Progress on electron cloud studies for HL-LHC

A. Axford, G. Iadarola, A. Romano, G. Rumolo

Acknowledgments: R. de Maria, R. Tomás

HL-LHC WP2 Task Leader Meeting, 24 April 2015

Outline

- **Electron-cloud driven instabilities in LHC**
  - PyHEADTAIL-PyECLOUD development
  - Benchmark against HEADTAIL
  - Application to LHC and HL-LHC for arc dipoles and quadrupoles at 450 GeV
- **Electron cloud build-up with/without beam screen baffles**
  - Angular heat load distribution on the triplet beam screen
  - PyECLOUD development for the simulation of non-convex structures

PyHEADTAIL-PyECLOUD development

- PyECLOUD module plugged into PyHEADTAIL to simulate the interaction of a bunch with an electron cloud

- The two tools can share most of the work of development and maintenance
  - All advanced e-cloud modeling features implemented in PyECLOUD (arbitrary chamber shape, secondary electron emission, arbitrary magnetic field map, Boris electron tracker, accurate modeling for curved boundary) become naturally available for PyHEADTAIL.

- This enables several new simulation scenarios. In particular:
  - All scenarios where the electron wall interaction cannot be neglected, e.g. with trailing edge multipacting (PS long bunches), doublet beams
  - Quadrupoles (including triplets, but this requires further development)
  - Other magnetic field configurations, e.g. combined function magnets, multipoles, arbitrary field maps

Benchmark against HEADTAIL

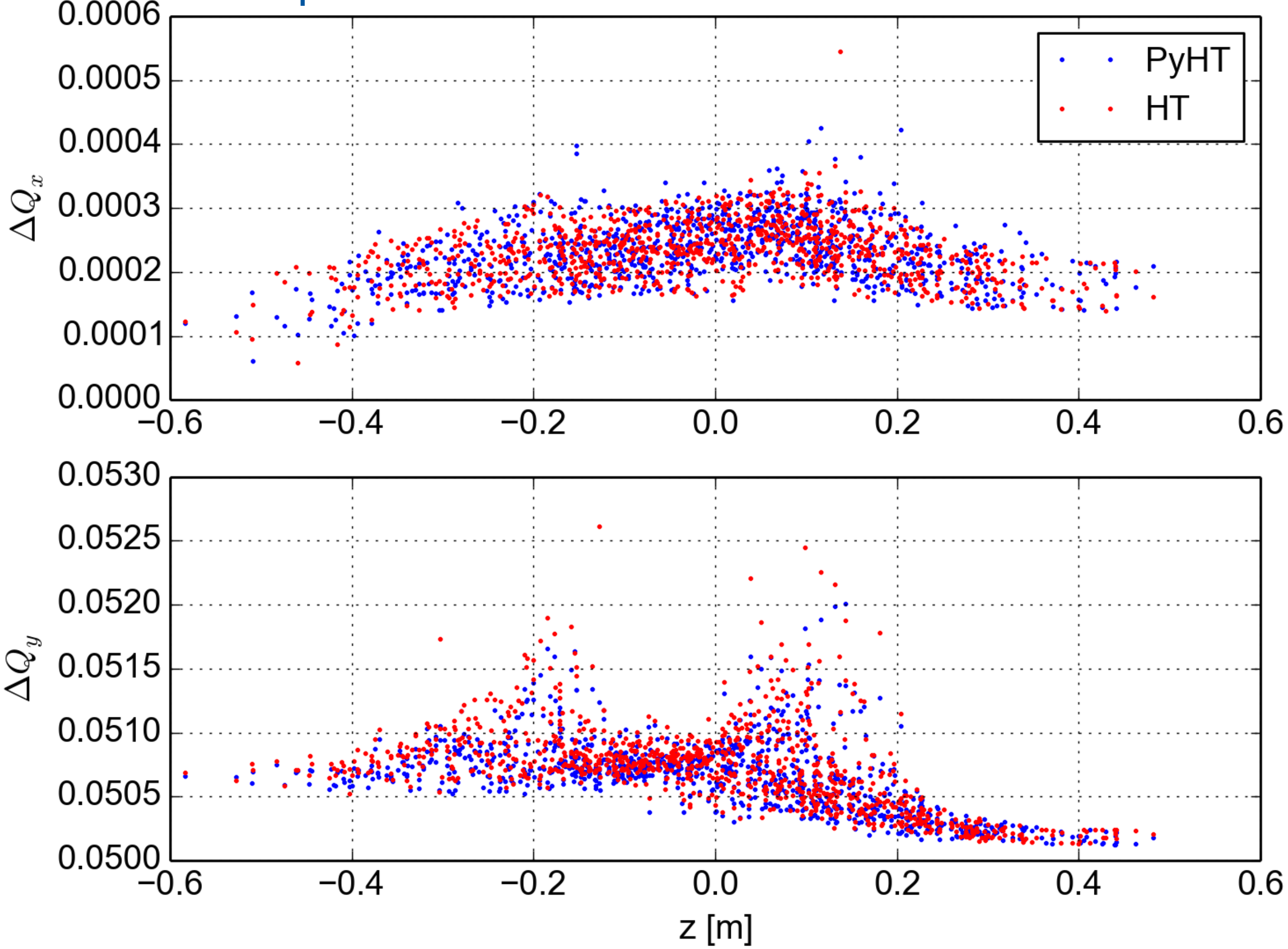
- PyHEADTAIL-PyECLOUD extensively benchmarked against HEADTAIL for SPS injection cases (simplified case of no chamber)

SPS @26 GeV/c, Q20 optics

Parameter	Value
N (p/b)	1.15×10^{11}
$\varepsilon_{\xi,y}$ (μm)	2.5
σ_z (m)	0.2
B (T)	0.5
N_{el} (e^-/m^3)	10^{11}
N_{kicks}	5
N_{MP} (e^-)	10^5
N_{MP} (p)	3×10^5
N_{slices} ($-3\sigma_z$, $3\sigma_z$)	64

Benchmark against HEADTAIL

Sample result



LHC and HL-LHC cases

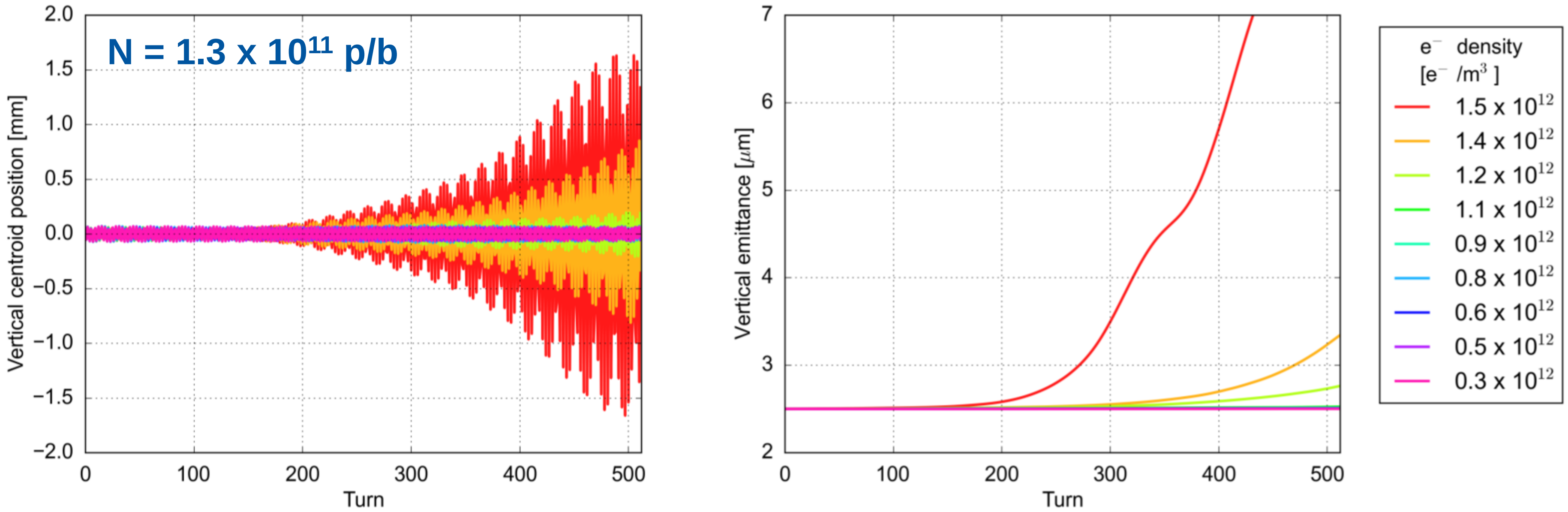
- PyHEADTAIL-PyECLOUD applied to study instability thresholds for electron cloud density in arc dipoles and quadrupoles, with
  - Realistic chamber
  - Initial uniform electron distribution

LHC @450 GeV/c

Parameter	Value
N (p/b)	$1.3 – 2.3 \times 10^{11}$
$\varepsilon_{\xi,y}$ (μm)	2.5
σ_z (m)	0.1
B (T, T/m)	0.53, 12
N_{el} (e^-/m^3)	$0.3 – 20 \times 10^{12}$
N_{kicks}	79
N_{MP} (e^-)	10^5
N_{MP} (p)	3×10^5
N_{slices} ($-2\sigma_z$, $2\sigma_z$)	64

Electron cloud in the arc dipoles (I)

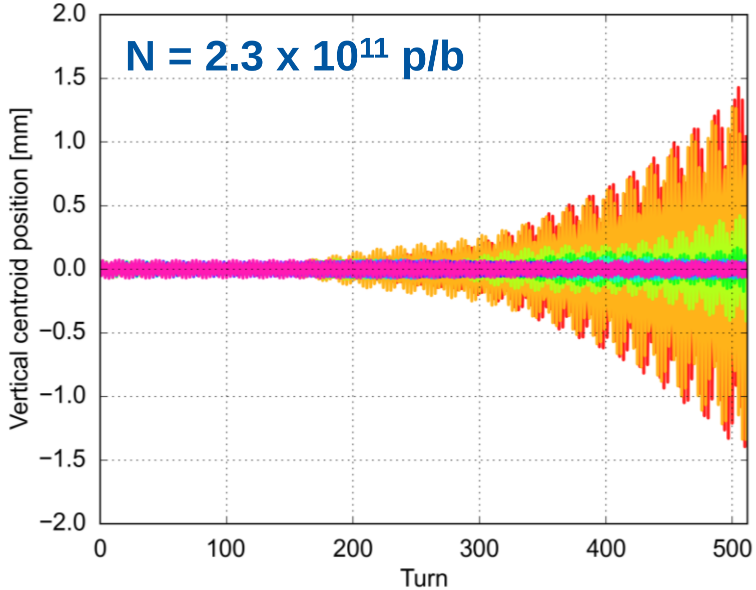
- Nominal intensity **1.3×10^{11} p/b**
- The electron cloud density is scanned between 0.5 and 1.5×10^{12} e^-/m^3
- The instability happens in the vertical plane, as the dipole magnetic field freezes the electron motion in the vertical plane (note that, unlike HEADTAIL, now a correct tracker in the magnetic field, is used)

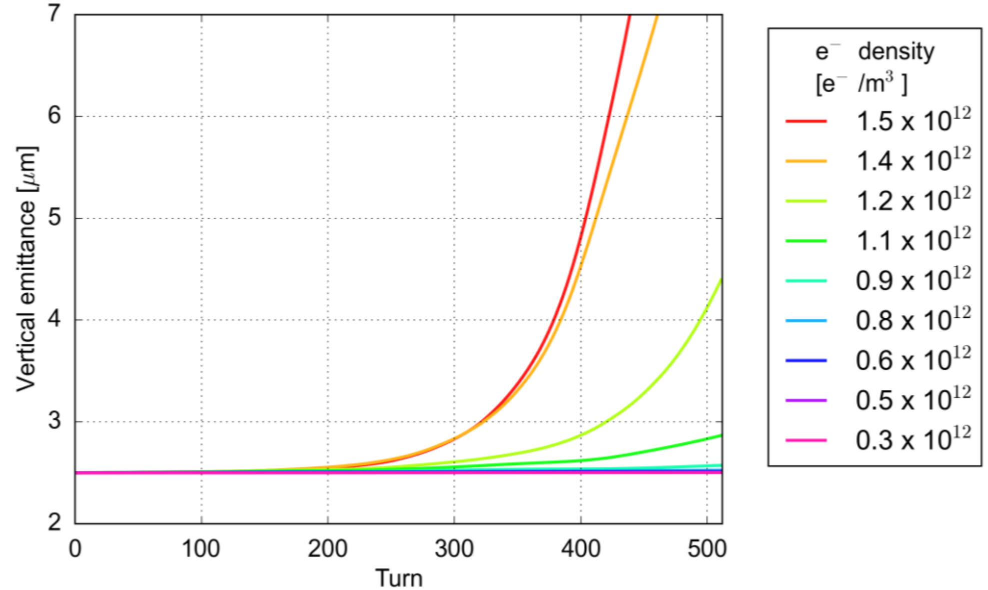


$N_{el}^{(thr)} = 1.15 \times 10^{12}$ e^-/m^3

Electron cloud in the arc dipoles (II)

- HL-LHC intensity **2.3 x 10^{11} p/b**
- The electron cloud density is scanned between 0.5 and 1.5 x 10^{12} e^-/m^3
- The instability happens in the vertical plane, as the dipole magnetic field freezes the electron motion in the vertical plane (note that, unlike HEADTAIL, now a correct tracker in the magnetic field, is used)

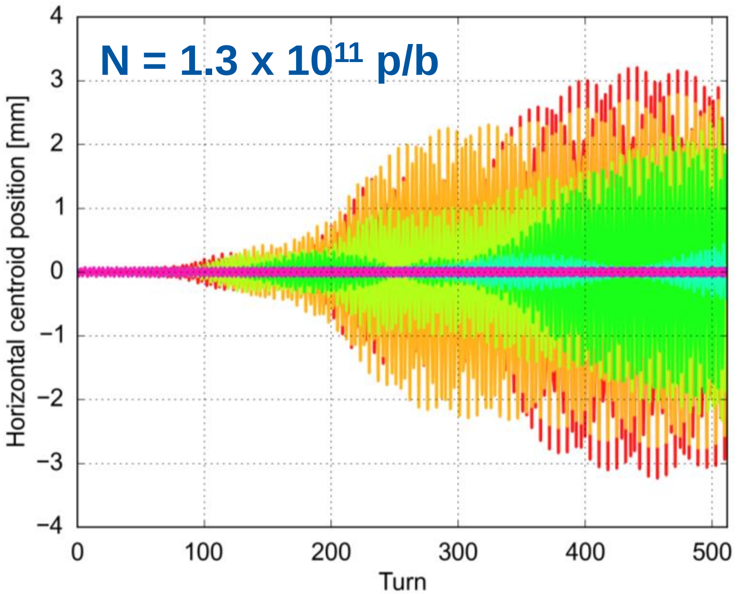


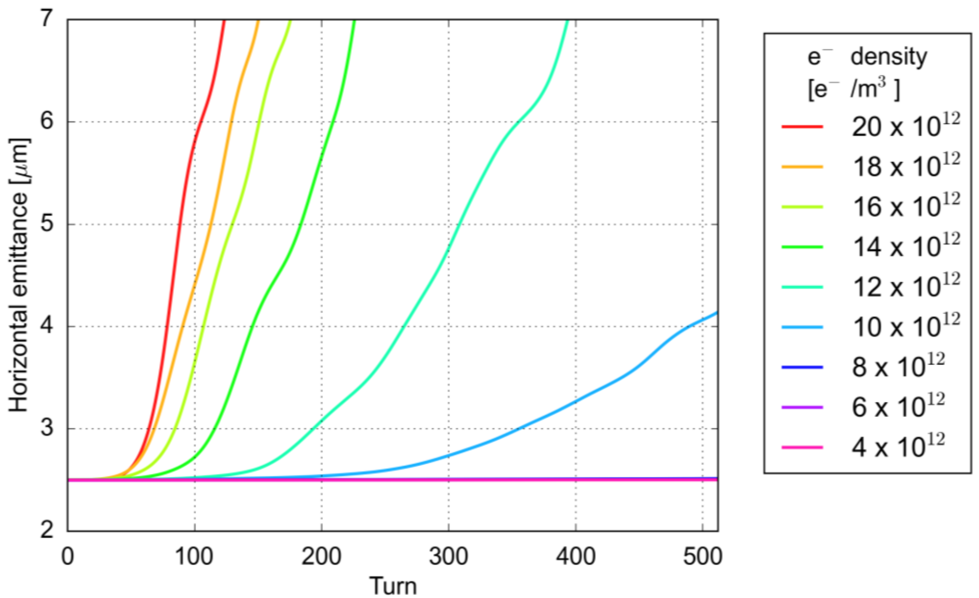


$N_{el}^{(thr)} = 1.0 \times 10^{12}\ e^-/m^3$

Electron cloud in the arc quadrupoles (I)

- Nominal intensity **1.3 x 10^{11} p/b**
- The electron cloud density is scanned between 4.0 and 20 x 10^{12} e^-/m^3 **
- The instability appears equally in the horizontal and vertical planes, the magnetic field lines do not cause an important asymmetry → **Horizontal**



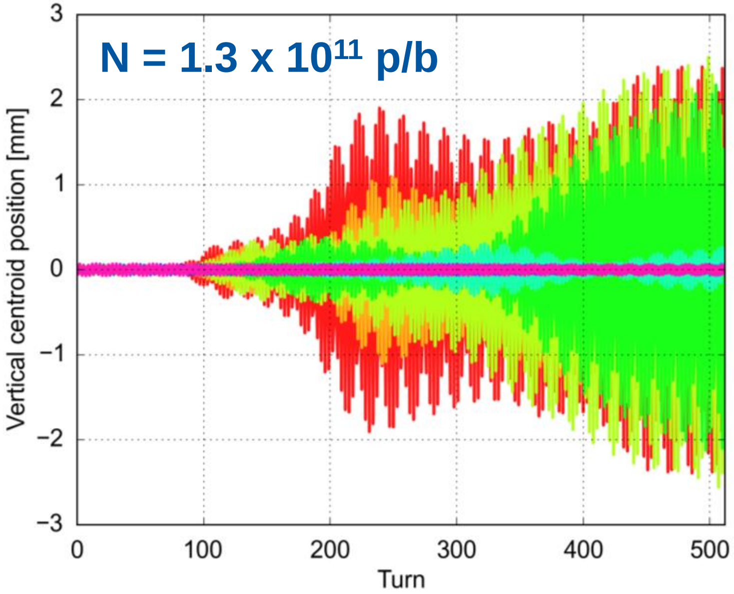


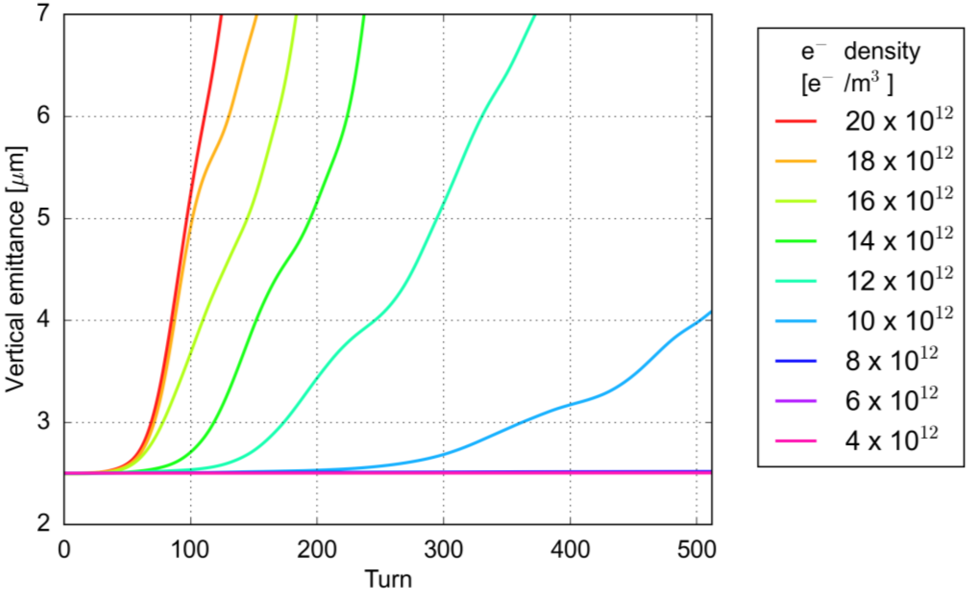
** About 10x higher than dipoles, because effect integrated over a ~15x shorter length

$N_{el}^{(thr)} = 9.0 \times 10^{12}\ e^-/m^3$

Electron cloud in the arc quadrupoles (II)

- Nominal intensity **1.3 x 10^{11} p/b**
- The electron cloud density is scanned between 4.0 and 20 x 10^{12} e^-/m^3
- The instability appears equally in the horizontal and vertical planes, the magnetic field lines do not cause an important asymmetry → **Vertical**

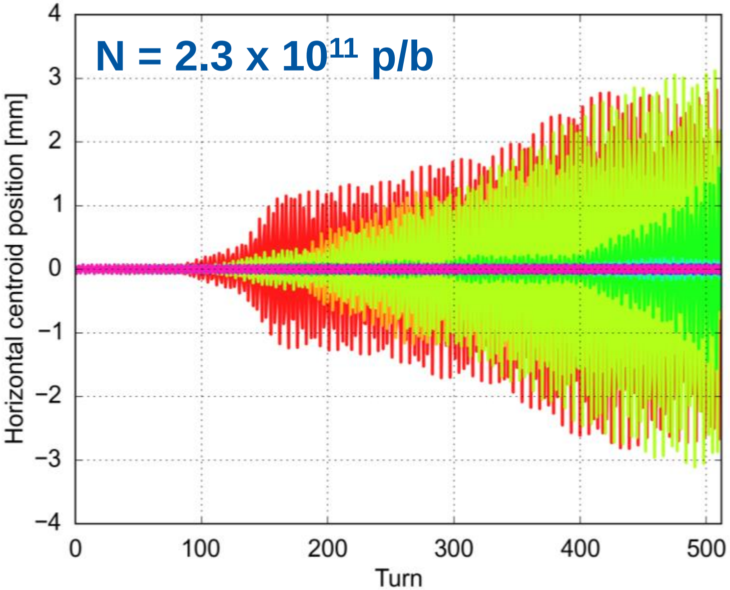


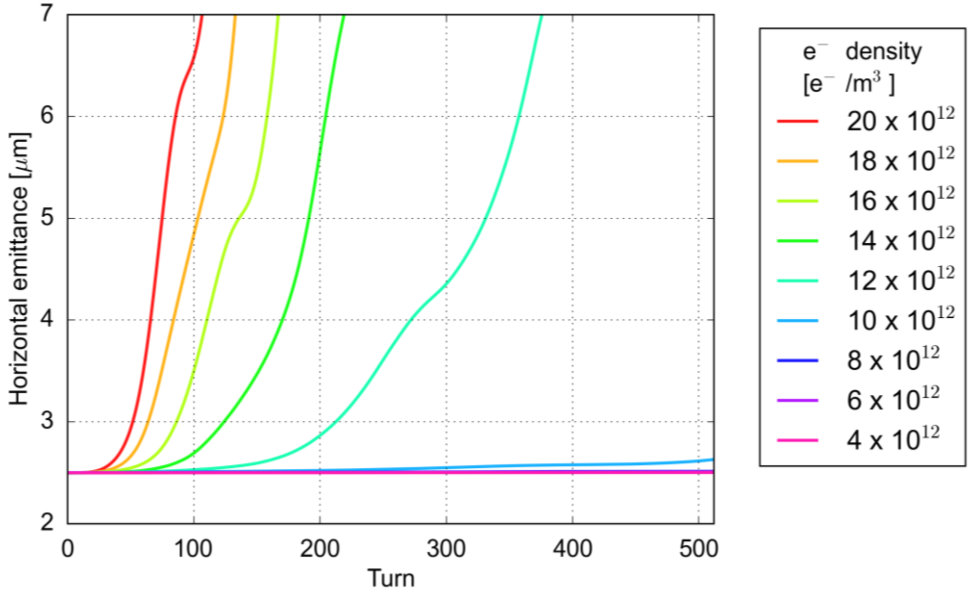


$N_{el}^{(thr)}$ = 9.0 x 10^{12} e^-/m^3

Electron cloud in the arc quadrupoles (III)

- HL-LHC intensity **2.3 x 10^{11} p/b**
- The electron cloud density is scanned between 4.0 and 20 x 10^{12} e^-/m^3
- The instability appears equally in the horizontal and vertical planes, the magnetic field lines do not cause an important asymmetry → **Horizontal**

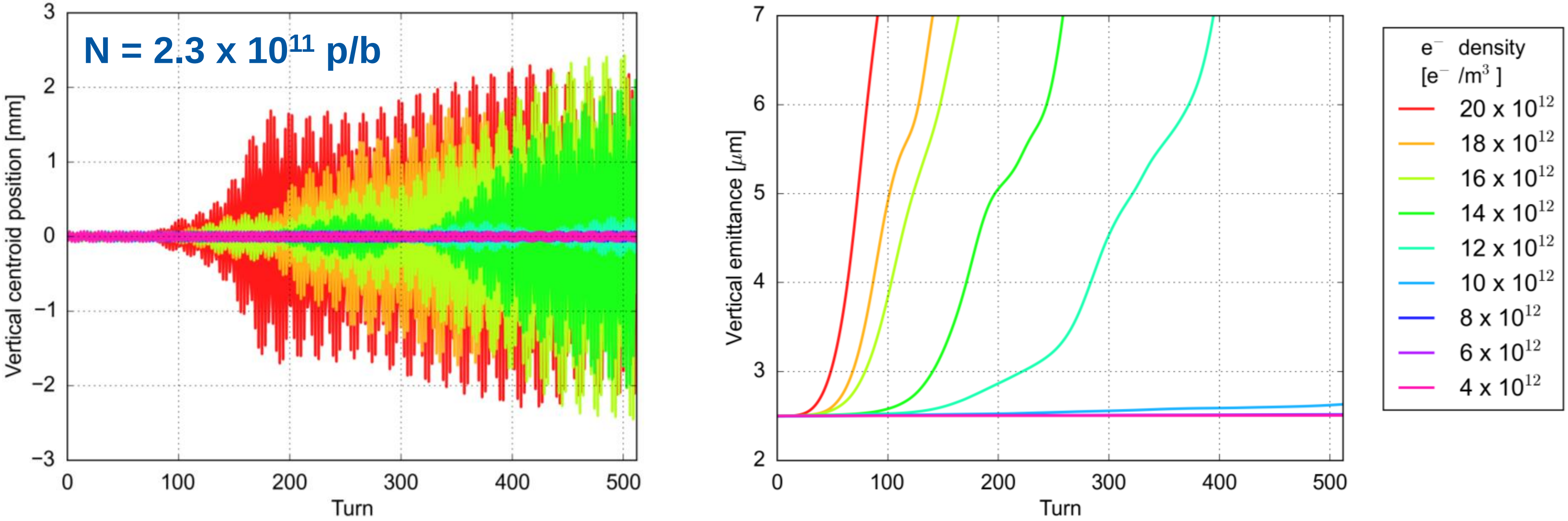




$$N_{el}^{(thr)} = 9.0 \times 10^{12}\ e^-/m^3$$

Electron cloud in the arc quadrupoles (IV)

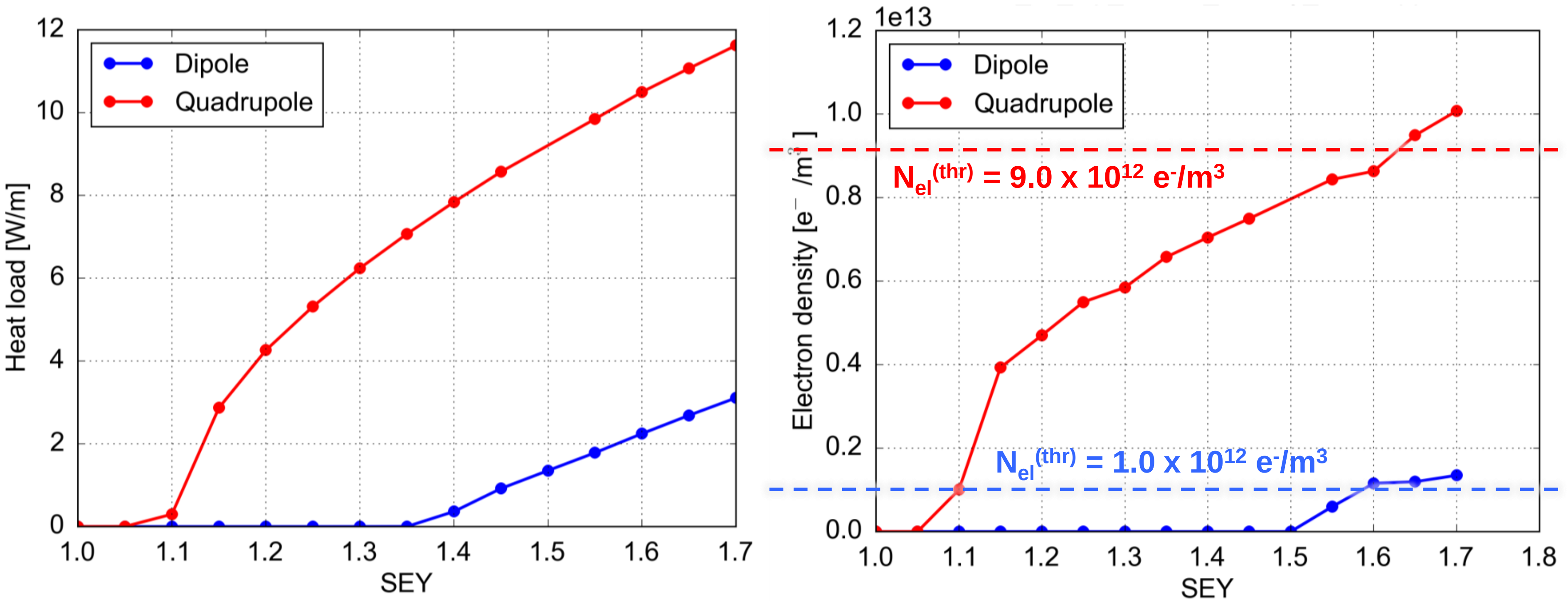
- HL-LHC intensity **2.3×10^{11} p/b**
- The electron cloud density is scanned between 4.0 and 20×10^{12} e^-/m^3
- The instability appears equally in the horizontal and vertical planes, the magnetic field lines do not cause an important asymmetry → **Vertical**



$N_{el}^{(thr)} = 9.0 \times 10^{12}$ e^-/m^3

Comparison with build up (I)

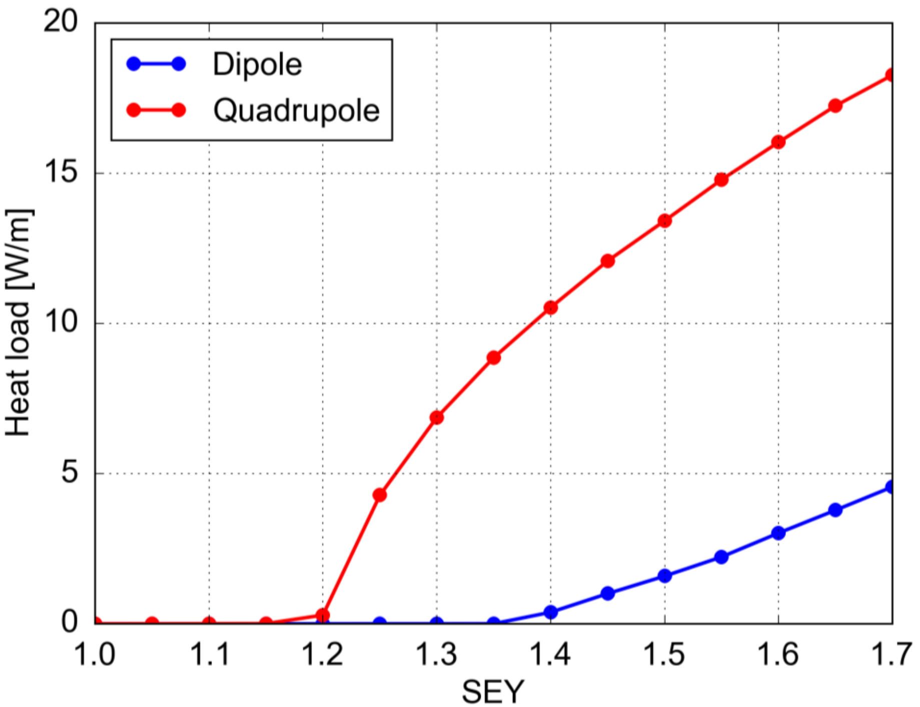
- Nominal intensity **1.3 x 10^{11} p/b**
- Build up simulations to find to which SEY the threshold densities are associated

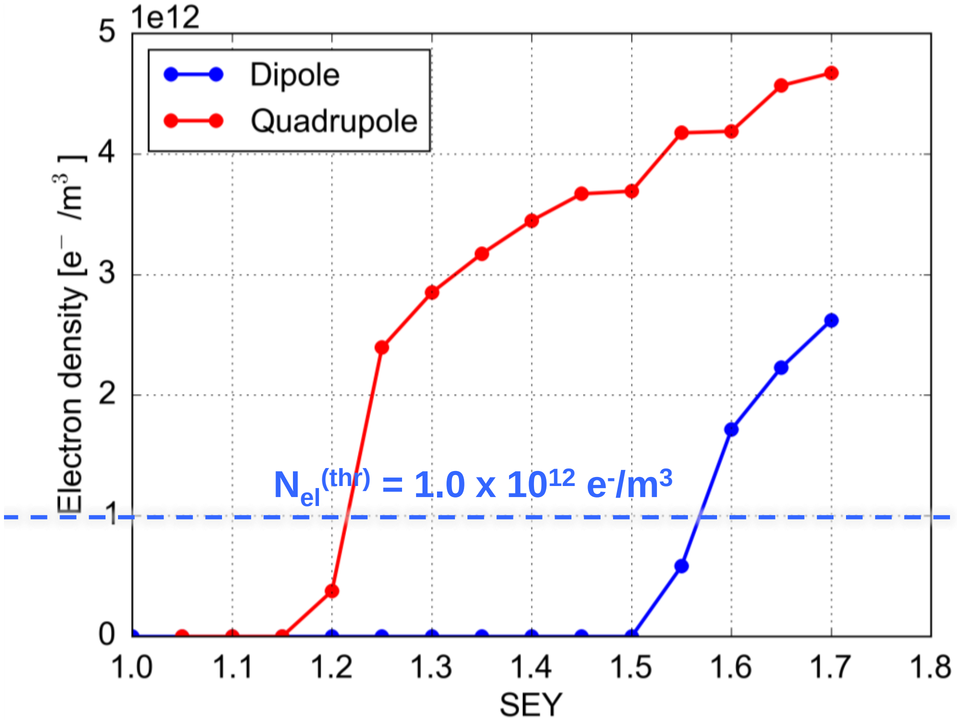


For stability: **SEY<~1.6** in both dipoles and quadrupoles

Comparison with build up (II)

- HL-LHC intensity **2.3×10^{11} p/b**
- Build up simulations to find to which SEY the threshold densities are associated





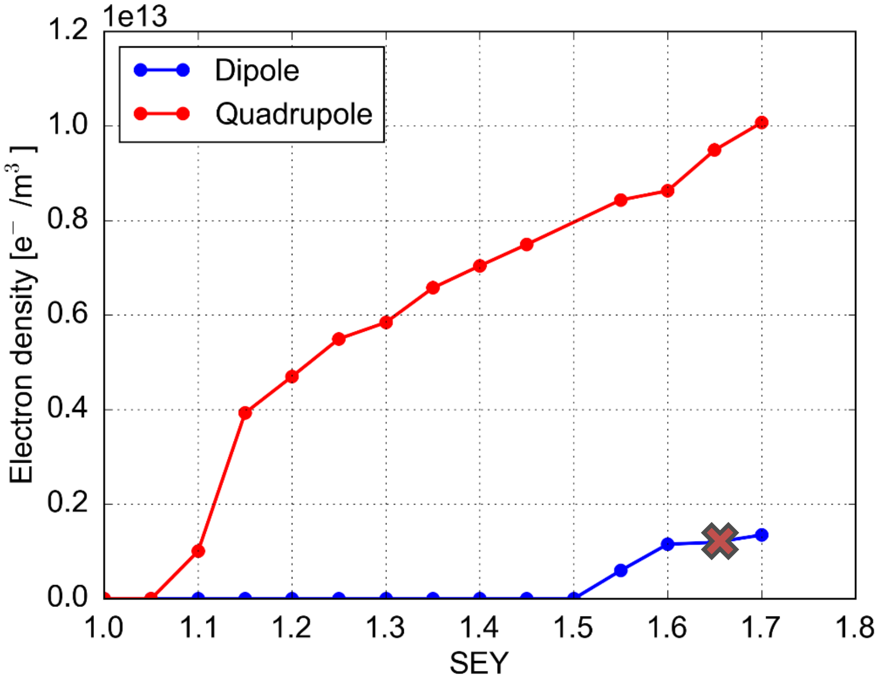
For stability: **SEY<~1.6** in dipoles
E-cloud in quadrupoles seems insufficient to trigger instabilities

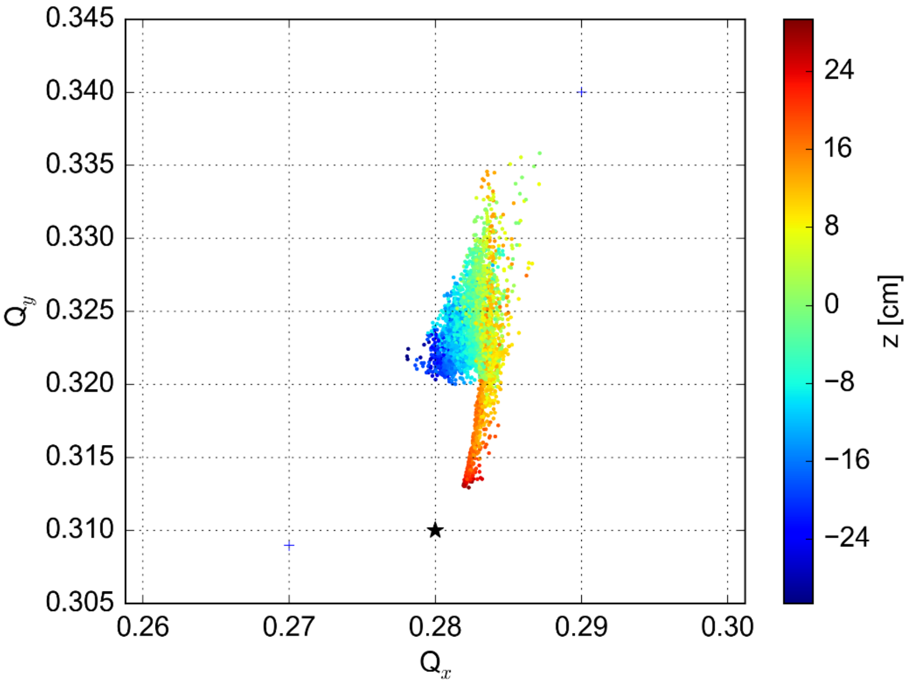
Incoherent Effects & Tune Footprints

- The incoherent effects of the electron cloud can be studied with special PyHEADTAIL simulations conceived for simulating a large number of turns (similarly to a frozen space-charge model)
  - The electric potential associated to the electron cloud pinch is calculated only at the beginning of the simulation and then it is stored
  - The corresponding forces are calculated at the bunch particles positions and applied to the particles turn after turn
  - In presence of emittance growth, the pinch needs to be refreshed after a certain number of turns to guarantee a certain self-consistency
- For the evaluation of the tune footprint, the longitudinal motion is also frozen

Incoherent effects
Tune footprints in dipoles (I)

- Nominal intensity **1.3 x 10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → above instability threshold

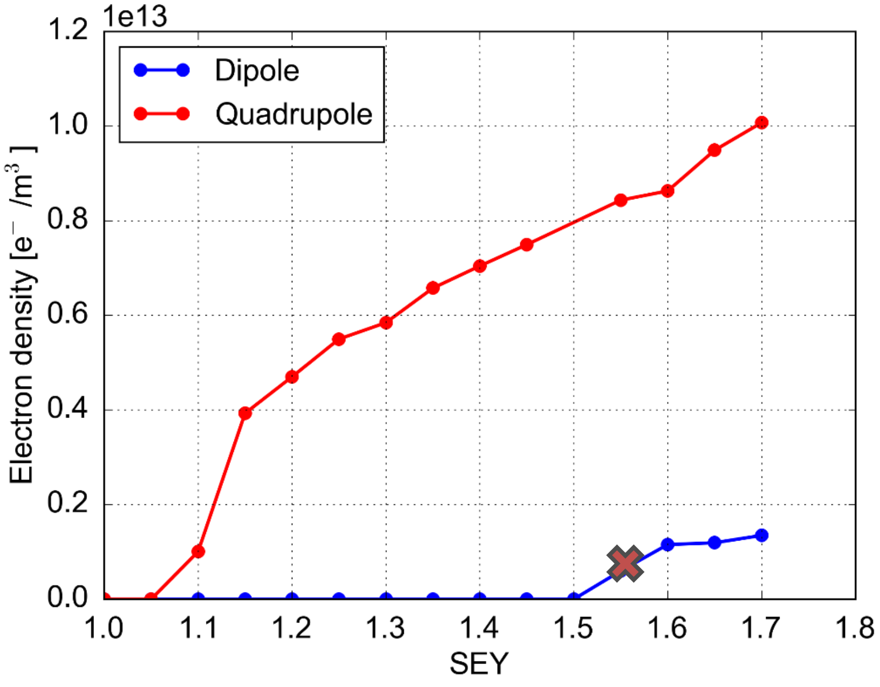


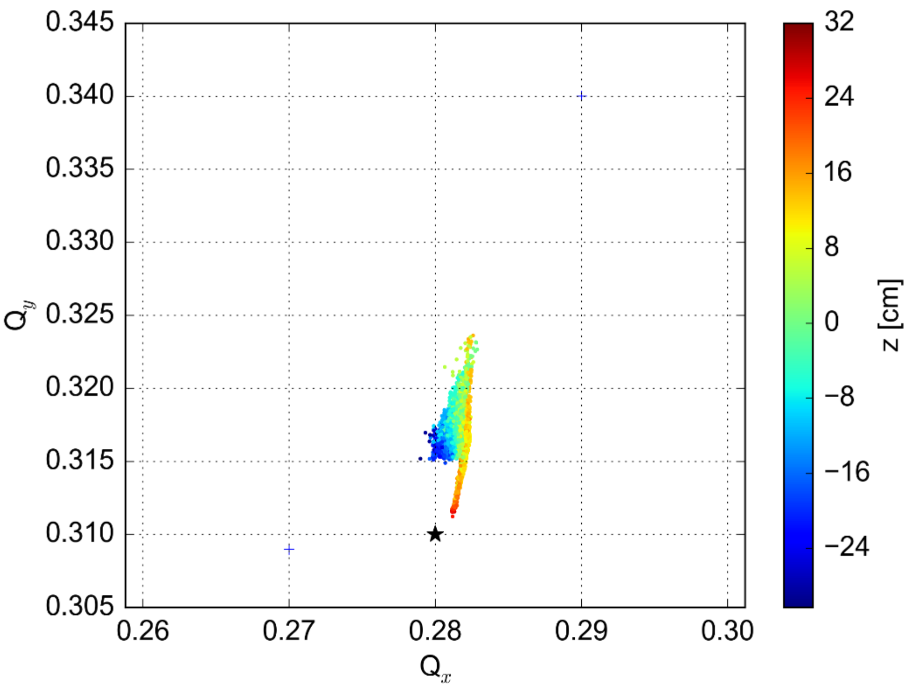


Color coding for footprint: longitudinal position along bunch
Asymmetric footprint, in H, slight defocusing effect due to the pinched stripes

Incoherent effects
Tune footprints in dipoles (II)

- Nominal intensity **1.3×10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → just below instability threshold

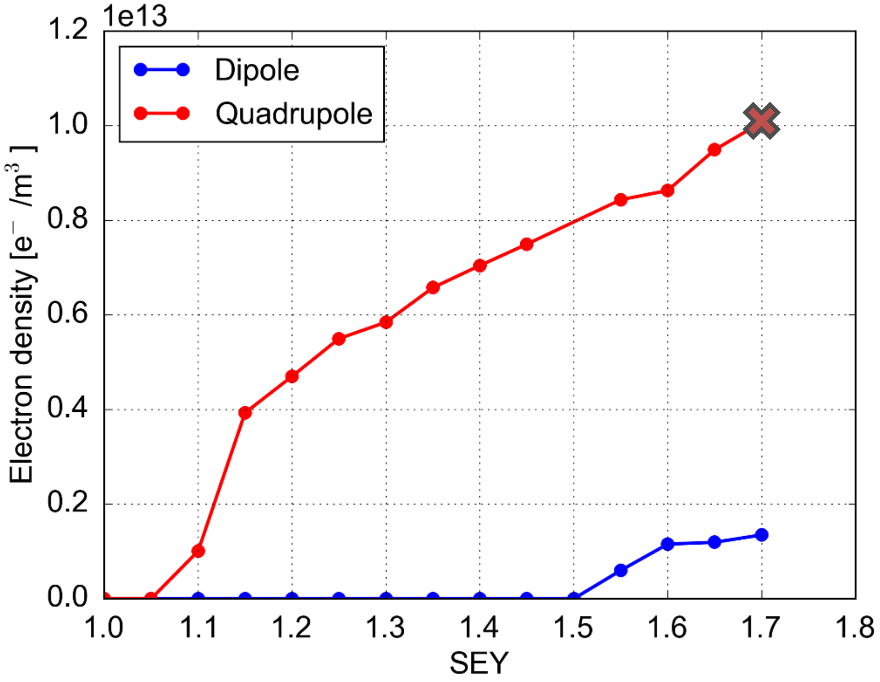


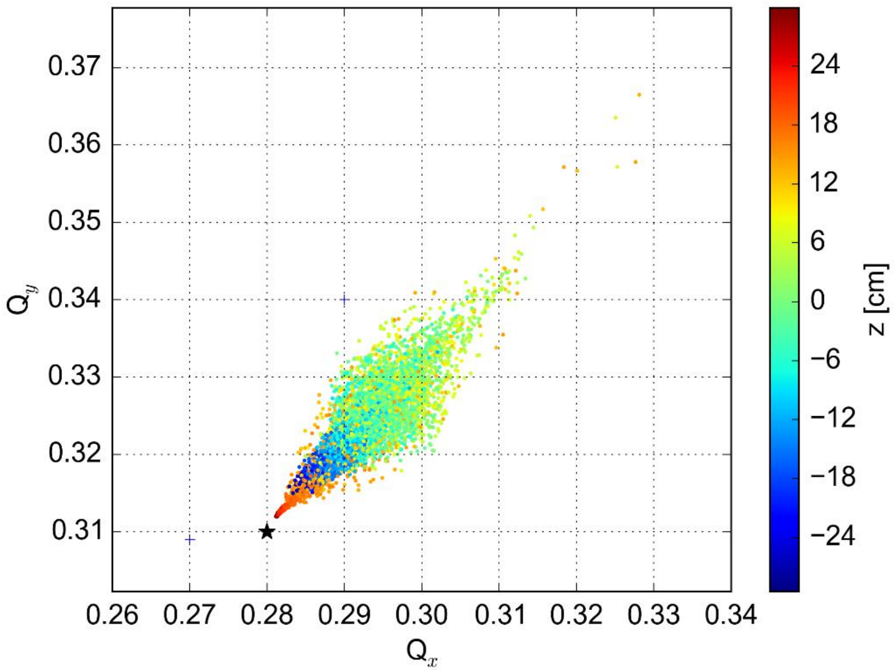


Color coding for footprint: longitudinal position along bunch
Asymmetric footprint, in H, slight defocusing effect due to the pinched stripes

Incoherent effects
Tune footprints in quadrupoles (I)

- Nominal intensity **1.3×10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → above instability threshold

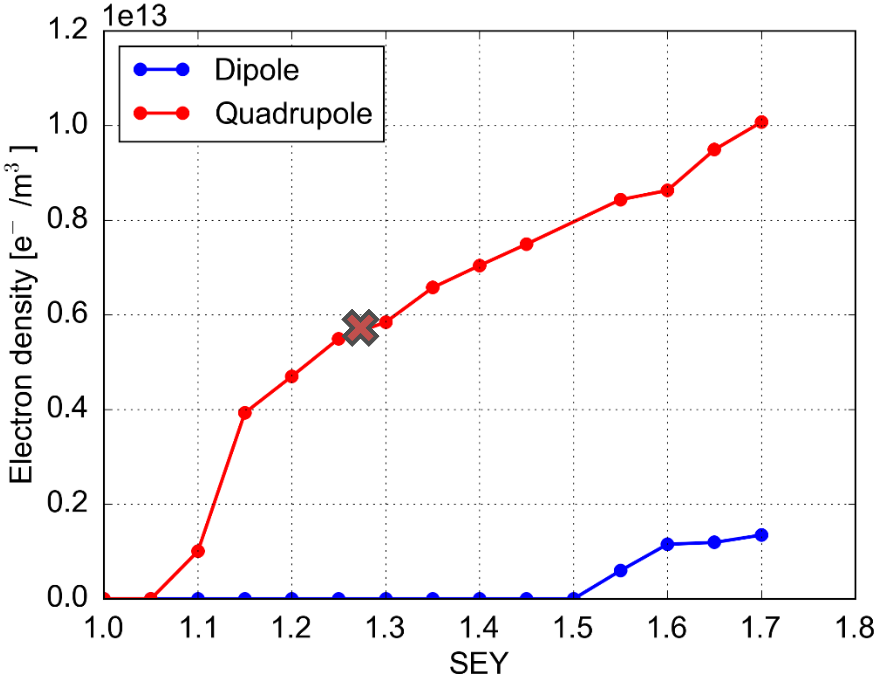


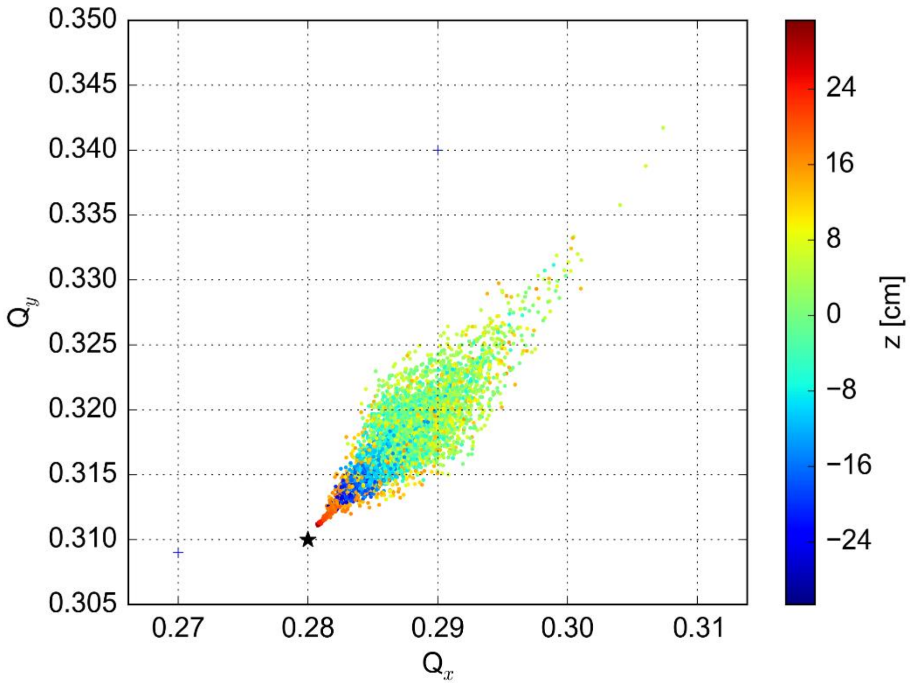


Color coding for footprint: longitudinal position along bunch
Symmetric, head and tail not much detuned, maximum detuning when pinching

Incoherent effects
Tune footprints in quadrupoles (II)

- Nominal intensity **1.3 x 10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → below instability threshold

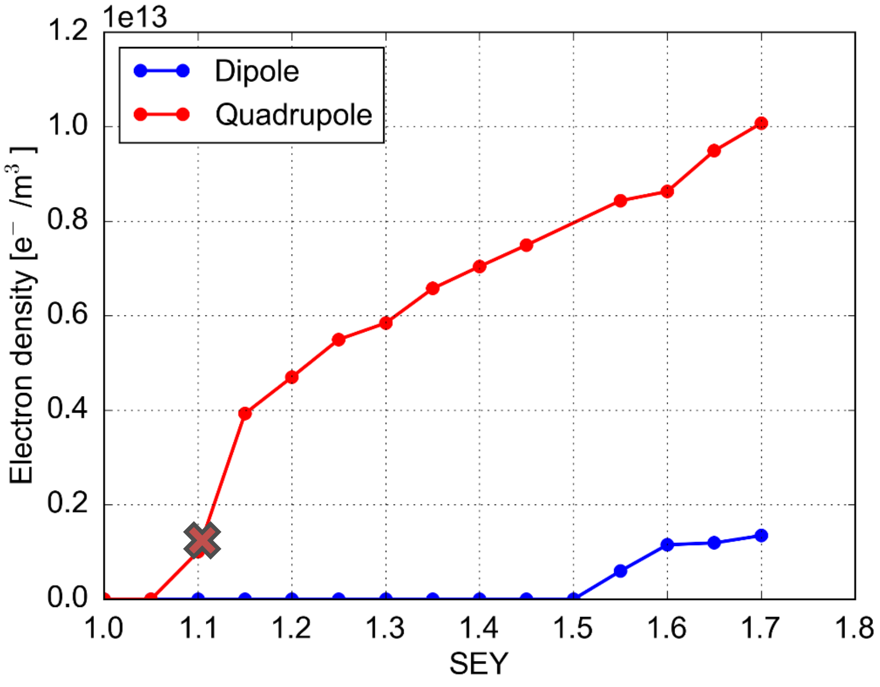


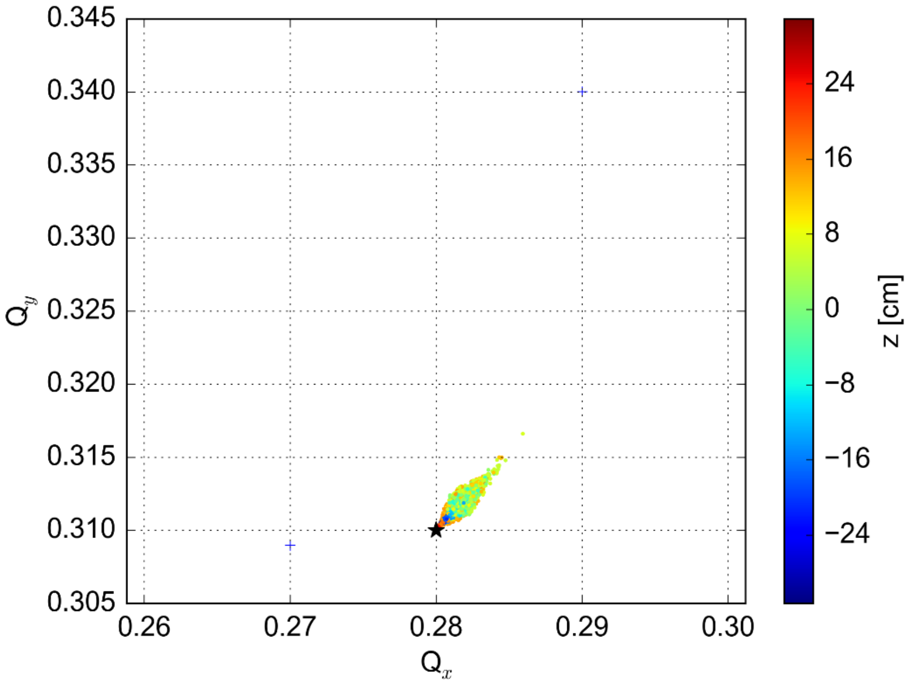


Color coding for footprint: longitudinal position along bunch
Symmetric, head and tail not much detuned, maximum detuning when pinching

Incoherent effects
Tune footprints in quadrupoles (III)

- Nominal intensity **1.3 x 10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → far below instability threshold, lower limit estimated from SAM measurements in 2012 (1.1 – 1.2)

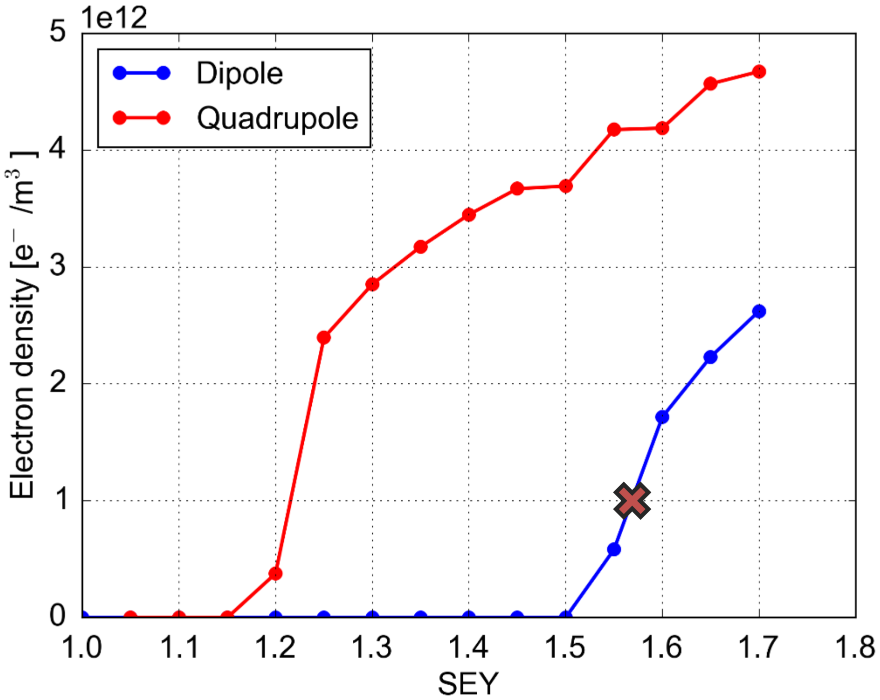


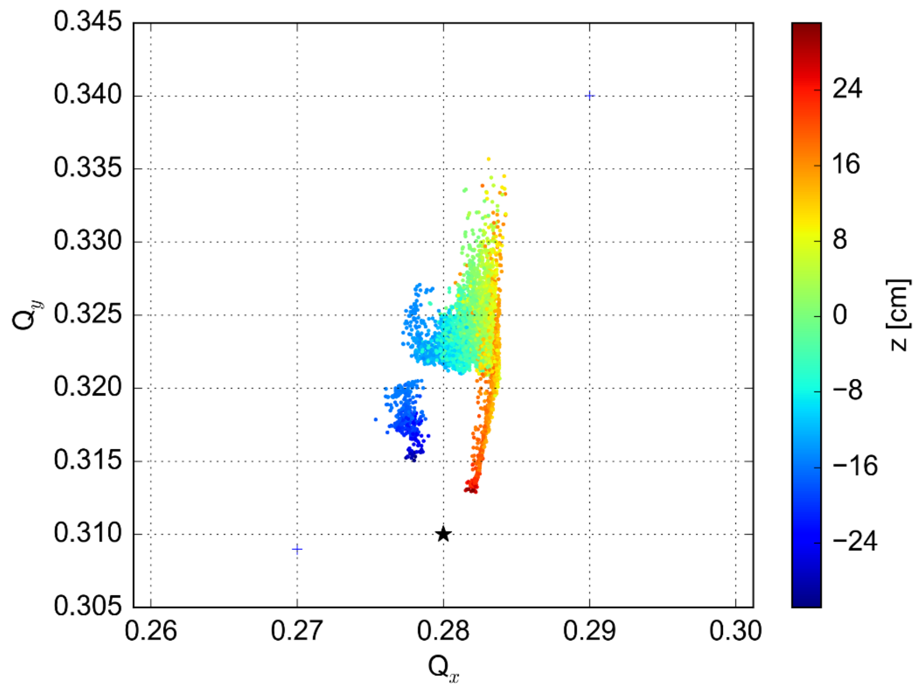


Color coding for footprint: longitudinal position along bunch
Symmetric, head and tail not much detuned, maximum detuning when pinching

Incoherent effects
Tune footprints in dipoles (I)

- HL-LHC intensity **2.3 x 10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → at the instability threshold

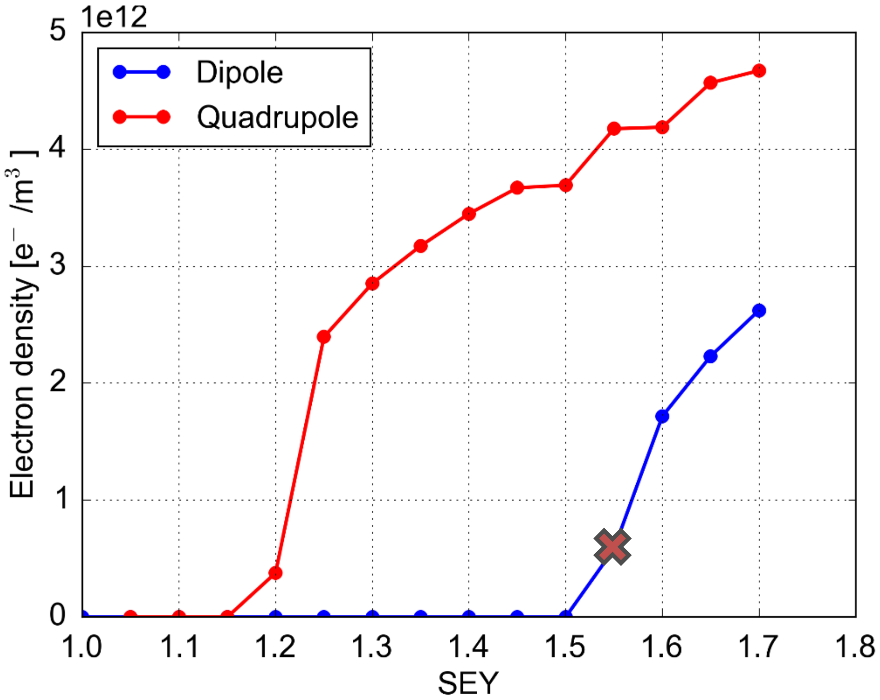


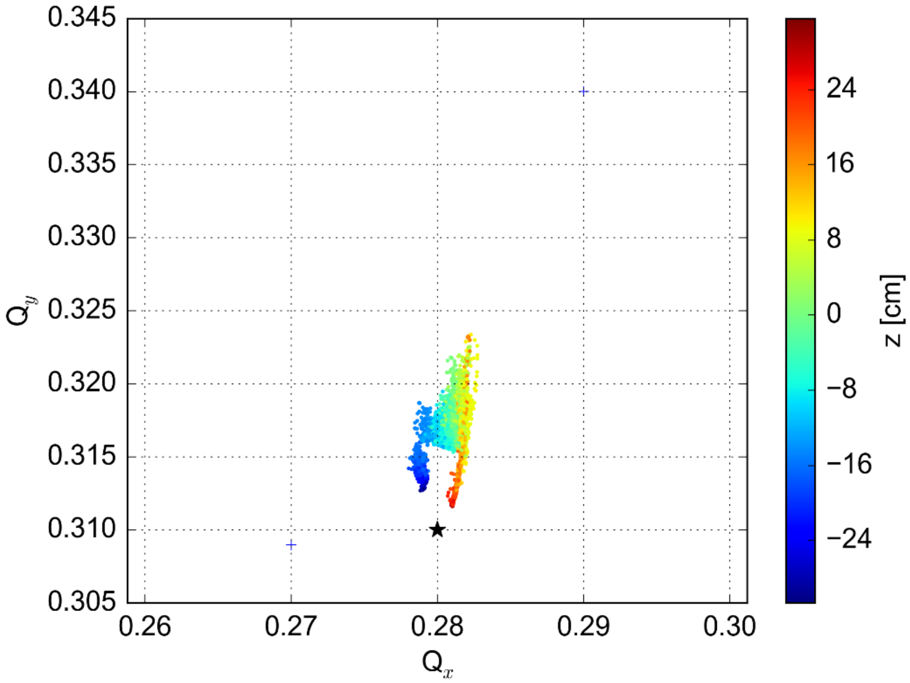


Color coding for footprint: longitudinal position along bunch
Asymmetric footprint, in H, slight defocusing effect due to the pinched stripes

Incoherent effects
Tune footprints in dipoles (II)

- HL-LHC intensity **2.3 x 10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → below the instability threshold

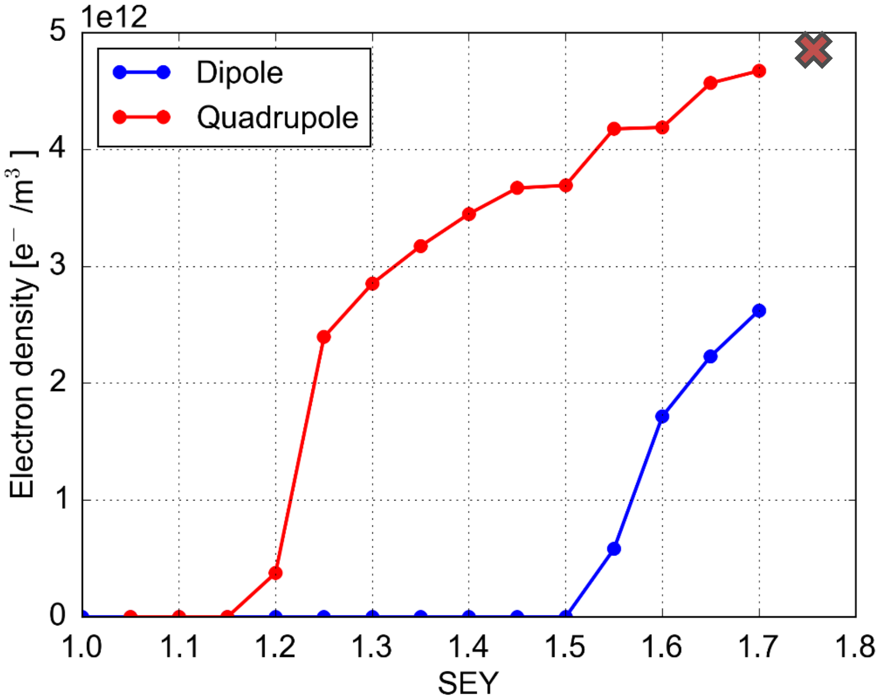


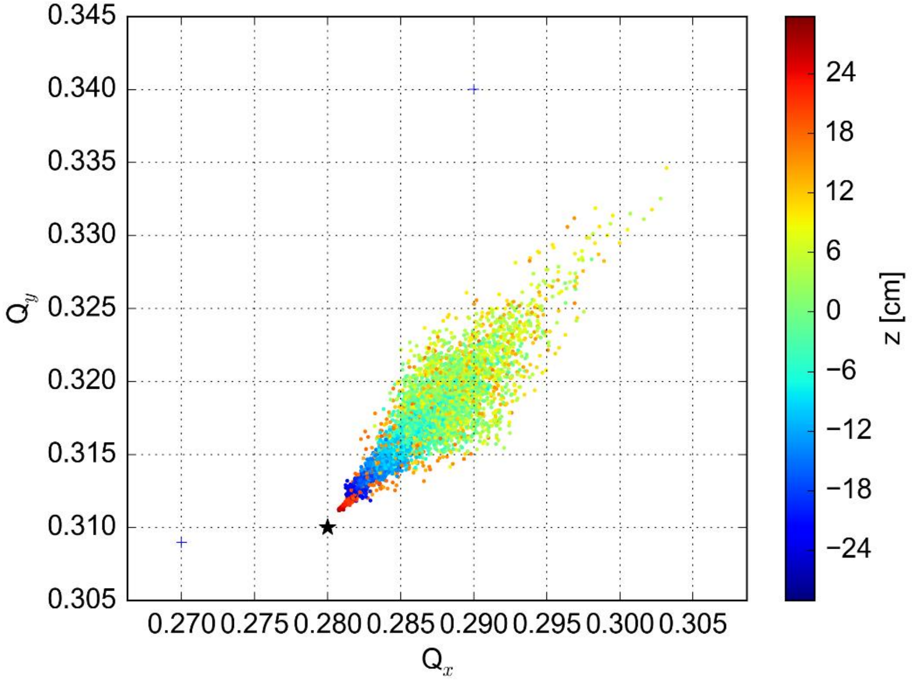


Color coding for footprint: longitudinal position along bunch
Asymmetric footprint, in H, slight defocusing effect due to the pinched stripes

Incoherent effects
Tune footprints in quadrupoles (I)

- HL-LHC intensity **2.3 x 10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → below the instability threshold

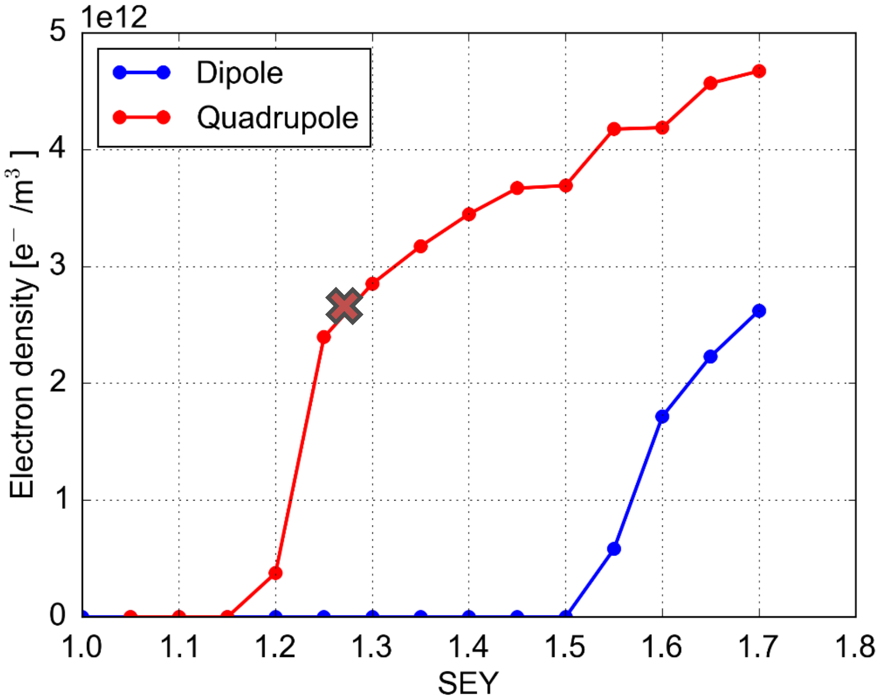


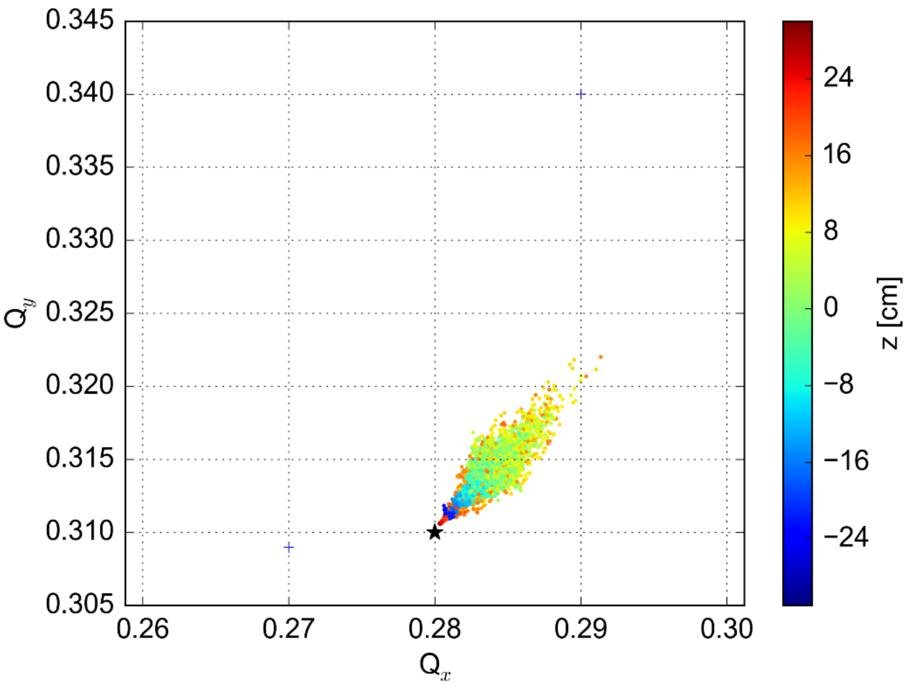


Color coding for footprint: longitudinal position along bunch
Symmetric, head and tail not much detuned, maximum detuning when pinching

Incoherent effects
Tune footprints in quadrupoles (II)

- HL-LHC intensity **2.3 x 10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → far below the instability threshold

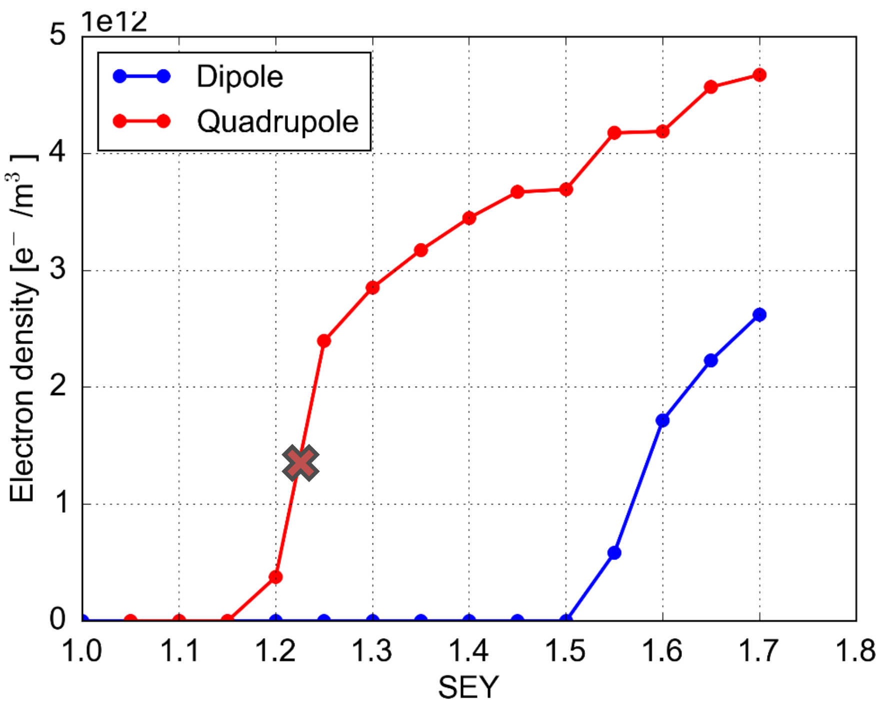


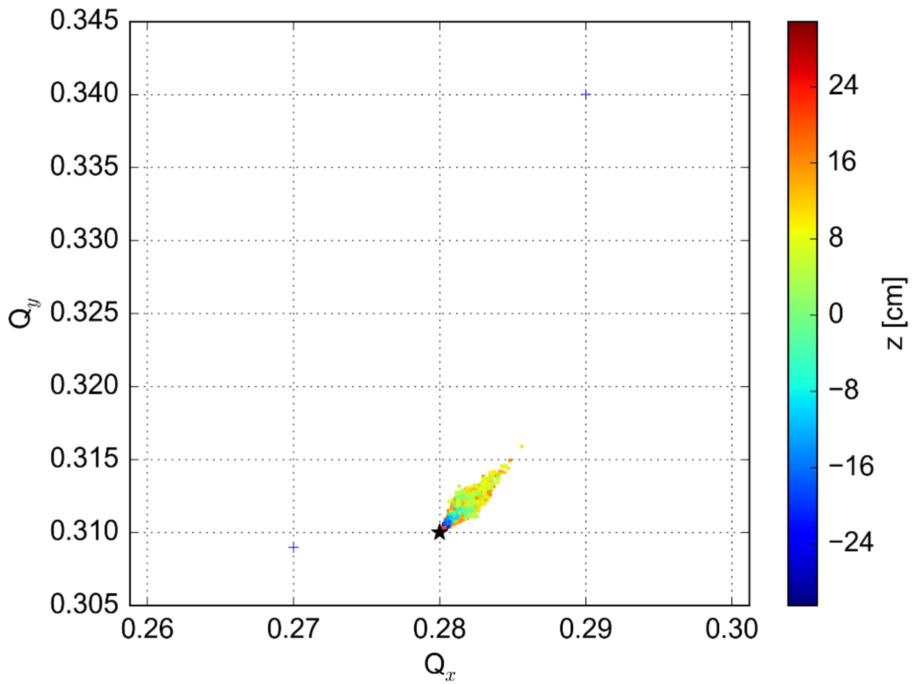


Color coding for footprint: longitudinal position along bunch
Symmetric, head and tail not much detuned, maximum detuning when pinching

Incoherent effects
Tune footprints in quadrupoles (III)

- HL-LHC intensity **2.3×10^{11} p/b**
- Calculate electron cloud footprints for different SEYs → far below the instability threshold, into the region of SEY estimated in 2012

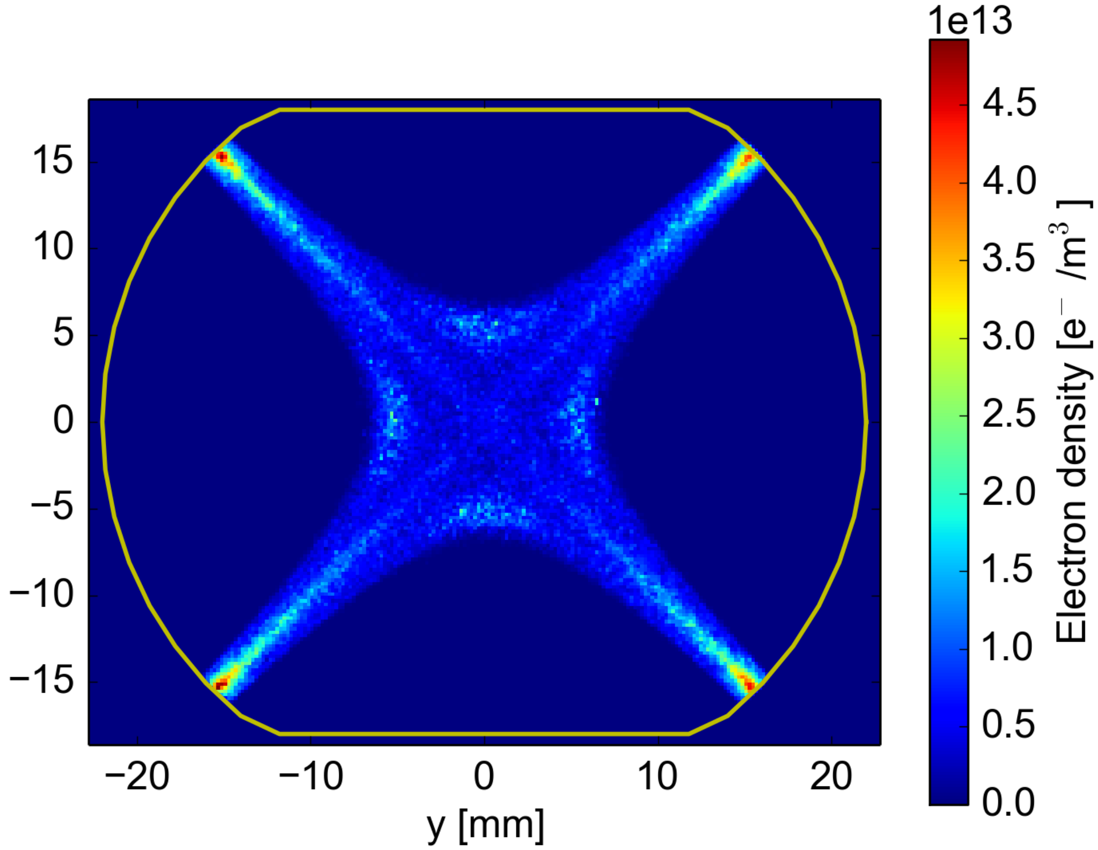




Color coding for footprint: longitudinal position along bunch
Symmetric, head and tail not much detuned, maximum detuning when pinching

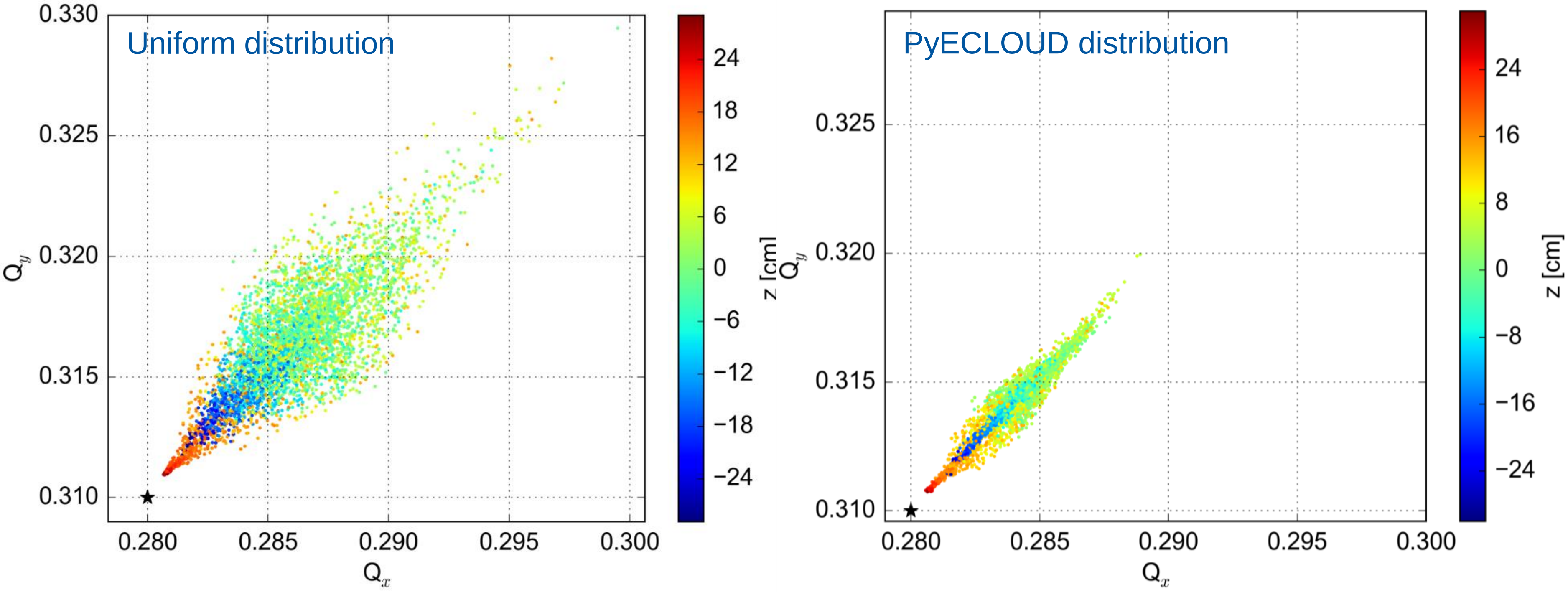
Incoherent effects
Tune footprints in quadrupoles: effect of distribution (I)

- Nominal intensity **1.2 x 10^{11} p/b**
- SEY = 1.2, build up simulation → use electron distribution at saturation just before bunch passage



Incoherent effects
Tune footprints in quadrupoles: effect of distribution (II)

- Nominal intensity **1.2×10^{11} p/b**
- SEY = 1.2, build up simulation → use electron distribution at saturation just before bunch passage



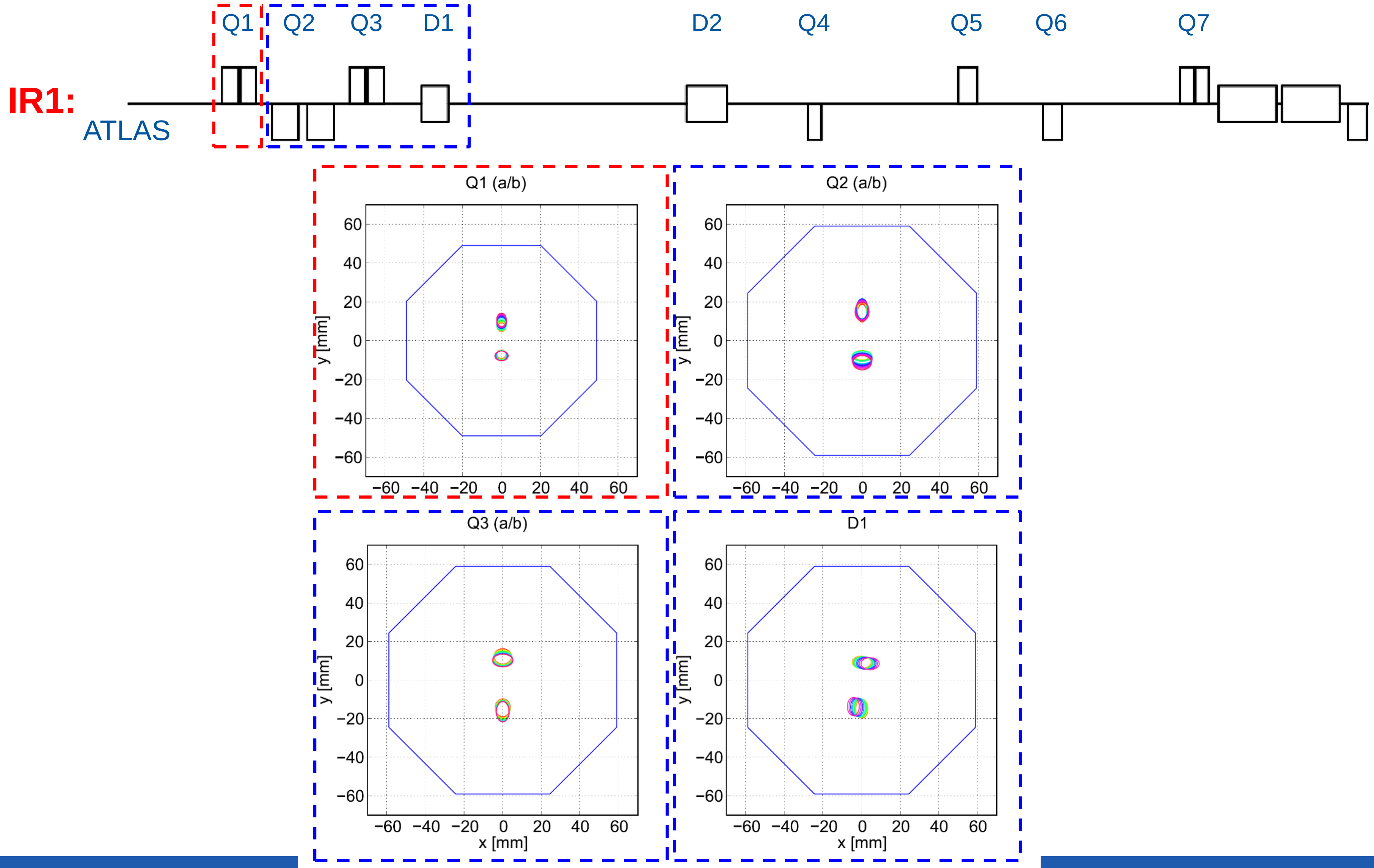
Footprint with self-consistent distribution is significantly smaller …

Part I: Conclusions & Outlook

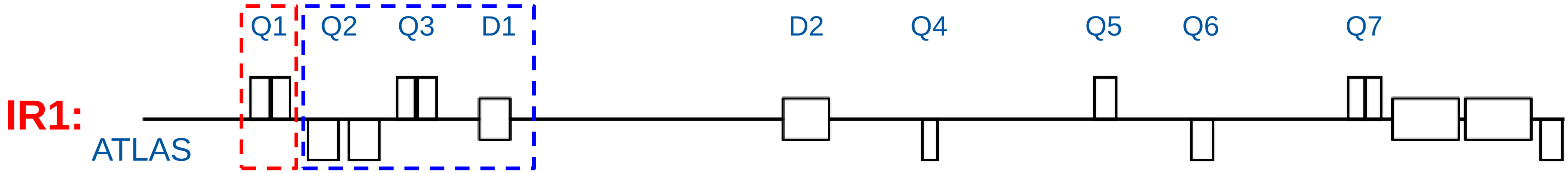
- **Electron-cloud driven instabilities in LHC**
  - PyHEADTAIL-PyECLOUD module fully functional
  - Effect of electron cloud in arc dipoles and quadrupoles on single bunch stability studied for nominal and HL-LHC parameters
    - SEY should be below instability threshold for present beam parameters (but need to study combined effect)
    - Electron cloud in quads alone seems to be insufficient to trigger electron cloud instabilities for HL-LHC parameters
  - Tune footprints generated for e-cloud in dipoles and quadrupoles → important to include self-consistent distribution from PyECLOUD

  → Next on the list:
    - Full blown simulations with self-consistent distributions, combined effects
    - Effect of triplets ('almost 3D' simulation → needs slicing with beta function variation, self-consistent distributions with enough macroelectrons in the center for each slice, weak-strong two-bunch pinch in LR points, off-axis beam with changing orbit, …)

Electron cloud in the HL-LHC triplets

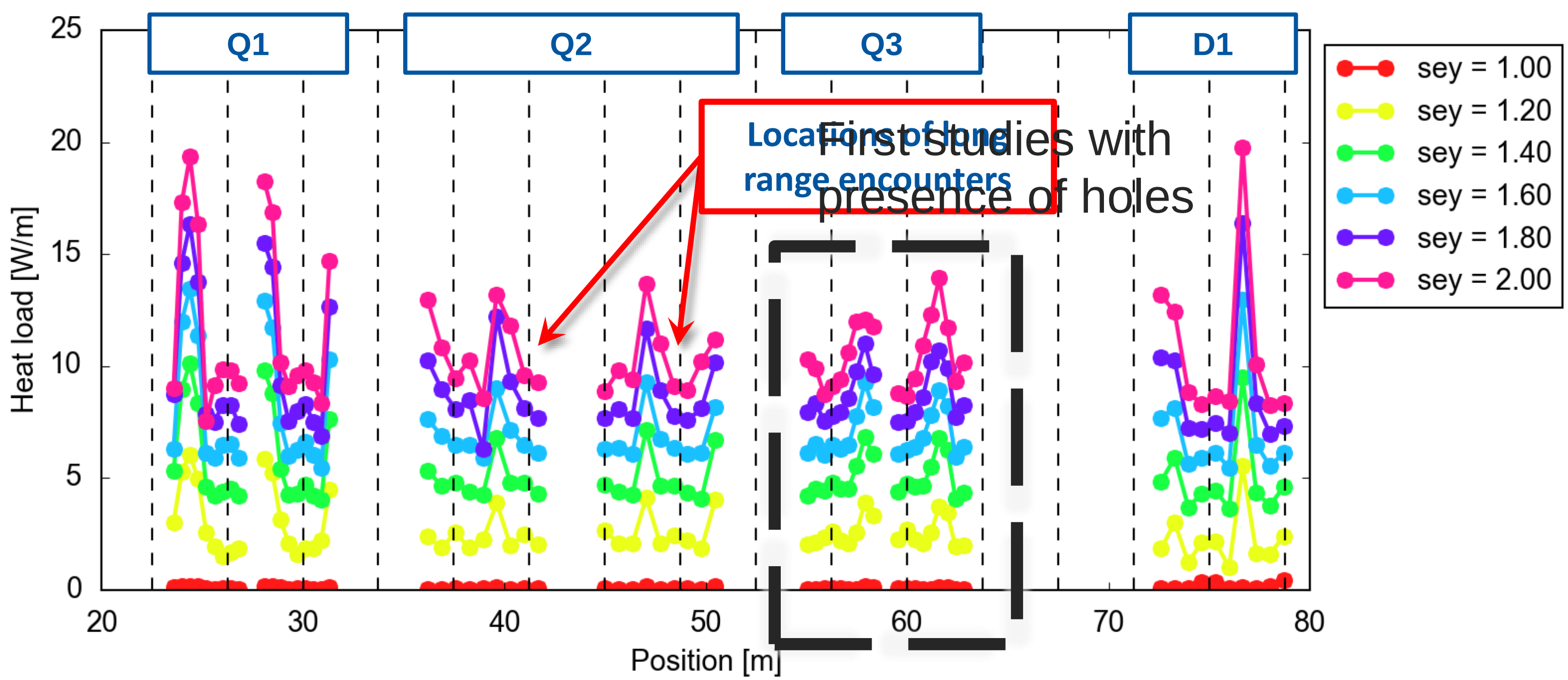


Electron cloud in the HL-LHC triplets



EC much weaker in the vicinity of **long range encounters**

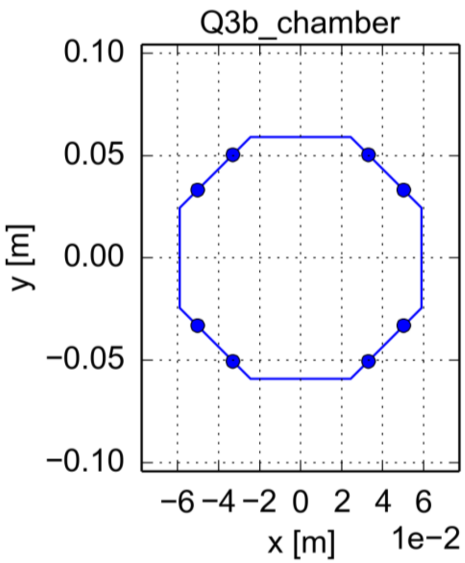
Modules with the **same beam screen and field structure** behave very similarly

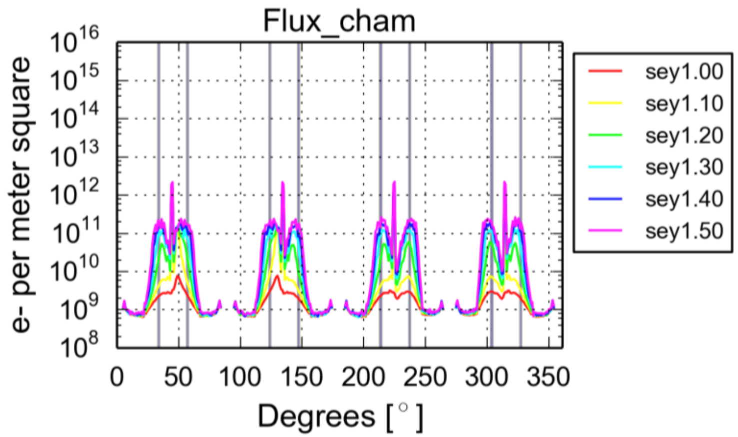


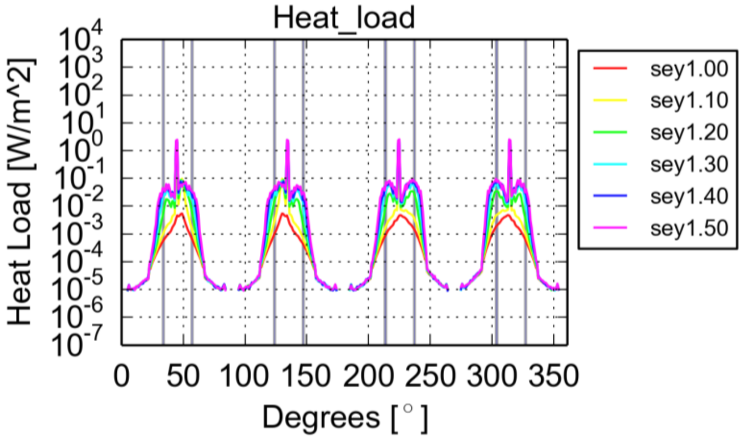
Electron cloud in the HL-LHC triplets

- First check: are the holes located at high impact positions?

→ Need to determine azimuthal dependence of heat load and electron flux

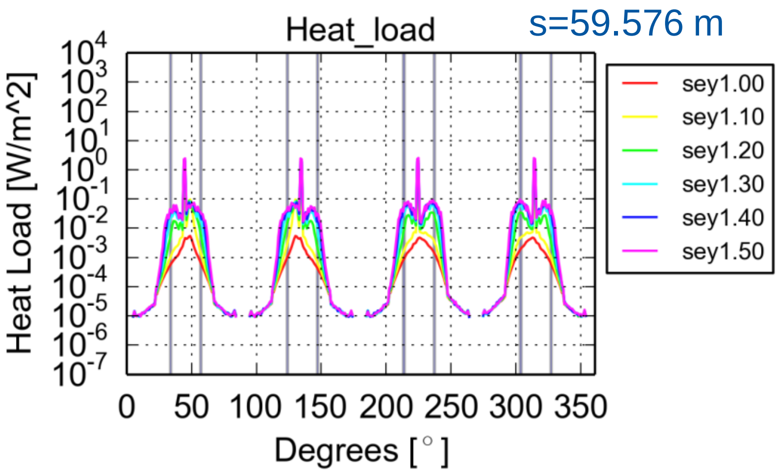


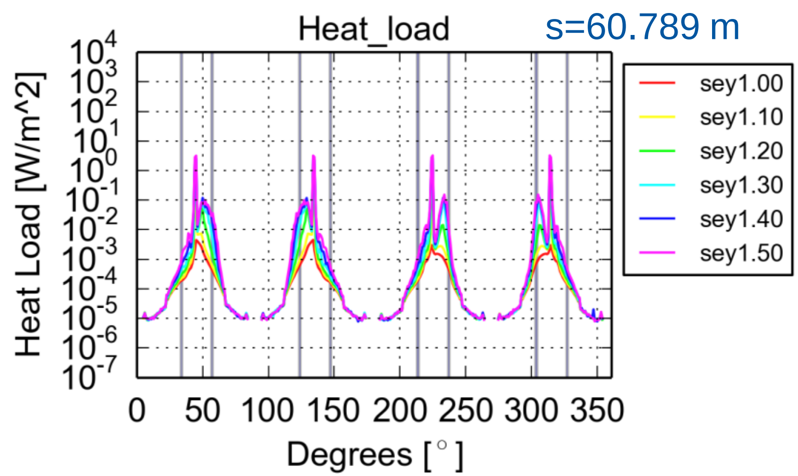


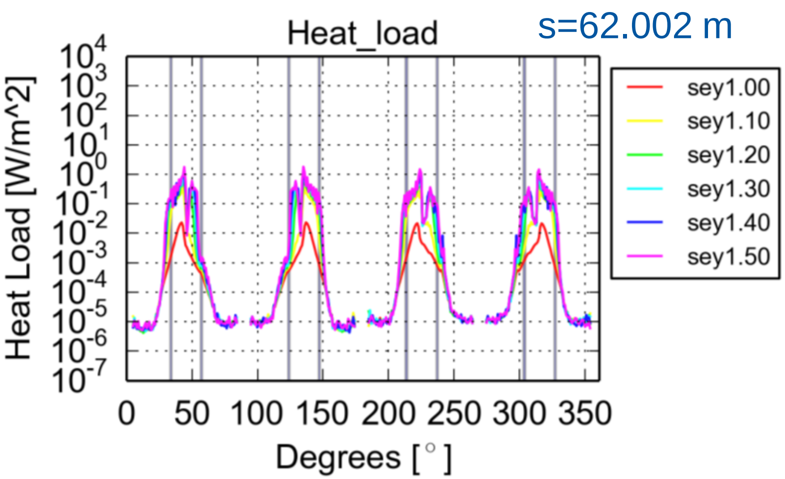


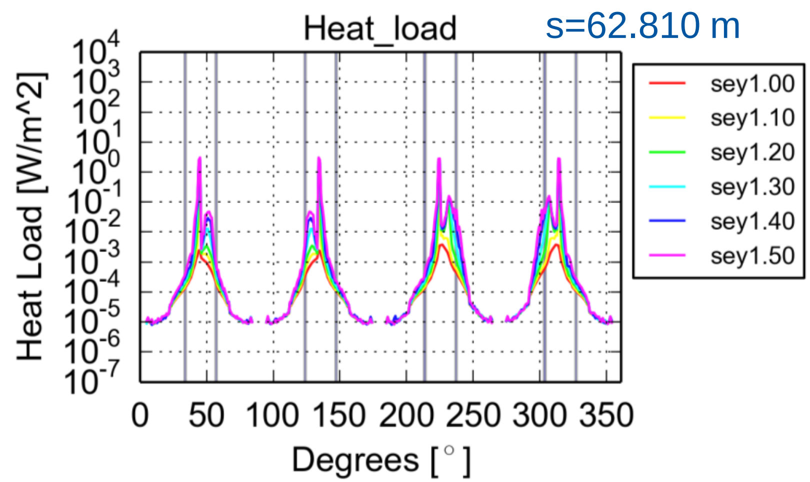
Electron cloud in the HL-LHC triplets

- Scan in the longitudinal direction → mainly high impact regions



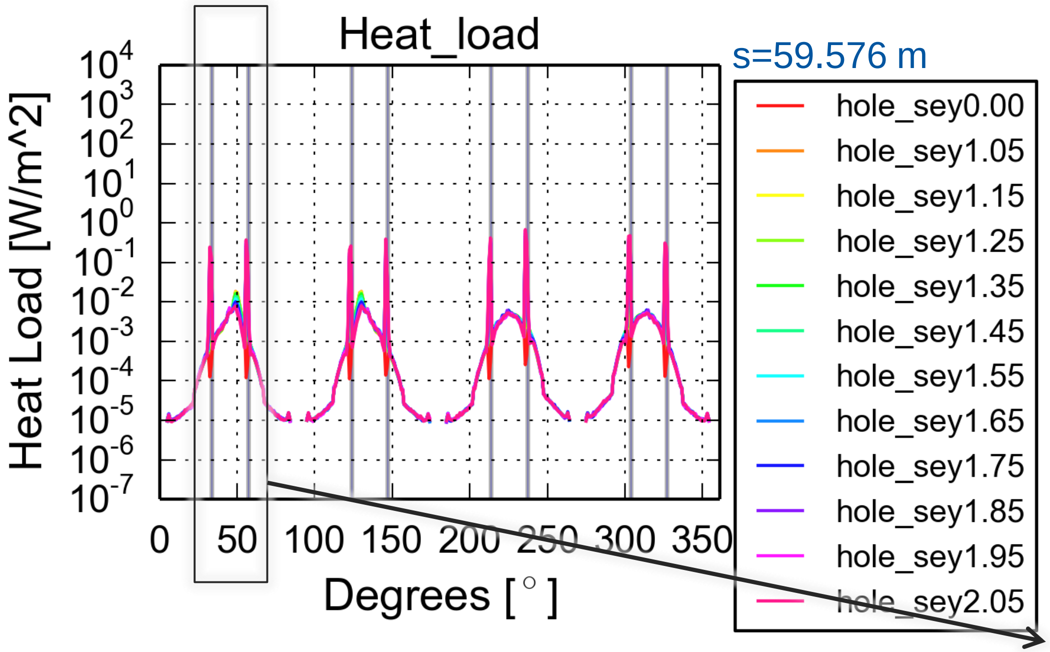


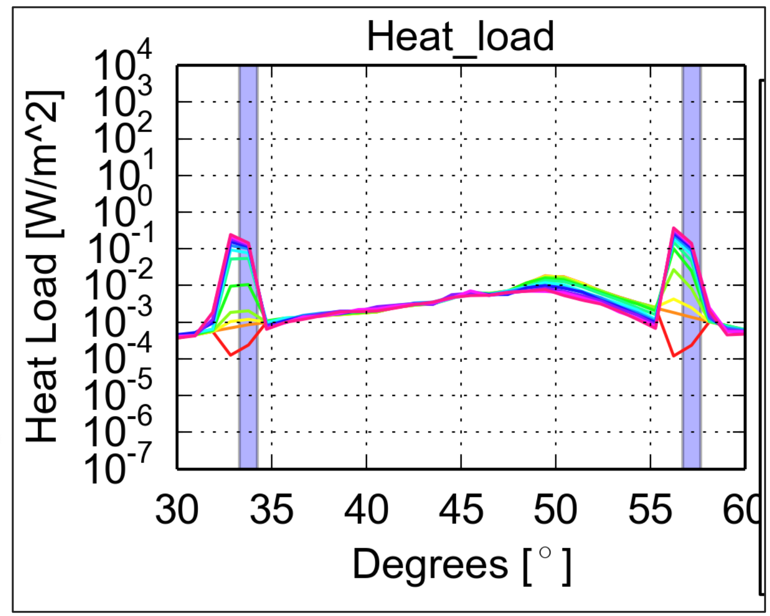




Electron cloud in the HL-LHC triplets

- Fix SEY_{screen}=1.05 (a-C coating)
- Scan SEY of holes from 0 (perfect absorbers) to 2.05 (uncoated and unscrubbed baffles)

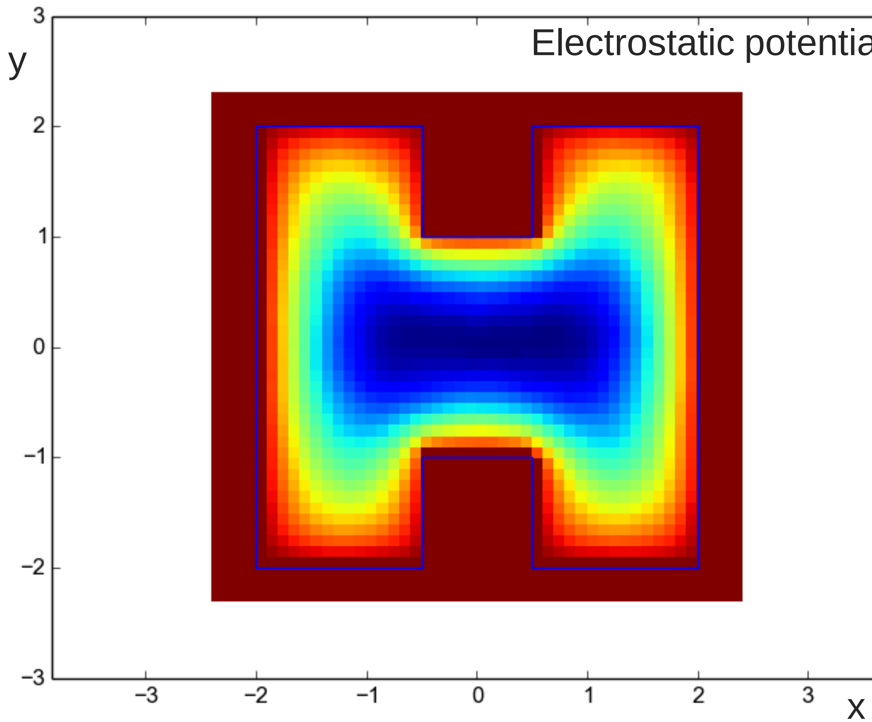


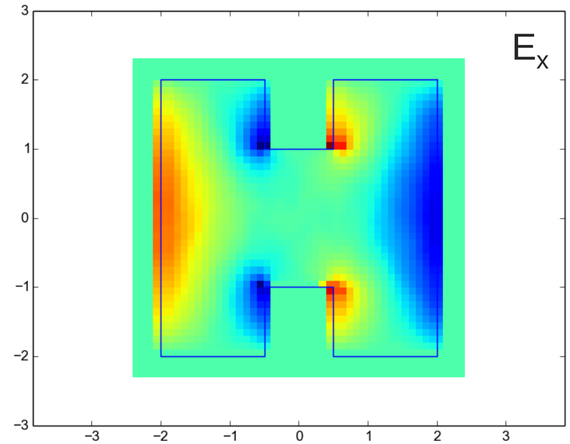


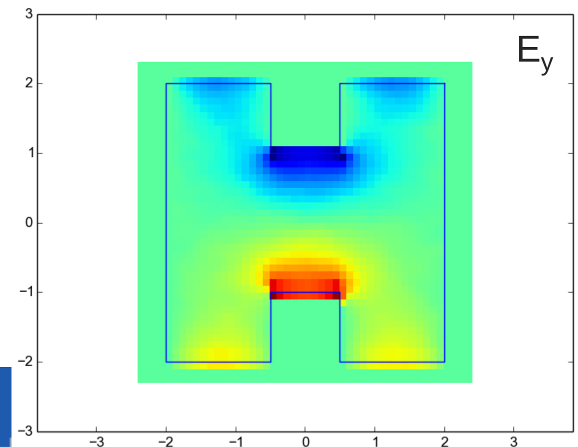
Basically "unperturbed" e-cloud with potential electron production spikes for uncoated baffles

Electron cloud in the HL-LHC triplets: next steps

- Implementation in PyECLOUD of non-convex boundaries for chamber geometries → **Done**
  The code now correctly manages:
  - Detection of in or out of the chamber particle positions
  - Impact of particles against the chamber wall
  - Poisson equation to determine electric potential and electric field across the chamber







Source: uniform distribution of electrons within the chamber

Electron cloud in the HL-LHC triplets: next steps

- Implementation in PyECLOUD of non-convex boundaries for chamber geometries → **Done**
  The code now correctly manages:
  - Detection of in or out of the chamber particle positions
  - Impact of particles against the chamber wall
  - Poisson equation to determine electric potential and electric field across the chamber

- After this development, more complicated geometries can be implemented to model screen with holes, cold bore and possible shielding behind the holes
  - It will be first applied to the LHC beam screen in the arc dipoles and check multipacting conditions with and without baffle plates
  - It will be then extended to the triplets and other cases of interest

Thanks for your attention

Electron cloud in the quadrupoles: heat load as a function of bunch intensity for different SEY's (simulations with Boris' tracker)