E-cloud studies for FCC-hh

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EuroCirCol
A key to New Physics

Outline

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- FCC-hh study
- FCC-hh impedance and instabilities
- Electron cloud study:
  - SEY threshold
  - Stopping power
- Summary

FCC-hh vs LHC: Beam stability

Growth rate for transverse instabilities: $\tau^{-1} = \Im(\Delta\Omega) \approx \frac{q^2 N}{m\gamma} \hat{\beta}_\perp \Re Z_\perp$

Larger circumference (3:1) -> lower frequency: **1 kHz vs 8 kHz**

Smaller screen diameter (2:3) -> **larger impedance** (factor 3), **e-cloud density ?**

20 W/m synchrotron radiation (100:1) -> **photoelectrons**

Larger average β-function (2:1) -> **growth rates**

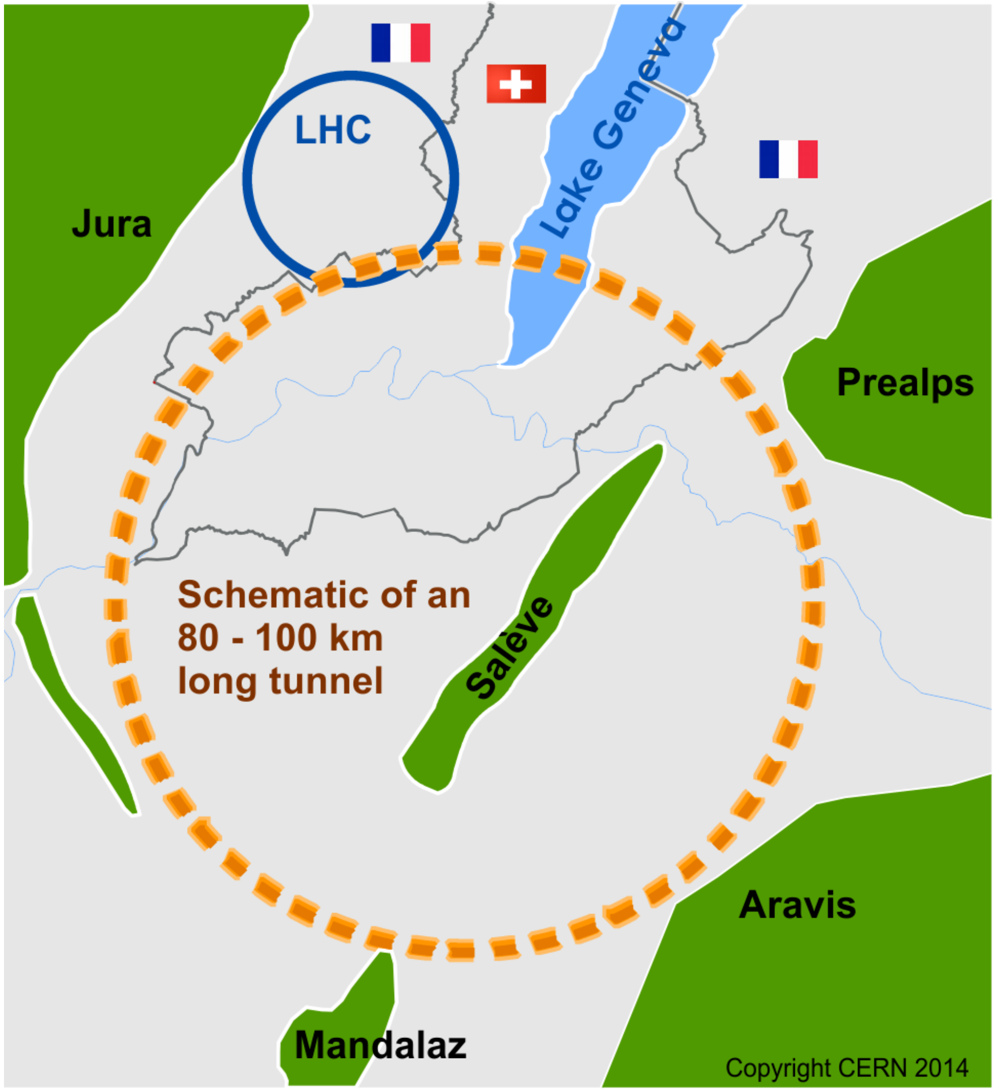
LHC-like bunches and 25 ns spacing (1:1)

Electron Cloud: ………

FCC-hh study

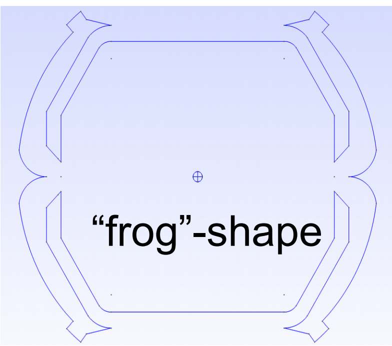
Design challenges for high luminosity:

- High stored energy and losses
- Impedance (optics, materials, laser treatment, etc…) and electron cloud (sawtooth or laser treatment, coating)
- Aperture should be minimized for dipole cost
- High synchrotron radiation load due to high beam energy → special screen

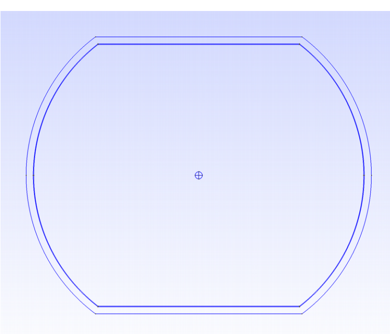


Resistive wall impedance: LHC and FCC-hh

FCC



LHC



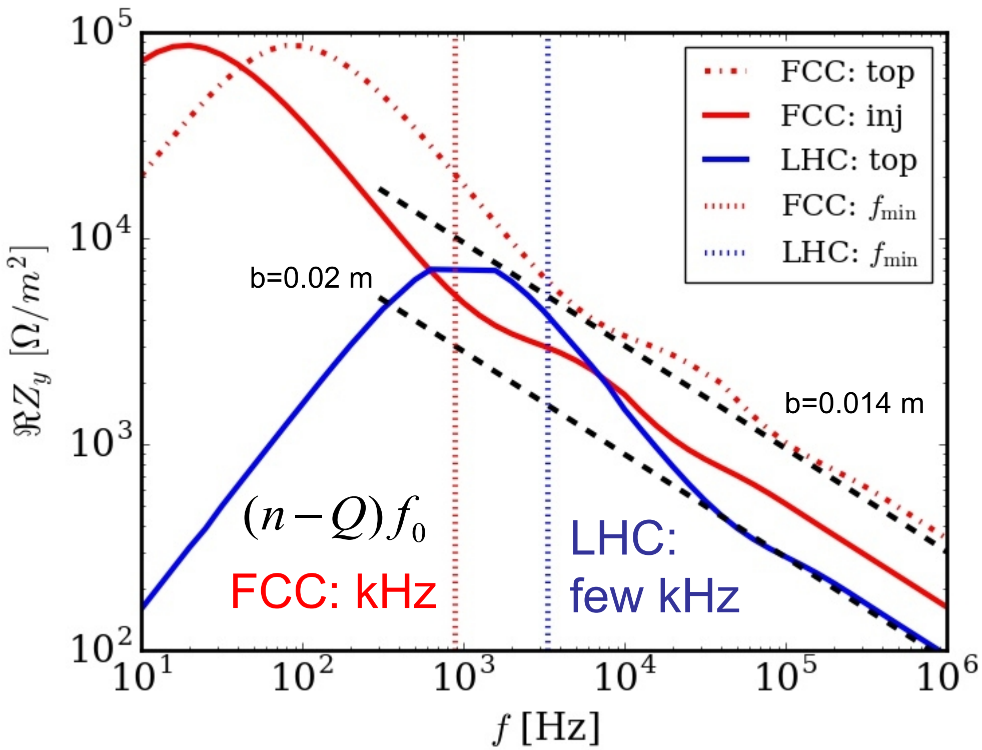
Growth rate:
(Sacherer 1974)

$$\tau_0^{-1} = \frac{j}{2Q\omega_0}\frac{e\beta I_0}{\gamma m_0 L}\Re(Z_{tr,0})$$

$$\omega_{min} = (n - Q_y)\omega_0$$

(lowest sideband)

Transverse impedances (only real part)



growth time at 3.3 TeV:
approx. 100 turns
at 50 TeV:
approx. 800 turns
LHC at 7 TeV:
approx. 2000 turns

$$Z_\perp(\omega) = (1-i)\frac{c}{\pi\omega b^3\delta_s\sigma_c}$$

(Thick) resistive wall impedance

BeamImpedance2D (U. Niedermayer)

Electron cloud studies for FCC-hh

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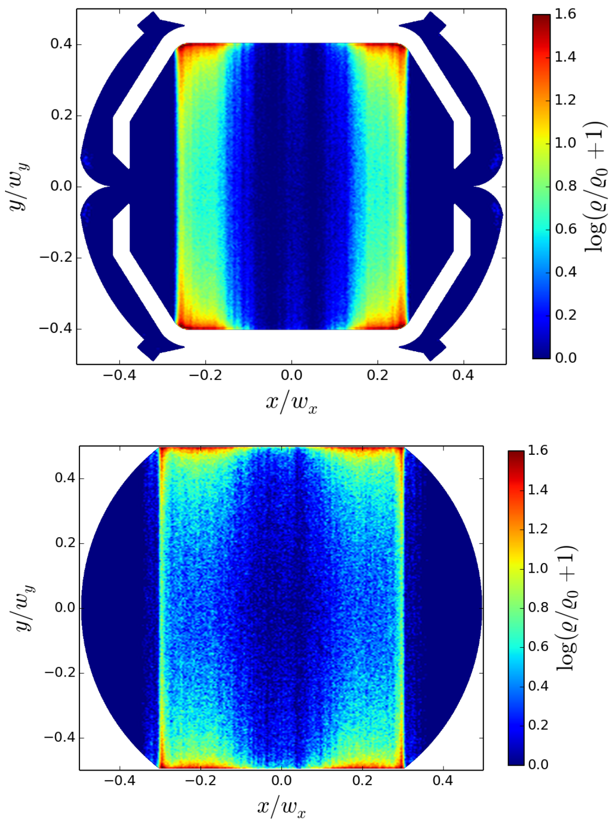
Electron cloud in the FCC-hh can cause:

coherent instabilities, incoherent emittance growth, heat load, vacuum degradation, tune shift and spread

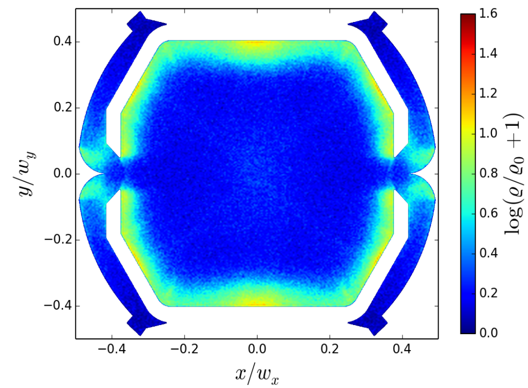


Motivation and Aims of this study:

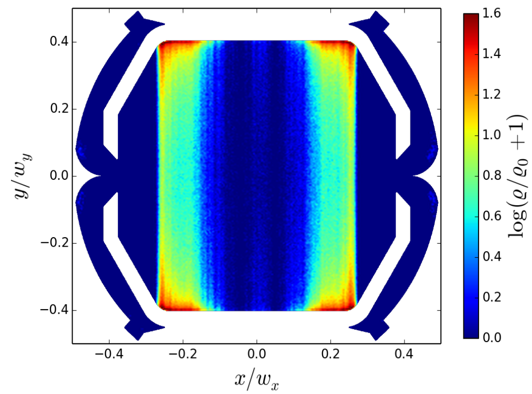
- Estimate build-up thresholds, SEYs, heat load
- Predict tune shifts, spreads and instability thresholds
- Effect of residual photo electrons
- Compare LHC vs. FCC-hh, understand energy scaling.

Electron cloud study

Assumptions:
1. Electrostatic field solver for electron space charge field
2. Ultra relativistic approximation of primary beam: Rigid bunch approximation
3. LHC/FCC bunches



Simulation 2D tool *openEcloud* for electron cloud studies:
– Finite Integration Technique (field solver)
– 2D LU Poisson Solver with arbitrary cut-cell boundaries
– Standard Particle-In-Cell for electrons
– Boundary interaction models for electrons



openEcloud : https://github.com/openecloud
e.g. F. Petrov, O. Boine-Frankenheim, O. Haas, PRAB (2014)
Fast 2D Poisson solver, PIC solver, SEY model, interfaces to PATRIC/pyORBIT

Secondary emission yield model

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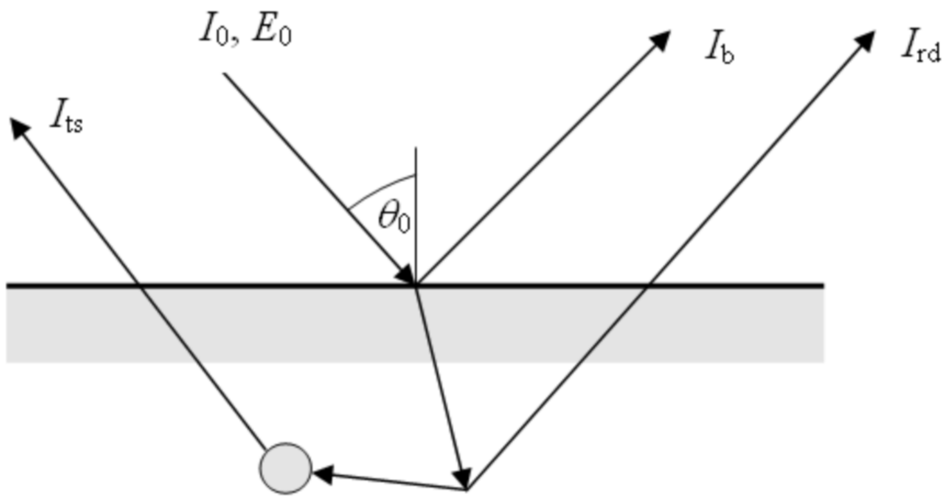

Cimino/Collins SEY model: $\delta = \delta_e + \delta_{ts}$

Furman/Pivi SEY model: $\delta = \delta_e + \delta_r + \delta_{ts}$

Same model, but different parametrization!

M. A. Furman and M. T. F. Pivi Phys. Rev. ST Accel. Beams 5, 124404
R. Cimino et al., Phys. Rev. Lett. 93, 014801
G. Iadarola's PhD Thesis; P. Dijkstal Master Thesis

Secondary emission yield model

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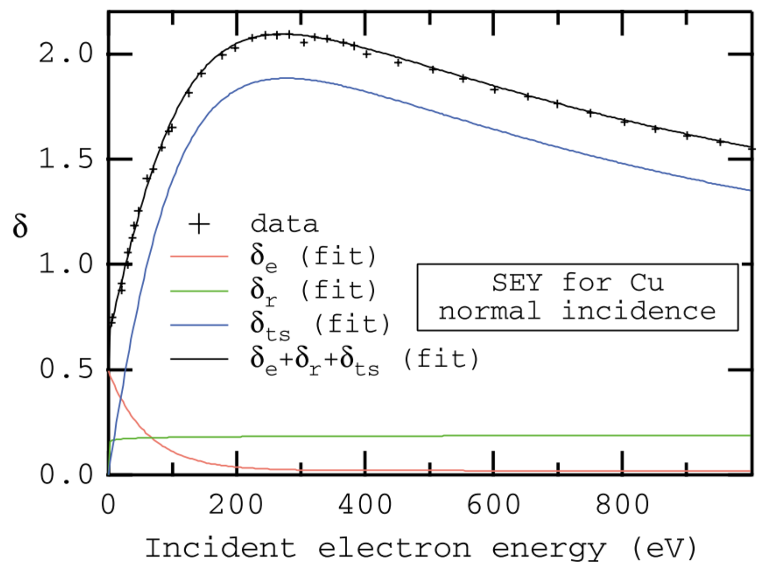
Furman/Pivi SEY model: $\delta = \delta_e + \delta_r + \delta_{ts}$

$\delta_{max} \approx 1.88$



$$\delta_{ts}(E_0,\theta_0)=\hat{\delta}(\theta_0)\,D(E_0/\hat{E}(\theta_0)) \qquad D(x)=\frac{sx}{s-1+x^2}$$

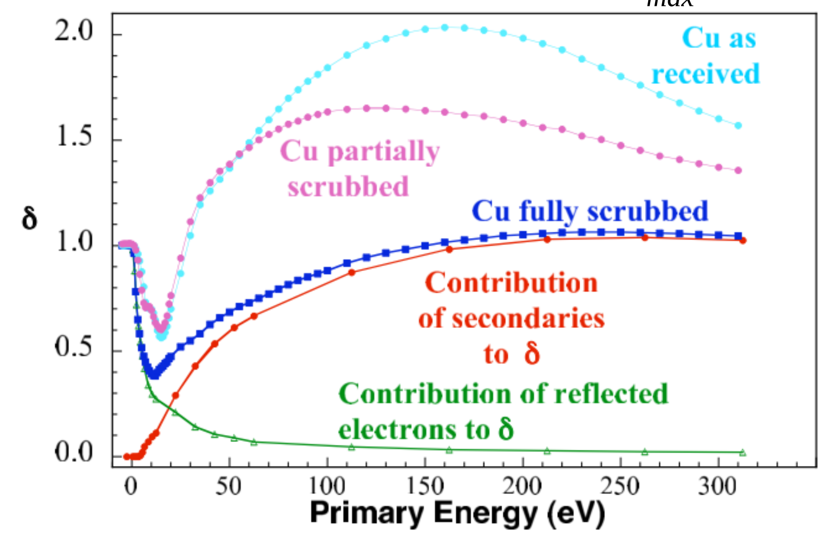
$$\hat{\delta}(\theta_0)=\hat{\delta}_{ts}[1+t_1(1-\cos^{t_2}\theta_0)]$$

$$\delta_{bs}=\hat{\delta}_{bs}(E_0,\theta_0)[1+e_1(1-\cos^{e_2}\theta_0)]$$

$$\delta_{rd}=\hat{\delta}_{rd}(E_0,\theta_0)[1+r_1(1-\cos^{r_2}\theta_0)]$$

Cimino/Collins SEY model: $\delta = \delta_e + \delta_{ts}$

$\delta_{max} \approx 1.7$



$$\delta_{elas}(E)=R_0\left(\frac{\sqrt{(E)}-\sqrt{(E+E_0)}}{\sqrt{(E)}+\sqrt{(E+E_0)}}\right)^2$$

$R_0 = 1\,?$

$$\delta_{true}(E,\theta_i)=\delta'_{max}(\theta_i)\frac{s\dfrac{E}{E'_{max}(\theta_i)}}{s-1+\left(\dfrac{E}{E'_{max}(\theta_i)}\right)^s}$$

$$\delta'_{max}(\theta_i)=\delta_{max}\,e^{\frac{1-\cos\theta_i}{2}}$$

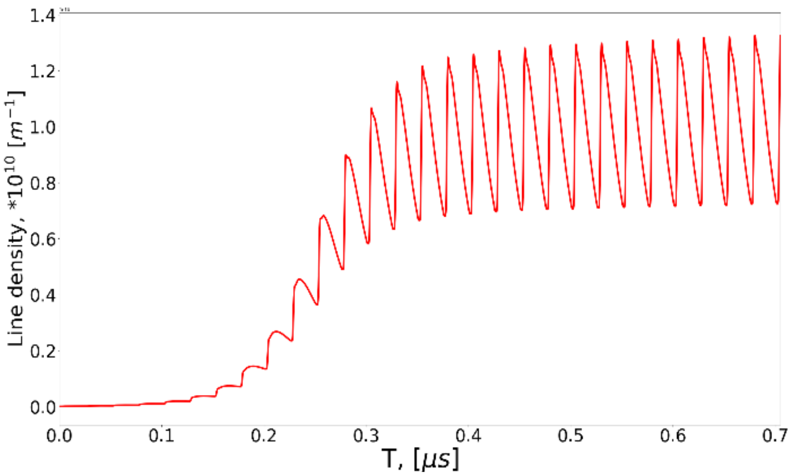
SEY threshold: from LHC to FCC-hh

Thresholds are defined as the highest SEY without build-up

Arc element	Furman/Pivi SEY model		Cimino/Collins SEY model	
	FCC-hh	LHC	FCC-hh	LHC
Drift	1.3	1.23	1.6	1.3
Dipole [injection/top energy]	1.25/1.25	1.1/1.1	1.56/1.56	1.32/1.32

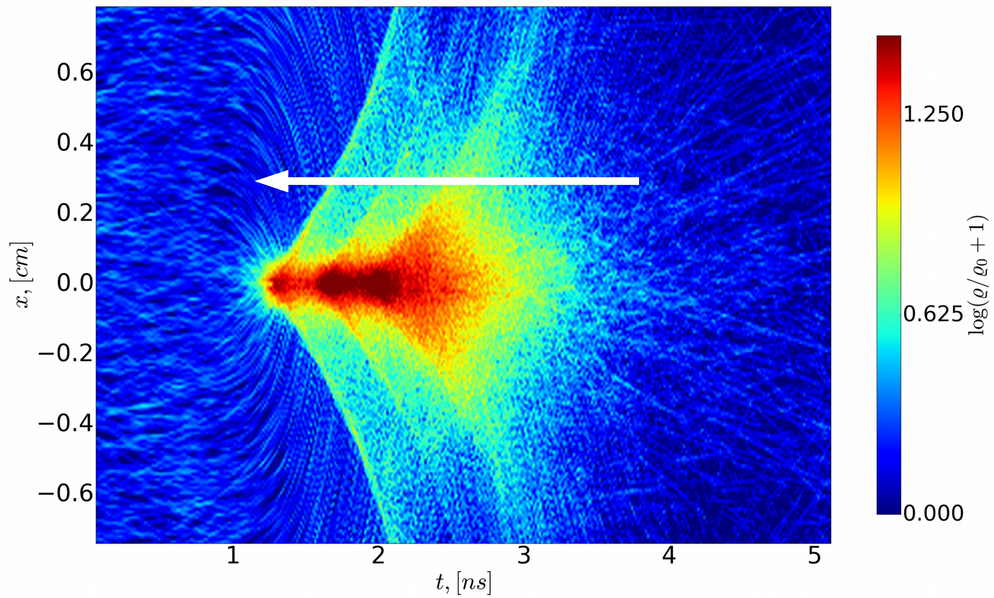
Dependence of SEY:
- energy and angle incidence of the primary particles
- geometry and material of the beam pipe

Electron cloud build-up by multipacting can be suppressed by sufficiently long scrubbing or **coatings (laser-treated Copper**, which increase the impedance at high frequencies, **or amorphous Carbon)**.

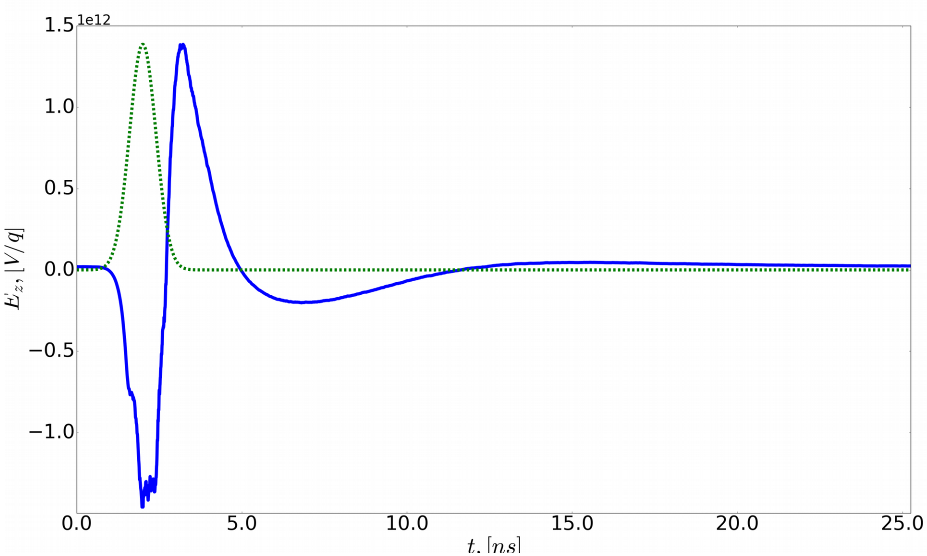


Electron cloud pinch in the FCC-hh

The effect is occurred if there is already an electron cloud when the bunch passes it is attracted towards the center of the bunch.



Density profile of electron cloud pinched in the field of the bunch in the absence of external B-field



The longitudinal electric field induced by a FCC-hh bunch in the saturated cloud

Stopping power and heat load

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The electron clouds can be the source of the energy loss as a results of the observed dependence in the LHC between the rf phase shift on the bunch spacing.

Stopping power – is a total energy loss of the bunch per length unit:

$$\frac{dW}{ds} = -\int \rho_i(r) E_z(r)\, dr = -q \int \lambda(z) E_z(z)\, dz$$

ρ_i – bunch charge density

$E_z(z)$ – longitudinal electric field induced by the bunch

$\lambda(z)$ – line density of the bunch

$q = e$ – particle charge

Energy loss per turn and particle:

$$\Delta W_z = \frac{L}{N_i} \frac{dW}{ds}$$

RF phase shift:

$$\sin(\Delta \phi_s) = \frac{\Delta W_p}{q V_{rf}}$$

Heat load:

$$P[W/m] = \frac{cS}{l_{bb}}$$

l_{bb} – bunch spacing

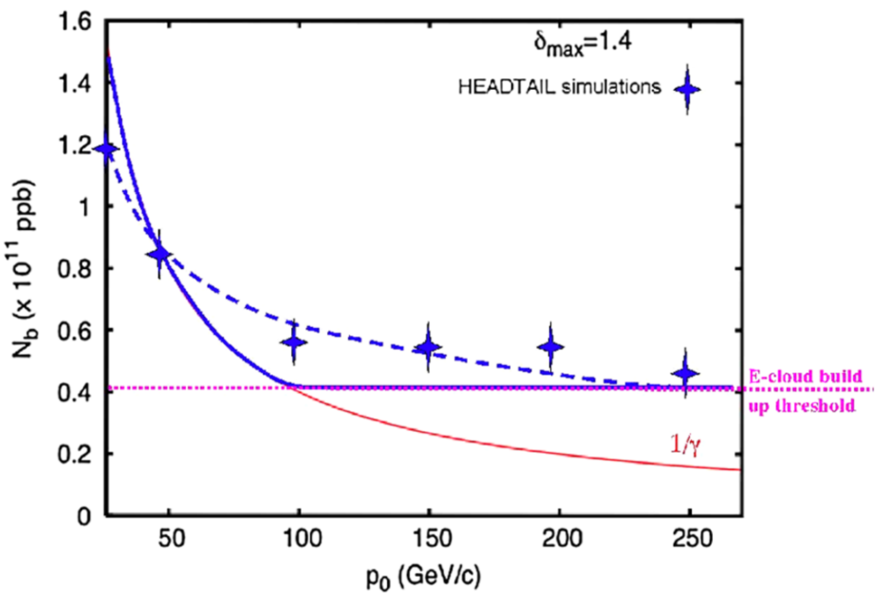


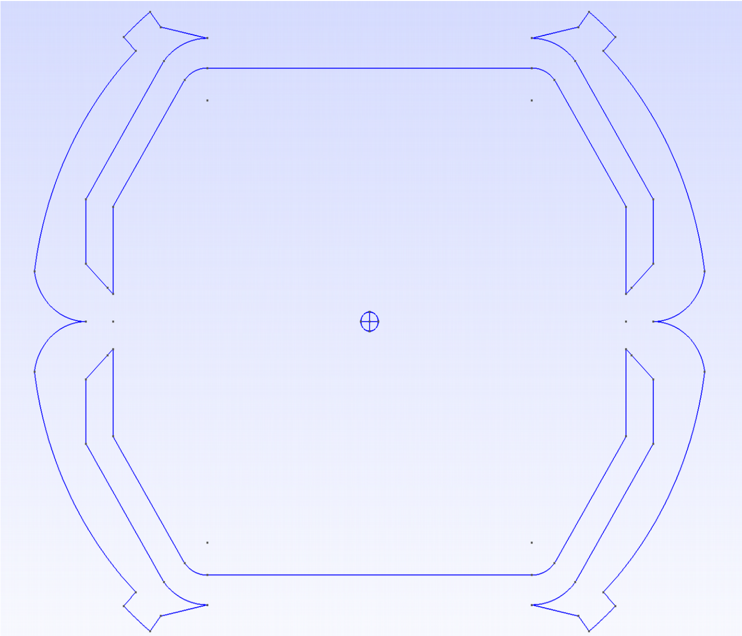
FIG. 3 (color online). Simulated ECI thresholds at different momenta, study done with quasi-self-consistent *e*-cloud distribution.

In conclusion, both simulations and experiments show that the ECI becomes more severe with increasing beam energy. As a consequence, upgrade plans with higher injection energy for proton machines which suffer from ECI must foresee a program of EC suppression. Promising EC

G. Rumolo, et al. Phys. Rev. Lett. 100, 144801

Stopping power and heat load (is in progress)

How can the high beam energy/gamma affect the stopping power?



The transverse beam size:

$$\sigma = \sqrt{\epsilon \beta^*} \propto \frac{1}{\sqrt{\gamma}} \qquad E_{inj} : \sigma \approx 10^{-3} m$$

$$\epsilon_n = const \qquad E_{top} : \sigma \approx 10^{-4} m$$

Requires a high resolution → a lot of memory to run simulations

Analytical model:

Energy loss of a short bunch in an (initially homogeneous) electron cloud: $\frac{d\mathcal{E}}{ds} \approx \frac{q^2 N_b^2 n_e r_e}{\varepsilon_0} \ln\left(\frac{b}{a}\right)$

O. Boine-Frankenheim, et al. Phys. Rev. ST Accel. Beams 15, 054402

Summary

SEY threshold depends on the chosen model:
- energy and angle incidence of the primary particles
- geometry and material of the beam pipe

Arc element	Furman/Pivi SEY model		Cimino/Collins SEY model	
	FCC-hh	LHC	FCC-hh	LHC
Drift	1.3	1.23	1.6	1.3
Dipole [injection/top energy]	1.25/1.25	1.1/1.1	1.56/1.56	1.32/1.32

Next steps:
- to estimate the stopping power from an analytical model and with the simulation tool
- to estimate the tune shift and tune spread as a function of beam energy
- implementation and estimation of the residual photoelectrons effect

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Thank you for your attention!

Back up: FCC-hh vs LHC

	LHC	FCC-hh
Circumference [km]	27	100
E_{inj} [TeV]	0.45	3.3
$E_{c.o.m.}$ [TeV]	7	50
Arc dipole field [T]	0.54...8.33	1...16
Bunch length [ns]	$1.07(8cm)$	$1.07(8cm)$
Bunch spacing [ns]	$25, 5$	25
Bunch population $[10^{11}]$	1.0	1.15
$Q_x/\ Q_y$ at injection	64.28/59.31	111.28/109.31
$Q_x/\ Q_y$ at collision	64.31/59.32	111.31/109.32
Revolution frequency, f_0 [Hz]	11245	3067