Hollow electron lenses for HL-LHC

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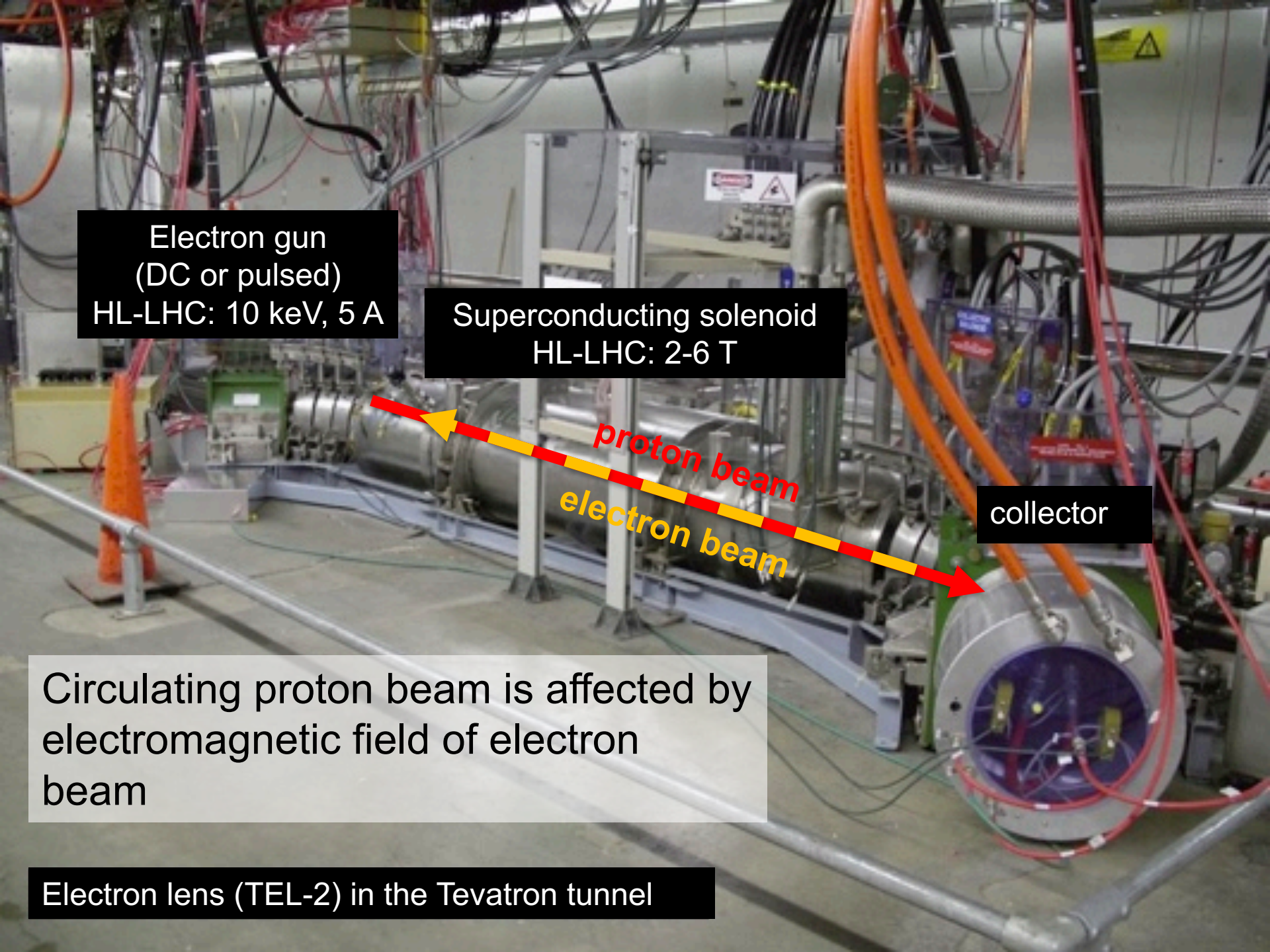
What is an electron lens?



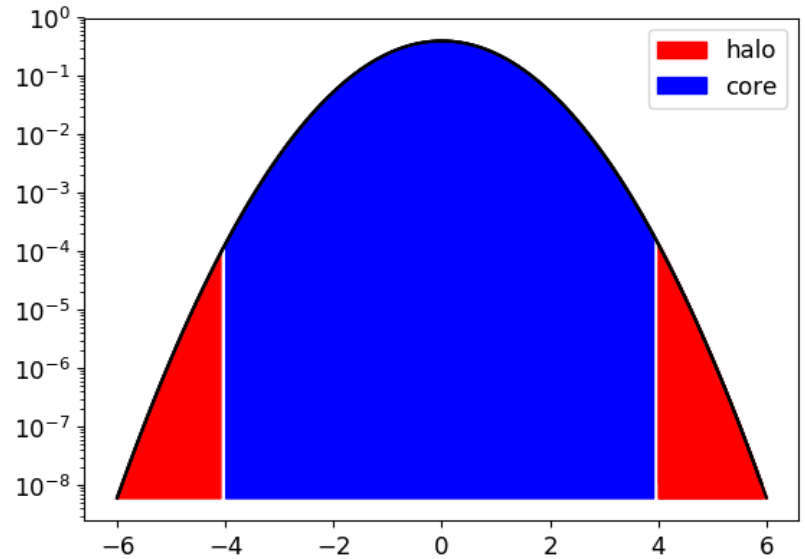
Circulating proton beam is affected by electromagnetic field of electron beam

Electron lens (TEL-2) in the Tevatron tunnel

Why do we need a hollow electron lens for HL-LHC?

Halo, core and luminosity

- **goal HL-LHC:** increase luminosity by a factor of 10 beyond the original design value (from 300 to 3000 fb^{-1})
- luminosity is generated by the particles in the **beam core**
- **halo particles** do not contribute to the luminosity, but they generate unwanted losses

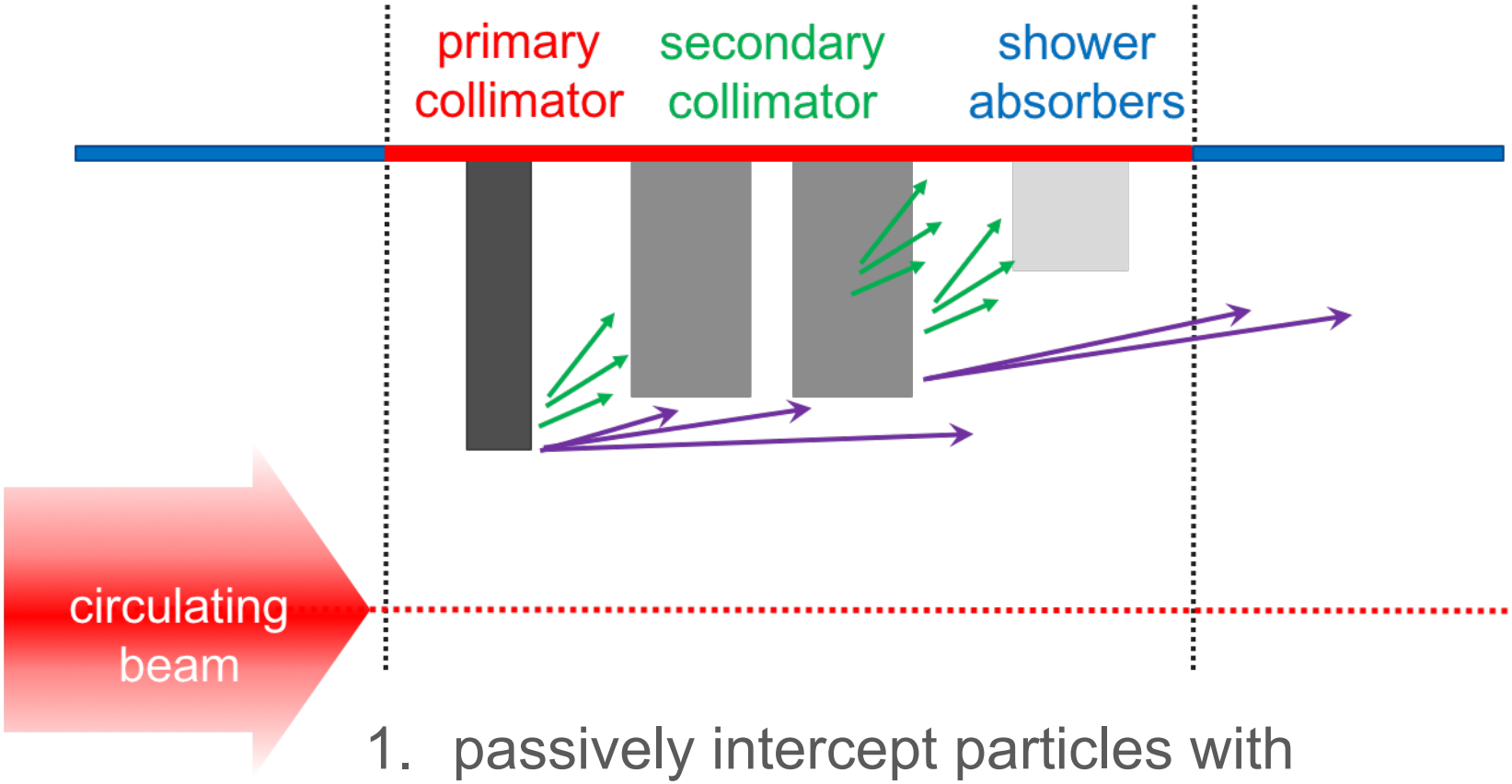


	stored beam energy [MJ]
Tevatron	2
LHC 2016	250
nominal LHC	362
HL-LHC	**692**

- **stored beam energy** increases by **factor 2** compared to **LHC** or **factor 350** compared to the **Tevatron**
- prediction for HL-LHC:
  33.6 MJ are stored in **tails**
  = 15 x Tevatron beam

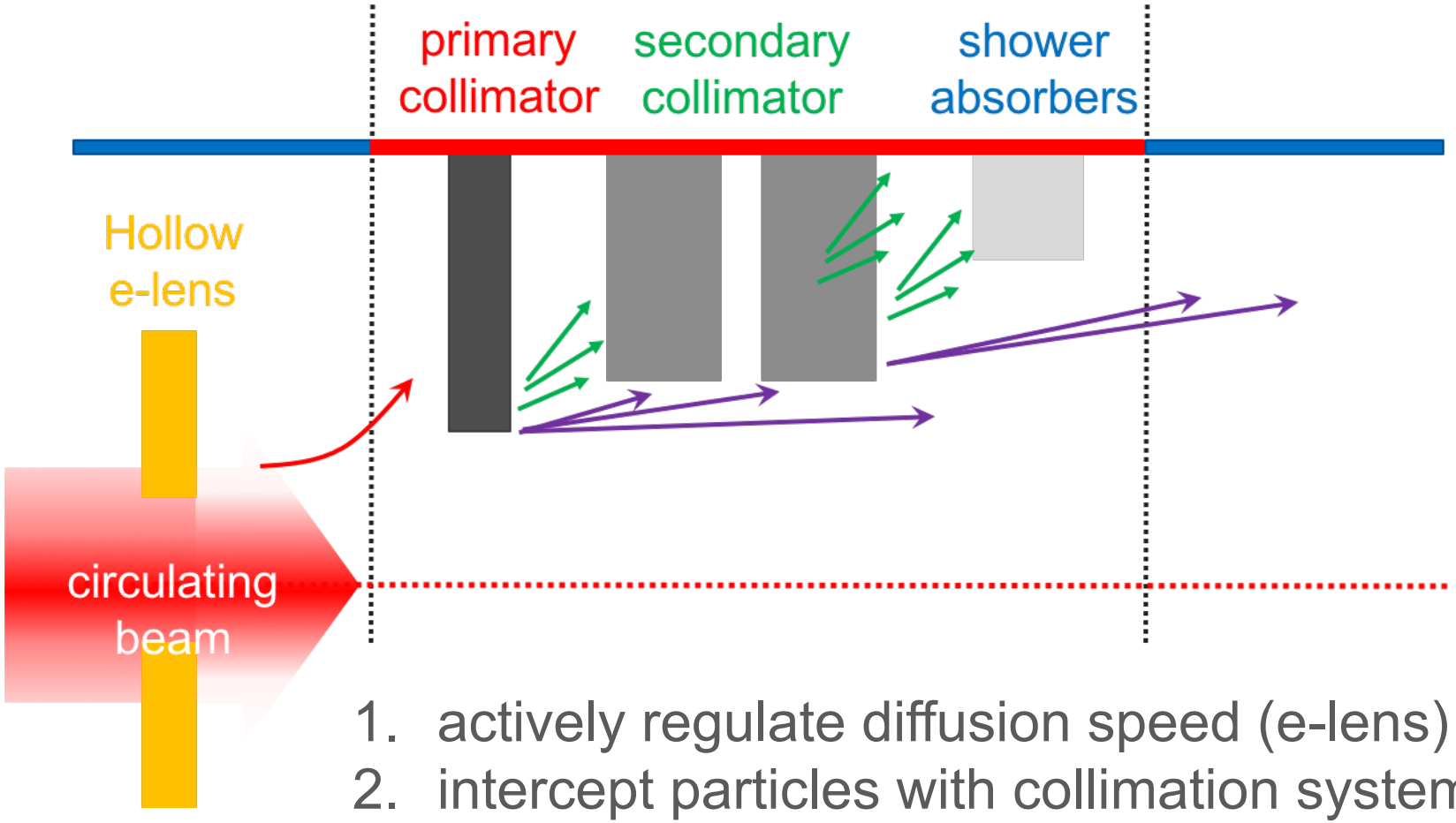
⇒ **electron lens controls losses with no luminosity loss**

Passive halo control



1. passively intercept particles with collimation system

Active halo control



1. actively regulate diffusion speed (e-lens)
2. intercept particles with collimation system

Why do we need active halo control for HL-LHC?

- HL-LHC: **factor 2 larger losses** for same loss assumption as for LHC
- **parameters and operational scenarios pushed well beyond LHC**
  - Doubled bunch intensity in smaller emittance
  - Operation with crab cavities, no experience with protons
  - Luminosity levelling

  ⇒ **Extrapolation of loss from LHC complex**
- Concerns from **fast failures** (crab cavities) in presence of **over-populated tails**

electron lens provides margin and thus reduces risk
⇒ inclusion in HL-LHC baseline strongly considered
(see e-lens reviews 1 & 2)

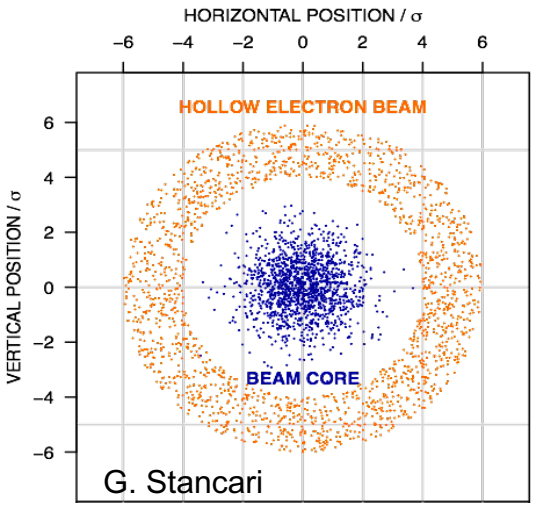
Controlling halo with an e-lens without affecting the core

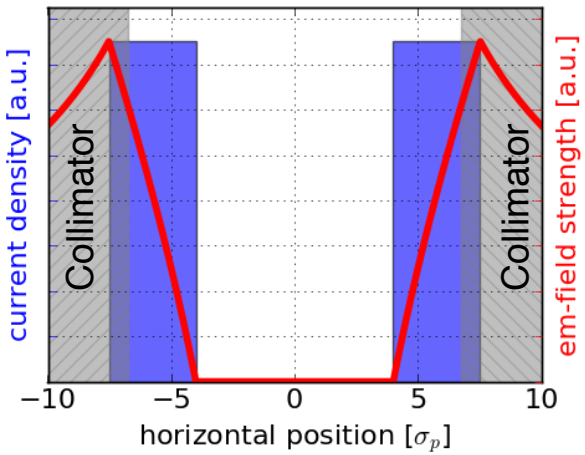
Due to **radial symmetry** the hollow electron lens yields a **strong non-linear field for halo** particles and **no field at core** region

⇒ active halo control

Past and future research:

- concept first tested at the Tevatron for antiprotons in 2011
- experiments at RHIC in spring 2018 with ions
- simulations to model experiments and predict performance for HL-LHC



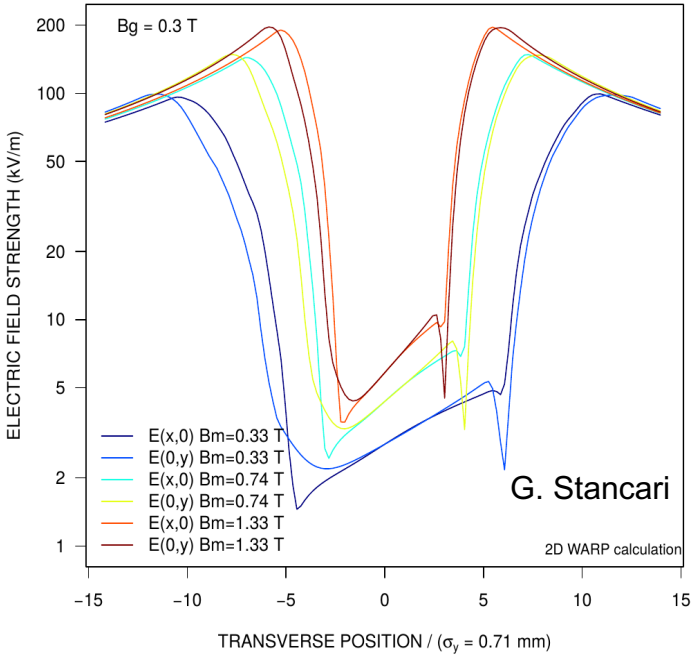


Controlling halo with an e-lens without affecting the core

BUT: Imperfections in the profile can **break the radial symmetry**

⇒ residual field at the beam core

- DC operation no problem
- pulsed operation induces noise on halo (wanted) and core (not wanted)
  - ⇒ luminosity loss



Past and future research:

- experiments at LHC in 2016 and 2017 using the kicker of the transverse damper and aiming at defining tolerances on field imperfections
- simulations to model experiments and define tolerances for HL-LHC

Summary

- HL-LHC pushes parameters and operational scenarios
- extrapolation of losses to these new parameters is not trivial
- electron lenses provide margin for machine protection through active halo control

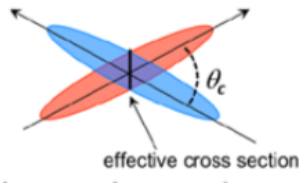
- strong consideration to include hollow electronlens in HL-LHC baseline

- first proof of principle of hollow electron lens collimation at the Tevatron (2011)
- experiments at the LHC to study effect on beam core in pulsed operation (2016-2017)
- further experiments at RHIC (2018)
- simulations to predict performance of the elecron lens for HL-LHC

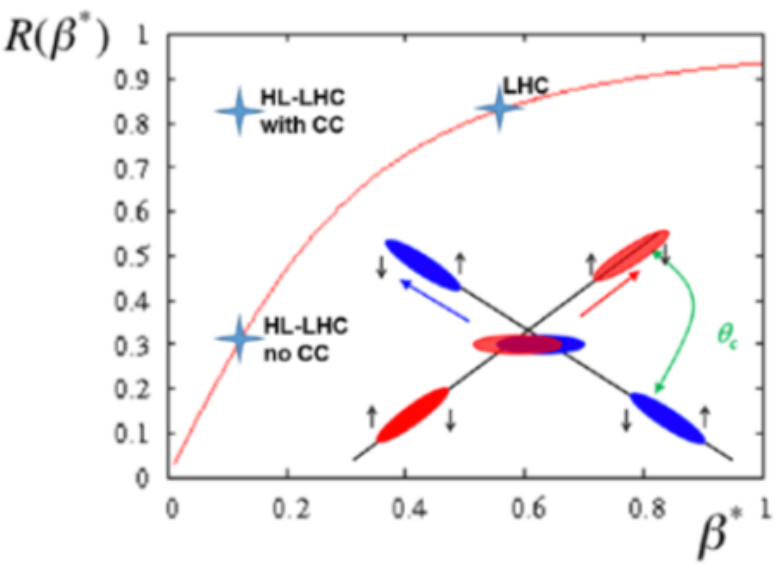
Questions?

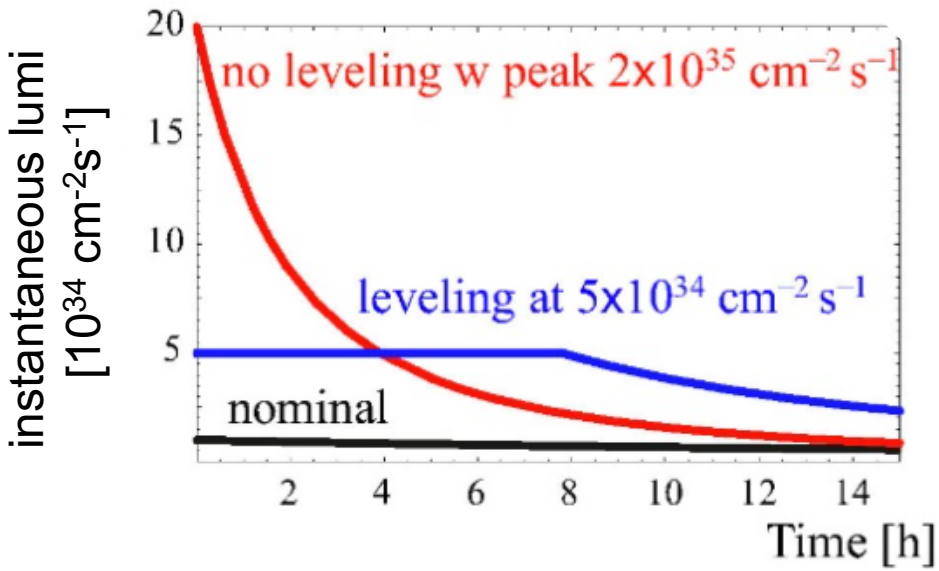
How to further increase luminosity in the LHC – the HL-LHC upgrade

$$L = \frac{n_b N_p^2 f_0}{4\pi\,\sigma^2} R(\sigma_z, \theta)$$



1. 1.9× number of particles N_p
2. 0.4× beam size at IP σ
3. 2× crossing angle θ → 0.3× luminosity reduction R
4. Crab Cavities for luminous area control → L=19×10^{34} cm^{-2}s^{-1} **too high!**
5. Luminosity levelling by dynamically changing focusing (β^*=0.7→0.15m) in store → L=5×10^{34} levelled





LHC vs HL-LHC

	LHC nominal	HL-LHC
Beam energy	7 TeV	
Number of bunches	2808 (25 ns)	2748 (25 ns)
protons / bunch [10^{11}]	1.15 (0.58A)	2.2 (1.09A)
Energy in one beam [MJ]	360	680
$\gamma\varepsilon_{x,y}$ [μm], rms	3.75	2.5
β^* [m] at IP1-5	0.55	0.15
X-angle [μrad], separation	285, 9.3σ	590, 12.5σ
Geometrical Luminosity loss factor	0.83	0.3 **Crab Cavities**→0.83
Quadrupole bore [mm], gradient [T/m]	70, 215	150, 132.6
Peak luminosity [10^{34}]	1.0	5.0
Pile up	25	138
Line pile up density [mm^{-1}]	0.1	1.25
Machine state during HEP store	static	dynamically changing focusing – β^* levelling

HiLumi HL-LHC PROJECT

LARP

What is an electron lens

- DC or pulsed low-energy e-beam
- circulating beam affected by electromagnetic field of e-beam
- e-beam confined and guided by strong solenoids