Interaction Region Constraints for *ep/eA* Colliders

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Overall goal of IR design: maximize luminosity

Luminosity formula for matched (= equal) beam sizes at the IP:

$$\mathcal{L} = \frac{N_e N_i f_c}{4\pi \sigma_x^* \sigma_y^*}$$

If beam sizes are not matched, the emittance of the larger beam tends to increase
→ luminosity degradation, poor luminosity lifetime.

Limiting factors, IR design viewpoint

- beam-beam parameter

$$\xi_{x,y}^+ = \frac{r_0^+ N^- \beta_{x,y}^{*,+}}{2\pi\gamma^+ \sigma_{x,y}^{*,-}(\sigma_x^{*,-} + \sigma_y^{*,-})}$$

Emittances of electron and ion beam are different; need to find the right compromise for high luminosity and acceptable beam-beam parameters.

For a fixed beam size ratio $r = \sigma_y^*/\sigma_x^*$ and given emittances, the beam-beam parameter does not depend on the actual beamsize.

Beam-beam parameter is irrelevant for linac beams.

- electron bunch intensity N_e : synchrotron radiation, beam-beam effect on ion beam

- ion bunch intensity N_i : beam-beam effect on electron beam

- collision frequency f_c : long-range beam-beam effects, injector chain, multibunch instabilities

- β^* : magnet strength, chromaticity, hourglass effect ($\beta^* >$ bunch length)

- bunchlength: beampipe heat load in superconducting magnets

Design goals

- Strong focusing to small spot sizes to maximize luminosity

- Accomodation of synchrotron radiation
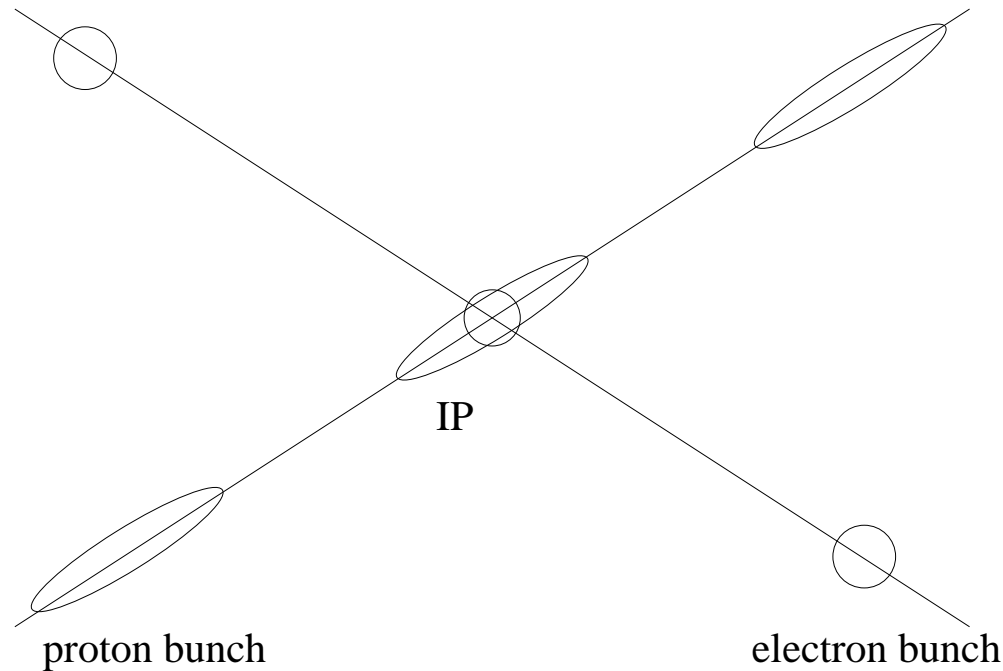
- Beam separation

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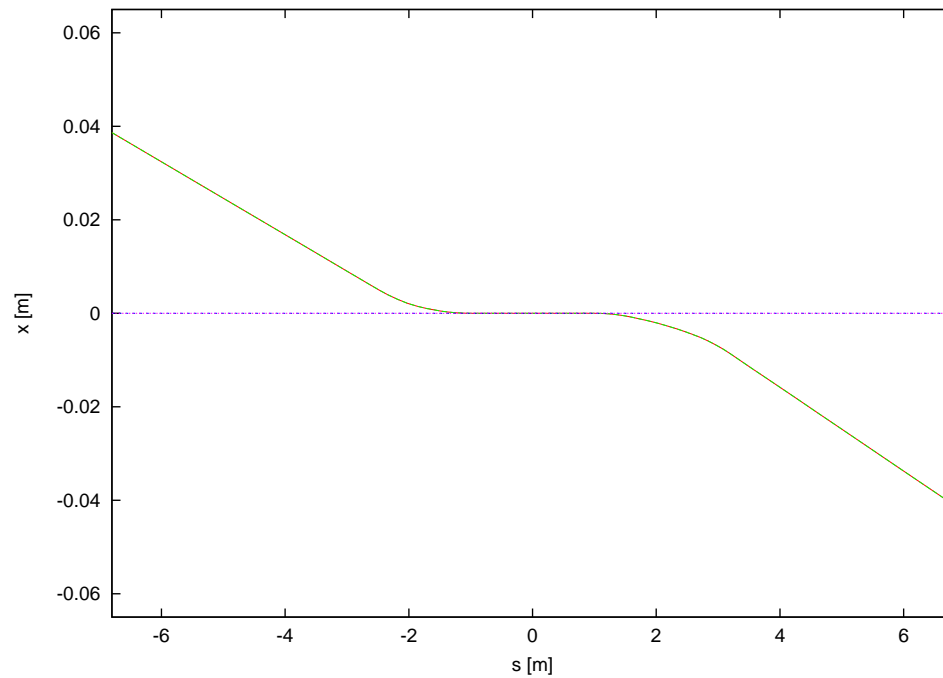
Beam energies differ by factor 10 (or so)
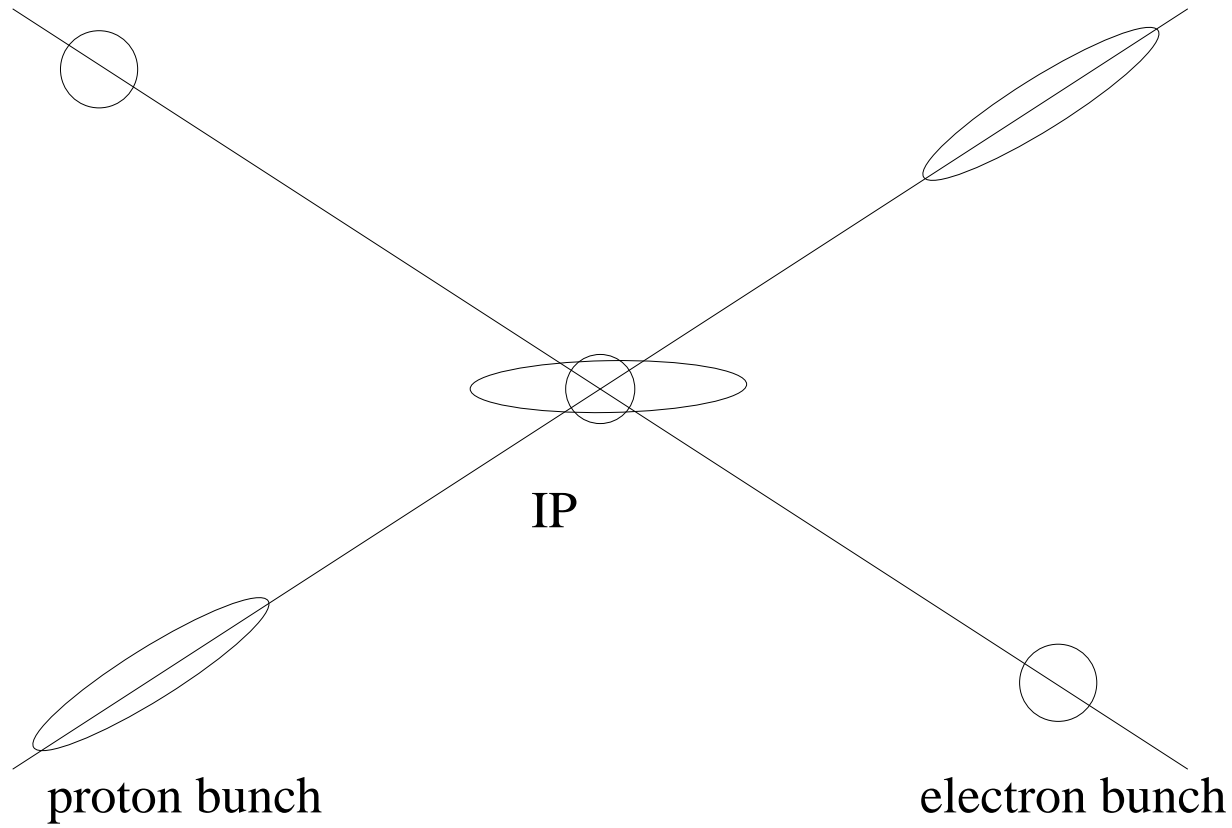→ separate focusing systems for both beams

Beam separation by a crossing angle

Easiest way to separate the beams, but:

Large crossing angle reduces luminosity by factor ≈ 5 due
to long hadron bunches

Crab Crossing

proton bunch   electron bunch

$\rightarrow$ Head-on collision in a co-moving frame.

Crab Cavity Voltage

Required transverse deflecting voltage:

$$V_\perp = \frac{cE \tan \phi_{\mathsf{crab}}}{e\omega_{\mathsf{RF}}\sqrt{\beta^*\beta_{\mathsf{crab}}}}$$

Typical voltages for EIC:

$$V_\perp = 10\ldots 100\,\mathsf{MV}$$

For comparison: RHIC RF voltage is $2\,\mathsf{MV}$, KEKB crab cavity voltage is 1.44 MV

Crab Cavity Noise

Since crab crossing needs to be applied to the ion bunches, RF noise causes emittance growth.

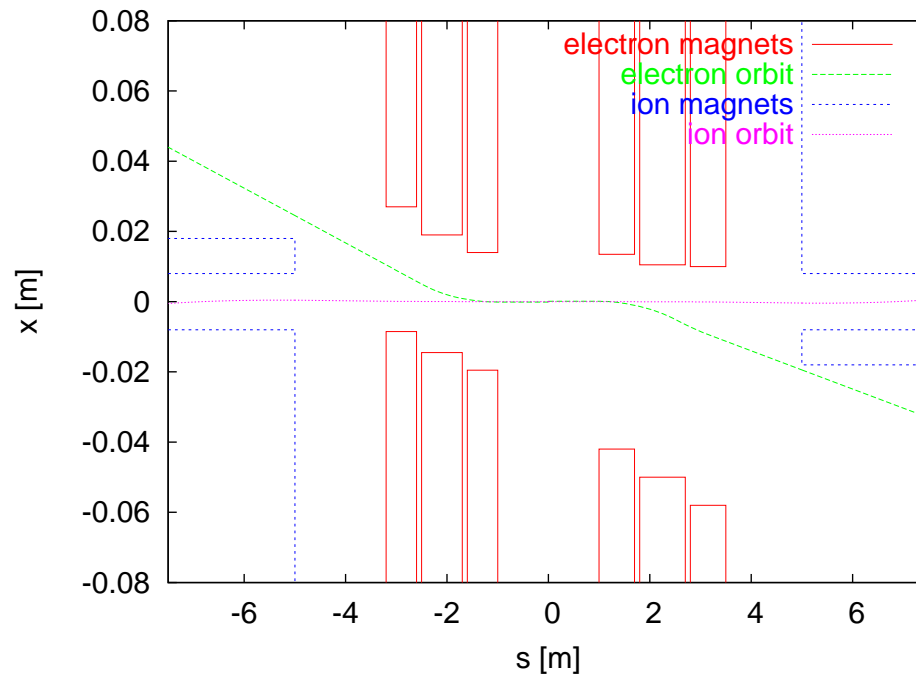Tolerable noise levels for emittance growth time τ :

$$\Delta\Theta \;=\; \frac{2\pi f_{\mathsf{crab}}\sigma_x}{c\cdot\tan(\phi_{\mathsf{crab}})}\bigg/\sqrt{f_{\mathsf{rev}}\cdot\tau} \qquad \text{phase jitter}$$

$$\frac{\Delta V}{V} \;=\; \frac{\sigma_x}{\sigma_s\cdot\tan(\phi_{\mathsf{crab}})}\bigg/\sqrt{f_{\mathsf{rev}}\cdot\tau} \qquad \text{voltage jitter}$$

Using typical EIC parameters and $\tau = 1\,\text{hour}$,

$$\Delta\Theta \leq 1\,\mu\text{rad}, \qquad \frac{\Delta V}{V} \leq -100\,\text{dB}$$

Beam separation with zero crossing angle

Electron low-β quads (if any) are common to both beams, but have almost no effect on high energy ion beam.
Beams must be separated at entrance of first ion quad.

To minimize required separation, horizontal beam sizes must be minimized at ion quad entry:

- ions:
  horizontal ion beam size at septum $\sigma_{x,i} \propto 1/\sqrt{\beta^*_{x,i}}$
  $\rightarrow$ lower limit on $\beta^*_{x,i}$
  $\rightarrow$ upper limit on luminosity

- electrons:
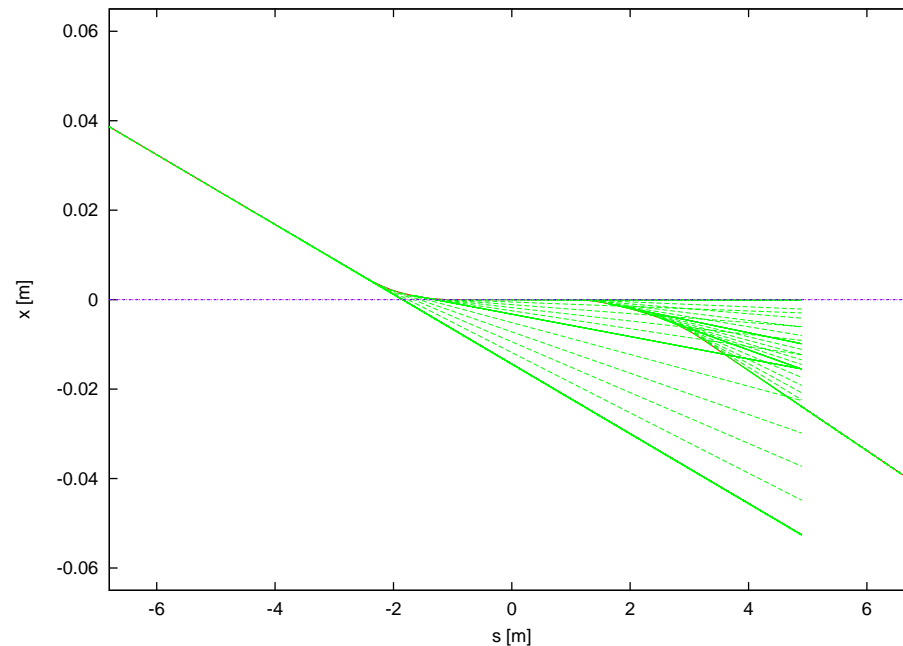 horizontal electron beam size at septum $\sigma_{x,e} \propto \sqrt{\epsilon_{x,e}}$,
  but smaller emittance $\epsilon_{x,e}$ requires larger $\beta^*_{x,e}$ to match beam sizes
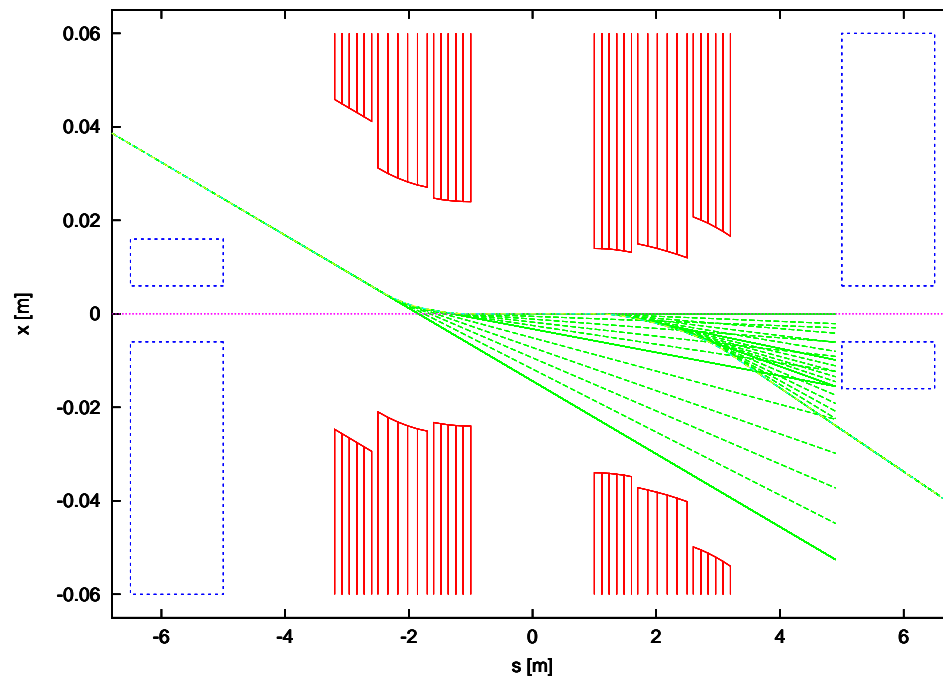 $\rightarrow$ larger beam-beam parameter
  $\rightarrow$ luminosity limitation for ring-ring design

- Accomodation of synchrotron radiation generated by beam separation

Electron low-β quads must accomodate both beams, plus the synchrotron radiation fan
$\rightarrow$ upper limit on focusing strength due to limited pole tip field

- Beam focusing to small spot sizes to maximize luminosity

Beam size at first quadrupole at distance s :

$$\sigma(s) = \sqrt{\epsilon\beta(s)} = \sqrt{\epsilon\beta^* + \epsilon\frac{s^2}{\beta^*}} \approx \sqrt{\epsilon\frac{s^2}{\beta^*}}, \ \ s \gg \beta^*$$

Important consequences:

- Small β^* (= high luminosity) leads to large beamsize at the quadrupole

- Large distance to first quadrupole (= more room for detector) leads to large beamsize at the quadrupole

For a given necessary quadrupole gradient, this increases the pole tip field
→ Limitation on luminosity

How close can quadrupoles be placed?

1. Zero crossing angle, ring-ring design:

   - magnets need to be staggered, electron quadrupoles first, shared with ion beam

2. Zero crossing angle, linac-ring design:

   - beam separation by detector-integrated dipole

   - no electron quads necessary $\rightarrow$ ion quads can be closer, but:

   - septum (= source of synchrotron radiation background) away from detector

3. Finite crossing angle:

- quads for electrons and ions can be placed side-by-side

- no septum necessary

- low background

- shorter bunch spacing possible

- requires crab-crossing (very challenging)

Conclusion

- Minimum β^* ("= maximum luminosity") given by bunch-length

- The larger the distance between IP and first quadrupoles, the larger the achievable β^* (= the smaller the luminosity)

- Linac-ring design provides higher luminosity

- Crossing angle "eliminates" synchrotron radiation fan in IR, provides better background conditions, and maximizes luminosity, but requires crab crossing (very challenging)