Availability and Luminosity in the Future Circular Electron-Positron Collider (FCC-ee)

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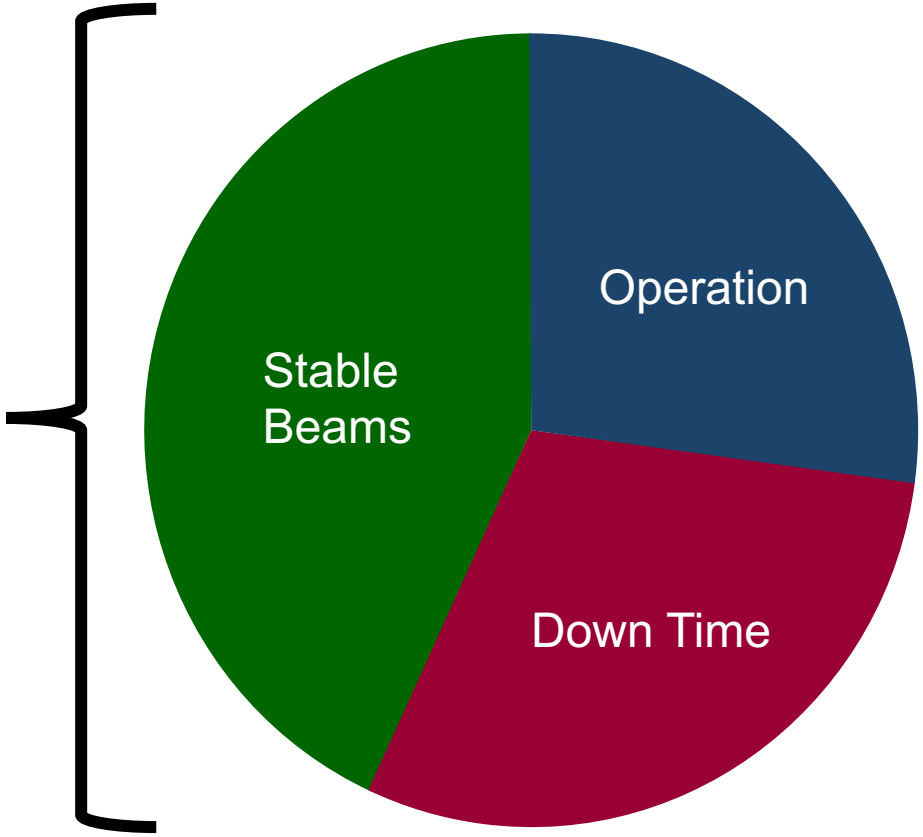
FUTURE CIRCULAR COLLIDER

https://fcc.web.cern.ch/

Availability and Luminosity

FCC-ee:

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



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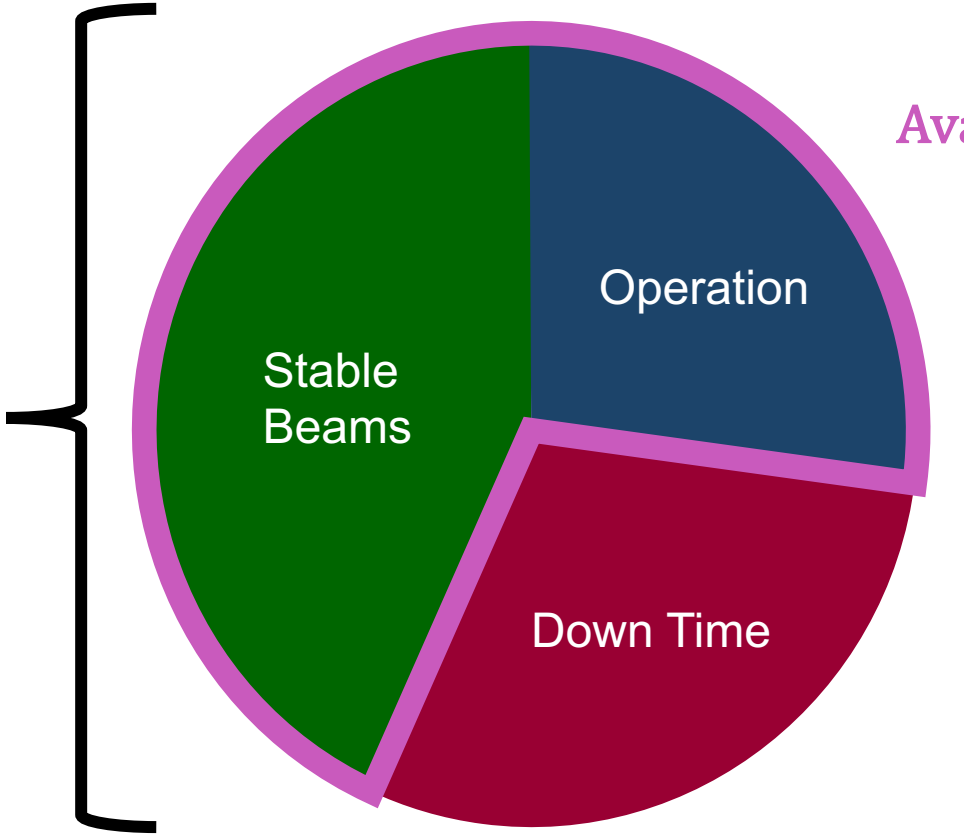

$$\text{Availability } A = \frac{\text{Up time}}{\text{Total physics time}}$$

Availability and Luminosity

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

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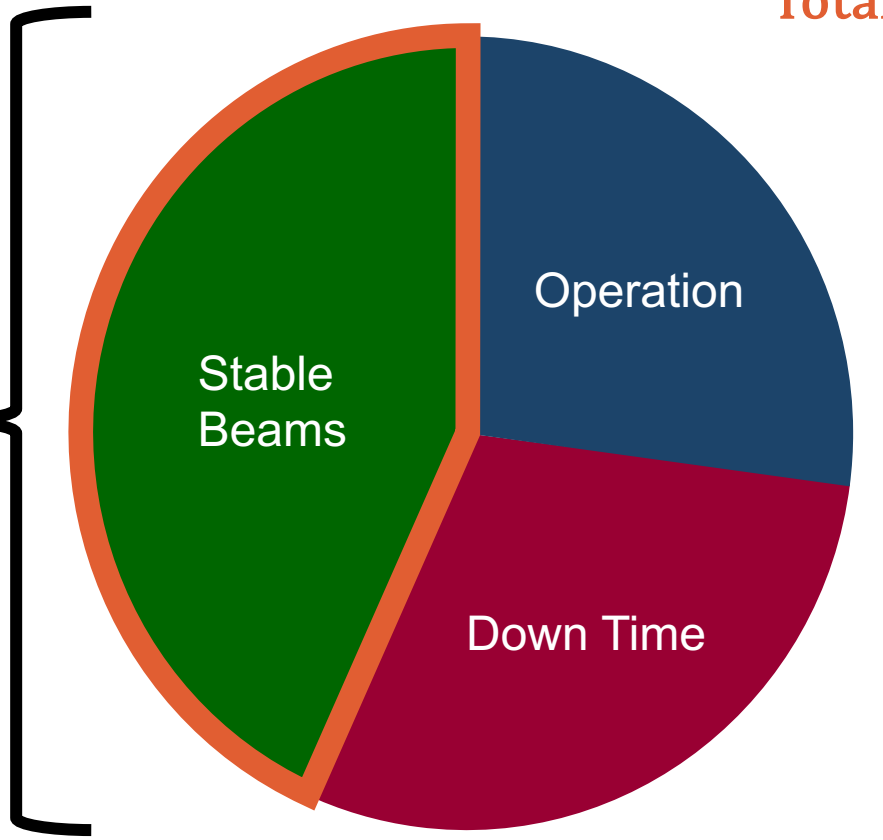


Availability and Luminosity

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

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

$$\text{Total physics time } T = 185 \text{ days}$$

$$\text{Nominal Luminosity } L$$

$$\text{Integrated Luminosity } L_{int} = ETL$$

Availability and Luminosity

To reach targets

$$\text{Availability } A = \frac{\text{Up time}}{\text{Total physics time}} = 80\%$$

$$\text{Total physics time } T = 185 \text{ days}$$

$$\text{Efficiency } E = \frac{\text{Stable Beams time}}{\text{Total physics time}} = A - 5\% = 75\%$$

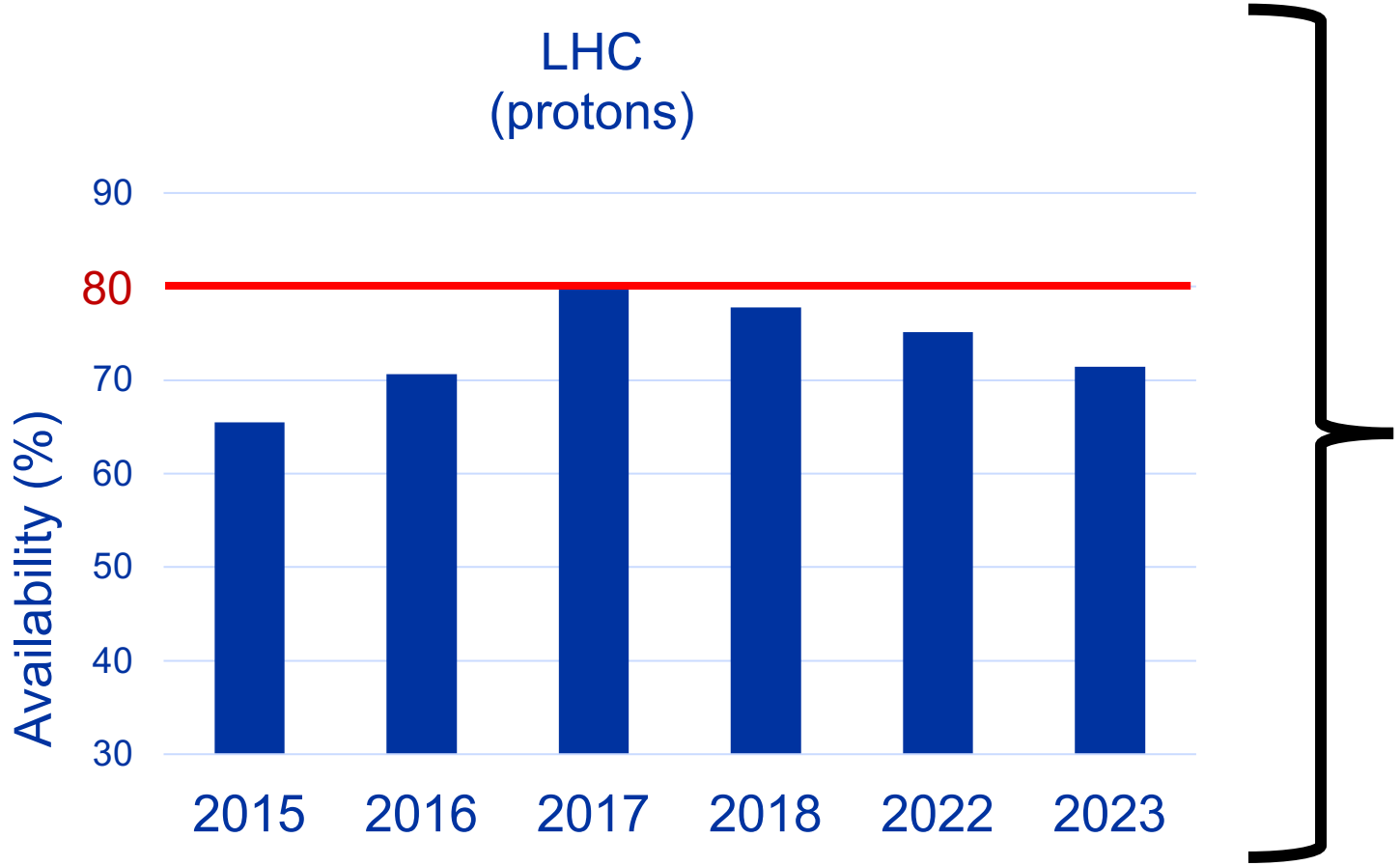
$$\text{Nominal Luminosity } L$$

$$\text{Integrated Luminosity } L_{int} = ETL$$

B. Auchmann *et al.*, "Future Circular Collider Midterm Report," CERN, Geneva, Switzerland, Tech. Rep., 2024, https://new-cds.cern.ch/records/zh1gz-52t41.

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, pp. 261–623, 2019. doi:10.1140/epjst/e2019-900045-4

Large Hadron Collider (LHC) Availability



LHC (27 km):

- 74% Availability

FCC is 91km !

Three-step approach

1. Targets

To reach overall 80% availability:

- "RF availability must be above…"
- "Top-up booster must be above…"
- …

2. Forecasts

Based on current designs & similar systems:

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

3. Solutions

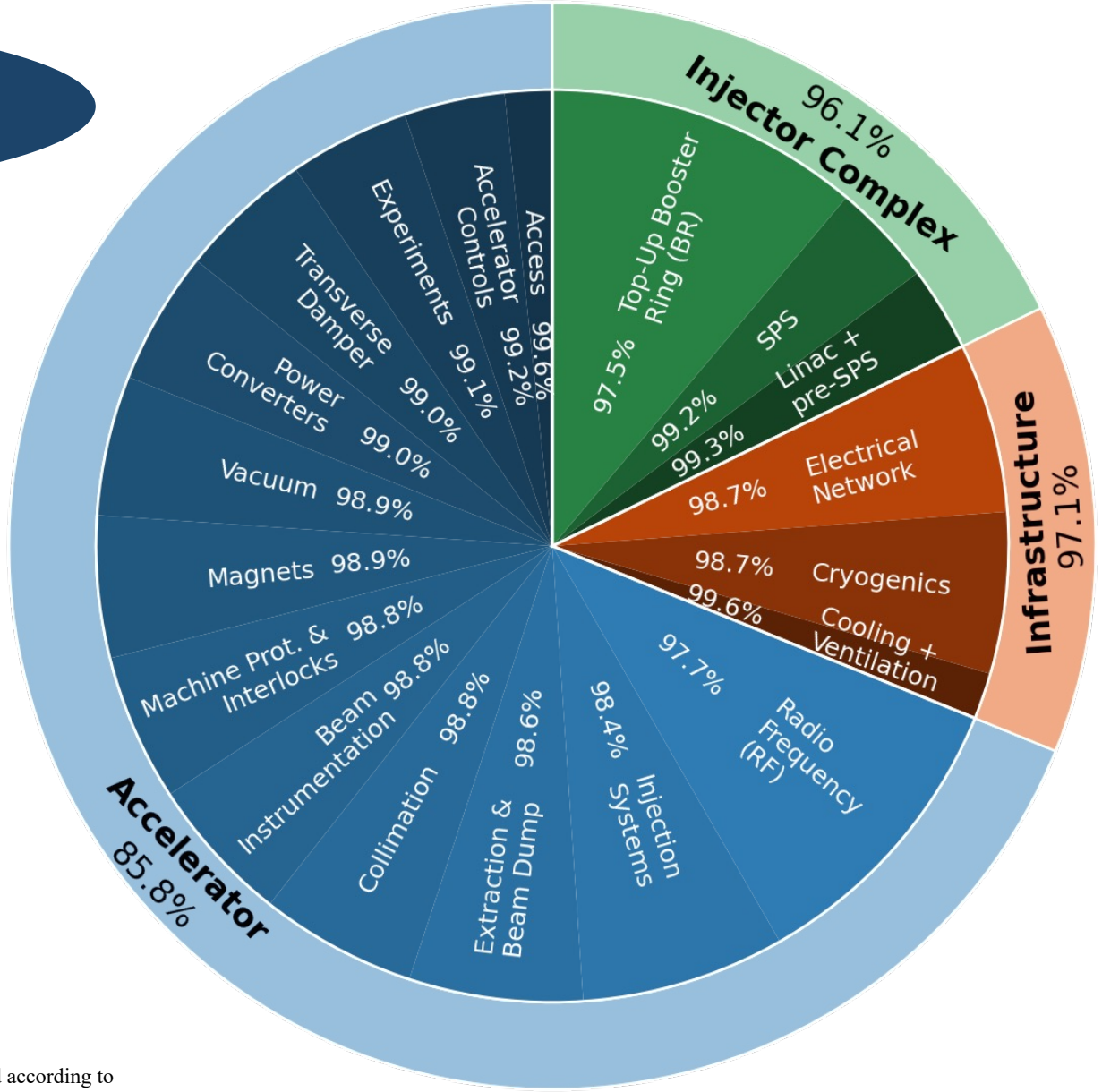
Where do we fall short?

What can we do about this?

- **Solution 1…**
- **Solution 2…**

1. Targets

- **FCC-ee availability targets**



J. W. Heron, L. Felsberger, D. Wollmann, J. Uythoven and F. Rodriguez-Mateos, "Availability targets scaled according to assurance complexity in the FCC-ee," Engineering; Accelerators and Storage Rings, 2023, https://cds.cern.ch/record/2880189 .

2. Forecasts

AvailSim4

Project ID: 131878

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

More info

M. Blaszkiewicz *et al.*, "Availsim4 – an open-source frame- work for availability and reliability simulations," in *Advances in Reliability, Safety and Security. ESREL Contributions*, 2024.

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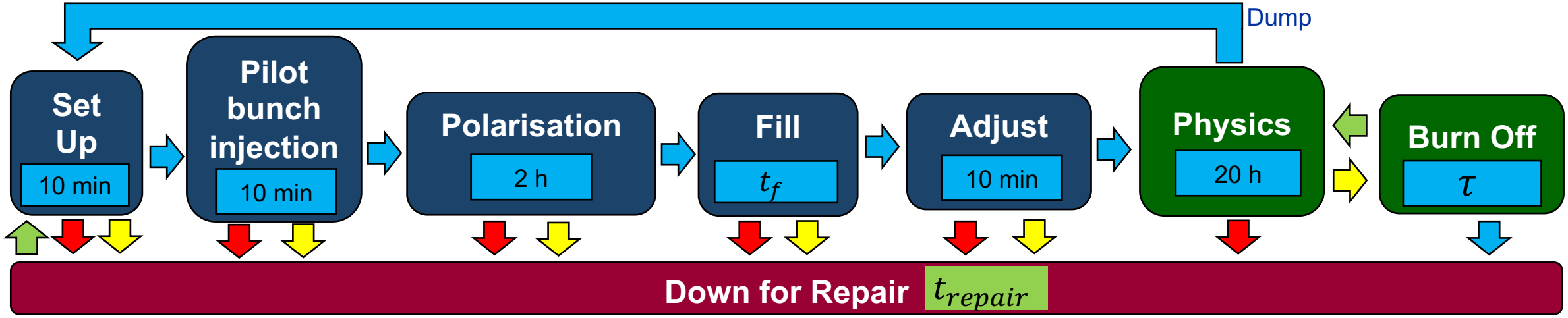
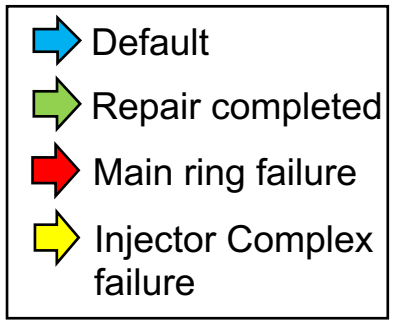
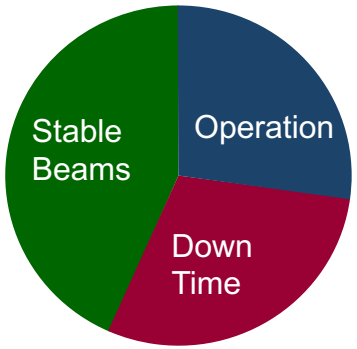
FCC-ee Operation Cycle

Z,W



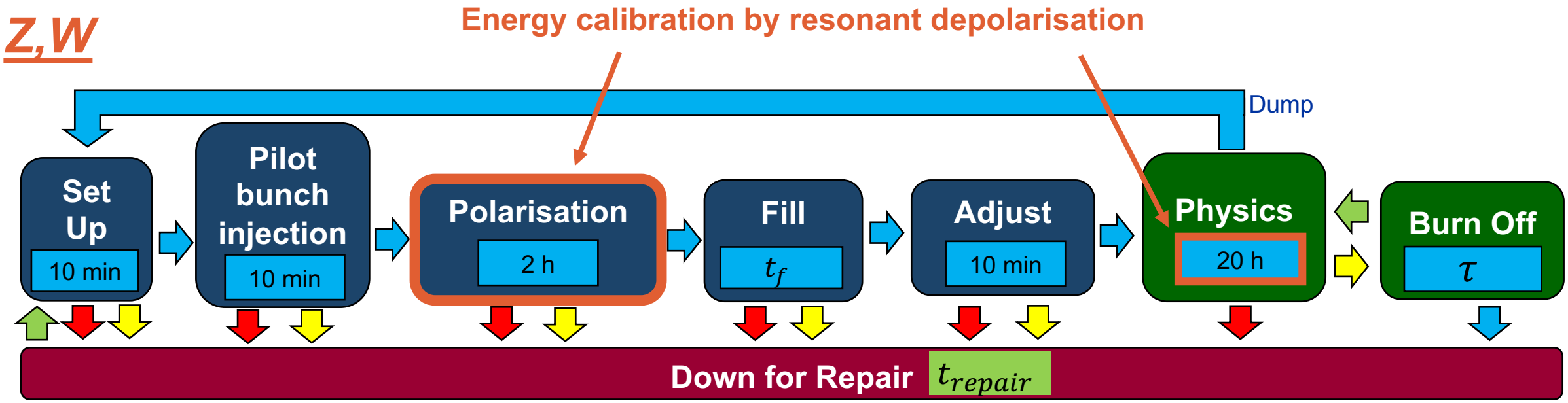


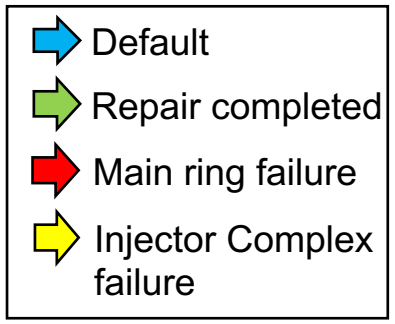


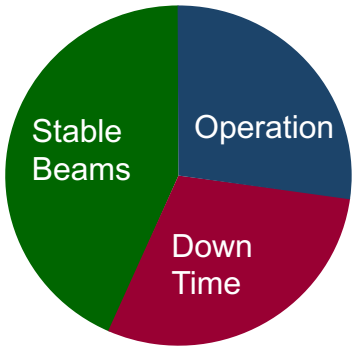
	Z	W
Fill time t_f (min)	7.7	2.5
Lifetime τ (min)	15	12

FCC-ee Operation Cycle

Z, W







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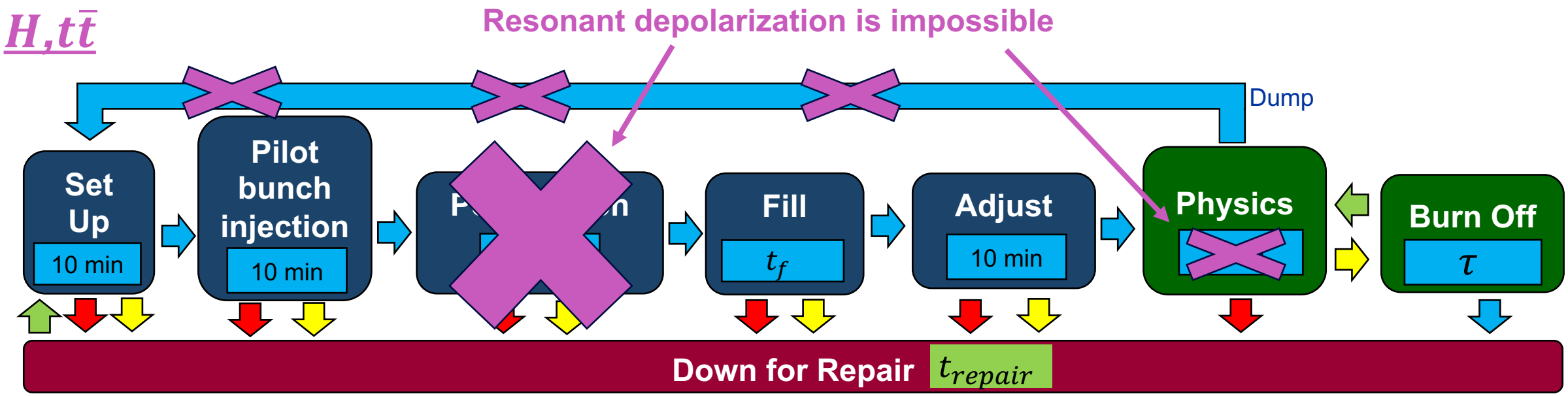
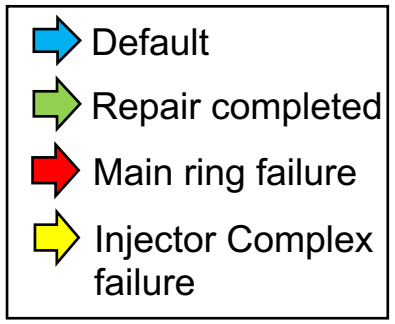
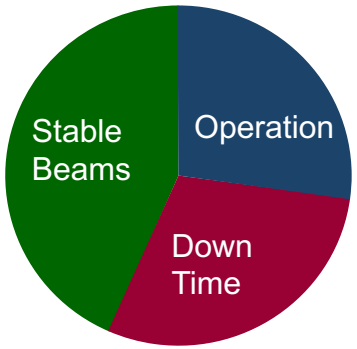






	Z	W
Fill time t_f (min)	7.7	2.5
Lifetime τ (min)	15	12

Two fault types:

Remote Repair Faults

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

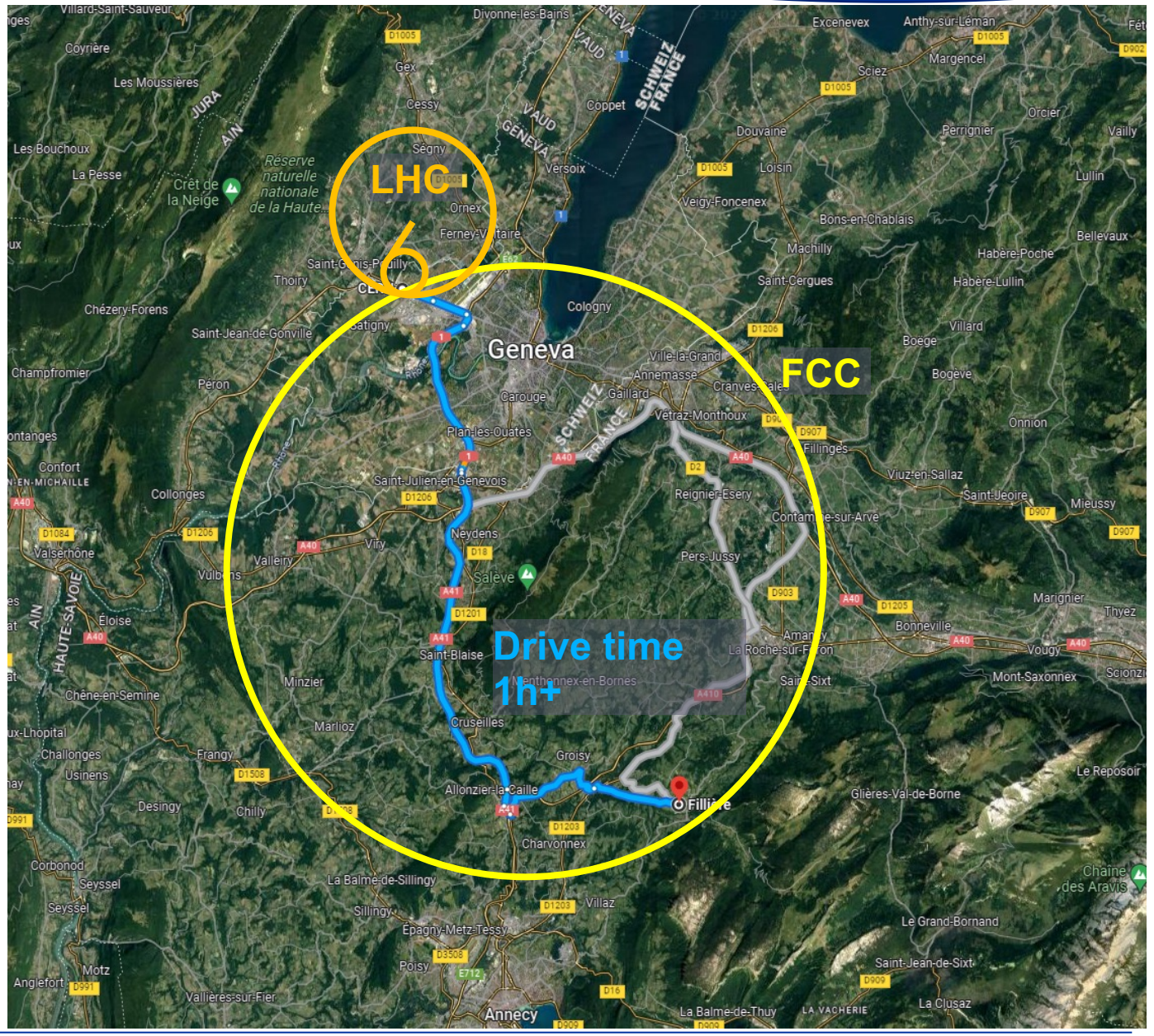
Human Repair Faults

- Requires human intervention
- Add approach time to the repair duration

https://www.istockphoto.com/vector/isometric-control-center-gm164401684-15526568
https://www.flaticon.com/free-icon/technician_6342684

Approach Time

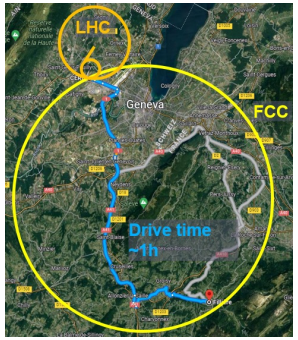
20 min – 1h+

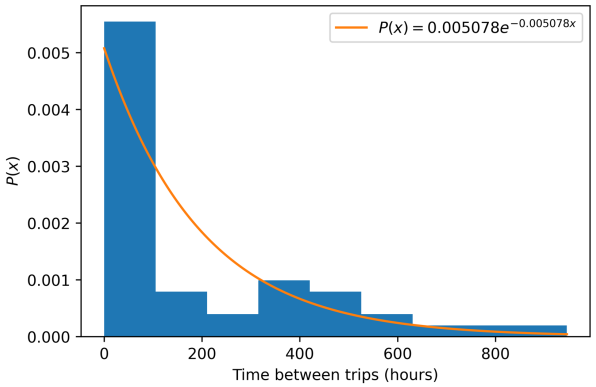


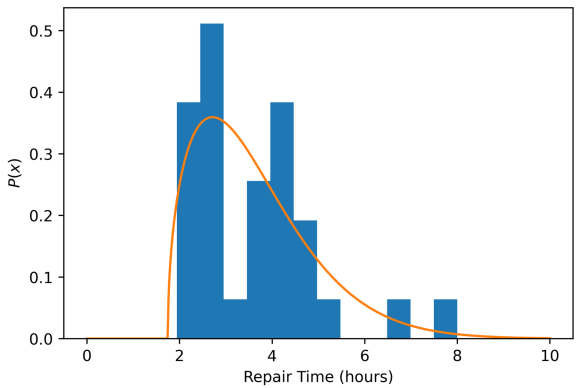
Inputs Required for each System

- **Probability distributions:**
  - Fault rate (MTBF)
  - Repair time (MTTR)

For remote and human repair faults

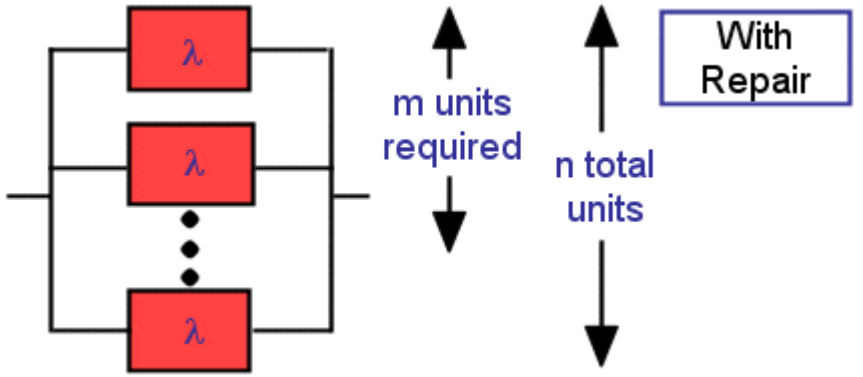






- **Approach time**
  - Based on location around the ring

- **Redundancy:**
  - "Can continue without 1 in 10 of these components"



https://reliabilityanalyticstoolkit.appspot.com/active_redundancy_with_repair

Only completed for RF system so far!

RF System

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)	80	140	1050	1050	2100	2100	9200‡	11300
Cavity voltage (MV)	1.43	5.83	7.95	18.75	7.95	18.75	18.85	18.83
Gradient (MV/m)	3.81	6.23	10.61	20.01	10.61	20.01	20.12	20.10
Beam current (mA)	1280	128	135	13.5	53.4	3	10	0.5
# Cells / cavity	1	5	2	5	2	5	5	5
# Cavities	56	24	132	56	264	112	752‡	600

Table 1: RF configurations in FCC-ee [50]
*Per beam; †Both beams; ‡Includes cavities from H mode

Z, W

- High current, beam loading
- 136-320 cavities

Originally:

- **RF trip => beam dump (0% redundancy)**

Latest analysis:

- **10% redundancy is the theoretical limit**

$H, t\bar{t}$

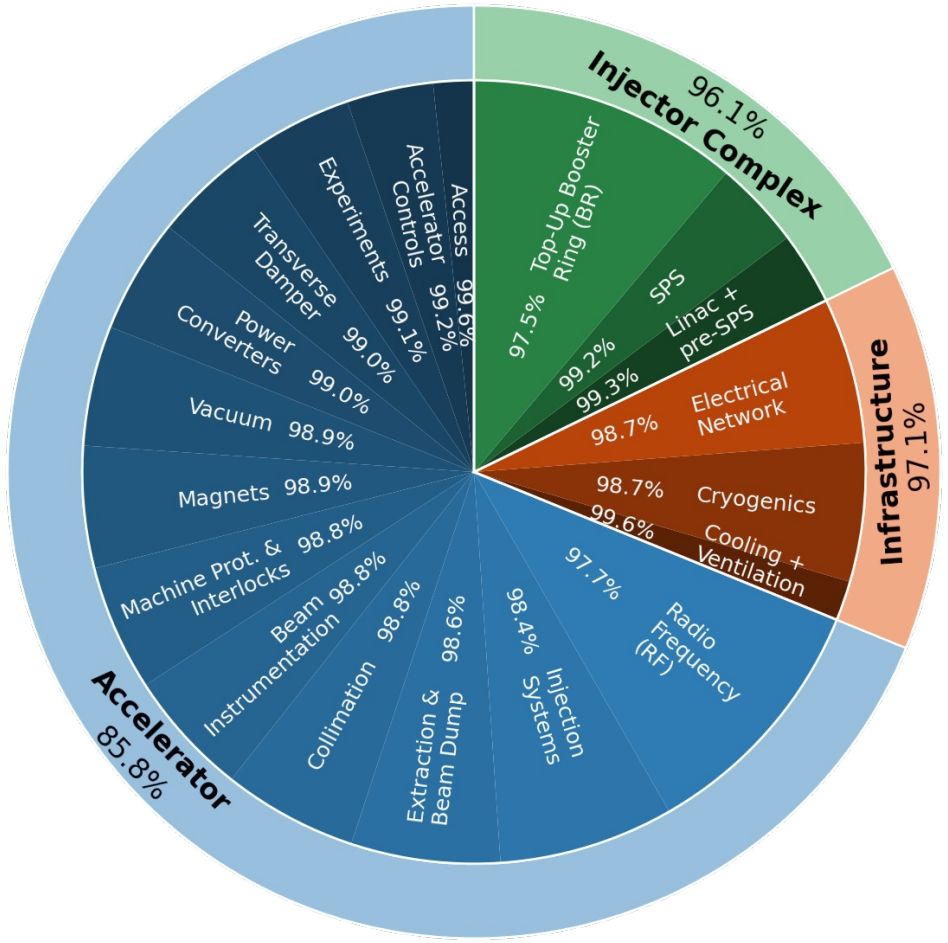
- Low current, high voltage
- 376-1352 cavities
- **10% voltage redundancy**

J. W. Heron *et al.*, "Machine protection and availability in the FCC-ee," *Engineering; Accelerators and Storage Rings*, 2023, https://cds.cern.ch/record/2880188

Ivan Karpov, "Status of the RF study on the 2-cell cavity for Z operation", *181st FCC-ee Optics Design Meeting & 52nd FCCIS WP2.2 Meeting*, 21st March 2024, https://indico.cern.ch/event/1392548/

All other systems

FCC-ee System Availability Targets A_s



For system *s:*

- $MTTR_s$ consistent with similar systems
- Drive time t_{ds} added according to system's location around the ring
- Exponential distributions used

$$MTBF_s = \frac{A_s}{1 - A_s}(MTTR_s + t_{ds})$$

J.W. Heron, L. Felsberger, D. Wollmann, J. Uythoven and F. Rodriguez-Mateos, "Availability targets scaled according to assurance complexity in the FCC-ee," *Engineering; Accelerators and Storage Rings*, 2023, https://cds.cern.ch/record/2880189.

Repair Schedules

Fault

All repairs begin in parallel, and will finish

Operation resumes here

Remote repairs

Diagnosis + attempts to reset from control room

We've got it!

Repairs will finish once started

Human repairs (or robots?)

Approach time

Humans in tunnel

Blind Repair
"We're not finished here!"

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https://www.flaticon.com/free-icon/technician_6342684
https://www.flaticon.com/free-icon/driving_7481812

Repair Schedules

Fault

All repairs begin in parallel, and will finish

Operation resumes here

Remote repairs

Diagnosis + attempts to reset from control room

We've got it!

Repairs are cancelled once operation can resume

Human repairs (or robots?)

Approach time

Humans in tunnel

Optimal Repair
"Dropping tools and getting out!"

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https://www.flaticon.com/free-icon/technician_6342684
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“Realistic” Repair Timeline:

Operation resumes if possible before humans are in the tunnel

Once human repairs start, they will finish.

Realistic Repair Operation resumes here

Fault

Remote repairs begin immediately

1 h

Diagnosis + attempts to reset from control room

We can’t fix it from here. Get someone out there!

Remote repairs

Human repairs

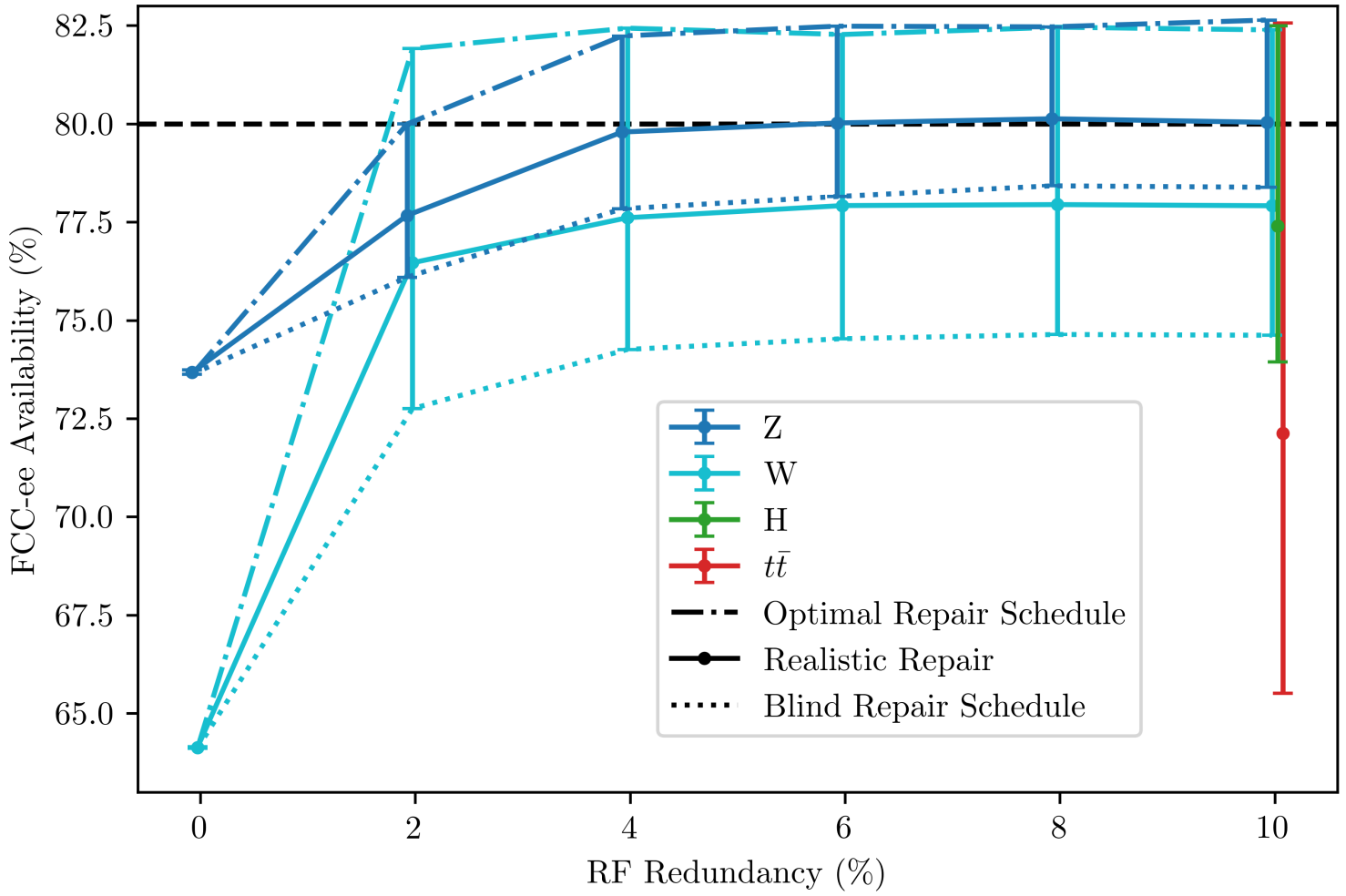
20 min - 1 h

Approach time

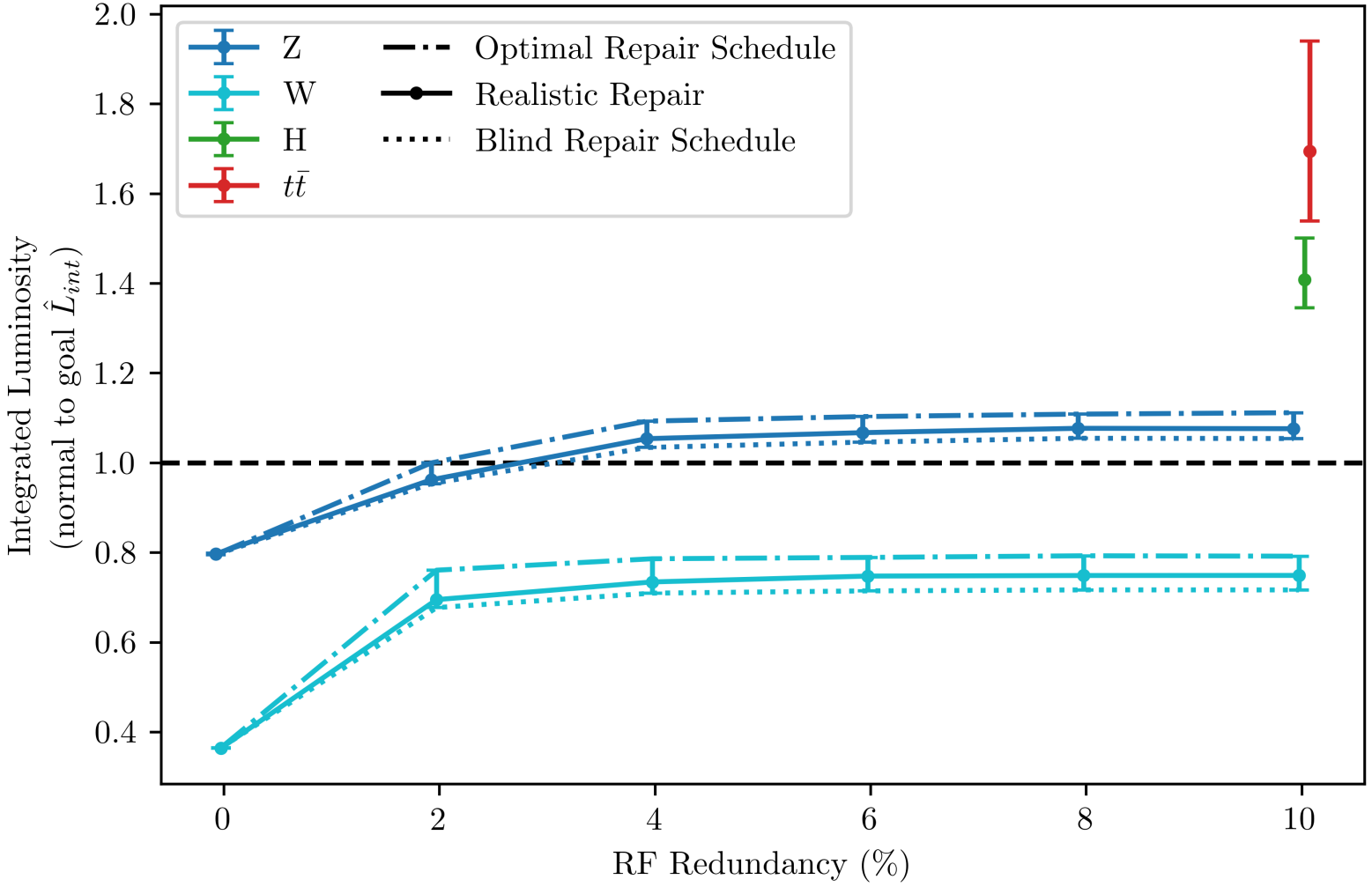
Repair

Humans in tunnel

Availability



Integrated Luminosity

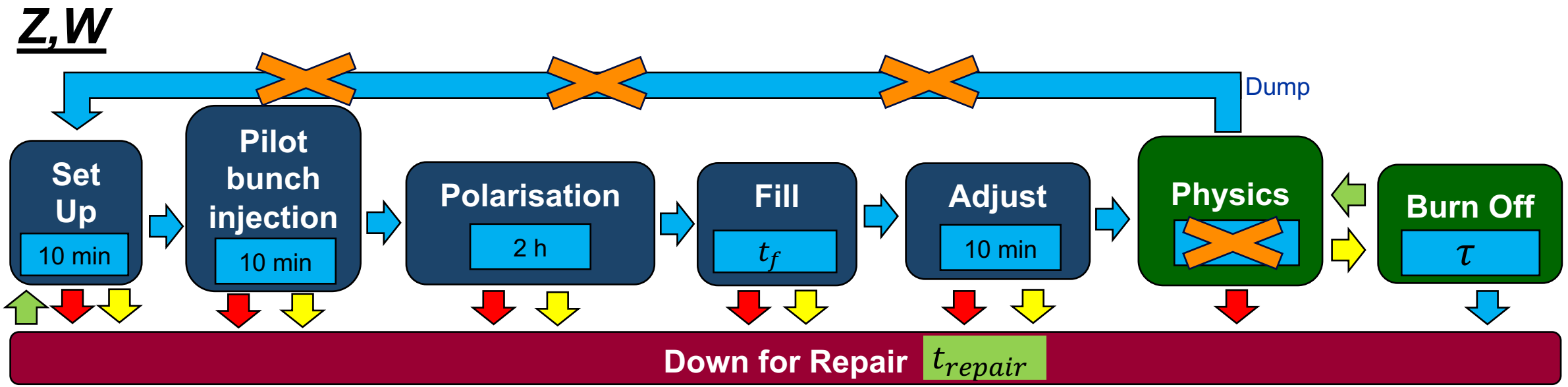


	Z	W	H	$t\bar{t}$
Integrated Luminosity goal $\hat{L}_{int}$ (ab^{-1})	150	10	5	1.5

Two R&D Opportunities

(1) Indefinite physics

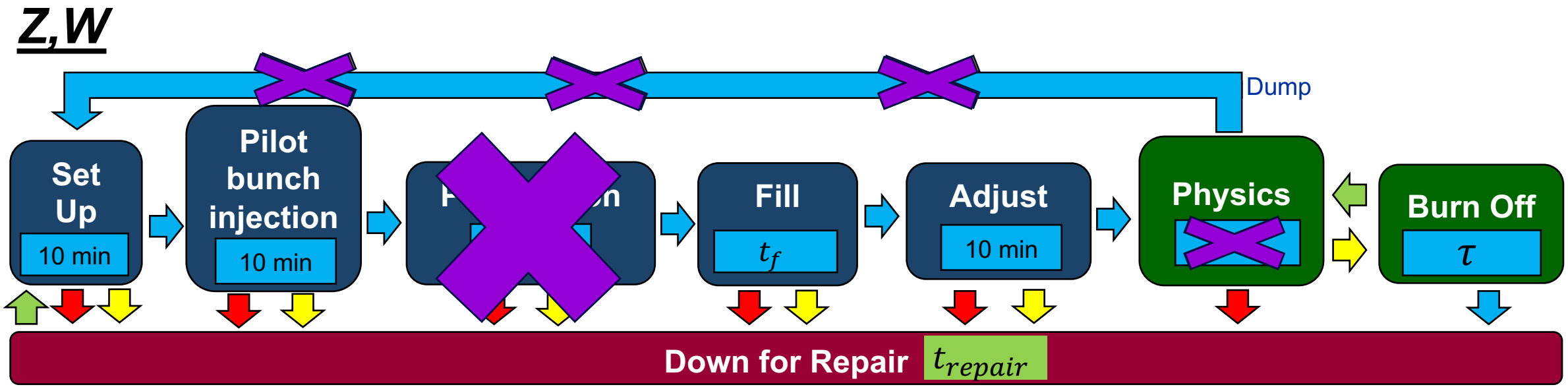
Pilot bunch lifetime > natural polarization time



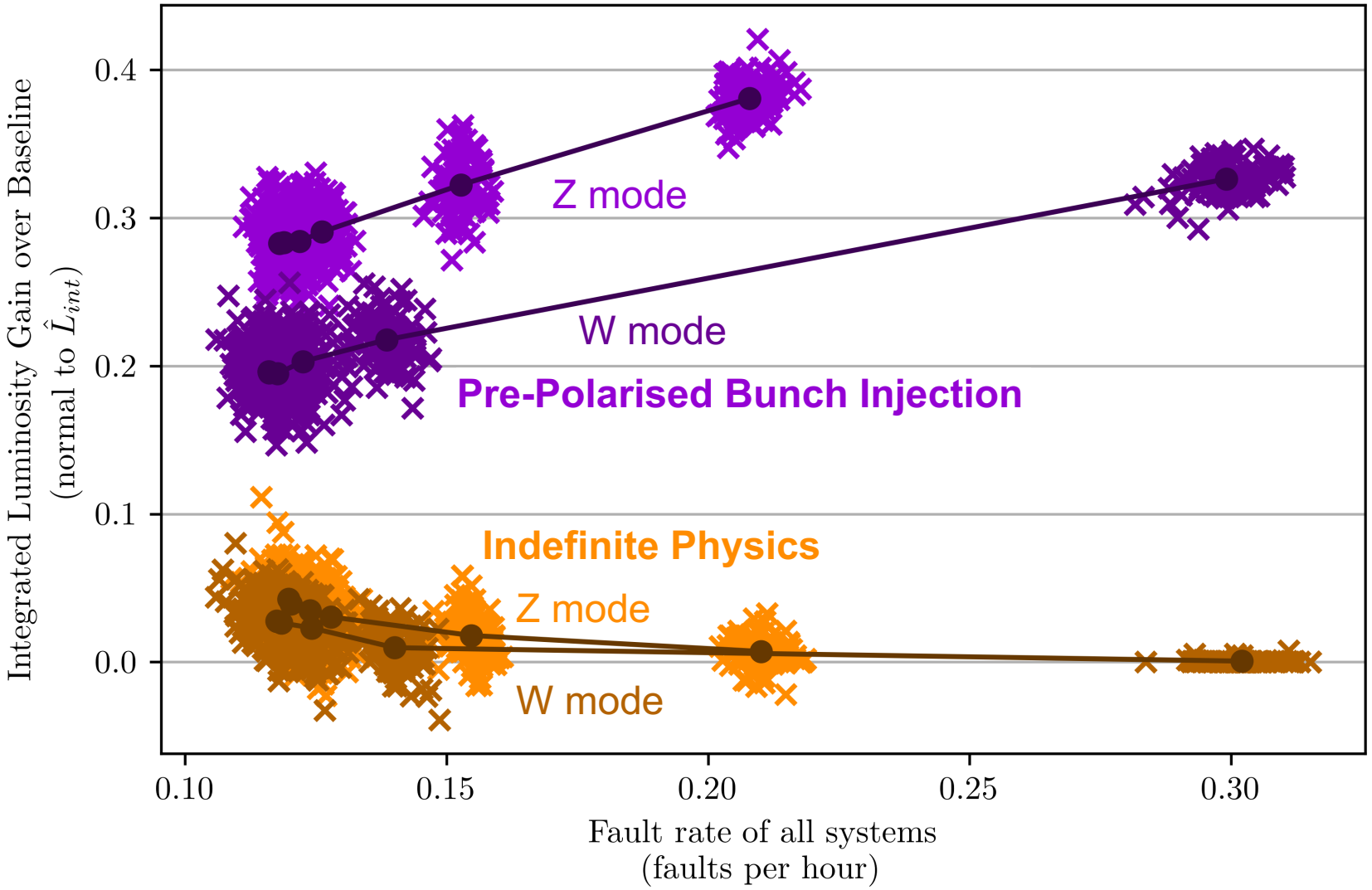
Two R&D Opportunities

(2) Pre-Polarised Bunch Injections (PPBI)

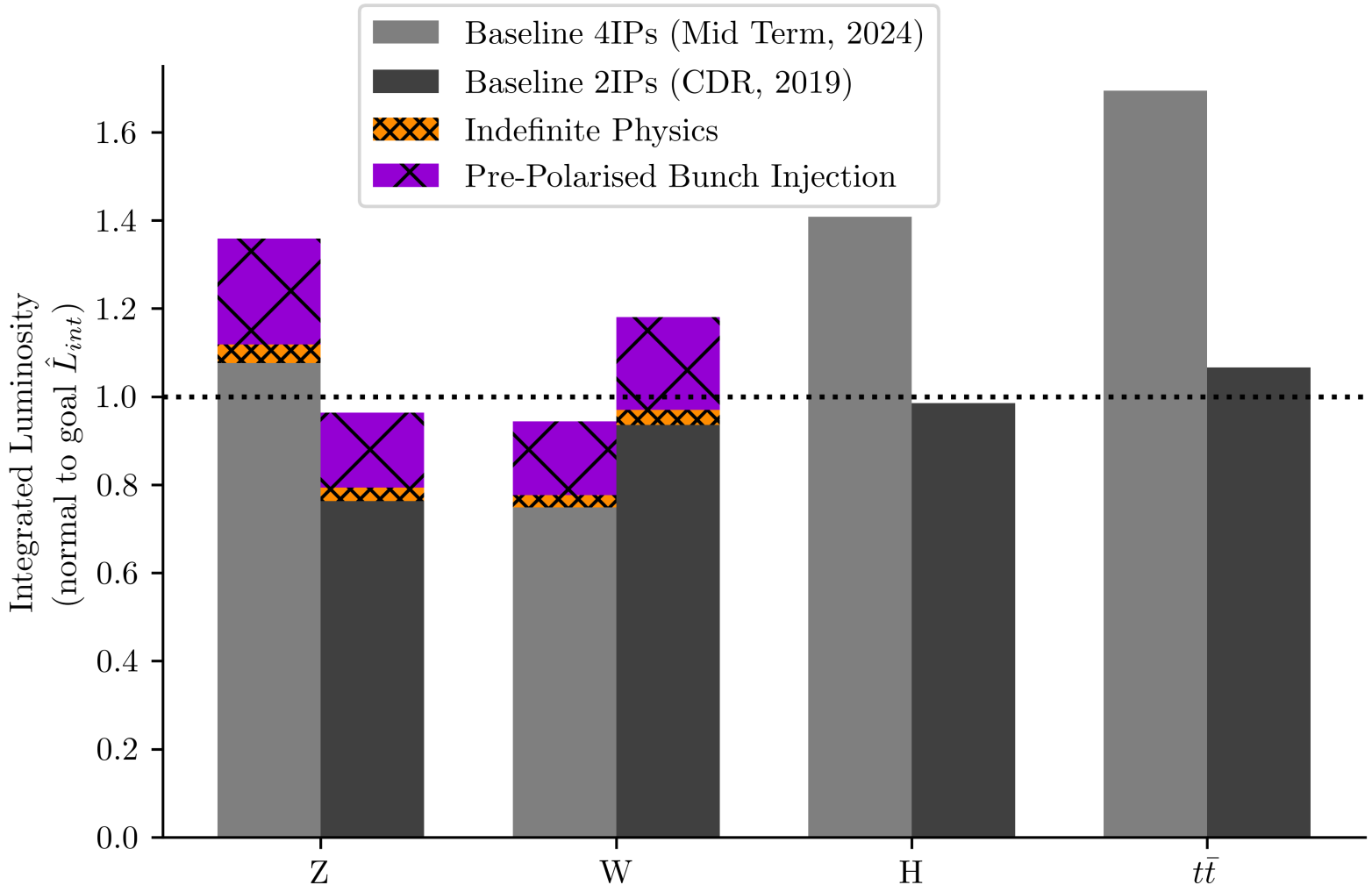
Inject already-polarized bunches



Gain over the baseline configuration



Four and two IPs

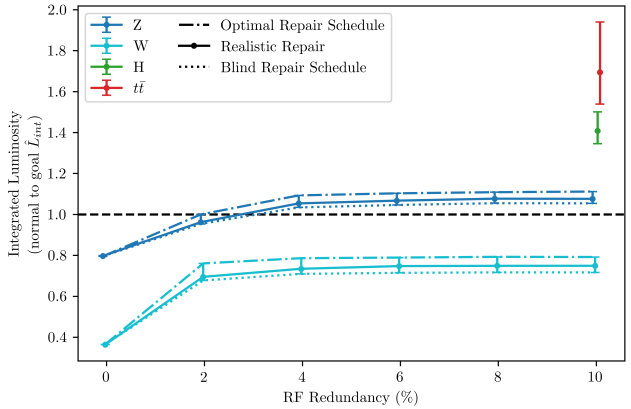


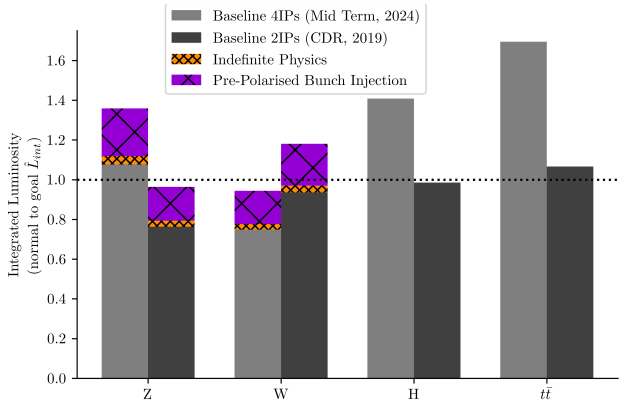
- “Realistic” repair schedule
- 10% RF redundancy

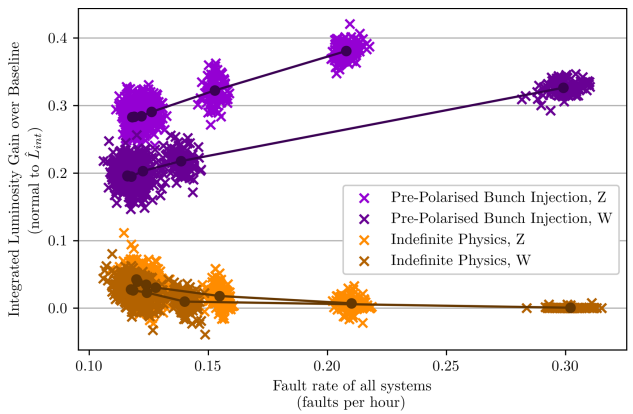
Conclusions

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

- **Simulation to formalize relationship between availability and integrated luminosity**
- **RF system**
  - Z mode minimum redundancy at 4%
- **Significant shortfall in integrated luminosity for W mode.**
  - Expected to get even worse as more systems are modelled in detail
- **Pre-Polarised Bunch Injection may be extremely valuable to boost luminosity:**
  - 15-40 % gain over the baseline configuration
  - Positive effect becomes even more relevant for increasing fault rate.
- **Outlook**
  - Continuation of bespoke modelling of systems (like for the RF)
  - Identify shortfalls and assess impact of solutions on accelerator performance
- **<u>The best time to model availability is now</u>**







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