The 2015 eRHIC Ring-Ring Design

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Ring-ring design goals

- Low- to no-risk approach
- Full energy range (up to 250 GeV protons on 20 GeV electrons) from the beginning
- Full physics reach in terms of IR design
- 80 percent electron polarization, 70 percent proton polarization
- Baseline design luminosity around 1E33
- Luminosity upgradeable
- Potential future upgradeability to linac-ring design

Beam parameters and luminosities

- 360 bunches (requires in-situ beam pipe coating and new injection kickers; now 120)

- Normalized proton emittance $\epsilon_{n,p} = 2.5\,\mu$m (achieved in RHIC)

- Proton rms bunch length $\sigma_s = 20\,$cm (achievable in RHIC at 250 GeV; requires electron cooling at low energies)

- Electron emittances $\epsilon_{x,e} = 53\,$nm, $\epsilon_{y,e} = 9.5\,$nm

- Proton β-functions $\beta^*_{x,p} = 2.16\,$m, $\beta^*_{y,p} = 0.27\,$m

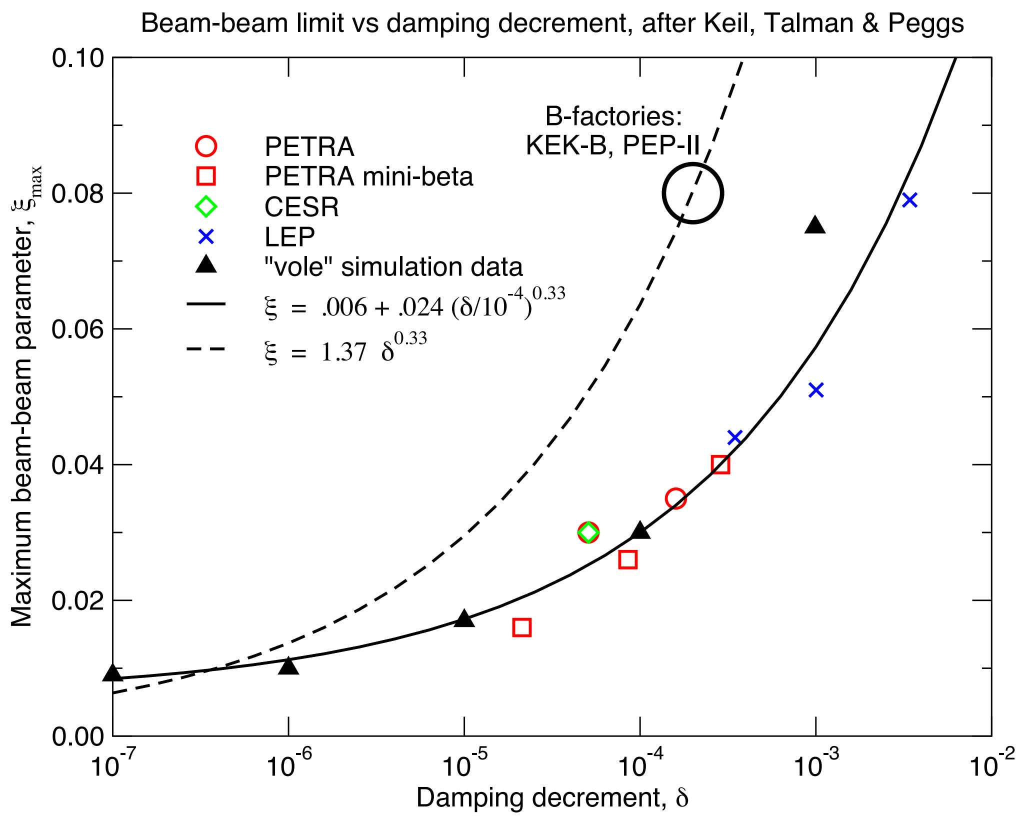
- Maximum proton bunch intensity $N_p = 3 \times 10^{11}$ (25 percent higher than achieved in RHIC)

- Beam-beam scaling with transverse damping decrement as in B-factories: $\xi_e = 1.37\delta^{1/3}$,
with $\delta = U_0/(2 \cdot E_e)$

- eRHIC: $\xi_y = 0.096$ at 20 GeV, $\xi_y = 0.178$ at 5 GeV with damping wigglers (N.B.: LEP200 reached $\xi_y = 0.115$)

- Use damping wigglers to increase damping decrement by increasing SR power to respective RF limit

Beam-beam parameter vs. damping decrement

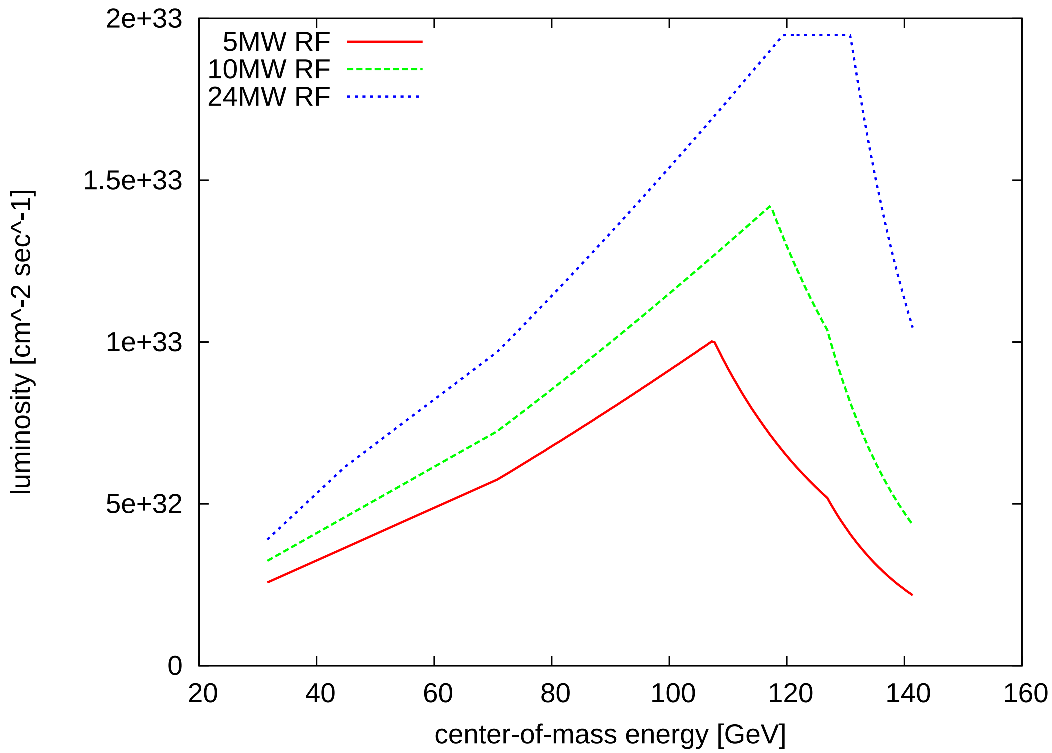


- Experimental data agree well with scaling rule
- B-factories significantly better due to half integer working point

Synchrotron radiation power losses

- Technical limit for linear synchrotron radiation power loss is $10\,\mathrm{kW/m}$ in the arcs
- With a total arc length of $2\pi \cdot 380\,\mathrm{m} = 2390\,\mathrm{m}$, that corresponds to $24\,\mathrm{MW}$ of RF power
- Typical klystron efficiency is about 60 percent, so we would need $40\,\mathrm{MW}$ of electrical power for the RF alone

How does luminosity scale with RF power?



• More RF power means more luminosity, esp. at high energies

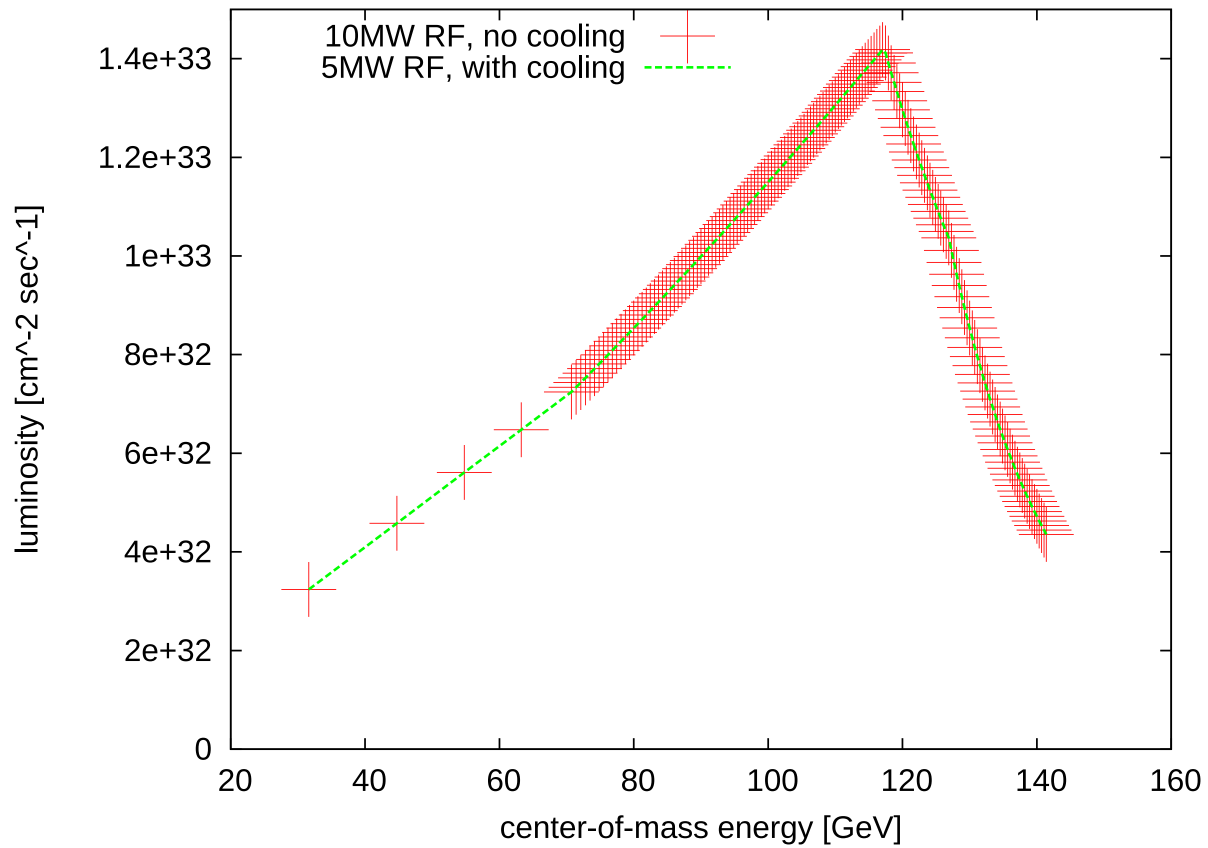
• Peak luminosity scales less than linear with RF power, but occurs at different energies

What can cooling do?

Assume moderate electron cooling:

- Reduce proton emittance by factor 2: $\epsilon_{n,p} = 1.25\,\mu$m
- Reduce proton bunchlength by factor 2: $\sigma_s = 10\,$cm
- Reduce electron β-functions by factor 2 to match size with cooled protons

Could use other scaling factors as well

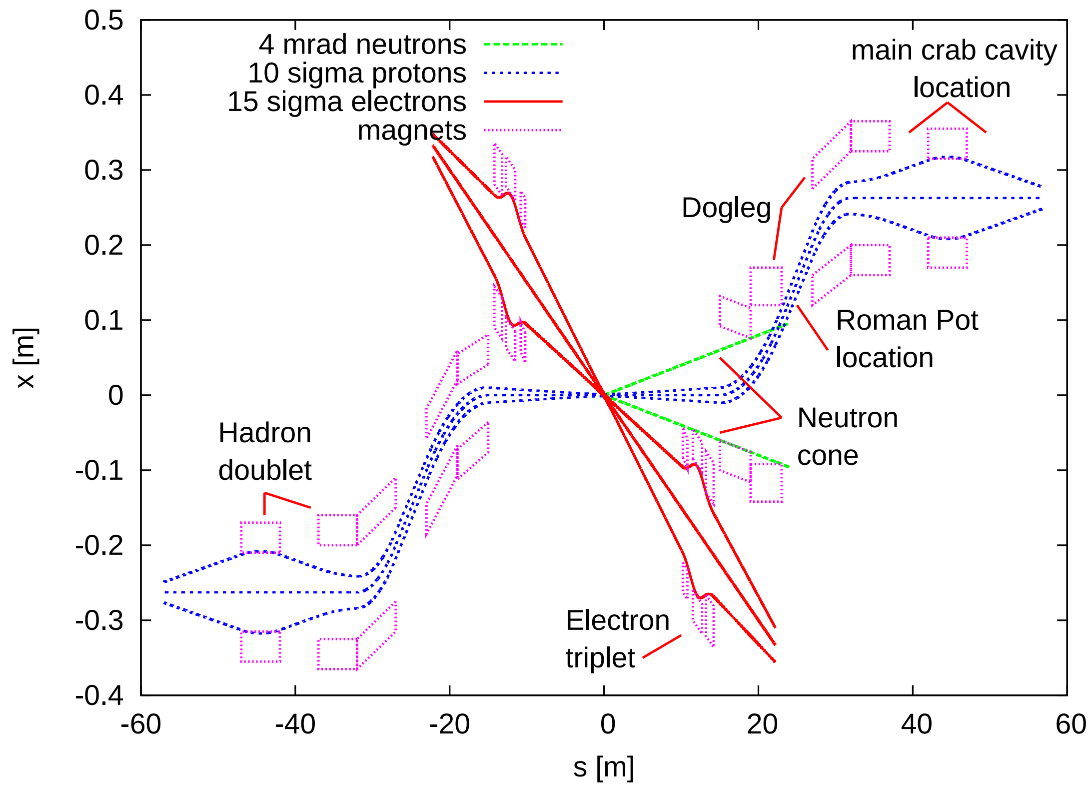


- Cooling gives us the same luminosity at half the synchrotron radiation power

IR design requirements

- ± 4.5 m element-free space around IP
- Unobstructed path for ± 4 mrad neutron cone
- $\approx$ 2 m space for Roman Pots, transverse momentum acceptance of $p_\perp \geq 200$ MeV/c
- Design aperture $10\sigma_p$ for protons, $15\sigma_e$ for electrons

IR layout (top view)



- Full dogleg and > 2 m space for Roman Pots
- 15 mrad crossing angle with crab cavities
- Proton quad aperture could be increased to accommodate low energy beams without cooling; peak field for apertures shown only 1.1 T

Crab crossing

Crab cavities provide a 4-bump for head and tail:

- Main crab cavities are adjacent to hor. focusing quad, at $\beta_{\text{crab},1} = 2400\,\text{m}$ and $\psi = 86^\circ$

- Non-ideal phase advance causes an angle error at the IP, described by $m_{22} = \sqrt{\beta_{\text{crab},1}/\beta^*}\cos\psi \approx 2$

- This angle error has to be corrected by a second crab cavity at $\psi = k \cdot 180^\circ$; this is described by $m_{22} = \sqrt{\beta_{\text{crab},2}/\beta^*}\cos\psi = \pm\sqrt{\beta_{\text{crab},2}/\beta^*}$

- If $\beta_{\text{crab,2}}$ is chosen such that $\sqrt{\beta_{\text{crab,2}}/\beta^*} > 2$, the voltage of this "trim crab cavity" is smaller than that of the main crab cavity

- This condition is fullfilled if $\beta_{\text{crab,2}} > 10\,\text{m}$ - practically everywhere

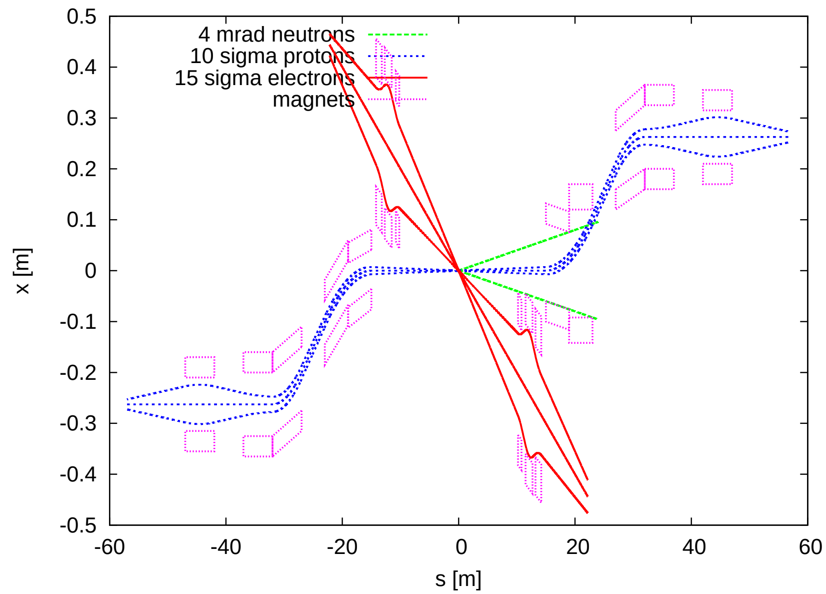
- $V_{\text{main crab}} = \frac{c \cdot E[\text{eV}]\Theta_{\text{crab}}}{\omega_{\text{RF}}\sqrt{\beta_{\text{crab,q}}\beta^*}} = 7.4\,\text{MV}$ at $f_{\text{RF}} = 168\,\text{MHz}$

IR design features

- 15 mrad crossing angle
- crab crossing, using 7.4 MV, 168 MHz crab cavities
- $\pm$4.5 m element-free space for central detector
- free space for $\pm$4 mrad neutron cone
- 8 m long, 25 mrad spectrometer dipole
- $>$ 2 m for Roman Pots

Required IR changes for moderate cooling

(Emittance reduction by factor 2 in all planes)



Modified layout:

- 20 mrad crossing angle instead of 15 mrad
- larger electron triplet aperture

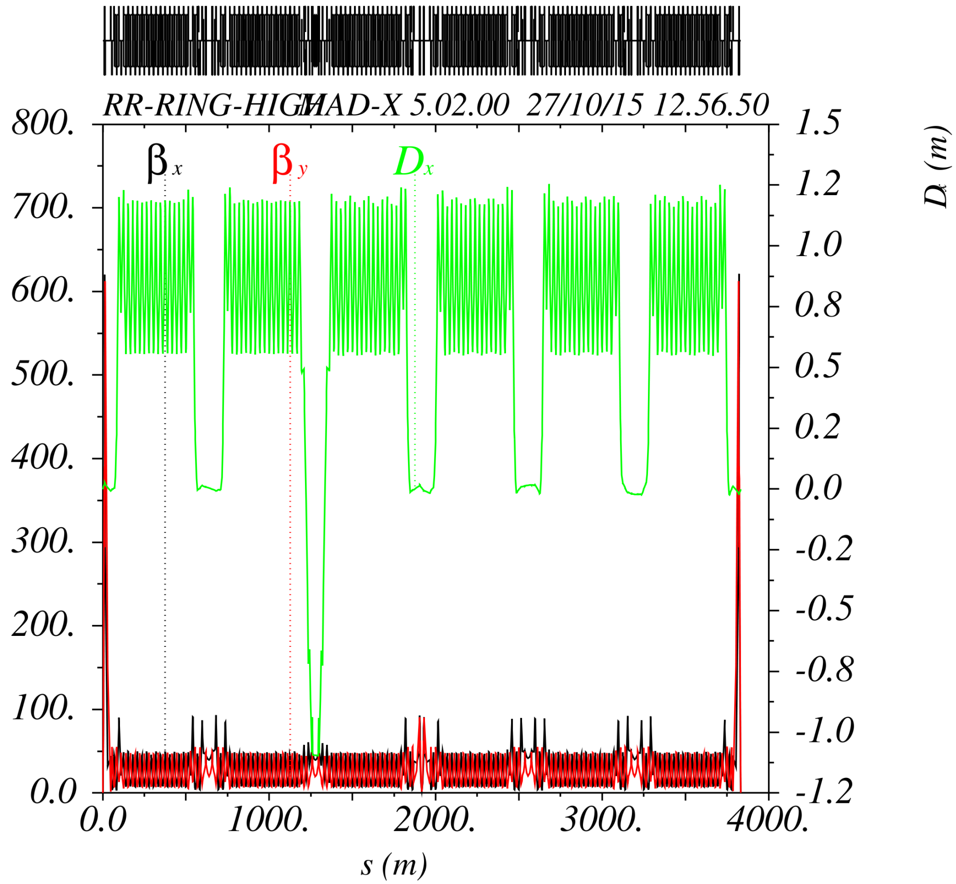
Cooling to even smaller emittances requires larger crossing angles; feasible if bunch length shrinks accordingly

Electron ring lattice

- 300 m dipole bending radius in 380 m radius tunnel

- 53 nm horizontal emittance, tuneable to 106 nm for collisions with 50 GeV protons

- Robinson wiggler for emittance adjustment via damping partition number manipulation

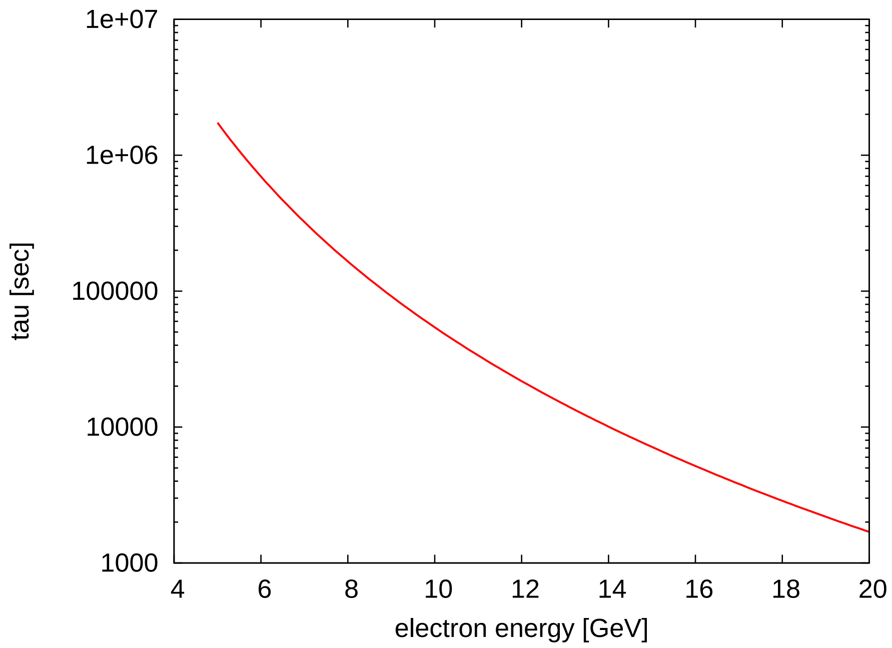


• Complete electron ring lattice with IR and Robinson wiggler for emittance adjustment

• No damping wigglers yet

Electron polarization

Ramping would destroy electron polarization
Electrons self-polarize at store due to synchrotron radiation:



Self-polarization is not viable except at highest energies
$\Rightarrow$ Need a full-energy polarized injector

Advantage of a full-energy polarized injector:

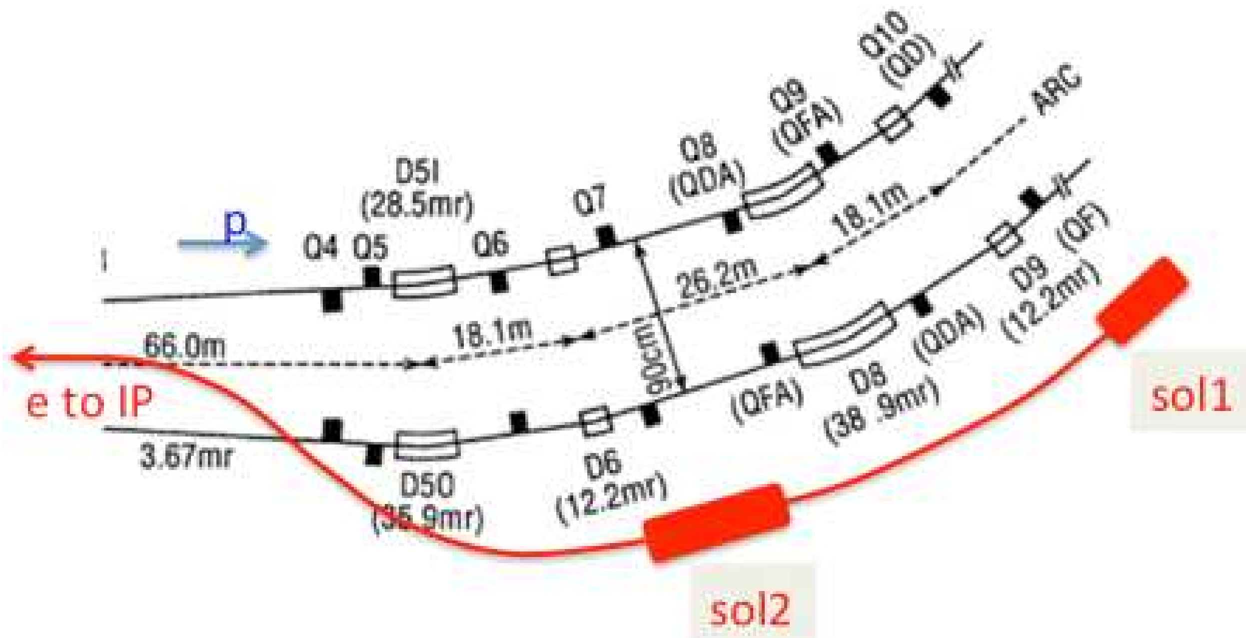
- Electron spin patterns with alternating polarization (as in RHIC proton fills) are highly desirable and likely required for single-spin physics

- Such fill pattern can be generated by a full-energy polarized injector

- Bunches with the “wrong” (unnatural) polarization direction will slowly flip into the “right” orientation. Time scale given by Sokolov-Ternov self-polarization time

- Bunch-by-bunch replacement at 1 Hz (360 bunches in 6 min) yields sufficient polarization even at full energy with $\tau_{\mathrm{S-T}} = 30\,\mathrm{min}$

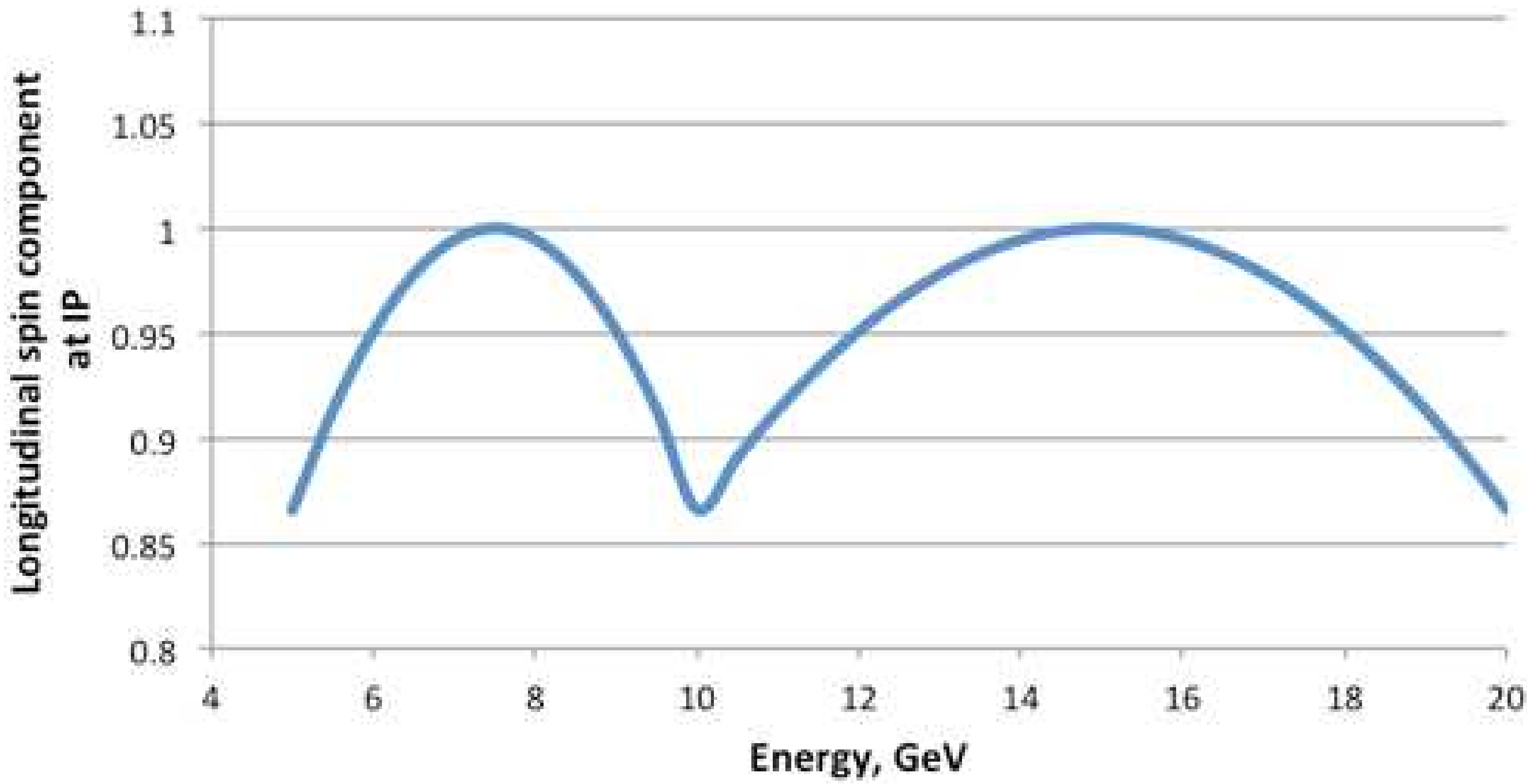
Electron spin rotators



- Two solenoid type spin rotators provide longitudinal polarization in two different energy regimes
- Integrated fields: $B \cdot l[\mathrm{Tm}] = 5.24E[\mathrm{GeV}]$;

26-53 and 52-105 Tm, resp.

Longitudinal spin vs. energy



Perfect longitudinal polarization at 7.5 and 15 GeV, some transverse component at other energies

Electron injector options

1. $\approx 0.8\,\mathrm{km}$ section of the SLAC linac, used twice
    - May need an accumulator ring after first linac pass to reach required bunch intensity
    - Second pass with full intensity bunch to reach full energy
    - Time critical; removal begins next spring
2. Figure-8 rapid cycling synchrotron
    - Spin tracking underway to ensure polarization preservation

3. Recirculating superconducting linac (CEBAF-type)

   - May need an accumulator ring as well
   - Only option upgradeable to linac-ring

All options still need detailed feasibility study

Path length adjustment

- Different proton beam energies require path length adjustment by up to $\Delta C = 65\,\text{cm}$ due to velocity changes

- Wigglers in electron ring increase path length and synchrotron radiation power - good for increased damping decrement at low electron energy, bad due to power losses at high energy

- Utilizing arcs from both RHIC rings provides a set of discreet proton energies with matched circumference. Polarity of YELLOW arcs needs to be reversed and arcs need to be physically moved - labor intensive but doable

Final solution will likely be a combination of both schemes

Leading risks

1. Electron cooling

   - Required to maintain 20 cm RMS bunch length at low proton energies (50-100 GeV)
   - Option to reduce power consumption or increase high energy luminosity
   - LEReC is a prototype for bunched beam electron cooling
   - Challenging linac design for full energy range: High energy, high intensity ERL

2. Crab cavities

- IR design with 15 mrad crossing angle requires crab cavities to restore luminosity
- 168 MHz crab cavities with 7.5 MV seem feasible
- Proof-of-principle exists at KEKB, but not for hadron beams. To be studied by tracking - may need to add harmonic cavities to straighten out bunches
- Eliminating the crossing angle requires a dipole field that generates several hundred kW of synchrotron radiation power with a critical energy of 120 keV or more, having serious impact on detector design and acceptance

Luminosity upgrade options

Two possible luminosity upgrade paths:

1. Linac-ring, using
   - ERL
   - FFAG
   - CeC

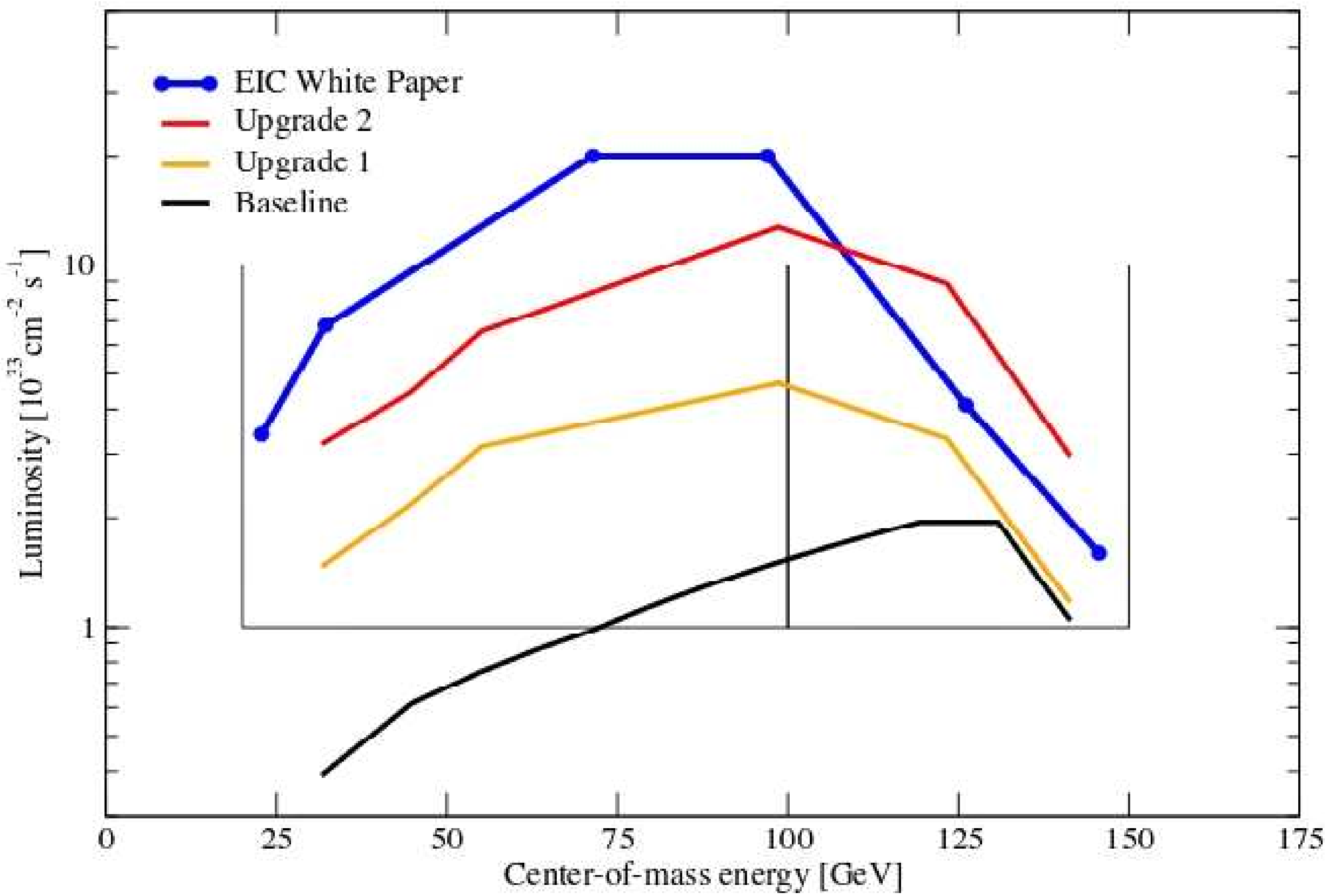
   To be cost effective this upgrade path practically requires a CEBAF-type injector for the ring-ring baseline

2. Ring-ring with many low emittance, low intensity bunches, as suggested by Y. Zhang:

Upgrade level	0	1	2
maximum no. of bunches	360	2000	6000
minimum hor. electron emittance [nm]	53	23	10
proton normalized RMS emittance [μm]	2.5	0.7	0.34
proton RMS bunch length [cm]	20	8	3.5
minimum β^* [cm]	27	8	4
maximum $\sigma'_{x,p}$ [mrad]	0.42	0.47	0.40
maximum $\sigma'_{x,e}$ [mrad]	0.37	0.7	0.7
crossing angle [mrad]	15	22	22
maximum luminosity [$10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	2	4.7	12.7

Requires (coherent) electron cooling and a new, advanced IR design with quadrupoles at 4.5 m to limit chromaticity

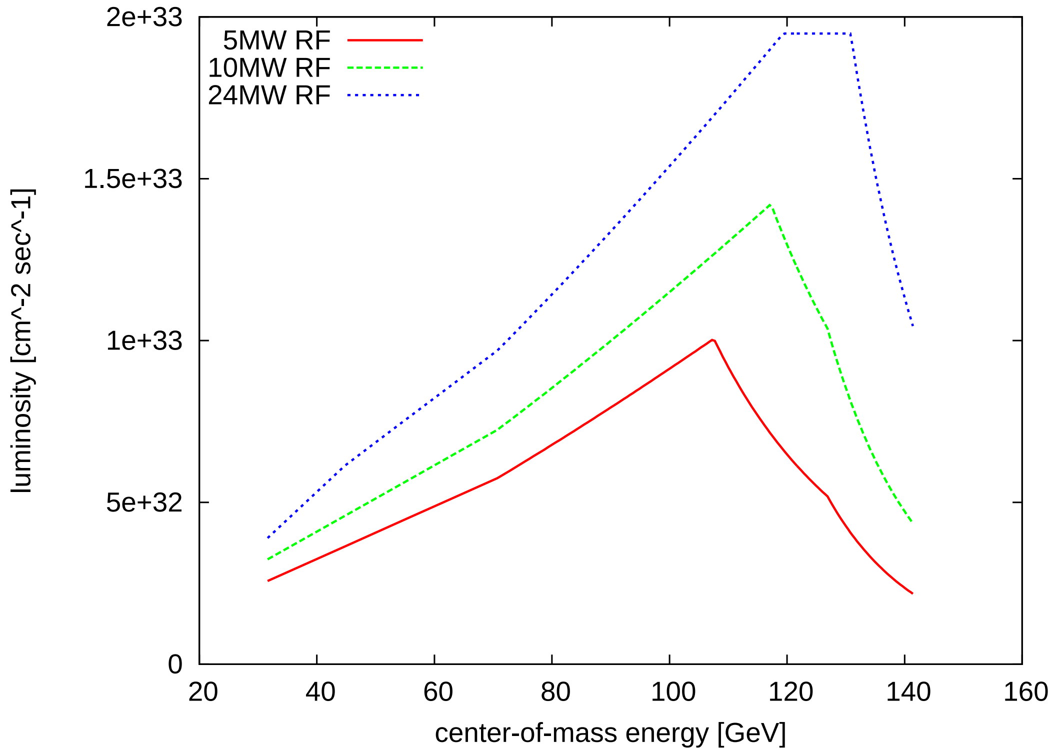
Luminosity in various upgrade stages/scenarios



Next steps

- Spin matching
- Tracking studies: Dynamic aperture, beam-beam (including realistic crab crossing), spin
- Spin tracking in Figure-8 injector synchrotron
- Detailed crab cavity design
- Electron cooler design
- Cost estimate

Summary

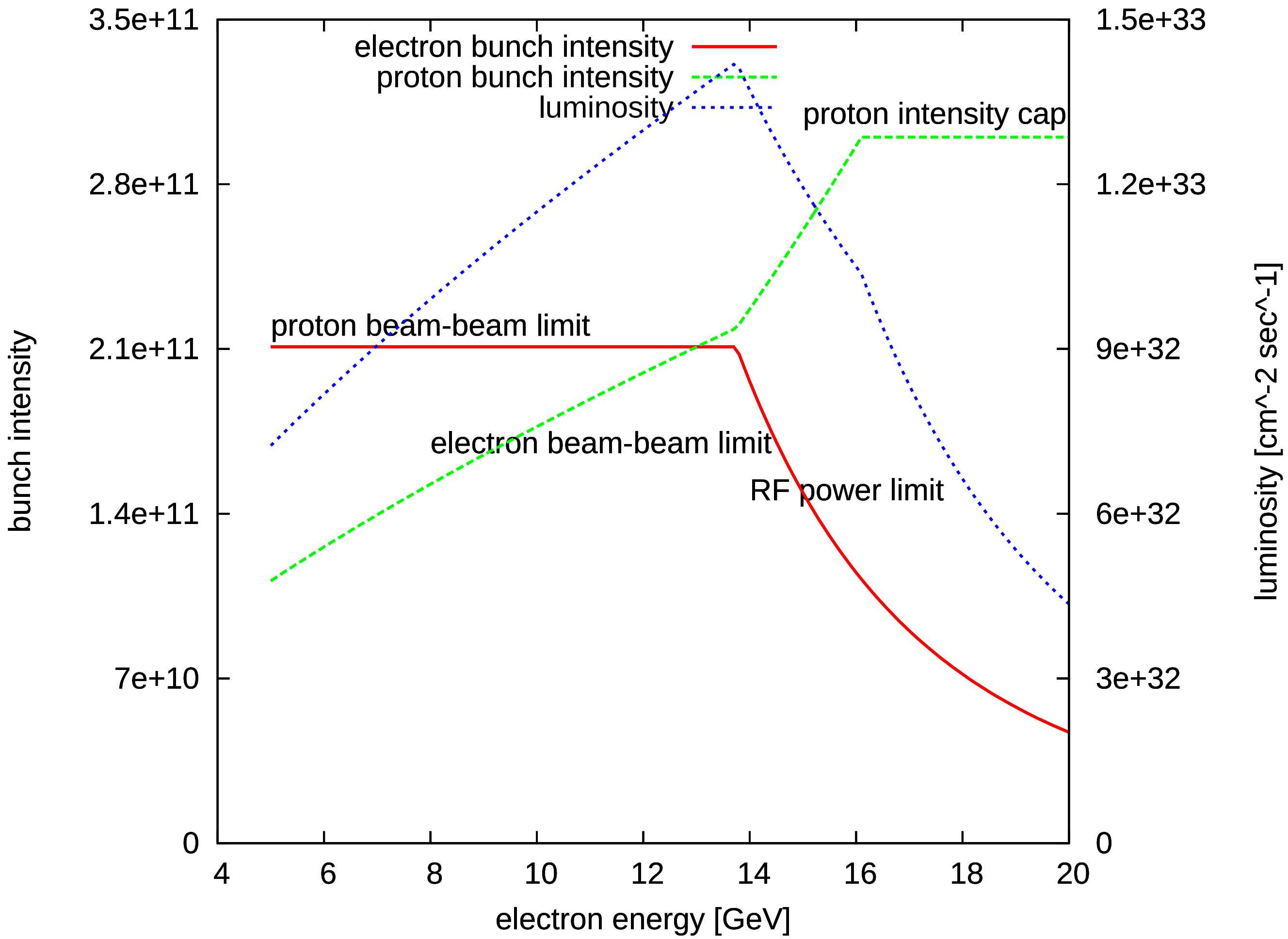


- Ring-ring approach provides $\approx 1 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ luminosity over the required energy range, depending on RF power

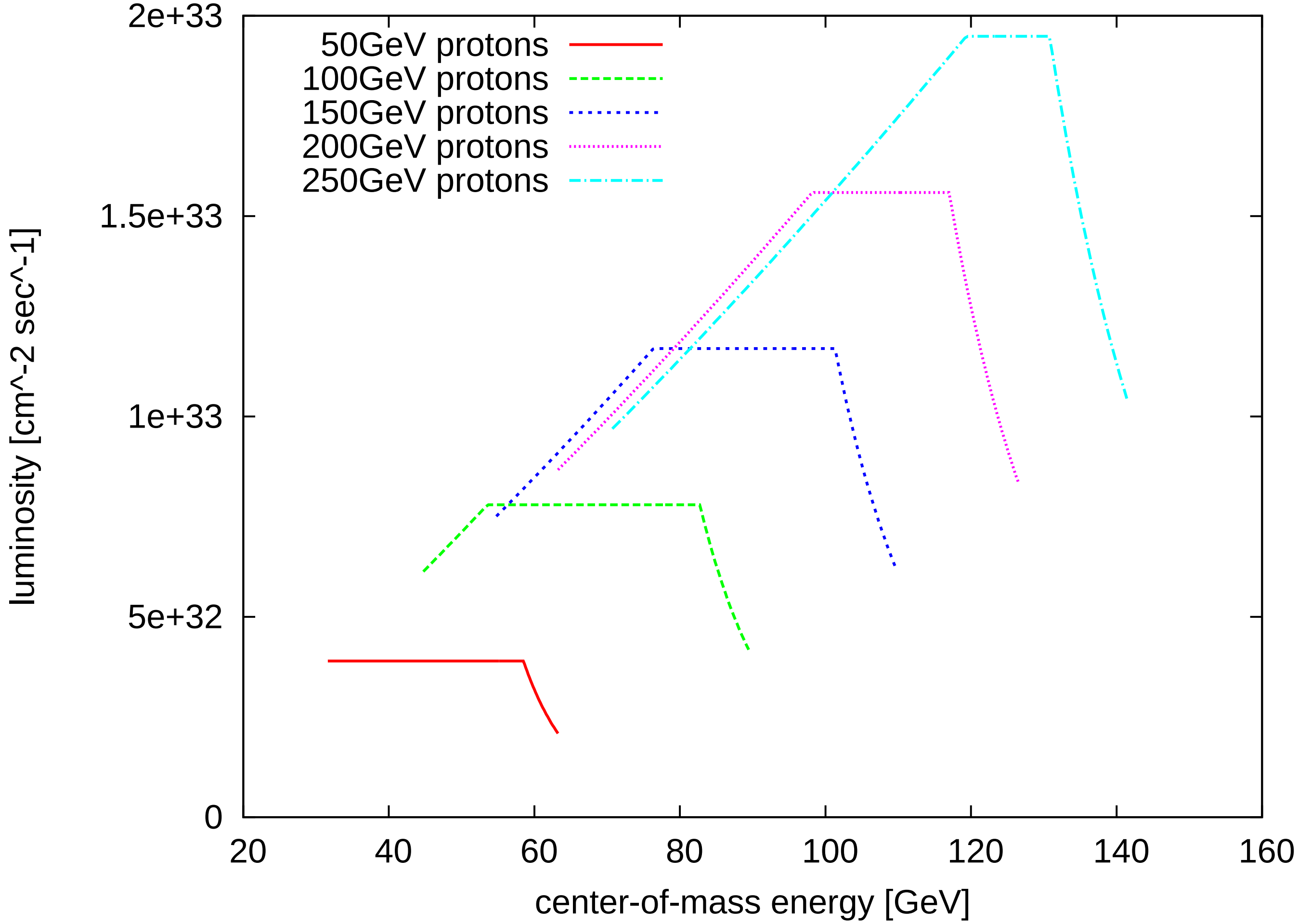
- IR design meets Physics requirements
- Low risk approach - electron cooling and crab crossing
- Longitudinal electron cooling needed for low proton energies (up to $\approx 100\,\mathrm{GeV}$)
- Electron cooling boosts luminosity, or reduces power consumption, over entire energy range
- Crossing angle requires crab cavities
- Luminosity upgrade path, including possible conversion to linac-ring (depending on injector option chosen)

Backup slides

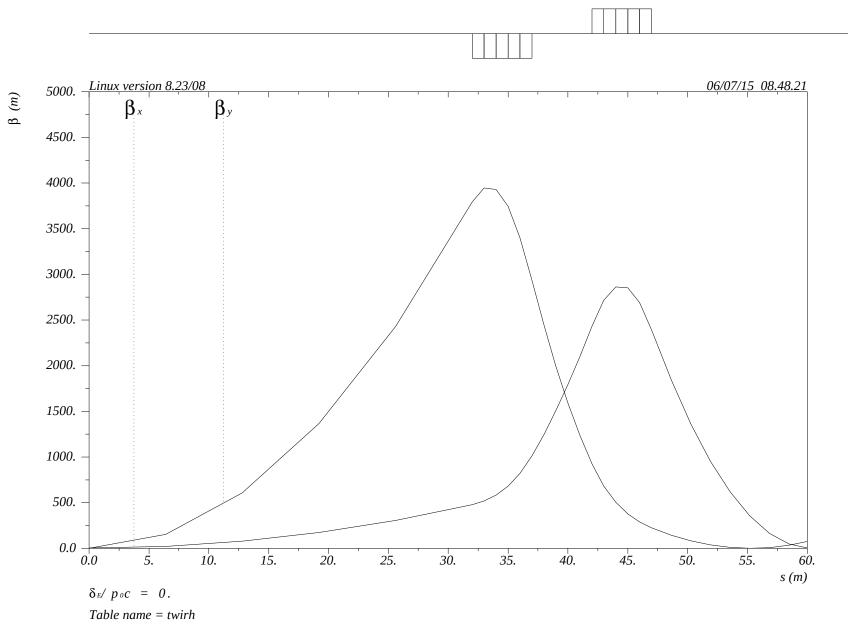
Bunch intensities for 250 GeV protons, 10 MW power limit



Luminosity curves for different proton energies



Proton low-β doublet



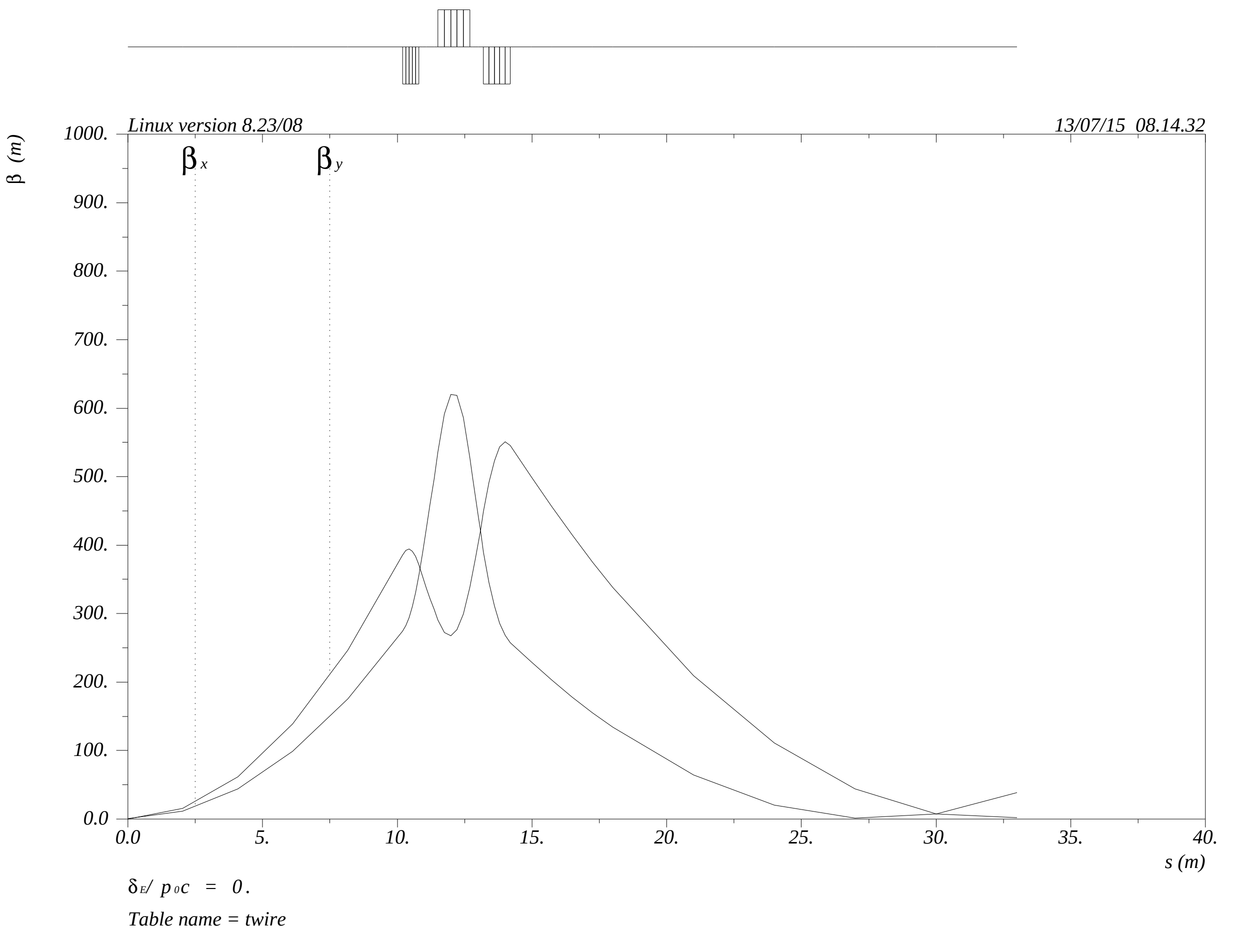
- Crab cavities adjacent to Q2
- β_x at crab cavities intentionally increased to minimize voltage, $\beta_{\text{crab}} = 2400\,\text{m}$
- Chromaticity for entire IR: $\chi = \frac{1}{4\pi}\int k\beta\,\text{d}s \approx 60 - 70\,\text{units}$

Proton magnet parameters

magnet	length	k	aperture radius	peak field
QP1	5.0 m	$-0.022/\mathrm{m}^2$	62 mm	1.14 T
QP2	5.0 m	$0.026/\mathrm{m}^2$	52 mm	1.13 T

- Maximized horizontal β-function at QP2 to help with crab crossing
- Phase advance between IP and crab cavity is 86 degrees. Need additional cavities to produce a closed 4-bump.
- Magnet apertures could be increased to allow same β^* at lower energies (=larger emittances)

Electron triplet



Electron magnet parameters

magnet	length	k	aperture radius	peak field
QE1	0.6 m	$-0.43/\mathrm{m}^2$	70 mm	2.1 T
QE2	1.2 m	$0.43/\mathrm{m}^2$	87.5 mm	2.5 T
QE3	1.0 m	$-0.3/\mathrm{m}^2$	68 mm	1.4 T

- Apertures given are for $15\sigma_x$
- Resulting minimum vertical aperture is $\approx 30\sigma_y$ (at QE3; could likely be increased somewhat)

Crab crossing geometry