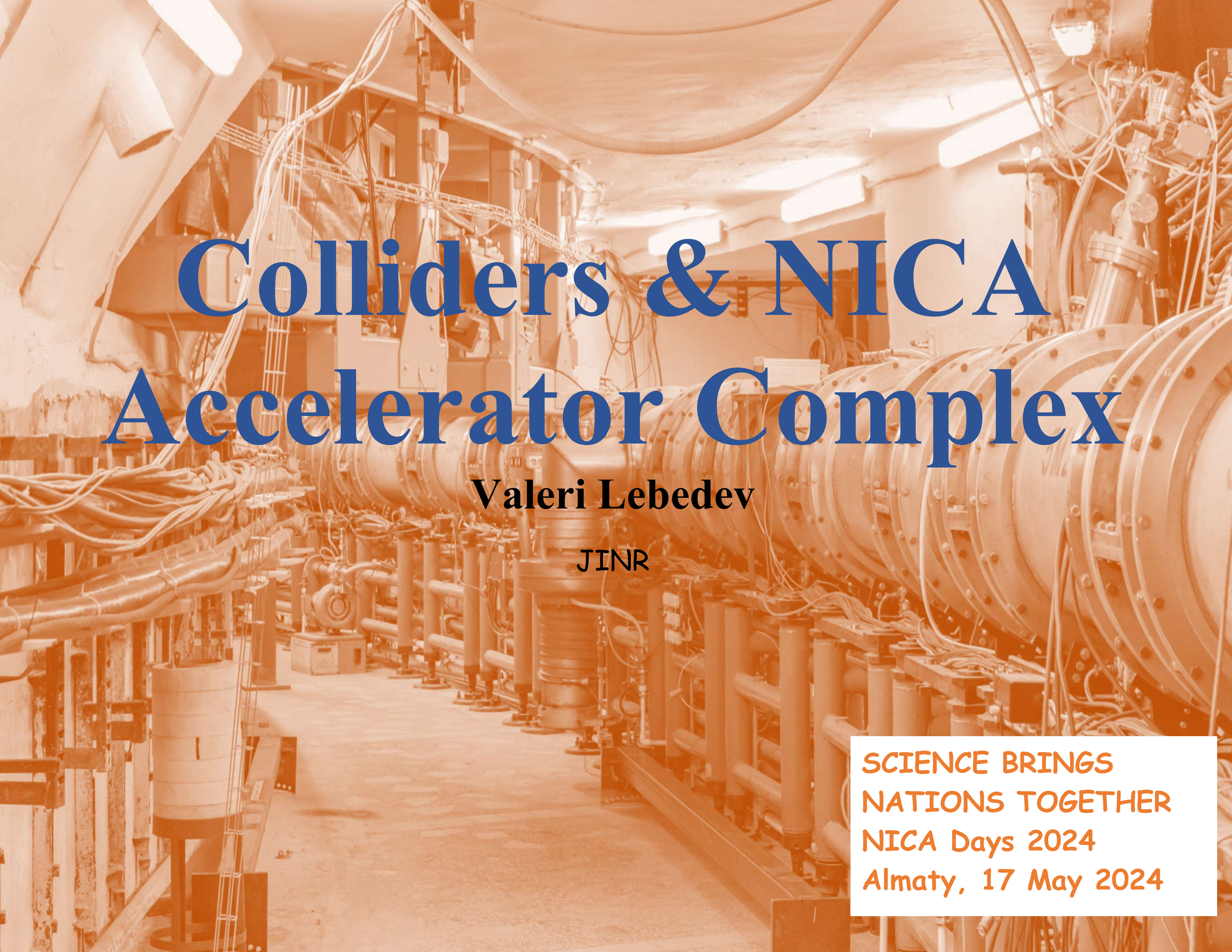


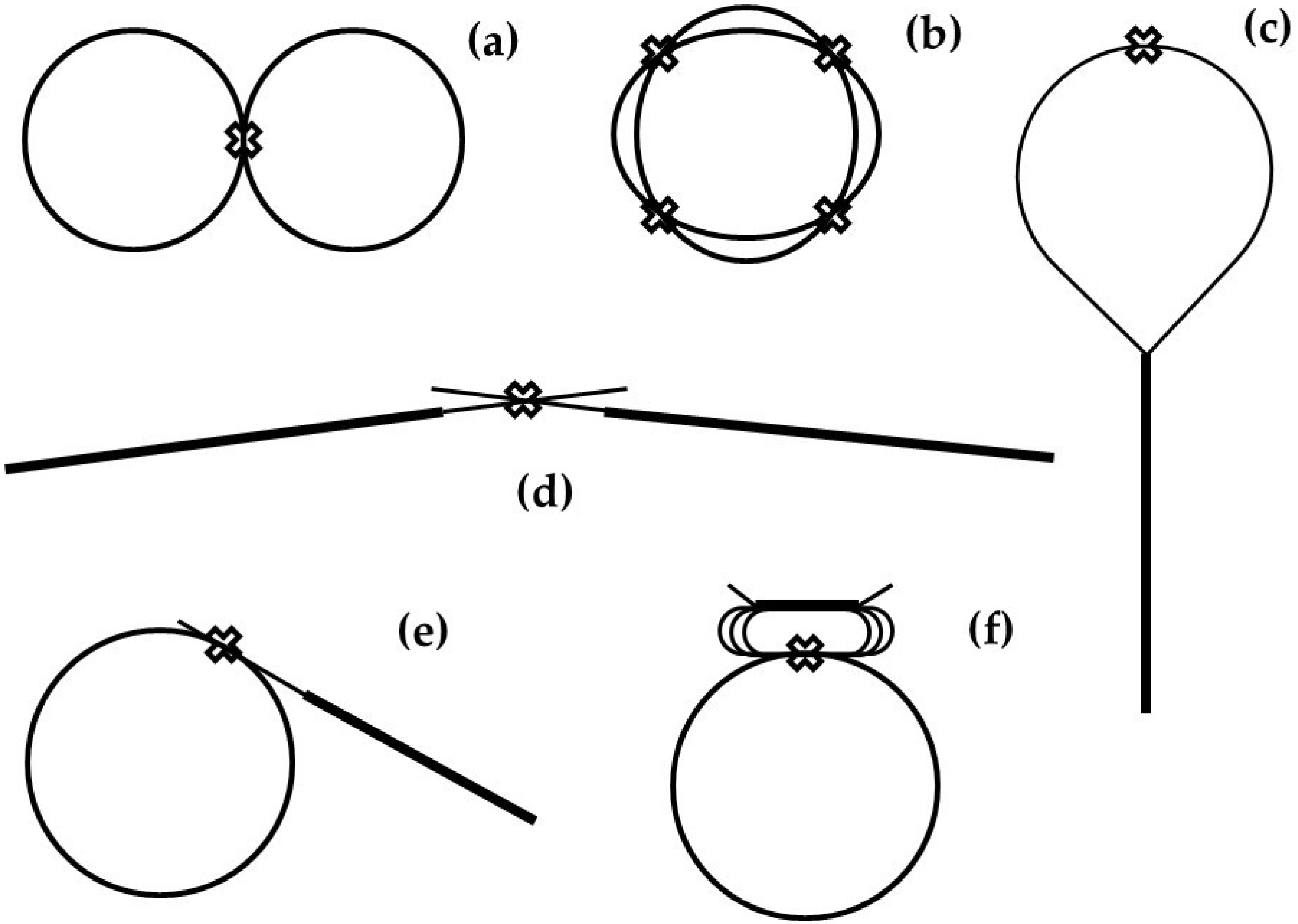
Colliders & NICA Accelerator Complex

Valeri Lebedev

JINR

SCIENCE BRINGS
NATIONS TOGETHER
NICA Days 2024
Almaty, 17 May 2024

Types of Colliding Beams Facilities



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

Collision Energy and Luminosity

- Collision energy
  - 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)

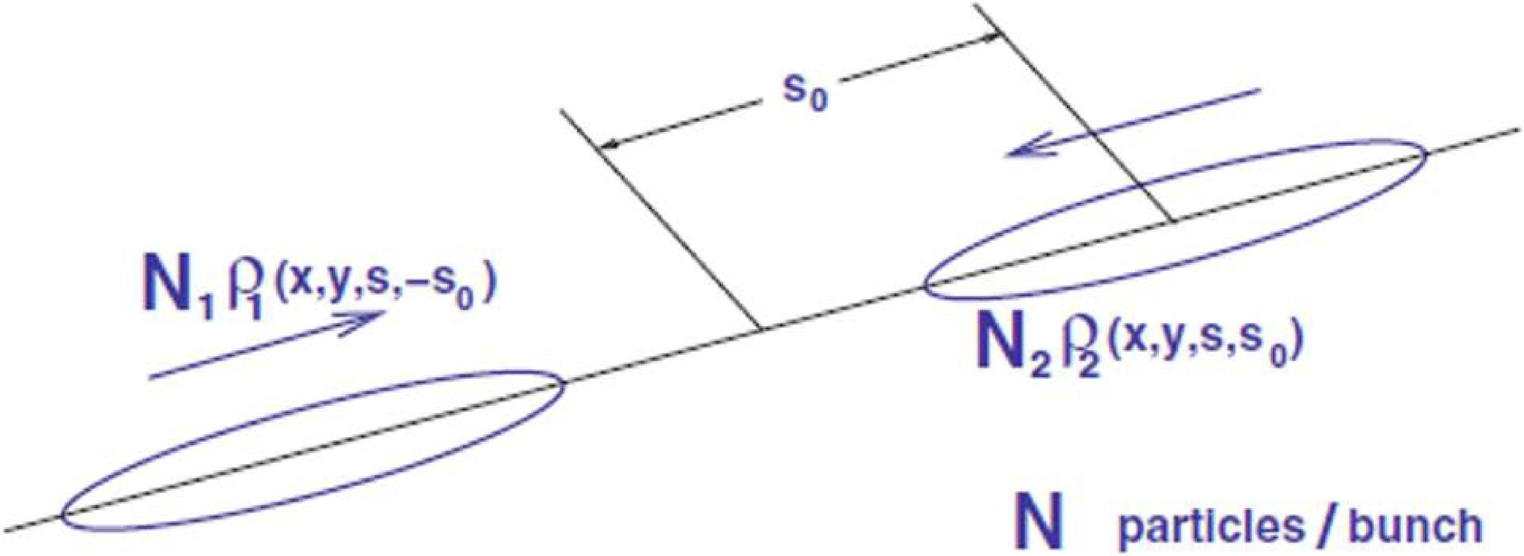
- Luminosity
  - Number of events in collisions:

$$\frac{dN_{\exp}}{dt} = L\sigma_{\exp}$$

    - The total cross section for Higgs boson production at the LHC operating at **s=13 TeV** is 43 pb = $5\cdot10^{-35}$ cm^2.
      ⇒ At luminosity of 10^{34} cm^{-2}s^{-1} the LHC makes 1 Higgs every 2 s
  - Higgs discovery potential: Tevatron versus LHC: $(E/E)^4(L/L)=6^4 30\approx4\cdot10^4$
  - <u>Particle physics detectors want constant luminosity!</u>

Luminosity

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



N particles / bunch

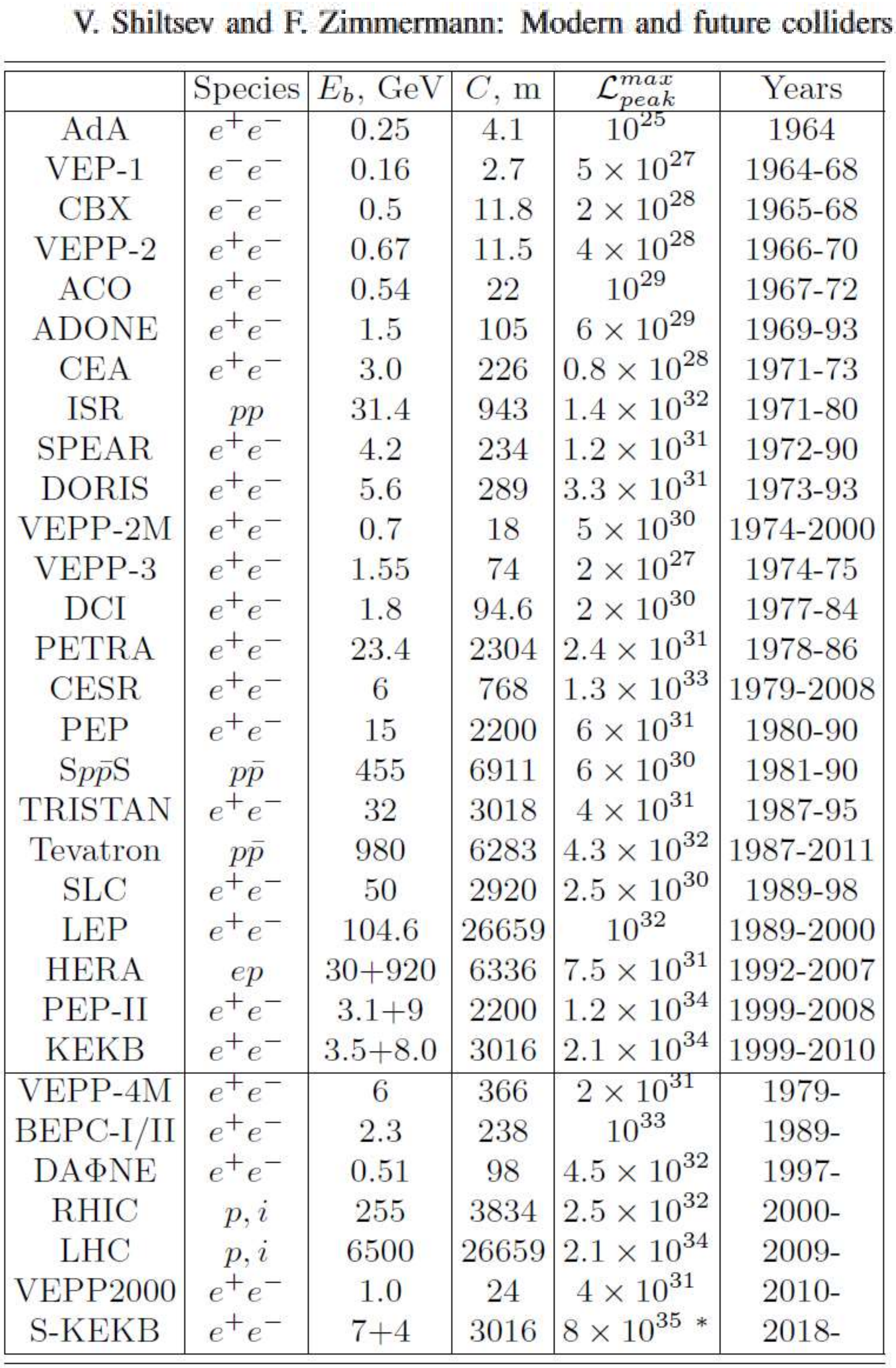
ρ density ≠ const.

For (same size) Gaussian bunches:

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

Colliders Landscape

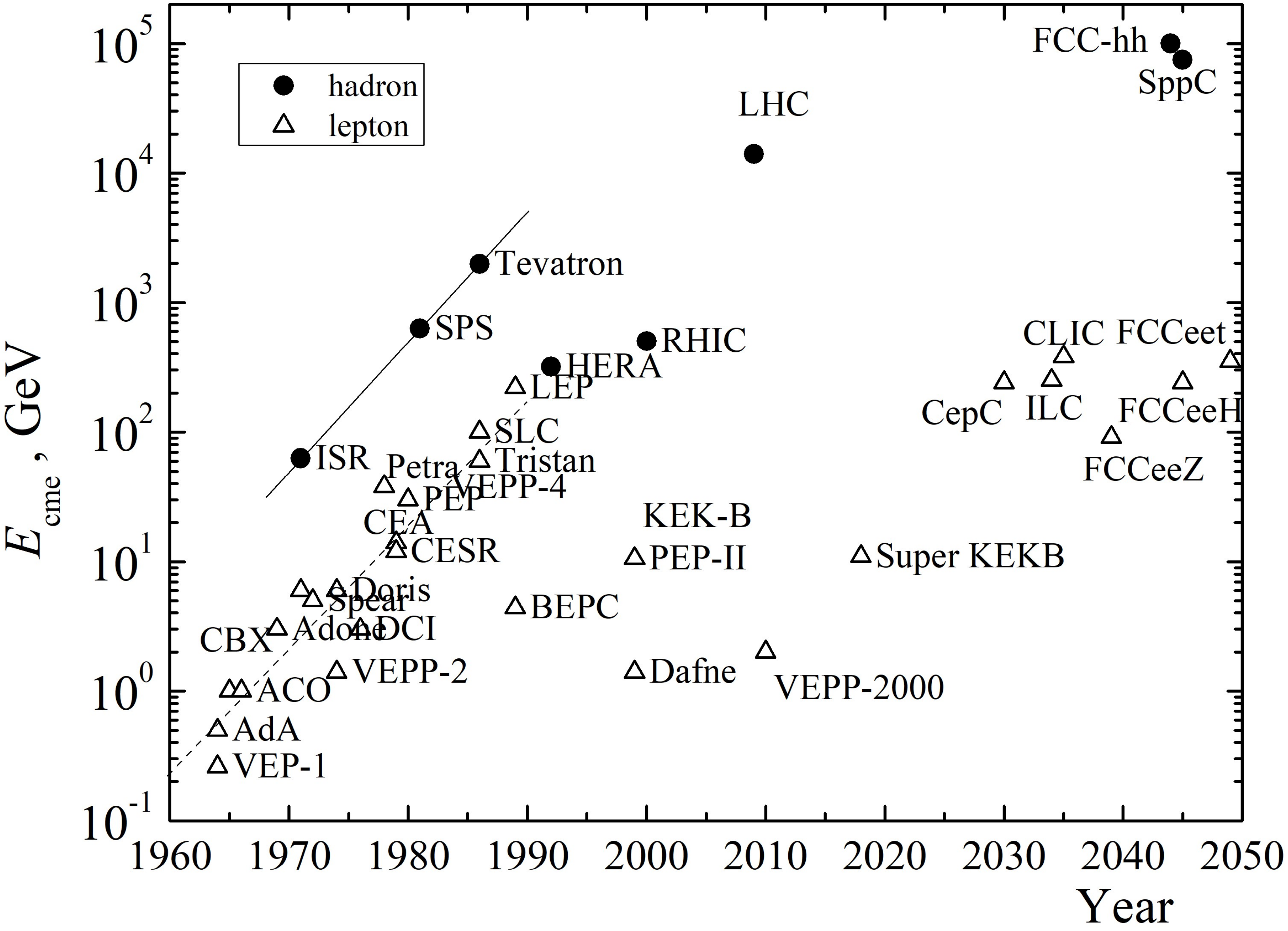
- 60 years since 1st collisions
  - Spring 1964 AdA and VEP-1
- 31 operated since
- 7 in operations now
  - S-KEKB, VEPP-2000, VEPP-4M, BEPC, DAFNE
  - LHC, RHIC
- 1 under construction
  - NICA (JINR)
- One in a project phase
  - EIC (BNL)
- Far plans
  - Higgs/Electroweak factories
    - ILC
    - FCC: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



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

	Species	E_b, GeV	C, m	$\mathcal{L}_{peak}^{max}$	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



Colliders: Luminosity

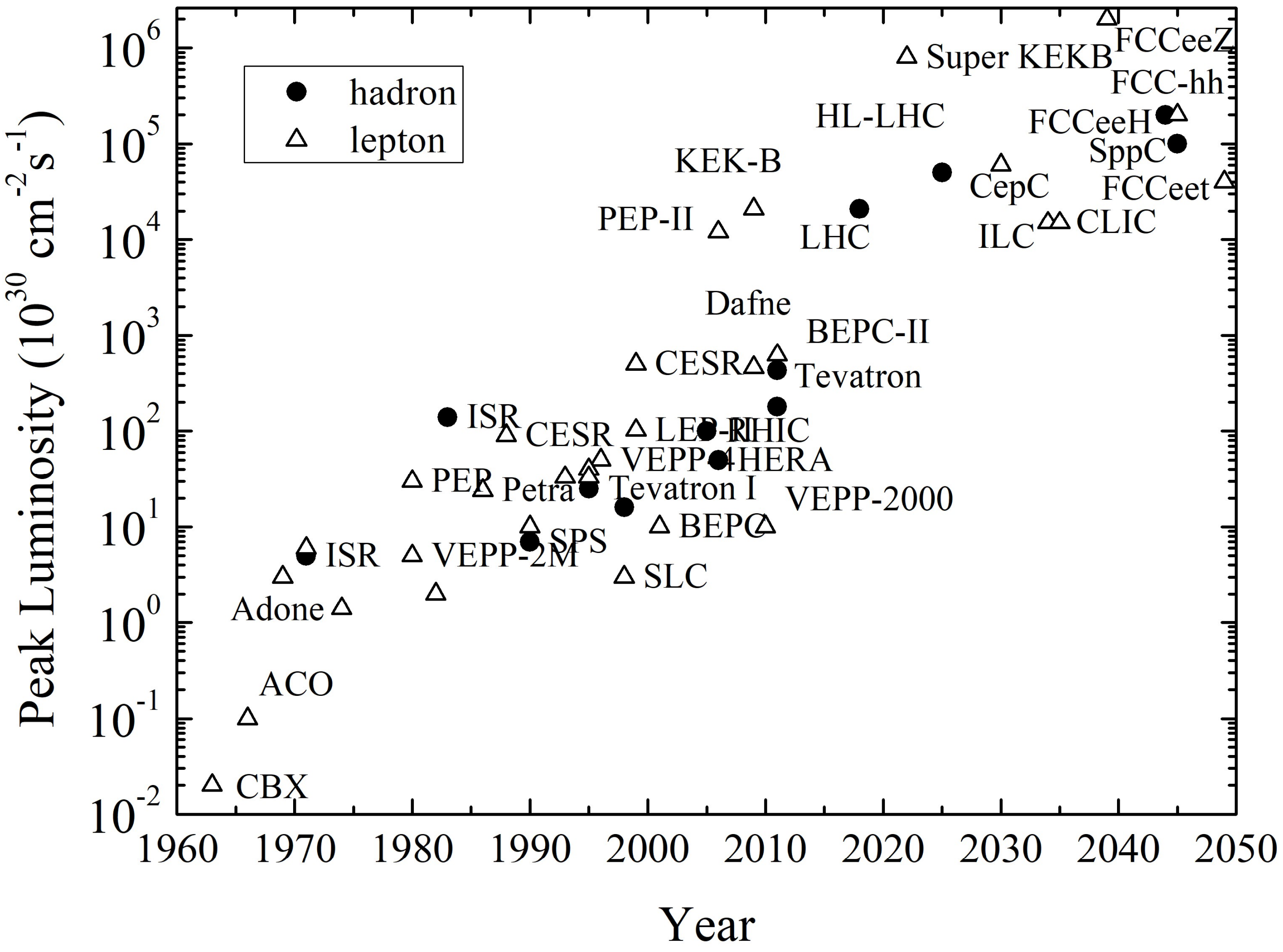
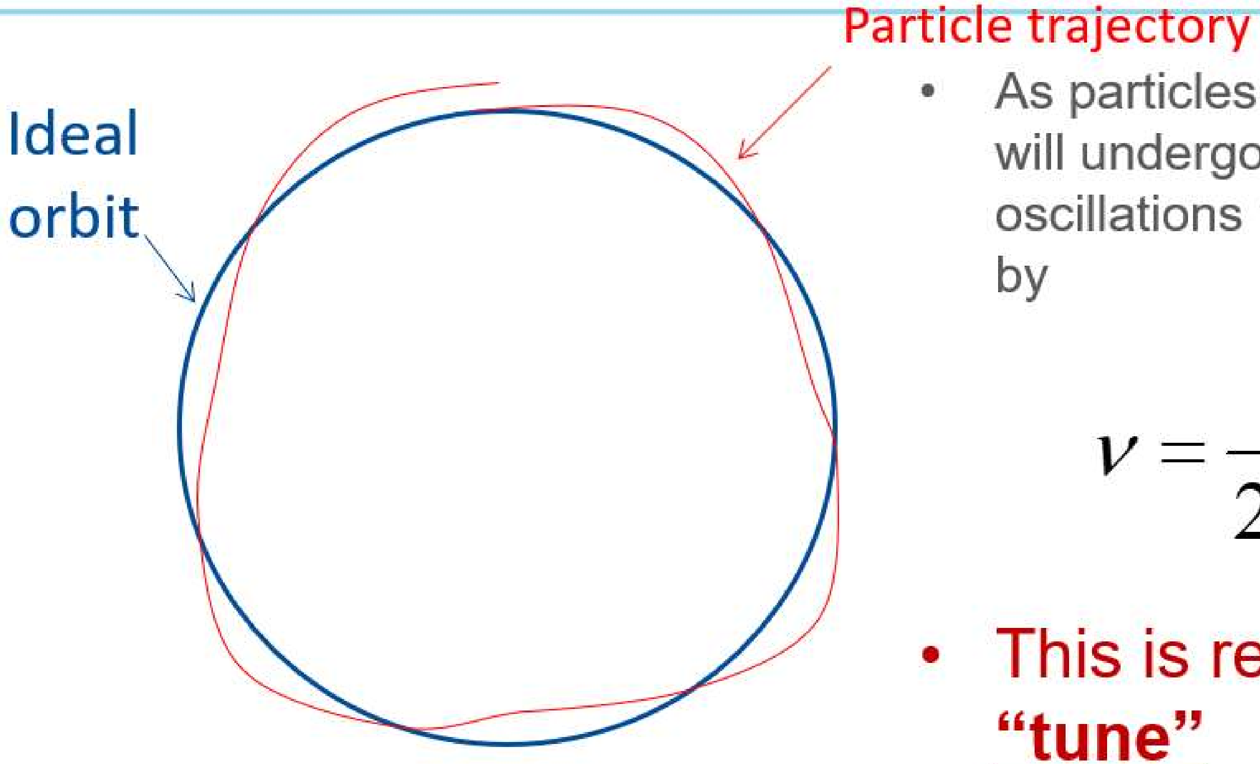


FIG. 3. Luminosities of particle colliders (triangles are lepton colliders and full circles are hadron colliders, adapted from [37]). Values are per collision point.

Some Basic Concepts of Accelerator Physics

Betatron Oscillations, Tune



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

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

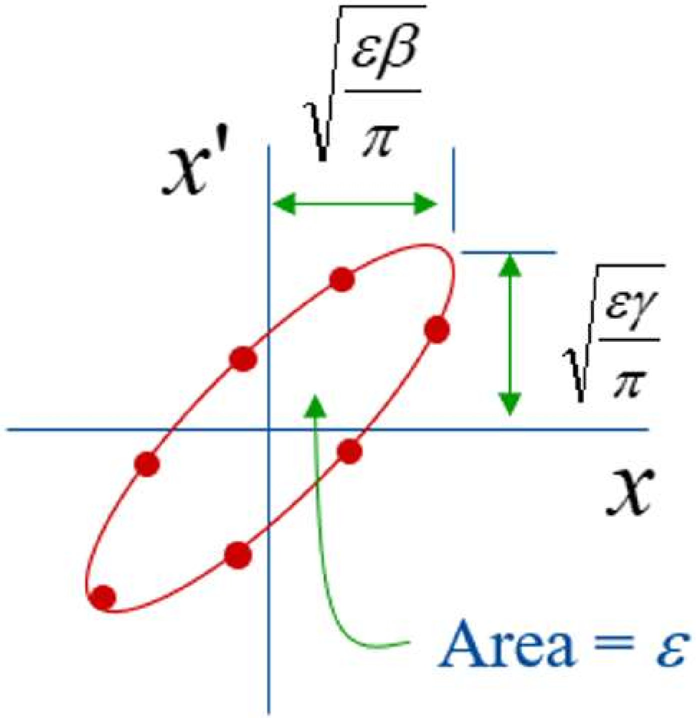
- This is referred to as the **"tune"**

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

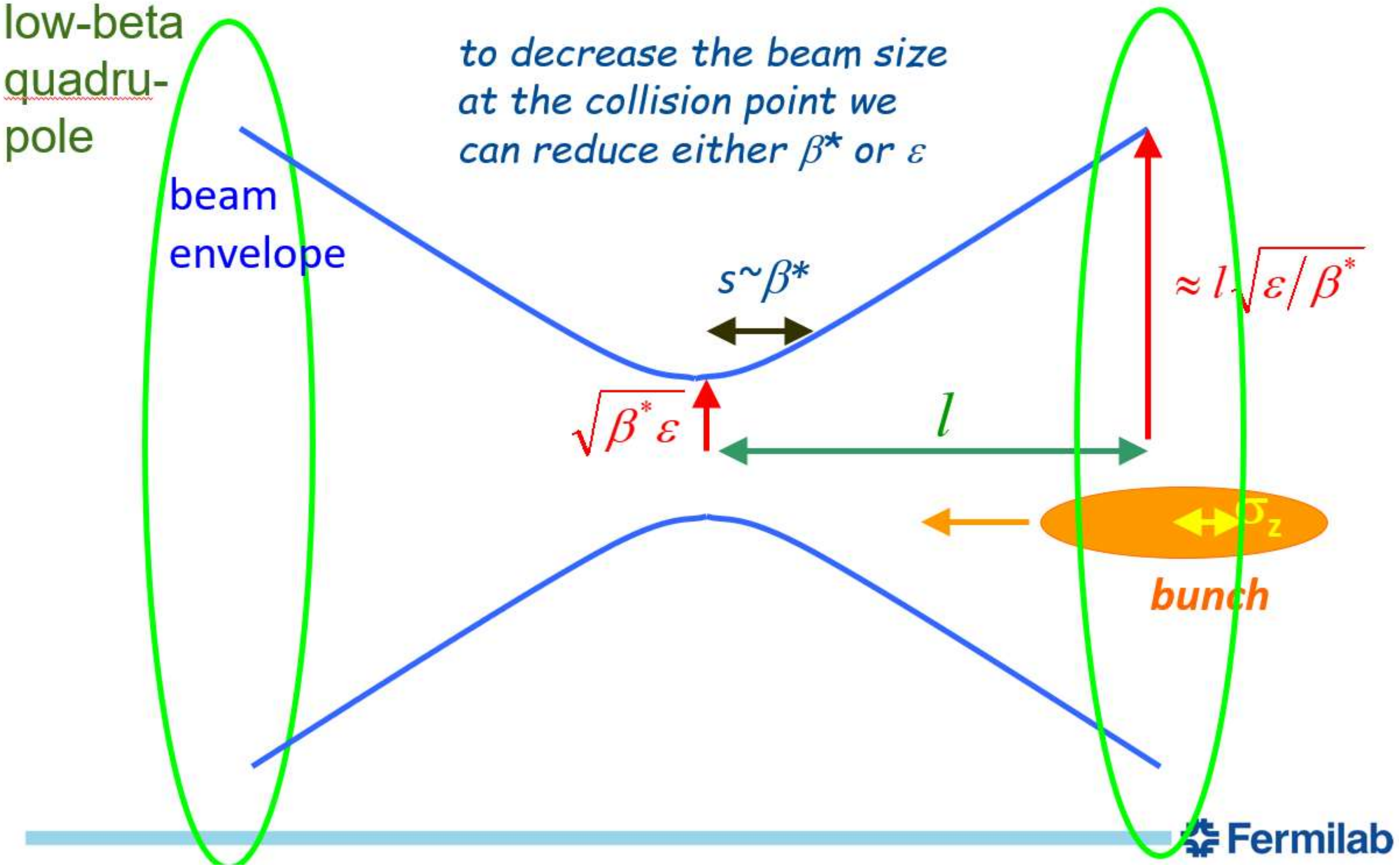
Integer : magnet/aperture optimization → **64.31** ← **Fraction: Beam Stability**

Emittance

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



Collider Spot Size

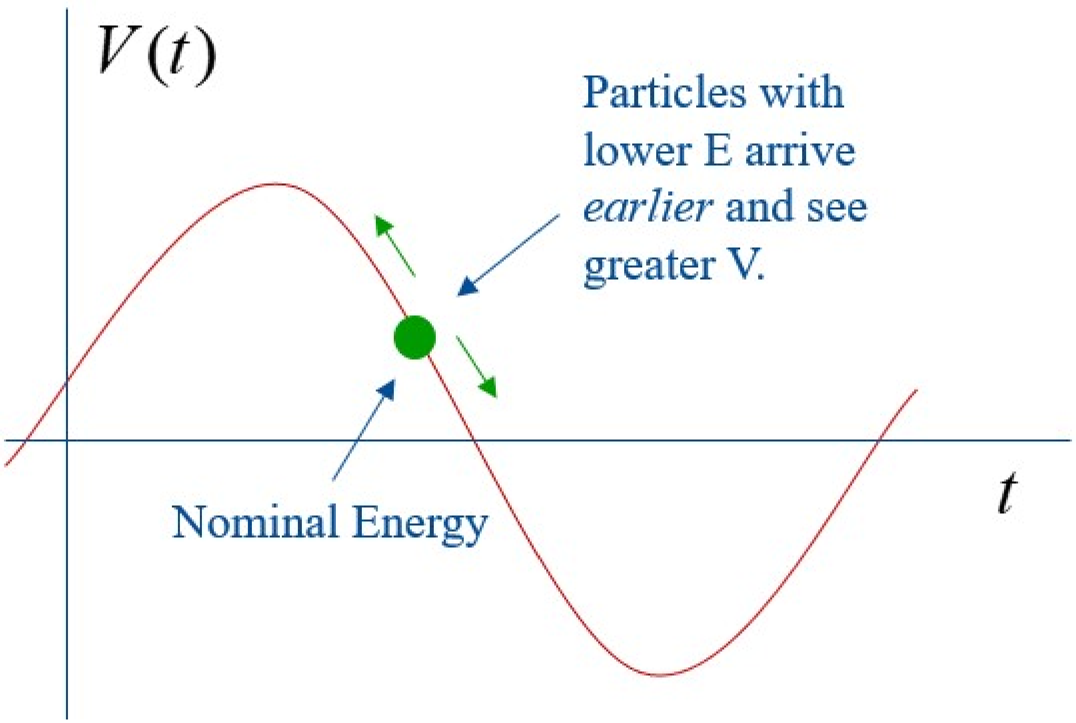


to decrease the beam size at the collision point we can reduce either β^* or ε

- β^* must be equal or 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 mostly on the energy deviation relative to “the reference (central) particle”



Betatron Tune Shift due to Beam Space Charge

- Dependence of betatron tunes on the betatron amplitude results in that the tunes of some particles stay at non-linear resonances
  - ♦ Consequently, particle amplitudes grow resulting in the beam loss
  - ♦ SC effect is diminishing fast with beam energy

$$\begin{bmatrix}\delta\nu_{SC_X}\\ \delta\nu_{SCY}\end{bmatrix} = \frac{r_p Z^2 N_i}{2\pi A\beta^2\gamma^3}\frac{C}{\sqrt{2\pi}\sigma_s}\left\langle \frac{1}{\left(\sigma_x+\sigma_y\right)}\begin{bmatrix}\beta_x/\sigma_x\\ \beta_y/\sigma_y\end{bmatrix}\right\rangle_s , \quad \sigma_{x,y}=\sqrt{\beta_{x,y}\varepsilon_{x,y}+\left(D_{x,y}\sigma_p\right)^2}$$

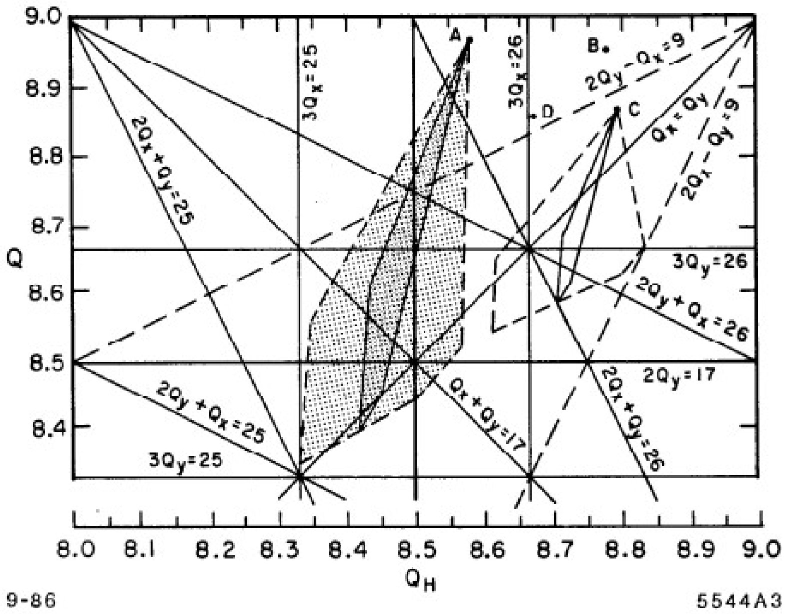


Fig. 3. Space charge tune shift of the AGS.

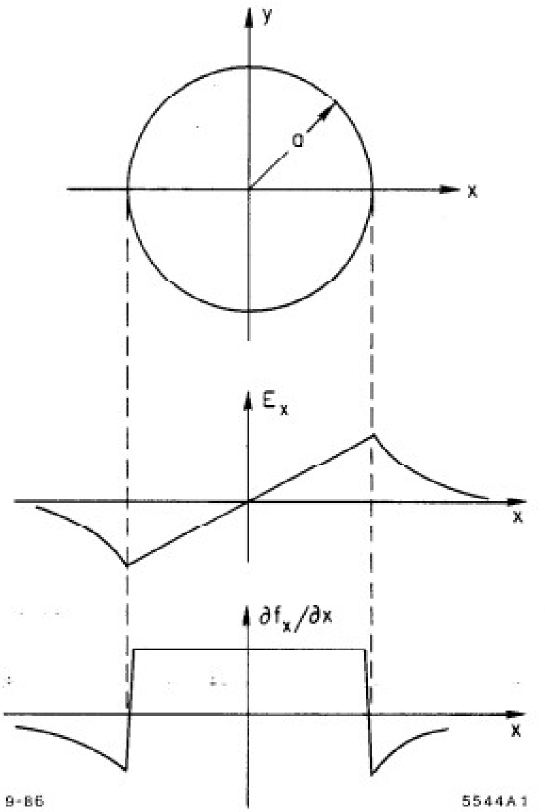


Fig. 1. Space Charge force of a uniform cylindrical beam.

- Beam magnetic field ~β^2, partially compensates electric field, $1-\beta^2=1/\gamma^2$

Beam-beam Effects

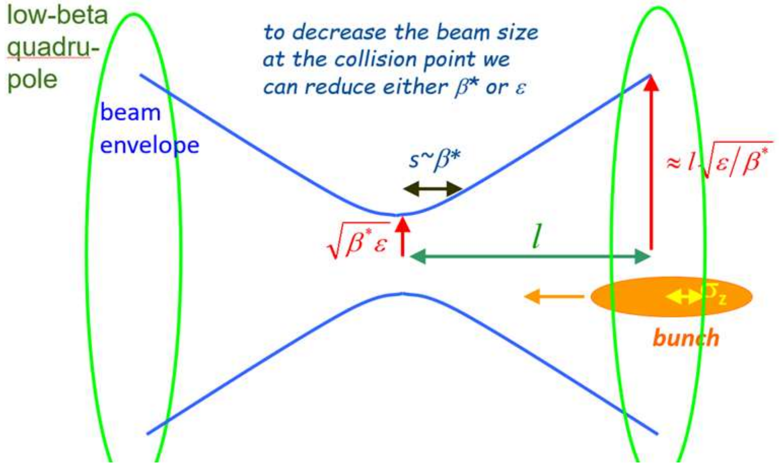
- The beam-beam tune shift is similar to the space charge tune shift but is engaged in the IPs only. The tune shift per IP:

$$\begin{bmatrix} \delta\nu_{BB_X} \\ \delta\nu_{BB_y} \end{bmatrix} = \frac{r_p Z^2 N_i}{4\pi A\beta^2\gamma}\frac{1+\beta^2}{\left(\sigma_x+\sigma_y\right)}\begin{bmatrix} \beta_x^*/\sigma_x \\ \beta_y^*/\sigma_y \end{bmatrix}, \quad \sigma_{x,y} = \sqrt{\beta_{x,y}^{\ *}\varepsilon_{x,y} + \left(D_{x,y}^*\sigma_p\right)^2}$$

For round beam

$$\delta\nu_{SC_X} = \frac{r_p Z^2 N_i}{8\pi A\beta^2\gamma}\frac{1+\beta^2}{\varepsilon}$$

  - Magnetic field of counter rotating beam almost doubles force, $1+\beta^2$
  - Note that for large synchrotron amplitude the tune shift increase due to larger beta-function with longitudinal displacement is compensated by decrease of space charge field
    => no dependance on bunch length



to decrease the beam size at the collision point we can reduce either β* or ε

- Smaller β^* yields larger β-function and beam size in quads

$$\beta(s) = \beta^* + s^2/\beta^*$$

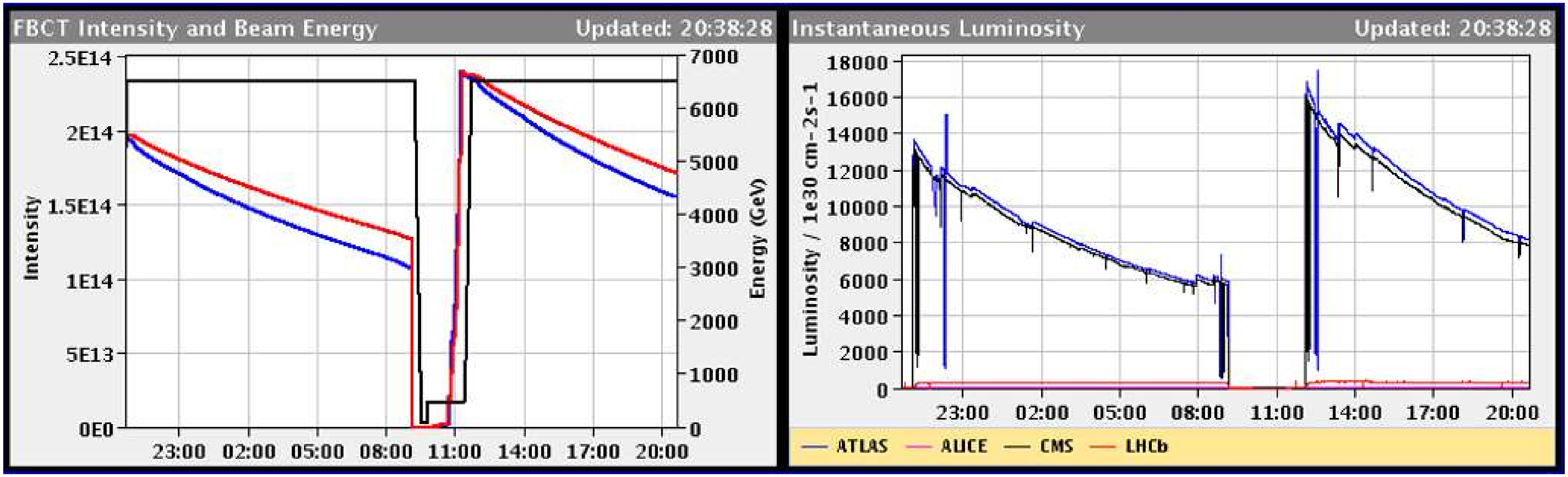
Luminosity Evolution

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

- 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

Electrons versus Protons

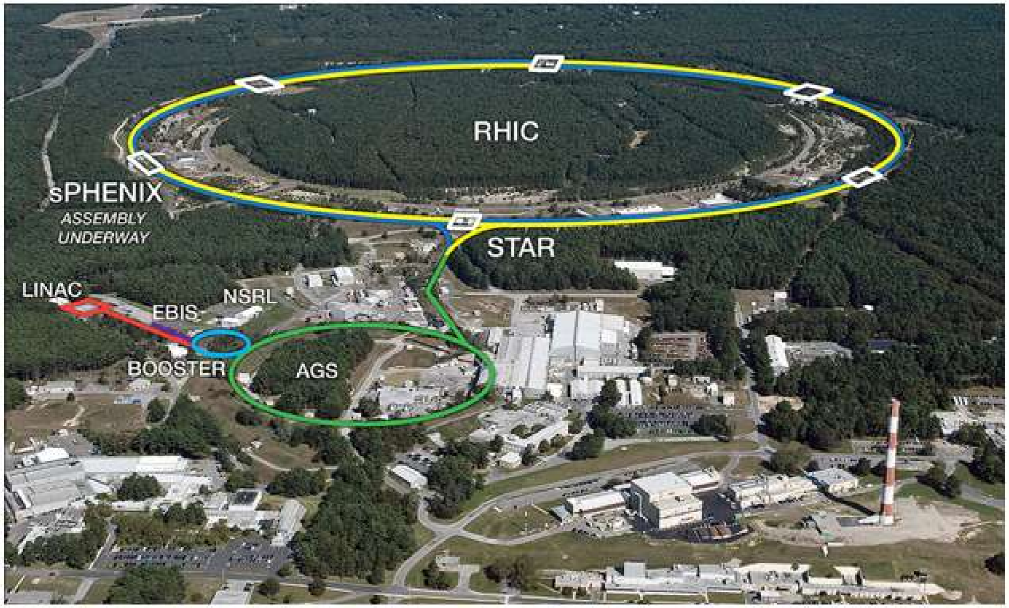
- Electrons
  - (+) Point-like objects
    => the entire energy may go to creation of a particle-of-interest
  - (+) Well-determined energy
    => better resolution; in particular, for narrow resonances
  - (+) Smaller backgrounds
    => Easier to separate events from backgrounds => less expensive detector
  - (-) Energy is limited by SR ($dE/dt \propto E^4$)
    - In LEP (LHC tunnel, C=26.7 km) operating at E=104 GeV
      the beam was losing 3% of its energy per turn
- Protons (Hadrons)
  - (-) Large nuclear cross sections => large background
  - (-) Quarks carry out a fraction of energy
    => effective energy = ~1/6 of total (LHC may create particles with $\sqrt{s} \le 2$ GeV)
  - (-) Wide PDF (parton distribution function) => poor knowledge of initial energy of collisions
  - (++) May operate at very high energy: LHC - E_{max}(protons)=6.8 TeV
  - (+) Much larger cross sections for creation of hadrons. For creation of B-mesons the cross section in LHCB is ~4 order of magnitude higher than in KEKB

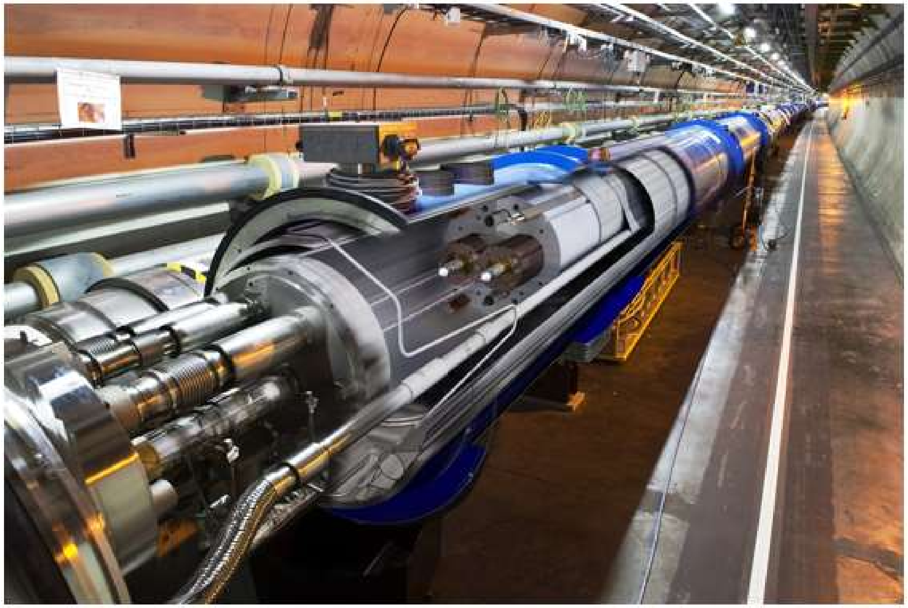
Electrons versus Protons (continue)

- Development of detector technology in the last ~50 years proved that in a proton collider a modern detector can deal with backgrounds even at luminosity few units of 10^{34} $cm^{-2}s^{-1}$
- If built, all other types of colliders have to be competitive to the proton colliders (i.e. to the LHC) in luminosity and/or energy

Present and Future Colliders

Present Hadron Colliders





RHIC (BNL, Brookhaven)

C=3.84 km,
E_{max}(protons)=255 GeV

- RHIC is our main competitor

LHC (CERN)

C=26.7 km,
E_{max}(protons)=6.8 TeV

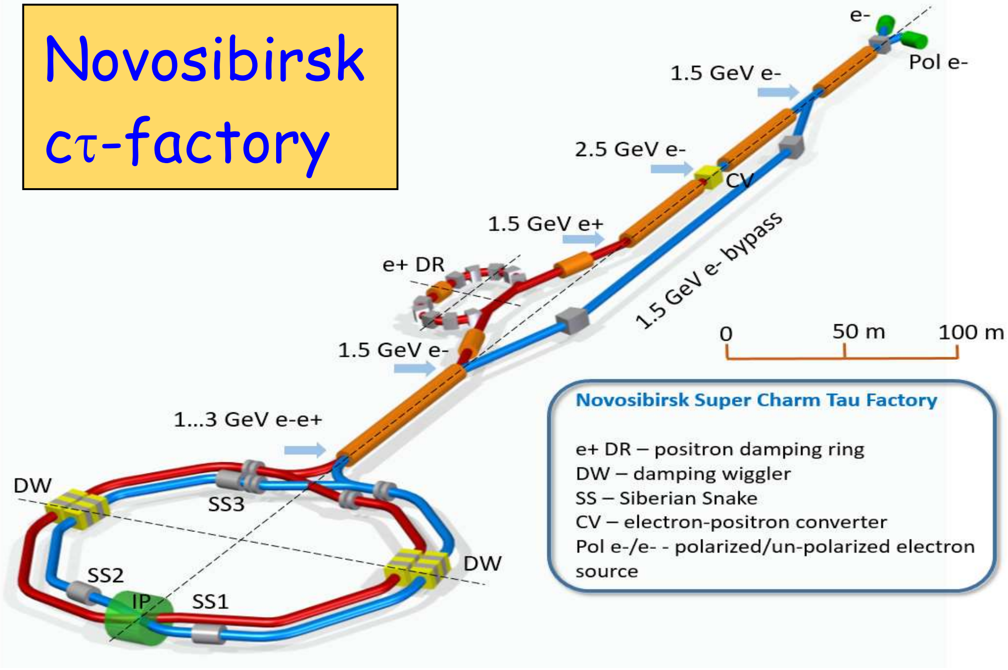
Colliders That Will Be

NICA (JINR, Dubna)

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

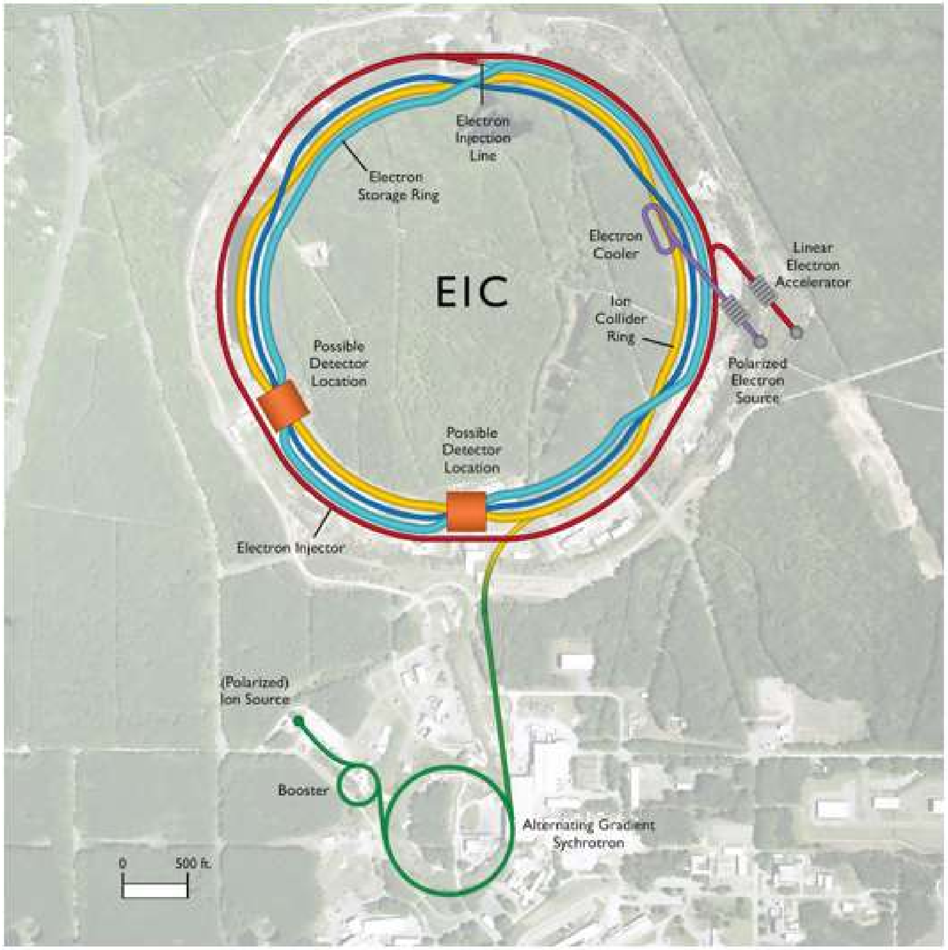
Novosibirsk cτ-factory



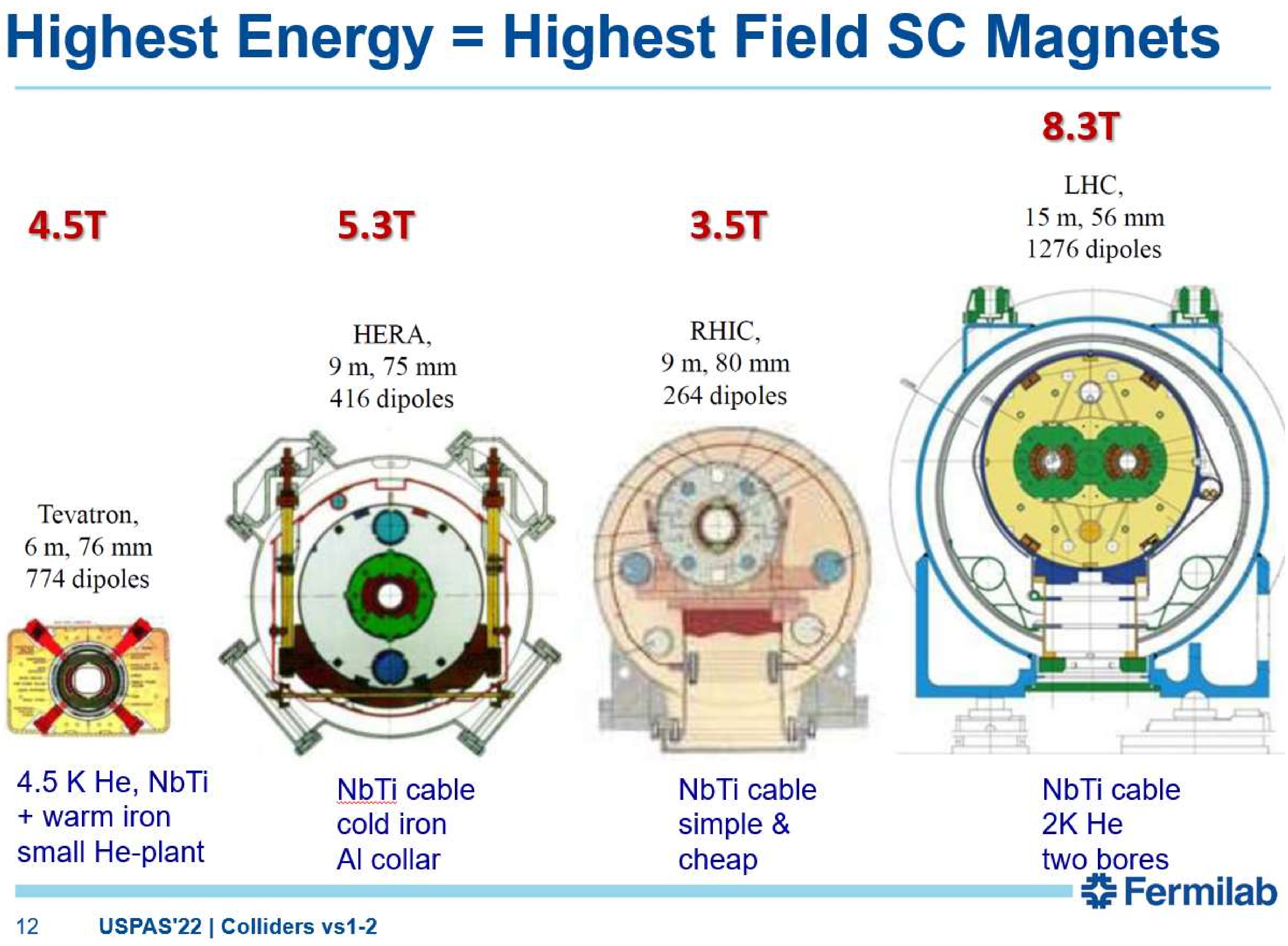
Novosibirsk Super Charm Tau Factory

e+ DR – positron damping ring
DW – damping wiggler
SS – Siberian Snake
CV – electron-positron converter
Pol e-/e- - polarized/un-polarized electron source

EIC (BNL, Brookhaven)



Some Important Accelerator Technologies



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

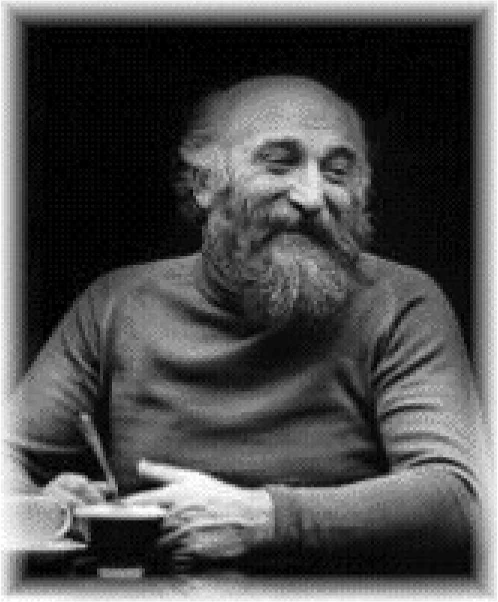
NbTi cable
simple &
cheap

8.3T

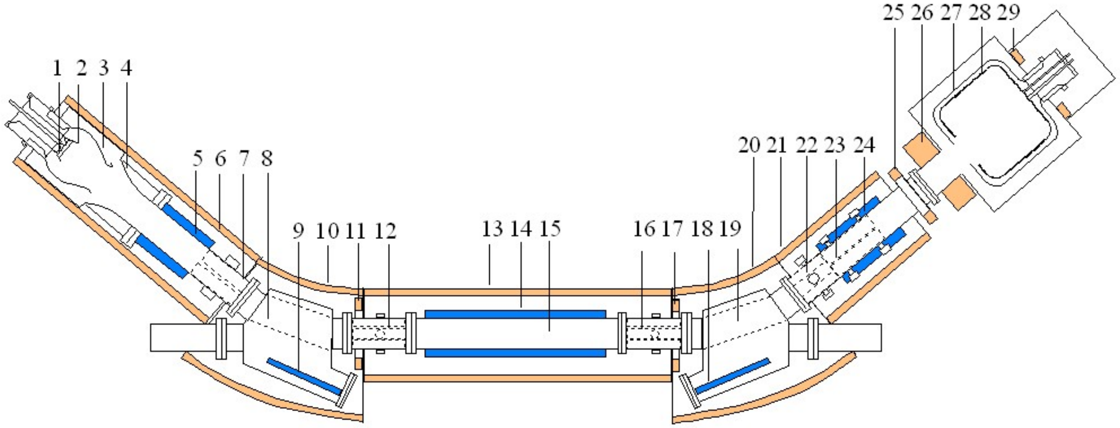
LHC,
15 m, 56 mm
1276 dipoles

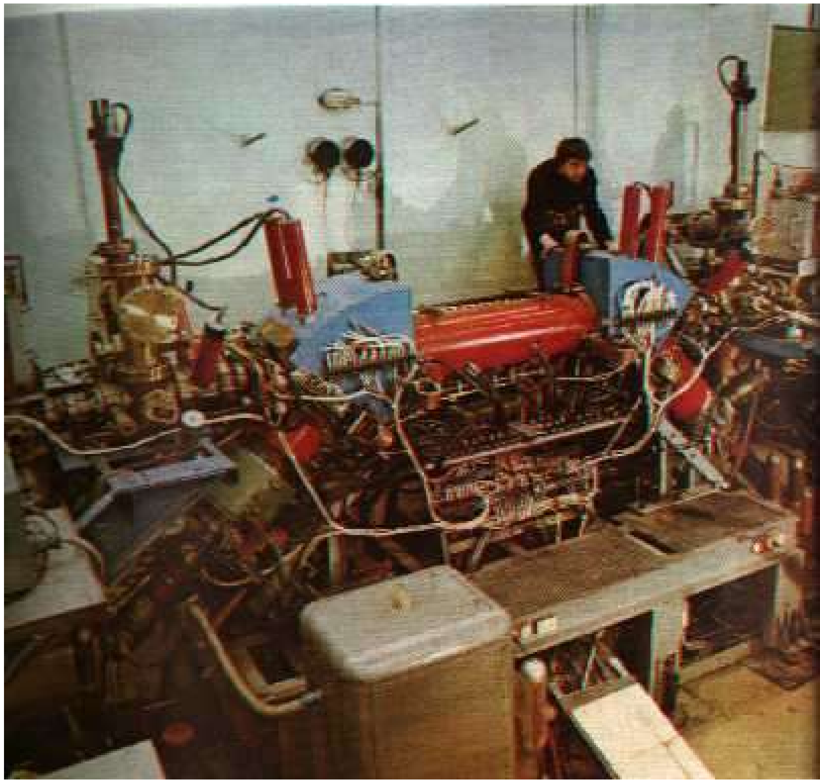
NbTi cable
2K He
two bores

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 protons)
  - ♦ Magnetized electron cooling





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

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

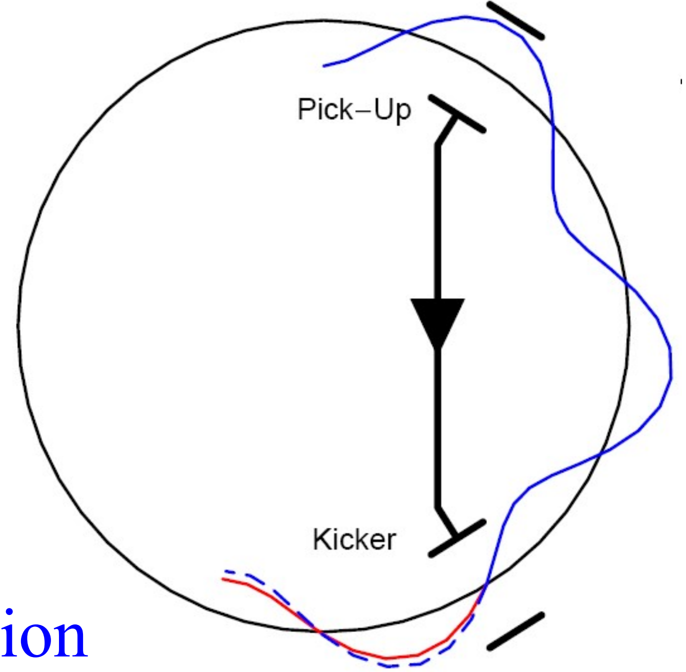
$$\delta\overline{\theta^2} = -\frac{1}{2}2g\overline{\theta^2} \equiv -g\overline{\theta^2}$$

- 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

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



- 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

Why NICA?

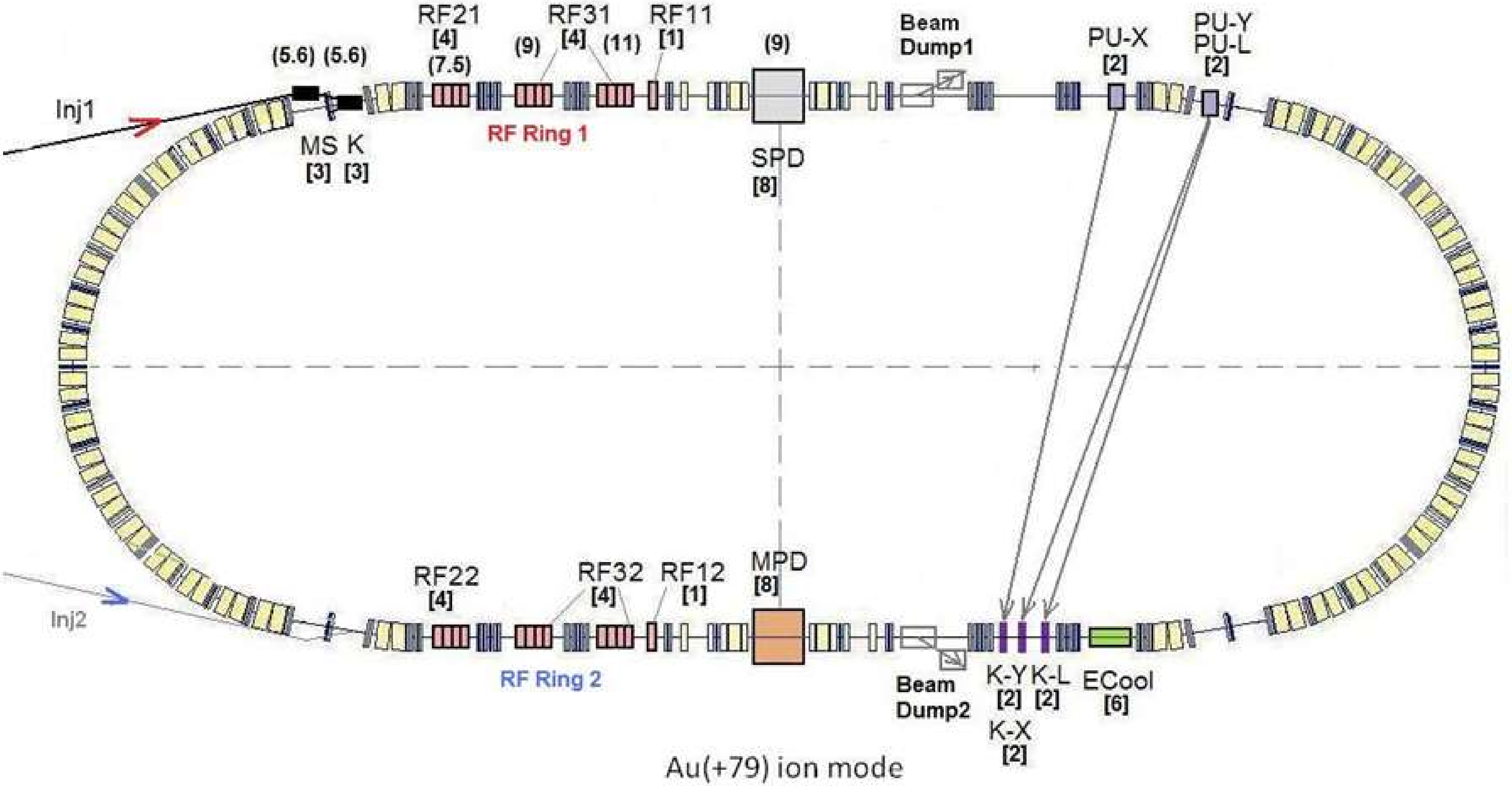
- NICA will have 2 detectors and is built to answer 2 questions
  - What are the phases of strongly interacting matter, and what roles do they play in the cosmos? (MPD)
  - Spin structure of the proton/deuteron (g-factor). (SPD)
- Unique niche
  - Two major competitors (LHC & RHIC) have too large energy 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 (superferric) magnets
  - Large beam current results in beam instabilities
  - Low-beta optics brings dynamic aperture limitations
  - Electron and stochastic cooling at collisions
  - Instrumentation and controls required for modern colliders

    …

NICA Layout

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

Scheme of the Collider Ring

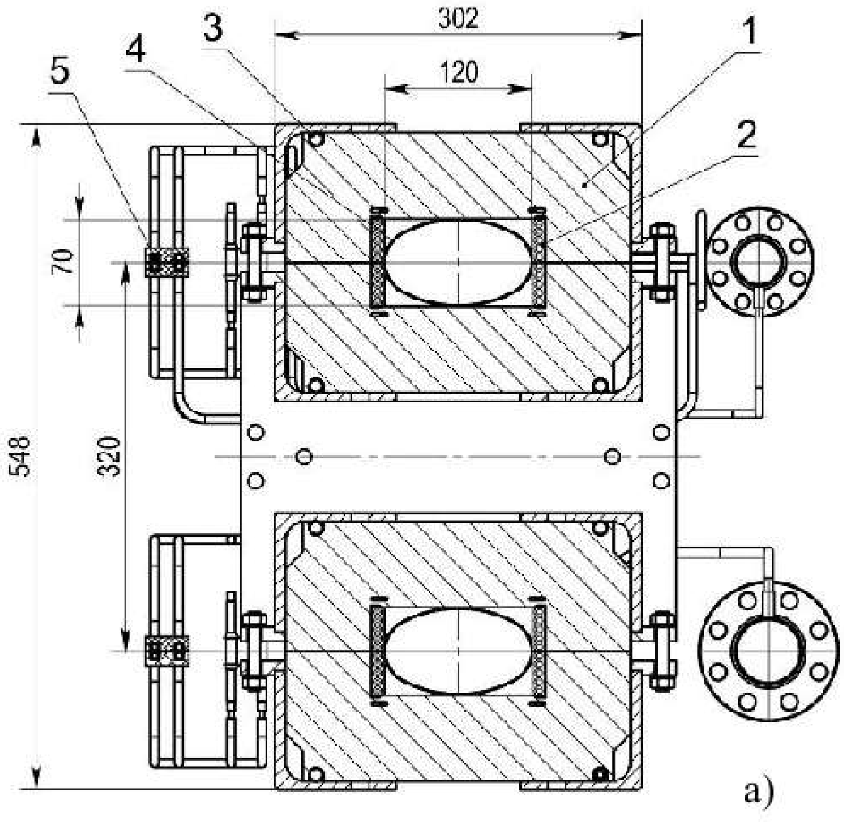


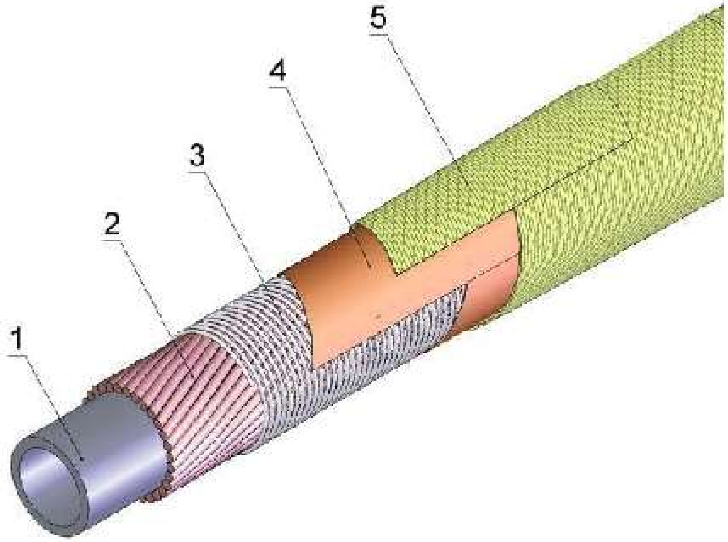
Two rings: one above another, 503 m circumference

Collision energy in the heavy ion mode: $\sqrt{s}=2\cdot(2.5 \div 5.5)$ GeV/n

1.5 – 4.5 GeV kinetic energy

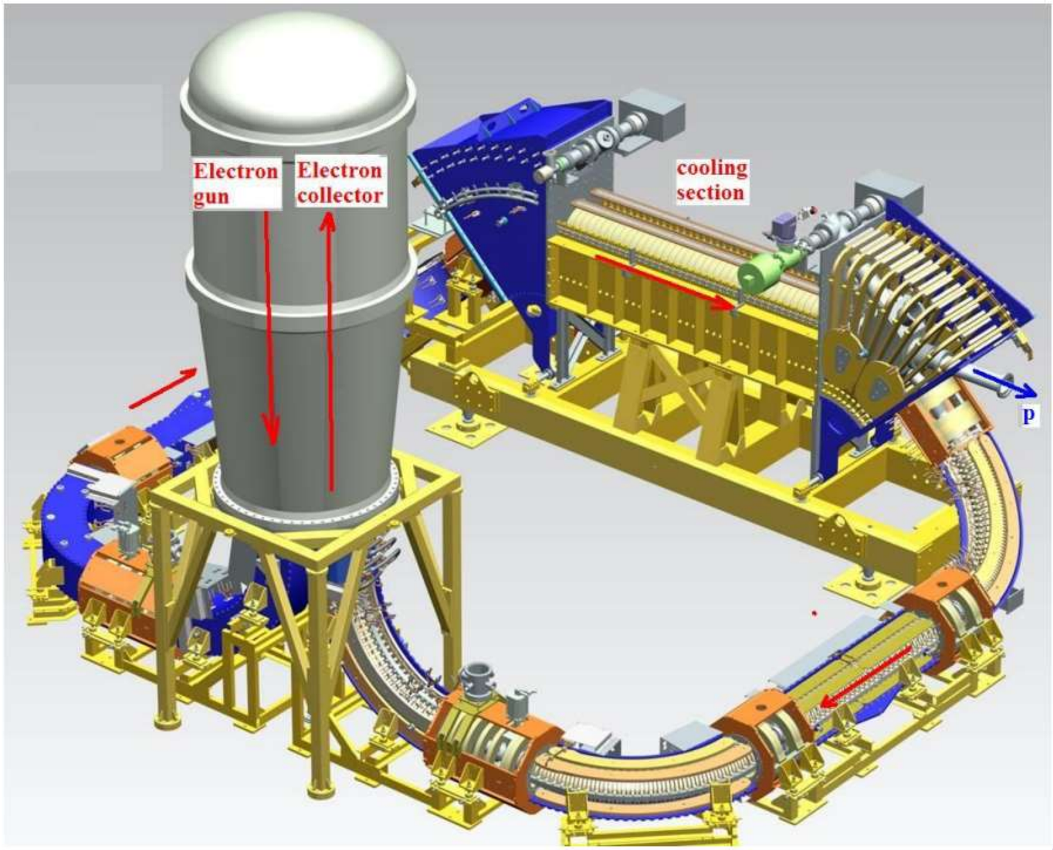
NICA Dipoles (Superferric)





Beam Cooling

- Two systems of beam cooling will be present in NICA: electron cooling and stochastic cooling
- They are complimentary
- Stochastic cooling
  - Initially was expected to be as the main and only cooling system
  - Poor performance below 2.5 GeV
- Electron cooling
  - Good expertise accumulated in Novosibirsk for high energy cooling
    - 2 MeV system was supplied to COSY, Julich, Germany
  - Very good cooling of small amplitudes. Much slower cooling at high amplitudes where help from stochastic cooling would be valuable
  - Poor beam lifetime due to capture of electrons by heavy ions



NICA: Most Important Topics/Effects

- Engineering of magnets, RF, Power supplies, vacuum, particle sources, targets, diagnostics, collimators, cryogenics, *etc*.
- Beam physics (incomplete list)
    - One particle: beam optics, long-term stability, resonances, losses, noises, diffusion/emittance growth, *etc*.
    - One beam: instabilities, beam-induced radiation deposition, intrabeam scattering, cooling, space-charge effects and compensation
    - Two-beams: beam-beam effects and compensation, instabilities in two-beam system, machine-detector interface, *etc*.
    - Beam cooling (electron, ionization, stochastic)
- Construction
    - Schedules, costs, deliveries of components
- Operations
    - Transition to whole year operation with 2-3 months shutdown
    - New operations department to drastically reduce staff required for operations

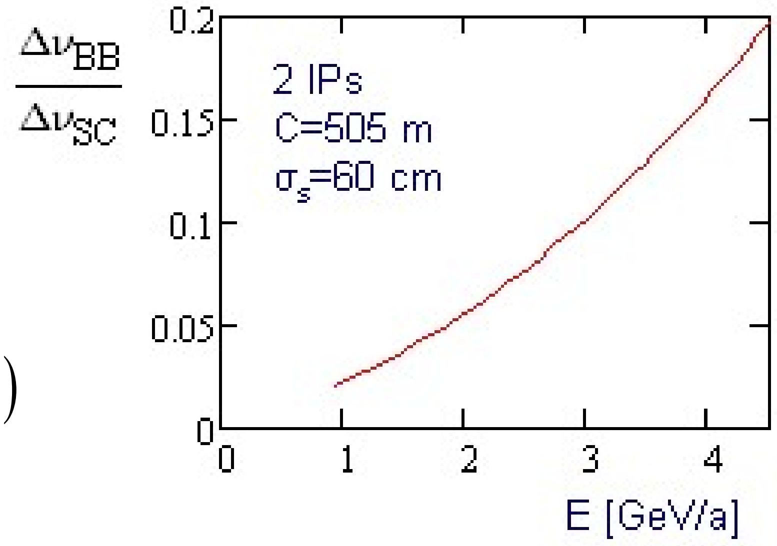
Instead of Conclusions

- In about 1 year we plan to inject beams into collider rings
- Recently we started operations of KRION ion source and heavy ion linac with the goal to increase particle flux by an order of magnitude relative to the last Run carried out in Nov. 2022 – Feb.2023 and being successful and extremely helpful for future
  - Be ready for beam accumulation in Booster with electron cooling
- Booster Run is expected in May – June
- In about 3 years we plan completion of all collider systems including high voltage electron cooling, stochastic cooling, feedbacks, all 3 RF systems of each ring and MPD detector
- The program with polarized protons and deuterons will be aimed at operation with the slow beam extraction to target(s)
  - SPD detector will follow later
- Although relatively small the NICA collider will be at the front line of modern accelerator and nuclear physics
  - We need you! Both on the accelerator and detector sides

Backup Slides

Possible Values of Tune Shifts

- Achieved values of tune shifts
  - Space charge
    - NAPM ~0.15 (strong el. cooling, 200000 turns)
    - Fermilab Booster ~0.3 (only ~2000 turns at low energy)
    - JPARK, PS Booster ~ 0.5-0.6 (high accuracy of super-periodicity)
  - Beam-beam
    - VEPP-2 ~0.2 (round beams)
    - Typical e^+e^- ~0.05 (fast SR damping)
    - Typical hadron beams (Tevatron, LHC) ~0.01-0.015 per IP
    - Low energy RHIC ~0.1 (bad life time)



- Ratio of tune shifts:

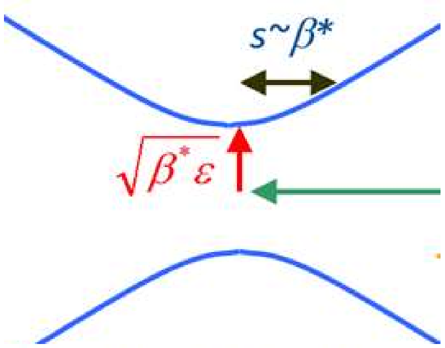
$$\frac{\delta\nu_{BB}}{\delta\nu_{SC}} = N_{IPs}\sqrt{\frac{\pi}{2}}\frac{\sigma_s}{C}\gamma^2\left(1+\beta^2\right)$$

- For the present NICA parameters, the beam-beam tune shifts are much smaller than the space charge ones and, in the first approximation, can be neglected
- Note that for the same tune shift the beam-beam effect is more destructive than the space charge due to kick concentration near IPs
- For NICA we choose total $\Delta\nu = \Delta\nu_{SC} + 2\Delta\nu_{BB}$ ~0.05
  - Cooling helps, still quite optimistic

Luminosity Limitation due to Beam Space Charge

- Luminosity of round beams ($\beta_x^*=\beta_y^*$ & head-on collisions)

$$L=\frac{f_0 n_b N_i^2}{4\pi\beta^*\varepsilon}H_L(\sigma_s/\beta^*)\,,\quad H_L(x)=\frac{2}{\sqrt{\pi}}\int_0^\infty\frac{\exp(-y^2)}{1+x^2y^2}dx$$



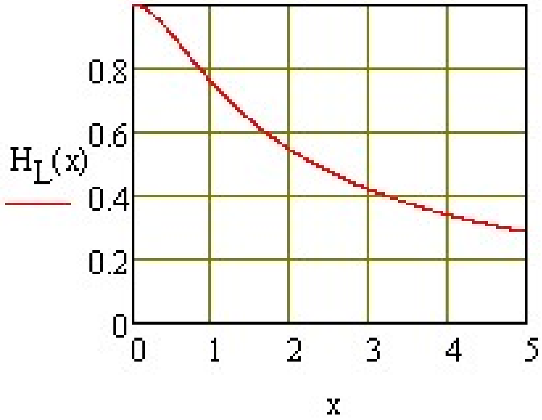
- SC tune shift: round beam, smooth focusing & D=0

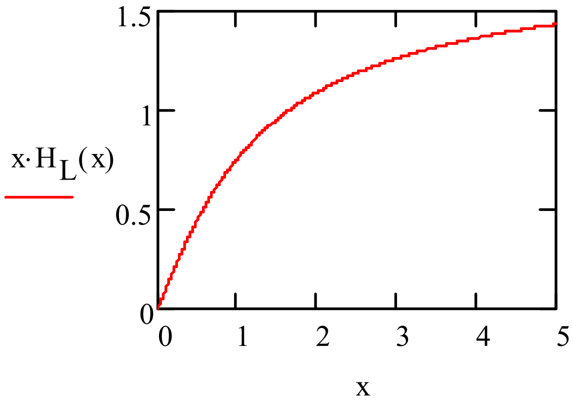
$$\delta\nu_{SC}\approx\frac{r_p Z^2 N_i}{4\pi A\beta^2\gamma^3\varepsilon}\frac{C}{\sqrt{2\pi}\sigma_s}$$

  - Weak dependence of SC tune shifts on optics
- SC limits the beam longitudinal density, N_i/σ_s
- Combining the above equations, one obtains a luminosity limitation

$$\boxed{L=\frac{\sqrt{2\pi}A\beta^2\gamma^3}{r_p Z^2}\frac{f_0 N_i}{(C/n_b)}\left(\frac{\sigma_s}{\beta^*}H\left(\frac{\sigma_s}{\beta^*}\right)\right)\delta\nu_{SC}}$$

  - Strong dependence of L on the beam energy
  - Longer bunch => larger luminosity
    - Still collisions must be within detector
    - Luminosity distribution along IP has the rms length of $\sigma_s/\sqrt{2}$ ~42 cm
  - $\varepsilon\propto N_i$ => larger luminosity -> larger acceptance





Intrabeam Scattering

- Intrabeam scattering is determined by two major mechanisms
  - Temperature exchange between degrees of freedom
    - Landau collision integral describes the temperature exchange:

$$\frac{\partial f}{\partial t} = -\frac{2\pi e^4 n L_c}{m^2}\frac{\partial}{\partial \mathrm{v}_i}\int\left(f\frac{\partial f'}{\partial \mathrm{v}'_j} - f'\frac{\partial f}{\partial \mathrm{v}_j}\right)\frac{u^2\delta_{ij} - u_i u_j}{u^3}d^3\mathrm{v}'$$

$$\mathbf{u} = \mathbf{v} - \mathbf{v}', \quad \int f d^3\mathrm{v} = 1$$

  - Additional heating related to non-zero dispersion
    - Scattering with particle momentum change results in additional betatron oscillations due to instant change of reference orbit

$$\Delta x = D\frac{\Delta p}{p} \xrightarrow[\text{approximation}]{\text{smooth lattice}} \Delta\varepsilon_x = \frac{1}{2}\frac{\Delta x^2}{\beta_x} = \frac{D^2}{2\beta_x}\left(\frac{\Delta p}{p}\right)^2$$

- Relatively simple equations in the smooth lattice approximation
  - Below transition there is an equilibrium state where no emittance growth
  - Particle mass changes “its sign” above the transition. That yields unlimited emittance growth (energy is taken from the beam energy)
- In heavy ion mode NICA operates in the regime of quasi-equilibrium (all 3 temperatures are approximately equal)

Detector MPD