Colliders: NICA and its Accelerator Technologies

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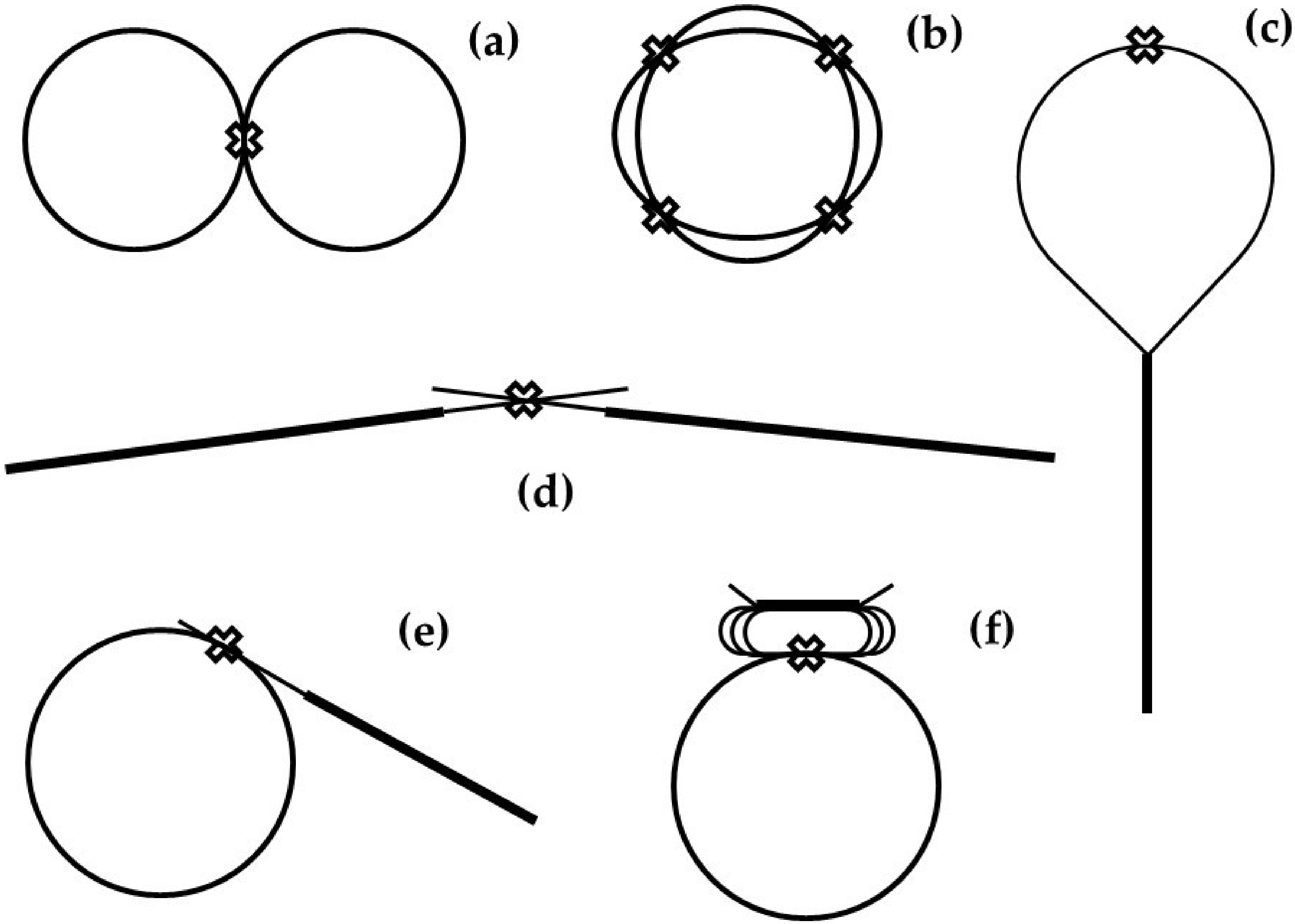
Outline

- Introduction to colliders
- Collider versus synchrotron
- Physics goals
- Unique niche for NICA
- Choice of major parameters
- Major technologies
- Linear and non-linear motion
- Integrable versus chaotic
- IBS
- Electron and stochastic cooling (Liouville theorem)

Types of Colliding Beam Facilities



- Since 60's colliders have been the major instrument in the particle physics

Collision Energy and Luminosity

- Gain in collision energy for ultra-relativistic particles
  - One particle stationary:

$$E_{cm} \approx \sqrt{2Emc^2}\ , \quad E \gg mc^2$$

  - Both particles move:

$$E_{cm} = 2E$$

(120 times gain for the LHC)

- Detectors want constant luminosity
- Number of events in collisions:

$$\frac{dN}{dt} = L\sigma$$

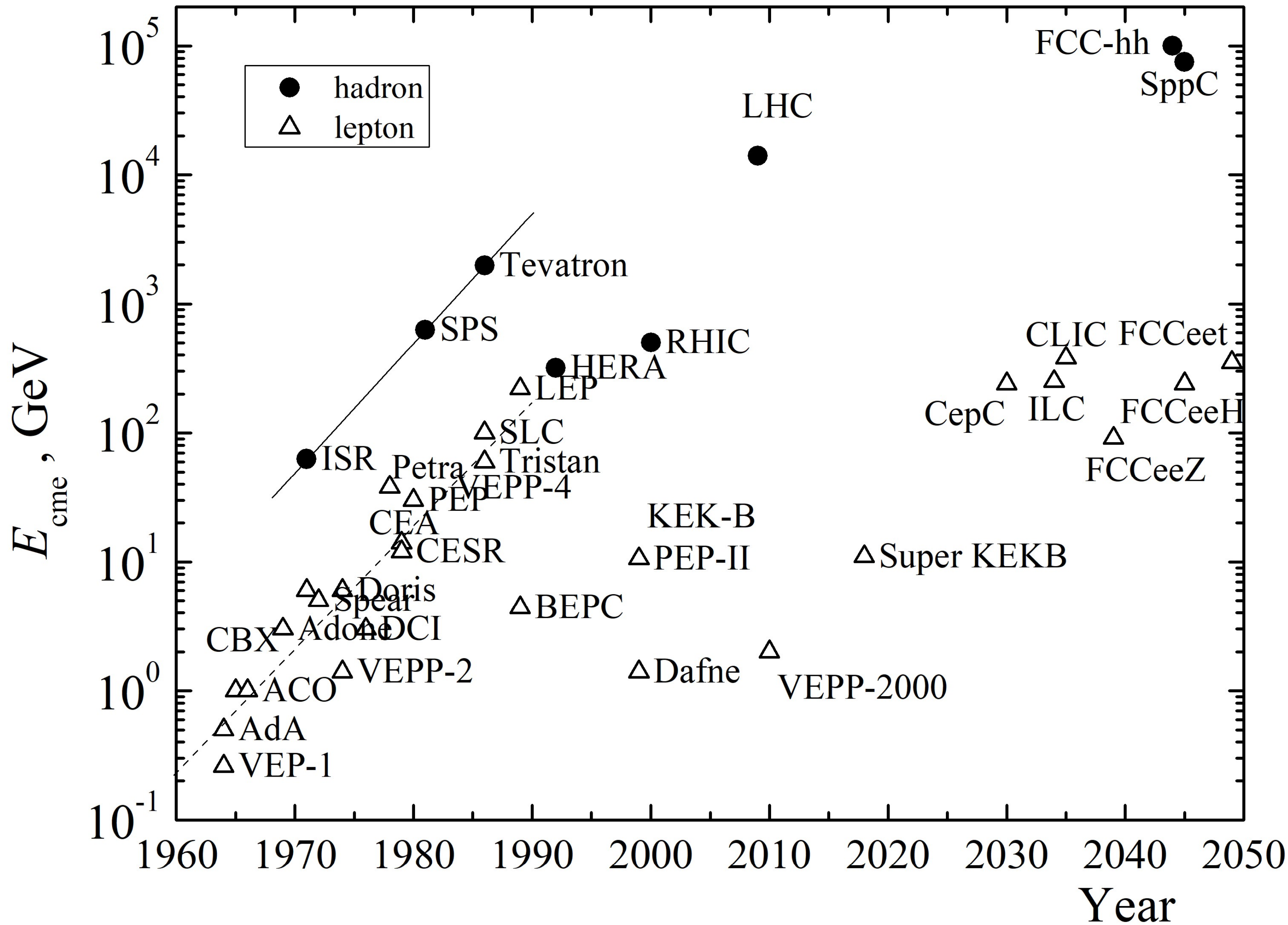
Colliders Landscape

- 58 years since 1st collisions
  - Spring 1964 AdA and VEP-1
- 31 operated since
- 7 in operations now
  - S-KEKB, VEPP-2000, VEPP-4M, BEPC, DAFNE
  - LHC, RHIC
- 1 under construction
  - NICA
- One in a project phase
  - EIC
- Far plans
  - Higgs/Electroweak factories
    - ILC
    - FCC: e^+e^-
  - Frontier ($E >> E_{LHC}$)
    - FCC: pp

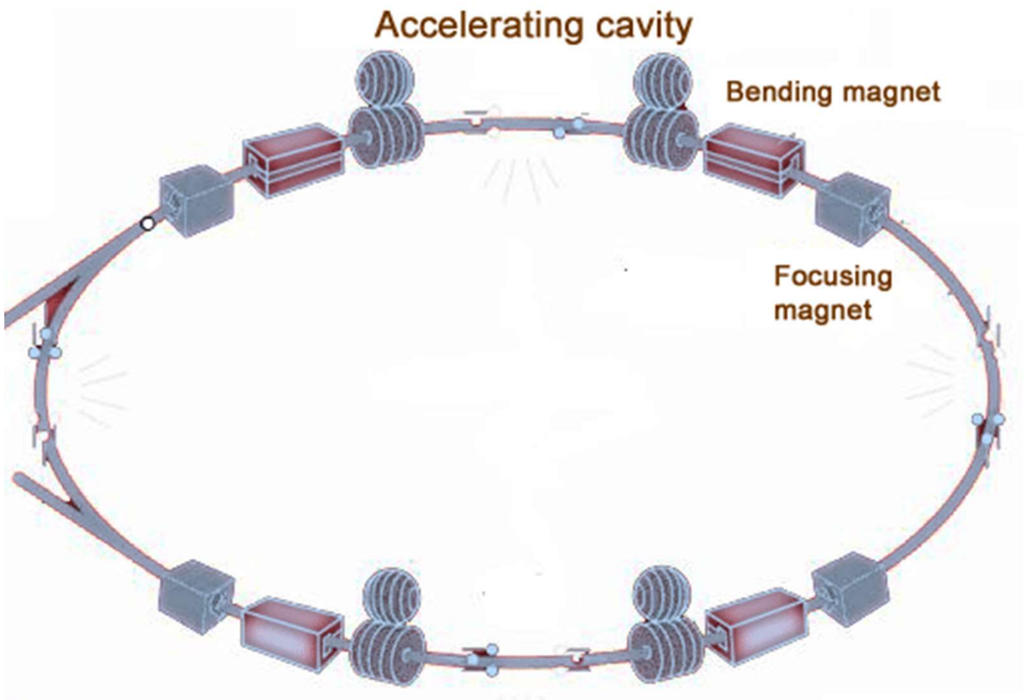
V. Shiltsev and F. Zimmermann: Modern and future colliders

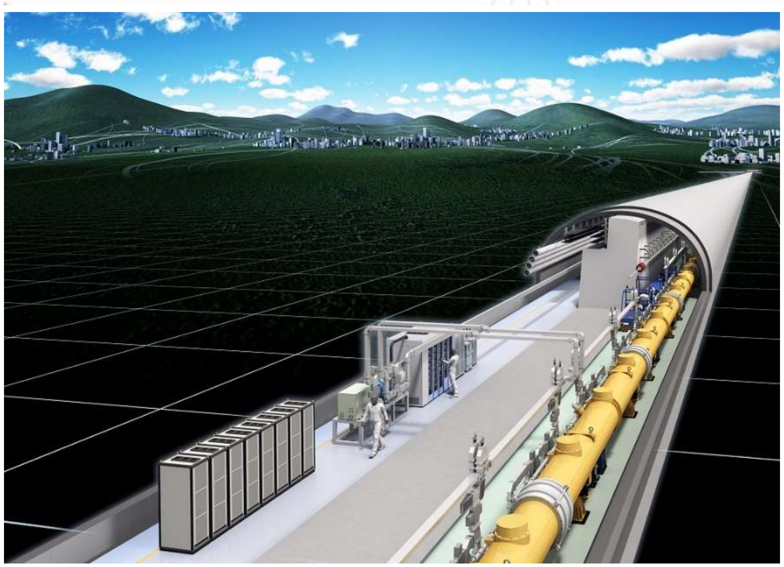
	Species	E_b, GeV	C, m	$\mathcal{L}^{max}_{peak}$	Years
AdA	e^+e^-	0.25	4.1	10^{25}	1964
VEP-1	e^-e^-	0.16	2.7	5×10^{27}	1964-68
CBX	e^-e^-	0.5	11.8	2×10^{28}	1965-68
VEPP-2	e^+e^-	0.67	11.5	4×10^{28}	1966-70
ACO	e^+e^-	0.54	22	10^{29}	1967-72
ADONE	e^+e^-	1.5	105	6×10^{29}	1969-93
CEA	e^+e^-	3.0	226	0.8×10^{28}	1971-73
ISR	pp	31.4	943	1.4×10^{32}	1971-80
SPEAR	e^+e^-	4.2	234	1.2×10^{31}	1972-90
DORIS	e^+e^-	5.6	289	3.3×10^{31}	1973-93
VEPP-2M	e^+e^-	0.7	18	5×10^{30}	1974-2000
VEPP-3	e^+e^-	1.55	74	2×10^{27}	1974-75
DCI	e^+e^-	1.8	94.6	2×10^{30}	1977-84
PETRA	e^+e^-	23.4	2304	2.4×10^{31}	1978-86
CESR	e^+e^-	6	768	1.3×10^{33}	1979-2008
PEP	e^+e^-	15	2200	6×10^{31}	1980-90
S$p\bar{p}$S	$p\bar{p}$	455	6911	6×10^{30}	1981-90
TRISTAN	e^+e^-	32	3018	4×10^{31}	1987-95
Tevatron	$p\bar{p}$	980	6283	4.3×10^{32}	1987-2011
SLC	e^+e^-	50	2920	2.5×10^{30}	1989-98
LEP	e^+e^-	104.6	26659	10^{32}	1989-2000
HERA	ep	30+920	6336	7.5×10^{31}	1992-2007
PEP-II	e^+e^-	3.1+9	2200	1.2×10^{34}	1999-2008
KEKB	e^+e^-	3.5+8.0	3016	2.1×10^{34}	1999-2010
VEPP-4M	e^+e^-	6	366	2×10^{31}	1979-
BEPC-I/II	e^+e^-	2.3	238	10^{33}	1989-
DAΦNE	e^+e^-	0.51	98	4.5×10^{32}	1997-
RHIC	p, i	255	3834	2.5×10^{32}	2000-
LHC	p, i	6500	26659	2.1×10^{34}	2009-
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010-
S-KEKB	e^+e^-	7+4	3016	8×10^{35} *	2018-

Colliders: Energy

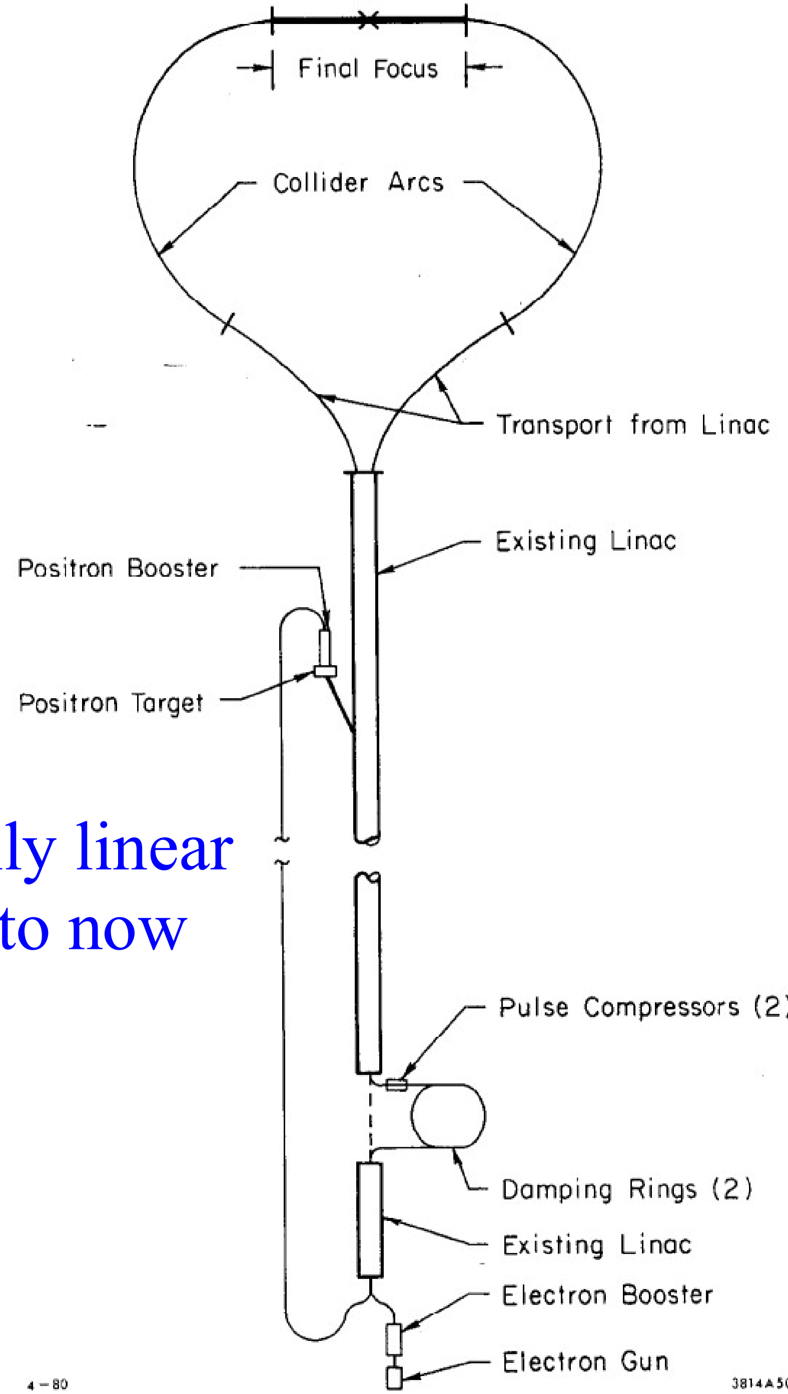


Rings vs Linacs





- SLC – the only linear collier built up to now



Highest Energy = Highest Field SC Magnets

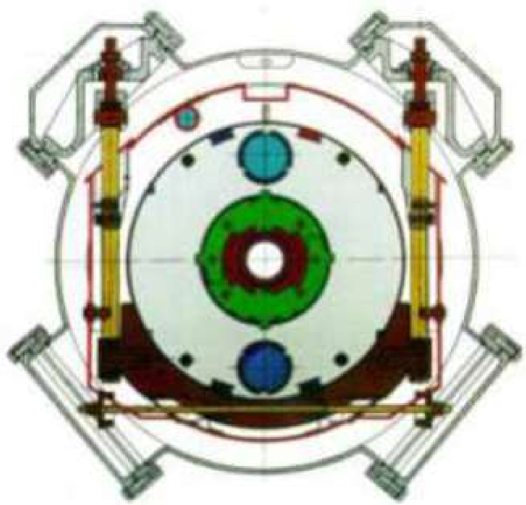
4.5T

Tevatron,
6 m, 76 mm
774 dipoles

4.5 K He, NbTi
+ warm iron
small He-plant

5.3T

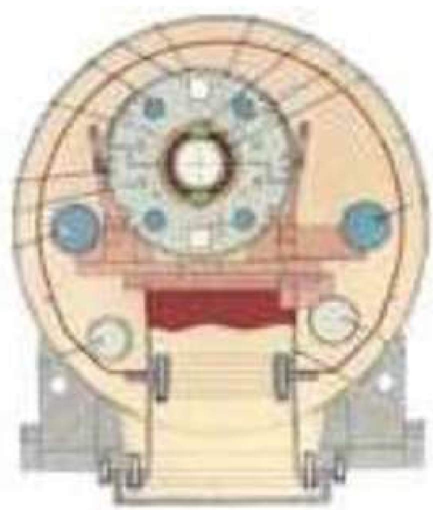
HERA,
9 m, 75 mm
416 dipoles



NbTi cable
cold iron
Al collar

3.5T

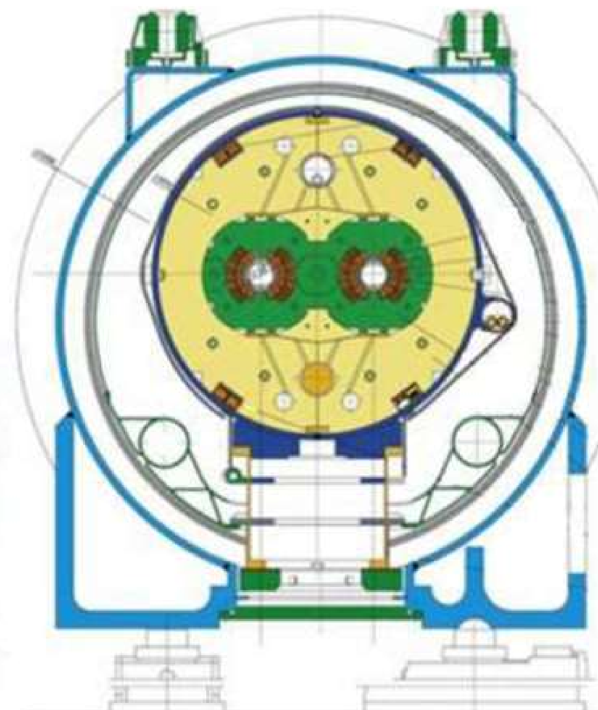
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

8.3T

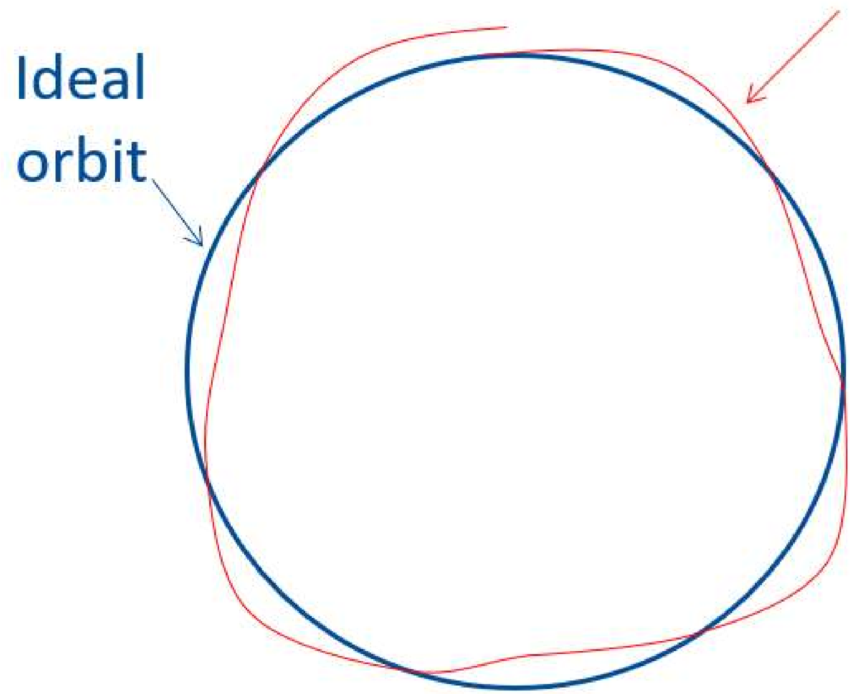
LHC,
15 m, 56 mm
1276 dipoles



NbTi cable
2K He
two bores

Some Basic Concepts of Accelerator Physics

Betatron Oscillations, Tune



- As particles go around a ring, they will undergo a number of betatron oscillations ν (sometimes Q) given by

$$\nu = \frac{1}{2\pi} \oint \frac{ds}{\beta(s)}$$

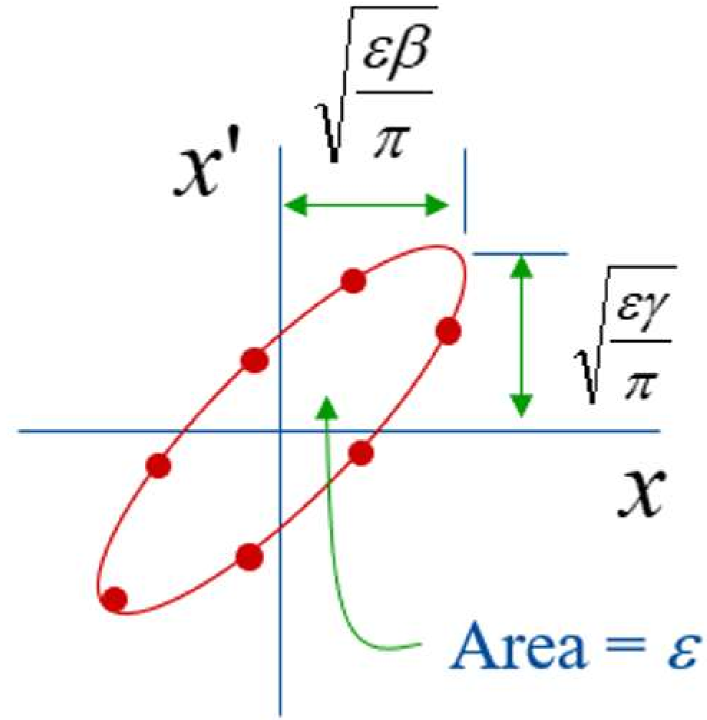
- This is referred to as the **"tune"**

- We can generally think of the tune in two parts:

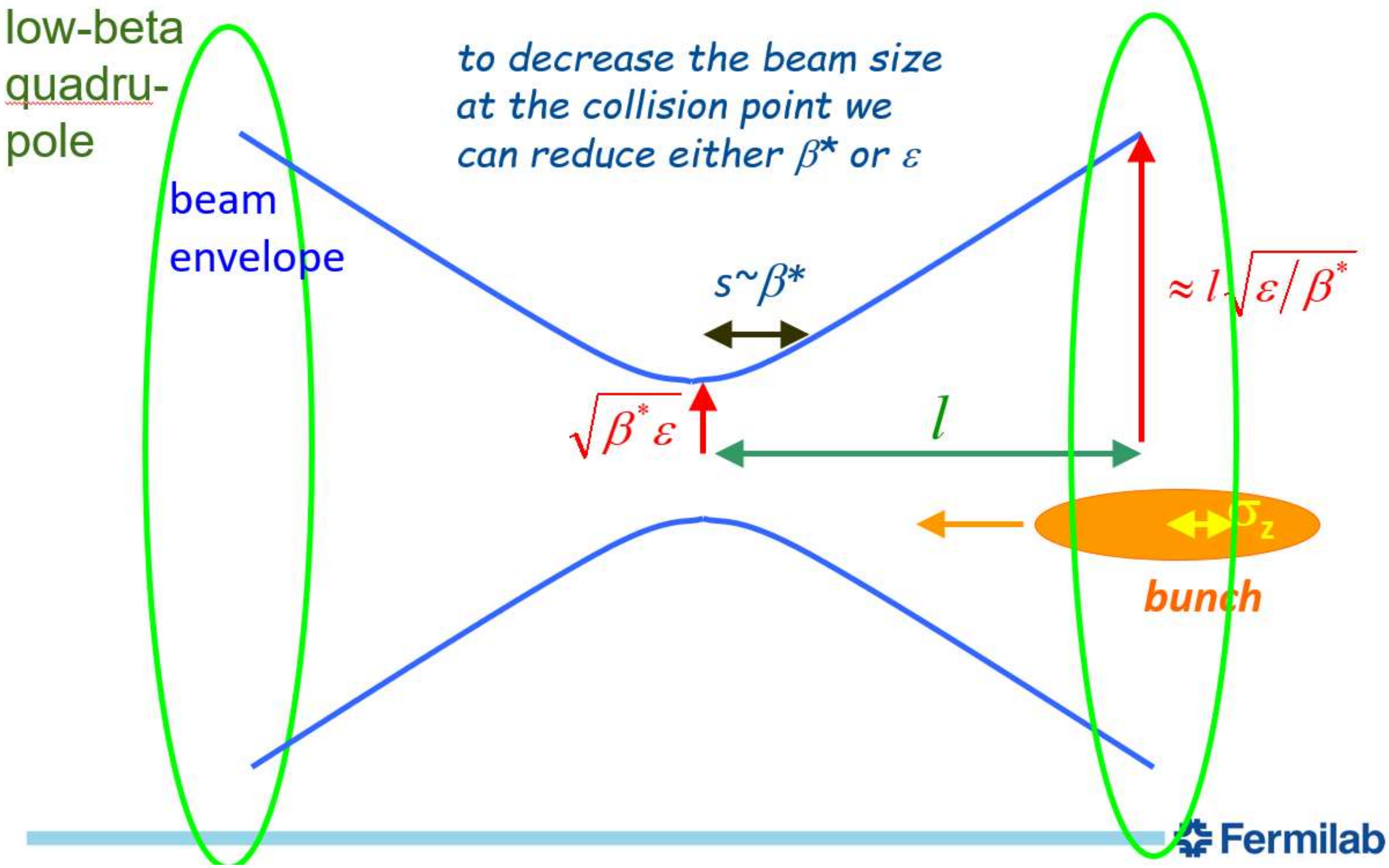
Integer : magnet/aperture optimization → **64.31** ← **Fraction: Beam Stability**

Emittance

- As a particle returns to the same point on subsequent revolutions, it will map out an ellipse in phase space
- Emittance = $\sigma_x \sigma_\theta$
- Normalized emittance:
  $\varepsilon_n = \varepsilon\gamma\beta$ - adiabatic invariant
- Beam size: $$\sigma_{x,y} = \sqrt{\frac{\varepsilon_n \cdot \beta_{x,y}}{\gamma}}$$
- Luminosity ~ $1/\varepsilon$



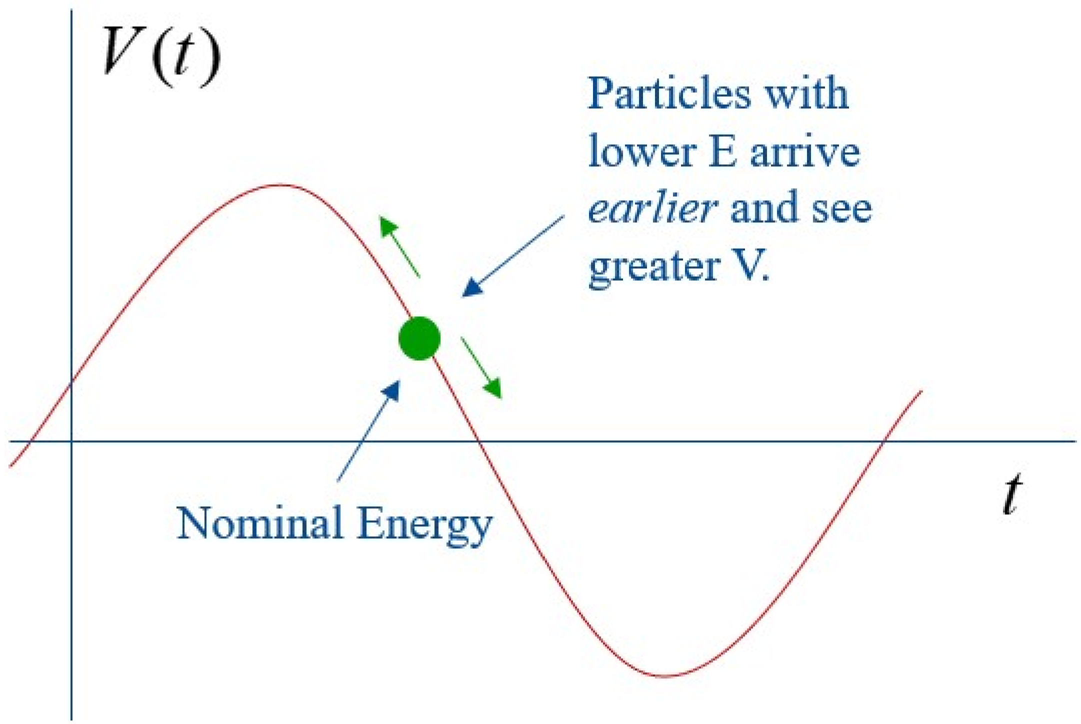
Collider Spot Size



- β^* must remain larger than σ_z ('hourglass effect')
  - with exception of crab-waist (e+e- colliders)
- Quadrupole aperture must be respected

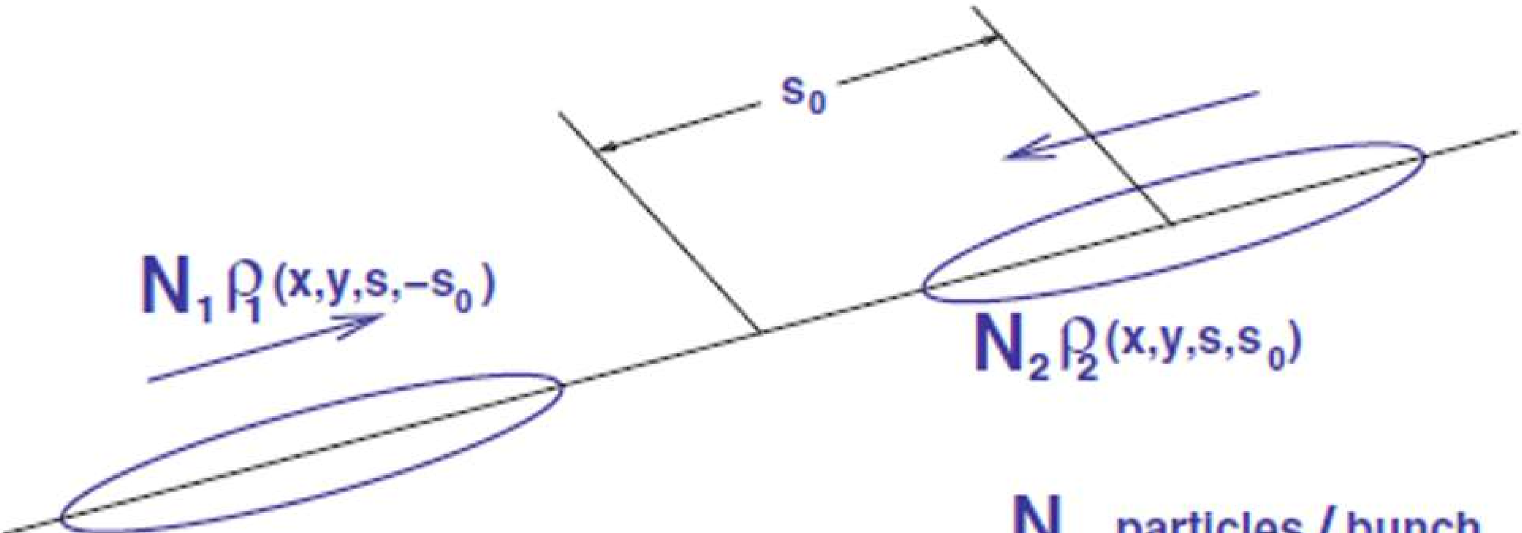
Longitudinal Motion: Phase Stability

- Particles are typically accelerated by radiofrequency (“RF”) structures.
- Stability depends on particle arrival time relative to the RF phase.
  - ♦ time of arrival depends only on the energy (in the bunch – energy deviation wrt “reference central particle”)



Luminosity

$$N_{\rm exp} = \sigma_{\rm exp} \cdot \int \mathcal{L}(t)dt.$$



N particles / bunch

ρ density ≠ const.

For (same size) Gaussian bunches:

$$\mathcal{L} = f_{\rm coll} \frac{N_1 N_2}{4\pi\sigma_x^* \sigma_y^*}$$

Colliders: Luminosity

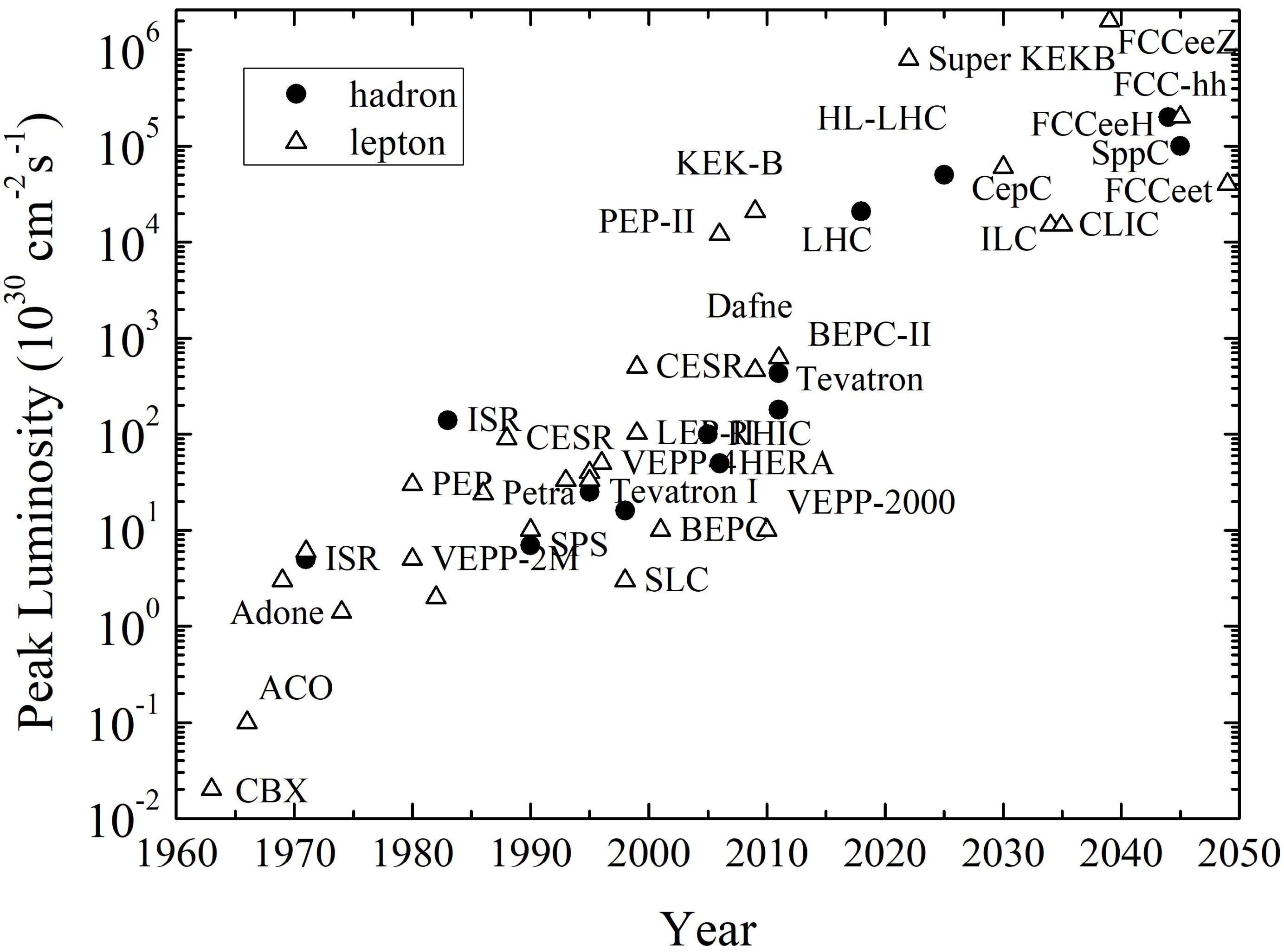


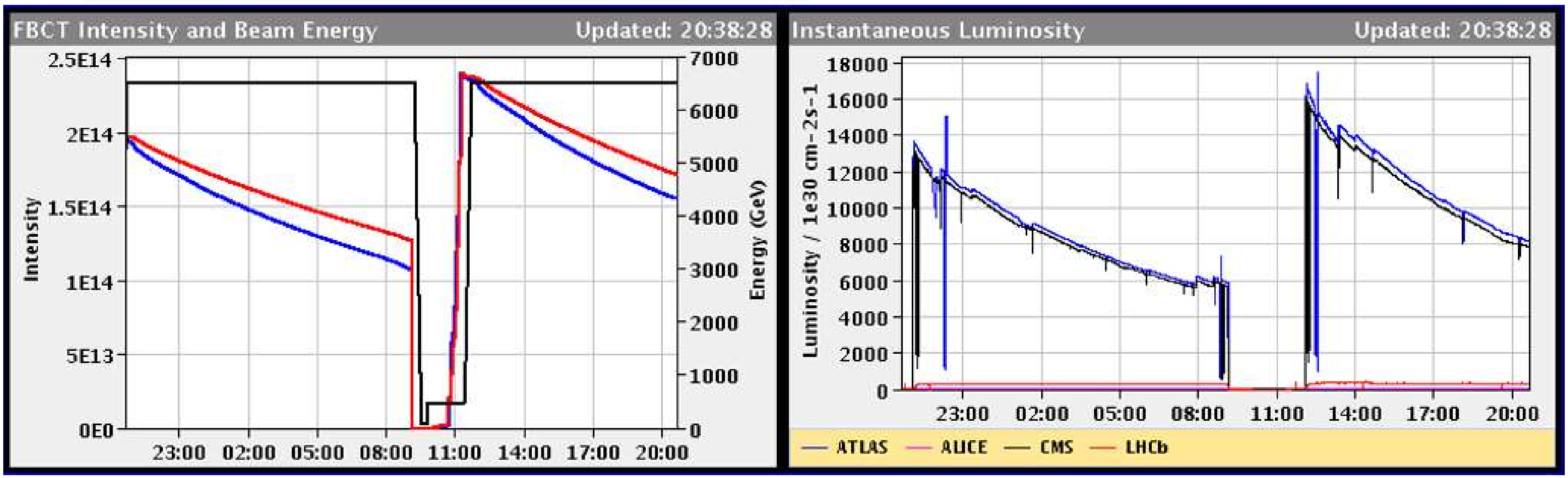
FIG. 3. Luminosities of particle colliders (triangles are lepton colliders and full circles are hadron colliders, adapted from [37]). Values are per collision point.

Luminosity Evolution

$$L = \gamma f_B \frac{N_1 N_2}{4\pi\beta^* \varepsilon} H(\sigma_s / \beta^*)$$

- Factors change in time: $L(t) = C \dfrac{N_1(t) N_2(t)}{\varepsilon(t)} H(t)$
- Therefore, in the absence of cooling the lifetime

$$\tau_L^{-1} = \frac{dL(t)}{L(t)dt} = \tau_{N1}^{-1} + \tau_{N2}^{-1} - \tau_\varepsilon^{-1} + \tau_H^{-1}$$

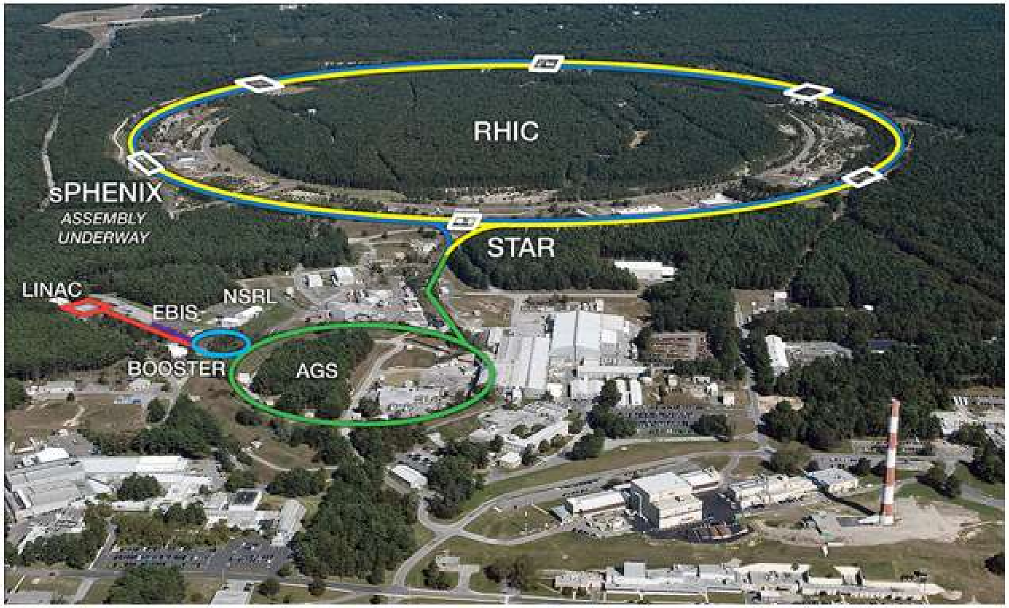


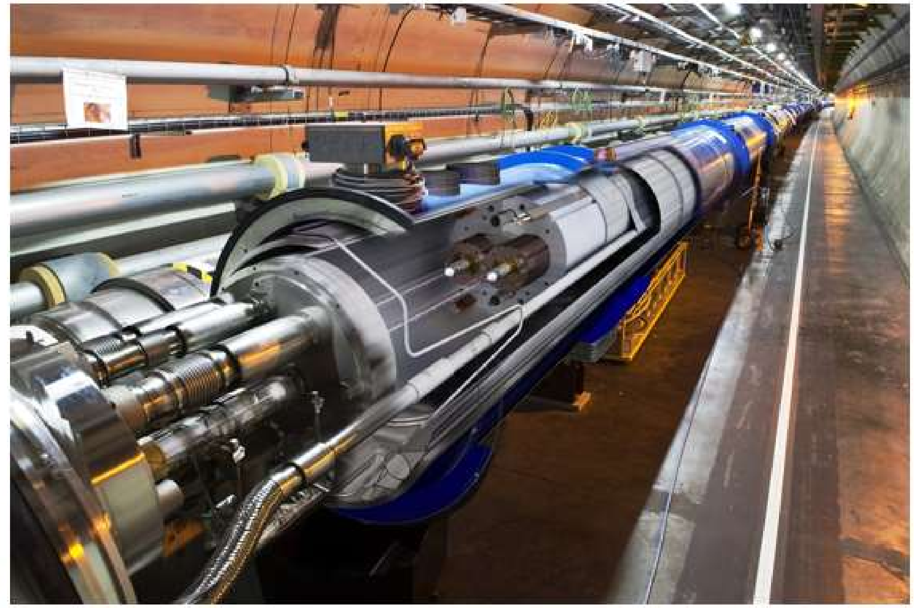
LHC luminosity plot

Colliders : Most Important Topics/Effects

- Engineering of magnets, RF, Power supplies, vacuum, particle sources, targets, diagnostics, collimators, etc
  - Exciting science: new acceleration techniques/plasma
- Beam physics (incomplete list)
  - One particle: beam optics, long-term stability, resonances, losses, noises, diffusion/emittance growth, etc
  - One beam: instabilities, synchrotron radiation, beam-induced radiation deposition, intrabeam scattering, cooling, space-charge effects and compensation
  - Two-beams: beam-beam effects and compensation, beamstrahlung, machine-detector interface, etc
  - Beam cooling (electron, ionization, stochastic)
- Assuming particle physics interest -> choice of accelerator scheme depends on
  - Readiness, cost and power consumption vs E, L reach

Present Hadron Colliders





RHIC (BNL, Brookhaven)

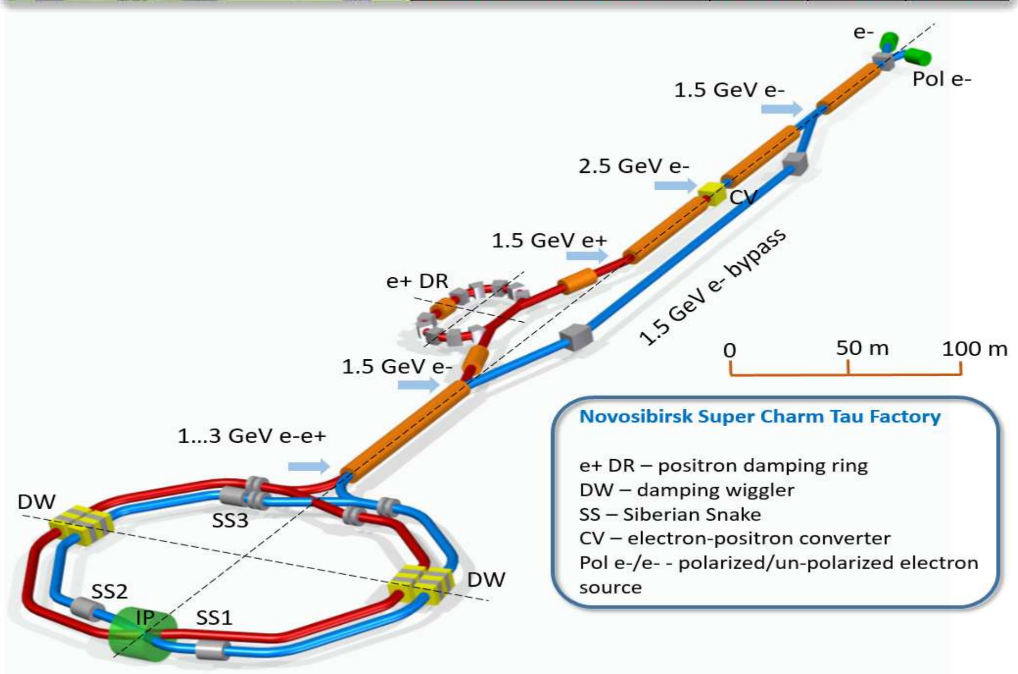
LHC (CERN)

- RHIC is our main competitor

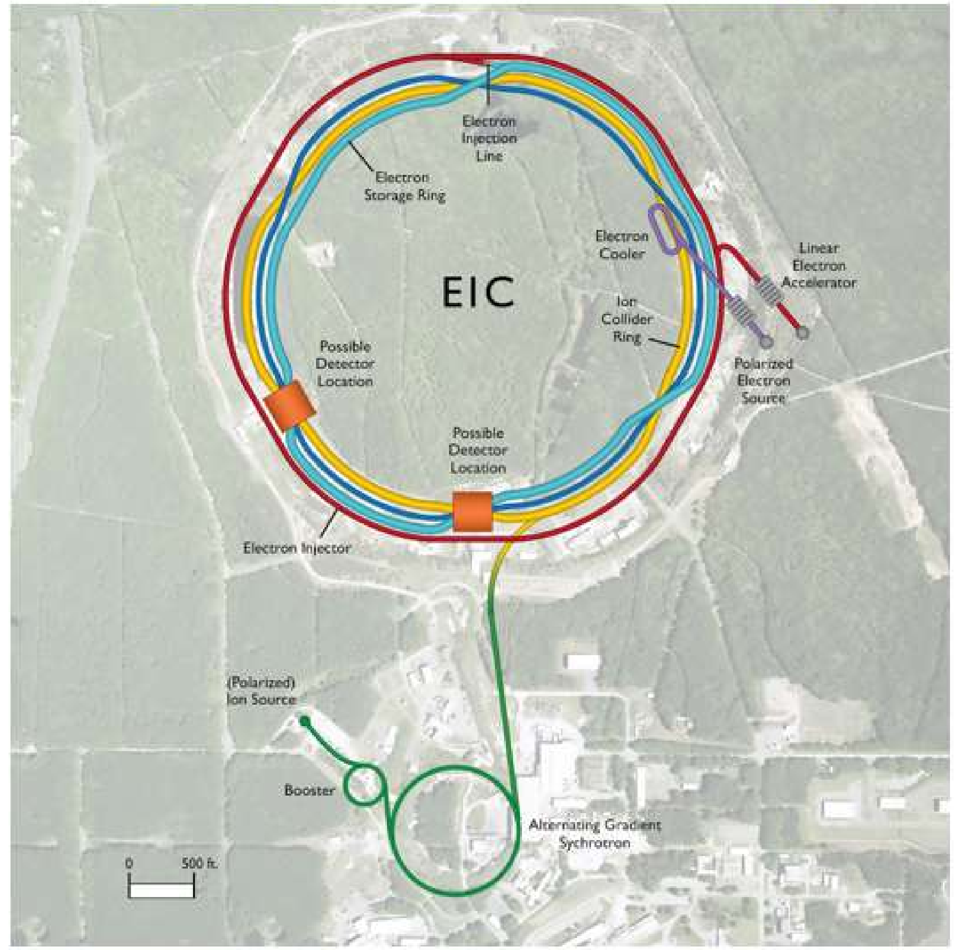
Colliders That Will Be

Main Parameters of The NICA Collider

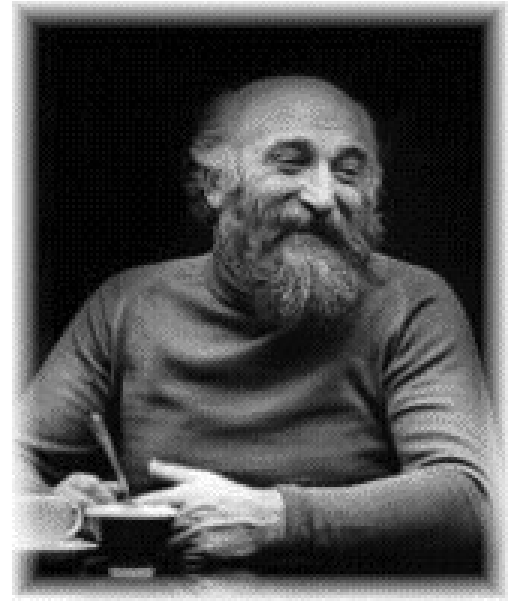
Circumference, m	503,04		
Bunch number per ring	22		
Mean-square bunch size, m	0.6		
Min. beta-function (β*), m	0.6		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch, 1e9	0.275	2.4	2.2
Peak luminosity, cm^{-2}·s^{-1}	0.9e25	0.9e27	6.3e27



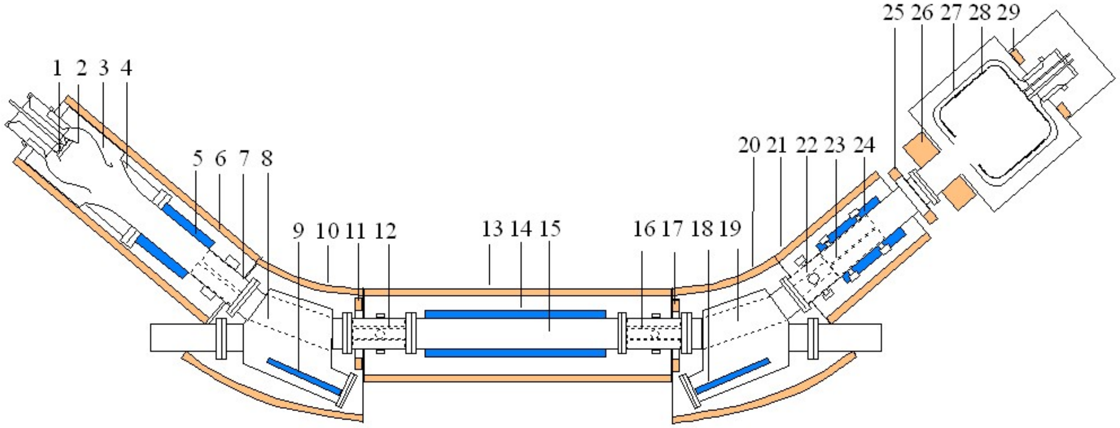
EIC (BNL, Brookhaven)

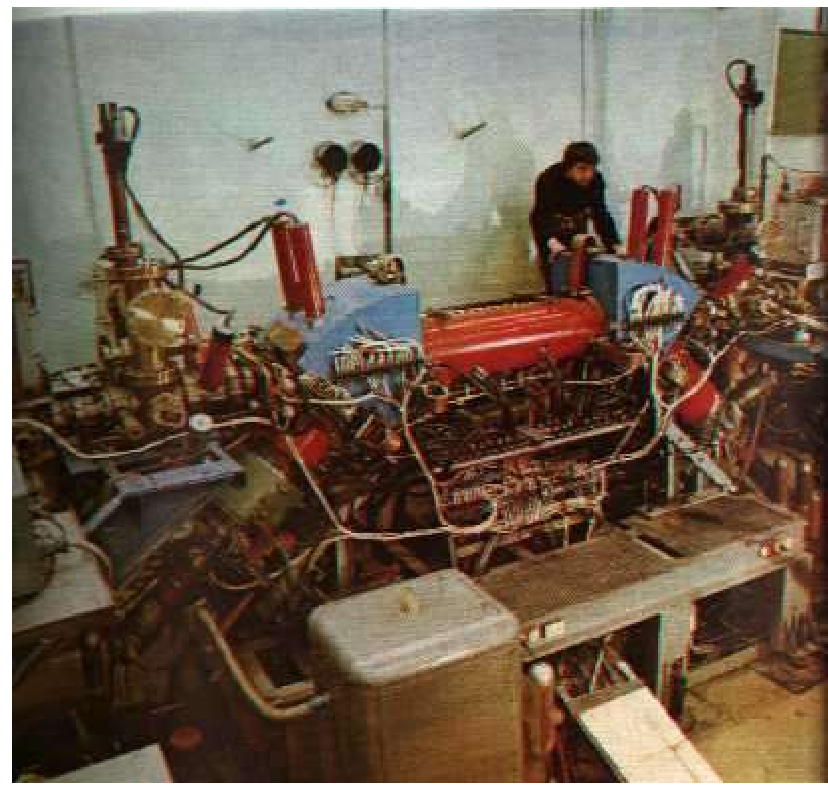


Electron cooling



- Invented in 1966 by A. M. Budker
  - In the beam frame - heavy particles come into equilibrium with electron gas
- Tested experimentally in BINP, Novosibirsk, in 1974-79 at NAP-M
  - 35 MeV electron beam (65 MeV per nucleon)
  - Magnetized electron cooling

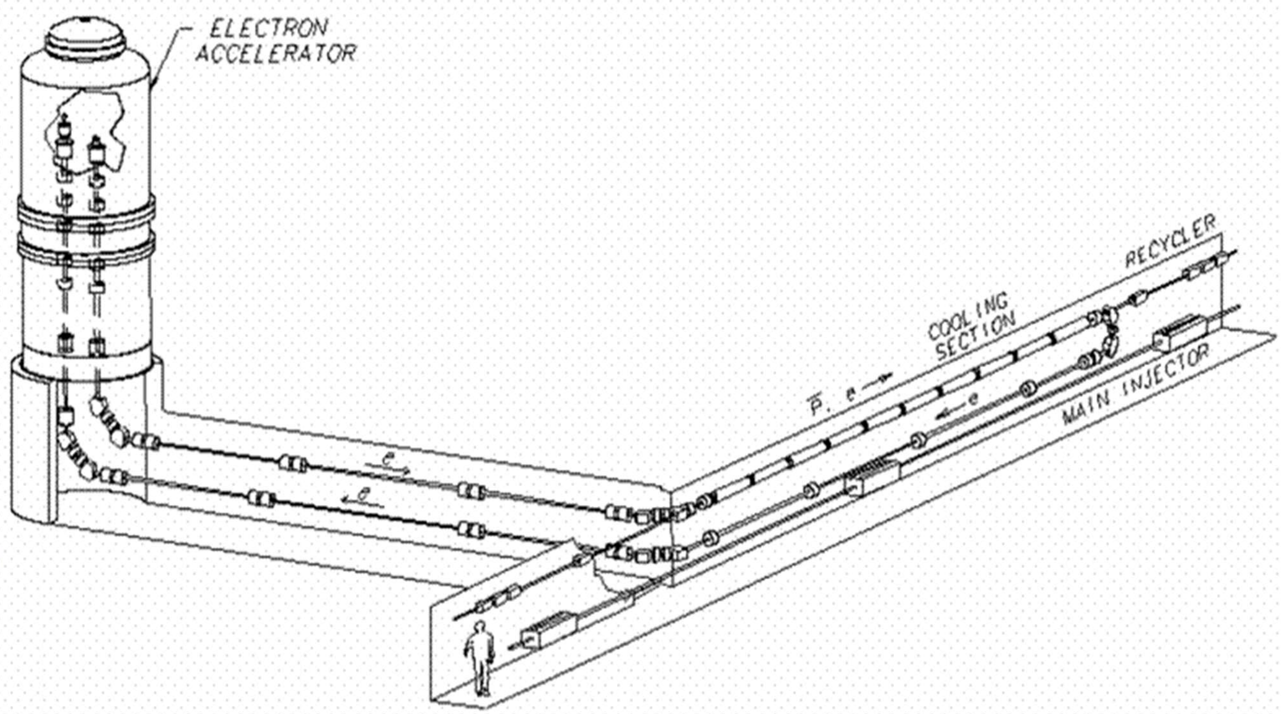




- Many installations since then, up to 300 kV electron beam (GSI, Darmstadt)
- FNAL 4.3 MeV cooler – next step in technology

Electron Cooling at FNAL (1)

- Fermilab made next step in the electron cooling technology
- Main Parameters
  - 4.34 MeV pelletron
  - 0.5 A DC electron beam with radius of about 4 mm
  - Magnetic field in the cooling section - 100 G
  - Interaction length – 20 m (out of 3319 m of Recycler circumference)



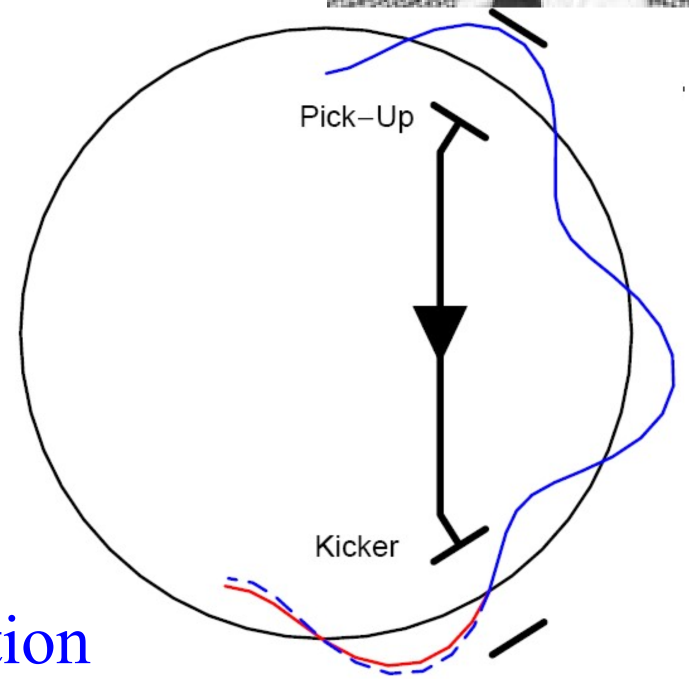
Stochastic Cooling

- Invented in 1969 by Simon van der Meer
- Naïve cooling model
  - 90 deg. between pickup and kicker

$$\delta\theta = -g\theta$$

Averaging over betatron oscillations yields

$$\delta\overline{\theta^2} = -\frac{1}{2}2g\overline{\theta^2} \equiv -g\overline{\theta^2}$$



- Adding noise of other particles yields

$$\delta\overline{\theta^2} = -g\overline{\theta^2} + N_{sample}g^2\overline{\theta^2} \equiv -\left(g - N_{sample}g^2\right)\overline{\theta^2}$$

- That yields

$$\delta\overline{\theta^2} = -\frac{1}{2}g_{opt}\overline{\theta^2} \quad , \quad g_{opt} = \frac{1}{2N_{sample}} \quad , \quad N_{sample} \approx N\frac{f_0}{W}$$

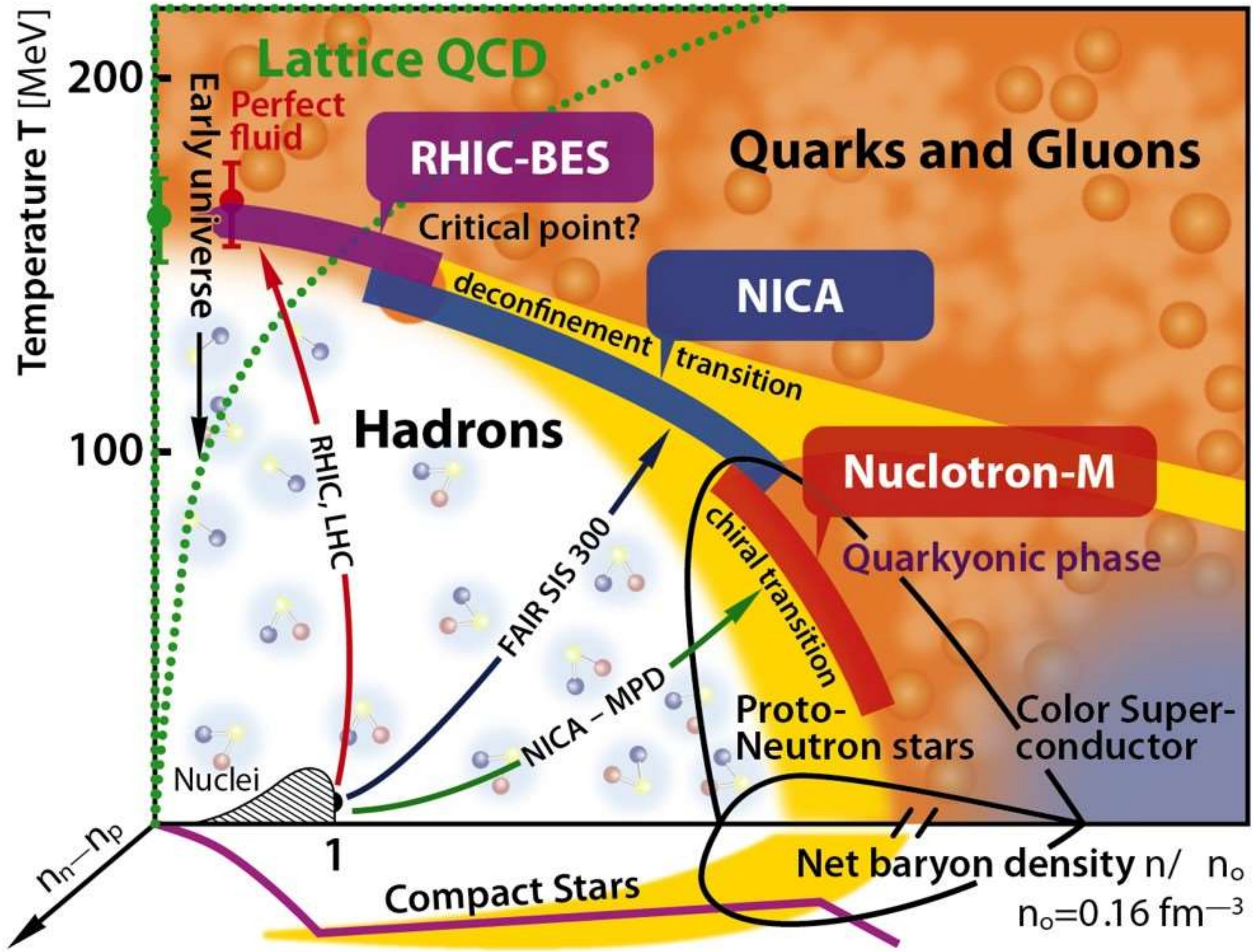
- In accurate analytical theory the cooling process is described by Fokker-Planck equation
  - The theory is built on the same principle as plasma theory – which is a perturbation theory (large number of particles in the Debye sphere versus large number of particles in the sample

NICA – the First Hadron Collider in Russia

Major Questions in High Energy Physics

- The Standard Model doesn't explain:
  - why the Higgs boson exists.
  - why the Higgs boson has the mass that it does. The Higgs turned out to be much less massive than predicted (a quadrillion times)
- We did not find a way how add gravity to the Standard model.
- Where did all the antimatter go after the big bang?
  - Known CP violation does not look sufficient
- Why lepton number is not conserved in neutrino oscillations?
  - Neutrino mass = 0 in standard model
- Is neutrino and antineutrino the same particle?
- What are the dark matter and dark energy?
  - WIMPs, axions
- Does the supersymmetry exist?
- …
- LHC has been dominating the high energy physics for more than a decade; and it will continue to dominate in feasible future

Major Questions in Nuclear Physics



- How do quarks and gluons give rise to the properties of strongly interacting particles?
- How does the structure of nuclei emerge from nuclear forces?
- What physics lies beyond the Standard Model?
- What are the phases of strongly interacting matter, and what roles do they play in the cosmos?
- Spin structure of the proton/deuteron (g-factor)

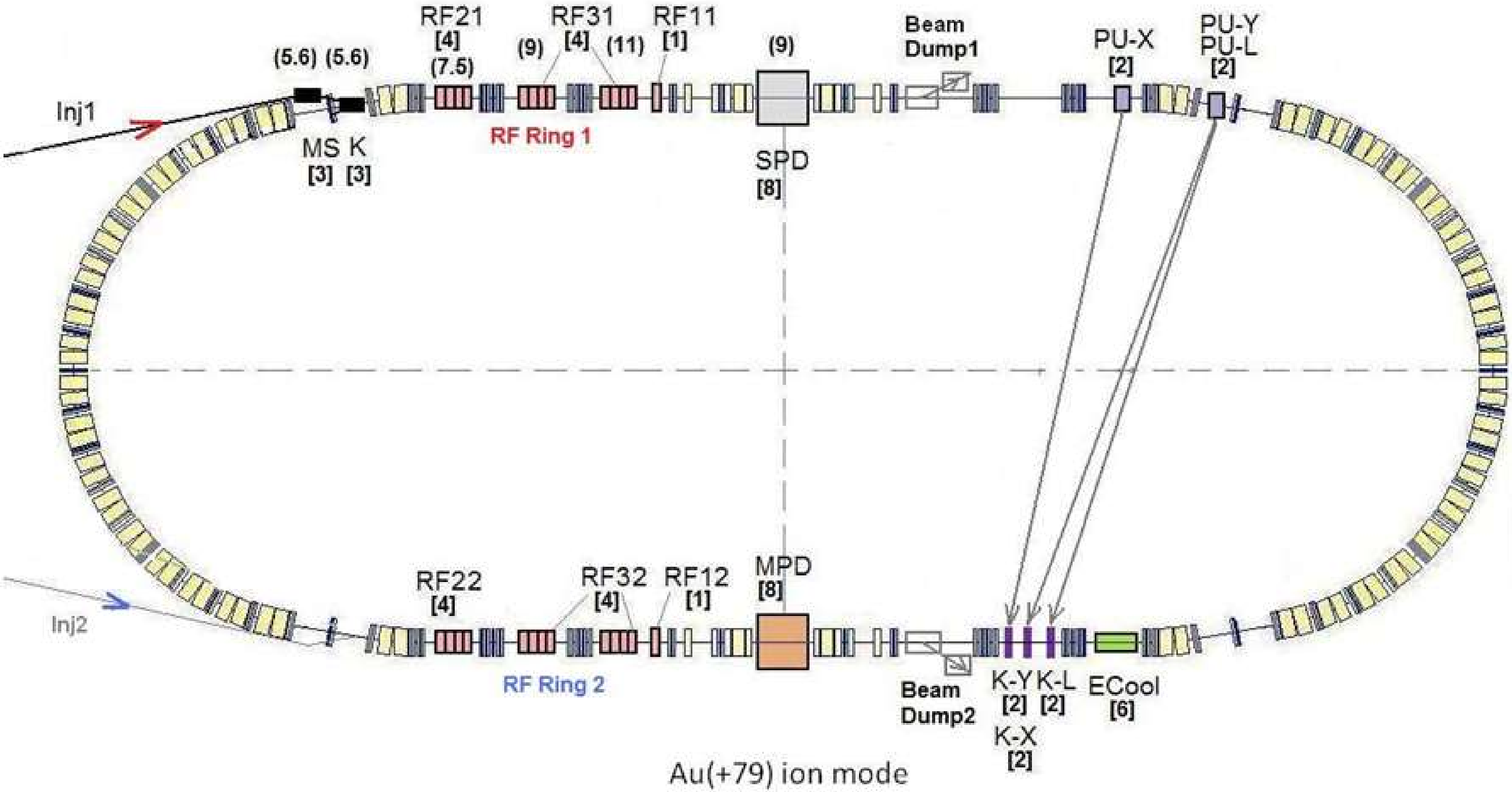
Why NICA?

- NICA is built to answer the last 2 questions
- Unique niche
  - Two major competitors (LHC & RHIC) have too large energy to get to the ultimate luminosity in the interesting region of low energy of few GeV/n
- From accelerator physics point of view NICA has complete set of problems/technologies present in modern hadron colliders
  - Ultrahigh vacuum
  - Superconducting magnets
  - Large beam current results in beam instabilities
    - ⇨ Feedback systems for suppression of instabilities
  - Low-beta optics brings dynamic aperture limitations
    - Careful design of machine optics, optical measurements and correction
  - Electron and stochastic cooling at collisions
  - Instrumentation and controls required for modern colliders
  - …

NICA Layout

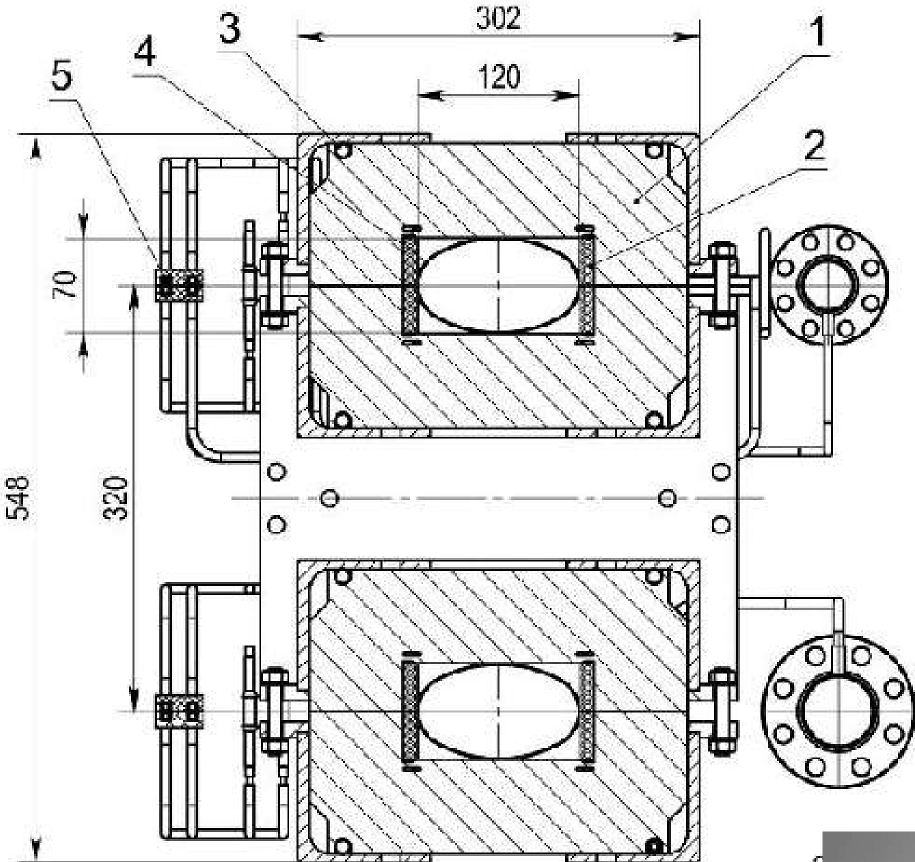
- Initial operation: Bi-Bi collisions
- The second stage (5-10 years later): collisions of polarized protons/deuterons (spin structure)

Scheme of the collider ring



Two rings: one above another

Collision energy in the ion mode: 2·(1.5 ÷4.5) GeV/n



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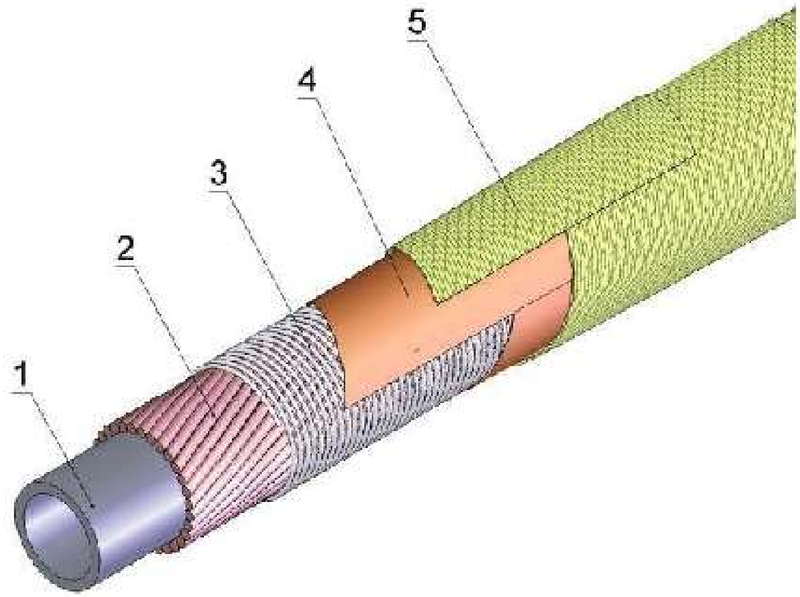

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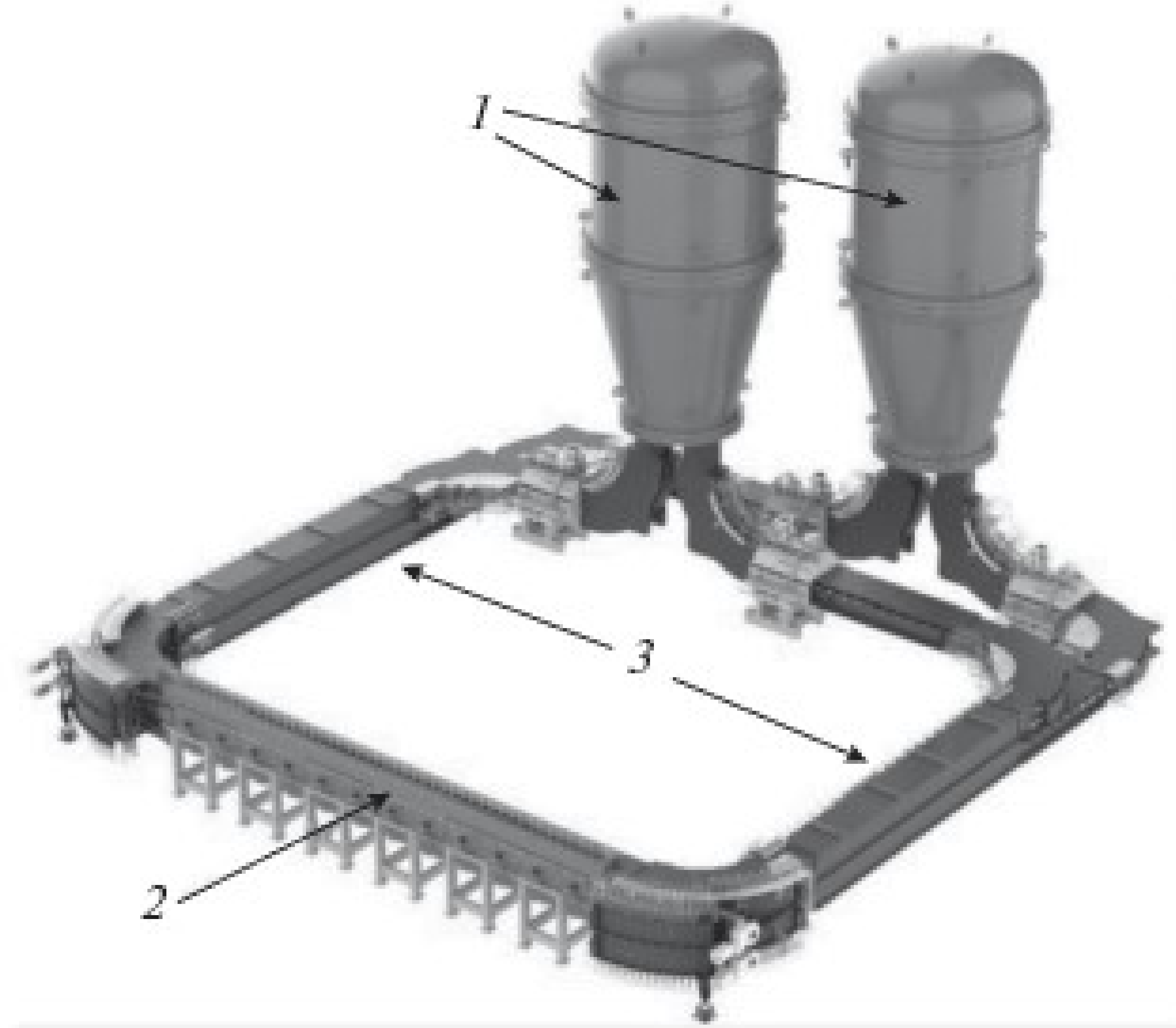
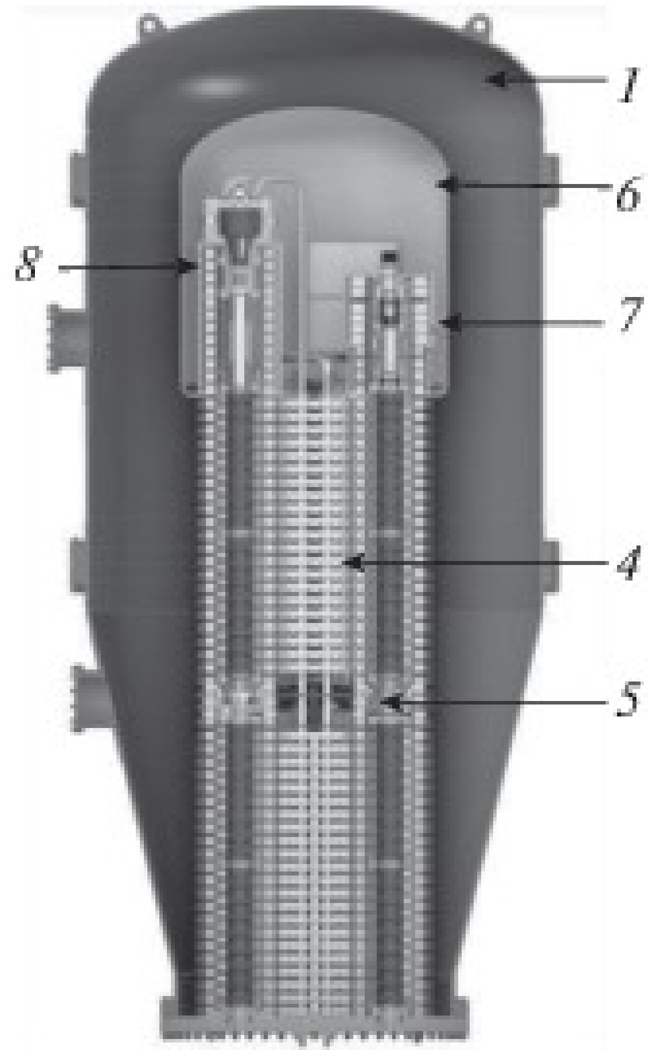
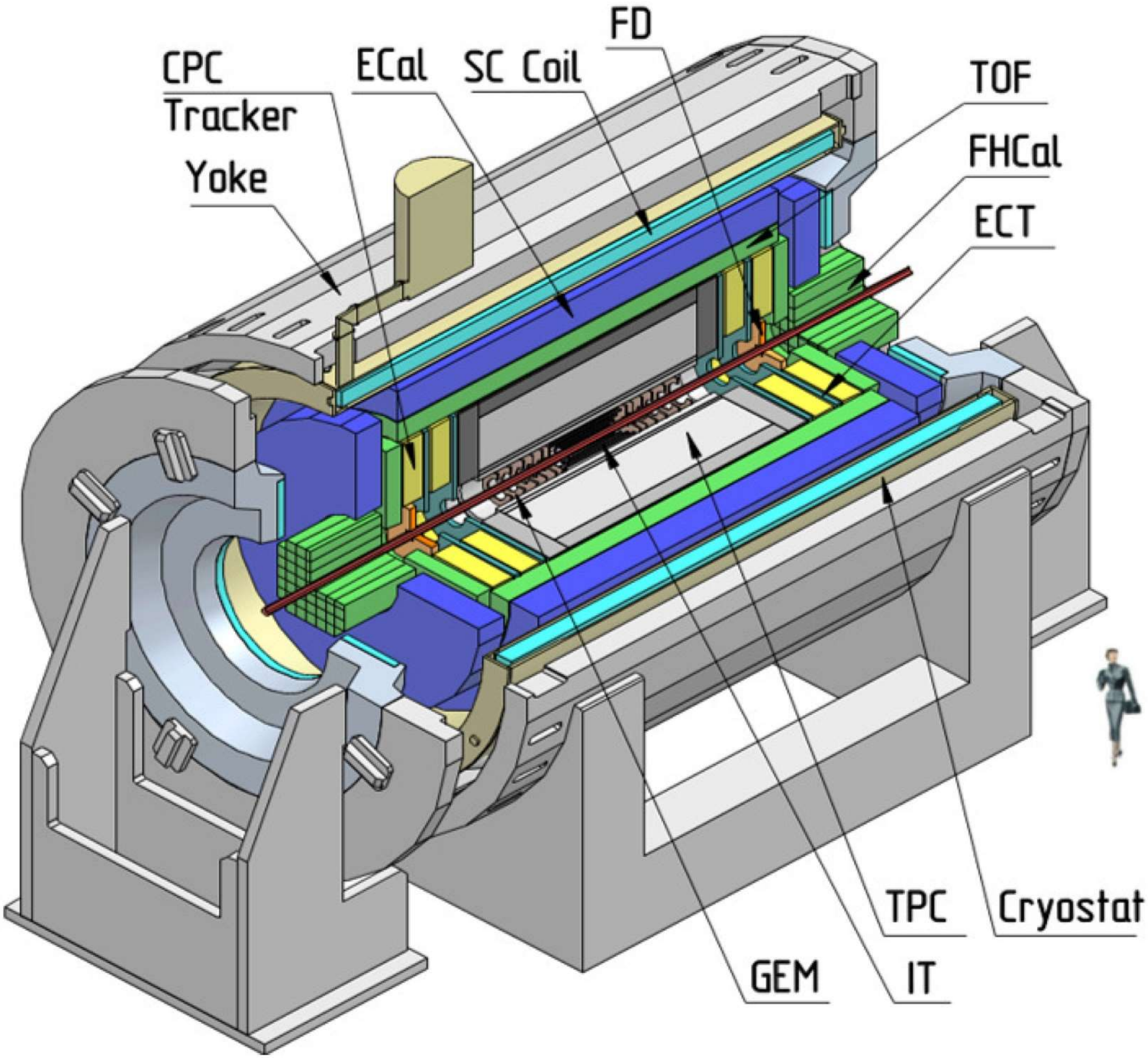
Colliders: NICA and its Accelerator Technologie

Collider Electron Cooler





Detector MPD



Questions