CERN

Alessandra Valloni on behalf of the LHeC collaboration

North American Particle Accelerator Conference

Beam Physics in Future Electron Hadron Colliders

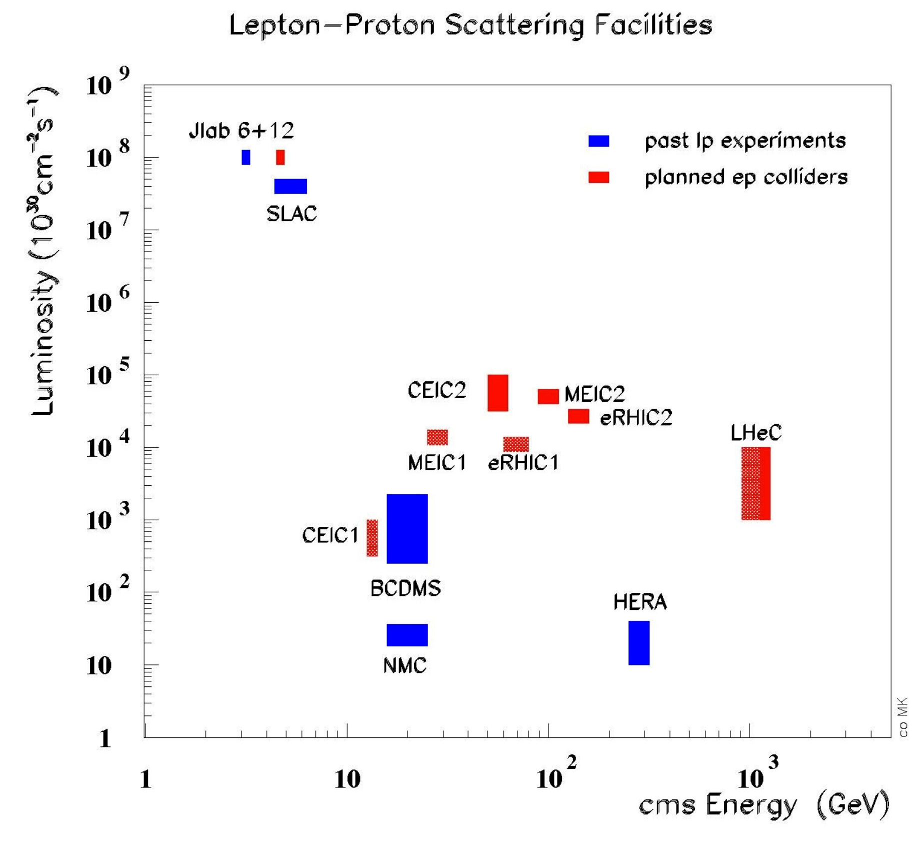
Pasadena Convention Center, 30th September - 4th October

Main EIC present projects in the world…

…present and possible future colliders

What should we expect from the next 20 years?

Expected Performance…
energy reach and luminosity*



- Much higher luminosity
- Variable CM Energy range
- Polarized protons and light ions (in addition to polarized e^{-})
- Heavy ion beams

*Max Klein

Outline

1. **Future Electron Hadron Colliders**
   - eRHIC, MEIC, LHeC:
     Baseline parameters and configurations

2. **Challenging issues**
   - BEAM PHYSICS LIMITS:
     Merit of different approaches and further research

3. **Beam dynamics concerns**
   - Selected subjects:
     e-beam polarization, SR related effects, multipass BBU and beam-beam effects, fast beam-ion instability, *e*-cooling

4. **Future plans and R&D activities at CERN**

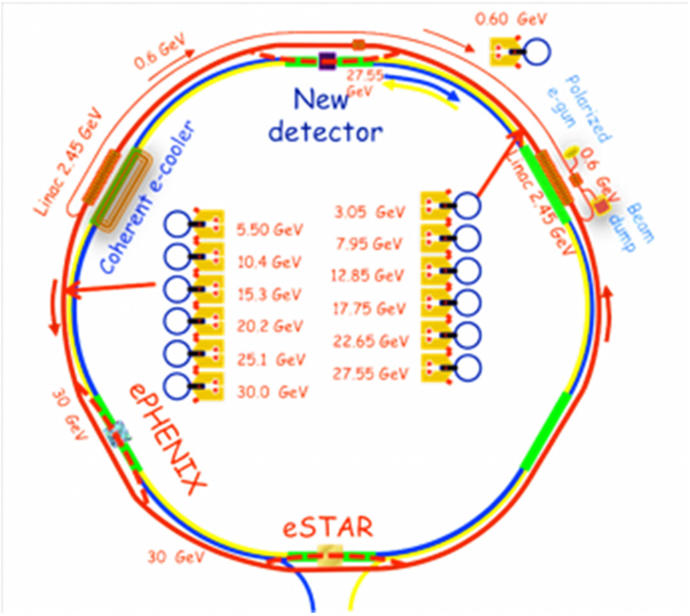
5. **Conclusions**

Future Electron Hadron Colliders*

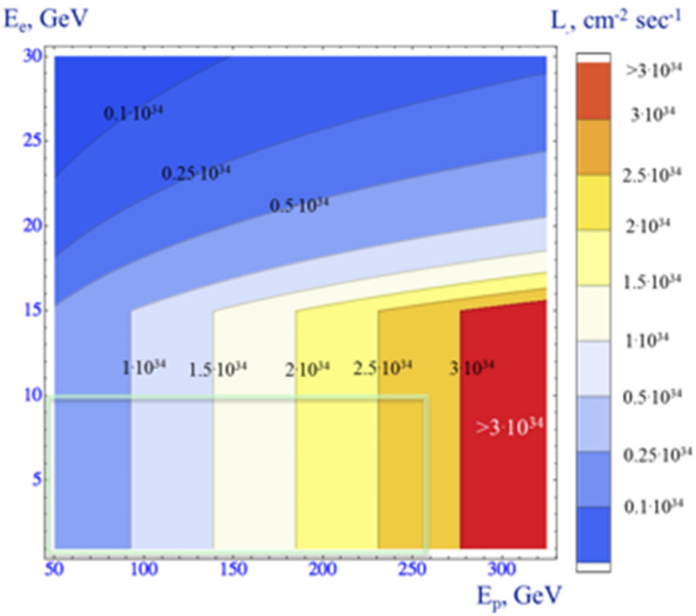
eRHIC, MEIC, LHeC:
Baseline parameters and configurations

***Electron-Ion Collider Proposals [TUZAA1]**
Yuhong Zhang, Jefferson Lab

eRHIC DESIGN



Luminosity as function of lepton and hadron beam energy



All-in tunnel staging approach uses two ERLs and 6 recirculation passes to accelerate the *e*-beam

Staging: the electron energy can be increased in stages, from 10 to 30 GeV, by increasing the linac lengths

Up to 3 experimental locations

$\sqrt{s}$ = 30 – 200 GeV

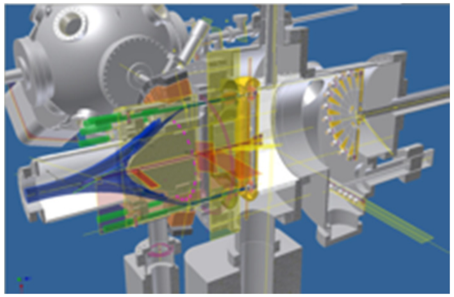
E_e = 10 – 30 GeV

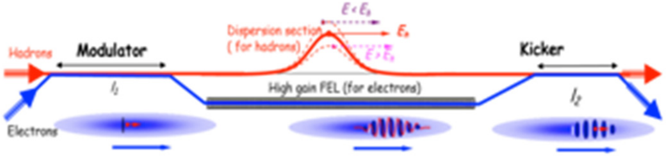
E_p = 50 –325 GeV

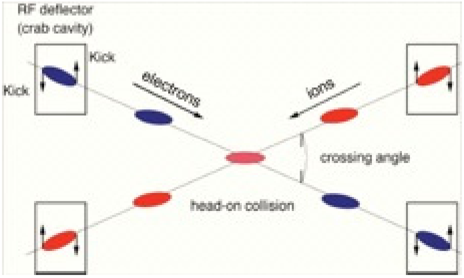
E_A = up to 130 GeV/u

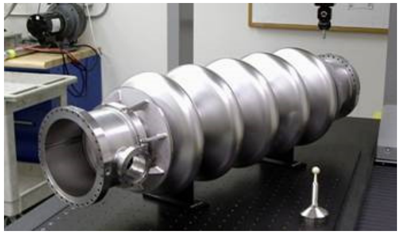
eRHIC DESIGN

R&D Advanced Accelerator Technology
Polarized electron gun -- 10x increase
Coherent electron Cooling -- New concept
Multi-pass SRF ERL 2x increase in current -- 30x increase in energy
Crab crossing -- New for hadrons
Polarized ^{3}He production
Understanding of beam-beam effects New type of collider
β*=5 cm -- 5x reduction
Multi-pass SRF ERL -- 3-4x in # of passes
Space charge compensation Requires verification



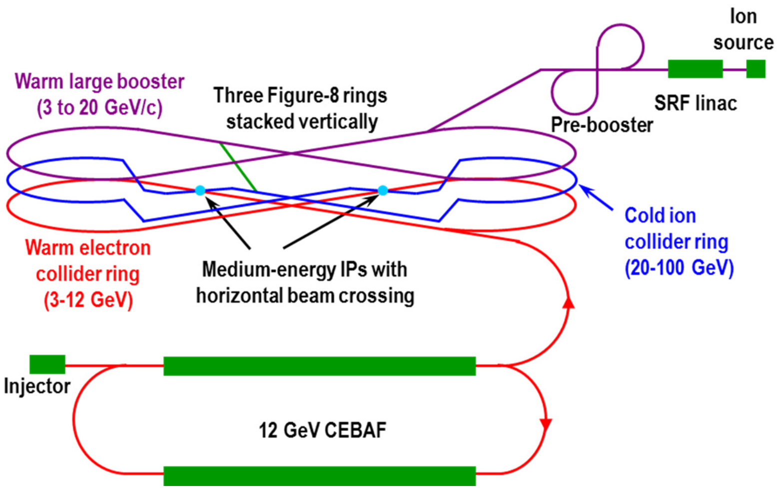






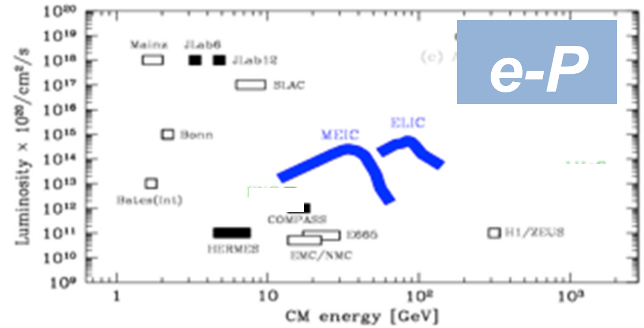
Vadim Ptitsyn, BNL

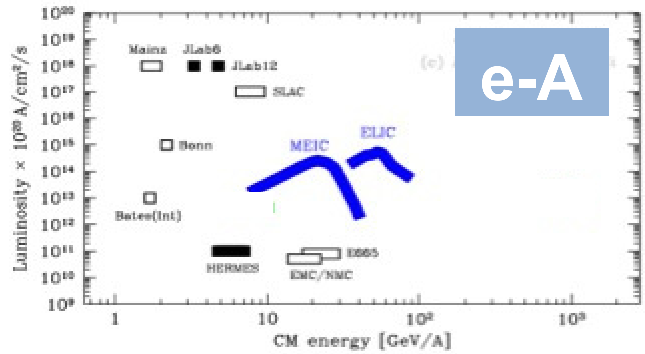
MEIC DESIGN

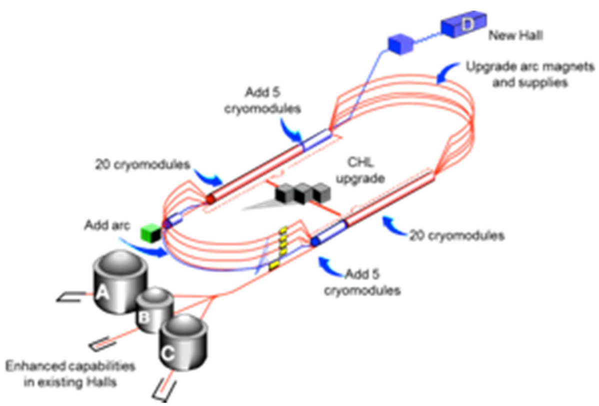


$\sqrt{s}$ = 15 – 66 GeV E_e = 3 – 12 GeV

E_p = 20 – 100 GeV E_A = up to 100 GeV/u







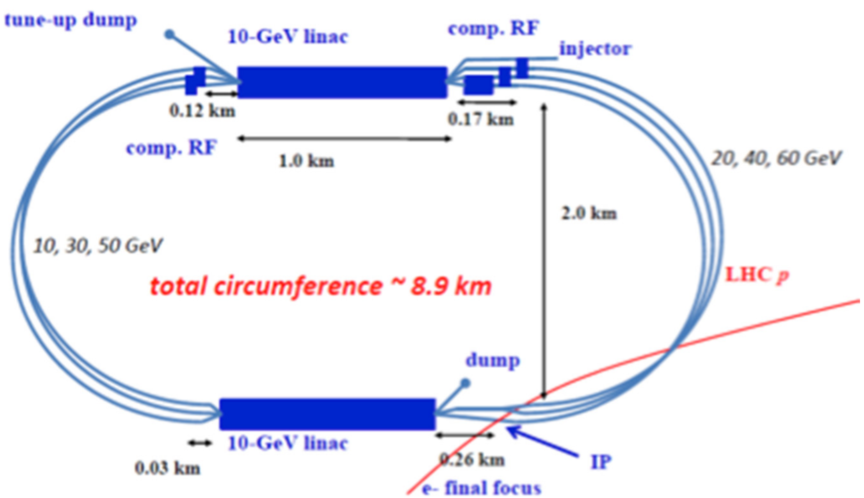
- Polarized light ions (p, d, ^{3}He), unpolarized ions up to A=200 (Au, Pb)
- New ion complex & two collider rings
- Up to 3 interaction points
- Vertical stacking for identical ring circumferences
- Ion beams execute vertical excursion to the plane of the electron orbit for enabling a horizontal crossing

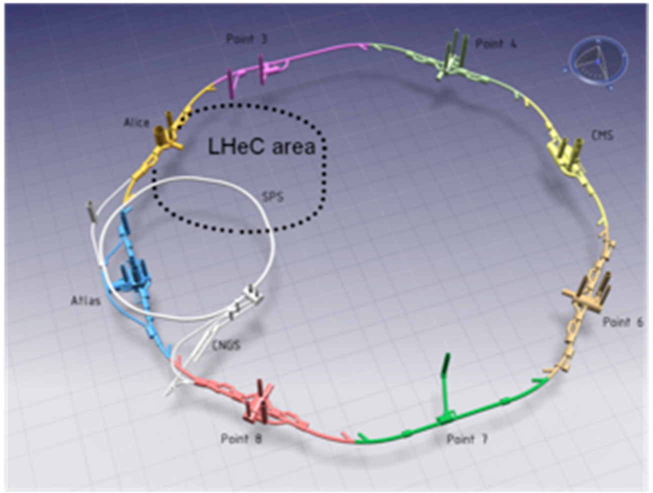
MEIC DESIGN

R&D Advanced Accelerator Technology*
Electron Cooling Proof of staged beam cooling concept Design of an ERL Circulator cooler Cooler test facility proposal
Interaction Region Design Detector/IR integration, small angle (to 0°) particle detection Nonlinear beam dynamics, chromatic compensation and dynamic aperture Implementation of crab crossing
Polarization Electron spin matching Proof of figure-8 ring concept Realization of fast spin flip
Beam-beam effect
Electron cloud effect in ion ring

*Rolf Ent, JLab

LHeC Design





RECIRCULATOR COMPLEX

1. 0.5 Gev injector
2. Two SCRF linacs (10 GeV per pass)
3. Six 180° arcs, each arc 1 km radius
4. Re-accelerating stations
5. Switching stations
6. Matching optics
7. Extraction dump at 0.5 GeV

Relevant Parameters at IP

	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
Beta Function $\beta^*_{x,y}$ [m]	0.10	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7
rms Divergence $\sigma'_{x,y}$ [μrad]	70	58
Beam Current [mA]	(860) 430	6.6
Bunch Spacing [ns]	25 (50)	25 (50)
Bunch Population	$1.7*10^{11}$	$(1*10^9)\ 2*10^9$

The baseline 60 GeV ERL option proposed can give an e-p luminosity of 10^{33} $cm^{-2}s^{-1}$ (extensions 10^{34} $cm^{-2}s^{-1}$ and beyond are being considered)*

*LHeC Collaboration,
On the Relation of the LHeC and the LHC
arXiv:1211.5102

LHeC Design

R&D Advanced Accelerator Technology
Superconducting RF Development High gradient superconducting cavities Q values above $2*10^{10}$ RF diagnostics and feedback loops RF coupler design optimized for ERL operation
Superconducting 3-beams IR magnet design Demonstration of the technical feasibility of the existing designs
Normal conducting compact magnet design
Interaction Region Design
Beam pipe Development
High intensity polarized positron sources
ERL Test Facility

Beam dynamics challenging issues

- *e*-beam energy losses and energy spread caused by the interaction with the beam environment (cavities, resistive walls, pipe roughness);
- incoherent and coherent synchrotron radiation (SR) related effects: energy losses, transverse and longitudinal emittance increase of the *e*-beam;
- effective energy loss and energy spread compensation schemes;
- *e*-beam filling patterns; ion accumulation;
- *e*-beam break-up (BBU), single beam and multi-pass;
- *e*-beam-ion and intra-beam scattering effects;
- *e*-beam polarization: depolarization effects;
- possible effects due to crab cavities;
- detailed beam dynamics with electron cooling;
- beam-beam effects, including the *e*-beam disruption and the hadron beam kink instability.

Electron Beam Polarization

Electron Beam Polarization: MEIC

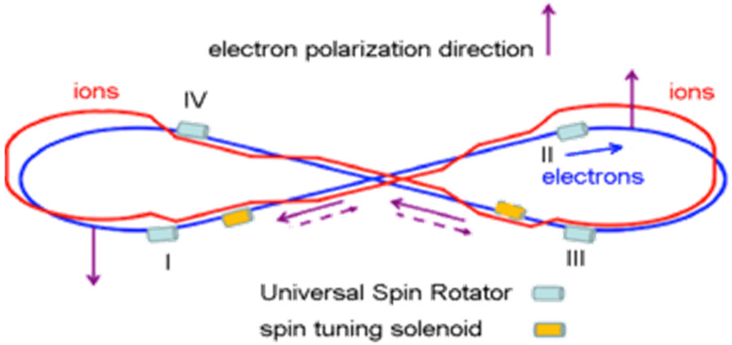
Requirements:

Polarization of 70% or above Longitudinal polarization at IPs Spin flipping

Strategies:

- Highly longitudinally polarized *e*-beams are injected from the CEBAF
- Polarization is designed to be vertical in the arc to avoid spin diffusion and longitudinal at collision points using spin rotators
- New developed universal spin rotator rotates polarization in the whole energy range
- Spin flipping can be implemented by changing the polarization of the photo-injector driver laser at required frequencies
- Figure-8 provides unique capabilities for manipulating beam polarization

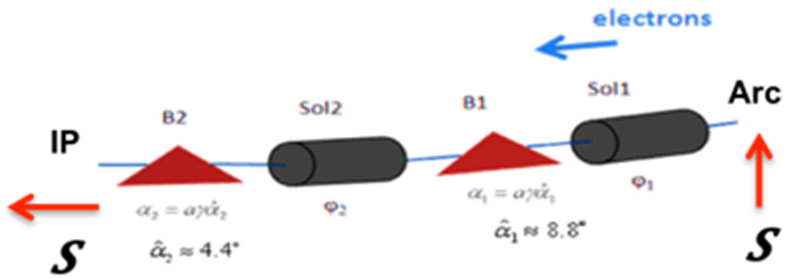
Illustration of polarization orientation*



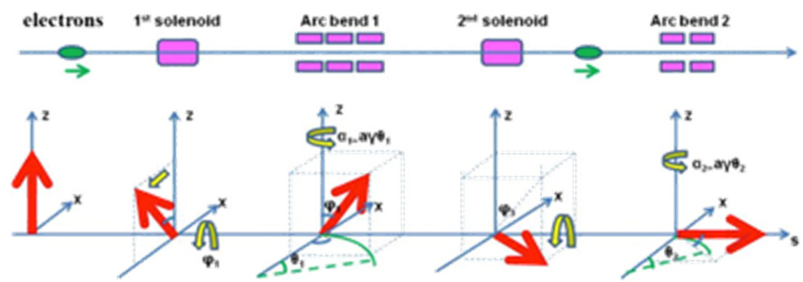
*F. Lin, PSPT 2013

Electron Beam Polarization: MEIC

Universal Spin rotator

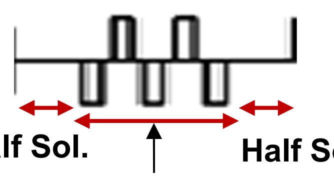


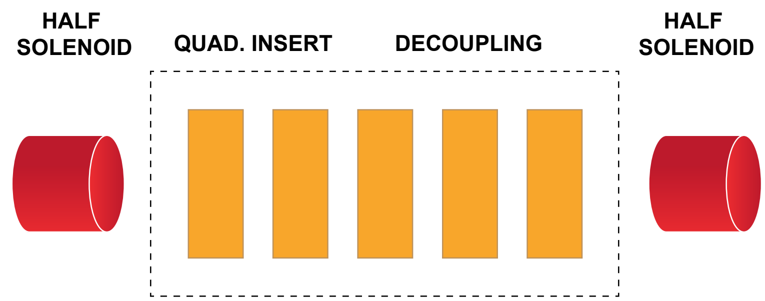
Step-by-step spin rotation by a USR



Solenoid Decoupling Scheme*

- A solenoid is divided into two equal parts
- Normal quadrupoles are placed between them
- Quad strengths are independent of solenoid strength





*V. Litvinenko, A. Zholents, BINP (Novosibirsk) (1981)

Electron Beam Polarization: LHeC and eRHIC

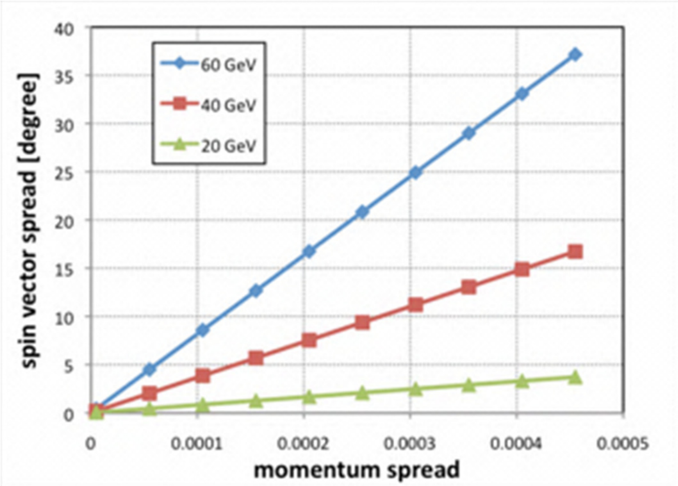
Option 1 @ LHeC: Low Energy Spin Rotator
Wien-filter in the injector to control spin direction

Pros

Economical and Straightforward

Cons

Spin spread due to different amount of spin rotation for particles with different energy

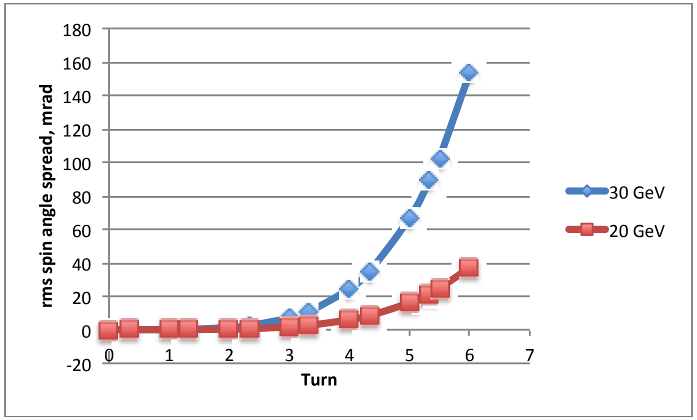


The effective polarization can be reduced by 10% due to the spread of the spin vectors*

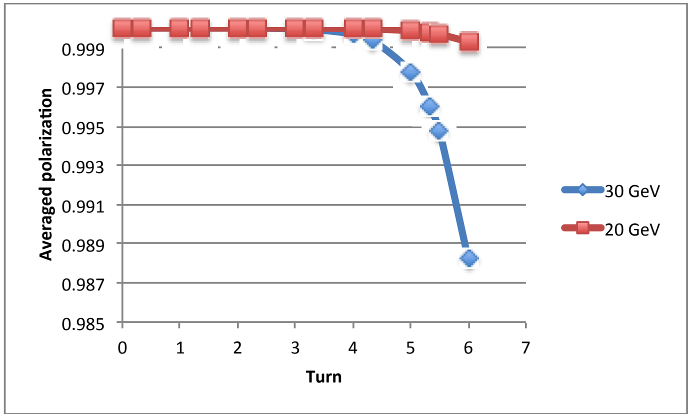
@ eRHIC**

Depolarization becomes noticeable only when accelerating to 30 GeV

Rms spin angle spread



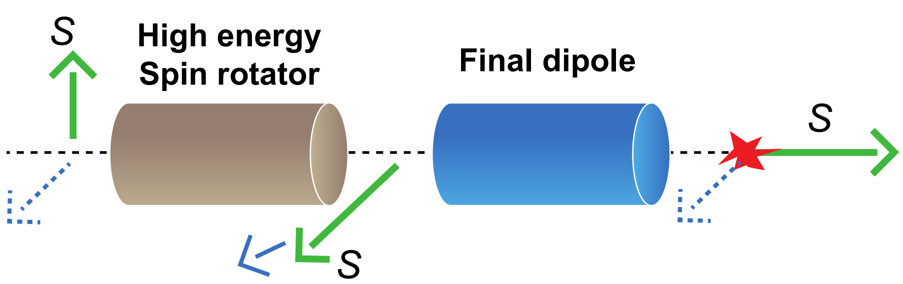
Averaged beam polarization

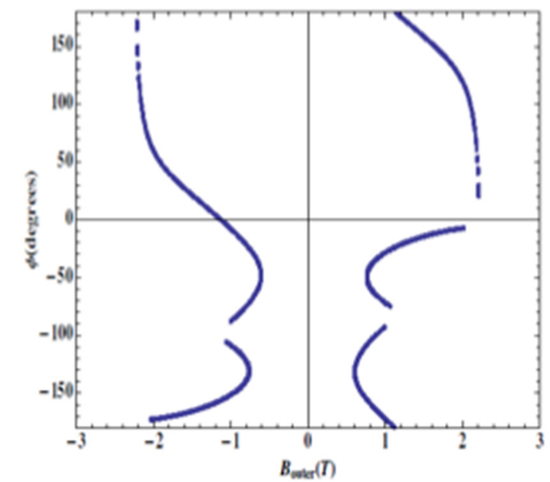


*M. Bai, CERN-ATS-2011-110
**V. Ptitsyn, PSTP 2013 Workshop

Electron Beam Polarization: LHeC

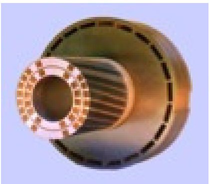
Option 2: Low & High Energy Spin Rotators

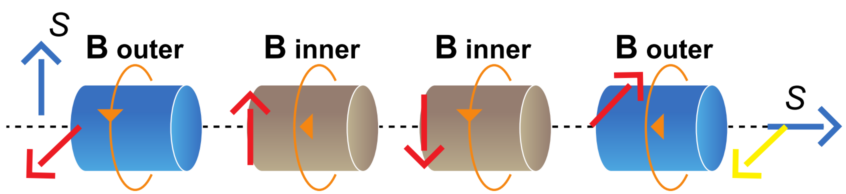


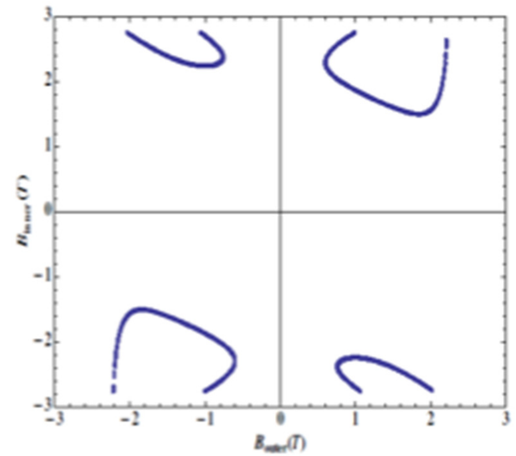


High energy spin rotator: RHIC type

Four helical dipoles to rotate spin vector by 90deg around an axis in the horizontal plane







B_{outer} = 0.46 T

SR power = 0.31 MW B_{inner} = 0.37 T

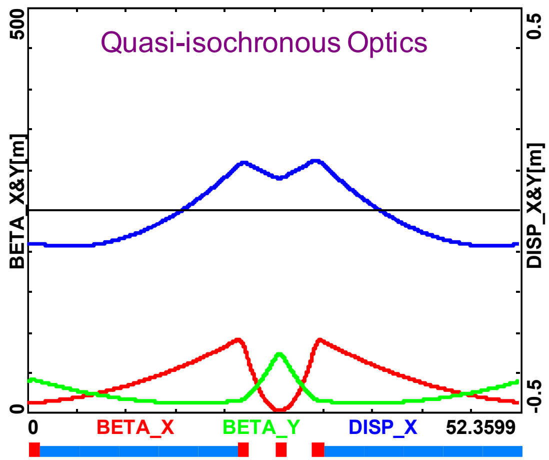
Optics Design and SR in return arcs

Optics Design and SR in return arcs: LHeC

Proper lattice design in the arcs to address
the effect of SR on electron beam phase-space:
cumulative emittance and momentum growth due to quantum excitations

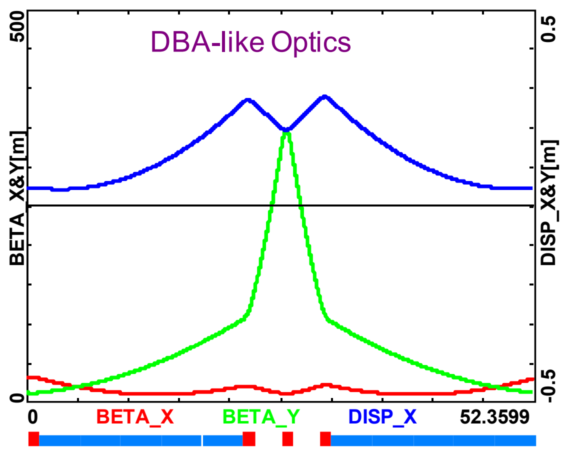
$$\Delta\varepsilon^N = \frac{2}{3} C_q \, r_0 \, \gamma^6 \langle H \rangle \frac{\pi}{\rho^2} \qquad H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Arc 1 and 2



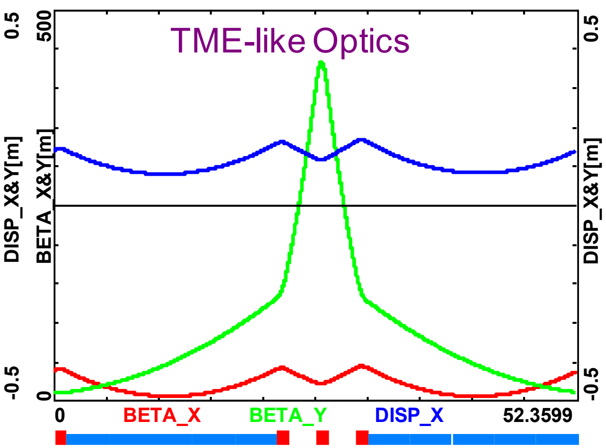
$$\langle H \rangle = 8.8 \times 10^{-3} \; m$$

Arc 3 and 4



$$\langle H \rangle = 2.2 \times 10^{-3} \; m$$

Arc 5 and 6



$$\langle H \rangle = 1.2 \times 10^{-3} \; m$$

Various flavors of FMC Optics used*

Emittance not exceeding 50 μm required for the LHeC luminosity

*Alex Bogacz

Synchrotron radiation in return arcs: LHeC

ARC	E [GeV]	ΔE [MeV]	σE/E [%]
1	10.4	0.678	0.00052
2	20.3	9.844	0.00278
3	30.3	48.86	0.00776
4	40.2	151.3	0.01636
5	50.1	362.3	0.02946
6	60	751.3	0.04829
7	50.1	362.3	0.06366
8	40.2	151.3	0.08065
9	30.3	48.86	0.10808
10	20.3	9.844	0.16205
11	10.4	0.678	0.31668
dump	0.500	0	6.66645

Energy loss and Integrated energy spread induced by SR

Total loss per particle about ~1.9 GeV

Compensated by additional linacs
20.3 MW

ARC	E [GeV]	$\Delta\varepsilon_{ARC}$ [μm]	$\Delta\varepsilon_{t}$ [μm]
1	10.4	0.0025	0.0025
2	20.3	0.140	0.143
3	30.3	0.380	0.522
4	40.2	2.082	2.604
5	50.1	4.268	6.872
6	60	12.618	19.490
5	50.1	4.268	23.758
4	40.2	2.082	25.840
3	30.3	0.380	26.220
2	20.3	0.140	26.360
1	10.4	0.0025	26.362

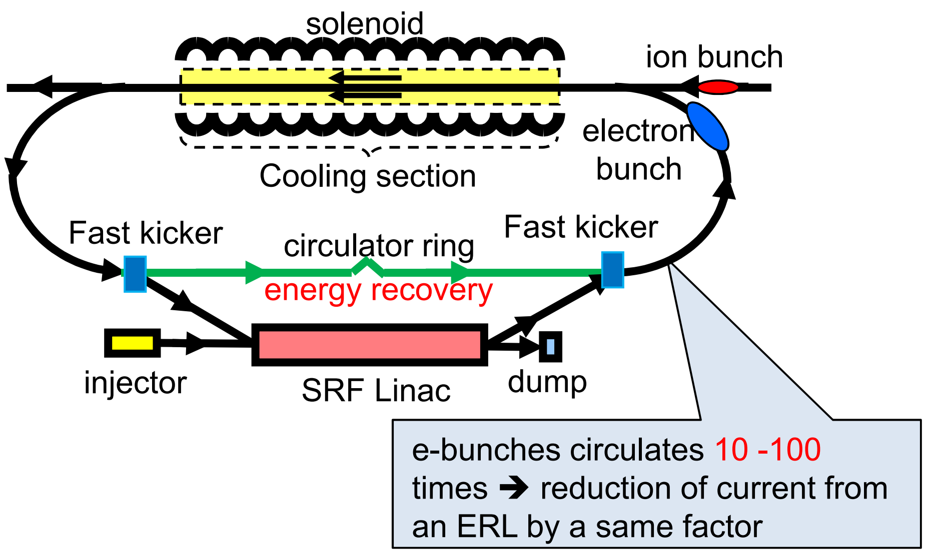
Integrated Emittance growth including all previous arcs

Before the IP a total growth of ~ 7 μm is accumulated
The final value is ~ 26 μm

Electron cooling

Electron cooling: MEIC

Initial cooling: after injection for reduction of longitudinal emittance
Final cooling: after boost & rebunching, for reaching design values of beam parameters
Continuous cooling: during collision for suppressing IBS & preserving luminosity lifetime



Design Choices

- Energy Recovery Linac
- Compact circulator ring to meet design challenges
- Large RF power (up to 81 MW)
- Long gun lifetime (average current 1.5 A)

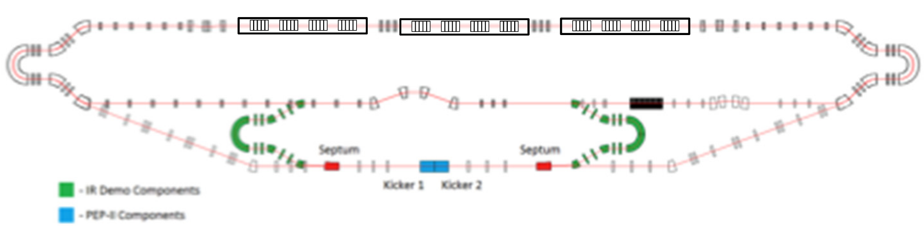
Required technologies

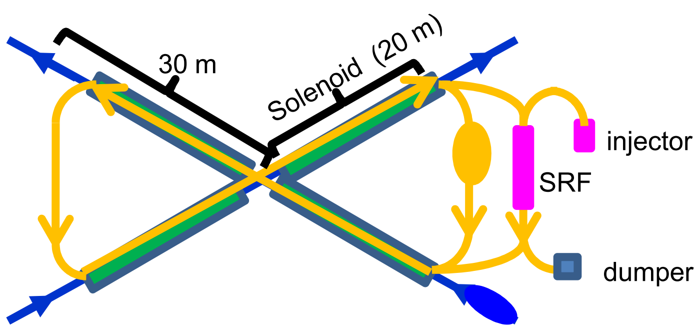
- High bunch charge magnetized gun
- High current ERL (55 MeV, 15 to150 mA)
- Ultra fast kicker

Optimization

Eliminating a long return path could double the cooling rate

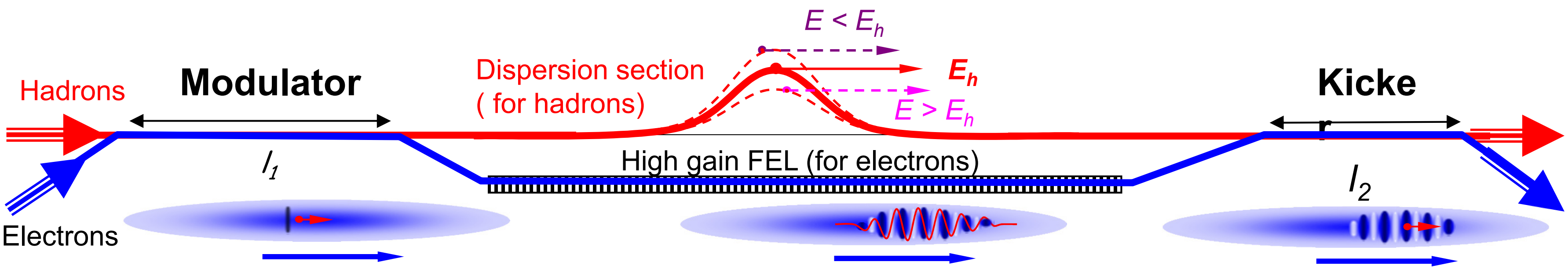
Proposal: A technology demonstration using JLab FEL facility



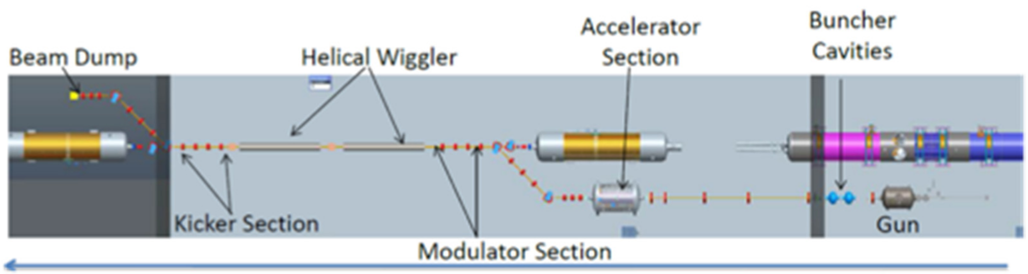


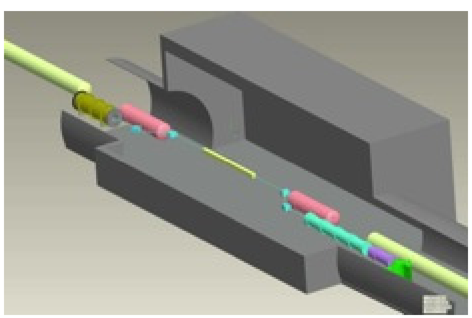
Coherent Electron cooling: eRHIC

CeC is required for significant increases in luminosity and energy reach



Layout for CeC proof-of-principle experiment in RHIC IR





3-D rendering of the CeC demonstration set-up in the RHIC's IP2

Parameter	
Species in RHIC	Au ions, 40 GeV/u
Electron energy	21.8 MeV
Charge per bunch	1 nC
Train	5 bunches
Rep-rate	78.3 kHz
e-beam current	0.39 mA
e-beam power	8.5 kW

Beam-beam effects and Multipass Beam breakup studies

The LHeC Beam Breakup studies

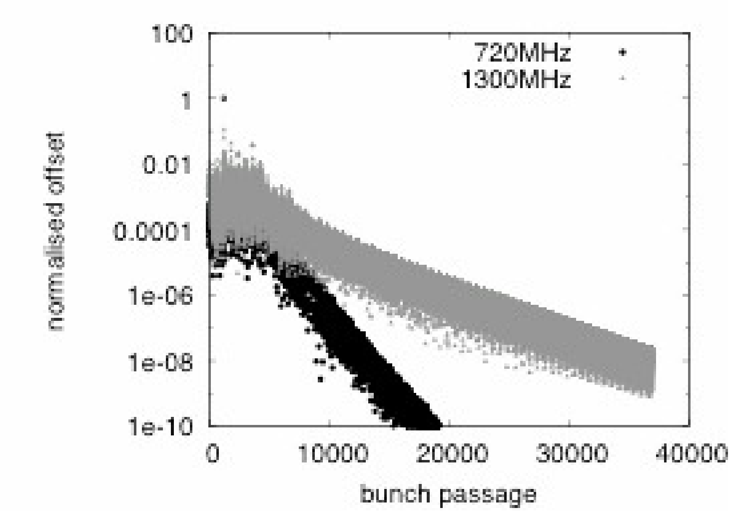
- ILC cavities from TESLA TDR
- SPL cavity dipole modes ($Q=10^5$)
- 0.1% mode detuning in both cases

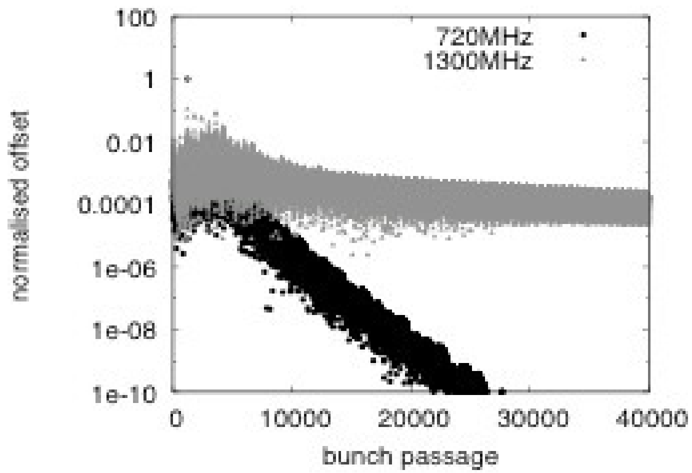
Dedicated code:

- Point-like bunches
- Response to one offset bunch

Use increased charge $N=3*10^9$ but ignore gaps

Beam-beam effect included
as linear kick (using small offset values)

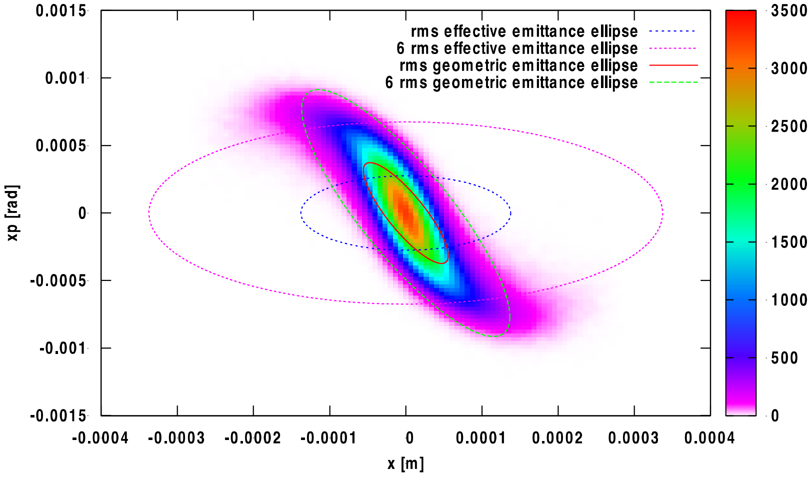


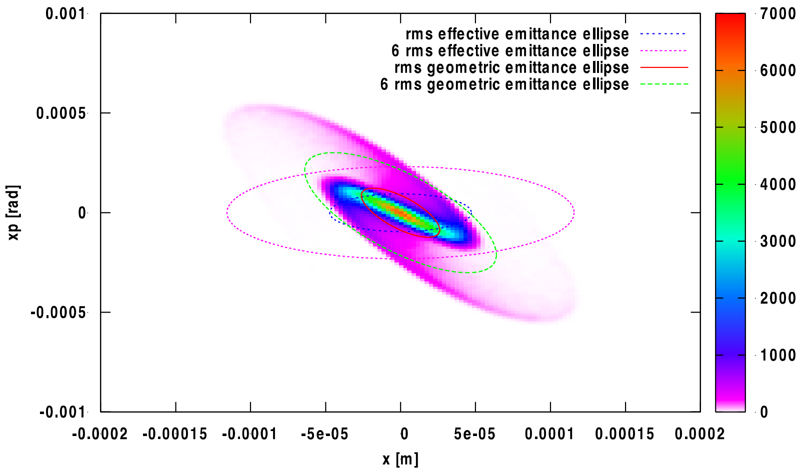


Coupling between multi-bunch wakefield effects and beam-beam is very important

Beam is stable but very small margin with 1.3GHz cavity

Disruption effect at MeRHIC





MeRHIC No cooling

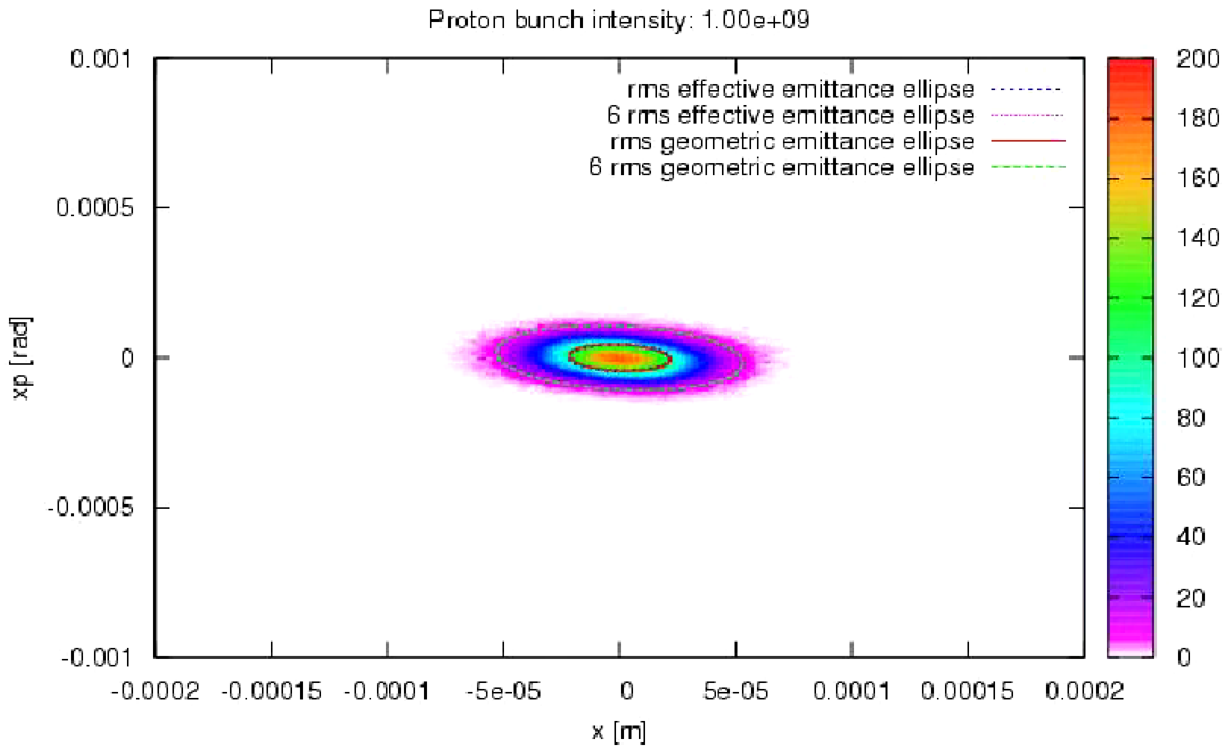
Parameter	Value
Bunch population (p)	$2*10^{11}$
Bunch population (e)	$0.31*10^{11}$
Energy p/e (GeV)	250/4
Bunch number	111
Emit. p/e [nm-rad]	9.4/9.4
β* p/e [m]	0.5/0.5
Proton bunch length [m]	0.2
Luminosity [$cm^{-2}s^{-1}$]	$1.1*10^{32}$

MeRHIC with CeC

Parameter	Value
Bunch population (p)	$2*10^{11}$
Bunch population (e)	$0.31*10^{11}$
Energy p/e (GeV)	250/4
Bunch number	111
Emit. p/e [nm-rad]	0.94/0.94
β* p/e [m]	0.5/0.5
Proton bunch length [m]	0.2
Luminosity [$cm^{-2}s^{-1}$]	$1.4*10^{33}$

Disruption effect at eRHIC

The deformation of the electron beam distribution by the beam-beam interaction:



Yue Hao, Vadim Ptitsyn, BNL

Fast beam-ion instability

Fast Beam-Ion Instability: LHeC

Collision of beam particles with the residual gas in the beam pipe leads to the production of positive ions that can be trapped in the beam

Studies need to
- Estimate whether ions are trapped
- Develop mitigation techniques
- Evaluate the damage effect

LHeC case: clearing gaps needed
- Clearing gaps of 10μs every 30μs

- Increase bunch charge by 50%

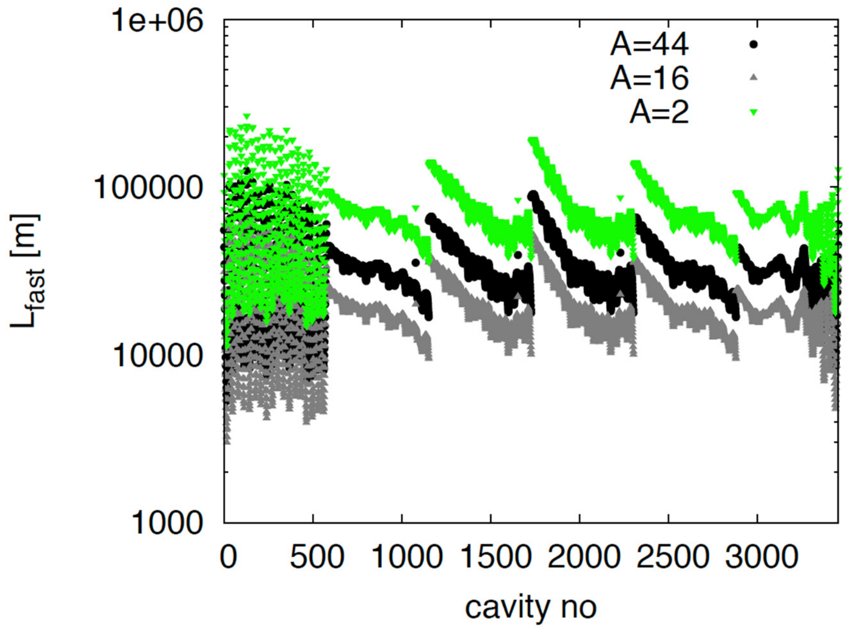
This fixes LHeC circumference to be 1/3 of LHC
Each bunch in LHC will either always collide with an e-bunch or never

Fast Beam-Ion Instability: LHeC

Estimate the impact of ions on the beam during the full train length of 20μs

The rise length is proportional to the pressure, here 10^{-11}hPa
Rise length for
CH_4^+: 14km , H_2^+: 25km

The beam will travel a total of 12km during the 6 passes



The typical time scale of the rise of the instability is longer than the life time of the beam and we expect no issue

Required pressure p=10^{-11}hPa

Measurements show 6×10^{-11},1×10^{-11}, 0.05×10^{-11} hPa for LEP, HERA, LHC

Future plans and R&D activities at CERN

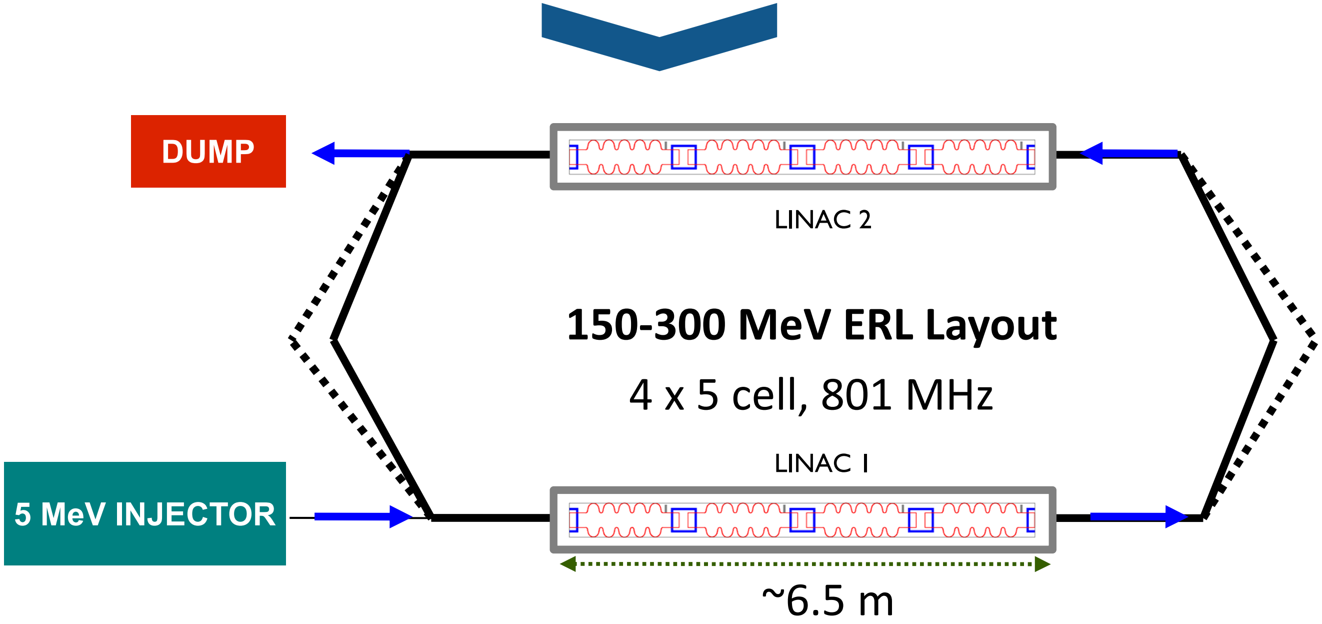
LHeC test facility

THE NEXT MAJOR STEP OF THE LHeC R&D IS A DEMONSTRATOR AT CERN OF AN ENERGY RECOVERY LINAC

- **The test facility would consist of SC linacs, recirculation and energy recovery**
- **Among the purposes of this test facility are**
  1. Demonstrating the feasibility of the LHeC ERL design
     - Study behaviour of a high energy multi-pass multiple cavity ERL for LHeC
     - Optics, RF power, synchronization & delay issues …
     - HOMs and HOM couplers, cryogenics, instrumentation, controls, LLRF …
  2. Injector studies (DC or SRF gun)
  3. Study real SCRF cavities with beam
  4. Analyzing electron beam dynamics challenge
  5. Reliability issues, operational issues
  6. Beam facility for controlled SC magnet quench tests
  7. Beam facility for HEP detector R&D
  8. Demonstrator and study facility for e-cooling
  9. Could it be foreseen as the injector to LHeC ERL ?

LHeC test facility: Possible Schematics (1)

100-MeV scale energy recovery demonstration of a recirculating superconducting linear accelerator



RECIRCULATOR COMPLEX

1. A 5 MeV in-line injector with an injection chicane
2. 2 SC linacs consisting of half cryomodule (4 RF cavities\ 5-cell per cavity)
3. Optics transport lines
4. Beam dump at 5 MeV

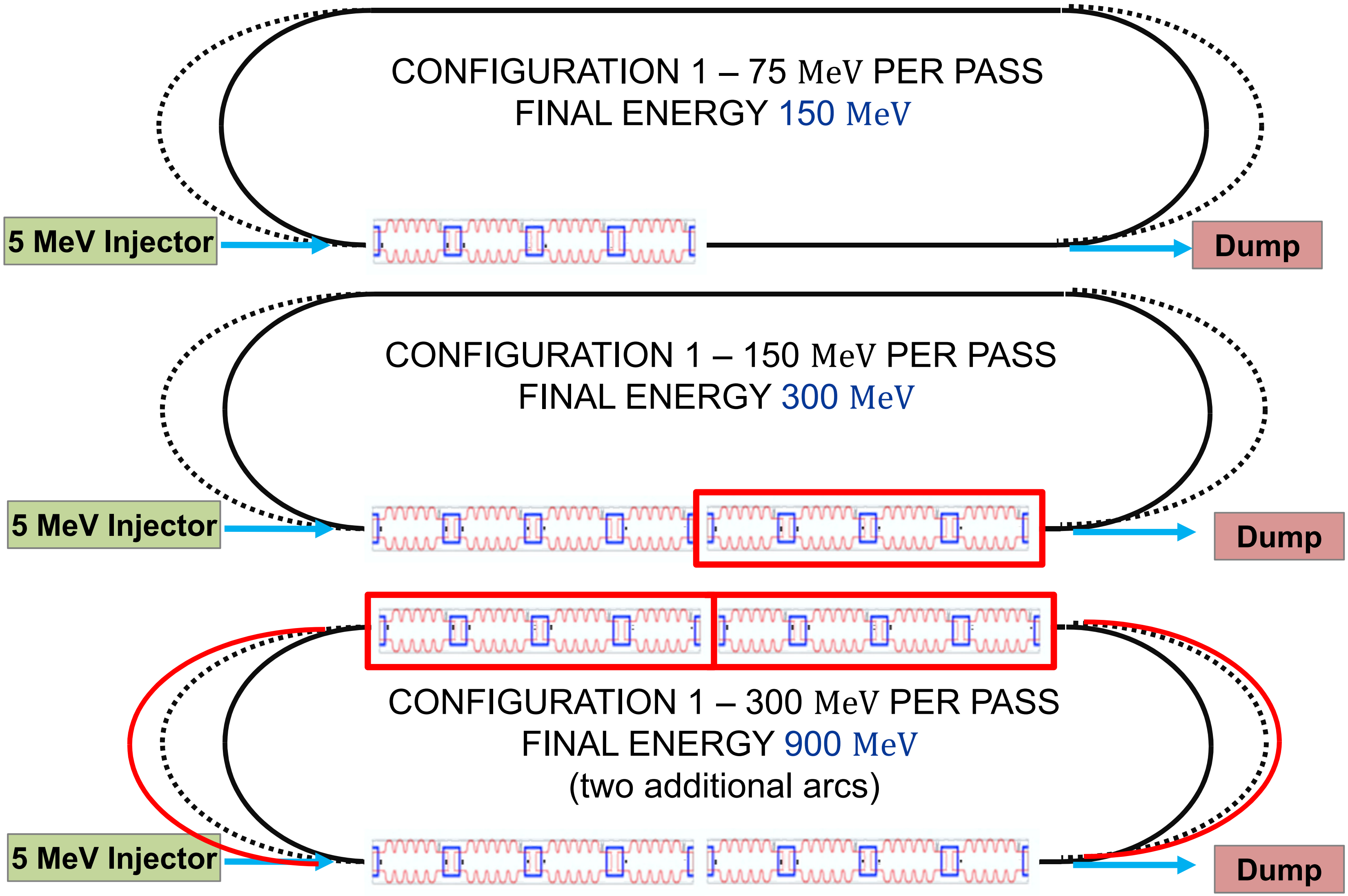
LHeC TF: Variations Built-in Flexibility

100-MeV scale energy recovery demonstration
of a recirculating superconducting linear accelerator

How much further can we go?

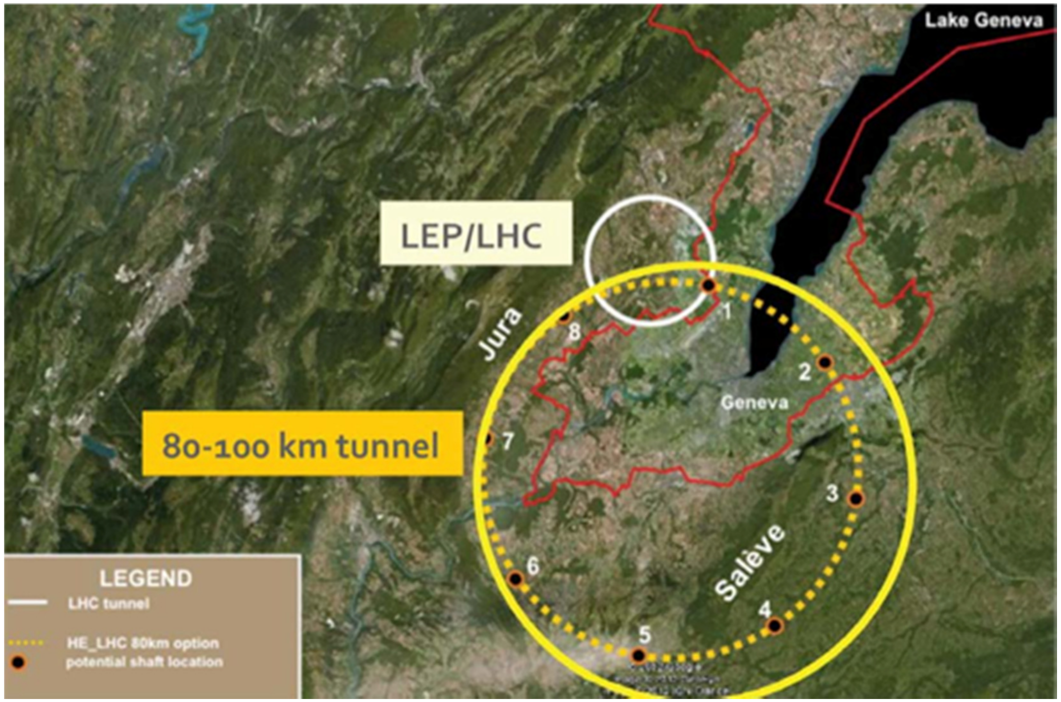
1-GeV scale energy recovery demonstration
of a recirculating superconducting linear accelerator

LHeC TF: Variations Built-in Flexibility



Future High Energy Frontier Colliders

TLHeC & VHE-TLHeC (e^- at 120 GeV)



Parameters	TLHeC		VHE-TLHeC	
Species	$e^{\pm}$	p	$e^{\pm}$	p
Beam energy [GeV]	120	7000	120	50000
bunch intensity [10^{11}]	5	3.5	5	3.5
Beam current [mA]	18.7	18.7	26.7	18.7
CM energy [TeV]	1.8		4.9	
Luminosity [$10^{34}cm^{-2}s^{-1}$]	0.5		1.6	

Summary and Outlook

Four colliders, covering CM energy range from 10 GeV to 2 TeV, are in various stages of development/design

- All these colliders are aiming at very high luminosity, two-to-four orders of magnitude beyond the luminosity demonstrated by HERA
  - The physics programs to a large degree are complimentary to each other and to the LHC physics
- Key accelerator physics issues, referring to eRHIC, MEIC and LHeC, have been presented
  - Beam physics and accelerator technology limits
  - Studies to analyze and compare the merits of different approaches

- **Additional R&D is needed**
  - Further improvements to overcome the state-of-art

Thank you for your attention

Some References

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Thank you for your attention