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Future Accelerator Facilities

for Particle Physics

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Natal School, October 2014

Outline

- Lecture 1: Introduction to accelerators
  - **Historical development & status including LHC & upgrades**
- Lecture 2: Overview of ideas for future facilities
  - **Hadron-hadron machines – LHC (& beyond)**
  - **Lepton-lepton Machines**
    - e^+e^- - linear (circular); $\mu^+\mu^-$
  - **Lepton-hadron machines**
  - **Plasma-wave acceleration**
- Lecture 3: The future in depth – the ILC Project – status & prospects

Lecture 1

- Introduction – the ubiquitous accelerator
- From the earliest days to the LHC – principles of accelerator physics explained via development of accelerators
- The LHC status, future plans and upgrades.

Accelerators everywhere

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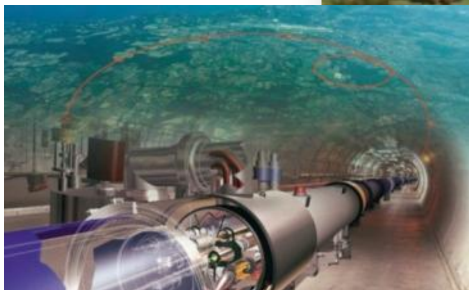

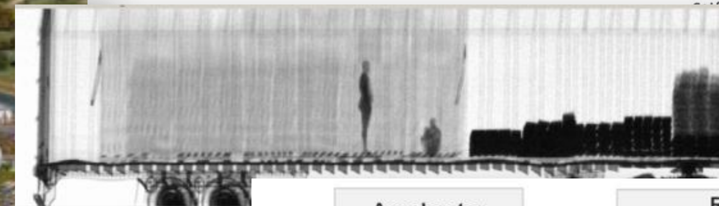

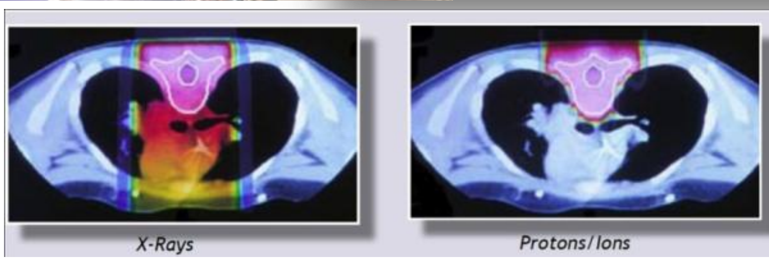

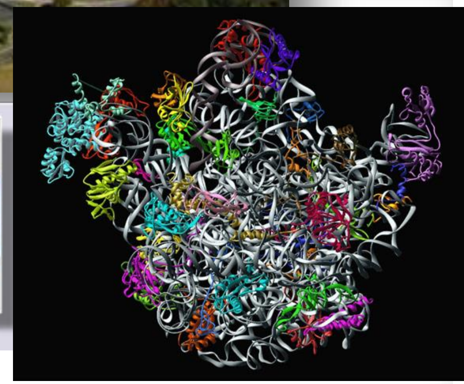

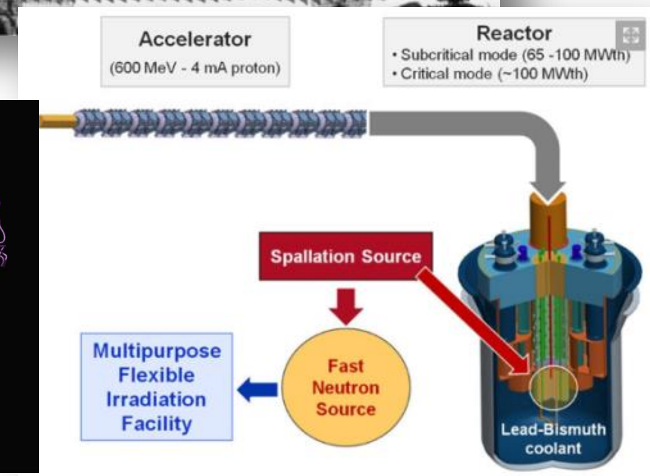

Accelerators: high energy physics, nuclear physics, healthcare, security, energy, life science, novel materials, industry, …

Tens of millions of patients receive accelerator-based diagnoses and treatment each year in hospitals and clinics around the world

products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500B

Around 30% of the Nobel prizes in Physics – and many in other areas – are directly connected to accelerators

Accelerators everywhere

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Why are accelerators so ubiquitous?

Generalisation – modern science is about structures – their determination and the interactions between them.

The cutting edge frontiers are in complex structures of very small size and interactions over very short time scales.

Quantum mechanics as always our guide: wave-particle duality; de Broglie λ; Heisenberg, etc.

Accelerators everywhere

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Diffraction => smallest possible λ to give best resolution => high-energy particles.

Highest intensity beams of probes to see rare properties of target.

Shortest possible bunch structure in time to resolve real-time atomic/molecular interactions.

Solution to all these requirements simultaneously is the particle accelerator - in all its many sizes and forms.

Back to basics

Accelerators work by interaction of electric And magnetic fields on charged particles.

First particle discovery

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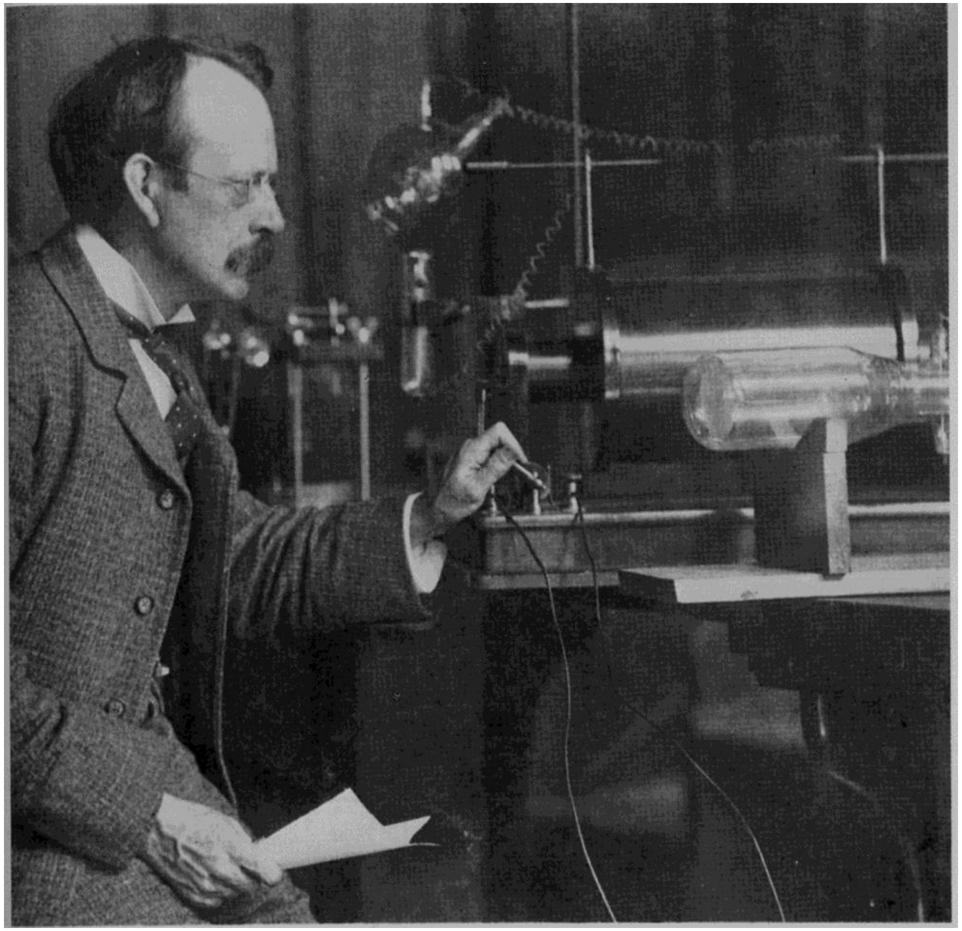
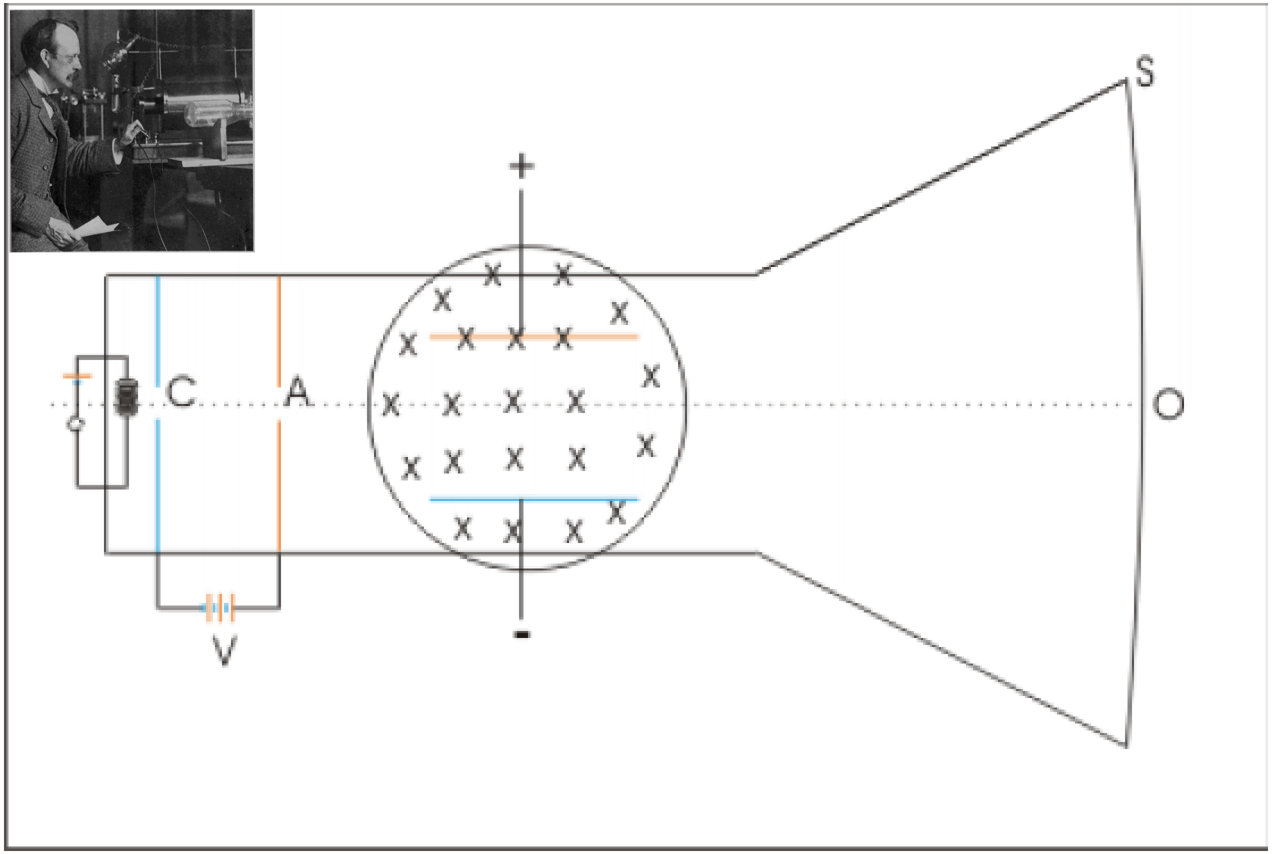
J.J. Thomson used Crookes tubes to discover the electron.



First particle discovery



Electrons accelerated between C & A by V.
K.E. = ½ mv^2= eV
=> v^2 = 2eV/m

Crossed **E & B** fields – first apply **E** & observed spot deviation; then switch off **E** and vary **B** to move spot to previous position. Forces then balanced eE = veB; substituting for v => $e/m = E^2/(2VB^2)$

Accelerator Basics

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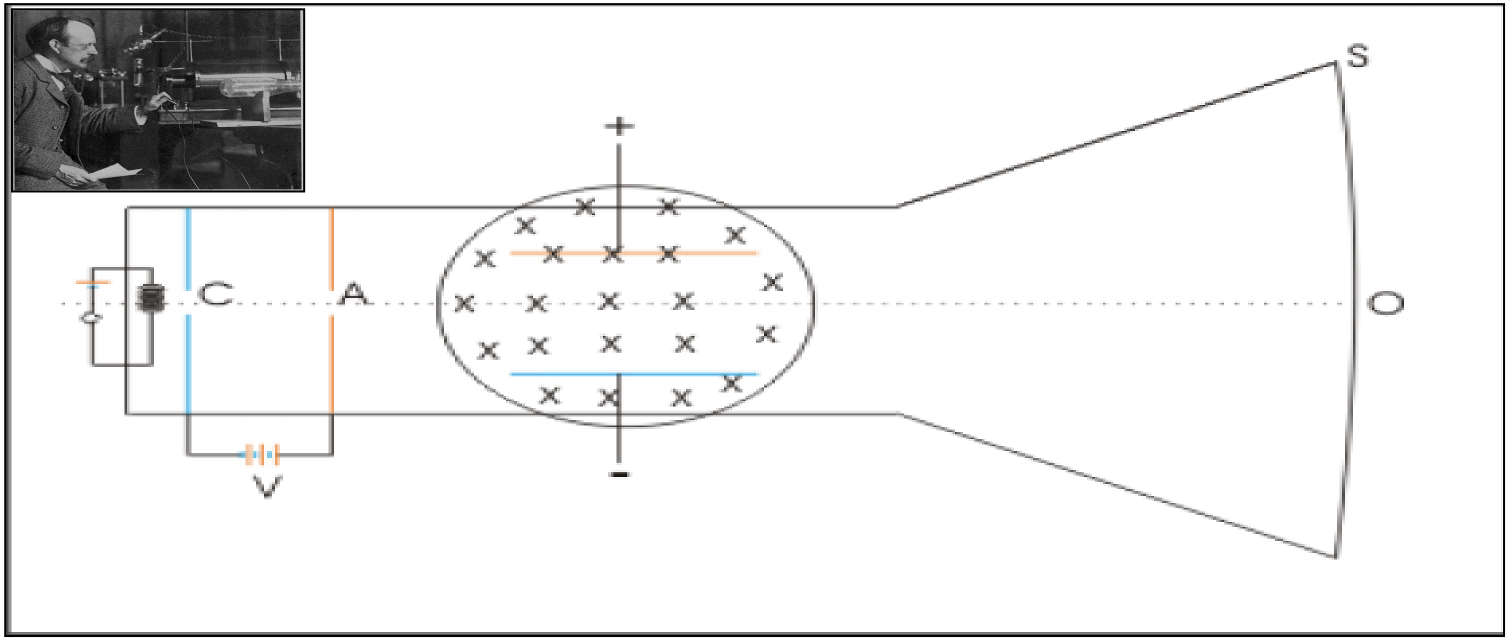

(Bunch &) Collimate

Source

Accelerate

Transport

○ ○ ○

Focus & Deliver

Nature’s Accelerator

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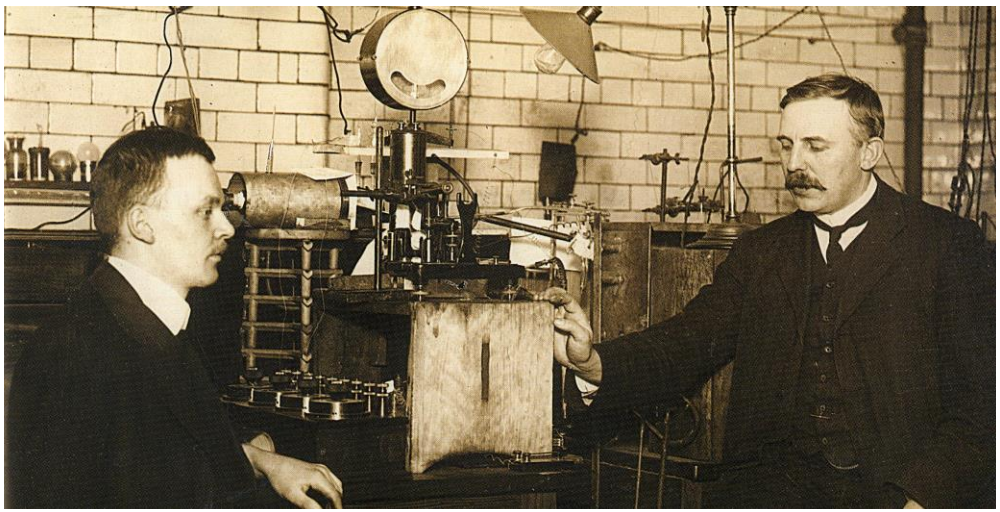
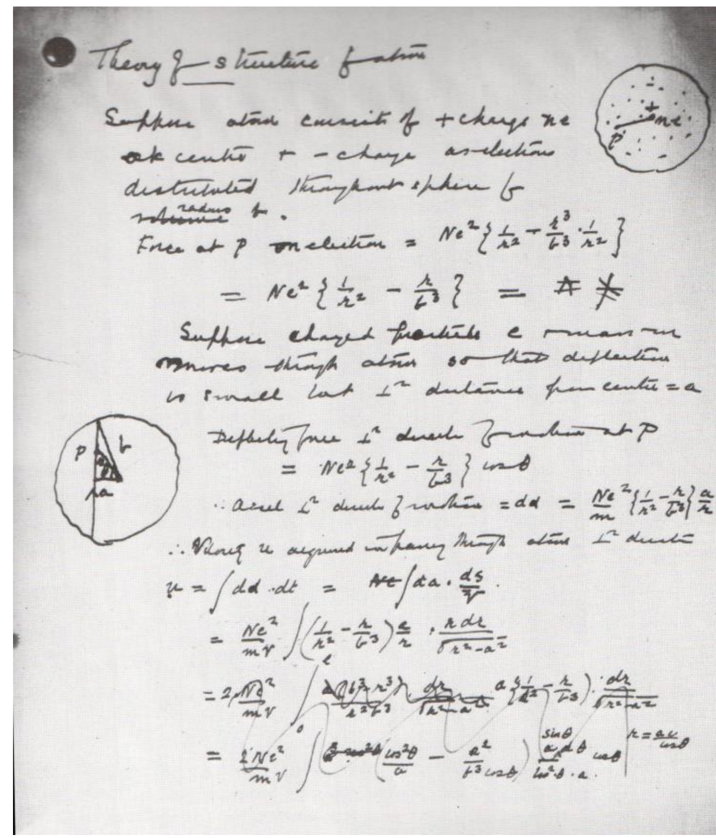
Rutherford utilised Radium from M. Curie to bombard atoms with energetic particles with low wavelength and for first time see inside atom.




Theory of structure of atom

Suppose atom consists of + charge ne at centre & − charge as electrons distributed throughout sphere of radius b.

The first artificial accelerator

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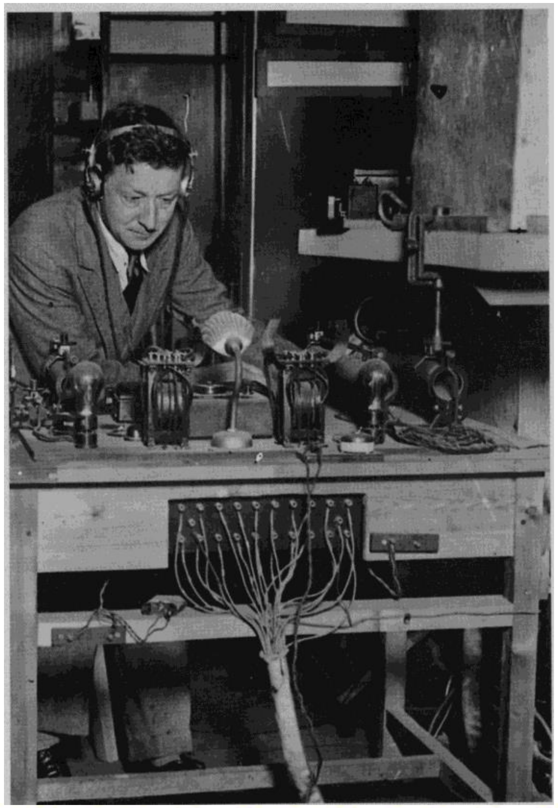
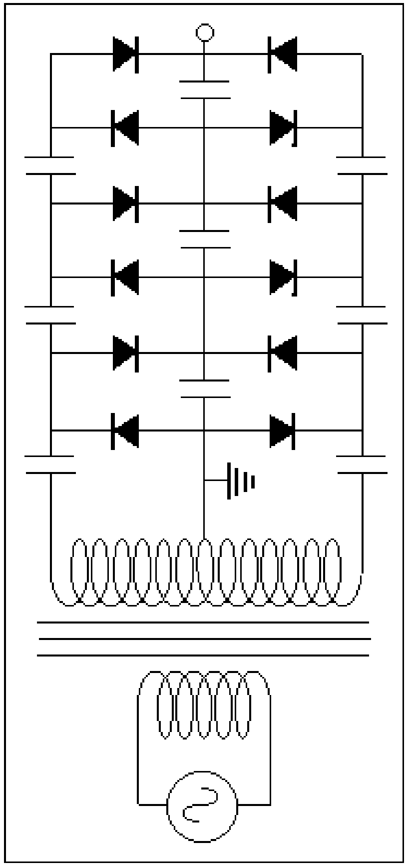
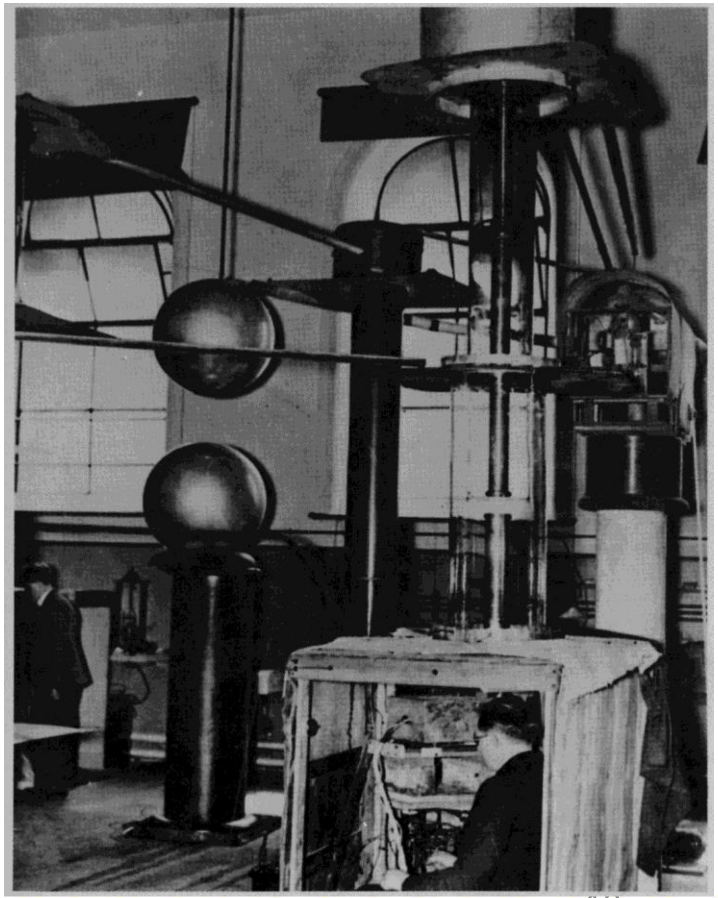
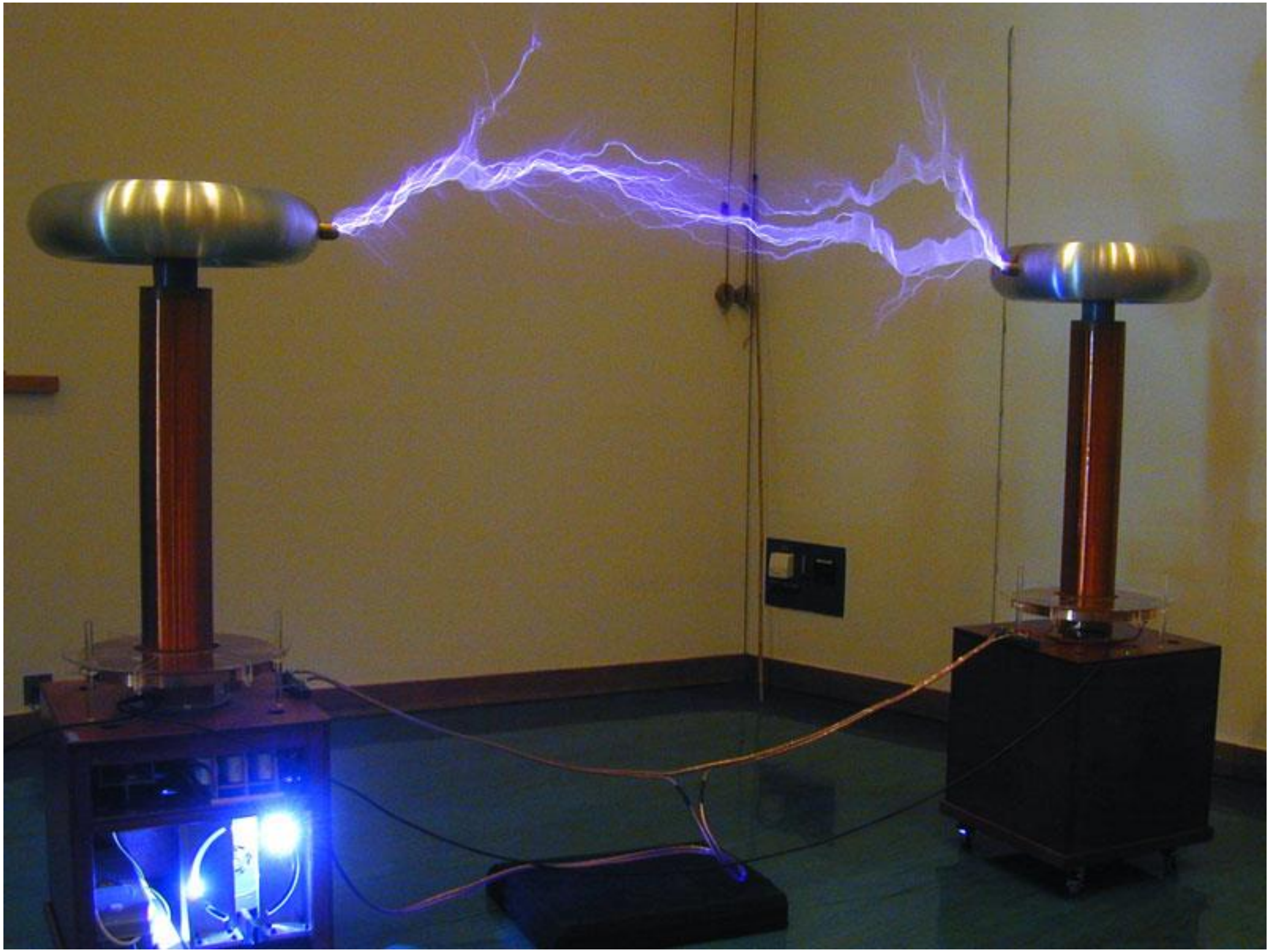
Cockroft and Walton in 1932 worked out how to produce high voltages (millions of volts) to accelerate particles – artificially split nucleus & discovered the neutron – Nobel Prize in 1951.





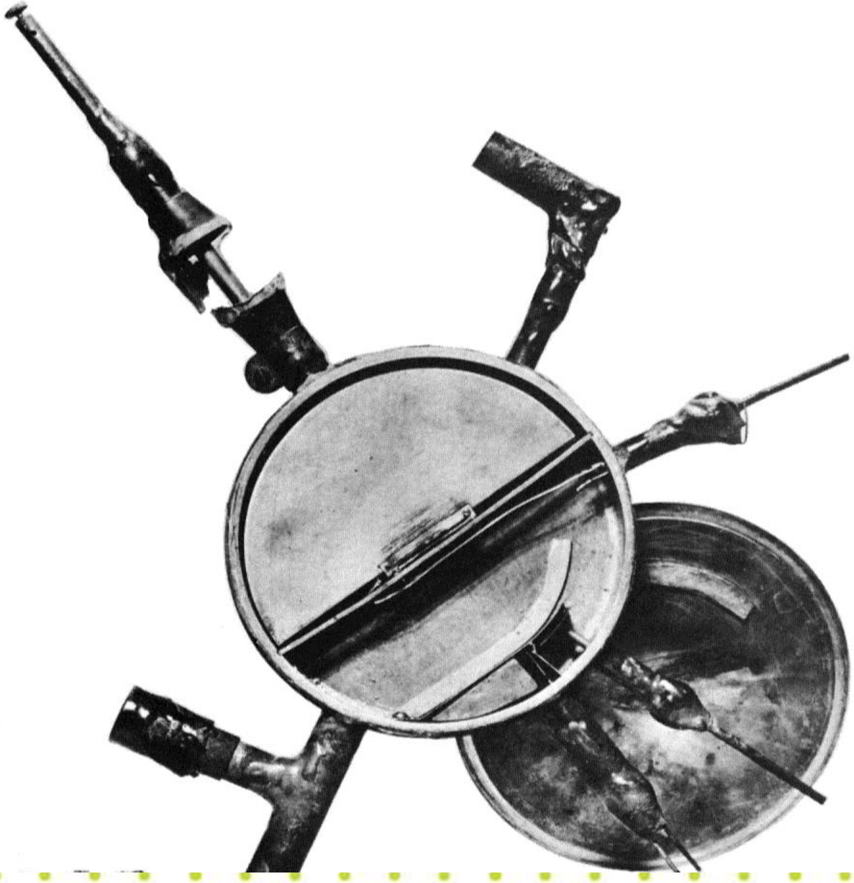


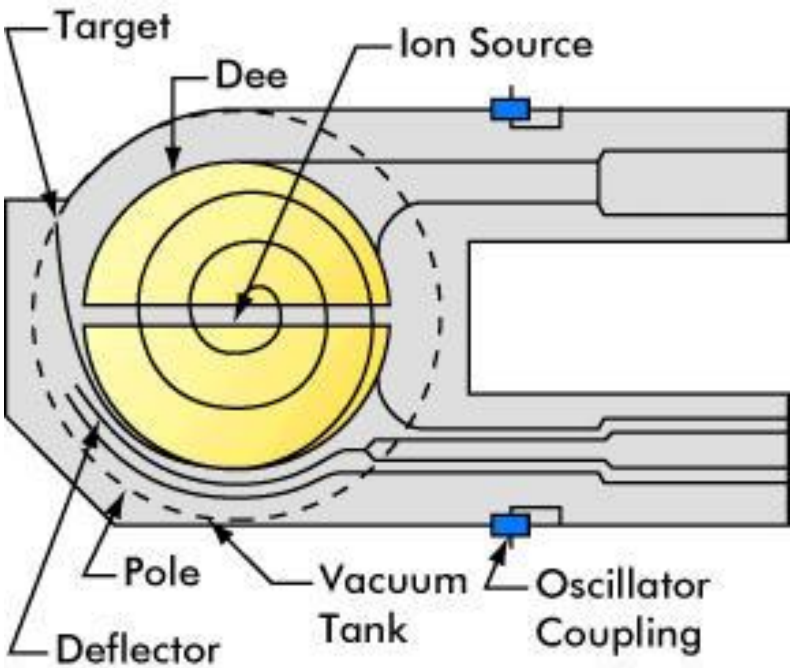
A Problem



First of the Big Machines

In 1930 in Berkeley in California, E.O. Lawrence had developed a new sort of accelerator – the cyclotron.





Principle of Cyclotron

$\mathbf{F} = d\mathbf{p}/dt = d(m\mathbf{v})/dt = e\,\mathbf{v} \times \mathbf{B}.$

Assume motion confined to x-y plane and $\mathbf{B} = B_z$

$\Rightarrow \mathbf{p} = m(v_x, v_y, 0)$

From above $d\mathbf{p}/dt = e(v_y B_z, -v_x B_z, 0)$ (1)

Differentiating (1) component by component & substituting e.g. $dv_y/dt = -ev_x B_z/m$ gives:

$d^2v_x/dt^2 + (eB_z/m)^2 v_x = 0$

$d^2v_y/dt^2 + (eB_z/m)^2 v_y = 0$

with solutions $v_x = v_0 \cos \omega t$; $v_y = v_0 \sin \omega t$

$\Rightarrow$ Circular motion with radius $R = m\sqrt{(v_x^2 + v_y^2)}/(eB_z)$

where ω is cyclotron frequency $(e/m)B_z$

The Bigger Machines

Virtue of cyclotron was that energy could be increased without encountering physics limitations – instead limitations were financial and logistical!

The Synchrotron

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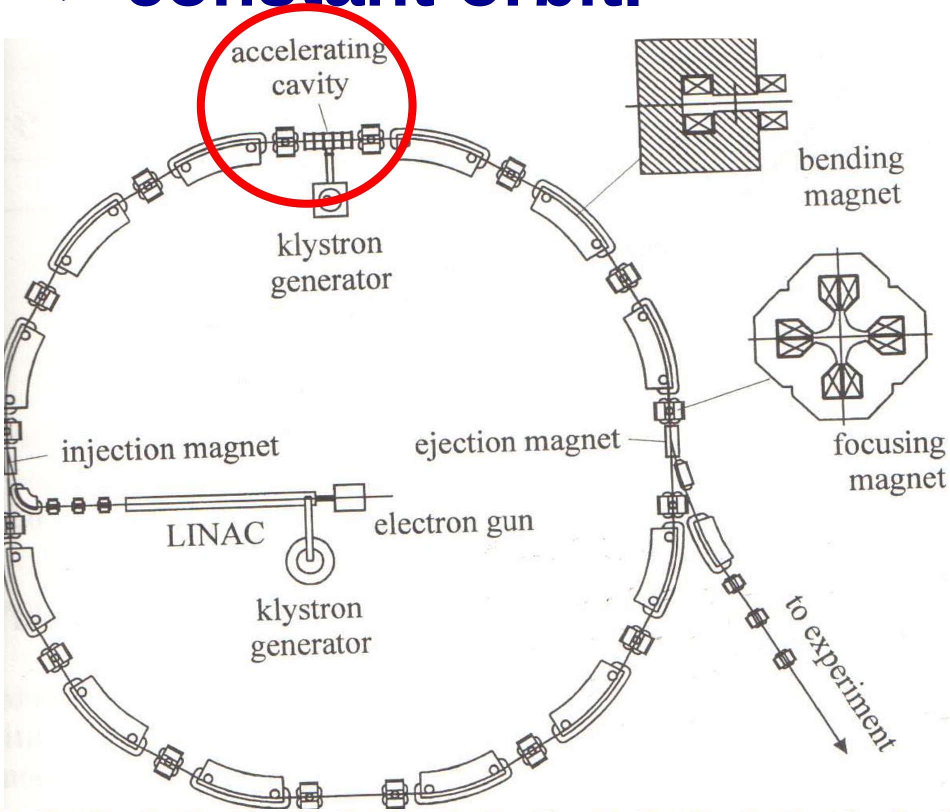
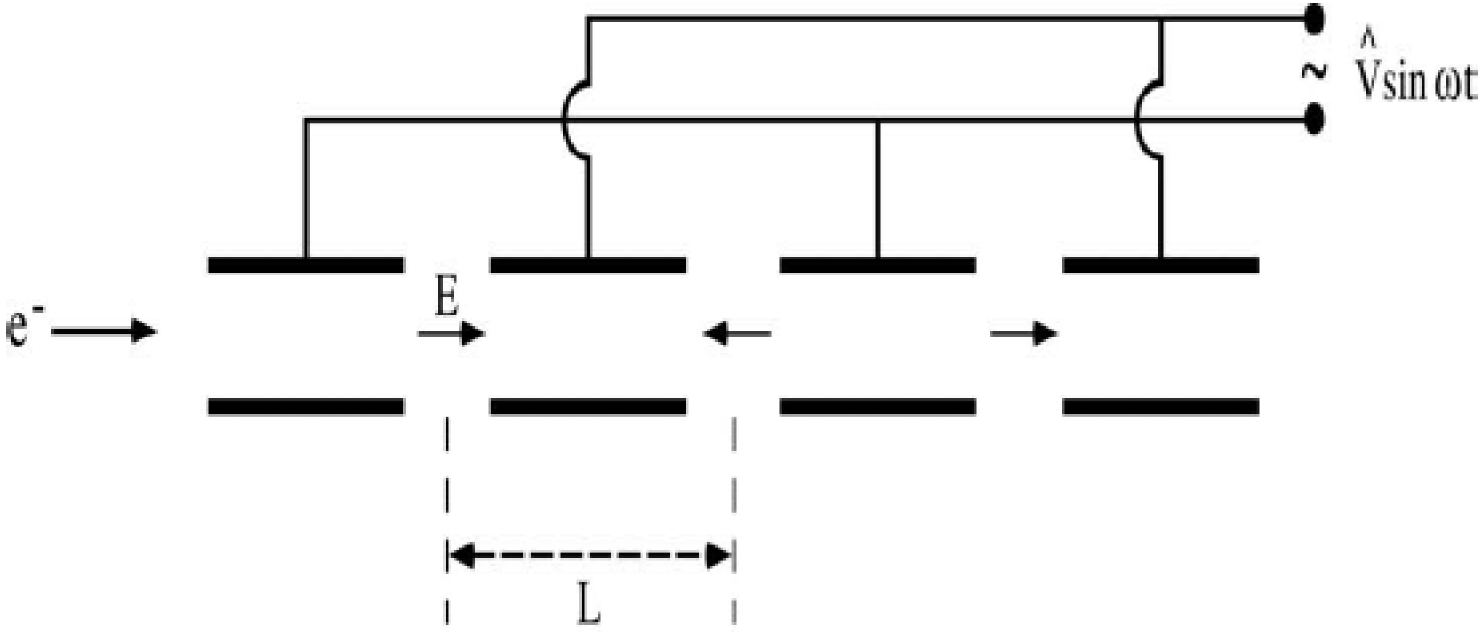
Limitations of cyclotron were overcome by development of synchrotron – split magnets into small ones in ring & ramp field so it increases as particle energy => constant orbit.



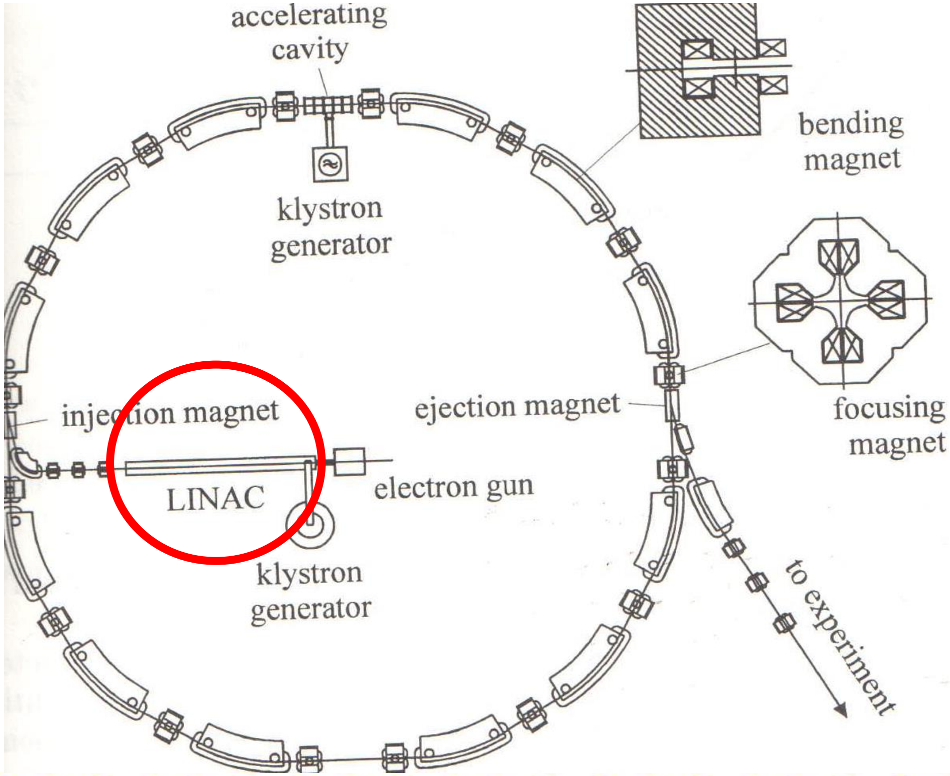
RF acceleration



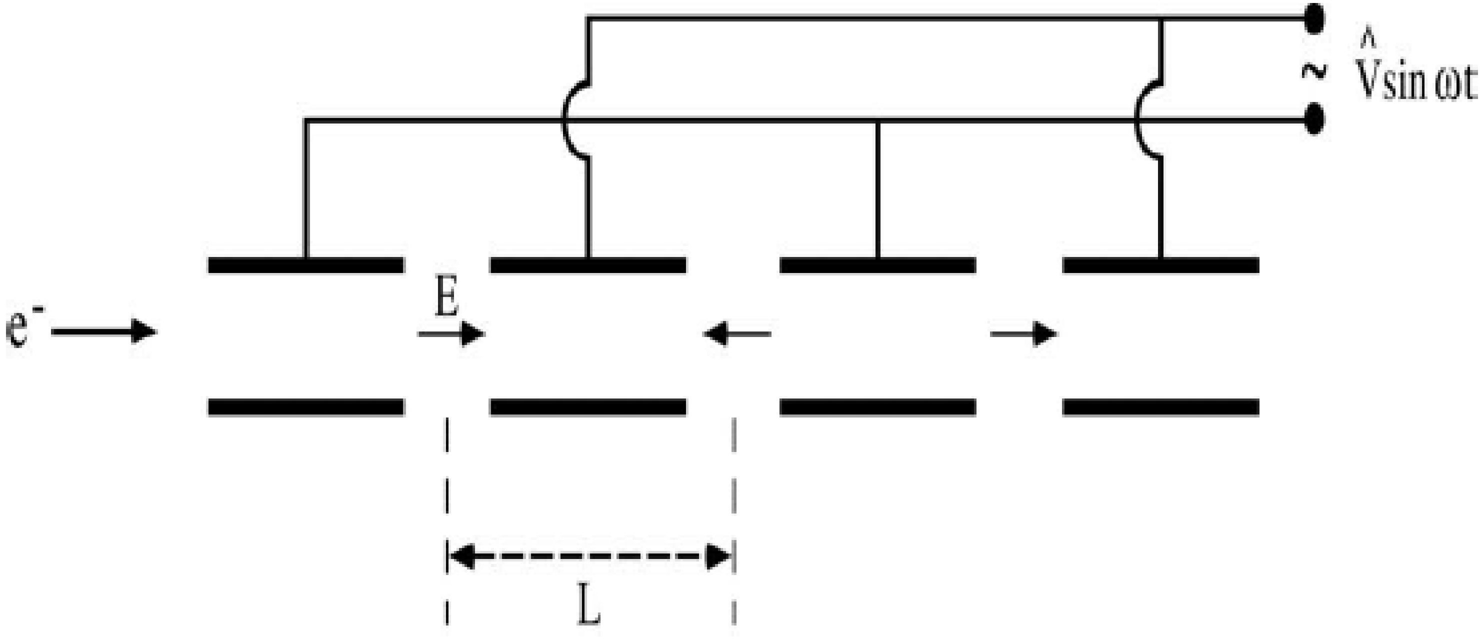
For relativistic particle travelling with v = c particle always accelerated if in synch.
$\Rightarrow$ L = c T/2 = c π/ω

The Synchrotron

Relativistic corrections.



RF acceleration



Non-relativistic particle also always accelerated if in synch.

L = v T/2 = v π/ω □ for initial linac from cathode,

v ≠ c so that spacing of electrodes must vary – increasing as √number counting from cathode.

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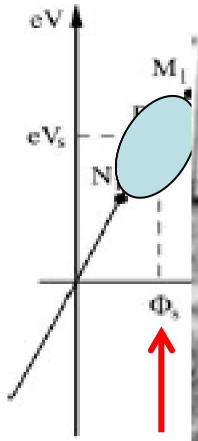


Synchr

P_1 & P_2 are s … les M_1 & N_1 are moved t … from P_2. "Principle o … ered 70 years ago th … millan!

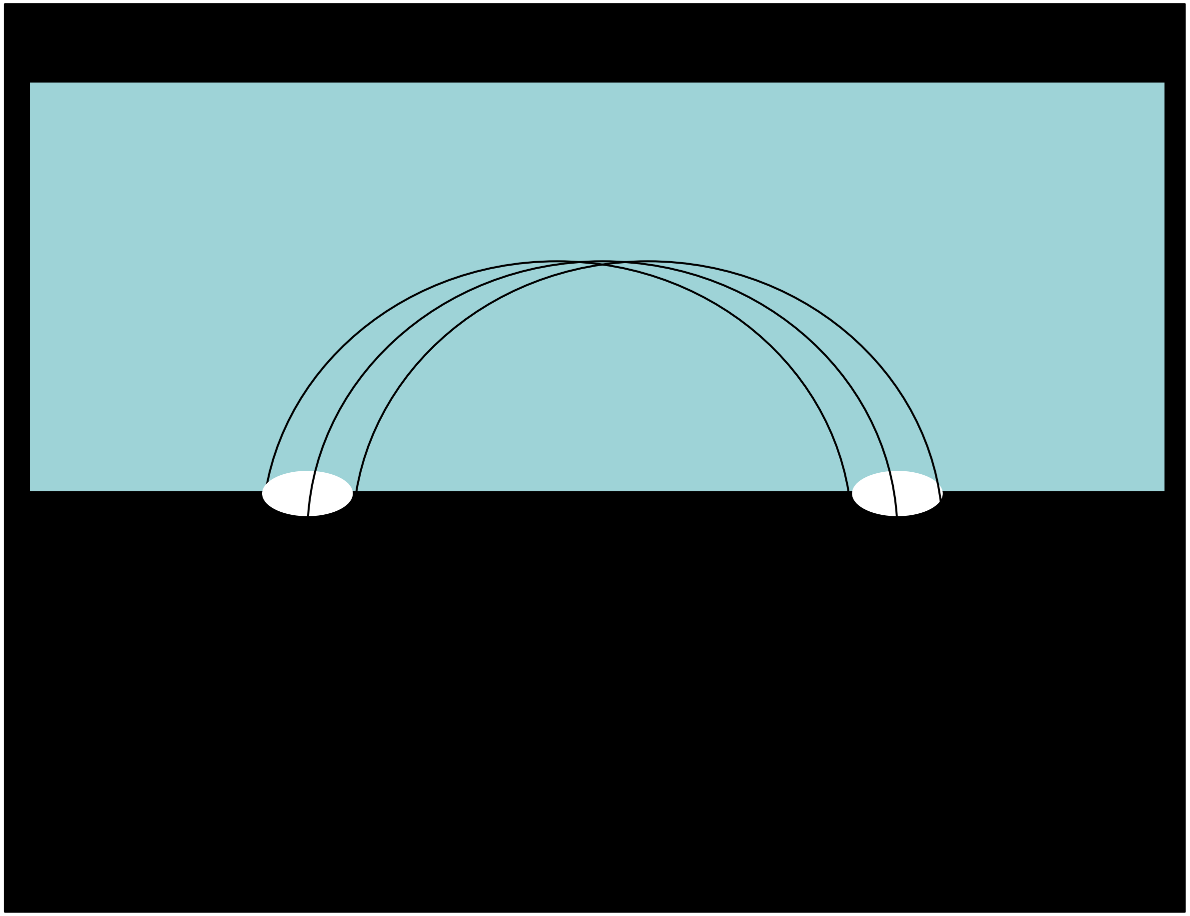
Phase stability

Longitudinal phase stability implies transverse defocusing - ~ Liouville's Theorem.

If □E_z/dz > 0 then debunching occurs => □E_z/dz < 0 . From Maxwell Eqns., $\nabla . E = 0$
So in 2D, □E_x/dx +□E_z/dz = 0 => **□E_x/dx** > 0. **So defocusing in transverse direction requires some form of external focusing to maintain stability.**

Weak focussing

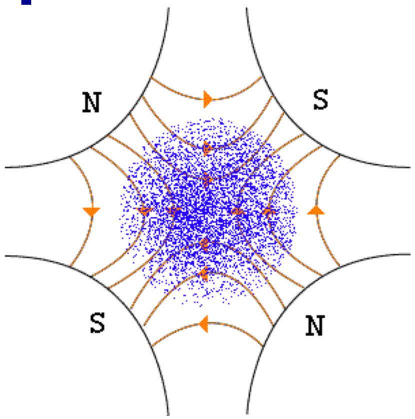
Need to consider bunches, not just single particles. What happens to bunch in dipole?



Vertical bending also possible by tilting pole-pieces. Focussing is much weaker however than the bending.

Strong focussing

Accelerators based on weak focussing were enormous both is size and expense – weight of iron – same problem as Lawrence's cyclotron. To make smaller => higher E, alternate magnetic field direction. Use specific focussing magnet – quadrupole.



Fine, but focussing in one dim. defocusses in other. Alternate quads with opposite polarity – alternating gradient – gives net focussing in both directions. FODO lattice.

The modern accelerator

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First machine with strong focussing was 1.5 GeV machin… t Cornell. Proton machine … ookhaven (AGS) followed. … n @ Dubna weighed 36000 t… eV. The PS weighed 3200 to… V.

Today's accelerators

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SLAC - Stanford, Ca.

CERN - Geneva, CH.

The colliders

So now we can focus beams onto a target and do experiments – fine for many years. But search for higher energies eventually required a diferent approach.

For beam hitting a target, CoM energy s given by
(E,0,0,p) + (m,0,0,0) = (E+m,0,0,p);
$s = E^2 + 2mE + m^2 - p^2 \sim 2mE$, for E >> m.

In a collider, $s = (E^*)^2 \Rightarrow E^* = \sqrt{(2mE)}$ e.g.
to produce charm quarks in fixed target from e^+e^- collisions requires a beam energy of 10 TeV.

The colliders

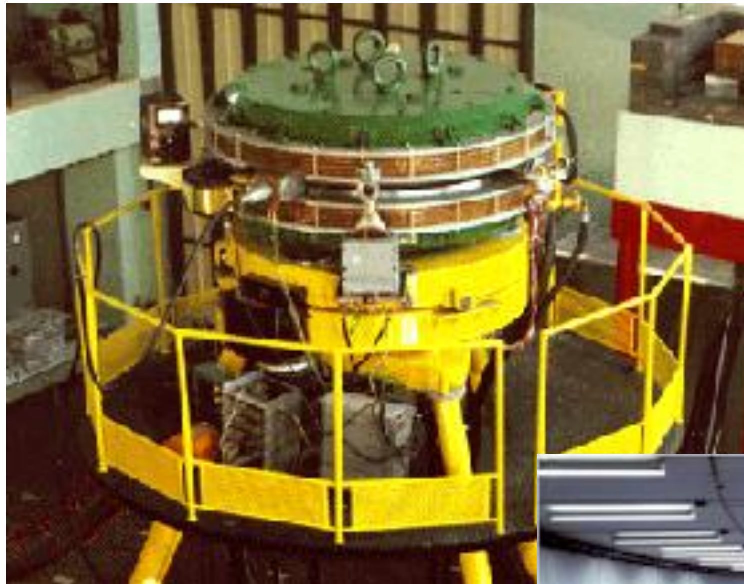
Collider gives excellent energy reach, but density of fixed target much greater than a beam of accelerated particles => much reduced collision rate. Need to maximise this in collider.

$$L = (1/4\pi)(fN_1N_2)/(\sigma_x\sigma_y)$$

Furthermore, cross section for point-like processes drops like 1/s – so as energy of interaction increases L must increase like E^2 to produce same number of interactions/sec.

The colliders

First collider ADA at Frascati – electron-positron.

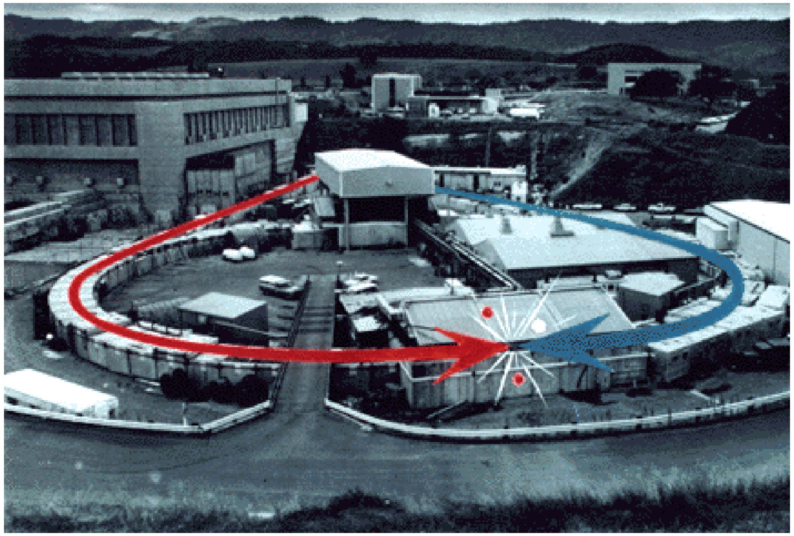


VEPP-1 e-e-
Budker Inst.

ISR pp

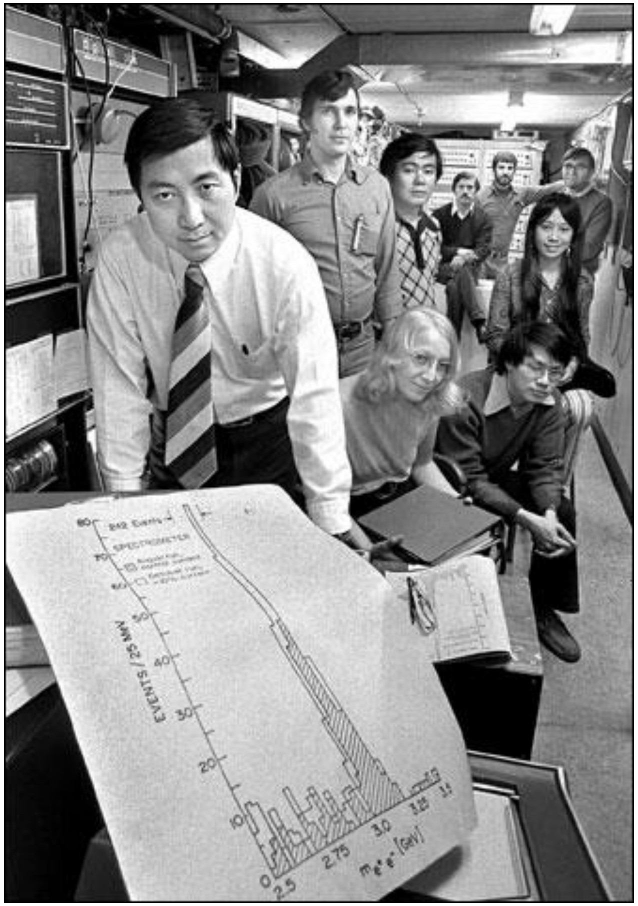
Complementarity – e^+e^-/ pp

SPEAR @ SLAC



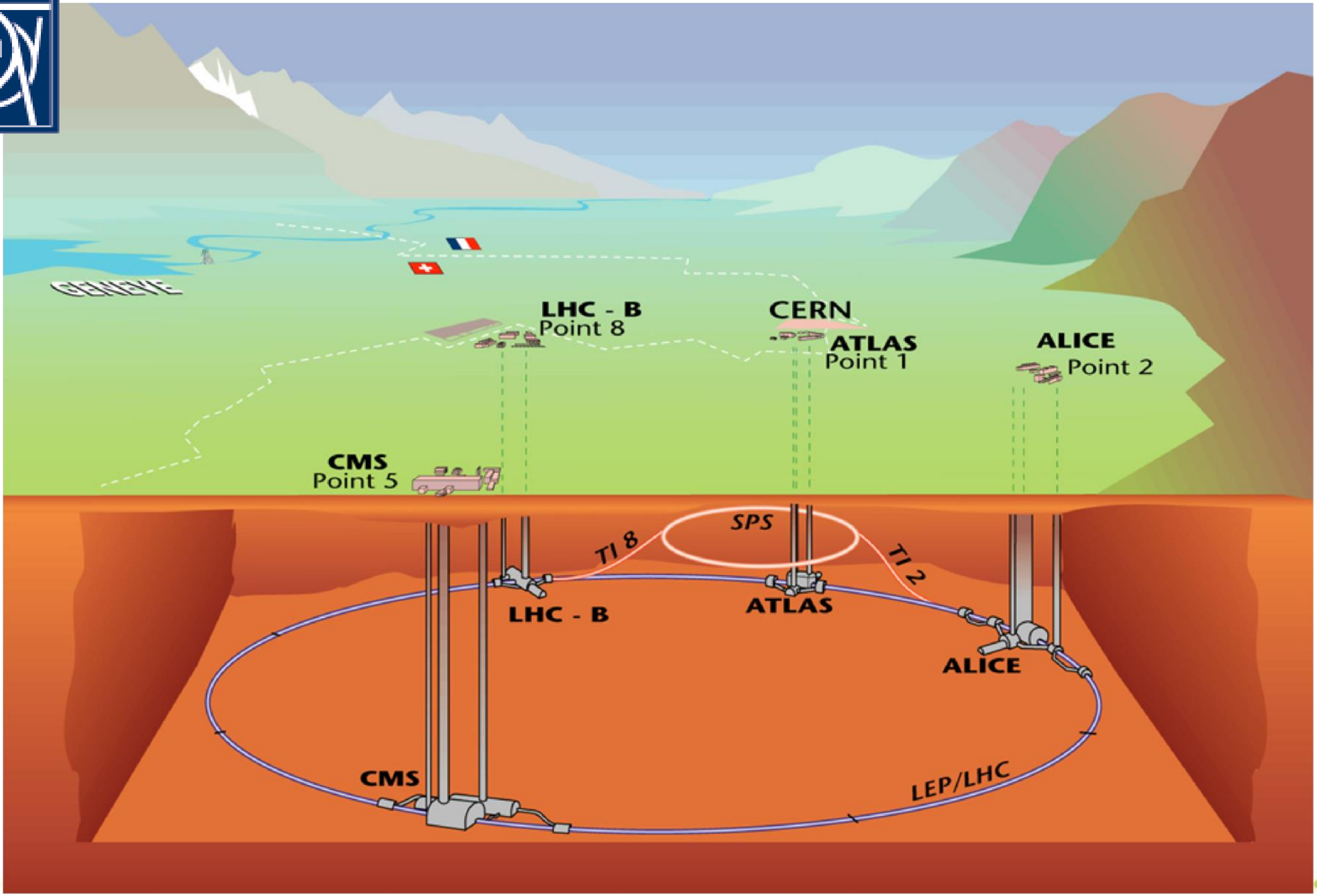
Ψ

AGS @ Brookhaven



J

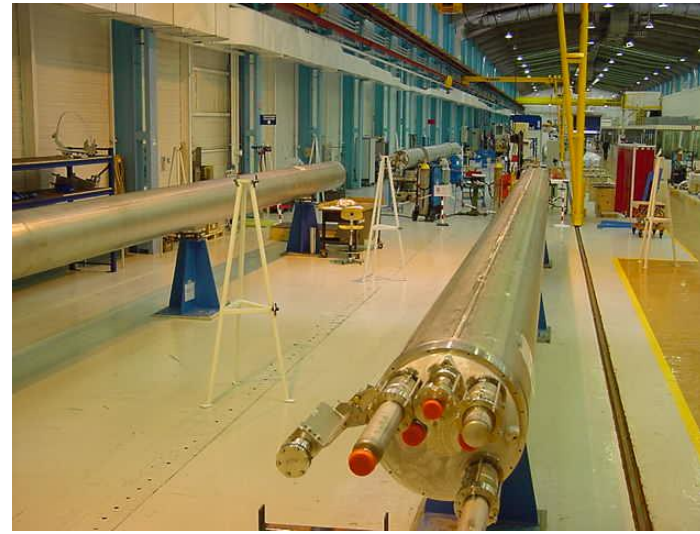
LHC Project

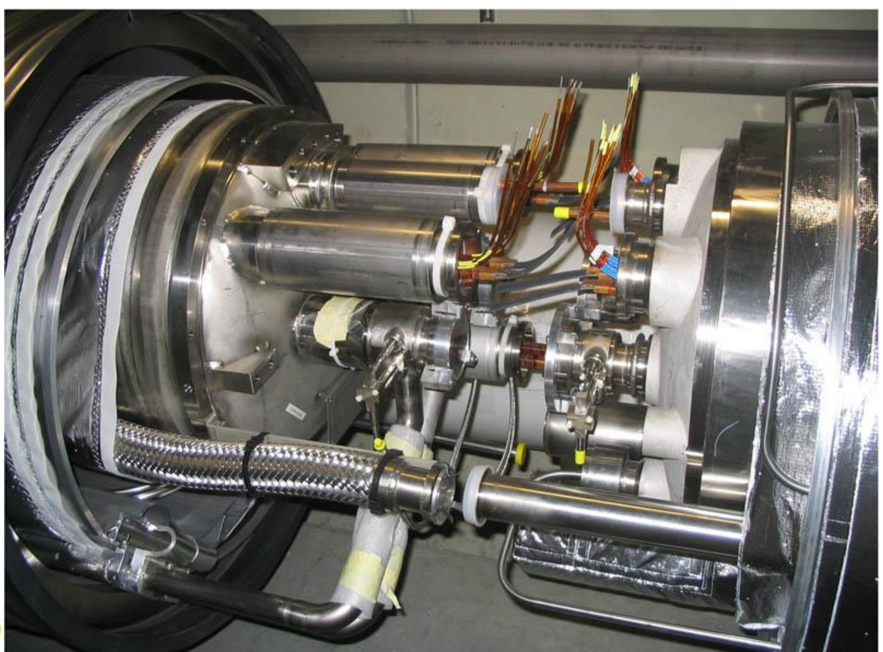


50m - 175m

The LHC Accelerator

The LHC is an amazing feat of engineering - 27 km of the most high-tech equipment in the world's biggest instrument.





LHC Physics

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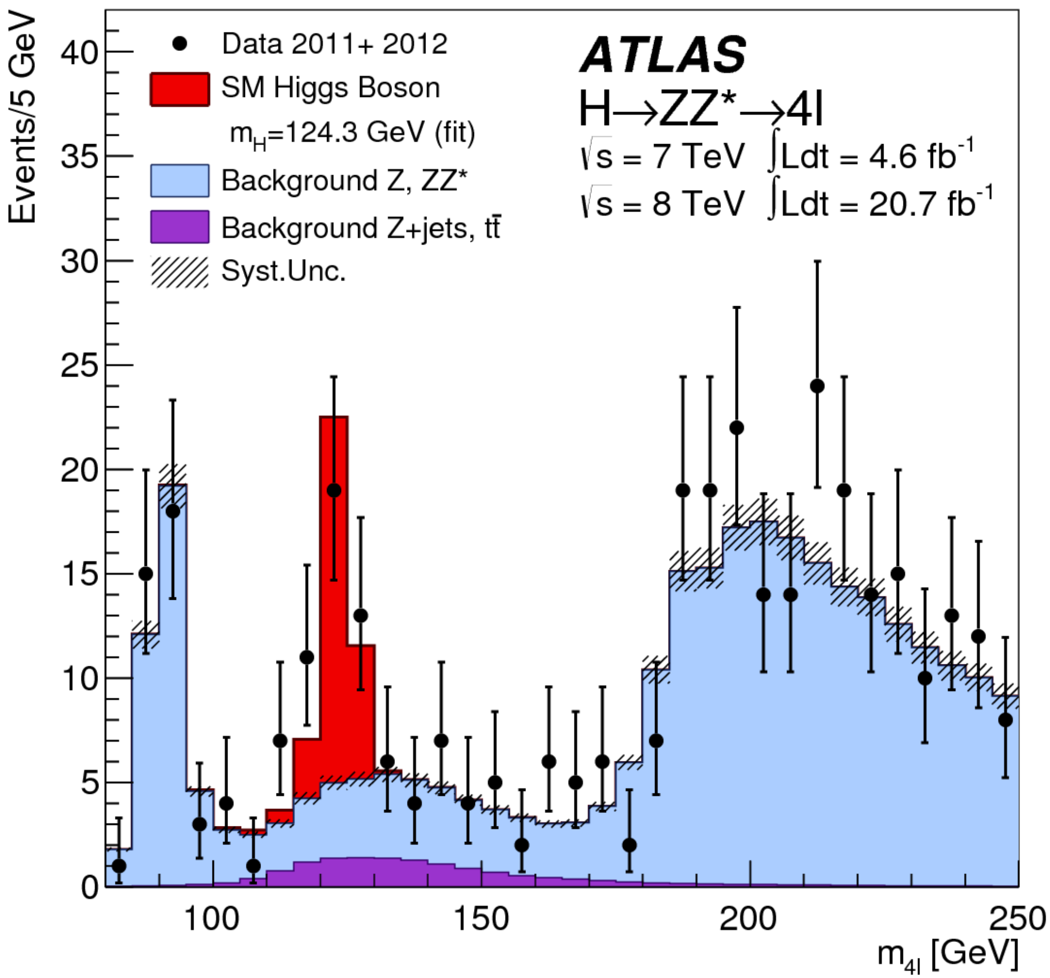
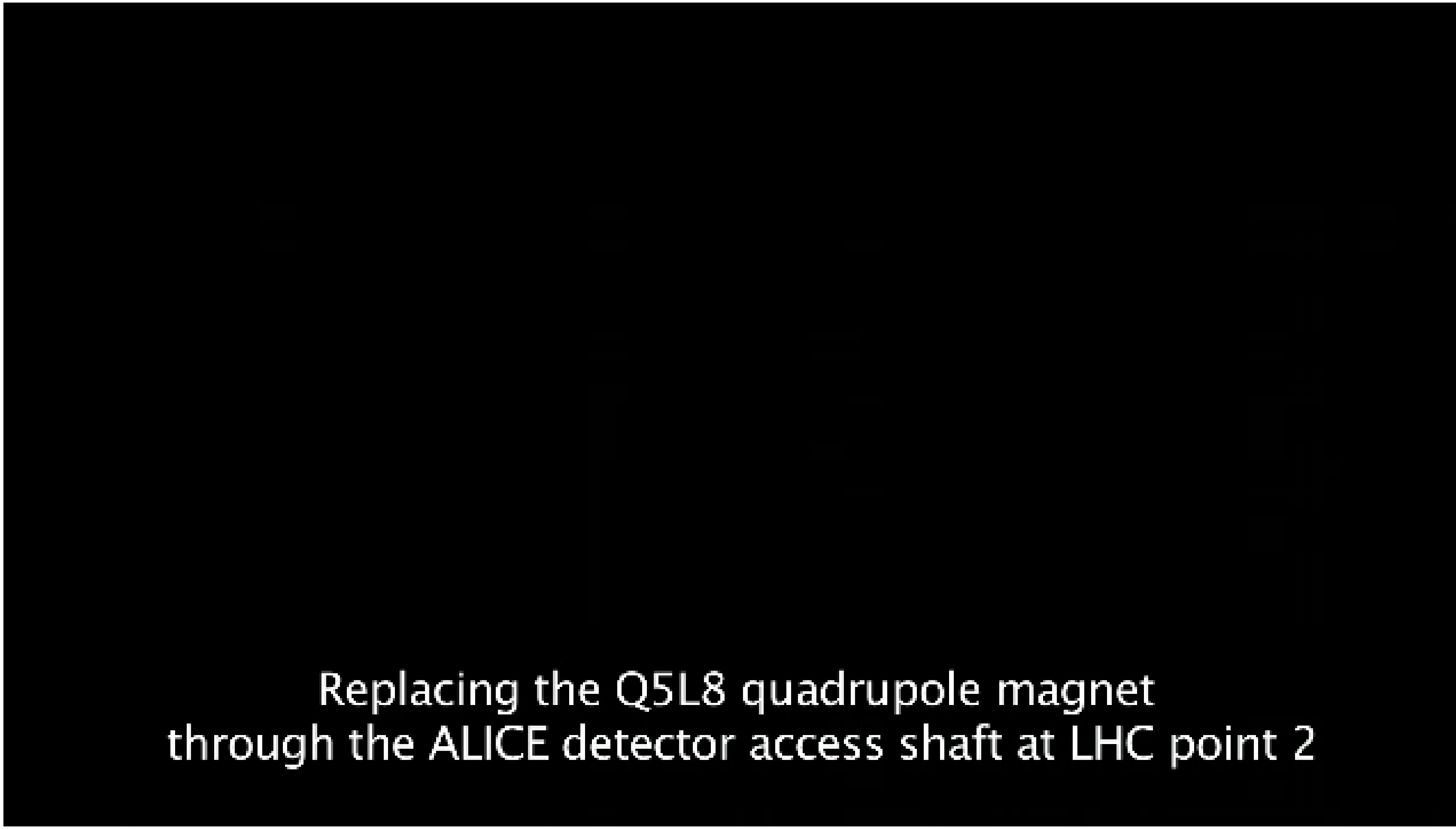
- ## Higgs



LHC Shutdown

LHC Shutdown



Run 2 Startup

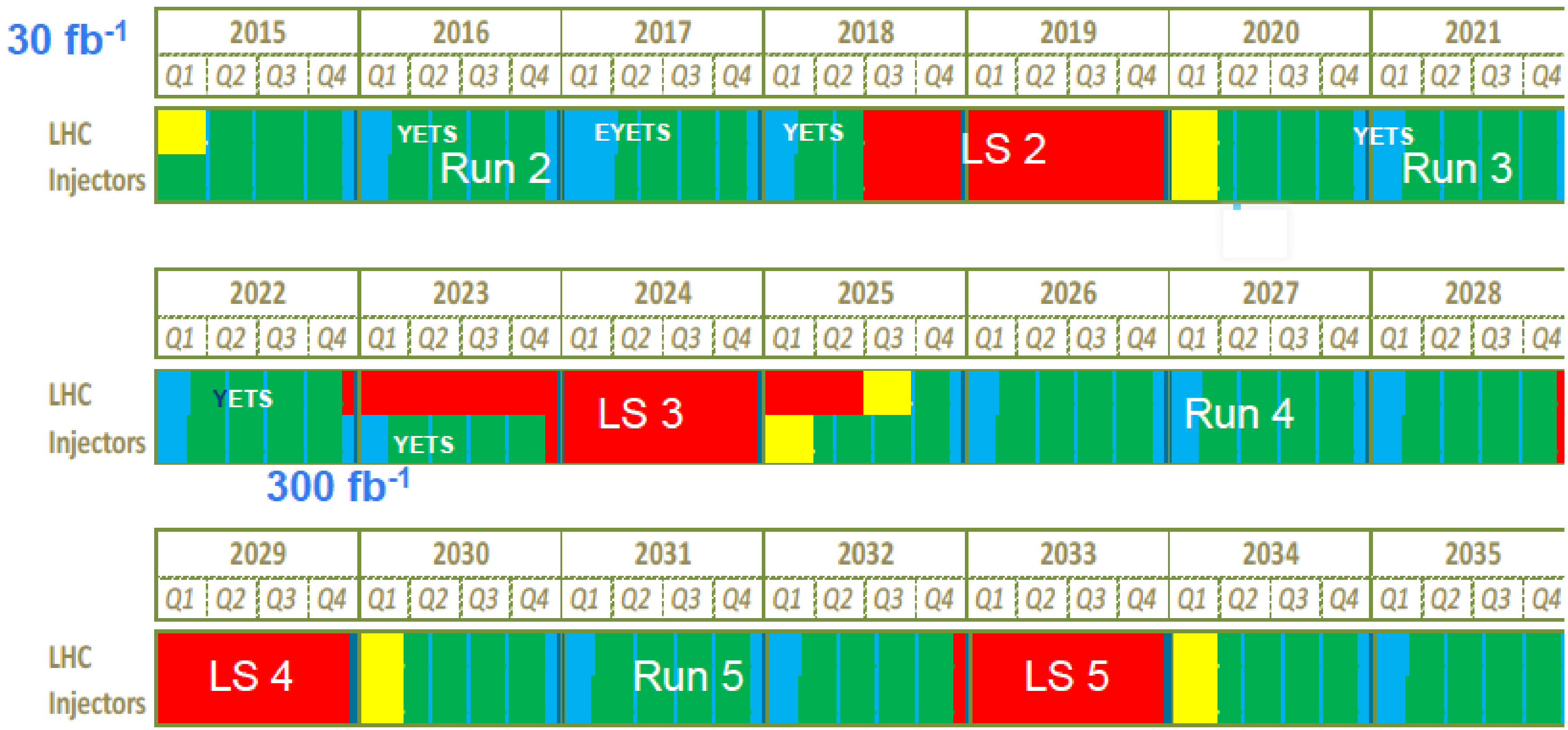
- Lastest plans as discussed at LHC Performance Workshop (Chamonix), September https://indico.cern.ch/event/315665/
- First beam planned for week of March 9th
- First collisions planned for week of June 4th
  - 100 days of collisions planned
- Beam energy: 6.5 TeV
- bunching spacing: 25ns (short period of running with 50 ns also envisaged)

LHC Strategy

LHC schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

- Physics
- Shutdown
- Beam commissioning
- Technical stop



(Extended) Year End Technical Stop: (E)YETS

3’000 fb^{-1}

HL-LHC

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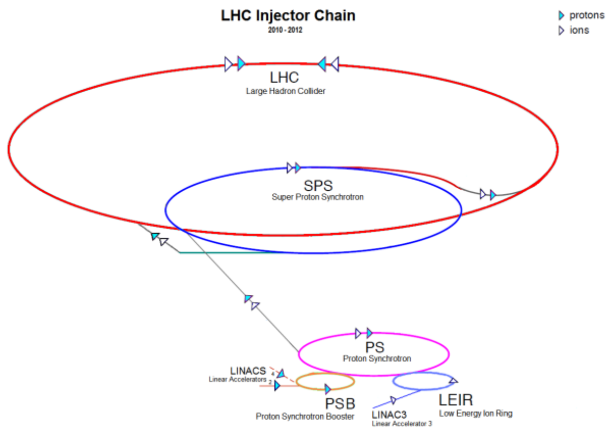
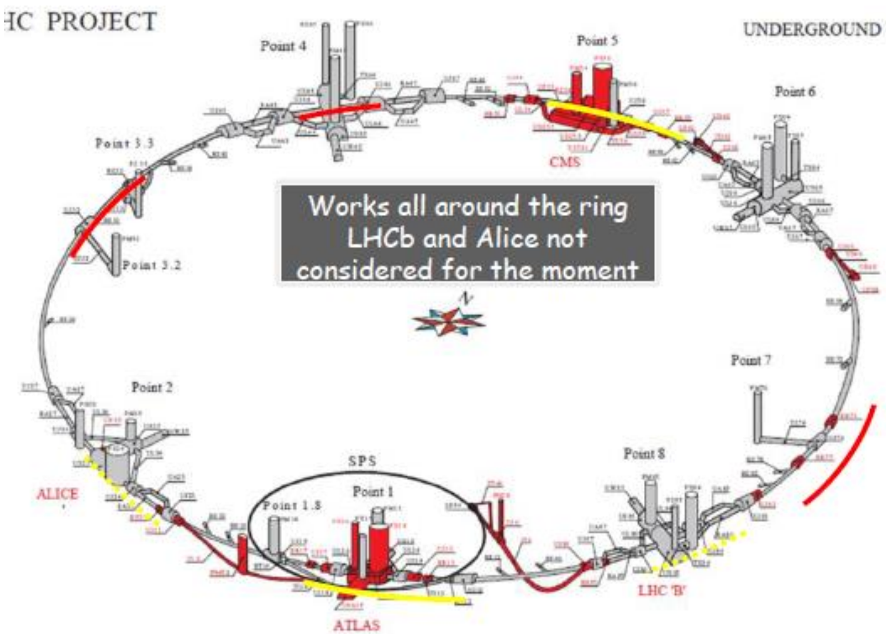
Goal is to obtain about 3 - 4 fb^{-1}/day (250 to 300 fb^{-1}/year)

Many improvements on the injector chain

- Linac 4 - PS booster
- PS
- SPS





Many improvements on the LHC ring

- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

LHC Technology

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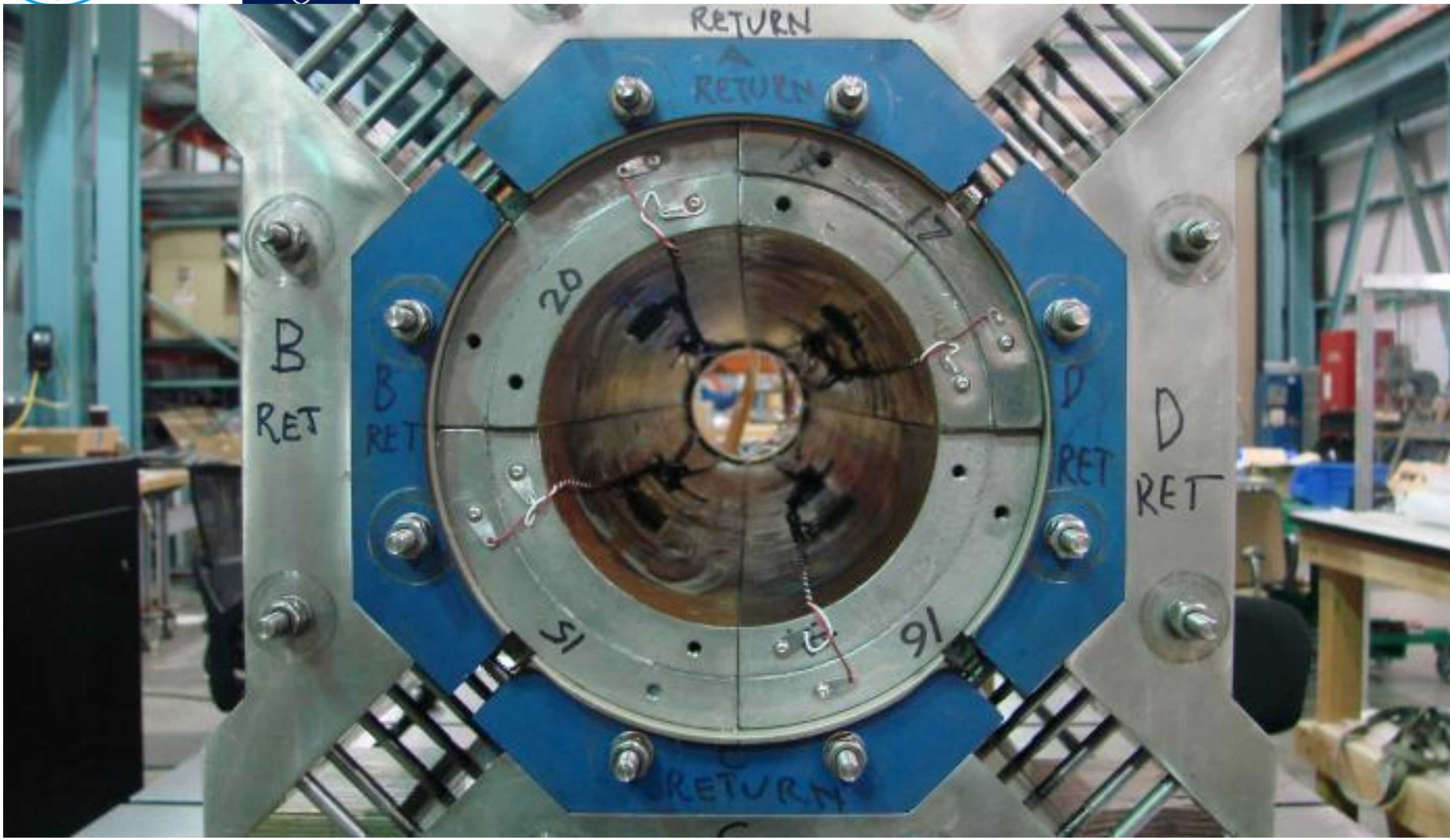
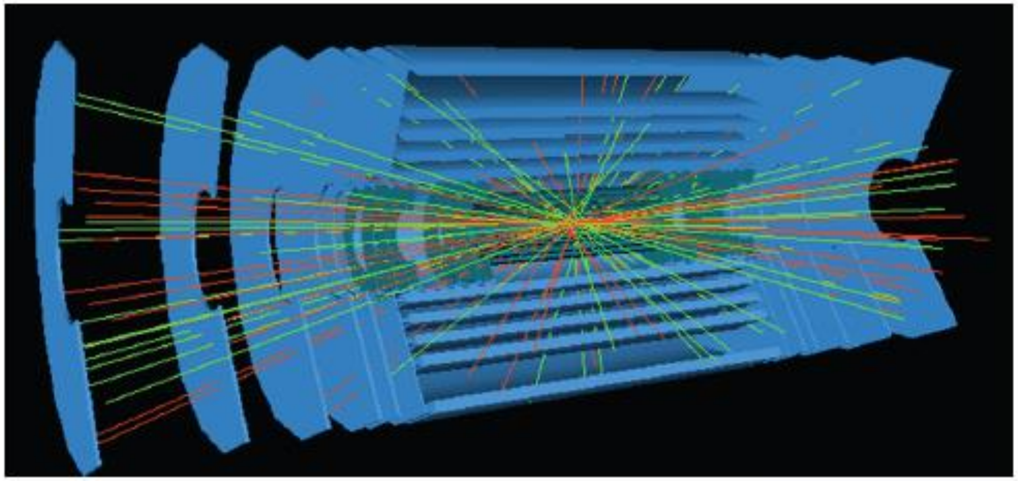


Successful US test in 2013 of new Nb_3Sn quads for IR

Pile-up

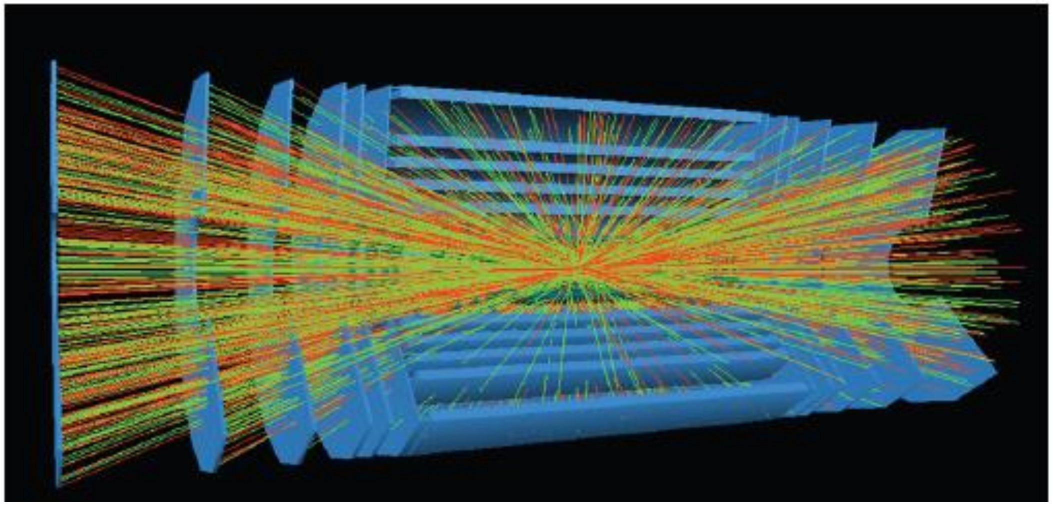
- Pileup = number of proton-proton collision per bunch crossing

Simulated pileup in ATLAS tracker

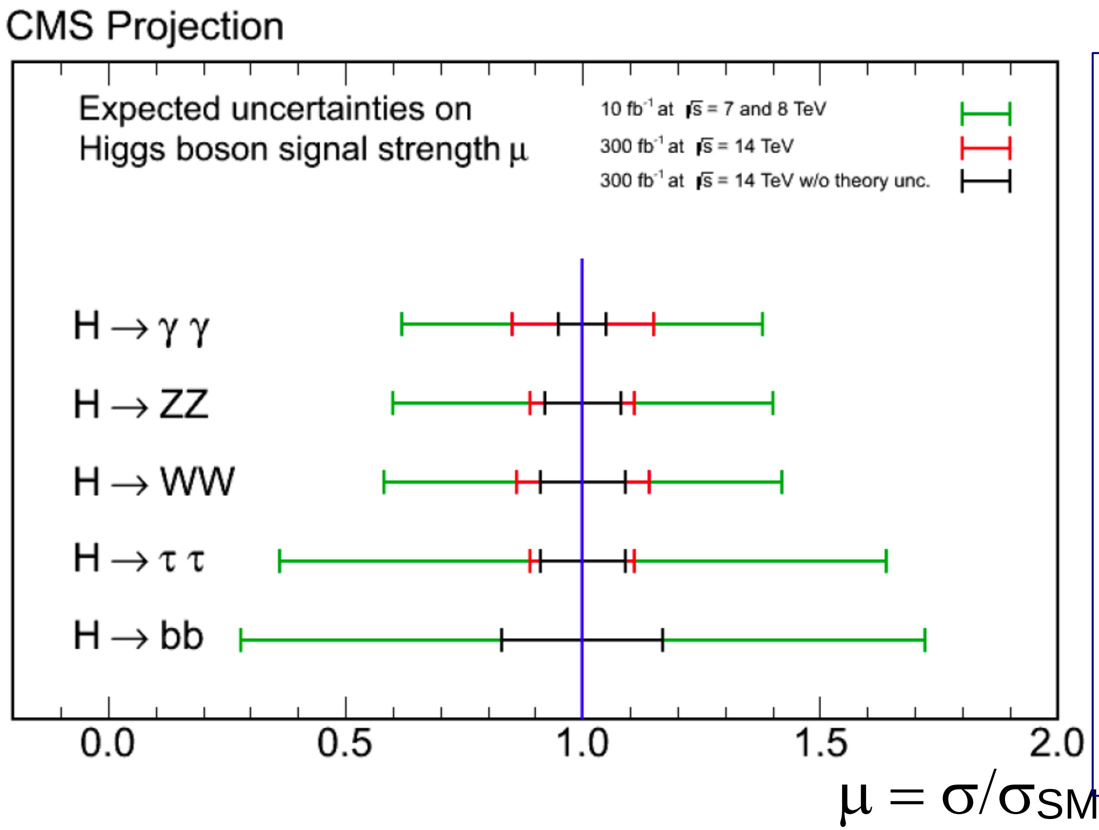


Run 1
Pile up of **23**

HL-HLC
Pile up of **230**



Example – Higgs



300 fb^{-1} at 14 TeV

Red: Scenario 1

Black: Scenario 3

Theory errors dominant for $\gamma\gamma$

Most difficult channel bb

Measurements at:

μ~10-20%

κ ~5-10%

Similar results obtained by ATLAS

High Energy LHC

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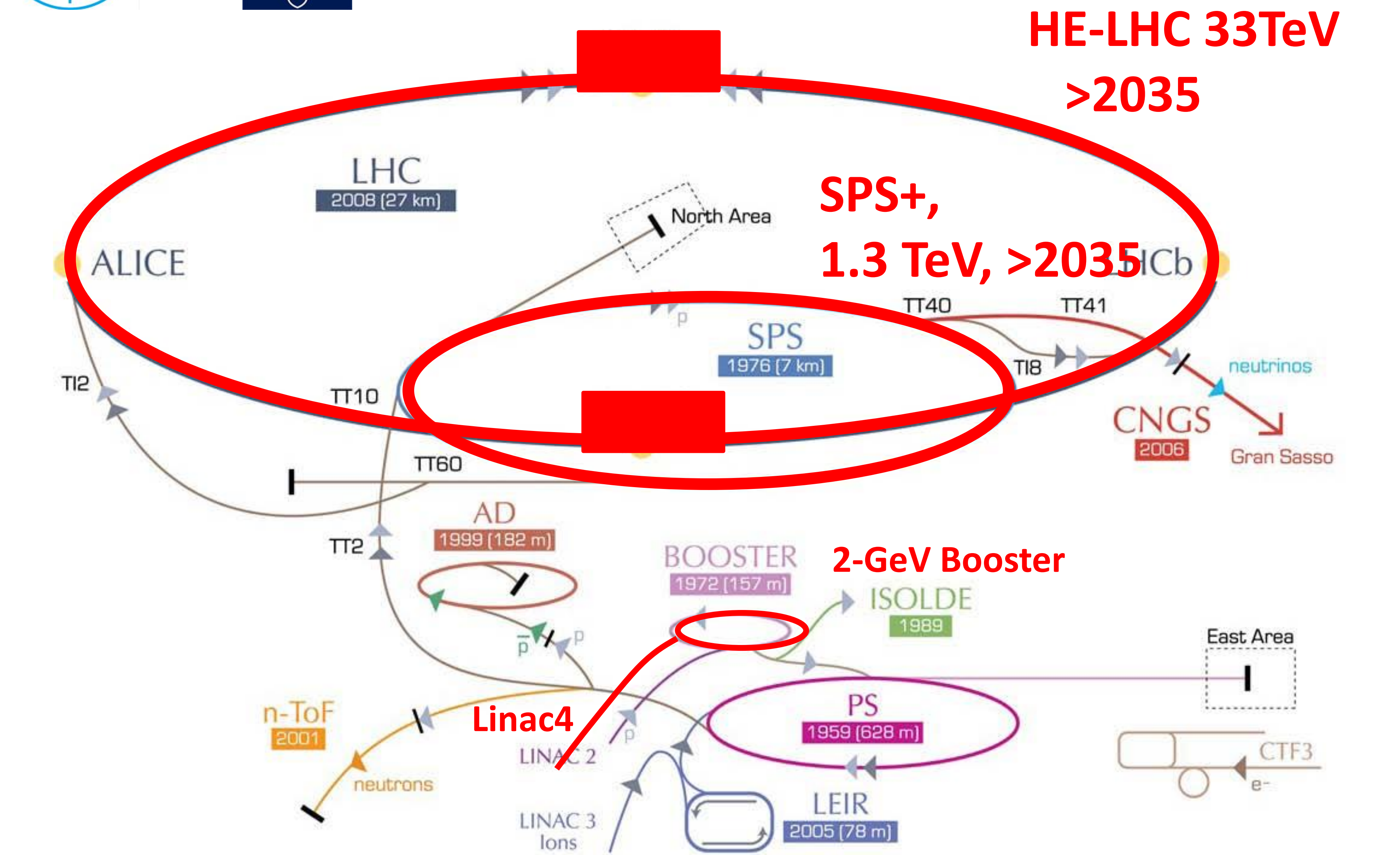
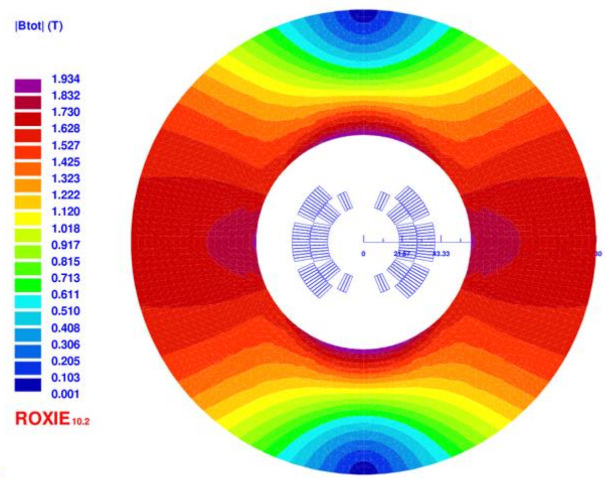


EU program FP7-Eucard2 (collaboration with JP and USA)

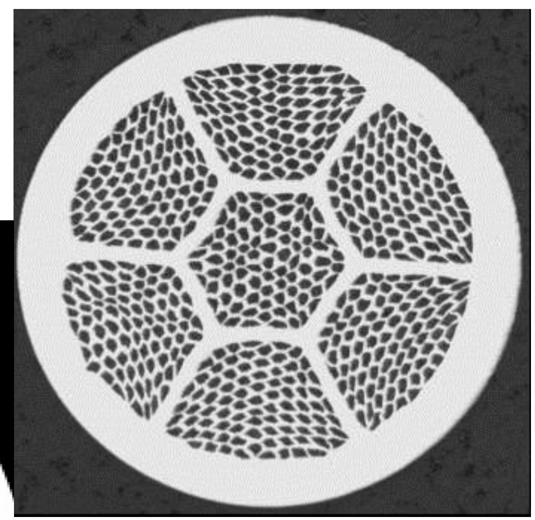
- Develop 10 kA class **HTS accelerator cables both Bi-2212 and YBCO**
  - Stability, Magnetization, strain resistance
  - Uniformity and High $J_{overall}$
- Test in a 5 T accelerator-quality dipole
- Then test in background field (10-13 T)
- Forseen for 2013-17

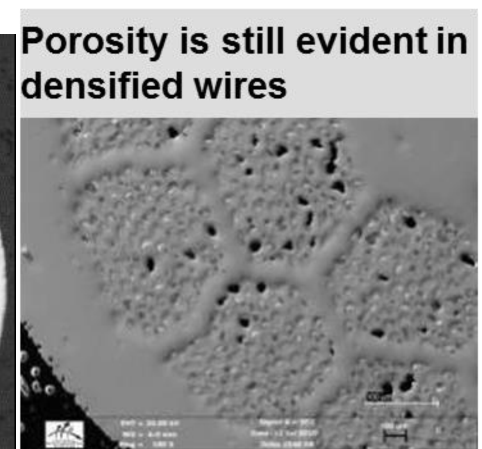


The « new » materials: HTS - Bi-2212

- Round wire, isotropous and **suitable to cabling**!
- HEP only users (good < 20K and for compact cable)
- Big issue: very low strain resistance, brittle
- Production ~ 0,
- cost ~ 2-5 times Nb_3Sn (Ag stabilized)

- DOE program 2009-11 in USA let to a factor 2 gain. We need another 50% and more uniformity, eliminating porosity and leakage

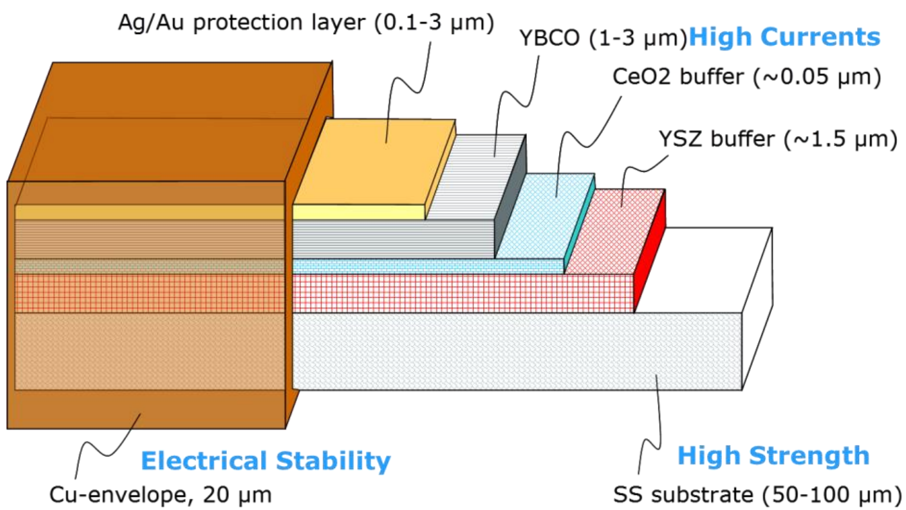


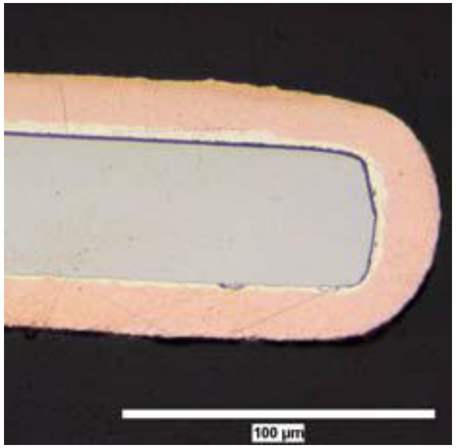


J. Jiang et al 2011

The « new » materials: HTS - YBCO

- Tape of 0.1-0.2 mm x 4-10 mm : difficult for compact (>85%) cables
- Current is EXCELENT but serious issue is the anisotropy;
- >90% of world effort on HTS are on YBCO! Great synergy with all community
- Cost : today is 10 times Nb_3Sn, target is same price: components not expensive, process difficult to be industrialize at low cost
- FP7 Eucard is developing EU YBCO





Summary

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Pioneers – Thomson, Rutherford, Cockcroft, Walton, Lawrence, Veksler, Macmillan, Wilson – invented and then increased the capability of accelerators until today we have the LHC.

The LHC has a long life in front of it – including several possible upgrades – but constructing the next accelerator that can achieve things the LHC cannot achieve takes a very long time.
Several options are already being considered.
We will discuss them in the next lecture.