Review on Electron Cloud simulation tools @ CERN

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in CERN-GSI Workshop on Electron Cloud

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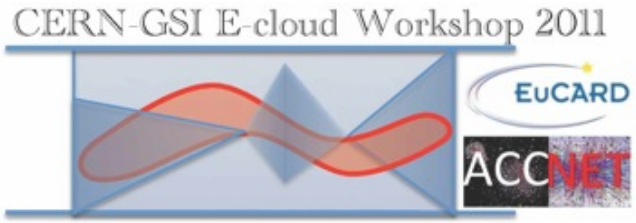
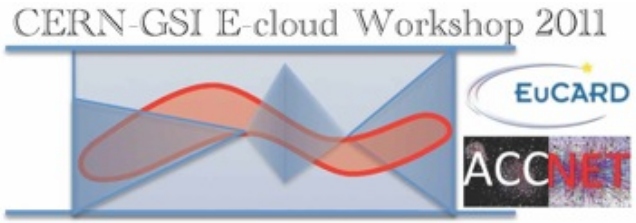
Acknowledgments: G. Arduini, G. Bellodi, E. Benedetto, J. Crittenden, O. Dominguez, W. Fischer, G. Franchetti, U. Iriso, K. Li, K. Ohmi, E. Shaposhnikova, F. Zimmermann

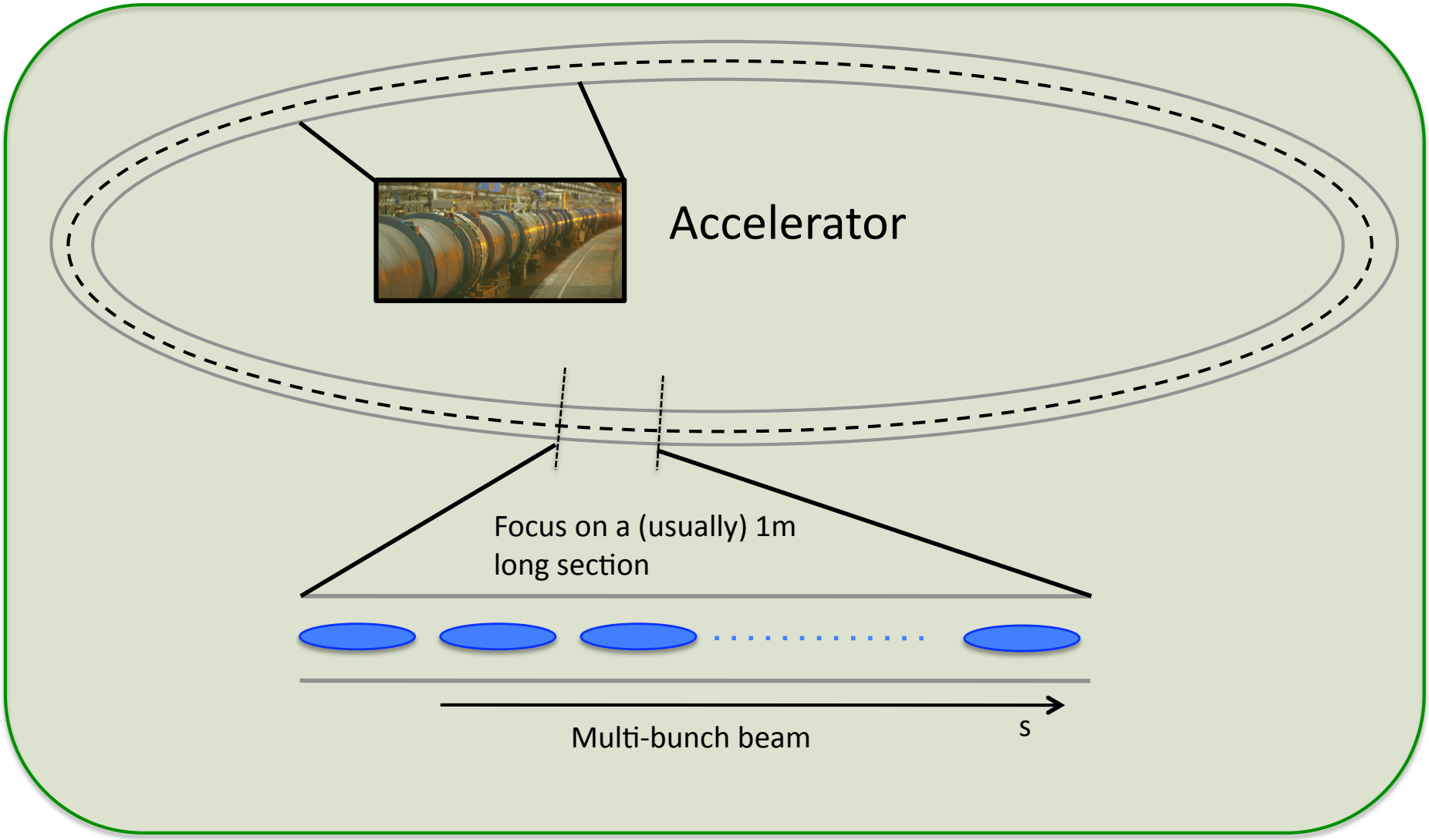


Outline

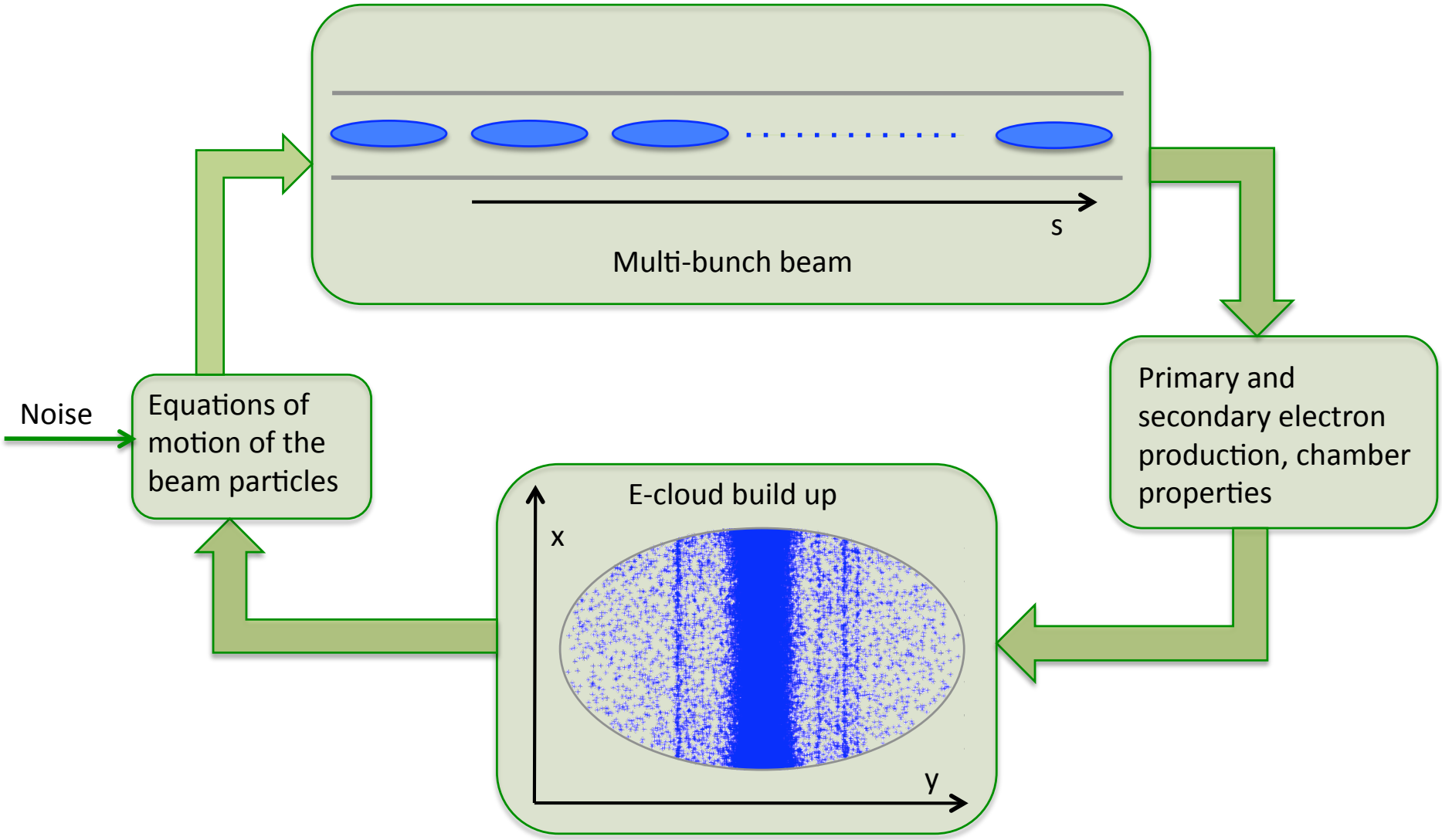
- General considerations on electron cloud simulations:
  - Beam induced build up
  - Effects on the beam
- CERN tools
  - ECLOUD
    - → Model and numerical parameters
    - → Sensitivity to physical parameters
  - HEADTAIL



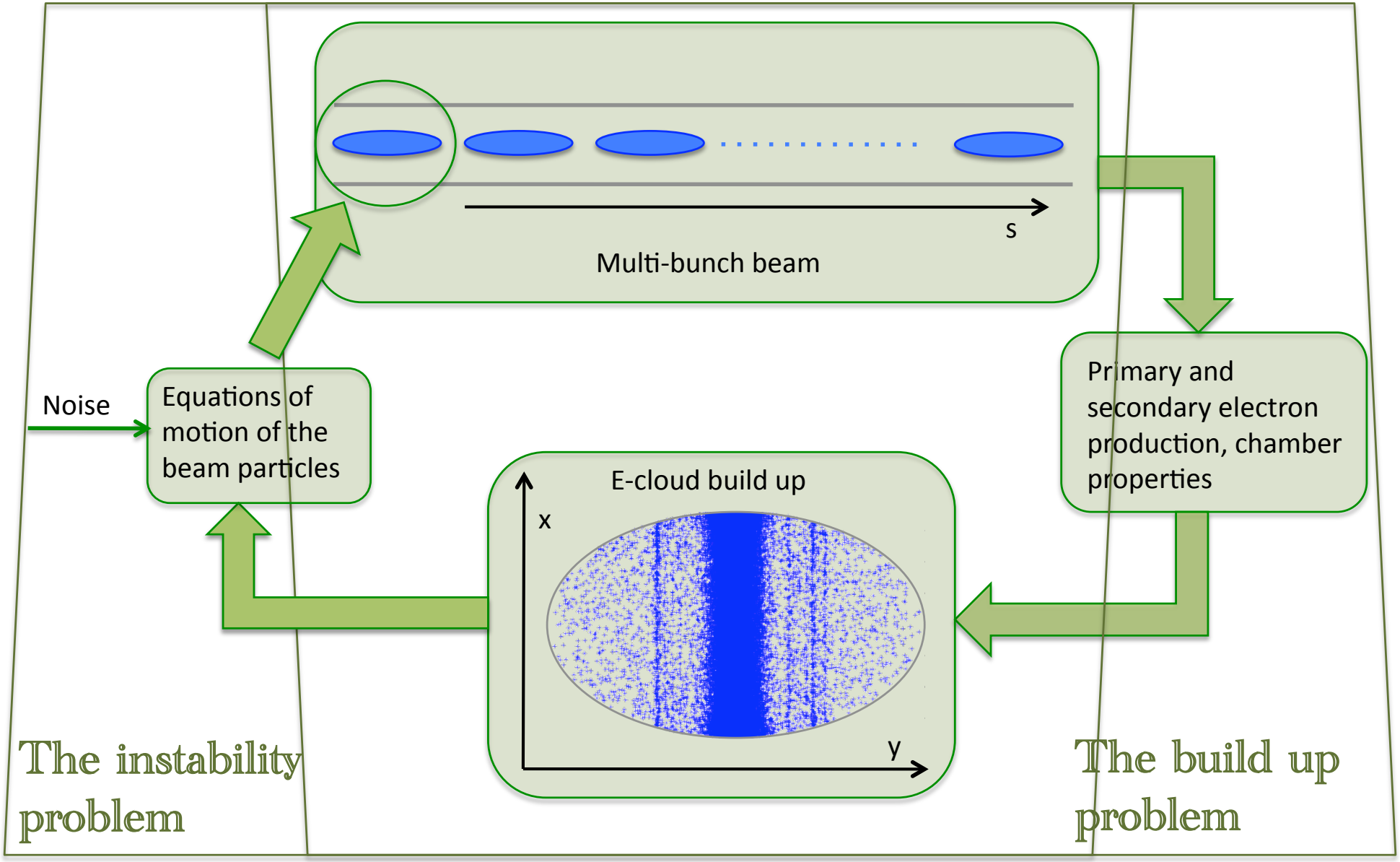
The electron cloud physics problem



Flow chart of the e-cloud physics problem



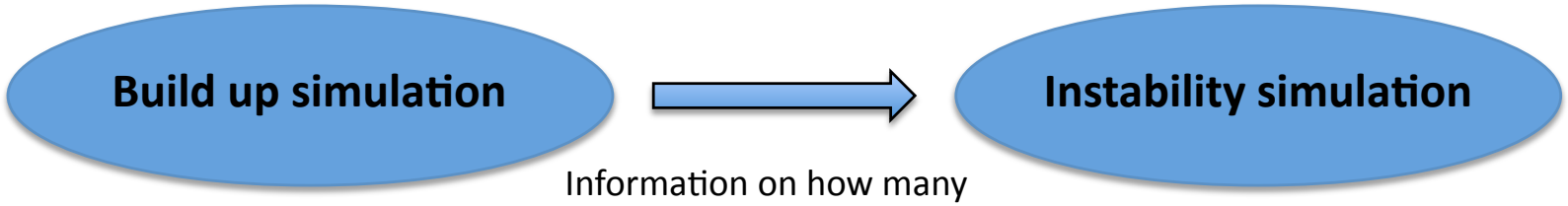
Splitting the problem…



In summary

- Coupled bunch electron cloud instability naturally needs a self-consistent solution of the electron cloud problem
  - Too broad range of time scales to cover

- So we choose to simulate the two branches separately:
  - **Electron cloud build up**
    - ✓ Multi-bunch
    - ✓ Usually single passage, single turn
  - **Electron cloud instability**
    - ✓ Single bunch
    - ✓ Multi-turn, or even multi-kick multi-turn



Information on how many electrons interact with a bunch:
- central density
- detailed distribution

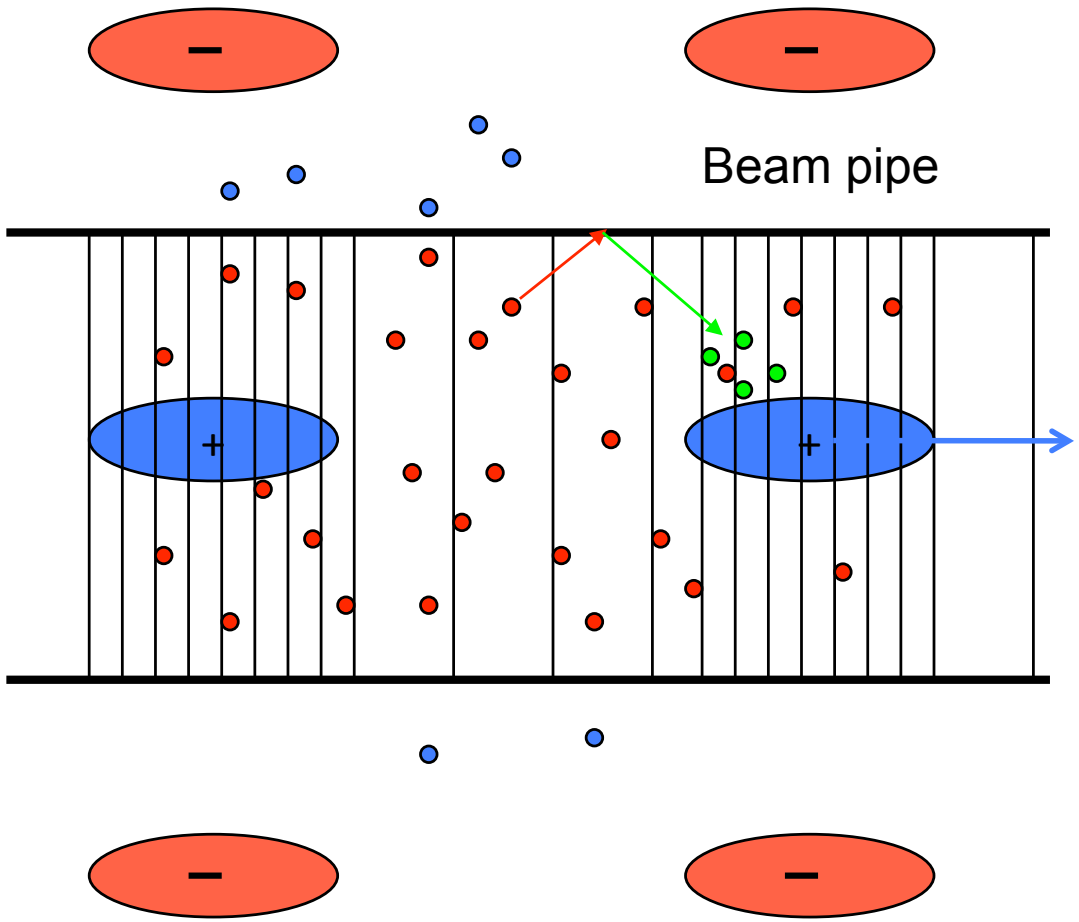
Simulation of e-cloud build up
Existing codes

- Electron cloud build up codes:
  - **ECLOUD** (*CERN*, Zimmermann, Bellodi, Brüning, Crittenden, Rumolo, Schulte, Xiang)
  - **POSINST** (*LBNL*, Furman, Pivi)
  - **CLOUDLAND** (*BNL-SLAC*, Wang)
  - **CSEC** (*BNL*, Blaskiewicz)
  - **PEI** (*KEK*, Ohmi)
  - **FAKTOR2** (*CERN*, Bruns)

Main ingredients of ECLOUD

- Multi-bunch passage, dipole/field-free/ solenoid sections, clearing voltage
- 3D electron kinematics
- Transverse beam-electron forces
- Transverse electron space charge effects
- Circular/elliptical/rectangular chamber
- Perfectly conducting walls

ECLOUD simulation
General principle



- focus on a beam line section (1m for ex.)
- slice bunch and interbunch gaps
- represent e- by macroparticles: create and accelerate e- in beam and image fields
- if the macroelectron hits the wall create secondaries by changing its charge and/or splitting into more macro-electrons

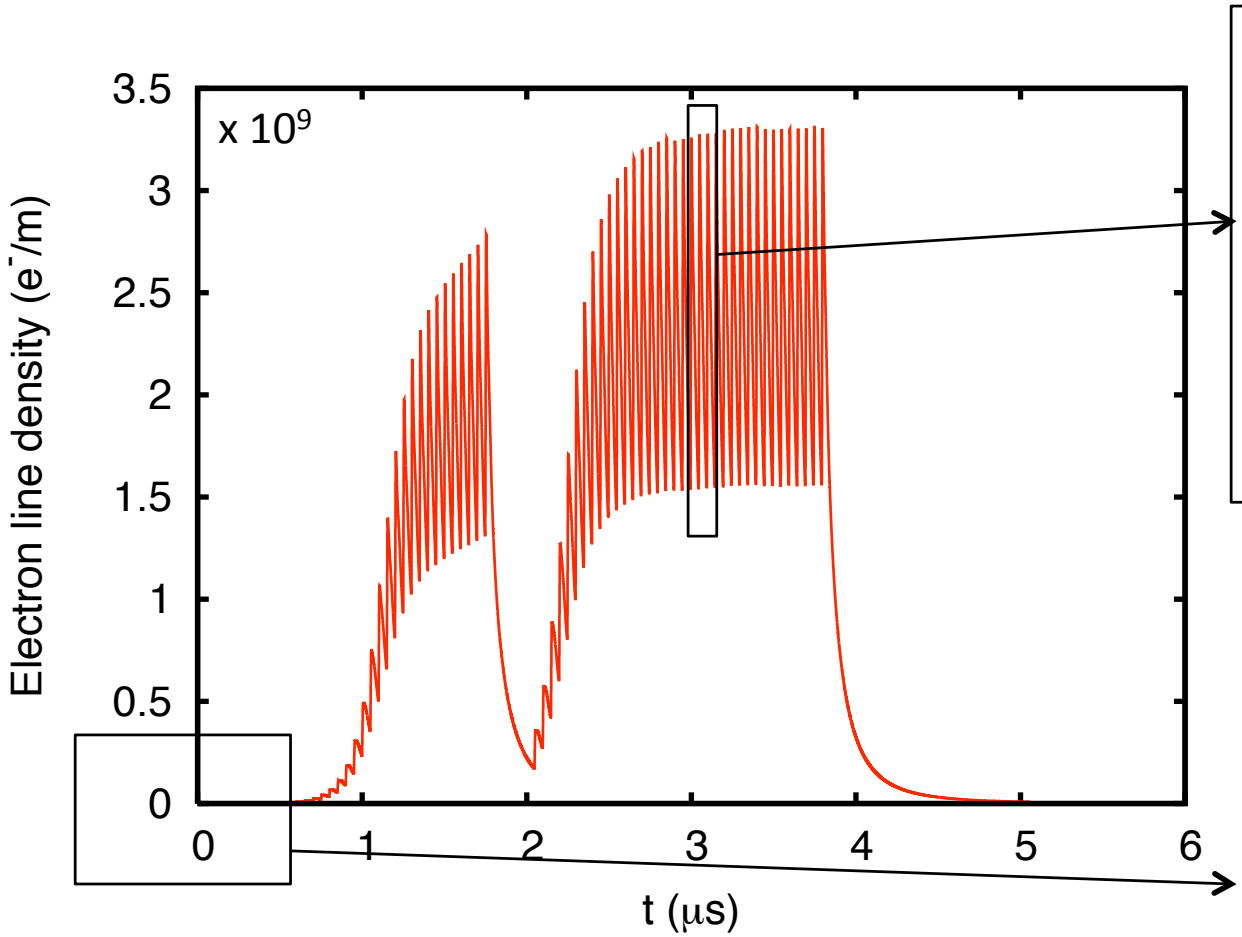
Dependence on numerical parameters

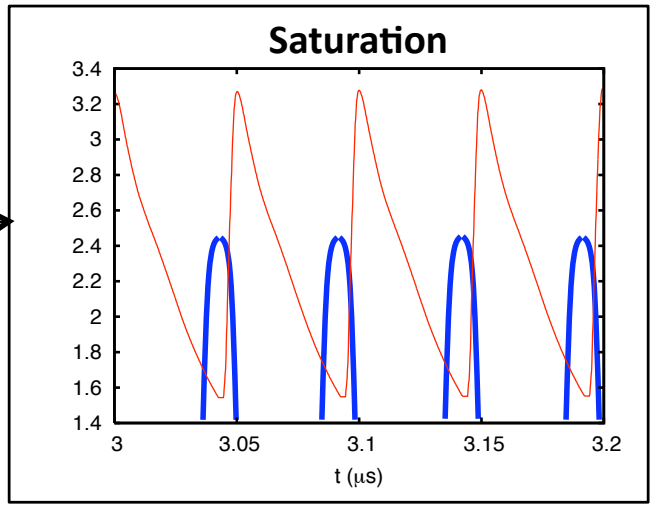
→ Electron cloud build up simulations are sensitive to a significant number of **numerical parameters**

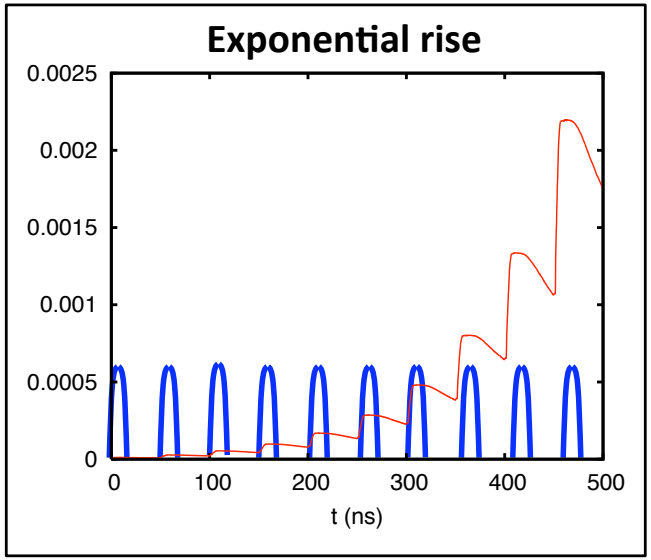
- Time steps:
  - ✓ During the bunch passage
  - ✓ During the inter-bunch gap
- Number of macro-electrons launched per bunch
- Maximum number of macro-electrons allowed in the simulation
  - ✓ Macro-electrons are not just produced all the time through the primary and secondary generation mechanisms
  - ✓ A 'clean' subroutine always reduces the number of macro-electrons back to the maximum allowed, when exceeded, and the "cleaned" charge is redistributed
- Limit charge for macro-electron splitting and maximum number of macro-electrons into which a macro-electron that has 'gained' too much charge can be split
- Number of mesh points for space charge calculation
- Multi-seed simulations for statistics

→ CPU times of typical electron cloud build up simulations range from few hours to several days, depending on the choice of the parameters above (determined by the problem)

ECLOUD sample result







→ Example of electron cloud build in LHC arc with two trains with 36 bunches of 50ns beam

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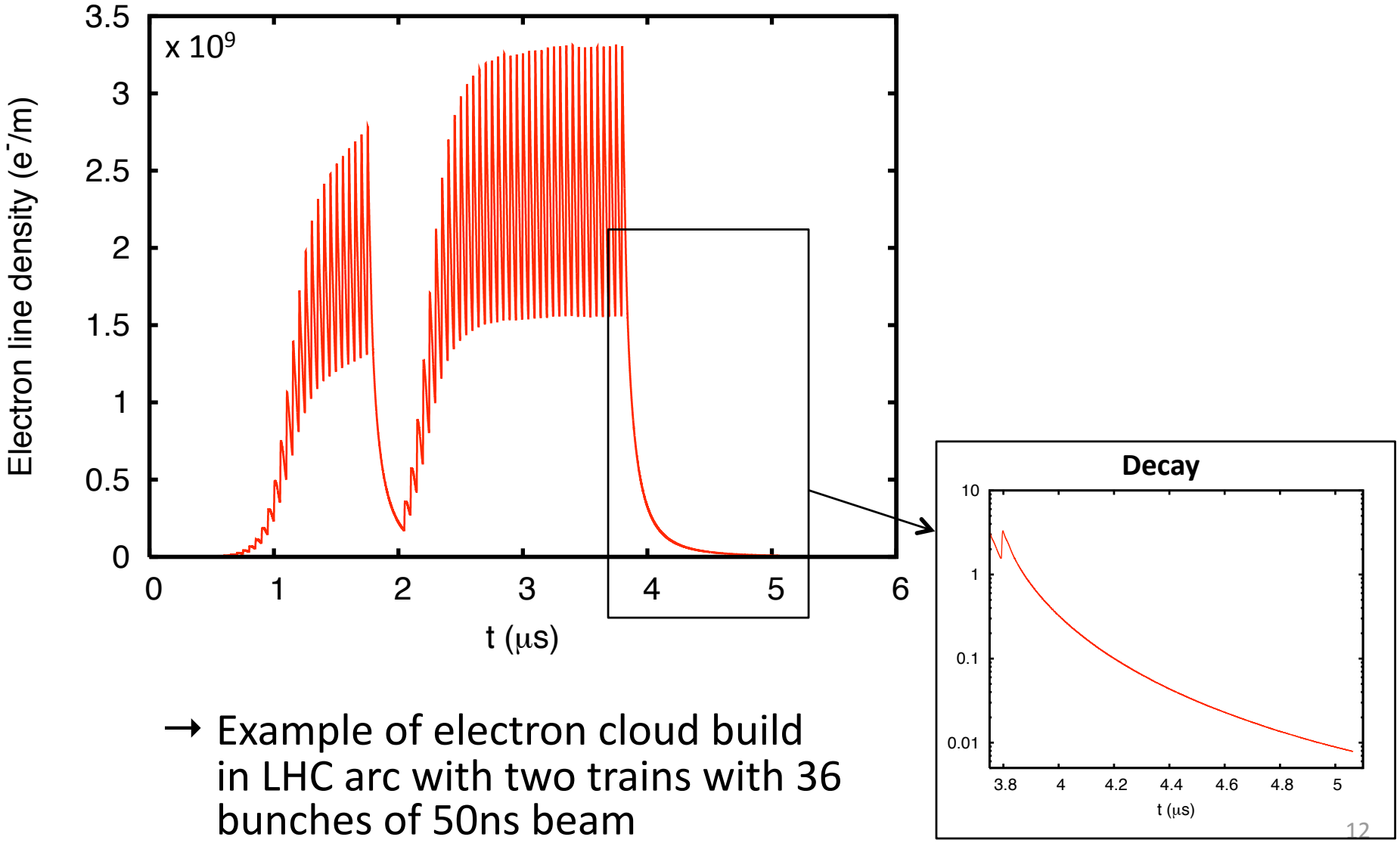

→ Example of electron cloud build in LHC arc with two trains with 36 bunches of 50ns beam

Dependence on physical parameters

→ Electron cloud build up depends on a significant number of parameters in a non-monotonic and non-trivial way

- Primary mechanism of electron generation
  - ✓ Gas ionization or beam loss (hadrons)
  - ✓ Photoemission (positrons, LHC)
- Surface properties:
  - ✓ Maximum SEY (δ_{max}) and energy at which it occurs (E_{max})
  - ✓ Probability of reflection at zero energy (R_0)
  - ✓ Existence and model of re-diffused electrons
- Bunch spacing and bunch length
- Beam pipe radius and shape
- Magnetic field (field-free, dipole, quadrupole)
- Beam transverse sizes
- Beam current (number of particles per bunch)

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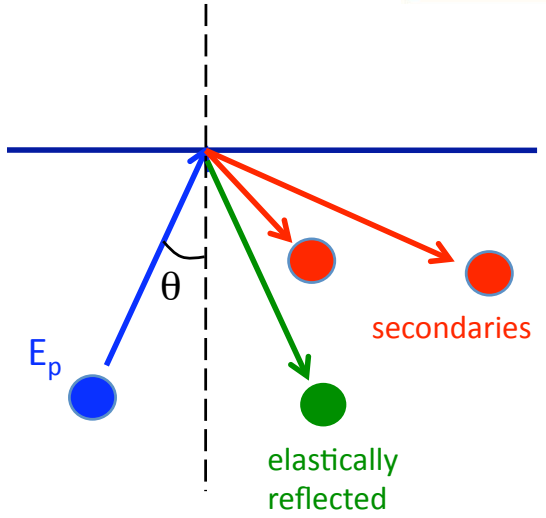
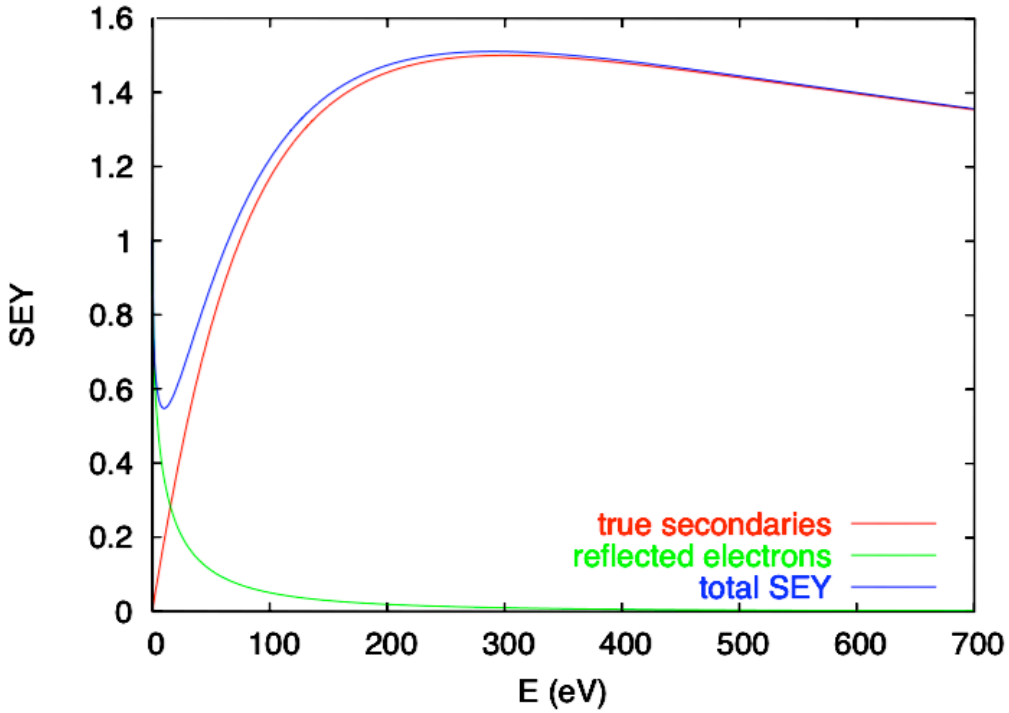
Surface model

- When electrons hit the pipe wall, they do not just disappear…..
  - High energy electrons easily survive and actually multiply through **secondary electron emission**
  - Low energy electrons tend to survive long because they are likely to be elastically reflected.
- **Secondary electron emission is governed by the curve below (as coded in ECLOUD)**





$$\delta_{\text{true}} = \delta_{\max} \frac{sx}{s - 1 + x^s} \qquad x = \frac{E}{E_{\max}}$$

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

$$\delta_{\text{tot}}(E) = \delta_{\text{true}}(E) + R_0 \cdot \delta_{\text{elas}}(E)$$

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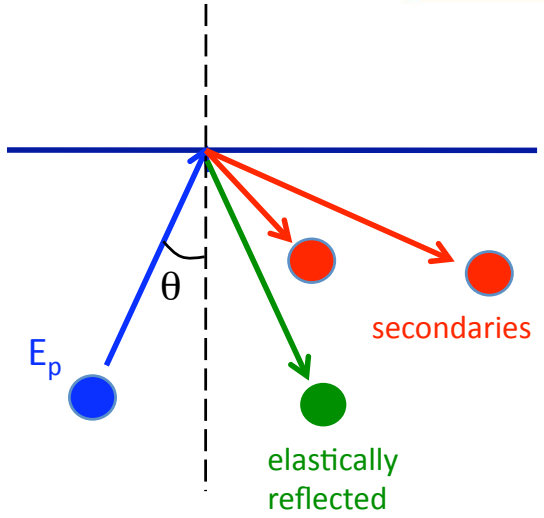

First three parameters on which simulation results depend

$$(R_0,\ E_{\max},\ \delta_{\max})$$

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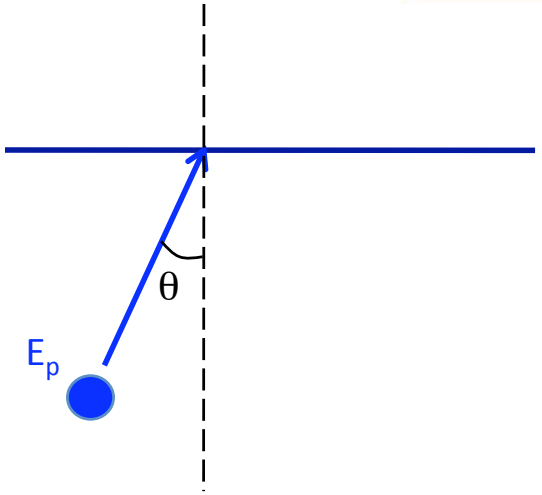
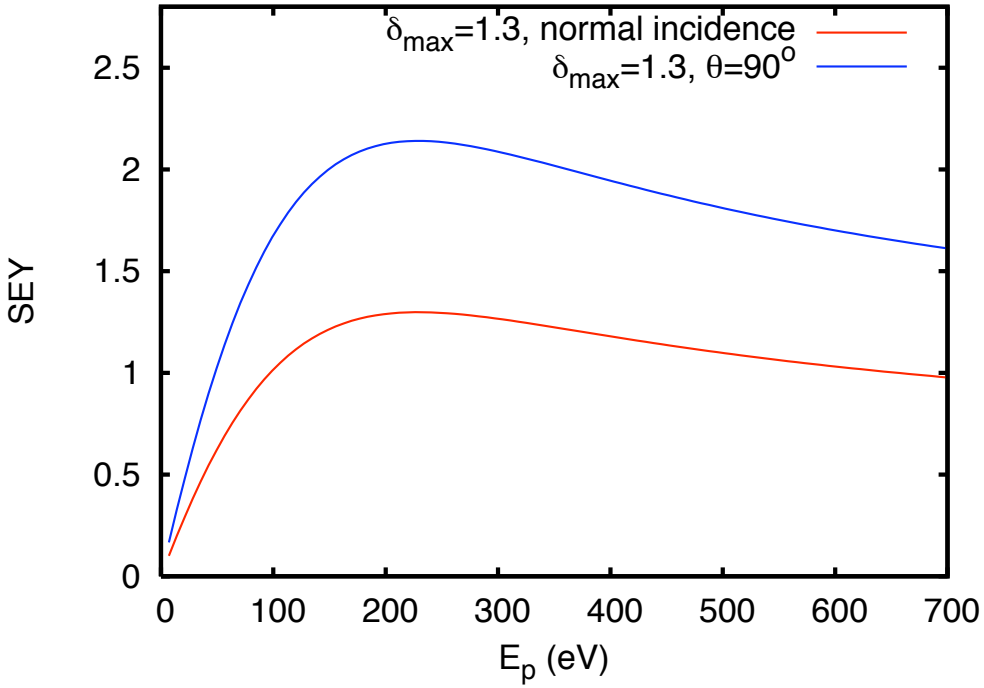


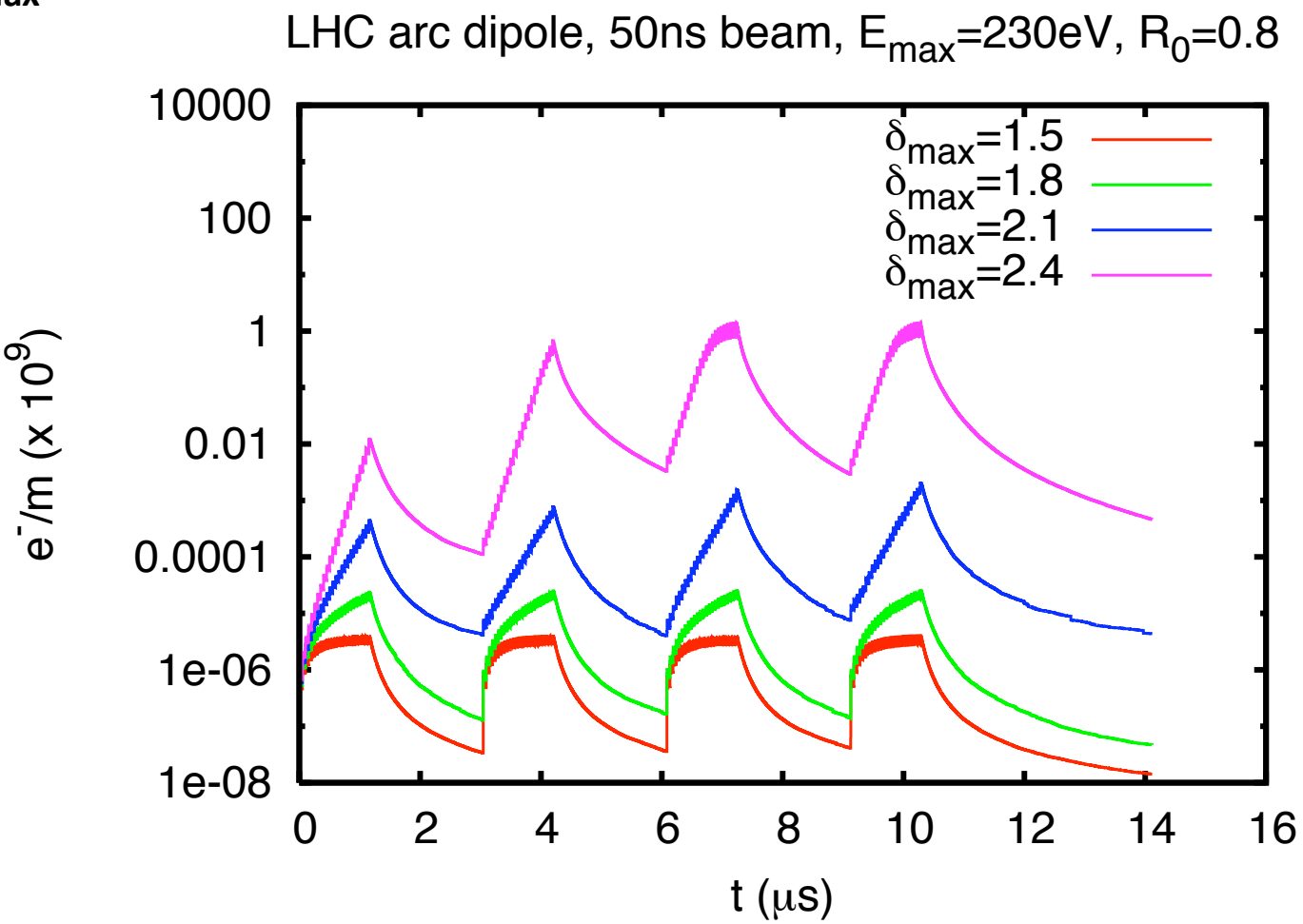


$$\delta^*_{\max}(\theta) = \delta_{\max} \exp\left[\frac{1}{2}(1-\cos\theta)\right]$$

$$E^*_{\max}(\theta) = E_{\max} \cdot [1 + 0.7(1-\cos\theta)]$$

Effects on the build up

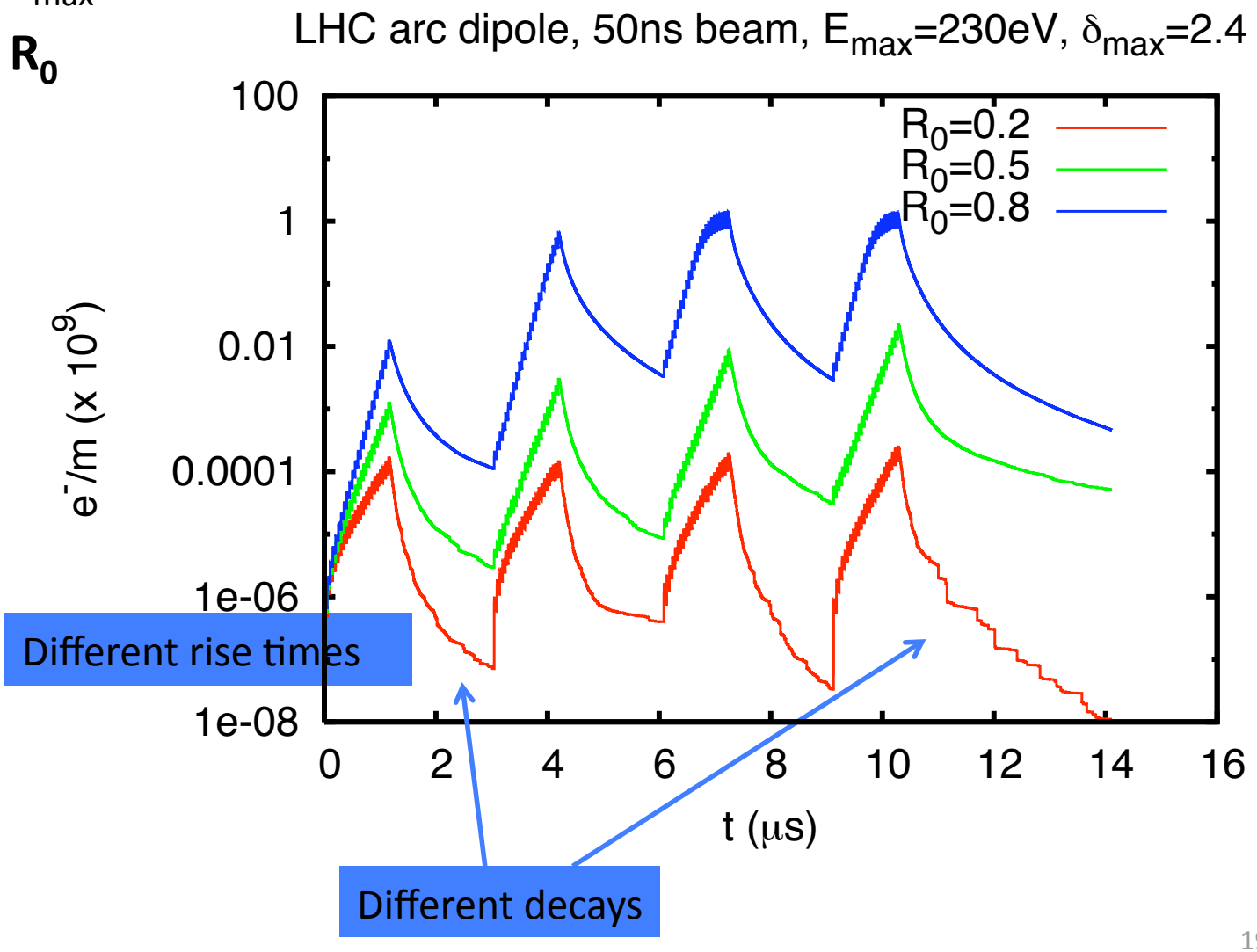
⇒ **Effect of δ_{max}**



Effects on the build up

⇒ Effect of δ_{max}

⇒ **Effect of R_0**

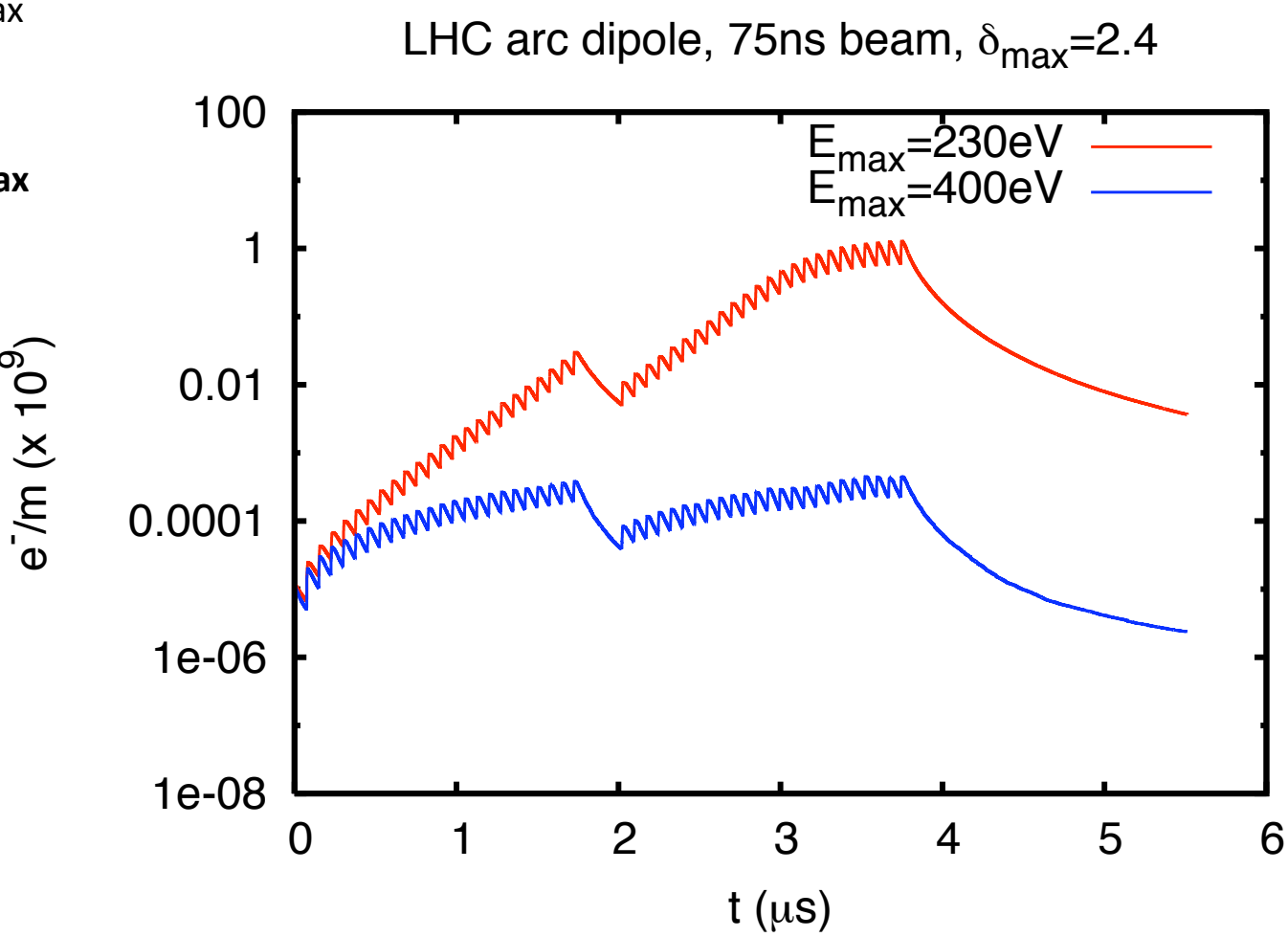


Effects on the build up

⇒ Effect of δ_{max}

⇒ Effect of R_0

⇒ **Effect of E_{max}**



See talks by Octavio, Ubaldo and Humberto for tuning of these numbers

Dependence on physical parameters

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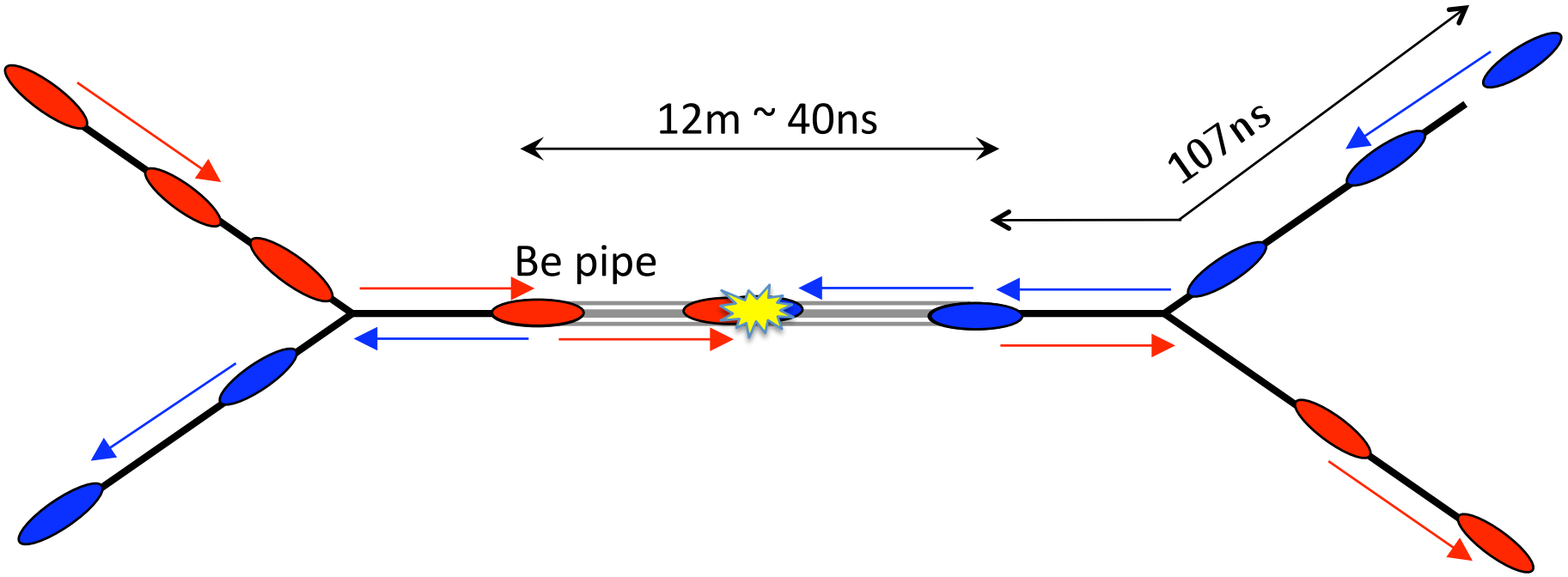
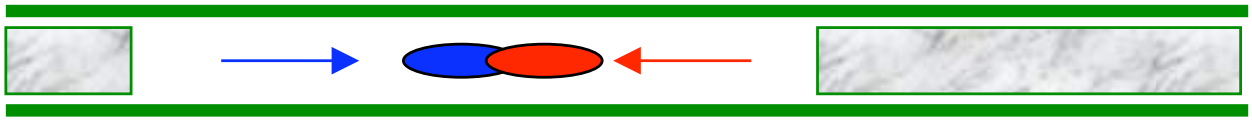
Dependence on bunch spacing and length



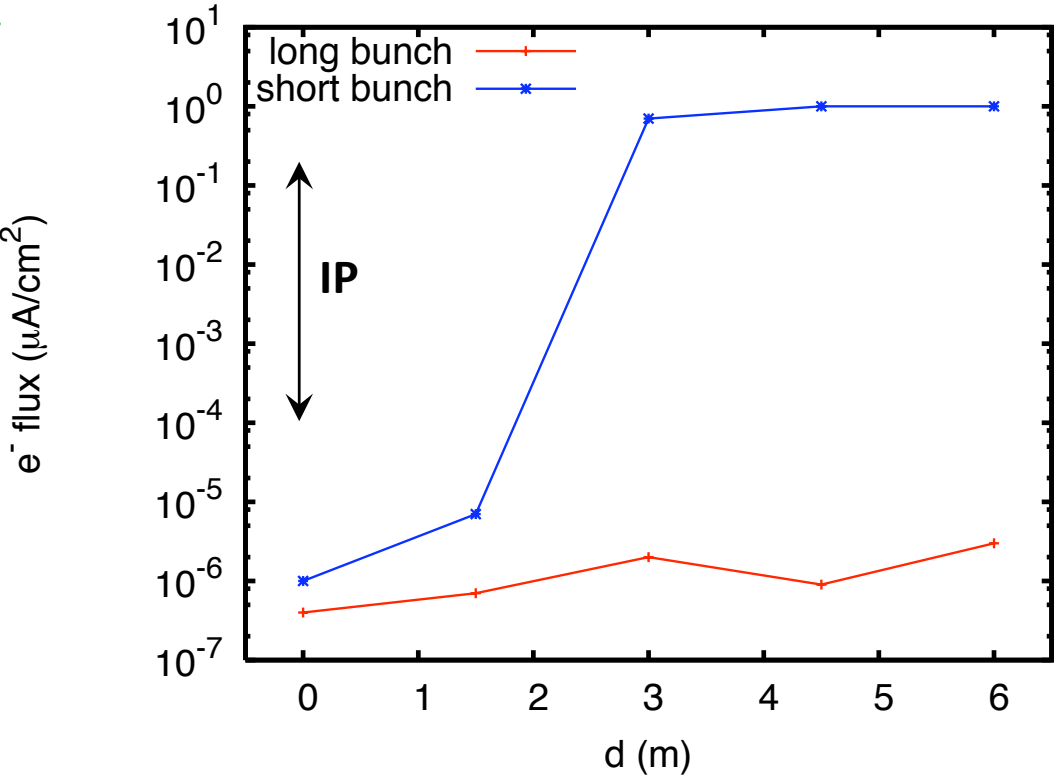
- One of the former experimental regions of RHIC (PHOBOS)
- Electron cloud is likely to build up, especially because in the experimental region there is a **beryllium pipe** (very high SEY), and the effective bunch spacing is reduced
- **Observation**: when bunches are compressed to half length, a severe pressure rise occurs in the PHOBOS region, which later "switches off" at some stage during the store.

Dependence on bunch spacing and length



Beryllium pipe

Electron flux to the wall in PHOBOS, simulated with ECLOUD



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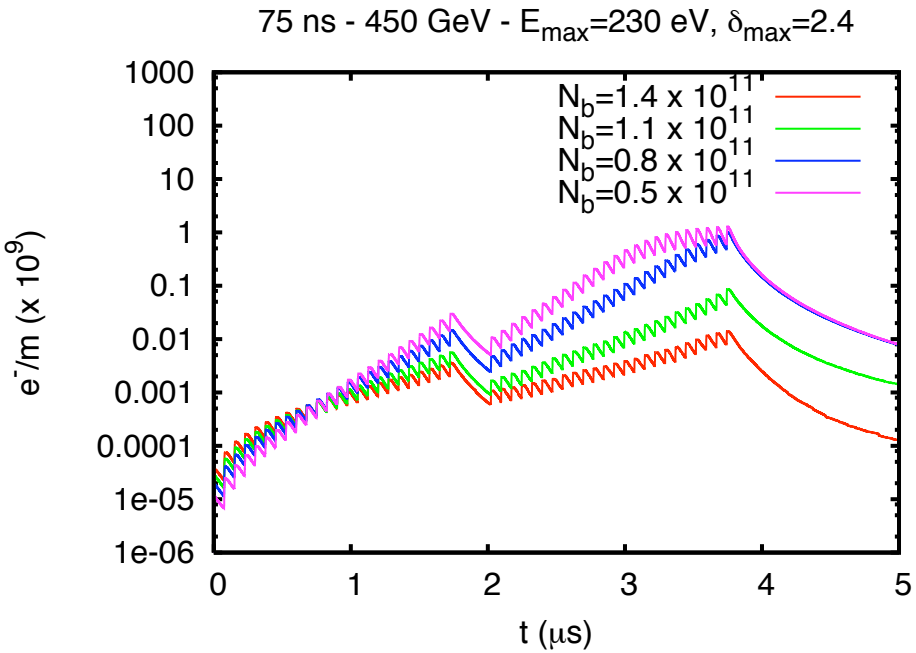
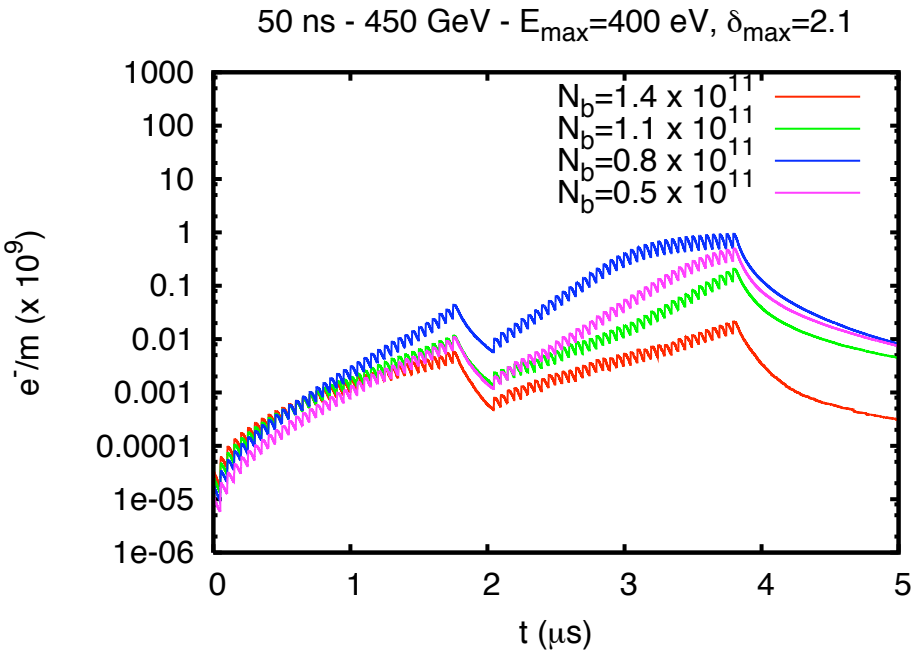
Effects on the build up

⇒ Effect of N_b





75ns → electron cloud decreasing function o 50ns → electron cloud is maximum for 8 x 10^{10} ppb

Non-monotonic & counterintuitive – to be experimentally verified!!

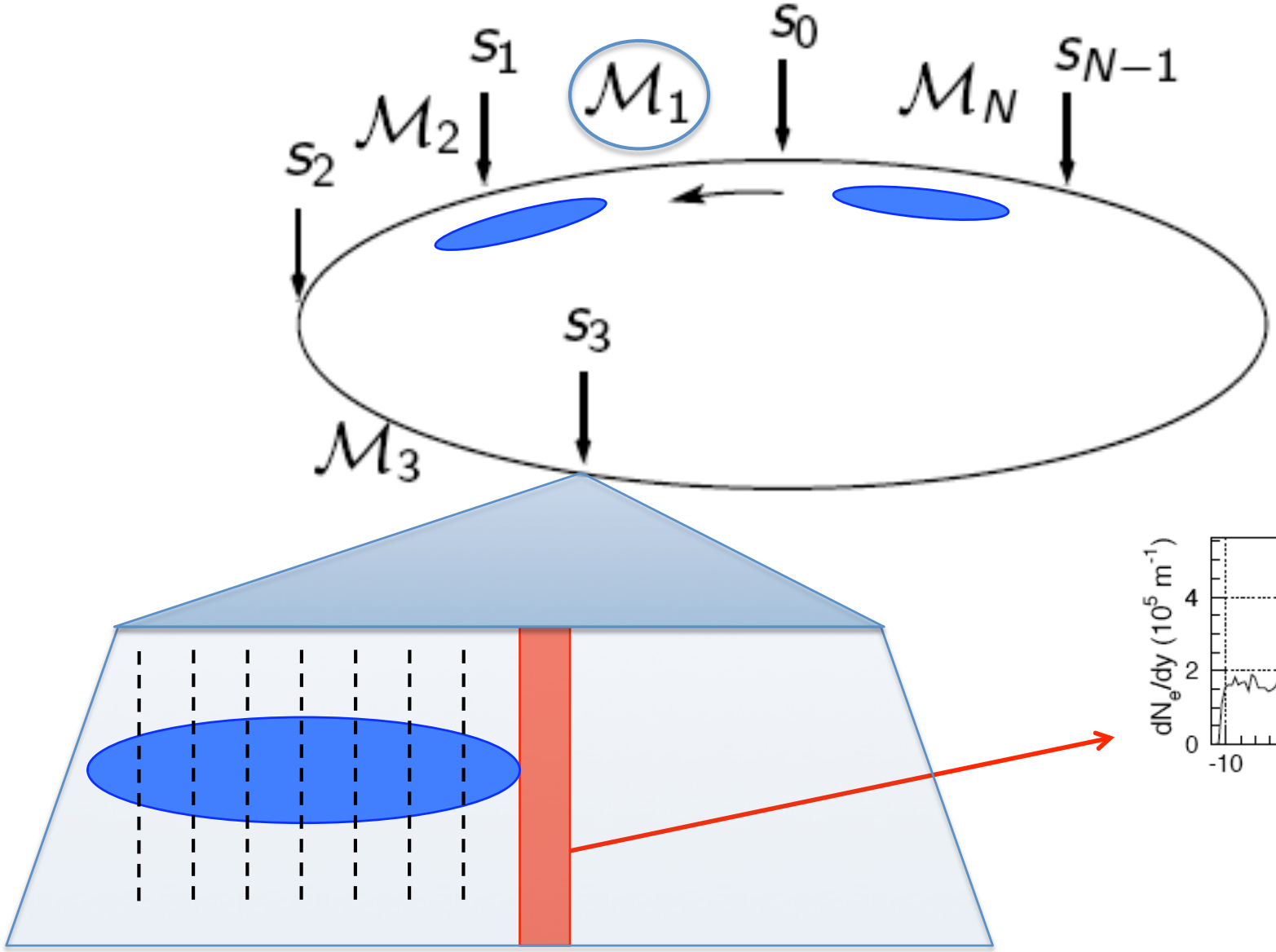
Simulation of e-cloud instability
Existing codes

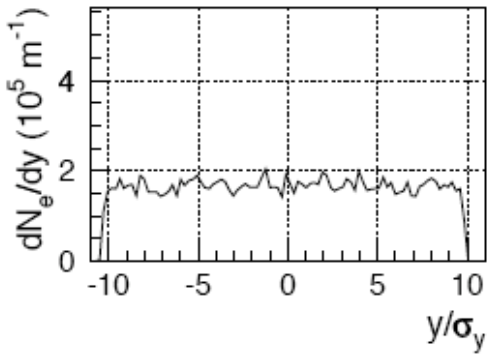
- Electron cloud instability codes:
  - **PEHTS** (*KEK*, Ohmi)
  - **HEADTAIL** (*CERN*, Rumolo, Zimmermann, et al.)
  - **QUICKPIC** (*USC-GSI*, Katsouleas, Ghalam, Rumolo, Benedetto, Beng)
  - **WARP-POSINST** (*LBNL*, Vay, Furman)
  - **CMAD** (*SLAC*, Pivi)

Main ingredients of HEADTAIL

- Single-bunch effect
- Multi-turn and multi-kick
- Dipole/field-free/solenoid sections
  - ✓ Can receive the electron distribution from ECLOUD
- 6D bunch description
  - ✓ Several options for the type of longitudinal motion
- Transverse mutual beam-electron forces
- Chromaticity, amplitude detuning

HEADTAIL simulation general principle





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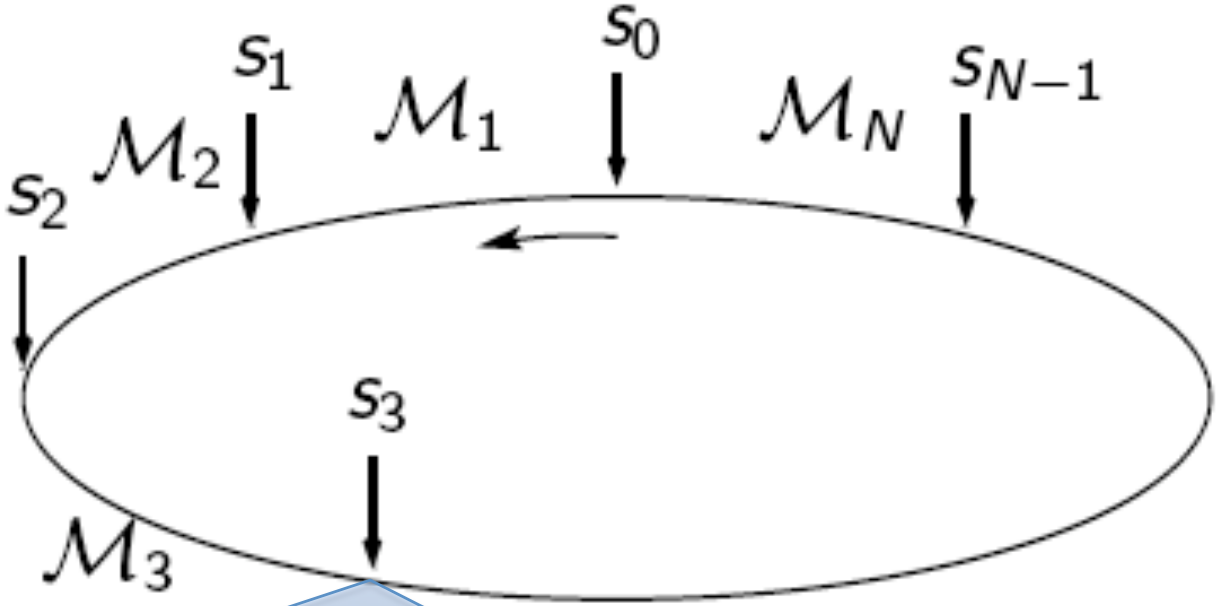

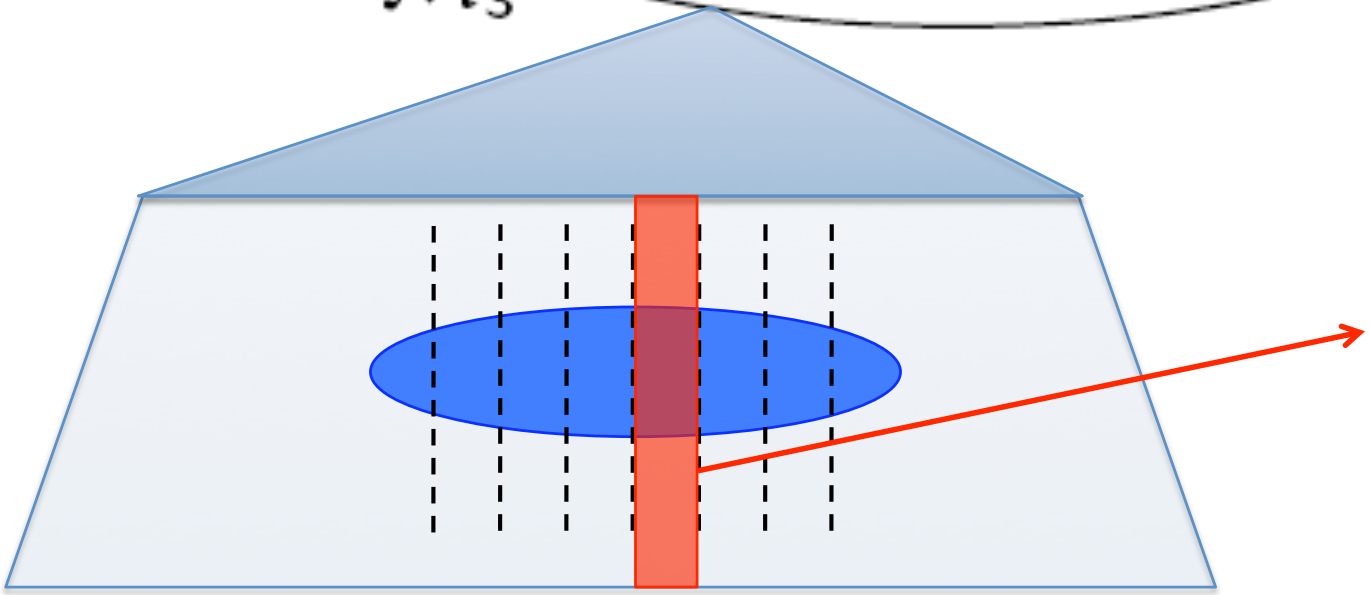

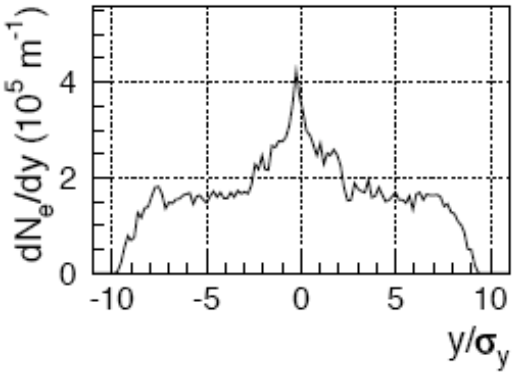

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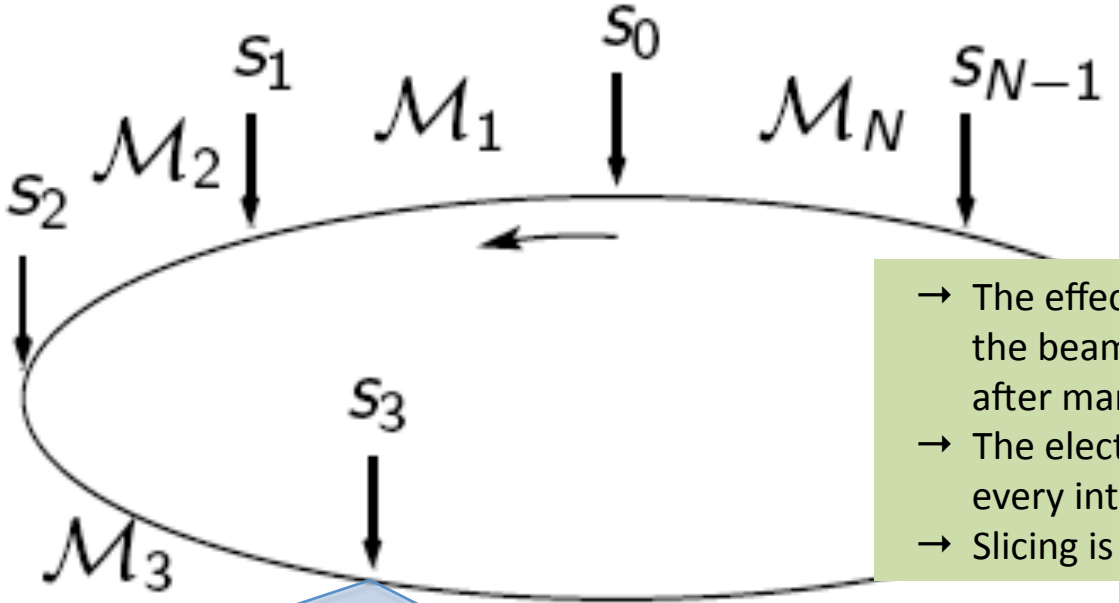
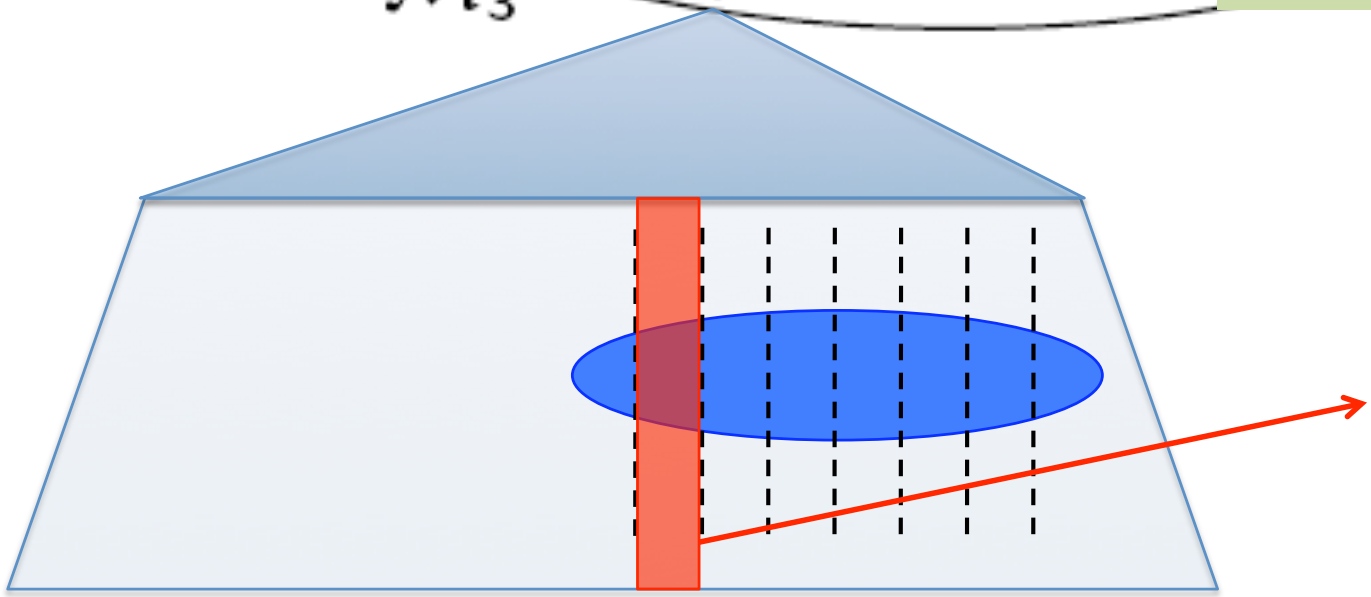
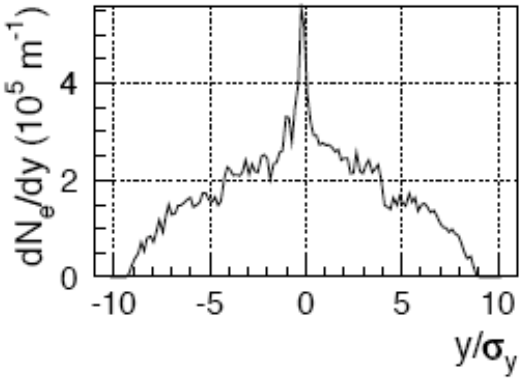


- → The effect of the electron cloud on the beam becomes visible only after many turns
- → The electron cloud is refreshed at every interaction point
- → Slicing is renewed at every turn





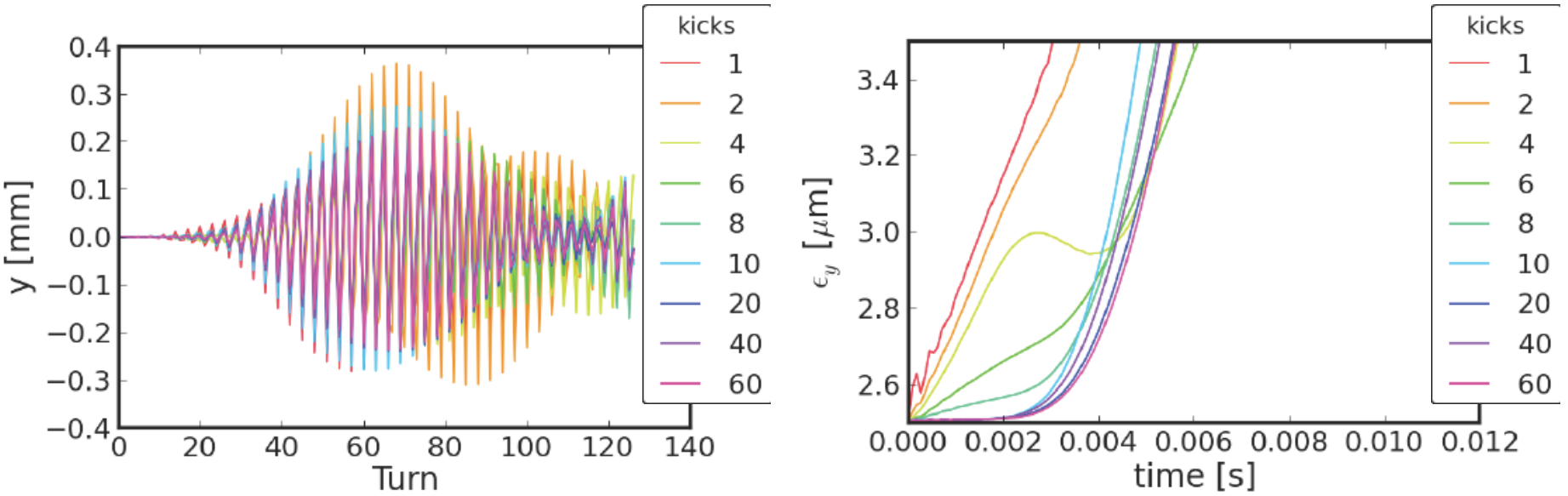
Dependence on numerical parameters

→ Electron cloud instability simulations are sensitive to a significant number of **numerical parameters**

- Time steps:
  - ✓ Number of slices chosen to represent the bunch
  - ✓ Number of electron kicks per turn
- Number of macro-particles
  - ✓ How many macro-electrons?
  - ✓ How many bunch macro-particles?
  - ✓ How many bunch macro-particles per bunch slice?
- Extension of the electron cloud transverse area, which is the grid to be meshed (usually a certain number of the beam transverse sigmas)
- Number of grid points for the Poisson mesh
- Type of Poisson solver (with or w/o boundary conditions on a rectangle)

→ CPU times for electron cloud instability simulations span from few hours to several days according to the settings

Importance of numerical parameters



→ Number of kicks per turn can be used

1. for 'lumping' in a certain number of locations the action of a continuous electron cloud, or
2. kicks represent real localized electron clouds in the accelerator

→ In case 1., if number of kicks per turn is too low, coherent motion may be turned into incoherent

Dependence on physical parameters

→ In principle both coherent instability and incoherent emittance growth could be predicted by these simulations

→ Evolution of a beam interacting with an electron cloud depends on a significant number of parameters in a non-trivial way

- Bunch length (longitudinal emittance)
- Beam transverse sizes (emittances and beta functions at the electron cloud location)
- Beam energy
- Beam current (number of particles per bunch)
- Chromaticity
- Magnetic field (field-free, dipole, quadrupole)
- Electron cloud density and distribution (in reality determined by many of the above parameters, but can be set independently in simulations)

See tomorrow talks by Elena, Kevin & Giuliano

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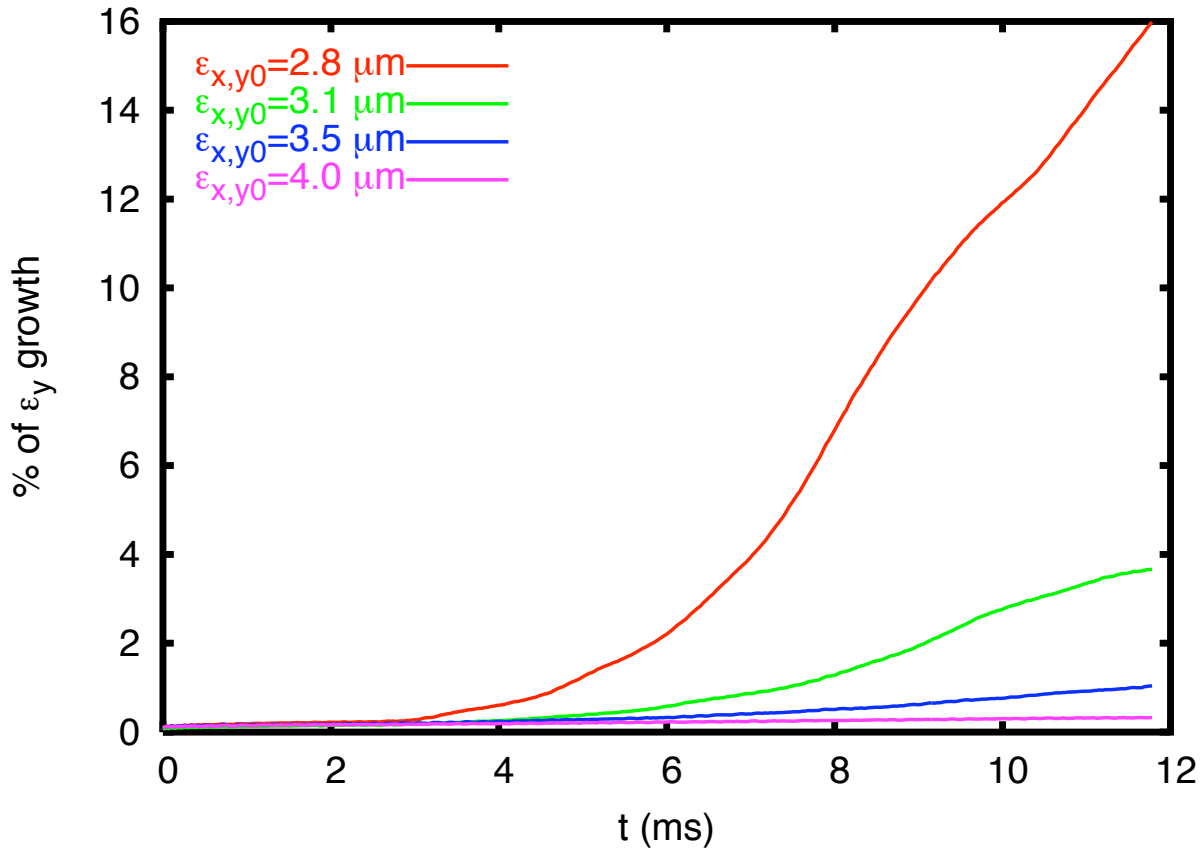
Effects on instability

⇒ **Effect of $\varepsilon_{x,y}$**

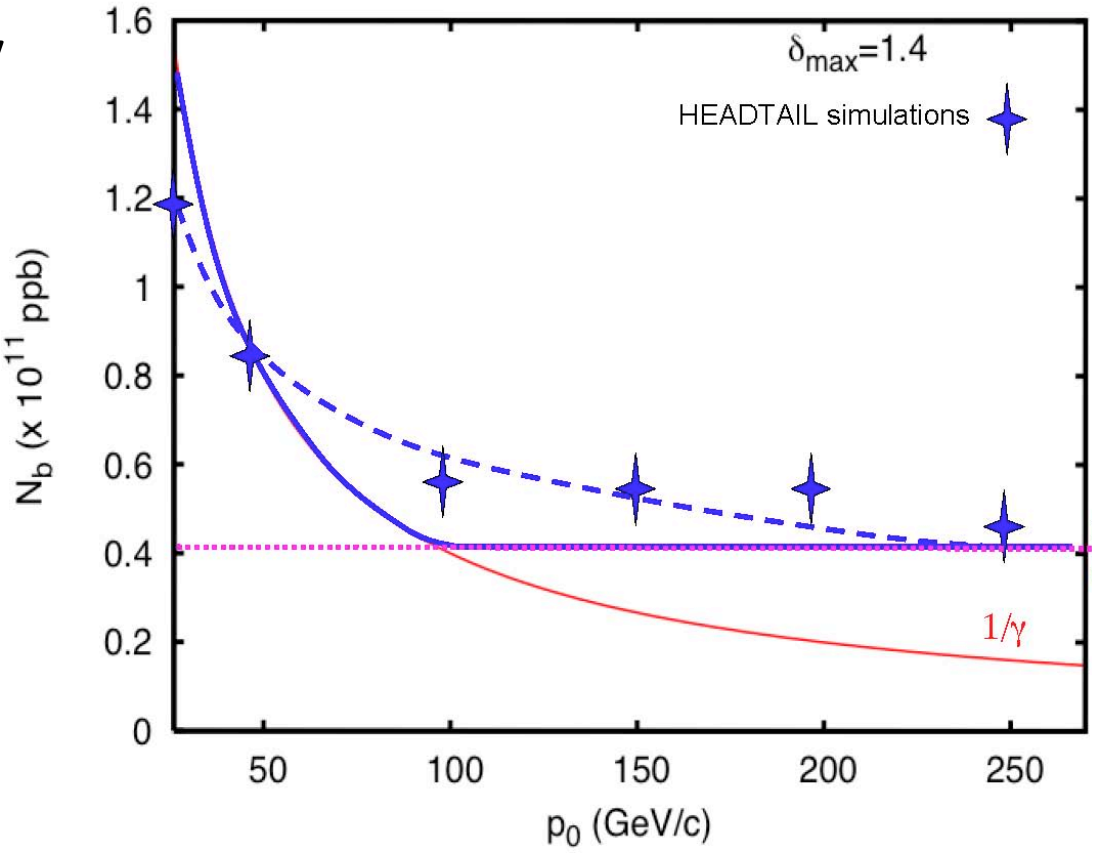


→ The pinch around small emittances is enhanced and makes the bunch more unstable

Effects on instability

⇒ Effect of $\varepsilon_{x,y}$

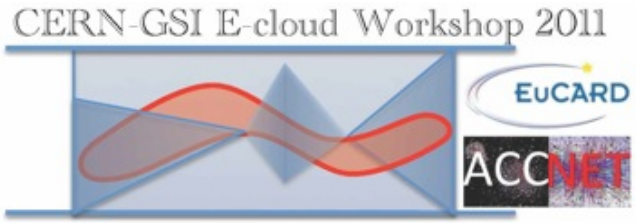
⇒ **Effect of beam energy**



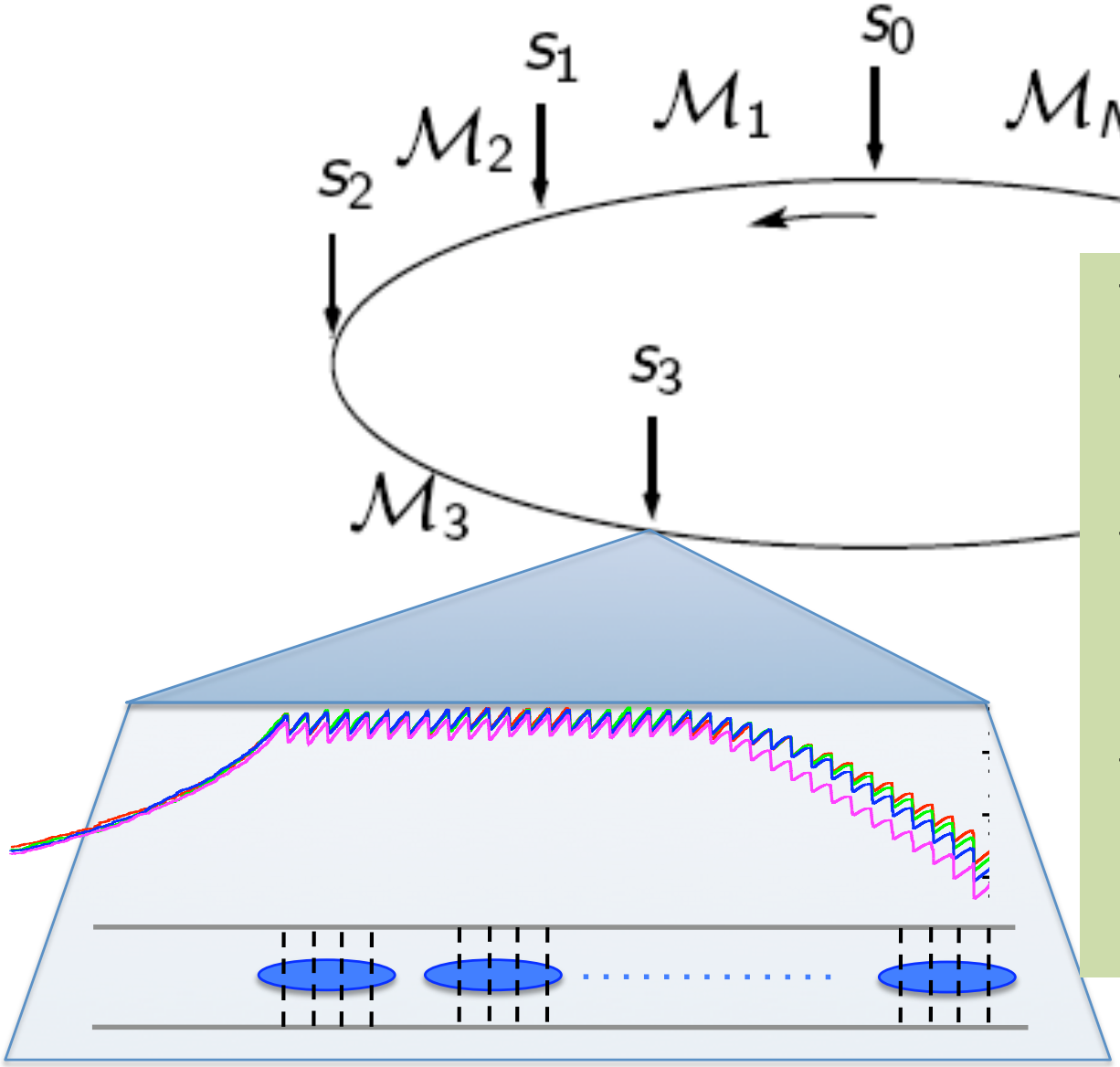
→ Instability threshold decreases with energy (keeping emittances + bunch length constant)

Conclusions & Outlook

- Electron cloud simulations are split into:
  - Build up simulations
  - Beam dynamics simulations
- CERN tools
  - ECLOUD & HEADTAIL
    - → Sensitive to several model and numerical parameters
    - → Unveiled non-trivial dependence on physical parameters
- Outlook: unify build up and instability simulations in one 3D self-consistent model ??



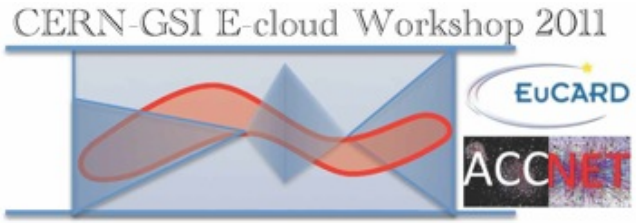
THE DREAM OF A 3D SELF-CONSISTENT DESCRIPTION…



- → Self-consistent build up electron cloud at each kick point
- → We need approximately the time of (n_{turn}*n_{kick}) ECLOUD simulations plus n_{bunch} HEADTAIL simulations
- → E. g.
  n_{kick}=1, n_{turn}=10^3
  n_{bunch}=10^3
  CPU time = 10^3 x (ECLOUD + HEADTAIL)
  CPU time ≈ 100d in the best case…
- → And memory requirements??
  Unmanageable if we want to keep turn-by-turn memory of the electrons at each kick point!!

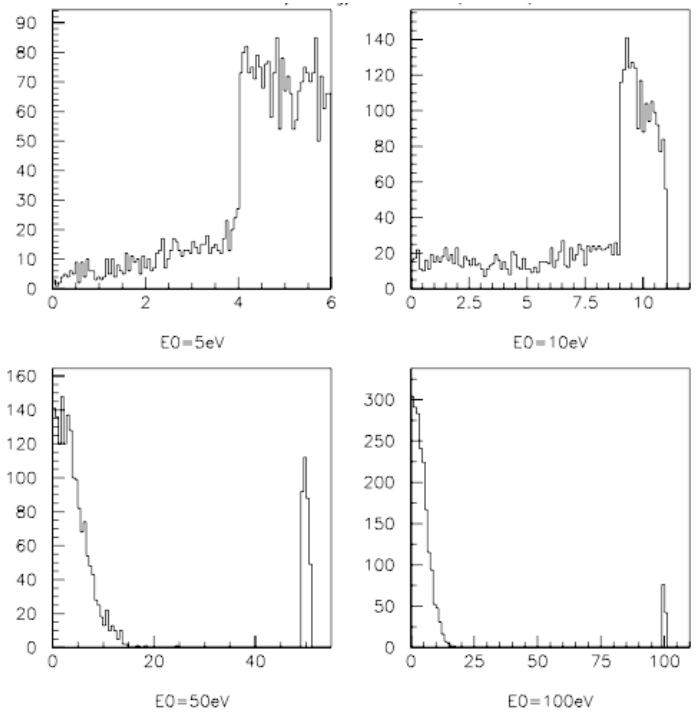
Conclusions & Outlook

- Electron cloud simulations are split into:
  - Build up simulations
  - Beam dynamics simulations
- CERN tools
  - ECLOUD & HEADTAIL
    - → Sensitive to several model and numerical parameters
    - → Unveiled non-trivial dependence on physical parameters
- Outlook: prove further & improve the reliability of our codes, develop & include more functionalities, grab the physics in our models



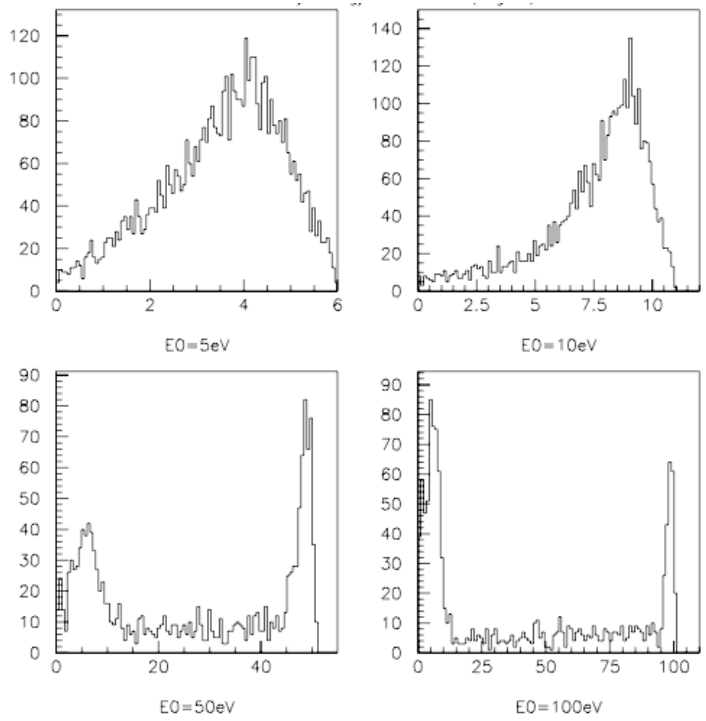
And re-diffused electrons are not included in the model…

⇒ In the present ECLOUD model, electrons are either reflected or cause secondary emission



No re-diffused (present model)

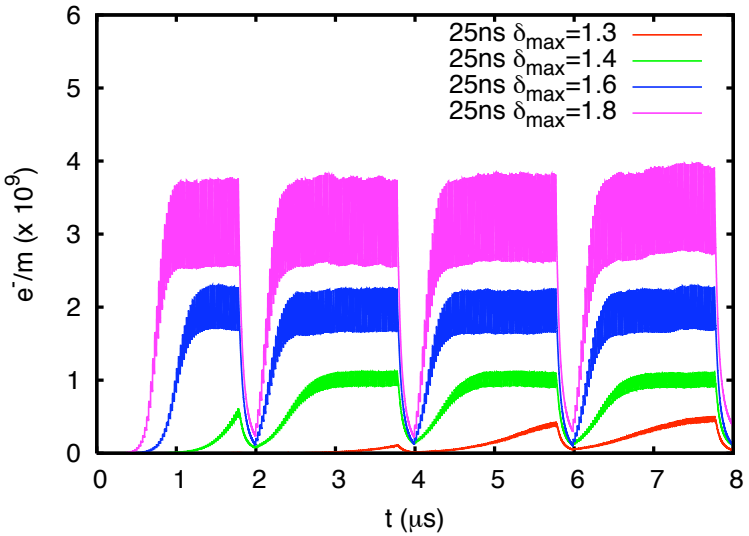
With re-diffused (G. Bellodi)

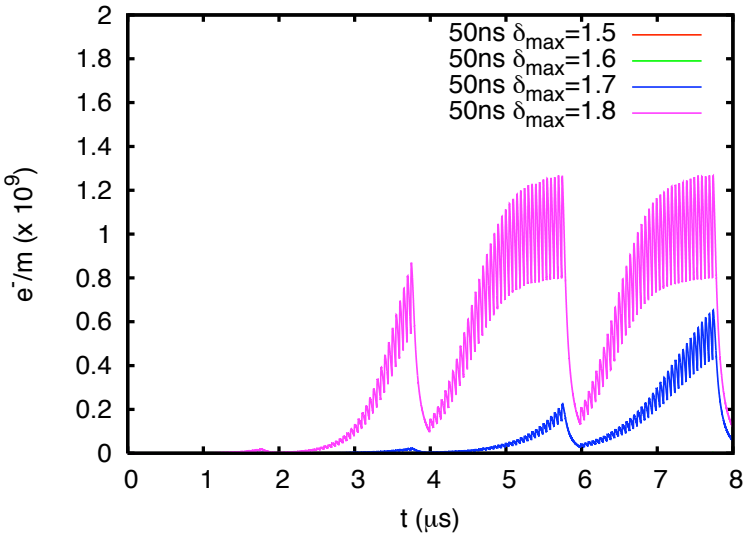


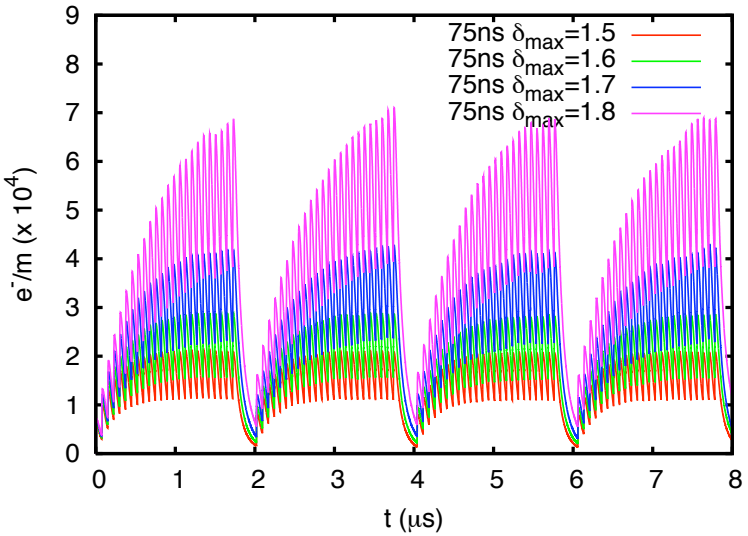
⇒ Re-diffused electrons enhance the build up

⇒ Can impact up to a factor 2 on heat load calculations (e.g. LHC, PS2)

Dependence on bunch spacing
Sample results







→ Example of electron cloud build in an SPS MKD kicker for different kinds of beam

- 25ns bunch spacing has electron cloud even for δ_{max}=1.3
- 50ns bunch spacing builds electron cloud for δ_{max}>1.6
- 75ns does not have electron cloud up to δ_{max}=1.8