Invited Talk at APAC’07, Indore, India

NEXT GENERATION ELECTRON-ION COLLIDERS

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Office of Nuclear Physics — Exploring Nuclear Matter - Quarks to Stars

Office of Science — U.S. DEPARTMENT OF ENERGY

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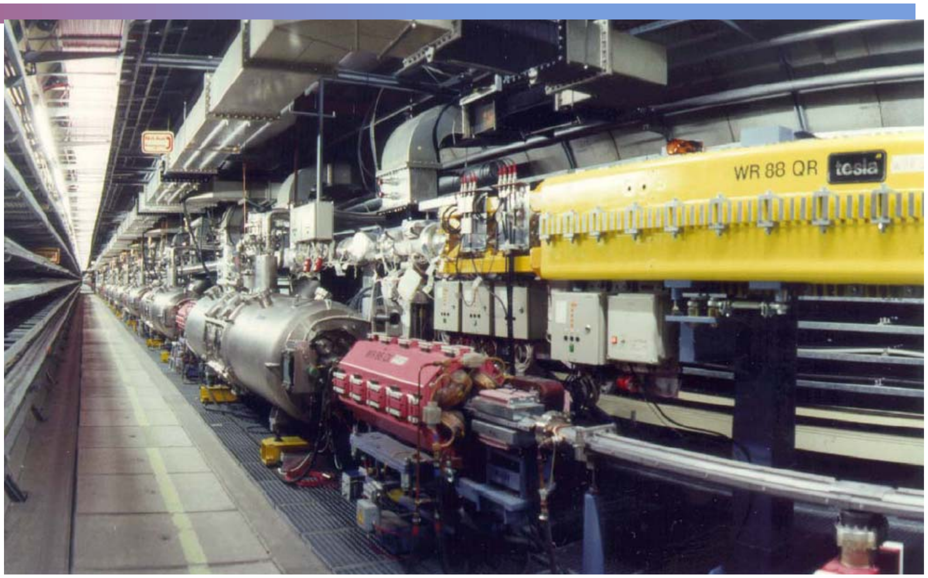
HERA - the Present Electron Ion Collider

- Unprecedented energy reach, luminosity and lepton polarization.
- Two 6.4 km long storage rings:
  - 920 GeV p with 5T SC magnets
  - 27.5GeV e or p with NC magnets
- Spin polarization of electrons and positrons by the Sokolov-Ternov effect.
- See invited talk “Experiences from HERA” by Ferdinand J. Willeke



HERA 2006

Parameter [Unit]	Electrons	Protons
Beam Energy [GeV]	27.5	920
Particles per bunch [10^{10}]	≤ 3.68	≤8.75
Number of Bunches	156	150
Horiz./vert. Emittance [nm]	20 / 3	3.8 / 3.8
Bunch length [cm]	0.9	12
Horiz./vert. β-function at IP [m]	0.62/0.26	0.18/2.45
Beam Lifetime in collision [h]	10-15	200
Longitudinal Polarization [%]	30-45	-
Peak Luminosity [$10^{31}cm^{-2}s^{-1}$]	3-5	
Average Luminosity [$pb^{-1}d^{-1}$]	1-2.5	

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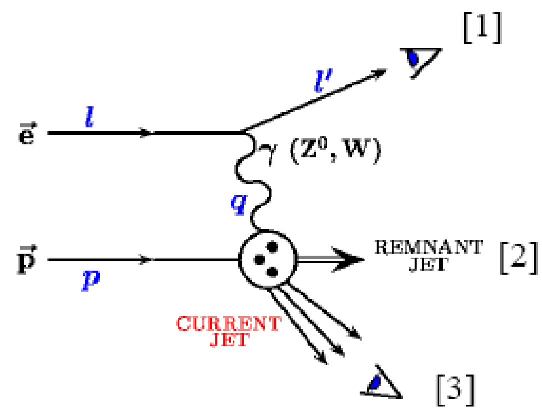
Directions for the Future

- Large range of nuclei
- Polarization of light nuclei
- Higher electron polarization
- Higher luminosity
- Large range of Center-of-Mass energy



$$Q^2 = -q^2 = sxy$$

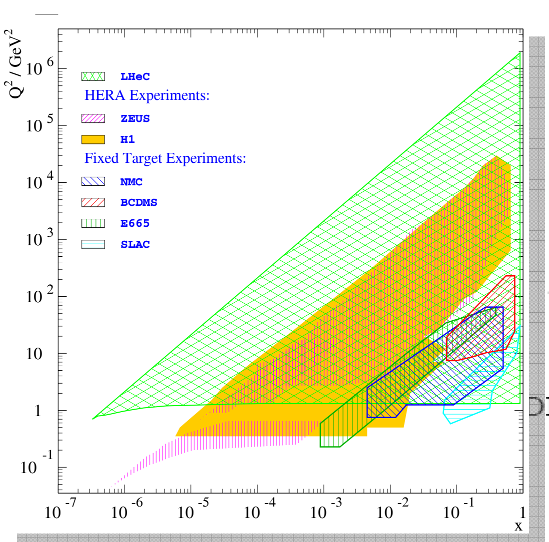
$$x = \frac{Q^2}{2p\cdot q}$$

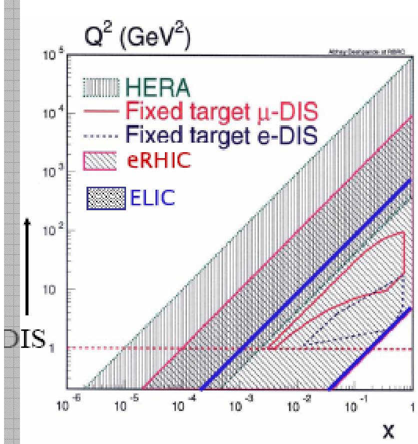
$$y = \frac{p\cdot q}{p\cdot l}$$

$$s = 4E_e E_p$$

$$W = (q+p)^2$$

- Observe scattered electron [1] inclusive measurement
- Observe [1] + current jet [2] semi-inclusive measurement
- Observe [1] + [2] + remnant jet [3] exclusive measurement
- Luminosity requirements goes up as we go from [1] --> [2] --> [3]
- Exclusive measurements also puts demanding requirement on detectors, interaction region *and hence deliverable luminosity*





There are many directions!

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The physics program is broad and extremely interesting

- Wide range of A
- High luminosity
- Polarized beams
- Full acceptance detector

- 3D structure of nuclear matter
- Spin structure
- **QCD dynamics in much greater detail**

Alan Caldwell, at Joint EIC2006 & Hot QCD Meeting

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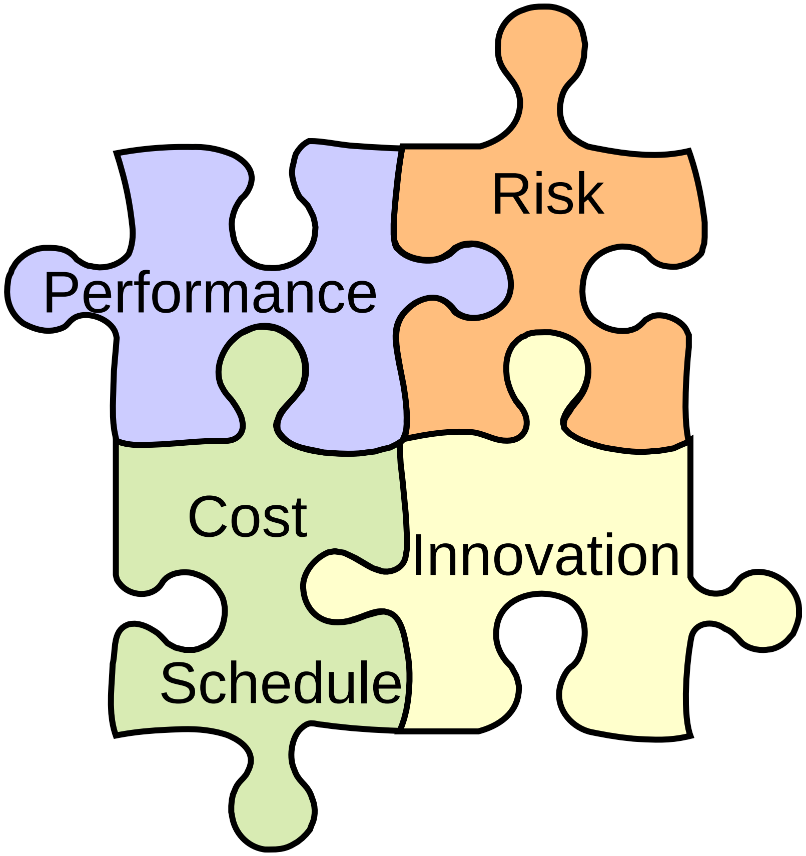
Strategies

- We must recognize that we are dealing with various sciences and objectives.
- Cost is a significant constraint, leading to adaptation of existing facilities, in particular the expensive ion accelerators.
- The impeding shut-down of HERA leads to schedule constraints.
- Performance can be enhanced by innovation, leading to risk.
- “The policy of being too cautious is the greatest risk of all” (Jawaharlal Nehru).



Issues and Technologies

- Large γ helps…
- The angular rms spreads σ' at the IP are limited by the aperture of the final focus quadrupoles.
- Known limits on ξ_i, ξ_e however ERL increases ξ_e
- Various limits on *f*, from parasitic collisions to electron cloud to detector time resolution ($\geq$2ns).
- Crab crossing can help in parasitic collisions and beam separation.
- Electron cooling is necessary

Assume round beams of equal size

$$L = \left(\frac{4\pi\gamma_i\gamma_e}{r_i r_e}\right)\left(\xi_i\xi_e\right)\left(\sigma_i^{'}\sigma_e^{'}\right)f$$

For ERL, if the electron bunch intensity and / or ion emittance can always be adjusted to reach the ion ξ_i

$$L = \gamma_i\, f\, N_i \frac{\xi_i Z_i}{\beta_i^* r_i}$$

ERL Science and Technology

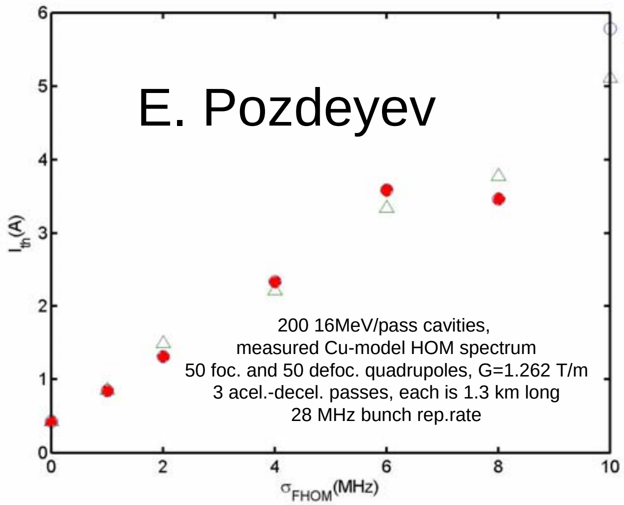
- The use of the ERL for the electron accelerator leads to a significant increase in luminosity and polarization (compared to S.T. self polarization ring).
- Following the development of “single mode” multi-cell cavities, a multi-pass ERL accelerator can be built with ~ampere current, leading to a significant cost saving.
- ERL provides full polarization transparency at all energies for the electron beam.
- ERL provides very long “element-free” straight section(s) for detector(s).
- Easy variation of the electron bunch frequency to match the ion bunch frequency at various ion energies.
- See “Advances in ERLs and Microwave Superconductivity for Lepton Accelerators, Colliders and Light Sources” by Swapan Chattopadhyay, and “Technological challenges of ERLs” by Lia Merminga, this conference

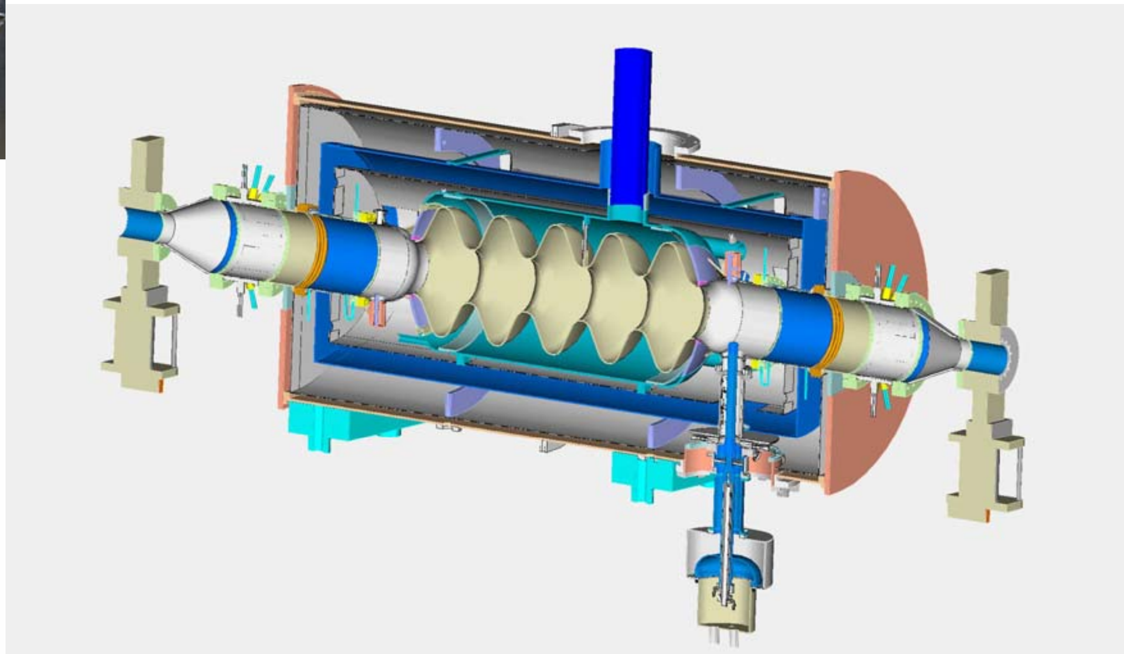
ERL Ampere-Class Cavity

Fully damped "single mode" cavity at 703.75 MHz

Allows ~ampere in 3 pass eRHIC.

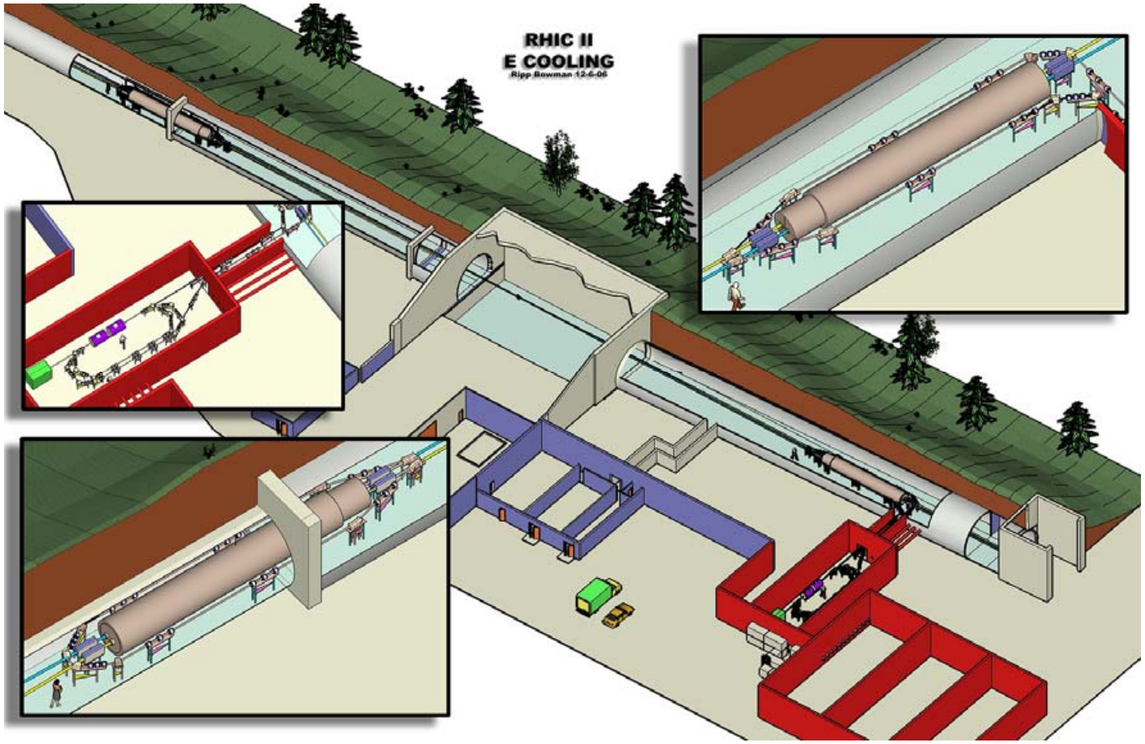
Also used for electron cooler.





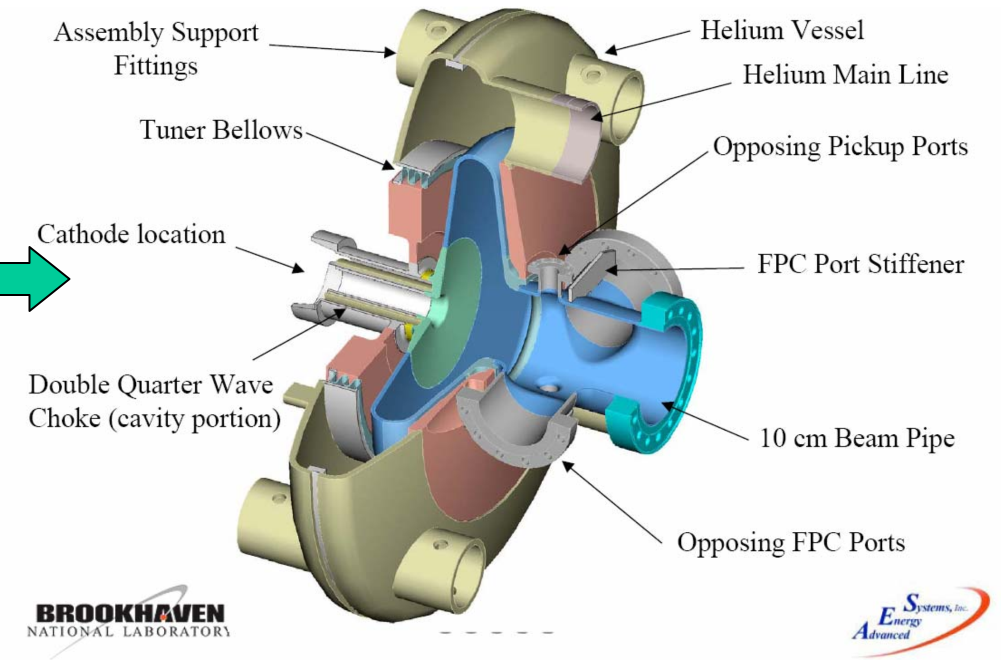
High-Energy Electron Cooling

- Cooling at high energy γ~100 to 150 is possible using high-charge, low-emittance electron beams from SRF guns and ERLs.
- R&D for electron cooling of RHIC is in advanced stage and ready to be implemented.
- I. Ben-Zvi, Invited Talk "The ERL High Energy Cooler for RHIC", EPAC'06



Electron Cooling in eRHIC and ELIC

- EC for RHIC
  - 55 MeV ERL at
  - 100 mA electron beam
  - Use of an SRF gun
  - Staged cooling
  - R&D in progress



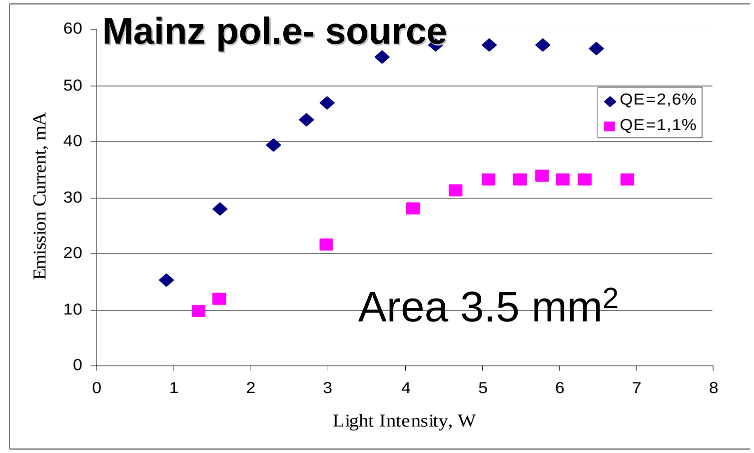
- EC for ELIC
  - 75 MeV at 2A electron beam
  - Use circulator ring with 100 revolutions
  - Staged cooling

Crab Crossing

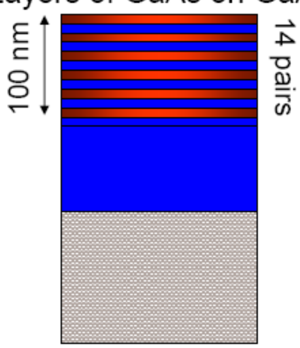
- ELIC and LHeC will rely on crab crossing.
- Crab cavities for LHC are being designed.
- KEK crab cavities are designed to deliver 1.44 MV kicks at designed peak surface field of 21 MV/m (Hosoyama et al, see talk by Yoshiyuki Morita this conference)
- ELIC ion beam will require 2x80 MV of installed kick voltage (~300 cavities at 1.5 GHz).
- The required amplitude and phase stability is challenging (10^{-7} in amplitude for ELIC's 100 mrad crab angle). Paper by Oide and Yokoya

Polarized Electron Source

- JLab beam polarization 85% typical, 80% guaranteed
- New fiber-based drive laser: high power, reliable
- High QE from superlattice GaAs
- Large current densities



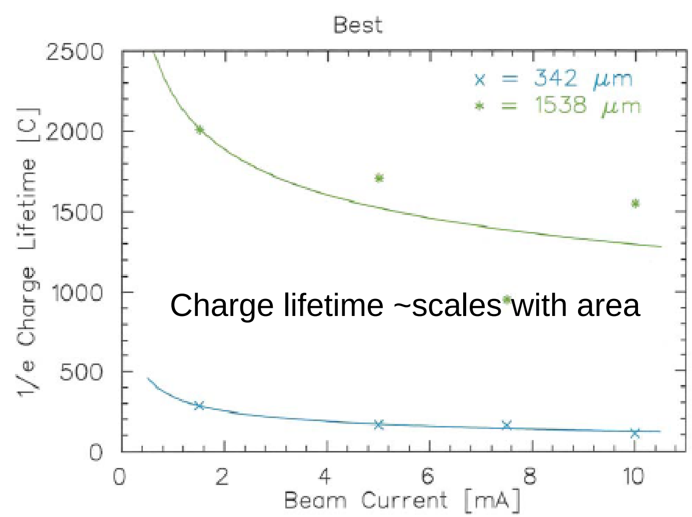
Superlattice GaAs:
Layers of GaAs on GaAsP



No strain relaxation
QE ~ 0.8%
Pol ~ 85%
@ 780 nm

Matt Poelker

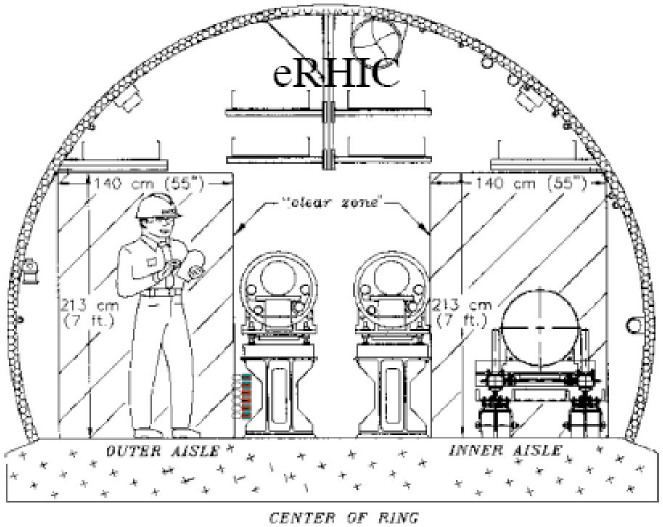
40 w for 250 mA

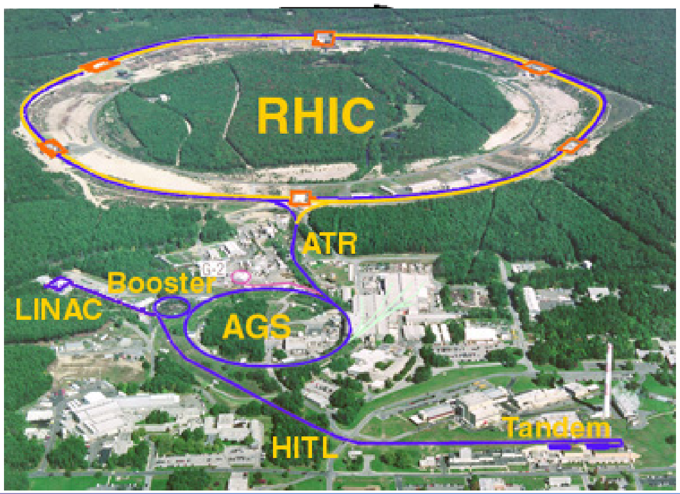


eRHIC

See Invited Talk
"RHIC status" by Thomas Roser

- eRHIC is a lepton hadron collider based on proven performance of RHIC
- Add a 20 GeV (5 pass) ERL placed in the straight sections of the 3.8 km RHIC tunnel
- Broad CM energy range 30-140 GeV (e-p) with full polarization
- Ion range protons to uranium
- Polarized positrons in ring made of last pass of ERL
- Luminosity $>10^{33}$ for 10 GeV electrons on 250 GeV protons, $>10^{31}$ for 100 GeV/n gold ions.





eRHIC Parameters, polarized electrons & protons

	High energy setup		Low energy setup	
	p	e	p	e
Energy, GeV	250	20	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity, 10^{11}	2	1.2	2.0	1.2
Beam current, mA	420	260	420	260
95% normalized emittance, π mm mrad	6	115	6	115
Rms emittance, nm	3.8	0.5	19	3.3
β*, x/y, cm	26	100	26	250
Beam-beam parameters, x/y	0.015	2.3	0.015	2.3
Rms bunch length, cm	20	0.7	20	1.8
Polarization, %	70	80	70	80
Peak Luminosity, 1.e33 $cm^{-2}s^{-1}$	2.6		0.53	
Luminosity integral /week, pb^{-1}	530		105	

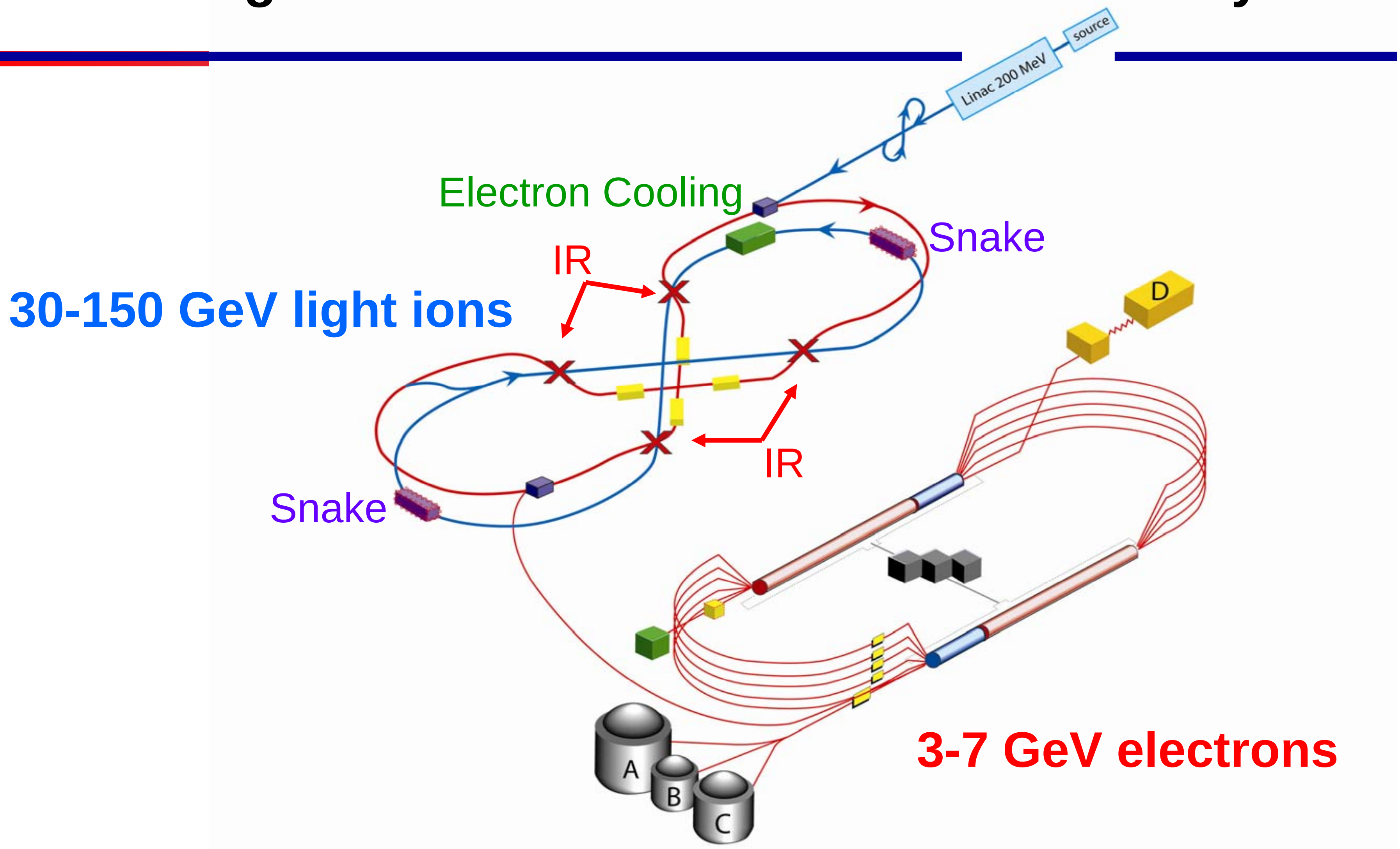
eRHIC parameters, electrons on gold

	High energy setup		Low energy setup	
	Au	e	Au	e
Energy, GeV (or GeV/u)	100	20	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity, 10^{11}	1.1	1.2	1.1	1.2
Beam current, mA	180	260	180	260
95% normalized emittance, π mm mrad	2.4	115	2.4	115
Rms emittance, nm	3.7	0.5	7.5	3.3
β* x/y, cm	26	200	26	60
Beam-beam parameters, x/y	0.015	1.0	0.015	1.0
Rms bunch length, cm	20	0.7	20	1.8
Polarization, %	0	0	0	0
Peak Luminosity (per nucleon), 1.e33 $cm^{-2}s^{-1}$	2.9		1.5	
Luminosity integral /week, pb^{-1}	580		290	

ELIC

- Based on the use of CEBAF with new ion facility and new electron colliding ring.
- Many novel ideas:
  - Large synchrotron tune – extremely short ion bunches
  - Large angle (0.1 radian) crab crossing
  - Figure 8 storage rings
  - Spin motion
  - Stacking scheme in booster
  - Flat beam cooling with recirculating ring
- Extremely high luminosity, in particular considering the low beam energies.
- Polarization of electrons, positrons, protons, deuterons, ^{3}He.

Electron Light Ion Collider at Jefferson Laboratory

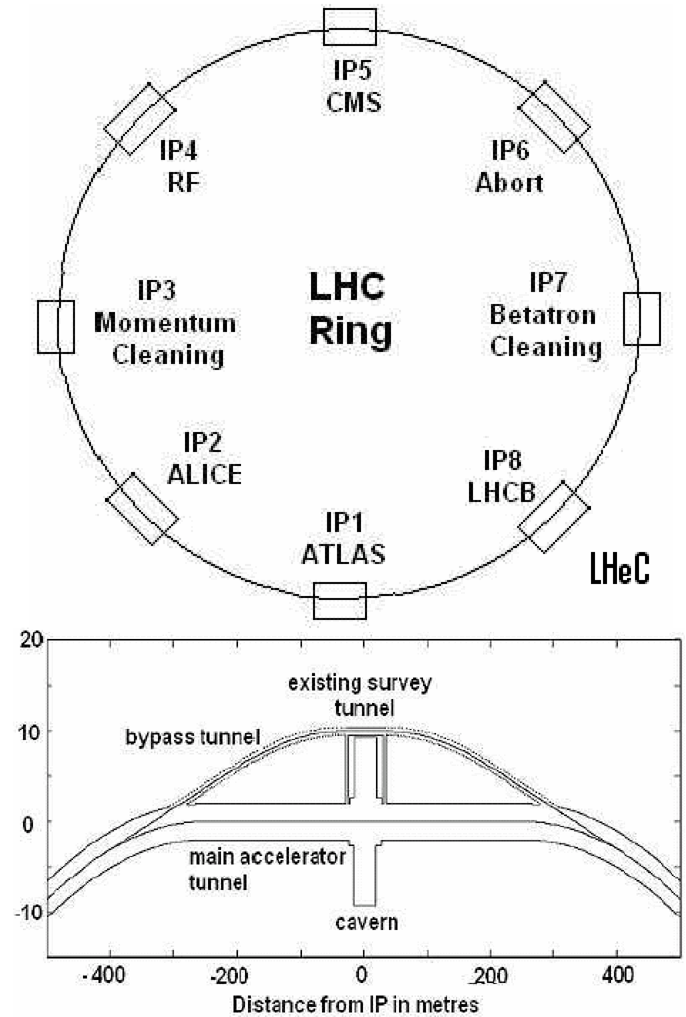


ELIC Parameters

Parameter	Unit	ERL	Ring-Ring		
Beam energy	**GeV**	**150/7**	**150/7**	**100/5**	**30/3**
Bunch collision rate	**GHz**	**1.5**			
Number of particles/bunch	**10^{10}**	**.4/1.0**	**.4/1.0**	**.4/1.1**	**.12/1.7**
Beam current	**A**	**1/2.4**	**1/2.4**	**1/2.7**	**.3/4.1**
Cooling beam energy	**MeV**	**75**	**75**	**50**	**15**
Cooling beam current	**A**	**2**	**2**	**2**	**.6**
Energy spread, rms	**10^{-4}**	**3/3**			
Bunch length, rms	**mm**	**5/5**			
Beta-star	**mm**	**5/5**			
Horizontal emittance, norm	**μm**	**1/86**	**1/86**	**.7/70**	**.2/43**
Vertical emittance, norm	**μm**	**.04/3.4**	**.04/3.4**	**.06/6**	**.2/43**
Beam-beam tune shift (vertical) per IP		**.01/.086**	**.01/.086**	**.01/.073**	**.01/.007**
Laslett tune shift (p-beam)		**.015**	**.015**	**.03**	**.06**
Luminosity per IP, 10^{34}	**$cm^{-2}\ s^{-1}$**	**7.7**	**7.7**	**5.6**	**.8**
Number of interaction points		**4**			
Core & luminosity IBS lifetime	**h**	**24**	**24**	**24**	**> 24**

LHeC

- Very solid design, based on re-installation of a LEP like storage ring back in the LHC tunnel.
- LHeC precision probe at the shortest length (~ 0.0001 fm) with high luminosity.
- Main issue is funding and time scale.
- $Q^2_{\text{LHeC}} \rightarrow 10^2 Q^2_{\text{HERA}}$
- $x_{\text{LHeC}} \rightarrow 10^{-2} x_{\text{HERA}}$
- $s_{\text{LHeC}} \rightarrow 20 s_{\text{HERA}}$



LHeC Parameters

Property	Unit	Leptons	Protons
Beam Energies	GeV	70	7000
Total Beam Current	mA	74	544
Number of Particles / bunch	10^{10}	1.04	17.0
Horizontal Beam Emittance	nm	25.9	0.501
Vertical Beam Emittance	nm	5	0.501
Horizontal β-functions at IP	cm	3.77	180
Vertical β-function at the IP	cm	4.44	50
Energy loss per turn	GeV	0.676	$6 \cdot 10^{-6}$
Radiated Energy	MW	50	0.003
Bunch frequency / bunch spacing	MHz / ns	40 / 25	
Center of Mass Energy	GeV	1400	
Luminosity	$10^{33}\text{cm}^{-2}\text{s}^{-1}$	1.04	

Conclusions and Outlook

- Proposed future electron ion colliders span a wide range of parameters and approaches to risk – innovation – performance –cost trade-offs.
- What is common to all is the high luminosity.
  - eRHIC is intermediate in CM energy, has the widest range of ions. It is based on an operating ion machine with polarized protons and high luminosity. eRHIC is intermediate in innovation
  - LHeC has the highest CM energy by far. The main shortcomings are the absence of proton polarization, and uncertainty with regard to electron polarization. The LHeC design is very conservative.
  - ELIC is lowest in energy but highest in luminosity. ELIC is by far the most innovative machine, using a recirculating ring for aggressive electron cooling, flat beams, very large beam-beam parameters, extremely short bunches and extremely small β^*, innovative spin preserving machine structures, very large crab angle and advanced injection techniques. Its bunch spacing is extremely small.

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Thanks to the audience for your patience

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