NATIONAL RESEARCH CENTRE «KURCHATOV INSTITUTE»
Institute for High Energy Physics

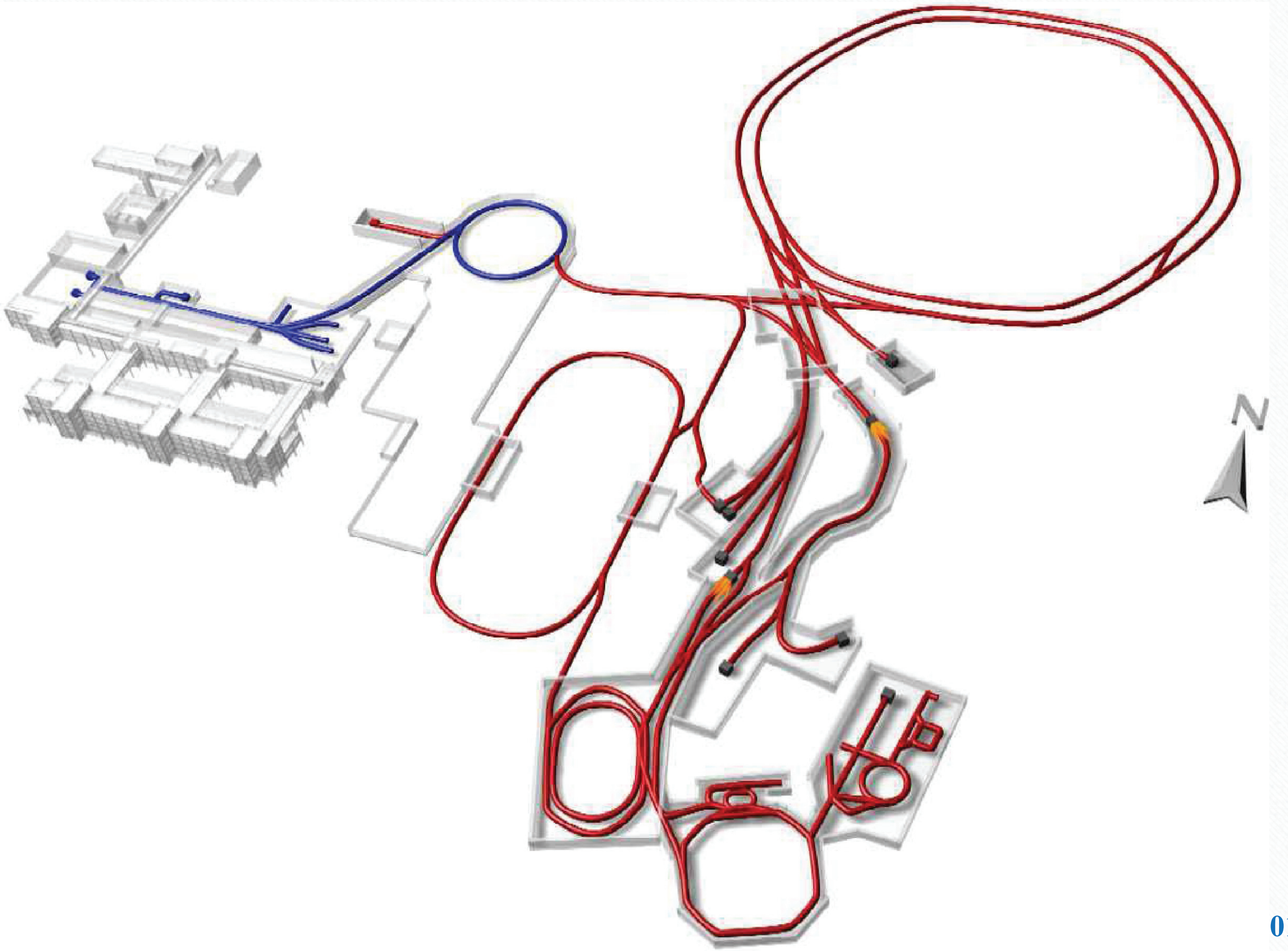
Development of HED@FAIR Quadrupoles

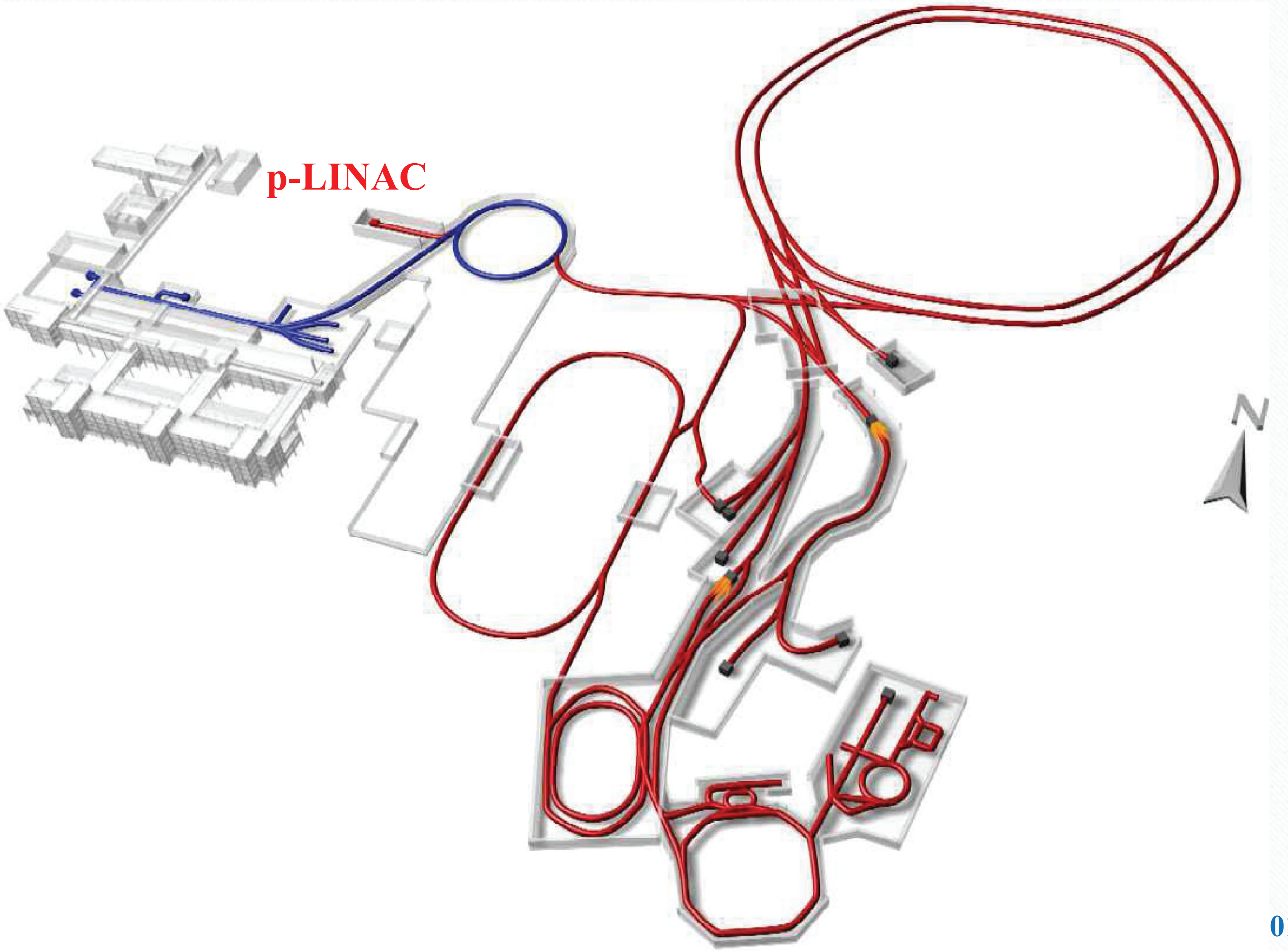
L. Tkachenko, A. Ageyev, Y. Altukhov, I. Bogdanov, E. Kashtanov, S. Kozub, P. Slabodchikov, M. Stolyarov, S. Zinchenko

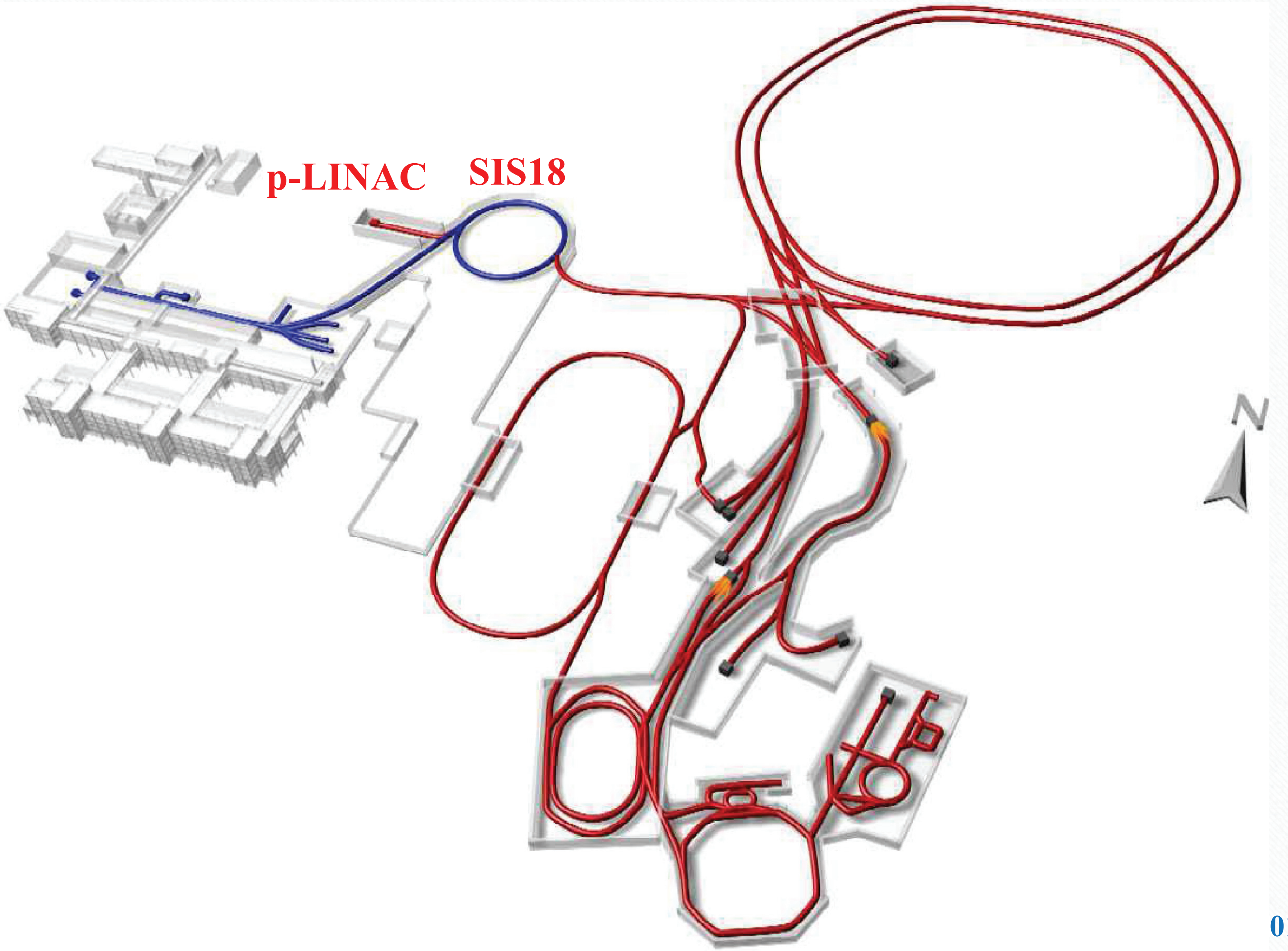
XXVI Russian Particle Accelerator Conference
Protvino, Russia, October 1-5, 2018

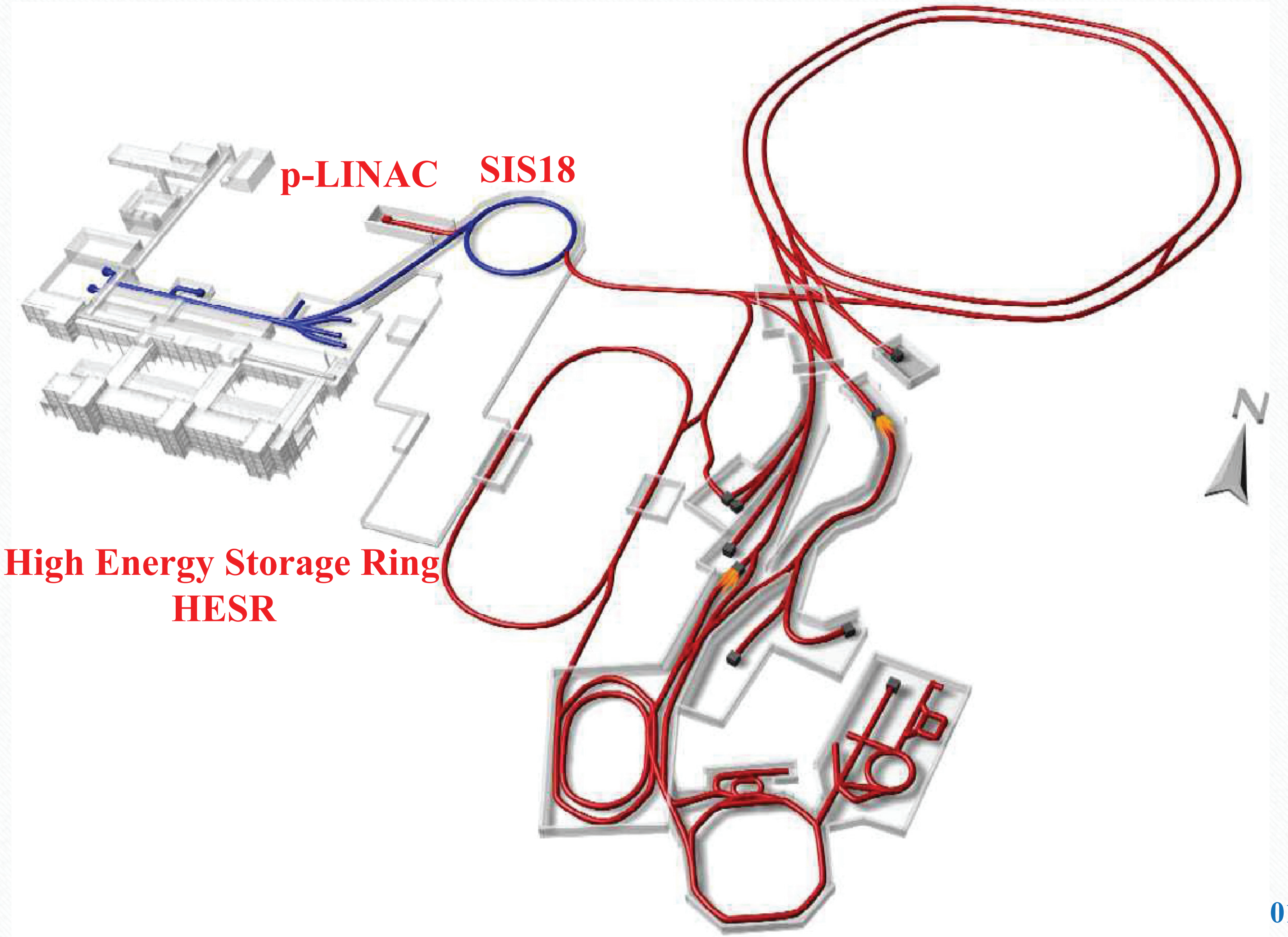
Introduction

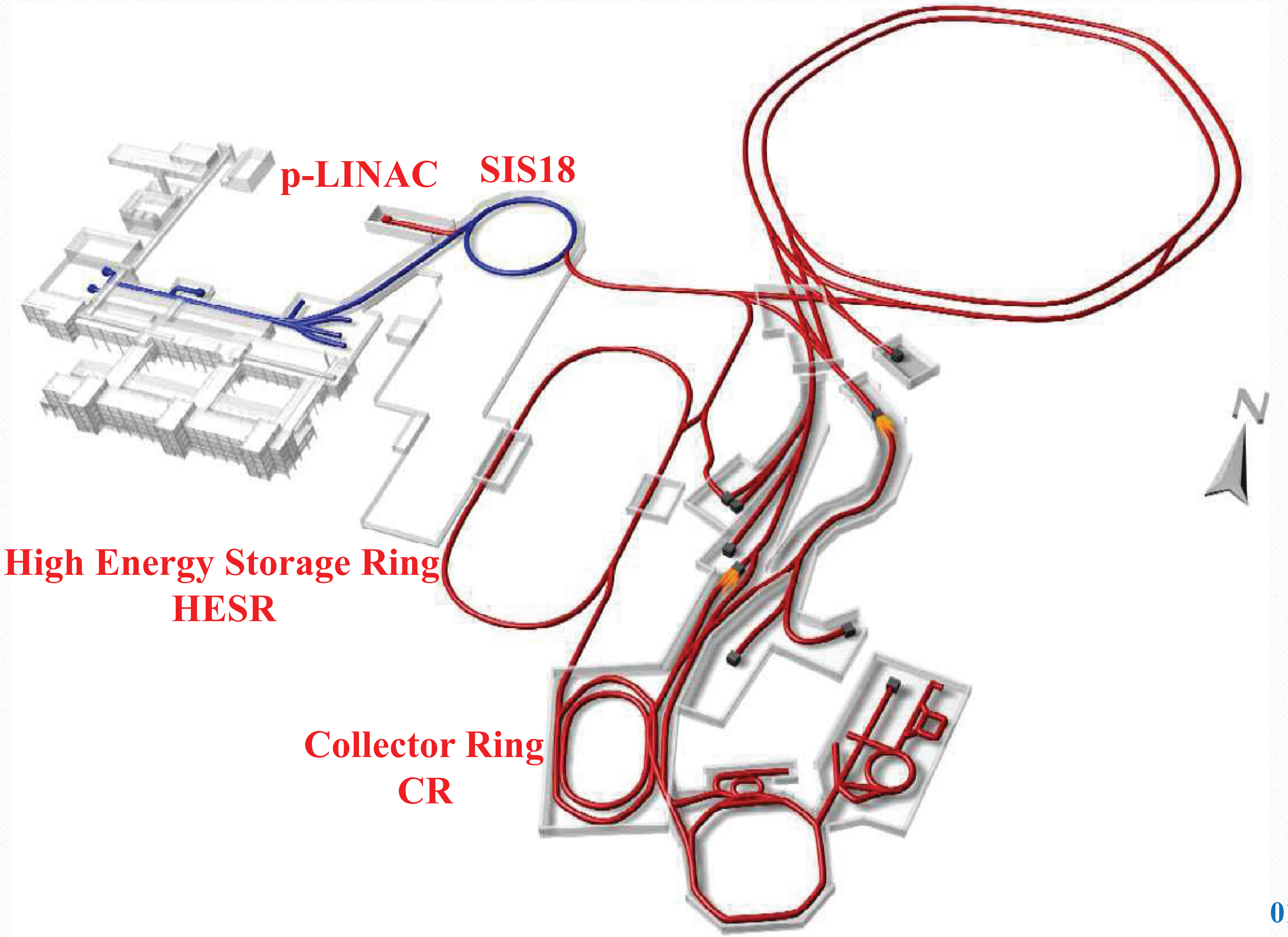
The HED@FAIR collaboration novel experiments to study thermo-physical, transport and radiation properties of high-energy-density matter that is generated by the impact of intense heavy ion beams on dense targets were proposed at FAIR. For strong transverse focusing, a special final focus system (FFS) has to be installed at the end of the HED@FAIR beam line. In order to provide a focal spot of the order of 1 mm, a large focal angle is needed and consequently, four large-aperture high-gradient quadrupole magnets have to be used in the FFS, which IHEP develops at present. This work examines the main characteristics of four wide-aperture quadrupoles, which will be used for focusing the heavy ion beams in these experiments.

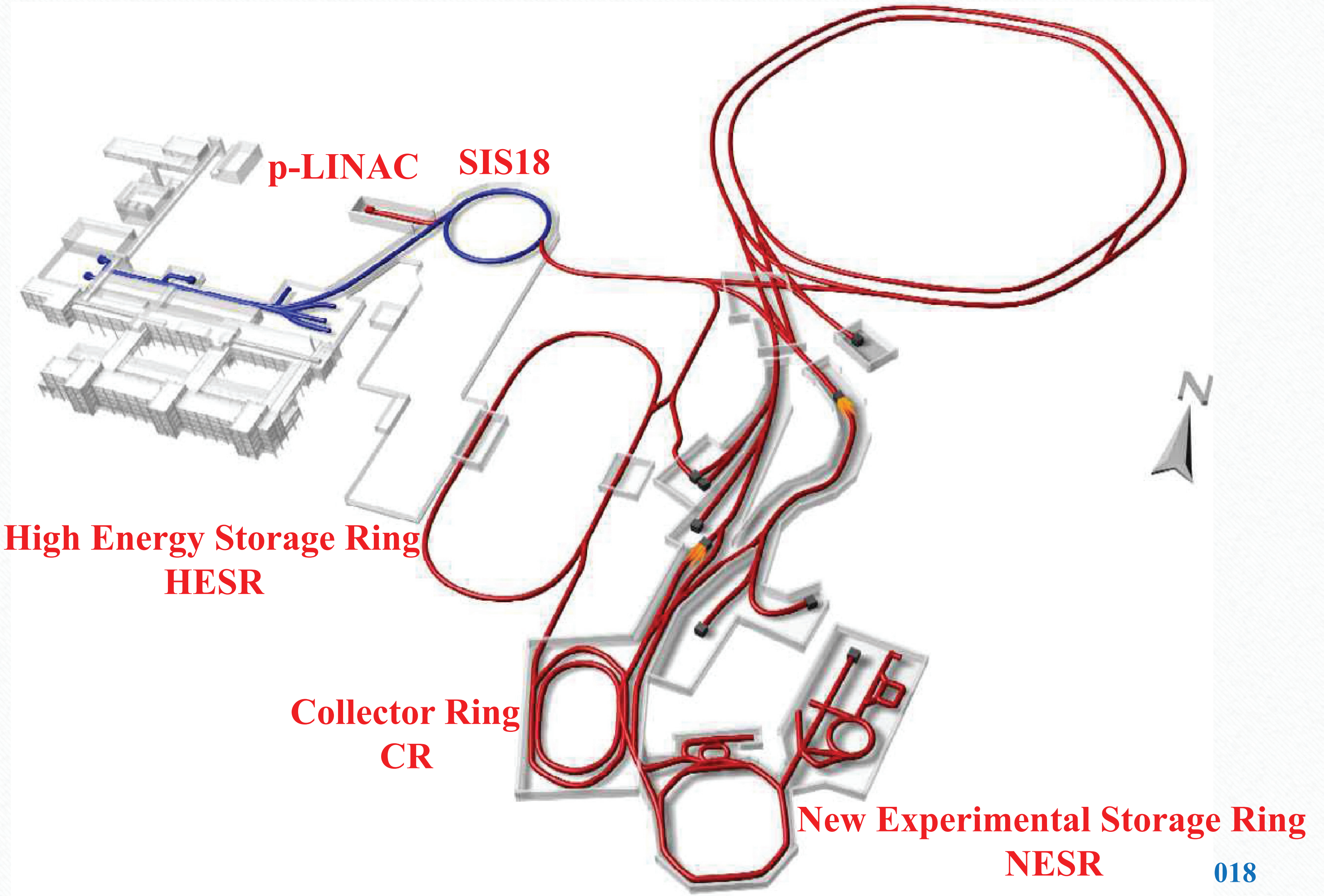

N

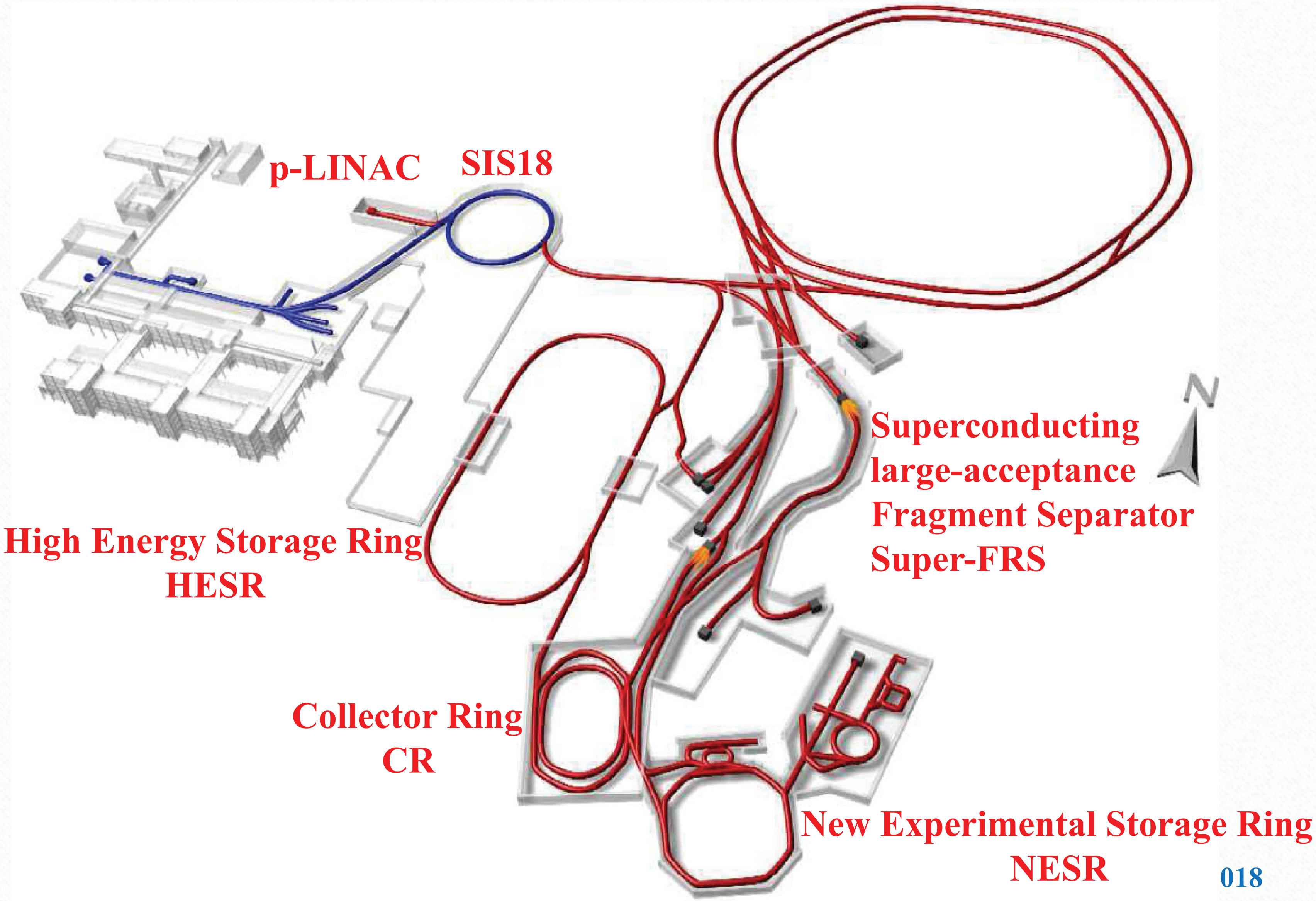

p-LINAC
N

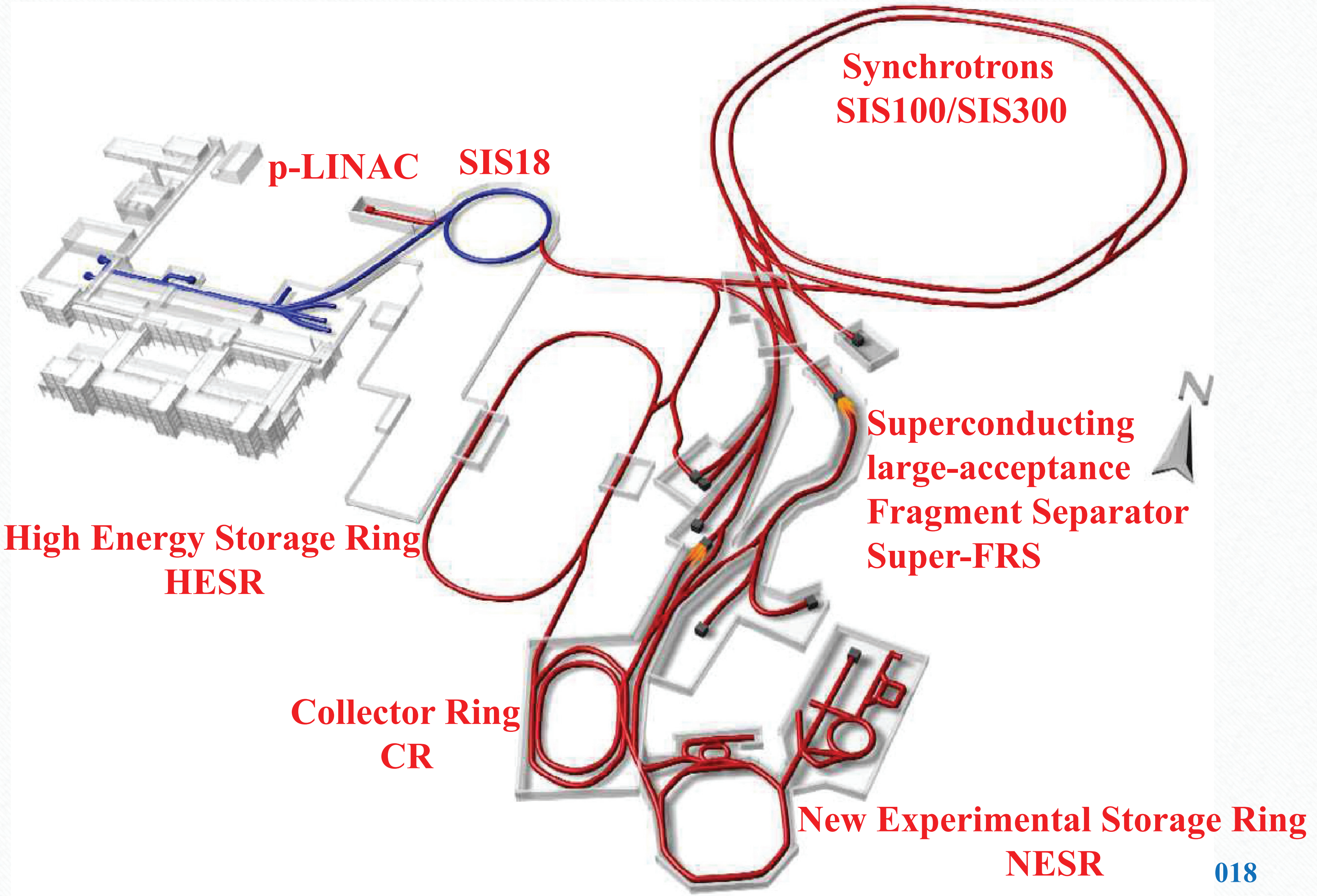

p-LINAC
SIS18
N

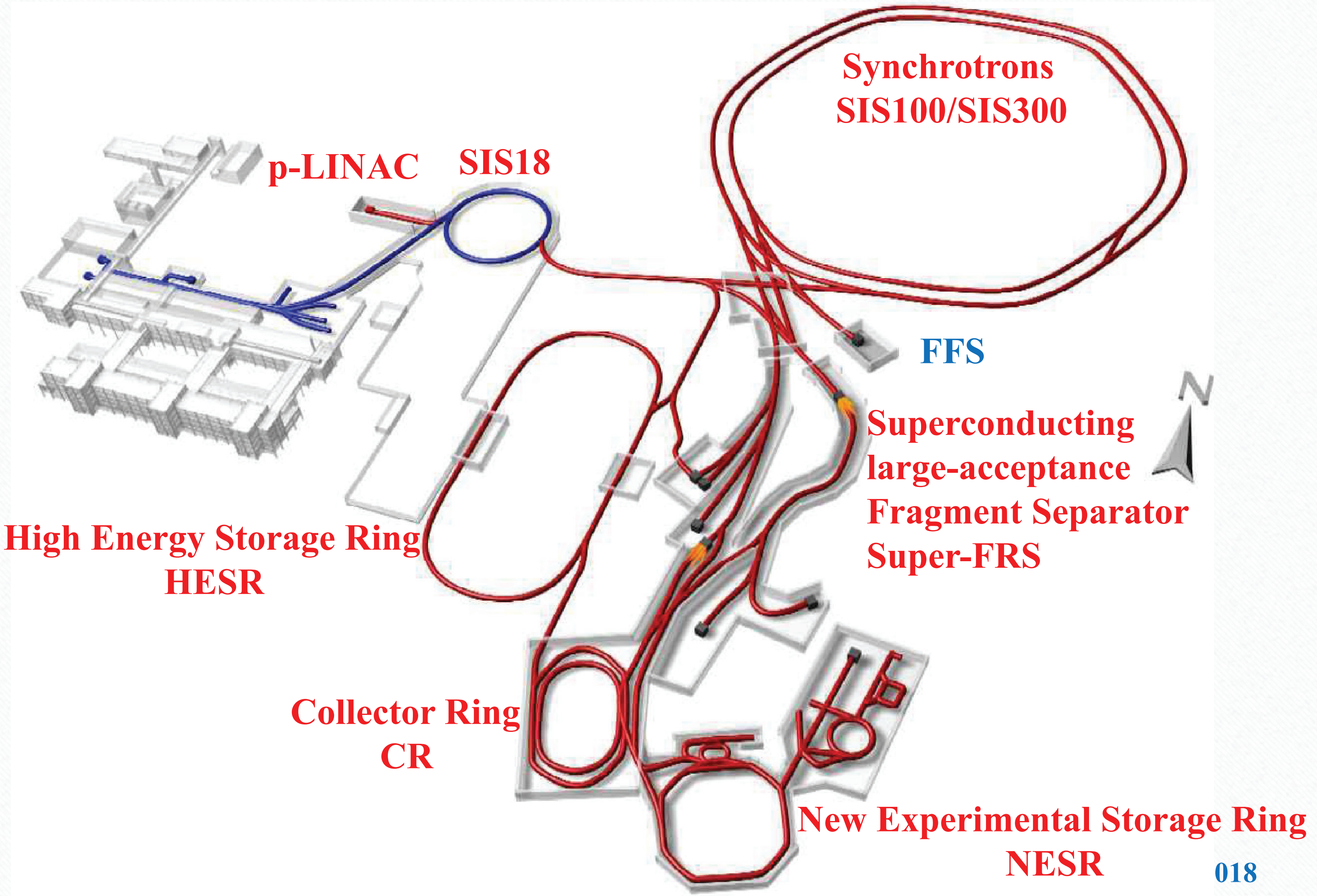

p-LINAC
SIS18
High Energy Storage Ring
HESR
N

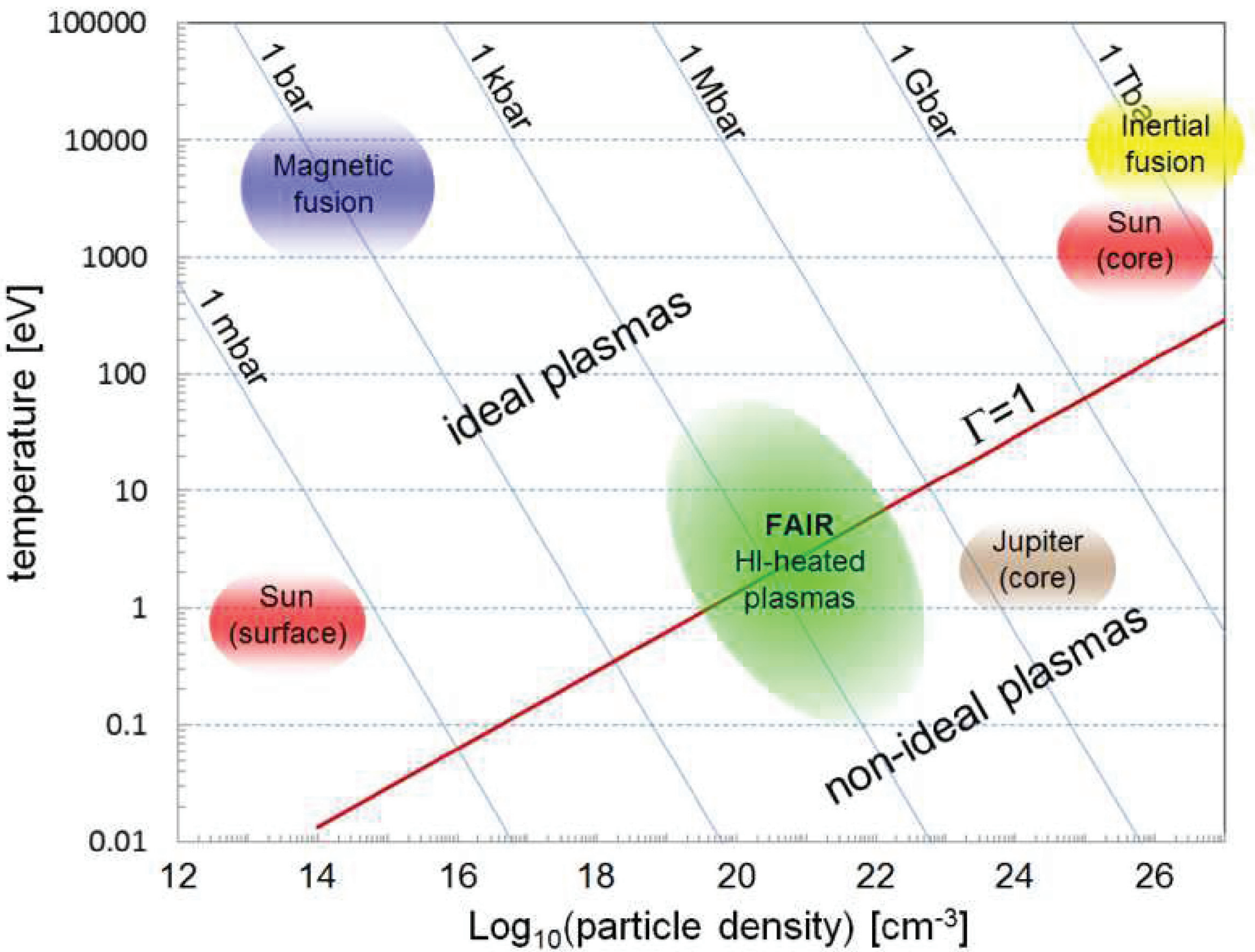

p-LINAC
SIS18
High Energy Storage Ring
HESR
Collector Ring
CR
N


p-LINAC
SIS18
High Energy Storage Ring
HESR
Collector Ring
CR
New Experimental Storage Ring
NESR
N


p-LINAC
SIS18
Superconducting
large-acceptance
Fragment Separator
Super-FRS
N
High Energy Storage Ring
HESR
Collector Ring
CR
New Experimental Storage Ring
NESR


Synchrotrons
SIS100/SIS300
p-LINAC
SIS18
Superconducting
large-acceptance
Fragment Separator
Super-FRS
N
High Energy Storage Ring
HESR
Collector Ring
CR
New Experimental Storage Ring
NESR


Synchrotrons
SIS100/SIS300
p-LINAC
SIS18
FFS
Superconducting
large-acceptance
Fragment Separator
Super-FRS
N
High Energy Storage Ring
HESR
Collector Ring
CR
New Experimental Storage Ring
NESR


100000
10000
1000
100
10
1
0.1
0.01
temperature [eV]
12
14
16
18
20
22
24
26
Log10(particle density) [cm-3]
1 bar
1 kbar
1 Mbar
1 Gbar
1 mbar
Magnetic fusion
Inertial fusion
Sun (core)
ideal plasmas
Γ=1
FAIR
HI-heated plasmas
Jupiter (core)
Sun (surface)
non-ideal plasmas

Requirements to Quadrupole

Requirements to Quadrupole

The main requirements to the quadrupole magnet

- DC operating mode;
- The coil inner diameter is 260 mm;
- The minimal distance between quadrupole centers of two nearby quads is 2.5 m;
- The integral of field gradient is 66 T;
- Temperature margin is about 1 K.

For geometry optimization the following criteria have been chosen:

For geometry optimization the following criteria have been chosen:

- ❑ the radius of the good field quality is 110 mm;
- ❑ the field multipole $|b_6|$ are less than 2×10^{-4};
- ❑ the integral multipoles $|b_n^{int}|$, n = 6, 10, 14 are less than 2×10^{-4};
- ❑ the temperature margin is about 1 K.

A spread of the above multipoles will be allowed no more 2×10^{-3} in the real geometry.

Note that in the real magnet the radius of a good field will be 95 mm.

For geometry optimization the following criteria have been chosen:

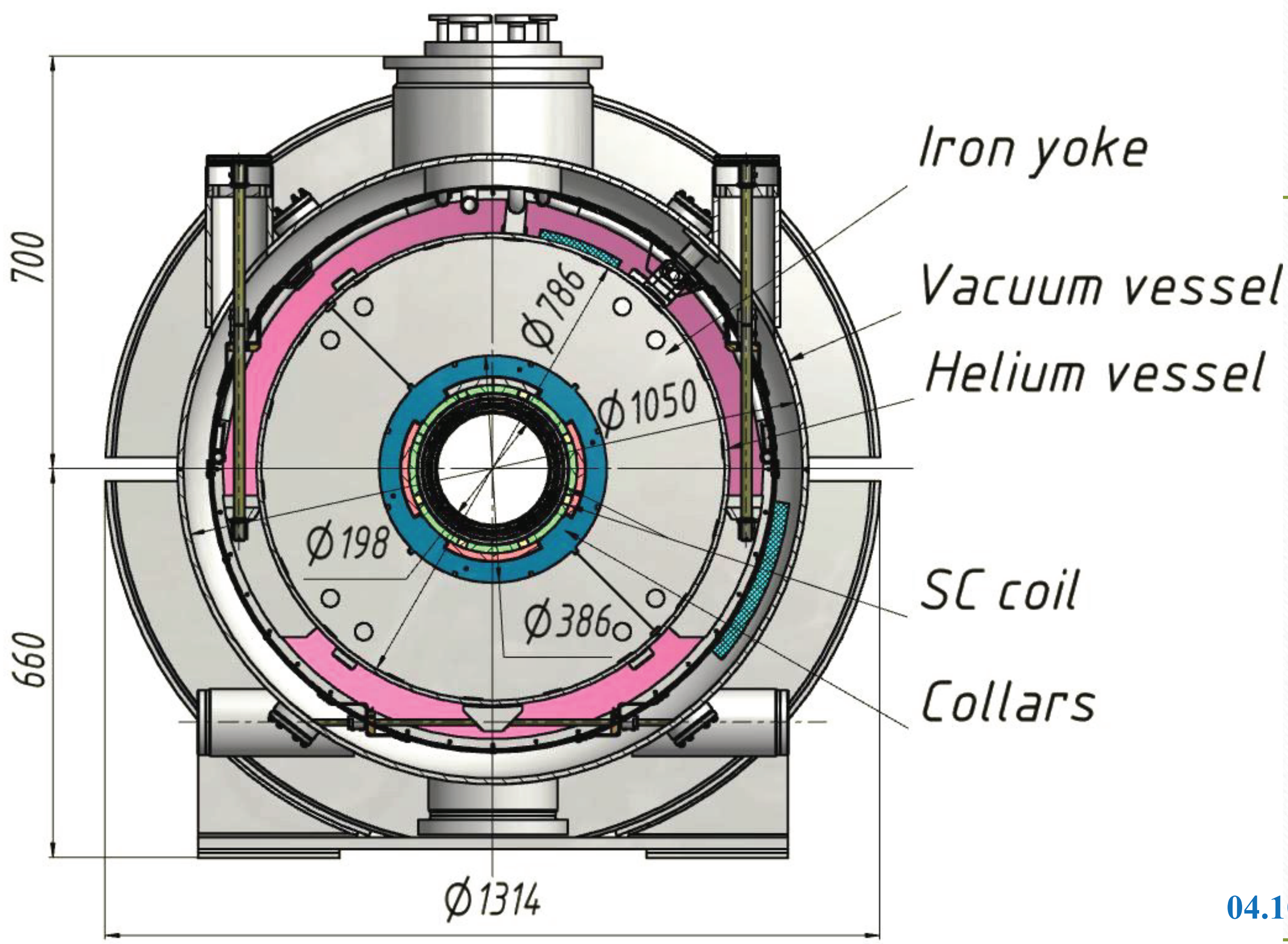
- the radius of the good field quality is 110 mm;
- the field multipole $|b_6|$ are less than 2×10^{-4};
- the integral multipoles $|b_n^{int}|$, $n = 6, 10, 14$ are less than 2×10^{-4};
- the temperature margin is about 1 K.

A spread of the above multipoles will be allowed no more 2×10^{-3} in the real geometry.

Note that in the real magnet the radius of a good field will be 95 mm.

Reduction b_6 => 0.48; b_{10} => 0.27; b_{14} => 0.15

. Cross section of the quadrupole



Materials

Materials

- The NbTi alloy (Nb-50wt% Ti) multifilamentary composite superconducting wire consists of 8910 filaments of 6 μm diameter, the critical current density at 5 T, 4.2 K is 2.4 kA/mm^2.
- The keystoned cable of Rutherford type has 28 strands. The insulated cable at 100 MPa pressure had 12.7 mm width and 1.71 mm middle thickness.
- The grade of 2081 steel (saturation magnetization is 2.19 T) will be used in the iron yoke.

Two geometries are considered

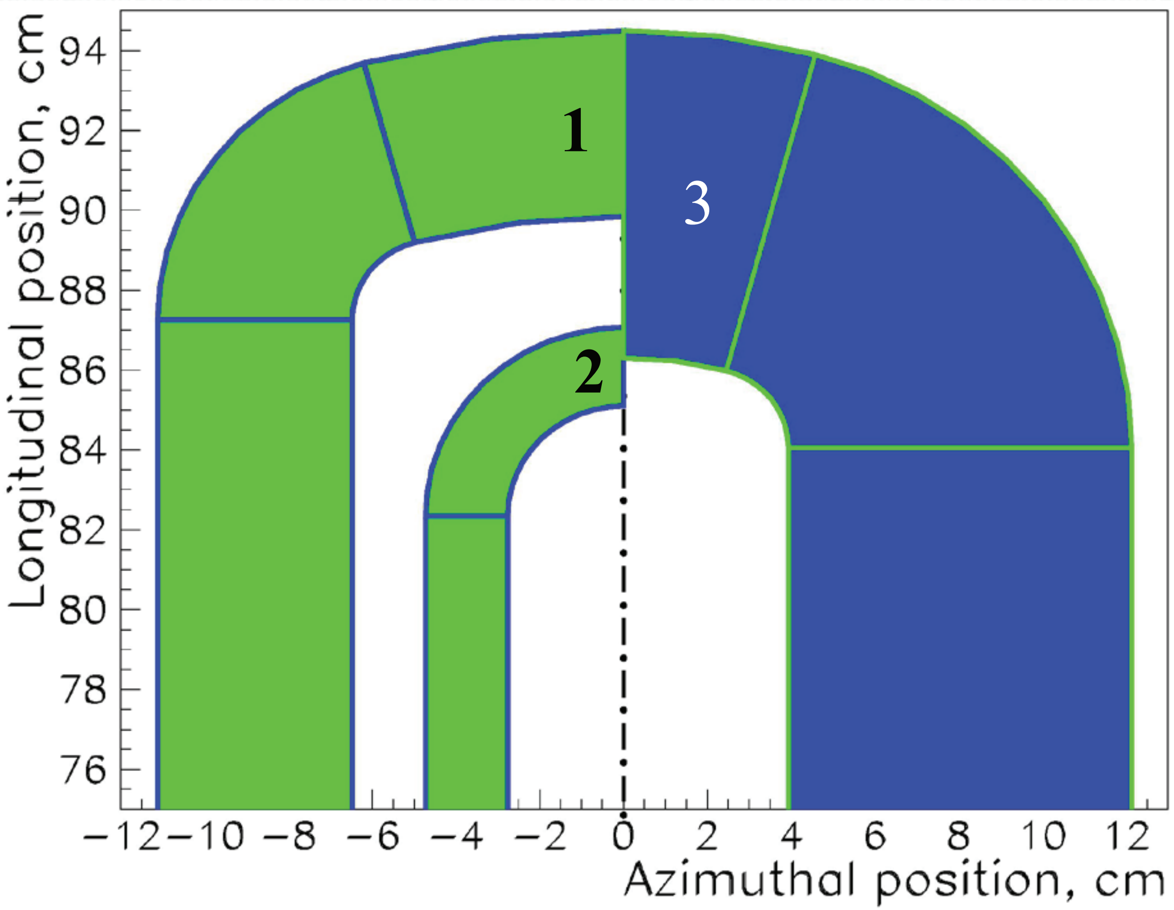
Two geometries are considered

- the field multipoles $|b_n|$, $n = 6, 10, 14$ are less than 2×10^{-4};
- the integral multipole $|b_6^{int}|$ is less than 2×10^{-4}.

Two geometries are considered

- the field multipoles $|b_n|$, $n = 6, 10, 14$ are less than 2×10^{-4};
- the integral multipole $|b_6^{int}|$ is less than 2×10^{-4}.

- the field multipole $|b_6|$ is less than 2×10^{-4};
- the integral multipoles $|b_n^{int}|$, $n = 6, 10, 14$ are less than 2×10^{-4}.



Involute of end parts of the optimized geometry;
left - the inner layer, right – the outer layer

Main geometric parameters of the cross section in the second geometry

N	φ, grad.	α, grad.	r_{in}, mm	a, mm	Turn
1	0.189	18.883	130.00	12.7	26
2	25.822	33.724	130.00	12.7	11
3	0.249	30.998	143.29	12.7	47

.Basic magnetic parameters of the second geometry

.Basic magnetic parameters of the second geometry

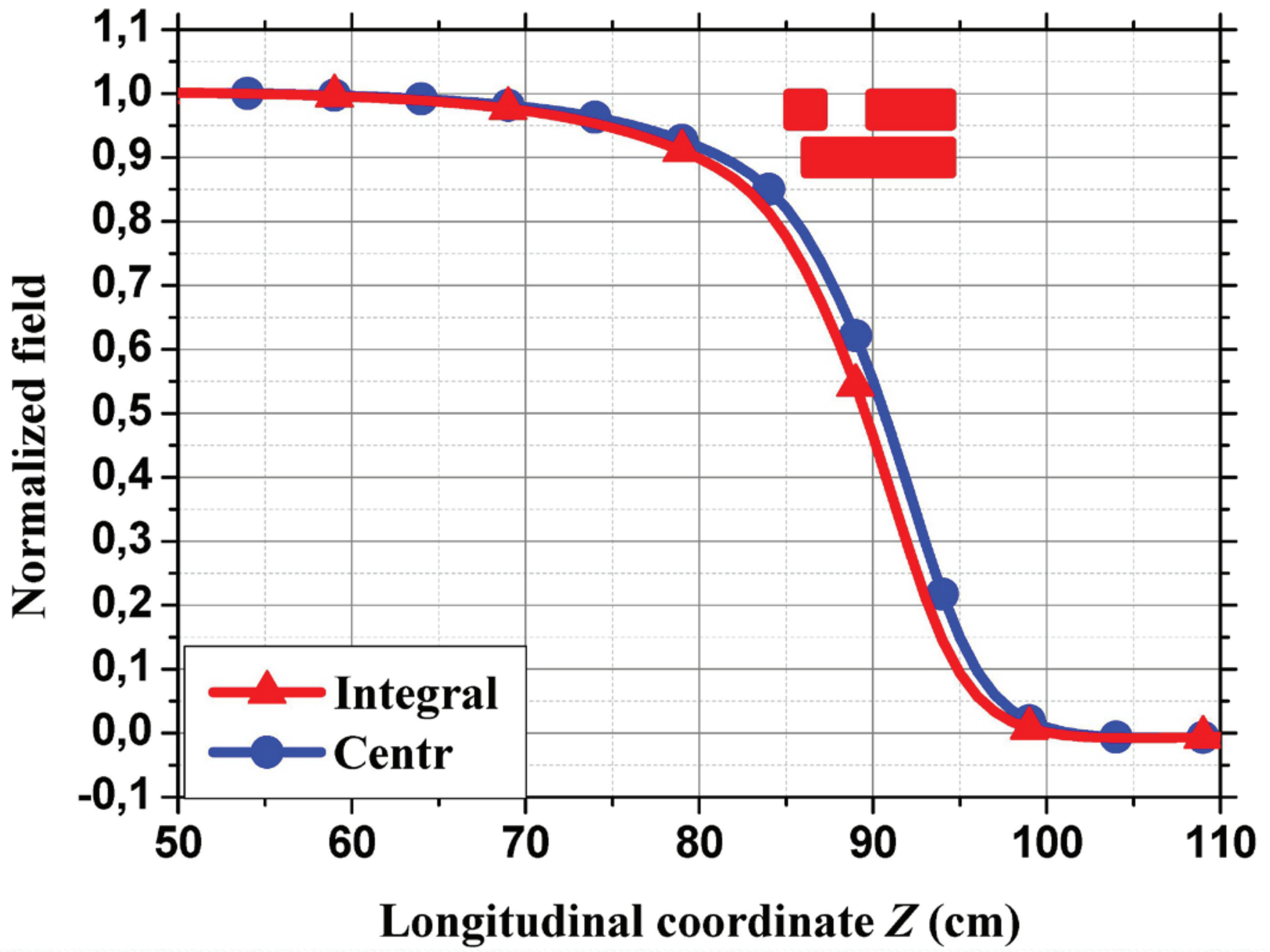
Operating current, kA	5.73
Central gradient, T/m	37.57
Maximal field, T	5.88
Critical temperature, K	5.84
Longitudinal length of the spacer, mm	48.89
Iron yoke shortening, mm	145
Geometric length of the coil, mm	1890
Effective length, mm	1756.8

Basic magnetic parameters of the second geometry

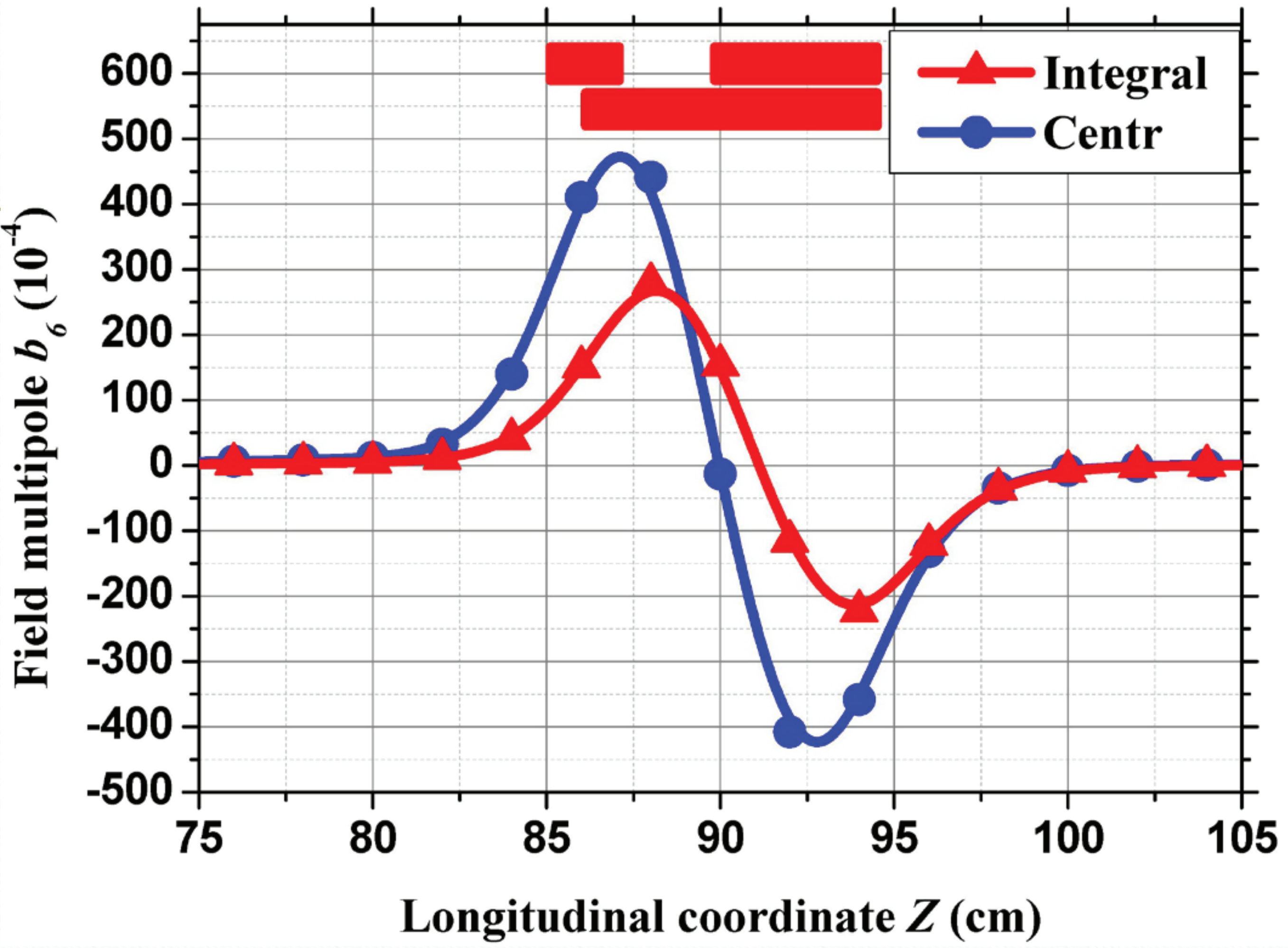
Operating current, kA	5.73
Central gradient, T/m	37.57
Maximal field, T	5.88
Critical temperature, K	5.84
Longitudinal length of the spacer, mm	48.89
Iron yoke shortening, mm	145
Geometric length of the coil, mm	1890
Effective length, mm	1756.8

Parameter	Value
b_6, 10^{-4}	0
b_{10}, 10^{-4}	8.9
b_{14}, 10^{-4}	7.9
b_6^{int}, 10^{-4}	0
b_{10}^{int}, 10^{-4}	0
b_{14}^{int}, 10^{-4}	0
E, kJ/m	592
F_{x0}, kN/m/octant	991
F_{y0}, kN/m/octant	-989
F_{r0}, kN/m/octant	642
$F_{\Theta 0}$, kN/m/octant	-1211
$\|F_0\|$, kN/m/octant	1400
F_{xe}, kN/octant	30.6
F_{ye}, kN/octant	-48.0
F_{ze}, kN/octant	59.9
$\|F_e\|$, kN/octant	82.7

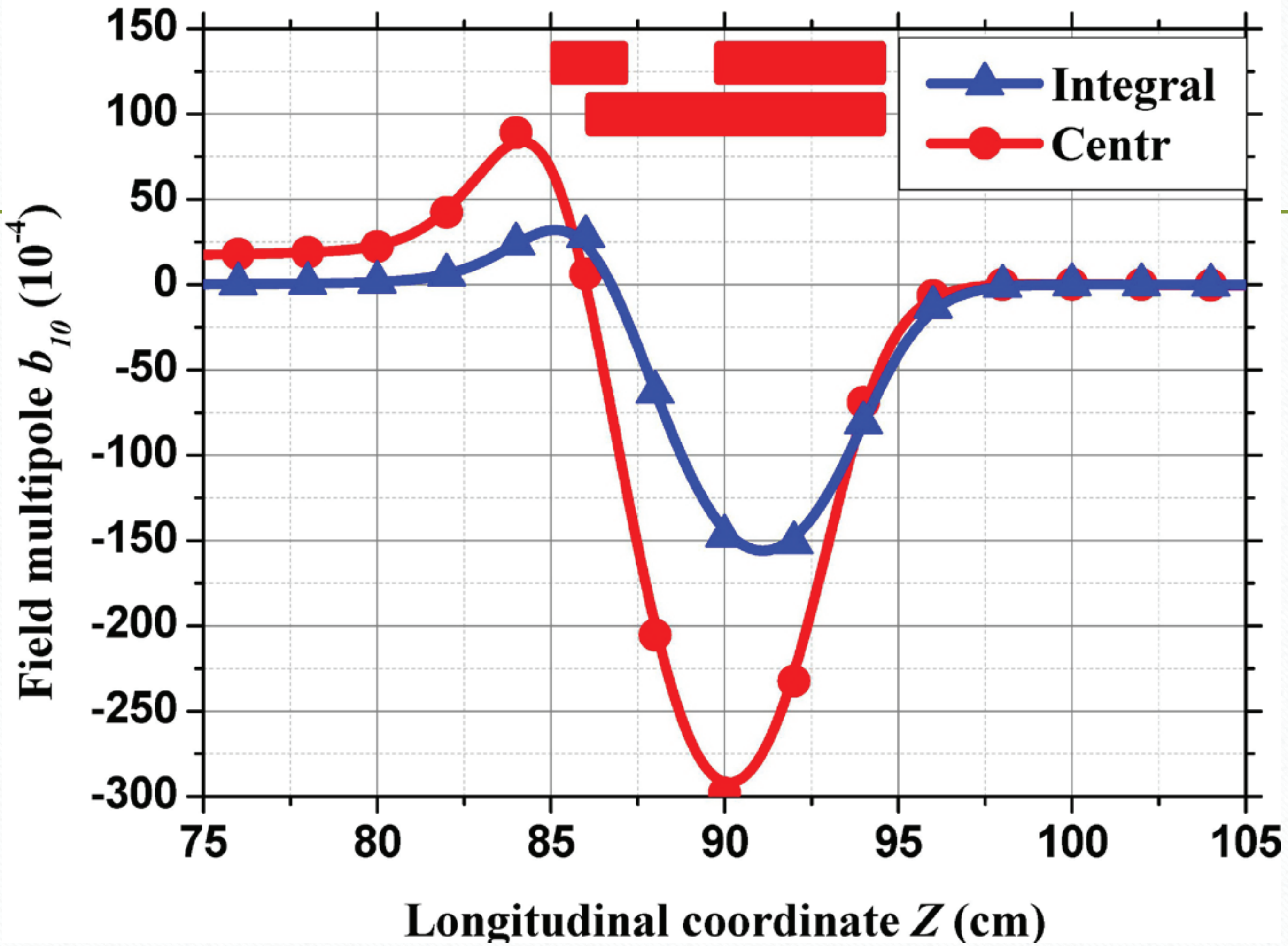
Distribution of the normalized gradient along *Z*-axis



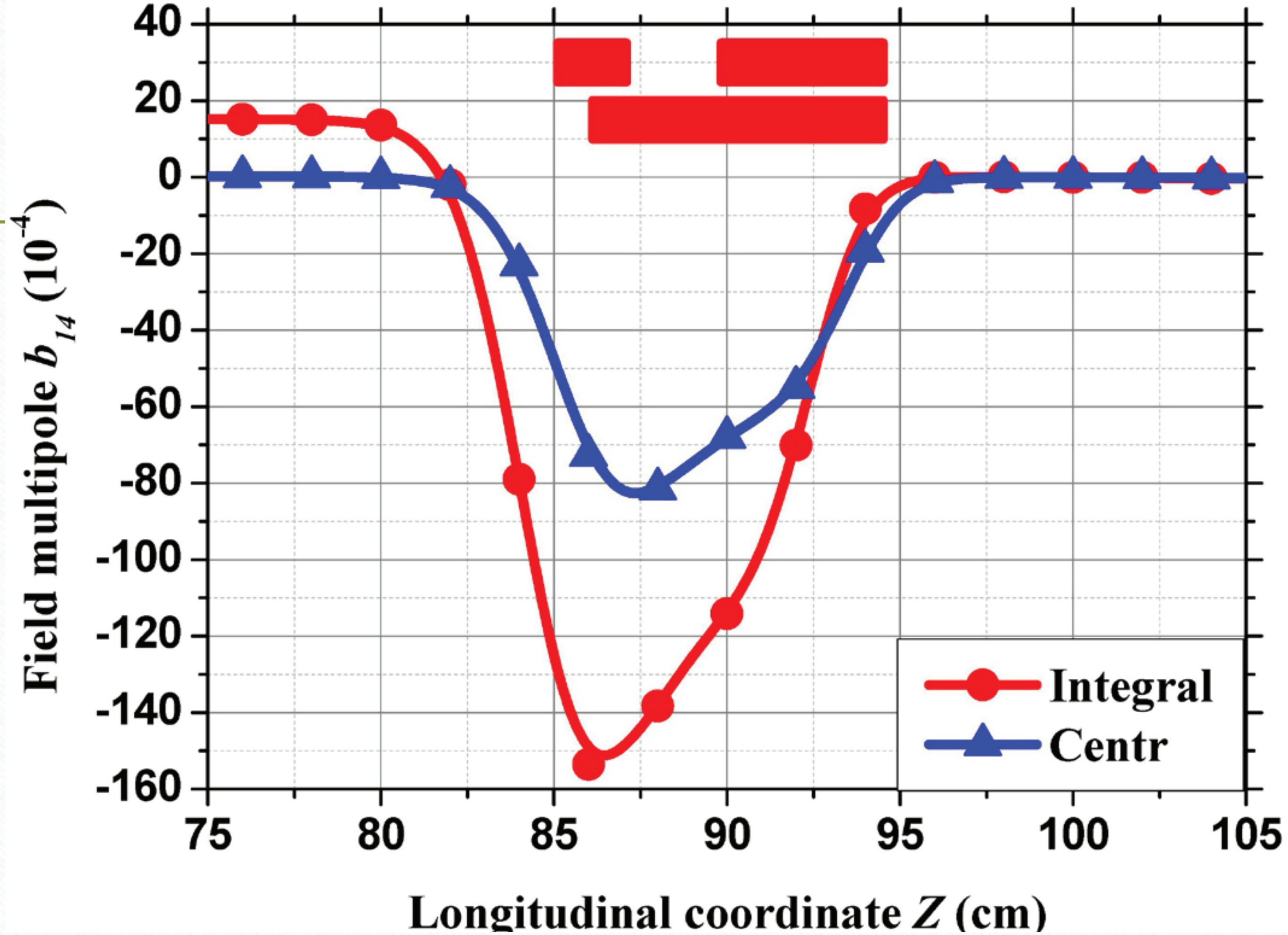
Distribution of the field multipole b_6 along Z-axis



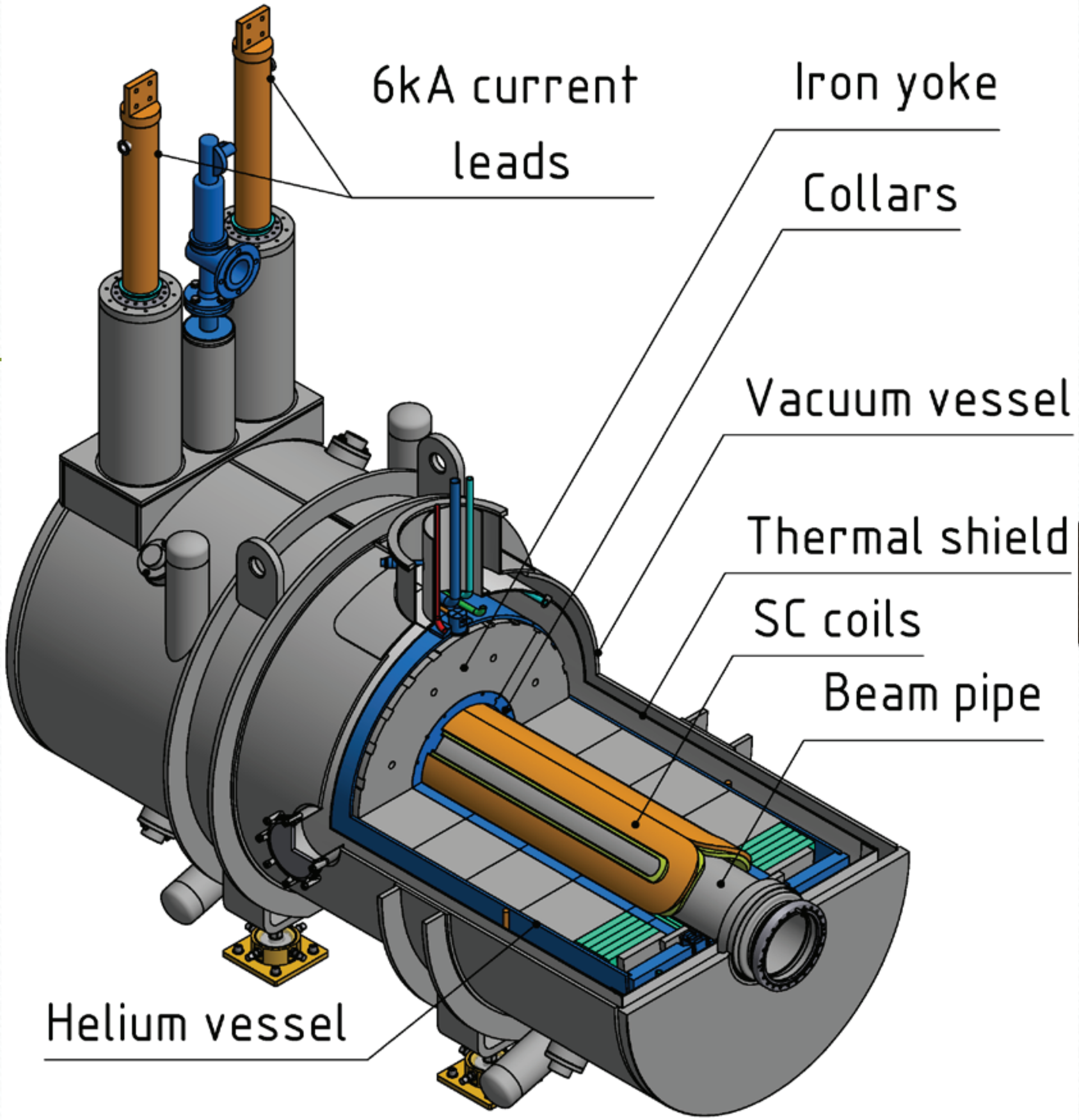
Distribution of the field multipole b_{10} along *Z*-axis



Distribution of the field multipole b_{14} along Z axis



General view of the quadrupole



Conclusion

Four wide-aperture superconducting quadrupoles for strong final focusing of energetic heavy ion beams in future plasma physics experiments at FAIR have been developed. The design of the magnets suppressed lower integral multipole fields of the 6, 10 and 14 orders as well as the 6 central harmonic. The quadrupoles have 37.57 T/m central gradient, 260 mm superconducting coil inner diameter and 1.89 m geometric length with the effective length of 1.757 m. The temperature margin is 1 K at 4.85 K outlet liquid helium temperature in the quadrupoles string.

Thank You for attention