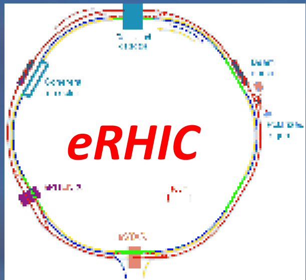


ERL Based Lepton-Hadron Colliders: eRHIC and LHeC

Frank Zimmermann

Linac 2012 Conference, Tel Aviv

13 September 2012

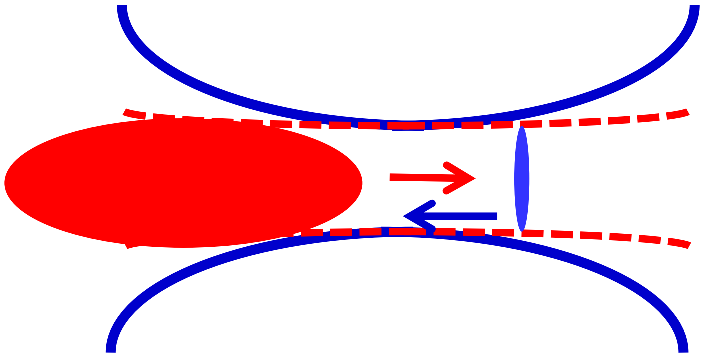
Many thanks to:

Jose Abelleira, Mei Bai, Sergey Belomestnkyh, Ilan Ben-Zvi, Alex Bogacz, Oliver Brüning, Rama Calaga, Ed Ciapala, Friedrich Haug, Erk Jensen, John Jowett, Max Klein, Vladimir Litvinenko, Vadim Ptitsyn, Louis Rinolfi, Stephan Russenschuck, Daniel Schulte, Mike Sullivan, Rogelio Tomas, Davide Tomassini, Joachim Tückmantel, …

colliding lepton & hadron beams

ring-ring

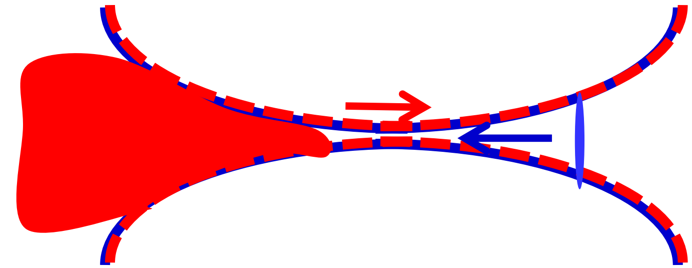
$\varepsilon_e >> \varepsilon_h$



minimum beta function and beam size limited by hourglass effect (large ε_e & large $\sigma_{z,h}$!) ;
small crossing angle acceptable;
little disruption

linac-ring

$\varepsilon_e \approx \varepsilon_h$



smaller beta function and beam size possible;
head-on collision required;
significant disruption

geometric overlap factor $H_{hg} = \frac{\sqrt{\pi} z e^{z^2} \mathrm{erfc}(z)}{S}$; $z \equiv 2 \frac{(\beta_e^*/\sigma_{z;h})(\varepsilon_e/\varepsilon_h)}{\sqrt{1+(\varepsilon_e/\varepsilon_h)^2}} S$; $S \equiv \sqrt{1 + \frac{\sigma_{z,h}^2 \theta_c^2}{8\sigma^{*2}}}$

luminosity of linac-ring collider

with round matched beams

$$L = \frac{1}{4\pi e} \frac{N_{h,p}}{\varepsilon_h} \frac{1}{\beta_h^*} I_e H_{hg} H_D$$

hadron beam brightness

hadron IP β function
- small *l**
- only one *hadron* beam
- new magnet technology Nb_3Sn

average e^- current boosted by energy recovery!

geometric overlap factor
- head-on collision
- small e^- emittance

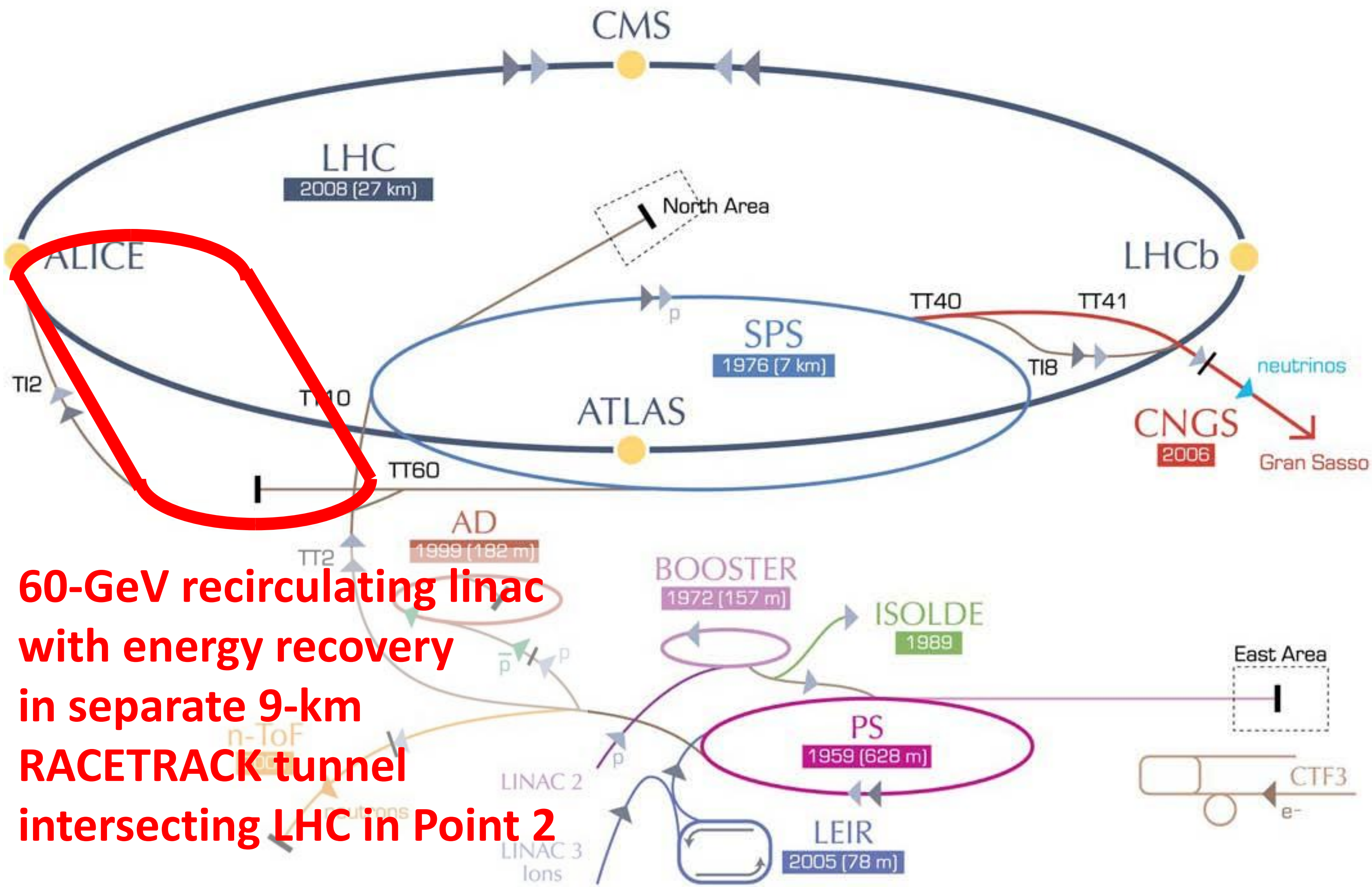
pinch enhancement (1.3 for e^-, 0.3 e^+)

→ ERL-ring collider

two proposals for ERL-ring lepton-hadron colliders:

- **LHeC based on the LHC at CERN**
  - 7 TeV *p* or few TeV/nucleon heavy-ion beams
  - **adding a 60-GeV ERL with 6.4 mA current**
- **eRHIC based on RHIC at BNL**
  - 250 (325) GeV polarized p's (& light ions) and 100 (130)-GeV unpolarized heavy ions
  - **adding a 5-30 GeV ERL with 50-220 mA current**

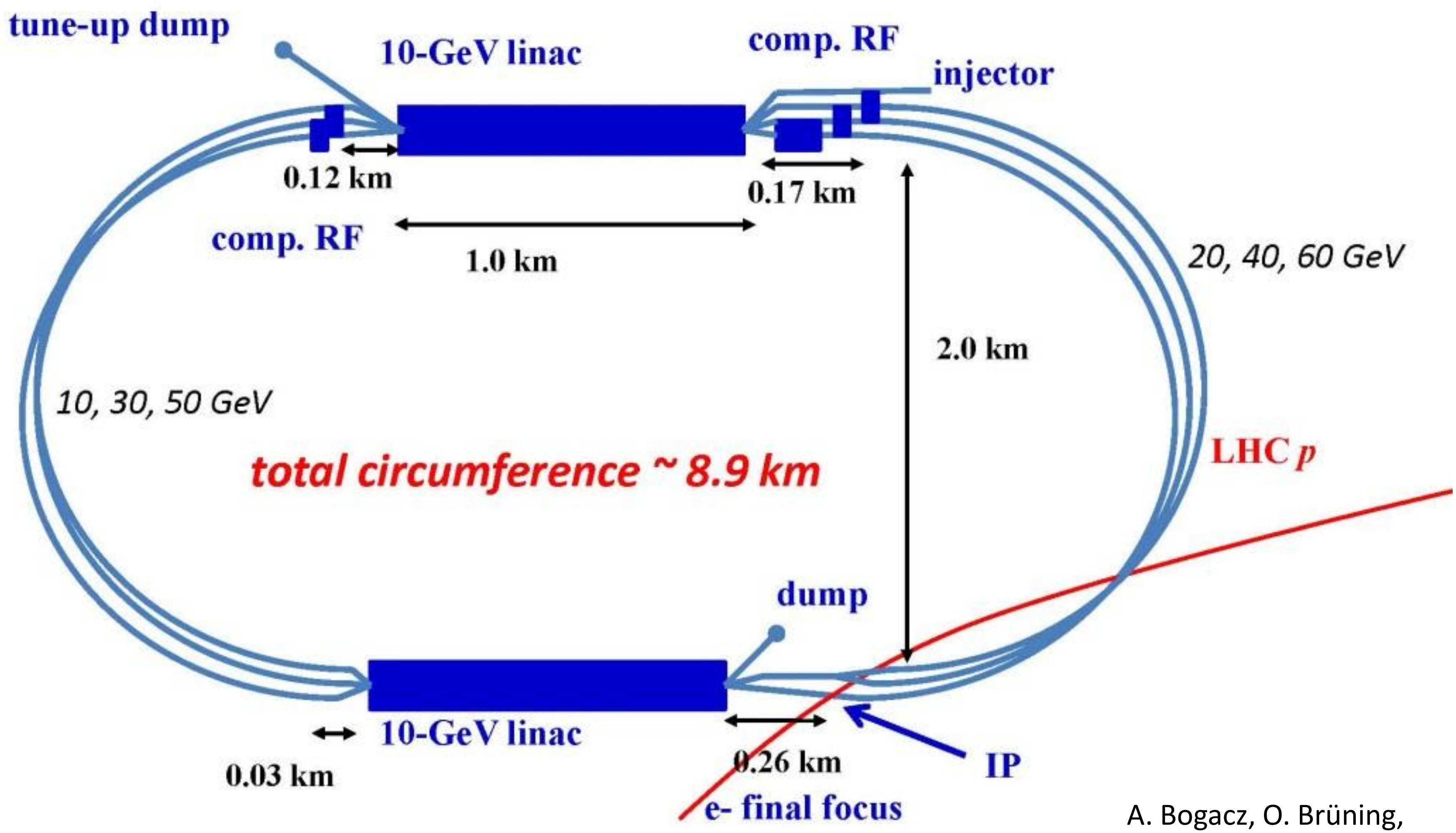
ERL-Ring LHeC



60-GeV recirculating linac with energy recovery in separate 9-km RACETRACK tunnel intersecting LHC in Point 2

LHeC ERL layout

two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e^-'s collide w. LHC protons/ions

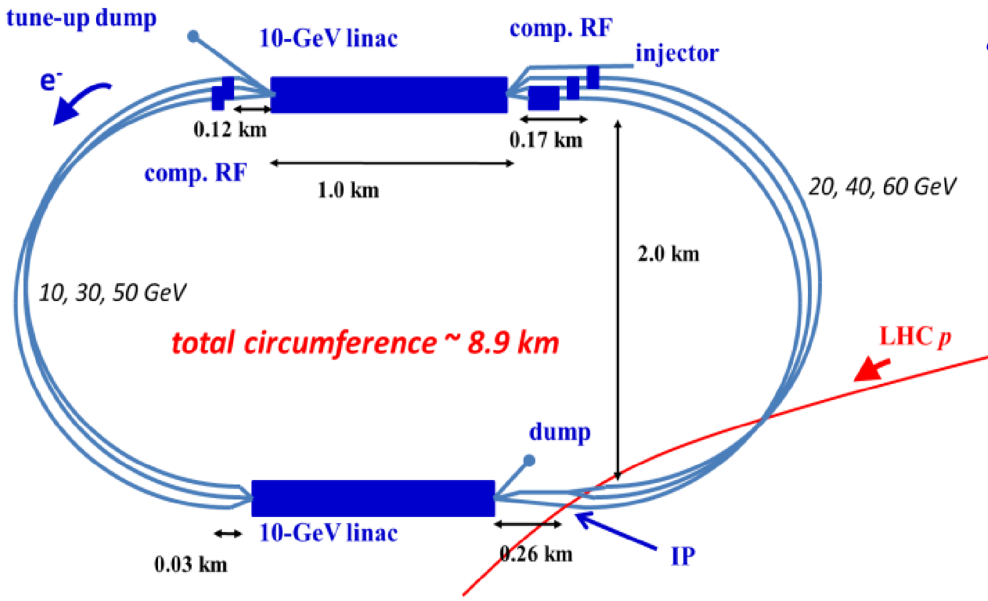


(C=1/3 LHC allows for ion clearing gaps)

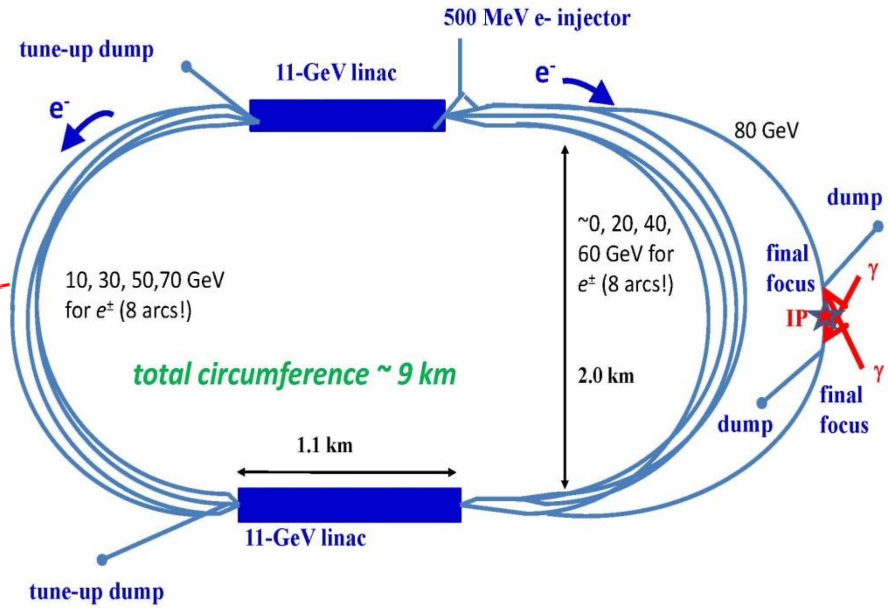
A. Bogacz, O. Brüning,
M. Klein, D. Schulte,
F. Zimmermann, et al

R&D for **LHeC SC linac in synergy with many future projects**: ILC, ν factory, *p*-driven plasma acceleration, and Higgs factory γγ collider

LHeC-ERL

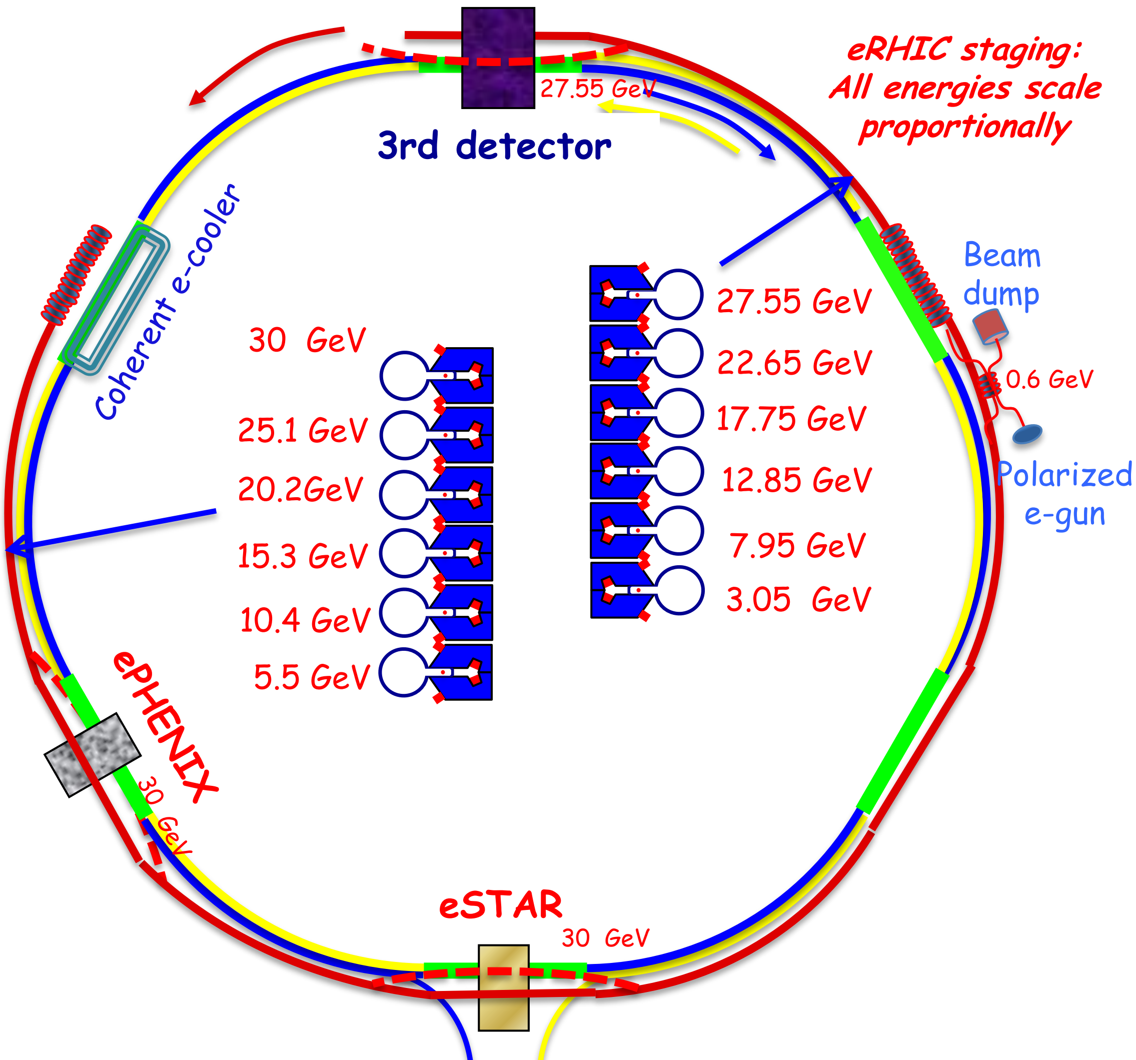


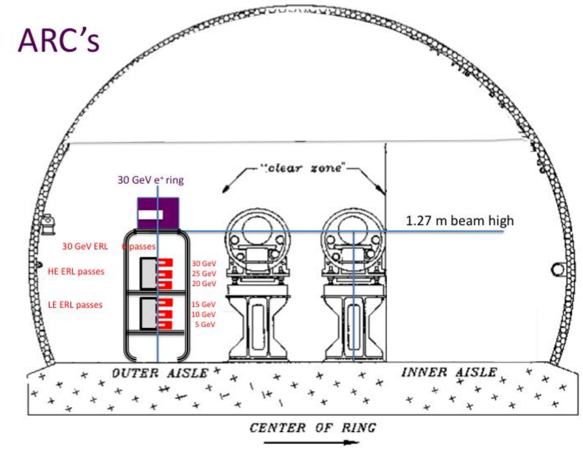
*SAPPHiRE** *γγ Higgs factory*



*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

ERL-Ring eRHIC





two 2.45-GeV SC linacs, 6-pass up, 6-pass down; 50(220)-mA 5-30 GeV (un)polarized e^{-}'s collide with RHIC polarized protons (250-325 GeV) or heavy ions (100-130 GeV / nucleon)

particle & nuclear physics program

LHeC	**eRHIC**
precision QCD	origin of the proton spin
electroweak physics	quantum phase space tomography of the nucleon
high parton densities	strong color fields
new physics at high energies	…

collider parameters

collider parameters	eRHIC (ult.)		LHeC (ult).	
species	*e*$^-$	*p*, $^{197}Au^{97+}$	***e***$^{\pm}$	*p*, $^{208}Pb^{82+}$
b. energy(/nucleon) [GeV]	15 (30)	325, 130	**60**	**7000, 2760**
bunch spacing [ns]	18	18	25, 100	25, 100
bunch intensity(nucl.)[10^9]	24	400, 600	1, 4	170, 25
beam current [A]	0.22 (.01)	3.3, 2.0	0.006	0.58, 0.006
rms bunch length [mm]	2	49	0.6	75.5
polarization [%]	**80**	**70**, 0	**90**(e^+ 0)	0, 0
norm. rms emittance [μm[	5.8-57	0.2,0.2 **CEC**	50	3.75, 1.5
$\beta_{x,y}$*[m]	0.05	0.05	0.12	0.1
$\sigma_{x,y}$* [μm]	**6**	**6, 8**	**7**	**7**
beam-beam parameter ξ_h		**0.015**		0.0001
lepton disruption *D*	**52, 22**		**6**	
CM energy [TeV]	140 (197)	88 (125)	1300	810
lum./nucl.[$10^{34}cm^{-2}s^{-1}$]	**14** (4), 8.2 (2.1)		**0.1**, 0.02	

eRHIC - special features

p polarization

55% now → 70%

high e^- current

50 mA polarized, 220 mA unpolarized

small hadron beam emittances ~1/10 LHC

achieved with novel Coherent Electron Cooling,

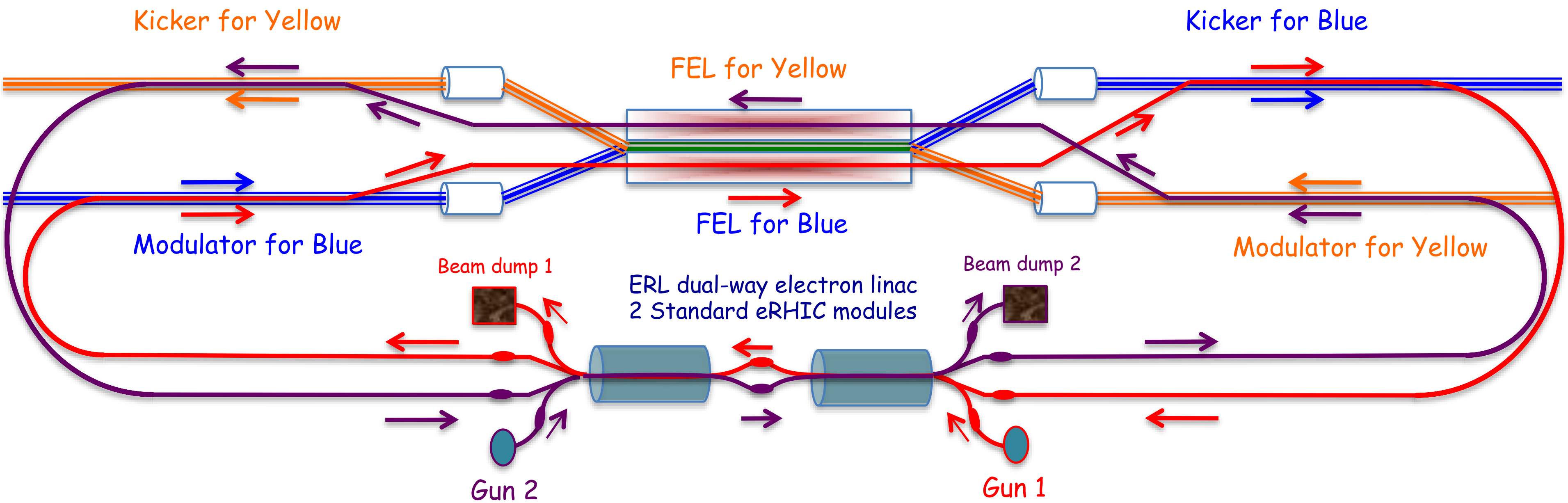
space-charge compensation with other e^- beam

staged installation

steps in beam energy every few years

Coherent Electron Cooling - CEC

V.N. Litvinenko, , Y.S. Derbenev,
PRL 102, 114801 (2009)



possible layout of CEC system for both RHIC hadron beams

Vladimir Litvinenko

SC linacs

(recirculating) SC linac parameters	eRHIC	LHeC
#linacs	**2**	**2**
length/linac [km]	0.2	1.0
energy gain / linac [GeV]	**2.45**	**10.0**
#acceleration passes	**6**	**3**
maximum final energy [GeV]	30	60
real estate gradient [MV/m]	12.45	10.0
energy gain / cavity [MeV]	**20.4**	**20.8**
cells / cavity ; cavities / linac	5 ; 120	5 ; 480
RF frequency [MHz]	**703.8**	**721**
cavity length [m]	1.065	1.04
R/Q [linac Ω]	506	570
Q_0 [10^{10}]	**4.0**	**2.5**
power loss / cavity [W]	23.7	32
electrical cryopower per linac [MW]	**2**	**10**

linac features

LHeC linac 5x longer with 4x the energy gain

(cavity filling factor 0.50 vs 0.64)

eRHIC linac: no focusing

LHeC linac: ~100 quadrupoles

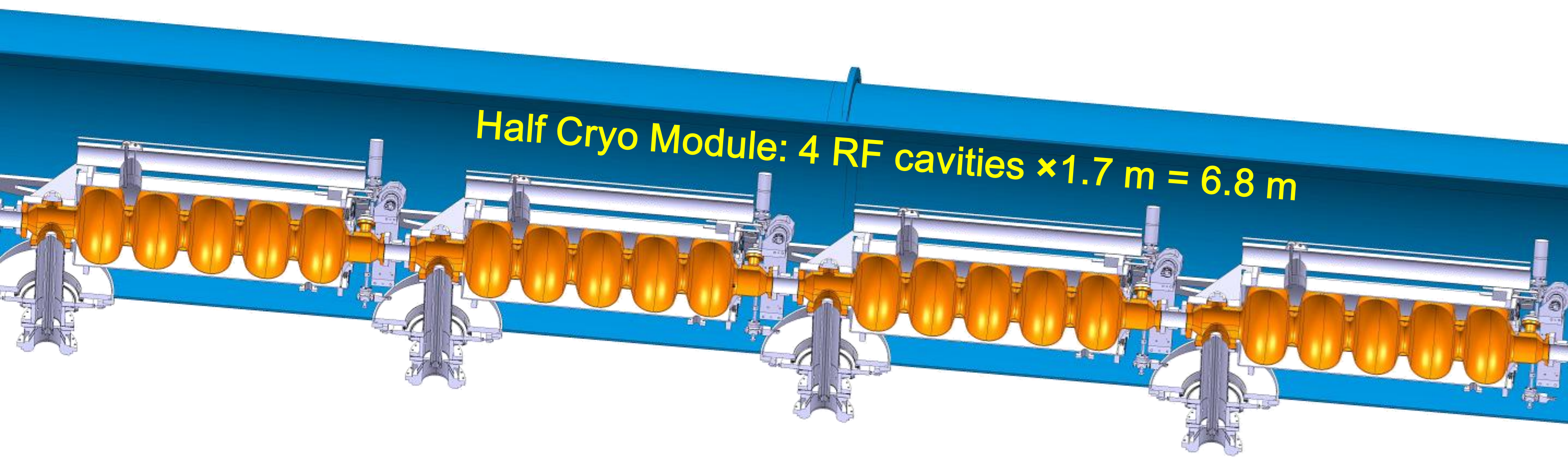
increase multi-pass BBU threshold

LHeC linac quadrupole options:

- electromagnets with indiv. powering
- clustered electromagnets
- permanent magnets

Q_0: a key parameter !

LHeC half cryo module - layout/specs



721.4 MHz RF, 5-cell cavity**:**

λ = 41.557 cm

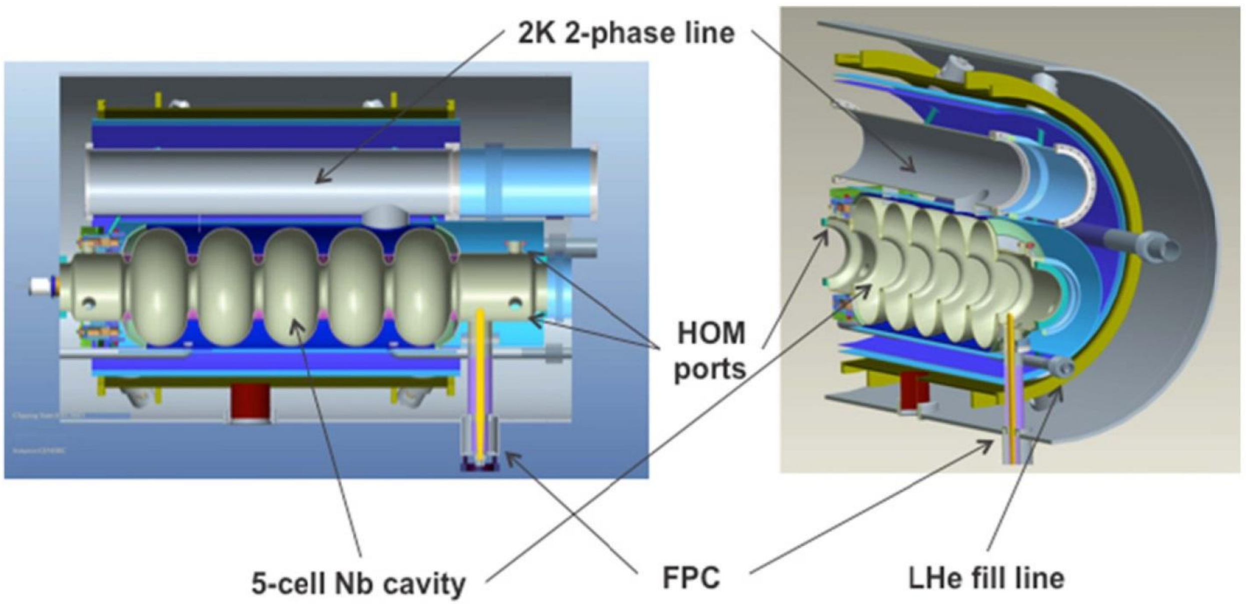
$L_c = 5\lambda/2 = 103.89$ cm

Grad = 20 MeV/m (20.8 MeV per cavity)

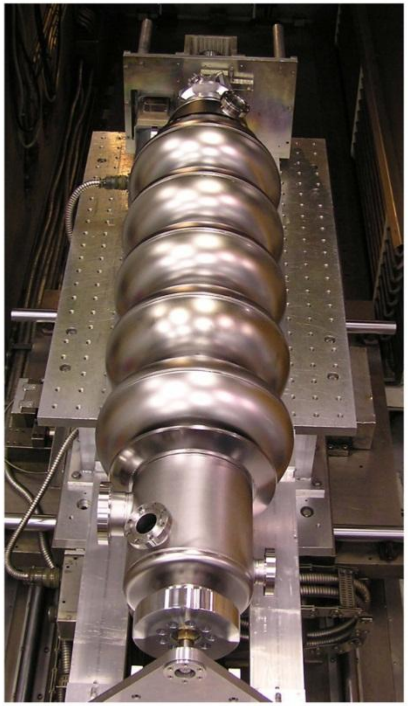
ΔE= 80 MV per Half Cryo Module

Daniel Schulte

eRHIC: no cryo module; cavity "cryounit" - easy addition or removal



preliminary layout of eRHIC cryounit



BNL3 *Nb* cavity

Sergey Belomestnykh

electrical power budgets

parameter	electrical power [MW]	
	eRHIC	**LHeC**
total main linac cryopower	4	**21**
RF microphonics control	5	**24**
extra RF for SR losses	**20**	**23**
extra-RF cryopower	0.3	2
e^- injector	2.6	6
arc magnets	**11**	3
total	**43**	**78**

design constraints: SR loss < 10 MW (eRHIC); total el. power <100 MW (LHeC)

arcs

energy loss from synchrotron radiation

LHeC: ρ=764 m (E_{max}=60 GeV), ΔE_{tot}=2 GeV

eRHIC: ρ=234 m (E_{max}=30 GeV), ΔE_{tot}=0.77 GeV

compensation with additional RF systems

LHeC: 750 MV at 60 GeV (721 MHz)

675 MV at lower energy (1.44 GHz)

eRHIC: 389 MV at 1.4 GHz at 27.55 GeV

eRHIC: 6 passes, low-emittance near isochronous arc lattice

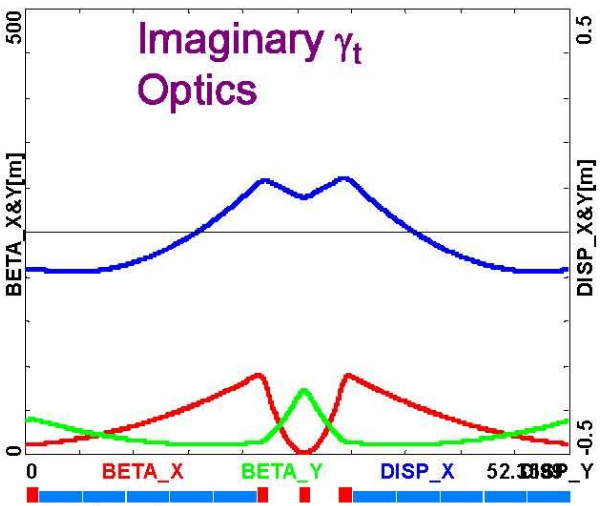
building block: 35 m long with 7 dipoles & 9 quadrupoles

LHeC: 3 passes, flexible momentum compaction arc lattice

building block: 52 m long with 2 (10) dipoles & 4 quadrupoles

LHeC flexible momentum compaction cell; tuned for small beam size (low energy) or low $\Delta\varepsilon$ (high energy)

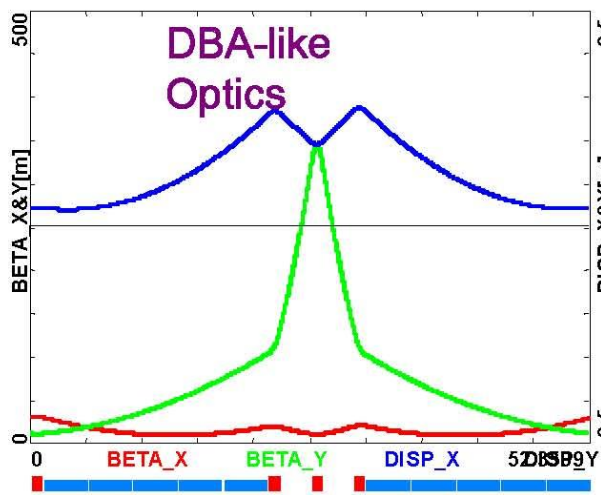
Arc 1 , Arc2



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

limit chamber size
(>12 σ at 25 mm diameter)

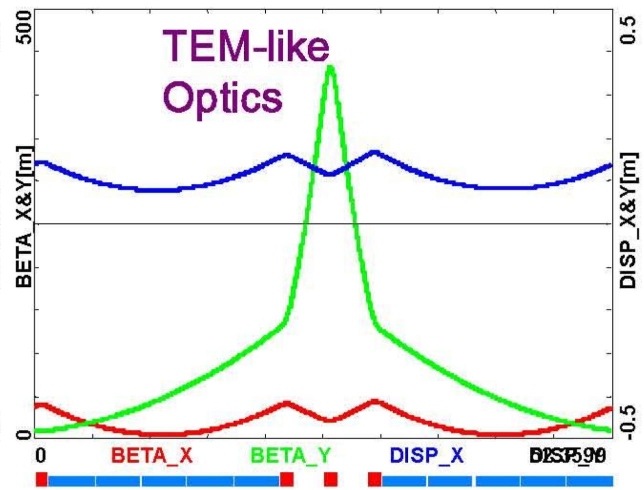
Arc 3, Arc 4



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

Alex Bogacz

Arc5, Arc 6



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

factor of 18 smaller than FODO

limit emittance growth

arc magnets

eRHIC dipole model

5 mm gap
max. field 0.43 T (30 GeV)

LHeC dipole model

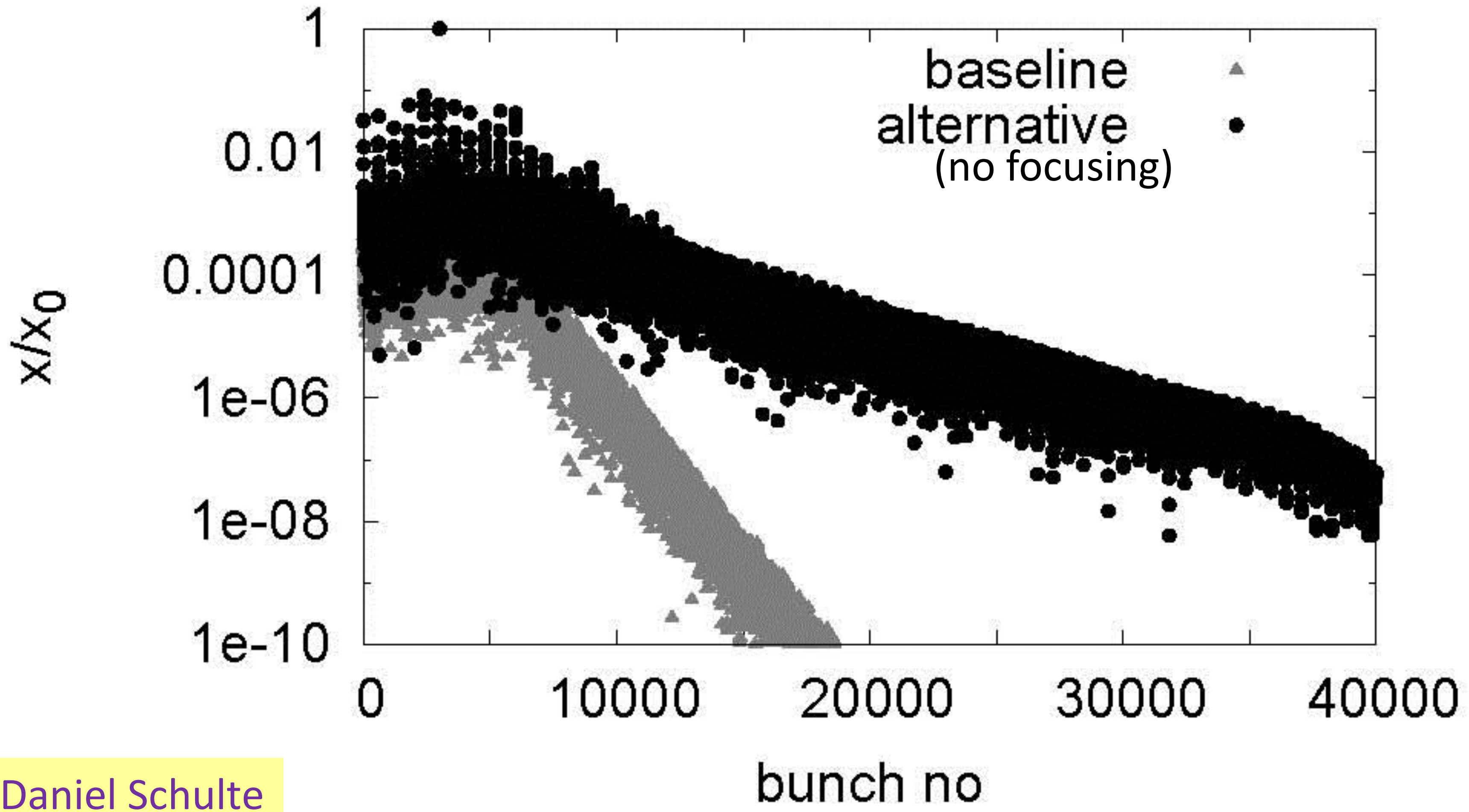
25 mm gap
max. field 0.264 T (60 GeV)

ERL beam dynamics

- multi-pass beam break up
  - suppressed by cavity HOM damping & detuning
  - further suppression possible using correlated energy spread & arc chromaticity if needed (V. Litvinenko, PRST-AB 15, 074401 (2012))
- ion accumulation & ion instabilities
  - clearing gaps (circumference choice), excellent vacuum in warm (10^{-9} hPa) and cold regions (10^{-11} hPa)
- others: resistive wall, surface roughness, CSR, Touschek effect

LHeC ERL Multi-Pass Beam-Break Up

beam stability requires both damping ($Q \sim 10^5$) & detuning ($\Delta f/f_{rms} \sim 0.1\%$) , 720 MHz



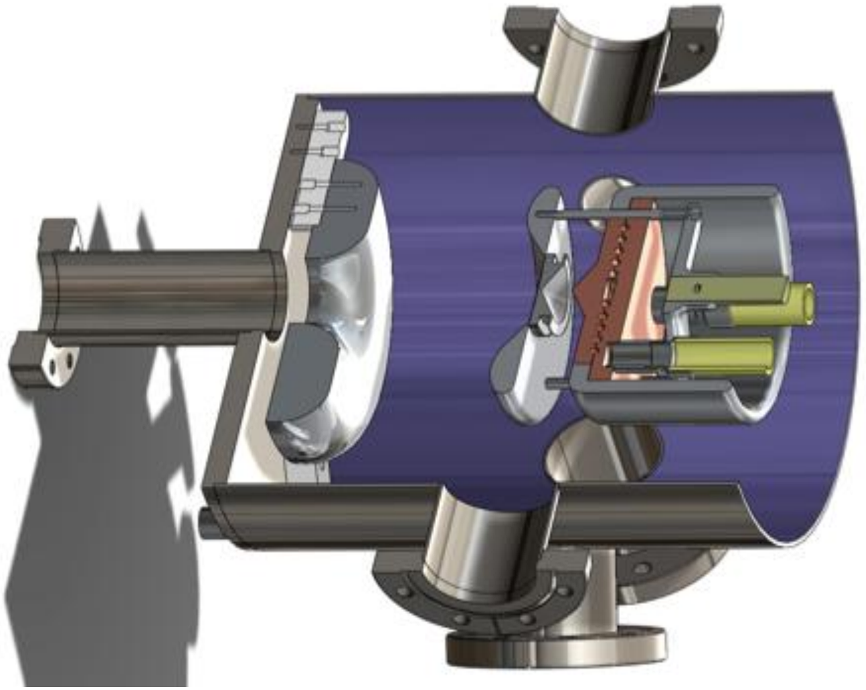
Daniel Schulte

injectors

source e^- beam parameters

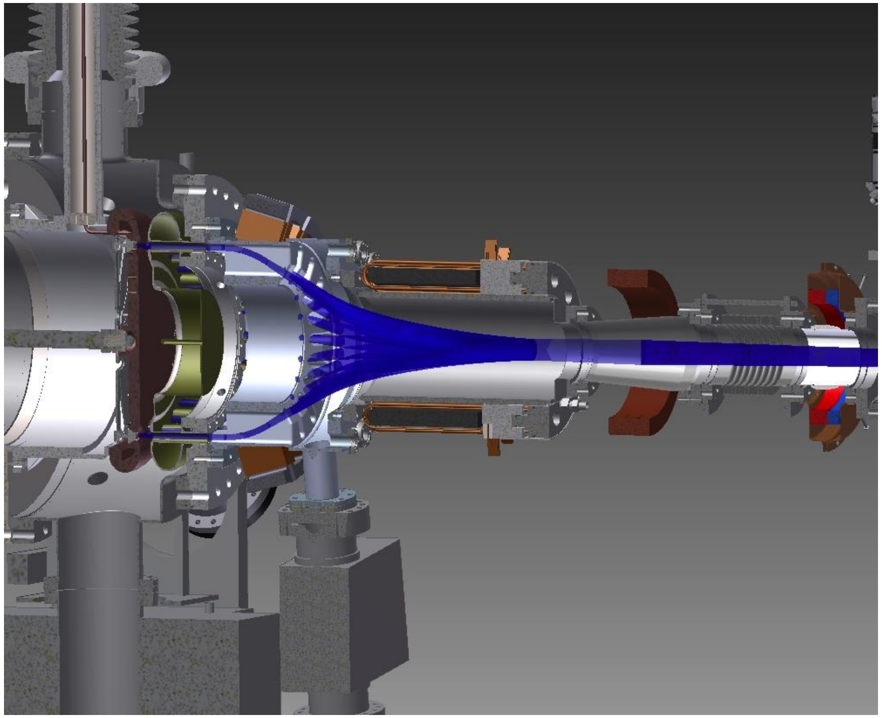
parameter	eRHIC	LHeC
e^-/bunch [10^9]	5.6, 24	1.1
charge / bunch [nC]	0.9, 3.8	0.18
rms bunch length [mm]	2	3-30
bunch spacing [ns]	18	25
average current [mA]	**50, 220**	7
bunch peak current [A]	50, 200	7-70
polarization	**85-90%, none**	>90%

eRHIC polarized electron gun - candidates



large-sized GaAs cathode gun

Evgeni Tsentalovich



Gatling gun, combing beams from an array of 24 GaAs cathodes

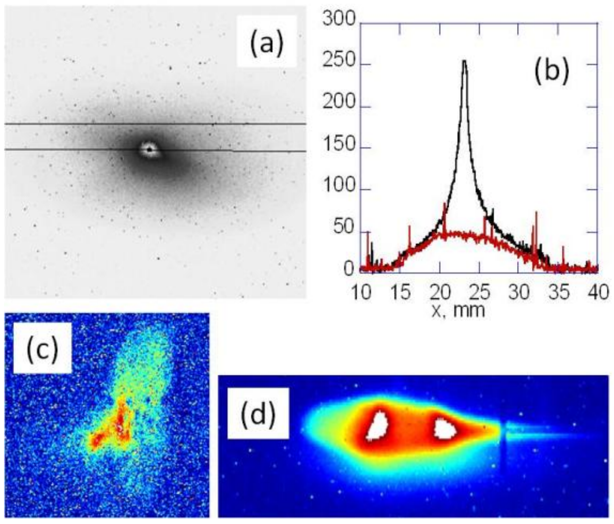
Vladimir Litvinenko

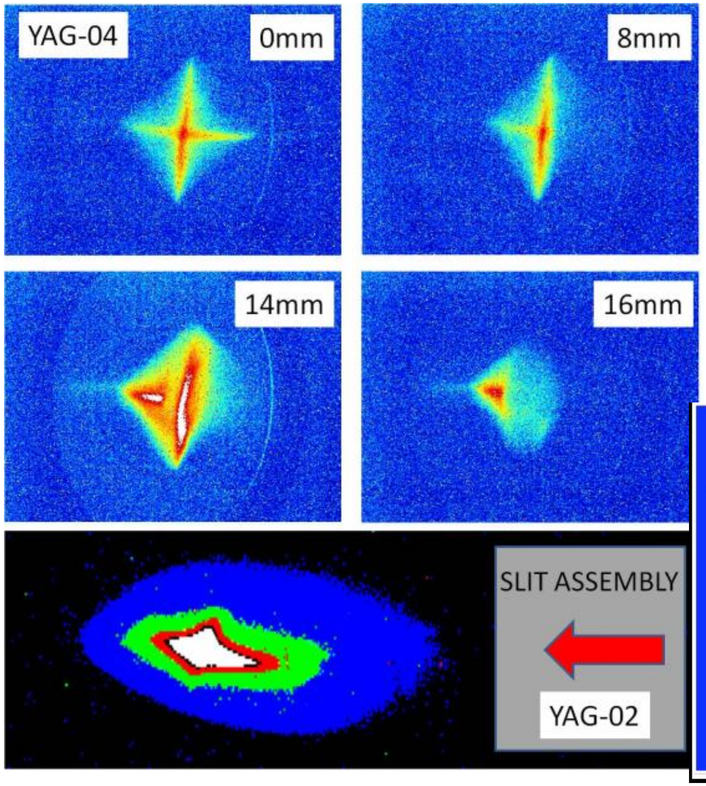
beam quality from DC gun

impact of non-Gaussian e^- beam shape on the hadron beam?

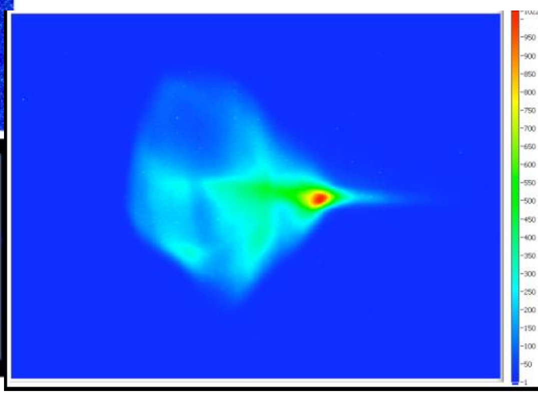
Yuri Saveliev

beam structure at ALICE with 230-kV DC gun voltage:



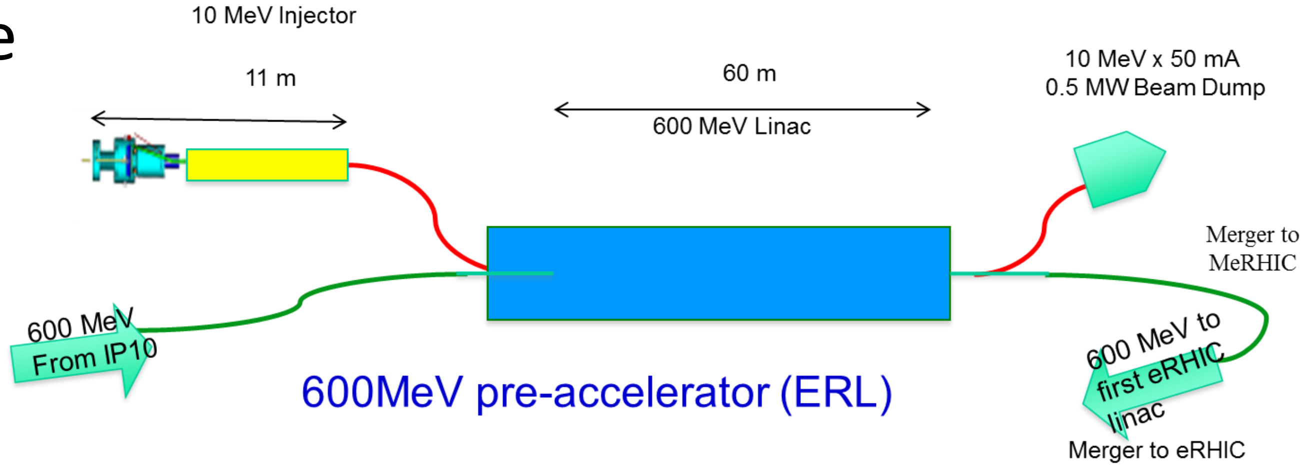


Jlab's "humming bird" beam image:



injector & dump

eRHIC: 60-m 600 MeV injector linac operated in energy recovery mode



Dmitry Kayran

50-mA beam is dumped at 10 MeV → 500 kW power

LHeC: 500-MeV injector

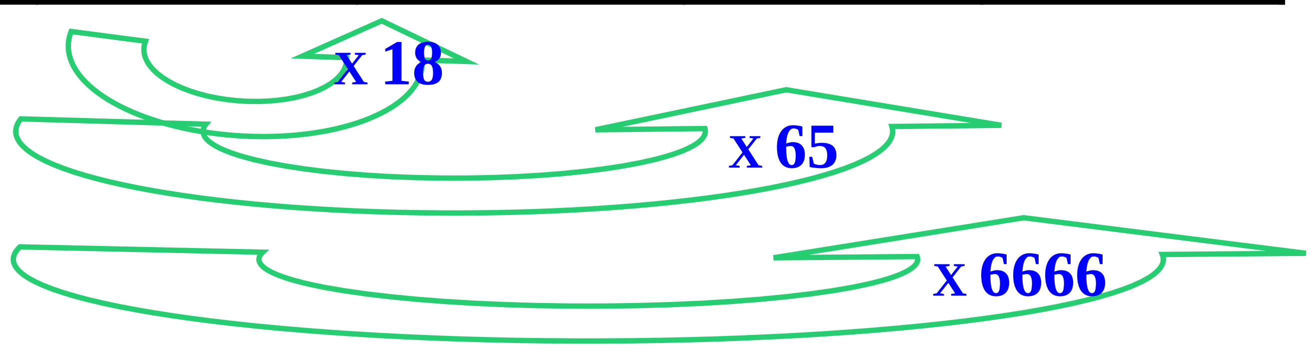
dumping 6.4-mA beam at 500 MeV → 3 MW ;

3 m^3 water dump (0.5 m diameter and 8 m length) with 3 m x 3 m x 10 m shielding

or energy recovery, decelerating 6.4-mA beam to 10 MeV → 64 kW

LHeC Linac-Ring e^+ source

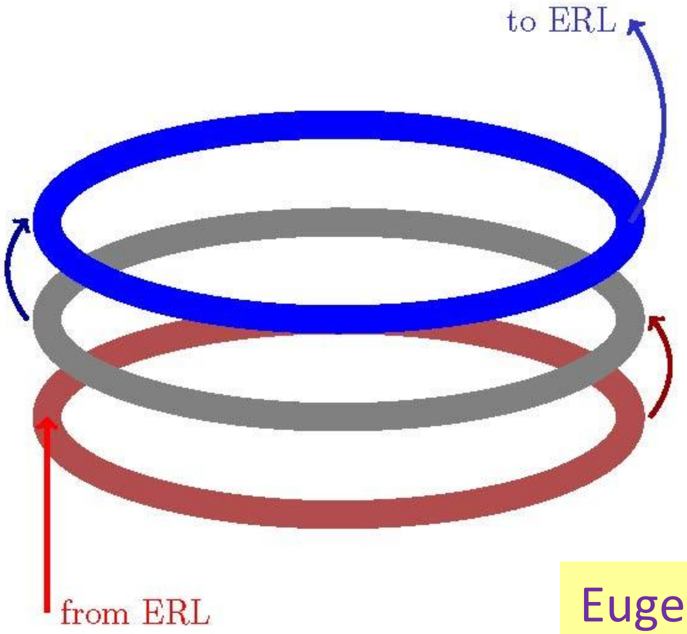
	SLC	**CLIC (3 TeV)**	**ILC (RDR)**	**LHeC**
Energy	1.19 GeV	2.86 GeV	5 GeV	60 GeV
e^+/ bunch at IP	40×10^9	3.72×10^9	20×10^9	2×10^9
e^+/ bunch before DR inj.	50×10^9	7.6×10^9	30×10^9	N/A
Bunches / macropulse	1	312	2625	N/A
Macropulse repet. rate	120	50	5	CW
Bunches / second	120	15600	13125	20×10^6
e^+ / second	**0.06×10^{14}**	**1.1×10^{14}**	**3.9×10^{14}**	**400×10^{14}**



Louis Rinolfi

LHeC e^+ source

- recycle, re-collide, re-cool e^+
- compact tri-ring scheme proposed for e^+ cooling



extraction ring (N turns)

fast cooling ring (N turns)

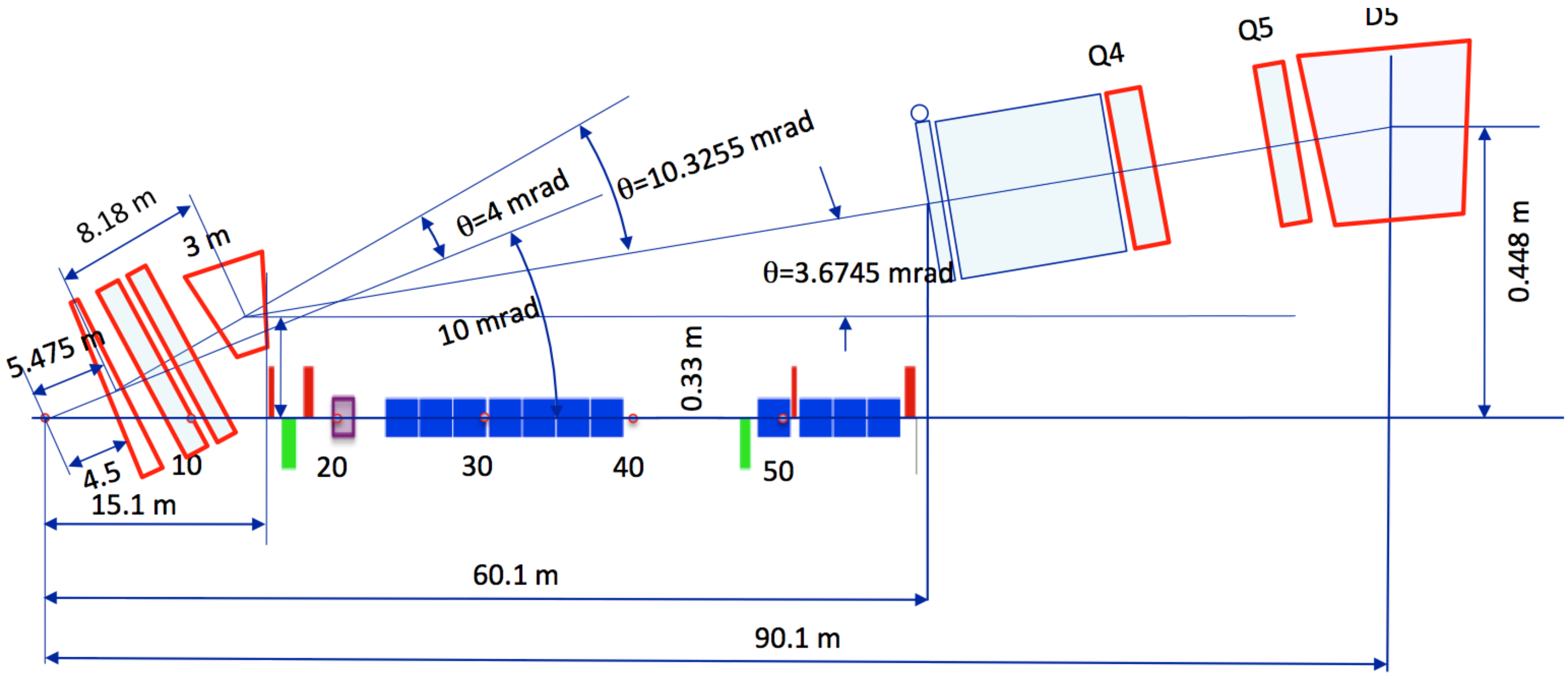
accumulator ring (N turns)

Eugene Bulyak

- remaining e^+ intensity produced by Compton ERL, Compton ring, or coherent pair production

interaction region

eRHIC IR layout



zero field on e^- trajectory , Q1 combined function magnet;

only 1.9 W of soft radiation through IR (from 2.4 mT field);

large crossing angle of 10 mrad:

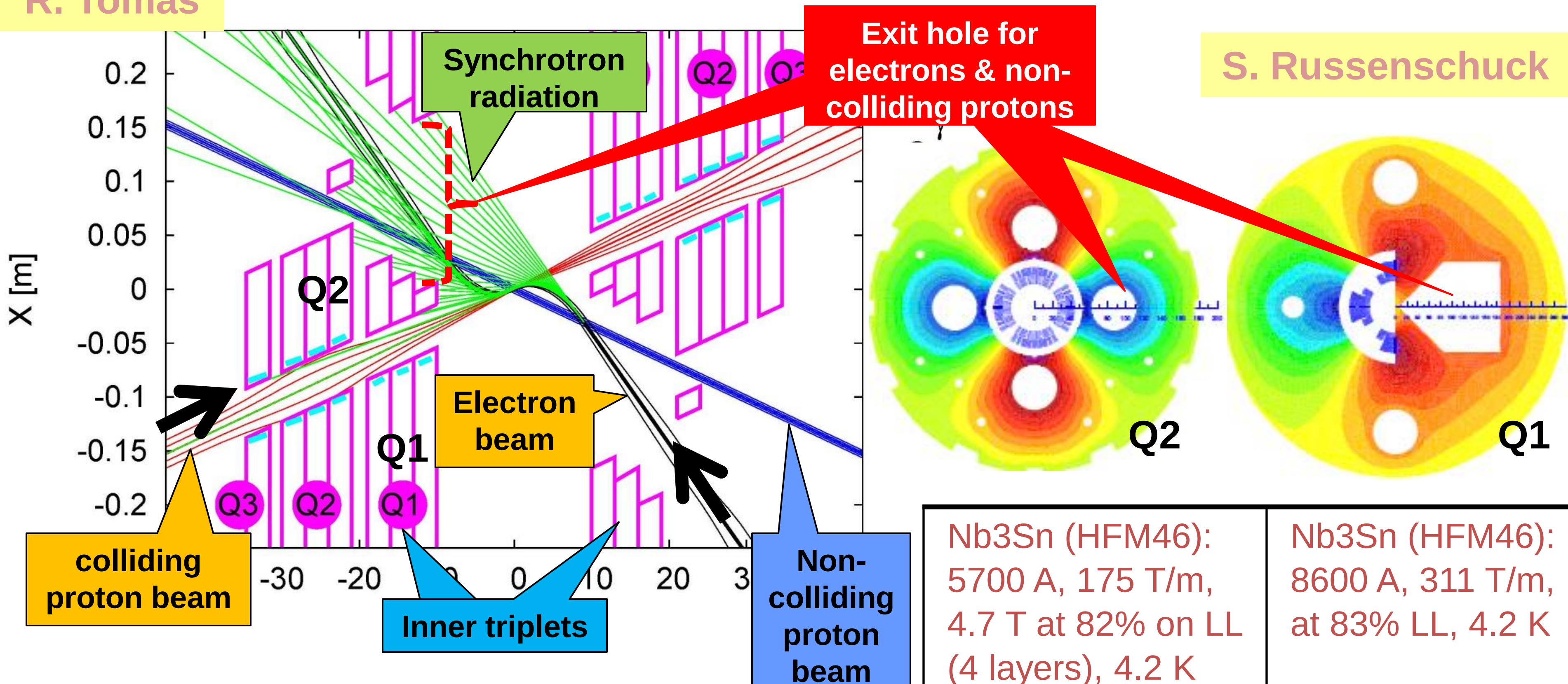
~23-MV ~200-MHz (+harm) crab-cavities for hadron beam

1-MV 700-MHz crab-cavity for lepton beam

LHeC IR layout & SC IR quadrupoles

R. Tomas

S. Russenschuck



High-gradient SC IR quadrupoles based on Nb3Sn for colliding proton beam with common low-field **exit hole for electron beam and non-colliding proton beam**

crab-cavity solution excluded ; head-on collision realized by **detector integrated dipole**: 0.3 T over +/- 9 m

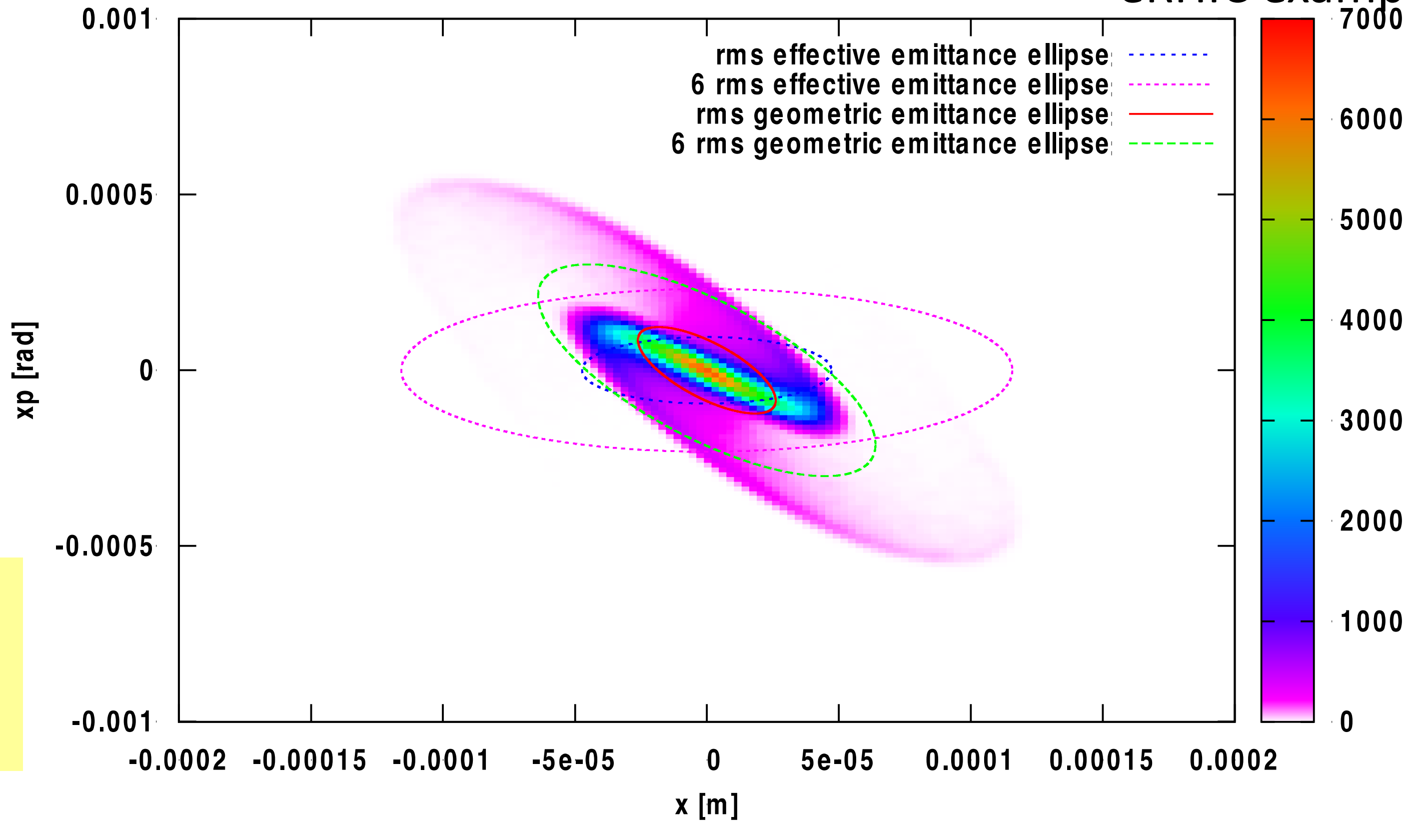
Nb3Sn (HFM46): 5700 A, 175 T/m, 4.7 T at 82% on LL (4 layers), 4.2 K	Nb3Sn (HFM46): 8600 A, 311 T/m, at 83% LL, 4.2 K
46 mm (half) ap., 63 mm beam sep.	23 mm ap.. 87 mm beam sep.
0.5 T, 25 T/m	0.09 T, 9 T/m

48 kW of X-rays (1.8×10^{18} γ/s)
critical energy 718 keV

beam-beam effects

e^- beam pinch & disruption

eRHIC example



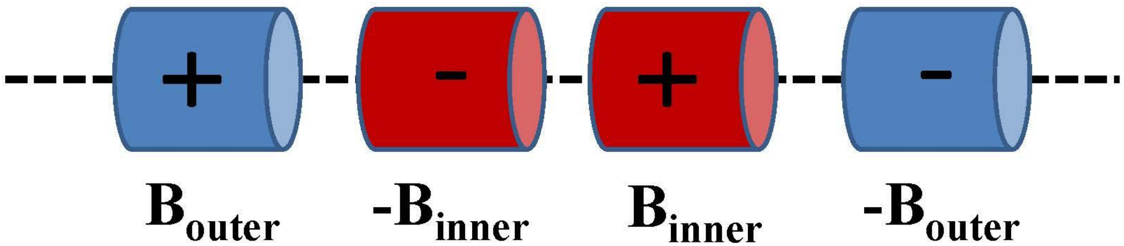
Yue Hao, Vladimir Litvinenko

e^- beam strongly focused by hadron beam → **emittance growth** by a factor of 2-3 in collision; effect minimized by re-matching exit line optics; aperture for deceleration must include these effects ; **beam-beam kink instability** - in eRHIC: cured by broad-band hadron-beam feedback, in LHeC: not expected to occur

e^- polarization

eRHIC: no e^- spin rotators; spin freely rotating in horizontal plane while beam passes through ERL; → condition on final beam energy $E=n$ 0.07216 GeV; **polarization loss due to finite energy spread = 5%** for 2×10^{-4} rms at 30 GeV

LHeC: spin is rotated into vertical direction prior to acceleration; **no depolarization**; full control of IP spin vector orientation by **RHIC type spin-rotator system at high energy**; e.g. 4 x 15 m long helical dipoles with fields 0.46 T and 0.37 T (→**0.3 MW SR**)



Mei Bai

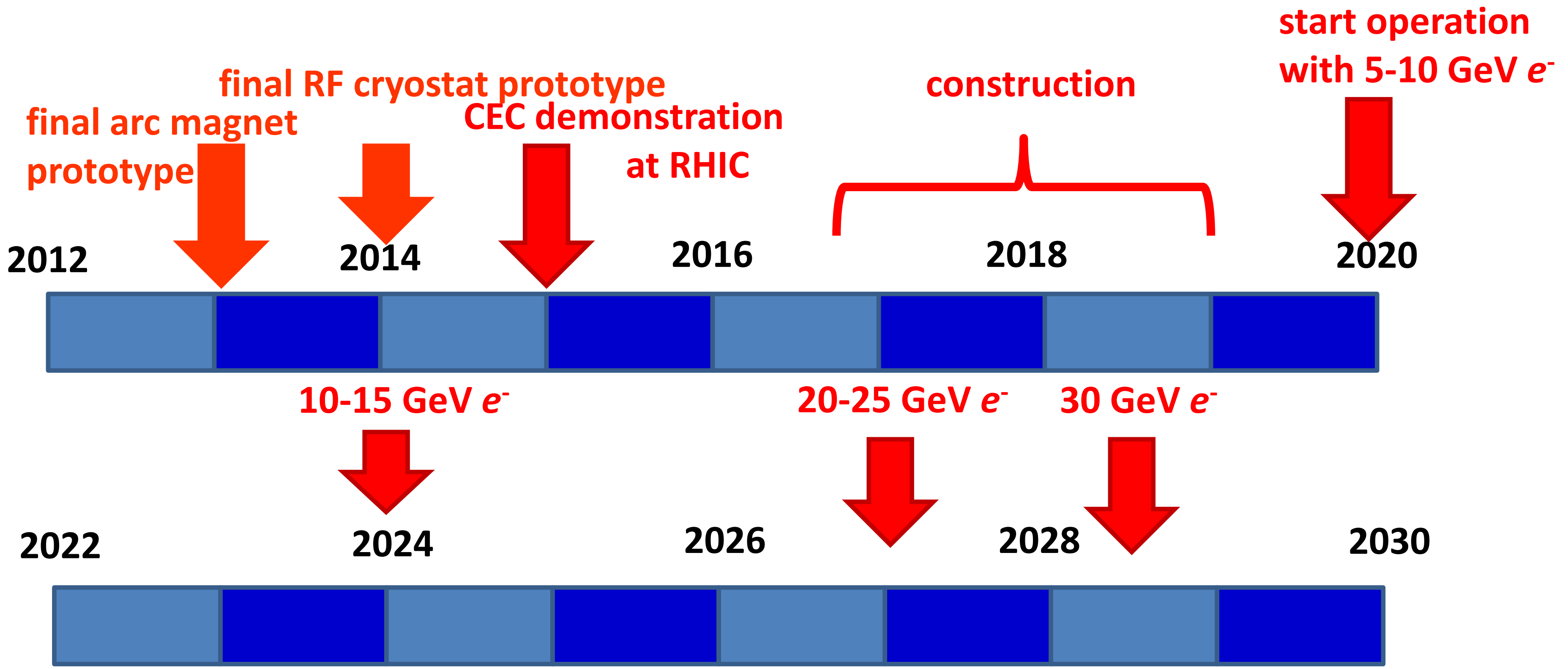
eRHIC R&D items & possible time line

50-mA CW polarized *e*⁻ source

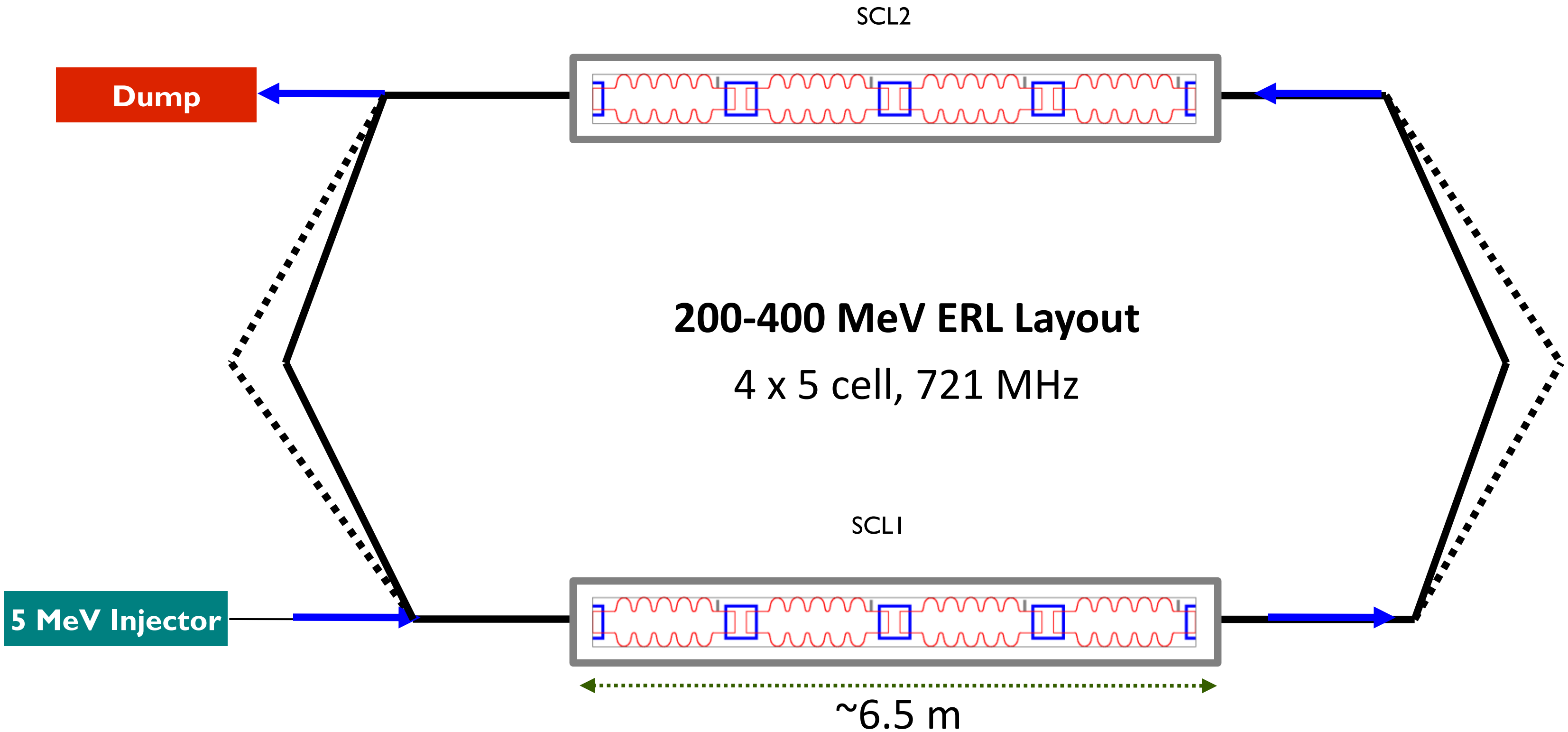
Coherent Electron Cooling POP experiment (with JLAB, Daresbury, BINP, and Tech-X)

SRF ERL technology on **BNL's existing R&D ERL**

RF cryostat, small-gap magnets, arc vacuum chambers



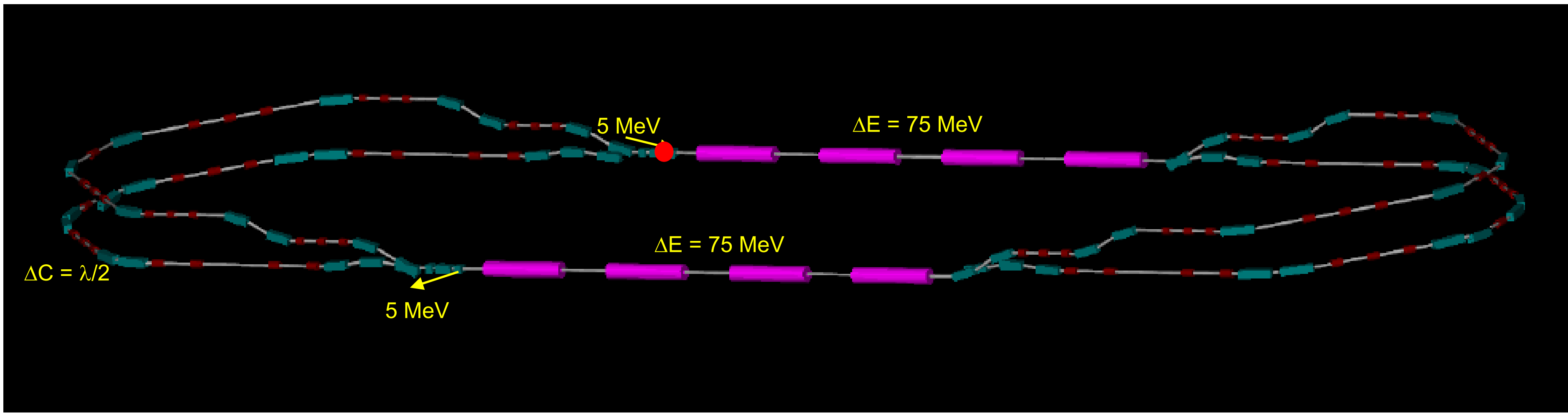
ERL-Test Facility (TF) at CERN



	units	1-CM	2-CM
Energy	[MeV]	100	200-400
Frequency	[MHz]	721	721
Charge	[pC]	~500	~500
Rep. rate		CW	CW

Rama Calaga

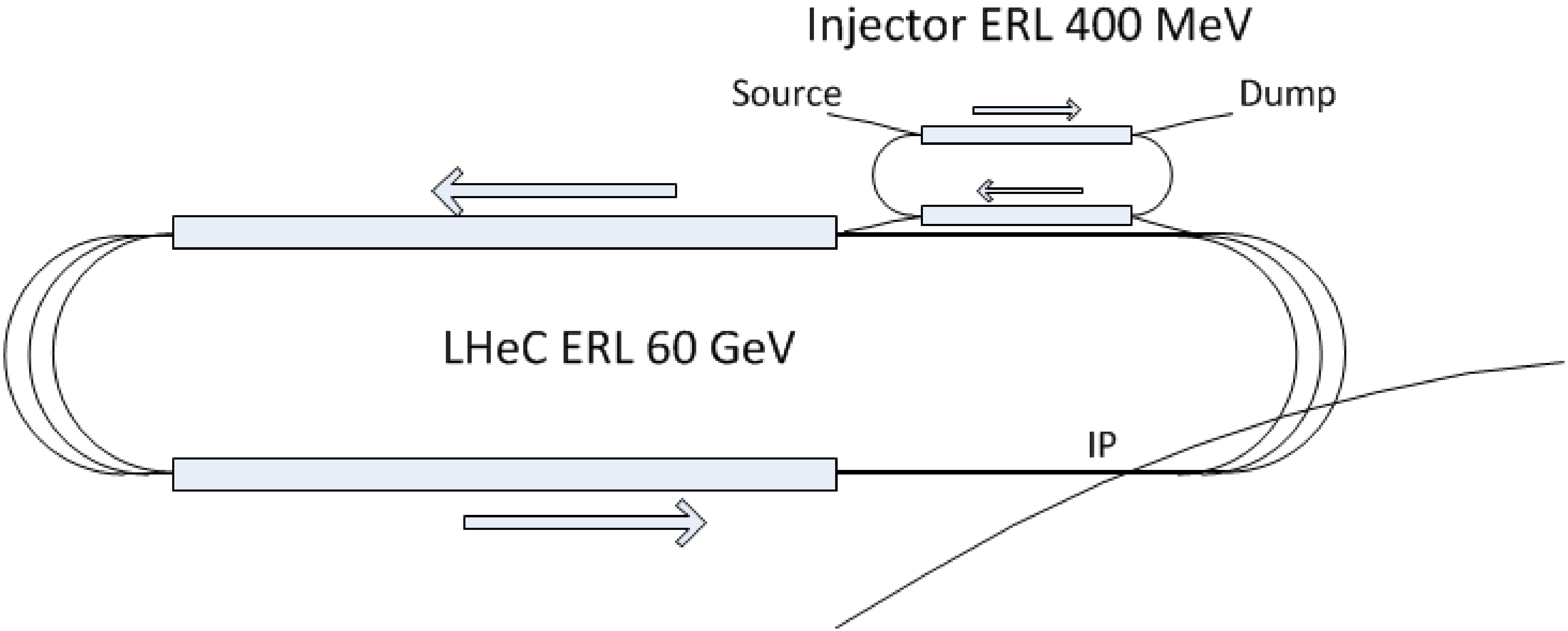
ERL-TF (300 MeV) – Layout



Two passes 'up' + Two passes 'down'

Alex Bogacz

could the LHeC TF later become the LHeC ERL injector ERL?



Rama Calaga & Erk Jensen

thank you for your attention!

for more details:

- LHeC web site http://cern.ch/lhec
- LHeC CDR, J.Phys.G:Nucl.Part.Phys. 39, 075001 (2012)
- eRHIC web site http://www.bnl.gov/cad/eRhic
- ICFA Beam Dynamics Newsletter No. 58, special issue on future electron-hadron colliders, August 2012