FCC electron cloud studies and its future plan

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G. Rumolo, D. Schulte

Formula for Single bunch instability

- Strong head-tail instability caused by electron cloud
- Threshold of electron density

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L}$$

$$K = \omega_e\sigma_z/c$$

$$Q = \min(\omega_e\sigma_z/c, 7)$$

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$$ Electron frequency in the beam field

$$\Delta\nu_{xy} = \frac{r_p}{\gamma}\rho_e\beta_{xy}L$$ Tune shift of the beam

Beam parameter and electron cloud instability (3.3TeV-50TeV)

		25 ns inj	25ns top	5ns inj	5ns top
beam energy	E (TeV)	3.3	50	3.3	50
bunch population	N_p (10^{10})	10	10	2	2
emittance	ε_{xy}(nm)	0.625	0.0413	0.125	0.00826
typical beta	β_{xy}(m)	200	200	200	200
bunch length	σ_z(cm)	8	8	8	8
synchrotron tune	ν_s	0.002	0.002	0.002	0.002
electron freq.	$\omega_e/2\pi$(GHz)	3.56	13.9	3.58	13.9
electron osc.	$\omega_e\sigma_z/c$	5.97	23.3	6.00	23.3
threshold density	$\rho_{e,th}$(m^{-3})	4.4×10^{10}	5.72×10^{11}	4.4×10^{10}	5.73×10^{11}
tune shift at thres.	$\Delta\nu(\rho_{e,th})$	0.00039	0.00033	0.00039	0.00033

Electron frequency in a bunch $$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$$

The electron density is averaged over ring

Synchrotron radiation

- Number of photon per meter, proton

$$N_\gamma = \frac{5\alpha}{2\sqrt{3}} \frac{\gamma}{\rho_{Bend}}$$

ρ_{bend}=11.3km

N_γ =0.0023/p.m (3.3TeV)
=0.035/p.m (50 TeV)

- Critical energy

$$E_c = \frac{3\hbar c}{2} \frac{\gamma^3}{\rho_{Bend}}$$

= 1.1eV (3.3 TeV)
= 3.96keV (50TeV)

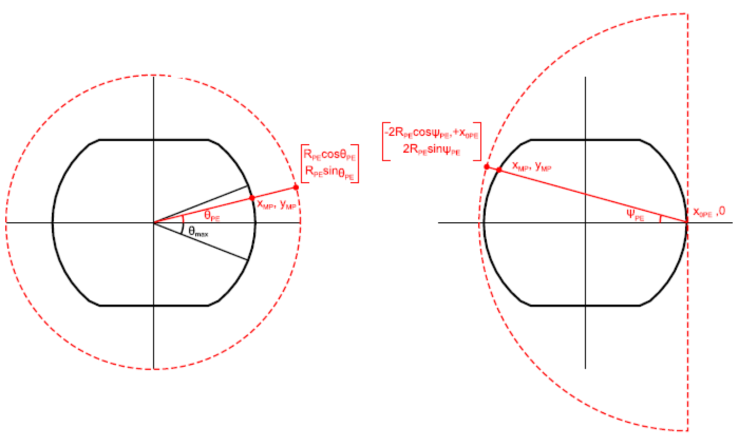
- Radiation power

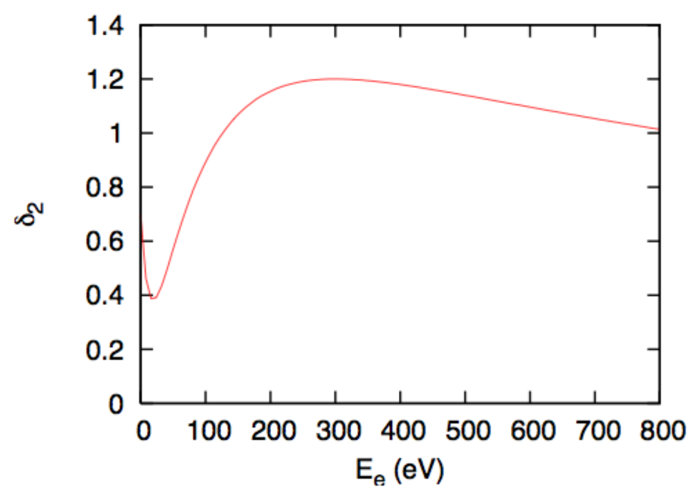
$$P_{SR} = N_p N_\gamma \frac{8E_c}{15\sqrt{3}} \frac{N_{bunch} f_0}{C}$$

=0.1 mW/m (3.3TeV)
=27.6 W/m (50 TeV)

Electron cloud build-up

- Photoelectron
  - direct photon N_γ Y produced at illuminated position.
  - reflected photon N_γ Y R distribute $\cos^2\theta$.
- Secondary electron
  - production rate/electron $\delta_2(E)$
  - characterized by $E_{2,max}$ and $\delta_{2,max}$



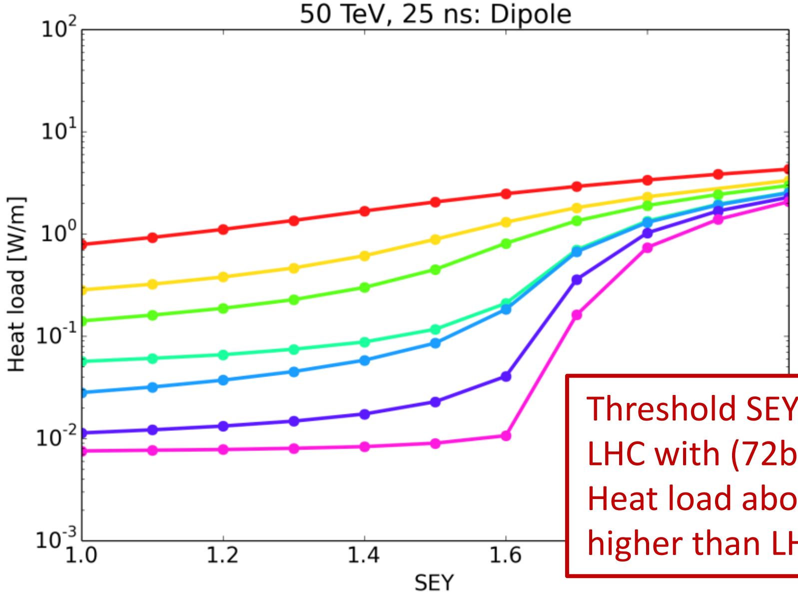


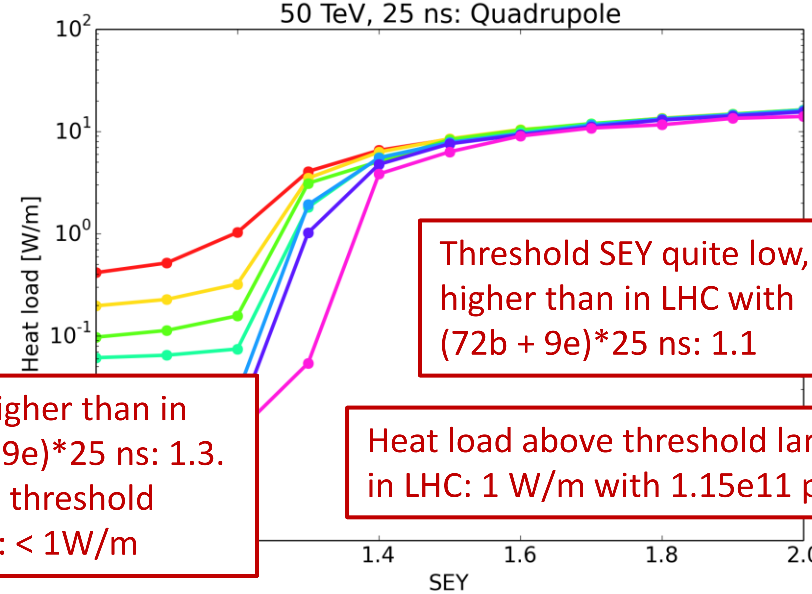
Electron production

- Y=0.2-0.3 for smooth copper, 0.02-0.05 for saw-tooth copper.
- Electrons $N_e=N_p N_\gamma Y=10^9\text{-}10^8$ m^{-1} are produced by a bunch. The chamber cross section is $10cm^2$.
- Average density produced by a bunch, $10^{11}\text{-}10^{10}$ m^{-3}, is already closed to the threshold.
- Most of electrons produced at illuminated position are protected by strong magnetic field of B and Q.
- Cure for Reflected photon and secondary emission are important.

1. V. Baglin et al, CERN-LHC-PROJECT-REPORT-206; V. V. Anashin et al, Nucl. Instrum.Meth. A 448 (2000) 76.
2. Y. Suetsugu et al, Journal of Vacuum Science & Technology A 21, 186 (2003).

Heat loads for 50 TeV, 25 ns beam in

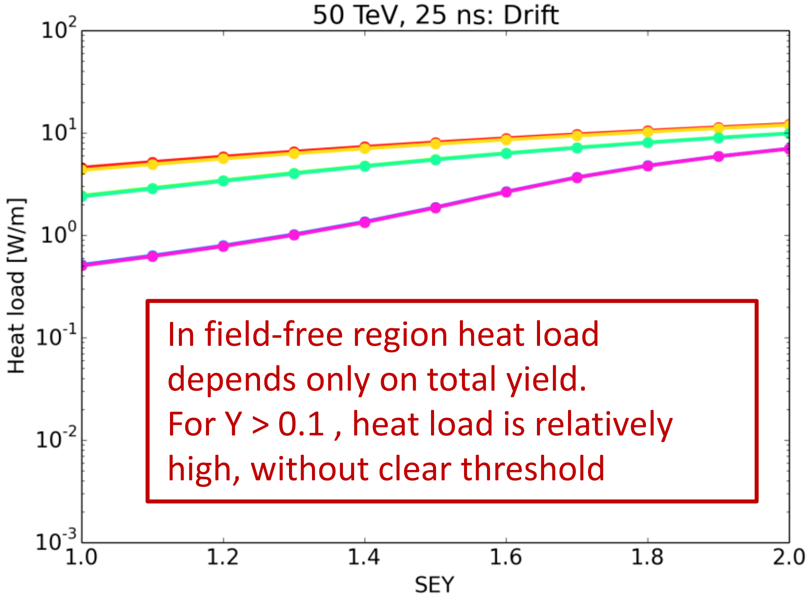




Threshold SEY higher than in LHC with (72b + 9e)*25 ns: 1.3. Heat load above threshold higher than LHC: < 1W/m

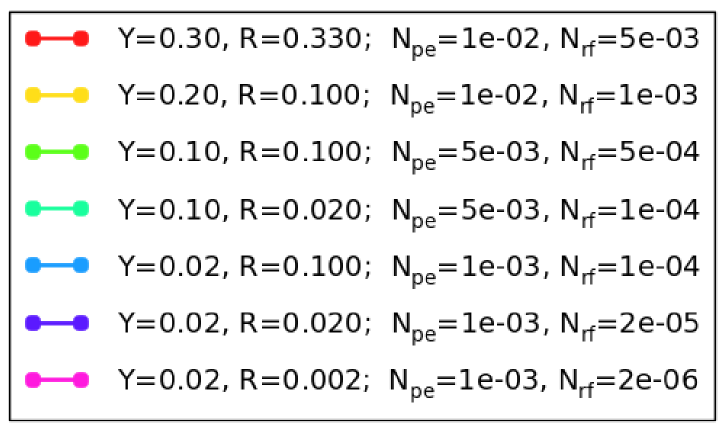
Threshold SEY quite low, but higher than in LHC with (72b + 9e)*25 ns: 1.1

Heat load above threshold larger than in LHC: 1 W/m with 1.15e11 p^+

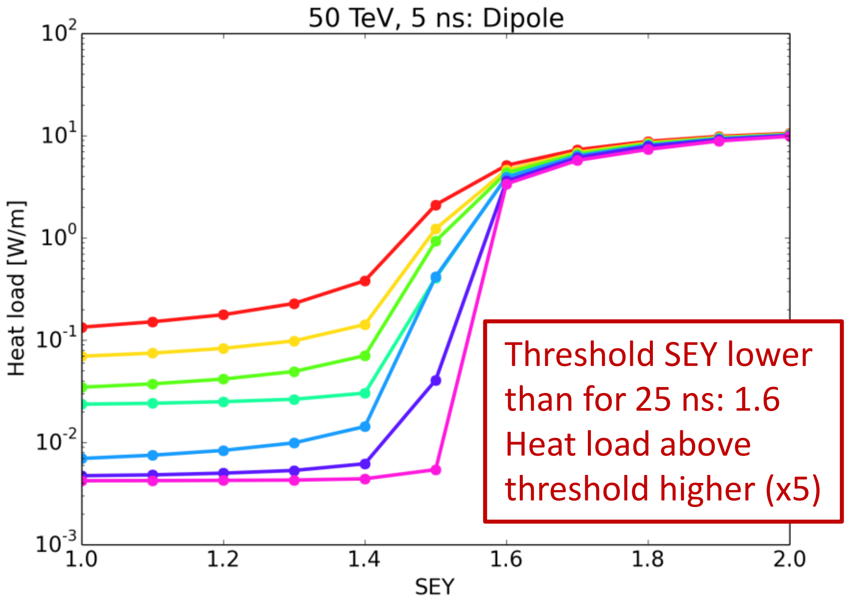


In field-free region heat load depends only on total yield. For Y > 0.1 , heat load is relatively high, without clear threshold

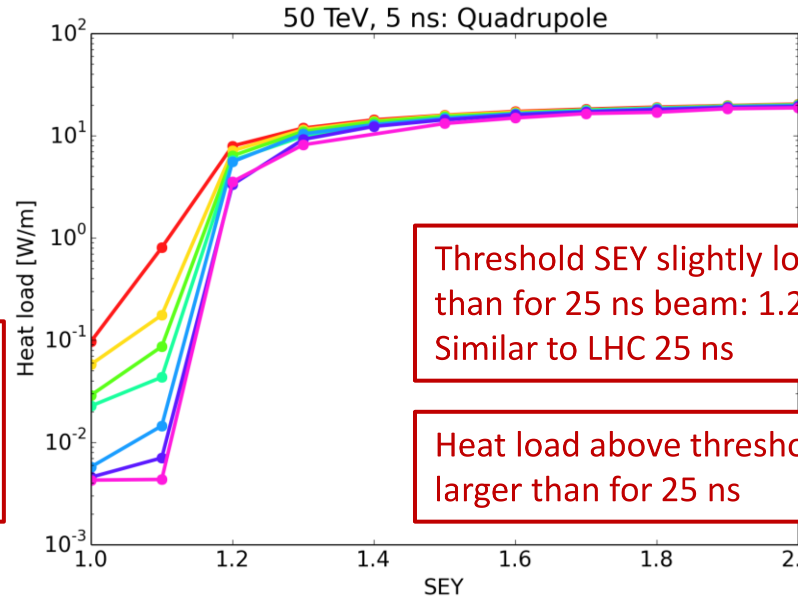
$$P_{SR} = 27.6W/m$$



Heat loads for 50 TeV, 5 ns beam in arc

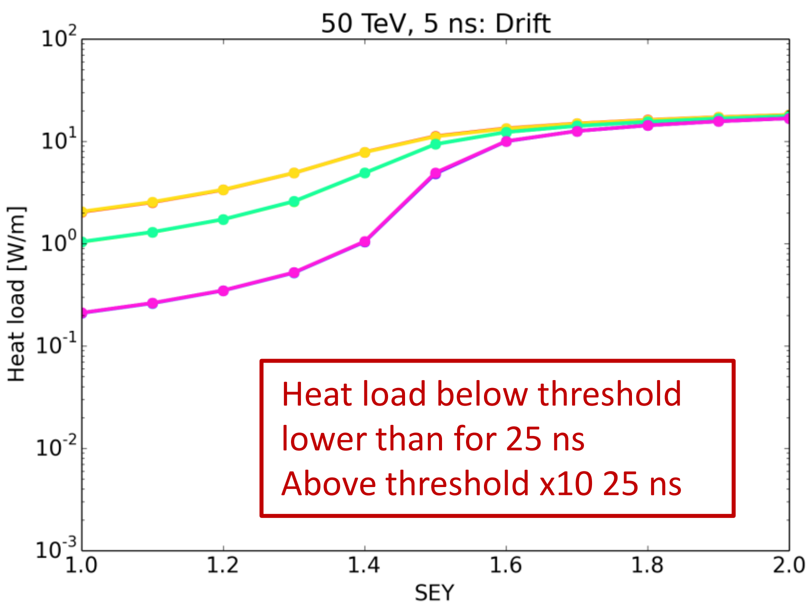


Threshold SEY lower than for 25 ns: 1.6
Heat load above threshold higher (x5)



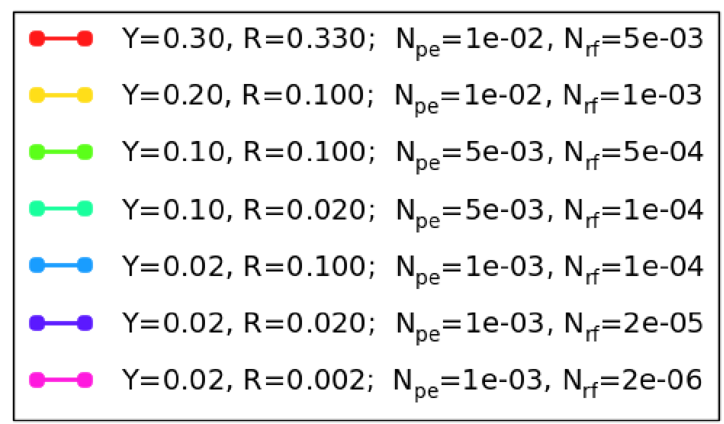
Threshold SEY slightly lower than for 25 ns beam: 1.2
Similar to LHC 25 ns

Heat load above threshold x0.5 larger than for 25 ns



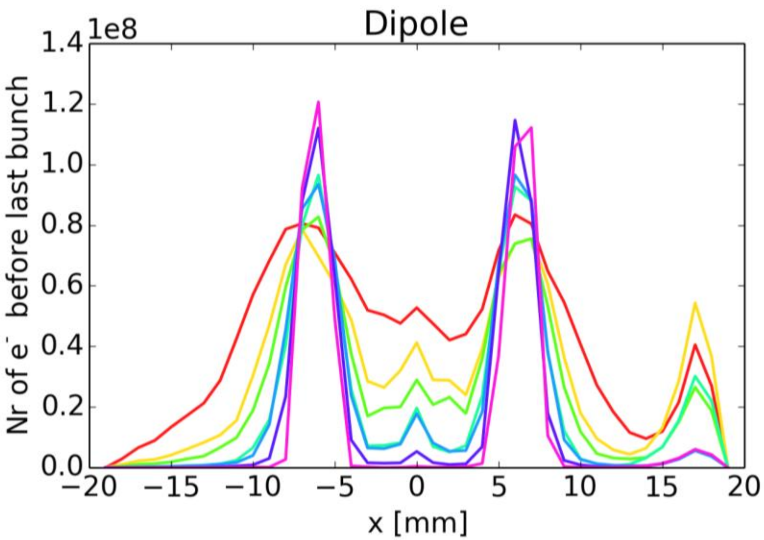
Heat load below threshold lower than for 25 ns
Above threshold x10 25 ns

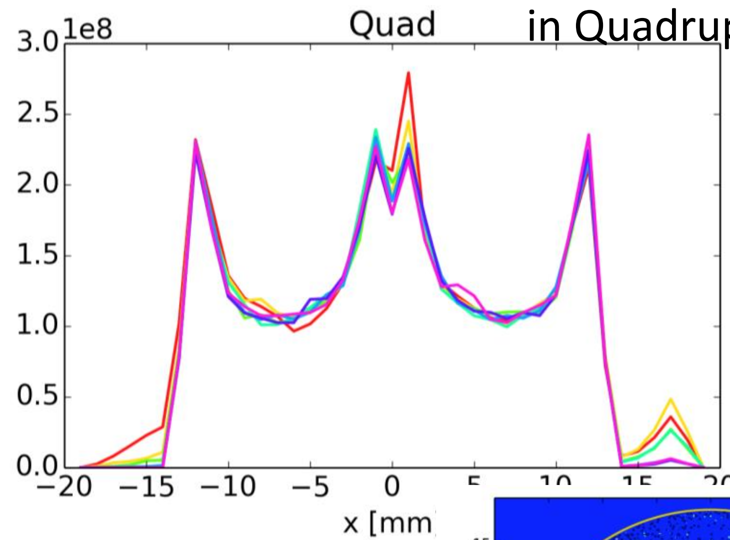
$$P_{SR} = 27.6W/m$$

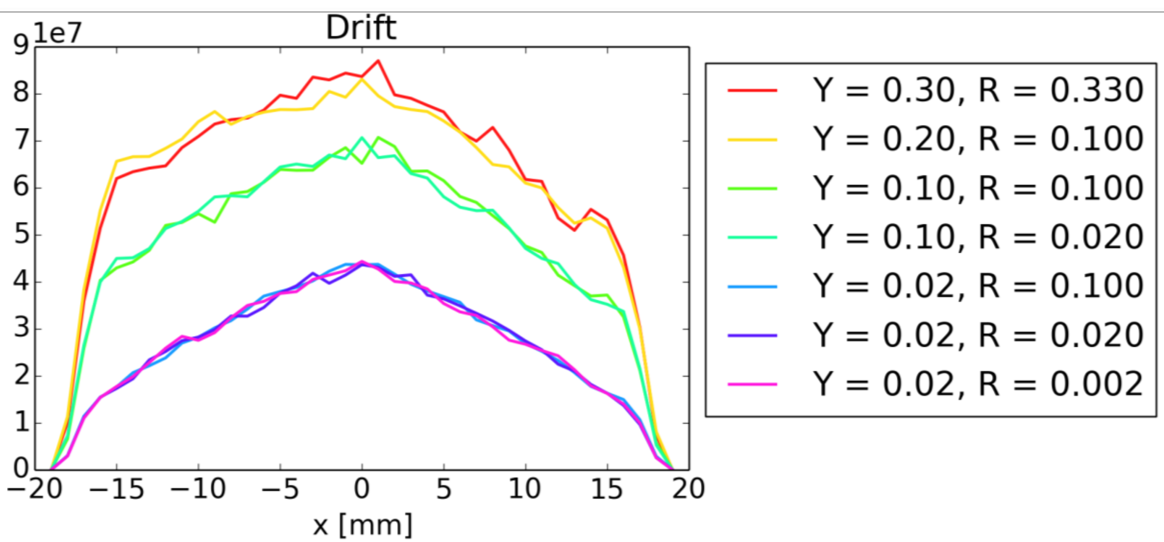


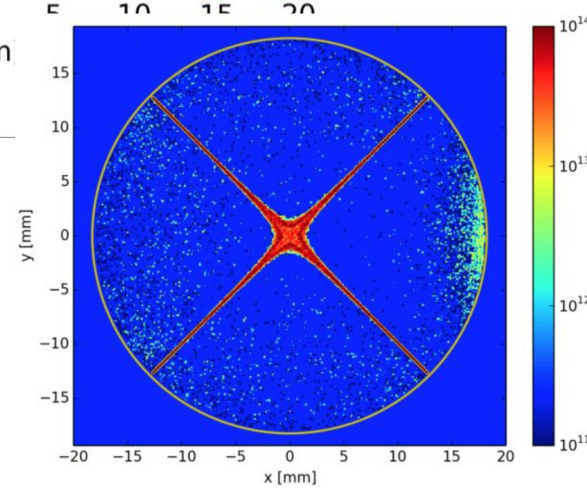
x-distribution of electrons in chamber

Most electrons in centre in Quadrupole





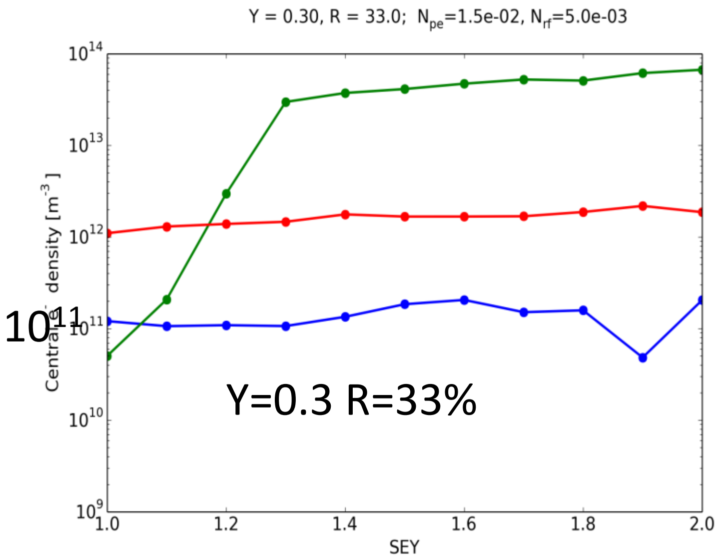




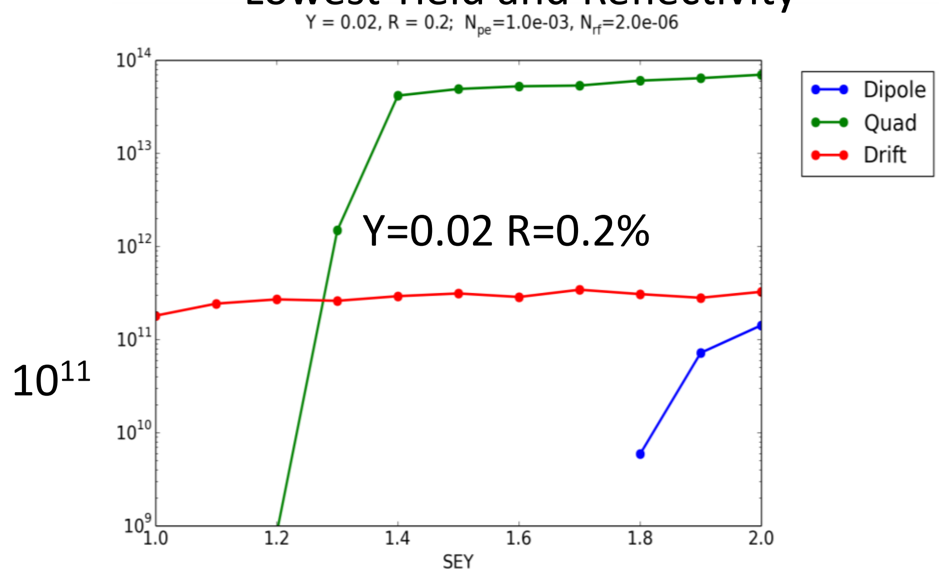
Electrons localize in Quad extremely.

Electron density in centre of chamber

Highest Yield and Reflectivity



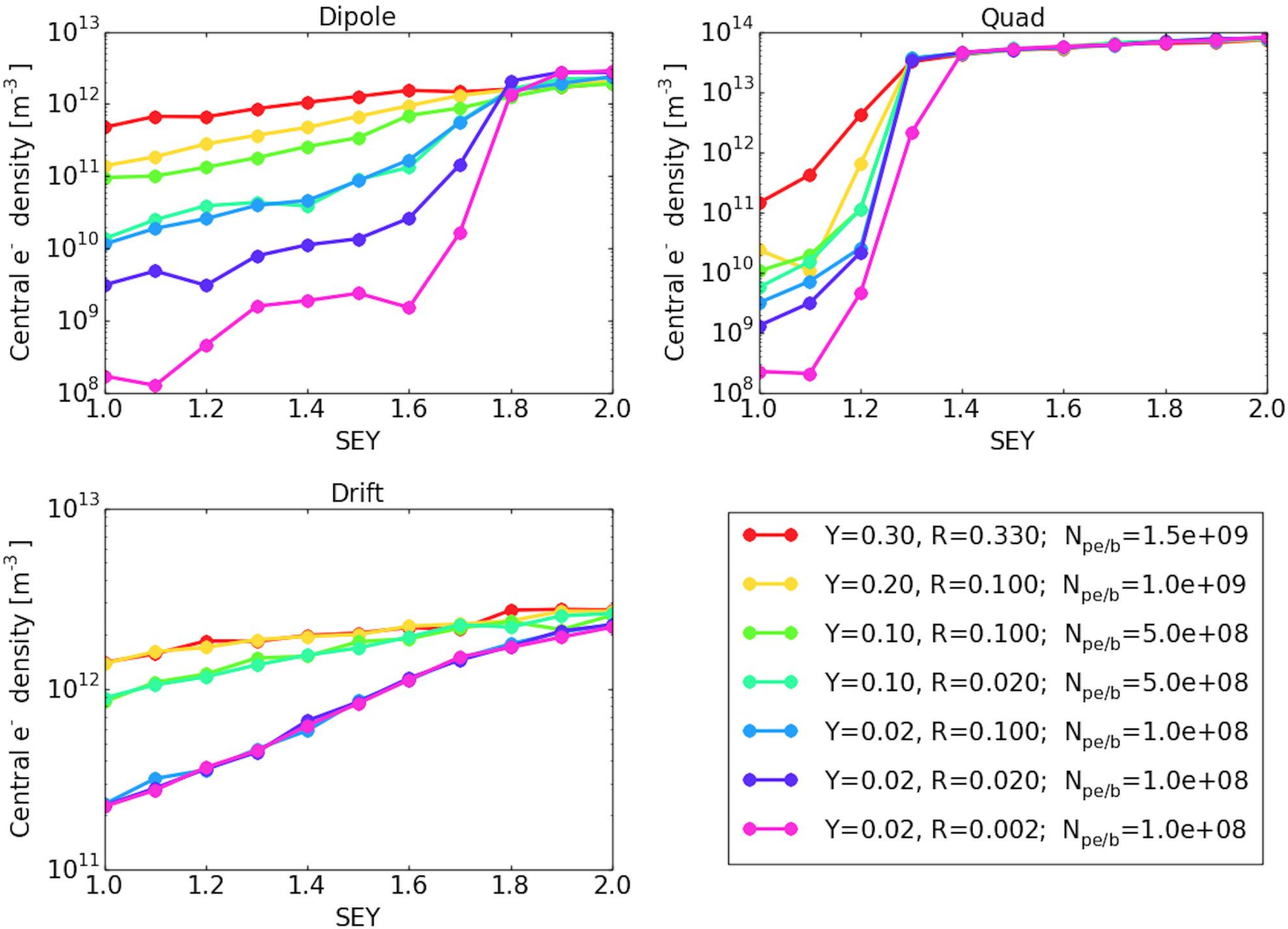
Lowest Yield and Reflectivity



- For YxR<0.1x2%,SEY<1.6, the density in bend is lower than the threshold.
- Central density in quadrupole 2-3 orders of magnitude higher than in dipole..
- The integrated density in quad dominates compare than bend.
- 10^{14} at quad is serious. SEY should be less than 1.2

FODO cell: 208.14 m, Dipole 170.40 m,
Quad: 10.34 m, Drift: 26.40 m

Central Density

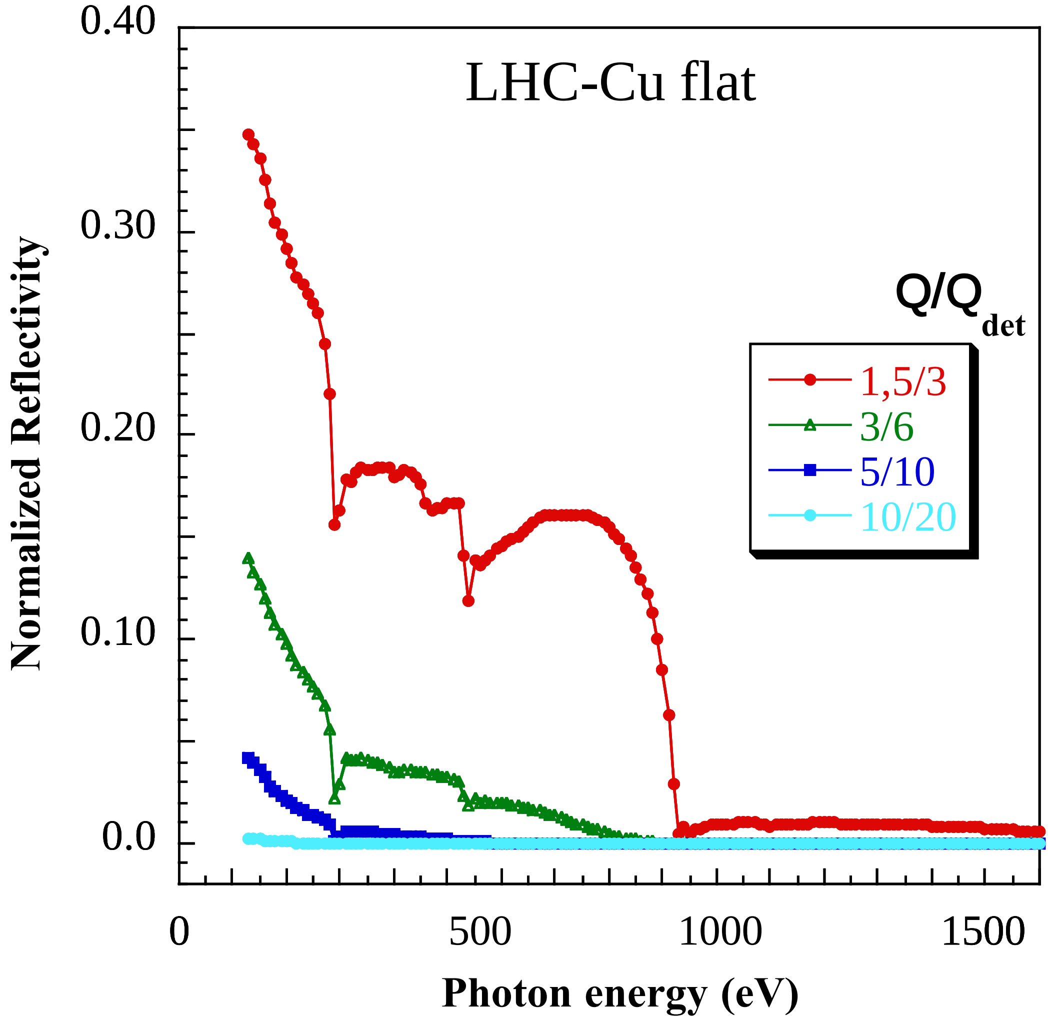


Measurement of R

Courtesy of R. Cimino

R has been measured!

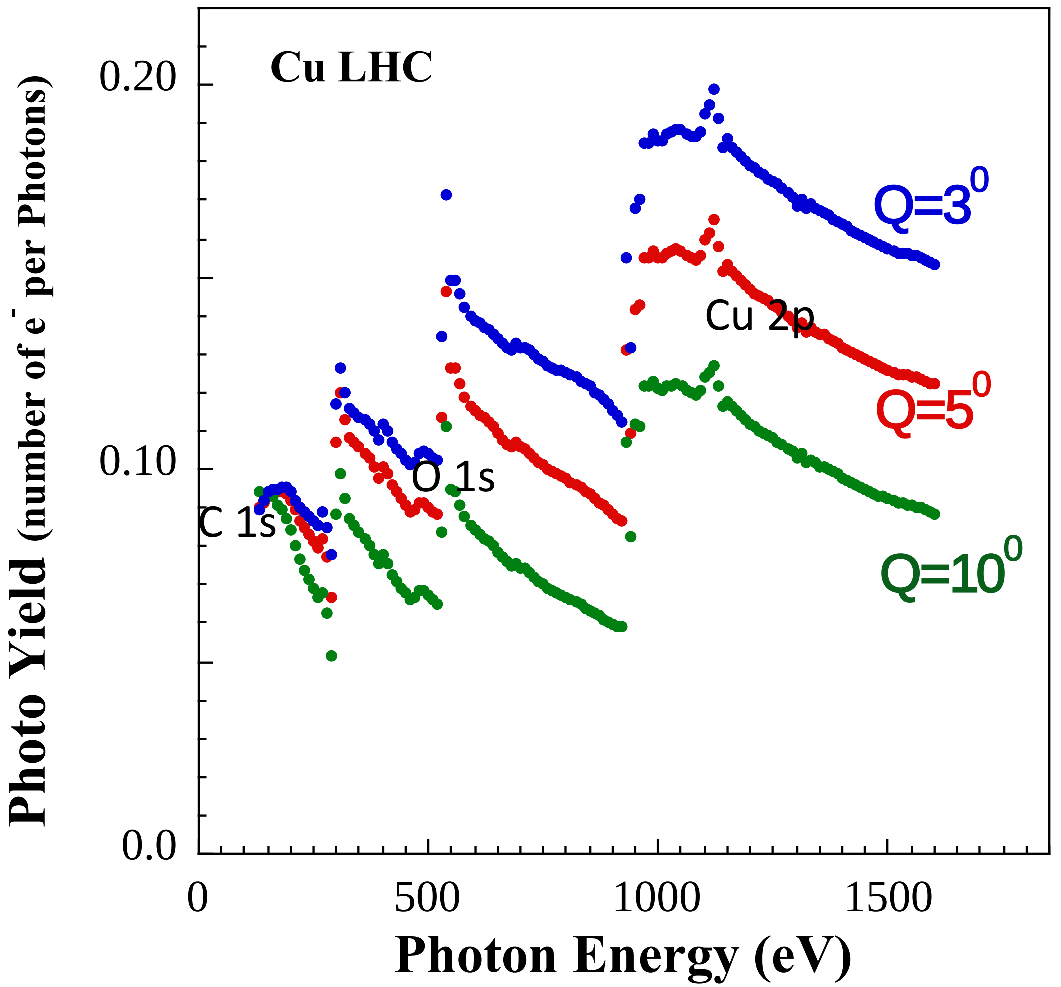
Reflectivity of LHC- Cu sample representative of the flat part of the beam screen, as function of photon energy for various incidence angles θ and emission angle 2θ.



Measurement of Y Courtesy of R. Cimino

PY can be and has been measured!

Photo yield (number of electrons emitted per incident photon) from a Cu Technical surface of LHC beam screen, as function of photon energy at different incidence angles.



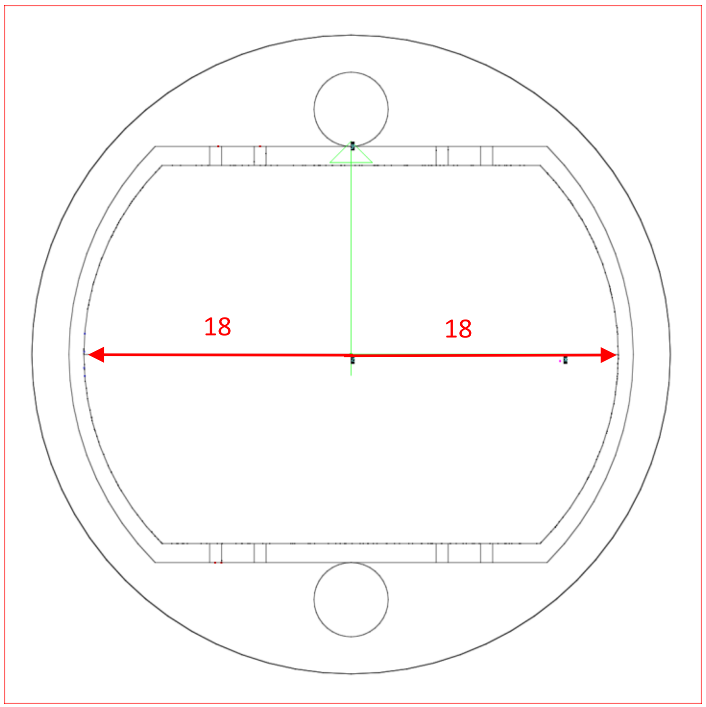
SR screen design study

Courtesy of R. Kersevan

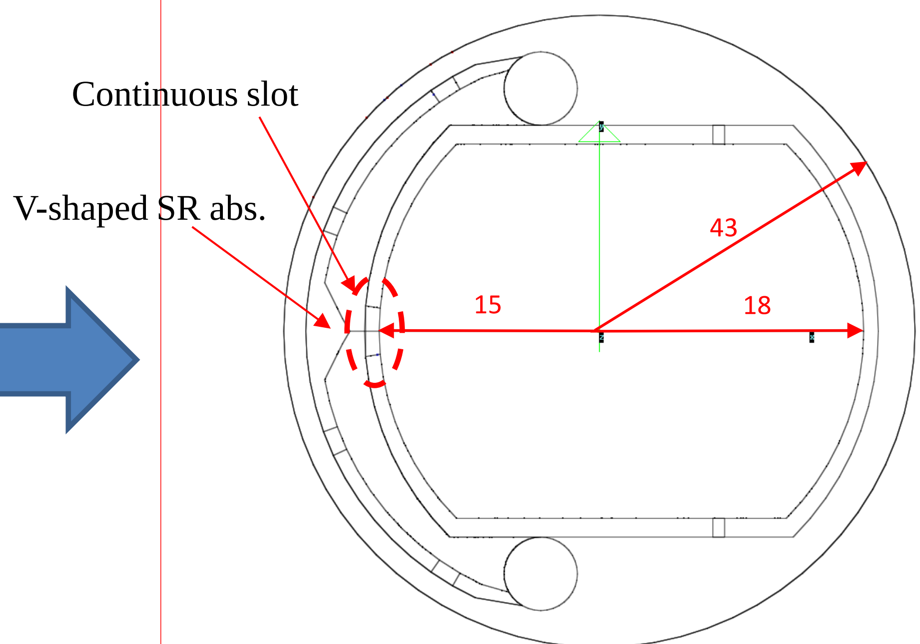
FCC:

Configuration:

A combined BS, made up of a LHC-like BS with a continuous slot and an “external” SR power absorber is proposed here.



LHC-like BS solution



Slotted BS solution
asymmetric

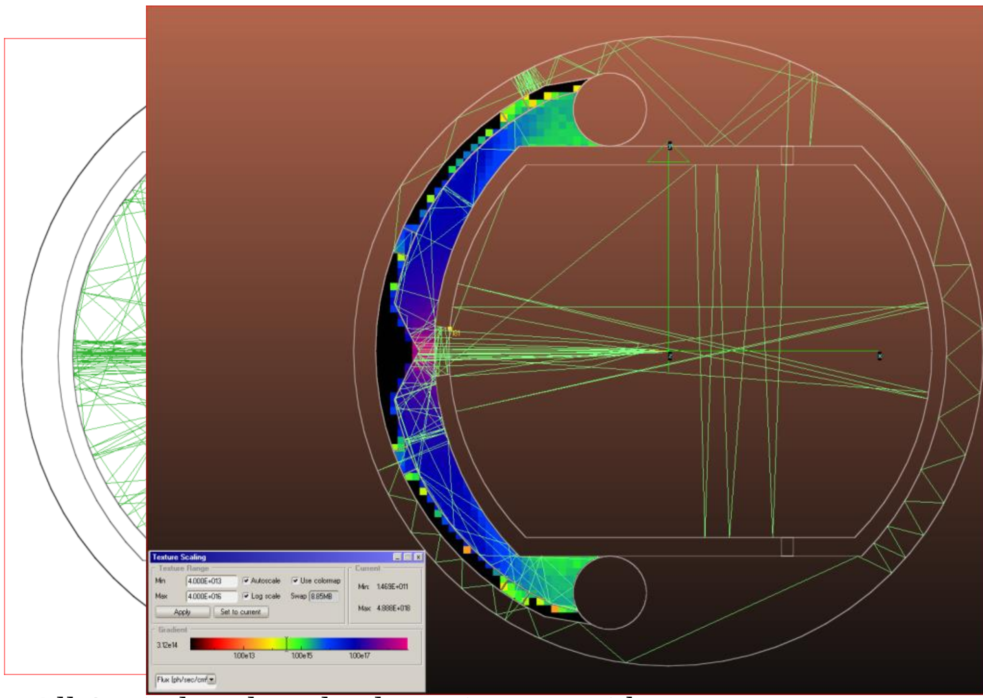
Courtesy of R. Kersevan

SR ray trace

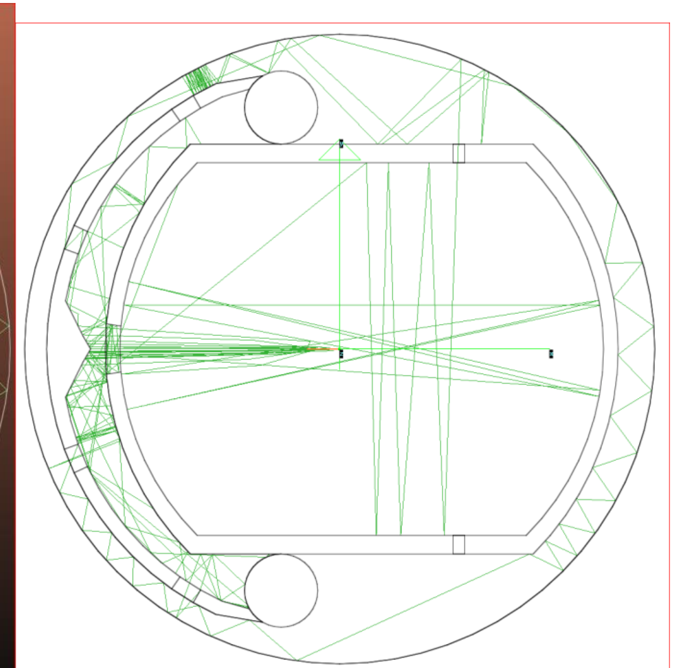
Courtesy of R. Kersevan

FCC: SR Ray-Tracing (Synrad+):

The high-energy small vertical angle opening of the primary SR fan passes almost unscathed inside of the 2x 1.57 mm-high continuous slot



All SR-induced gas load may interact with the beam



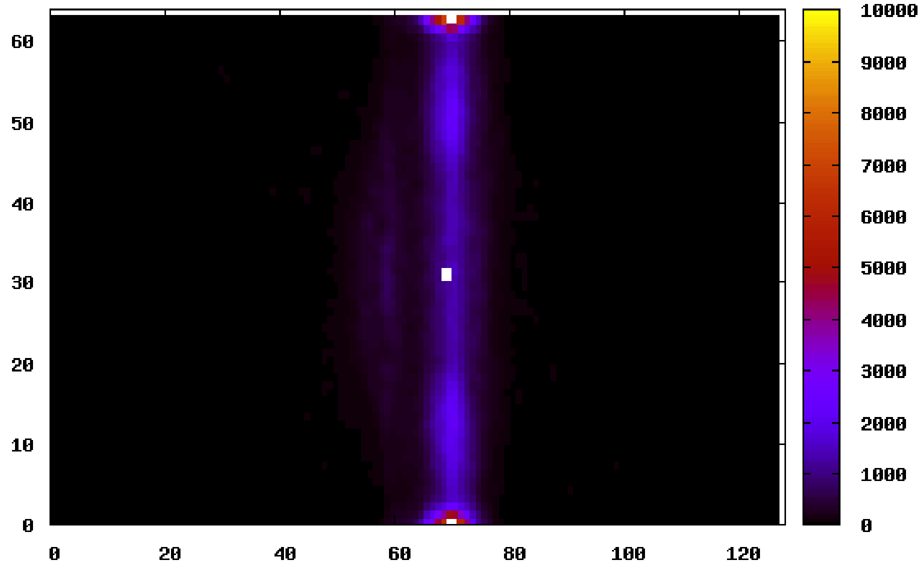
Only a fraction of the SR-induced gas load may interact with the beam

Other beam phenomena due to electron cloud

- Coupled bunch instability
- Incoherent Emittance growth

Coupled bunch instability

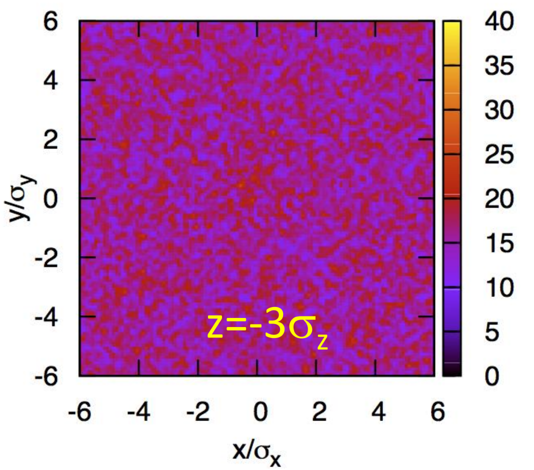
- Corrective motion between beam and electron cloud.
- Instability due to electron cloud in bending magnet in DAFNE (rectangular chamber).

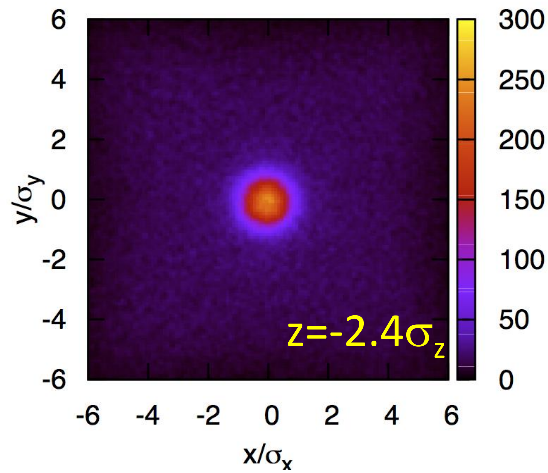


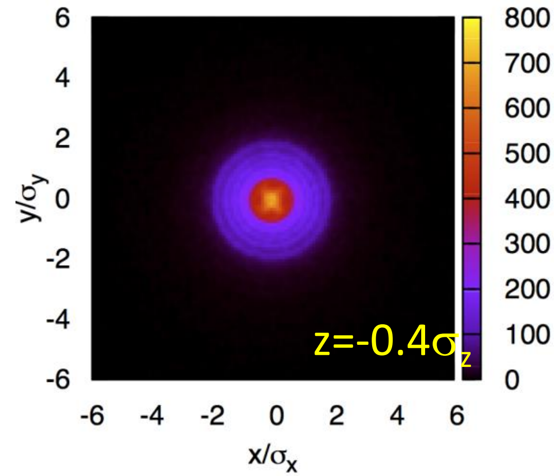
White : beam center
Violet: electron cloud

Electron density during interaction with beam

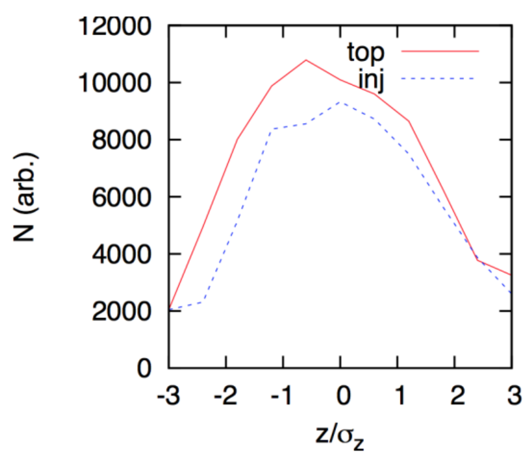
- Transverse electron profile along z. (drift space)
- Electron initial energy $v_0=10^6$ m/s (3eV) is assumed.

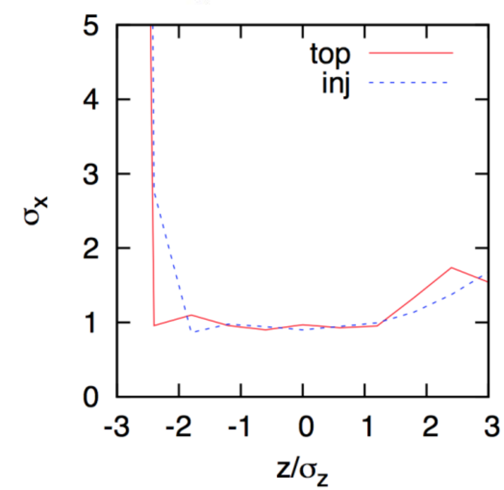




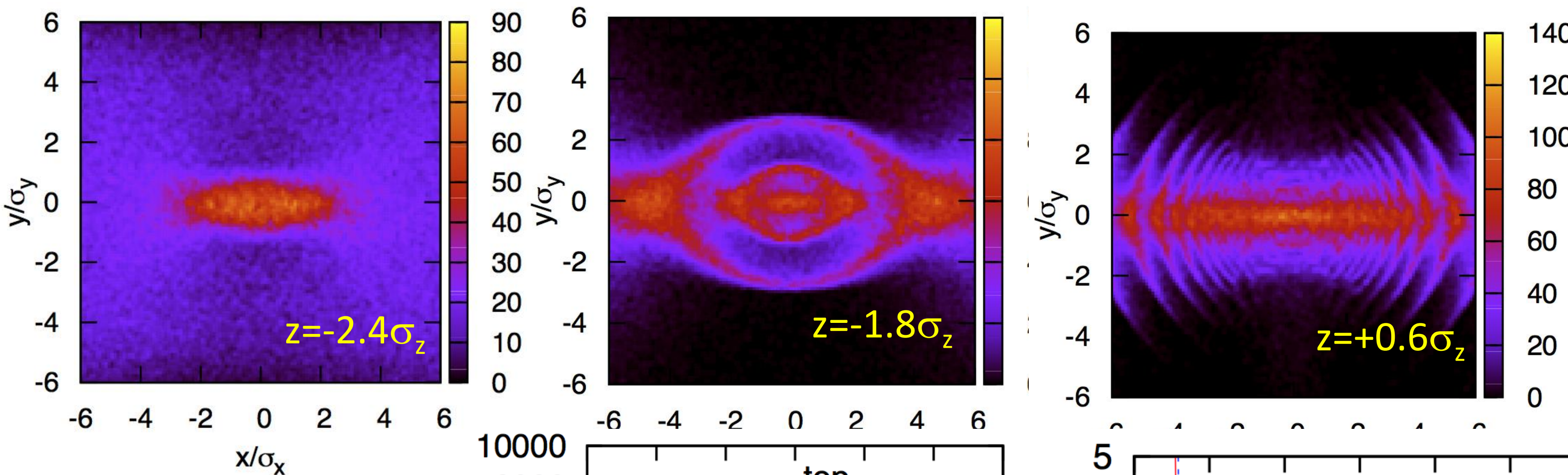


- Variation of electron density and size along the bunch interaction, z.
- Density increase to 25x of initial.
- The increase is the same in Quad.

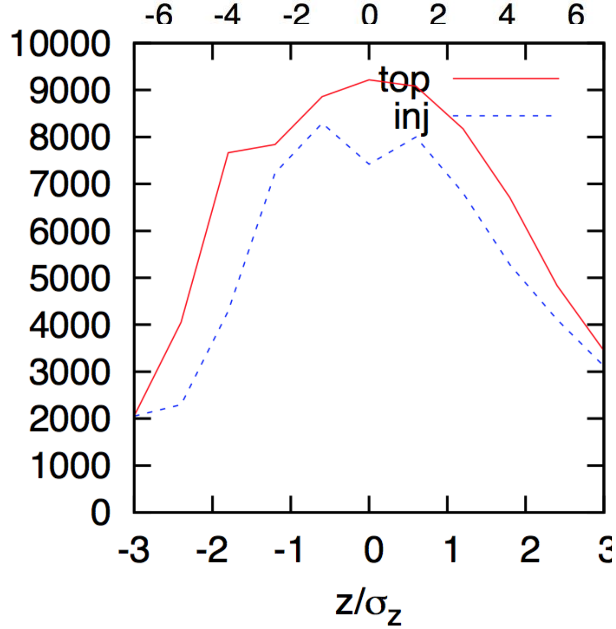


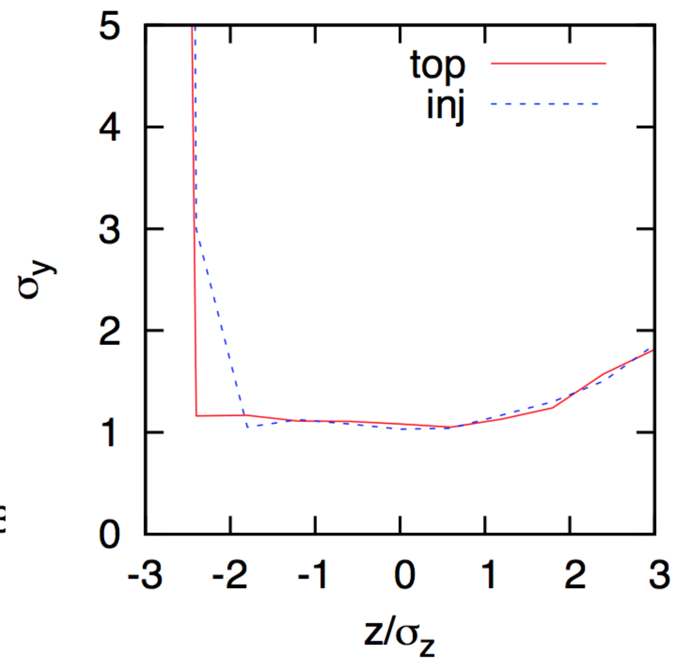


• In strong Bending magnet



- Variation of electron density and size along the bunch interaction, z.
- Density increase to 5x of initial in bend.





Emittance growth caused by electron cloud

- Electron cloud potential induces tune spread and resonances.

$$\Delta\nu_{xy} = \frac{r_p}{\gamma}\rho_e\beta_{xy}L$$

- The strength of the resonances are characterized by the width in amplitude space, ΔJ.
- Modulation of the resonances due to synchrotron motion etc. results in emittance growth.

Electron cloud induced tune spread and resonance term

- U(x,y): integrated effective potential due to electron cloud
- Resonance driving term is Fourier component of U.

$$U(x,p_x,y,p_y,s) = \oint e^{:H_0:}U(x,y,s')e^{-:H_0:}ds'$$

H_0: lattice transformation of s' to s

$$U(J_x,\phi_x,J_y,\phi_y) = \sum_{m_x,m_y=0}^{\infty} U_{m_x,m_y}\cos(m_x\phi_x + m_y\phi_y)$$

Tune spread is given by U_{00}.

$$U_{m_x,m_y}(J_x,J_y) = \frac{\lambda_p r_p}{\beta^2\gamma^3}\oint ds\int_0^{\infty}\frac{du}{\sqrt{2\sigma_x^2+u}\sqrt{2\sigma_y^2+u}}$$

$$\left[\delta_{m_x0}\delta_{m_y0} - \exp(w_x - w_y)(-1)^{(m_x+x_y)/2}I_{m_x/2}(w_x)I_{m_y/2}(w_y)e^{-im_x\varphi_x - im_y\varphi_y}\right].$$

$$w_x = \frac{\beta_x J_x}{2\sigma_x^2 + u}$$

Summary

- The threshold of single bunch instability is $\rho_e = 5\mathrm{x}10^{10}$(inj) $-5\mathrm{x}10^{11}$ m^{-3}(top).
- For YxR<0.1x2%, the density in Bend is lower than ρ_e. SEY<1.2 is required for the threshold in Quad.
- The numbers should be refined by detailed studies.
  - Measurement of Y,R,SEY
  - Beam screen design
  - Cross check of electron buildup codes, PyECLOUD and PEI.

Beam dynamics studies

- Evaluate coupled bunch instability growth rate. Requirement for feedback damper.
- Evaluate unstable Modes in quadrupole to check which magnet is dominant for electron cloud.
- Tune shift is very small, $\Delta\nu$=0.0003, even at the threshold of coherent instability.
- The tune shift can be x25 (in quad) higher due to pinching, $\Delta\nu$=+0.008. Not very large.
- IR Q located at high beta will be studied.
- Evaluate Resonance width and simulation using resonance model to study emittance growth.

Tune shift and slope due to Gaussian electron cloud

- Tune shift

$$2\pi\Delta\nu_x = -\frac{\lambda_p r_p}{\beta^2\gamma^3}\oint ds \frac{\beta_x}{\sigma_x^2}\int_0^\infty \frac{d\eta}{(2+\eta)^{3/2}(2r_{yx}+\eta)^{1/2}}\left[e^{-w_x-w_y}(I_0(w_x)-I_1(w_x))I_0(w_y)\right]$$

$$2\pi\Delta\nu_y = -\frac{\lambda_p r_p}{\beta^2\gamma^3}\oint ds \frac{\beta_x}{\sigma_x^2}\int_0^\infty \frac{d\eta}{(2+\eta)^{1/2}(2r_{yx}+\eta)^{3/2}}\left[e^{-w_x-w_y}I_0(w_x)(I_0(w_y)-I_1(w_y))\right]$$

- Tune slope

$$\frac{\partial^2 U_{00}}{\partial J_x^2} = -2\pi\frac{\partial \nu_x}{\partial J_x}$$

$$= \frac{\lambda_p r_p}{\beta^2\gamma^3}\oint ds \frac{\beta_x^2}{\sigma_x^4}\int_0^\infty \frac{d\eta}{(2+\eta)^{5/2}(2r_{yx}+\eta)^{1/2}}\left[e^{-w_x-w_y}\left\{\frac{3}{2}I_0(w_x)-2I_1(w_x)+\frac{1}{2}I_2(w_x)\right\}I_0(w_y)\right]$$

$$r_{yx} = \sigma_y^2/\sigma_x^2 \qquad w_x = \frac{\beta_x J_x/\sigma_x^2}{2+\eta} \qquad w_y = \frac{\beta_y J_y/\sigma_y^2}{2+\eta/r_{yx}}$$