ELECTRON COOLING and ELECTRON-NUCLEI COLLIDERS

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Electron Cooling, proposed and developed at INP (Novosibirsk) in 1960s and 1970s /1/, is used now actively at many laboratories throughout the world.

There are different types of experiments and problems to apply Electron Cooling:
- storing of secondary stable and long enough living hadrons, nuclei and ions (in most cases - in combination with Stochastic Cooling - to rise effective acceptance);
- achieving of very low "temperature" of stored particles;
- suppression of beam blow-up due to diffusive effects of different nature (multiple scattering by "targets", external noise, multiple intra-beam scattering, …).

But the use of continuous cooling for improving the average luminosity of the colliders (involving heavy particles) /2/ is still in projects, only. In our discussion we would focus on electron-nuclei (fully stripped) collider, although many aspects are similar for nuclei-nuclei collider, also.

What for to cool at "full energy of experiment in a collider"? The reasons could be the following:
- to compress ion beam after all the perturbative steps of preparation, storing, acceleration for to enhance luminosity of ion -ion or electron-ion colliders – a <u>single</u> cooling stage, if no diffusion processes work during collision;
- to compensate multiple scattering during internal target experiments - continuous cooling;
- to compensate the multiple intra-beam scattering diffusion - continuous cooling.
- to compensate beam-beam induced diffusion processes in a collider - continuous cooling.

The latter statement needs some clarification, because the complexity of this highly non-linear problem can not be solved analytically. According the experience in electron-positron colliders, when the collider operational conditions are optimally tuned, the maximal betatron beam-beam tune shift ξ_{max}, at which beams do not blow-up and do not loose in life-time, depends on the number of beam meetings per cooling time $N_{col/cool}$ (for flat beams!), roughly as:

$$\xi_{max} = \frac{2}{N_{col/cool}^{1/3}}$$

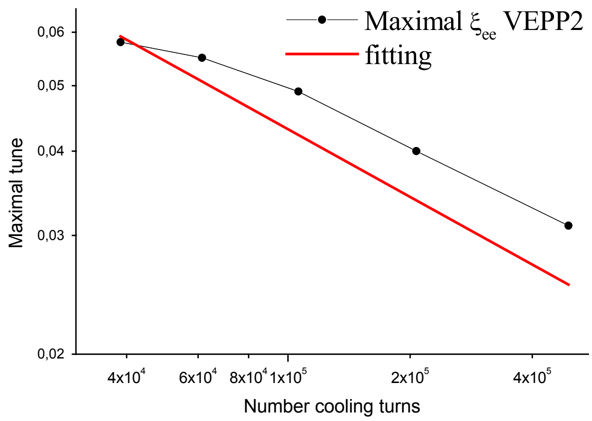


Figure 1. The experimental dependence of maximal beam-beam tune shift, obtained at

VEPP-2M collider; lower line ("fitting") is derived from the above formula.

Powerful continuous cooling is quite important for high luminosity electron-ion collider (double ring, single collision per turn, particles are relativistic) – to keep ion beam emittance as small as needed for maximal average luminosity. And there are 2 most interesting cases. The one is when ion space charge limits the ion beam emittance and number of electrons per bunch is limited by "external reasons":

$$L_{eZspcb} = \frac{c}{2\pi} \cdot \frac{A}{Z^2} \cdot \beta_Z \gamma_Z^3 \frac{\Delta\nu}{R_{Zav} D_{bb}} \cdot N_{be}$$

$$N_{bZ} := \frac{2}{r_p} \frac{A}{Z} \cdot \beta_Z^2 \cdot \gamma_Z^3 \frac{\beta_0 \cdot \Delta\nu}{R_{Zav}} \cdot \varepsilon_{spc}$$

The other one is when the beam-beam tune shifts are the limiting factors for both beams:

$$L_{eZbb} = \frac{4\pi c}{r_e r_p} \cdot \frac{A}{Z^2} \cdot \beta_Z \gamma_e \gamma_Z \cdot \frac{\xi_e \xi_Z}{\beta_0 D_{bb}} \varepsilon$$

$$N_{bZ} = \frac{4 \cdot \pi}{r_e} \frac{1}{Z} \cdot \gamma_e \cdot \xi_e \cdot \varepsilon_{bb}$$

Here:
R_{zav} – the average collider radius (the same for both rings);
D_{bb} – the distance between bunches (the same for both rings for relativistic nuclei);
ξ_e, ξ_Z – beam-beam tune shifts for electron and nuclei beams;
$\Delta\nu$ - the nuclei beam tune shift due to its space charge repulsion;
ε - the transversal emittance, equal for both beams and for both directions.

In practice, ξ_e, ξ_Z and $\Delta\nu$ are about 0.005 for "no cooling" case, and up to 0.1 for very strong cooling $N_{col/cool} < 4 \cdot 10^5$ – for "round beams" option, when $N_{col/cool}$ required is about

$$N_{col/cool} \approx \left(\frac{8}{\xi_{max}} \right)^3$$

(still not tested earnestly!).

The effective electron cooling can be reached for so called "magnetized electrons" case, when Larmour radius of electrons in guiding longitudinal magnetic field is "small".

To clarify this very important issue (fully understood 25 years ago, but still not familiar for many physicists involved), let us consider the hierarchy of impact parameters, important for the cooling process due to nuclei-electrons pair collisions. The result of a single ion-electron collision is strongly dependent, especially at high longitudinal field, on impact parameter, which should be compared with:

$$\rho_B = \frac{2e^2}{m_e} \cdot \frac{Z}{v_{ecm}^2}$$

- impact parameter, at which electron scattering angle is 1 or larger (if such parameters play important role, the friction force in electron cloud for negative particles is larger, than for positive ones);

$$\rho_L = \frac{m_e c v_{etr}}{eH_{cool}}$$

- the electron Larmour radius;

$$\rho_f = \frac{L_{cool}}{2c\gamma} \cdot V_{icm}$$

- the effective shift of the ion of velocity V_{icm} during the flight through the cooling section (in rest frame);

$$\rho_D = \sqrt{\frac{m_e}{4\pi e^2} \cdot \frac{v_{ecm}^2 \gamma}{n_e}}$$

- the radius of Debye screening, where n_e is electron density in laboratory system;

$$R_{be} = \sqrt{\kappa \varepsilon \beta_{Zcool}}$$

- the electron beam radius in the cooling section (electron beam emittance is κ times larger than of ion).

Another condition for "good magnetizaion" is: the number of Larmour rotations at one passage of the cooling section should be big (close relative to $R_L \ll \rho_f$!); consequently, the cooling section L_{cool} should be long enough:

$$L_{cool} \gg \frac{m_e c^2}{e} \cdot \frac{\gamma_Z}{H_{long}}$$

Yet another condition for full rate of cooling is – the deviations in H_{long} direction should much smaller than ion angles (in lab sys) to be cooled:

$$\vartheta_{H_{long}} \ll \sqrt{\frac{\varepsilon_Z}{\beta_{Zcool}}}$$

(β_{Zcool} - ion beta-function in the cooling section.)

If magnetization is good the effective collisions are adiabatic (relative to Larmour circling).

The usual formula for Electron Cooling time looks as:

$$\tau_{cool} = \frac{1}{2\pi r_e r_p c^4} \cdot \frac{A}{Z^2} \cdot \frac{1}{L_{C\,eff}} \cdot \frac{\gamma_Z^2}{n_e \eta} \cdot V_{cm\,eff}^3$$

- all quantities are in LabSys, except $V_{cm\,eff}$; η - the cooling section fraction of the perimeter.

If effective velocities are electron velocities in CM, especially if we require recombination life-time really long (as is usual for colliders), cooling time is too long to be interesting at "high" energy storage rings.

In this case, good magnetization (the use of high enough longitudinal guiding field H_{long}) solves the problem: instead of very high v_{etr} , in V_{cmeff} enter ion velocities and longitudinal electron velocities (resulting from electron energy spread), which are much smaller – hence, the cooling faster!

The main contribution to Electron Cooling in this case give impact parameters in ion-electron collisions between ρ_L and some ρ_{max}; the real value of ρ_{max} depend on many parameters - specific for every case. These effective collisions are adiabatic (relative to Larmour circling). The corresponding Coulomb logarithm becomes in this case smaller:

$$L_{Ad} = \ln\left(\frac{\rho_{max}}{\rho_L}\right)$$

where

$$\rho_{max} = \min(\rho_f, \rho_D, R_{be})$$

A convenient interpolation formula (V.Parkhomchuk) looks as following:

$$L_{Ad} = \ln\left[\frac{\left[\sqrt{2\pi r_e\cdot\frac{n_e}{\gamma_Z^3}}+\frac{1}{\sqrt{2}L_{cool}}\right]^{-1}\cdot\sqrt{\frac{\varepsilon}{\beta_{Zcool}}}+\frac{m_e c}{e}\cdot\frac{v_{etr}}{H_{long}}}{\frac{m_e c}{e}\cdot\frac{v_{etr}}{H_{long}}+\frac{r_e}{2}\cdot\frac{\beta_{Zcool}}{\gamma_Z^2\varepsilon}}\right]$$

The cooling time in the magnetized case could be quite small (because of very small $V_{cm\,eff}$):

$$\tau_{cool} = \frac{1}{2\pi r_e r_p c^4}\cdot\frac{A}{Z^2}\cdot\frac{1}{L_{Ad}}\cdot\frac{\gamma_Z^2}{n_e\eta}\cdot V_{cm\,eff}^3$$

The ion life-time, additionally to the usual processes in collisions, is limited by (radiative) recombination events with cooling electrons.
The life-time due to this process is

$$\tau_{Zrec} = \frac{1}{30\alpha r_e^2 c^2}\frac{\gamma_Z^2}{Z^2 n_e\eta\ln\left(\frac{Z\alpha c}{v_{etr}}\right)}\cdot v_{etr}$$

This time could unacceptably short, especially for heavy nuclei. To make it longer, we need to rise transversal electron velocities v_{etr} and longitudinal magnetic field (or to use "hollow electron beam"?).

Important remark:
All ξ_{max} estimations were based on SR cooling experience (decrement is independent on colliding particle amplitude). But for ECooling we need to operate with a decrement falling with amplitude, hence – urgent need for good simulations!

The electron-nuclei colliders are of very interest for wide range of energies. And in most cases for optimal operation of colliders the electron cooling of nuclei is of primary importance. But up to now electron cooling devices can cool nuclei not higher than 600 MeV/A (electron energy 300 keV). As an example of modern device for such energy range, we can look at the cooler now under construction at Novosibirsk for the Institute of Modern Physics (Lanzhou, China) (Figure 2).

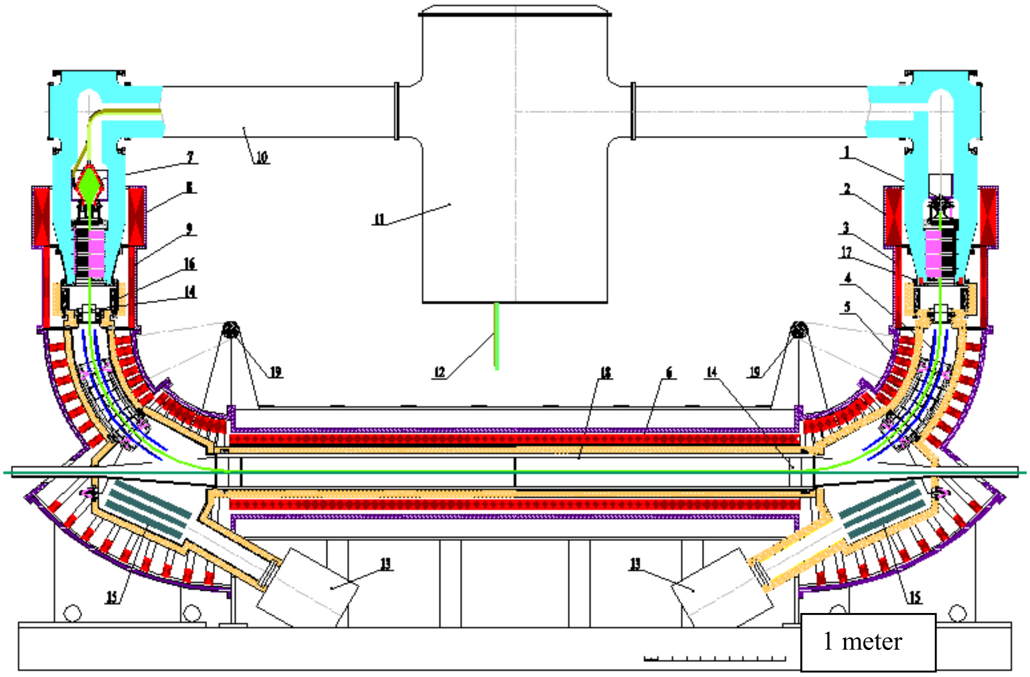


Figure 2. Electron cooler for IMF project (300 keV).
1 - electron gun; 2- main “gun solenoid”; 4 - electrostatic deflectors;
5 - toroidal solenoid; 6 - main solenoid; 7 - collector; 8 - collector solenoid; 11 - main HV rectifier;
12 - collector cooling system.

Very similar device could operate, according to Novosibirsk pre-design, up to 1.2 MeV (Figure 3).

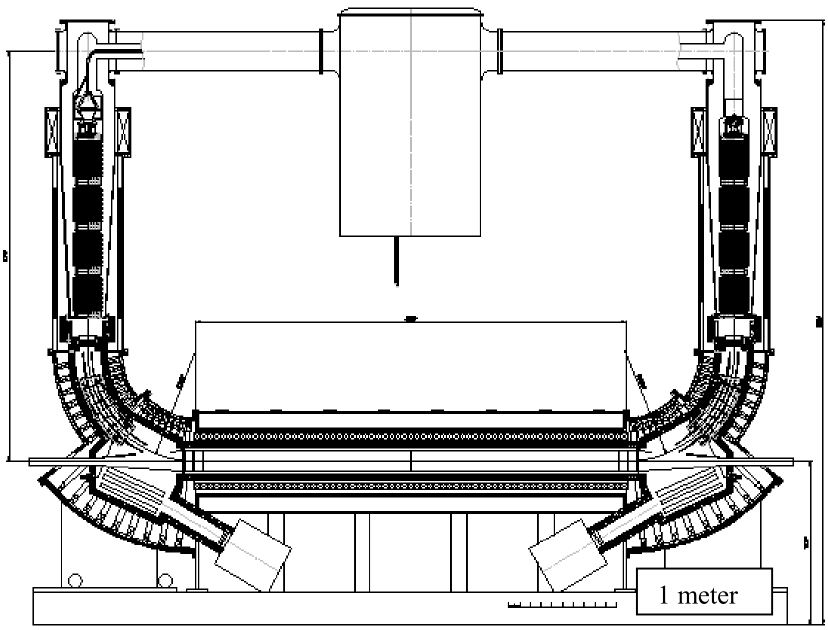


Figure 3. Draft project for 1.2 MeV electron cooler

Our confidence in the design is partially based on the successful prototype operation we reached in 1990 (Figure 4) /3/.

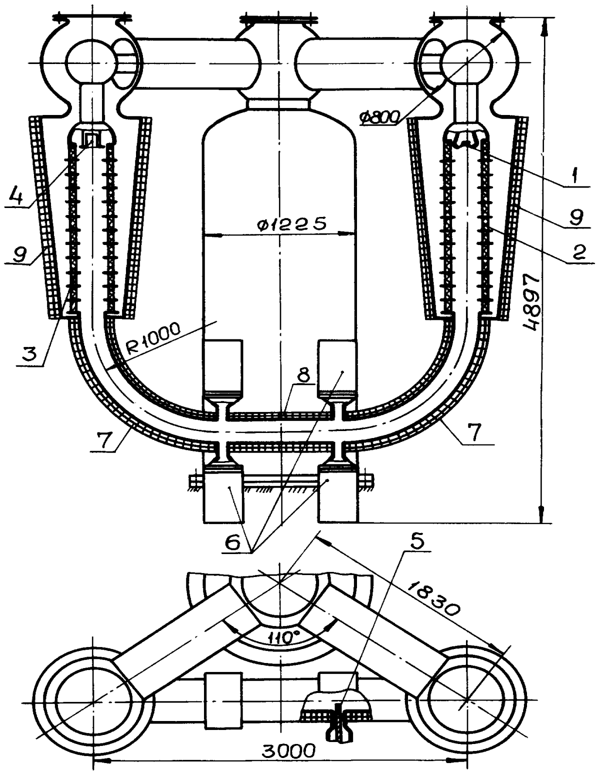


Figure 4. Operational prototype of accelerator-recuperator cooling device 1 MeV, 1 A (DC).

To the moment, for electron energies above 10 MeV we consider RF Accelerator-Recuperator approach as the most promising for practice. Our draft design of such device for cooling of nuclei at RHIC collider (BNL) with electron energies up to 50 MeV is shown at Figure 5 – the goal of the project is 10-fold increase for Nuclei-Nuclei average luminosity, and make productive Electron-Nuclei collisions. The same concept of Accelerator-Recuperator is the background of high power free electron laser, now under construction at Novosibirsk /4/.

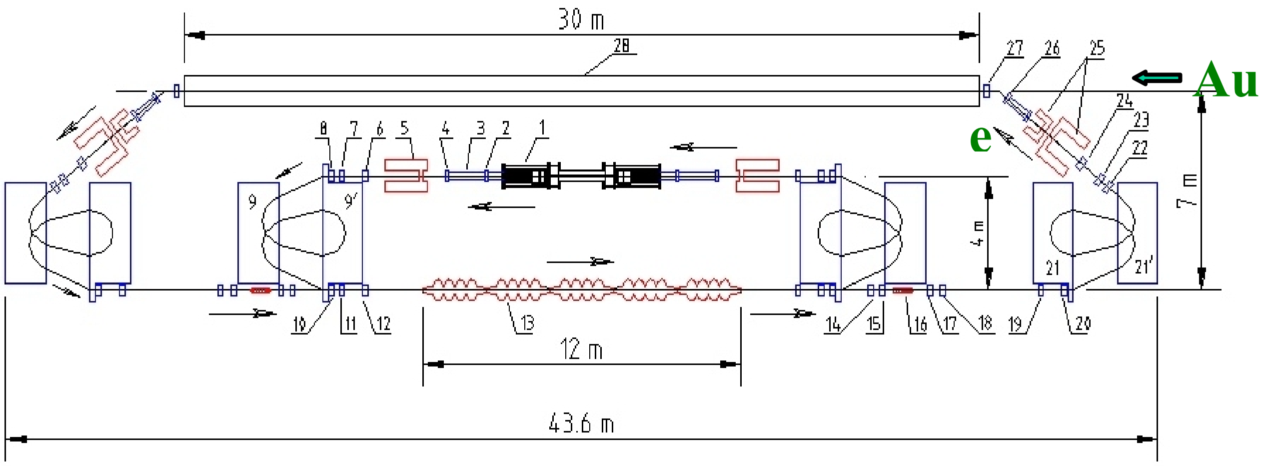
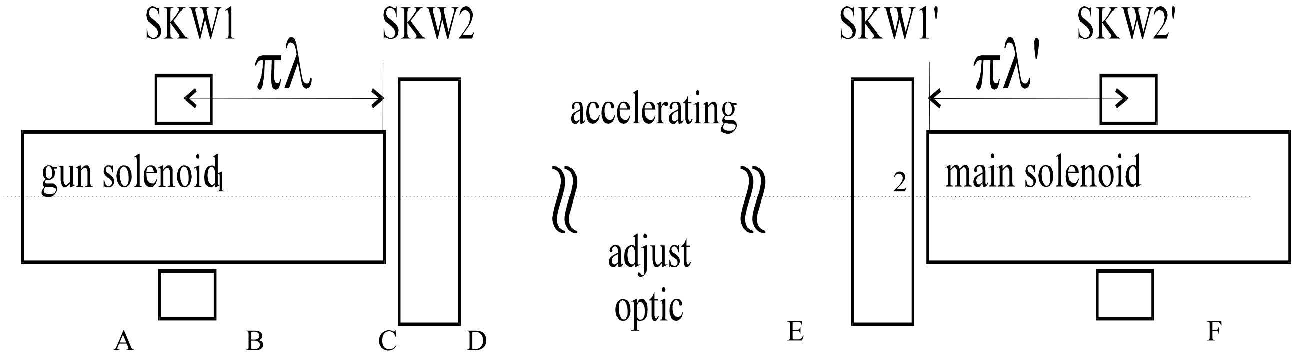


Figure 5. RF accelerator-recuperator for RHIC (draft design).

In all previous “low energy” coolers the longitudinal guiding field was continuous – from immersed electron gun up to the collector; this option is the most convenient (and easy to understand). But for RF acceleration case we need to interrupt the guiding field. In this case, the gun and the cooling section again should be immersed in the longitudinal magnetic field of appropriate strength (and quality!). But in between, the optical focusing structure (Figure 6)



(here λ is Larmour length divided by 2π!)
Figure 6. The optical matching of gun and cooling sections.

should match the shape of electron beam emittance – to prevent unacceptable rise of Larmour radius in the cooling section.

Almost from the very beginning /1/ we considered options with electron storage ring as a source for the cooling electron beam. For higher energies, the option with synchrotron radiation cooled electron beam with suppression of influence of betatron electron velocities in the cooling section by very strong focusing was considered also.
The attempts to find good storage ring based solution are continued by different authors.

Up to now, only electron-proton high energy (900 GeV protons and 30 GeV electrons/positrons) ring HERA was constructed, and is producing many very interesting results – still without any use of electron cooling (preliminary considerations, only).

But electron-nuclei colliders are crucially important for other studies, also. Thus, high luminosity electron-proton collider at, say, 5 GeV electrons and 30 GeV protons (especially in case of longitudinal polarization of both beams) at luminosity around $1*10^{33}$ $cm^{-2}sec^{-1}$ (such colliders are under consideration in several labs, starting by GSI-Novosibirsk collaboration /5/, Figure 7). To reach such a high luminosity at lower beam currents it is worth to use electron cooling of the proton beam. But if the aim is to reach the same electron-nucleon luminosity for heavy nuclei, the use of electron cooling is a must, for both needs – to prevent fast emittance growth due to multiple intra-beam scattering in ion beam, and to prevent beam-beam diffusion /2/.

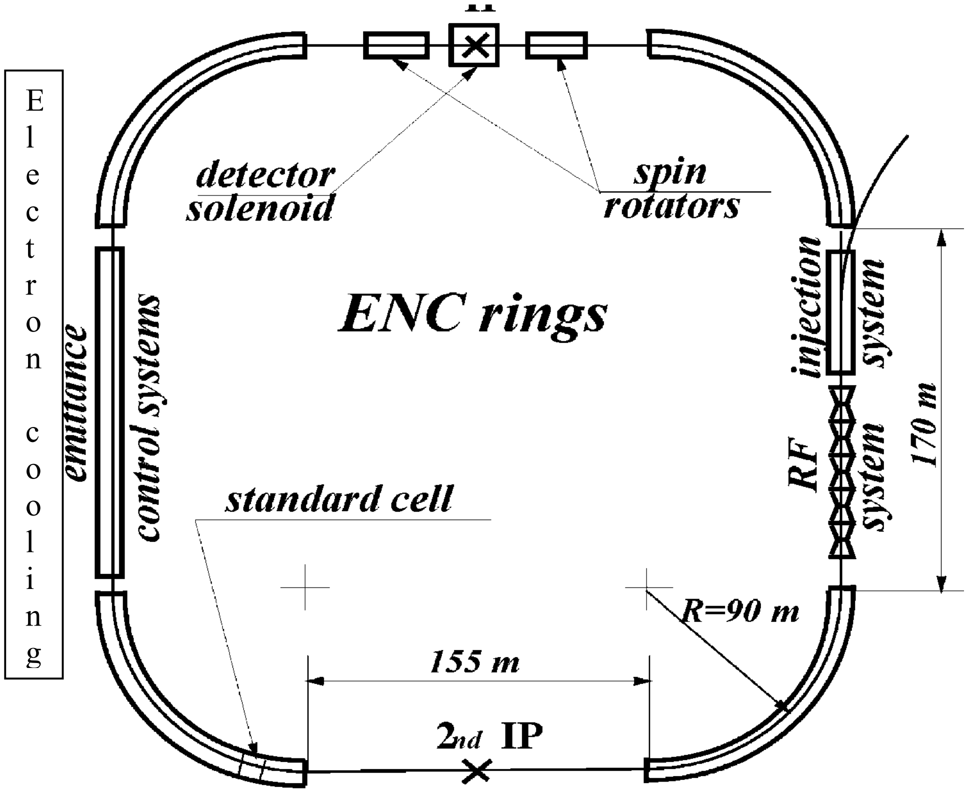


Figure 7. The draft scheme of high luminosity electron-nuclei collider /GSI-Novosibirsk/.

The other extreme case is the study of structure of the nuclei far from stability in electron-nuclei collider /6/ (Figure 8). In this case number of stored nuclei is strongly limited, and the acceptable luminosity could be reached for very small nuclei beam emittance – thus the electron cooling is badly needed.

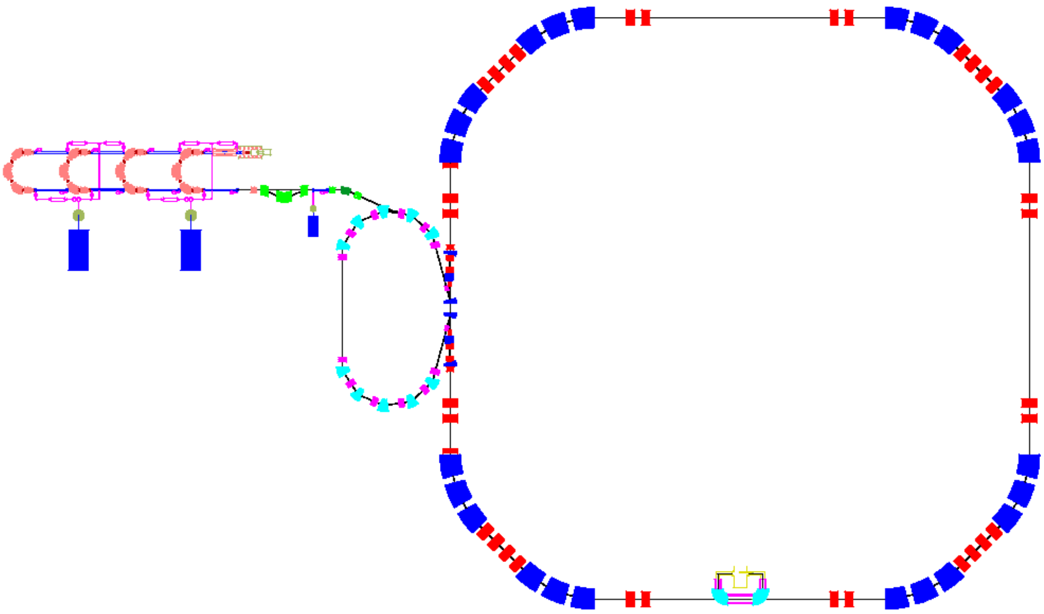


Figure 8. The draft scheme of Electron – Nuclei Fragment Collider (GSI-Novosibirsk)
[around 500 MeV/nucleon and 500 MeV electrons].

The electron-fragment collider is accepted for RIKEN project, and we (BINP) hope to collaborate and contribute actively to this project.

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