Colliders

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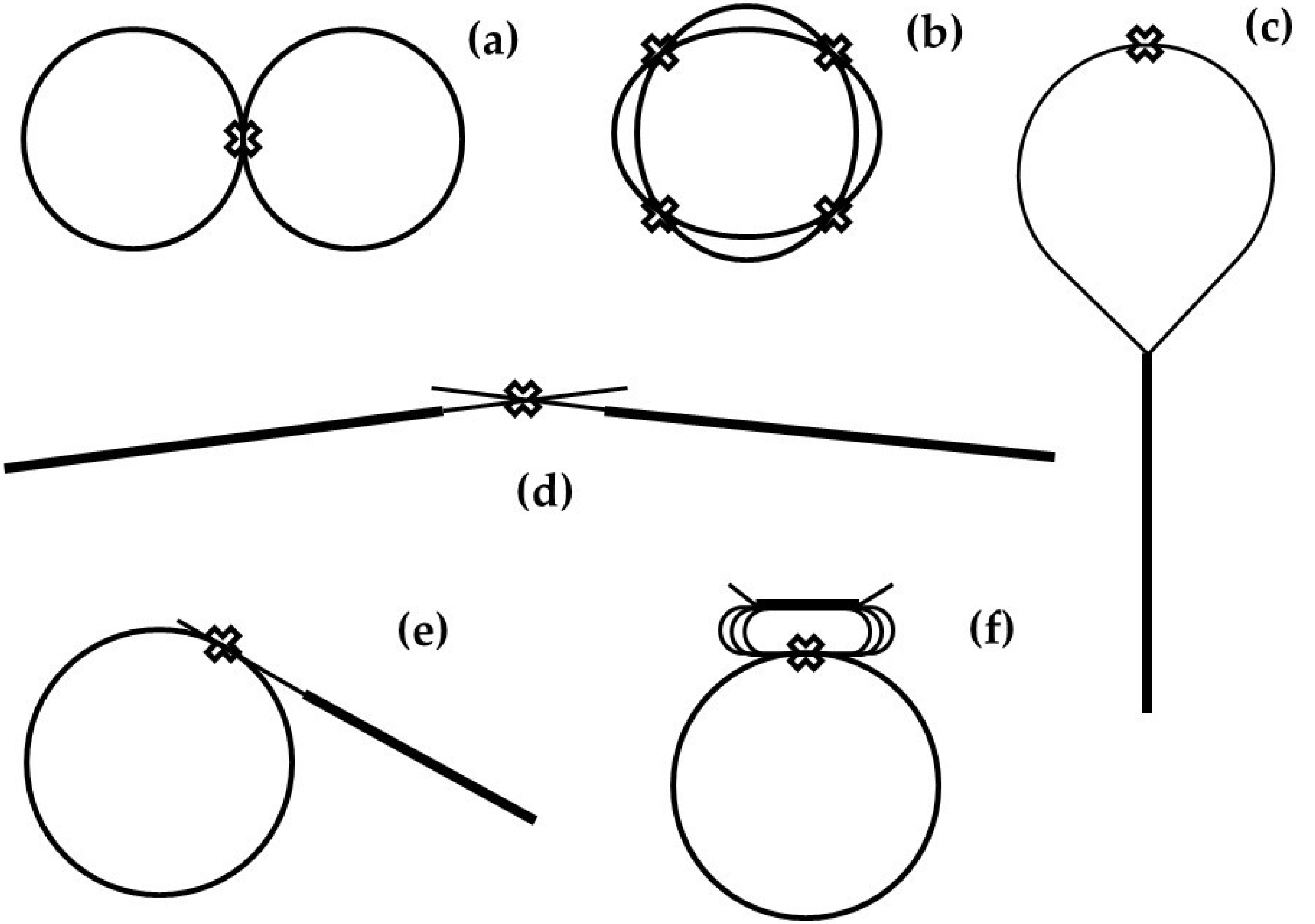
Outline

- Types of colliders
- Collision energy and luminosity
- Collider’ landscape
- Basics concepts
- Present and Future colliders
- Beam cooling

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)

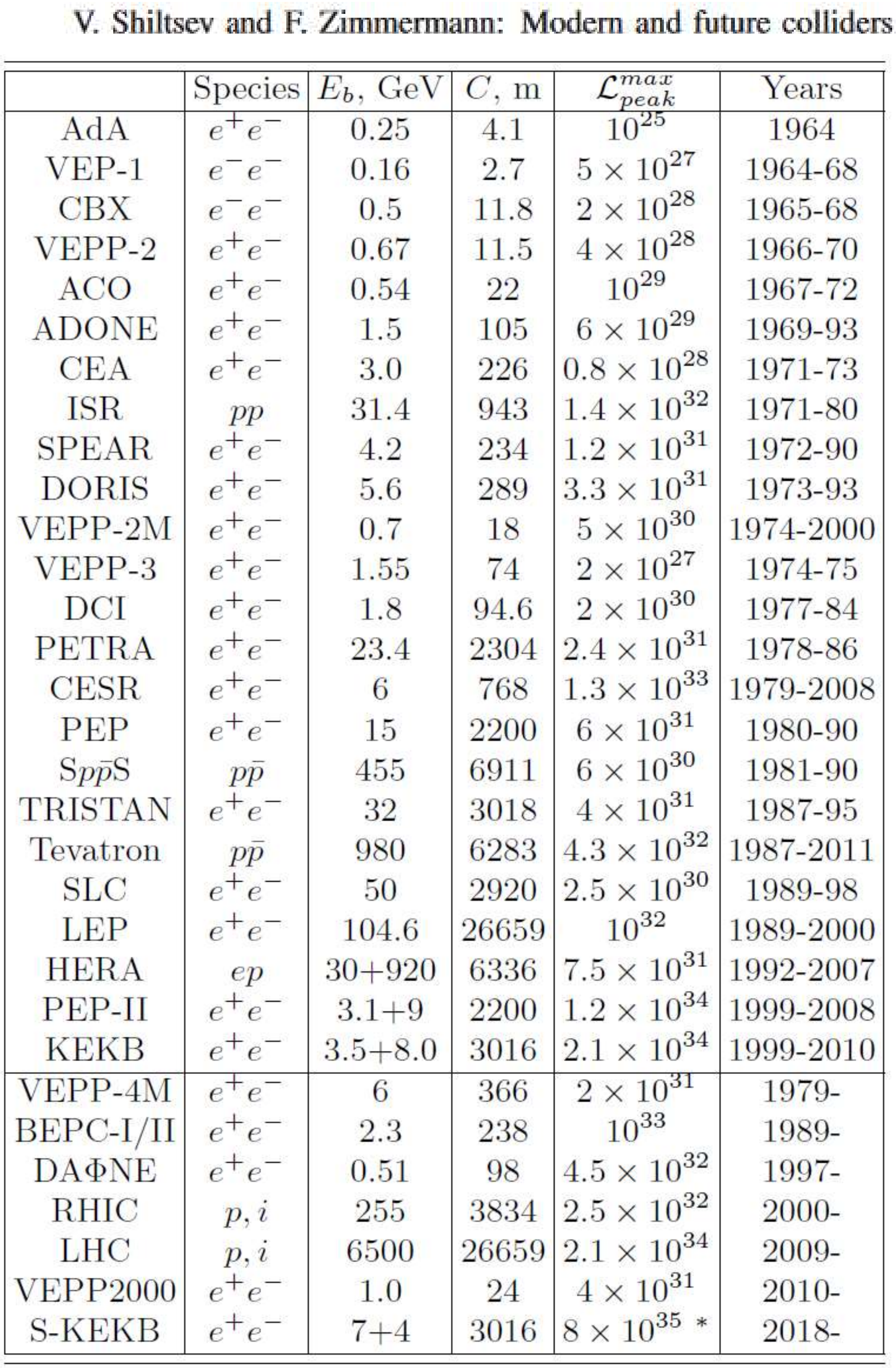
- Number of events in collisions:

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

- Detectors want constant luminosity

Colliders Landscape

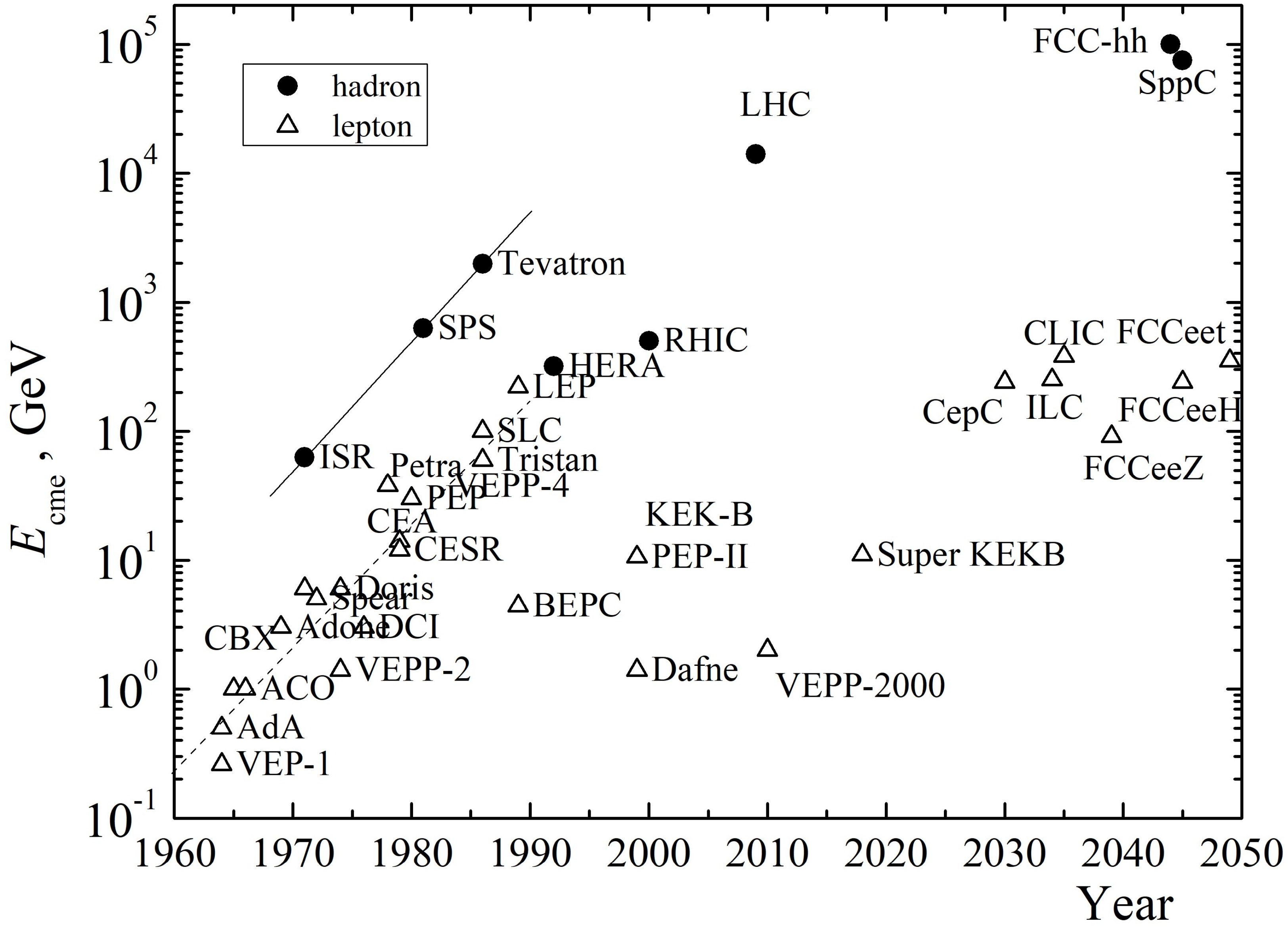
- 59 years since 1st collisions
    - Spring 1964 AdA and VEP-1
- 31 operated since
- 7 in operations now
    - S-KEKB, VEPP-2000, VEPP-4M, BEPC, DAFNE
    - LHC, RHIC
- 1 under construction
    - NICA
- One in a project phase
    - EIC
- Far plans
    - Higgs/Electroweak factories
        - ILC
   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



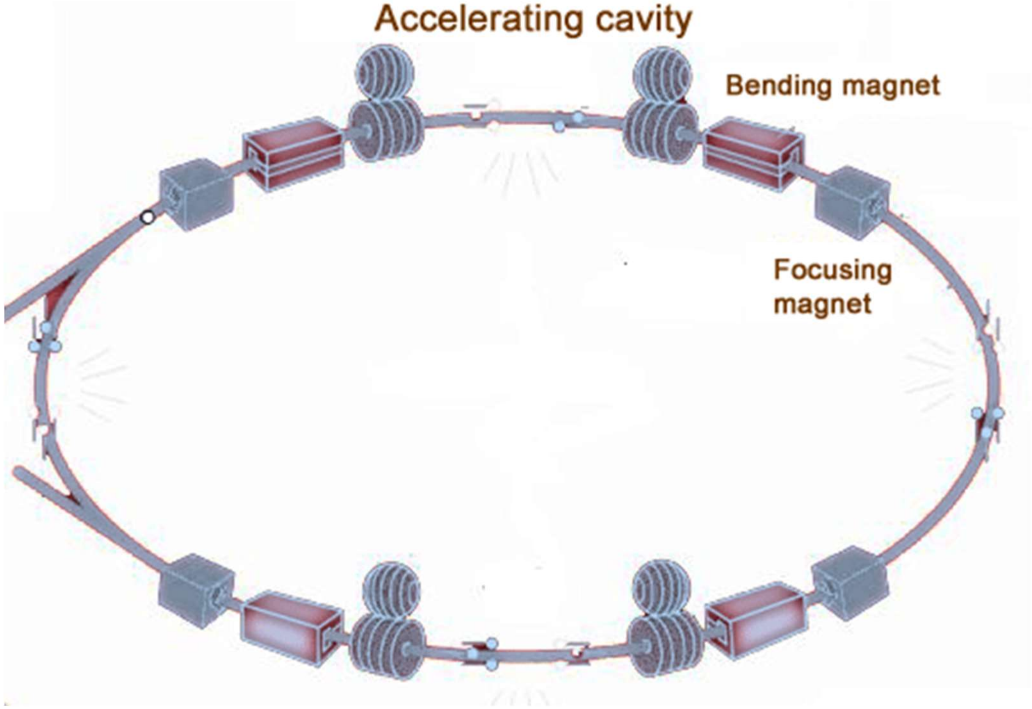
V. Shiltsev and F. Zimmermann: Modern and future colliders

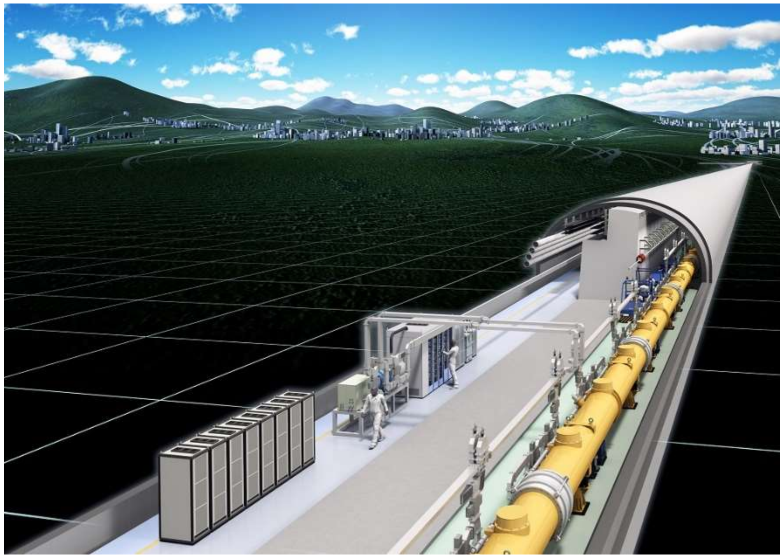
	Species	E_b, GeV	C, m	$\mathcal{L}^{max}_{peak}$	Years
AdA	e^+e^-	0.25	4.1	10^{25}	1964
VEP-1	e^-e^-	0.16	2.7	5×10^{27}	1964-68
CBX	e^-e^-	0.5	11.8	2×10^{28}	1965-68
VEPP-2	e^+e^-	0.67	11.5	4×10^{28}	1966-70
ACO	e^+e^-	0.54	22	10^{29}	1967-72
ADONE	e^+e^-	1.5	105	6×10^{29}	1969-93
CEA	e^+e^-	3.0	226	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

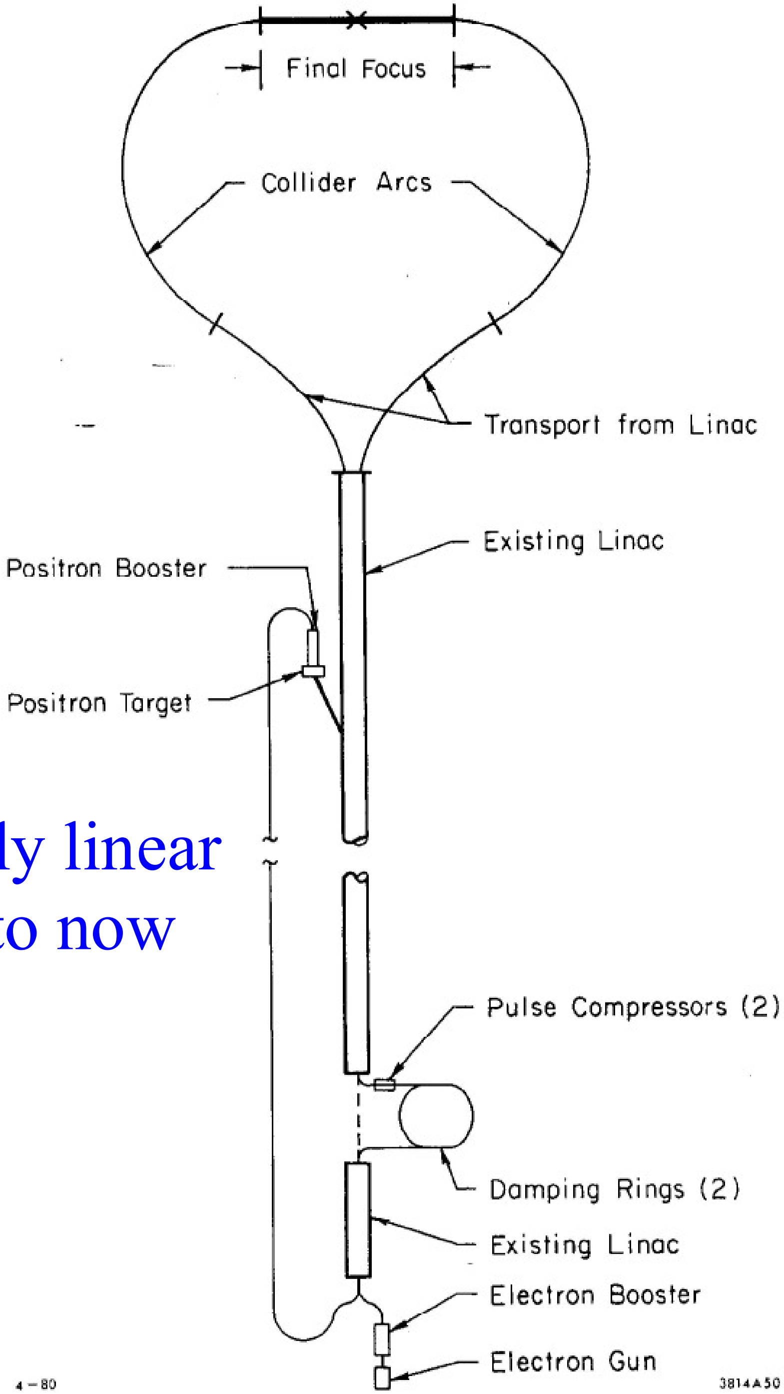


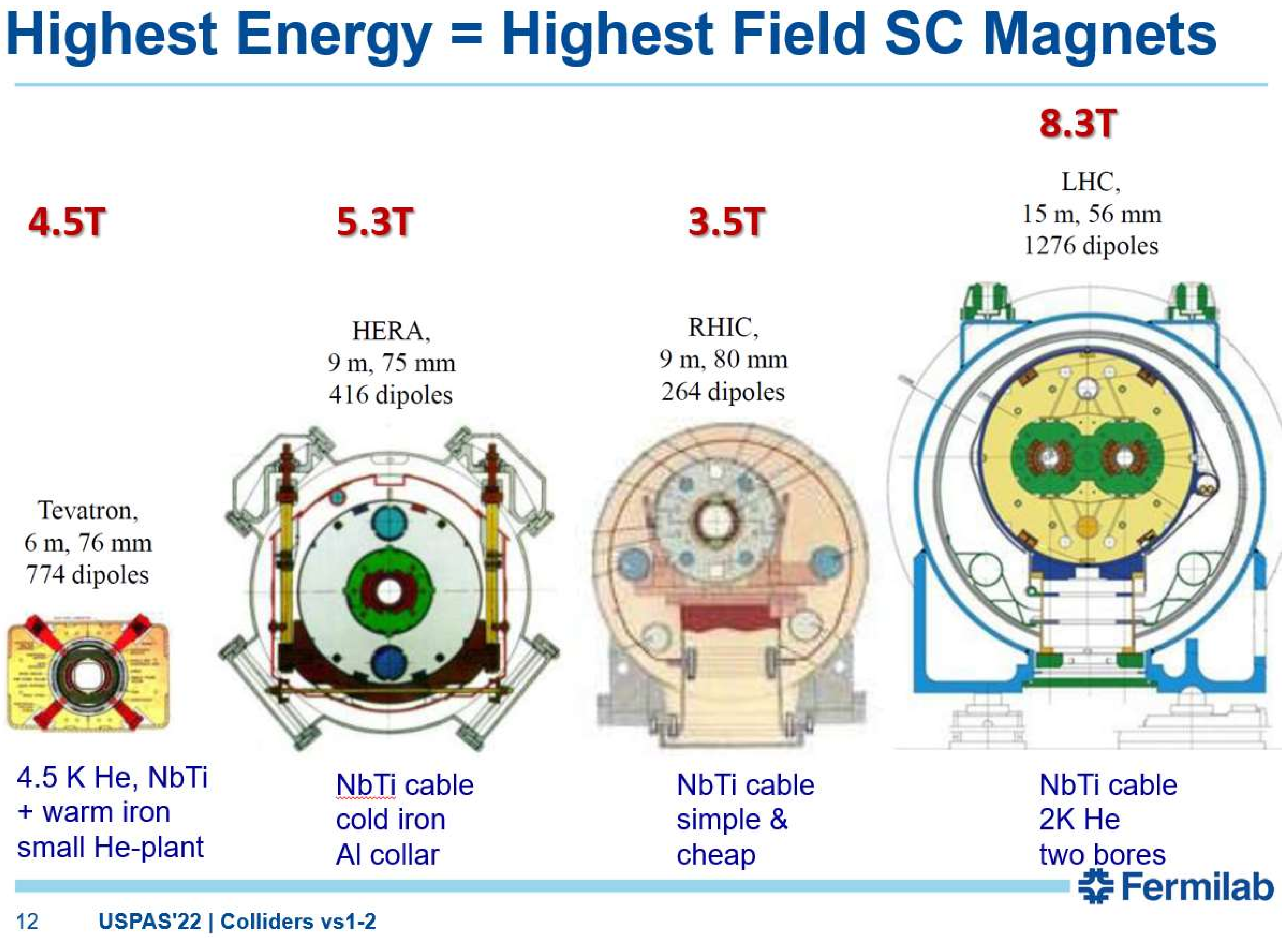
Rings vs Linacs





- 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

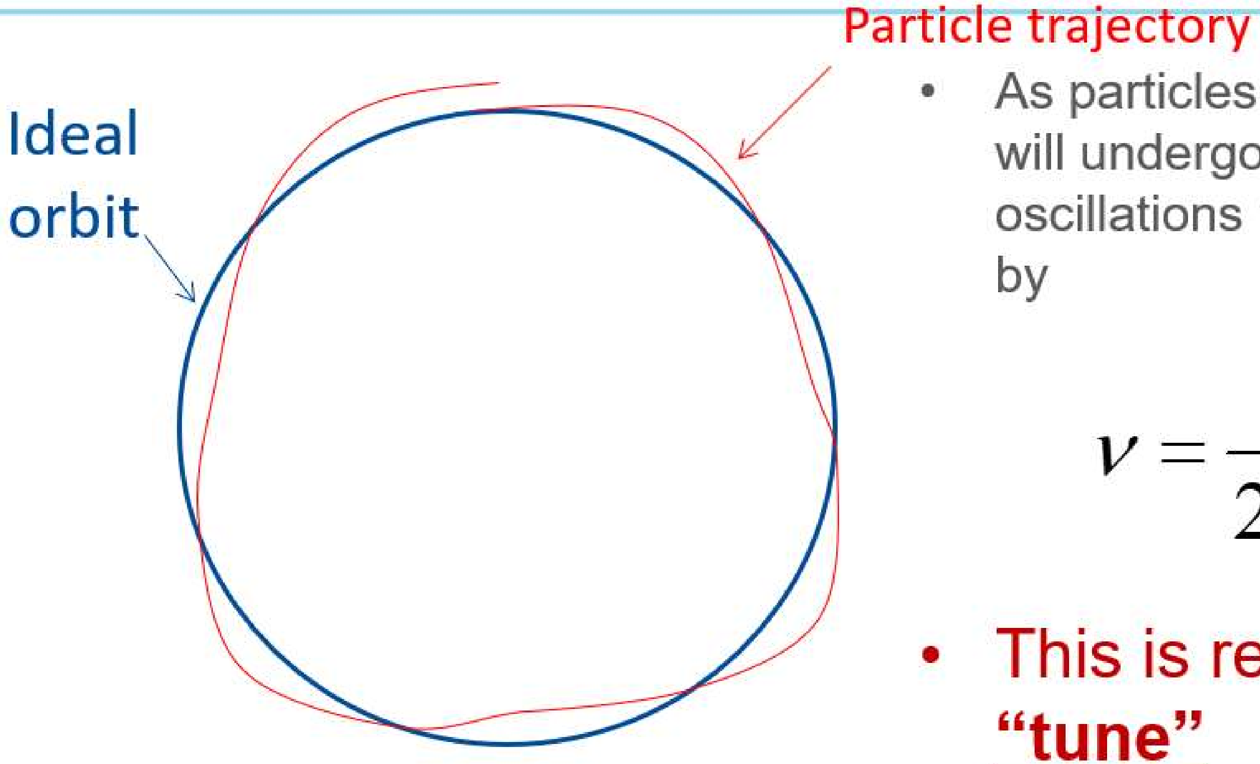
8.3T

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 *v* (sometimes Q) given by

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

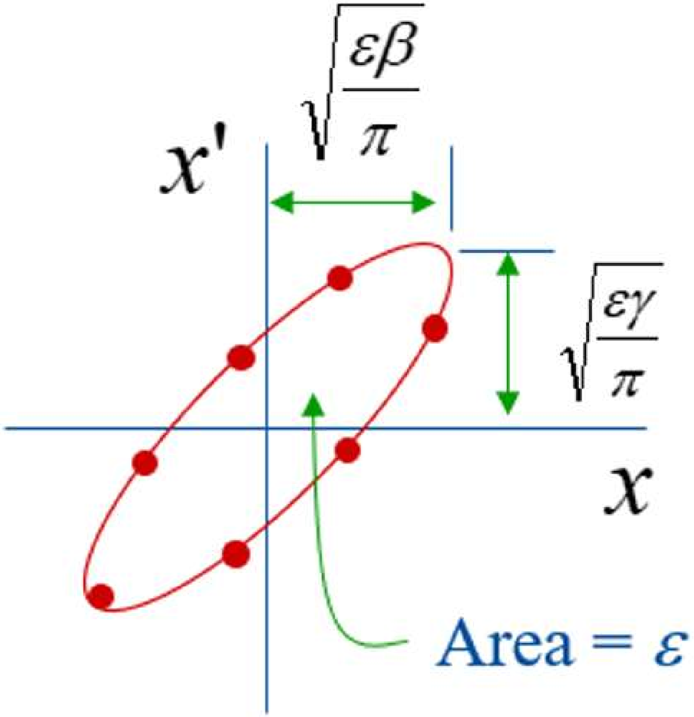
- This is referred to as the **"tune"**

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

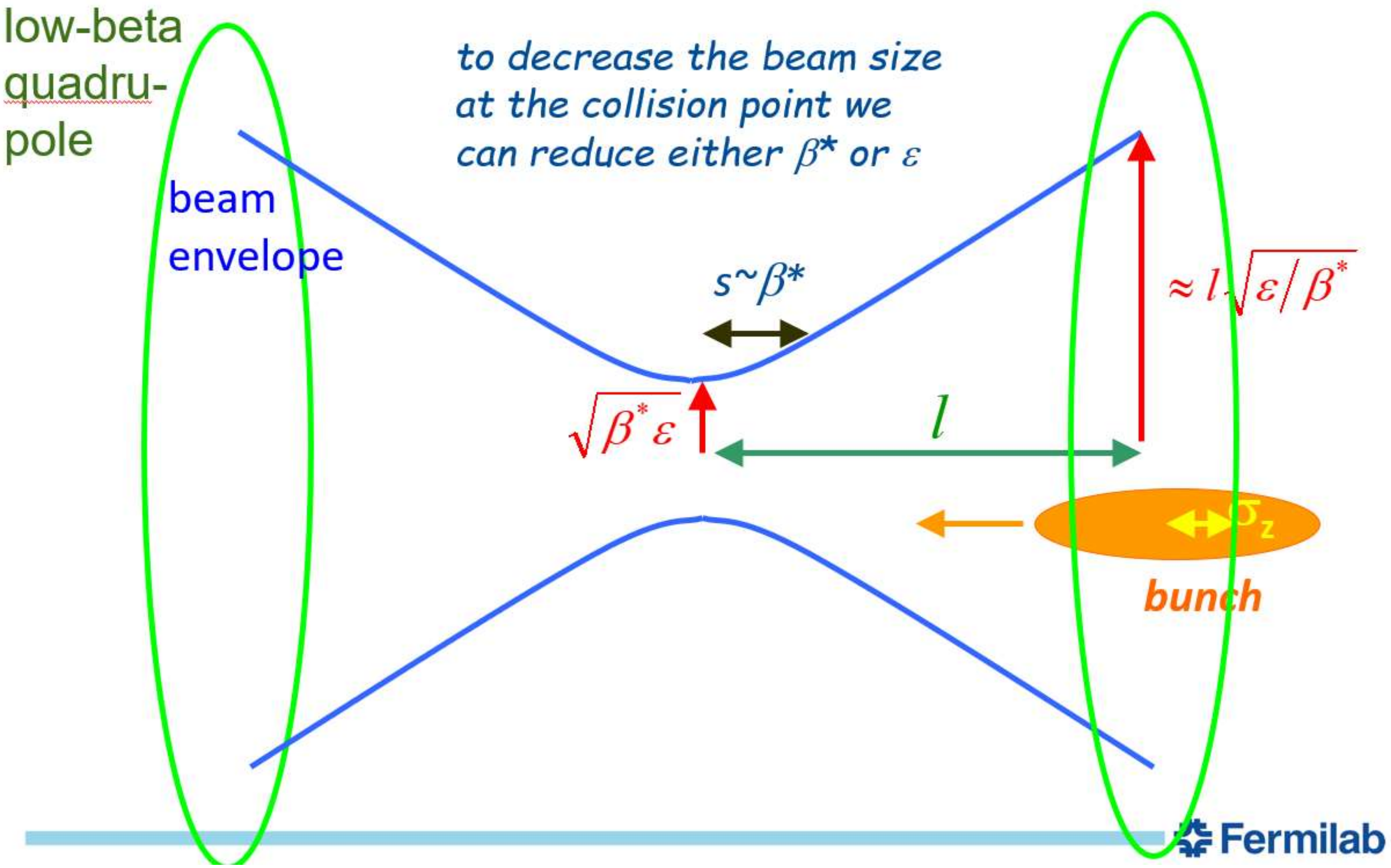
Integer : magnet/aperture optimization → **64.31** ← **Fraction: Beam Stability**

Emittance

- 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: $\boxed{\sigma_{x,y} = \sqrt{\dfrac{\varepsilon_n \cdot \beta_{x,y}}{\gamma}}}$
- Luminosity ~ 1/ε



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

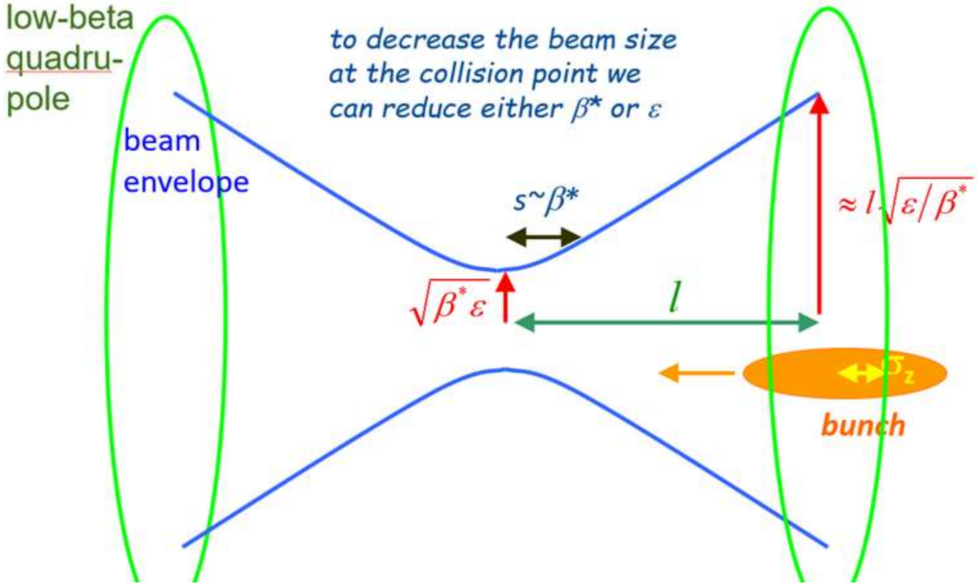
Beam-beam Effects

- 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

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



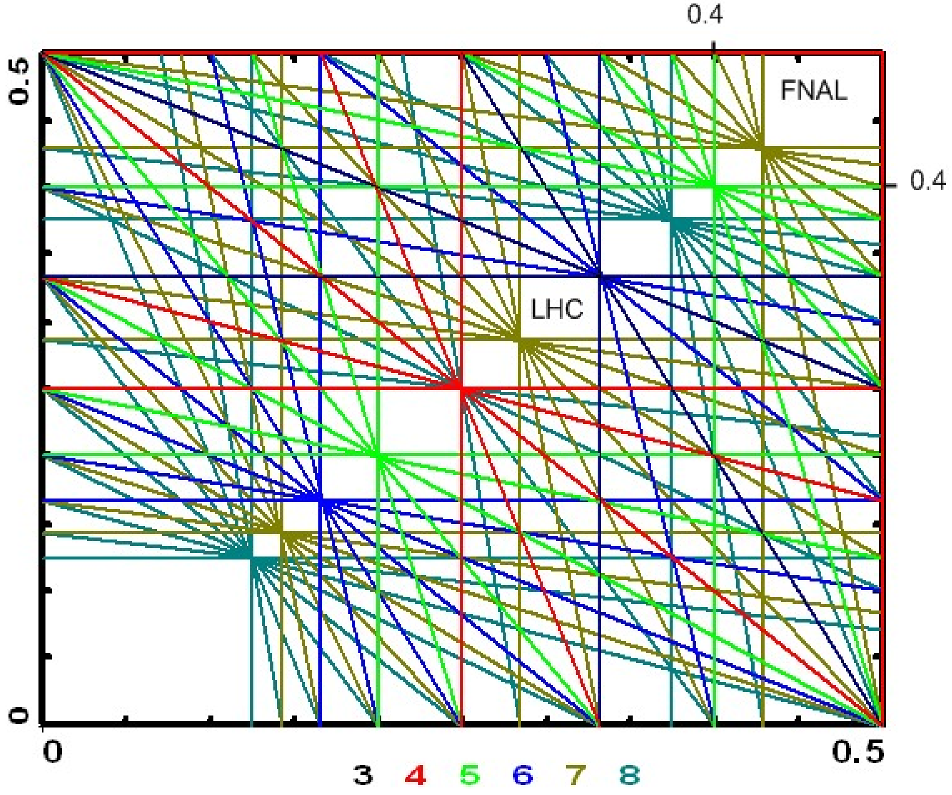
  - ♦ Magnetic field of counter rotating beam almost doubles force, $1+\beta^2$
  - ♦ Note that for large synchrotron amplitude the tune shift increase due to larger beta-function with longitudinal displacement is compensated by decrease of space charge field => no dependance on bunch length

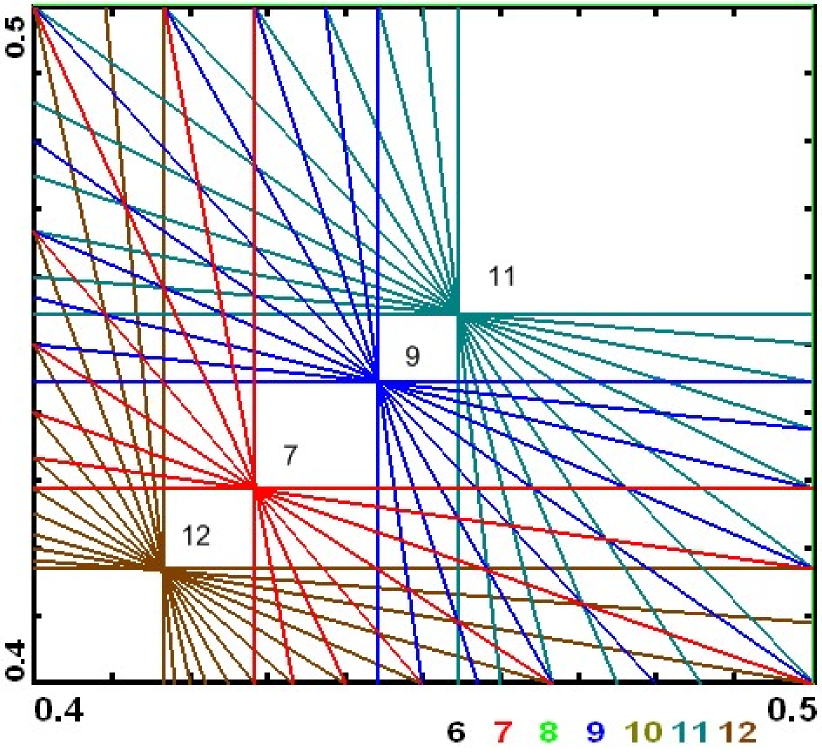
- Smaller β^* yields larger β-function and beam size in quads

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

Collider Betatron Tunes

- Stochastic cooling requires betatron tunes close to half-integer to avoid the Schottky band overlap
- Odd resonances are suppressed in the absence of parasitic collisions
- Tunes ~[x.42, x.46] are chosen for NICA (same as Recycler)
  - Inversion of Tevatron tunes (~0.582 -> 0.418)
- Tevatron suffers from 7-th order (parasitic collisions) and 12-th order (will be suppressed by cooling in NICA)

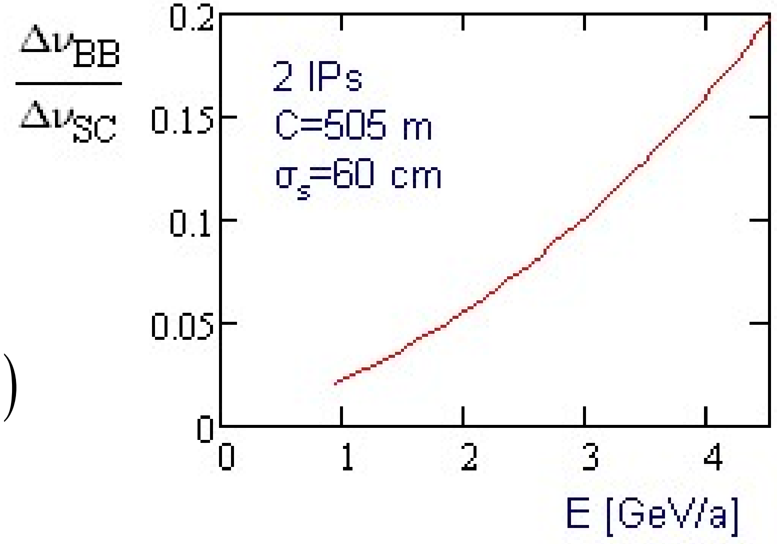




Possible Values of Tune Shifts

- 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

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

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

- 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)

Luminosity Lifetime

- Sources of particle loss
  - Scattering at the residual gas
    - Rutherford scattering
    - Nuclear scattering
    - Capture of residual gas electrons (fully stripped heavy ions,E<1 GeV)
    - Multiple small-angle scattering leading to $d\varepsilon/dt$ in cooling absence

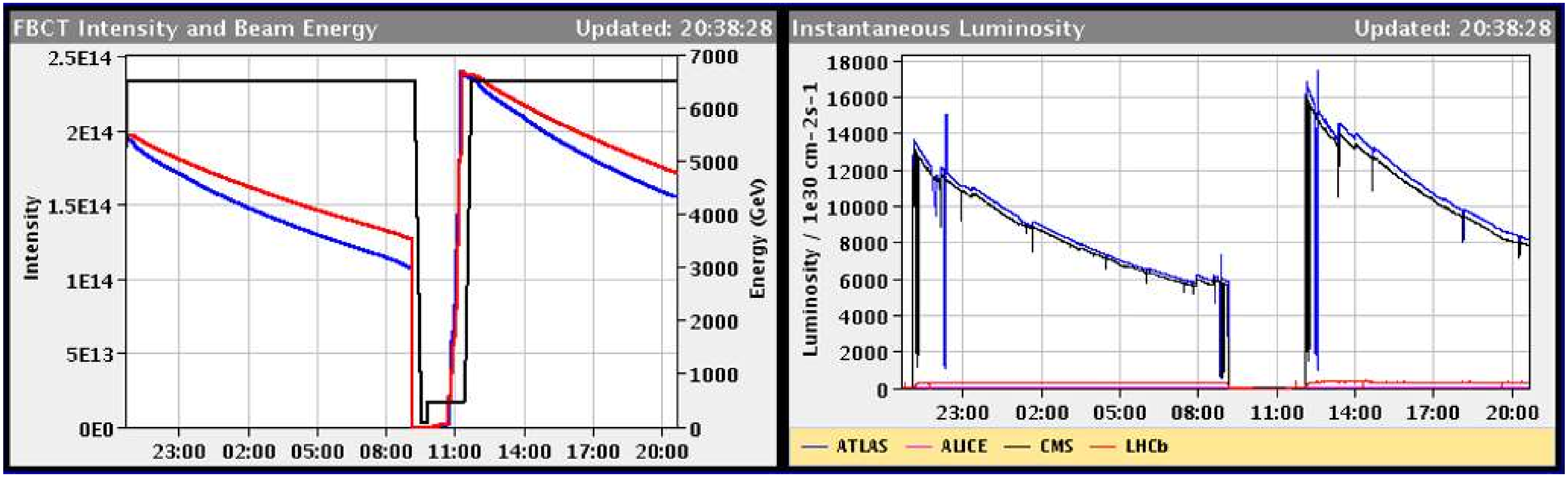
      Without cooling more powerful mechanism than single scattering
  - Nuclear and Rutherford scattering in the IPs
  - Noise in RF system (phase and amplitude)
  - Electron capture in the electron cooler
  - Non-linear resonances due to space charge and beam-beam effects
    - Very powerful mechanism typically observed at the store beginning in the absence of cooling
    - Electron cooling rate grows fast with decrease of amplitude. That can lead to overcooling and particle loss increase with time
      - Observed in Fermilab Recycler

Luminosity Evolution

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

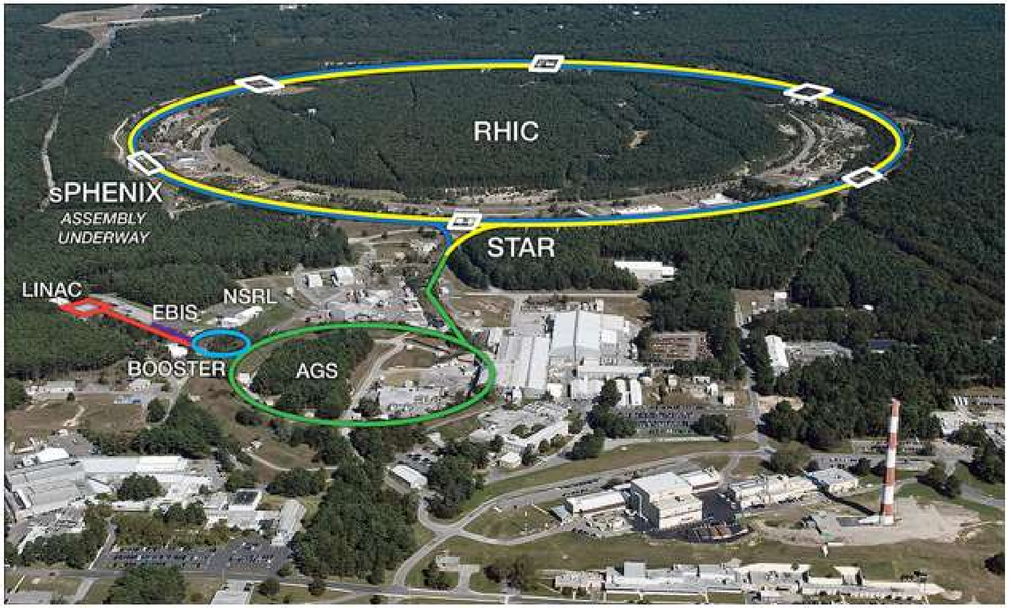
- Factors change in time: $L(t) = C\dfrac{N_1(t) N_2(t)}{\varepsilon(t)} H(t)$
- Therefore, in the absence of cooling the lifetime

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

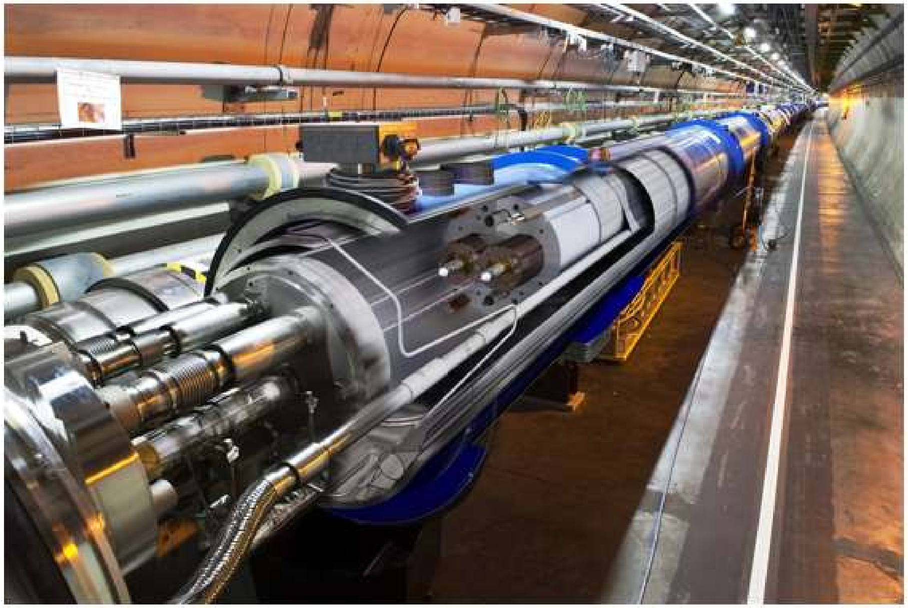


LHC luminosity plot

Present Hadron Colliders



RHIC (BNL, Brookhaven)



LHC (CERN)

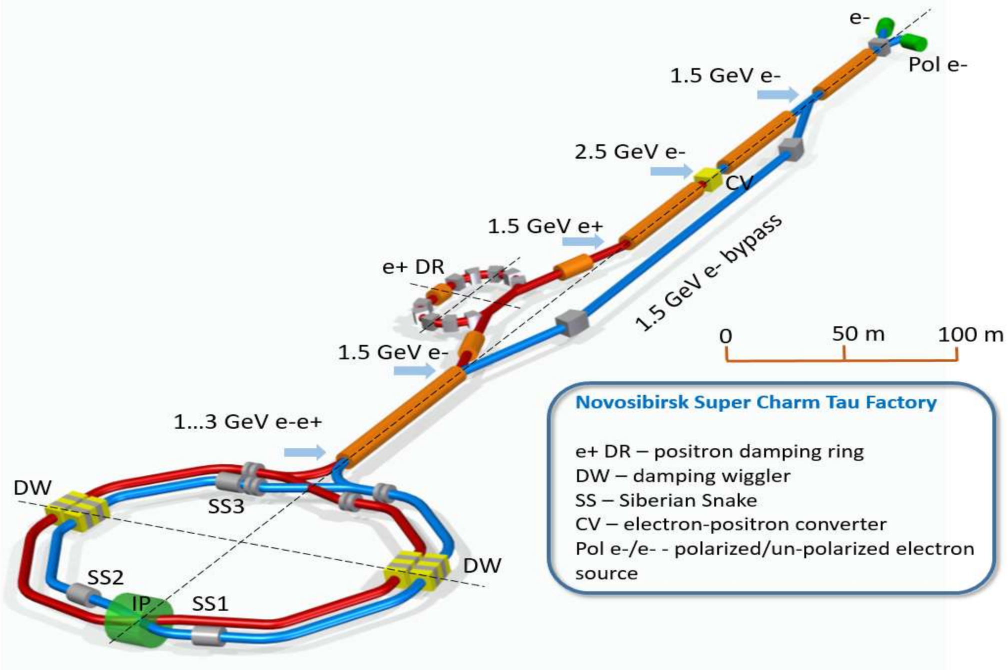
- RHIC is NICA's main competitor

Colliders That Will Be

NICA (JINR, Dubna)

Main Parameters of The NICA Collider

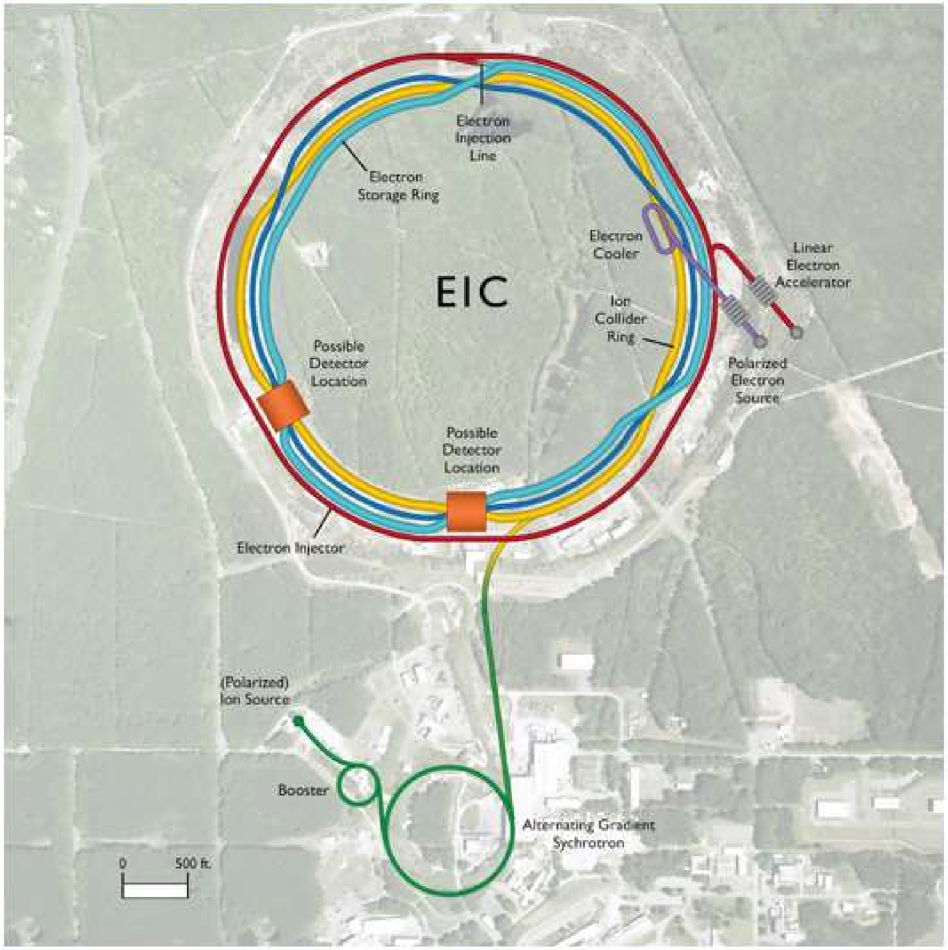
Circumference, m	503,04		
Bunch number per ring	22		
Mean-square bunch size, m	0.6		
Min. beta-function (β^*), m	0.6		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch, 1e9	0.275	2.4	2.2
Peak luminosity, cm^{-2}·s^{-1}	0.9e25	0.9e27	6.3e27



Novosibirsk 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)



Cooling at Collision Energy

- The planned luminosities of hadron colliders cannot be achieved without beam cooling at collisions (LHC has SR damping)
- Present cooling technologies are good enough to support NICA
- However, there is a great challenge to cool dense high energy bunches at the collision energy in ep-collider planned by BNL
    - BNL demonstrated stochastic cooling of heavy fully stripped ions at ~150 GeV/a at RHIC
    - However, due to much larger number of protons per bunch in ep-collider, the cooling rate for proton beam are way too small to be useful
- We need cooling method capable to cool dense ultra relativistic bunches
    - Present electron cooling technology does not allow cooling above 10 GeV
    - Present technology of stochastic cooling based on microwaves (<10 GHz) has cooling rates 2-3 orders of magnitude below required
- Possible was to address the problem: stochastic cooling at optical frequency & electron cooling not based on electrostatic acceleration

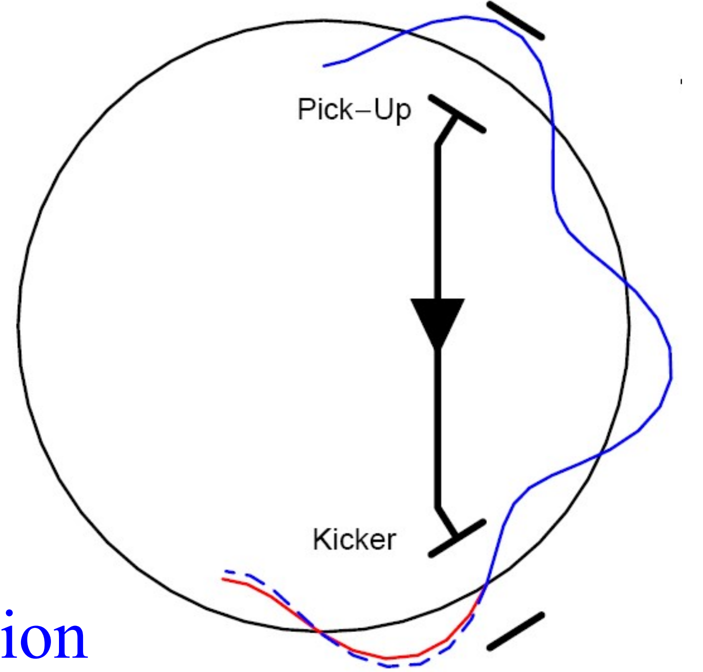
Stochastic Cooling

- 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

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

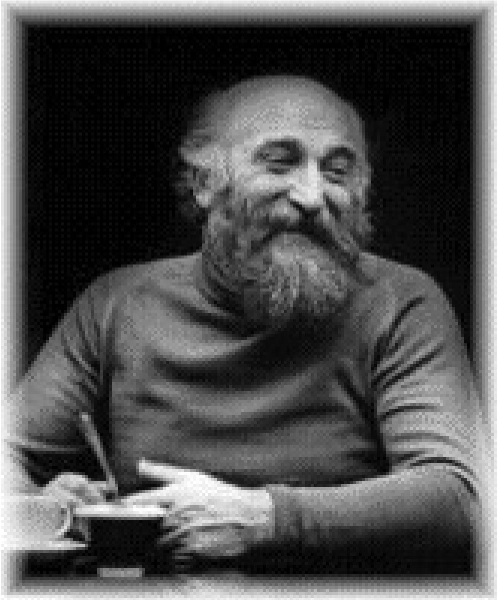
- That yields

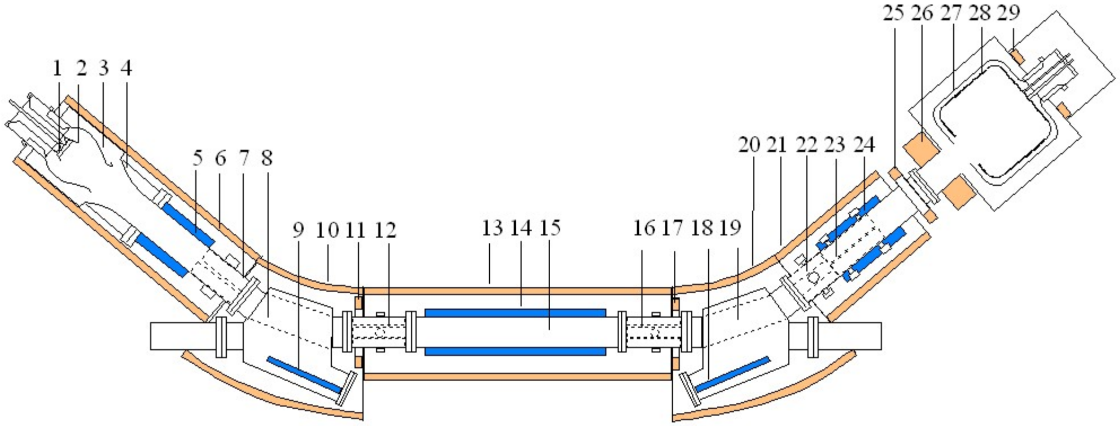
$$\boxed{\delta\overline{\theta^2} = -\frac{1}{2}g_{opt}\overline{\theta^2} \quad , \quad g_{opt} = \frac{1}{2N_{sample}} \quad , \quad N_{sample} \approx N\frac{f_0}{W}}$$

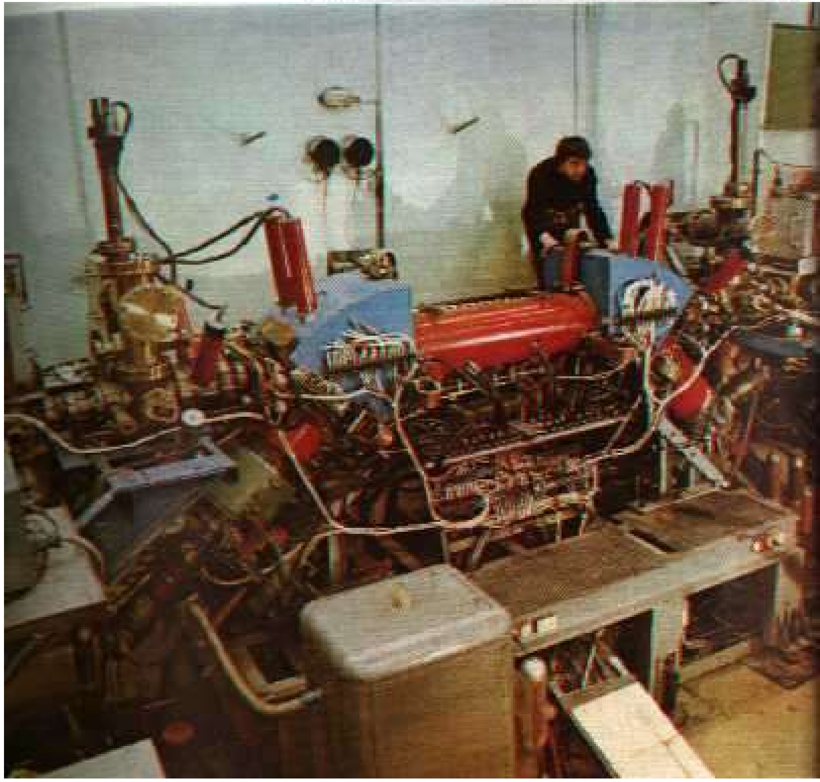
- In accurate analytical theory the cooling process is described by Fokker-Planck equation
  - The theory is built on the same principle as plasma theory – which is a perturbation theory (large number of particles in the Debye sphere versus large number of particles in the sample

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



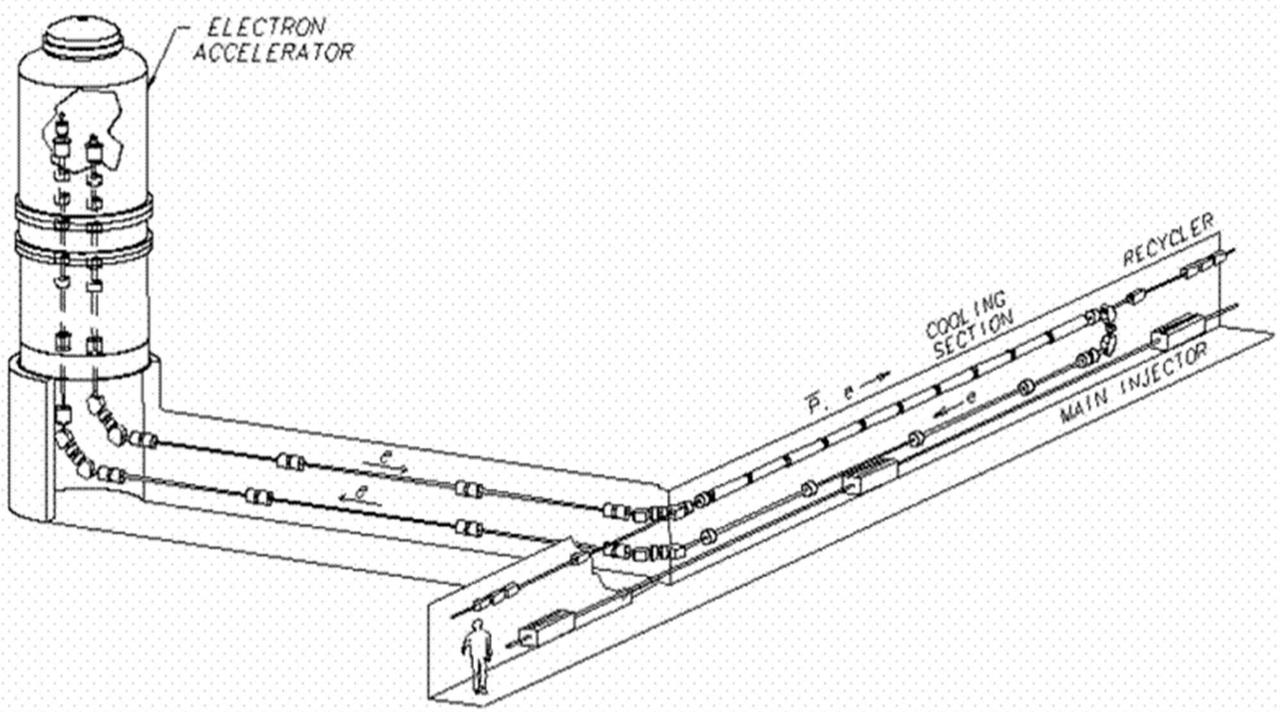




- Many installations since then, up to 300 kV electron beam (GSI, Darmstadt)
- FNAL 4.3 MeV cooler was the next step in technology
- 2 MeV cooler for COSY built by BINP

Electron Cooling at FNAL (1)

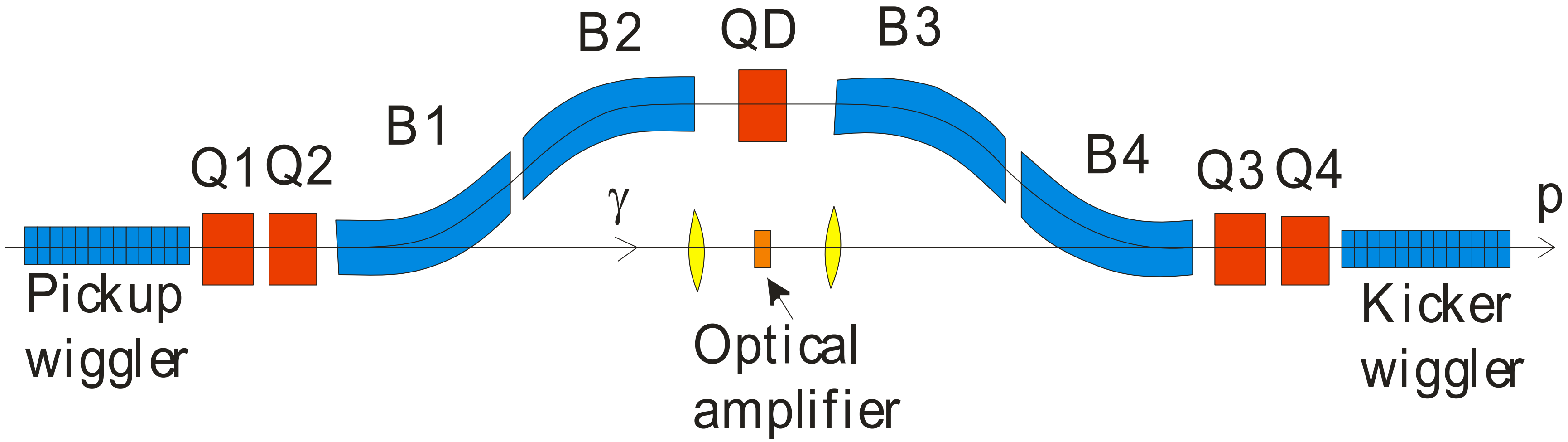
- Fermilab made next step in the electron cooling technology
- Main Parameters
  - 4.34 MeV pelletron
  - Up to 0.5 A DC electron beam with radius of about 4 mm
  - Magnetic field in the cooling section - 100 G
  - Interaction length – 20 m (out of 3319 m of Recycler circumference)



Stochastic Cooling at Optical Frequencies

- Coherent electron cooling (Derbenev, ~1980)
  - FEL based (Derbenev, Litvinenko, ~2006)
  - Techniques suggested to increase the relative bandwidth
    - Microbunch instability based (D. Ratner)
    - Plasma cascade instability (Litvinenko)
- Optical stochastic cooling (OSC) (~2005)
  - Suggested by Zolotorev, Zholents and Mikhailichenko
  - OSC is the only cooling method tested experimentally which is capable to cool a proton bunched beam at collisions for energies above ~300 GeV
- Electron cooling (20 – 100 MeV)
  - Based on an energy recovery linac
  - Based on an electron beam rotated in a ring

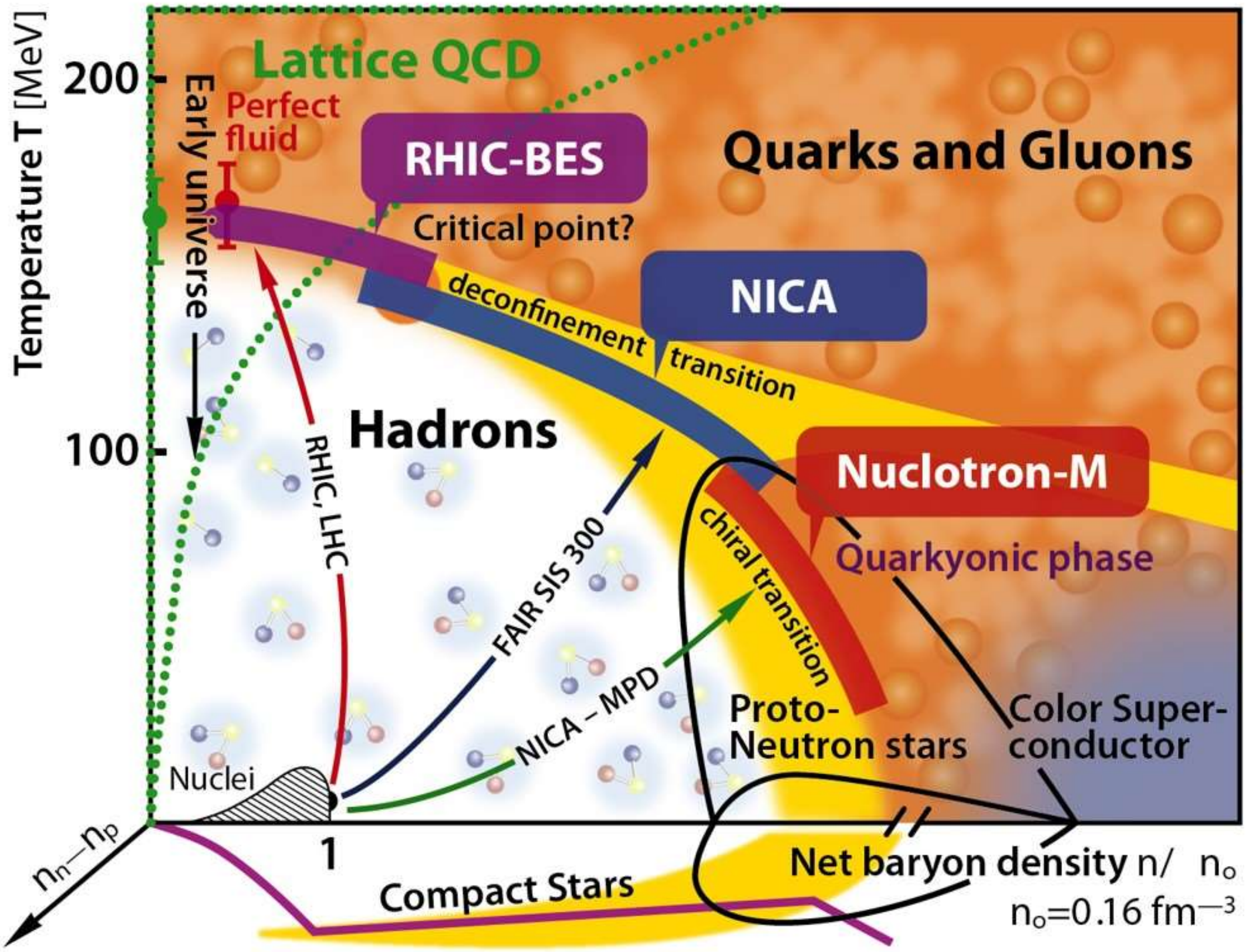
Optical Stochastic Cooling



- The test was carried out with 100 MeV electrons in a passive regime. OSC increased the SR radiation cooling rates for all degrees of freedom by almost an order of magnitude
- Test of OSC in active regime (with OA) is planned to happen within few years

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)



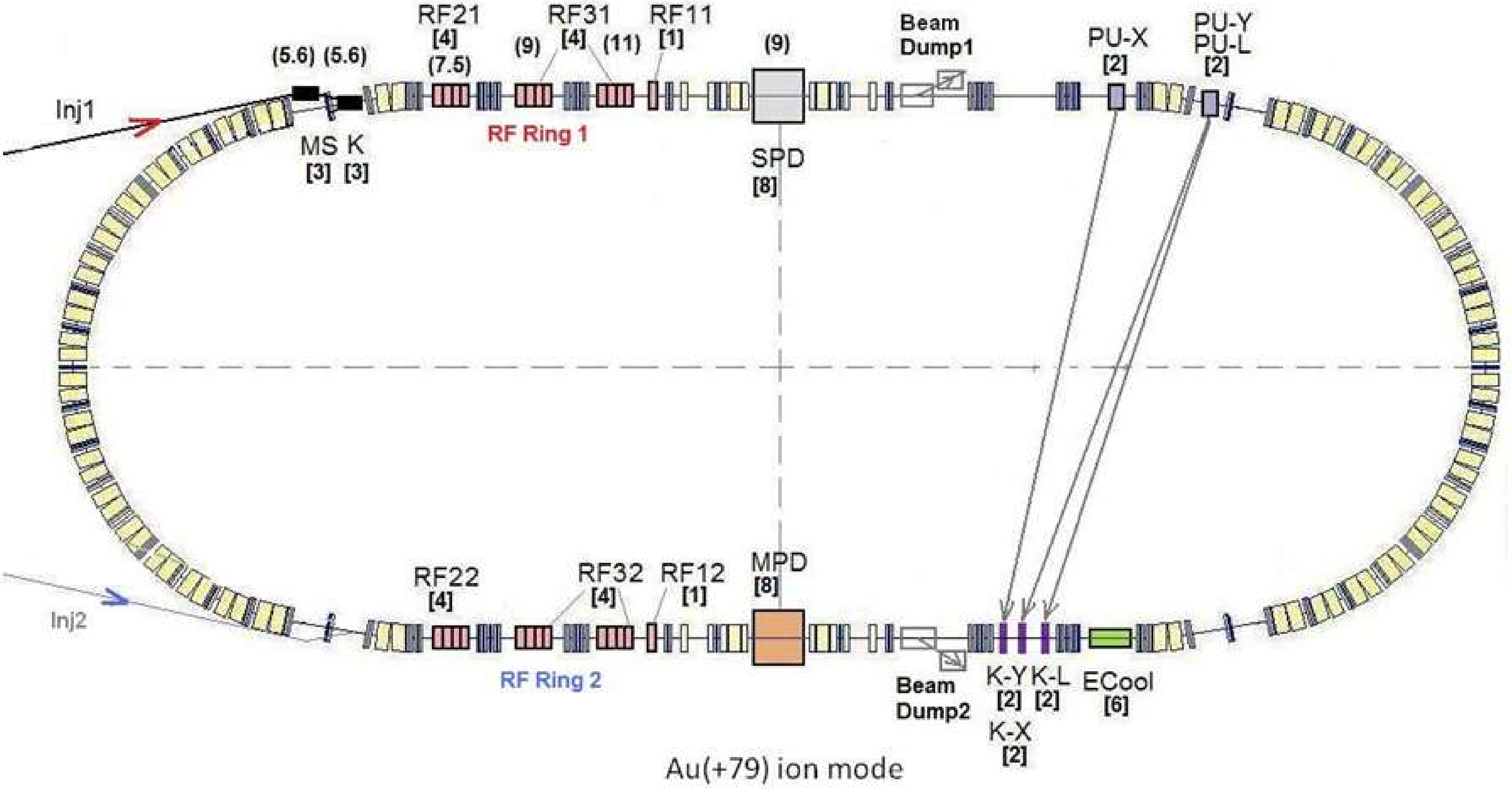
Why NICA?

- 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)

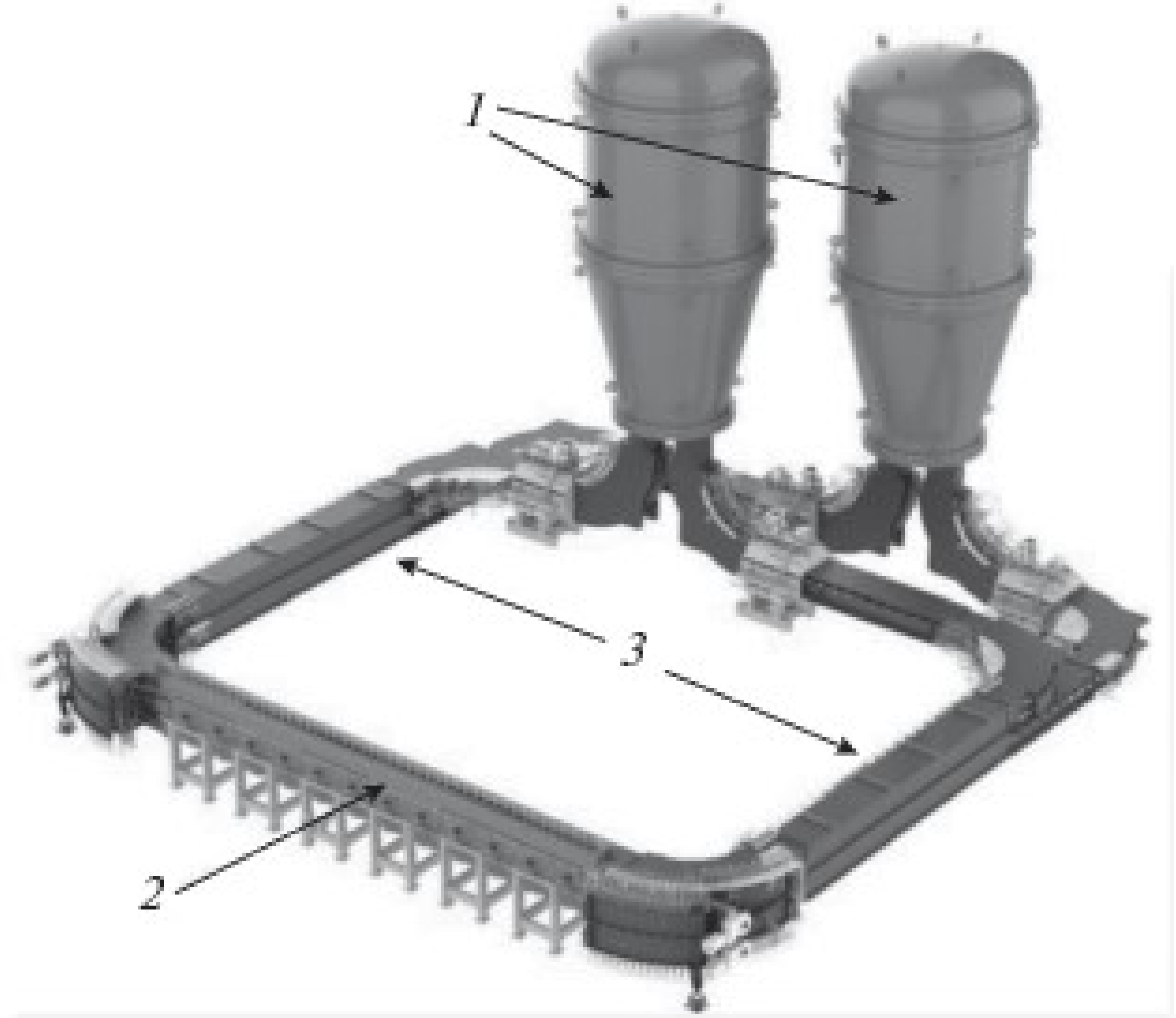
Scheme of the collider ring

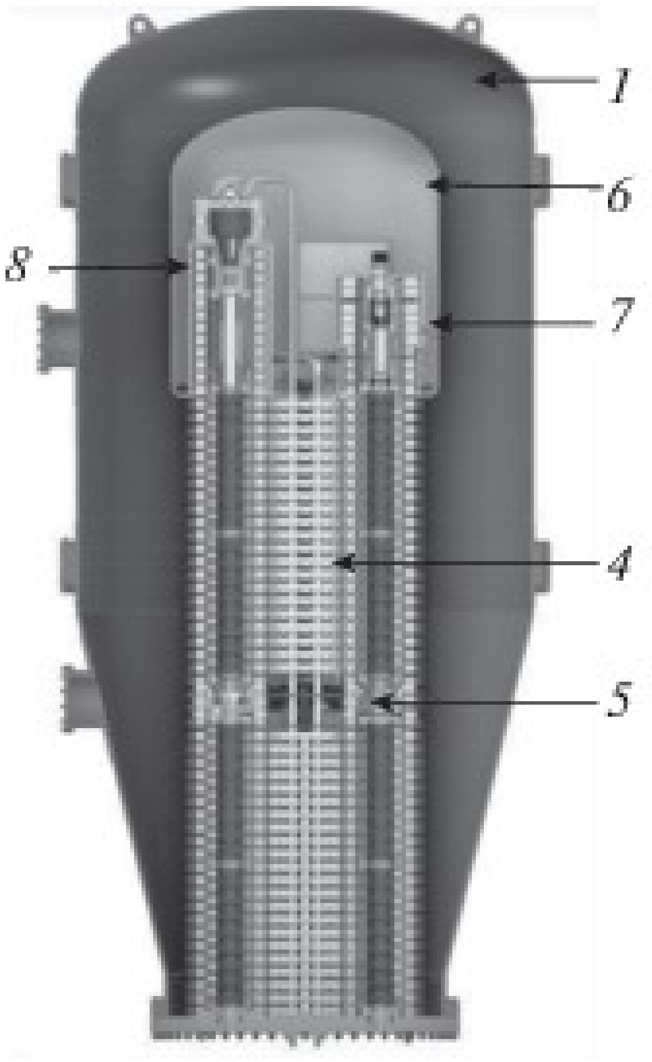


Two rings: one above another

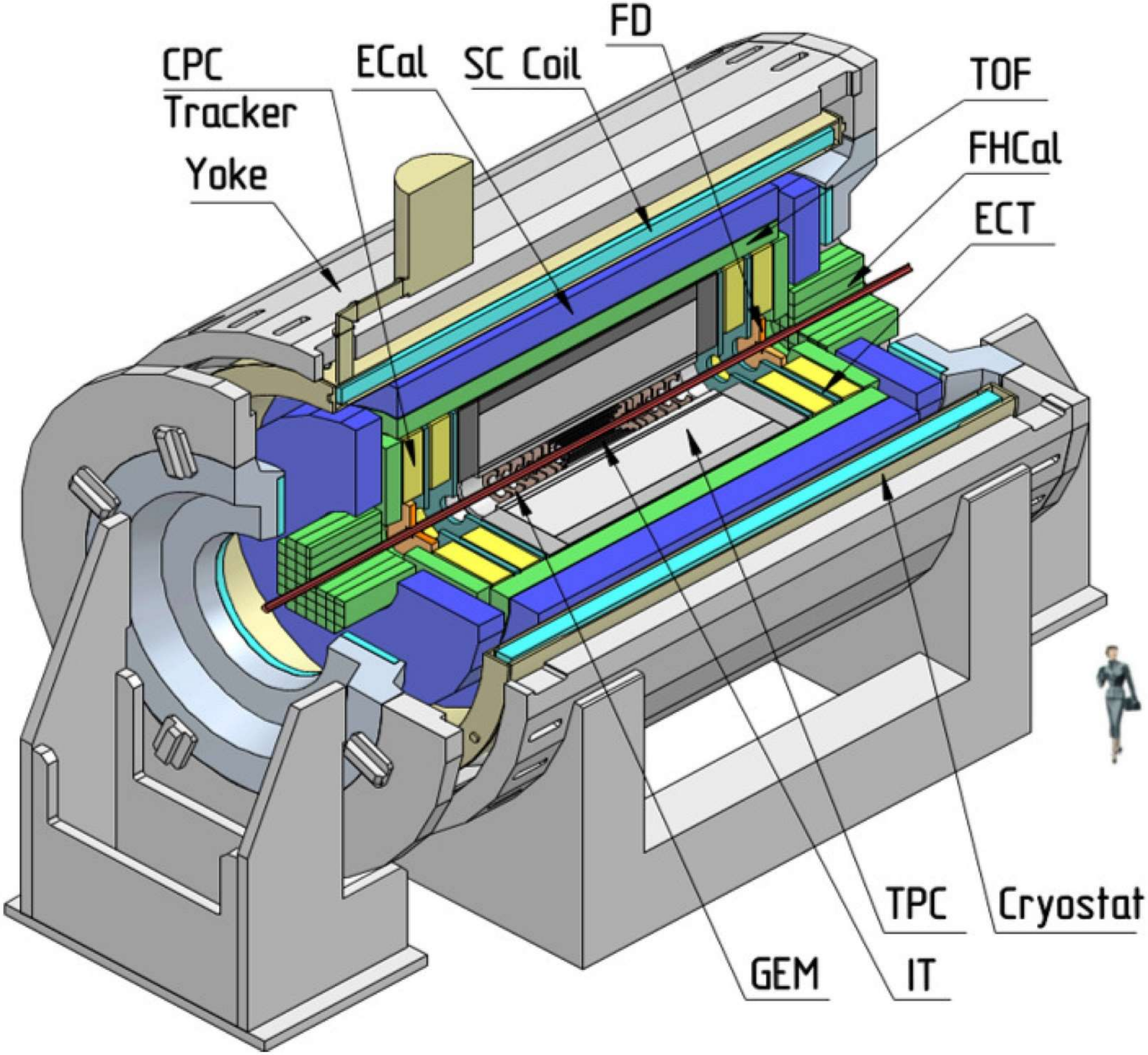
Collision energy in the ion mode: 2·(1.5÷4.5) GeV/n

Collider Electron Cooler





Detector MPD



Colliders : Most Important Topics/Effects

- Engineering of magnets, RF, Power supplies, vacuum, particle sources, targets, diagnostics, collimators, etc
- 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)