Development of some ERL applications

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- Subpicosecond x-ray source with high (15 T) field magnet(s) on 1-GeV ERL.
- Few-GeV collider (e. g., charm-tau factory) with beam-beam compensation using positron storage ring(s) and electron ERL(s).
- Electron cooling of relativistic hadrons.

1. Subpicosecond x-ray source with high (15 T) field magnet(s) on 1-GeV ERL.

This option could intensify ERL activity, transforming, for example, test facility PERLE or ERL projects for x-ray lithography FEL, to unique user facility (storage rings can not provide so short x-ray pulses, and linacs can not provide average intensity).

Critical energy of SR photons

$$\varepsilon_c = \frac{hc}{\lambda_c} = \frac{3}{2}\gamma^2 e \frac{\hbar}{mc} B = 0.665 E^2 \left[GeV\right] B\left[T\right] keV$$

Radiation from superconducting magnet:

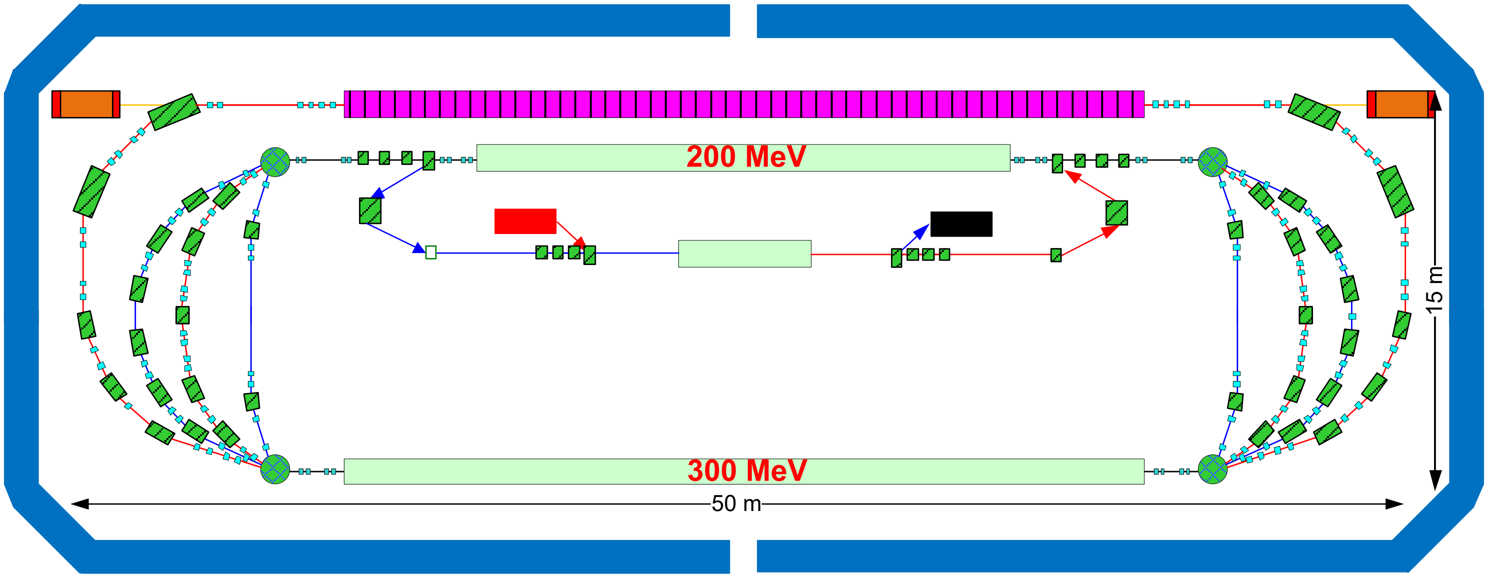
B = 15 T, E = 1 GeV,

ε_c = 10 keV

It means, that there is significant flux of photons with energies up to 30 keV. This energy range satisfies most of users with small enough specimens.

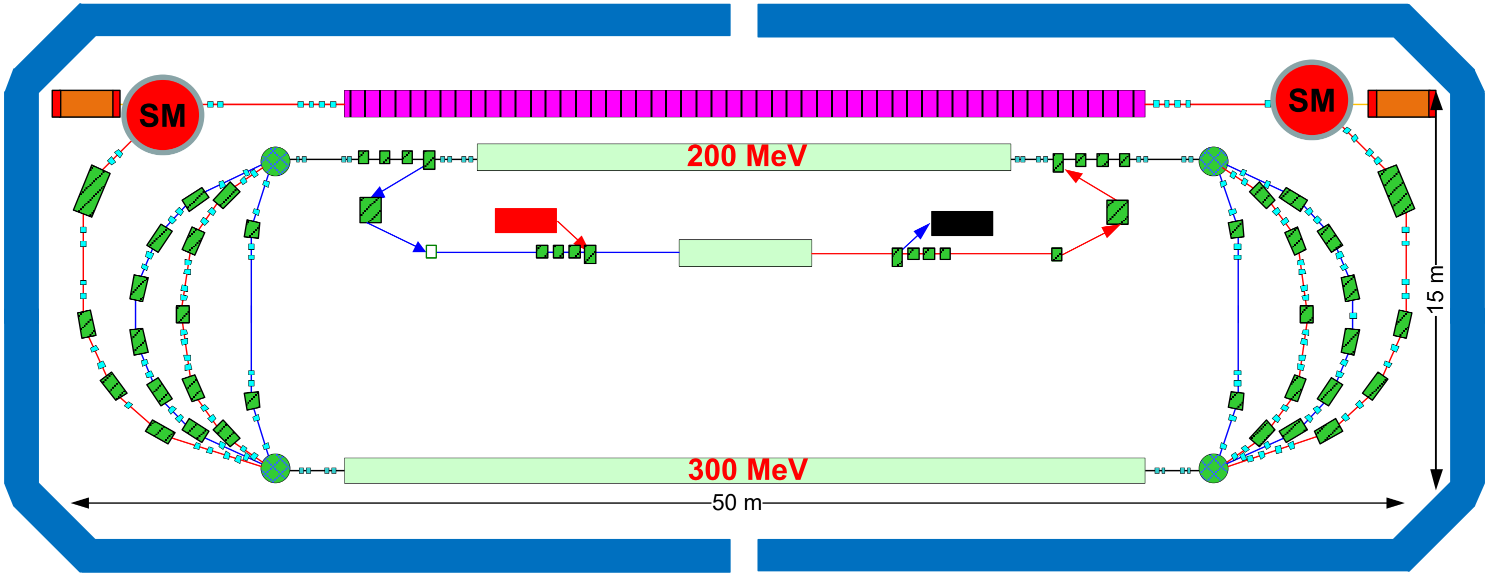
"Compact" ERL

(Compact 13.5-nm free-electron laser for extreme ultraviolet lithography, Y. Socol, G. N. Kulipanov, A. N. Matveenko, O. A. Shevchenko and N. A. Vinokurov, PRST AB, Vol. 14, No 4. – 040702-1 – 040702-7, 2011)



Wavelength	13.5 nm
Electron energy	1 GeV
Average EUV power	5 kW
Beam average current	5-10 mA
Sizes	$20 \times 50\ m^2$
SR source	Undulator with 2-3 cm period

Short x-ray pulses generation



With 15-T superconducting magnet (SM) the 1-GeV ERL may be used to generate subpicosecond periodic x-ray pulses, which are necessary for time-resolved experiments. Such experiments use femtoslicing technique at storage rings now. But, the number of useful photons per pulse at ERL will be thousands times more.

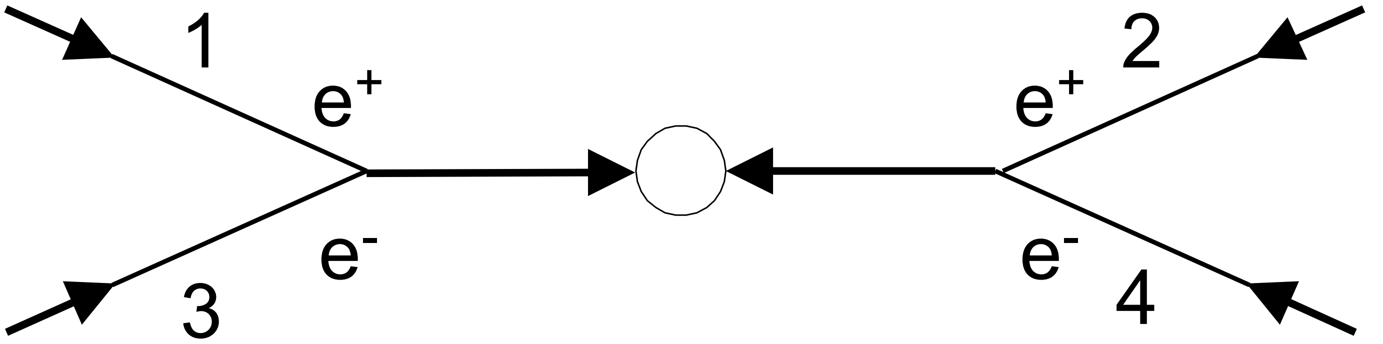
2. Few-GeV collider (e. g., charm-tau factory) with beam-beam compensation using positron storage ring(s) and electron ERL(s)

(N. A. Vinokurov, "Four-Beam Compensation with Two Beams", 26th Russian Particle Accelerator Conference, http://accelconf.web.cern.ch/rupac2018/papers/tuymh02.pdf,

S. B. Lachynov and N. A. Vinokurov, "Beam-Beam Compensation in a Collider Based on Energy Recovery Linac and Storage Ring" AIP Conference Proceedings 2299, 020011 (2020); https://doi.org/10.1063/5.0030416).

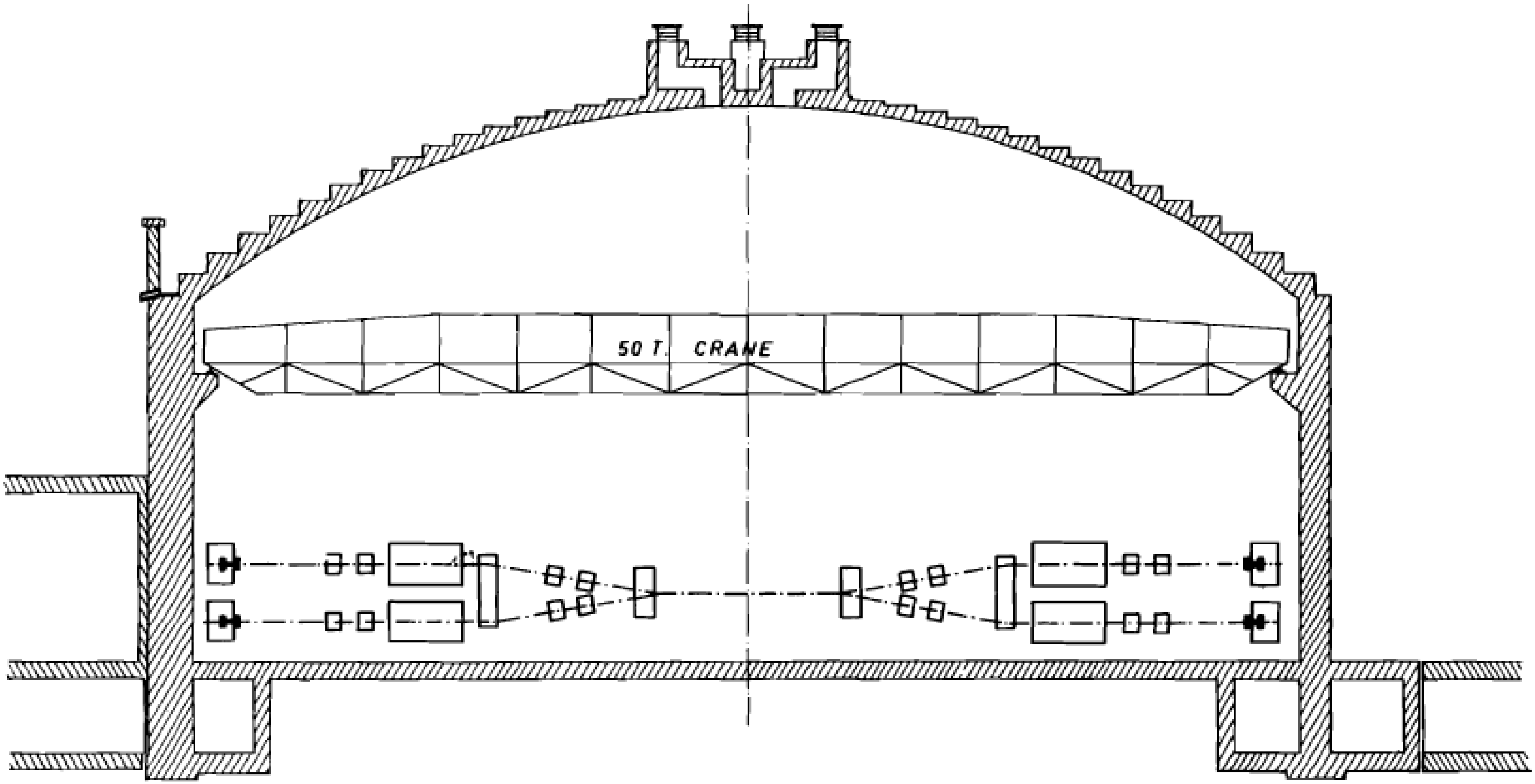
The compensation of non-linear focusing in the storage ring colliders by the opposite-charge beam, circulating in other storage ring, was proposed and tested many years ago.

Scheme of the four-beam collision

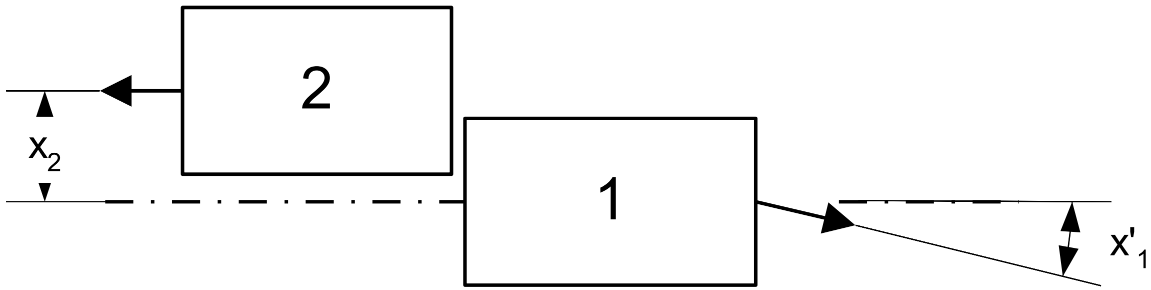


The Orasy compensated colliding beam ring D. C. I.

(France, 1972)



Displaced bunch 2 kicks bunch 1.



$$\beta\gamma x_1' = -d x_2$$

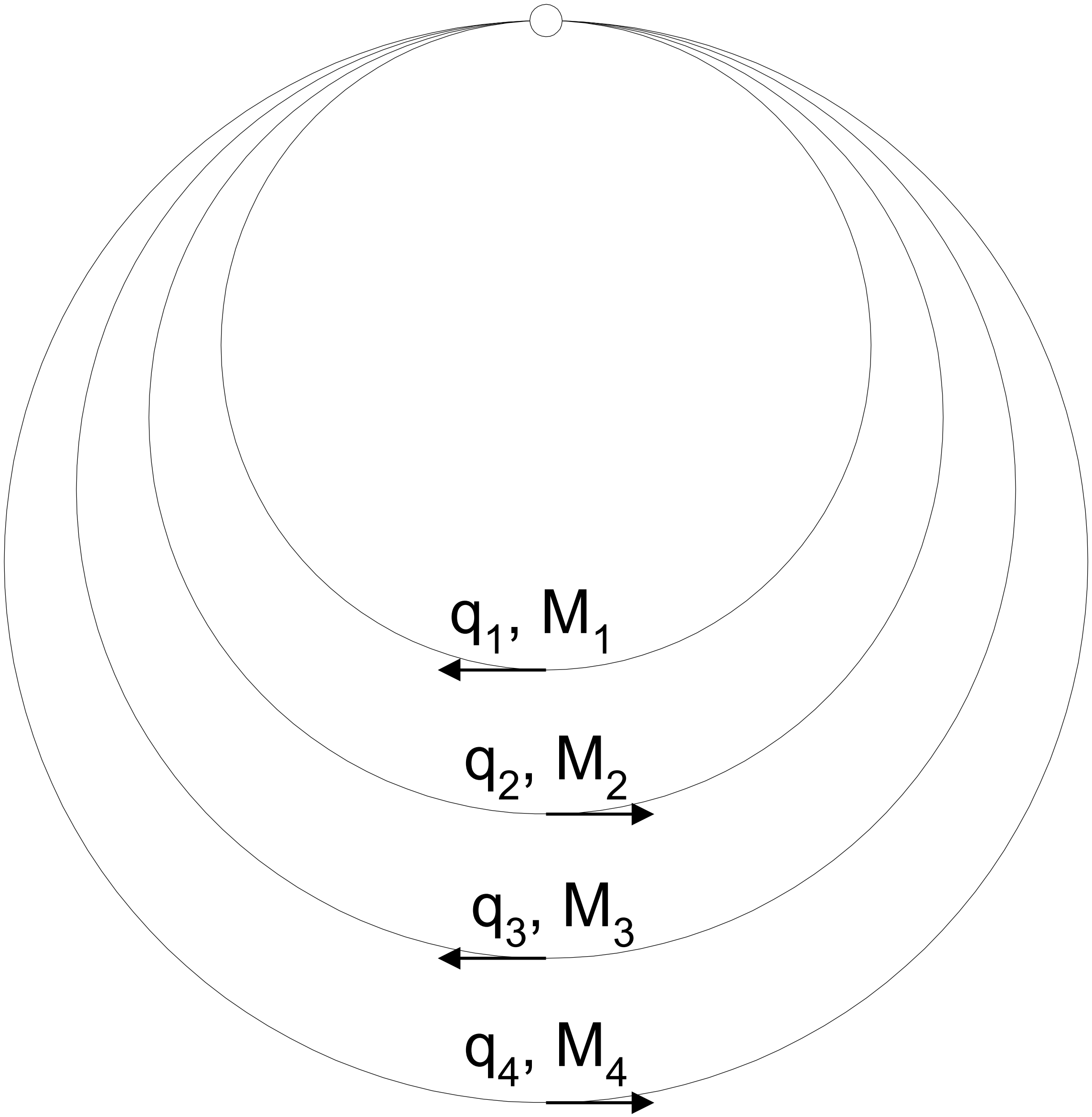
d is the interaction parameter (optical strength of the beam field focusing, multiplied by $\beta\gamma$).

Ya. S. Derbenev had shown (1972) first that the scheme suffers from the tune shifts of coherent betatron oscillations, which shift betatron frequencies to nearest integer or half-integer resonance.

The possible solution of the problem is to change the standard scheme and replace the electron storage ring(s) by ERL(s).

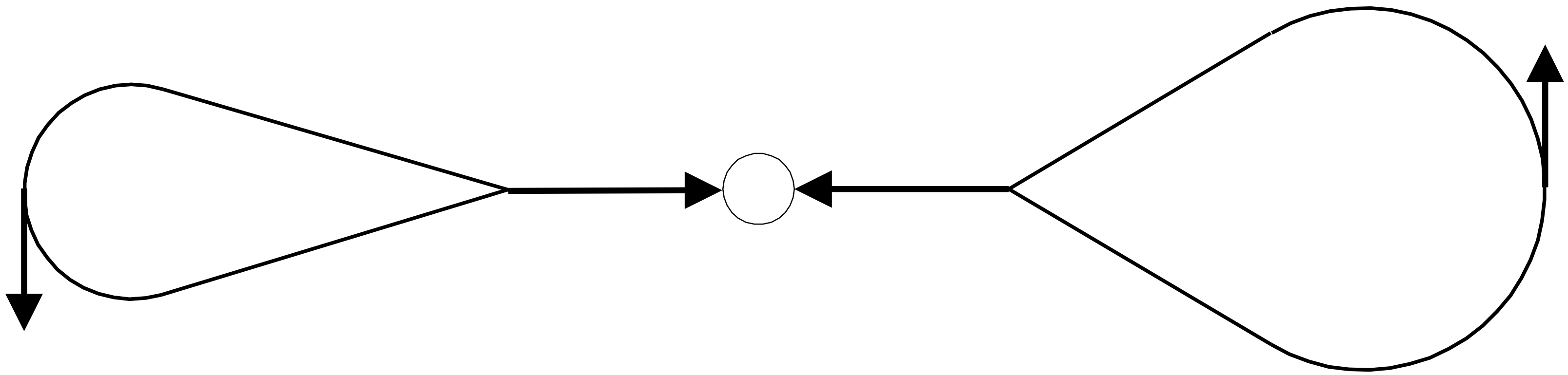
CONVENTIONAL SCHEME

Scheme of the four-ring collider



«FIGURE-8» COLLIDER

Consider first the electron-electron collider with "self-osculating" orbit



All electrons are moving near the same equilibrium orbit in the same direction. Therefore, one can say that it is single-beam (but, certainly, multi-bunch) collider.

Injecting positrons in such a collider, one can obtain beam-beam compensation.

This scheme was considered in 1991 for the project of the Novosibirsk φ - factory.

STATUS OF THE NOVOSIBIRSK PHI-FACTORY PROJECT.

L.M. Barkov, S.A. Belomestnykh, V.V. Danilov, N.S. Dikansky, A.N. Filippov, B.I. Grishanov, P.M. Ivanov, I.A. Koop, O.B. Malyshev, B.L. Militsyn, S.S. Nagaitsev, I.N. Nesterenko, E.A. Perevedentsev, D.V. Pestrikov, L.M. Schegolev, I.K. Sedlyarov, Yu.M. Shatunov, E.A. Simonov, A.N. Skrinsky, I.B. Vasserman, V.G. Vescherevich, P.D. Vobly, E.I. Zinin
Institute of Nuclear Physics, Novosibirsk, USSR

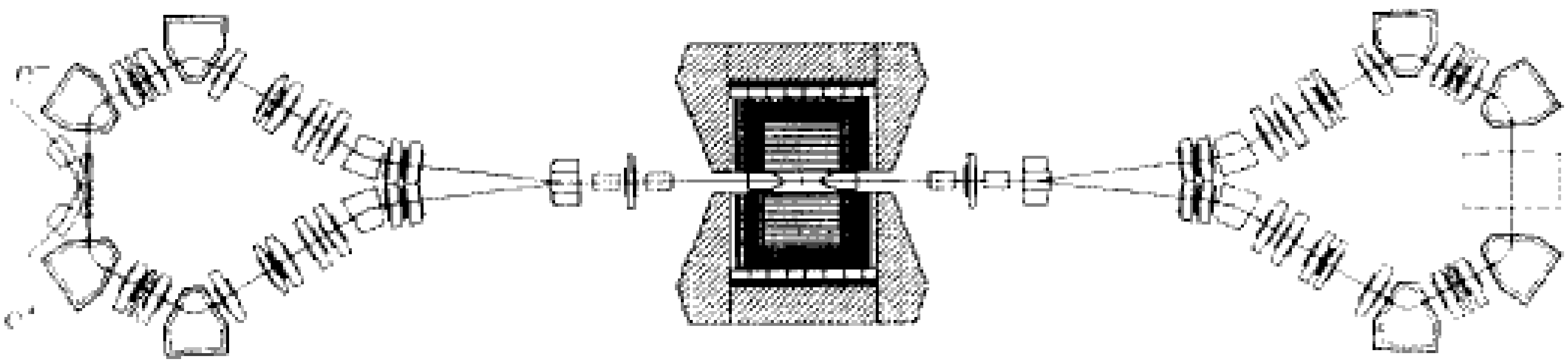
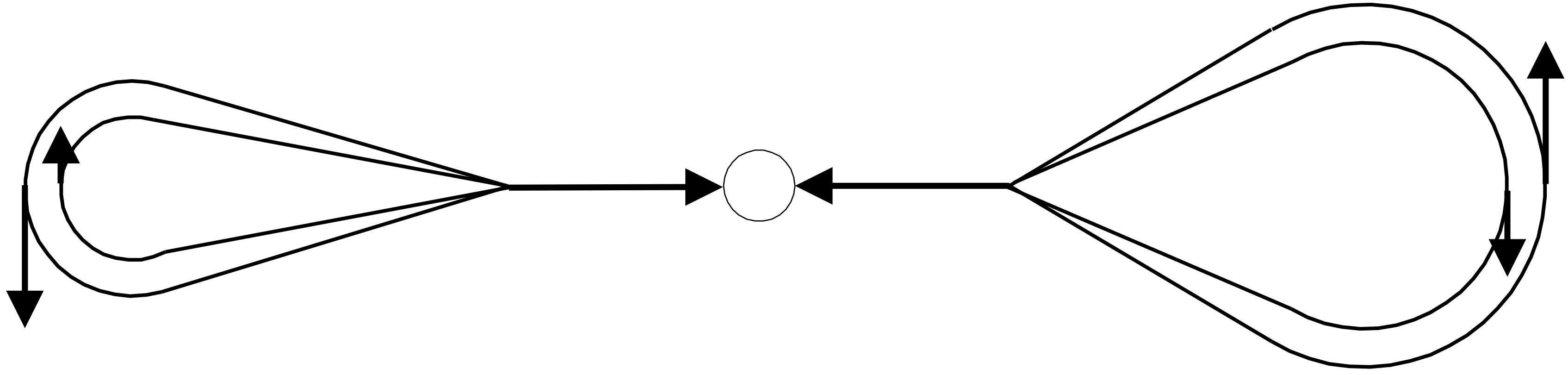
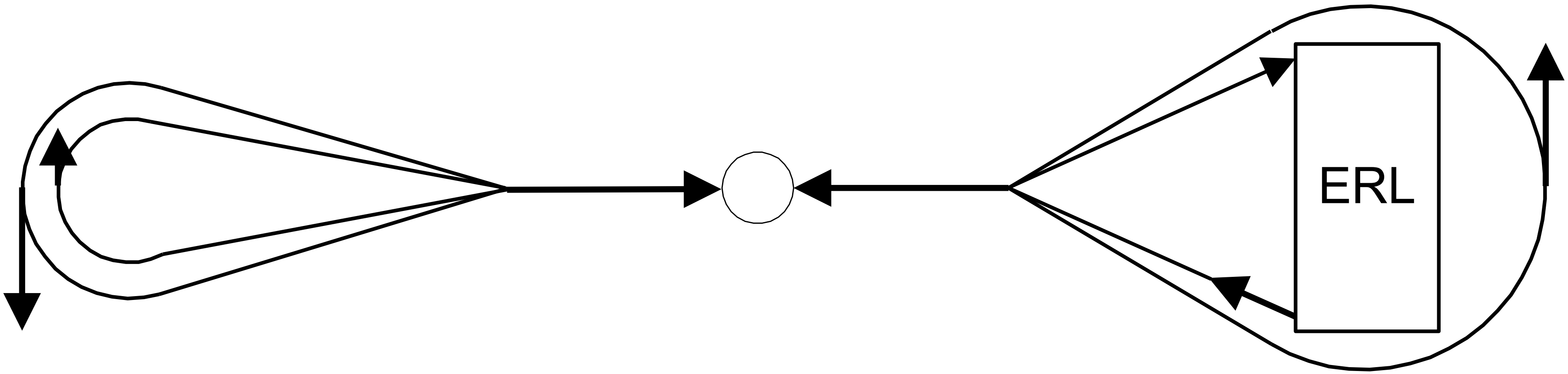


Fig.1. Layout of the Novosibirsk φ-factory.

In more general case of different energies of electrons and positrons, their orbits will be separated outside the collision straight section



The scheme may be modified by replacing the electron storage ring with the energy recovery linac (ERL).



Estimations show that this scheme could provide significantly higher threshold beam currents, and, therefore, higher luminosity of the collider.

3. Electron cooling of relativistic hadrons

(A. Skrinsky, “Continuous Electron Cooling for High Luminosity Colliders”, Nucl. Instr. and Meth. A, vol. 441, 1-2, p. 286-293, Febr. 2000,

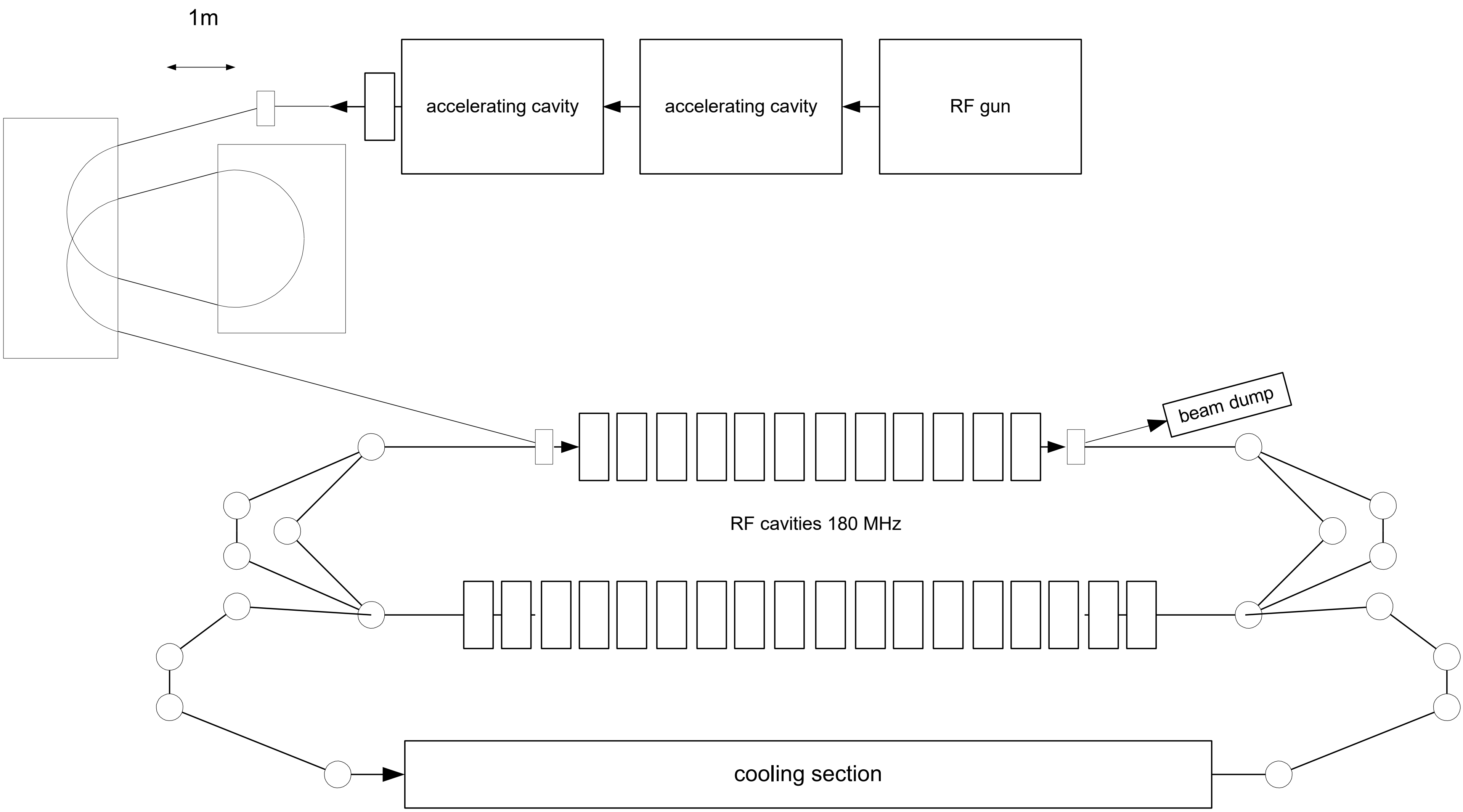
N. A. Vinokurov, V. V. Parkhomchuk, A. N. Skrinsky, “RF Accelerator for Electron Cooling of Ultrarelativistic Hadrons”, 12th Workshop on Beam Cooling and Related Topics,

http://accelconf.web.cern.ch/cool2019/papers/tuy01.pdf).

To obtain high bunch charge, it is necessary to increase the cathode diameter and decrease the RF and bunch repetition frequencies. A frequency of 30 MHz seems to be as a reasonable compromise between increasing the RF cavity size and obtaining more than 10 nC in each bunch. With a peak cathode current of 4 A and an initial bunch duration of about 4 ns, one can obtain a bunch charge of 16 nC. To have a significant accelerating gradient in an RF structure, it is necessary to use a higher RF frequency. Then, for further RF acceleration it is necessary to compress the bunch.

The proposed compression system compresses the 2 MeV, 16 nC bunch from 4 ns to 0.5 ns duration. It uses the energy chirp of 2 MeV bunches, additional energy modulation in an auxiliary RF cavity, operating at a sub-harmonic of the main accelerating structure frequency of 180 MHz, and a magnetic buncher. For the required energy modulation to have an acceptable value (less than ±10%), the buncher shall have a high value of the longitudinal dispersion R_{56}. A second-order achromat is desirable for operation with large energy spread.

Scheme of cooling ERL



Let us estimate the cooling rate in the case of a long superconductive solenoid with a magnetic field B = 1 T.

Let the electron bunch length l_b be 60 cm. The longitudinal emittance ε_s = 10 keV·ns will define the energy spread of bunch $\sigma_E = c\varepsilon_s / l_b$ =5 keV, where c is the velocity of light. Then the longitutinal electron velocity spread in the beam rest frame is $V_{se} = c\sigma_E / E =$ $3 \cdot 10^6$ cm/s. For an ion beta function β_i = $3 \cdot 10^4$ cm and an ion normalized transverse emittance ε_i = 10^{-4} cm, the transverse velocity spread in the beam rest frame is $V_{xi} = c\sqrt{\gamma\varepsilon_i / \beta_i} =$ $1.7 \cdot 10^7$ cm/s, and the

transverse beam size is $a_i = \sqrt{\varepsilon_i \beta_i / \gamma} =$ 0.17 cm (γ = 100 is Lorentz factor). Let the flat electron beam enter the flat solenoid edge. For a vertical beta function β_y = 100 cm, the vertical beamsize is $a_y = \sqrt{\varepsilon_t \beta_y / \gamma} =$ 0.032 cm, and the

vertical angular spread is $\theta_x = \sqrt{\varepsilon_t / (\gamma\beta_x)} =$ $3.2 \cdot 10^{-4}$.

For a horizontal beta function β_x = 40000 cm, the horizontal beamsize is $a_x = \sqrt{\varepsilon_t \beta_x / \gamma} =$ 0.64 cm and the horizontal angular spread is $\theta_x = \sqrt{\varepsilon_t / (\gamma \beta_x)} =$ $1.6 \cdot 10^{-5}$, which is much less than the r. m. s. horizontal kick $a_y/R = 2 \cdot 10^{-3}$ ($R = \gamma mc^2/(eB)$ = 17 cm) at the flat edge of the solenoid. Then the r. m. s. Larmor radius is equal to a_y. After transformation in solenoid we obtain a round beam with an r. m. s. sizes a_e of 0.15 cm, which exceeds the r. m. s. Larmor radius 5 times. The peak electron current is $qc/(\sqrt{2\pi} l_b) =$ 3.2 A, and the electron rest-frame density is $n_e = N_e / (2^{3/2} \pi^{3/2} l_b a_e^2 \gamma)$ $=5 \cdot 10^7$. The cooling rate in the lab frame can be estimated as

$$\delta_{cool} = \frac{2\pi n_e r_e r_i c^4}{\left(V_{xi}^2 + V_{se}^2\right)^{3/2}} \frac{\eta}{\gamma} \ln \frac{a_e}{R}$$

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where r_e is the classical radius of electron, r_i is the classical radius of ion, and η is the fraction of the collider perimeter occupied by the cooling section.

For ions with the charge Z = 92, atomic weight A = 200, and η = 0.01,

$$\tau_{cool} = 1/\delta_{cool} = 100 \text{ s.}$$

This result shows good prospects for using this cooling system with a low-frequency ERL.

Thank you for your attention.