LHeC as an electron-nucleus (e-A and e-D) Collider

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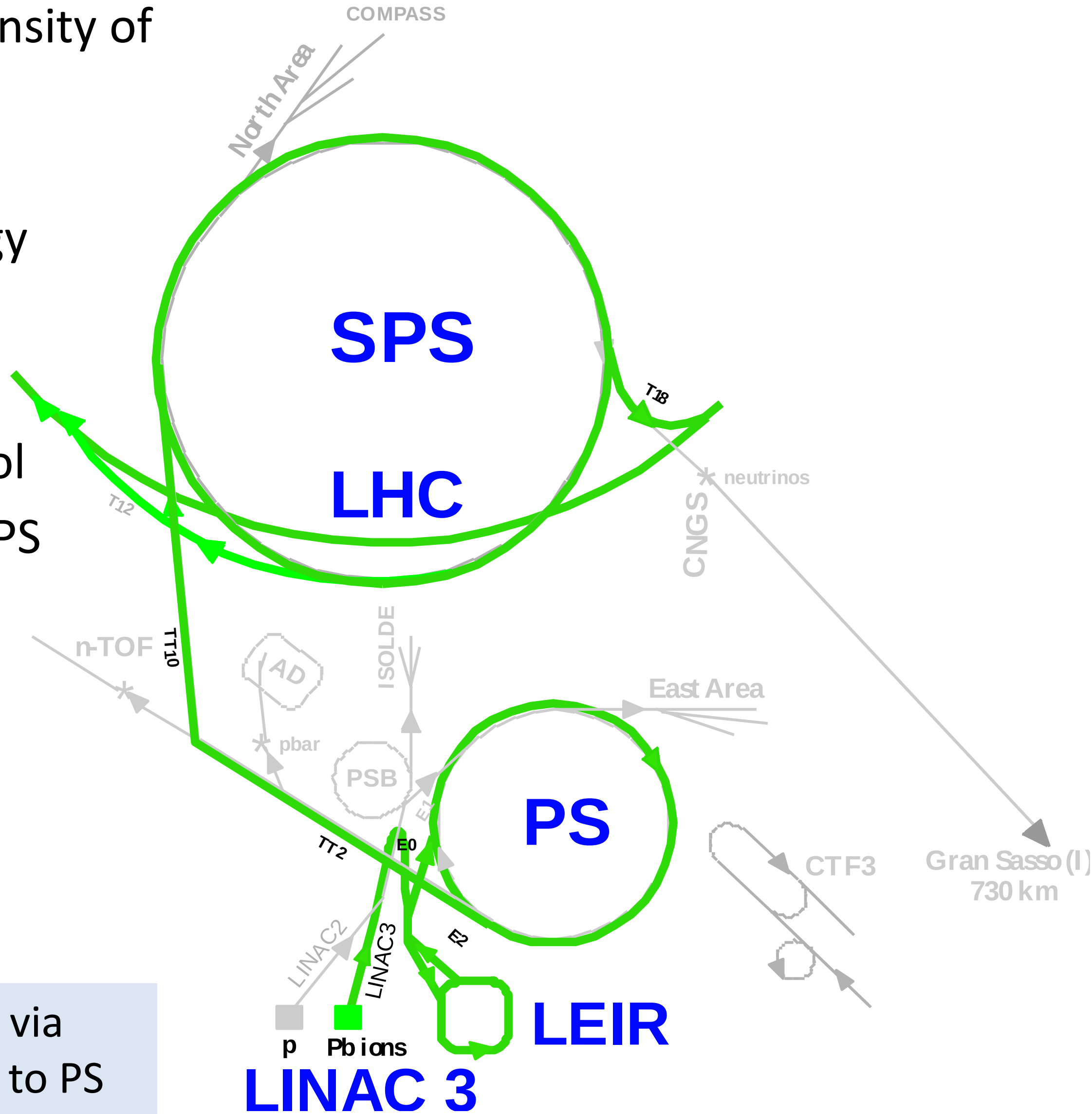
From LHeC CDR, Section 7.13.1

- With the first collisions of lead nuclei ($^{208}Pb^{82+}$) in 2010, the LHC has already demonstrated its capability as a heavy-ion collider and this naturally opens up the possibility of electron-nucleus (e-A) collisions in the LHeC.
- In order to avoid interference with the high luminosity proton-proton operation, this mode of operation would naturally be included in the **annually-scheduled ion operation period of the LHC**. (~ 1 month)
- In principle, the CERN complex could provide A-A (or even p-A) collisions to the LHC experiments while the LHeC operates with e-A collisions.

Present LHC Ion Injector Chain

- ECR ion source
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR
  - Accumulate and electron-cool
  - Prepare bunch structure for PS
- PS
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS
  - Define filling scheme of LHC

Protons come from different source via Linac2 (later Linac4) and PS Booster to PS



Heavy ion beams available in LHC

- Mainly $^{208}Pb^{82+}$ (now colliding in LHC)
  - Pb beam parameters quite well known, most interest
  - First p-Pb run expected this year
- Soon $^{40}Ar^{18+}$ or $^{129}Xe^{54+}$ for SPS fixed target
  - Ar-Ar collisions planned for 2021 in LHC
  - No solid intensity values for now
  - Other species possible in principle but it takes time to switch present source (~ 1 species /year)
  - (Additional source discussed later for deuterons)

- One can imagine doing e-A with LHeC while LHC is doing A-A or p-A where A and A are any of above
  - (But Pb-Pb collisions reduce integrated e-Pb luminosity.)

Luminosity estimate for e-Pb in Ring-Ring (1)

- Assume design Pb beam, 100 ns bunch spacing
  - more or less achieved although 200 ns may be better and 100 ns not yet used in LHC
  - Same geometric beam size as nominal protons so easy to take over optics and luminosity considerations
  - In practice Pb more blown up by IBS at injection

		Design Pb	Ultimate Pb
Energy	E_{Pb}	574. TeV	
Energy per nucleon	E_N	2.76 TeV	
No. of bunches	n_b	592	
Ions per bunch	N_{Pb}	$7. \times 10^7$	1.2×10^8
Normalised emittance	ε_n	1.5 μm	

  - Since e-A physics focused on low x, using the RR High Acceptance (1° optics)

Luminosity estimate for e-Pb in Ring-Ring (2)

- Assume e- injectors can create matching bunch train
- Increase electron bunch intensity by factor 2808/592 to use the have same total current and total RF power

Detector Option		1°		10°	
Quantity	unit	electrons	protons	electrons	protons
Number of bunches			2808		
Particles/bunch N_b	10^{10}	9.5	17	1.96	17
Horiz. beta-function	m	0.4	4.0	0.18	1.8
Vert. beta-function	m	0.2	1.0	0.1	0.5
Horiz. emittance	nm	5.0	0.5	5.0	0.5
Vert. emittance	nm	2.5	0.5	2.5	0.5
Distance to IP	m	6.2	22	1.2	22
Crossing angle	mrad	1.0		1.0	
Synch. Rad. in IR	kW	51		33	
absolute Luminosity	$m^{-2}\ s^{-1}$	$8.54 * 10^{32}$		$1.8 * 10^{33}$	
Loss-Factor S		0.86		0.75	
effective Luminosity	$m^{-2}\ s^{-1}$	$7.33 * 10^{32}$		$1.34 * 10^{33}$	

Table 7.11: Parameters of the mini beta optics for the 1° and 10° options of the LHeC Interaction Reg

Luminosity estimate for e-Pb in Ring-Ring (3)

- This gives us an idea of the peak luminosity that can be expected **electron-nucleon** luminosity

$$L_{eN} = \frac{n_b f_0 N_e (A N_{\mathrm{Pb}})}{4\pi \sqrt{\beta^*_{xe}\varepsilon_x}\sqrt{\beta^*_{ye}\varepsilon_y}} = \begin{cases} 2.6 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & (\mathrm{Nominal\ Pb}) \\ 4.5 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & (\mathrm{Ultimate\ Pb}) \end{cases}$$

- N.B. electron-nucleus luminosity (usually quoted for Pb-Pb at LHC) is 208 times less
- Can hope for more with an upgraded (more bunches? cooled?) Pb beam
- Luminosity lifetime determined by intensity decay of Pb due to Pb-Pb collisions in LHC (about twice Pb-Pb value)
- Could be higher in dedicated e-A mode
  - Even growing luminosity thanks to strong radiation damping for Pb ions (twice that of protons)

Electron-deuteron (e-D) collisions

- No deuteron beams in present CERN complex
- Linac4 cannot accelerate D, even with a D- source
- Linac2 should be shut down, eventually
- Only possibility with existing accelerators is to use present heavy ion Linac3
  - Requires new D source, RFQ, switchyard,
  - Several years' lead time to develop
  - Uncertain how LEIR would perform with D
  - Present studies of new light ion source (He to Ne) under way (medical use of LEIR), might be extended to D if officially requested (presently no formal request for LHC)
- Possible alternative (D. Kuchler): cyclotron injecting ~1 mA D directly to PS synchrotron
  - Could be cheaper, even table-top if injecting to LEIR

Luminosity estimate for e-D (1)

- Very rough for now … help from D. Kuchler

  Present source gives $^{208}\mathrm{Pb}^{29+}$ with $Q/A = 1/7.2$.
  Space charge limit entrance of Linac3 $\approx 200\ \mu$A.
  For D with $Q/A = 1/2$, expect space charge limit $\approx 55\ \mu$A

- However, this gives a big margin in fields and there are no losses from stripping.
- If source is intense enough and losses in Linac can be tolerated, can hope for 200-500 µA at end of linac (with somewhat degraded beam quality).

  Scaling from Pb values to intensity in LHC

  $$\frac{200-500\mu A}{50\mu A}\frac{82}{2}7\times10^{7} = 1.5\times10^{10}\ \text{D/bunch in LHC}$$

- Take safety reduction factor 5 for unknowns in PS, SPS, etc.

Luminosity estimate for e-D (2)

- Again assume similar geometrical emittances as for p and Pb
- Assume electron beam as for Pb
- Can hope for **electron-nucleon** luminosity of order

$$L_{eN} \sim 10^{31}\ \mathrm{cm^{-2}s^{-1}}$$

- Perhaps a few times more with cyclotron option, etc.

Luminosity estimate for e-Pb in Linac-Ring (1)

Verify ERL frequency tunability for p → Pb bunch frequency in LHC

Very small, probably OK

8.4.1 Heavy nuclei, e-Pb collisions

The Pb beam is specified in Table 7.33. Assuming that the 60 GeV electron beam specified in Table 8.7 can be adapted to the irregular 100 ns spacing of the Pb beam, the luminosity follows from Eq. 8.1 (including the additional factor of $A = 208$ to obtain the electron-nucleon luminosity):

$$L_{eN} = \begin{cases} 9 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Nominal Pb)} \\ 1.6 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Ultimate Pb)} \end{cases} \tag{8.21}$$

where we assume $H_{hg} = H_D = 1$ for the additional factors in Eq. 8.1.

8.4.2 Electron-deuteron collisions

An estimate of the parameters for deuteron beams in the LHC is also given in Section 7.13. Proceeding in the same manner as above, we find that *electron-nucleon* luminosities of order $L_{eN} \gtrsim 3 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ could be accessible in e-D collisions in a Linac-Ring LHeC.

Future work

- Ensure that capabilities of HI injector chain and LHC are maintained / upgraded up to LHeC era
  - High Pb intensity at high energy (collimation losses in LHC, losses from luminosity at LHC experiments, …)
  - Cooling of HI beams in LHC (stochastic cooling, coherent electron cooling, …) ?
- Launch studies for deuteron source and performance of injector chain (Linac3 to SPS)
- Evaluate performance at lower electron beam energy
  - N. Armesto's talk

Summary

- Assuming that the electron beams can be adapted to the filling scheme of the LHC’s heavy ion beams, the LHeC could operate as an electron-ion collider in parallel with normal operation as heavy-ion collider
  - Integrated luminosity could be better in dedicated mode

- Deuterons require a study on source and pre-injectors to be started with several years lead time
- ^{4}He beams may be easier if acceptable for physics ??