# Electron Cloud Simulations with ECLOUD

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Main contributors to the code:
Frank Zimmermann
Oliver Brüning
Xiao Long Zhang
Giovanno Rumolo
Daniel Schulte
Giulia Bellodi

A little embarrassing:
I was invited to talk about the code
I am not the main author of the code but only introduced some changes last year

# ECLOUD

The code simulates the local build-up of the electron cloud

another code is used to simulate the instability (HEADTAIL)

one can simulate different bunch patterns

e.g. trains with gaps (SPS+LHC)

sources of electrons are

- ionisation
- synchrotron radiation
- secondary emission
- reflection

# History

- The code has grown over many years
- several people contributed
- it is written in FORTRAN

⇒ it will not win any beauty contest

⇒ it would need quite some resources to rebuild it from scratch

- code is small and not too slow
  - needs about $8$–$20\,\mathrm{MB}$
  - 72 bunches in dipole field $\approx 30\,\mathrm{min}$ on $1\,\mathrm{GHz}$-pentium-III PC

⇒ it was decided to continue

# Recent Code Improvements

Port on new system caused some trouble

- fixed, but still need special compiler flags

validation of different modules by looking at the code and results

- fixed quite a number of small to more significant problems

improvement of modelling, see later

improvement of speed

- quadrupoles: factor ≈8.5
- drifts and simplified dipoles: 5–10
- full dipoles: 10–200

⇒ allows more simulations

⇒ allows better simulation of ionisation effects

# Recent Modelling Improvement

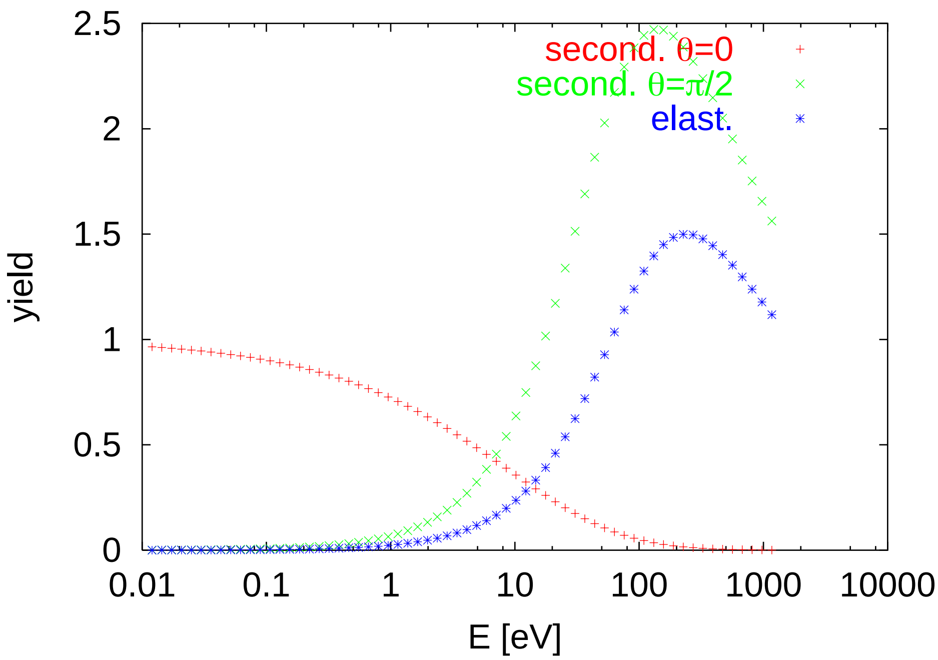
Main code parts

- secondary emission/reflection of electrons
- calculation of field
- tracking in fields
- detection of particles

the modelling has been improved in several places, e.g.

- reflection at the chamber wall
- completed rectangular chamber
- more flexible boundary condition solver
- more realistic detectors

# Reflection Model




Mixture of results from R. Cimino, I. Collins, N. Hilleret, R. Kirky and M. Furman

significant source of uncertainty

agreed on one model as default for now

but needs to be verified

$\Rightarrow$ try to find experiments to contrain

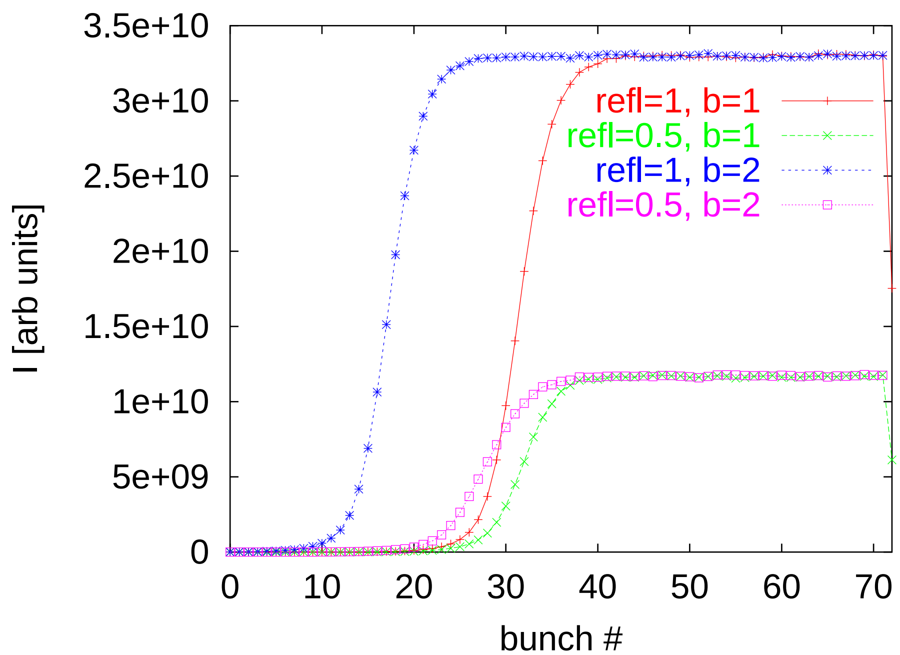
# Electron Survival

Rise to saturated electron cloud is faster in the second batch

$\Rightarrow$ low energy electrons survive between batches

$\Rightarrow$ seed electrons for next electron cloud build-up

consistent with observations in SPS

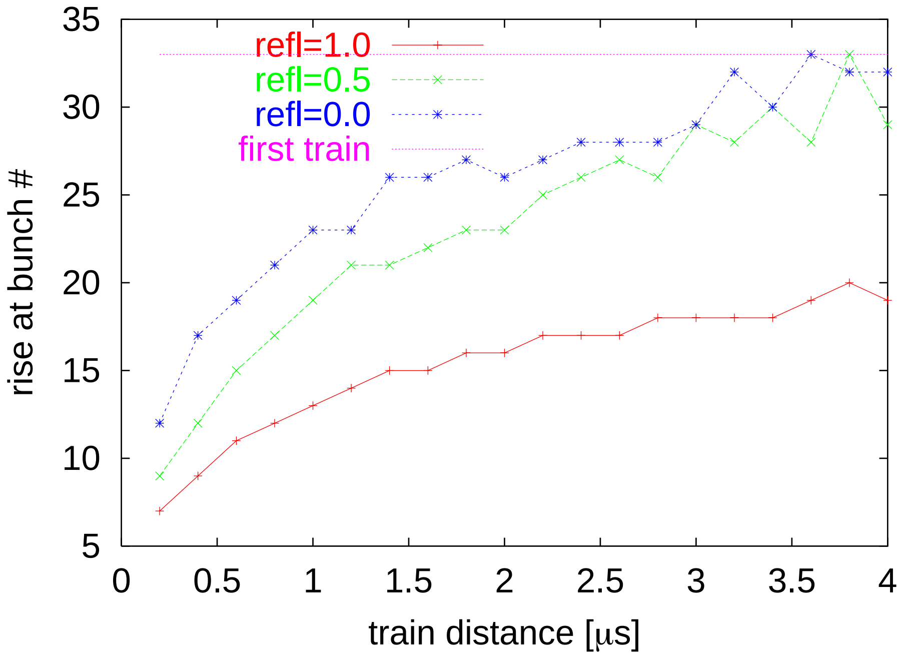



SPS measurement consistent with $50\%$ or $100\%$

dedicated experiment to measure decay can contrain reflection

# Confirming Reflection

For reflection below 100% electron survival time should be shorter




⇒ measuring the survival time can be used to bench-mark low energy reflection

# Beam and Space Charge Fields

Different boundary conditions

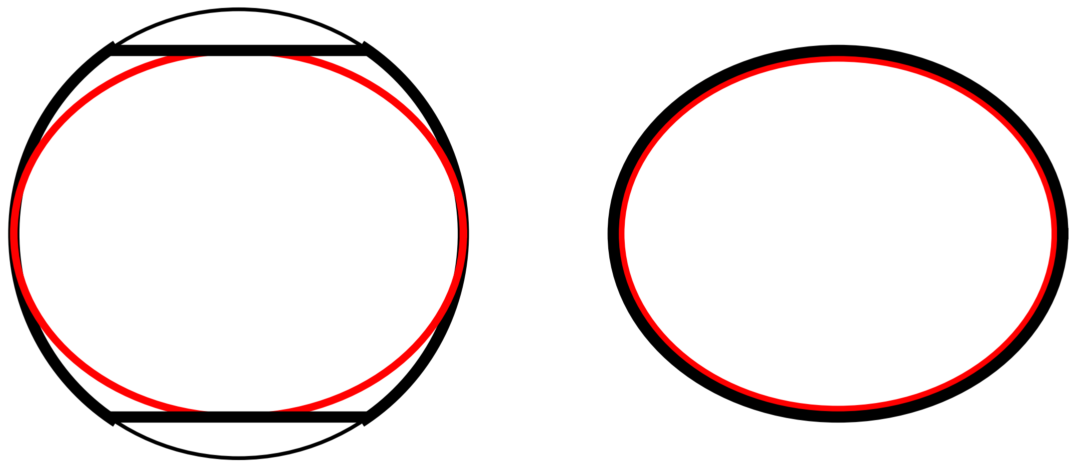
- round beam pipe
- elliptical beam pipe
- rectangular beam pipe
- LHC-shaped beam pipe, but uses elliptical boundary conditions for field
- being added: new realistic beam pipe

$\Rightarrow$ benchmarking one boundary condition does not necessarily ensure that others are OK

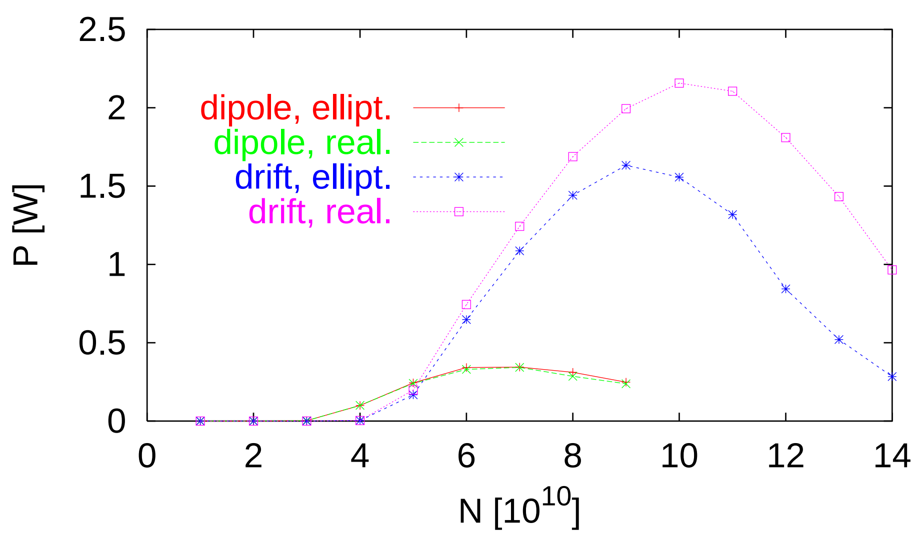
space charge solvers are a bit primitive

but normally they do not limit speed

# LHC Beam Pipe Effect



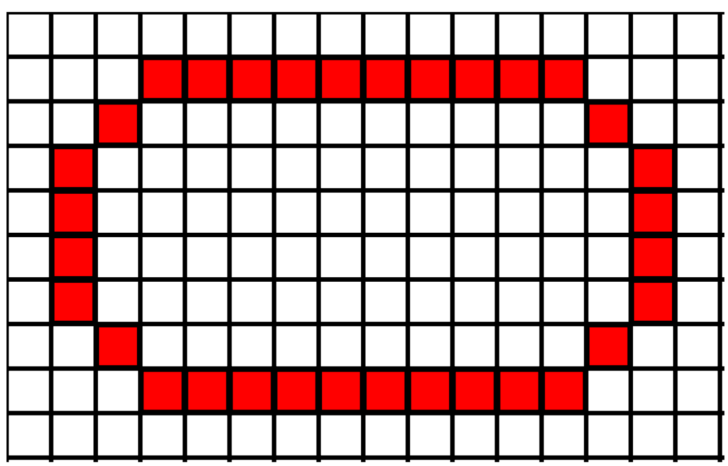
- Use real boundaries for reflection, ellipse for field
- use ellipse for reflection and field
- use real boundaries for reflection and field (new)




one batch used

# General Space Charge Solver

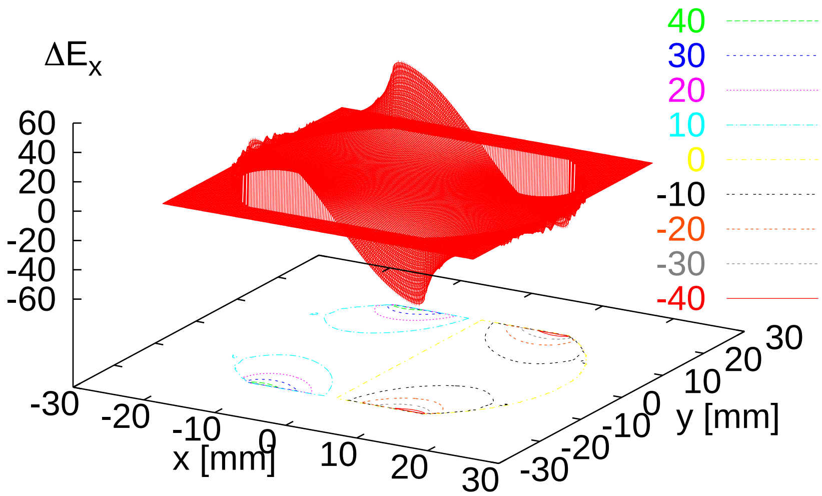
- Caculate free space solution (FFT based on FFTW)
- solve linear system to calculate charges in boundary cells that zero potential in these cells
- add charges in these cells and recalculate free space solution
- or calculate correction only (beam field) using free space solution



done outside ecloud

loaded at run time

$\Rightarrow$ for now all bunches must have same position


ΔEx
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x [mm]
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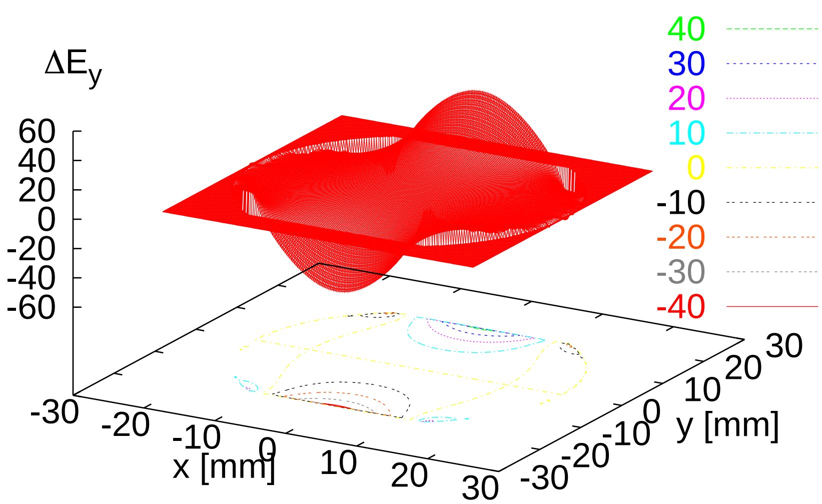
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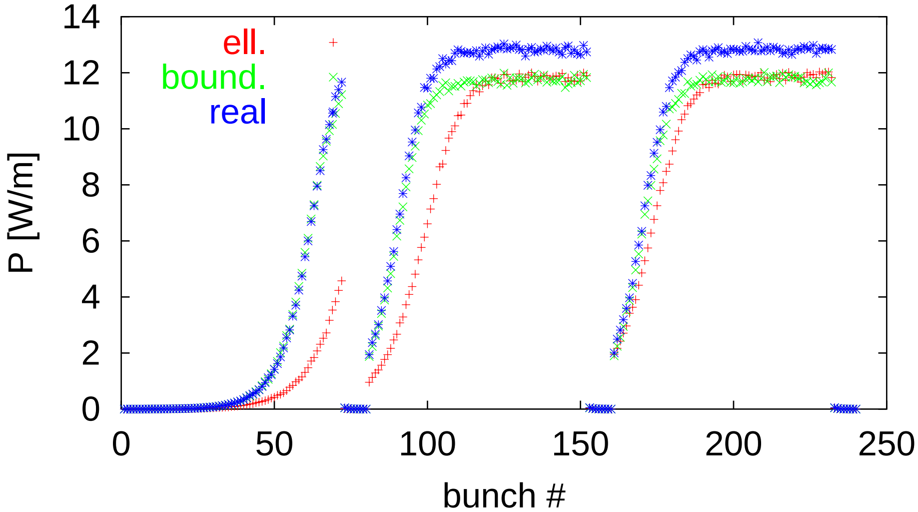
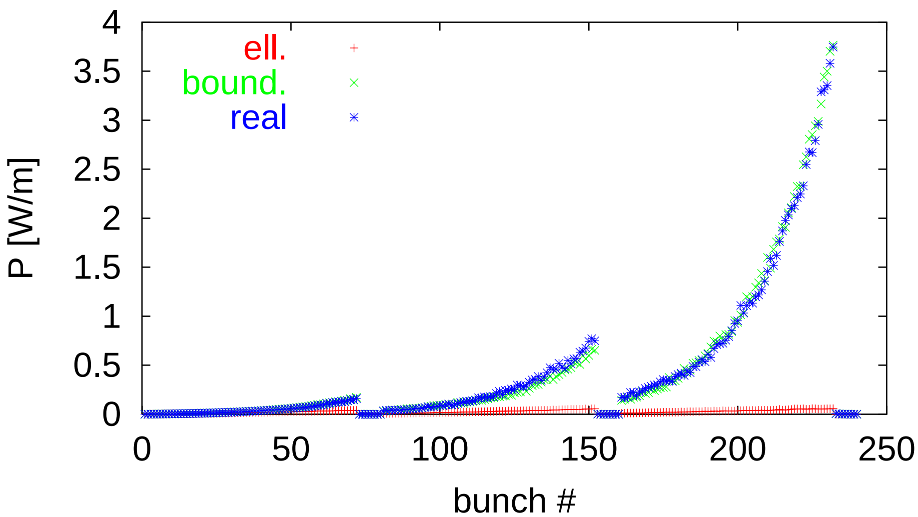
# Results




LHC top energy, no field, ionisation only

$\Rightarrow$ saturation level quite close

$\Rightarrow$ rise time very different

elliptical approximation is in saturation

# Tracking

Four different possibilities

- drifts

  are trivial

- high field dipoles

  movements follow field lines

- low field dipoles

  analytic helix, ignoring relativity
  (before PDE-solver, much slower)

- complex field

  integration of partial differential equation

  fastest method found: Bulirsch-Stoer

  now new fast tracker will become available

⇒ benchmarking of one method does not ensure correctness of all of them

# New Tracker

Simulation of quadrupoles is extremely slow

$\Rightarrow$ all the time spent in integration of equation of motion

new tracker based on same idea as Romberg integration and Bulirsch-Stoer PDE

- modified midpoint method for stepping
- Richardsons deferred approach to the limit

approximate local trajectory as helix

- each step is more costly
- but often needs fewer steps

can in principle accept any field

$\Rightarrow$ could be improved by limitation to quadrupole field

benchmarking

in quadrupole field about 8.5 times faster than original integration

# Effect of Detector

Considering strip detector

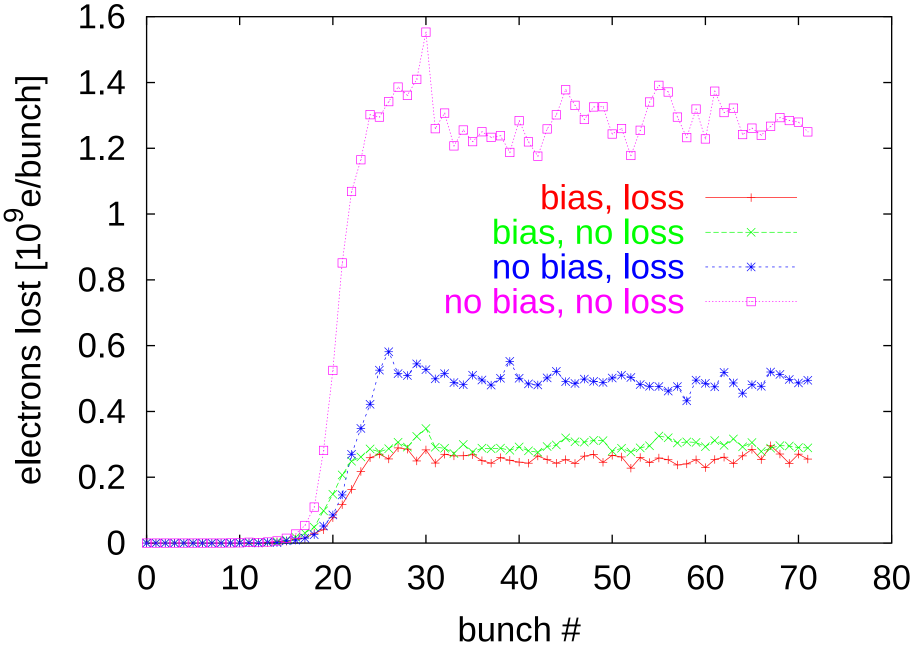
several small holes drilled into beam pipe

bias voltage to repell low energy electrons

modelling of detector:

- include bias voltage
  cut in vertical momentum not in energy
- effect of extraction of measured particles

# Example




Secondary emission yield 2.0

assumed only detected electrons are lost

⇒ significant without bias voltage

⇒ small effect with bias voltage

- but can we loose electrons without detecting them?

⇒ more work needed

# Flux Measurements

Comparison of flux for different bunch spacings should work

different fields can be problematic, because scrubbing is local

cold detector, simulation assumes: $\delta = 2.2$, $\epsilon = 280\,\mathrm{eV}$ elliptical beam chamber (thanks to M. Jinenez for data [$10^{-4}\mathrm{A/m}$]

| | measured | simulated |
|---|---|---|
| field free | $18.0$ | 20 |
| dipole field | $36$ | 130 |

warm detector, simulation assumes: $\delta = 1.5$, $\epsilon = 240\,\mathrm{eV}$

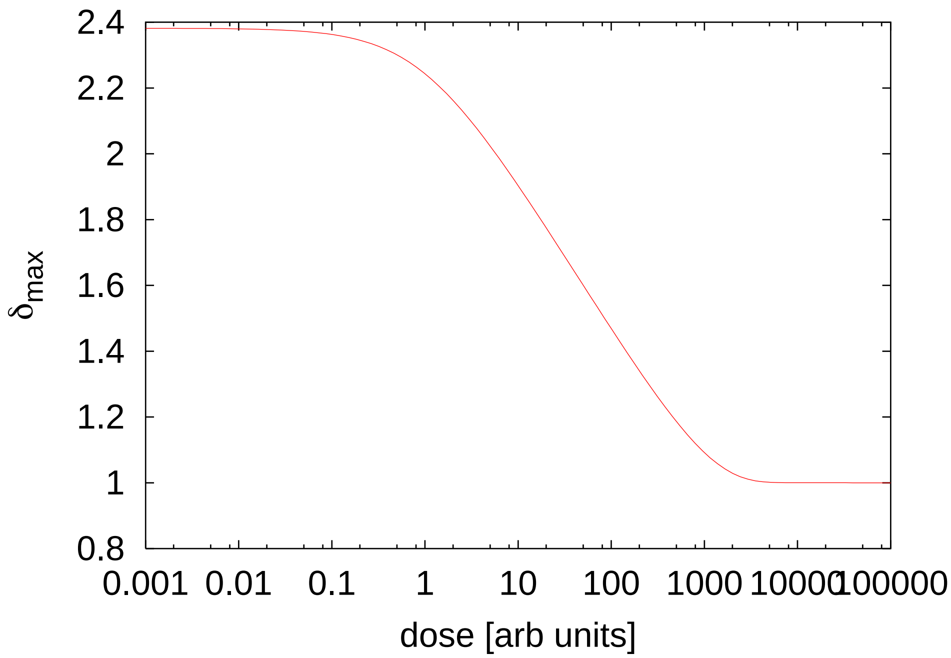
| | measured | simulated |
|---|---|---|
| field free | $2.0$ | $\leq 1$ |
| dipole field | $22$ | 62 |

$\Rightarrow$ agreement could be better

with field $75\,\mathrm{ns}$ spacing yields 20 times less flux in cold experiment

$\Rightarrow$ same in simulation

# Evolution of Scrubbing



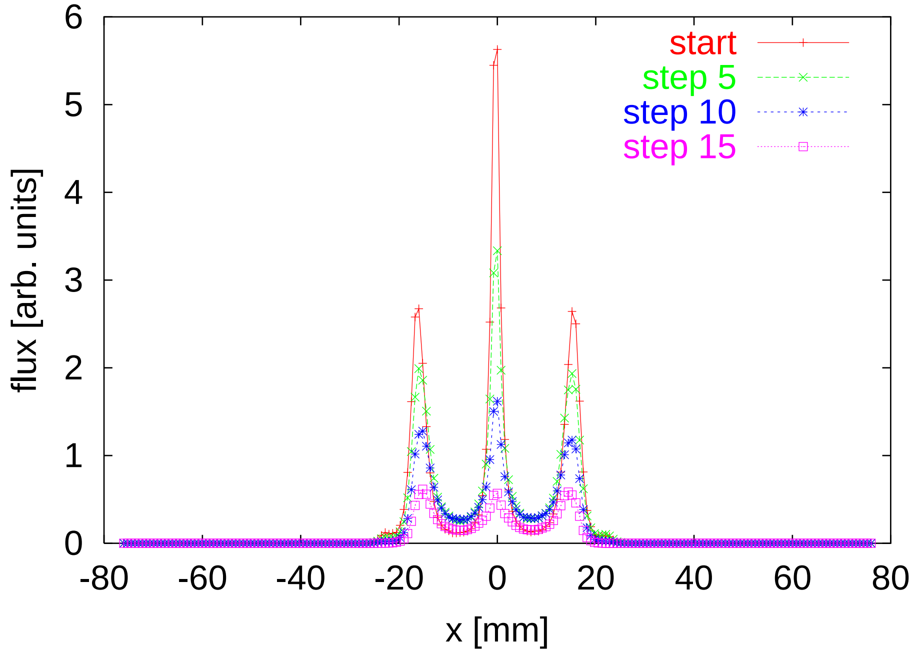

New routines allow local definition of secondary emission (yield and energy of maximum)

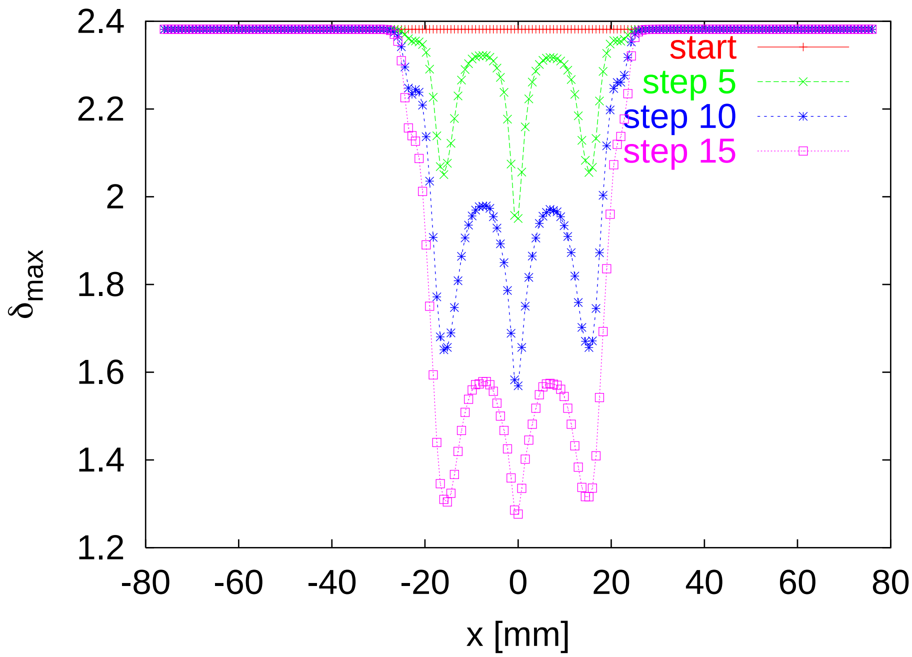
the dose can be recorded

$\Rightarrow$ with a simple script one can simulate evolution of scrubbing

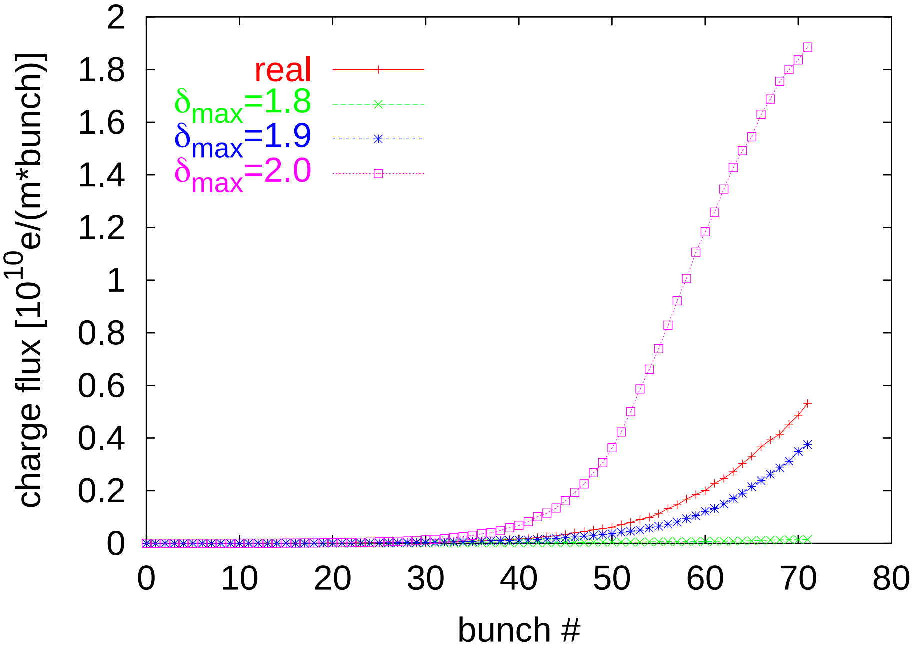
- run simulation
- calculate new yields (step size control to ensure $\Delta\delta_{max} \leq 0.1$)
- iterate

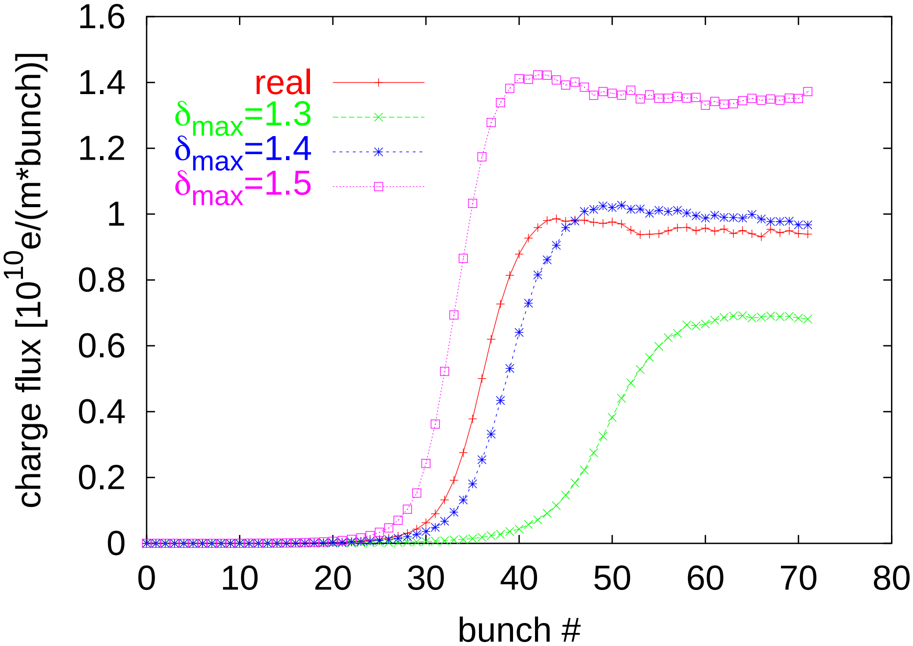
# Yield Evolution



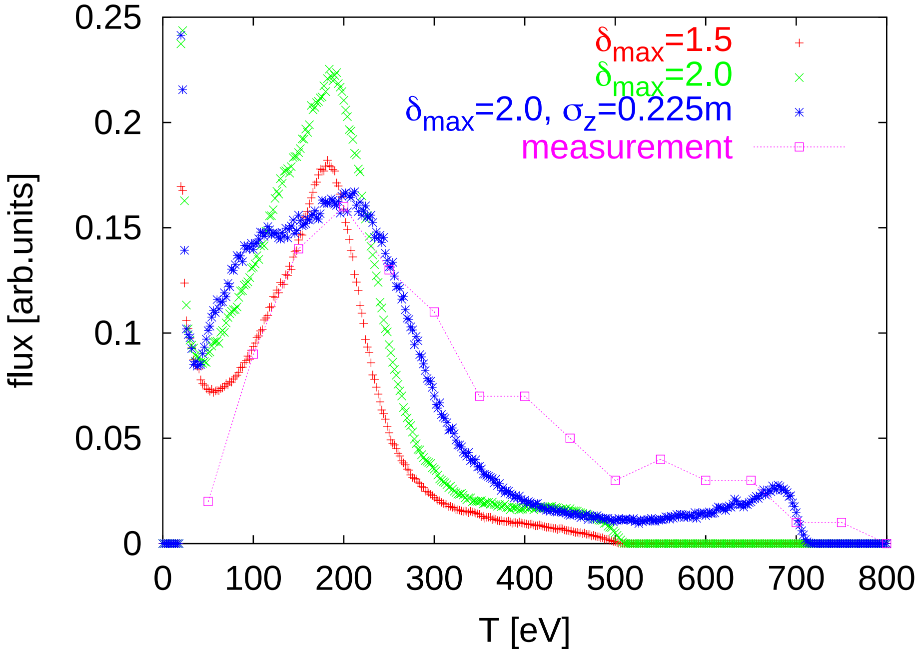



# Effective Secondary Emission Yield



# Energy Spectrum




Thanks to M. Jimenez

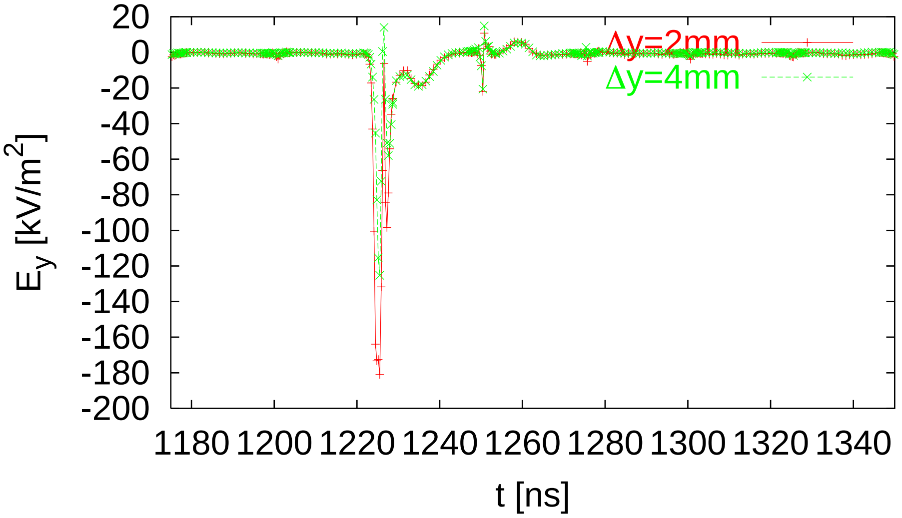
detector bias voltage is taken into account

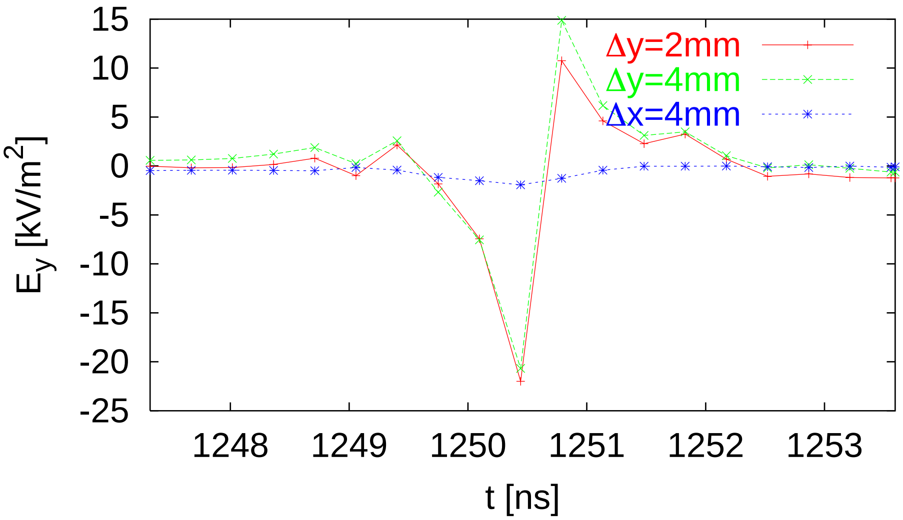
agreement not perfect

but peak is in good location

more detailed simulation of detector may resolve remianing differences

# Wakefield of Electron Cloud



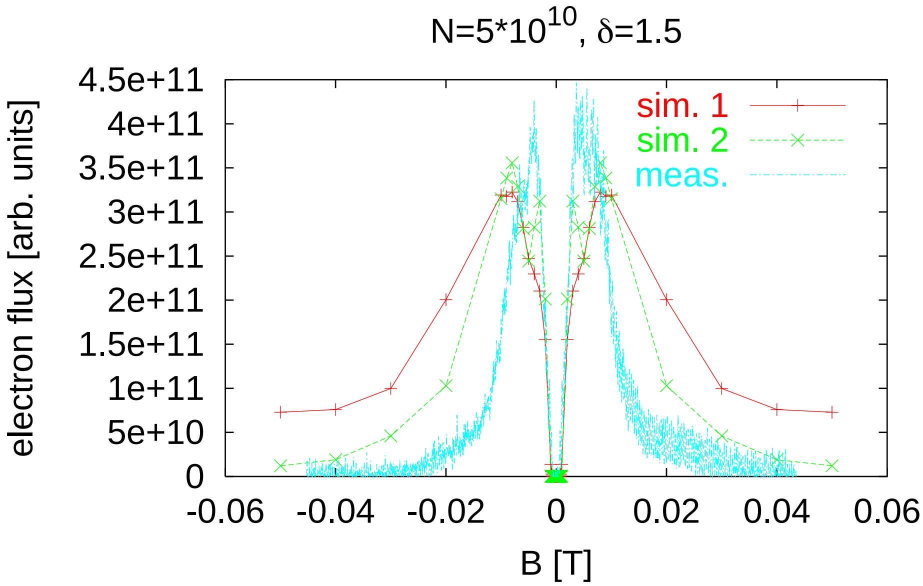



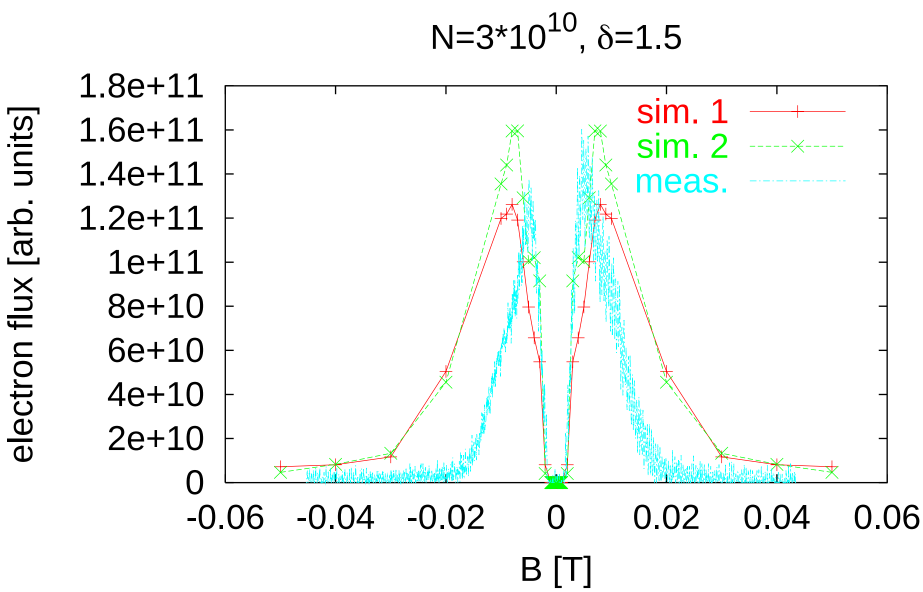

Very noisy

$\Rightarrow$ need many runs

change of sign during bunch passage

# Dependence on the Magnetic Field



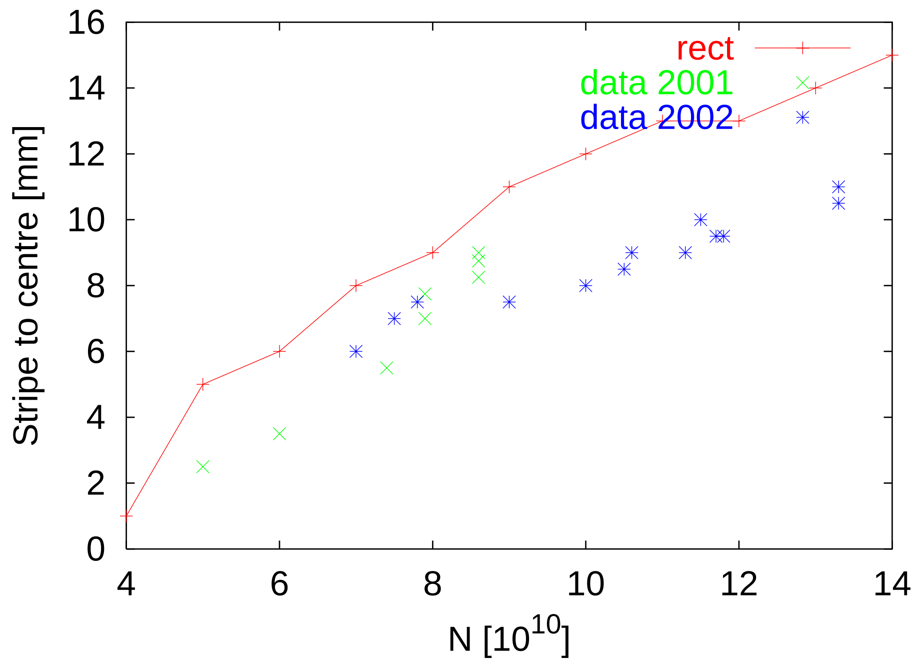

Measurement without bias voltage (2001)

$\Rightarrow$ qualitative agreement for small fields is good

$\Rightarrow$ but relative scaling factor changes with intensity

$\Rightarrow$ less suppression at high fields

# Stripe Position vs. Intensity



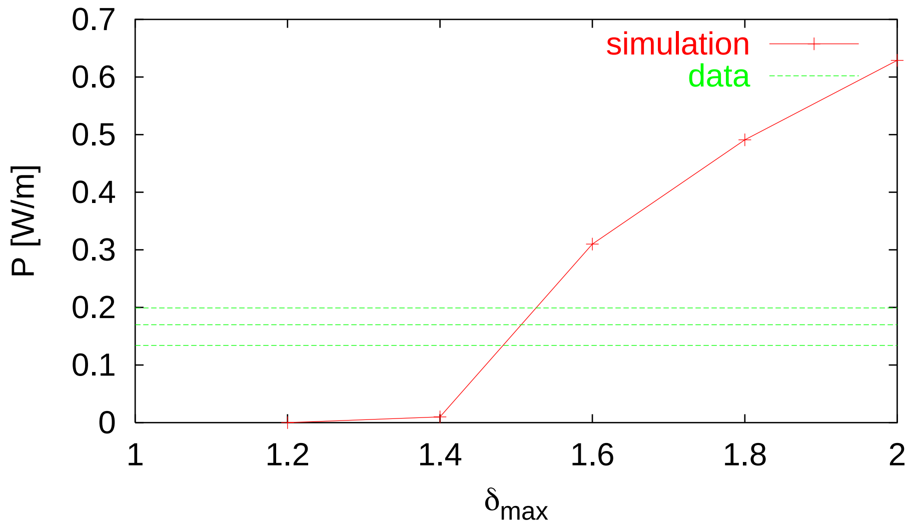

Has successfully been compared before

but significant changes performed

⇒ new comparison

the agreement is not too bad

# Heat Load in WAMPAC 1




Round chamber

nominal beam parameters ($25\,\mathrm{ns}$)

⇒ agreement is good for expected value $\delta_{max} \approx 1.5$

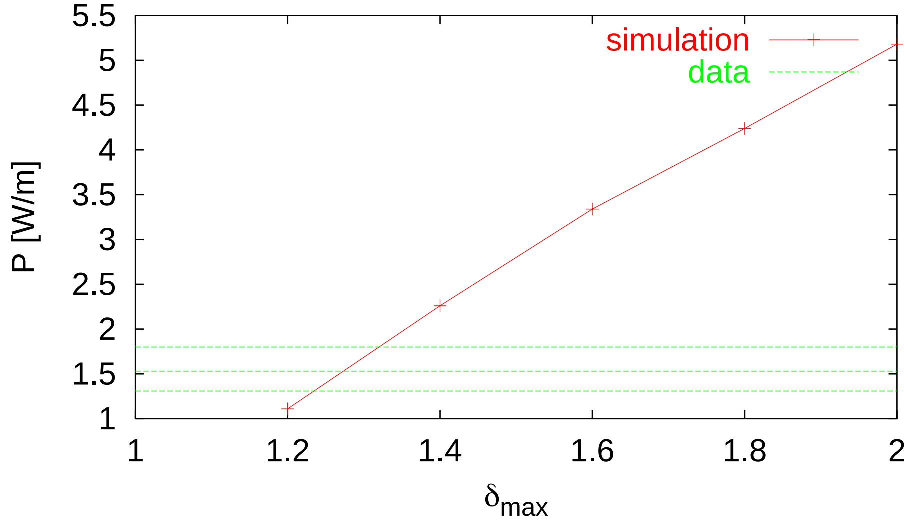
$75\,\mathrm{ns}$ spacing: no heatload predicted nor measured

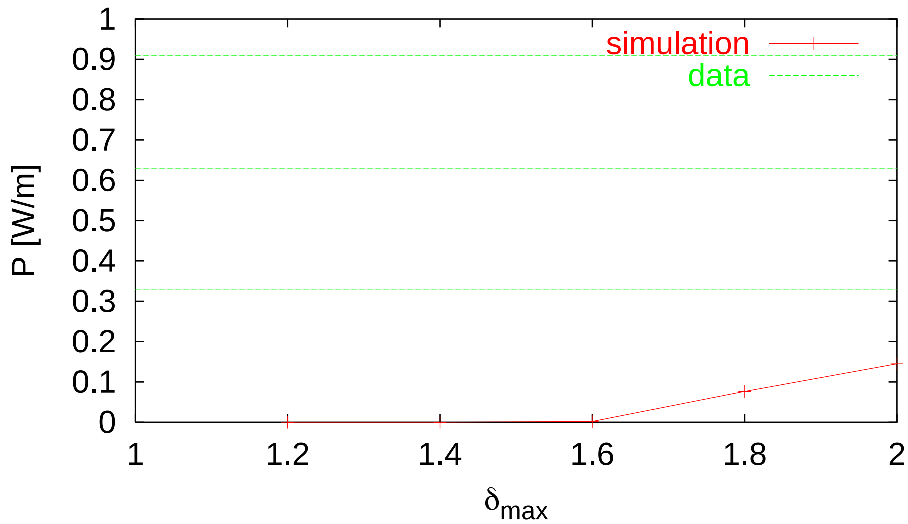
⇒ agreement is good

agreement for WAMPAC3 seems not as good, prediction is too high

⇒ see V. Baglin (and thanks to F. Zimmermann)

# WAMPAC 3



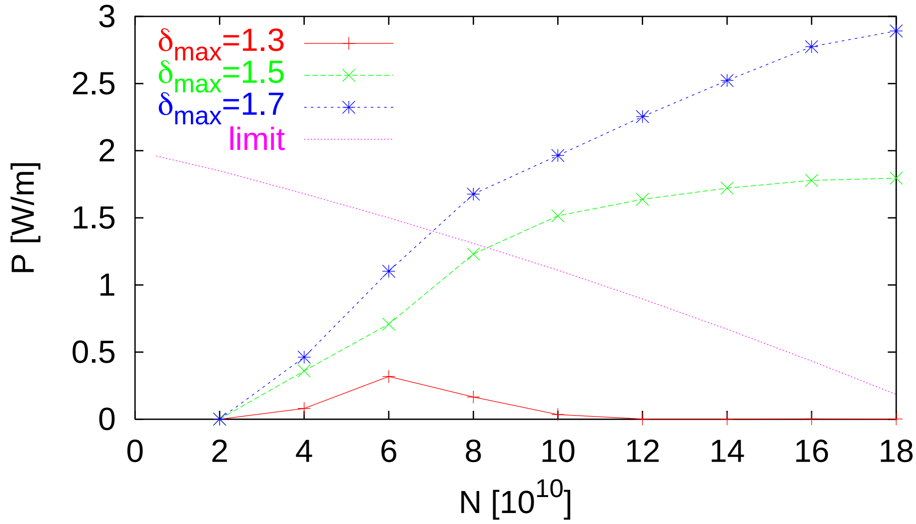

$\Rightarrow$ $25\,\mathrm{ns}$ agree for $\delta_{max} \approx 1.3$

$\Rightarrow$ but inconsistent for $75\,\mathrm{ns}$ (additional heat source)

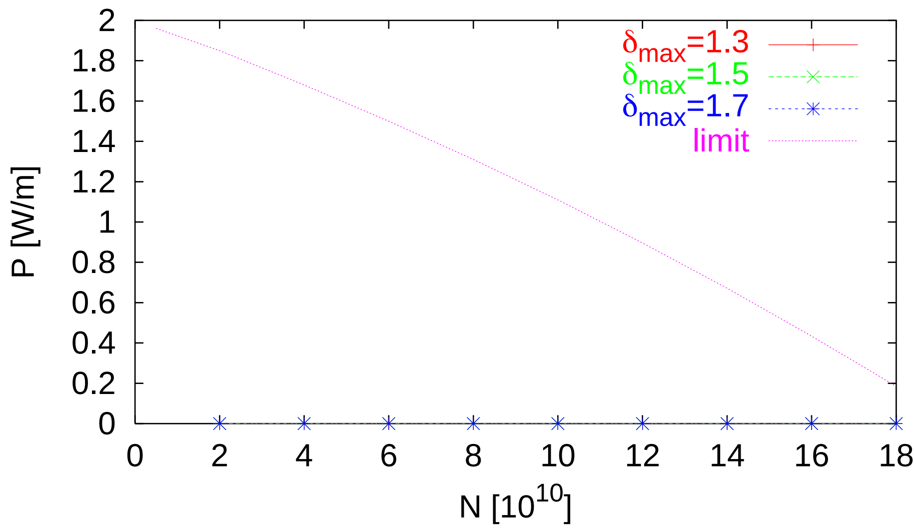
$\Rightarrow$ additional heat source and $\delta_{max} \approx 1.2$ could explain results, but may have other reasons

thanks to F. Zimmermann

# Heat Load in LHC at Injection (thanks to F. Zimmermann)



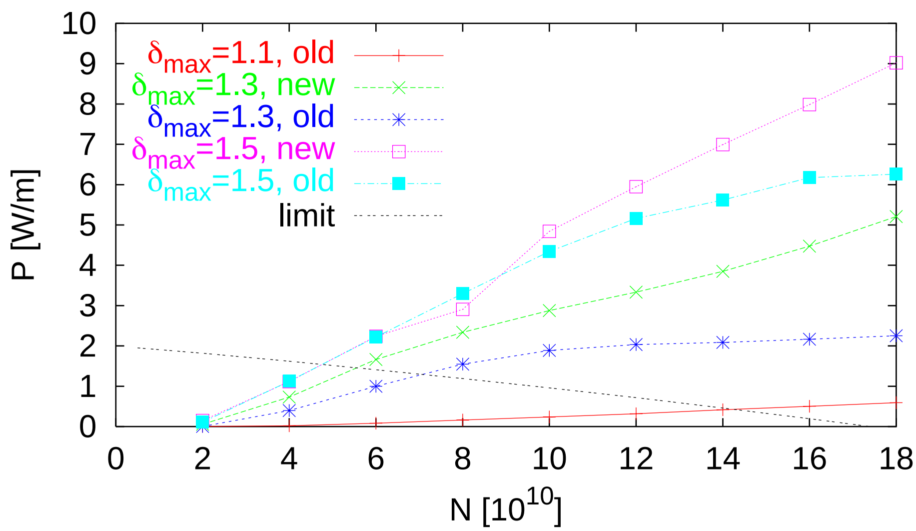

Four trains simulated at $\delta_{max} = 1.3$, two for other cases ($25\,\mathrm{ns}$)




for $75\,\mathrm{ns}$ much lower load

compared to limit for heat load from L. Tavian

# Heat Load at Top Energy

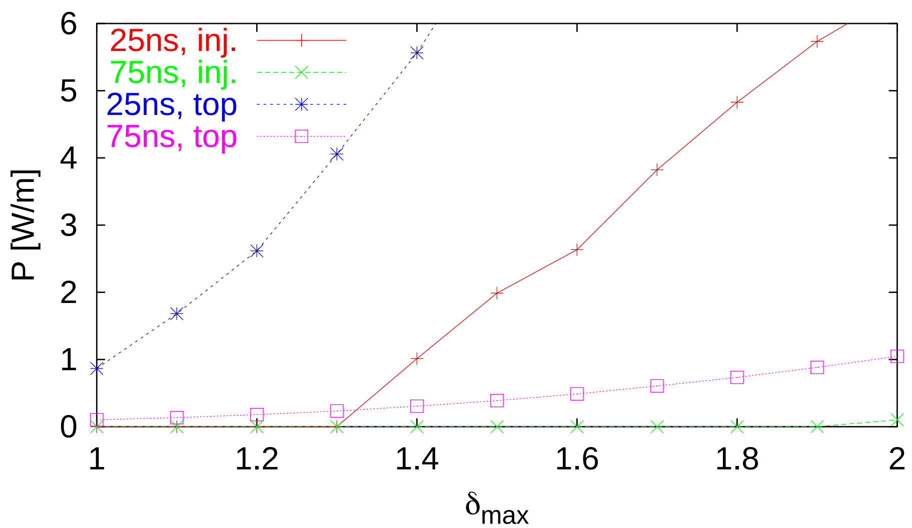



One train simulated (but small difference)

⇒ results seem worse than before

⇒ need low $\delta_{max}$

⇒ verification required



# Conclusion

The `ecloud` code has been significantly developed in the past year

- modelling has improved
- bugs have been removed
- program become faster

benchmarking is progressing

- agreement improved
- but more work to be done

more experiments should be performed in the SPS and elsewhere

# Thanks to

F. Zimmermann, G. Arduini, V. Baglin, B. Jenninger, J. M. Jimenez, J.-M. Laurent, A. Rossi, F. Ruggiero