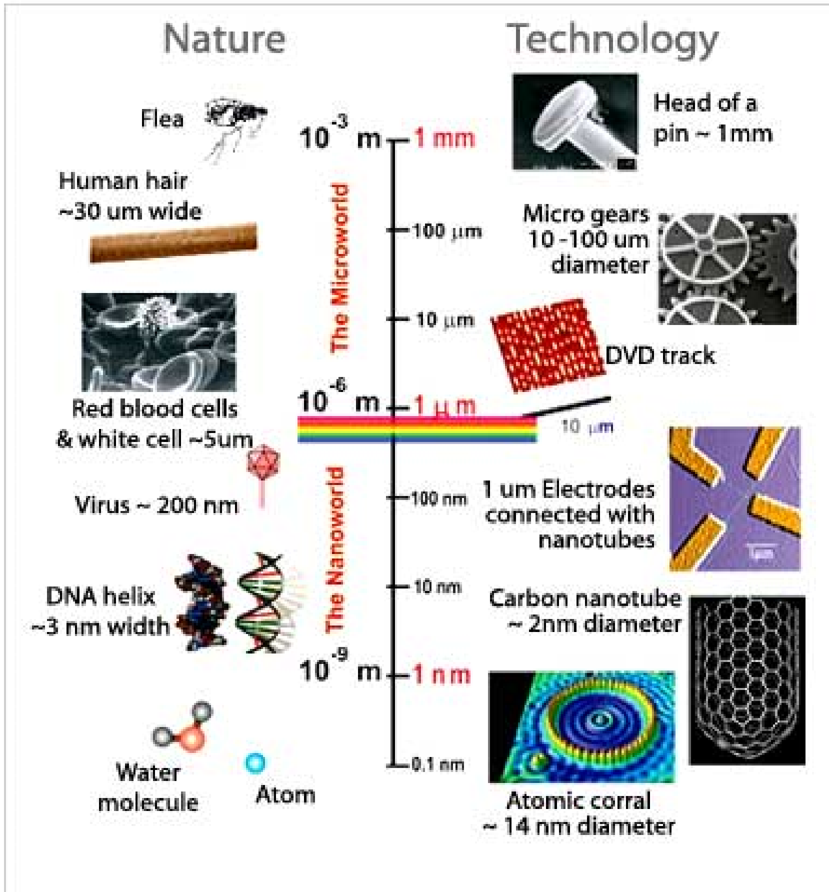
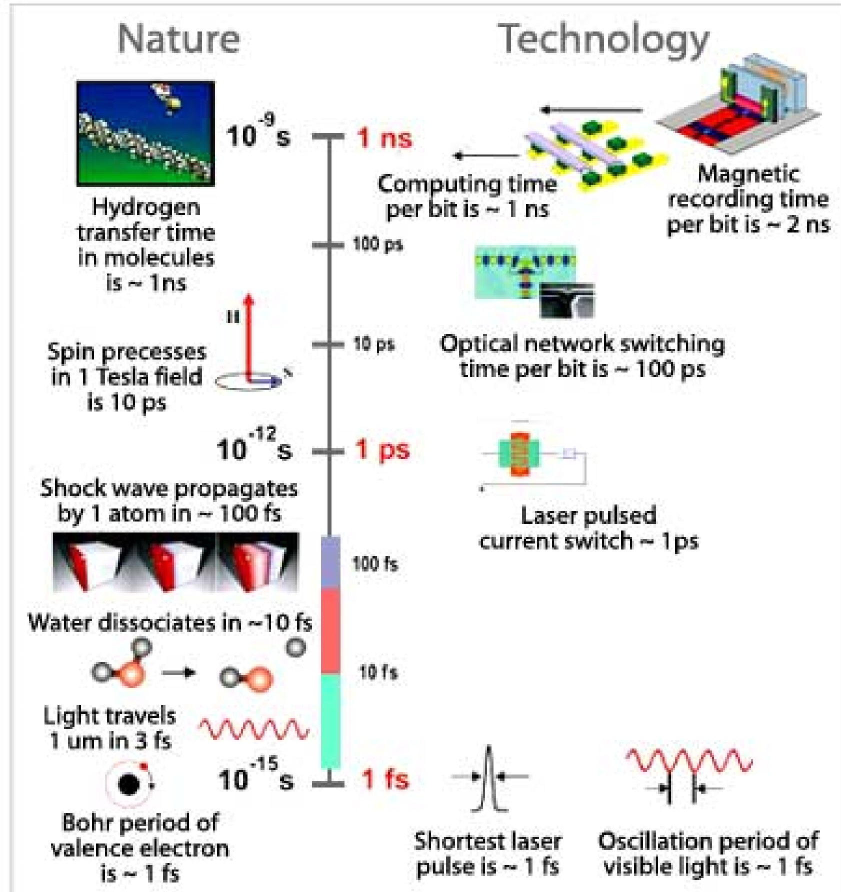
What Light Sources Are For?

Ultra-Small

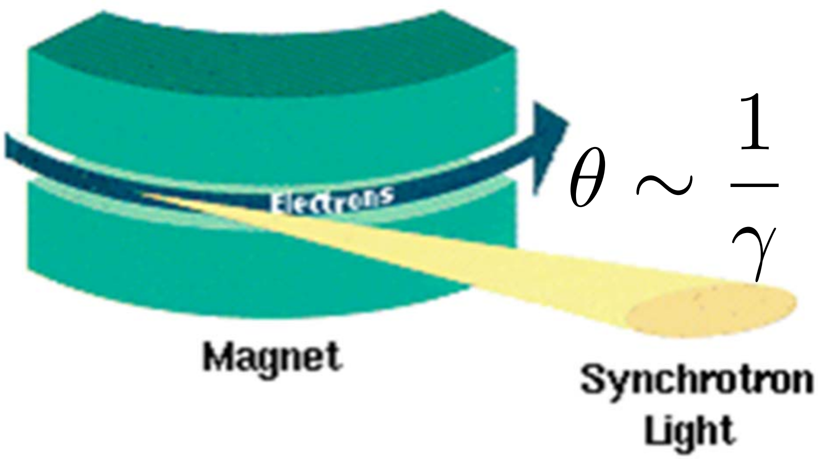


Ultra-Fast

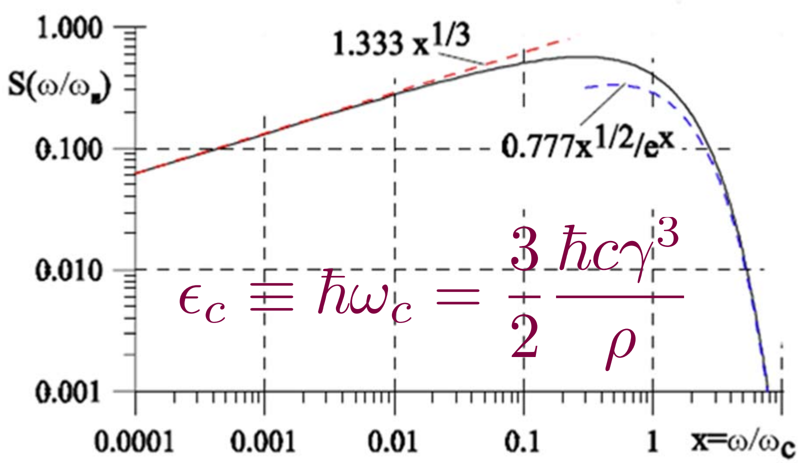


http://www.sc.doe.gov/bes/scale_of_things.html

SR from Bending Magnet



$$\theta \sim \frac{1}{\gamma}$$

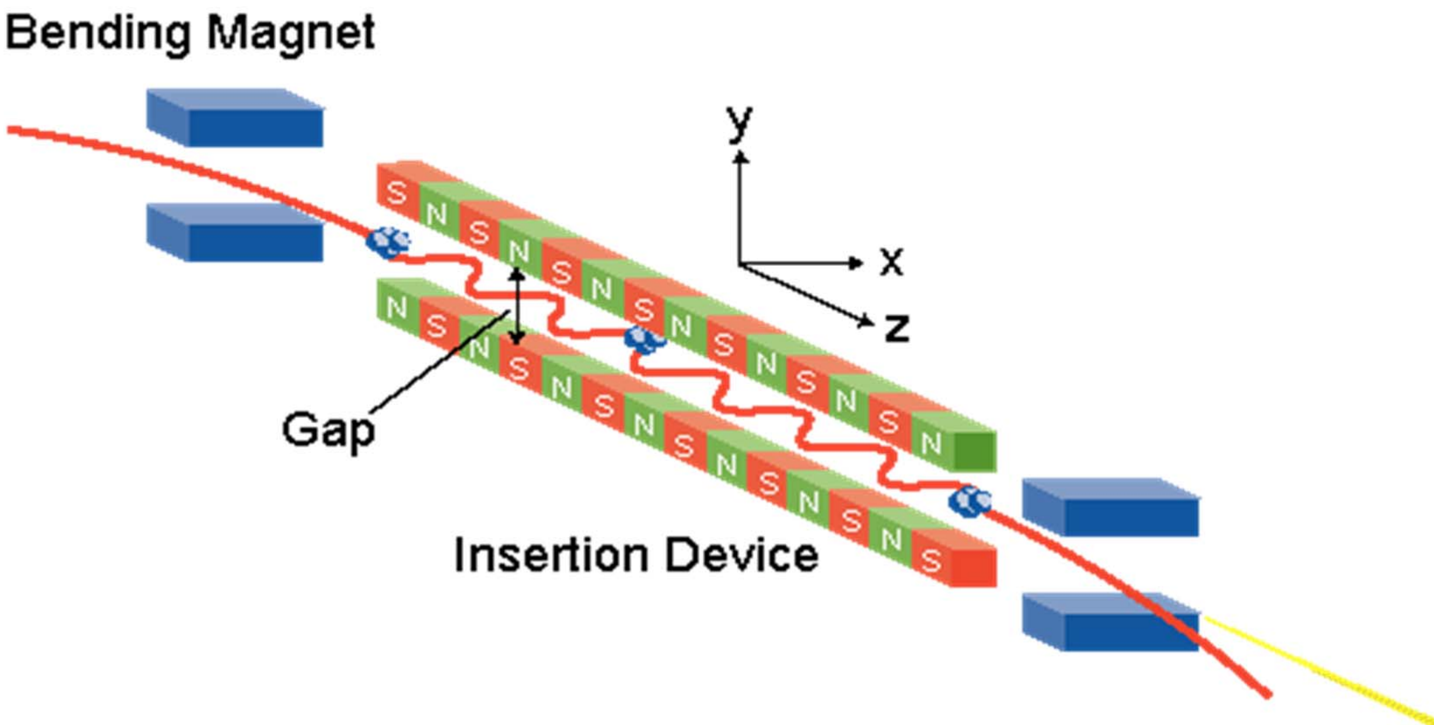


$$\epsilon_c \equiv \hbar\omega_c = \frac{3}{2}\frac{\hbar c\gamma^3}{\rho}$$

$$P = \frac{e^2 c}{6\pi\varepsilon_0}\frac{\gamma^4}{\rho^2}$$

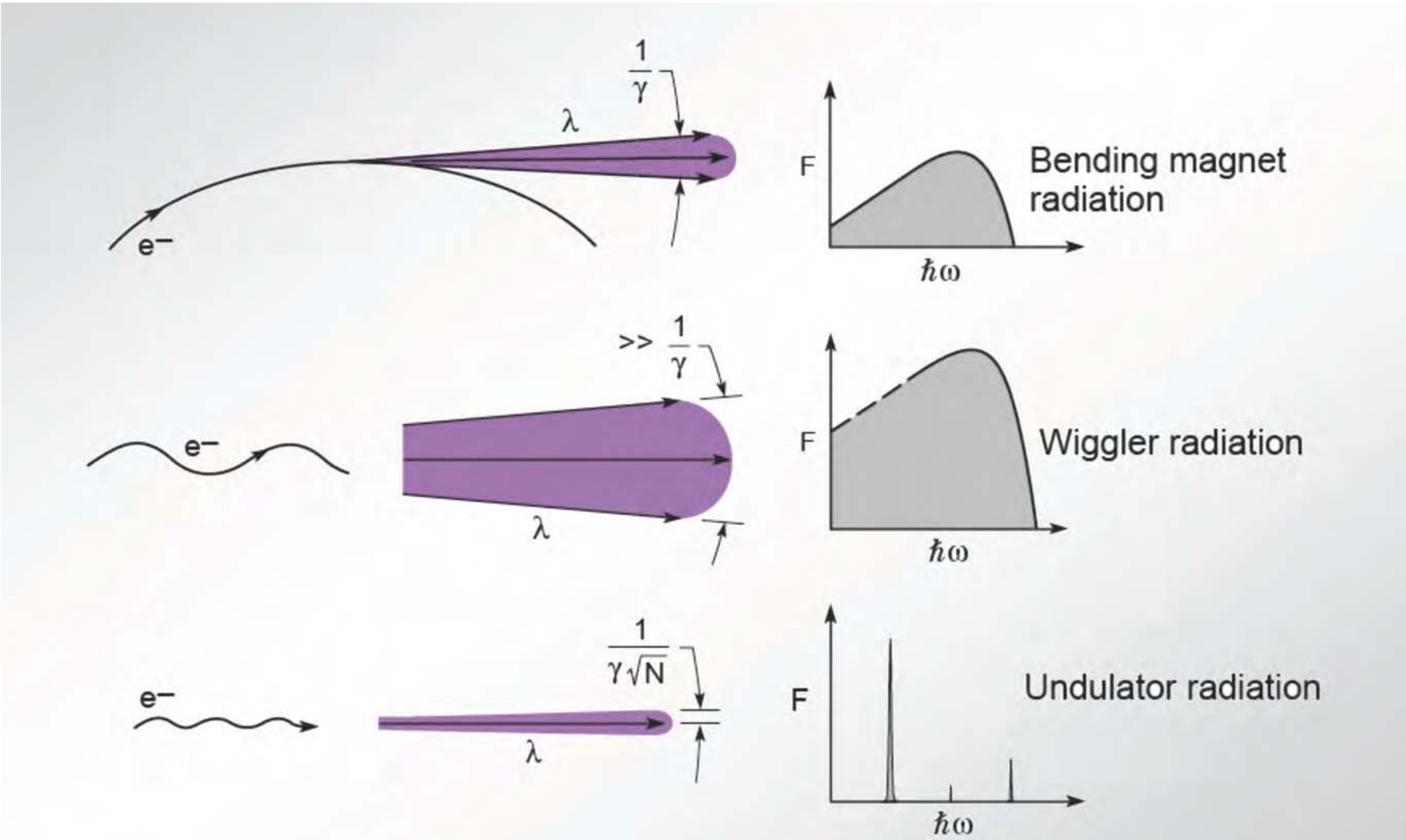
- Goods
  - Simple, inexpensive
  - Broad spectral range
  - Many beamlines
- Bads
  - Limited hard x-ray components
  - Not very bright

SR from Undulator/Wiggler



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

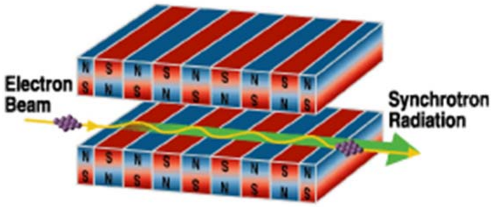
Difference between bending magnet and Undulator/Wiggler



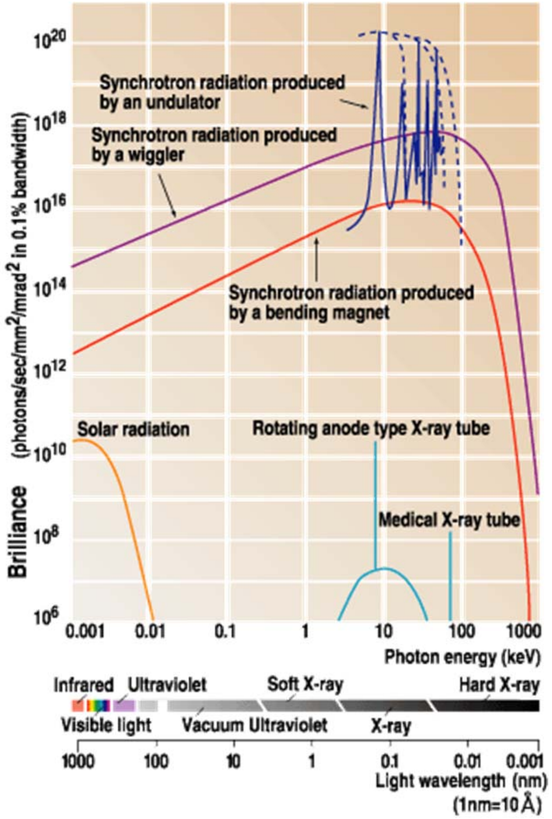
Courtesy of W. Barletta

Extremes of e$^+$/e$^-$ beams : Light Sources

- **Emittance**
  - *1 Å·rad (ESRF @ 1GeV)*



- **Bunch length**
  - *100 fsec (ATF @ BNL, TESLA - not in the rings!)*
- **Brilliance** [*ph/sec/μm^2/10^{-3}BW*]
  - *Average 10^{20} (ESRF, APS, Spring-8)*
  - *Peak 10^{30} (X-ray FELs- not in the rings!)*



NSLS II

- **New Light source at BNL**
- **50-fold better than present state-of-the-art light sources**

SR Light Source Worldwide

ESRF, 6 GeV

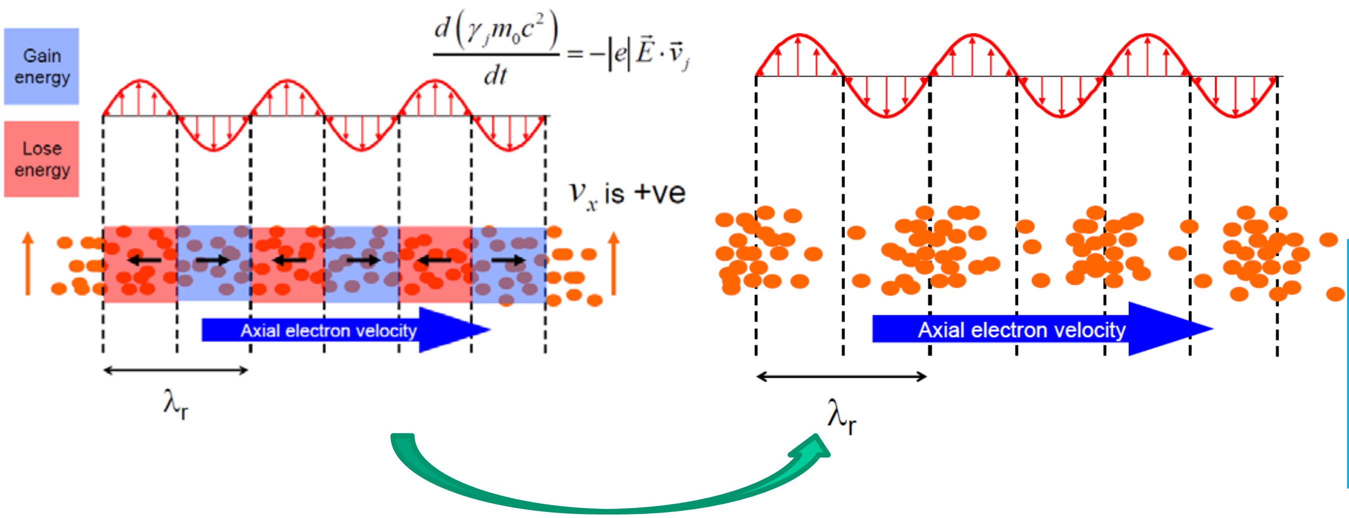
SPring-8, 8 GeV

NSLS II, 3 GeV

SSRF, 3.5 GeV

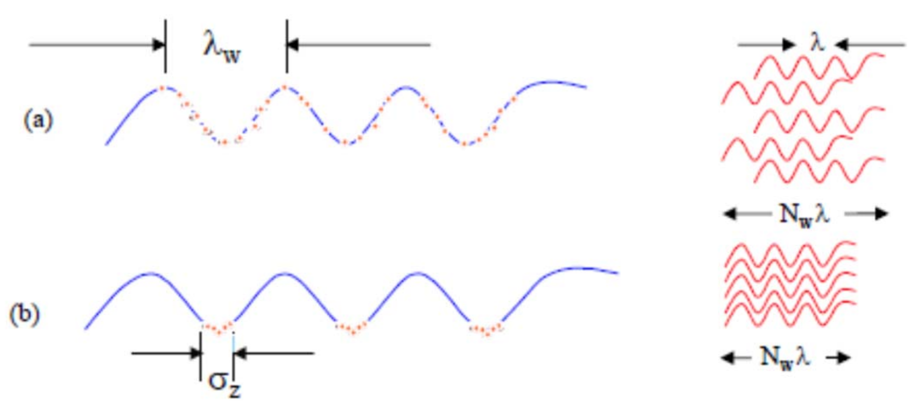
FEL: Micro-Bunching

1. Energy kick from radiation field + dispersion/drift -> electron density bunching;

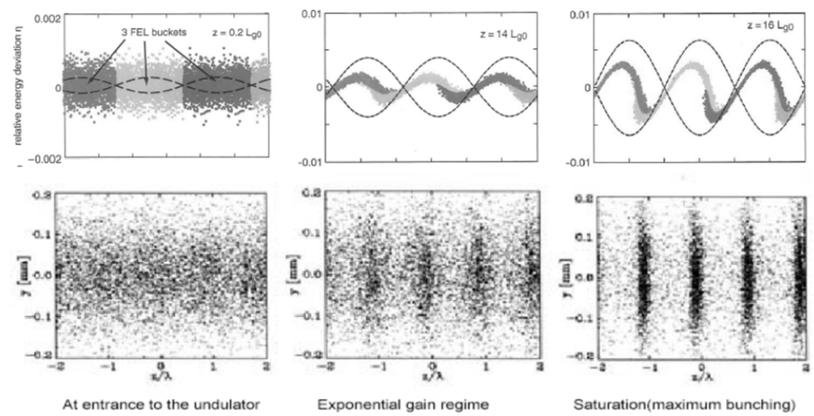


The positive feedback loop between radiation field and electron density bunching is the underlying mechanism of high gain FEL regime.

2. Electron density bunching makes more electrons radiates coherently -> higher radiation field;

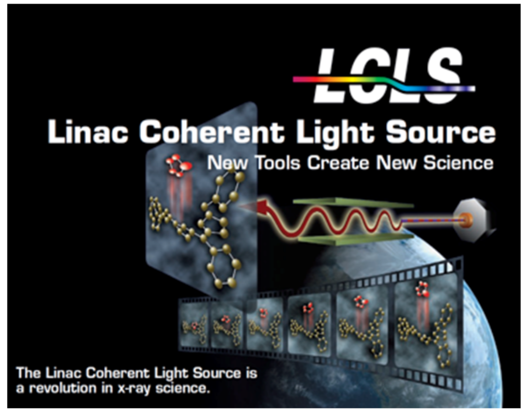


3. Higher radiation fields leads to more density bunching through 1 and hence closes the positive feedback loop -> FEL instability.

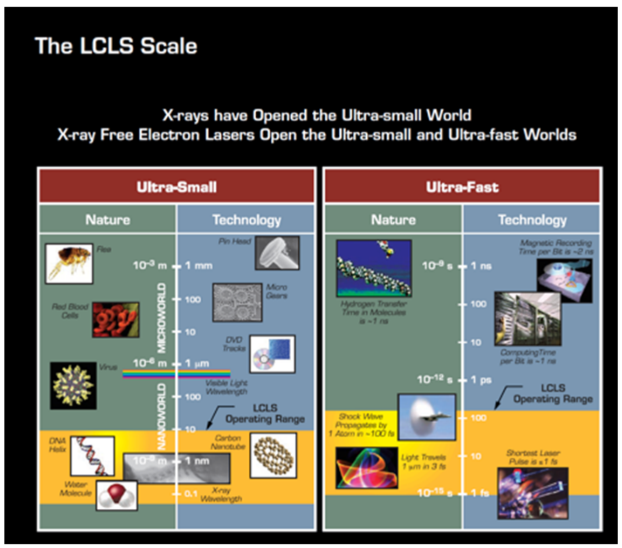


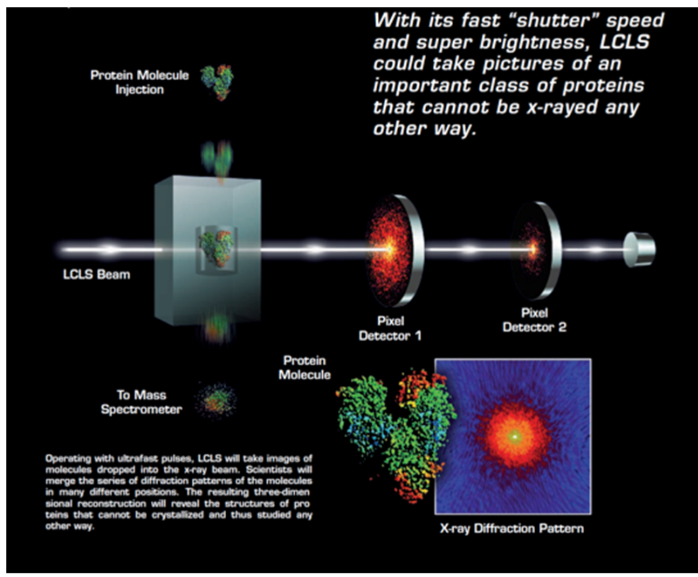
The Ultimate Tasks are for Free Electron lasers!

- TASK 1: To see one single protein or cell *in a single shot* one needs a blast X-ray photons within a few femtosecons (1 fsec $=10^{-15}$ sec)

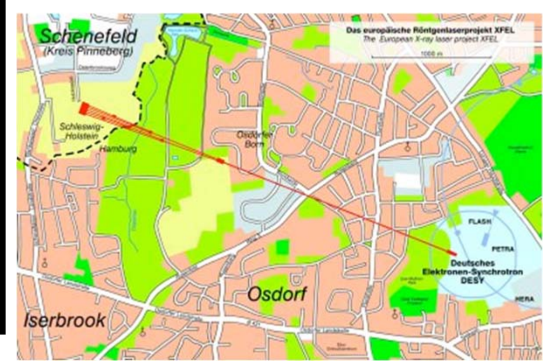


LCLS at SLAC





The European X-Ray Laser Project XFEL



http://www-ssrl.slac.stanford.edu/lcls/
http://xfelinfo.desy.de/en/start/2/

Other 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

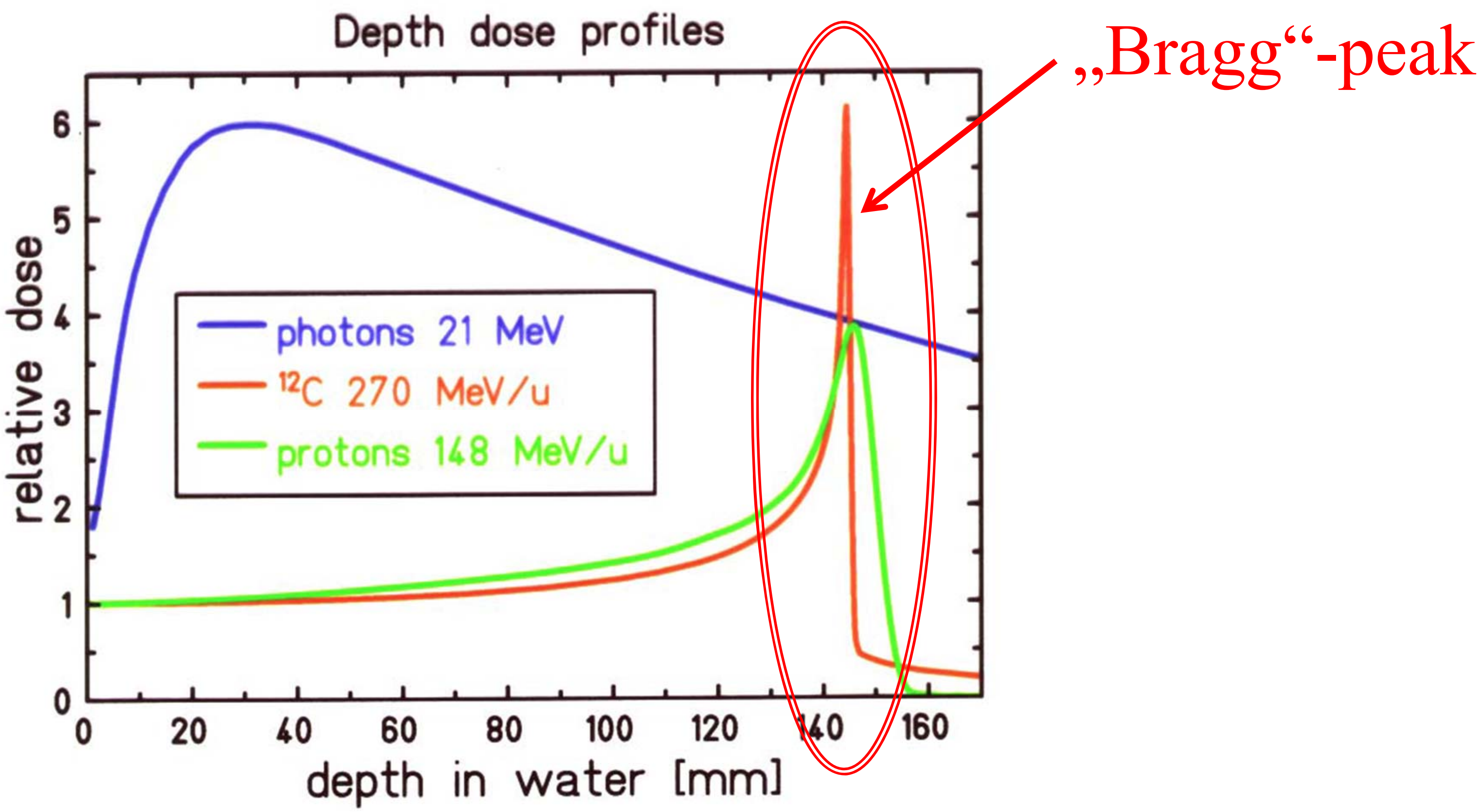
http://www.acceleratorsamerica.org/resources/applications/index.html

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 know 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

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

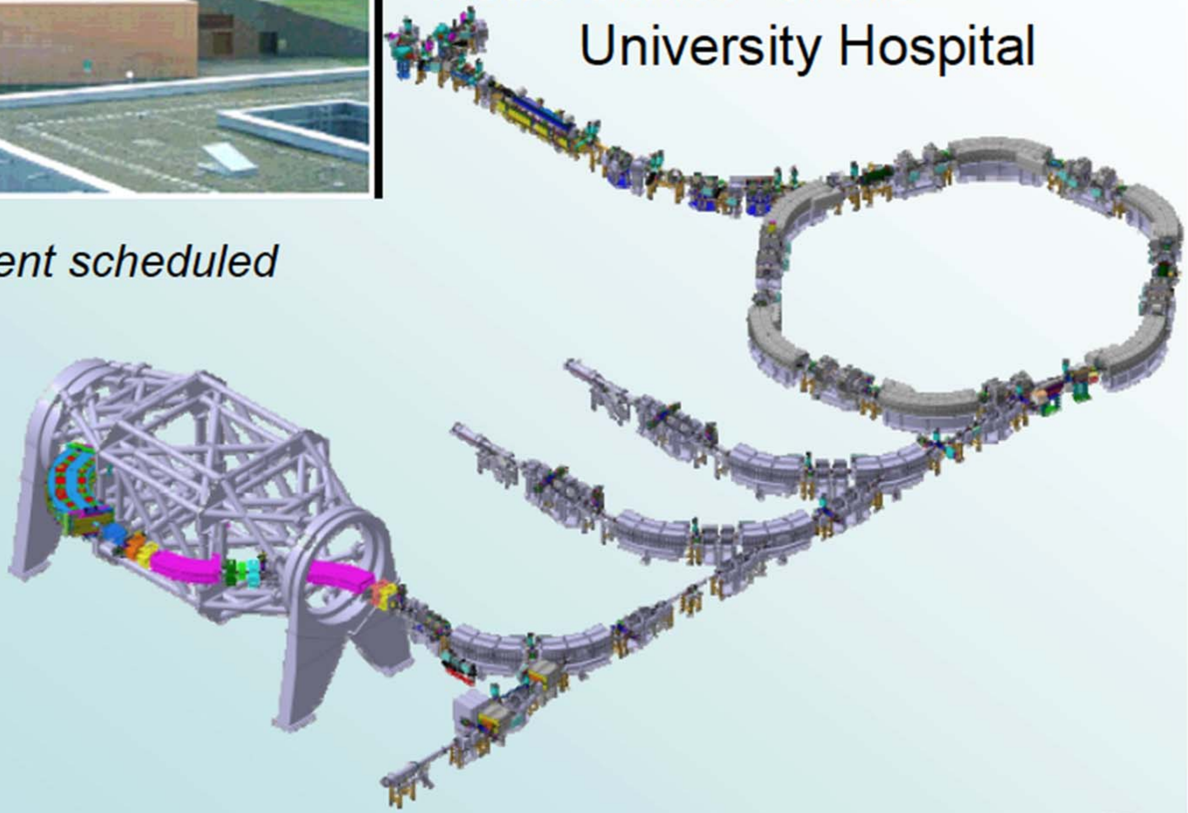


Hadron therapy centers

Particle Therapy Facilities – HIT/Heidelberg

Compact building (60 x 70 m², 3 levels), directly linked to the "Head Clinics" of the University Hospital

Start of patient treatment scheduled in 2 weeks

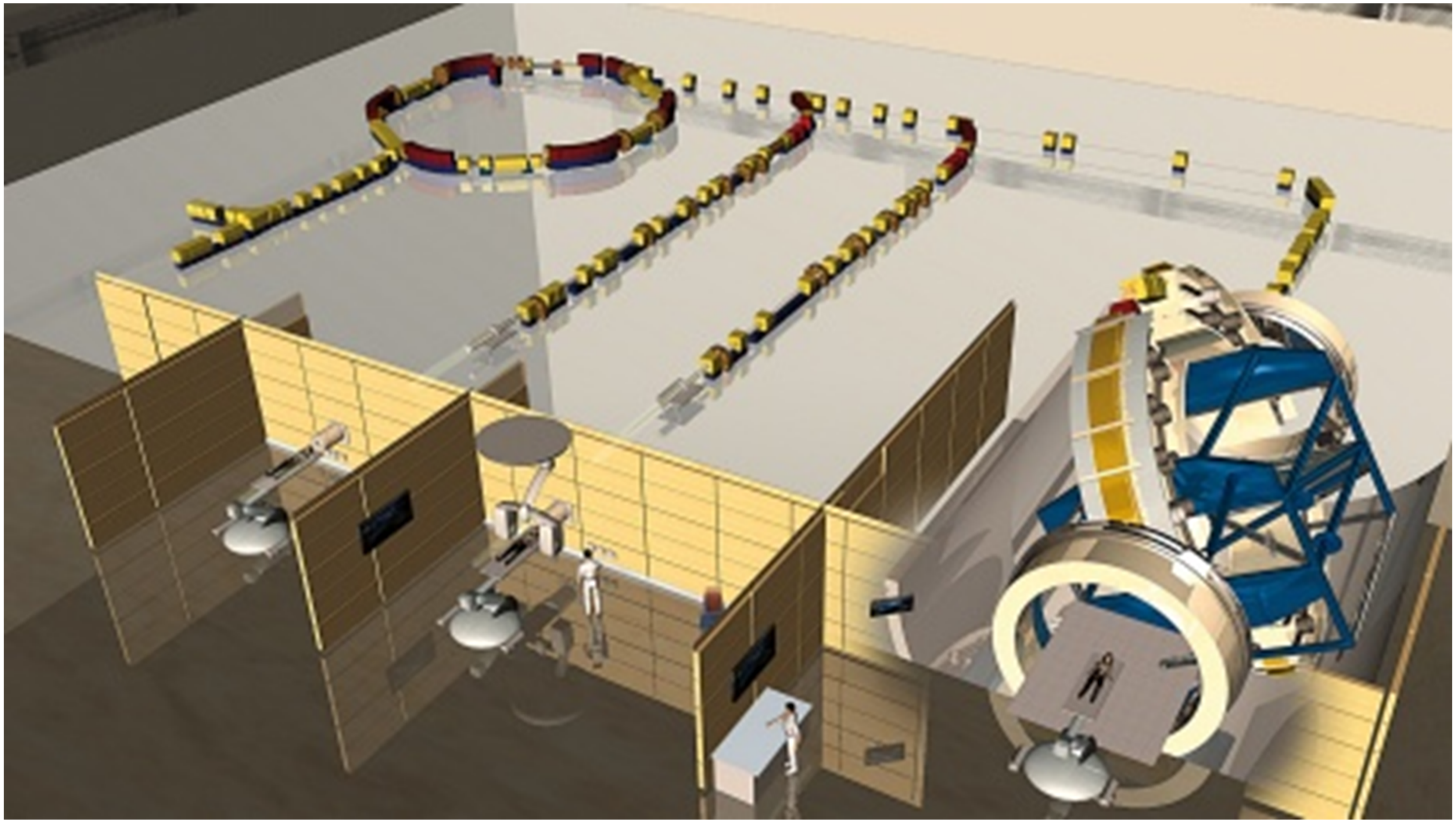


HIT
Heidelberger Ionenstrahl-Therapiezentrum

Accelerator Parts

Gantries: monsters in modern accelerators

The HIT facility. Source: Photo Gallery of the HIT.



Accelerator Parts

Gantries: monsters in modern accelerators

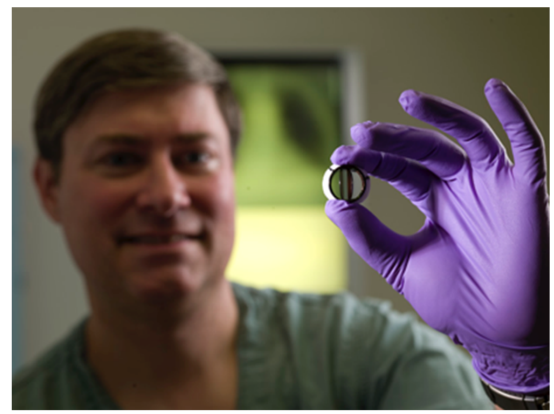
Accelerators for Industrial Application

- **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

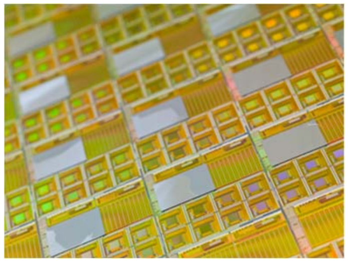
The auto industry uses particle accelerators to treat the material for radial tires, eliminating the use of solvents that pollute the environment.

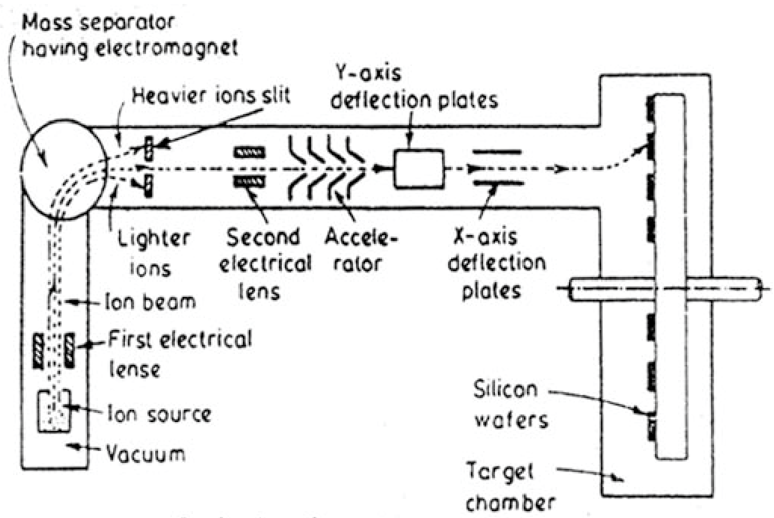


There is a hope to improve the safety of artificial heart valves by forming them from material bombarded by ions

Ion implantation

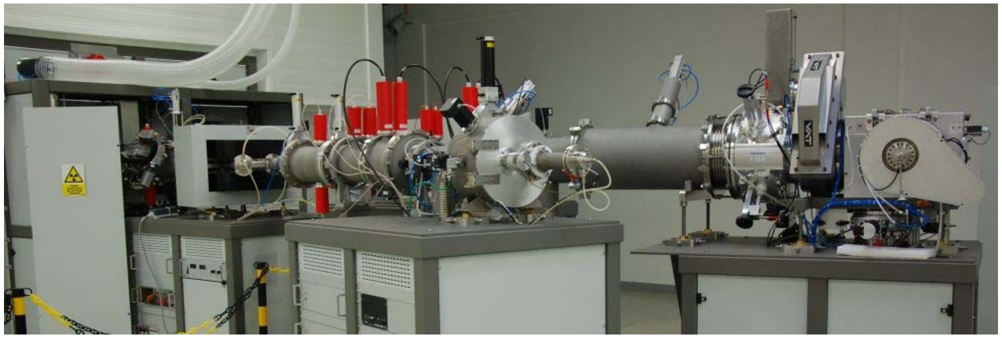
The semiconductor industry relies on accelerator technology to implant ions in silicon chips.





Ion implantation system.

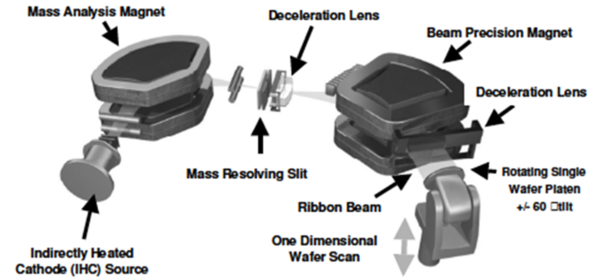
- Semiconductors are usually made from silicon - sometimes germanium - that has been **doped.**
- **Doping** is the process of adding impurities to the silicon so that an electric current flows through the material (silicon crystal is an insulator).
- The doping of silicon is done by a process known as **ion implantation.** In this process, **a beam of ions is fired at a target material.** The ions then penetrate and come to rest within the material at a penetration depth related to the energy of the beam.
- The development of ion implantation technology leads to **better and cheaper semiconductor production,** which in turn drives down the cost of electronics and improves the quality of the product.



Ion implantation

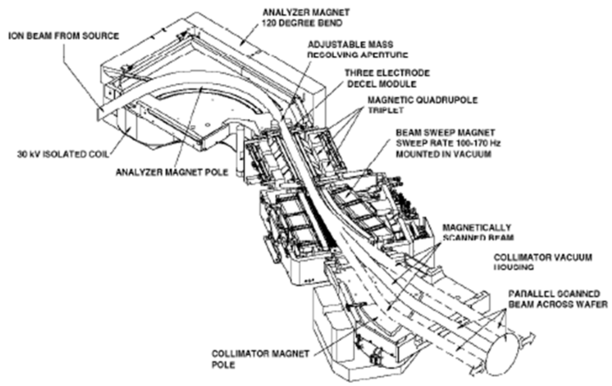
Ion Implantation Accelerators

Accelerator classifications



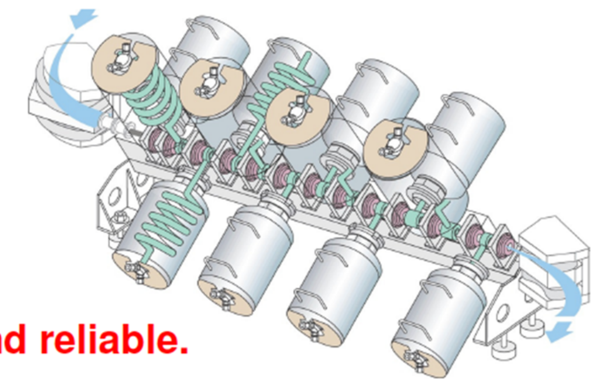
•Low energy/ high current

- "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.



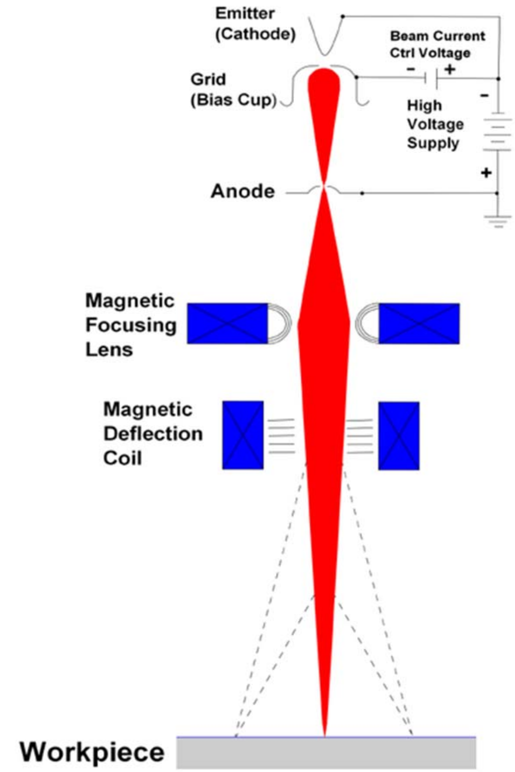
•High energy/ low current

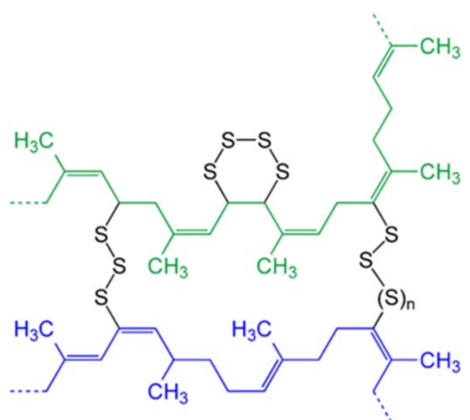
- Variable energy from 1 to 10 MeV
- Beam currents to hundreds of microamperes.
- Can be linacs or tandem charge-exchange columns
- Both use high-charge-states for upper energy range.

These systems have become highly specialized and reliable.

Crosslinking

- A cross-link is a bond that links one polymer chain to another.
- When cross links are added to long rubber molecules, the flexibility decreases, the hardness increases and the melting point increases as well.
- **High energy electron beam can be used to help with the cross-linking process**
    - A shower of fast moving electrons strike your product as it is conveyed through the beam.
    - The long chain molecules of the polymer are ionized by the fast electrons.
    - The ionized polymer chains connect to each other and crosslinked polymer matrix is created.
    - The polymer matrix has improved physical properties compared to original material.

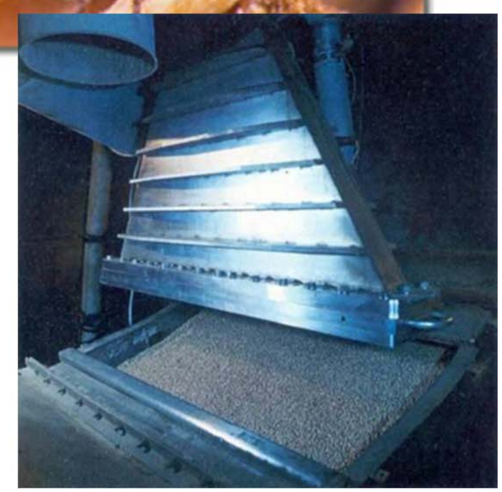




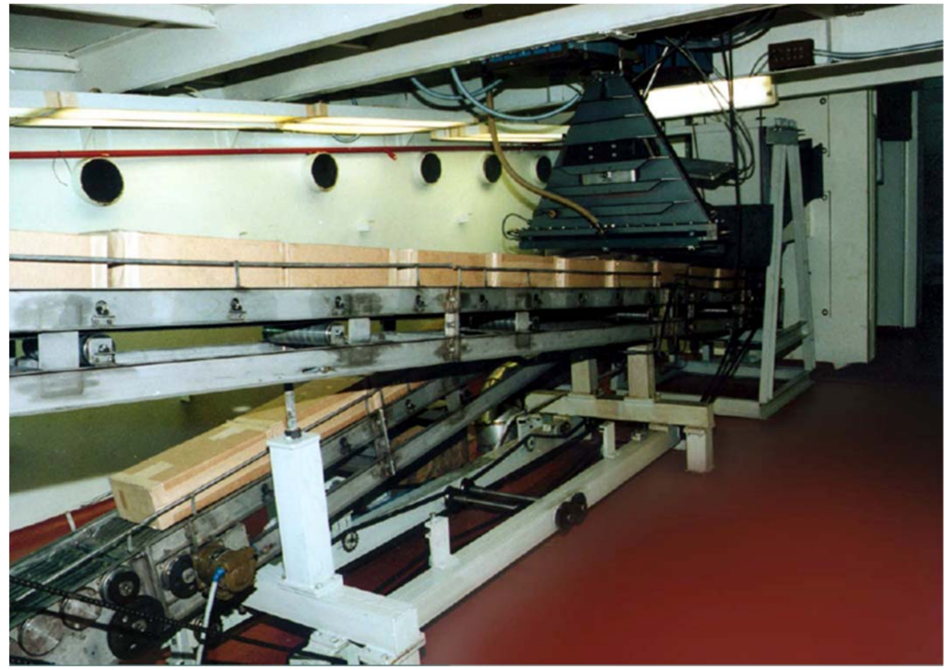
Vulcanization is an example of cross-linking. Schematic presentation of two "polymer chains" (blue and green) cross-linked after the vulcanization of natural rubber with sulfur (n = 0, 1, 2, 3 …).

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.
- ✓ Electron 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.



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.

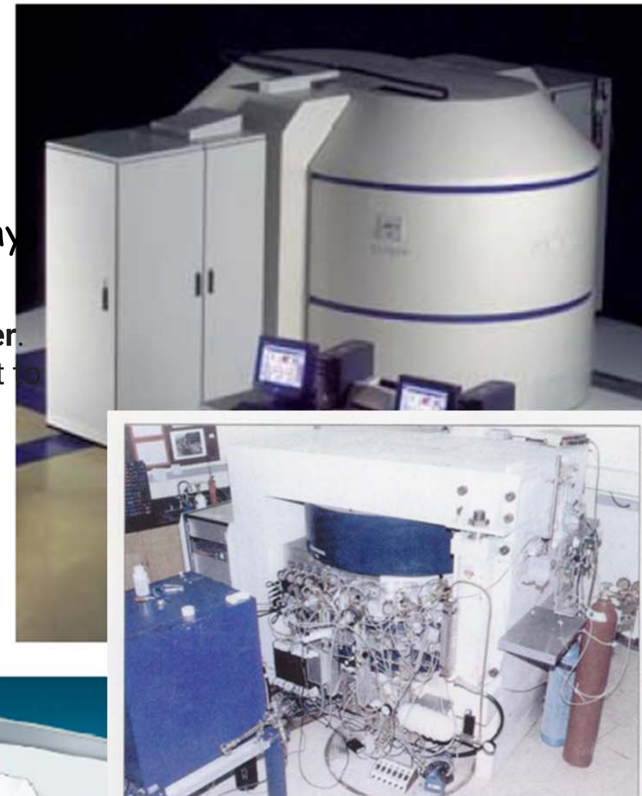
A significant area for this technology is the herb and spice industry. These commodities are valued for their distinctive flavors, aromas and colors. They can be processed by this technology to reduce bacterial contamination without compromise to their sensory properties.

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

Radioisotope Production

- **Applications** (>50 routine radioisotopes)
  - Industrial – Gauging & calibration
  - Medical – Diagnostics & treatment
    - SPECT (Single-photon emission computed tomography)
    - PET (Positron emission tomography)
    - Brachytherapy **a type of radiation therapy used to treat cancer**. It places radioactive sources inside the patient to kill cancer cells and shrink tumors.
- **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)

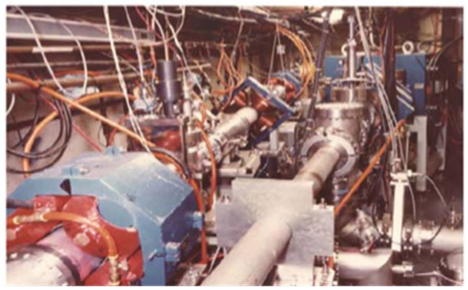


Large growth in compact accelerators for PET.

Brookhaven LINAC Isotope Producer (BLIP)

Figure 2. The LINAC supplies protons to the Booster for high energy physics. Excess pulses (~85%) are diverted to BLIP. Energy is incrementally variable from 118-202 MeV.

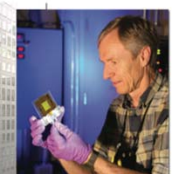
Figure 3. The BLIP beam line directs protons up to 105μA intensity to targets; parasitic operation with nuclear physics programs



Large Scale Accelerator-Based Production of the Cancer-Treatment Agent Actinium-225

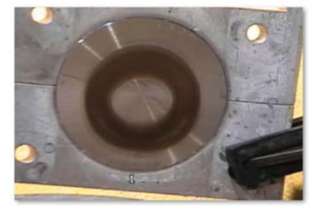
DOE's Office of Science, Office of Nuclear Physics has recently granted approval of a Tri-Lab research effort to provide accelerator-produced ^{225}Ac for radioimmunotherapy. Oak Ridge National Laboratory (ORNL), Brookhaven National Laboratory (BNL) and Los Alamos National Laboratory (LANL) make up the Tri-Lab team. The Tri-Lab team will leverage accelerator capabilities at BNL's Brookhaven Linac Isotope Producer and LANL's Isotope Production Facility along with ORNL's extensive experience with the processing of ^{225}Ac from ^{229}Th. The long term goal is to provide up to curie amounts of ^{225}Ac to users each year.

New York City's Times Square



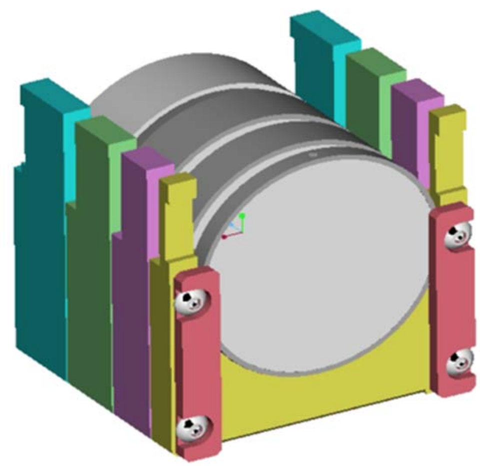
Los Alamos scientist Meiring Nortier holds a thorium foil test target for the proof-of-concept production experiments. Research indicates that it will be possible to match current annual, worldwide production of Ac-225 in just two to five days of operations using the accelerator at Los Alamos and analogous facilities at Brookhaven.

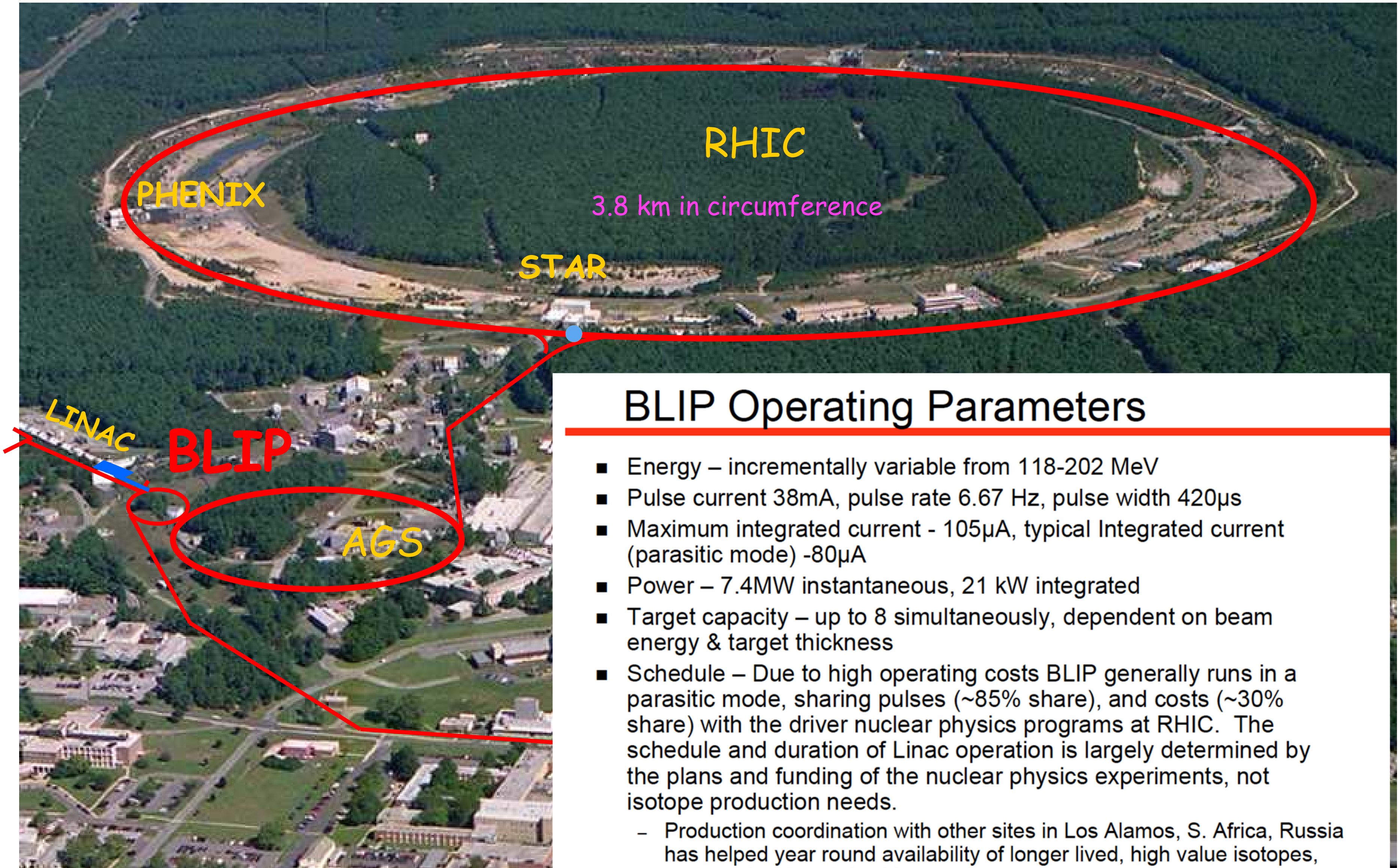
The initial research scope is concentrated on production target development, chemical process methodology improvements, and irradiation parameters to evaluate the associated impacts on the quality of both a final ^{225}Ac product and a ^{225}Ac/^{213}Bi generator. One of the key impacts to be assessed under the Tri-Lab collaboration relates to the content of ^{227}Ac in the final product and its associated influence on the direct application of ^{225}Ac or on use of the associated generator product, ^{213}Bi. Quality is initially being assessed via a series of evaluation campaigns in which small amounts of accelerator-produced ^{225}Ac product and/or ^{225}Ac /^{213}Bi generators are being made available to researchers and clinicians to evaluate the applicability of the accelerator-produced material relative to material derived from ^{229}Th. Preliminary feedback from early ^{225}Ac /^{213}Bi generator evaluation experiments has been encouraging. The generators produce a ^{213}Bi product of equal quality and applicability, with the direct labeling efficiency being similar to that of the ^{229}Th generated material. Near-term effort will focus on the toxicity and dosimetry impacts of ^{227}Ac associated with the direct application of accelerator-produced ^{225}Ac.



10g Th target irradiated at IPF in support of preliminary ^{225}Ac /^{213}Bi generator evaluation studies. Note the uniform, rastered beam pattern in the exit window.

Isotope	Half- life	Typical application
Be-7	53.3d	γ source
Zn-65	244d	Zn tracer, multiple uses
Cu-67	61.9h	Radioimmunotherapy
Ge-68/Ga-68	271d/68m	PET calibration
As-73	80.3d	As environmental tracer
Sr-82/Rb-82	25.4d/75s	PET studies of heart
Y-88	106.6d	Y-90 tracer, γ source
Tc-95m	61d	Tc tracer





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.