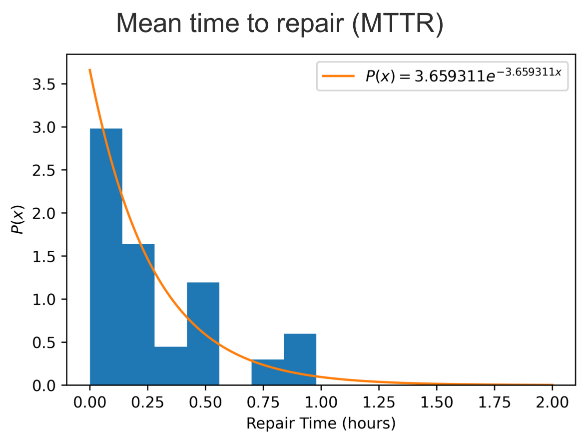
94 RF Faults in LHC Run 2

Repair

< 1h → > 1h

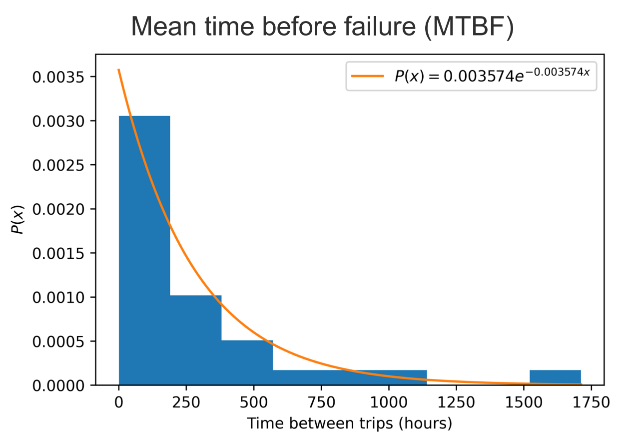
Short Faults

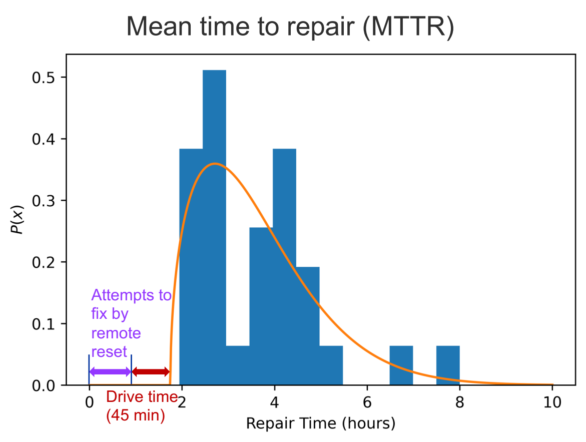




- Repair achieved without human intervention
- E.g. by remote reset
- Achievable while beam is running

Long Faults

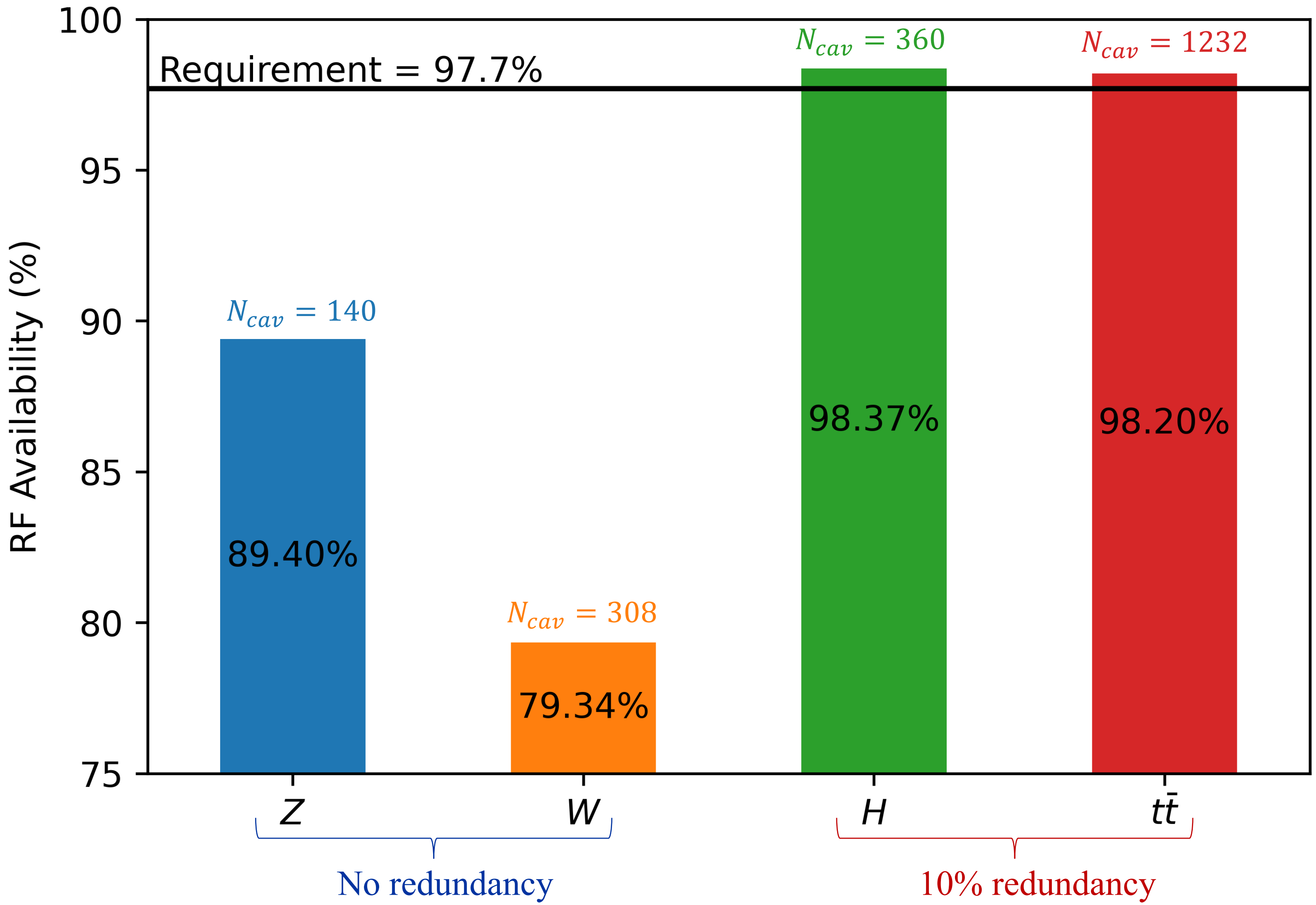




- Requires human intervention
- Add a 45 minute drive time for FCC-ee
- Must wait until system is "down for repair"

2. Shortfalls

FCC-ee
RF only



2. Shortfalls

KEK-B:

Gradient (MV/m)	6
Beam Current (mA)	1400

KEK-B RF is more similar to FCC-ee in Z,W modes

FCC-ee:

Energy Mode	Z 45.6 GeV		W 80 GeV		H 120 GeV		$t\bar{t}$ 182.5 GeV	
	main*	booster	main*	booster	main†	booster	main†	booster
Voltage (MV)	120	140	1050	1050	2100	2100	10300‡	11300
Cavity voltage (MV)	2.14	5.00	8.20	20.19	8.08	21.00	21.10	21.08
Gradient (MV/m)	5.72	5.34	10.95	21.55	10.78	22.42	22.52	22.42
Beam current (mA)	1400	140	135	13.5	53.4	5.3	10	1
# Cells / cavity	1	5	2	5	2	5	5	5
# Cavities	56	28	128	52	260	100	696‡	536

Table 1: RF configurations in FCC-ee [12]

*Per beam; †Both beams; ‡Includes cavities from *H* mode

RF System fault statistics

	MTBF (days)	Number of cavities	MTBF / cav (days)	Reliability (LHC equivalent)
LHC (Run 2, 2016-2018)	5	16	80 days	**1**
KEK-B (1999-2007)	2	8	16 days	**0.2**

If we use KEK-B fault statistics, FCC-ee availability is 5 times worse!

Y. Morita, et al. "KEKB Superconducting Accelerating Cavities and Beam Studies for Super-KEKB" in *Proceedings of IPAC 2010*, Kyoto, Japan, pp. 1537.
K. Nakanishi, et al. "SRF Systems for KEKB and SuperKEKB" in *Proceedings of the 62nd ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2018),* Feb. 2019, pp. 256

Three-step approach

1. Targets

To reach overall 80% availability:

- "RF availability must be above 97.7%"
- "Top-up booster must be above 97.5%"
- …

2. Shortfalls

Based on current designs & similar systems:

- "RF Availability will likely be 89 & 79%"
- "Top-up booster will likely be..."
- …

3. Opportunities

Where do we fall short? RF system in Z & W modes

What can we do about this?

- Solution 1…
- Solution 2…

3. Opportunities

Increase reliability

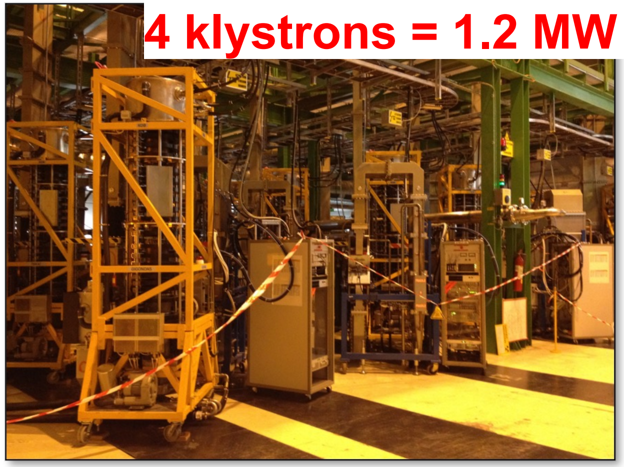
- MTBF per cavity circuit
- Hardware approach

E.g. Solid State Power Amplifiers (SSPAs) vs Klystrons

LHC Klystron Assembly

Power Converter

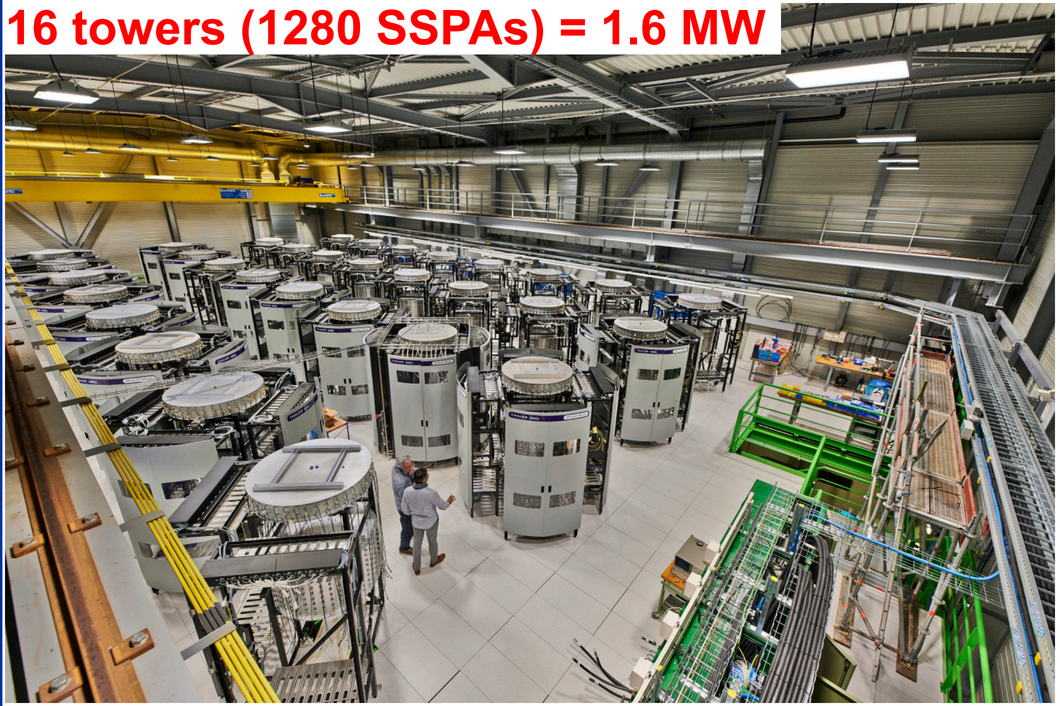
HV bunker



4 klystrons = 1.2 MW

SPS SSPA Towers

16 towers (1280 SSPAs) = 1.6 MW



L. Felsberger, A. Apollonio, T. Cartier-Michaud, E. Montesinos, J.C. Oliveira, J. Uythoven, “Availability Modeling of the Solid-State Power Amplifiers for the CERN SPS RF Upgrade” in 12th International Particle Accelerator Conference (JACoW Publishing, Campinas, SP, Brazil, 2021), pp. 2308–2311.

J. Cai, I. Syratchev, G. Burt, “Two Stage High Efficiency Klystron for FCC-ee” in FCC Week 2021.

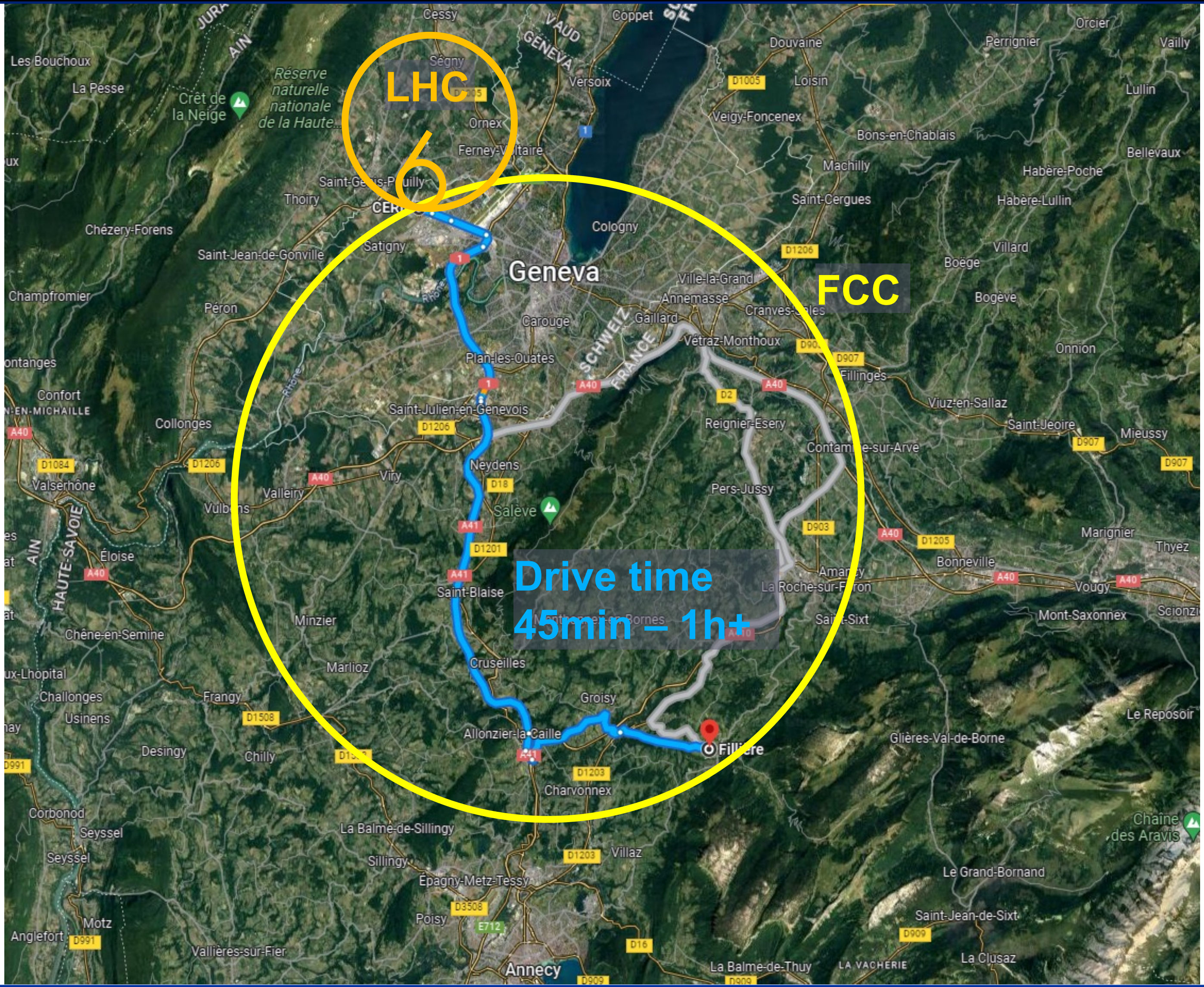
3. Opportunities

Drive time

- 45 min – 1h+

Reduce / anticipate

- Scatter teams of technicians
- Helicopter transport
- Robot Maintenance (slide 17)
- Late-stage prognostics (slide 18)



3. Opportunities

Robot Maintenance

Repair more faults while the beam is running

“Short” : “Long” fault ratio

(also eliminates drive time)

M. Di Castro, et al. “Robotic Solutions for the Inspection and Remote Maintenance of Particle Accelerators”, *FCC Week 2023*

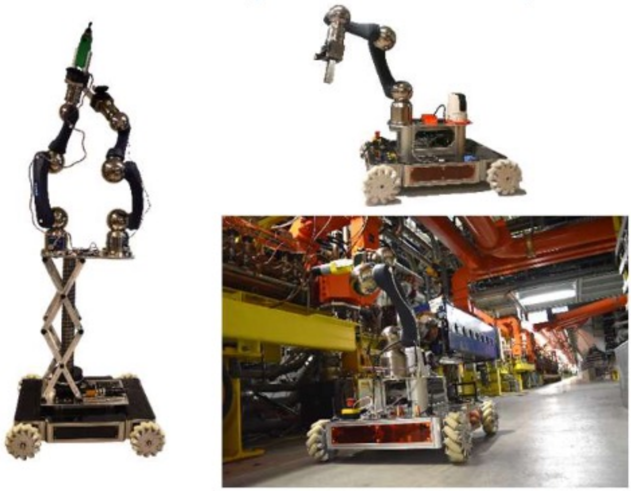
Train Inspection Monorail (TIM) for inspection & RP measurements in LHC

ISOLDE & MEDICIS robots for target exchange

Radioactive samples fine handling

Telemax & Teodor for inspection and telemanipulation

CERNbot for inspection and telemanipulation



CRANEbot for accessing complicated areas

3. Opportunities

Fault Prediction

1. Identify and diagnose a deterioration in health
2. Repair / replace relevant components before the fault occurs

Also prevents child faults & collateral damage

Physical models ("white box")

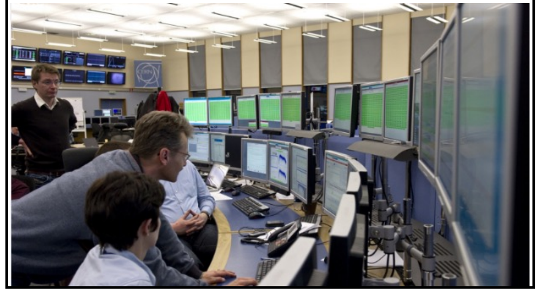
- E.g. X-ray monitoring for cavity degradation

Statistical models ("black box")

- E.g. unsupervised anomaly detection

Applied to Long faults only.

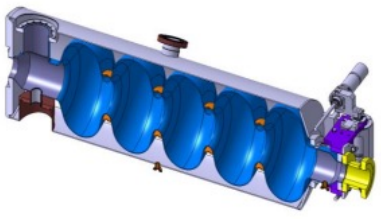
Control Center



Health insights:
- Performance
- Efficiency
- Anomalies

Actions:
- Testing
- Maintenance
- Replace parts

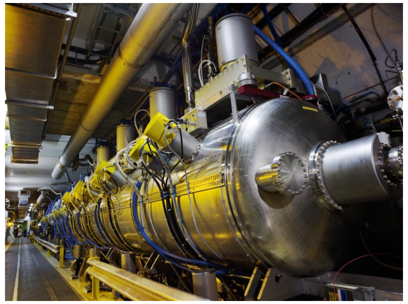
Digital Twin



- Virtual models of system + processes
- Analysis of sensor data

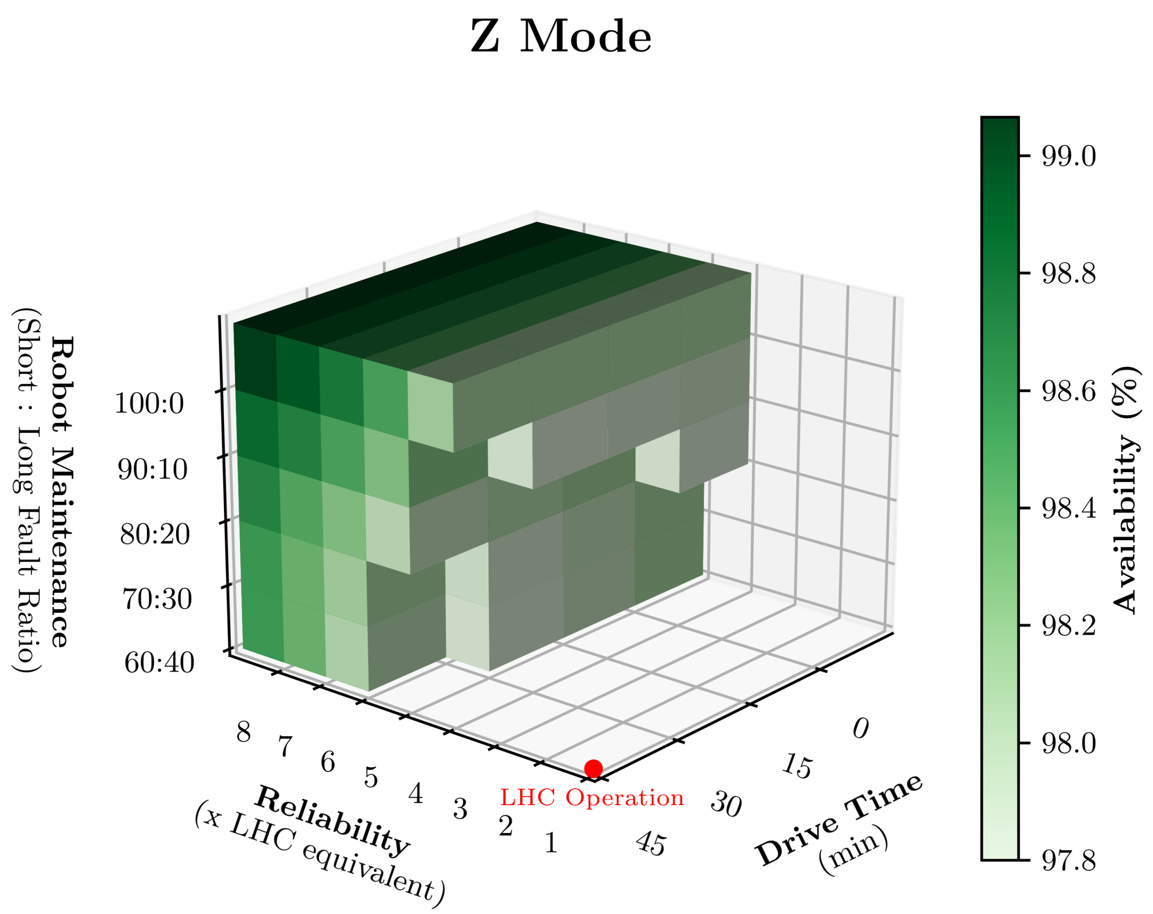
Sensor data
(performance, health, events)

Physical System

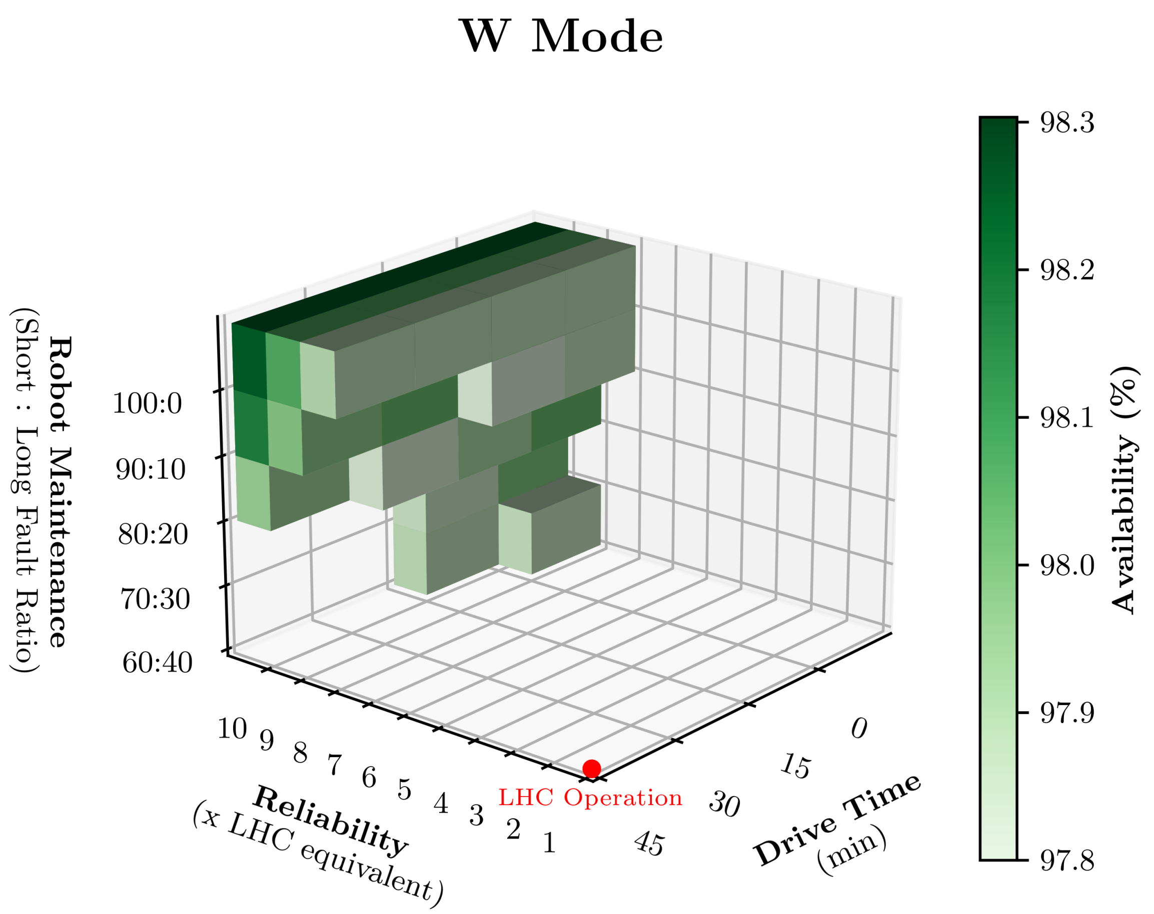


- Physical system
- Sensors

Results

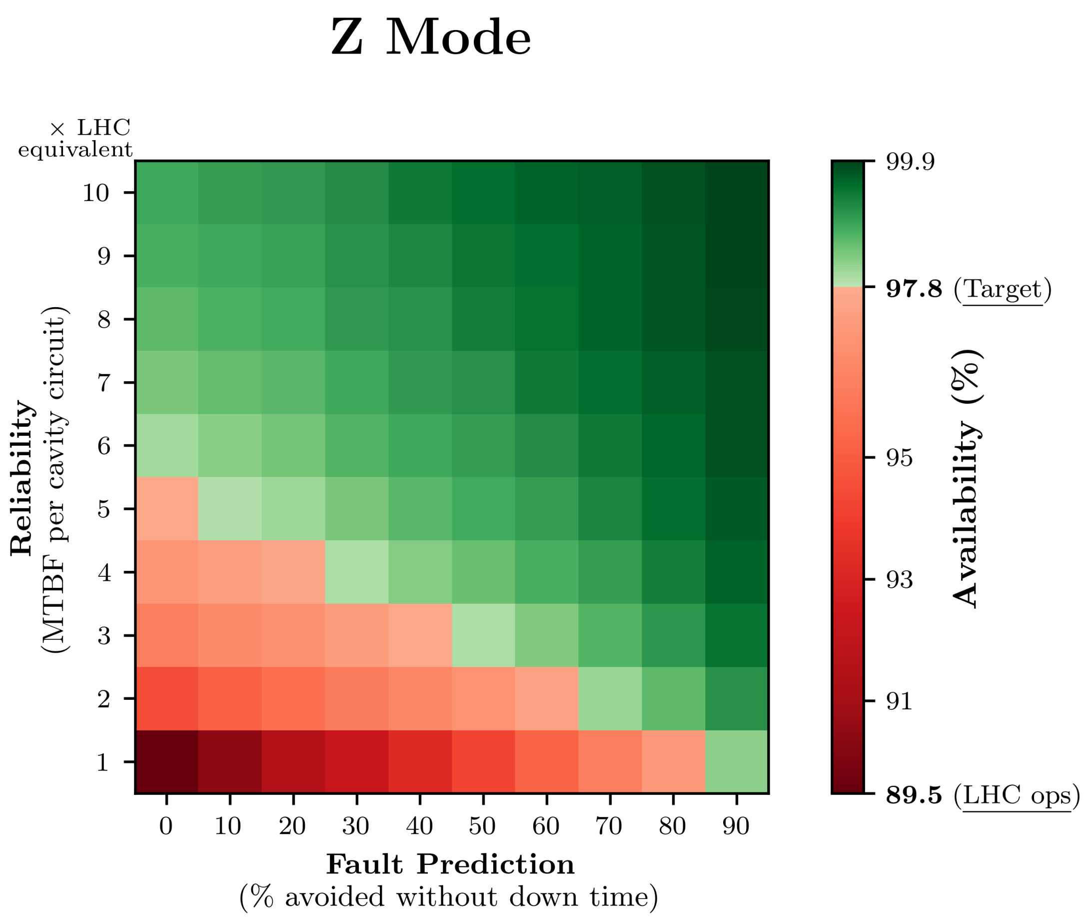


Z Mode
Robot Maintenance
(Short : Long Fault Ratio)
100:0
90:10
80:20
70:30
60:40
8
7
6
5
4
3
2
1
Reliability
(x LHC equivalent)
LHC Operation
0
15
30
45
Drive Time
(min)
99.0
98.8
98.6
98.4
98.2
98.0
97.8
Availability (%)

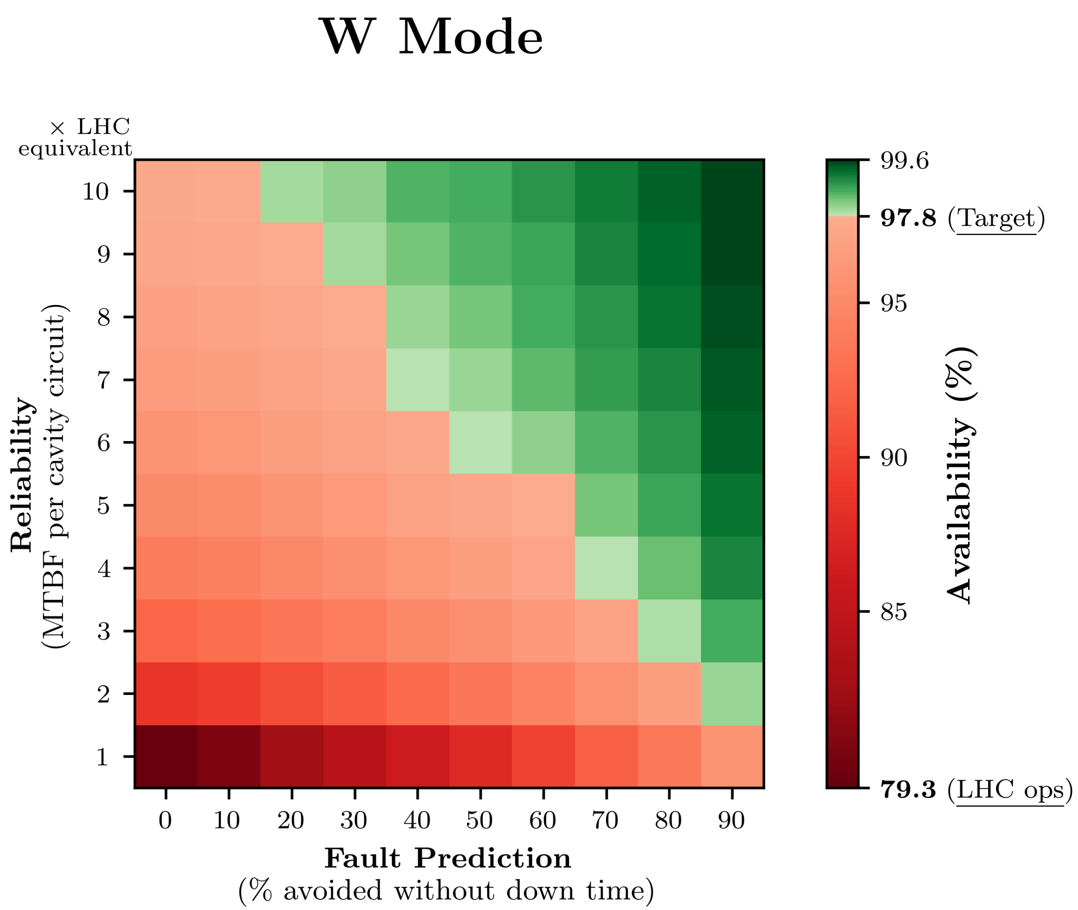


W Mode
Robot Maintenance
(Short : Long Fault Ratio)
100:0
90:10
80:20
70:30
60:40
10
9
8
7
6
5
4
3
2
1
Reliability
(x LHC equivalent)
LHC Operation
0
15
30
45
Drive Time
(min)
98.3
98.2
98.1
98.0
97.9
97.8
Availability (%)

Results



Z Mode
× LHC equivalent
Reliability
(MTBF per cavity circuit)
10
9
8
7
6
5
4
3
2
1
0
10
20
30
40
50
60
70
80
90
Fault Prediction
(% avoided without down time)
99.9
97.8 (Target)
95
93
91
89.5 (LHC ops)
Availability (%)

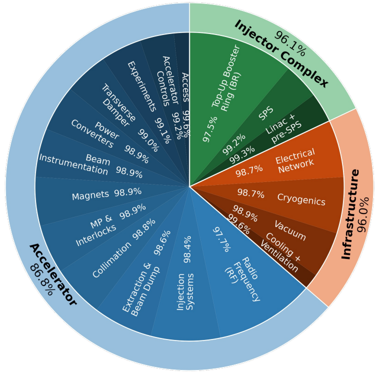


W Mode
× LHC equivalent
Reliability
(MTBF per cavity circuit)
10
9
8
7
6
5
4
3
2
1
0
10
20
30
40
50
60
70
80
90
Fault Prediction
(% avoided without down time)
99.6
97.8 (Target)
95
90
85
79.3 (LHC ops)
Availability (%)

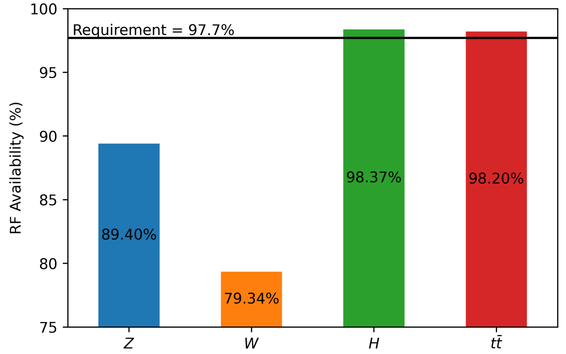
Summary

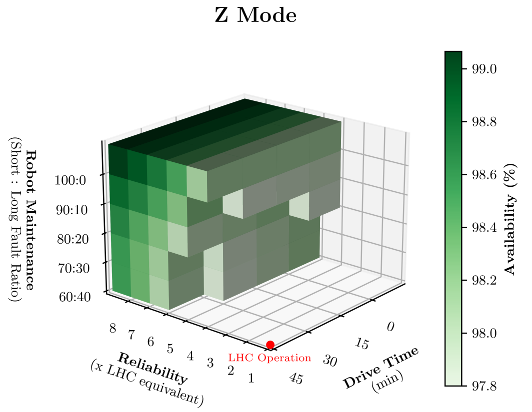
- **Targets:** Availability requirements defined at system level (for the first time!)
  - Scaled according to complexity of availability assurance
- **Shortfalls:** Projected RF availability in Z & W modes (according to LHC data) is worryingly low.
  - Even worse if we look at more similar systems e.g. KEK-B
- **Opportunities:** Four solutions are analysed
  1. Increase reliability (pure hardware approach)
  2. Reduce / anticipate drive time
  3. Robot Maintenance
  4. Fault prediction

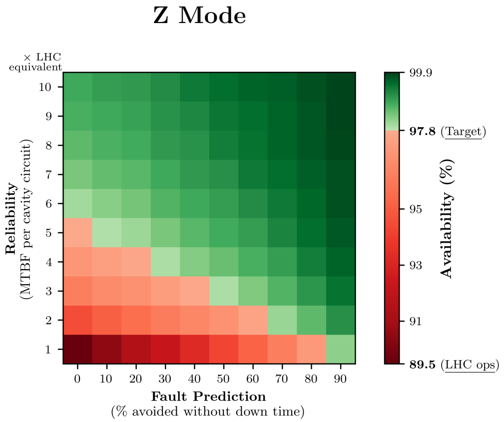
FCC-ee Availability Requirements:



FCC-ee Projected Availability assuming LHC operation and maintenance paradigm:



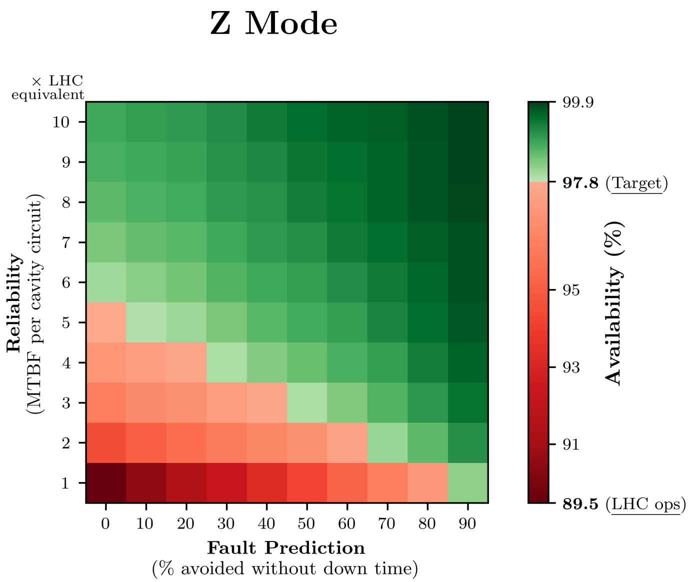


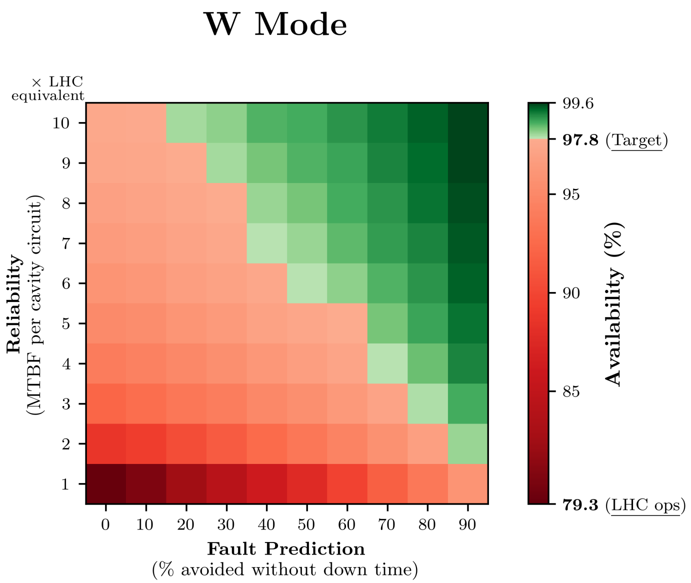


Conclusions

- The availability challenge is real.
- A seismic shift in operation & maintenance paradigm is required.
- Most compelling solutions for RF:
  - Reliability per cavity circuit
  - Fault Prediction

- <u>Reliability per cavity circuit must improve significantly.</u>
- <u>Fault prediction is potentially game-changing.</u>





Outlook

1. Targets

Top-Up Booster:

To reach overall 97.5% availability:

- "RF availability must be above…"
- "Power converters must be above…"

Also breakdown of other systems.

2. Shortfalls

Based on current designs & similar systems:

- "RF Availability will likely be 89 & 79%"
- "Top Up Booster will likely be…"
- "Injection Systems will likely be…"
- " ⋮ ⋮ will likely be…"

3. Opportunities

Where do we fall short? RF system in Z & W modes

What can we do about this?

- Can we avoid losing beam on RF trips?
- Scope for reliability & fault prediction

home.cern