NICA

Designing a collider.

NICA collider — a real life example

Anatoly Sidorin
JINR, Dubna

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Ion Colliders
Dubna, 28 October — 7 November 2019

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- Low energy Heavy ion collider

Possible future colliders

-Linear colliders (ILC, CLIC – not earlier than 2035)

-High energy electron – Ion collider

-Future Circular Colliders (FCC, CepC/CppC)

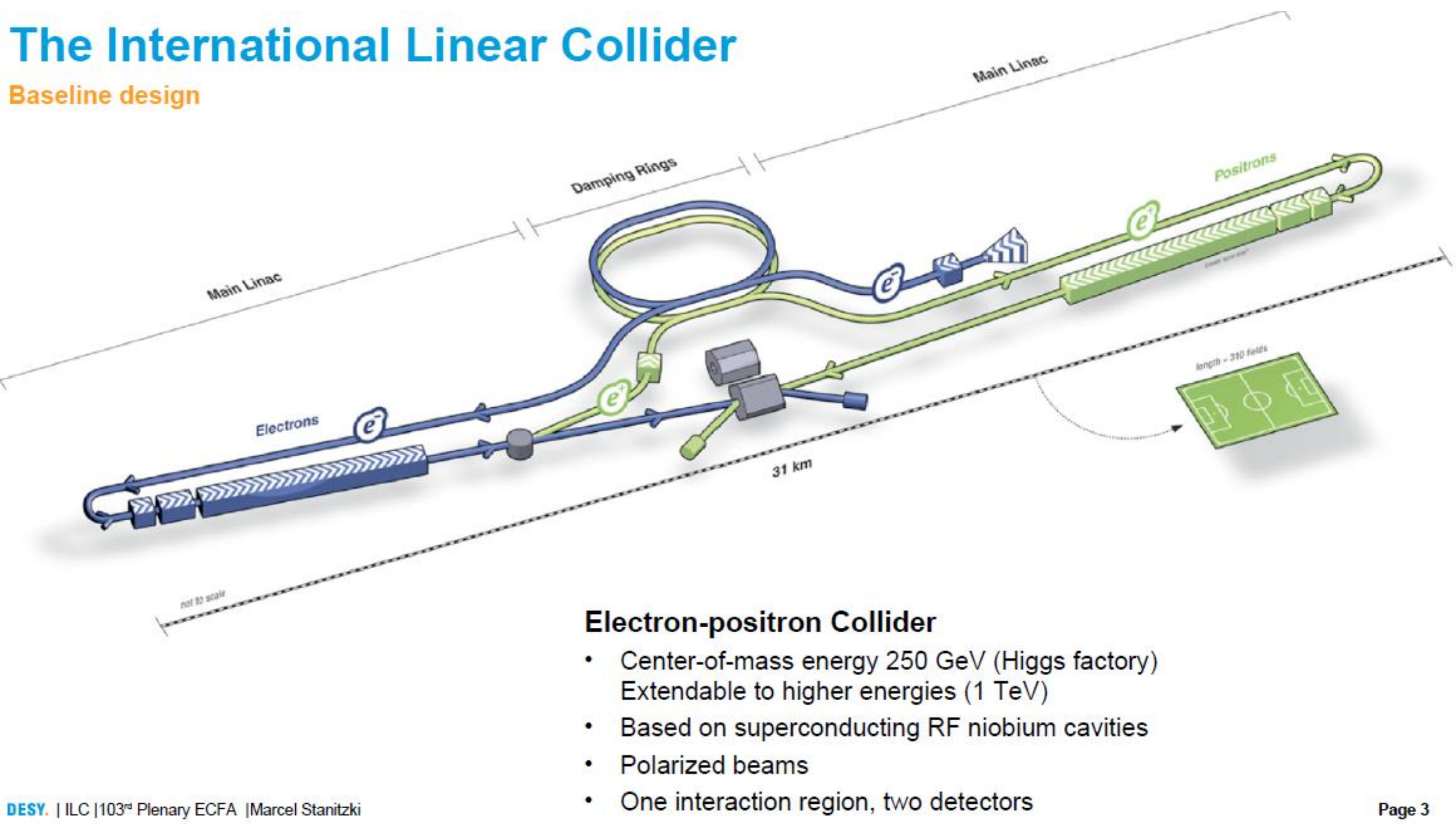
-Low energy electron – ion collider

-Low energy heavy ion collider

-Collider of light polarized beams

-Asymmetric ion collider

-Ion-ion collider with merging beams



The International Linear Collider

Baseline design

Electron-positron Collider

- Center-of-mass energy 250 GeV (Higgs factory)
  Extendable to higher energies (1 TeV)
- Based on superconducting RF niobium cavities
- Polarized beams
- One interaction region, two detectors

DESY. | ILC |103rd Plenary ECFA |Marcel Stanitzki

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Discovery of a Higgs boson in 2012
Higgs as new window into physics beyond the Standard Model

The ILC is a Higgs factory at all energies!
At 250 GeV: Very clean and easy to reconstruct HZ final state. Precision access to many Higgs properties

Re-baselining the ILC

Moving the initial energy from 500 GeV to 250 GeV

ILC250 Baseline Design

ILC250

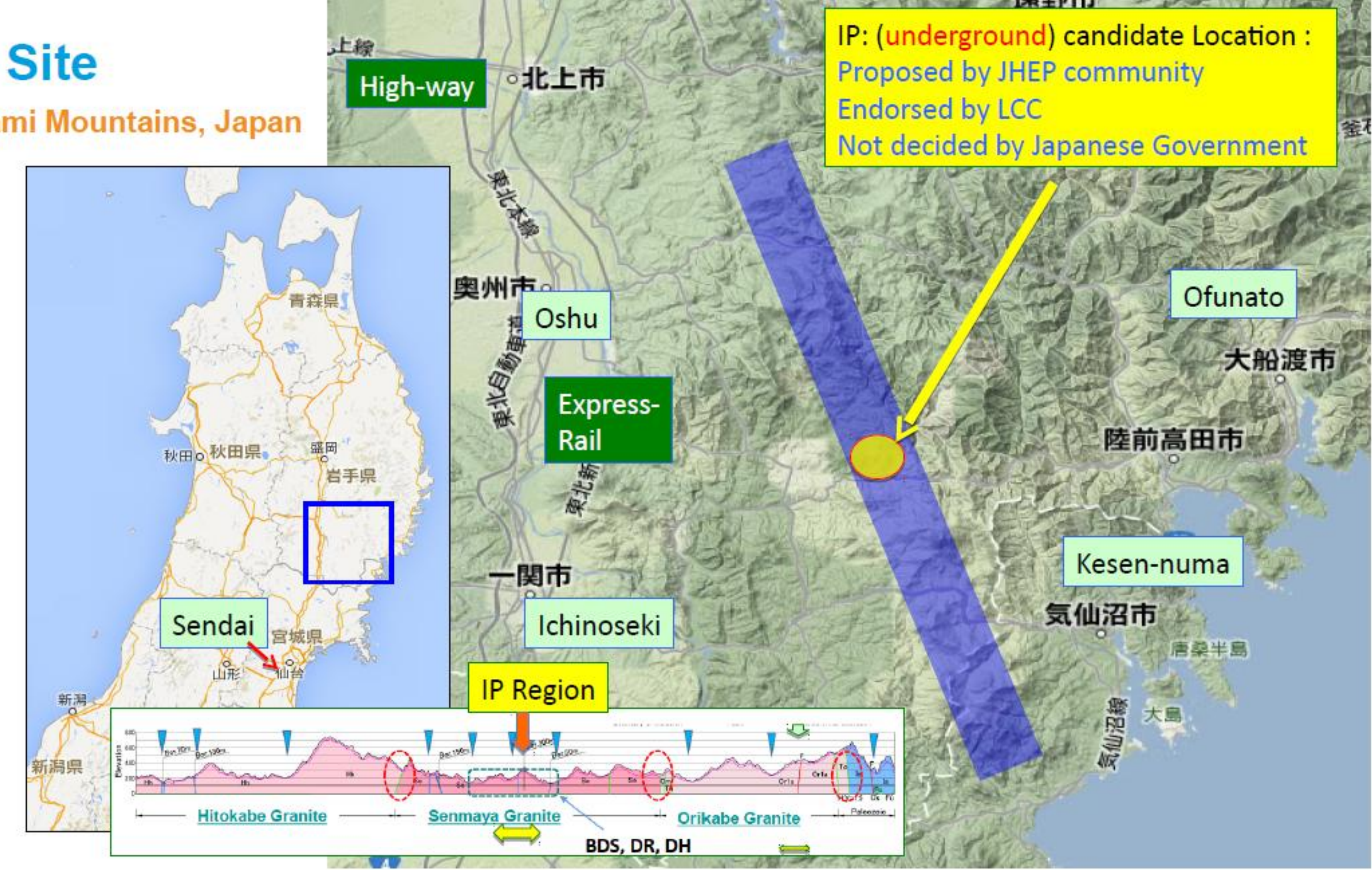
- 20 km long
- Acceleration
  - 8370 superconducting cavities in 930 cryo-module
  - Gradient 31.5 MV/m (35 MV/m)
  - 1.3 GHz RF
- 129 MW power consumption
- Beam parameters
  - 2×10^{10} particles/bunch
  - 554 ns spacing
  - $L = 1.8 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Beam polarization 80/30 (e^-/e^+)

ILC costing model

- Established for the TDR
  - Including set-up and learning curves
- TDR (500 GeV)
  - 7.98 Billion US-$
- Updates since
  - All experiences from the E-XFEL, ESS, LCLS-II
  - Higher Gradient Cavities
- ILC 250 baseline
  - 40% cost reduction
  - 1/3 Construction (CFS)

ILC Site

Kitakami Mountains, Japan



IP: (underground) candidate Location :
Proposed by JHEP community
Endorsed by LCC
Not decided by Japanese Government

ILC Site

Kitakami Mountains, Japan

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Potential ILC Timeline

Excluding Political Consideration

Pre-Preparation Phase

- End 2018 " Statement from Japan"

Project Preparation Phase - 4 years

- International Agreements,
- Construction Preparations
- Collaboration Formation

Construction Phase – 8 years

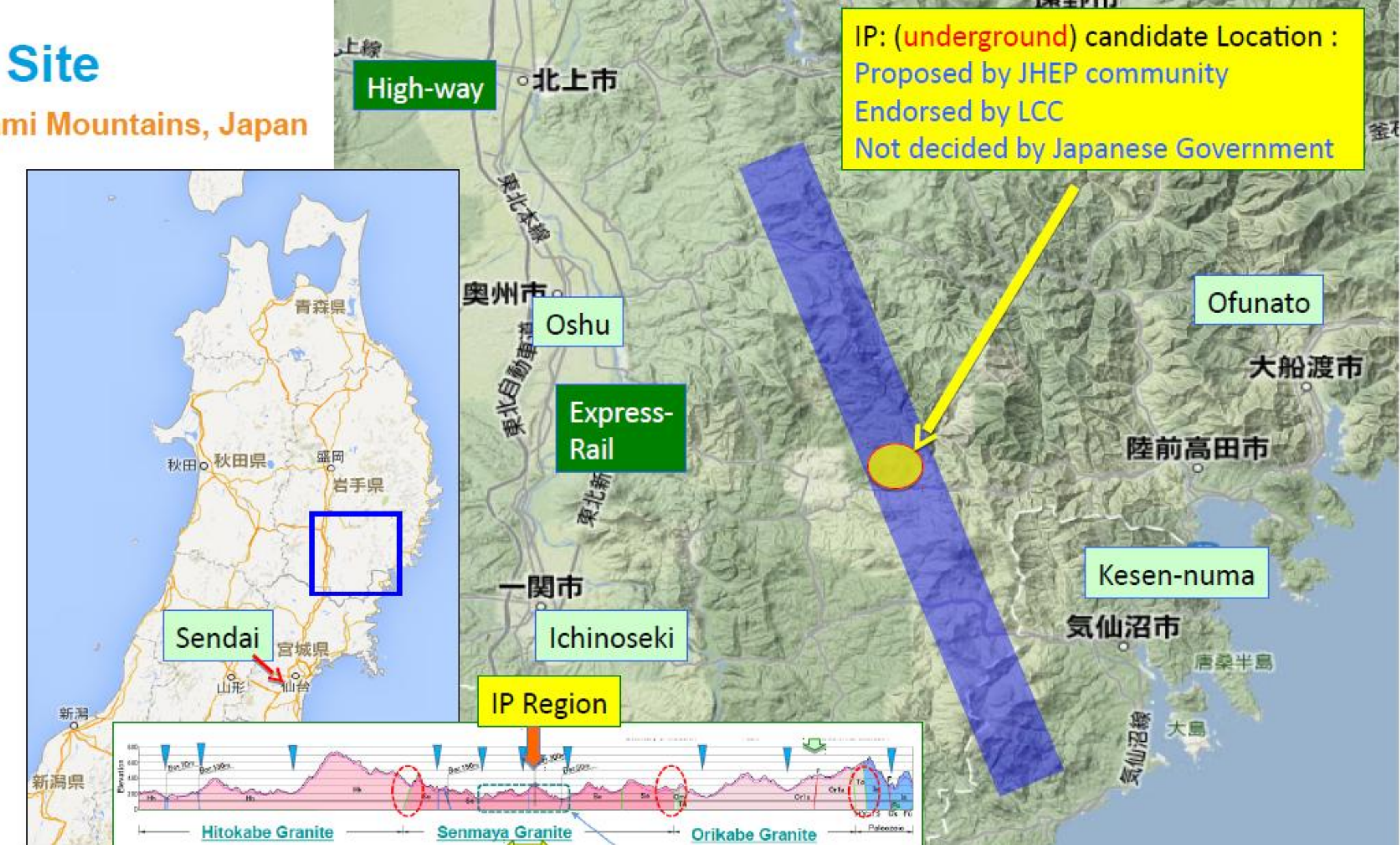
- Begin of Construction

Commissioning & Physics

2030

ILC Site

Kitakami Mountains, Japan



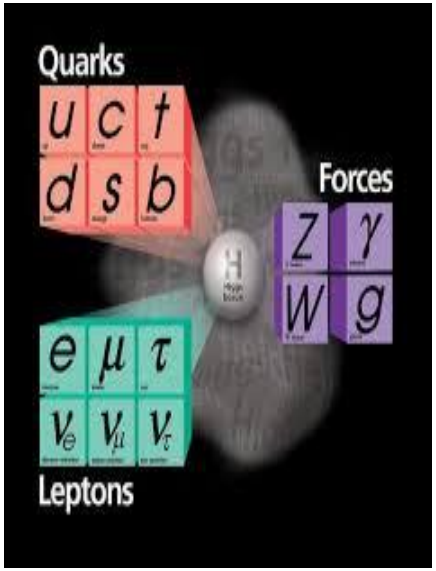
IP: (underground) candidate Location :
Proposed by JHEP community
Endorsed by LCC
Not decided by Japanese Government

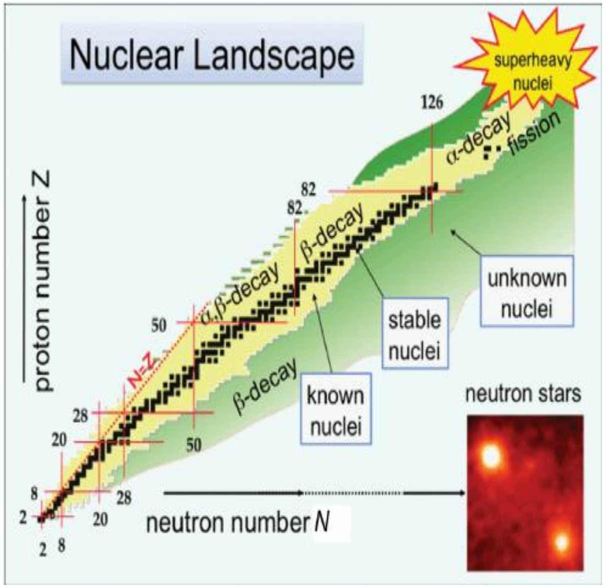
On 7 March 2019, the Japanese government has expressed its position for the International Linear Collider, a proposed particle physics project that would be hosted in Japan. The government has decided to not make a proposal to host the project, but has expressed interest in the ILC project and signaled to continue discussion it with other governments.

203?

Electron Ion Collider: The next QCD frontier

To precisely understand the universal gluon dynamics in QCD and its consequences in the visible world.





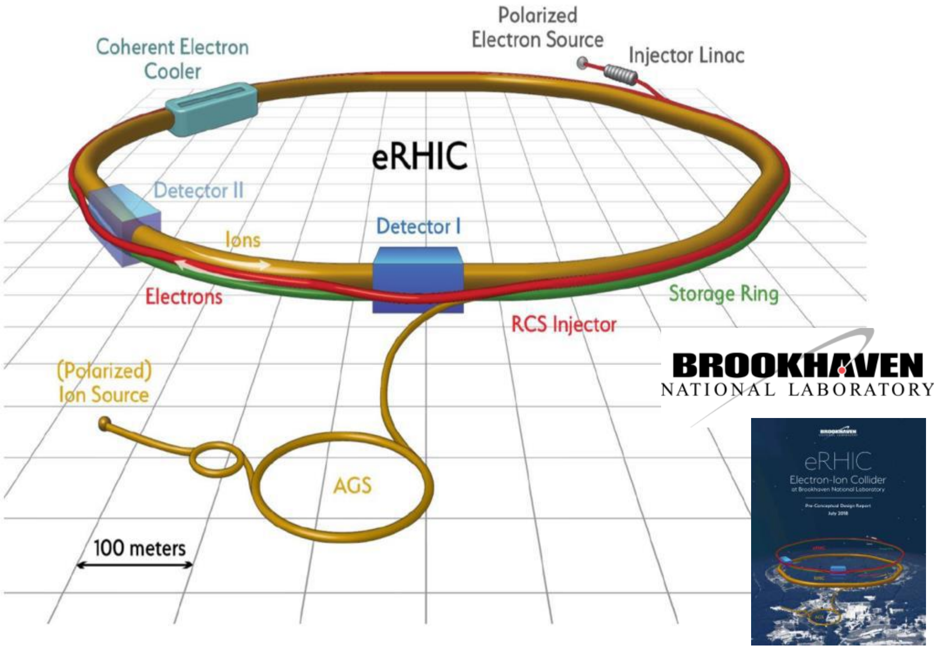
The Electron Ion Colliders

For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
  - ✓ 20-100 (140) GeV Variable CoM

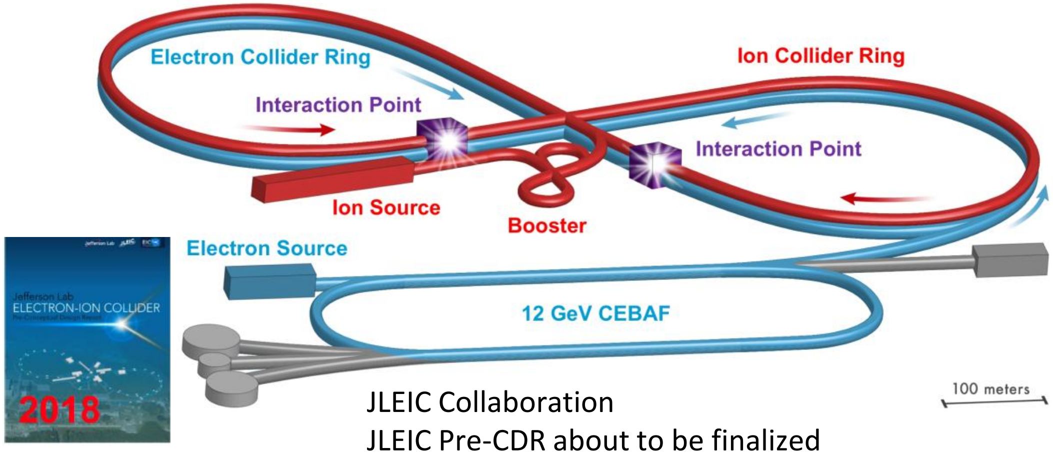
For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy



World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure



JLEIC Collaboration
JLEIC Pre-CDR about to be finalized

U.S. Electron-Ion Collider Planning 2007-18

- Strong endorsement by the NAS (July 2018)

- BNL and JLab working together with the US DOE towards realizing the project.

- Technically driven schedule: the future
  - CD0 (critical decision process of the US DOE) in near future

  - EIC-Proposal’s Technical & Cost review → Site selection → CD1-3

  - According to NSAC LRP 2015 major construction funds (“CD3”) ~2023

  - *Earliest First* collisions in 2029/30

The National Academies of | SCIENCES ENGINEERING MEDICINE

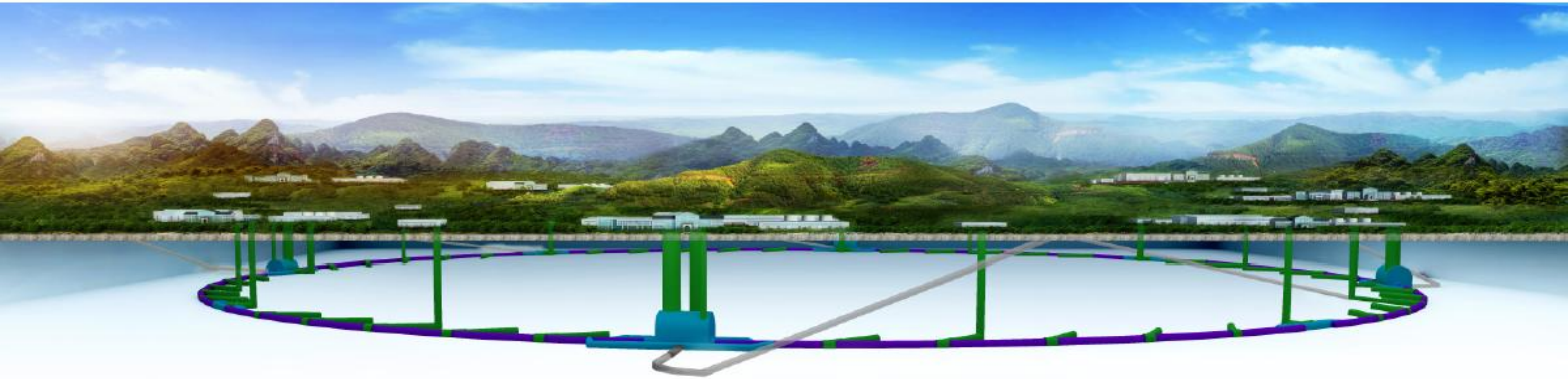
A very strong endorsement of the EIC Science:
Compelling, timely and fundamental

CEPC-SppC Project

Q. Qin for the CEPC team

IHEP

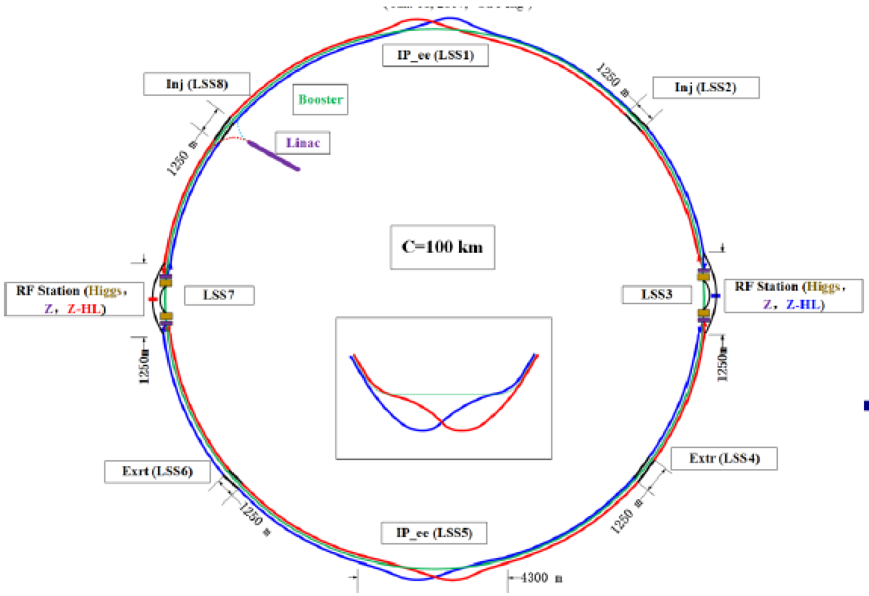
16th Nov., 2018



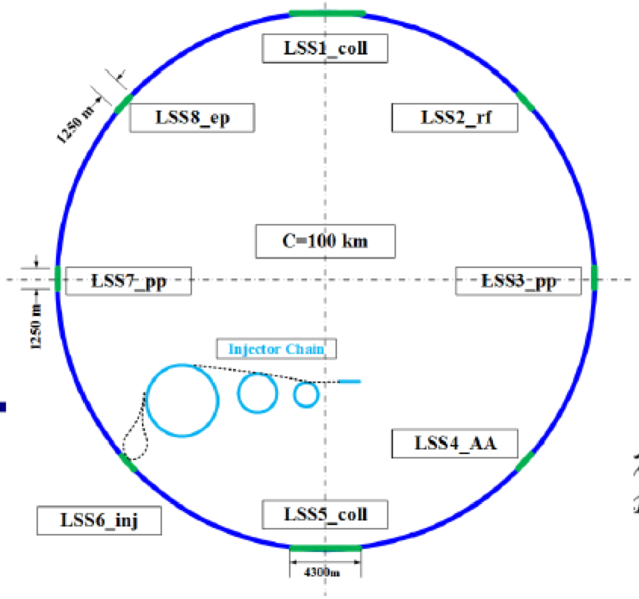
Compatibility between CEPC and SPPC

- CEPC first to be built, with potential to add SPPC later
- Allow ep collision in the future, three machines in one tunnel: e booster, ee double-ring collider, pp double-ring collider (keeping ee detectors together with SPPC in doubt)
- Several rounds of interactions between CEPC and SPPC design teams
- Layout: 8 long straights and arcs, LHC-like DS lattice, lengths for LSSs

CEPC double-ring layout- 100km



SPPC layout- 100km



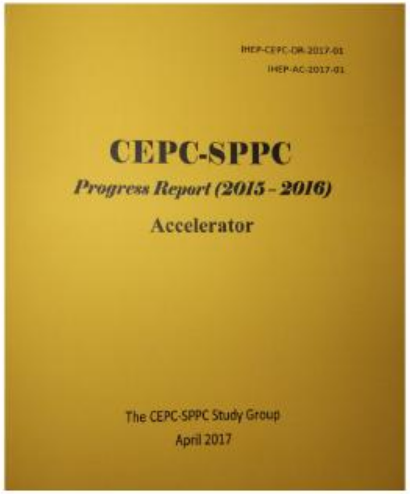
Pre-CDR, Progress report, and CDR are available now

http://cepc.ihep.ac.cn

IHEP-CEPC-DR-2015-01
IHEP-AC-2015-01

CEPC-SPPC
Preliminary Conceptual Design Report
Volume II - Accelerator

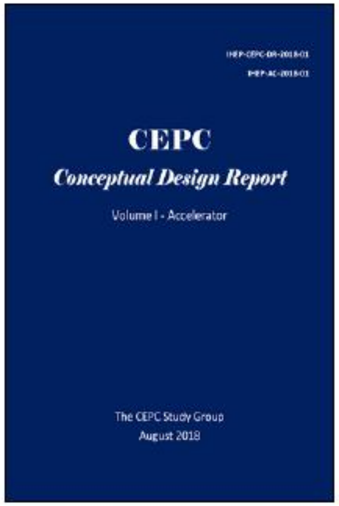
The CEPC-SPPC Study Group
March 2015



IHEP-CEPC-DR-2017-01
IHEP-AC-2017-01

CEPC-SPPC
Progress Report (2015 - 2016)
Accelerator

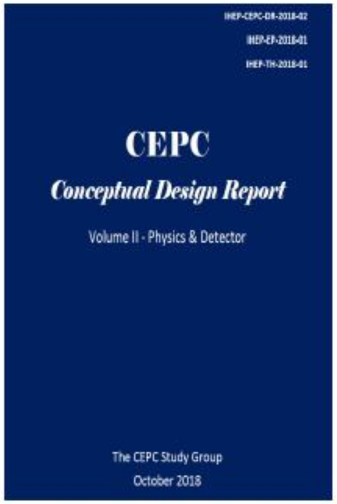
The CEPC-SPPC Study Group
April 2017



IHEP-CEPC-DR-2018-01
IHEP-AC-2018-01

CEPC
Conceptual Design Report
Volume I - Accelerator

The CEPC Study Group
August 2018



IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01

CEPC
Conceptual Design Report
Volume II - Physics & Detector

The CEPC Study Group
October 2018

CEPC CDR was released in Aug. & Oct., 2018

Public release of printed CDR volumes in IHEP on 14th Nov., 2018

Possible future high energy colliders

The projects

-Linear colliders (ILC, CLIC – not earlier than 2035)

-High energy electron – Ion collider

-Future Circular Colliders (FCC, CepC/CppC)

have a chance to be realized in the future

Price of each facility 5 – 10 Billion US$

Long term of construction
(even optimistic scenario – start of operation after 2030)

Real life

-Low energy electron – ion collider:

Second stage of FAIR, DERICA in Dubna, …

-Low energy heavy ion collider

-Collider of light polarized beams

-Asymmetric ion collider:

NICA experimental program

-Ion-ion collider with merging beams:

Second stage of HIAF (China),

Possible future NICA development

Low energy heavy ion collider

The global scientific goal of the low energy heavy ion collider is to explore the phase diagram of strongly interacting matter in the region of high compression.
The program allows to search for possible signs
of the phase transitions and critical phenomena
in heavy ion collisions.
The centre-of-mass energy lies between 4 - 11 GeV/u.

Maximum baryonic density corresponds to kinetic energy of 3.5 – 4 GeV/u

General requirement :

Optimum load of the detector in maximum energy range

Optimum Luminosity

The count rate $\dot{N}_{event}$ is limited by the detector electronics

$$L(E) = \dot{N}_{event} / \sigma(E)$$

NICA example:

Maximum count rate of MPD $\dot{N}_{event} \leq 7\,kHz$

The cross-section $\sigma \approx 7 \cdot 10^{-24}\ cm^{-2}$

Required luminosity: $L_{optimum} = \dot{N}_{event} / \sigma \ \leq 1 \cdot 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

This level is typical for RHIC (Au-Au) and LHC (Pb-Pb),

However ***the ion kinetic energy is below 4.5 GeV/u***

Technical limit

Technical limit related with the ion production rate by injection chain:

$$\dot{N}_{pr} = \dot{N}_{loss}$$

$$\dot{N}_{loss} = \dot{N}_{event} + \dot{N}_{other\,loss}$$

$$L \leq \dot{N}_{pr} / \sigma$$

The ion production rate most important limit for:

- Experiments with antiprotons

-Radioactive Ion beams
(Fragment separator can be more expensive than e-RI collider)

Technical limit

NICA heavy ion injection chain

is designed to provide 10^9 Au nuclei each 5 sec:

$$\dot{N}_{pr} = 2\cdot 10^8\ \mathrm{s}^{-1}$$

$$L \le 3\cdot 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Four orders of magnitude of the technical reserve permits
to use the injection chain for a few experiments in parallel.

The NICA collider luminosity is limited by particle dynamics

Luminosity of the collider

$$L = N_b f_o \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - \frac{[\vec{v}_1 x \vec{v}_2]^2}{c^2}} \int_V \int_t \rho_1 \rho_2 \, dxdydzdt.$$

$$\rho_1 = N_1 \frac{\exp\left[- \frac{x_1^2}{2\,\sigma_{x1}^2} - \frac{y_1^2}{2\,\sigma_{y1}^2} - \frac{(z_1 - v_1 t)^2}{2\,\sigma_{z1}^2} \right]}{(2\pi)^{3/2}\, \sigma_{x1}\, \sigma_{y1}\, \sigma_{z1}}$$

$$\rho_2 = N_2 \frac{\exp\left[- \frac{x_2^2}{2\,\sigma_{x2}^2} - \frac{y_2^2}{2\,\sigma_{y2}^2} - \frac{(z_2 - v_2 t)^2}{2\,\sigma_{z2}^2} \right]}{(2\pi)^{3/2}\, \sigma_{x2}\, \sigma_{y2}\, \sigma_{z2}}$$

Luminosity of the collider

For round beams at the same cross-section

$$L = \frac{n_b N_b^2}{4\pi\varepsilon\beta^* T_{rev}} f\left(\frac{\sigma_s}{\beta^*}\right) \qquad f\left(\frac{\sigma_s}{\beta^*}\right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-u^2)du}{\left[1+\left(\frac{u\sigma_s}{\beta^*}\right)^2\right]}$$

Number of bunches n_b has to be as large as possible**,**
but the inter-bunch distance $l_{bb} = C/n_b$ is to be large enough
to avoid parasitic collisions inside detector

At high energies (Tevatron, RHIC, LHC)
the collider is used for the beam acceleration also.
Train of bunches is prepared by injection chain
-the bunch intensity N_b has to be maximum,
-the emittance ε growth has to be minimized in all elements of injection chain

Beta function in collision point β^* has to be as small as possible,
but comparable with bunch length σ_s
to avoid luminosity reduction due to “hour-glass” factor

Space charge effects

The bunch brightness N_b/ε can be limited by two main space charge effects:

Incoherent shift of the betatron tune (Laslett tune shift)

$$\Delta Q = -\frac{Z^2 r_p}{A}\frac{N_b}{4\pi\varepsilon\beta^2\gamma^3}F_{sc}F_b$$

$$F_b = \frac{C}{\sqrt{2\pi}\sigma_s}$$ - Bunching factor

Beam-beam parameter
(linear part of the tune shift due to fields of opposite bunch)

$$\xi = \frac{Z^2 r_p}{A}\frac{N_b}{4\pi\varepsilon\beta^2\gamma}\frac{1+\beta^2}{2}$$

The bunch brightness can be increased to the limit by beam cooling application:
-Synchrotron cooling at electron-positron colliders
-Stochastic cooling at RHIC

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Lasslett tune shift fast decreases with energy (as γ^3),
because the magnetic field compensates electrical repulsion

Space charge effects

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The beam-beam parameter decreases with energy as γ, because the magnetic field of the opposite bunch increases electrical repulsion

Space charge effects at low energy

At high energy (RHIC, LHC):
Lasslett tune shift is negligible,
the luminosity is limited by beam-beam parameter

At low energy:
Beam-beam parameter and Laslett tune shift can be comparable (RHIC BES)
or Laslett tune shift dominates (NICA: $\xi \sim 0.1 \cdot \Delta Q$)

Important difference:

ξ does not depend on the ring circumference C

while $\Delta Q \sim C$ (via bunching factor)

$$F_b = \frac{C}{\sqrt{2\pi}\sigma_s}$$

Space charge effects at low energy

At low energy the beam brightness can be expressed
from maximum achievable tune shift ΔQ that gives for luminosity:

$$L_{SC} = \frac{A}{Z^2 r_p}\frac{N_b c}{\beta^*}\frac{\sqrt{2\pi}\sigma_s}{C l_{bb}}\gamma^3\beta^3 f\left(\frac{\sigma_s}{\beta^*}\right)\Delta Q$$

(l_{bb}- interbunch distance)

This formula relates to the case when the bunch intensity is constant
and determined by injection chain performance

To reach this maximum value the beam emittance must be varied with energy

$$\varepsilon = \frac{Z^2 r_p}{A}\frac{N_b}{4\pi\beta^2\gamma^3\Delta Q}\frac{C}{\sqrt{2\pi}\sigma_s}$$

active formation of the beam phase volume (beam cooling) is mandatory

Space charge effects at low energy

The way to increase the luminosity is to vary bunch intensity with energy, in this case

$$L_{SC} = \left(\frac{A}{Z^2 r_p}\right)^2 \frac{\varepsilon}{\beta^*} \frac{8\pi^2\sigma_s^2 c}{C^2 l_{bb}} \gamma^6 \beta^5 f\left(\frac{\sigma_s}{\beta^*}\right) \Delta Q^2$$

Optimum choice of the collider and beam parameters

$$L_{SC} > L_{optimum}$$

in the maximum working energy range

If $L_{SC} < L_{optimum}$ - **Space Charge (SC) dominated regime**

Space charge effects at low energy

The way to increase the luminosity is to vary bunch intensity with energy, in this case

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Optimum choice of the collider and beam parameters

$$L_{SC} > L_{optimum}$$

in the maximum working energy range

If $L_{SC} < L_{optimum}$ - **Space Charge (SC) dominated regime**

SC dominated regime

In difference with high energy collider

$$L \sim \frac{\varepsilon \Delta Q^2}{C^2}$$

-**The beam emittance has to be as large as possible**

(close to acceptance limit)

-The bunch intensity should be varied with energy (to provide maximum ΔQ)

-***The ring circumference has to be minimum***

-The working point has to be far from low order resonances (to reach large ΔQ)

The luminosity during experiments can be limited by

- The ring dynamic aperture (limits the emittance)
- Power of the cooling system (maximum achievable ΔQ)
- Coherent instability of the beam
  (Increase of the emittance requires increase of particle number – large peak current)
- Formation of “electron clouds”

NICA collider for gold-gold collisions

Circumference of the ring, m	**503.04**		
Number of bunches	**22**		
R.m.s. bunch length, m	**0.6**		
β-function in IP, m	**0.6**		
Betatron frequinces, Q_x/Q_y	**9.44/9.44**		
Acceptance, π mm·mrad	**40**		
Momentum acceptance, $\Delta p/p$	**0.010**		
Critical energy factor , γtr	**7.088**		
Energy of Au^{79+}, GeV/u	**1.0**	**3.0**	**4.5**
Number of ions per bunch	**$2.0 \cdot 10^{8}$**	**$2.4 \cdot 10^{9}$**	**$2.3 \cdot 10^{9}$**
R.m.s. momentum spread, $\Delta p/p$	**$0.55 \cdot 10^{-3}$**	**$1.15 \cdot 10^{-3}$**	**$1.5 \cdot 10^{-3}$**
R.m.s. emittance, π mm·mrad	**1.1/0.95**	**1.1/0.85**	**1.1/0.75**
Luminosity, $cm^{-2}\ s^{-1}$	**$0.6 \cdot 10^{25}$**	**$1.0 \cdot 10^{27}$**	**$1.0 \cdot 10^{27}$**

SC dominated
(Electron cooling)

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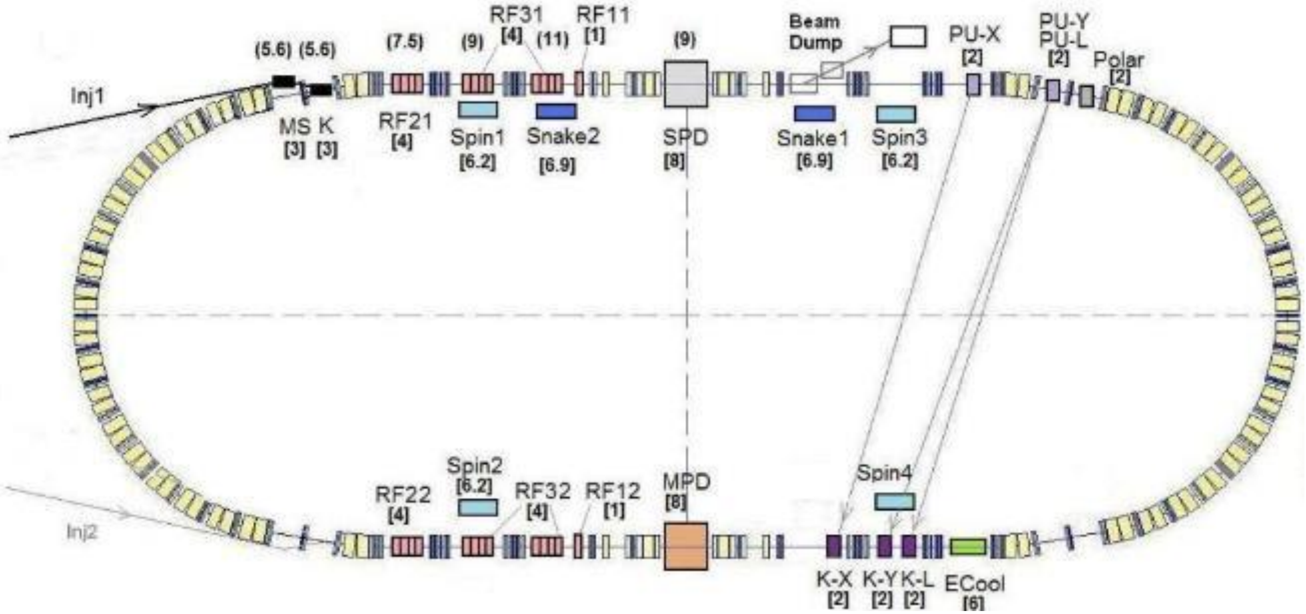
R.m.s. emittance, π mm·mrad	1.1/0.95	1.1/0.85	1.1/0.75
Luminosity, $cm^{-2}\ s^{-1}$	$0.6\cdot10^{25}$	$1.0\cdot10^{27}$	$1.0\cdot10^{27}$

SC dominated
(Electron cooling)

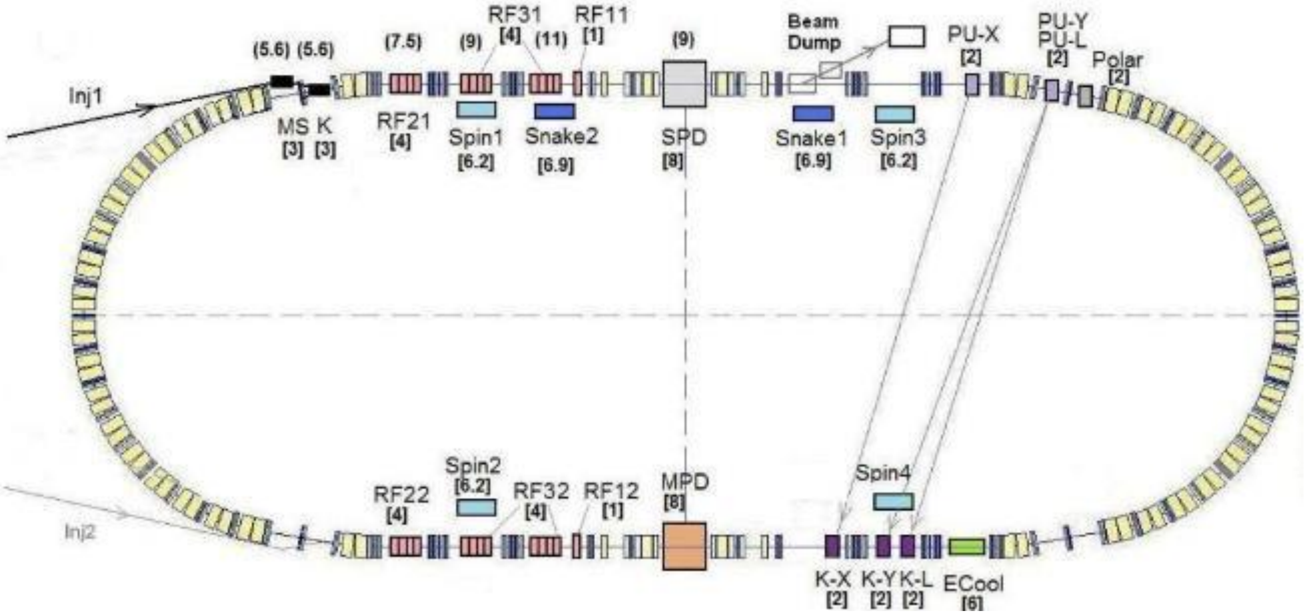
Why 0.5 km?



Length of arc sections is determined by the bending field value

Superferric magnets – maximum bending field is 1.8 T

Why 0.5 km?



Length of long straight sections:

Multy functional ring – two interaction points, length of each detector ~ 10 m + beam superposition and separation

Necessity of the particle number and emittance variation with energy: beam storage and bunch formation in the collider (3 RF systems)

Two cooling systems:
electron (SC dominated) and stochastic (IBS dominated regime)

Limitations of mean luminosity

For the NICA collider

$$L_{SC} > L_{optimum}$$

at energy larger than about 3 GeV/u.

One can provide the peak luminosity equal to optimum one

Next step of a collider design is to provide long luminosity life-time

The limiting factors:

- *Particle losses due to:*
  - single scattering and recombination on residual gas atoms
  - interaction in crossing points (burn off)
  - recombination in electron cooling section
  - ….

- *Diffusion due to:*
  - noise of the magnet power supply
  - multiple scattering on residual gas atoms
  - high order non-linear resonances
  - Intra Beam Scattering
  - ….

Limitations of mean luminosity

Cures:
- Proper design of high vacuum system
- Choice of optimum regime of the beam cooling operation
- All the diffusion processes have to be suppressed by cooling
- …

Important peculiarity of low energy collider:
Fast grows of the beam phase volume due to **Intra-Beam Scattering (IBS)**:

RHIC ~ 4 h
LHC >> 10 h

NICA 3 ÷ 30 minutes

NICA:
at energy larger than 3 GeV/u – IBS dominated regime

IBS dominated regime

IBS:

Particle loss due to **single scattering on large angle**

(Tushek effect)

Negligible for ions

Multiple IBS:

- “Maxwelization”

- Relaxation to equal temperatures of the degrees of freedom

- Diffusion increase of phase volume

Minimum of the diffusion corresponds to thermal equilibrium

IBS dominated regime

Thermal equilibrium

$$T_\perp \sim \frac{\varepsilon}{\langle \beta \rangle} \qquad T_{||} \sim \left(\frac{\Delta p}{p}\right)^2$$

Large emittance requires large momentum spread

At bunch length ~ 60 cm and momentum spread ~ 10^{-3}

RF Voltage ~ 1 MV

Complicated, powerful (and long) RF system

Low energy Heavy ion collider

If the heavy ion program at NICA and FAIR

will demonstrate its great importance,

one can dream about new experimental facility,

dedicated to this task only.

Challenges for low energy collider

- Minimum collider circumference

- Effective scheme of beam storage and bunch formation, adjustment of bunch emittance and intensity at each energy

- Large dynamic aperture of the ring

(Maximum achievable beam emittance)

- Large acceptance on momentum deviation

(Large momentum spread corresponding to minimum IBS rates)

- Correction system

(Control of tune spread to achieve maximum ΔQ)

- High energy electron cooling (a few MeV of electron energy),
- Stochastic cooling of bunched beam

(Beam cooling during storage, bunch formation and experiment)

Low energy Heavy ion collider

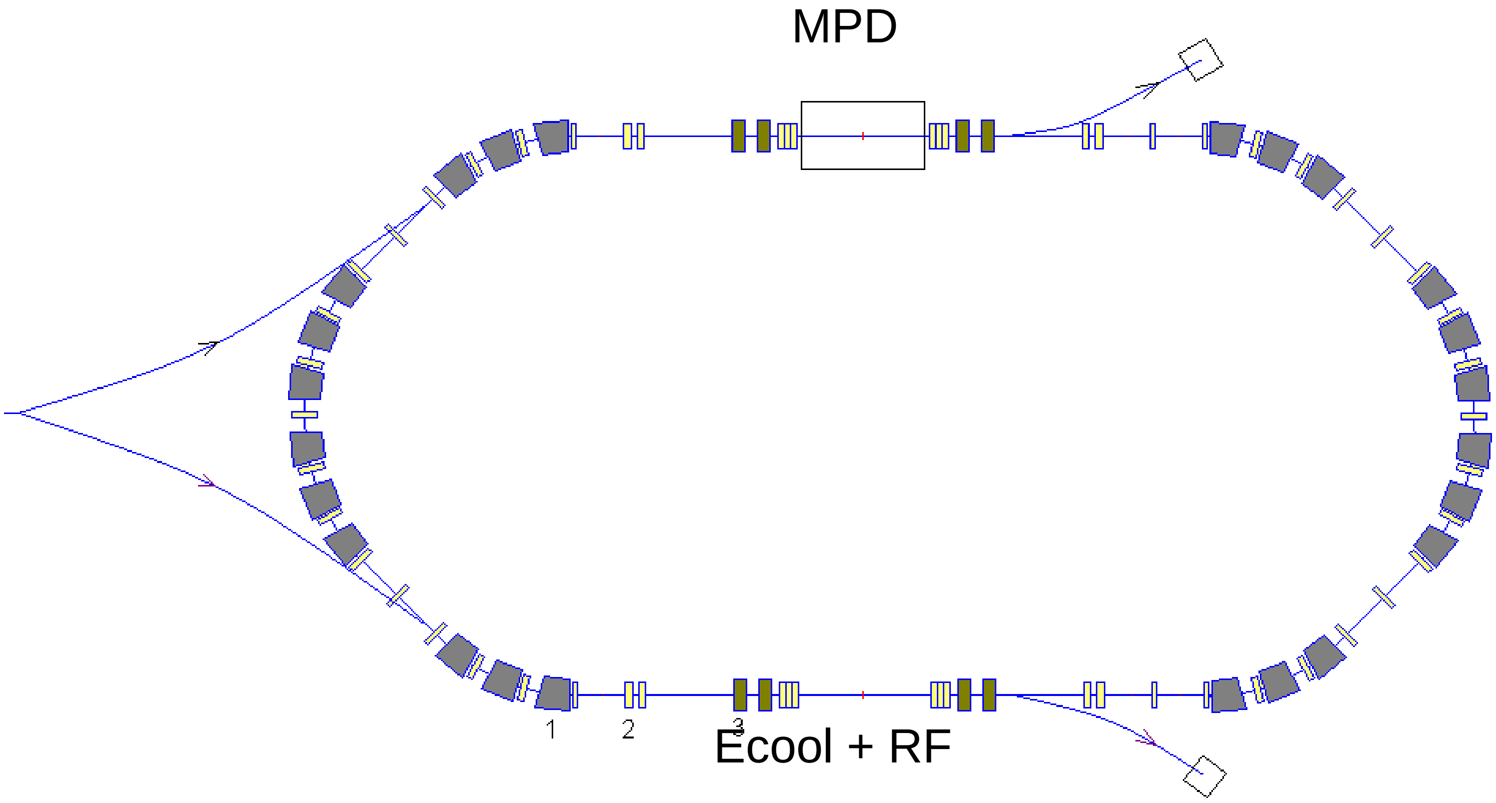
Optimum structure of a heavy ion collider complex:

-**Main synchrotron** (with corresponding injection chain)

-***Collector***
(providing beam storage and formation of two bunch trains,
these trains are transferred to the collider rings during single turn)

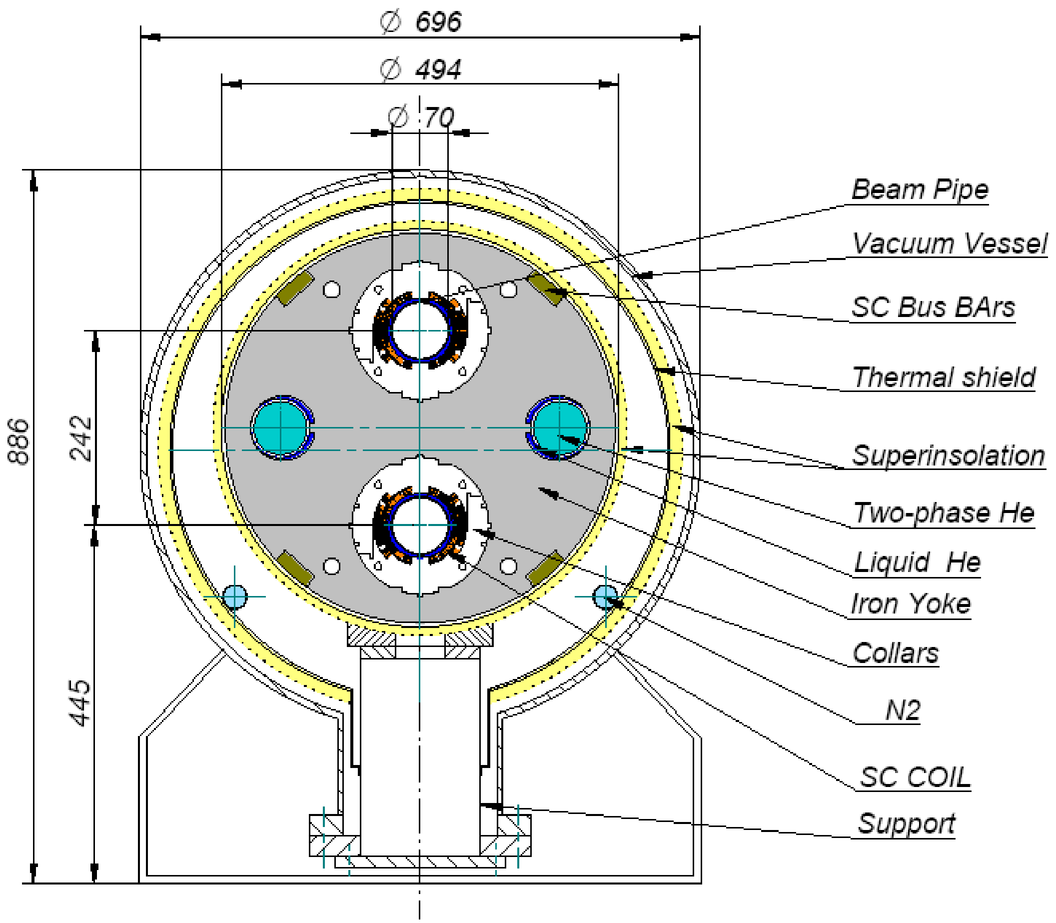
-**Collider at short circumference including minimum equipment only**:
one harmonic RF
Electron cooling system
Beam injection and dump
Feed-back system (if necessary)

Dedicated ring for heavy ion collisions



Circumference ~ 200 m

High field magnets



4 T magnets

Small distance between apertures permits to minimize the length of the beam superposition section near IP

At opposite section the distance between planes is increased for Ecool and RF

The goal

$L \sim 1 \cdot 10^{29}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the total energy range

Thank your for attention