Electron cloud and trapped modes in the FCC-ee IR

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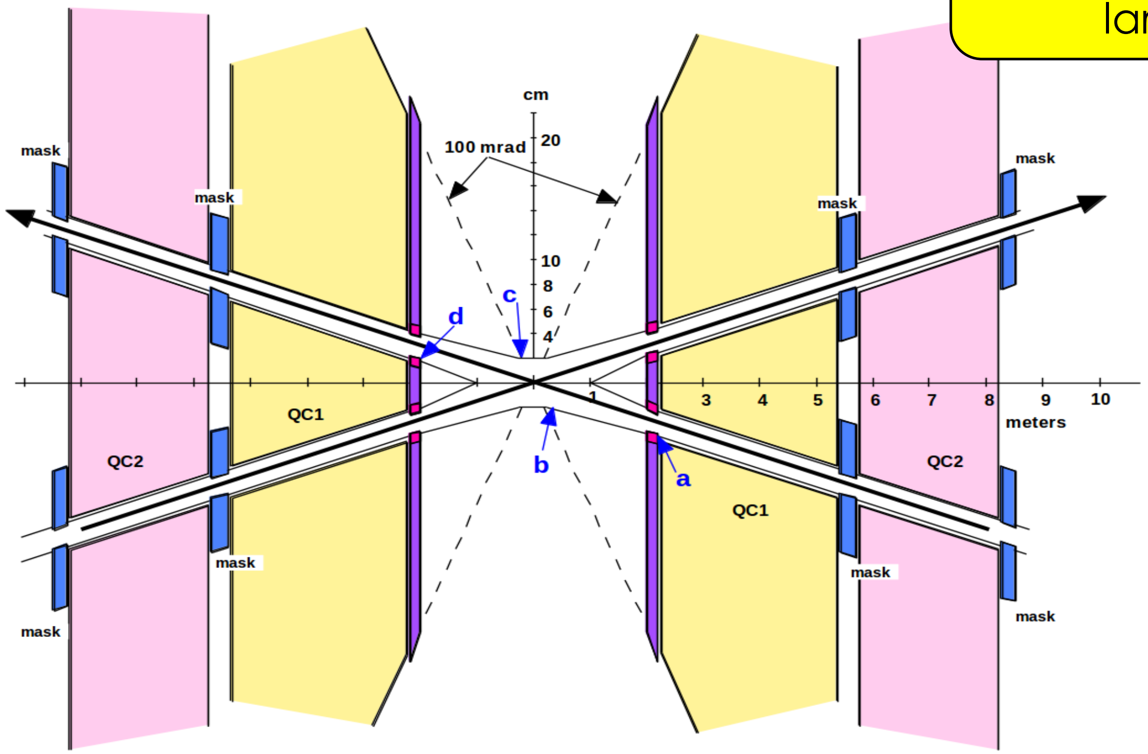
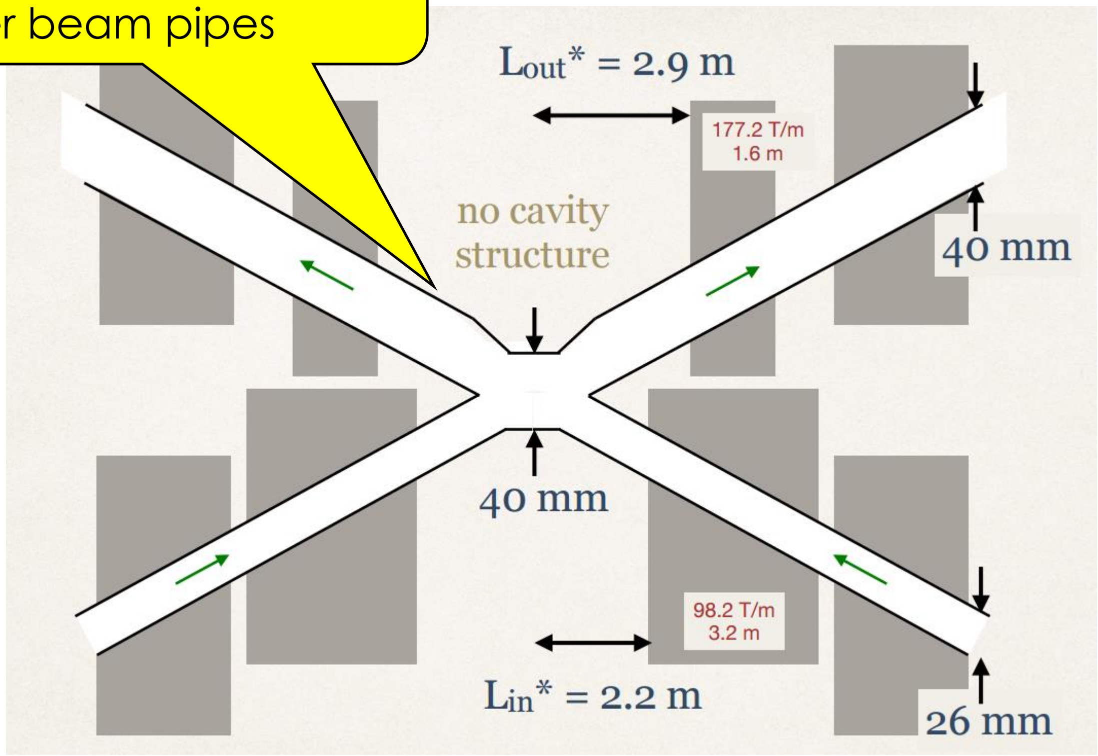
Trapped modes in the IR

- Small variations in the beam pipe geometry can produce trapped modes
- These modes cannot propagate into the pipe and therefore they remain localized near the discontinuity, producing narrow resonance peaks of the impedance.
- Possible source of heating

Trapped modes can escape to the outside through the larger beam pipes





Power loss

- Power loss of a bunch

$$P_{loss} = N^2 e^2 f_0^2 \sum_p |\lambda(p\omega_0)|^2 \, Re[Z_{\parallel}(p\omega_0)]$$

- Worst case when $\omega_r \simeq p\omega_0$ (resonant frequency close to an integer of the revolution frequency)
- Heating power

$$P_{loss} = 2NeI \frac{c}{s_b} R_s$$

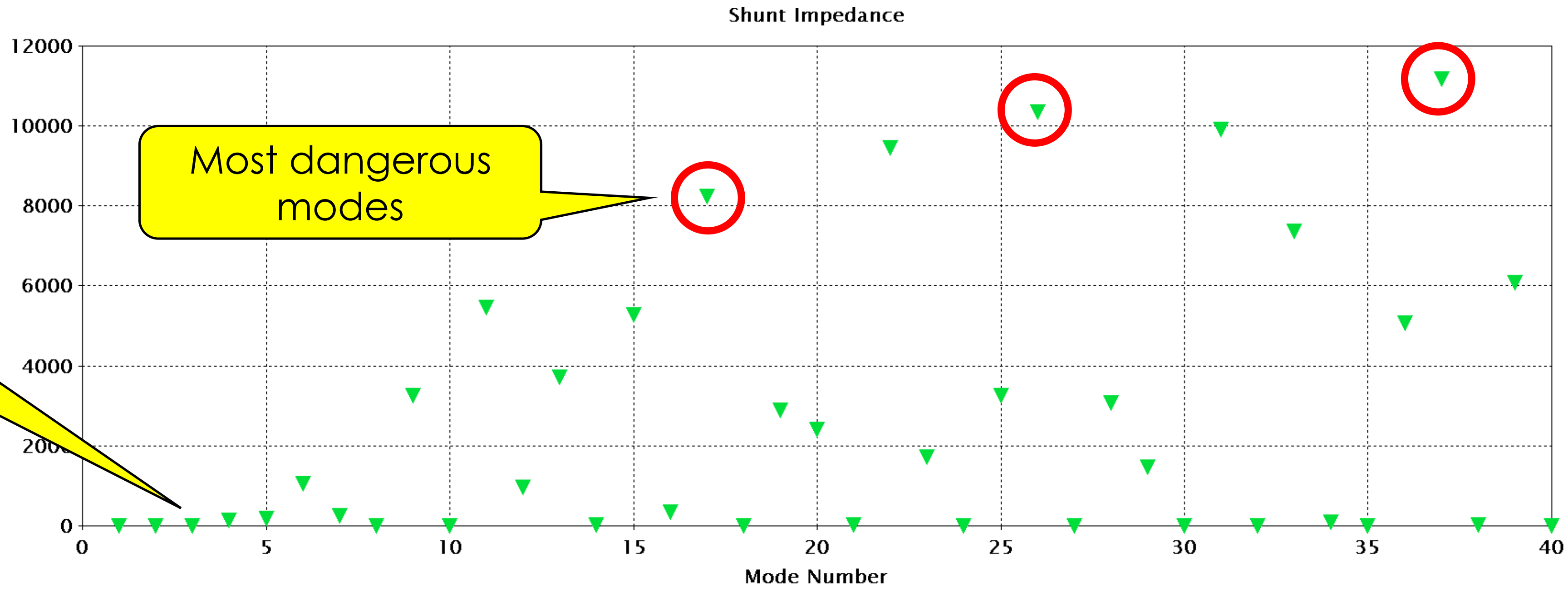
Shunt impedance

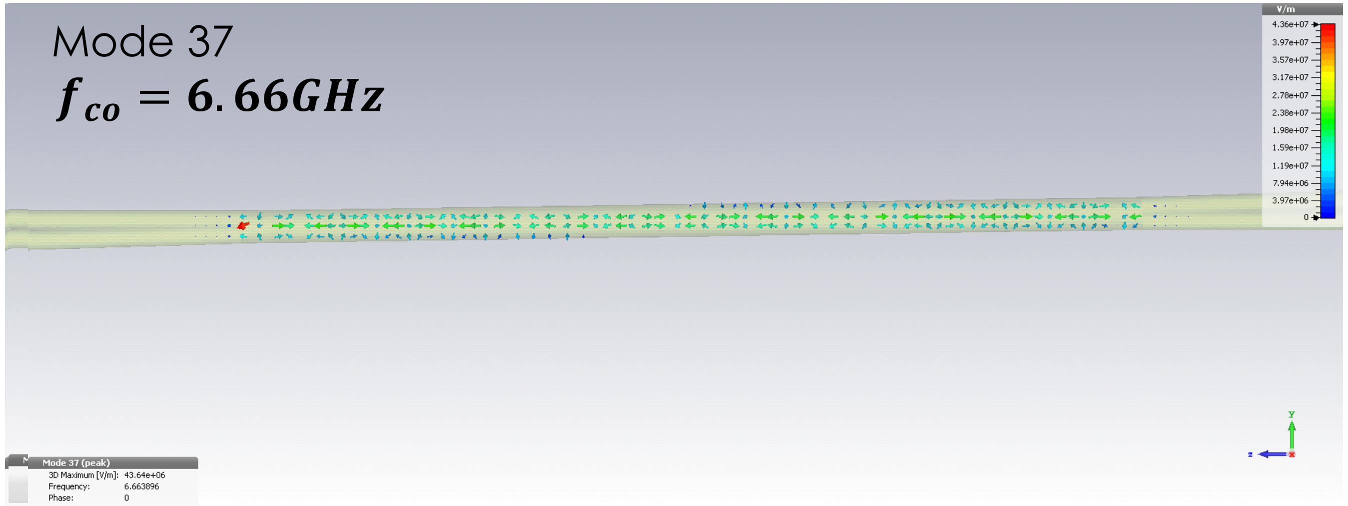
- General method to study HOMs in IR
  - ❑ Build a CST model of the IR
  - ❑ Eigenmode simulation in frequency domain
  - ❑ Extract parameters R_s, Q

Symmetric layout

$$f_{cutoff} = \begin{cases} = 9.57\text{GHz for outgoing pipes with r=12mm radius} \\ = 5.73\text{GHz for the central pipe with r=20mm radius} \end{cases}$$

Trapped modes below cutoff with a low R_s





@45.6GeV

$N = 0.33e11$

$I = 1.45A$

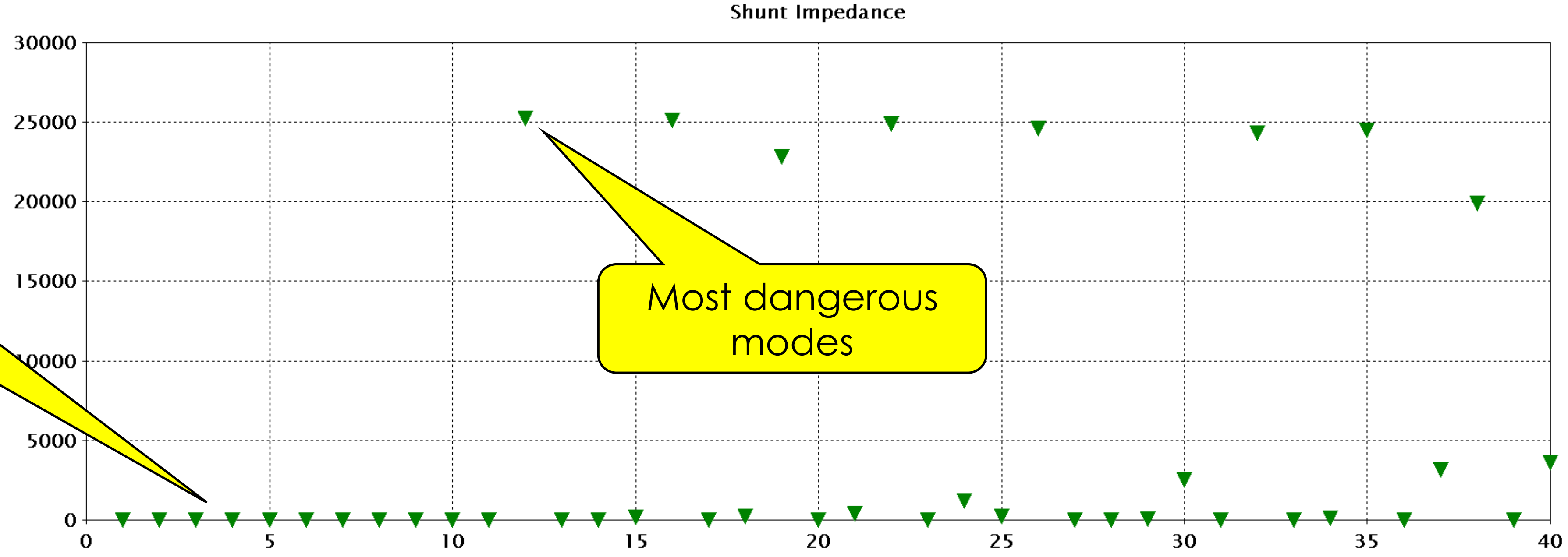
$s_b = 2.5ns$

$R_s = 11.173\text{k}\Omega$

$P_{loss} \approx 68.5kW$

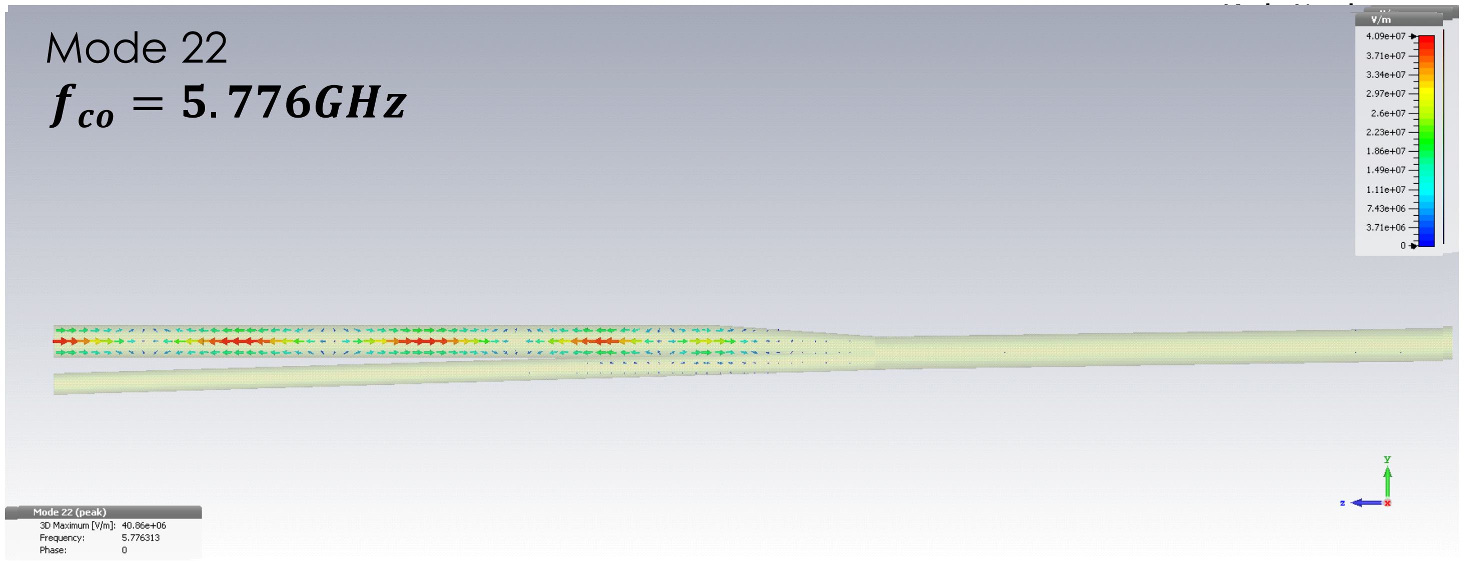
Asymmetric layout

$f_{cutoff} = 5.737GHz$ for TM_{01} and $r = 20mm$ pipe radius



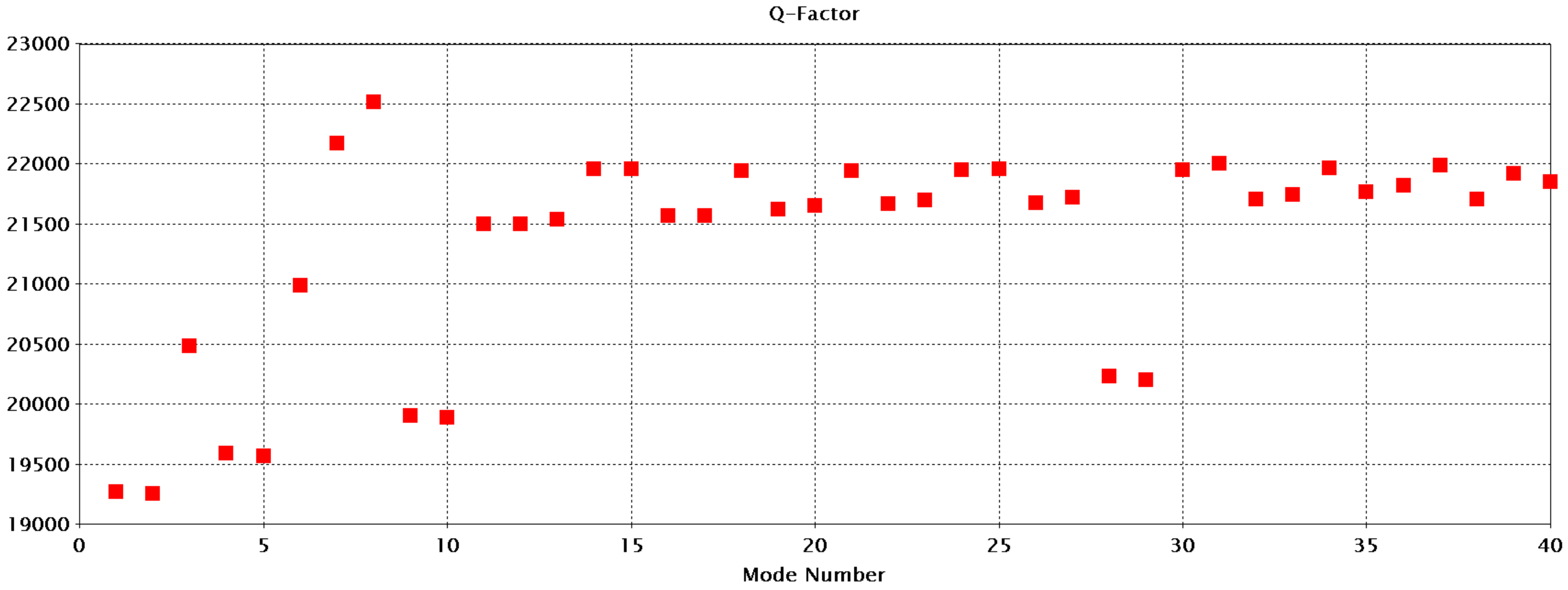
Trapped modes below cutoff with a low R_s

Most dangerous modes



It seems that the most dangerous modes are not trapped in the asymmetric layout case (**as expected**)

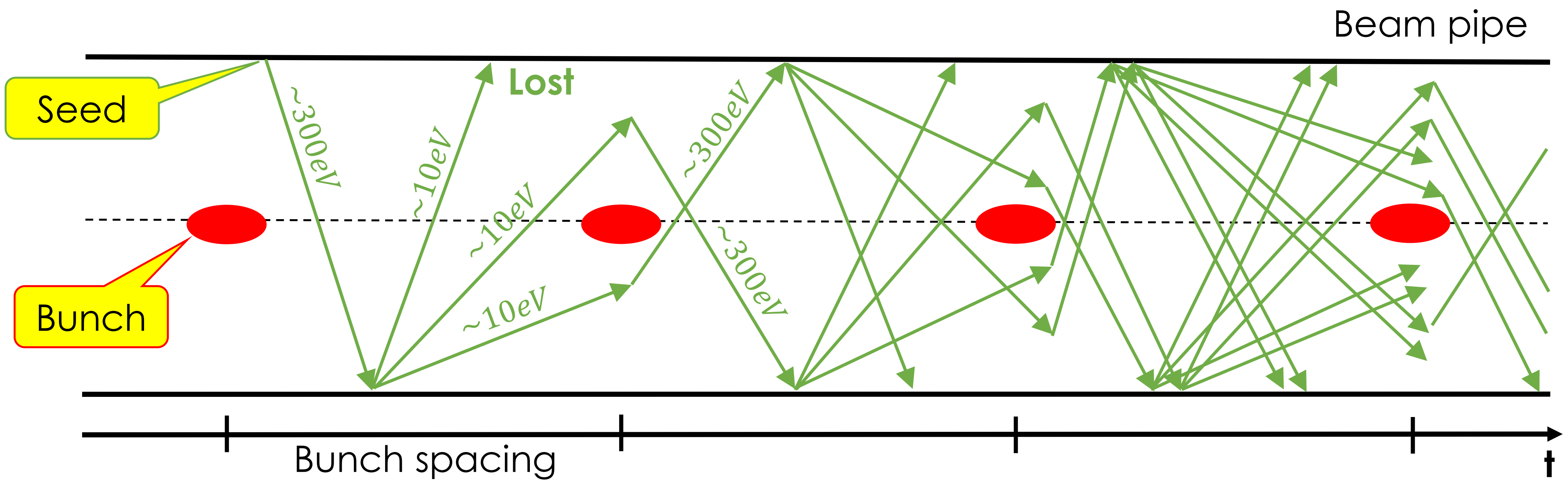
Asymmetric layout



- Very high quality factors (closed pipes)
- Next simulations with longer pipes to confirm results

Electron cloud build up

- Positively charged bunches passing through a section of an accelerator
- Primary or Seed Electrons
  - Residual gas ionization
    Molecules of the residual gas in the vacuum chamber can be ionized by the beam
  - Photoemission due to synchrotron radiation
    Emitted photons hitting the wall can have enough energy to extract electrons from the pipe's wall (***photoelectrons***)



Electron cloud build up

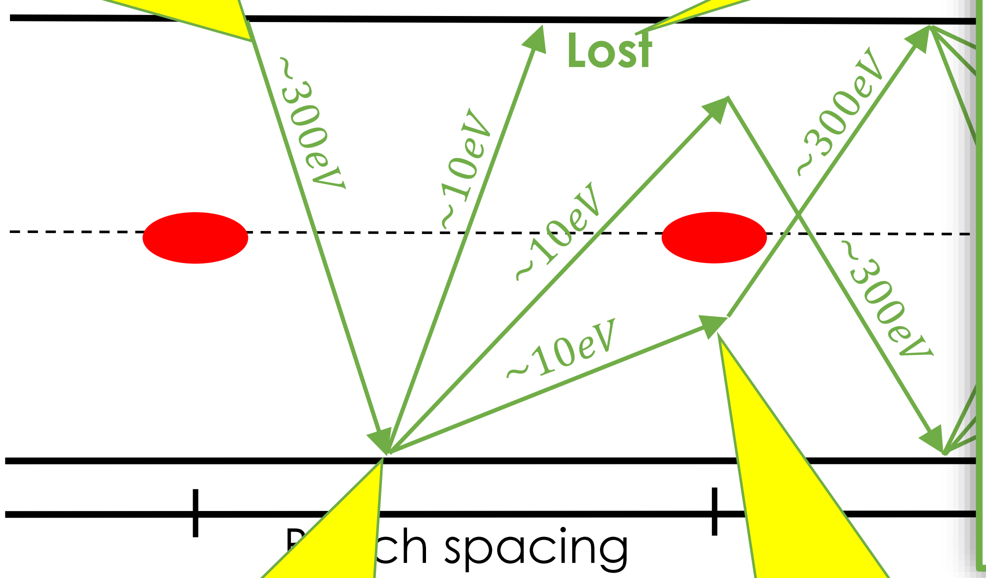
1. Primaries are attracted and accelerated by the beam to energies up to several hundreds of eV

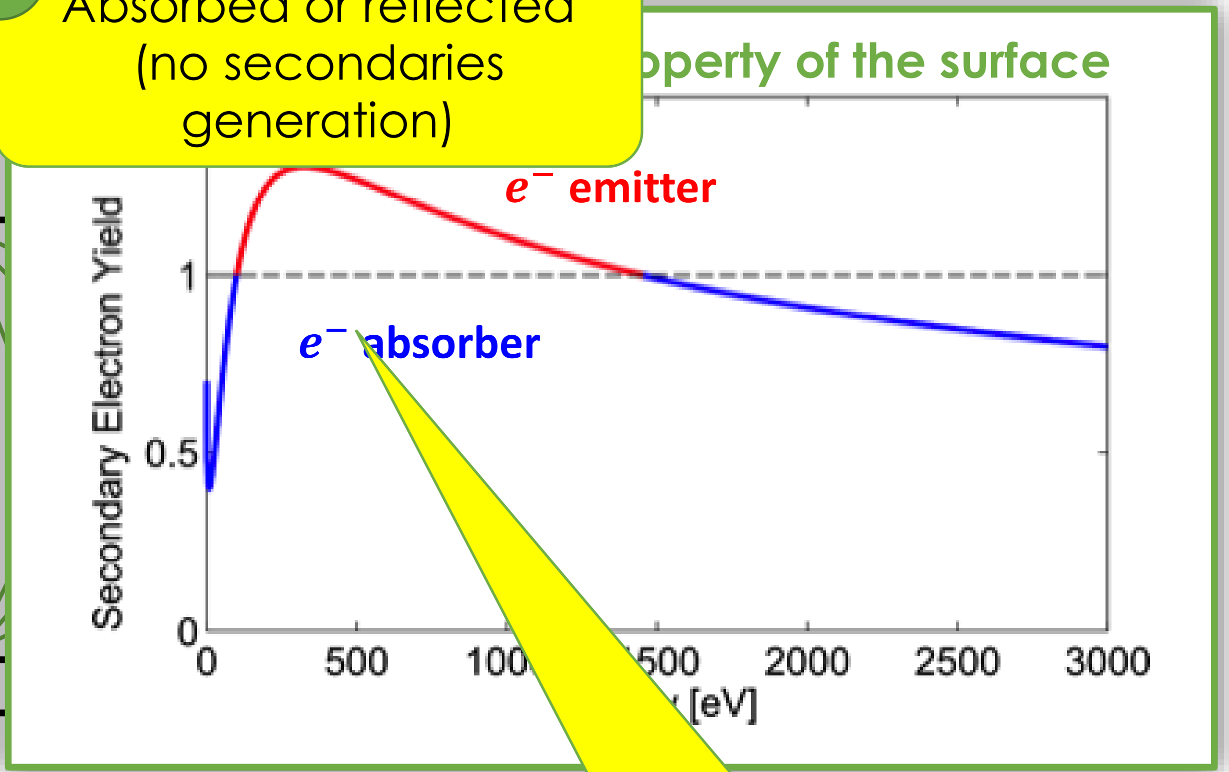
2. Emission of secondary electrons (energies up to few tens of eV)

3. Absorbed or reflected (no secondaries generation)

4. Accelerated by the following bunch (secondaries production)

5. Avalanche electron multiplication (***multipacting effect***)





g: SEY r
bombardment

Electron cloud effects

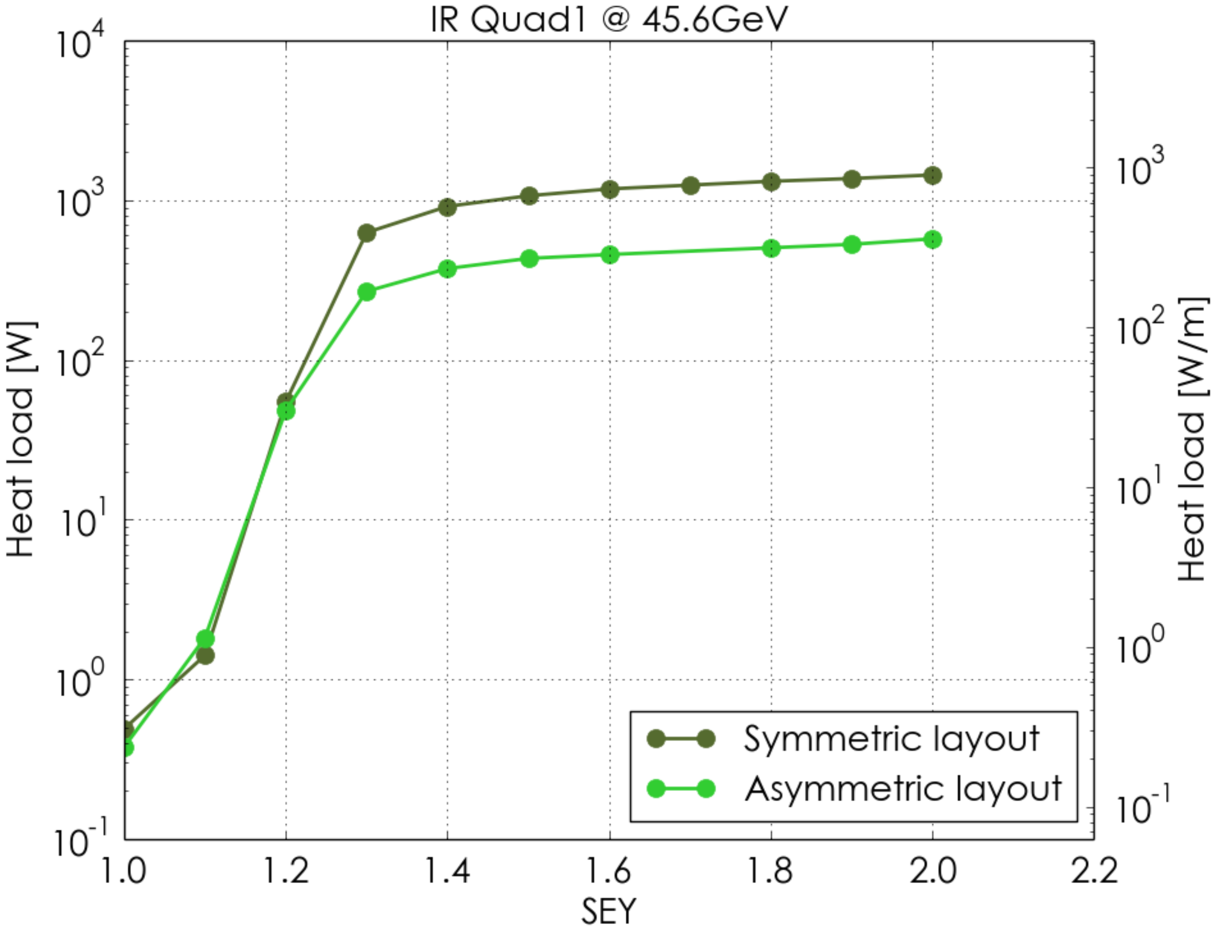
The presence of the Electron Cloud in the vacuum chamber represents **one of the major limitations** in the accelerator performance

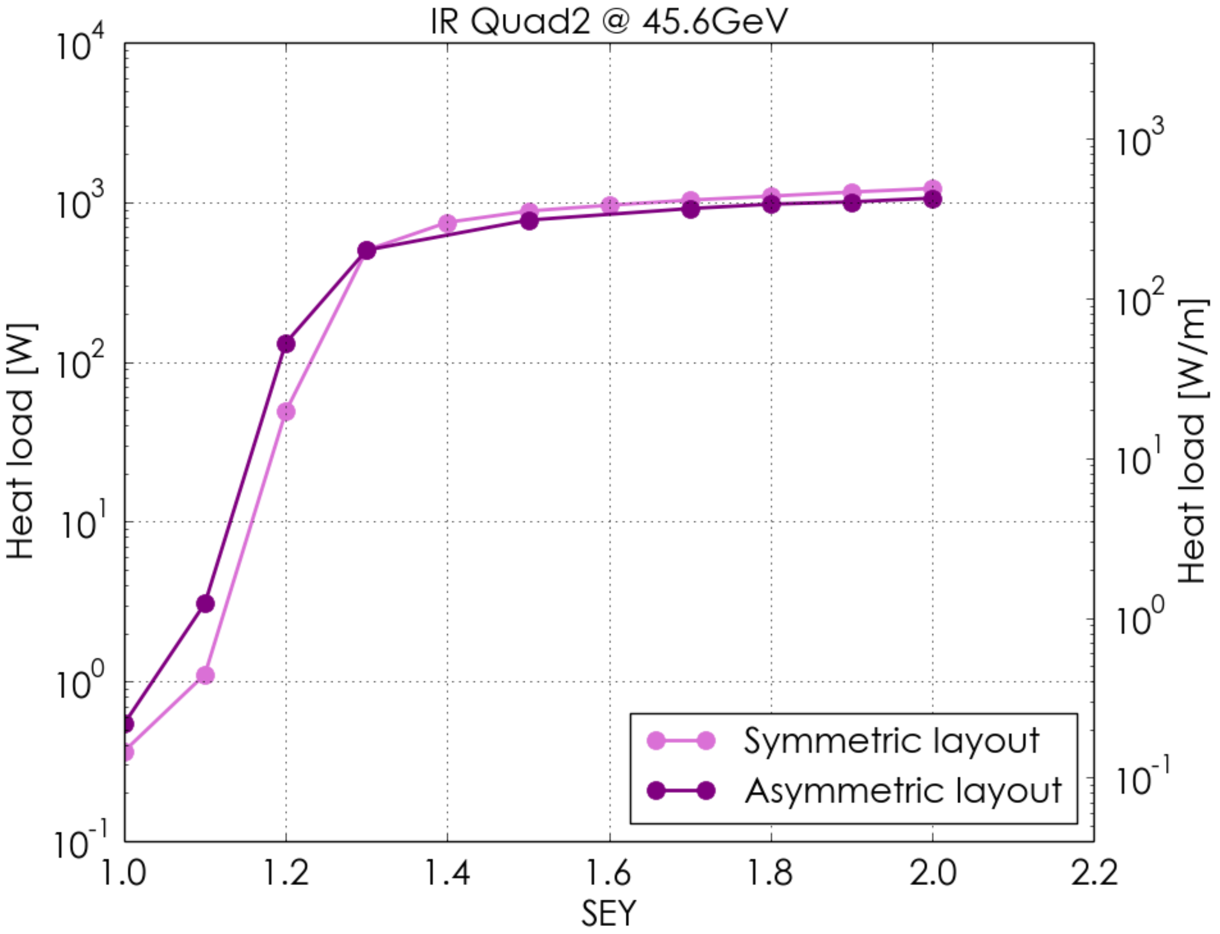
- Transverse beam instabilities
- Emittance blow-up
- Tune shift and spread
- Particle losses
- Degradation of the vacuum and on the beam diagnostics
- Heat load
  - Initial uniform electron distribution
  - SEY scan

Parameter list for EC studies

<table>
<tr><td>Energy [GeV]</td><td colspan="6">45.6GeV</td></tr>
<tr><td>Bunch spacing</td><td colspan="4">7.5 ns</td><td colspan="2">2.5 ns</td></tr>
<tr><td>Bunch population [10^{11}]</td><td colspan="4">1.0</td><td colspan="2">0.33</td></tr>
<tr><td>Horizontal emittance [nm]</td><td colspan="4">0.2</td><td colspan="2">0.09</td></tr>
<tr><td>Vertical emittance [pm]</td><td colspan="4">1</td><td colspan="2">1</td></tr>
<tr><td>Bunch length [mm]</td><td colspan="4">6.7</td><td colspan="2">3.8</td></tr>
<tr><td>Bunch train pattern</td><td colspan="6">300b</td></tr>
<tr><td rowspan="5">IR elements</td><td colspan="2"></td><td>L[m]</td><td>B[T] or G[T/m]</td><td>β_x[m]</td><td>β_y[m]</td></tr>
<tr><td rowspan="2">Quadrupole QC1R</td><td>Sym</td><td>3.2</td><td>26.6</td><td>53.3</td><td>8934</td></tr>
<tr><td>Asym</td><td>1.6</td><td>46.2</td><td>34.6</td><td>10265</td></tr>
<tr><td rowspan="2">Quadrupole QC2R</td><td>Sym</td><td>2.5</td><td>18.7</td><td>341</td><td>4488</td></tr>
<tr><td>Asym</td><td>2.5</td><td>16.3</td><td>297</td><td>4082</td></tr>
</table>

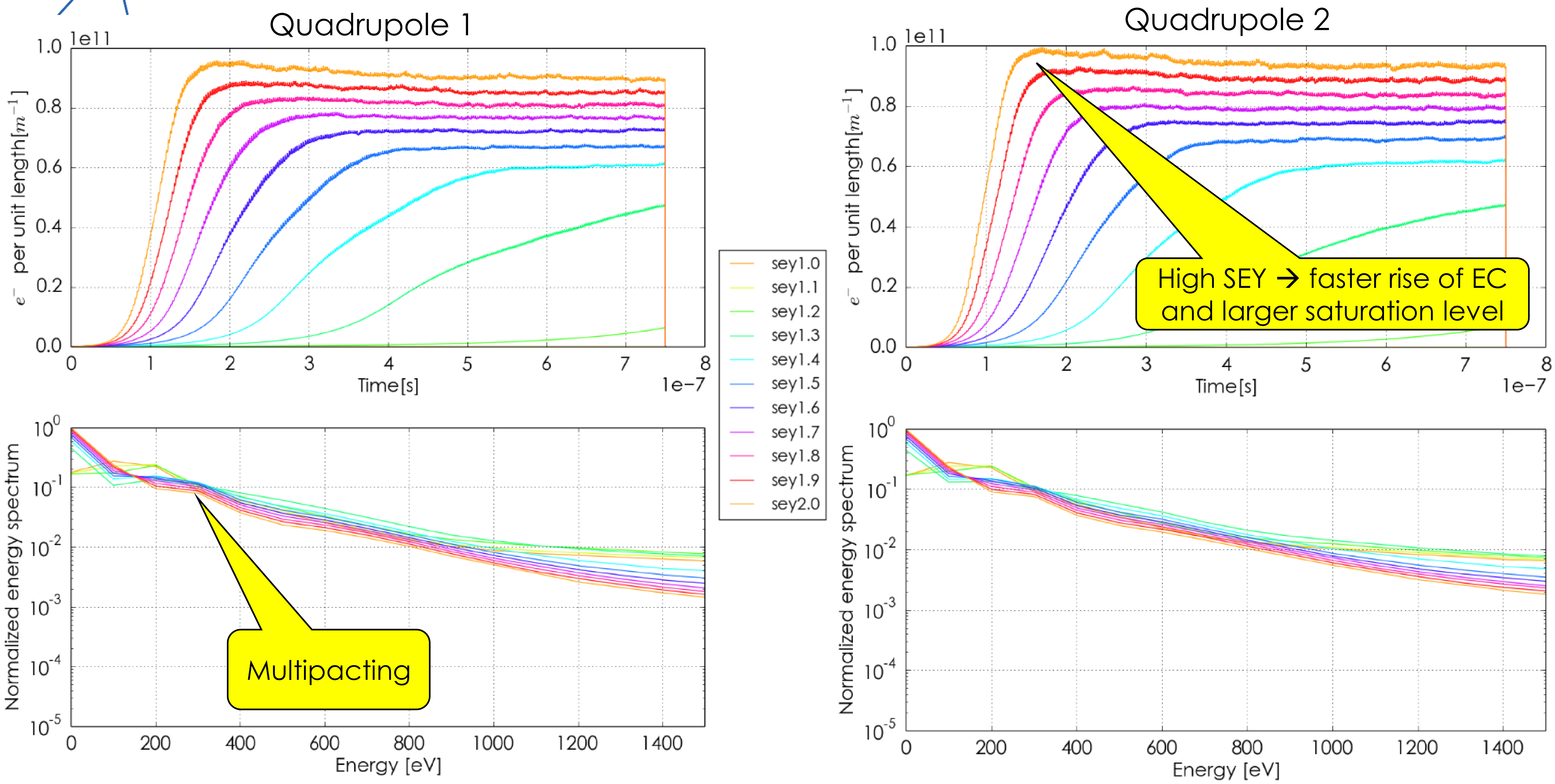
Heat load in the Interaction Region





- ➢ Multipacting threshold in IR quadrupoles ≈ 1.1-1.2
- ➢ For quadrupole 1, heat load up to 3 times lower in the case of asymmetric layout

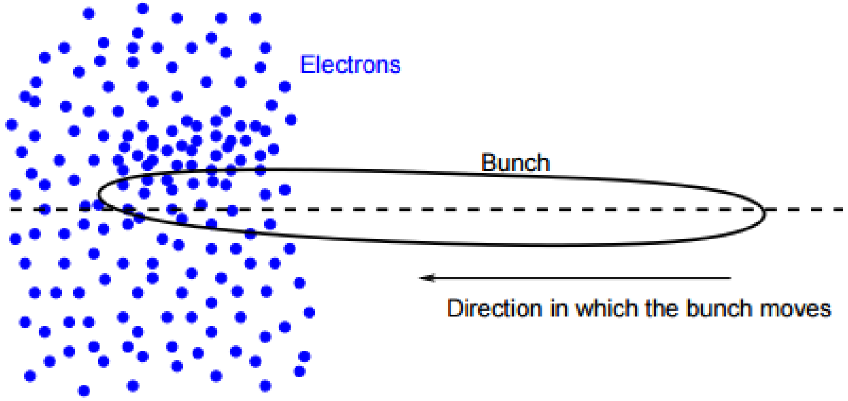
EC build up in final quadrupoles (SL)



Single bunch head-tail instability

- Electron cloud acts as a short range wake field with frequency

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}$$

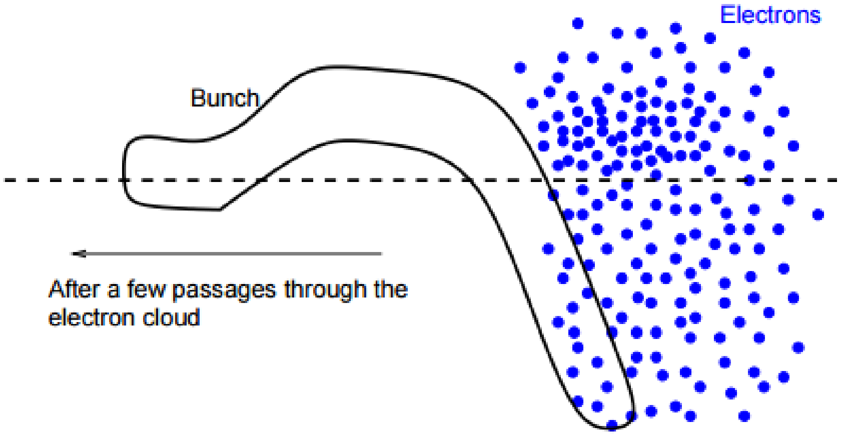


- Threshold electron density of the head-tail instability

$$\rho_{\mathrm{e,th}} = \frac{2\gamma \upsilon_s \omega_e \sigma_z / c}{\sqrt{3} K Q r_0 \beta C}$$

with

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



Energy [GeV]	45.6		175
Bunch spacing [ns]	7.5	2.5	4000
Synchrotron tune	0.036	0.025	0.075
Electron frequency $\omega_e/2\pi$ [GHz]	4330	5330	196
Electron oscillation $\omega_e \sigma_z / c$	607.46	424.33	10.25
Threshold density ρ_{th} $[10^{10}/m^3]$	**1.88**	**1.3**	**15**

What's next?

- Hp: initial uniform electron distribution
- Photoemission due to SR
  - Number of SR photons per particle per meter

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

	LHC	FCC-hh	FCC-ee
E [GeV]	7000	50000	45.6
γ	7400	53300	89236
ρ [km]	2.8	11.3	11.3
$\mathbf{N_\gamma/p^+m}$	0.028	0.05	0.085

3 times higher than LHC and roughly twice than FCC-hh at collision

- No experimental data for photoelectron yield and photon reflectivity
  - ✓ Scan of Y and R_γ

Conclusions

- **Trapped modes**
  - Asymmetric layout seems to be the best choice for the HOMs
  - Further studies needed
- **Electron cloud**
  - Multipacting threshold in IR quadrupoles ≈ 1.1-1.2
    - SEY < 1.1 to avoid EC in the Interaction Region
  - Heat load in Quad1 3 times lower in asymmetric layout (to be confirmed)
  - More simulation studies to be performed
    - photoelectron yields and reflectivity scan
    - beam intensities scan
    - beam dynamics studies

Thanks for your attention