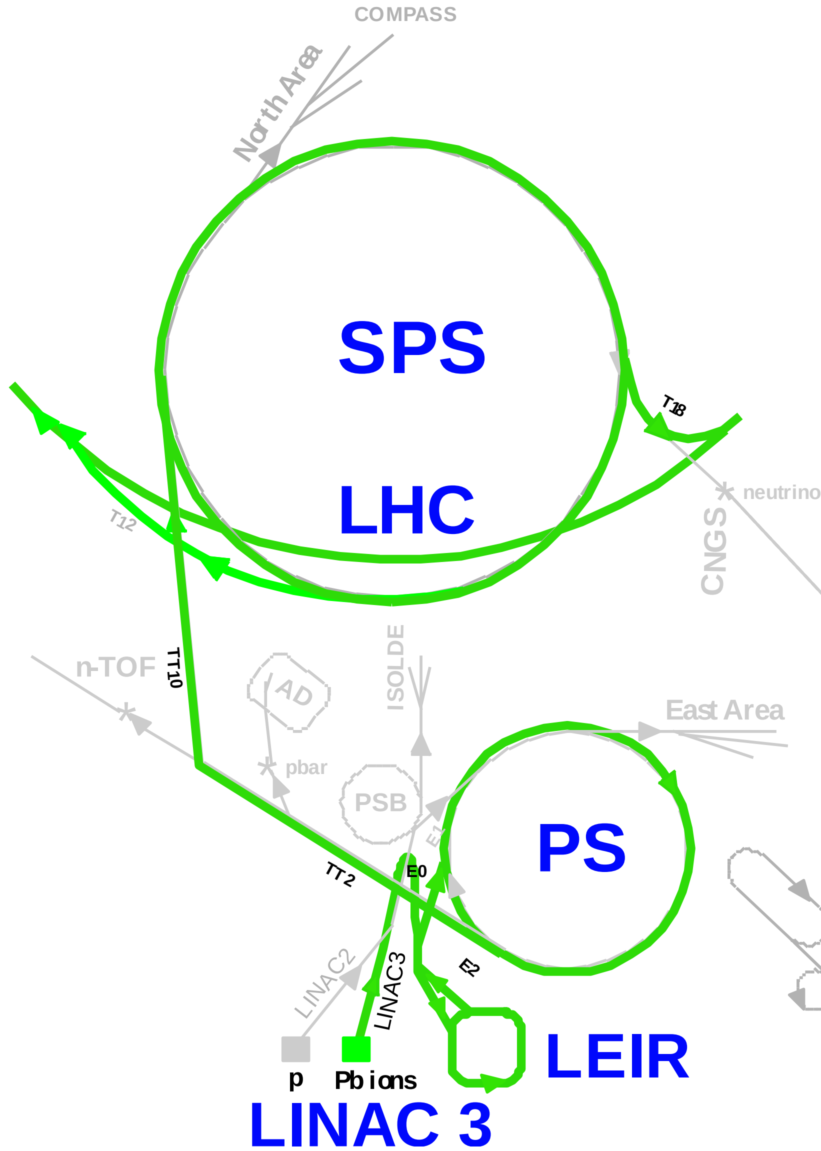
LHeC Ring-Ring option: electron-nucleus collisions

John Jowett
CERN

Present LHC Ion Injector Chain

- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC



Electron-nucleus (e-A) collisions

- The LHC will operate as a nucleus-nucleus (initially Pb-Pb) collider
  - Physics programme is expected to include:
    - Pb-Pb at $\sqrt{s_{NN}} = 5.5\,\text{TeV}$
    - p-Pb at
    - A-A where A may be Ca, O, …
- Natural possibility of colliding electrons with $^{208}Pb^{82+}$ nuclei
  - Requires maintenance of LHC ion injector complex (source-LINAC3-LEIR) through to the time of operation of LHeC
  - Also requires inclusion of ion capability in new generation of injector synchrotrons (PS $\rightarrow$ PS2, SPS $\rightarrow$ SPS2 ??)
- Electron-deuteron e-d collisions would require a completely new source (at least!)
  - Present CERN complex does not foresee deuterons

e-Pb collisions in Ring-Ring

- Present nominal Pb beam for LHC
  - Same beam size as protons, fewer bunches

$$k_b = 592 \text{ bunches of } N_b = 7\times 10^7 \;\; {}^{208}\text{Pb}^{82+} \text{ nuclei}$$

- Assume lepton injectors can create matching train of e^-

$$k_b = 592 \text{ bunches of } N_b = 1.4\times 10^{10} \;\; e^-$$

- Lepton-nucleus or lepton-nucleon luminosity in ring-ring option at 70 GeV

$$L = 1.09\times 10^{29} \text{ cm}^{-2}\text{s}^{-1} \quad \Leftrightarrow \quad L_{en} = 2.2\times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$$

gives 11 MW radiated power

  - May be possible to exploit additional power by increasing electron single-bunch intensity by factor 592/2808=4.7.

e-Pb collisions in Linac-Ring (1)

- Present nominal Pb beam for LHC
  - Same beam size as protons, fewer bunches

$k_b = 592$ bunches of $N_b = 7 \times 10^7$ $^{208}Pb^{82+}$ nuclei

- Assume lepton injectors can create matching train of e$^-$ - non-regular bunch spacing *with same average beam current and power*
  - Scale from F. Zimmermann in EPAC2009

The electron beam size is assumed to be matched to the size of the protons, $\sigma_p^* = \sigma_e^*$, as a smaller electron beam could have adverse effects on the proton beam lifetime. For round-beam collisions, the luminosity is

$$L = \frac{1}{4\pi e} \frac{N_{b,p}}{\epsilon_p} \frac{1}{\beta_p^*} I_e \, H_{\rm hg}, \qquad (1)$$

where e denotes the electron charge, and the subindices p or e refer to protons or electrons. The luminosity (1) depends only on the p beam brightness $(N_{b,p}/\epsilon_p)$ with $N_{b,p}$

e-Pb collisions in Linac-Ring (2)

	LHeC-RR	LHeC-RL high lumi
e^- energy at IP [GeV]	60	60
luminosity [10^{32} cm^{-2}s^{-1}]	29	$29^\dagger$ ($2.9^\ddagger$)
bunch population [10^{10}]	5.6	$0.19^\dagger$ ($0.02^\ddagger$)
e^- bunch length [μm]	$\sim$10,000	300
bunch interval [ns]	50	50
norm. hor.&vert. emittance [μm]	4000, 2500	50
average current [mA]	135	$7^\dagger$ ($0.7^\ddagger$)

$$L = 1.19 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1} \quad \Leftrightarrow \quad L_{\text{en}} = 2.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$$

which is about a factor 2 better than Ring-Ring with similar level of optimism about using available power (or a factor 10 if Ring-Ring is taken to be limited in bunch intensity).

Electron-deuteron collisions?

- Needs new source at CERN
- Two possibilities after source:
  - Existing Pb ion injector chain (Linac3, RFQ, LEIR) could be used but many details need study intensity will be limited
    - Rough estimate: 1/100 charge per bunch of p in LHC
  - New pre-injector Linac4 (under construction), PSB, d^- injection, etc.
    - Not designed for deuterons, would require new RFQ, first simulation indicated limited transmission but may hope for more than Linac3
    - Feasibility of this option needs more study of whole injector chain, probably need shutdown to switch to/from protons
    - Rough estimate: 1/10 charge per bunch of p in LHC
- Both options need new RFQ + other modifications, will cost few MCHF, feasibility cannot be guaranteed at this stage.

Very(!) tentative e-D luminosity

- Rough guess for beam via Linac3
  - Same beam size as protons, fewer bunches as for Pb

$$k_b = 592 \text{ bunches of } N_b = 1.7\times 10^{9} \text{ deuterons}$$

- Assume lepton injectors can create matching train of e^-

$$k_b = 592 \text{ bunches of } N_b = 1.4\times 10^{10} \text{ e}^-$$

- Lepton-nucleus or lepton-nucleon luminosity in ring-ring option at 70 GeV

$$L = 2\times 10^{30} \text{ cm}^{-2}\text{s}^{-1} \quad \text{gives 11 MW radiated power}$$

  - Optimist might hope for maybe 10-50 times more if Linac4 and other systems work well.
  - A lot of further study required!!

e-A collisions Summary

- Natural possibility of colliding electrons with $^{208}Pb^{82+}$ nuclei but requires long-term policy:
  - Maintenance of LHC ion injector complex (source-LINAC3-LEIR) through to the time of operation of LHeC
  - Also requires inclusion of ion capability in new generation of injector synchrotrons (PS $\rightarrow$ PS2, SPS $\rightarrow$ SPS2 ??)
- Other nuclei such as Ca (expected for use in LHC AA collisions) should also be possible with present ion source and pre-injectors.
- Electron-deuteron e-D collisions would require a completely new source (at least!)
- Linac-Ring has potential for few times higher luminosity at Ring-Ring accessible energies.

Backup slides

Nominal Pb-Pb collision parameters

		Injection	Collision
Beam parameters			
Lead ion energy	[GeV]	36900	574000
Lead ion energy/nucleon	[GeV]	177.4	2759.
Relativistic "gamma" factor		190.5	2963.5
Number of ions per bunch		$7. \times 10^7$	
Number of bunches		592	
Transverse normalized emittance	[μm]	1.4^a	1.5
Peak RF voltage (400 MHz system)	[MV]	8	16
Synchrotron frequency	[Hz]	63.7	23.0
RF bucket half-height		1.04×10^{-3}	3.56×10^{-4}
Longitudinal emittance (4σ)	[eV s/charge]	0.7	2.5^b
RF bucket filling factor		0.472	0.316
RMS bunch length[c]	[cm]	9.97	7.94
Circulating beam current	[mA]	6.12	
Stored energy per beam	[MJ]	0.245	3.81
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2	[m]	10.0	0.5
RMS beam size at IP2	μm	280.6	15.9
Geometric luminosity reduction factor F[d]		-	1
Peak luminosity at IP2	[$cm^{-2}sec^{-1}$]	-	$1. \times 10^{27}$

Nominal Pb-Pb, lifetime parameters

		Injection	Collision
Interaction data			
Total cross section	[mb]	-	514000
Beam current lifetime (due to beam-beam)[a]	[h]	-	11.2
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.9	1.10
RMS bunch length	[cm]	9.97	7.94
Longitudinal emittance growth time	[hour]	3	7.7
Horizontal emittance growth time[b]	[hour]	6.5	13
Synchrotron Radiation			
Power loss per ion	[W]	3.5×10^{-14}	2.0×10^{-9}
Power loss per metre in main bends	$[\mathrm{Wm}^{-1}]$	8×10^{-8}	0.005
Synchrotron radiation power per ring	[W]	1.4×10^{-3}	83.9
Energy loss per ion per turn	[eV]	19.2	1.12×10^{6}
Critical photon energy	[eV]	7.3×10^{-4}	2.77
Longitudinal emittance damping time	[hour]	23749	6.3
Transverse emittance damping time	[hour]	47498	12.6
Variation of longitudinal damping partition number[c]		230	230
Initial beam and luminosity lifetimes			
Beam current lifetime (due to residual gas scattering)[d]	[hour]	?	?
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 11.2
Luminosity lifetime[e]	[hour]	-	< 5.6