EIC Parameters vs. Cooling Assumptions

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The talk will describe, and motivate, the eRHIC operating parameters, with three different assumed levels of cooling.

1. Requirements
2. Round vs. flat beams
3. Ring-Ring vs. Linac-Ring
4. Divergences Options
5. Transverse Cooling Options
6. IBS
7. Longitudinal Cooling Options
8. Option without crab cavity
9. Cooling methods
10. Conclusions

Requirements

1. C of mass Energy 30 to 140 GeV
2. Luminosity 1 to 10 $10^{33}\ cm^{-2}s^{-1}$
3. Reasonable efficient observation and measurement of forward protons down to transverse momenta of 200 MeV/c for diffractive physics.
4. Very efficient observation of 1.3 GeV pt forward protons, again for diffractive physics.
5. Neutron detection in forward angles to 4 mrad
6. Forward charged track detection up to 22 mrad
7. Low beam divergences to reduce uncertainties on the initial states.
8. Low beam energy spreads to again reduce uncertainties on the initial states, and also to control beam transverse spreads in forward detectors where there is dispersion.

Flat vs. Round

1. Matching asymmetry of electron emittances.

   Possible $\epsilon_{ye} << \epsilon_{xe}$ $\rightarrow$ Desirable $\epsilon_{yp} << \epsilon_{xp}$

2. Quads are asymmetric

   Lower β_y^* if $\beta_y^* << \beta_x^*$ for same chromaticity than for $\beta_x^* = \beta_y^*$

3. Luminosity for fixed beam-beam parameters, betas, & currents

$$\mathcal{L} \propto \sqrt{(1+K)(1+1/K)} \; \bar{E} \; \bar{I} \; \frac{\bar{\xi}}{\bar{\beta}*} \tag{1}$$

$$where \qquad K = \sigma_x/\sigma_y \tag{2}$$

$$\text{For } (\sigma_x >> \sigma_y) \text{ then } \mathcal{L} \propto \frac{\sqrt{K}}{2} \tag{3}$$

4. With short bunches, operation possible without crab cavities (see later)

Ring-Ring vs. Linac Ring

- Again
$$\mathcal{L} \propto \sqrt{(1+K)(1+1/K)}\ \bar{E}\ \bar{I}\ \frac{\bar{\xi}}{\bar{\beta}^*} \tag{4}$$

$$\xi_{e\ RR} \approx 0.1 \qquad \xi_{e\ LR} \approx 4$$

$$\mathcal{L}_{LR}/\mathcal{L}_{RR} = 40$$

- Offset by

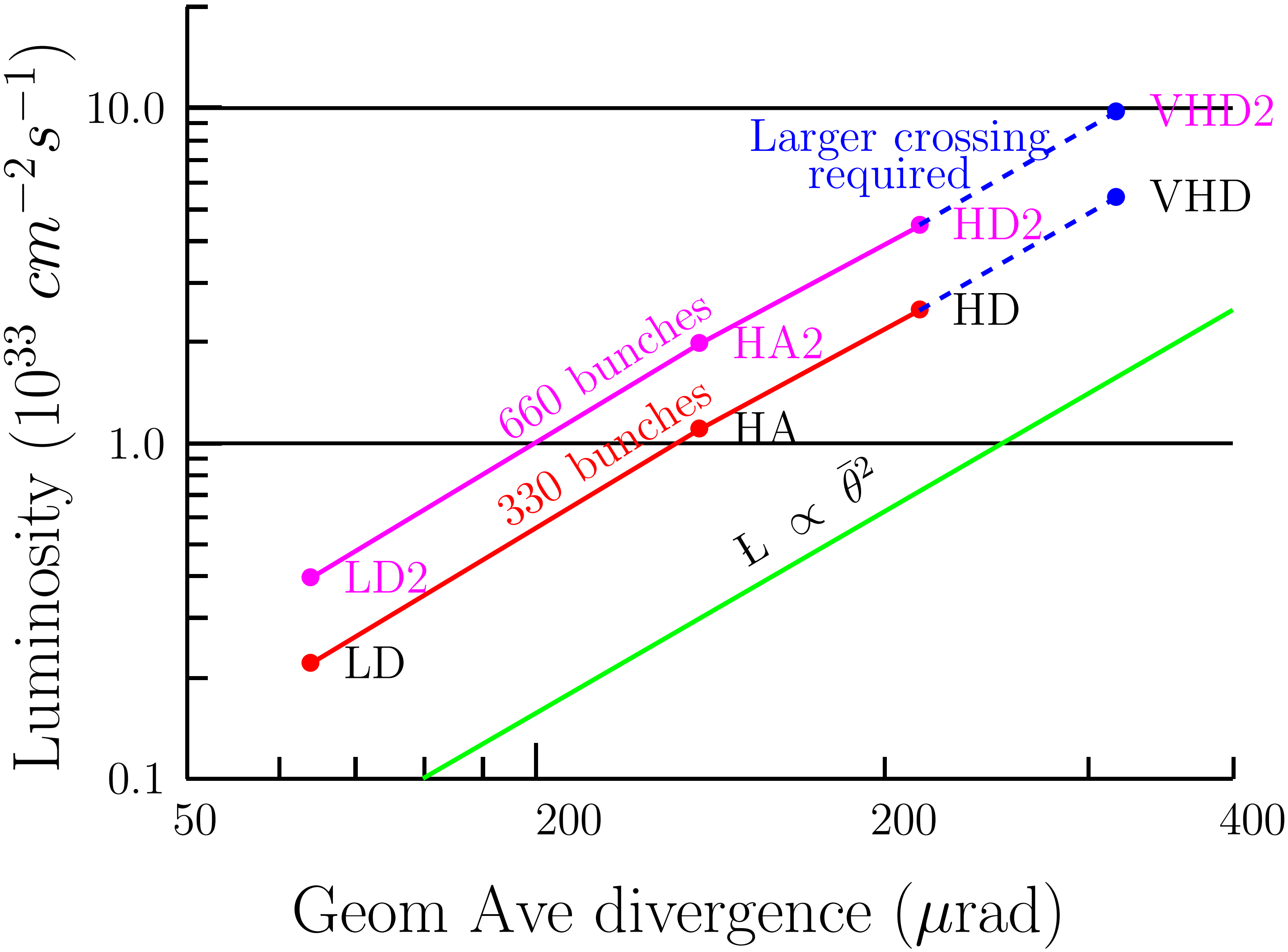
$$I_e(RR) \approx 2\ \mathrm{A}\ \ (e.g.\ PEPII) \qquad I_e(LR) \approx 50\ \mathrm{m}A\ \ (Gun\ limit)$$

$$\mathcal{L}_{LR}/\mathcal{L}_{RR} = \frac{1}{40}$$

- High $\xi_e \propto N_p/(\epsilon_e \gamma_e)$ gains luminosity by raising N_p,

But High N_P increases IBS

Luminosity dependence on Divergence



$$\mathcal{L} \propto \frac{1}{\sigma_x\ \sigma_y}$$

$$= \frac{x'\ y'}{\epsilon_x\ \epsilon_y}$$

if $\quad \bar{\theta} = \sqrt{x'\ y'}$

then $\quad \mathcal{L} \propto \bar{\theta}^2$

- $x'\ y'$ relationship seen
- With a larger crossing angle one could get 10^{34}, but the large divergence would hurt some physics

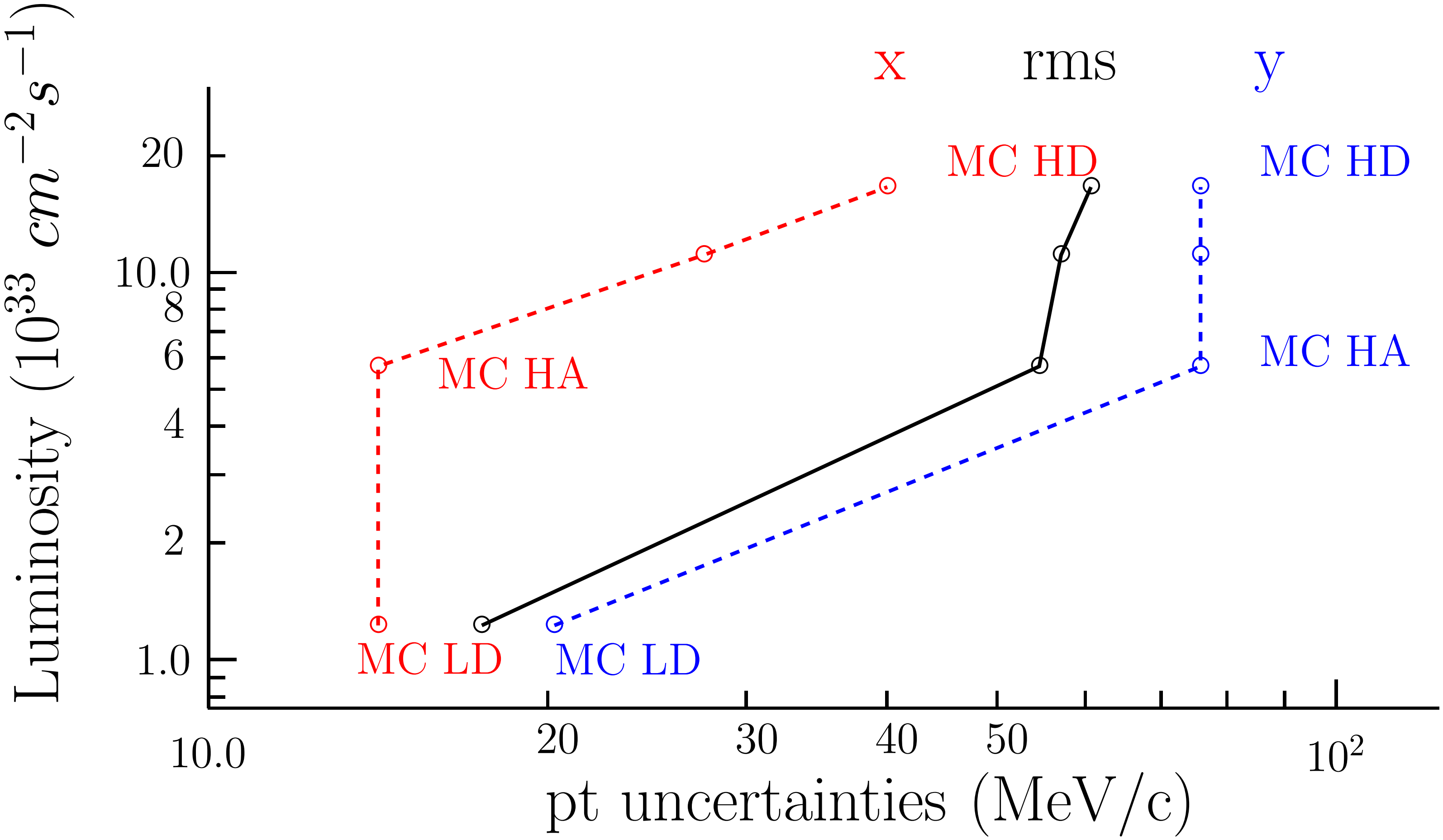
Choices of Divergences

1. "High Divergence" (HD) cases with luminosity maximized by using the largest divergences consistent with the IR design;

2. High Acceptance (HA) cases with reduced horizontal (x) divergences to allow at least 50 % efficiency for observing outgoing forward protons with transverse momenta down to 200 MeV/c. To keep the luminosity as high as possible, the y divergences are maintained as in the High Divergence cases.

3. With the same High acceptance criterion maintained, the"Low Divergence" (LD) cases have vertical (y) divergences reduced to near the x divergence needed for high acceptance. With both divergences now low, the initial state transverse momentum uncertainties are much smaller than either HD or HA cases.

Example for Moderate Cooling

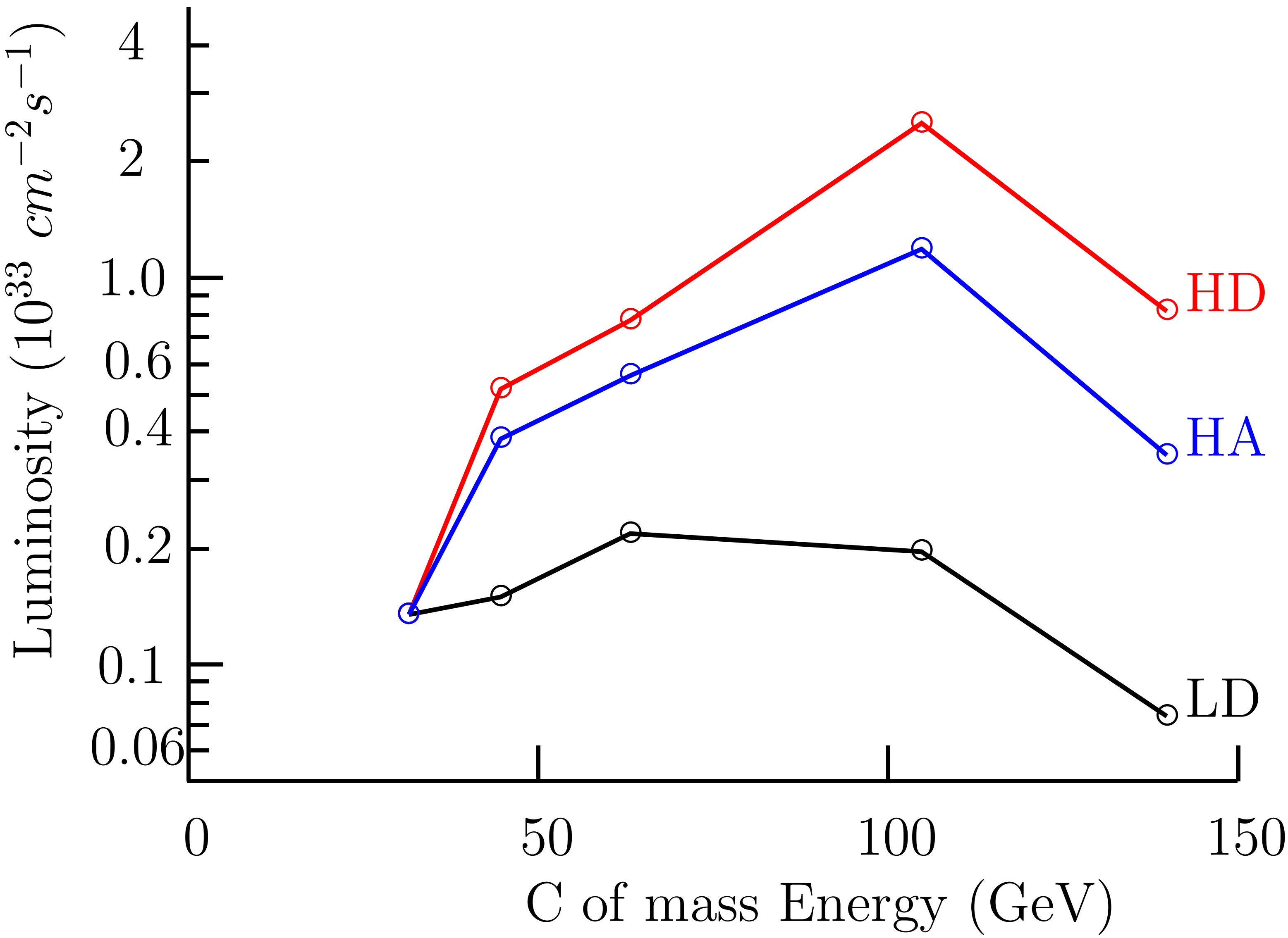


High Divergence (HD): large uncertainties in both x and y

High Acceptance (HA): small uncertainties in both x, but large in y

Low Divergence (LD): small uncertainties in both x and y

Luminosities vs. Energy



LD Low Divergence HA High Acceptance HD High Divergence

Three Levels of Cooling

NC) No cooling assuming a $\epsilon_{Np\perp} = 1.8\mu$m ,
A good first phase, but does not meet luminosity specified

MC) Moderate cooling with a $\epsilon_{Np\perp} \approx 0.5\mu$m, and
Hopefully possible with multiple cooling methods

SC) Strong cooling with a $\epsilon_{Np\perp} \approx 0.12\mu$m.
Probably possible, if at all, only with CeC

Initially Selected Parameters

	ϵ_{Nx} μm	ϵ_{Ny} μm	ϵ_{Nz} eVsec	N_p 10^{10}	dp/p 10^{-4}	σ_z cm	β_{yp} cm	freq MHz	Volts MV	$\tau_{\parallel}$ hr	$\tau_{\perp}$ hr	Q_{100m} nC	I_{cool} A	Lum 10^{33}
a)	Base													
NC HD	5.26	1.79	0.92	1.3	6.50	8.0	4.20	394	15.20	10.2209	5.7652	61.6	1.59	2.94
MC HD	2.73	0.47	0.46	0.6	6.50	4.0	2.10	394	60.81	3.5721	0.7063	20.7	2.14	13.73
SC HD	2.73	0.12	0.46	0.6	6.50	4.0	2.10	394	60.81	1.6944	0.1618	16.0	1.65	21.21

Needs no cooling Needs cooling

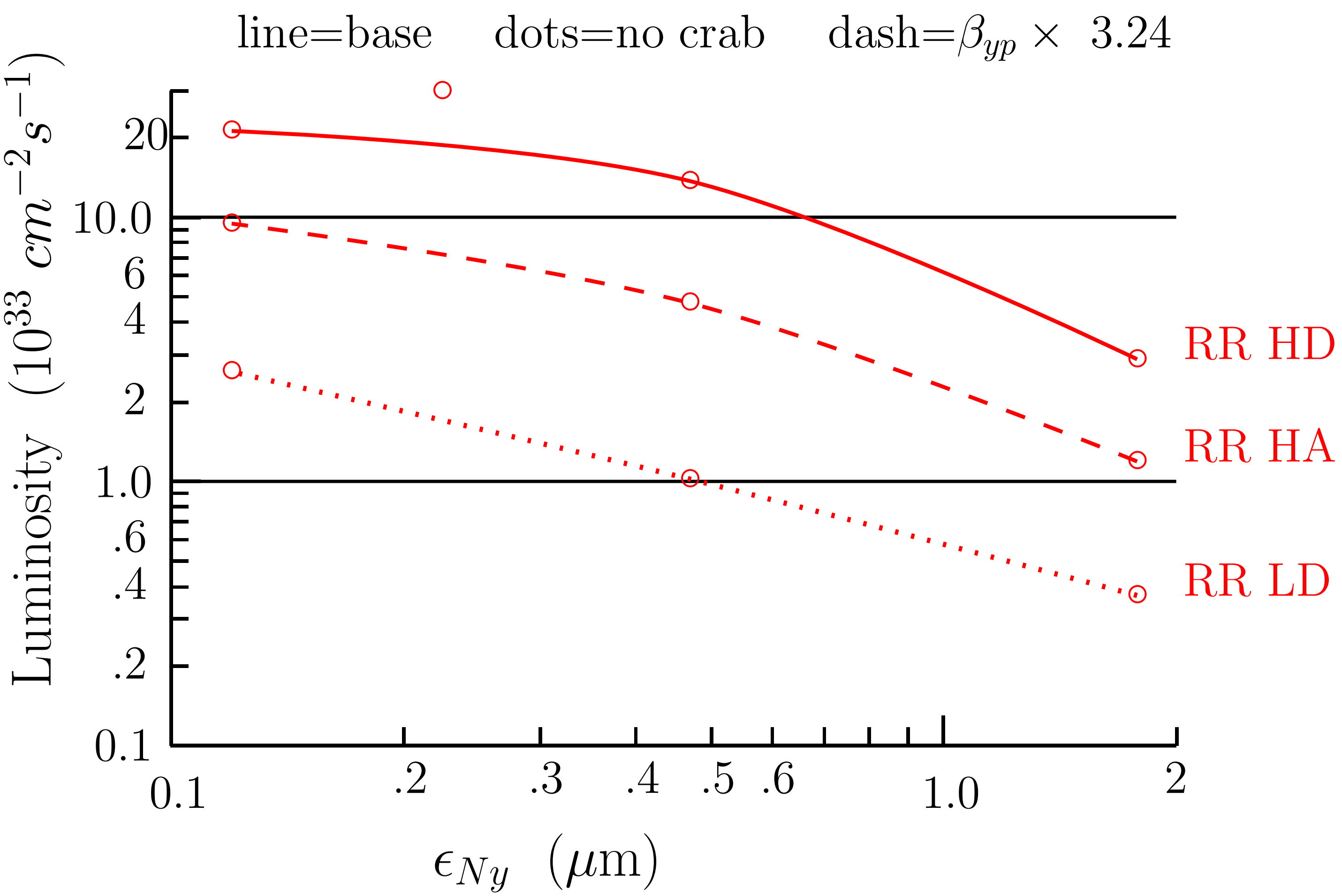
a) line 1) With No Cooling

- $\tau \approx$ 5.5 hr. Efficiency $\approx 58\%$ $<\mathcal{L}>\approx$ 1.7 $10^{33}\ cm^{-2}s^{-1}$
- dp/p $=$ 6.5 10^{-4}

a) lines 2 & 3) With transverse, but no longitudinal, cooling

- $Q_{cooling}$ falls with strength of cooling! 16 nC for strong
- Cooling current very high. Recirculating, as at JLEIC, essential.
- $\delta = 6.5\ 10^{-4}$ is scary
- rf V very high (60 MV!)

Luminosity vs. Emittance



NC) No cooling assuming a $\epsilon_{Np\perp} = 1.8\mu$m ,

MC) Moderate cooling with a $\epsilon_{Np\perp} \approx 0.5\mu$m, and

SC) Strong cooling with a $\epsilon_{Np\perp} \approx 0.12\mu$m.

Parameters with added Longitudinal Cooling

	ϵ_{Nx} μm	ϵ_{Ny} μm	ϵ_{Nz} eVsec	N_p 10^{10}	dp/p 10^{-4}	σ_z cm	β_{yp} cm	freq MHz	Volts MV	$\tau_{\|\|}$ hr	$\tau_{\perp}$ hr	Q_{100m} nC	I_{cool} A	Lum 10^{33}
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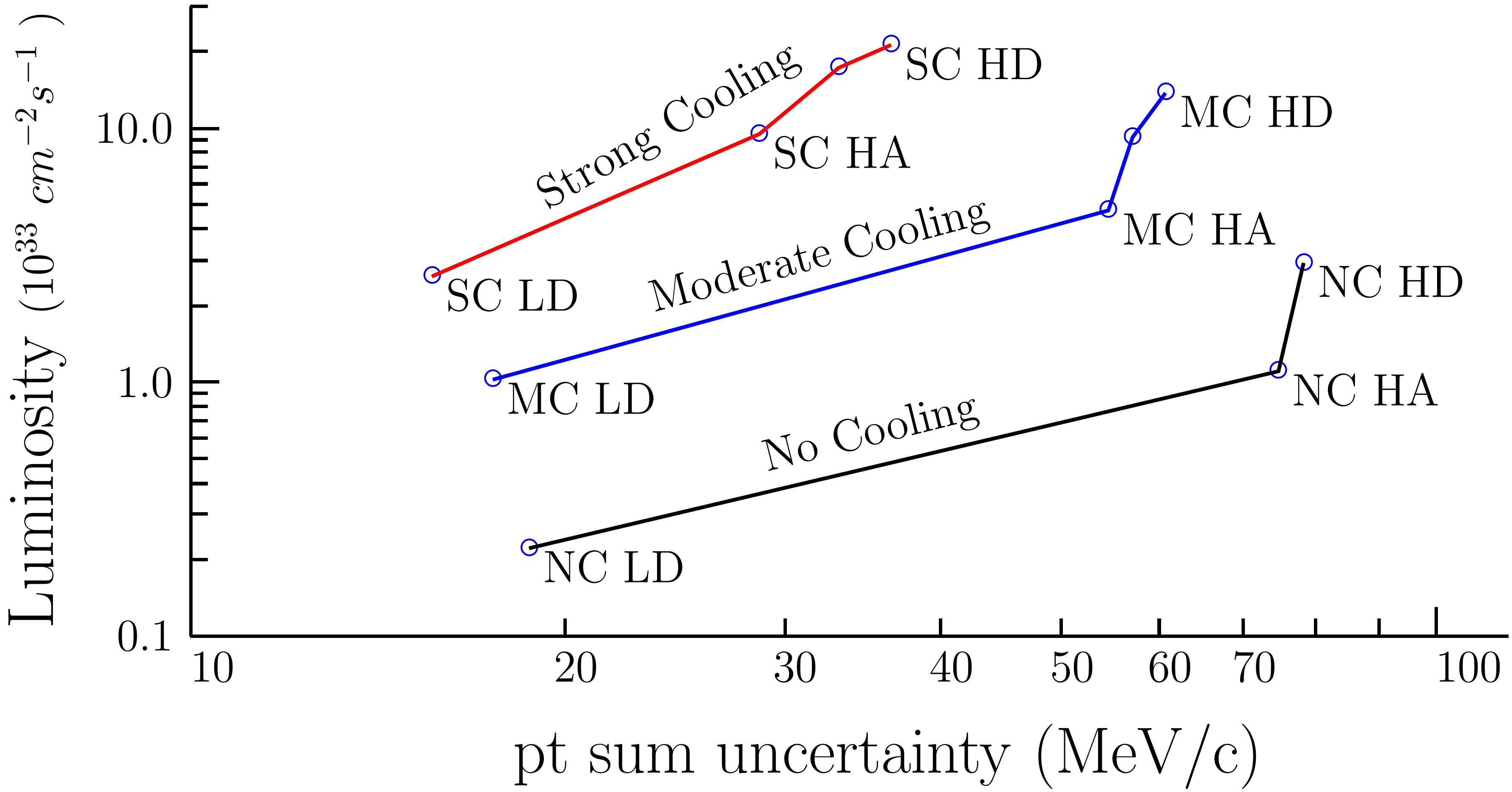
b)	Add	long	cool											
NC HD	5.26	1.79	0.92	1.3	6.50	8.0	4.20	394	15.20	10.2209	5.7652	61.6	1.59	2.94
MC HD	2.73	0.47	0.20	0.6	2.90	4.0	2.10	394	12.10	0.4749	0.4718	31.1	3.21	13.73
SC HD	2.73	0.12	0.15	0.6	2.10	4.0	2.10	394	6.35	0.1005	0.0920	28.2	2.91	21.21

Needs no cooling   Needs cooling

b) With transverse and longitudinal Cooling

- dp/p reduced ($3\ 10^{-4}$ for Moderate $2.1\ 10^{-4}$ for Strong
- rf Voltage $\rightarrow$ 15 MV (now for all)
- Q_{cool} increased (16$\rightarrow$23 nC for Moderate $\rightarrow$39 nC for Strong
- This appears to be a preferable unless increase in Q_{cool} unacceptable

Uncertainty of pt from Divergences



For much physics: HD uncertainties ≈ 70 MeV/275 GeV= $2.5\ 10^{-4}$ OK

But for DVCS: HD uncertainties ≈ 70 MeV/200 MeV = 35 %

LD with ≈ 20 MeV/200 MeV = 10% has $10^{33}\ cm^{-2}s^{-1}$

Intra-Beam Scattering

Fitting to BETACOOL Linac-Ring data[?] gave the approximate IBS time constants:

$$\tau_{\|} \approx 4.78 \times 10^{25} \frac{\gamma^{2.65}\ \epsilon_{\mathcal{T}}^{1.15}\ \sigma_z \delta^{2.5}}{N_p} \text{ (minutes)} \tag{5}$$

$$\tau_{\perp} \ \approx\ 4.60 \times 10^{27}\ \frac{\gamma^{2.65}\ \epsilon_{\mathcal{T}}^{2.2}\ \sigma_{\|}\ \delta^{0.5}}{N_p} \text{ (minutes)} \tag{6}$$

$$\text{assuming} \qquad \epsilon_{\mathcal{T}} = \sqrt{\epsilon_x\ \epsilon_y} \tag{7}$$

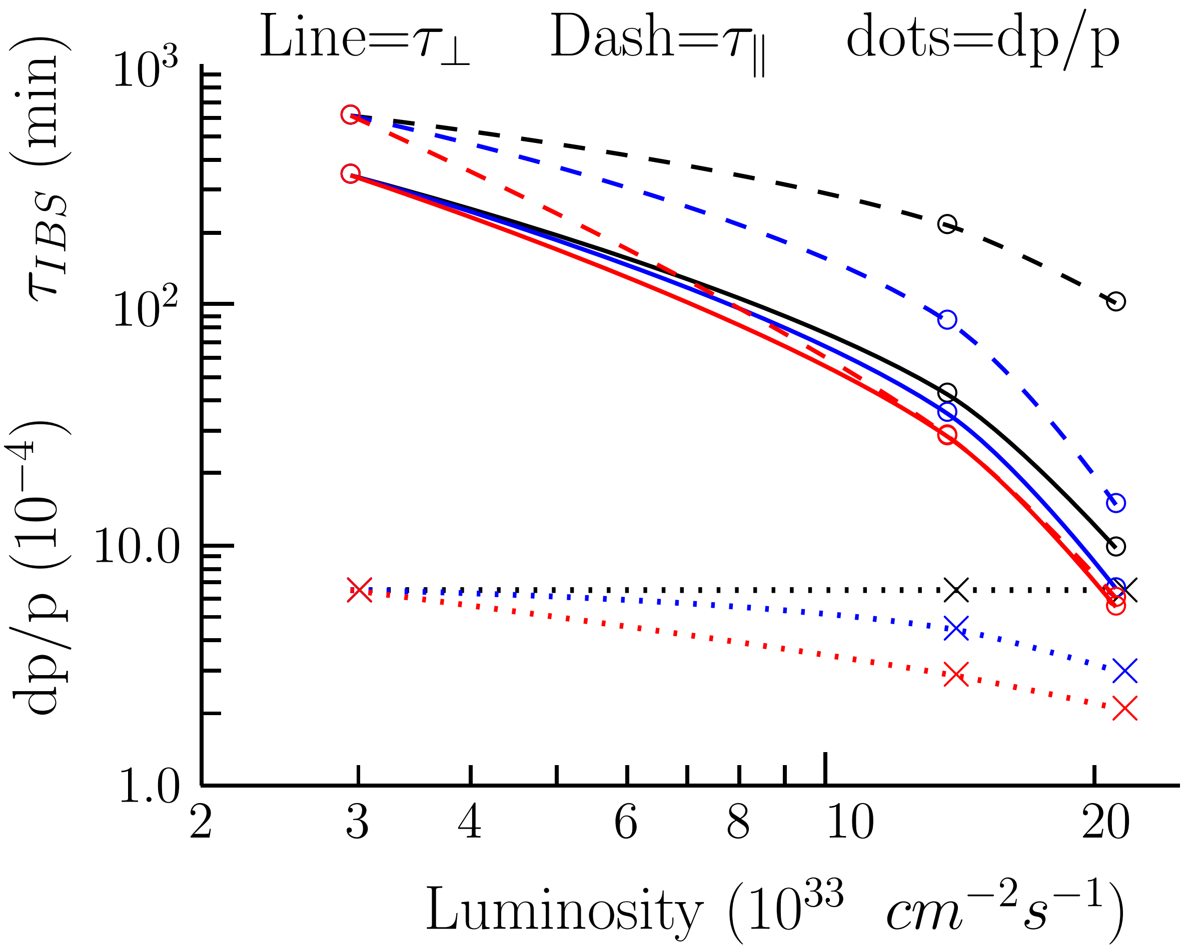
Equation 6 was obtained by fitting BETACOOL with full xy mixing.

For both eRHIC and JLEIC $\epsilon_x >> \epsilon_y$, mixing must be very small. Then

$$\tau_x \ \approx\ \frac{\tau_{\perp}}{2} \qquad\qquad \tau_y\ \approx\ \infty \tag{8}$$

The approximations eq. 7 seems bad: There is a spurious agreement between this formula with coupling, and a BETACOOL simulation without coupling (Vadim)

IBS rates vs. Lum



$$\tau_\parallel \propto \frac{\gamma^{2.65}\ \epsilon_T^{1.15}\ \sigma_z \delta^{2.5}}{N_p}$$

$$\tau_\perp \propto \frac{\gamma^{2.65}\ \epsilon_T^{2.2}\ \sigma_\parallel\ \delta^{0.5}}{N_p}$$

- Moderate $\rightarrow$ Strong Cooling: $\tau_\perp$ 42 $\rightarrow$ 10 min
- If dp/p lowered 6.5 $\rightarrow$ 2.9 10^{-4}, then $\tau_\perp$(moderate): 42 $\rightarrow$ 39 min.
- Lower dp/p helps directly on errors, and in late Roman pots

Luminosities without Crab Cavities

	ϵ_{Nx} μm	ϵ_{Ny} μm	ϵ_{Nz} eVsec	N_p 10^{10}	dp/p 10^{-4}	σ_z cm	β_{yp} cm	freq MHz	Volts MV	$\tau_{\parallel}$ hr	$\tau_{\perp}$ hr	Q_{100m} nC	I_{cool} A	Lum 10^{33}
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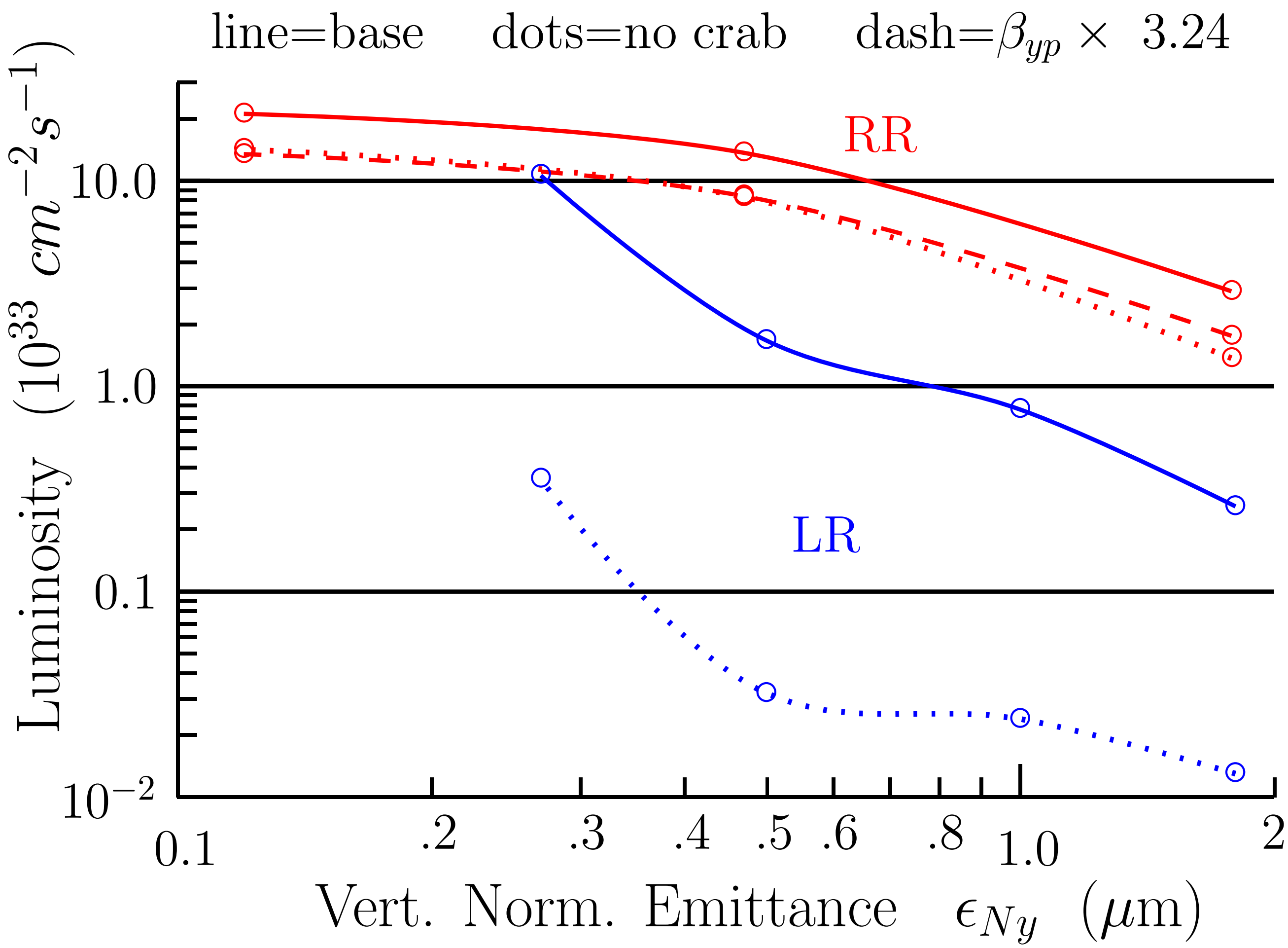
SC HD	2.73	0.12	0.15	0.6	2.10	4.0	2.10	394	6.35	0.1005	0.0920	28.2	2.91	21.21
c)	No	crab	cav.											
NC HD	5.26	1.79	0.46	1.3	6.50	4.0	4.20	788	30.41	5.1104	2.8826	61.6	1.59	1.37
MC HD	2.73	0.47	0.07	0.6	2.90	1.3	2.10	1576	28.87	0.1538	0.1527	31.1	3.21	8.33
SC HD	2.73	0.12	0.05	0.6	2.10	1.4	2.10	1576	13.84	0.0340	0.0311	28.2	2.91	14.2

c) Without Crab cavities with reduced bunch lengths

- line 2) With Moderate Cooling with increased rf frequency, bunch length $\rightarrow$ 1.3 cm when Lum without crab cavities: 14 $\rightarrow$ 9.23 10^{33} $cm^{-2}s^{-1}$.
- Bunch lengths (in lines 3) $\rightarrow$ 1.4 cm (limited by space charge tune shift)
- IBS time shorter from lower σ_z
- Lum without crab cavities: 24 $\rightarrow$ 14.7 10^{33} $cm^{-2}s^{-1}$.

Luminosities without crab cavities



- Comparison with LR did not include efforts to further reduce LR bunch lengths.
- The dashed line shows luminosities if the minimum β_{yp} is increased to 6.8 cm (as in LR)

Non-Magnetic Electron Cooling

- Electron beam must have emittance ≈ that of hadrons
- Maybe possible with "Moderate" normalized emittance of 0.5 μm
- Not plausible with "Strong" normalized emittance of 0.1 μm
- Strategies for coping with high average current
  - half the number of bunches
  - Recirculate electrons (as JLab proposes)
  - Use multiple guns

Magnetic Electron Cooling

- Less severe emittance specification.
- But severe magnet straightness requirement for "Strong Cooling"
- Both much easier with 5 times greater "Moderate" emittance
- Strategies for coping with high average current
  - half the number of bunches
  - Recirculate electrons (as JLab proposes with I$\approx$ 1 Amp)
  - Use multiple guns

CeC

- Charge set by FEL amplifier gain $\rightarrow$ 360 mA average current
- If needed cw. for Strong Cooling, this is "beyond current technology"
- For "Moderate" cooling, if cw. this is probably stronger cooling than needed
- Cooling could then be intermittent, lowering average gun current
- Micro-bunch instability amplification might also lower current
- Again, multiple guns is also an option

Discussions have started with Vladimir to explore this option

Conclusion on Cooling

- We do not have a sure cooling option, but
- For "Moderate Cooling all three mechanisms have some hope of a solution, while
- For "Strong Cooling" probably only CeC has any chance

- It would be wise, therefore to "chose" the Moderate Cooling option
- It meets 10^{34} specification for low cross section 1.3 GeV pt tracks
- And achieves 10^{33} for 200 MeV pt DVCS tracks
- If CeC works well enough, no significant changes would be required to go to Strong Cooling later: exceeding stated goal
- But to commit to Strong Cooling now, risks a perceived failure.

Important Questions

- Run BETACOOL with new specifications and search for a better parametrization of IBS with flat beams.
- Study CeC for the Moderate Cooling case.

Interesting Questions

- Determine if a flat beam Linac-Ring design has advantages over round-beam LR designs.
- Explore further again doubling the number of bunches and raising the luminosity to 30 $10^{33}\ cm^{-2}s^{-1}$ (plotted on slide 11)