PHY 554
Fundamentals of Accelerator Physics
Lectures 25-26
Scientific and Societal Applications of Accelerators

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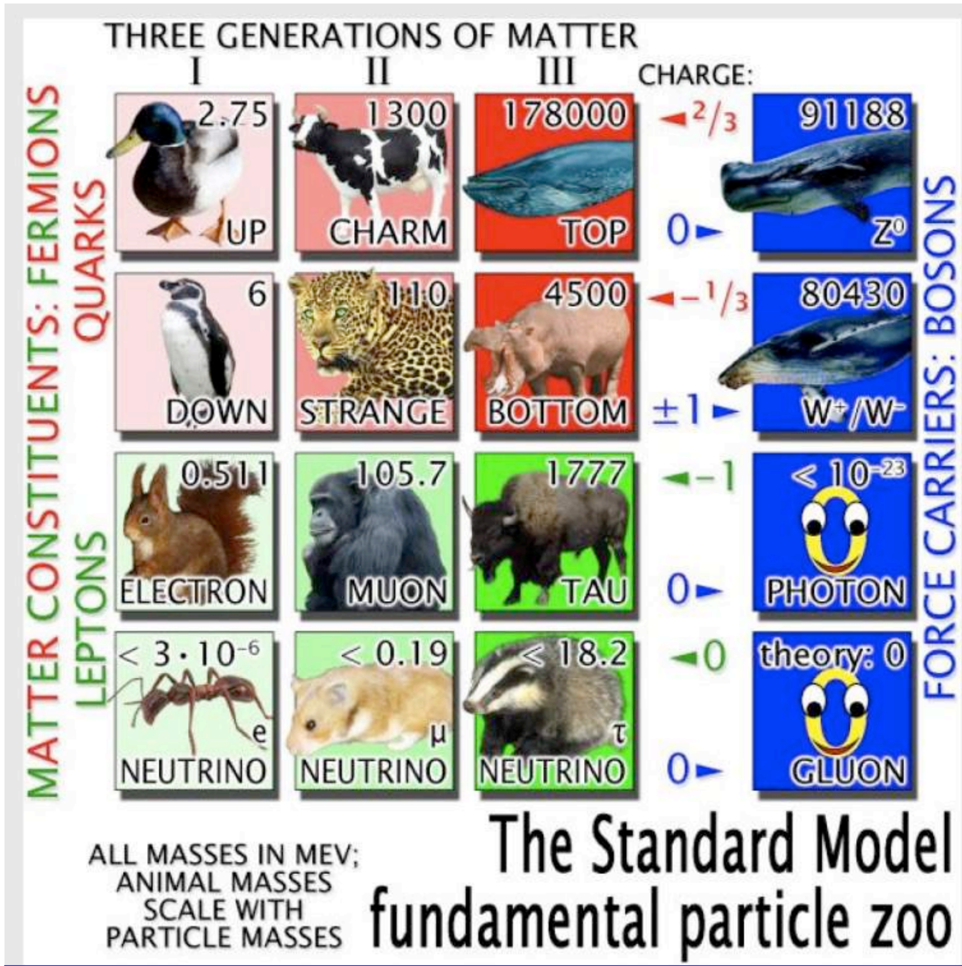
Fist lecture: Scientific Applications
Second lecture: Societal Applications

Scientific Applications

- **High energy and Nuclear Physics** – colliders
- **Neutron sciences** – neutron spallation sources
- **Photon Sciences** – light sources
  - **Pharmaceutical research:** Powerful X-ray beams from synchrotron light sources allow scientists to analyze protein structures quickly and accurately, leading to the development of new drugs to treat major diseases such as cancer, diabetes, malaria and AIDS.
  - **DNA research:** Synchrotron light sources allowed scientists to analyze and define how the ribosome translates DNA information into life, earning them the 2009 Nobel Prize in Chemistry. Their research could lead to the development of new antibiotics.
- http://www.acceleratorsamerica.org/resources/applications/index.html

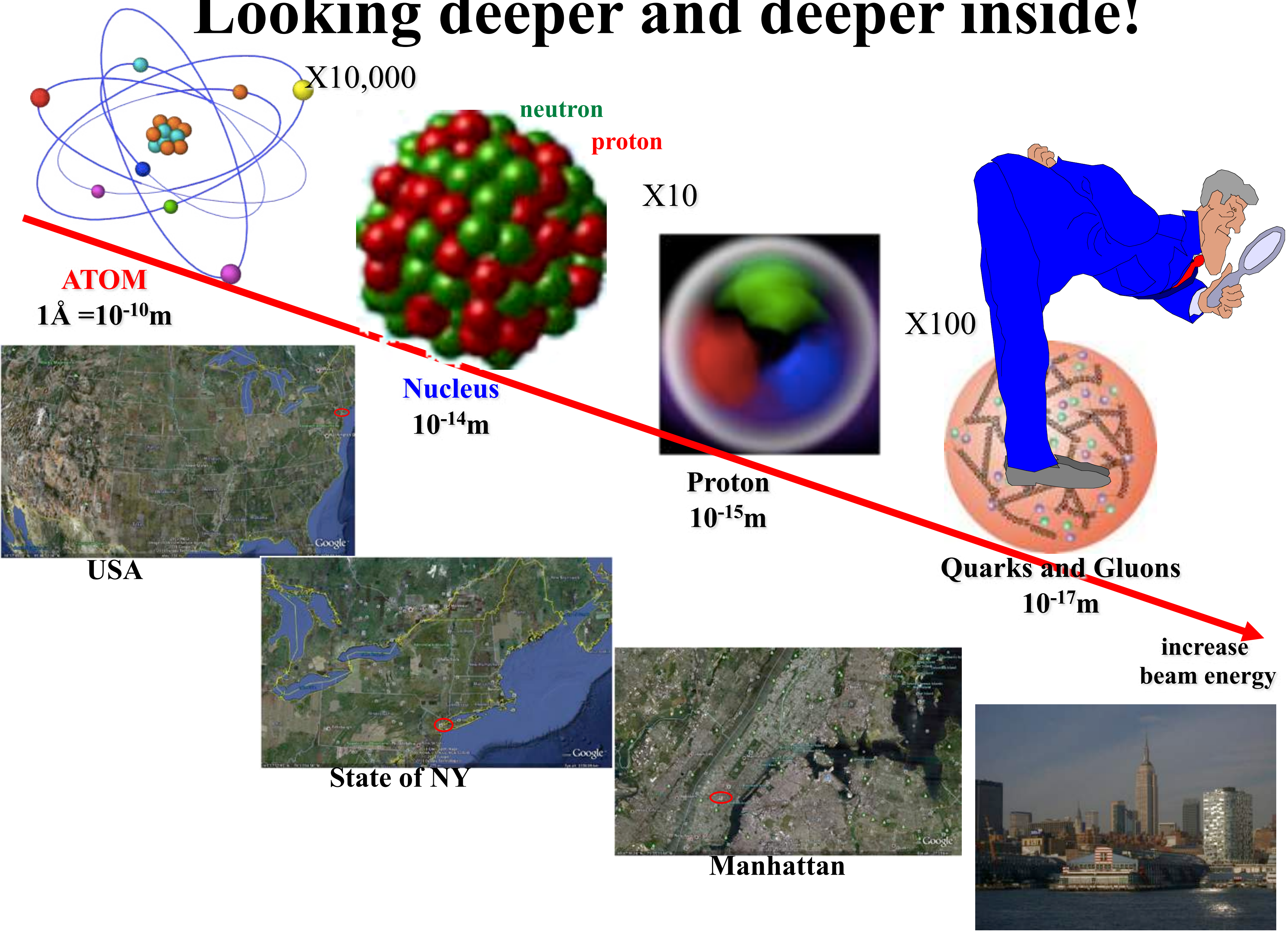
Why we need Colliders?

Accelerator allowed us to discover the entire zoo of elementary particles and their combinations (states)



HIGS 125,180 MeV

Looking deeper and deeper inside!



High Energy and Nuclear Physics

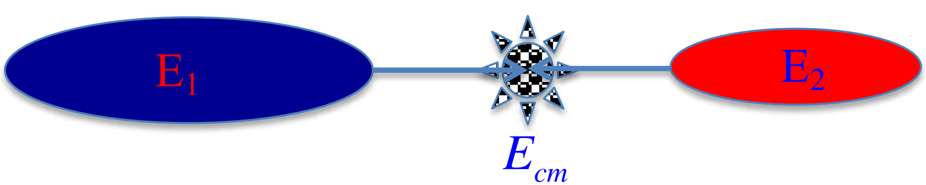
- Colliders – world's most powerful microscopes
- Hence, they allow to look into the matter on smaller and smaller scale, and, sometimes, discover new states of mater or new particles

$$\delta x \cdot \delta p \geq \hbar \qquad \delta p \leq \frac{E_{cm}}{c}; \quad \delta x \geq c\frac{\hbar}{E_{cm}}$$

or for new particles

$$M_{part} \leq \frac{E_{cm}}{c^2}$$

- For ultra-relativistic particles the c.m. energy is a simply twice the geometrical average of the colliding particles



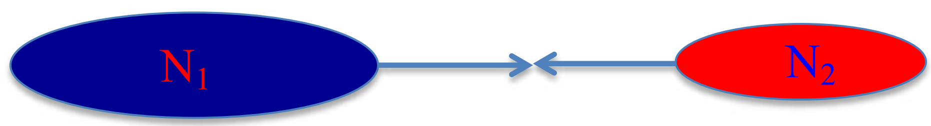
$$E_{cm} \cong 2\sqrt{E_1 E_2}$$

Collider	E_1, GeV	E_2, GeV	E_{cm}, GeV
RHIC	250 p	250 p	500.0
eRHIC	250 p	21.2 e-	145.6
LHC	6500 p	6500 p	13,000
B-factory	3.5 e-	10.58 e+	12.2
Fixed target	E_1, GeV	E_2, GeV	E_{cm}, GeV
CEBAF	6 e-	0.938 p	4.7
	12 e-	0.938 p	6.7
	6 e-	0.00051 e-	0.1
	12 e-	0.00051 e-	0.2

Productivity of colliders

- LUMINOSITY

$$L = f_c \frac{N_1 N_2}{A} \cong f_c \frac{N_1 N_2}{2\pi\sqrt{\beta_{x1}\varepsilon_{x1} + \beta_{x2}\varepsilon_{x2}}\sqrt{\beta_{y1}\varepsilon_{y1} + \beta_{y2}\varepsilon_{y2}}}$$



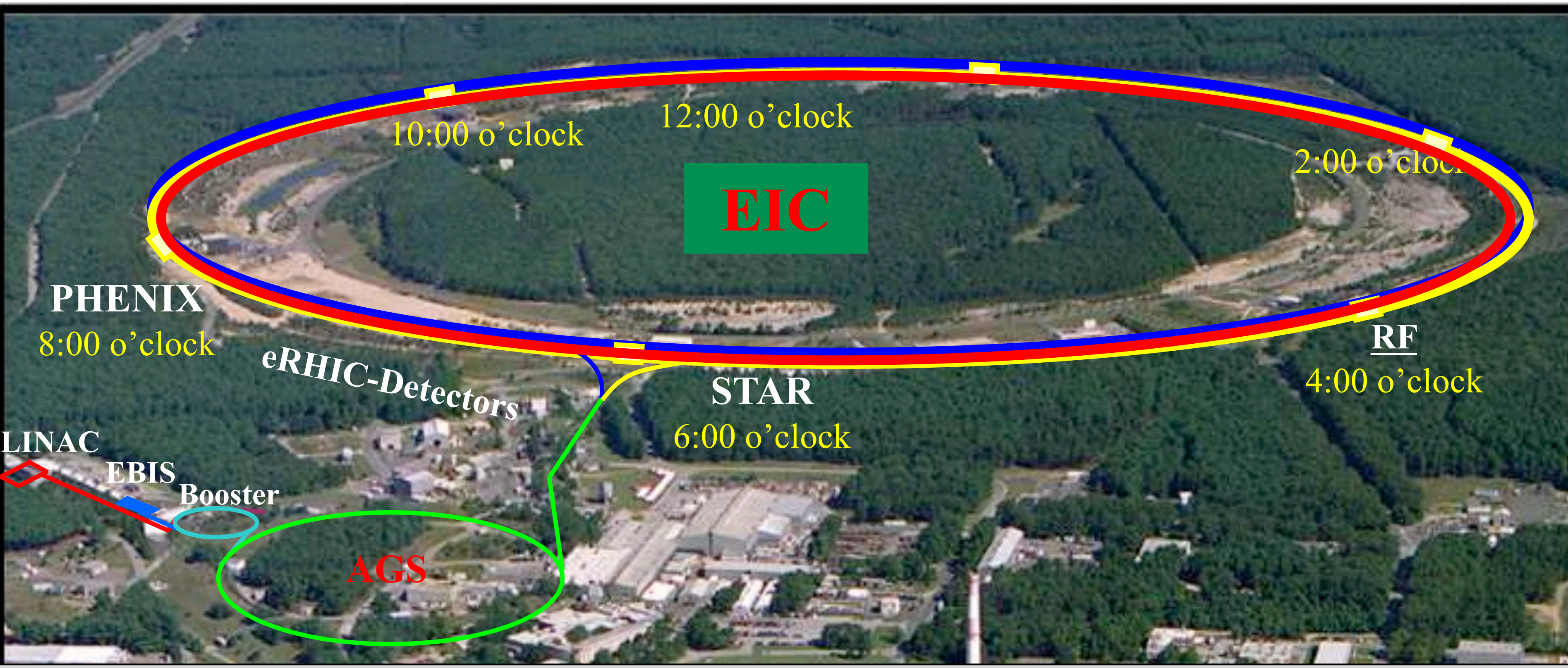
If an event A->B has a cross-section $\sigma_{A\to B}$ (for example generating Higgs particle), then the speed of producing them is simply given by the pProduct of the cross-session and the luminosity

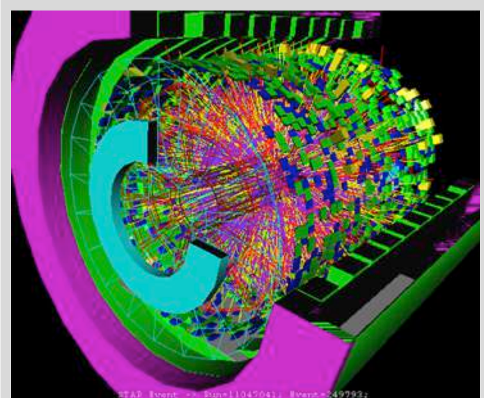
$$\dot{N}_{A\to B} = \sigma_{A\to B} \cdot L$$

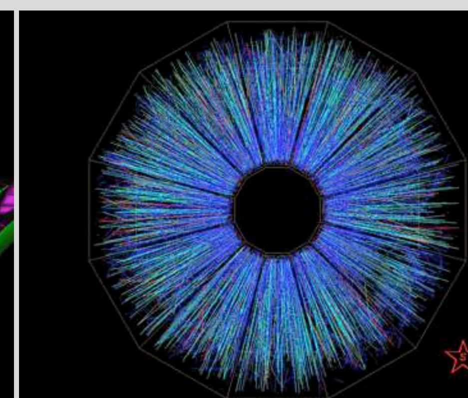
Luminosity is measured in $cm^{-2}sec^{-1}$

Collider	L
RHIC	10^{32}
eRHIC	10^{33} - 10^{34}
LHC	10^{34}
B-factory	10^{34}
Fixed target	L
CEBAF	10^{35}

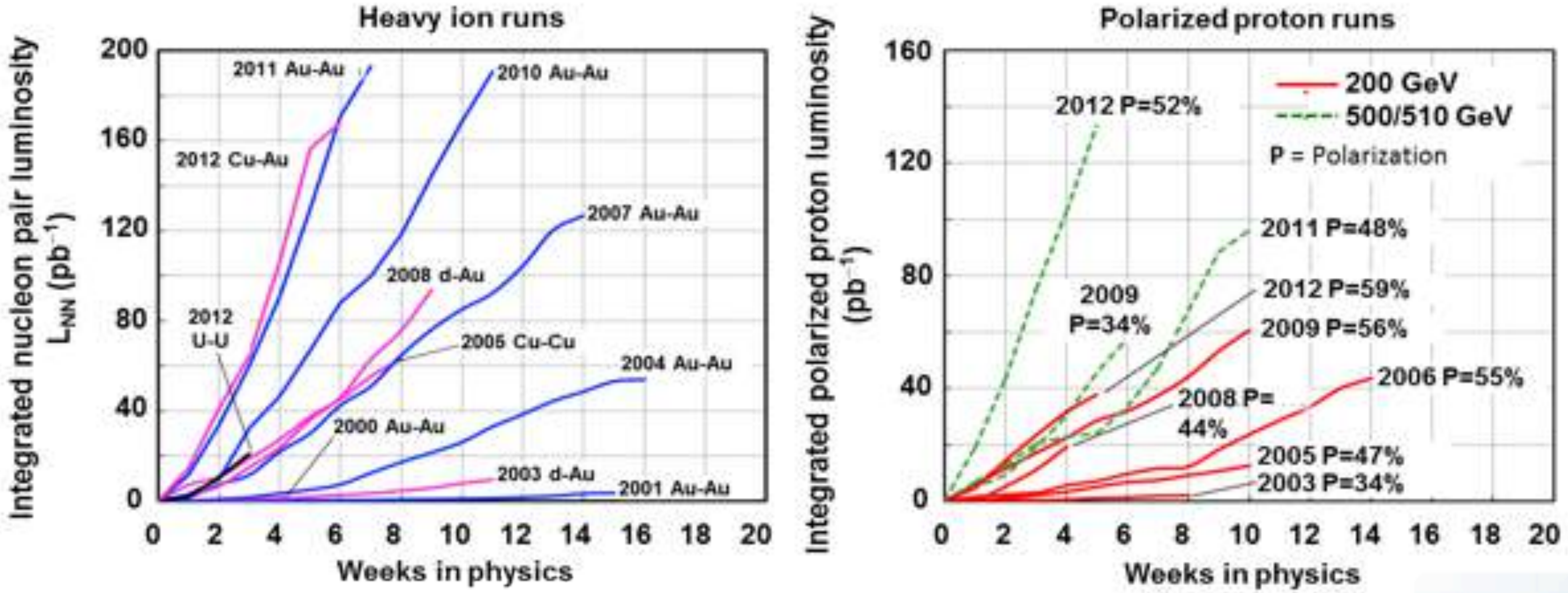
Close to Home: From RHIC to eRHIC







Dramatic Improvements in Performance & Versatility



Collision partners	Beam energies (GeV/nucleon)	Peak pp-equivalent luminosities achieved to date, scaled to 100 GeV/n[b)]
Used to date		
Au+Au	3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 31, 65, 100	195×10^{30} cm^{-2}s^{-1}
d+Au[a)]	100	100×10^{30} cm^{-2}s^{-1}
Cu+Cu	11, 31, 100	80×10^{30} cm^{-2}s^{-1}
p↑+p↑ (polarized)	11, 31, 100, 205, 250, 255	165×10^{30} cm^{-2}s^{-1} at 255 GeV
Cu+Au[a)]	100	230×10^{30} cm^{-2}s^{-1}
U+U	96	60×10^{30} cm^{-2}s^{-1}
Considered for future		
Au+Au	2.5, 7.5	
p+Au	100	
p↑+ ^{3}He↑ [a)]	166	

2 new colliding beam species / combinations in 2012

© W. Fischer

Run-18 Overview

Very flexible operation

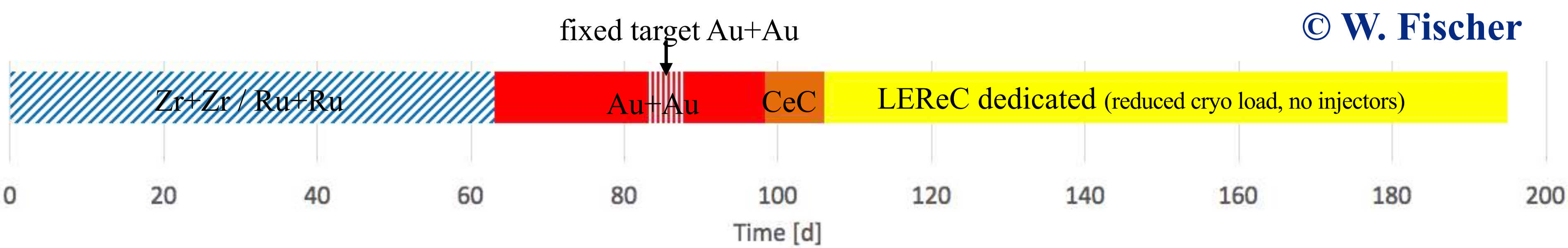
6 modes, frequent parallel activities, frequent changes

in addition running Linac for BLIP and EBIS/Booster for NSRL (including the Galactic Cosmic Ray Simulator – up to 33 beams in 1 h 20 min), and Tandem for industrial and academic users

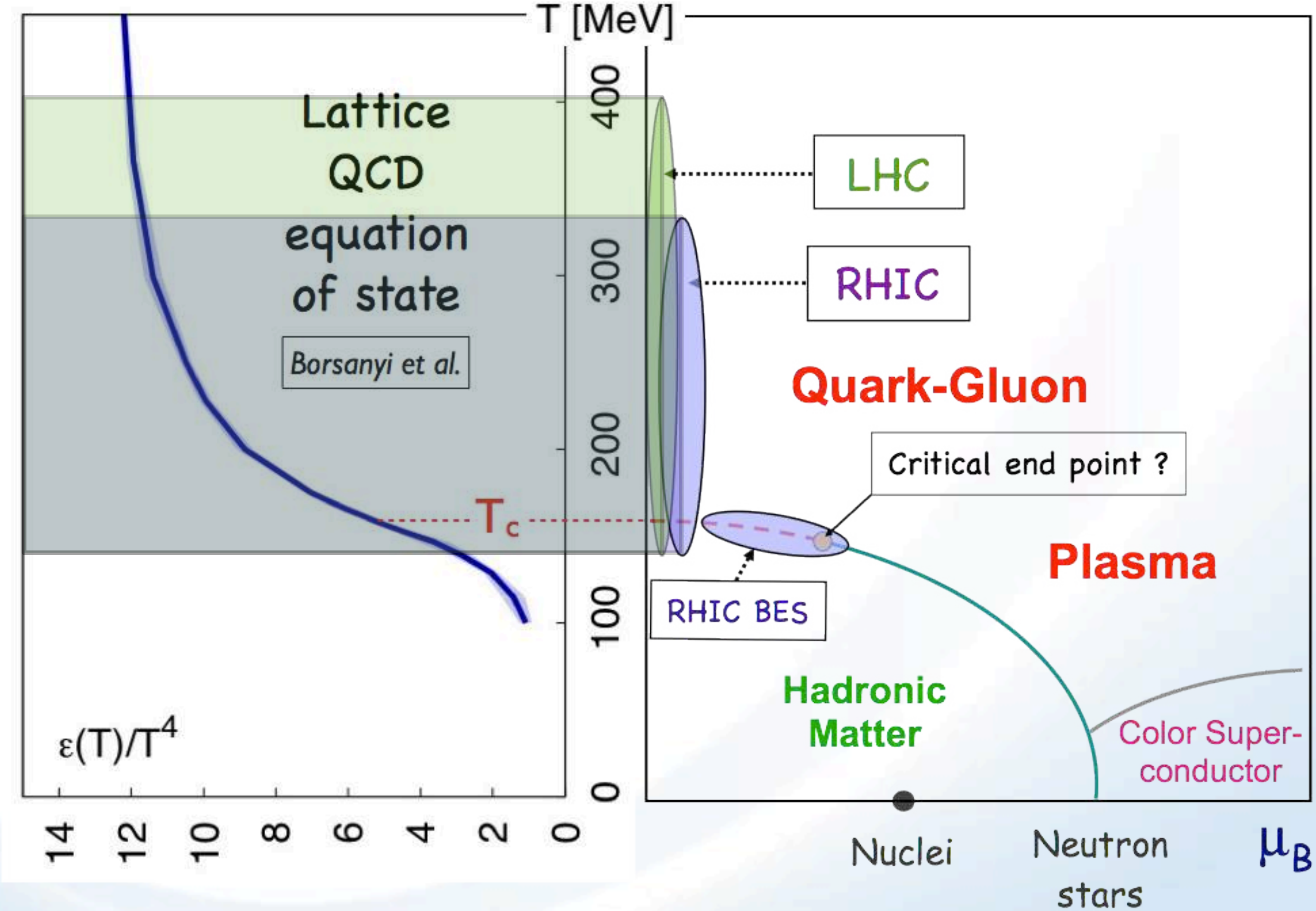
most challenging in terms of flexibility to date

Mode	Primary activity with beam energy per nucleon	Secondary activities in parallel or within	Time [d]
1* 2*	Zr+Zr 100 GeV Ru+Ru 100 GeV	CeC, LEReC CeC, LEReC	63
3A	Au+Au 13.5 GeV	CeC, LEReC, Mode 3B	30.7
3B	Au+Au 3.85 GeV fixed target	LEReC Machine Development for BES-II	4.6
3C	CeC PoP dedicated, Au 26.5 GeV	Au+Au 26.5 GeV fixed target	7.7
4	LEReC dedicated	CeC	89

* First collider operation ever with species switch store-by-store.
Setup for Modes 1/2 in record 6 days - with 3 beams (Au, Zr, Ru) and including 2 snow storms with multiple power dips.



QCD Phase Diagram



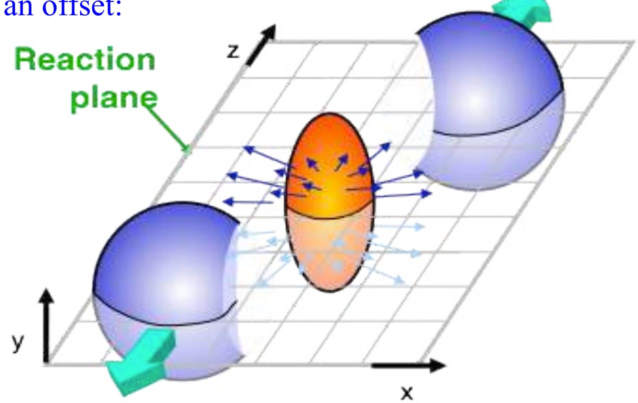
Anisotropic flow: The Perfect Liquid

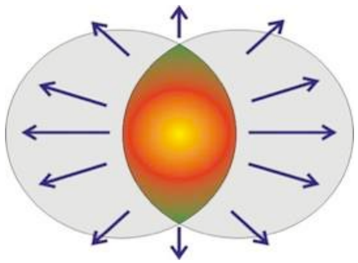
$\eta/s = 0$

$\eta/s = 1/4\pi$

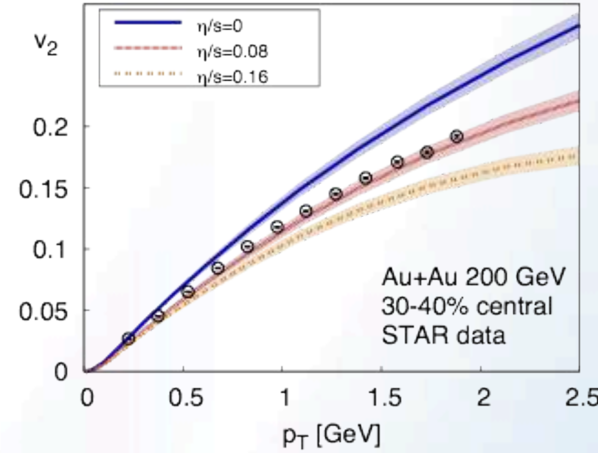
$\eta/s = 2/4\pi$

- two nuclei collide rarely head-on, but mostly with an offset:





only matter in the overlap area gets compressed and heated

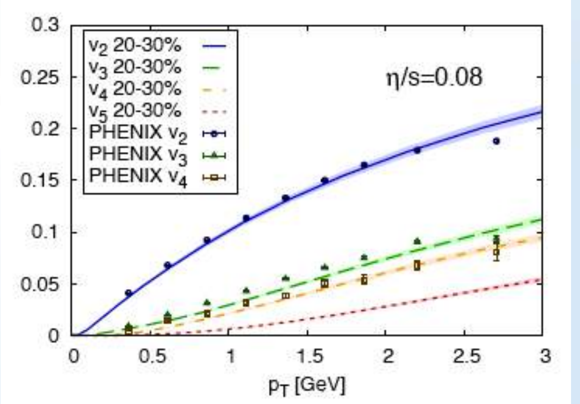


$\eta/s \rightarrow 1/4\pi$

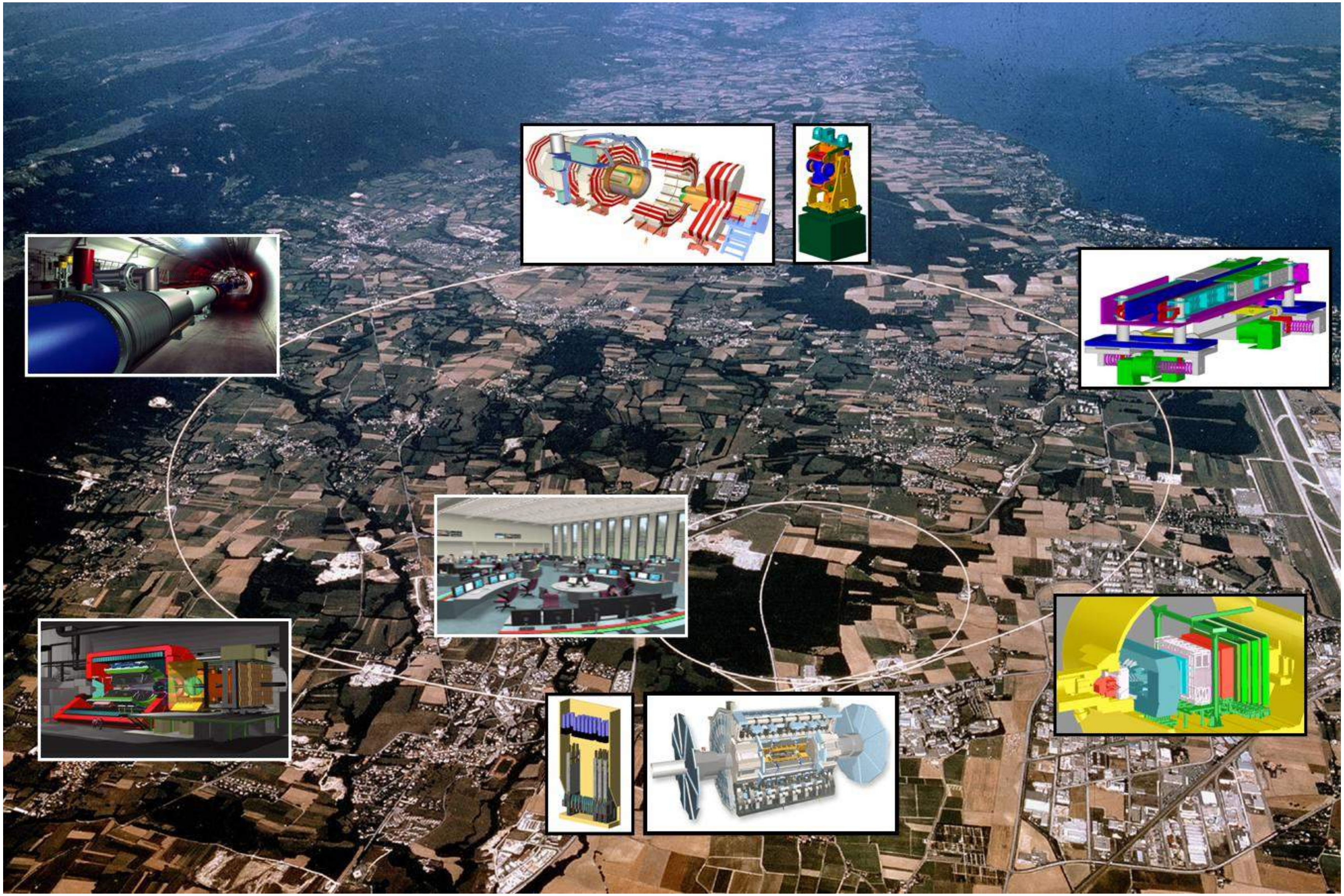
$$2\pi\frac{dN}{d\phi} = N_0\left(1+2\sum_n \mathrm{v}_n(p_T,\eta)\cos n\left(\phi-\psi_n(p_T,\eta)\right)\right)$$

anisotropic flow coefficients

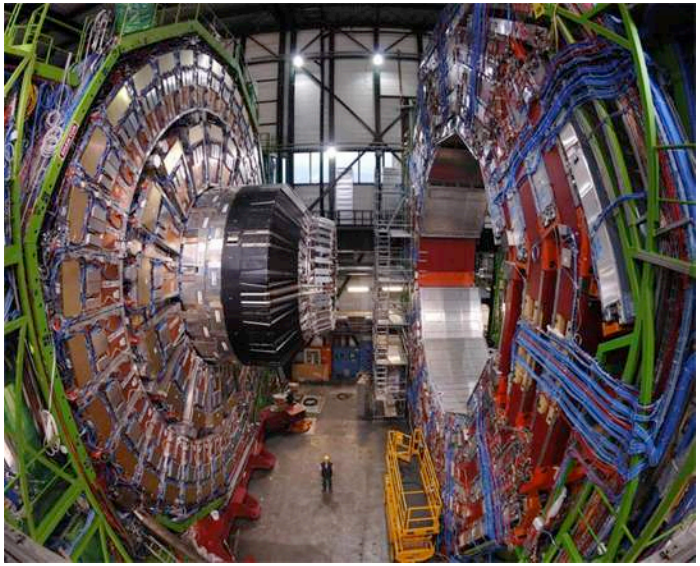
event plane angle

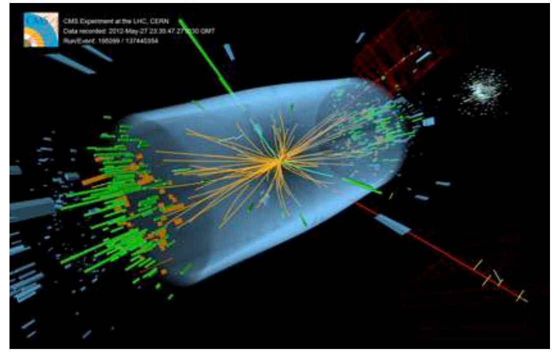


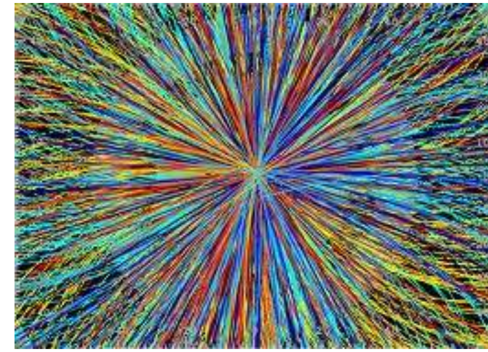
LHC – energy frontier

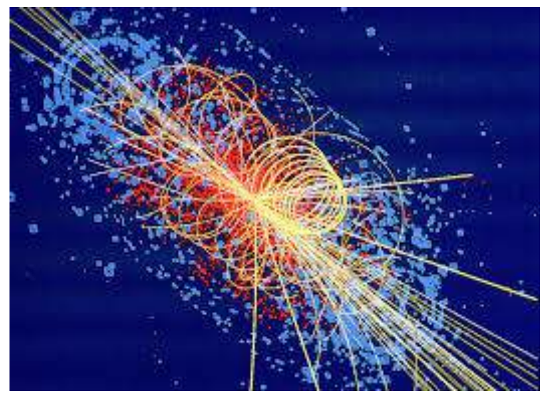


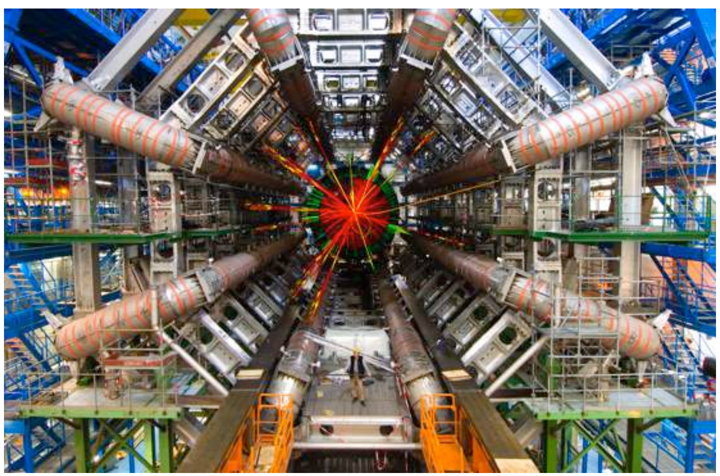
LHC – energy frontier

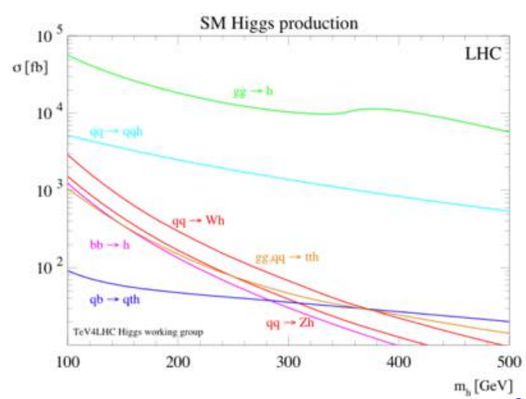


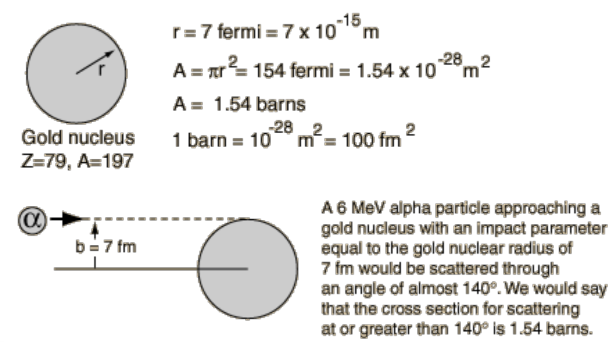






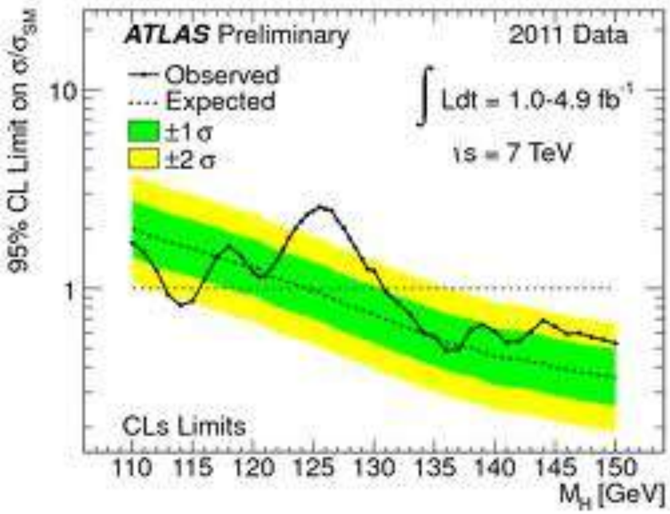


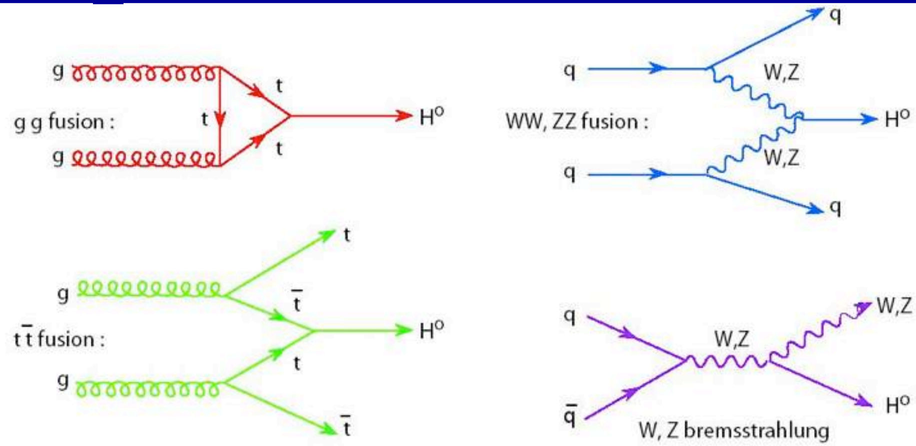


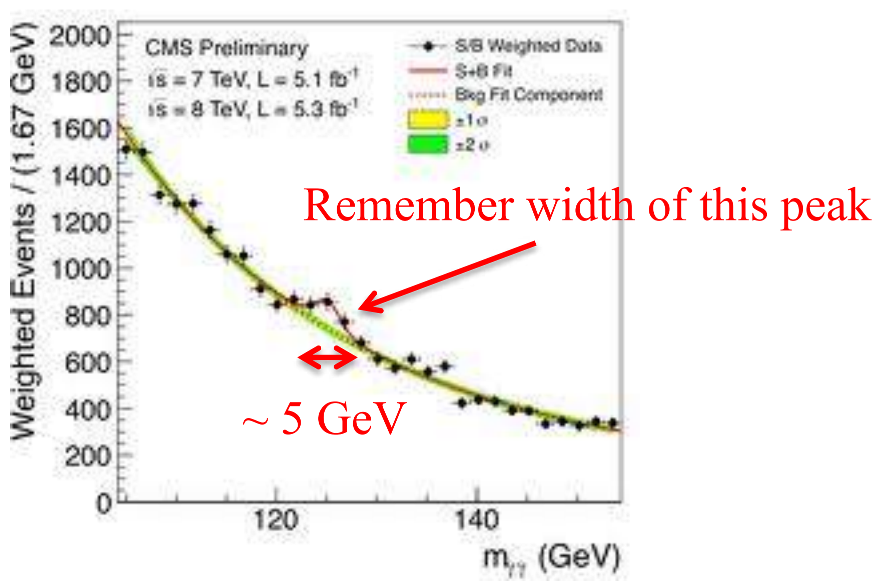


1 Barn=10^{-28} cm^2, 1 fb=10^{-43} cm^2

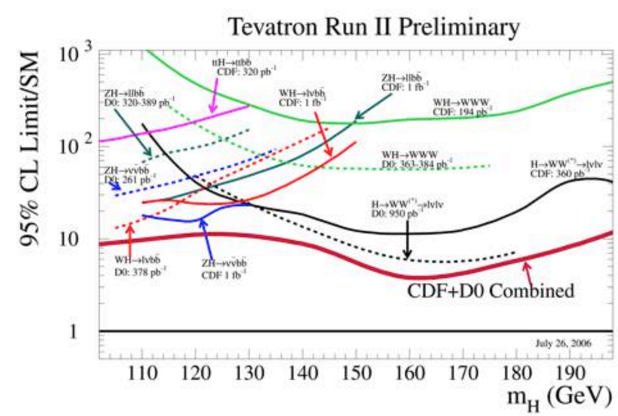
Higgs at LHC: blip in cross-section





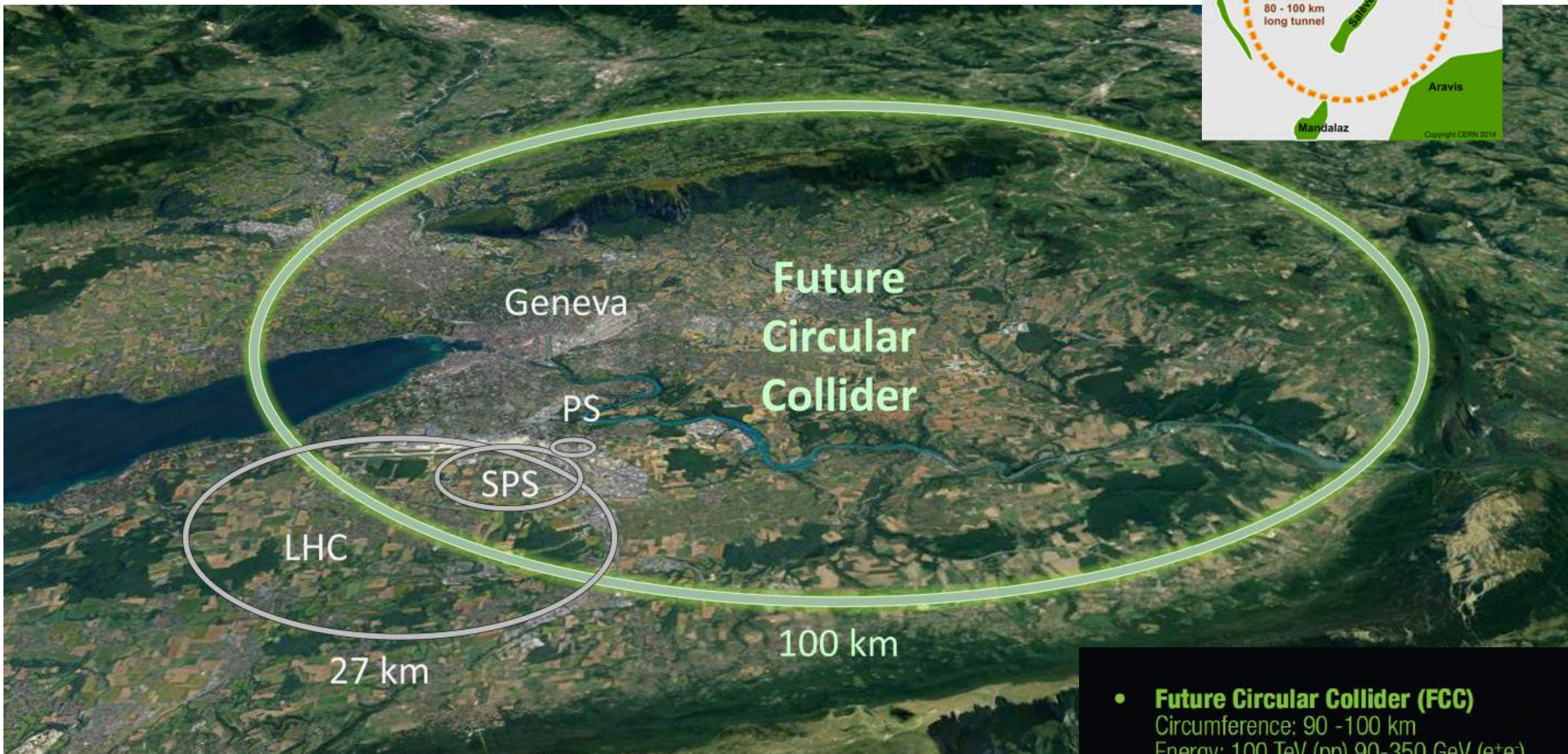


Tevatron at FERMILAB has necessary energy reach but did not had enough luminosity to find
Higgs – it only had "hints"



Proposal for Future Circular Collider (FCC) at CERN

C.M. Energy: 365 GeV e^+e^-, 100 TeV pp,



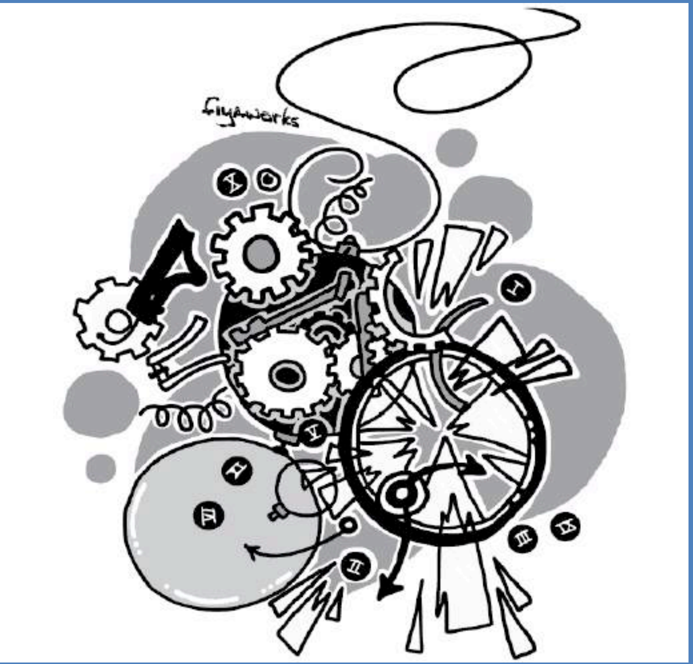
- **Future Circular Collider (FCC)**
  Circumference: 90 -100 km
  Energy: 100 TeV (pp) 90-350 GeV (e^+e^-)
- **Large Hadron Collider (LHC)**
  Large Electron-Positron Collider (LEP)
  Circumference: 27 km
  Energy: 14 TeV (pp) 209 GeV (e^+e^-)
- **Tevatron**
  Circumference: 6.2 km
  Energy: 2 TeV ($p\bar{p}$)

New challenge: SR power of proton beam is large and has to be evacuated from inside 4K SC magnets…

Why leptons and not hadrons?

Scattering of protons on protons
is like colliding Swiss watches to find out how they are built.

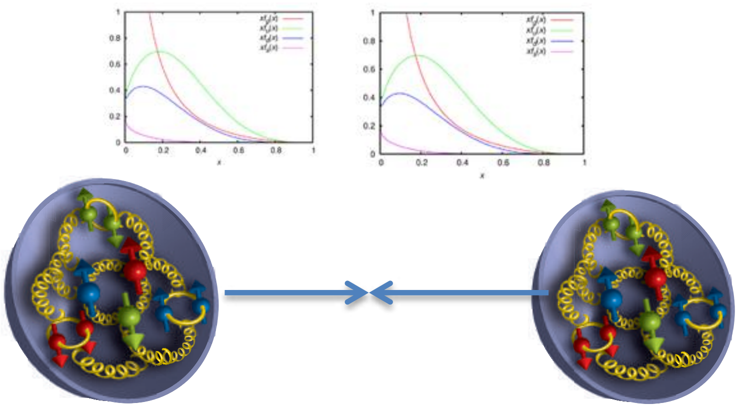
R. Feynman



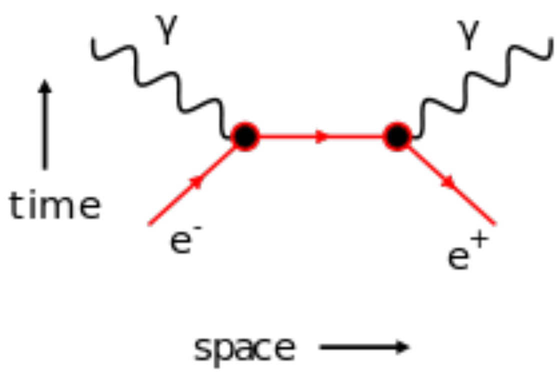
Courtesy of Mathew Lamont

Why e^+e^- or e^-h colliders?

To the best of our knowledge electrons and positions (or muons) do not have internal structure



Colliding hadron is as colliding two caps of quark-gluon soup (+ sea quarks): energies and polarization are varying and initial state is unknown



Pure initial state (energy of annihilated electron-positron pair)

Very precise knowledge of the energy and polarization

B-factories

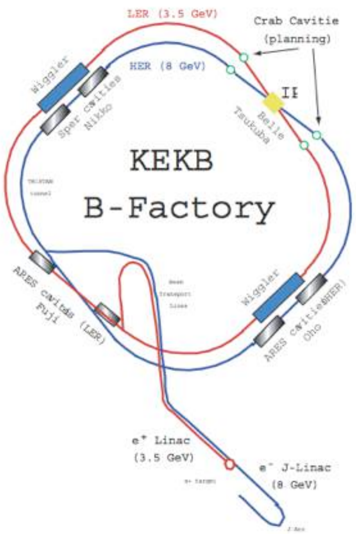
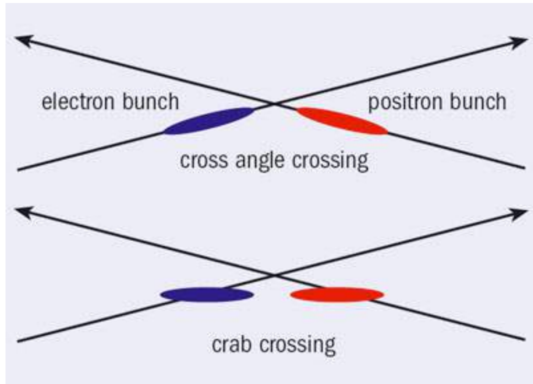
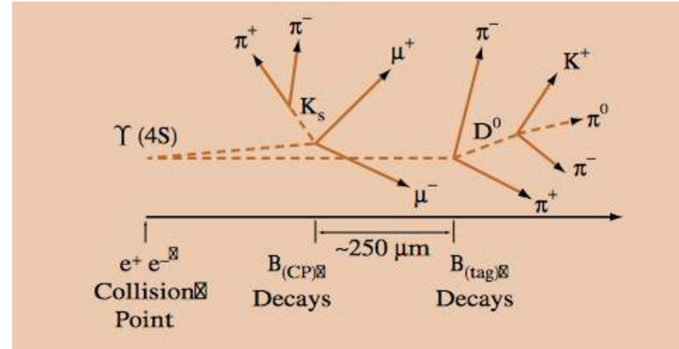


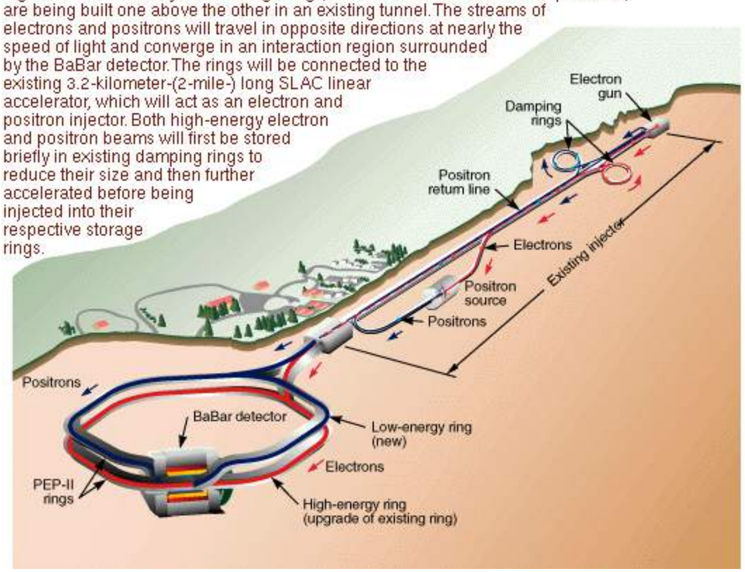
Figure 1: A schematic view of the KEKB.

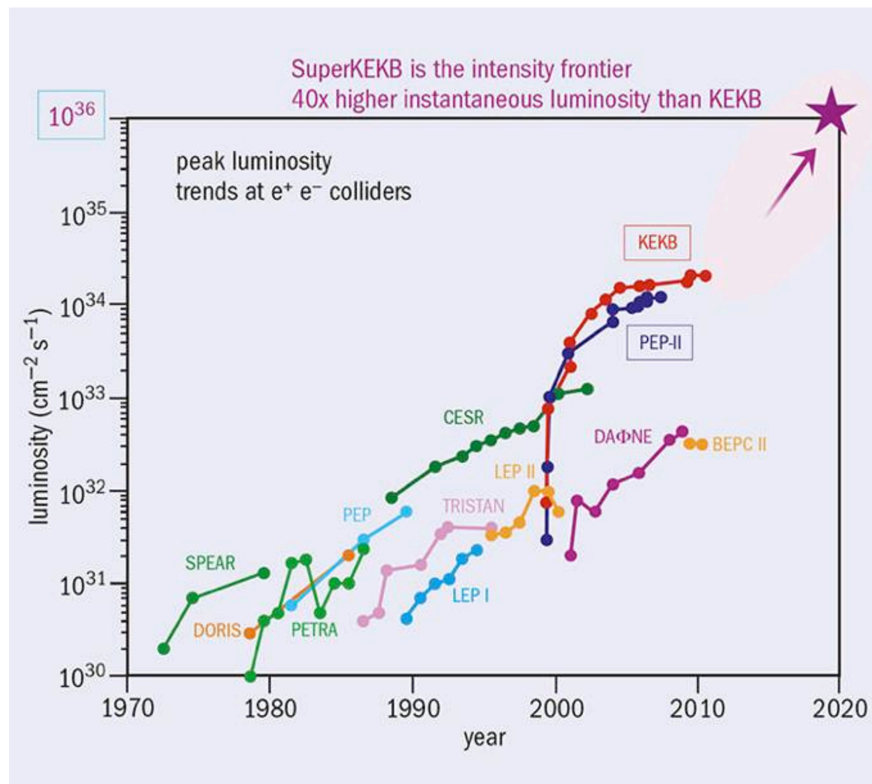




A typical "golden event" at an asymmetric B *factory. The first* B *meson decays into a* J/ψ *(which immediately decays to* $\mu^+\mu^-$*) and a* K_S*, while the second* B *yields a clear tag.*

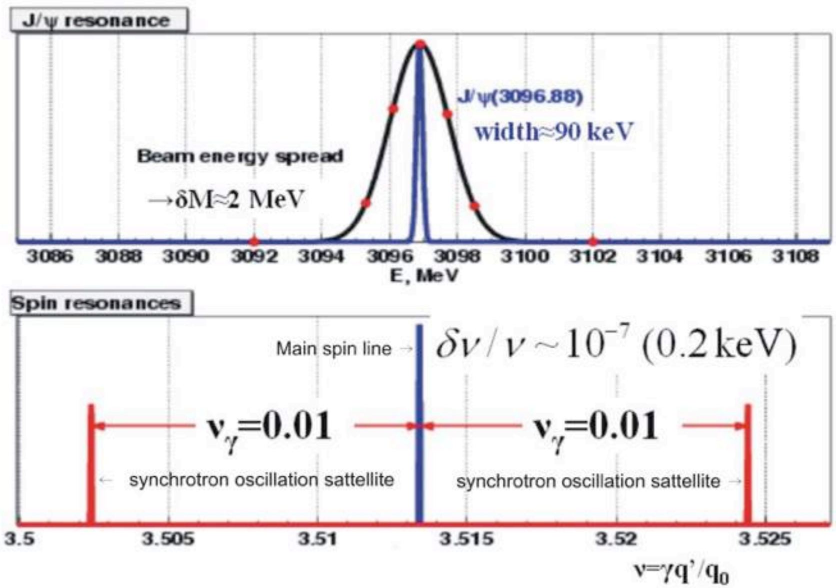
Figure 2. The B-Factory's two storage rings, one for electrons and one for positrons, are being built one above the other in an existing tunnel. The streams of electrons and positrons will travel in opposite directions at nearly the speed of light and converge in an interaction region surrounded by the BaBar detector. The rings will be connected to the existing 3.2-kilometer-(2-mile-) long SLAC linear accelerator, which will act as an electron and positron injector. Both high-energy electron and positron beams will first be stored briefly in existing damping rings to reduce their size and then further accelerated before being injected into their respective storage rings.

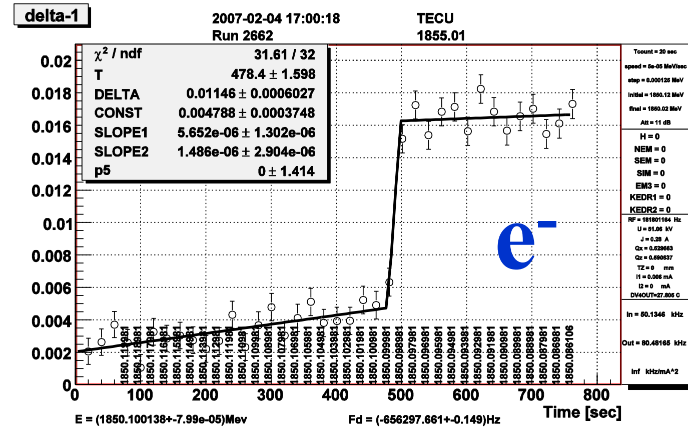


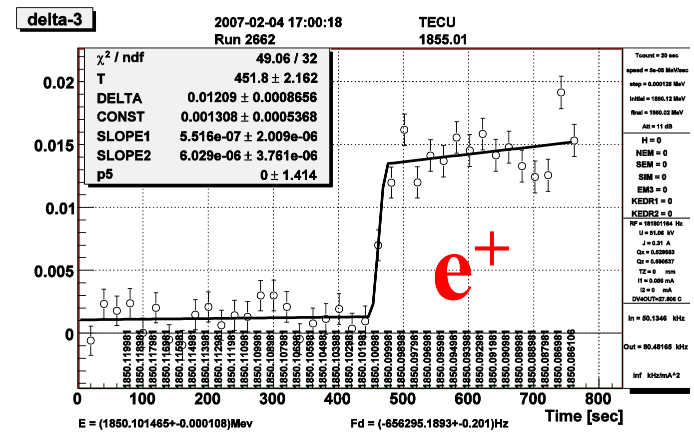


Resonance depolarization method

BEAM ENERGY SPREAD AND SPIN SPECTRA at VEPP-4M







In homogeneous magnetic field a width of the spin spectra is ~10^{-9} !
In real storage ring it is ~10^{-7} due to betatron oscillations and nonlinearity of magnetic field and noise in magnet system

E_p - E_e =(1.32±0.14) keV: 0.4 p.p.m. energy accuracy

Compare this with 1% scale resolution in p-p collisions

Largest e^+e^- collider - LEP

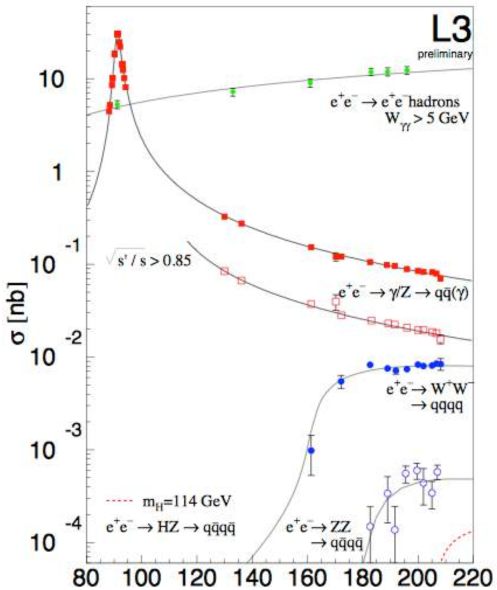
PR04.00 23.06.00

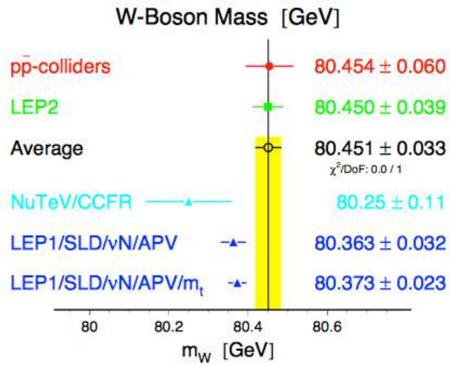
The LEP machine at CERN is the largest particle collider in the world. In a ring 27 km in circumference, buried about 100 m underground, bunches of electrons and positrons race round in opposite directions...

Last sprint for LEP

The Director General, Prof. Luciano Maiani, began his report with the performance of the Laboratory's flagship accelerator, the Large Electron-Positron collider, LEP, during its final year. LEP is achieving its highest energy collisions ever with beams of over 104 GeV, well exceeding its design energy and giving experiments a final chance of discovering the still-elusive Higgs particles before the end of it's experimental programme in September. Thanks to precision data from LEP and elsewhere, scientists already know that Higgs particles, if they exist, must be within range of LEP's successor, the LHC.

LEP – W & Z factory





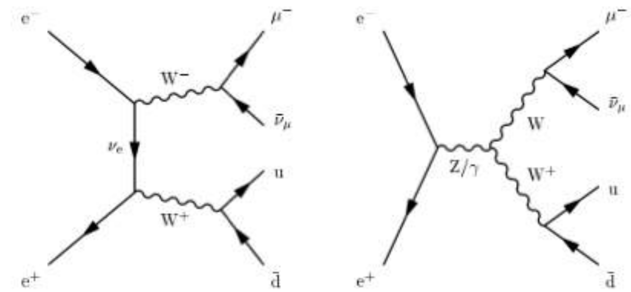


Figure 16. CC03 diagrams for W^+W^- production with subsequent decay into $u\bar{d}$ and $\mu\bar{\nu}_\mu$.

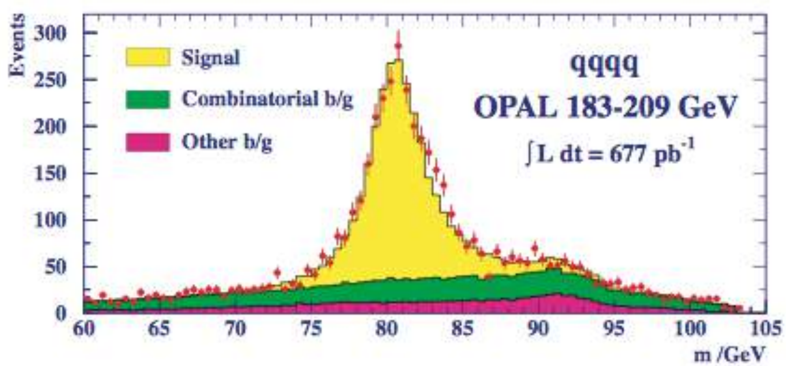


Figure 19. Reconstructed W mass distribution for all OPAL $W^+W^- \to q\bar{q}q\bar{q}$ data from $\sqrt{s} = 183$ to 209 GeV. The histogram shows the SM expectation for $M_W = 80.42$ GeV.

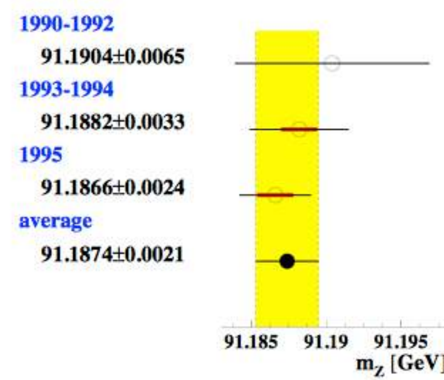


Figure 5. m_Z combined by EWWG for the different periods of data taking.

$$m_W = 80.450 \pm 0.026(stat.) \pm 0.030(syst.) GeV.$$

$$m_Z = 91.1874 \pm 0.0021\ GeV.$$

Under discussions

CERN

Future Circular Colliders (FCC)

	√s	Ring(km)
FCC-ee	90-365 GeV	100
FCC-hh	100 TeV	100

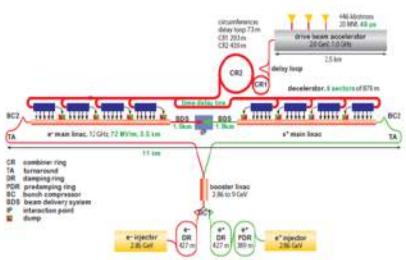
Integrated FCC program: FCC-ee as a first step, then FCC-hh

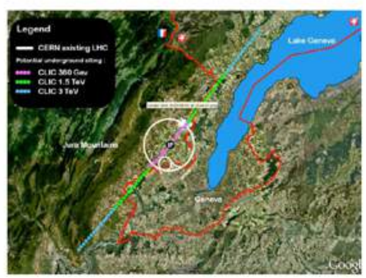
Options		
FCC-eh	3.5 TeV	Needs FCC-hh
HE-LHC	27 TeV	LHC tunnel
LE-FCC	37.5 TeV	100km

Conceptual Design Report in 2018

Common layout for FCC ee and hh

CLIC Collider at CERN



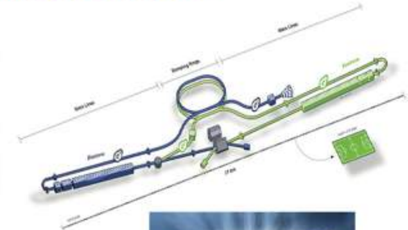


- CLIC is a linear e⁺e⁻ collider based on "warm" RF technology with 70+ MV/m acceleration
  - The only way to get to multi-TeV e⁺e⁻
- 11km long for 380 GeV in the center of mass
- Under active design development

Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

Japan

International Linear Collider

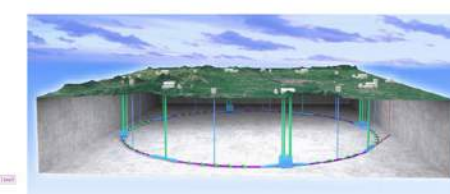


- ILC or International Linear Collider is e⁺e⁻ linear collider with the following main parameters
  - Center of mass energy 250 GeV (upgradeable to higher energies)
  - Luminosity >10^{34} $cm^{-2}s^{-1}$
- No synchrotron radiation, but long tunnel to accelerate to ~ 125 GeV/beam
  - Excellent Higgs factory with many Higgs production and decay channels accessible

China

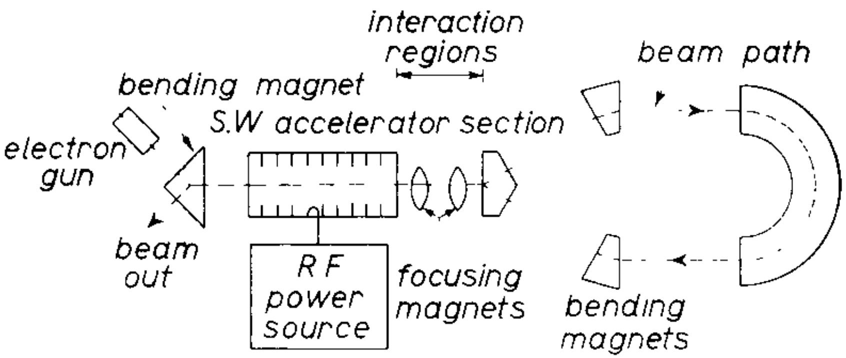
Proposals for Colliders in China: CepC and SppC

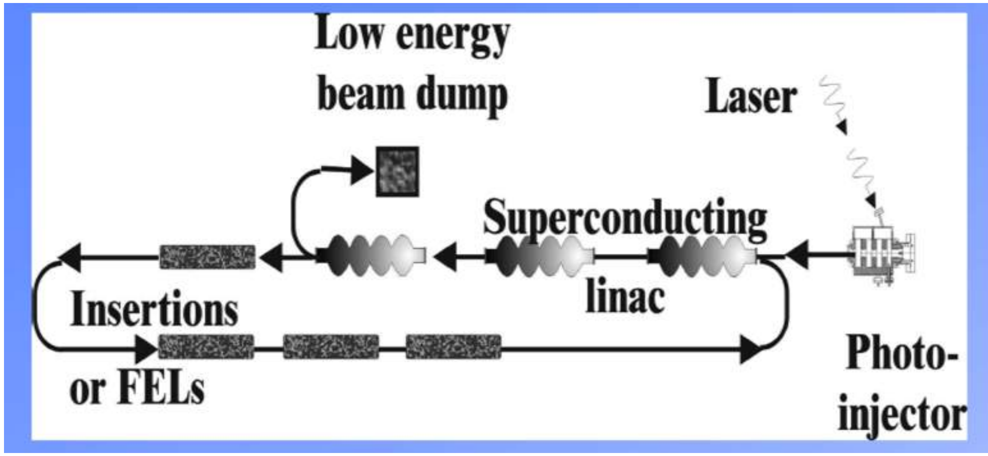
- CepC – Circular Electron Positron Collider
  - ~100 km long ring
  - 90-250 GeV in the center of mass
  - Z boson and Higgs factory
- SppC – Super Proton Proton Collider
  - In the same ring as CepC
  - ~100 TeV with 16 T magnets



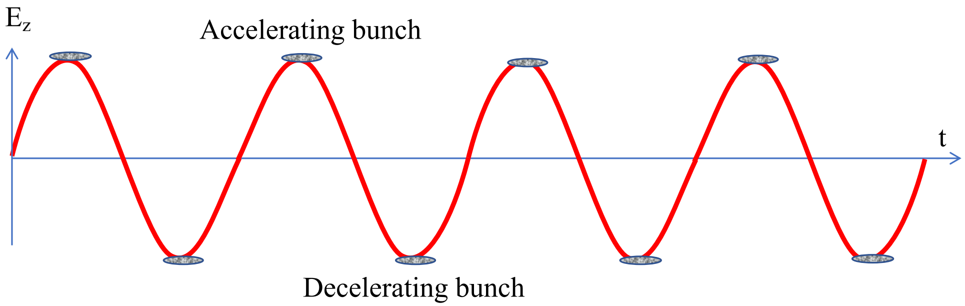
Superconducting RF Energy Recovery Linac

- Invented by M. Tigner, Nuovo Cimento **37** 1228 (1965)





- followed by Stanford, BINP, Jefferson Lab, JAERI, BNL, Cornell, LBNL, Daresbury *and more …*



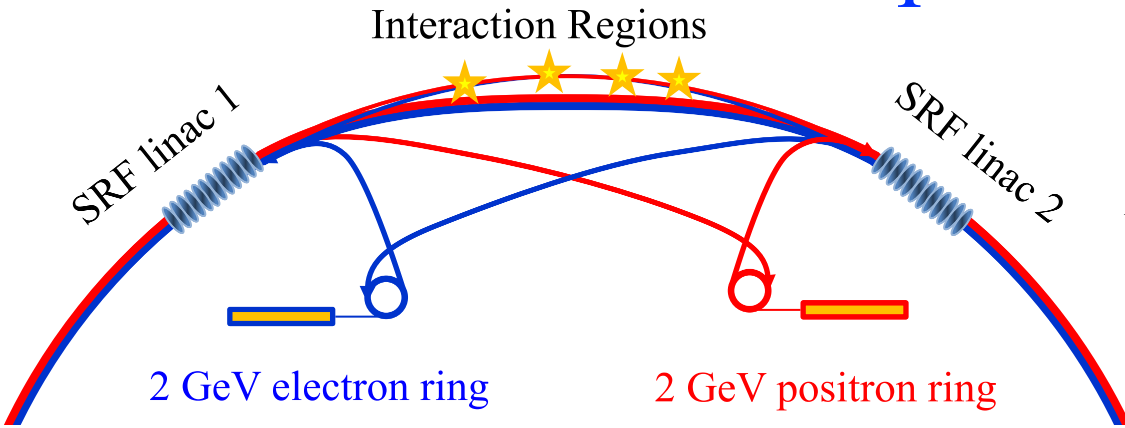
ERLs - path to the future

As compared to a ring, the beam properties are largely determined by the injector system:

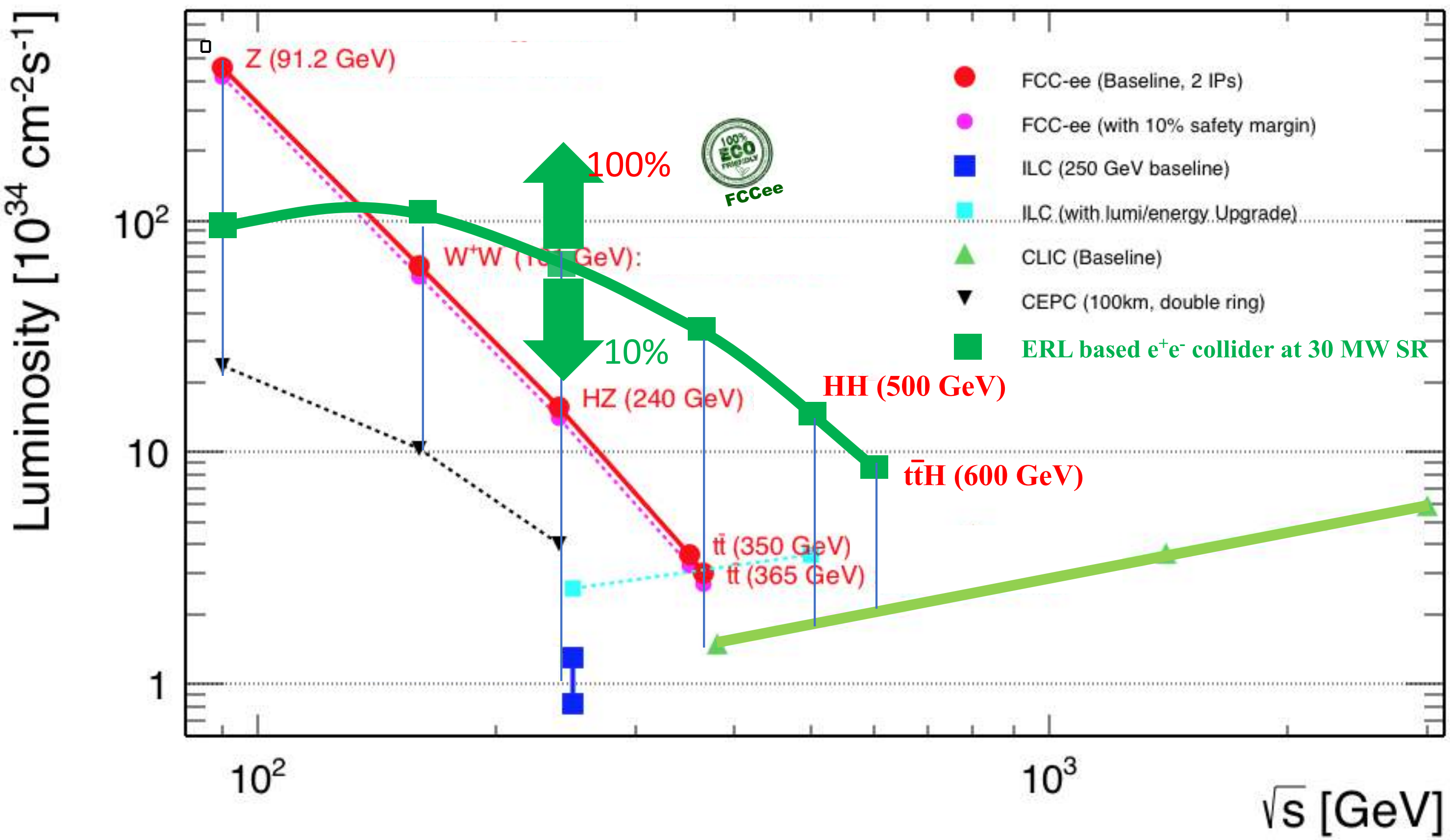
- **The bunch length can be in fsec range**
- **Smaller emittances**
- **Higher coherence fraction**

Current of 0.1 A and energy of 200 GeV leads to a beam power of 20 GW !!!
The energy of the spent beam has to be recaptured for the new beam.

ERL collider concept



CERN Courier News:
"US proposal teases FCC-ee energy boost"
https://cerncourier.com/a/us-proposal-teases-fcc-ee-energy-boost/



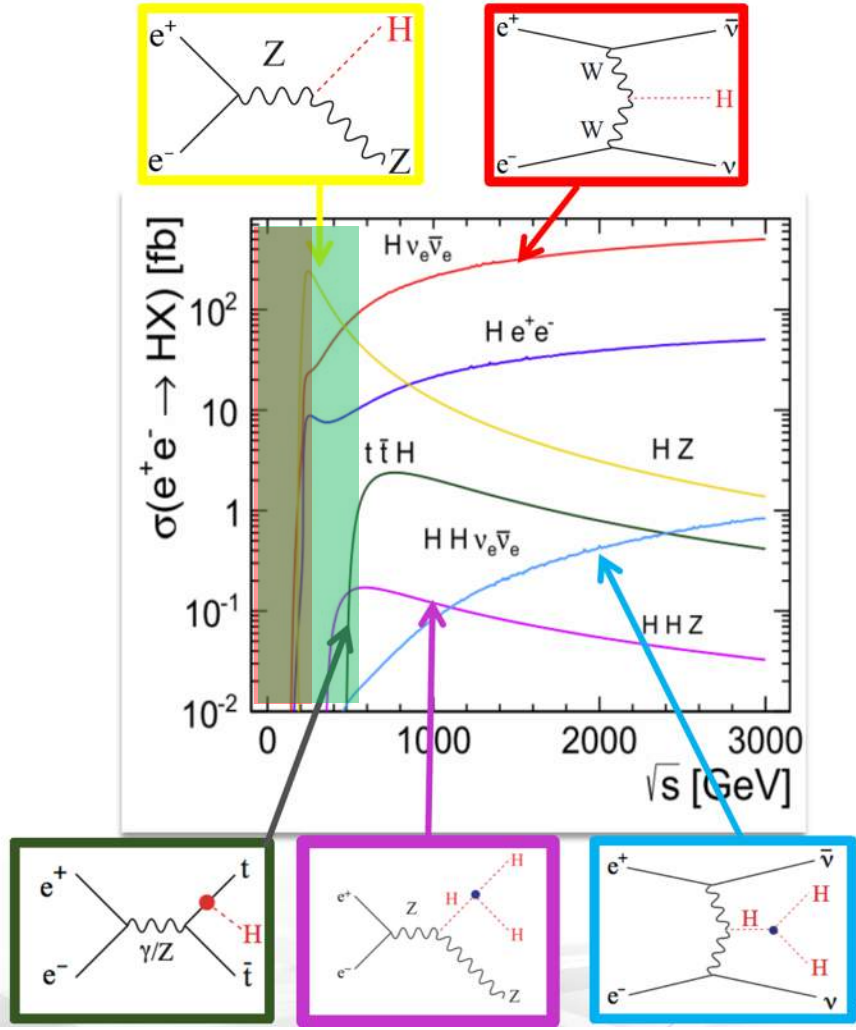
- F
- B
- B
- A ... RF linac
- D ... epeats

e^+e^- colliders

√s [GeV]	Science Drivers
90-200	EW precision physics, Z, WW
250	Single Higgs physics (HZ), Hvv
365	tt
500-600	HHZ, ttH direct access to Higgs self-couplings, top Yukawa couplings
1000-3000	HH*vv* Higgs self-couplings in VBF

ERL ee

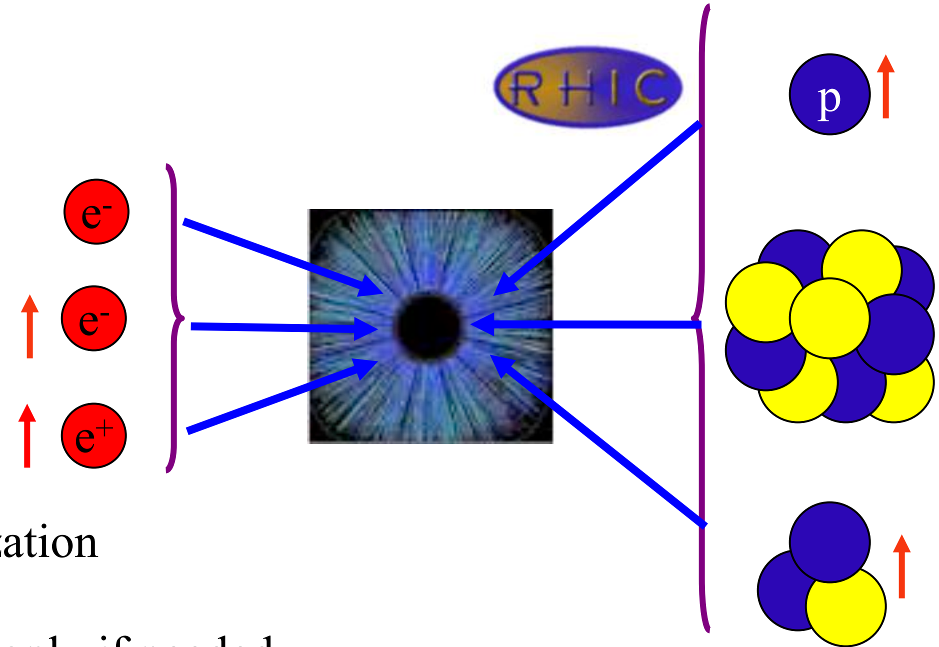
FCC ee



Precision measurement and search for new physics studying deviations from the SM
→ Need high luminosity (and energy)

An ERL e^+e^- collider would provide higher luminosity and high-energy up to c.m. energy of 500 or 600 GeV to enable double-Higgs and $t\bar{t}H$ production

eRHIC: QCD Facility at BNL



Un-polarized and polarized leptons 10-20 GeV

Polarized protons 50-250 GeV

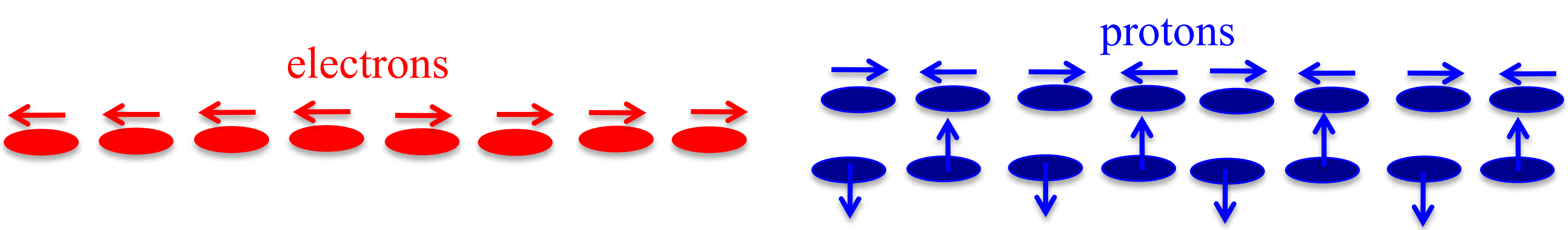
Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 GeV/u

Polarized light ions
He^3 166 GeV/u

80% e^- beam polarization

Polarized positrons only if needed

Center mass energy range: $\sqrt{s}$=30-140 (175) GeV;
Luminosity ~ 10^{33}-10^{34} cm^{-2} sec^{-1}

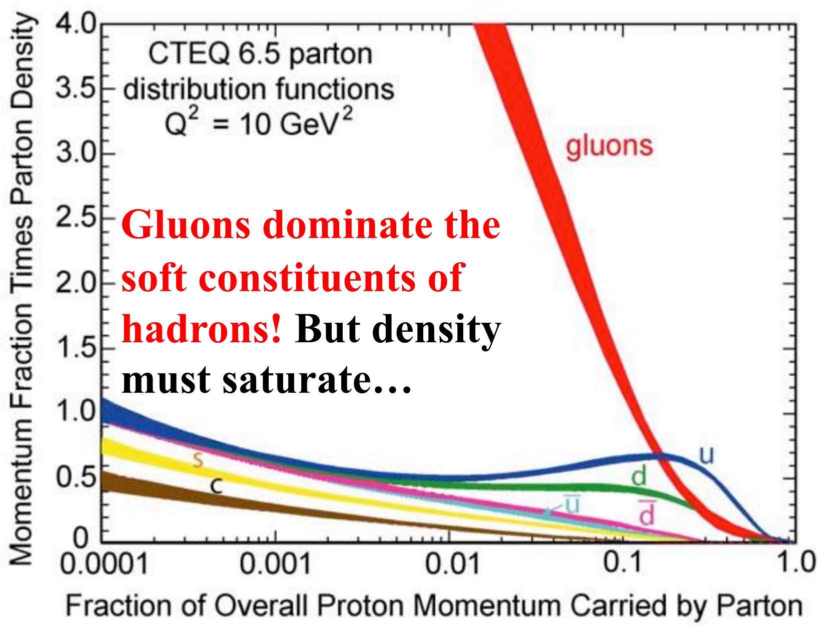


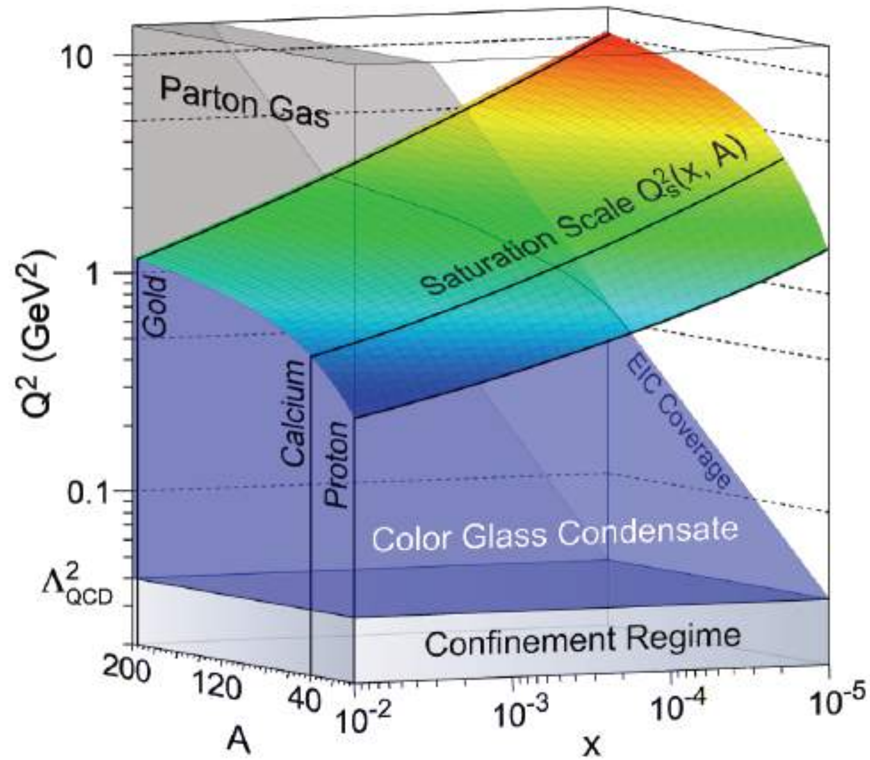
EIC Science: Gluon-Dominated Cold Matter in e+A

Search for supersymmetry @ LHC, ILC (?):
seeking to unify matter and forces

Electron-Ion Collider: ***reveal that Nature blurs the distinction***

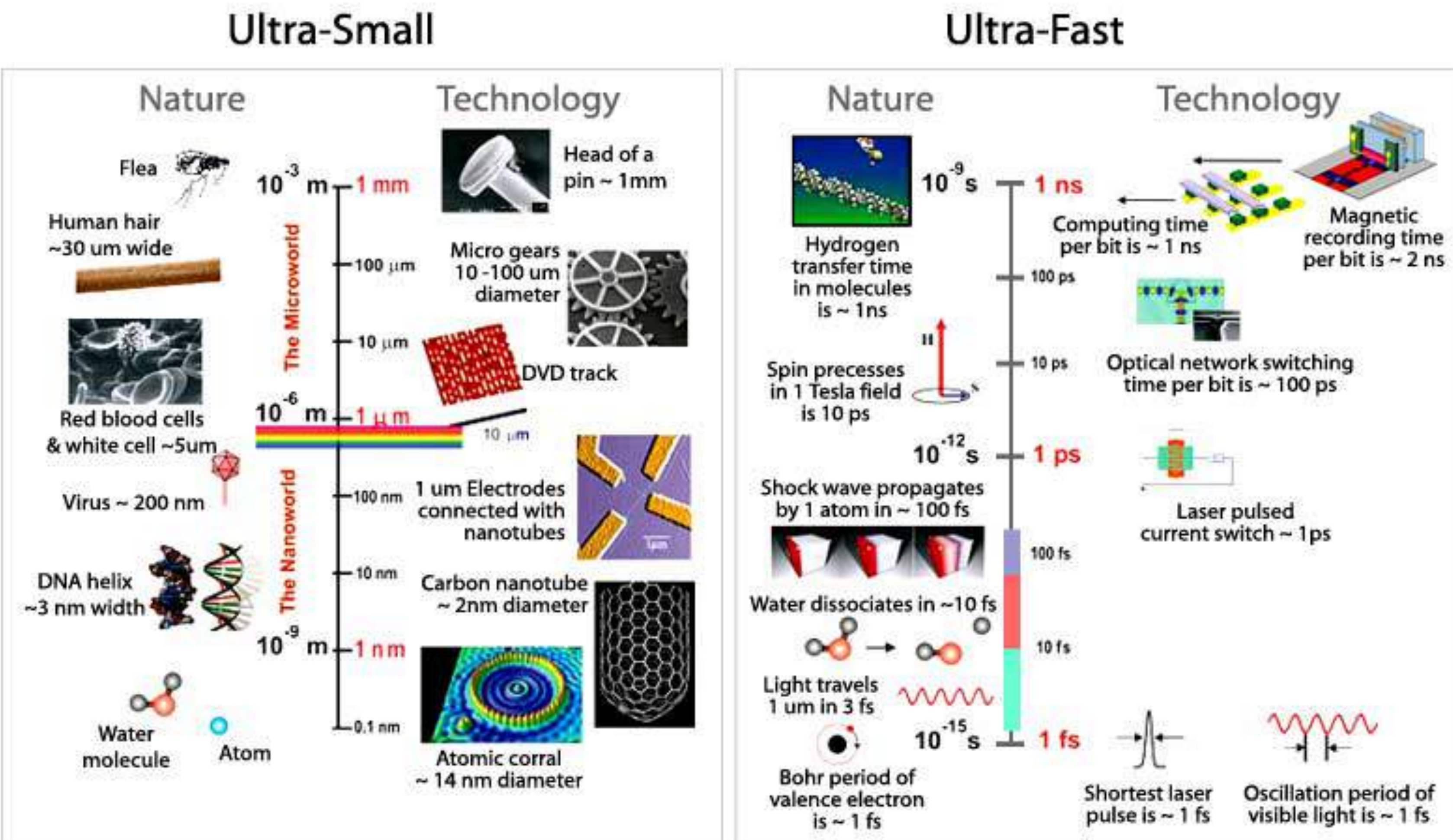
Deep inelastic scattering @ HERA ⇒





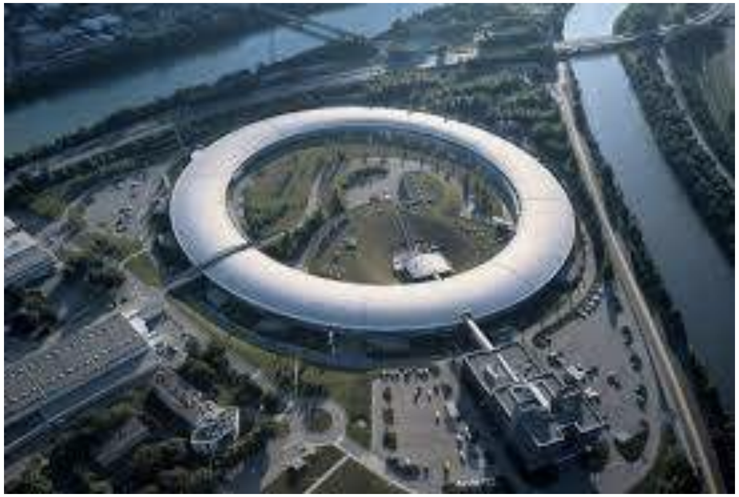
EIC probes *weak* coupling regime of very high gluon density, where gauge boson occupancy >> 1. *All ordinary matter has at its heart an intense, semi-classical force field* -- can we demonstrate its universal behavior? Track the transition from dilute parton gas to CGC? “See” confinement reflected in soft-gluon spatial distributions inside nuclei?

What Light Sources Are For?



http://www.sc.doe.gov/bes/scale_of_things.html

SR Light Source Worldwide: 4 out of few dozens



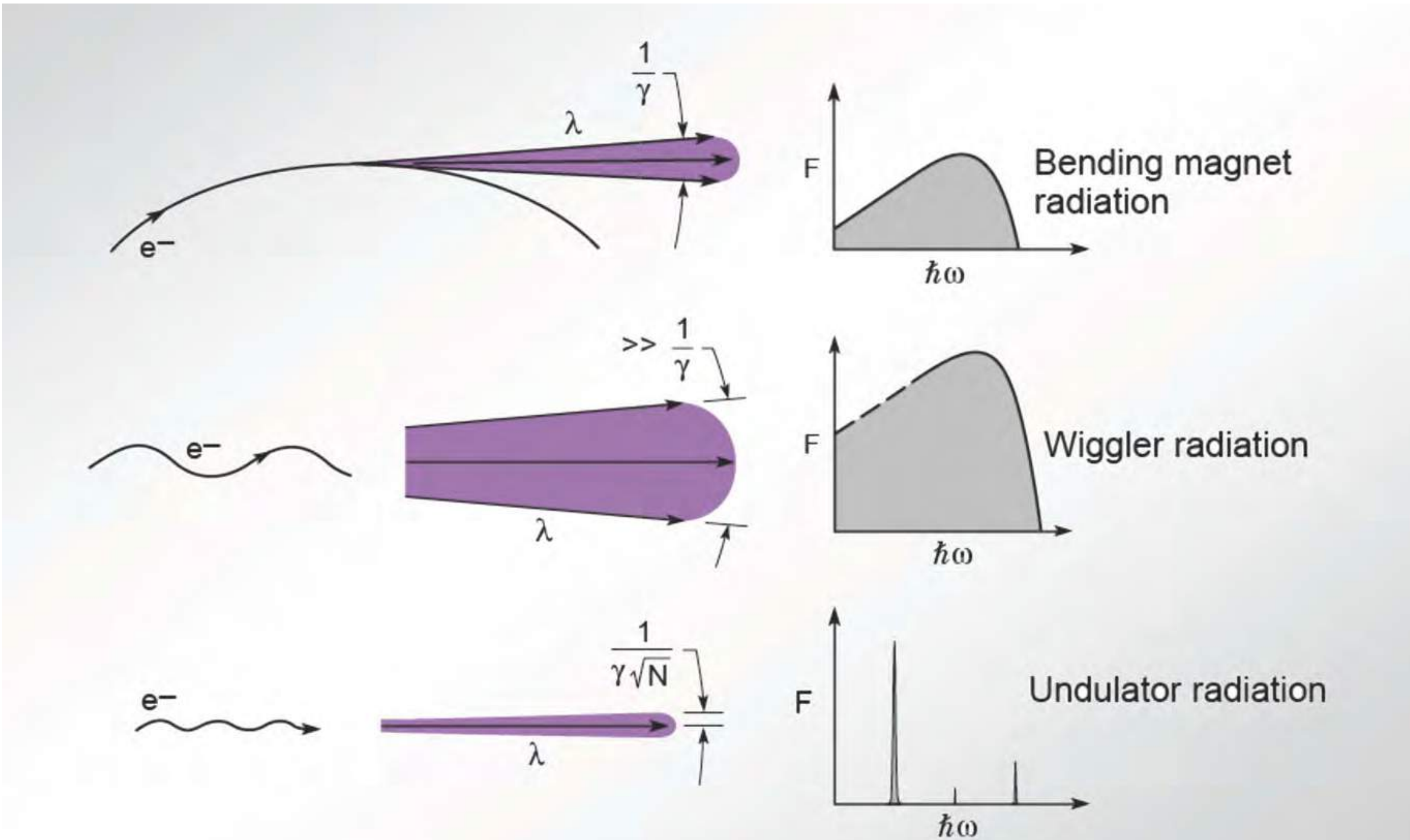
ESRF, 6 GeV

SPring-8, 8 GeV

NSLS II, 3 GeV

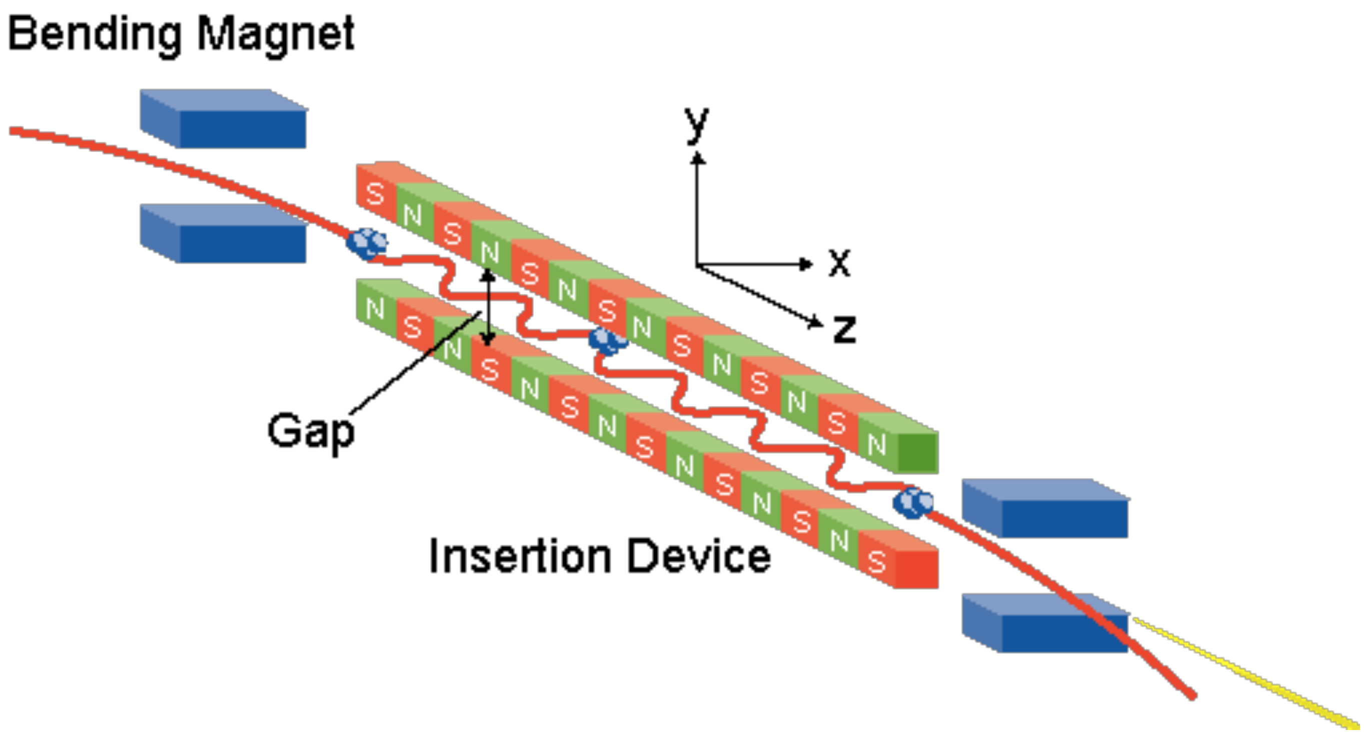
SSRF, 3.5 GeV

Difference between bending magnet and Undulator/Wiggler radaition



Courtesy of W. Barletta

SR from Undulator/Wiggler



They are called ‘insertion devices’ in straight sections.
Modern accelerators provides many long straight sections.

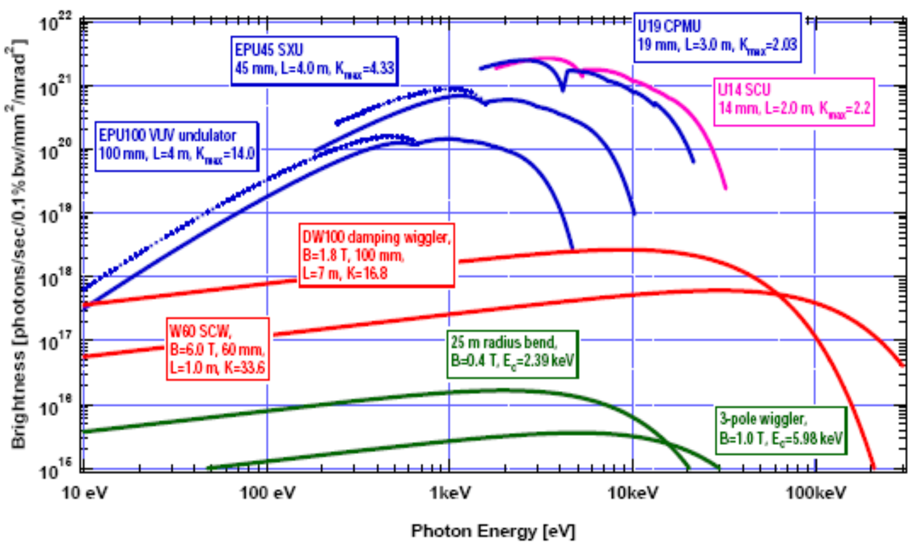
Undulator: Power scales an N_e

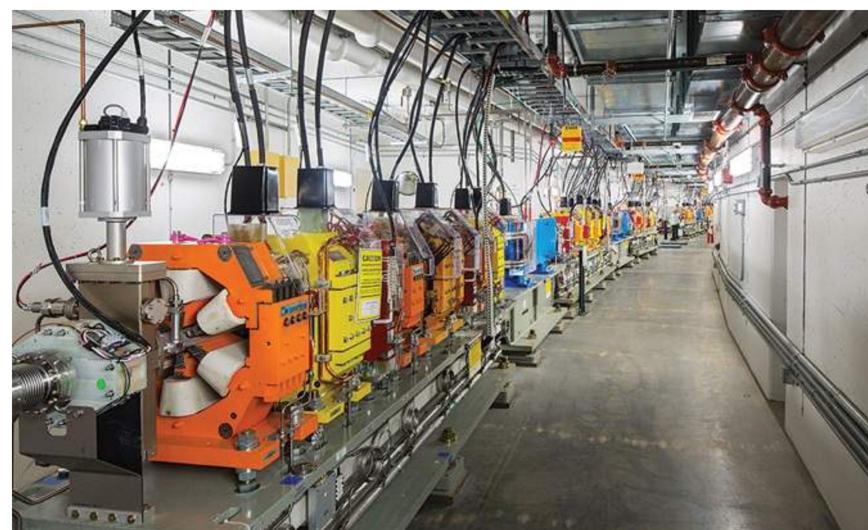
Close to home: NSLS II

Discovery-Class Science

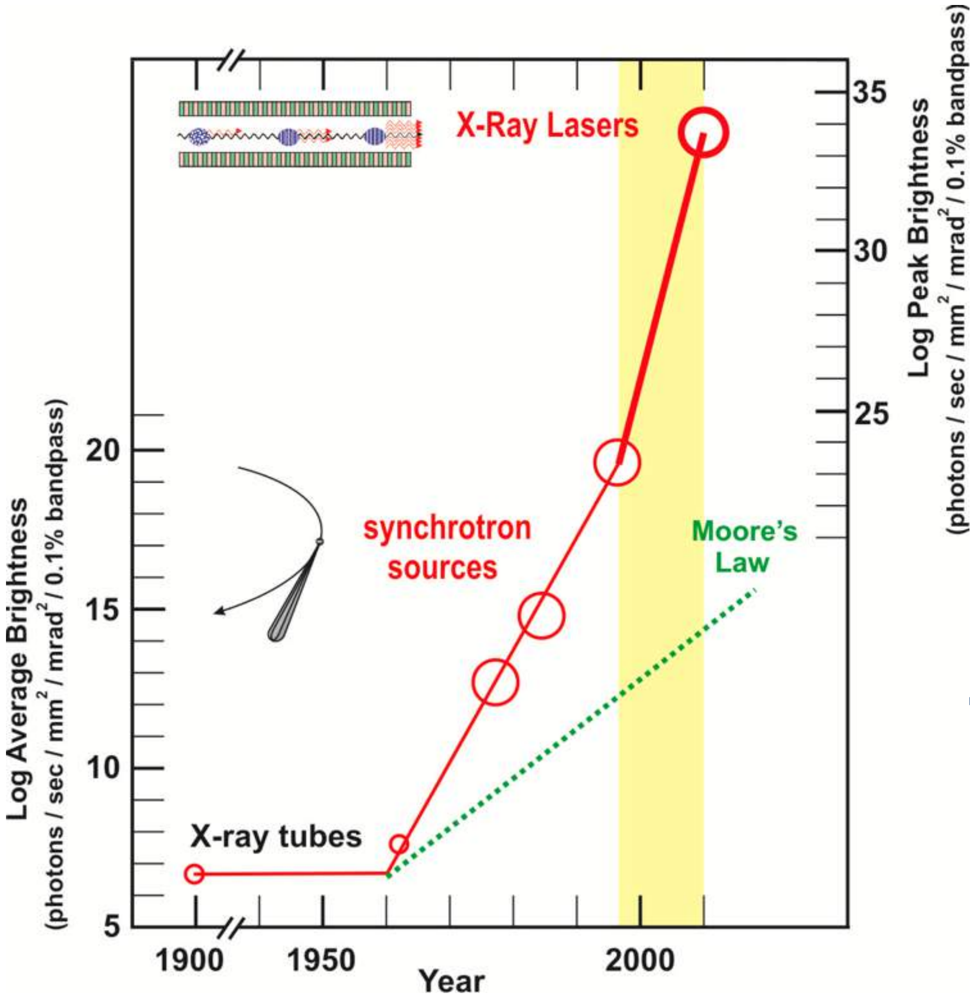
Clean and Affordable Energy: new materials that use sunlight to split water for hydrogen production and harvest solar energy with high efficiency and low cost.
Molecular Electronics: new electronic materials that scale beyond silicon could be used to make faster, less expensive, energy-efficient electronics.
Self-assembly: hierarchical structures from nanometer-scale building blocks, mimicking nature to assemble nanomaterials into useful devices more simply and economically.
High-Temperature Superconductors may lead to materials that allow super-efficient electricity transmission at room temperature.

50-fold brighter than other state-of-the-art light sources in USA

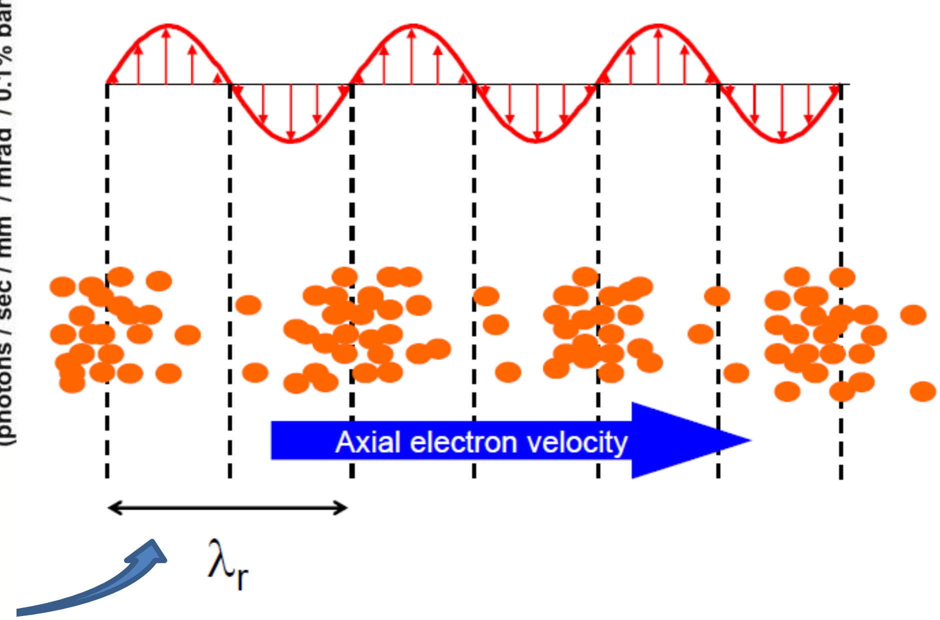




FEL: Micro-Bunching and Coherent Radiation
Inventor: John Madey



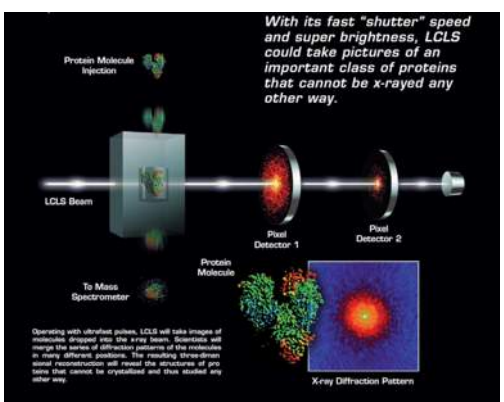
FEL: Power scales as N_e^2



X-ray Free Electron lasers

https://lcls.slac.stanford.edu/overview

LCLS at SLAC
First X-ray laser



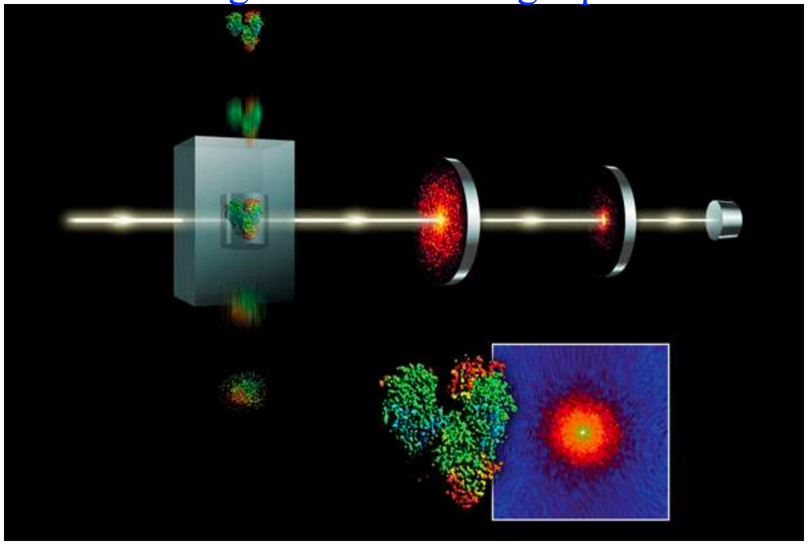
SACLA X-ray FEL
Japan

PAL X-ray FEL
South Korea

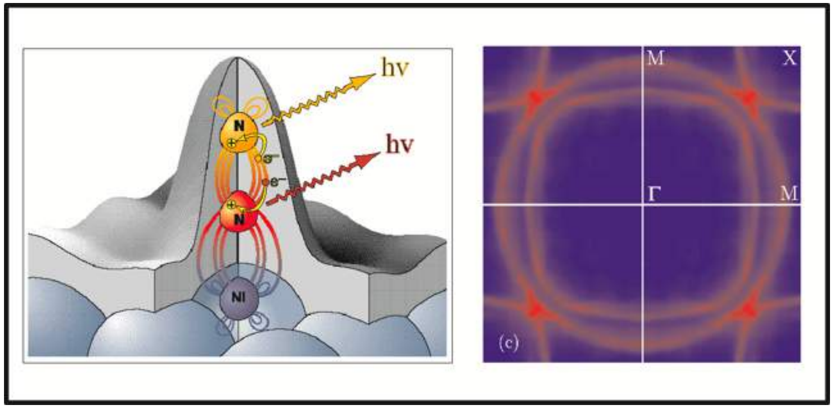
The European X-ray FEL with SRF linac

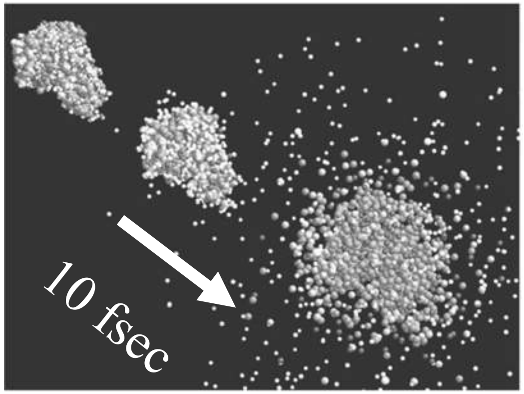
Some applications

Single shot X-ray diffraction:
Restoring structure of single protein

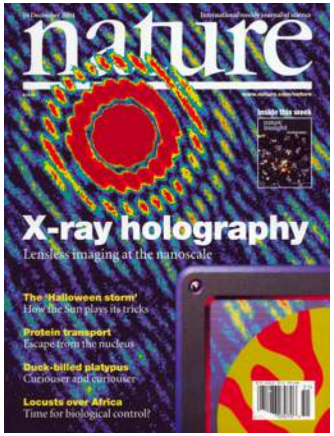


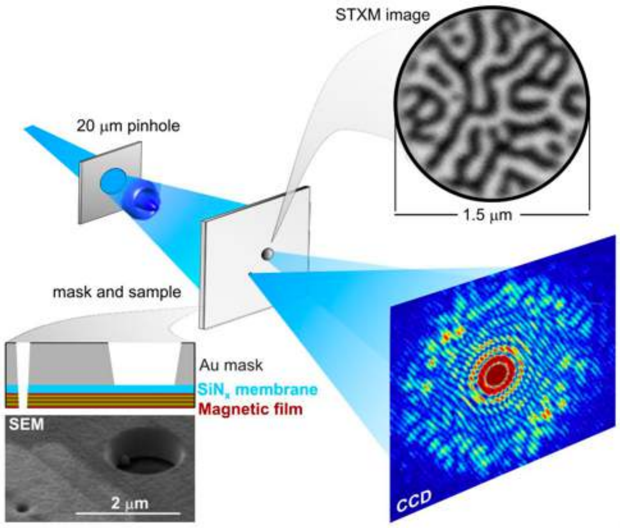
Locating electrons





To decipher a single protein or a cell one needs a single shot fsec pulse with lot of X-ray photons



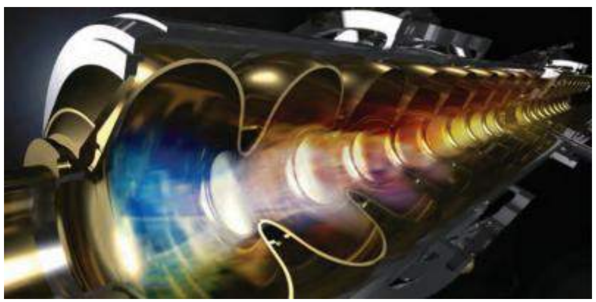


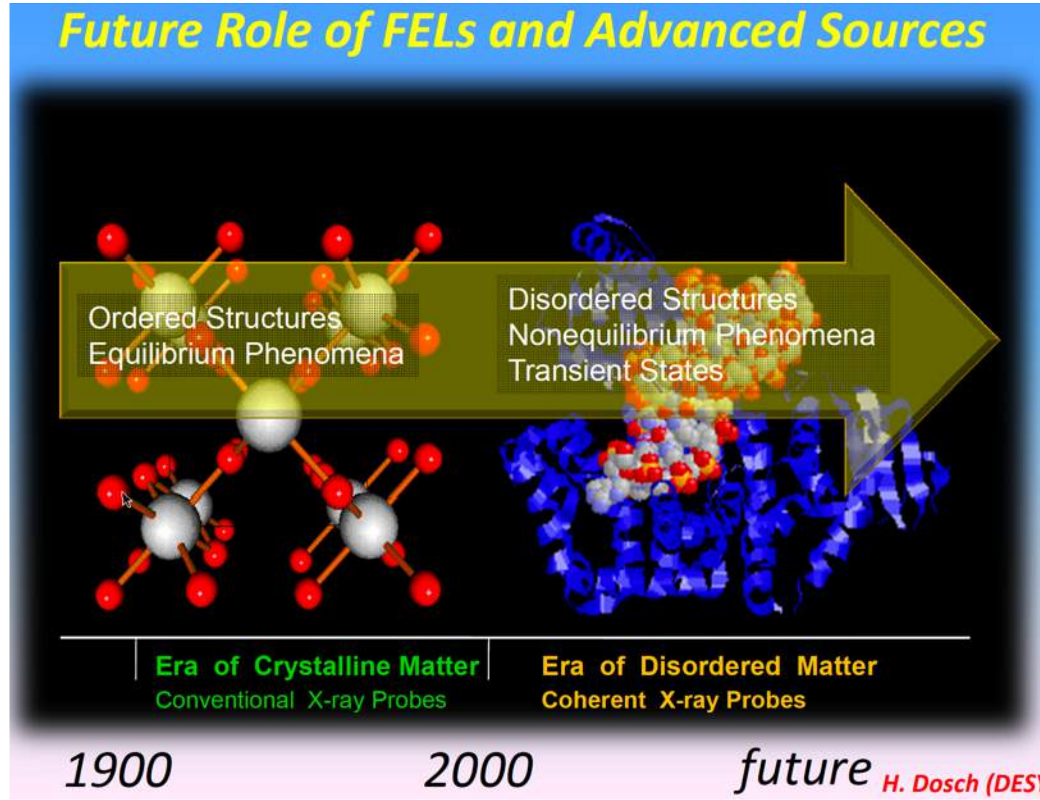
S. Eisebitt, J. Lüning, W.F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt & J. Stöhr / *Nature*, 16 Dec 2004

LenslessImagingF1.ai

Future FELs - 1000 brighter

LCLS II – CW FEL
with SRF linac





and X-ray FEL oscillators…..

https://lcls.slac.stanford.edu/lcls-ii

End of first lecture

Societal Applications of Accelerators

- **Semiconductors:** The semi-conductor industry relies on accelerator technology to implant ions in silicon chips, making them more effective in consumer electronic products such as computers, smart phones and MP3 players.
- **Clean air and water:** Studies show that blasts of electrons from a particle accelerator are an effective way to clean up dirty water, sewage sludge and polluted gases from smokestacks.
- **Cancer therapy:** When it comes to treating certain kinds of cancer, the best tool may be a particle beam. Hospitals use particle accelerator technology to treat thousands of patients per year, with fewer side effects than traditional treatments.
- **Medical diagnostics:** Accelerators are needed to produce a range of radioisotopes for medical diagnostics and treatments that are routinely applied at hospitals worldwide in millions of procedures annually.
- **Pharmaceutical research:** Powerful X-ray beams from synchrotron light sources allow scientists to analyze protein structures quickly and accurately, leading to the development of new drugs to treat major diseases such as cancer, diabetes, malaria and AIDS.
- **DNA research:** Synchrotron light sources allowed scientists to analyze and define how the ribosome translates DNA information into life, earning them the 2009 Nobel Prize in Chemistry. Their research could lead to the development of new antibiotics.
- **Nuclear energy:** Particle accelerators have the potential to treat nuclear waste and enable the use of an alternative fuel, thorium, for the production of nuclear energy.

http://www.acceleratorsamerica.org/resources/applications/index.html

Industrial Applications

- ✓ Ion Implantation
- ✓ Electron beam materials processing
- ✓ Electron beam irradiators
- ✓ Radioisotope production
- ✓ Ion Beam Analysis
- ✓ High Energy X-ray Inspection
- ✓ Neutron generators
- ✓ Synchrotron radiation
- ✓ ……..

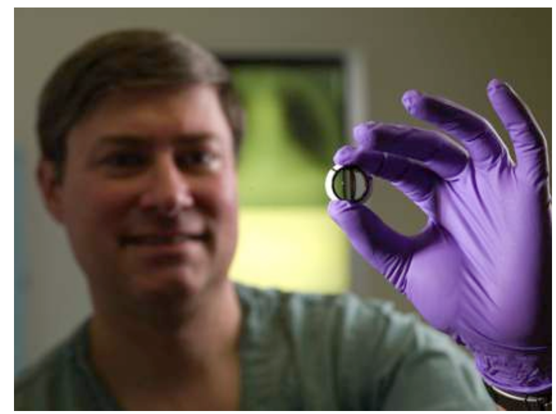
Industrial Accelerators

- **DC Voltage**
  - Van de Graaff – Use a charge carrying belt or "chain". Energies range from 1 to 15 MeV at currents from a few nA to a few mA.
  - Dynamitron & Cockcroft Walton generator – Basically voltage multiplier circuits at energies to up to 5 MeV and currents up to 100 mA.
  - Inductive Core Transformer (ICT) – A transformer charging circuit with energies to 3 MeV at currents to 50 mA.
- **RF Linacs**
  - Electron linacs – standing wave cavities from 0.8 to 9 GHz. Energies from 1 to 16 MeV at beam power to 50 kW.
  - Ion linacs – all use RFQs at 100 to 600 MHz. Energies from 1 to 70 MeV at beam currents up to mA.
- **Circular**
  - Cyclotrons – ion energies from 10 to 70 MeV at beam currents to several mA.
  - Betatrons – electron energies to 15 MeV at few kW beam power.
  - Rhodotron – electron energies from 5 to 10 MeV at beam power up to 700 kW.
  - Synchrotron – electron energies up to 3 GeV and ion energies up to 300 MeV/amu.

Materials modification

Electron beams make shrink wrap tougher and better for storing food and protecting other products, such as board games, CDs and DVDs

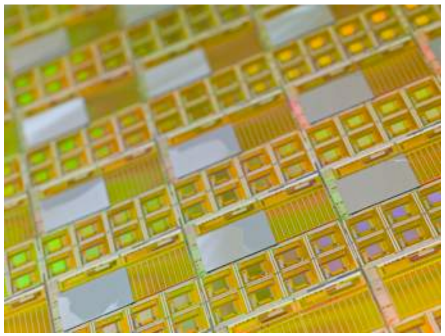
The auto industry uses particle accelerators to treat the material for radial tires, eliminating the use of solvents that pollute the environment.



There is a hope to improve the safety of artificial heart valves by forming them from material bombarded by ions

Ion implantation

The semiconductor industry relies on accelerator technology to implant ions in silicon chips.



Semiconductors

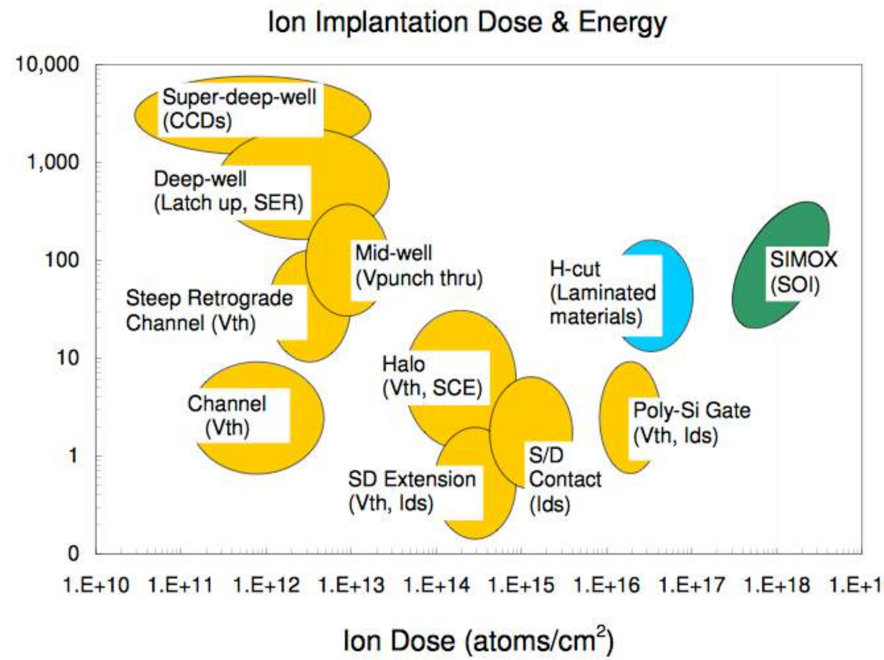
- CMOS fabrication
- SIMOX
- Cleaving silicon
- MEMS

Metals

- Harden cutting tools
- Artificial human joints

Ceramics & glasses

- Harden surfaces
- Modify optics



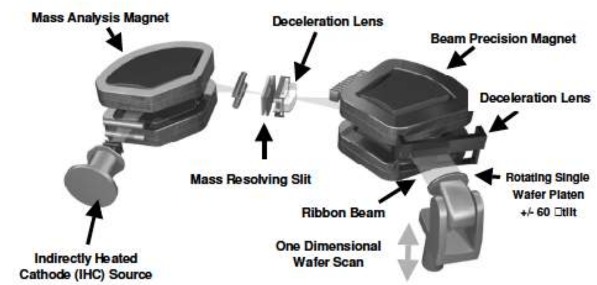
All digital electronics now dependent on ion implantation.

Ion implantation

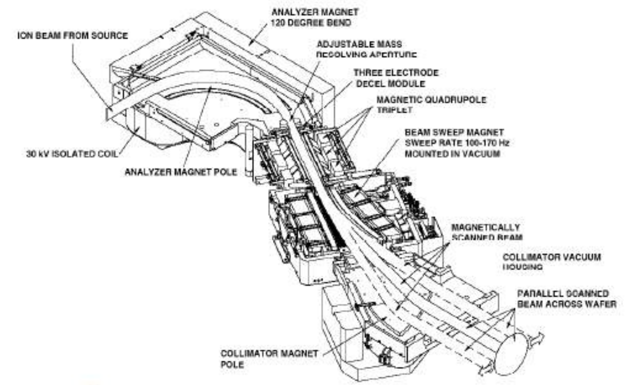
Ion Implantation Accelerators

Accelerator classifications

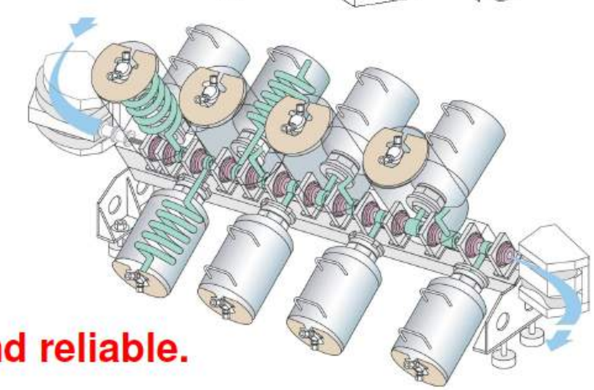
- **Low energy/ high current**
  - "High current implanters"
  - Ion energies from few hundred eV to tens of keV.
  - Variable energy, single gap with currents to 50 mA.



- **Medium energy/ medium current**
  - Original ion implanter
  - Variable energies of 50 to 300 keV range
  - Currents in the 0.01 to 2 mA range.
  - Usually multi-gap direct voltage units using voltage-multiplier HV power supply.



- **High energy/ low current**
  - Variable energy from 1 to 10 MeV
  - Beam currents to hundreds of microamperes.
  - Can be linacs or tandem charge-exchange columns
  - Both use high-charge-states for upper energy range.



These systems have become highly specialized and reliable.

Material Processing/Modifications

- Electron beam processing involves irradiation (treatment) of products using a high-energy electron beam

- Electron beam processing is used in industry primarily for three product modifications:

  - Crosslinking of polymer-based products to improve mechanical, thermal, chemical and other properties

  - Material degradation often used in the recycling of materials

  - Sterilization of medical and pharmaceutical goods, foods and other products

Material Processing/Modifications

Electron Beam Irradiators

- Cross linking of materials (largest application)
- Sterilization of single-use disposable medical products – surgical gowns, surgical gloves, syringes, and sutures (growing applications)
- Food and waste irradiation (largest potential applications)

Cross linking applications

Product	Applications
Cross-linked polyethylene(PE) and PVC	Heat and chemical-resistant wire insulation; pipes for heating systems
Cross-linked foam polyethylene	Insulation, packing and flotation material
Cross-linked rubber sheet	High quality automobile tires
Cross-linked polyurethane	Cable insulation
Cross-linked nylon	Heat and chemical resistant auto parts
Heat resistant SiC fibers	Metal and ceramic composites
Vulcanized rubber latex	Surgical gloves and finger cots
Cross-linked hydrogel	Wound dressings
Acrylic acid grafted PE film	Battery separators
Grafted polyethylene fiber	Deodorants
Curing of paints and inks	Surface coating and printing

Cross linking by industry

Total of $50 billion per year

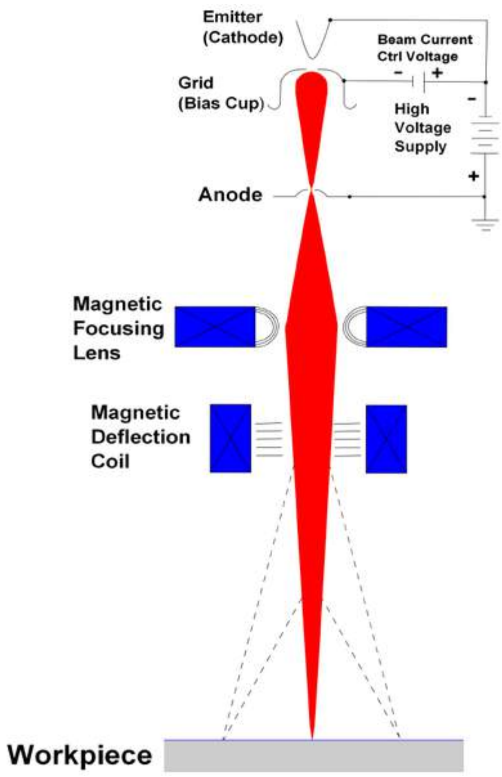
Material Processing/Modifications

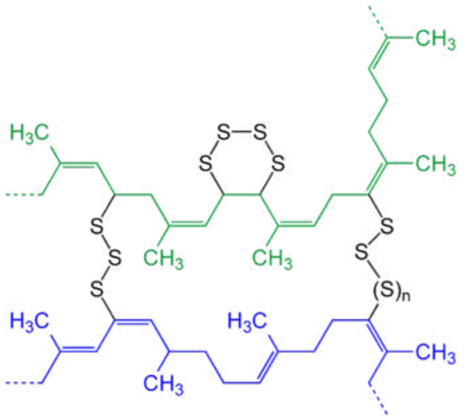
Electron Beam Irradiation Accelerators

- 100 to 300 keV — Single gap, self-shielded sheet beam systems without beam scanning. Beam currents from 10 to 2000 mA; treat 1 to 3 m wide material. Used for curing thin film coatings and cross-linking laminates and single strand wire.
- 450 to 1000 keV — Larger dc systems with scanned beams and self-shielding. Beam currents from 25 to 250 mA; treat 0.5 to 2 meter wide material. Mainly used for cross-linking, curing and polymerization processes in the tire, rubber and plastics industry.
- 1 to 5 MeV — Scanned beam dc systems capable of 25 to 200 kW beam power; scanned beam width up to ~2 meters. Used for cross-linking and polymerization of thicker materials, and for sterilization of medical products.
- 5 to 10 MeV — High energy scanned beam systems capable of 25 to 700 kW beam power. Used for medical product sterilization and cross-linking and polymerization of even thicker materials. They are also used as x-ray generators for food irradiation, waste water remediation, and gemstone color enhancement for topaz and diamonds.

Crosslinking

- A cross-link is a bond that links one polymer chain to another.
- Cross-linking is used in both synthetic polymer chemistry and in the biological sciences.
- Although the term is used to refer to the "linking of polymer chains" for both sciences, the extent of crosslinking and specificities of the crosslinking agents vary. Of course, with all science, there are overlaps, and the following delineations are a starting point to understanding the subtleties.
- **When cross links are added to long rubber molecules, the flexibility decreases, the hardness increases and the melting point increases as well.**





Vulcanization is an example of cross-linking. Schematic presentation of two "polymer chains" (blue and green) cross-linked after the vulcanization of natural rubber with sulfur (n = 0, 1, 2, 3 …).

Micro-biological sterilization

- ✓ Electron beam processing has the ability to break the chains of DNA in living organisms, such as bacteria, resulting in microbial death and rendering the space they inhabit sterile.
- ✓ E-beam processing has been used for the sterilization of medical products and aseptic packaging materials for foods as well as disinfestation, the elimination of live insects from grain, tobacco, and other unprocessed bulk crops.
- ✓ Sterilization with electrons has significant advantages over other methods of sterilization currently in use. The process is quick, reliable, and compatible with most materials, and does not require any quarantine following the processing.

Granary weevil

Granary weevil (*Sitophilus granarius*): An adult lays up to 450 eggs singly in holes chewed in cereal grains. Each egg hatches into a white, legless larva, which eats the grain from the inside. The larva pupates within the grain and the adult then chews its way out. The exit holes are characteristic signs of weevil damage. The life cycle takes about one month under summer conditions and adults may survive for a further eight months. The granary weevil is a small dark brown-black beetle about 4mm long with a characteristic rostrum (snout) protruding from its head. It has biting mouth parts at the front of the rostrum and two club-like antennae.

Sterilization of products

Pest & Pathogen Control:

Example: Half of grain produced on the Earth is infested by bugs: they have to be stopped, or grain is gone…

Electron Beam processing as a disinfestation method replaces antiquated environmentally unfriendly methods such as fumigation and chemical dipping.

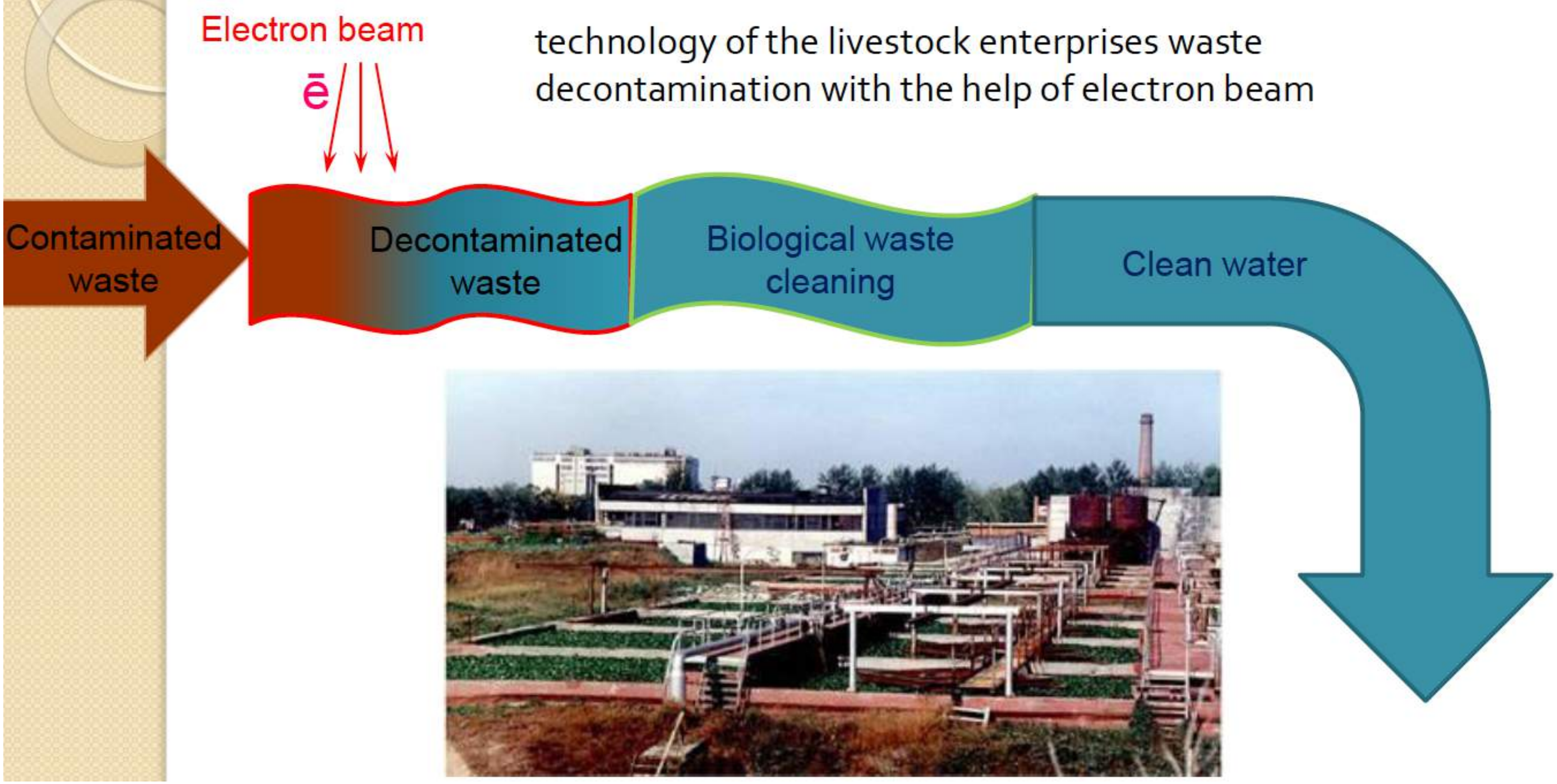
A significant area for this technology is the herb and spice industry. These commodities are valued for their distinctive flavors, aromas and colors. They can be processed by this technology to reduce bacterial contamination without compromise to their sensory properties.

Fruits, vegetables, grains and other food items can be processed by Electron Beam to control fruit flies and other insects that use these commodities as a host for propagation.

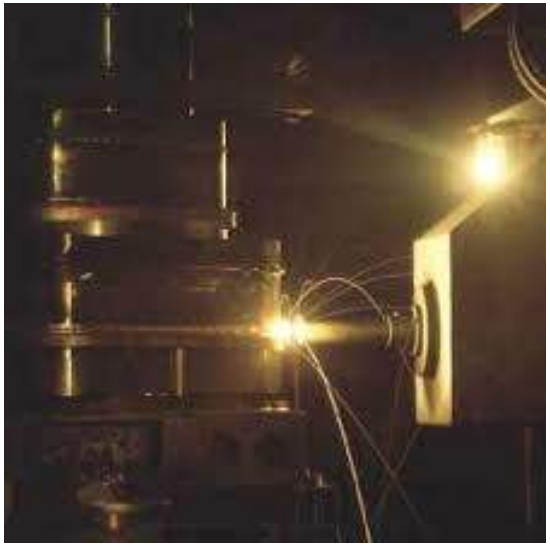
Suitable as a quarantine measure, several countries rely on this technology to treat food commodities prior to exporting

Sterilization of *other, less testy,* products

technology of the livestock enterprises waste decontamination with the help of electron beam



What else?



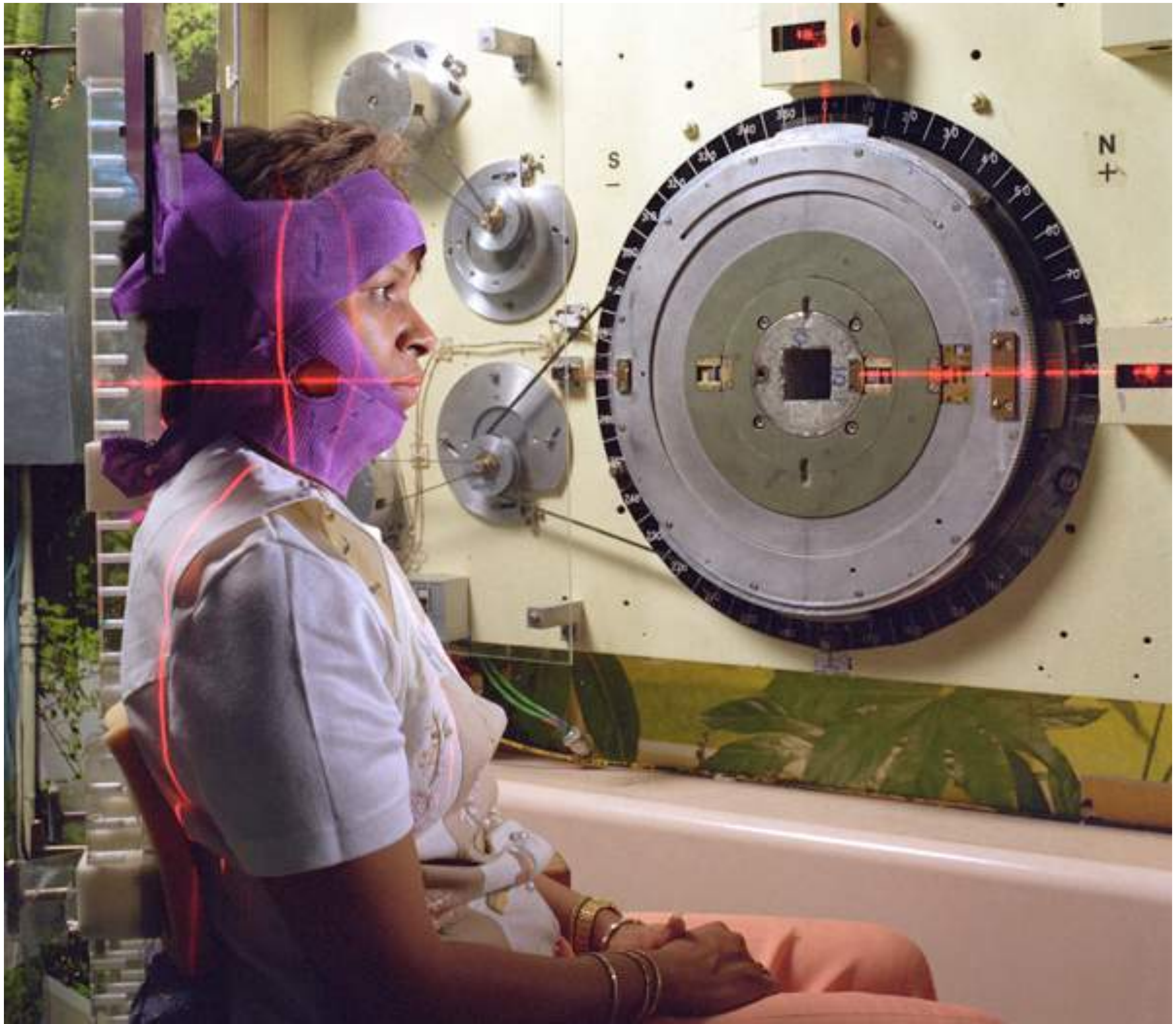
Key advantages

- Using electron beam with energies below 10 MeV (e.g. below giant nuclear resonance!) does not leave residual radioactivity
- To a large degree, it is just a use of electrical power to eliminated the intruders
- Hence, such treatment does not change chemical structure of the irradiated products while effectively killing leaving bugs or bacteria
- Replacing dangerous (killer!) chemicals with is environmentally neutral treatment

Medical Applications

- In contrast with other applications, medical applications of any technology is most humane and broadly accepted by society.
- Some of accelerator applications in medicine – like radiation therapy – are well known.
- Many are known only to experts.
- Here is a short (and incomplete) list of accelerator applications in medicine :
    - Hadron radiation therapy
    - Gamma-ray (Photon) radiation therapy
    - X-ray tubes
    - Sterilization of material & equipment
    - Isotopes
    - Angiography
    - Neutron capture therapy
    - Genome project
    - Reconstruction of protein structures
    - Developing new drugs and new materials

γ-Ray Radiation Therapy



X-ray tubes are well known

History of medical applications of accelerators

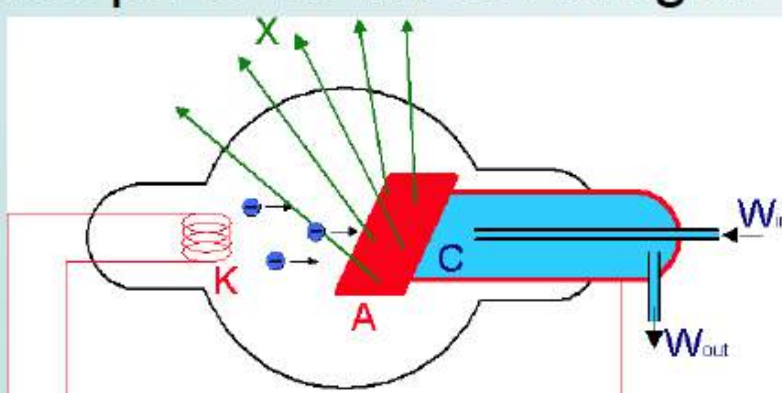
1895 *Wilhelm Conrad Röntgen* (1845 – 1923) discovers the X-rays on 8th November at the University in Würzburg

1896 On 23rd January Röntgen announced his discovery and demonstrated the new kind of radiation by a photograph of the hand of his colleague *Albert von Kolliker*

1897 First treatments of tissue with X-rays by *Leopold Freund* at University in Vienna

1901 Physics Nobel prize for W.C. Röntgen

Schematics of an X-ray tube – an “electrostatic accelerator”



X-ray tubes and beyond

History of medical applications of accelerators

1899 First X-ray treatment of carcinoma in Sweden by *Stenbeck* and *Sjögren*

1906 Vinzenz Czerny founded the "Institute for Experimental Cancer research" in Heidelberg – the first of its kind

1913/4 Invention of part- and full-rotation radiation instrumentation

1920´s Industrially manufactured X-ray apparatus; example from Reiniger-Gebbert & Schall AG (later: Siemens), Erlangen; 1922) with a high-voltage of 150 kV – without shielding!

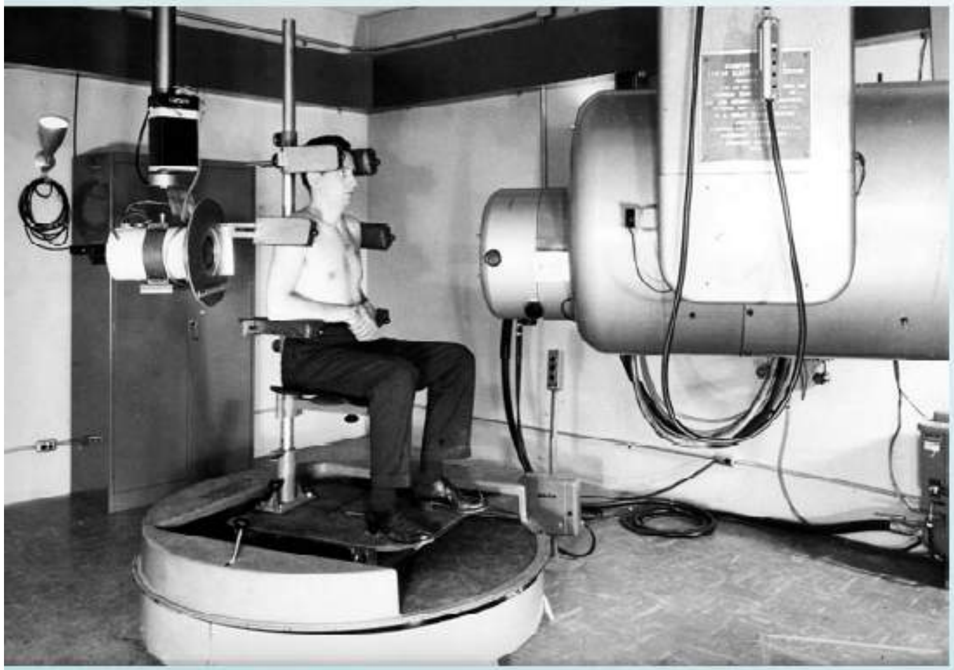
1930 First linear accelerator principle invented by *Rolf Wideroe*

1949 *Newberry* developed first linear accelerator for therapy in England

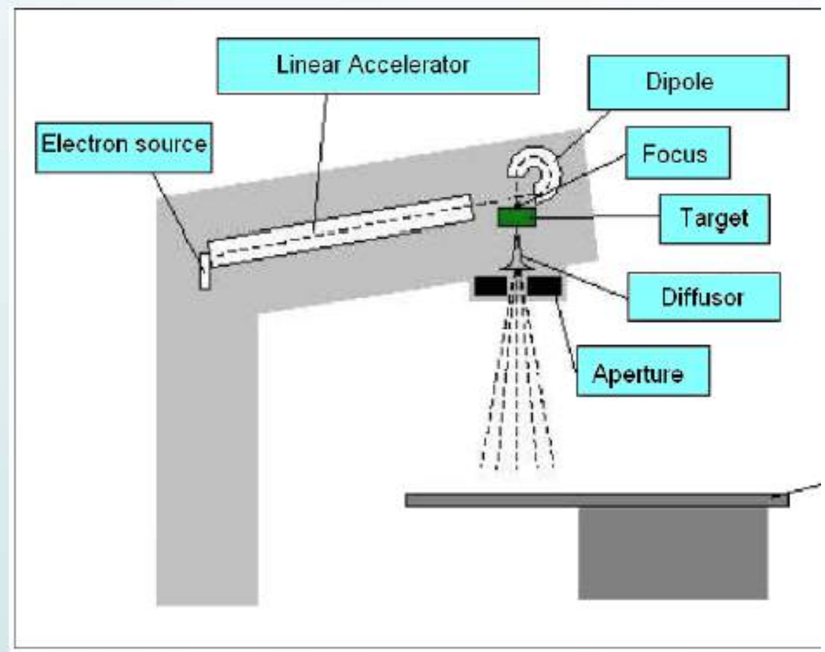
X-ray tubes and beyond

History of medical applications of accelerators

1950´s and later — Development of compact linear accelerators by Varian, Siemens, GE, Philipps and others with energies up to around 25 MeV (and above)



radiotherapy (Stanford linac)



modern linac for therapy

Linac-based γ-Ray Radiation Therapy

Started in 1956 and since then treated about 50 million patients

In developed countries there is 5-10 medical linacs per 1 million inhabitants

It simply means that there are thousands of such accelerator!

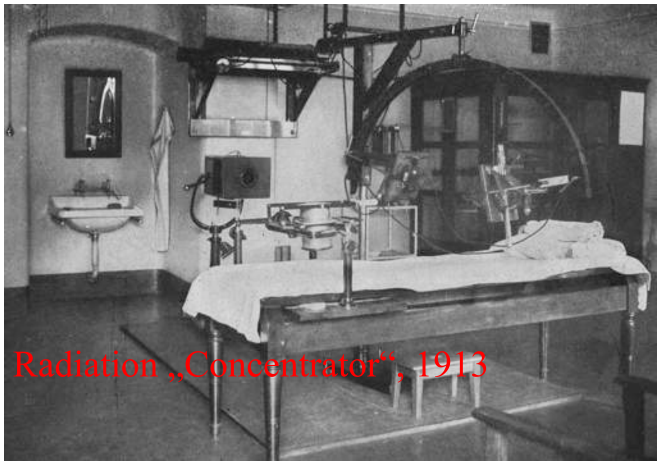


Table 1
Number of Radiotherapy units in France, on 1 January 1995 [1]

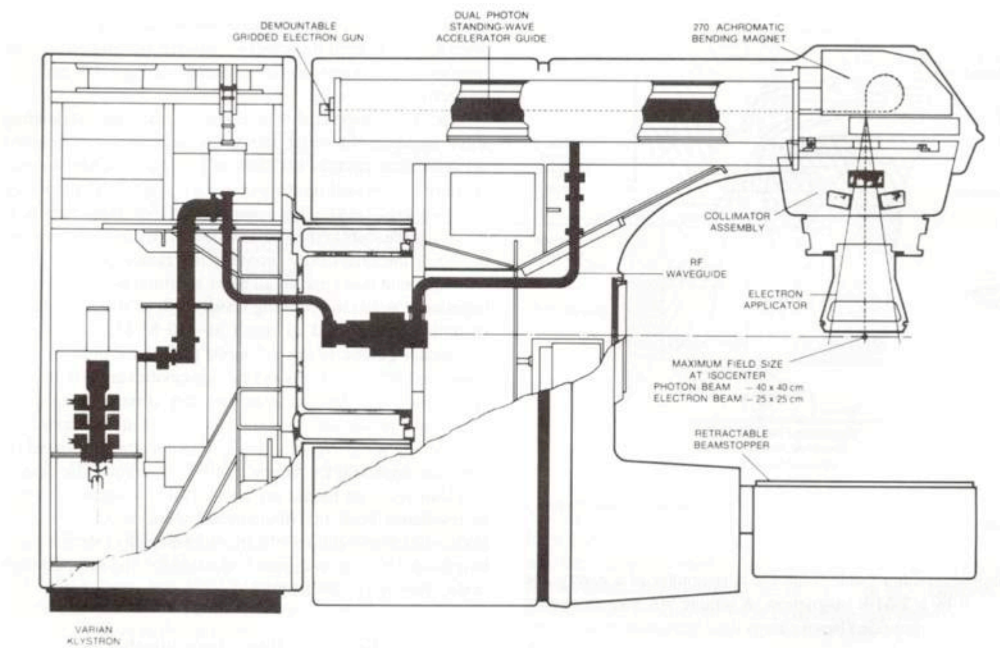
A. ELECTRON LINEAR ACCELERATORS					
	GE-CGR MeV		Other Companies		Total *
4-6 MV	Orion 5	19	Siemens (Mevatron)	3	36
			Philips (SL 75/5)	9	(+5)
			Clinac 600 C		
10 MV	Neptune 10	26			29
	Saturne 1M	3			(-1)
15 MV	Saturne 15	5	Siemens (Mevatron MD)	8	51
	Saturme 1	9	Philips (SL 18)	6	(+17)
	Saturne 41	23			
20 MV	Saturne 20	8	Philips (SL 75/20)	3	31
	Saturne 11	9	Clinac 2100C	6	(-17)
	Saturne 42	5			
25-40 MV	Sagittaire 32 MV	7			15
	Sagittaire 40 MV	3			(-2)
	Saturne 25 MV	5			
20-25 MV	Saturne 111	4			4
25 MV	Saturne 43	37	Philips (SL 75/25)	9	56
			Siemens (Mevetron KD2)	10	(+12)
Total Linear Accelerators		163		59	222
					(+14)

B. OTHER TYPES OF RADIATION THERAPY UNITS	
Cobalt Units	133 (-11)
Betatron	1
Hadron Therapy	
Cyclotron: neutron therapy (Orléans)	1
Cyclotron: neutron + protontherapy (Nice)	1
Synchrotron: protontherapy (Saclay)	1

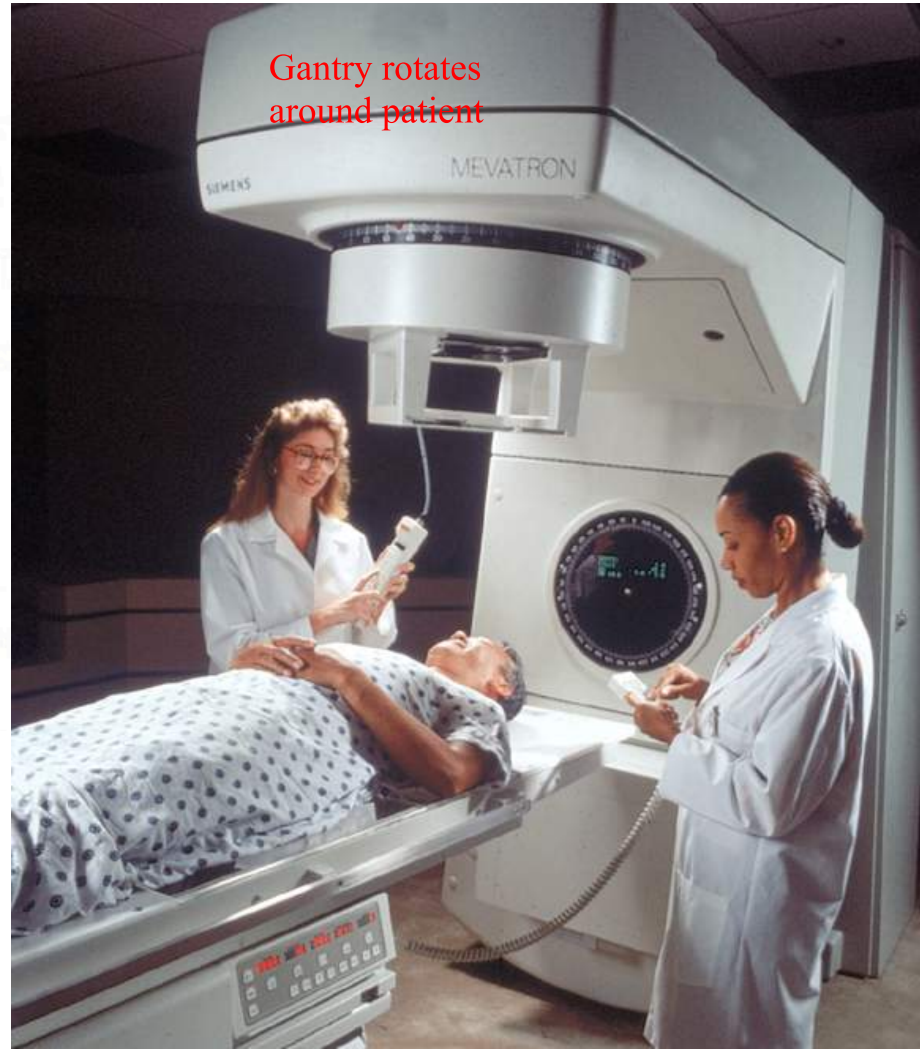
* The differences since 01.01.1994 are given (+) or (-)

Linear accelerators are manufactured by several vendors

γ-Ray Radiation Therapy
The systems can be rather compact

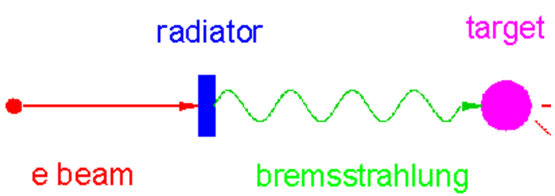


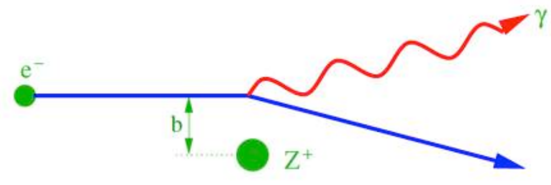
Varian Clinac 1800
Medical linear accelerator



γ-Rays Production

Medical linacs use monoenergetic electron beams between 4 and 25 MeV. Electron beam collides with a a high-density (such as tungsten) target generating via process called Bremsstrahlung (from *bremsen* "to brake" and *Strahlung* "radiation", http://en.wikipedia.org/wiki/Bremsstrahlung) hard-X-rays and γ-Rays with energy spectrum up to the electron beam energy





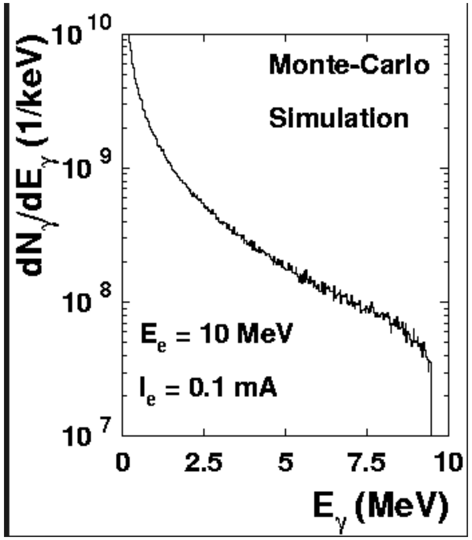
$$\frac{d\sigma}{dk d\Omega} = \frac{2\alpha^2 e^2}{\pi k m^4}\left\{\left[\frac{2\epsilon-2}{(1+u^2)^2}+\frac{12u^2(1-\epsilon)}{(1+u^2)^4}\right]Z(Z+1) + \left[\frac{2-2\epsilon-\epsilon^2}{(1+u^2)^2}-\frac{4u^2(1-\epsilon)}{(1+u^2)^4}\right]\left[X-2Z^2 f_c((\alpha Z)^2)\right]\right\}$$

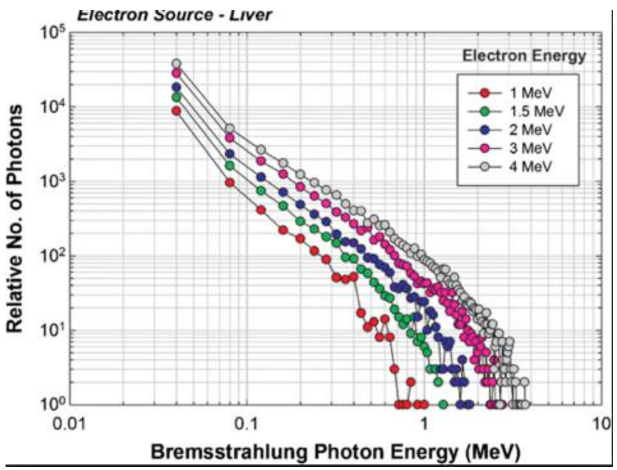
$$u = \frac{E\theta}{m}$$

$$X = \int_{t_{min}}^{m^2(1+u^2)^2}\left[G_Z^{el}(t)+G_Z^{in}(t)\right]\frac{t-t_{min}}{t^2}dt$$

$G_Z^{el,in}(t)$ atomic form factors

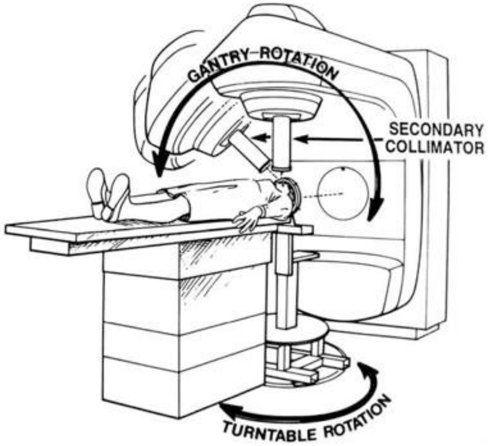
$$t_{min} = \left[\frac{km^2(1+u^2)}{2E(E-k)}\right]^2 = \left[\frac{\epsilon m^2(1+u^2)}{2E(1-\epsilon)}\right]^2$$

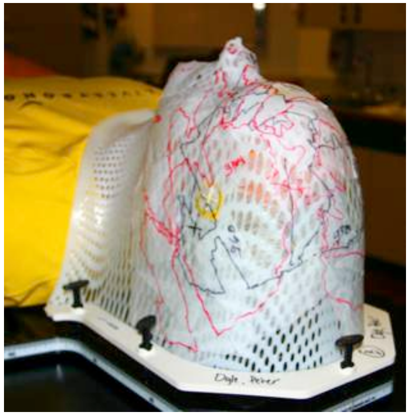


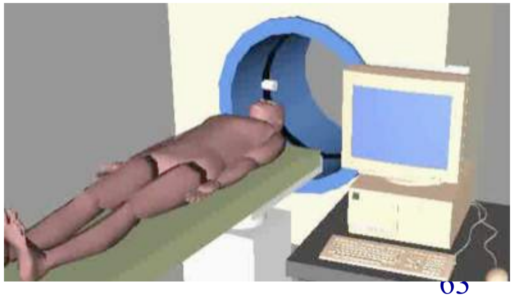


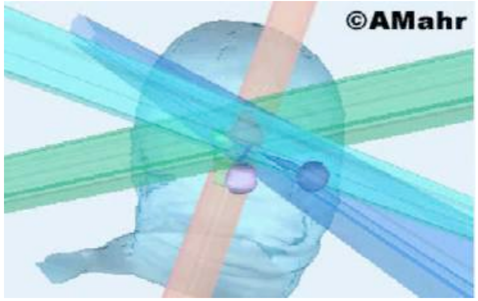
γ-Ray Radiation Therapy

- The gamma-rays beam is further filtered to remove soft photons, collimated, shaped to fit specific task
- The beam is then delivered at multiple angles to minimize the radiation exposure of the surrounding tissue and to deliver the necessary dose of the radiation to a tumor
- It is all computer controlled from the patient model
- This is a BIG business…







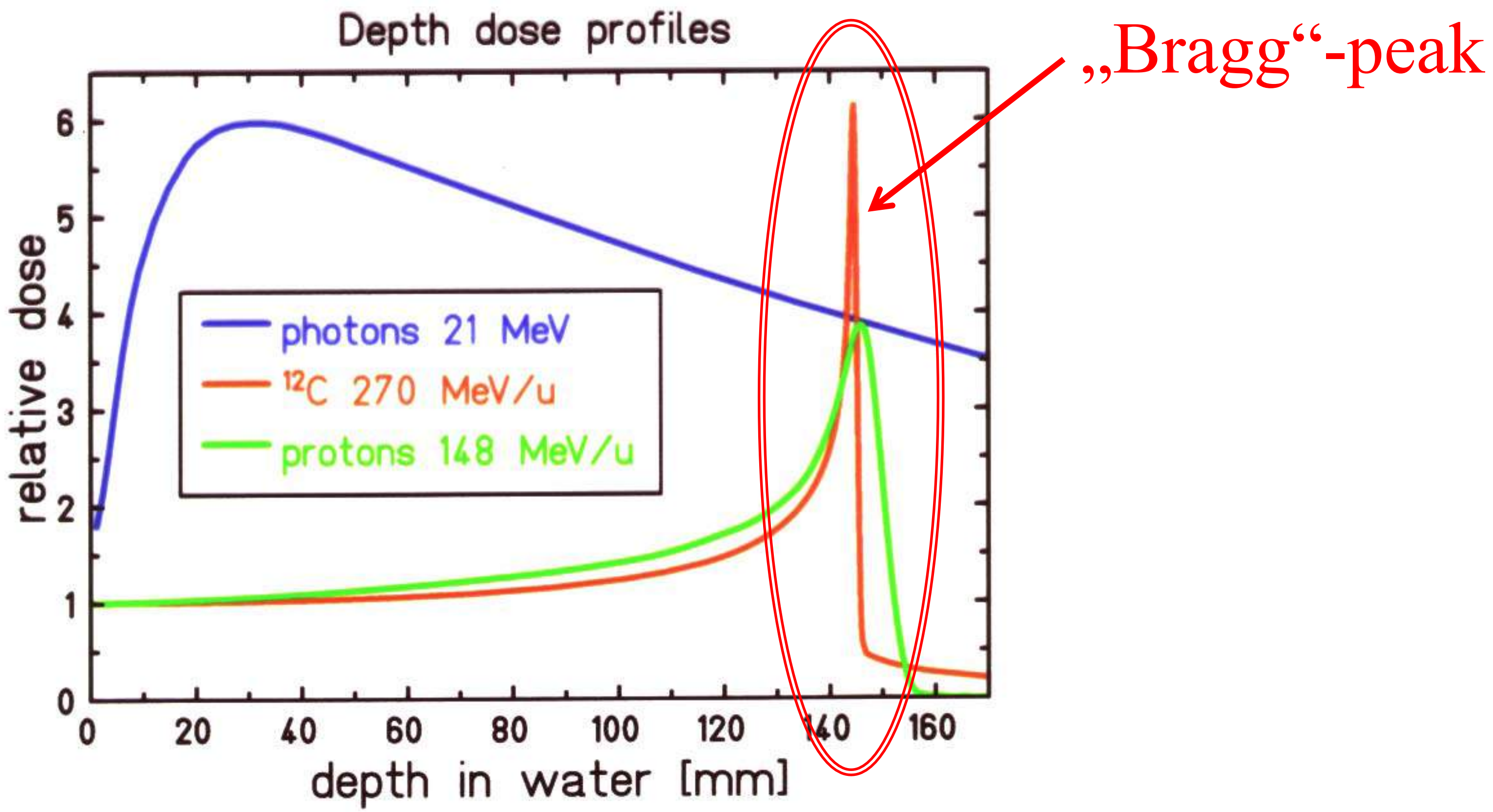


Hadron radiation therapy

- Comparing with γ-ray radiation therapy it is more effective, but also much more expensive
- Instead of room it occupies a building with the hadron beam source located in well-shielded accelerator hall
- There are fewer hadron (proton or ion) therapy centers

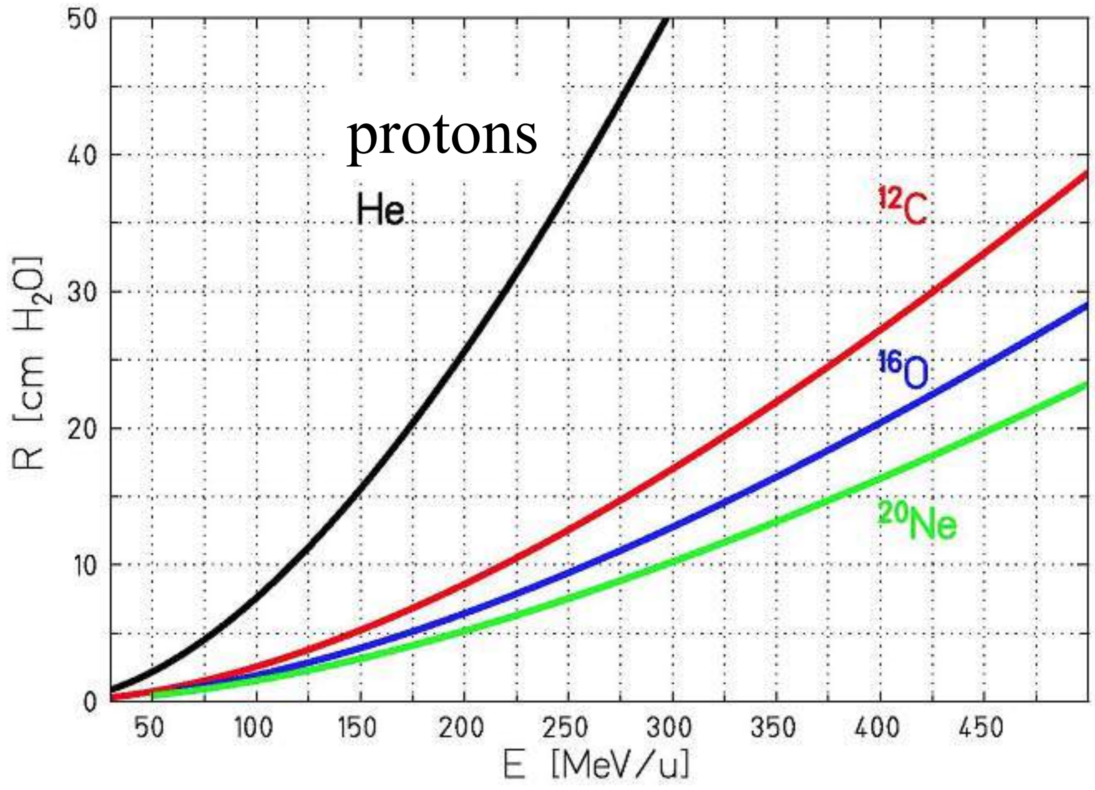
Why Hadron radiation therapy?

- Hadron Beams Slow Down And Stop depositing the energy at the very end of the pass
- While γ-rays deposit the energy evenly through the tissue
- Thus with hadron it is possible to concentrate the exposure where it is needed and reduce damage to the surrounding healthy tissue by 4-6 fold
- In medicine it can be difference between life and death

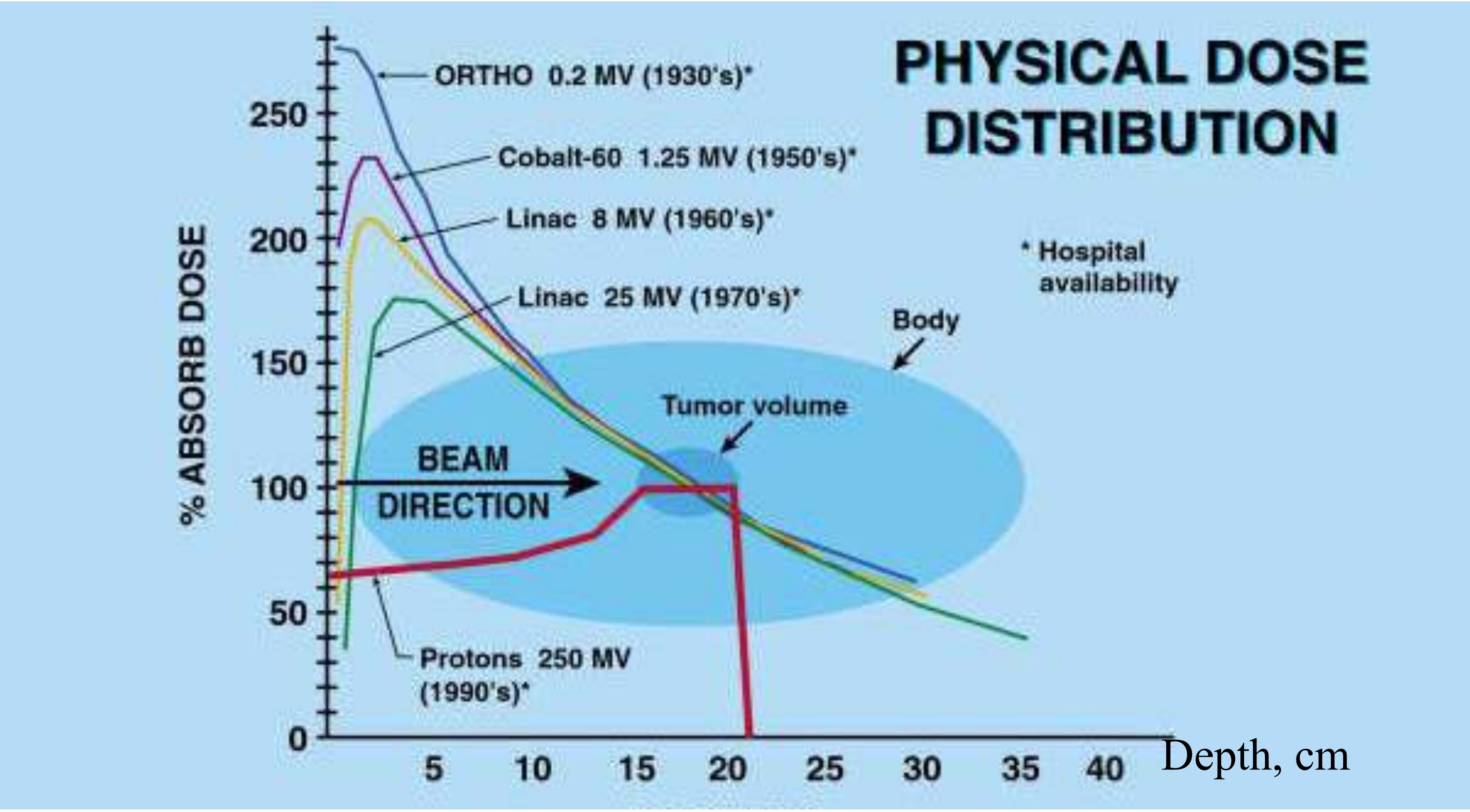


Hadron radiation therapy
It's simply the physics!

Depth range of the beam penetration in water should be ~30 cm. It defines the energy of the accelerator: p ~ 220 MeV, C ions ~ 430 MeV/u



Hadron radiation therapy
It's simply the physics!



History of Hadron radiation therapy

History of medical applications of accelerators

1929 Invention of cyclotron by *Ernest Lawrence*

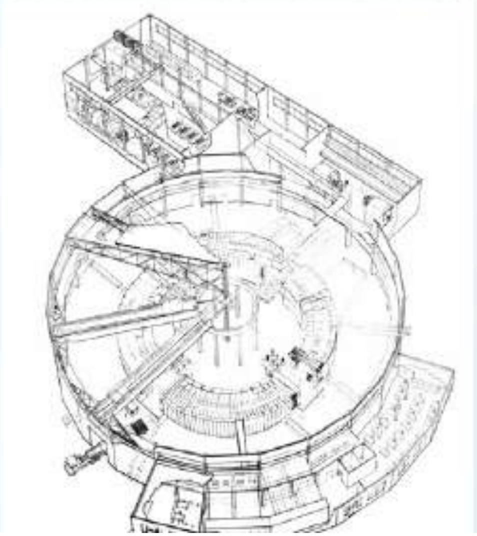
1930´s Experimental neutron therapy

1946 R. R. Wilson proposed proton & ion therapy

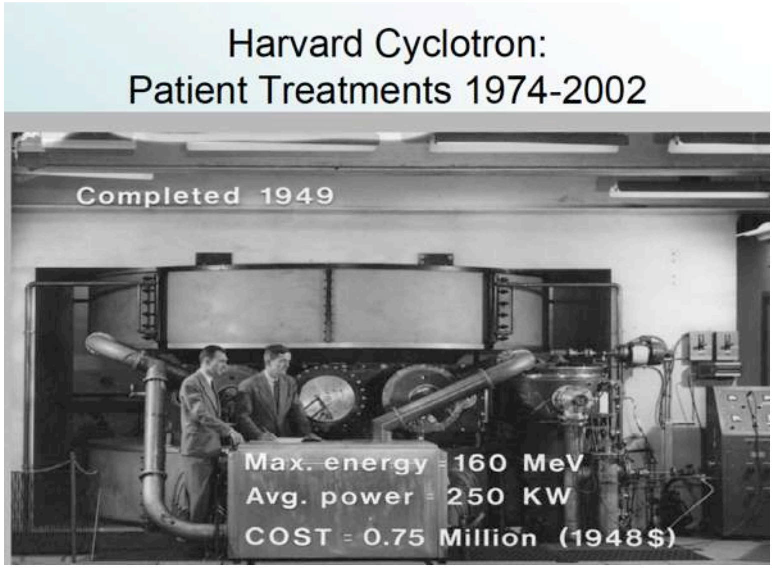
1950's Proton therapy, LBL Berkeley (184” cyclotron)

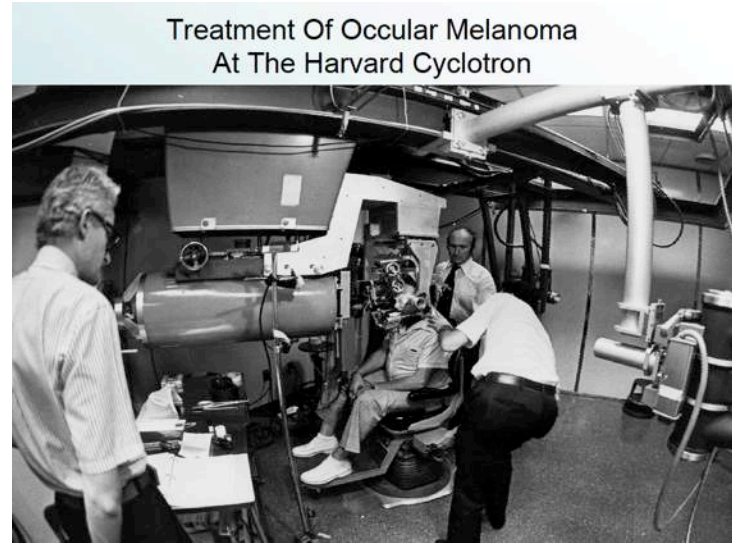
1945 *Edwin Mattison McMillan* at University of California and *Vladimir Iosifovich Veksler* (Soviet Union) invented the synchrotron principle

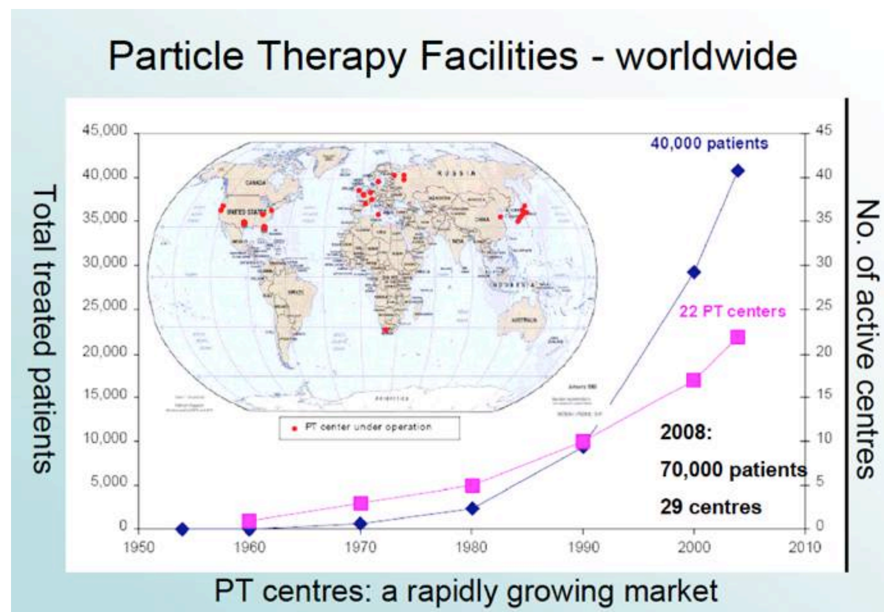
1975 Begin of carbon therapy in Bevalac synchrotron (Berkeley)



History of Hadron radiation therapy

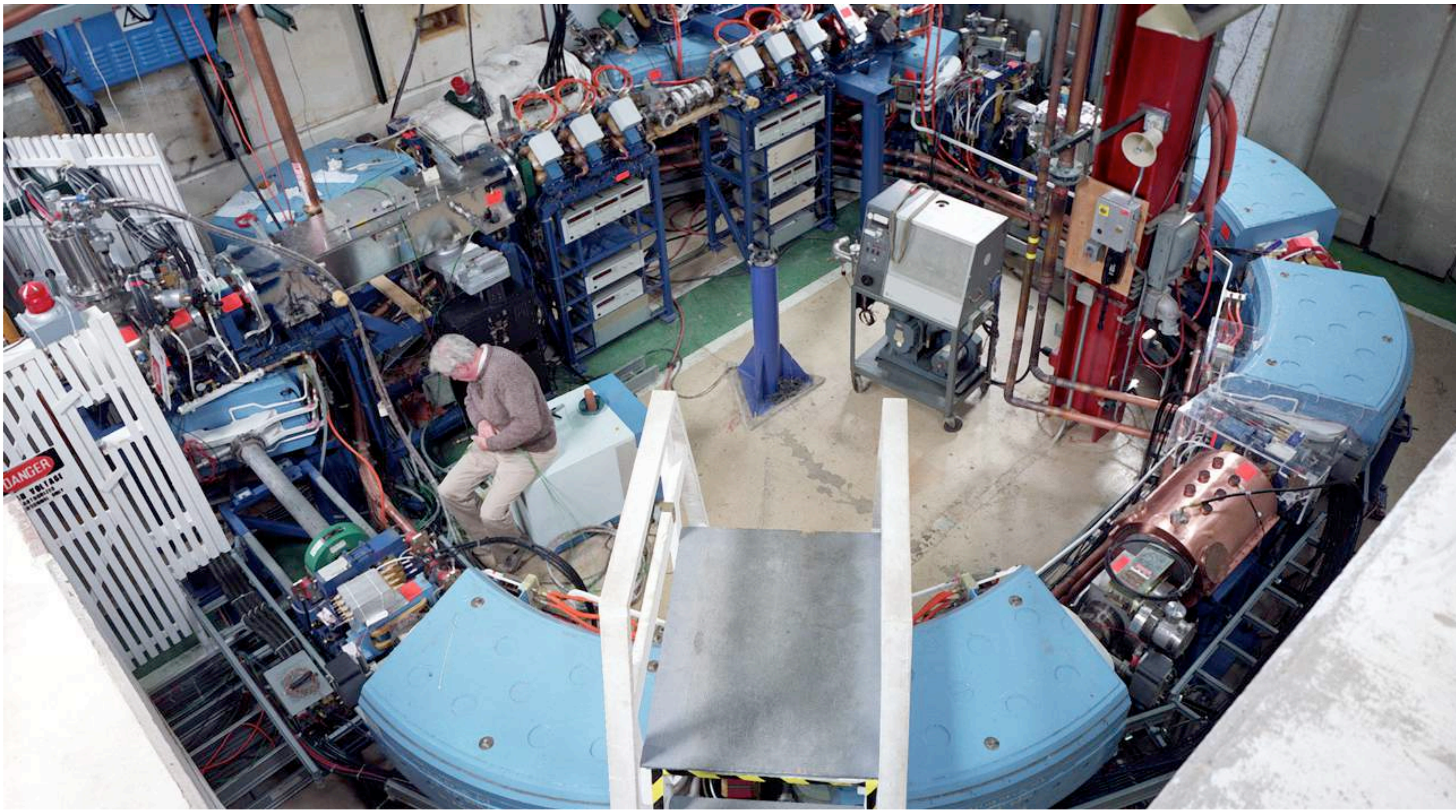






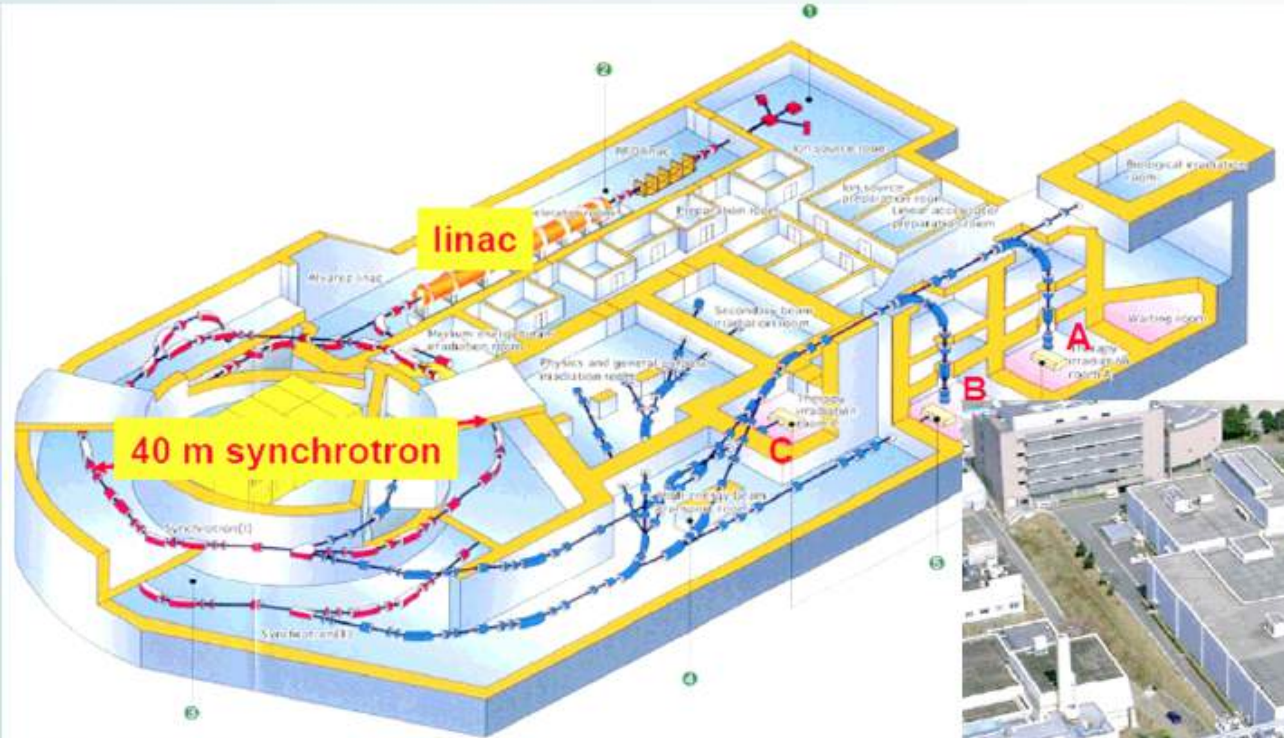
Accelerator Parts

Proton Therapy Synchrotron at Fermilab



Hadron therapy centers

Particle Therapy Facilities – HIMAC/Japan



The Heavy Ion Medical Accelerator of NIRS (since 1994)

Two identical 800 MeV/u synchrotrons for ions up to Argon; mainly Carbon is used

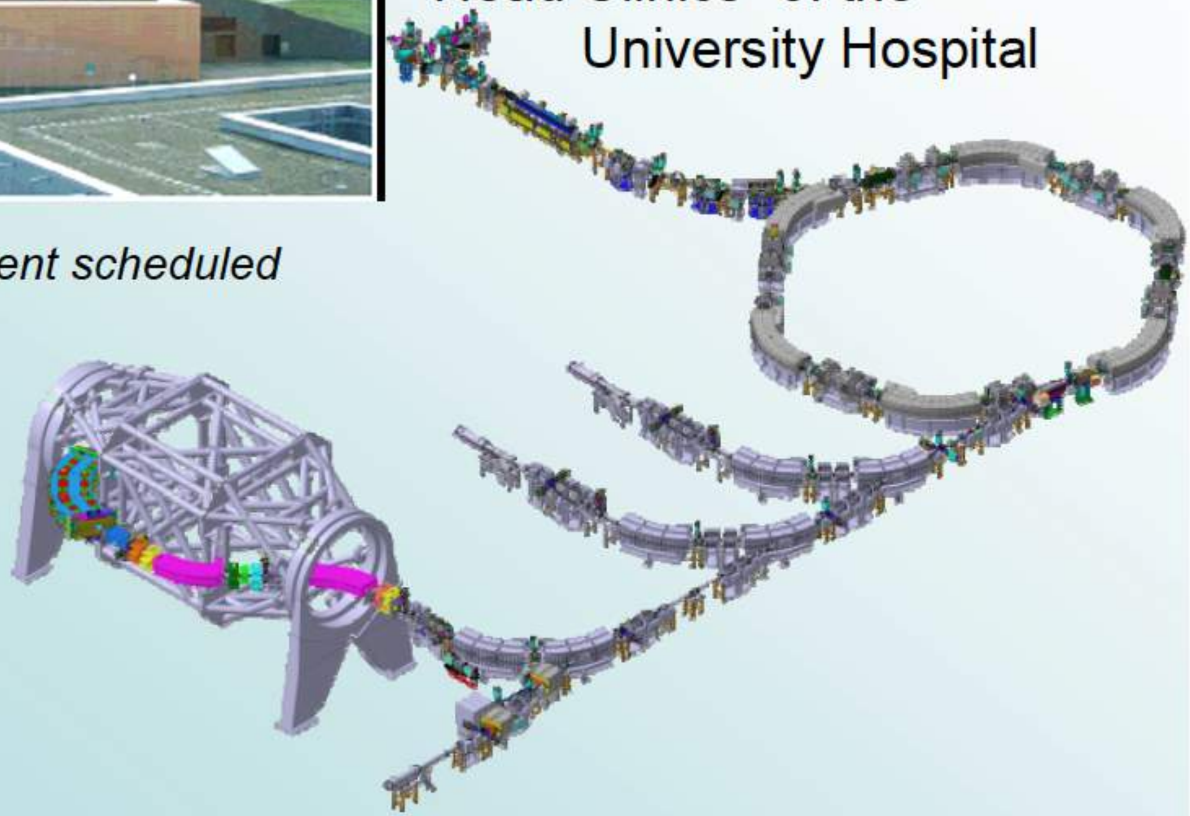
4,500 patients treated

Hadron therapy centers

Particle Therapy Facilities – HIT/Heidelberg

Compact building (60 x 70 m^2, 3 levels), directly linked to the "Head Clinics" of the University Hospital

Start of patient treatment scheduled in 2 weeks



HIT
Heidelberger Ionenstrahl-Therapiezentrum

Accelerator Parts

Therapy Facility HIT/Heidelberg

World's first isocentric ion gantry –including a scanning system: Ø = 13m, 25m long, 600 tons, 0.5 mm max. deformation

Accelerator Parts

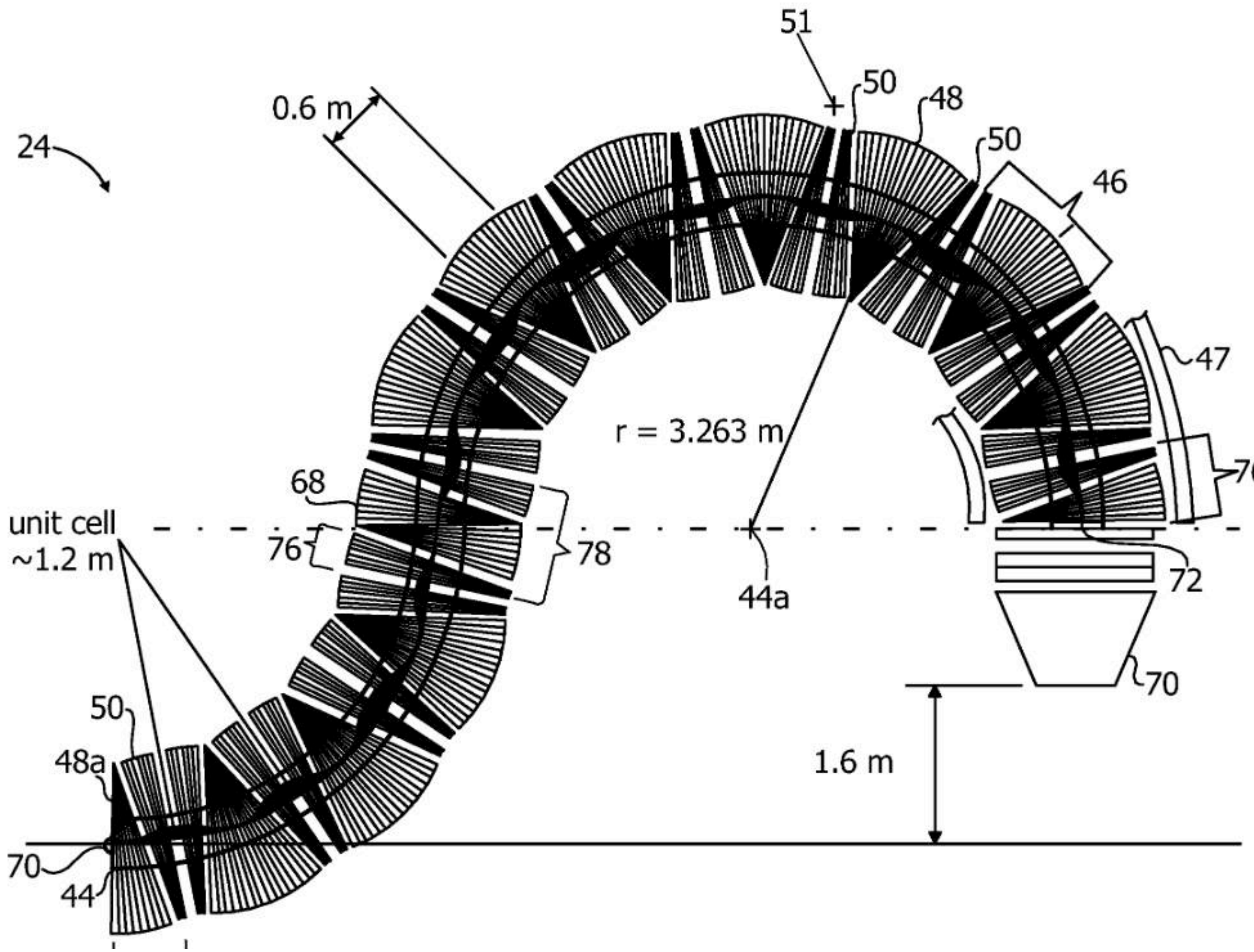
Gantries: goal is to propagate an focus hadron beam with variable energies

Accelerator Parts

Gantries: monsters in modern accelerators

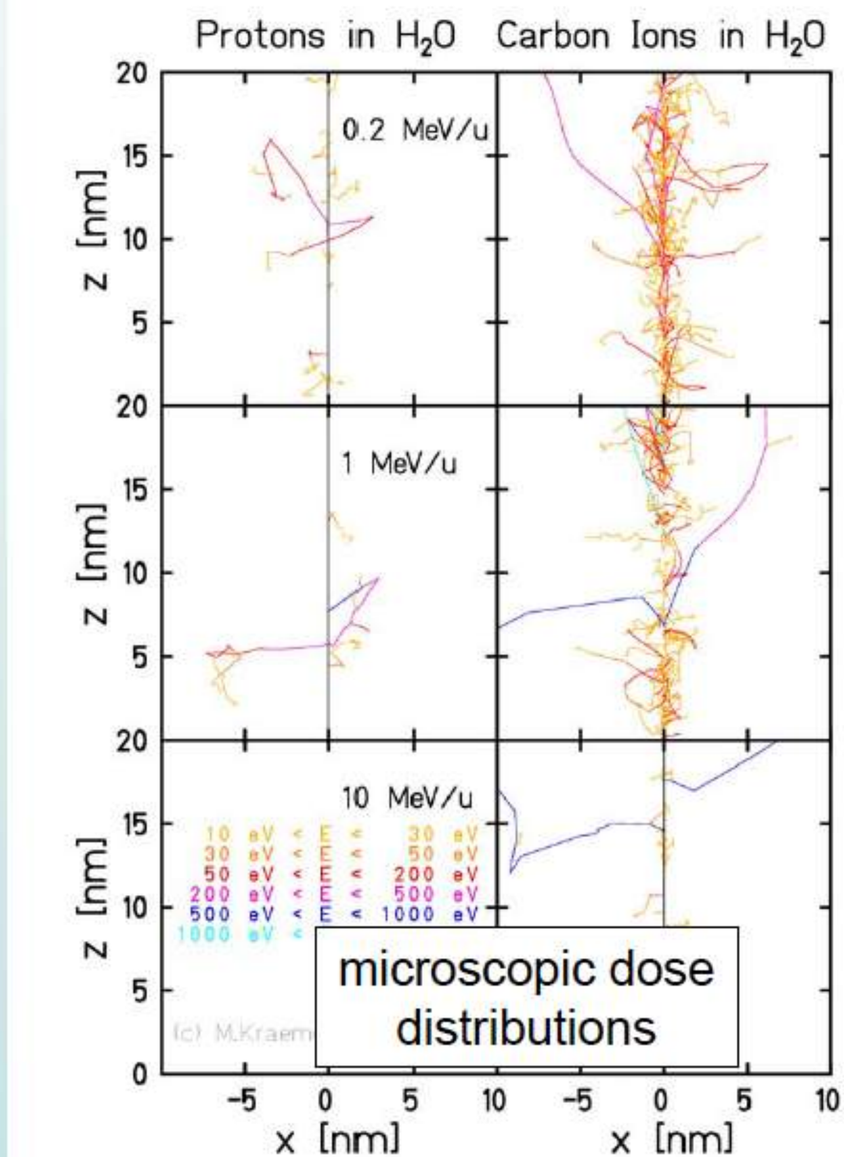
Accelerator Parts

New ideas: compact FFAG gantry (© D. Trbojevic, BNL)

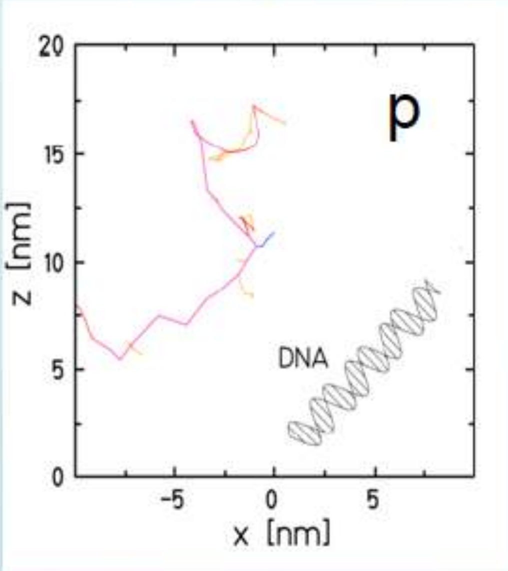


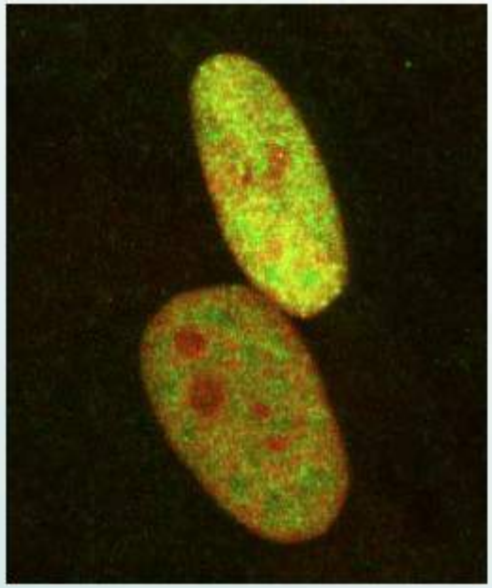
Physics and Biology of radiation therapy

Basic effect of radiation on cells: energy loss in matter leads to defects in the DNA – double strand breaks of the DNA kills the cell. Tumor cells have less repair capabilities than normal cells.



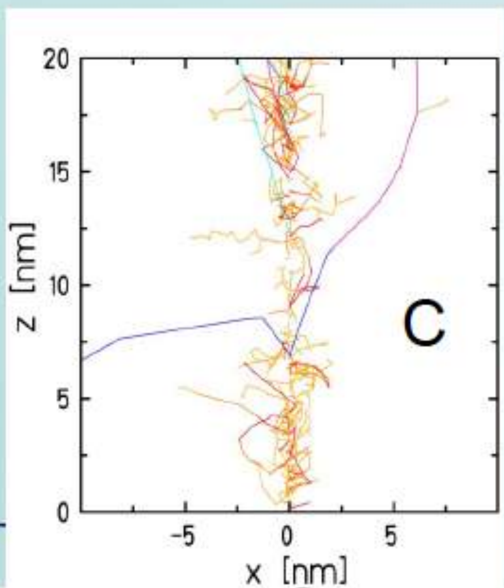
Physics and Biology of radiation therapy

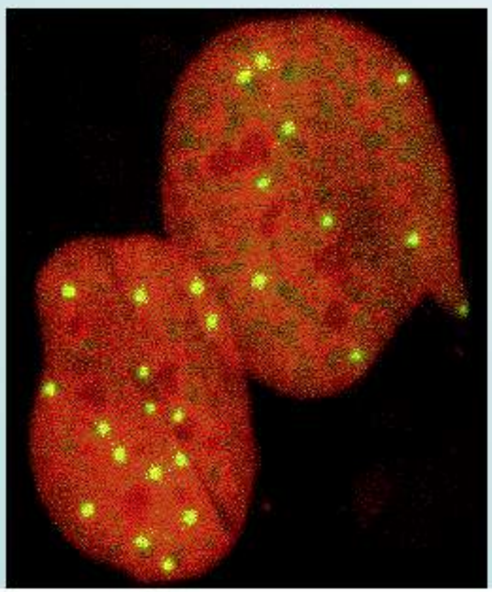




Low LET

Homogeneous deposition of dose





High LET

Local deposition of high doses

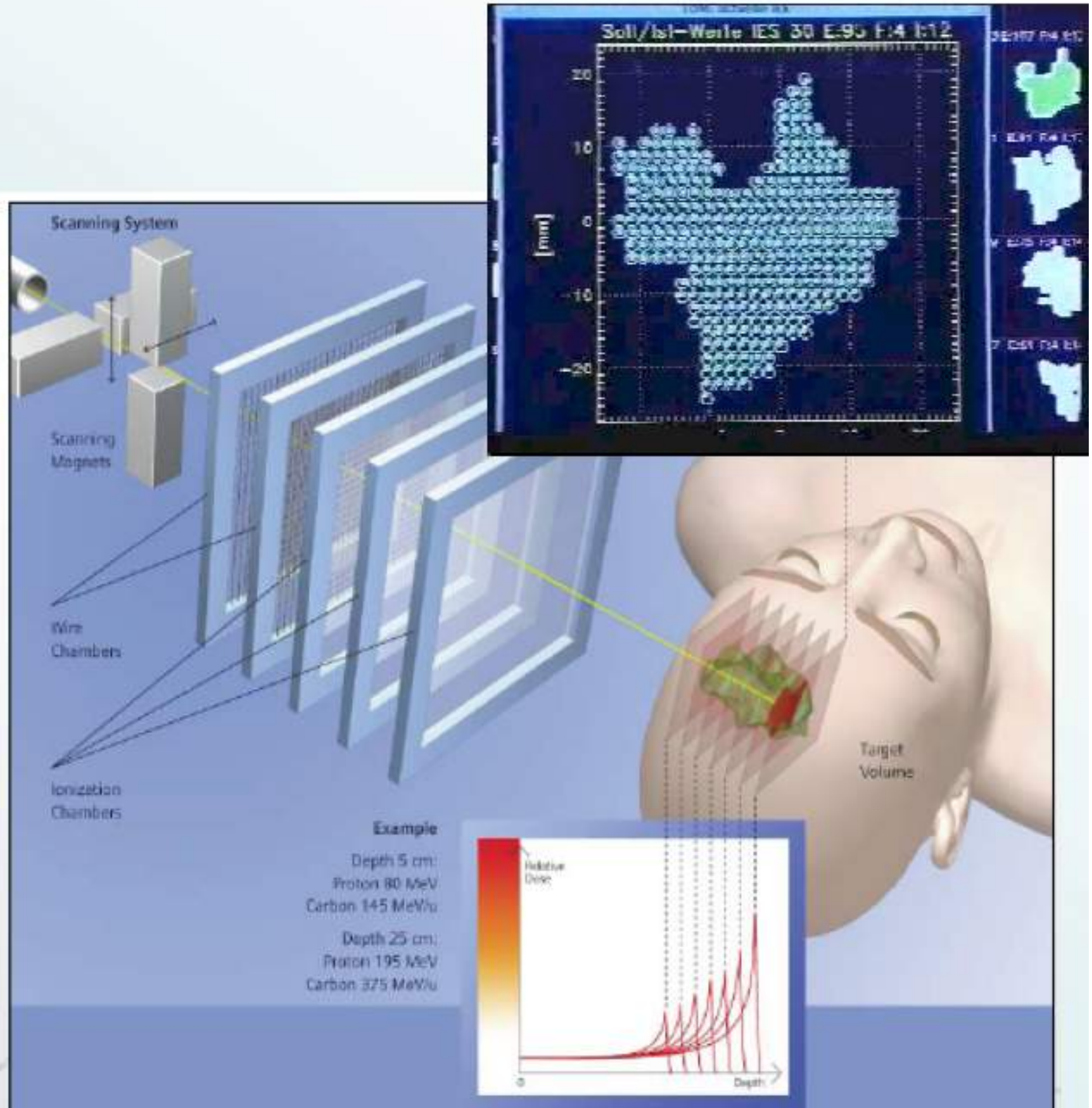
LET: Linear energy transfer

Optimized Treatment By Beam Scanning

Development in the 90ies:
Scanning techniques

a) Protons (Pedroni PSI): spot scanning gantry (1D magnetic pencil beam scanning) plus passive range stacking (digital range shifter)

b) Ions (Haberer et al.): raster scanning (2D magnetic pencil beam scanning) plus active range stacking (spot size, intensity) in the accelerator

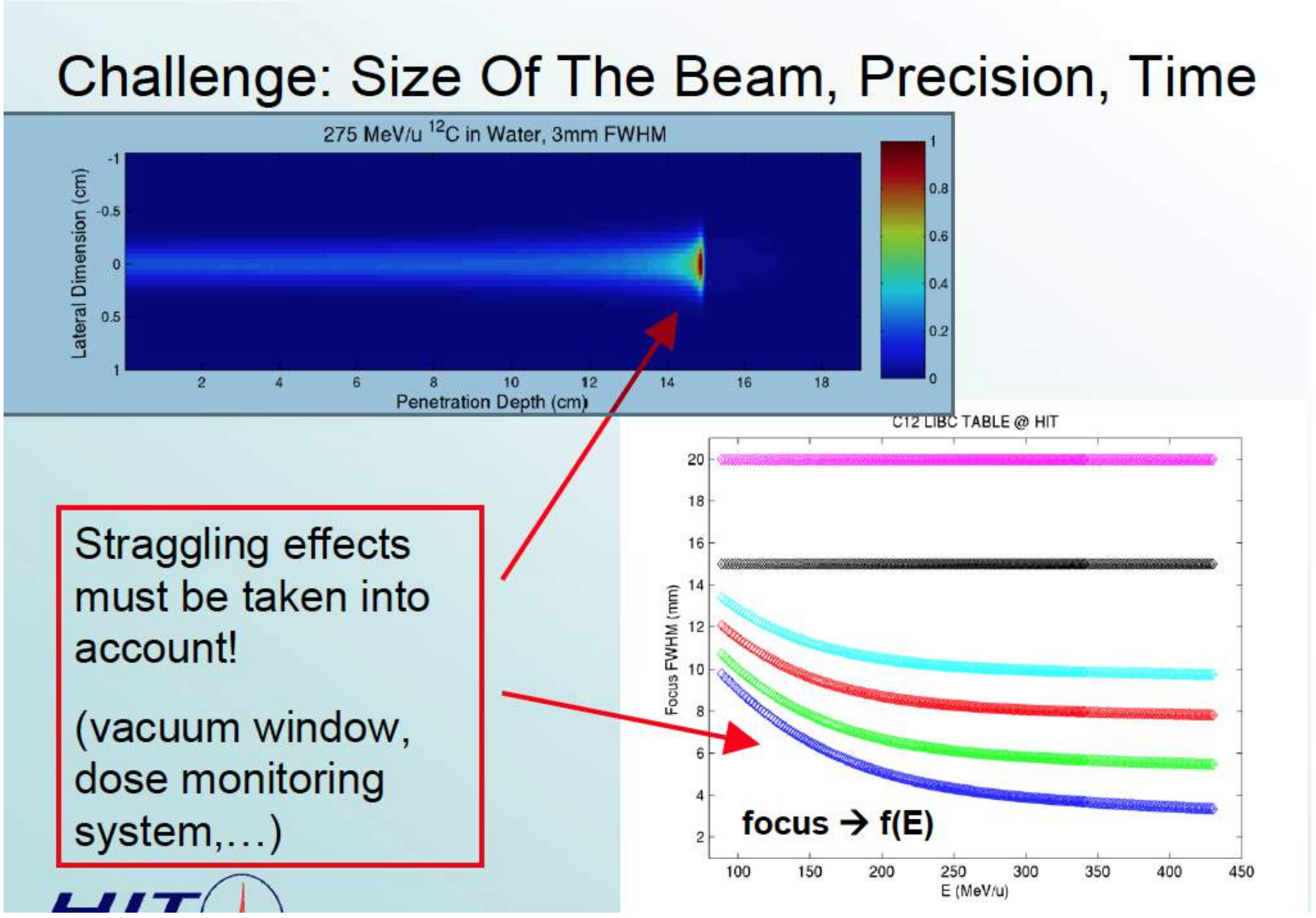


Intensity-Controlled Rasterscan Technique, Haberer et al., GSI, NIM A,1993

HIT
Heidelberger Ionenstrahl-Therapiezentrum

Optimization of the treatment

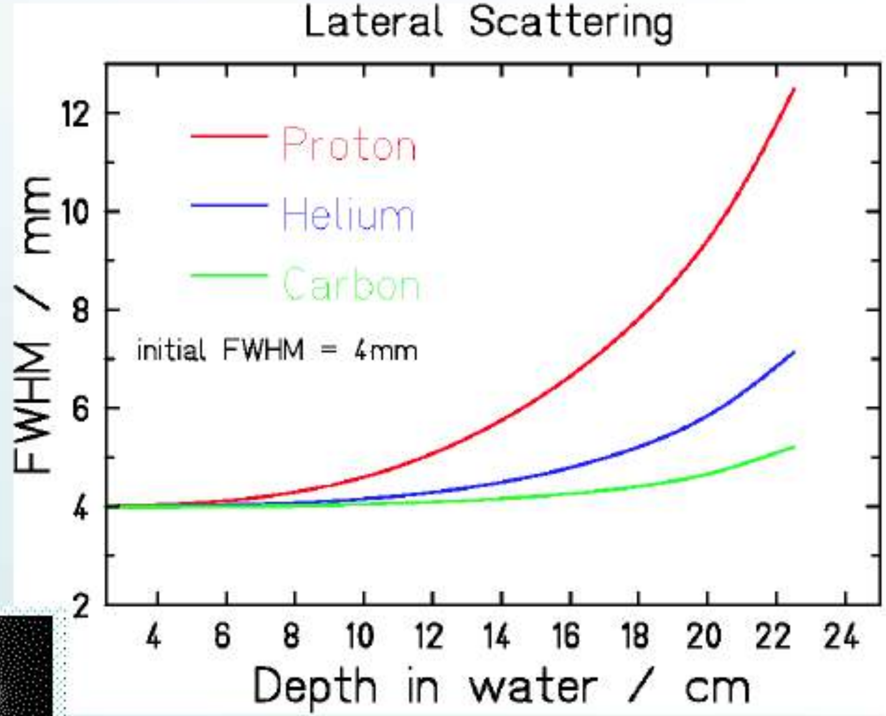
- ✓ Modern trend is to have exposures from multiple directions with multiple energies
- ✓ Hence, accelerator should provide a well controlled intensity shots of the beam with programed energy – not a trivial fit for a hadron accelerator

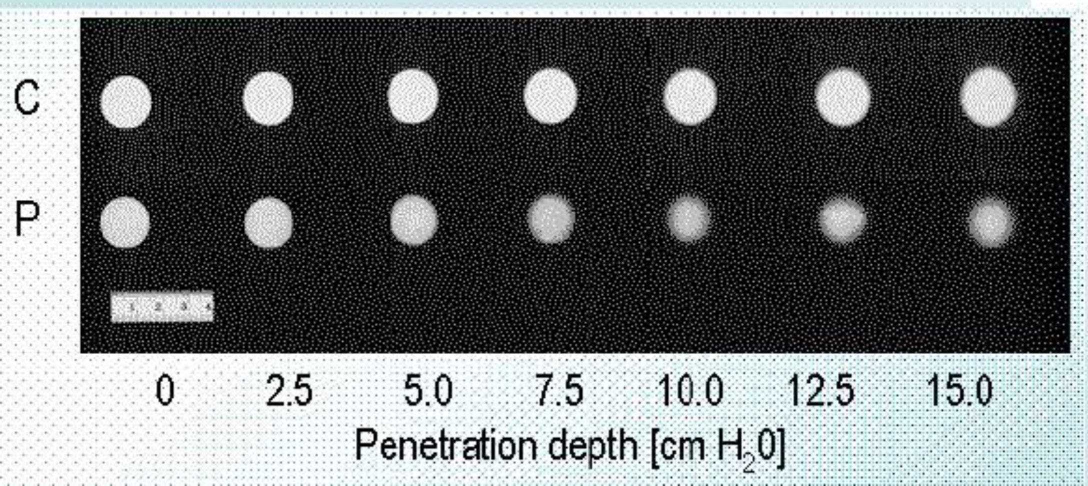


Optimization of the treatment

Beam Size

Higher local precision with carbon for deep-seated tumour treatment





What is a good medical isotope?

- For applications in medicine, nature and "man-made" physics approaches provide many different radionuclides to choose from.
- The choice of radionuclide is critical for achieving successful diagnostic imaging and cancer treatment outcomes.
- Objectives:

1) Diagnostic nuclear medicine: high quality images of activity in the patient, with low patient radiation dose
2) Therapeutic nuclear medicine: high amount of energy imparted to the target tissue (to destroy cancer cells) relative to critical normal organs and tissues (to prevent radiation damage and side-effects)

Medical isotope shortages

Officials Scramble for Solutions to Global Isotope Shortages

As global demand continues to grow for the medical isotope necessary for imaging procedures, most of the reactors used to produce technetium-99m (Tc-99m) will be permanently decommissioned within six years. A task force set up last year in the EU to consider solutions to isotope shortages released its first report this month to the European Commission. The report suggests convening stake-holders to discuss alternative diagnostic and therapeutic procedures.

Reactor shutdown causes another isotope shortage

Updated Fri. Dec. 12 2008 7:08 PM ET

CTV.ca News Staff

A temporary shutdown at the Chalk River, Ont. nuclear reactor is causing a shortage of medical isotopes, forcing Canadian doctors to scramble to cancel and rearrange appointments with their patients.

The isotope shortage is expected to last until the middle of next week, CTV News has learned.

The shortage is expected to affect Ontario, Quebec, parts of the Maritimes, the northern United States and perhaps even Mexico.

Atomic Energy of Canada Ltd., responsible for the Chalk River nuclear facility, told CTV News that the shutdown was "normal" on Thursday night, but on Friday said the shutdown was "longer than expected."

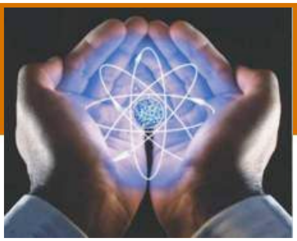
Radiopharmaceuticals

- Positron Emitters
- Beta/gamma Emitters
- Alpha Emitters

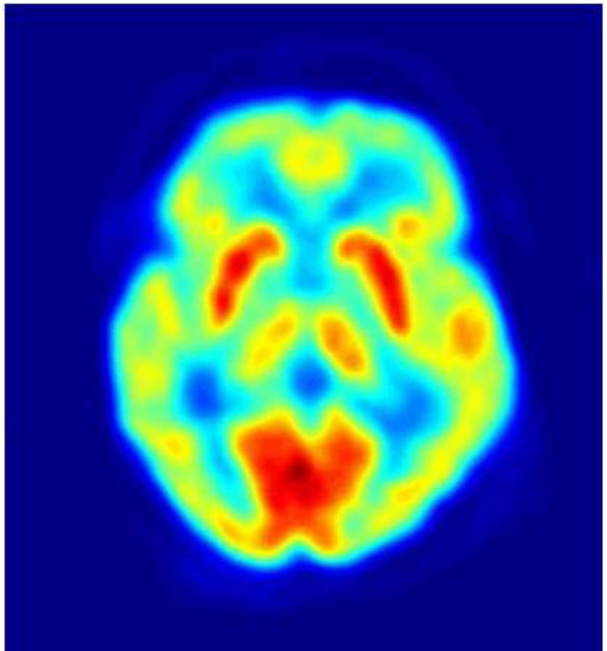
Medical Devices

- Sealed Sources
- Microsphere Applications
- Nanosphere Applications

Positron emitters



- Cancer Metabolism and Functional Imaging
  - F-18-fluorodeoxyglucose (FDG) glucose analog, measures hexokinase activity (glucose metabolism), phosphorylated by hexokinase to F-18-FDG-6-PO_4, elevated in tumor cells, chemically trapped in cells
  - F-18-amino acids (phenylalanine, tyrosine) image metastatic lesions
  - F-18-fluorothymidine measures thymidine kinase activity (DNA synthesis)
  - F-18-flouromisonidazol (FMISO) images tumor hypoxia
  - F-18-estradiol breast tumor detection



Radioisotope Production

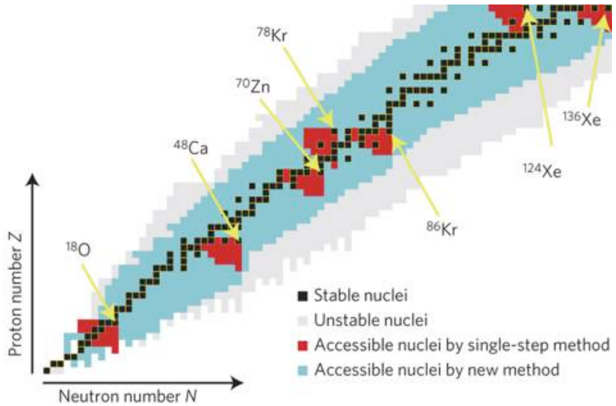
- **Applications** (>50 routine radioisotopes)
  - Industrial – Gauging & calibration
  - Medical – Diagnostics & treatment
    - SPECT
    - PET
    - Brachytherapy

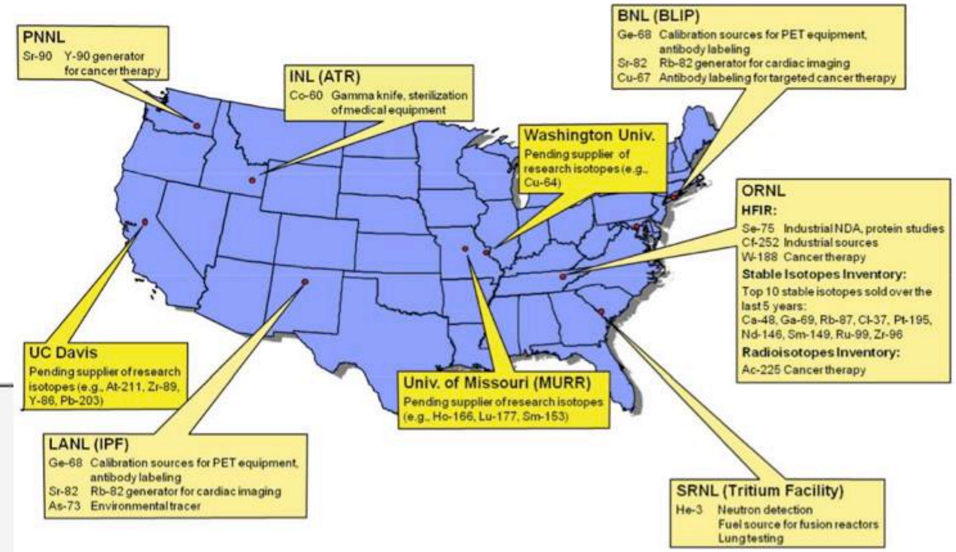
- **Cyclotrons & Linacs** – both protons & deuterons
  - PET – self shielded systems from 7 to 18 MeV with current < 200 µA)
  - SPECT – energies from 22 to 70 MeV with currents up to 2 mA

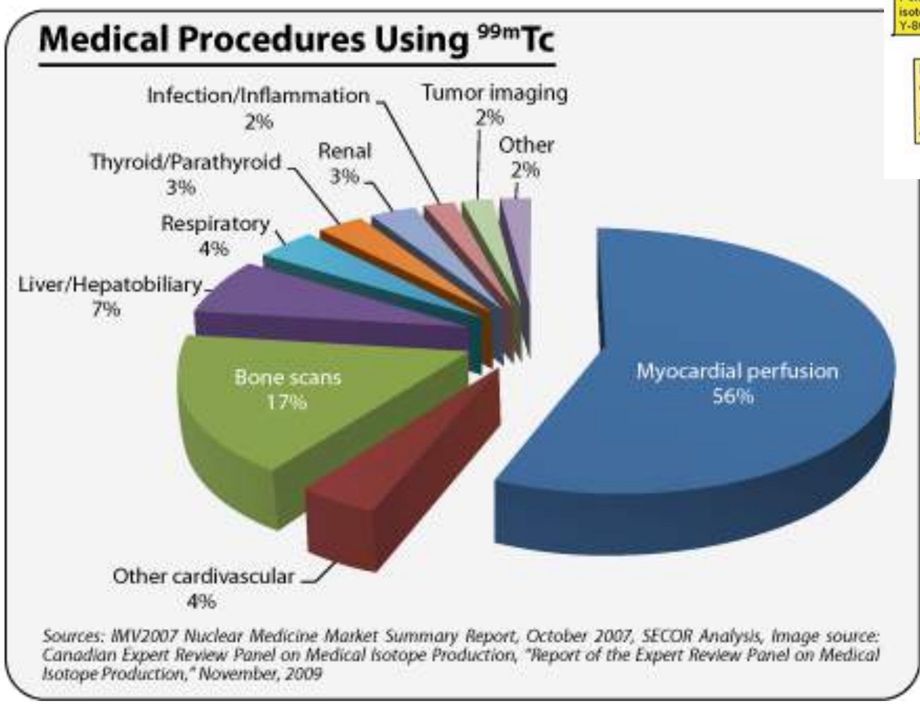
- **Vendors**
  - GE Healthcare (Sweden)
  - Siemens Medical Systems (USA)
  - Ion Beam Applications SA (Belgium)
  - Advanced Cyclotron Systems (Canada)
  - Sumitomo Heavy Industries (Japan)
  - Samyoung Unitech Co. (Korea)
  - Thales GERAC (France)
  - AccSys Technology, Inc. (USA)

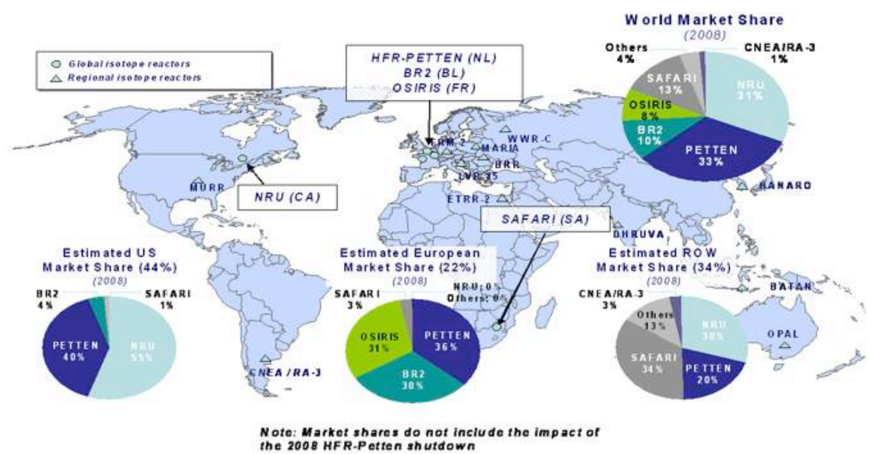
Large growth in compact accelerators for PET.

Radio isotope production

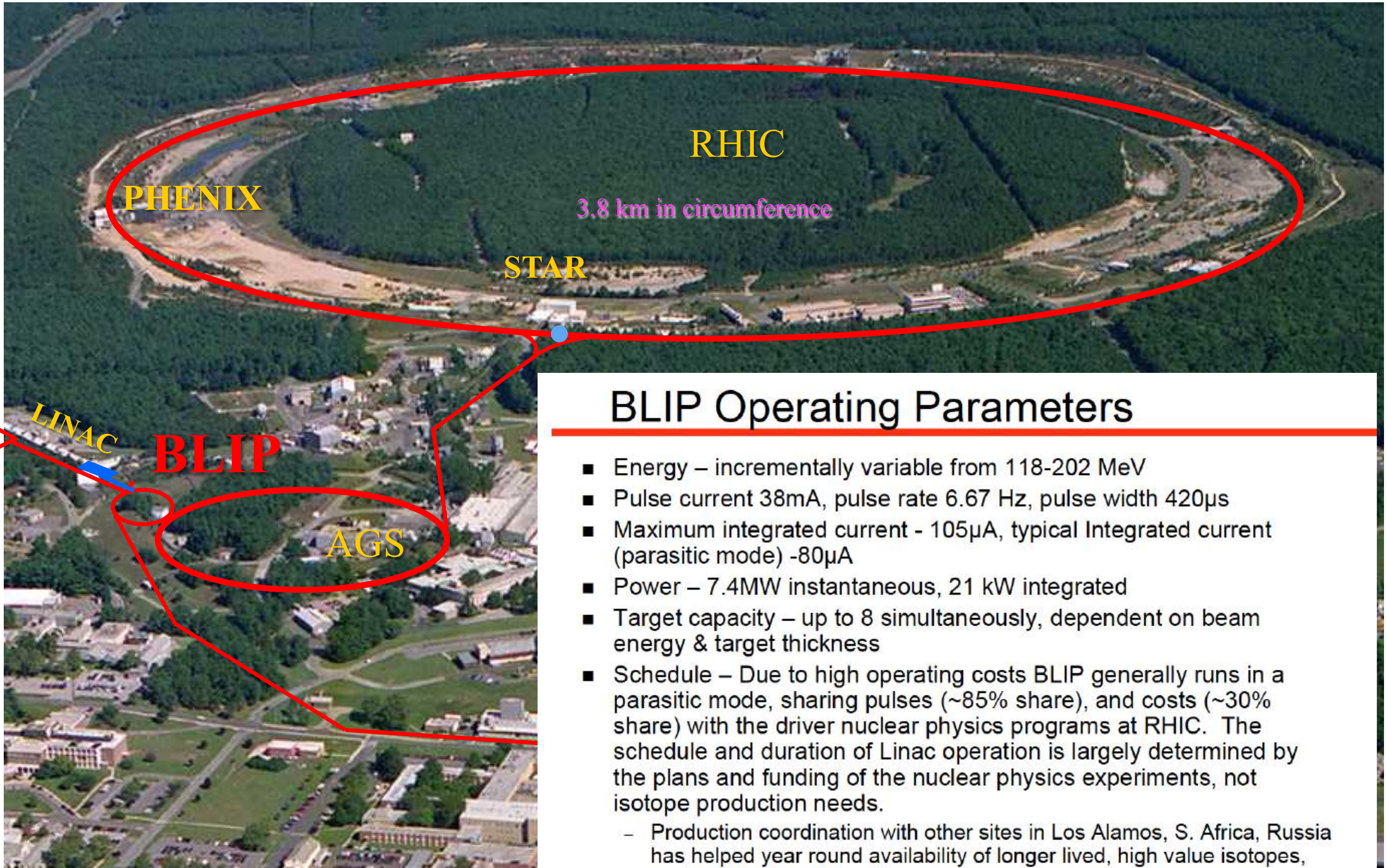








Close to home: BLIP at BNL



BLIP Operating Parameters

- Energy – incrementally variable from 118-202 MeV
- Pulse current 38mA, pulse rate 6.67 Hz, pulse width 420μs
- Maximum integrated current - 105μA, typical Integrated current (parasitic mode) -80μA
- Power – 7.4MW instantaneous, 21 kW integrated
- Target capacity – up to 8 simultaneously, dependent on beam energy & target thickness
- Schedule – Due to high operating costs BLIP generally runs in a parasitic mode, sharing pulses (~85% share), and costs (~30% share) with the driver nuclear physics programs at RHIC. The schedule and duration of Linac operation is largely determined by the plans and funding of the nuclear physics experiments, not isotope production needs.
  - Production coordination with other sites in Los Alamos, S. Africa, Russia has helped year round availability of longer lived, high value isotopes, such as Sr-82 and Ge-68.

Summary

- We only touched upon a variety of practical/societal applications of accelerators
- Accelerators play and will continue playing an important role in technological progress of the humanity – both through direct economical impact and spin-off from the knowledge obtained using accelerators or technology developed for them
- Advances in accelerator technology, especially tend towards a compact accelerators, are closely watched by industrialist
- BTW, this is why finding industrial position for accelerator physicists and engineers is a relatively easy fit…

End of lectures

Instead of conclusion

- You learned quite a bit about the accelerators, accelerator science and accelerator applications
- We hope that you would use this knowledge in your future studies and research