On Electron-Nuclei Colliders

A.Skrinsky (for ECooling & Colliders INP Teams)

WORKSHOP @ JLab

15-17/3/2004

What for we need to use electron-nuclei collider approach?

* Obviously: when we want to reach the effective energy higher than in
electron accelerator → target case
(there is no "very high energy electron accelerators").

SLAC & HERA-e – the only (and successful) examples!

* When we need to study rare nuclei (secondary and/or unstable?!).

* Less obvious – when we need to study bare nuclei (no background events with target electrons).

*Even less obvious - when we want to study collisions of longitudinally polarized electrons with longitudinally polarized nuclei with high degree of polarization and high luminosity ("no" unpolarized nuclei or, in some layouts, no unpolarized electrons).

* When we need the combination of extreme luminosity and high monochromaticity, small angular spread and small interaction spot (no energy losses and scattering of electrons – external or internal)

*Somewhat similar csae: not to disturb reaction products (mostly hadron interacting remnants) – do not spoil purity and accuracy of the experiments.

* Special case: interest to compare electron-nuclei processes with positron-(same) nuclei ones (e.g., of two-photon type) – especially when we need polarized positrons)

Now it became a common sense: to reach high luminosity and good experimental quality for different types of experiments it is wise to apply Electron Cooling.

Reasons to apply Electron Cooling (continuous or at some stages; maybe, in combination with Stochastic Cooling – to rise effective acceptance):

* storing of secondary stable and long enough living hadrons, nuclei and ions;

* achieving of very low "temperature" of stored particles;

* suppression of beam blow-up due to diffusive effects of different nature (multiple scattering by "internal targets", external noise, multiple intra-beam scattering, beam-beam effects, …).

* suppression of injection errors to prevent emittances growth.

Reqirements for electron cooling beam (still not very familiar):

* to receive all the advantages of "electron beam magnetization", the longitudinal guiding field in the cooling section should "unidirectional" within angular spread better than ion beam emittance angular spread.

* not to excite additional oscillations in ion beam, the angle(s) between guiding field and the ion closed orbit should be also smaller than equilibrium angles in ion beam.

* To prevent radiative recombination losses for heavy highly charged ions, keeping fast damping for large amplitude ions, there are 2 options:

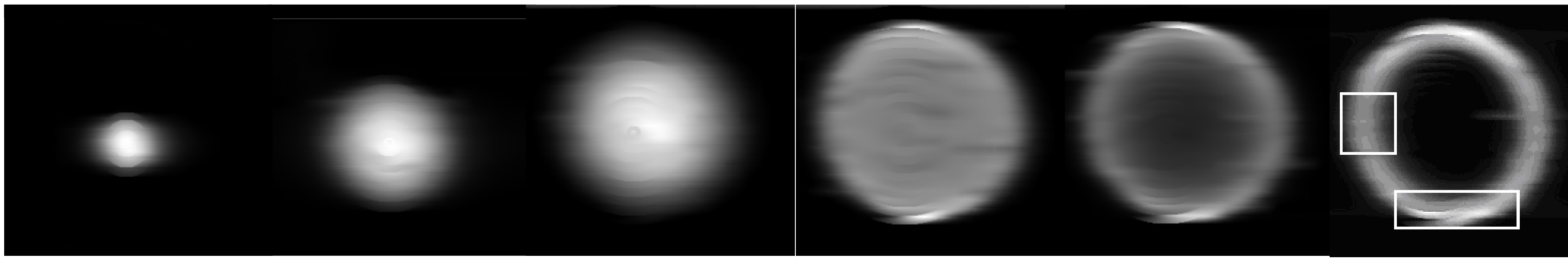
1. to make Larmor velocities high enough (damping rate diminish logarithmically, only).

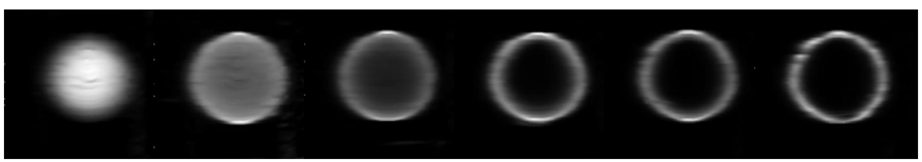
2. to arrange "hollow electron cooling beam" with the same full current, but with much lower density in the core part of ion beam cross-section.

Hollow beams are useful to prvent overcooling (e..g., pbars).

Another option for prevention – to use “monochromatic instability”.

Variation of electron beam profile for optimization cooling





The electron beam distribution for different voltage on the control electrode - 0, 100, 200, 350, 400, 600 V.
The measuring was made with using tungsten wire by scanning across the electron beam. Beam diameter 3 cm.

Many crucial aspects of achieving high luminosity and, simultaniously, high quality of the experiments (especially, under continuous Electron Cooling were presented in my talks (as our Team representative) at Workshops at Uppsala (...), Indiana (…) and Brookhaven (…)
(and references in that publications),

and in many talks of my colleagues (especially, V.V.Parkhomchuk, Yu.M.Shatunov and I.A.Koop) and our collaborators.

Now, I intend to present some examples of projects we participate, and most important steps, related to the development of Electron Cooling for the kind of applications under discussion at the Workshop.

Projects:

- GSI
- Lanzhou
- Brookhaven (Bates,….)
- CERN - LEIR

Improvements

- hollow beams
- electrostatic bending
- High Voltage + contintinuous solenoids
- :

List of “recent” design and constructions

ECoolers –

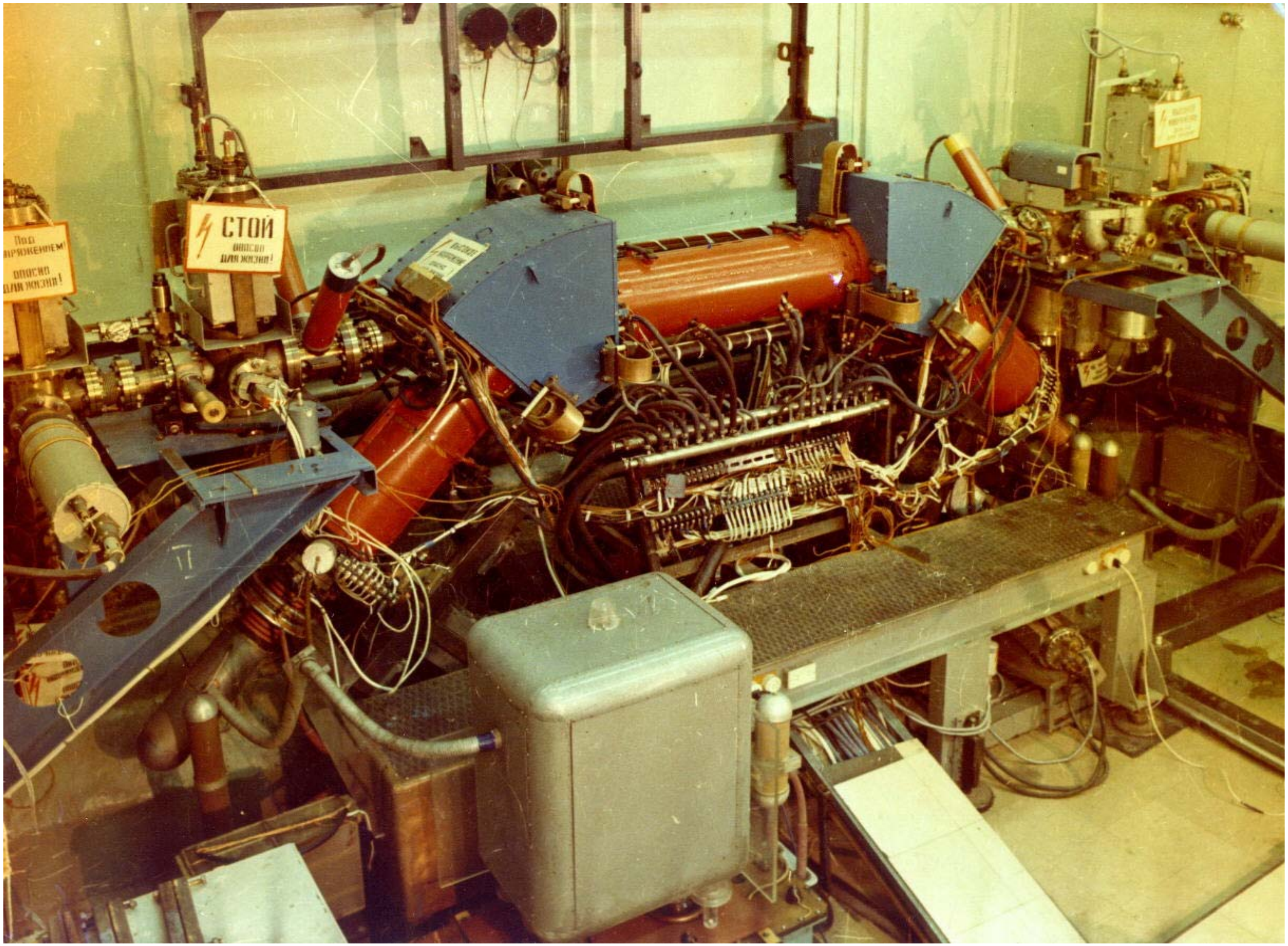
- storage rings.

ELECTRON COOLING PIONEERING @ NOVOSIBIRSK

(Start of ECooling activity -1965)

Proton Storage Ring NAP-M (experimental success – 1974)

(the view from injector side)

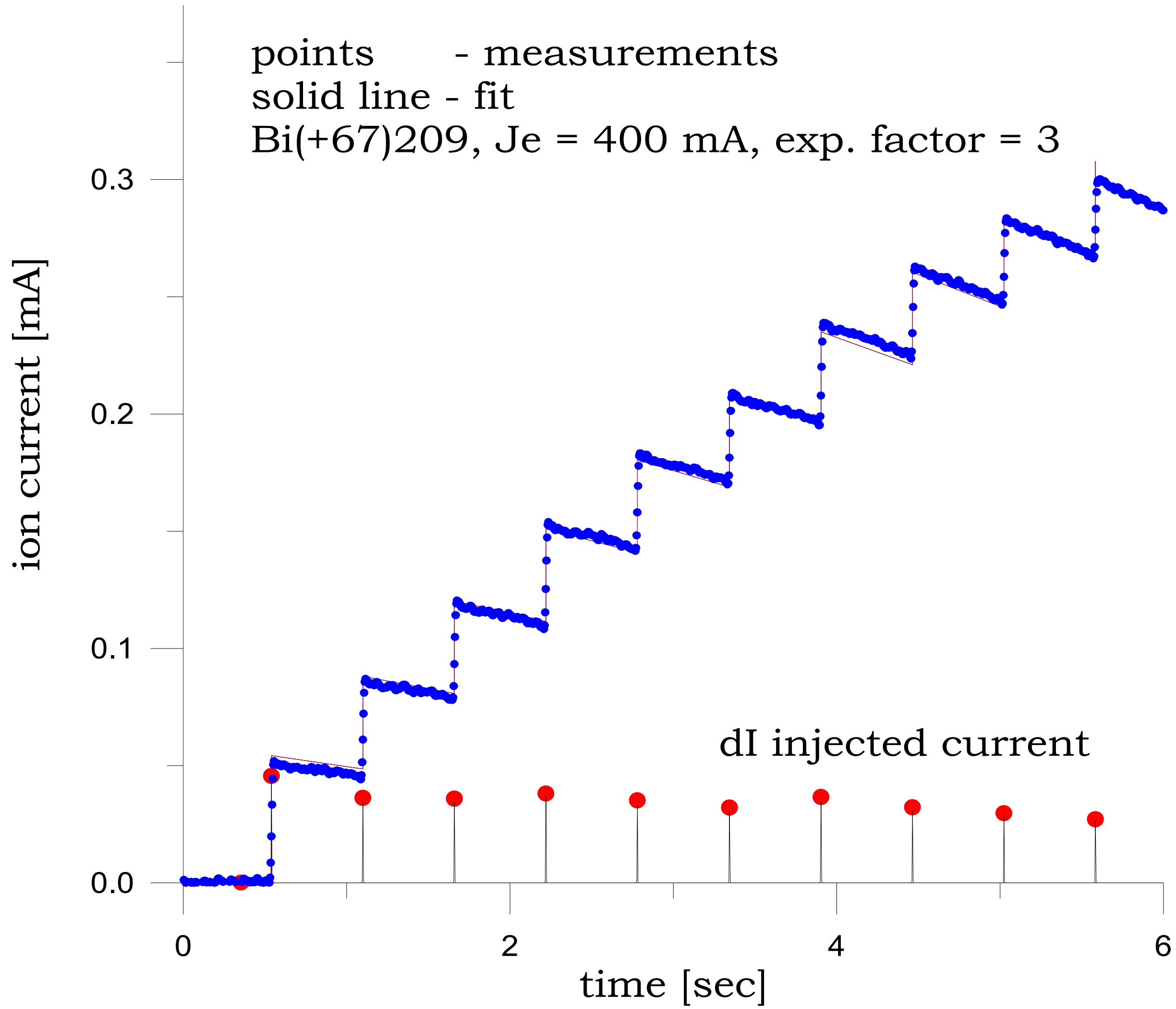


Electron Cooler, installed at NAP-M

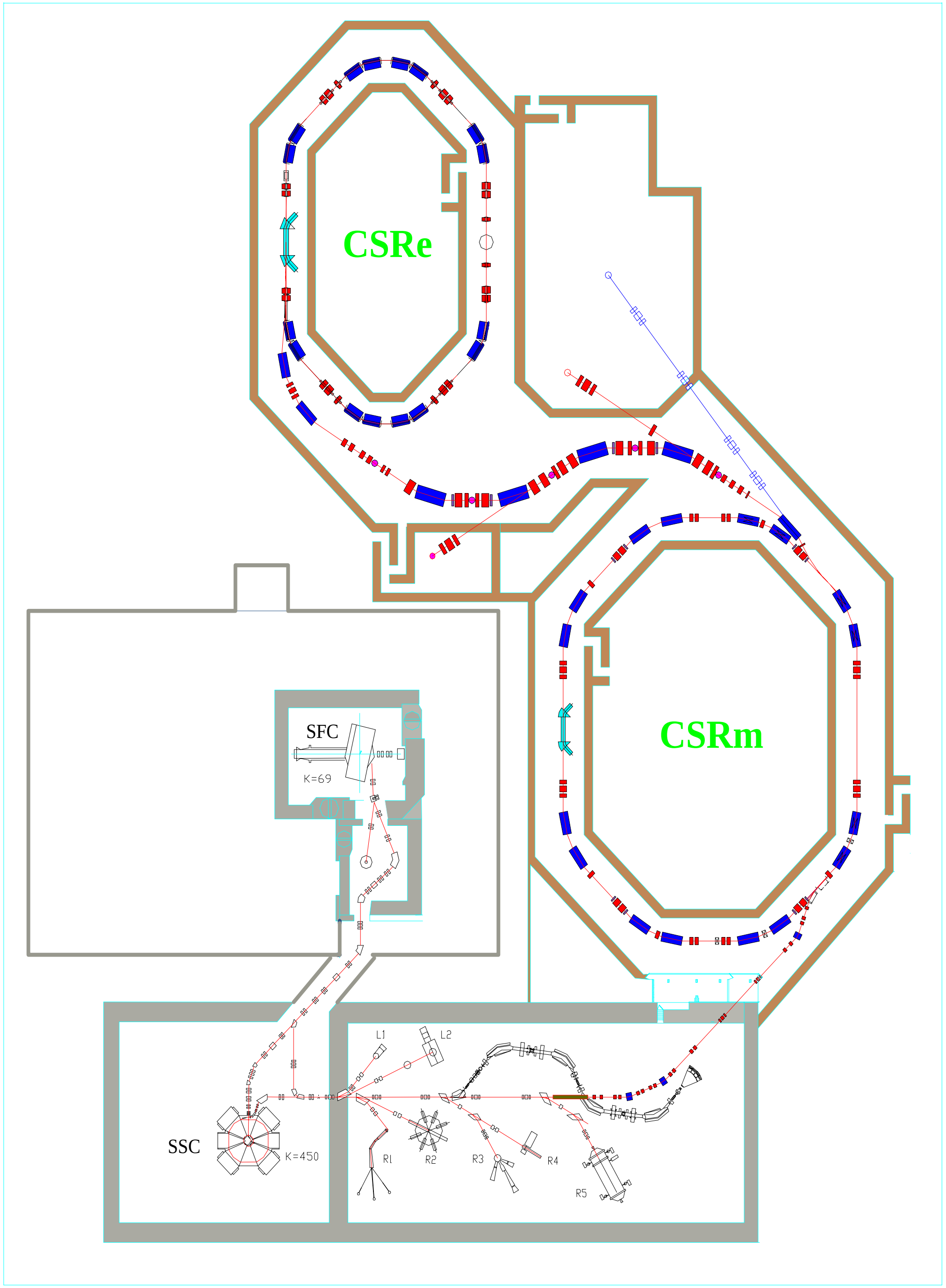

GUN
Dipole
Toroïd
DRIFT
BINP made cooler
at SIS-18


INP GSI

Accumulation Bi ions at SIS-18 @ GSI (May 1998)

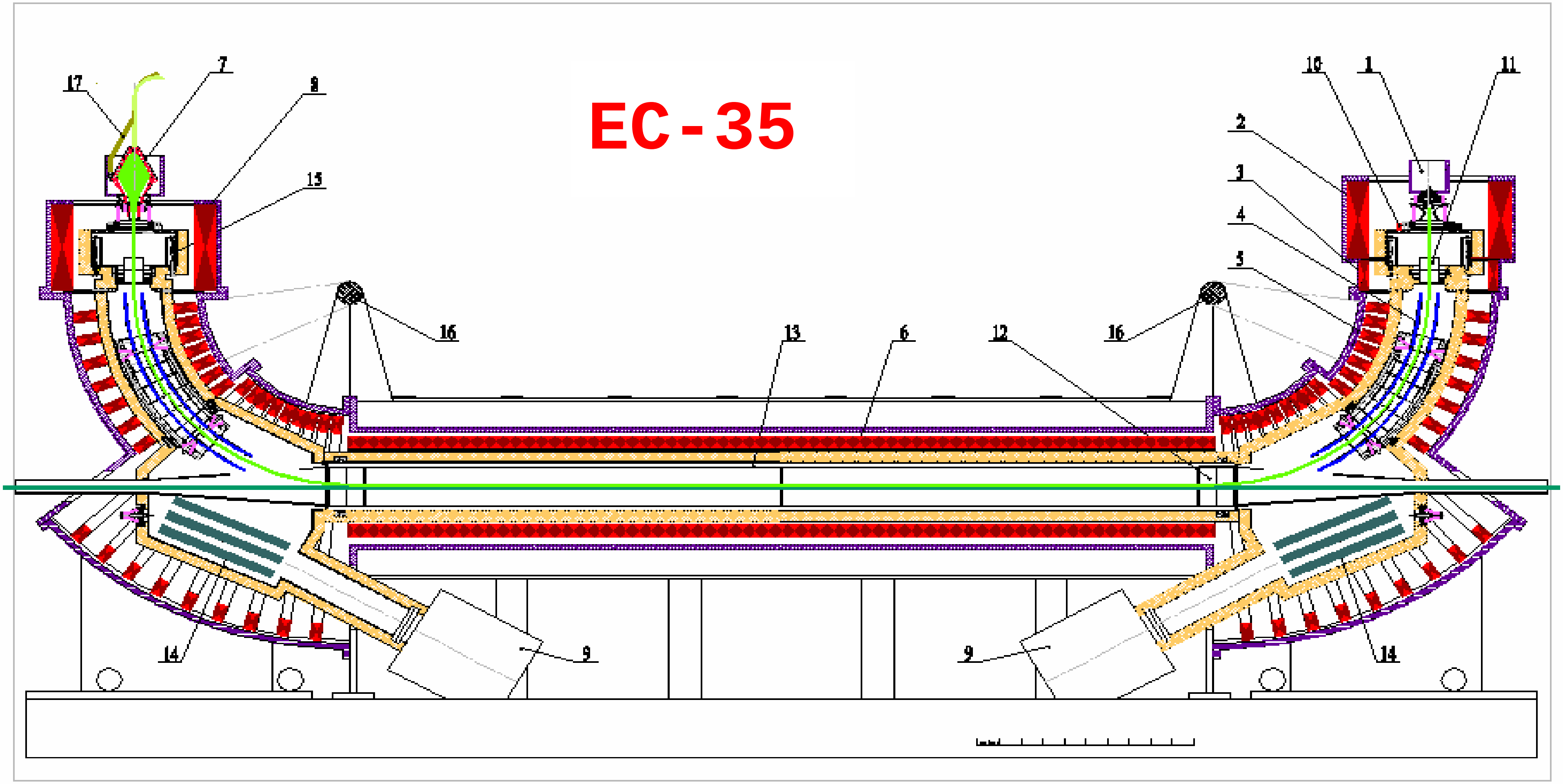


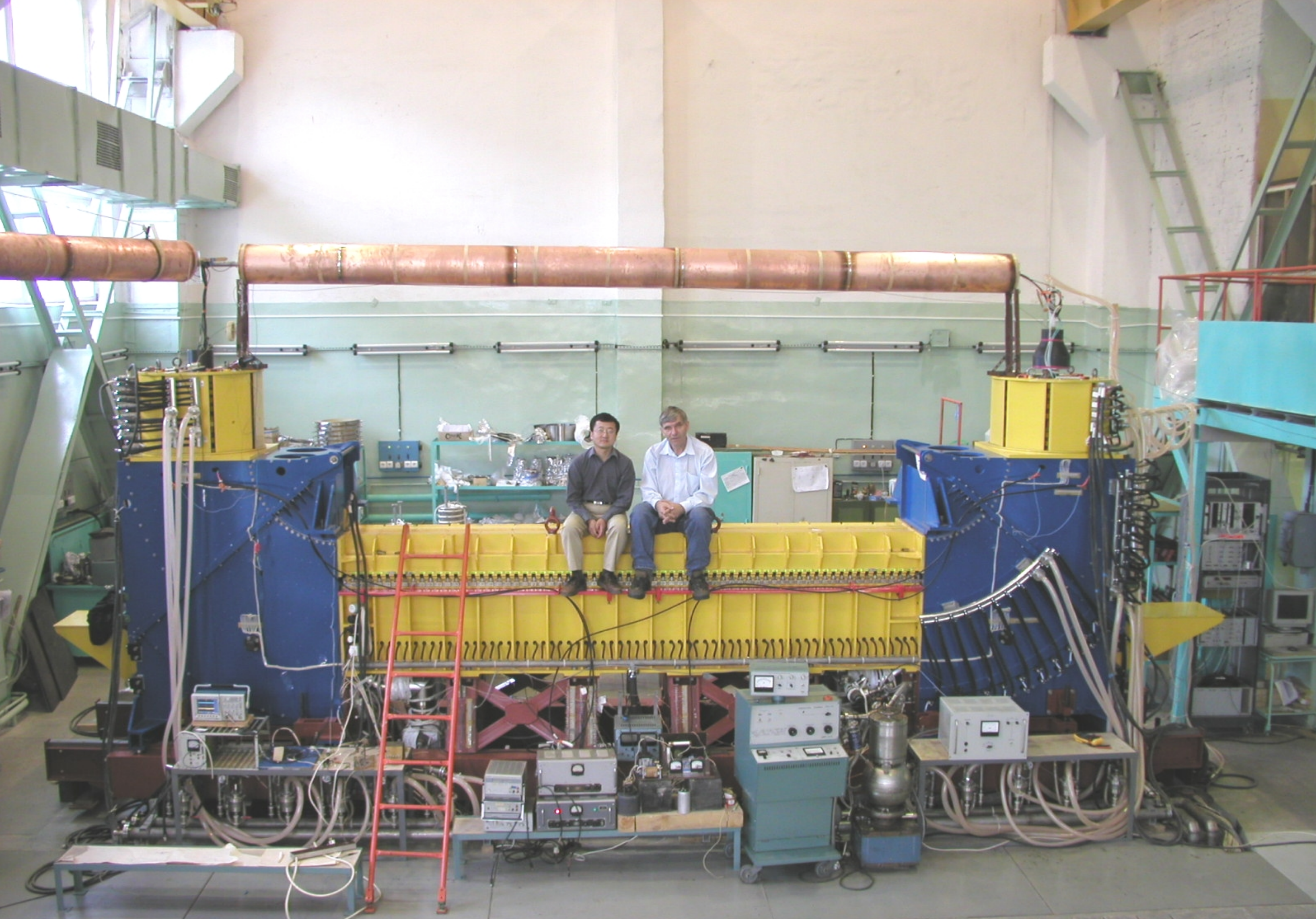
IMP (Lanzhou) - project



35 kV Electron Cooler

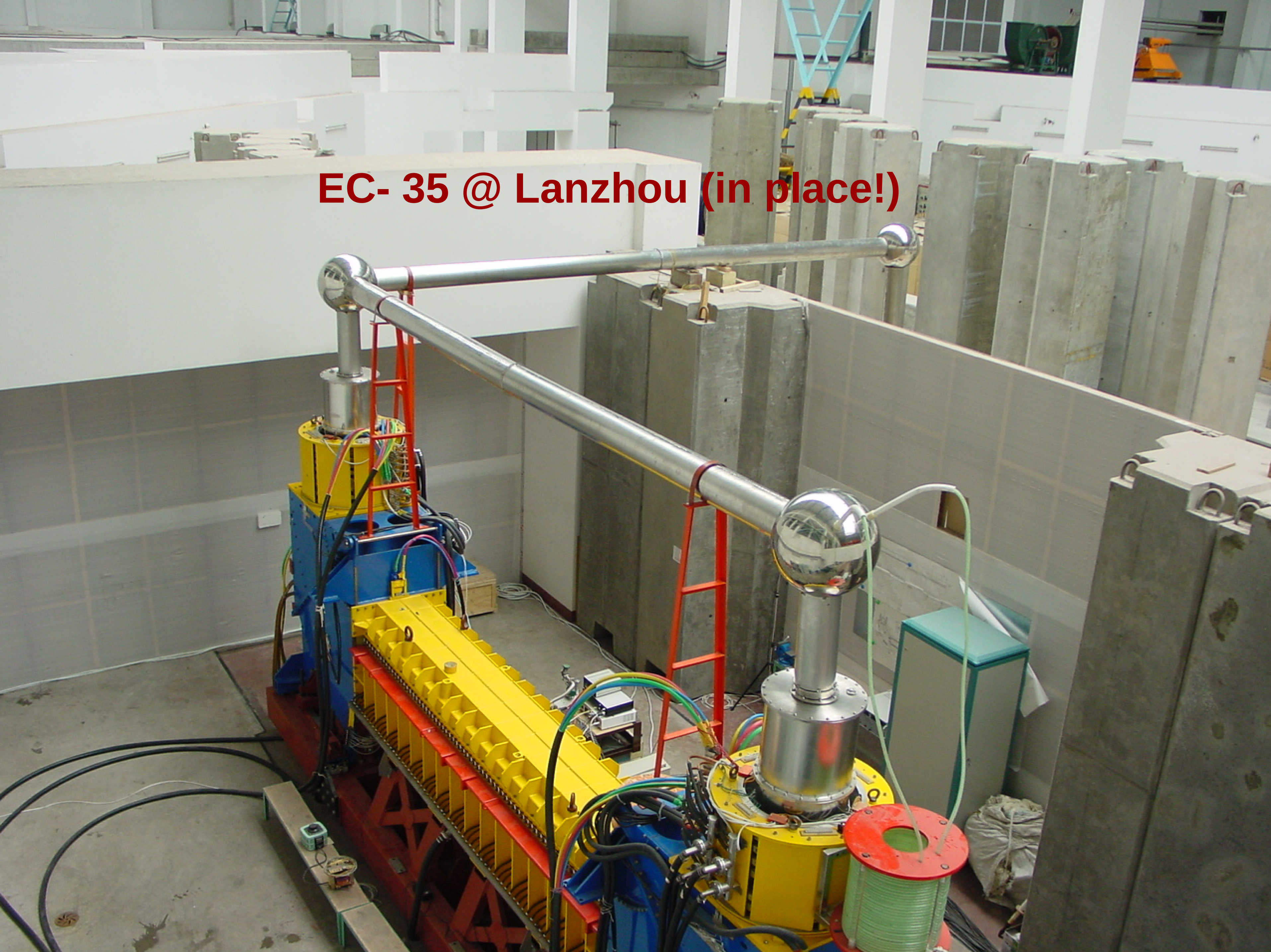
1. Variable profile electron beam for suppression of the heating and electron capture
2. Electrostatic bends (suppression of current losses, better vacuum → 10^{-11} mbar now)
3. Precise pancake design of cooling section.



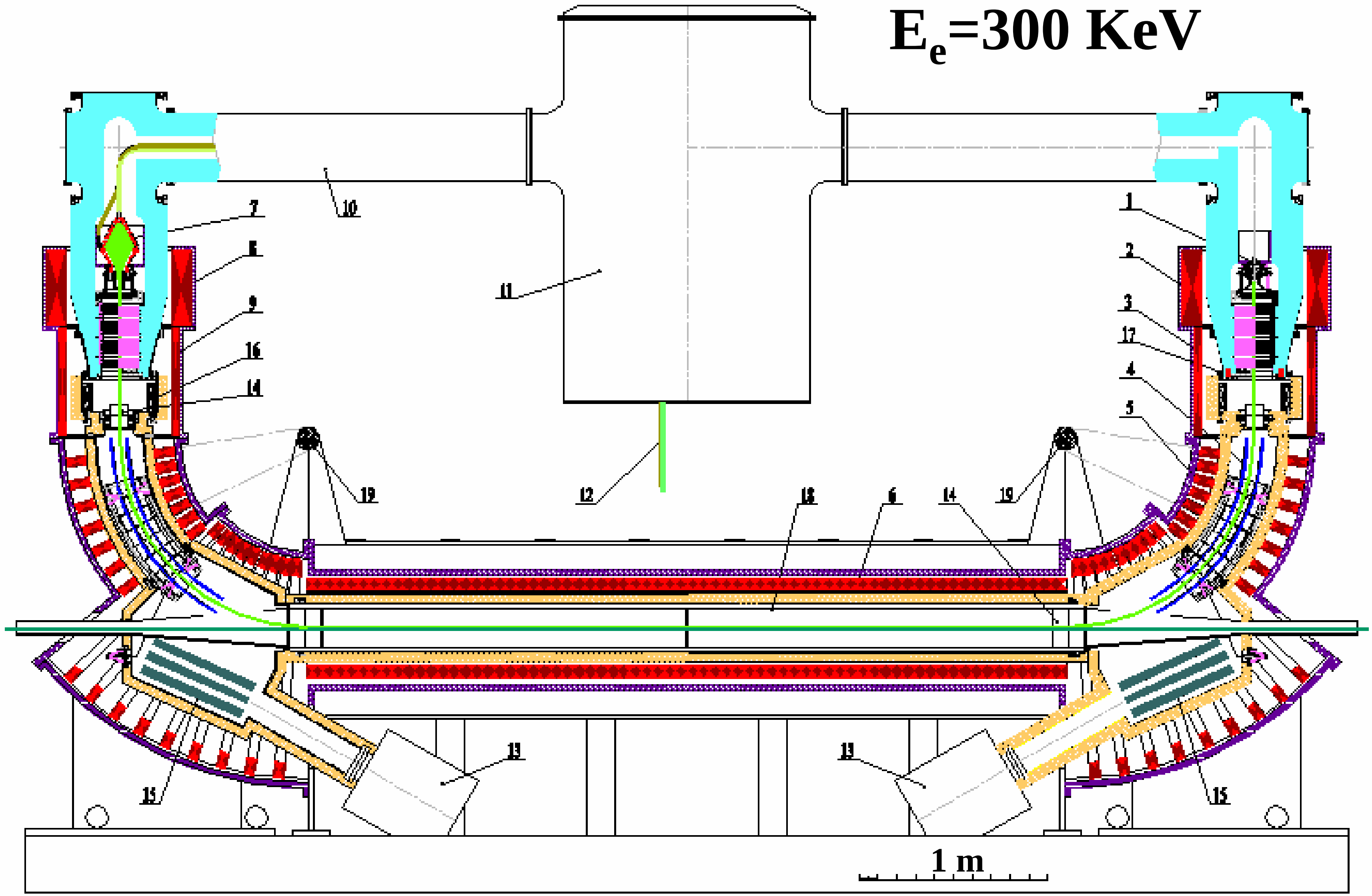


EC- 35 @ Novosibirsk

EC- 35 @ Lanzhou (in place!)

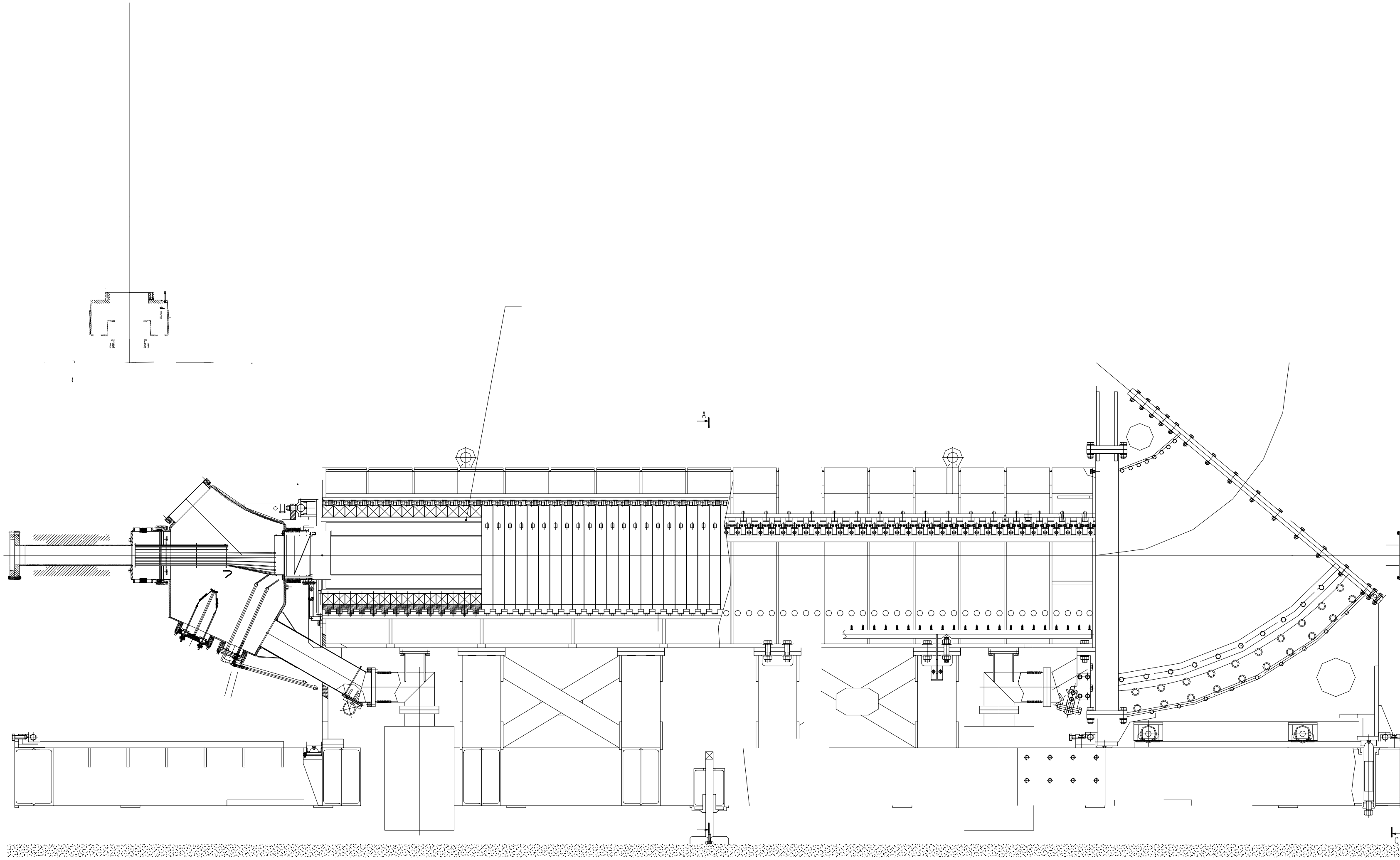


E_e=300 KeV



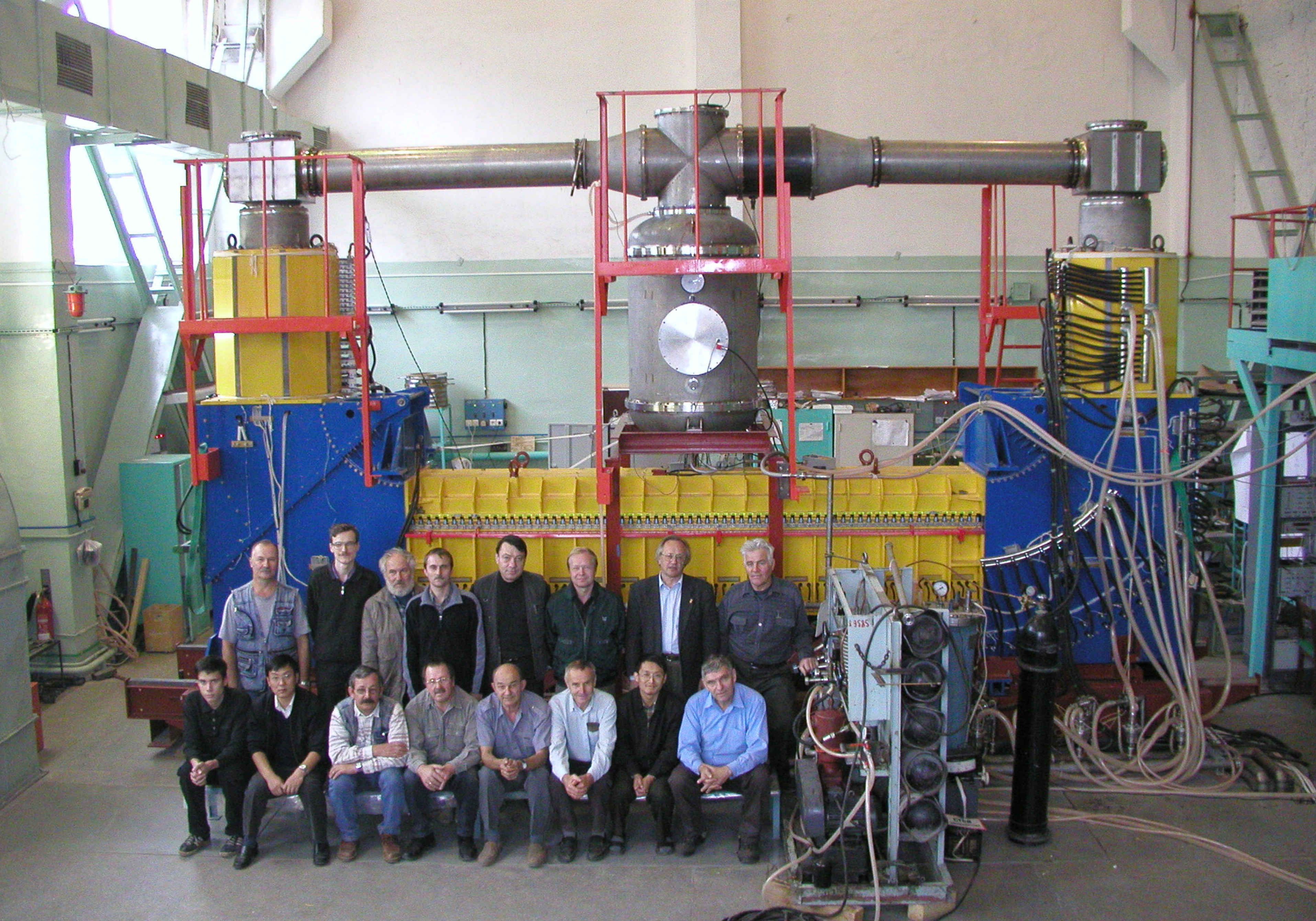
1 - electron gun; 2- main "gun solenoid"; 4 - electrostatic deflectors;

5 - toroidal solenoid; 6 - main solenoid; 7 - collector; 8 - collector solenoid; 11 - main HV rectifier; 12 - collector cooling system.



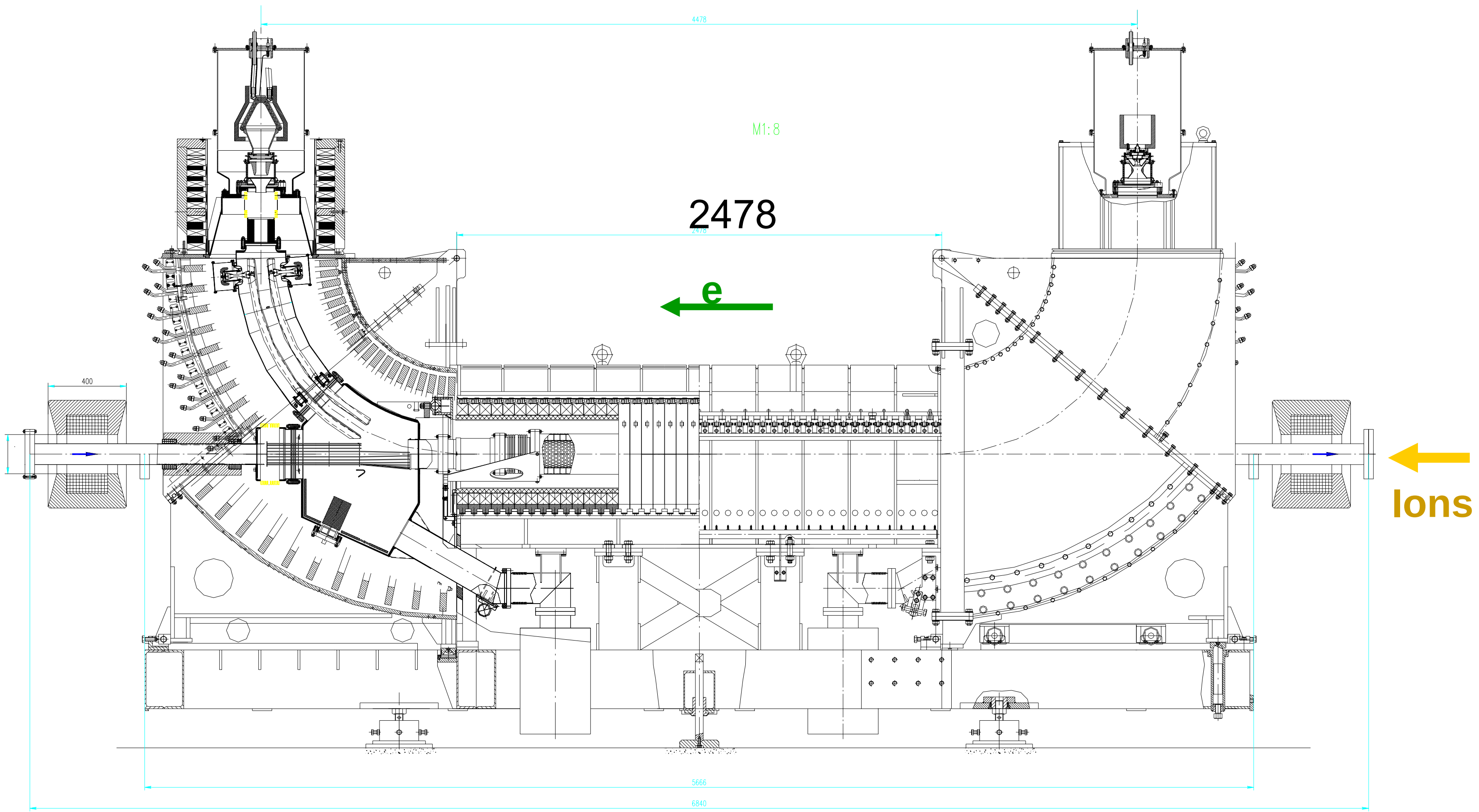
Установка электронного охлаждения на 300 кВ: 1 – высоковольтный фидер, 2 – магнитный концентратор коллектора, 3 – коллектор, 4 – ускорительная (замедляющая) трубка коллектора, 5 – катушки магнитного поля коллектора, 6 – поворотный участок с электростатическими поворотами, 7 – катушки тороидального магнитного поля, 8 – катушки магнитного поля секции охлаждения (прямолинейный участок магнитного поля), 9 – бак высоковольтного генератора, 10 – магнитопровод соленоида, 11 – магнитопровод тороидального участка магнитного поля, 12 – титановые сублимационные насосы, 13 – катушки магнитного поля электронной пушки, 14 – магнитопровод соленоида электронной пушки, 15 – ускорительная трубка электронной пушки, 16 – электронная пушка, 17 – концентратор магнитного поля электронной пушки, 18 – местоположение высоковольтного терминала, содержащего цифровую и силовую электронику управления пушкой и коллектором, 19 – ионный насос, 20 – дипольные корректоры ионного пучка.

Last picture at Novosibirsk



EC-300 @ Lanzhou now – assembly process.

LEIR:
space for future ECooler.



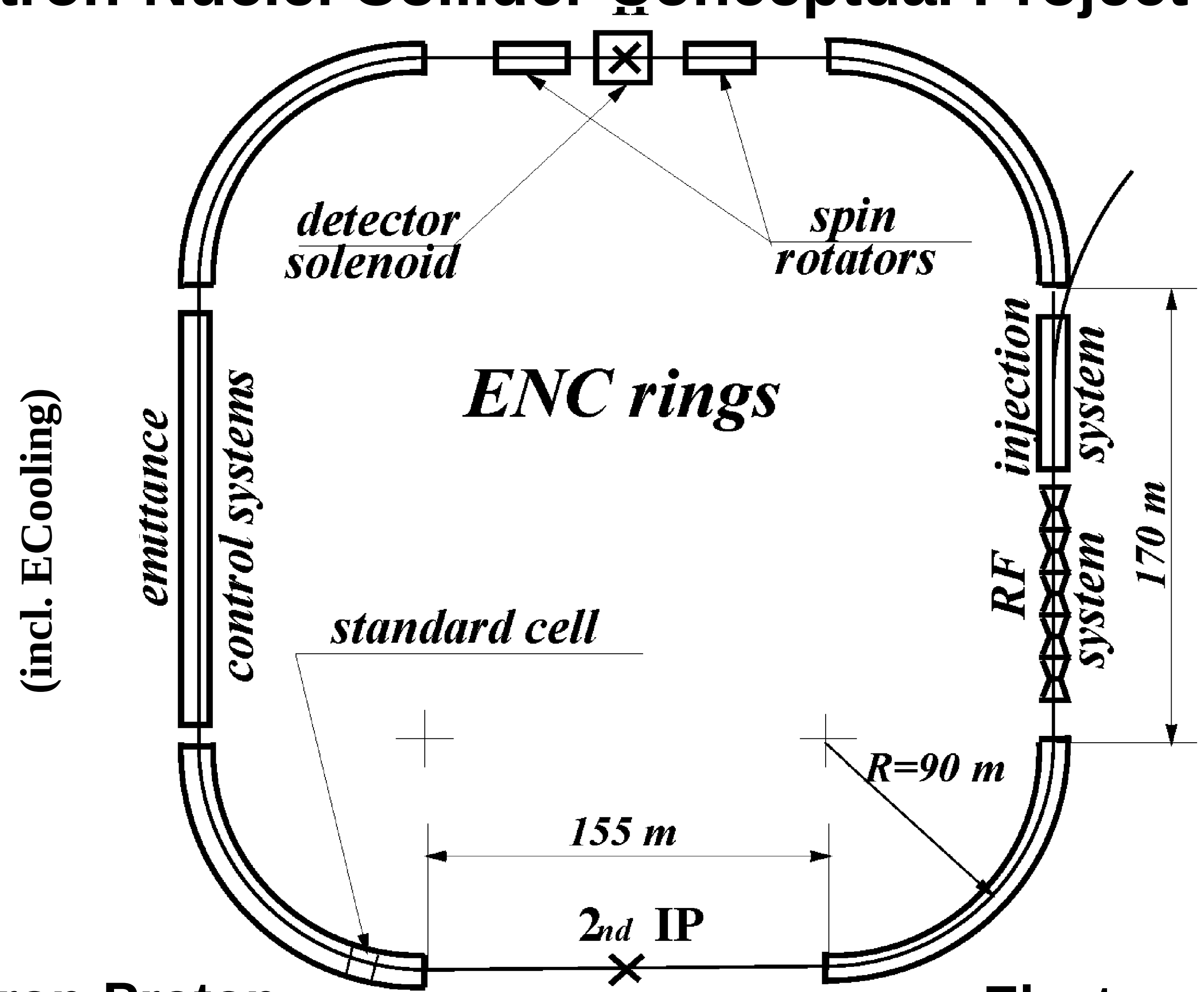
Future LEIR – in process @ Novosibirsk

ECoolers –

- for higher energies and Colliders.

Electron-Nuclei Collider Conceptual Project (for GSI)

!?



Electron-Proton

Electron-Uranium

$$\sqrt{s_{\max e-nucleon}} = 30 \;\; GeV \qquad \mathrm{L}_{\mathrm{e-nucleon}} = 1\cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Table 2.4: Parameter set for an electron-U^{92}_{238} collider calculated assuming that $(\Delta\nu_L)_{th} = \xi_i$; RF-voltage in the ion ring 7 kV, and $\xi_i = 0.05$.

ENC (GSI)

Electron-Uranium

$$\sqrt{s_{max}} = 30\ \text{GeV}$$

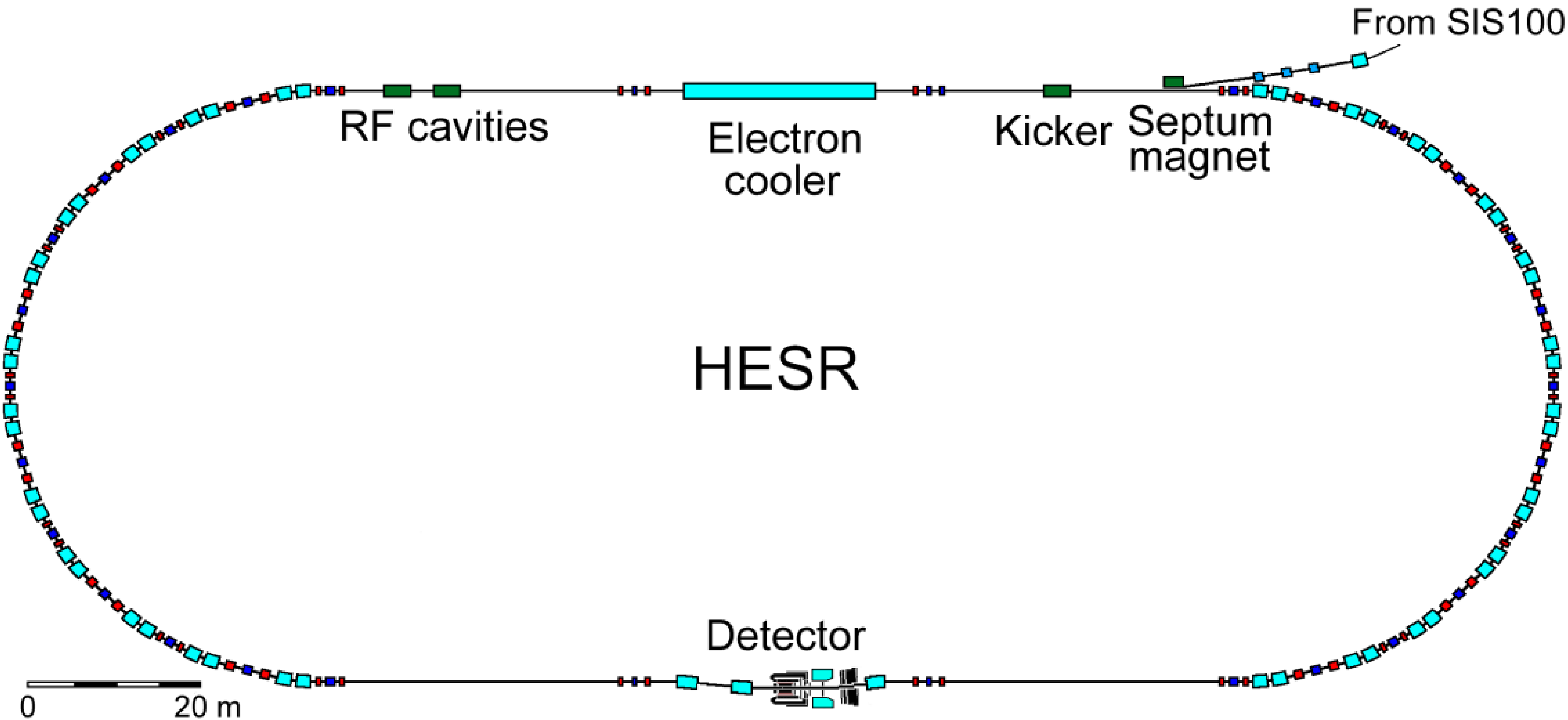
- per e-nucleon

$$L_{e-nucleon} = 1\cdot 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$$

$\sqrt{s}$ [GeV]	10	20	30
Specific Luminosity ($\times 10^{-21}$) [1/cm²s]	7.6	21.4	39.4
$N_i \times 10^{-7}$	7.5	5.32	4.35
Ion Beam Current [mA]	66.5	47	38.4
Ion Energy [Gev/u]	13.57	19.19	23.51
Emittans [nm]	8.6	2.1	1
Momentum Spread$\times 10^5$	2.1	1.5	1.3
Z/n [Ohm]	11.5	23	33
$\Delta f_{load}/f_0 \times 10^3$	3	2	2
IBS Growth Time [ms]	6	2	0.7
Cooling Time [ms]	4	1	0.5
Betatron Cooling Time [ms]	120	30	13
Longitudinal Cooling Time [ms]	5	4	0.6
Density of Cooling Beam ($\times 10^{-7}$) [1/cm³]	5.6	15.8	29.
Current of Cooling Beam [mA]	28.8	20.4	16.6
Rms Beam Radius [cm]	0.13	0.065	0.044
Current Density of Cooling Beam [A/cm²]	0.27	0.76	1.4
Radiat. Recombination Lifetime [s]	786	556	434
$N_e \times 10^{-10}$	13.2	4.7	2.5
Electron Beam Current [A]	1.3	0.45	0.24
Electron Energy [GeV]	1.8	5.2	9.6
Emittance [nm]	8.56	2.14	0.95
Synchr. Radiat. Energy Loss per Turn [MeV]	0.017	1.1	12.6
RF-Power [MW]	0.022	0.5	3.0
Z/n [Ohm]	0.16	6.	51
$\Delta f_{load}/f_0$	0.73	0.004	0.0002
Bremsstrahlung Lifetime [s]	1672	766	520

HESR objectives

- *Antiproton energy 0.8 – 14.5 GeV*
- *Number of stored antiprotons up to 10^{11}*
- *Luminosity of antiproton-proton collisions up to 2×10^{32} cm^{-2} sec^{-1}*
- *Target thickness 1×10^{15} to 1×10^{16} atoms/cm^2 (H_2 jet or pellets)*
- *Momentum spread of antiprotons ~ 10^{-5}*
- *Length of straight sections 105 m*



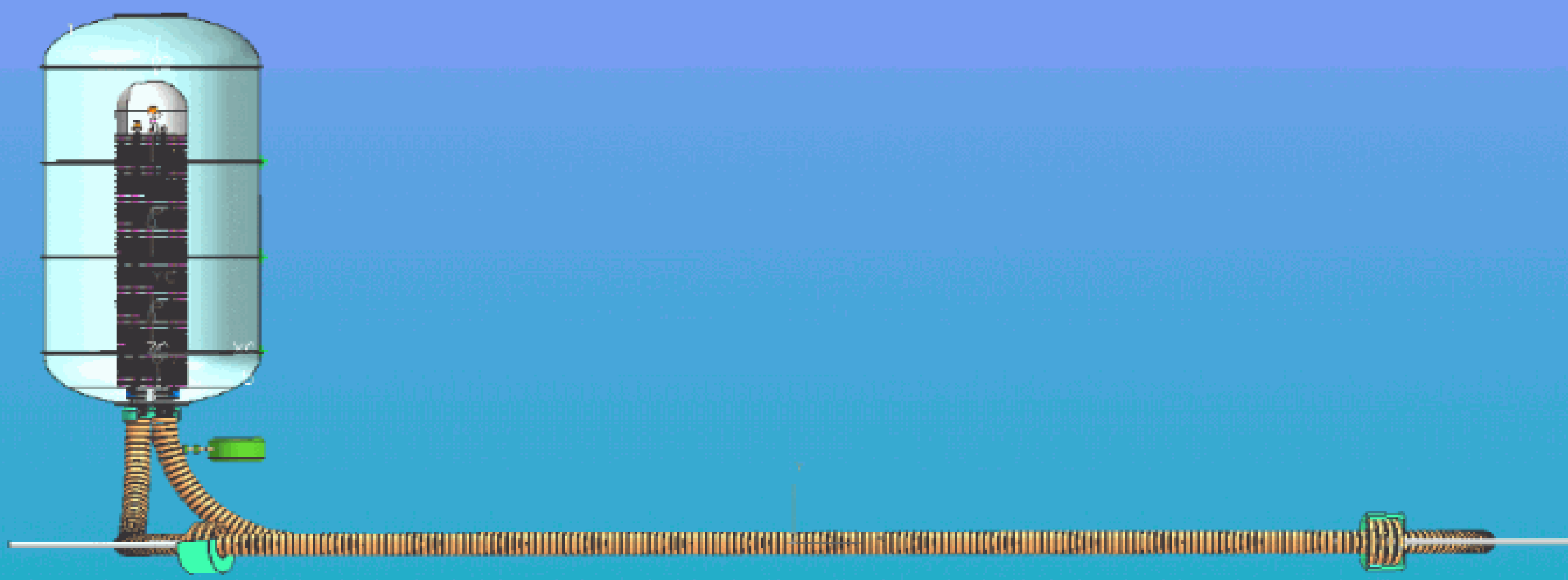
General view of the HESR

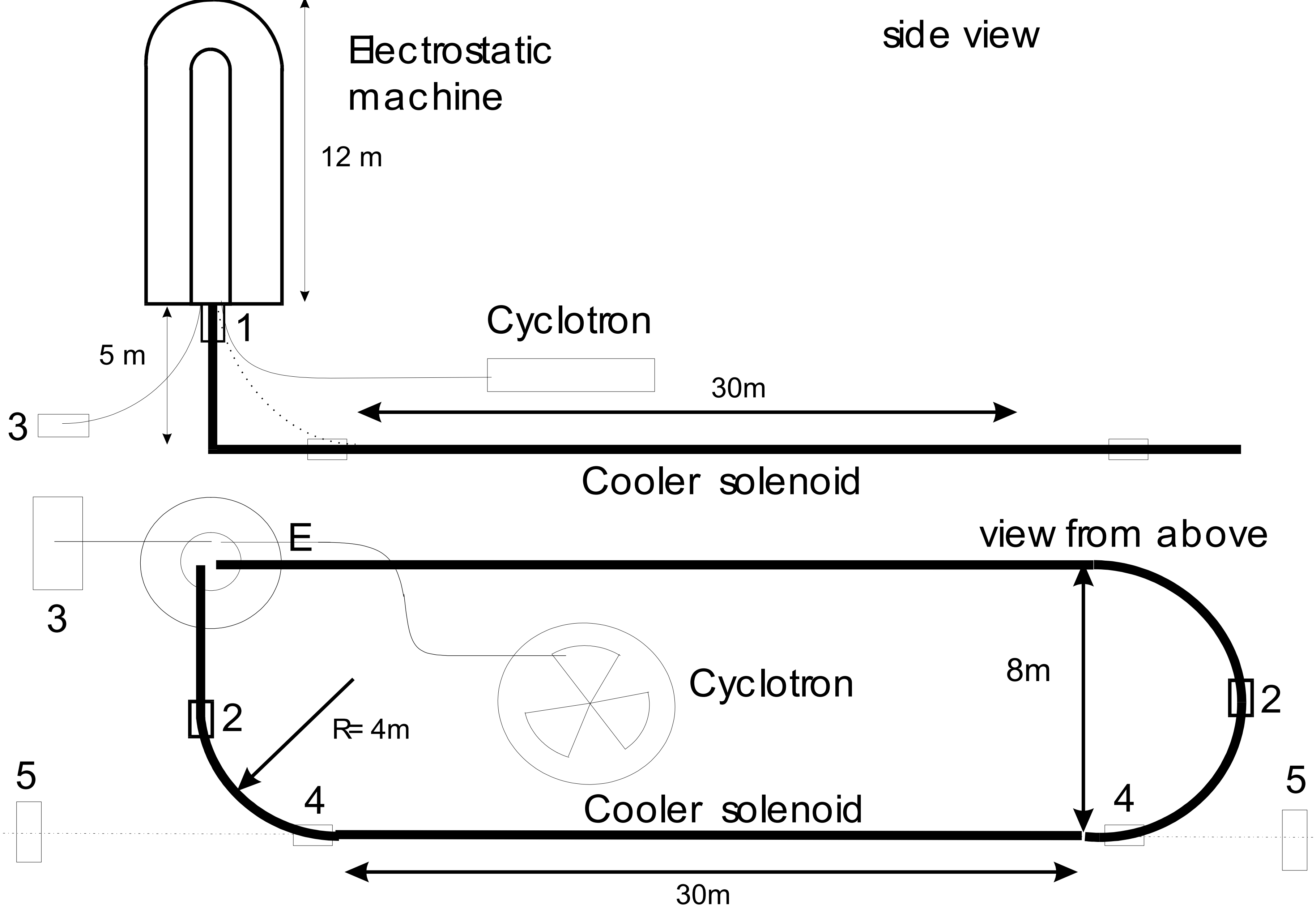
For HESR the optimal solution is

8 MeV × 1 A ***<u>electrostatic</u> cooler***

1. ***easy change e- energy(0.8 ↔ 8 MeV)***
2. ***DC electron beam***
3. ***low amplitude of HV ripple***

8 MeV e-cooler

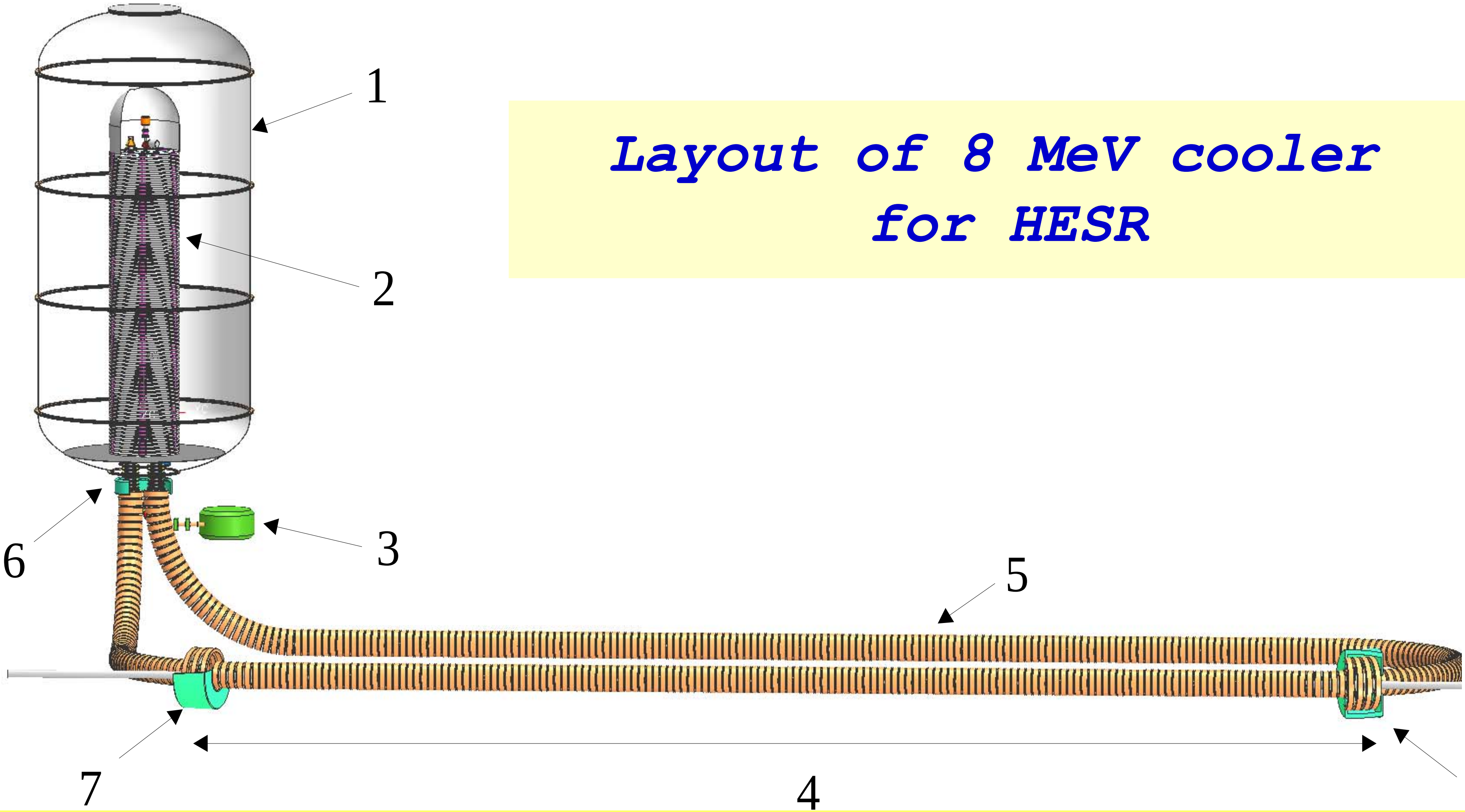




Very schematic view of the electron cooling device for HESR

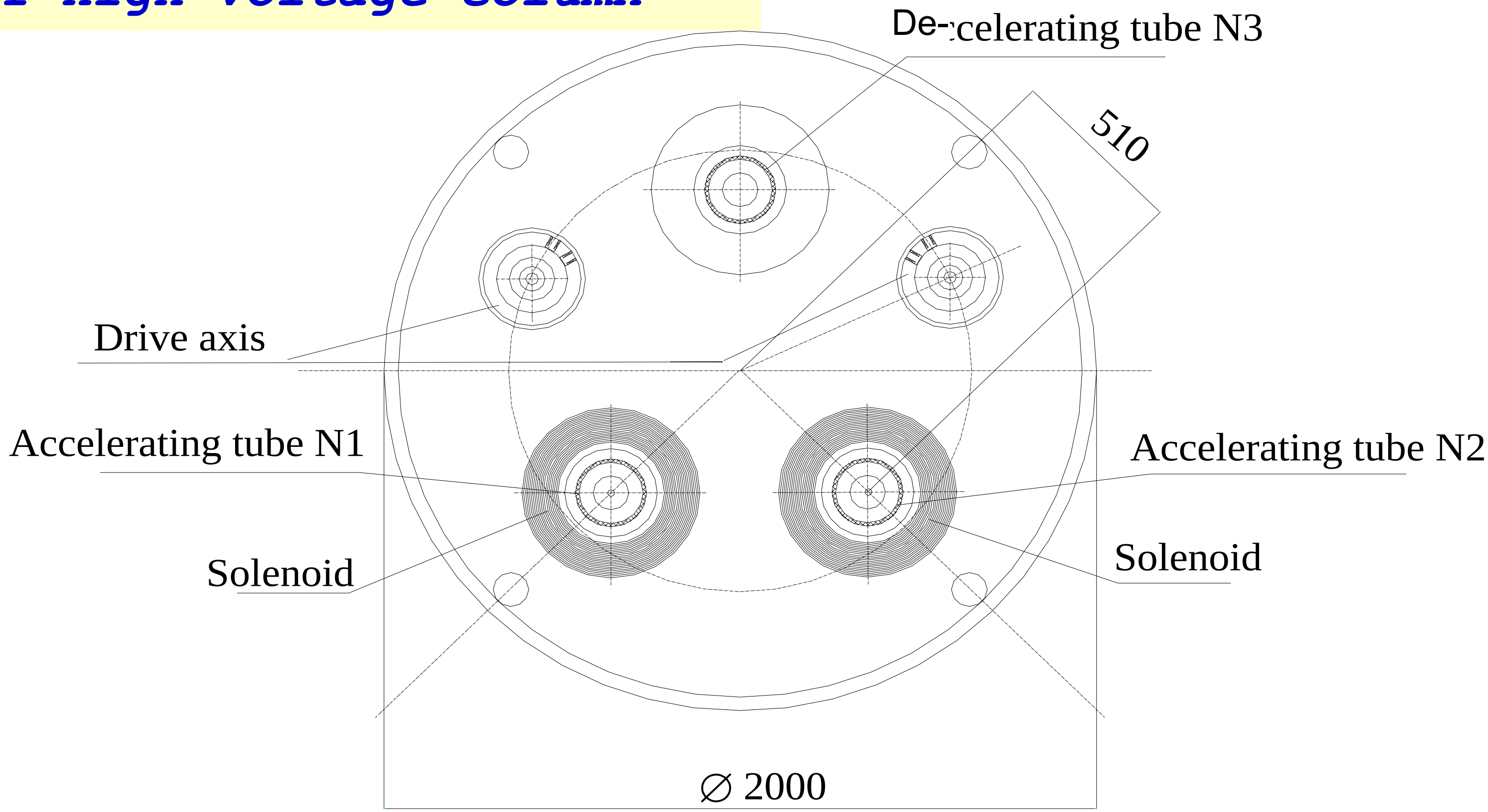
(H⁻cyclotron - for charging the e-generator up to 8 MeV!)

Layout of 8 MeV cooler for HESR



1 – high voltage tank; 2 – electrostatic column;
3 – cyclotron for charging of electrostatic column head;
4 – cooling section (30 m length); 5 – return trace,
6 – magnetic flux iron yoke,
7 – edges of cooling section.

Transverse cross-section of high voltage column



1. Electrostatic DC accelerator with 3 accelerating tubes for:
   - acceleration of e- beam
   - deceleration of return e- beam
   - charge of HV terminal by H- ion beam from small cyclotron.
2. Solenoids along electron beams ar powered by motor-generators along high voltage column (common drive-shaft) (locally powered!).

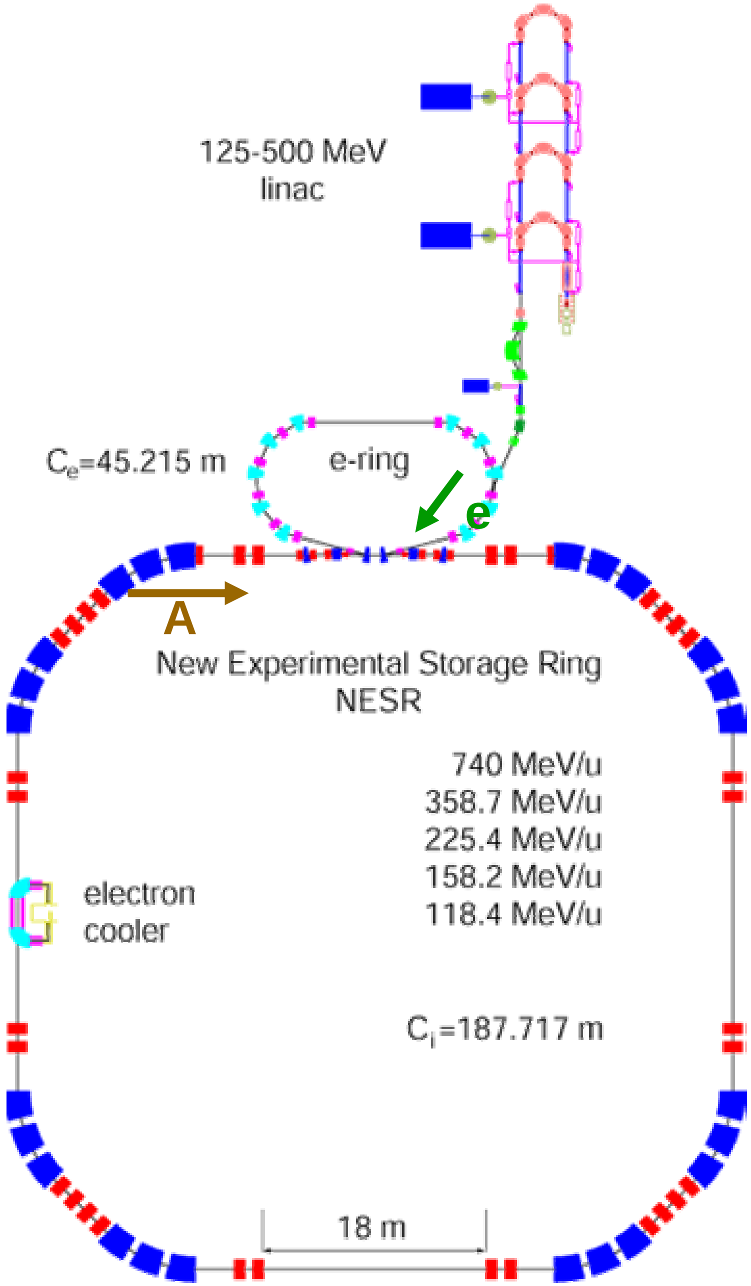
Preliminary engineering parameters of the cooler

Acceleration column	
Electron energy on the output	0.44 – 7.9 MeV
Length	8.0 m
Average electrostatic intensity along accelerated column	0.5 – 10 kV/cm
Magnetic field	500 G
Cathode diameter (beam diameter)	∅ 2 cm
Hight of high-voltage vessel	13.0 m
Diameter of high-voltage vessel with SF_6 gas	6.0 m

Bending section.	
Magnetic field	5 kG (E_e=1.6 – 7.9 MeV) 2 kG (E_e=0.44 – 1.6 MeV)
Bending radius	400 cm
Beam diameter	∅ 0.6 cm (5 kG) – 1.0cm (2 kG)

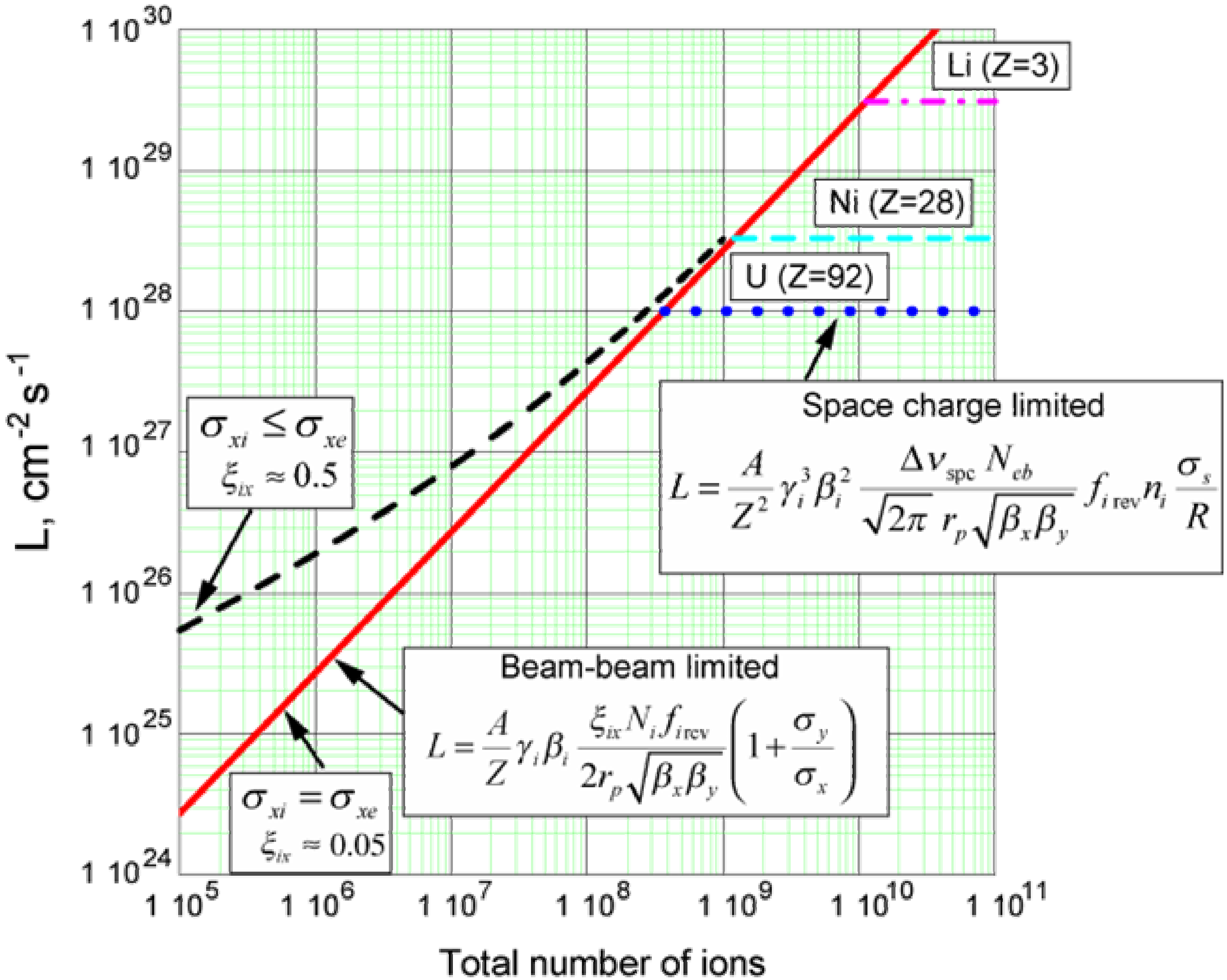
Cooling section.	
Magnetic field	5 kG (E_e=1.6 – 7.9 MeV) 2 kG (E_e=0.44 – 1.6 MeV

NESR – based colliders



General layout of e-A collider

Luminosity of e-fragment collider vs. total number of stored ions



General requirements for e-fragment collider based on NESR storage ring @ GSI

- **Revolutions of ion and electron beams are synchronized (quantized):** $\frac{F_e}{F_i} = 5, 6, 7, 8, 9$

- **Energies:** $E_i \le 740$ MeV/u, $E_e \le 500$ MeV

- **Momentum transfer range:** $20 \le q \le 400$ MeV/c

- **Typical fragment yields** $\approx 10^{-7} \div 10^{-5}$

  - $10^{12}\ {}^{248}U_{92} \rightarrow 10^5 \div 10^7$ fragments/pulse
  - Stacking provides: $10^7 \div 10^{10}$ isotopes

  (Depending on their lifetimes)

- **Intense electron cooling!!!**
  - **Provides stacking and suppress blow-up due to intrabeam scattering**
  - **Low momentum spread and emittance control**
  - **Significantly increase achievable beam-beam limit**

- **Electron beam energy spread**: $\Delta E_e \le 50 \div 100$ keV
- **Electron beam angular divergence:** $\Delta\theta_e \le 1$ mrad

- **Electron bunch intensity limitation:** $N_{be} \le 5 \cdot 10^{10}$
- **Bunch length:** $\sigma_s = 10$ cm

General parameters of the e-fragment collider for the case of A=238, Z=92 and β_i=0.8303

	Units	Electron ring	Ion ring
Circumference	m	45.215	187.717
Energy	GeV, GeV/u	0.500	0.740
Revolution frequency	MHz	6.63	1.326
Betatron tunes, ν_x, ν_y		3.8, 2.8	3.8, 3.8
Compaction factor, α		0.056	0.036
Bending radius	m	1.25	8.125
Number of bunches		8	40
Bunch to bunch spacing	m	5.65	4.7
Bunch population		$5 \cdot 10^{10}$	$0.92 \cdot 10^{7}$
Beam currents	mA	425	7.2
Energy losses/turn	keV	4.423	
Total radiated power	kW	1.88	
Damping time, τ	ms	34	20
Beam emittances, $\varepsilon_{x,y}$	µm·mrad	50	50
Beta functions at IP, $\beta_{x,y}$	cm	100, 15	100, 15
Beam size at IP, $\sigma_{x,y}$	µm	220, 87	220, 87
Beam divergence at IP, $\sigma_{x',y'}$	mrad	0.22, 0.58	0.22, 0.58
Momentum spread, $\sigma_{\Delta p/p}$		0.00036	0.0004
Bunch length, σ_s	cm	4	15
Beam-beam parameters, $\xi_{x,y}$		0.005, 0.002	0.046, 0.018
Laslett tune shift, $\Delta\nu$			0.1
Luminosity	$cm^{-2}s^{-1}$	$1 \cdot 10^{28}$	

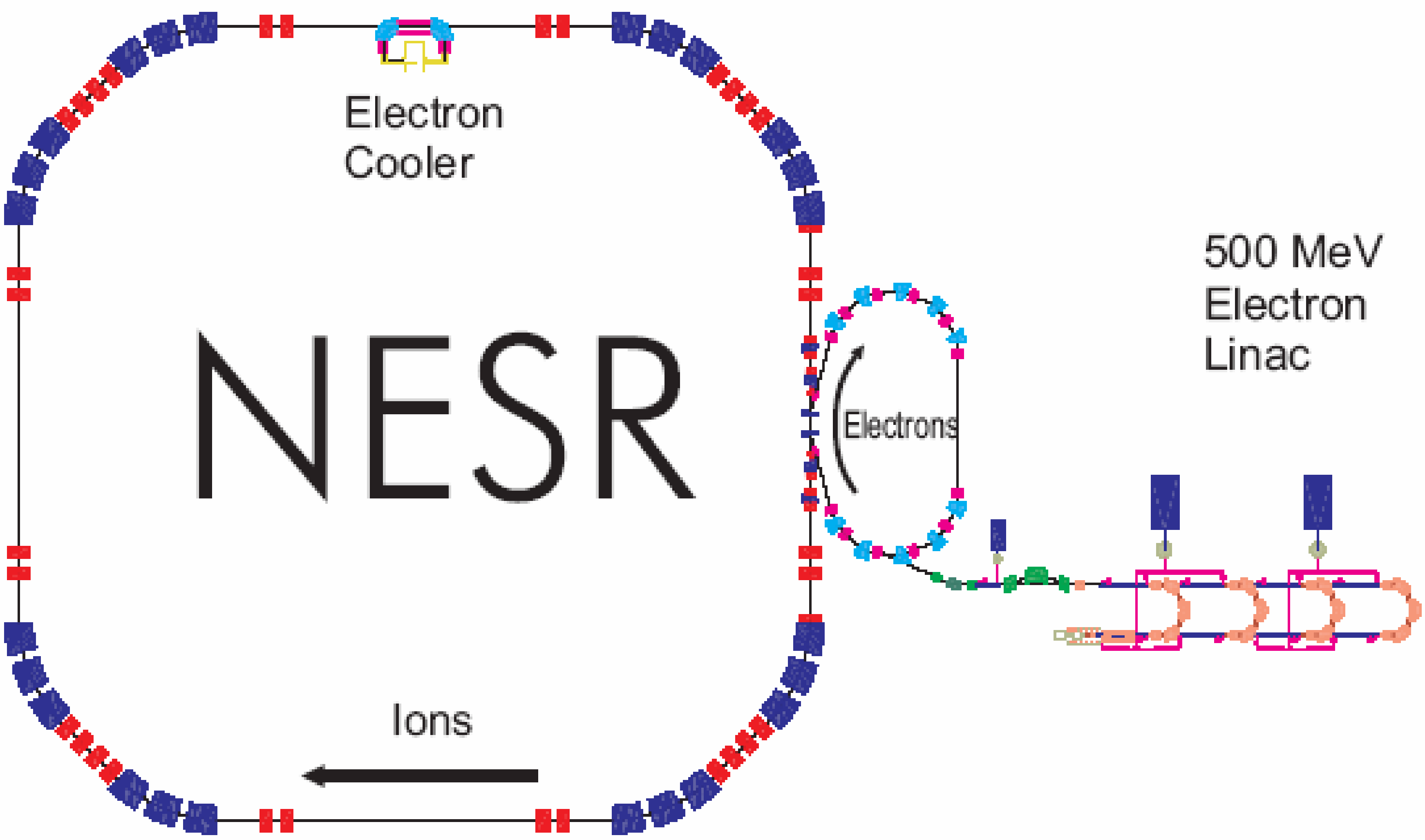
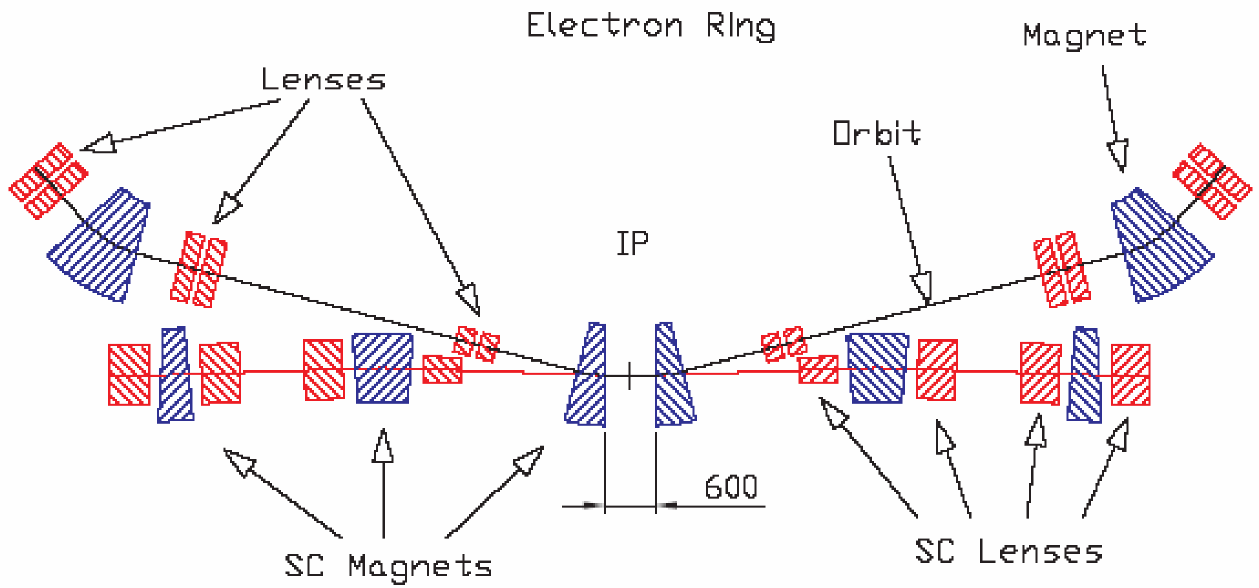
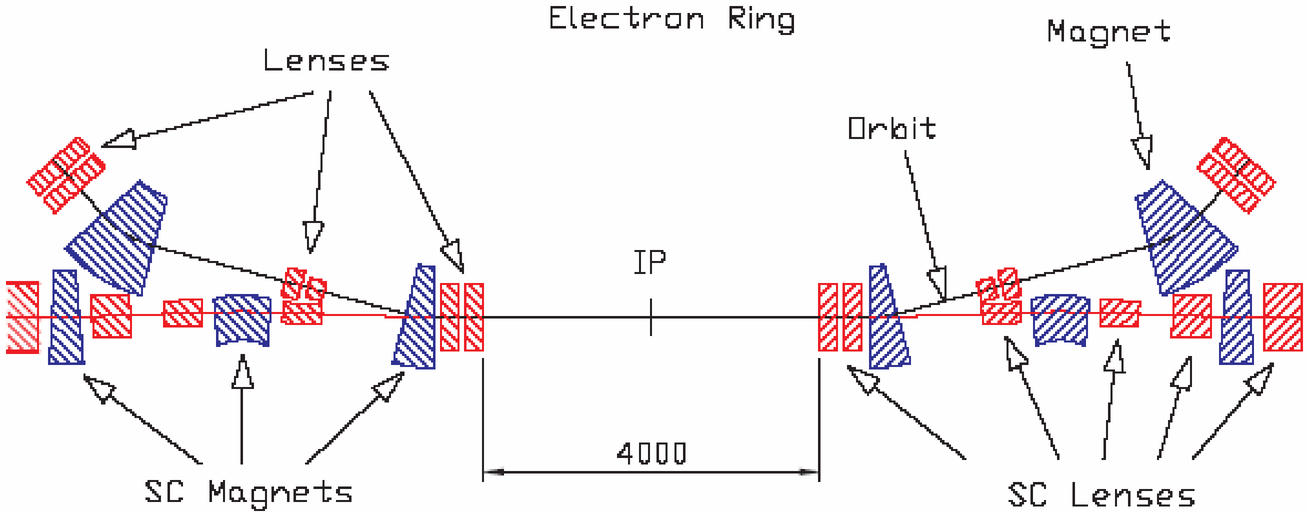
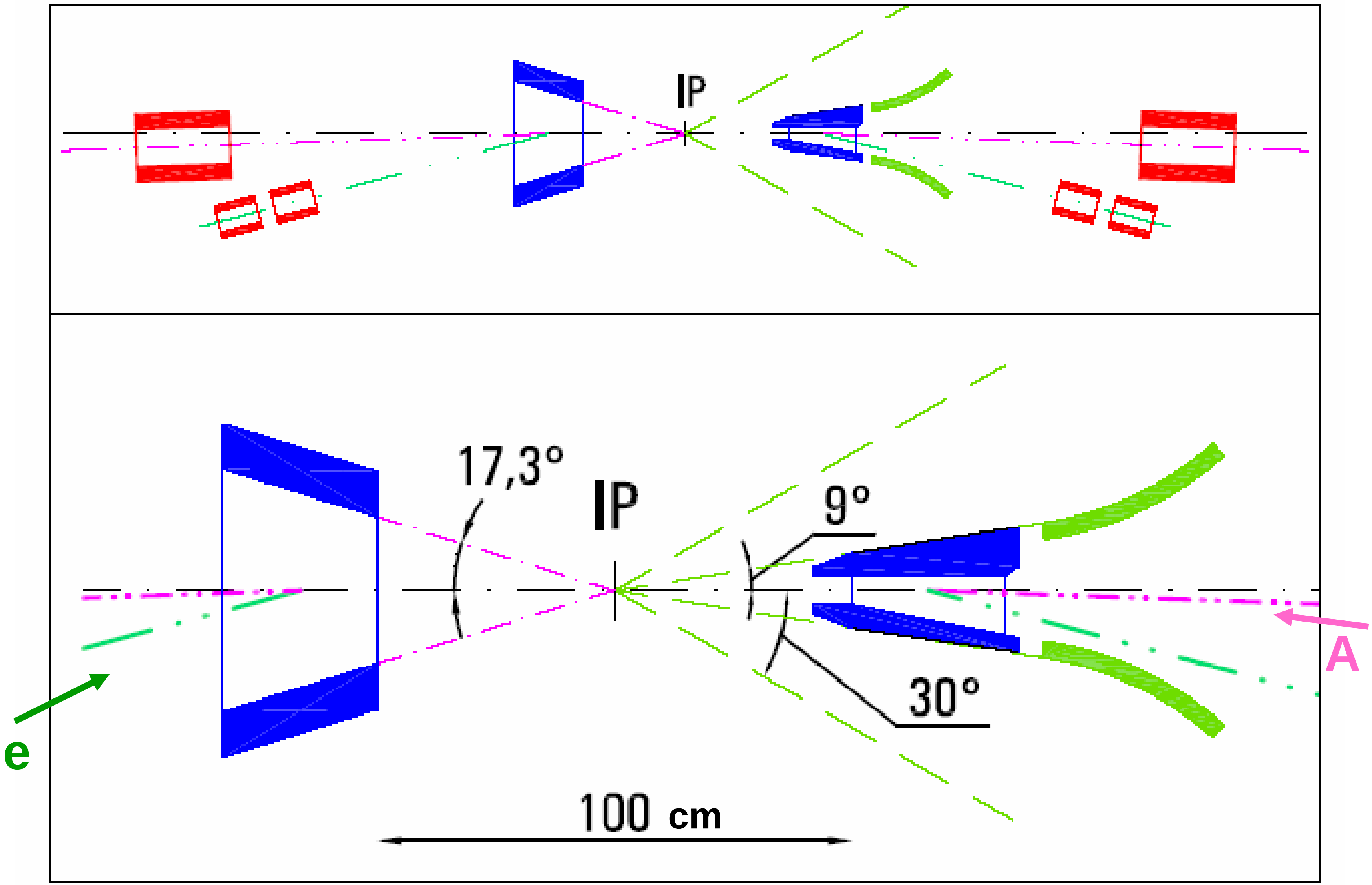


Figure 1: General layout of the e-A collider





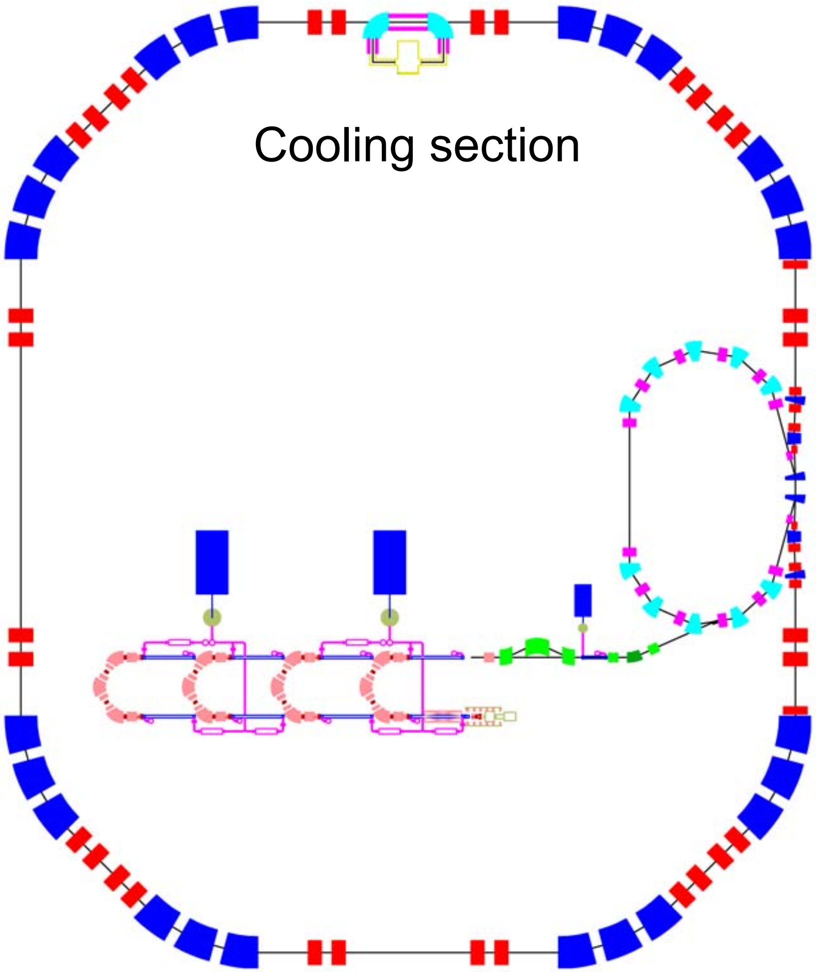
Closer look on the interaction region layout.
Different versions with different magnet free space near IP.



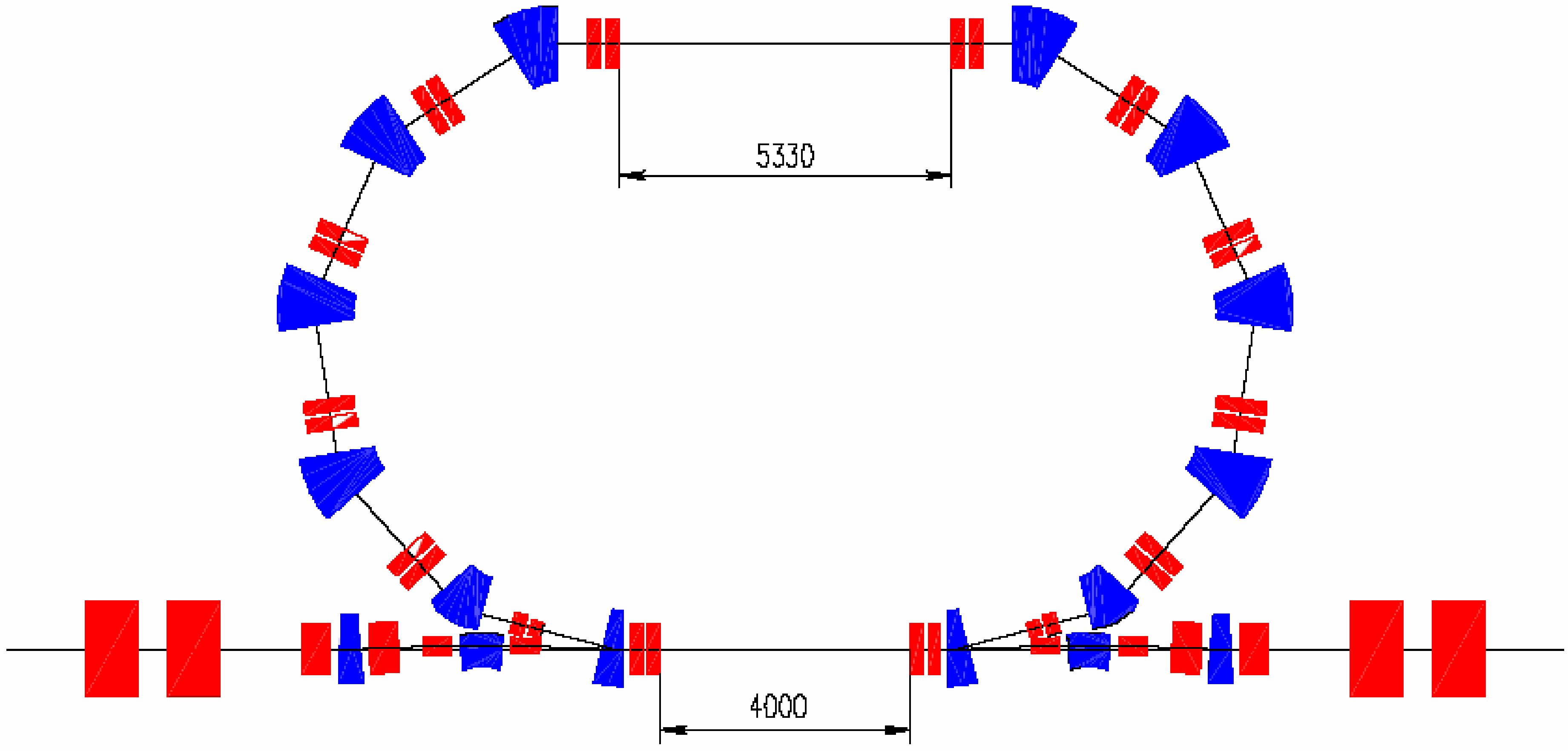
Layout of the interaction region of the e-A collider.

Electron cooling and eA Collider for NESR

(another layout)

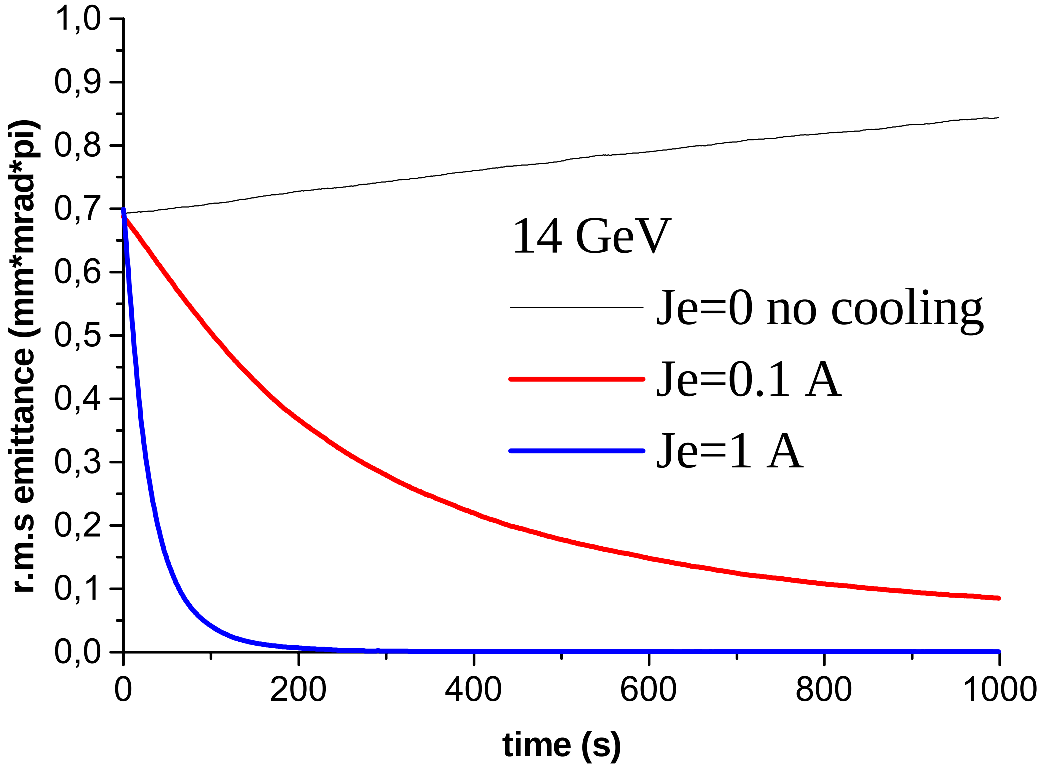


Accelerating voltage	2—450	kV
Maximum electron current	2	A
Electron beam diameter	25	mm
Magnetic field strength	0.2	T
Transverse electron temperature	0.2	eV
Length of cooling section	4	m
Field parallelity in cooling section, B_{trans}/B_{long}	5×10^{-4}	



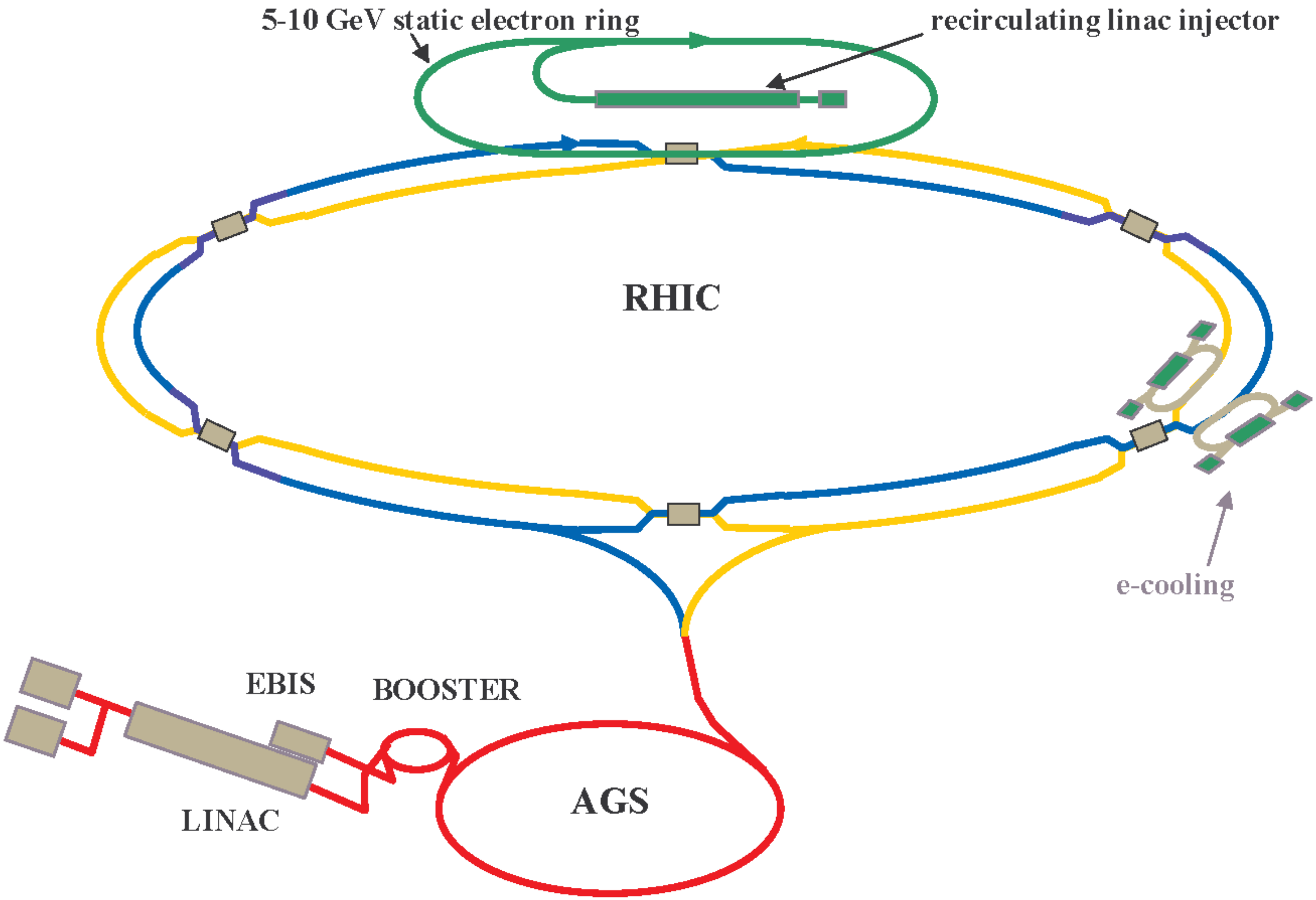
Yet another layout of the electron ring.
Version with ±2.0 m of a magnet free space near the IP.
(maybe, <u>for pbar-A collisions?</u>)

Cooling for HESR



R.M.S. emittance vs. time with and without electron cooling

General view of the eRHIC Collider



GOLD-GOLD @ RHIC

Electron Cooling for Luminosity Enhancement

Initial parameters for the electron cooling system for RHIC

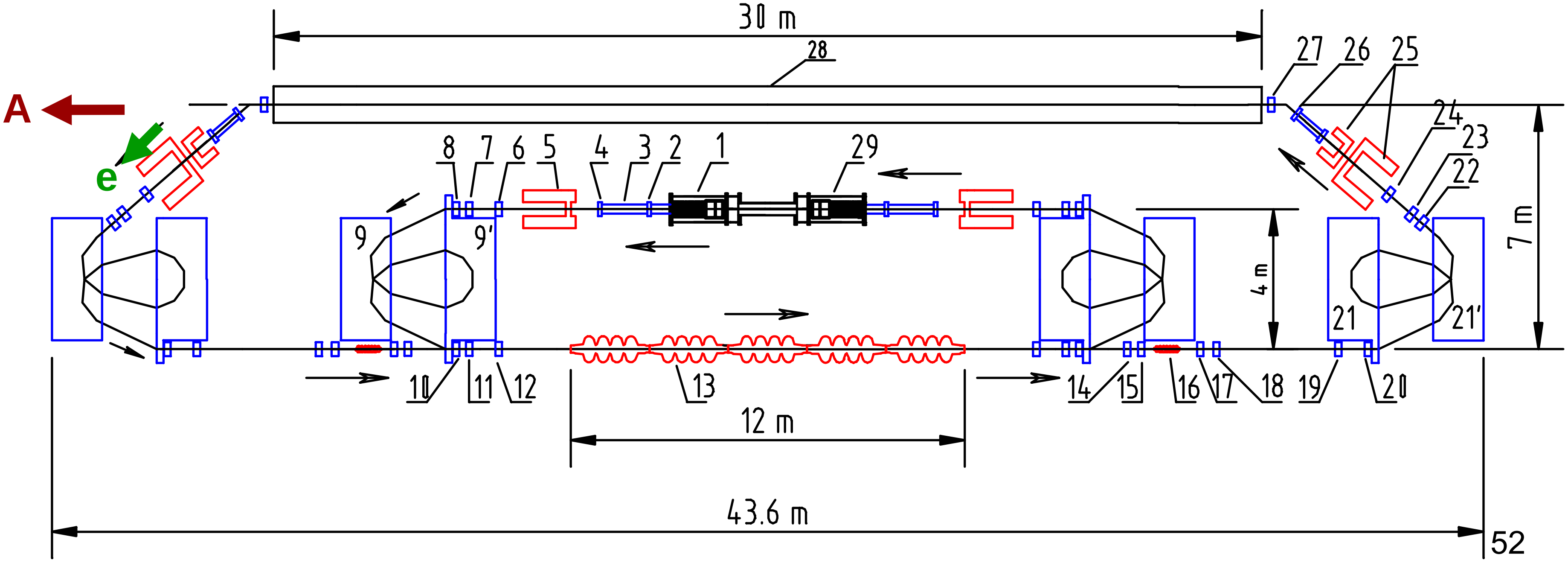
Parameter	**Symbol**	**Value**	**Units**
Electron beam energy	E_e	50	MeV
Peak electron beam current	J_e	1	A
Length of electron bunch	L_e	50	cm
Fraction cooler at circumference	η_e	0.0078	
Number of electron at bunch	N_e	10^{10}	
DC electron current	$Je_{DC}=e*N_e*f_b$	7.4	mA
Beta function at cooling section	β_x	60	m
Ion beam radius	$a_e=\sqrt{(\varepsilon_{nt}*\beta_x/\gamma\beta)}$	0.08	cm
Ion beam divergence at cooling sect.	$\theta=\sqrt{(\varepsilon_{nt}/(\beta_x\beta_\gamma))}$	$1.3\cdot10^{-5}$	rad
Ions transverse velocity at the ion beam's reference system	$V_i=\gamma\beta_c\theta$	$3.8\cdot10^{7}$	cm/s
Electron beam density at the ion beam's reference system	n_e	10^{8}	cm^{-3}

Plus: RHIC based Electron - Nuclei Collider.

Schematic layout of the cooling system

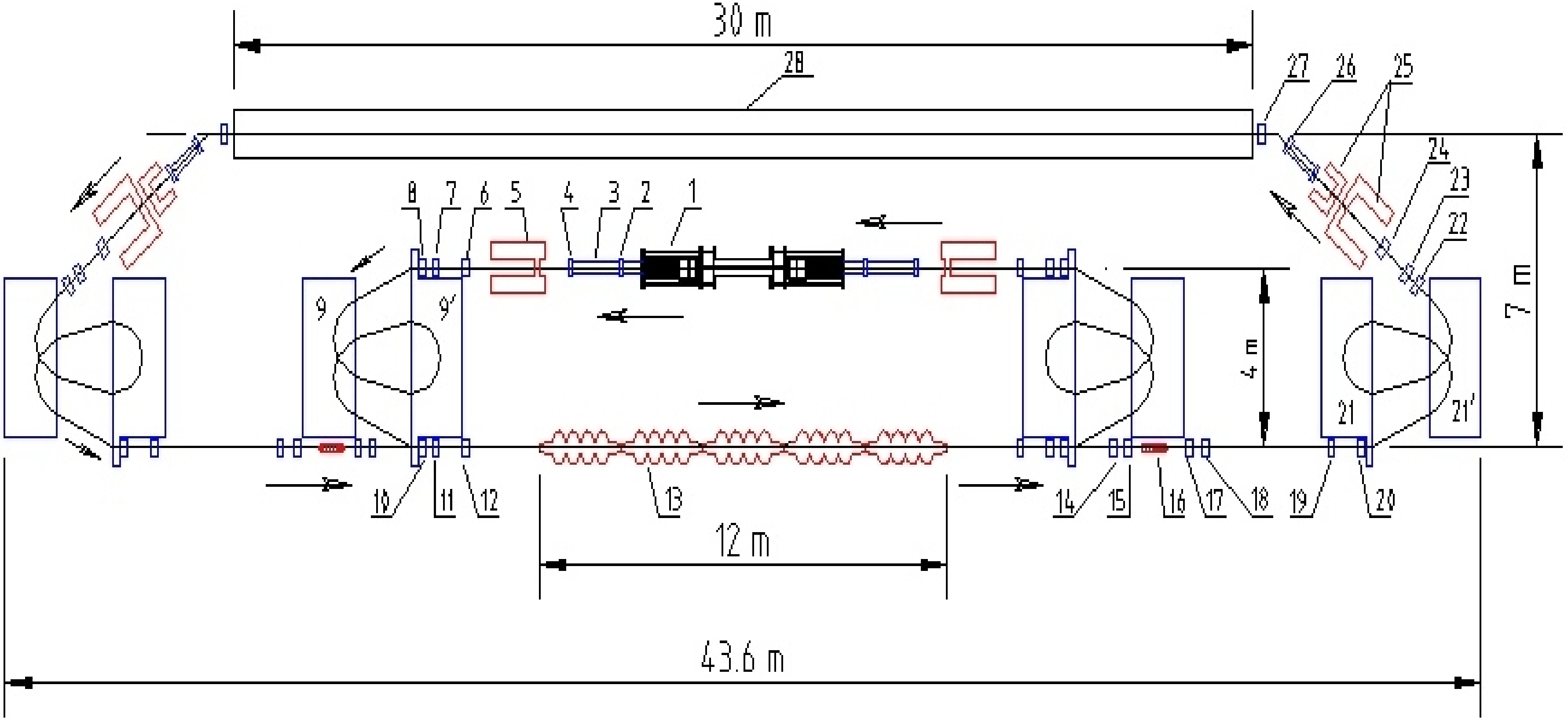
(next to a RHIC interaction point)

The hope: <u>10 times</u> higher average luminosity for A-A, for eA and for lngitudinally polarized ep collisions.



Project of electron cooling for RHIC

50 MeV ×1 A



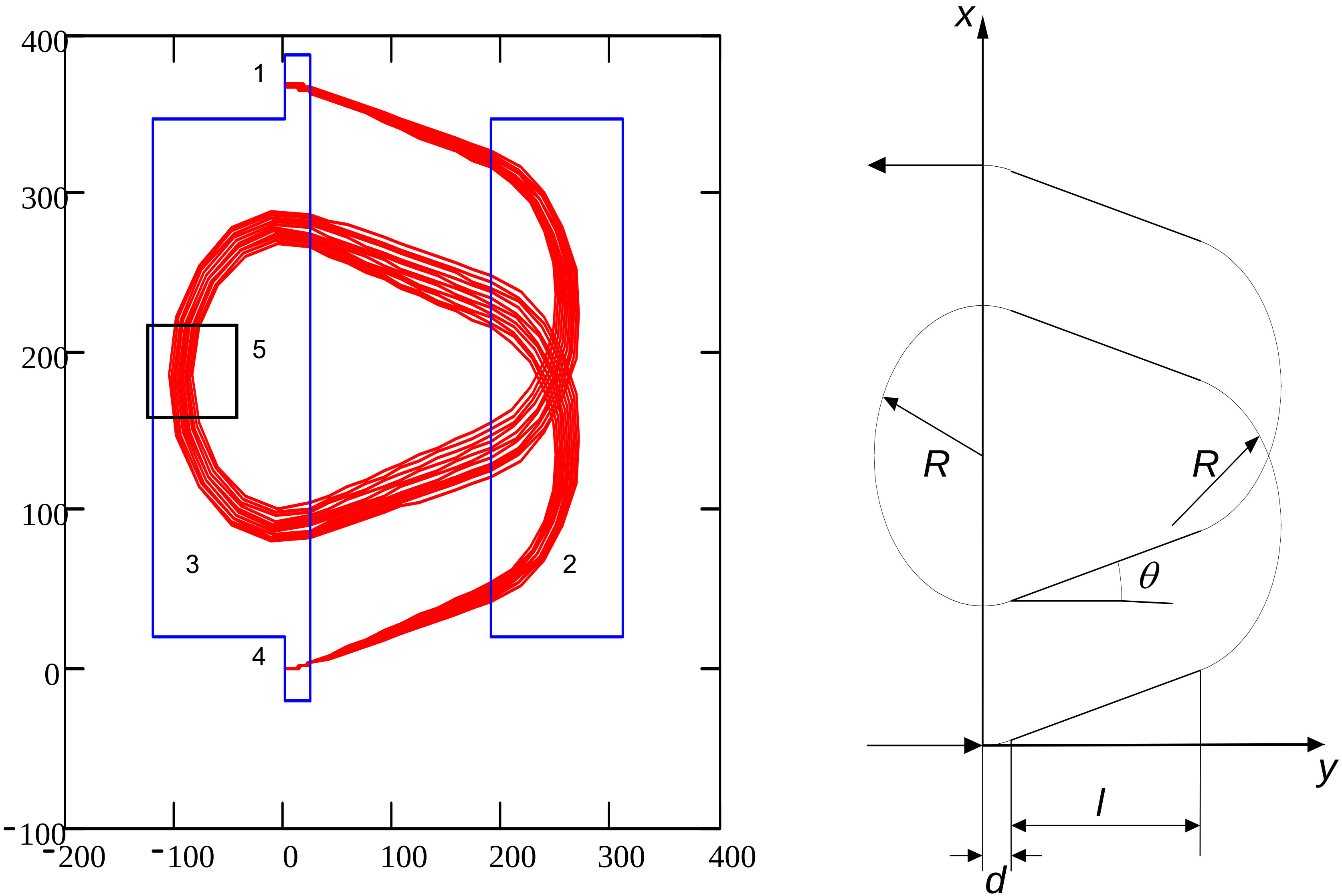
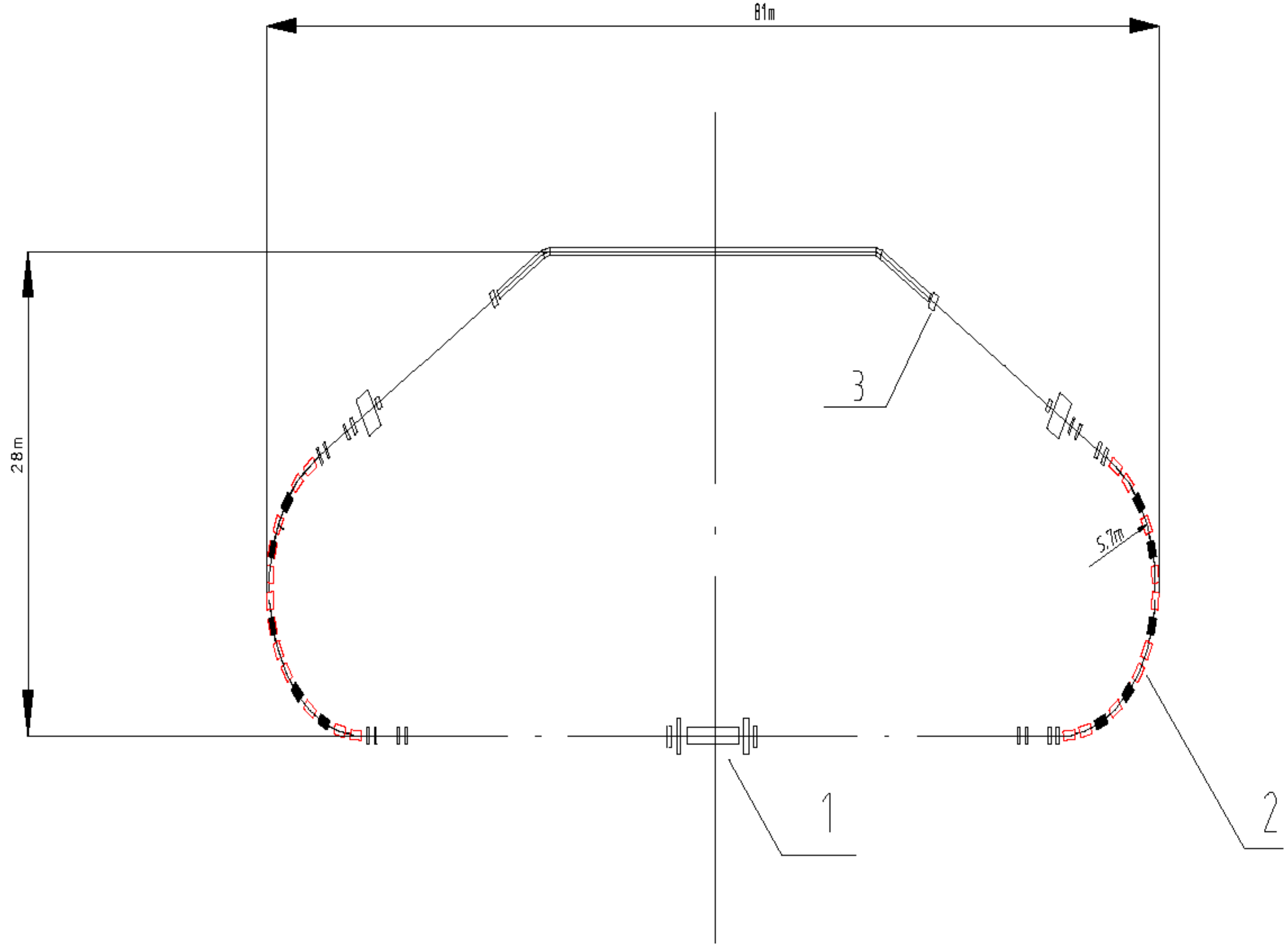


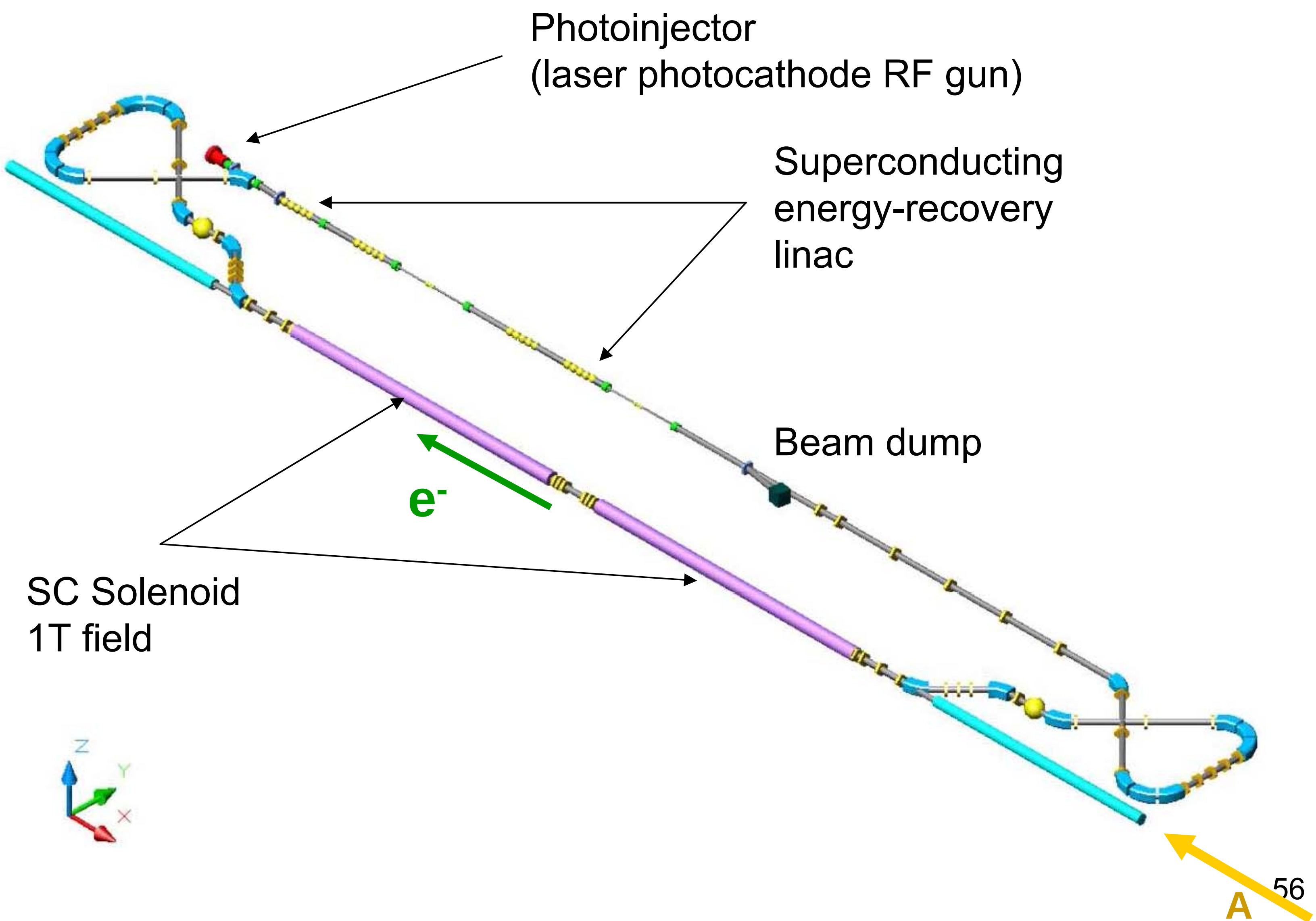
Figure 3.4.1. Achromatic bend. 1 and 4 – parallel edges magnets, 2 and 3 – magnetic mirrors, 5 – sextupole corrector.

Electron cooling for e-p collider



1 — main linac, 2 — Chicane magnet system for bunching/debunching,
3 — adaptor for to come in/out solenoid.

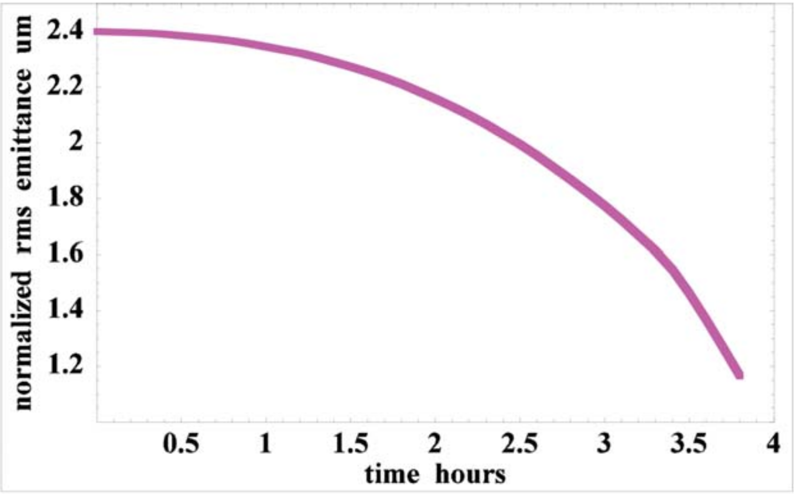
Schematic Layout of Electron Cooling for RHIC



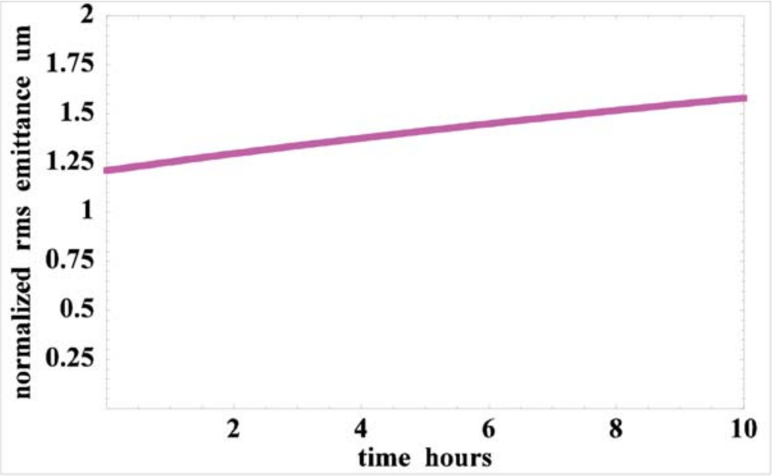
Electron cooling in eRHIC

The needs for electron cooling:

1. E-cooling for gold beam at storage phase → to control MIBS and reduce emittance.
2. E-cooling for protons at injection - to reduce transverse beam emittance.
3. Cooling the longitudinal emittance → bunch shortening to match with a low β* in the IP.

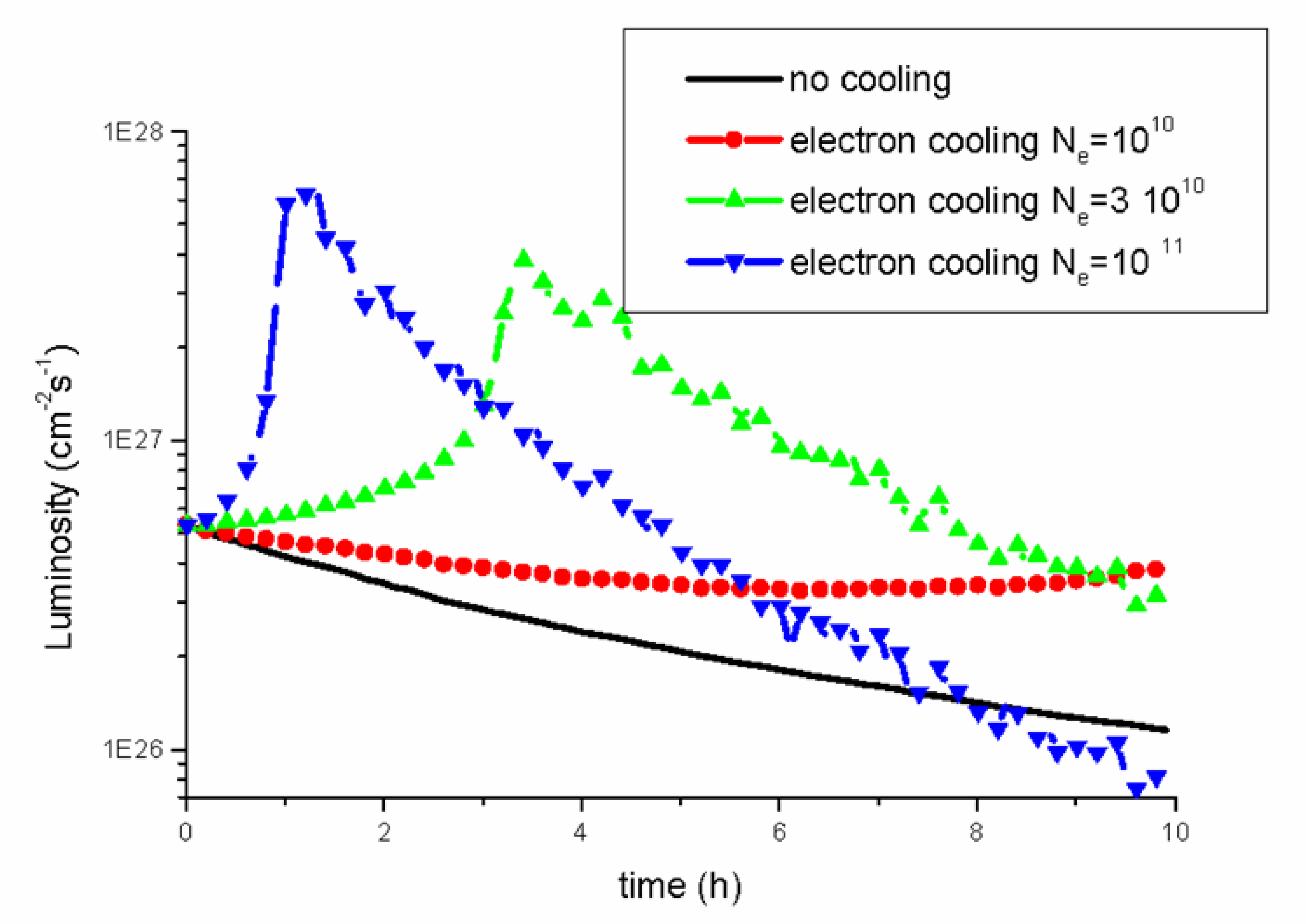


Cooling of proton bunch ($N_p=2\times10^{11}$, 27 GeV)

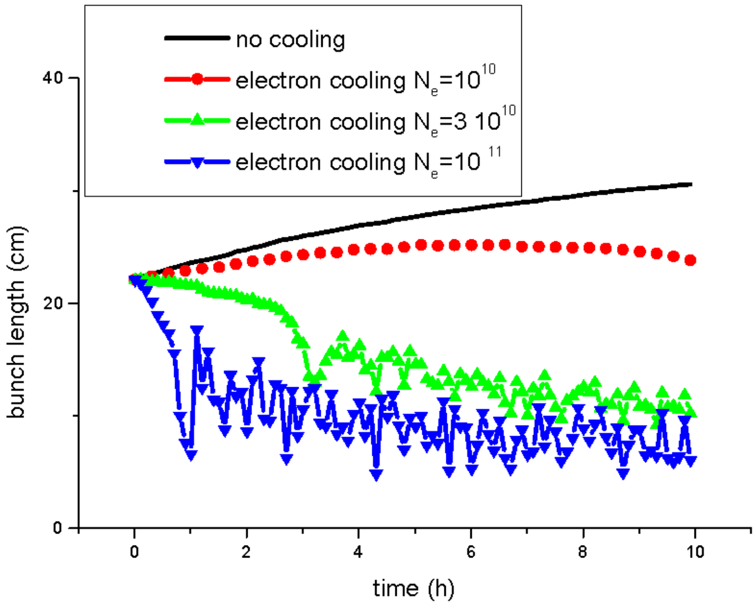


Emittance growth of the cold proton bunch stored at 250 GeV (no cooling)

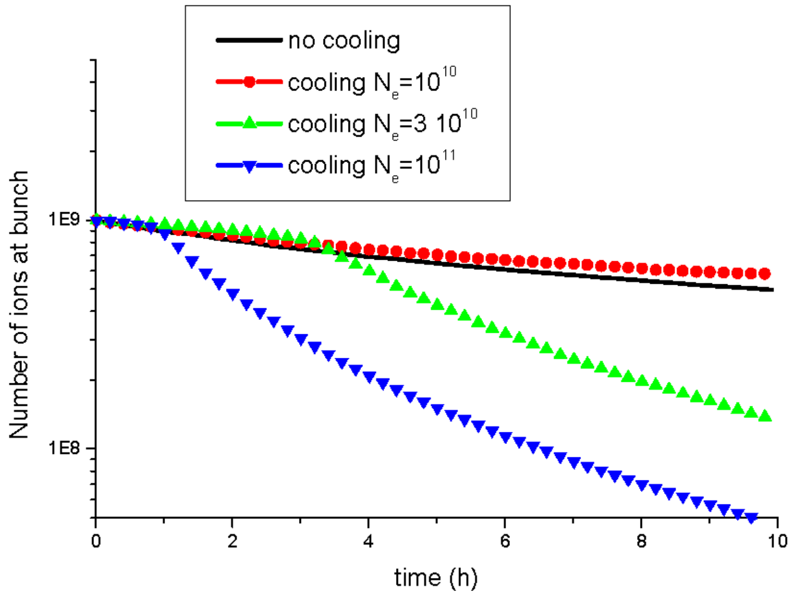
Luminosity of gold-gold collisions



Cooling at RHIC



The longitudinal bunch length
vs. time for various cooling currents.



The number of ions in a single bunch
vs. time for various cooling currents.

Schematic layout of the cooling system next to a RHIC interaction point

The electron cooling equipment comprises the following key elements:

1 – A 2 MeV injector with a magnetized cathode (the magnetic field on the cathode of the injector is ~100 G).

3 – A solenoid extension of the longitudinal magnetic field of the injector (100 G).

2,4 –Skew quadrupoles for the transformation of the magnetized beam into a flat beam

6 – Energy modulating cavity for reducing the electron bunch length from 4 ns to 0.06 ns. It consists of two 70 MHz RF-cavity (the gap voltage is 350 kV) and one 210 MHz (36 kV) RF-cavity.

5,7,8 – Electron optical elements of the bunching system.

9,9' – Magnetic compressor (an a-magnet, with a bending radius of 1m).

10,11,12,13 – Electron optical elements of the bunching system.

14 – RF linac structure (350 MHz LEP structure).

15 – A bending magnet for a compensation of the action of the last high-energy (50 MeV) bending magnet (9'').

18 –Third harmonic of the RF linac (1.05 GHz), for compensation of the non-linearity of fundamental accelerating field.

16,17,19,20,22,23 – Electron optical elements of the debunching system.

21,21' –Magnetic de-compressor (an a-magnet, with a bending radius of 1m).

24 –RF-cavity for eliminating the linear energy chirp. It consists of 80 MHz RF cavity (the gap voltage is 4.6 MV) and 240 MHz (0.24 kV). This cavity should be superconducting.

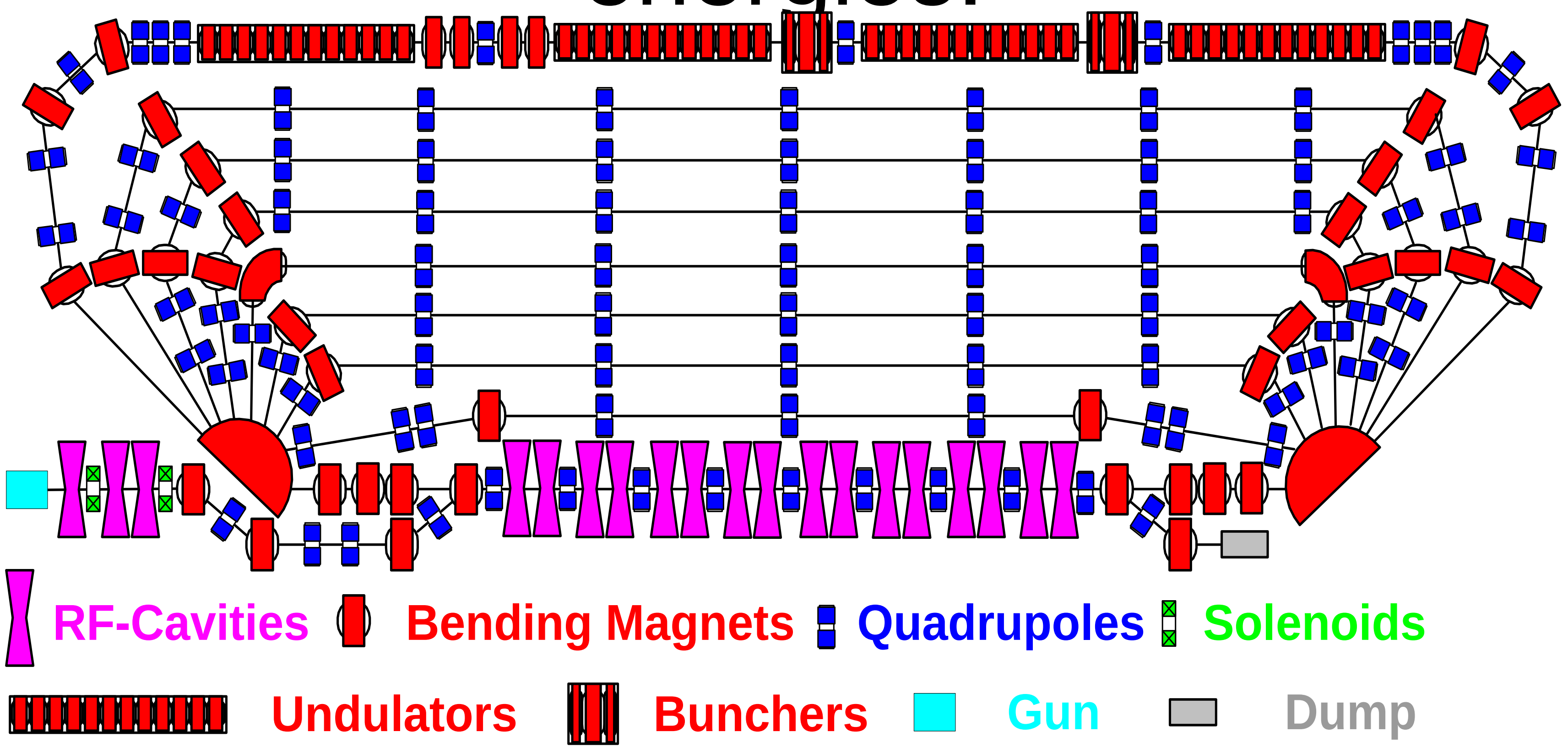
25 – Transfer optics from a flat to a round beam electron beam, for injection into the main solenoid.

26 –Bending magnet.

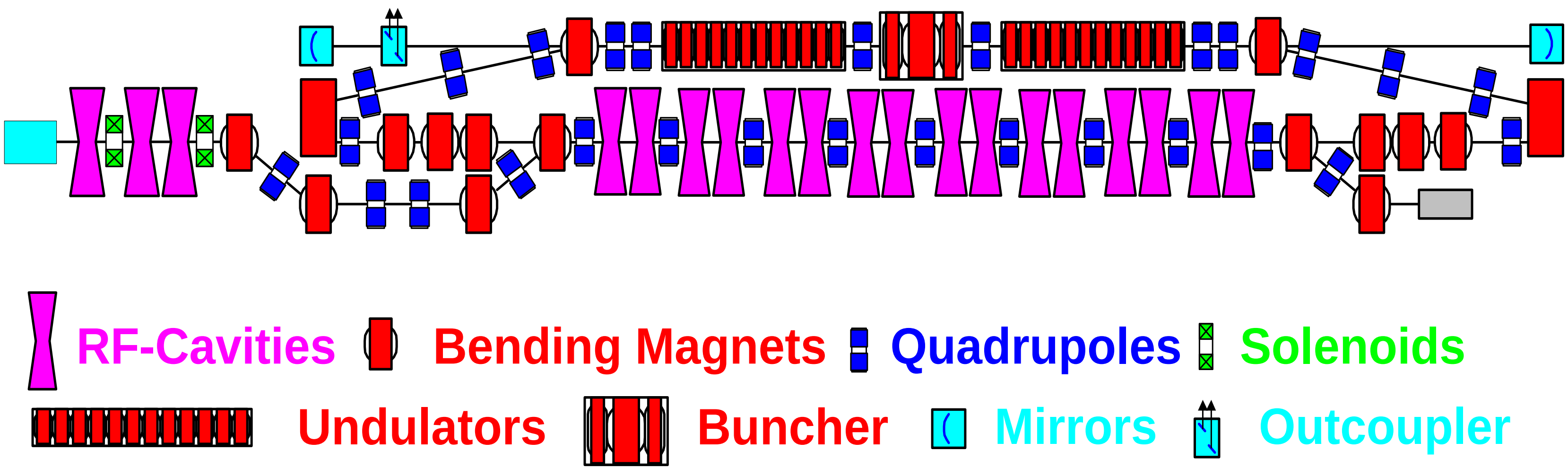
27 –Main solenoid (104 G).

28 –Beam-dump or system of beam recuperation.

Schematic Drawing of the FEL Driven by an Accelerator-Recuperator – good as prototype for ECooler at high energies!



Schematic Drawing of the Submillimeter FEL and AR (the first step – single turn)



14 MeV accelerator-recuperator – in operation.

ENC (GSI)

Electron-Proton

$$\sqrt{s_{max}} = 30\ \text{GeV}$$

$$L_{ep\,max} = 1 \cdot 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$$

Table 2.2: Parameter set for an electron-proton collider, calculated assuming that $(\Delta\nu_L)_{th} = \xi_i$; RF-voltage in the proton ring 50 kV, and $\xi_i = 0.05$.

$\sqrt{s}$ [GeV]	10	20	30
Specific Luminosity ($\times 10^{-21}$) [1/cm^{2}s]	2.3	6.5	12
$N_i \times 10^{-10}$	3.6	2.6	2.1
Proton Beam Current [A]	0.35	0.25	0.2
Proton Energy [Gev]	17.21	24.34	29.81
Emittans [nm]	57	14	6.3
Momentum Spread$\times 10^5$	7.1	5	4
Z/n [Ohm]	1.8	3.3	4.5
$\Delta f_{load}/f_0$	0.14	0.1	0.1
IBS Growth Time [s]	6.4	1.6	0.7
Cooling Time [s]	0.13	0.03	0.02
Betatron Cooling Time [s]	3.3	0.8	0.4
Longitudinal Cooling Time [s]	0.14	0.036	0.02
Density of Cooling Beam ($\times 10^{-10}$) [1/cm^3]	0.4	1.15	2.1
Current of Cooling Beam [A]	14	9.9	8
Rms Beam Radius [cm]	0.34	0.1	0.11
Current Density of Cooling Beam [A/cm^2]	19	55	101
Radiat. Recombination Lifetime [h]	87	61	50
$N_e \times 10^{-10}$	43.3	15.3	8.3
Electron Beam Current [A]	4.	1.5	0.8
Electron Energy [GeV]	1.45	4.1	7.5
Emittance [nm]	57	14	6.4
Synchr. Radiat. Energy Loss per Turn [MeV]	0.007	0.43	4.9
RF-Power [MW]	0.028	0.63	4
Z/n [Ohm]	0.027	1.0	8.5
$\Delta f_{load}/f_0$	6.2	0.034	0.0016
Bremsstrahlung Lifetime [h]	50	22	15