Availability, Operation & Energy
(some preliminary thoughts)

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Introduction

Machines and infrastructure conceptual designs

- Infrastructure
- Hadron collider conceptual design
- Hadron injectors
- Lepton collider conceptual design
- Safety, operation, energy management environmental aspects

How we will operate the machines has an impact on the design.

Learn from the experience of operating large facilities around the world:

There is a huge pool of expertise in the international community!

Scale it to the FCC case

Set up operational scenarios

Use them to identify key areas that impact on:

- **Infrastructure, layout and design**
- **Equipment design**
- **R&D requirements**

Not forgetting Energy consumption as a major challenge

Proposed FCC Work Breakdown Structure

Operation and energy efficiency	
Global operation scenarios	
	Global Operation Concepts
	Compatibility with CERN operation program
	Technical Infrastructure Operation
	Requirementts for Fixed target test beams
	Overall operation scenarios
	Overall energy consumption and efficiency
	Incident handling and repair concepts
	Maintenance concepts
Hadron complex operation	
	Power consumption
	Operation concept
	Operation efficiency and turnaround
	Energy management and saving
	Performance and availability assessment
	Reliability and Availability

Contributions from anyone interested is very welcome!

Aspects common to all Machines

And specific scenarios for each

Closely linked to the machine studies themselves

Lepton complex operation	
	Power consumption
	Operation concept
	Operation efficiency and turnaround
	Energy management and saving
	Performance and availability assessment
	Reliability and Availability
Hadron-Lepton complex operation	
	Power consumption
	Operation concepts for lepton-hadron LR collider
	Operation concepts for lepton-hadron RR collider
	Operation efficiency and turnaround
	Energy management and saving
	Performance and availability assessment
	Reliability and Availability

Some Preliminary Ideas for discussion on:

Availability :

- ➥ Maximizing the time the machine(s) are able to take beam
- ➥ Minimizing down time

Operation :

- ➥ How the machine(s) will operate – over the years
- ➥ An operational Cycle … how we will do Physics

Energy :

- ➥ What kind of electrical load is it likely to represent
- ➥ Identification of major energy consumers for optimization

Most of the talk will concentrate on the hadron machine (FCC-hh)
some additional comments concerning the specificities of FCC-ee
Discussion based on recent LHC experience

Efficiency

= time actually spent doing physics / the time scheduled to do physics

In a slow cycling machine it can never be 100% ….

LHC Design

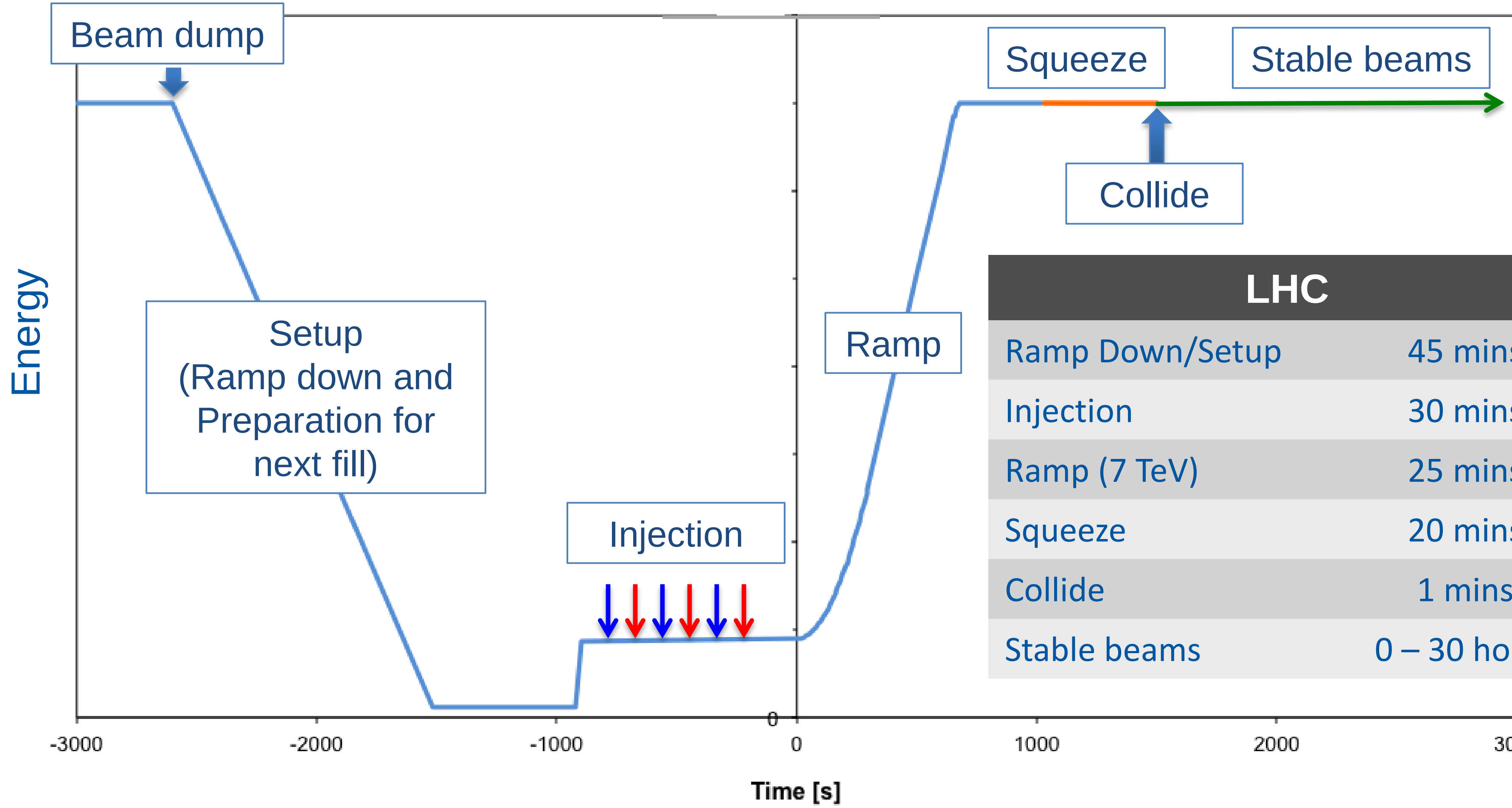
2 hours preparing for physics
10 hours physics fills

Theoretically 83%

LHC In practice is much lower

- The real time to prepare for physics is longer than the minimum possible
- The length of physics fills is shorter. Unforeseen dumps
- Special fills for commissioning/qualification
- Equipment faults or non-availability of beam

Operational Cycle



LHC	
Ramp Down/Setup	45 mins
Injection	30 mins
Ramp (7 TeV)	25 mins
Squeeze	20 mins
Collide	1 mins
Stable beams	0 – 30 hours

Should take this as a basis for FCC-hh as well and see the impact

FCC-hh Impact of Operational Cycle: 2h to fill, 10h fill length

Injection

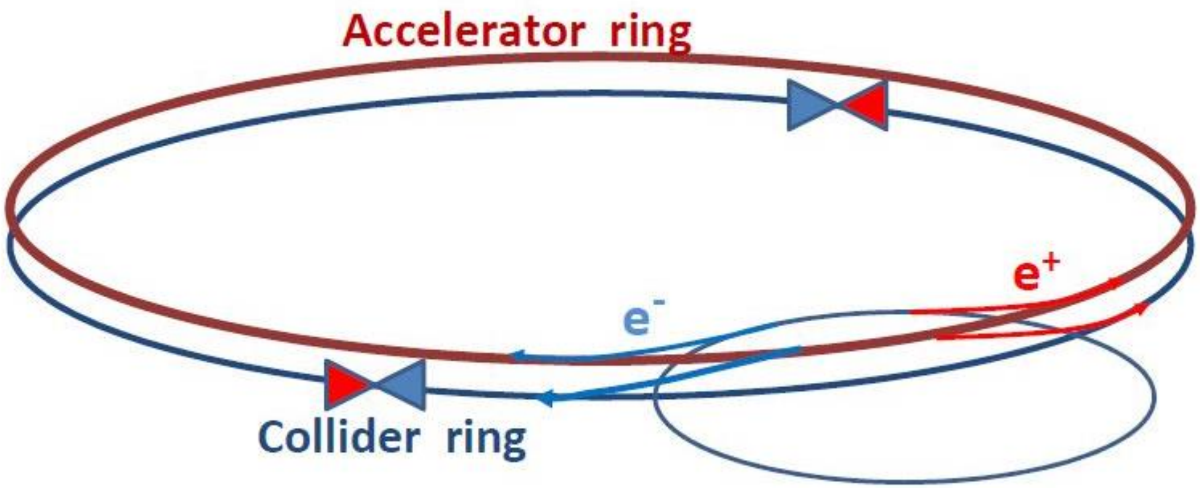
- LHC can be filled theoretically in 8 min.
- In practice with present injector cycles is takes 30 mins (minimum)
- But for FCC, 4 times the number of bunches and a new injector!
  - Transferring large beam energies between machines!!
- Filling FCC in 10-30 mins has a big impact on the injector design

Ramp

- FCC-hh will have a similar energy swing as LHC (~ x16)
- Maximum ramp rate in LHC 10 A/s
- Maintaining a similar ramp time in FCC-hh has big implications on:
  - Powering Sector length – giving total inductance in the main circuits
  - Magnet design if higher voltages are needed and for magnet inductance
  - Both of these have implications on stored energy in the magnets and powering protection systems
- Similar considerations for ramp down and squeeze

FCC-ee – Operational Cycle

The short beam lifetime in collision requires “top-up” operation



Collider ring runs in DC at the physics energy

The Accelerator ring cycles at ~0.1Hz

Theoretically the efficiency can be 100%

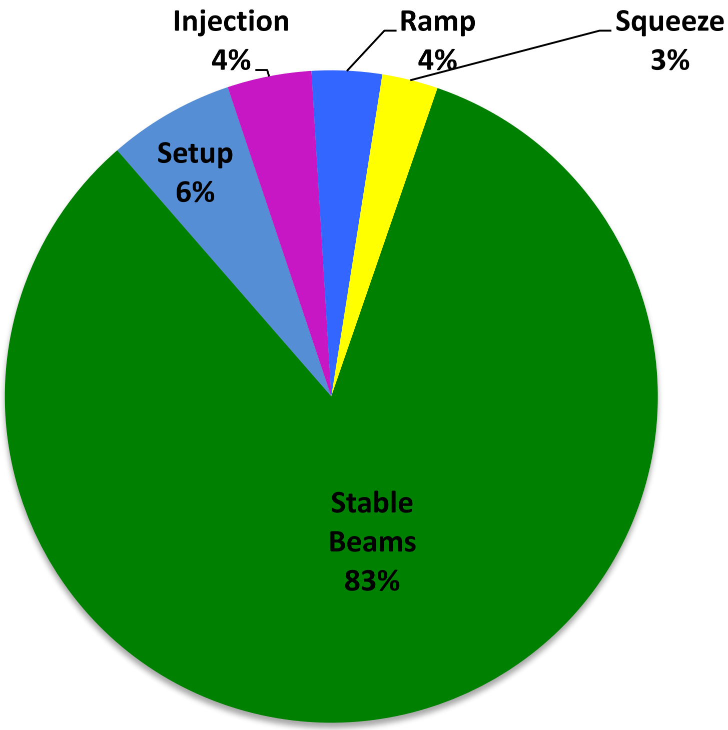
The last stage in the injector is included as part of the design.

However FCC-ee will be much more to exposed to faults in the Injector complex
- **LHC (FCC-hh) Can ride through some injector downtime by staying longer in physics.**

LHC Operational Efficiency

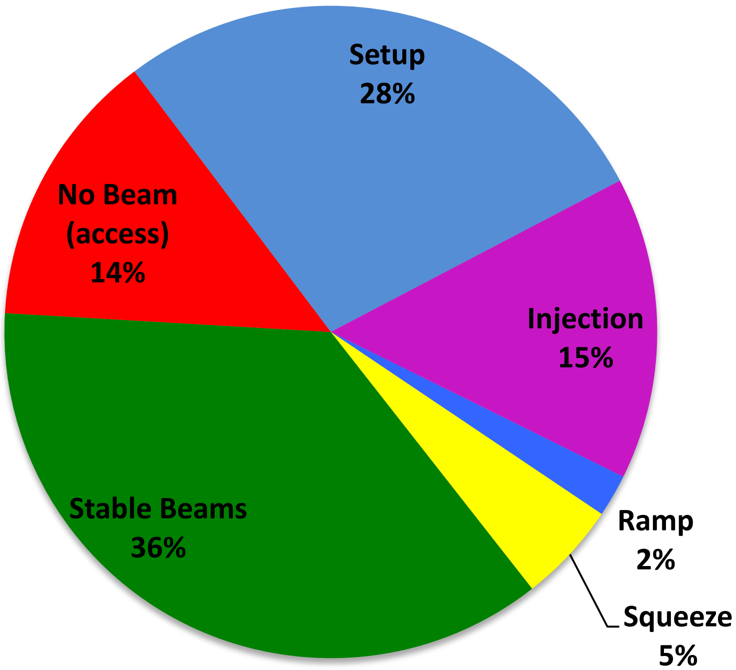
LHC Design

Minimum Time for each operation
10 hour Physics Coasts
No Faults, or down time



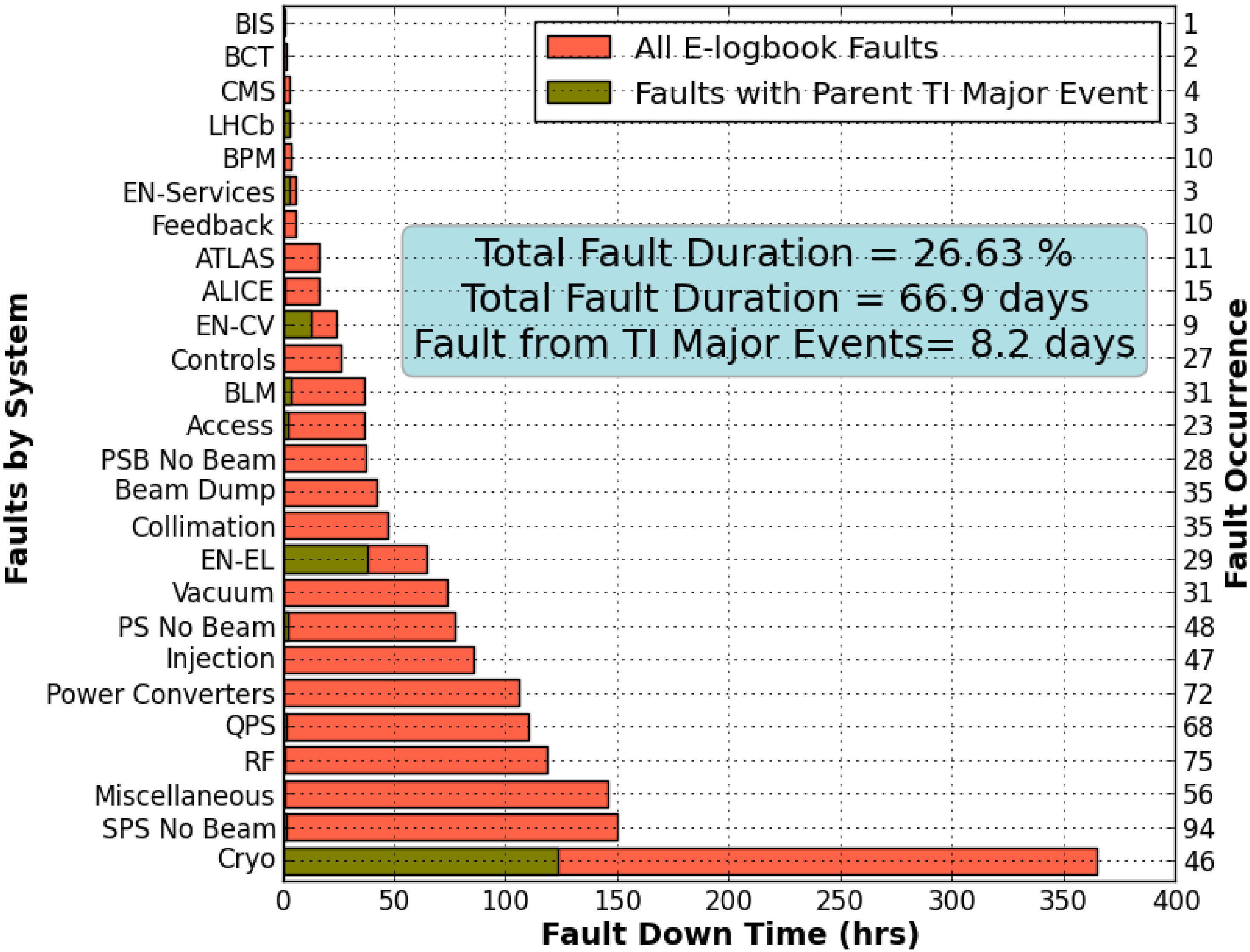
LHC 2012

Average Time in each phase
6 hour Average Physics Coasts
Faults and down time mainly in No Beam, Setup & Injection Phases



In spite of how it looks LHC operation in 2012 was very good !!

LHC 2012 Major Fault Catagories



Considerations for FCC

Gross scaling : FCC-hh = 4xLHC in terms of equipment

If we assume fault time scales in the same way then, based on 2012 LHC statistics, FCC it will never do any Physics!

Note too:

- **LHC was not running at its nominal Energy or intensity**
- **In LHC single event upsets are an issue with a lot of electronics in the underground areas**
- **One of the largest sources of downtime in LHC is beam availability from the injectors**

The sub-systems of the machine need to be built with reliability in mind

- **minimizing fault time, remote diagnostics etc.**

Avoiding radiation effects on electronics:

- **equipment galleries, RadHard design, or not installing underground**

Some systems are particularly critical (cryogenics) as they have an amplifying effect on down time

A Word on interventions

If a fault occurs ideally it can be remotely diagnosed and reset

- ➢ **Even here they can be expensive if they have lead to a beam abort**

Interventions on-site become increasingly expensive:

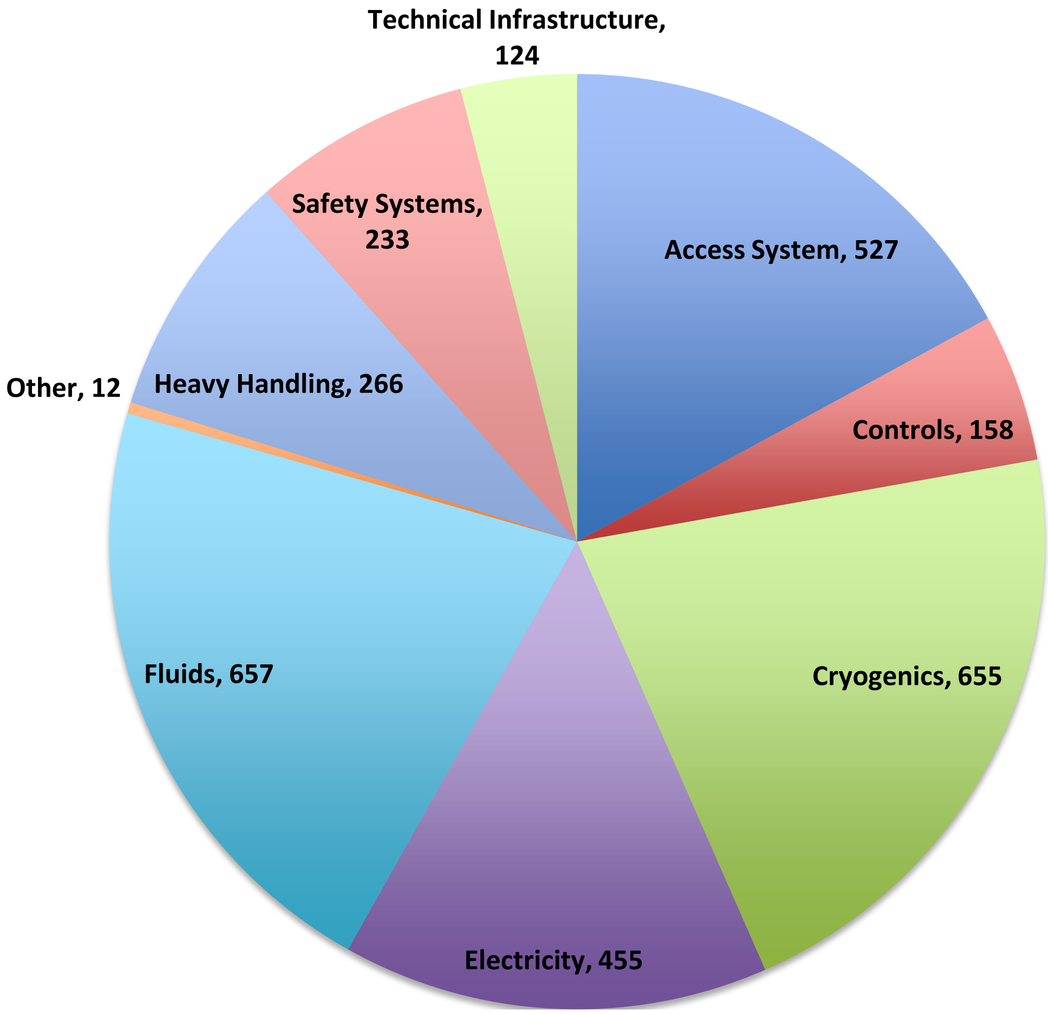
Fault occurs

+ **Time to Diagnose the fault**
+ **Time to call the relevant standby service and for him to travel to the surface point**
+ **Time to enter the machine and travel to the location**
+ **Time to repair the fault**
+ **Time to leave the machine**
+ **Time to restart the machine – and recover the magnetic history of the machine**

Stopping this chain early is clearly desirable

- ➢ **Design of the equipment and Infrastructure**

LHC 2012 Infrastructure Corrective Maintenance Interventions



A total of 3087 interventions on the infrastructure systems in 2012

Many were not directly connected to down time of the machine

Will probably scale to FCC
- **12500 interventions/year**
- **35 interventions/day!**

FCC-ee Power Consumption Estimates

Based on the 80km Machine Study – Should not be too different to a 100km version. Pre-injectors not included.

It includes the infrastructure scaled to the need for TLEP and not that which would be installed to allow a future installation of a pp machine.

TLEP (175)	MW
RF System	218
Cryogenics	24
Cooling & Ventilation	60
Magnet Systems	6
General Services	15
Experiments	25
Total	353

The Key Driver here is the RF system: Cavity characteristics and efficiency of the RF power sources (assumed 55%)

FCC-hh Power Consumption

System	LHC	FCC-hh
Power Converters	20	80
Machine Cryogenics	35	140
Cooling	20	80
Ventilation	14	56
RF	18	72
Other Machine	2.5	10
Experiments	22	30?
Total / MW	131.5	468

To first approximation:

Most will scale to FCC-hh very approximately according to length (ie x4)

The Experiments are likely to be more than LHC but not by a large factor

Beware: This is a ball-park figure to set a rough scale!!

Clearly the Cryogenics is a key driver
But the infrastructure itself (cooling/ventilation) will also be a large consumer
The RF system itself (if >60MV is needed) is significant

- **same R&D for ee and hh machines !!**

Energy Footprint

There are two aspects to energy efficiency both of which must be taken into account at the design stage of the machines & Infrastructures

Reduction/Minimization of the total power required

- **Power efficiency in equipment design**
- **High Efficiency RF power sources (FCC-ee)**
- **Cryogenic system design and cold mass optimization (FCC-hh)**

Total (annual) Energy Consumption

- ~~**Run less?! (not exactly an option)**~~
- **Waste heat recovery**
- **Power reduction during idle periods when beam not available**

Standby Mode

There are inevitably periods when beam can't be put into the machine

During the design efforts should be made to allow equipment to be easily put in an energy saving mode :

- **Identification of something that prevents beam in the machine**
- **Refined estimates of the time to complete**
- **Definition of a threshold time (for each system?) Where switching off is worth while …**
- **Easy mechanisms to put systems into standby (and recover afterwards)**
  - ➥ **One of the biggest difficulties with present machines!**

Some past experience with LEP (Critical Days)

Recently added more dynamic energy saving systems to SPS

➥ **Simple low-energy cycle system, saves ~12 GWh/year**

But this would be much easier if taken on as a major design goal!

Global Operation Concepts

Previous machines (such as LEP) operated on an annual run basis

- **Roughly 6-7 months operation, 5-6 months annual shutdown**
- **Extensions to the shutdown where more major upgrades were needed.**

LHC Introduced a new model (for CERN) - pluri-annual runs:

- **Long "Runs" of around 3-4 years**
- **Followed by Long Shutdowns of 1-2 years**
- **During the run only technical end-of year stops (2-3 months) for essential maintenance**
- **Driven by the overhead to warm and cool the machine**
- **Run duration limited by the time allowed between major maintenance of systems such as cryogenics.**
- **Major upgrades also scheduled inside the long shutdowns.**

A future FCC-hh is likely to follow this model
(remember that the injector complex must follow)

A future FCC-ee is more likely to follow the annual operation model.

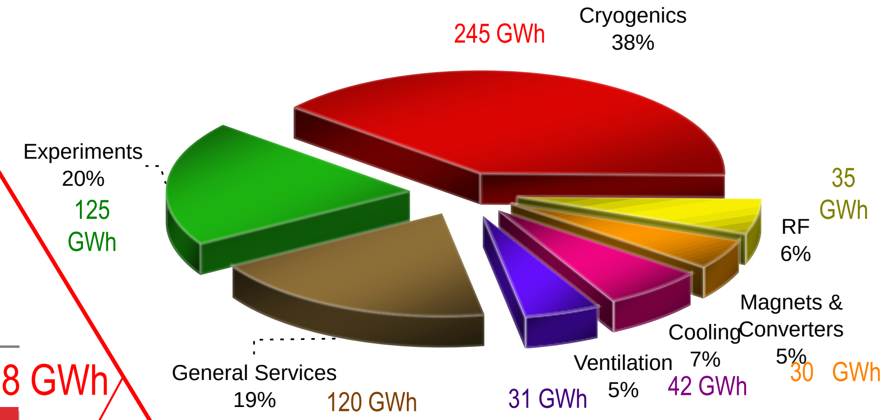
Pluri-Annual Planning for LHC Operation

Recent energy consumption

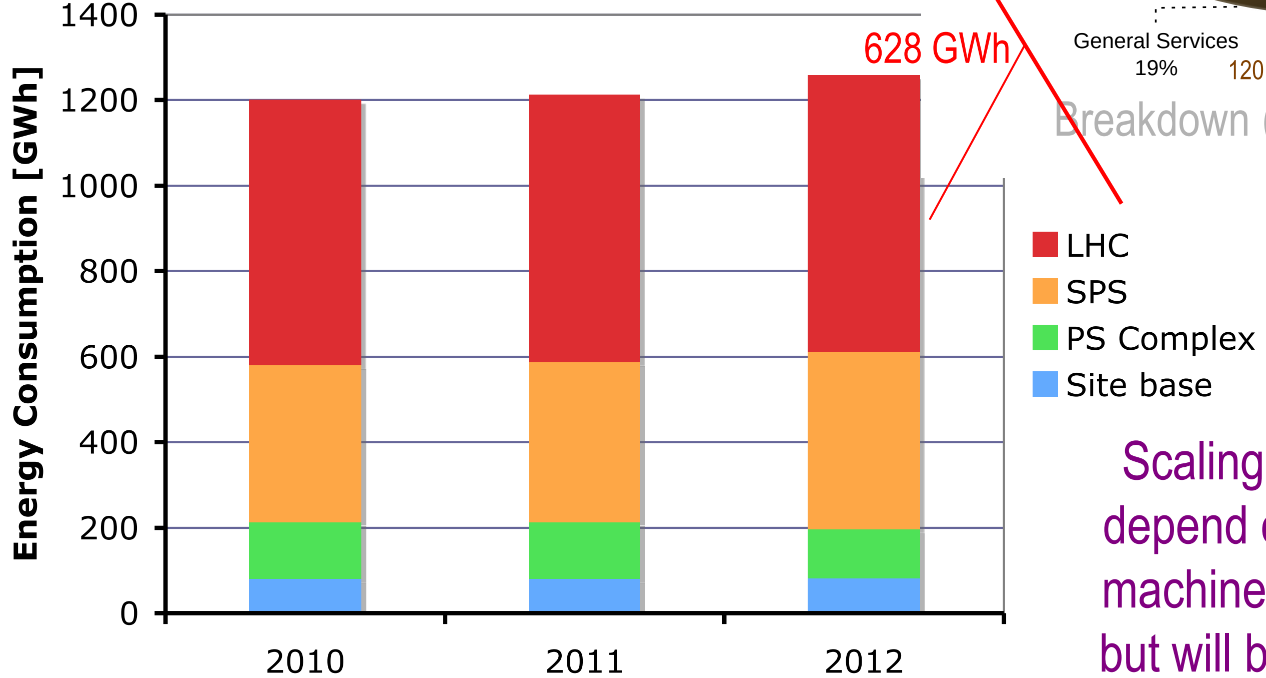
Compiled from yearly EN-EL Energy flyers

But Beware: as a metric

The higher the efficiency of the machine ..
… the higher the energy consumption



Breakdown (averaged) per major system for LHC



Scaling for FCC-hh (or ee) will depend on multi-100eMW power machines AND their duty cycles, but will be a major design issue !

Conclusions I

The Operational Scenario for machines such as FCC-hh and FCC-ee is an important part of the design

- **After all the machine must not only work, but be operable over many years!!**
- **How we plan to operate can also have a direct impact on the design**
  - ➥ Transferring multi-100 MJ beams between machines
  - ➥ Sectorization of the powering circuits
  - ➥ Radiation fields within the accelerator
  - ➥ Access and safety systems

We will rely on the experience from running other large facilities at CERN and around the world.

Conclusions II

Even a very superficial study shows that reliability will a key aspect for FCC

Reliability of the whole machine including the injector complex and the underlying technical infrastructure.

- **The inter-dependencies between systems can be crucial**

Reliability of each system

- **MTBF for each component**
- **Fault tolerance**
- **Remote diagnostics and reset**
- **Radiation tolerance for equipment in the tunnel**
- **Remember: Some systems just cannot fail! (eg. beam abort)**

Design in such a way to minimize interventions in the tunnel:

- **Access into the tunnel will be 'expensive' with long travel times and the probable need to restore the magnetic history of the machine**

Conclusions III

Energy for large research infrastructures

Scientific goals at minimising primary energy consumption

- **Energy efficiency from design stage onwards:**
  - ➥ **Energy consumption considered in selection and design of lattice and sub-systems (minimised global "capital plus operating" costs)**
- **Energy management and awareness:**
  - ➥ **Foreseen stand-by modes (1min, 1hr, 1wk, 1month)**
  - ➥ **Operation scenario (seasonal, weekly, daily)**
- **Waste heat recovery**
  - ➥ **At the highest possible temperature for direct use**

=> Getting some of these ideas implemented on few specifically selected on-going activities would be an efficient way to be prepared for FCC !

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