Outline: Accelerators and beam physics

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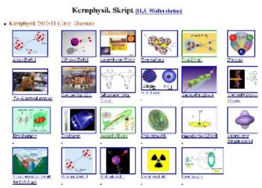

1. what are accelerators used for?
2. relativity and units
3. how do we see an object
4. detectors – the eye of a physicist
5. energy, wavelength and resolution

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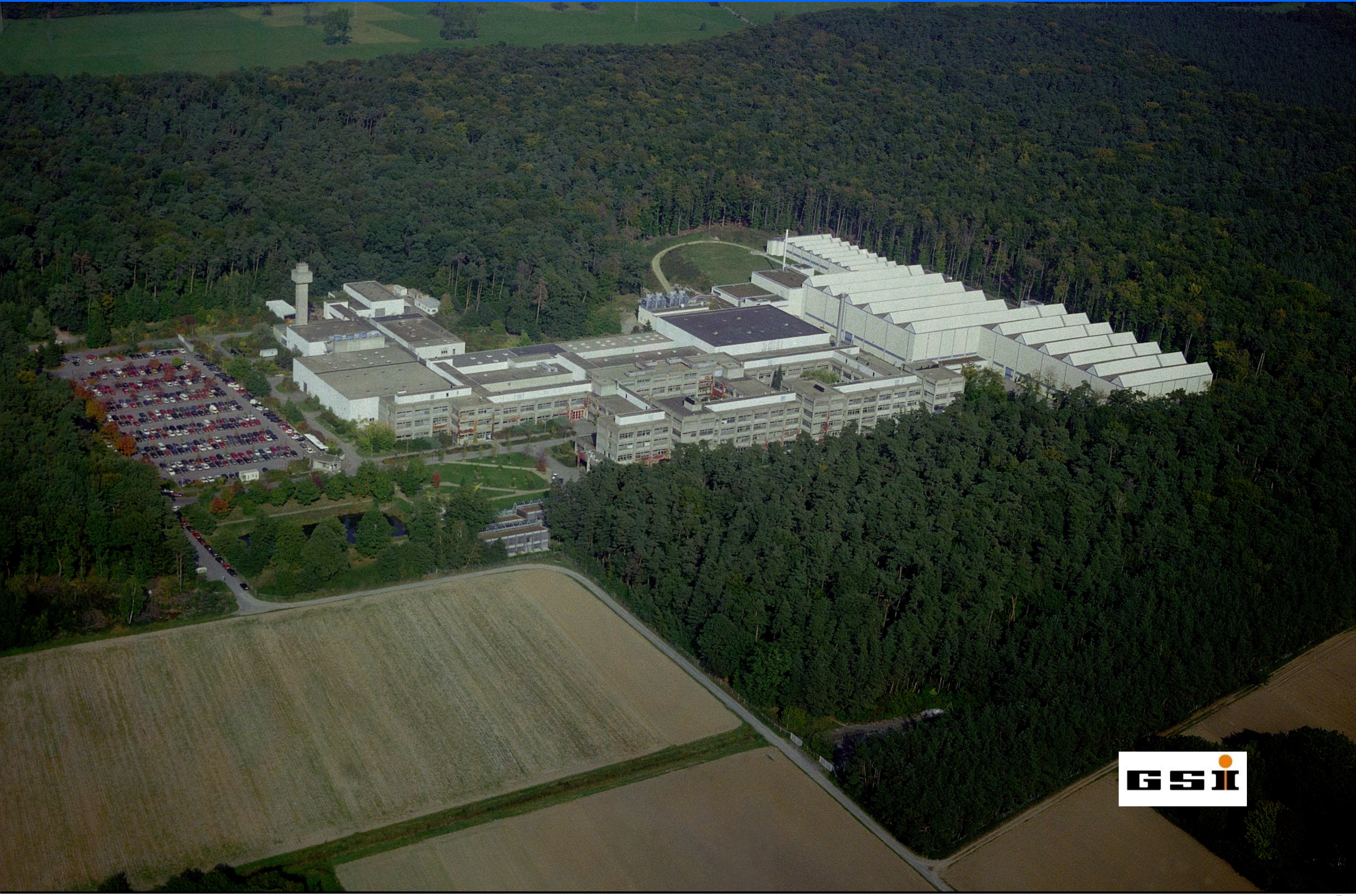


Tentative outline of accelerator lecture series

❖ A History of Particle Accelerators
cathode rays are particles
Rutherford scattering
natural particle acceleration
electrostatic accelerators:
Cockroft Walton multiplier
Van de Graaff accelerator
Tandem accelerator

❖ Cyclotron
motion in E- and B-fields
cyclotron frequency and K-value
sector focusing cyclotron

❖ Radio-frequency accelerator
Wideroe structure
Alvarez structure
synchrotron

❖ Accelerator facility at GSI
heavy ion source
charge stripper to increase the efficiency
UNILAC, SIS-18

❖ Radioactive Ion Beams
projectile fragmentation
fragment separator at GSI
target fragmentation
isotope separation on line
ISOLDE at CERN

❖ Storage Rings
beam emittance
stochastic cooling
electron cooling
laser cooling
experimental storage ring at GSI

❖ Large Hadron Collider
electron vs. proton machine
fixed target vs. colliding beam experiment
LHC layout and experiments

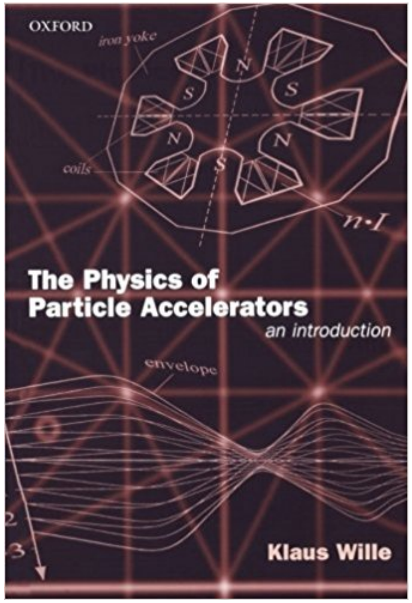
❖ Magnets
dipole, quadrupole, n-pole magnets

❖ Accelerator light source
Bremsstrahlung
Synchrotron radiation
Inverse Compton scattering

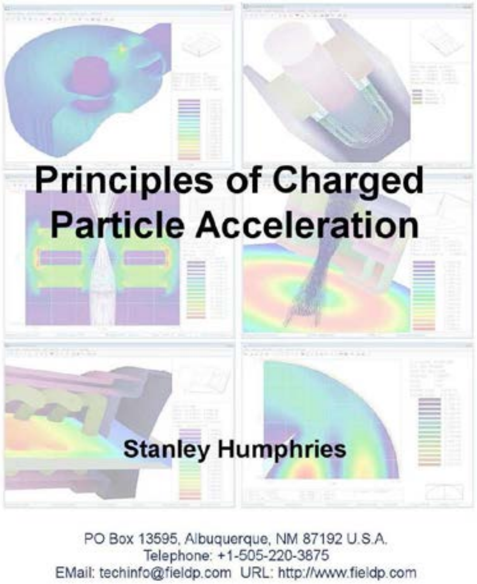
❖ Application
Medical application
Ion implantation
Spallation target
Scanning
Transmutation
Radiocarbon dating

❖ Wakefield Accelerator
Three orders of magnitude higher field gradient

Literature



❖ Recommended Textbook



❖ Recommended e-book

Additional material:

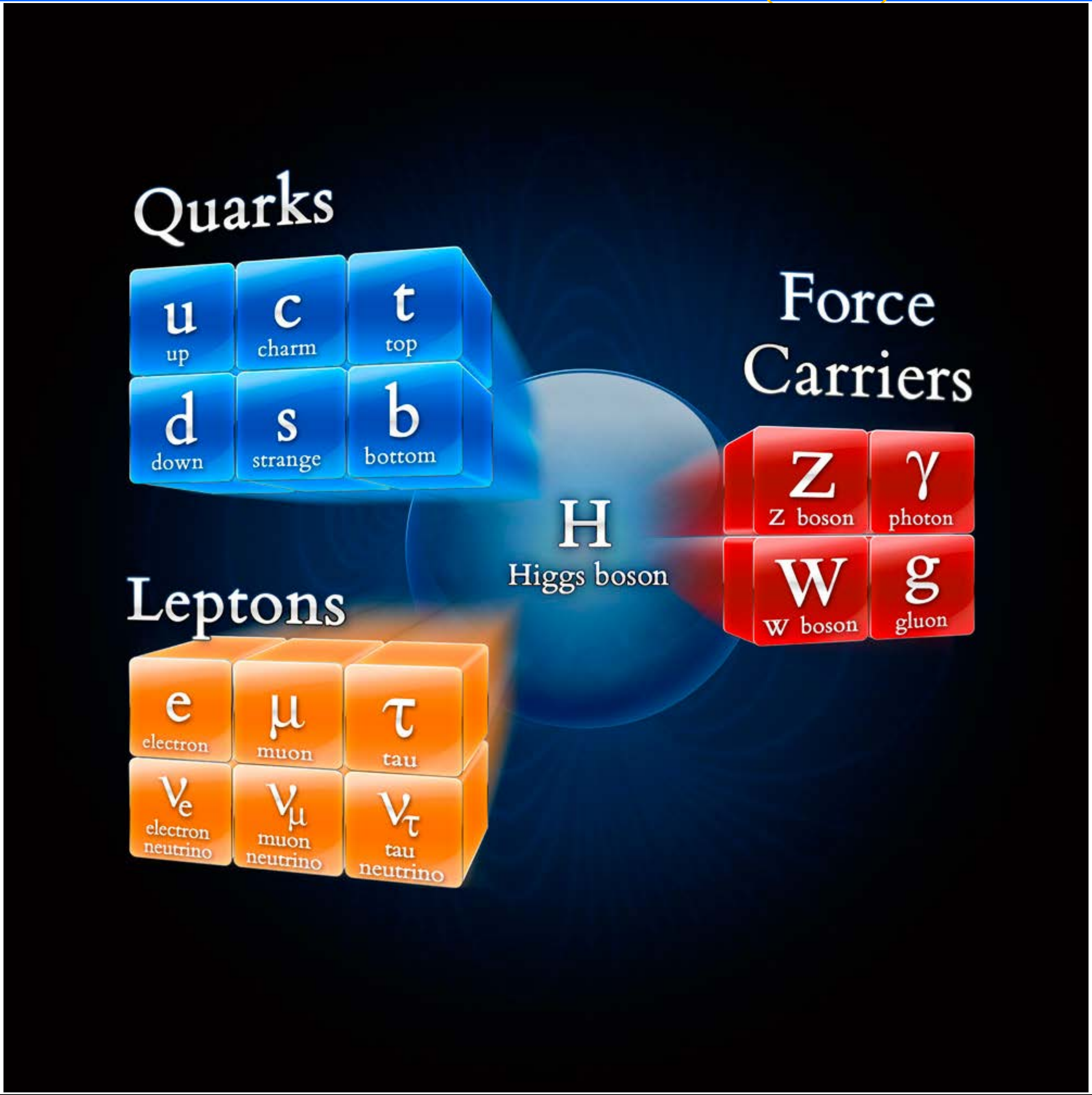
http://uspas.fnal.gov/materials/materials-table.shtml

What are accelerators used for?

- High Energy Physics & Nuclear Physics
  - Understand the fundamental building blocks of nature and the force that act upon them
  - Understanding the structure and dynamics of nuclear matter
  - In short search for answer of the most fundamental questions
- Chemistry, Biology, Medicine, Material Sciences
  - Find the structure of molecules, proteins, cells … with ultimate goal of determining structure of a single organic molecule as complex as a protein!
  - Determine structure of material and their properties (physics, chemistry, biology, medicine)
  - Resolve structural changes in a natural (femto-sec and atto-sec) time scales
- Civil, Industrial and Military Applications
  - Medical treatment of tumors and cancers
  - Production of medical isotopes
  - Ion implantation to modify the surfaces of materials
  - National security: cargo inspections, …

This list will never be complete …

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



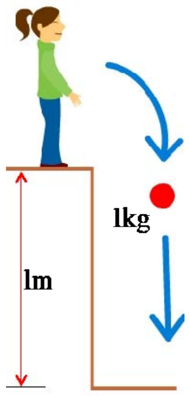
What do we accelerate?

- We can accelerate charged particles:
  - electrons (e-) and positrons (e+)
  - protons (p) and antiprotons ($\bar{p}$)
  - ions (e.g. H^{1-}, Ne^{2+}, Au^{79+}, …)
- Few accelerators use positrons or antiprotons
  - which are created by smashing accelerated electrons or protons onto a target
- These particles are typically "born" at low-energy
  - e^-: emission from thermionic gun at ~100 kV
  - p/ions: sources at ~50 kV
- A few dedicated facilities accelerate unstable ions
  - radioactive ion facilities
- Finally, there is a discussion and developments towards a more exotic collider using unstable muon beams
  - with 2 microsecond lifetime in the rest frame

- The main characteristics of an accelerator:
  - energy and luminosity

Units of energy: Electron Volts

- An "electron-volt" is the energy gained by a particle of unit charge is accelerated over 1V potential



- It is really small
  - 1 eV = $1.6 \cdot 10^{-19}$ (=0.00000000000000000016) Joules – our usual unit of energy.
  - A 1 kg weight dropped 1m would have $6 \cdot 10^{18}$ eV of energy!

- On the other hand, it's a very useful unit when talking about individual particles
  - If we accelerate a proton using an electrical potential, we know exactly what the energy is.
  - It's also useful when thinking about mass/energy equivalence

$$(proton\ mass) \cdot c^2 = 938\,000\,000\ eV \approx 1\ billion\ eV = 1\ GeV$$

$$(electron\ mass) \cdot c^2 = 511\,000\ eV \approx \frac{1}{2}\ MeV$$

speed of light (c): $2.99792 \cdot 10^8$ m/s

Few numbers and units

Particle	Charge	Charge, C	Rest mass, kg	Rest mass, eV/c^2
Electron, e^-	-e	$-1.6\cdot10^{-19}$	$9.11\cdot10^{-31}$	$0.511\cdot10^{6}$
Positron, e^+	+e	$+1.6\cdot10^{-19}$	$9.11\cdot10^{-31}$	$0.511\cdot10^{6}$
Proton, p	+e	$+1.6\cdot10^{-19}$	$1.67\cdot10^{-27}$	$938.3\cdot10^{6}$
Antiproton	-e	$-1.6\cdot10^{-19}$	$1.67\cdot10^{-27}$	$938.3\cdot10^{6}$
Ion, ${}^{A}_{Z}X$	Ze	$+Z\cdot1.6\cdot10^{-19}$	~A·u	~A·u
Atomic mass unit, u			$1.66\cdot10^{-27}$	$931.5\cdot10^{6}$

Understanding Energy

- High Energy Physics is based on Einstein's equivalence of mass and energy

$$E = m \cdot c^2$$

- All reactions involve some mass changing either to or from energy

0.00000005 % of mass converted to energy

~ 0.1 % (of just Hydrogen!) converted

- If we could convert a kilogram of mass entirely to energy, it would supply all the electricity in the United States for almost a day.

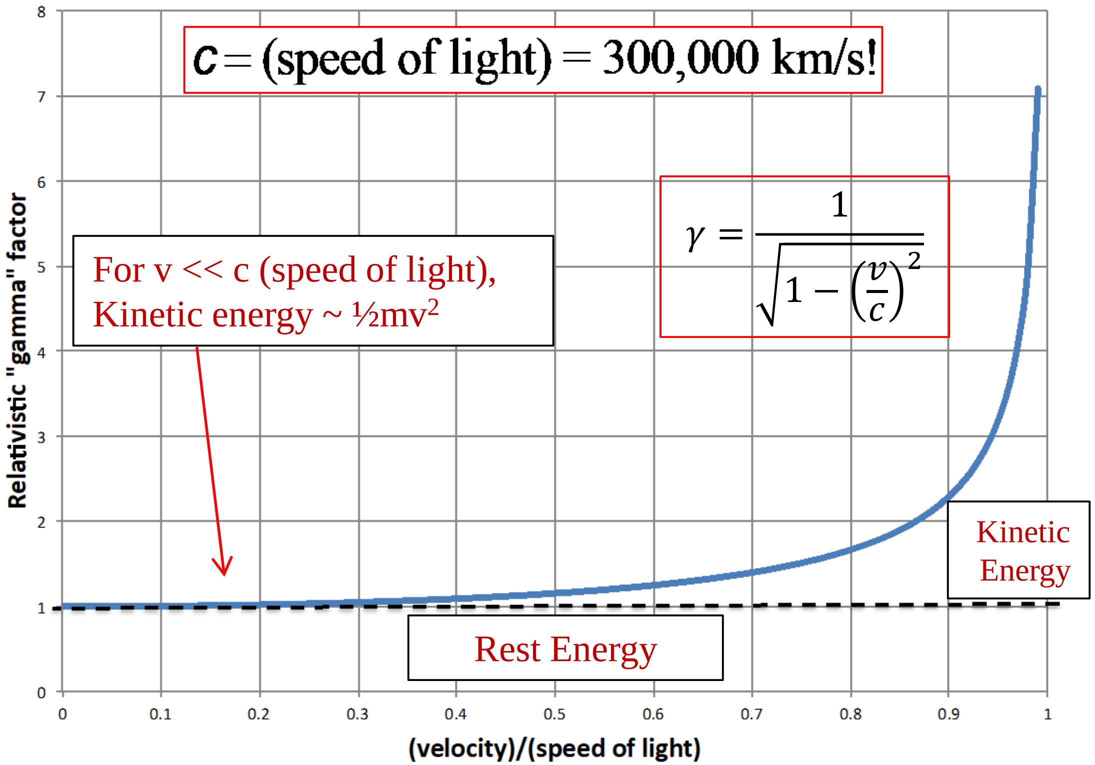
Kinetic Energy

- A body in motion will have a total energy given by

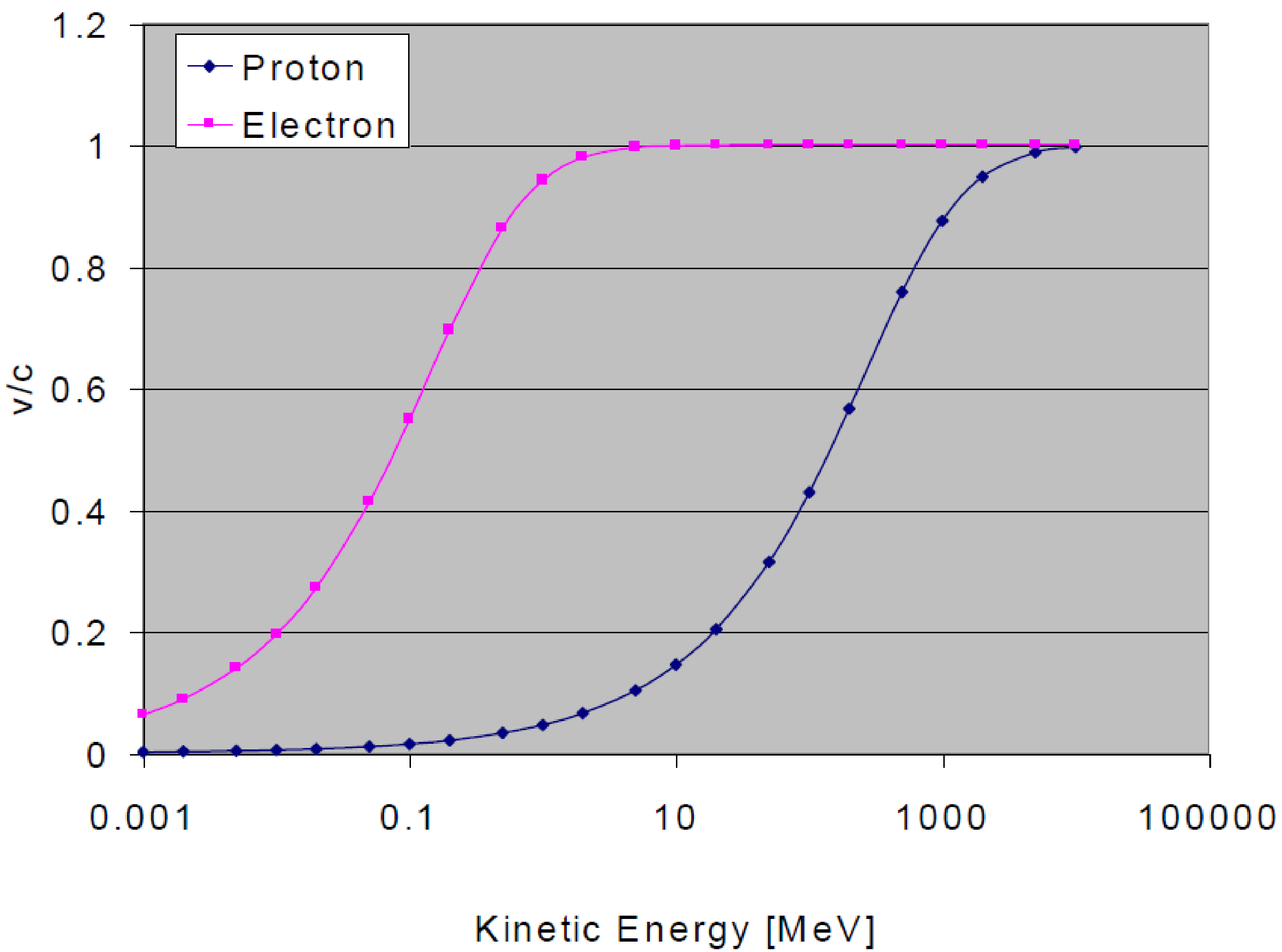
$$E = \frac{m_0 c^2}{\sqrt{1-\left(\frac{v}{c}\right)^2}} \equiv \gamma \cdot m_0 c^2$$

- The difference between this and $m_0 c^2$ is called the ***kinetic energy***

$$T_{kin} = m_0 c^2 \cdot (\gamma - 1)$$



Proton and electron velocities vs. kinetic energy



Relevant Formulae

The relevant formulae are calculated if A_1, Z_1 and A_2, Z_2 are the mass number (amu) and charge number of the projectile and target nucleus, respectively, and T_{lab} is the kinetic energy (MeV) in the laboratory system

$$E = T_{lab} + m_0 \cdot c^2$$

$$m \cdot c^2 = T_{lab} + m_0 \cdot c^2$$

$$\frac{m_0 \cdot c^2}{\sqrt{1-\beta^2}} = T_{lab} + m_0 \cdot c^2$$

beam velocity:

$$\beta = \frac{\sqrt{T_{lab}{}^2 + 1863 \cdot A_1 \cdot T_{lab}}}{931.5 \cdot A_1 + T_{lab}}$$

Lorentz contraction factor:

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

$$\gamma = \frac{931.5 \cdot A_1 + T_{lab}}{931.5 \cdot A_1}$$

$$\beta \cdot \gamma = \frac{\sqrt{T_{lab}{}^2 + 1863 \cdot A_1 \cdot T_{lab}}}{931.5 \cdot A_1}$$

Basic Relativity

total energy: $E = \gamma \cdot m_0 c^2$

kinetic energy: $T_{lab} = E - m_0 c^2 = m_0 c^2 \cdot (\gamma - 1)$

momentum: $p = \gamma \cdot m_0 v = \gamma \cdot \beta \cdot m_0 c = m_0 c \cdot \sqrt{\gamma^2 - 1}$

$$E = \sqrt{(m_0 c^2)^2 + (pc)^2}$$

$$p = \sqrt{(\gamma \cdot m_0 c)^2 - m_0^2 c^2}$$

Units

- For the most part, we will use SI units, except
  - Energy: eV (keV, MeV, etc.) [1 eV = $1.6 \cdot 10^{-19}$ J]
  - Mass: eV/c^2 [proton = $1.67 \cdot 10^{-27}$ kg = 938.3 MeV/c^2]
  - Momentum: eV/c [proton @ $\beta = 0.9$, $\rightarrow$ 1.94 GeV/c]

Another way to look at energy

- Quantum mechanics tells us all particles have a wavelength

Planck constant

$$\lambda = \frac{h}{p} \approx \frac{(size\ of\ a\ proton)}{Energy\ [GeV]}$$

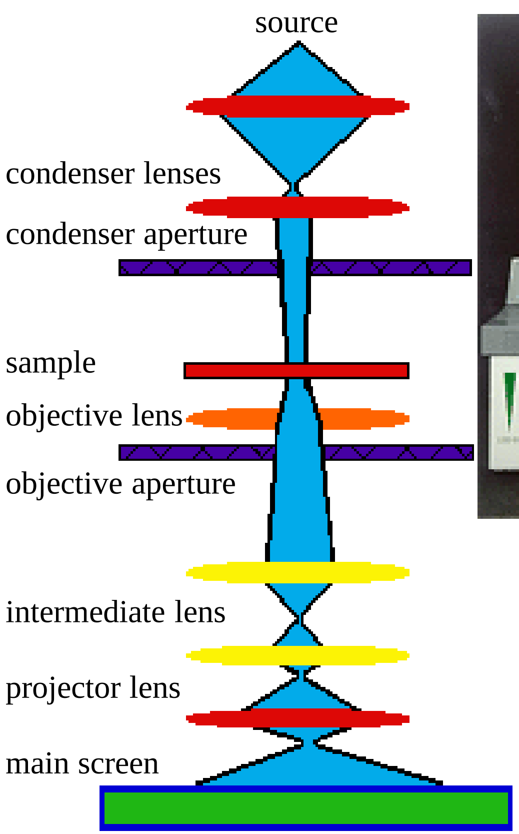
momentum

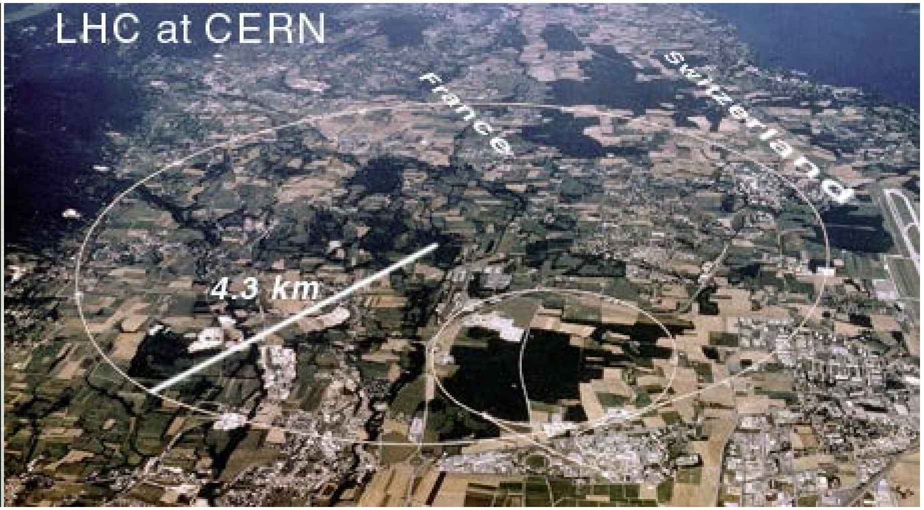
as **v** approaches **c**

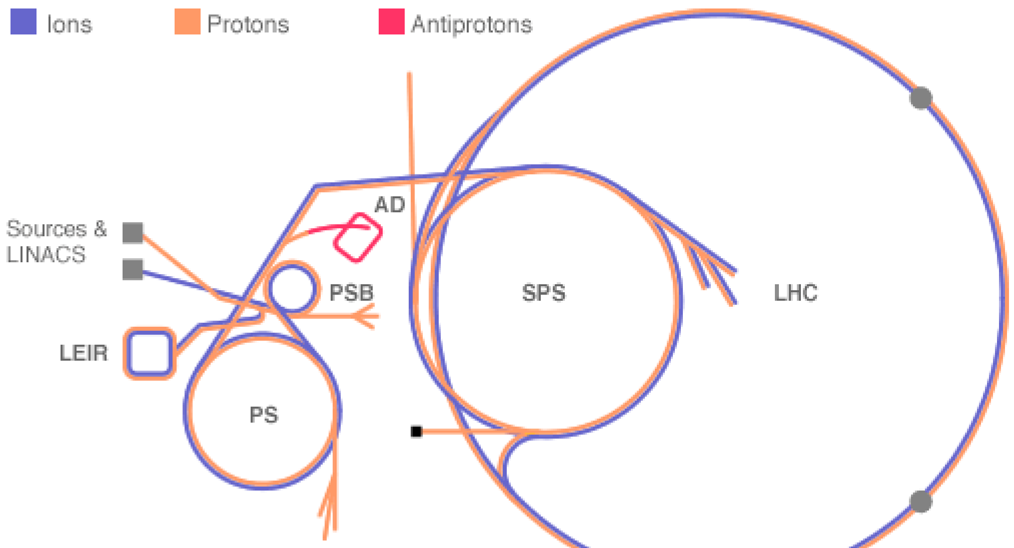
- So going to high energy allows us to probe smaller and smaller scales

- If we put the high equivalent mass and the small scales together, we have …

Different accelerators







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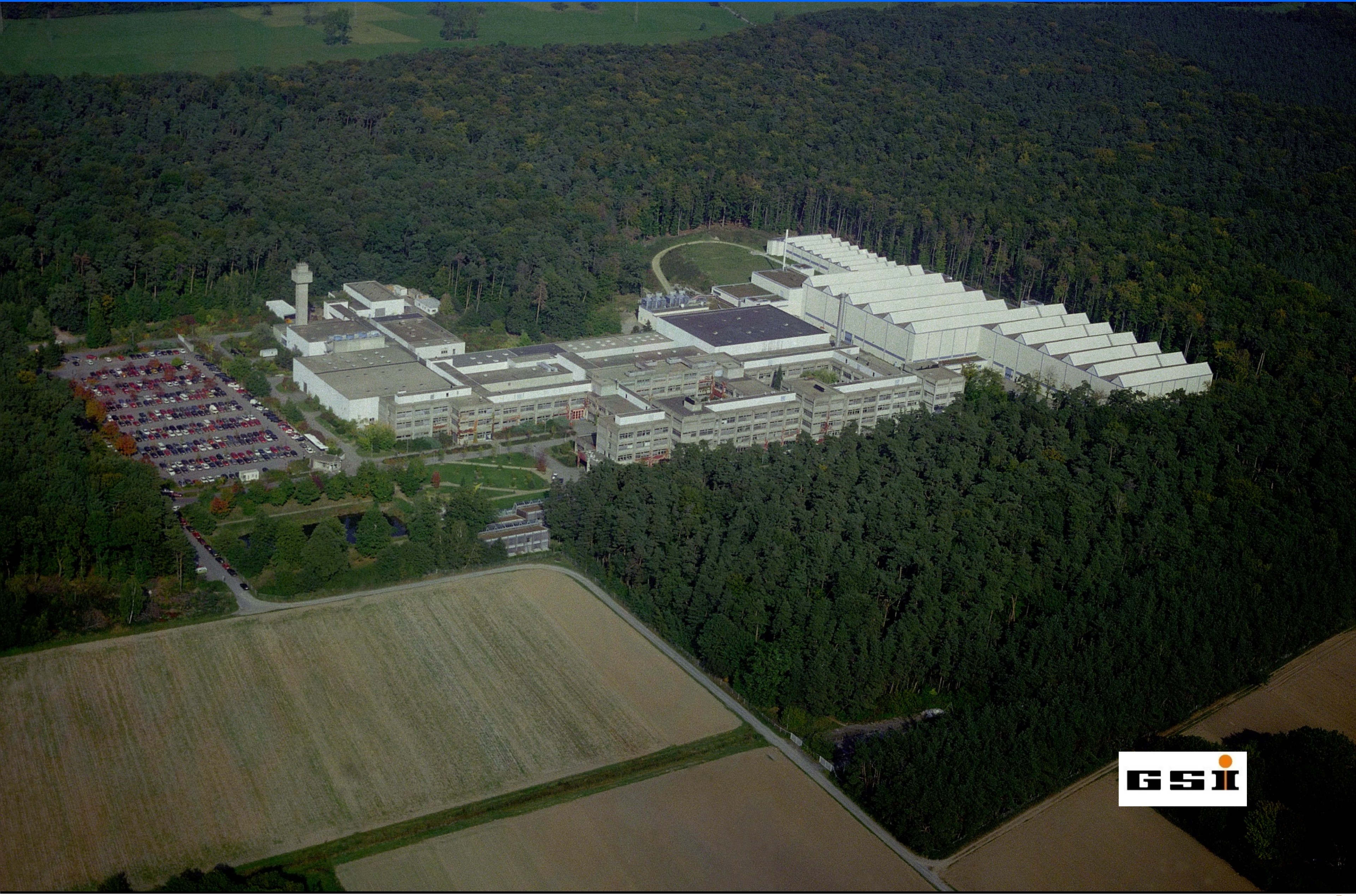
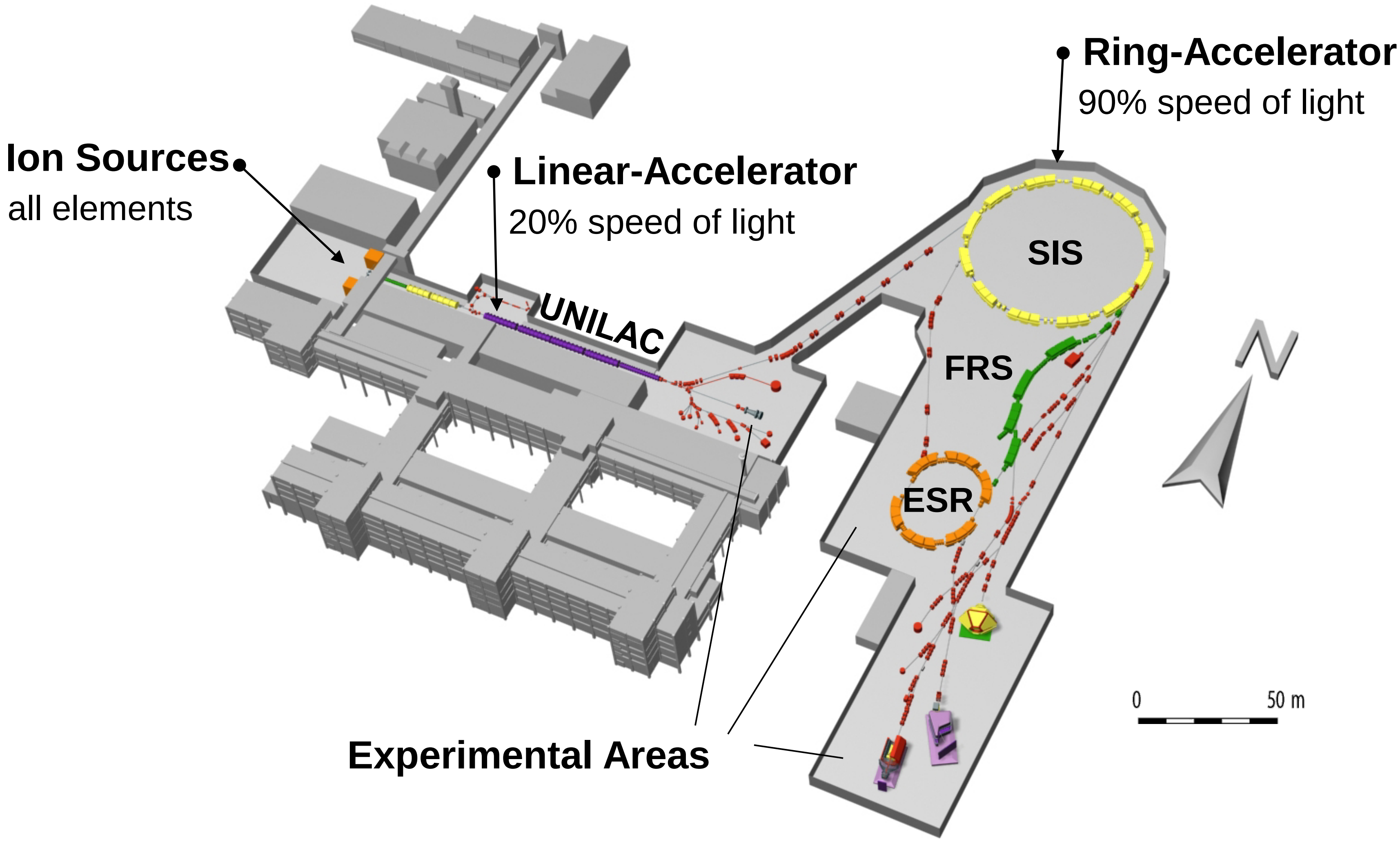
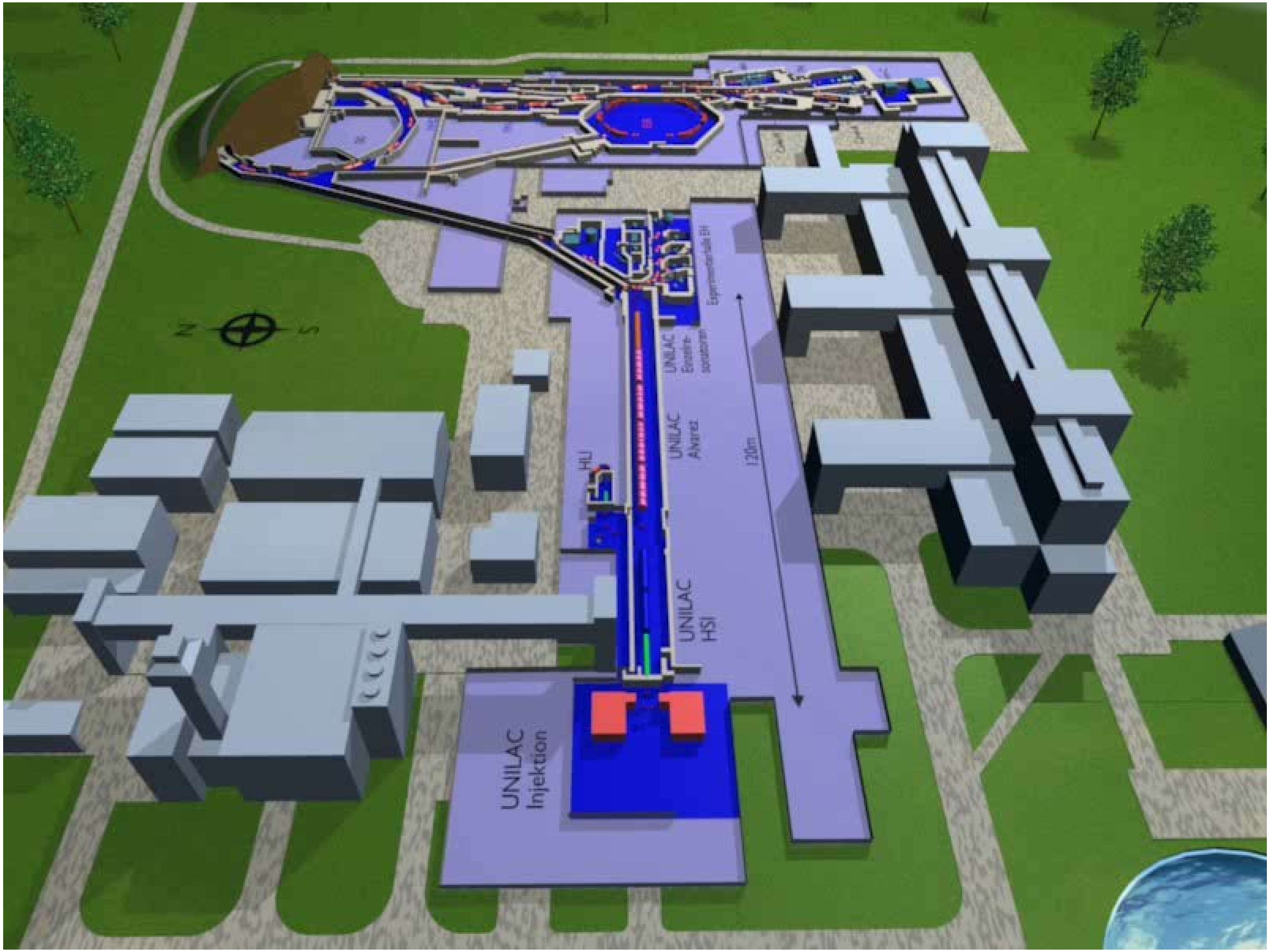


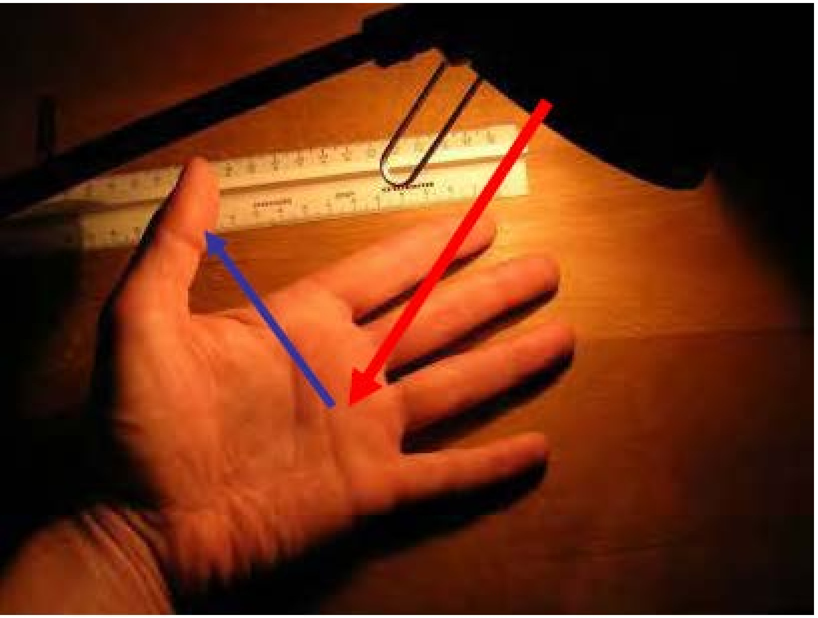
Accelerator facility



Accelerator facility



How do we see an object?



A light bulb shines on a hand and the different reflections make the fine structure visible.
With a magnifying glass or microscope more details can be seen, but there is a fundamental limit:
The wavelength of the light (1/1000 mm) determines the size of the resolvable objects.

available wavelength

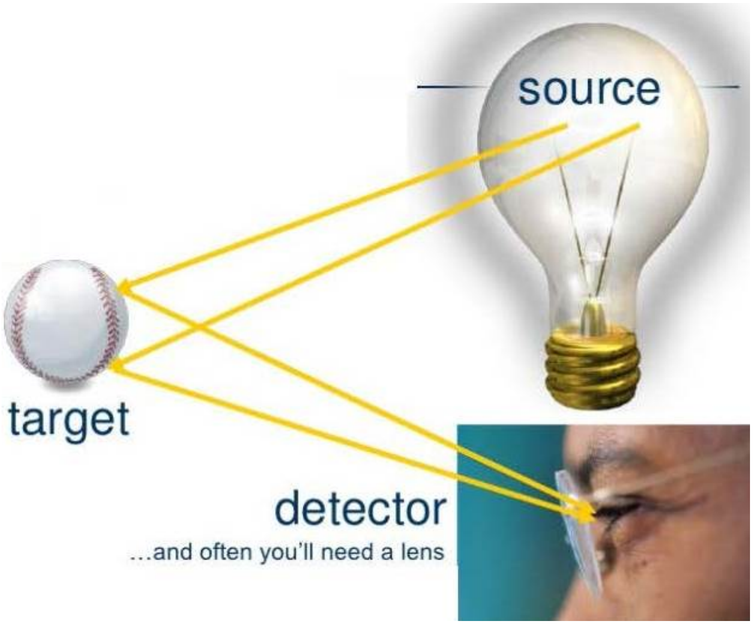
→ electromagnetic waves $E = \frac{hc}{\lambda}$

LW	3000 m	
MW	300 m	
KW	30 m	
UKW	3 m	
GPS	0.3 m	
Infrared	10^{-6} m	
light	$5\cdot10^{-7}$ m	2 eV
UV	10^{-7} m	10 eV
X-ray	10^{-10} m	10^{4} eV
γ-ray	10^{-12} m	10^{6} eV

light bulb → accelerator
magnifying glass or microscope → detector

Detectors – the eyes of a particle physicist

- What means visibility?
- visibility = capability to create an image

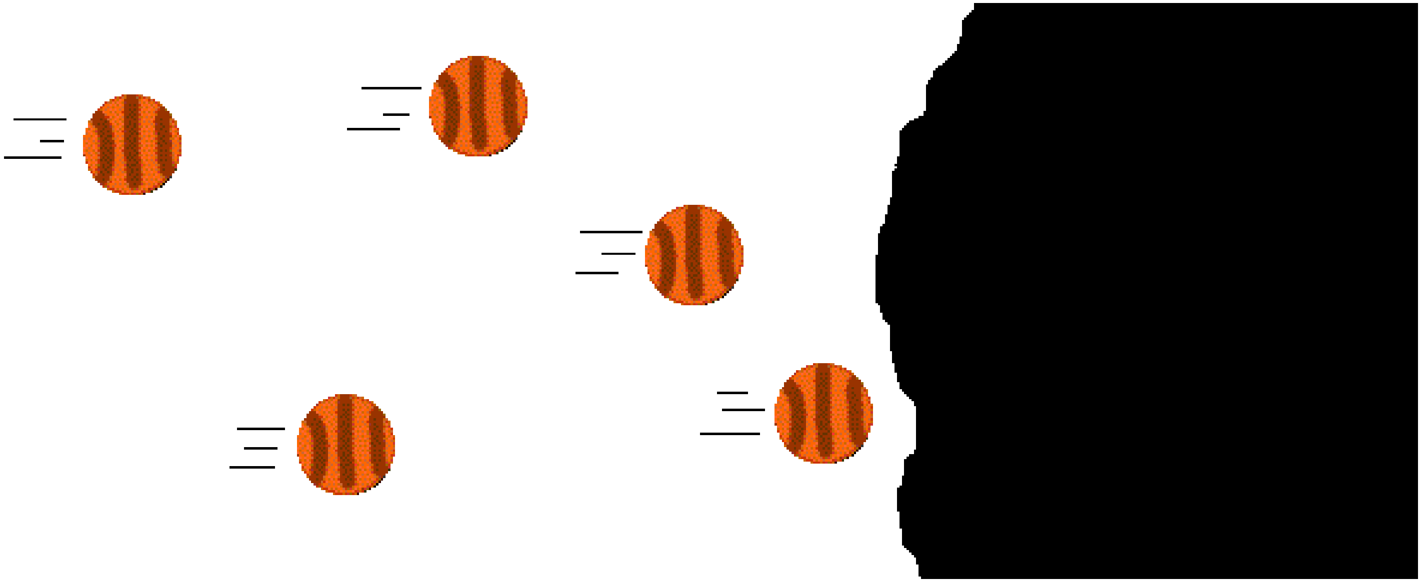


- Projectiles → Target → Detector

- One needs:
  1. size of projectile « size of object
  2. target accuracy « size of object

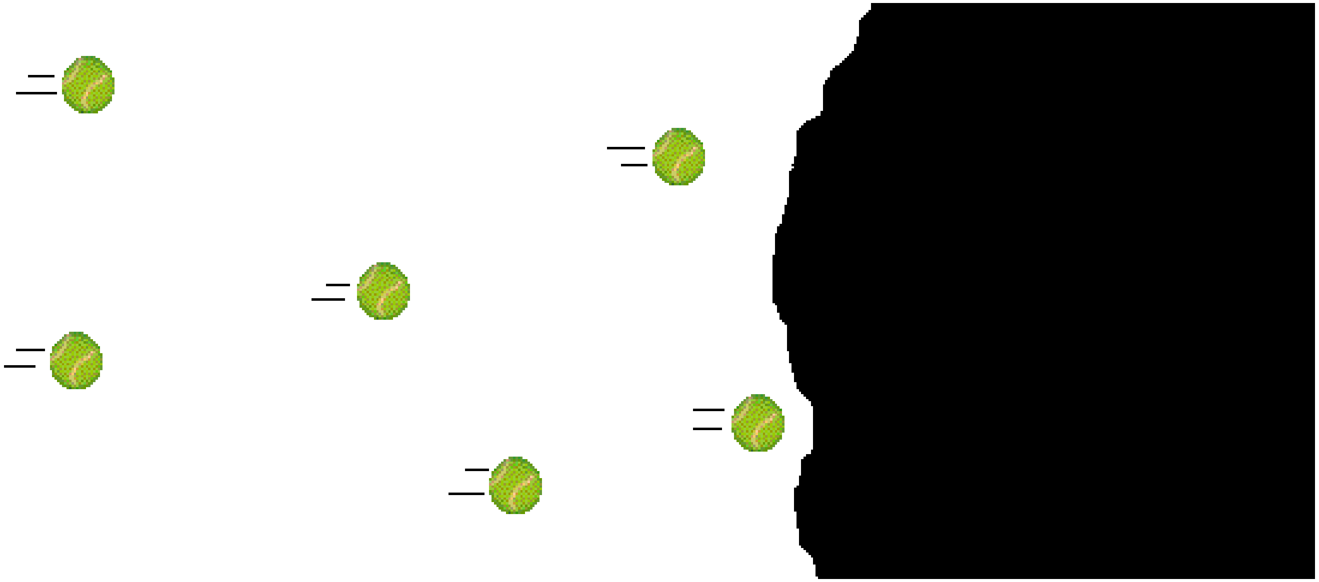
How do we detect what´s happening?

- Projectile: glow-in-the-dark basketballs



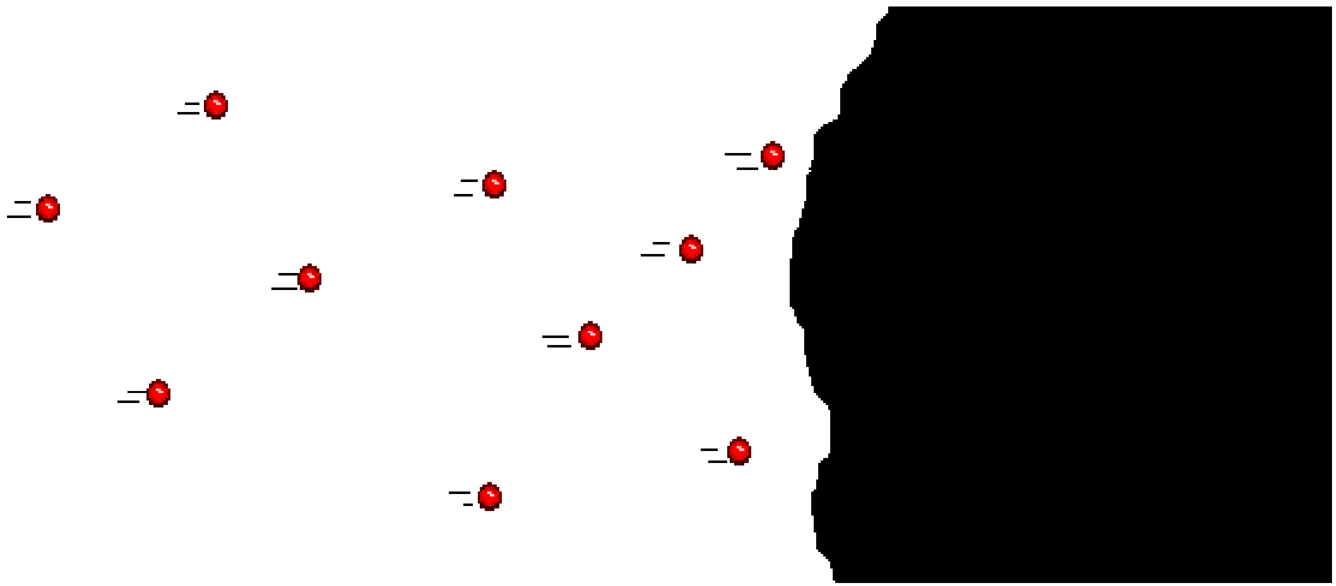
How do we detect what´s happening?

- Projectile: glow-in-the-dark tennis balls



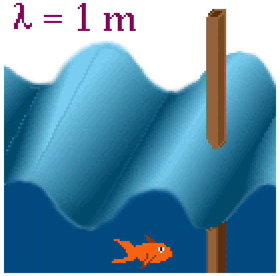
How do we detect what´s happening?

- Projectile: glow-in-the-dark marbles



...let`s get out of here!

Energy, wavelength and resolution



wavelength versus resolution

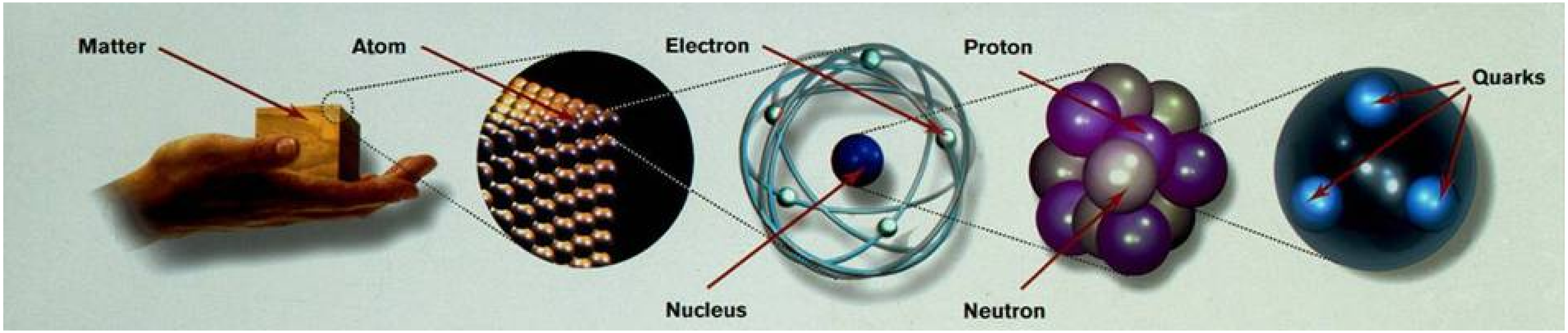
Small objects (smaller than λ) do not disturb the wave
→ small object is not visible
Large objects disturb the wave
→ large object is visible

❖ **all particles have wave properties:**

$$\lambda = \frac{h}{p} = \frac{hc}{\sqrt{E_{kin} \cdot (E_{kin} + 2m_0c^2)}}$$

de Broglie wavelength

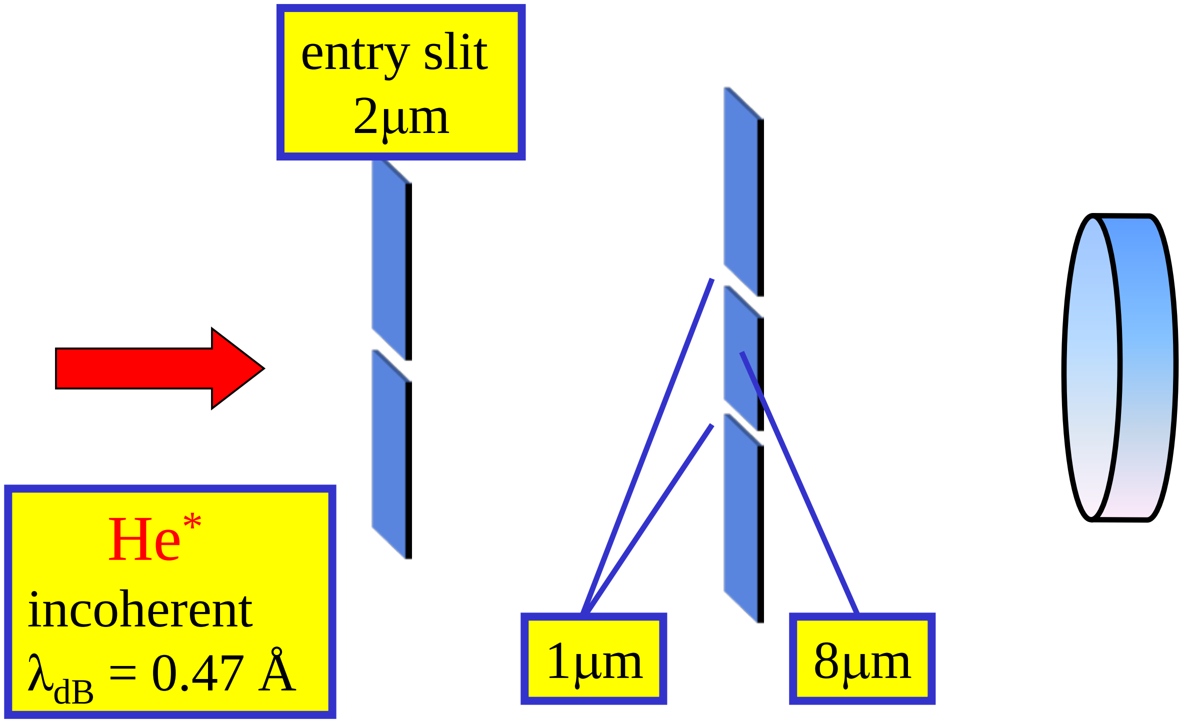
Louis de Broglie

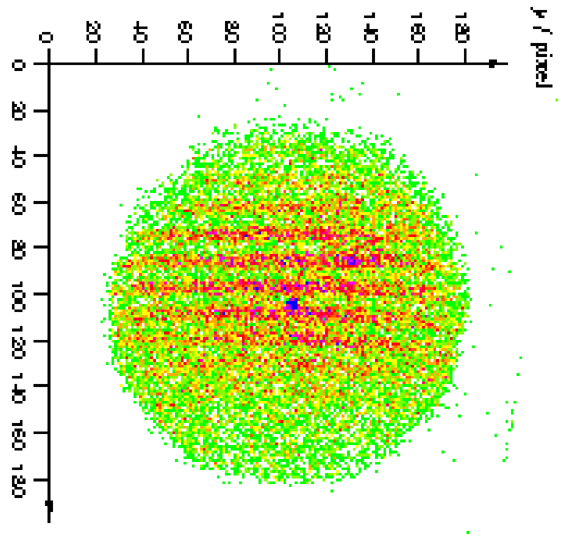


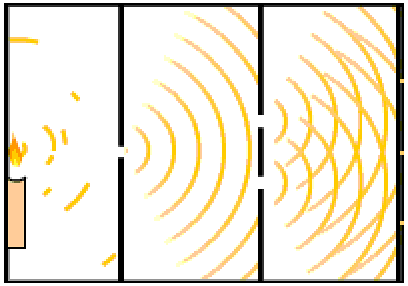
10^{-1}m 10^{-9}m 10^{-10}m 10^{-14}m 10^{-15}m

h·c = 1239.84 [MeV fm]

Wave properties of atoms







- excited Helium is easier to detect
- wavelength (i.e. velocity) has a resolution of 5%
- slits!!

Carnal&Mlynek, PRL 66,2689)1991
Graphik: Kurtsiefer&Pfau

Importance of high particle energies

For the investigation of small dimensions (10^{-15} m) high photon energies are needed:

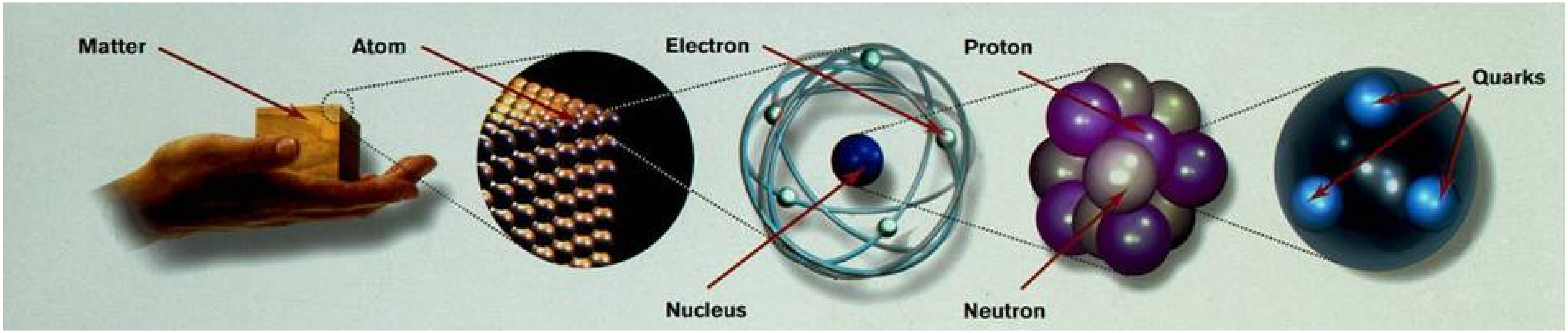
$$E_\gamma = h \cdot \nu = \frac{hc}{\lambda} = 2 \cdot 10^{-10}\ [J]$$

In case of Bremsstrahlung, the electron energy is given by

$$E_e > E_\gamma \quad with \quad E_e = e \cdot U$$

An extremely high voltage is needed

$$U = \frac{E_e}{e} = 1.2 \cdot 10^{9}\ [V]$$



10^{-1}m 10^{-9}m 10^{-10}m 10^{-14}m **10^{-15}m**

Appendix: Basic concepts

- Speed of light: $c = 2.99792458\times10^{8}$ [m/s]
- Relativistic energy: $E = mc^2 = m_0\gamma c^2$
- Relativistic momentum: $p = mv = m_0\gamma\beta c$

$$\beta = \frac{v}{c} \qquad \beta = \frac{\sqrt{T_{lab}{}^2 + 1863\cdot A_1\cdot T_{lab}}}{931.5\cdot A_1 + T_{lab}} \qquad \gamma = (1-\beta^2)^{-1/2} = \frac{931.5\cdot A_1 + T_{lab}}{931.5\cdot A_1}$$

- E – p relationship: $\frac{E^2}{c^2} = p^2 + m_0{}^2c^2$

ultra – relativistic particles $\beta \approx 1$, $E \approx pc$

- Kinetic energy: $T = E - m_0c^2 = m_0c^2(\gamma - 1)$
- Equation of motion under Lorentz force $\frac{d\vec{p}}{dt} = \vec{F} \quad \rightarrow \quad m_0\frac{d}{dt}(\gamma\vec{v}) = q\left(\vec{E} + \vec{v}\times\vec{B}\right)$
- Electron charge: $e = 1.6021\times10^{-19}$ [C]
- Electron volts: 1 [eV] = 1.6021×10^{-19} [Joule]
- Energy in eV: E [eV] = $\frac{mc^2}{e} = \frac{m_0\gamma c^2}{e}$
- Energy and rest mass: 1 eV/c^2 = 1.78×10^{-36} [kg]

- Electron $m_0 = 0.511$ MeV/c^2 = 9.109×10^{-31} kg
- Proton $m_0 = 938.3$ MeV/c^2 = 1.673×10^{-27} kg
- Neutron $m_0 = 939.6$ MeV/c^2 = 1.675×10^{-27} kg