EIC Accelerator Frontiers and Challenges

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With thanks to my eRHIC, JLEIC and LHeC colleagues for help & materials

Luminosity

- Luminosity formula (ignoring crossing angle)

$$L = \frac{N_i f_c \gamma_i \left(\xi_{x,i} \beta_{y,i} + \beta_{x,i} \xi_{y,i} \right)}{2 r_p \beta_{x,i} \beta_{y,i}}$$

  - note: all parameters are for the ion ring!
- So what happens to the electrons…

$$\xi_{y,e} = \frac{r_e N_i \beta_{y,e} \xi_{y,i} \gamma_i}{\gamma_e \beta_{y,i} r_p N_e} = \frac{N_i}{N_e} \frac{E_i}{E_e} \frac{\beta_{y,e}}{\beta_{y,i}} \xi_{y,i}$$

  - …they can get whacked if $N_i \bullet E_i >> N_e \bullet E_e$
    - some factor >1 is ok for ring-ring due to radiation damping
    - much larger and the electrons limit luminosity.

Ring-Ring *vs* Ring-Linac(ERL)

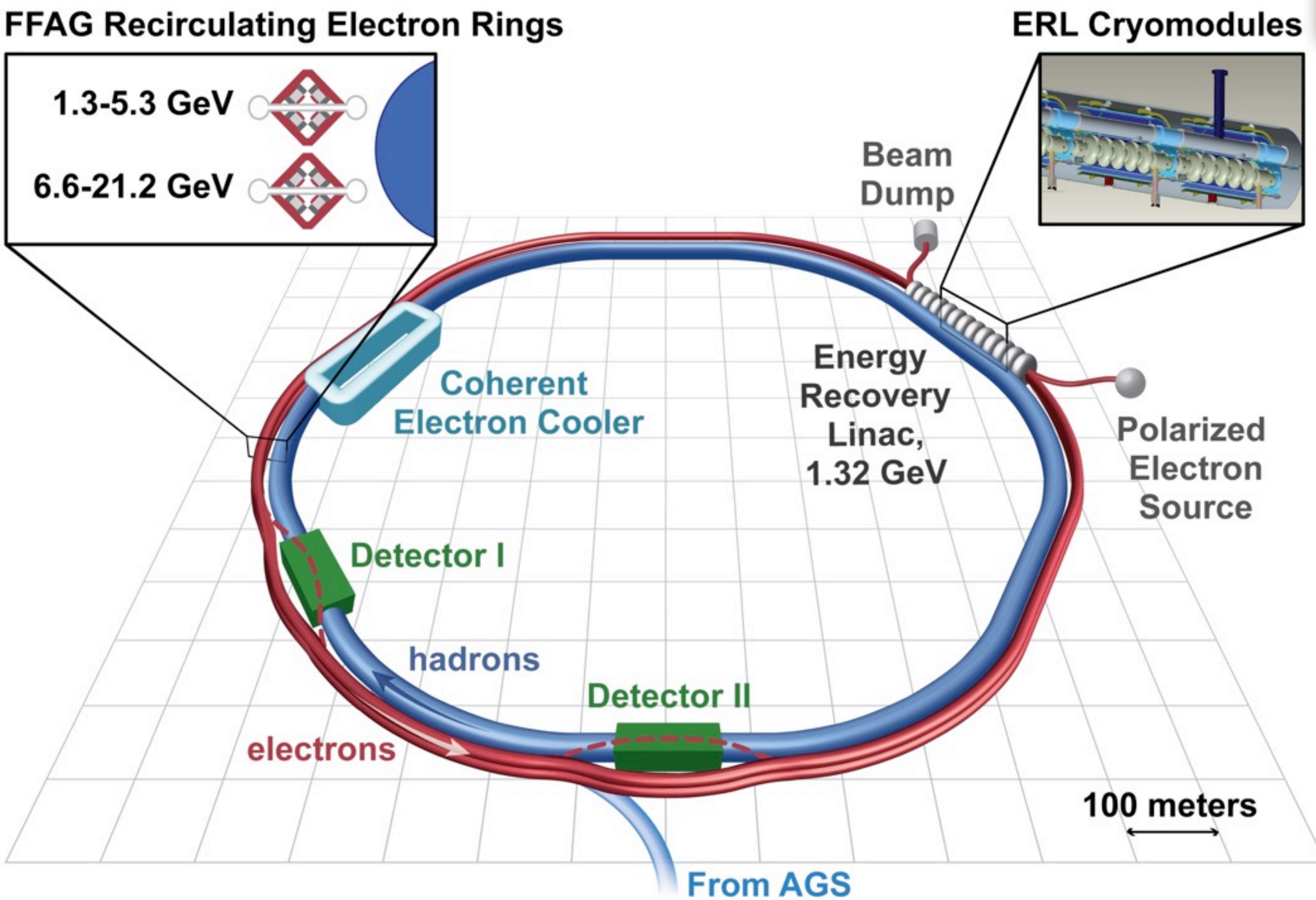
- Ions in storage ring
  - tune shift limited to $0.005 \le \xi_i \le 0.015$
  - Tevatron, LHC, RHIC, …
- Ring-Ring
  - taylor beam intensity and β ratio to make ξ_e / ξ_i <10(maybe)
    - $0.1 \ge \xi_e \ge 0.05$ has been achieved (CESR, LEP, KEKB, PEP-II)
    - many bunches (f_c), small β^*
    - high electron-beam current
- Ring-Linac
  - electron "tune shift" ($\propto$ disruption D) no longer as limiting
    - electron beam intensity limited by linac(ERL) and gun.
- High circulating e^- current *vs* ERL and high-intensity gun.

Ring-Linac (ERL)

- Example: eRHIC: Ion ring parameters given or anticipated (eRHIC DR Dec. 2014, 250 GeV):
  - N_i: 3x10^{11}, ξ_i: 0.004, β^*: 5 cm, f_c: 9.4 MHz (100 bunches in RHIC)
  - => if we have 7x10^9 e^-/bunch, same β^*
    - 0.7 nmrad emittance ($\gamma\varepsilon \approx$ 23 µm-rad @ 15.9 GeV), σ_e = 4 mm
    - ξ_e: 2.8 ($D \approx 14$)
    - 7x10^9 e^-/bunch at 9.4 MHz = 10 mA, 159 MW @ 15.9 GeV. Needs ERL
- $L \approx$ 4x10^{33} /cm^2/s
- Per eq. on slide 1, increasing L implies
  - increase N_i, ξ_i, f_c; lower β^*
- L scales directly with ion energy
- Challenges: ERL at high energy & current & sr energy loss source for 10 mA (cw) of pol. e^-

eRHIC Ring-ERL

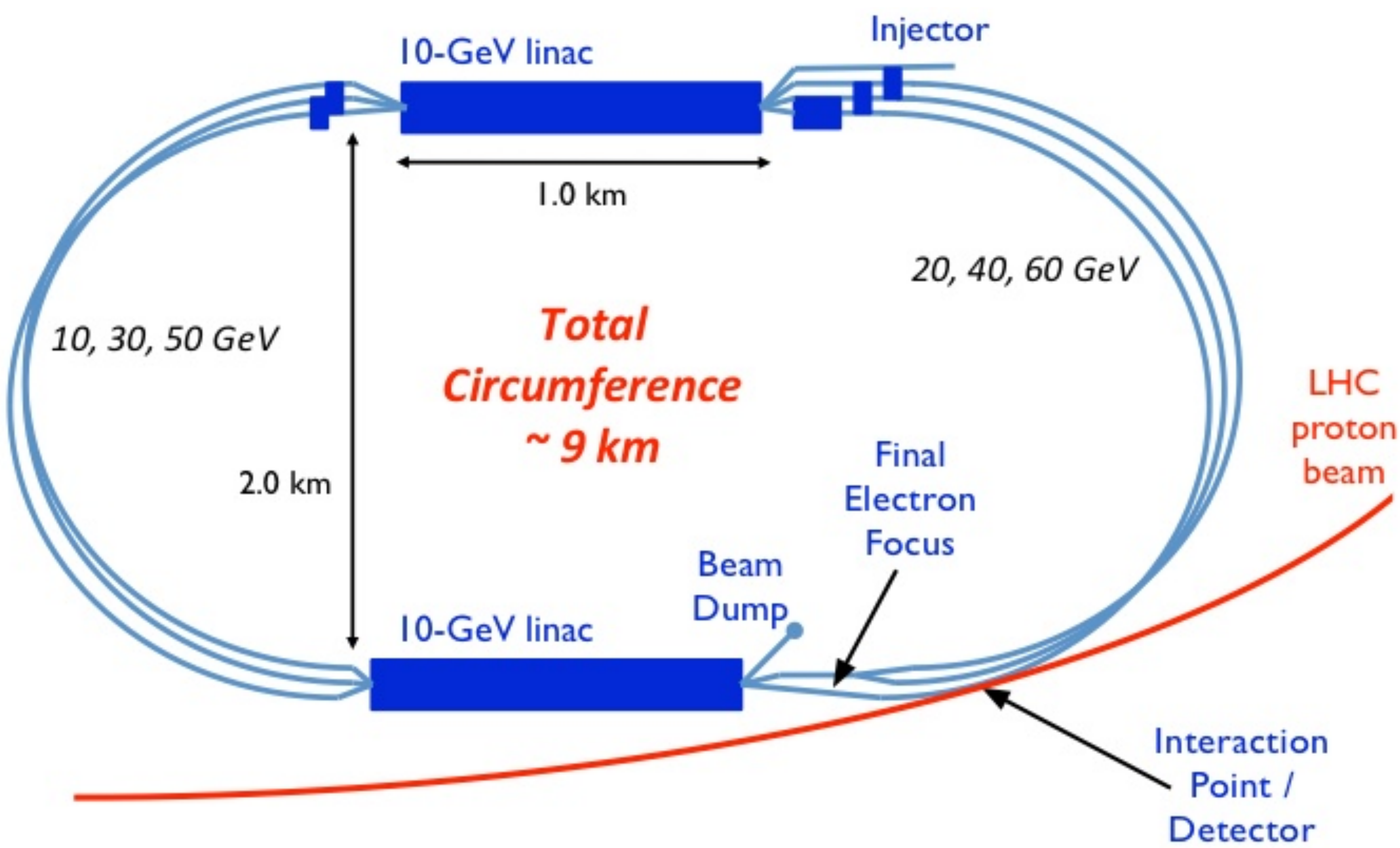
T. Roser



LHeC

- L=10^{34} /cm²/s for e-p, 7 TeV protons
  - ≈ 10^{11} p on 10^{9} e^{-} per bunch, f_c = 40 MHz

P. Newman

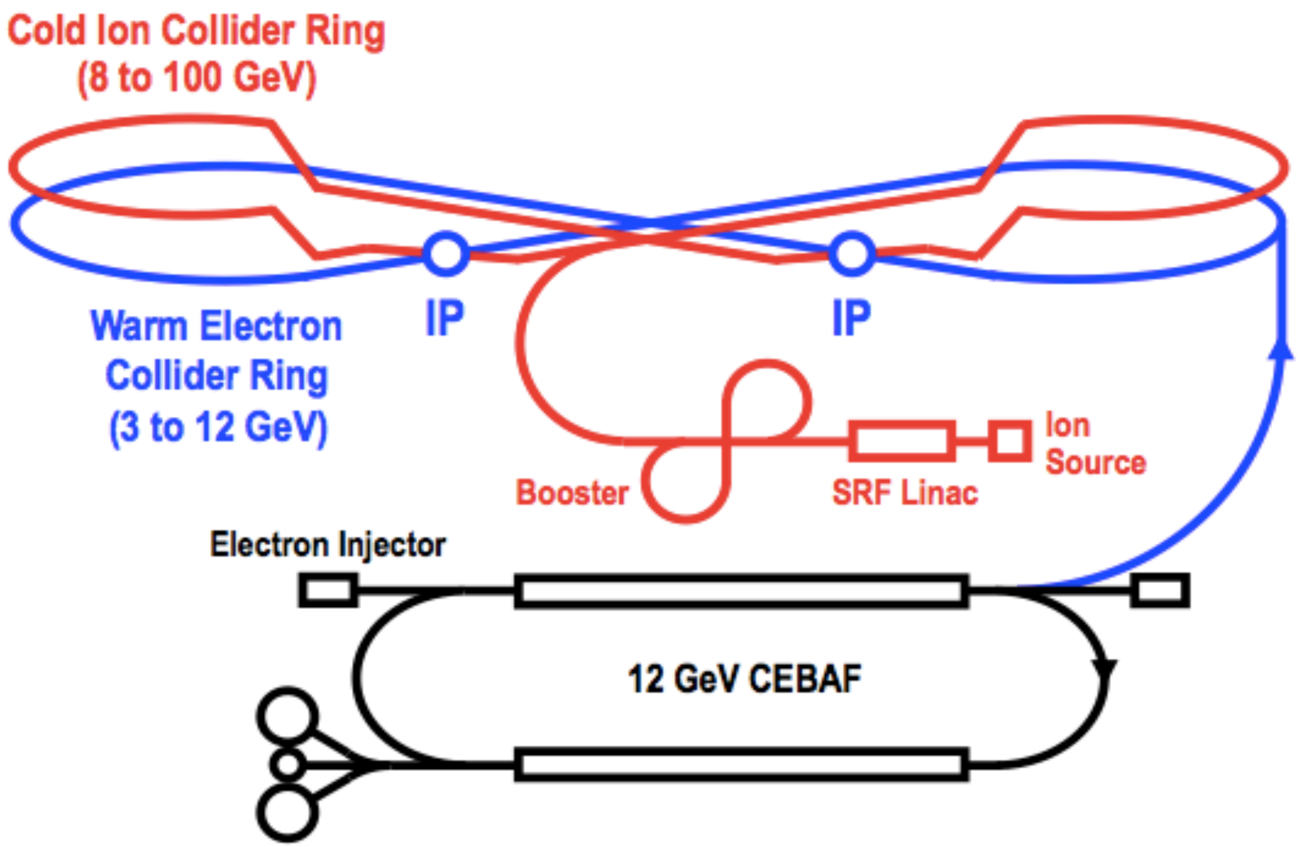


Ring-Ring

- Example: JLEIC
  - N_i: 4.2x10^9, ξ_i: 0.014, β^*: $2_y/10_x$ cm, f_c: 750 MHz
  - N_e: 2.5x10^{10}/bunch; 3 A total
    - 5.7 nmrad emittance ($\gamma\varepsilon \approx 54$ µm-rad)
    - ξ_e: 0.03
    - 5:1 aspect ratio x:y
  - *L = 5.6x10^{33}*
  - So the bunch-charge ratio is inverted c.f. Ring-Linac
    - mitigates the beam-beam effect on the electrons
    - and f_c gains by a factor 75
  - Flat-ish beams
- Challenges: 3 A e^- beam current; 1 cm long ion bunches at 0.5 A ion beam current

JLEIC Layout

F. Pilat



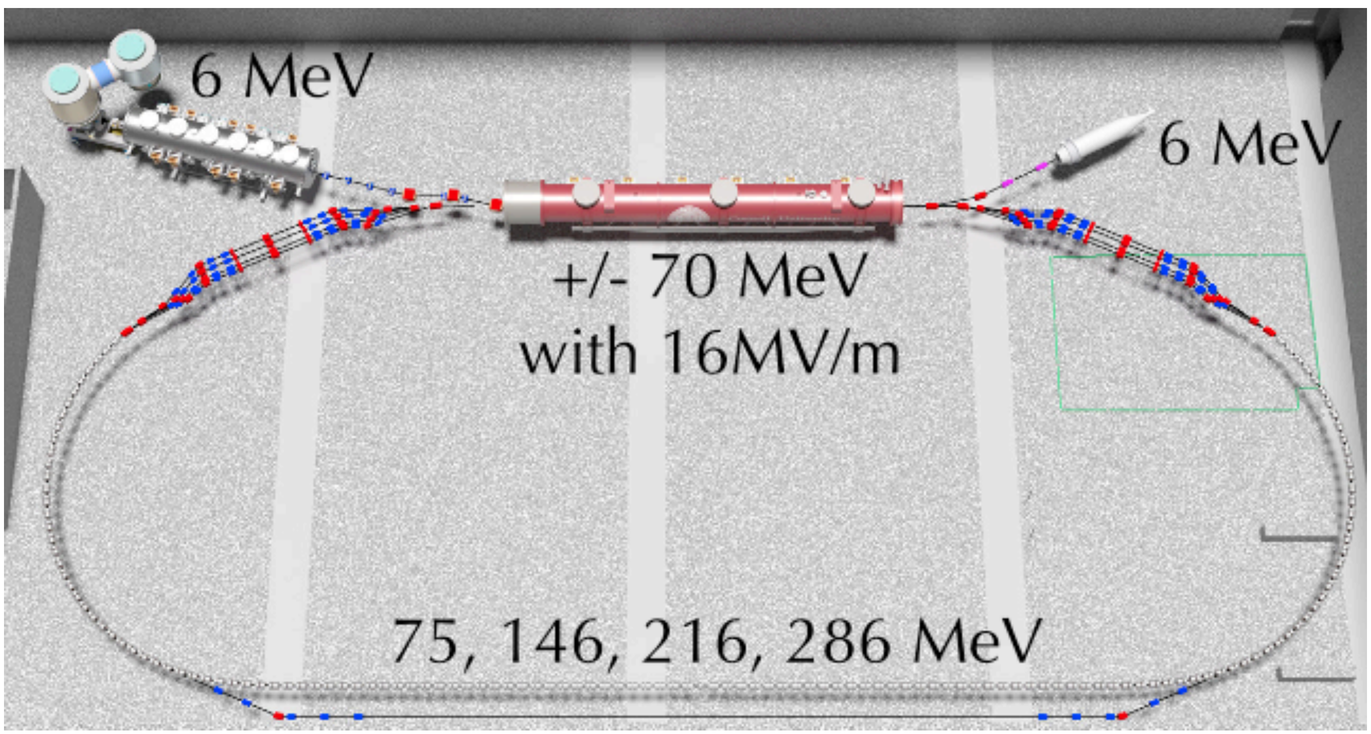
Design Challenges

- FFAG-ERL
  - Unique combination
  - tests planned at Cornell (FFAG-ERL) and maybe CERN (ERL)
- Next-generation cooling schemes
  - Coherent electron Cooling
  - Bunched-beam electron cooling
- Spin manipulation
  - Figure-8 rings
- Varying speed of not-fully-relativistic ions
- Highly asymmetric interaction regions
- High ion-beam intensity with short bunches

Multi-pass test-ERL at Cornell – an eRHIC prototype

- Uses existing 6 MeV low-emittance and high-current injector and 70 MeV CW SRF Linac
- ERL with single four-pass recirculation arc with x4 momentum range
- Permanent magnets used for recirculation arc
- Adiabatic transition from curved to straight sections
- Test of spreader/combiner beam lines
- High current will be used to test HOM damping of eRHIC accelerating cavity

T. Roser



CERN ERL Test Facility (proposed)

- 150 MeV/linac, 3 passes, $2x10^9$ e^-/bunch
  - maximum-scope configuration
  - could have its own physics program.

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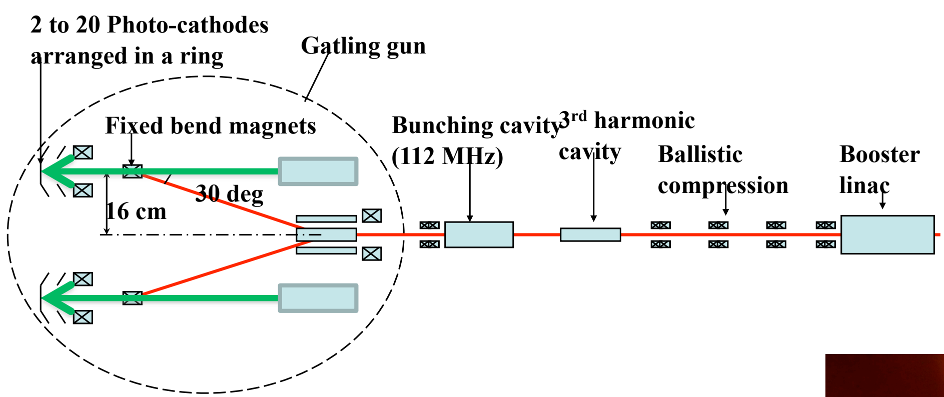
ERL Test Facility:

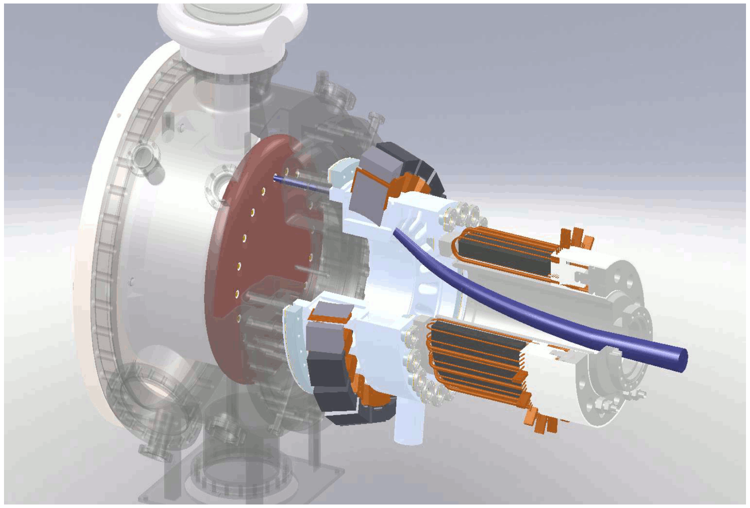
- Test centre for accelerator development, LHeC prototype
- Most ambitious design (2 x 150 MeV linacs, 3 passes → 900 MeV) has significant physics potential of its own (10^{40} cm^{-2} s^{-1} fixed target) … EW parameters, proton radius, photonuclear physics, dark photons …
- Conceptual Design Report by end 2015

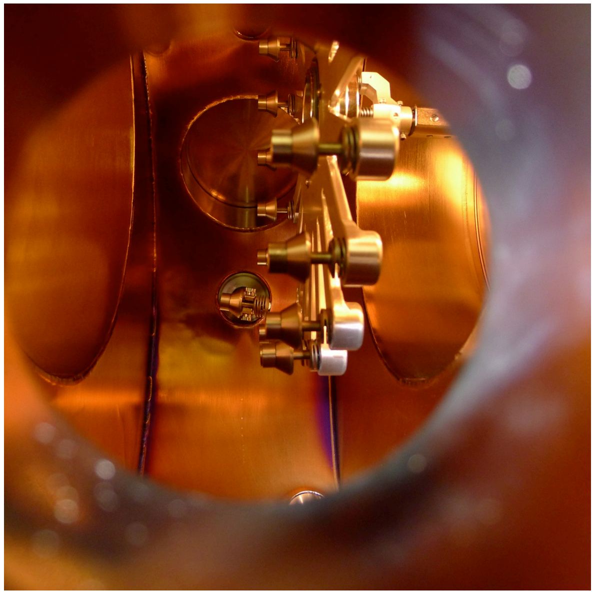
High-Current Gun Development (BNL "Gatling" Gun)

2-cathode test @ Stangenes

I. Ben-Zvi
V. Litvinenko
J. Skaritka







Cooling

- Cooling is essential to reach highest luminosities.
  - Stochastic cooling rate:

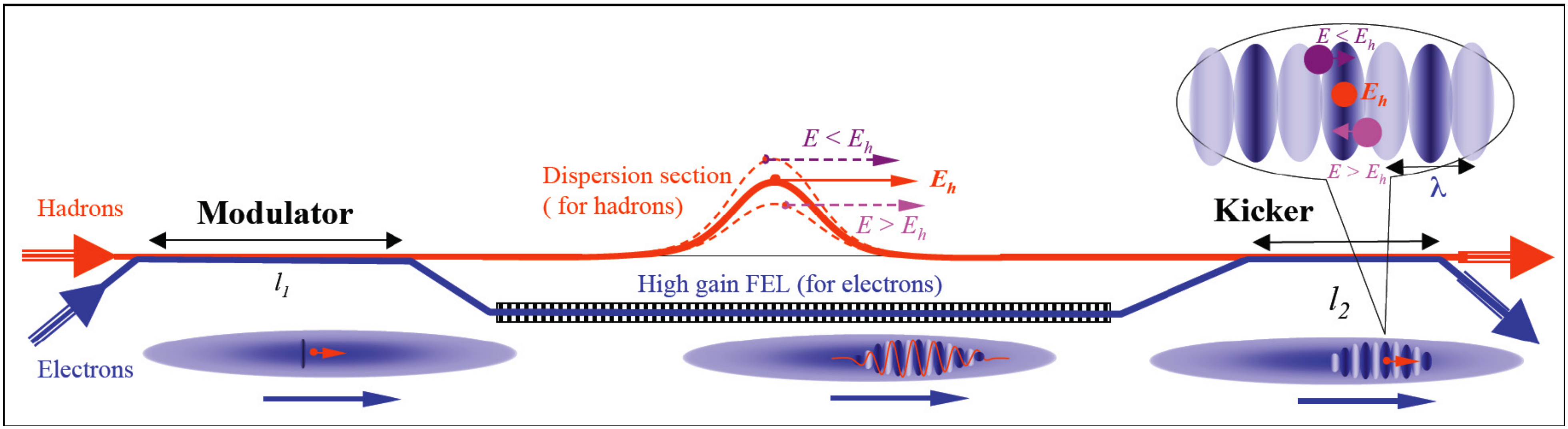
$$\frac{\frac{d\varepsilon}{\varepsilon}}{dt} \propto \frac{W}{N}\left(2g - g^2\left(M+U\right)\right);\ \text{W=bandwidth, g=gain} \propto \frac{1}{E}$$

  - Coherent electron cooling (CeC) to increase W
  - Stochastic bunched-beam cooling to counteract IBS
  - Bunched-beam electron cooling
- Need experimental verification of anticipated performance parameters
  - CeC experiment at RHIC
  - Bunched-beam electron cooling experiment at IMP

Coherent Electron Cooling (Derbenev/Litvinenko)

SLAC

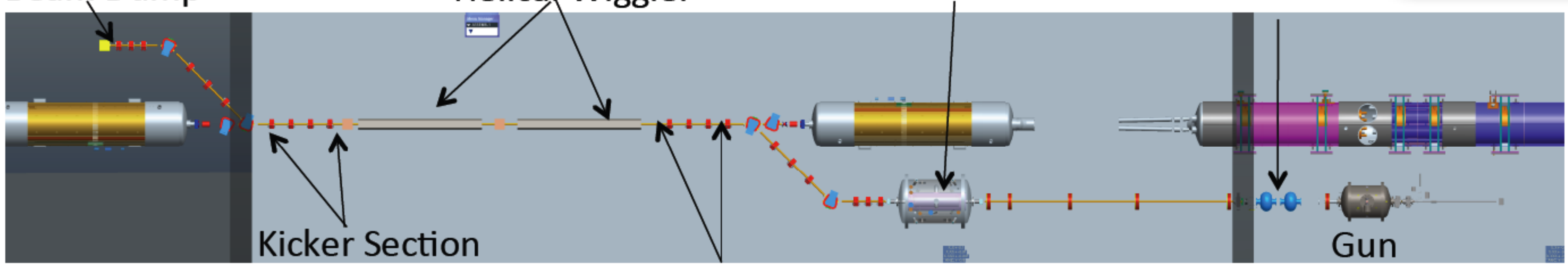
- Stochastic cooling at extreme bandwidth (10^{13} Hz).
- Pickup: Modulate an e^- beam
- Amplifier: Amplify modulation in an FEL
  Provide R_{56} for path length difference with $\delta_{E/E}$
- Kicker: Kick in longitudinal plane to reduce $\delta_{E/E}$
  - transverse cooling by emittance exchange, modified kicker
- ≈ 2 O-magnitude increase in cooling rate *vs* stochastic or e^- cooling



U. Wienands
EICUG, UCBerkeley, 6-Jan-2016

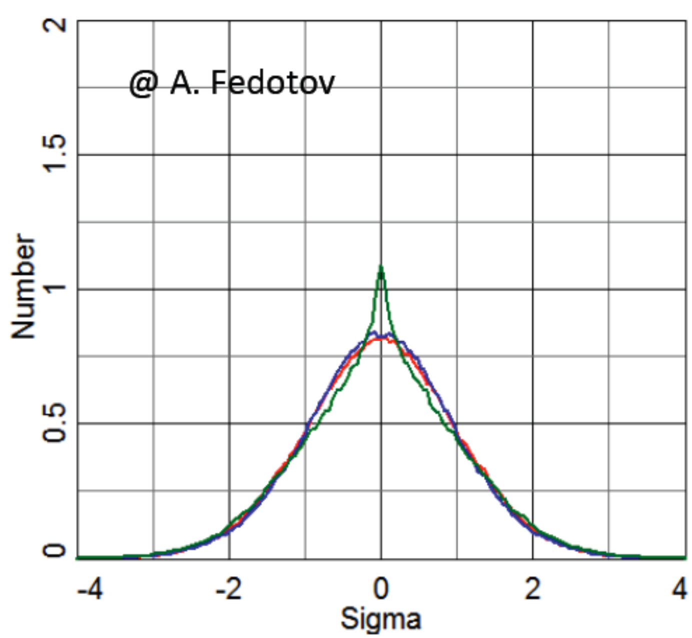
Coherent Electron Cooling Experiment (RHIC)

V. Ptitsyn



V.N. Litvinenko, I. Pinayev, G. Wang………………

- •PoP experiment in RHIC by the collaboration: BNL, Tech-X Co., Budker INP, Jefferson Lab, , Daresbury Lab
- •Commissioning: 2014-2015
- •Aim : to demonstrate longitudinal cooling of 40 GeV/u Au ion beam in RHIC



Expected longitudinal profile modification of Au bunch due to few seconds of the cooling

DC Cooler and Bunched Beam Cooler

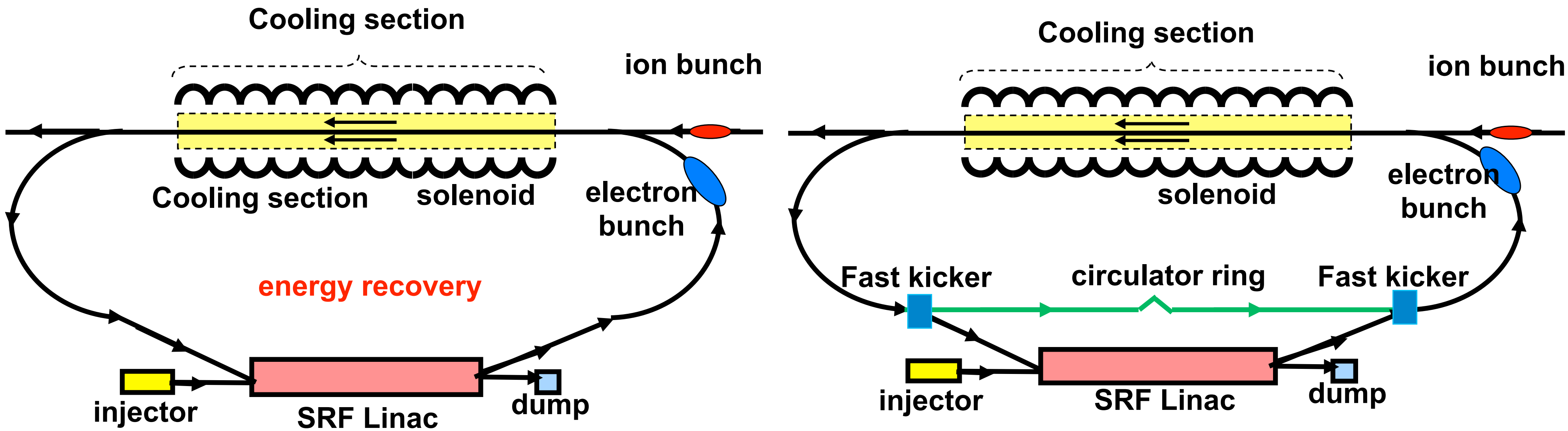
H. Zhang

MEIC needs two electron coolers

- DC cooler (within state-of-art, a 2 MeV cooler is in commissioning at COSY)
- Bunched beam cooler (Needs R&D):
  - ERL single pass cooler (I_e = 0.2 A, MEIC baseline design, no circulator ring)
  - ERL circulator cooler (I_e = 1.5 A, lower emittance, higher luminosity)

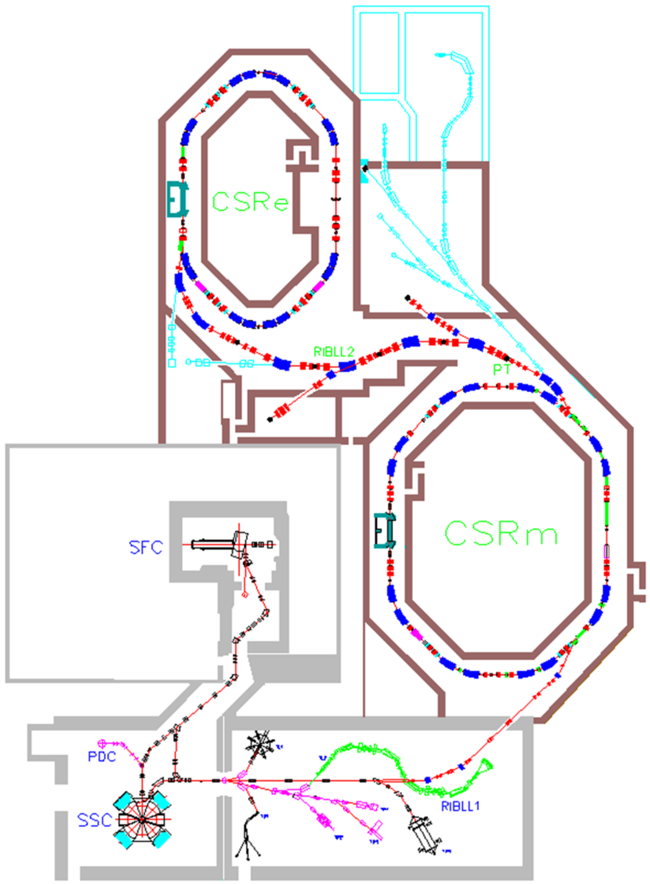
Challenges of the high energy bunched cooler

- Cooling by a bunched electron beam
- Making and transport of high current/intensity magnetized electron beam



Bunched-e⁻ Cooling Expt. at IMP (Lanzhou)

H. Wang



IMP Bunched Beam Electron Cooling Experiment Parameters				
$^{12}C^{6+}$	Kinetic energy	7	30	MeV/u
	particle γ	1.007	1.032	
	particle β	0.121	0.247	
	Geometric emittance x/y	5	5	umrad
	dp/p	4.00E-04	4.00E-04	
e^-	Number of particles	5.E+08	5.E+08	
	Kinetic energy	3.812	16.339	keV
	Radius	2.5	2.5	cm
	Average current	30	70	mA
	Temperature x/y	0.05	0.1	eV

Polarization

- RHIC has polarized protons up to 250 GeV
  - Developing polarized ^3He source (BNL-MIT)
- ERL relies on polarized electrons from gun
  - no resonant depolarization in the few-pass ERL.
  - spin rotators for the experiments??
- JLEIC proposes an innovative Figure-8 scheme
  - overall spin tune ≈ 0
  - only a very small (solenoidal) field required to establish the stable spin direction.
  - need spin rotators to prepare helicity states at the detector(s).
  - works for ions as well, even *d*.
- JLEIC takes advantage of extant polarization capability of CEBAF

RHIC Snakes and Spin Rotators

48 helical dipoles, 2.4 m ea., 1…4 T

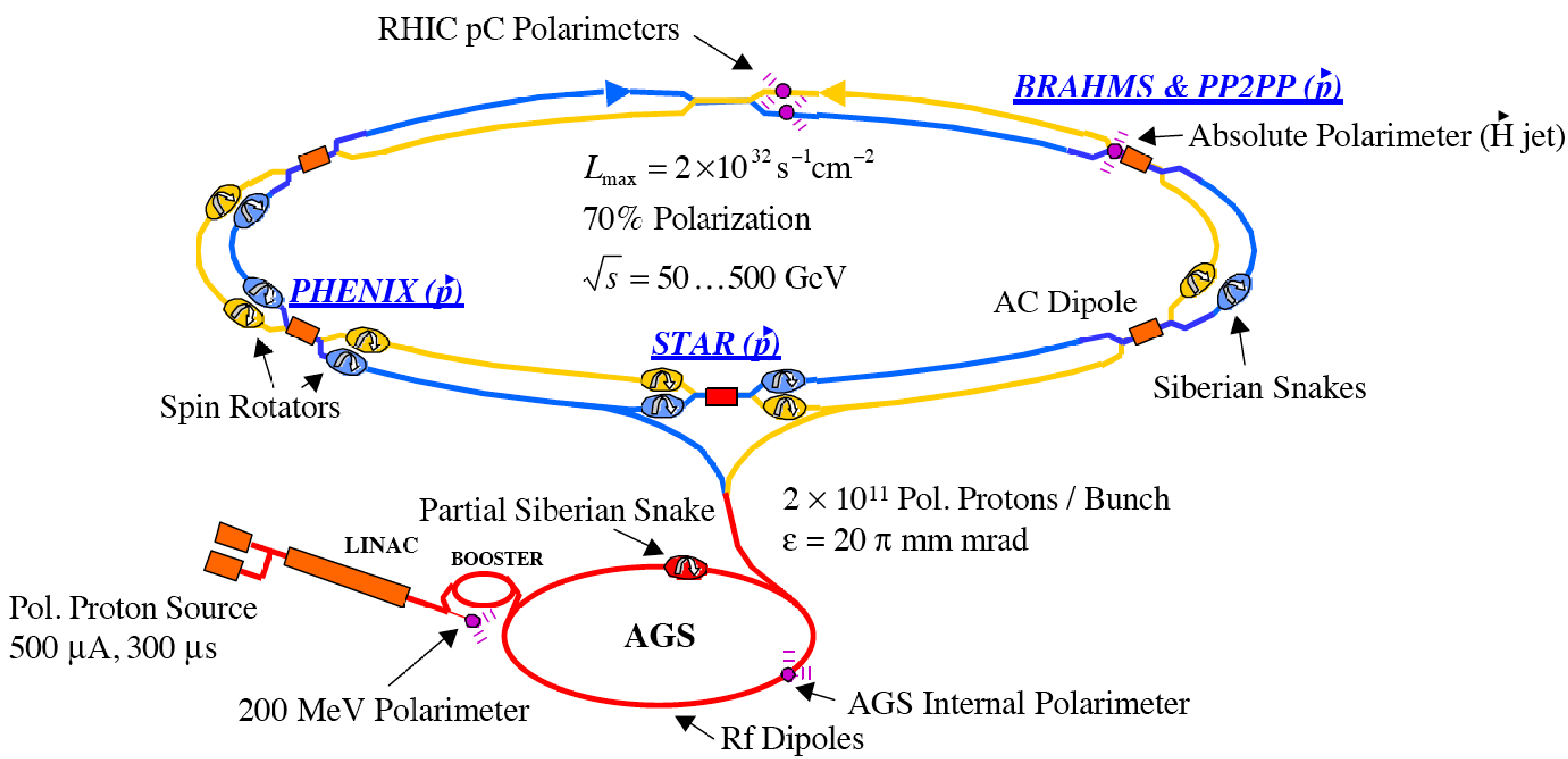


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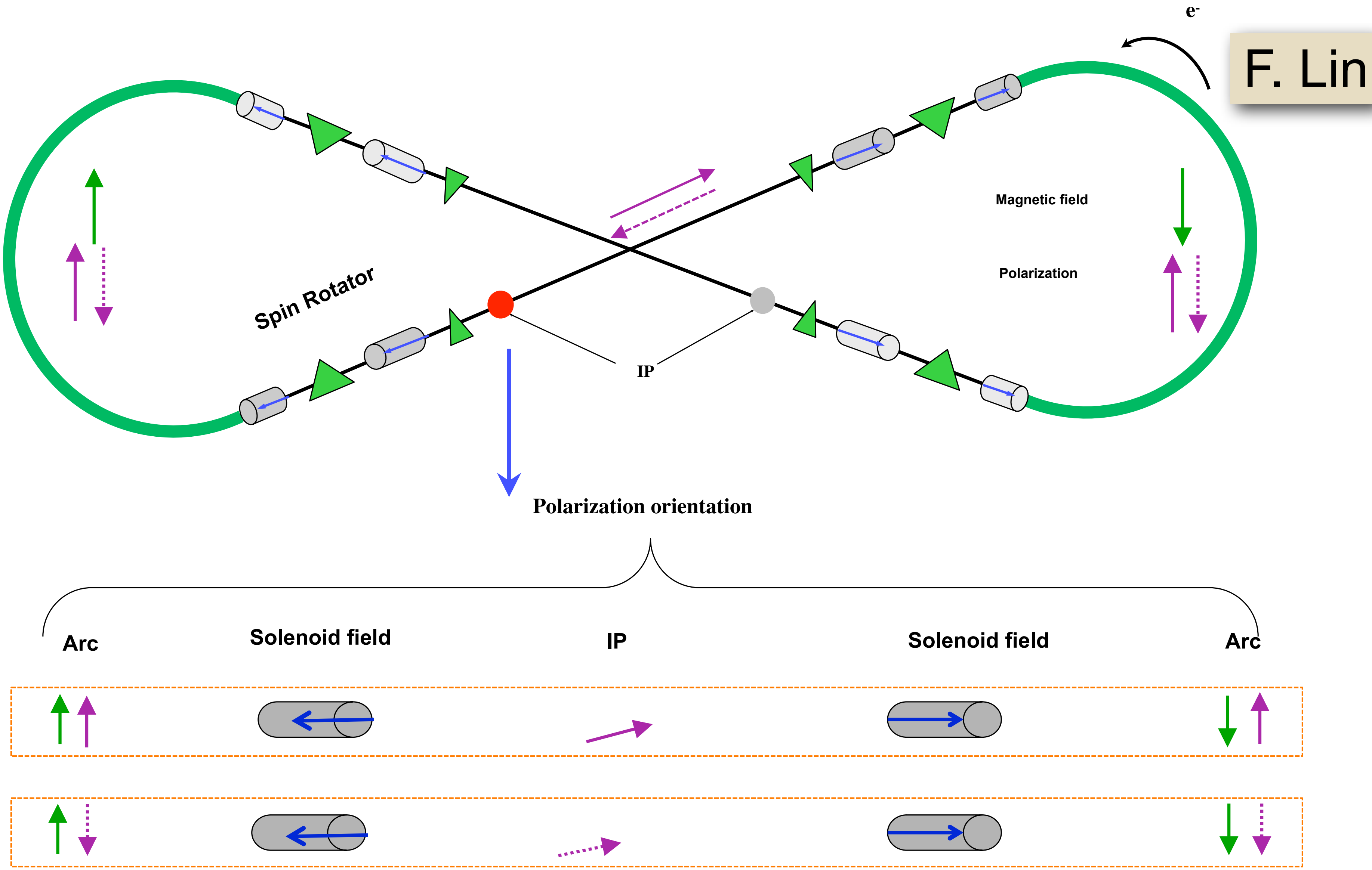
Figure-8 Polarization control

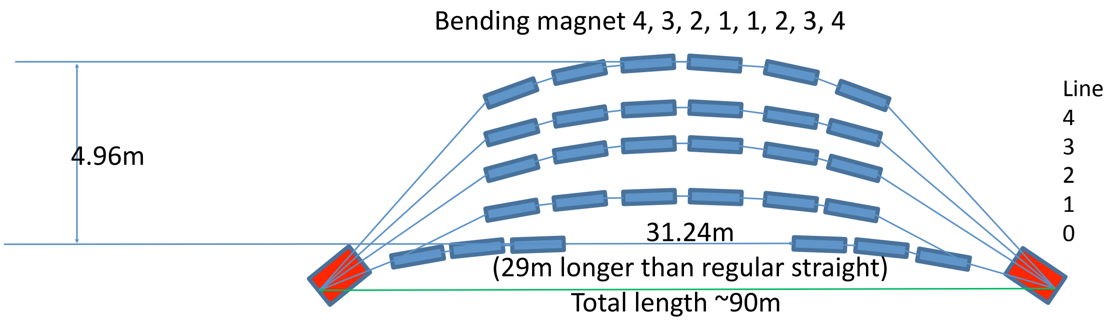


Energy Changes

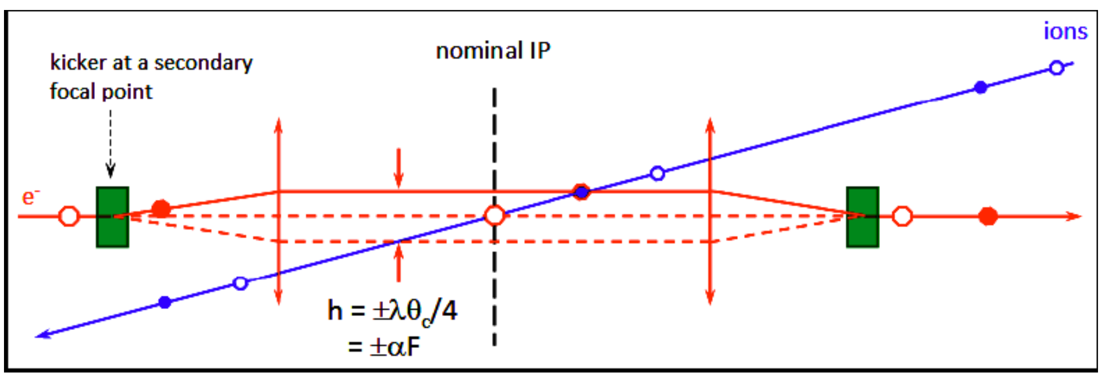
- Ions are not fully relativistic => frequency changes with energy and species of the ion beam
  - ideally, change hadron pathlength by sufficient amount
    - impractical as it requires large-scale moves
  - combine path-length changes with changes in harmonic number
- eRHIC proposes 16 cm pathlength change in the ion ring
  - range of radial steering available
  - rest with harmonic changes in ERL
- JLEIC needs a wider range: ± 33 cm with harmonic change
  - coherent beam-beam instability is a potential issue in ring-ring
    - lowest order can probably be controlled by feedback, but limits ξ ?
  - Gaps in beam -> will precess against each other
    - needs study
  - Moving focus scheme would avoid chicanes…

JLEIC Synchronizations (possible schemes)

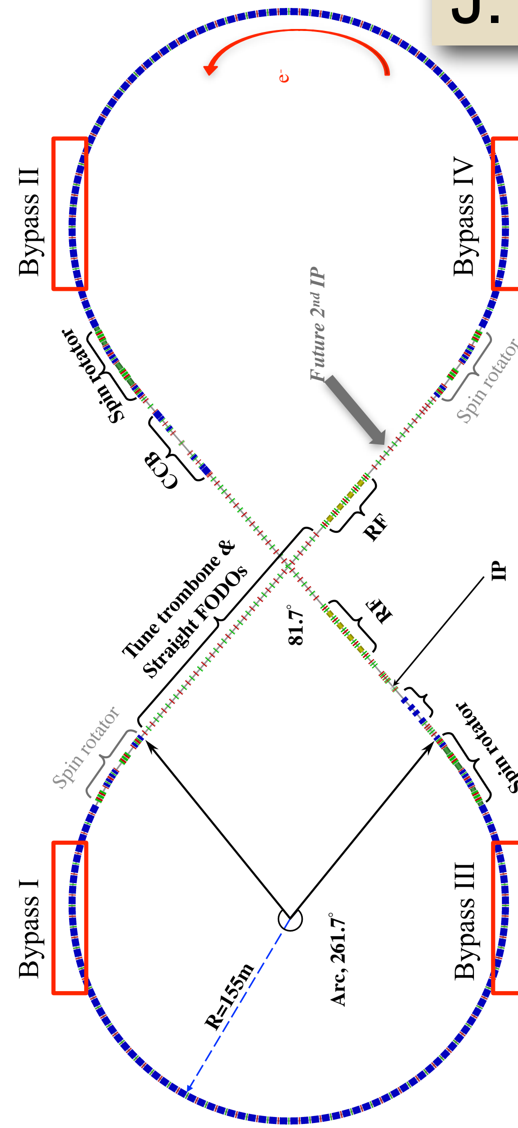
Chicanes



Scanning



J. Guo



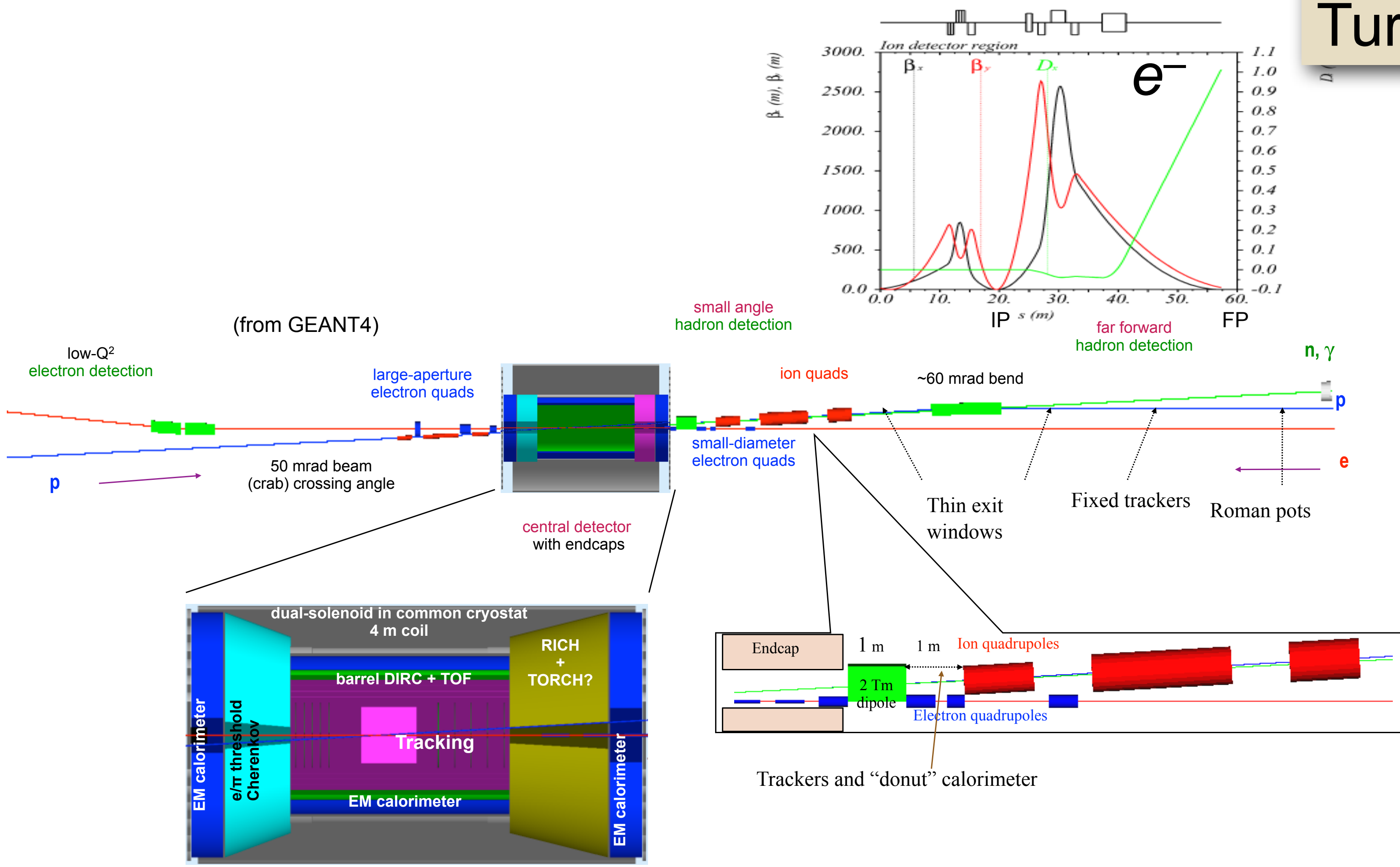
IR design and MDI

- Hard X-rays from e^- are a challenge
  - difficult to mask, keep them away from detector!
  - B-Factories have shown that s.r. can be managed.
- 0-degree requirement for detector a real challenge
  - optics wants to keep L^* as short as possible
    - Is it possible to share innermost quad ("Q_0")??
  - ERL may have a somewhat easier time here
    - lower electron-beam current
    - but beam is round; need to watch radiation in the vertical plane also.

JLEIC IR Layout

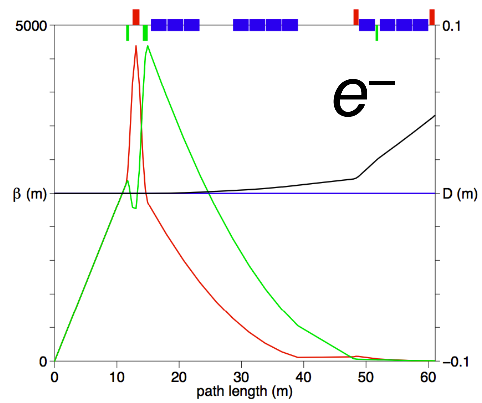
SLAC

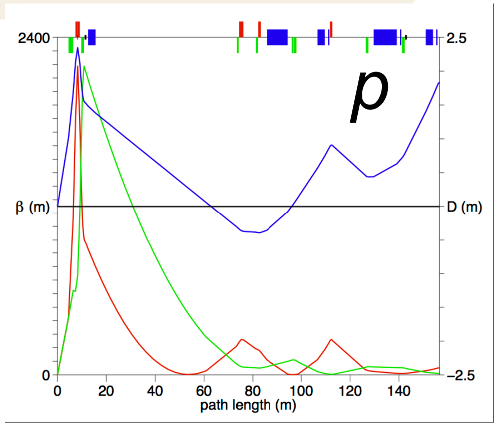
P. Nadel-Turonski



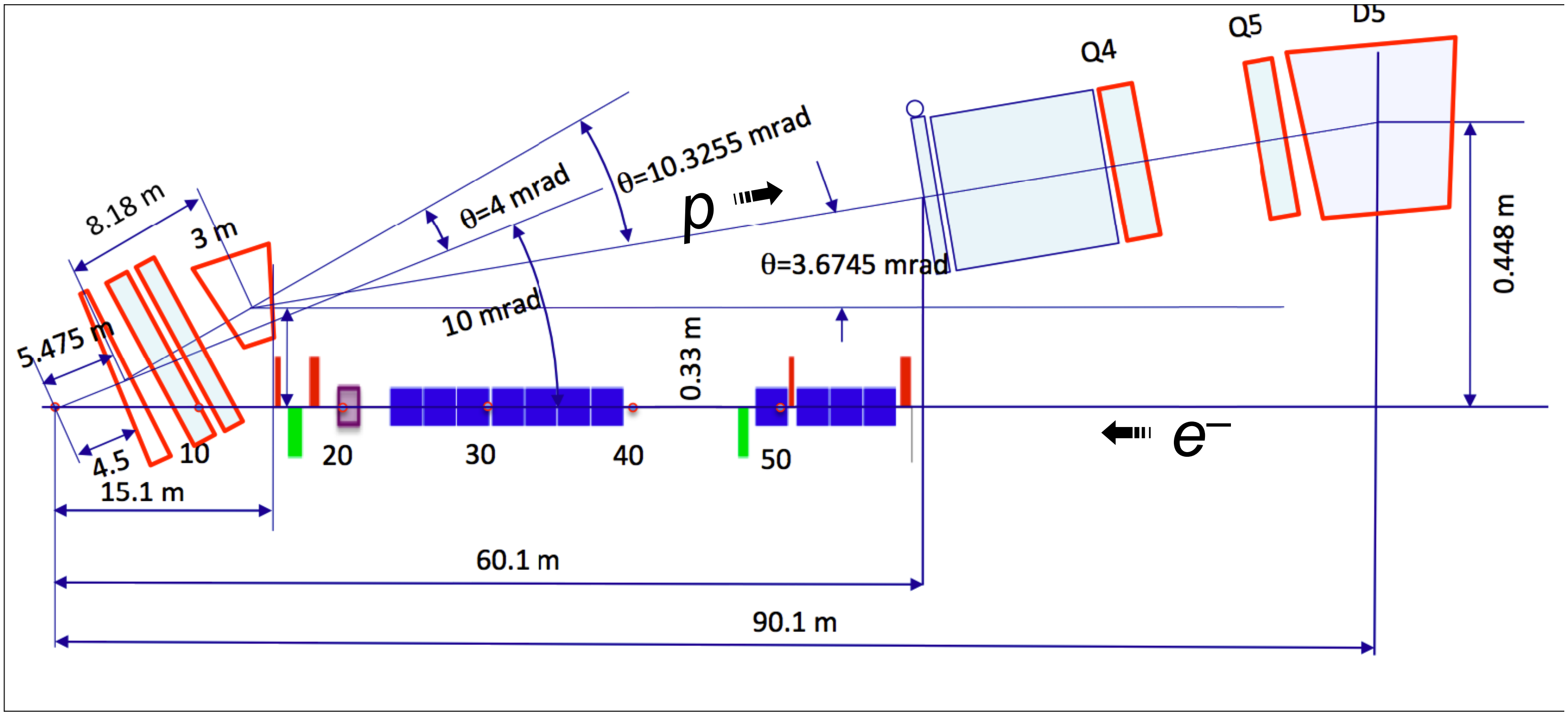
eRHIC IR Layout

SLAC





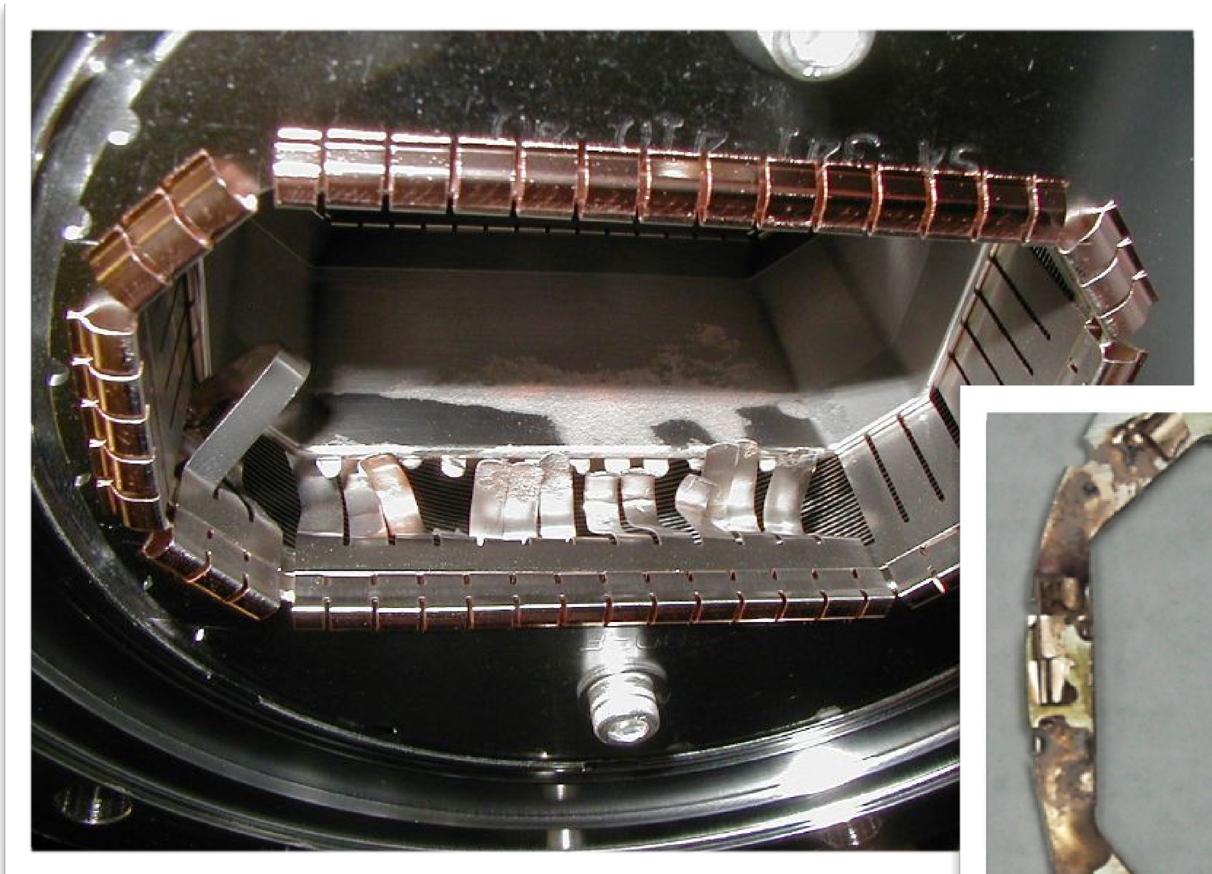
D. Trbojevic



High Beam Current & Short Bunches

- Short bunches => rich in high-frequency content
  - loss factor k tends to go up with $f^{somepower}$
  - in vacuum, even small wattage can be issue
  - any gap has potential for arcing
- IR with irregular cross section & crotches
  - trapped modes possible: impedance, power
- cryogenic heat load can be significant
  - same current as LHC (0.5 A) but shorter bunches (LHC: 8 cm)
    - $\sqrt{8}$ times the heat load for JLEIC??

Effect of High Current (2 A) in Short Bunches (1 cm)



Bellows rf shield

rf seal at Flex Flange

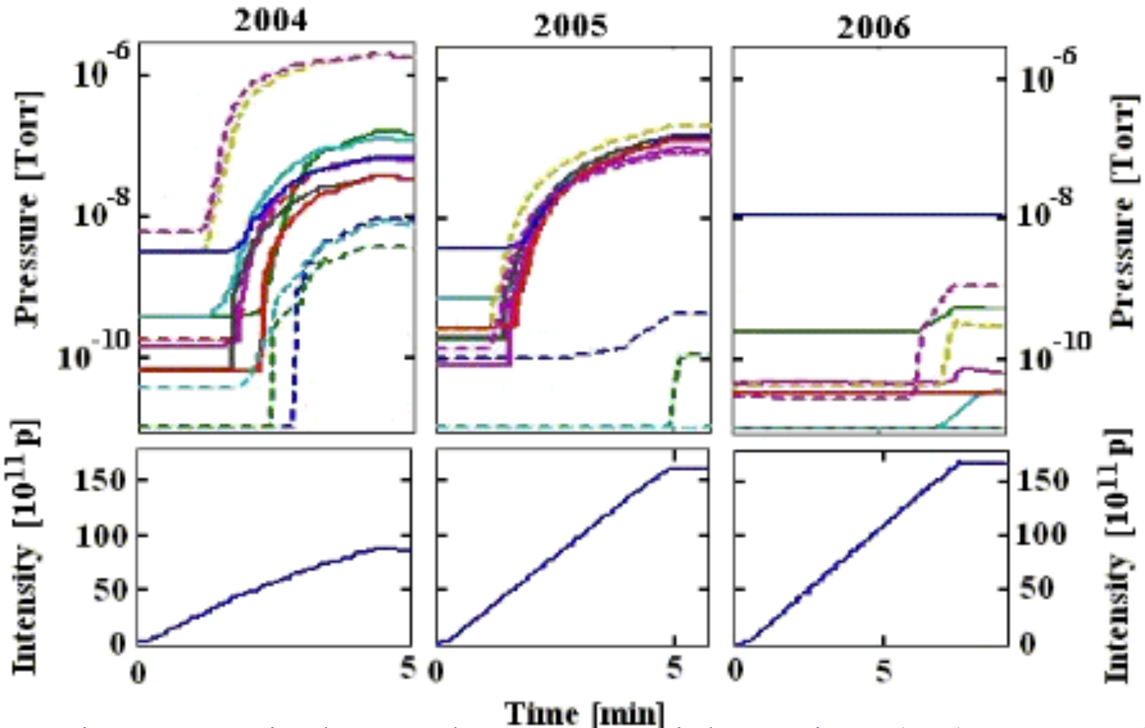
Likely only a few watts of heat

e-Cloud Effect

- Positively charged beams attract electrons that form a cloud about the beam and cause emittance growth
  - PEP-II, KEKB, LHC all had or have to deal with it
  - solenoidal field effective in drift regions, not possible in dipoles
  - controllable by gaps in beam; at expense of total # of bunches
- Mitigations include solenoidal fields (in drift regions) and gaps in the beam (problem if different harmonic ?)
  - low-emission vacuum chamber important (TiN or NEG coat)
  - antechambers help in e^+ rings, not clear in ion rings.
  - scrubbing will reduce effect, at expense of time.
- Dependent on bunch spacing, length and patterns.
  - dedicated diagnostics may be worthwhile investment.

e-Cloud in RHIC

H. Huang

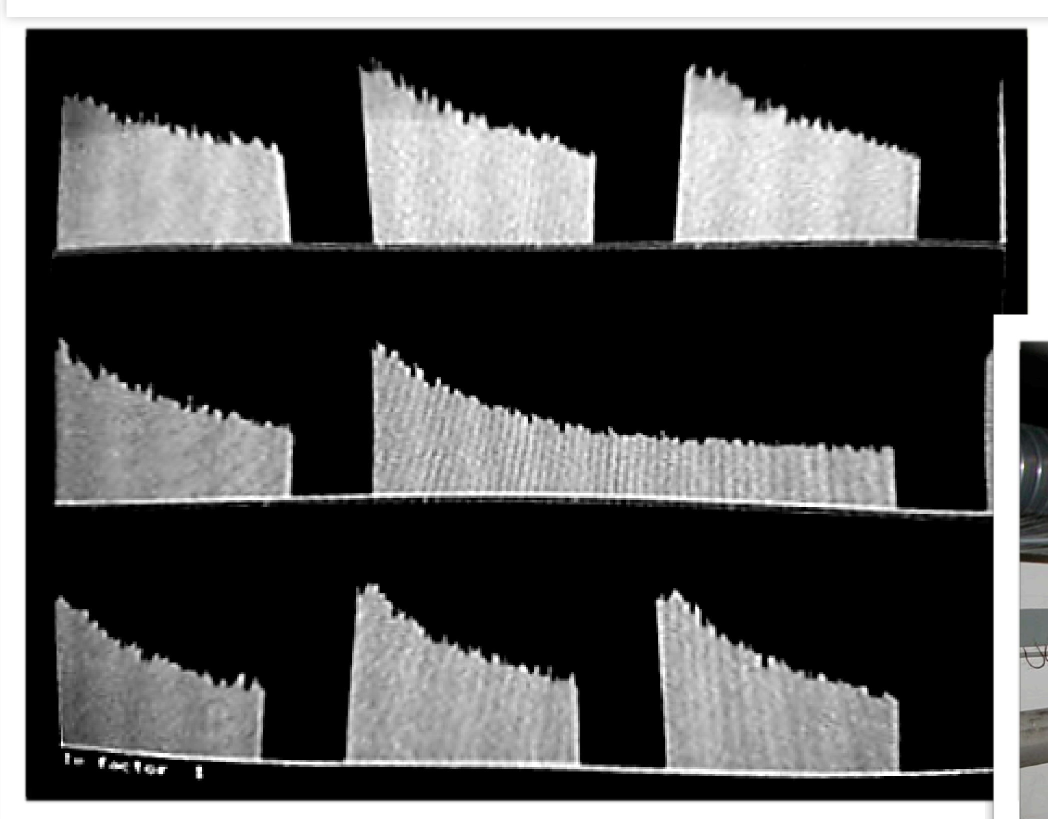


Dynamic pressure in the 12 Blue warm straight sections (top), measured by a single gauge in each, while proton beam with 108 ns bunch spacing is filled (bottom). With completely NEG coated pipes, the pressure in 3 sections in 2005, and 5 sections in 2006, remained at 10^{-11} Torr.

Cure: baking to 200C, NEG(non-evaporable getter) coating(very effective), scrubbing(take long time, but effective)

e-Cloud in PEP-II LER

Luminosity droop along bunch trains before solenoids (8.4 ns bunch spacing)



anti-e-cloud solenoids

Beam Life Time

- ion beam typically has hours of lifetime (small beam-beam)
- in Linac-Ring, lifetime concept not applicable to electron beam
- in Ring-Ring, electron beam lifetime tends to be short
  - continuous injection built-in feature
    - B-Factories proved practicality and operational benefits
    - need sufficient aperture and small enough injecting emittance to control background
    - expensive if injector chain is new (throughput, programmability)
  - side-benefits:
    - balance bunch lifetimes (to a degree)
    - compensate for residual depolarization in ring as well.

Summary

- Electron-Ion Colliders are not “trivial” machines
- Some qualitatively new challenges and approaches
  - Ion Cooling at high energy
  - Figure-8 scheme for polarization control
  - Path-length change due to variable energy of ions
- …and a number of quantitatively new ones
  - Highly asymmetric beam-beam interaction (HERA, *B*-Fac)
  - e-Cloud effect in the ion beam (*B*-Fac, RHIC, LHC)
  - s.r. management of the e^{-} beam (*B*-Fac, LEP)
  - Complex IR design incl. s.r. management (HERA, *B*-Fac)
  - Polarization (of both beams) (HERA, RHIC, LEP)

Summary cont'd

- Some challenges specific to the fundamental design choice
  - Ring-Ring
    - very high s.r. power and electron-beam current
    - very low β^* and very short bunches of both beams
    - harmonic difference (or not?) due to path length change
  - Linac-Ring
    - High-current (10 mA or more) ERL at high energy and high s.r. loss
    - High average current polarized e^- gun.
- Significant overlap in R&D
  - Cooling
  - Collective effects, esp. e-Cloud
  - Polarization and spin rotators
- Innovative work is being pursued
  - A number of collaborations established to tackle the issues