Conceptual Study for Polarized Proton-Antiproton Collider at FAIR

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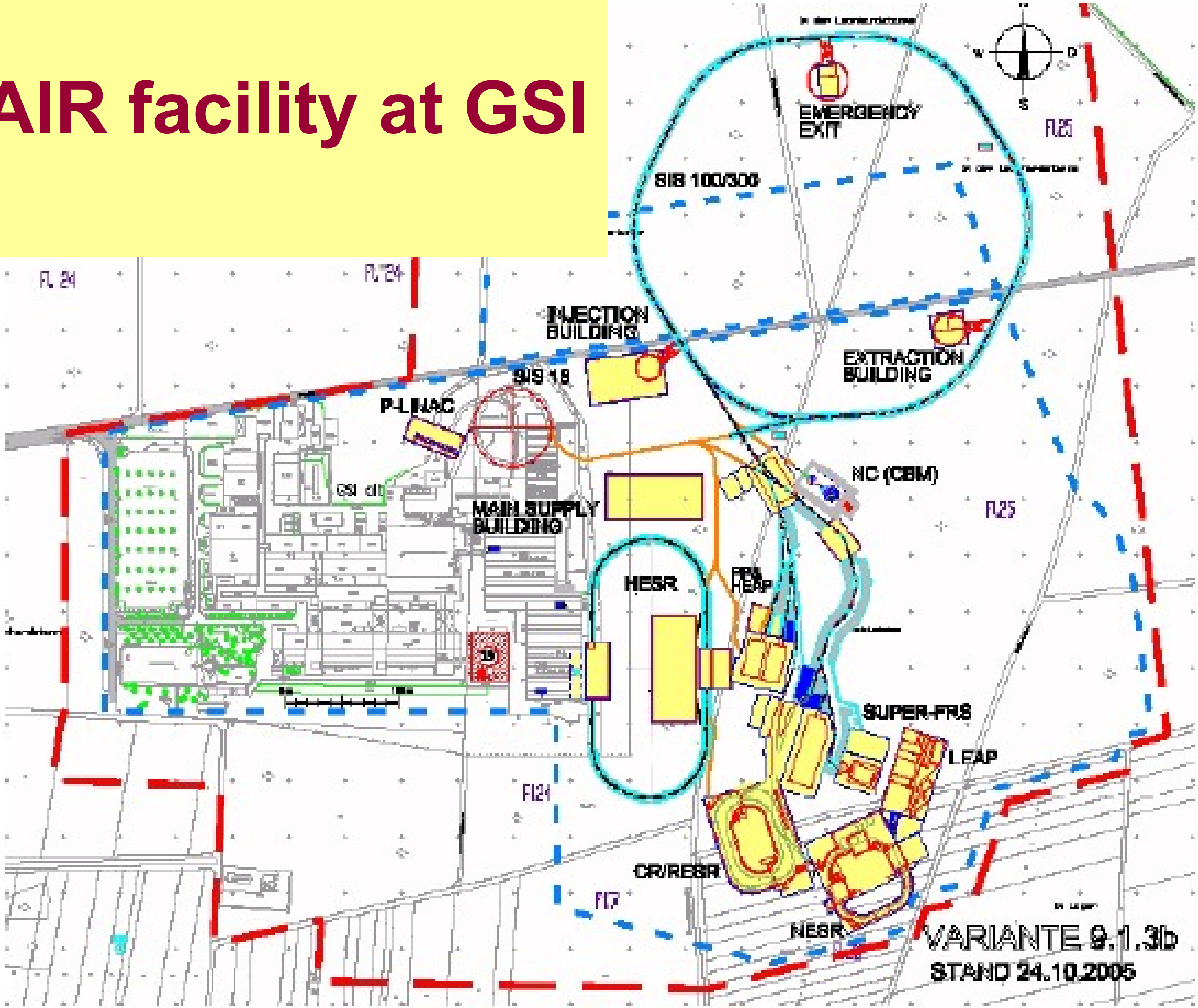
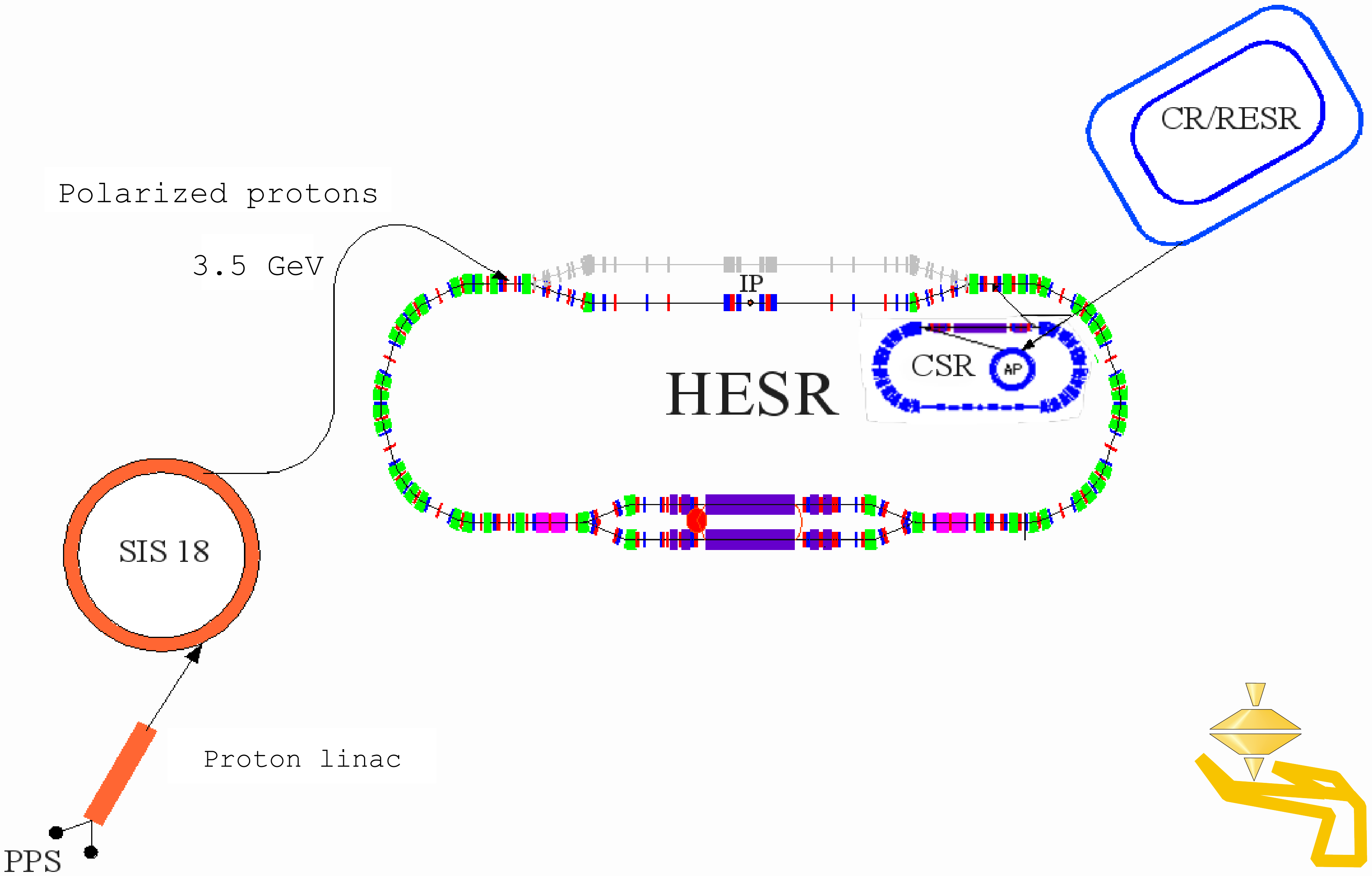
topics

- HESR collider option (15×15 GeV)
- luminosity considerations
- intra beam scattering and electron cooling
- basic parameters of p-pbar collider
- optics of the collider
- asymmetric collider option (3.5×15 GeV)
- polarized proton acceleration at SIS-18
- polarized antiprotons
- summary

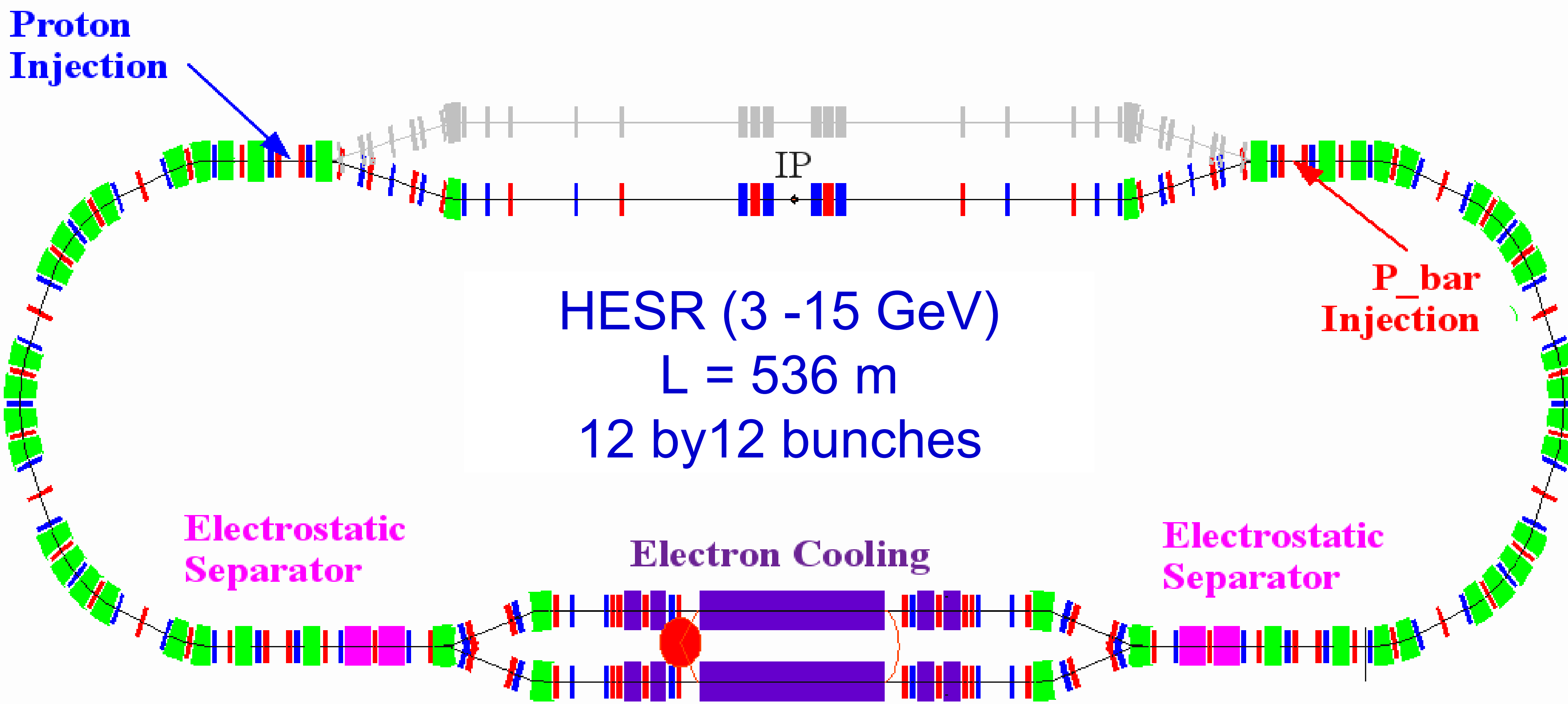
FAIR facility at GSI



Schematic layout of polarization facility



Layout of the p-pbar collider



Luminosity considerations

$$\dot{N}_{\bar{p}} = 2 \times 10^6\ s^{-1}$$

rate of polarized p-bar production

$$L_{max} = \frac{\dot{N}_p}{\sigma_{total}} = 5 \times 10^{31} cm^{-2} s^{-1}$$

$$\sigma_{total} = 40\ mb$$

p-bar losses total cross section

Coulomb scattering cross-section: $\sigma_{Coulomb} = \frac{\pi r_p^2}{\gamma^2 \beta^4 \theta_{max}^2} = 12\mu barn$ $(\theta_{max} = 5\ mrad)$

Assumptions:

- $N_p = 10^{12}$ distributed in $n_b = 12$ bunches.
- $N_{\bar{p}} = (0.1 \leftrightarrow 1) \cdot 10^{12}$
- $\sigma_s = \beta_0 = 30\ cm$
- round beams
- electron cooling will squeeze beams to the space charge limit

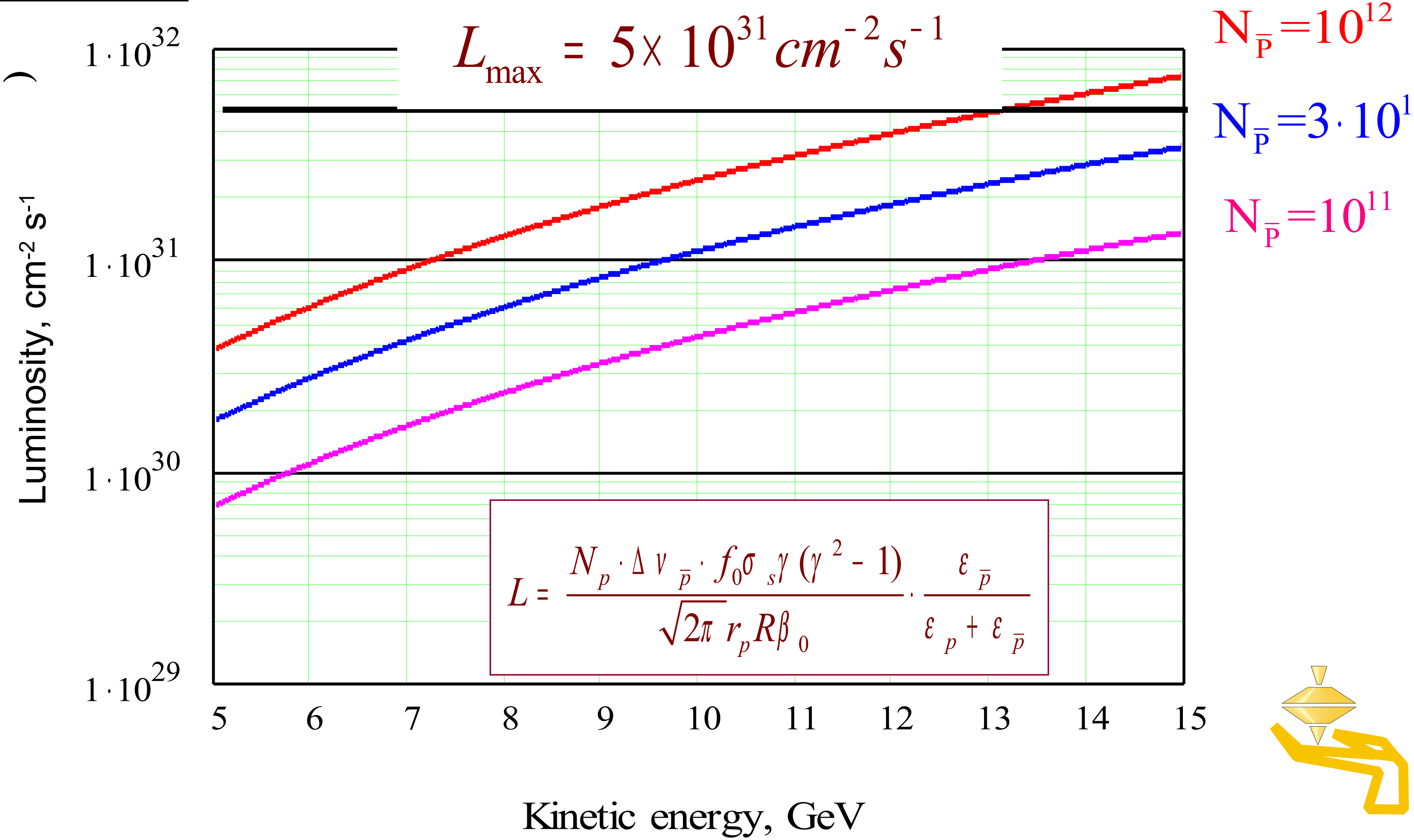
$$L = \frac{N_p N_{\bar{p}} f_0}{n_b 2\pi (\varepsilon_p + \varepsilon_{\bar{p}}) \beta^*}$$

Limitations:

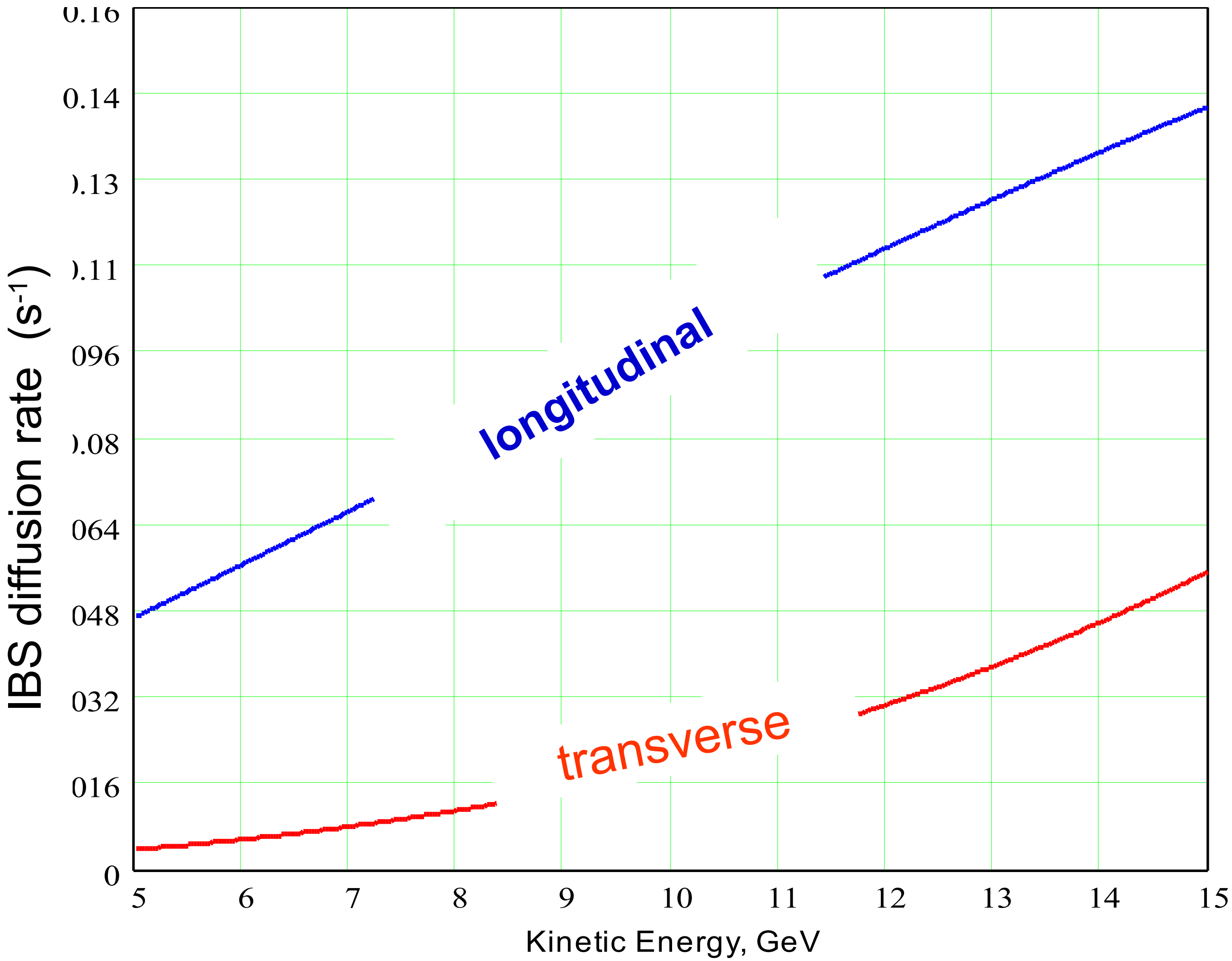
- space-charge effect $\Delta \nu_p = \frac{N_p r_p R}{2\sqrt{2\pi}\, n_b \sigma_s \varepsilon_p \gamma (\gamma^2 - 1)} \le 0.1$
- instabilities in electron cooler: $N_b = 0.8 \cdot 10^{11}$
- beam-beam effect $\xi_{\bar{p}} = \frac{N_p r_p}{4\pi\ n_{p,\bar{p}} \gamma_{\bar{p}} \varepsilon_p} = 0.03$

Luminosity of p – p_bar collider

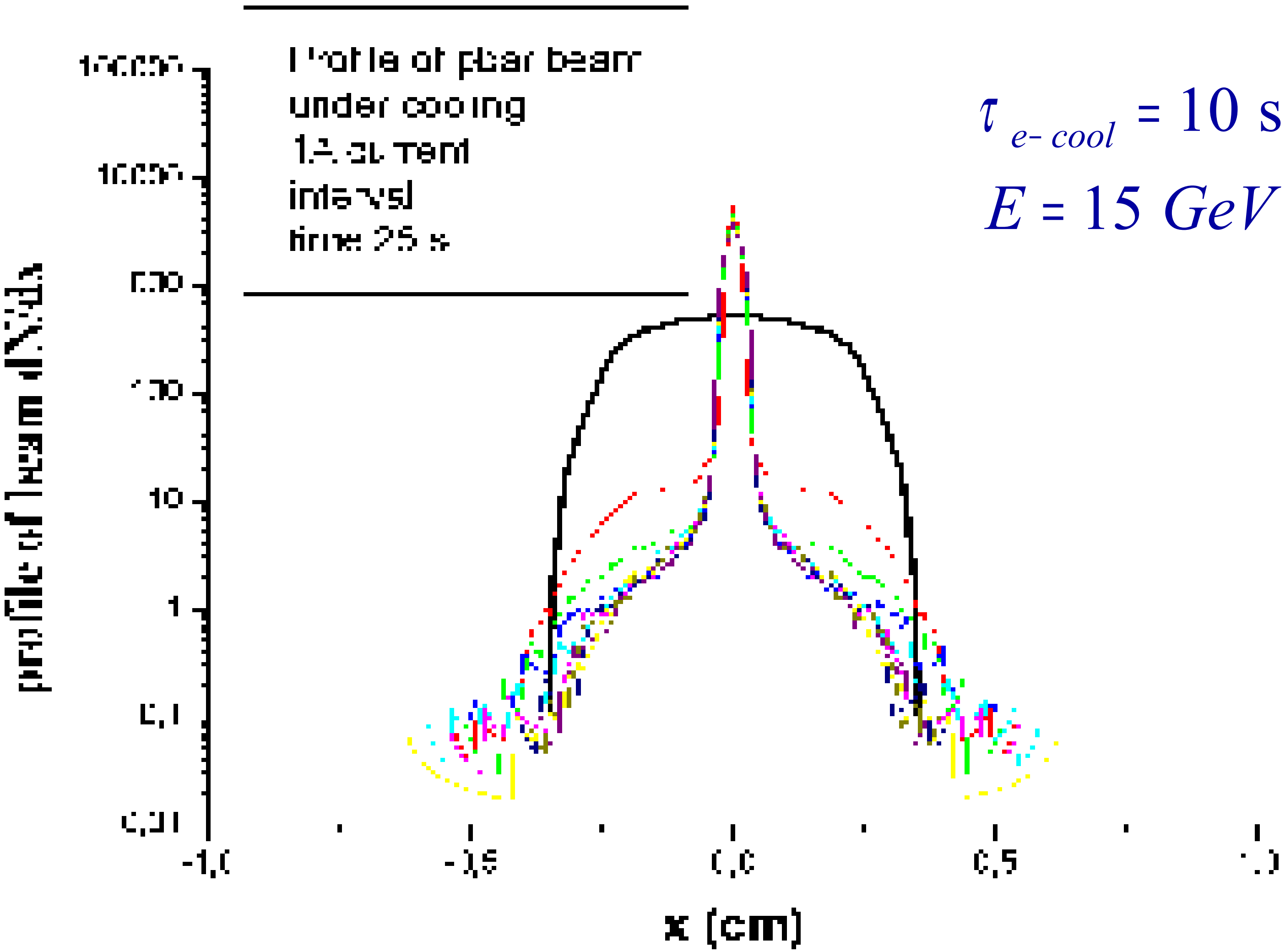
$N_P = 10^{12}$



Intra Beam Scattering



Simulation of electron cooling



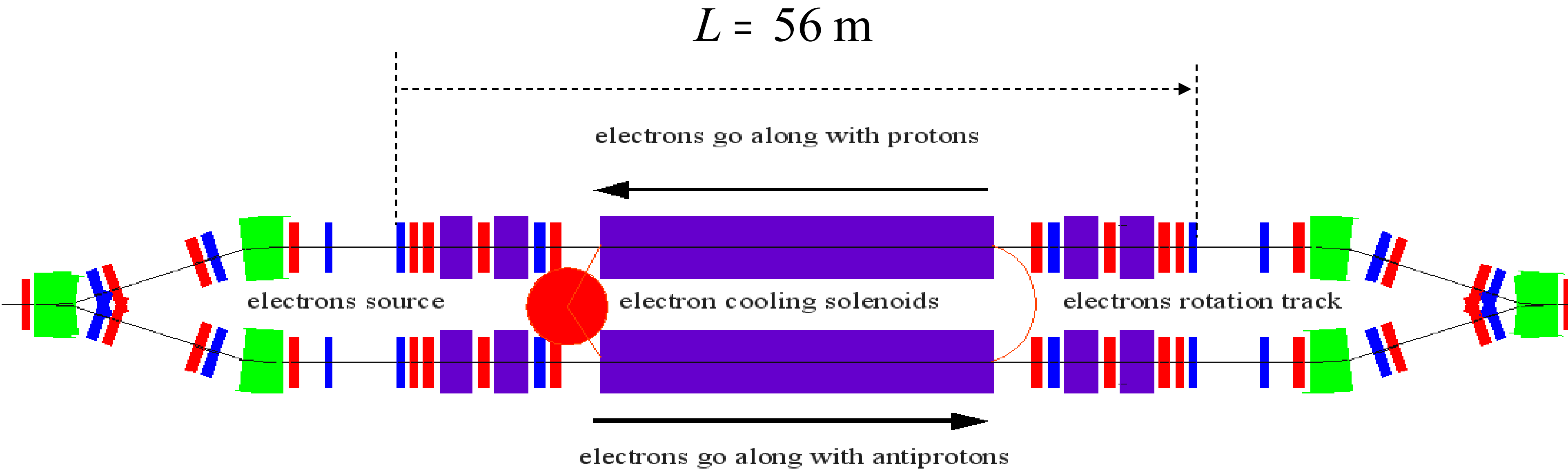
$\tau_{e\text{-}cool}$ = 10 sec

E = 15 GeV

Preliminary parameters of the electron cooler for HESR

Acceleration column	
Electron energy on the output	0.44–7.9 MeV
Length	8.0 m
Electrostatic field along accelerator column	0.5–10 keV/cm
Magnetic field	500 G
Cathode diameter (beam diameter)	2 cm
Height of high-voltage vessel	13.0 m
Diameter of high-voltage vessel	6.0 m
Cooling section	
Length	30 m
Magnetic field	5 kG (E_e=1.6–7.9 MeV)

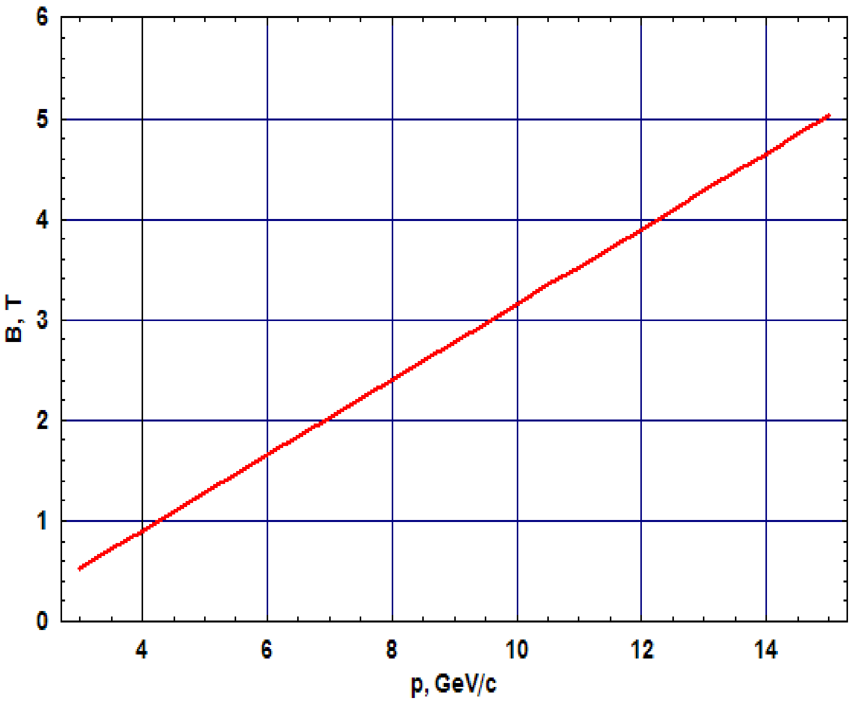
e-cooler and Siberian snakes



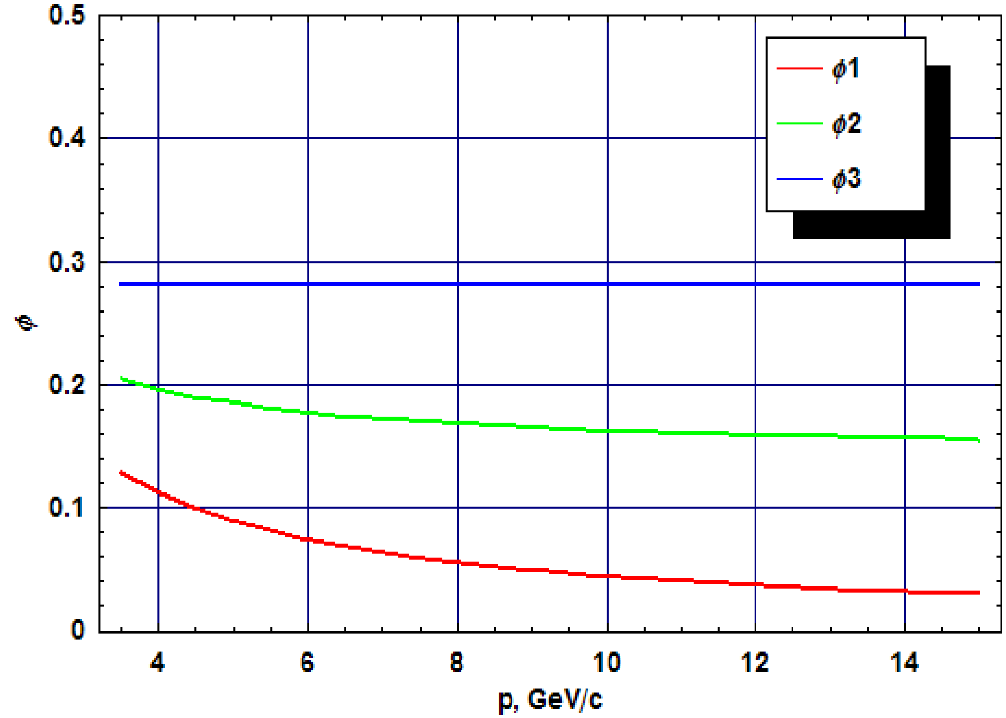
Transfer matrix

$$T_x = -T_z, \quad T_z = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix},$$

Magnetic field in the snake solenoids vs. the beam energy



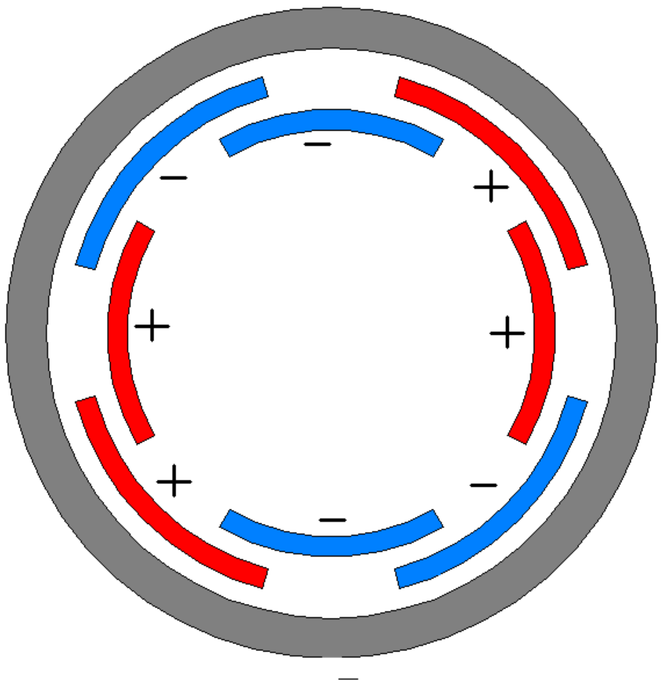
Snake skew-quads angles vs. the beam energy

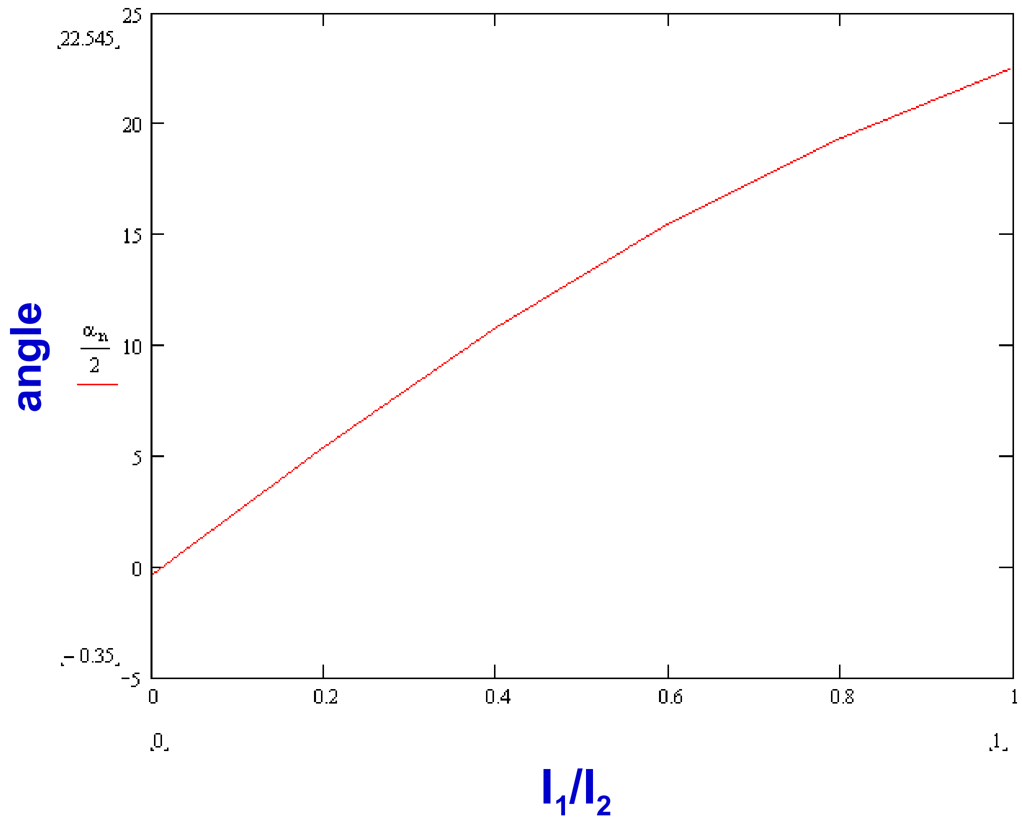


To compensate coupling from solenoids, all quads should be rotated by the angle:

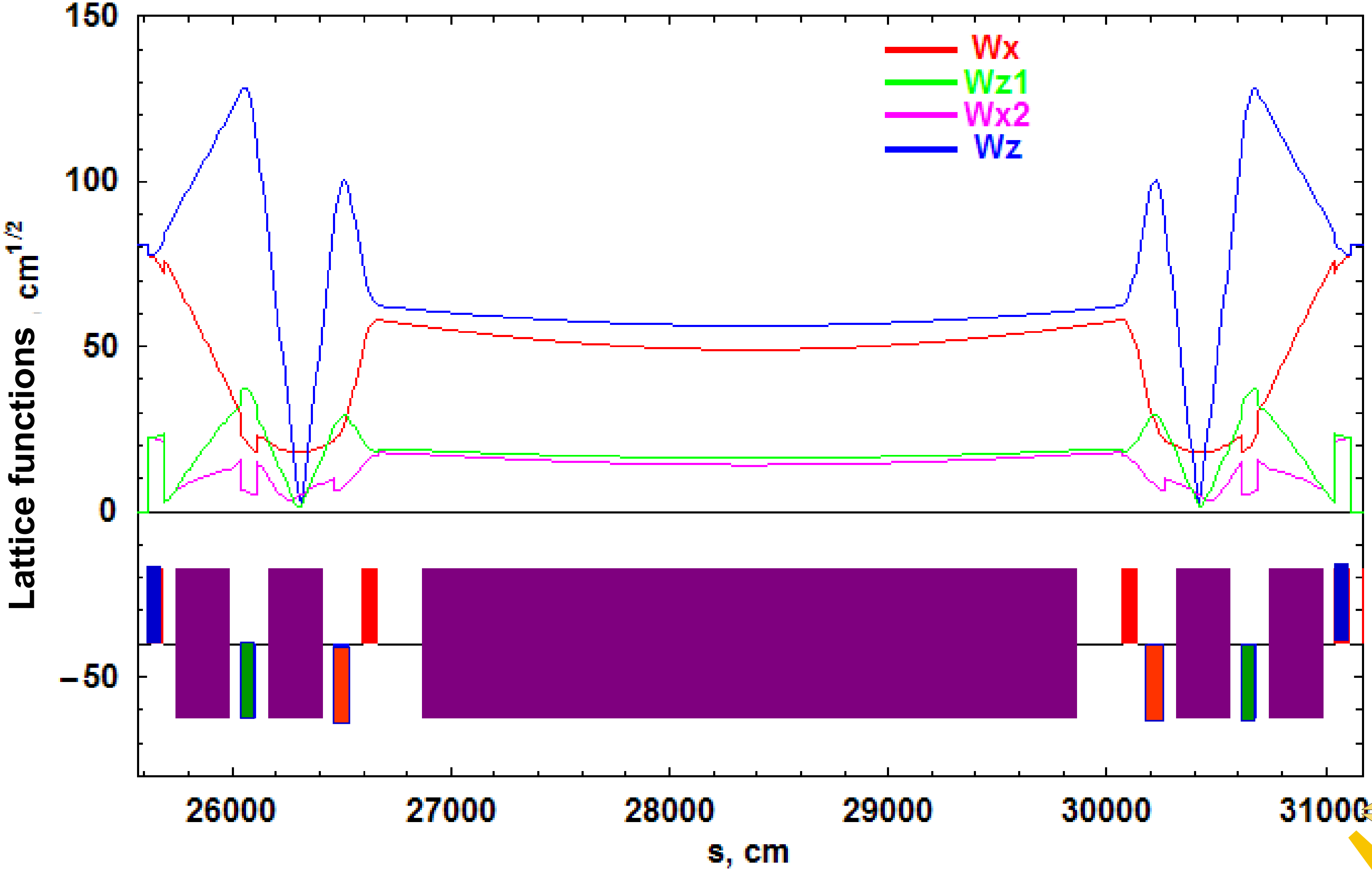
$$\phi = \frac{1}{2}\int_0^s B\,ds \Big/ B\rho$$

"Rotating" quads

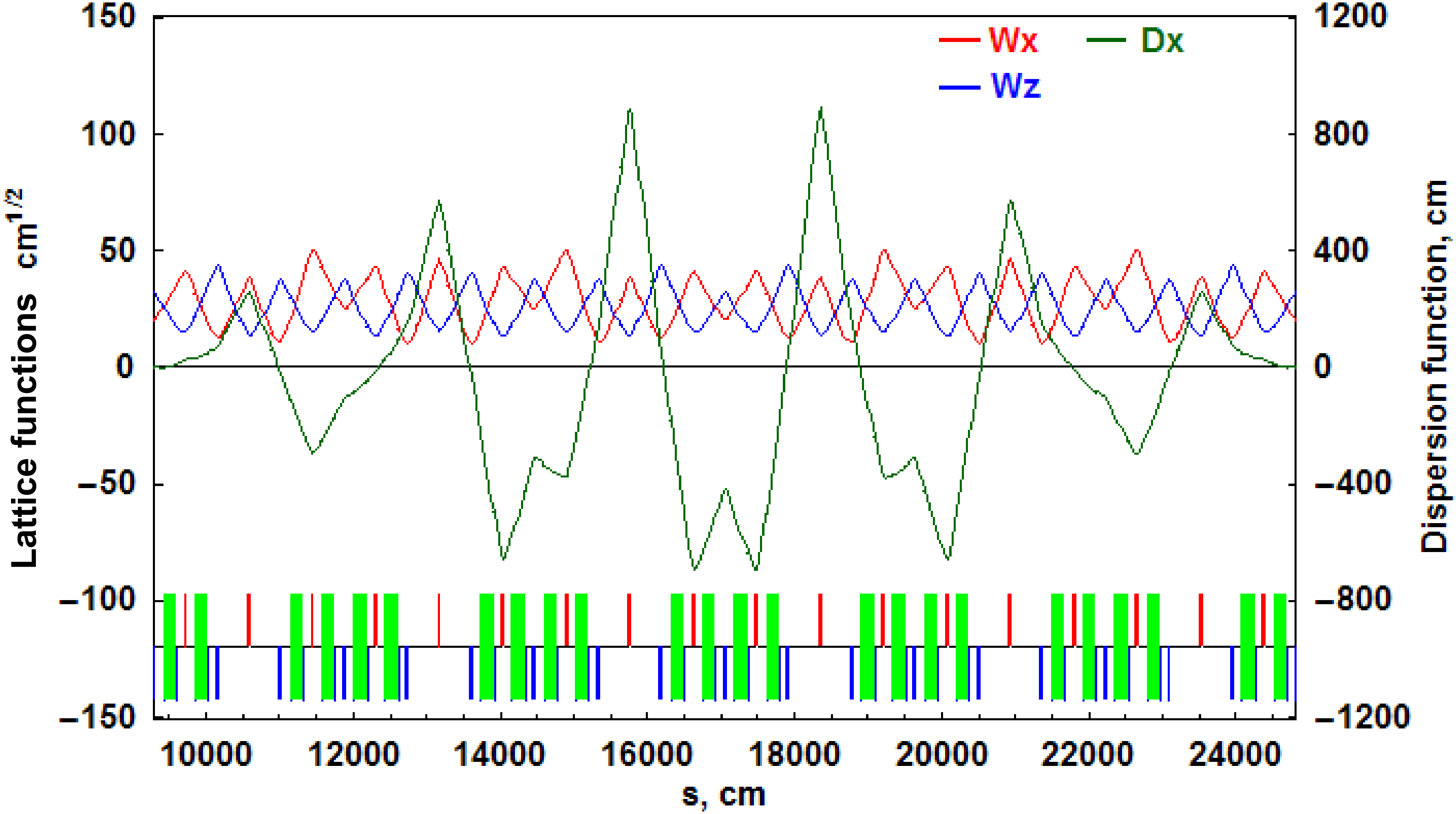




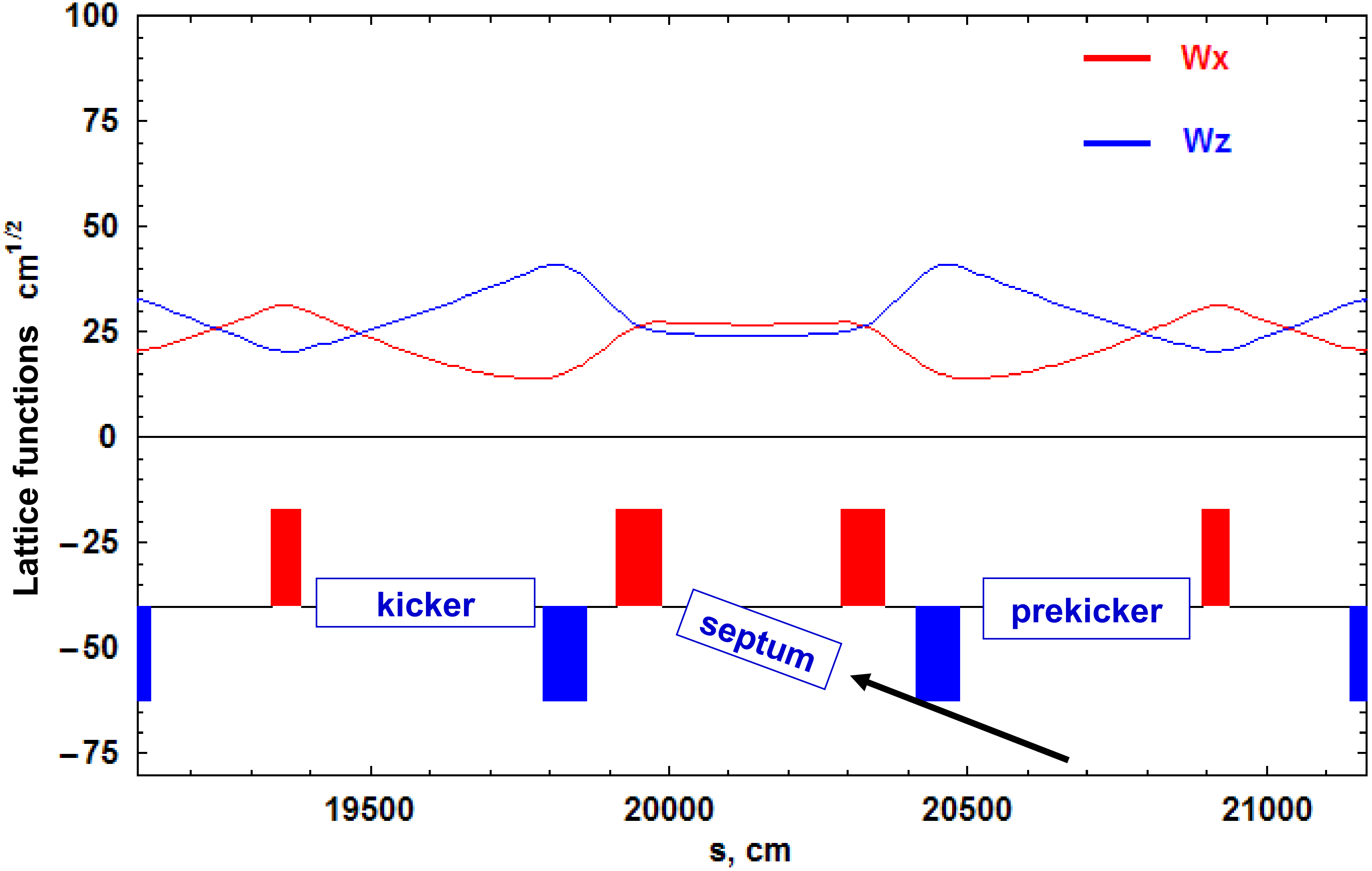
Optical structure of the cooler/snake insertion



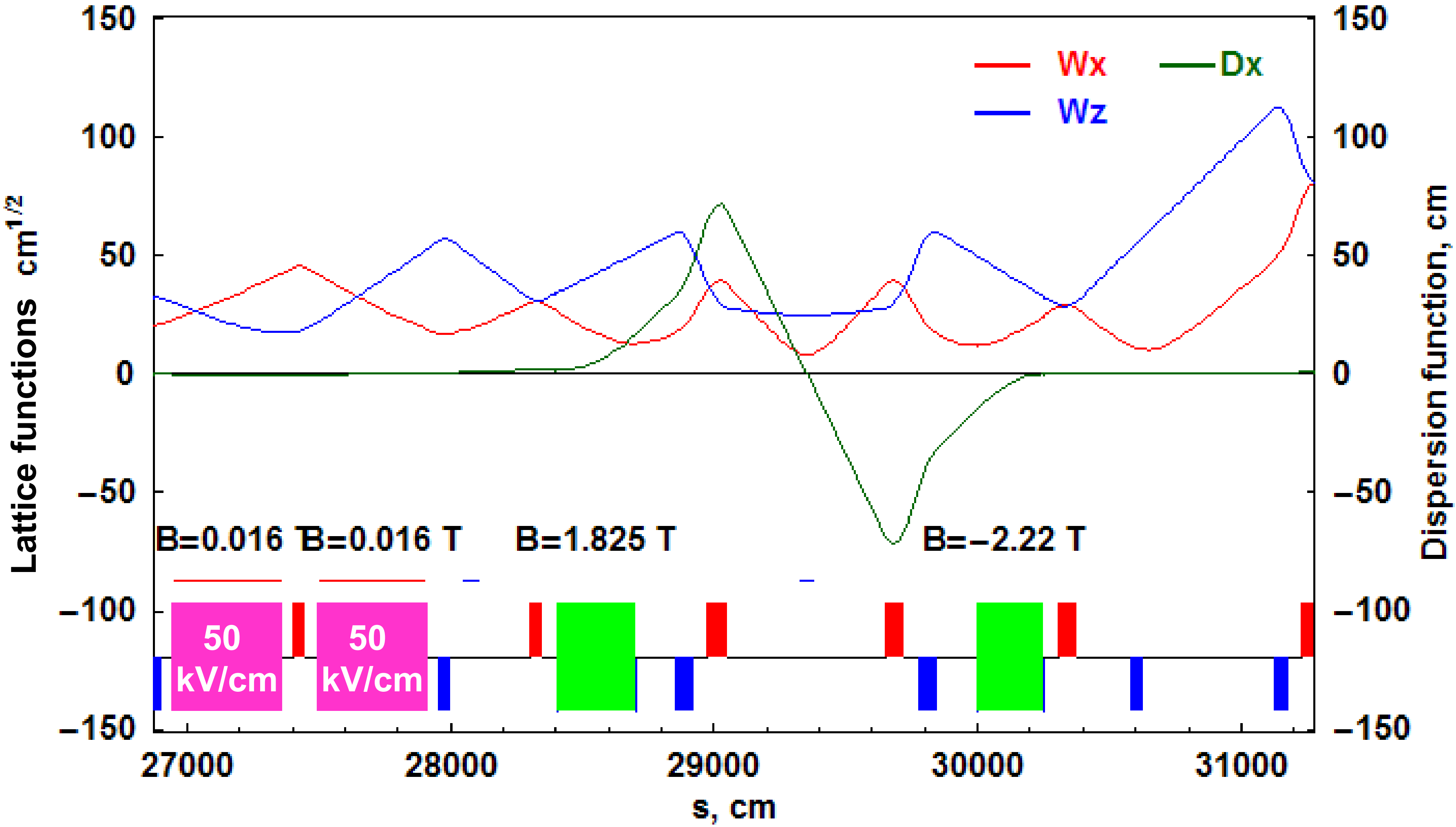
Arc lattice (6 fold – 4 fold)



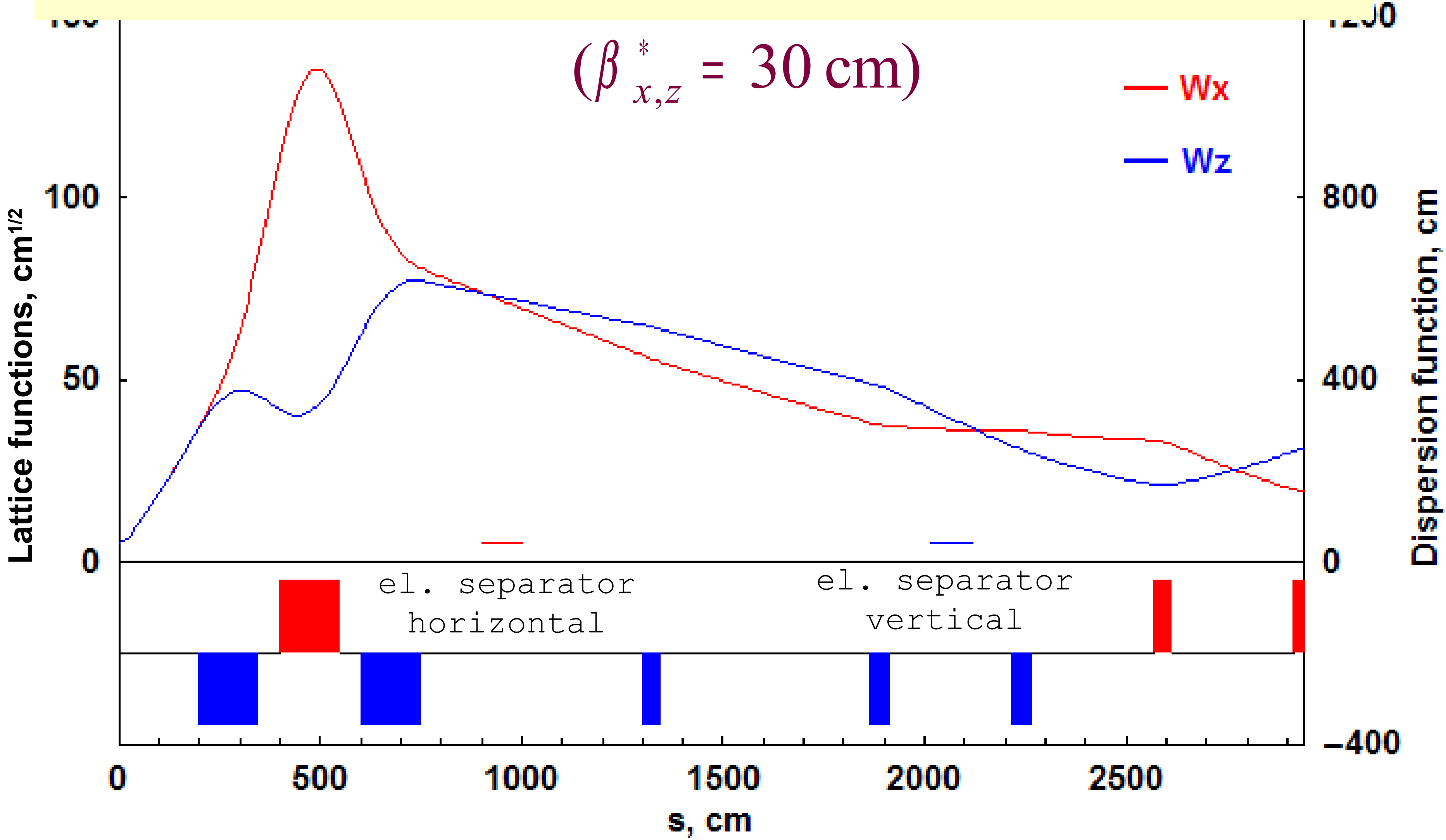
Injection insertion



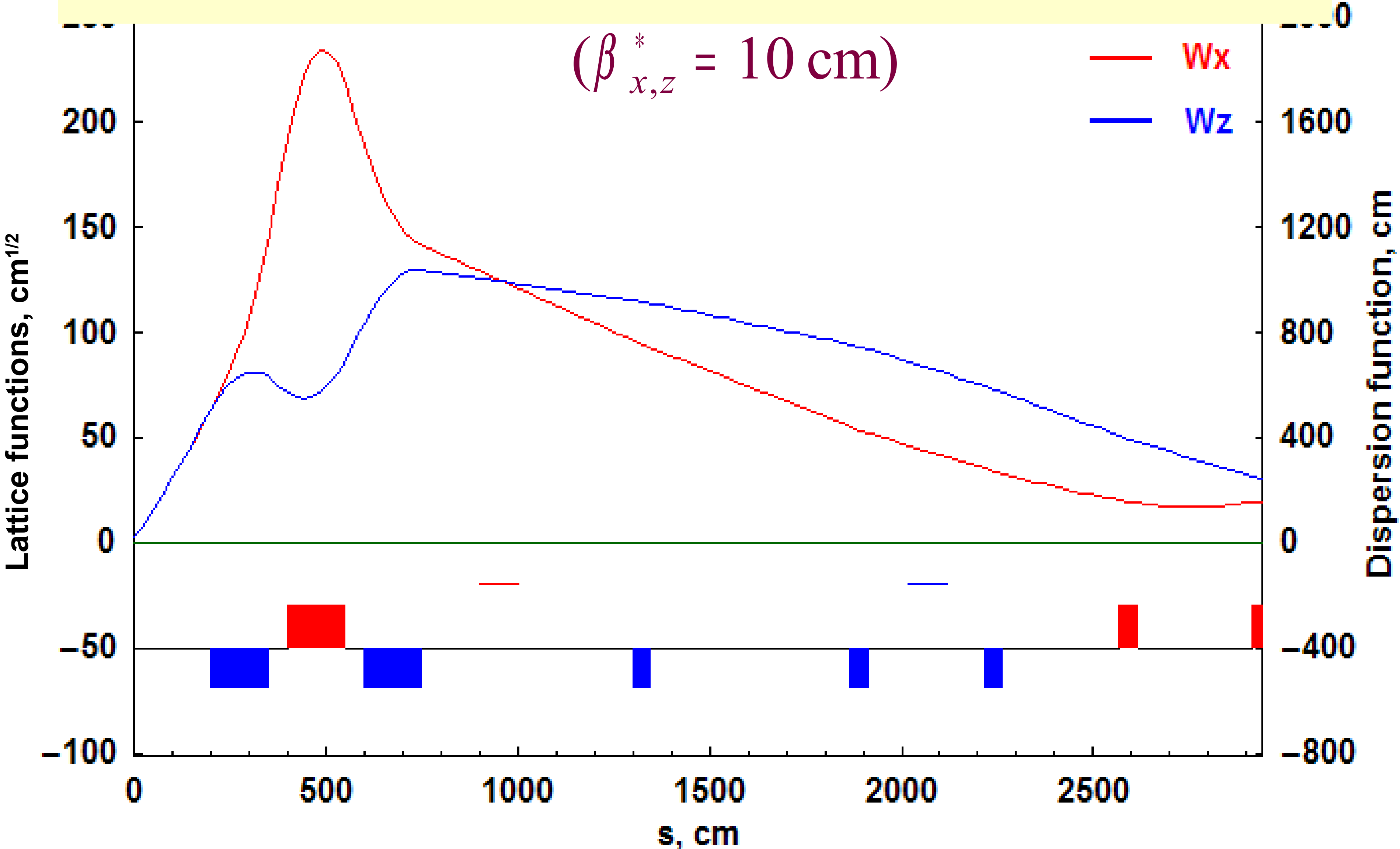
p-pbar electrostatic separator



Interaction region layout

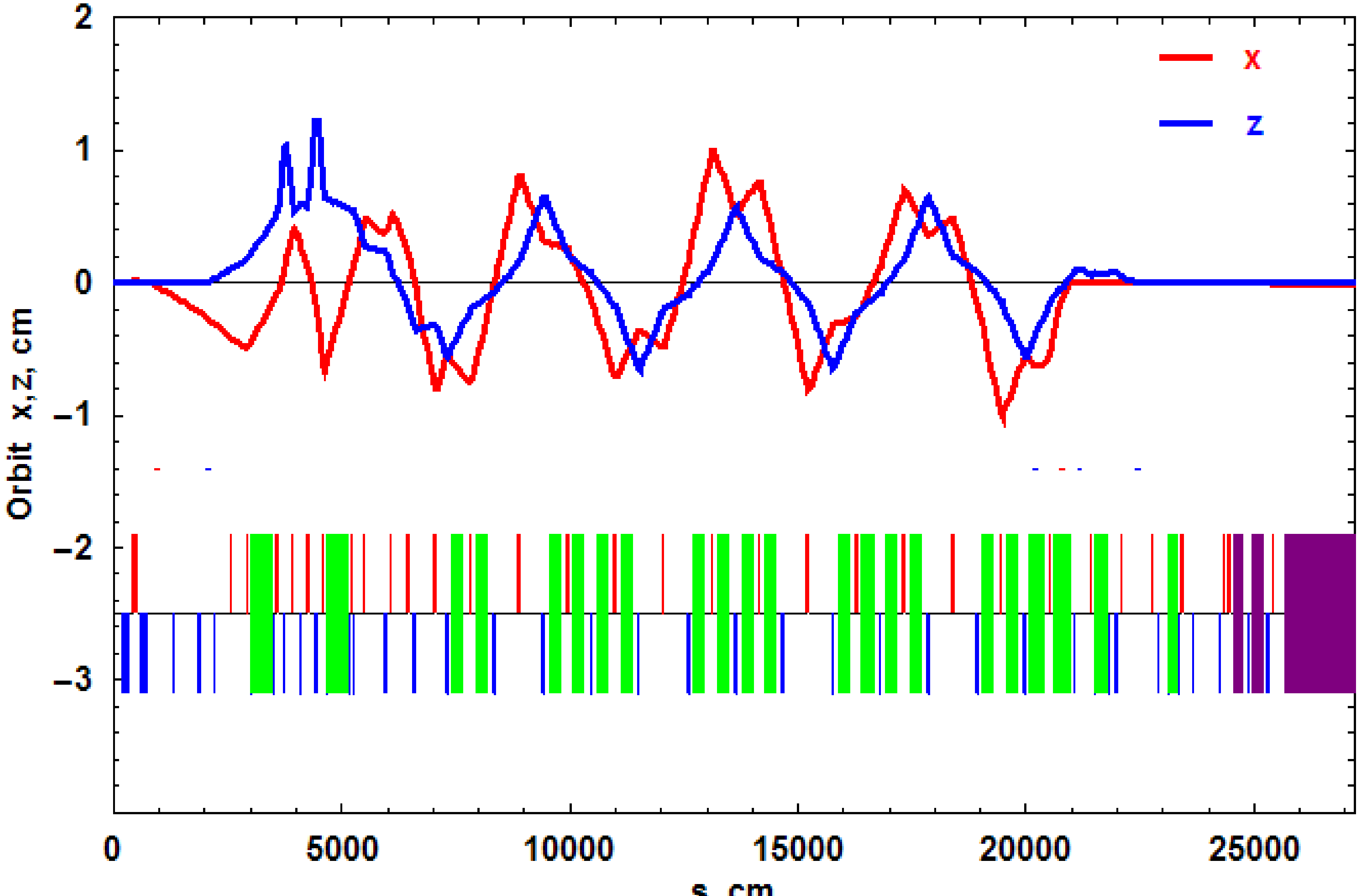


Interaction region layout

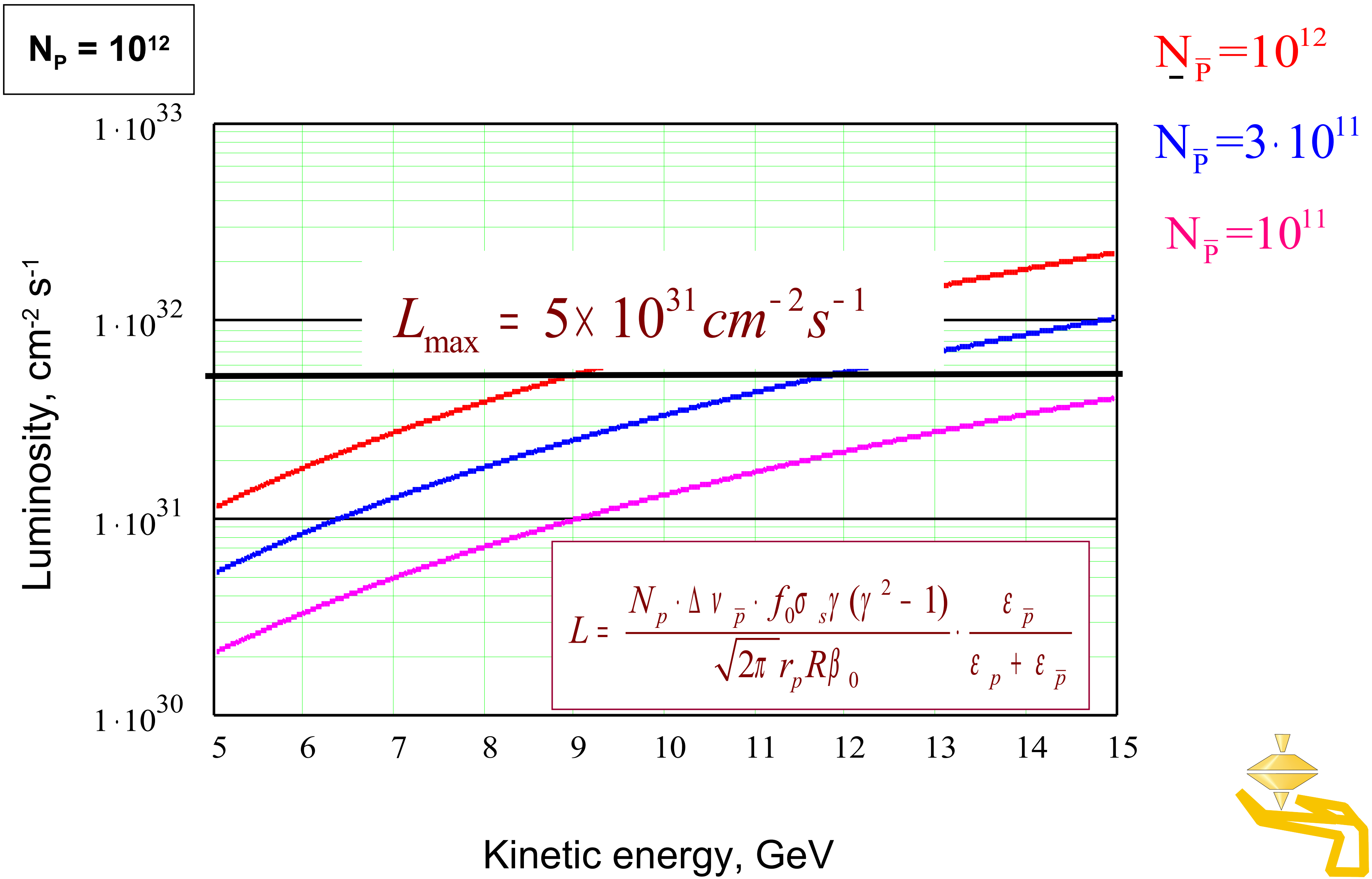


Electrostatic “helical” orbit separation

(one half ring)



Luminosity of p – p_bar collider (β* = 10 cm)



$$L = \frac{N_p \cdot \Delta\nu_{\bar{p}} \cdot f_0 \sigma_s \gamma(\gamma^2 - 1)}{\sqrt{2\pi}\, r_p R \beta_0} \cdot \frac{\varepsilon_{\bar{p}}}{\varepsilon_p + \varepsilon_{\bar{p}}}$$

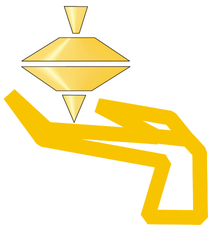
List of the p-pbar collider parameters

Collider circumference,	l	536	m
Revolution frequency,	f_0	0.56	MHz
Total number of antiprotons,	$N_{\bar{P}}$	0.1/ 0.3 / 1	10^{12}
Total number of protons,	N_P	1 / 1 / 1	10^{12}
Number of bunches per beam,	n_b	12	
Distance to first parasitic crossing,		22.5	m
Proton beam emittance,	ε_P	2 / 2 / 2	10^{-6} cm · rad.
Antiproton beam emittance,	$\varepsilon_{\bar{P}}$	02 / 0.6 / 2	10^{-6} cm · rad
Space charge tune shift,	$\Delta\nu_{P,\bar{P}}$	01/ 0.1 / 0.1	
Beam-beam parameter,	$\xi_{P,\bar{P}}$	0.03 /0.03/ 0.03	
e- cooling and IBS time	τ_{IBS} : $\tau_{e\text{-}cool}$	10	s
Luminosity	L_{max}	1.2/ 2.8 / 5.0	10^{31} cm^{-2} · s^{-1}

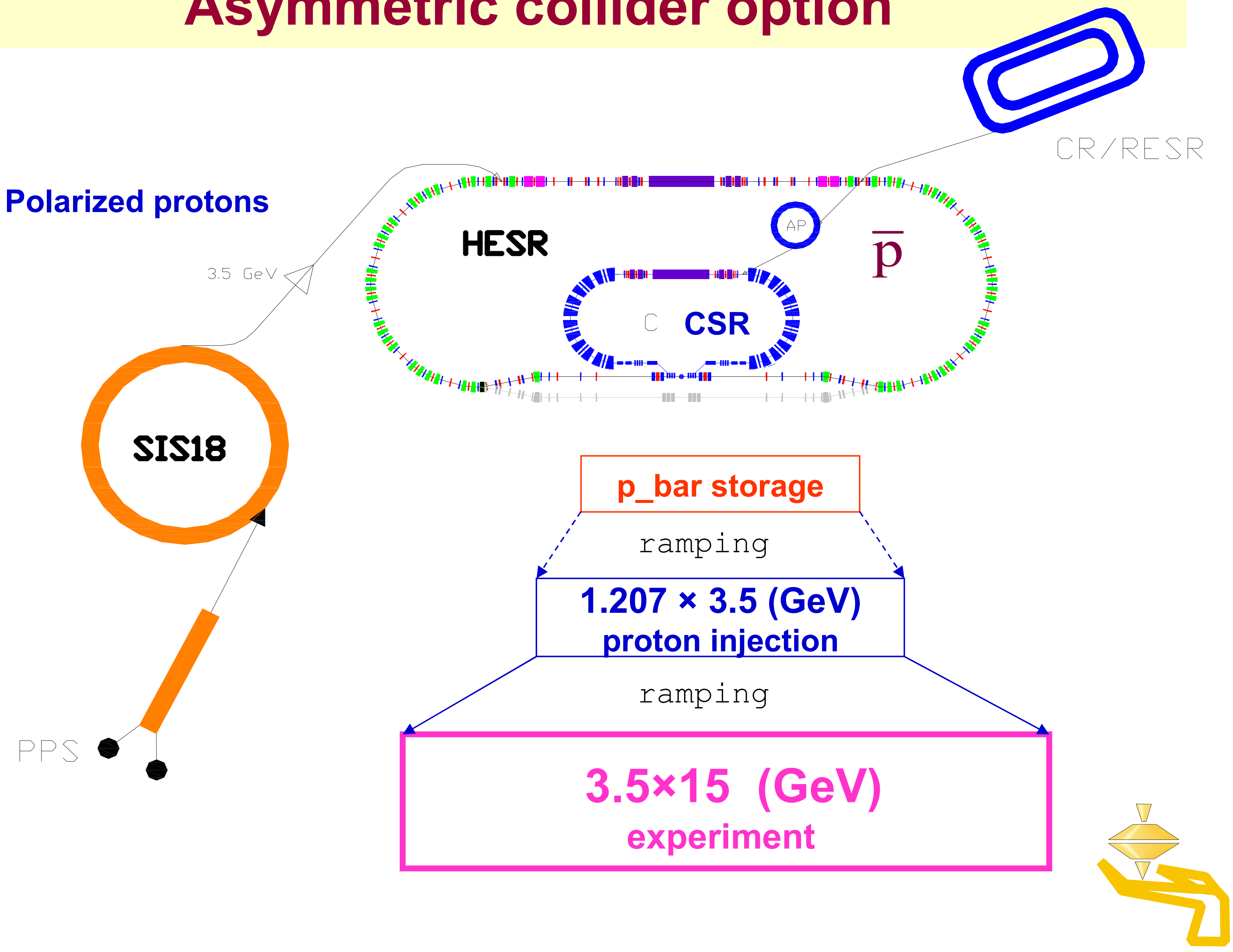
$N_{\bar{P}}=10^{12}$

$N_{\bar{P}}=3\cdot 10^{11}$

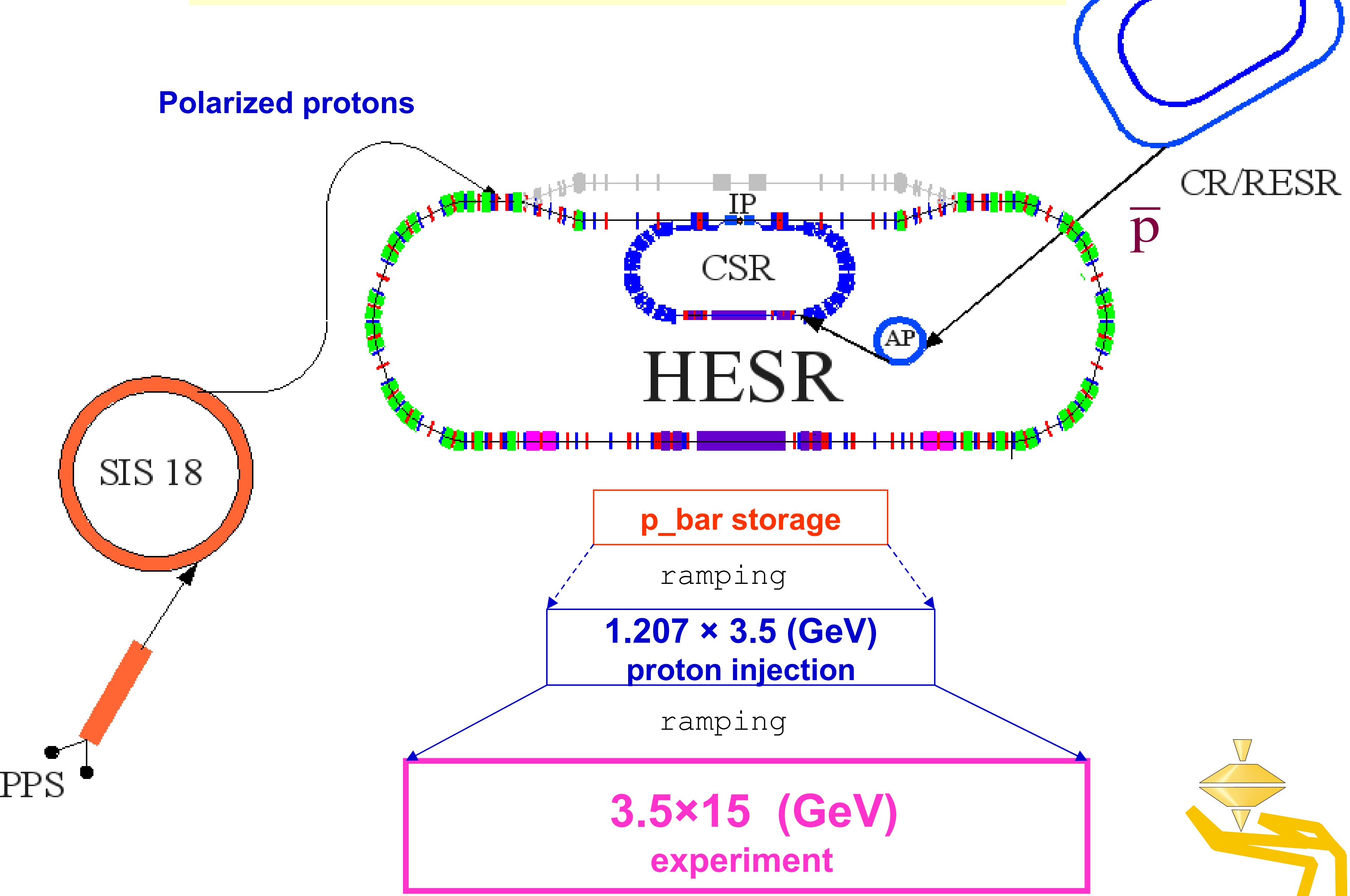
$N_{\bar{P}}=10^{11}$



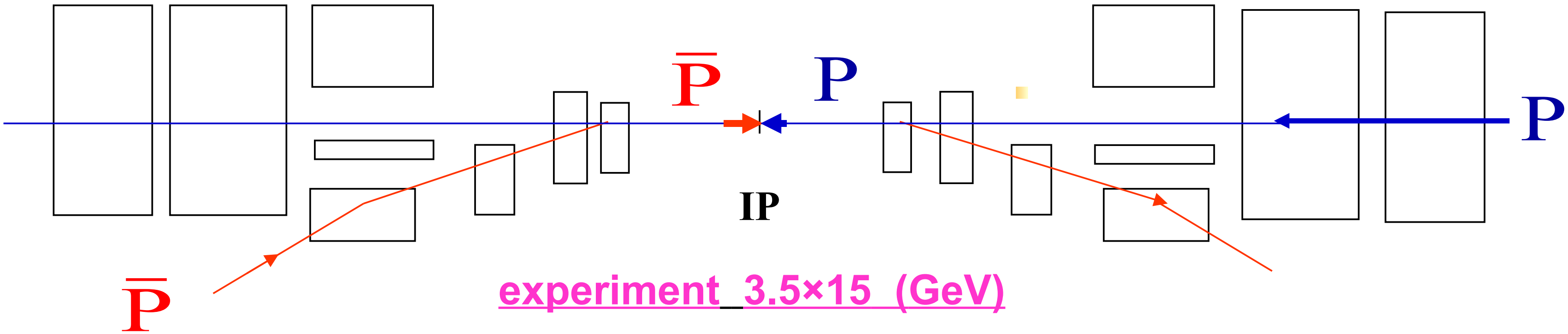
Asymmetric collider option



Asymmetric collider option



Sketch of the interaction area



experiment 3.5×15 (GeV)

(E = 1.207 GeV)   at proton injection in HESR   (E = 3.5 GeV)

Limitations:

- space-charge effect $$\Delta \nu_p = \frac{N_p r_p R}{2\sqrt{2\pi}\, n_b \sigma_s \varepsilon_p \gamma (\gamma^2 - 1)} \leq 0.1$$
- instabilities in electron cooler: $N_b = 0.8 \cdot 10^{11}$
- beam-beam effect $$\xi_{\bar{p}} = \frac{N_p r_p}{4\pi\; n_{p,\bar{p}} \gamma_{\bar{p}} \varepsilon_p} = 0.1$$

Assumptions:

- $N_p = 10^{12}$ $n_b = 40$ bunches.
- $N_{\bar{p}} = 10^{11} \Leftrightarrow 10^{12}$ $n_b = 10$ bunches.
- $\sigma_s = \beta_y^* = 30$ cm

Asymmetric p-pbar collider parameters

$N_P = 7 \times 10^{12}$

$N_{\bar{P}} = 10^{12}$

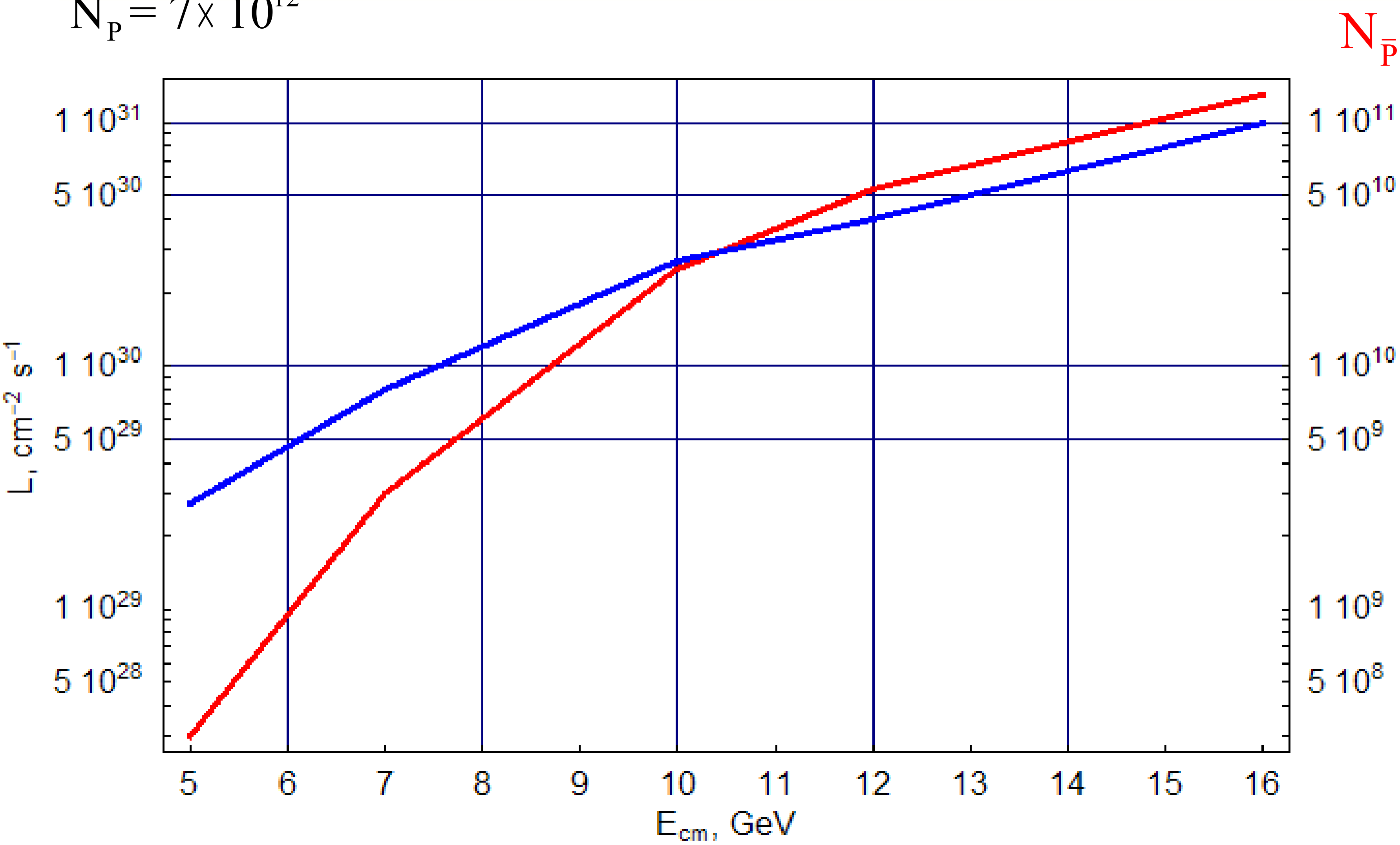
$N_{\bar{P}} = 3 \cdot 10^{11}$

$N_{\bar{P}} = 10^{11}$

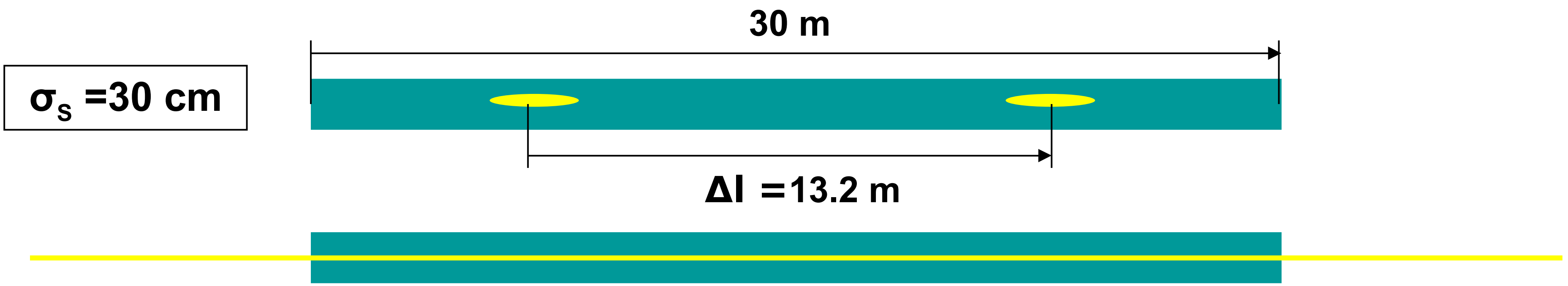
Ring circumferences,	l_1 / l_2	536 /134	m
Beam energies	E_P / E_{P_bar}	15 / 3.5	GeV
Total number of antiprotons,	$N_{\bar{P}}$	0.1 / 0.3 / 1	10^{12}
Total number of protons,	N_P	1 / 1/ 1	10^{12}
Number of bunches per beam,	n_b	40 / 10	
Proton beam emittance,	ε_P	20 / 20 / 20	10^{-6} cm · rad.
Antiproton beam emittance,	$\varepsilon_{\bar{P}}$	4.5 / 14 / 45	10^{-6} cm · rad
Space charge tune shift,	$\Delta\nu_{\bar{P}}$	0.1 / 0.1 / 0.1	
Beam-beam parameter,	$\xi_{\bar{P}}$	0.03 / 0.03 / 0.03	
Luminosity	L_{max}	0.8 / 1.8 / 3.0	10^{31} cm^{-2} · s^{-1}

Luminosity vs. c.m. energy
(asymmetric option)

$N_P = 7 \times 10^{12}$



Asymmetric p-pbar collider with coasting beams



- IBS increment is weak ($\sigma_s / \Delta l$)
- Limit beam emittance smaller
- Space charge

$$\Delta \nu_{1,2} = \frac{N_{1,2}\, r_p}{4\pi\, \varepsilon_{1,2} \gamma (\gamma^2 - 1)} \le 0.1$$

- Beam-beam

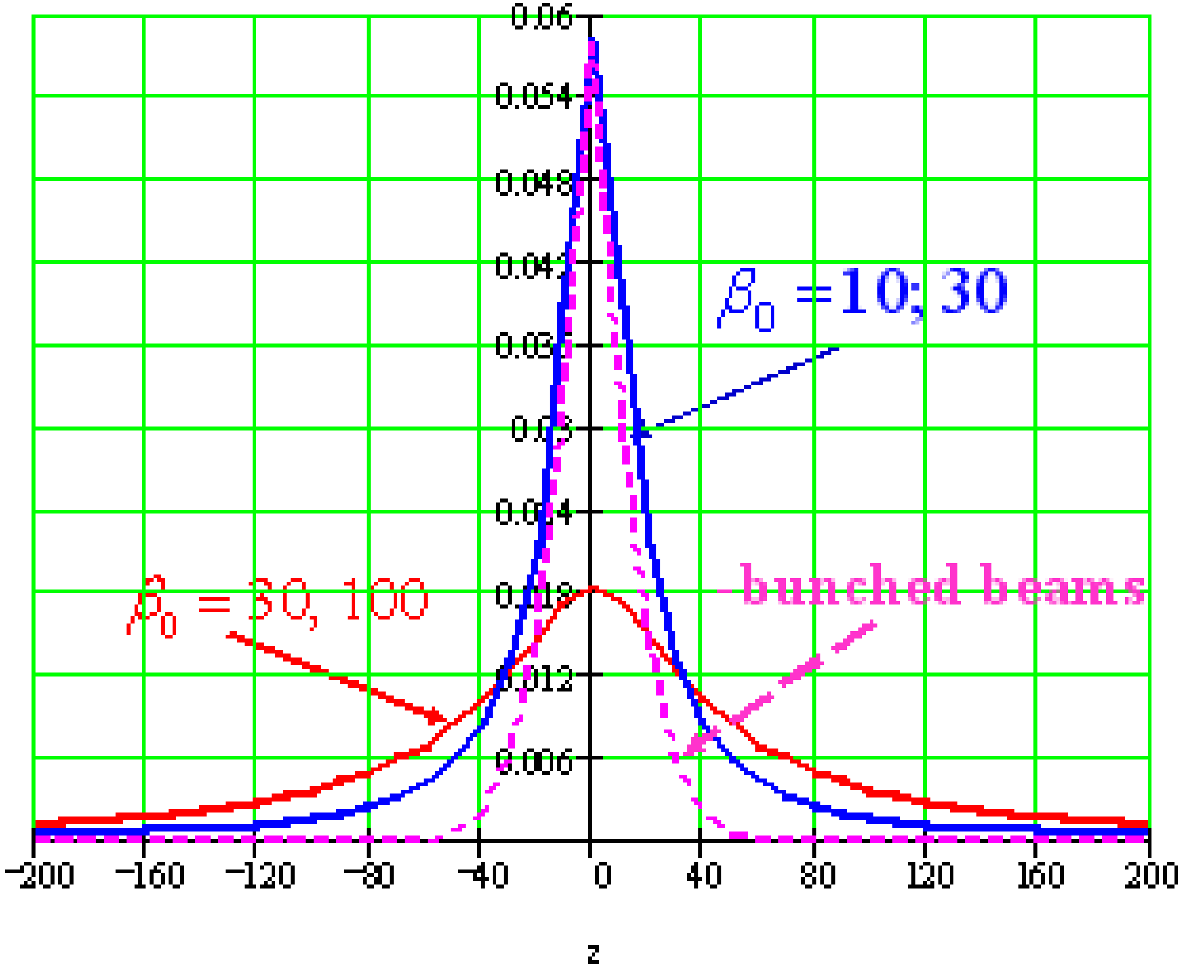
$$\xi_{1,2} = \frac{N_{2,1}\, r_p (1+\beta_1 \times \beta_2) \cdot l}{8\pi^2\, \gamma_{1,2} \cdot \beta_{1,2}^2 \cdot \varepsilon_{2,1} \cdot R_{2,1}} = 0.03$$

- Length of the *IR* (l >>β*)

$$L2 := \frac{N_1 \cdot N_2 \cdot c \cdot (\beta_1 + \beta_2)}{4 \cdot \pi^2 \cdot R_1 \cdot R_2} \cdot \frac{1}{\pi \cdot (\varepsilon_1 + \varepsilon_2)} \cdot \mathrm{atan}\left(\frac{l}{2 \cdot \beta_0}\right)$$

Longitudinal distribution of the luminosity

(coasting beams)



Asymmetric p-pbar collider parameters
(coasting beams)

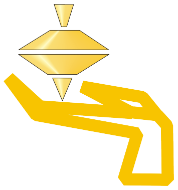
$$N_P = 7 \times 10^{12}$$

$$N_{\bar{P}} = 10^{12} \qquad N_{\bar{P}} = 3 \cdot 10^{11} \qquad N_{\bar{P}} = 10^{11}$$

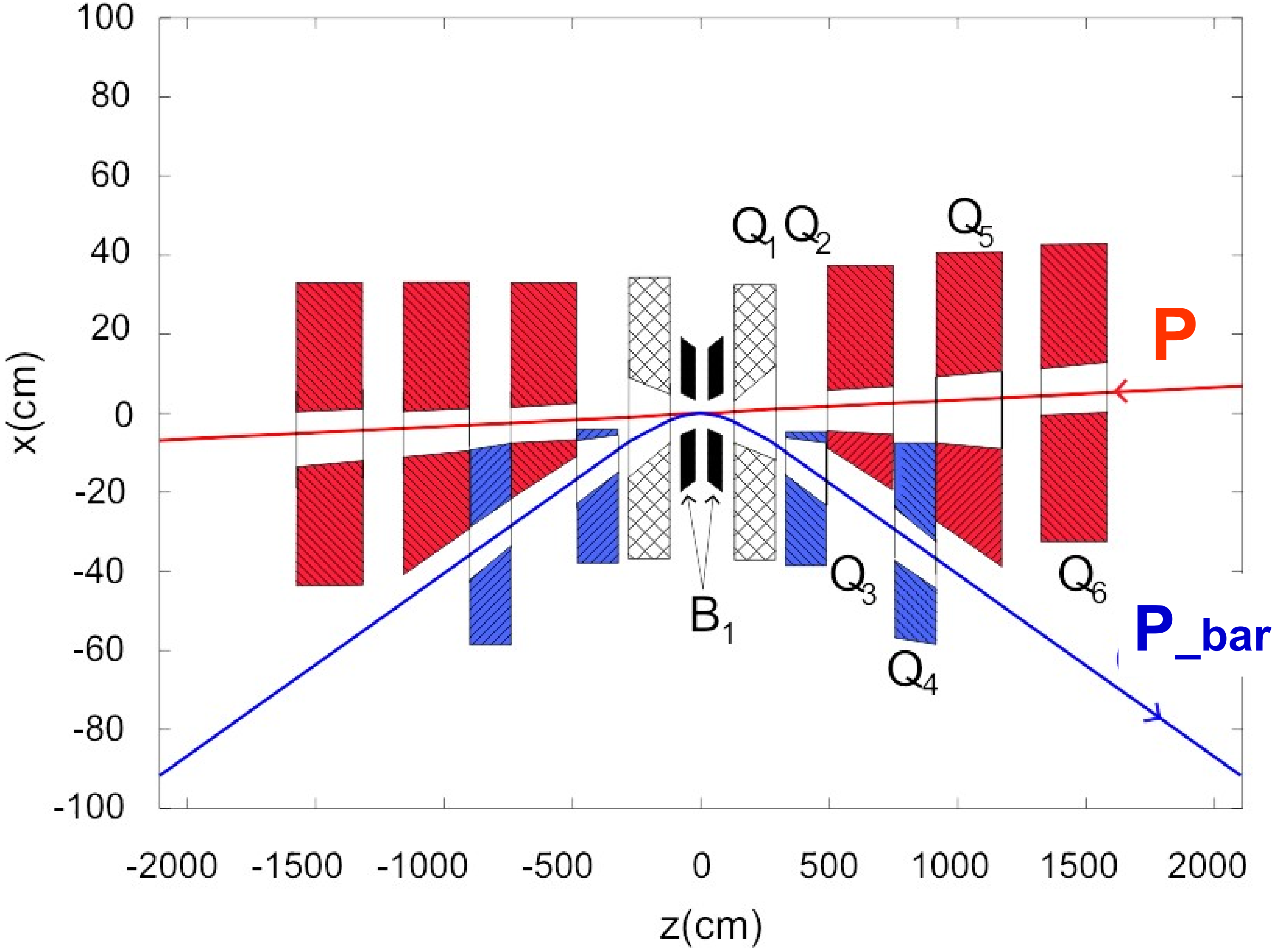
Ring circumferences,	l_1 / l_2	**536 /134**	**m**
Beam energies	E_P / E_{P_bar}	**15 / 3.5**	**GeV**
Total number of antiprotons,	N_P	**0.1 / 0.3 / 1**	10^{12}
Total number of protons,	$N_{\bar{P}}$	**7 / 7/ 7**	10^{12}
Proton beam emittance,	ε_P	**2.5 / 2.5 / 2.5**	10^{-6} cm · rad.
Antiproton beam emittance,	$\varepsilon_{\bar{P}}$	**0.25 / 0.75 / 2.5**	10^{-6} cm · rad
Space charge tune shift,	$\Delta\nu_{\bar{P}}$	**0.1 / 0.1 / 0.1**	
Beam-beam parameter,	$\xi_{\bar{P}}$	**?**	
Luminosity	L_{max} *(l=2m)*	**5 / 5 / 5**	10^{31} cm^{-2} · s^{-1}

Conclusion

- conceptual study of polarized p-p_bar collider options at HESR is done
- the collider can achieved luminosity $5 \cdot 10^{31}$ $cm^{-2} \cdot s^{-1}$ in symmetric and asymmetric options
- symmetric collider can cover energy range 10 – 30 GeV
- polarized protons from PPS will be accelerated up to 3.5 GeV in SIS 18
- polarization of antiprotons is terra incognita today
- proper study of the p_bar filtering can be done at NESR before construction of an antiproton polarizer
-

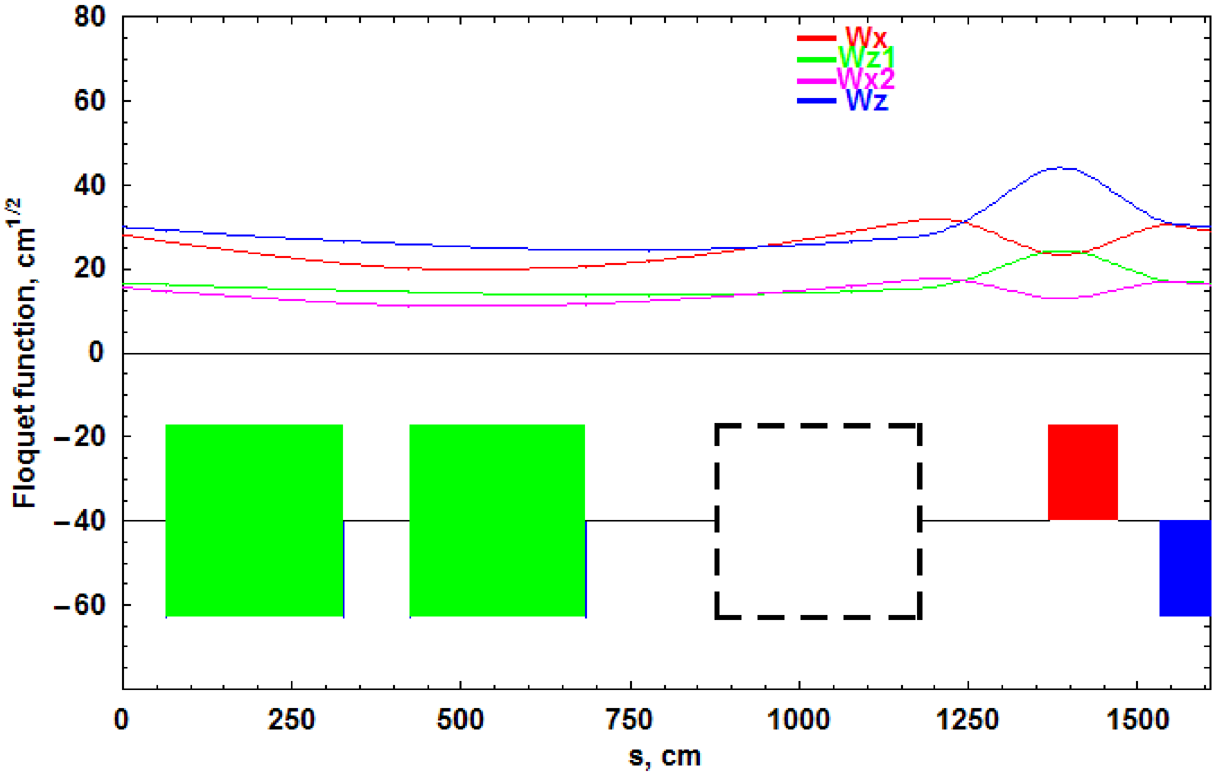


Sketch of the interaction area
(β* = 10 cm)



Polarized proton acceleration at SIS-18

1) Partial Siberian snake (pulse solenoid against resonances ν =k



- Q-jump on linear intrinsic resonance $\nu = Q_z = 3.28$

P_bar polarization study ?

$$d\sigma_{P\bar{P}} = d\sigma_0(\theta,E) + \zeta_P^p \zeta_P^{\bar{p}} d\sigma_1(\theta,E) + \zeta_\perp^p \zeta_\perp^{\bar{p}} d\sigma_2(\theta,E)$$

$$d\sigma_0 : d\sigma_{1`} : d\sigma_2$$

T_{kin} = 20 — 500 MeV