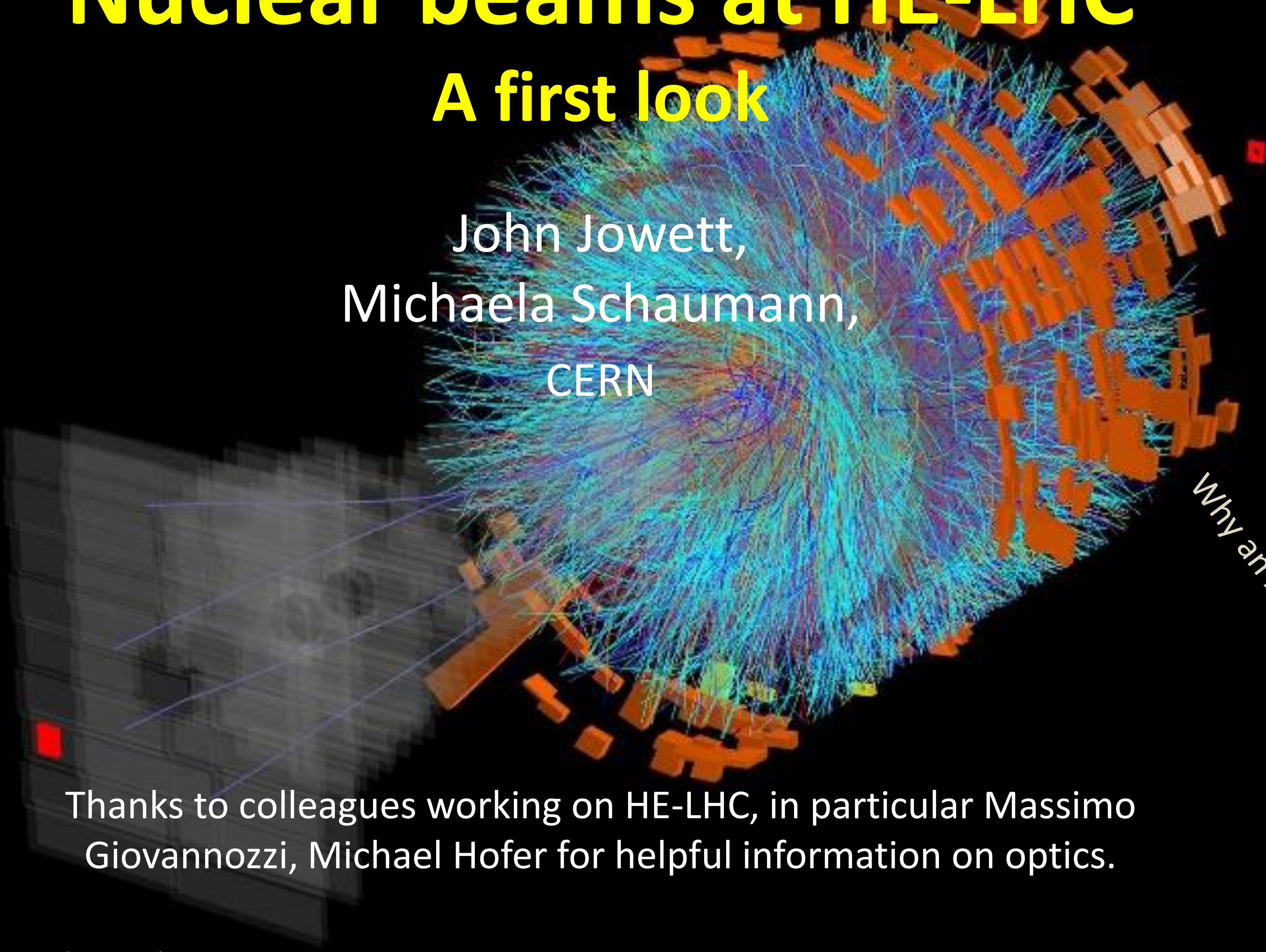
Nuclear beams at HE-LHC

A first look



John Jowett,
Michaela Schaumann,
CERN

Why an Xe-Xe picture?

Thanks to colleagues working on HE-LHC, in particular Massimo Giovannozzi, Michael Hofer for helpful information on optics.

Abstract

- We take a first look at the performance of the HE-LHC as a heavy-ion collider, based on the beams foreseen to be available during the high-luminosity heavy-ion phase of the LHC that will start in 2021.

- Like the FCC, the HE-LHC benefits from the faster radiation damping of heavy ions but beam losses due to collimation and ultraperipheral collisions at the interactions points have different consequences.

So far, *zero* FTEs have been available to work on heavy ions at HE-LHC.
Little participation in HE-LHC working groups.

This is just a first look, based on experience with LHC and the studies for FCC.

See talk on FCC as a nucleus-nucleus collider given earlier today.

Assumptions for first look at Pb-Pb operation

- Similar Pb beam as projected for HL-LHC
- Simplified scenario - see talks by JMJ and H Bartosik at LHC Performance Workshop, Chamonix 2017
  https://indico.cern.ch/event/580313/contributions/2359517/
- https://indico.cern.ch/event/580313/contributions/2359507/

  - All bunches are equal (consider single bunch pair simulation)
  - Initial bunch intensity (start of stable beams, slightly improved over HL-LHC)

$$\langle N_b \rangle = 2 \times 10^8$$

  - Initial emittance (start of stable beams)

$$\varepsilon_{xn} = 1.5 \times 10^{-6} \mathrm{m}$$

  - Other bunch parameters as LHC nominal, scaled with HE-LHC energy
- Simulation with Collider-Time-Evolution (CTE) program

LIU baseline (Jan 2017) parameters at start of collisions

- Simplified scenario - see talks by JMJ and H Bartosik
  - All bunches are equal (consider single bunch pair simulation)
  - Initial bunch intensity (start of stable beams)

$$\langle N_b \rangle = 2 \times 10^8$$

  - Initial emittance (start of stable beams)

$$\varepsilon_{xn} = 1.65 \times 10^{-6}\,\mathrm{m} \quad (\text{> design, some blow up from injected } 1.5 \times 10^{-6}\,\mathrm{m})$$

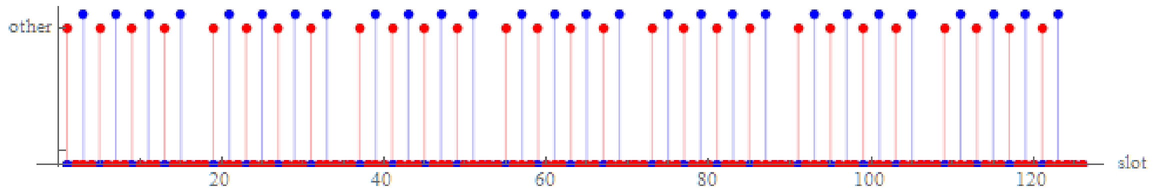
  - Other bunch parameters as nominal LHC with appropriate scaling to HE-LHC energy.

$$E \approx pc = \underbrace{13.5\,Z\ \mathrm{TeV}}_{\substack{\text{Energy per charge,} \\ \text{relation to proton energy}}} = \underbrace{5.32\,A\ \mathrm{TeV}}_{\text{Energy per nucleon}} = \underbrace{1107.\ \mathrm{TeV}}_{\substack{\text{Simply the energy} \\ \text{of the particle,} \\ \text{for all calculations}}}$$

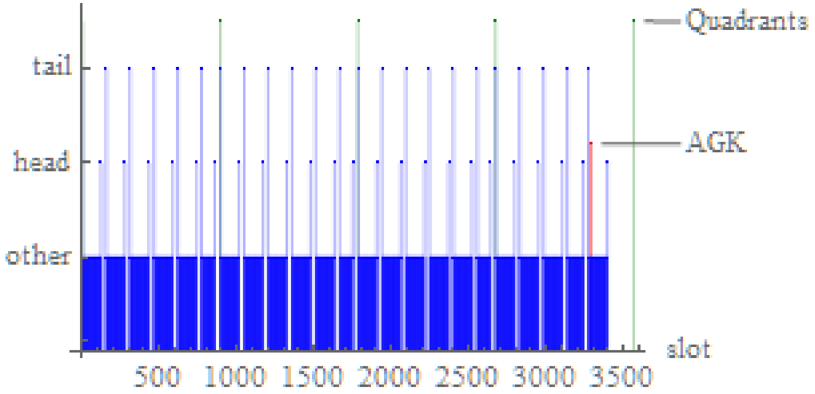
Centre-of-mass energy for nucleon pairs in collision

$$\sqrt{s_{NN}} \approx 10.64\ \mathrm{TeV}$$

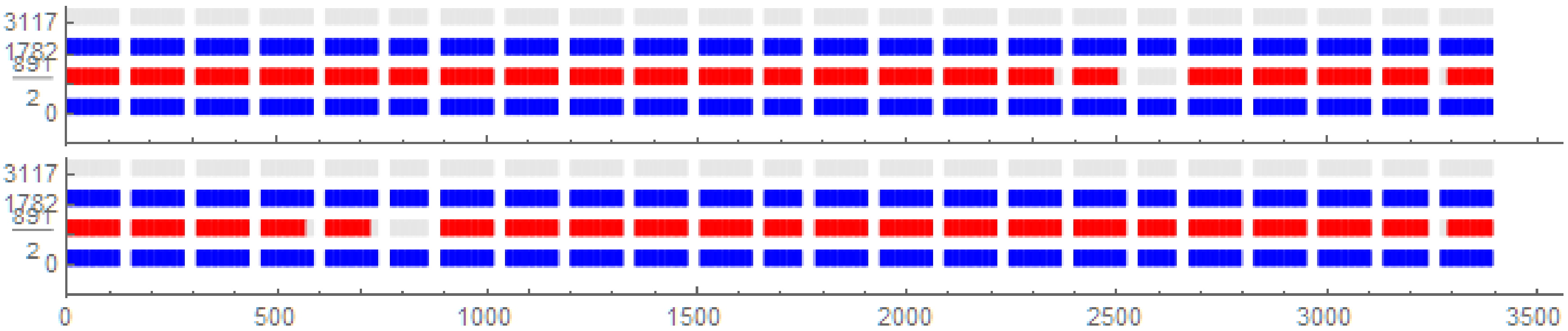
Filling scheme for HL-LHC Pb-Pb (LIU TDR baseline)



56 bunch SPS train
after slip-stacking in SPS

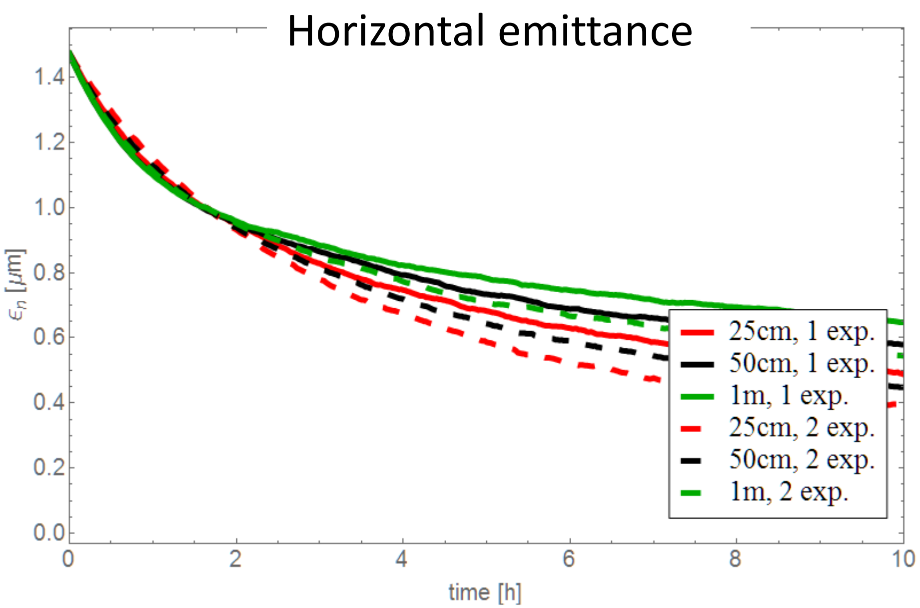


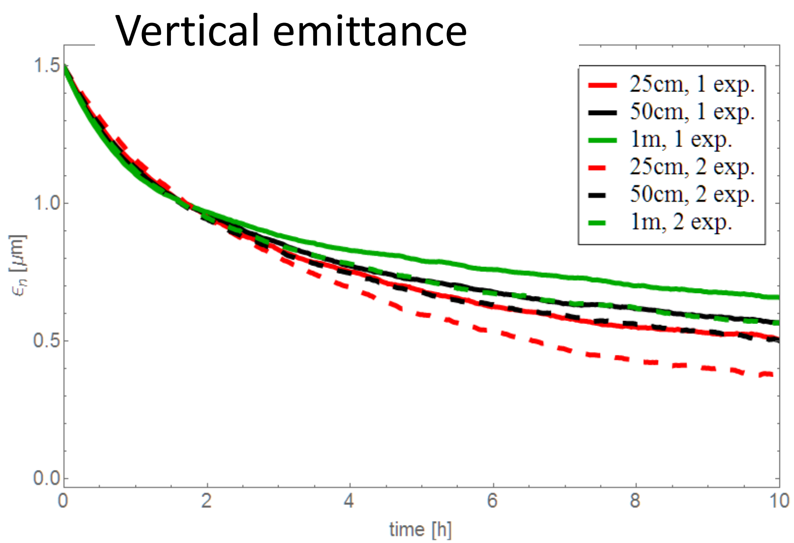
Two beams are identical, maximal filling with quadrant symmetry



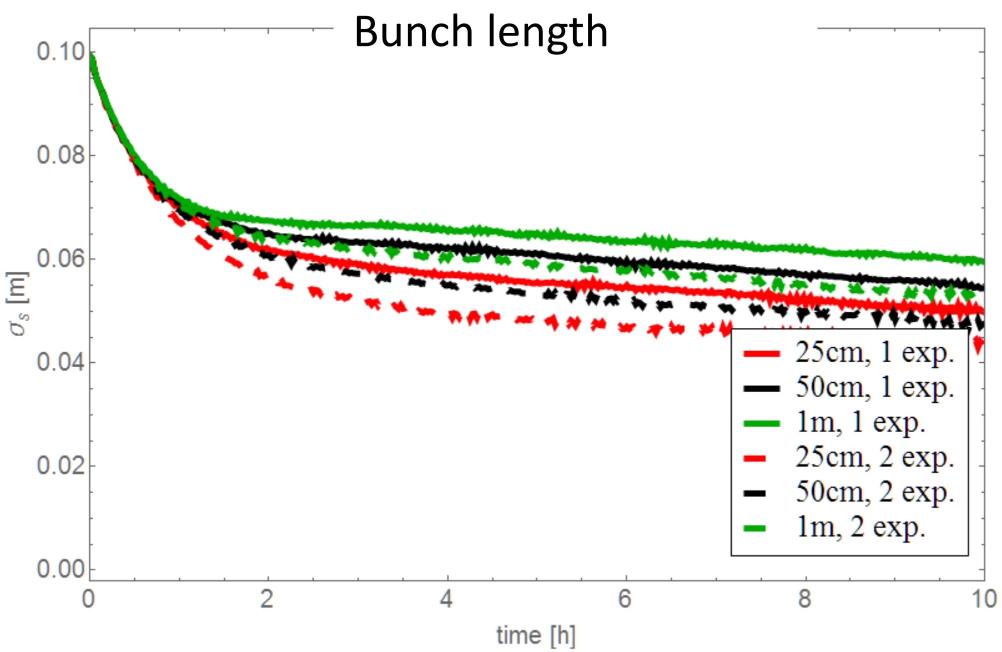
23 injections of 56-bunch trains give total of 1232 in each beam.
1232 bunch pairs collide in ATLAS CMS, 1168 in ALICE, 0 in LHCb.

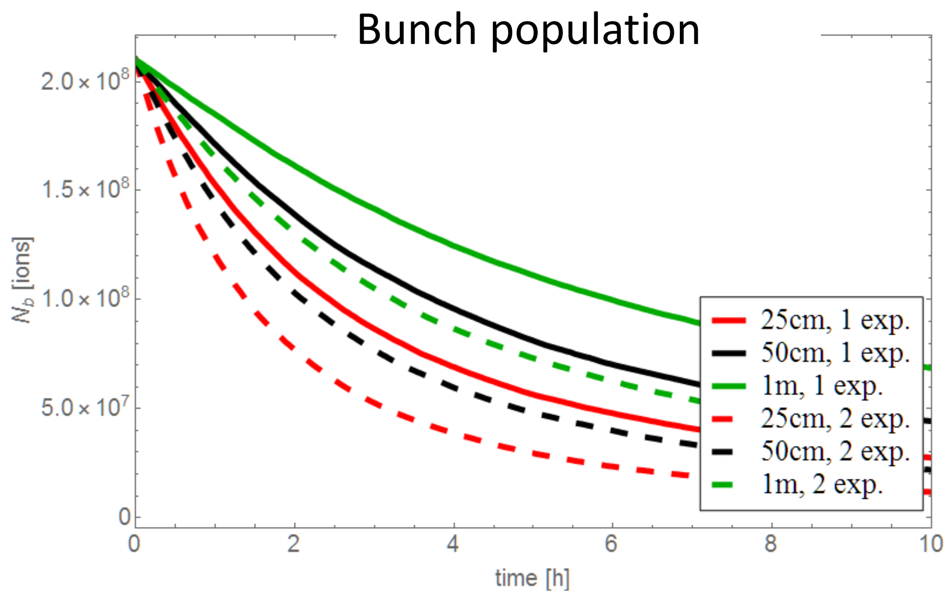
Beam parameter evolution in simulated Pb-Pb fill



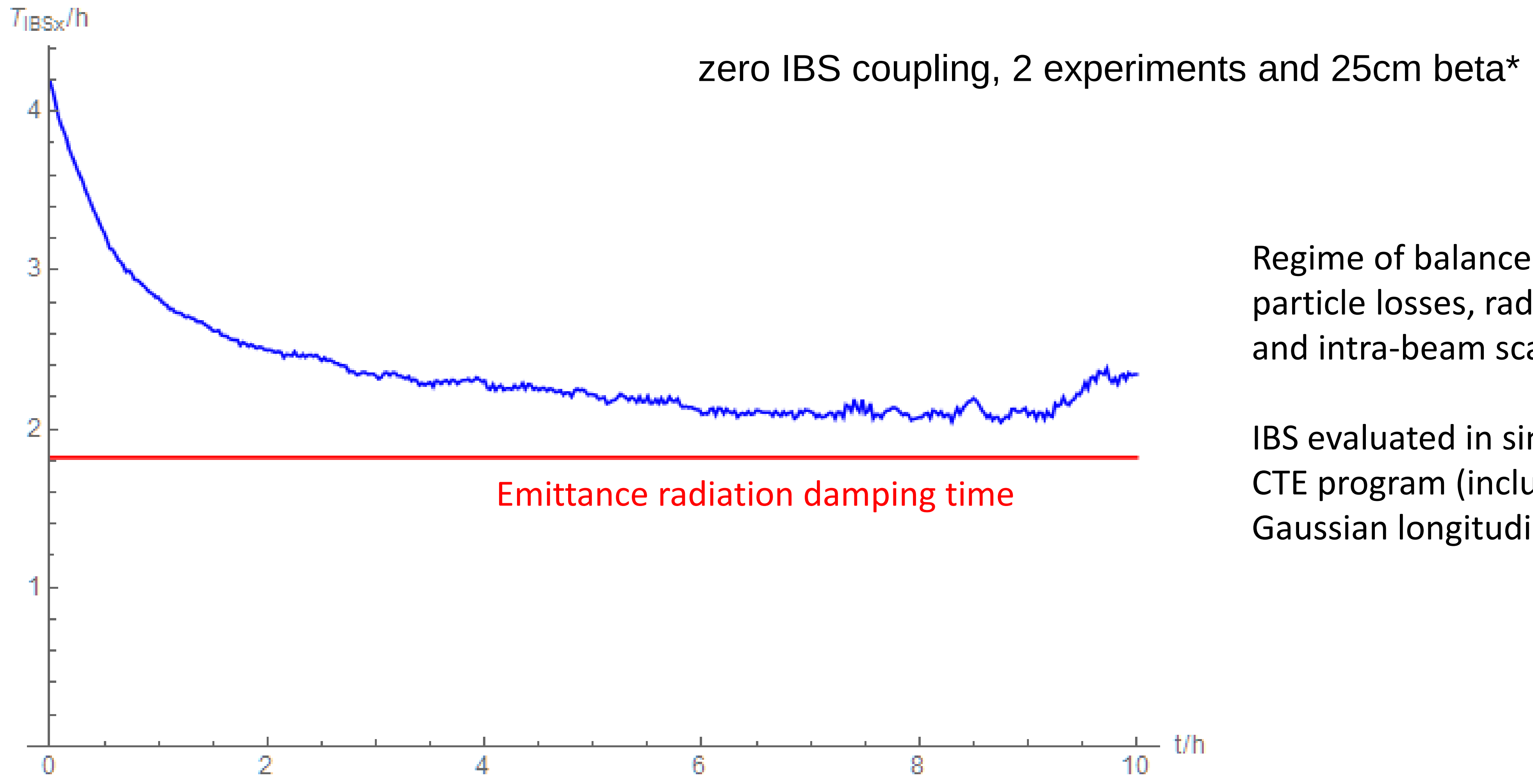


Consider optics as in V0.2 physics configuration but also some additional cases with higher β*.





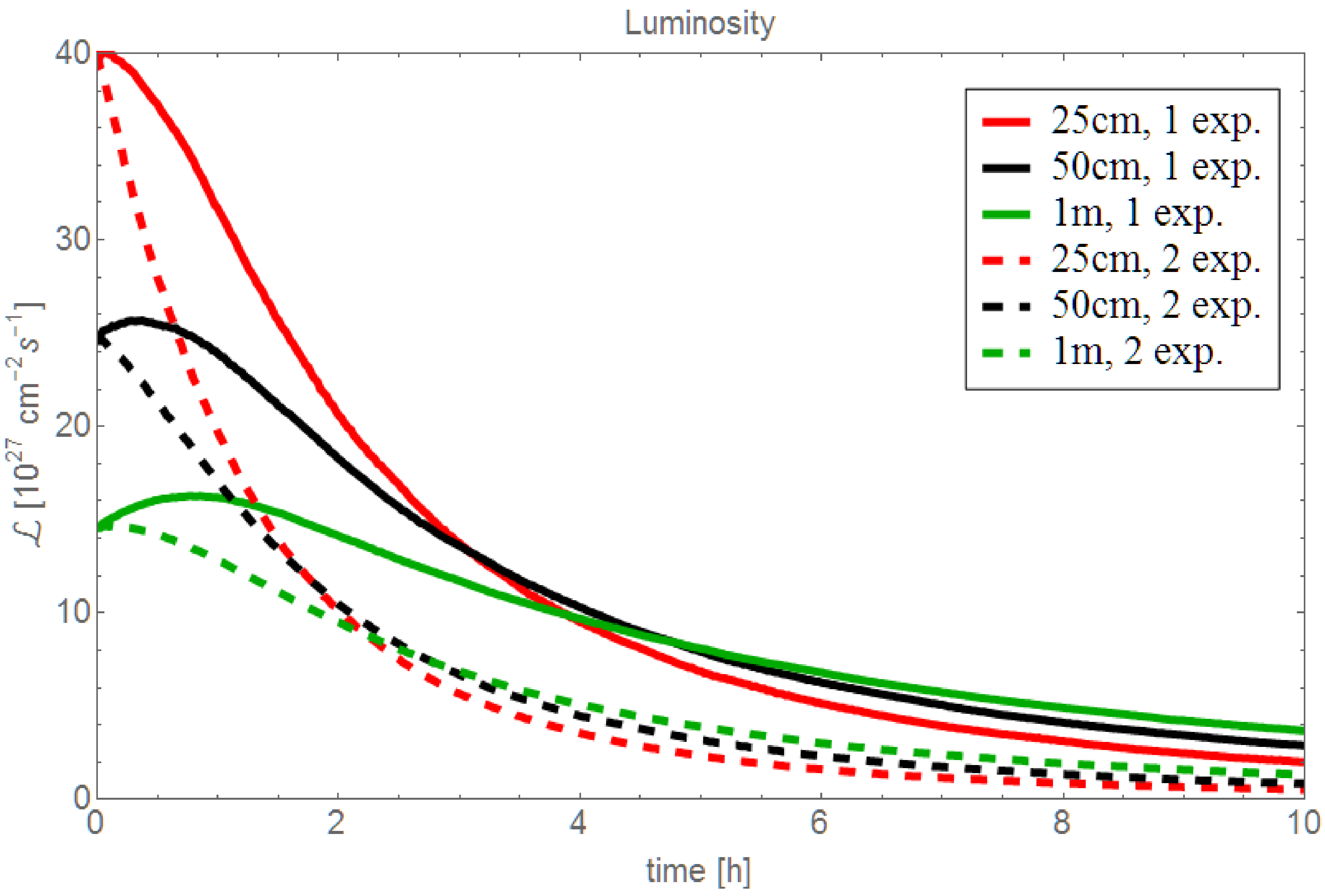
Emittance growth time from IBS and radiation damping



Regime of balance between particle losses, radiation damping and intra-beam scattering.

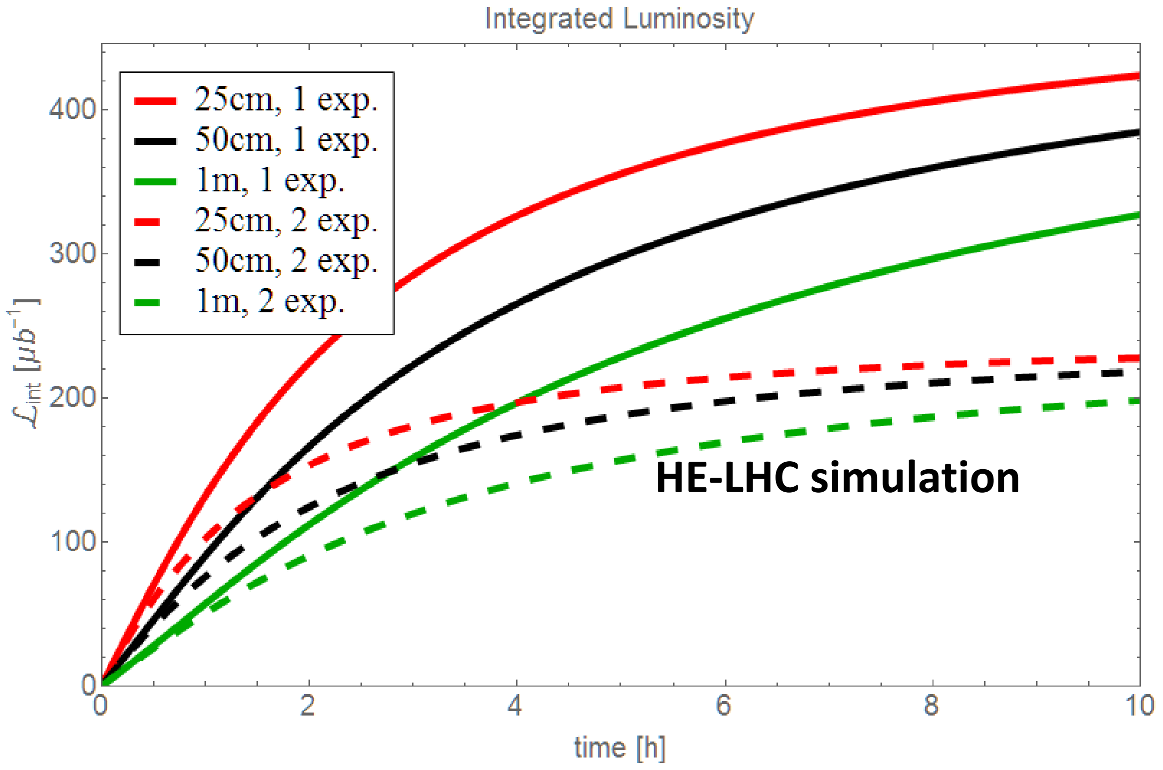
IBS evaluated in simulation with CTE program (includes non-Gaussian longitudinal distribution).

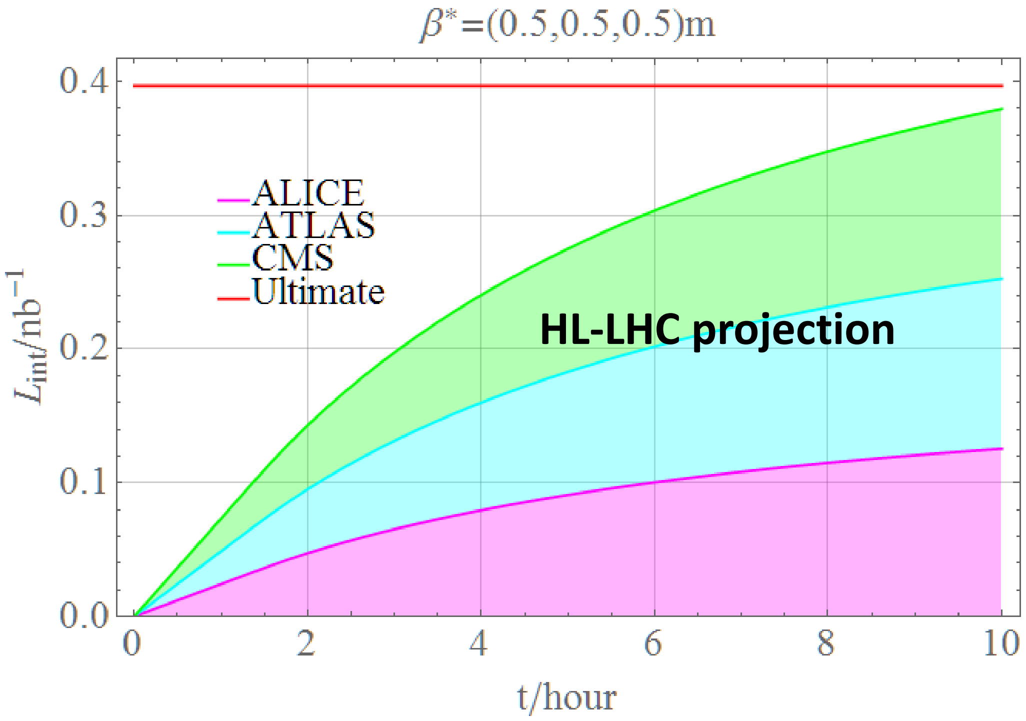
Luminosity evolution in a fill



Consider optics as in V0.2 physics configuration but also some additional cases with higher β*.

Integrated luminosity in a fill compared with Pb-Pb at HL-LHC





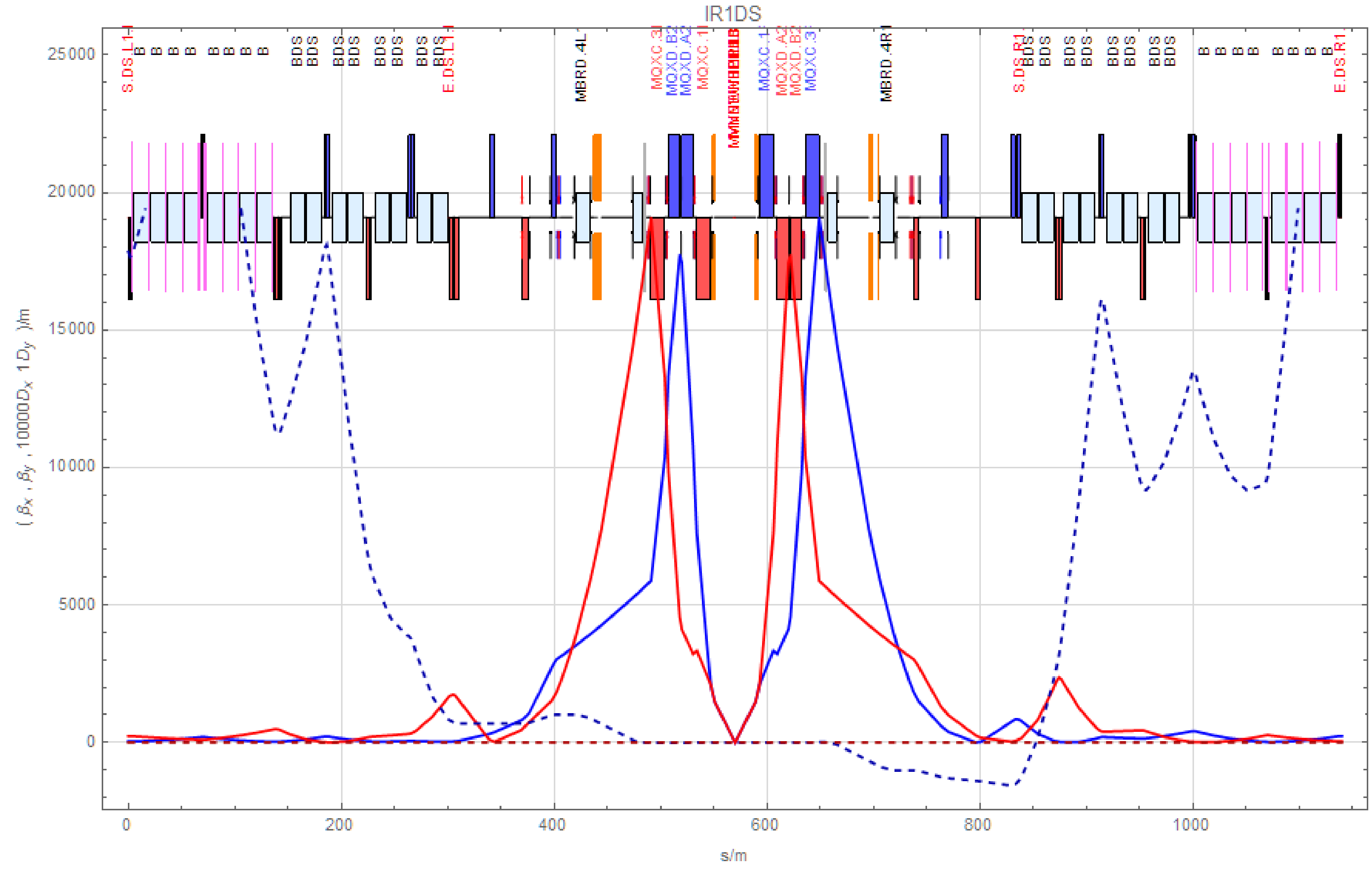
Ultimate luminosity to share per fill

$$L_{int,max} = \frac{k_c N_b}{\sigma_c}$$

The gain in integrated luminosity over HL-LHC is fairly small and is strongly affected by turn-around time – not surprising since we are assuming essentially the same injected beam.

HL-LHC projections are for 3.85 nb^{-1} per one-month run

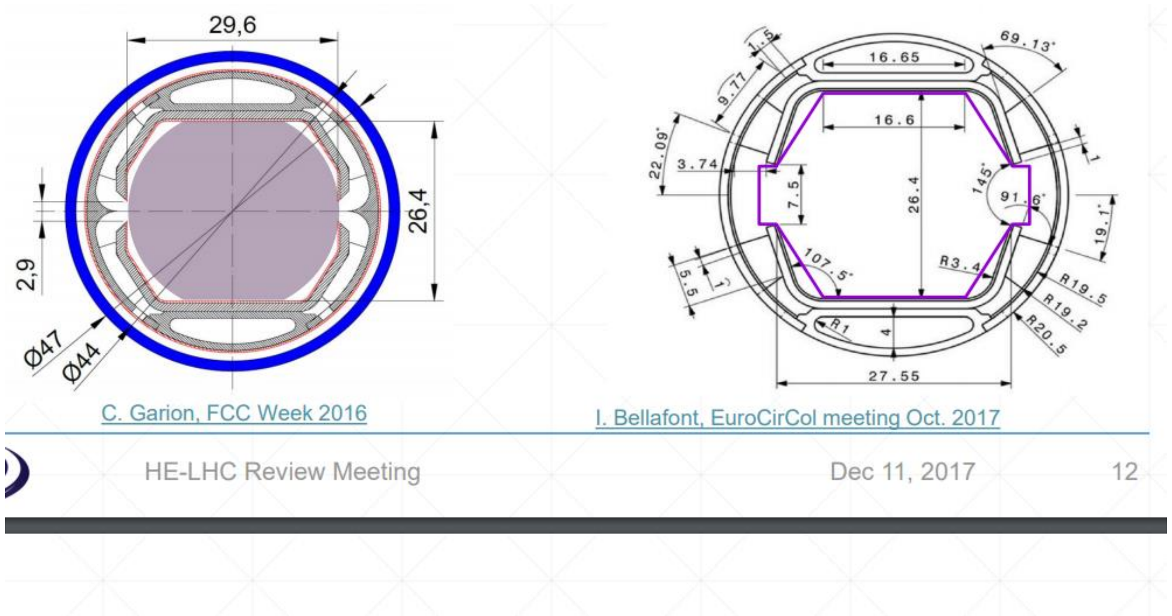
Physics optics in IR1, V0.2



Weaker focussing in arcs and DS than LHC.

Higher D_x and also different matching from LHC.

Aperture available



γ-γ and γ-A processes in Pb-Pb collisions

Nuclei are surrounded by intense EM fields: collisions of almost-real photons in Fermi-Weizsacker-Williams picture.

Ultra-peripheral electromagnetic interactions dominate the total cross-section during Pb-Pb collisions.

Bound-Free Pair Production

BFPP1: $^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \longrightarrow ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{81+} + e^{+},$

$\sigma = 294\ \text{b}, \quad \delta = 0.01235$

BFPP2: $^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \longrightarrow ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{80+} + 2e^{+},$

$\sigma \approx 10\ \text{mb}, \quad \delta = 0.02500$

Electro-magnetic Dissociation of nucleus

EMD1: $^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \longrightarrow ^{208}\text{Pb}^{82+} + ^{207}\text{Pb}^{82+} + n\ ,$

$\sigma = 200\ \text{b}, \quad \delta = -0.00485$

EMD2: $^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \longrightarrow ^{208}\text{Pb}^{82+} + ^{206}\text{Pb}^{82+} + 2n\ ,$

$\sigma = 35\ \text{b}, \quad \delta = -0.00970$

Hadronic cross section is 8 b (so much less power in debris).

Each of these makes a secondary beam emerging from the IP.

Effects now familiar in Pb-Pb at LHC

rigidity change:

$$\delta = \frac{1 + \Delta m / m_{\text{Pb}}}{1 + \Delta Q / Q} - 1$$

Electromagnetic dissociation cross-sections

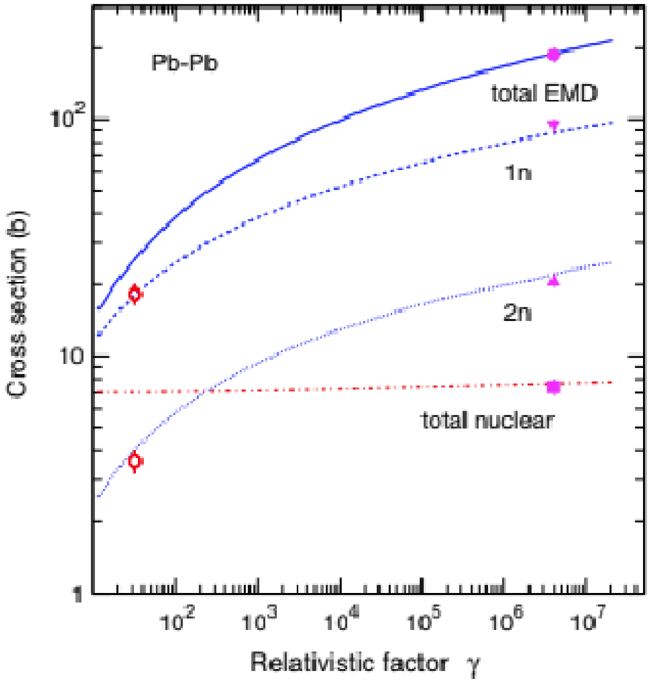


FIG. 1. Total electromagnetic dissociation and nuclear cross sections for Pb-Pb collisions as a function of the effective relativistic γ factor. The results of calculations of the total EMD cross section and partial cross sections in $1n$ and $2n$ channels are shown by solid, dashed and dotted lines, respectively. Total nuclear cross section calculated in the DPMJET-III model is shown by dot-dashed line. Results from the ALICE collaboration [22] for the total EMD and nuclear cross sections are shown by the full circle and full box, respectively. The measurements for $1n$ and $2n$ channels are shown by open circles [19] and full triangles [22].

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Hadronic and electromagnetic fragmentation of ultrarelativistic heavy ions at LHC

H. H. Braun,[1] A. Fassò,[2] A. Ferrari,[3] J. M. Jowett,[3] P. R. Sala,[4] and G. I. Smirnov[3,5,*]
[1]*Paul Scherrer Institut, 5232 Villigen PSI, Switzerland*
[2]*ELI Beamlines, Prague, Czech Republic*
[3]*CERN, CH-1211 Geneva, Switzerland*
[4]*INFN, Via Celoria 16, 20133 Milano, Italy*
[5]*Laboratory for High Energy Physics, JINR, Dubna, Russia*
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Used to predict total electromagnetic dissociation cross-section at HE-LHC energy

Bound-free pair-production cross-section

TABLE I. Cross section for the bound-free pair production of *one* ion *only* for different bound states are given for RHIC and LHC conditions for different ion-ion collisions. Also given are the parameters A and B to be used in Eq. (28) for the dependence on the Lorentz factor γ_c.

Bound state	σ(RHIC) (b)	σ(LHC) (b)	A (b)	B (b)
^{1}H-^{1}H	$\gamma_c=250$	$\gamma_c=7500$		
1s	2.62×10^{-11}	4.25×10^{-11}	5.36×10^{-12}	-3.40×10^{-12}
2s	3.28×10^{-12}	5.31×10^{-12}	6.70×10^{-13}	-4.23×10^{-13}
2p(1/2)	3.75×10^{-17}	6.10×10^{-17}	7.73×10^{-18}	-5.20×10^{-18}
2p(3/2)	1.47×10^{-17}	2.41×10^{-17}	3.10×10^{-18}	-2.42×10^{-18}
3s	9.70×10^{-13}	1.57×10^{-12}	1.98×10^{-13}	-1.26×10^{-13}
^{20}Ca-^{20}Ca	$\gamma_c=125$	$\gamma_c=3750$		
1s	1.61×10^{-2}	2.92×10^{-2}	3.84×10^{-3}	-2.48×10^{-3}
2s	2.00×10^{-3}	3.62×10^{-3}	4.78×10^{-4}	-3.07×10^{-4}
2p(1/2)	1.39×10^{-5}	2.52×10^{-5}	3.35×10^{-6}	-2.33×10^{-6}
2p(3/2)	3.63×10^{-6}	6.70×10^{-6}	9.02×10^{-7}	-7.27×10^{-7}
3s	5.90×10^{-4}	1.07×10^{-3}	1.41×10^{-4}	-9.10×10^{-5}
^{47}Ag-^{47}Ag	$\gamma_c=109$	$\gamma_c=3264$		
1s	3.51	6.46	8.68×10^{-1}	-5.63×10^{-1}
2s	4.33×10^{-1}	7.98×10^{-1}	1.07×10^{-1}	-6.94×10^{-2}
2p(1/2)	2.81×10^{-2}	5.21×10^{-2}	7.05×10^{-3}	-5.02×10^{-3}
2p(3/2)	3.80×10^{-3}	7.16×10^{-3}	9.87×10^{-4}	-8.31×10^{-4}
3s	1.26×10^{-1}	2.34×10^{-1}	3.13×10^{-2}	-2.02×10^{-2}
^{79}Au-^{79}Au	$\gamma_c=100$	$\gamma_c=3008$		
1s	94.9	176	23.8	-14.7
2s	12.1	22.4	3.04	-1.87
2p(1/2)	3.62	6.77	9.27×10^{-1}	-6.56×10^{-1}
2p(3/2)	2.10×10^{-1}	4.01×10^{-1}	5.62×10^{-2}	-4.93×10^{-2}
3s	3.46	6.40	8.67×10^{-1}	-5.34×10^{-1}
^{82}Pb-^{82}Pb	$\gamma_c=99$	$\gamma_c=2957$		
1s	121	225	30.4	-18.7
2s	15.5	28.8	3.91	-2.39
2p(1/2)	5.21	9.76	1.34	-9.46×10^{-1}
2p(3/2)	2.78×10^{-1}	5.33×10^{-1}	7.50×10^{-2}	-6.61×10^{-2}
3s	4.42	8.20	1.11	-6.79×10^{-1}
^{92}U-^{92}U	$\gamma_c=97$	$\gamma_c=2900$		
1s	263	488	66.0	-39.0
2s	34.4	63.7	8.63	-5.10
2p(1/2)	16.7	31.3	4.30	-3.00
2p(3/2)	6.77×10^{-1}	1.30	1.83×10^{-1}	-1.63×10^{-1}
3s	9.67	17.9	2.43	-1.44

Cross section for Bound-Free Pair Production (BFPP)

$$Z_1 + Z_2 \rightarrow \left(Z_1 + e^-\right)_{1s_{1/2},K} + e^+ + Z_2$$

has very strong dependence on ion charges (and energy)

$$\sigma_{PP} \propto Z_1^5 Z_2^2 \left[A \log \gamma_{CM} + B\right]$$

$$\propto Z^7 \left[A \log \gamma_{CM} + B\right] \quad \text{for } Z_1 = Z_2$$

$$\approx \begin{cases} 281 \text{ b for Pb-Pb LHC} \\ 293 \text{ b for Pb-Pb HE-LHC} \\ 354 \text{ b for Pb-Pb FCC} \end{cases}$$

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Bound-free electron-positron pair production in relativistic heavy-ion collisions

Helmar Meier, Zlatko Halabuka, Kai Hencken, and Dirk Trautmann
Institut für theoretische Physik der Universität Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

Gerhard Baur
Institut für Kernphysik (Theorie), Forschungszentrum Jülich, 52425 Jülich, Germany

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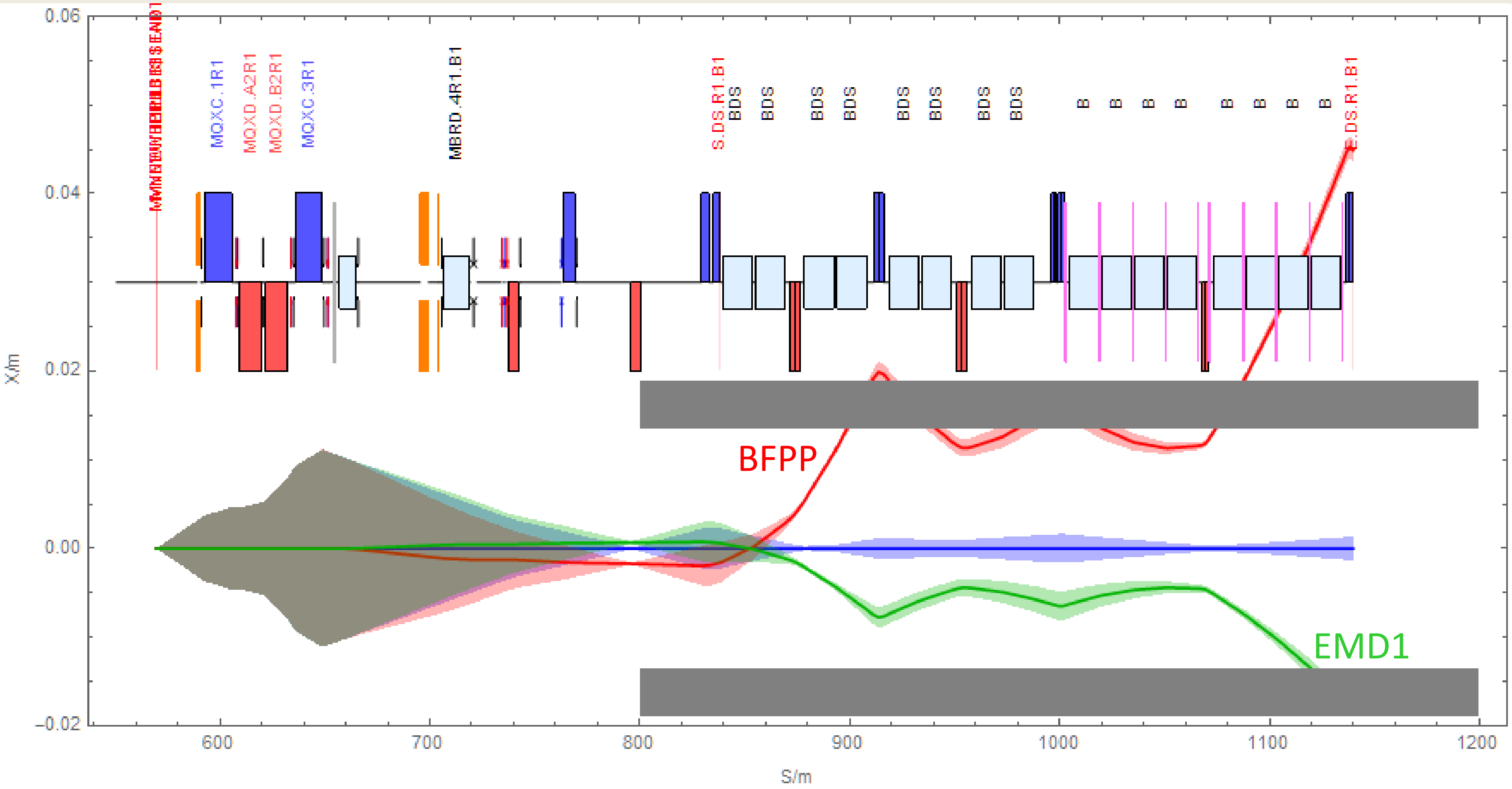
Secondary beams from IP in Pb-Pb



Consequences of small beam pipe and weaker focussing:

Impact point of BFPP beam is not near the missing magnet slot in the DS and the solutions adopted for LHC will not work.

May help with EMD1 beam.

Can the matching be changed?

Secondary beam has few 100 W power.

Can the first 3 dipole magnets be moved closer to the IP to make a space for collimators?
Scheme used for earlier proposal for DS collimators in LHC – would not need >22 T dipoles … talk by JMJ at 2009 LHC Collimation Review https://indico.cern.ch/event/55195/

Another solution is to only collide nuclei with low enough Z. Acceptable for the physics programme ?

e-Pb collisions at HE-LHC (HE-LHC-eh)

Table 3: Baseline parameters of future electron-ion collider configurations based on the electron ERL, in concurrent eA and AA operation mode.

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2
bunch spacing [ns]	50	50	100
no. of bunches	1200	1200	2072
ions per bunch [10^8]	1.8	1.8	1.8
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
electrons per bunch [10^9]	4.67	6.2	12.5
electron current [mA]	15	20	20
IP beta function β^*_A [cm]	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3
bunch filling H_{coll}	0.8	0.8	0.8
luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	7	18	54

Potential electron-ion collider based on HE-LHC also benefits from upgraded bunch intensities already realised at LHC.

Also requires further detailed study.

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Future Circular Collider Study
FCC-he Baseline Parameters

Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool

Conclusions

- A first look at Pb-Pb collisions in HE-LHC suggests that integrated luminosity can be somewhat more than at HL-LHC (assuming similar injected beams)
  - Fills short, cycling and turn-around times are critical
- BFPP and EMD losses from IP may be unmanageable because of small beam pipe and weak focussing
  - Alternative layouts for the dispersion suppressors to install collimators ?
  - Limit colliding species to lighter nuclei, eg, Xe ?
- Heavy-ion operation of HE-LHC requires serious study:
  - BFPP and EMD losses from IPs, mitigations, solutions
  - Collimation and cleaning inefficiency
  - Best choice of colliding species for physics and machine ?
  - Injection, operational cycle
  - Hybrid proton-nucleus collisions, p-Pb, etc.