深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

Cycle of Seminars by Carlo Pagani

Seminar # 1

Brief Introduction to Particle Accelerators

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INFN LASA

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Introduction

Particle accelerators have been conceived and developed to investigate the nature of matter and its fundamental governing laws. Beyond their relevance in terms of knowledge, a variety of applications have been developed, that are having a great impact on several fields, from applied science to human health and security.

Bibliography

Jacow (Particle Accelerators Conference database)

http://www.jacow.org/

The CERN Accelerator Schools

https://cas.web.cern.ch/previous-schools

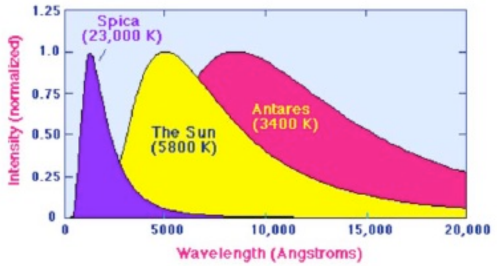
Particles

Particles are the building blocks of our Universe

- They can be elementary or complex
- They can carry a variety of different properties

Since the origin, **our knowledge grown using particles**, well before conceiving their existence and understanding what they were.

- Light is made up of particles, called photons, and our eyes are very sensitive and sophisticated particle detectors
- Our star, the Sun, is sending us a huge flux of photons:
  - they warm up the matter letting life to occur
  - they are reflected by matter letting our eyes to see



Microscopes have been invented to match our eyes capabilities with the photons coming from small objects, but

- The light photons are too “big” to see very small object
- The “size” (wavelength) of the photons limit the resolution of what can be seen.

Particle accelerators to see smaller

Because of "Quantum Physics", **also massive particles**, as electrons, protons and neutrons, **are waves**, with an associated wavelength, i.e., "size": $\lambda = h/(mv)$

The wavelength depends on their rest mass and their kinetic energy

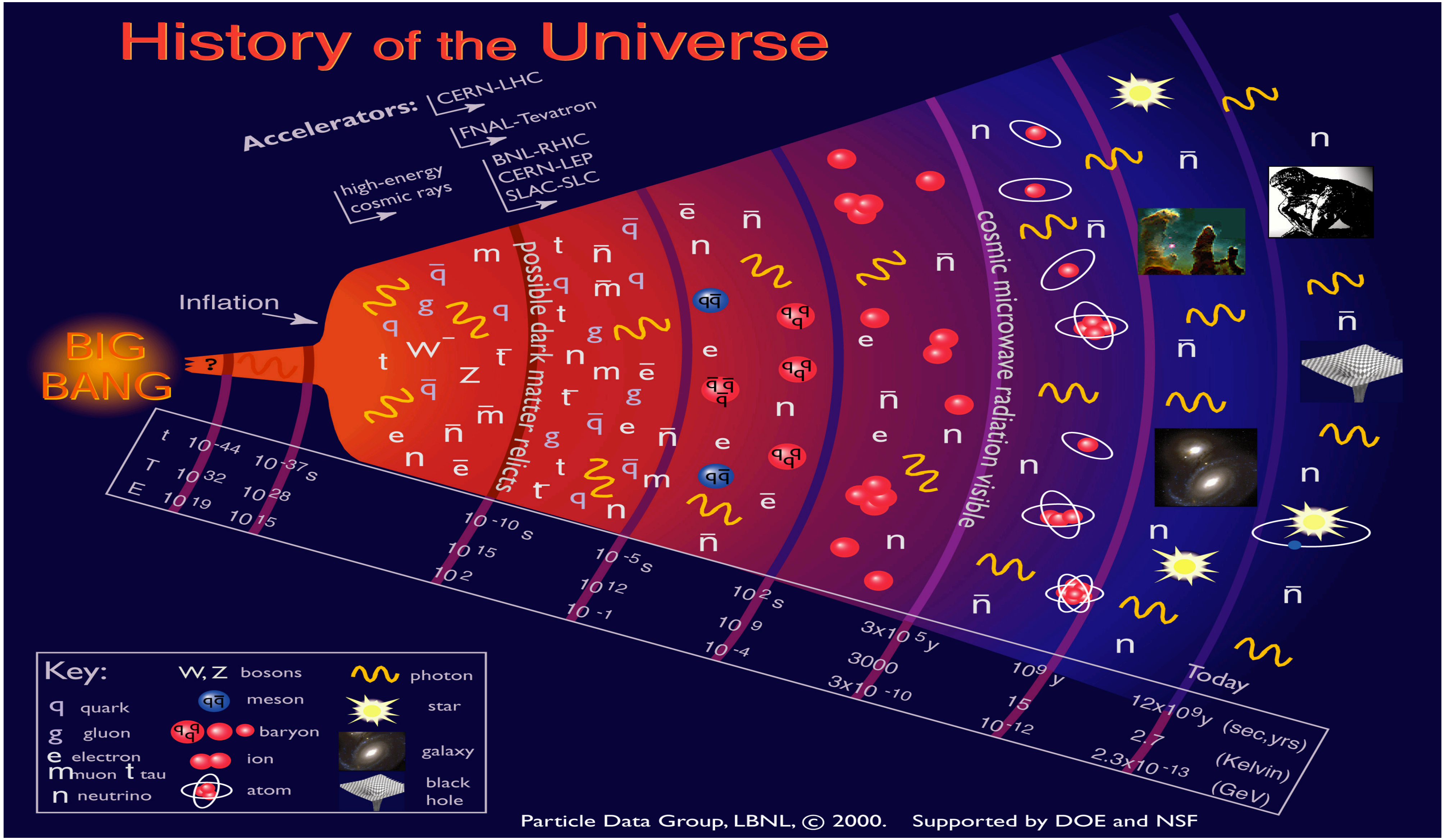
Developing a proper particle beam and a proper "eye", objects of very small size can be "seen" and studied.

Mass and energy are two aspects of a common nature. The conversion from one aspect to the other is following the **Einstein equation**: $E = mc^2$

Giving two particles, moving one against the other, an energy much bigger than the one associated to their mass, their **collision creates new particles**.

As high is the energy available at the collision point, as close we are to the conditions at the origin of the universe, just after the **Big Bang**

History of the Universe



Large Instruments for Science and Society

Particle Accelerators

- **To study what is extremely small**
  - Nuclei are excited and their behavior observed
  - Particles are created from energy and analyzed
  - Short wavelength photons and neutrons are indirectly generated to observe the invisible world
- **As intense particle sources for applications**
  - cancer therapy and radio-isotope production
  - nuclear waste transmutation to reduce toxicity
  - intense photon beams for: micro-lithography, food, catalysis, etc.

Large Telescopes

- **To study what is extremely far away and big**
  - Viewing far in space and time
  - Observing large phenomena at their extreme conditions

What is a Particle Accelerator ?

- **A particle Accelerator is a machine designed to transfer energy to a charged particle beam**. In most cases the particle beam extracts energy from an electromagnetic field that is stored or traveling in low losses structures, called cavities.

$$E_{gain}\ [eV] = q\ [e]\ V\ [Volt]$$

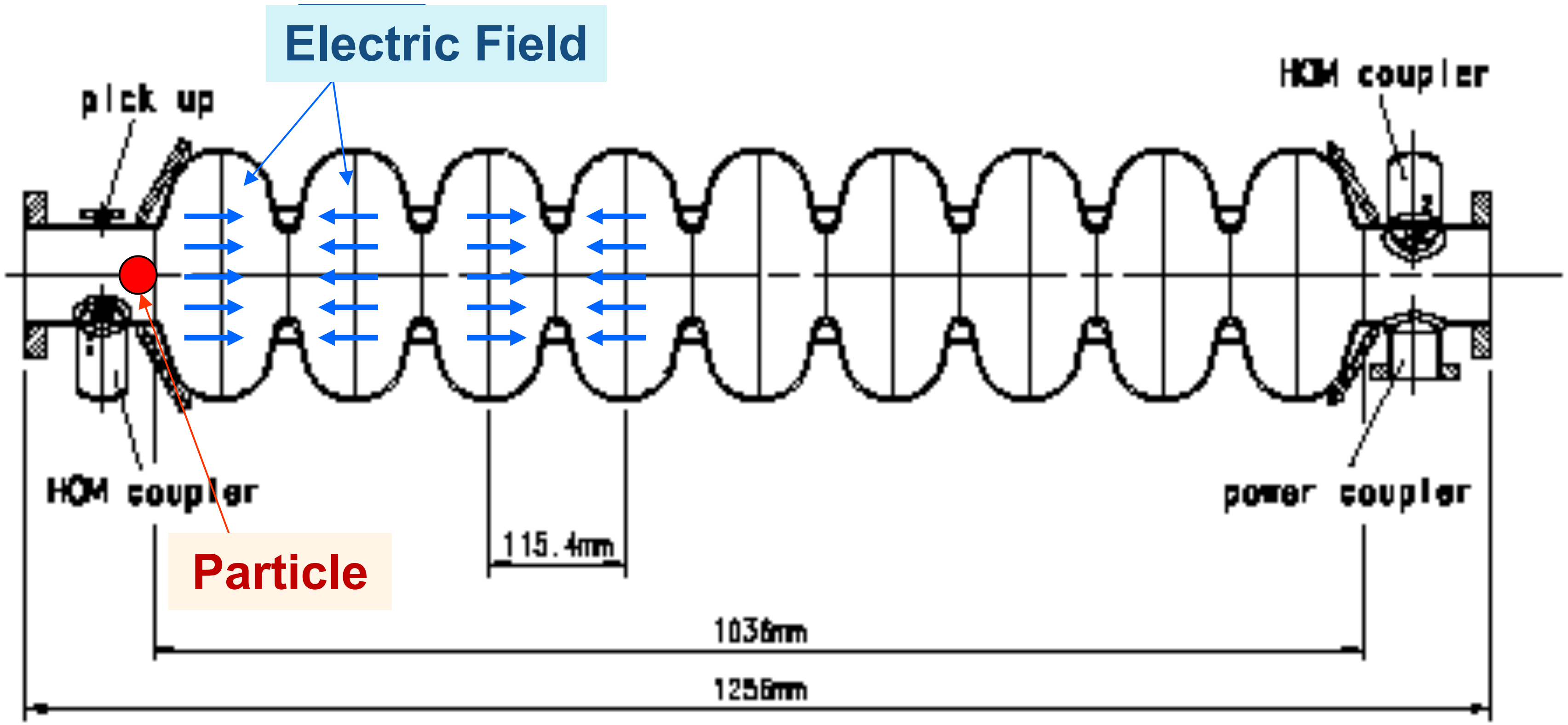
- Particles are taking energy from the electric field, $\mathbf{E}$, and are guided by the magnetic field, $\mathbf{B}$, according to the Lorentz equation

$$\frac{\partial \boldsymbol{p}}{\partial t} = \mathbf{F} = q\ (\mathbf{E} + \mathbf{v}\ x\ \mathbf{B})$$

- The charged accelerated particles can be:
  - **electrons** (& positrons) [i.e. leptons: “elementary” particles]
  - **protons** (& antiprotons) [i.e. hadrons, “composite” particles]
  - **ions** (i.e. ionized atoms)
- An intense primary beam can be used to produce a secondary beam that could not be accelerated: photons, neutrons, neutrinos, etc.

Acceleration inside a TESLA Cavity

- An electromagnetic field is resonating inside the "cavity". The electric field inverts its direction according to the frequency determined by the cavity resonator shape.
- If the charged particle beam has the proper synchronism, moving from one cell to the other it sees always the field in the right direction and gains energy: $E_{gain} = q \cdot V$

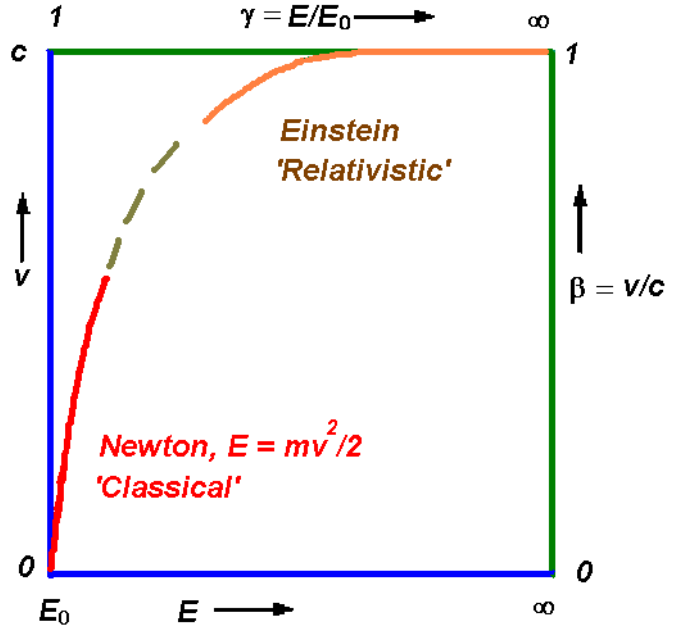


Particle Accelerator Components

- **source of charged particles**
  electrons, protons, heavy ions, special cases: positrons & anti-protons
- **accelerating elements**
  radiofrequency cavities to provide the electric fields that transfer energy to the particles
- **beam guiding elements**
  mainly magnetic, in order to maintain (focus) the beam on the wanted trajectory
  and to provide the orbit (closed for a synchrotron) in the case of a circular machine
- **vacuum and beam diagnostics**
  high vacuum is needed to avoid perturbation of the beam by collisions with residual gas, and beam diagnostics assure the monitoring of the beam trajectories
- **user installations**
  experimental set-ups including targets, spectrometers, detectors, patients, etc.

Acceleration ?

- Modern accelerators can accelerate particles to speeds very close to that of light.
- At low energies, the velocity of the particle increases with the square root of the kinetic energy (**Newton**).
- **At relativistic energies, the velocity increases very slowly asymptotically approaching that of light (Einstein).**
- It is as if **the velocity of the particle 'saturates'**.
- One can pour more and more energy into the particle, giving it a shorter De Broglie wavelength so that it probes deeper into the sub-atomic world.

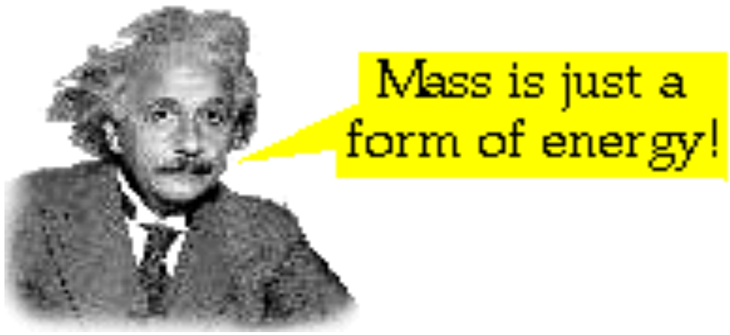


What does special relativity tell us, e.g. for an electron?

Energy	1 MeV	→	→	1 GeV
$\beta = v/c$	0.95	0.99	0.999	0.999 999 9
$\gamma = m/m_0$	3	7	22	2000

The speed increases, but not as spectacularly as the mass. In fact, it would be more correct to speak of the momentum (*mv*) increasing.

Energy and Mass



$$m = \gamma m_0 \qquad E_0 = m_0 c^2$$

$$\gamma = (1-\beta^2)^{-1/2} \qquad \beta = v/c$$

$$E = m c^2$$

Momentum $\quad p = m v \approx m_0 \gamma c = m c \quad$ when $v \approx c$

Kinetic energy $\quad K = E - E_0 = (\gamma - 1)\, m_0 c^2$

Speed of light: $c \equiv 2.99792458 \cdot 10^8\ \mathrm{ms^{-1}}$

Energy unit: $1\ \mathrm{eV} = 1.6021 \cdot 10^{-19}\ \mathrm{J}$

Electron rest energy: $E_0 = 0.511\ \mathrm{MeV/c^2}$

Proton rest energy: $E_0 = 938\ \mathrm{MeV/c^2}$

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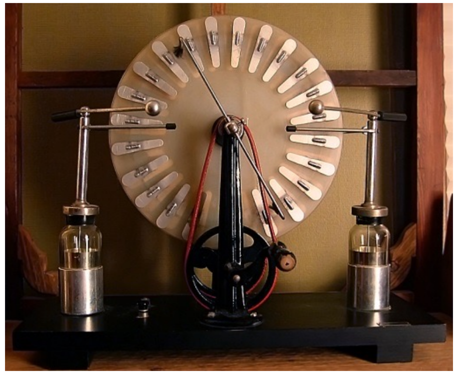
Energy Evolution

<100 keV electrons from Wimshurst-type machines:

1895 Lenard electron scattering on gases (Nobel Prize 1905 for work on cathode rays).

1913 Franck and Hertz excited electron shells by electron bombardment.

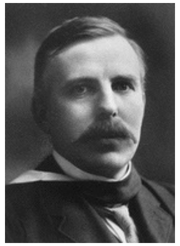


http://www.youtube.com/watch?v=Zilvl9tS0Og

Few MeV from natural alpha particles:

1906 Rutherford bombards mica sheet with natural alphas

1919 Rutherford induces a nuclear reaction with natural alphas.



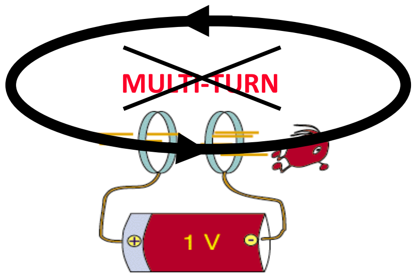
To go ahead an accelerator was needed for physics research

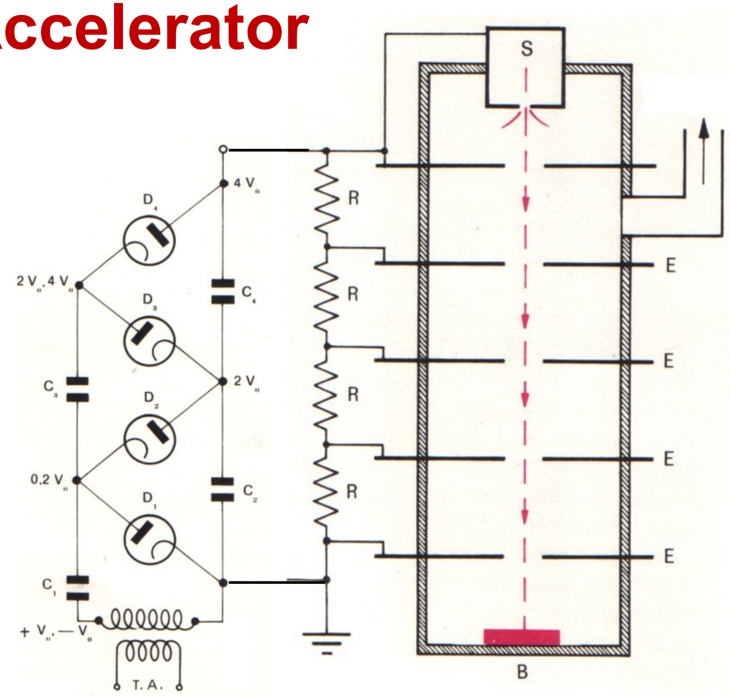
- 1928 Cockcroft & Walton start designing an 800 keV generator encouraged by Rutherford.
- 1932 Cockcroft & Walton construct first “high-energy” accelerator, 700 eV, and produce first artificially generated nuclear reaction: p + Li -> 2 He
- 1932 Lawrence and Livingston construct first cyclotron giving 1.2 MeV protons

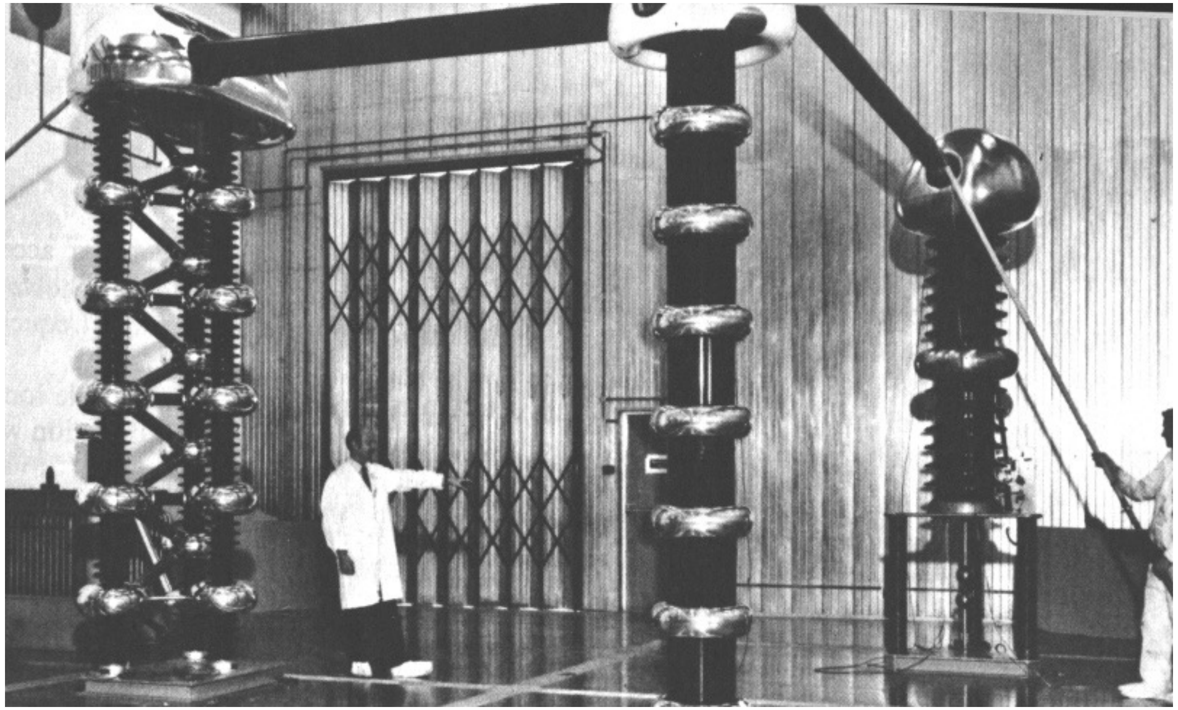
Cockroft & Walton Generator/Accelerator

Electrostatic Accelerator

$$\nabla \times \boldsymbol{E} = 0$$



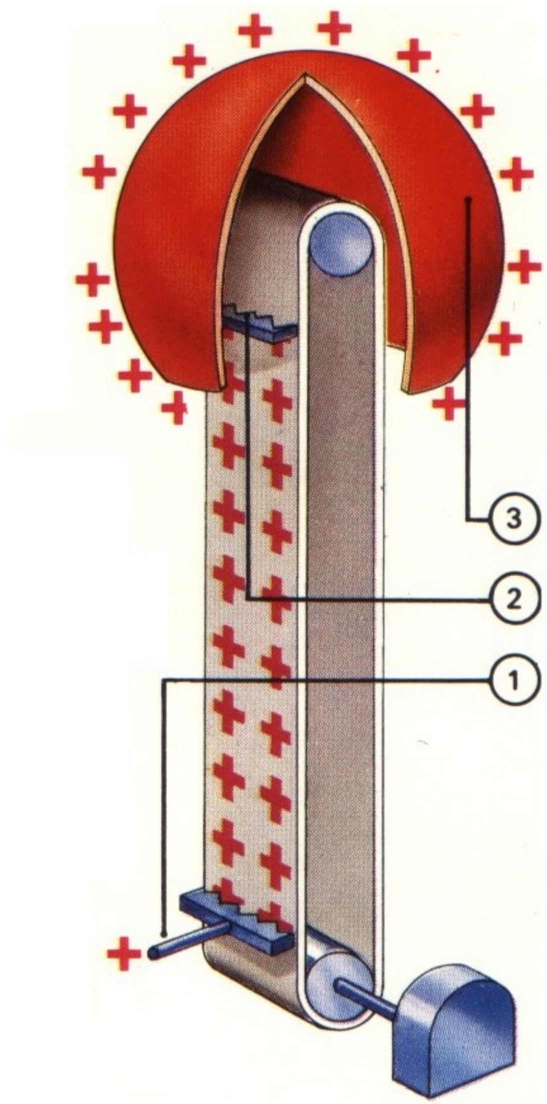




Cockcroft-Walton generator injecting protons into the synchrotron at Rutherford laboratory (1964-1978).

The Cockcroft-Walton accelerator allows to reach high beam currents, of interest for many applications, but the voltage is **practically limited to somewhat above 1 MV**, because of breakdown of insulation

Van de Graaff Accelerator Principle

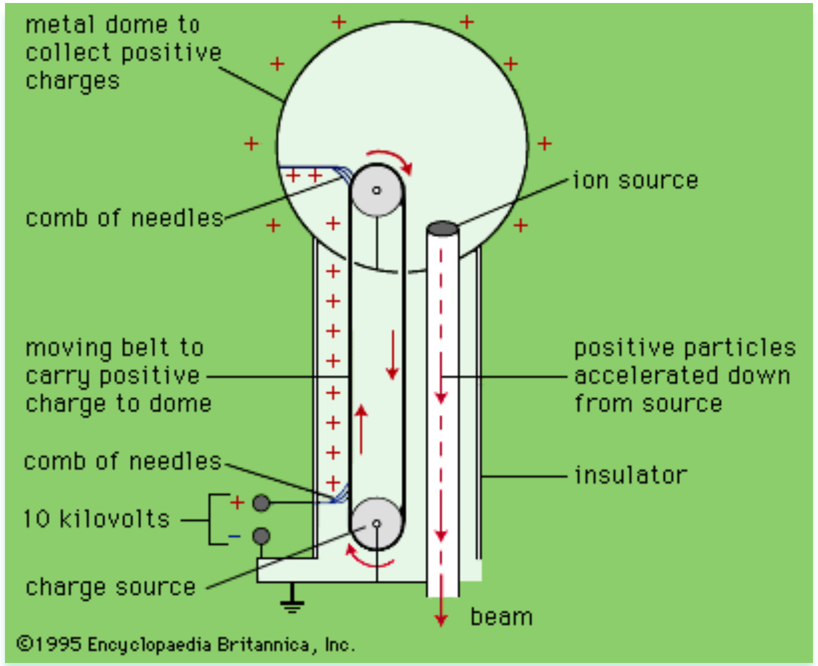


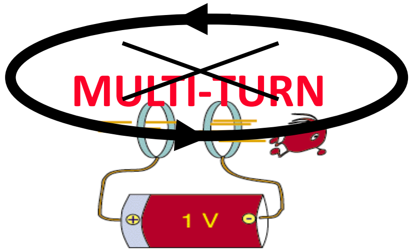
High voltage for electro-static accelerator

- the concept of charge transport (see left) has been introduced by R. J. van de Graaff
- a comb-like electrode (1) sprays charges on an insulating conveyor belt (the high-voltage generator typically being again a rectifier multiplier)
- The conveyor transports the charges inside the sphere-shaped terminal (3), which forms in fact a Faraday cage
- The charges are collected by a second comb like electrode (2) which is connected to the sphere
- consequently, the charges accumulate on the outside of the sphere and the inside get charge free, ready to accept further charging
- In practice, one can reach up to **25 MV**, provided one uses (expensive) **SF_6 gas** for limiting breakdowns

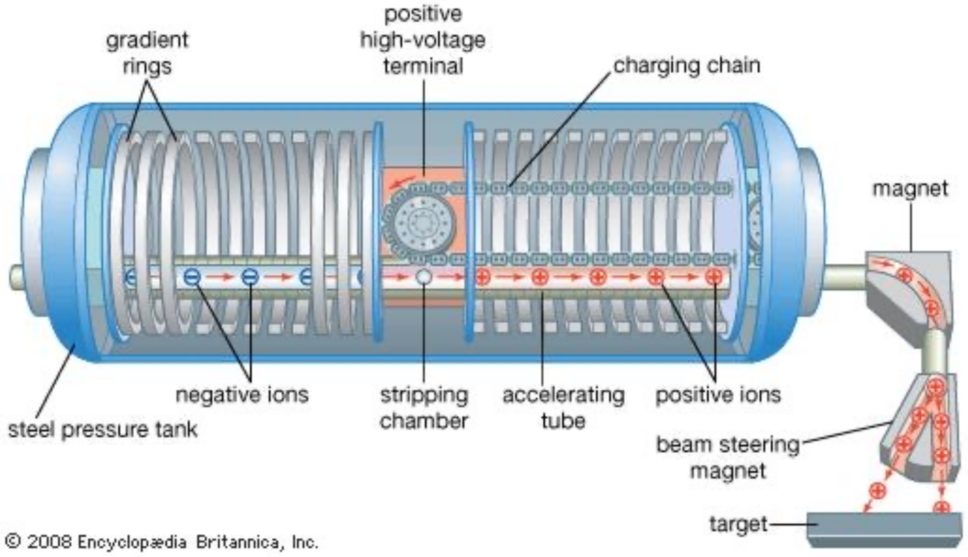
The Van de Graff (1929) and the Tandem

The Van de Graff Accelerator



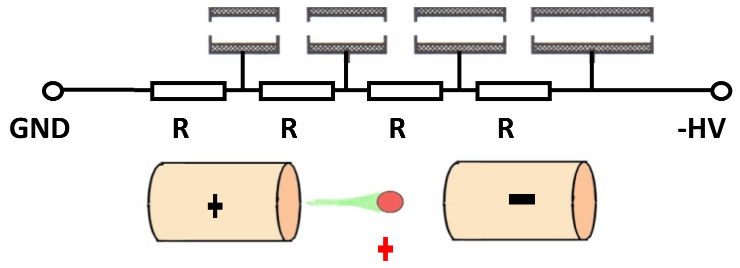


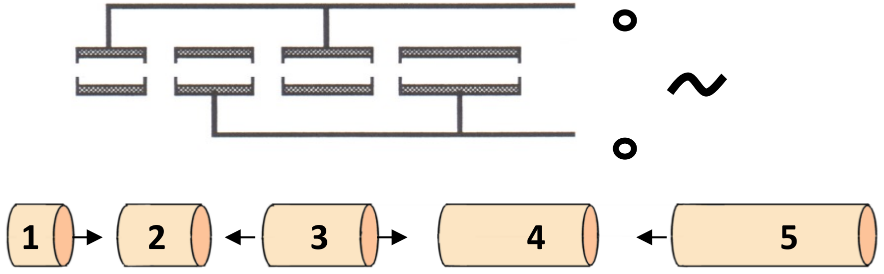
The Tandem Accelerator



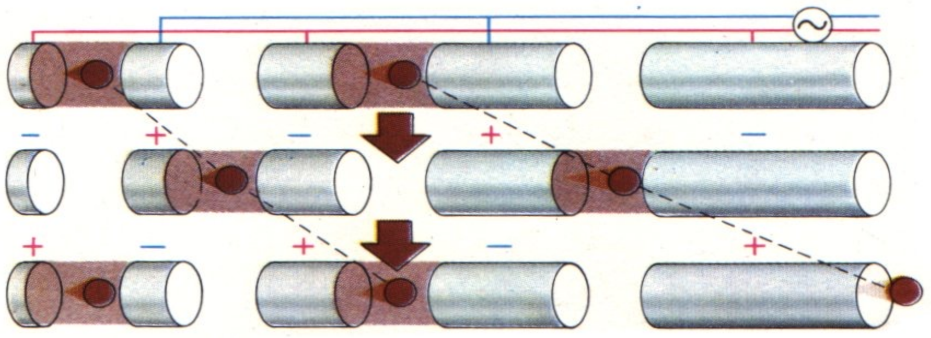
In the Tandem, also invented by van de Graaff, the voltage is used twice: source and target are at ground voltage and a stripping foil change the charge state in the positive high voltage terminal

The Wideroe Linear Accelerator (1928)





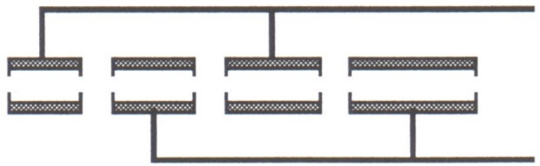
π mode

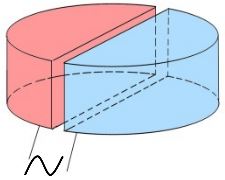


- With a **DC accelerator** the electric field E is constant, $\nabla \times E = 0$ and the field can be used once.
- consider now such a column, but driven with an **alternating voltage**, in such way that **consecutive electrodes** are connected to **opposite polarity** of the RF generator, $\nabla \times E \neq 0$, field can be used many times
- suppose now, that the **RF frequency** is such that it accelerates the particle between electrodes 1&2 (and also 3&4), whereas the field is opposite, at that moment, between **accelerating gaps**, 2&3 and 4&5, respectively
- if this particle arrives now at the gap between 2&3, when the RF has changed to opposite phase, acceleration occurs again, and so on.
- note that while the polarity change occurs, the particle is in the field-free space of the **drift tube** of such a **Wideroe linac**. Further, to stay in phase with the RF, as the **speed** of the particle **increases**, the **length of the drift tubes has to increase**

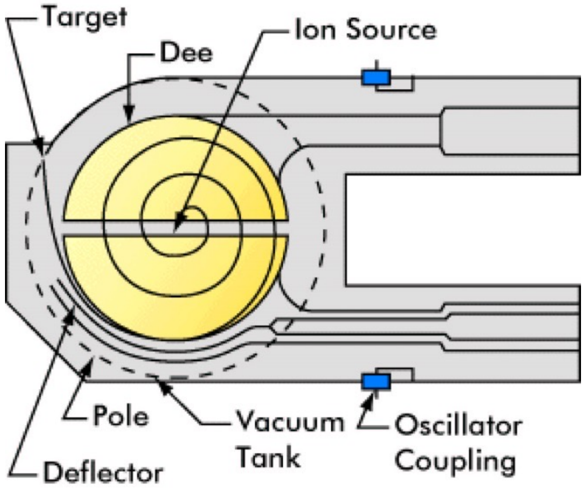
RF acceleration: Cyclotron

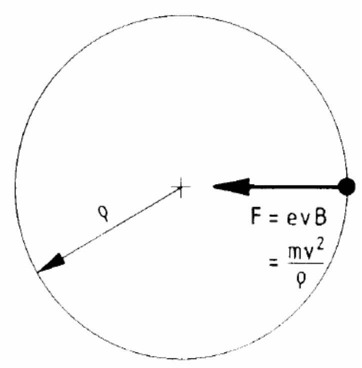
Folded Wideroe Linac in a constant magnetic field





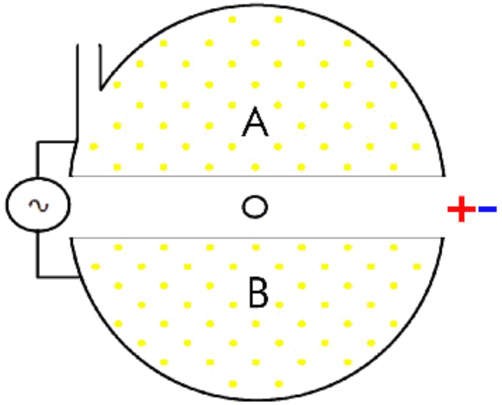
$$\frac{m\,v^2}{\rho} = q\,v\,B$$





$$B\rho = \frac{mv}{q} = \frac{p}{q}$$

$$f_{rev} = \frac{\omega_{rev}}{2\pi} = \frac{1}{2\pi}\frac{v}{\rho} = \frac{1}{2\pi}\frac{qB}{m}$$

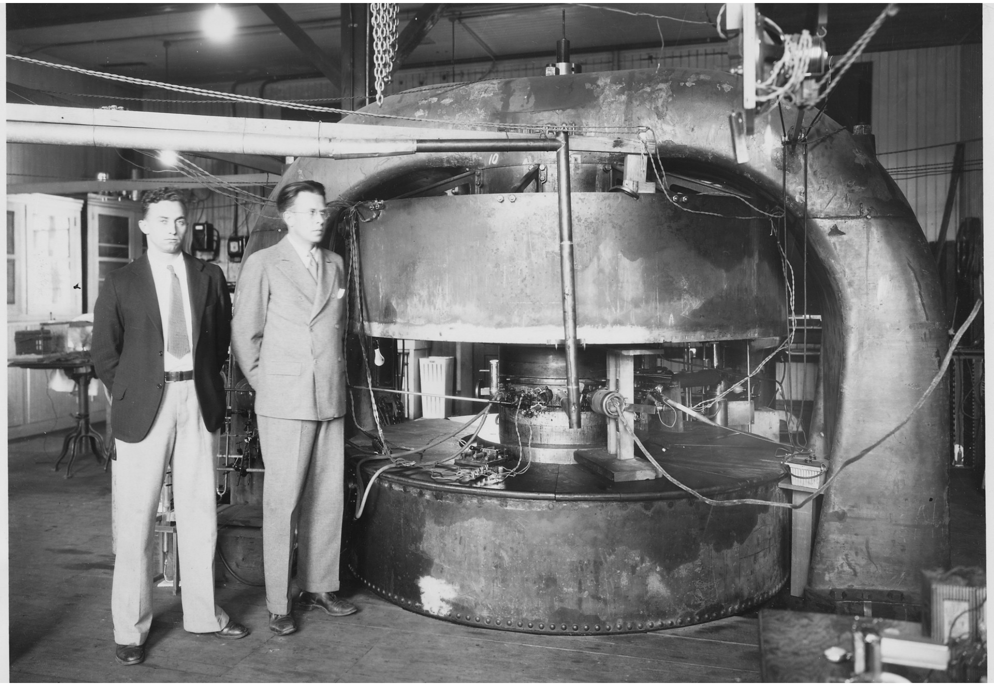


For m and B = constant

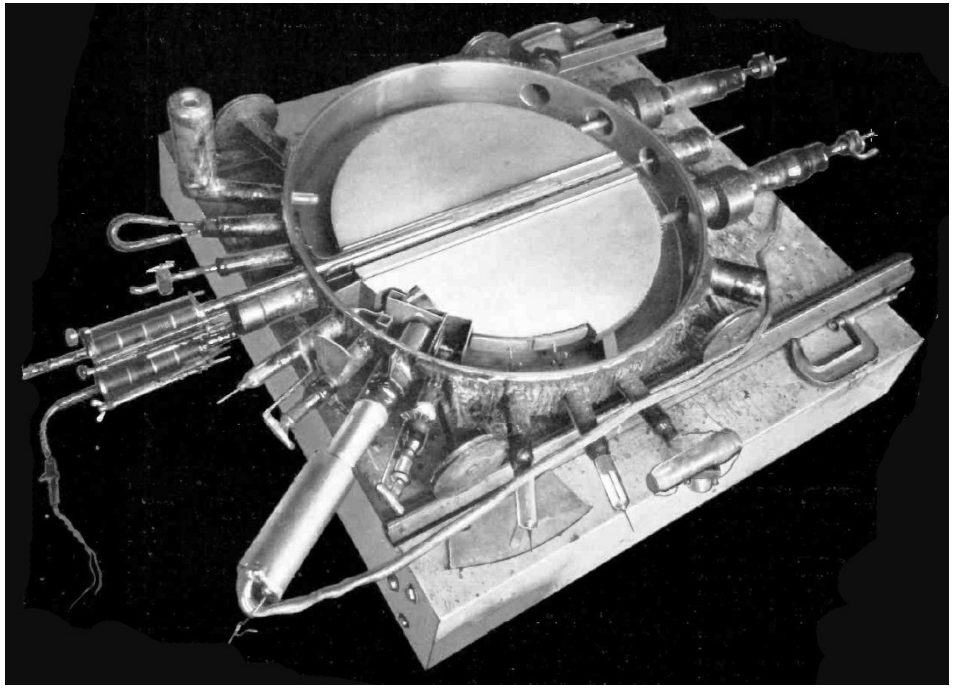
also f_{rev} = constant

$$E_c/A\,[\text{MeV}] = K_{cycl.}\,(Z/A)^2$$

The First real Accelerator at Berkeley (1932)

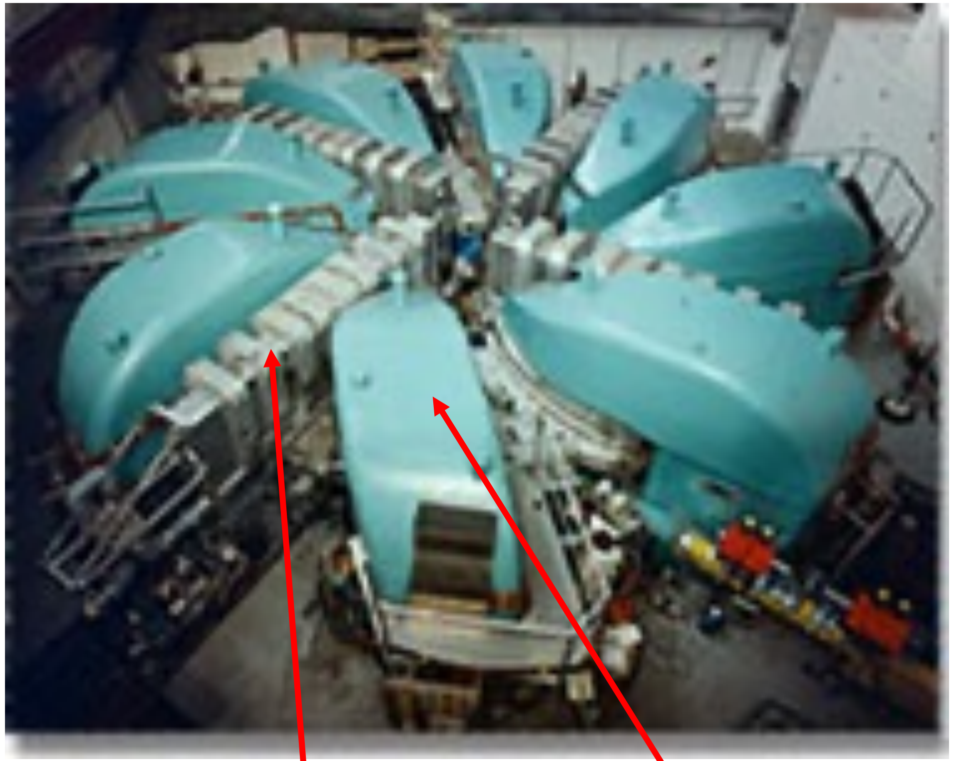


M. Stanley Livingston and Ernest O. **Lawrence** *(right)* in front of Lawrence's 69 cm (27 in) cyclotron at the **Lawrence Radiation Laboratory**. The curving metal frame is the magnet's core, the large cylindrical boxes contain the coils of wire that generate the magnetic field. *The vacuum chamber containing the "dee" electrodes is in the center between the magnet's poles*.

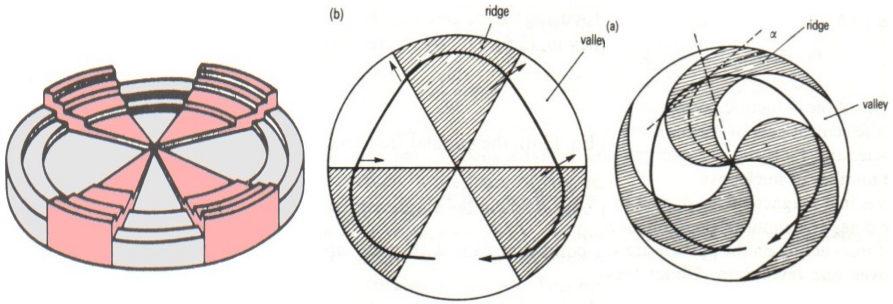


Vacuum chamber of Lawrence **69 cm (27 in) 1932 cyclotron** with cover removed, showing the dees. The **13,000 V RF** accelerating potential at about **27 MHz** is applied to the dees by the two feedlines visible at top right. The beam emerges from the dees and strikes the target in the chamber at bottom.

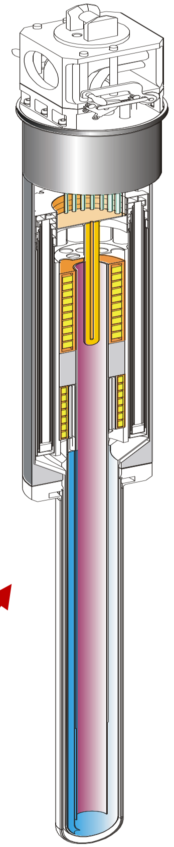
The PSI Cyclotron Facility



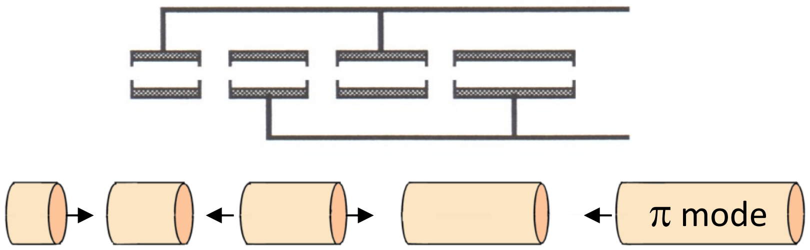
accelerating cavity   sector magnet

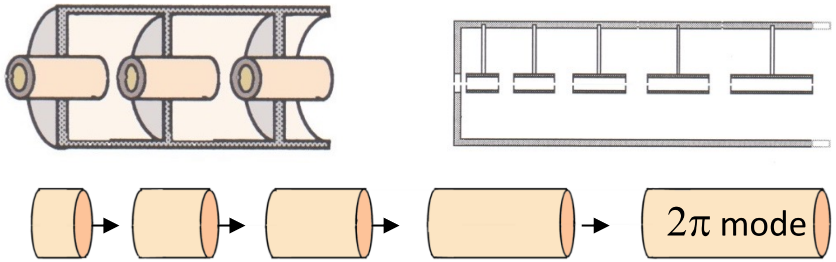


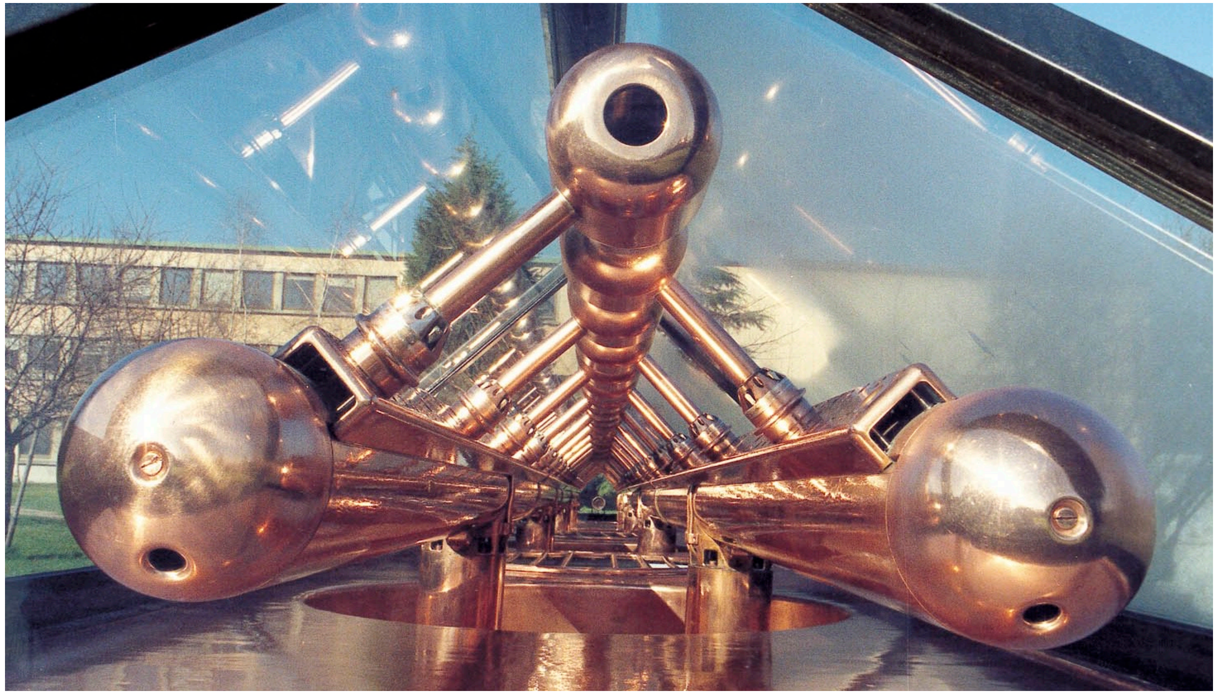
- The **K=590 cyclotron** of the **PS facility** is a 8 separated sector machine with 4 accelerating cavities
- The **injection energy of 70 MeV** iprovided by another cyclotron
- The accelerator is in operation **since the 1970's**, and has been very carefully optimised for this long period
- The exceptional experience gained at PSI allows now to approach an intensity of almost **2 mA**
- These high current **590 MeV** proton beams feed the SINQ spallation neutron source
- The SINQ solid metal target has been temporarily replaced by the prototypical (e.g. for an ADS) molten metal target MEGAPIE (see right)



French Linear Accelerators in 1946







Historical examples: a **Wideroe type** structure (ALICE heavy ion injector, IPN Orsay)

A drift tube linac (**DTL – Alvarez type**) (Saturne, CEA Saclay)

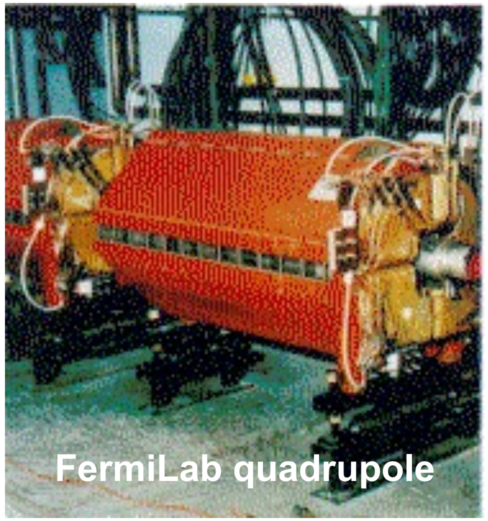
Some Milestones for Accelerators

- 1928 Cockcroft&Walton develop a 700kV **electrostatic accelerator** based on a voltage multiplier.
- 1928 first Linac by **Wideroe** based on the concept of **resonant acceleration**.
- 1929 Lawrence invents the **cyclotron**.
- 1944 MacMillan, Oliphant & Veksler develop the **synchrotron**
- 1946 Alvarez builds a proton linac with **Alvarez** structures (2π mode)
- 1954 Courant, Livingston and Snyder implant **strong focusing** at the Brook-haven Cosmotron Synchrotron
- 1956 Kerst stresses in a paper the concept of a collider
- 1961 **Colliding beams** demonstrated at Frascati (AdA)
- 1970 Kapchinski & Telyakov invent the radio-frequency quadrupole (**RFQ**).
- mid 70‘s **superconducting magnets** for cylotrons and synchrotrons considerably boost the performance (energy for size), in particular for colliders
- mid 80’s very the development of **superconducting accelerating cavities** provides high power conversion efficiency, and CW operation for high luminosity

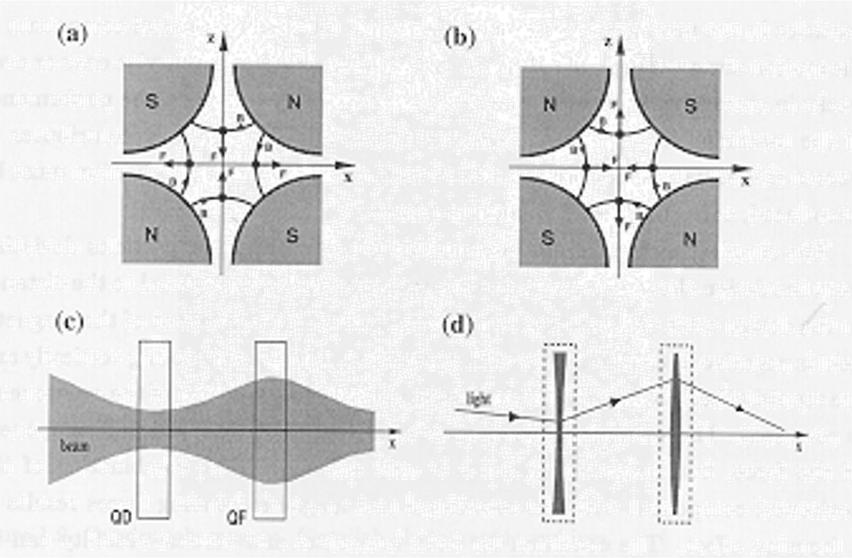
$$B\rho = \frac{mv}{q} = \frac{p}{q}$$

Transverse "Strong Focusing"

- **Alternating gradient** (AG) principle (1950's)
- A sequence of focusing-defocusing fields provides a stronger net focusing force.
- **Quadrupoles** focus horizontally, defocus vertically or vice versa.
  Forces are proportional to displacement from axis.
- A succession of opposed elements enable particles to follow stable trajectories, making small oscillations about the design orbit.



- **Technological limits** on magnets are high: iron saturation and dissipated power for high current
- **Superconducting magnets** are required for high field
- **Solenoids** are preferred **at low energy**, with high space charge forces: continuous focusing

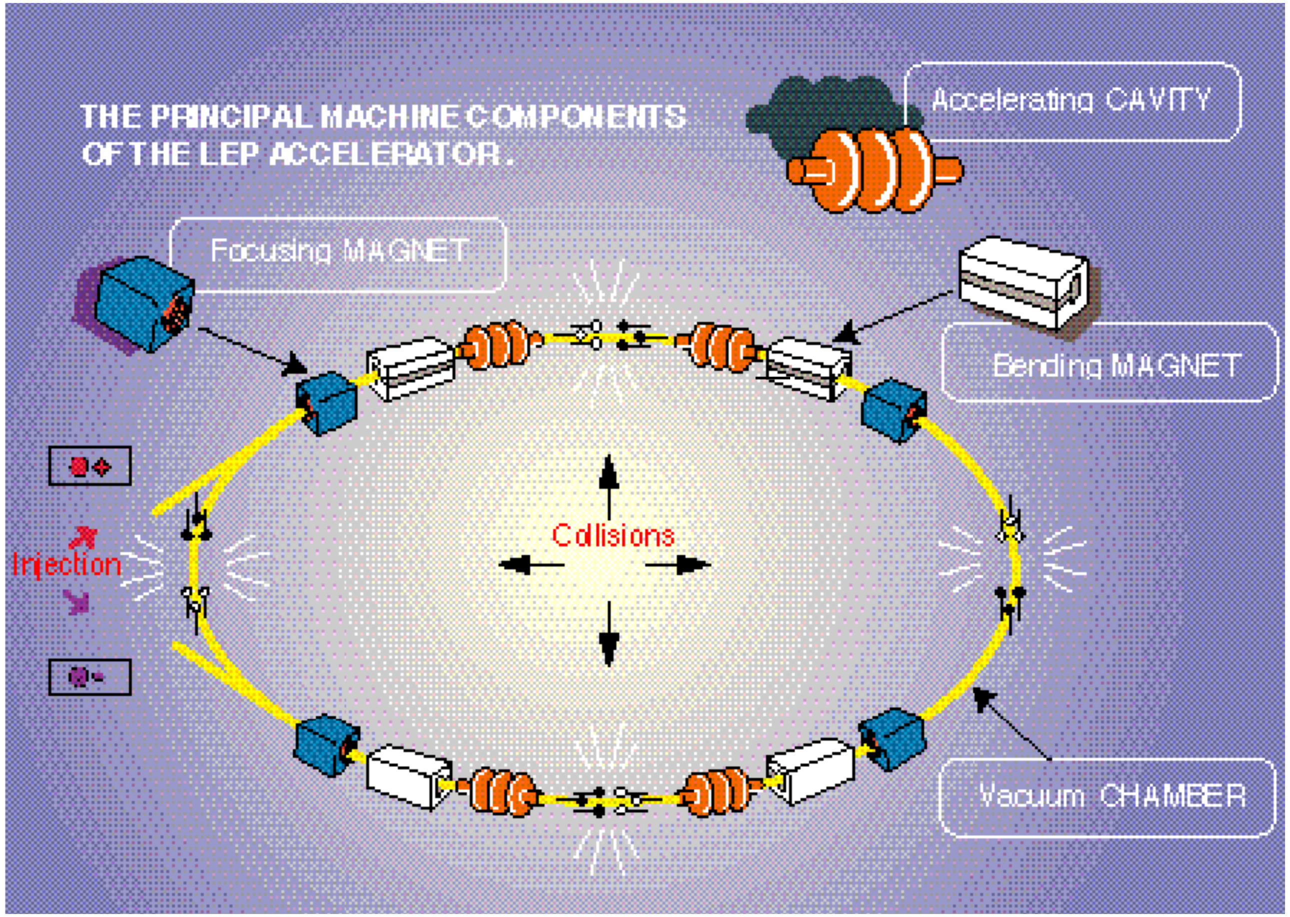


RF acceleration: Synchrotron

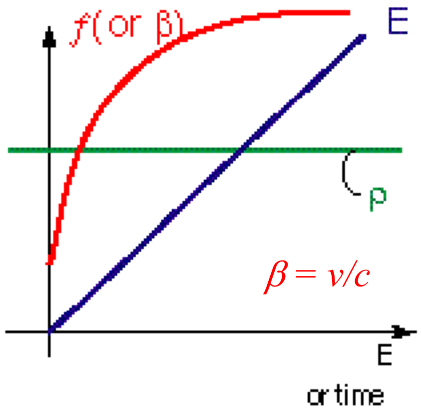
The LEP Example

Cyclotron: constant B **Synchrotron: constant ρ**

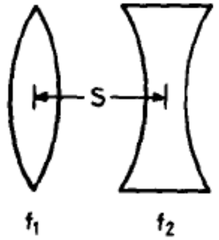
$$B\rho = \frac{mv}{q} = \frac{p}{q}$$



Accelerating cycle



Strong focusing concept



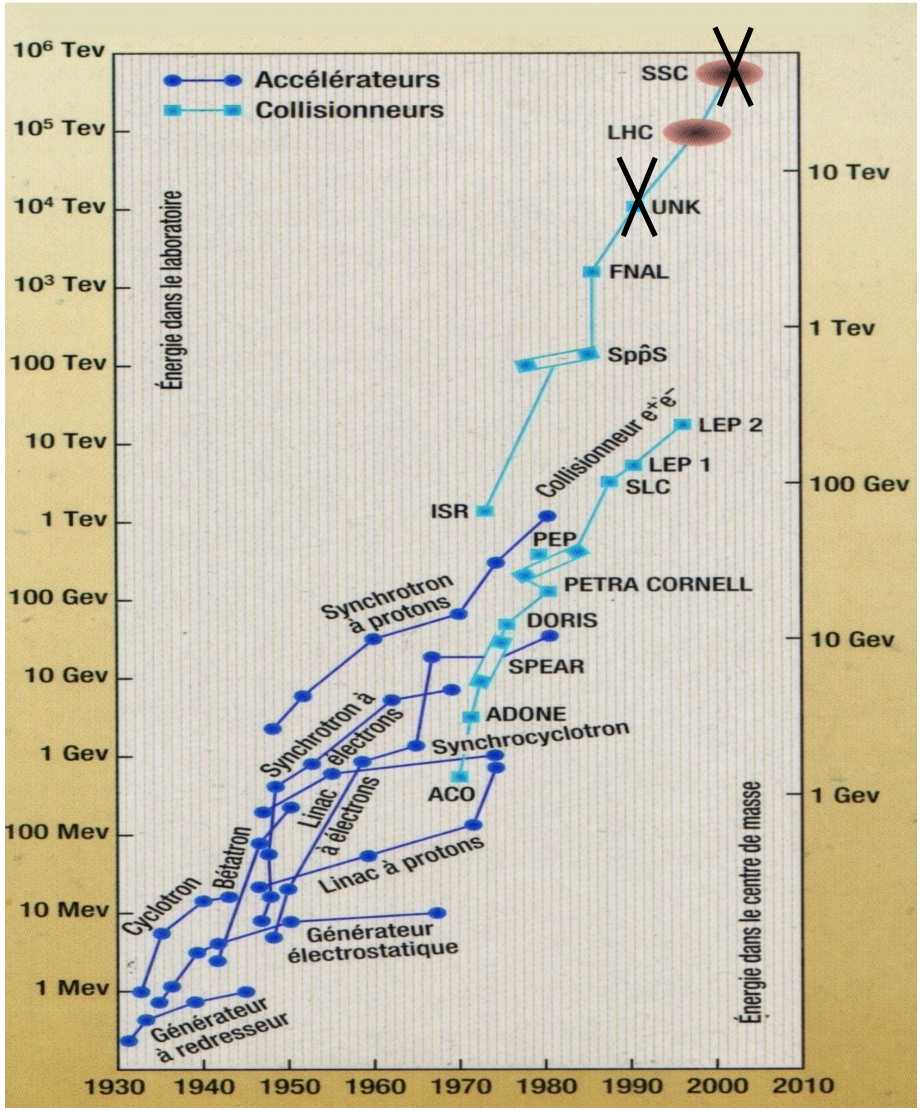
$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{s}{f_1 \cdot f_2}$$

For $v \approx c$ ⟶ $E\,[GeV] \approx 0.3\,B\,[T] \cdot \rho\,[m]$

Contents

The Livingston Chart

- Around 1950, **Livingston** made a quite remarkable observation: Plotting the **energy** of an accelerator as a function of its **year of construction**, on a **semi-log scale**, the energy gain has a **linear dependence**.
- **50 years later**, that **was still true**.
- In other words, builders of accelerators have managed exponential growth, every ten years, roughly a actor of 33 is won.
- Note that for a given "family" of accelerators, generally, saturation of maximum energy sets in after some time.
- **After 2000 this behaviour is lost**



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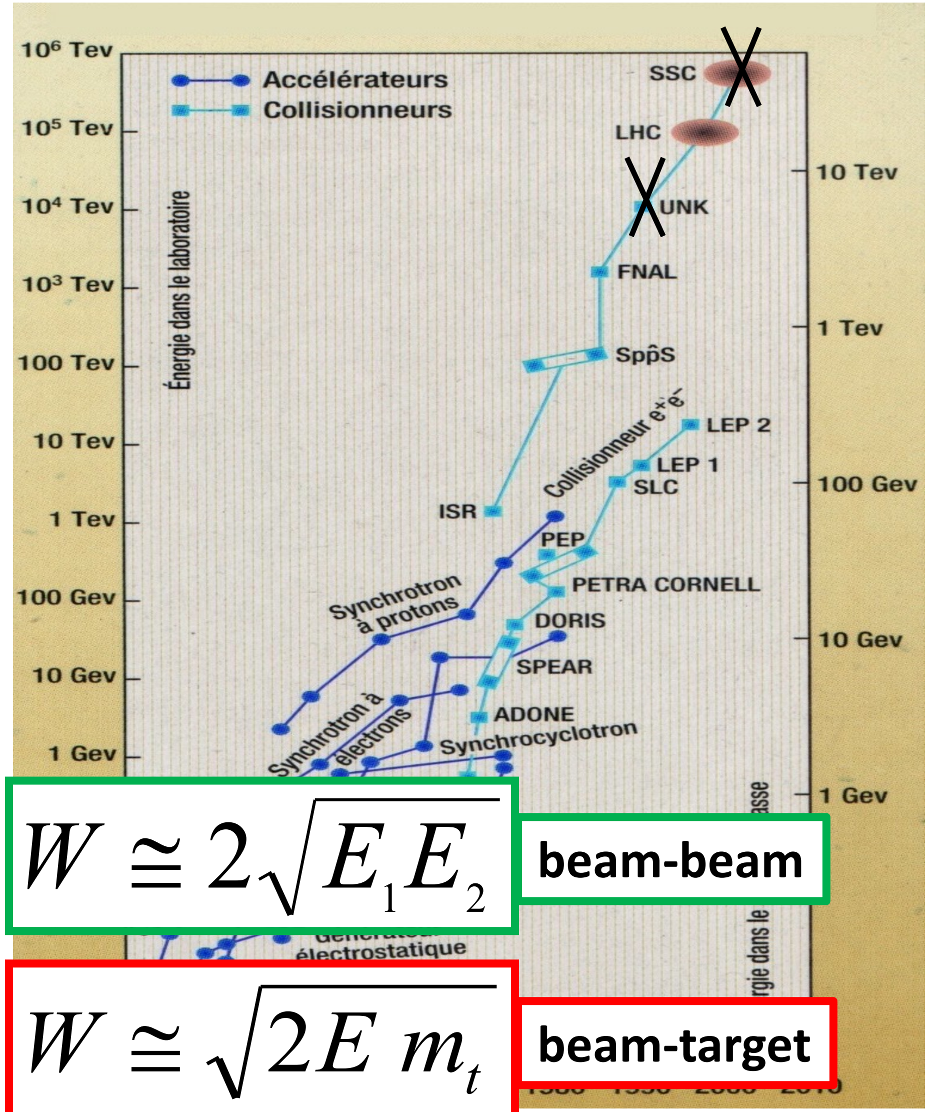
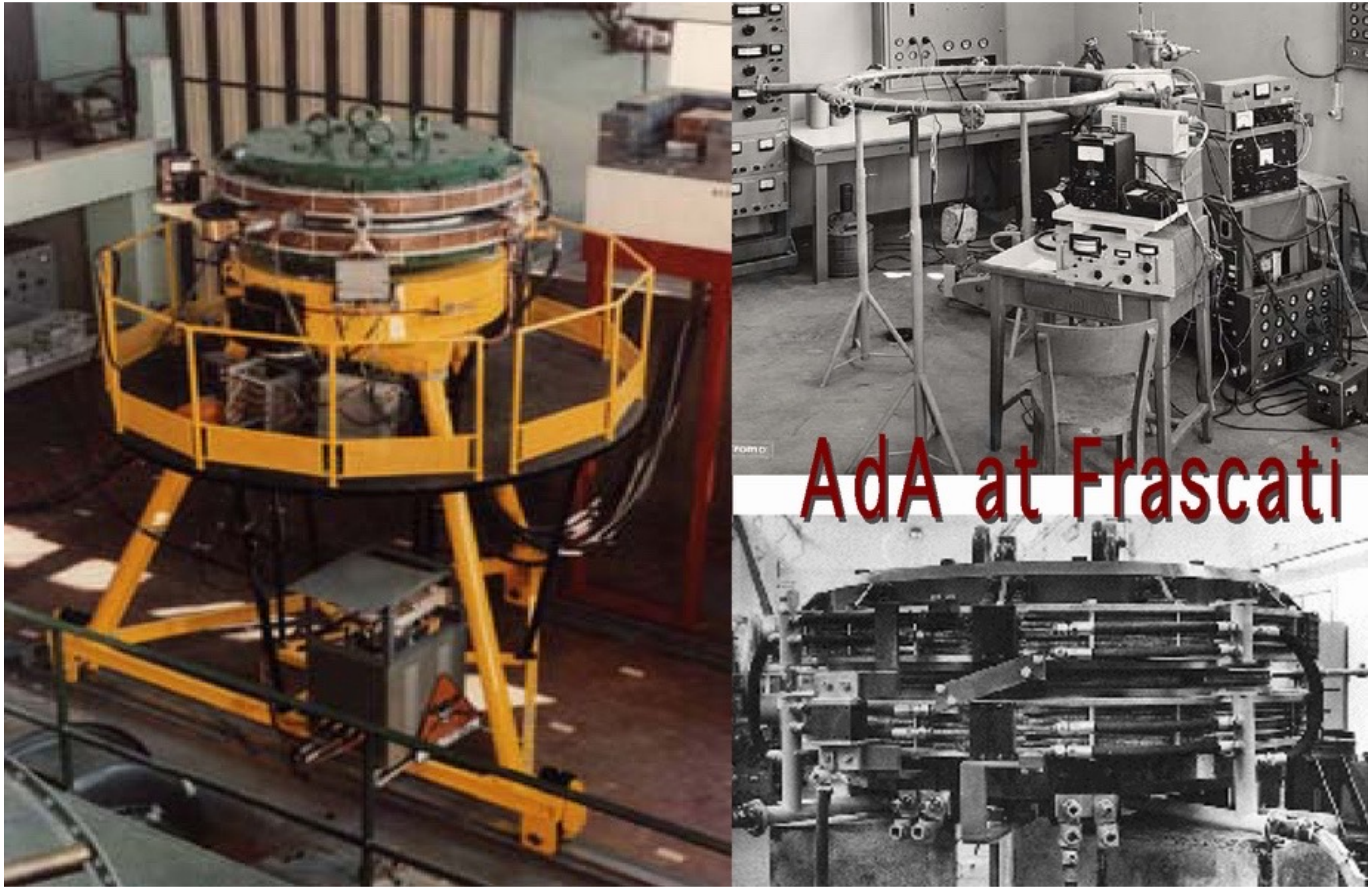


$$W \cong 2\sqrt{E_1 E_2}$$ **beam-beam**

$$W \cong \sqrt{2E\, m_t}$$ **beam-target**

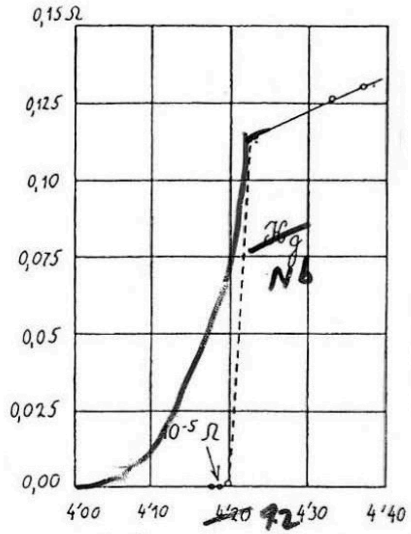
1961: AdA the first Collider



Superconductivity

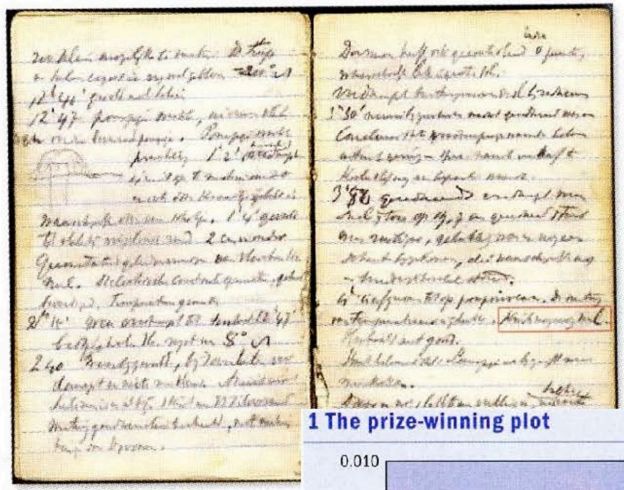
The Cockcroft Institute
of Accelerator Science and Technology

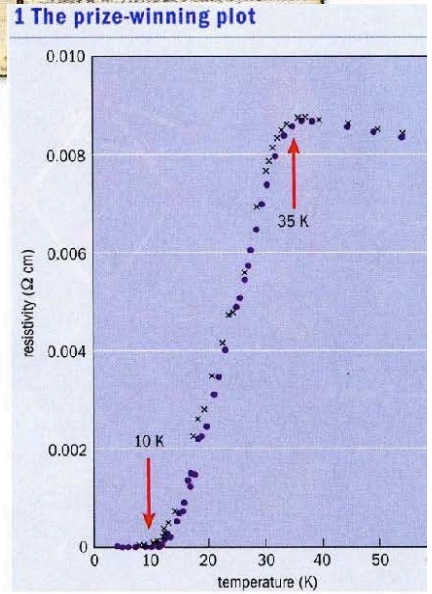
Heike Kammerlingh-Onnes, 1911: SC in mercury



surement of superconductivity by Ka...

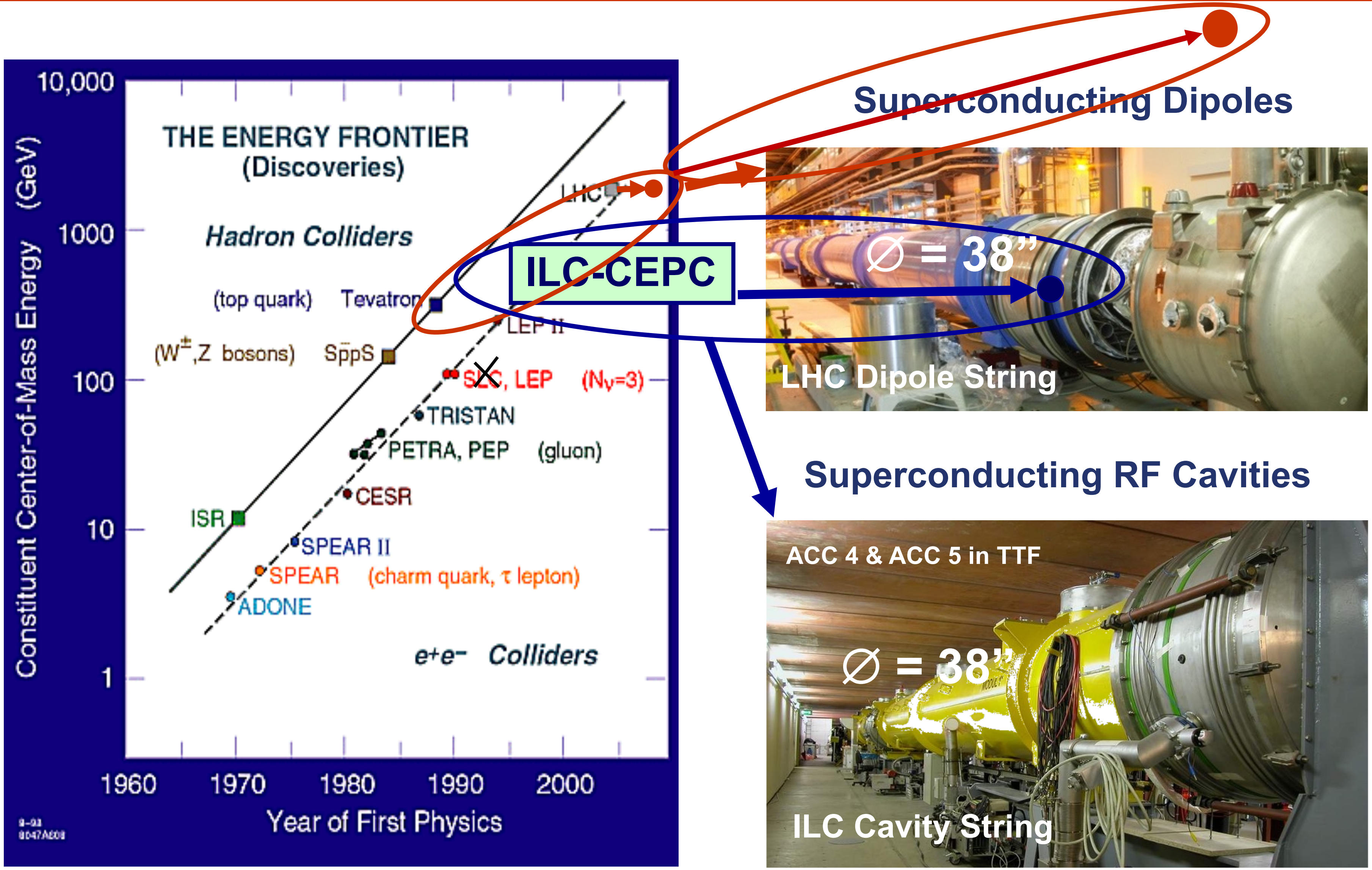
Figure 1-2. Heike Kamerlingh Onnes.



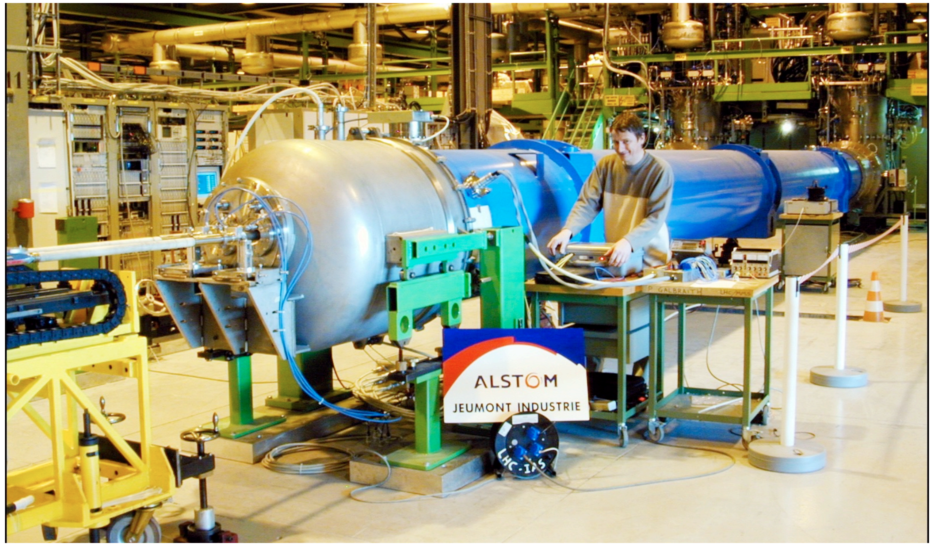


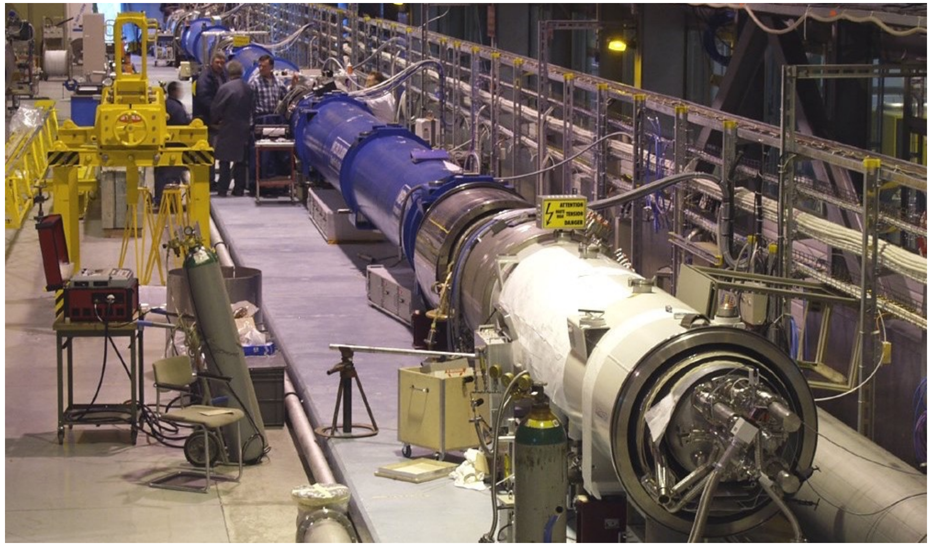
Critical page from 8 April 1911 in Kammerlingh Onnes's notebook

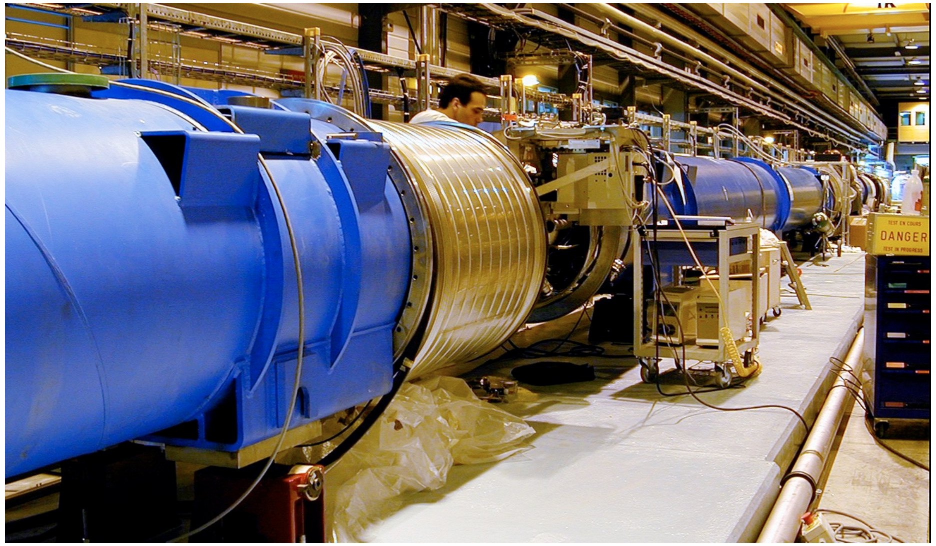
Energy Frontier and Accelerator Technology



Superconducting Magnets for Higher Energy

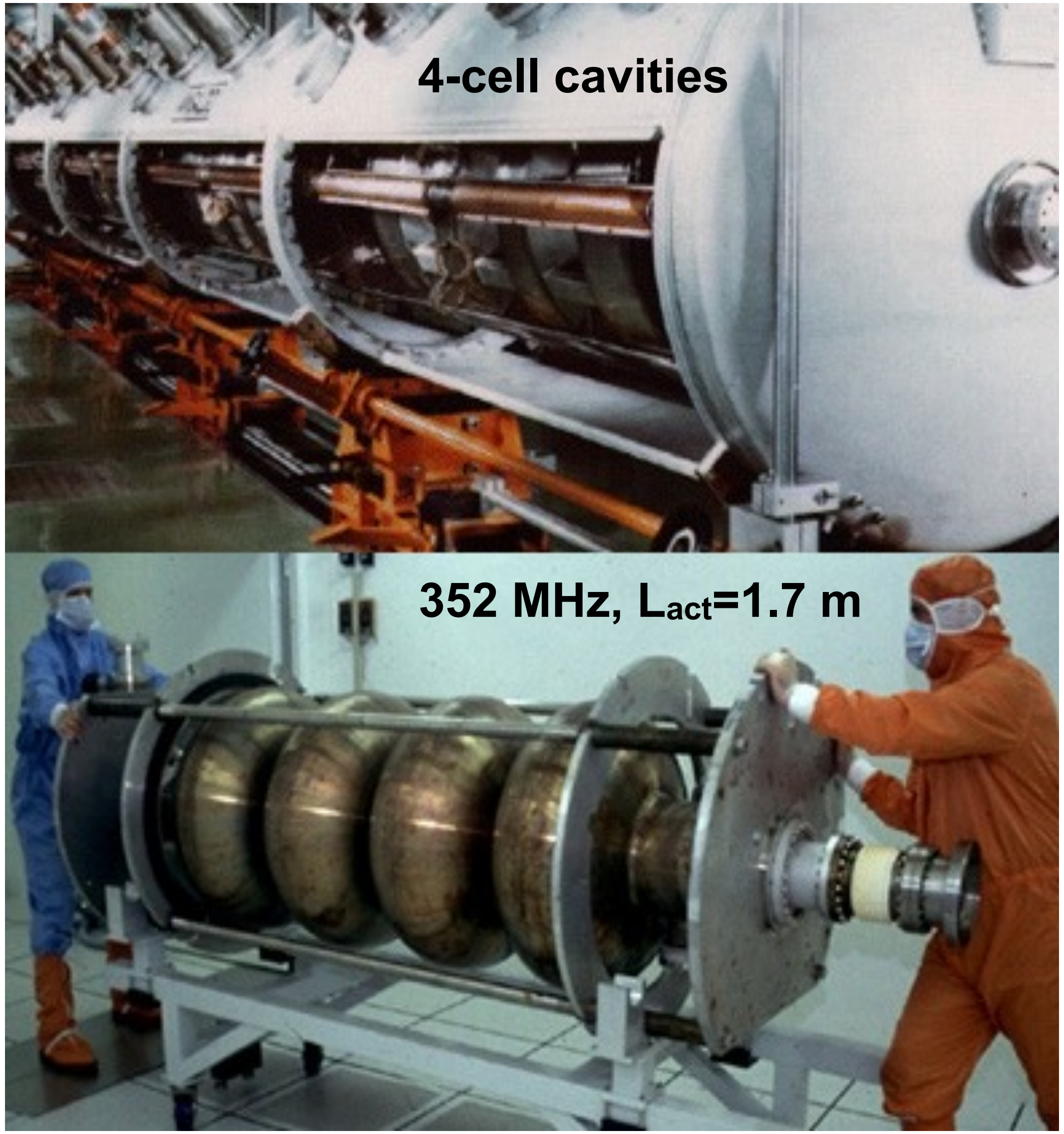






One of LEP2/LHC cryogenic plants (4.3MW)

Superconducting RF for Beam Power (CW)



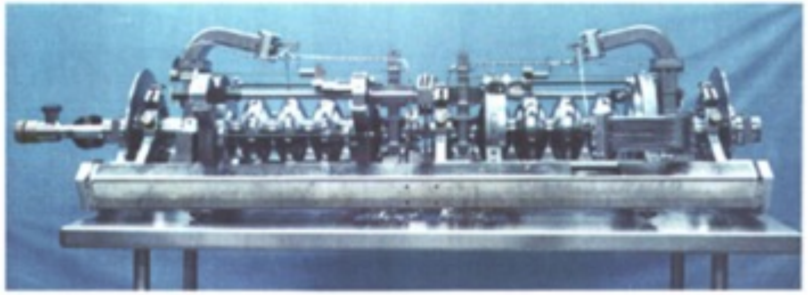
LEP II & CERN

32 bulk niobium cavities

- Limited to 5 MV/m
- Poor material and inclusions

256 sputtered cavities

- Magnetron-sputtering of Nb on Cu
- Completely done by industry
- **Field improved with time**
  $\langle E_{acc} \rangle$ = 7.5 MV/m (Cryo-limited)



CEBAF & Jlab

338 bulk niobium 5-cell cavities – 1.5 GHz

Produced by industry & Processed at TJNAF in a dedicated infrastructure

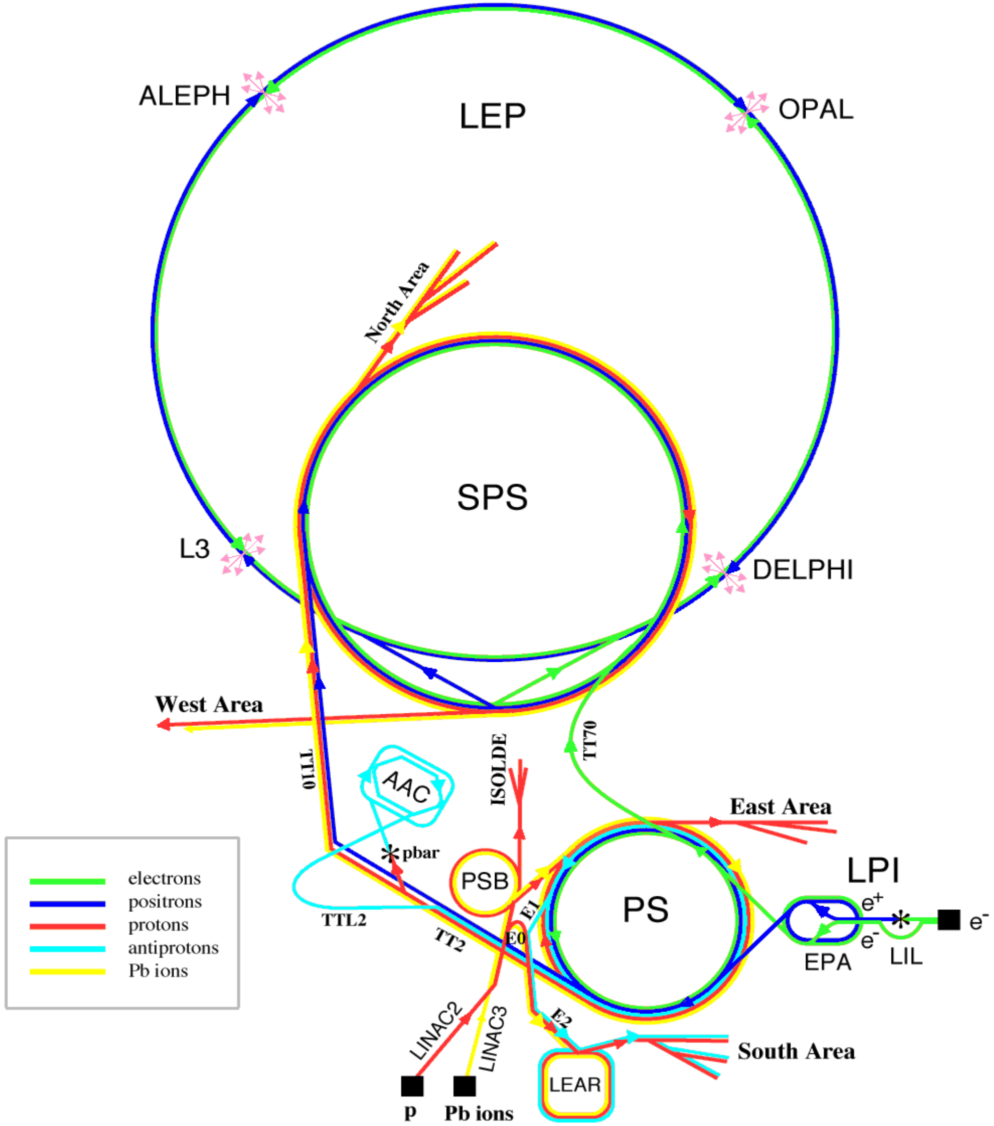
LEP @ LHC in the CERN area

W.Van Doninck Collisions Namur 22/11/2001

The LEP Accelerator Complex @ CERN

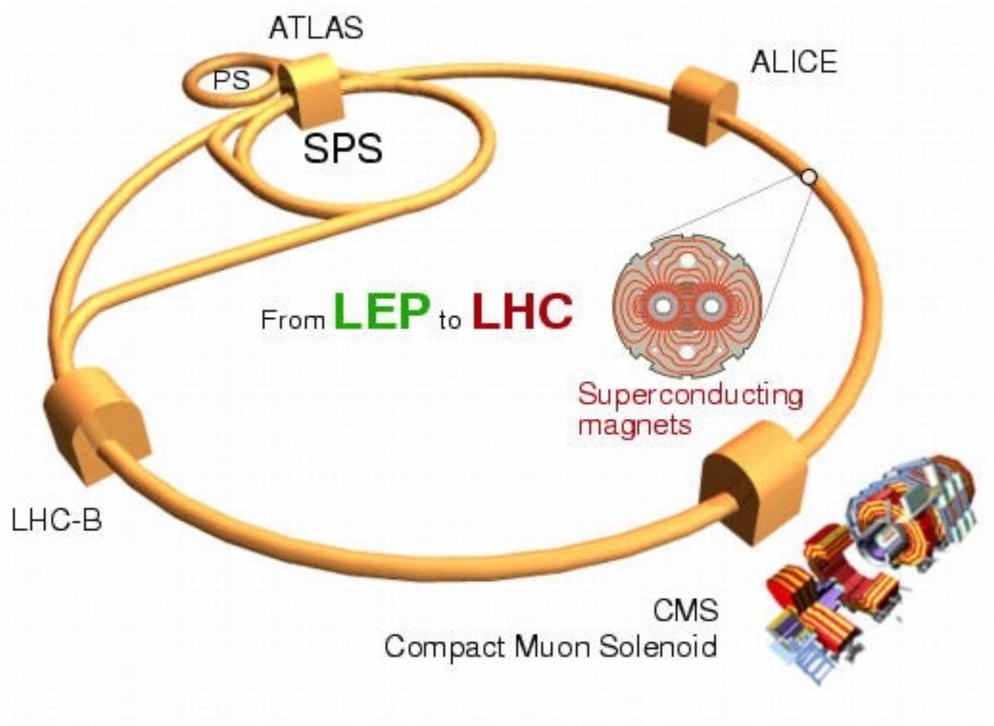

Aerial view of the CERN site with an indication of the circular LEP tunnel

- Linacs and synchrotrons were used to inject in the 28 km synchrotron where both electron and positrons were accelerated up to 100 GeV to collide with a centre of mass energy of 200 GeV
- LHC now in commissioning is making use of most of the LEP injection accelerator complex



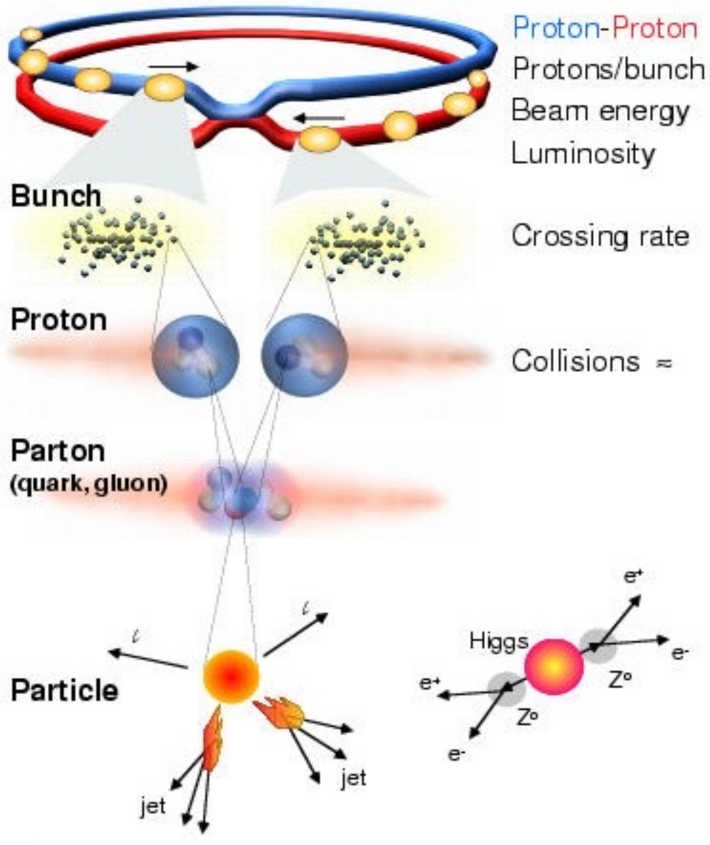
From LEP to LHC

The Large Hadron Collider (LHC)



	Beams	Energy		Luminosity
LEP	e+ e-	200	GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

Collisions at LHC



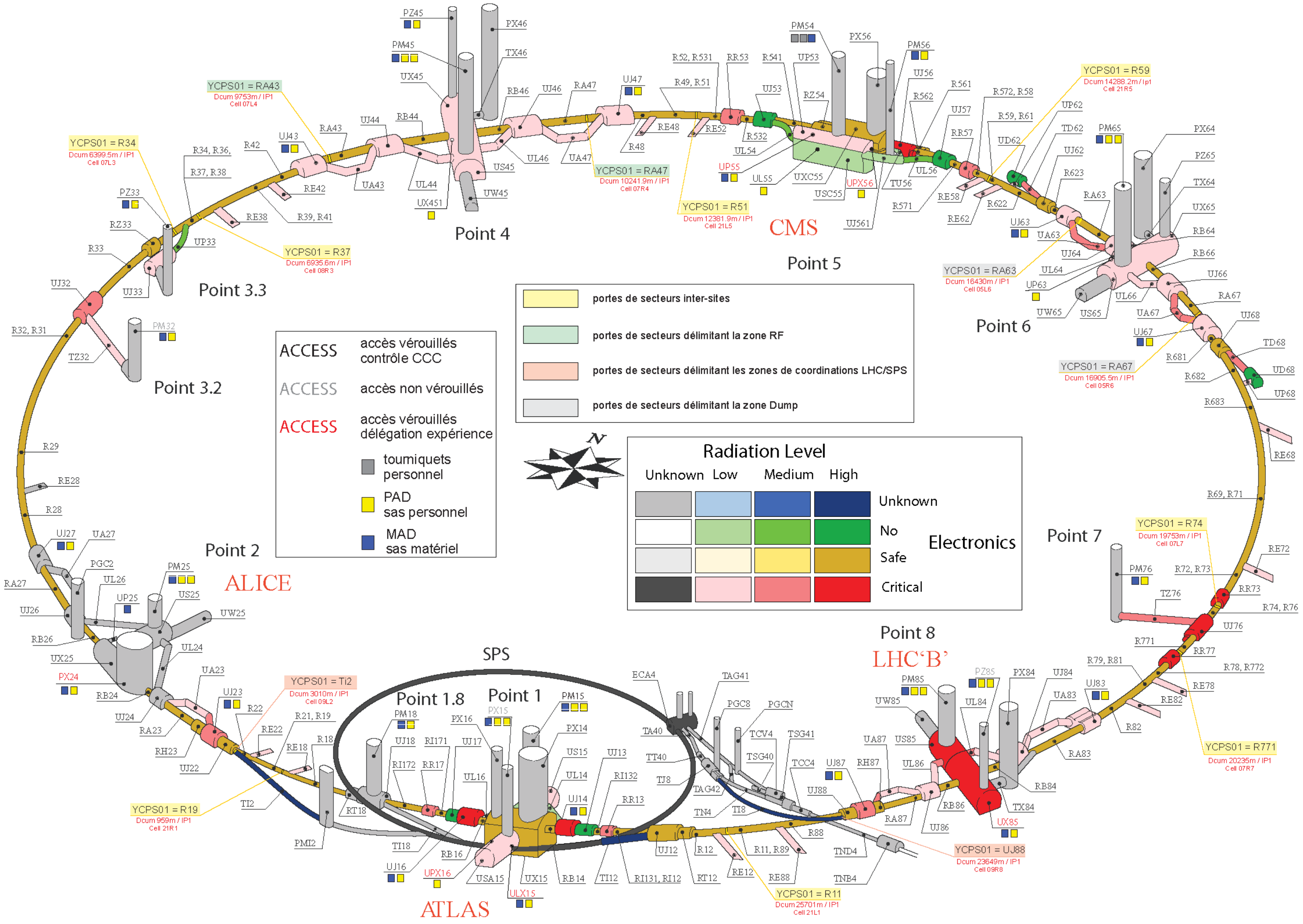
Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz

Higgs

SUSY.....

Selection of 1 in 10,000,000,000,000

LHC Layout



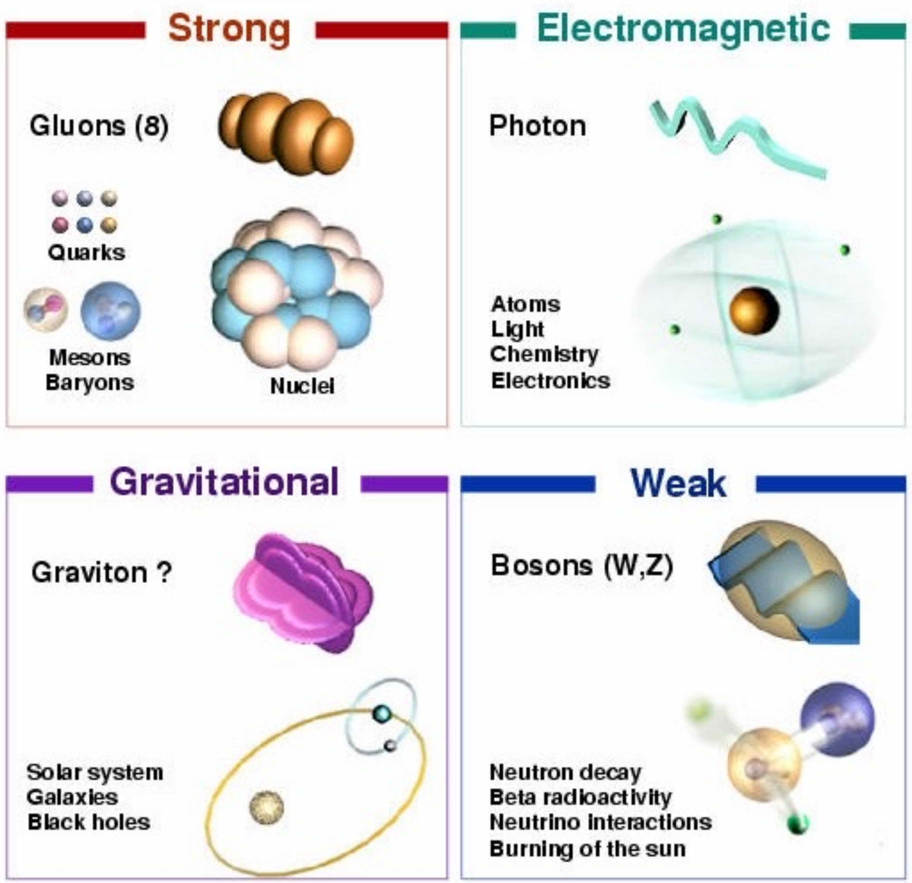
Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
ATLAS
ALICE
CMS
LHC'B'
ACCESS
accès vérouillés contrôle CCC
ACCESS
accès non vérouillés
ACCESS
accès vérouillés délégation expérience
tourniquets personnel
PAD sas personnel
MAD sas matériel
portes de secteurs inter-sites
portes de secteurs délimitant la zone RF
portes de secteurs délimitant les zones de coordinations LHC/SPS
portes de secteurs délimitant la zone Dump
Radiation Level
Unknown
Low
Medium
High
Unknown
No
Safe
Critical
Electronics
N
YCPS01 = RA43
YCPS01 = R34
YCPS01 = R37
YCPS01 = RA47
YCPS01 = R51
YCPS01 = R59
YCPS01 = RA63
YCPS01 = RA67
YCPS01 = R74
YCPS01 = R771
YCPS01 = UJ88
YCPS01 = R11
YCPS01 = Ti2
YCPS01 = R19

Basic Physics Discovery before LHC

Short history and new frontiers

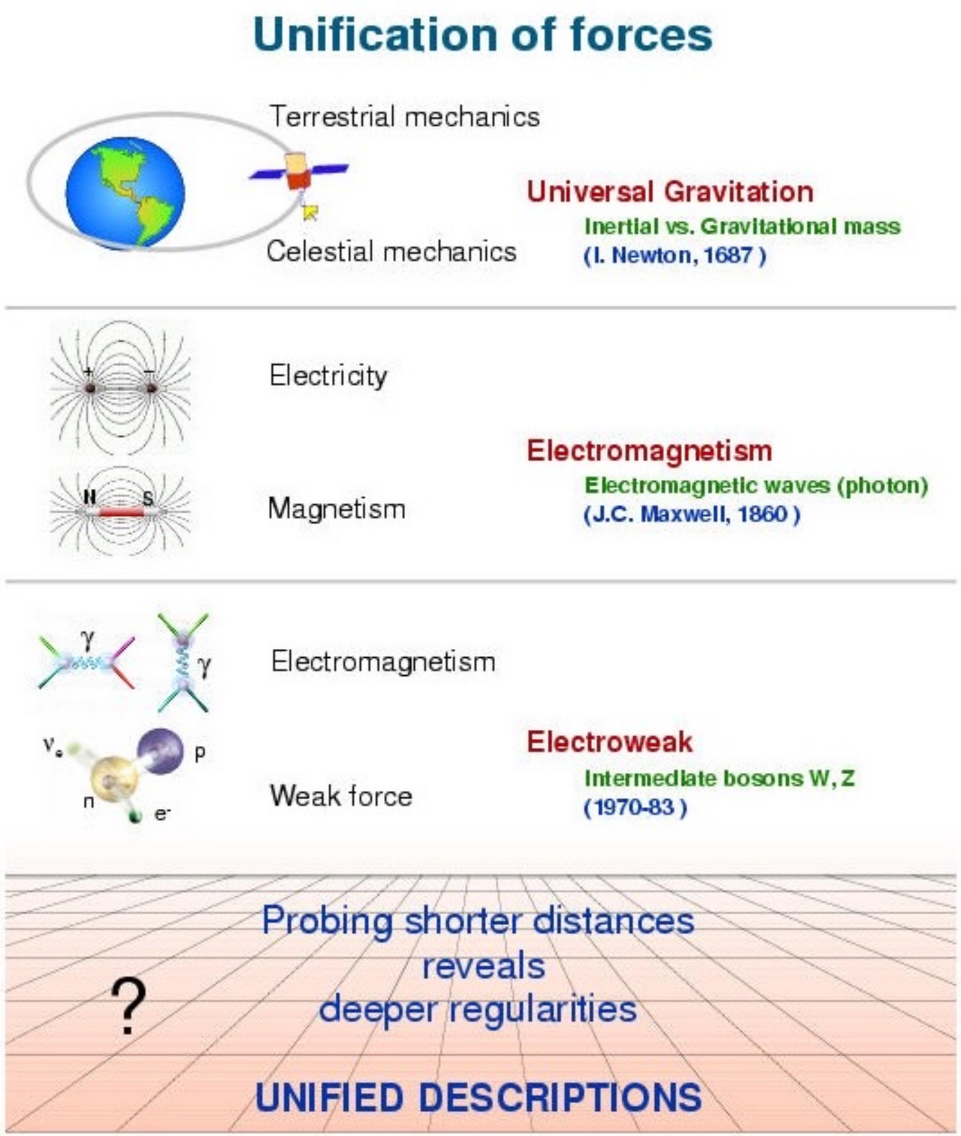
	$\lambda = h/p$		$T \approx t^{-1/2}$	
	10^{-10} m	≤ 10 eV	>300000 Y	**1900....** Quantum Mechanics, Atomic Physics
γ e^+ γ e^-				**1940-50** Quantum Electro Dynamics
	10^{-15} m	MeV - GeV	≈ 3 min	**1950-65** Nuclei, Hadrons, Symmetries, Field theories
	10^{-16} m	>> GeV	≈ 10^{-6} sec	**1965-75** Quarks, Gauge theories
u, $\bar{u}$, Z, e^+, e^-	10^{-18} m	≈ 100 GeV	≈ 10^{-10} sec	**SPS, $p\bar{p}$ 1970-83** ElectroWeak Unification, QCD
6 Leptons: ν_e e, ν_μ μ, ν_τ τ; 6 Quarks: u d, c s, t b; 3 "Colors" each quark R G B				**LEP 1990** 3 families; **Tevatron 1994** Top quark
Origin of masses, The next step...	10^{-19} m	≈ 10^3 GeV	≈ 10^{-12} sec	**LHC 2005** Higgs ? Supersymmetry ?
Proton Decay ?	10^{-32} m	≈ 10^{16} GeV	≈ 10^{-32} sec	**Underground Labs** GRAND Unified Theories ?
The Origin of the Universe	10^{-35} m	≈ 10^{19} GeV (Planck scale)	≈ 10^{-43} sec	?? Quantum Gravity? Superstrings ?

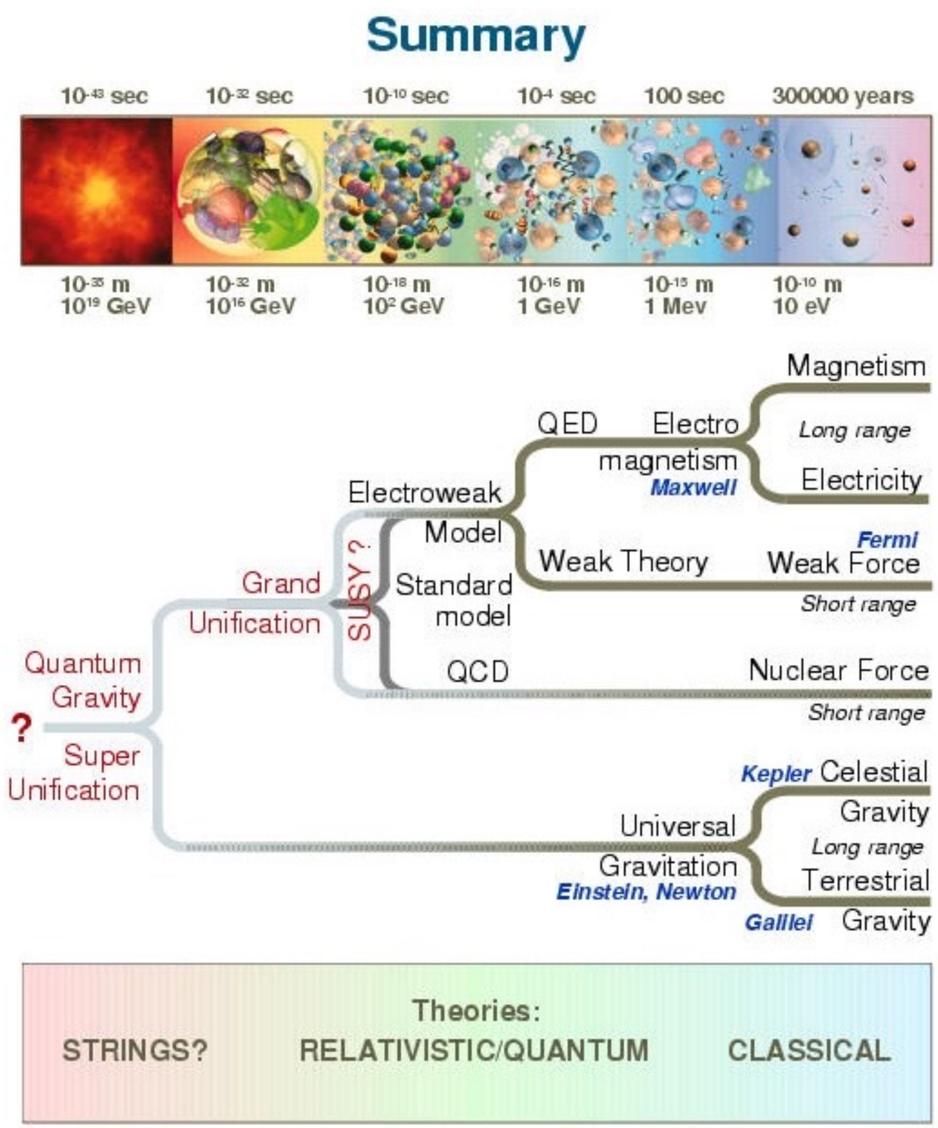
Forces



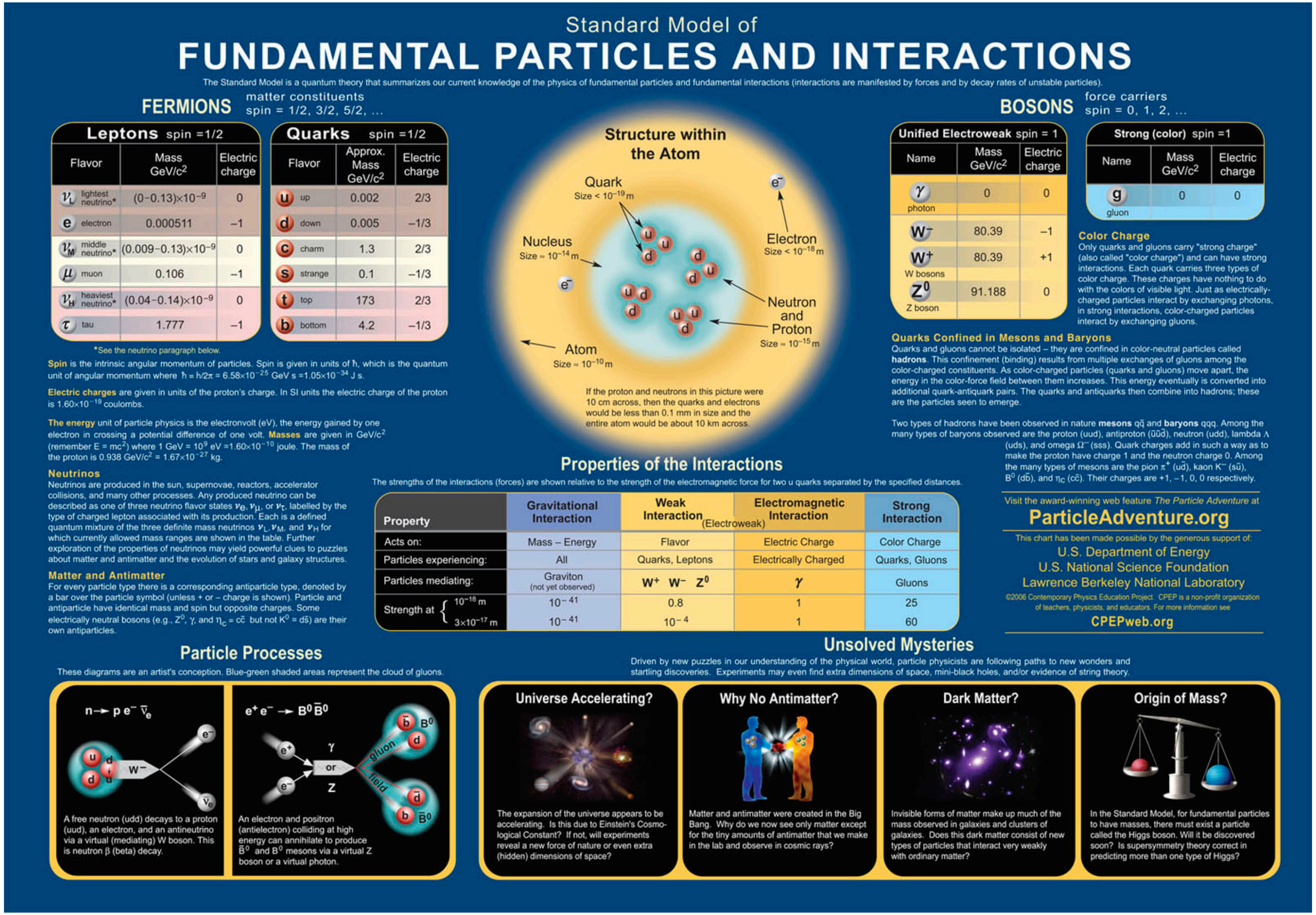
The particle drawings are simple artistic representations

Unification of forces





Standard Model Chart before LHC (2008)



LHC General Parameters (protons)

LHC General Parameters		
Energy at collision	7	TeV
Energy at injection	450	GeV
Dipole field at 7 TeV	8.33	T
Coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Luminosity	1	E34 $cm^{-2}s^{-1}$
Beam beam parameter	3.6	E-3
DC beam current	0.56	A
Bunch spacing	7.48	m
Bunch separation	24.95	ns
Number of particles per bunch	1.1	E11
Normalized transverse emittance (r.m.s.)	3.75	µm
Total crossing angle	300	µrad
Luminosity lifetime	10	h
Energy loss per turn	7	keV
Critical photon energy	44.1	eV
Total radiated power per beam	3.8	kW
Stored energy per beam	350	MJ
Filling time per ring	4.3	min

Higgs Particles and Higgs Field

Higgs Particles

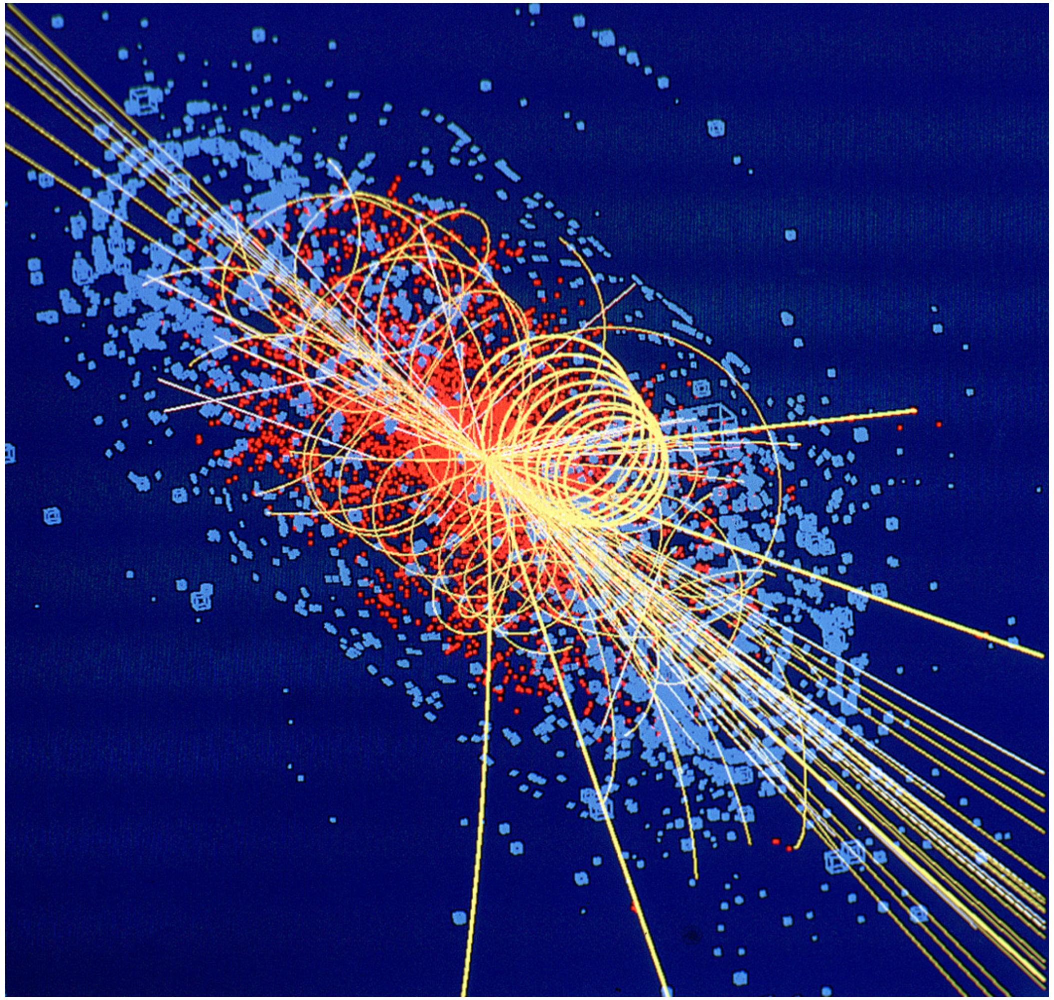
- also called: **God Particles** and **Holy Grail** of Particle Physics
- They are spin=0 Bosons
- **The Higgs is neither matter nor force**
- The Higgs is its own antiparticle
- The **Higgs is just different**
- This would be **the first fundamental scalar ever discovered**

Higgs Field

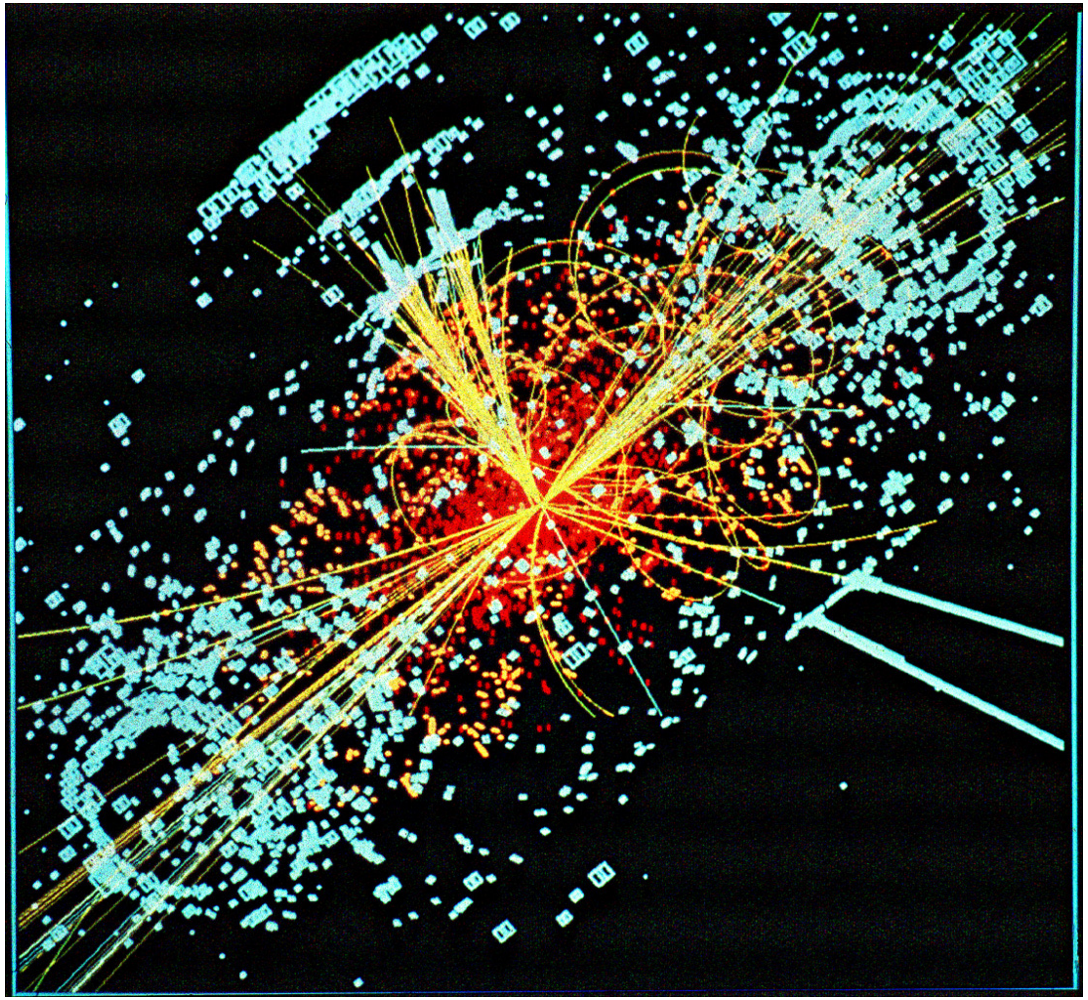
- **Neutral scalar field that fills the entire universe**
- **Particles** traveling through the universe **interact with this field & become massive**
- Importantly, the W and Z bosons receive mass but not the photon in the Standard Model
- The Higgs field is thought to fill the entire universe.
- Could give a handle on dark energy (scalar field) ?

Higgs Particles as a very powerful probe of new physics

Simulations of Higgs events at CERN/CMS

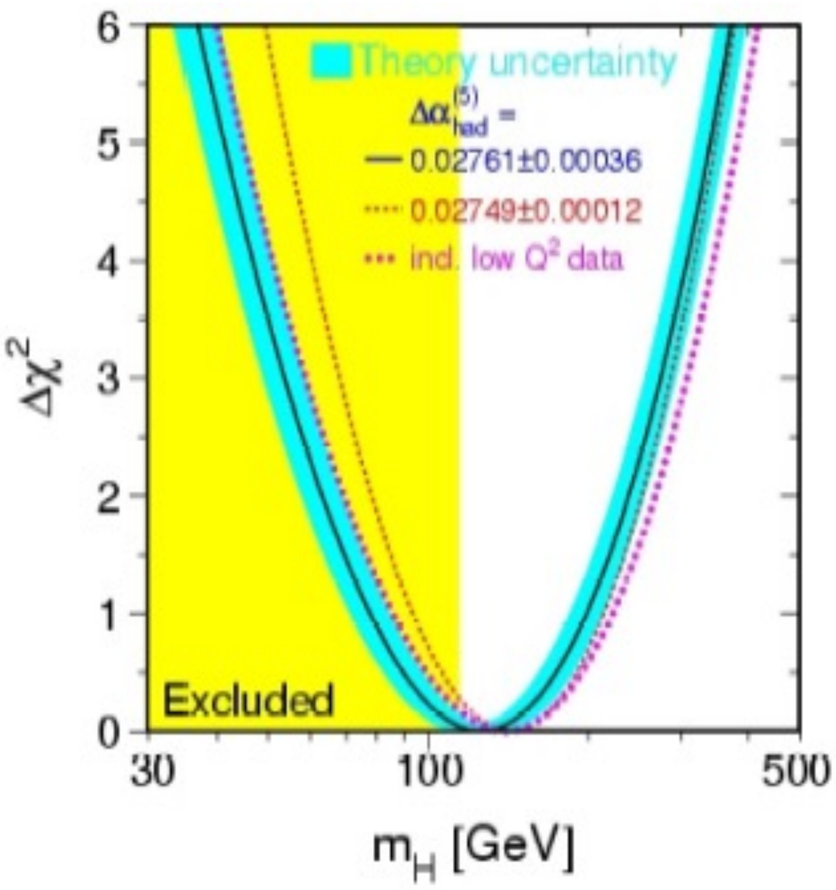


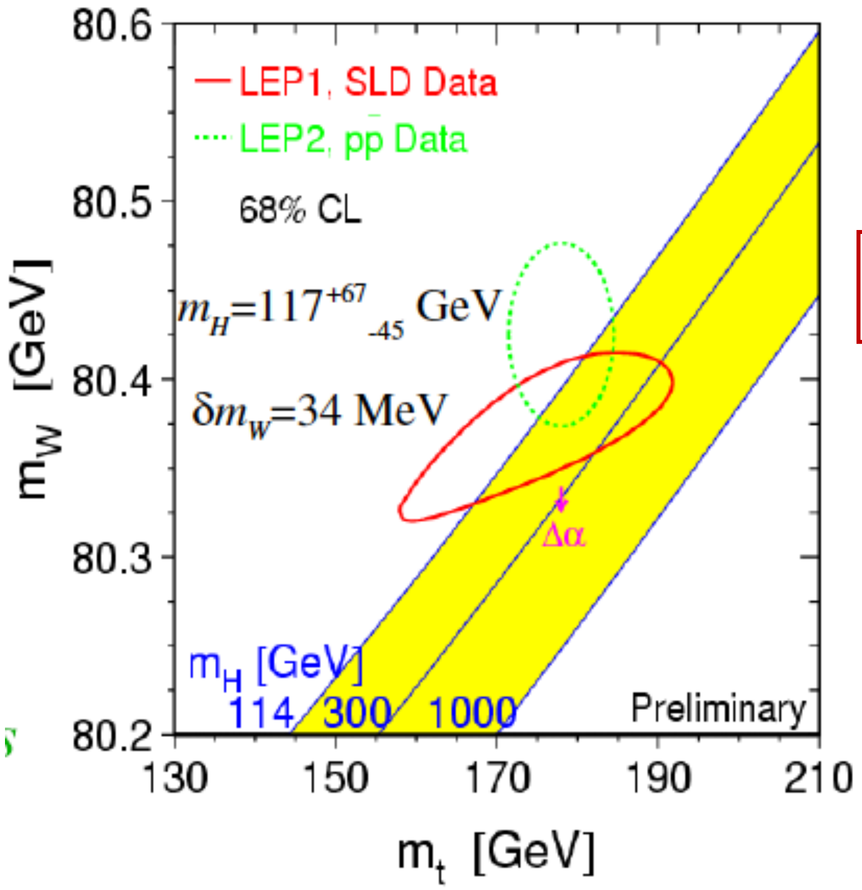
CERN-EX-9710002_05



CERN-EX-9710002_10

SM Higgs mass from LEP2 & Tevatron



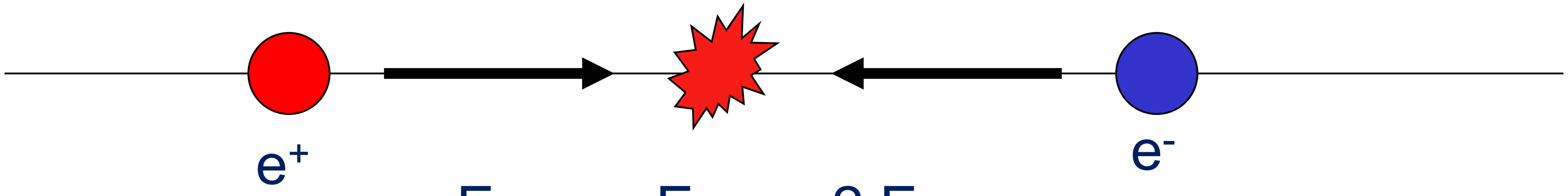


Fumihiko Takasaki
May 20, 2006

$$m_H = 117^{+67}_{-45}\ \mathrm{GeV}/c^2$$

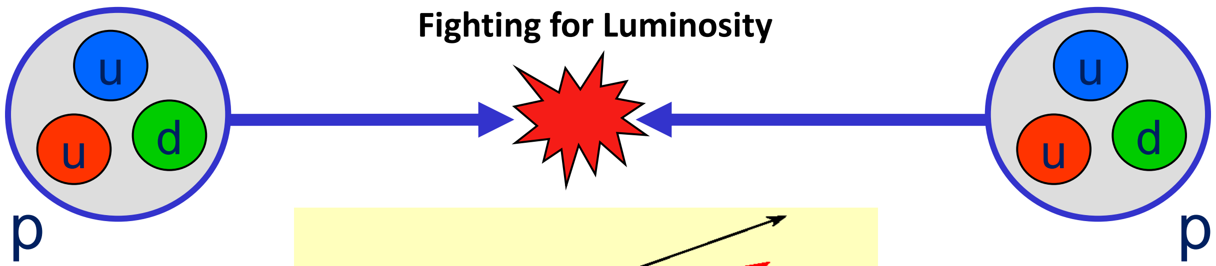
Why we insist for leptons ?

Leptons (e^-, e^+, μ^-, μ^+) are Fermions, i.e. matter constituents

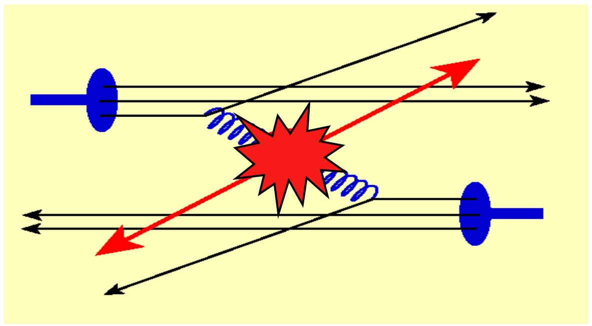


$$E_{react.} = E_{c.m.} = 2\ E_{beam}$$

Hadrons (p, $\bar{p}$, ions) are complex composite particles



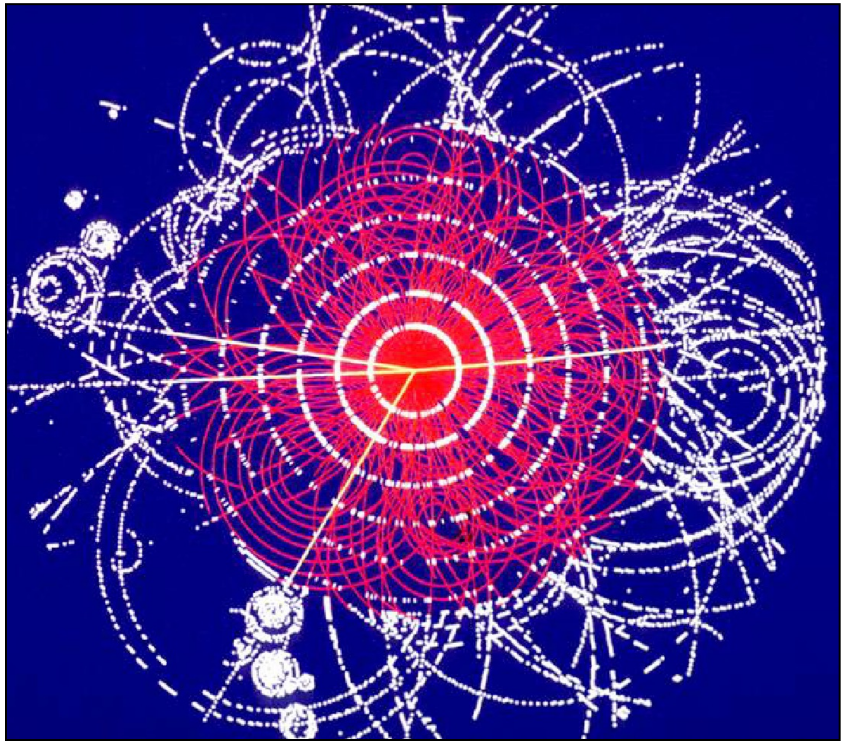
$E_{react.} << 2\ E_{beam}$

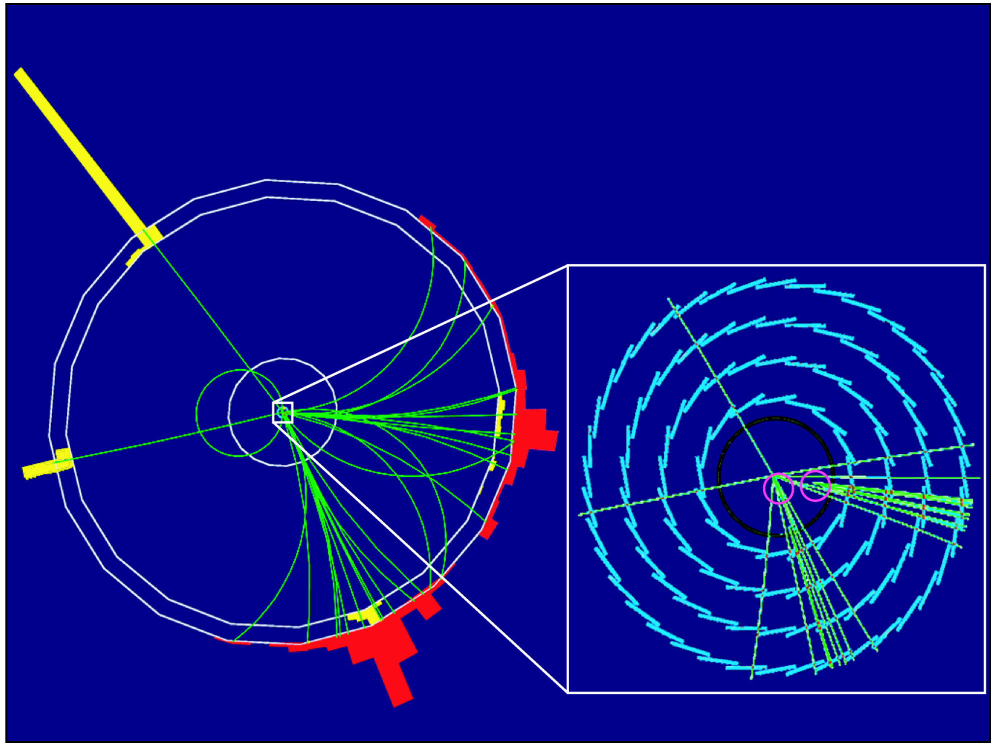


Gluon-Gluon Collision

$E_{react.}$ cannot be controlled and it is unknown

Higgs event Simulation Comparison





LHC **ILC**

$e^+ e^- \rightarrow Z H$

$Z \rightarrow e^+ e^-, H \rightarrow b\bar{b}$

Relation of LHC and ILC

C. Pagani - ISLC08 - Lecture 1
Oak Brook, October 20, 2008

Since the ILC will start after the start of LHC, it **must add significant amount of information**. **This is the case!**

Neither LC nor HC's can draw the whole picture alone. ILC will add new discoveries and precision of ILC will be essential for a better understanding of the underlying physics.

There are probably pieces which can only be explored by the LHC due to the higher mass reach. **Joint interpretation of the results** will improve the overall picture

In the Higgs Boson Scenario

LHC will make the **discovery**

ILC will behave as a **Higgs Boson factory** to precisely determine its properties and the consequences for physics beyond the standard model

Linear Collider Conceptual Scheme

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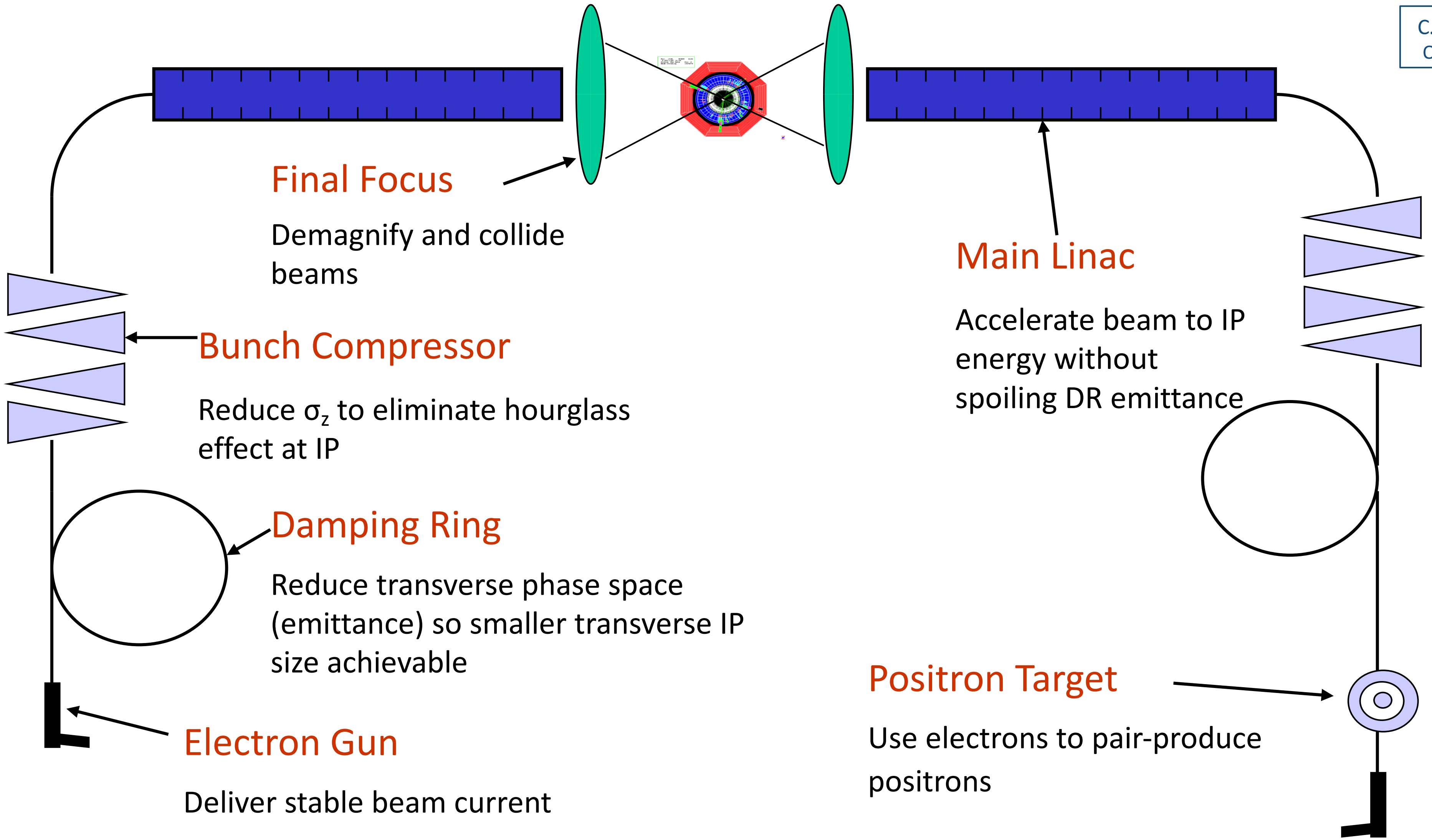
Oak Brook, October 20, 2008



Competing technologies for the ILC Linac

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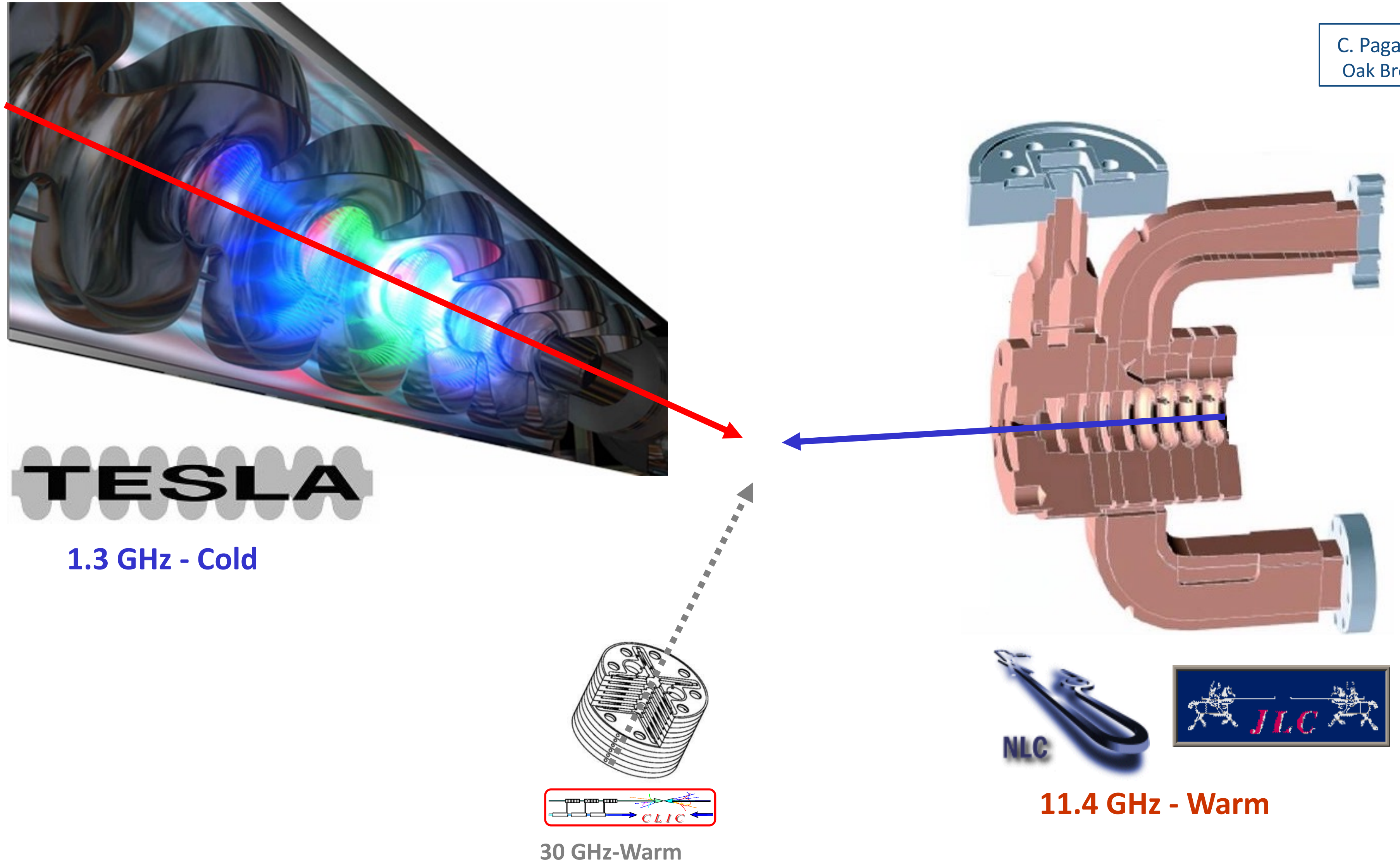

Competing RF Structures for the ILC Linac

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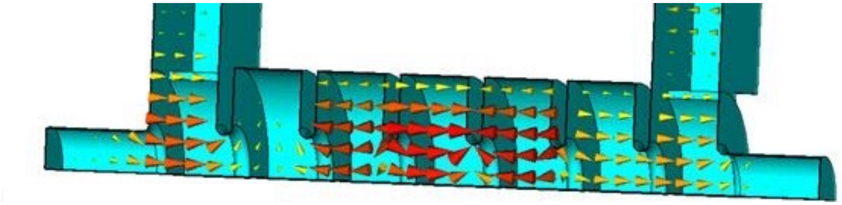
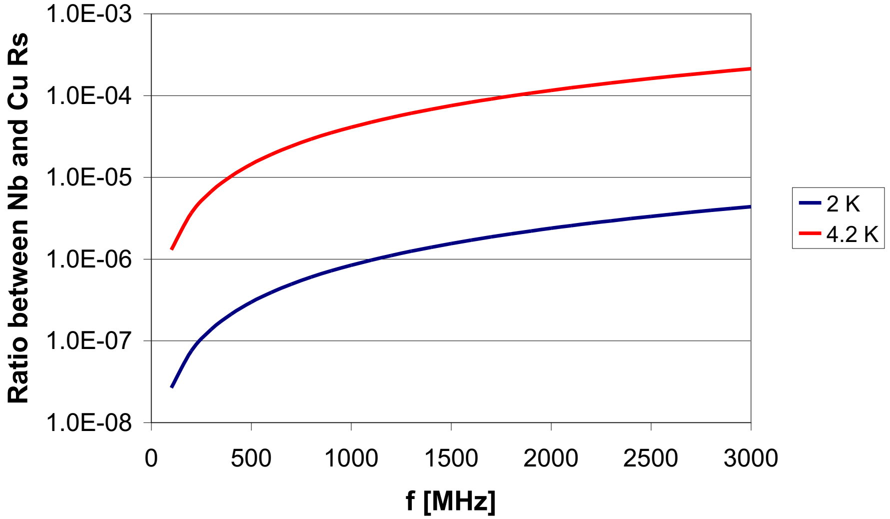
NC Traveling wave

$v_{ph} \approx c$ and $v_g < c$ Nornal Conducting

NLC/GLC: f = 11.4 GHz

CLIC f = 30 GHz

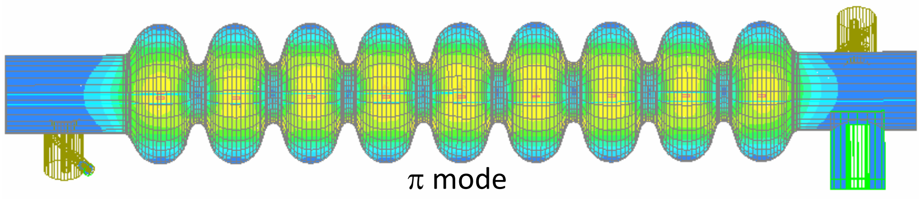




SC Standing wave

$v_{ph} = 0$ and $v_g = 0$ Super Conducting

TESLA: f = 1.3 GHz



Remembering that the power dissipated on the cavity walls to sustain a field is:

$$P_{diss} = \frac{R_s}{2} \int_S H^2 dS$$

standing wave case

a pulsed operation is required to reduce the time in which the maximum allowable field is produced to accelerate the particles

All Linear Colliders are pulsed

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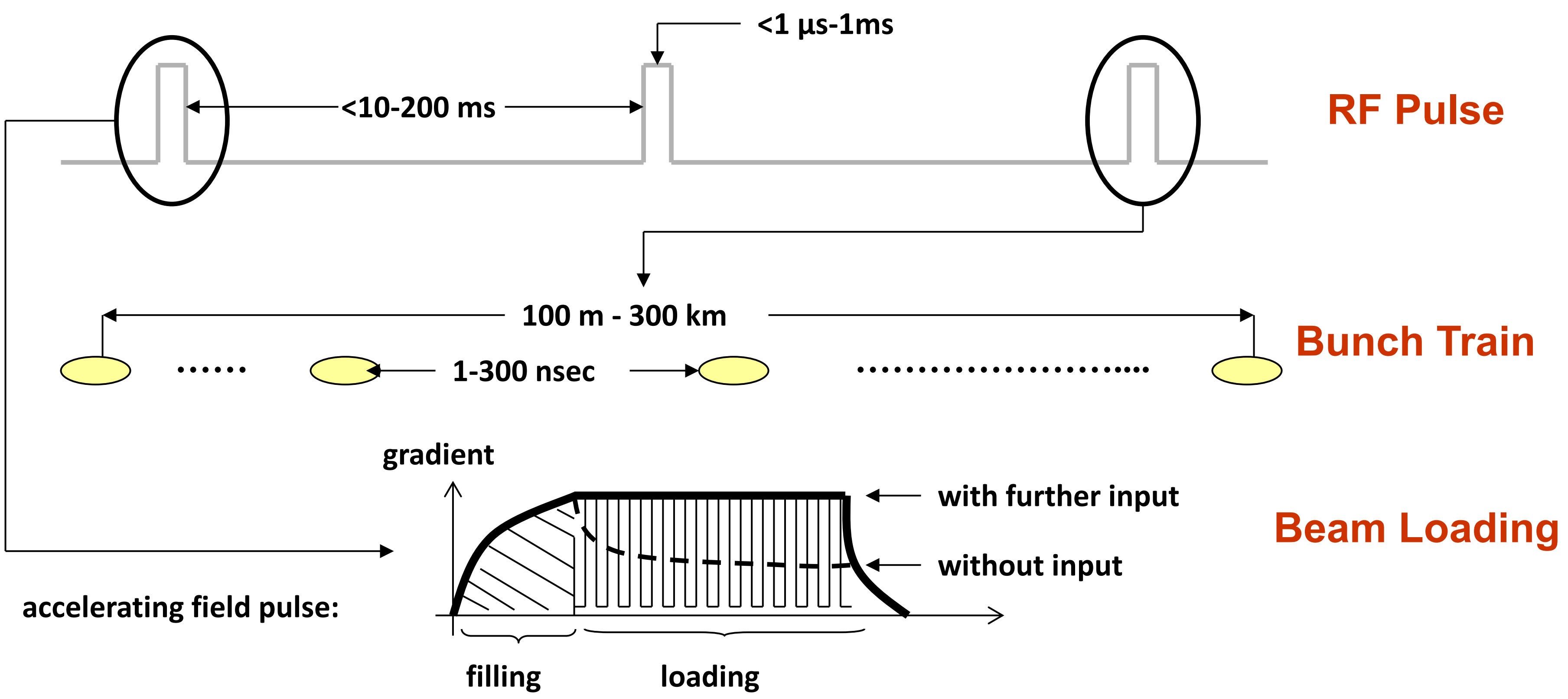
All the LCs must be pulsed machines to improve efficiency. As a result:

- duty factors are small
- pulse peak powers can be very large



Fighting for Luminosity

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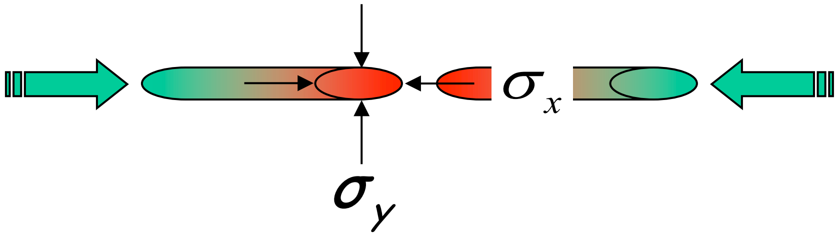
$$L \propto \frac{N_e^2}{\sigma_x \sigma_y}$$



$$L \propto n_b \times f_{rep}$$

L = Luminosity

N_e = # of electron per bunch

$\sigma_{x,y}$ = beam sizes at IP

IP = interaction point

$$L \propto \frac{P_b}{E_{c.m.}} \times \frac{N_e}{\sigma_x \sigma_y}$$

n_b = # of bunches per pulse

f_{rep} = pulse repetition rate

P_b = beam power

$E_{c.m.}$ = center of mass energy

Parameters to play with

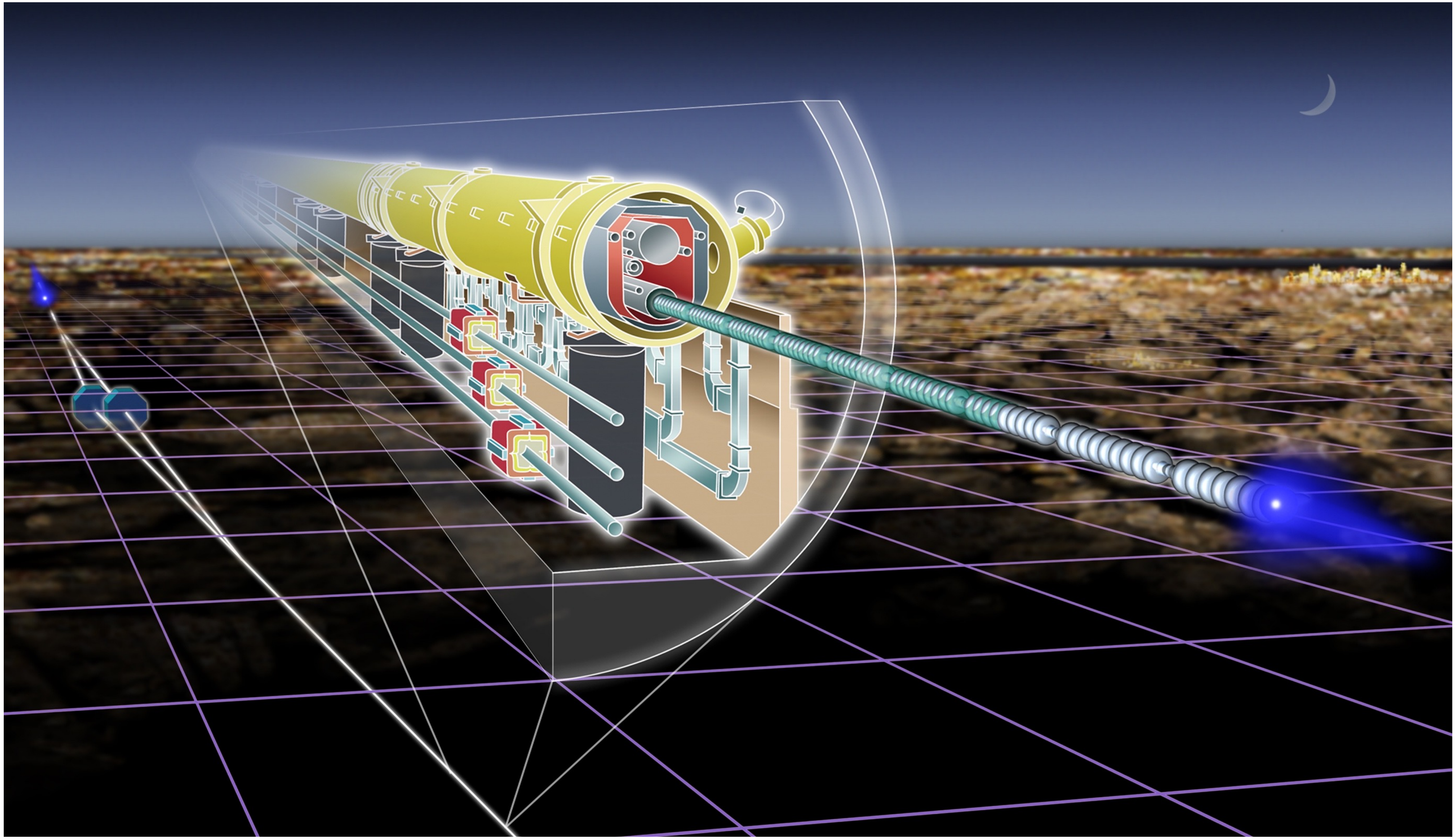
↓ Reduce beam emittance ($\varepsilon_x \cdot \varepsilon_y$) for smaller beam size ($\sigma_x \cdot \sigma_y$)

↑ Increase bunch population (N_e)

↑ Increase beam power $\left(P_b \propto N_e \times n_b \times f_{rep}\right)$

↑ Increase beam to-plug power efficiency for cost

ILC: Pictorial View of the Winner



Glossary

- **Units of Energy** : eV (Electron Volt)
  MeV ; Mega Electron Volt : 10^6 eV
  GeV ; Giga Electron Volt : 10^9 eV
  TeV ; Tera Electron Volt : 10^{12} eV
- **Particle Masses**
  Electron : 0.5 MeV/c^2, Proton : 938 MeV/c^2
- **Cross section** : σ
  nb : 10^{-33} cm^2 , pb : 10^{-36} cm^2 , fb : $10^{-39} cm^2$
- **Luminosity** : L
  Number of Particle collisions per unit time per unit area
  e.g. : the KEKB recorded $L = 1.6 \times 10^{34}\ cm^{-2} sec^{-1}$
- **Integrated Luminosity** : $\int L$
  Luminosity integrated over some time interval,
  e.g. : the KEKB recorded $\int L = 10^{39} cm^{-2} = fb^{-1}$ in a day.

About Orders of Magnitude

Linear Sizes in the Universe

Quark	10^{-19}	m
Proton & Neutron	10^{-15}	m
Atoms	10^{-10}	m
Cells	10^{-8} - 10^{-3}	m
Human being	10^{0}	m
Earth	10^{7}	m
Sun	10^{9}	m
Solar System	10^{13}	m
Milky Way	10^{21}	m
Univers	10^{26}	m

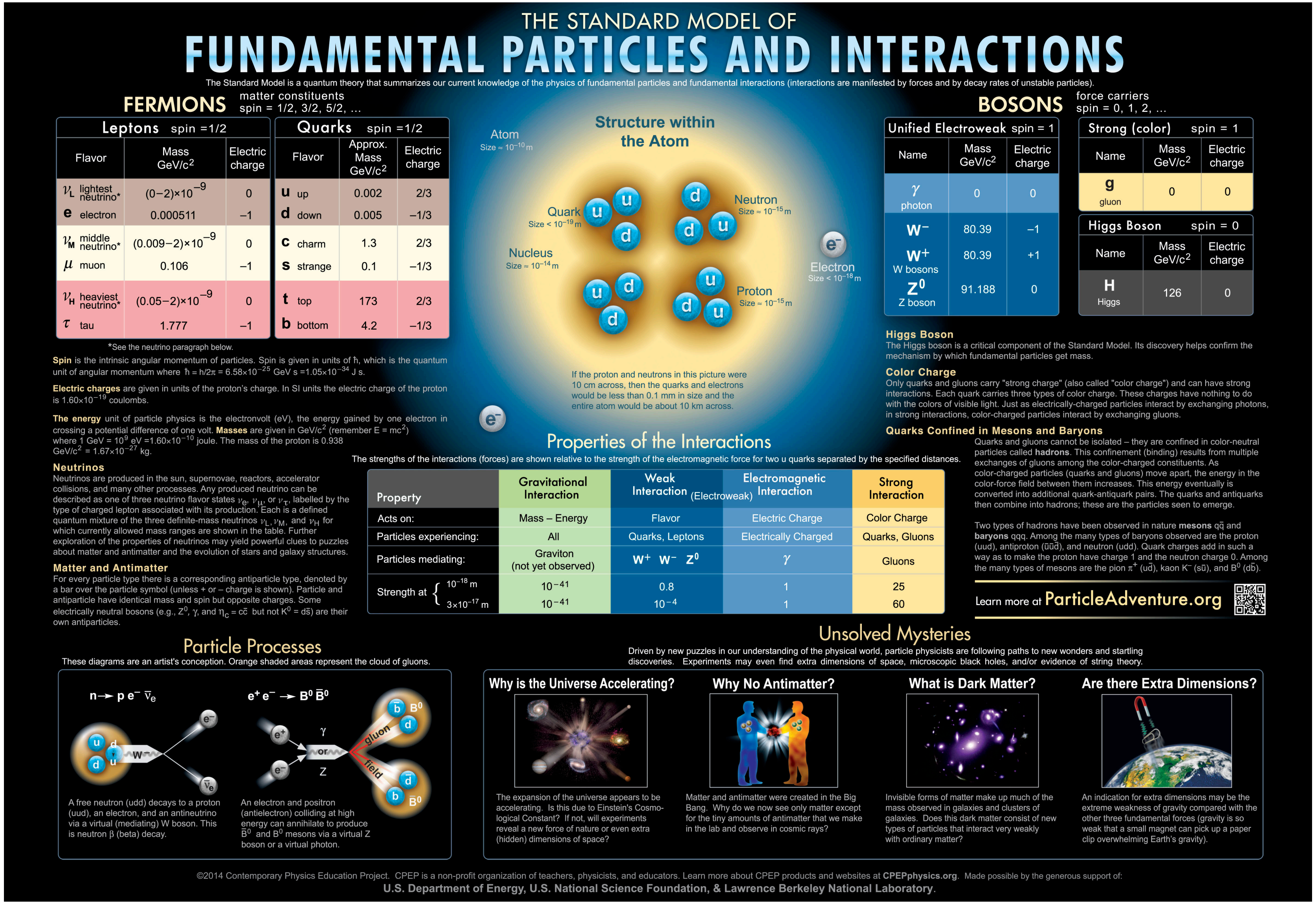
Just for fun

Linear Ratio between the sizes of the universe and the quark

$$\frac{\Phi_{universe}}{\Phi_{quark}} \approx 10^{45} \longrightarrow \textbf{45 digits}$$

60 digits **are used for encrypting codes !**

Standard Model Chart including LHC (2014)



Basic Knowledge after LHC

Proton
Size ≈ 10^{-15} m

Size < 10^{-18} m

Z^0 Z boson	91.188	0

H Higgs	126	0

ton and neutrons in this picture were
ross, then the quarks and electrons
less than 0.1 mm in size and the
om would be about 10 km across.

ies of the Interactions

strength of the electromagnetic force for two u quarks separated by the specified distances.

Weak Interaction	(Electroweak) Electromagnetic Interaction	Strong Interaction
Flavor	Electric Charge	Color Charge
Quarks, Leptons	Electrically Charged	Quarks, Gluons
W^+ W^- Z^0	γ	Gluons
0.8 10^{-4}	1 1	25 60

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at ParticleAdventure.org

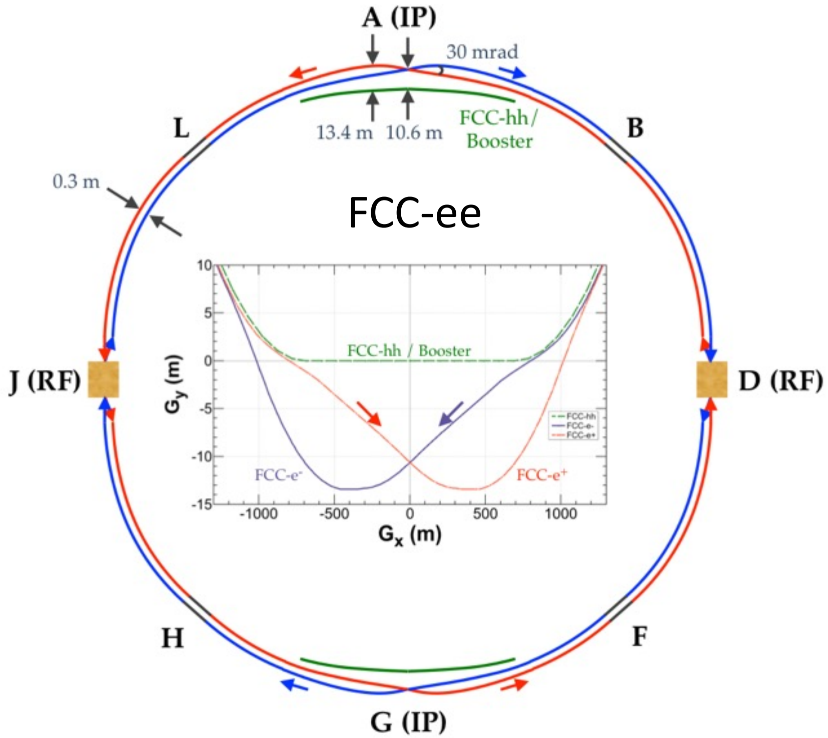
Different attitudes by different actors

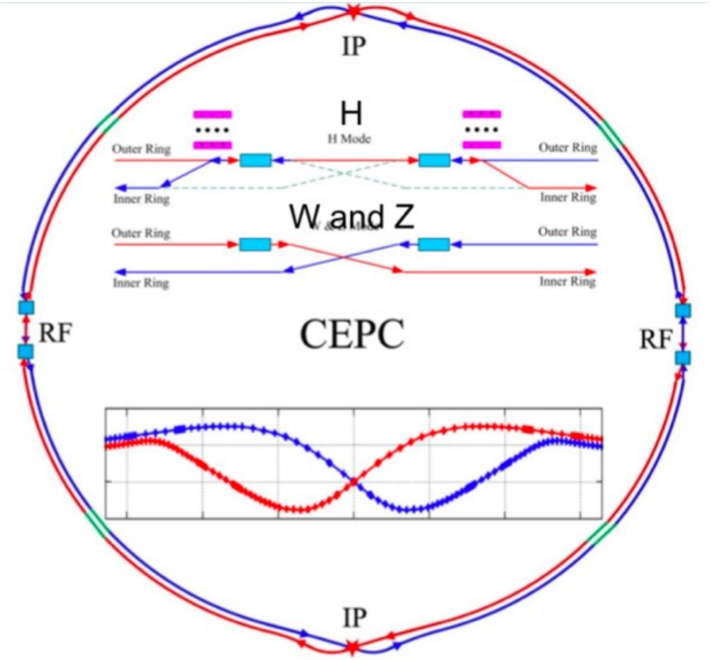
- Most of the major actors are taking advantage of the developed cold technology investing in large infrastructures for applied science
- CERN concentrated the efforts in the LHC upgrade toward a100TeV, 100km, Hadron Collider, while resurrecting the interest on CLIC and Muon Colliders.
- US and China focused their attention on the more accessible neutrino Physics, well matched with the growing impact of astrophysics
- Japan organized the effort to adapt the ILC to the lower energies demanded by a high luminosity boson factory
- China, following the large ring idea, inverted the priorities focusing on the design of an Higgs Factory first.

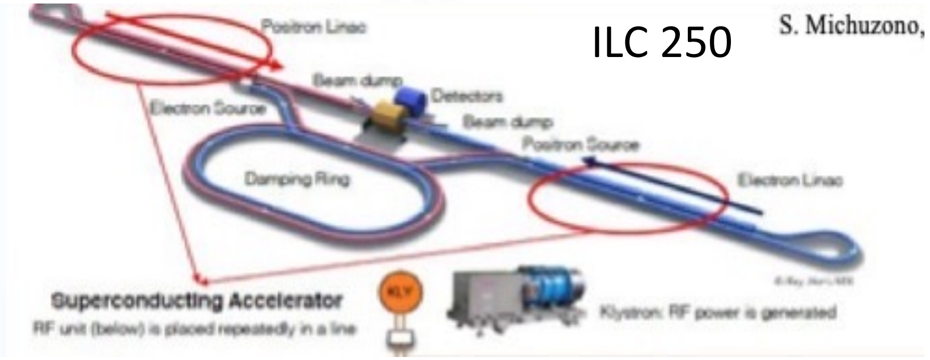
Beyond the Standard Model (> 2035) e^+-e^-

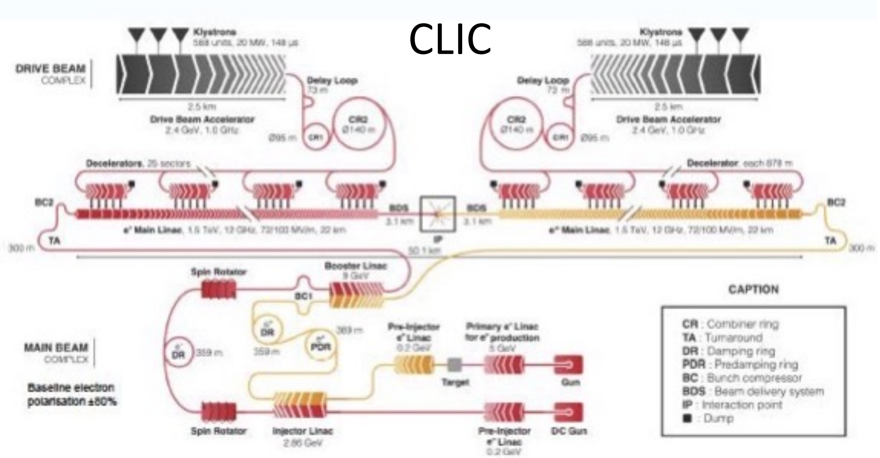
e^+e^- Colliders

Competing Projects





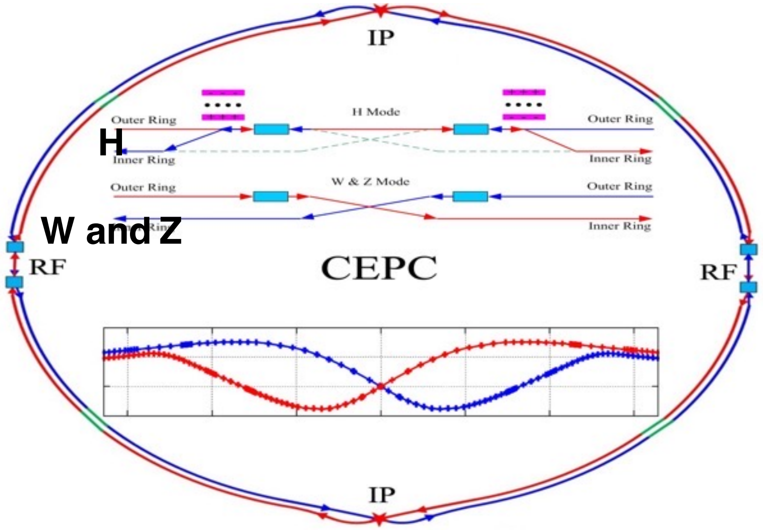




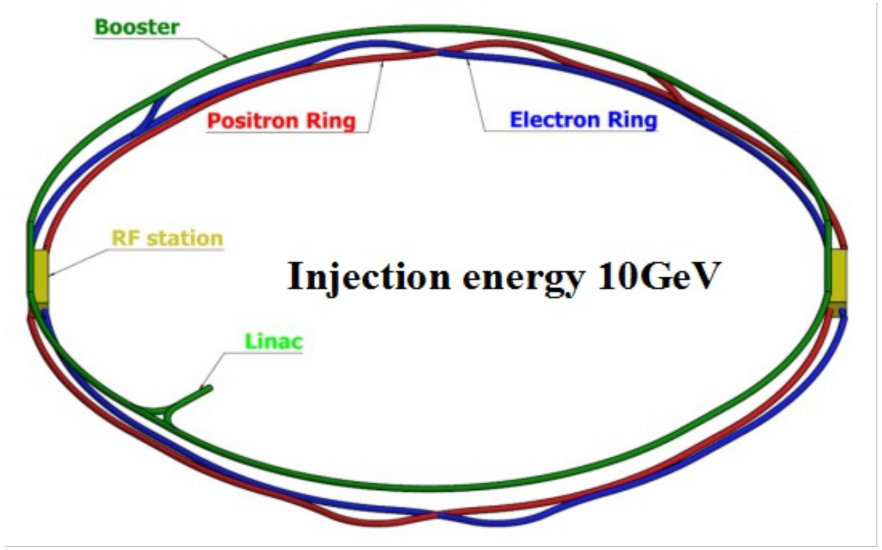
FCC-ee collider parameters *(F. Zimmermann)*

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

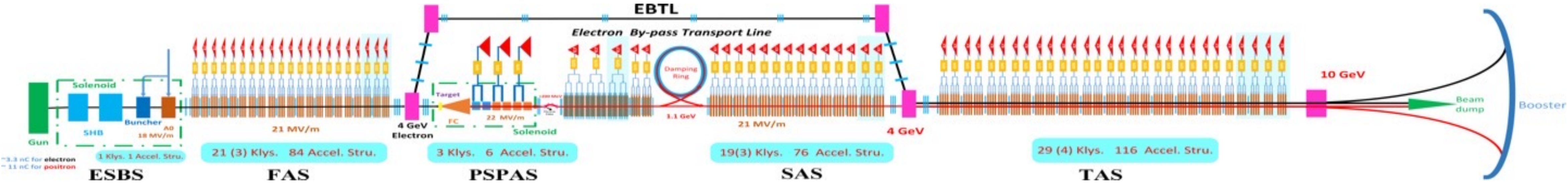
CEPC CDR Baseline Layout



CEPC collider ring (100km)



CEPC booster ring (100km)

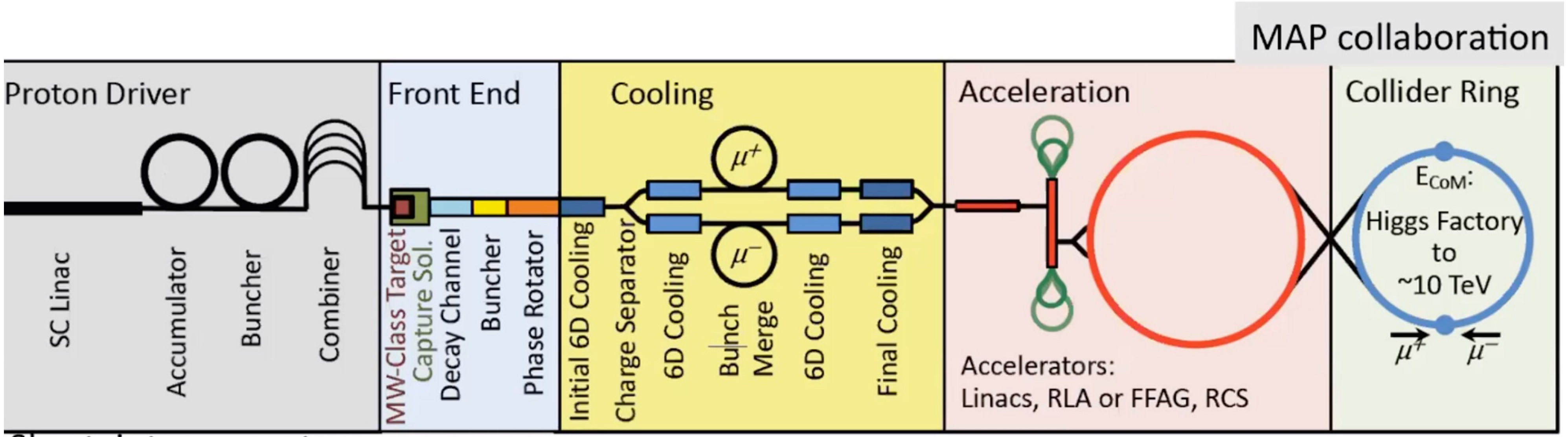


CEPC Linac injector (1.2km, 10GeV)

Beyond the Standard Model (> 2050) μ^+-μ^-

Proton-driven **Muon Collider Concept** 3-10 GeV

The design is driven by the short muon lifetime = 2.2 µs



Short, intense proton bunches to produce hadronic showers

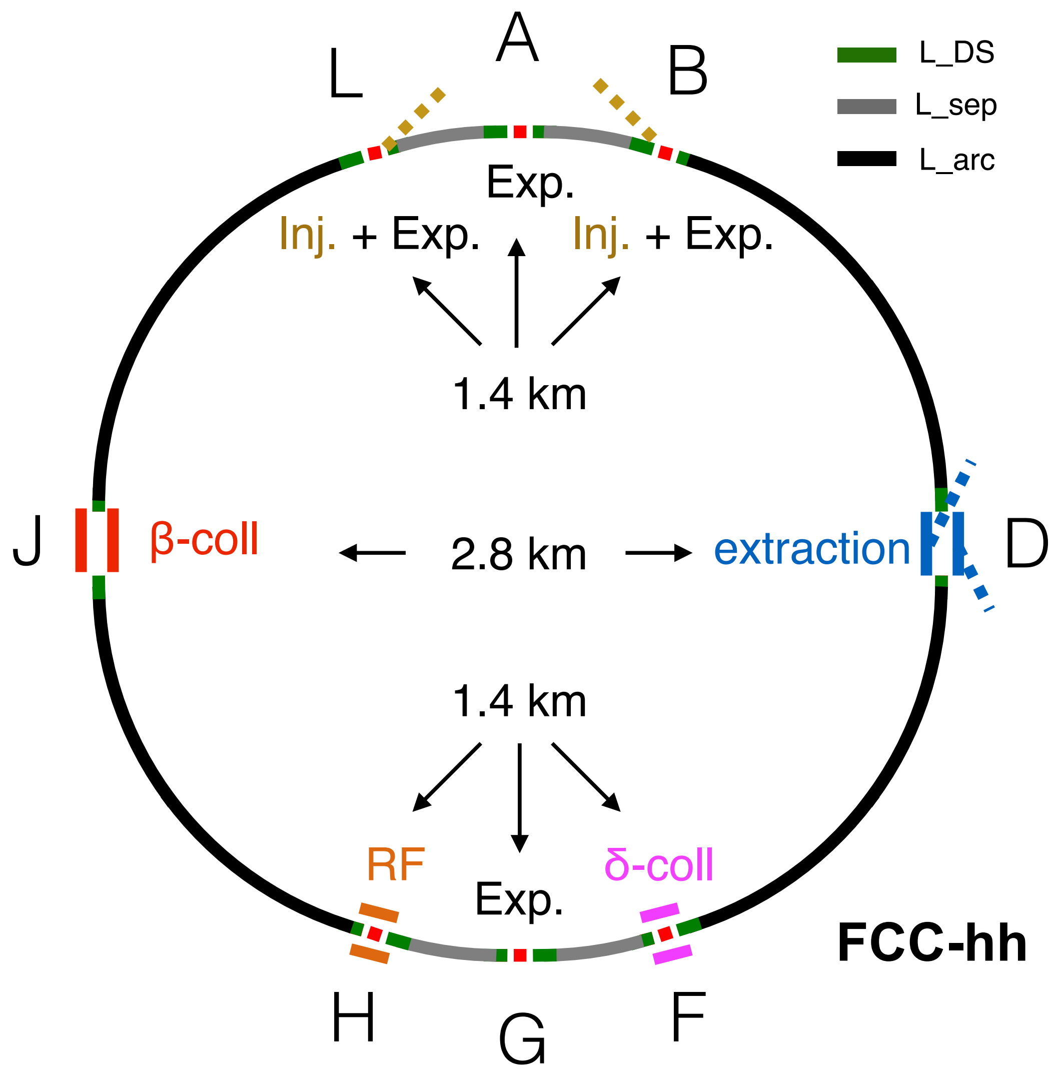
Muon are captured, bunched and then cooled by ionisation cooling in matter

Collision

Acceleration to collision energy

Protons produce pions
Pions decay to muons

Beyond the Standard Model (> 2050) *p-p*



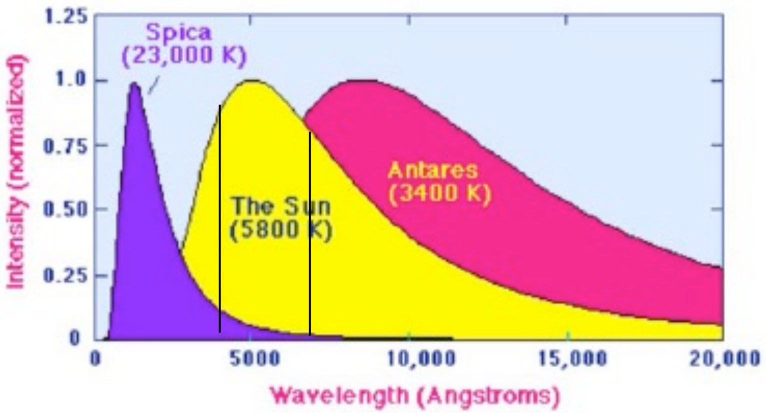
parameter	FCC-hh	
collision energy cms [TeV]	100	
dipole field [T]	16	
circumference [km]	97.75	
beam current [A]	0.5	
bunch intensity [10^{11}]	1	1
bunch spacing [ns]	25	25
synchr. rad. power / ring [kW]	2400	
SR power / length [W/m/ap.]	28.4	
long. emit. damping time [h]	0.54	
beta* [m]	1.1	0.3
normalized emittance [μm]	2.2	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30
events/bunch crossing	170	1000
stored energy/beam [GJ]	8.4	

Contents

The "small" photon adventure

1 Angstroms = 10^{-10} m

Human eye detects photon wavelength ranging from 4,000 to 7,000 Angstroms
(4×10^{-7} to 7×10^{-7} m)



1 Angstroms is the size of one atom

Normal inorganic molecules are sizing a few Angstroms

Biological molecules and cells are much bigger but they are composed by atoms

Image resolution is limited by the photon wavelength

To see what is smaller than 4,000 Angstroms we need:

- Smaller photons, with respect to the visible light
- A different detector, with respect to our eyes

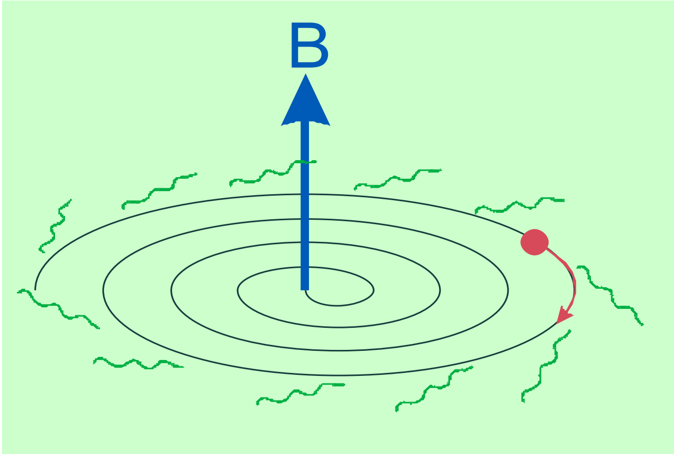
Particle accelerators give energy to electrons

Bending the energetic electron trajectory
photons are produced

High energy produces small photon wavelength,
that is **X-rays**

Energy lost [GeV] per turn

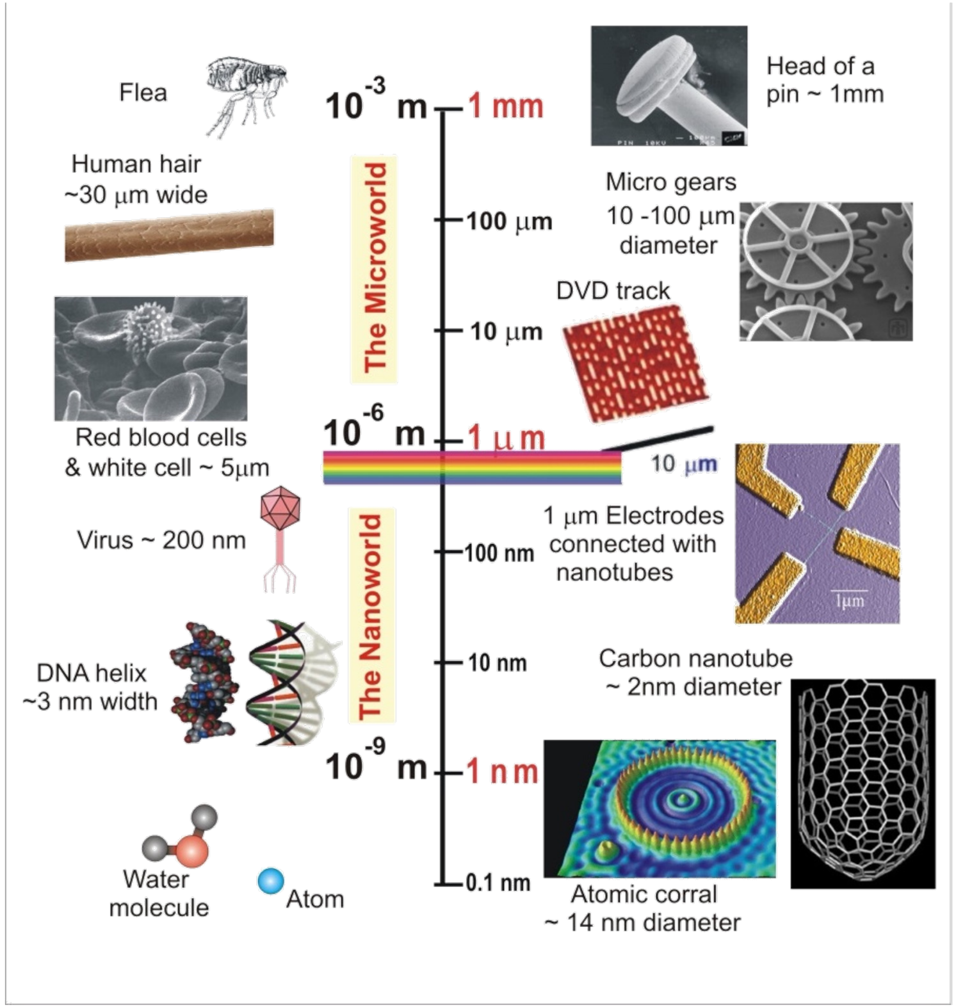
$$U_{SR}[\mathrm{GeV}] = 6 \cdot 10^{-21} \cdot \gamma^4 \cdot {}^{1}\!/_{r[km]}$$

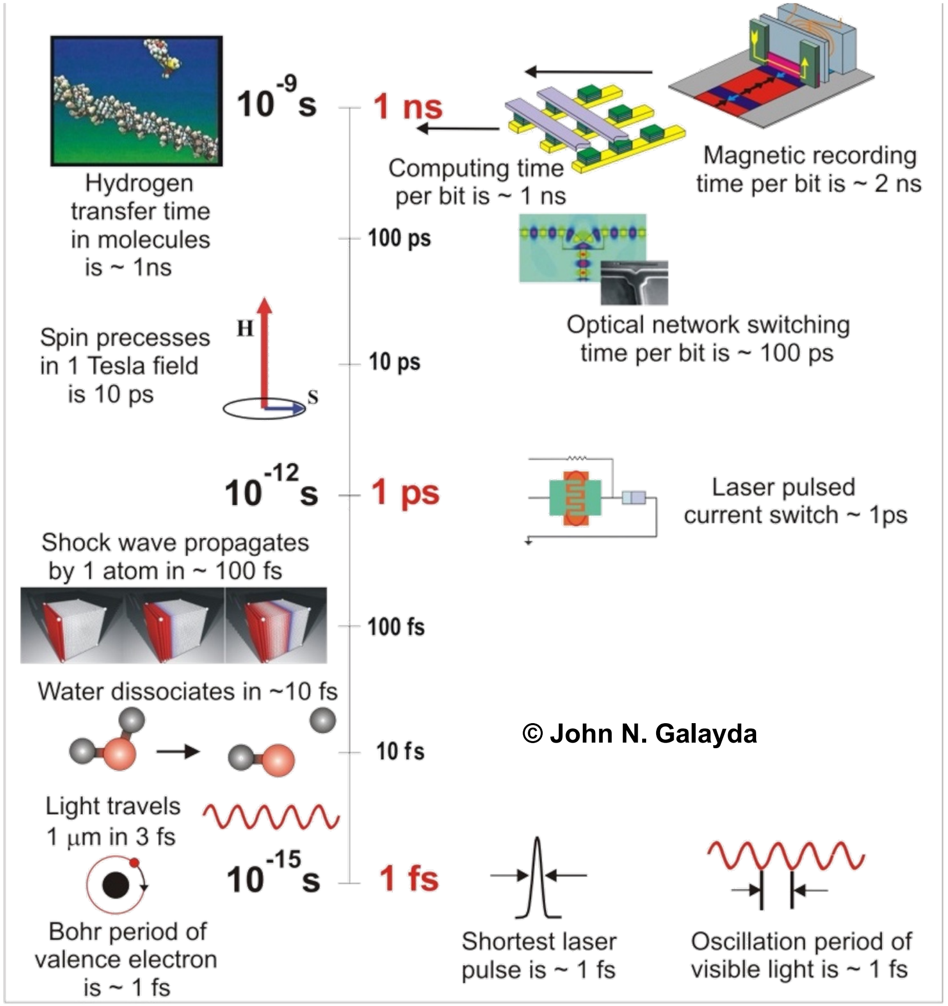


X-ray sources and X-ray Lasers

X-ray (from synchrotron sources) **have opened the Ultra-Small World**
Coherent X-ray (from XFEL) **for the Ultra-Small and Ultra-Fast Worlds**

Ultra Small



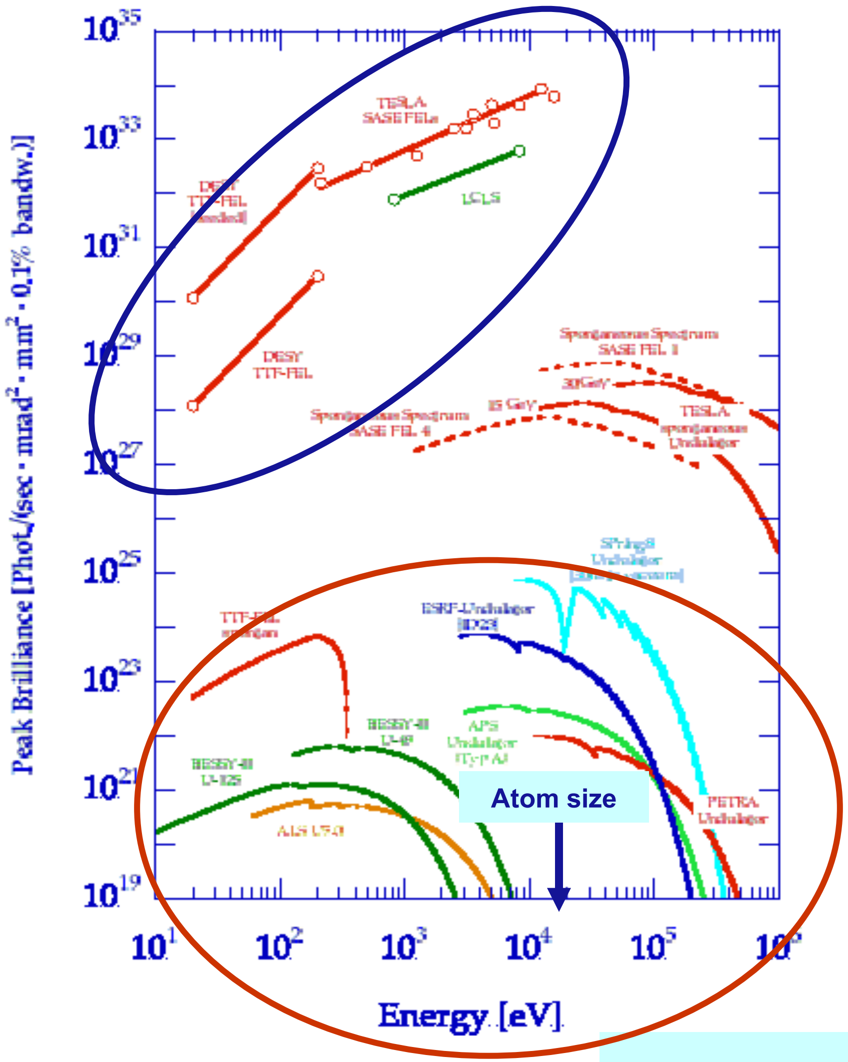


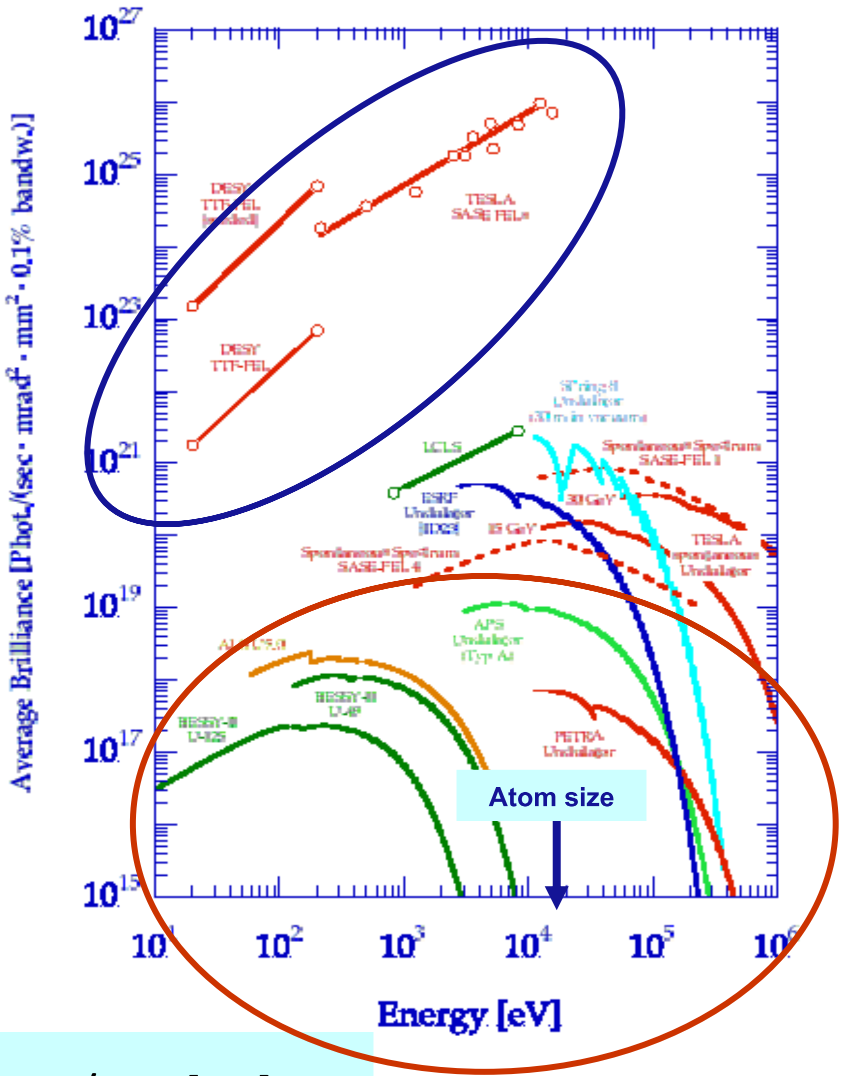
Ultra Fast

Brilliance vs Photon Energy

FEL
&
X_FEL

Synchrotron Light Sources

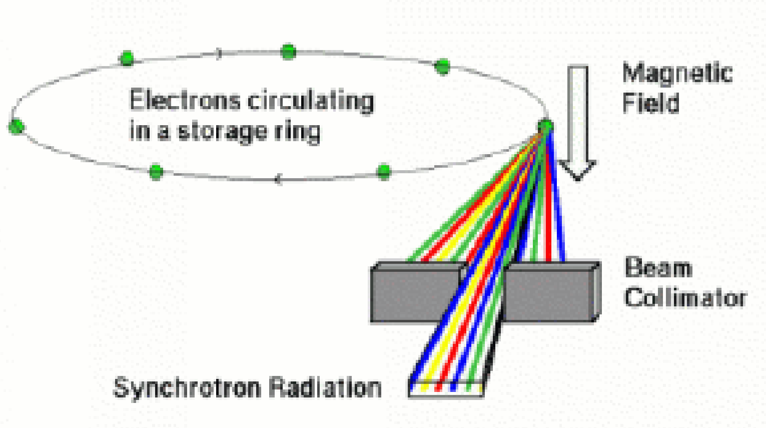




FEL = Free Electron Laser

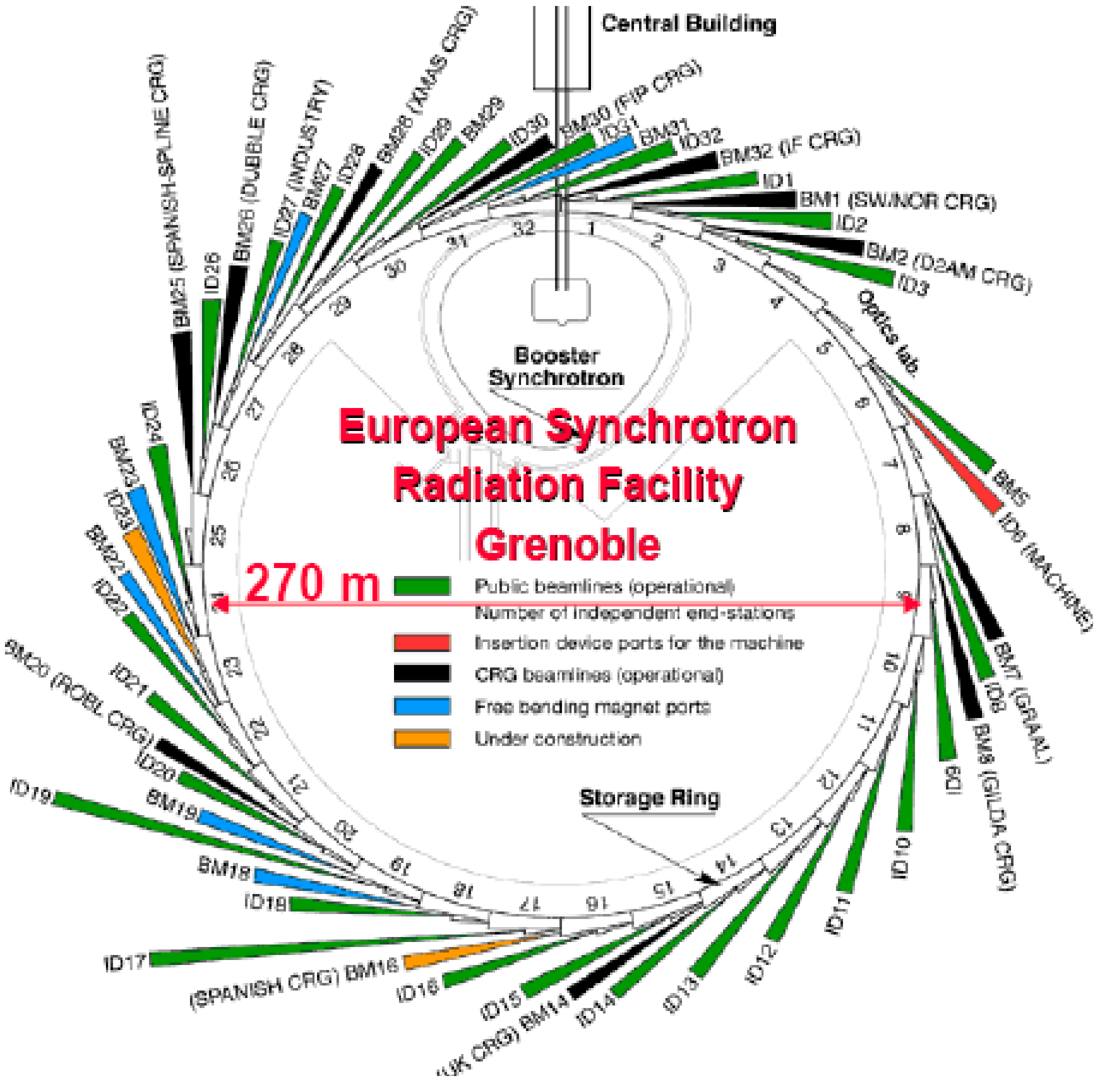
λ_{ph} [μm] = 1.24 / E_{ph} [eV]

Synchrotron light sources for X-rays



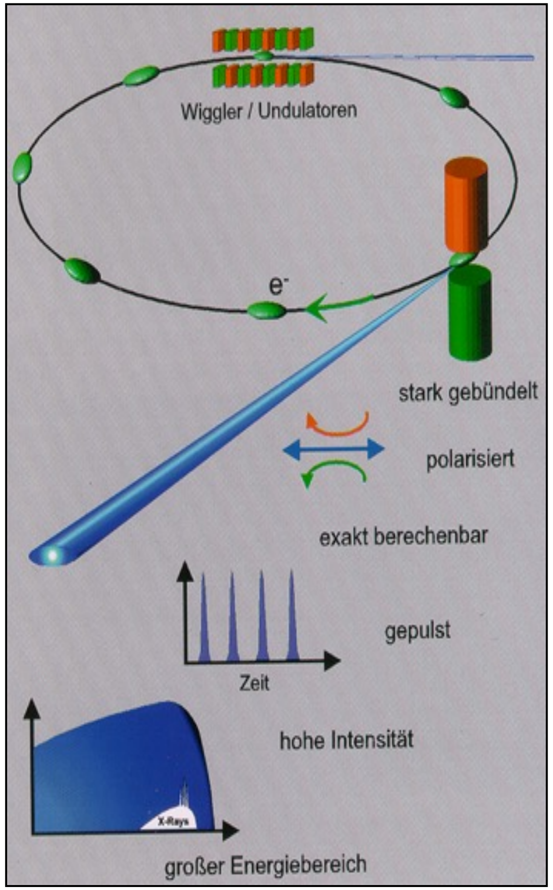
Synchrotron light is used for

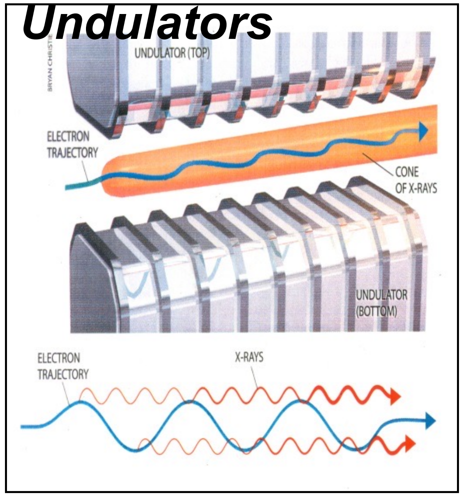
- **Physics and Chemistry**
  - Crystallography
  - Material science
  - Fast Chemical Reactions
- **Biology and Medicine**
  - Structural Biology
  - Biological Imaging
  - Medical Imaging
  - Microbeam radiotherapy
- **Engineering**
  - Lithography
  - Micromachining



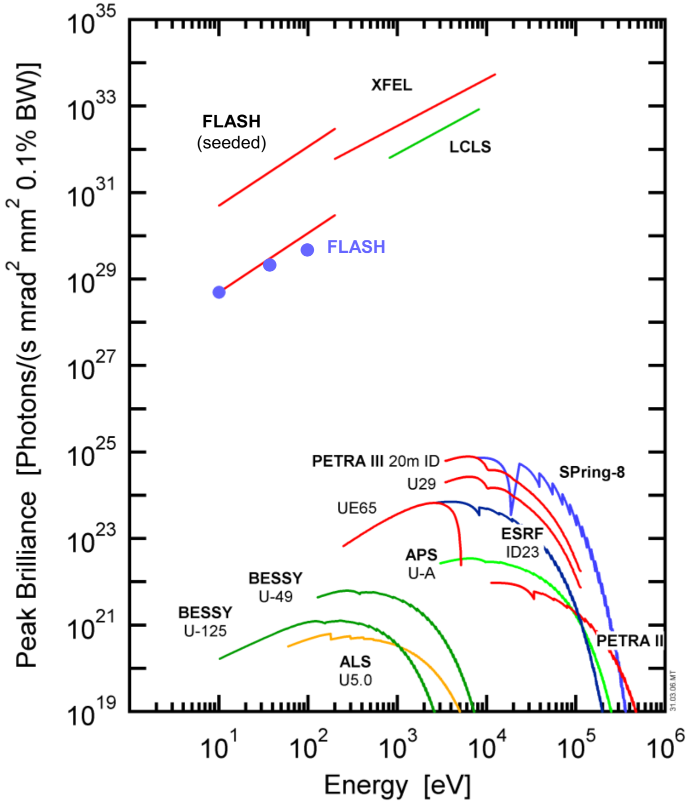
Synchrotron Radiation and XFEL

http://www.xfel.eu/

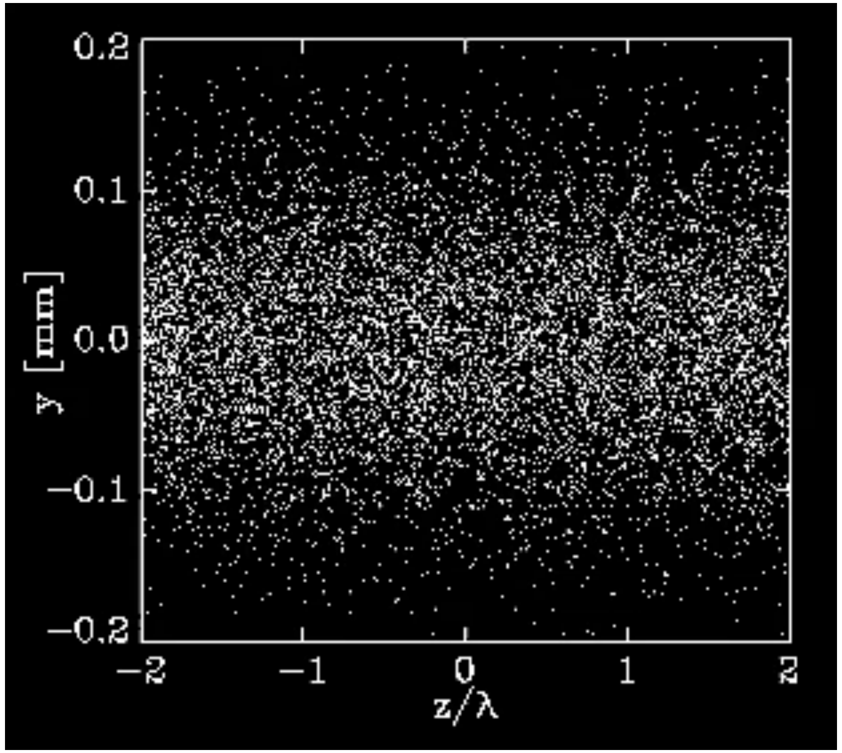




- *line spectrum*
- *much higher intensity*
- *extremely focused*

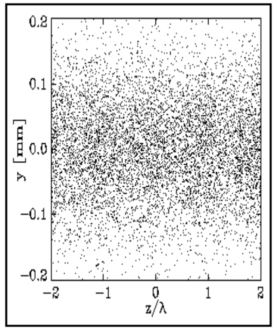


Modulation of the electron bunches

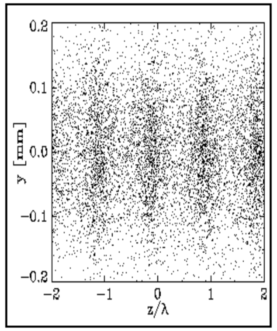


*GENESIS s*imulation of the TTF parameters
Sven Reiche (UCLA)

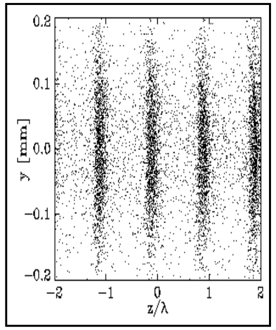
undulator entrance



half-way saturation



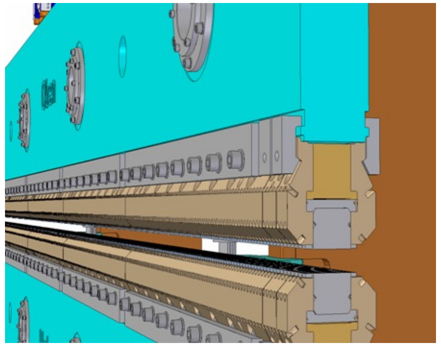
full saturation

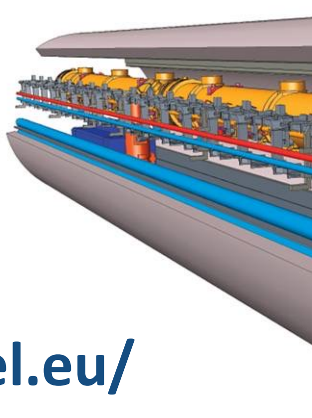


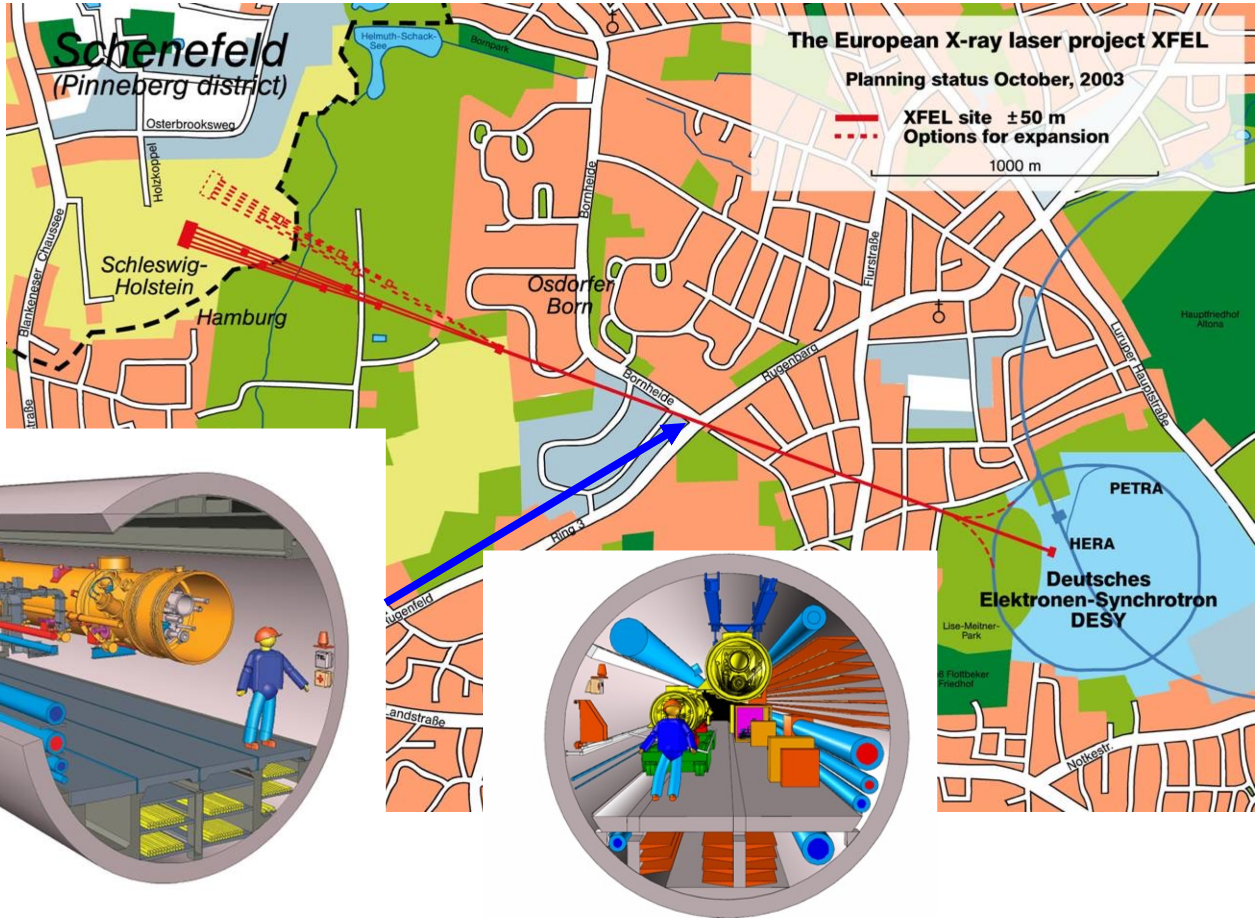
European XFEL: completed in 2016

https://www.youtube.com/watch?v=p3G90p4glQA

3.4km

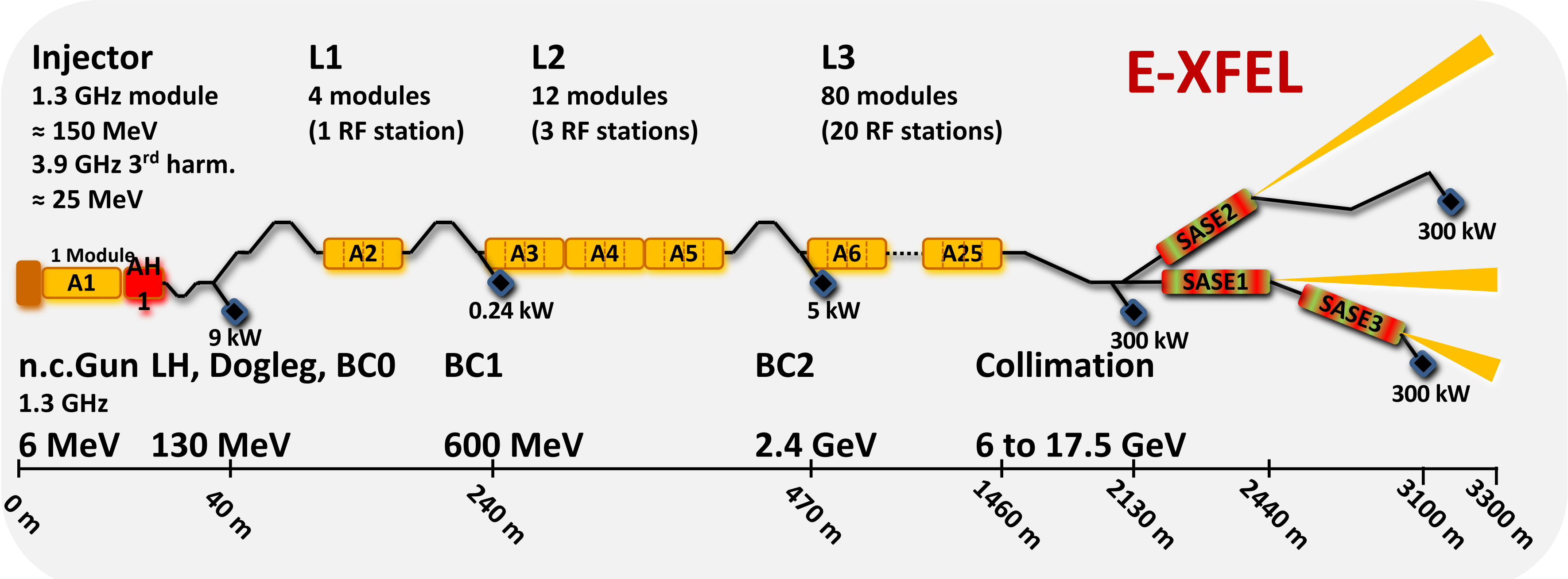


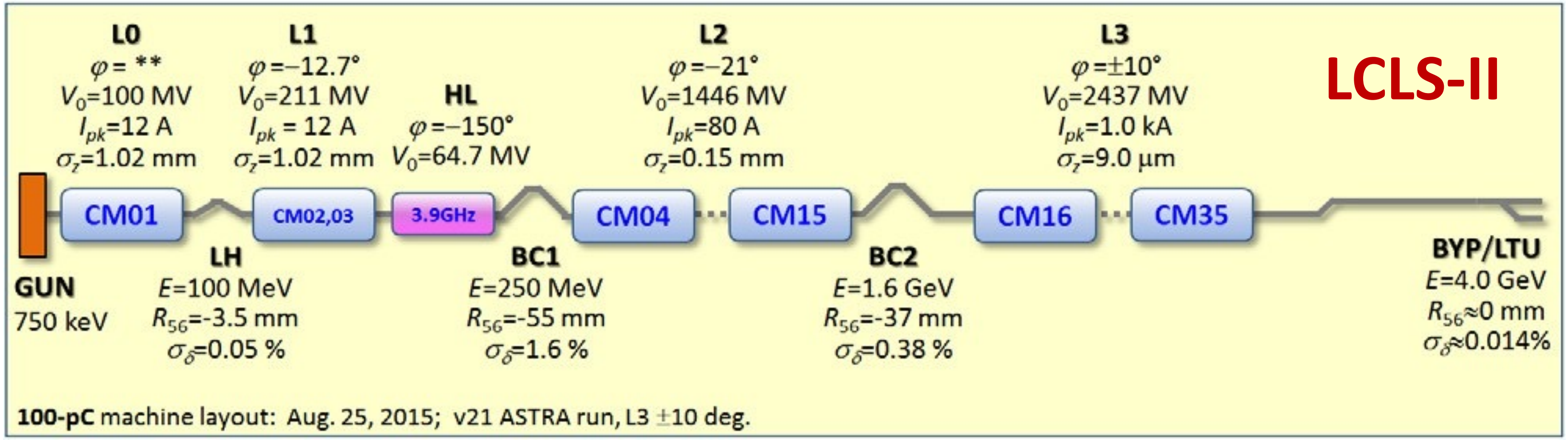




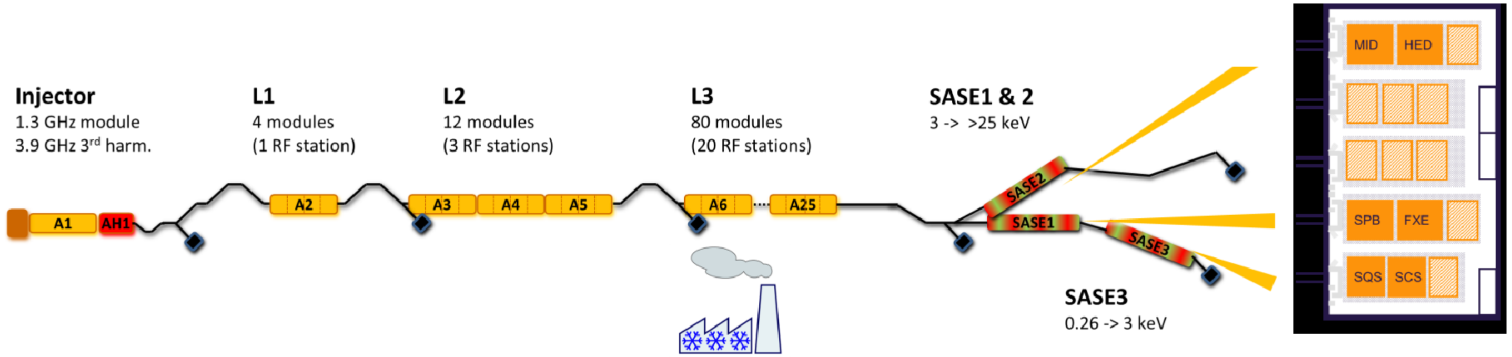
http://www.xfel.eu/

Eu-XFEL & LCLS-II use TESLA SRF Tech.



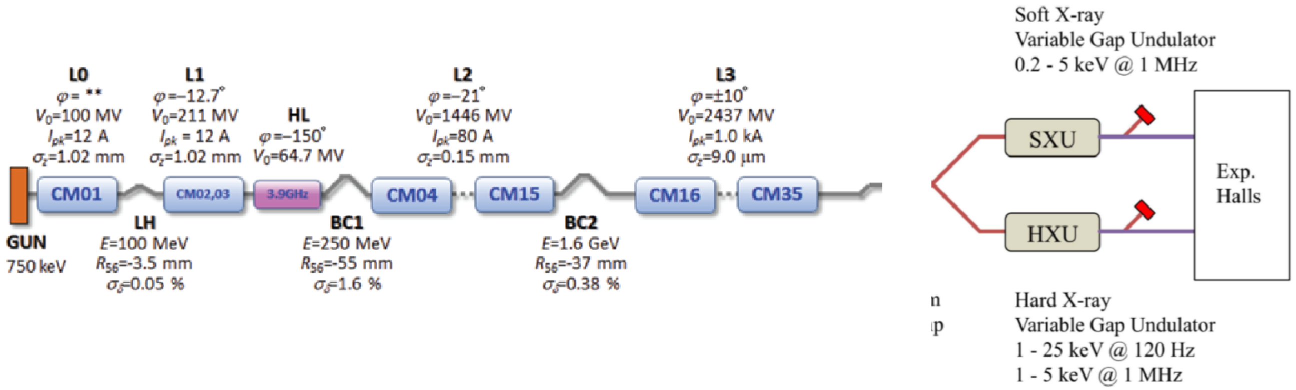


The 3 major facilities use the TESLA. Tech.



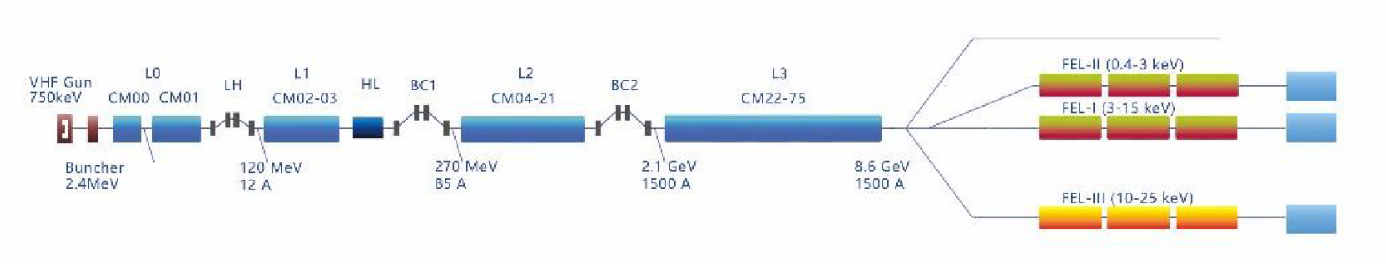
European XFEL

construction during 2009 – 2016
in operation since 2017
cw upgrade after 2025 (?, tbc)



LCLS-II

under construction since 2014
first lasing expected in 2021
HE 8 GeV upgrade until 2026

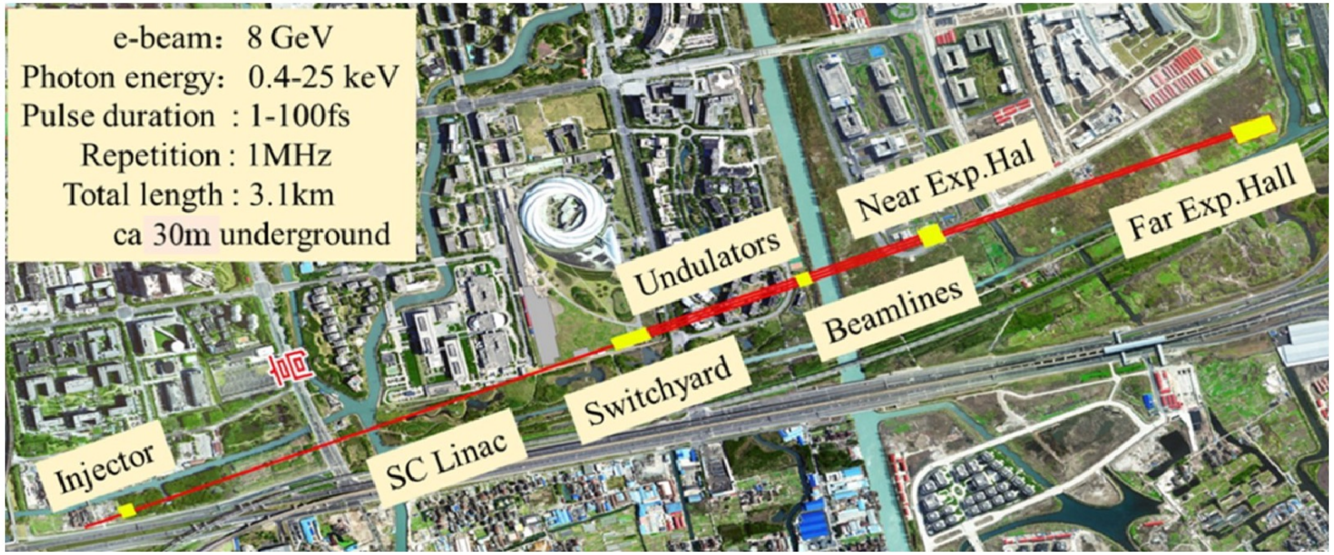


SHINE SARI

under construction since 2018
to be commissioned in 2025
goal: cw and 8 GeV

Hans Weise @ FEL2021

Satellite Picture of the three XFEL Facilities



All three facilities

- have a total length of approx. 3 km
- are (being) built in a long tunnel
- SHINE has enormous similarities with E-XFEL
- LCSL-II will be the first cw X-ray FEL and can profit from the existing klystron gallery
- Experiments halls at E-XFEL and SHINE are of soccer field size

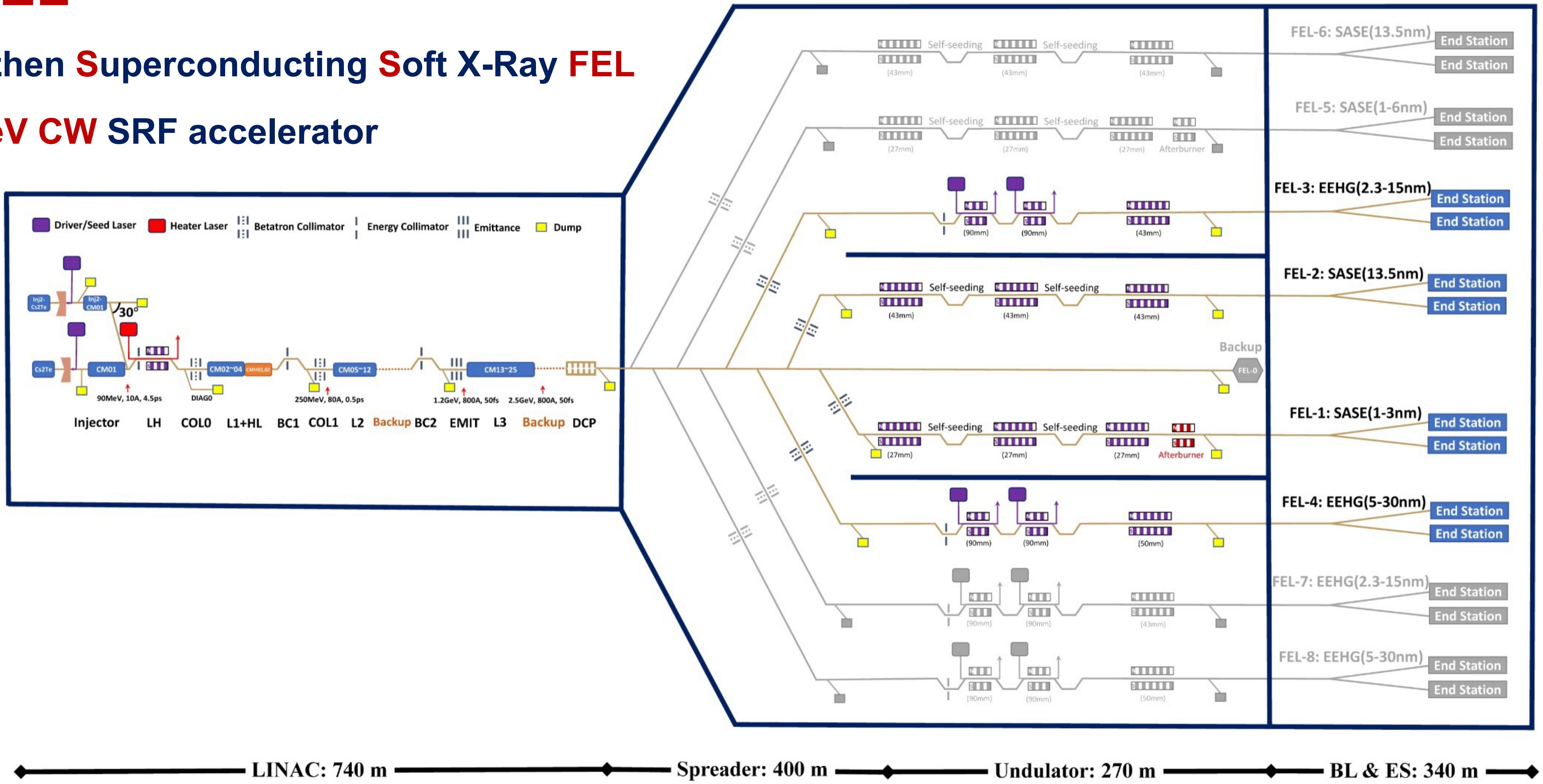
Hans Weise @ FEL2021

Two more funded in China for Soft X-Ray

S3FEL

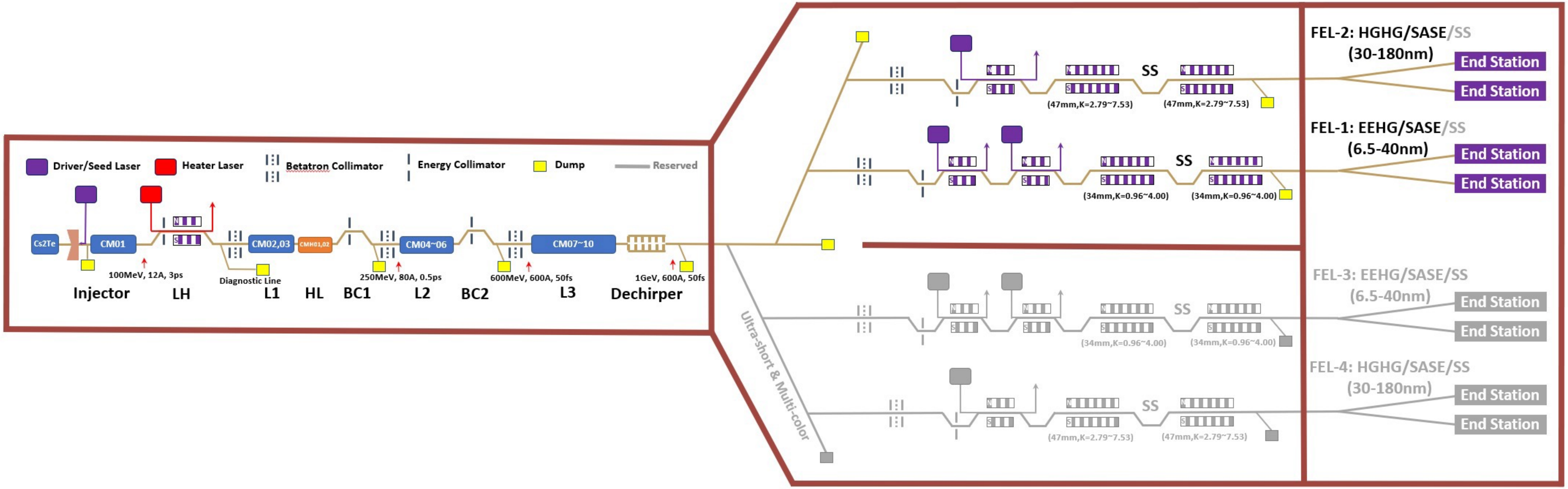
Shenzhen Superconducting Soft X-Ray FEL

2.5 GeV CW SRF accelerator



DALS

Dalian Advanced Light Source



Contents

Particle Accelerators for cancer therapy

Particles are used to kill the tumor cells, stopping their reproduction

Not all cancers are sensitive to the same particles

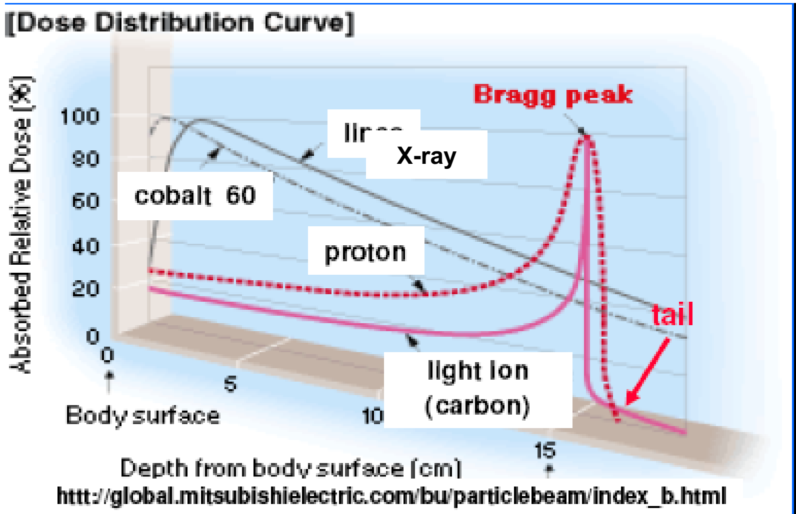
The tissues around the cancer can be damaged

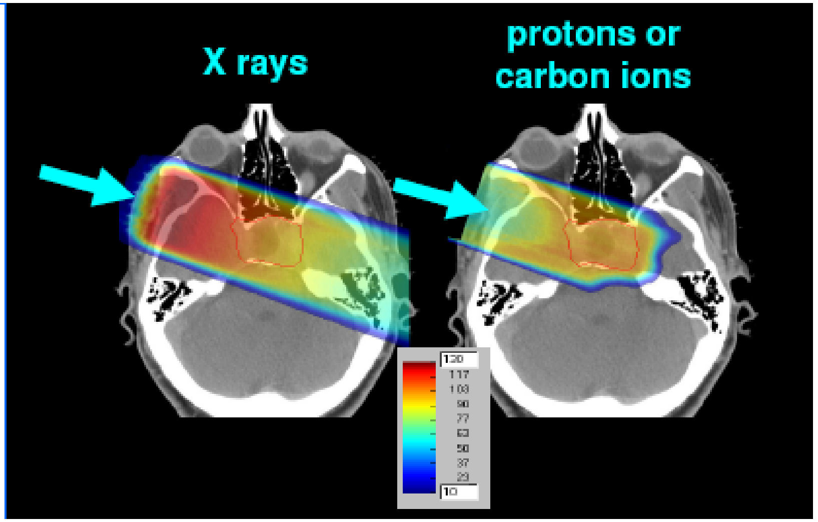
The level of damage depends on the particles used and on the complexity/cost of the system

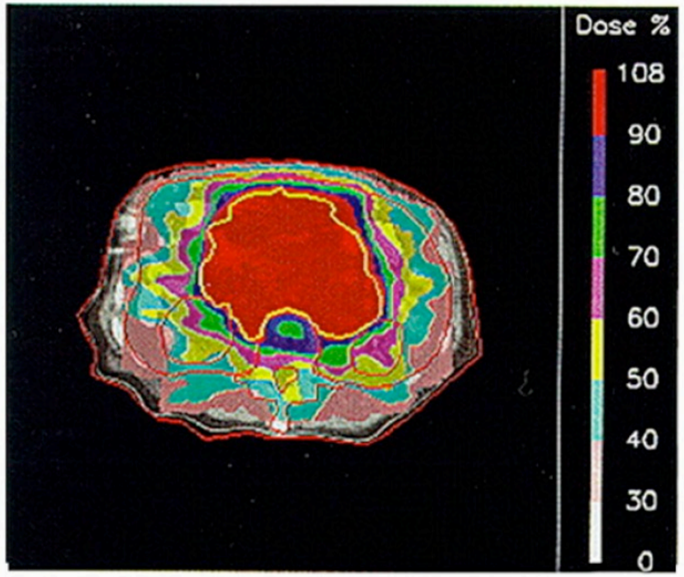
- **Radio-therapy** with photons (X-ray)
  - An electron linear accelerator produces a 20-30 MeV electron beam that produces photons through a tungsten target
  - The machine is simple and thousands have been installed

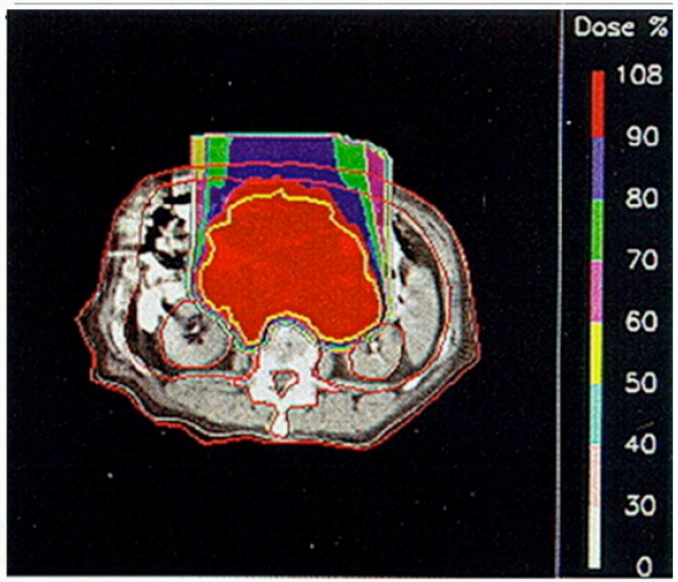
- **Hadron-therapy** with protons or carbon ions, ^{12}C
  - Cyclotrons or Synchrotrons are both used.
  - The beam energy determines the penetration depth into the biological tissue
  - They can be much more "precise" but the cost is 10 to 100 times higher

Hadrons are better that Photons (X-ray)





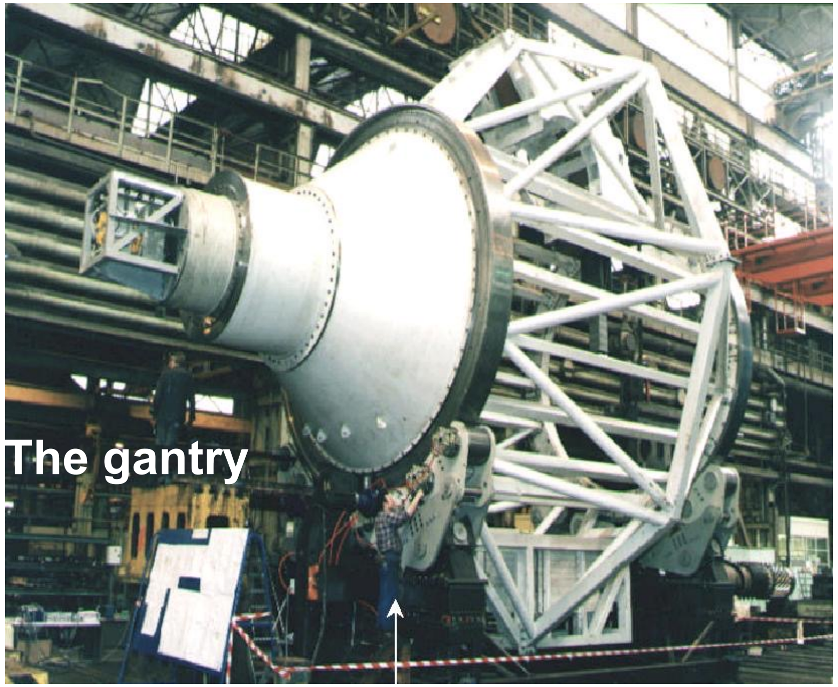




Hadron therapy at the MGH – Michigan


The 230 MeV Cyclotron

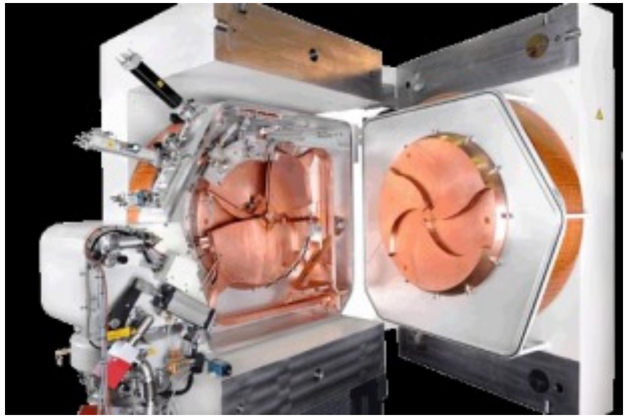

The treatment room


The gantry

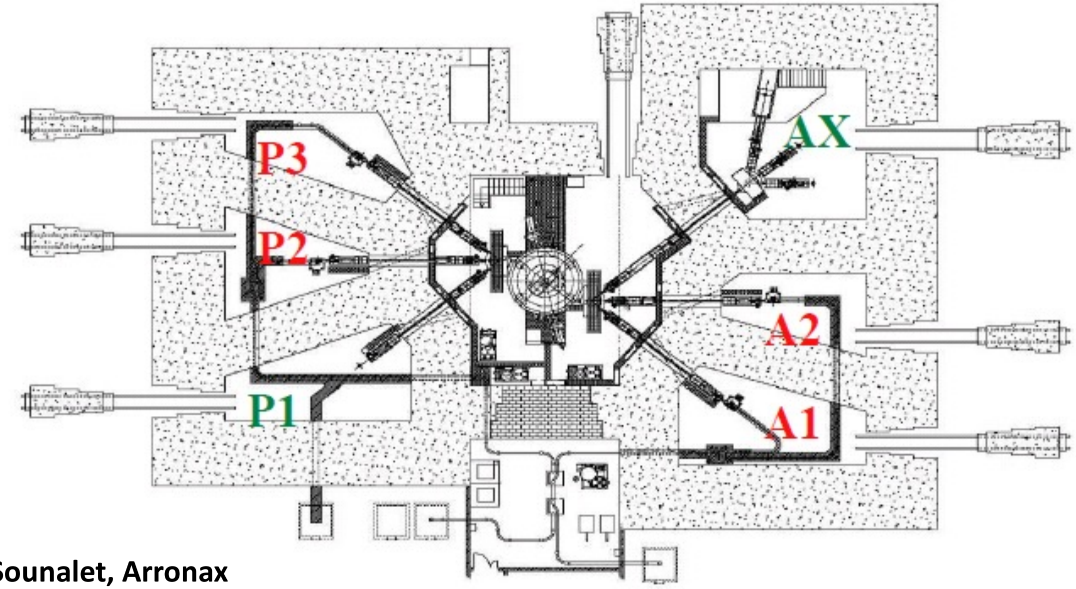
Cyclotrons for Isotope Production

IBA cyclotron at ARRONAX

PET trace series of General Electrics



70 MeV
35kW



T. Sounalet, Arronax

10 MeV
1kW

M. Jensen, RISO

Isotopes for PET (positron emission tomography)

Nuclide	Half-life (min)	Decay mode	Maximum energy (MeV)	Mean energy (MeV)	Max. range (mm)	Max. SA (theoretical) (Ci/μmol)[a]
C-11	20.4	100% β^+	0.96	0.386	4.1	9 220
N-13	9.98	100% β^+	1.19	0.492	5.4	18 900
O-15	2.03	100% β^+	1.7	0.735	8.0	91 730
F-18	109.8	97% β^+	0.69	0.250	2.4	1 710
Cu-62	9.74	99.7% β^+	2.93	1.314	14.3	19 310
Ga-68	68.0	89% β^+	1.9	0.829	9.0	2 766
Br-75	96.0	75.5% β^+	1.74	0.750	8.2	1 960
Rb-82	1.25	95.5% β^+	3.36	1.5	16.5	150 400
I-122	3.62	75.8% β^+	3.12	1.4	15.3	51 950
I-124	6019.2	23.3% β^+	2.13	0.8	10.2	31

ADS - Accelerator Driven System

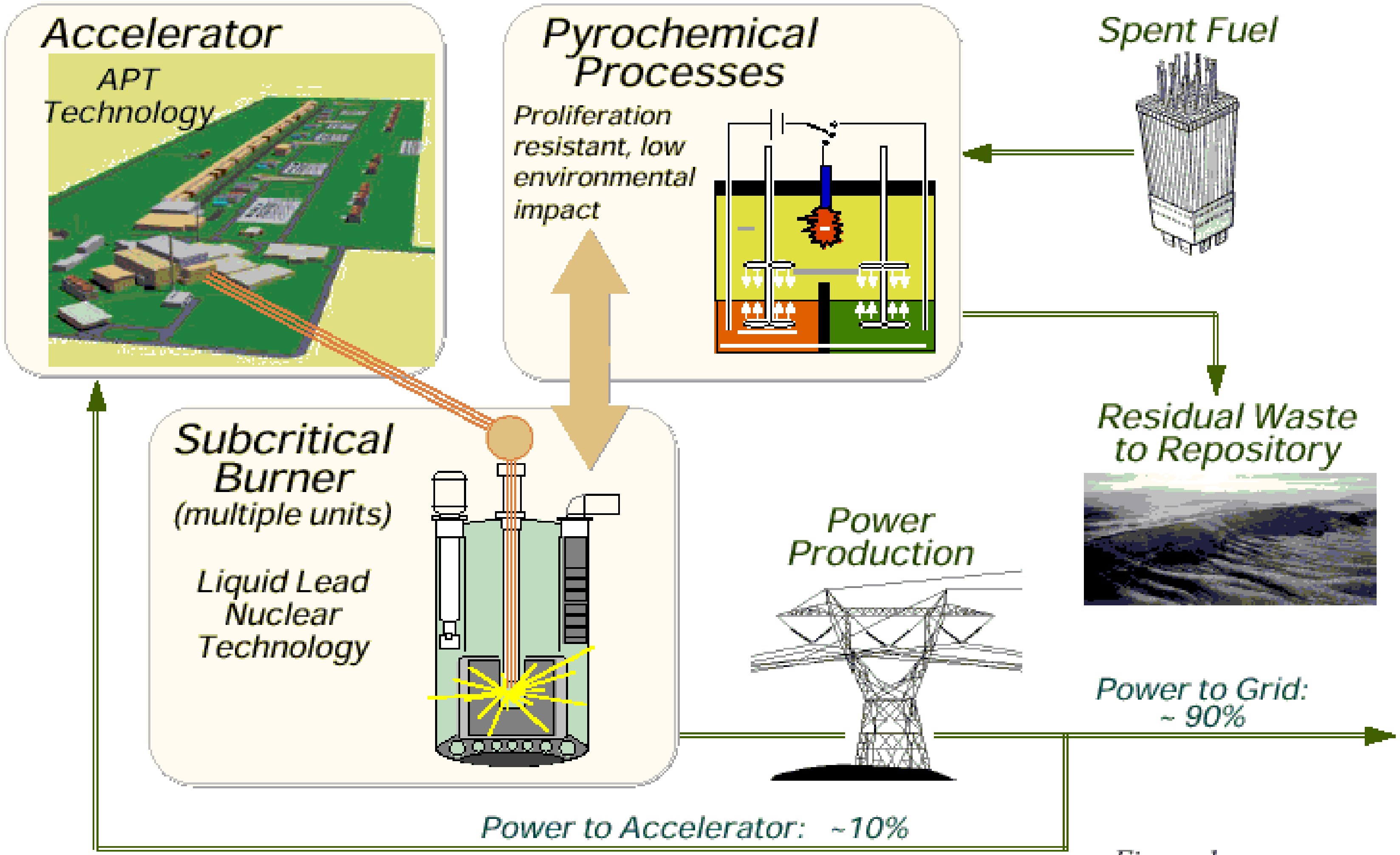
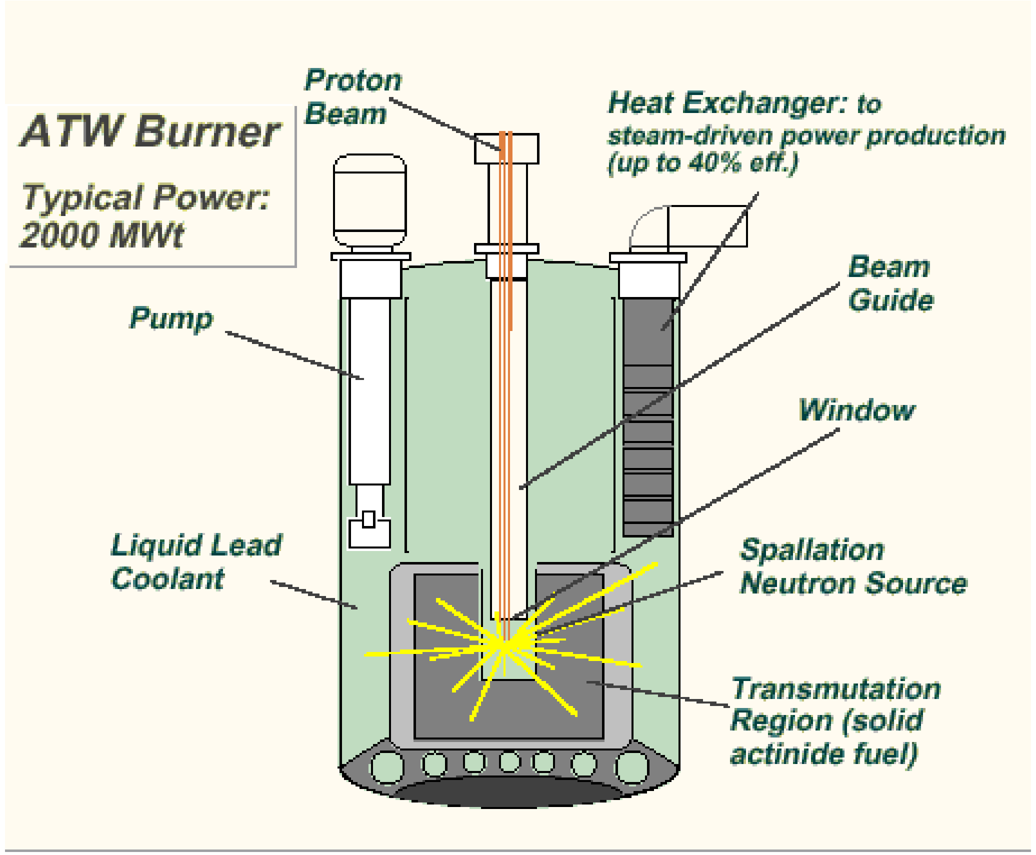


Figure 1

The subcritical core

Accelerator Drive (Subcriticality) enables versatile and effective Nuclear Waste Destruction

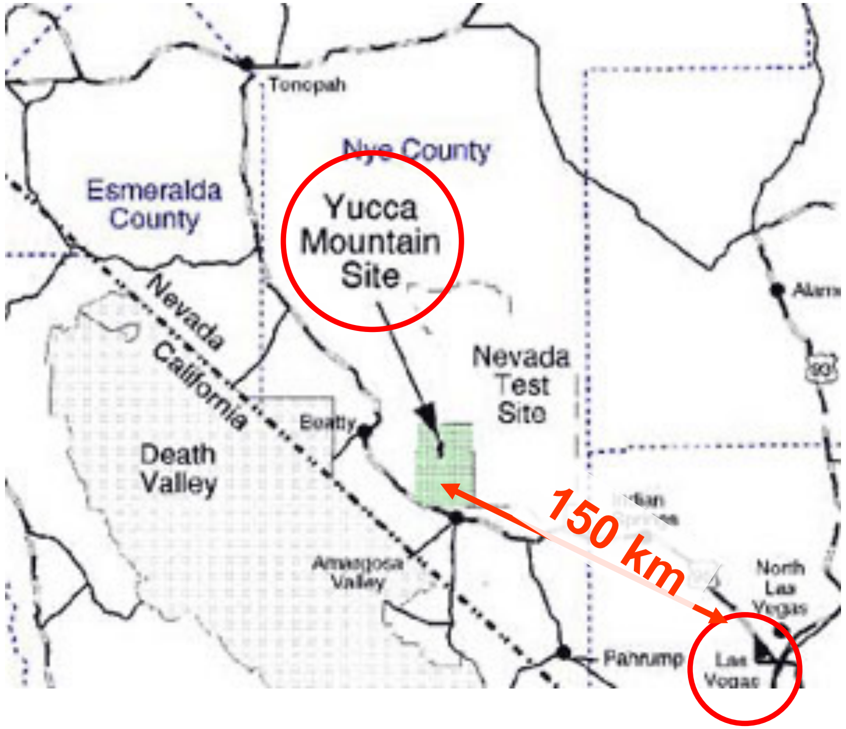


why subcriticality has advantage for waste destruction:

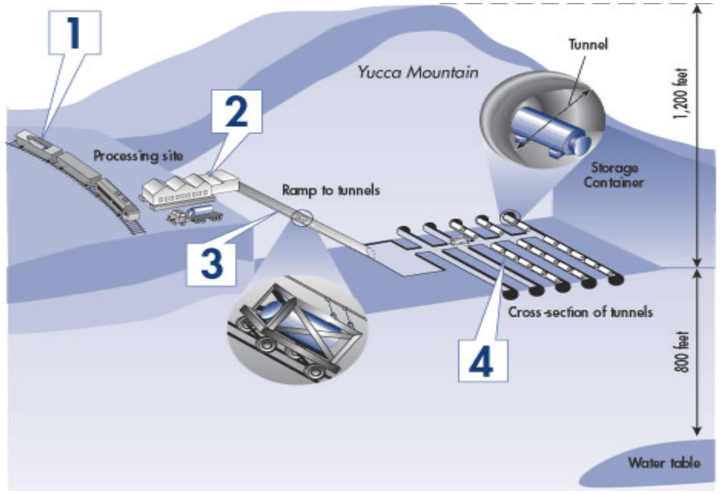
- Power control is <u>not linked to reactivity feedbacks, delayed neutrons or to control rods</u>, but only to the accelerator drive
- ATW has <u>no need for fertile materials</u>. ATW uses pure transuranic cores
- Subcritical systems work <u>independently of the fuel composition</u>
- <u>EOL inventory is not limited by criticality.</u> Possible to have EOL burndown of inventory
- Neutronics and thermohydraulics are effectively <u>decoupled</u>

Figure 4

From Physics Today, May 2006



(Yucca Mountain)



- 55000 tons in 100 temporary repositories in 39 States
- 2000 tons/y produced in USA
  70000 tons is the total Yucca Mountain capacity
- Safety analysis after 1 My required for licensing !

The Washington Post

Mountain of Trouble

Mr. Obama defunds the nuclear repository at Yucca Mountain. Now what?

Sunday, March 8, 2009

BY STRIPPING the funding for the nuclear repository at Nevada's Yucca Mountain, President Obama has succeeded in killing the contentious project that remains unfinished 22 years after Congress selected the site. He compounds the error by not offering an alternative. If the president's vision for a clean energy future is to be believed or is to come to fruition, nuclear energy must be a part of the mix, and the safe disposal of its radioactive waste must be given more serious consideration.

The project has burned through $7.7 billion. It was supposed to start accepting spent material from the nation's operating nuclear reactors (now numbering 104) in 1998. Our longstanding support of the Yucca Mountain facility has been grounded in the belief that the center of a desert mountain 1,000 feet underground and more than 90 miles northwest of Las Vegas was an appropriate place for the nation's nuclear waste. Instead, storage is spread over 121 above-ground sites located within 75 miles of more than 161 million people in 39 states.

Obama to zero out Yucca Mountain funding, pull license

Las Vegas Sun

By Lisa Mascaro (contact)

Published Sunday, Jan. 31, 2010 | 11:50 a.m.

Updated Monday, Feb. 1, 2010 | 9:22 a.m.

WASHINGTON - President Barack Obama plans to zero out funding for Yucca Mountain and "take steps" to withdraw the project's pending license application, according to a preview of the 2011 budget that will be announced Monday.

The president's intention to pull the license application -- a promise he made while campaigning in Nevada -- would be one of the most critical moves yet in stopping the proposed nuclear waste dump in Nevada.

Senate Majority Leader Harry Reid, who has been in ongoing talks with Obama over the dump, called the development "great news."

"President Obama is keeping his word to Nevada and I thank him for working with me as we try to find a safer solution for dealing with the nation's nuclear waste," Reid said Sunday.

Reid's office released information from Obama's coming budget that showed: "The Department of Energy's Office of Civilian Radioactive Waste Management will be merged into the Office of Nuclear Energy. As part of the merger, funding for the proposed Yucca Mountain project will be eliminated and the Department will take steps to withdraw the license application in the near future. This reflects the Administration's commitment to pursuing a responsible, long-term strategy through the appointment of a high-level Blue Ribbon Commission on America's Nuclear Future."

Funds cut to zero in 2011

Most Accelerators are built not for Science

About 30,000 accelerators are in use worldwide (2015)

- Sales of accelerators > $ 2 B /yr and growing
- Accelerators touch over $ 500B/yr in products
- Major Impact on our economy, health, and well being

Some Products:

N. Lockyer

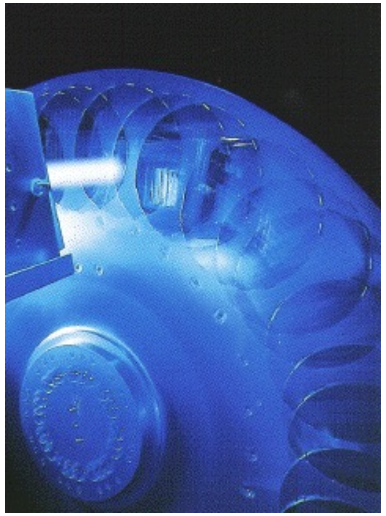
Accelerators: Essential Tools in Industry - 1

Ion Implantation

- Accelerators can precisely deposit ions modifying materials and electrical properties (boron, phosphorous)

Semi Conductors

- CMOS transistor fabrication of essentially all IC's
- CCD & CMOS imagers for digital cameras
- Cleaving silicon for photovoltaic solar cells
- Typical IC may have 25 implant steps



Metals

- Harden cutting tools
- Reducing friction
- Biomaterials for implants

Ceramics and Glasses

- Harden surfaces
- Modify optics
- Color in Gem stones!

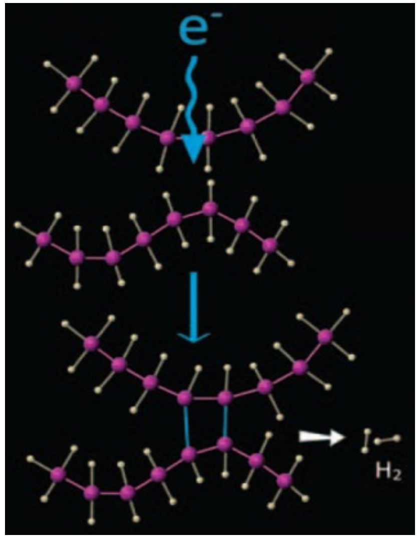
N. Lockyer

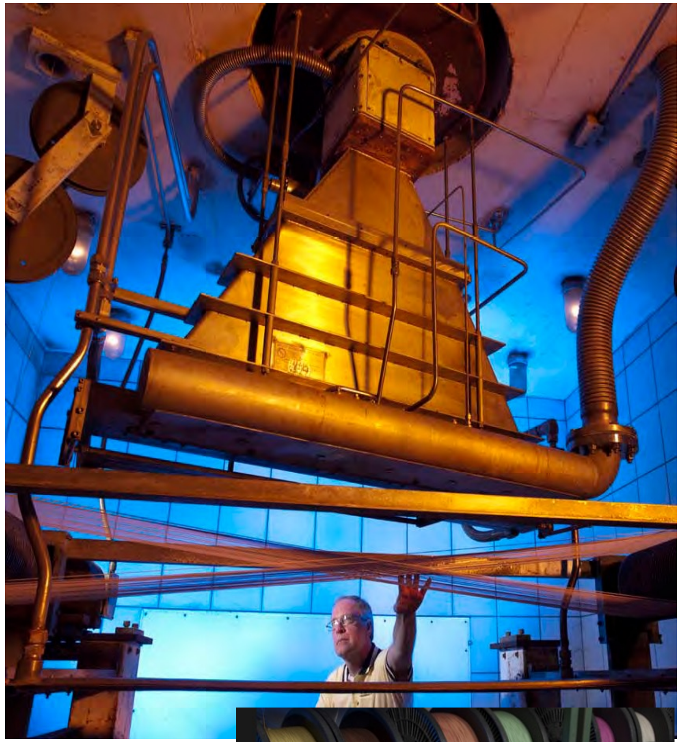
Accelerators: Essential Tools in Industry - 2

A wide-range of industrial applications makes use of low-energy beams of electrons to drive chemistry

0.1-10 MeV up to MW beam power

electrostatic, linac, betatron accelerators





Electron Beam Irradiation

Improved heat resistance of coatings, wire and cable, crosslinking polymers, radial tires, etc)

1500 dedicated facilities worldwide

N. Lockyer

Accelerators: Essential Tools in Industry - 3

Electron beam printing

- Conventional printing requires use of enormous amounts of solvents that are created, evaporated, and must be disposed of … all with significant environmental impact
- EB printing can print 12 colors at a speed of 10 m/s with water based inks
- EB's also enables new packaging methods for food (foil-glue-foil)
- Your milk carton or potato bag may have been manufactured with this technology

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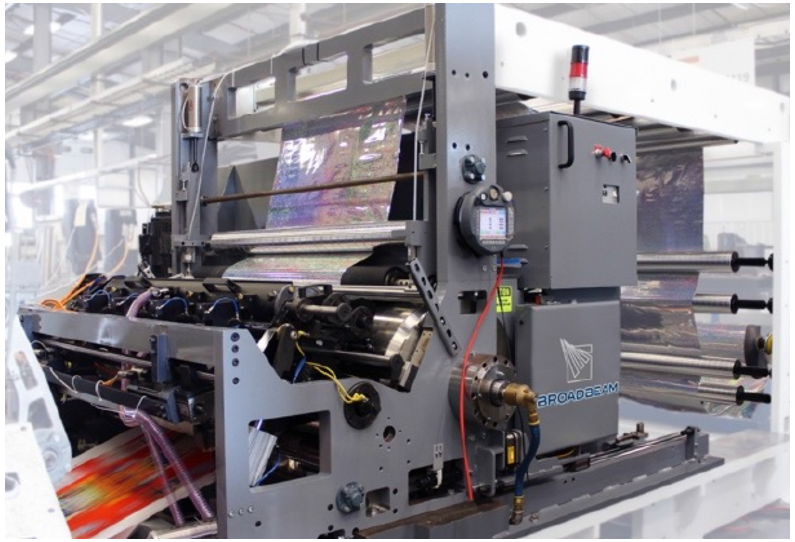
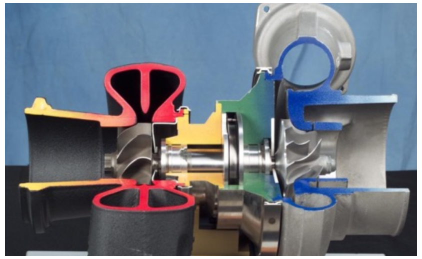


Electron Beam Packaging

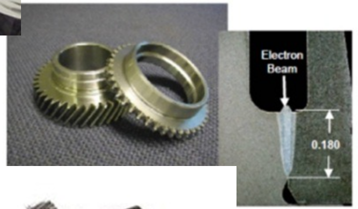
Electron Beam Welding and Machining

- Deep welds, low weld shrinkage
- Dissimilar or refractory metals, etc
- Widely used in automotive and aerospace industry
- Drill 3000 holes/sec!

Fuel injectors



Turbo chargers



Weld gear boxes
Harden gears

Jet engines &
Gas turbines

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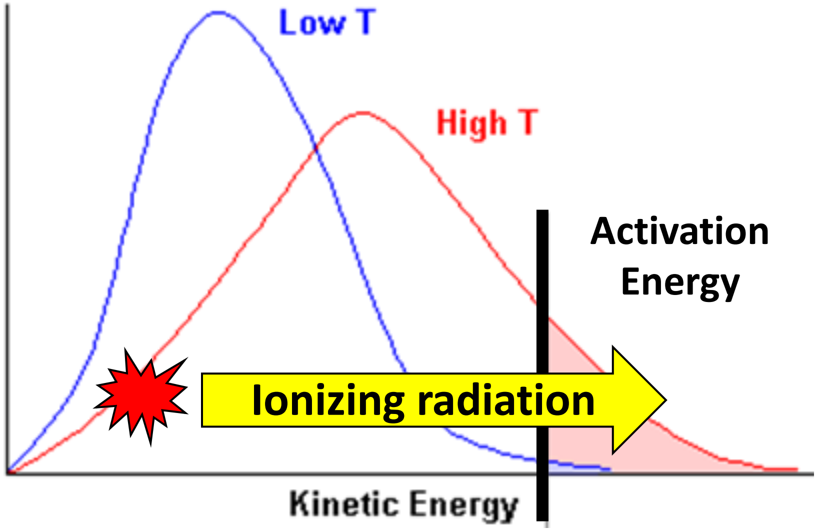
Accelerator Driven Chemistry

Thermal energy is very strongly coupled to **Translational, Rotational and Vibrational modes** of the energy absorber. Ionization, bond rupture and other processes leading to chemical reactions occur only in the high energy region of the Maxwellian tail.



Ionizing radiation is almost entirely absorbed by the electronic structure of absorber, which increases the energy level of its orbital electrons.

Energy in the form of large quanta have more pronounced chemical effects than energy in the form of small quanta (ie processes can occur at lower temperatures →more efficient!)

Effective & efficient generator of reactive species

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Accelerators: Food Preservation

Low-energy beams of electrons can help beat food-borne Illness

- ~60 people die from food-borne illness in the U.S. each week
- Food poisoning is estimated to cost the US $152 billion a year.
- Electron beams and/or X-rays can kill bacteria like E. coli, Salmonella, and Listeria.
- Currently in use for: Spices, fruit, lettuce, ground beef, milk, juice, military rations…

- Many more opportunities exist
- Barriers = cost & public acceptance

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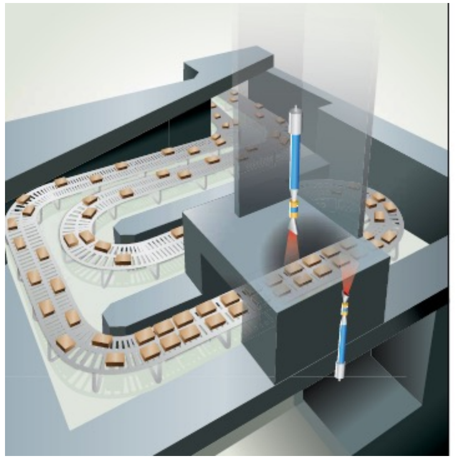
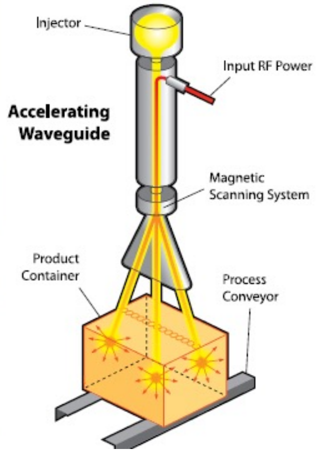
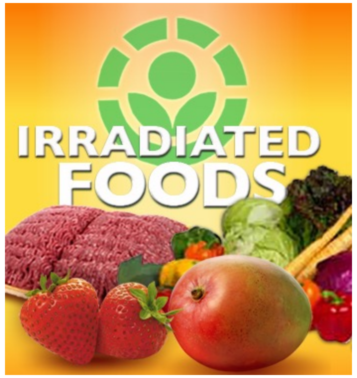
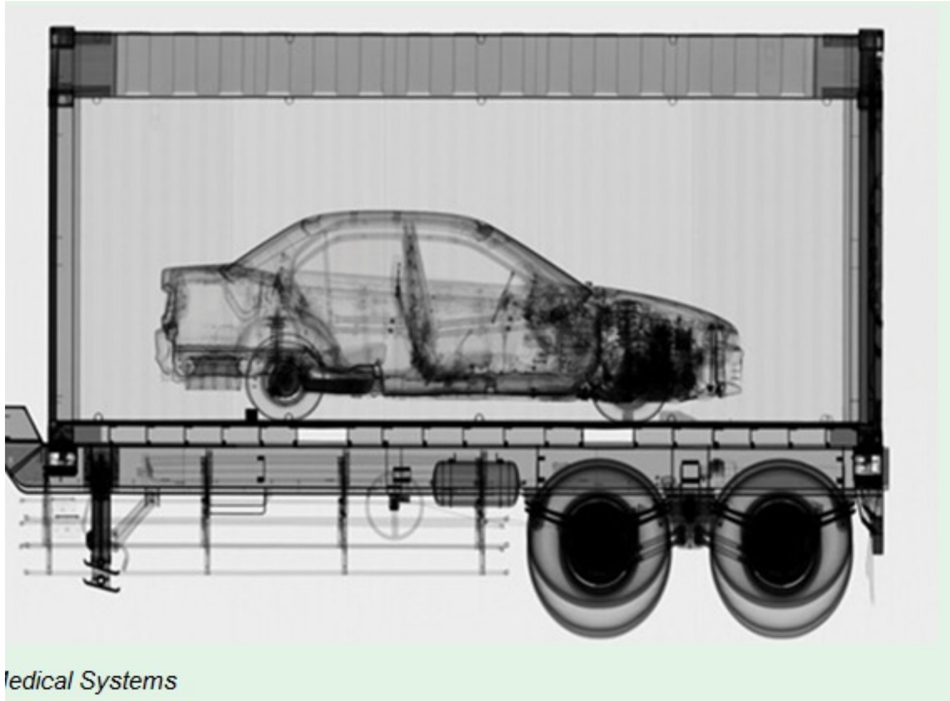






Accelerators for Security



- More than two billion tons of cargo pass through U.S. ports and waterways annually.
- Accelerators are used for cargo scanning and "active interrogation" to detect special materials

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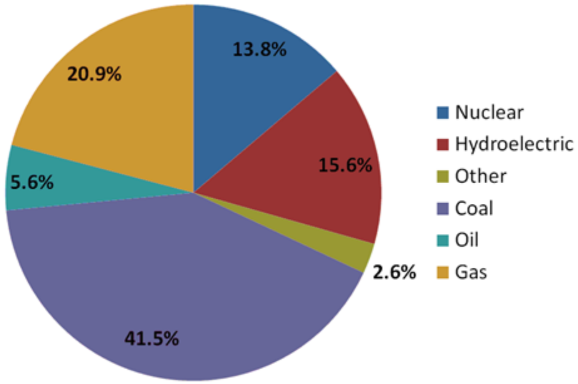
Accelerators for the Environment: Coal

41% of all electrical power worldwide is generated by burning coal

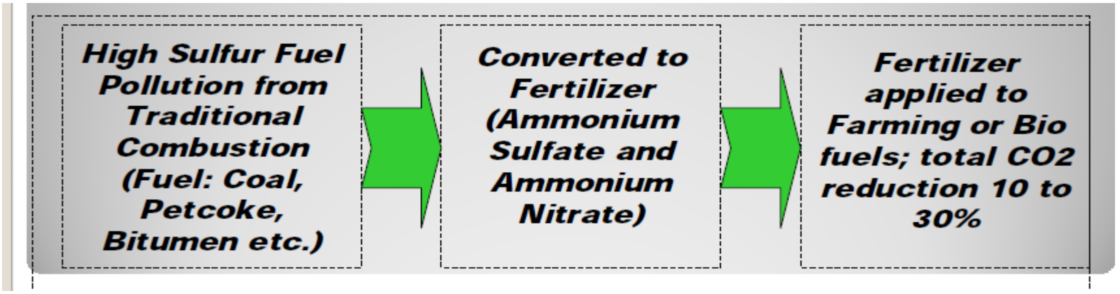
The three major actors, China, India and the US are still using a lot of of coal for electrical power generation.



Emission of NOx and SOx is a serious environmental issue

Accelerators can treat flue gas turning NOx and SOx into fertilizer

1[st] step towards sequestration of CO_2



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Accelerators for the Environment: Flare Gas

Many wells produce both oil and natural gas, but not all gas is recoverable

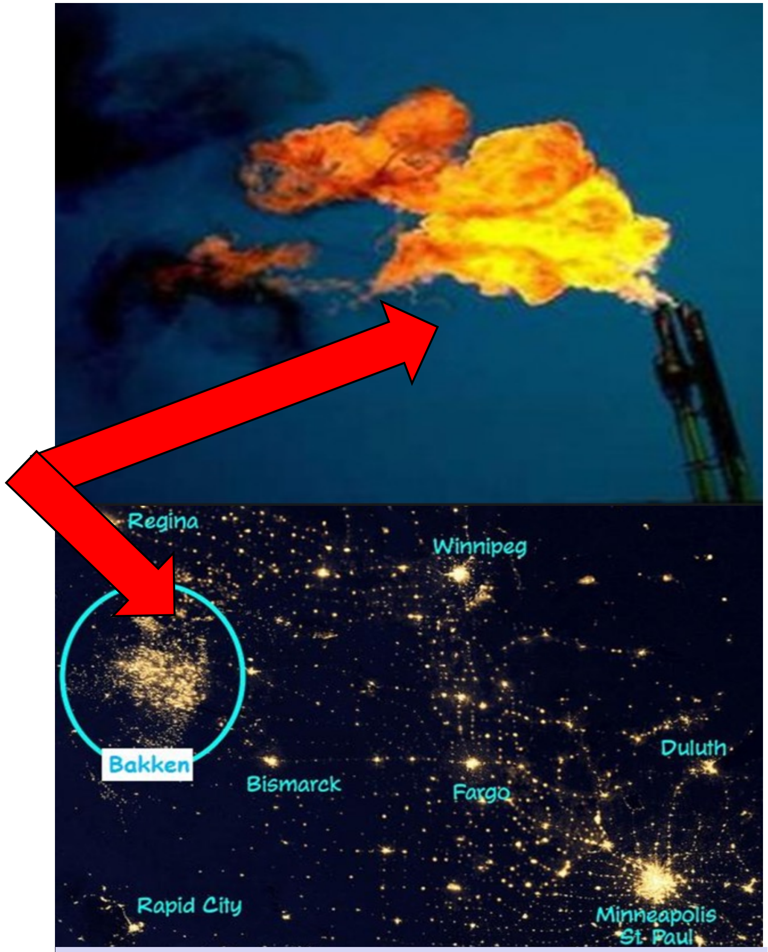
- Remote, so pipelines are not economical
- Produce a burst of gas for only a few years
- Methane is a powerful green house gas… so most companies “Flare” stranded gas at the well

World wide $ 30 B/yr of gas is flared

- Equal to 25% of the natural gas usage of U.S.
- Adds CO_2 with no useful work for mankind

Some Company can convert gas to liquid hydrocarbons but requires large plants for high temperature/pressure reactions

Mobile accelerators could in principle break C-H bonds to efficiently convert stranded gas to liquid hydrocarbons at the well head, could also lower viscosity of heavy oils



Gas flares in ND

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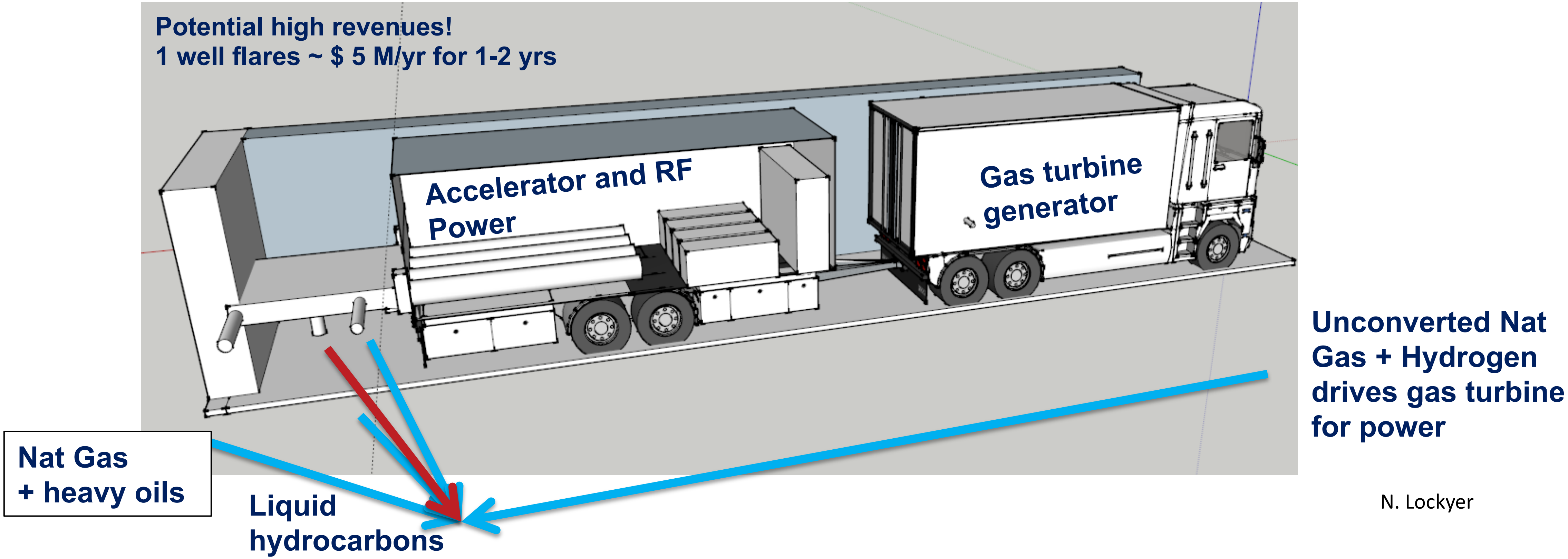
Portable Accelerator to avoid Flare Gas

Trailer mounted **high power electron accelerators**

Natural gas turbines provide the local electrical power

Liquid hydrocarbons created can be mixed and collected with crude oil produced by the well



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Thank you for your attention