Useful things to know about accelerators – part II

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Science and Technology Facilities Council

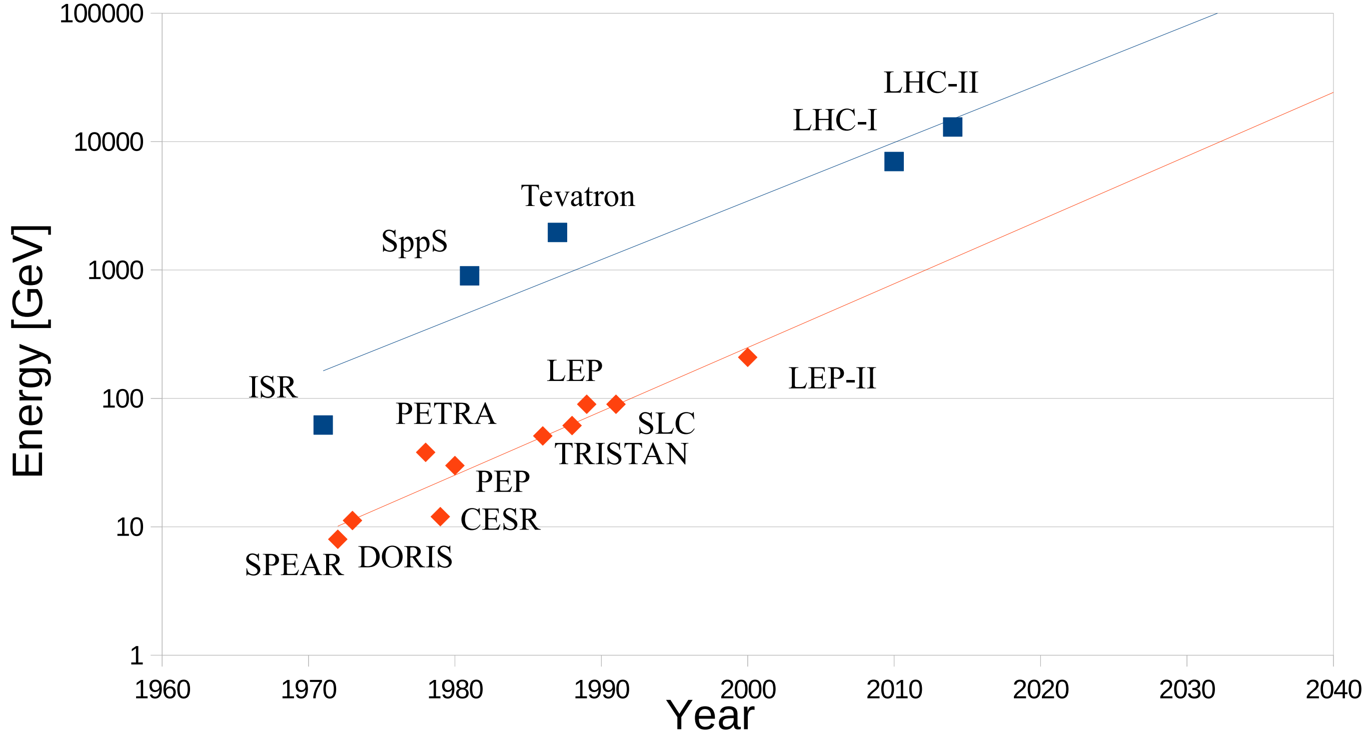
A Window on Nature

- Particle accelerators have provided unique insight into the nature of matter
  - What is matter made of?
  - What generates forces between matter?
- Culminating in the Large Hadron Collider
  - Discovery of the Higgs particle
- Many open questions remain
  - Why do different particles have such radically different masses?
  - Why are different particles sensitive to different forces?
  - Why is there so little antimatter in the universe?
  - Are there any undiscovered fundamental particles?
  - What is dark matter?

The Problem

- Exploring these questions needs bigger and bigger particle accelerators
  - Higher energy
- What limits accelerator energy?
  - Proton colliders → magnetic bending field
  - Electron linear colliders → RF accelerating field
  - Electron circular colliders → synchrotron radiation
- Proposals for the next generation involve huge accelerators
  - Is there a better way?
  - To answer, we need to go back to the origins of particle physics…

Livingston Plot



- Effort to explore phenomena at higher and higher energies
- Corresponds to smaller scales
  - Atomic physics
  - Subatomic physics
- Learn about the constituents of matter

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What Limits Collider Energy?

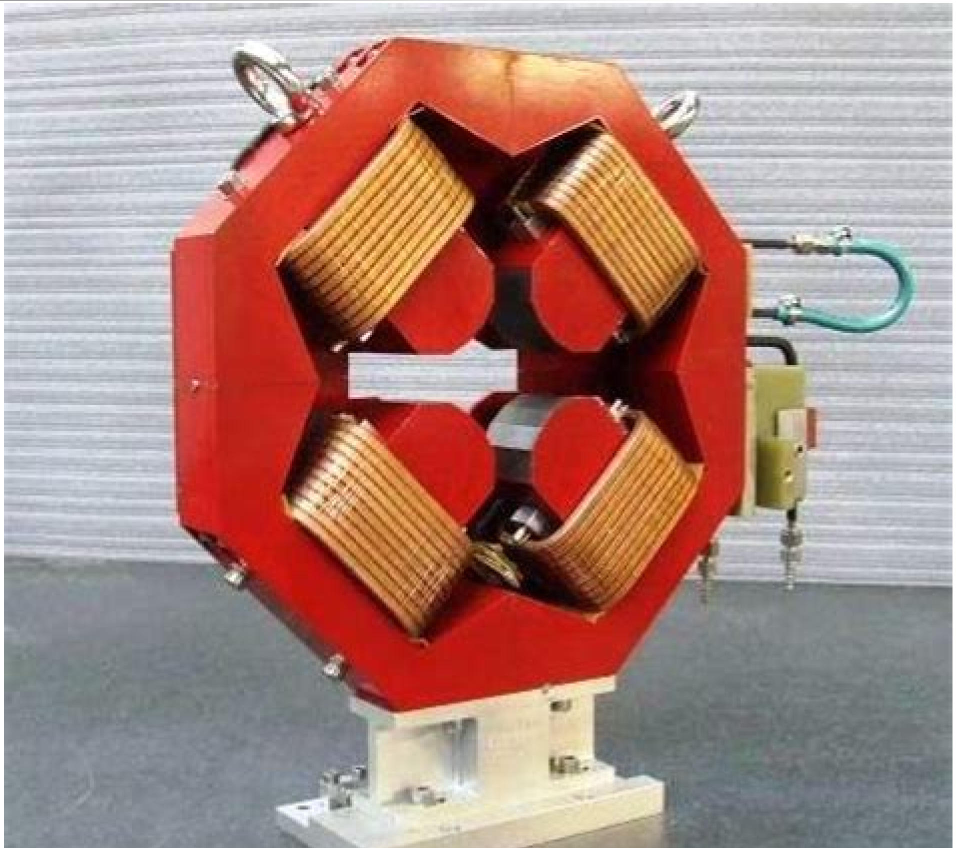
- Proton colliders are limited by magnetic field strength
  - Limits the bending radius – and hence tunnel length
- Electron rings are limited by synchrotron radiation
  - Energy is lost to x-rays
  - Note – synchrotron radiation is much stronger for low mass particles
- Linacs are limited by available acceleration
  - Can’t accelerate electrons without incredibly long tunnels

Magnet Technology

- Different technologies are suitable for different uses
- What field magnitude is required?
- What field shape is required? Dipole? Multipole?
- How well do we need to know the field?
- Is the magnet pulsed? What time constant?
- Cost? Maintenance? Radiation environment?
- Running costs?

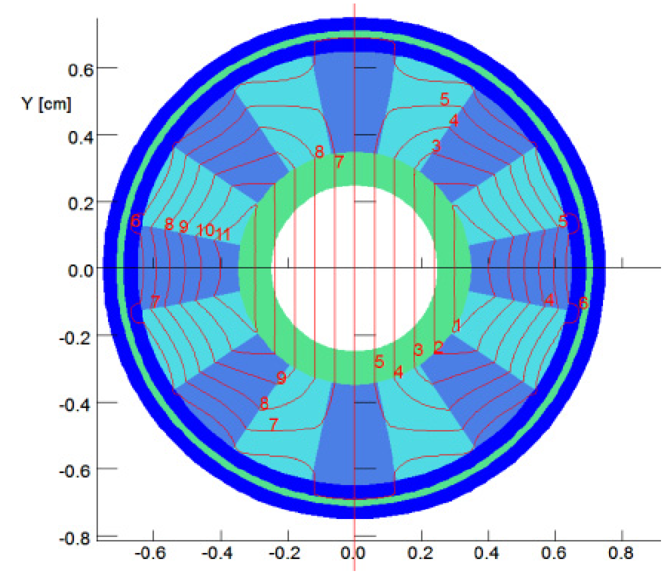
Normal Conducting Magnets

- Coils provide magnetic field
  - Hollow core, water cooled
- Shaping done using iron
- Pros
  - Cheaper
  - Hands-on maintenance
- Cons
  - Field < ~2 T due to heating
  - Higher power consumption
  - Water leaks

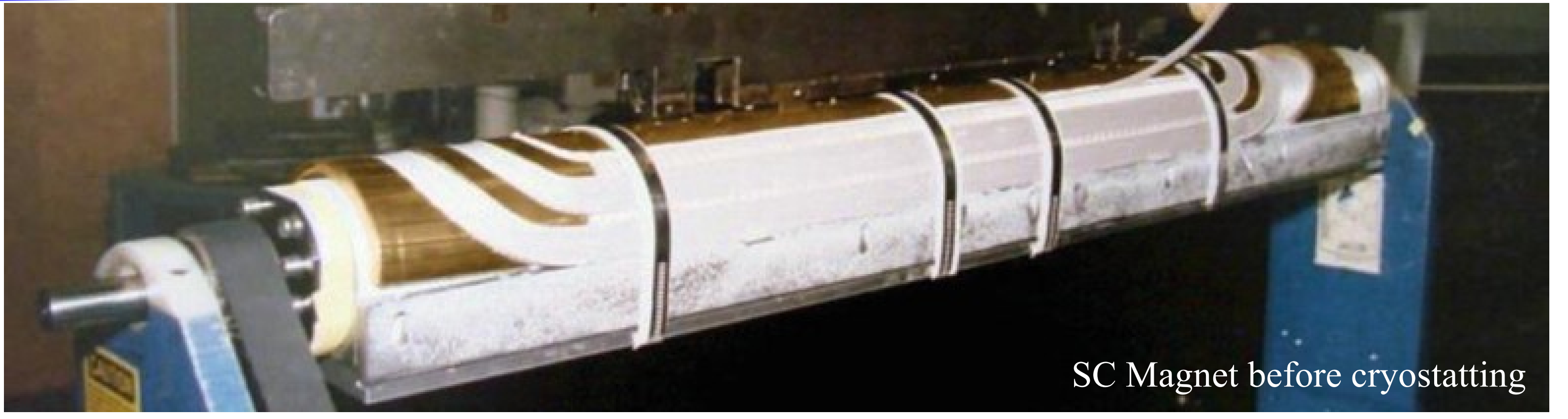

Normal conducting quadrupole magnet Triumf.ca

Permanent Magnets

- Permanent magnets provide the magnetic field
  - Iron used to shape the field
  - Tune field by moving magnet sections
- Pros
  - No running costs
- Cons
  - Fixed field – can't pulse the magnets
  - Sensitive to radiation damage/heating
  - Limited field quality



Superconducting Magnets



- At lHe temperature, some materials become superconducting
  - Resistivity drops to 0
- Pros
  - Can reach high fields (~10 T)
- Cons
  - Quench runaway process
    - heating → increased resistivity → more heating
  - Cryogenics management
  - Slow ramping
  - Cost

Quenches and QPS

- Quenches
  - Local heating of Helium
    - e.g. from coil movement
  - Resistivity of wire increases
  - Causes more heating of Helium
  - Runaway Process
- Quench Protection System (QPS)
  - Protect superconductor in quench
  - Detect excess resistance/voltage
  - Actively heat the superconductor
  - Extract energy through copper supports into dump resistors

LH

Page last updated at 11:55 GMT, Saturday, 20 September 2008 12:55 UK

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Hadron Collider halted for months

Superconducting magnets are cooled down using liquid helium

The Large Hadron Collider near Geneva will be out of action for at least two months, the European Organization for Nuclear Research (Cern) says.

Part of the giant physics experiment was turned off for the weekend while engineers probed a magnet failure.

But a Cern spokesman said damage to the £3.6bn ($6.6bn) particle accelerator was worse than anticipated.

The LHC is built to smash protons together at huge speeds, recreating conditions moments after the Big Bang.

Scientists hope it will shed light on fundamental questions in physics.

Section damaged

On Friday, a failure, known as a quench, caused around 100 of the LHC's super-cooled magnets to heat up by as much as 100 degrees.

The fire brigade were called out after a tonne of liquid helium leaked into the tunnel at Cern, near Geneva.

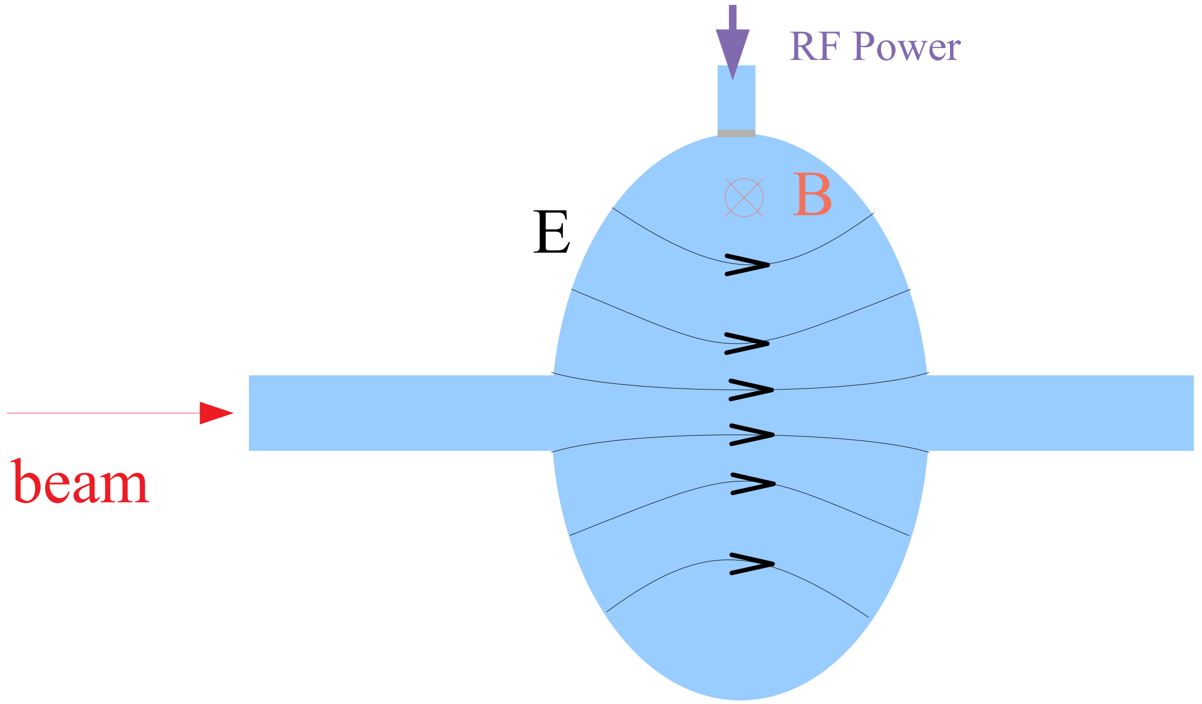
LHC QPS failure (2008)

Magnet quenched during ramping. Discharge current tried to enter copper busbar but weld failed. Arc across the weld caused Helium vessel to rupture leading to total failure of magnet.

As a result the entire magnet (many tonnes) moved a couple of feet. Repair to the magnet system delayed start-up for more than a year.

RF cavities

- RF cavities are resonant structures
  - Radius ~ 2.4/frequency
  - High frequency RF cavities are small!
- Oscillating electric field in direction of beam
  - Magnetic field azimuthally out of phase with electric field



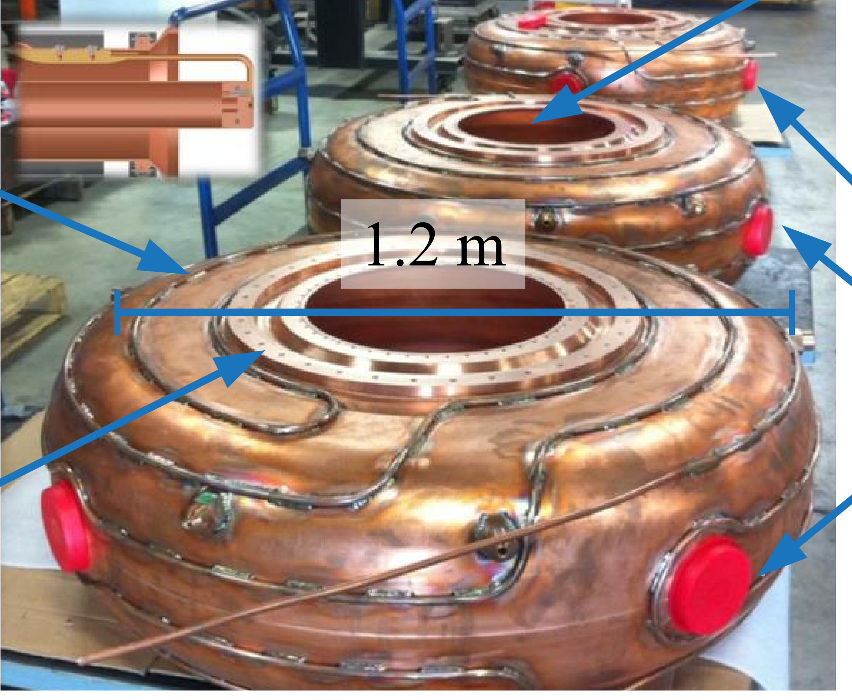
RF Cavity issues

- Damping of the resonance due to wall resistance
  - RF power → heat
  - Superconducting cavities reduce wall resistance
- Loss of power into beam limits max beam current
  - "Beam loading"
- Breakdown (spark formation) limits max voltage
  - Electric field pulls electrons from cavity surface
  - Electrons can strike cavity surface causing more sparks
    - Multipacting
  - Breakdown suppressed at higher frequencies
    - Kilpatrick limit
  - → Higher frequency cavities have higher max voltage
  - Nb: higher voltage → more cavity heating

E.g. Normal conducting 200 MHz RF

Internal surfaces treated to suppress breakdown

Water cooling pipes

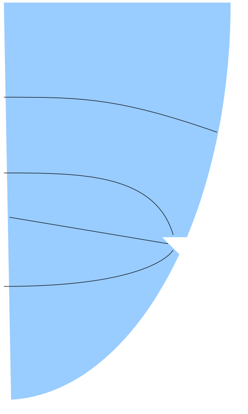


Ports for RF power

Mounting point for frequency tuners

Superconducting 1300 MHz RF

- E.g. 1.3 GHz SCRF cavity
  - Niobium superconductor
  - Superconductor → lower losses to walls
- Peak voltage ~ 30 MV/m
  - Breakdown caused by field amplification due to surface imprefections
- Surface cleaning to improve voltage
  - Electro polishing
  - Buffer Chemical Polishing
  - Ultrapure water rinsing



Surface imperfection causes field amplification

Questions?

Questions?

- You are designing a high energy proton collider
  - What sort of magnet would you use for the main magnets? Why?
  - What sort of RF cavity would you use? Why?
- You are designing a high current proton accelerator for neutrinos
  - What sort of magnet would you use? Why?
  - What sort of RF cavity would you use? Why?

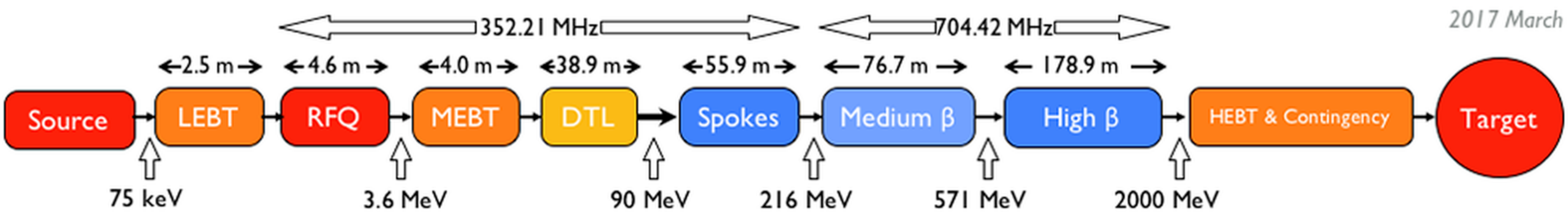
Questions?

- You are designing a high energy proton collider ring
  - What sort of magnet would you use for the main magnets? Why?
    - High field → High momentum! Superconducting
  - What sort of RF cavity would you use? Why?
    - Long pulse → Superconducting
    - Large stored energy → 400 MHz (lower frequency)
- You are designing a high current proton accelerator for neutrino production
  - What sort of magnet would you use? Why?
    - Robust to radiation; rapid cycling time → Normal conducting
  - What sort of RF cavity would you use? Why?
    - Normal conducting, lower frequency? More robust to beam loading
    - Superconducting – sensitive to beam loss; but potentially lower operating costs

Types of Accelerator

- Several different types of accelerator
  - Depending on application
- Linear accelerator (linac)
  - Accelerate in a straight line
  - High current, long beam pulse applications
- Cyclotron (and FFA)
  - Accelerate through a big dipole, increasing radius
  - Rotational frequency constant for non-relativistic bunches
  - Reuse equipment → cheaper than linac
  - High current, non-relativistic
- Synchrotron
  - Ramp magnets as beam accelerated, keep radius constant
  - Rotational frequency varies → sweep RF frequency
  - Can only accelerate one pulse at a time
  - Lower current, fully relativistic

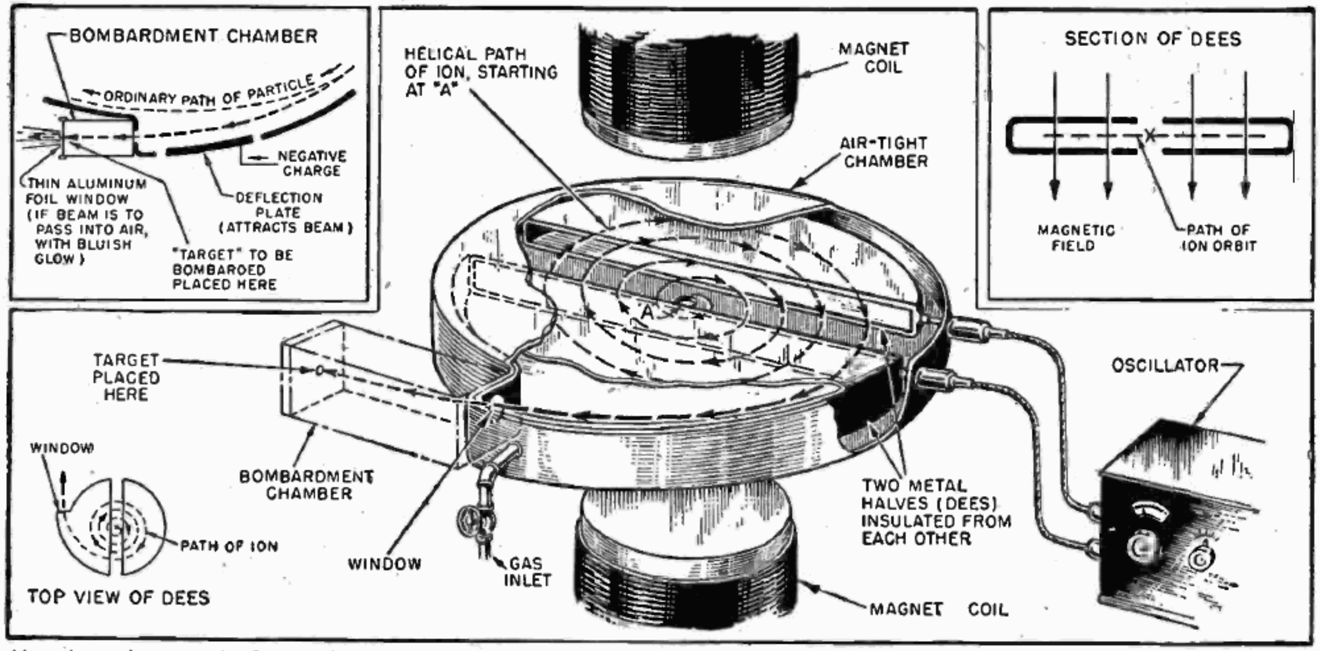
Linear Accelerator



European Spallation Source (protons)

- Source
  - Protons/H$^-$ ions: excited hydrogen gas
  - Electrons: heated cathode (long pulse)
  - Electrons: Laser cathode (short pulse)
- Acceleration
  - Protons/ions → non-relativistic acceleration
    - High space charge
    - Cavity phasing issues
  - High energy acceleration
- Critical issues
  - High current, high quality source
  - Control of space charge

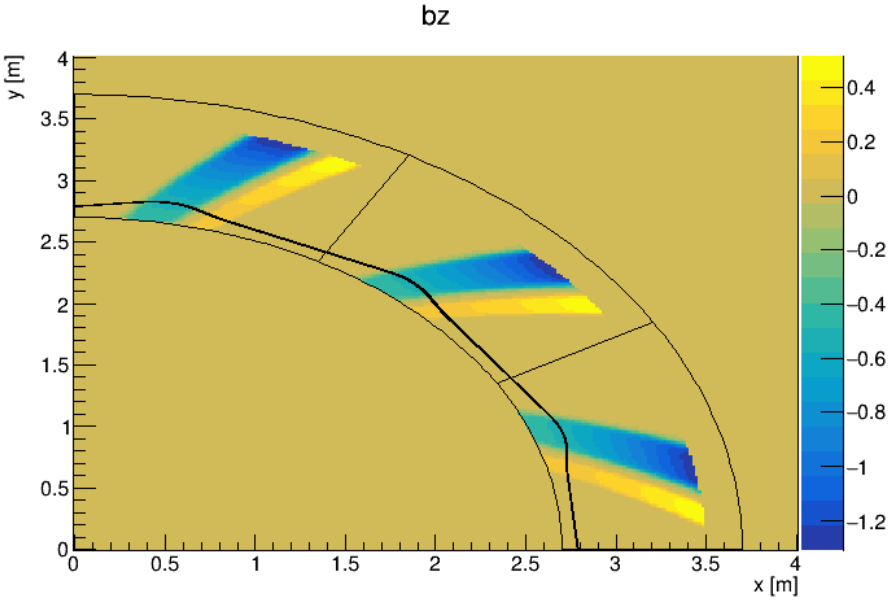
Cyclotron



- For non-relativistic particles
  - Path Length $$L = 2\pi\rho$$
  - Magnetic rigidity $$B\rho = \frac{p}{q} = \frac{mv}{q}$$
  - Time of flight $$t = \frac{L}{v} = \frac{2\pi m}{qB}$$

Fixed Field Alternating Gradient

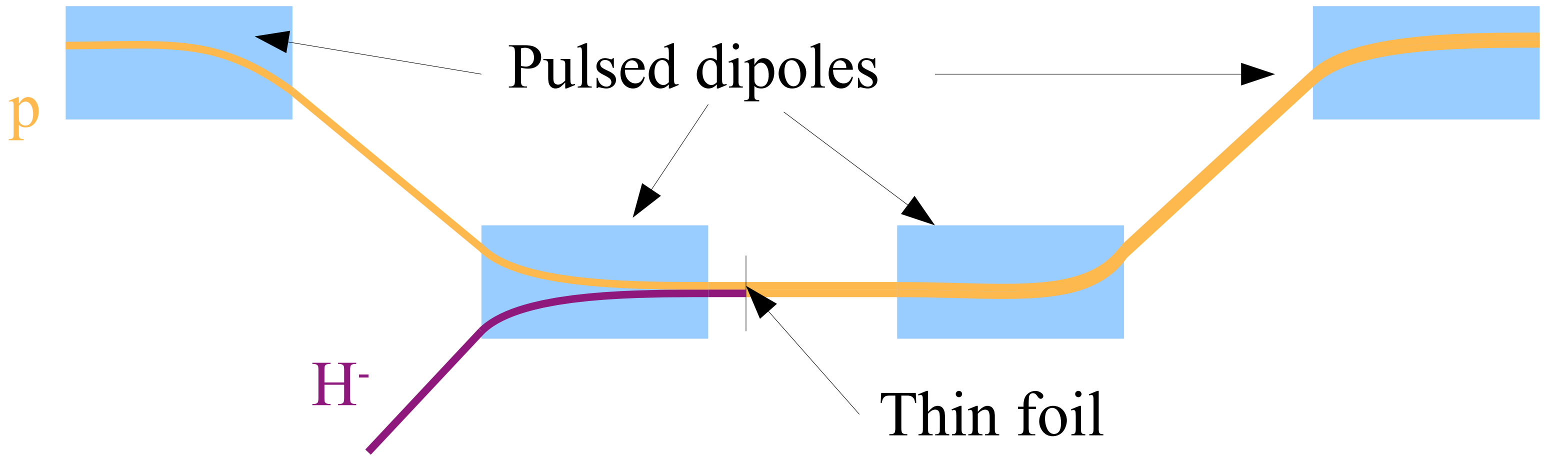
- For relativistic particles
  - Vary dipole field with radius
    - Need to control tune
  - Vary RF cavity frequency in time
    - Can only accelerate a single bunch
  - Eventually the dipoles become too large
- Concept of Fixed Field Alternating Gradient accelerator "FFA"
  - Vary focussing strength proportional to momentum
  - In principle, get achromatic lattice
    - No tune variation at all
  - Large field gradient → smaller magnets



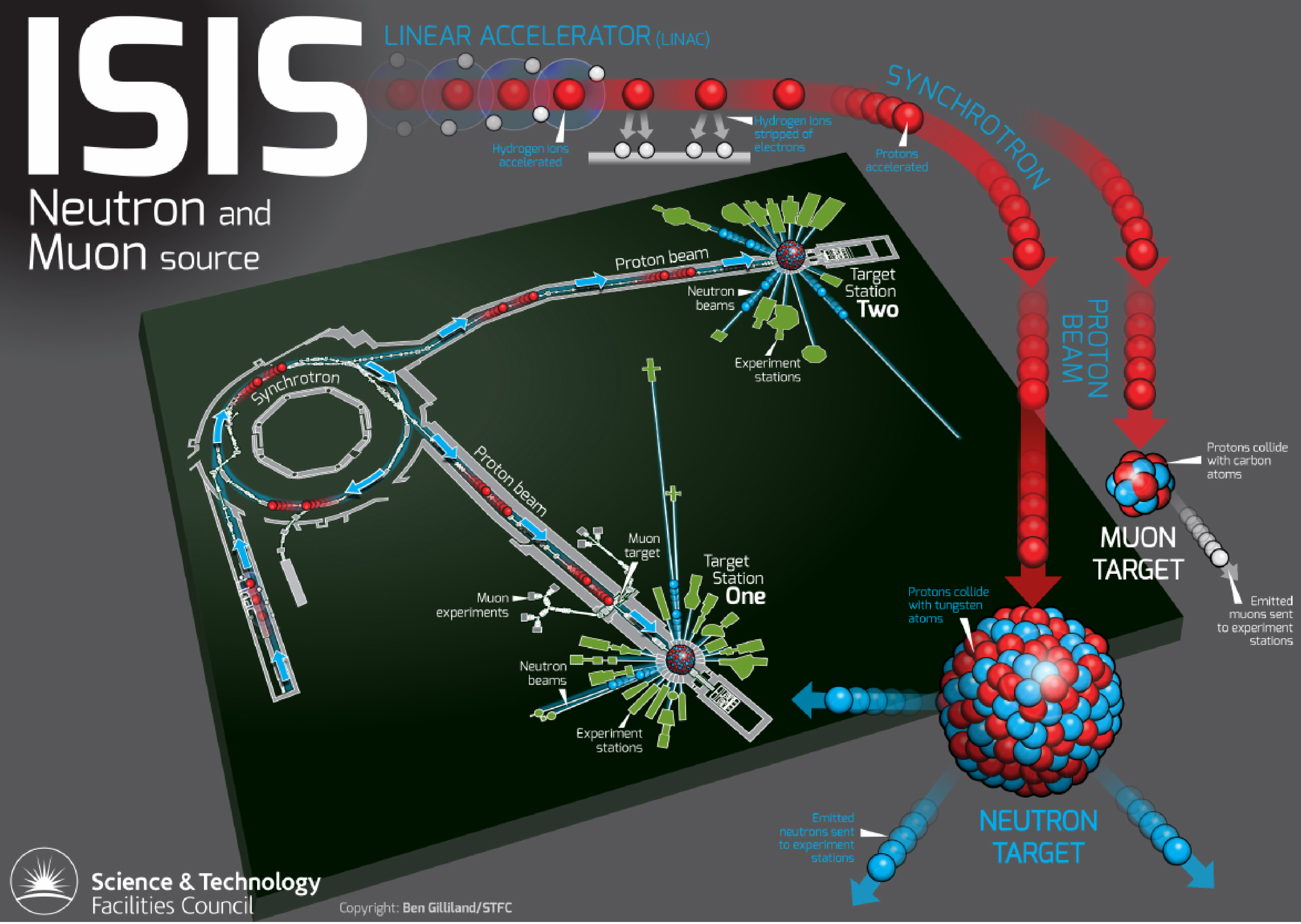
Synchrotron

- Most HEP facilities use linac followed by synchrotron
  - Linac to accelerate past space charge limit
  - Accumulate beam over a number of turns in synchrotron
  - Then ramp fields and accelerate to high energy
- Synchrotron varies magnetic field in time
  - Match bending field with beam momentum
    - Fast ramping can be quite tricky
  - Vary RF frequency and voltage to match revolution time and RF bucket size

Charge Exchange Injection



- High current → accumulate beam over many turns
  - Charge exchange injection of H^- ions through a thin foil
  - Foil removes electrons
  - Issues: Scattering and energy loss of protons in foil
- Painting of beam into synchrotron acceptance using fast “bumper” magnets
  - Move recirculating beam around in horizontal and vertical phase space
  - Fill a much larger acceptance


ISIS
Neutron and Muon source
LINEAR ACCELERATOR (LINAC)
Hydrogen ions accelerated
Hydrogen ions stripped of electrons
Protons accelerated
SYNCHROTRON
PROTON BEAM
Protons collide with carbon atoms
MUON TARGET
Emitted muons sent to experiment stations
Protons collide with tungsten atoms
NEUTRON TARGET
Emitted neutrons sent to experiment stations
Proton beam
Neutron beams
Target Station Two
Experiment stations
Synchrotron
Proton beam
Muon target
Target Station One
Muon experiments
Neutron beams
Experiment stations
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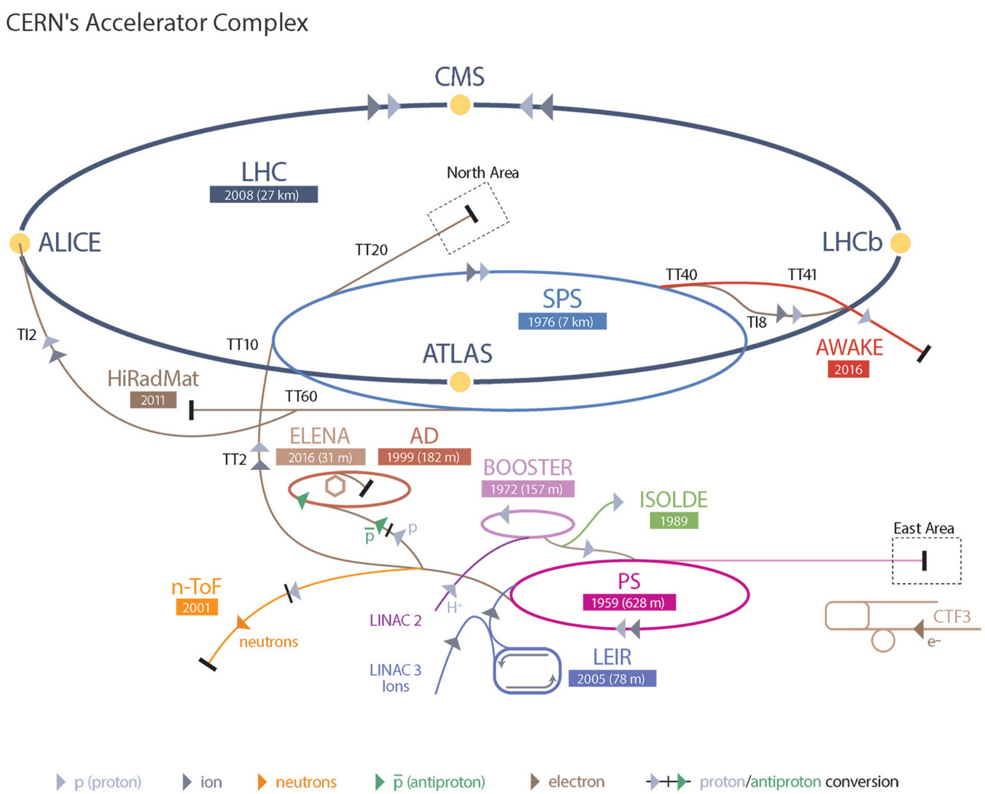
HEP Accelerator Facilities

- Proton accelerators
  - CERN complex (including LHC) - Switzerland
  - Fermilab complex - US
  - J-PARC complex - Japan
- Electron accelerators
  - Super KEKB - Japan
  - DAFNE - Italy
  - BEPC II - China

Non-HEP Accelerator Facilities

- Most large accelerator facilities are not for HEP
  - Neutron and X-Ray diffraction for material studies
  - Proton and electron radiation for cancer treatment
  - Nuclear physics
- Proton/Ion accelerators – O(£Billion) facilities
  - ISIS (UK), ESS (Sweden), PSI (Switzerland), SNS (US), RHIC (US), FRIB (US), TRIUMF (Canada), JPARC (Japan)
- Electron accelerators – O(£Billion) facilities
  - Diamond (UK), European XFEL (Germany), ESRF (France), PETRA-III (Germany), MAX-IV (Sweden), LCLS (US), SPring-8 (Japan), APS (US), CHESS (US)
- Many more…

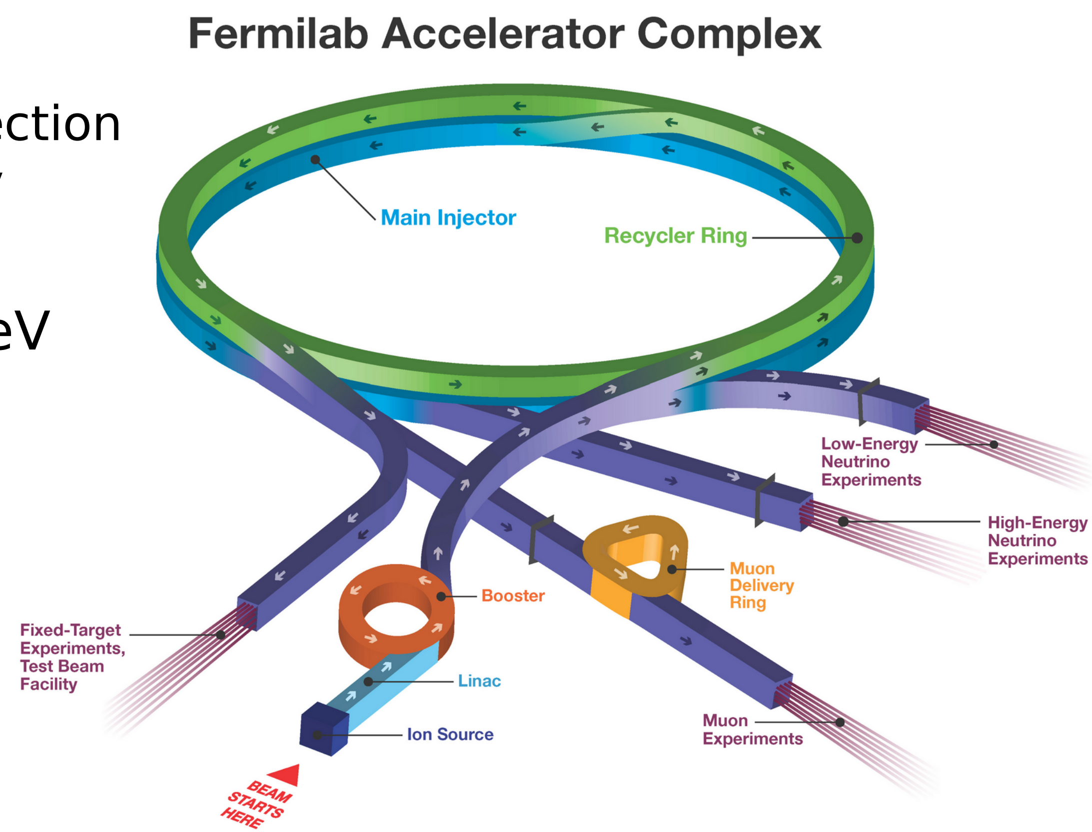
CERN complex



- (Linac2 → 50 MeV)
  - Space charge limit
- Linac4
  - H- to 160 MeV
- PSBooster
  - Charge exchange injection
  - Protons → 1.4 GeV
- PS → 25 GeV
- SPS → 450 GeV
- LHC → 6.5 TeV

Fermilab Complex

- Linac
  - H- accelerated to 400 MeV
- Booster
  - Charge exchange injection
  - Acceleration to 8 GeV
  - 15 Hz rep rate
- Main Injector → 120 GeV
- (Tevatron → 980 GeV)



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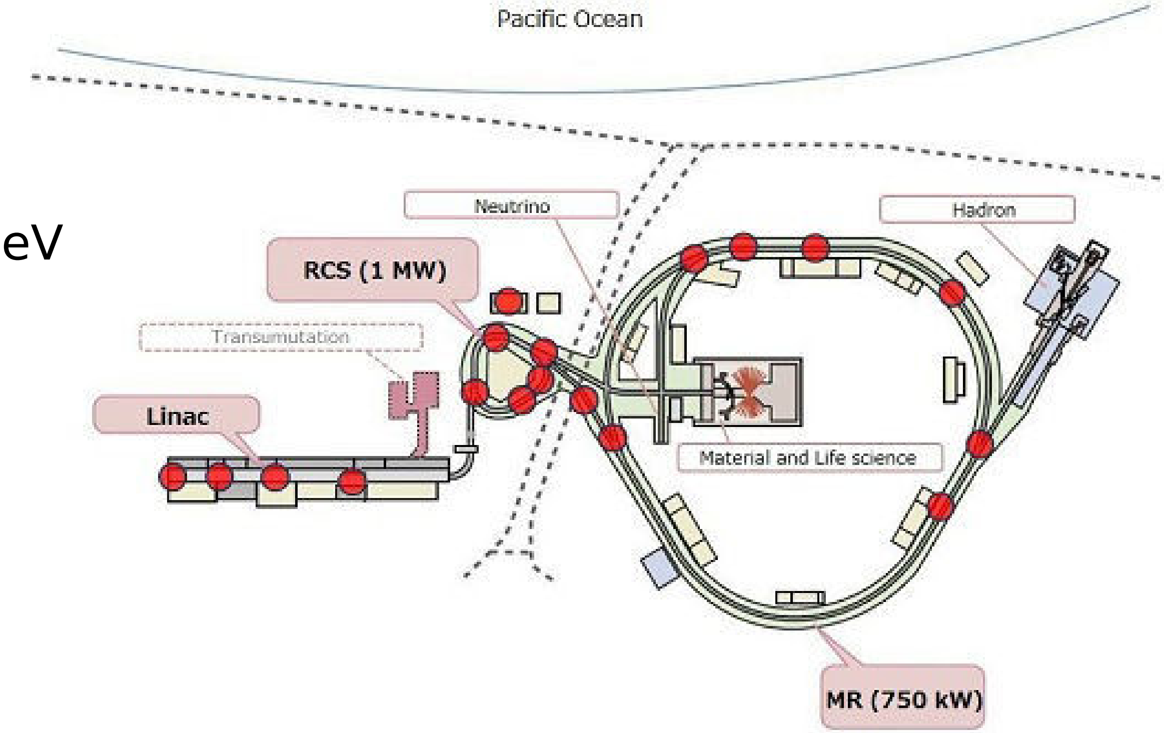
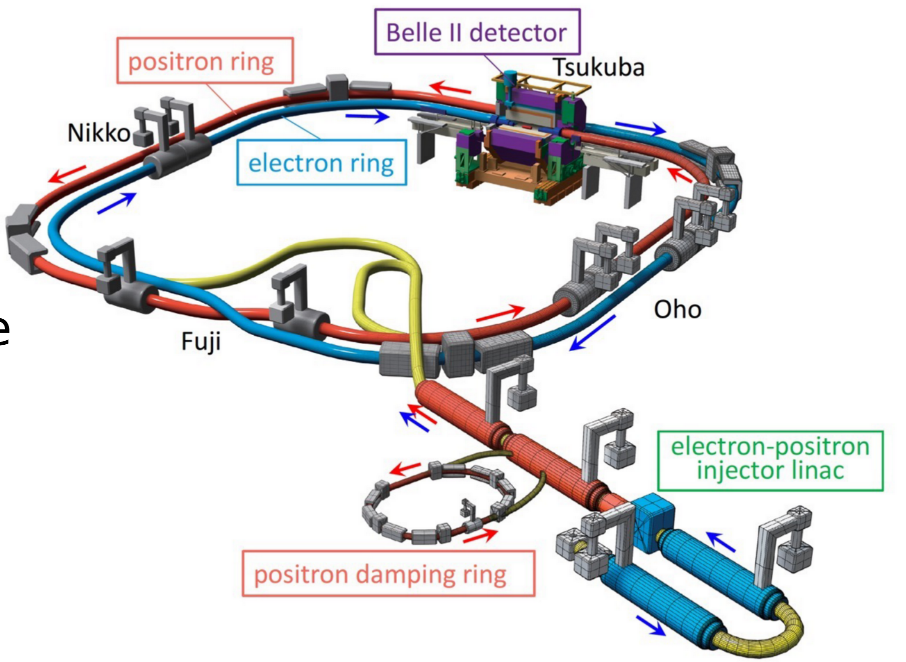
J-PARC Complex

- Linac
  - H-
  - Accelerate to 400 MeV
- Rapid Cycling Synchrotron (RCS)
  - Charge exchange injection
  - Accelerate to 3 GeV
  - 15 Hz Rep Rate
- Main Ring
  - Accelerate to 50 GeV
  - 0.3 Hz Rep Rate



Super KEK B

- Electrons produced on photocathode
- Positrons produced by firing electrons onto target
- Positron damping ring
  - Use synchrotron radiation damping to reduce emittance
  - → Improve luminosity
- Linac
  - e^- to 7 GeV
  - e^+ to 4 GeV
- Collider ring
  - Continuously top-up the beam
  - Synchrotron radiation damping to control emittance



Questions?

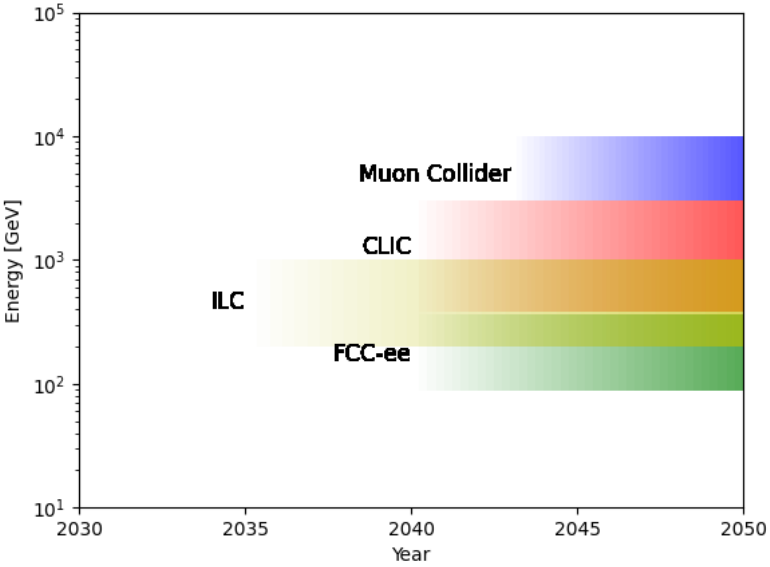
Questions

- Why do JPARC and Fermilab have higher energy linacs vs LHC?
- Why do JPARC and Fermilab have higher rep rates vs LHC?
- What limits the rep rate of JPARC and Fermilab?
- Why do the positrons need a special damping ring at SuperKEKB

Questions

- Why do JPARC and Fermilab have higher energy linacs vs LHC?
  - Space charge limits peak current
  - High peak current → More neutrinos
- Why do JPARC and Fermilab have higher rep rates vs LHC?
  - Higher (average) current → More neutrinos
- What limits the rep rate of JPARC and Fermilab?
  - Magnet rise time
- Why do the positrons need a special damping ring at SuperKEKB
  - Positron target makes large emittance positron beams

Future Accelerator Facilities



- HL-LHC will become operational ~late 2020s
  - Run for 10-20 years
  - No further upgrades possible
- Lead time for a new facility about 25 years
  - Now need to determine the next collider
  - Decisions in next ~ 5-10 years determine future of particle physics for 50-100 years

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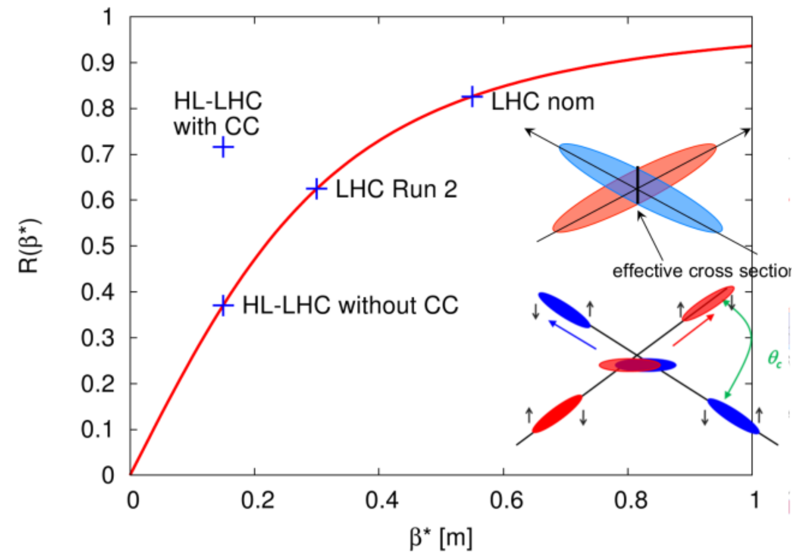
HL LHC



- HL-LHC plan:
  - Improved final focus quads
  - Crab cavities
  - More collimators and improved magnet fridge
  - Better shielding for ring injection
  - Injector upgrade

$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi\, \beta^*\, \varepsilon_n} R$$

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Future Collider Facilities

- No more colliders

- CLIC/ILC
  - 200 – 3000 GeV electron linac collider
- FCC/CEPC
  - Up to 360 GeV electron ring collider
  - 100 TeV proton ring collider
- Muon collider
  - 3-14 TeV muon collider
- NuStorm
  - Neutrino source from decay of high energy muons

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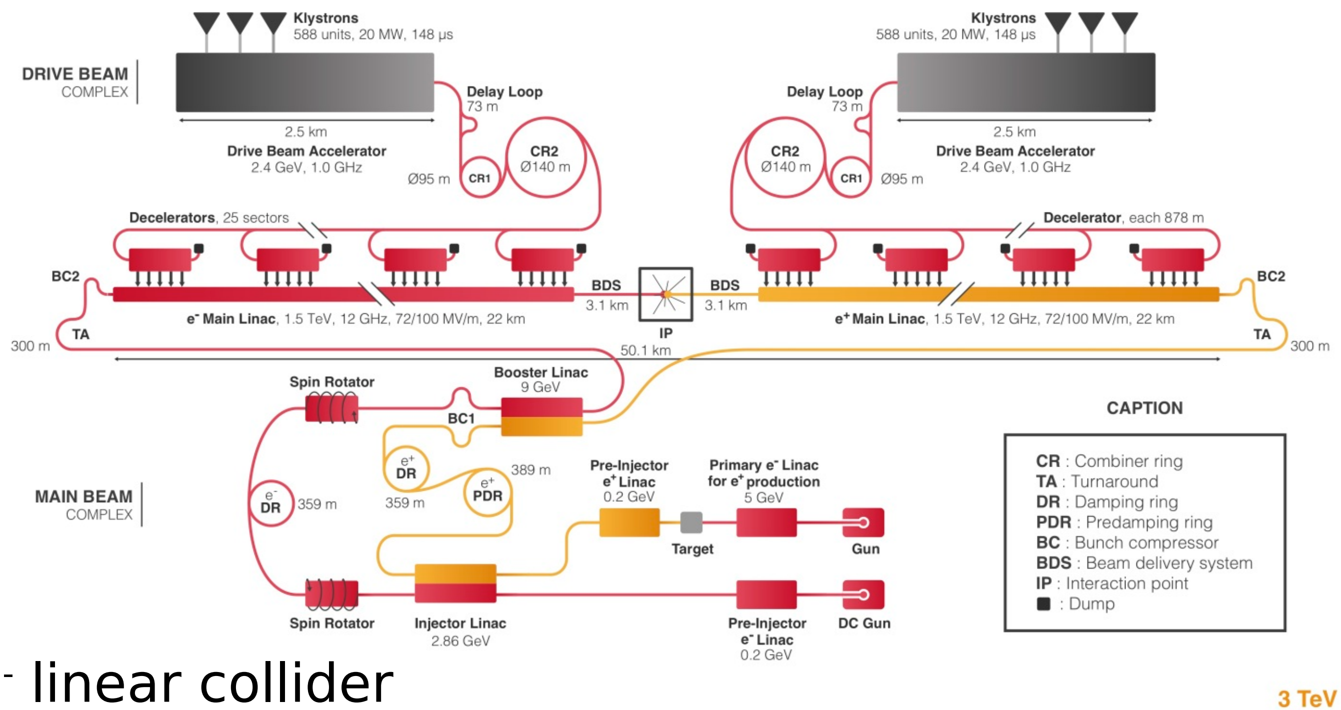
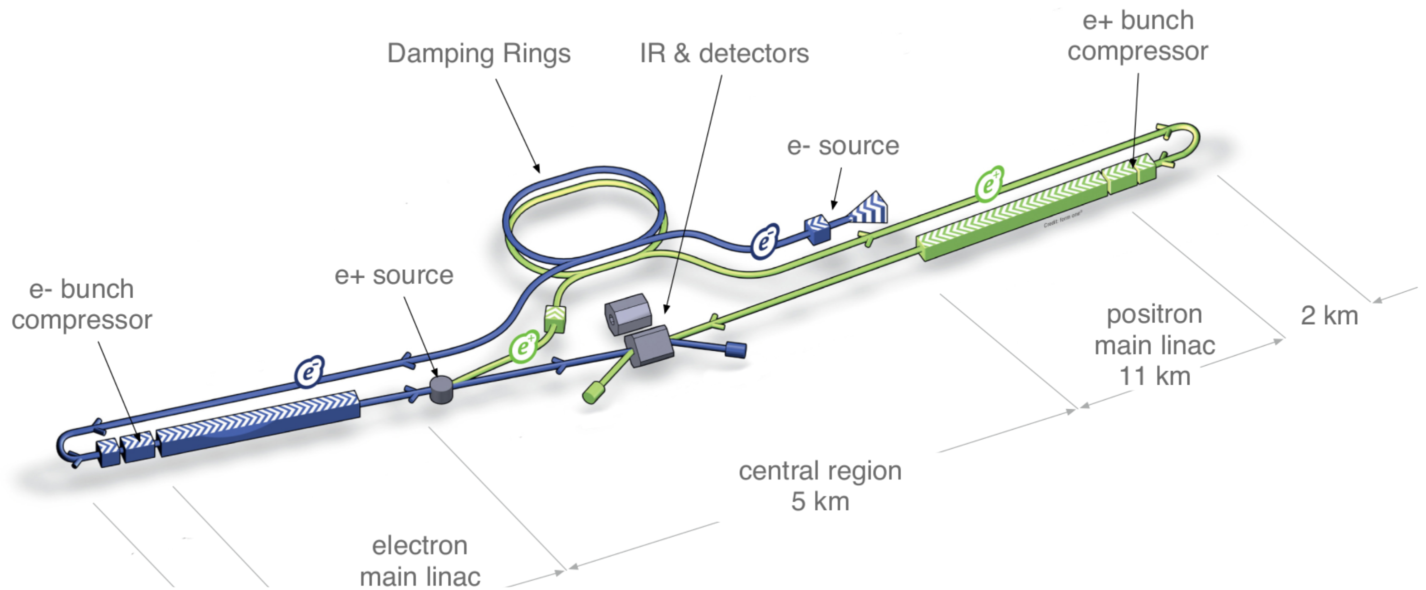
CLIC/ILC



- $e^+ e^-$ linear collider
  - 380 GeV CoM energy
  - Potential to go to 3 TeV
- 12 GHz normal-conducting RF filled by “drive” e^- beam
- Challenges
  - Novel accelerating structures
  - Beam alignment

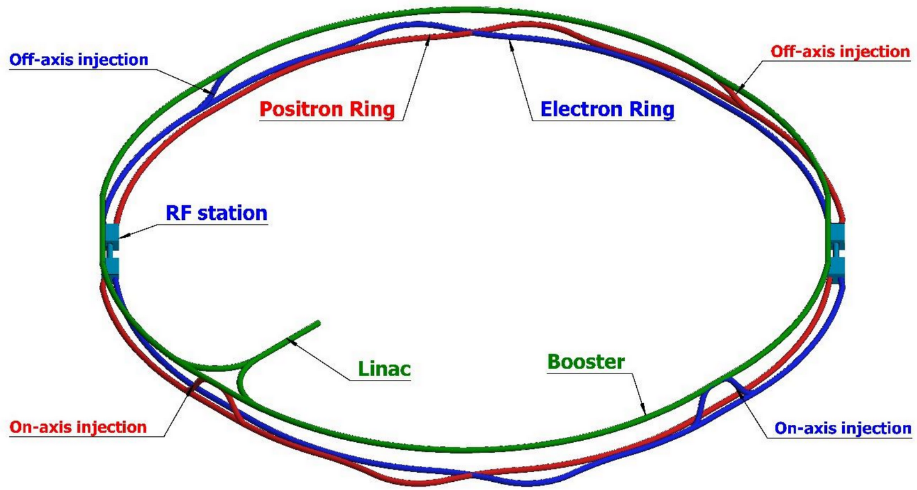
ILC



- $e^+ e^-$ linear collider
  - 200-500 GeV CoM energy
  - Potential to go to 1 TeV
- 1.3 GHz super-conducting RF (now used in many projects)
- Challenges
  - High accelerating RF gradients
  - Beam alignment
  - Electron cloud in the positron damping rings

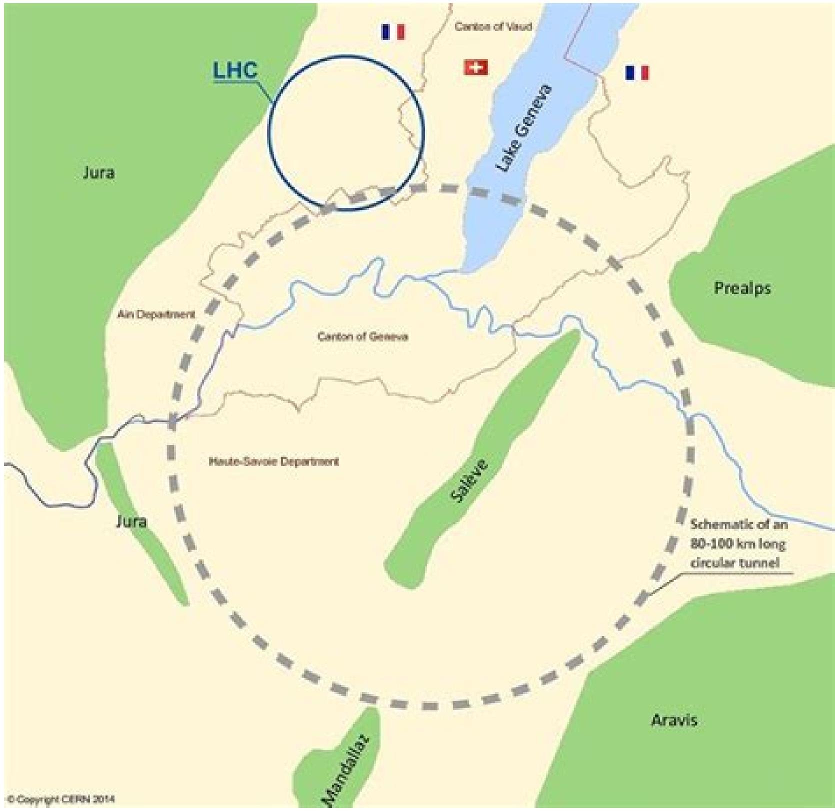
FCC and CEPC ee

- e^+e^- synchrotron collider
  - 360 GeV CoM energy
  - Upgrade to pp collider
- Challenges
  - ~100 km circumference collider ring
  - Huge civil engineering task
  - Management of synchrotron radiation
  - Power consumption



FCC-pp and SppC

- pp synchrotron collider
  - 100 TeV CoM energy
- Challenges
  - Huge number of ~15 T magnets
  - Cryogenic systems
  - Power requirements (580 MW)
  - Extraction/injection systems



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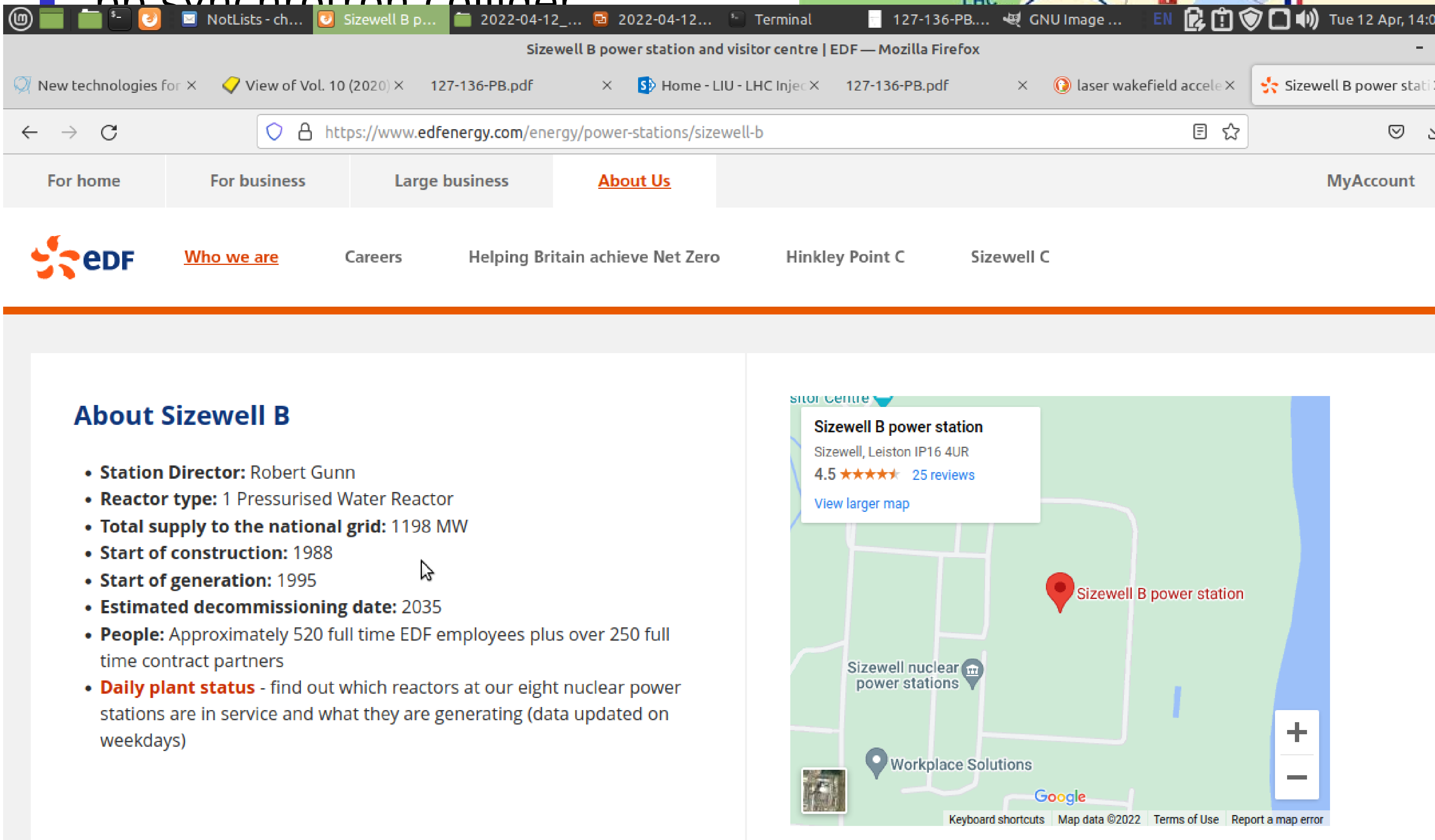
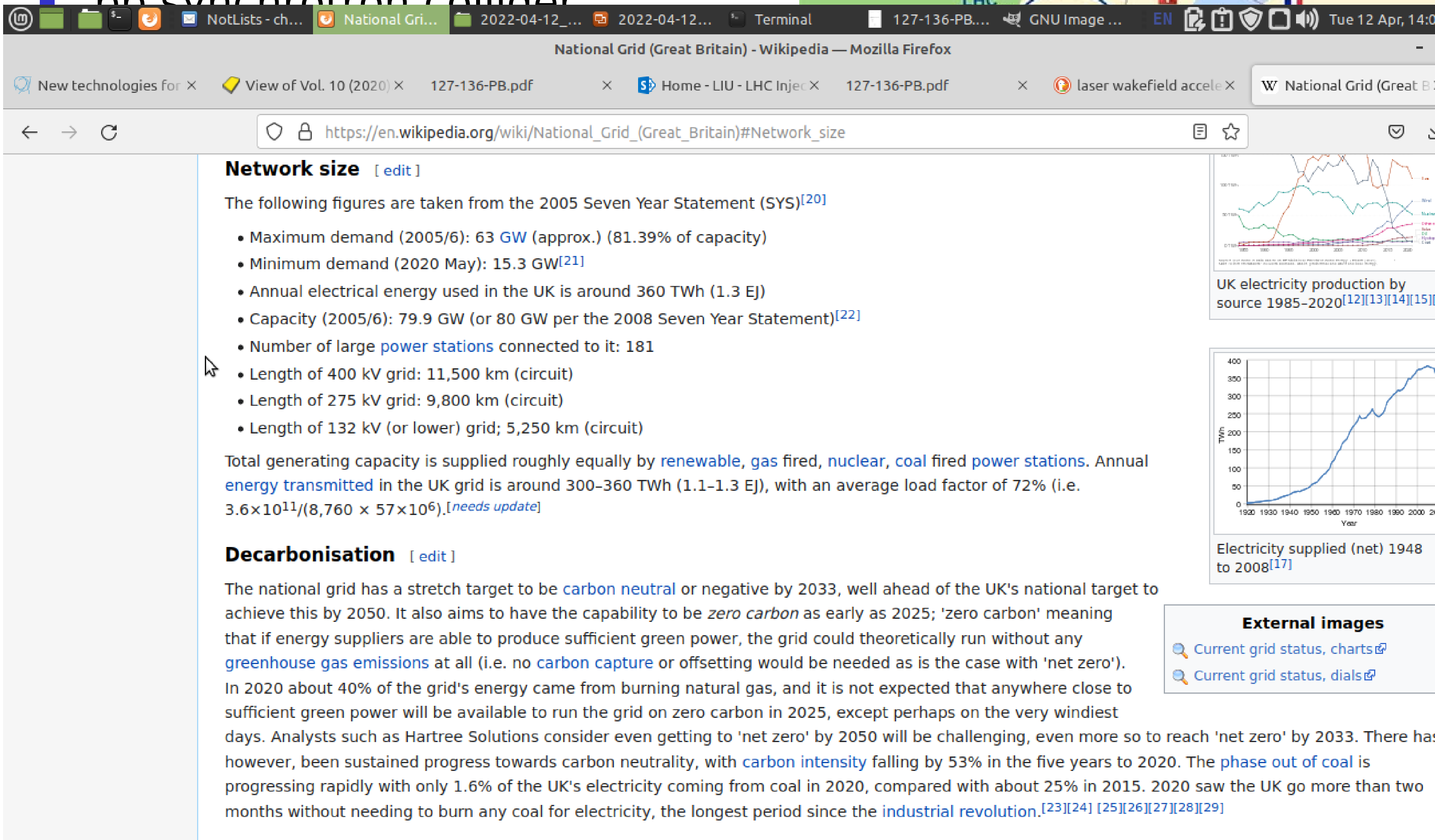
FCC-pp and SppC

- pp synchrotron collider



FCC-pp and SppC

- pp synchrotron collider



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National Grid (Great Britain) - Wikipedia — Mozilla Firefox

https://en.wikipedia.org/wiki/National_Grid_(Great_Britain)#Network_size

Network size [edit]

The following figures are taken from the 2005 Seven Year Statement (SYS)[20]

- Maximum demand (2005/6): 63 GW (approx.) (81.39% of capacity)
- Minimum demand (2020 May): 15.3 GW[21]
- Annual electrical energy used in the UK is around 360 TWh (1.3 EJ)
- Capacity (2005/6): 79.9 GW (or 80 GW per the 2008 Seven Year Statement)[22]
- Number of large power stations connected to it: 181
- Length of 400 kV grid: 11,500 km (circuit)
- Length of 275 kV grid: 9,800 km (circuit)
- Length of 132 kV (or lower) grid; 5,250 km (circuit)

Total generating capacity is supplied roughly equally by renewable, gas fired, nuclear, coal fired power stations. Annual energy transmitted in the UK grid is around 300–360 TWh (1.1–1.3 EJ), with an average load factor of 72% (i.e. $3.6\times10^{11}/(8,760 \times 57\times10^{6})$.[*needs update*]

UK electricity production by source 1985–2020[12][13][14][15][16

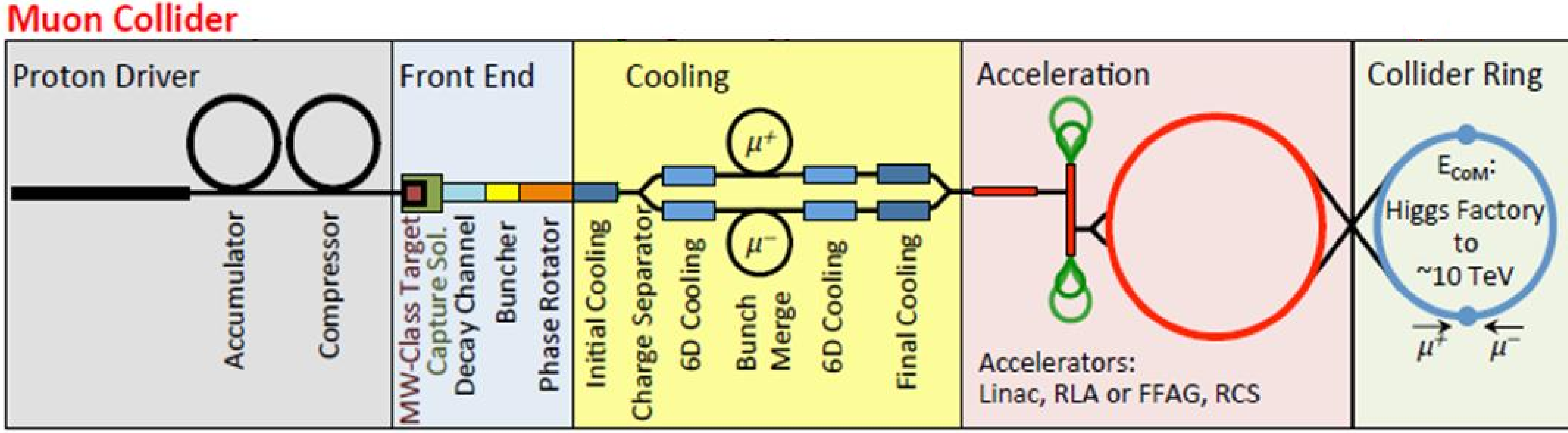
Electricity supplied (net) 1948 to 2008[17]

Decarbonisation [edit]

The national grid has a stretch target to be carbon neutral or negative by 2033, well ahead of the UK's national target to achieve this by 2050. It also aims to have the capability to be *zero carbon* as early as 2025; 'zero carbon' meaning that if energy suppliers are able to produce sufficient green power, the grid could theoretically run without any greenhouse gas emissions at all (i.e. no carbon capture or offsetting would be needed as is the case with 'net zero'). In 2020 about 40% of the grid's energy came from burning natural gas, and it is not expected that anywhere close to sufficient green power will be available to run the grid on zero carbon in 2025, except perhaps on the very windiest days. Analysts such as Hartree Solutions consider even getting to 'net zero' by 2050 will be challenging, even more so to reach 'net zero' by 2033. There has, however, been sustained progress towards carbon neutrality, with carbon intensity falling by 53% in the five years to 2020. The phase out of coal is progressing rapidly with only 1.6% of the UK's electricity coming from coal in 2020, compared with about 25% in 2015. 2020 saw the UK go more than two months without needing to burn any coal for electricity, the longest period since the industrial revolution.[23][24] [25][26][27][28][29]

External images
- Current grid status, charts
- Current grid status, dials

Muon collider



- $\mu^+\mu^-$ collider
  - 3-14 TeV CoM energy (equivalent to ~30-100 TeV protons)
- Challenges
  - Muon production and ionisation cooling
  - Rapid acceleration
  - Neutrino radiation
- Conflict of interest...

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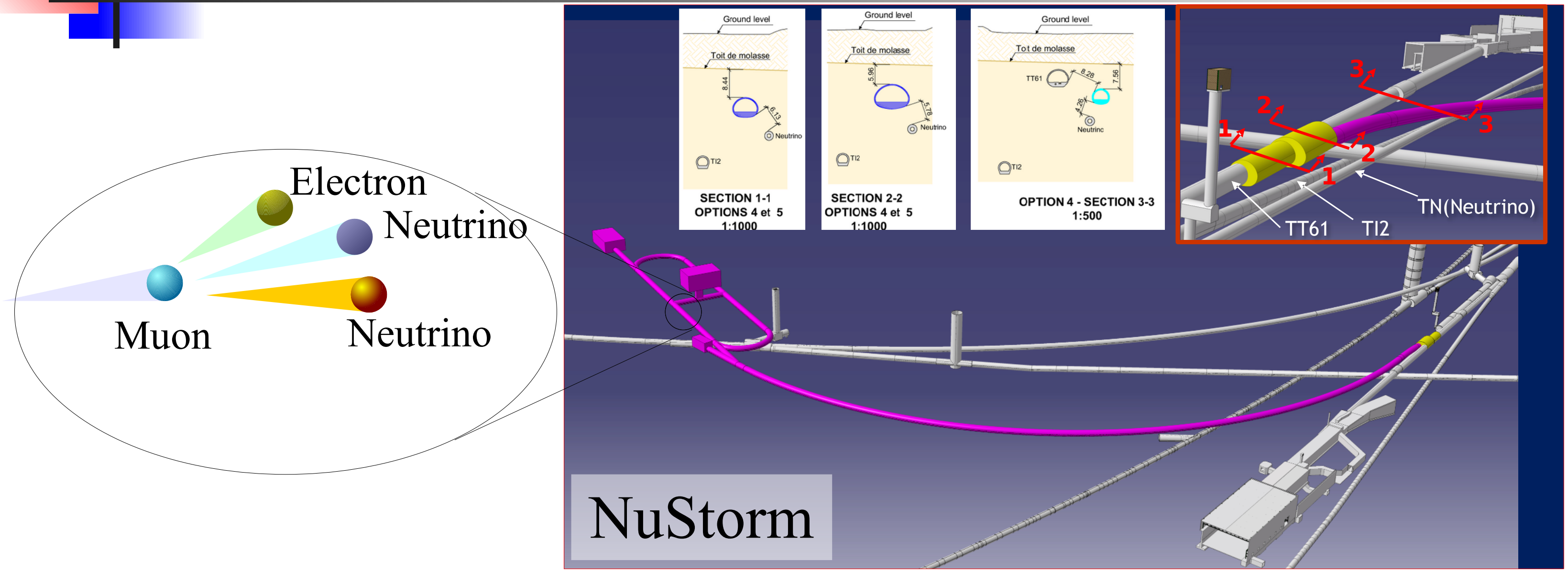
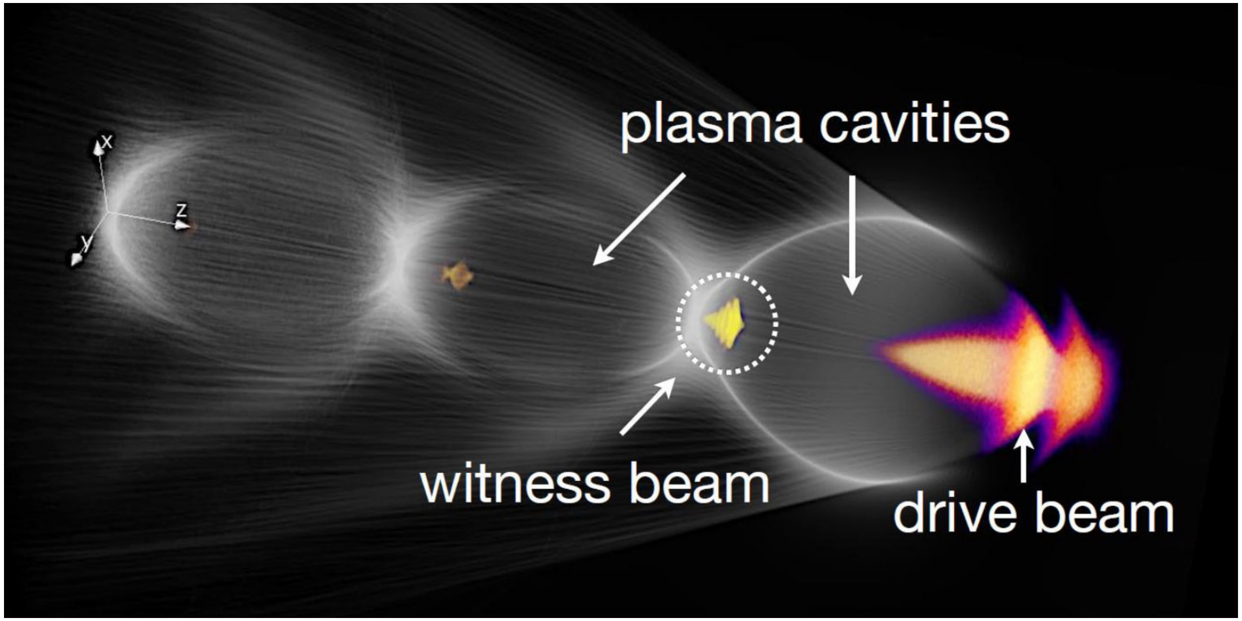
NuStorm (Proposed)



- Precise measurement of ν interactions with matter “NuStorm”
  - Well-characterised muon beam decays to neutrinos
- Challenges
  - Large dynamic aperture muon storage ring
  - Pion decay injection

Plasma Wakefield Accelerators



- Linear colliders limited by RF gradients
  - Breakdown
- Use a laser or electron beam to drive a plasma
  - Very short
- Challenges
  - Positron acceleration
  - Luminosity challenging to achieve
  - Wall plug power

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Questions

- Why is RF a challenge for linear colliders?
- Why does the FCC-ee need such a large ring?
- Why does the FCC-hh need such a large ring?
- Why is muon capture hard?

Questions?

Questions

- Why is RF a challenge for linear colliders?
  - Getting high energy in shorted distance
- Why does the FCC-ee need such a large ring?
  - To minimise synchrotron radiation
- Why does the FCC-hh need such a large ring?
  - To minimise magnet field strength requirement
- Why is muon capture hard?
  - Muons are produced as tertiary particles
  - Muons have very short lifetime

Conclusions

- A number of technologies involved in particle accelerators
  - Magnets
  - RF
- A number of types of accelerators
  - Linac
  - Cyclotron
  - Synchrotron
- Existing facilities
  - Deliver intense beams for secondary particle production
  - High energy beams for colliders
- Future facilities
  - Future beyond LHC
  - Pure neutrino sources

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Quadrupole coils Geek3
https://en.wikipedia.org/wiki/Quadrupole#/media/File:VFPt_quadrupole_coils_1.svg