Colliders and NICA

Valeri Lebedev

JINR

Outline

- HEP: Directions, Status and Plans
- Colliders
- Some Basic Concepts of Accelerator Physics
- Present and Future Colliders
- Some Important Accelerator Technologies
- NICA – the First Hadron Collider in Russia

International school of accelerator physics: Linear accelerators, Verbilki, Moscow. Reg. 24-29 Aug., 2025

HEP: Directions, Status and Plans

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 to 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 Goals & Directions of High Energy Physics

The goal is to determine the most fundamental building blocks of matter and to understand the interactions between these particles

- Presently the high energy physics extends far beyond the accelerator based HEP
  - Cosmology & Astrophysics
    How our universe was created and which laws determine its expansion?
    - High resolution digital map of the universe observed at different wave lengths
    - Gravitational waves
  - Detection of radiation coming from space
    - ν - Discovery of neutrino mass difference (Nobel prize)
    - ν - Highest observed energy 3×10^{20} eV (far beyond our accelerators)
    - γ - Microwave background radiation
    - γ - Search for dark matter and dark energy
    - $e^{\pm}$, $p^{\pm}$, nuclei, …
- The strongest limitation on the neutrino mass came from analysis of the microwave background radiation and universe expansion

Major Directions of Accelerator Based HEP

- LHC is a leader in collider-based physics
  - Finding physics beyond the standard model
    - Higher energy and luminosity
    - Improvement of detector resolution (space and time)
    - Detailed measurements of Higgs boson
    - FCC is planned as the next step of the CERN program
- Mixing and oscillations of neutrinos
  - New generation machines come at the end of this decade
    - DUNE (Fermilab) and
      Hyper-Kamiokande (Institute for Cosmic Ray Research of University of Tokyo & JPARC & KEK)
  - The goal: finding CP violation in neutrino sector and neutrino mass hierarchy
- Physics beyond standard model
  - g-2 experiment (Fermilab) – difference disappears with more data
  - μ-to-e experiment (Fermilab, the Paul Scherrer Institute (Zurich))
    - lepton number violation is observed in neutrino sector

Colliders

Collision Energy and Luminosity

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

$$E_{cm} = \frac{1}{2}E \xrightarrow[case,\quad E \gg mc^2]{ultra\ \ relativistic} E_{cm} \approx \sqrt{2Emc^2}$$

    - Both particles move:

$$E_{cm} = 2E$$

(120 times gain for the LHC)

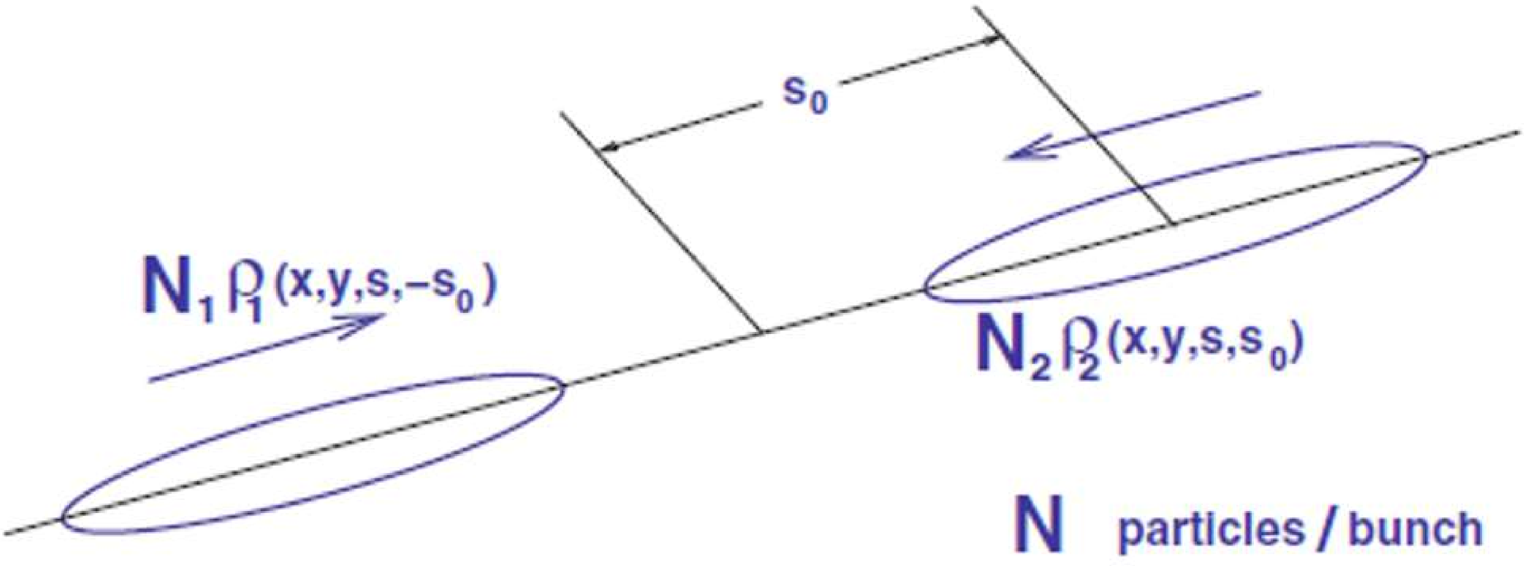
- Luminosity
  - Number of events in collisions:

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

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

Luminosity

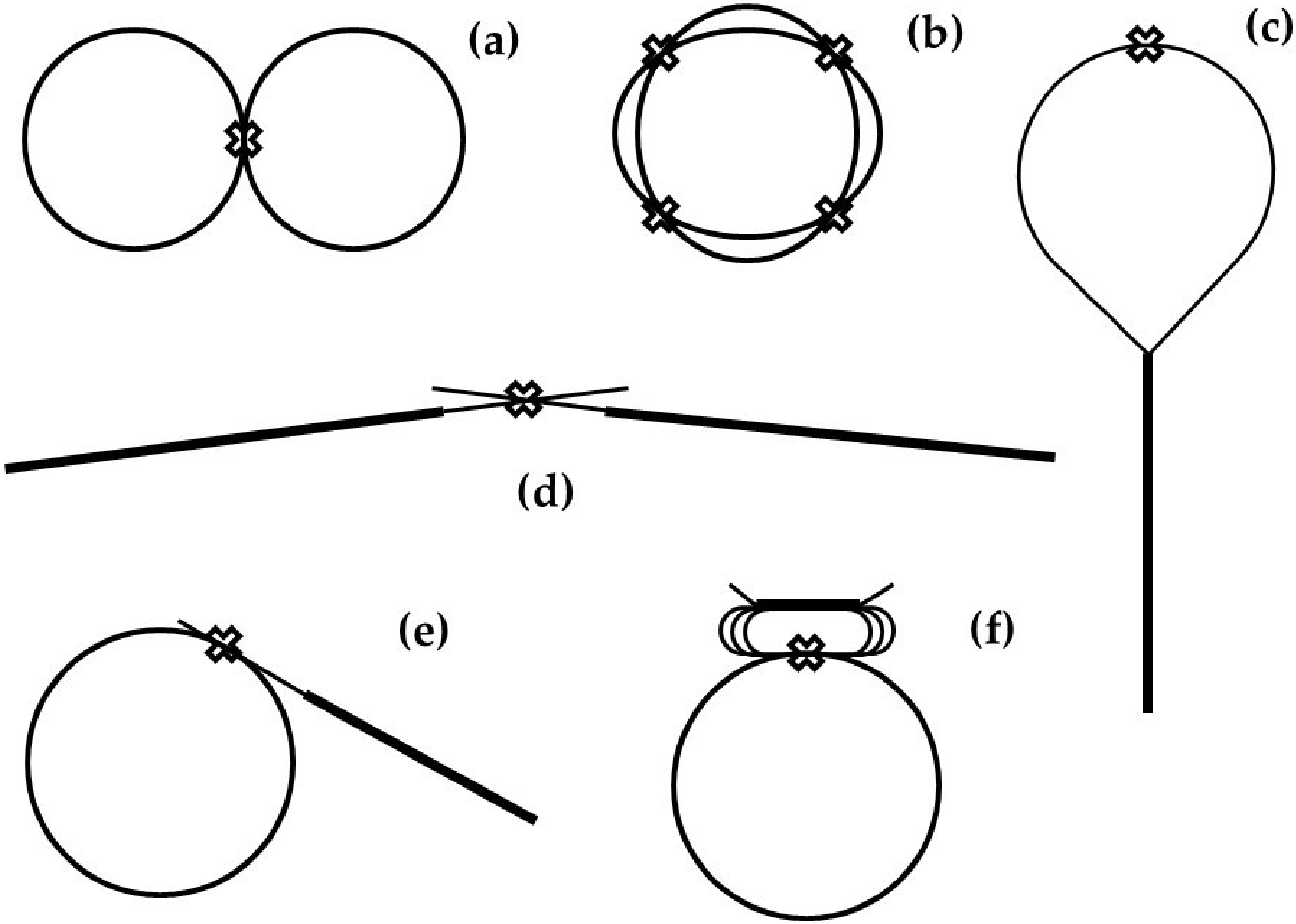
$$N_{\rm exp} = \sigma_{\rm exp} \cdot \int \mathcal{L}(t)dt.$$



For (same size) Gaussian bunches:

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

Types of Colliding Beams Facilities



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

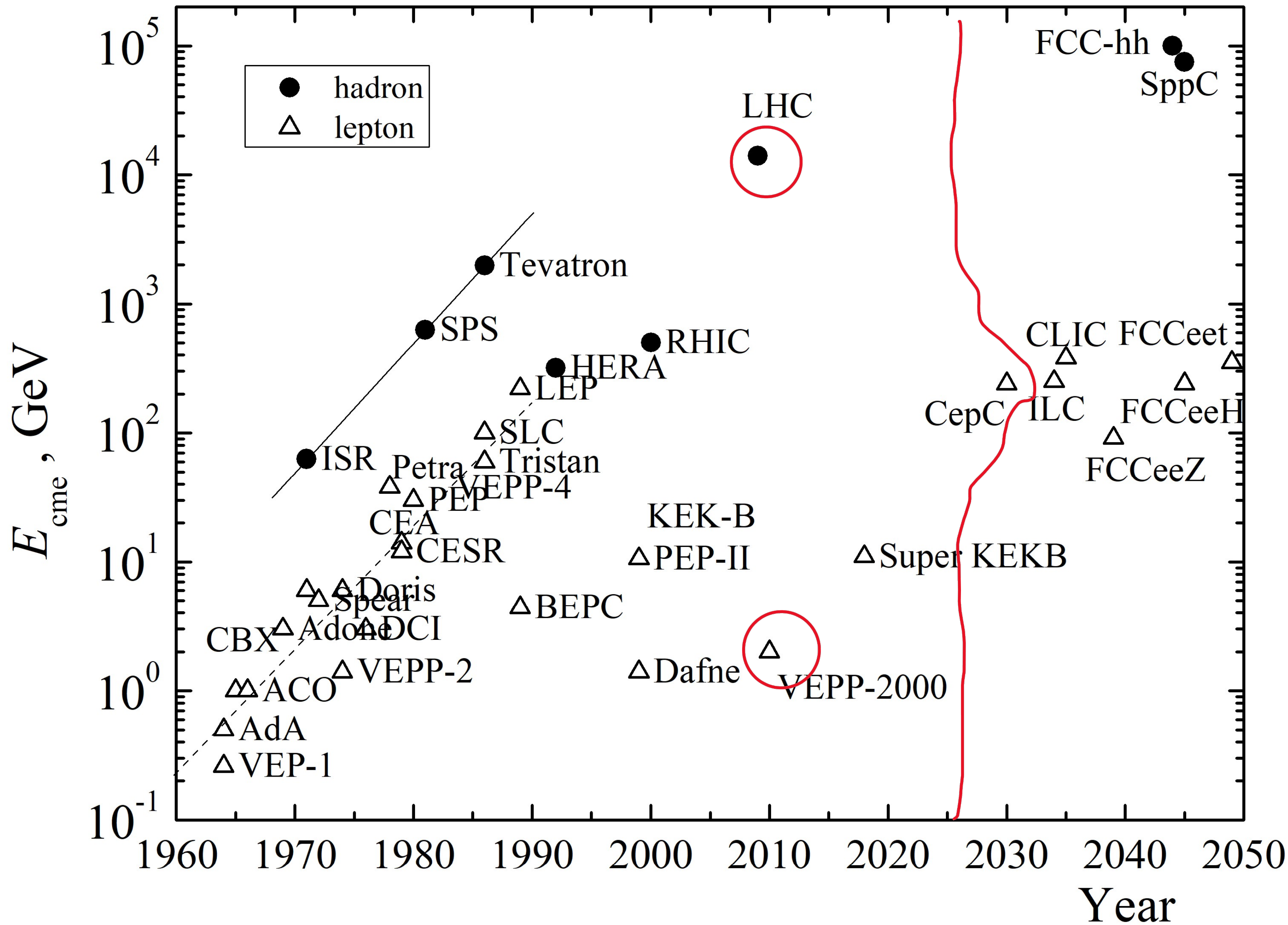
Colliders Landscape

- 61 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	$\mathcal{L}^{max}_{peak}$	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



Colliders: Luminosity

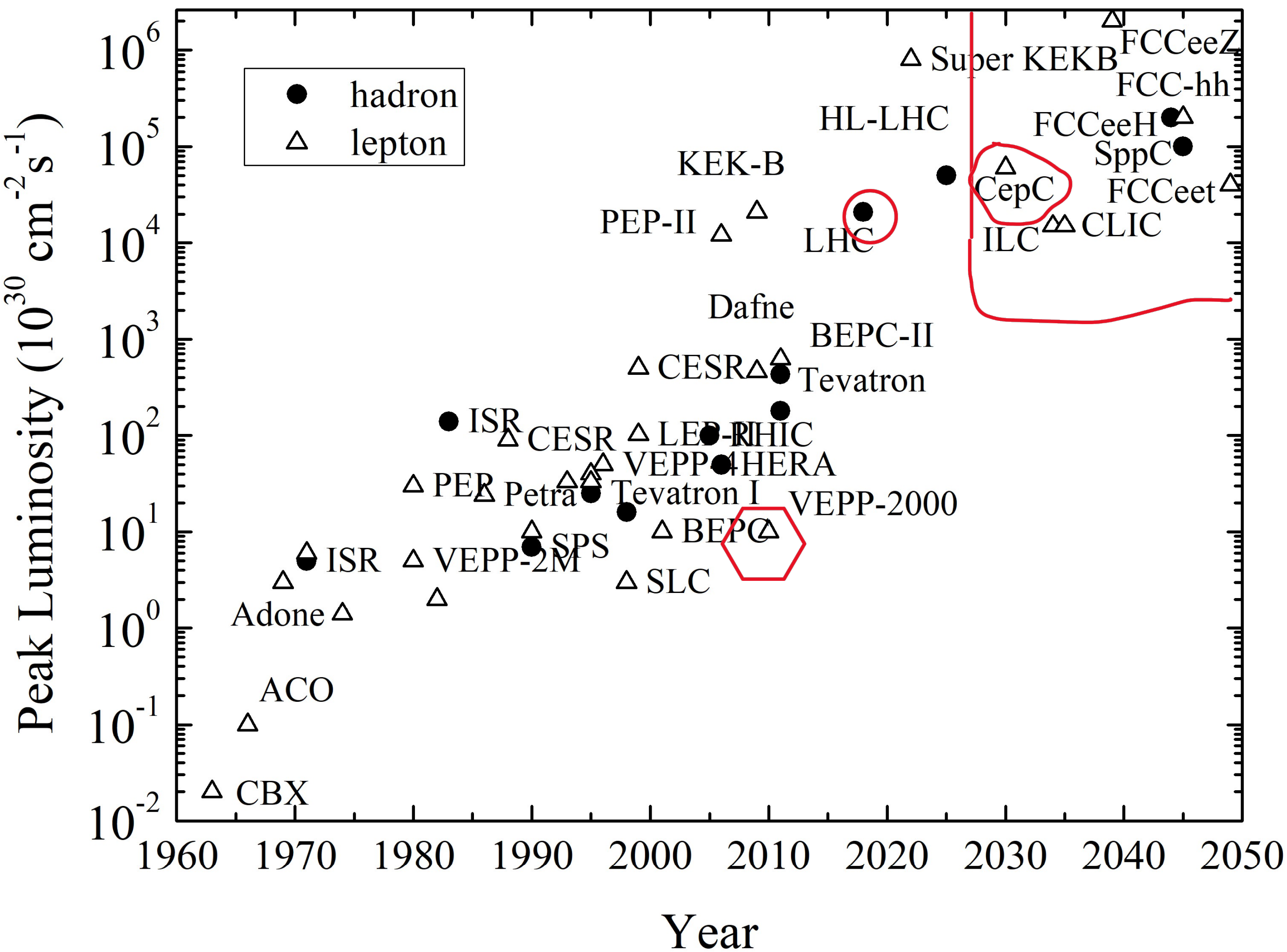
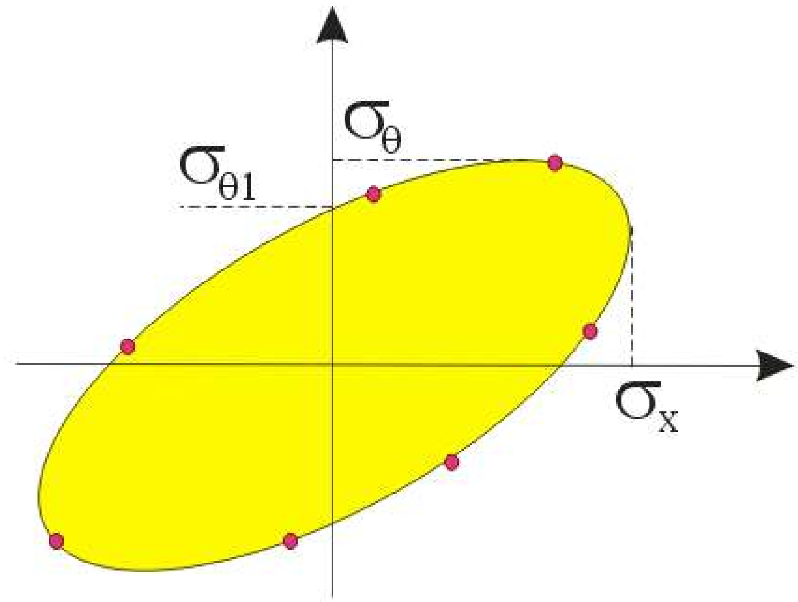


FIG. 3. Luminosities of particle colliders (triangles are lepton colliders and full circles are hadron colliders, adapted from [37]). Values are per collision point.

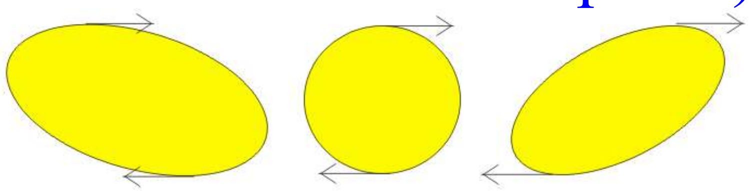
Some Basic Concepts of Accelerator Physics

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 = $\sigma_x \sigma_\theta$
  (σ_θ – local momentum spread)



$$\varepsilon = \sigma_x \sigma_{\theta 1}$$

$$\sigma_x = \sqrt{\varepsilon \beta_x}$$

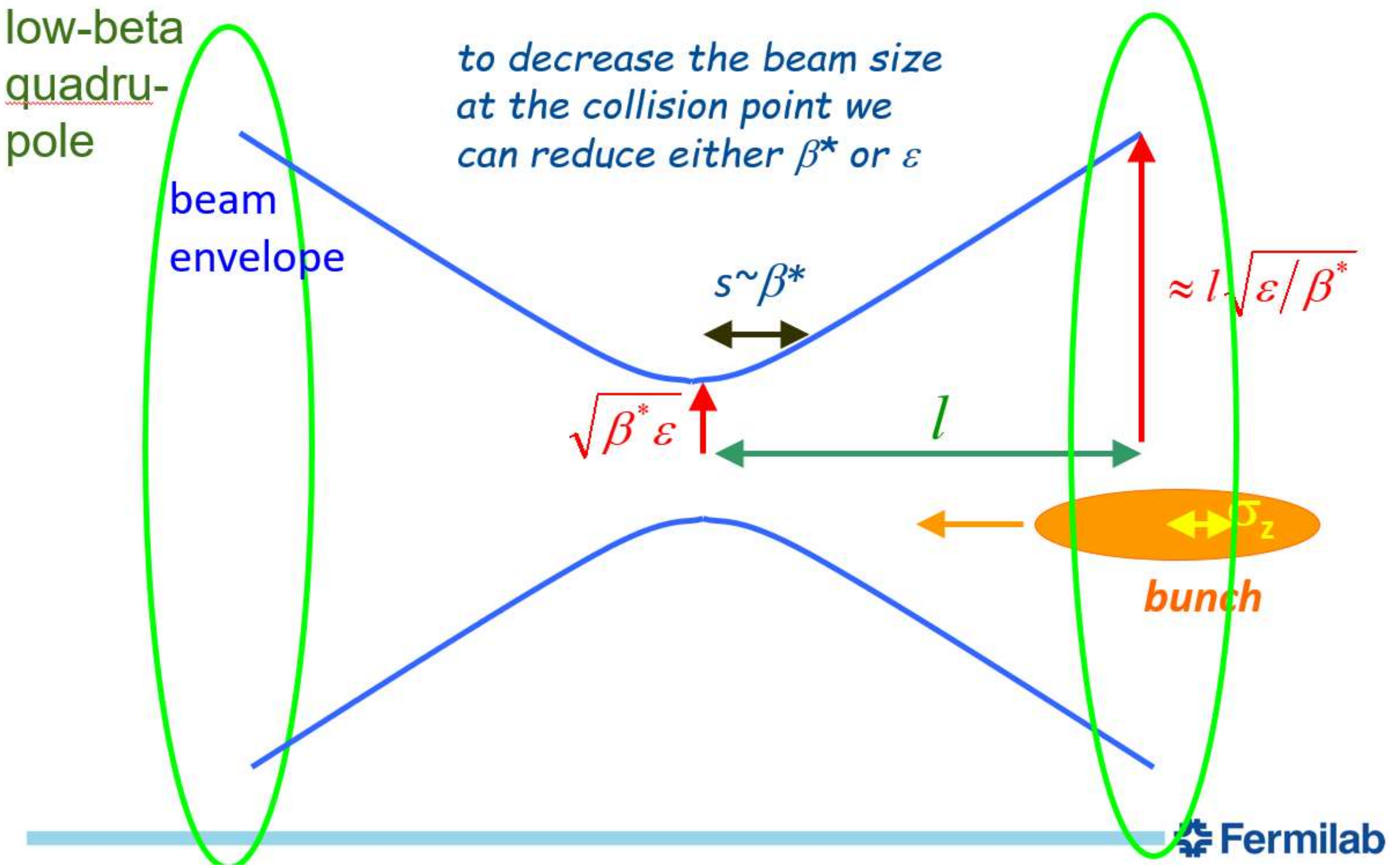
$$\sigma_{\theta 1} = \sqrt{\frac{\varepsilon}{\beta_x}}$$

$$\sigma_\theta = \sqrt{\frac{\varepsilon\left(1+\alpha_x{}^2\right)}{\beta_x}}$$

$$\alpha_x = -\frac{1}{2}\frac{d\beta}{ds}$$

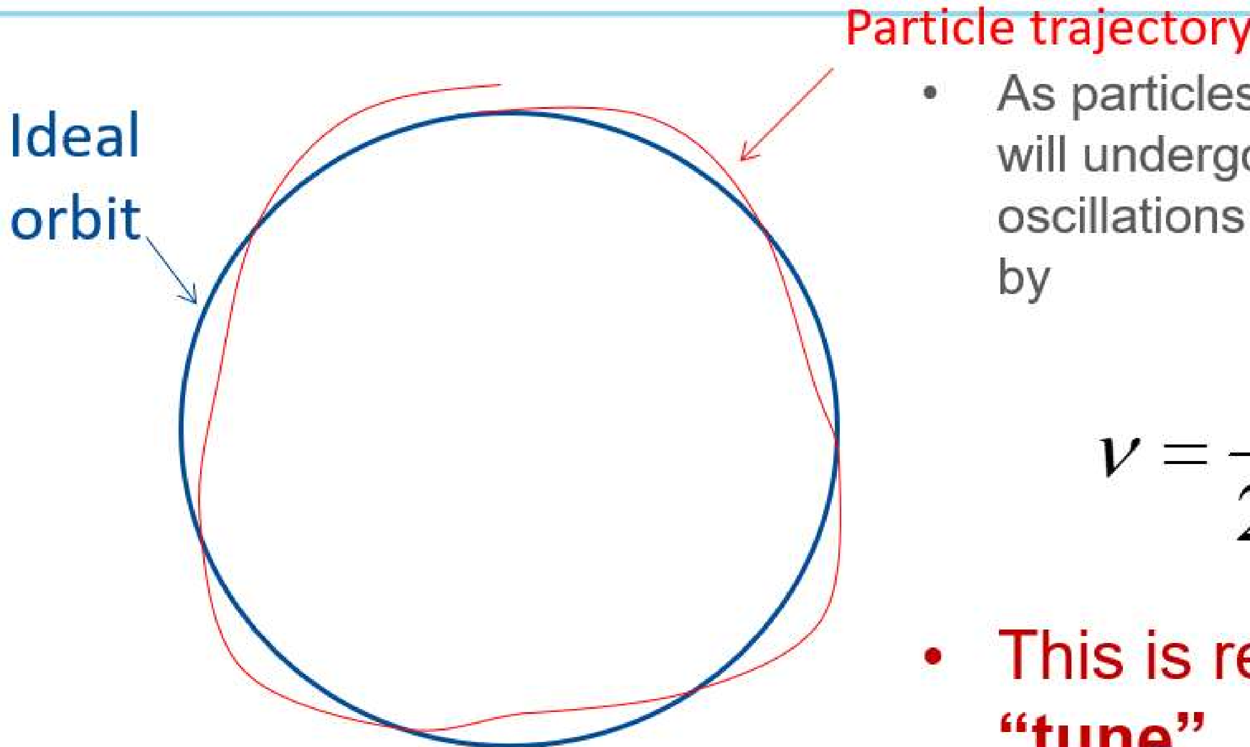
- Normalized emittance:
  $\varepsilon_n = \varepsilon\gamma\beta$ - adiabatic invariant
- Beam size: $$\sigma_{x,y} = \sqrt{\frac{\varepsilon_n \cdot \beta_{x,y}}{\gamma}}$$
- Luminosity ~ $1/\varepsilon$

Collider Spot Size



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

Betatron Oscillations, Tune



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

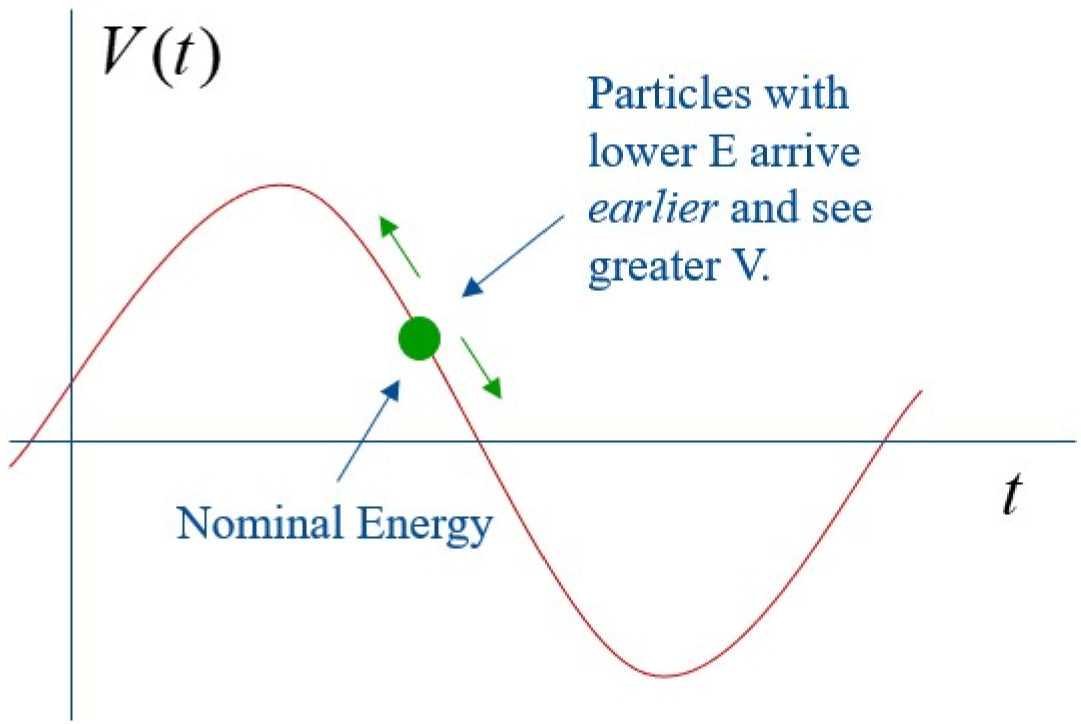
$$\nu = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

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

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

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"

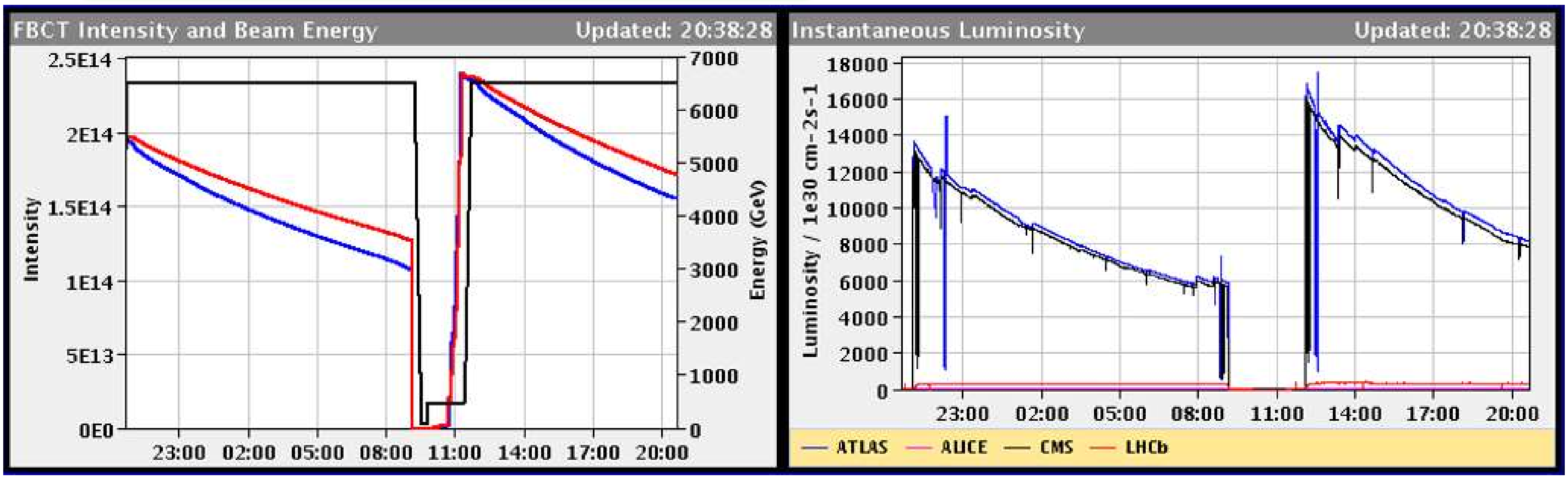


Luminosity Evolution

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

- Factors change in time: $L(t) = C\frac{N_1(t)N_2(t)}{\varepsilon(t)}H(t)$
- 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

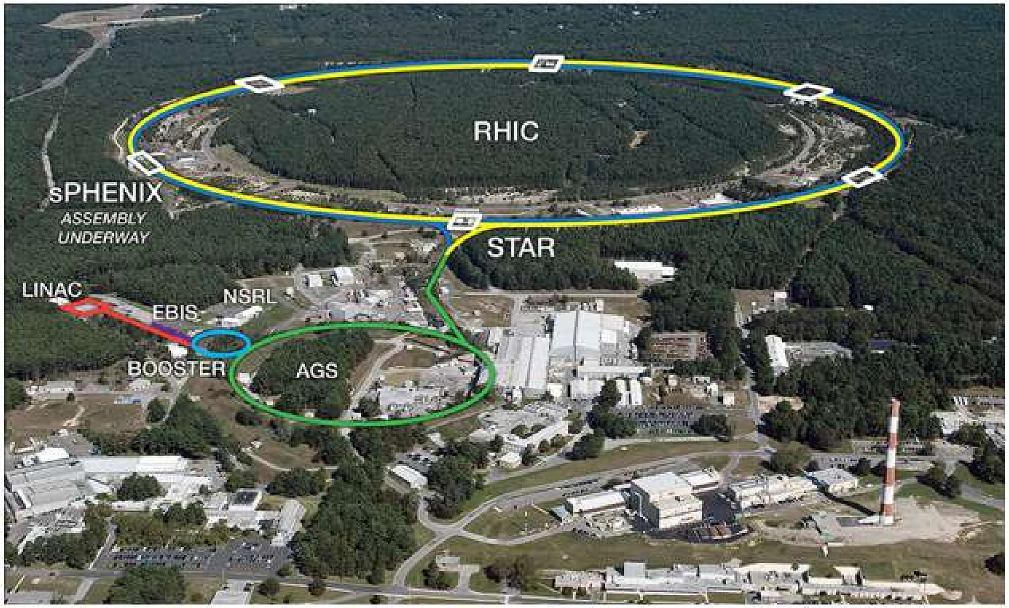
- Electrons
  - (+) Point-like objects
    => the entire energy may go to creation of a particle-of-interest
  - (+) Well-determined energy
    => better resolution; in particular, for narrow resonances
  - (+) Smaller backgrounds
    => Easier to separate events from backgrounds => less expensive detector
  - (-) 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
  - (-) 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

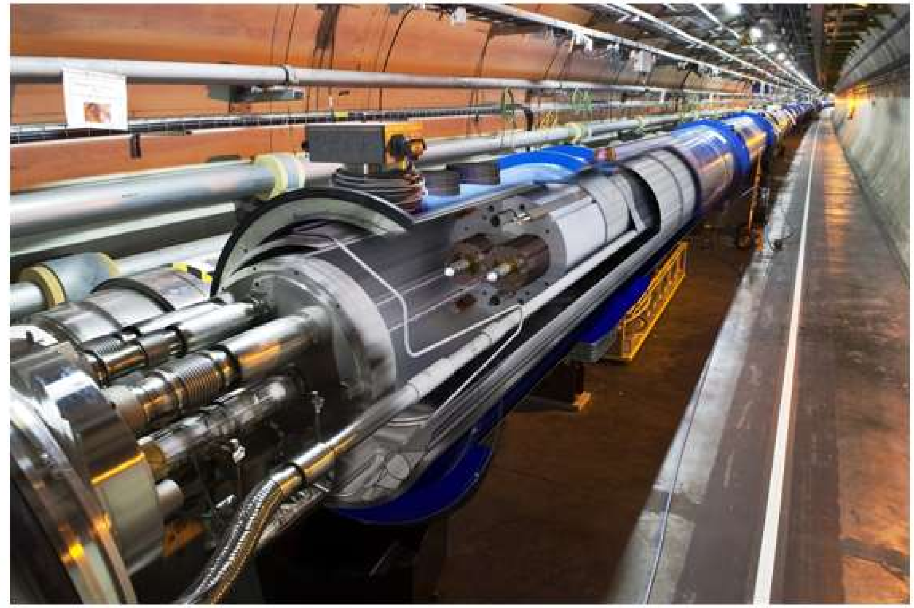
Electrons versus protons (continue)

- 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
- ILC – International Linear collider
  - Very expensive, looks like cannot not reach the design luminosity for reasonable time. SLC did not get the design luminosity (4 orders lower ILC) after 10 years of commissioning
    - Looks like is coming too late with too little E & L, compared to LHC
  - FCC e+e- looks much better choice – CERN's choice – requires ~doubling of CERN budget
- Muon collider looked as a very promising choice
  - Point-like particles, small SR but muons survive only about 1000 turns => cannot compete with LHC in the luminosity
  - Some people still believe that we can built one

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)

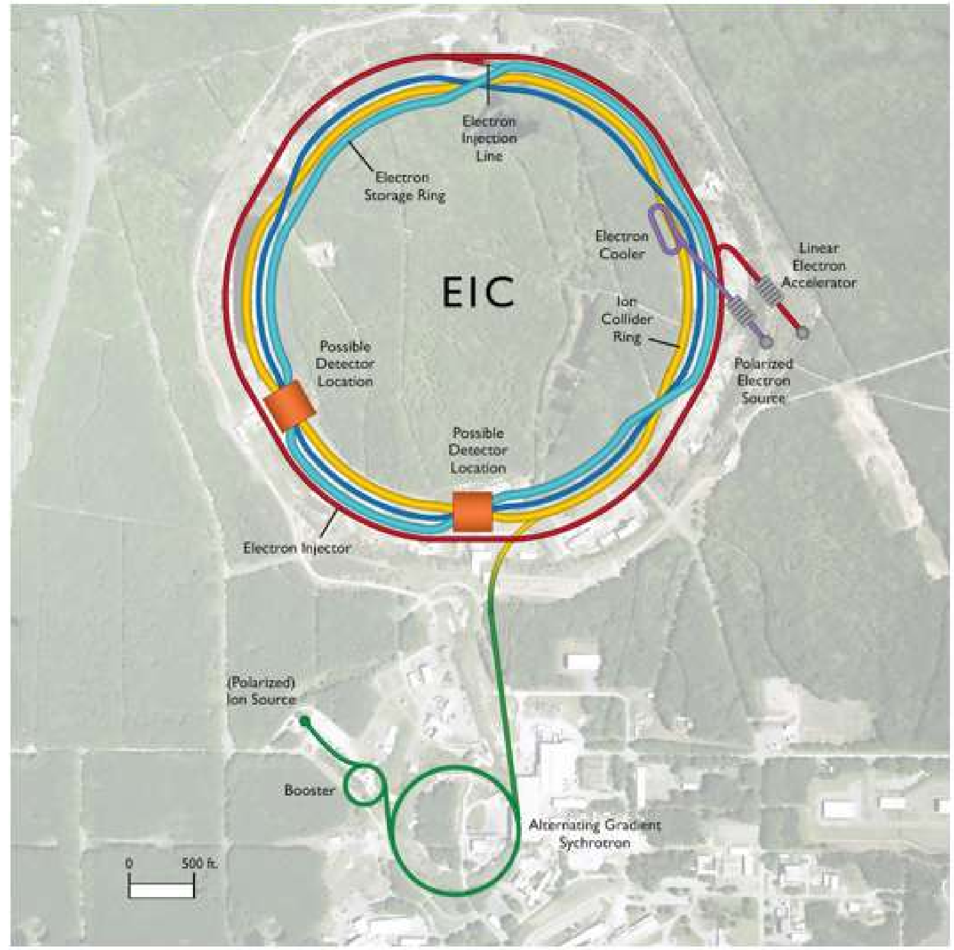
C=26.7 km,
E_{max}(protons)=6.8 TeV

Colliders That Will Be

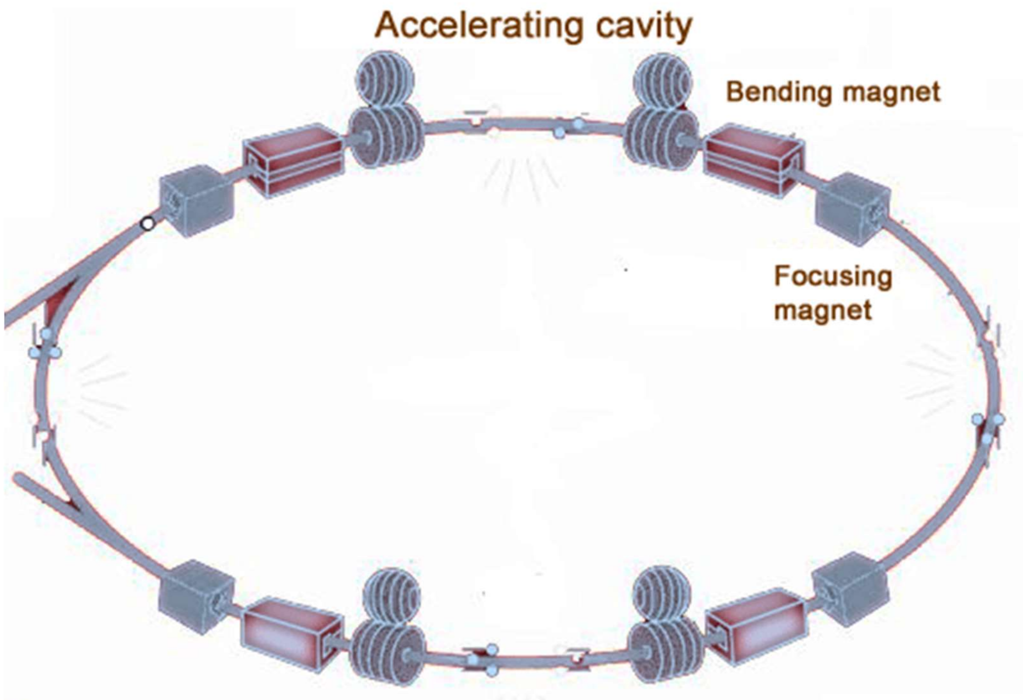
Main Parameters of The NICA Collider

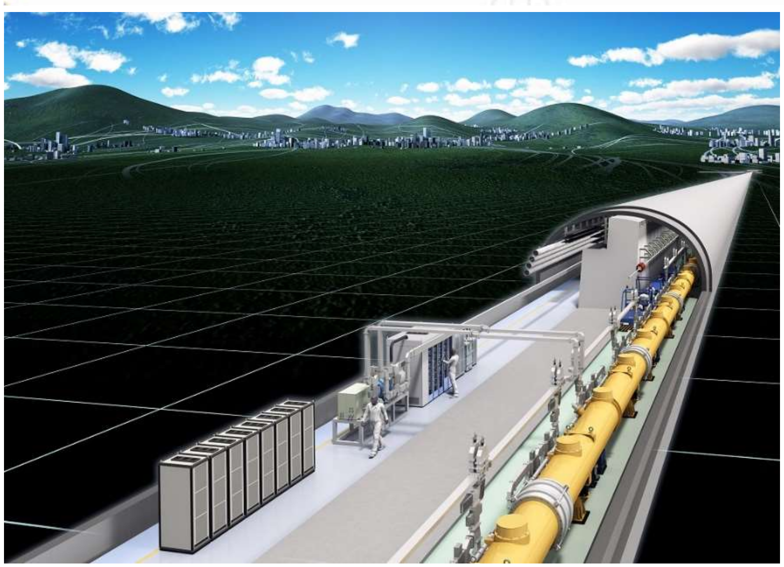
Circumference, m	503,04		
Bunch number per ring	22		
Mean-square bunch size, m	0.6		
Min. beta-function (β*), m	0.6		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch, 1e9	0.275	2.4	2.2
Peak luminosity, cm^{-2}·s^{-1}	0.9e25	0.9e27	6.3e27

EIC (BNL, Brookhaven)

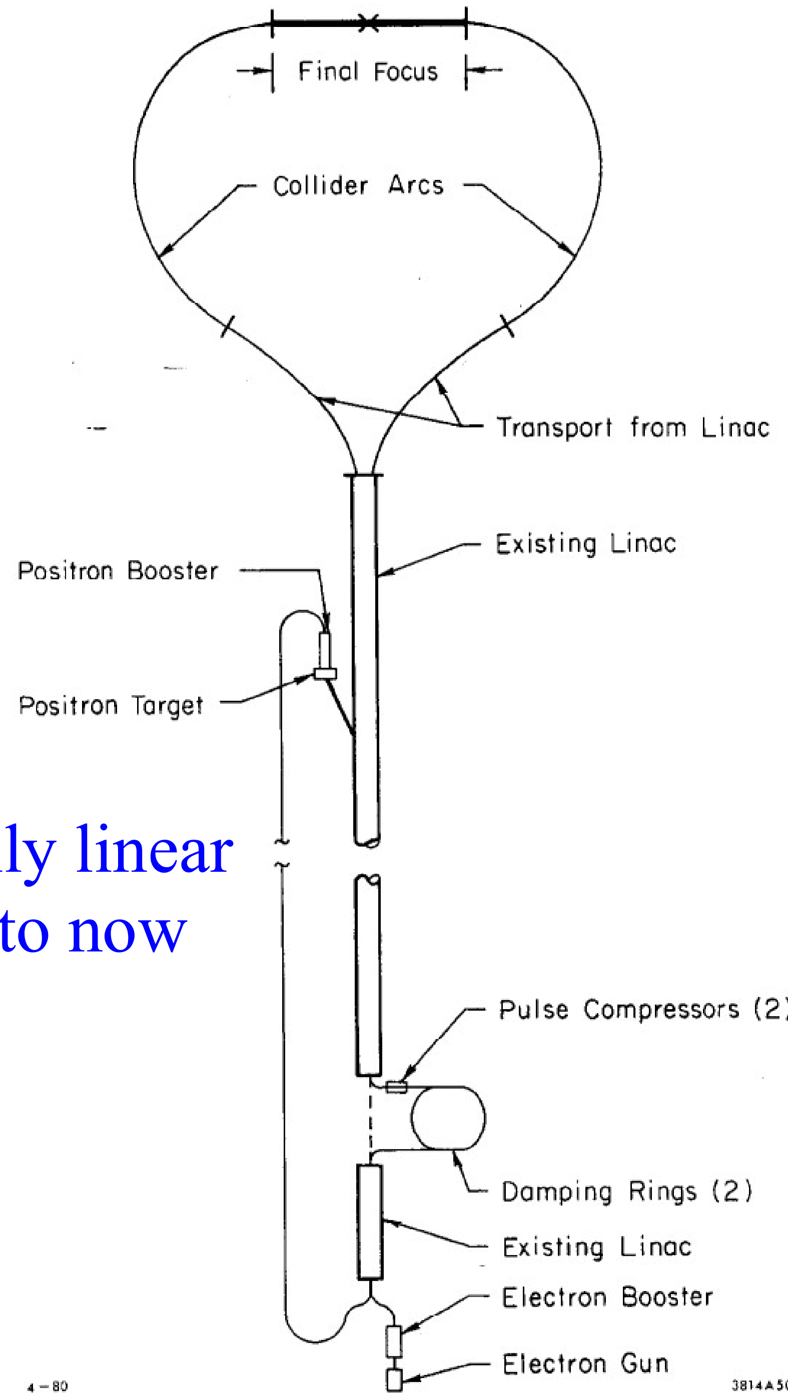


e^+e^-: Rings vs Linacs





- SLC – the only linear collier built up to now

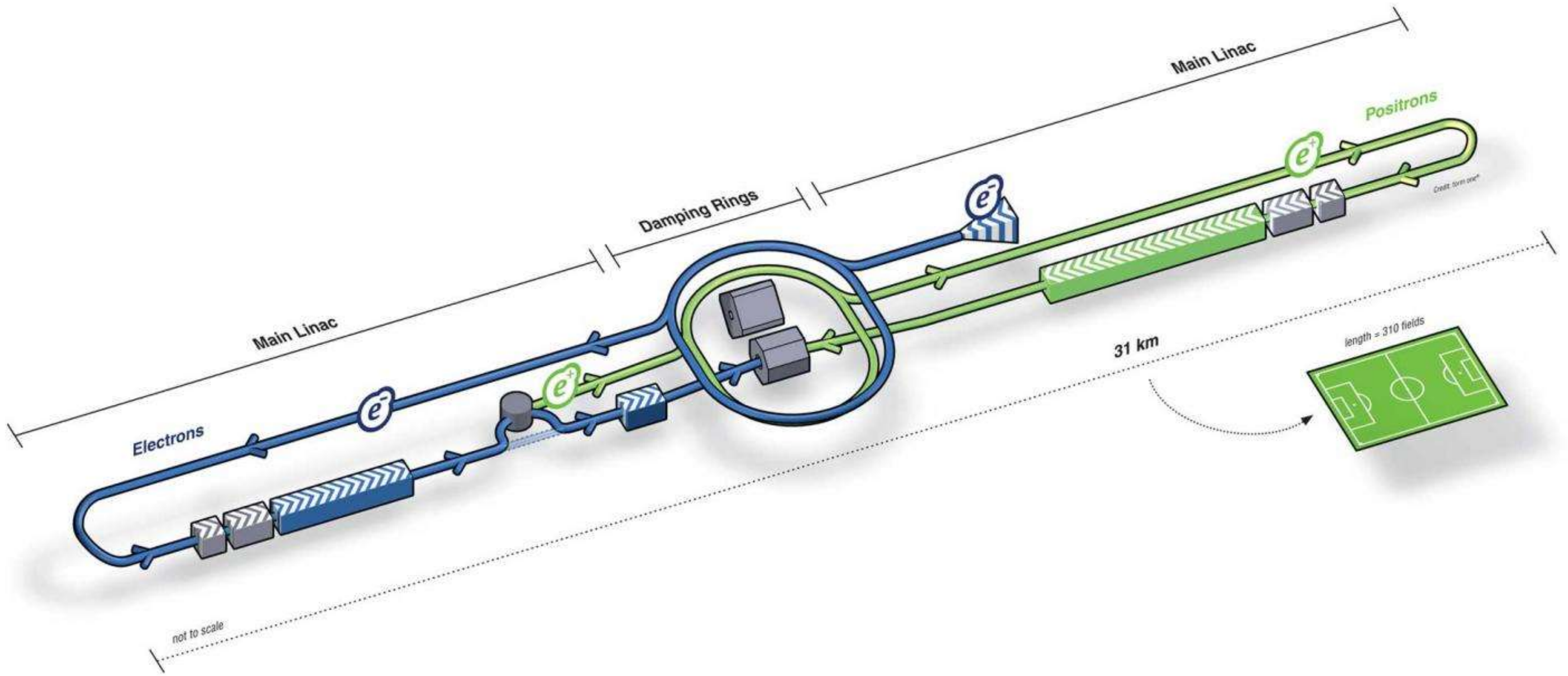


ILC (e^+e^-)

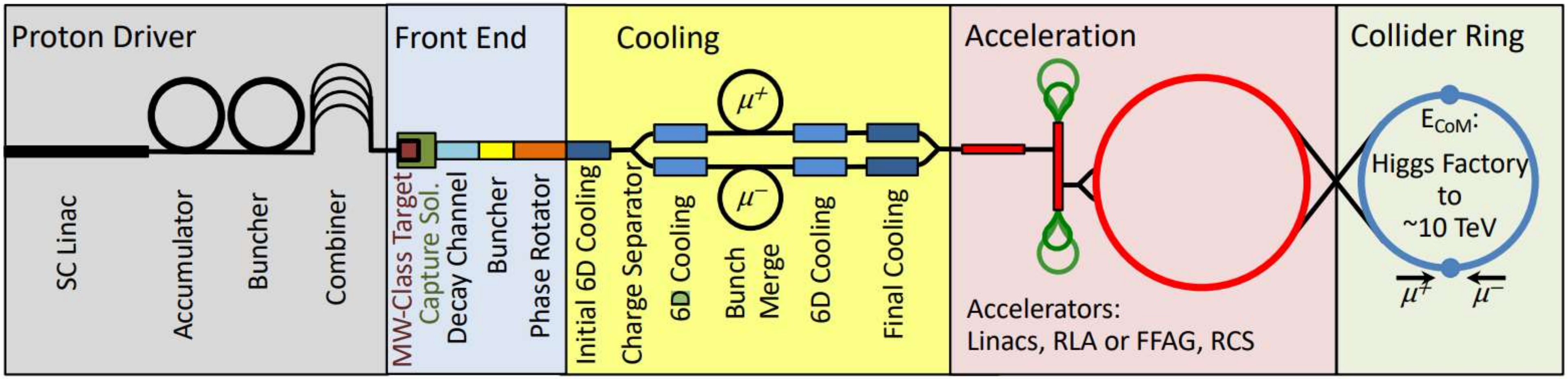
$\sqrt{s}$ =500 -> 1000 GeV

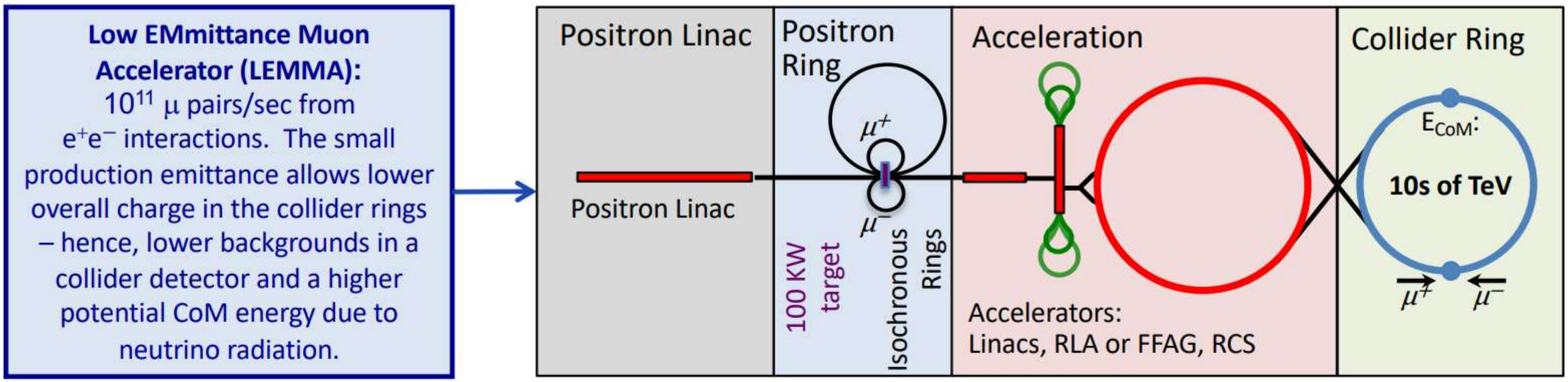
C=30 -> 50 km

Polarized electrons and positrons



Muon Collider





- Great challenge in accumulation and cooling muons
  - Multimegawatt proton driver
  - Ionization cooling
- Higgs factory: $L \approx 10^{29}$ cm^{-2}s^{-1} doable, $L \approx 10^{32}$ cm^{-2}s^{-1} needed,
  - Expected Higgs width 4.1 MeV, $W/M \approx 3 \cdot 10^{-5}$ ($\sqrt{s} \le 125$ GeV, s-channel)

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

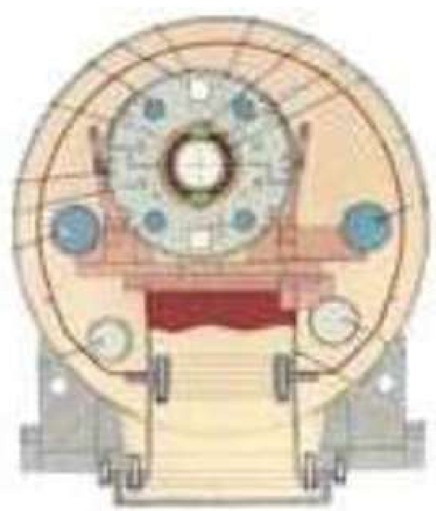
5.3T

HERA,
9 m, 75 mm
416 dipoles

NbTi cable
cold iron
Al collar

3.5T

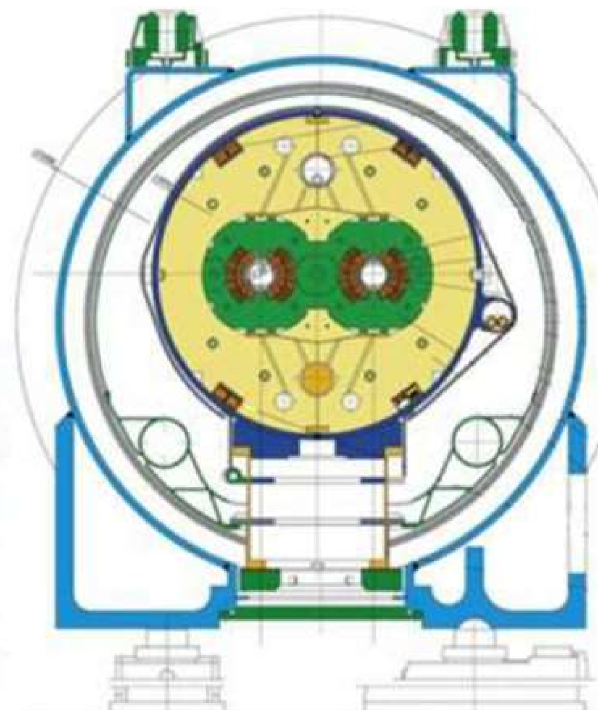
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

8.3T

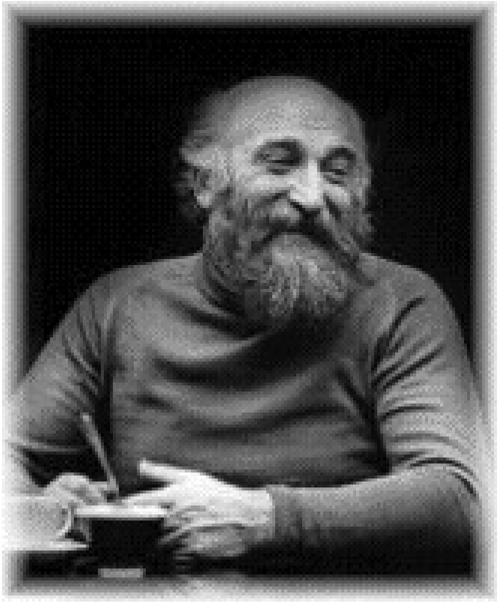
LHC,
15 m, 56 mm
1276 dipoles

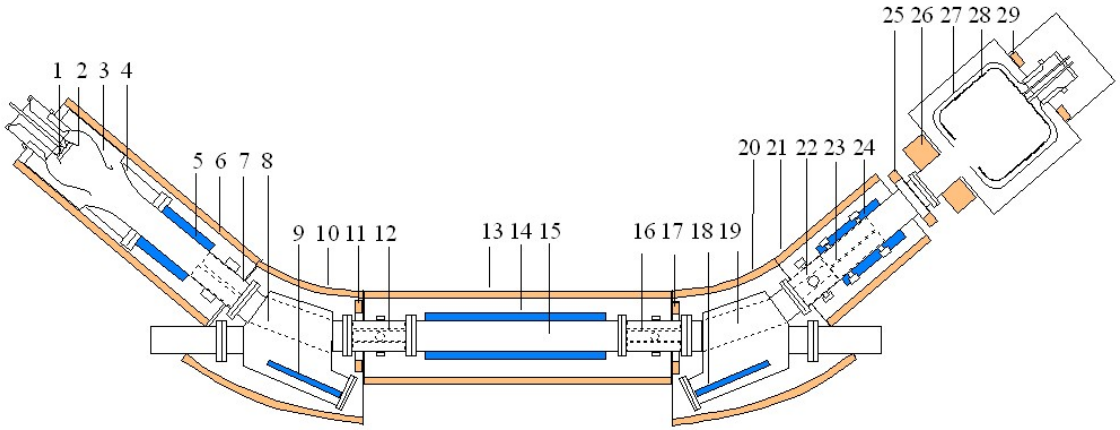


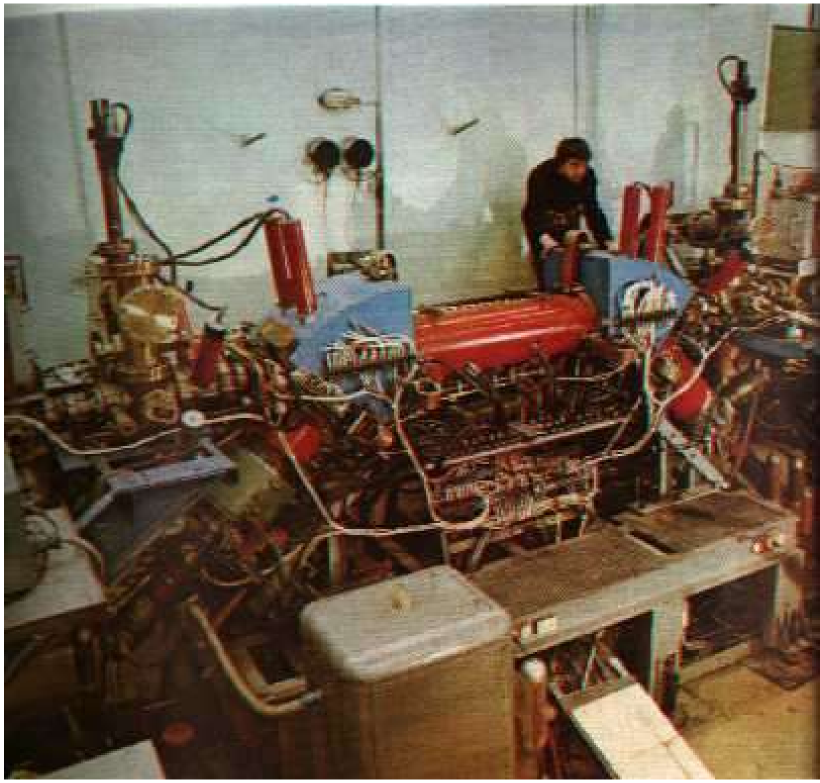
NbTi cable
2K He
two bores

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



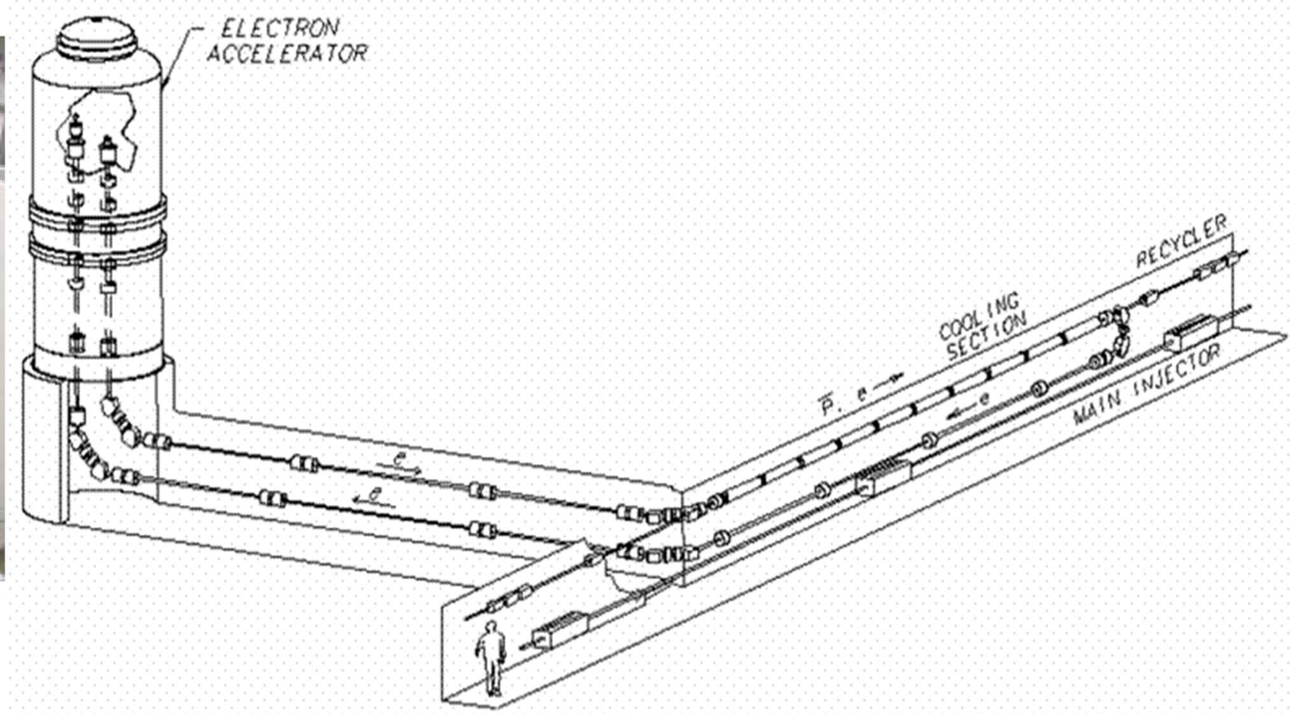




- Many installations since then, up to 300 kV electron beam (GSI, Darmstadt)
- FNAL 4.3 MeV cooler – next step in technology

Electron Cooling at FNAL

- Fermilab made next step in the electron cooling technology
- Main Parameters
  - 4.34 MeV pelletron
  - 0.5 A DC electron beam with radius of 6 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

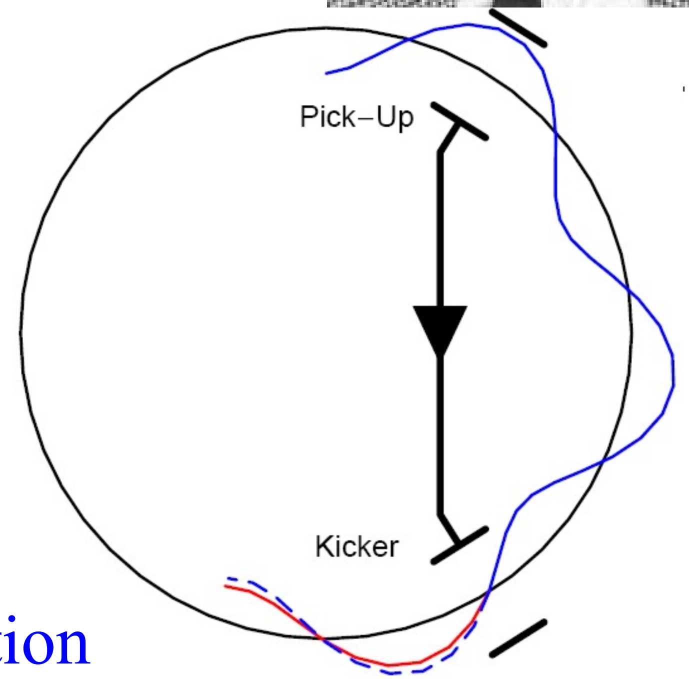
$$\delta\overline{\theta^2} = -\frac{1}{2}2g\overline{\theta^2} \equiv -g\overline{\theta^2}$$

- 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

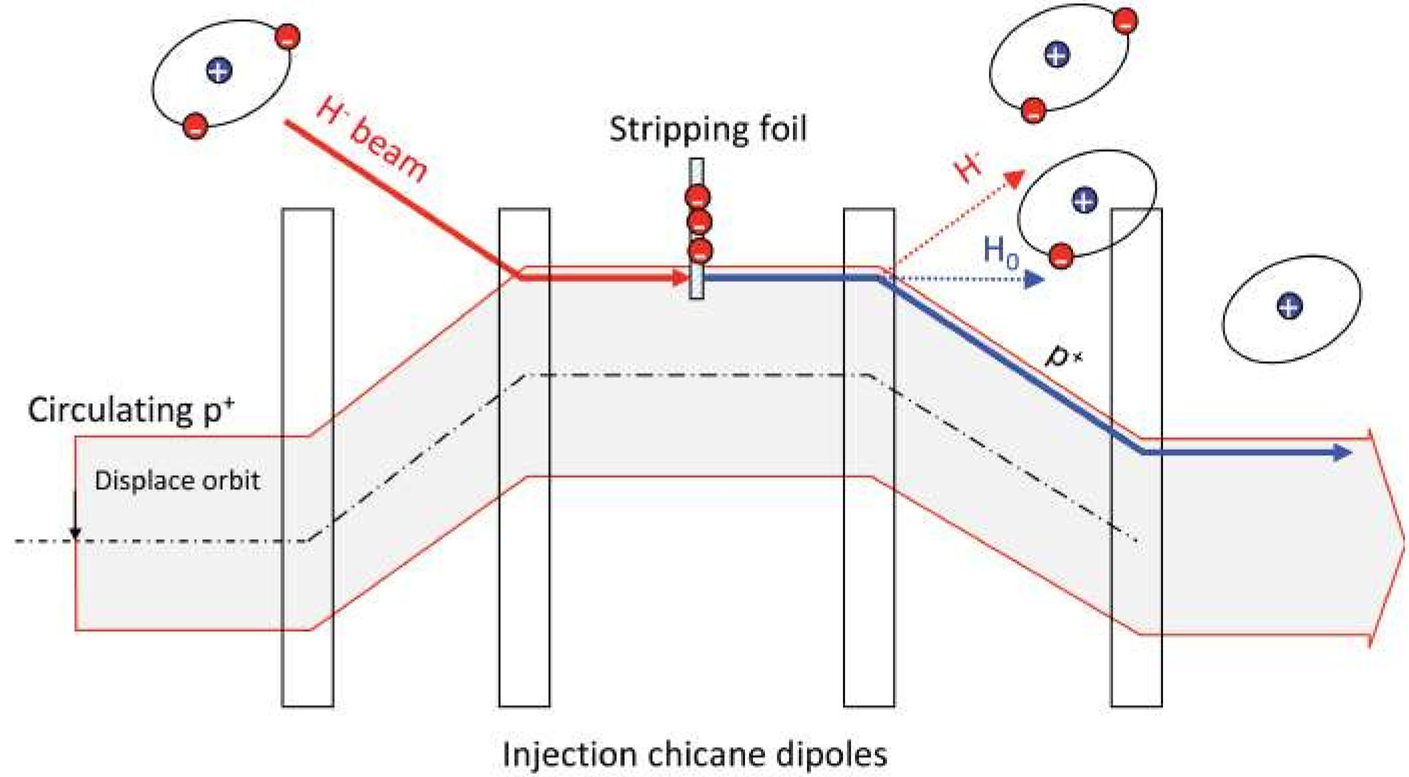
$$\delta\overline{\theta^2} = -\frac{1}{2}g_{opt}\overline{\theta^2} \quad , \quad g_{opt} = \frac{1}{2N_{sample}} \quad , \quad N_{sample} \approx N\frac{f_0}{W}$$



- 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

Strip Injection

- Invented by Budker, First implemented in INP (Novosibirsk)
- Used in many labs: Fermilab, CERN, Oakridge NL, JPARK, …

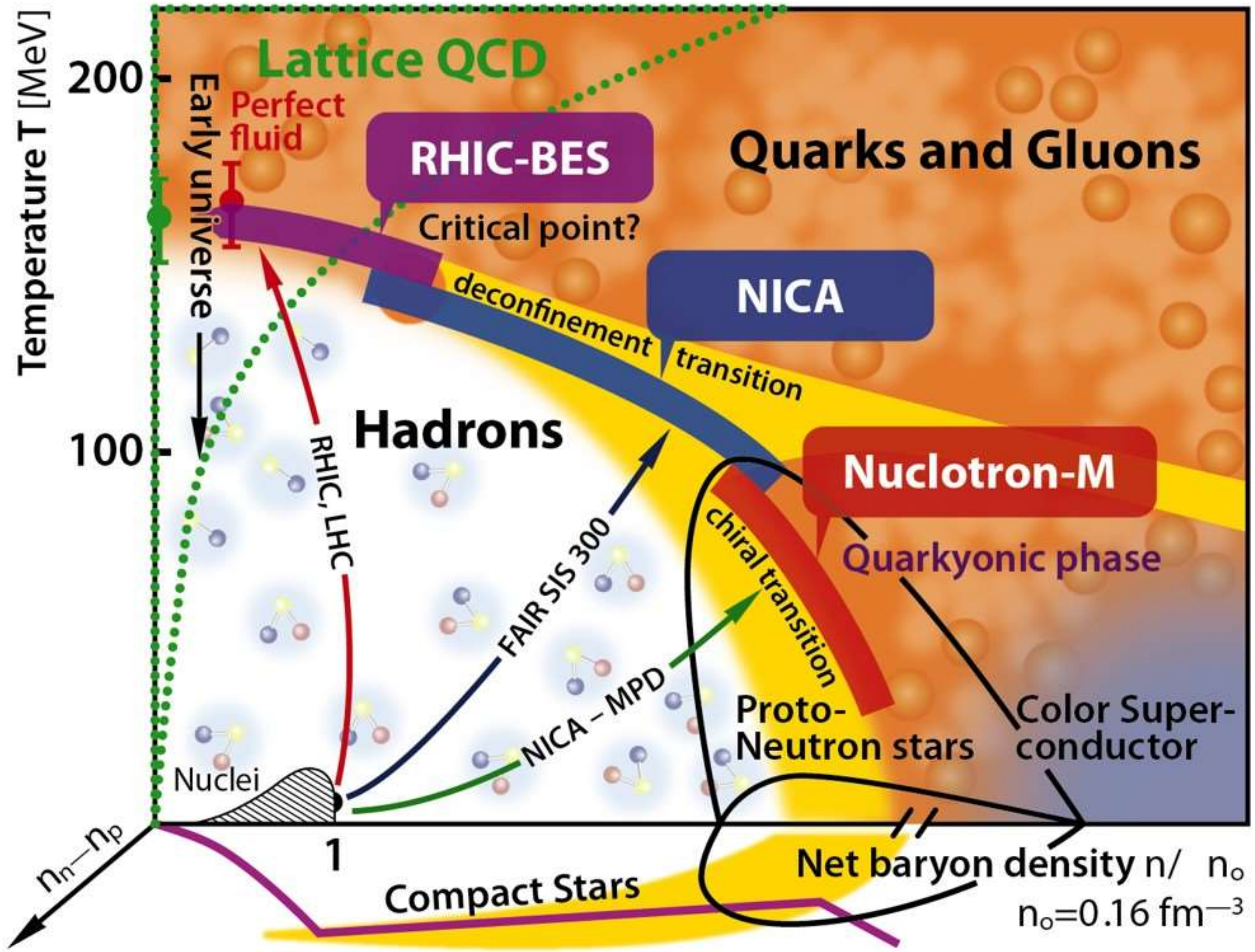


- Modern reincarnations (suggested in SNS in Oakridge):
  - Painting
  - Laser stripping

NICA – the First Hadron Collider in Russia

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? (MPD)
- Spin structure of the proton/deuteron (g-factor). (SPD)

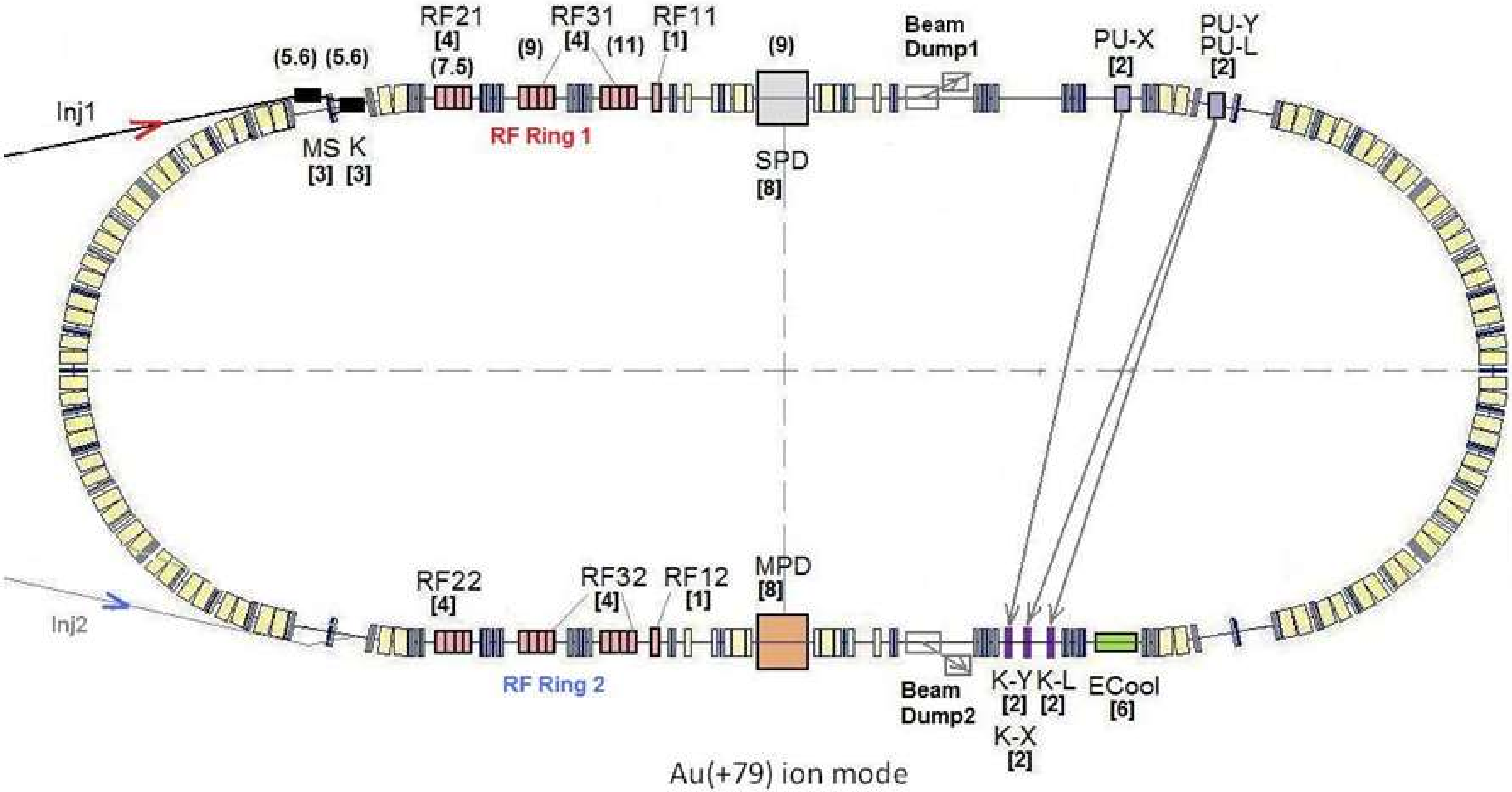
Why NICA?

- 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 (superferric) 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 (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

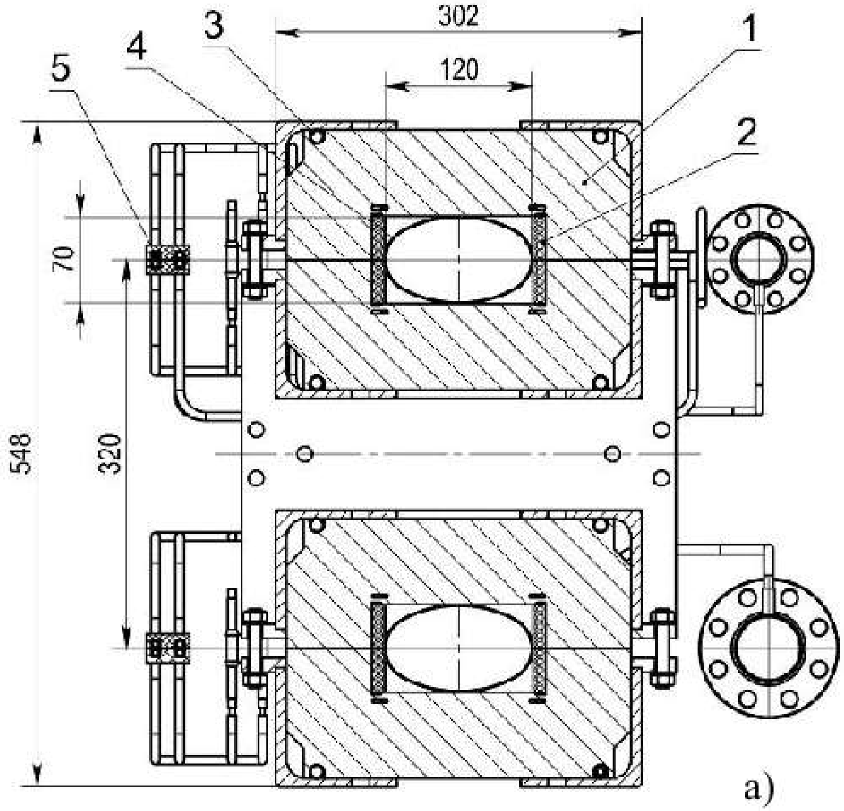


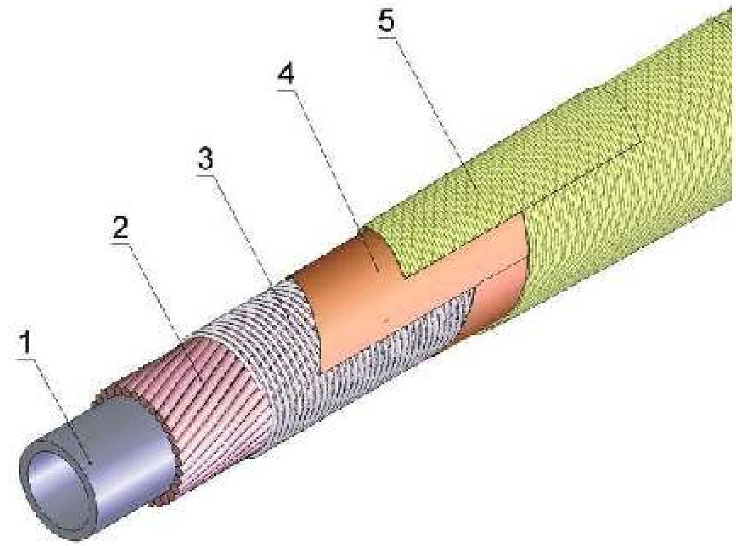
Two rings: one above another, 503 m circumference

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

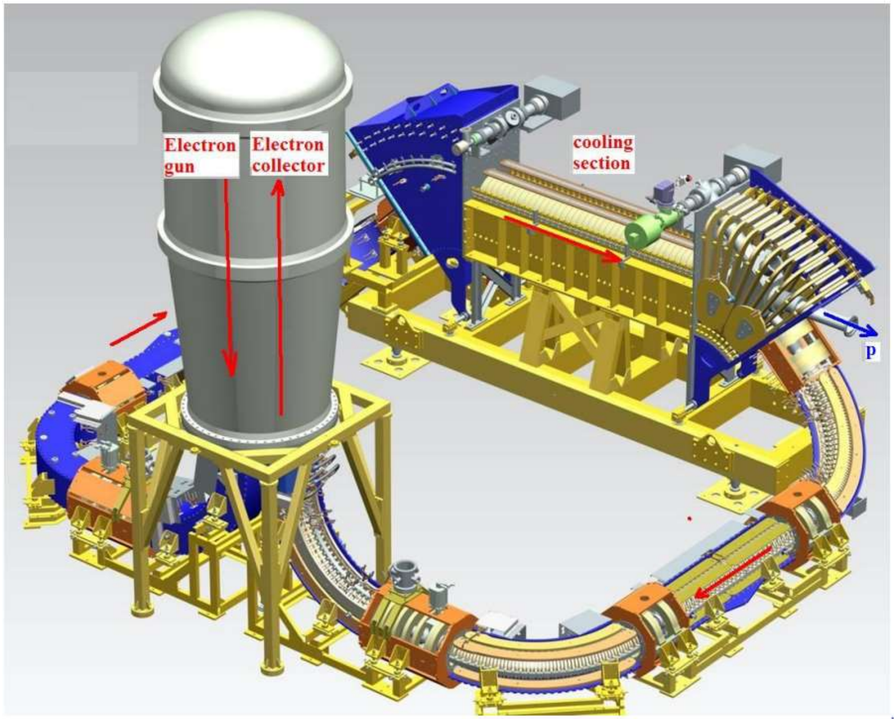
NICA dipoles





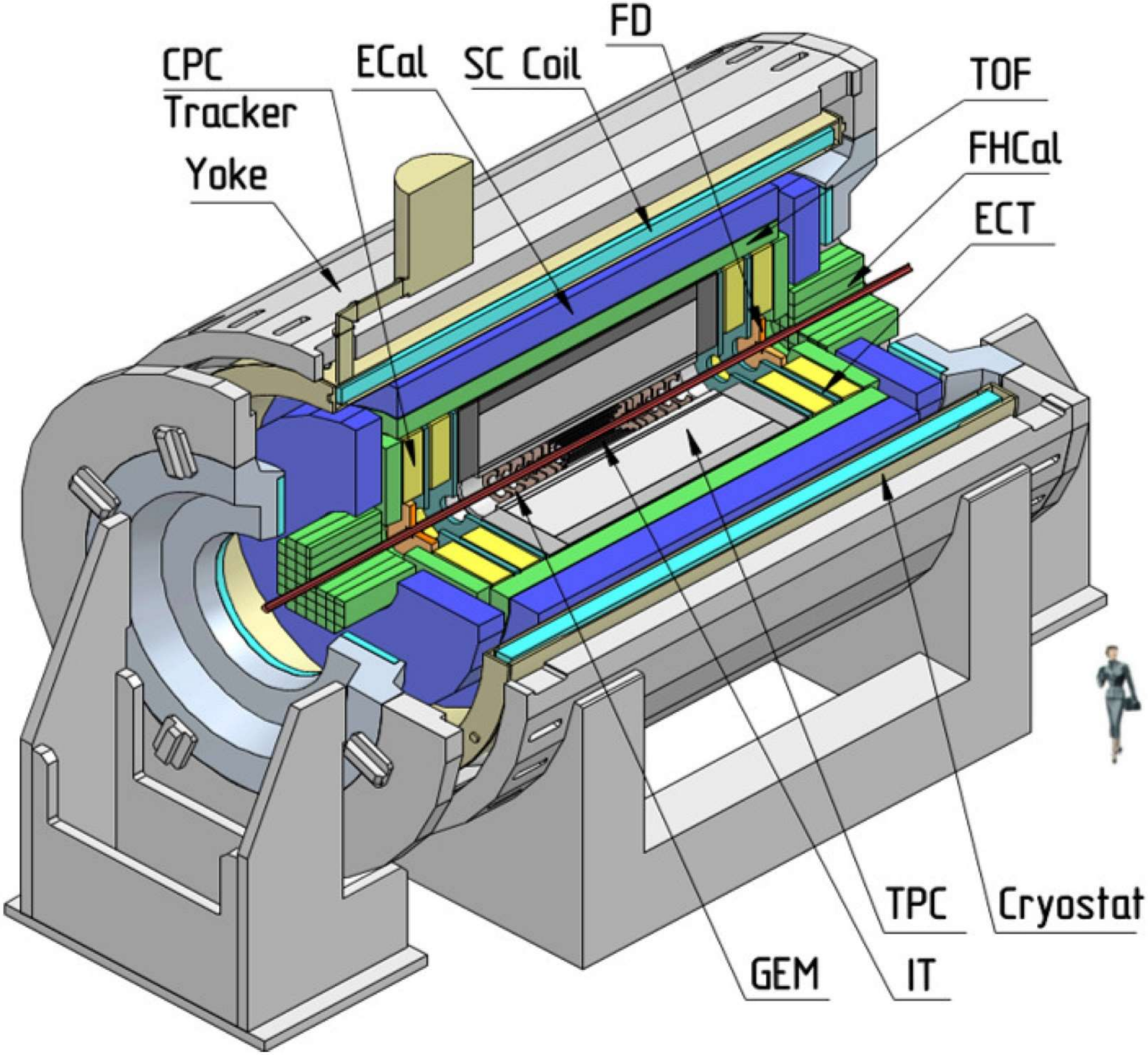
Beam Cooling

- 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
  - Lack of expertise strongly delayed its development
  - Still, we plan it be ready in ~2 years
  - Quite challenging system to cool a bunched beam. Very little margin for errors for cooling at the collisions. 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

Detector MPD



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

- At the end of this year we plan to inject beams into collider
- At the year beginning we started operations of injection complex (KRION ion source, heavy ion linac, Booster & Nuclotron)
  - The goal is an increase of particle flux by at least an order of magnitude relative to the last Run carried out 2.5 years ago
  - The means: beam accumulation with electron cooling in Booster and loss reduction in the accelerator string
- In about 2 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 are looking for young and enthusiastic people

Backup slides

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

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

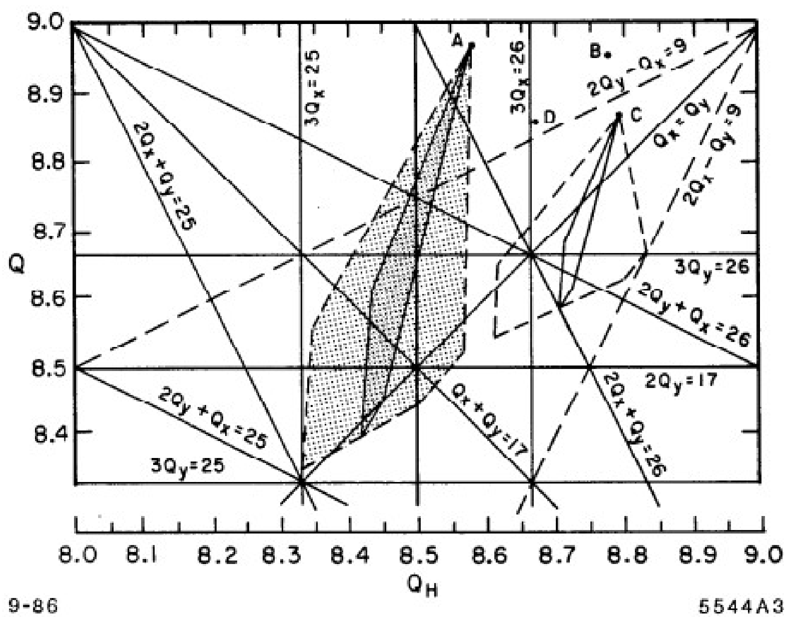


Fig. 3. Space charge tune shift of the AGS.

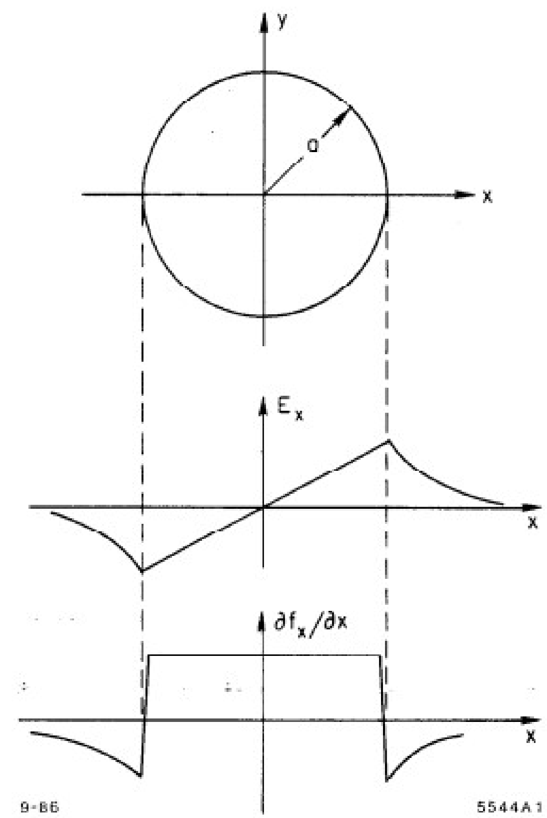


Fig. 1. Space Charge force of a uniform cylindrical beam.

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

Beam-beam Effects

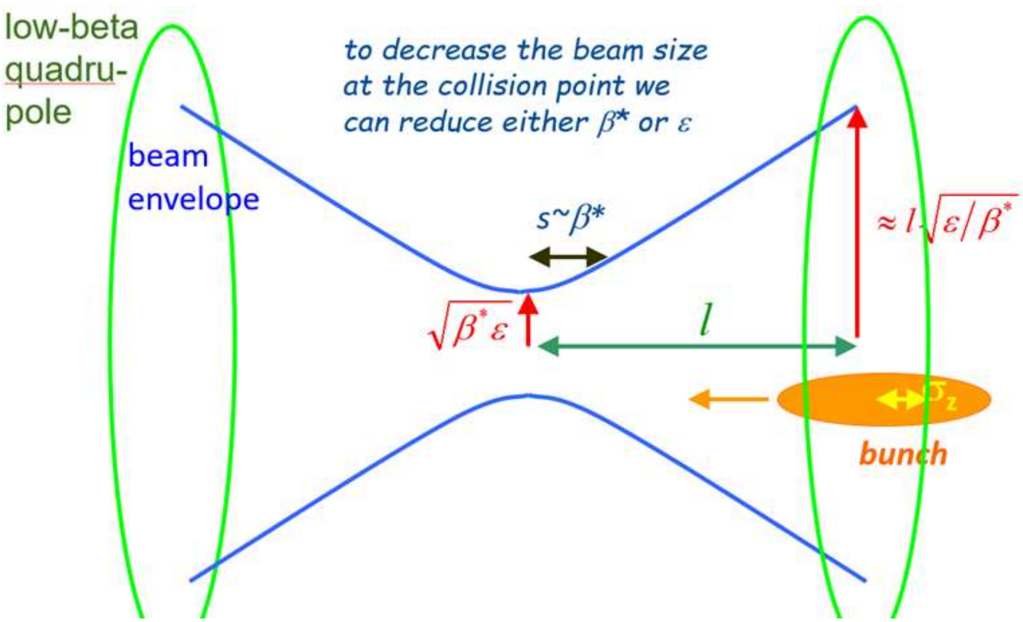
- The beam-beam tune shift is similar to the space charge tune shift but is engaged in the IPs only. The tune shift per IP:

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

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

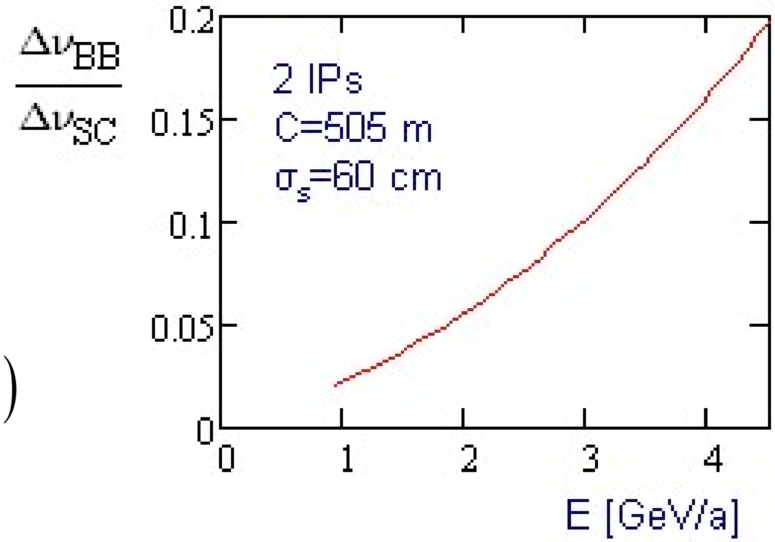


- Smaller β^* yields larger β-function and beam size in quads

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

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:

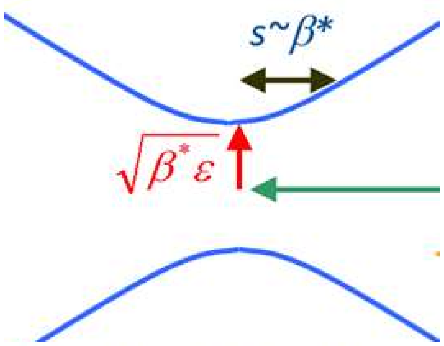
$$\frac{\delta\nu_{BB}}{\delta\nu_{SC}} = N_{IPs}\sqrt{\frac{\pi}{2}}\frac{\sigma_s}{C}\gamma^2\left(1+\beta^2\right)$$

- 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)

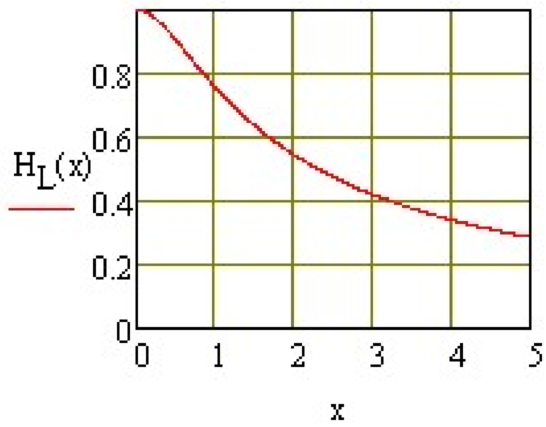
$$L = \frac{f_0 n_b N_i^2}{4\pi\beta^*\varepsilon} H_L(\sigma_s / \beta^*), \quad H_L(x) = \frac{2}{\sqrt{\pi}} \int_0^\infty \frac{\exp(-y^2)}{1 + x^2 y^2} dx$$



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

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

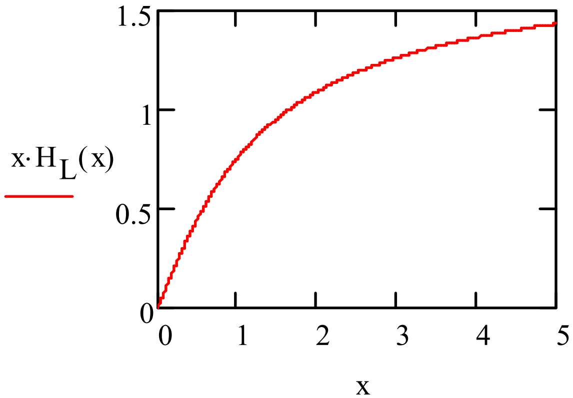
  - Weak dependence of SC tune shifts on optics



- SC limits the beam longitudinal density, N_i / σ_s
- Combining the above equations, one obtains a luminosity limitation

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

  - 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)