PHY 514
A Bit of Accelerator Physics

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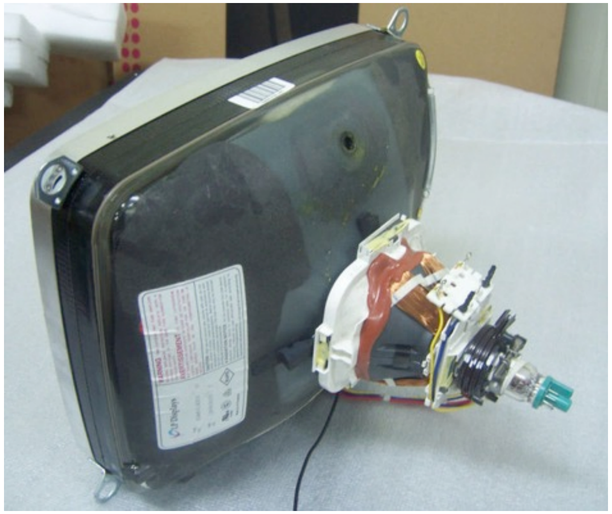
http://www-case.physics.sunysb.edu/wiki/index.php/Main_Page



Billions of these tubes were made in 20th century – now most of them are in the landfills…

Plan to talk about:

- Accelerators - what they are useful for?
- Ways of accelerating charged particles?
- RF accelerations - the best way known?
- Circular accelerators: bending, focusing & auto-phasing
- Energy recovery linacs - new direction in accelerators

What Accelerators Are Good For

- High Energy Physics
  - Explore the electro-weak bosons Z, W (LEP)
  - Find and exploit "new" and heavy quarks (Tevatron)
  - Find the HIGGS ? (LHC)
  - Well, this list will never be complete .....
- Nuclear Physics (RHIC, SPS)
  - First evidence of a new state of matter, quark gluon plasma? (SPS)
  - Create the QGP and determine its properties (RHIC)
  - Could it be something else? (RHIC II, eRHIC)
- Chemistry, Biology, Medicine, Material Sciences
  - Find the structure of molecules, proteins, cells…
  - Could people survive interstellar travel? (NASAs NSRL)
  - Time-resolved structural changes in a natural (fsec) time scale
- Civil, Industrial and Military Applications
  - Treat cancers, produce isotopes for medical imaging, sterilize products…
  - Scan containers in ports for undesirable content (n's?)
  - High power free electron lasers as weapons for a ship defence

What Are Accelerators and how 'good' are they?

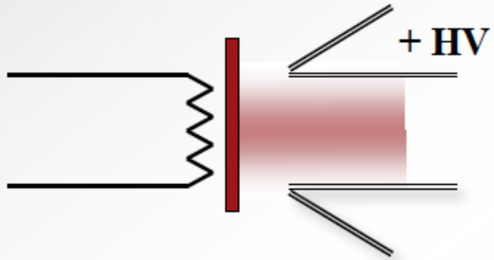
- Type of accelerated particles: electrons or positrons, protons or antiprotons, ions, muons, atoms….
- Energy of the particle : keV, MeV, GeV, TeV…
  - Au… 28 TeV at RHIC, 7 TeV protons at LHC, 10 keV electrons in X-ray tube, few MeV protons in Van-De-Graph (SBU basement),
- Performance – luminosity or event rate, instantaneous and integrated luminosity
- Beam intensity - Number of particles per second, I.e. beam current (=> instantaneous luminosity)
- Beam quality - transverse and longitudinal emittance, which is simply phase-space (remember Louisville theorem) occupied by the particles and its projections (=> instantaneous luminosity)
- Beam lifetime – number of particles lost per second, i.e. Loss rate, lifetime limiting processes (=> integrated luminosity)
- Method(s) of acceleration: electrostatic, induction, Radio-Frequency (RF) fields

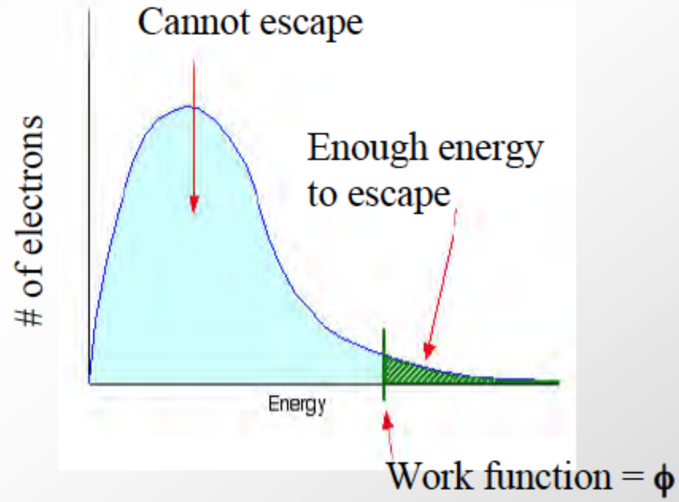
1keV = 10^3 eV, 1 MeV = 10^6 eV, 1 GeV = 10^9 eV , 1TeV= 10^{12}eV, …1eV = 1.6 10^{-19} J

1 nsec = 10^{-9} sec, 1 psec = 10^{-12} sec, 1 fsec = 10^{-15} sec, 1 asec = 10^{-18} sec….

Thermionic electron source

- Heated metals
  - Some electrons have energies above potential barrier



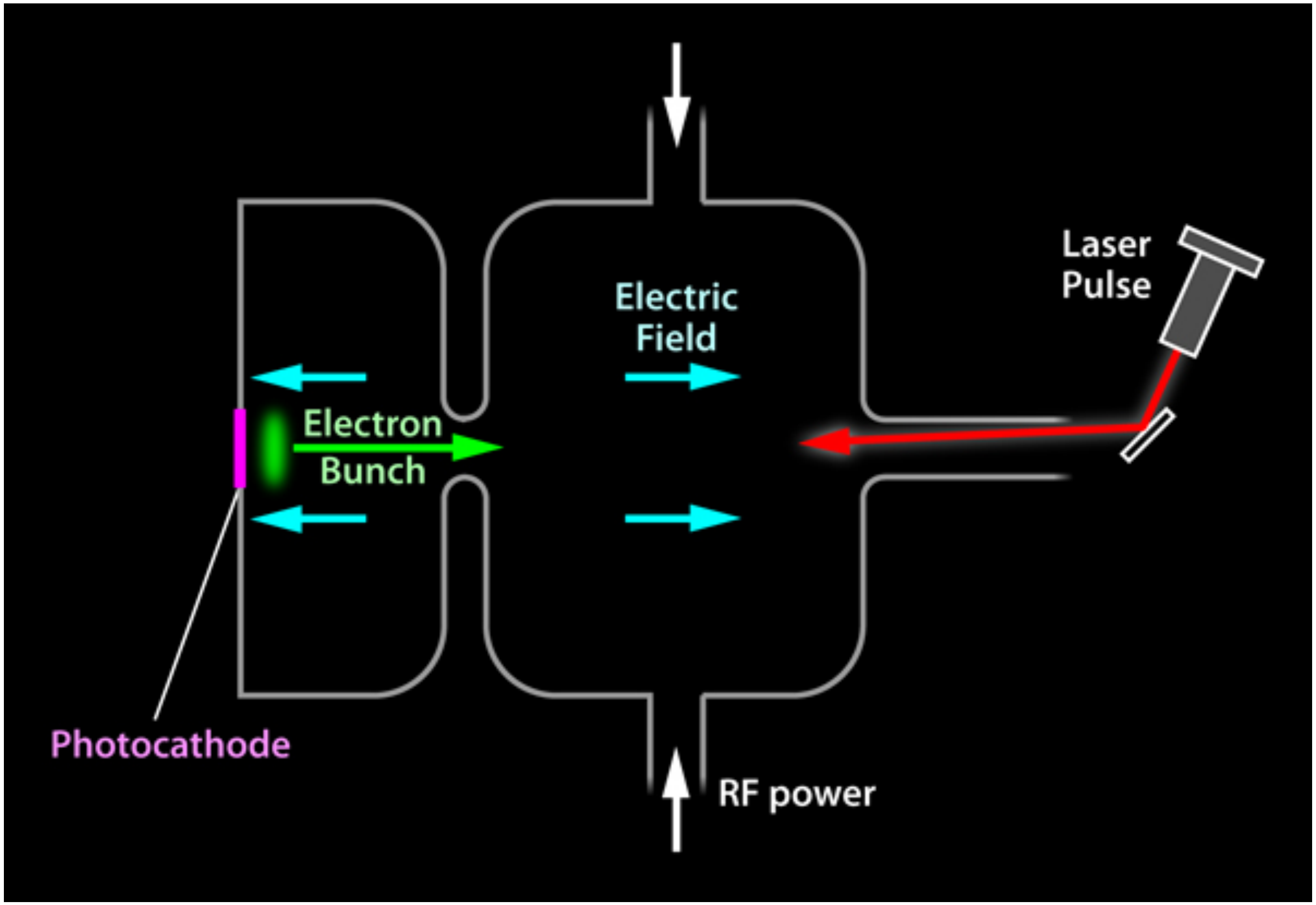


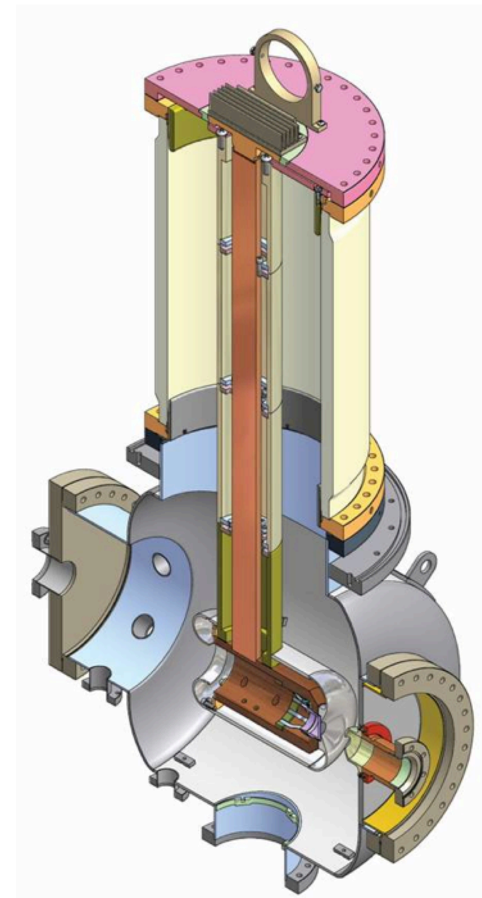
Electrons in a metal obey Fermi statistics

$$\frac{dn(E)}{dE} = A\sqrt{E}\,\frac{1}{\left[e^{(E-E_F)/kT}+1\right]}$$

Courtesy of W. Barletta

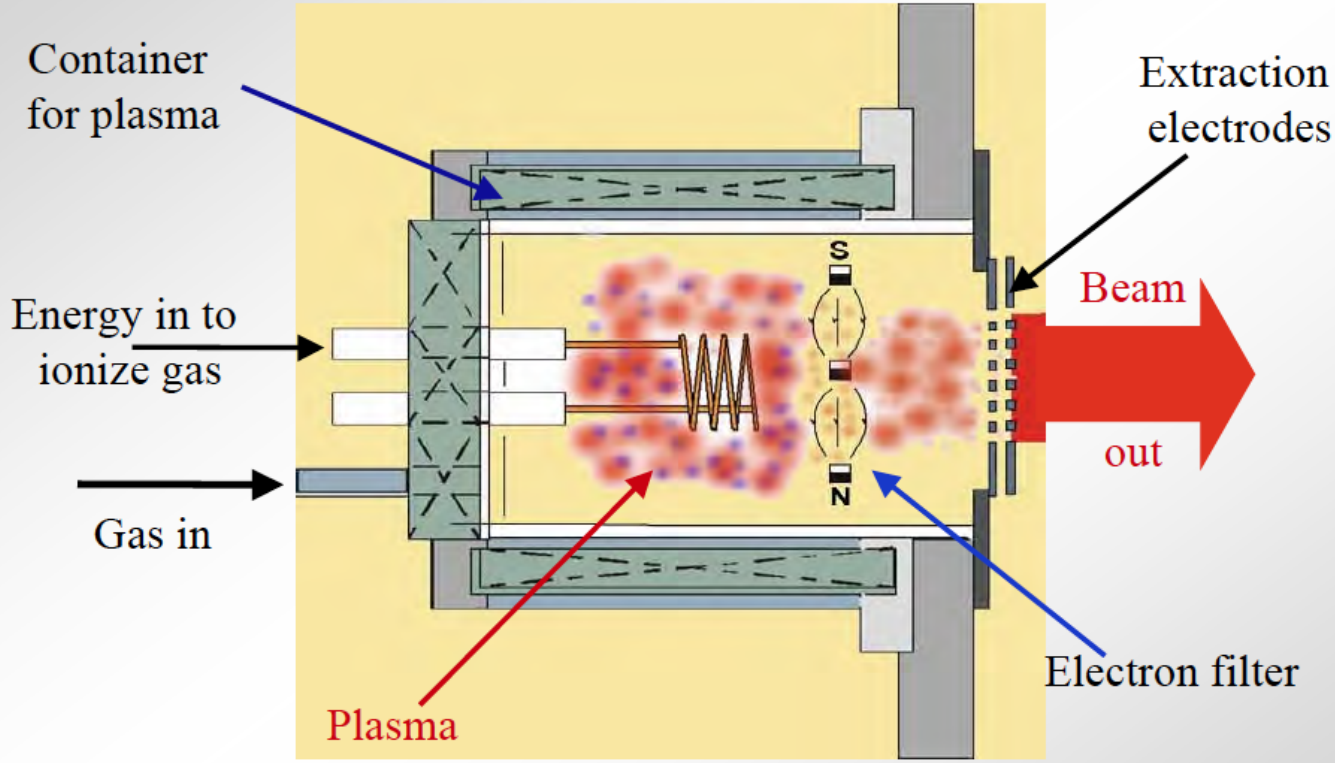
Photo-emission electron source





http://newscenter.lbl.gov/wp-content/uploads/electron-gun.jpg

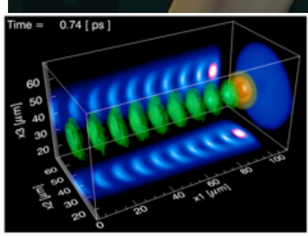
Typical ion source



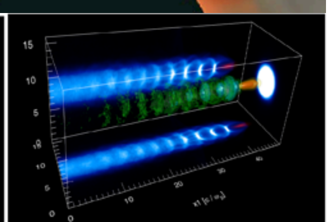
Electron beams can also be used to ionize the gas or sputter ions from a solid

Courtesy of W. Barletta

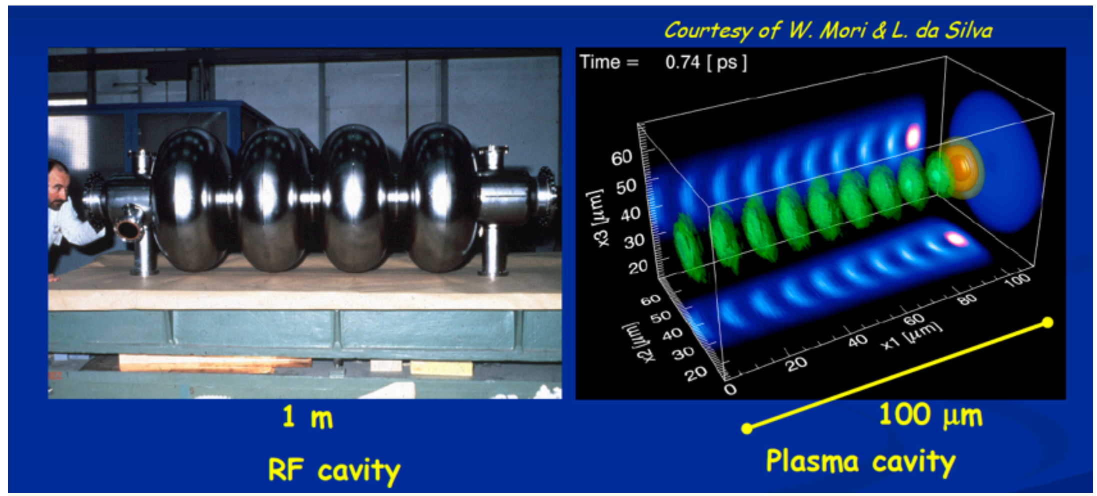
Plasma accelerators

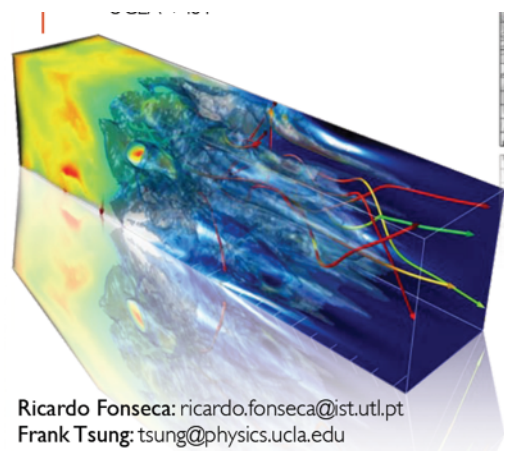


Laser Wake



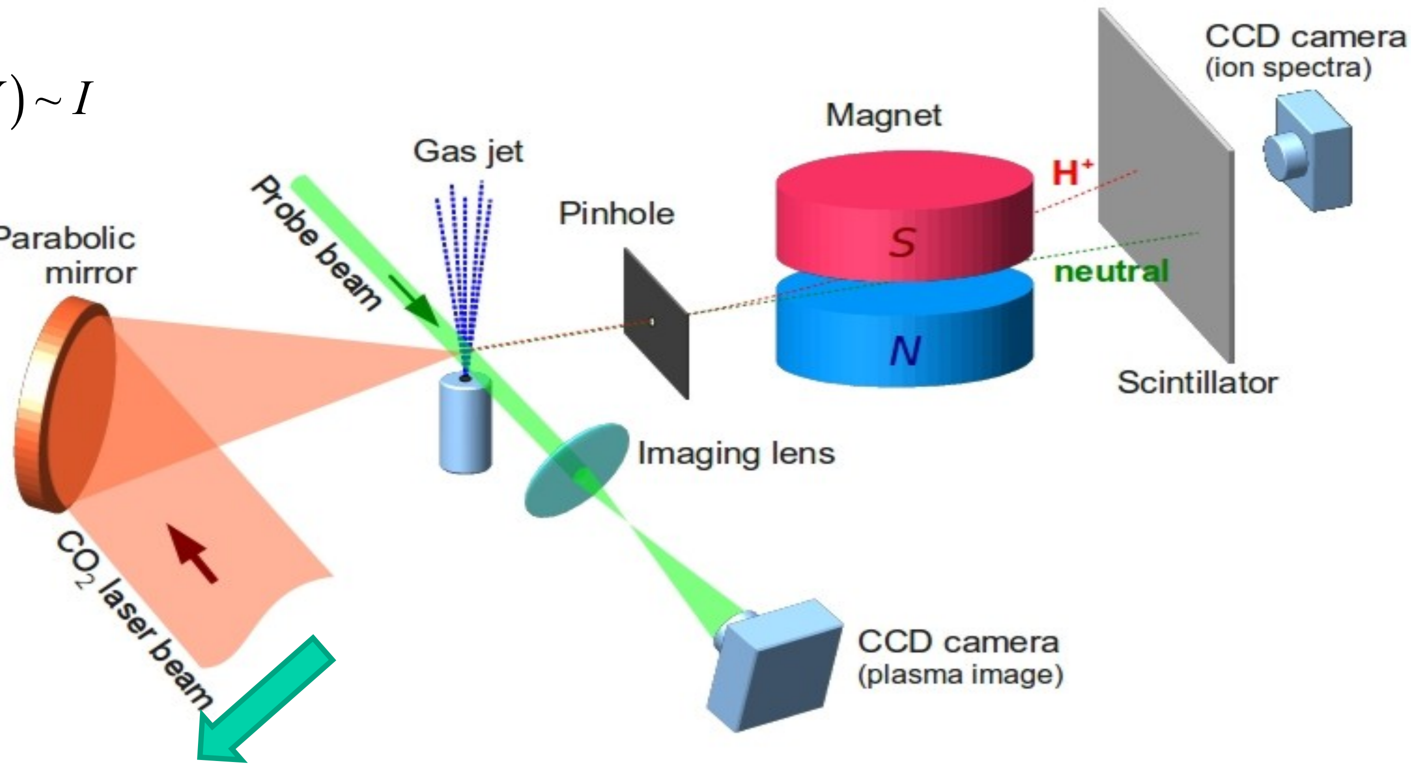
Electron beam Wake





Novel methods: ATF at BNL

$$E_{max}(MeV) \sim I$$

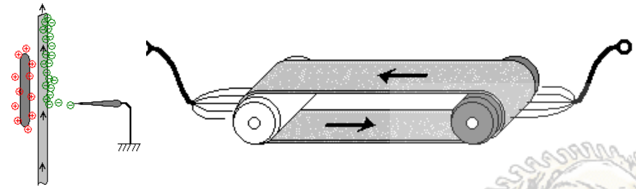


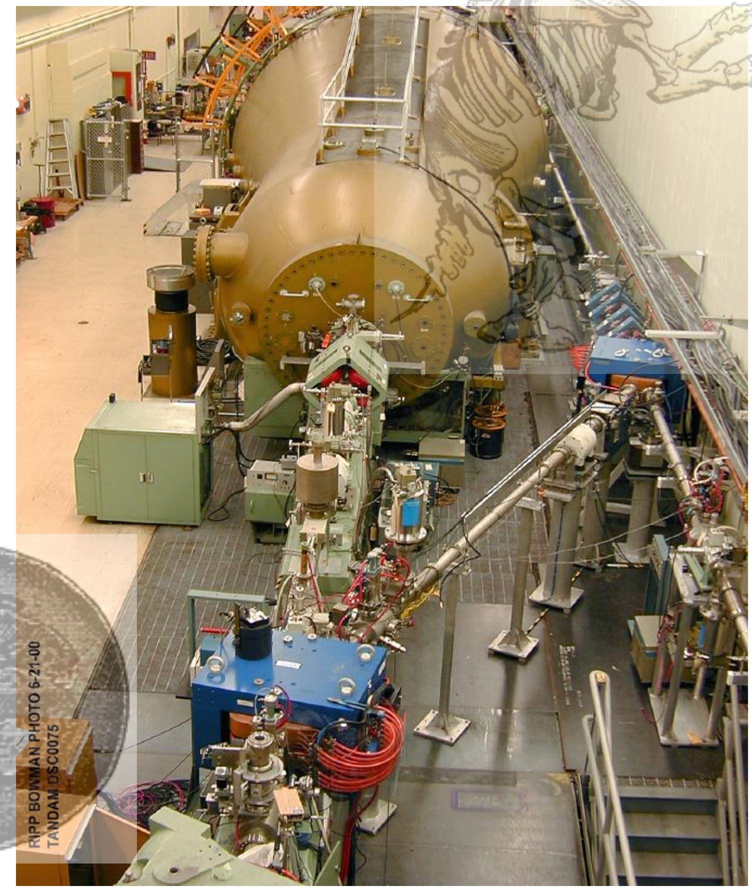
A monoenergetic proton beam is observed from the interaction of a short-pulse infrared laser with a gas jet target. Electron's pushed out of the gas jet (or metal foil) by high laser pulse , then pull out ions and accelerate them.

How to Accelerate charged particle?

Electrostatic: Van De Graff Generator = *Accelerator Archeology*

$$E_p = E_o + q \cdot \varphi(\vec{r})$$

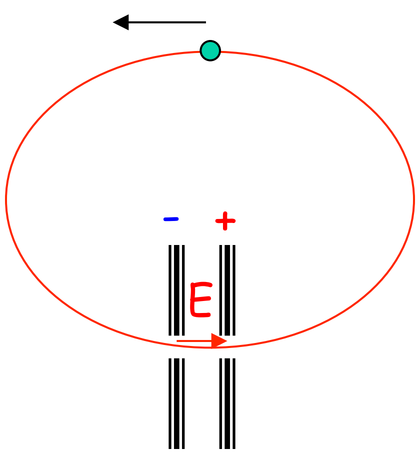




What LIMITS electrostatic acceleration?

Is it possible to accelerate particle many times in the same accelerator?

NO!



EM II: 1st pair of Maxwell's Equations

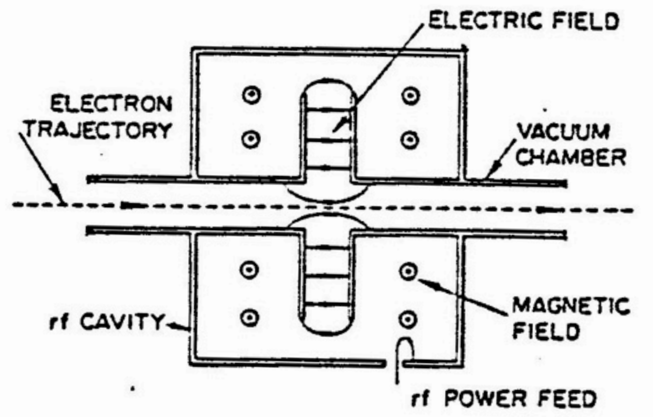
$$\vec{E} = -grad\varphi - \frac{1}{c}\frac{\partial \vec{A}}{\partial t};$$

$$\vec{H} = curl\vec{A};$$

$$d\mathrm{E} = q\left(\vec{E}\cdot d\vec{r}\right) \Rightarrow \Delta\mathrm{E}_{turn} = q\oint \vec{E}\cdot d\vec{r} = -q\left(\varphi(\vec{r}_o, t+\tau) - \varphi(\vec{r}_o, t) + \frac{1}{c}\oint \frac{\partial \vec{A}}{\partial t}\cdot d\vec{r}\right);$$

Hence static field has limitation: $\frac{\partial \vec{A}}{\partial t} = 0, \; \frac{\partial \varphi}{\partial t} = 0 \Rightarrow \Delta\mathrm{E}_{turn} = 0;$

RF accelerators

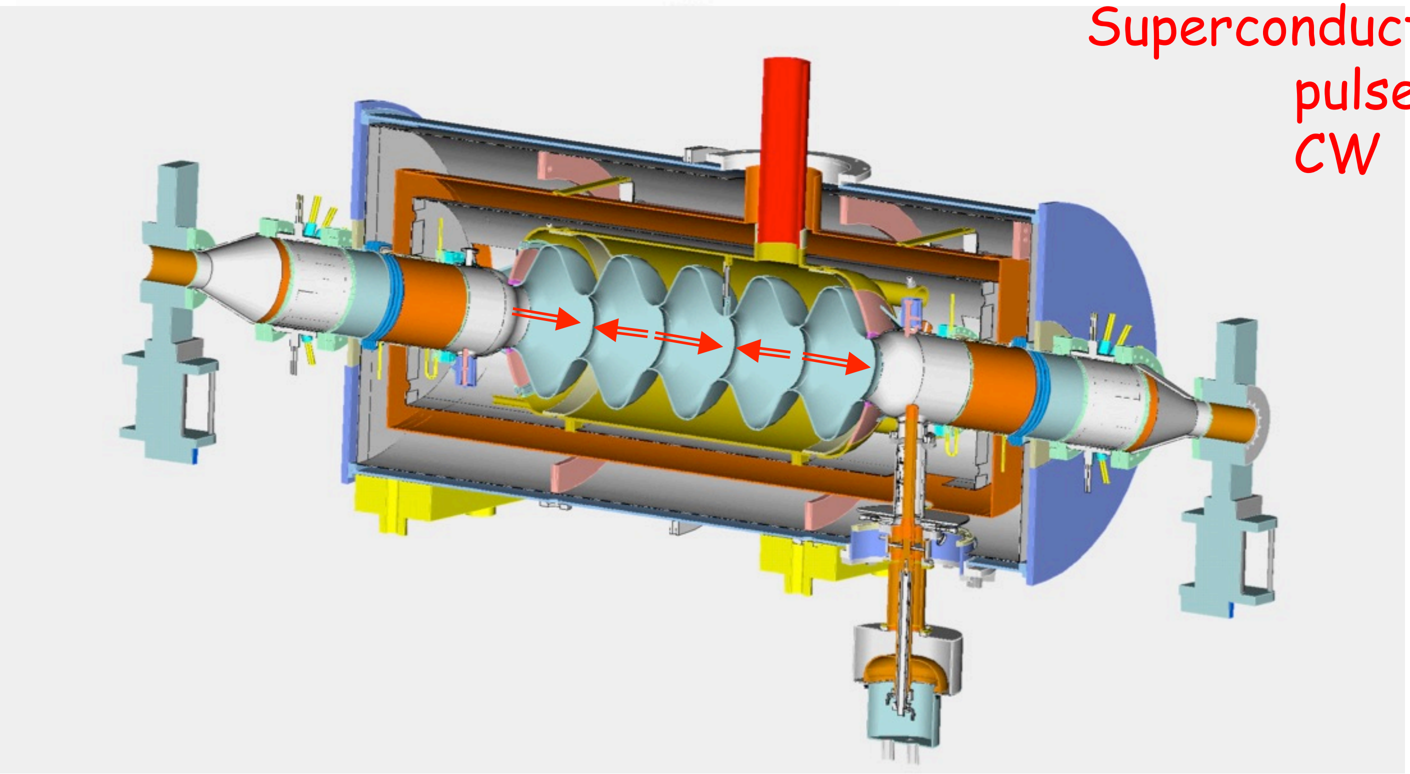


$$dE_p = q\left(\vec{E}\cdot d\vec{r}\right) = q\left(\vec{E}\cdot\vec{v}\right)dt$$

RF accelerators limits:

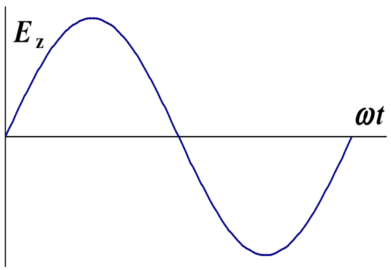
Room t°: pulsed ~150 MV/m
CW ~2 MV/m

Superconducting (2K°)
pulsed ~50 MV/m
CW ~20 MV/m

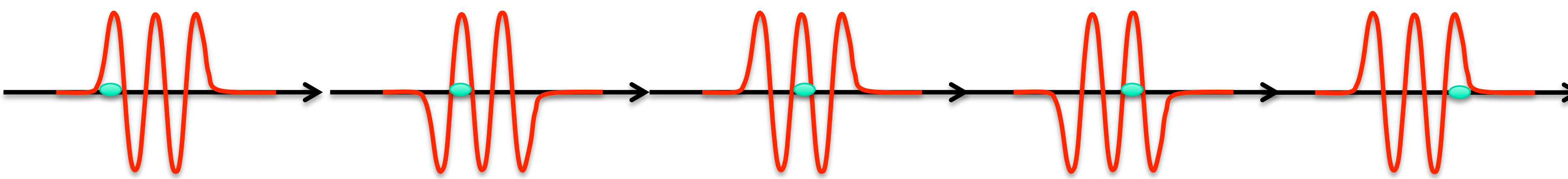


Interlude: RF accelerator

$$\frac{dE}{dt} \equiv mc^2 \frac{d\gamma}{dt} = e\vec{\mathbf{E}}(\vec{r},t) \cdot \vec{\mathrm{v}};$$

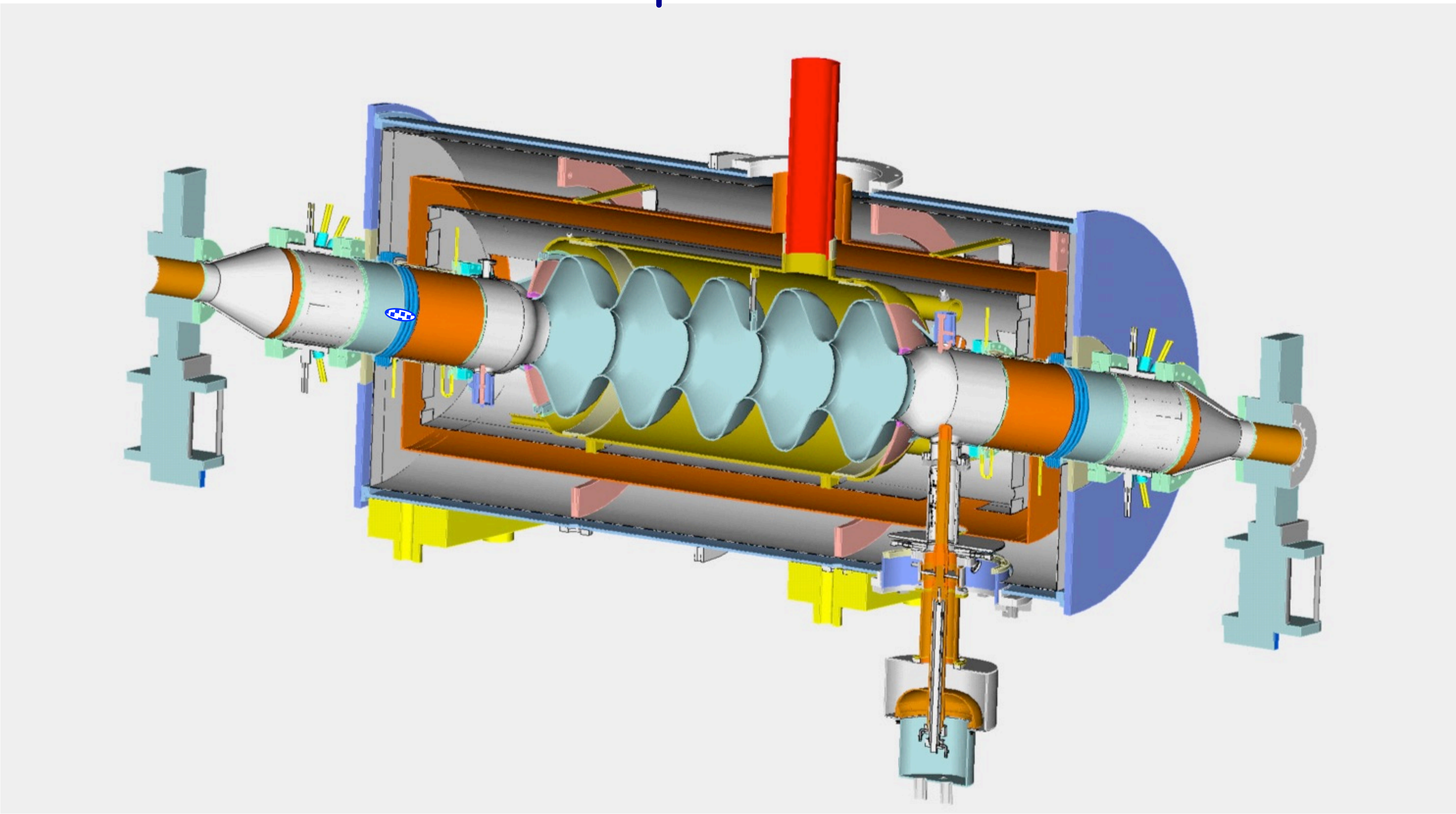


$$V_1 = \int_{-\lambda/4}^{\lambda/4} \mathbf{E}_o(z)\cos(2\pi z)dz = 0 \quad V_2 = \int_{-\lambda/4}^{\lambda/4} \mathbf{E}_o(z)\cos(2\pi z)dz = 0 \quad V_3 = \int_{-\lambda/4}^{\lambda/4} \mathbf{E}_o(z)\cos(2\pi z)dz = 0 \quad V_4 = \int_{-\lambda/4}^{\lambda/4} \mathbf{E}_o(z)\cos(2\pi z)dz = 0 \quad V_5 = \int_{-\lambda/4}^{\lambda/4} \mathbf{E}_o(z)\cos(2\pi z)dz = 0$$



$$\left\langle e\vec{\mathbf{E}}(\vec{r},t) \cdot \vec{\mathrm{v}} \right\rangle \neq 0$$

How β=1 RF accelerator works?
In pictures



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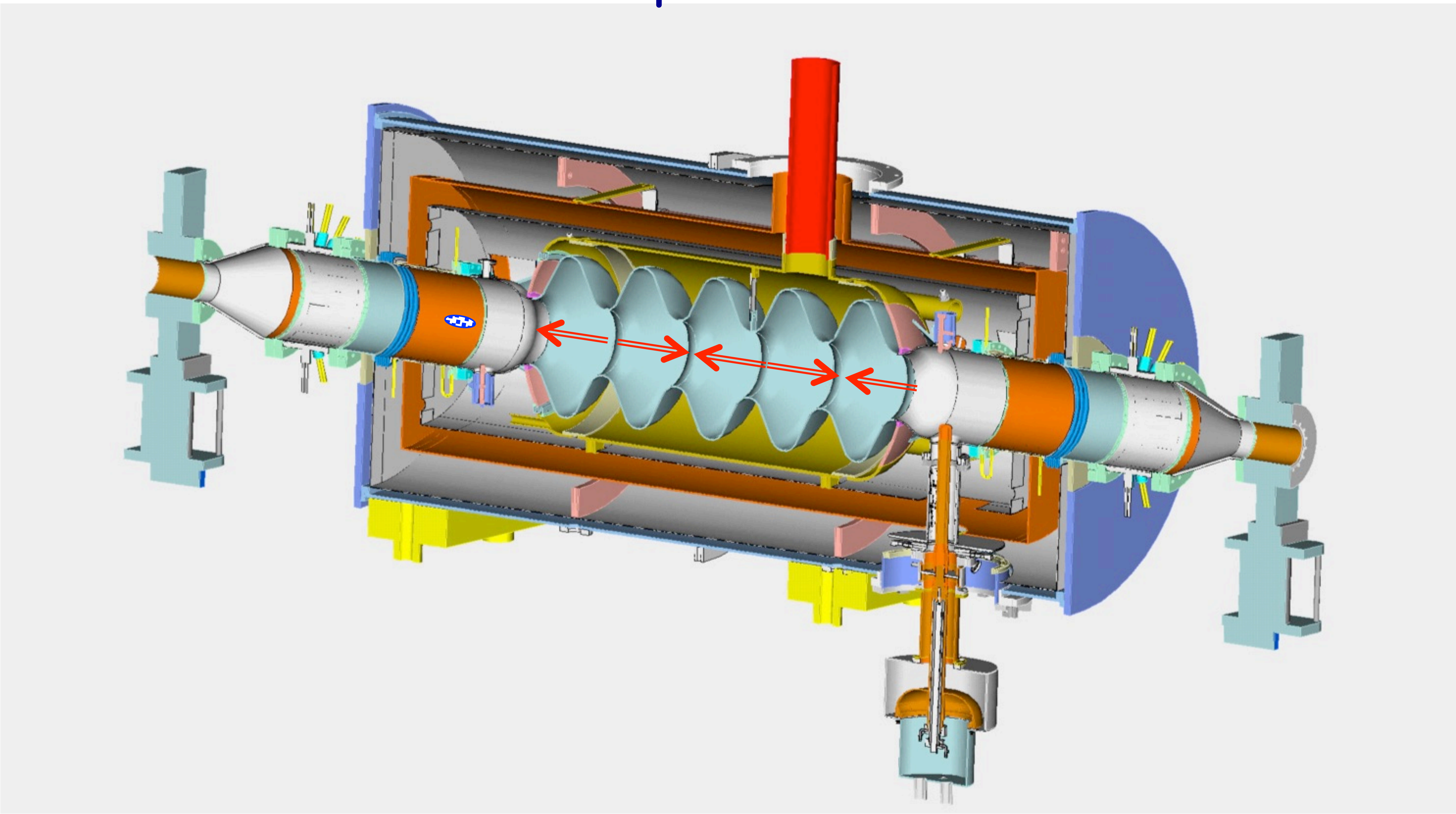

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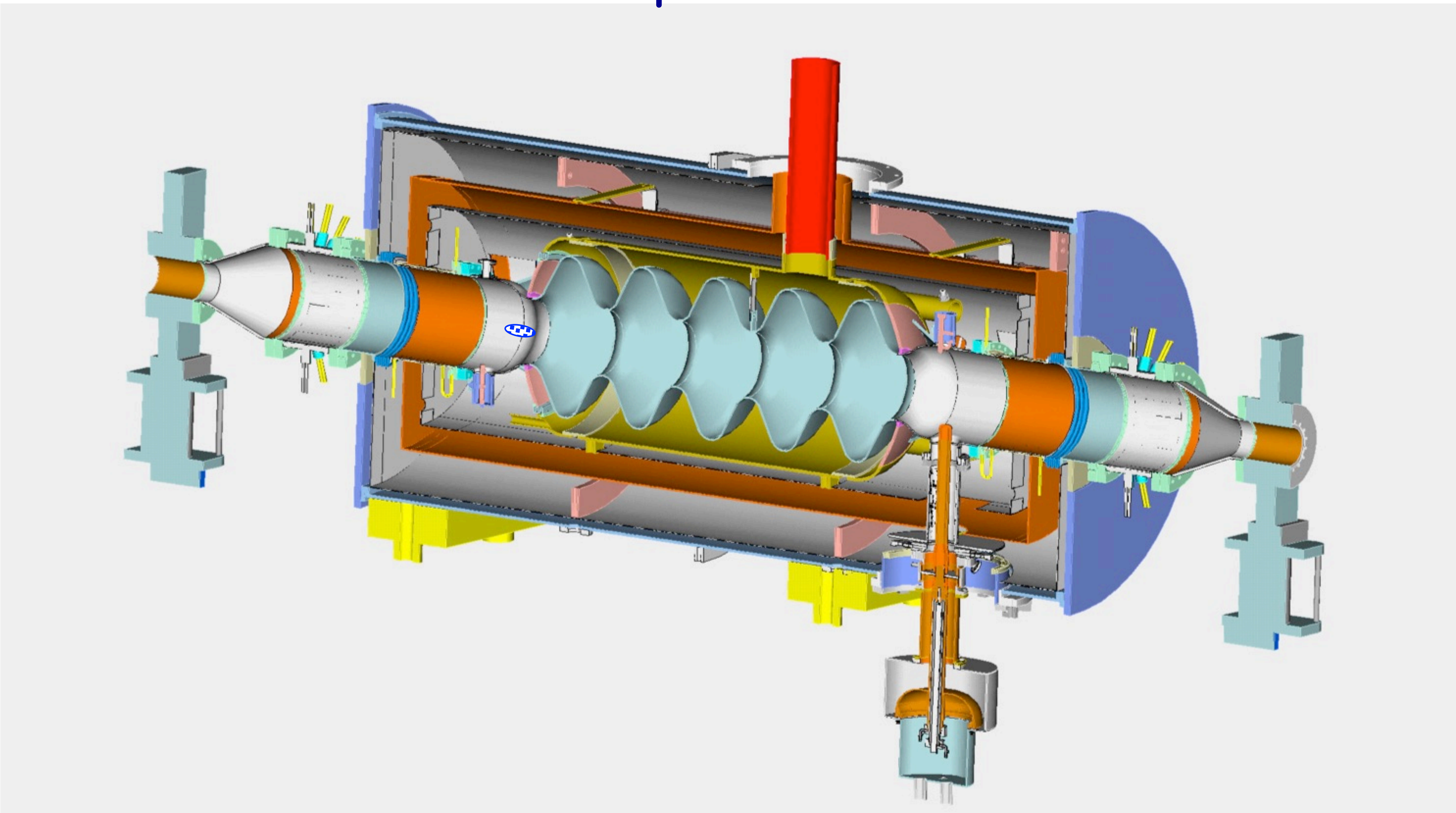

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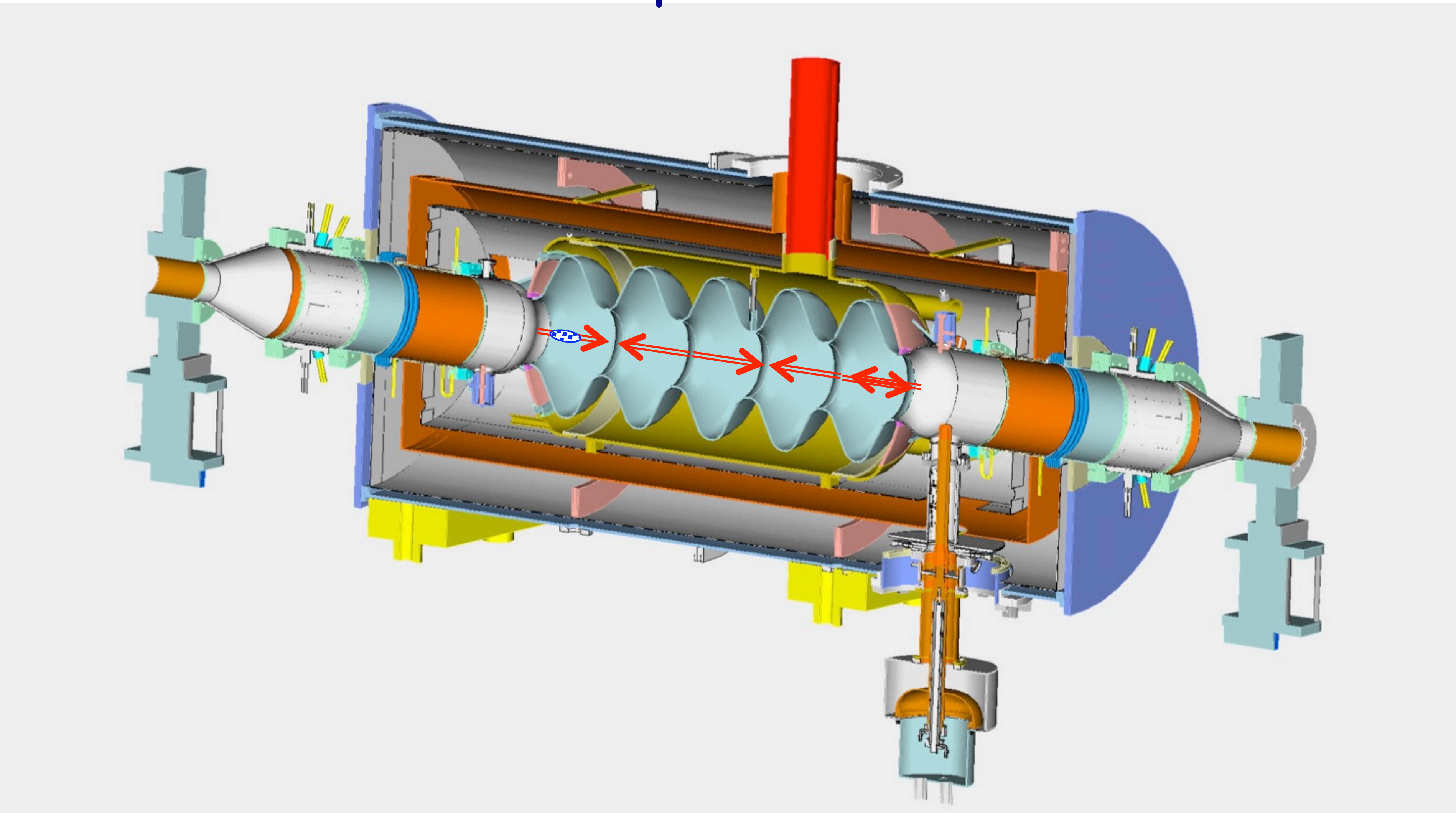

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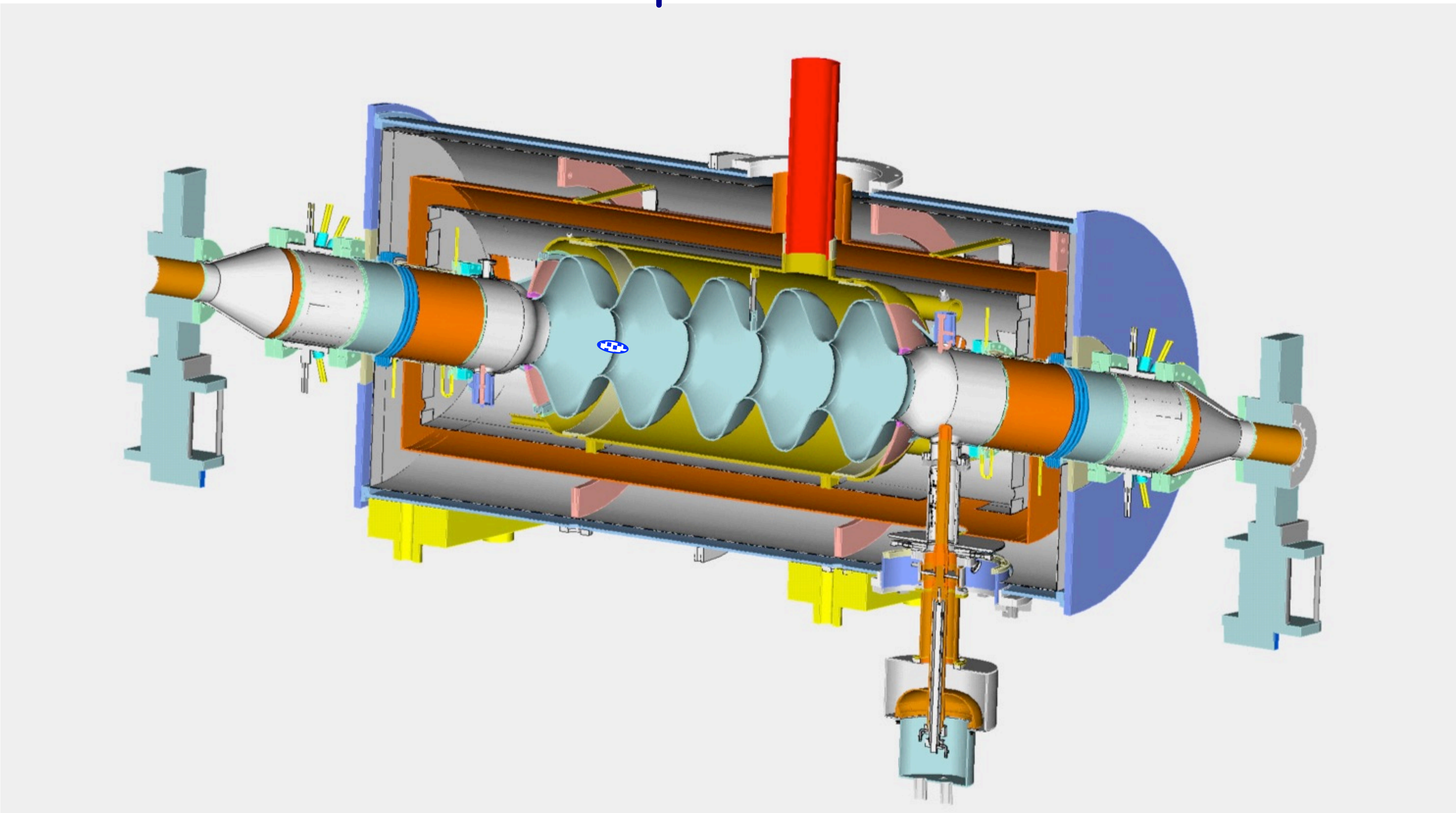

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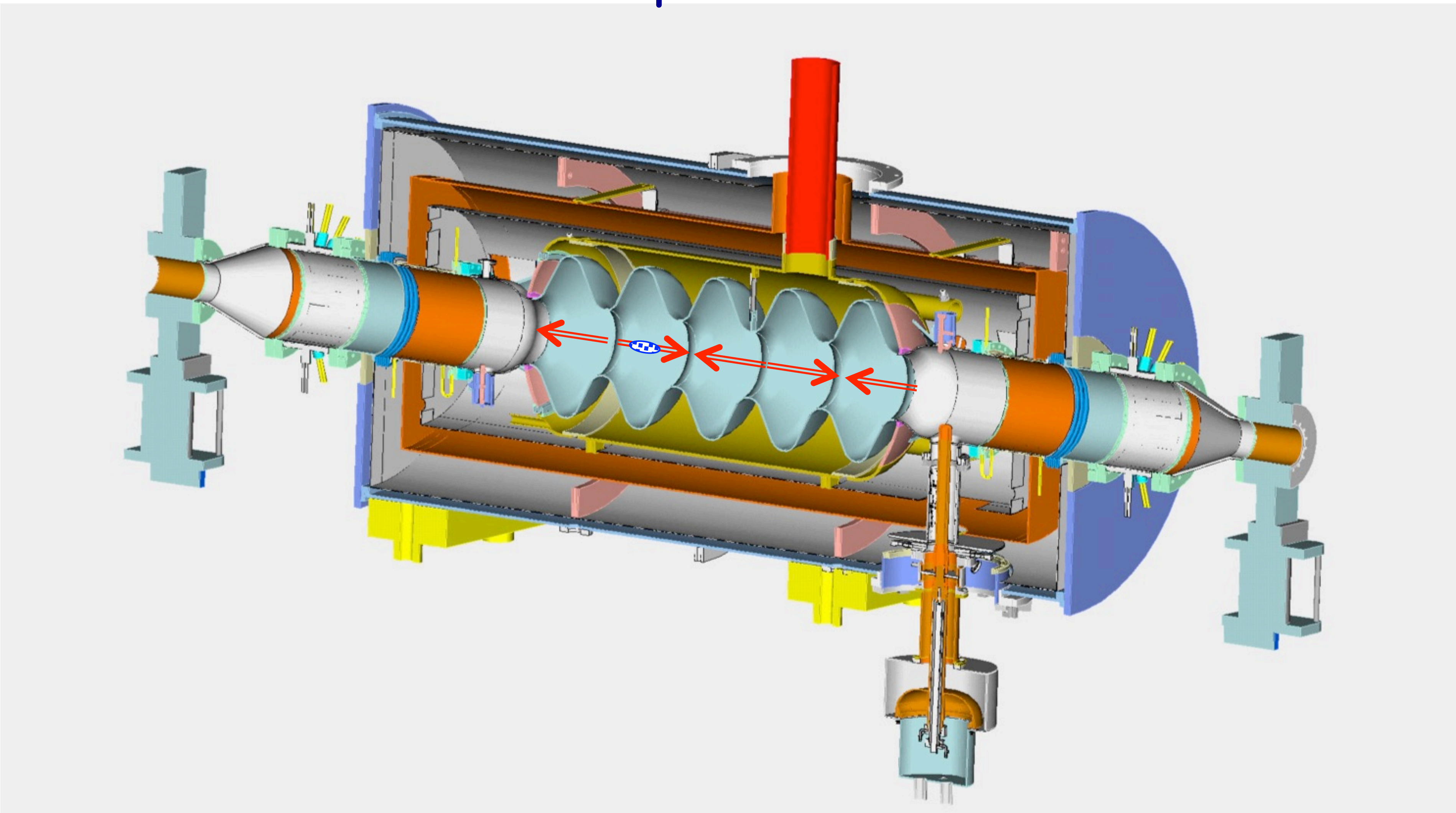

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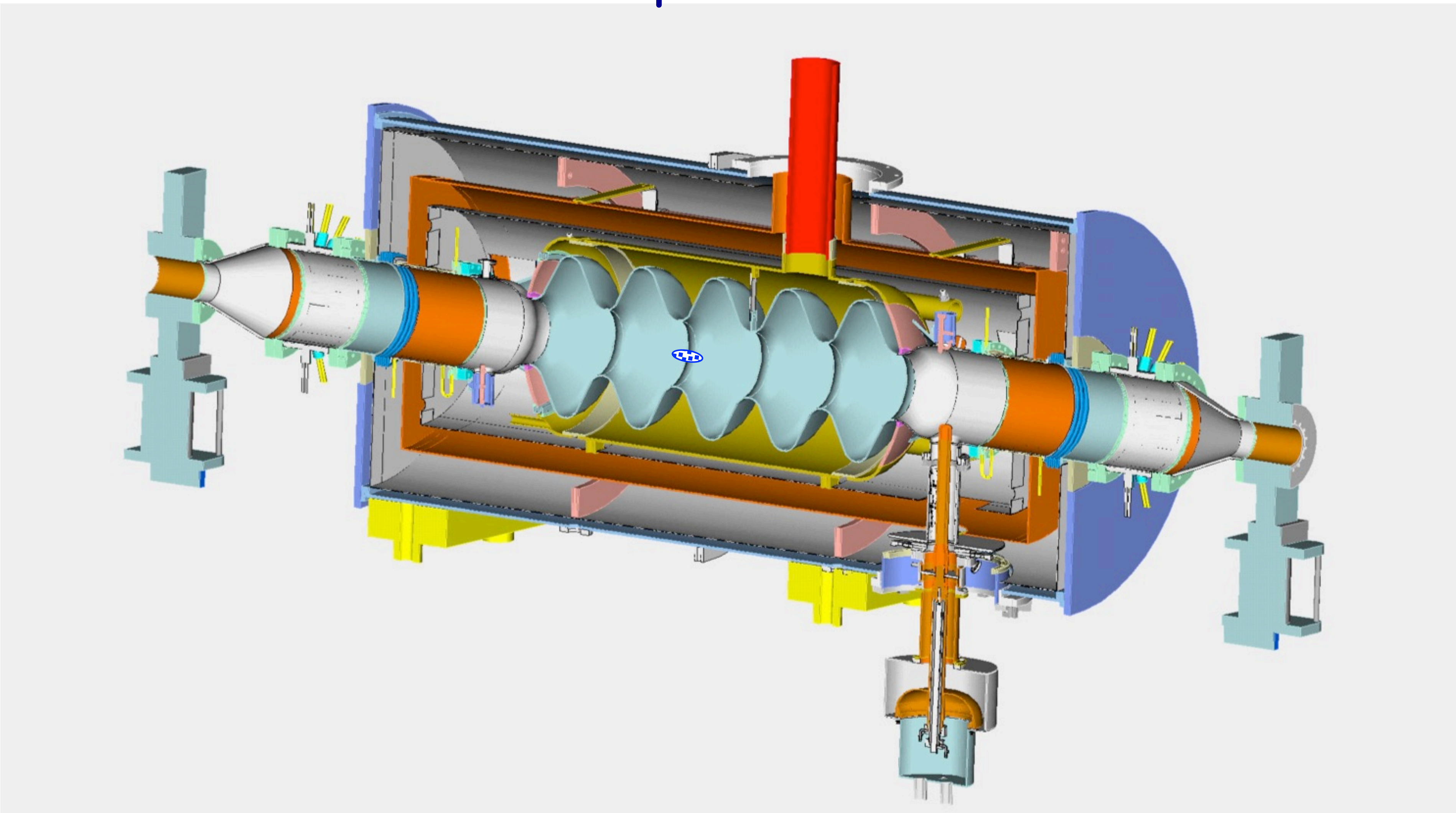
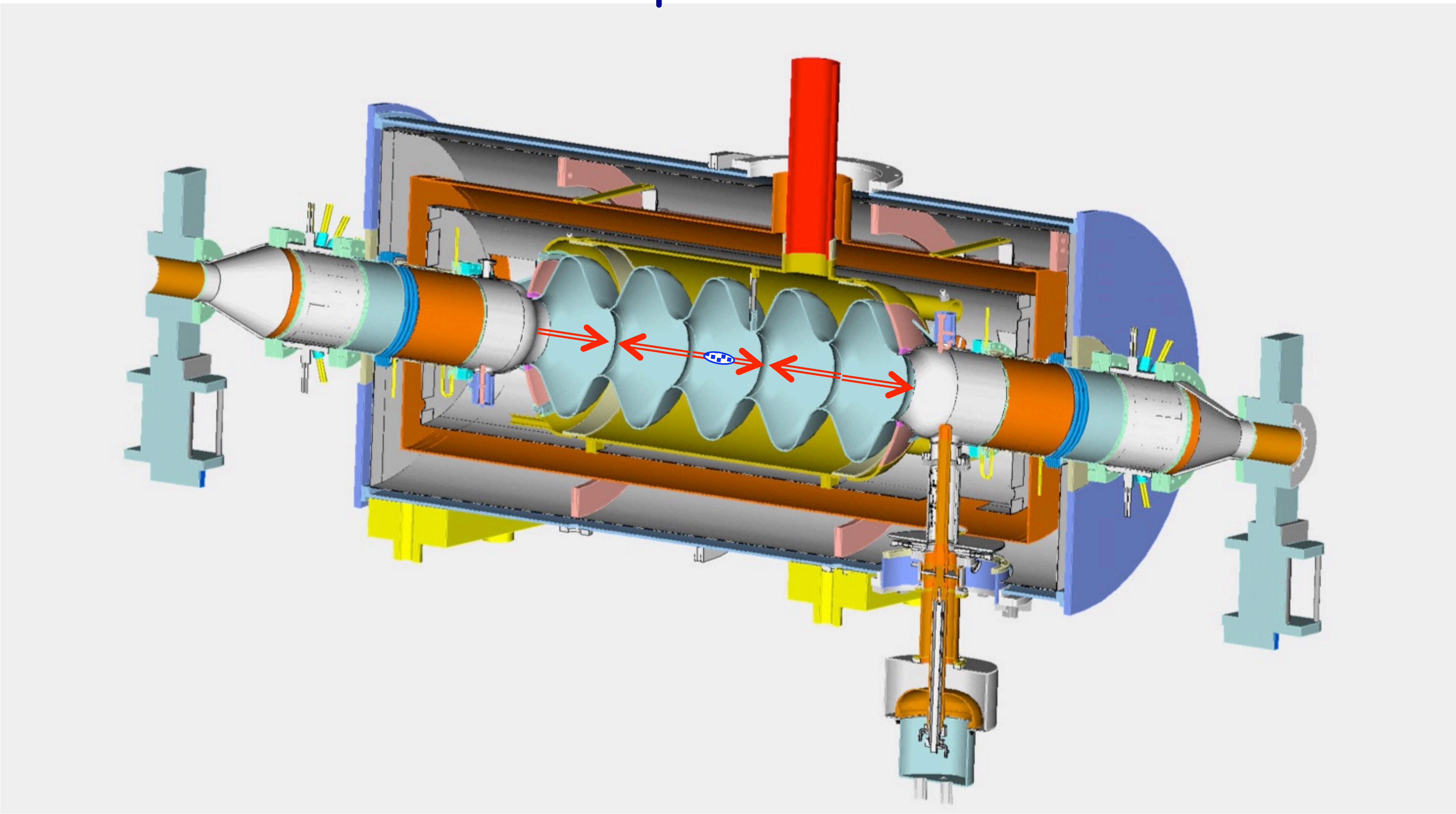


How β=1 RF accelerator works?
In pictures



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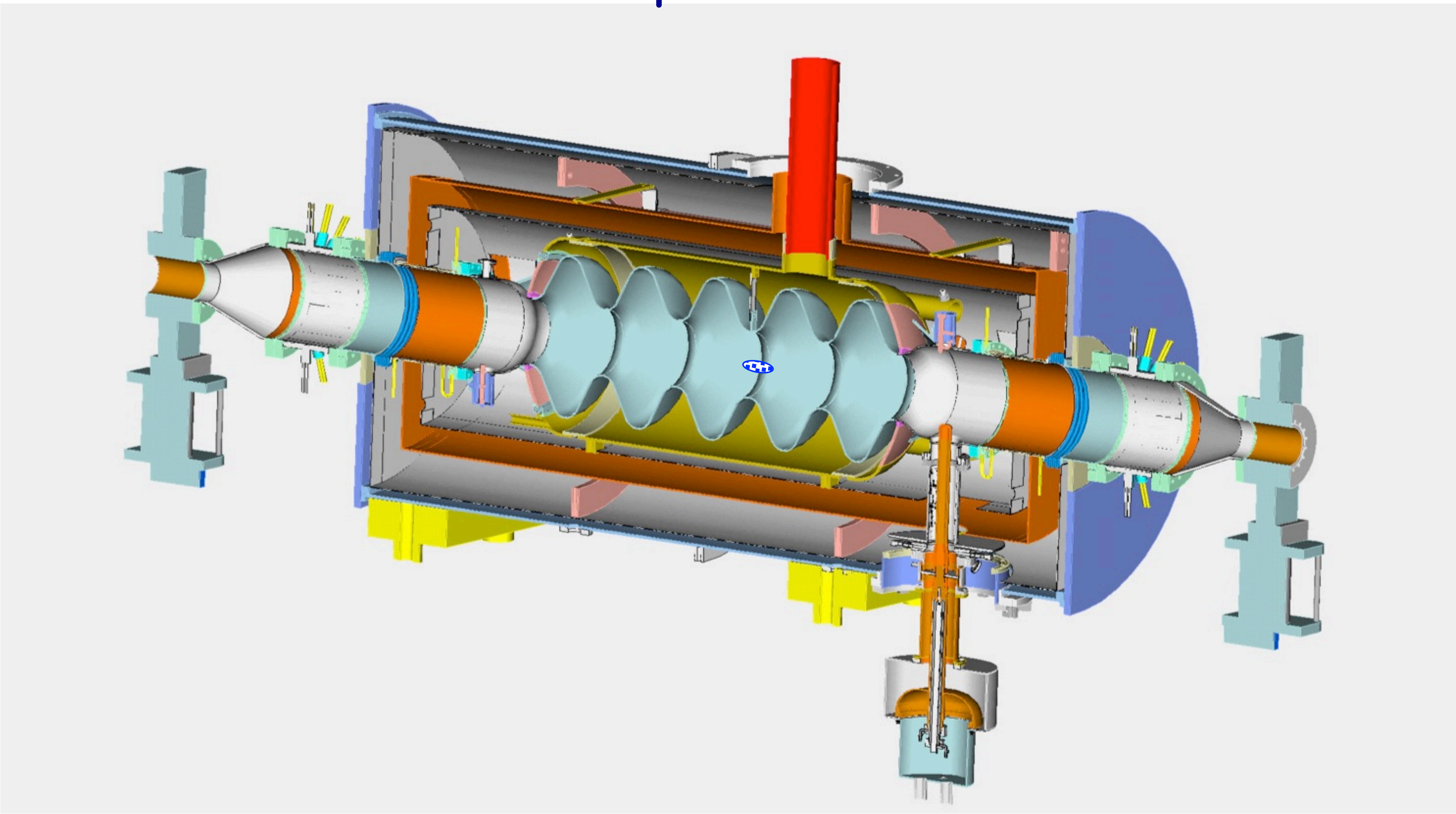

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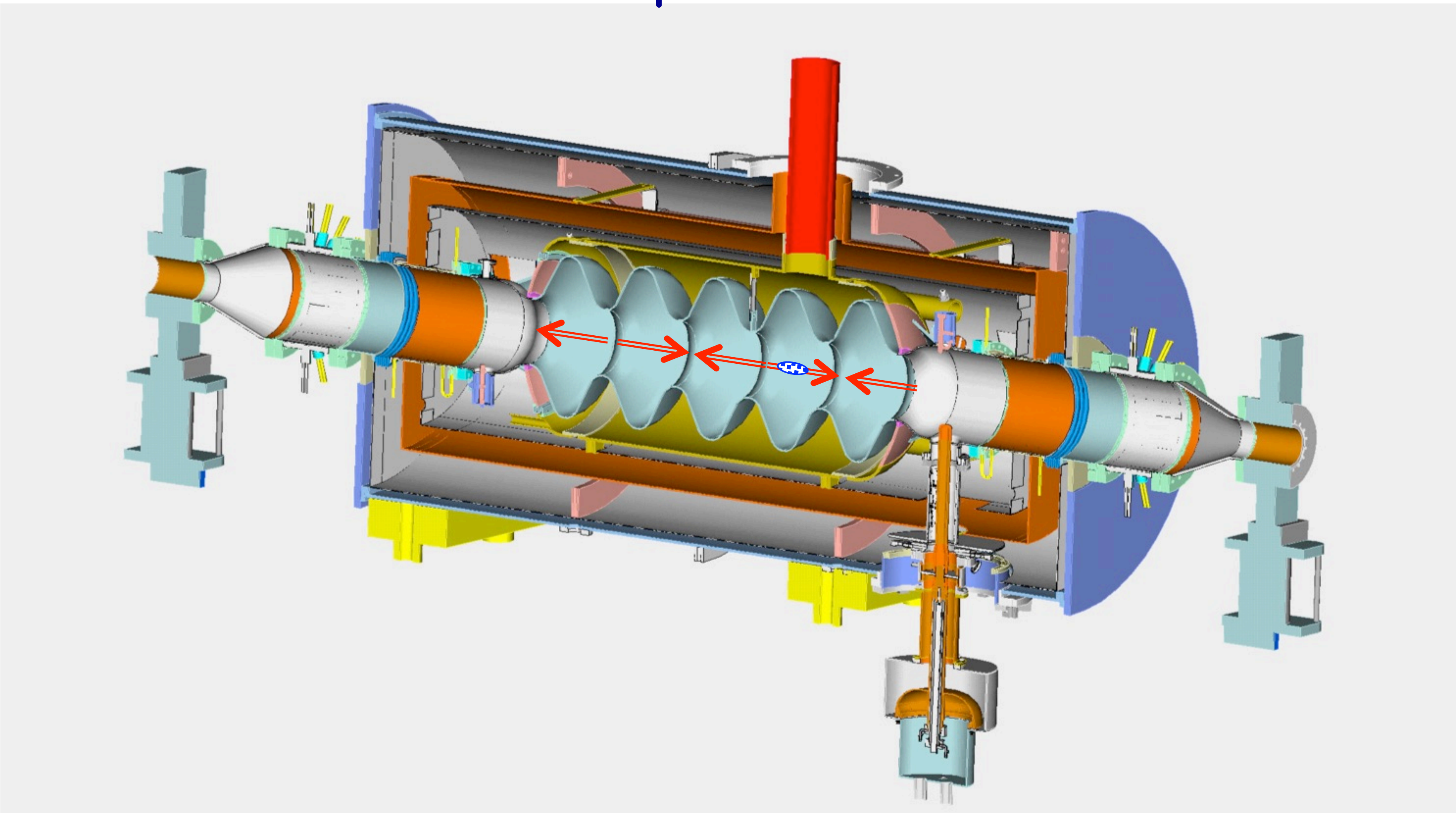

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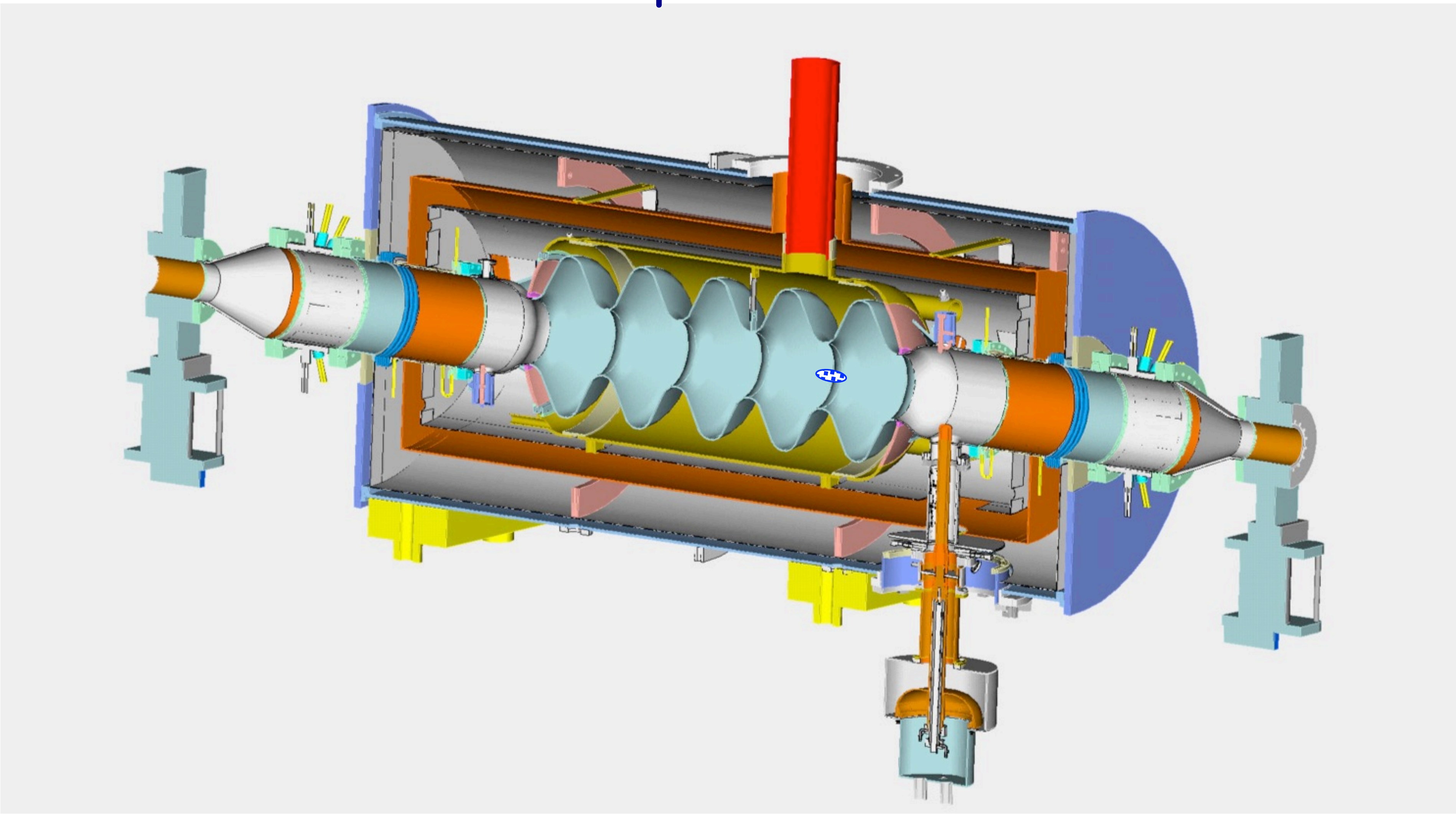

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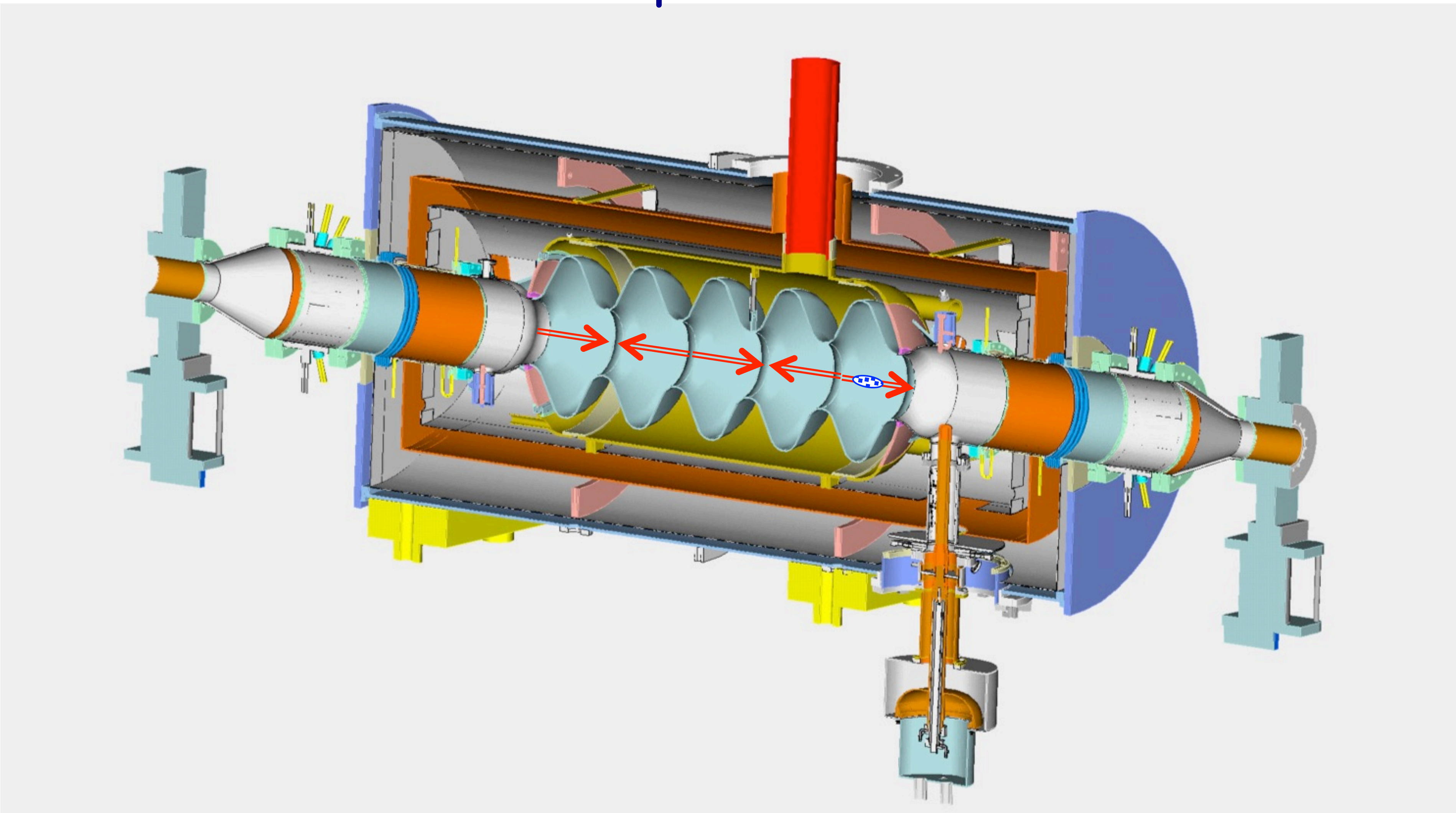

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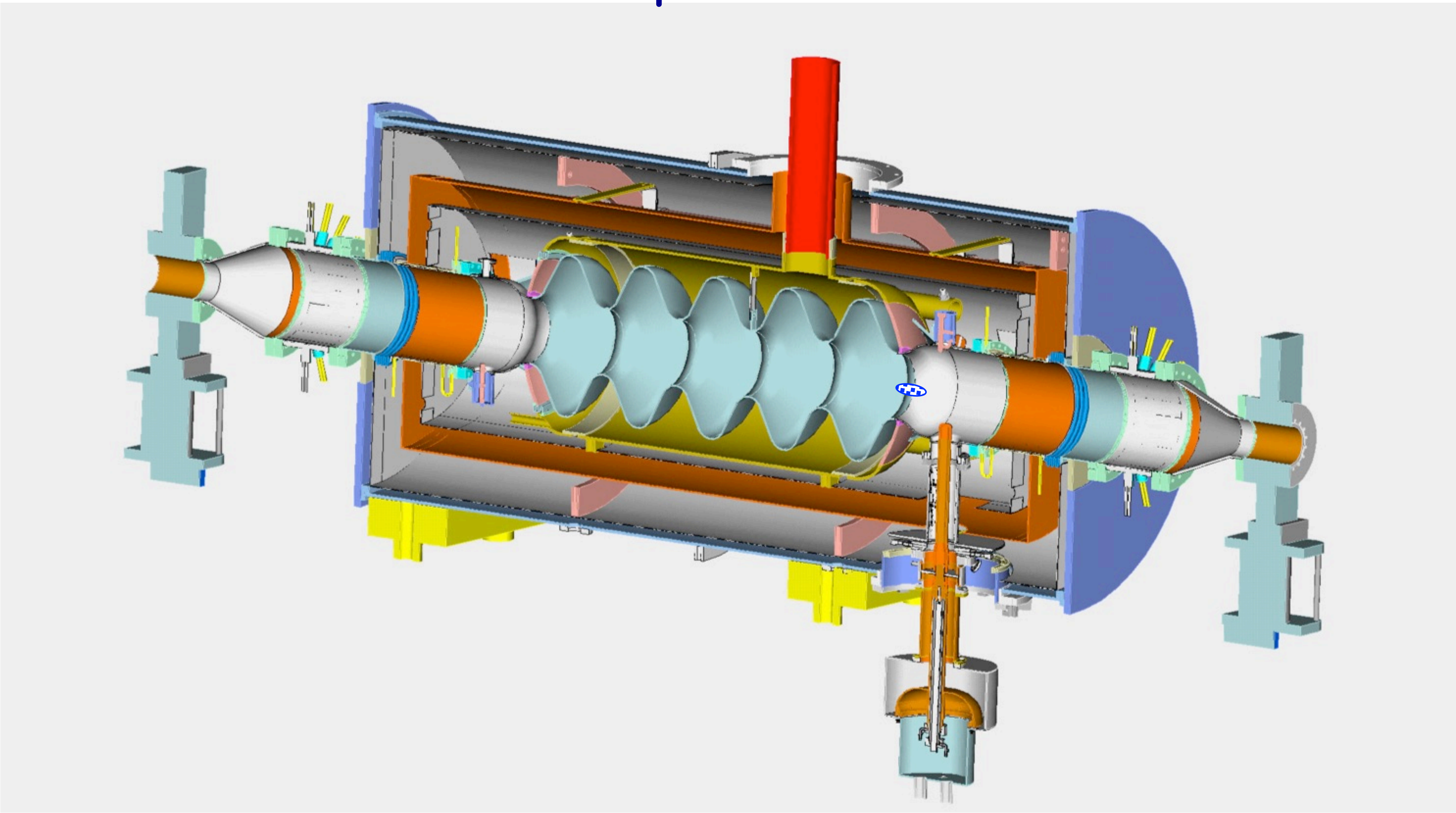

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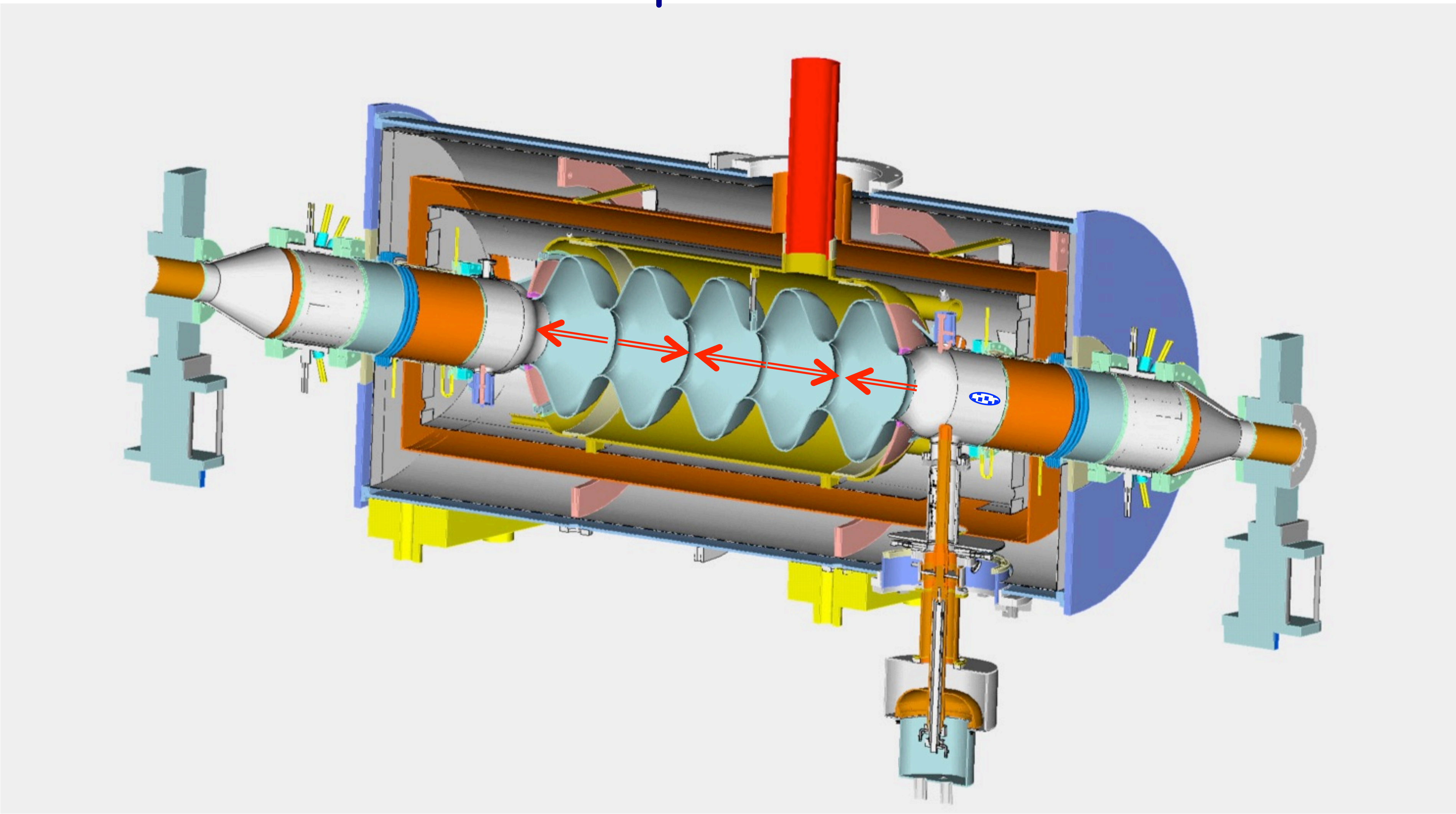

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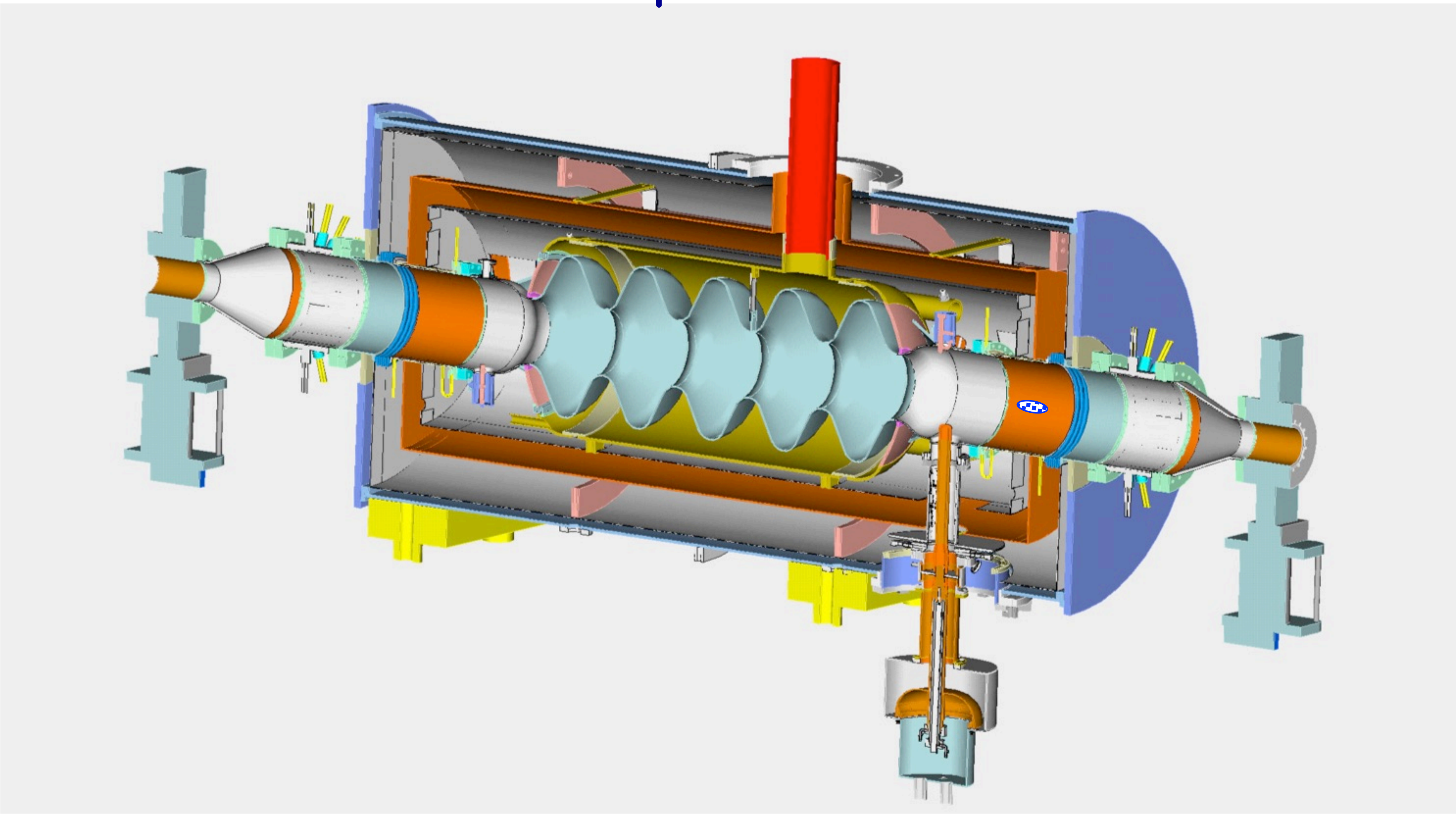
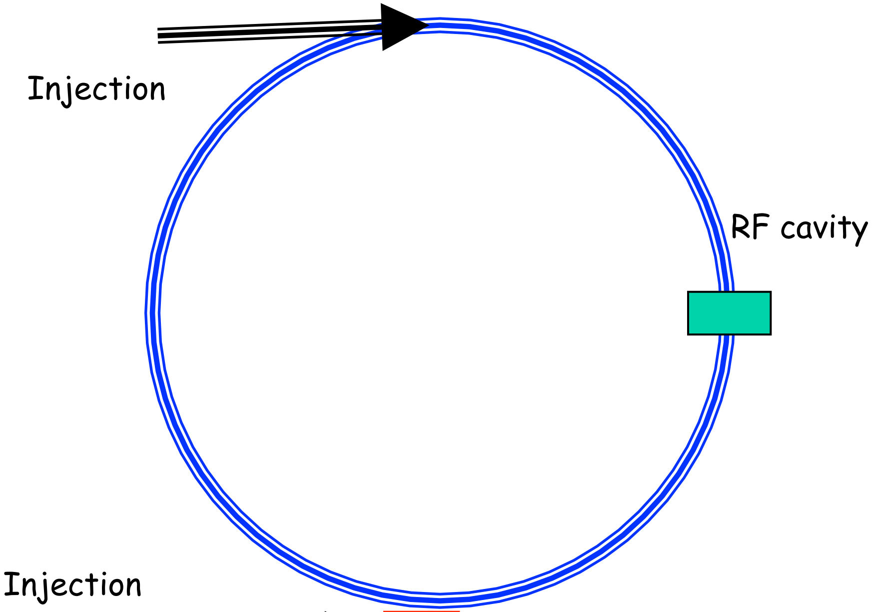
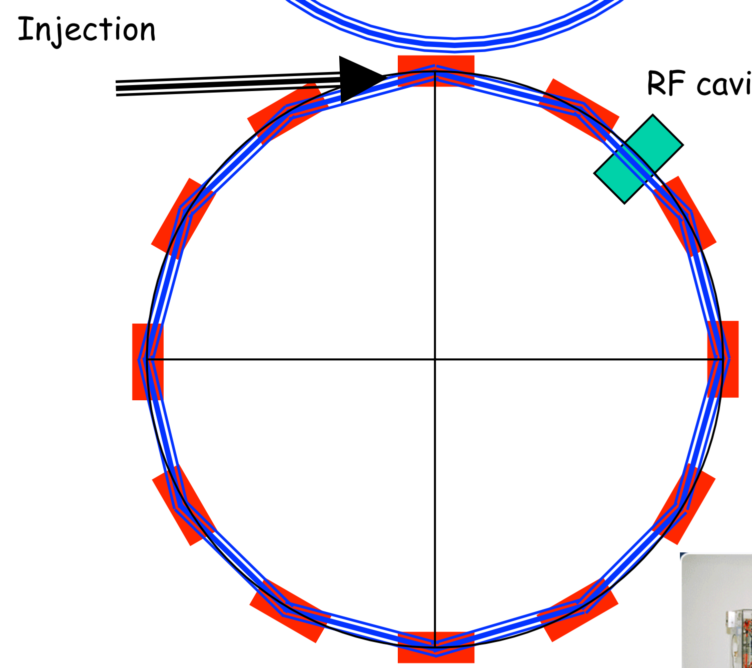
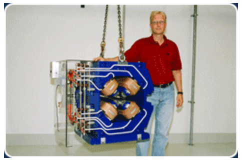


Circular accelerators

- Allow to accelerate or store particles to millions and billions of turns
- Larges energies of colliding beams today - **hadrons** 1 TeV for proton-antiproton (10^{12} eV) at Tevatron , 24 TeV in Au-Au at RHIC, **electron-positron:** 208 GeV at LEP (discontinued)
- Many medium energy electron accelerators (1-8 GeV) as synchrotron radiation sources
- Electrons and positrons radiate too much at high energy (~ E^4 - you should learn it soon) - hence this is the main limit to their energy







Why to use magnetic field to guide particles?

Why not electric field?

It is practical matter of what you can do easier or what you can do at all?

1 Gs = 29979 V/m -> warm magnet 20 kGs (2T) .eq. to 600 MV/m
-> superconducting magnets 15T .eq. to 4.5 GV/m

Almost everything arcs at few MV/m

There is no chance to create DC electric field at Earth with the same intensity as DC magnetic filed - it has something to do with absence of magnetic charges and, hence, no arcing………

1997 - BERKELEY, CA -- The world record for field strength in a dipole magnet has been shattered by researchers at the Ernest Orlando Lawrence Berkeley National Laboratory (Berkeley Lab). A one-meter long superconducting electromagnet, featuring coils wound out of 14 miles of niobium-tin wire, reached a field strength as high as 13.5 Tesla, far-surpassing the previous high of 11.03 Tesla set by a Dutch group in 1995.

Arithmetic of Circular Accelerator

$$E = \sqrt{m^2c^4 + p^2c^2} \equiv \gamma mc^2$$

E is constant in magnetic field

$$\vec{p} = \gamma m\vec{v} \equiv \gamma mc\vec{\beta};$$

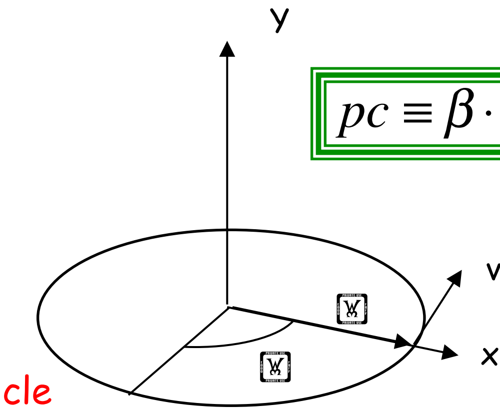
$$\vec{\beta} = \frac{\vec{v}}{c}; \; \gamma = 1 \Big/ \sqrt{1-\vec{\beta}^2}$$

As the result value of the momentum, velocity and relativistic factors (γ,β) are constant, but vectors change direction

$$\beta = \sqrt{1 - 1/\gamma^2} \quad \rightarrow \cong 1 - 1/2\gamma^2$$

For any ultra-relativistic particle with γ>>1 its speed is almost that of the light

$$pc \equiv \beta \cdot E$$



$$\vec{\omega} = \left[\vec{v} \times \vec{K}\right] \rightarrow \omega = \frac{v}{\rho}; \quad \vec{v} = \hat{e}_\theta v;$$

$$\vec{B} = \hat{e}_y B_o; \; \frac{d\vec{p}}{dt} = \frac{e}{c}\left[\vec{v} \times \vec{B}\right] = \left[\vec{\omega} \times \vec{p}\right]$$

$$\frac{e}{c} v B_o = \frac{v}{\rho} p \quad \Rightarrow$$

$$\rho = \frac{pc}{eB_o} \rightarrow \rho[cm] = \frac{pc[MeV]}{0.29979 \;\; B_o[kGs]}$$

$$\rho[m] = \frac{pc[GeV]}{0.29979 \;\; B_o[T]}$$

$$m_e c^2 \cong 0.511 \; MeV; \quad m_p c^2 \cong 938.272 \text{MeV}$$

The mass of the electron is approximately $^1/_{1836}$ of the mass of the proton

Stability in Circular Accelerators: Auto-phasing

$$V_{rf} = V_o \cdot \sin\left(2\pi \cdot f_{rf} \cdot t\right); \quad f_{rf} = h / T_o$$

Synchronous particle: n is just a turn number

$$2\pi \cdot f_{rf} \cdot t_s(n) = N\pi \quad \rightarrow \sin\left(2\pi \cdot f_{rf} \cdot t_s(n)\right) = 0$$

$$t(n) = t_s(n) + \tau(n)$$

$$\tau(n+1) = \tau(n) + \alpha_c T_o \frac{\Delta \mathbf{E}(n)}{\mathbf{E}_o};$$

$$\Delta \mathbf{E}(n+1) = \Delta \mathbf{E}(n) \pm q V_o \cdot \sin\left(f_{rf} \cdot \tau(n+1)\right)$$

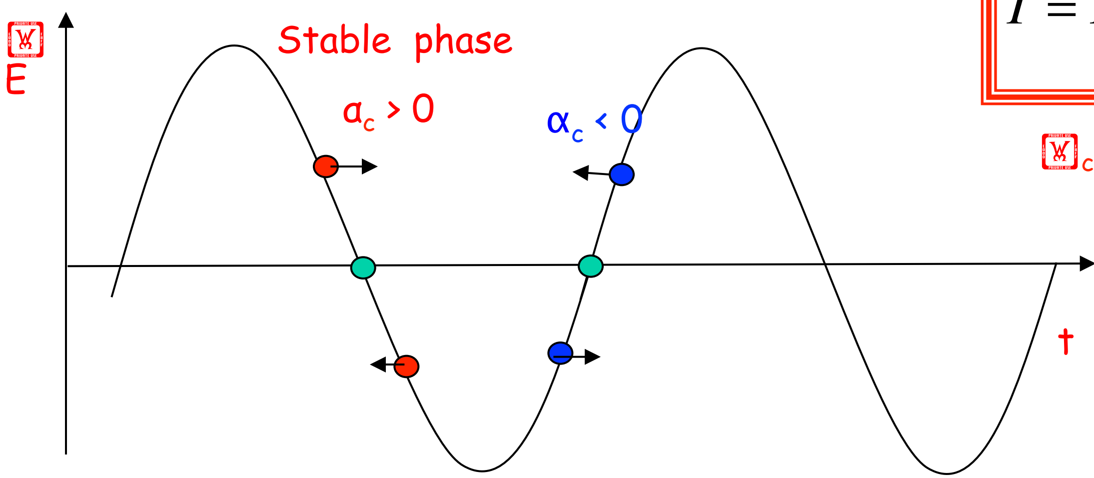
Revolution Time T=Circumference/velocity

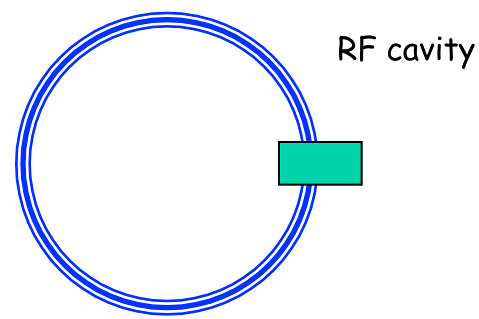
$$C = C(\mathrm{E}); \quad v = c \cdot \sqrt{1 - \left(\frac{mc^2}{E}\right)^2}$$

$$T = \frac{C(\mathrm{E})}{c \cdot \sqrt{1 - \left(\frac{mc^2}{E}\right)^2}}$$

$$T = T_o \cdot \left(1 + \alpha_c \frac{\Delta \mathbf{E}}{\mathbf{E}_o} + \ldots\right); \quad \Delta \mathbf{E} \equiv \mathbf{E} - \mathbf{E}_o$$

α_c is a function of accelerator lattice

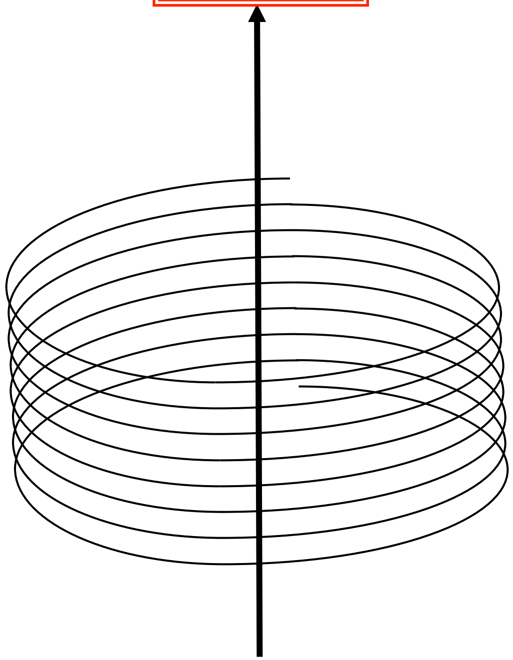




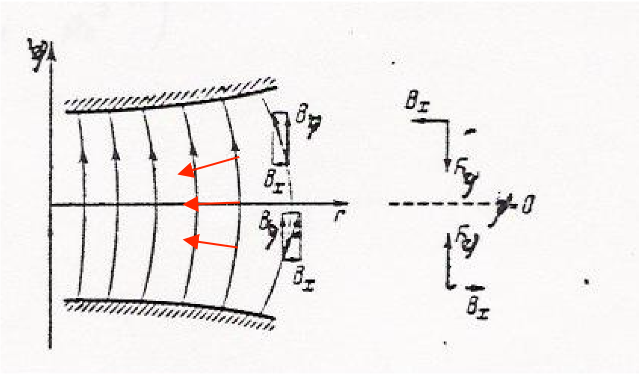
α_c = 0 is a special case and called a transition

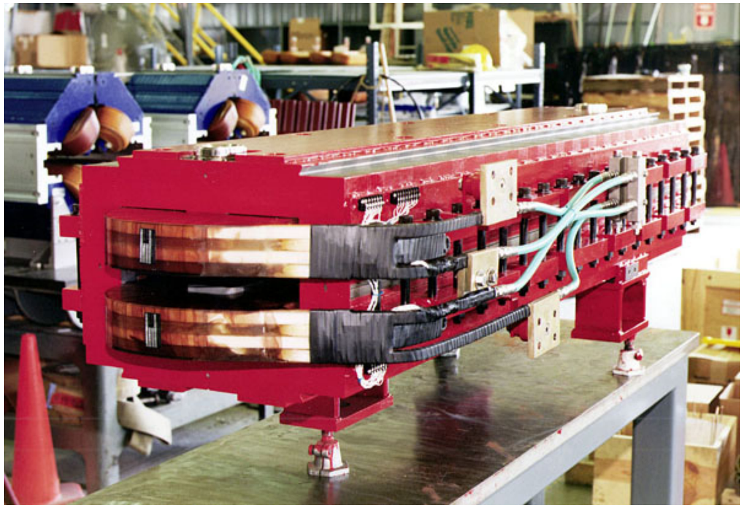
Stability in Circular Accelerators

$$\vec{B} = \hat{e}_y B_o$$



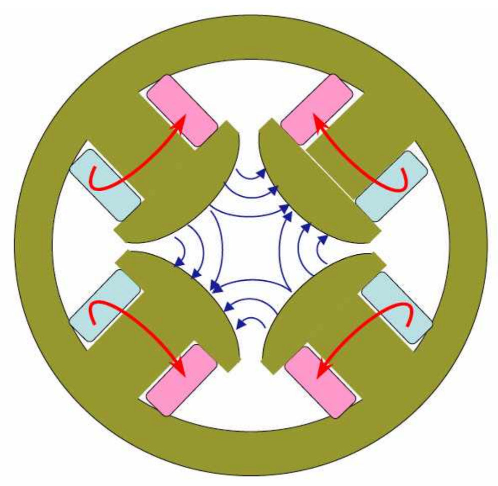
Weak focusing: dipole magnets have a gradient of the field to make both vertical and horizontal motion stable

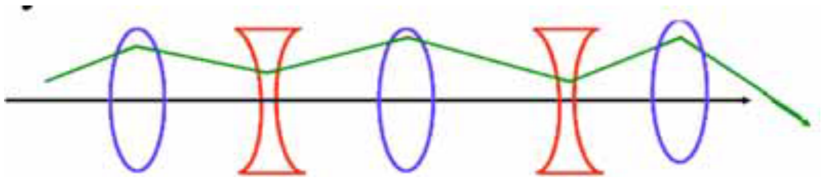




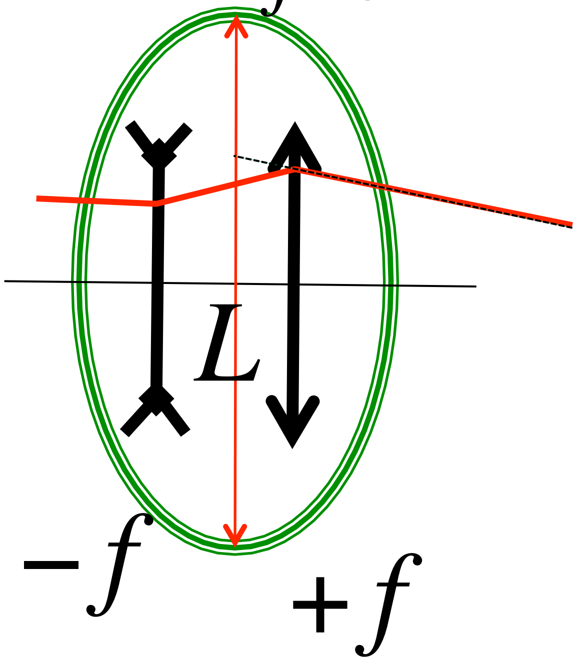
Guiding field is not sufficient for particles trajectories to be stable: helix is trajectory of a charged particle in homogeneous field is unstable

Strong focusing: Quadrupoles





$$F = f^2 / L$$

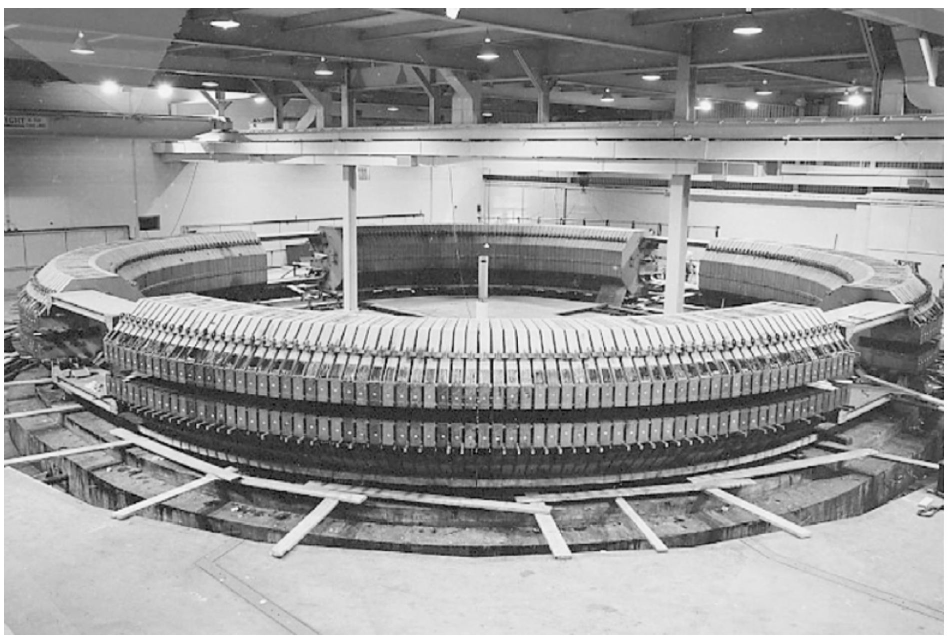


$$curl\vec{B} = \hat{z}\left(\frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x}\right) = 0 \Rightarrow G = \frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x};$$

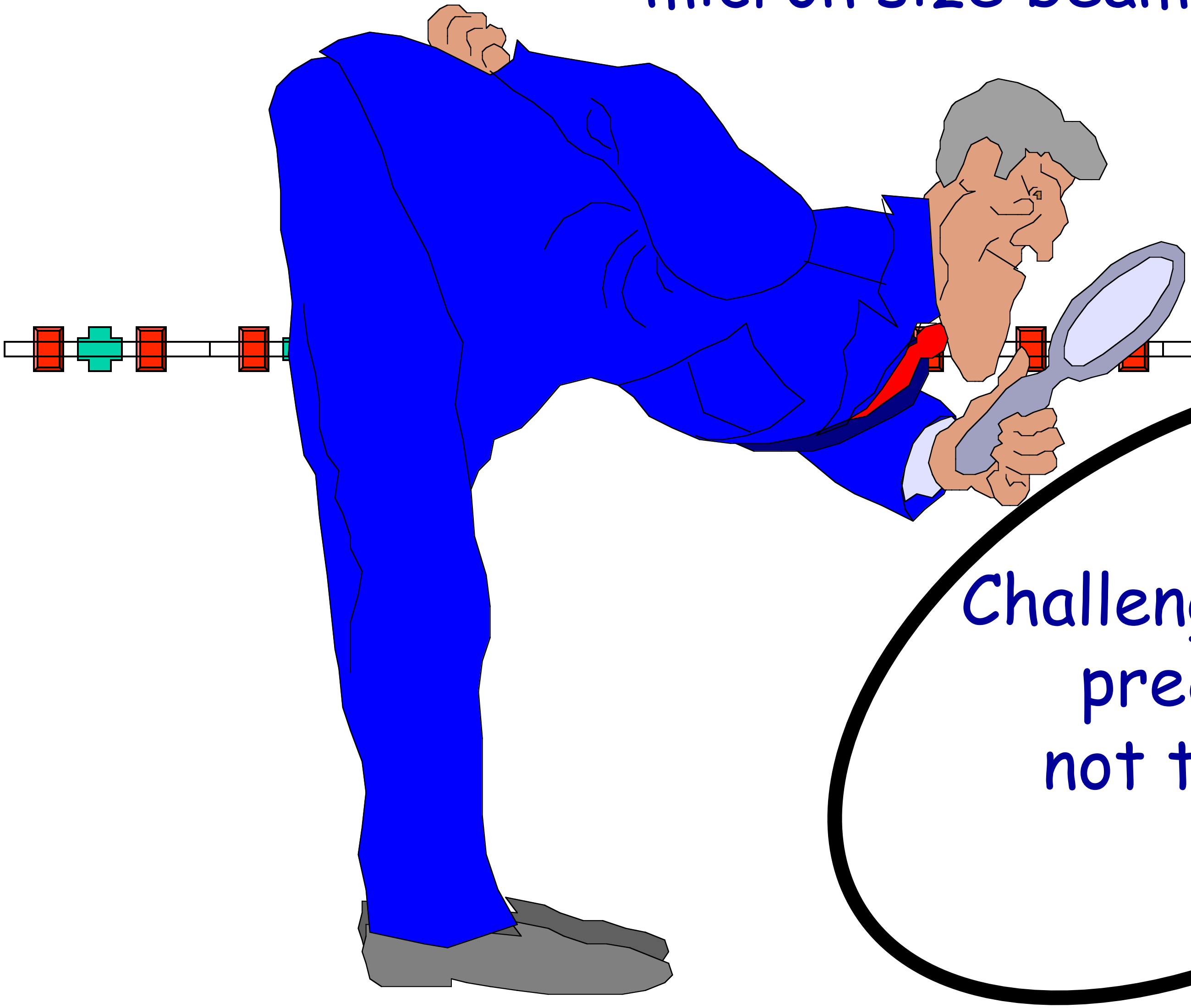
$$B_x = G \cdot x; \quad B_y = G \cdot x; \quad \hat{z} \times \hat{y} = \hat{x}$$

$$\vec{F} = -\frac{e}{c}\left[\vec{\mathrm{v}} \times \vec{B}\right]; \ \vec{\mathrm{v}} = \hat{z}\mathrm{v} \Rightarrow \vec{F} = \frac{eG}{c}\left(-\hat{x} \cdot x + \hat{y} \cdot y\right)$$

Weak focusing synchrotrons in 1950s: you can have lunch inside its vacuum chamber



Strong focusing - micron size beams



Challenge is the precision not the size

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.

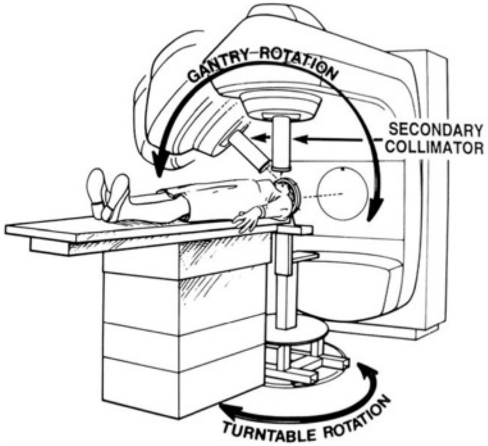
http://www.acceleratorsamerica.org/resources/applications/index.html

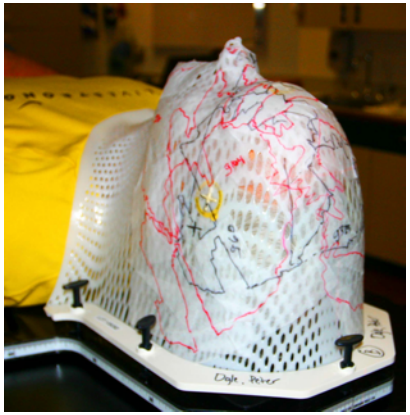
Medical Applications

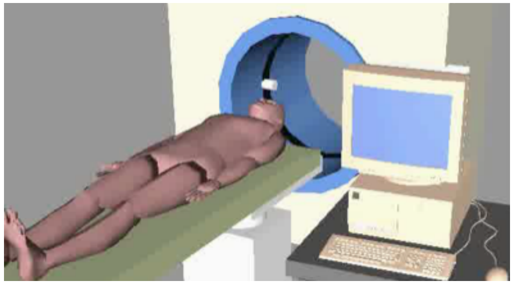
- ✓ In contrast with other applications, medical applications of any technology is most humane and broadly accepted by society.
- ✓ Some of accelerator applications in medicine – like radiation therapy – are well known.
- ✓ Many are know only to experts.
- ✓ Here is a short (and incomplete) list of accelerator 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

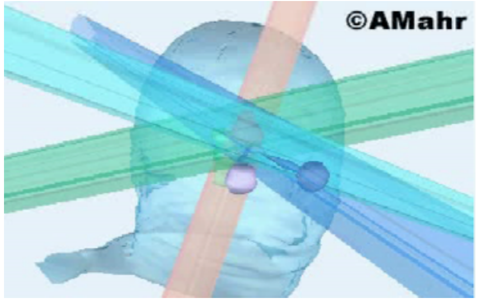
γ-Ray Radiation Therapy

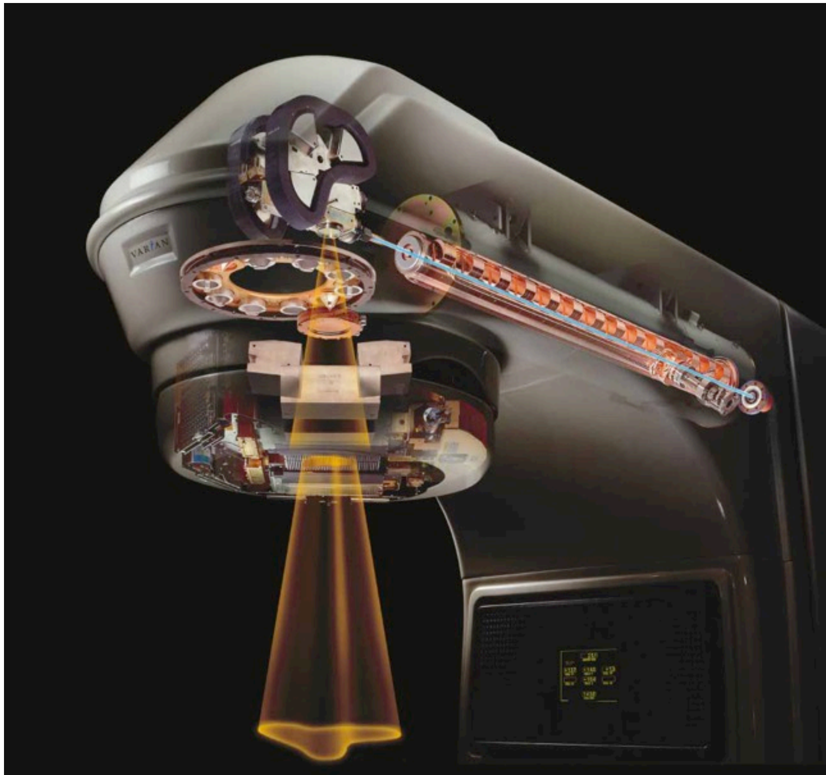
- The gamma-rays beam is further filtered to remove soft photons, collimated, shaped to fit specific task
- The beam is then delivered at multiple angles to minimize the radiation exposure of the surrounding tissue and to deliver the necessary dose of the radiation to a tumor
- It is all computer controlled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





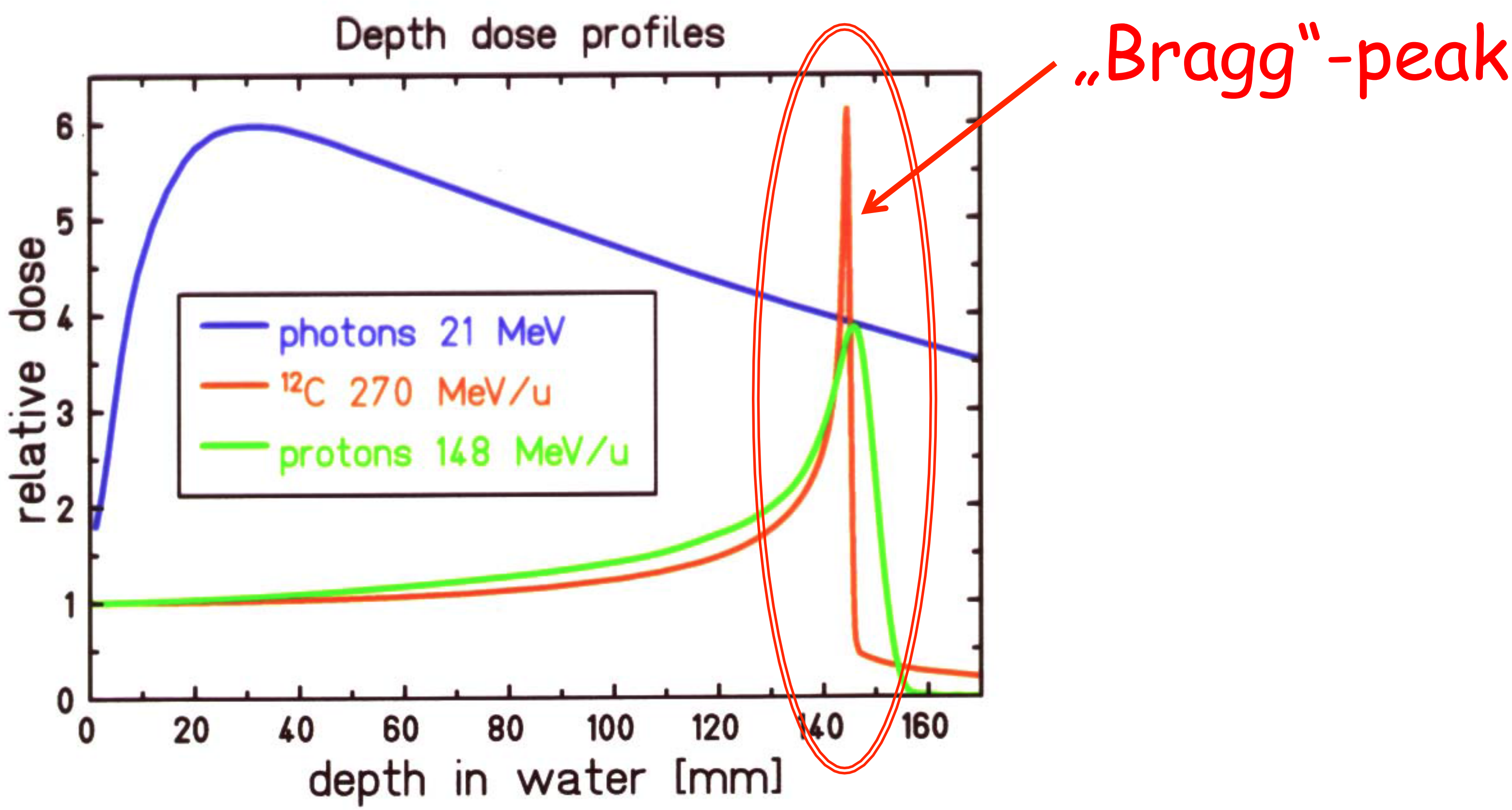






Why Hadron radiation therapy?

- 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

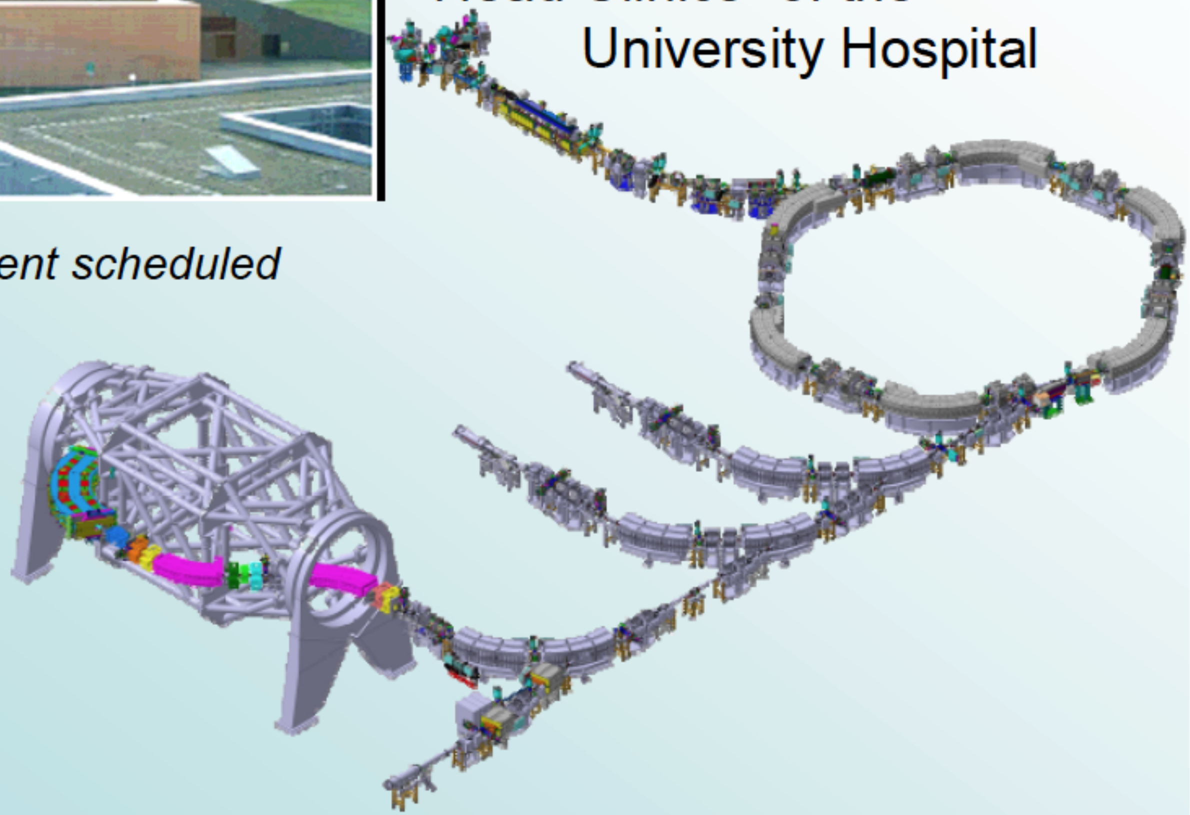


Hadron therapy centers

Particle Therapy Facilities – HIT/Heidelberg

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

Start of patient treatment scheduled in 2 weeks

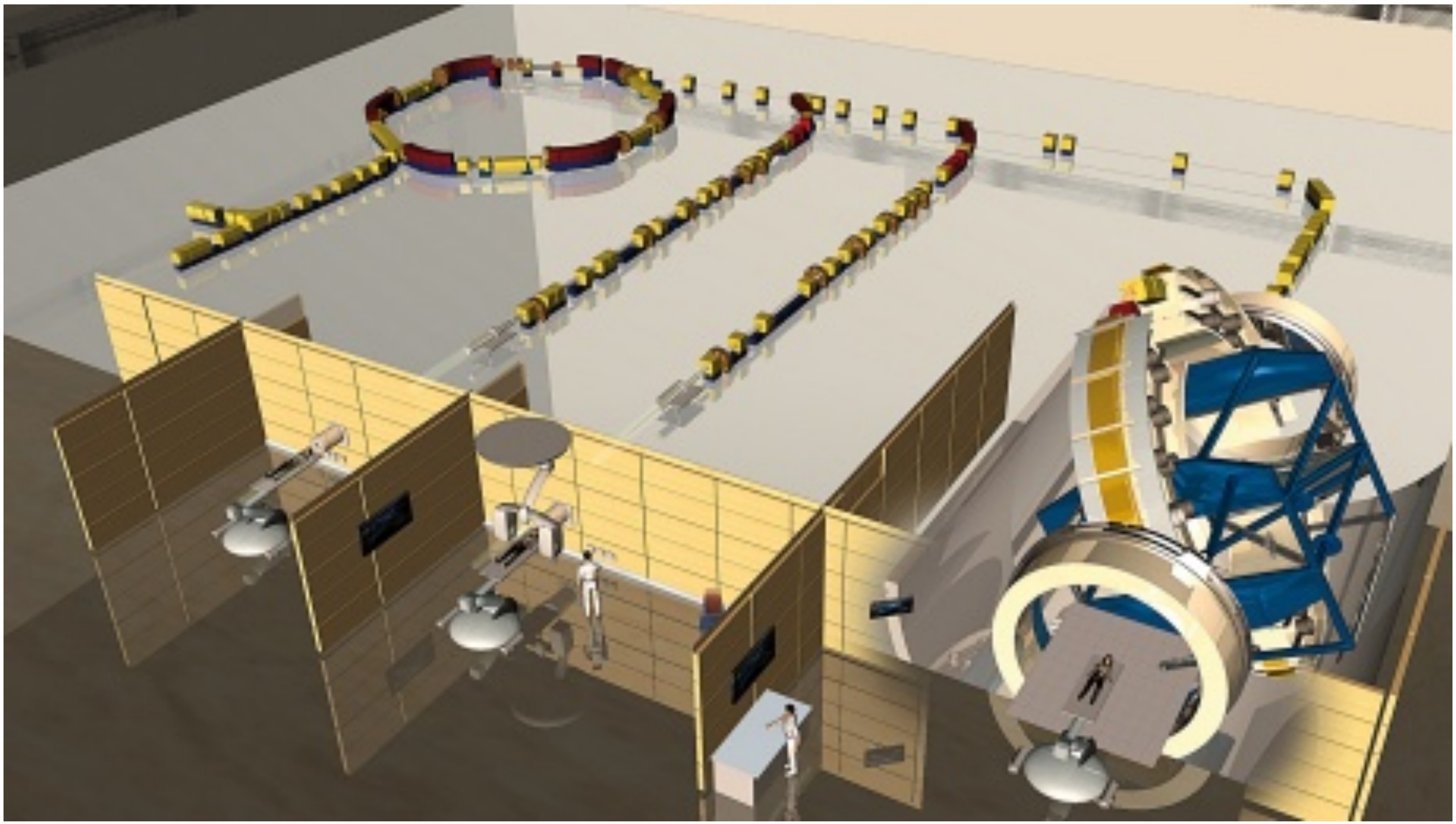


HIT

Accelerator Parts

Gantries: monsters in modern accelerators

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



Accelerator Parts

Gantries: monsters in modern accelerators

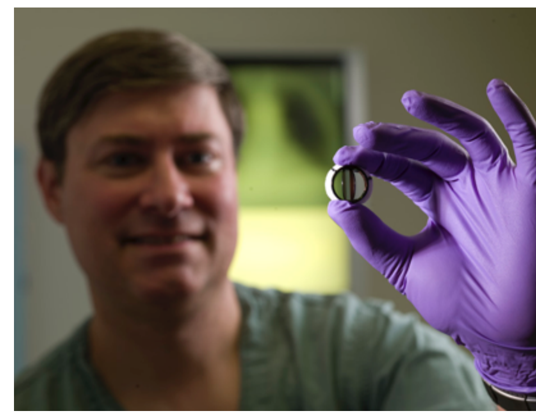
Industrial Accelerators

- **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

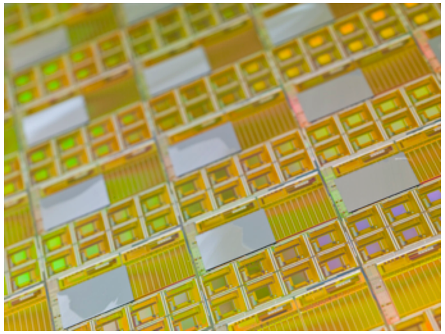
The auto industry uses particle accelerators to treat the material for radial tires, eliminating the use of solvents that pollute the environment.



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

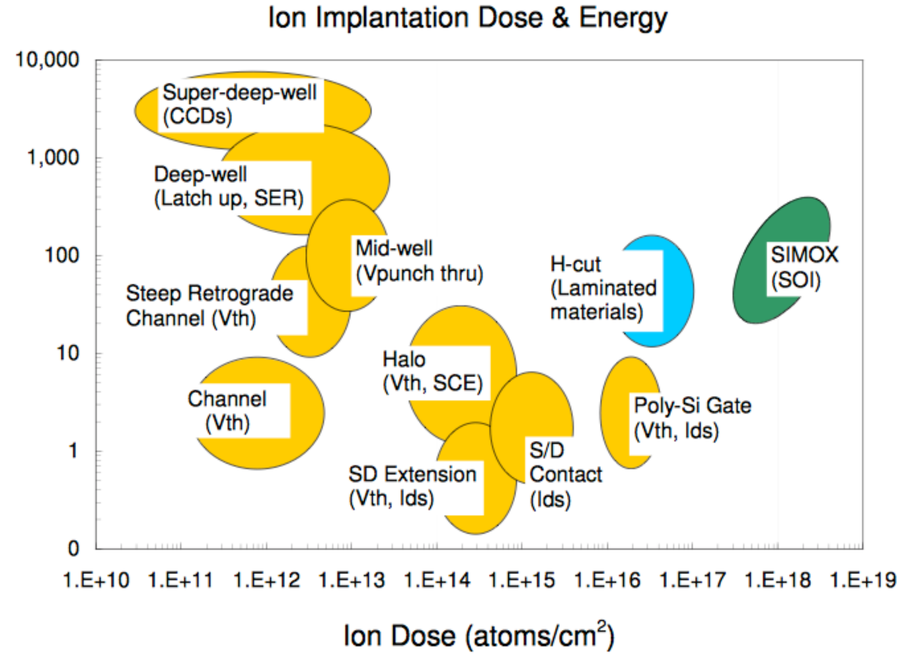
- CMOS fabrication
- SIMOX
- Cleaving silicon
- MEMS

Metals

- Harden cutting tools
- Artificial human joints

Ceramics & glasses

- Harden surfaces
- Modify optics



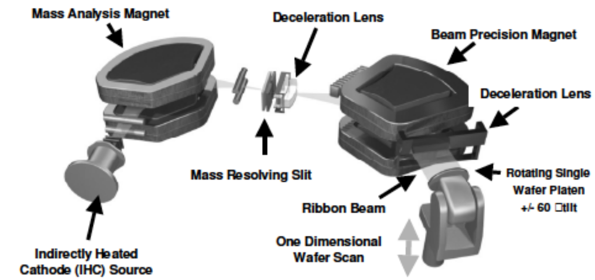
All digital electronics now dependent on ion implantation.

Ion implantation

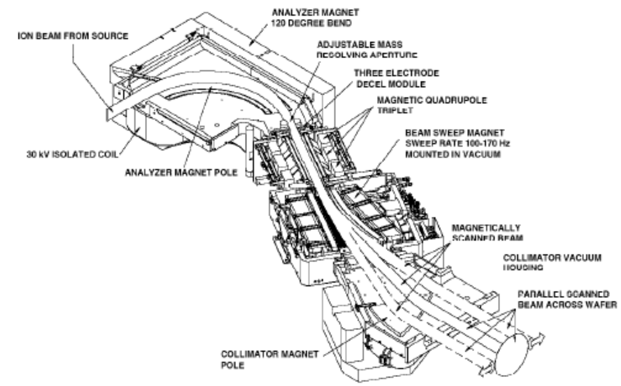
Ion Implantation Accelerators

Accelerator classifications

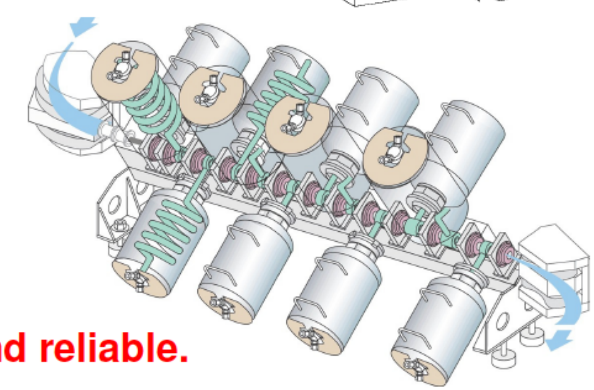
- **Low energy/ high current**
  - "High current implanters"
  - Ion energies from few hundred eV to tens of keV.
  - Variable energy, single gap with currents to 50 mA.



- **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.

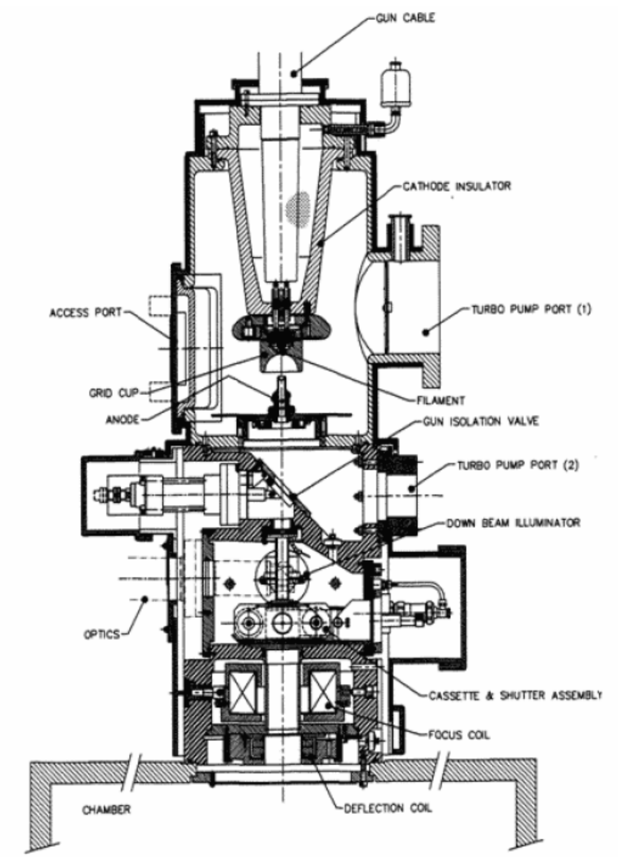
Material Processing/Modifications

Electron Beam Materials Processing

- Application of electron guns dating to 1905
  - Critical to automotive production
  - Refractory metals
  - Dissimilar metals
  - Precision cutting and drilling
- Beam energy from 60 to 200 keV
- Beam power from 6 to 200 kW

- **Major Vendors**
  - Sciaky, Inc. (USA)
  - All Welding Group AG (PTR Group and Steigerwald Strahltechnik) (Germany)
  - Cambridge Vacuum Engineering (UK)
  - Bodycote Techmeta (France)

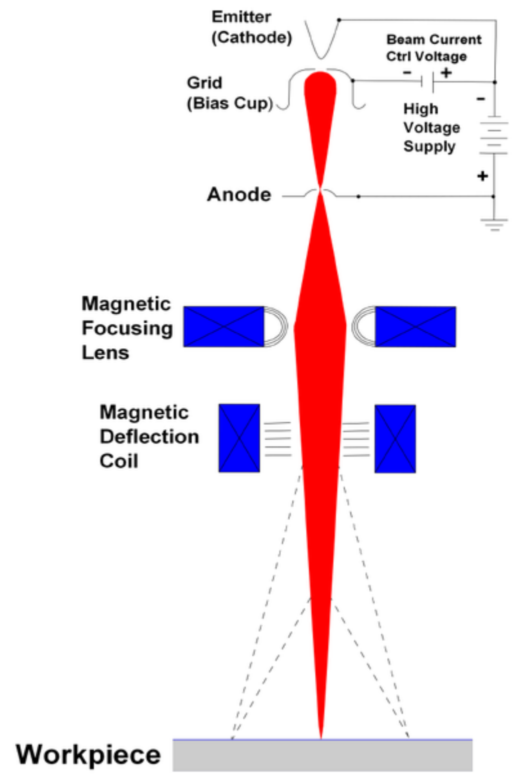
- **Smaller vendors**
  - Pro-beam (Germany)
  - Orion (Russia)
  - Mirero (Korea)
  - Omegatron (Japan)
  - NEC Corporation (Japan)
  - Mitsubishi Electric Corporation (Japan)

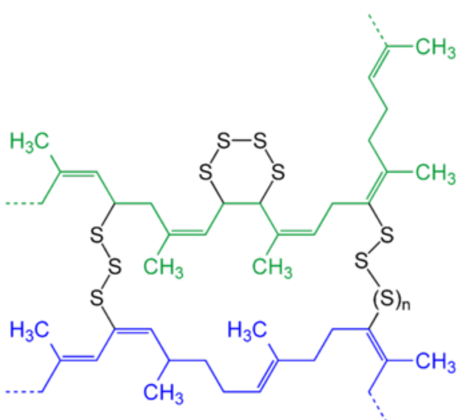


A mature business with large growth now in developing countries

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 …).

Crosslinking: rubber

- Crosslinking is the core chemical process of linking the plastic rubber molecules into a three-dimensional network structure with elastic properties, namely the finished rubber. The choice of crosslinking agent, the desired crosslinking density and the reactivity of the crosslinking system used have a decisive influence on the material properties. As a result, there may be substantial changes in their stress values, tensile strength, hardness, elasticity, gas permeability, high-temperature or swelling resistance during the crosslinking reaction.

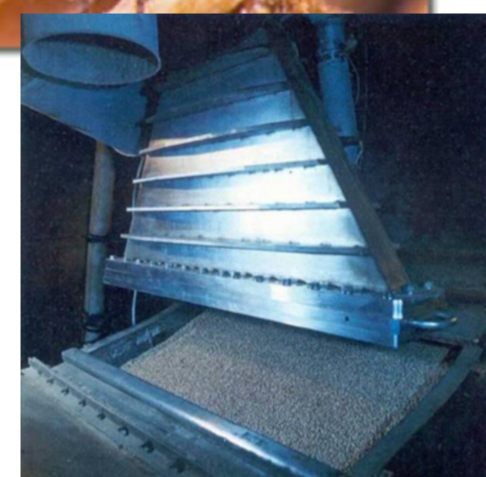
- The most well-known crosslinking agent is elemental sulfur, which is used in conjunction with zinc oxide, stearic acid and compounds known as vulcanization accelerators. In addition, sulphur-free systems are used as well, such as p-quinone dioxime together with oxidizing agents, peroxides with crosslinking coagents, diamino compounds, resins or metal oxides.

- The choice of crosslinking systems is determined on the one hand by the chemical characteristics of the polymer. For instance, rubbers containing diene groups, such as NR, IR, SBR, BR or EPDM, can be crosslinked with numerous versions of the classical sulphur system. However, similar attempts with EVA, AEM or FKM would be doomed to failure.

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.





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.

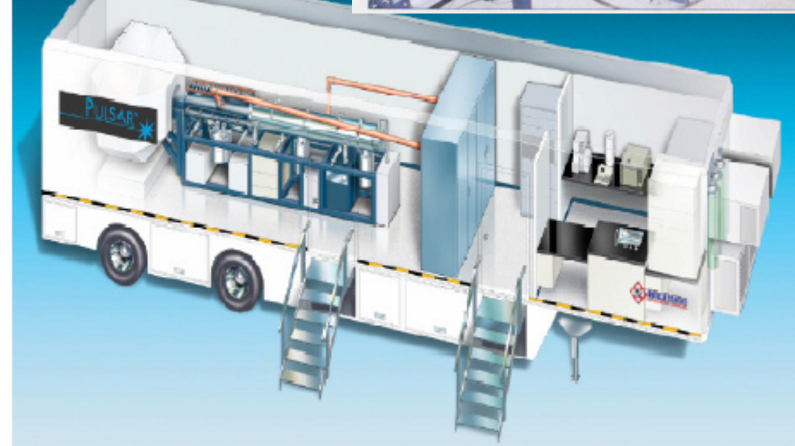
Suitable as a quarantine measure, several countries rely on this technology to treat food commodities prior to exporting

Radioisotope Production

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

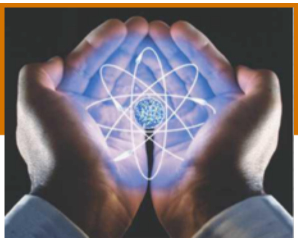
- **Cyclotrons & Linacs** – both protons & deuterons
  - PET – self shielded systems from 7 to 18 MeV with current < 200 μA)
  - SPECT – energies from 22 to 70 MeV with currents up to 2 mA

- **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)

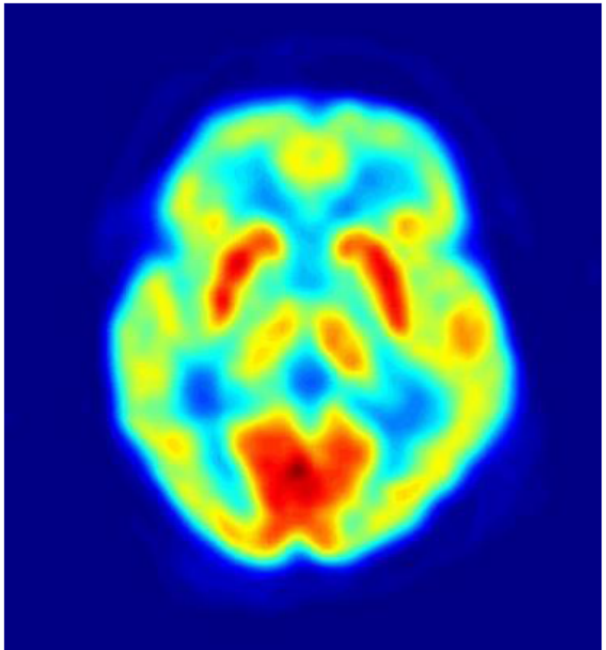


Large growth in compact accelerators for PET.

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



Bone pain agents

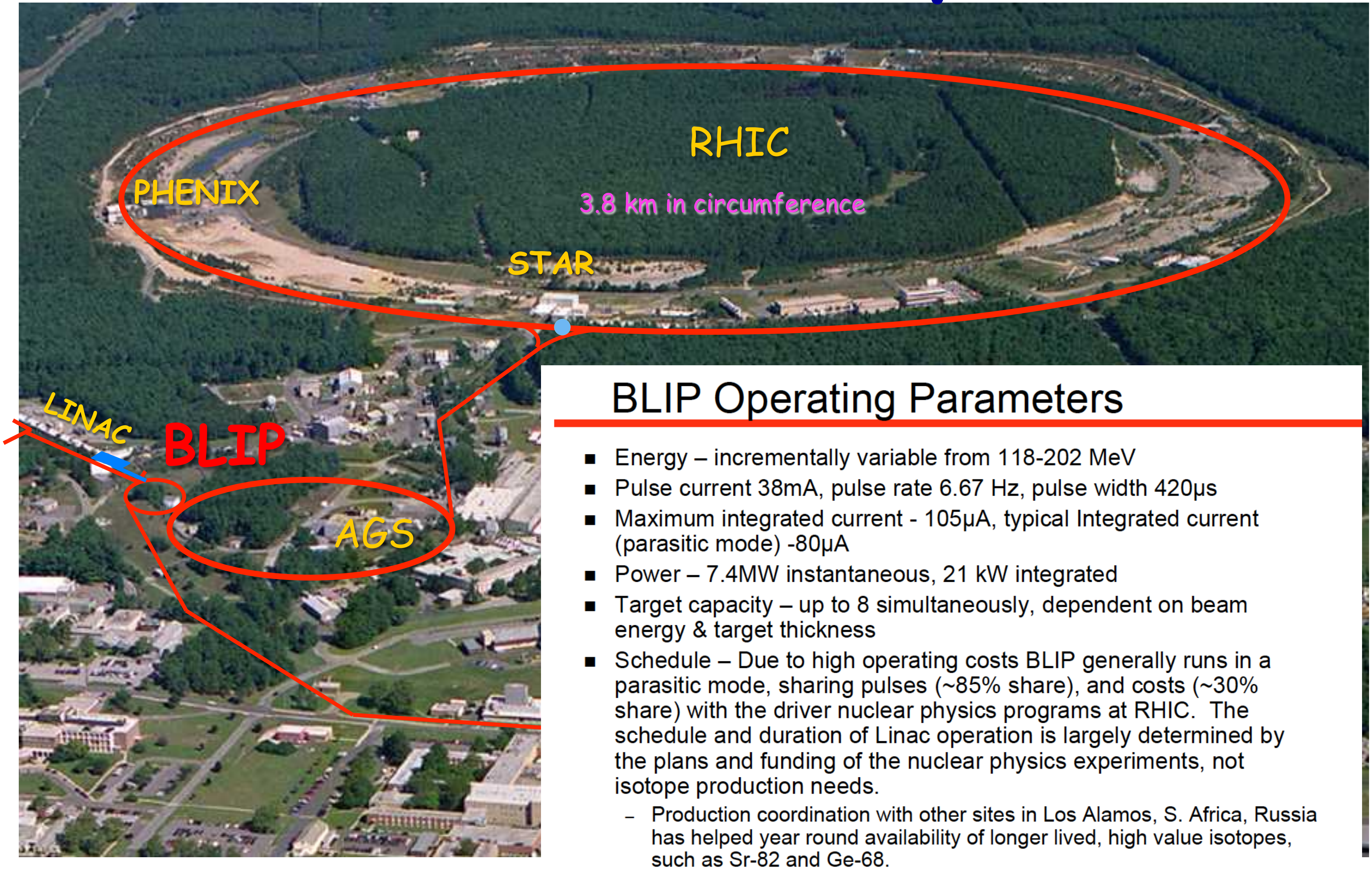
P-32-orthophosphate
Sr-89 chloride (Metastron)
Sm-153-EDTMP phosphonate (Quadramet)
Ho-166-EDTMP phosphonate
Sn-117m(stannic 4+)-DTPA
Lu-177 DOTMP/EDTMP
Re-188-hydroxyethylidene diphosphonate (HEDP)
Re-186, -188-HEDP hydroxyethylidene diphosphonate
Re-188 dimercaptosuccinic acid
I-131-α-amino(4-hydroxybenzylidene)-disphosphonate
Y-90-chloride
Ra-223-chloride (AlphaRadin)

Pacific Northwest
NATIONAL LABORATORY

We do it at BNL....

- Isotope Production and Distribution at BLIP
  - Distribution for sale; process & target development to improve quality & yield.
  - Sr-82/Rb-82 for human heart scans with PET
  - Ge-68 for calibration of PET devices
  - Zn-65 tracer for metabolic or environmental studies
- Radioisotope R&D
  - Sn-117m, Cu-67, for cancer therapy applications
  - Y-86 for cancer imaging
- Radiation damage studies
  - target and magnet materials for future high power accelerators, collaboration with BNL Physics & ES&T Departments
  - high temperature superconductors for FRIB, collaboration with BNL Magnet Division and ES&T Department
- Training
  - Support (space, equipment, faculty) for DOE funded Nuclear Chemistry Summer School, a 6 week undergraduate course in nuclear and radiochemistry

eRHIC: QCD Facility 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.

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.

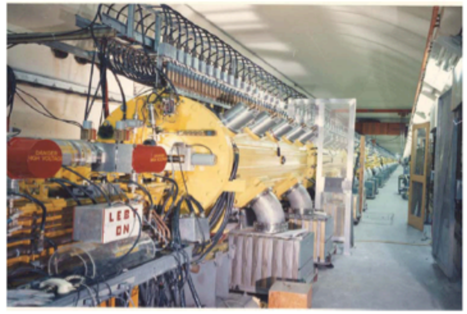
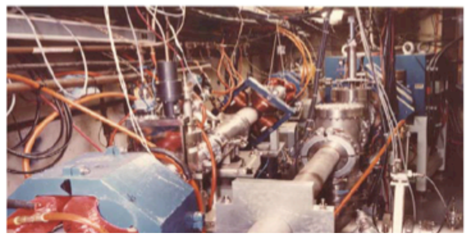
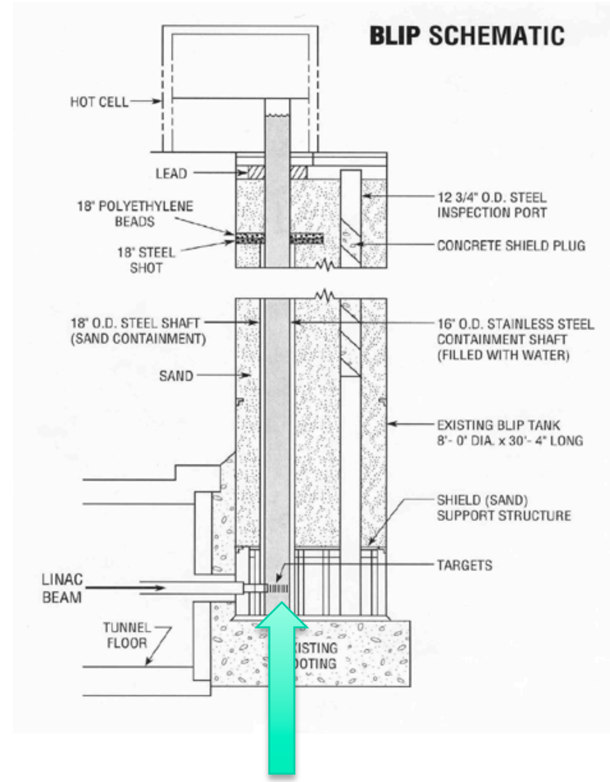
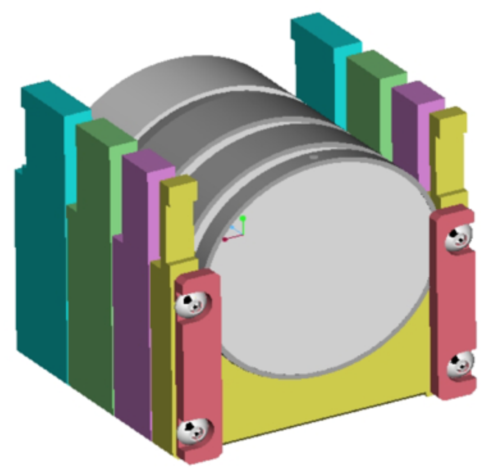


Figure 3. The BLIP beam line directs protons up to 105μA intensity to targets; parasitic operation with nuclear physics programs





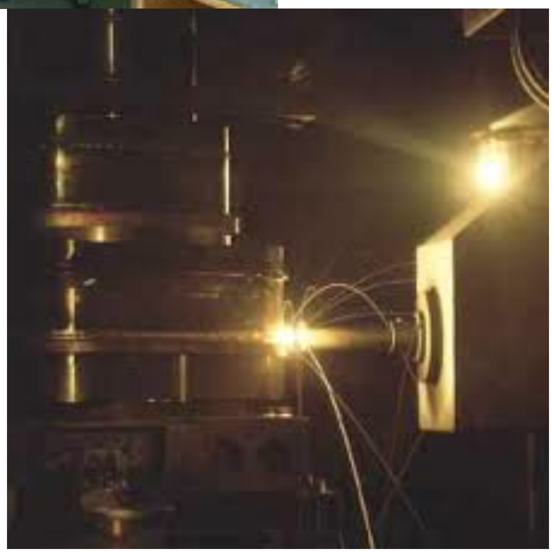


Radioisotopes Developed at BLIP

Isotope	Half-life	Decay mode	Nuclear reaction	Typical application
^{7}Be	53.3d	EC	^{12}C(p,spall)	☎ source
^{28}Mg	21h	β^-	Cl(p,spall)	Mg tracer
^{22}Na	2.6y	β^+	Al(p,spall)	☎ source
^{47}Sc	3.4d	β^-	^{48}Ti(p,2p)	Radioimmuno-therapy (RIT)
^{52}Fe	8.3h	β^+(57%),EC	Ni(p,spall)	PET tracer, Fe metabolism
^{55}Co	17.5h	β^+(81%),EC	^{56}Fe(p,2n)	PET label
^{64}Cu	12.7 h	β^+/β^-	^{64}Ni(p,n)	PET label; RIT
^{65}Zn	244d	EC	^{69}Ge(p,✂n)	Zn tracer
^{67}Cu	61.9h	β^-	^{68}Zn(p,2p)	RIT
$^{68}Ge/^{68}Ga$	271d/68m	EC	^{nat}Ga(p,2n/4n)	PET calibration
^{73}As	80.3d	EC	^{74}Ge(p,2n)	As tracer
$^{81}Rb/^{81m}Kr$	4.6h/13s	EC/IT	^{nat}Kr(p,4n)	Lung imaging

What else?

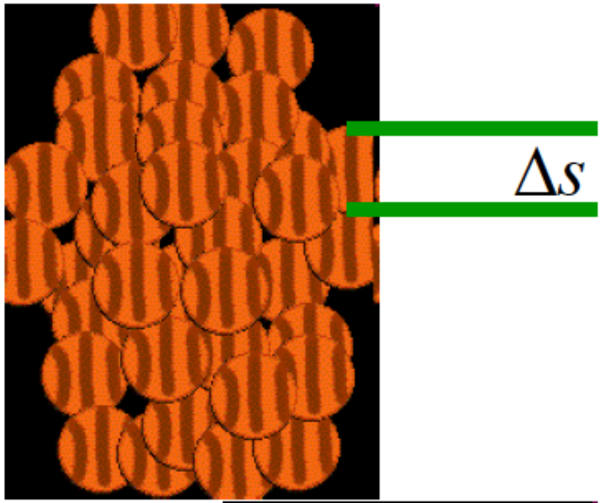


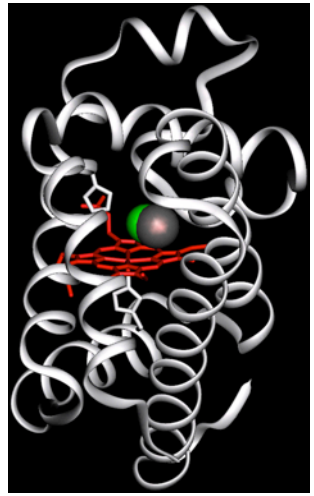



Scientific Applications

- ✓ Fundamental particle physics - colliders
- ✓ Applied (material, geology, medicine, pharmacology…) and fundamental sciences (physics, biology, chemistry) using of synchrotron radiation, and neutron and FEL sources of radiation

Resolution

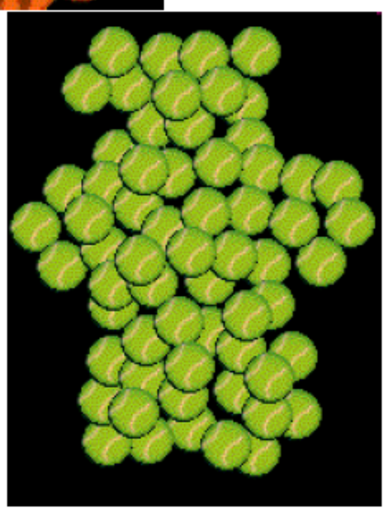




$$E = h\nu = h \cdot \frac{c}{\lambda} = 2\pi \frac{\hbar c}{\lambda}$$

$$\Delta s \geq \lambda = \frac{hc}{E}$$

Massless particles:
The resolution is inversely proportional to the radiation energy.
Massive particles:
de-Broglie wavelength.



$$\lambda = \frac{h}{p}$$

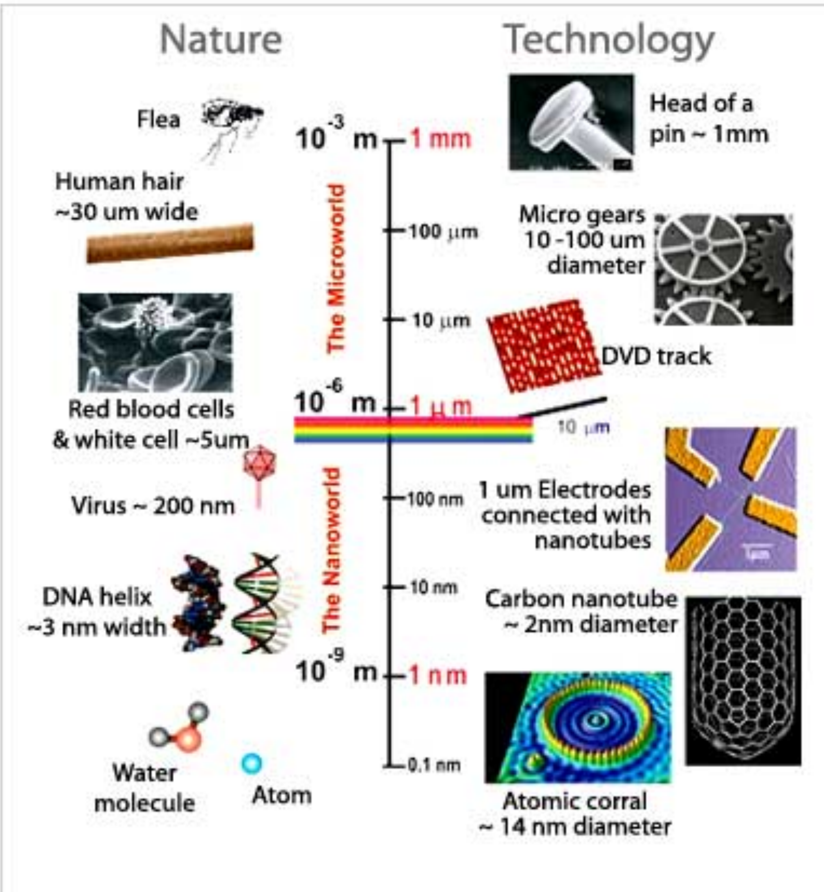
$$\Delta s \geq \lambda = \frac{h}{p} = \frac{h}{\gamma\, m\, v} = \frac{h}{\gamma\, m\, v}$$

$$\lambda = 2\pi \frac{\hbar c}{pc} = 2\pi \frac{197\ \mathrm{MeV\ fm}}{pc}$$

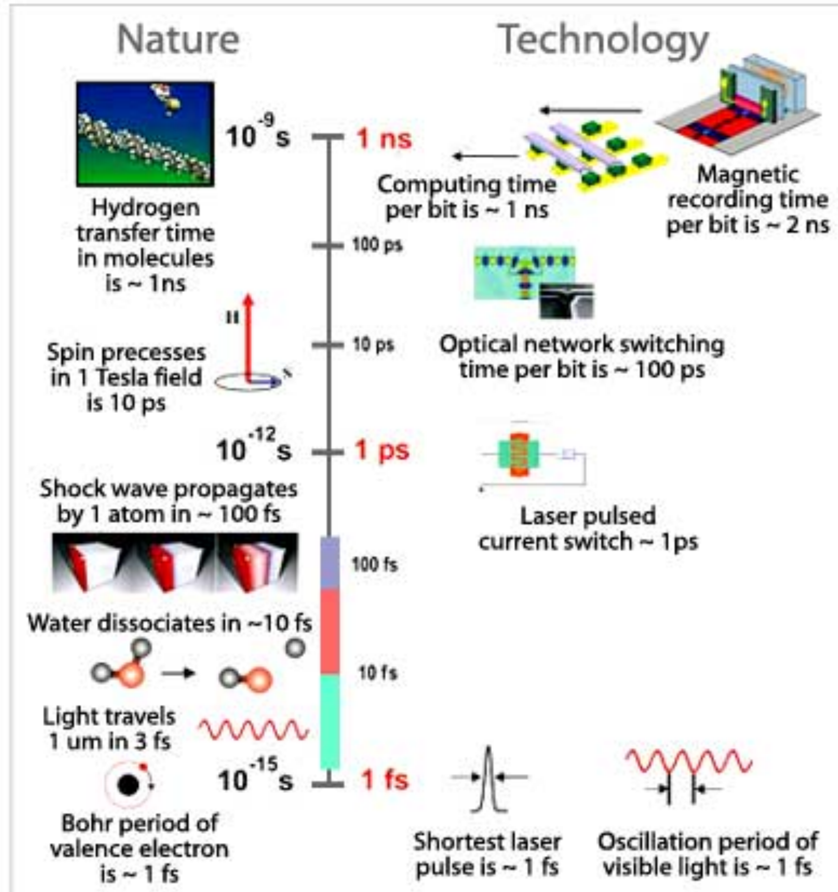
http://www.solstice.de

What Light Sources Are For

Ultra-Small

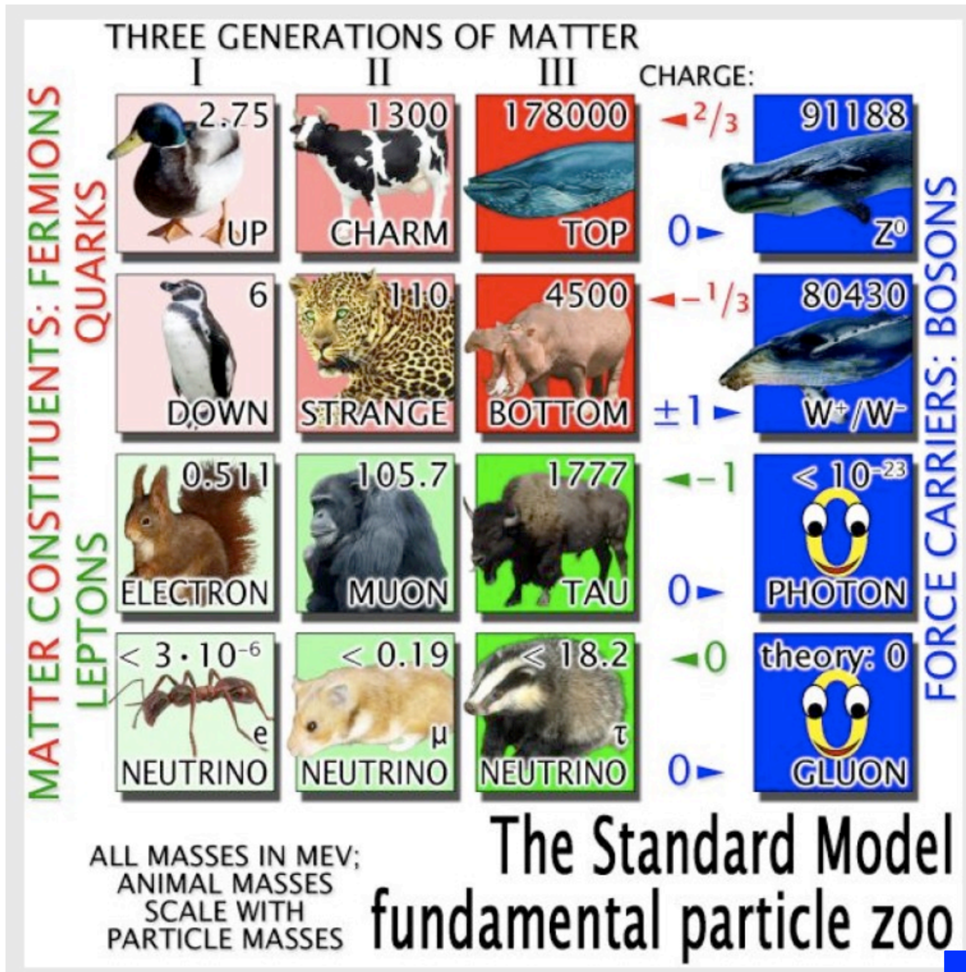


Ultra-Fast



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

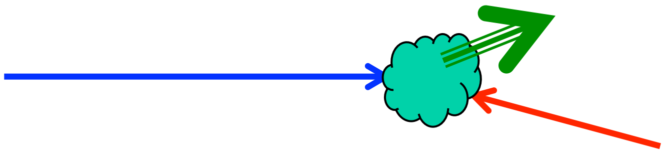
Accelerator allowed us to discover the entire Zoo of elementary particles and their combinations (states)



HIGS

Why accelerator (particle) energy is a figure of merit for fundamental physics ?

Second: it allows us to create new heavy particles.



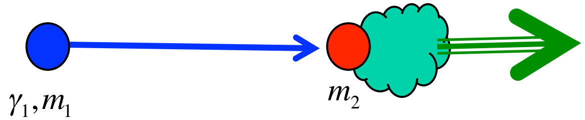
The minimum energy required to create a particle (or group of particle) with total mass M is:

$$E_{\min} = Mc^2; \;\; M = \sum m_i$$

In practice the energy of colliding particles has to be higher, both to allow the created particles to separate and, in some geometry, for their common motion.

Fixed target experiments

A particle from an accelerator is directed towards a stationary particle:



In the co-moving frame of created particles the energy is equal to (or exceeds) Mc^2

The conservation of the energy states that

$$E = \gamma_1 m_1 c^2 + m_2 c^2; \quad \vec{P} = \gamma_1 m_1 \vec{\mathrm{v}}_1; \quad \gamma_1 = 1/\sqrt{1 - \vec{\mathrm{v}}_1^2 / c^2}$$

and the available energy for creating particles is

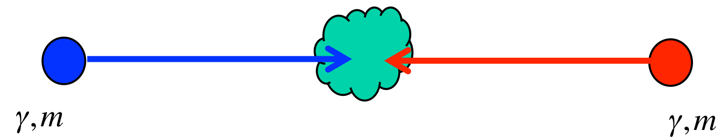
$$M_{eff}^2 c^4 = E^2 - \vec{P}^2 = \left(m_1 c^2\right) + 2\gamma_1 m_1 c^2 m_2 c^2 + \left(m_2 c^2\right)^2$$

$$\gamma_1 >> 1 \;\; \Rightarrow \;\; M_{eff} c^2 \cong \sqrt{2 E_1 m_2 c^2}$$

with most of the energy lost for the common motion of the products of the reaction

Collider experiments

A particle from an accelerator is directed towards a stationary particle:



The conservation of the energy states that

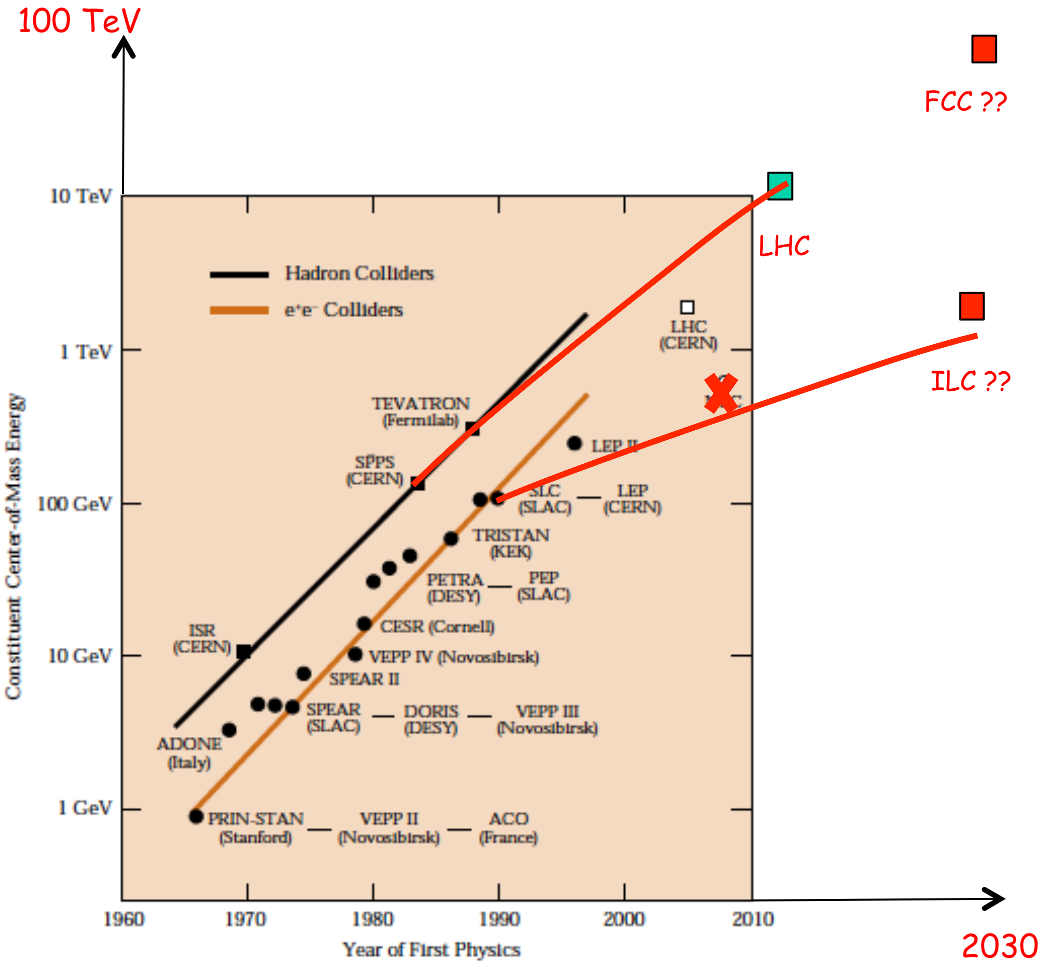
$$E = 2\gamma mc^2; \;\; \vec{P} = \gamma m\vec{v} - \gamma m\vec{v} = 0;$$

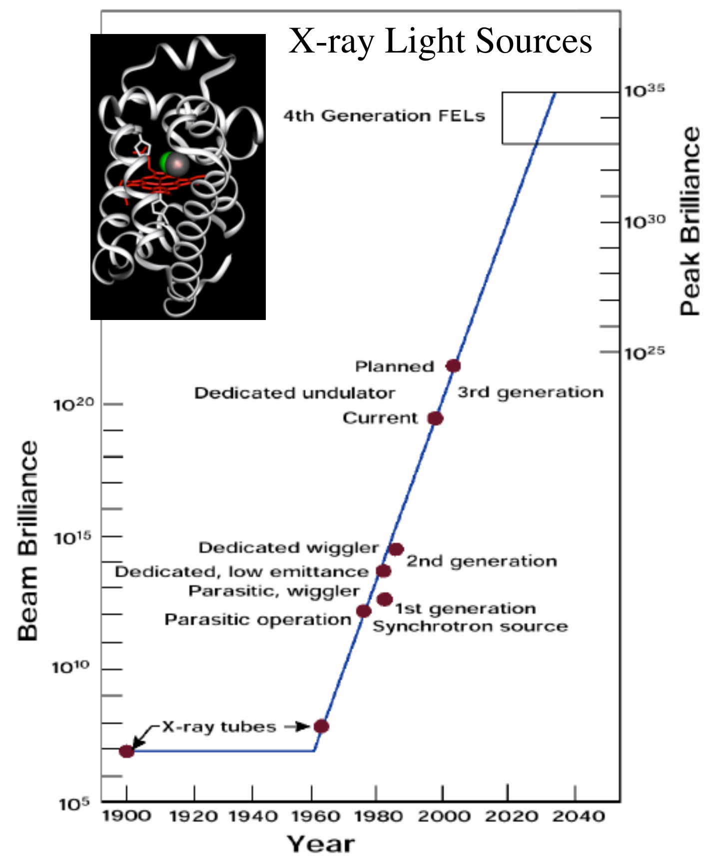
and the available energy for creating particles is maximized

$$\left(M_{eff}c^2\right)^2 = \left(2\gamma mc^2\right)^2 - 0 \;\Rightarrow E_{CM} = M_{eff}c^2 = 2\gamma mc^2 = E_1 + E_2$$

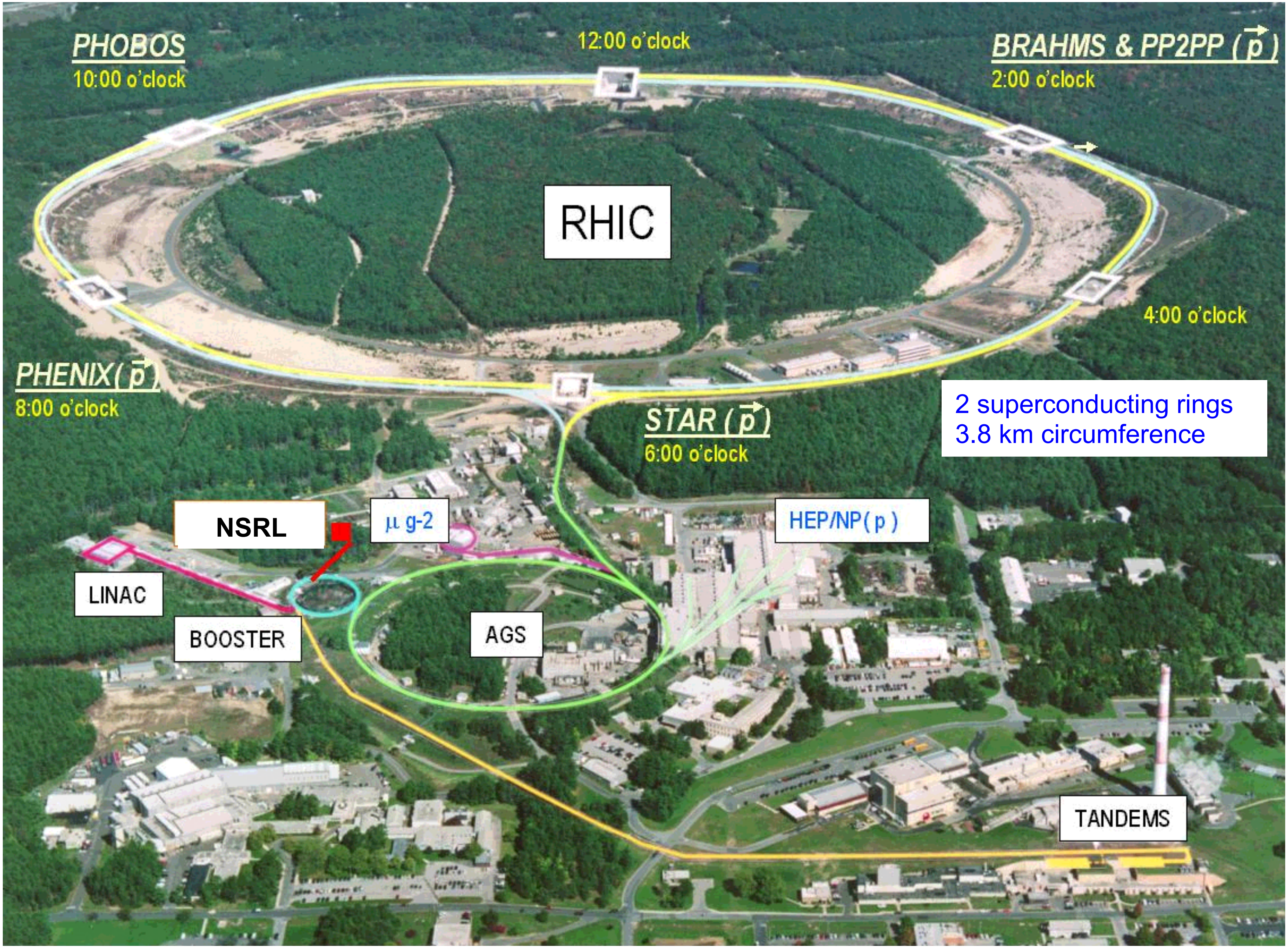
Achieved: e^+e^- - 200 GeV; $p\bar{p}$ – 2 TeV; pp – 10 TeV

Two Moors laws for accelerator plots: Livingston plot for C.M. energy and peak brightness plot for light sources

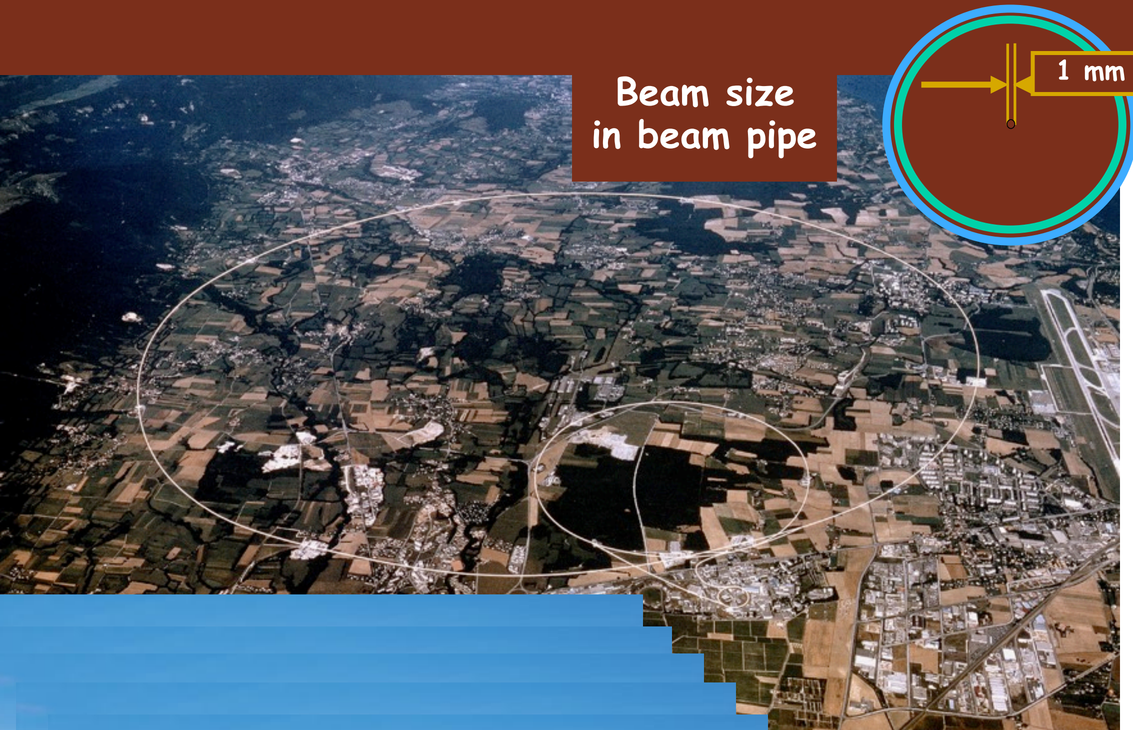




by WOLFGANG K. H. PANOFSKY


PHOBOS
10:00 o'clock
12:00 o'clock
BRAHMS & PP2PP ($\vec{p}$)
2:00 o'clock
RHIC
4:00 o'clock
PHENIX ($\vec{p}$)
8:00 o'clock
STAR ($\vec{p}$)
6:00 o'clock
2 superconducting rings
3.8 km circumference
NSRL
μ g-2
HEP/NP (p)
LINAC
BOOSTER
AGS
TANDEMS

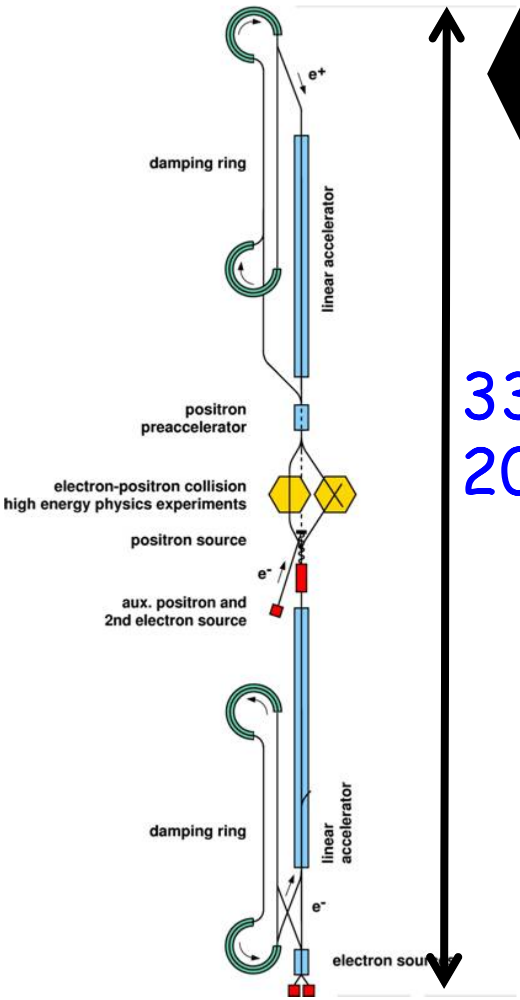
CERN – Large Hadron Collider (LHC)



Time	2007-
Circumference [km]	26.7
Energy [GeV]	7000 p 580000 Pb
Particles	p-p Pb-Pb
Peak luminosity [$10^{30}cm^{-2}s^{-1}$]	**10000 (design)**

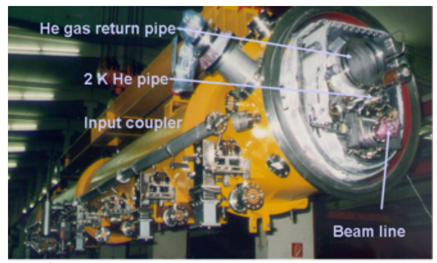
350MJ stored energy per beam inside super-conducting magnets = kinetic energy of 20 fully loaded class 8 trucks (120,000lbs) at 55mi/hr

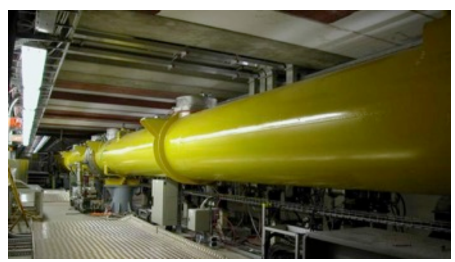
International Linear Collider *B10$+*



TESLA TDR
500 GeV (800 GeV)

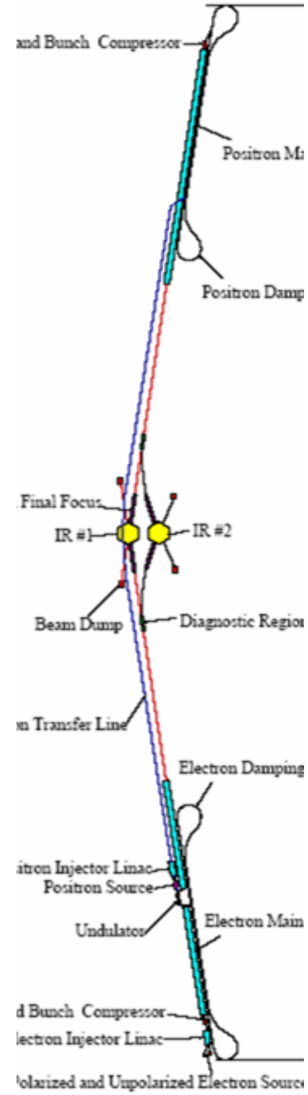
33km
20 miles





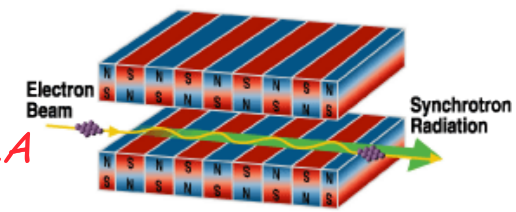
47 km
30 miles

US Options Study
500 GeV (1 TeV)

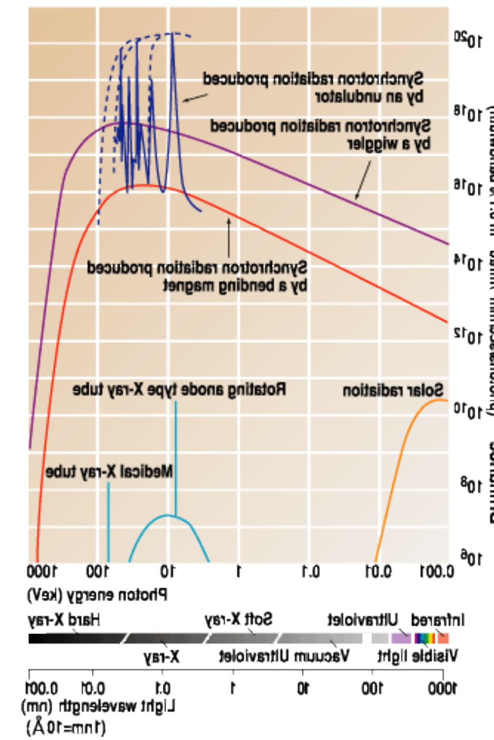


Extremes of e^+/e^- beams : Light Sources

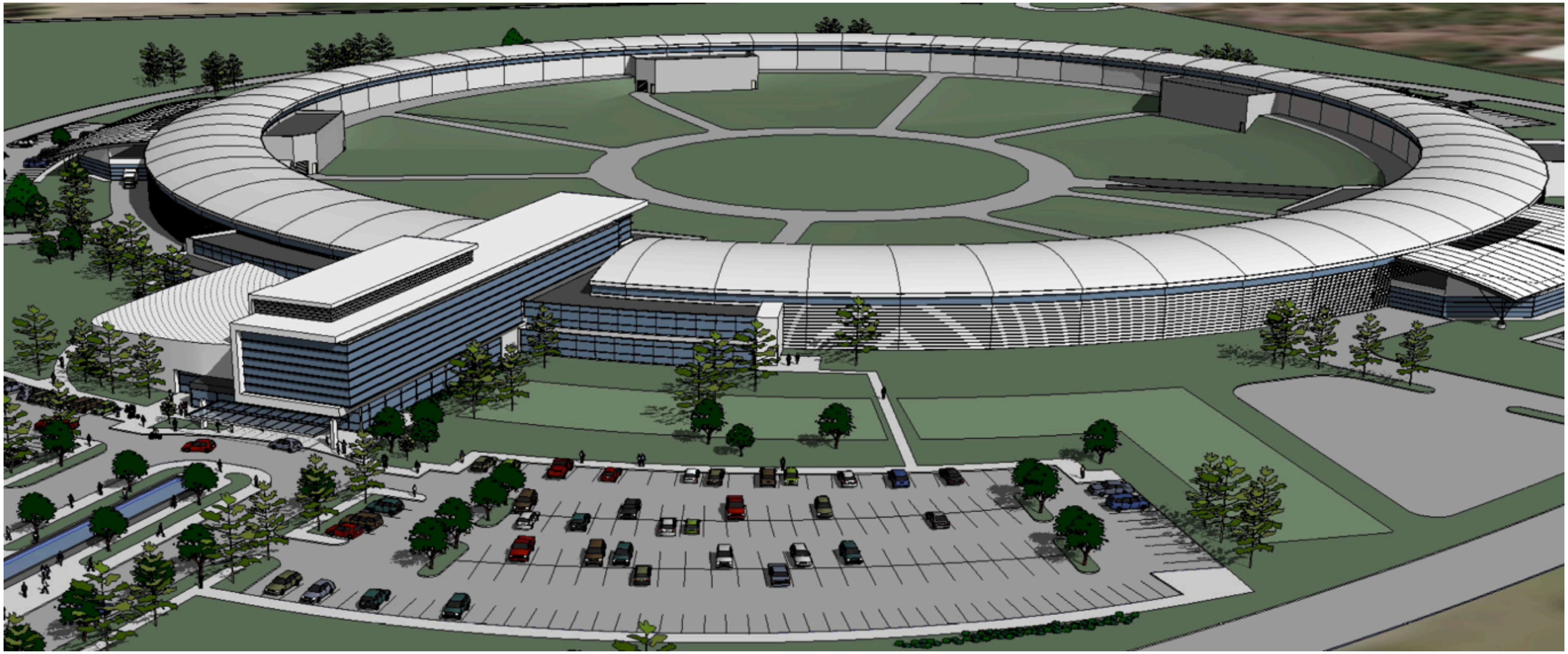
- **Emittance**
  - 1 Å·rad (ESRF @ 1GeV)
- **Bunch length**
  - 100 fsec (ATF @ BNL, TESLA



- **Brilliance** [ph/sec/[illegible]m^2/10^{-3}BW]
  - Average 10^{20} (ESRF, APS, Spring-8)
  - Peak $4 \cdot 10^{28}$ (TESLA FEL @ 100 nm - 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

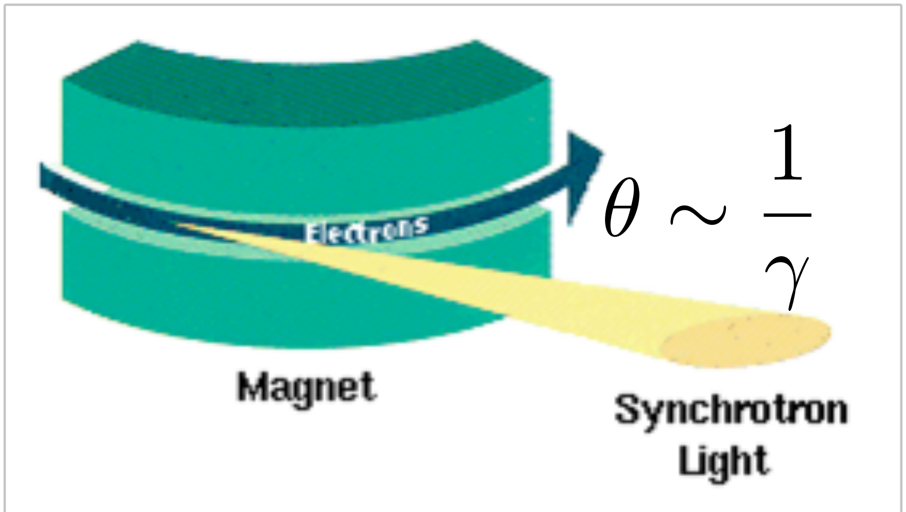
ESRF, 6 GeV

SPring-8, 8 GeV

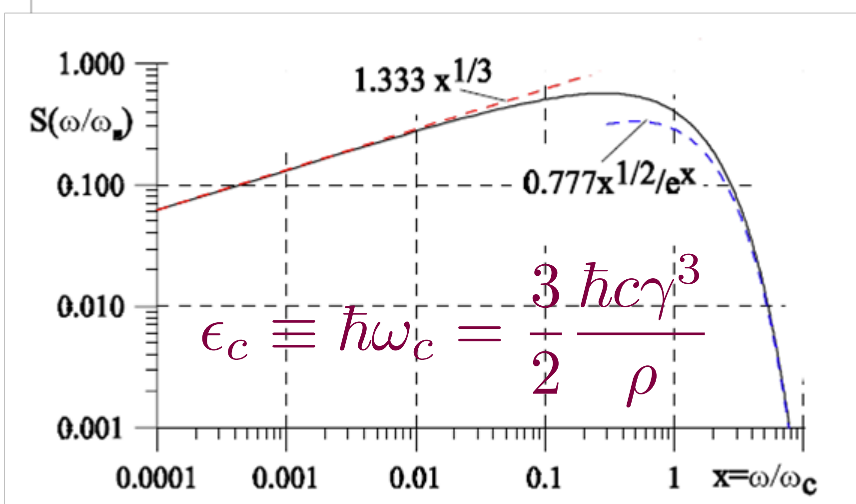
NSLS II, 3 GeV

SSRF, 3.5 GeV

SR from Bending Magnet



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

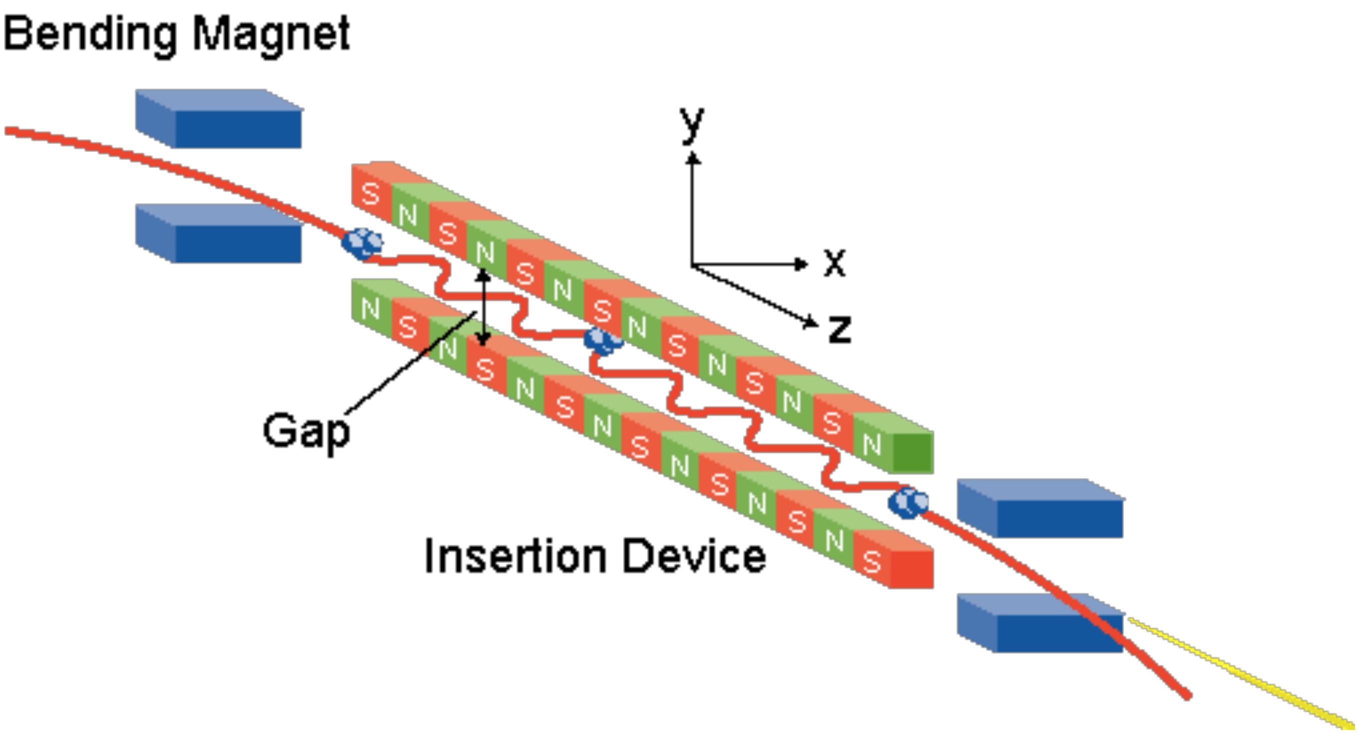


$$\epsilon_c \equiv \hbar\omega_c = \frac{3}{2}\frac{\hbar c \gamma^3}{\rho}$$

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

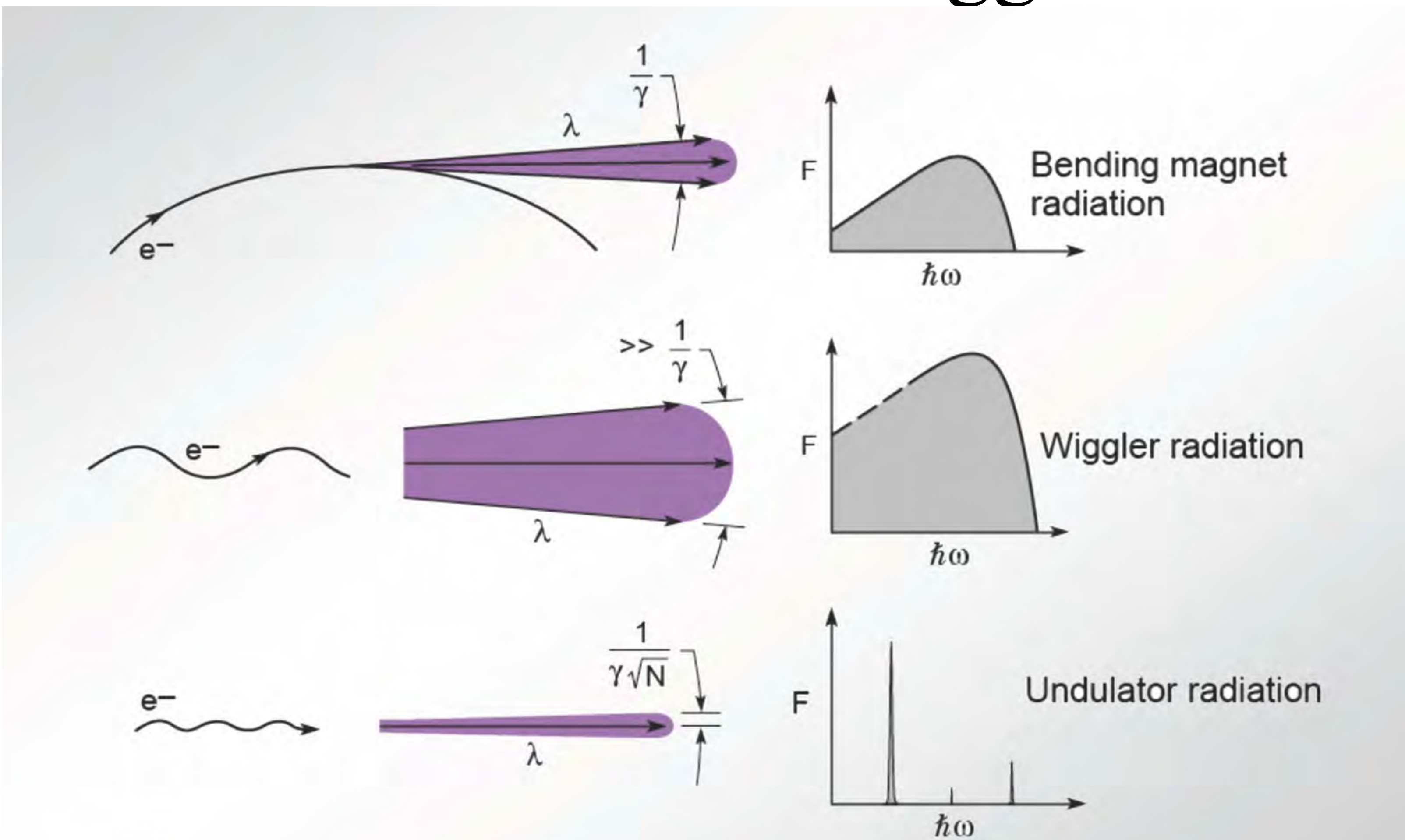
- Goods
  - Simple, inexpensive
  - Broad spectral range
  - Many beamlines
- Bads
  - Limited hard x-ray components
  - Not very bright

SR from Undulator/Wiggler



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

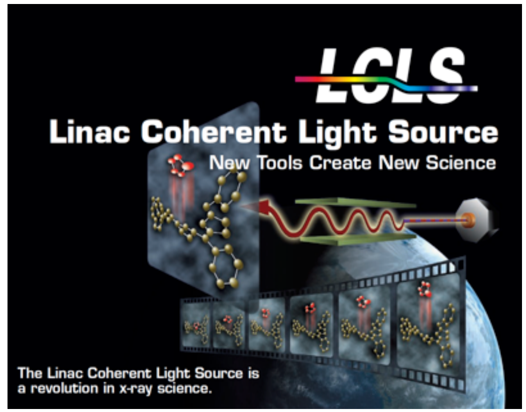
Difference between bending magnet and Undulator/Wiggler



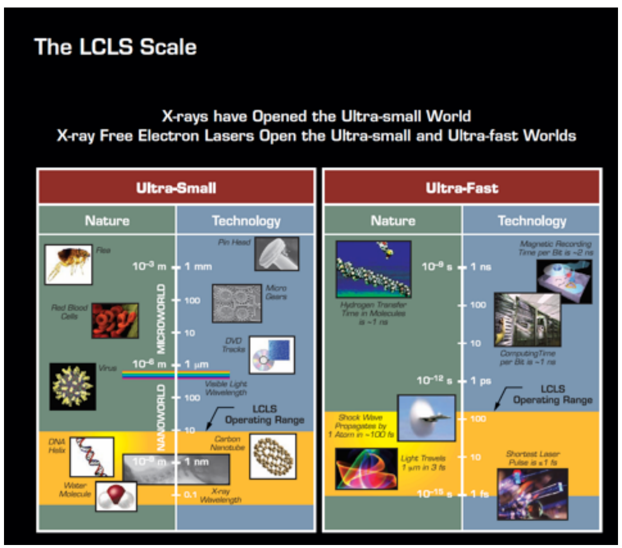
Courtesy of W. Barletta

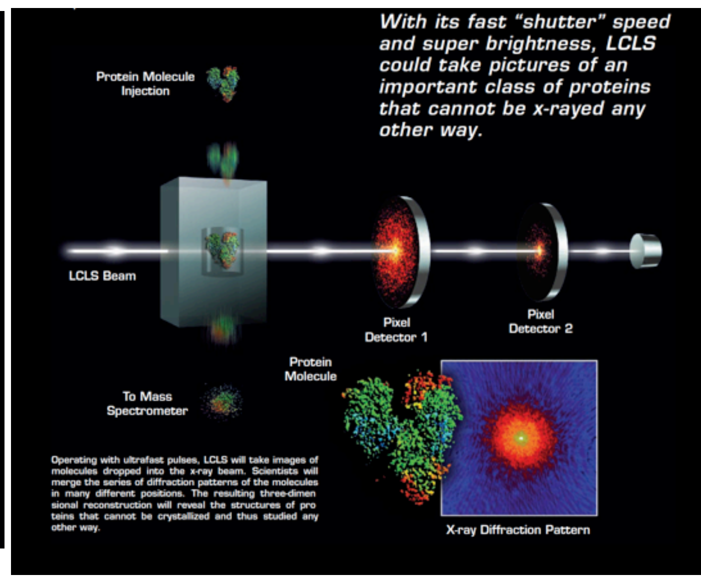
The Ultimate Tasks are for Free Electron lasers!

- 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)

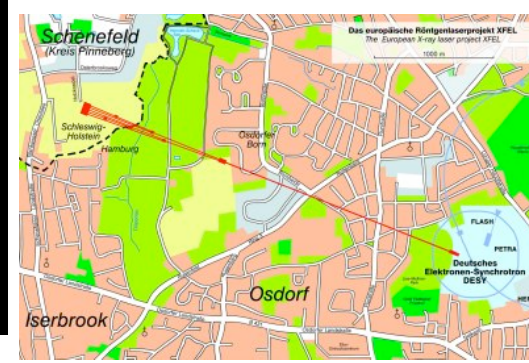


LCLS at SLAC





The European X-Ray Laser Project XFEL

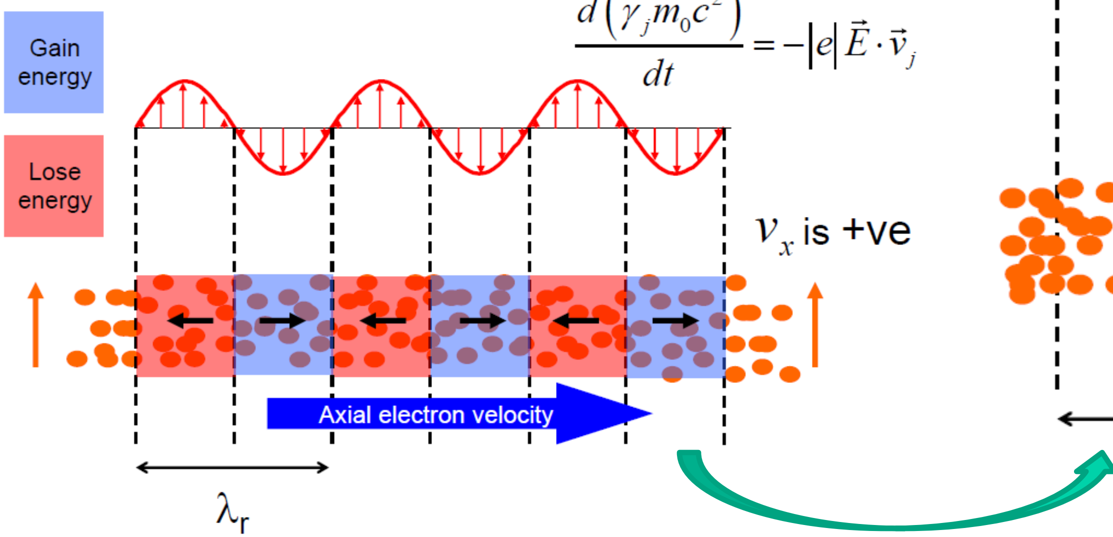


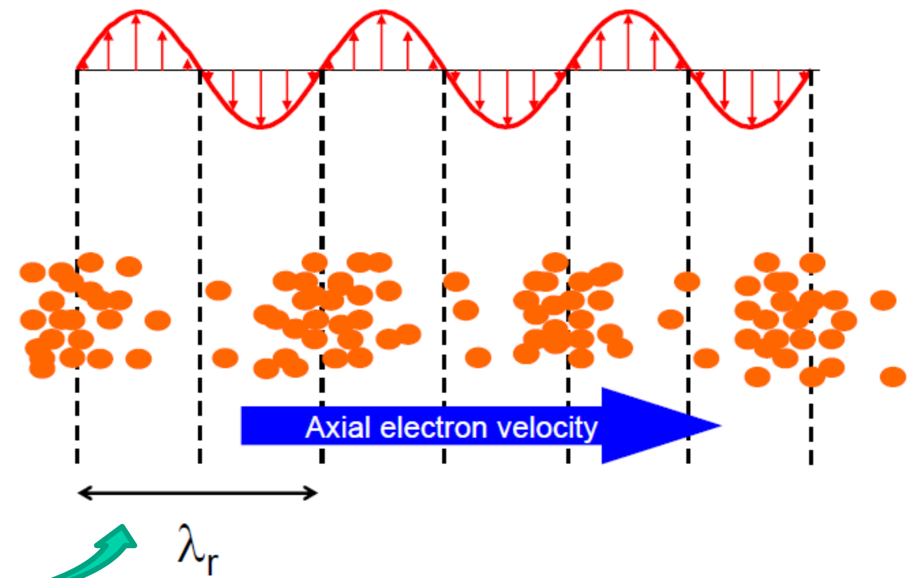
http://www-ssrl.slac.stanford.edu/lcls/
http://xfelinfo.desy.de/en/start/2/

FEL II: Micro-Bunching

The energy change has a sinusoidal form, Therefore:

$$\frac{d\left(\gamma_j m_0 c^2\right)}{dt} = -|e|\vec{E}\cdot\vec{v}_j$$





Or we can write down differential equation for the energy exchange phase and the energy deviation. It is a pendulum equation which defines the separatrix.

$$\frac{d\theta}{dz} = 2k_u\eta$$

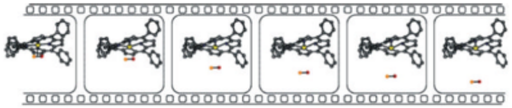
$$\frac{d\eta}{dz} = \frac{eE_0K[JJ]}{2\gamma_r^2 mc^2}\sin\theta$$

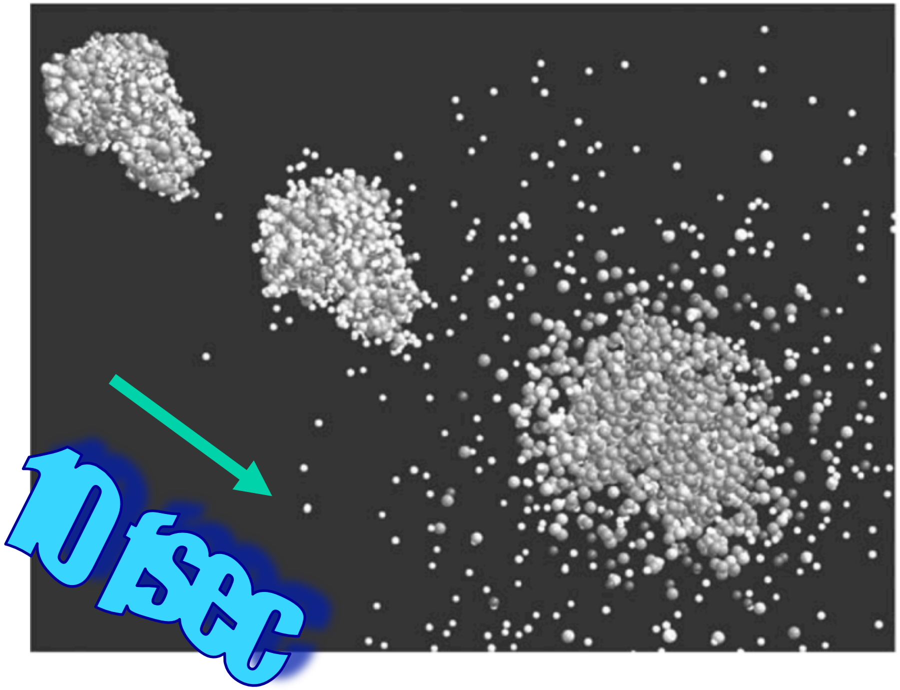
$$\eta = \frac{\gamma - \gamma_r}{\gamma_r}, \theta = (k + k_u)z - \omega t + \theta_0$$

$$[JJ] = J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right)$$

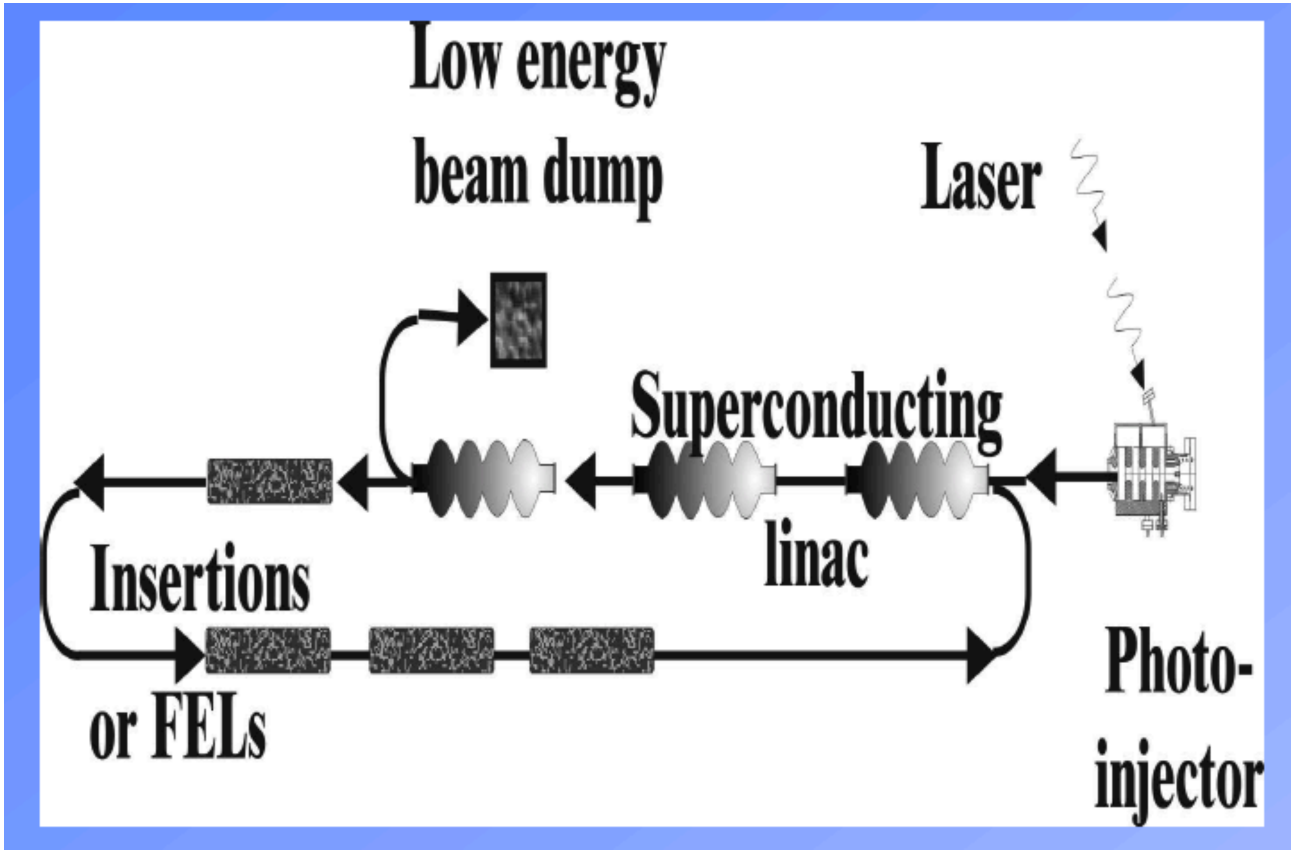
The Ultimate Task!

- To see one single protein or cell - it needs it all fsec duration and a lot of X-ray photons in a single shot



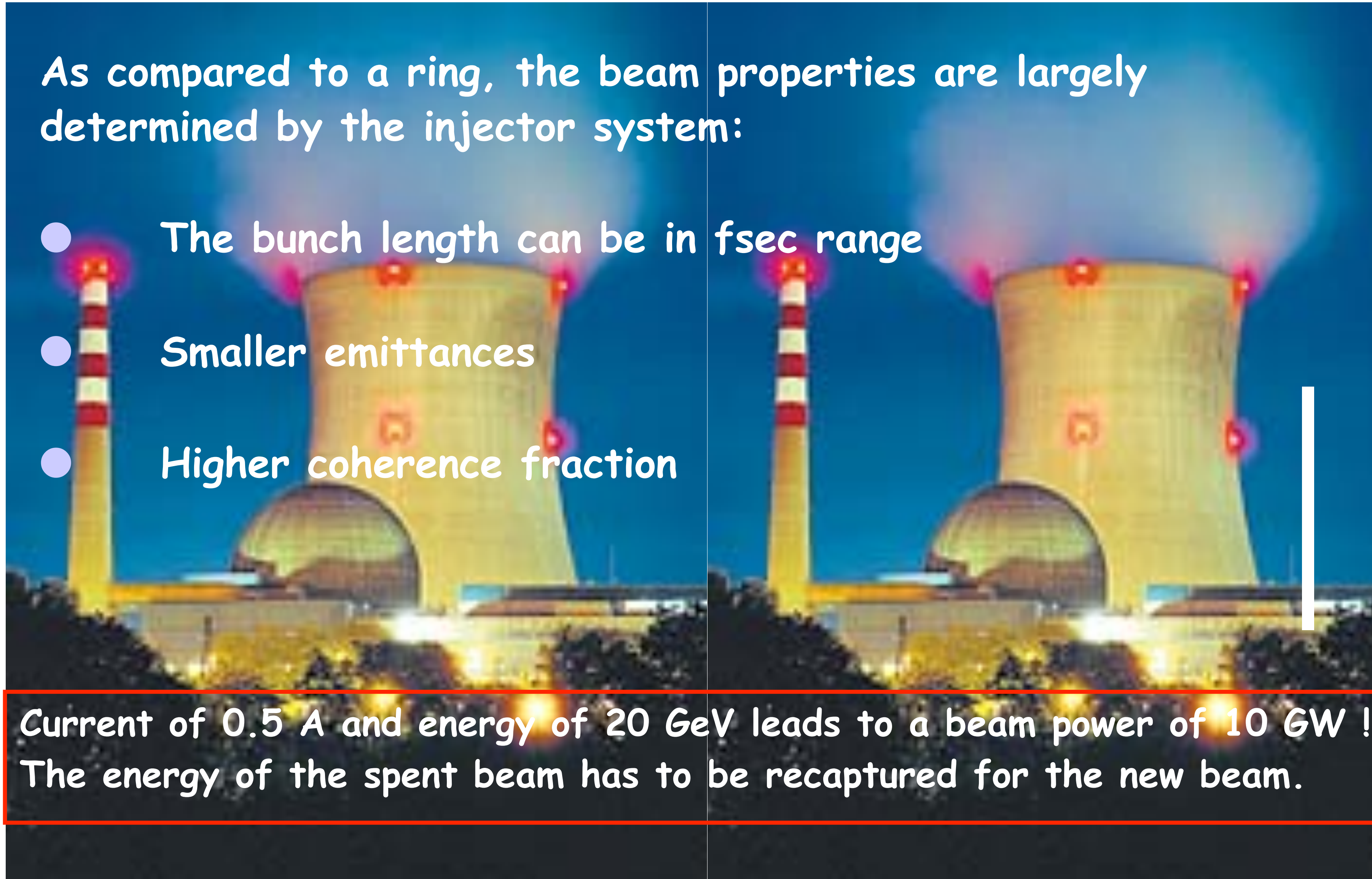


Energy Recovery Linac



M. Tigner (1965) - SC ERL, followed by
BINP, Jefferson Lab, BNL,Cornell, LBNL, KEK
and more ...

ERLs - path to the future



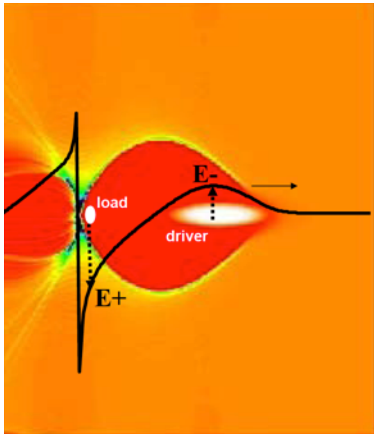
As compared to a ring, the beam properties are largely determined by the injector system:

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

Current of 0.5 A and energy of 20 GeV leads to a beam power of 10 GW !!!
The energy of the spent beam has to be recaptured for the new beam.

Plasma accelerators

$$a_0 = \frac{eE_o\lambda_o}{2\pi mc^2} \equiv \frac{eE_o}{mc\omega_o} \equiv \frac{eA_o}{mc^2} << 1$$



Electrons motion is nonrelativistic, linear plasma

$$a_0 = \frac{eE_o\lambda_o}{2\pi mc^2} >> 1$$

Relativistic motion of electrons, nonlinear plasma, blow-out regime (e.g.

Scaling

$$l_{buble} \sim \frac{c}{\omega_p}; \;\; r_{buble} \sim l_{buble}/2; \;\; E \sim \frac{4\pi q}{\pi r^2_{buble}} \cong 4\pi e n_o \frac{l_{buble}\pi r^2_{buble}}{\pi r^2_{buble}} \cong \frac{4\pi e c n_o}{\omega_p} = e\sqrt{\frac{4\pi n_o}{r_e}}$$

$$r_e = 2.8\cdot 10^{-13}\,cm; \;\; n_o = 10^{19}\,cm^{-3}; e = 4.8\cdot 10^{-10}\text{ esu}; \;\; E \sim 10^7\,Gs = 3GV/cm$$

Compare this 300 GeV/m with 150 MeV/m in RF linacs

END

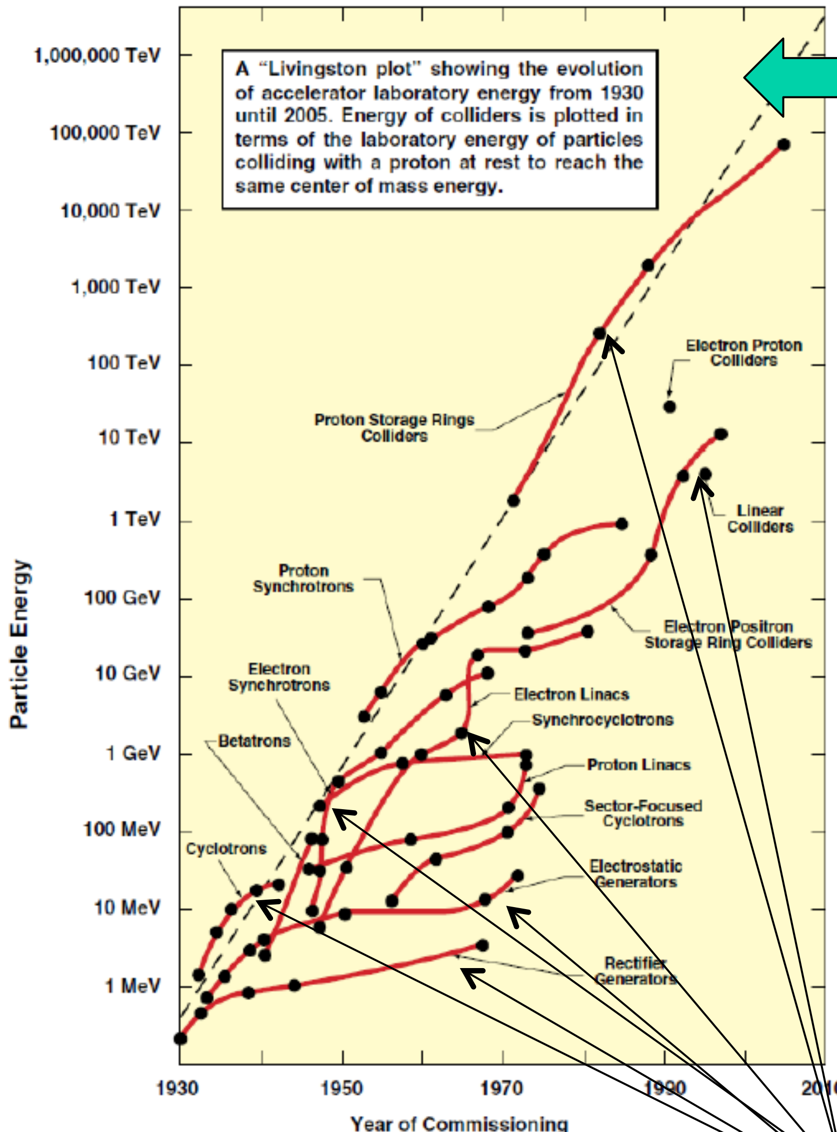
Future Technology & Applications

- **Free Electron Laser (FEL)**
  - *Next generation of synchrotron light source.*
  - Uses electrons from linac with PM wiggler to create tunable light source for many applications now performed at electron synchrotron facilities.

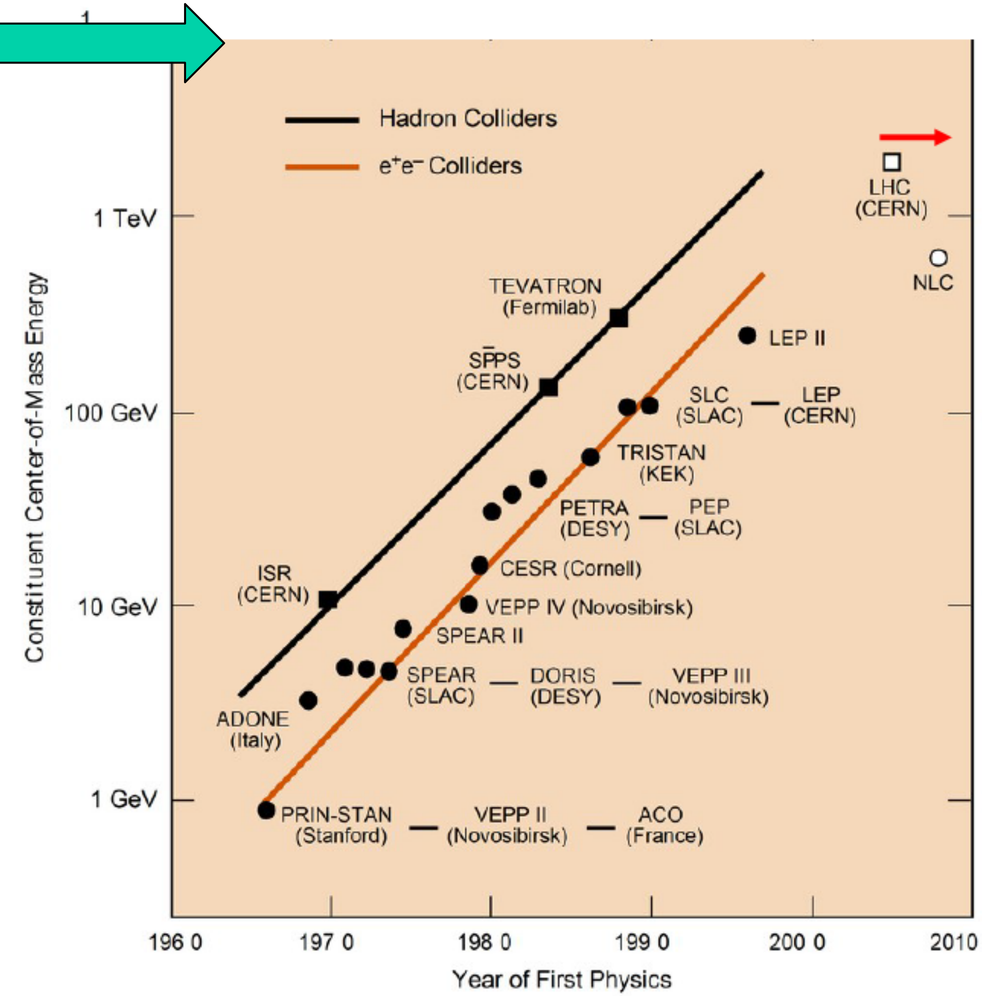
- **Superconducting Linacs & Cyclotrons**
  - Improvements in cryogenic technology from widespread use in large research and medical accelerators
  - Increase in efficiency and size reduction of systems for cancer therapy, and radioisotope and neutron production.

- **Fixed Field Alternating Gradient (FFAG) Cyclotron**
  - Being developed for high energy physics research at national labs.
  - Also being developed as a neutron source for BNCT, and if proven, will be quickly adapted for other neutron beam applications.

Colliders and their effective energy



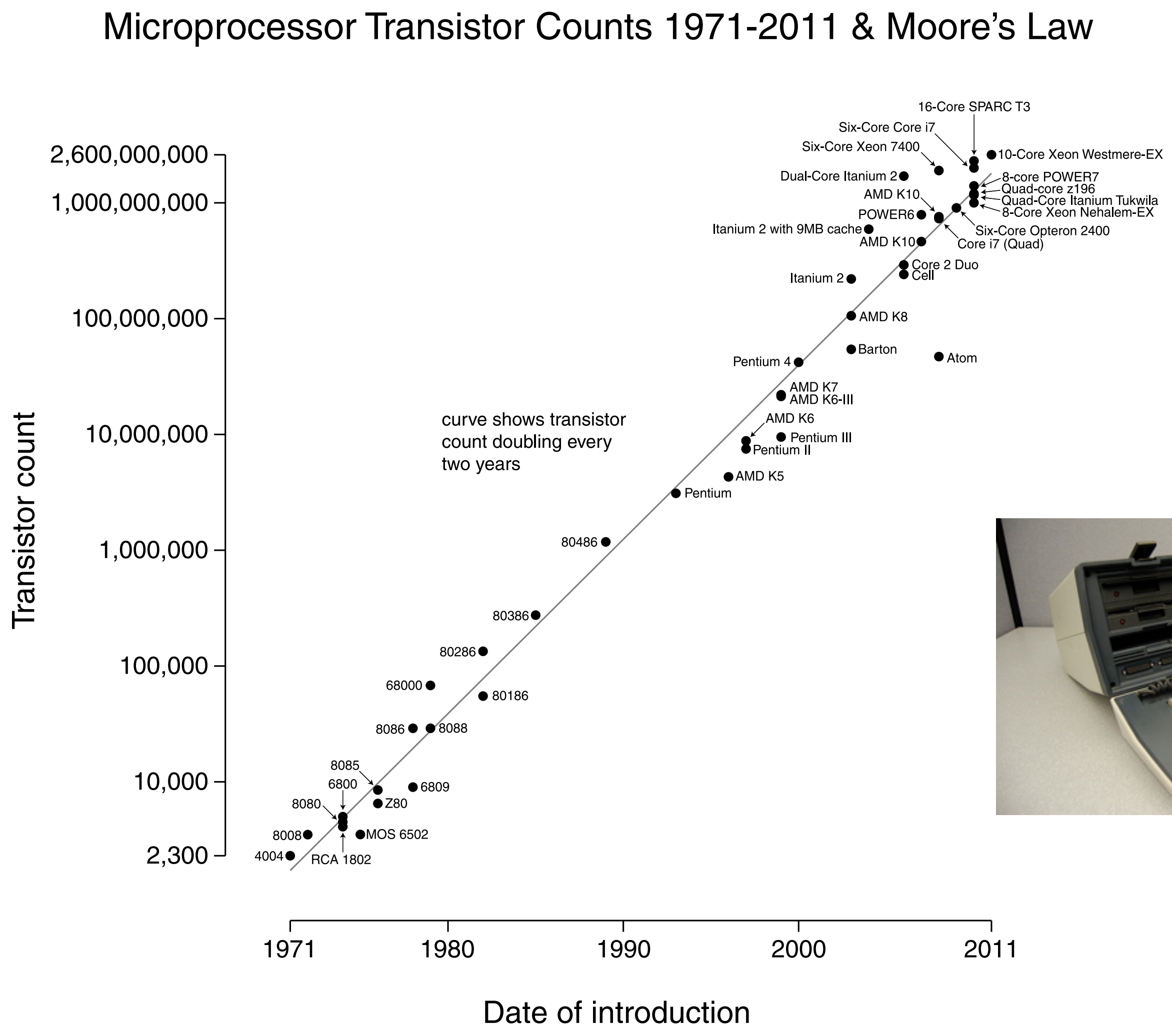
Courtesy: Stanley Livingston



Courtesy: Stanley Livingston

We will discuss some (but not all!) of these branches

Every rapidly advancing field has its logarithmic plot: example is the Moorse Law Plot



Plot of CPU transistor counts against dates of introduction.
Note the logarithmic vertical scale; the line corresponds to exponential growth with transistor count doubling every two years.

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