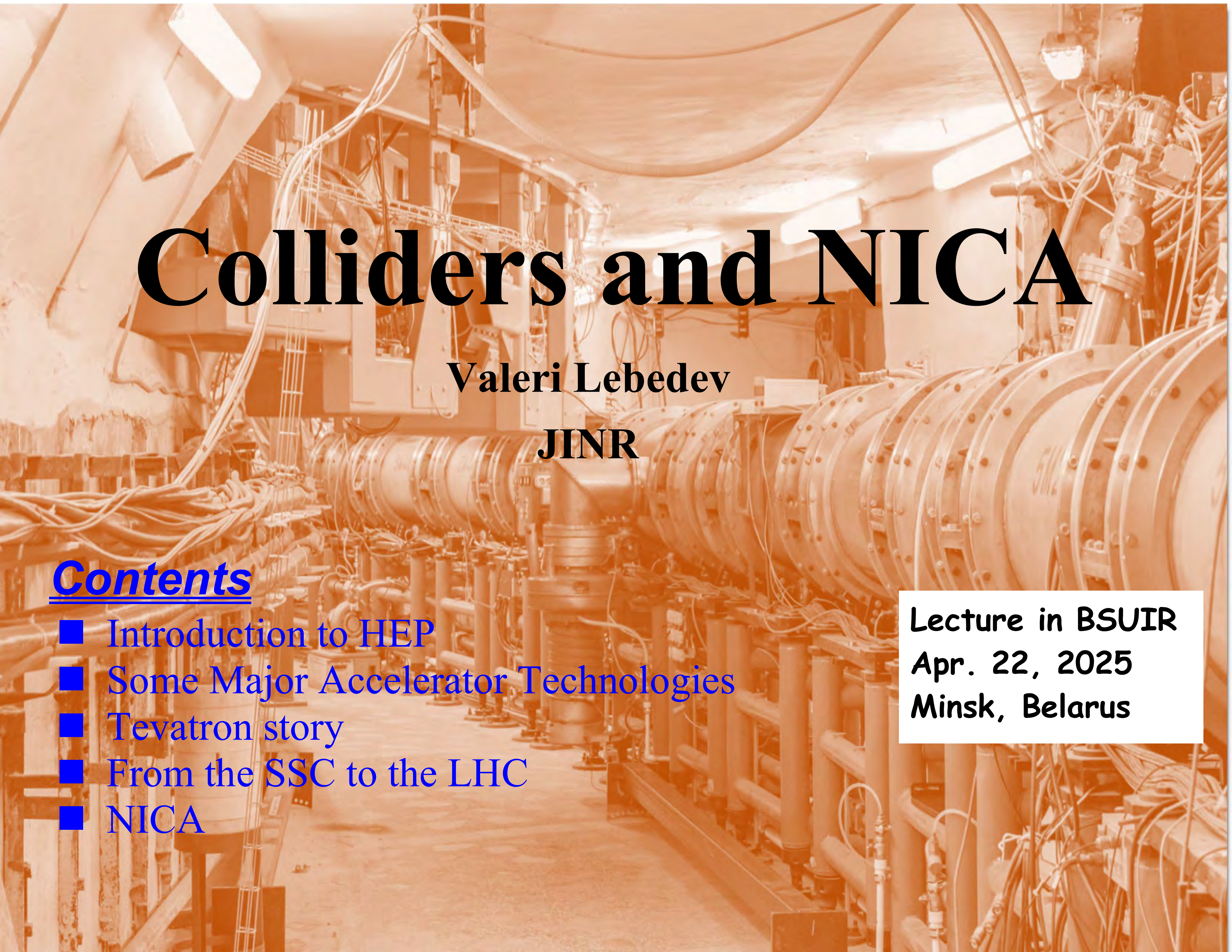

Colliders and NICA

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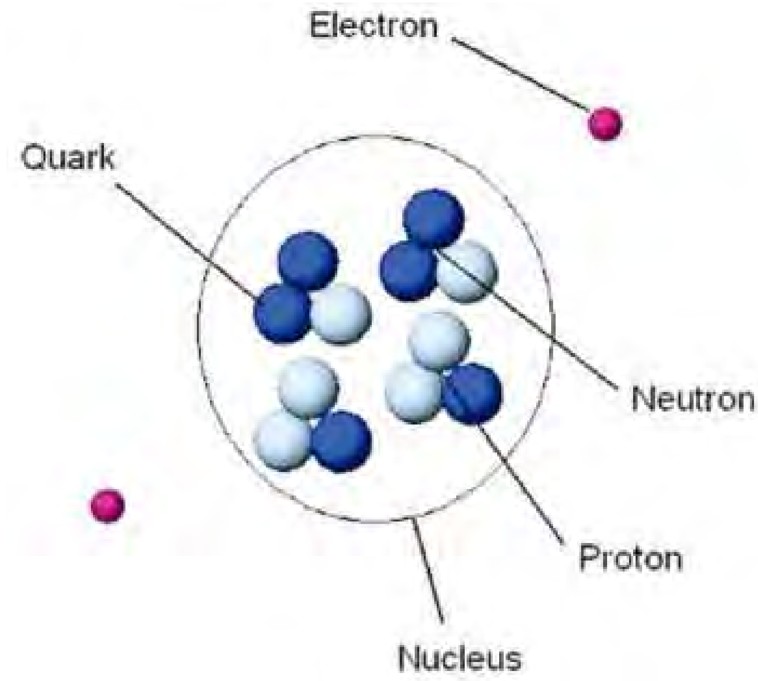
JINR

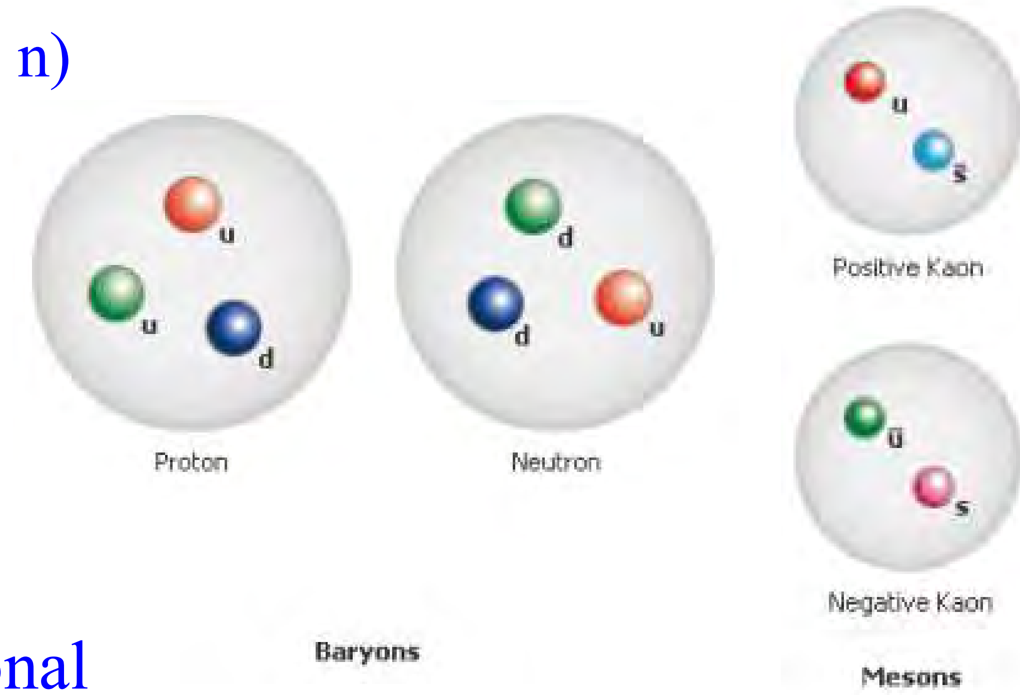
Contents

Lecture in BSUIR
Apr. 22, 2025
Minsk, Belarus

Looking Dipper and Dipper

- Atom (electrons and nucleus);
  atom size ~10^{-8} cm
  Binding force – electro-magnetic
- Nucleus (protons and neutrons);
  nucleus size ~$\sqrt[3]{A}\,1.2\cdot 10^{-13}$ cm
  Binding force – strong interaction
- Hadrons (quarks and gluons)
  Mesons (2 quarks)
  Baryons (3 quarks) (include p & n)
  Tetraquarks
  Pentaquarks
  …
  Only proton has long life
- Leptons
  electron, muon, tau
- 4 types of interactions:
  strong, e.-m., weak, gravitational





Bricks and Glues

Elementary particles

Elementary fermions
Half-integer spin
Obey the Fermi–Dirac statistics

Quarks and antiquarks
Spin = $\frac{1}{2}$
Have color charge
Participate in strong interactions
and electroweak interactions

Three generations

1. Up (u), Down (d)
2. Charm (c), Strange (s)
3. Top (t), Bottom (b)

Leptons and antileptons
Spin = $\frac{1}{2}$
No color charge
Electroweak interactions

Three generations

1. Electron (e^-), [†] Electron neutrino (ν_e)
2. Muon (μ^-), Muon neutrino (ν_μ)
3. Tau (τ^-), Tau neutrino (ν_τ)

Elementary bosons
Integer spin
Obey the Bose–Einstein statistics

Gauge bosons
Spin = 1, 2 [‡]
Force carriers

Four kinds

1. Photon (γ; electromagnetic interaction)
2. W and Z bosons (W^+, W^-, Z^0; weak interaction)
3. Eight types of gluons (g; strong interaction)
4. Graviton (hypothetical) (G; gravity) [‡]

Scalar bosons
Spin = 0

One kind

Higgs boson (H^0)

From the micro-scale to the scale of Universe

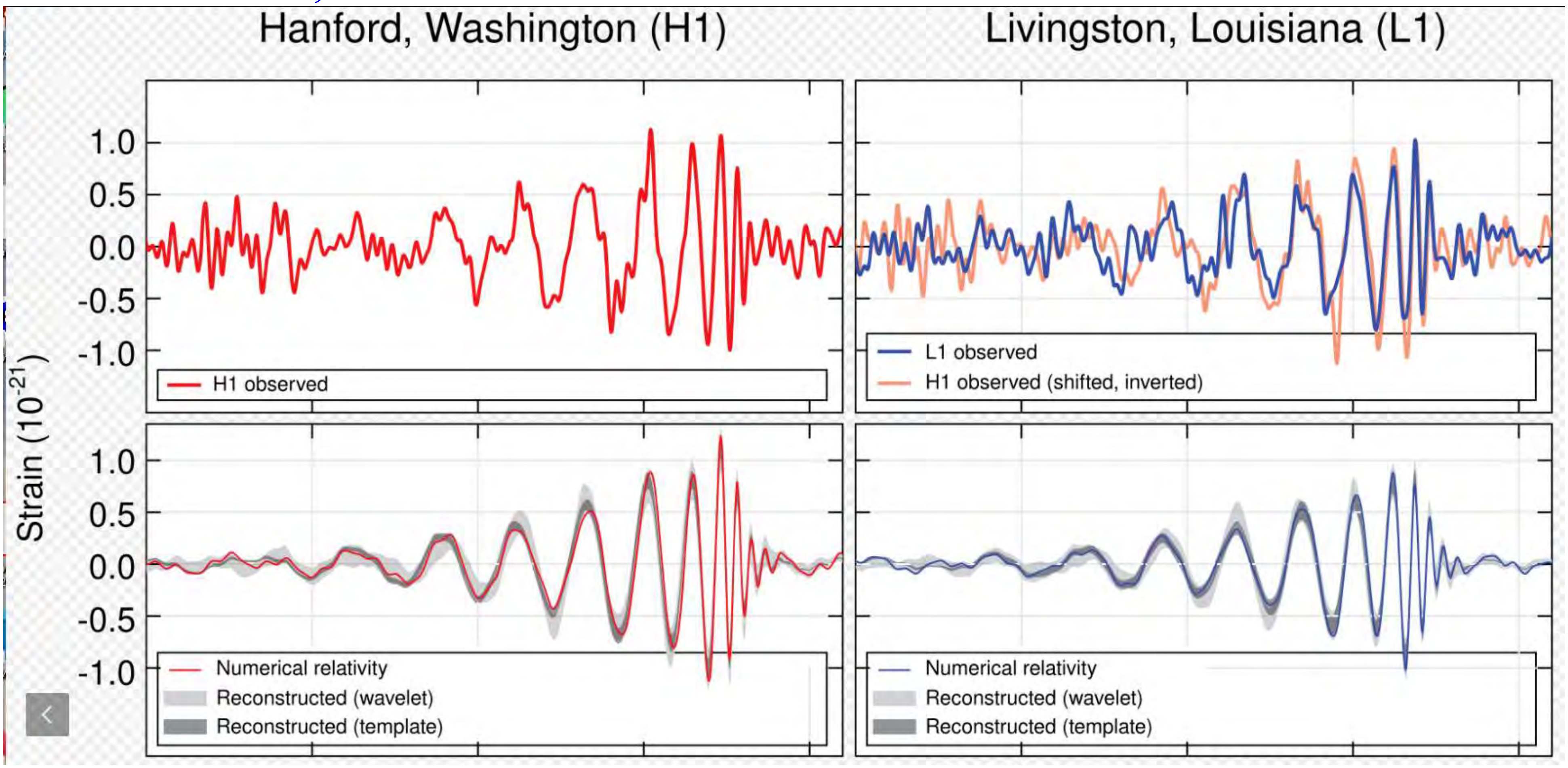
- There are ~10^{11} - 10^{12} galaxies in the observable universe
- Typical galaxy has 10^{11} - 10^{12} stars
  - Our galaxy (Milky Way) has ~10^{11} stars
- Modern astronomy uses similar means of research as particle physics
  - Digitization of images and their analysis with computer algorithms
- Astrophysics and particle physics have been getting closely related
  - The best limitation on neutrino mass comes from astrophysics

A Hubble Telescope photograph of galaxies deep in Universe

— Hipparcos mapped millions of stars in our galaxy, but how many more are there?

Gravitational Waves

- 1st direct observation of gravitational waves was made on Sep. 14, 2015 and announced by LIGO and Virgo collaborations on Feb. 11, 2016

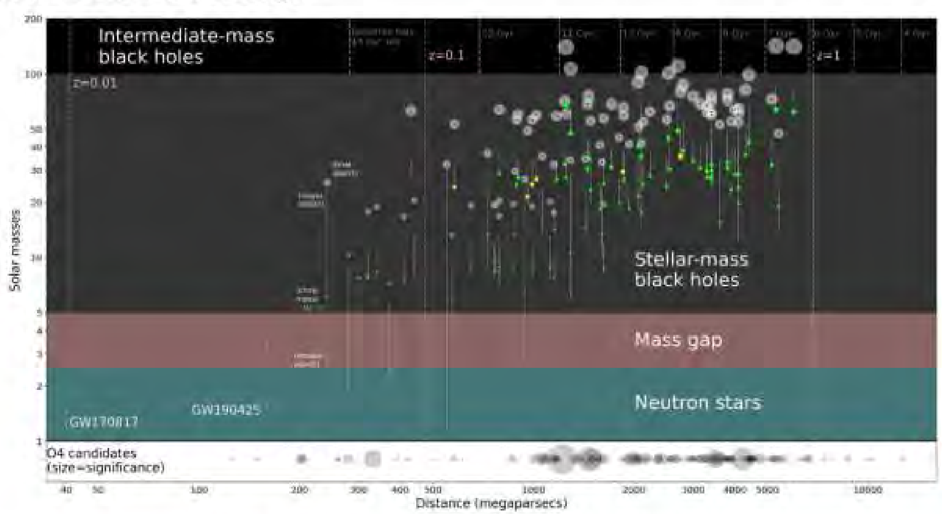


Gravitational Waves (2)

- Gravitational wave was emanating from the inward spiral and merger of two black holes (of 36M⊙ and 29M⊙) located at Distance $1.4\cdot10^9$ ly
  - The universe lifetime is $13.5\cdot10^9$ years.
- Since then, ~100 merges were observed

Northern arm of the LIGO Hanford Gravitational-wave observatory

Events from LIGO & Virgo



Distance and mass for events up to O4 in 2023

Large Hadron Collider (LHC)

- Circumference ~27 km
- p-p and Pb-Pb collisions
- Beam energy - 6.5 TeV for protons

Introduction to Colliders

When it was started?

- In the fall of 2024 in BINP we marked 60 years of the VEP-1 (2*160 MeV) collider and 50 years of electron cooling
  - Few months earlier than VEP-1 the collider ADA started operation in France
    - Built in Italy by Frascati National Laboratory and relocated to Orsay, France
    - First electron-positron collisions (2*250 MeV) were recorded at the end of 1963
- Strong competition from the very beginning

ВЭП-1 теперь историческая реликвия. Участники запуска (слева направо): Г. Н. Кулипанов, С. Г. Попов, А. Н. Скринский и Г. М. Тумайкин

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)

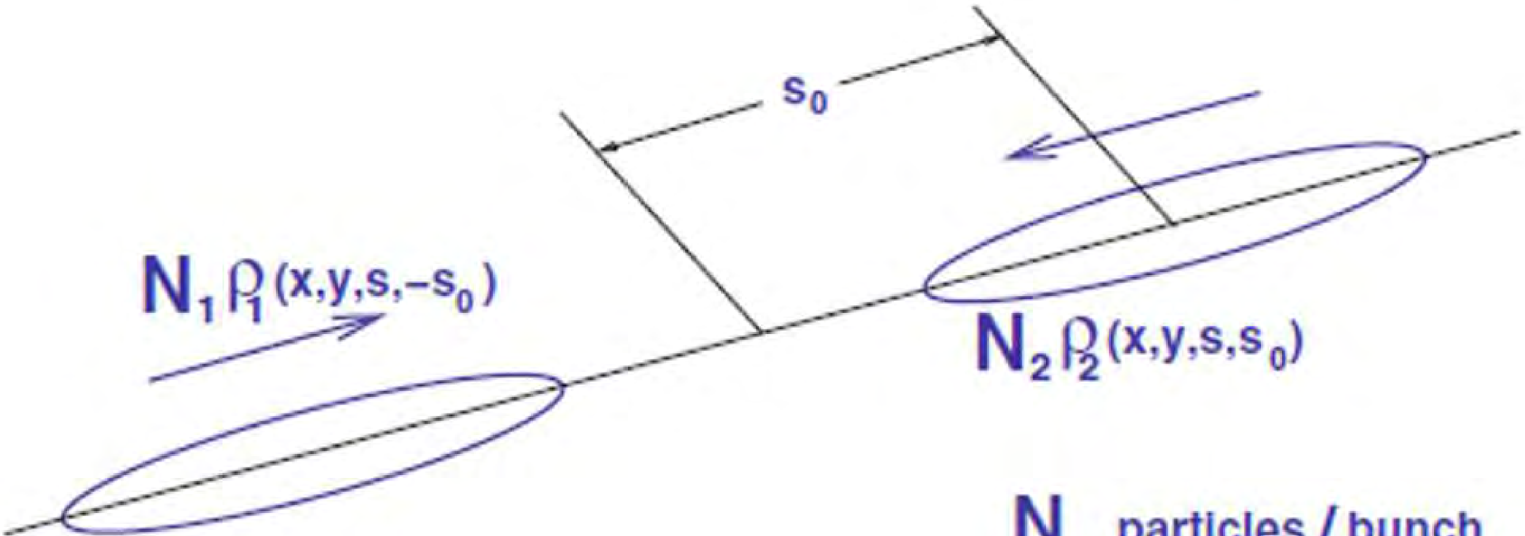
- Luminosity
  - Number of events in collisions:

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

    - The total cross section for Higgs boson production at the LHC operating at $\sqrt{s}$**=13 TeV** is 43 pb = $4.3\cdot10^{-35}$ 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: $(E/E)^4(L/L)=6^4 30\approx4\cdot10^4$
  - <u>Particle physics detectors want constant luminosity!</u>

Luminosity

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



N particles / bunch

ρ density ≠ const.

For (same size) Gaussian bunches:

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

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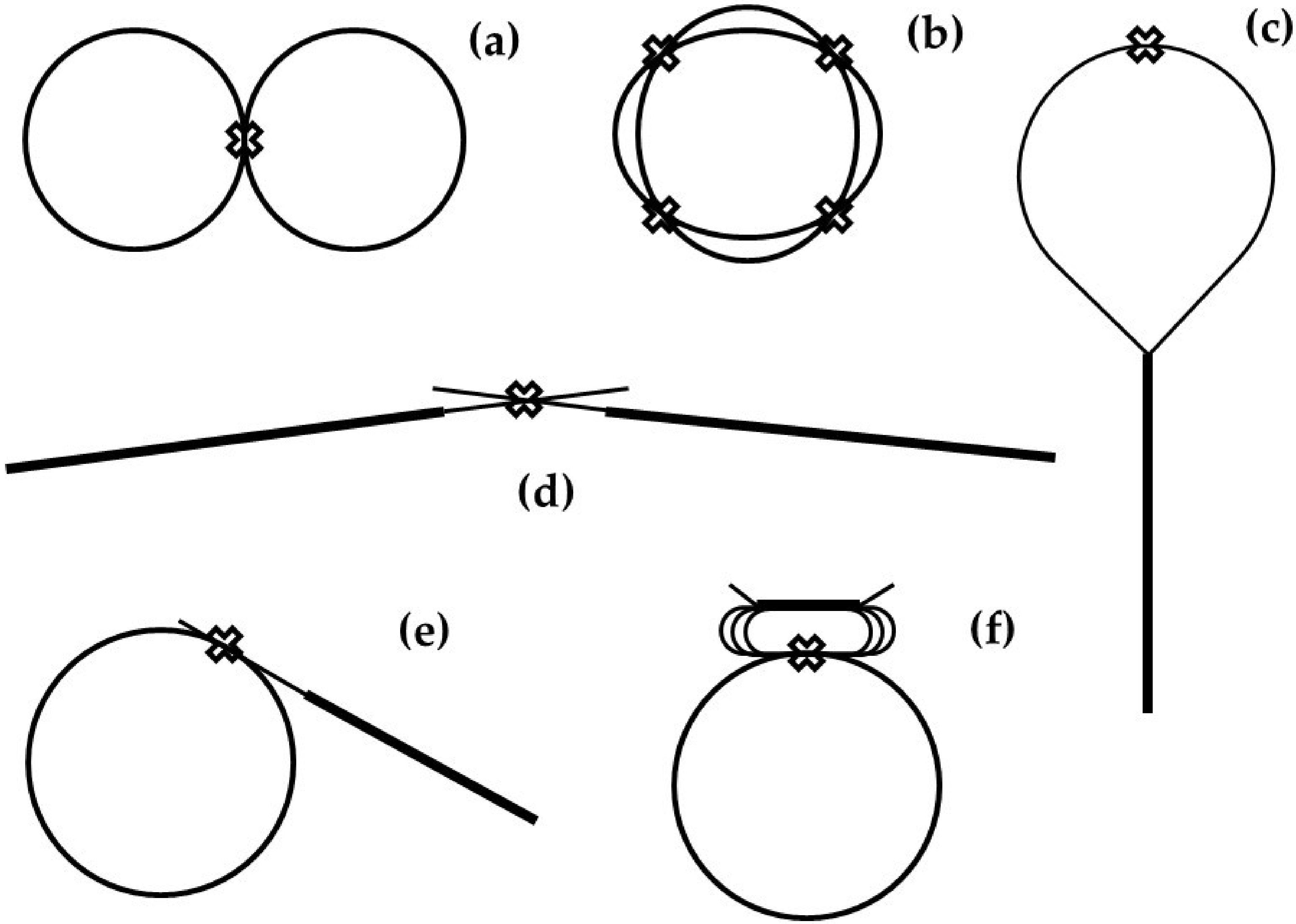
Fermilab

Types of Colliding Beams Facilities



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

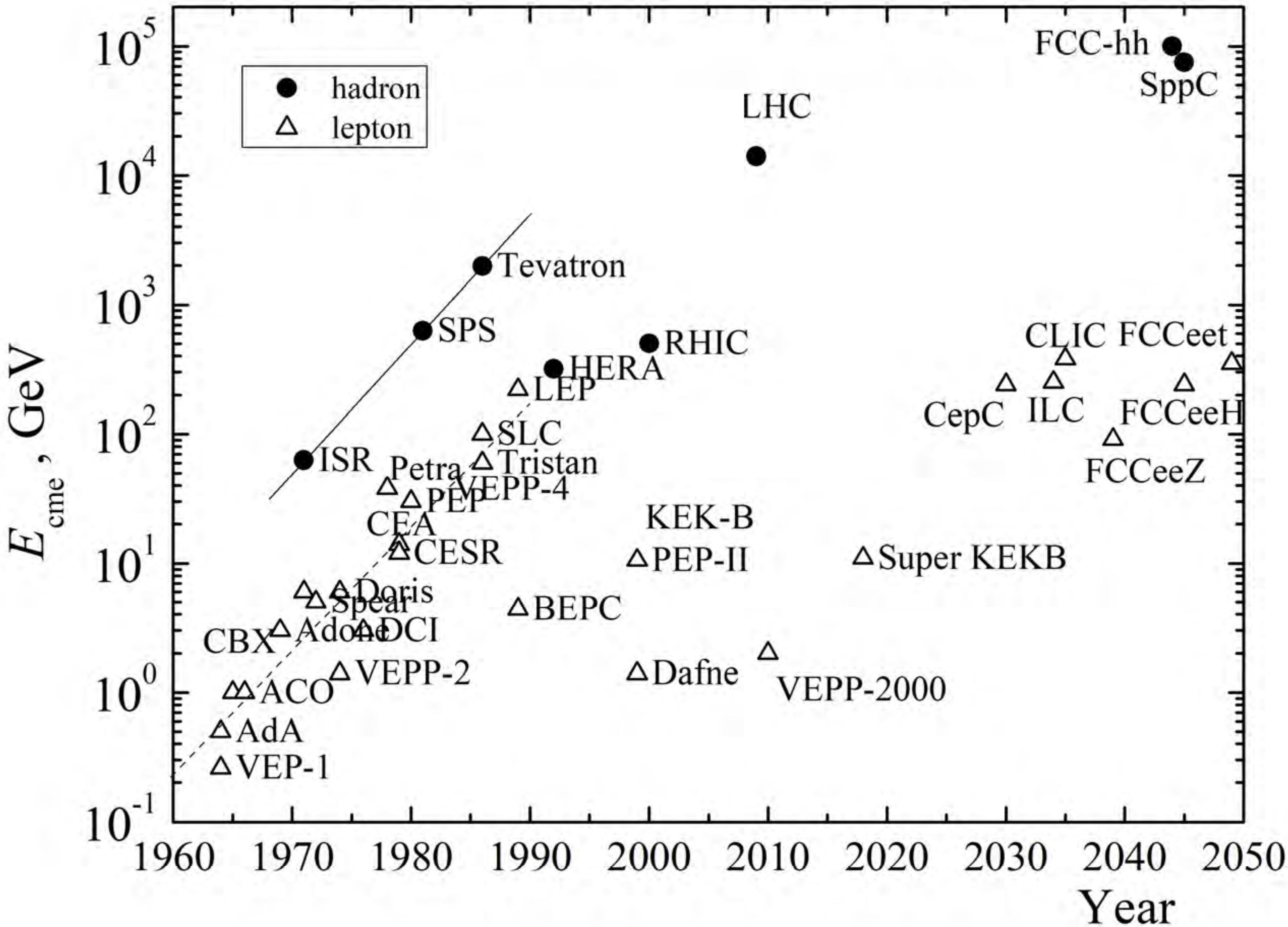
Colliders Landscape

- 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^- → (CEPC, China)
  - Frontier ($E >> E_{LHC}$)
    - 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
$Sp\bar{p}S$	$p\bar{p}$	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

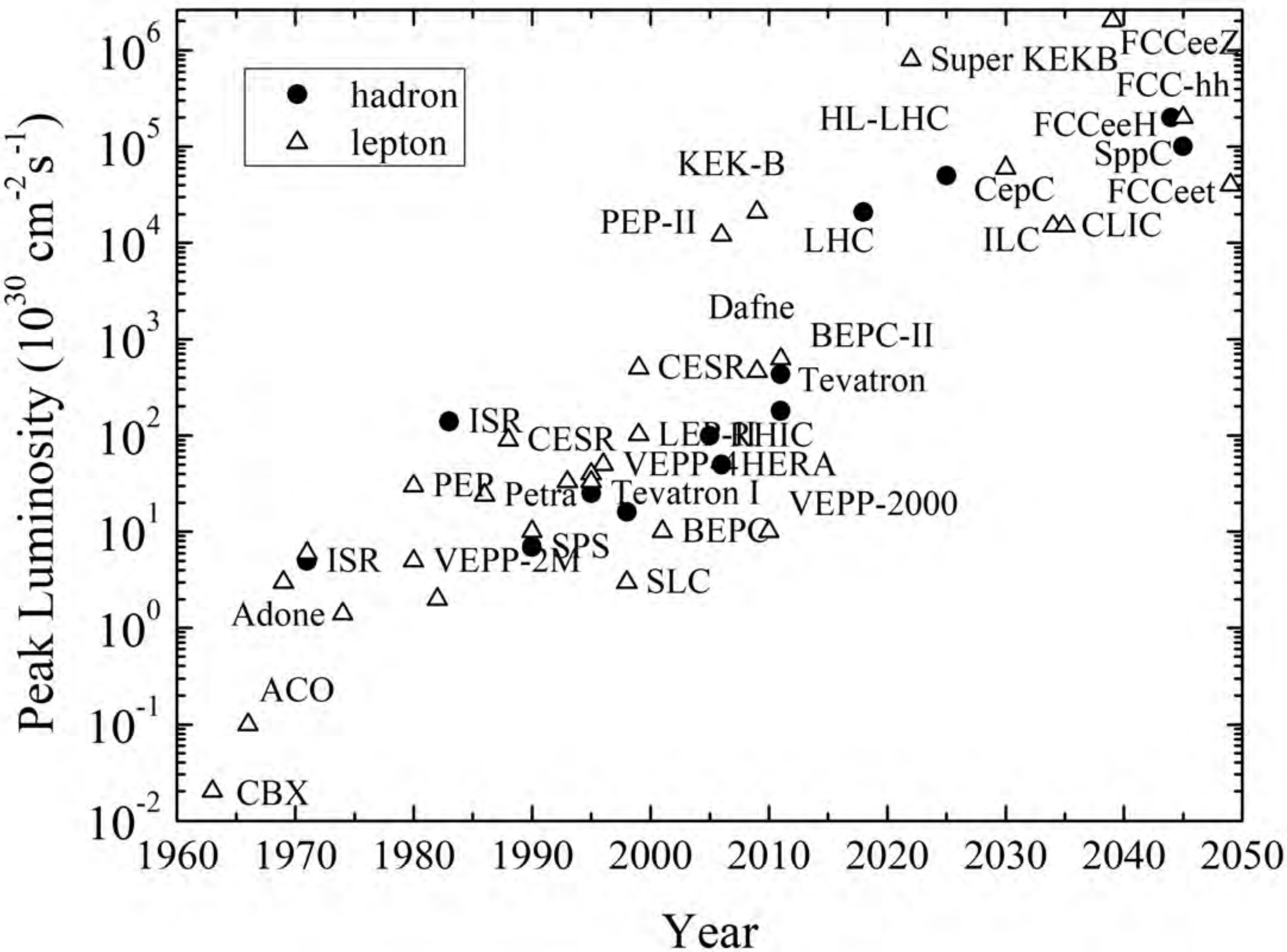


FIG. 3. Luminosities of particle colliders (triangles are lepton colliders and full circles are hadron colliders, adapted from [37]). Values are per collision point.

Electrons versus Protons

- Electrons
  - (+) Point-like objects
    => the entire energy may go to creation of a particle-of-interest
  - (+) Well-determined energy
    => better resolution; important for narrow resonances
  - (+) Smaller backgrounds
    => Easier to separate events from backgrounds => less expensive detector
  - (-) For circular colliders the 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 $\sqrt{s} \leq 2$ TeV)
  - (-) 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

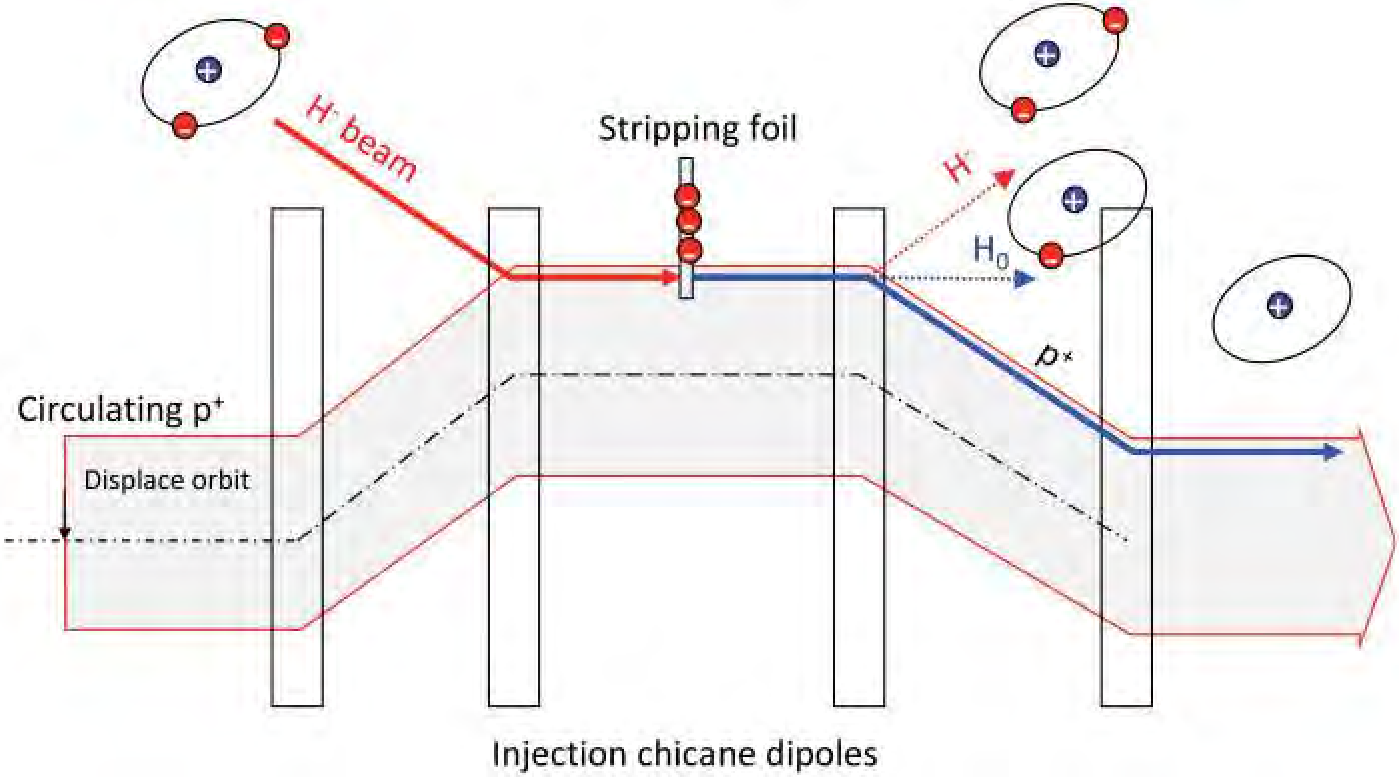
Electrons versus Protons (2)

- 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
    - Thousands 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 (i.e.widths), …) but have to be competitive in luminosity
- Any future collider of any type has to be competitive to the LHC in its physics reach (luminosity, energy, accuracy, …)
  - That's extremely challenging

Some Major Collider Technologies and Major Luminosity Limitations

Strip Injection – fights with Liouville theorem

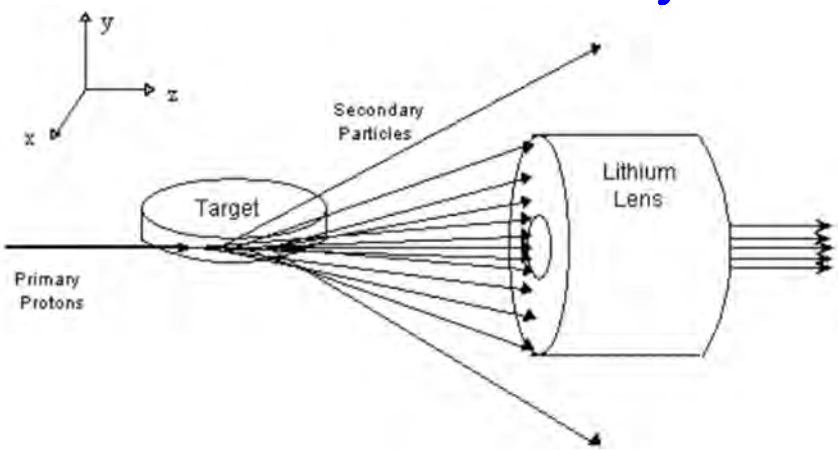
- Invented by Budker, first implemented in INP (Novosibirsk)
- Used in many labs: Fermilab, CERN, Oakridge NL, JPARK, …

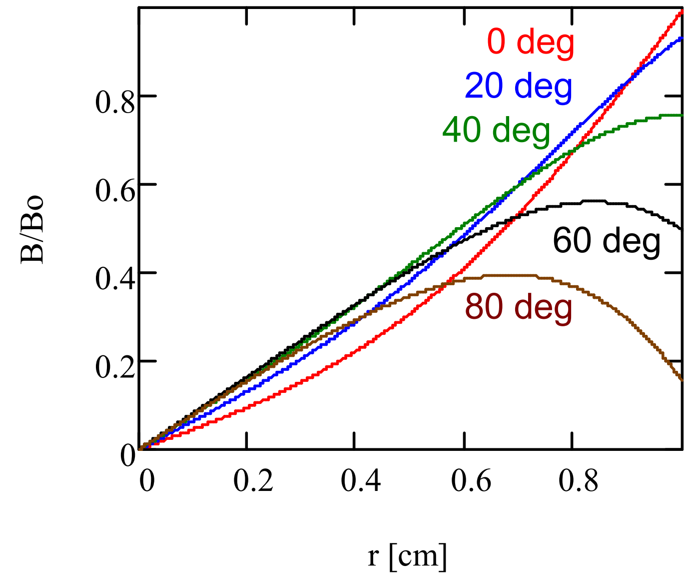


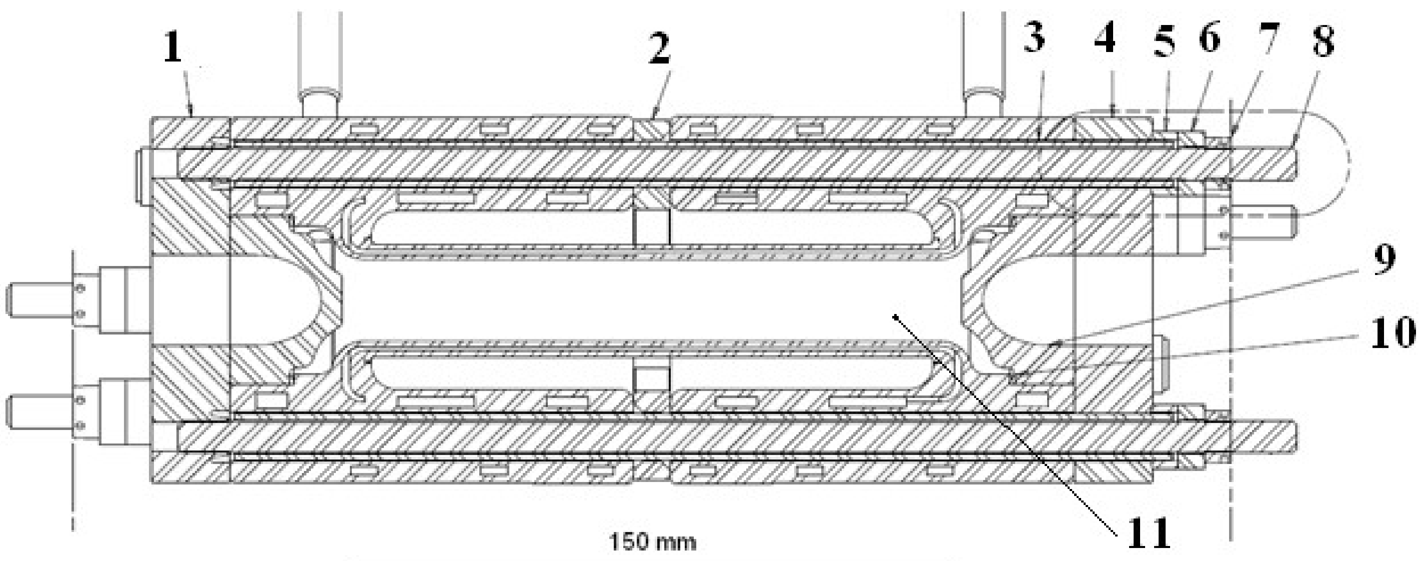
- Modern reincarnations (suggested in SNS in Oakridge, USA):
  - Painting
  - Laser stripping

Lithium Lens

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

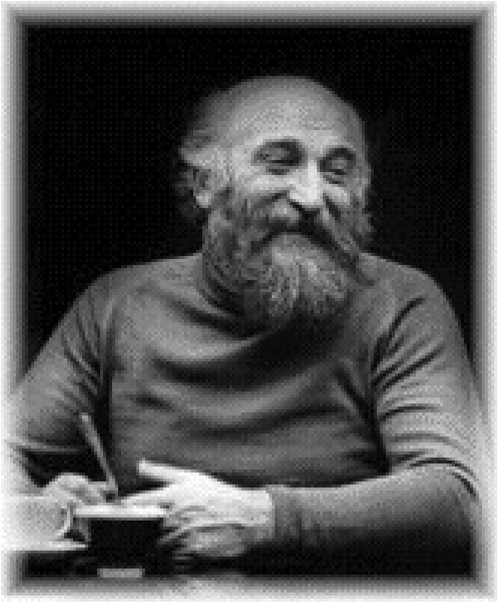


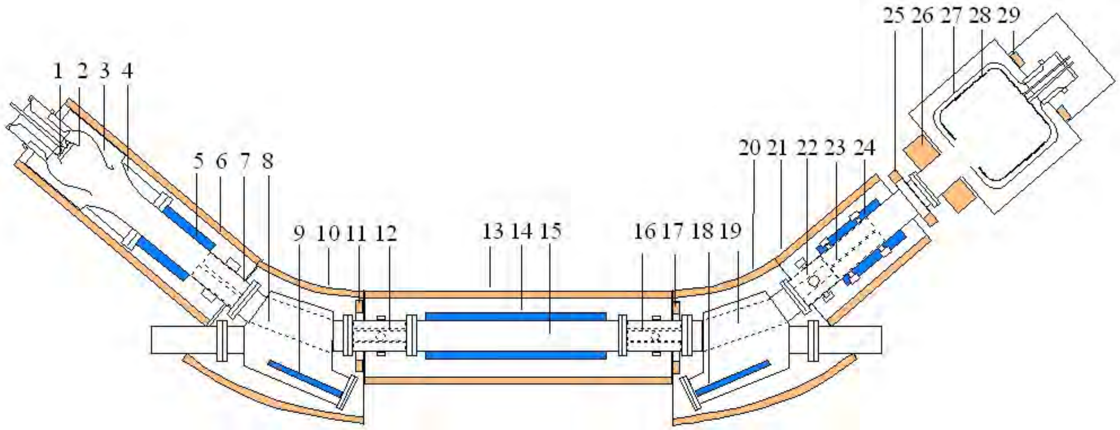


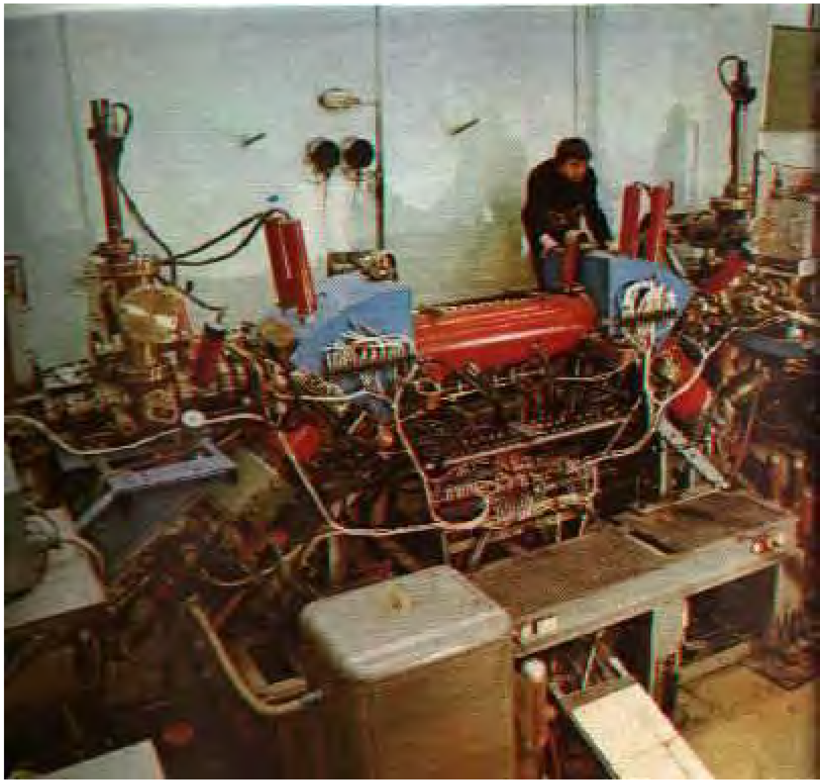


Electron cooling

- 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



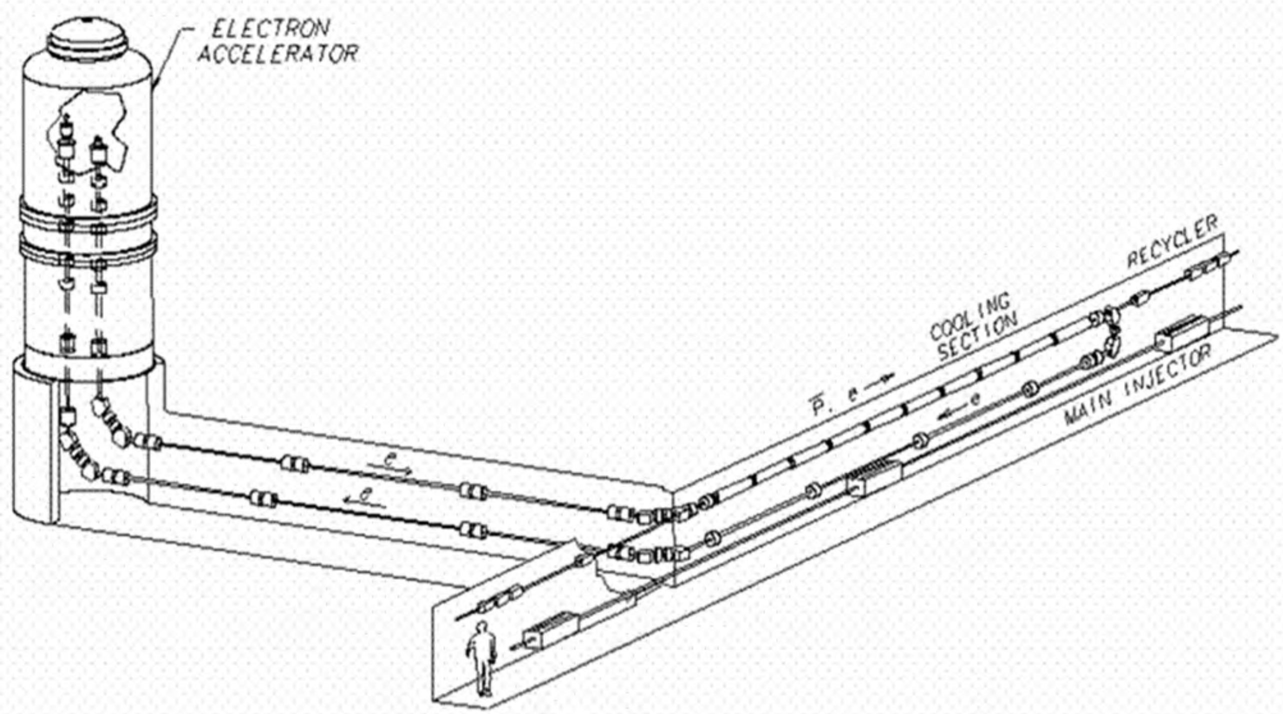




- Many installations since then, up to 1.2 MV electron beam (COSY, Yülich)
- FNAL 4.3 MeV cooler – was the next step in technology

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 (Nobel prize)
- Naïve cooling model
  - 90 deg. between pickup and kicker

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

Averaging over betatron oscillations yields

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

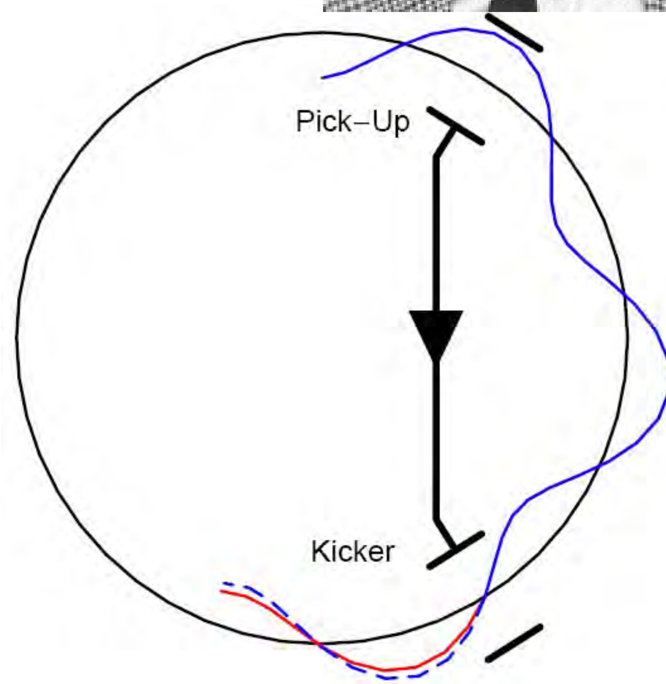
- Adding noise of other particles yields

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

- That yields:

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

$$\boxed{\lambda \approx N/W}$$



- In accurate analytical theory the cooling process is described by Fokker-Planck equation

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

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

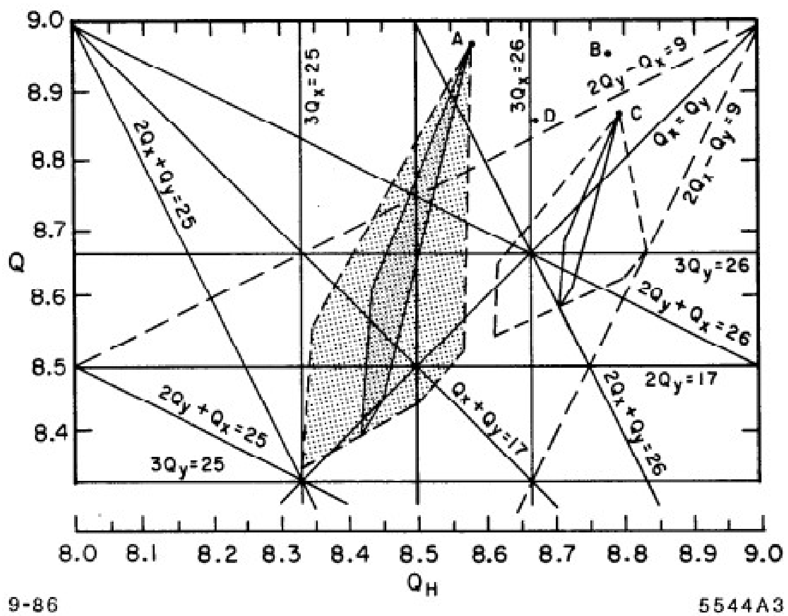


Fig. 3. Space charge tune shift of the AGS.

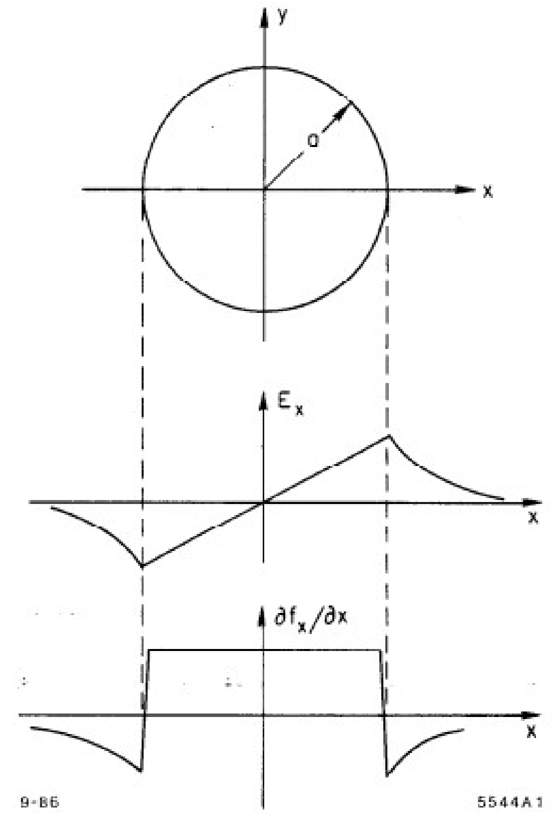


Fig. 1. Space Charge force of a uniform cylindrical beam.

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

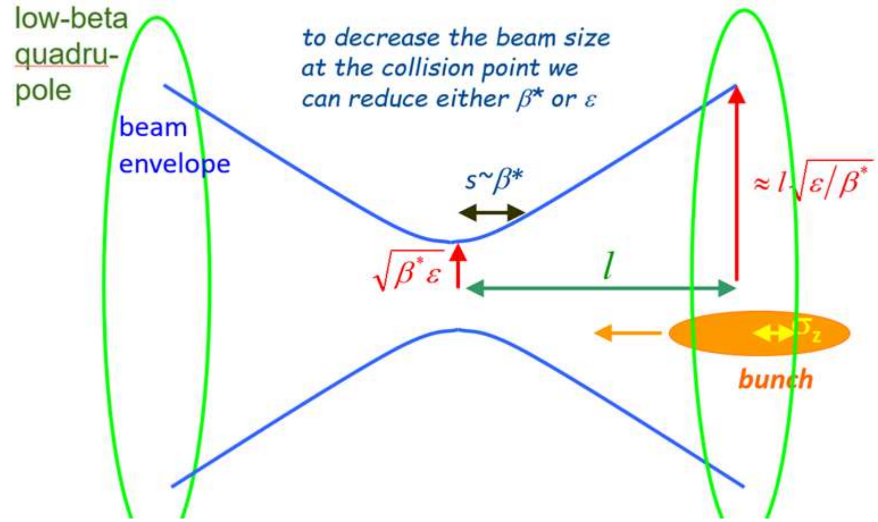
Beam-beam Effects

- 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

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



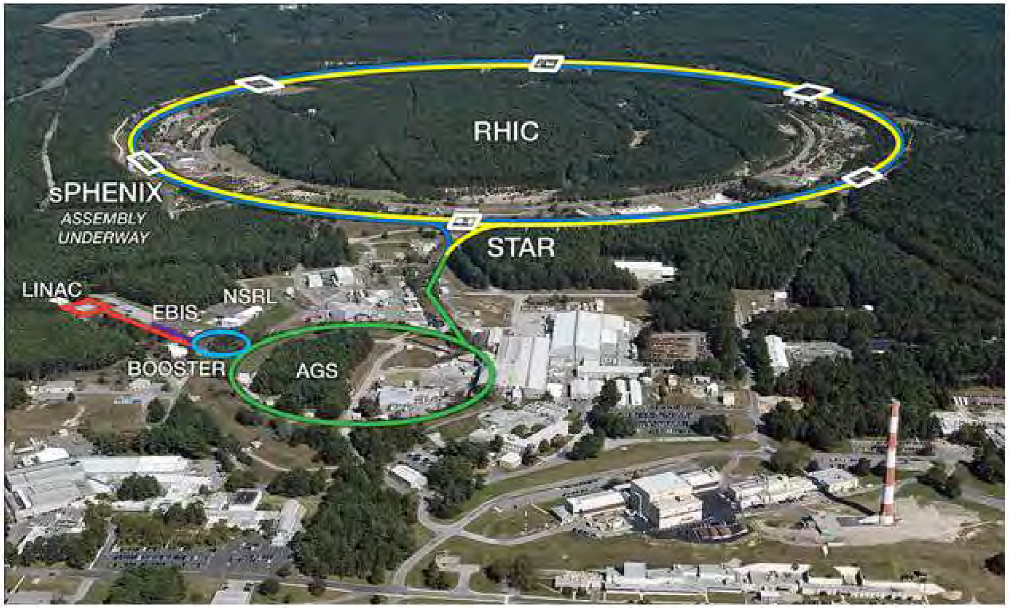
- ♦ Magnetic field of counter rotating beam almost doubles force, $1+\beta^2$
- ♦ Note that for large synchrotron amplitude the tune shift increase due to larger beta-function with longitudinal displacement is compensated by decrease of space charge field
  => no dependance on bunch length

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

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

Present and Future Hadron Colliders

Present Hadron Colliders



RHIC (BNL, Brookhaven)

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

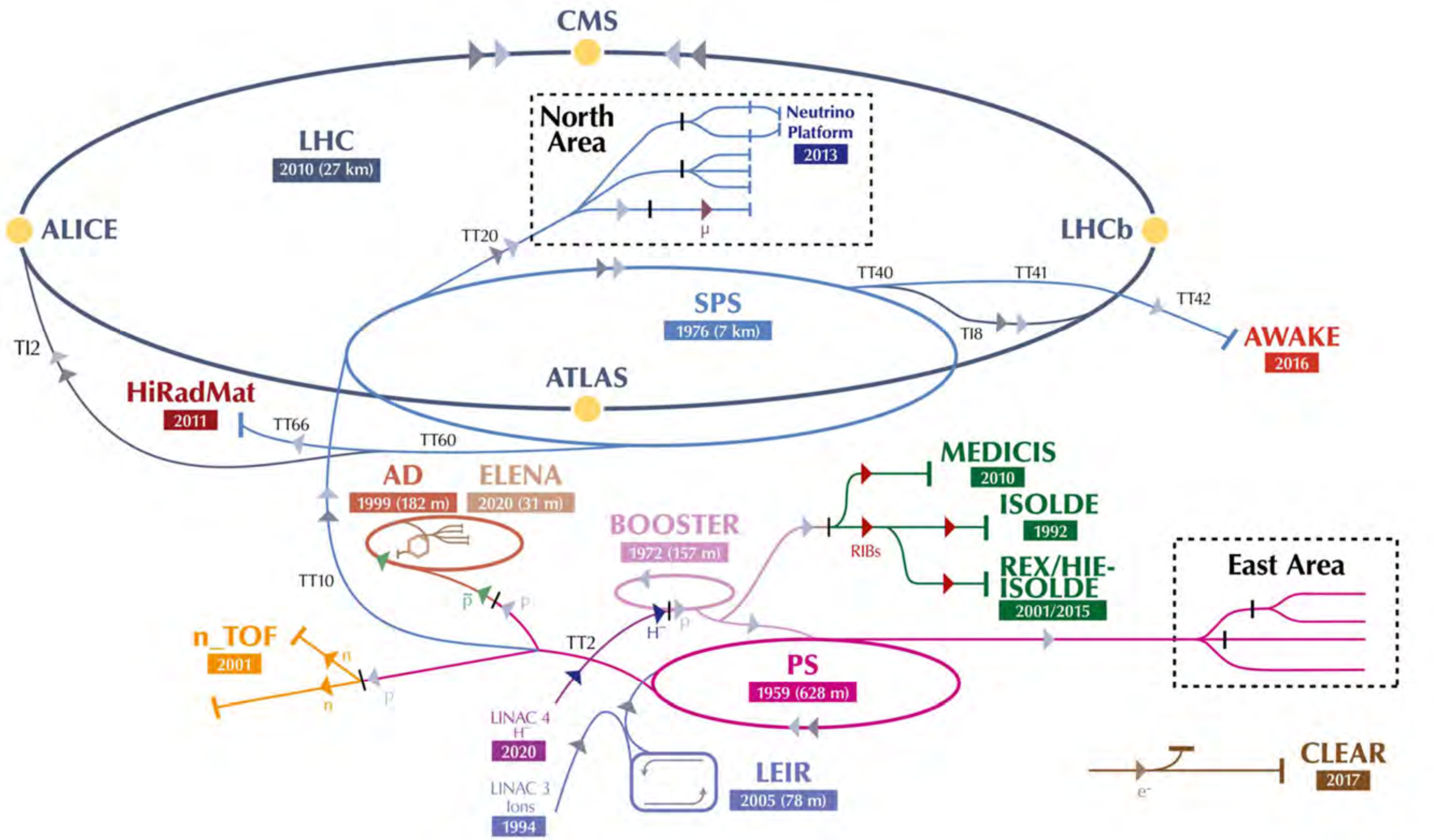
- RHIC is NICA main competitor

LHC (CERN)

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

LHC

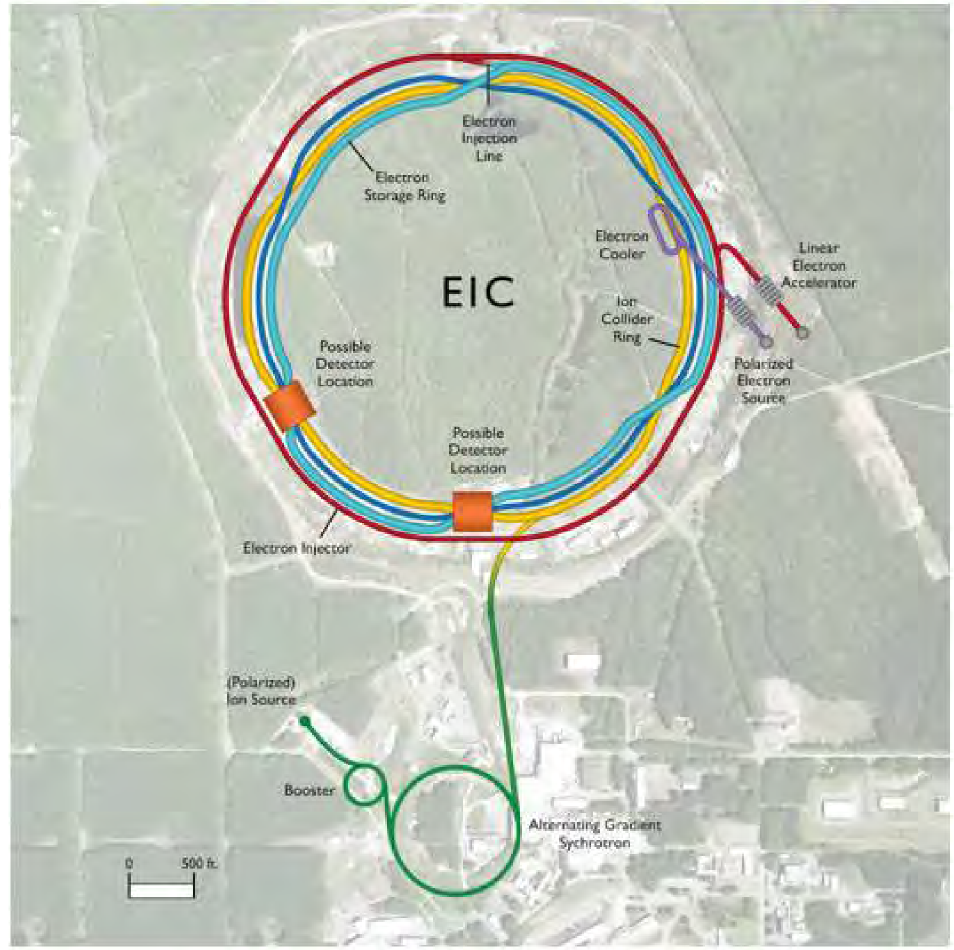
- LHC is the most powerful collider in the world
- With coming upgrades, it will dominate High Energy physics for decades



Colliders That Will Be

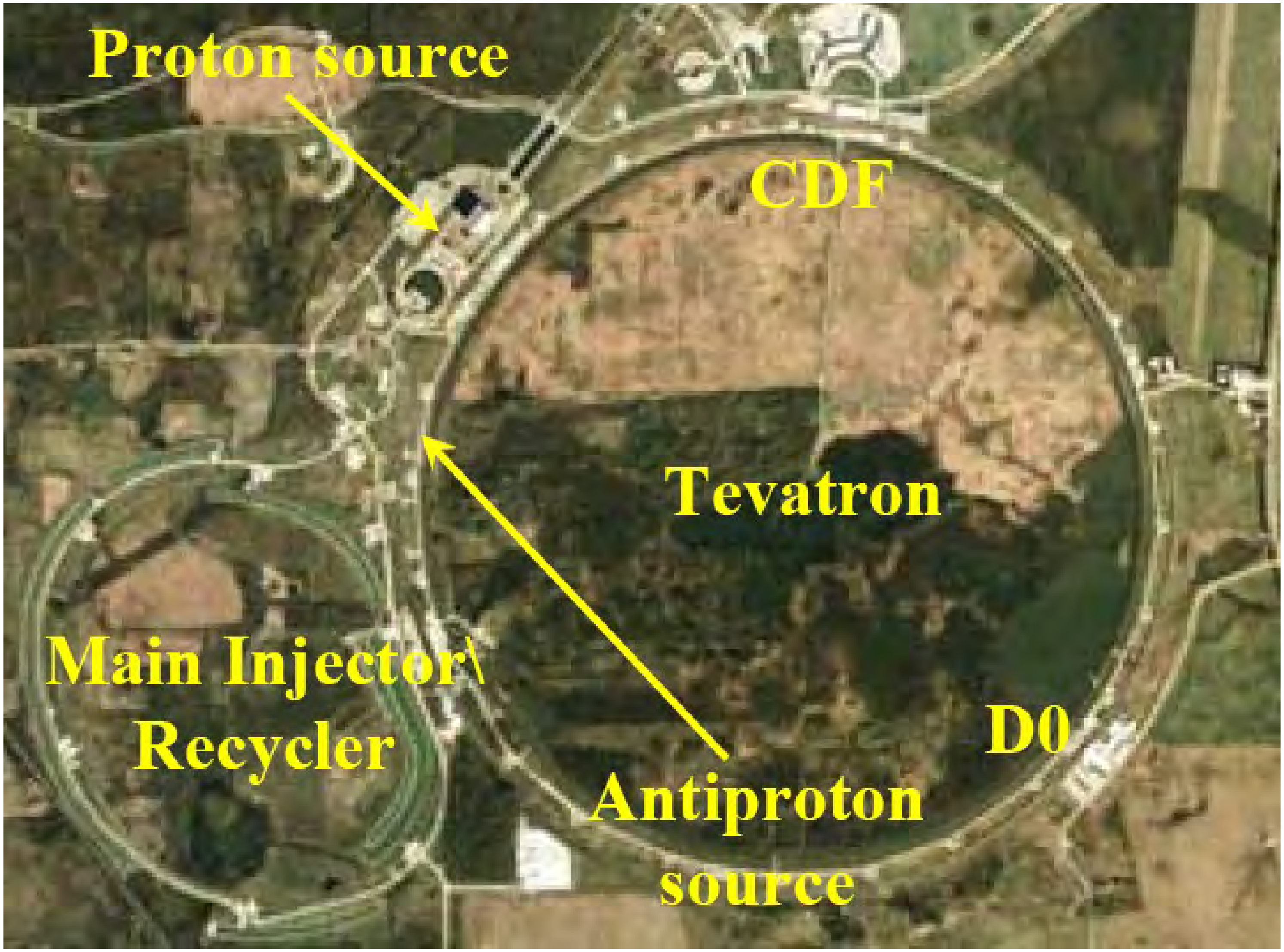
Main Parameters of The NICA Collider			
Circumference, m	503,04		
Bunch number per ring	22		
Mean-square bunch size, m	0.6		
Min. beta-function (β^*), m	0.6		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch, 1e9	0.275	2.4	2.2
Peak luminosity, $cm^{-2} \cdot s^{-1}$	0.9e25	0.9e27	6.3e27

EIC (BNL, Brookhaven)



Tevatron Story

Tevatron - $P-\bar{P}$ Collider Operating at 980 GeV



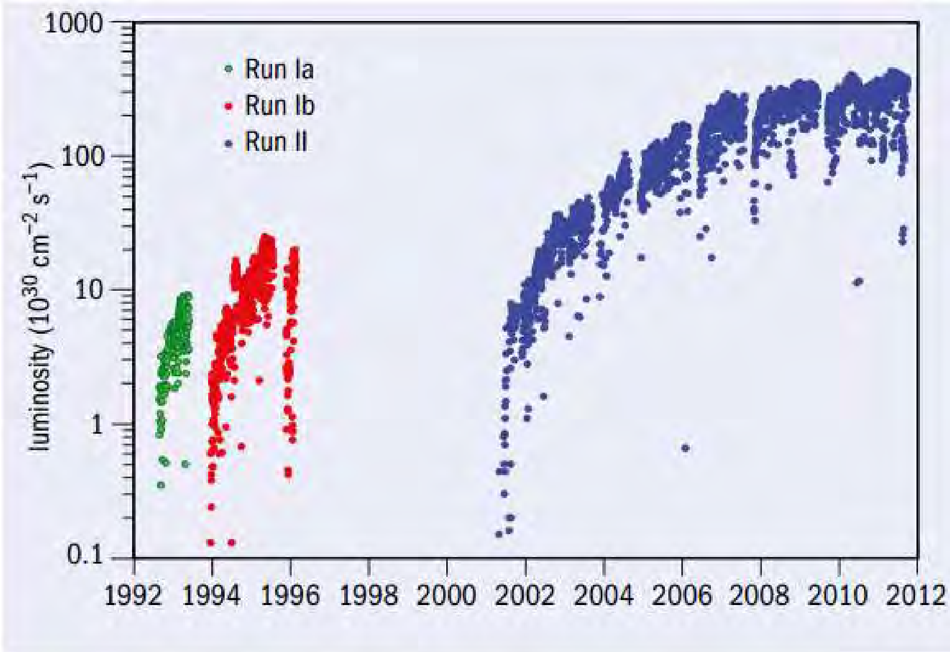
- H^- source, 35mA
- RFQ 750 keV
- Linac, 0.4 GeV
- Booster, 0.4–8 GeV
- Main injector, 8-150 GeV
- Debuncher, 8 GeV
- Accumulator, 8 GeV
- Recycler,8 GeV
- Tevatron, 980 GeV C=6.28 km

- Run I: 1992 – 1996, $\int Ldt = 0.187\ fb^{-1}$ for each detector, (t-quark)
- Run II: Feb. 2001 - Sep. 2011, $\int Ldt = 10\ fb^{-1}$, (3σ Higgs boson)

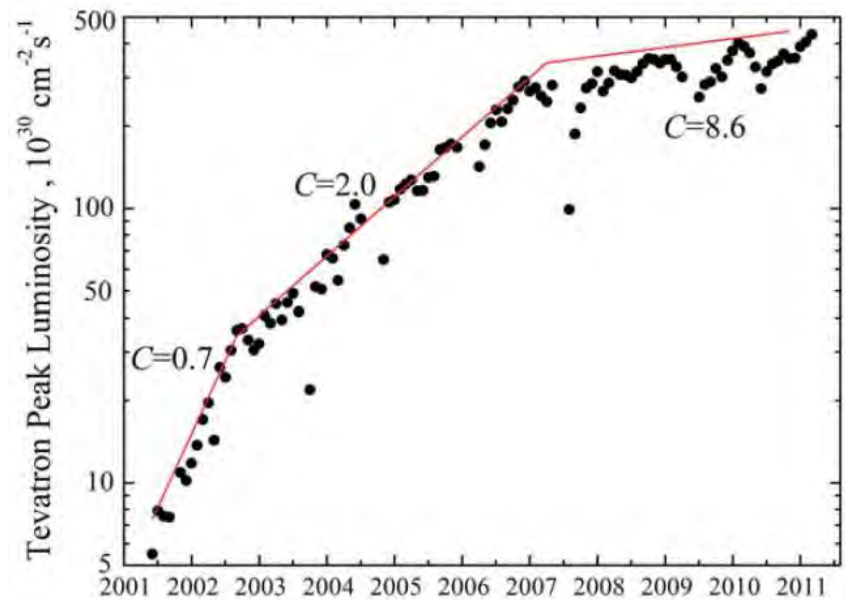
Luminosity Progress

- 10 times peak luminosity increase from Run I to Run II
  - 3 stages
    - Fast restoration of Luminosity to the Run I level (~1.5 year)
    - Steady progress with luminosity doubling every 1 year and 5 months (~5 years)
    - Operation for ~4 years without substantial luminosity growth
- Peak luminosity $4\cdot10^{32}$ $cm^{-2}s^{-1}$
- Collider operation was stopped when LHC discovery potential exceeded the Tevatron's one

$\sigma_{HIGGS} \propto E^4$ $(3.5^4 \approx 150)$



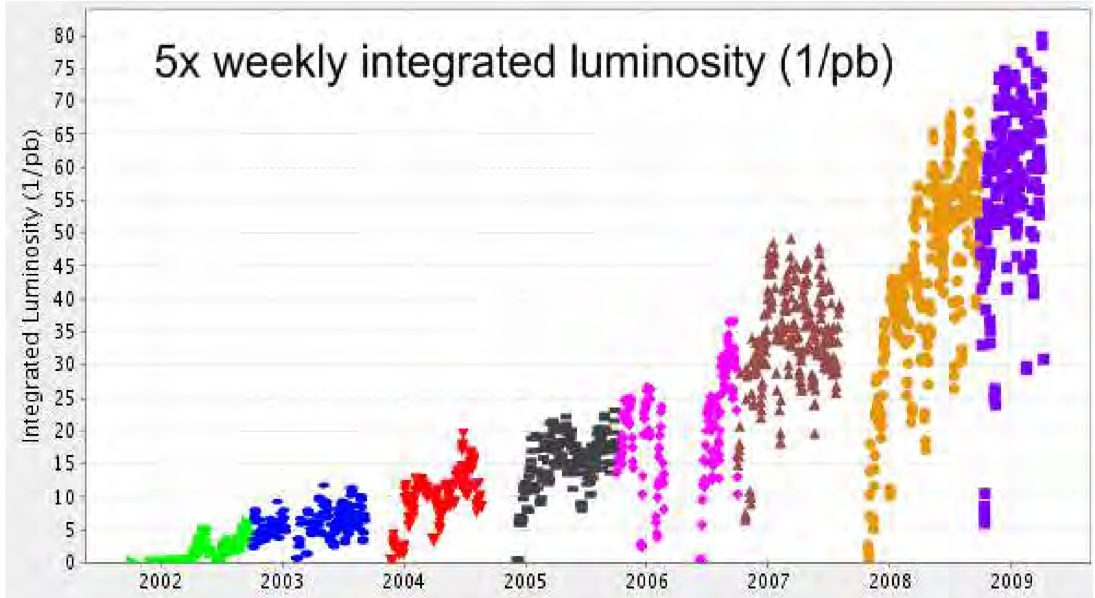
Initial Luminosity for all stores in Collider Runs

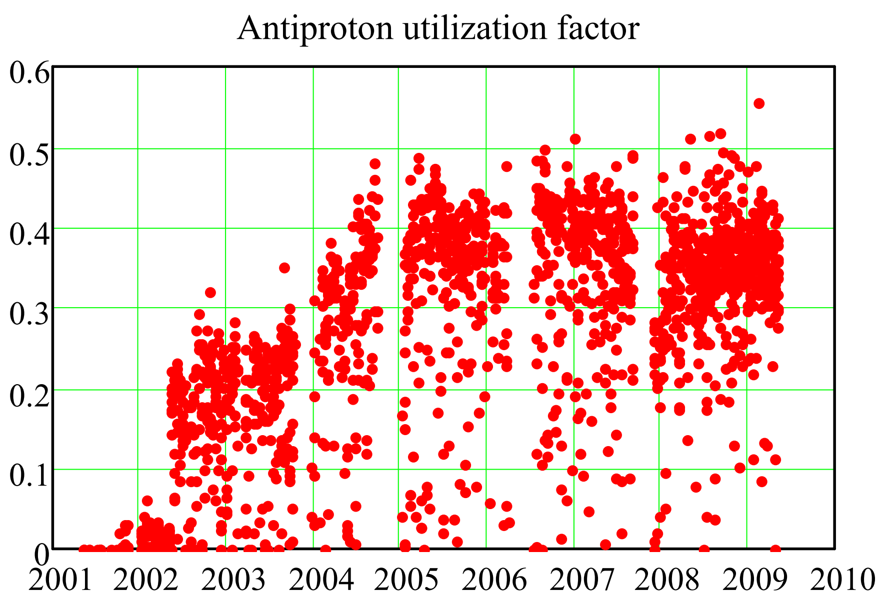


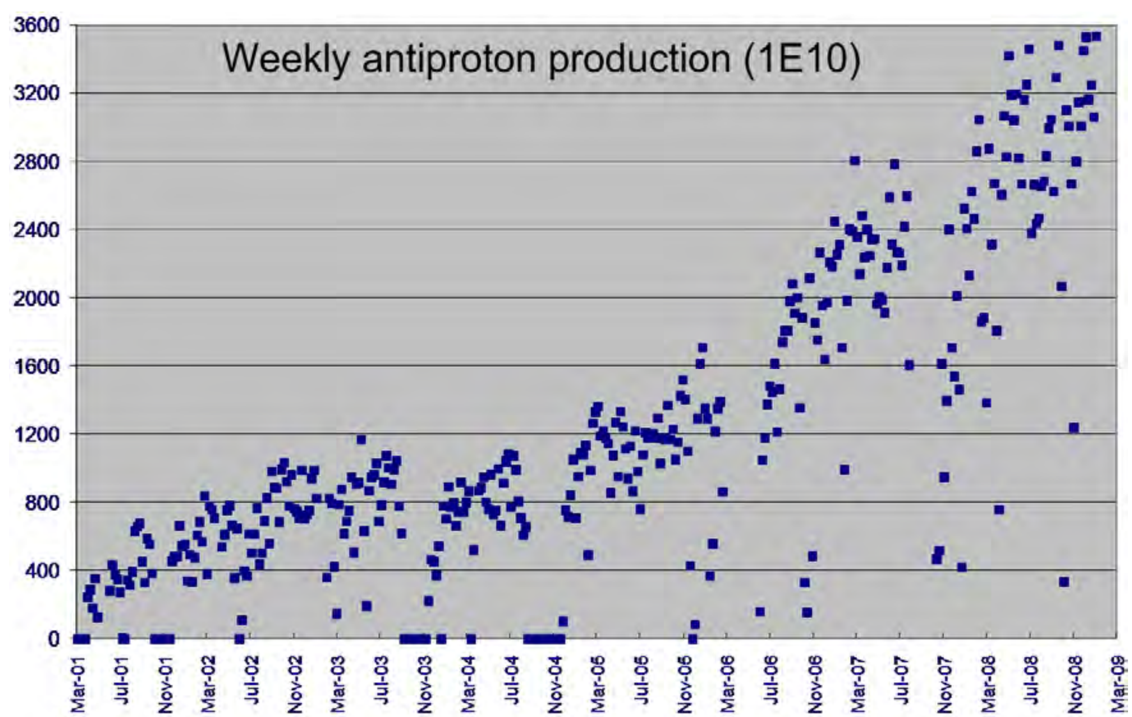
Tevatron peak luminosity progress during Run II

Luminosity Constituents

- Antiproton production
- Brightness loss at transfers
- Tevatron ability to deliver luminosity
  - ~40% pbars are burned in nuclear interactions
  - Major limitations
    - IBS
    - Beam-beam effects

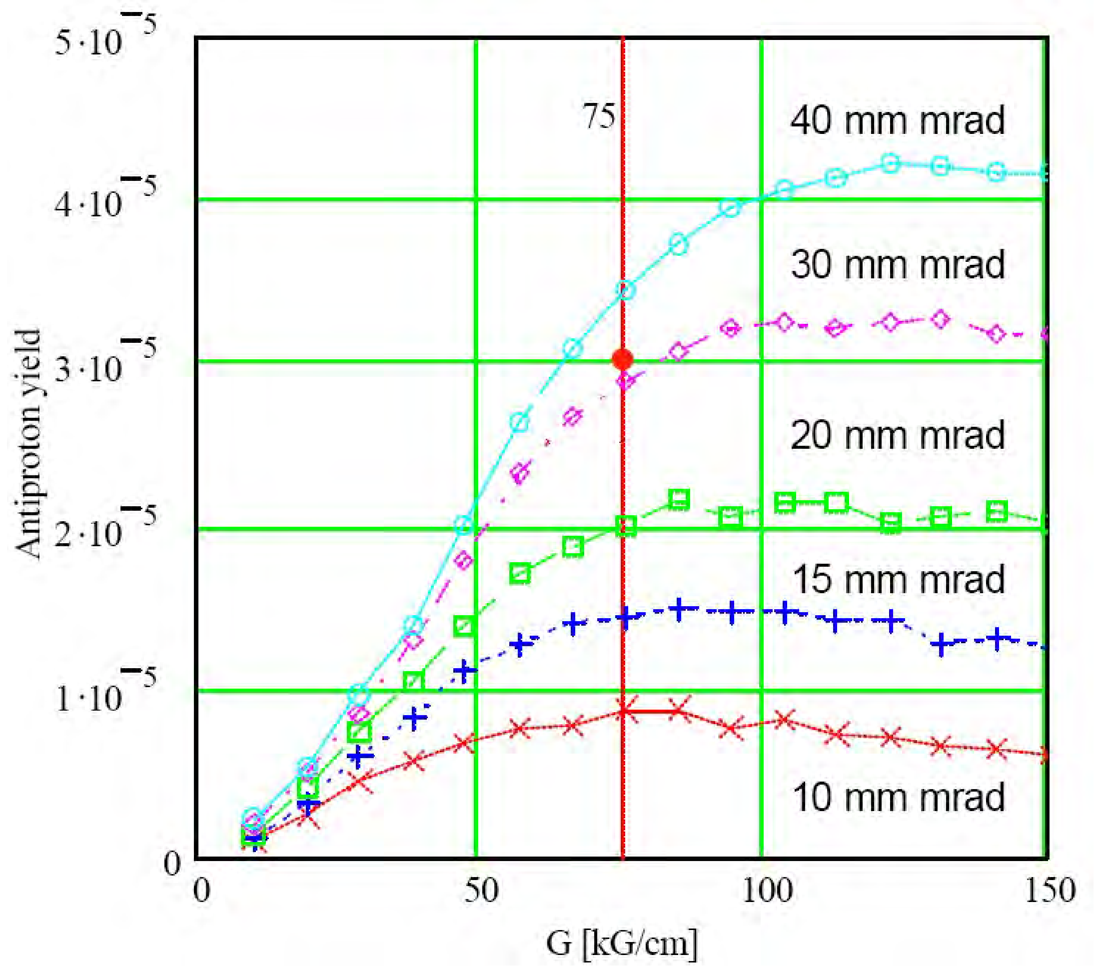






Lithium Lens

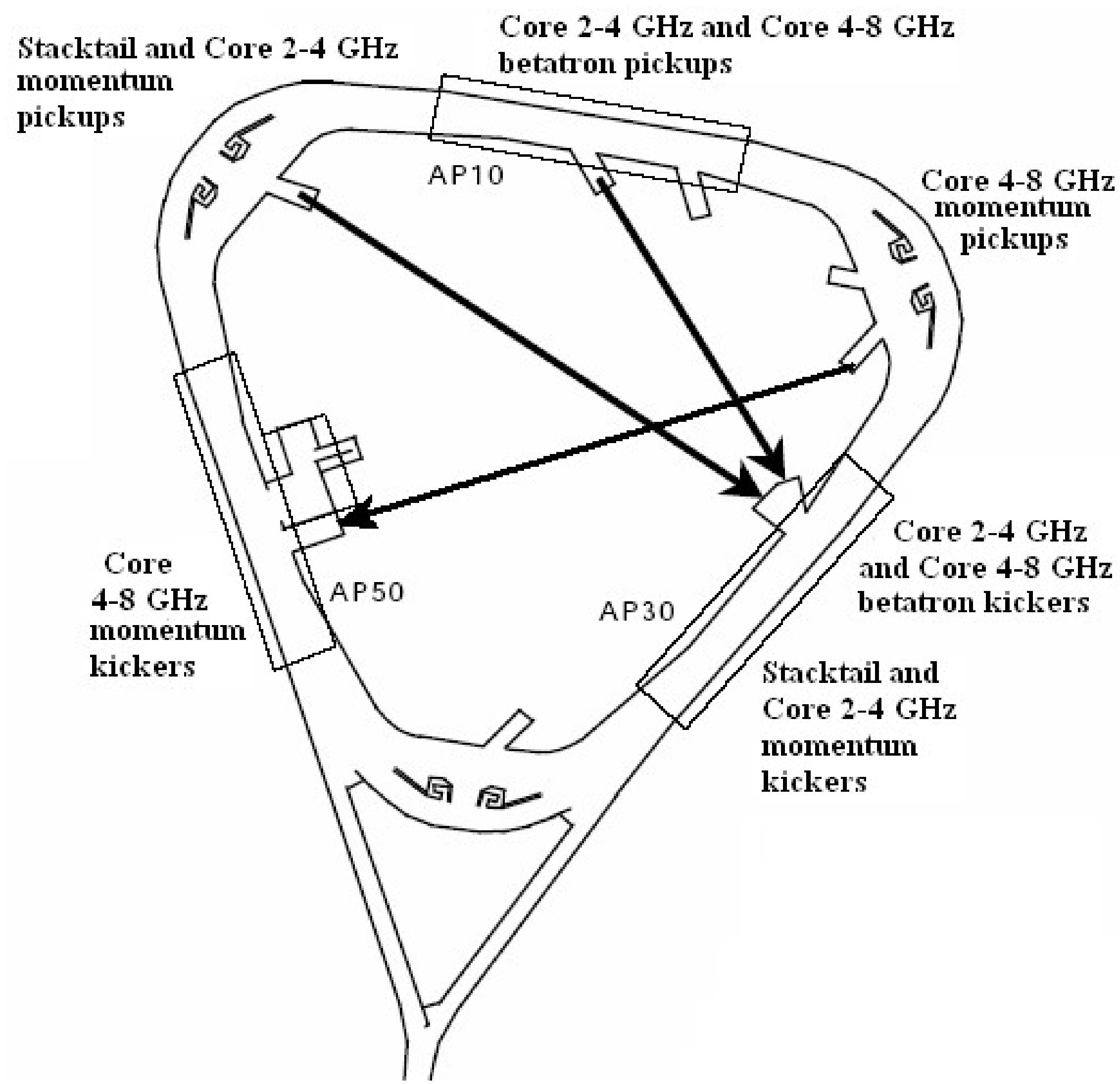
- INP designed and manufactured the 1st Li lens
  - Excellent parameter optimization
- Multiyear effort in FNAL resulted in ~20% field increase
  - Design is based on diffusion bonding
- Work on the liquid Li lens did not proceed since for 35 µm acceptance further increase of gradient did not yield large increase in number of pbars
  - Radiation safety concerns were also considerable



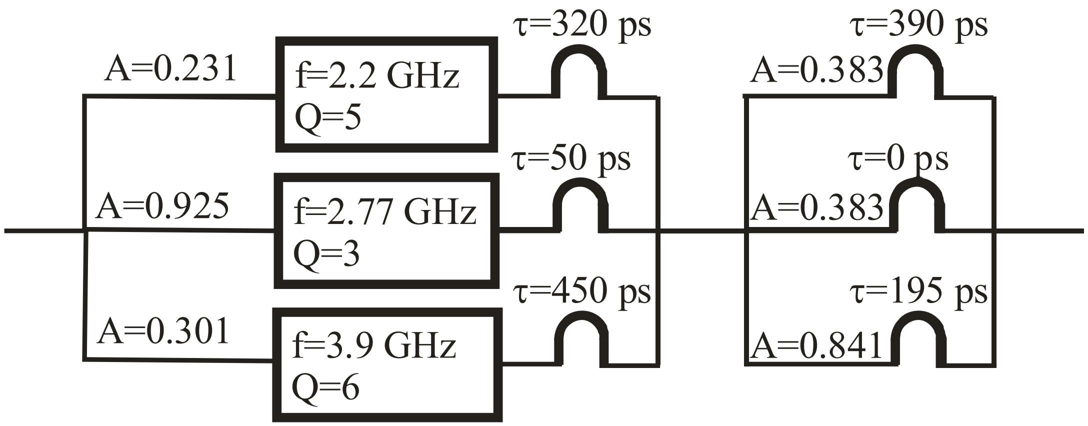
Dependence of Computed Antiproton yield on Debuncher acceptance and lithium lens gradient. Achieved Debuncher acceptance ~35 µm

Cooling and Stacking in Accumulator

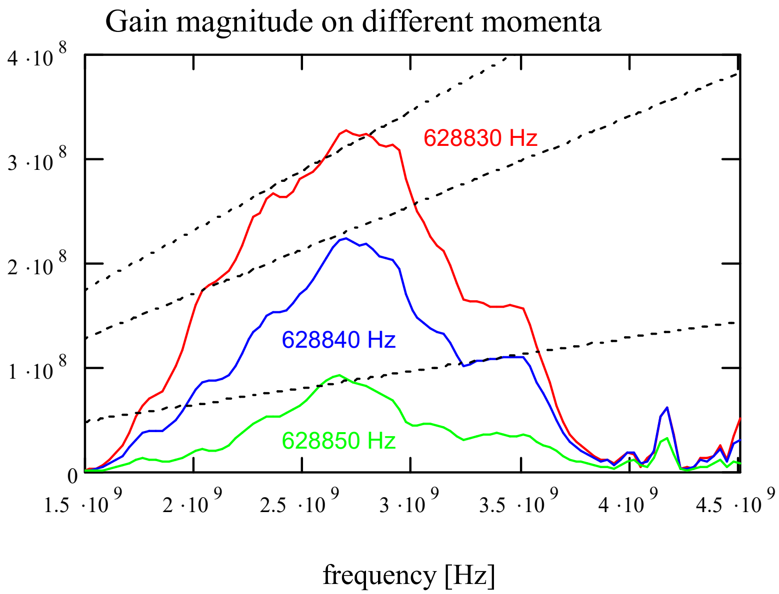
- 5 cooling systems
  - Core cooling
    - H & V – 4-8 GHz
    - Longitudinal: 2-4 GHz and 4-8 GHz
    - Stacktail - 2-4 GHz
- Stacktail system moves injected antiprotons to the core
  - It was a major limitation of stacking rate increase
  - Since 2006 all stacking rate improvements were closely related to operation and improvements of the Stacktail system
    - It was the last bottle neck limiting the staking rate

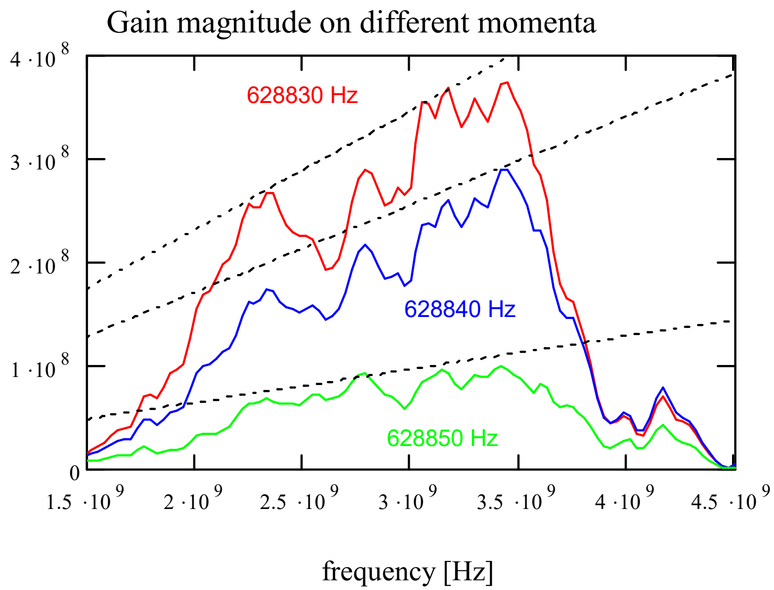


Stacktail Equalizer



- 3 branches with different delay enable to overcome casualty limitations resulting phase changes at the band boundaries





Dependence of stacktail gain on frequency before and after installation of the equalizer

From the SSC
to the LHC

The SSC

- The Superconducting Super Collider (SSC) was a particle accelerator complex under construction in the vicinity of Waxahachie, Texas, United States.
- Its planned ring circumference was 87.1 kilometers with an energy of 20 TeV per proton
  - It was designed to be the world's largest and most energetic particle accelerator.
  - After 22.5 km of tunnel had been bored and about $2B spent, the project was canceled by the US Congress in 1993.

Emittance Growth due to Noise in ⊥ kicks

- Emittance growth is driven by transverse kicks excited by noise in magnetic field of dipoles or transverse displacement of quads

$$\left(\frac{d\varepsilon}{dt}\right)_0 = \frac{\omega_0^2}{4\pi}\sum_{k}^{\substack{all\\ sorces}} \beta_k \sum_{n=-\infty}^{\infty} P_{\theta k}\left(\frac{2\pi n-\mu}{T}\right)$$

- Spectral density of noise increases fast with frequency decrease
  - An increase of machine circumference decreases the revolution frequency and the frequency of betatron side bands and, consequently, the spectral density at the betatron sidebands
  - For the SSC $\Delta B/B \le 7\cdot 10^{-10}$
- If a transverse damper suppresses the beam motion faster than particles decohere then emittance growth is suppressed

$$\frac{d\varepsilon}{dt} \approx \frac{16\pi^2\overline{\Delta\nu^2}}{g^2+16\pi^2\overline{\Delta\nu^2}}\left(\left(\frac{d\varepsilon}{dt}\right)_0 + \frac{f_0 g^2}{2}\left[\frac{\overline{x^2}}{\beta}\right]_{BPM}\right) \xrightarrow{g^2 \gg 16\pi^2\overline{\Delta\nu^2}} 8\pi^2 f_0\overline{\Delta\nu^2}\left[\frac{\overline{x^2}}{\beta}\right]_{BPM}$$

- Thus, if noise in the damper is sufficiently small the emittance growth is strongly suppressed
  - It was our conclusion for the SSC in 1993
- The story continued ~15 years later

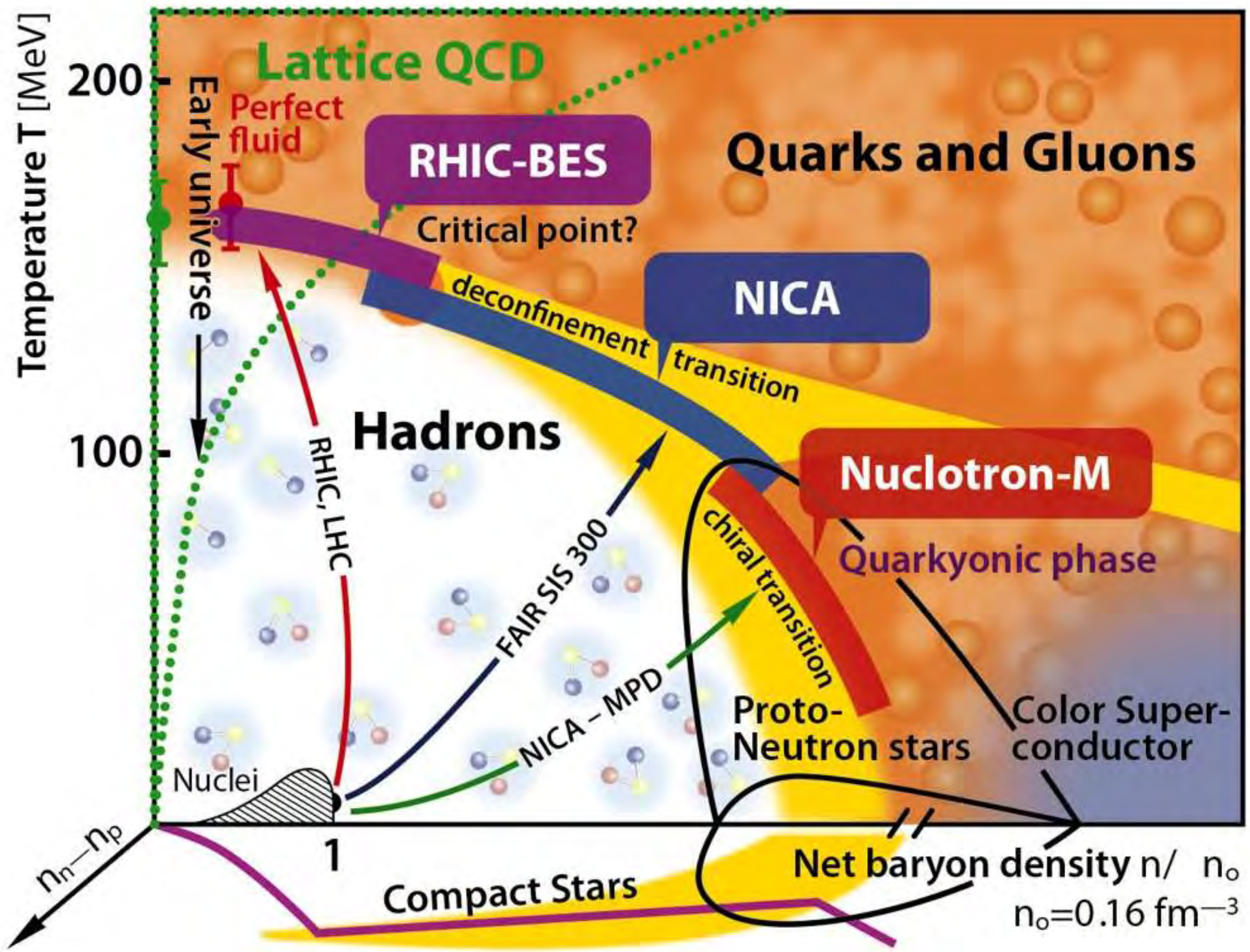
LHC Hump

- LHC hump, uncontrolled emittance blowup at injection energy, was observed at the very beginning of LHC beam commissioning at the first half of 2009
- If not suppressed it would stop further commissioning before remedy found
- The remedy was simple:
  - increase the damper gain by 20 dB
  - Redistribute the gain in the damper to decrease ADC noise
  - It worked due to excellent work of Wolfgang Höfle and team
- Major sources of problems (corrector power supplies) were found and fixed in about half year
  - BUT noise driven emittance growth was visible even in Tevatron at the top energy
  - And it is still a major "feature" in the LHC

NICA

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-factors) (SPD detector)
- NICA is built to answer the last 2 questions

Why NICA?

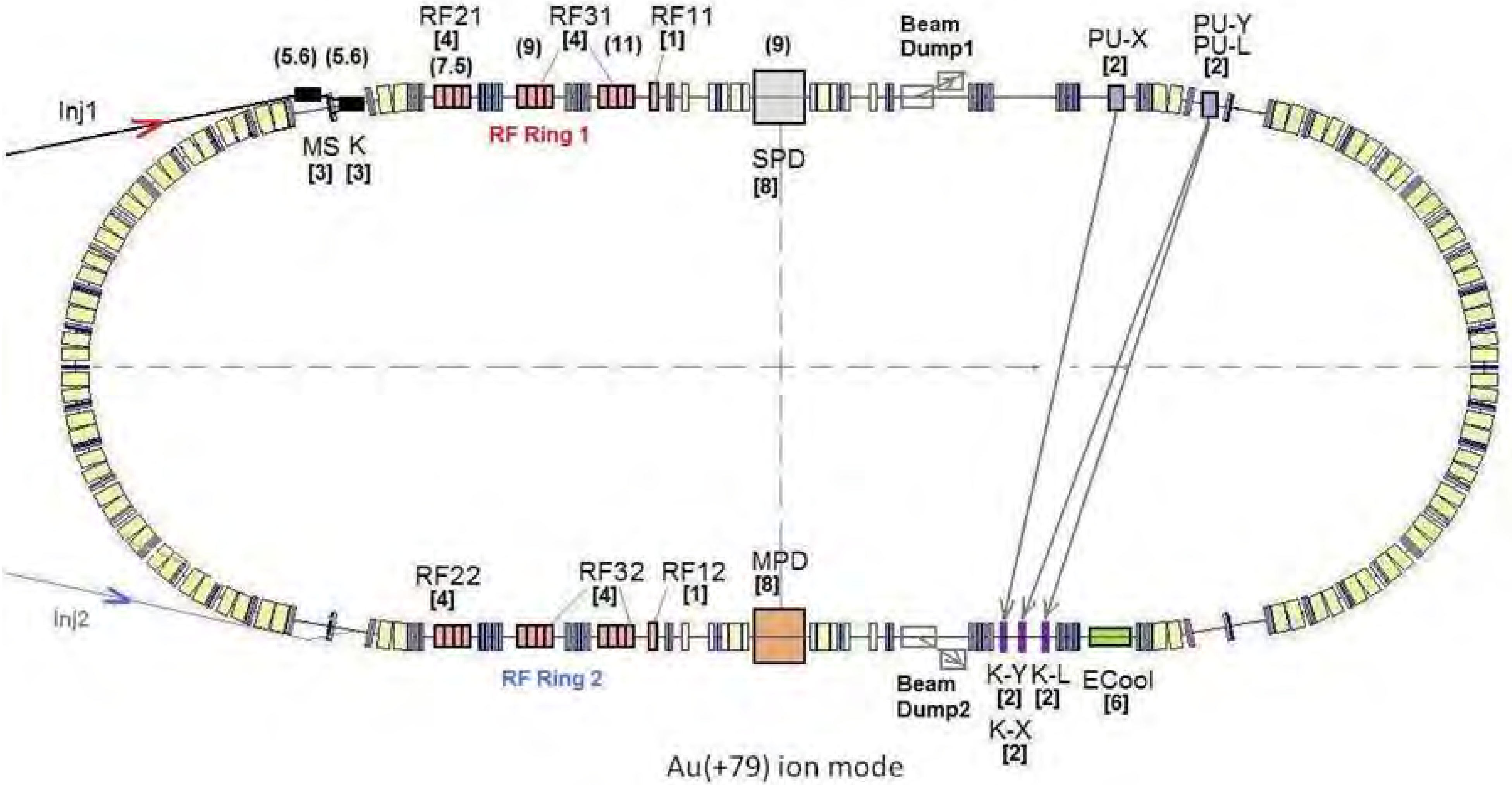
- Unique niche
  - Two major competitors (LHC & RHIC) have too large energy to get to sufficiently large luminosity in the interesting region of low energy of few GeV/n
  - Beam slowly extracted from the SPS (CERN) has the same energy reach but all reaction products go forward
- From accelerator physics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

- NICA conceptual design has been based on the experience obtained in the Tevatron Run II commissioning
- This experience will be also greatly helpful in NICA commissioning

- 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

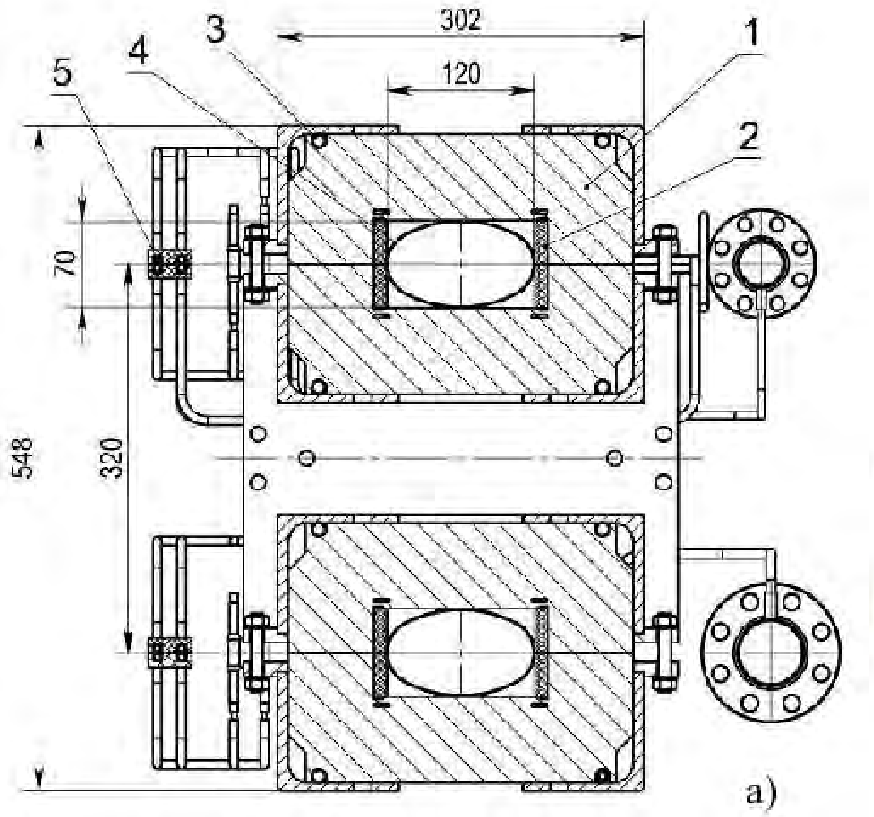


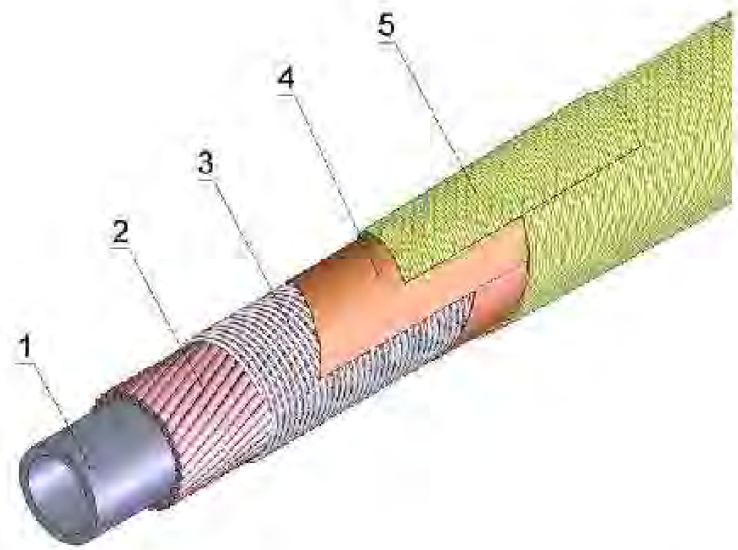
Two rings: one above another, 503 m circumference

Collision energy in the heavy ion mode: $\sqrt{s}=2\cdot(2.5\div5.5)$ GeV/n

1.5 – 4.5 GeV/n kinetic energy

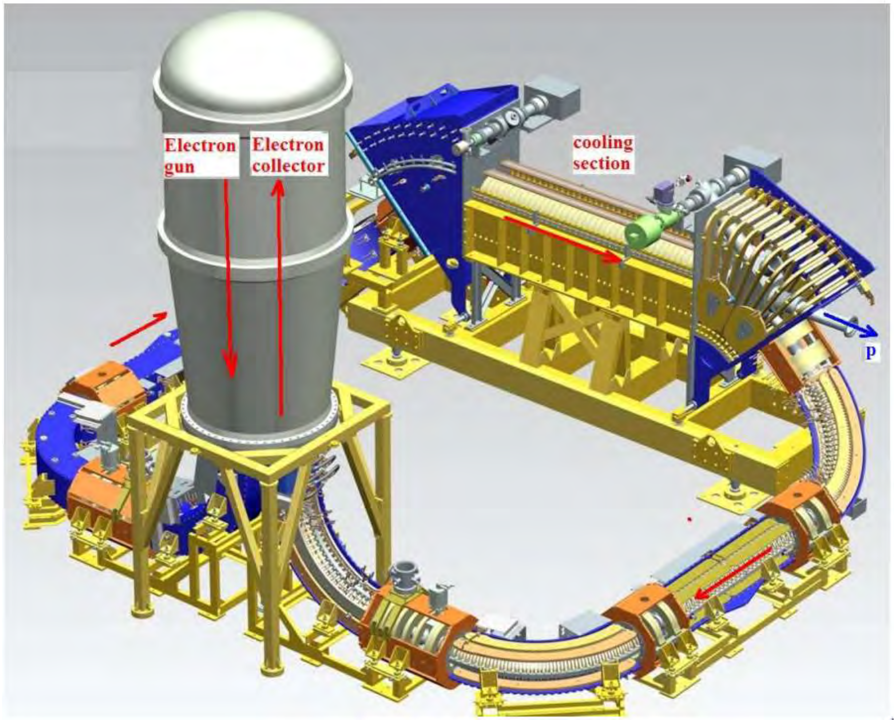
NICA dipoles





Beam Cooling

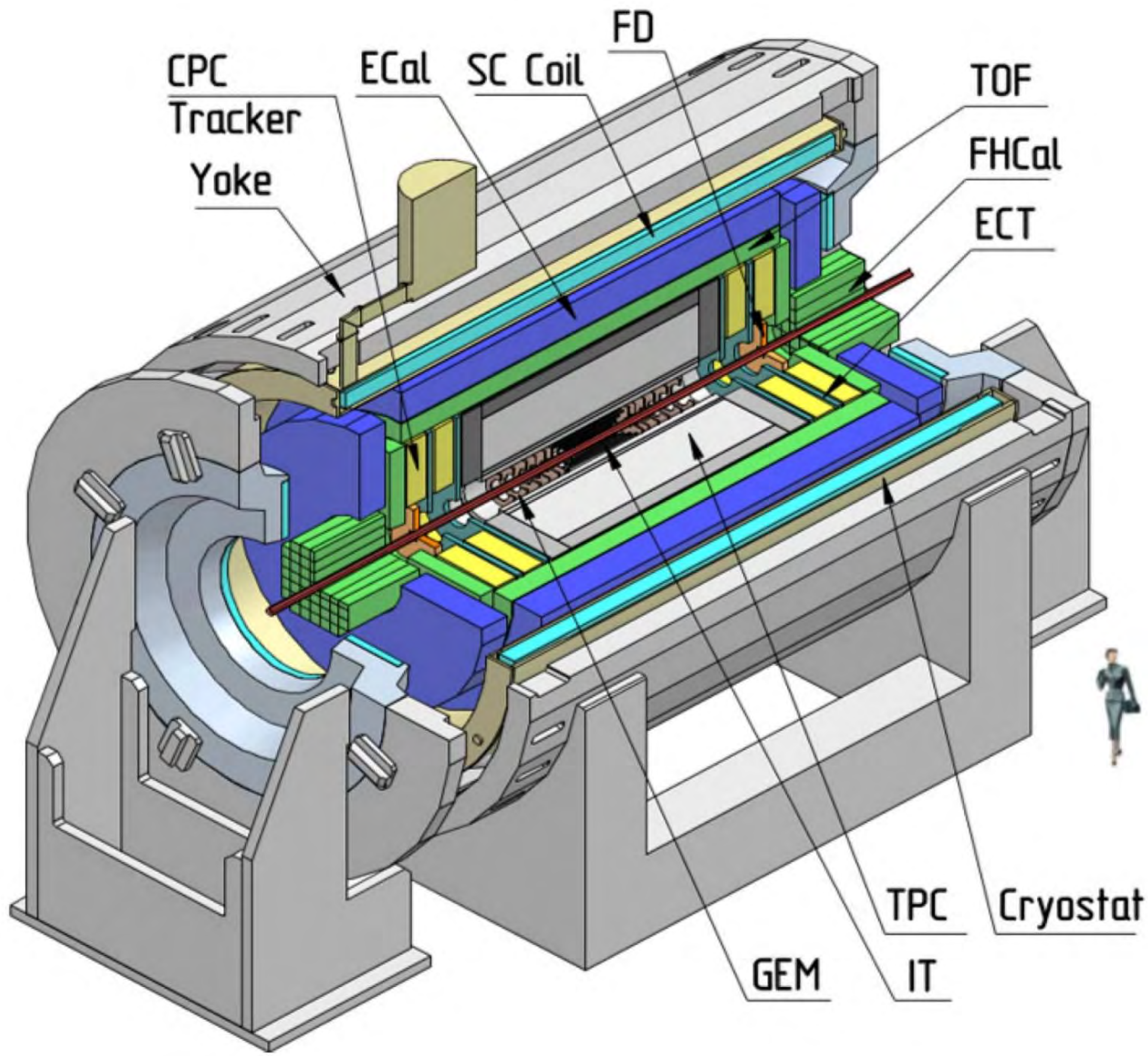
- Two systems of beam cooling will be present in NICA: electron cooling and stochastic cooling
- They are complimentary
- Stochastic cooling
  - Initially was expected to be as the main and the only cooling system
  - Lack of expertise strongly delayed its development
  - Still, we plan it be ready in ~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 collisions)

Detector MPD

- TPC has excellent space resolution but limits the collision rate to about 7 kHz
  - Still not a problem for heavy ion collisions
- MPD cannot operate with light polarized ions due to much higher collision rate



Владимир Путин посетил комплекс NICA (источник: Atomic Energy)

Commissioning of NICA technical systems was started in June of 2024

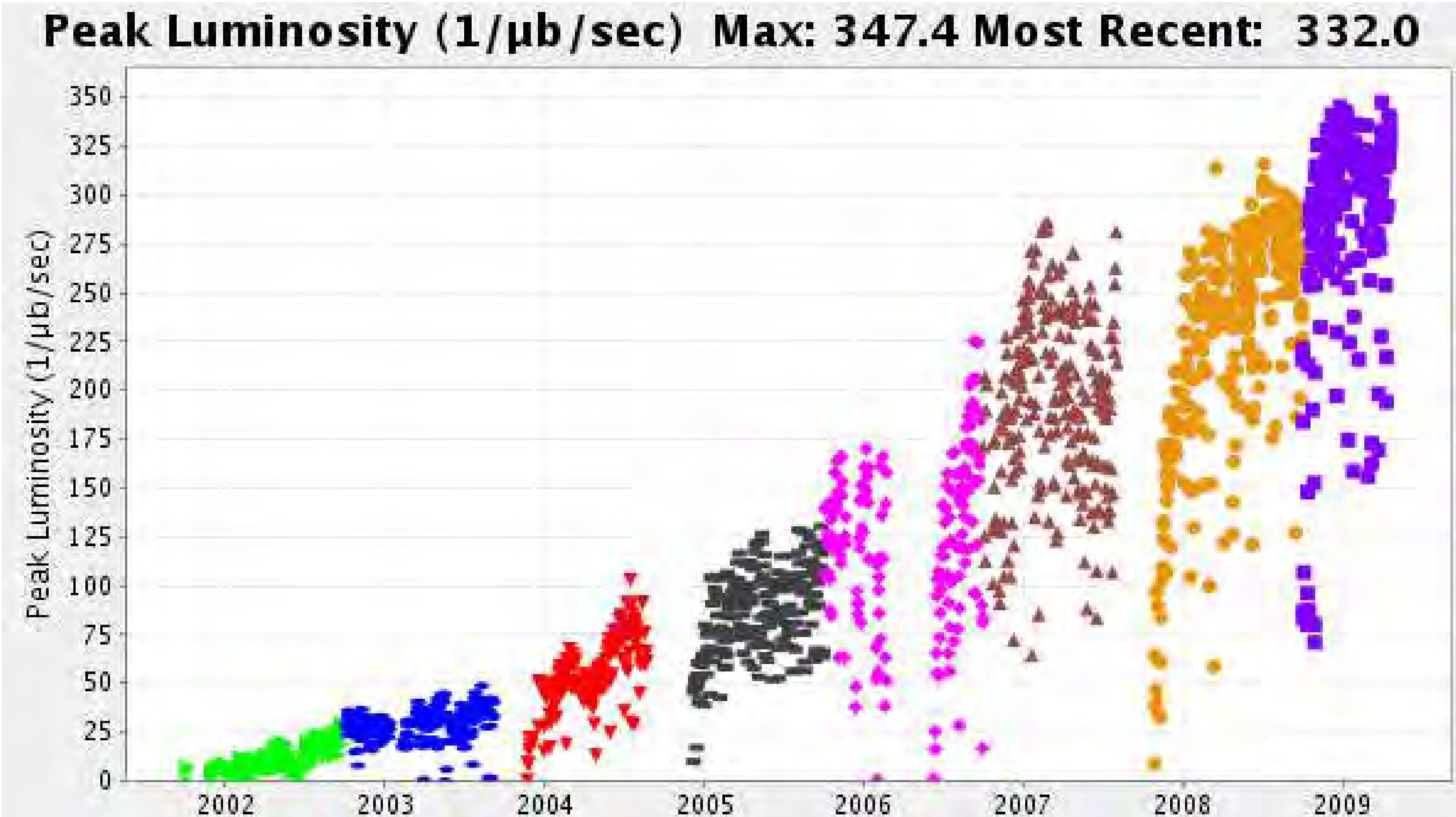
The Road to Success

- Injection complex
  - Beam accumulation in Booster and minimization of beam loss in acceleration
  - The goal: acceleration of 10^9 ions in ~5.5 s cycle
- Commission beam lines
- NICA
  - Orbit correction
  - Beam optics measurements and correction (linear and non-linear)
  - Machine characterization and maximization of its aperture
  - Commissioning RF systems
  - Commissioning of cooling systems
  - Optimizing collimation
  - Automation of beam accumulation and transition to collisions
  - Making collisions and its further optimization
  - Suppression of instabilities
- It is going to be multiyear effort of perfecting each step
  - Tevatron and LHC achieved the design luminosity in 8 years
  - NICA is expected to have a similar pace

Instead of Conclusions

- In less than half-year we plan to inject beams into collider rings
- Recently we started operations of KRION ion source, heavy ion linac and Booster 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
  - Next month: beam accumulation in Booster with electron cooling and recommissioning of Nuclotron
- 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 is aimed at operation with the slow beam extraction to external target
  - SPD detector will be installed 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

It will be challenging to keep the same pace



Tevatron: Peak Luminosity

https://lhep.jinr.ru/wp-content/uploads/2024/06/accelerator-complex-operator.pdf

- We need
  - Accelerator physicists
  - RF engineers
  - Vacuum engineers
  - Cryogenic engineers
  - Computer specialists
  - Electrical engineers
  - …

In other words – intelligent, inventive and energetic people

Инженер-оператор ускорительного комплекса

Общие сведения

Международная межправительственная научная организация Объединенный институт ядерных исследований, г. Дубна.

В Лаборатории физики высоких энергий ОИЯИ развивается подразделение, основной задачей которого является эксплуатация нового ускорительного комплекса NICA. Идет подбор сотрудников, которые хотели бы стать частью большой команды физиков и инженеров. Ускорительный комплекс NICA (Nuclotron based Ion Collider fAsility), являясь одним из приоритетных проектов класса Мегасайенс в России, включает два линейных, два кольцевых сверхпроводящих ускорителя и коллайдер. Он займет важную нишу в мировой ускорительной инфраструктуре для проведения фундаментальных исследований в области релятивистской ядерной физики на ближайшие десятилетия.

Обязанности

В обязанности **инженера-оператора** входят следующие основные функции, которые чередуются понедельно во время штатной работы комплекса:
(1) сменная работа в главной пультовой для управления и поддержания работы ускорительного комплекса;
(2) работа над инженерными или научными проектами, направленными на его развитие.

Профессионально-квалификационные требования

Высшее техническое образование. Рассматриваются соискатели от выпускников ВУЗов до кандидатов наук включительно. Требуются базовые знания в физике и технике ускорителей.
Полный допуск к работе в пультовой будет осуществляться после обучения, включая обучение на рабочем месте, и сдачи всех необходимых экзаменов.
Важным требованием является желание и способность к обучению.

Дополнительные навыки

Приветствуются знания в области SCADA-систем, опыт программирования промышленных контроллеров, написания программ на языках Python, JavaScript, C++, управления и диспетчеризации технически сложных объектов.
Желательно владение английским языком.

Условия работы

Достойный уровень заработной платы, соответствующий квалификации (определяется по результатам собеседования).
Примерно половина рабочего времени в году предполагает сменный круглосуточный режим. Вторая половина - дневной режим работы: 5 рабочих дней по 8 часов с двумя выходными.
Предусмотрена возможность и время для научной/инженерной работы, включая подготовку научных публикаций, участие в семинарах и конференциях, защиту диссертационной работы.
Социальный пакет включает ДМС, льготные абонементы в спортивные объекты института и санаторные путевки. Иногородним оказывается помощь в обеспечении жильем.
Управление ускорительным комплексом дает возможность быть в центре современной науки, на практике увидеть работу всех систем коллайдера, получить широкие знания в ускорительной физике и технике, общаться с лучшими специалистами в этой области и самому стать одним из них.

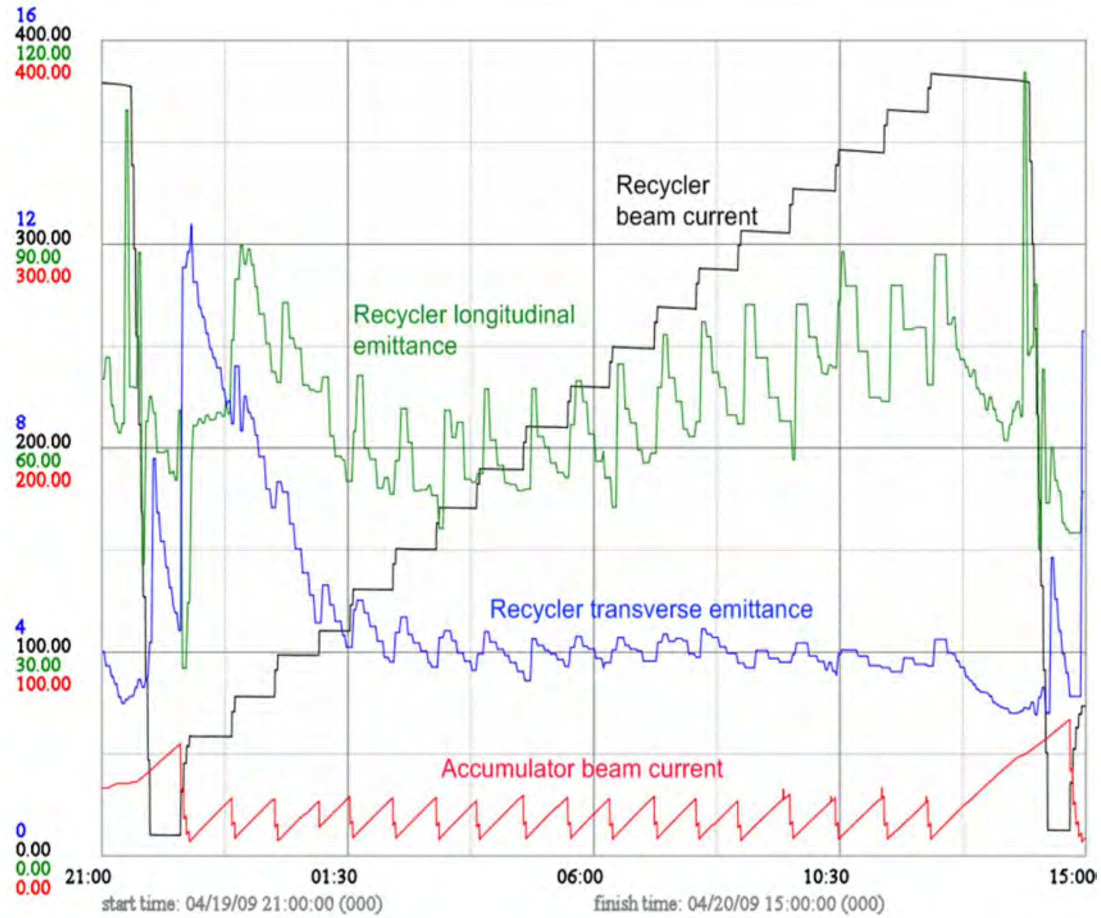
Заявка на замещение вакансии

Заявка должна включать подробное резюме - CV, краткое изложение научных интересов, список профильных публикаций, желательны рекомендательные письма.
Адрес для направления заявки: valebedev@jinr.ru

Backup slides

Recycler Operating Scenario

- Barrier buckets keep beam in one ~1.5 km long bunch
- RR operates below transition $\Rightarrow$ IBS makes equal temperatures for all three planes
- IBS temperature exchange ~6 times faster than IBS heating
  - for ε=2 mm mrad
    $\tau_{rel} \sim 0.2$ hour
    $\tau_{IBS} \sim 1.2$ hour
- In normal operating conditions the cooling time is ~2 hour (see picture)
  - 7 min - for small emittances

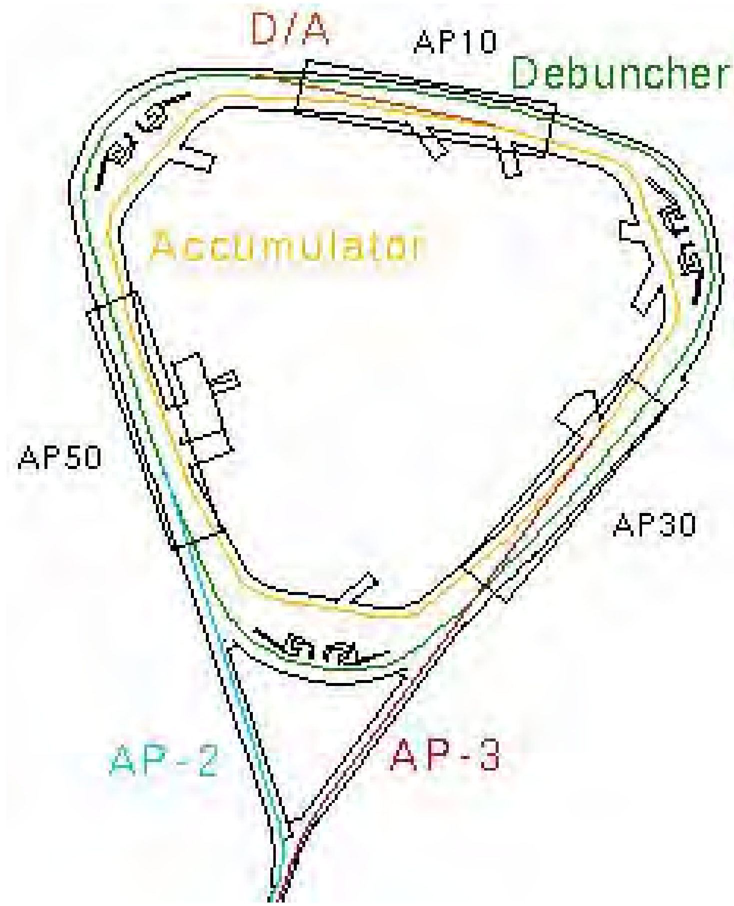


Typical cycle of Recycler operation;

Transverse emittance computed as average of H&V emittances measured by Schottky monitor. It exceeds the flying wire measurements by ~1.5 times because of non-Gaussian tails created by fast drop of electron cooling efficiency with betatron amplitudes

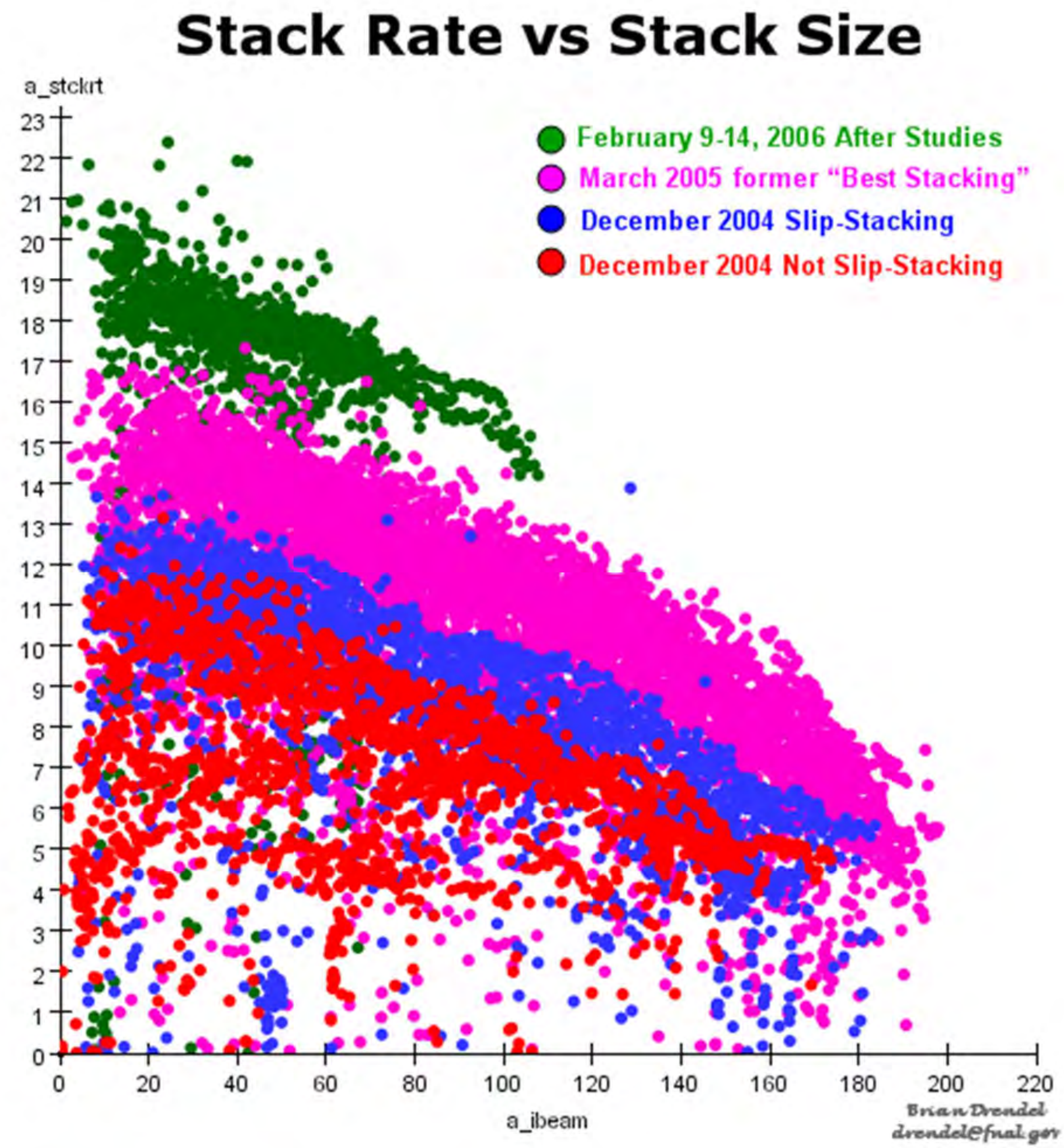
Antiproton Production

Simplified review of operations at Run end



- Every 2.2 s $8\cdot10^{12}$ protons at 120 GeV from Main Injector sent to the target of about 10 cm length (Inconel-600)
- Li lens located at ~30 cm from target (center-to-center) reduces initially large angular spread
- 8 GeV (±2.5%) antiprotons and other secondaries (μ, π, …) are transported to Debuncher, $N_{pbar} \approx 2.3\cdot10^8$
- After stochastic L&⊥ cooling in Debuncher antiprotons are sent to Accumulator
- 4 stochastic cooling systems (stacking, long. core, H and V) are used to stack and cool antiprotons in Accumulator
- After storing $\sim2\cdot10^{11}$ antiprotons in Accumulator (~50 min.) they are sent to Recycler
- $\sim3\cdot10^{12}$ antiprotons are stored and cooled in Recycler (~16 hour) and then sent to Tevatron

Antiproton Production Progress



Antiproton Cooling and Accumulation in Recycler

- Recycler ring
  - 3.3 km circumference antiproton accumulator operating at 8 GeV
  - Stochastic cooling
    - ⊥: 2-4 GHz, limited by band overlap
    - ||: 1-2 GHz
  - Electron cooling
    - 100 mA, r_b~2.5 mm, 4.3 MeV, 20 m
- Stochastic & electron coolings supplement each other
  - Electron cooling is
    - extremely efficient for particles with small amplitudes
    - allows one to get small emittances with large number of particles
    - but is not effective for particles with large amplitudes
  - St. cooling cools large amplitude particles ⇒ improves lifetime

Pelletron

Cooling section

Recycler Operating Scenario

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- RR operates below transition ⇒ IBS makes equal temperatures for all three planes
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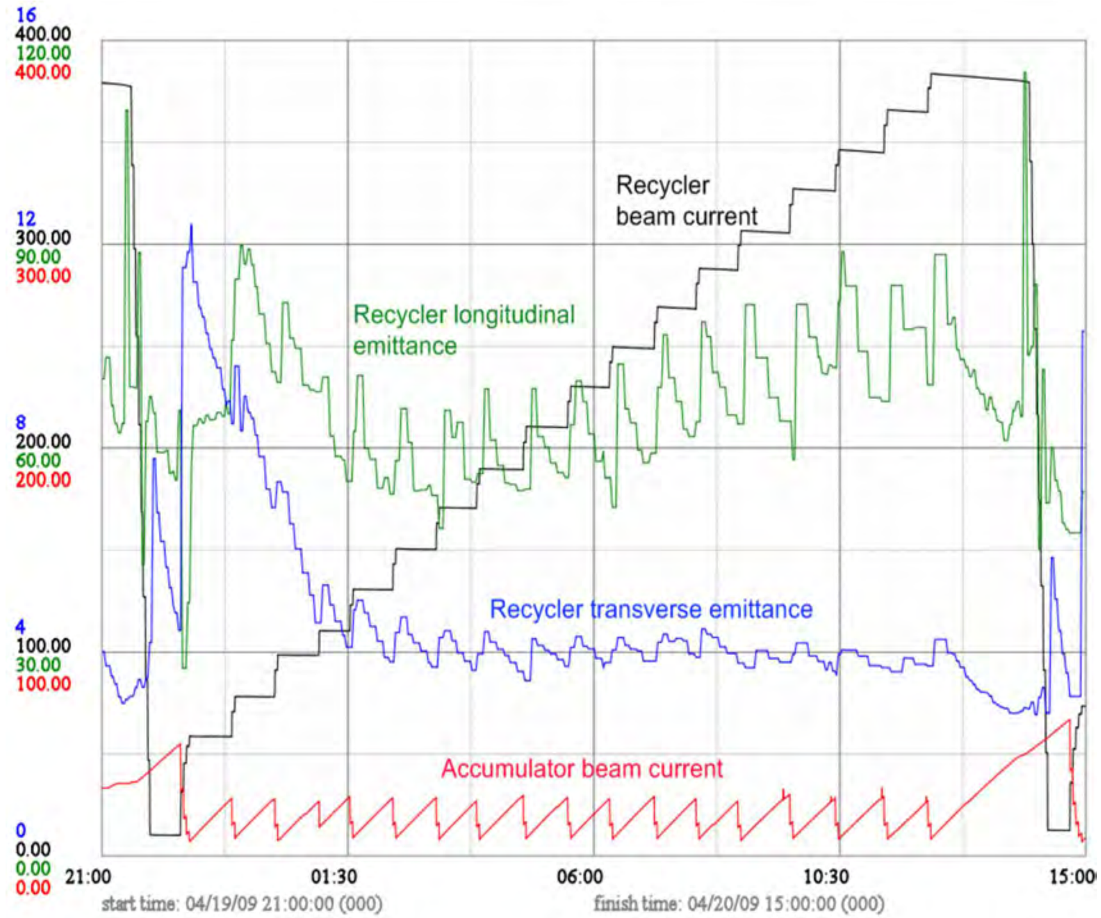

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Tevatron: Luminosity Evolution Model

- The model ignores the beam-beam effects
  - Comparison to meas. shows that usually they result in ≤10% loss in ∫Ldt
- All tune shifts (protons, pbars, X, &Y) are ~0.02-0.025 at store beginning
  - Protons suffer more from beam-beam effects because of larger emit.