LHeC with ~100% energy recovery linac

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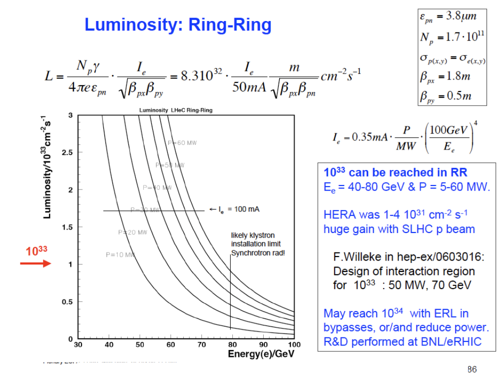
Observations from the other side of the pond

- Three design options for LHeC:
  - **Ring-ring**: Luminosity is limited by allowable power for synchrotron radiation, which limit the e-beam current

$$U_{SR} = C_\gamma \cdot \frac{E_e^4}{R} \propto 9\ \ GeV \cdot \frac{(E_e/100GeV)^2}{R[km]} \qquad \pounds \sim \frac{L_{RR}}{E_e^4}$$

$$P_{SR} = U_{SR} \cdot I_e < \frac{100\ \ MW}{2}$$

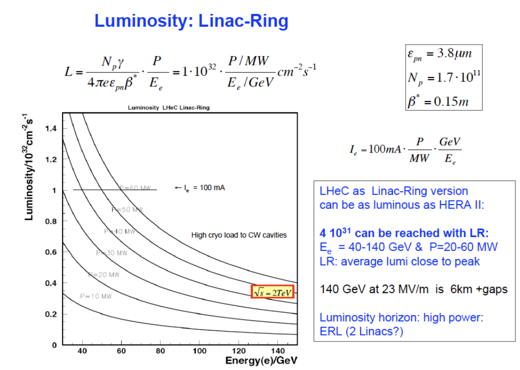


Max Klein

  - **Linac-ring**: Luminosity is limited by allowable power for accelerating the e-beam, which limits its current

$$P_L = C_{cryo} \cdot E_e + 2 \cdot \frac{E_e \cdot I_e}{e} \qquad \pounds \sim \frac{L_{LR}}{E_e} \qquad E_{e\max} \le \frac{100\,MW}{C_{cryo}}$$

$$I_{beam}[mA] < \frac{50}{E_e[GeV]}$$



  - **ERL-ring**: Luminosity is limited by efficiency of energy recovery
    - re-circulating beam at full energy limits the beam current below ring-ring option

$$P_{ERL} = C_{cryo} \cdot E_e + 2 \cdot \frac{E_{e\_dump} \cdot I_e}{e} + P_{SR}$$

Observations from the other side of the pond: continued

- I all options luminosity is not limited by beam-beam effects for protons
  - It means that tune shift for proton beam can be increased by 10-20 fold
  - Electron beam can be abused in L-R and ERL-R cases, which gives additional luminosity boost ~ 10 fold in the LHC-upgrade case

Ring-Ring Parameters

Luminosity safely $10^{33} cm^{-2}s^{-1}$

LHC upgrade: N_p increased.
Need to keep e tune shift low:
by increasing β_p, decreasing β_e
but enlarging e emittance,
to keep e and p matched.

LHeC profits from LHC upgrade
but not proportional to N_p

Tuneshift Limit:

$$\Delta\nu_{xe} = \frac{\beta_{xe} r_e}{2\pi\gamma_e} * \frac{N_p}{\sigma_{xp}(\sigma_{xp}+\sigma_{yp})}$$

Experience:

LEP	$\Delta\nu_e = 0.048$
LHC-B	$\Delta\nu_p = 0.0037$
HERA	$\Delta\nu_e = 0.051$
	$\Delta\nu_p = 0.0016$

Standard Parameter	Protonen	Elektronen	
	Np=1.15*10^11	Ne=1.4*10^10	nb=2808
	Ip=582 mA	Ie=71mA	
Optics	βxp=180 cm	βxe=12.7 cm	
	βyp= 50 cm	βye= 7.1 cm	
	εxp=0.5 nm rad	εxe=7.6 nm rad	
	εyp=0.5 nm rad	εye=3.8 nm rad	
Beamsize	σx=30 µm	σx=30 µm	
	σy=15.8 µm	σy=15.8 µm	
Tuneshift	Δνx=0.00055	Δνx=0.0484	
	Δνy=0.00029	Δνy=0.0510	
Luminosity	L=8.2*10^32		
Ultimate Parameter	**Protonen**	**Elektronen**	
	Np=1.7*10^11	Ne=1.4*10^10	nb=2808
	Ip=860mA	Ie=71mA	
Optics	βxp=230 cm	βxe=12.7 cm	
	βyp= 60 cm	βye= 7.1 cm	
	εxp=0.5 nm rad	εxe=9 nm rad	
	εyp=0.5 nm rad	εye=4 nm rad	
Beamsize	σx=34 µm		
	σy=17 µm		
Tuneshift	Δνx=0.00061	Δνx=0.056	
	Δνy=0.00032	Δνy=0.062	
Luminosity	L=1.03*10^33		
Upgrade Parameter	**Protonen**	**Elektronen**	
	Np=5*10^11	Ne=1.4*10^10	nb=1404
	Ip=1265mA	Ie=71mA	
Optik	βxp=400 cm	βxe= 8 cm	
	βyp=150 cm	βye= 5 cm	
	εxp=0.5 nm rad	εxe=25 nm rad	
	εyp=0.5 nm rad	εye=15 nm rad	
Strahlgröße	σx=44 µm		
	σy=27 µm		
Tuneshift	Δνx=0.0011	Δνx=0.057	
	Δνy=0.00069	Δνy=0.058	
Luminosität	L=1.44*10^33		

Bernhard Holzer

Upgrade Parameter	Protonen	Elektronen	
	Np=5*10^11	Ne=1.4*10^10	nb=1404
	Ip=1265mA	Ie=71mA	
Optik	βxp=400 cm	βxe= 8 cm	
	βyp=150 cm	βye= 5 cm	
	εxp=0.5 nm rad	εxe=25 nm rad	
	εyp=0.5 nm rad	εye=15 nm rad	
Strahlgröße	σx=44 µm		
	σy=27 µm		
Tuneshift	Δνx=0.0011	Δνx=0.057	
	Δνy=0.00069	Δνy=0.058	
Luminosität	L=1.44*10^33		

Observations from the other side of the pond: continued
Focus of Energy Recovery Linac

- Based on a simple scaling, one can see that without limitation on e-beam current, LHeC luminosity can be ~10^{34}-10^{35}
- The question is:
  - Can this luminosity potential be realized?
  - If yes, that how it can be done? And it what cost?

$$\Delta \nu_{xe} = \frac{\beta_{xe} r_e}{2\pi \gamma_e} * \frac{N_p}{\sigma_{xp}(\sigma_{xp} + \sigma_{yp})}$$

$$\beta_e^* \varepsilon_e = \beta_i^* \varepsilon_i \Rightarrow \xi_i = \frac{N_e}{4\pi} \cdot \frac{r_i}{\gamma_i \varepsilon_i}$$

Bernhard Holzer R-R

Upgrade Parameter	Protonen	Elektronen	
	$N_p=5*10^{11}$	$N_e=1.4*10^{10}$	nb=1404
	Ip=1265mA	Ie=71mA	
Optik	βxp=400 cm	βxe= 8 cm	
	βyp=150 cm	βye= 5 cm	
	εxp=0.5 nm rad	εxe=25 nm rad	
	εyp=0.5 nm rad	εye=15 nm rad	
Strahlgröße	σx=44 μm		
	σy=27 μm		
Tuneshift	Δvx=0.0011	Δvx=0.057	
	Δvy=0.00069	Δvy=0.058	
Luminosität	$L=1.44*10^{33}$		

ERL-R: match emittances
Gain is 12 fold

Parameter	Protons	**Electrons**
# per bunch	5.00E+11	**1.40E+10**
Beam current, A	1.265	**0.035**
Emittance, nm rad	0.5	**0.5**
Beta*, cm	20	**20**
Tune shift	**0.0005**	**irrelevant**
Luminosity		**1.7E+34**

Observations from the other side of the pond: continued
Focus of Energy Recovery Linac

- Increase e-beam current till the p-beam tune-shift limit allows up to 40-fold!

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R-R

Upgrade Parameter	Protonen	Elektronen	
	$Np=5*10^{11}$	$Ne=1.4*10^{10}$	nb=1404
	Ip=1265mA	Ie=71mA	
Optik	βxp=400 cm	βxe= 8 cm	
	βyp=150 cm	βye= 5 cm	
	εxp=0.5 nm rad	εxe=25 nm rad	
	εyp=0.5 nm rad	εye=15 nm rad	
Strahlgröße	σx=44 µm		
	σy=27 µm		
Tuneshift	Δvx=0.0011	Δvx=0.057	
	Δvy=0.00069	Δvy=0.058	
Luminosität	$L=1.44*10^{33}$		

ERL-R

$$N_e = 4\pi \cdot \xi_p \cdot \frac{\gamma_p \varepsilon_p}{r_p}$$

$$\beta_e^* \varepsilon_e = \beta_i^* \varepsilon_i \Rightarrow \xi_i = \frac{N_e}{4\pi} \cdot \frac{r_i}{\gamma_i \varepsilon_i}$$

Parameter	Protons	**Electrons**
# per bunch	5.00E+11	**6.00E+11**
Beam current, A	1.265	**1.518**
Emittance, nm rad	0.5	**0.5**
Beta*, cm	20	**20**
Tune shift	**0.02**	**irrelevant**
Luminosity		**7.1E+35**

Observations from the other side of the pond: continued

Focus of Energy Recovery Linac

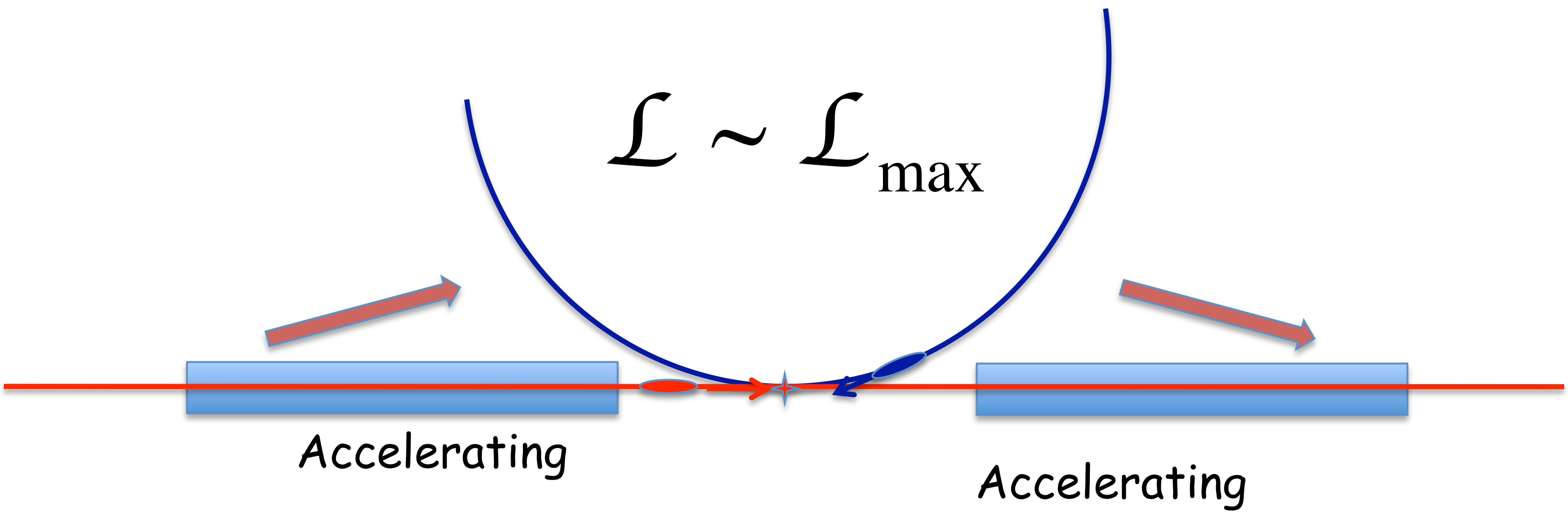
- Taking off limit on electron beam tune-shift allows 12 fold increase in the luminosity
- Removing beam current limitations may allow additional 40-fold increase in the luminosity
- Full potential is 500x increase in the luminosity above the ring-ring case
- **Question is how to get there?????**

LHeC Extreme

Parameter	Protons	Electrons
# per bunch	5.00E+11	6.00E+11
Beam current, A	1.265	1.518
Emittance, nm rad	0.5	0.5
Beta*, cm	20	20
Tune shift	0.02	irrelevant
Luminosity		7.1E+35

<u>First guess</u>

100% Energy recovery – needs 2 linacs
What to do with the energy?



e-beam current is ~ 1 A
Energy of e-beam is ~ 100 GeV
Energy to transfer ~ 100 GW
Best RF coupled do 1 MW ->
2 x 100,000 couplers, 100,000 high precision waveguides…. – simply out of this world

First guess

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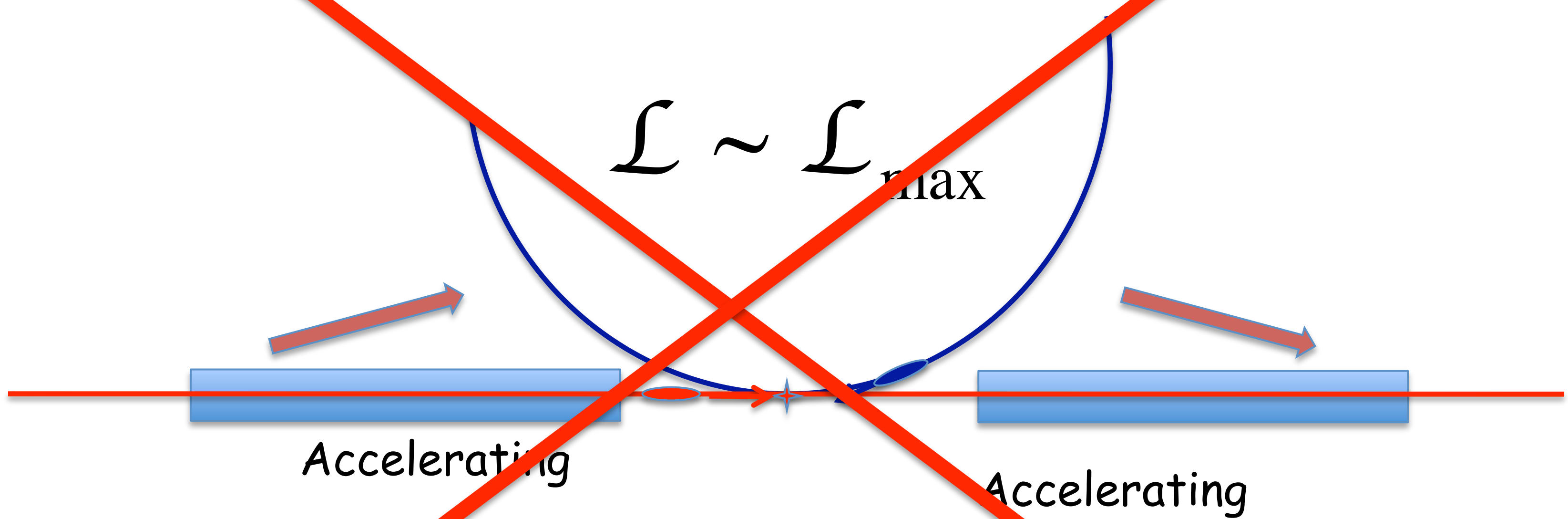
What to do with the energy?

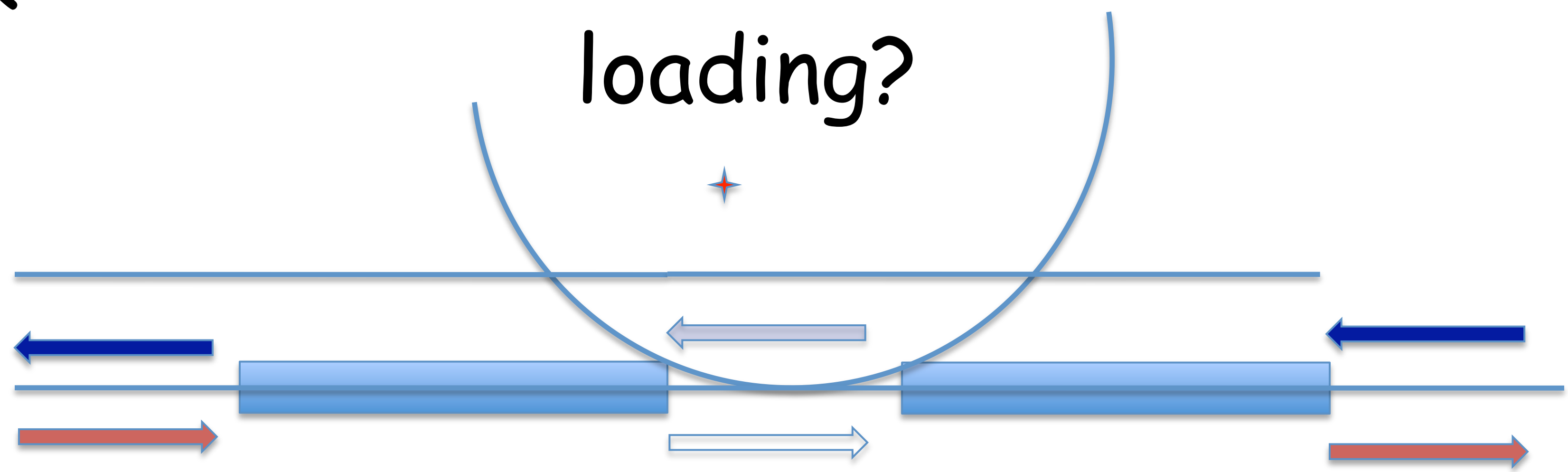


e-beam current is ~ 1 A
Energy of e-beam is ~ 100 GeV
Energy to transfer ~ 100 GW
Best RF coupled do 1 MW ->

2 x 100,000 couplers, 100,000 high precision waveguides…. – simply out of this world

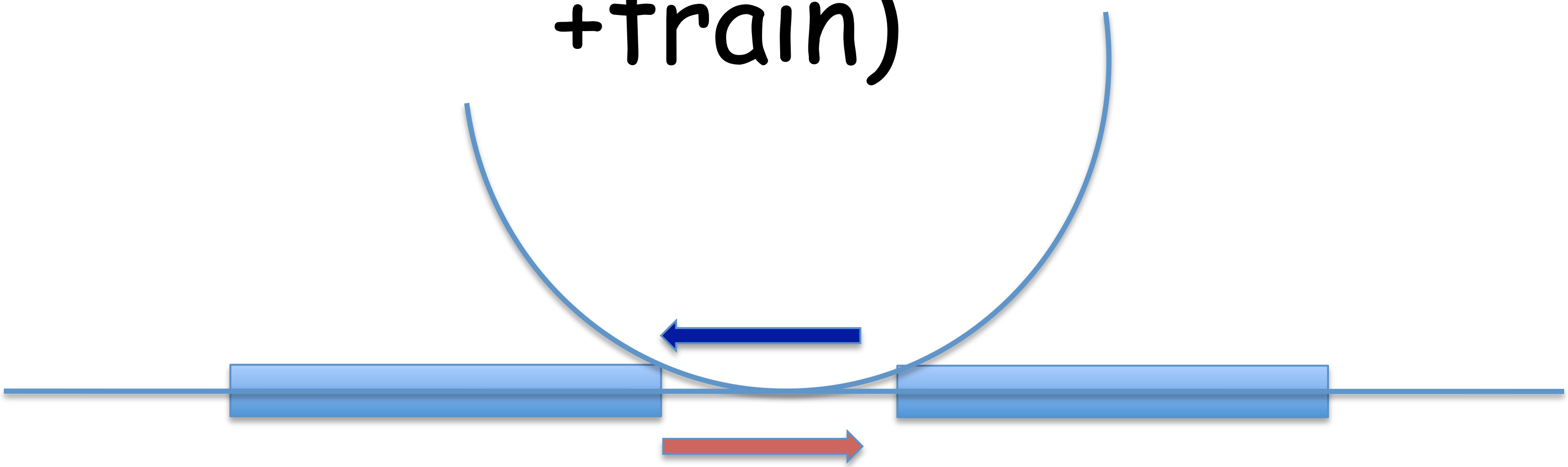
First guess: add a beam to carry the energy

100% Energy recovery
Period between = 2*(Linac+train)
Question – what is maximum transient loading?

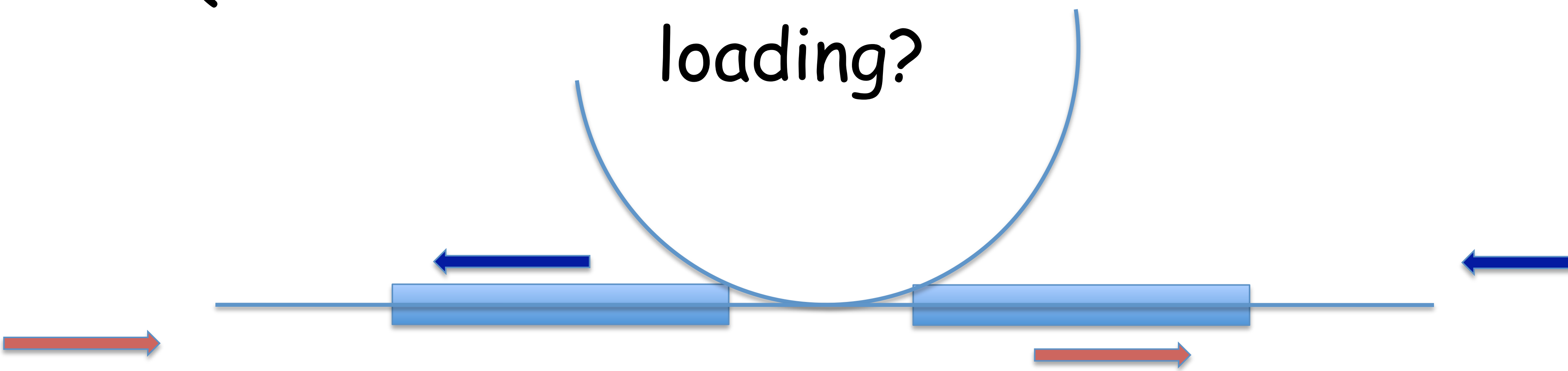


$$\mathcal{L} \sim \frac{T}{L+T}$$

100% Energy recovery Period between = 2*(Linac +train)

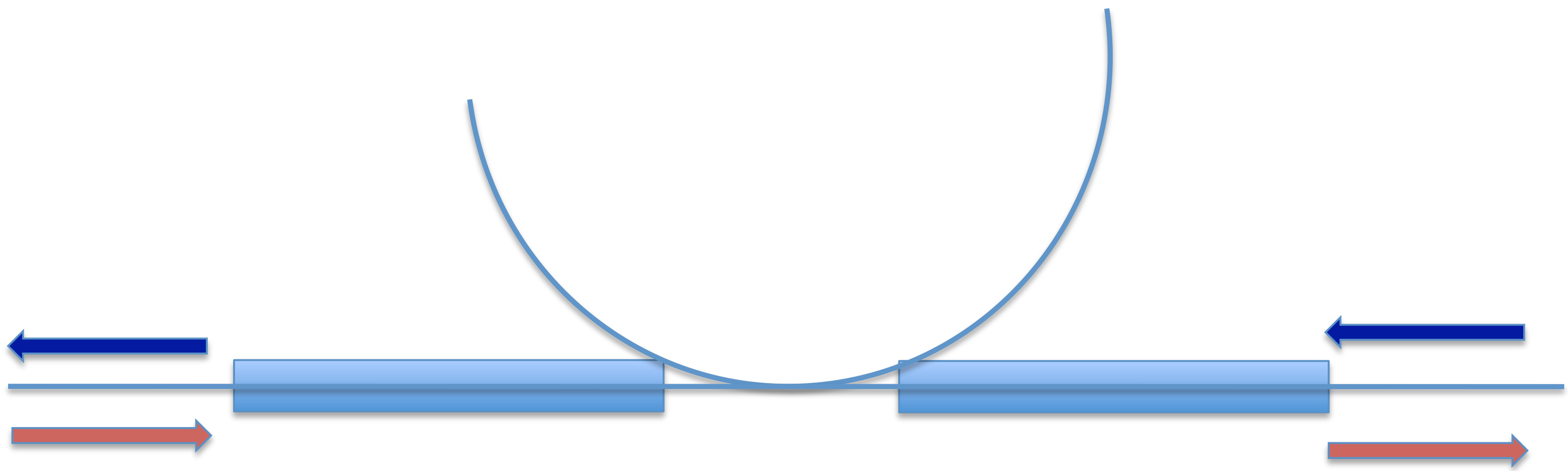


100% Energy recovery
Period between = 2*(Linac+train)
Question - what is maximum transient loading?



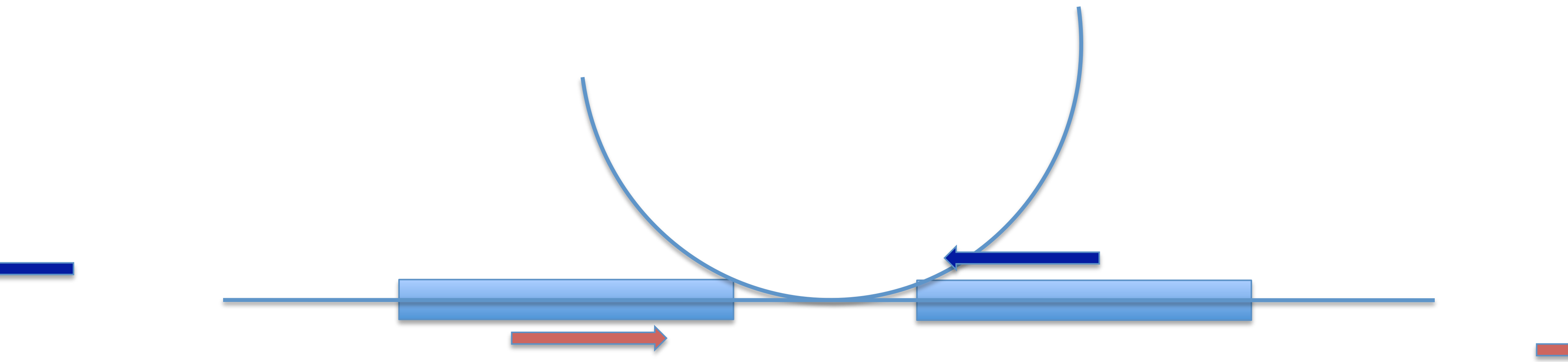
$$\mathcal{L} \sim \frac{T}{L+T}$$

100% Energy recovery
Period between = 2*(Linac+train)



$$\mathcal{L} \sim \frac{T}{L+T}$$

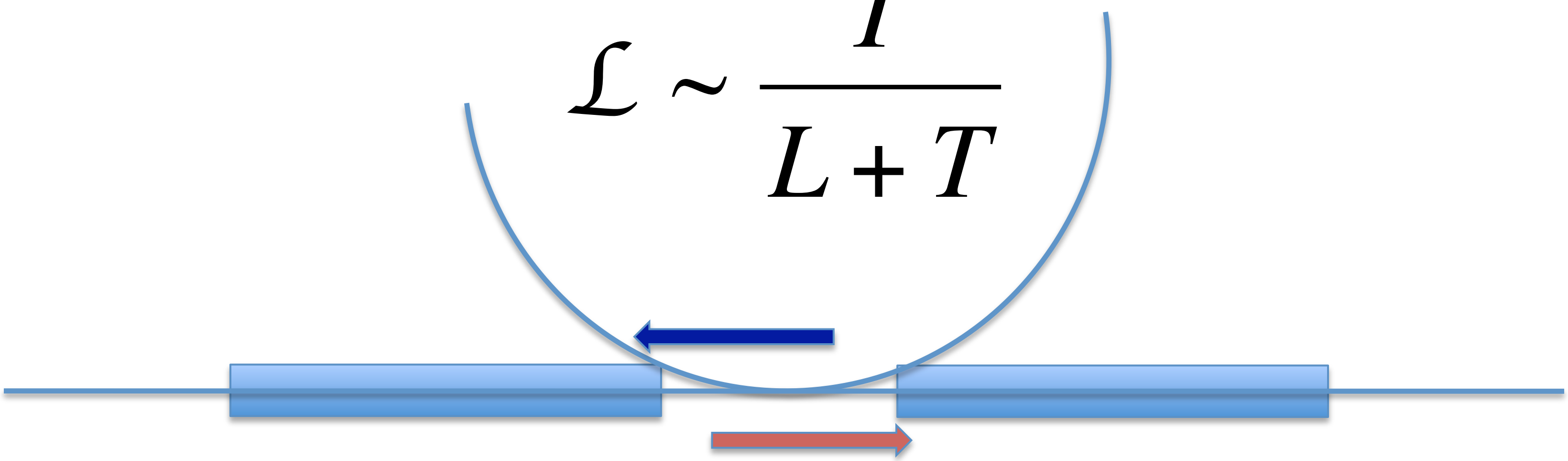
100% Energy recovery
Period between = 2*(Linac+train)



$$\mathcal{L} \sim \frac{T}{L+T}$$

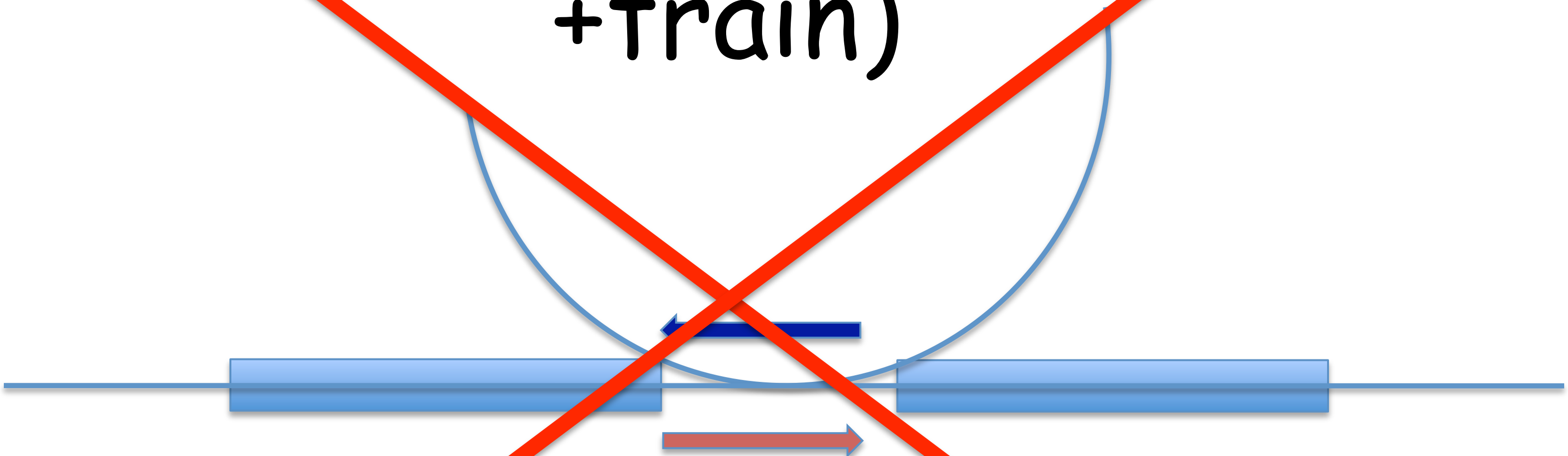
100% Energy recovery
Period between = 2*(Linac+train)

$$\mathcal{L} \sim \frac{T}{L+T}$$



Question – what is maximum transient loading?

100% Energy recovery Period between = 2*(Linac +train)



Synchrotron radiation power

- Assume that you are turning around N beams with E/N energy, that you loose N^3 less energy compared with turning the full energy beam (like in a ring or in re-circulating ERL)
- Turning ten 10 GeV beams, reduces power for synchrotron radiation 1,000 times. Even using 10 times smaller radius (i.e. R= 300 m) gives 100 fold saving in radiated power
- In such scenario SR power can be reduced below 1 MW level to become irrelevant

LHeC Electrons ; Intensity / Power considerations

f_{rev} = 11245. 5 Hz given by LHC circumference #bun = 2800

high collision frequency f = #bun × frev = 31.5 MHz and high beam current

beam current I = n e f e = 1.60218×10^{-19} As

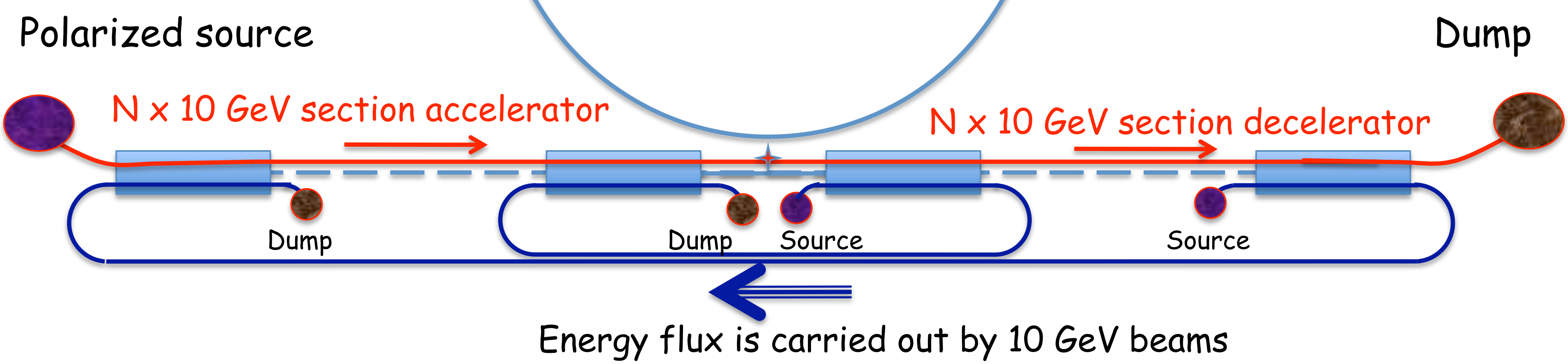
Ring : loss in SynRad $U_0 = C_\gamma E^4/\rho$ ρ = 2997 m LEP had ρ_{eff} = 3026.42 m

LINAC : beam power P = V I

machine	N / bun	#bun	Ntot / beam	I beam	V [GV]	P_{acc}= V I [MW]	U_0 [GeV]	Psyn [MW]
LEP 2	4.16E+11	4	1.67E+12	4×0.75 mA	100	300	2.923	8.77
LHeC, ring-e	1.40E+10	2800	3.92E+13	70.63 mA	70	4944	0.708[illegible]	50.05

H.Burkhardt

100% energy recovery
E = 30 - 150… GeV
N=3-15



What is the cost

- **Twice the length of the linac – initial cost**
- **Double the cryogenics (~ 1kW/1GeV CW at 2 K?)**
  - This seem to be the main limiting factor
  - 2 x 150 GeV CW linacs will need ~ 150-300 MW AC power for refrigirator
  - The way to go around it to operate at modest duty factor ~ 10%, to reduce energy consumption well below 100 MW
- **With 10% duty factor luminosity limit will**

LHeC Extreme, 10% Duty factor

Parameter	**Protons**	**Electrons**
# per bunch	**5.00E+11**	**6.00E+11**
Beam current, A	**1.265**	**0.15**
Emittance, nm rad	**0.5**	**0.5**
Beta*, cm	**20**	**20**
Tune shift	**0.02**	**irrelevant**
Luminosity		**7.1E+34**

Conclusion

- There is the way of building LHeC with luminosity above 10^{34} cm^{-2} sec^{-1} , electron energy well above 100 GeV and with power consumption well below 100 MW
- Even with 1% duty factor it can deliver luminosity of $7 \cdot 10^{33}$ cm^{-2} sec^{-1}
- In this case the luminosity does depend on electron beam energy, i.e. there is no need of compromise Lumi vs. E
- It will require to double length of the linac structure
- This system, excluding IR, is completely independent from the LHC
- This scenario, being linac, is perfect for staging, starting at modest energy of e-beam and adding 10 GeV modules
- Details ate important and effect on the proton beam should be properly simulated