

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

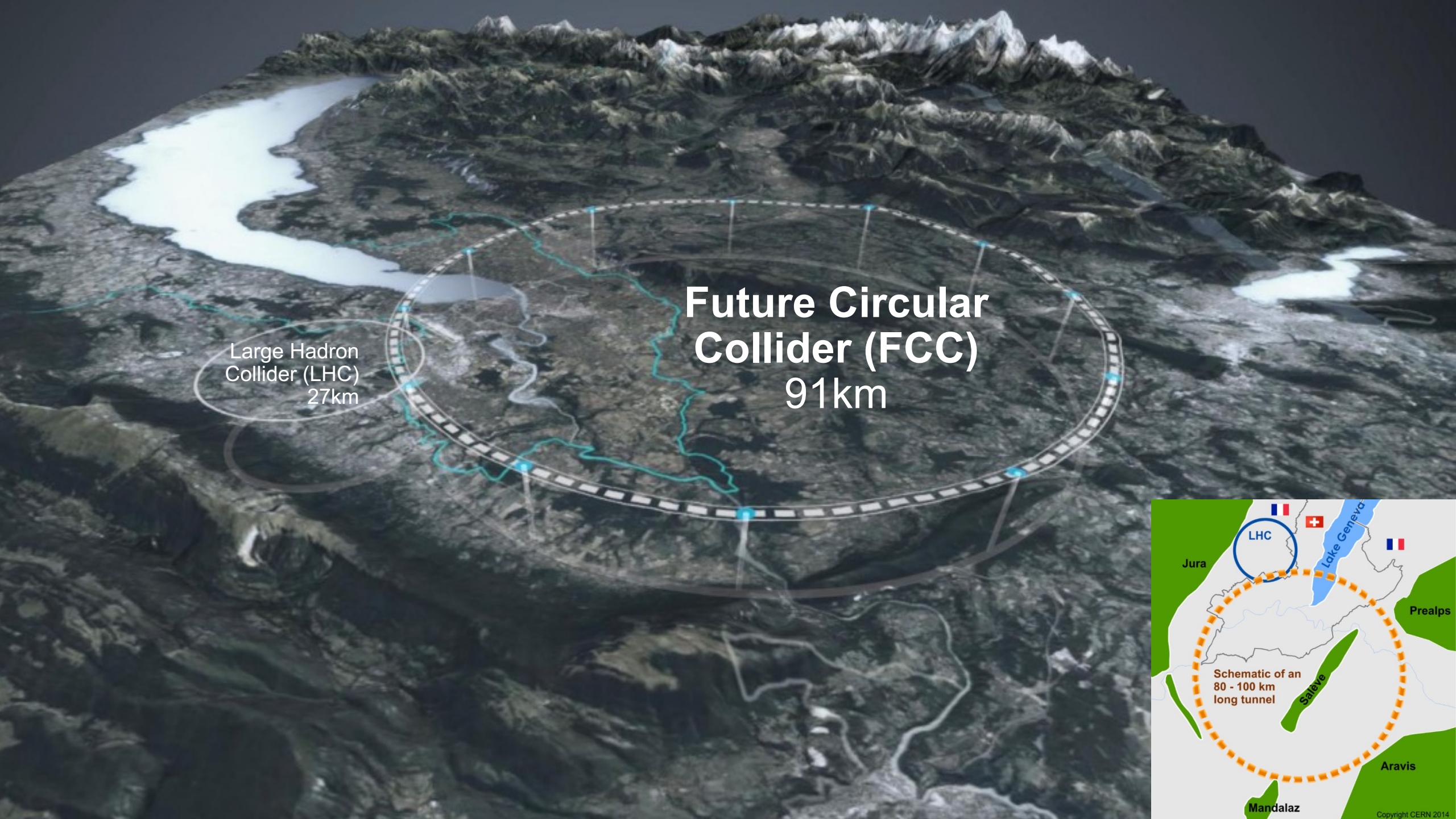
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22nd May 2024

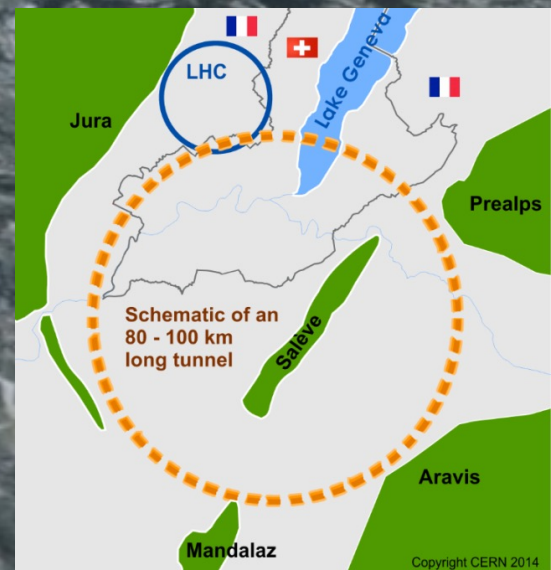


<https://fcc.web.cern.ch/>



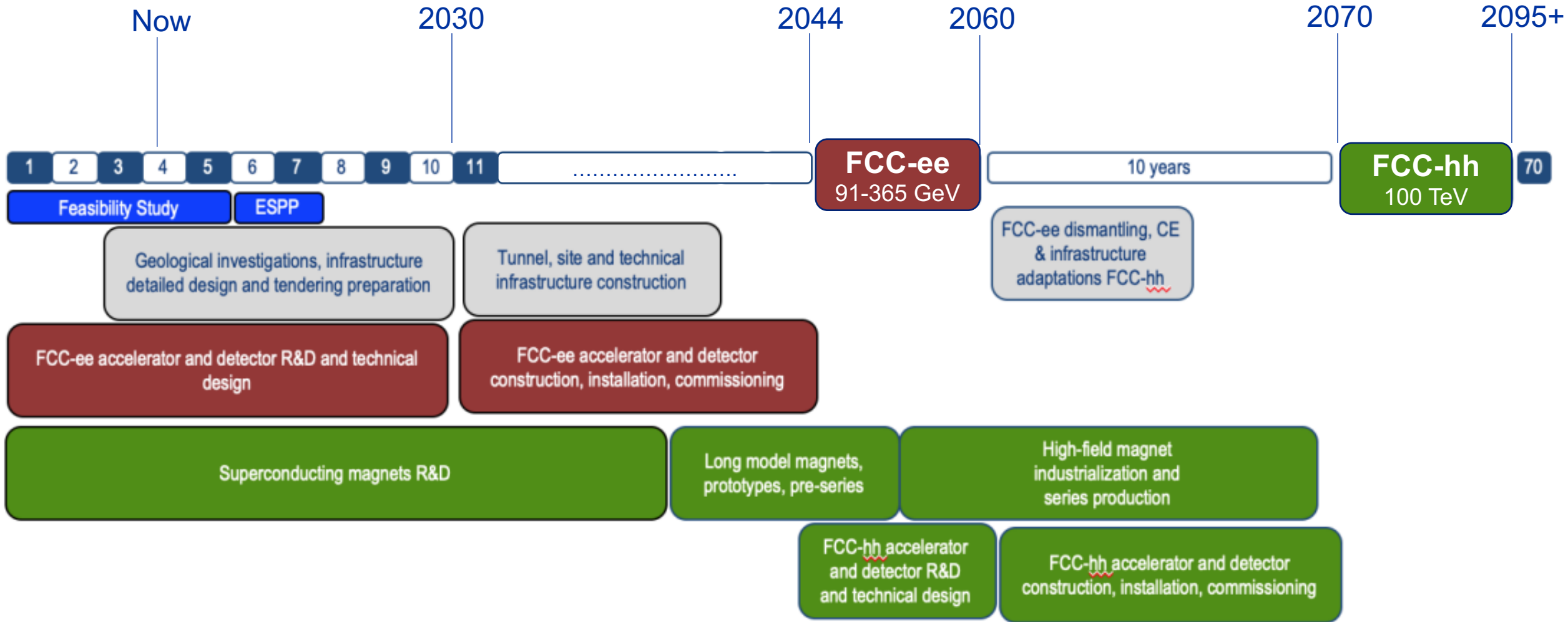
Large Hadron Collider (LHC)
27km

Future Circular Collider (FCC)
91km

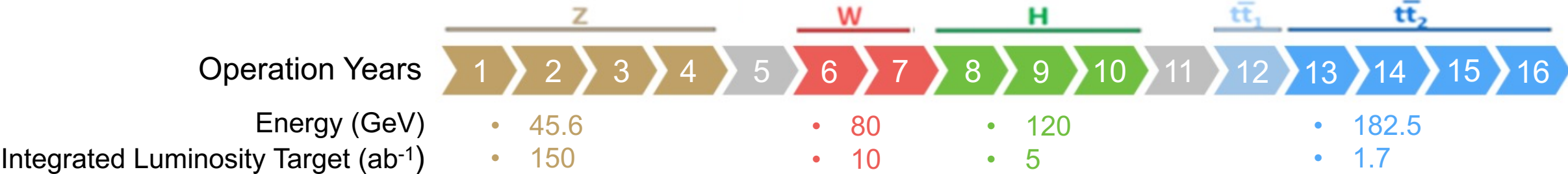


Schematic of an
80 - 100 km
long tunnel

FCC Timeline



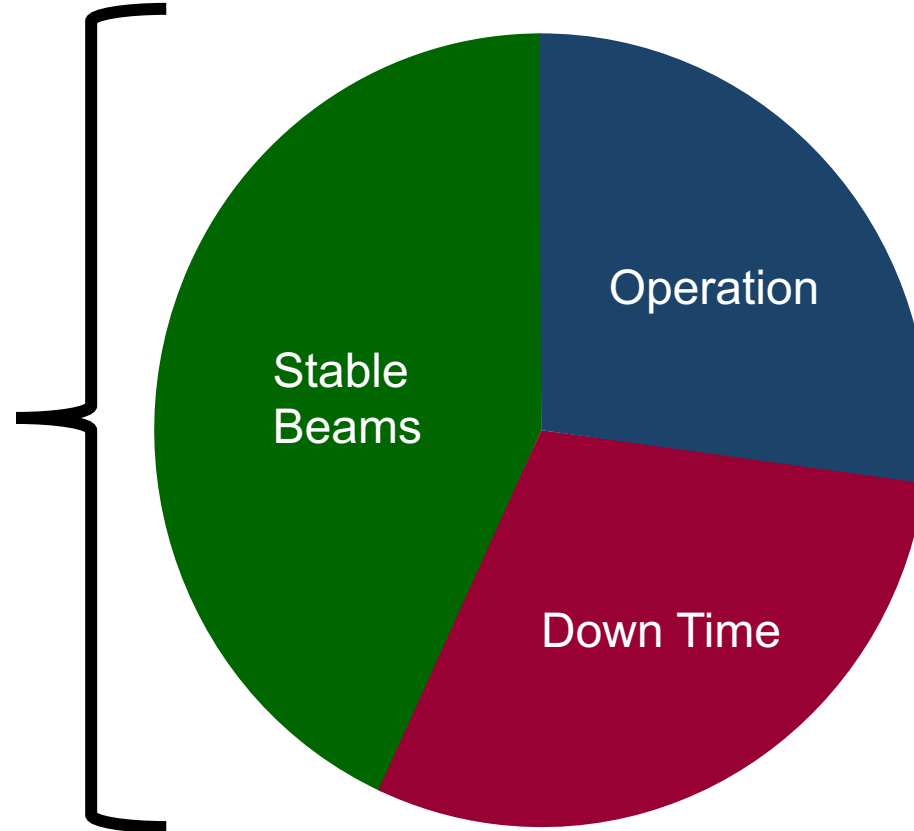
FCC-ee (electron-positrons)



Availability and Luminosity

FCC-ee:

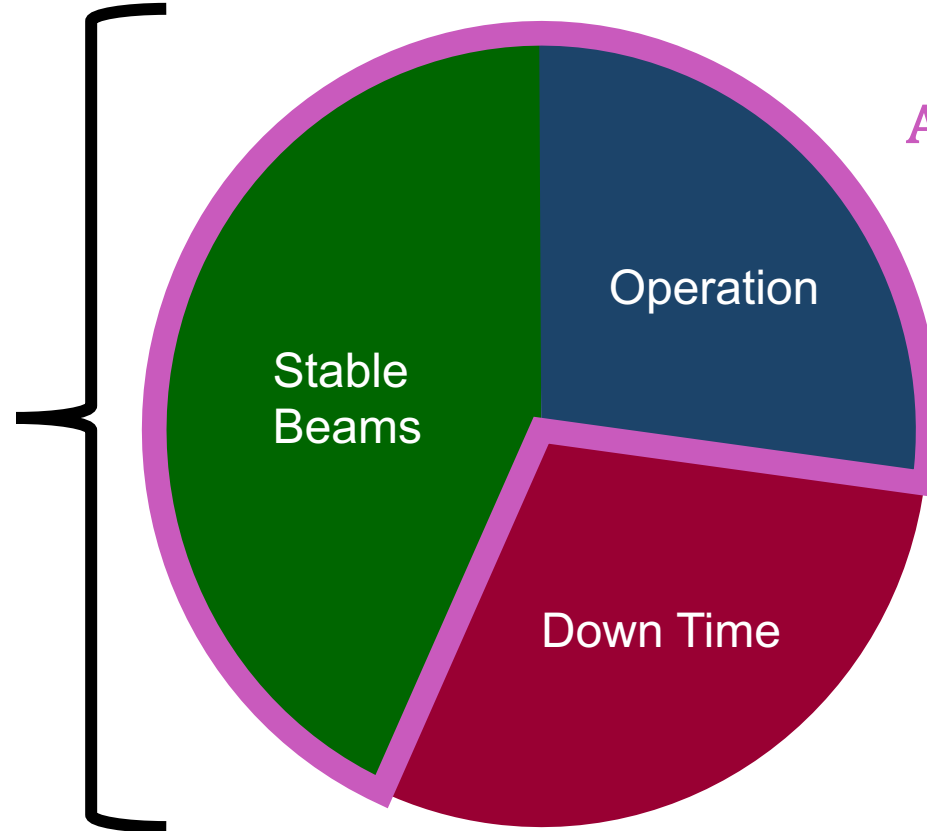
- 365 days
- 120 (extended shutdowns)
- 30 (annual commissioning)
- 20 (machine development)
- 10 (technical stops)
- 185 days for physics**



Availability and Luminosity

FCC-ee:

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



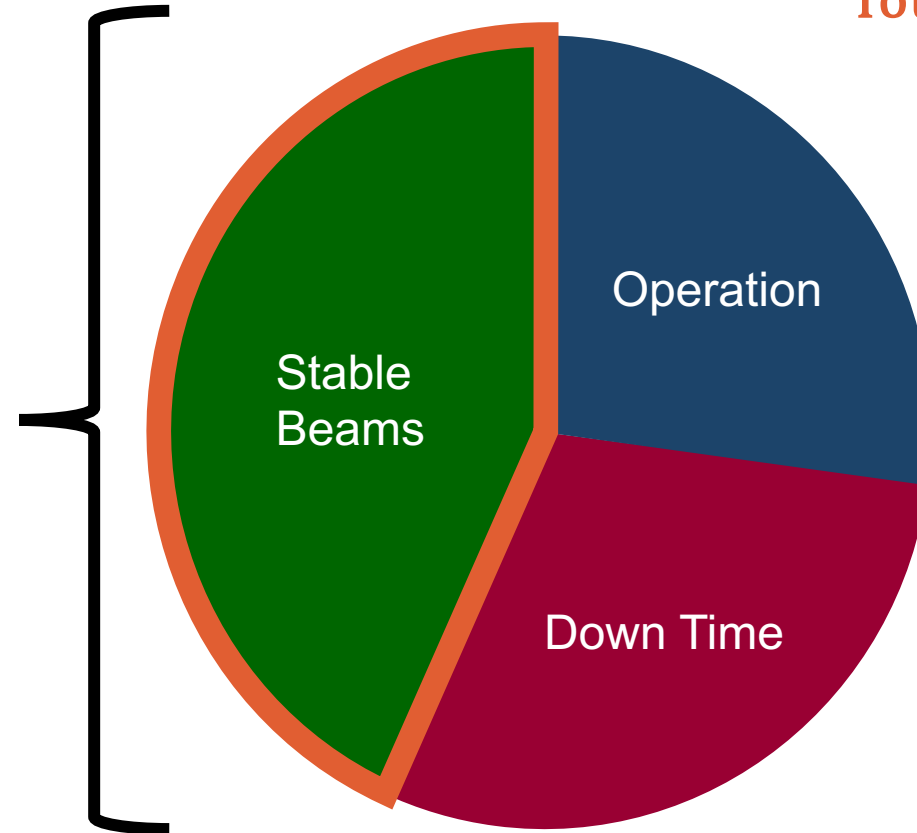
$$\text{Availability } A = \frac{\text{Up time}}{\text{Total physics time}}$$

Availability and Luminosity

FCC-ee:

- 365 days
- 120 (extended shutdowns)
- 30 (annual commissioning)
- 20 (machine development)
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185 days for physics



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

Availability and Luminosity

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

Total physics time $T = 185$ days

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

Nominal Luminosity L

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

Availability and Luminosity

To reach targets

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

Total physics time $T = 185$ days

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

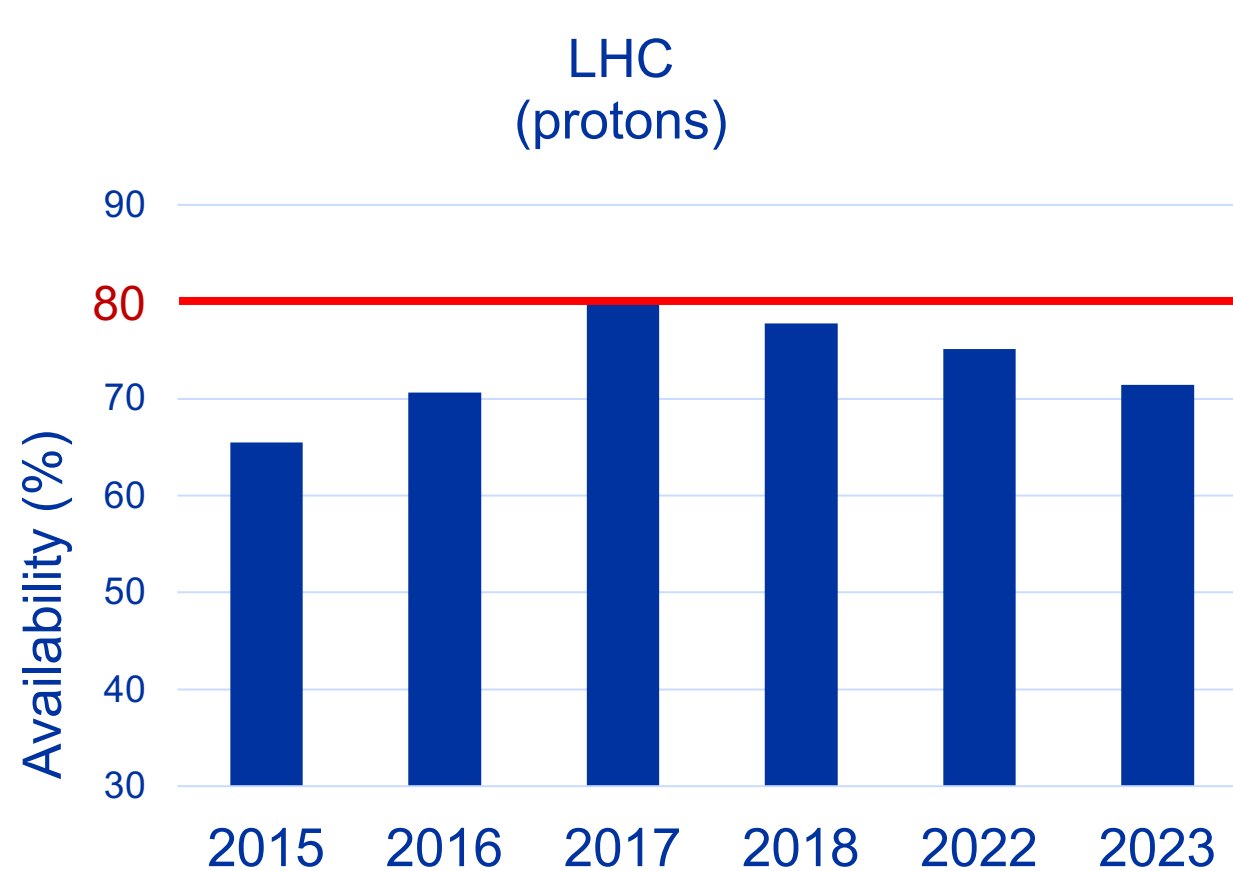
Nominal Luminosity L

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

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

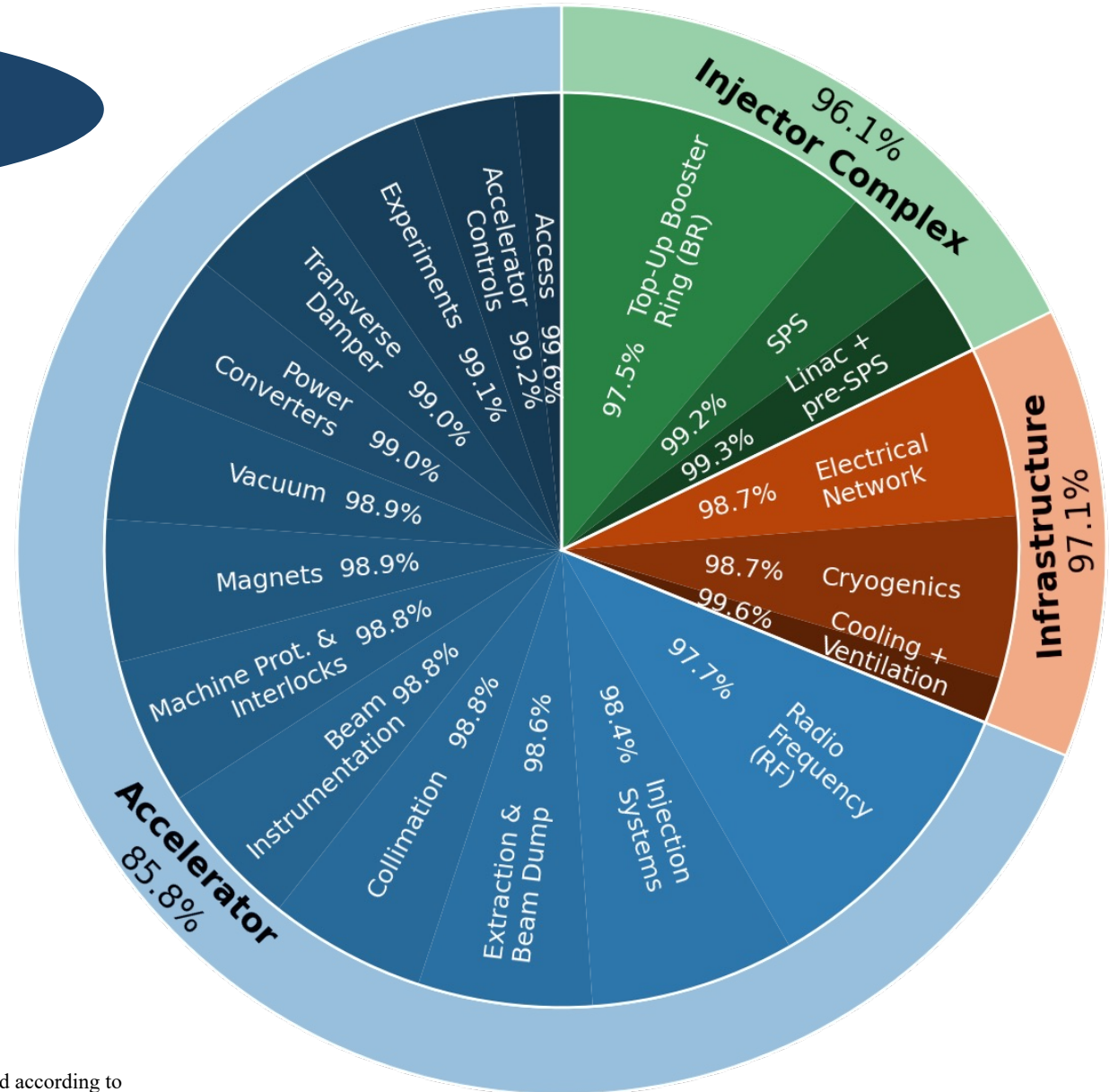
Where do we fall short?

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/>



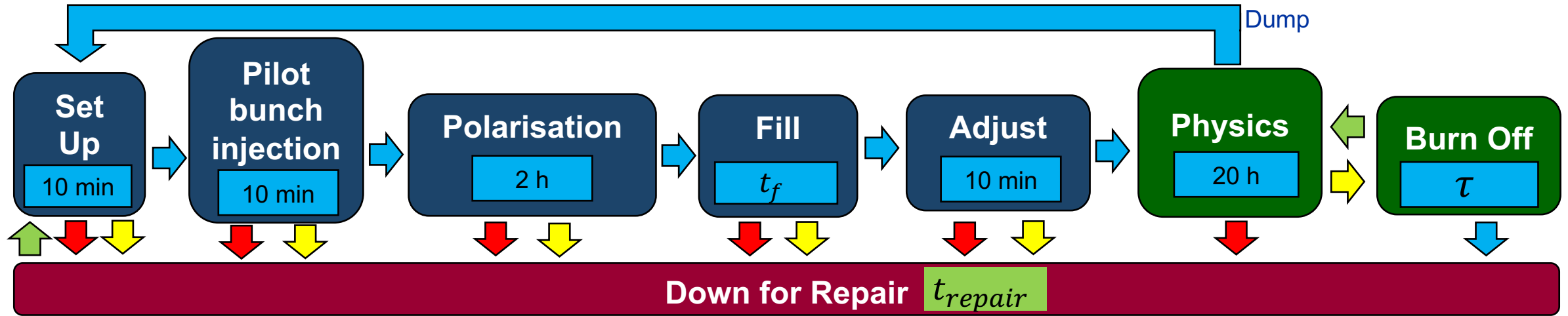
More info

M. Blaszkievicz *et al.*, “Availsim4 – an open-source framework for availability and reliability simulations,” in *Advances in Reliability, Safety and Security. ESREL Contributions*, 2024.

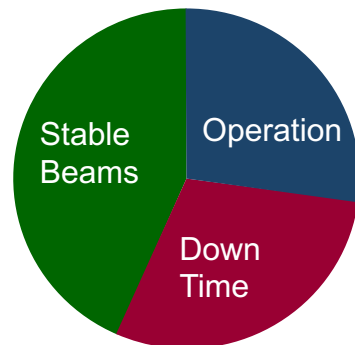
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FCC-ee Operation Cycle

Z,W



- Default
- Repair completed
- Main ring failure
- Injector Complex failure

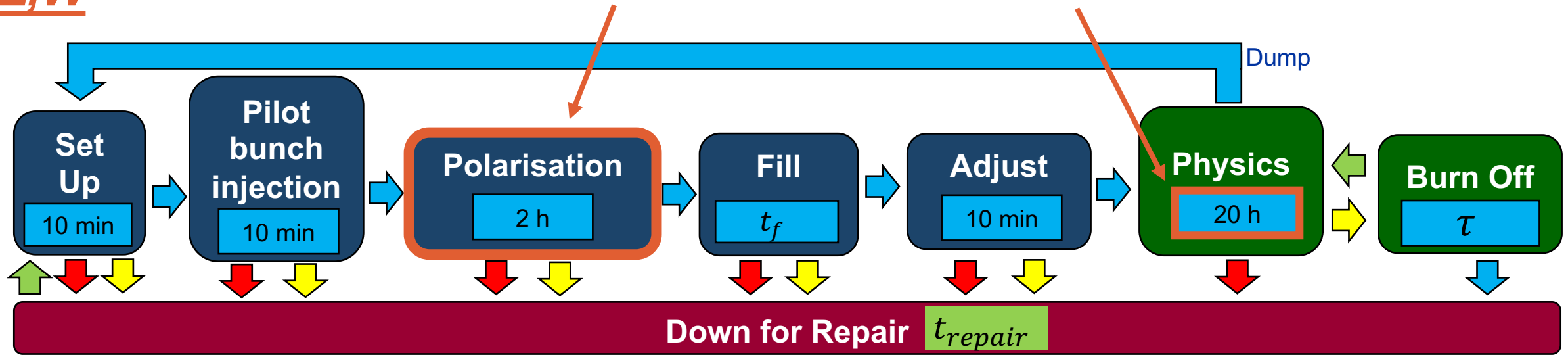


| | Z | W |
|-----------------------|-----|-----|
| Fill time t_f (min) | 7.7 | 2.5 |
| Lifetime τ (min) | 15 | 12 |

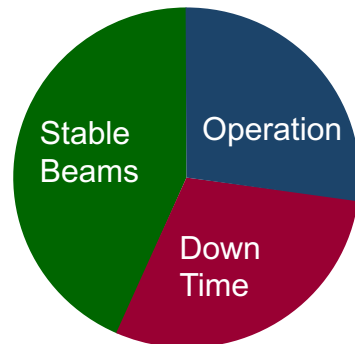
FCC-ee Operation Cycle

Z,W

Energy calibration by resonant depolarisation



- ➡ Default
- ➡ Repair completed
- ➡ Main ring failure
- ➡ Injector Complex failure

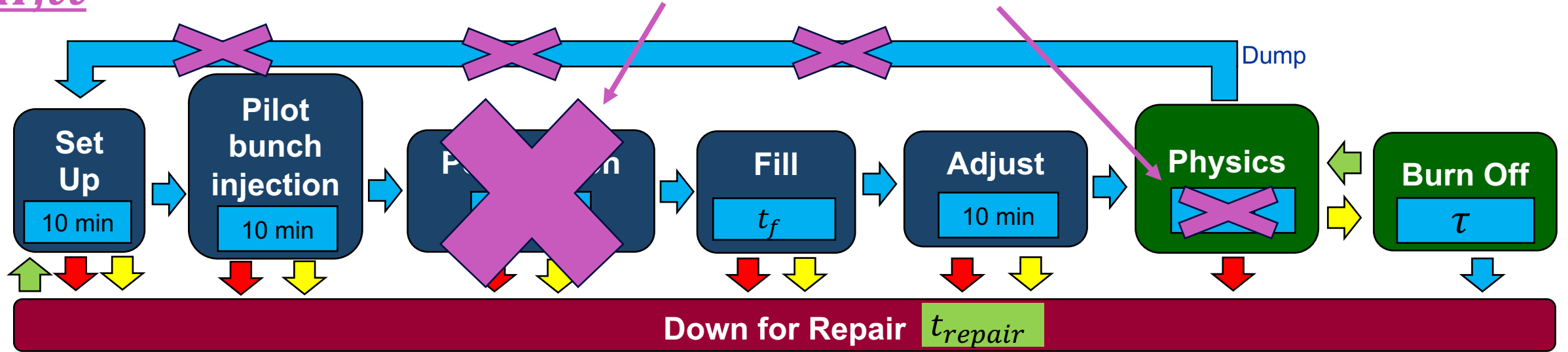


| | Z | W |
|-----------------------|-----|-----|
| Fill time t_f (min) | 7.7 | 2.5 |
| Lifetime τ (min) | 15 | 12 |

FCC-ee Operation Cycle

$H, t\bar{t}$

Resonant depolarization is impossible



- Default
- Repair completed
- Main ring failure
- Injector Complex failure



| | 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

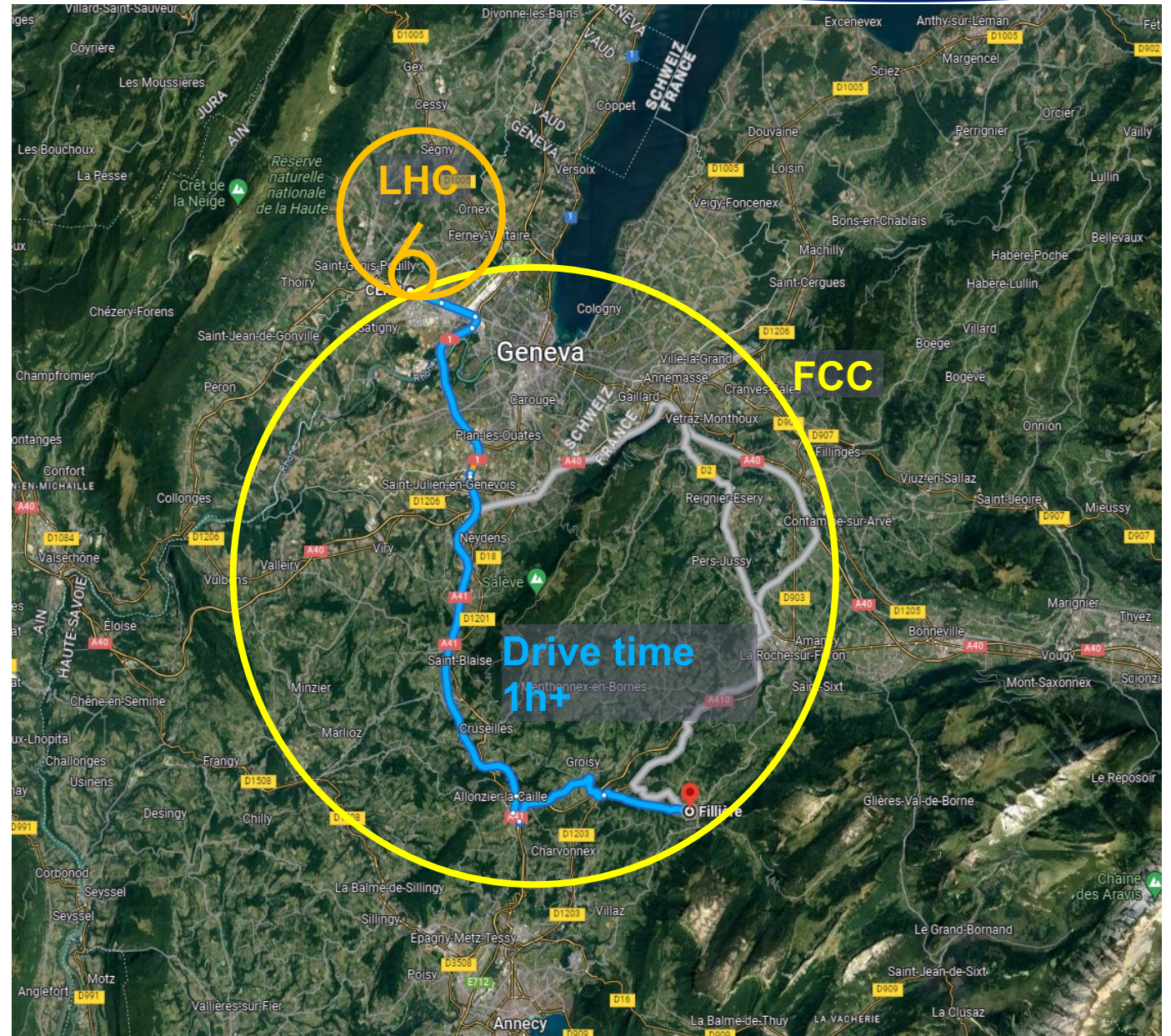
Human Repair Faults



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

Approach Time

20 min – 1h+



Inputs Required for each System

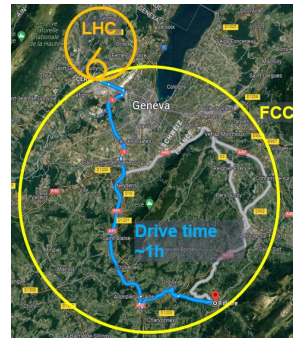
- **Probability distributions:**

- Fault rate (MTBF)
- Repair time (MTTR)

For remote and human repair faults

- **Approach time**

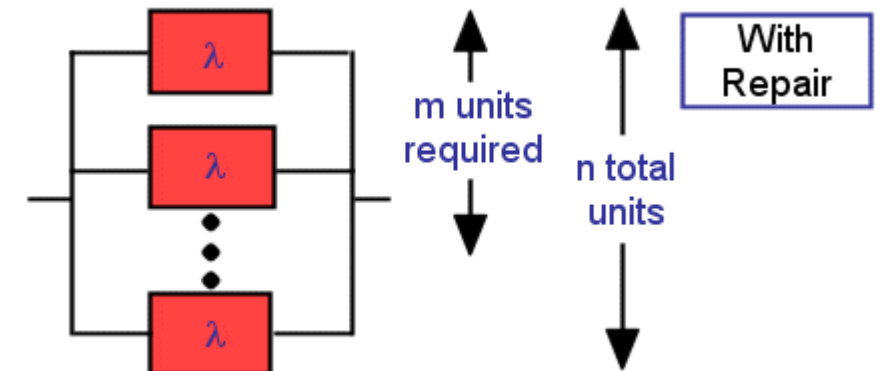
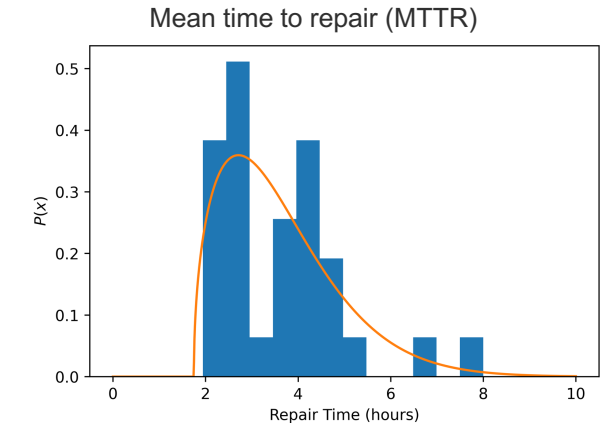
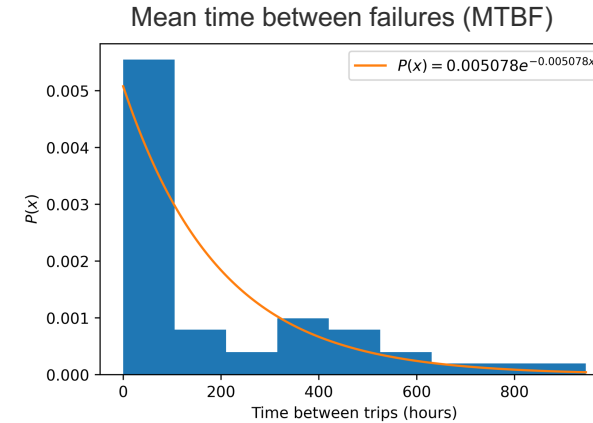
- Based on location around the ring



- **Redundancy:**

- “Can continue without 1 in 10 of these components”

Only completed for RF system so far!



https://reliabilityanalyticstoolkit.appspot.com/active_redundancy_with_repair

RF System

| Energy Mode | Z | | W | | H | | $t\bar{t}$ | |
|---------------------|----------|---------|--------|---------|-------------------|---------|-------------------|---------|
| | 45.6 GeV | | 80 GeV | | 120 GeV | | 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 |

Z, W

- High current, beam loading
- 136-320 cavities

Originally:

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

Latest analysis:

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

Table 1: RF configurations in FCC-ee [50]

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

$H, t\bar{t}$

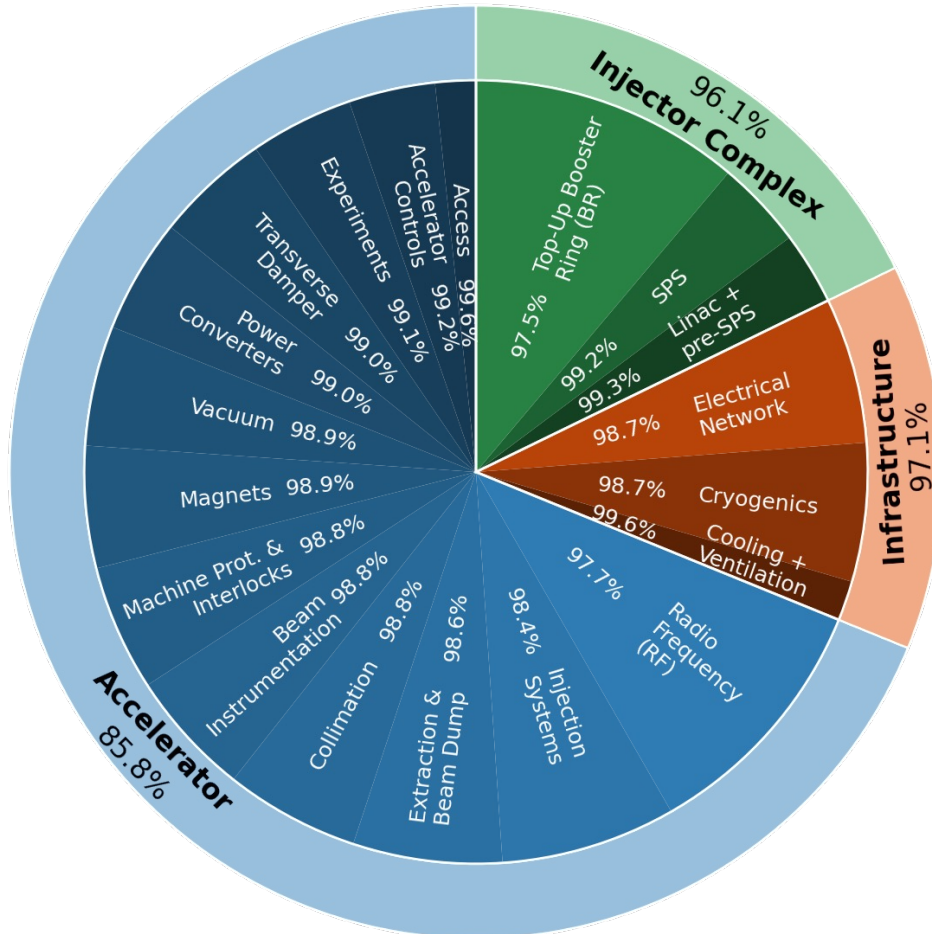
- Low current, high voltage
- 376-1352 cavities
- **10% voltage redundancy**

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!

Human repairs (or robots?)

Approach time



Humans in tunnel



Blind Repair
"We're not finished here!"

Repairs will finish once started

<https://www.iStockphoto.com/vector/isometric-control-center-44164401684-15526568>
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



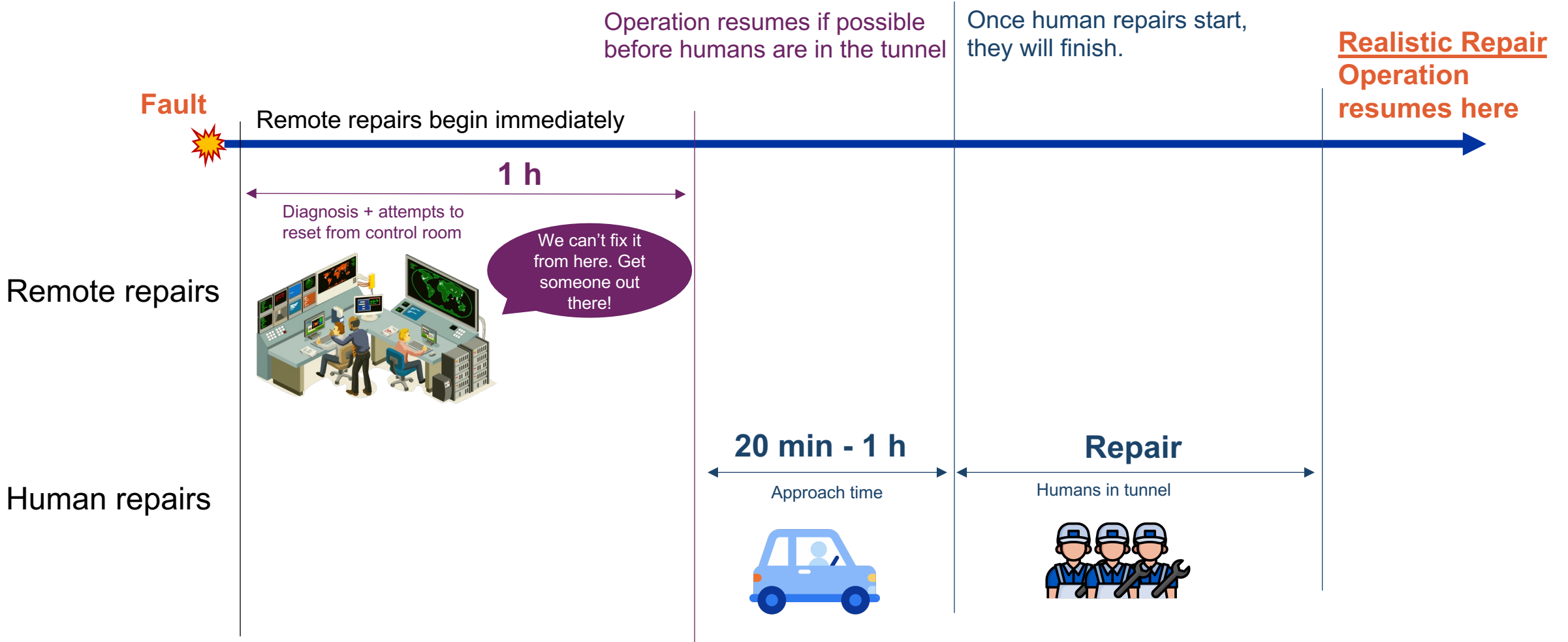
Humans in tunnel



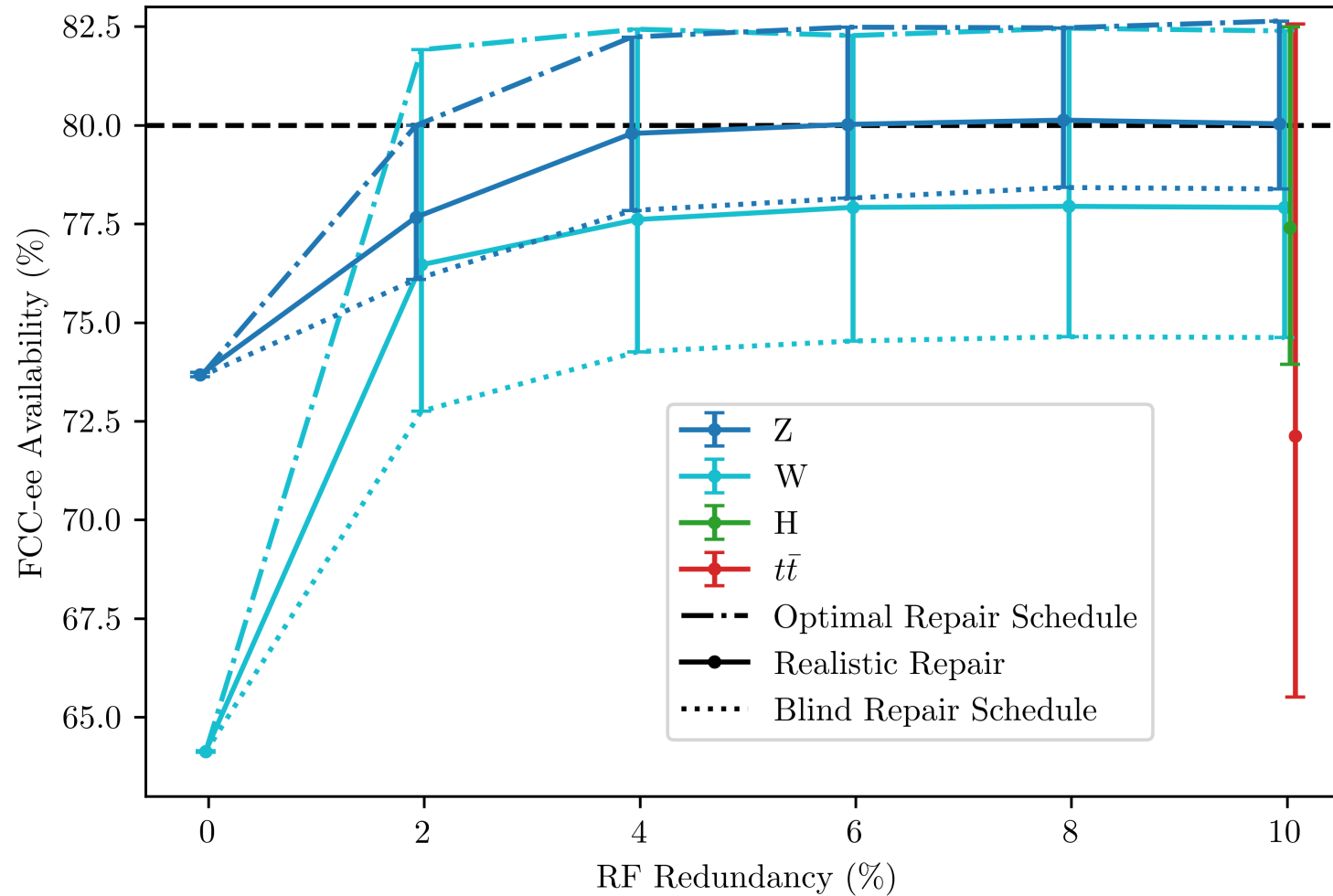
Optimal Repair
"Dropping tools and getting out!"

<https://www.iStockphoto.com/vector/isometric-control-center-64401684-15526568>
https://www.flaticon.com/free-icon/technician_6342684
https://www.flaticon.com/free-icon/driving_7481812

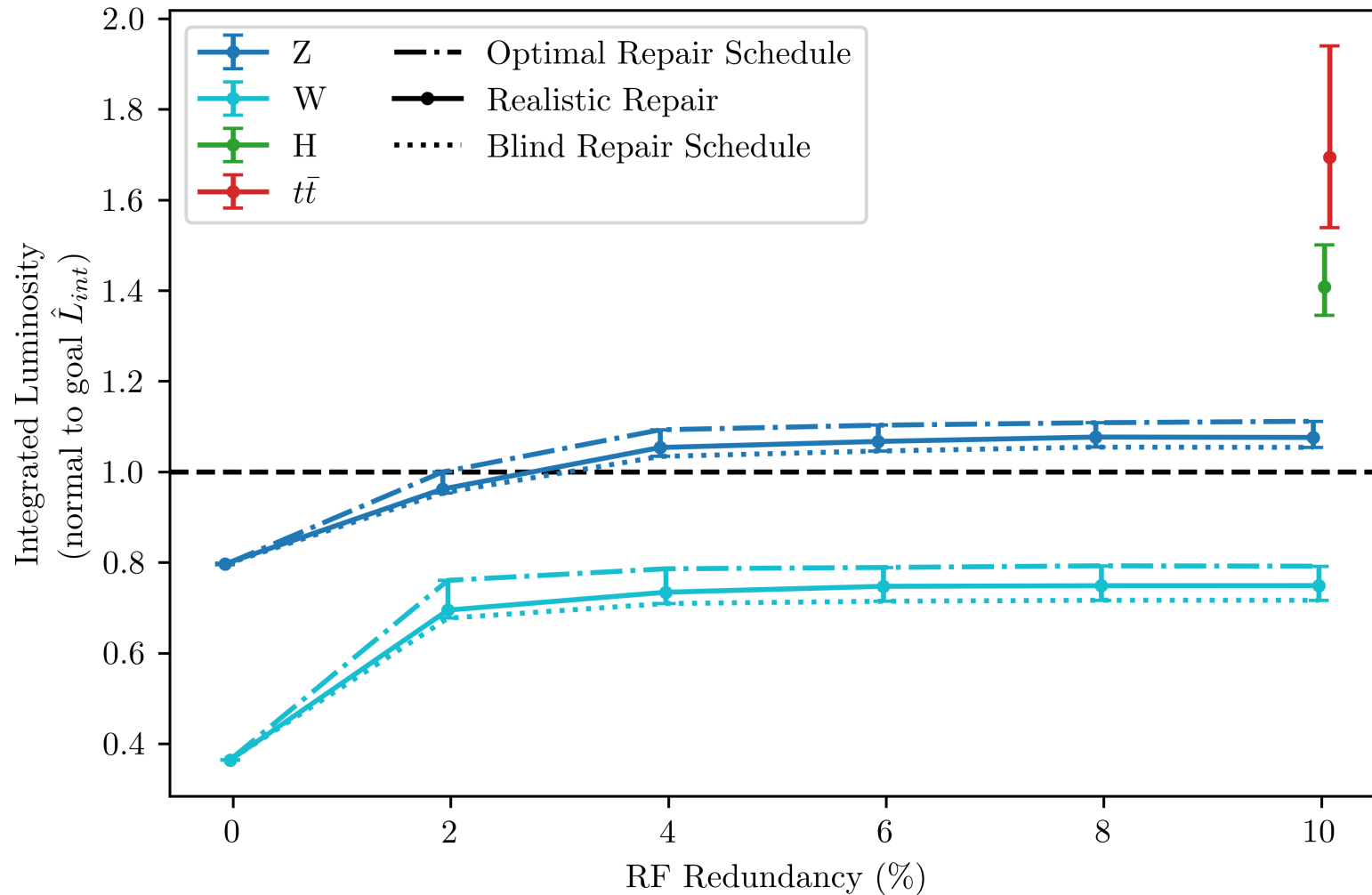
“Realistic” Repair Timeline:



Availability



Integrated Luminosity

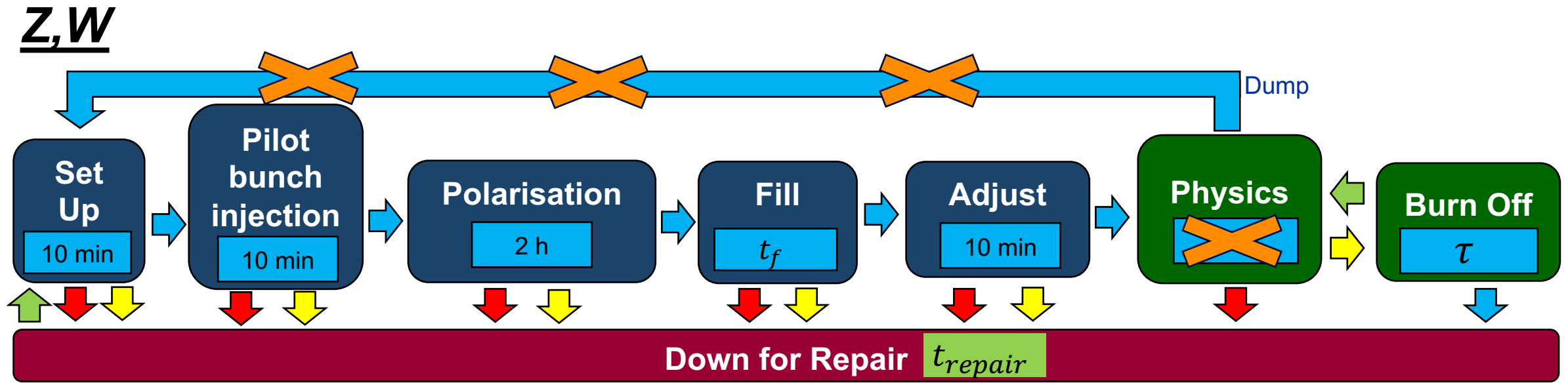


| | <i>Z</i> | <i>W</i> | <i>H</i> | <i>t\bar{t}</i> |
|--|----------|----------|----------|------------------------------|
| Integrated Luminosity goal \hat{L}_{int} (ab^{-1}) | 150 | 10 | 5 | 1.5 |

Two R&D Opportunities

(1) Indefinite physics

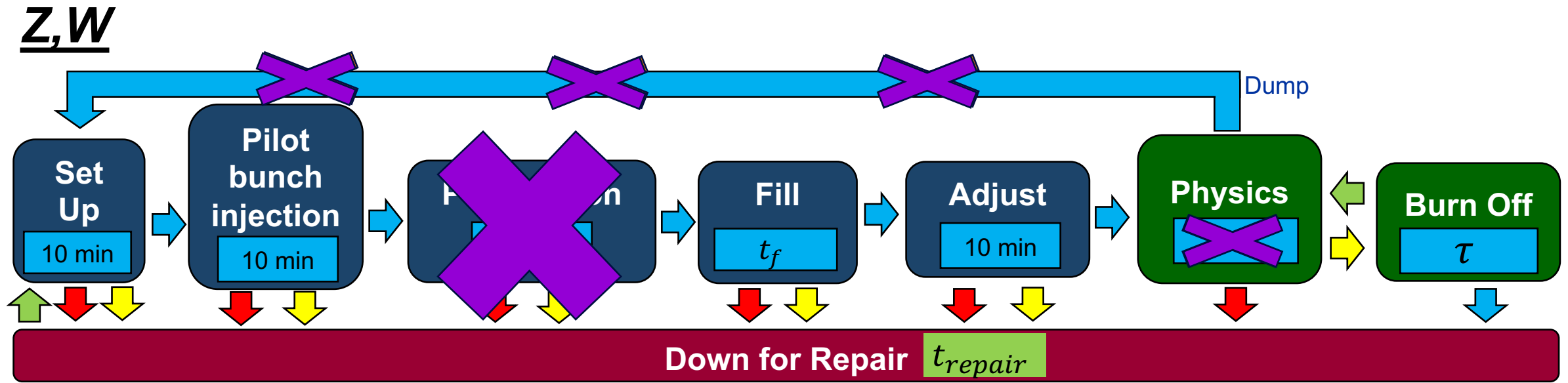
Pilot bunch lifetime > natural polarization time



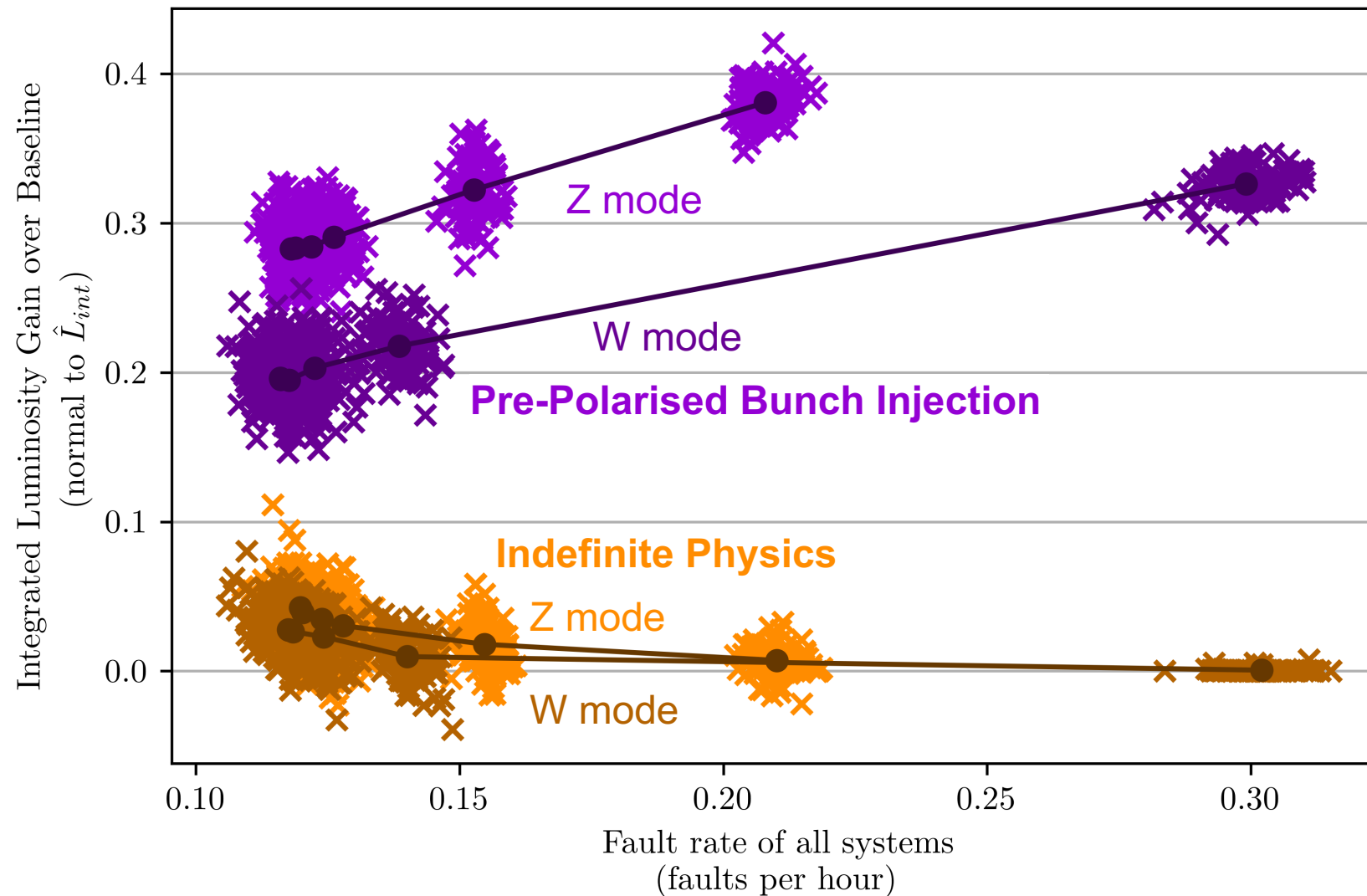
Two R&D Opportunities

(2) Pre-Polarised Bunch Injections (PPBI)

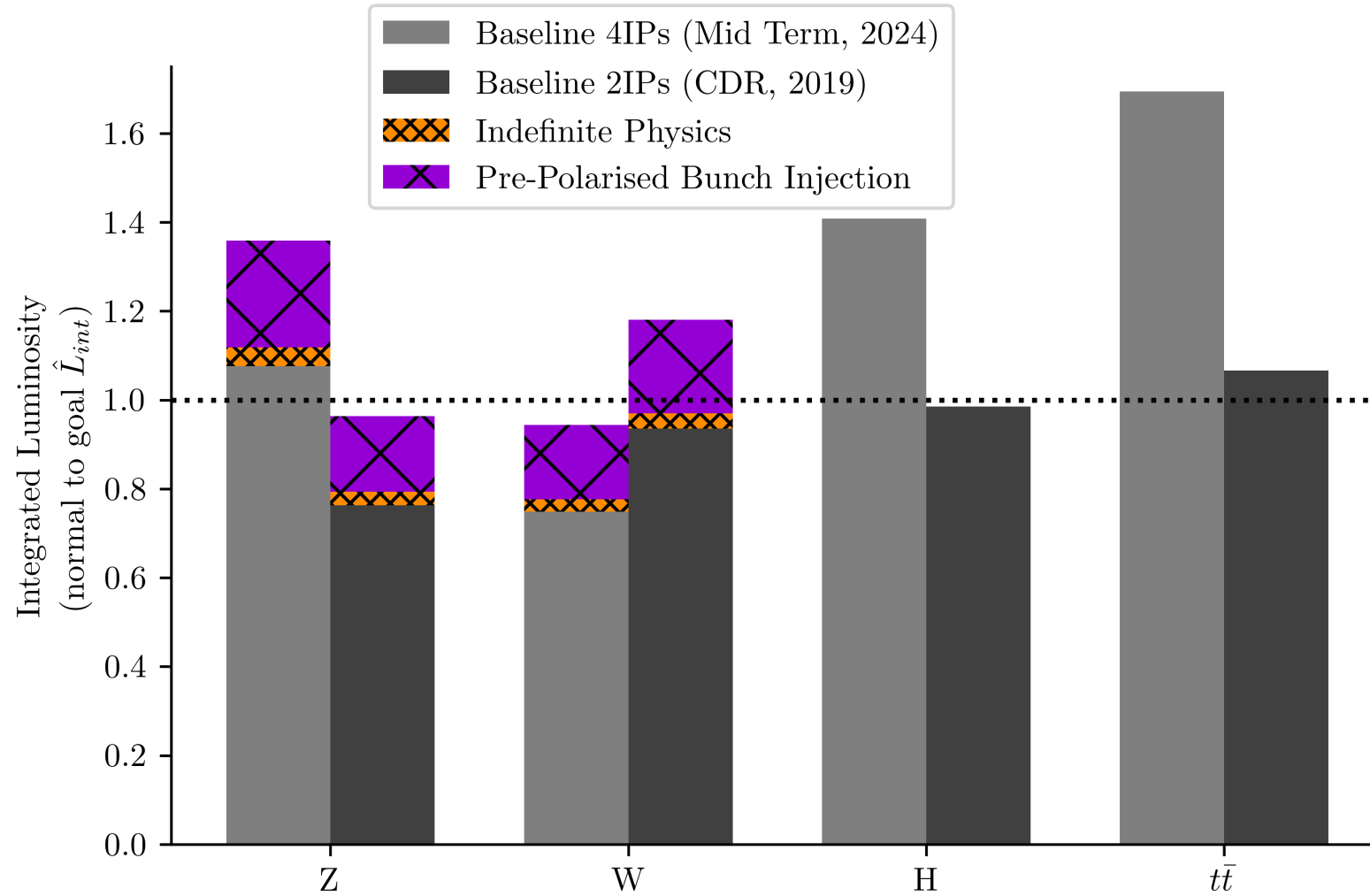
Inject already-polarized bunches



Gain over the baseline configuration



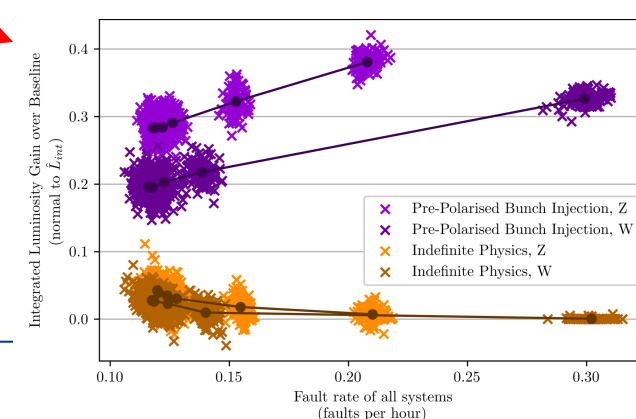
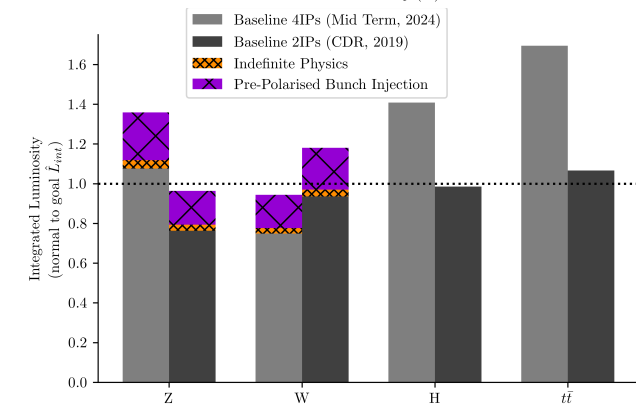
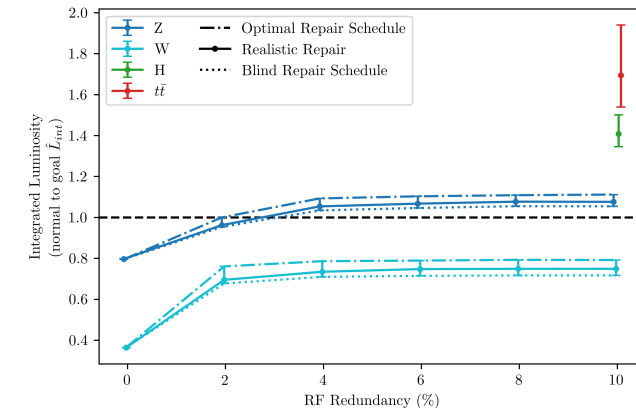
Four and two IPs



- “Realistic” repair schedule
- 10% RF redundancy

Conclusions

- **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
- **The best time to model availability is now**





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Instantaneous Luminosity

- **4IPs:** Mid Term Configuration, 2024
- **2IPs:** CDR Configuration, 2019

| | Number of IPs | Z | W | H | $t\bar{t}$ |
|---|------------------|-----|-----|-----|------------|
| Luminosity L per IP ($10^{34} \text{cm}^{-2} \text{s}^{-1}$) | 2 | 230 | 28 | 8.5 | 1.55 |
| | 4 | 141 | 20 | 5 | 1.25 |

Instantaneous Luminosity

