Modern acceleration physics

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Accelerators and their use

Charged particle **accelerators** are devices in which beams of high-energy charged particles (electrons, protons, mesons, etc.) are created and controlled under the action of electric and magnetic fields.

U – 70 Protvino, Russia (Synchrotron)

Stanford Linear Collider, Stanford, USA

LHC, Geneva, Suisse (Collider)

Accelerators and their use

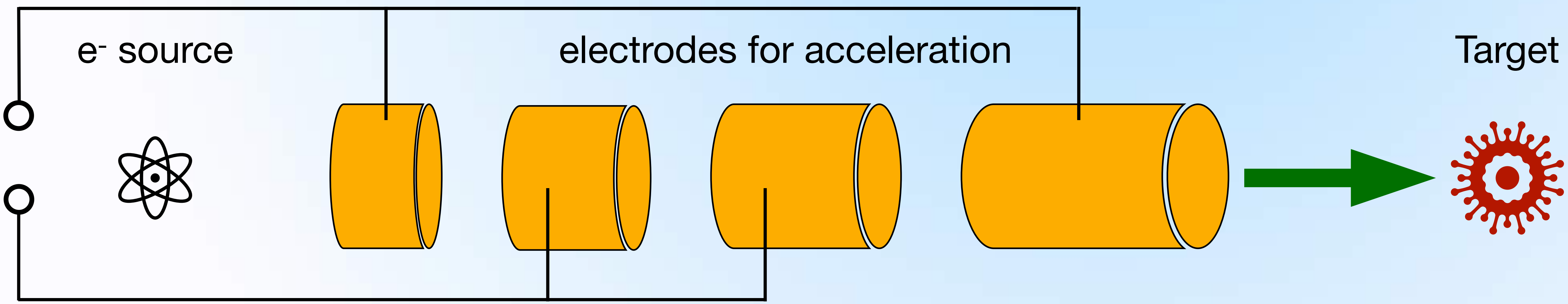
Particle accelerator could be subdivided to:

- Linear accelerators
  - Electrostatic linear accelerators
  - Linear resonans accelerators
  - Linear Colliders
- Circular accelerators
  - Betatrons
  - Cyclotrons
  - Synchrocyclotrons
  - Synchrotron
  - Synchrophasotrons

Linear accelerators

Electrostatic linear accelerators

Particles are accelerated by an electrostatic field created by a high-voltage generator. A charged particle passes through the field once: the charge q, passing through the potential difference $\phi 1$ - $\phi 2$, acquires kinetic energy $K = q(\phi 1 - \phi 2)$. In this way, the particles are accelerated up to ≈ 10 MeV. Their further acceleration with constant voltage sources impossible due to leakage of charges, breakdowns, etc.



Linear accelerators

Linear resonance accelerators

Acceleration of charged particles is carried out by an alternating electric field of microwave frequency, which changes synchronously with the motion of particles. In this way, protons are accelerated to energies of the order of tens of MeV, and electrons, to tens of GeV. A general view of a linear accelerator on a traveling wave is shown in Figure. Charged particles repeatedly pass through the accelerating gap in the two resonators.

Linear accelerators

Linear colliders

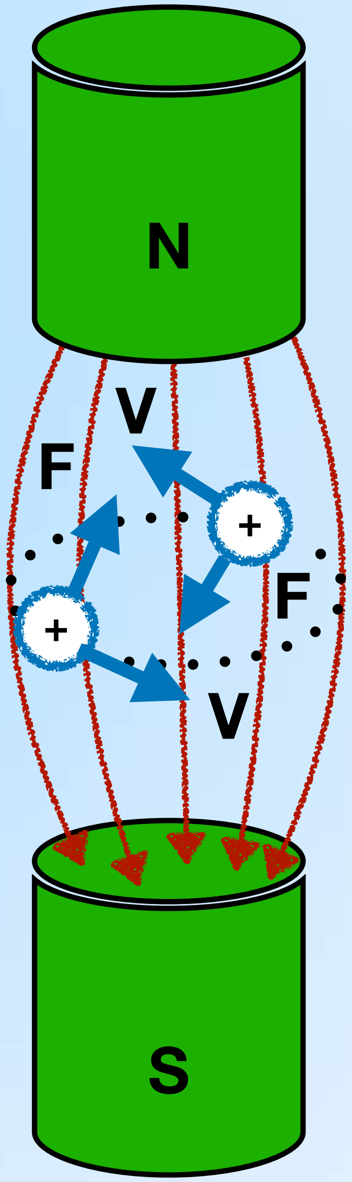
In 1966, the largest linear electron accelerator 3.2 km long with an output energy of 23 GeV was built at the Stanford Accelerator Center. After 20 years, on the basis of the old accelerator, a new project began - the creation of the world's first linear collider SLC. Beginning in the spring of 1987, over the course of two years, the efforts of the thousandth staff of the center resolved numerous physical and technical problems and launched parallel beams of electrons and positrons with energies of 50 GeV. At the output, the beams are deflected into two large arcs, and a head-on collision occurs. This accelerator is equivalent to a single-beam accelerator with energy T_{L0} ~ 10 TeV.

Cycle accelerators

Cycle accelerators

In a magnetic field, a particle is affected by a Lorentz force F=evB. It is perpendicular to the particle velocity, therefore, it is centripetal force F = mV²/R, The particle moves in a circle, radius which R = mV/eB.

The particles are accelerated in the accelerating gap between two half-cylinders - dees, located in the vacuum chamber.



With the help of resonant tanks, the dees are connected to a high-frequency generator, which creates an alternating voltage of 300 kV between them.
In the gap between the dees, the particle is accelerated by the electric field; inside the dees, it moves in a circle under the action of the magnetic field. As a result, the trajectory particle is an unfolding spiral.

Cycle accelerators

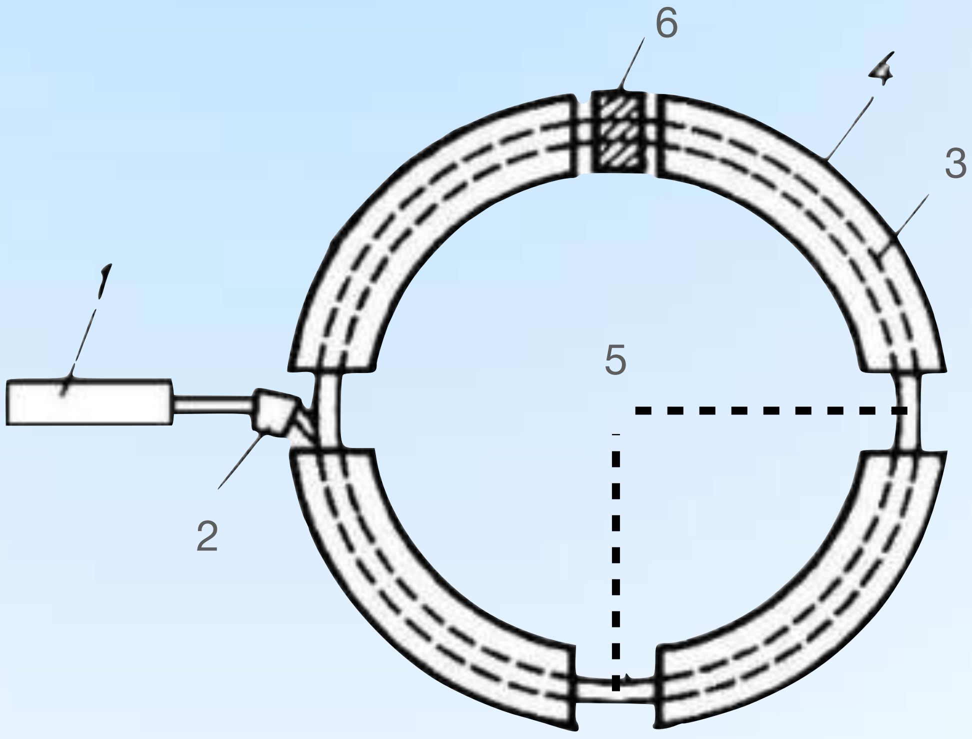
Synchrotrons

Synchrotron is cyclic resonant accelerator of ultrarelativistic particles, in which the control magnetic field changes with time, and the frequency of the accelerating electric field is constant.

Synchrophasotrons

In the synchrophasotron, the principle of autophasing reaches its highest development. Here the technical features of the synchrotron and the phasotron are combined. To keep the radius constant, the magnetic field induction increases with increasing energy.

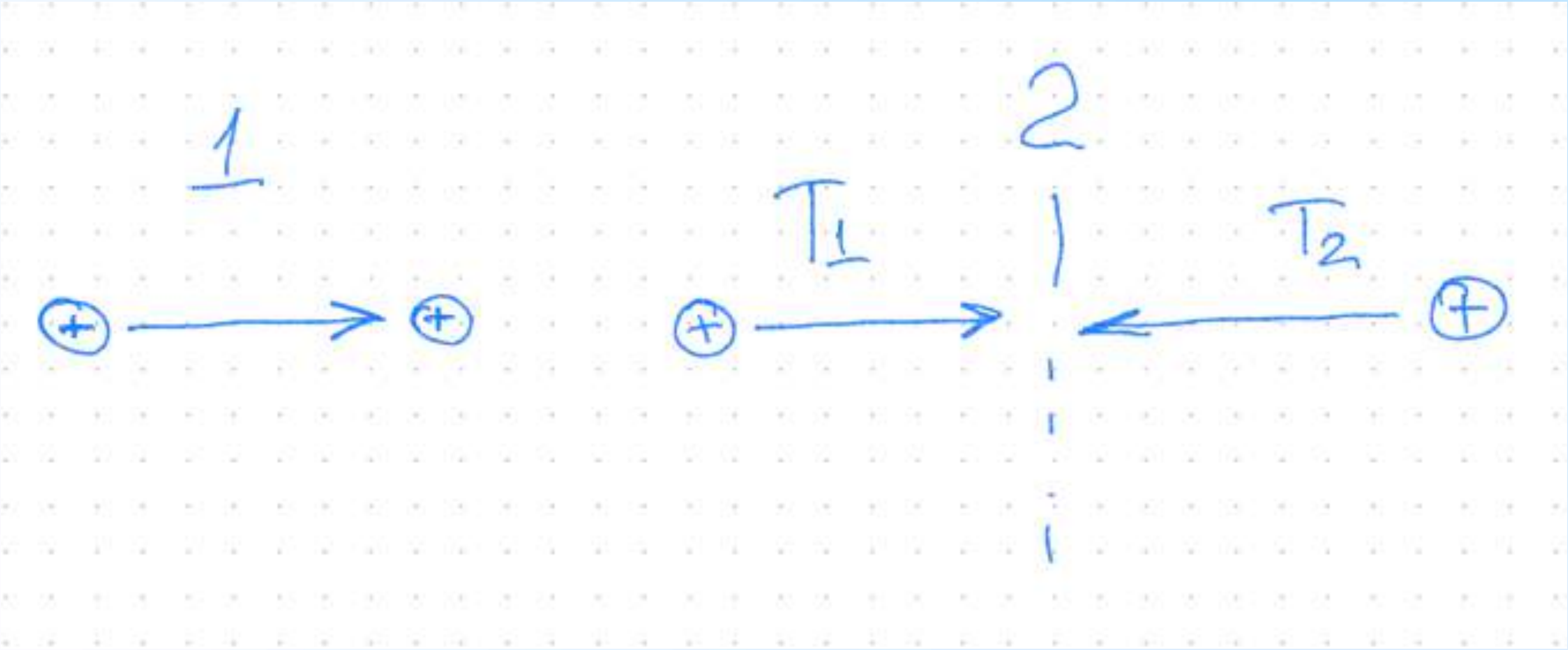
synchrotron: 1 – electron injector; 2 - rotary magnet; 3 – electron beams; 4 - control electromagnet; 5 – vacuum toroidal chamber; 6 - accelerating gap.



Example of tasks

Linear accelerators

One of the possibilities for a significant increase in the energy of colliding particles is to use colliding beams of these particles. What kinetic energy should be imparted to a proton hitting a proton at rest so that their total kinetic energy K_{eq} in the center of mass system would be the same as that of two protons moving towards each other with kinetic energies K_1 = 10 GeV?



Example of tasks

Solution:

If a collision of colliding beams of particles is carried out, then the effect will be the same as in a collision with a stationary proton with an equivalent energy K_{eq}.

W – total energy

Due to theory of relativity:

$W^2 = p^2c^2 - m^2c^4$ (1) m and c are invariants

So: $\frac{W^2}{c^2} - p^2 = m^2c^2 - inv$ Independed on the choising frame of reference

$W = T + W_0$ (2) eq. in the frame of reference rel. to the center of m for protons:

$$\frac{(E_{eq} + 2W_0)^2}{c^2} - p^2 = (2W_0 + 2E_1)^2$$

from: $E^2 - p^2c^2 = m^2c^4$ and $T = E - mc^2$

$$p^2 = \frac{T(T + 2mc^2)}{c^2}$$

Then:

$$\frac{(T + 2W_0)^2}{c^2} - \frac{T(T + 2W_0)}{c^2} = \frac{2(W_0 + E_1)^2}{c^2}$$

Obtain:

$$T = E_{eq} = \frac{2E_1(E_1 + 2W_0)}{W_0}$$

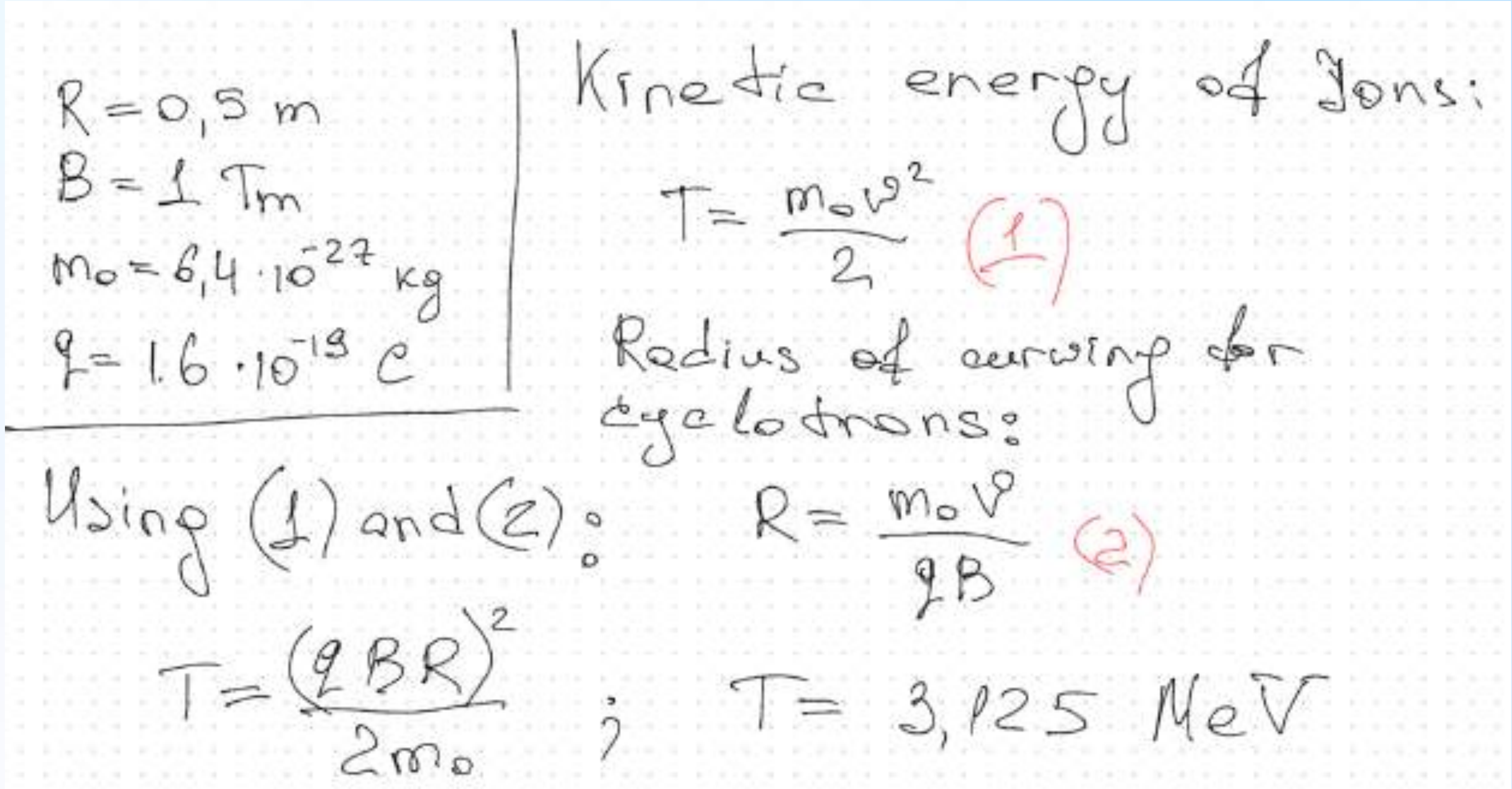
$W_0 = 0{,}938$ GeV; $E_{eq} = 250$ GeV

Thus, using the method of colliding beams, it is theoretically possible to obtain an energy that is 25 times higher than the kinetic energy of moving protons.

Example of tasks

Cyclotrons

A singly ionized helium ion He^+ is accelerated in the cyclotron so that the maximum radius of curvature of its trajectory is R = 0.5 m. Determine the kinetic energy K of helium ions at the end of acceleration if the magnetic field induction inside the cyclotron is B = 1 T.



An analysis of the dependence obtained shows that in order to increase the energy of charged particles in a cyclotron, it is necessary to increase the magnetic field induction and increase the radius of the electromagnet poles.

Example of tasks

Synchrophasotrons:

The kinetic energy T of protons in the Protvino synchrophasotron reaches 76 GeV. Calculate, neglecting the action of the vortex electric field, the maximum momentum of the proton and the maximum radius of its orbit, if the magnetic field induction B in the synchrophasotron is 1.07 Tm

$T = 76\ GeV = 1{,}2 \cdot 10^{-8}\ J$

$m_0 = 1{,}67 \cdot 10^{-27}\ kg$

$W_0 = 0{,}938\ GeV = 1{,}5 \cdot 10^{-10}\ J$

Kinetic energy $T > W_0$, then have to take into account relativistic affects

$\beta = \frac{v}{c}$; $T = W - W_0$

$$p = \frac{m_0 v}{\sqrt{1-\beta^2}} = \frac{1}{c}\sqrt{W^2 - W_0^2};$$

$$p = \frac{1}{c}\sqrt{T(T + 2m_0c^2)}, \quad T \gg m_0c^2, \text{ then:}$$

$$p \approx T/c, \text{ then } p = \frac{1{,}2 \cdot 10^{-8}}{3 \cdot 10^{8}} = 4 \cdot 10^{-17}\ kg\,m/s$$

Maximum radius of orbit:

$$R_{max} = \frac{m v_{max}}{qB} = \frac{p_{max}}{qB} = \frac{\sqrt{T(T+2m_0c^2)}}{qBc},$$

$$R_{max} \approx \frac{T}{qBc}; \quad R_{max} \approx 236\ m$$

$$p = 4 \cdot 10^{-17}\ kg \cdot m/s; \quad R_{max} \approx 236\ m$$

У – 70 Протвино

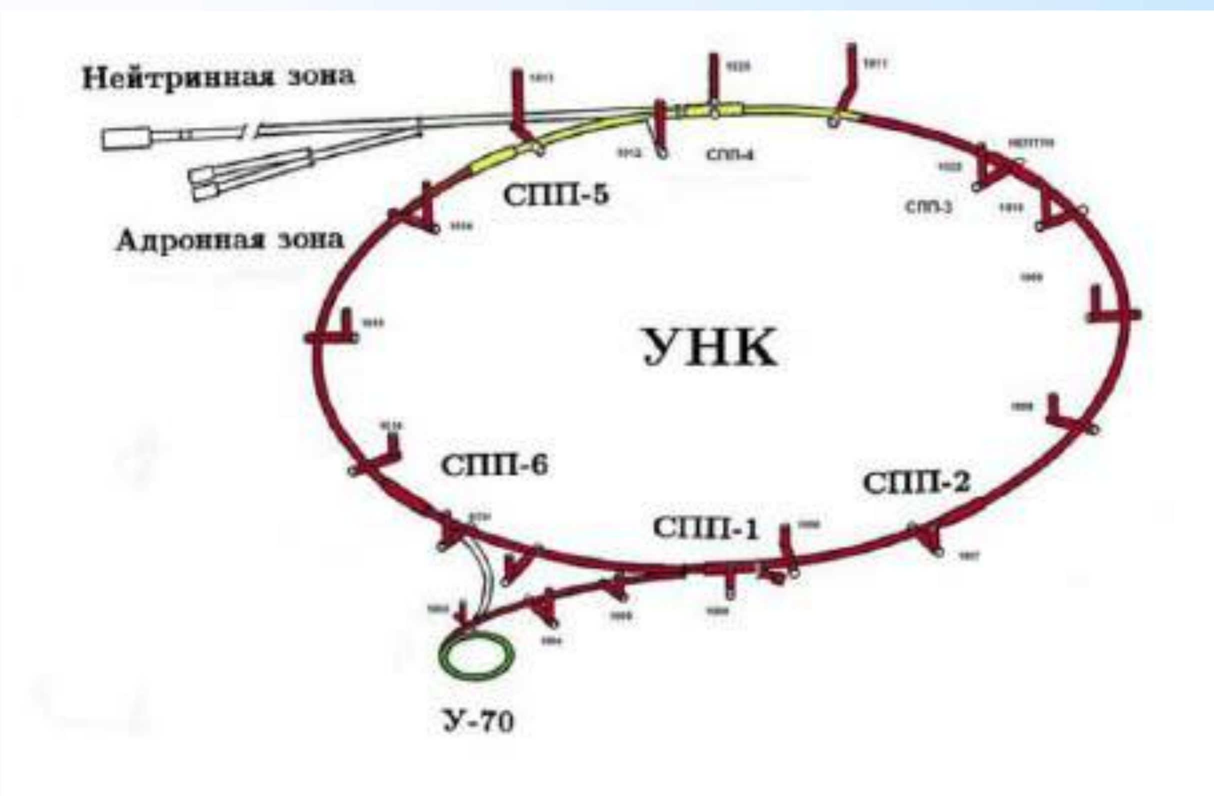
U-70 is a 70 GeV proton synchrotron built in 1967 at the Institute for High Energy Physics, Protvino. At the time of construction, the energy of the accelerator was a record, so far the U-70 is the highest-energy accelerator in Russia. For the development and commissioning of the U-70 synchrotron, a team of scientists was awarded the Lenin Prize in 1970.

Was originally created to search for quarks — indivisible particles of matter that make up protons and neutrons. One of the first experiments at the U-70 accelerator was the search for particles with a fractional electric charge, that is, quarks that have an electric charge that is a multiple of 1/3 of the electron charge. The result of the search was negative: even at the high energies that were available, the quarks could not be seen. This was the first step towards understanding such a phenomenon as quark confinement, or quark trapping.

УНК

UNK – an unfinished project to create a proton-proton collider based on superconducting magnets at the Institute for High Energy Physics (Protvino). The design beam energy is 3000 GeV. The length of the main ring is 21 km; it was planned to use the operating U-70 proton synchrotron as the first "upper stage" stage.

Work on the creation of the accelerator began in 1983. Within 12 years, a tunnel was built in stable and dry rocks at a depth of 20 to 60 meters (depending on the terrain) (driving was completed on December 9, 1994), the inner diameter of which was 5 meters.



Thank you for your attention!