EIC Collider Performance

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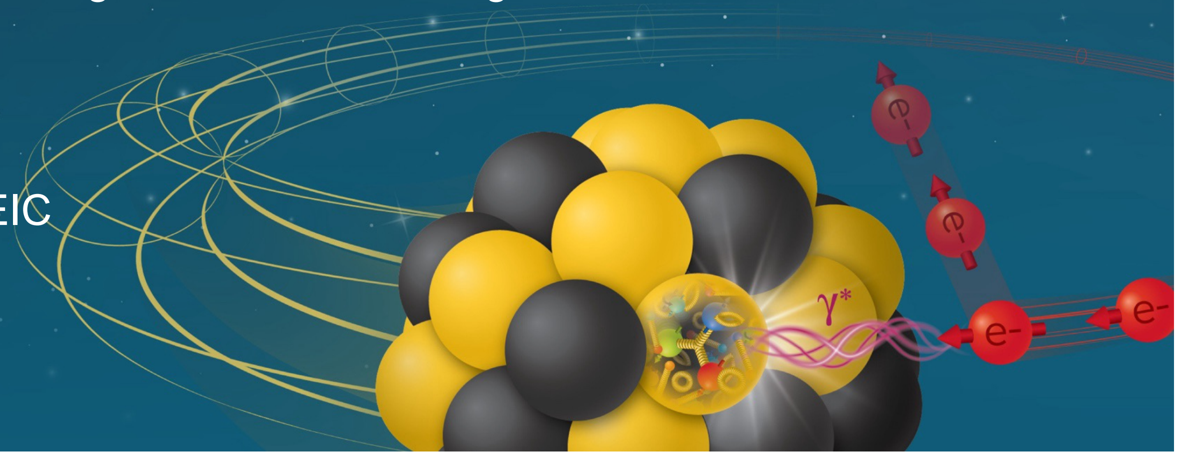
With thanks to E. Aschenauer, W. Bergan, other EIC colleagues

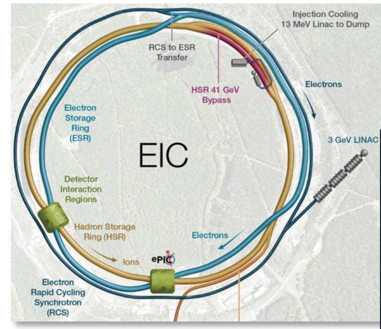
Uncovering New Laws of Nature at the EIC
November 20, 2024

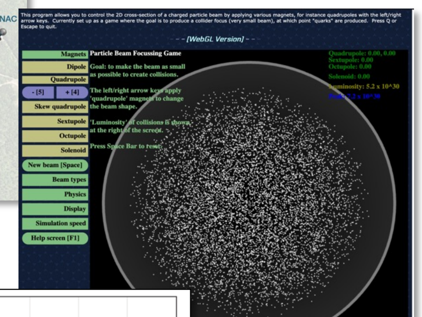


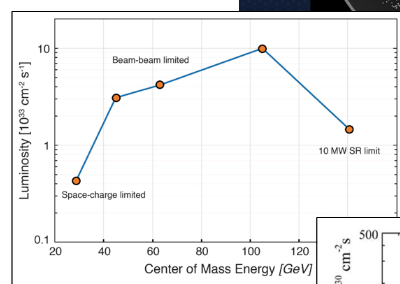
Electron-Ion Collider

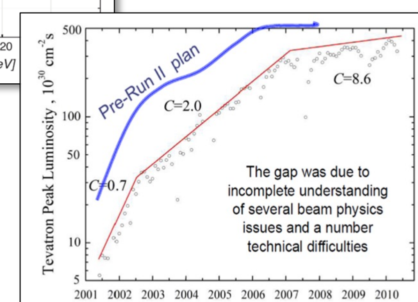
Outline: EIC Collider Performance

- Present Design Approach
- Parameters for Luminosity
- Luminosity Optimization Parameters
  - Luminosity demonstration/game
- CD-1 Design Luminosity Curve
  - Low E_{cm}: Space charge beam dynamics
  - Mid E_{cm}: Beam-beam dynamics
  - High E_{cm}: Synchrotron radiation power/RF power
- Proposed Early Science Program
  - Luminosity curves and limits
- Luminosity Evolution and Complexity









Present EIC Design Approach

S. Nagaitsev – Sep 2024 MAC

Ultimate EIC Performance Parameters:

- High Luminosity: L= 10^{33} – 10^{34} cm^{-2} s^{-1}
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 28 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Forward Acceptance and Good Background Conditions
- Possibility to Implement a Second Interaction Region (IR)/Detector

Accelerator Status in a glance:

✓ Polarized ion/proton source

✓ Ion injection and initial acceleration systems – Linac (200 MeV), Booster (1.5 GeV), AGS (25 GeV)

UPGRADE Hadron Storage Ring (40-275 GeV) – HSR

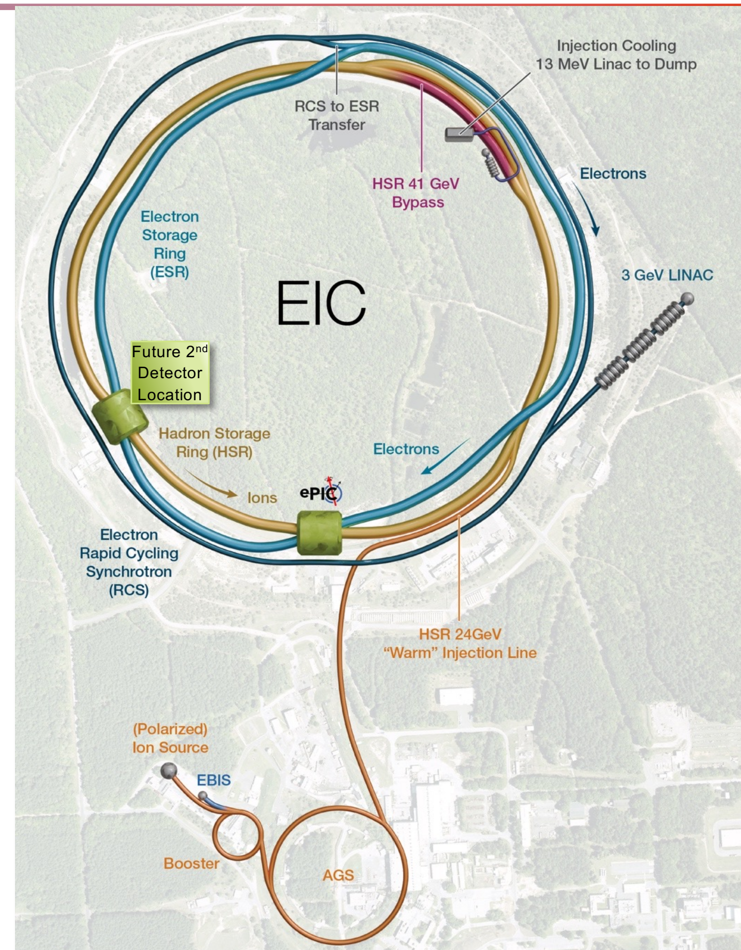
NEW Electron Pre-Injector (3 GeV) – EPI

NEW Electron Rapid Cycling Synchrotron (3 GeV – top energy) – RCS

NEW Electron Storage Ring (5 GeV – 18 GeV) – ESR

NEW Interaction Region(s) – IR

NEW Strong Hadron Cooler System – SHC



Luminosity Optimization Parameters

$$L \propto f_{\text{coll}} N_1 N_2 / \sigma_x^\star \sigma_y^\star$$

f_{coll} : collision frequency

$N_{1,2}$: particles per bunch

$\sigma_{x,y}^\star$: (equal) beam sizes at IP

Every parameter optimized separately and collectively in the EIC design

Try multiplying out the given numbers – should be very close to 10^{34} $cm^{-2}s^{-1}$

- **Maximize collision frequency (~90 MHz)**
  - Limited by kicker rise times
  - Limited by parasitic collisions (crabbing)
- **Maximize particles per bunch (~10^{11})**
  - Limited by sources, space charge
  - Limited by collective effects
    - Interaction of beam with impedances
    - Also total currents: $I_{1,2}=q_{1,2}N_{1,2}f_{coll}$ ~1-3A
- **Minimize beam sizes at IP (~250/25 um)**
  - Limited by IR focusing, magnets
  - Limited by chromatic dynamic aperture
  - Limited by emittance growth (IBS)

Just For Fun: Final Focus/Luminosity Game

$$L \propto f_{\mathrm{coll}} N_1 N_2 / \sigma_x^\star \sigma_y^\star$$

f_{coll} : collision frequency

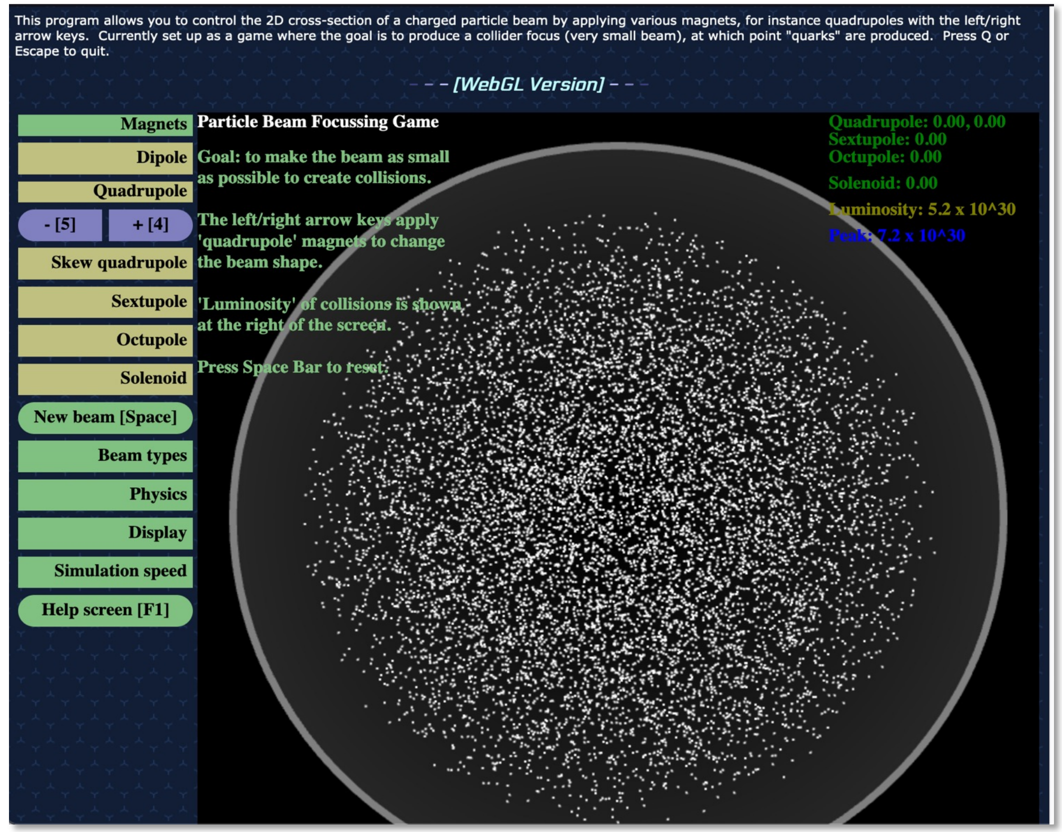
$N_{1,2}$: particles per bunch

$\sigma_{x,y}^\star$: (equal) beam sizes at IP

http://stephenbrooks.org/ap/beam2d/

Can **you** achieve a peak luminosity of 10^{34} cm^{-2} s^{-1}?

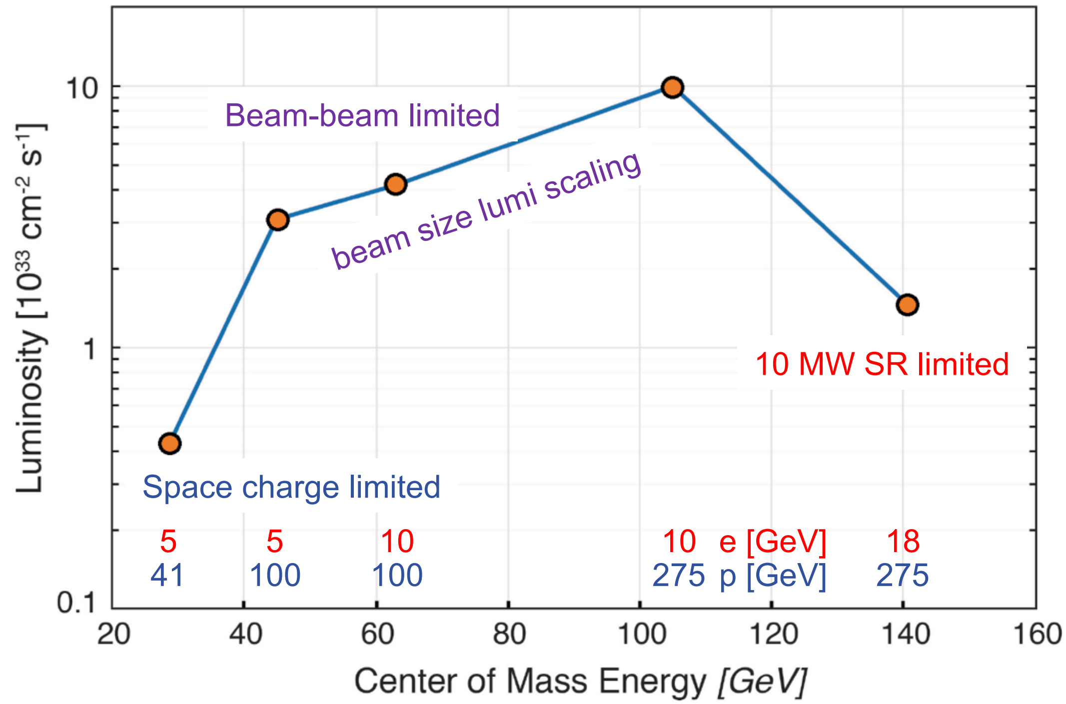
- Use the [5] and [4] keys to horizontally focus/defocus)
- Click Help Screen for other keys/magnets



CD-1 Design Luminosity Curve

	Electrons	Protons
Beam energies	2.5 - 18 GeV	41- 275 GeV
Center of mass energy range	E_{cm} = 20-140 GeV	

	Electrons	Protons
Beam energies	10 GeV	275 GeV
Center of mass energy	E_{cm} = 105 GeV	
number of bunches	nb =1160	
crossing angle	25 mrad	
Bunch Charge	$1.7 \cdot 10^{11}$e	$0.7 \cdot 10^{11}$e
Total beam current	2.5 A	1 A
Beam emittance, horizontal	20 nm	9.5 nm
Beam emittance, vertical	1.2 nm	1.5 nm
β- function at IP, horizontal	43 cm	90 cm
β- function at IP, vertical	5 cm	4 cm
Beam-beam tuneshift, horizontal	0.073	0.014
Beam-beam tuneshift, vertical	0.1	0.007
Luminosity at E_{cm} = 105 Gev	**$1 \cdot 10^{34} cm^{-2} s^{-1}$**	



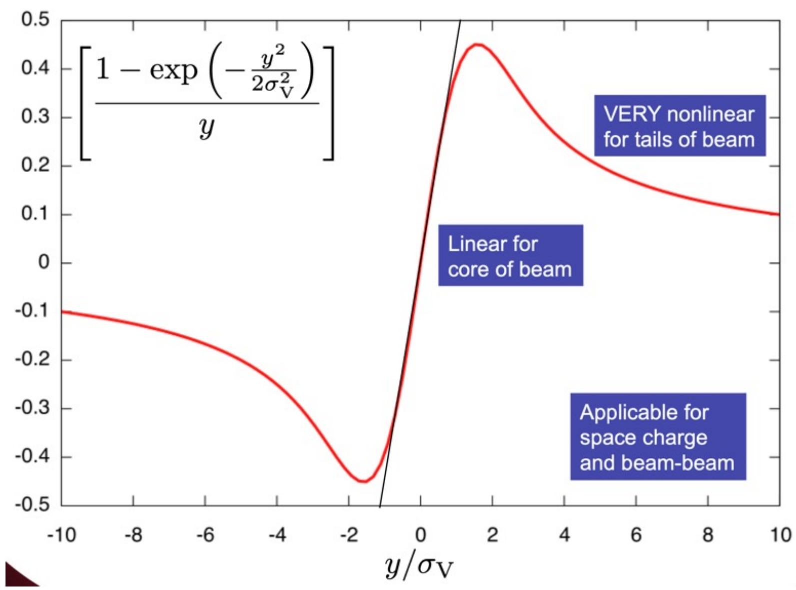
- Result of collective parameter optimization
- CM energy and luminosity limiting factors are correlated
  - Three fundamental luminosity limiting factors
- Later: acceptance and luminosity inversely correlated

Luminosity at Low E_{cm}: Hadron Space Charge

- Dense charged particle bunches **electrostatically repel** in rest frame
- Creates **nonlinear** space charge force and equation of motion in lab frame
- Fortunately scales with $1/\gamma^3$ so worst at low energies
  - Great example of time dilation
  - Limits high-intensity injector emittances
  - Force applies continuously within beam
- Tolerable linear "space charge tune spread" of 0.05 limits total current of 41 GeV proton beam to ~0.4A.

- (IBS: intra-beam hard scattering also contributes)

$$\frac{d^2y}{d\theta^2} + Q_V^2 y = \frac{2Nr_0R^2}{l\beta^2\gamma^3}\left[\frac{1-\exp\left(-\frac{y^2}{2\sigma_V^2}\right)}{y}\right]$$

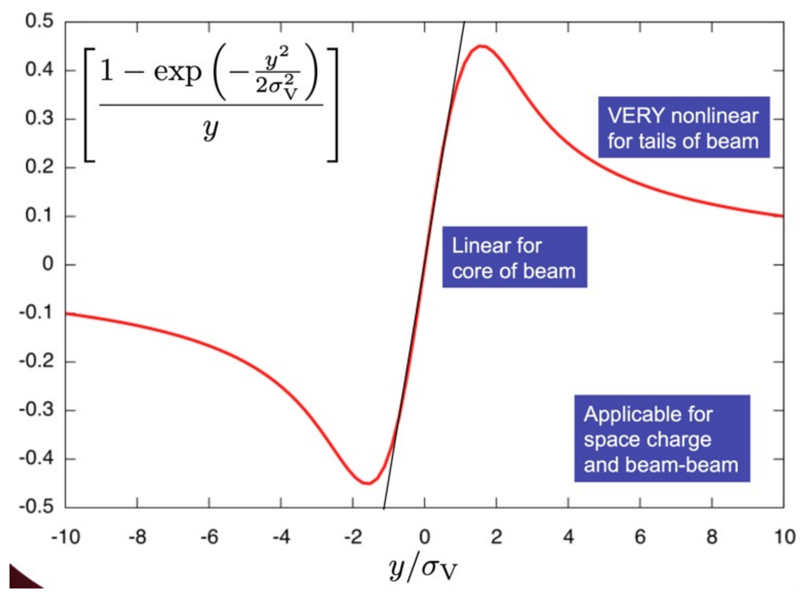


$N_{1,2}$: particles per bunch

Luminosity at Central E_{cm}: Colliding Beam-Beam Forces

- Colliding beams see each other's collectiv charge distributions
- Creates **nonlinear** beam-beam force and equation of motion similar to space charge
  - **BUT** now the fields and force are in the lab frame already
  - **NO** benefit of relativistic scaling
  - **Force applies only once per turn**
- Tolerable "beam-beam tune spead" of 0.015 limits highest EIC luminosity

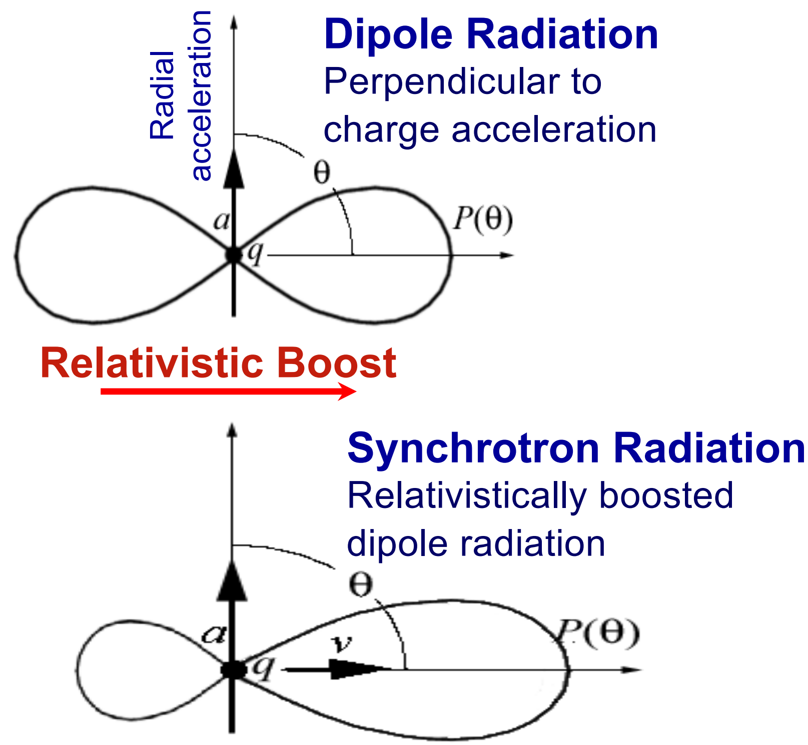
$$F(r) = \frac{Nq^2}{2\pi\epsilon_0 l} \frac{1+\beta^2}{r} \left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$$



$\sigma^\star_{x,y}$: (equal) beam sizes at IP

Luminosity at High E_{cm}: Electron Synchrotron Radiation Power

- Accelerated charged particles emit photons
  - Electrons in synchrotron: radially accelerated
  - **Synchrotron radiation** emitted in forward cone
    - Cone opening angle $\propto 1/\gamma$
    - Radiated power $$P_\gamma = \frac{2}{3}\frac{e^2 c}{4\pi\epsilon_0}\frac{(\gamma\beta)^4}{\rho^2}$$
  - γ scaling **much** worse for electrons
    - 18 GeV e: γ=3.5x10^4 vs 255 GeV p: γ=3x10^2
- **Design: 9 MW** @ 18 GeV (facility limit 10 MW)
- **Expensive:** Power must be provided by SRF
- Raise electron energy last (e- current limit)



$N_{1,2}$: particles per bunch

Accelerator at Day One and Ultimate

EIC for Early Science		Ultimate EIC
RCS: 7nC / bunch 5 – 10 GeV polarized e-	→	change injection scheme to reach 28 nC / bunch and 18 GeV electrons
ESR: 7nC / bunch 5 – 10 GeV polarized e-	→	add more RF cavities to reach 28 nC / bunch and 18 GeV electrons
HSR: 100 – 250 GeV polarized p 100 GeV/u nuclear beams pre-cooling at injection	→	update PS to reach 275 GeV protons and 110 GeV/u nuclei add 41 GeV bypass to get full HSR beam energy capabilities

Proposal for the Day-One Physics and the initial years of science is driven by

- Start of the promised NSAC/NAS science program
- Alignment with expected order in commissioning the collider and ramp up of performance that comes with gain of operational experience
- Having access to new physics results early to get high impact publications, i.e. PRLs, ……

Proposed Early Science Program incorporates comments from EIC-UG/ePIC Summer Meeting

Proposal for EIC Science Program in the First Years

Year - 1

Start with Phase 1 EIC

New Capability:
Commission electron polarization in parallel

Run:
10 GeV electrons on 115 GeV/u heavy ion beams (Ru or Cu)

Physics:
gives world-wide new data on nPDFs, NFF and a first look on saturation

Year - 2

Start with Phase 1 EIC
Commission electron polarization in parallel

New Capability:
Commission hadron polarization in parallel

Run:
10 GeV electrons on 130 GeV/u Deuterium

Physics:
- gives world-wide new data → critical baseline for nPDFs and saturation
- free vs. bound proton structure

Run:
Last weeks 10 GeV electrons and 130 GeV polarized protons

Physics:
first look to 3d imaging of the proton

Year - 3

Start with Phase 1 EIC
Commission electron polarization in parallel
Commission hadron polarization in parallel

New Capability:
Commission running with hadron spin rotators

Run:
10 GeV electrons on 130 GeV transverse polarized protons

Physics:
3d imaging of the proton / mass of the nucleon

Run:
Last weeks switch to longitudinal proton polarization

Physics:
first look helicity structure of the proton – unravel quark, gluon and orbital angular contributions

Year - 4

Start with Phase 1 EIC
Commission electron polarization in parallel
Commission hadron polarization in parallel
Commission running with hadron spin rotators

New Capability:
Commission hadron accelerator to operate with not centered orbits

Run:
10 GeV electrons on 100 GeV Au

Physics:
gives world-wide new data on A-dep.of nPDFs, nFF and saturation

Run:
10 GeV electrons on 250 GeV transverse and longitudinal polarized protons

Physics:
- 3d imaging of the proton at low x
- helicity structure of the proton – unravel quark, gluon and orbital angular contributions

Year - 5

Start with Phase 1 EIC
Commission electron polarization in parallel
Commission hadron polarization in parallel
Commission running with hadron spin rotators
Commission hadron accelerator to operate with not centered orbits

Run:
10 GeV electrons on 100 GeV Au

Physics:
gives world-wide new data on A-dep.of nPDFs, nFF and saturation

Run:
10 GeV electrons on 166 GeV transverse and longitudinal polarized He-3

Physics:
- 3d imaging of the nucleons → flavor separation
- helicity structure of the nucleon– unravel helicities for different quark flavors
- first look to nuclear binding

Time to install additional ESR RF and HSR PS to reach design Current and max Energies

E. Aschenauer

Proposal for EIC Science Program in the First Years

Year - 5

Start with Phase 1 EIC
Commission electron polarization in parallel
Commission hadron polarization in parallel
Commission running with hadron spin rotators
Commission hadron accelerator to operate with not centered orbits

Run:
10 GeV electrons on 100 GeV Au

Physics:
gives world-wide new data on A-dep.of nPDFs, nFF and saturation

Run:
10 GeV electrons on 166 GeV transverse and longitudinal polarized He-3

Physics:
- 3d imaging of the nucleons → flavor separation
- helicity structure of the nucleon– unravel helicities for different quark flavors
- first look to nuclear binding

Year - 6

Start with Phase 1 EIC
Commission electron polarization in parallel
Commission hadron polarization in parallel
Commission running with hadron spin rotators
Commission hadron accelerator to operate with not centered orbits

New Capability:
Commission ESR & HSR at max. energy and beam currents

Run:
18 GeV polarized electrons on 275 GeV/u polarized (longitudinal & transverse) proton beams

Physics:
- 3d imaging of the proton at low x
- helicity structure of the proton – unravel quark, gluon and orbital angular contributions

Year - 7

Start with Phase 1 EIC
Commission electron polarization in parallel
Commission hadron polarization in parallel
Commission running with hadron spin rotators
Commission hadron accelerator to operate with not centered orbits
Commission ESR & HSR at max. energy and beam currents

New Capability:
Operate HSR with 41 GeV bypass

Run:
5 GeV polarized electrons on 41 GeV transverse polarized proton beams

Physics:
first look to moderate-x 3d imaging and Kaon structure/ mass

E. Aschenauer

Assumptions and Luminosity Calculation

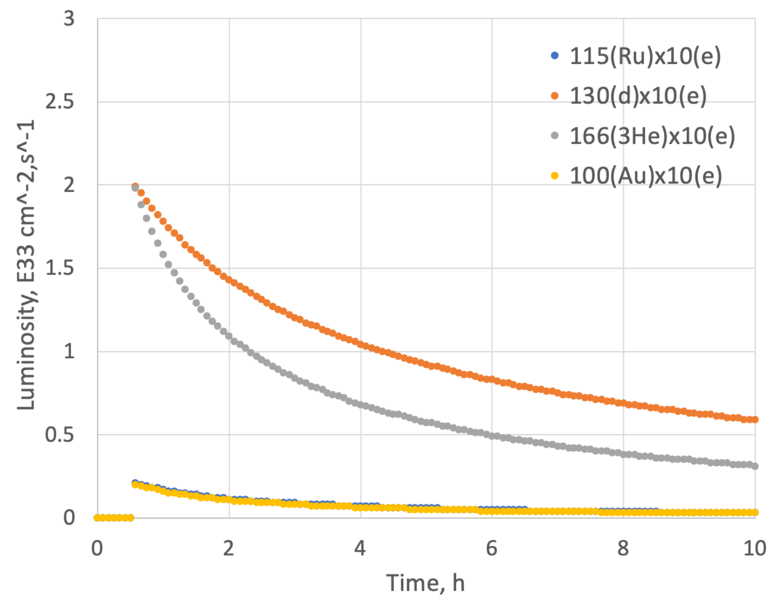
- 7 nC electron bunch charge compared to 28 nC (CDR)
- Constant proton beam IP divergencies are maintained throughout the store by gradual increase of proton IP beta-functions as the beam emittance increases.
- The electron IP beta-functions are adjusted accordingly to match electron and proton transverse beam size.
- Ion beam is cooled at low energy (24 GeV/u) but no stochastic cooling is used in the store
- 1 Run is ½ year operation at 80% uptime
- 2 h store turnaround time
- 30 min at the beginning of the store is taken by the ESR fill and detector turn-on

- Not yet included a ramp of of luminosity through the Run
  - → at RHIC: 1st week 25% of projected lumi / week
    2nd week 50% of projected lumi / week
    3rd week 75% of projected lumi / week
    4th week to X week 100% of projected lumi / week
  - → First guess for EIC early years (1 to ~5?)
    1st week 10% of projected lumi of the run / week
    increase by 10% every → 10 weeks to reach projected lumi / week

Luminosity eA in Early Years

Possible Beam energies:
electron: 5 GeV, 10 GeV and ultimately 18 GeV
proton: 41 GeV, 100 GeV to 255 GeV ultimately 275 GeV
Au: 41 GeV, 100 GeV to 110 GeV ultimately
A: 41 GeV, 100 GeV to Max ~255 / (A/Z) ultimately ~275 / (A/Z)

	Lumi per Fill (5 h)	Lumi per Year
10 GeV e x 115 GeV Ru	1.3 pb^{-1}	0.9 fb^{-1}
10 GeV e x 100 GeV Au	1.2 pb^{-1}	0.84 fb^{-1}
10 GeV e x 130 GeV d	16 pb^{-1}	11.4 fb^{-1}
10 GeV e x 166 GeV ^{3}He	12 pb^{-1}	8.65 fb^{-1}



Note:
eA luminosity is per nucleon

Luminosity ep in Early Years

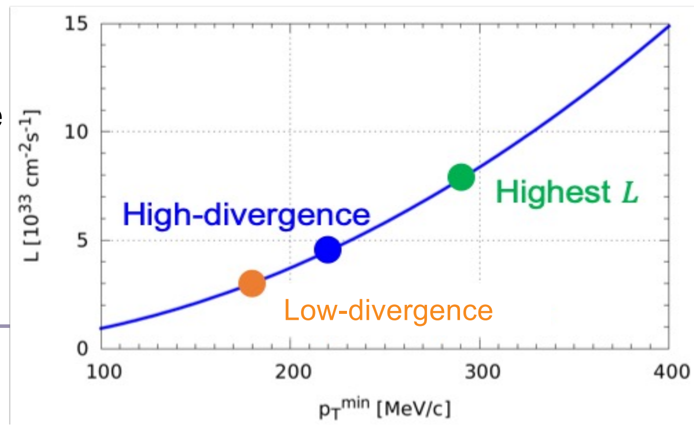
Possible Beam energies:

electron: 5 GeV, 10 GeV and ultimately 18 GeV
proton: 41 GeV, 100 GeV to 255 GeV ultimately 275 GeV
Au: 41 GeV, 100 GeV to 110 GeV ultimately
A: 41 GeV, 100 GeV to Max ~255 / (A/Z) ultimately ~275 / (A/Z)

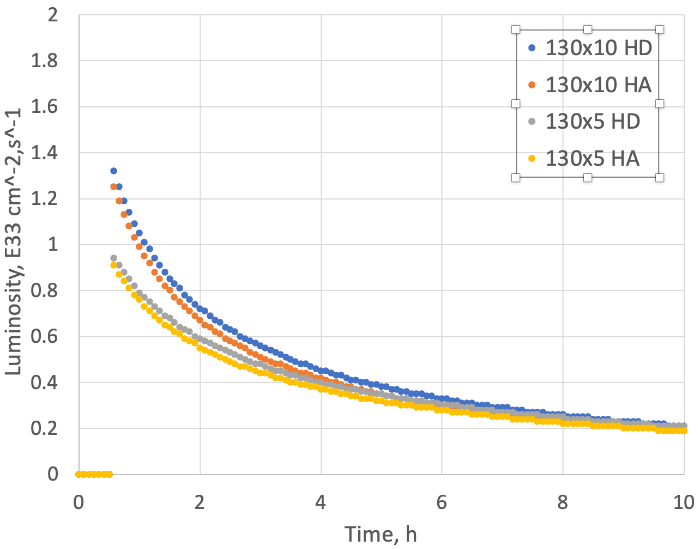
High Divergence	Lumi per Fill (5 h)	Lumi per Year	Low Divergence	Lumi per Fill (5 h)	Lumi per Year
5 GeV e x 250 GeV p	9.26 pb^{-1}	6.48 fb^{-1}	5 GeV e x 250 GeV p	6.81 pb^{-1}	4.78 fb^{-1}
10 GeV e x 250 GeV p	13.12 pb^{-1}	9.18 fb^{-1}	10 GeV e x 250 GeV p	8.8 pb^{-1}	6.19 fb^{-1}
5 GeV e x 130 GeV p	6.3 pb^{-1}	4.36 fb-1	5 GeV e x 130 GeV p	5.8 pb^{-1}	4.1 fb^{-1}
10 GeV e x 130 GeV p	7.6 pb^{-1}	5.33 fb^{-1}	10 GeV e x 130 GeV p	7.1 pb^{-1}	4.95 fb^{-1}

Remember:

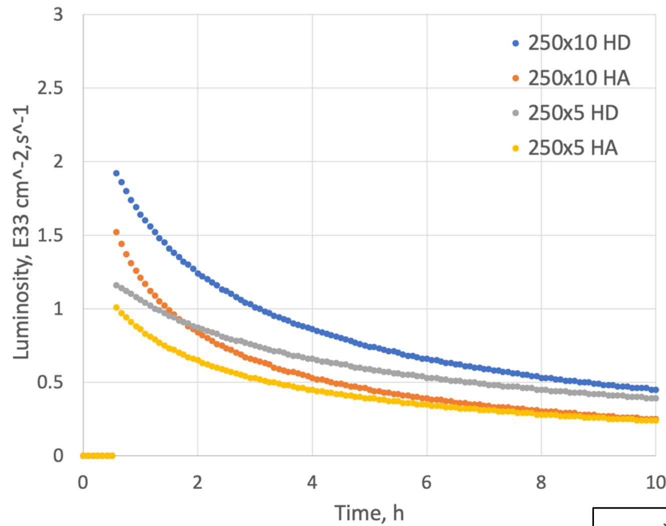
high divergence: higher lumi, but reduced acceptance for low forward particle p_T^{min}
low divergence: lower lumi, but increased acceptance for low forward particle p_T^{min}



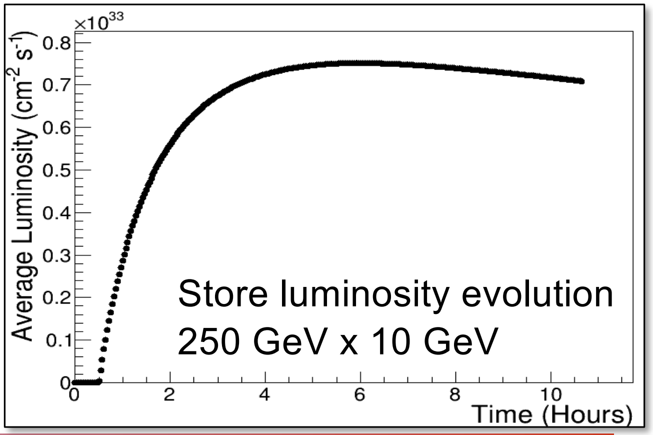
Luminosity ep in Early Years



Compare to HERA peak luminosity of 5×10^{31} cm^{-2} s^{-1}



Max average luminosity:
0.8×10^{33} cm^{-2} s^{-1} with 5.9 hr store



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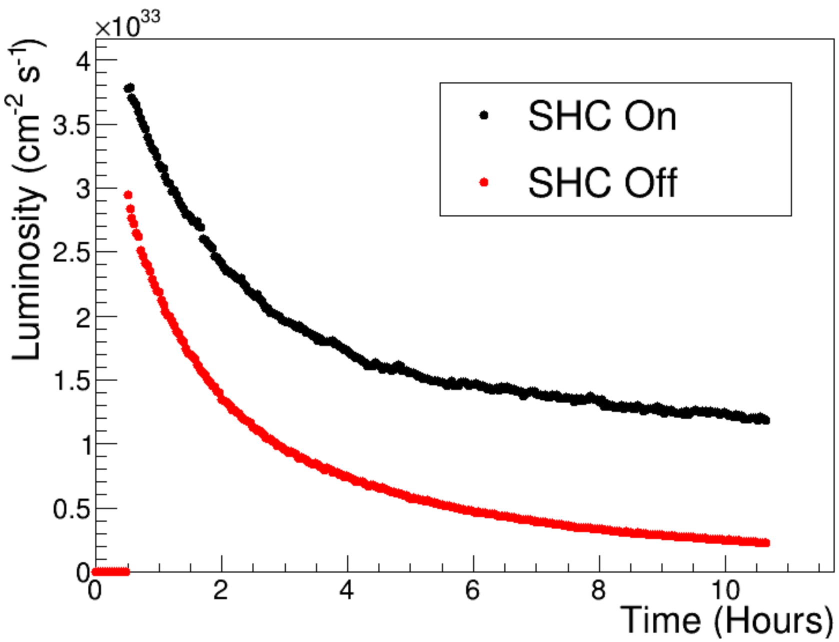
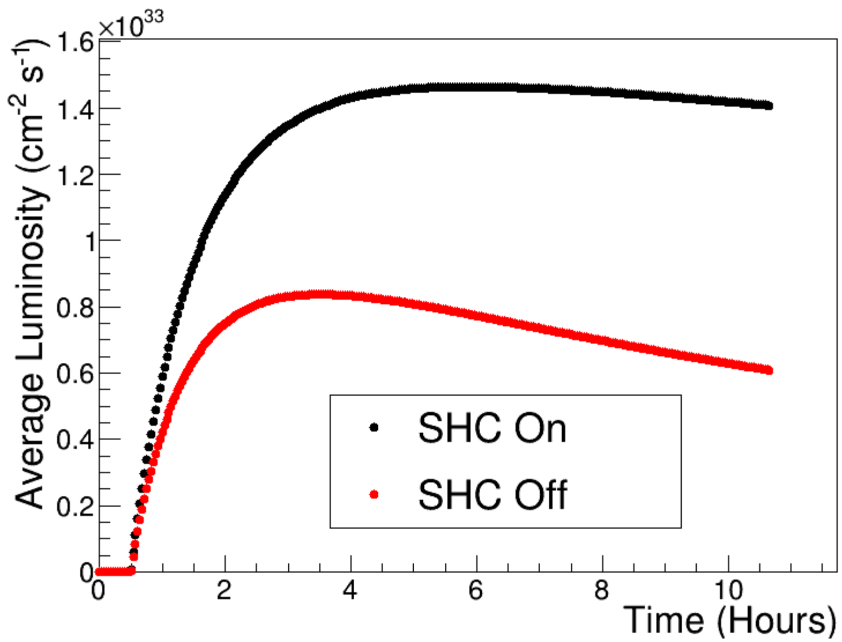
Onwards to Full Luminosity Maturity

After Year 5 will have full bunch current for electrons 7 nA to 28 nA
→ increase in luminosity ~4
Adding Strong Hadron Cooling will increase the integrated current by fill another factor of 2
Example: 10 GeV electrons x 100 GeV protons
Early years of operations will also provide insights and development time for luminosity development





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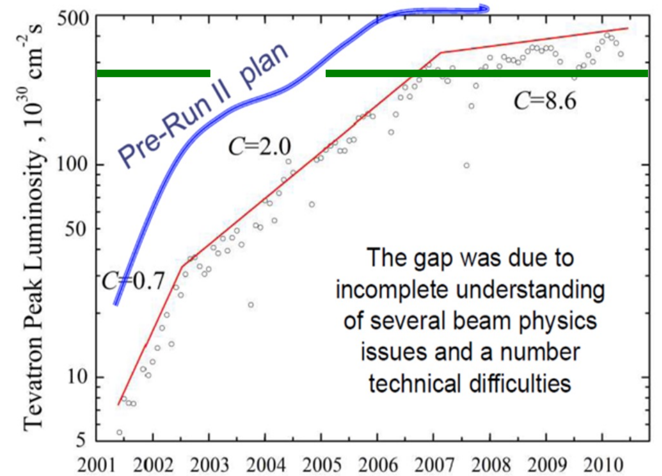
Luminosity Lessons

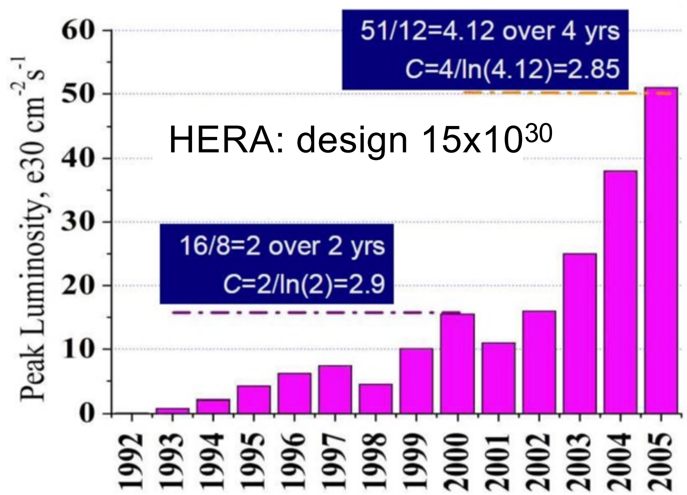
- Luminosity ramp-up to design takes years
  - Useful paper: arxiv 1202.3950 (V. Shiltsev)
  - Contextualizes Tevatron Run-II and early LHC
  - Luminosity ramp-up parameter C: **complexity**
    - **C: time (years) to increase luminosity by e**
    - C=2: factor of e luminosity increase in 2 years
  - Early commissioning can make quick strides
    - C<1 (or <<1) but do not get too exuberant
  - Long-term commissioning is usually C~2-3

- **EIC is an exceptionally complex collider**

- EIC will most likely take years to reach design luminosities
  - **We will get there!**

Tevatron Run-II: design 275×10^{30}






Thank You!


QUESTIONS

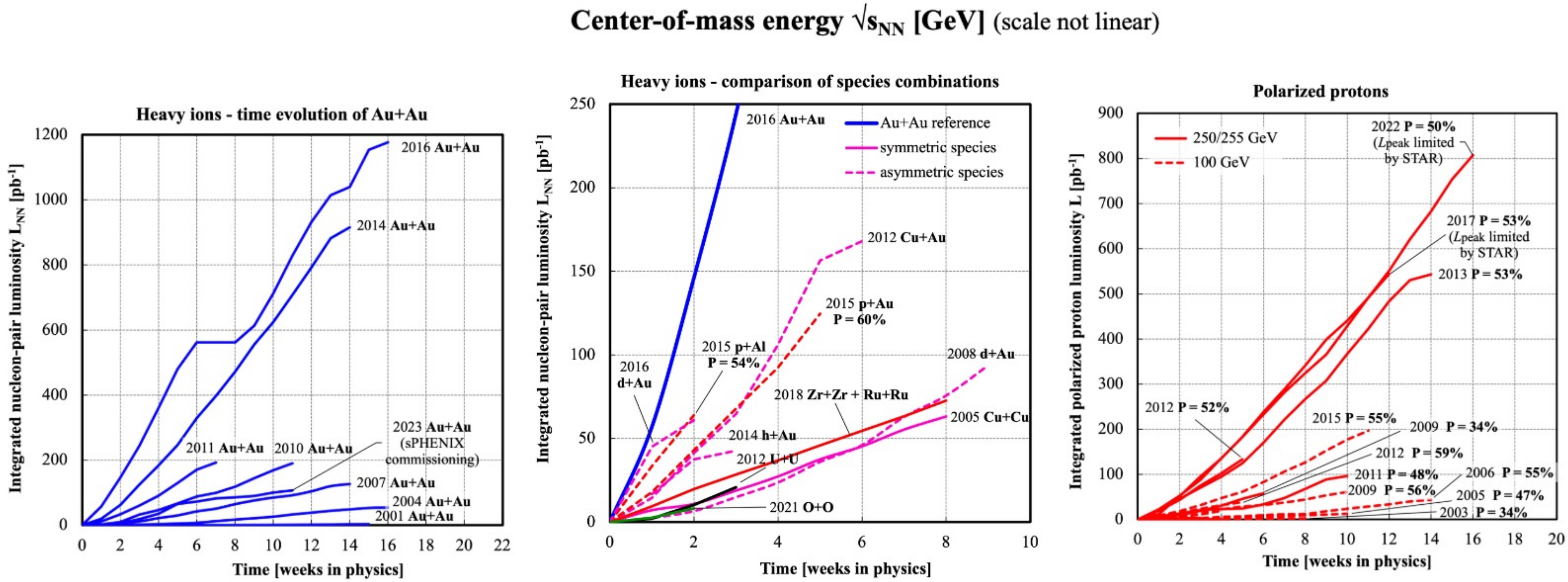

BACK UP

Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [µm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [µm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [µrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

EIC CDR
CD-1 with
SHC

RHIC Runs



Note: The nucleon-pair luminosity is defined as $L_{NN} = A_1 A_2 L$, where L is the luminosity, and A_1 and A_2 are the number of nucleons of the ions in the two beams respectively. The proton polarization is intensity and time averaged over the whole run, as measured by the H-jet.

Tabulated Complexities from Shiltsev Paper

Table II: "Complexities" of colliding beam facilities.

	C	*years*
CESR *e+e-*	***4.3***	1883-1988
LEP I *e+e-*	***3.3***	1989-1995
SLC *e+e-*	***1.5***	1989-1997
HERA I, II *p-e*	***2.9***	1992-00-2005
ISR *p-p*	***3.0***	1972-1982
SppS *p-pbar*	***2.0***	1982-1990
Tevatron Run II *p-pbar*	***2.0***	2002-2007
RHIC *p-p*	***2.2***	2000-2004
Tevatron startup	***0.03***	1987
LHC startup	***0.06***	2010

Shiltsev Paper Conclusions

One should not expect that the period of incredibly fast growth of the LHC luminosity - as in 2010- will last long. At some point the progress will most probably turn to the rate corresponding to complexity of $C \sim 2$. Such a period of exploration and fight for ultimate performance with $C \approx 2$ might take as short as 3-4 years and as long as 6-10 years It will be followed by relative stabilization of performance (either running out of ideas or preparing for a major upgrade). *A numerical example*: progress from $L=3\times10^{33}$ cm^{-2}s^{-1} to $L=5\times10^{34}$ cm^{-2}s^{-1} might take 6-9 years if C=2-3.

Expectations management is crucial. As in the case of the Tevatron, the LHC goals may need to be expressed in terms of two goals: "base" goal – that is believed has very high degree of certainty of being achieved and the "design" or "stretched" goal that represents your "best estimate" of the limit of performance to which the facility can be pushed. The goals and the ratio of "base" to "design" goals will depend on the level of understanding of the machine, e.g. the ratio might change from larger to smaller to reflect lower level of uncertainty in later years.