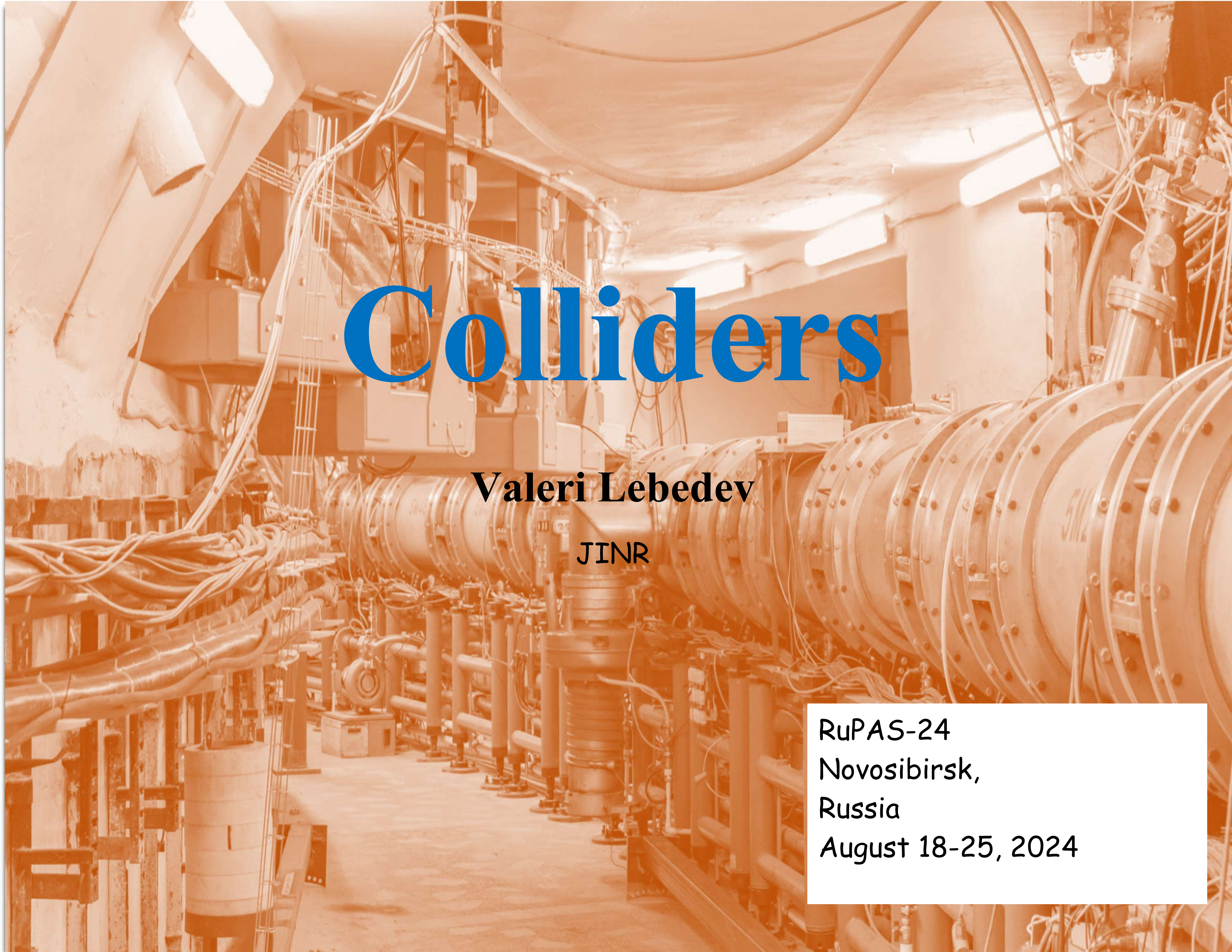

Colliders

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Russia
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Outline

- Why we need colliders?
- Short review of collider developments and their history
- Future colliders
- NICA – the First Hadron Collider in Russia

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 6.5 TeV LHC; 630 times for 100 GeV LEP)

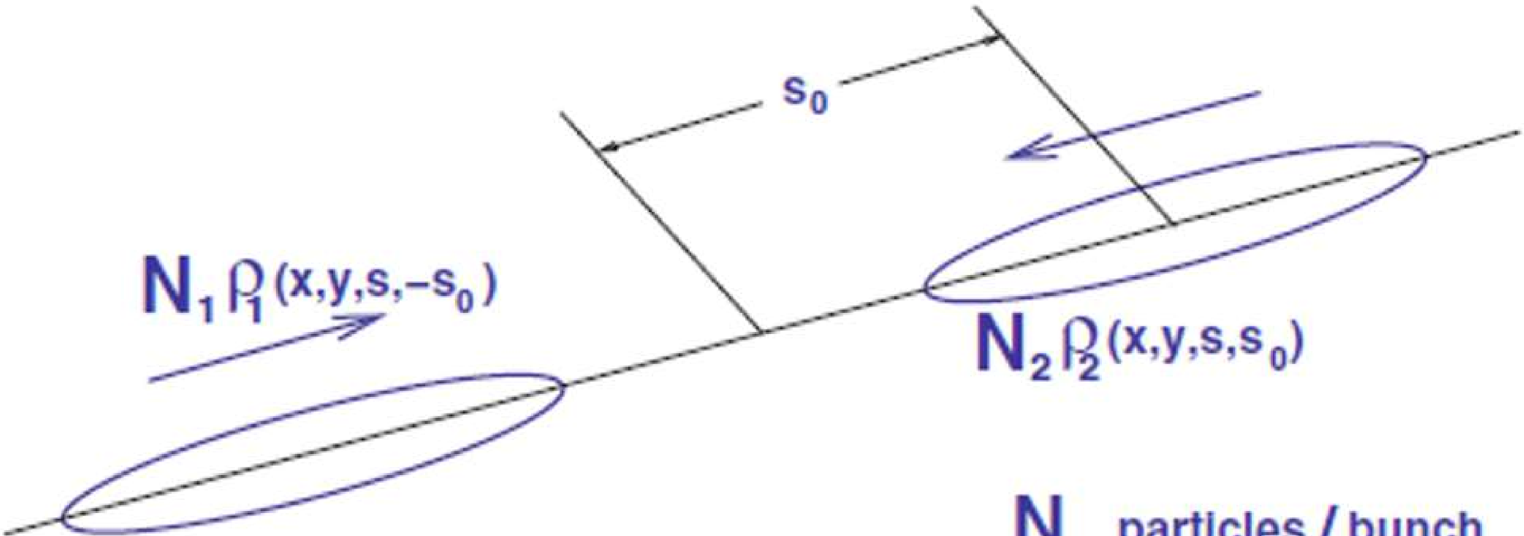
- Luminosity
  - Number of events in collisions:

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

    - The total cross section for Higgs boson production at the LHC operating at **s=13 TeV** is 43 pb = $4.3 \cdot 10^{-35}$ 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: $(E/E)^4(L/L) = 6^4 30 \approx 4 \cdot 10^4$
  - <u>Particle physics detectors want constant luminosity!</u>

Luminosity

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



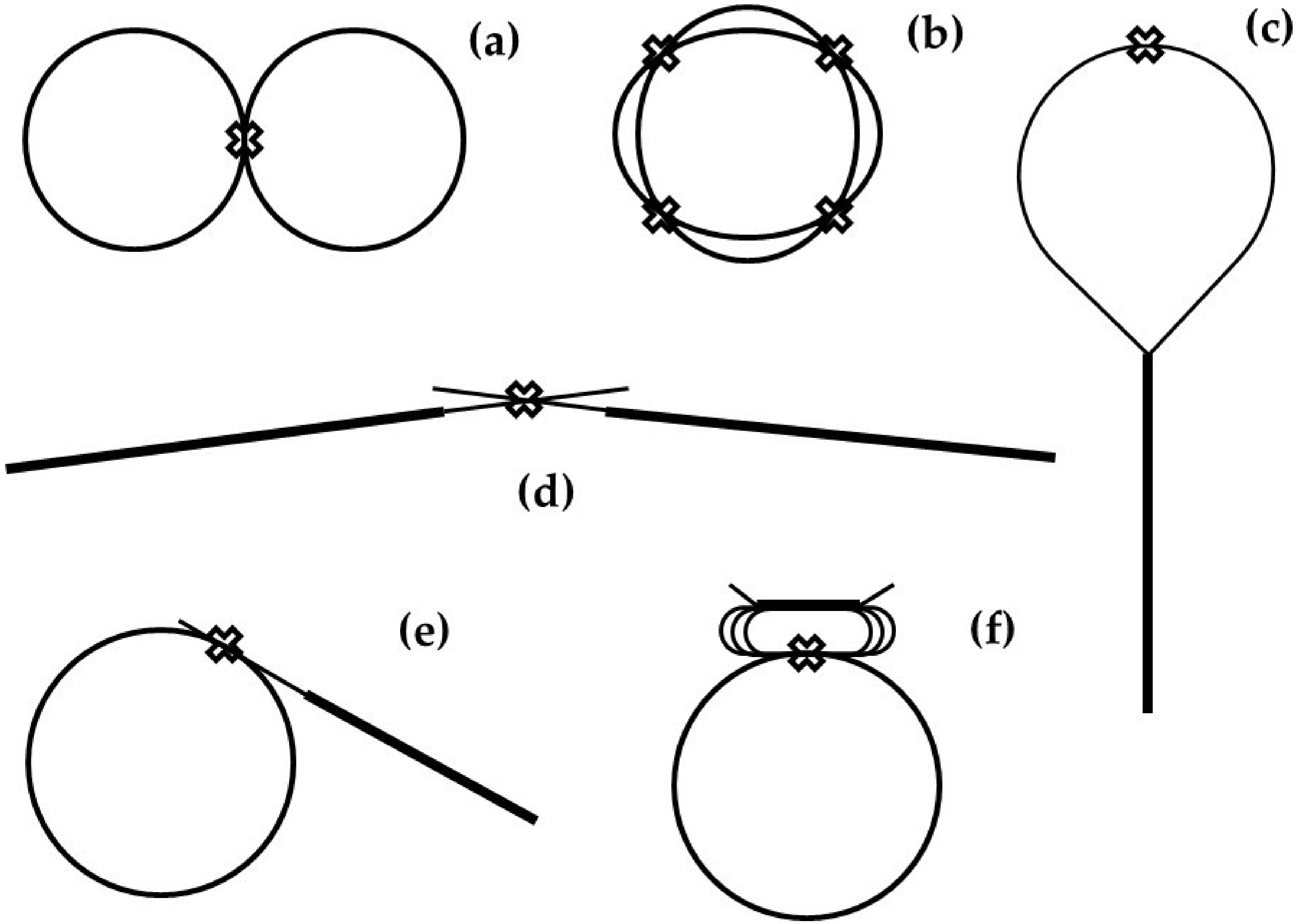
N particles / bunch

ρ density ≠ const.

For (same size) Gaussian bunches:

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

Types of Colliding Beams Facilities



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

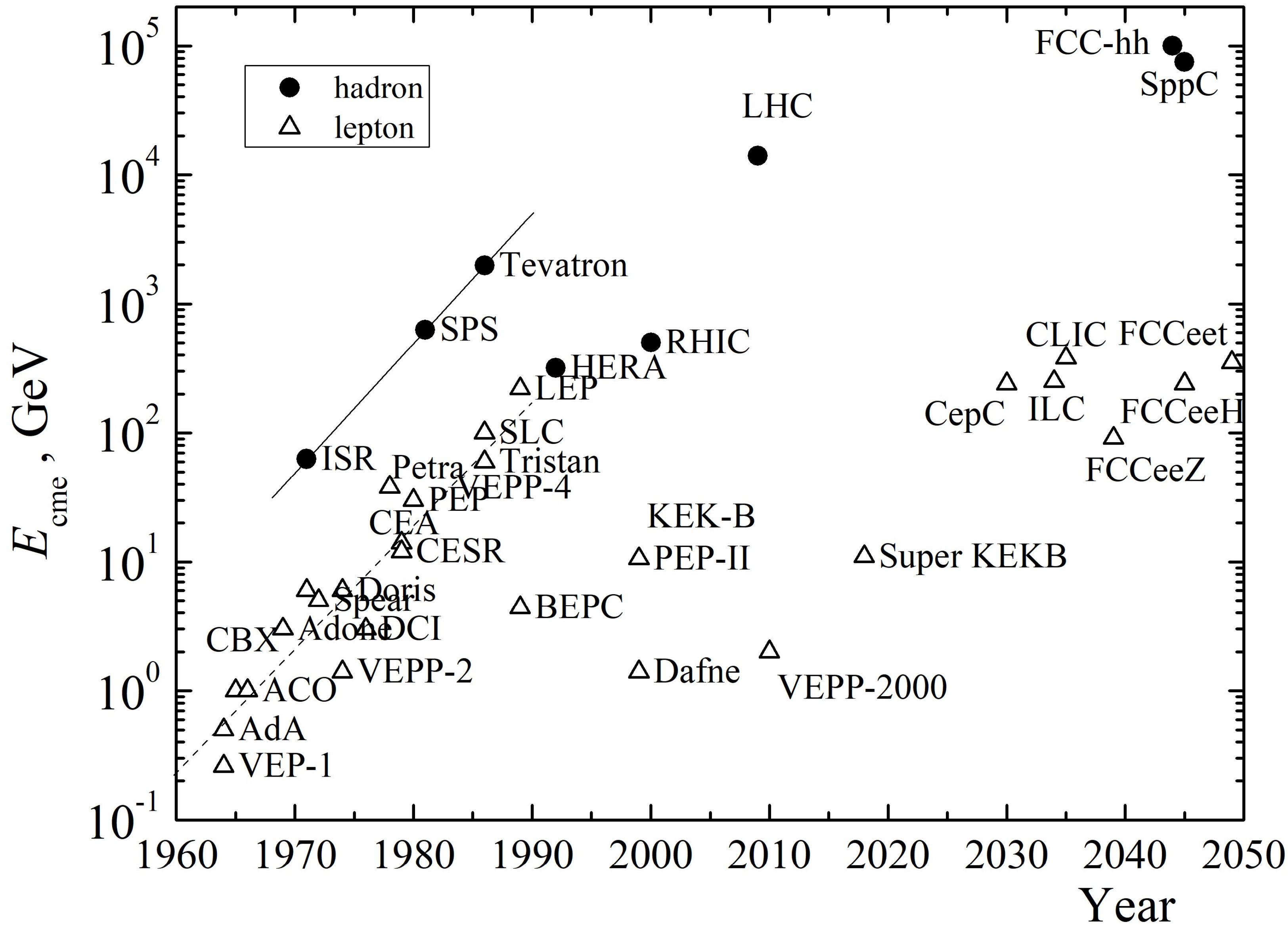
Colliders Landscape

- 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 ($E >> E_{LHC}$)
    - 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

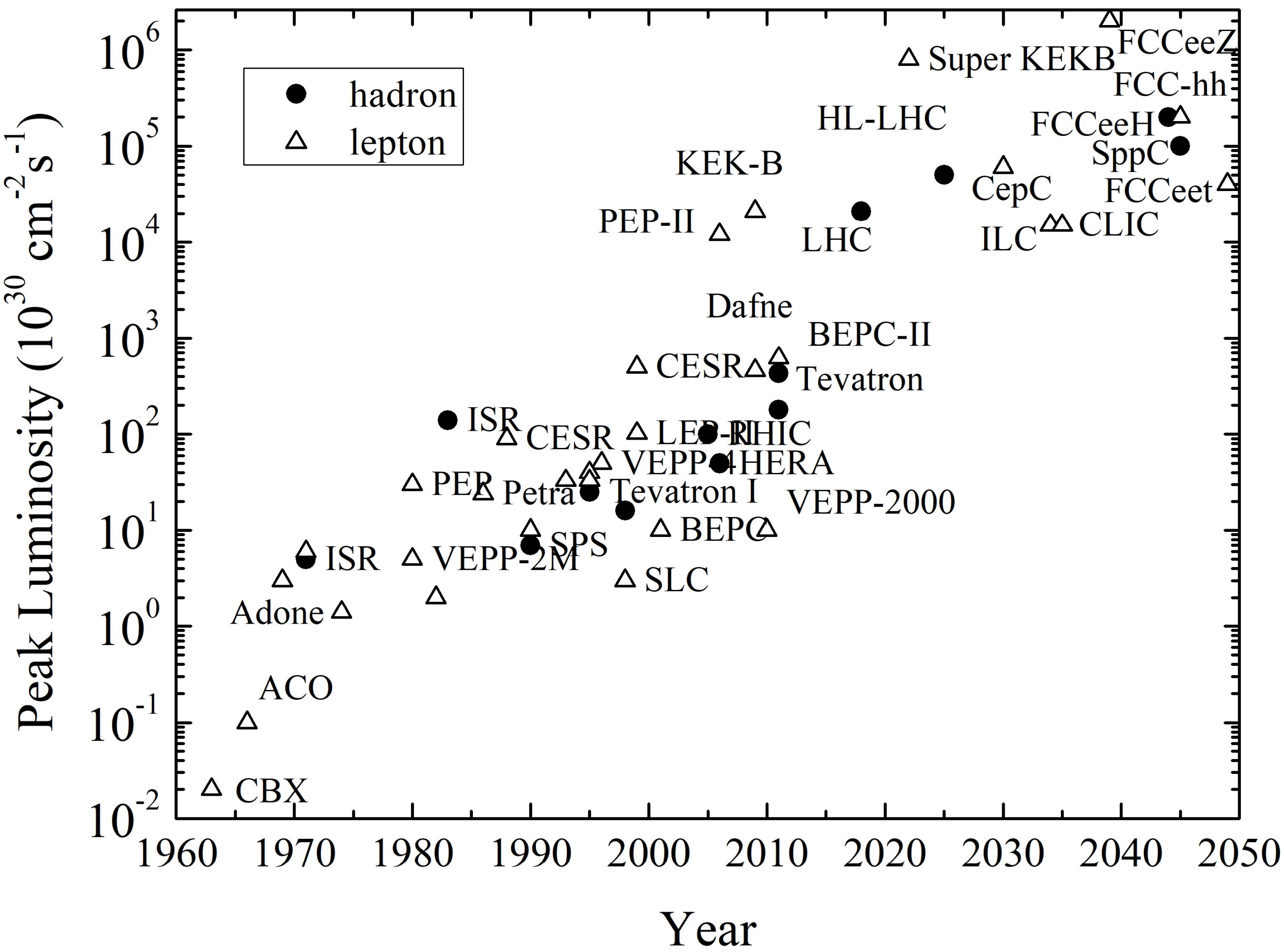


FIG. 3. Luminosities of particle colliders (triangles are lepton colliders and full circles are hadron colliders, adapted from [37]). Values are per collision point.

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 colliding partons
  - (+) 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

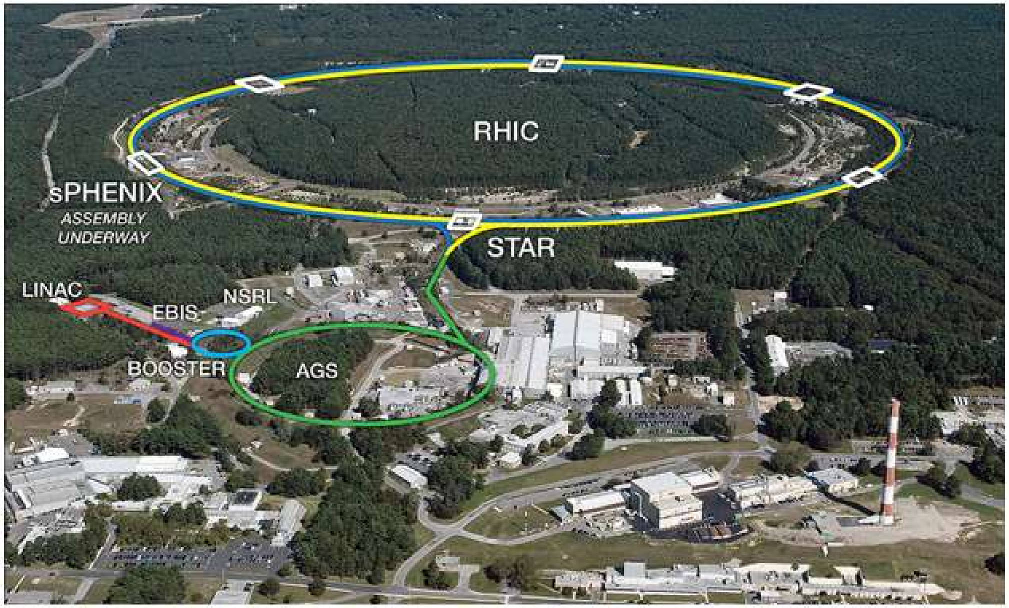
Electrons versus Protons (2)

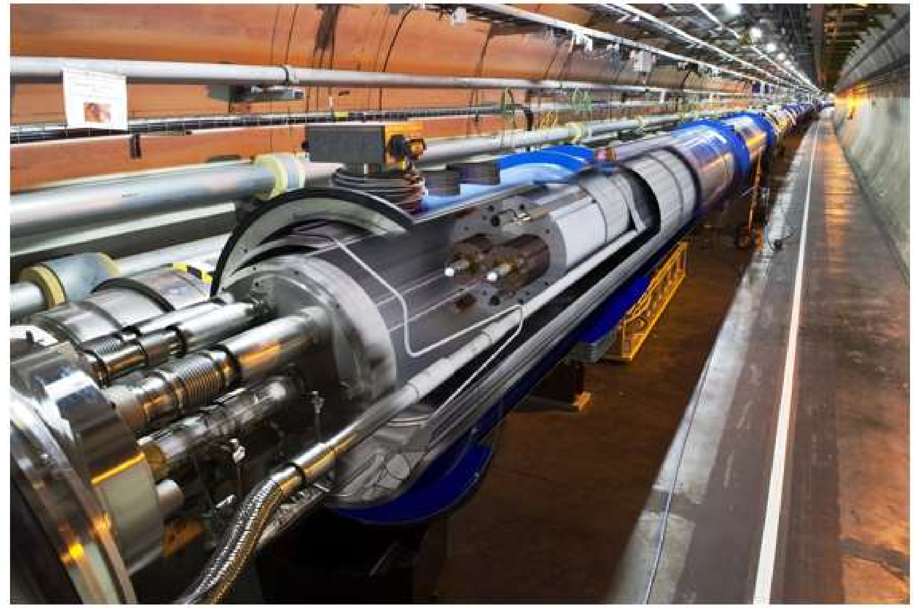
- Achievable energy
  - Proton energy is limited by circumference and magnetic field; LHC: C=26.7 km, B=77 kG, E_{max}=6.8 TeV, ΔE_{SR}=500 MeV/turn
  - Electron energy is limited by SR; i.e. RF power and circumference LEP: C=26.7 km, B=1.2 kG, E_{max}=104 GeV, ΔE_{SR}=3.43 GeV/turn (3.3%)
- Hadron colliders do not have natural SR damping
  - Therefore, each step in the beam acceleration and transfers has to be polished to perfection
  - Achievement of design luminosity requires very large number of tuning steps. Typically, each of them yields 10-30% improvement but altogether the luminosity grows by orders of magnitude
  - Consequently, commissioning of hadron collider to the design luminosity takes much longer time
    - 8 years for both Tevatron and LHC
    - More than twice faster for KEK and SLAC B-factories
  - ILC does not have "damping" at top energy, i.e. it belongs to the "Hadron Collider" group => long commissioning time

Electrons versus protons (3)

- Development of detector technology in the last ~50 years proved that the present state of the art particle detectors can operate with very high backgrounds
  - In the LHC at $L=10^{34}$ $cm^{-2}s^{-1}$ there are 25 collisions per crossing
    - 10^9 events per second @ 40 MHz bunch frequency
    - Thousand tracks in detectors
  - Consequently, the role of e^+e^- colliders as a "precise" machine has been somewhat diminished
    - One can compare physics results of LHCB and KEKB
  - In other words
    - proton collider is a discovery machine – finds new particles
    - lepton colliders (e^+e^- , $\mu^+\mu^-$) study them in details (branchings, lifetimes (widths), …)
- Any future collider of any type has to be competitive to the LHC in its physics reach (luminosity, energy, accuracy, …)
  - That's extremely challenging

Present Hadron Colliders





RHIC (BNL, Brookhaven)

C=3.84 km,

E_{max}(protons)=255 GeV

- RHIC is main NICA competitor

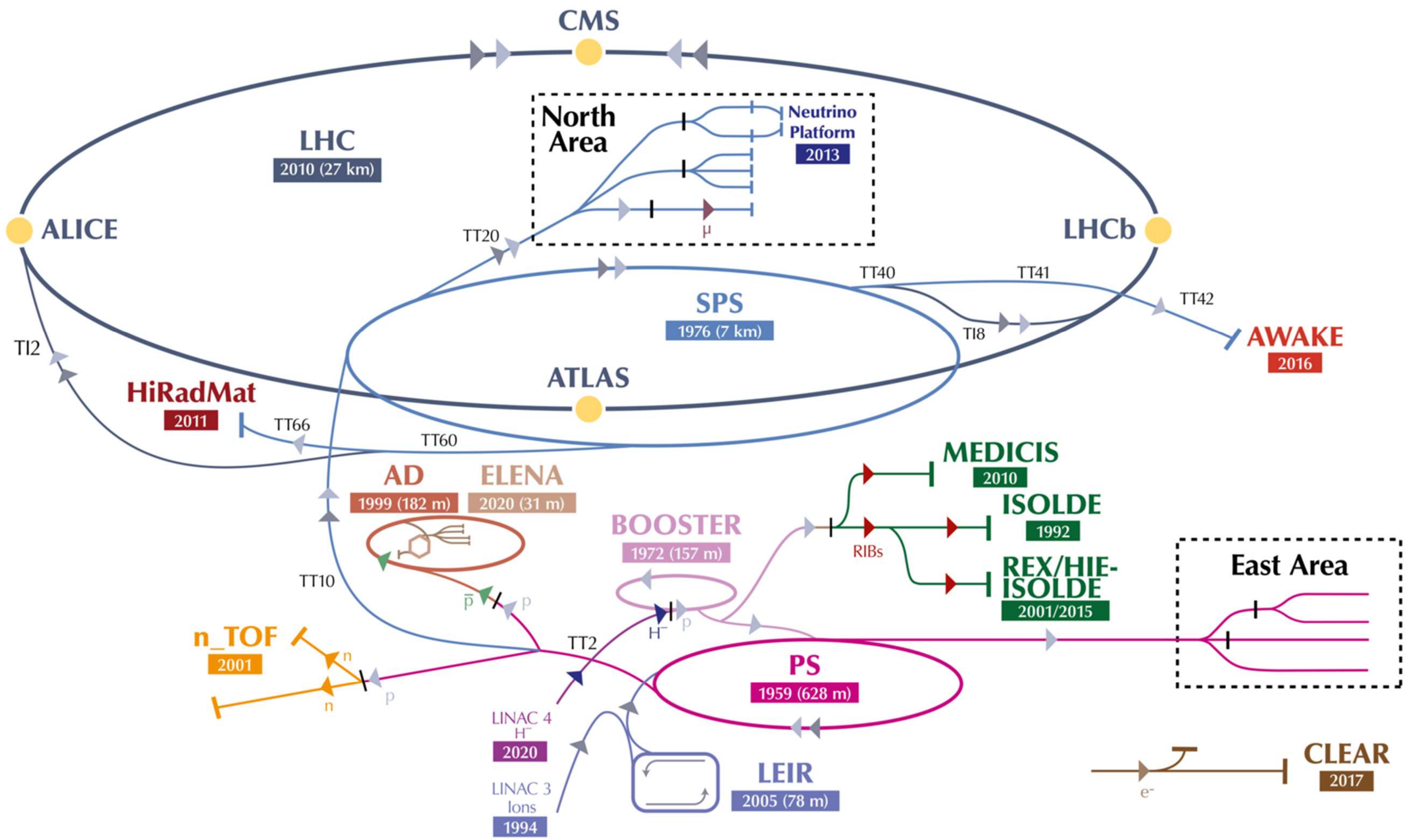
LHC (CERN)

C=26.7 km,

E_{max}(protons)=6.8 TeV

LHC

- LHC is the most powerful collider in the world
- With coming upgrades, it will dominate High Energy physics for decades

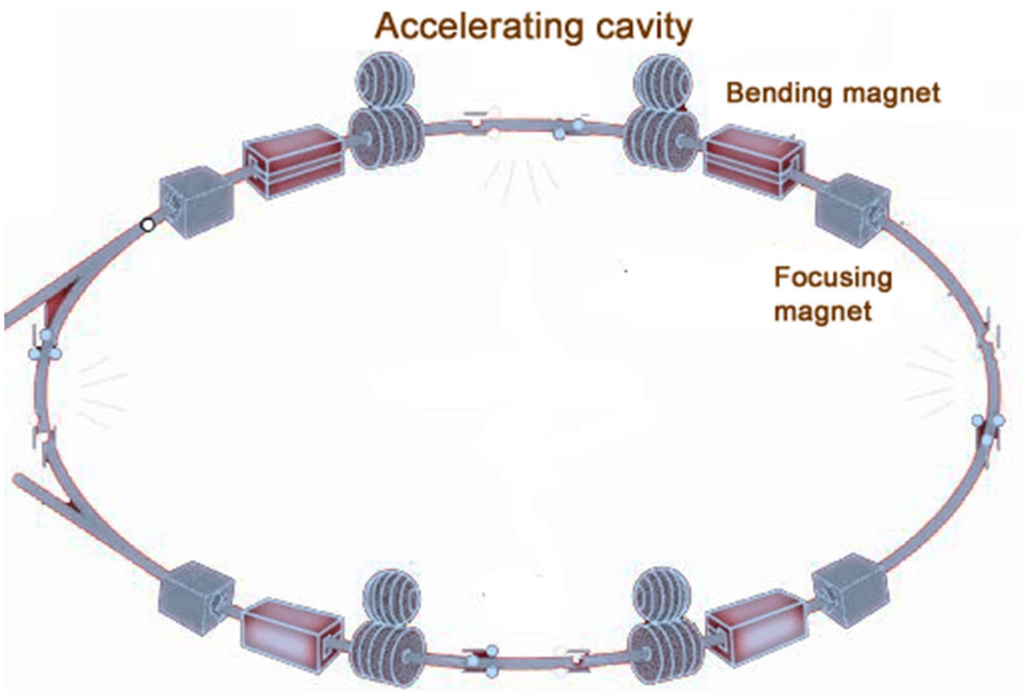


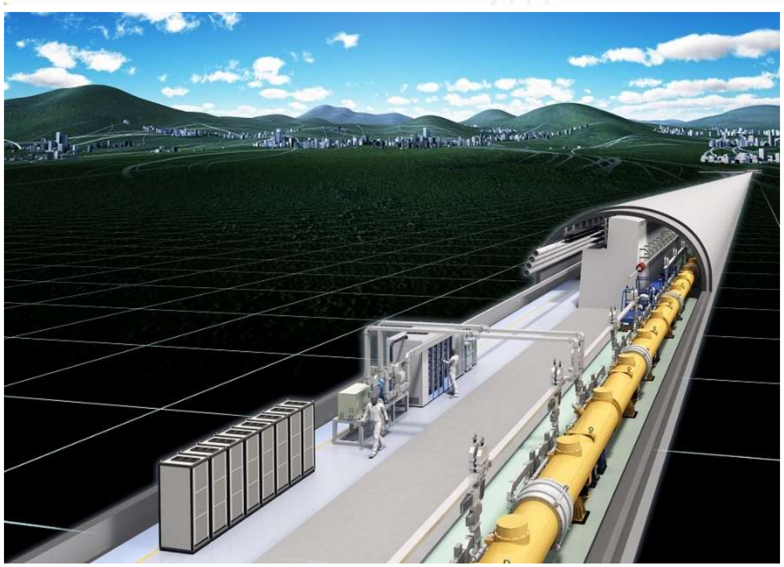
What Could Come after the LHC?

- Main proposals/ideas which were suggested during last ~30 years
  - e^+e^- linear colliders (ILC, CLIC)
  - Muon collider (Higgs factory as a first step)
  - FCC: FCCee -> FCChh

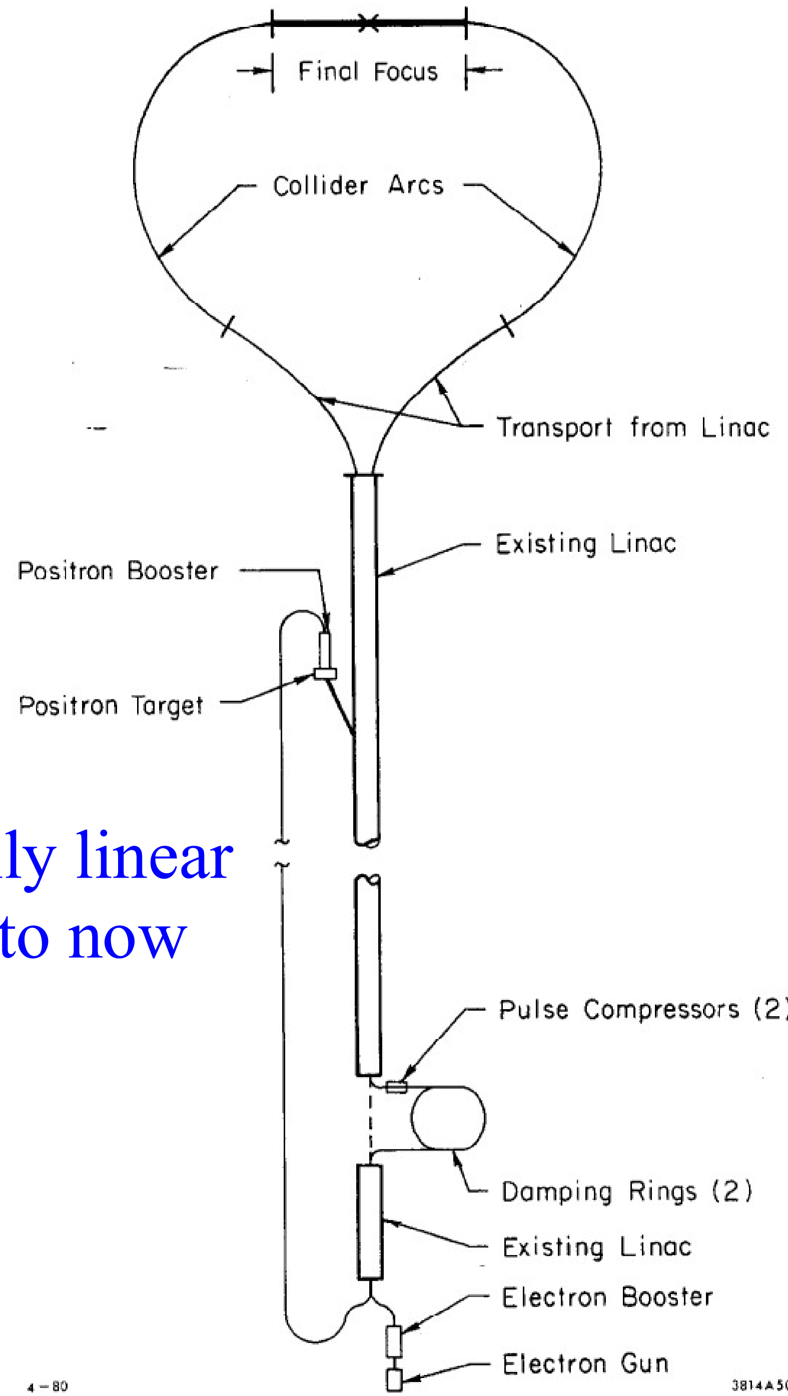
- So far, "the plasma-based colliders" has been an empty shot
  - Much larger accelerating gradient but
    - Great problems with acceleration of intense electron bunch
    - No solution for acceleration of intense positron bunch
    - $\gamma-\gamma$ collider is not excluded but does not look as a realistic proposal

e^+e^-: Rings vs Linacs

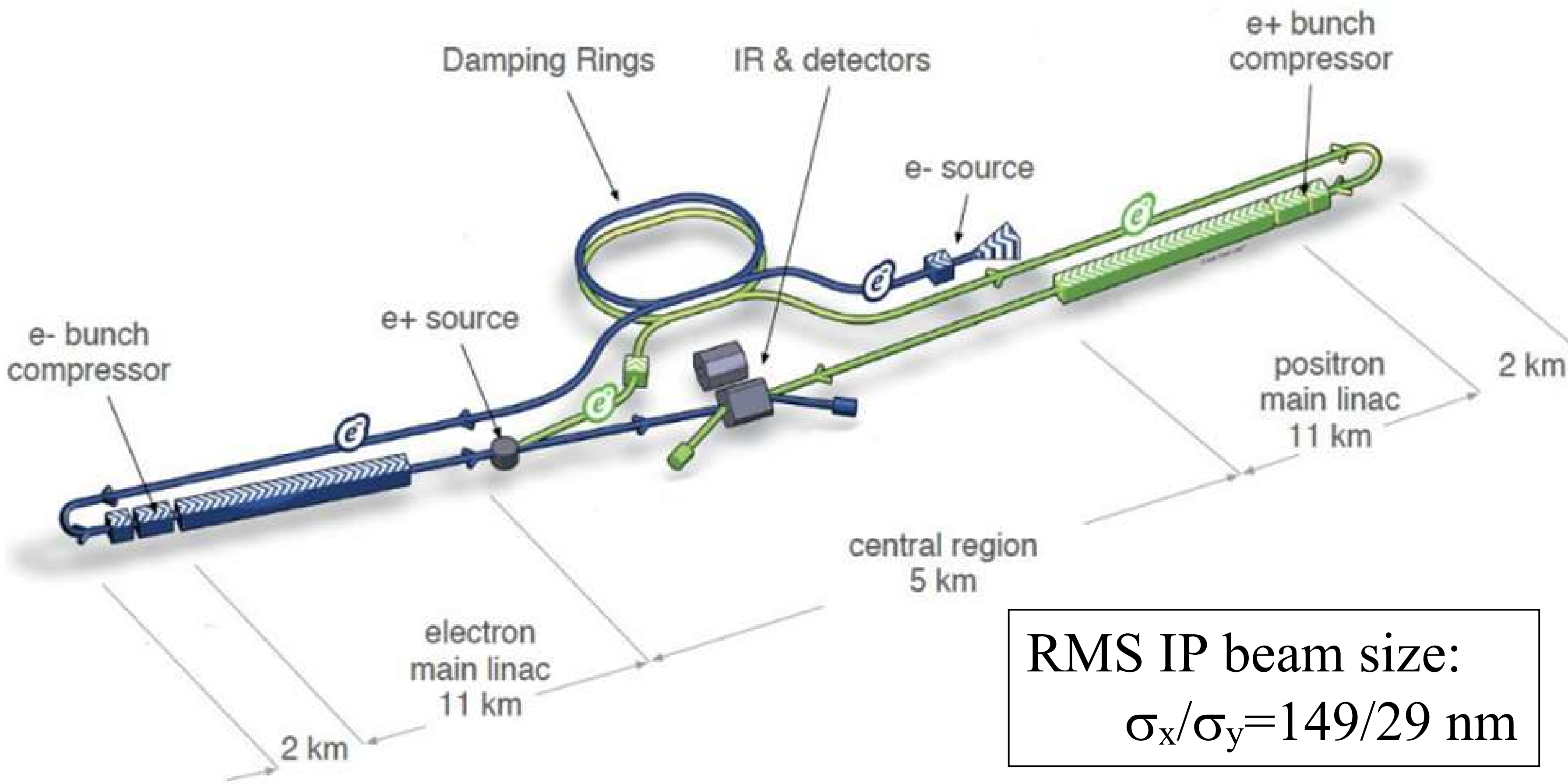




- SLC – the only linear collier built up to now



ILC - International Linear collider



RMS IP beam size:
σ_x/σ_y=149/29 nm

- Very expensive, looks like cannot not reach the design luminosity within 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

ILC and CLIC Main Parameters

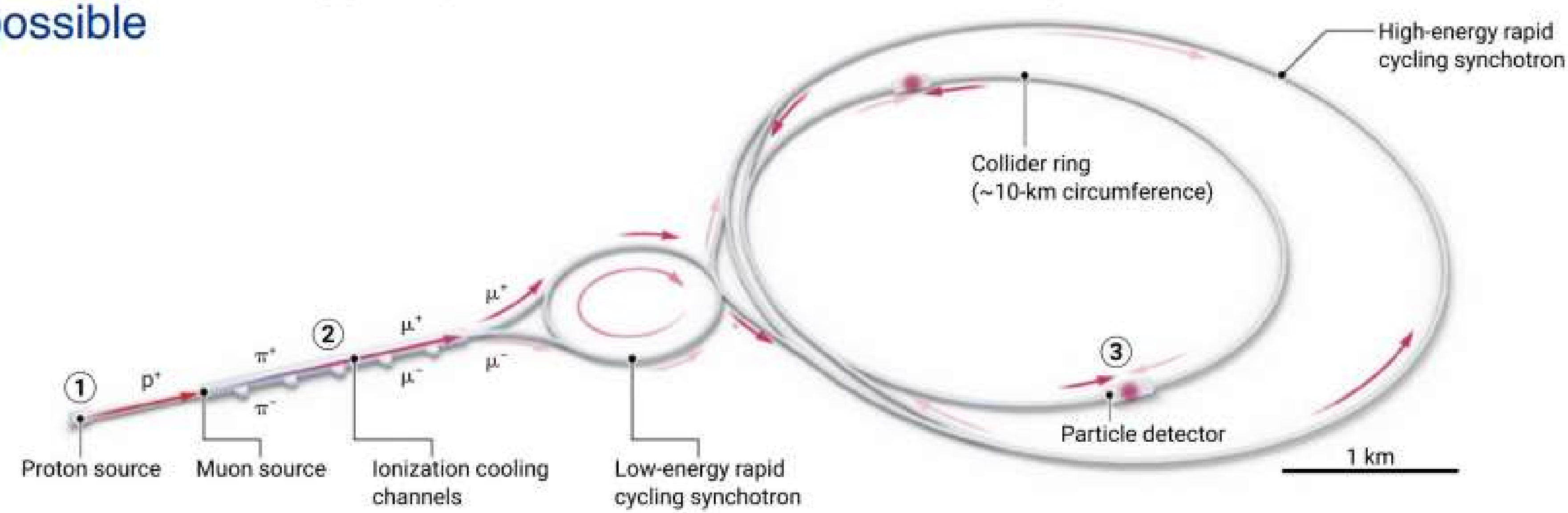
Parameter	Symbol [unit]	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	500	380	3000
Total luminosity	L [10^{34}cm^{-2}s^{-1}]	1.8	1.5	6
Luminosity in peak	$L_{0.01}$ [10^{34}cm^{-2}s^{-1}]	1	0.9	2
Particles per bunch	N [10^9]	20	5.2	3.72
Bunch length	σ_z [μm]	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	474/5.9	149/2.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	35	40	20
Geometric luminosity	L_{geom} [10^{34}cm^{-2}s^{-1}]	0.75	0.8	4.3
Enhancement factor	H_D	2.4	1.9	1.5

- ILC has been designed to operate with $L=1.36\cdot10^{34}$ cm^{-2}s^{-1} at 6560 Hz bunch rate (1300 bunches at 5 Hz train rep. rate)
  - Lower bunch frequency more difficult to filter out background
  - Beamstrahlung increases the effective energy spread: $\Delta E/E \gg 10^{-3}$, which is typical value for circular colliders

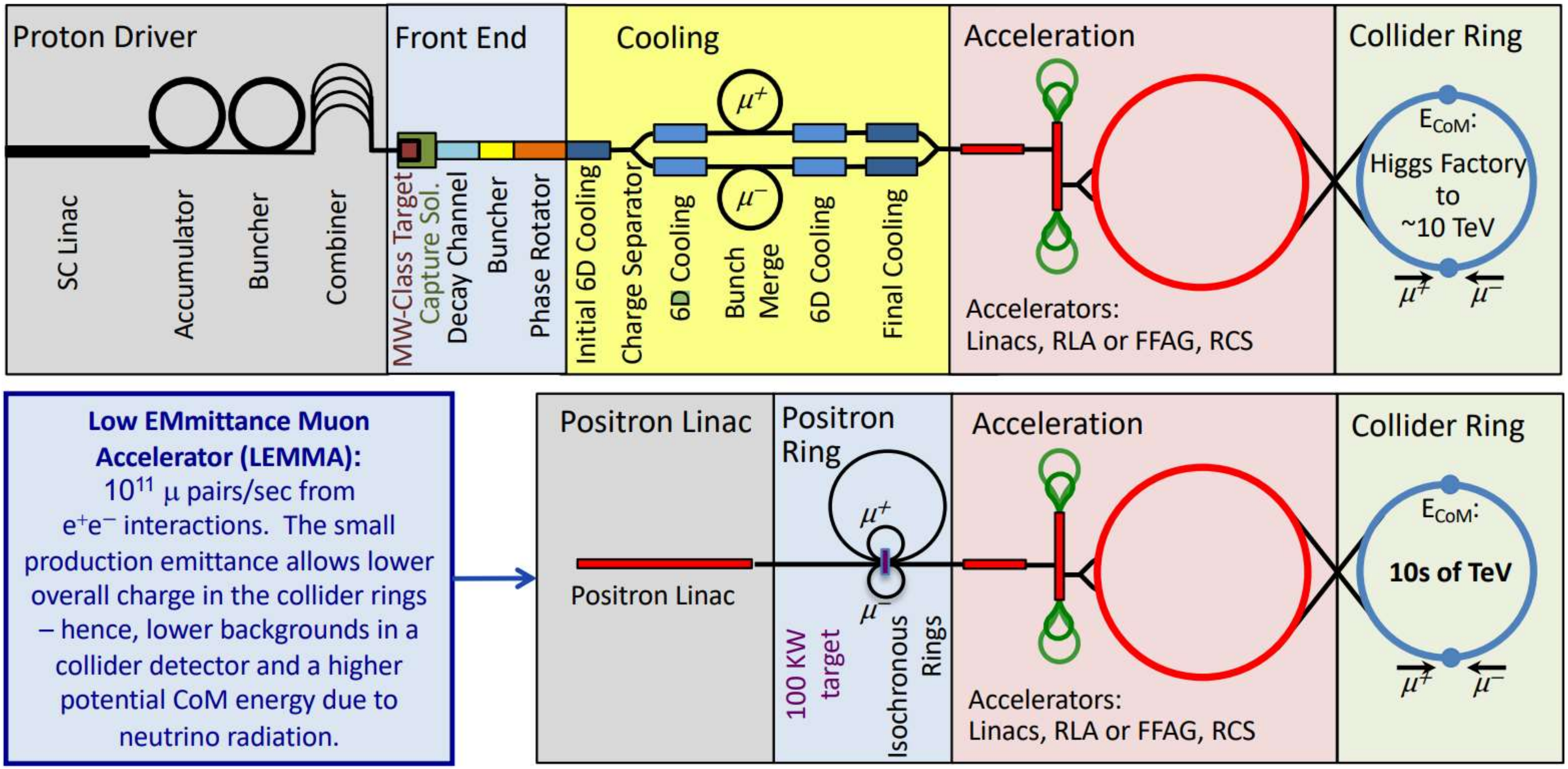
Muon Collider

- (+) Muons are point-like particles – entire energy may go to reaction
- (+) Muons are heavier than electrons – SR is not a problem
- (-) Muon do not exist in nature
  ⇨ very expensive production
- (-) Muons live only for about 1000 turns in ~10 T dipole field
- Road to the luminosity is based on the ionization cooling
- No obvious first step, i.e. low energy (inexpensive) collider to develop technology
  - Higgs factory still requires too large luminosity

- The goal is to get to **10 TeV center-of-mass** energy with L ~ 10^{35} cm^{-2} s^{-1} (driven by the Higgs physics requirements)
- **Staging in energy** (e.g. 3→10 TeV) or **in luminosity** (a la LHC→HL-LHC) are possible



Muon Collider (2)

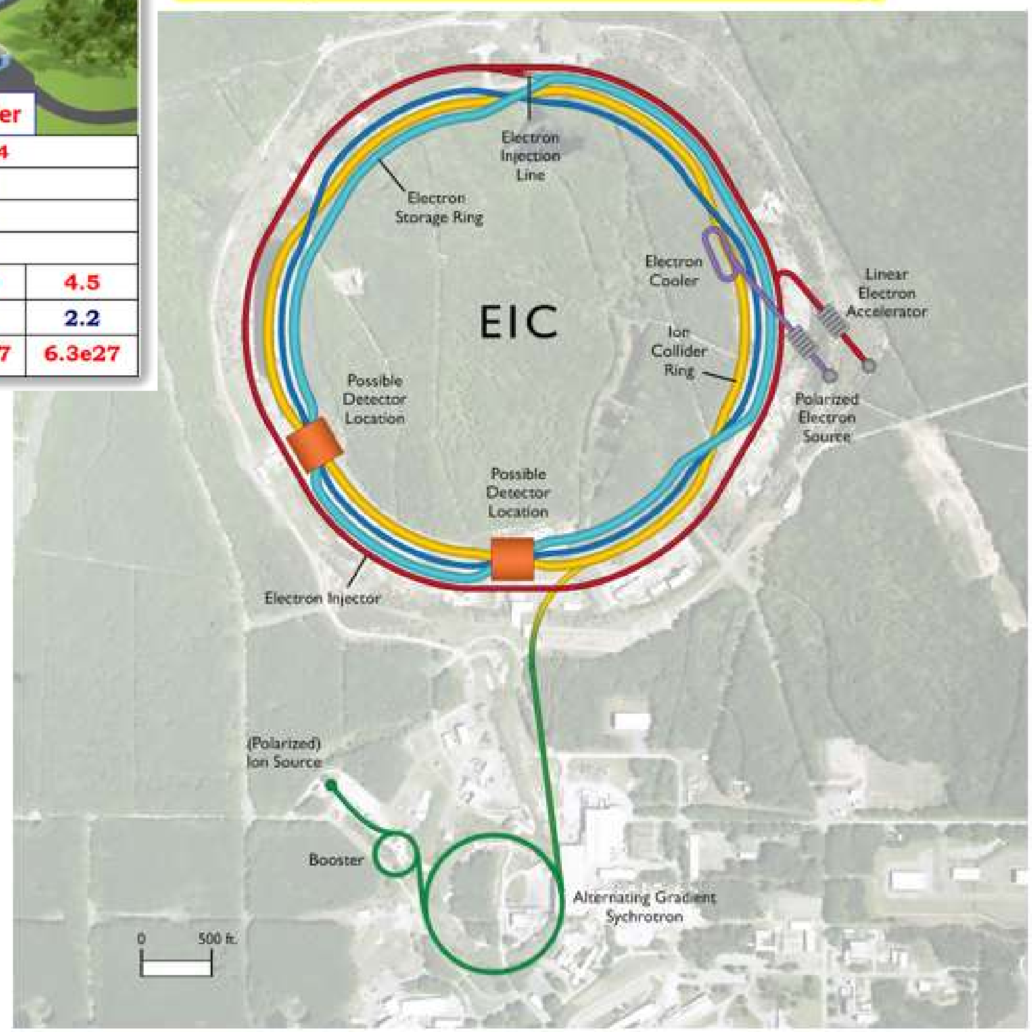


- Great challenge in accumulation and cooling muons
  - Multimegawatt proton driver
  - Ionization cooling requires large accelerating fields in large B
- Higgs factory: L≈10^{29} cm^{-2}s^{-1} doable, L≈10^{32} cm^{-2}s^{-1} needed,
  - Expected Higgs width 4.1 MeV, W/M≈$3\cdot10^{-5}$ ($\sqrt{s} \le 125$ GeV, s-channel)

Colliders That Will Be

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$^{-2}\cdot$s^{-1}	0.9e25	0.9e27	6.3e27

EIC (BNL, Brookhaven)



Far Future

- FCC is accepted as the primary choice for future machine in CERN – looks as a very pragmatic choice
  - Same as the LHC it has two steps: FCCee & FCChh
    - Circumference is ~100 km
    - FCCee – large luminosity at Higgs production energy (>2*125 GeV), can get to t-quark (2·173 GeV) with smaller luminosity which is reduced due to increased SR power
      Detailed study of Higgs and t-quark
    - FCChh has ~7 times LHC energy ($\sqrt{s}$=100 TeV). We still do not have dipoles which produce the design magnetic field
      We still do not have any real signs of "New Physiscs"
  - FCC Requires significant increase of CERN budget
  - In my view a construction of such collider looks more probable in China
    - Expected to be included in the next 5-year plan in China
  - In addition to big money, construction of such collider requires very large number of scientists. That is also a great challenge for the HEP community.

Far future (continue)

- ILC
  - Construction is supported by outstanding achievements in R&D
  - The project has solid technical proposal
  - The hope was that it will be built in Japan – Looks it is not going to happen
- ILC comes too late to be competitive to the LHC upgrade
  - Extremely challenging and expensive project
    - It will require long time to achieve the design luminosity
    - SLC had the design luminosity four orders of magnitude lower but did not get to it after 10 years operation
- Muon collider is still considered as a promising choice
  - Not supported by realistic proposal
    Some people still believe that we can built one
- Plasma based linear collider has problems at the fundamental level.
- Thus, after decades of development of other possible alternatives the community comes back to a circular collider - FCC

Cornerstones of Collider Accelerating Physics

- Beam-beam effects
  - Head-on collisions and collisions under angle
  - Parasitic collisions and their compensation
  - Crab-crossing and Crab-waist
- Different heating mechanisms
  - RF phase and amplitude noise
  - Noise on magnetic field
  - Multiple and single IBS
- Instabilities
- State-of-the-art feedback systems for suppression of instabilities
- Beam cooling
  - Electron cooling
  - Stochastic cooling
  - Optical stochastic cooling

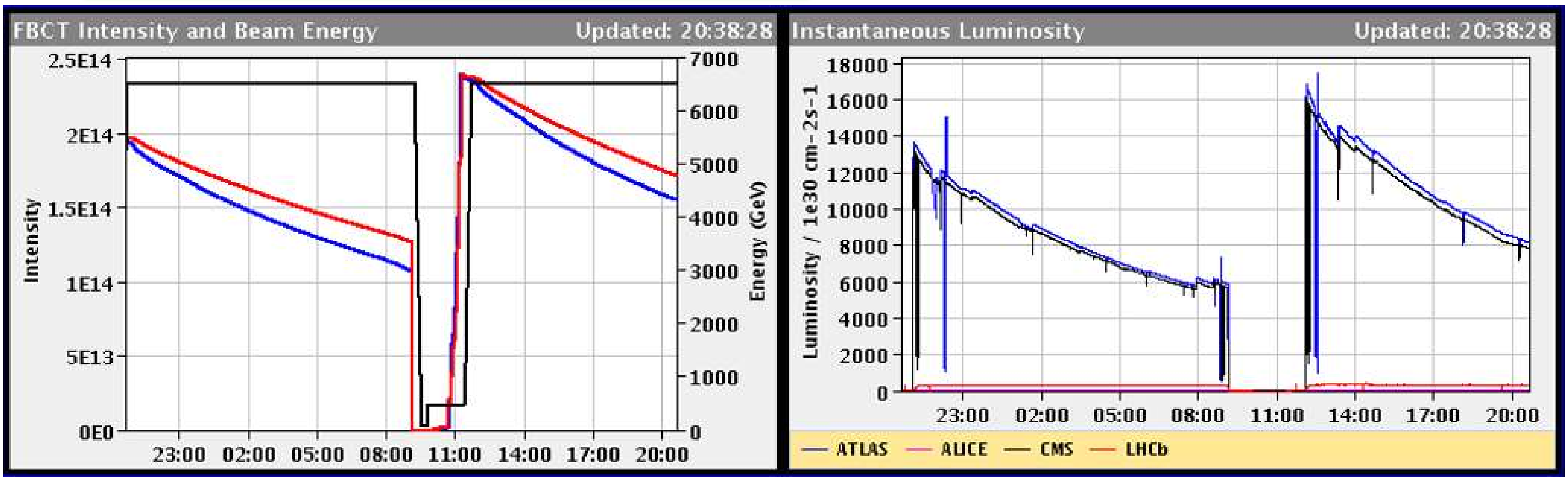
Luminosity Evolution

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

- 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

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

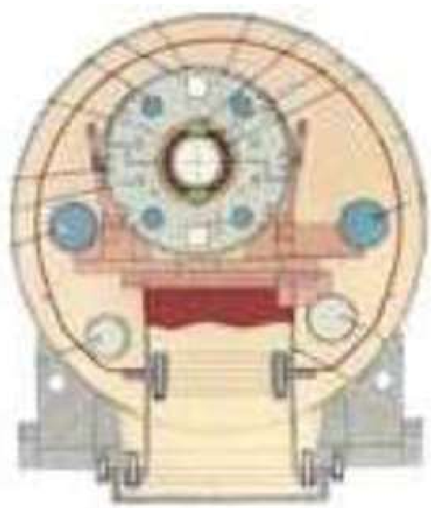
5.3T

HERA,
9 m, 75 mm
416 dipoles

NbTi cable
cold iron
Al collar

3.5T

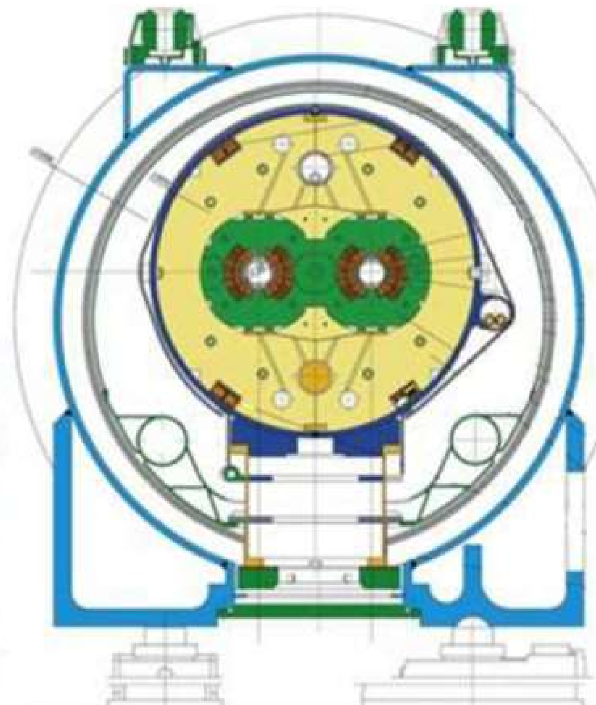
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

8.3T

LHC,
15 m, 56 mm
1276 dipoles



NbTi cable
2K He
two bores

Highest Accelerating Gradients

ILC cavity

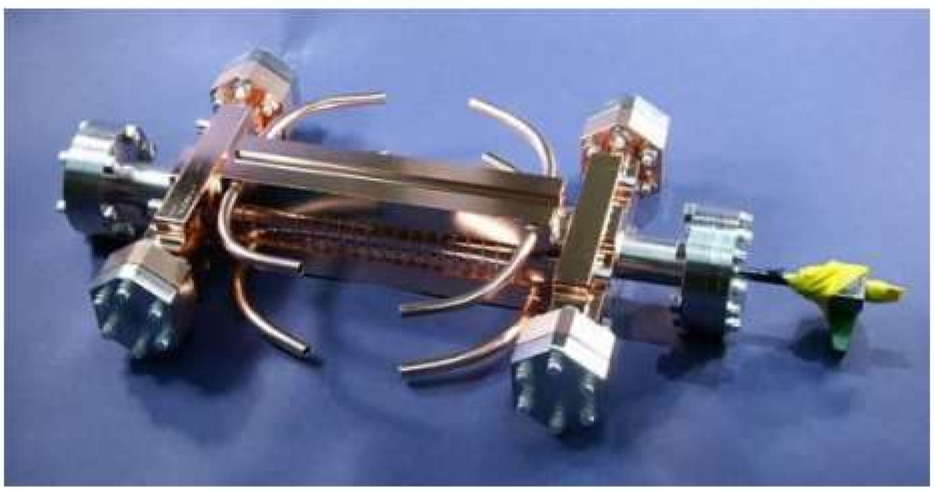
1.3 GHz, superconducting

Target effective operational 31.5MV/m

Target gradient 35MV/m

$Q_0 \approx 10^{10}$

CLIC accelerating structure



12 GHz, normal conducting

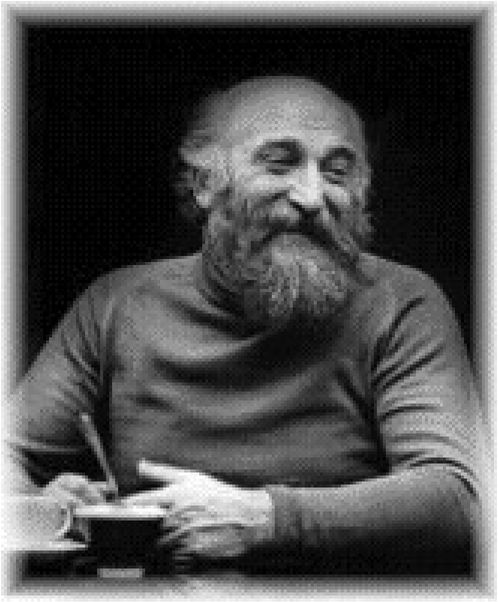
Target loaded gradient 100MV/m

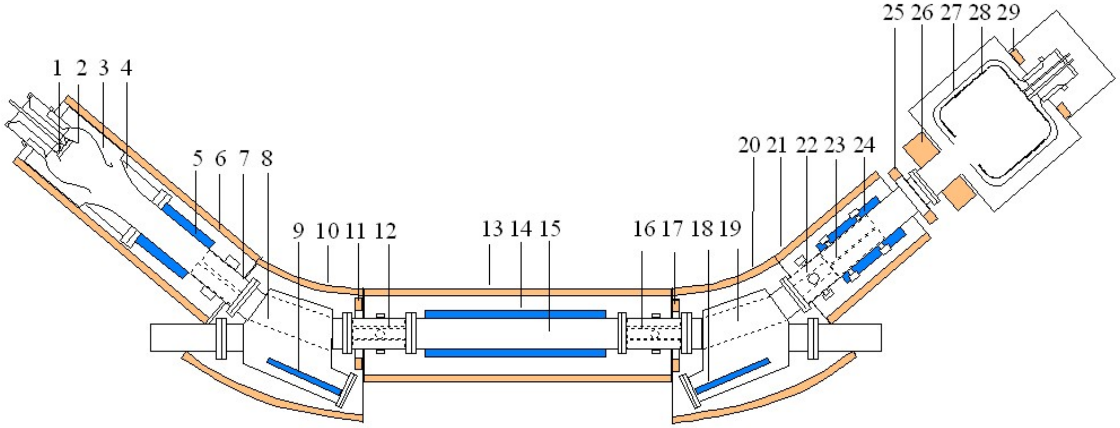
Target unloaded gradient 120MV/m

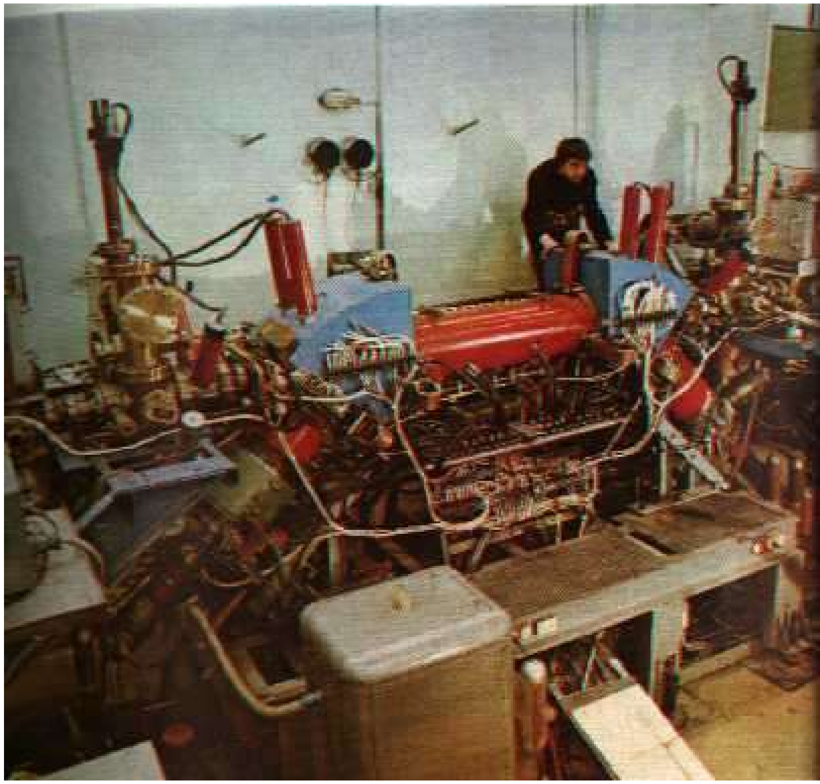
$Q_0 \approx 6\ 10^3$

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



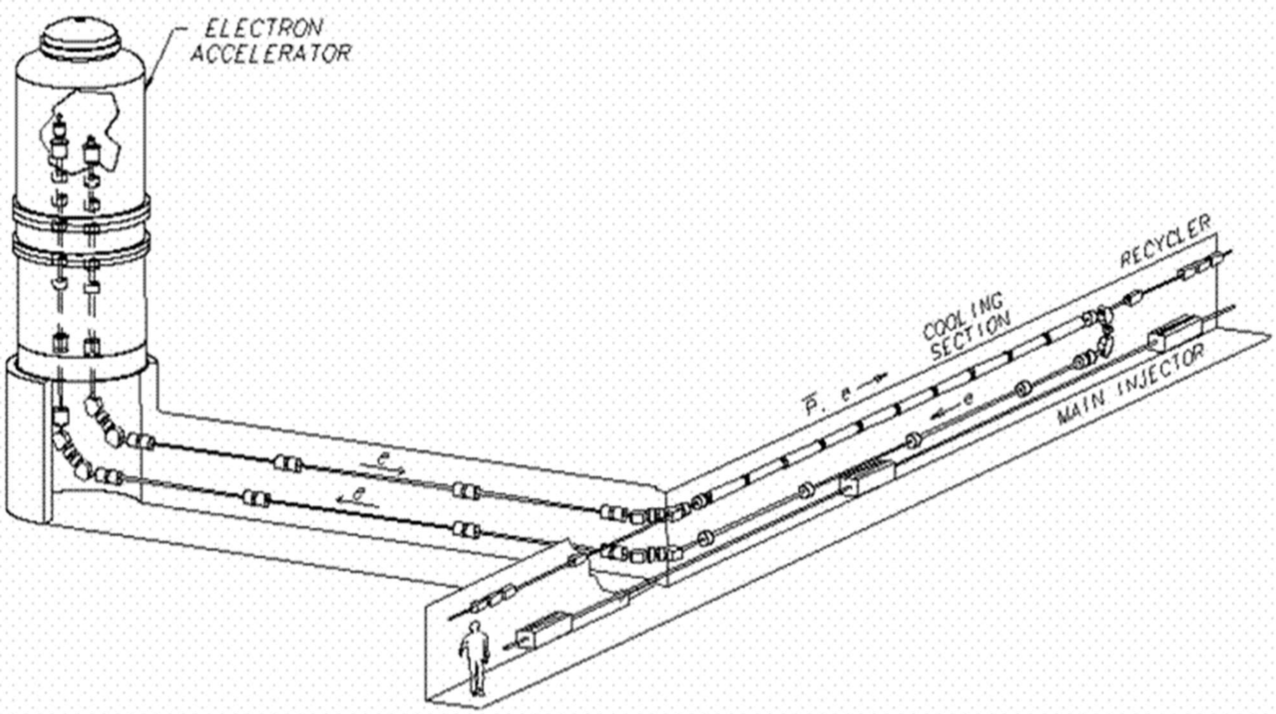




- Many installations since then, up to 1.2 MV electron beam (COSY, Yülich)
- FNAL 4.3 MeV cooler – was next step in technology

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

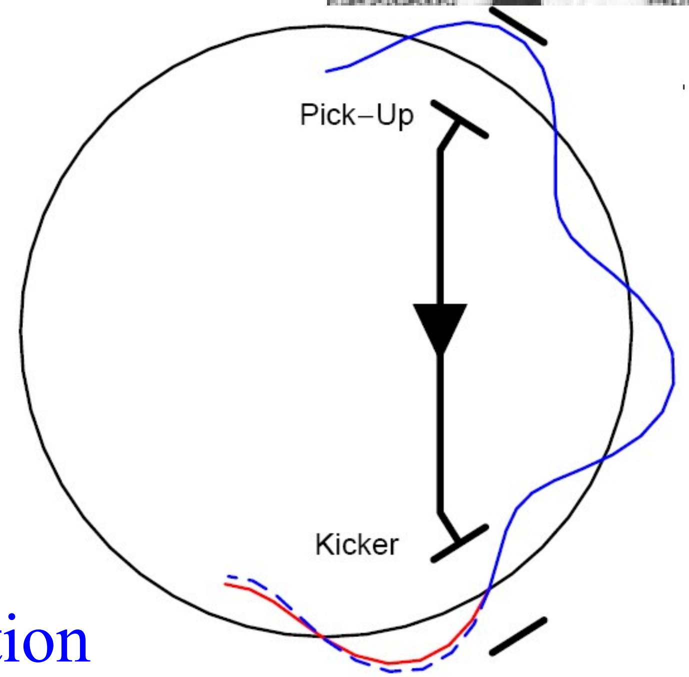
$$\delta\overline{\theta^2} = -\frac{1}{2}2g\overline{\theta^2} \equiv -g\overline{\theta^2}$$

- 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

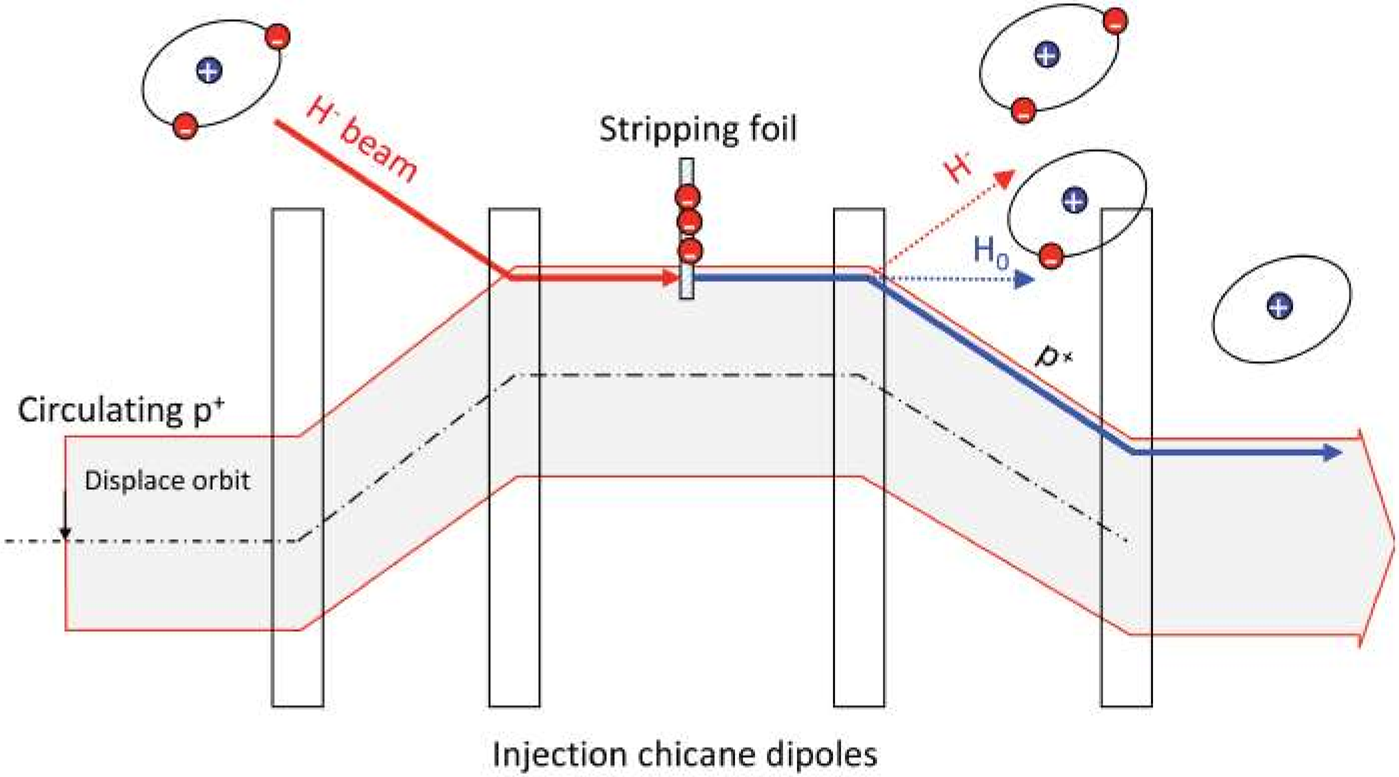
$$\boxed{\delta\overline{\theta^2} = -\frac{1}{2}g_{opt}\overline{\theta^2} \quad , \quad g_{opt} = \frac{1}{2N_{sample}} \quad , \quad N_{sample} \approx N\frac{f_0}{W}}$$



- 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

Strip Injection

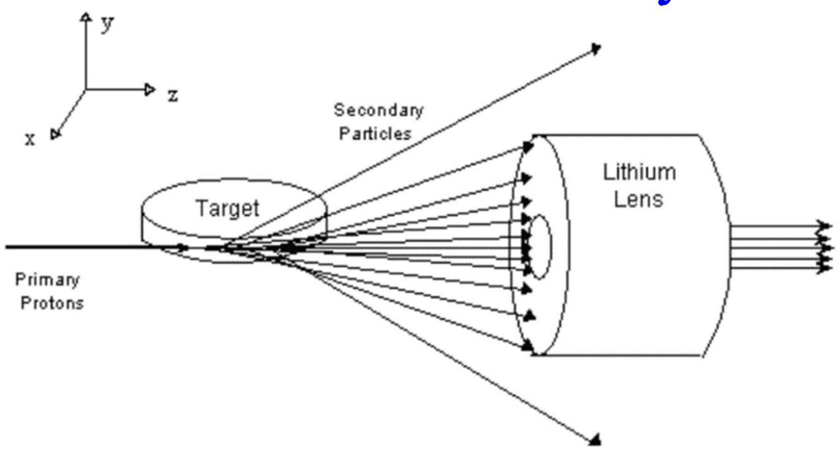
- Invented by Budker, First implemented in INP (Novosibirsk)
- Used in many labs: Fermilab, CERN, Oakridge NL, JPARK, …

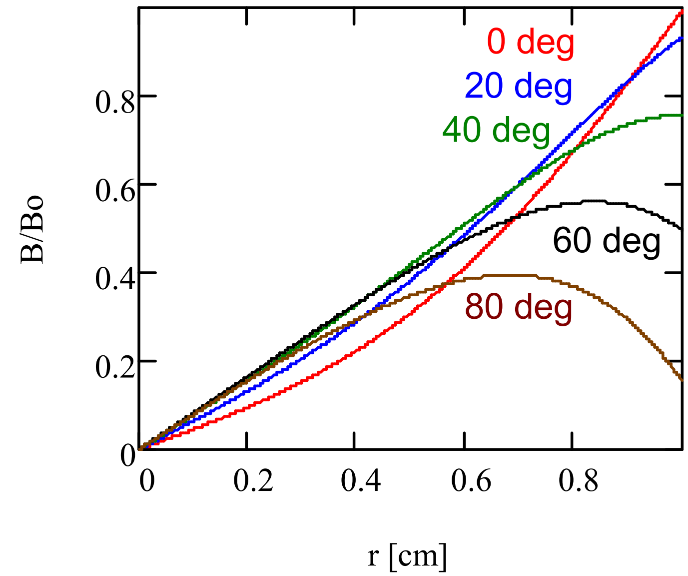


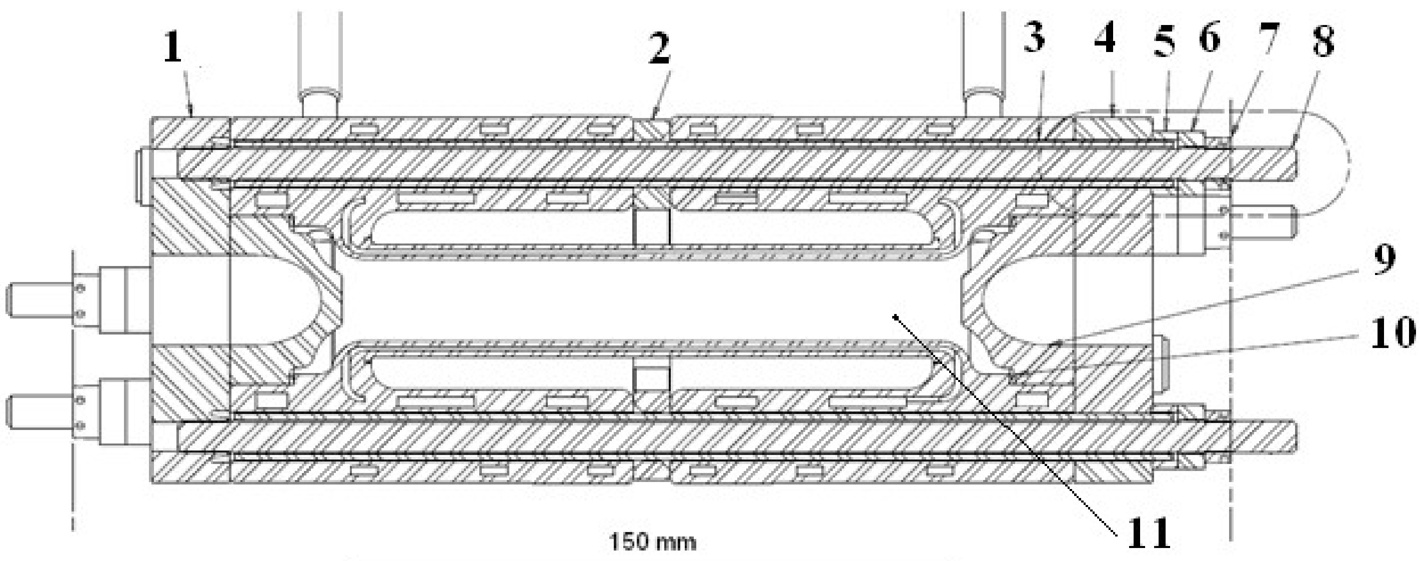
- Modern reincarnations (suggested in SNS in Oakridge):
  - Painting
  - Laser stripping

Lithium Lens

- Invented by Budker; first, built and tested in Novosibirsk for Fermilab
- Addresses chromaticity of focusing



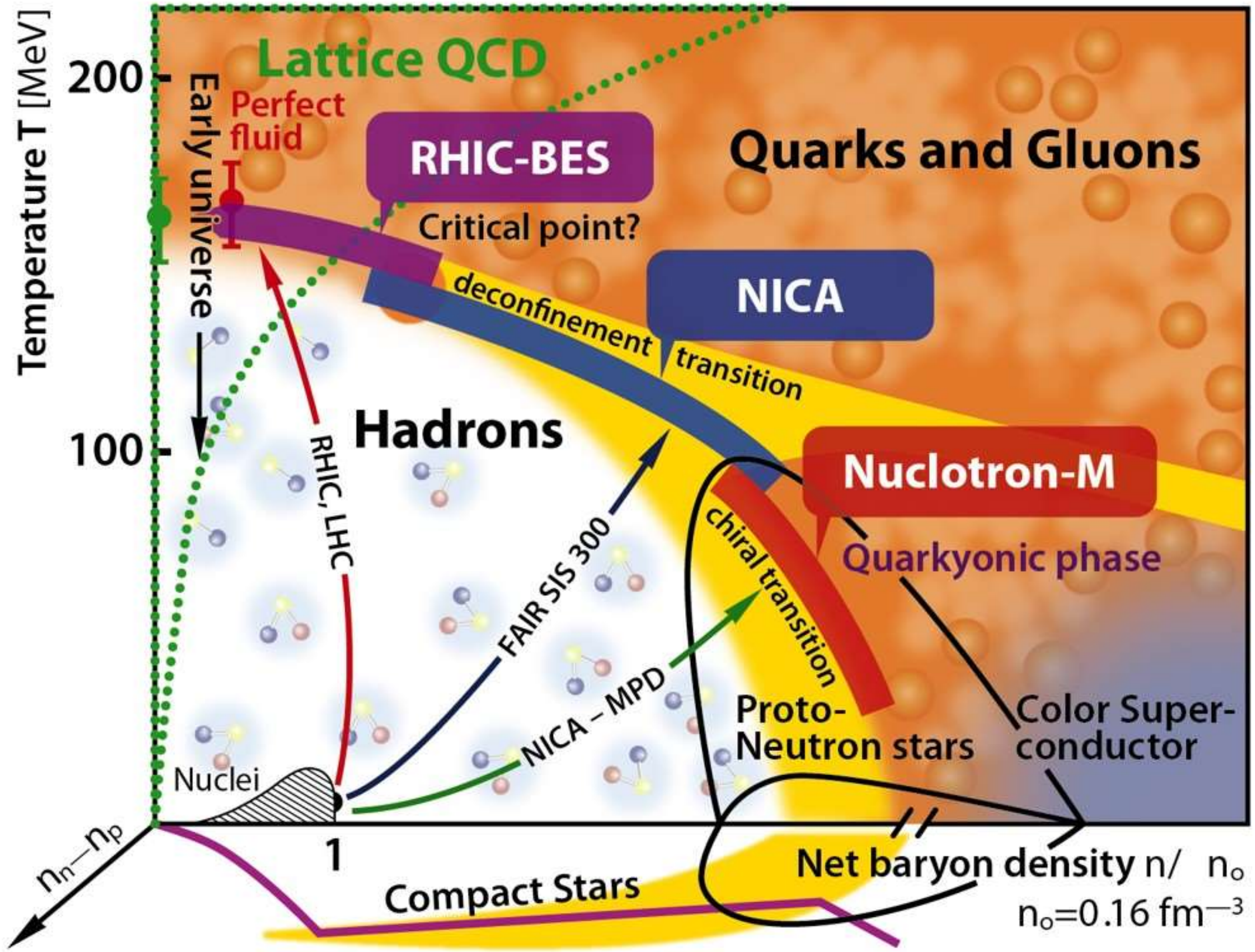




NICA – the First Hadron Collider in Russia

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 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)
- NICA is built to answer the last 2 questions

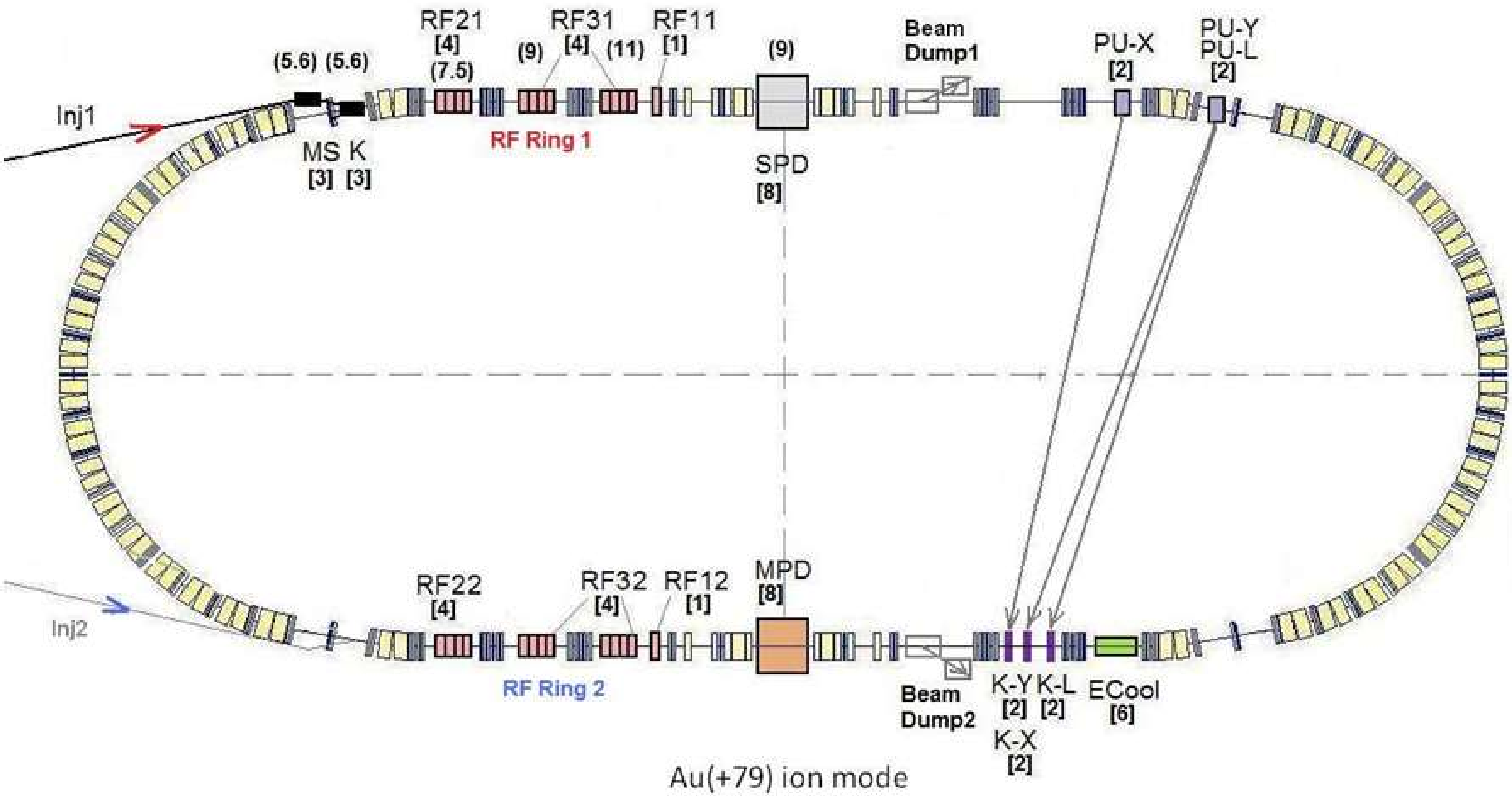
Why NICA?

- Unique niche
  - Two major competitors (LHC & RHIC) have too large energy to get to sufficiently large luminosity in the interesting region of low energy of few GeV/n
  - Beam slowly extracted from the SPS (CERN) has the same energy reach but all reaction products go forward
- 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/n kinetic energy

Objectives used for the Collider Proposal

- Maximize the luminosity basing on the experience already obtained by accelerator physics community
  - Look into optimal strategy & Parameter interdependence
- Proton mode
  - Proton mode requires additional insight and, may be, an additional place in the straight lines: snakes, etc.
  - presently we assume the same optics as for heavy ions, but it may be changed in the future
- Major effects affecting the machine design
  - Beam-beam and space charge
  - Beam optics including non-linear effects
  - IBS
  - Cooling
  - Luminosity lifetime
  - Instabilities

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, an increase of particle amplitudes results in the beam loss

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

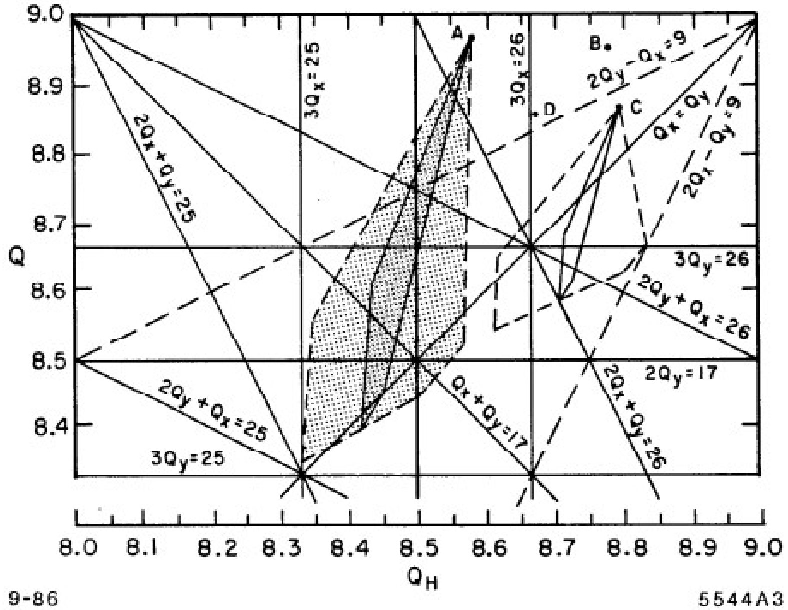


Fig. 3. Space charge tune shift of the AGS.

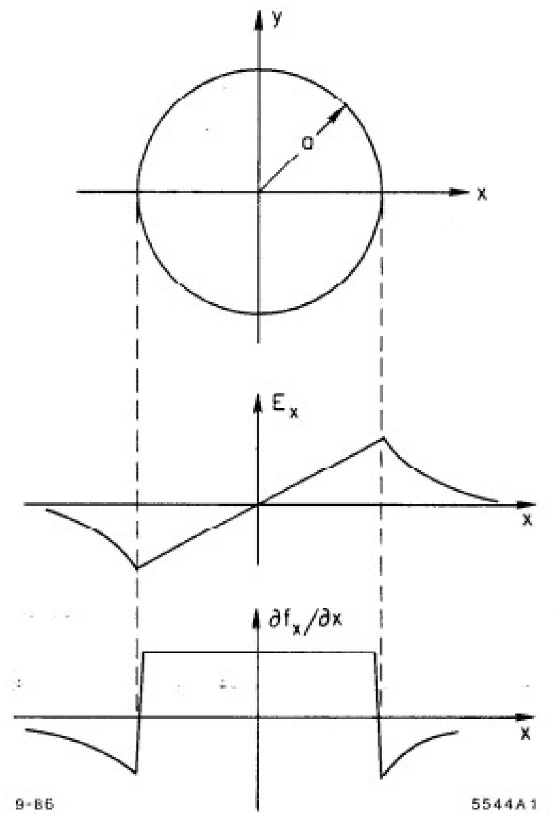


Fig. 1. Space Charge force of a uniform cylindrical beam.

- Beam magnetic field $\sim\beta^2$, partially compensates electric field, $1-\beta^2=1/\gamma^2$
  - SC effect is diminishing fast with beam energy

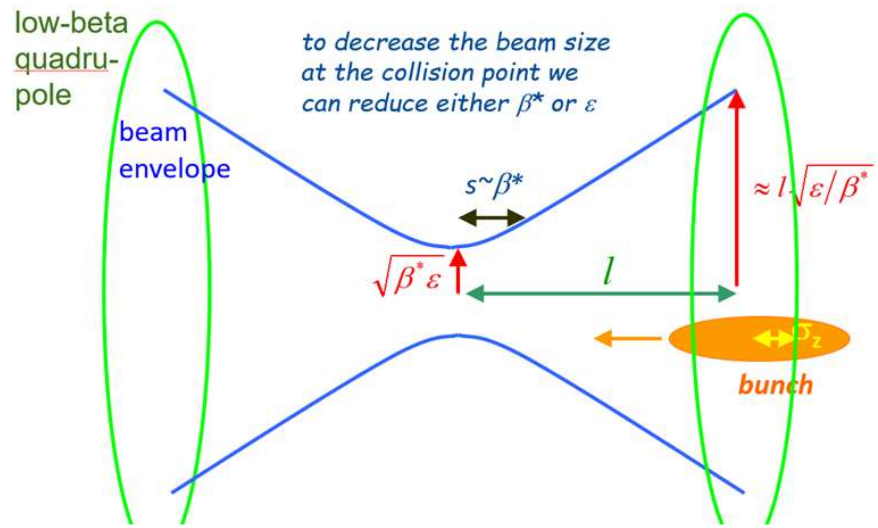
Beam-beam Effects

- 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

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



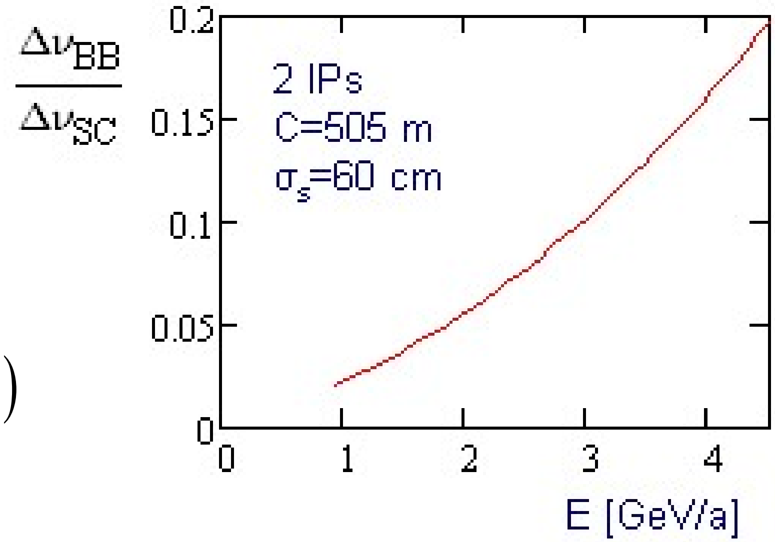
- Magnetic field of counter rotating beam almost doubles force, $1+\beta^2$
- Note that for large synchrotron amplitude the tune shift increase due to larger beta-function with longitudinal displacement is compensated by decrease of space charge field
  => no dependance on bunch length

- 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)

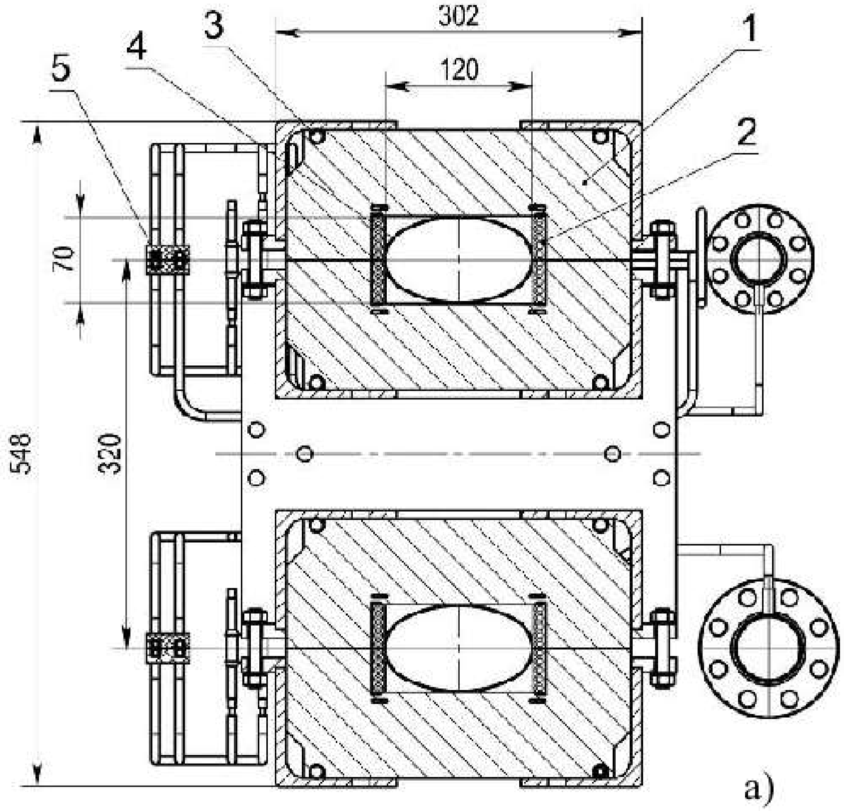


- Ratio of tune shifts:

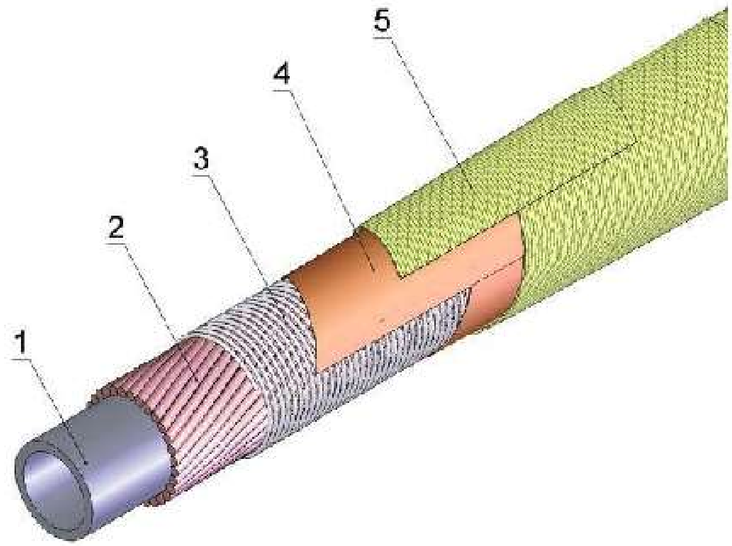
$$\frac{\delta\nu_{BB}}{\delta\nu_{SC}} = N_{IPs}\sqrt{\frac{\pi}{2}}\frac{\sigma_s}{C}\gamma^2\left(1+\beta^2\right)$$

- 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

NICA dipoles

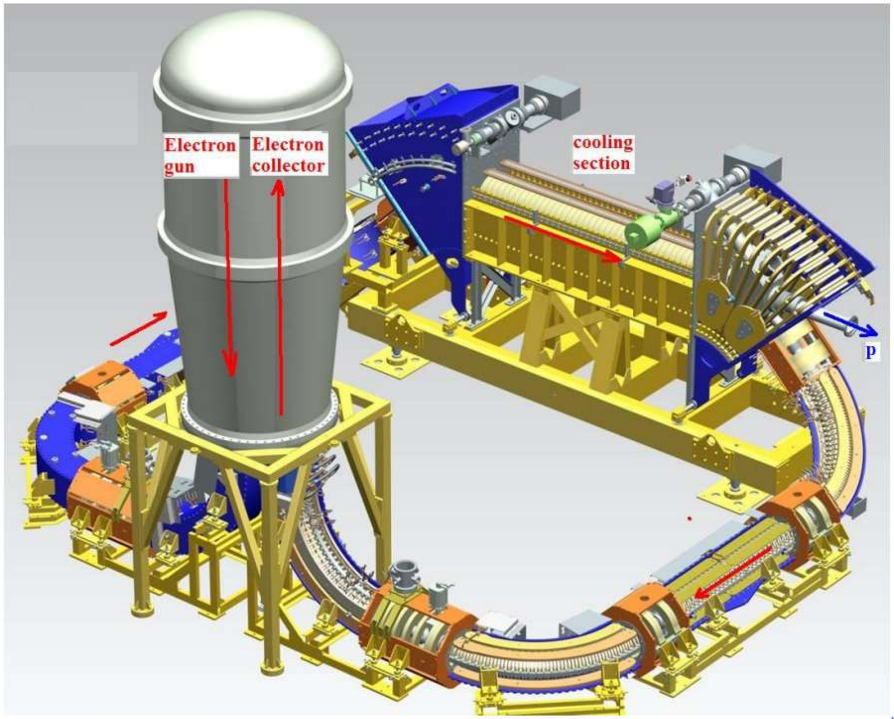


a)



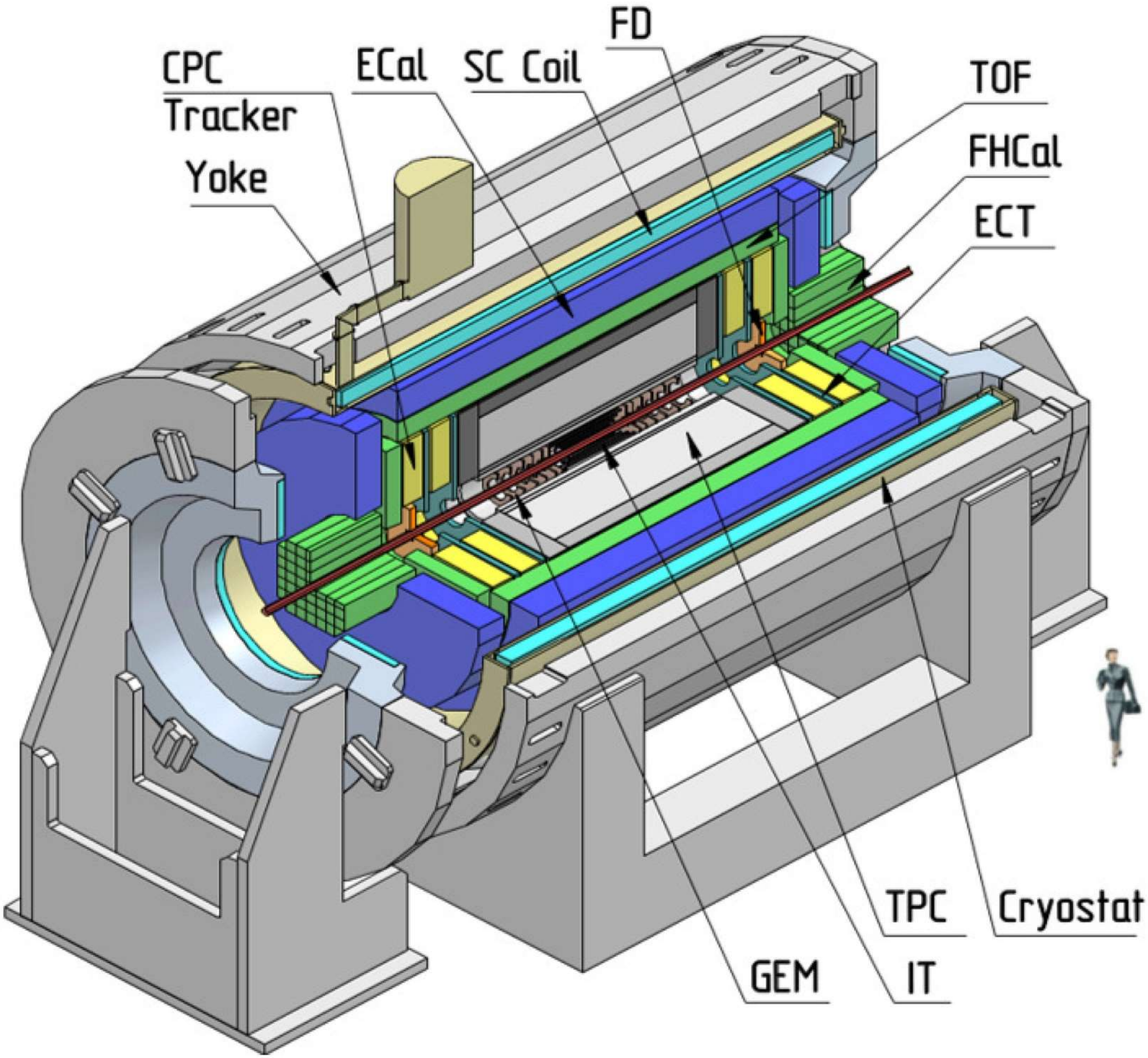
Beam Cooling

- 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 the 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 (tested to 1.5 MV)
  - 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 (10-20 hour at collissions)

Detector MPD

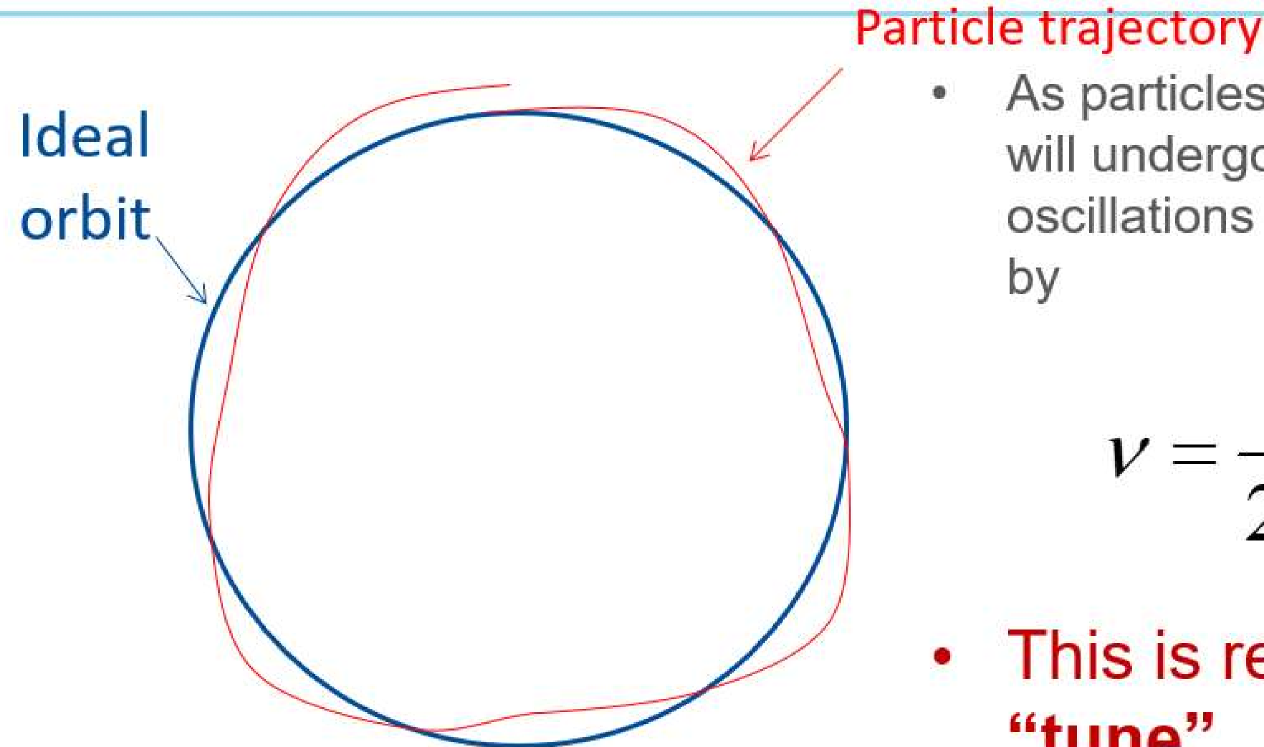


Instead of Conclusions

- In less than 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. It was successful and extremely helpful for future
  - Be ready for beam accumulation in Booster with electron cooling
- Booster Run delayed to the year-end due to vac. incident in LEBT
- 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
- For now the program with polarized protons and deuterons is 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 side

Backup Slides

Betatron Oscillations, Tune



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

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

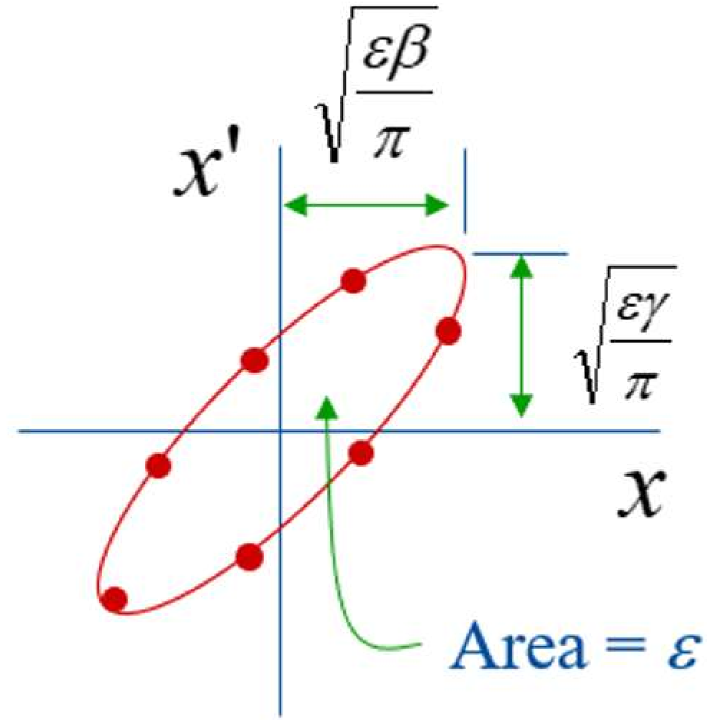
- This is referred to as the **"tune"**

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

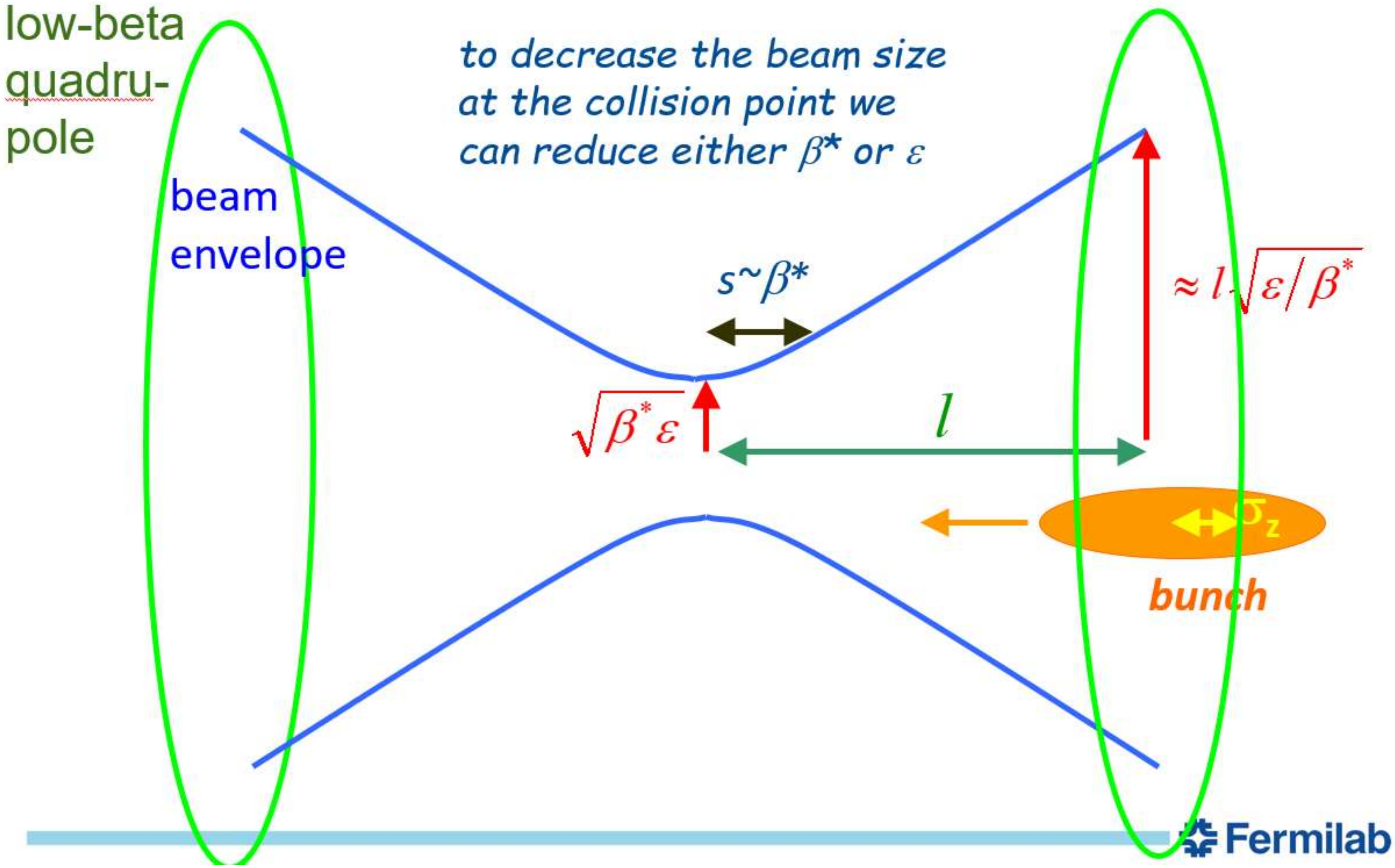
Integer : magnet/aperture optimization → **64.31** ← **Fraction: Beam Stability**

Emittance

- 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 ~ $1/\varepsilon$



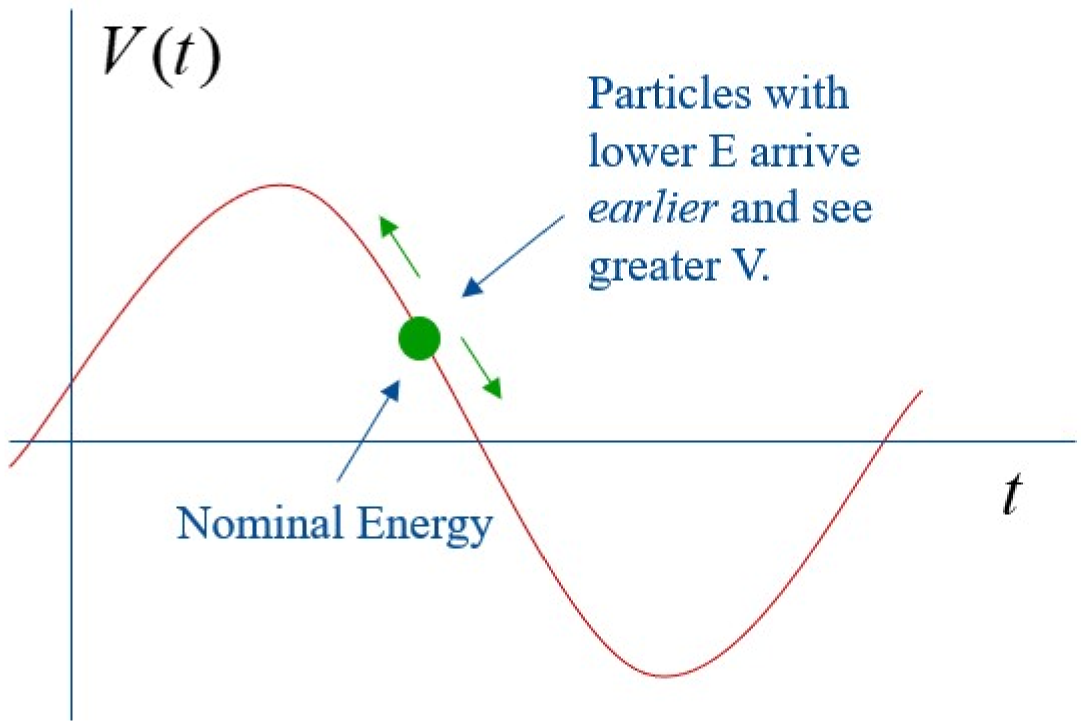
Collider Spot Size



- 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

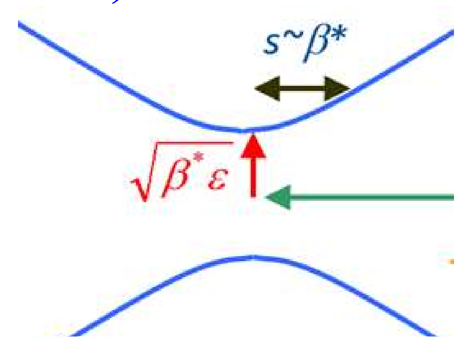
- Particles are typically accelerated by radiofrequency ("RF") structures.
- Stability depends on particle arrival time relative to the RF phase.
  - Time of arrival depends mostly on the energy deviation relative to "the reference (central) particle"



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

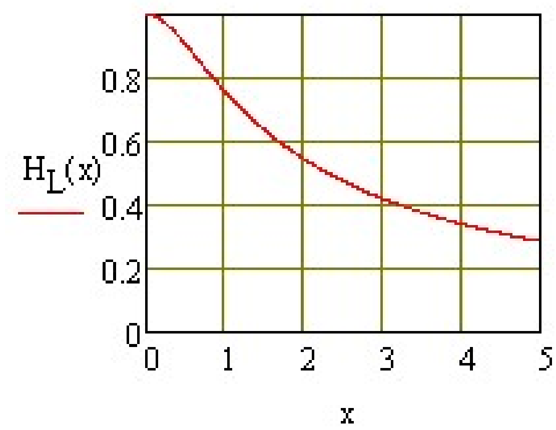
$$\delta\nu_{SC}\approx\frac{r_p Z^2 N_i}{4\pi A\beta^2\gamma^3\varepsilon}\frac{C}{\sqrt{2\pi}\sigma_s}$$

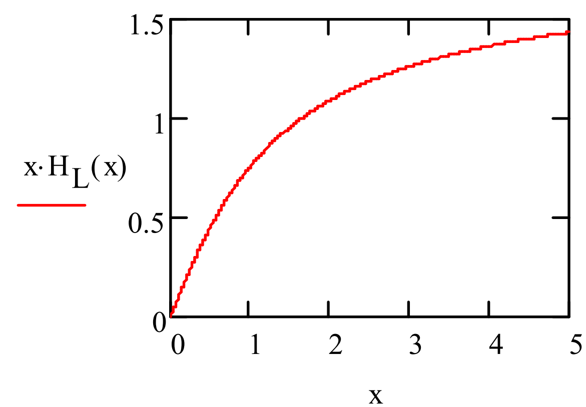
  - ♦ Weak dependence of SC tune shifts on optics

- 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)

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