Possible EIC-relevant tests at CERN's ERL TF

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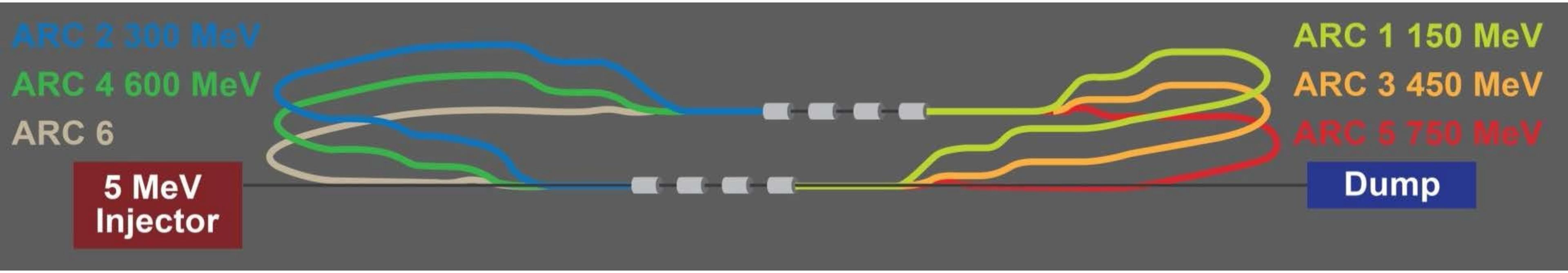
LHeC

20-21 January 2014

Chavannes-de-Bogis

ERL TF @ CERN



TARGET PARAMETER*	VALUE	
Injection Energy [MeV]	5	
Final Beam Energy [MeV]	1000	-> 1500
Normalized emittance $\gamma\varepsilon_{x,y}$ [µm]	50	5
Beam Current [mA]	10	100
Bunch Spacing [ns]	25 (50)	50
Bunch Population	$2*10^9$	$2*10^{10}$

*in few stages

Courtesy of Alessandra Valloni

Main Accelerator Challenges for LHeC

(modified from the list of eRHIC's main acceleratror challenges

Polarized electron gun
Coherent Electron Cooling - ???
Multi-pass SRF ERL
Understanding of beam-beam affects New type of collider
β^*=10 cm
Feedback for kink instability suppression Novel concept

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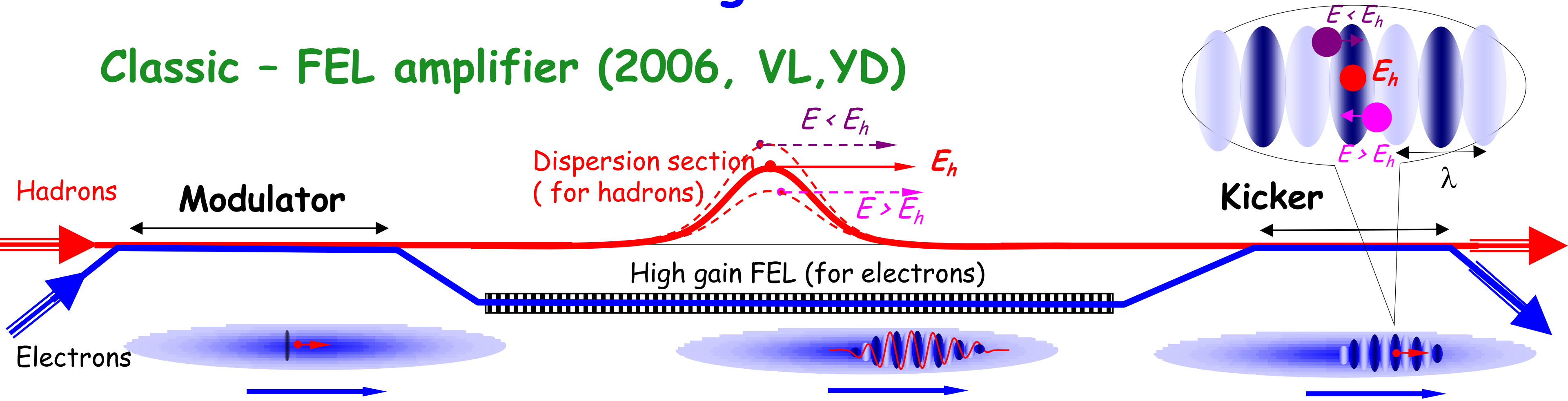
Content: EIC relevant ERL R&D

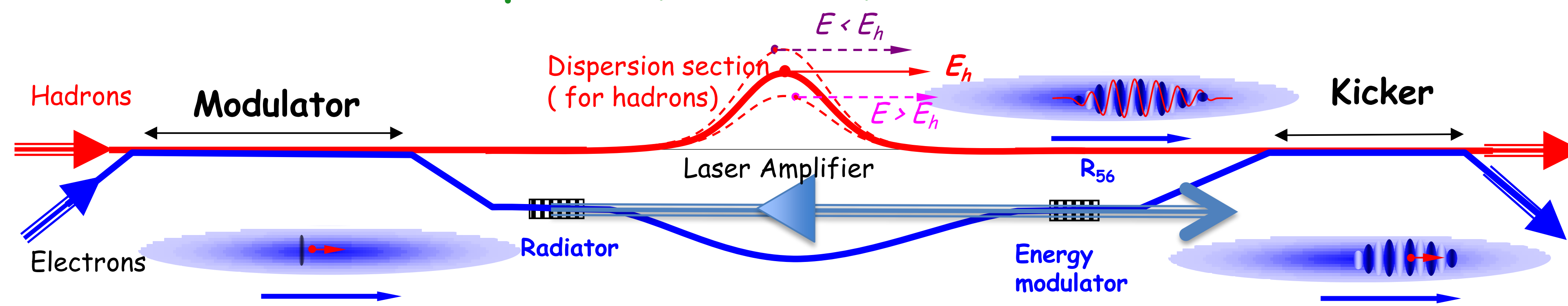
- ERL TF itself (covered by others)
- Hadron Cooling
  - CeC (both classical and MBEC)
- Linac-ring beam-beam effects
- Testing crab-crossing (?)
- Testing detector elements for eP/eA (?)

Coherent Electron Cooling Schemes

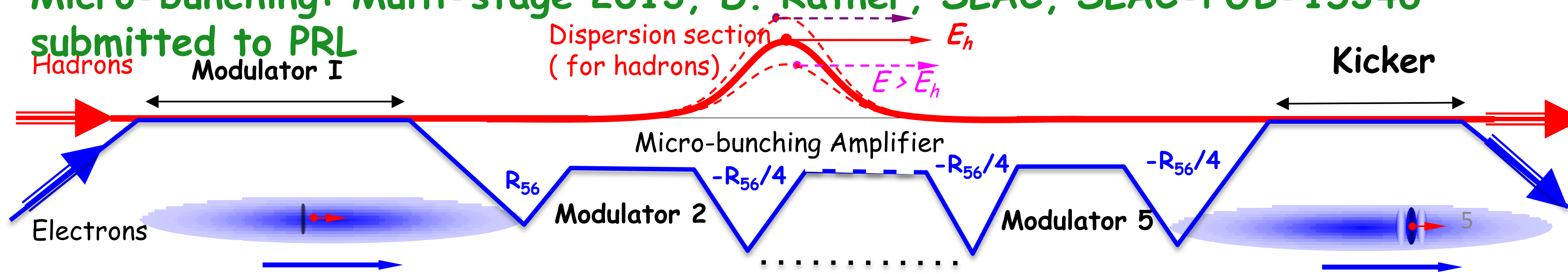
Classic – FEL amplifier (2006, VL,YD)



Blended – laser amplifier (2007, VL)



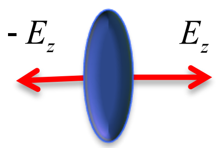
Enhanced bunching: single stage - VL, FEL 2007
Micro-bunching: Multi-stage 2013, D. Ratner, SLAC, SLAC-PUB-15346 submitted to PRL



Why Coherent Electron Cooling ?

$\gamma = E_p / m_p c^2$

- Has potential of a rather large bandwidth W ~ 10^{13} -10^{17} Hz
- Electrons are easy to manipulate, force to radiate, bunch etc.
- **THE MOST IMPORTANT: Longitudinal electric field of bunched electron clamp is very effective way of cooling high energy hadrons – see the example below**



$q = -e$

- Let's assume that as result of CeC interaction a proton induced a density clamp (pancake) in the e-beam with charge of one electron
- Longitudinal electric field induced by this charge (from the Gauss law)

$$E_z = -2\pi \frac{e}{A}; \quad A = 2\pi \frac{\beta \cdot \varepsilon_n}{\gamma} - \text{beam area}$$

- The proton energy change in the kicker with length $L = \beta$

$$\frac{\Delta E}{E} \sim \frac{eE_z L}{\gamma m_p c^2} = -\frac{r_p}{\varepsilon_n};$$

- And cooling time will be

$$\tau \approx \frac{1}{f_o} \frac{\sigma_E}{E} \frac{\varepsilon_n}{r_p}; f_o - \text{revolution frequency}$$

Putting parameters for 250 GeV RHIC proton beam: normalized RMS emittance of 2 mm mrad and relative energy spread of 2 x10^{-4} we get cooling time of 0.93 hours!

For the LHC it would be under 7 hours. Gain ~ 10 puts it under an hour.

The CeC based on the longitudinal electric field is very effective, especially when compared with using transverse fields!

CeC for LHC

- 7 TeV protons
  - 50 m modulator + 100 m FEL + 50 m kicker
  - FEL: 10 cm period, K=10; λ=90 nm
  - Cooling time ~ ½ hour
- 2.8 TeV/u Pb ions
  - 50 m modulator + 100 m FEL + 50 m kicker
  - FEL: 10 cm period, K=5; λ=150 nm
  - Cooling time ~ 2 minutes

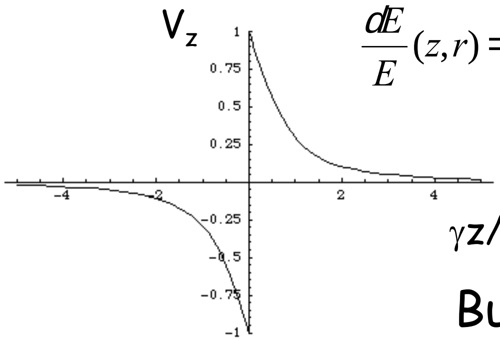
CeC with ERL TF

- Can precool protons or ions at injection
- The job is tougher that on the full energy – wavelength is longer… but <1 hr cooling time can be achieved
  - Require beam parameters: average current – 100 mA, I_{peak} – 30 A, 3 nC per bunch, 5 mm mrad norm emittance
- With 1.5 GeV ERL ion beams can be cooled at operation energy if 2.76 TeV with few minutes cooling time
- ERL TF can test transverse CeC (not planned at RHIC)

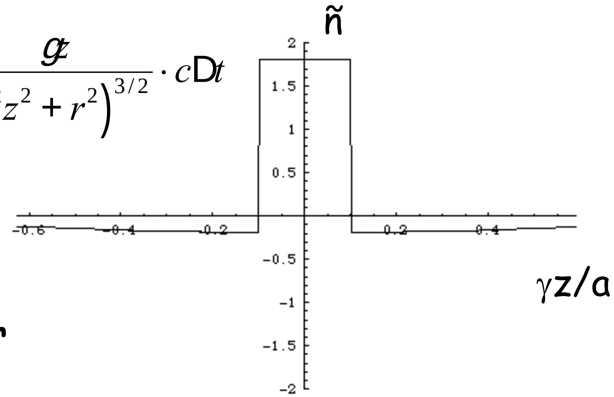
Testing MBEC/EeC

- With potential of 10^{17} Hz bandwidth, EeC/MBEC is most promising technique for cooling LHC/LHeC proton beams with few minutes cooling time
- It may boost luminosity of p-p in LHC
- It can open an opportunity of *(dedicated ?)* operation mode for LHeC with luminosity reaching towards 10^{35} cm^{-2} sec^{-1}

Bunching for high energy beams ($\omega_p t \ll 1$)

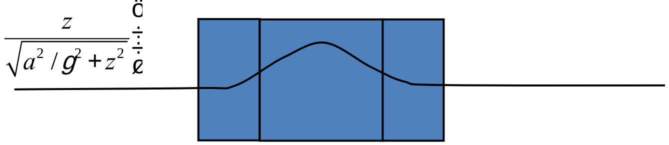


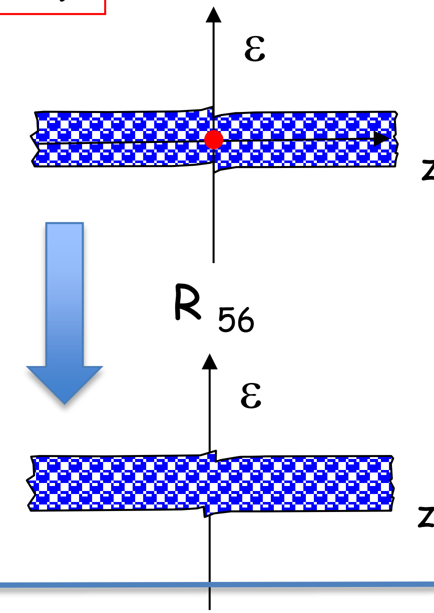
$$\frac{dE}{E}(z,r) = -Zr_e \frac{\gamma z}{\left(\gamma^2 z^2 + r^2\right)^{3/2}} \cdot c\Delta t$$



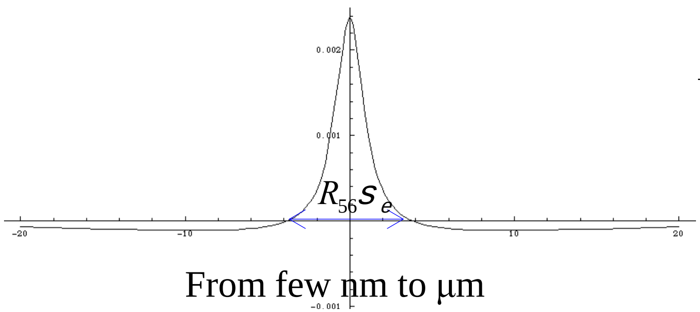
Buncher

$$\left\langle \frac{dE}{E} \right\rangle \cong 2Z \frac{r_e}{a^2} \times \frac{L_{pol}}{\gamma} \times \left(\frac{z}{|z|} - \frac{z}{\sqrt{a^2/\gamma^2 + z^2}} \right)$$





Exact calculations: solving Vlasov equation



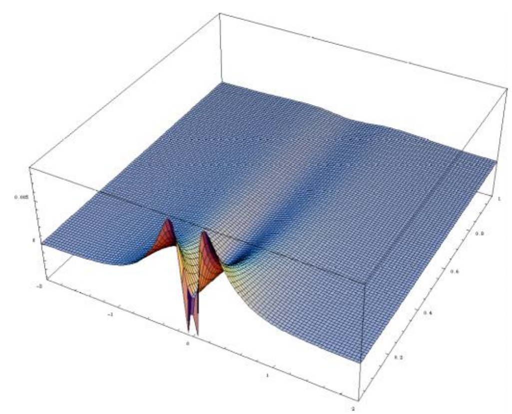
From few nm to µm

$$\frac{\gamma_o z_i}{\left(r_i^2 + \gamma_o^2 z_i^2\right)^{3/2}}; \; z = z_i + R_{56}\left(\frac{d\gamma_i}{\gamma_o} - A \frac{\gamma_o z_i}{\left(r_i^2 + \gamma_o^2 z_i^2\right)^{3/2}} \right);$$

$$\Omega = \frac{Z r_e L}{\beta_o^2 R_{56}^2 \gamma_o^3 \sigma_e^3}$$

$$N_e \approx 4\pi Z n_o \frac{r_e L |R_{56}|}{\beta_o^2 \gamma_o}$$

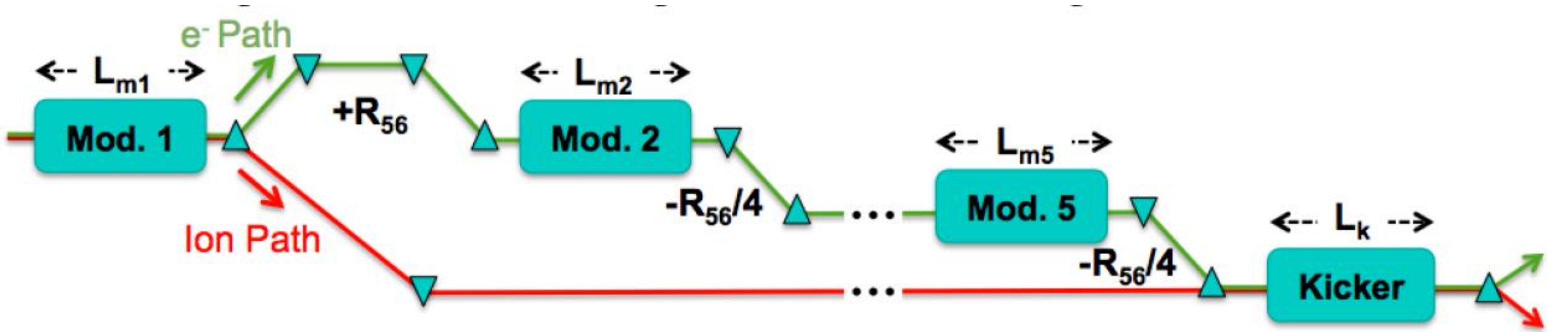
$$\tilde{\rho}\left(z \cdot R_{56}\sigma_e\right) = \pi c_o \cdot \int_0^\infty Y\, dY \cdot \left\{ \frac{Erf\left(\frac{Y - \Omega Y^{-2} + z}{\sqrt{2}}\right) + Erf\left(\frac{Y - \Omega Y^{-2} - z}{\sqrt{2}}\right)}{1 - \Omega Y^{-3}} - Erf\left(\frac{Y+z}{\sqrt{2}}\right) - Erf\left(\frac{Y-z}{\sqrt{2}}\right) \right\};$$



For 7 TeV p in LHC CeC case: My simple "gut-feeling" estimate gave 22.9 boost in the induced charge by a buncher, while exact calculations gave 21.7. Maximum bunching depends on the e-beam quality

Coherent Electron Cooling

Micro-bunching (2013, D. Ratner, SLAC, submitted to PRL)



PRL 111, 084802 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Microbunched Electron Cooling for High-Energy Hadron Beams

D. Ratner*
SLAC, Menlo Park, California 94025, USA
(Received 11 April 2013; published 20 August 2013)

Electron and stochastic cooling are proven methods for cooling low-energy hadron beams, but at present there is no way of cooling hadrons as they near the TeV scale. In the 1980s, Derbenev suggested that electron instabilities, such as free-electron lasers, could create collective space charge fields strong enough to correct the hadron energies. This Letter presents a variation on Derbenev's electron cooling scheme using the microbunching instability as the amplifier. The large bandwidth of the instability allows for faster cooling of high-density beams. A simple analytical model illustrates the cooling mechanism, and simulations show cooling rates for realistic parameters of the Large Hadron Collider.

DOI: 10.1103/PhysRevLett.111.084802 PACS numbers: 29.27.−a, 41.60.Cr, 41.75.Ak, 41.75.Ht

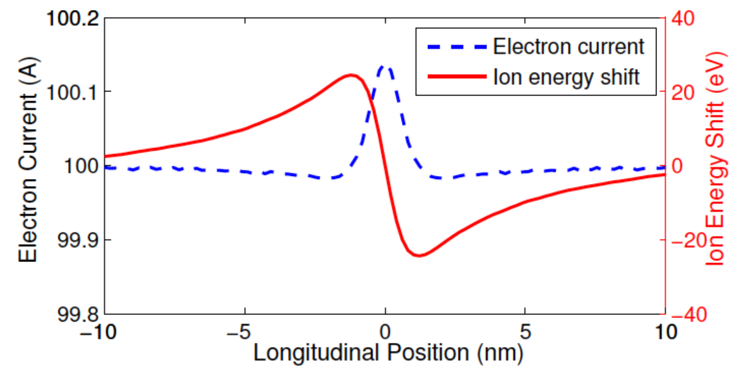
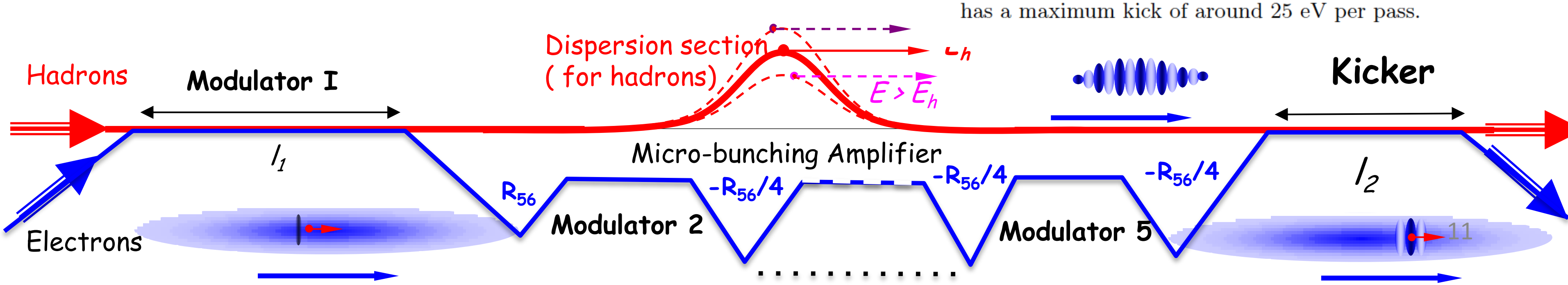


FIG. 4. The blue dashed line shows the final electron current from a fluid model without shot noise for LHC-like parameters of Table I . The corresponding ion energy shift (solid red line) has a maximum kick of around 25 eV per pass.



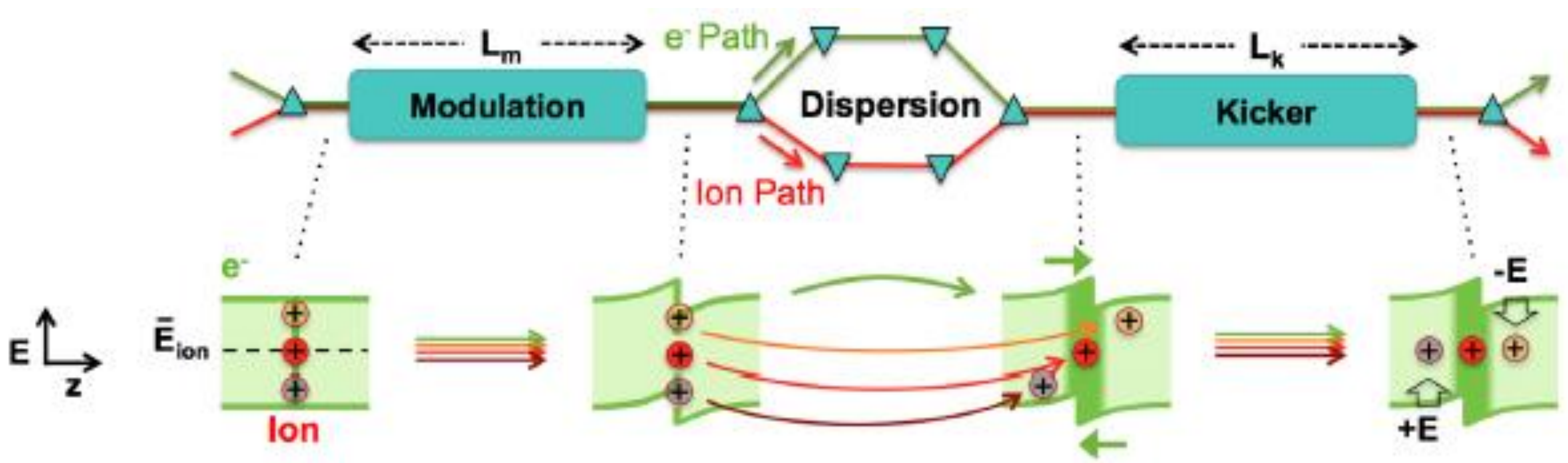
Go boldly where no one has gone before…

(We note that a dispersive section was first introduced by Litvinenko to accelerate the plasma oscillation in CeC prior to the amplification stage [10]. Here we use the dispersion as the amplifier itself). Microbunched electron cooling (henceforth, MBEC) offers two benefits. First, the instability creates only a single density spike for each hadron, maximizing the bandwidth of the amplifier. The large amplifier bandwidth is crucial for cooling high-density bunched beams, such as those at the LHC. Second, the scheme is relatively simple, consisting only of drift and dispersive regions.

The question what is the maximum attainable amplification is not addressed or even raised in the PRL – it was assumed that it is unlimited and is proportional to R56.

In fact, there is limitation, but at BNL we had proven that gain>2 and even ~ 100 is attainable (conditions apllied!)

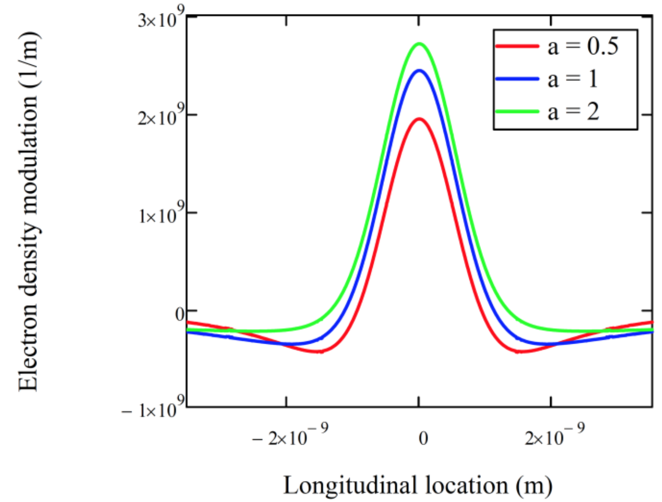
Thus, the letter is correct! And MBEC/EeC will work!

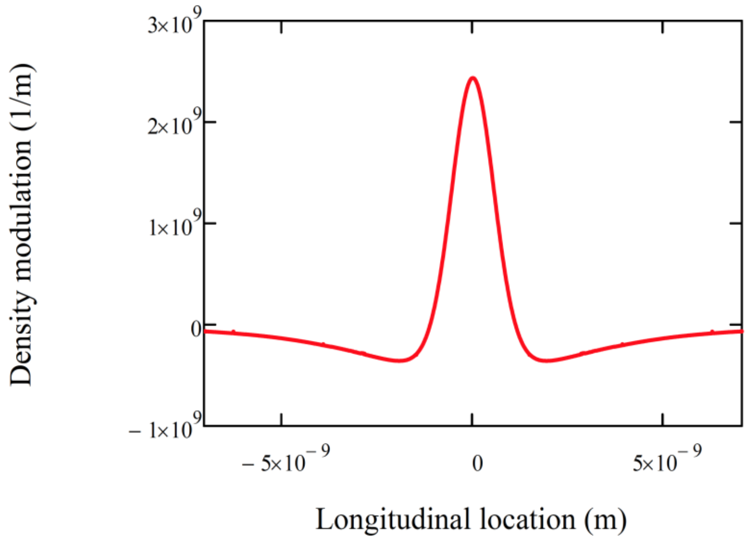


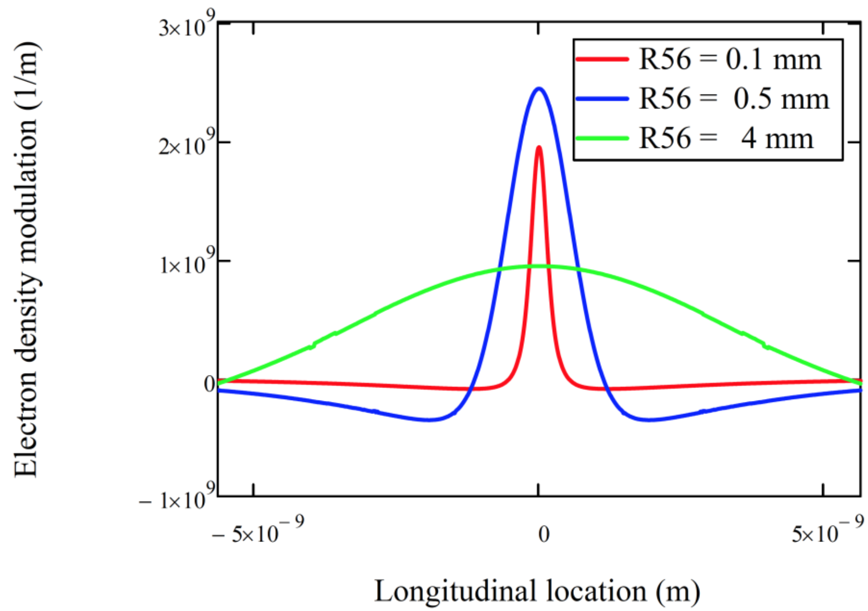
Enhanced e-cooling

γ	7461	R_{56} (mm)	0.5
$\varepsilon_{n,rms}$ (μm)	0.5	Bunch length (full,cm)	1.5
Q_e (nC)	0.5	$\Delta\gamma/\gamma$, rms	1E-6
I_{peak} (A)	10	Beam width, rms (μm)	30
β (m)	13	Plasma phase advances (rad)	0.064
L_{mod} (m)	25	Back ground line density (1/m)	2.1E11

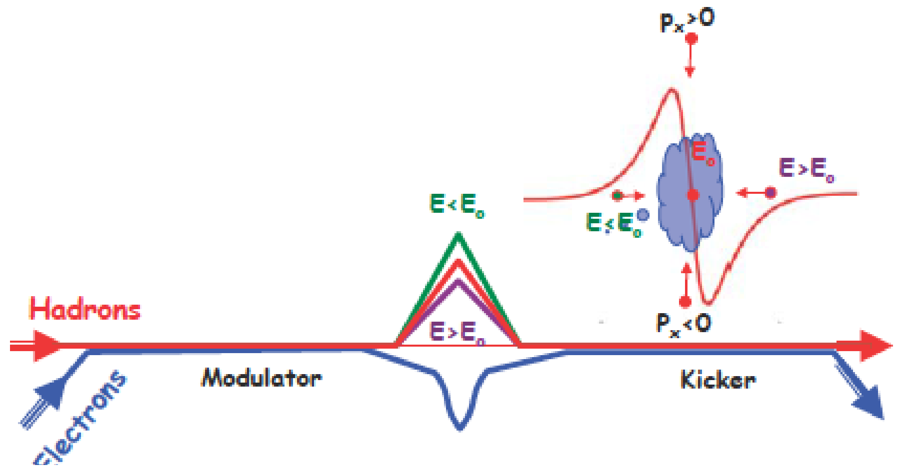
Table 1: parameters applied in generating Fig. 1-6.







1-stage MBEC or Enhanced e-cooling



$$\tilde{\rho}\left(z\cdot\frac{R_{56}\sigma_\gamma}{\gamma_o}\right) = 2\pi n_o \sigma_\gamma^2 R_{56}\left|R_{56}\right|\cdot\int_0^\infty Y\,dY\left\{\frac{H(z,Y_1)}{Y_1}-\frac{H(z,Y_2)}{Y_2}\right\};\ \Omega=\frac{Zr_eL}{R_{56}^2\sigma_\gamma^3\beta_o^2};\ \alpha=\frac{a}{D\sigma_\gamma};$$

$$Y_1 = Y\left(1-\frac{\Omega}{Y^3}\right);Y_2 = Y\left(1-\frac{\Omega}{\left(Y^2+\alpha^2\right)^{3/2}}\right);\ H(z,Z)=\frac{1}{2}\left(Erf\left(\frac{z+Z}{\sqrt{2}}\right)-Erf\left(\frac{z-Z}{\sqrt{2}}\right)\right).$$

Main challenge -> to have a very low energy spread in electron beam

ERT TF can be used for

- Demonstrating the EeC/MBEC amplification using ion beam (not cooling!)
- Generate and accelerate in ERL TF an e-beam with eV-range energy spread suitable for EeC/MBeC LHC cooler
- Using a cleaver set of beam optics and RF cavities should allow to preserve eV-rage energy spread from the gun to operation energy

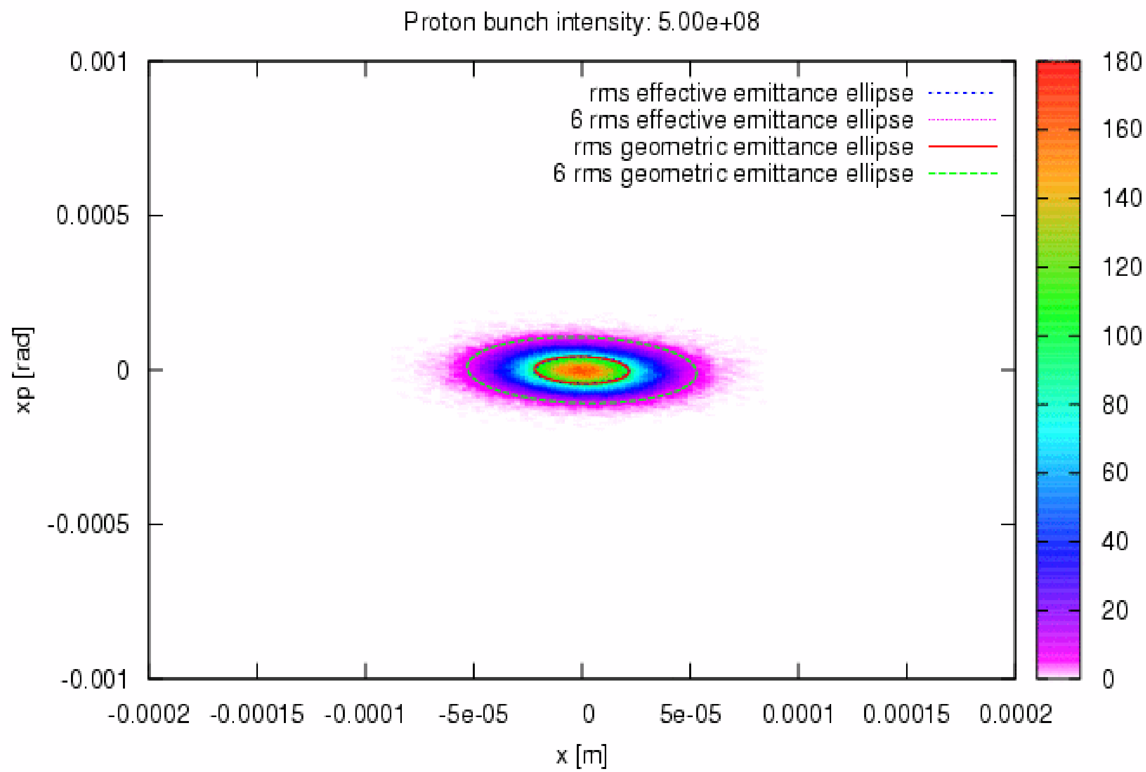
Presently, the slice energy spread in high brightness guns and linacs is dominated by the spread induced by non-zero beam size in accelerating structures. For example, the energy spread of the high-brightness photocathodes is measured in eV; after acceleration in an RF linac slice (instantaneous) energy spread grows to few KeV, an increase of about three orders of magnitude [56-58]. It is well known (as a consequence of Maxwell equations) that energy gain in an RF accelerator depends on the radial position of the particle. Hence, a non-zero beam size in the RF gun and in the linac leads to accumulation of the local energy spread. For a given beam size, the energy gain variation is proportional to the square of the RF frequency.

LHeC baseline parameters incl. e-Pb – cont'd

parameter [unit]			
species	***e-***	***p***	***Pb*** (ult.)
hadron beam-beam parameter ξ	**0.0001 (0.0002)**		**0.0001**
lepton disruption parameter *D*	**6**		**0.3**
crossing angle	0		0
hourglass reduction factor H_{hg}	0.91		0.91
pinch enhancement factor H_D	1.35		1.0
c.m. energy (/nucleon) [GeV]	1300		814
luminosity / nucleon [10^{33} cm^{-1}s^{-1}]	**1.3**		**0.1**

Courtesy of Frank Zimmerman

Electron disruption effect

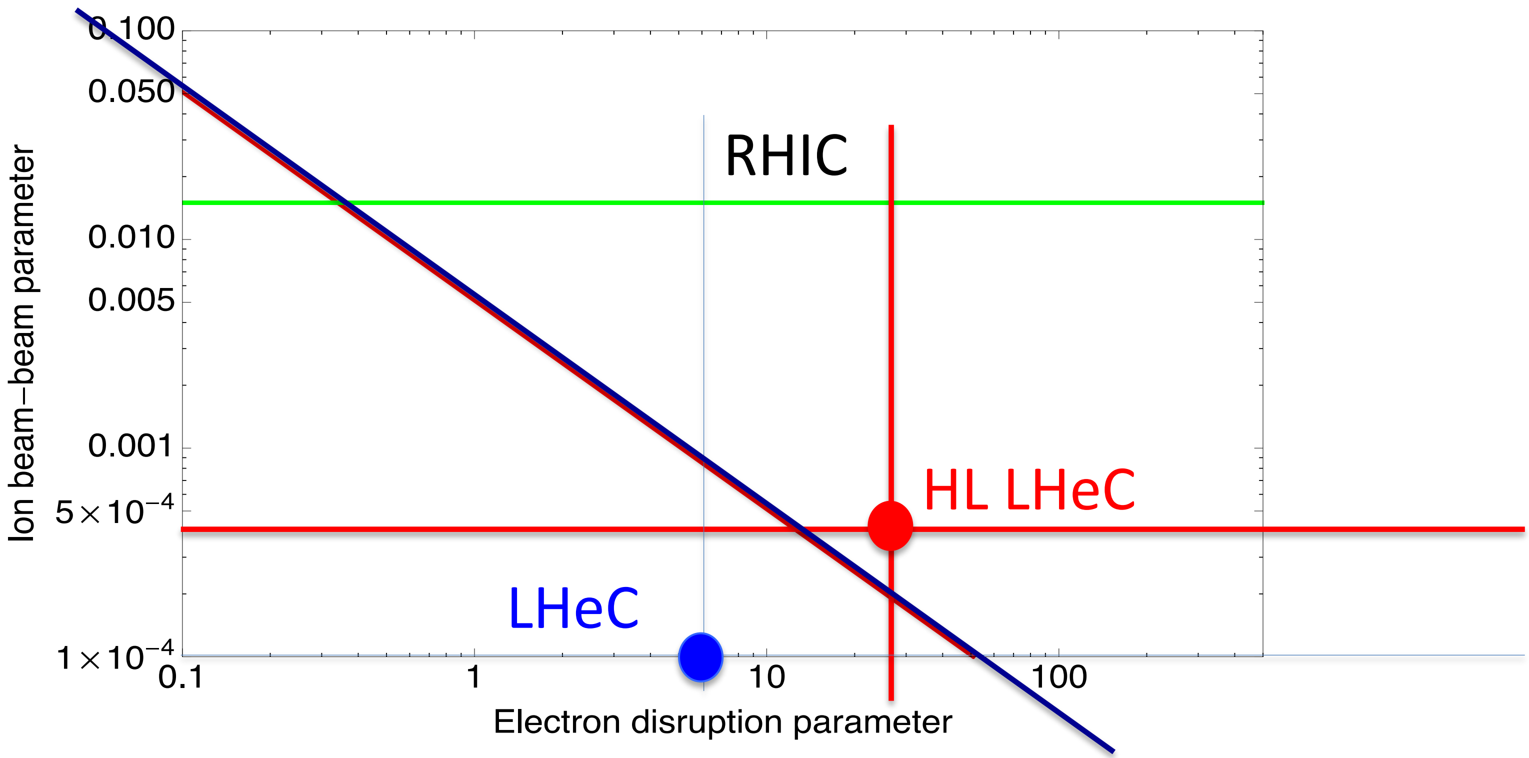


Courtesy of Y. Hao

LHeC Higgs factory (LHeC-HF) parameters

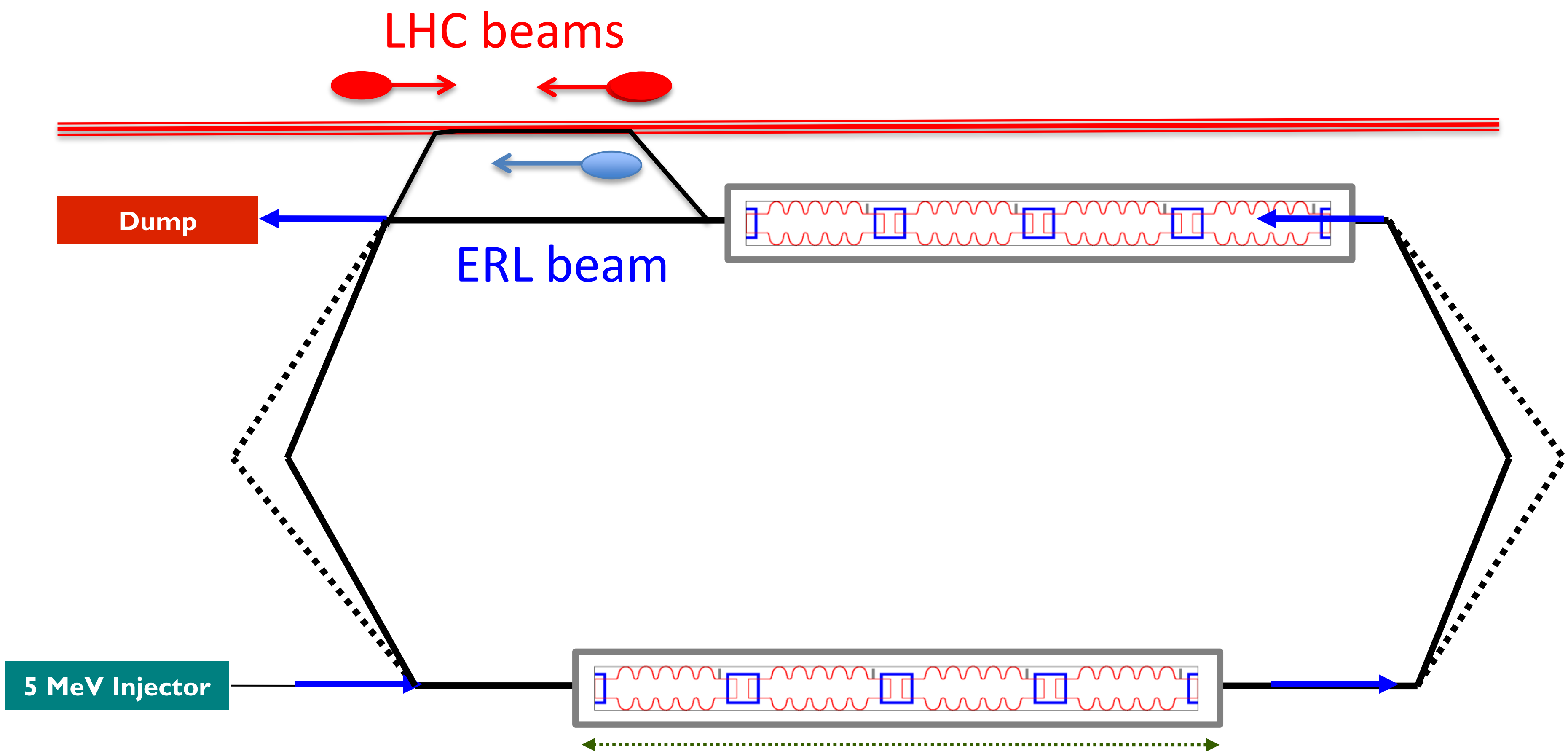
parameter [unit]	Courtesy of Frank Zimmerman	
species	***e-***	***p***
beam energy (/nucleon) [GeV]	60	7000
bunch spacing [ns]	25	25
bunch intensity (nucleon) [10^{10}]	**0.1 → 0.4**	**17→ 22**
beam current [mA]	**6.4 → 25.6**	**860 → 1110**
normalized rms emittance [μm]	50 → **20**	**3.75 → 2.5**
geometric rms emittance [nm]	**0.43 → 0.17**	**0.50 → 0.34**
IP beta function $\beta_{x,y}$* [m]	**0.12 → 0.10**	**0.10 → 0.05**
IP rms spot size [μm]	7.2 → **4.1**	7.2 → **4.1**
lepton *D* & hadron ξ	**6 → 23**	**0.0001→ 0.0004**
hourglass reduction factor H_{hg}	0.91→ **0.70**	
pinch enhancement factor H_D	1.35	
luminosity / nucleon [10^{33} cm^{-1}s^{-1}]	**1.3 → 16**	

The threshold of kink instability HL LHeC may be just on the brink?



Courtesy of Y. Hao

ERL-Test Facility (TF) & LHC
Cooling & Beam-beam collisions



The C.M. energy of collisions with 140-200 GeV
Is nothing to frown about and can be used to test both the conditions in and the components of EIC detectors

Conclusions

- ERL TF itself is important for EHC/EIC R&D
- Coherent electron Cooling (both FEL and MB based) can be tested at ERL TF
  - And can be also used to precool LHC hadron beams at injection
- It also could be used to study EHC/EIC effects
  - Linac-ring beam-beam effects
  - Testing crab-crossing
  - Testing detector elements for eP/eA (?)

ERL TF

Back-up

Ultimate case: 7 TeV LHC p

- γ=7460.52
- Peak current: 30 A
- Norm emittance 1 mm mrad
- RMS energy spread 2.5e-5
- λw=10 cm
- a_w = 10
- λo=90.73 nm
- Mc = 140

Model independent formula gives

$$g_{\max} \sim 144 \times \sqrt{\frac{I_p[A] \times \lambda_o[\mu m]}{M_c}} = 20$$

3D Genesis 1.3 simulations; Green-function saturates at $g_{\max}$ =18.7

32 random shot-noise seeds

Green function is the averaged difference (not RMS!) between the resulting bunching from (Shot Noise +δ-function) minus from (Shot Noise)

We plan to use – g= 8.5!