Overview of Electron-Ion Collider Projects

Petr Shatunov, BINP, Novosibrsk

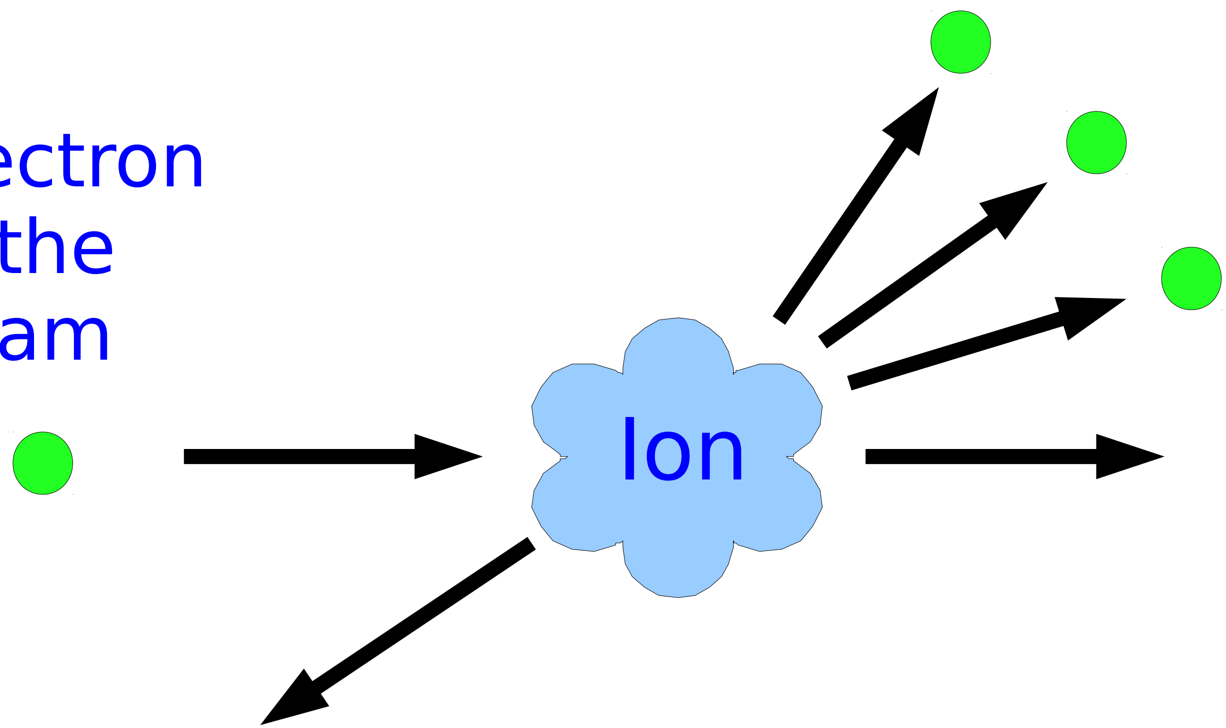
Joint US-CERN-Japan-Russia Accelerator School on Ion Colliders
Dubna, 29.10.2019

Why do we need EIC?

«Towards nuclear physics in electron-radioactive ion collisions»
L. Grigorenko 30.10.2019

Interacted electrons gain energy and angle deviation

Electron in the beam



Not interacted electrons return to the ring

Ions can change Z/A state

«super electron microscope»

What is important?

- High Luminosity
- Ability to work with different Ions — from H to U
- Wide energy range — up to and over 150GeV
- Maximum angle of detection
- High level polarization of particles

What do we need to create a Collider #1 ?

Two rings

Different circumference

Electron Ring

$\beta_I \neq \beta_e$ $\beta_e \rightarrow 1$

$$F_i \cdot n_i = F_e \cdot n_e$$

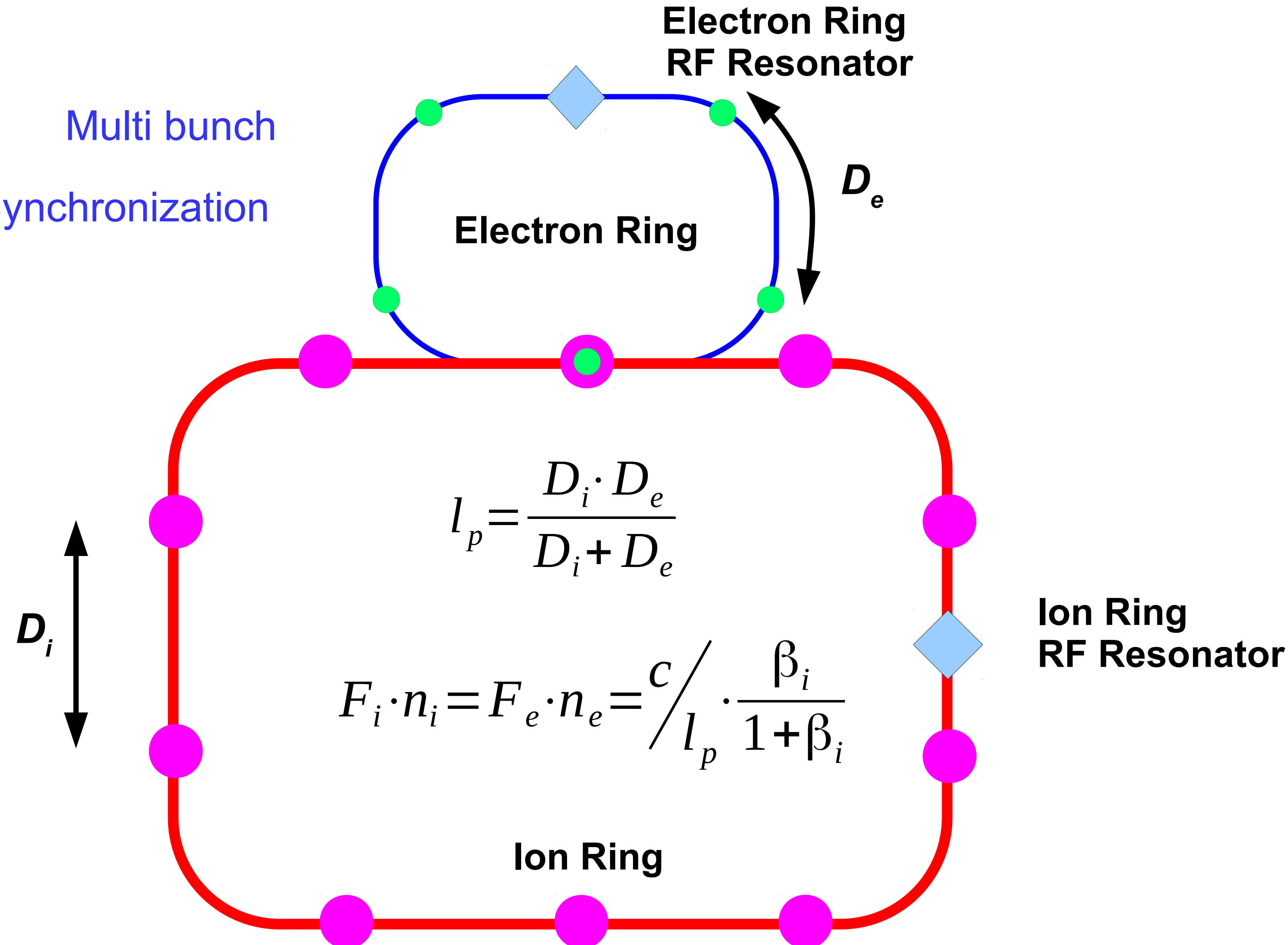
$$l_i / l_e = \beta_i \frac{n_i}{n_e}$$

Ion Ring

What do we need to create a Collider #2 ?

Multi bunch

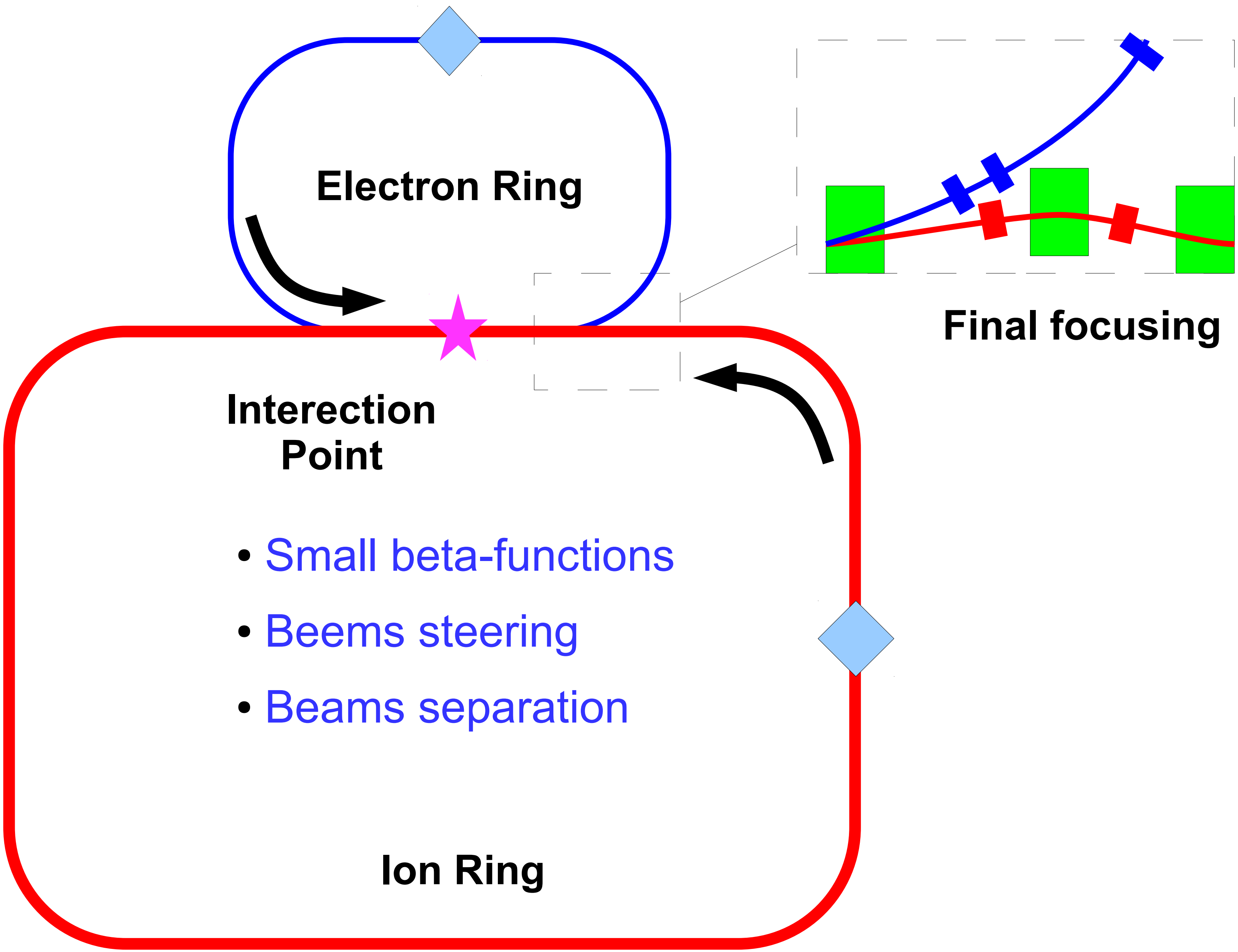
Synchronization



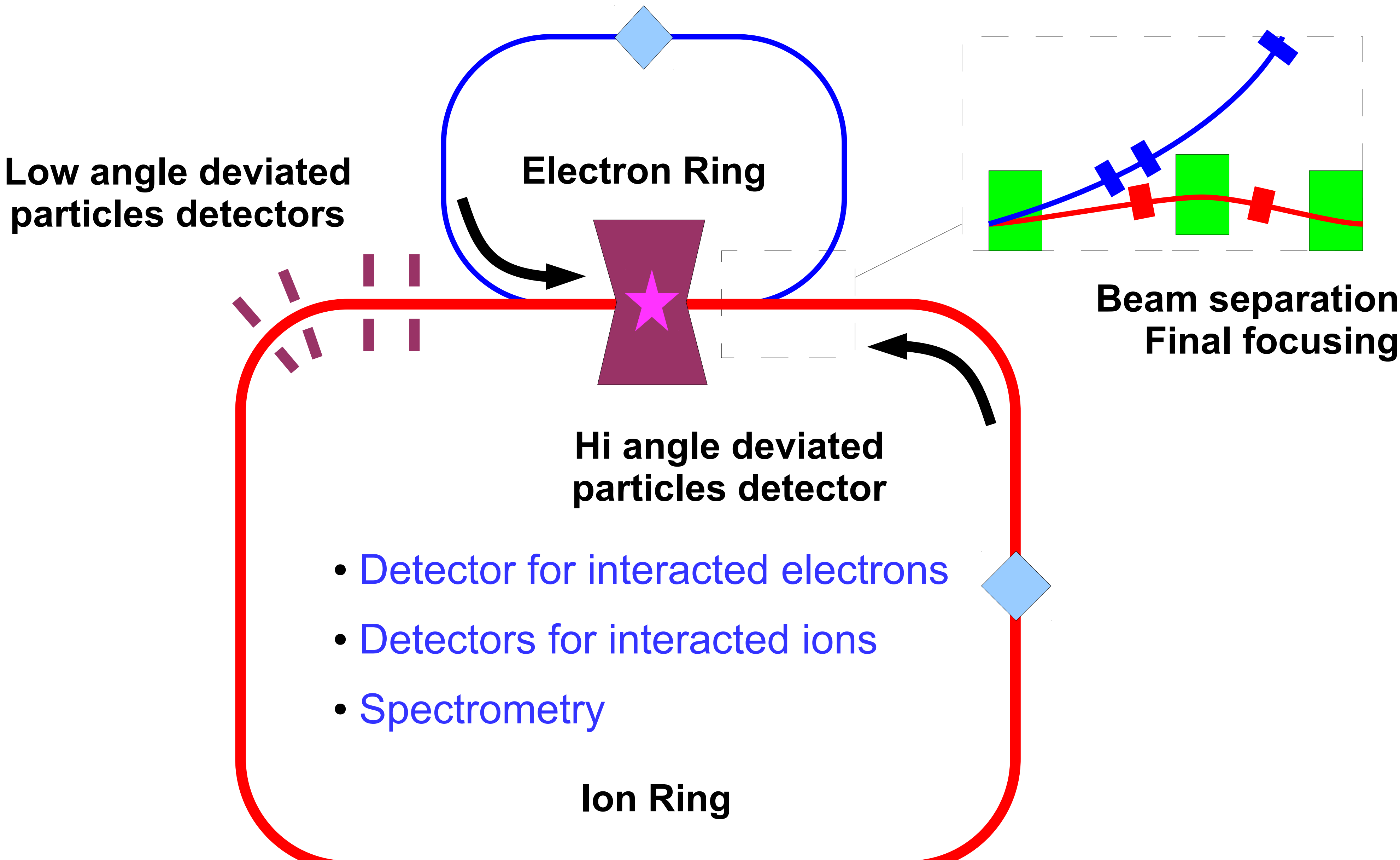
$$l_p = \frac{D_i \cdot D_e}{D_i + D_e}$$

$$F_i \cdot n_i = F_e \cdot n_e = c / l_p \cdot \frac{\beta_i}{1+\beta_i}$$

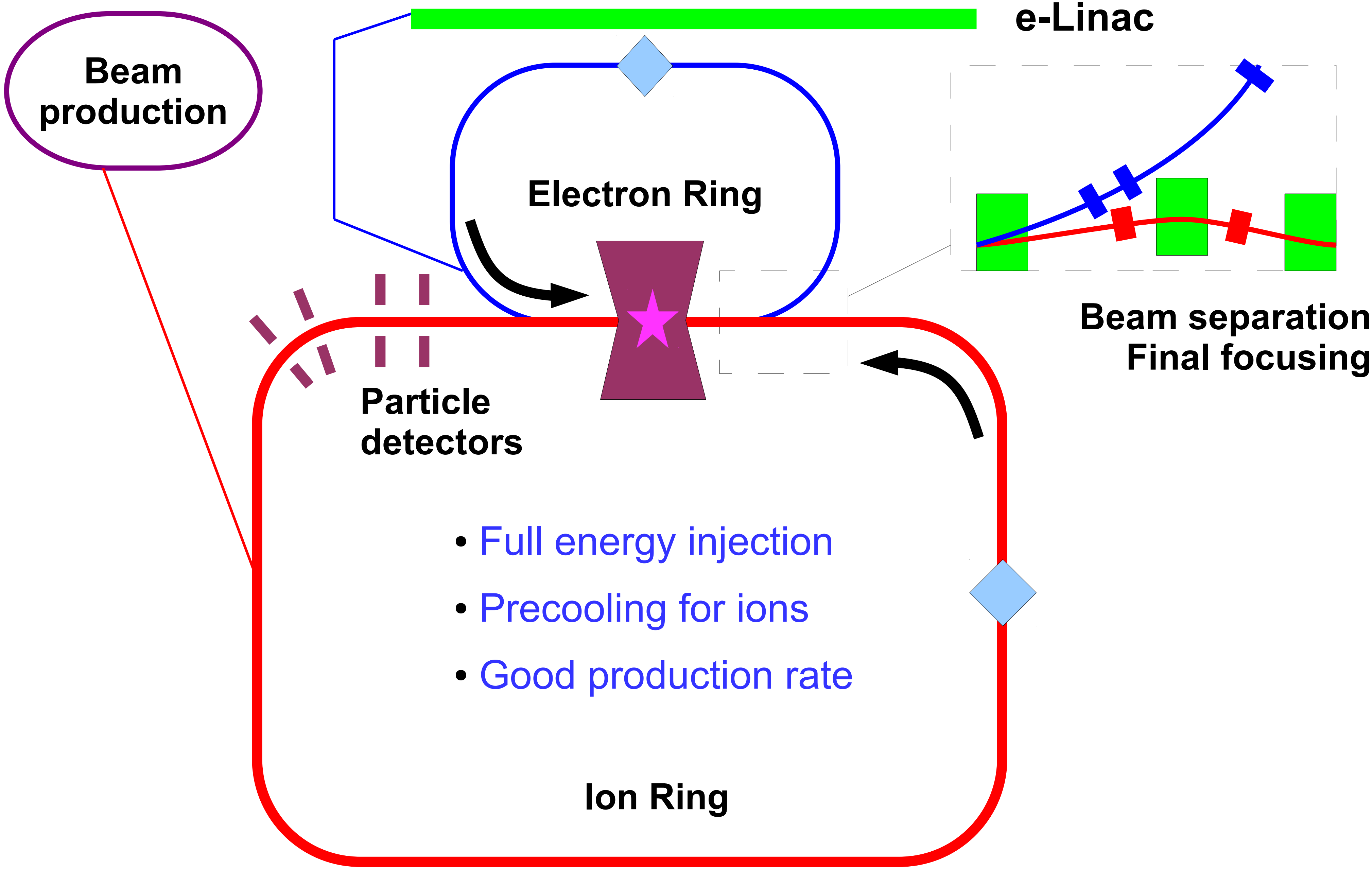
What do we need to create a Collider #3 ?



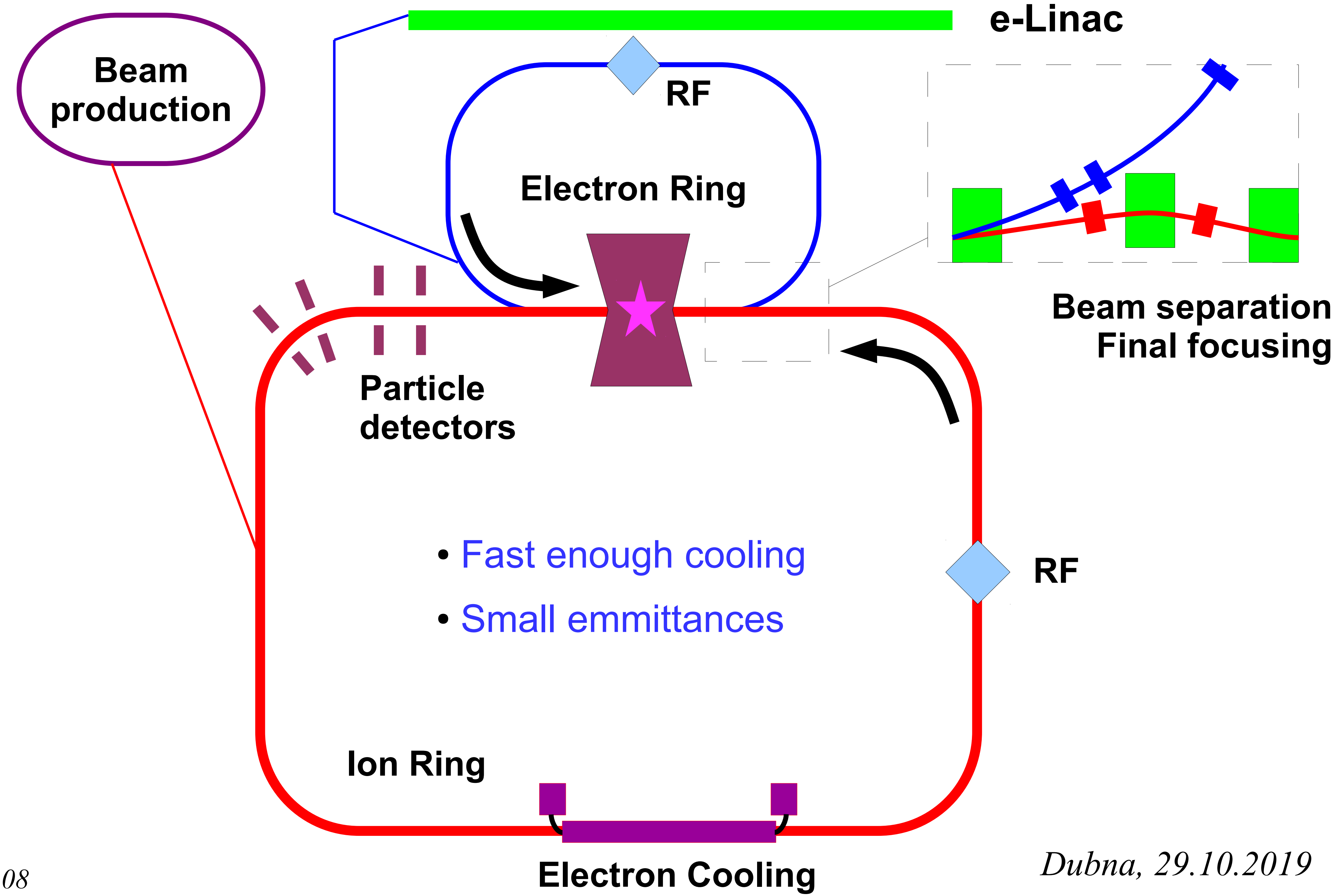
What do we need to create a Collider #4 ?



What do we need to create a Collider #5 ?



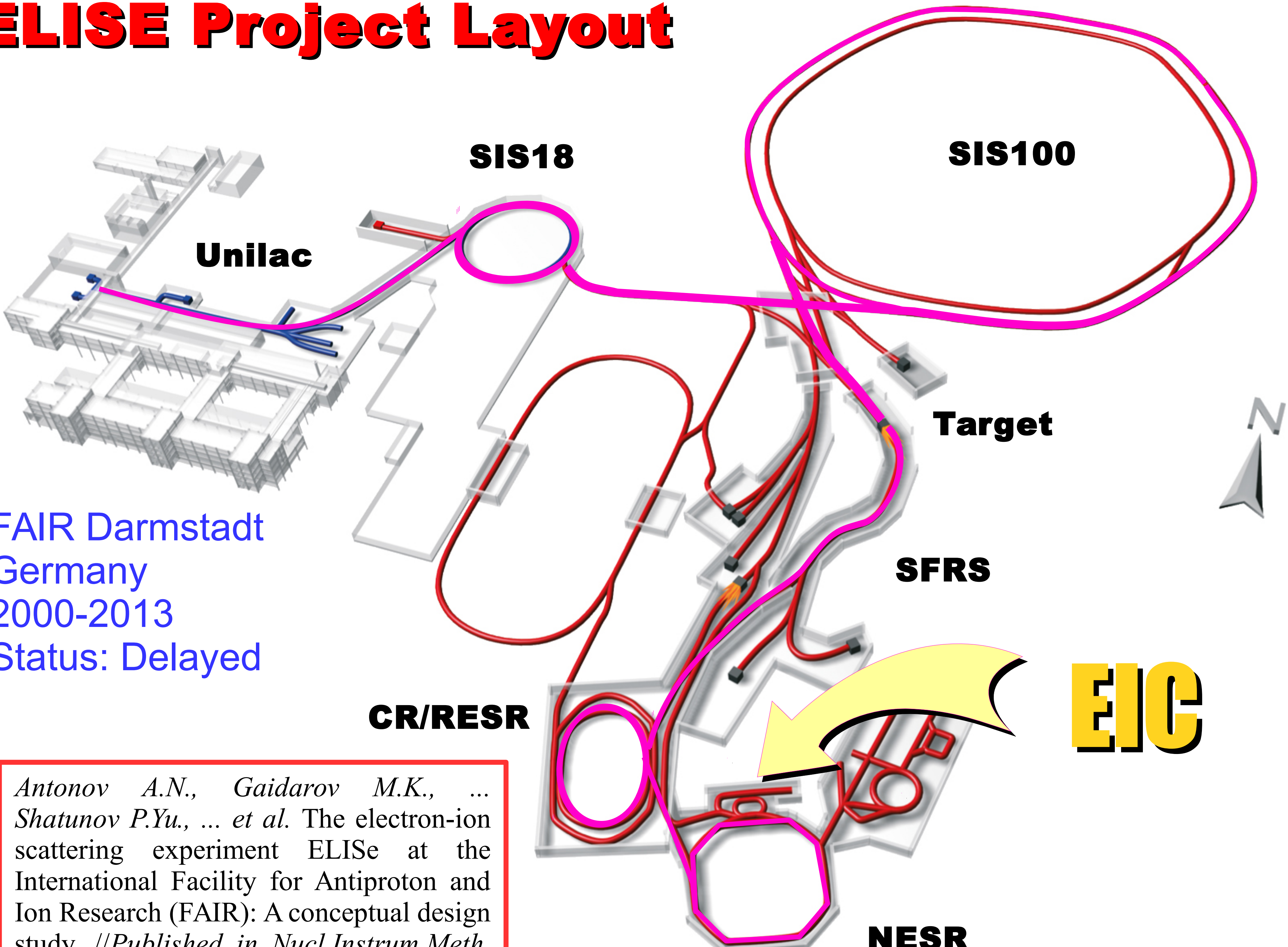
What do we need to create a Collider #6 ?



What do we need to create a Collider?

- Two rings
- Multiple bunches
- RF-system
- Final focusing & Beam separation
- Particle detectors and spectrometers
- Beam production system
- Cooling system

ELISE Project Layout



FAIR Darmstadt
Germany
2000-2013
Status: Delayed

Antonov A.N., Gaidarov M.K., ... Shatunov P.Yu., ... et al. The electron-ion scattering experiment ELISe at the International Facility for Antiproton and Ion Research (FAIR): A conceptual design study. //*Published in Nucl.Instrum.Meth.* – 2011. – A637. –Pp. 60-76

Dubna, 29.10.2019

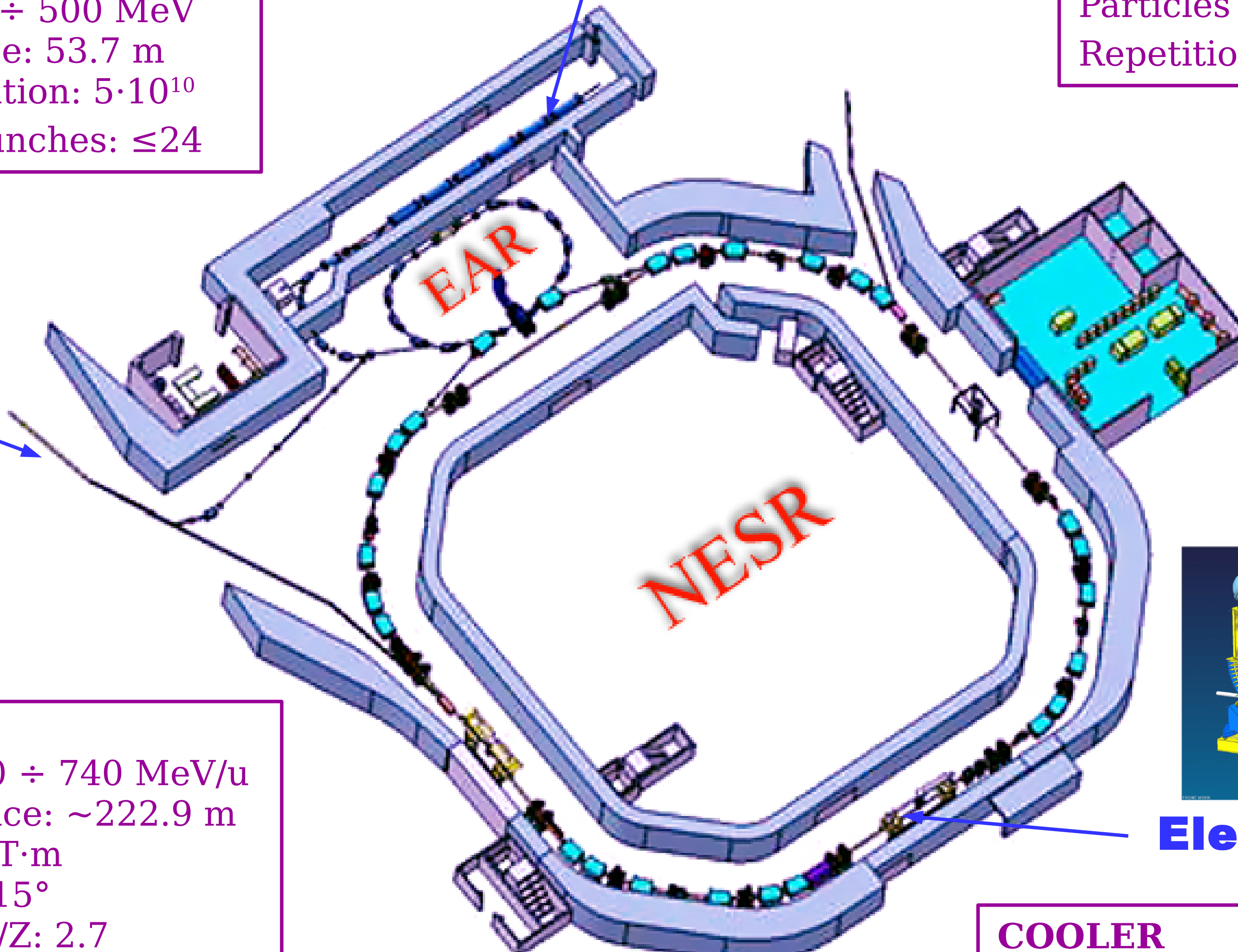
ELISE: Collider layout

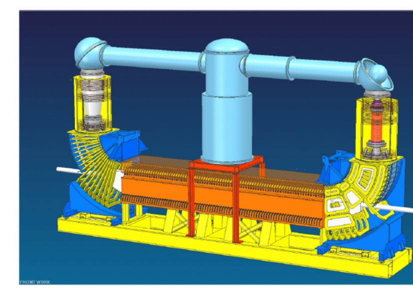
EAR
Energy: 125 ÷ 500 MeV
Circumference: 53.7 m
Bunch population: $5 \cdot 10^{10}$
Number of bunches: ≤24

Electron LINAC

LINAC
Energy: 125 ÷ 500 MeV
Length: ~35 m
Particles per pulse: $5 \cdot 10^{10}$
Repetition rate: 10Hz

Injection from CR/RESR





Electron Cooling

NESR
Energy: 120 ÷ 740 MeV/u
Circumference: ~222.9 m
Rigidity: 13 T·m
Bends: 24 · 15°
Reference A/Z: 2.7
Number of bunches: ≤120

COOLER
Length: 6 m
Magnetic field: 1 T
Cooling time: 20 ms

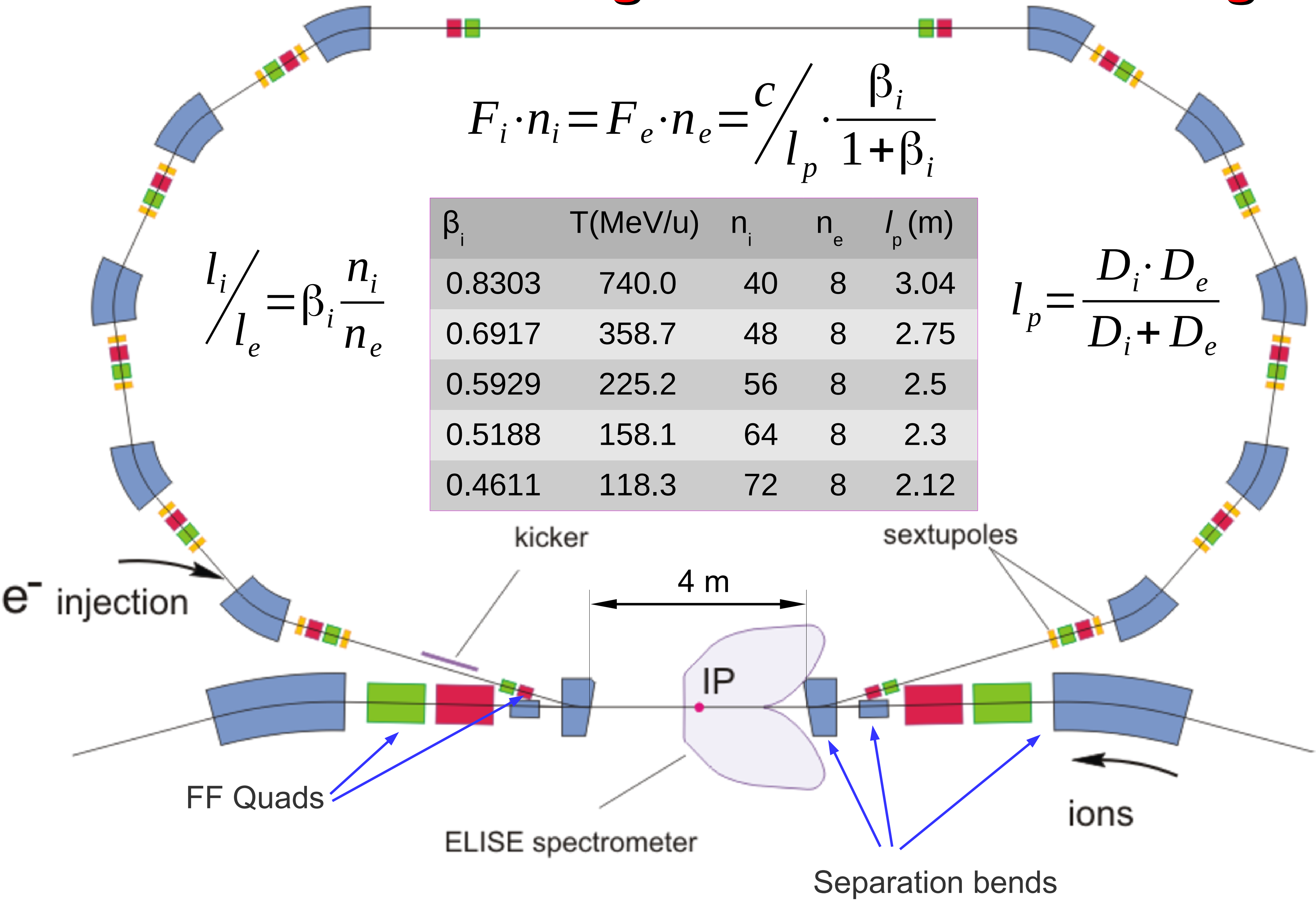
Interection Region and Electron Ring

$$F_i \cdot n_i = F_e \cdot n_e = {}^{c}\!/_{l_p} \cdot \frac{\beta_i}{1+\beta_i}$$

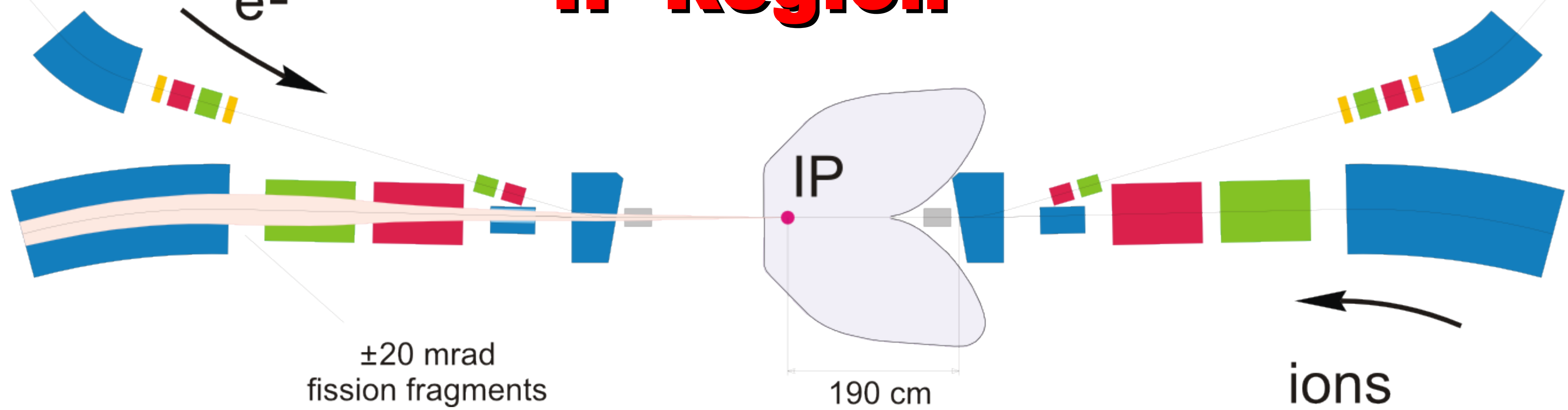
$${}^{l_i}\!/_{l_e} = \beta_i \frac{n_i}{n_e}$$

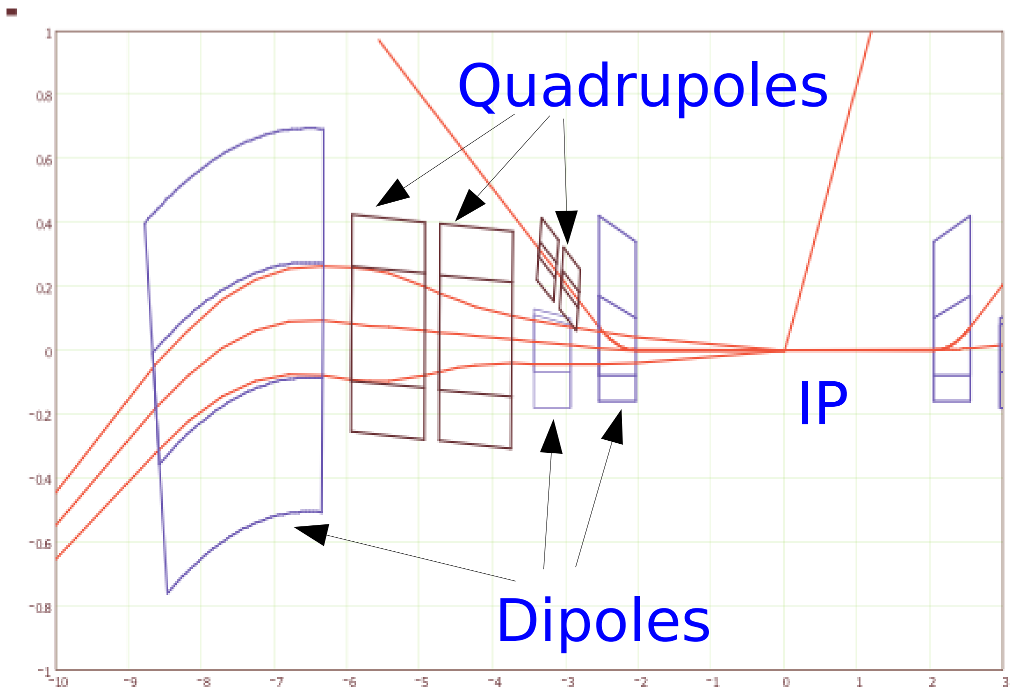
β_i	T(MeV/u)	n_i	n_e	l_p (m)
0.8303	740.0	40	8	3.04
0.6917	358.7	48	8	2.75
0.5929	225.2	56	8	2.5
0.5188	158.1	64	8	2.3
0.4611	118.3	72	8	2.12

$$l_p = \frac{D_i \cdot D_e}{D_i + D_e}$$

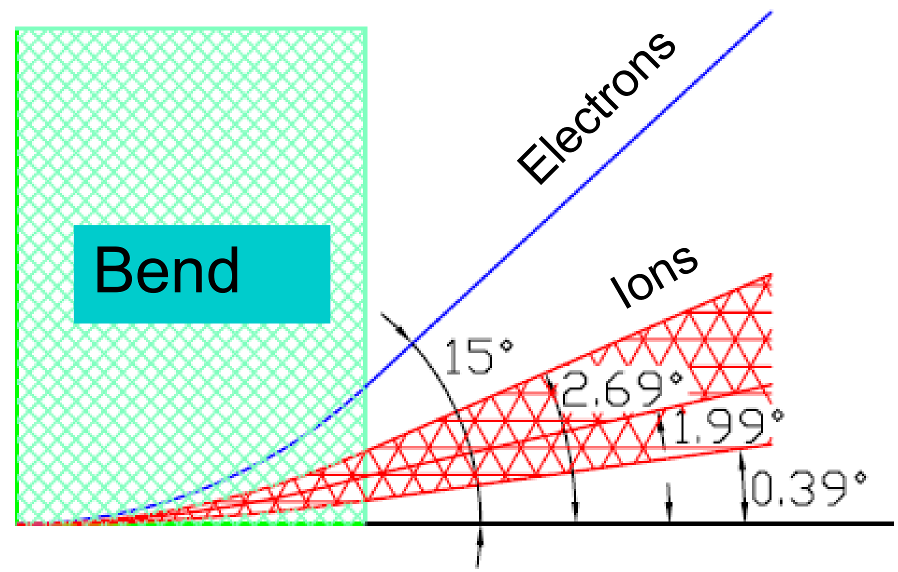


IP Region





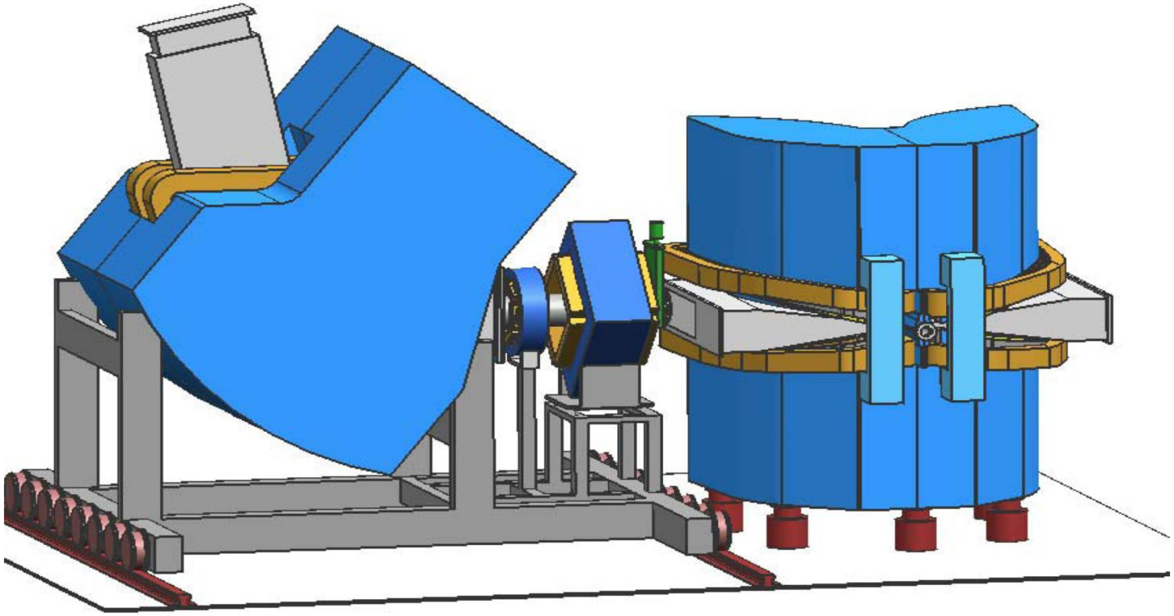
Final focusing



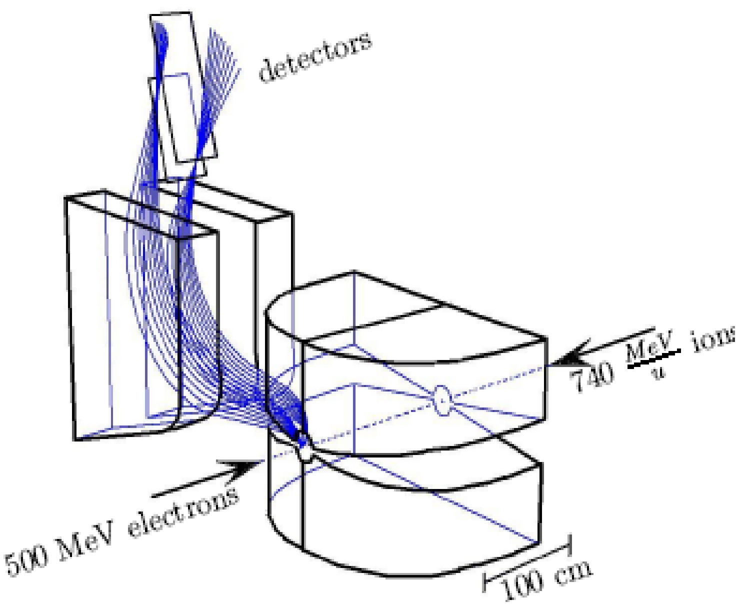
Beam separation

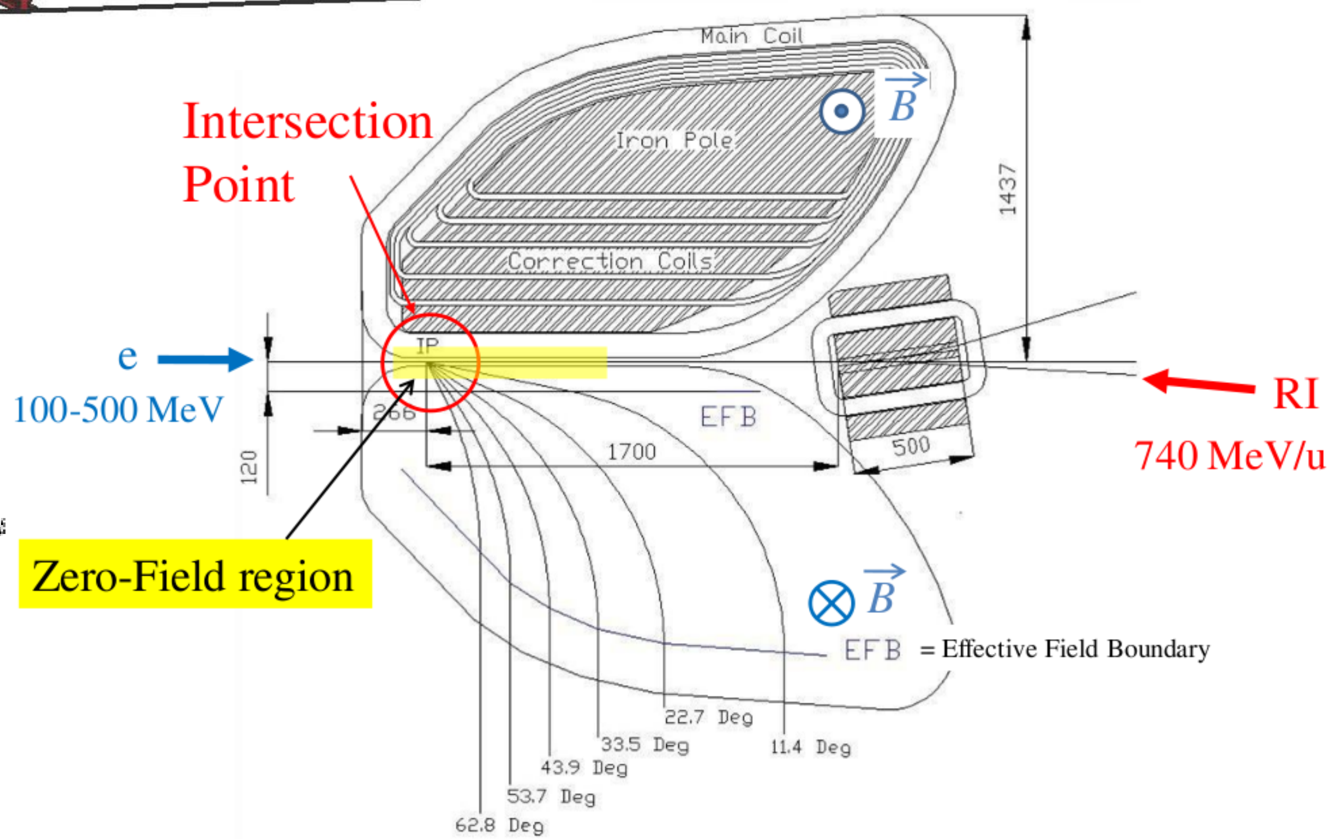
Electron Spectrometer

Angle 10° ÷ 45°



Midplane



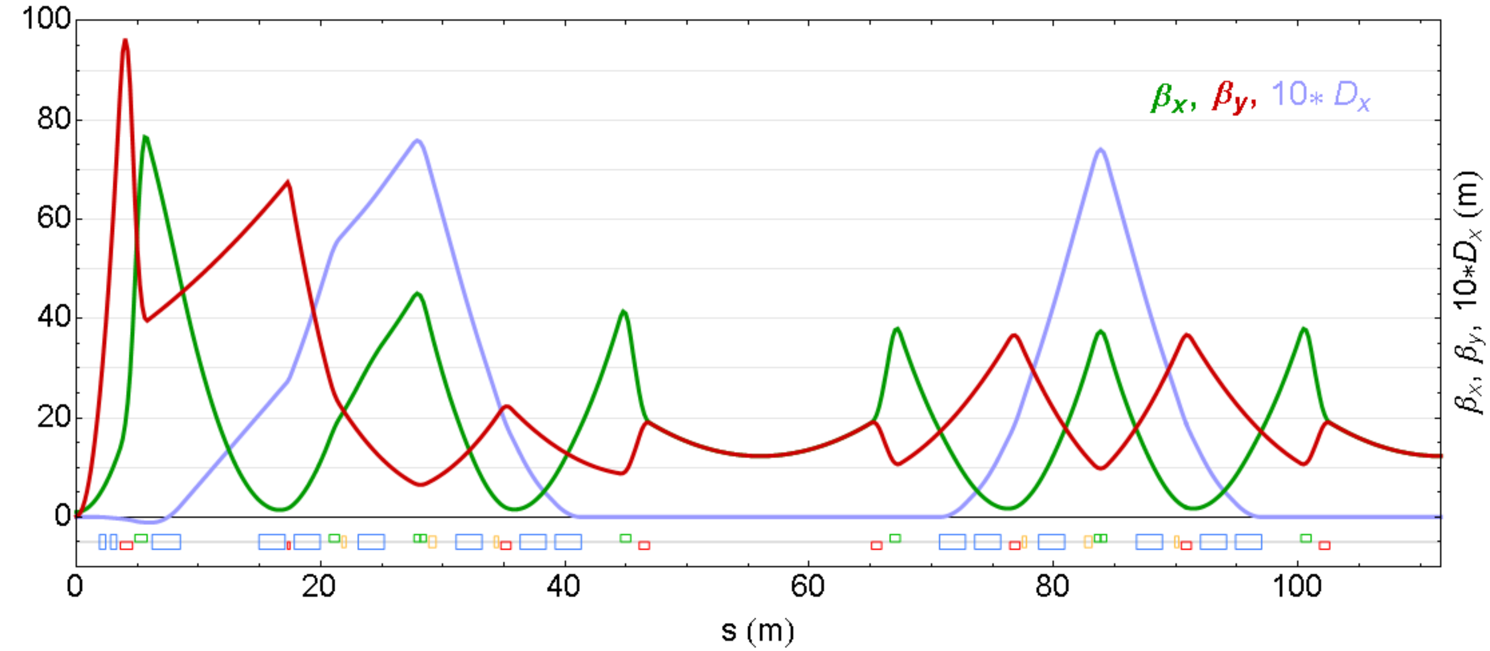


Georg Berg

Structure Funtions

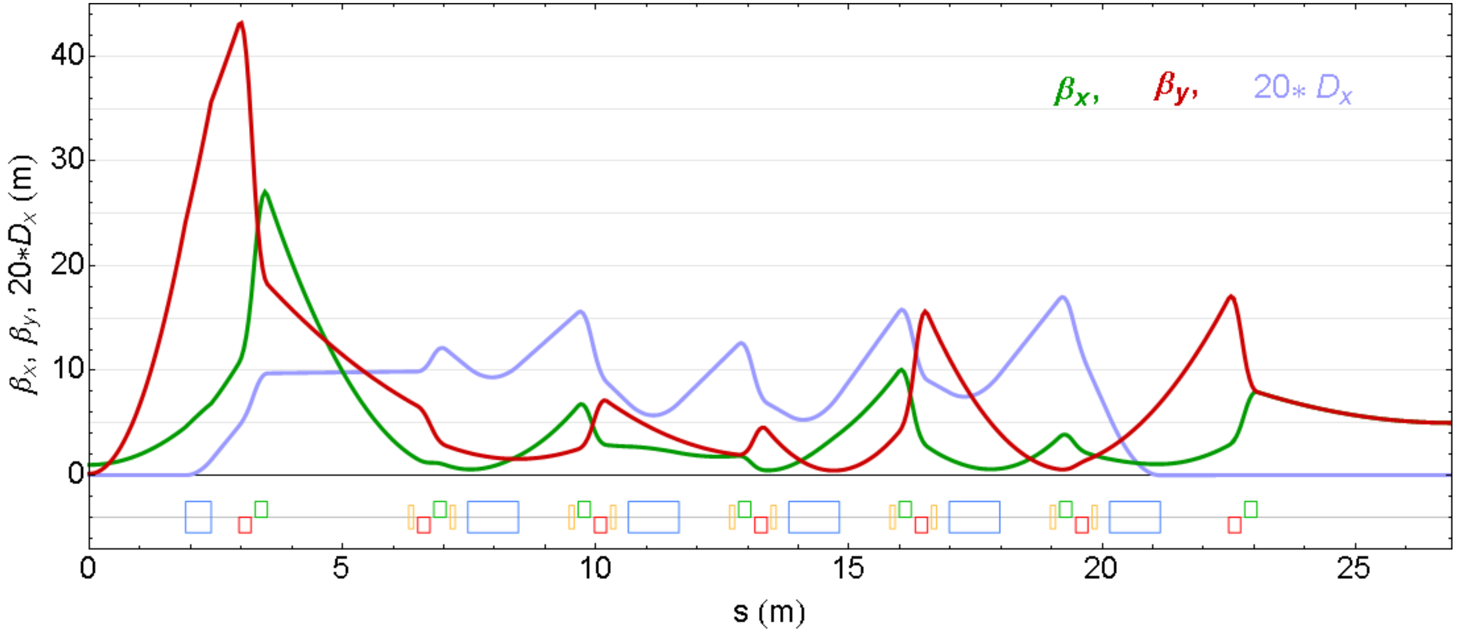
Ion ring

BetaX(IP): 150 cm
BetaZ(IP): 15 cm
BetaX(FF): 75 m
BetaZ(FF): 90 m
$\nu_x = \nu_z = 0.55$
$\varepsilon_x = \varepsilon_z = 50\ \mu m \cdot mrad$

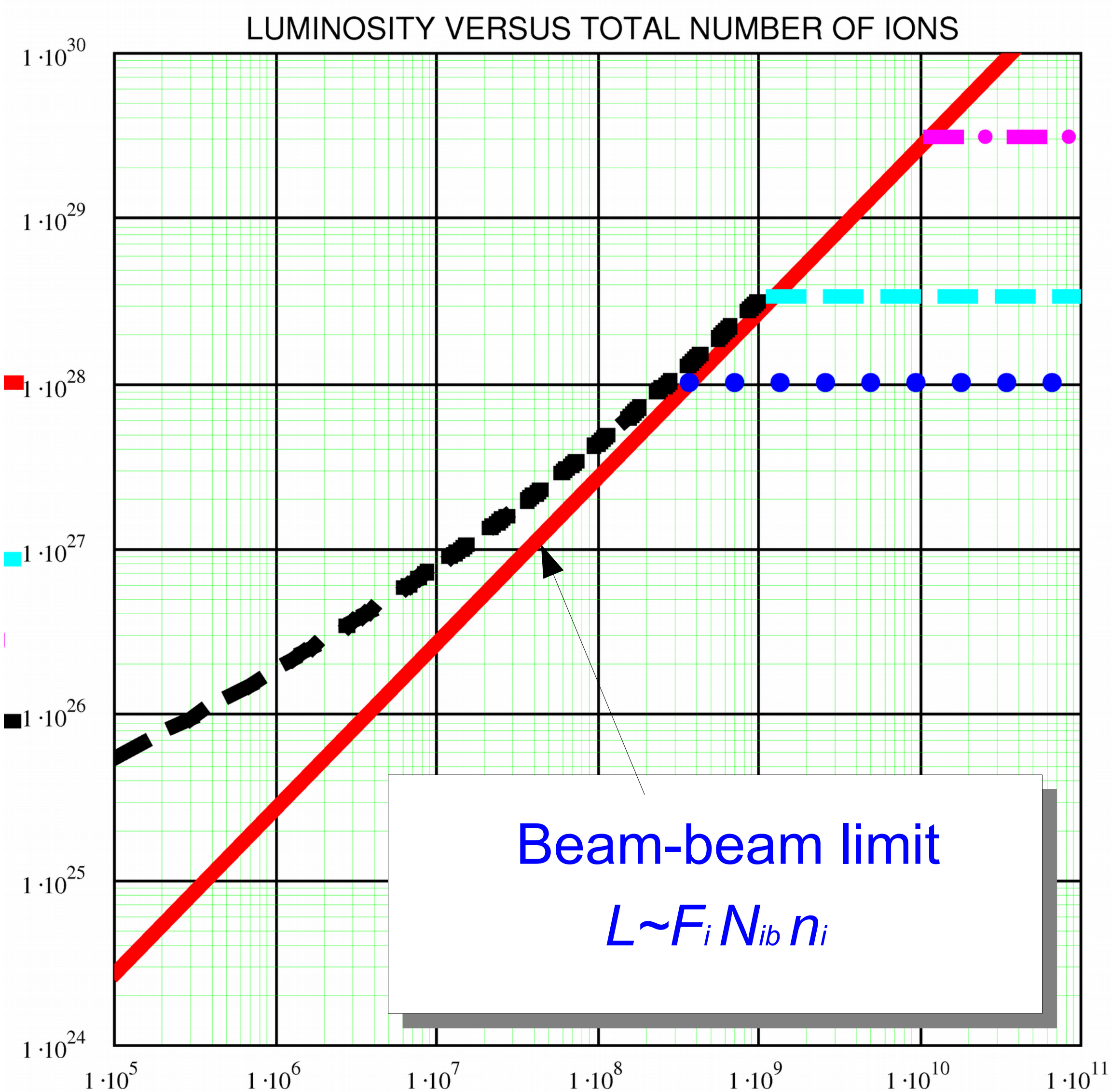


Electron ring

BetaX(IP): 150 cm
BetaZ(IP): 15 cm
BetaX(FF): 27 m
BetaZ(FF): 43 m
$\nu_x = \nu_z = 0.2$
$\varepsilon_x = \varepsilon_z = 50\ \mu m \cdot mrad$



Luminosity considerations



$$L = F_e n_e \frac{N_{eb} N_{ib}}{4\pi\sigma_x\sigma_z}$$

$$\xi_{ix} = \frac{Z}{A} \cdot \frac{N_{eb} r_p \beta_x}{2\pi\gamma_i\beta_i(\sigma_x+\sigma_z)\sigma_x}$$

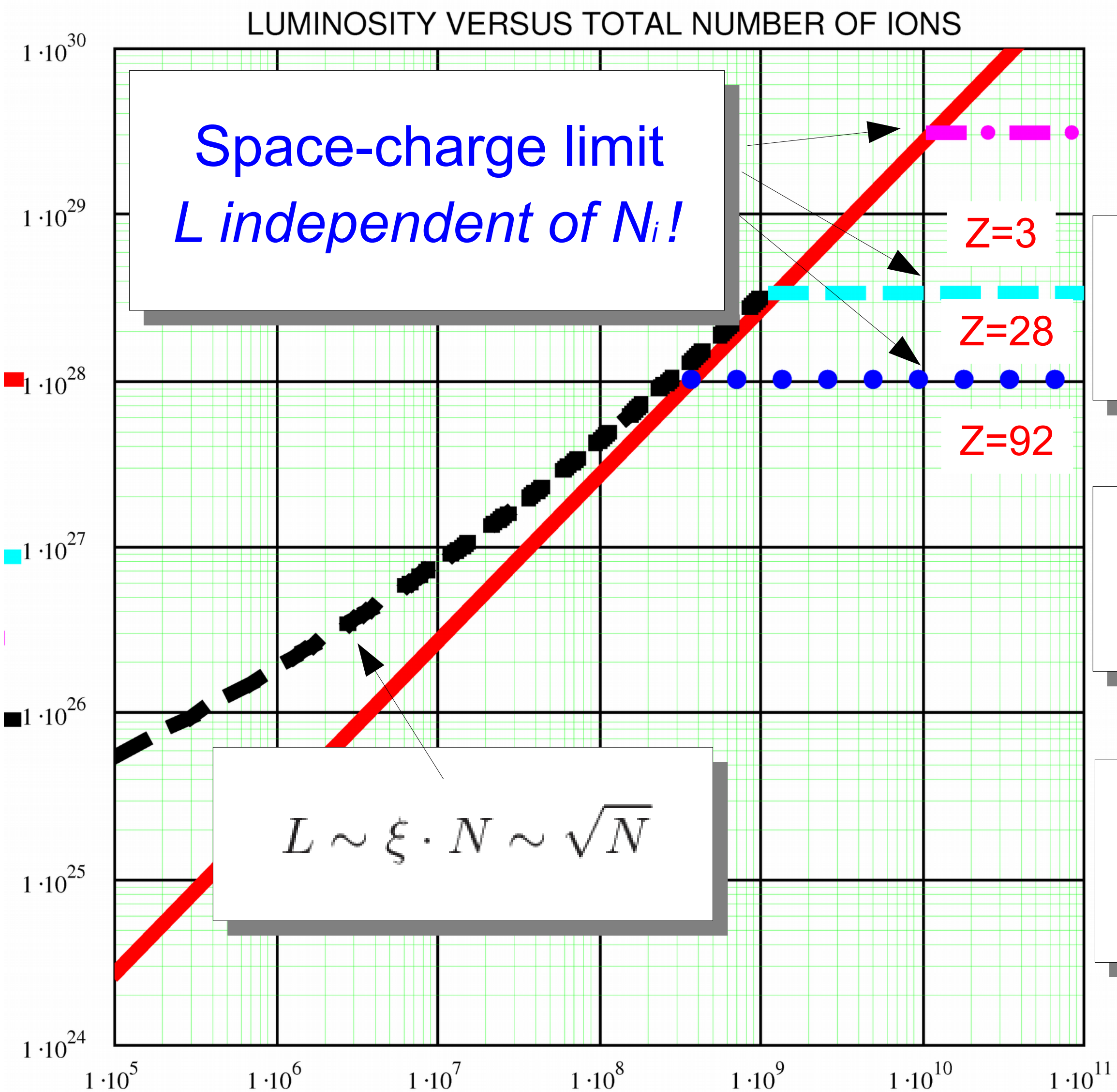
$$\xi_{iz} = \frac{Z}{A} \cdot \frac{N_{eb} r_p \beta_z}{2\pi\gamma_i\beta_i(\sigma_x+\sigma_z)\sigma_z}$$

$$\xi_{ix} = 0.05$$

$$\frac{N_{eb}}{2\pi\sigma_x\sigma_z} = \frac{A}{Z} \cdot \frac{\xi_{ix}\gamma_i\beta_i}{\sqrt{\beta_x\beta_z}} \cdot \left(1+\frac{\sigma_z}{\sigma_x}\right)$$

$$L_\xi = F_i n_i \cdot \frac{A}{Z} \cdot \left(1+\frac{\sigma_z}{\sigma_x}\right) \cdot \frac{N_{ib}\xi_{ix}\gamma_i\beta_i}{2r_p\sqrt{\beta_x\beta_z}}$$

Luminosity considerations



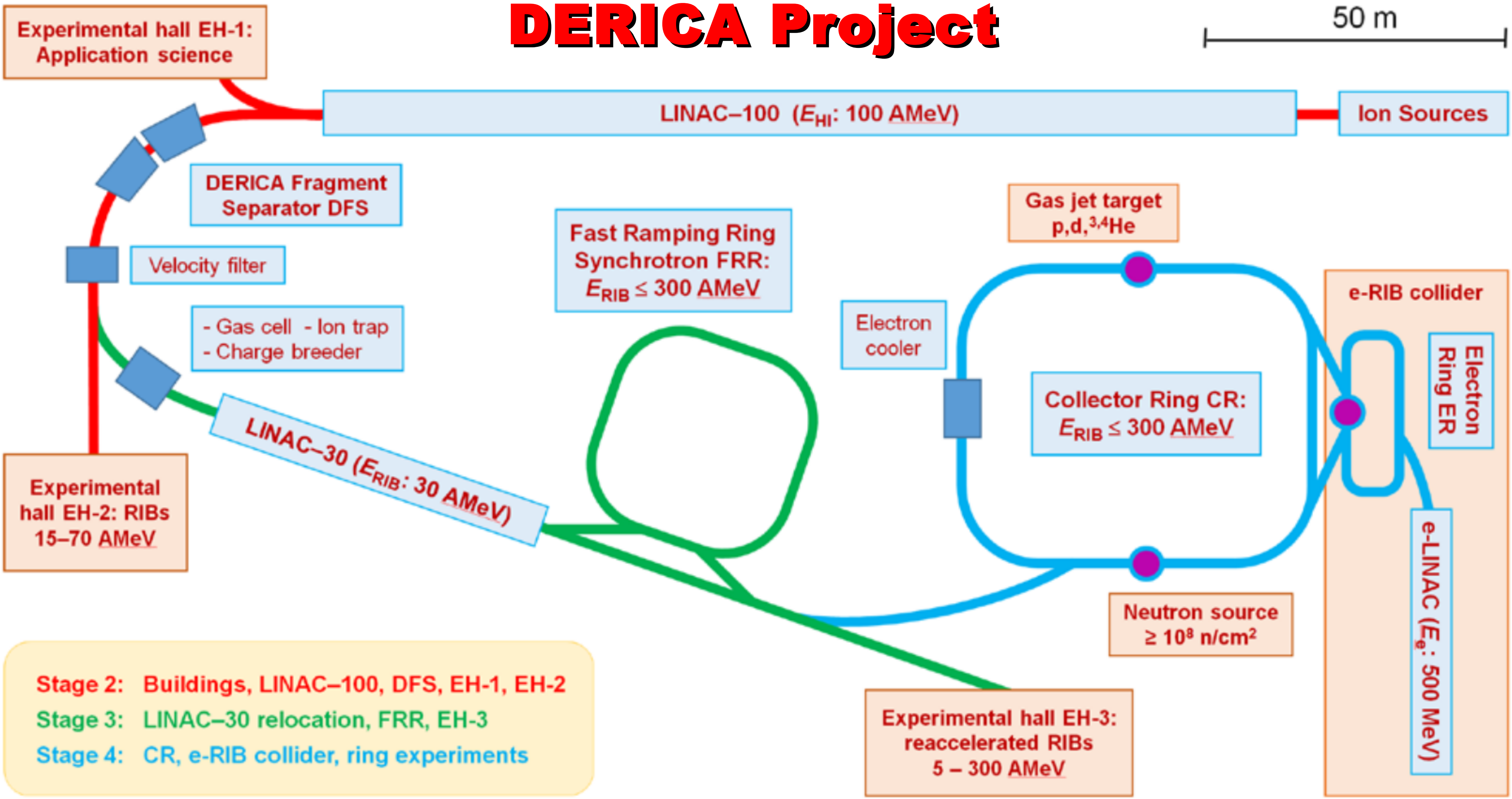
$\Delta\nu \approx 0.08$

$$\Delta\nu = \frac{Z^2}{A} \cdot \frac{N_{ib} r_p}{\gamma_i^3 \beta_i^2 \varepsilon} \cdot \frac{R}{2\sqrt{2\pi}\sigma_s}$$

$$\varepsilon = \frac{Z^2}{A} \cdot \frac{N_{ib} r_p}{\gamma_i^3 \beta_i^2 \Delta\nu} \cdot \frac{R}{2\sqrt{2\pi}\sigma_s}$$

$$L_{Ne} = F_e n_e \frac{A}{Z^2} \cdot \frac{N_{eb} \Delta\nu \gamma_i^3 \beta_i^2}{4\pi r_p \sqrt{\beta_x \beta_z}} \cdot \frac{2\sqrt{2\pi}\sigma_s}{R}$$

DERICA Project



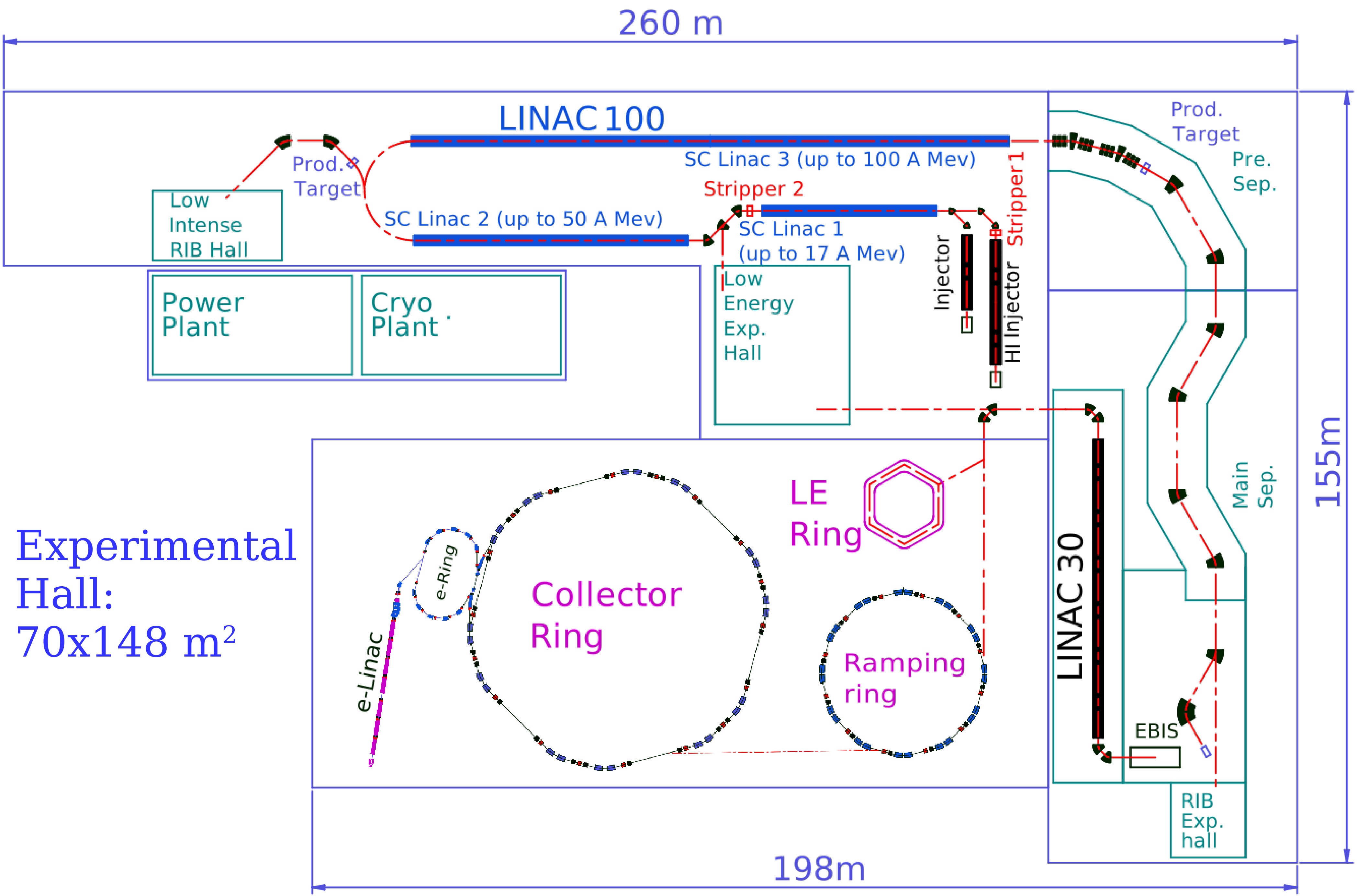
Energy (max): 300 MeV/u
Circumference CR: 222.9 m
β_i (max): 0.654
Circumference ER: 56.8 m (68.7)
Bunches rate: 1*6 (1*5)
A/Z: 2.7
Rigidity: 7.55 T·m

Status: In Development

Goal: 2030

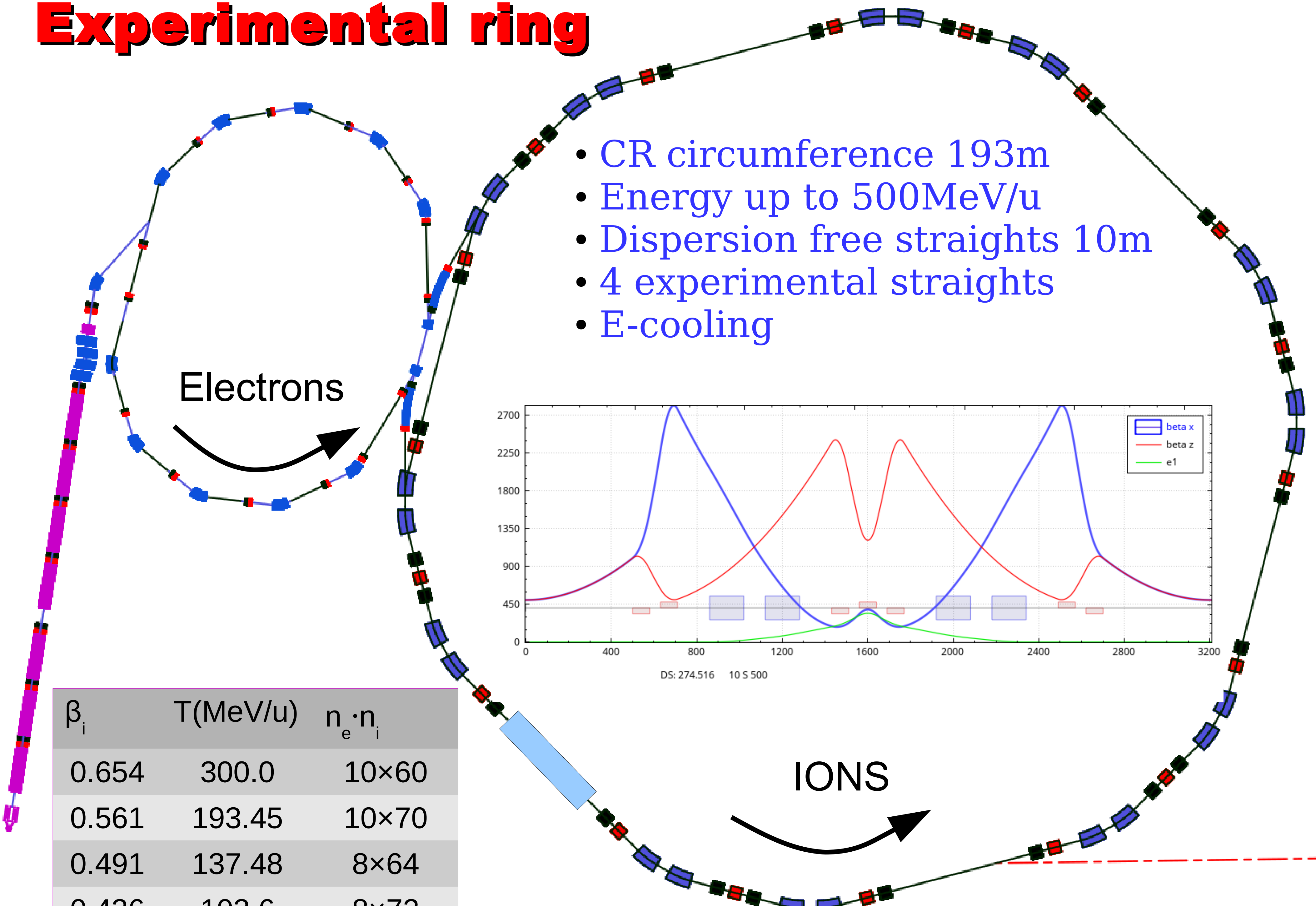
«Scientific programof DERICA –prospective acceleratorand storage ring facilityfor radioactive ion beam research» L. Grigorenko et al. UFN2019

Derica Project Layout



Experimental Hall:
70x148 m²

Experimental ring

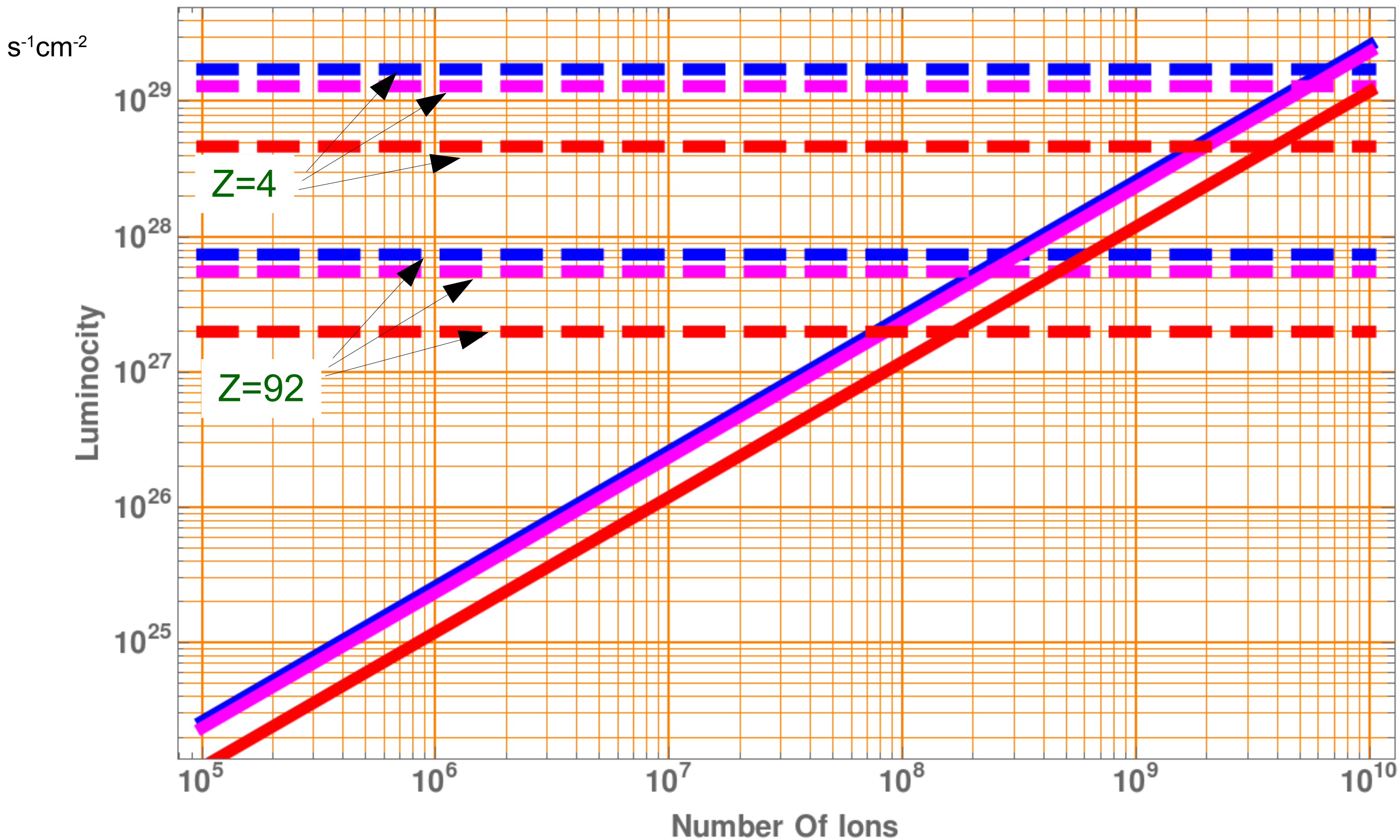


- CR circumference 193m
- Energy up to 500MeV/u
- Dispersion free straights 10m
- 4 experimental straights
- E-cooling

β_i	T(MeV/u)	$n_e \cdot n_i$
0.654	300.0	10×60
0.561	193.45	10×70
0.491	137.48	8×64
0.436	103.6	8×72

Luminosity comparison

	$^{11}Be^{4+}$	$^{248.4}U^{92+}$	Circumference	Energy MeV/u	Bunches
ELISE	$2.1 \cdot 10^{10}$	$4 \cdot 10^{8}$	222.9 m	740.0	8×40
MESR	$2.1 \cdot 10^{10}$	$4 \cdot 10^{8}$	173.56 m	485.35	8×40
DERICA	$1.5 \cdot 10^{10}$	-	222.9 m	300.0	11×55



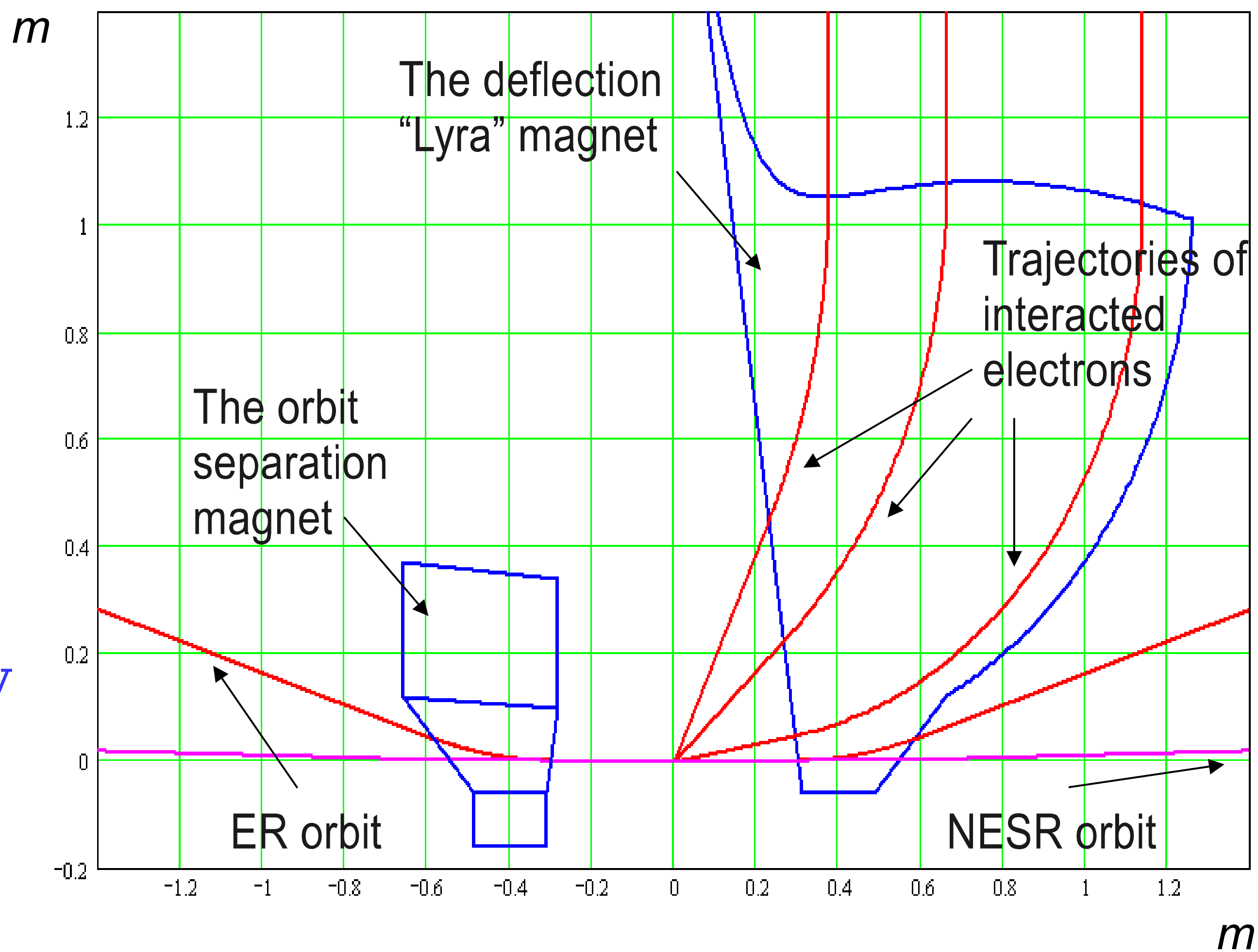
Electron Spectrometer Alternative

Disadvantages

- Complicated design
- Increased cost
- Supercoductivity

Advantages

- Angle 10° ¸ 75°
- Tight integration with Final Focusing
- Increased luminocity by factor of 3 ÷ 5
- Increased $F_i n_i$
- Supercoductivity



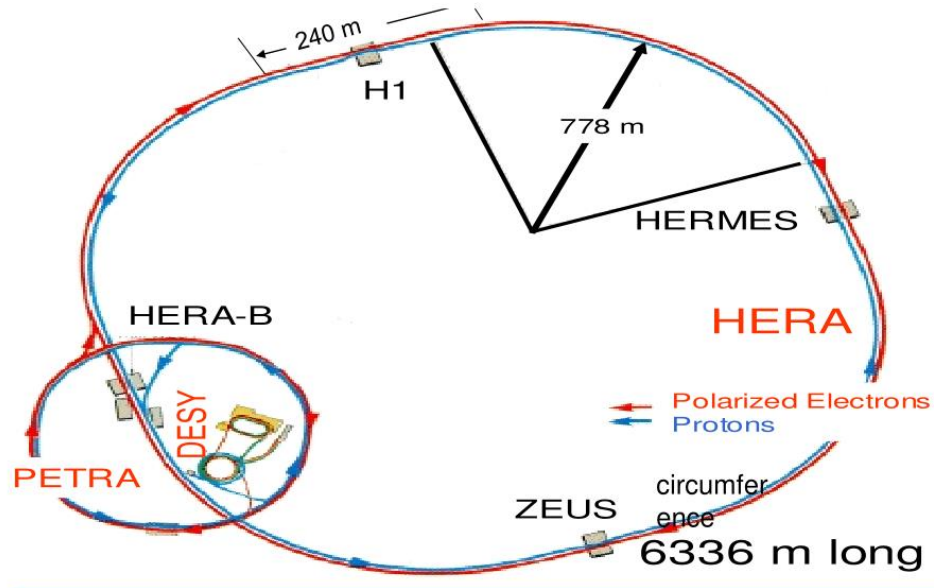
Ivan Koop

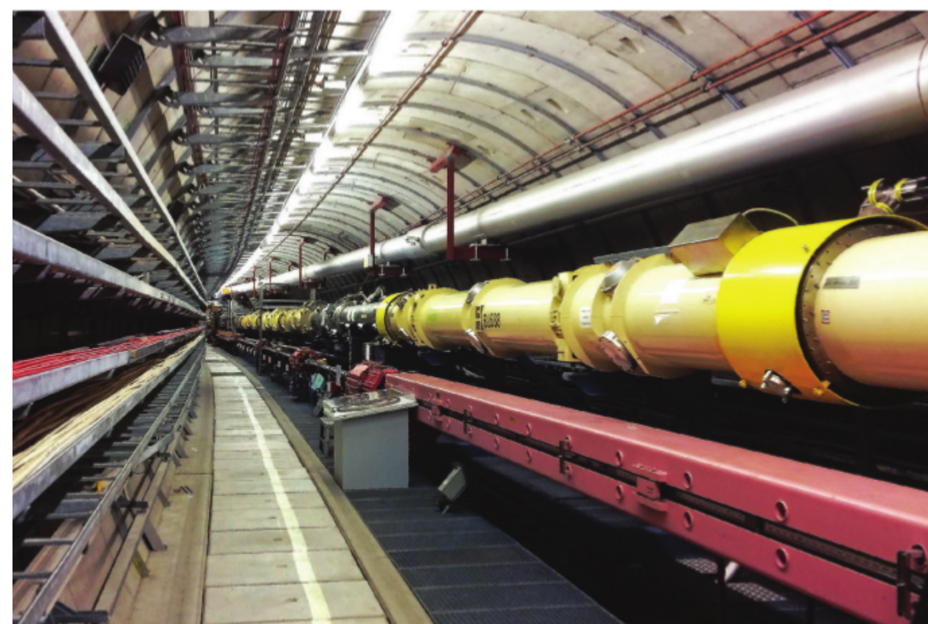
HERA Desy/Hamburg

1991-2007 ~1 fb^{-1}

Parameter	Units	Electron ring	Proton ring
Nominal energy	GeV	30	820
Circumference	m	6335.83	6335.83
Revolution frequency	s^{-1}	47317	47317
No. of bunches		210	210
No. of particles per bunch		3.65×10^{10}	10^{11}
Average current	mA	58	163
Transverse beam emittances ϵ_x/ϵ_z	10^{-9}m	41/5.1	8/3.4
Betafunctions at IP β_x/β_z	m	2/0.7	10/1
Beam size at IP $\sigma_x/\sigma_z = \sqrt{\epsilon\beta}$	mm	0.286/0.06	0.28/0.058
Luminosity	$cm^{-2}s^{-1}$	1.6×10^{31}	
Tune shift $\Delta Qx/\Delta Qz$		0.02/0.02	$10^{-3}/5 \times 10^{-4}$
Synchr. radiation loss per turn	MeV	125	6×10^{-6}
Synchr. radiation power	MW	7.2	10^{-6}
rf voltage	MV	200	2.4
rf frequency	MHz	500	208/52
Synchrotron tune		0.07	1.6×10^{-3}
Relative energy spread $\Delta E/E$		10^{-3}	10^{-4}
Bunch length (1σ)	cm	0.85	19
Length of beam-beam interaction (1σ)	cm	9.5	
Free space for detectors	m	±5.5	
Polarization time	min	35	—
Bending magnet length	m	9.185	8.824
Bending radius in the arcs	m	608.1	584
Bending field	T	0.165	4.68
Bending magnet aperture	mm	154 × 51	75 Ø
Vacuum chamber aperture	mm	80 × 40	56 Ø
Length of FODO cell	m	23.5	47
Horizontal and vertical betatron tune		47.2/48.35	31.3/32.3

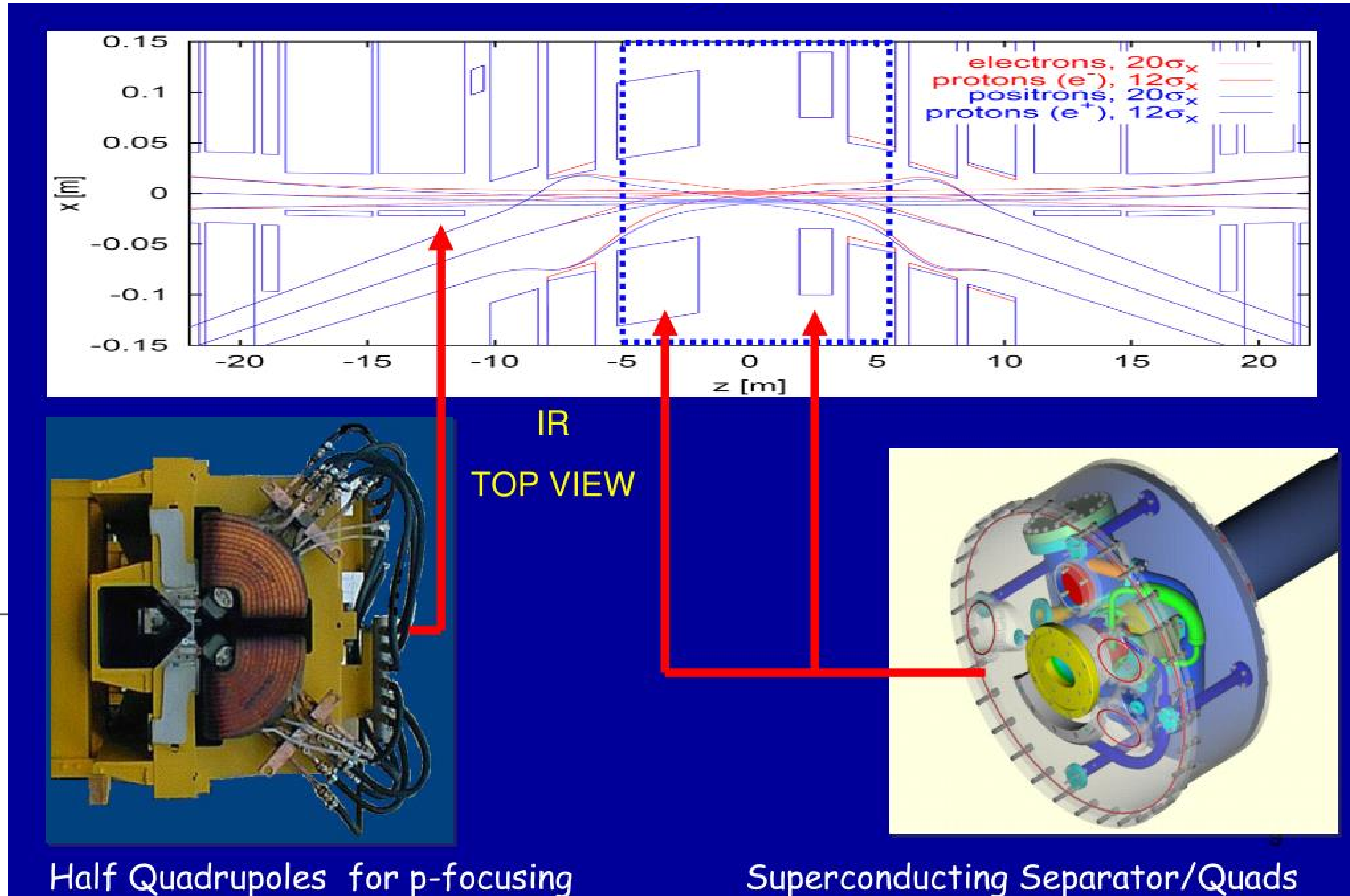
HERA Footprint

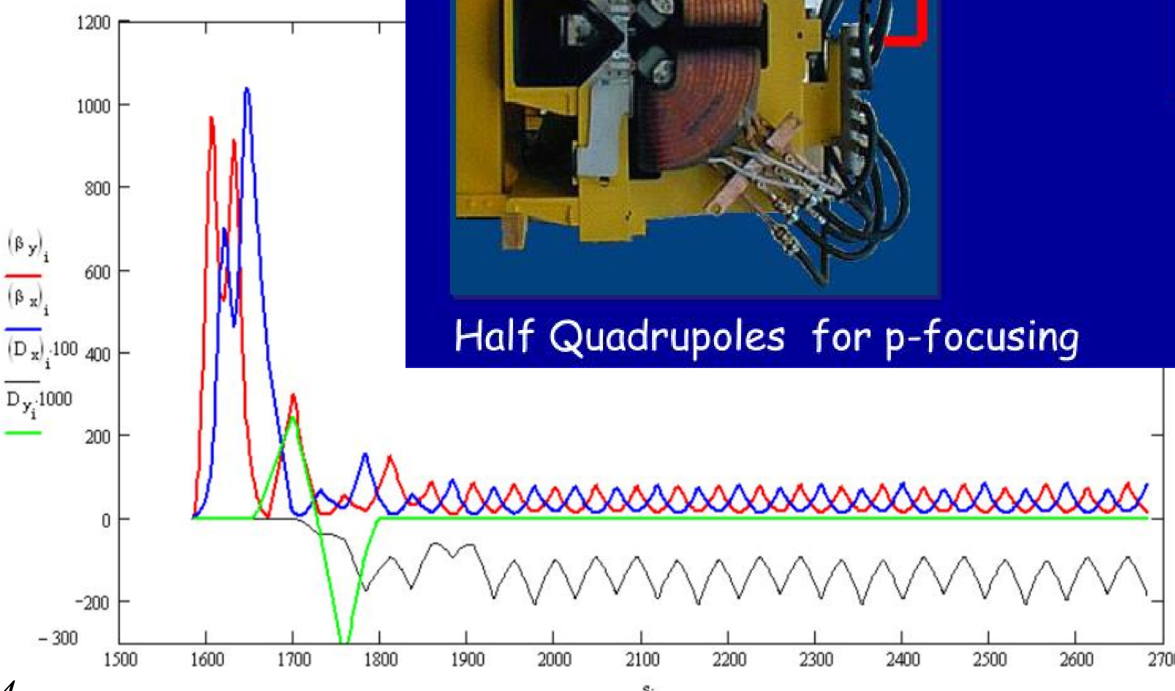




«THE ELECTRON-PROTON COLLIDER HERA»
G.-A. Voss and B. H. Wiik, 1994

HERA IP Region

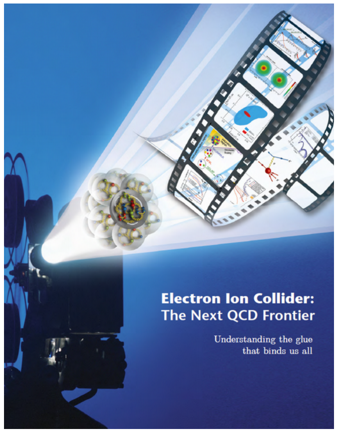




«HERA Luminosity» ZEUS Weekly Collaboration Meeting, January 22, 2007, F. Willeke

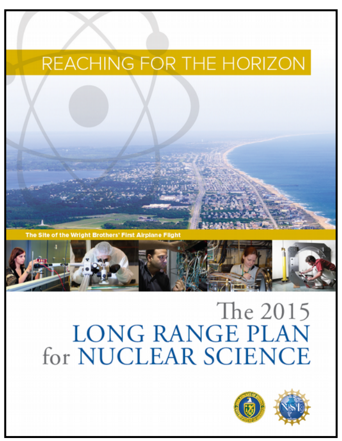
Dubna, 29.10.2019

Electron-Ion Collider Project, USA



Goal: Start experiment at 2030

The EIC is designed to meet the requirements set forth in the Community White Paper and re-emphasized in 2015 NSAC Long Range Plan and the NAS report:

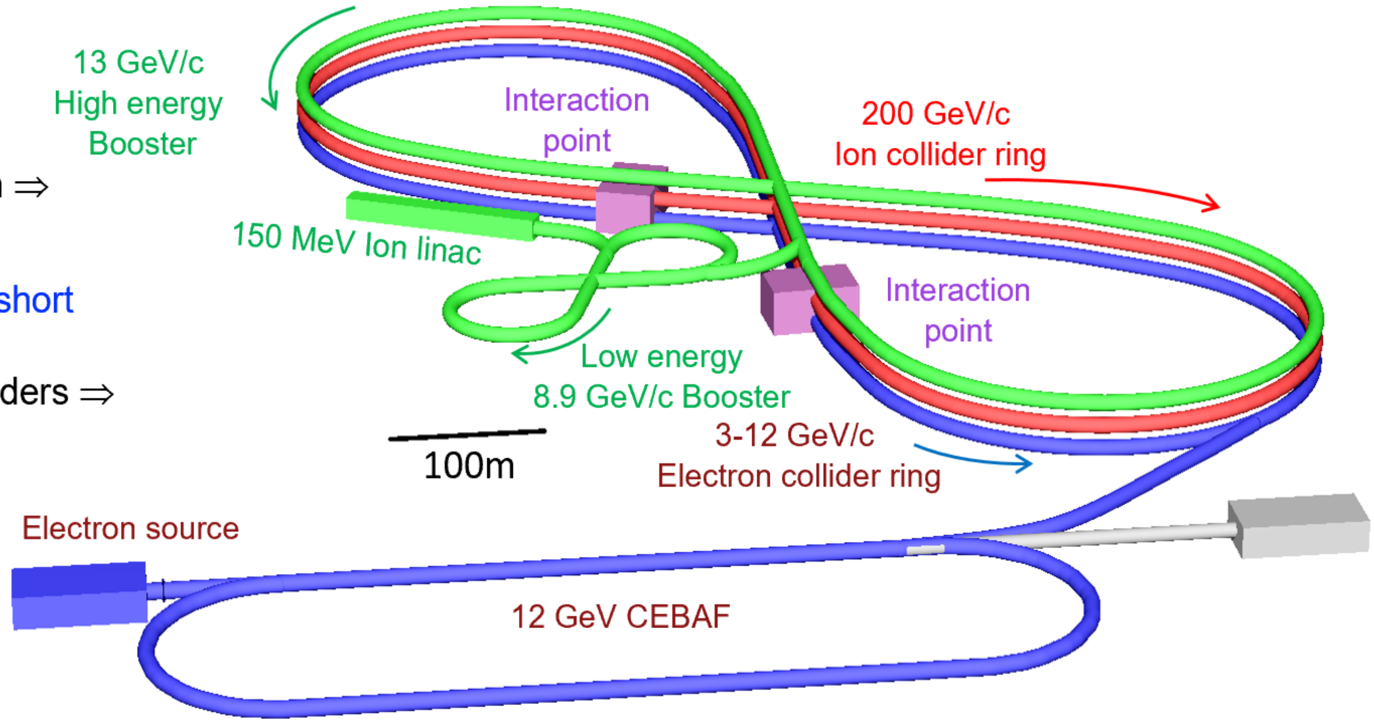


- Highly polarized (~70%) electron and nucleon beams
- Ion beams from deuterons to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~20 - ~100 GeV, upgradable to ~140 GeV
- High collision luminosity $\sim 10^{33} - 10^{34}$ $cm^{-2}s^{-1}$
- Possibilities of having more than one interaction region

«EIC accelerator overview» Vadim Ptitsyn, Workshop on Physics and Detector Requirements at Zero-Degree of Colliders, Stony Brook 2019

JLEIC Scheme

- Full-energy top-up injection of highly polarized electrons from CEBAF ⇒ High electron current and polarization
- Full-size high-energy booster ⇒ Quick replacement of colliding ion beam ⇒ High average luminosity
- High-rate collisions of strongly-focused short low-charge low-emittance bunches similarly to record-luminosity lepton colliders ⇒ High luminosity
- Multi-stage electron cooling using demonstrated magnetized cooling mechanism ⇒ Small ion emittance ⇒ High luminosity

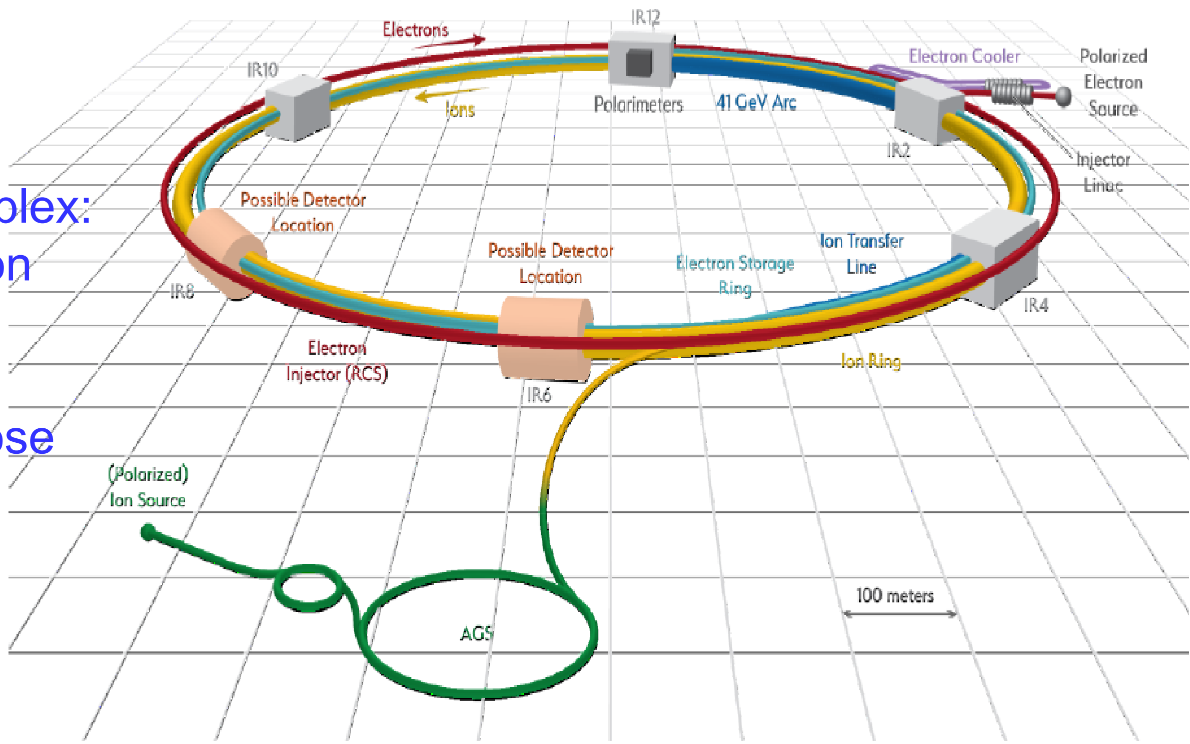


- Figure-8 ring design ⇒ High electron and ion polarizations, polarization manipulation and spin flip
- Integrated full acceptance detector with far-forward detection sections being parts of both machine and detector
- Upgradable to 140 GeV CM by replacing the ion collider bending dipoles only with 12 T magnets

«THE US ELECTRON-ION COLLIDER ACCELERATOR DESIGNS» A. Seryi et al. Proceedings of NAPAC2019.

eRHIC Scheme

- **Hadrons up to 275 GeV**
  eRHIC is using the existing RHIC complex: Storage ring (Yellow Ring), injectors, ion sources, infrastructure,
- Need only few modifications for eRHIC
- Todays RHIC beam parameters are close to what is required for eRHIC

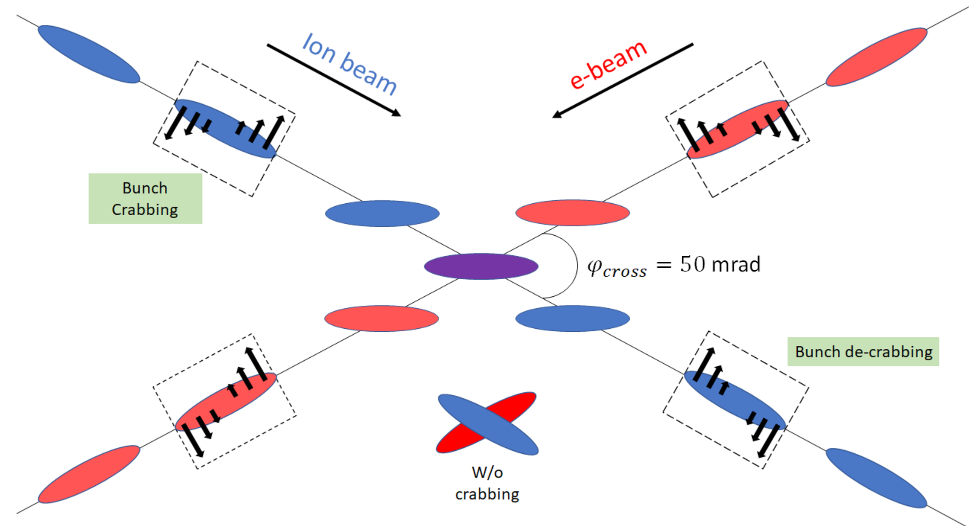


Electrons up to 18 GeV

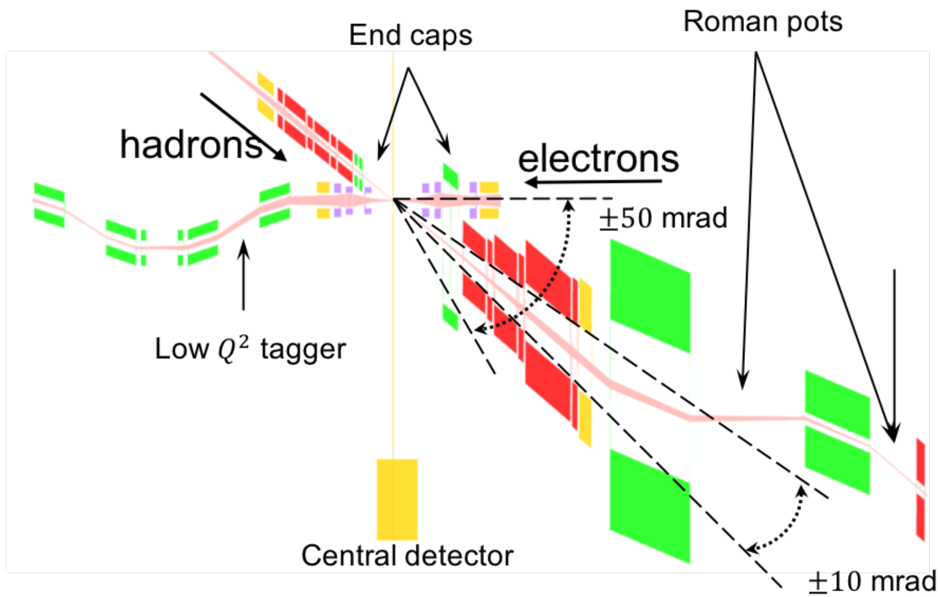
- Electron storage ring with up to 18GeV ® E_{cm} = 20 GeV -141 GeV installed in RHIC tunnel. Beam current are limited by the choice of installed RF power 10 MW.
- Electron beams with a variable spin pattern accelerated in the on-energy, spin transparent injector: Rapid Cycling Synchrotron with 1-2 Hz cycle frequency in the RHIC tunnel
- Polarized electron source and 400 MeV s-band injector linac in existing tunnel
- Design meets the high luminosity goal of **$L = 10^{34} cm^{-2} s^{-1}$**

EIC Interection regions

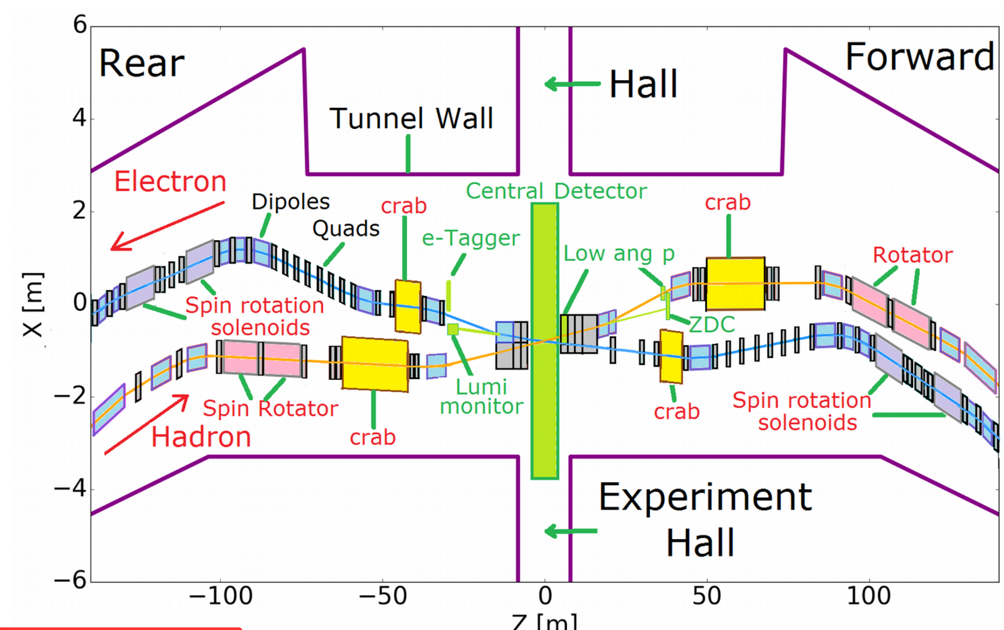
Crossing angle is necessary to avoid parasitic collisions due to short bunch spacing, make space for machine elements, improve detection and reduce detector background, θ_c = 50 mrad (JLEIC), 25mrad (eRHIC)



JLEIC

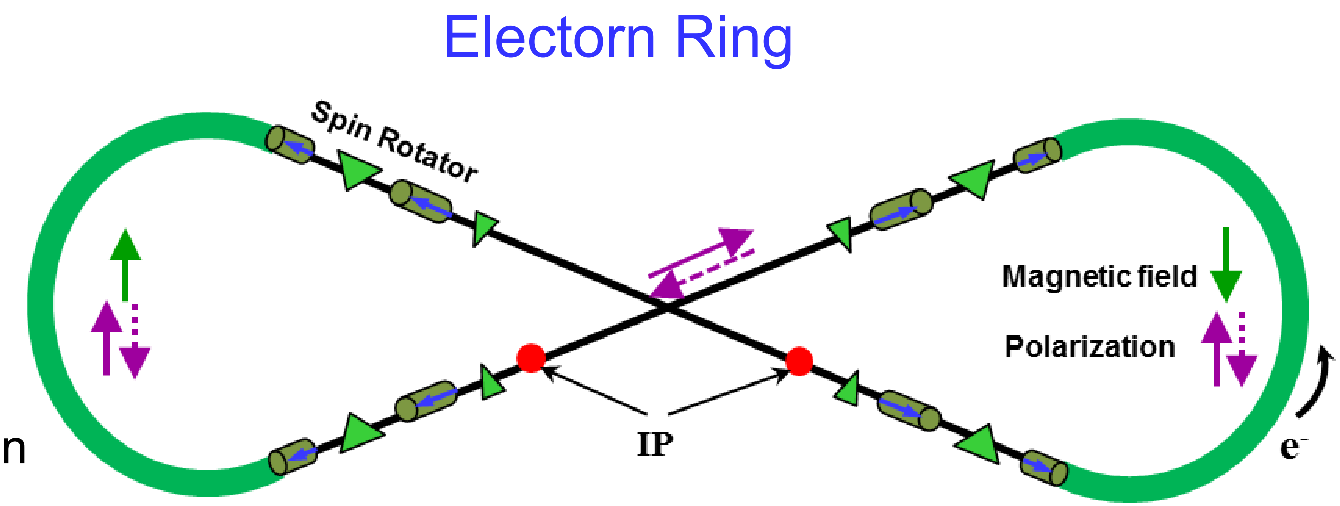


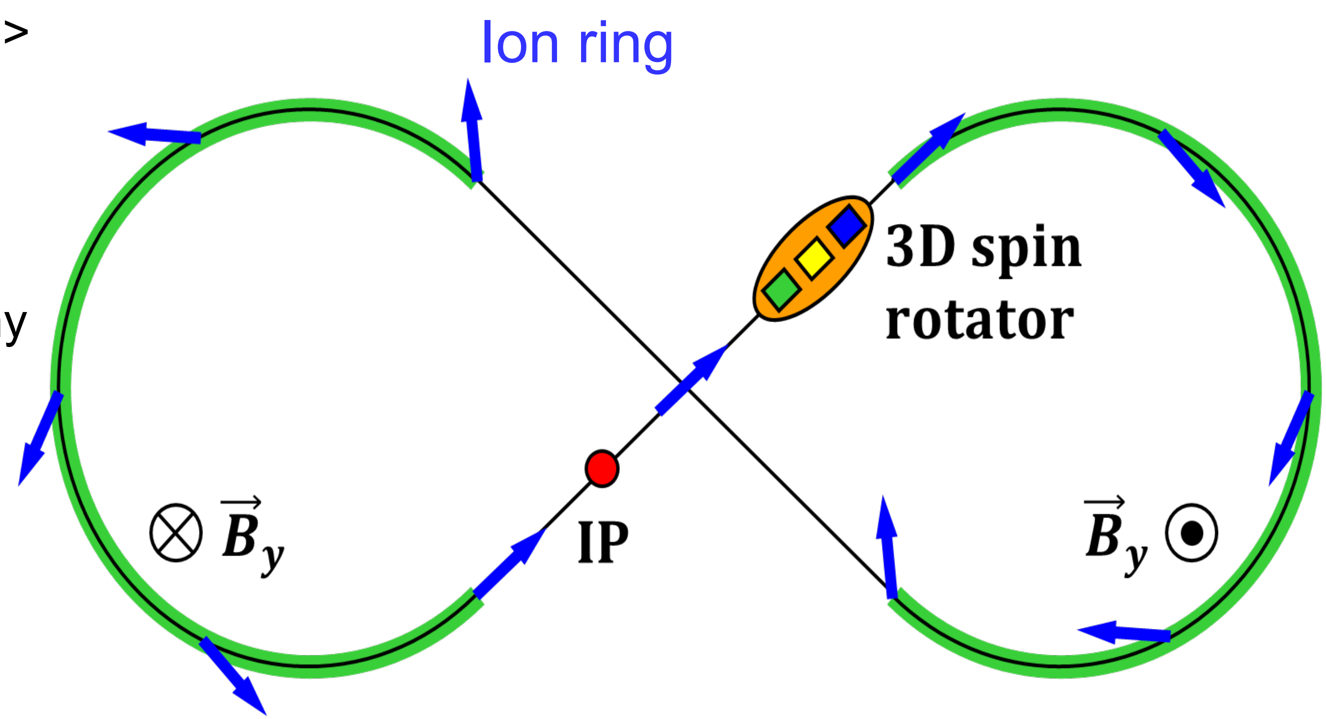
eRHIC



«ELECTRON ION COLLIDER MACHINE DETECTOR INTERFACE» B. Parker et al. Proceedings of NAPAC2019.

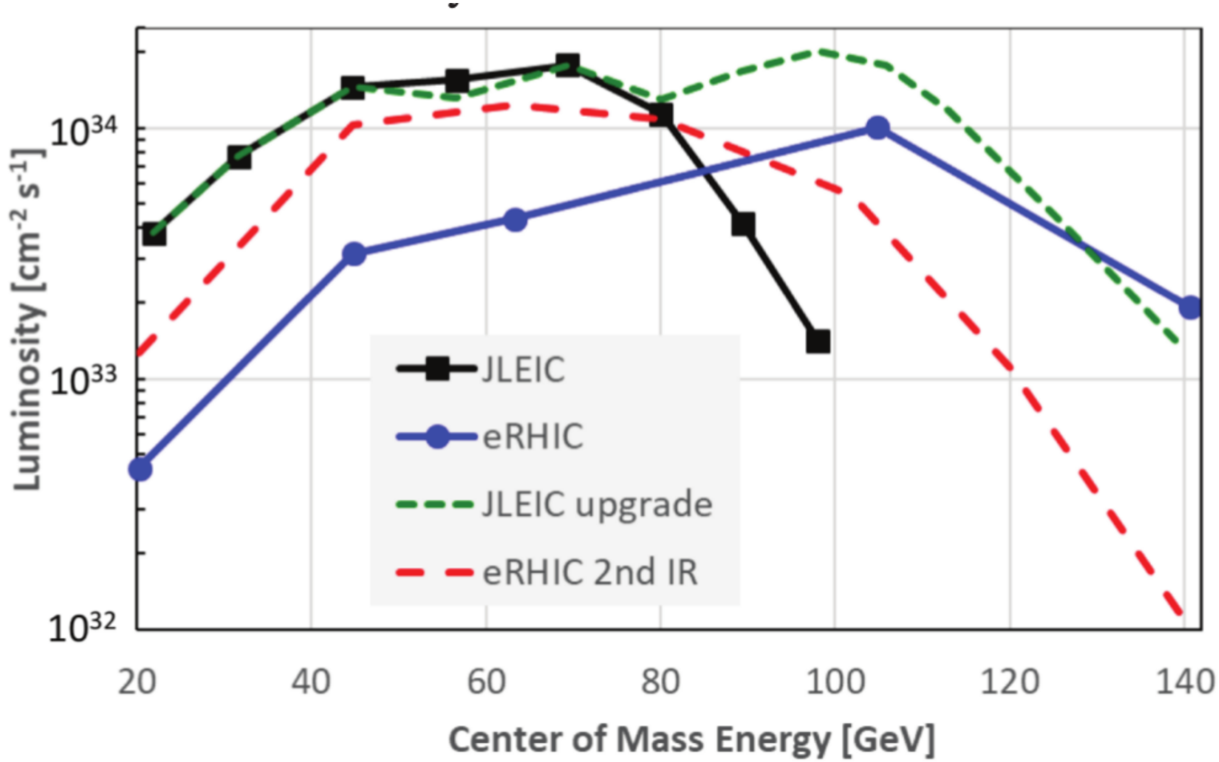
JLEIC Polarization





- Figure-8 concept: Spin precession in one arc is exactly cancelled in the other
- Criterion: induced spin rotation >> spin rotation due to orbit errors
- 3D spin rotator: combination of small rotations about different axes provides
- any polarization orientation at any point in the collider ring
- No effect on the orbit
- Polarized deuterons
- Frequent adiabatic spin flips

EIC Parameters and Luminosity

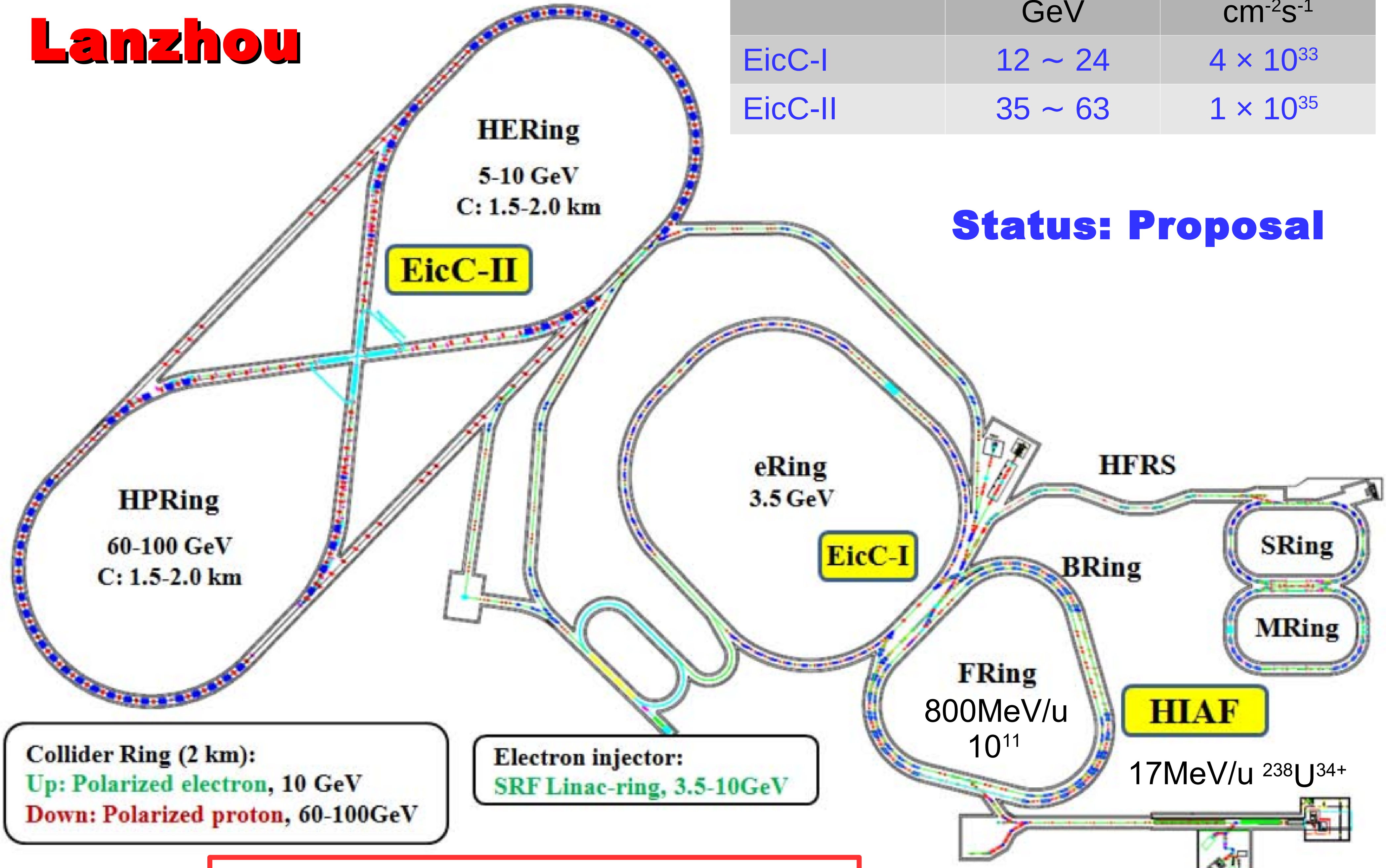


design	eRHIC		JLEIC		eRHIC-opt.		JLEIC-upgrade	
parameter	proton	electron	proton	electron	proton	electron	proton	electron
center-of-mass energy [GeV]	104.9		44.7		63.3		105.8	
energy [GeV]	275	10	100	5	100	10	400	7
number of bunches	1160		3456		2320		864	
particles per bunch [10^{10}]	6.9	17.2	1.06	4.72	3.4	8.6	4.2	19.3
beam current [A]	1.0	2.5	0.75	3.35	1.0	2.5	0.75	3.4
beam polarization [%]	80	80	85	85	80	80	85	85
total crossing angle [mrad]	25		50		50		50	
ion forward acceptances [mrad]	±20/±4.5		±50/±10		±35/±8		±50/±5.6	
h./v. norm. emittance [μm]	2.8/0.45	391/24	0.65/0.13	83/16.6	1.5/0.15	391/24	3/0.5	228/45.6
bunch length [cm]	6	2	2.5	1	4	2	3.5	1
β_x^* / β_y^* [cm]	90 / 4.0	43 / 5.0	8 / 1.3	5.72 / 0.93	18 / 2	13 / 2.4	40 / 2.25	16.9 / 0.8
hor./vert. beam-beam param.	.014/.007	.073/.1	.015/.0135	.049/.044	.012/.013	.036/.062	.014/.008	.076/.037
peak lumi. [10^{34}cm^{-2}s^{-1}]	1.01		1.46		1.24		1.78	
average lumi. [10^{34}cm^{-2}s^{-1}]	0.93*		1.4		0.95*		1.47*	

EIC China Lanzhou

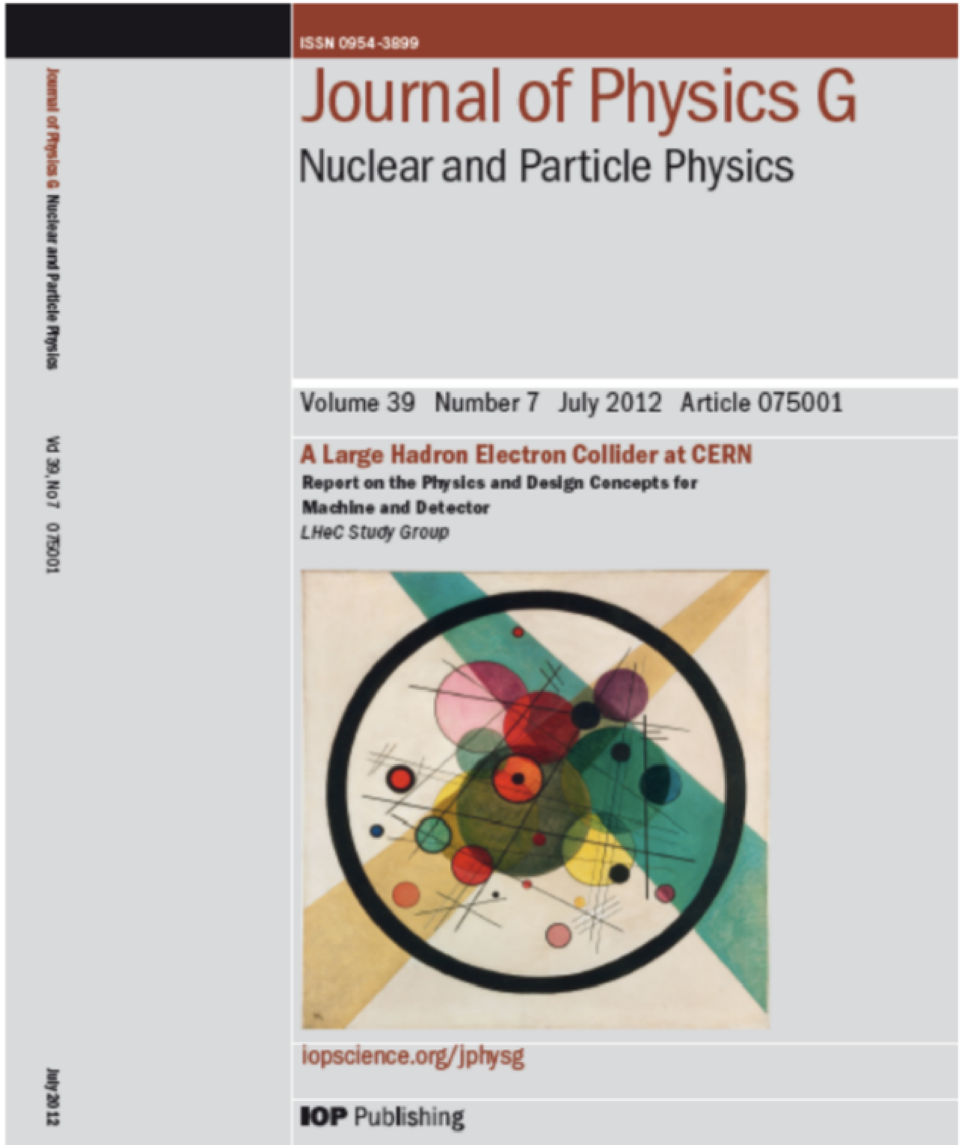
	CMS Energy GeV	Luminosity $cm^{-2}s^{-1}$
EicC-I	12 ~ 24	4×10^{33}
EicC-II	35 ~ 63	1×10^{35}

Status: Proposal



X. Chen, A Plan for Electron Ion Collider in China, PoS DIS2018 (2018) 170

LHeC CERN



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A Large Hadron Electron Collider at CERN
Report on the Physics and Design Concepts for Machine and Detector
LHeC Study Group

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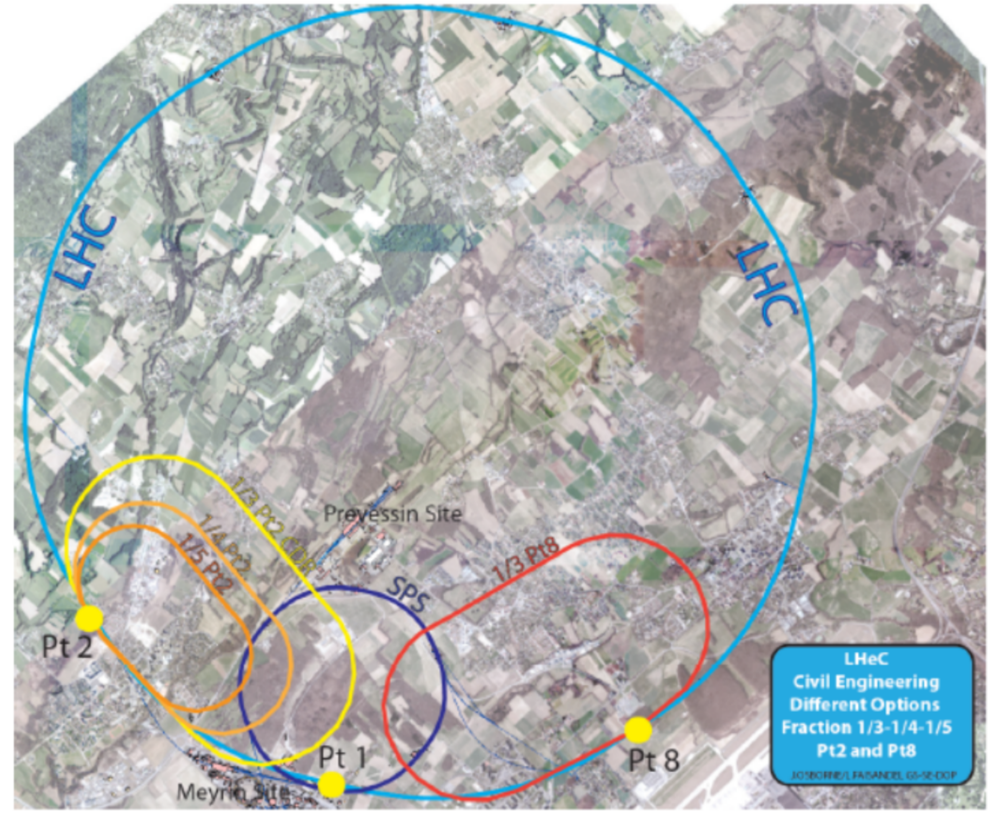

Status:
Published 600 pages conceptual design report (CDR) written by 200 authors from 60 Institutes in 2012
Goal: 2040?

«The Case for the LHeC» Max Klein, Contribution to a Panel on Future DIS, 17.4.2018, Kobe

LHeC on One Page

E_e = 10-60 GeV, E_p =1-7 TeV: √s = 200 – 1300 GeV. **Kinematics**: $0 < Q^2 < s$, $1 > x \geq 10^{-6}$ (DIS)
Electron Polarisation P=±80%. Positrons: significantly lower intensity, unpolarised
Luminosity: $O(10^{34})$ $cm^{-2} s^{-1}$. integrated O(1) ab^{-1} for HL LHC and 2 ab^{-1} for HE LHC/FCCeh
e-ions 6 10^{32} $cm^{-2} s^{-1}$ O(10)fb^{-1} in ePb . O(1)fb^{-1} for ep F_L measurements

Physics: QCD: develop+break? The worlds best microscope. BSM (H, top, ν, SUSY..)
Transformations: Searches at LHC, LHC as Higgs Precision Facility, QCD of Nuclear Dynamics
The LHeC has a deep, unique QCD, H and BSM precision and discovery physics programme.

Time: Determined by the Large Hadron Collider (HL LHC needs till ~2040 for 3 ab^{-1})
LHeC: Detector Installation in 2 years, earliest in LS4 (2030/31).
HE LHC: re-use ERL. In between HL-HE, 10 years time of ERL Physics (laser, γγ..)
Very long term: FCC-eh

Challenges: Development of ERL Technology (high electron current, multi-turn)
Design 3-beam IR for concurrent ep+pp operation, New Detector with Taggers - in 10 years.

The LHeC is a great opportunity to sustain deep inelastic physics within future HEP.
The cost of an ep Higgs event is O(1/10) of that at any of the 4 e^+e^- machines under consideration
It can be done: the Linac is shorter than 2 miles and the time we have longer than HERA had.

CERN and world HEP: Vital to make the High Luminosity LHC programme a success.

Thank You!