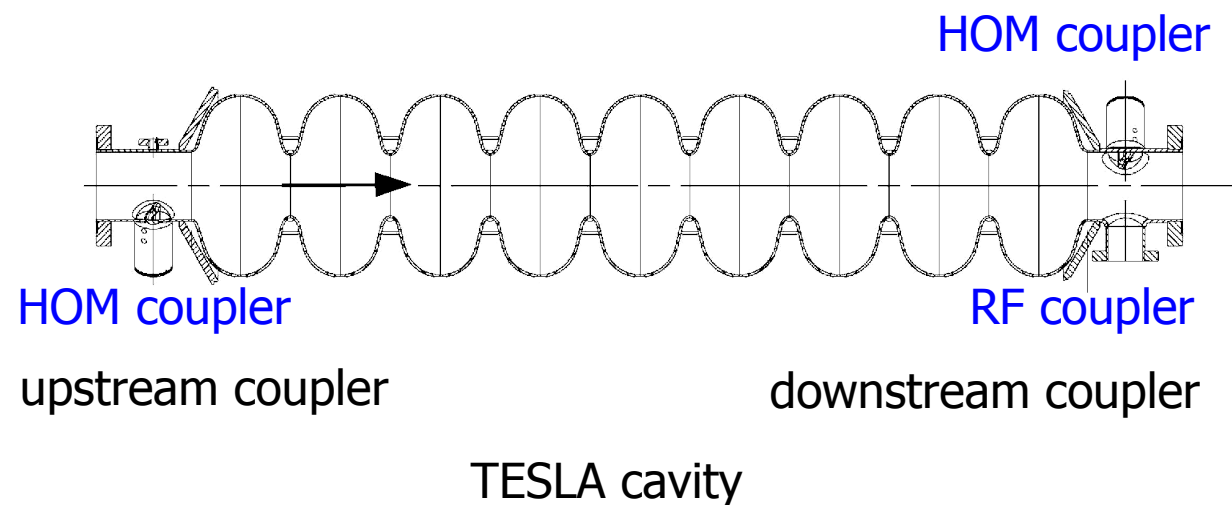# Simulations of the Main Linac with Coupler Kicks
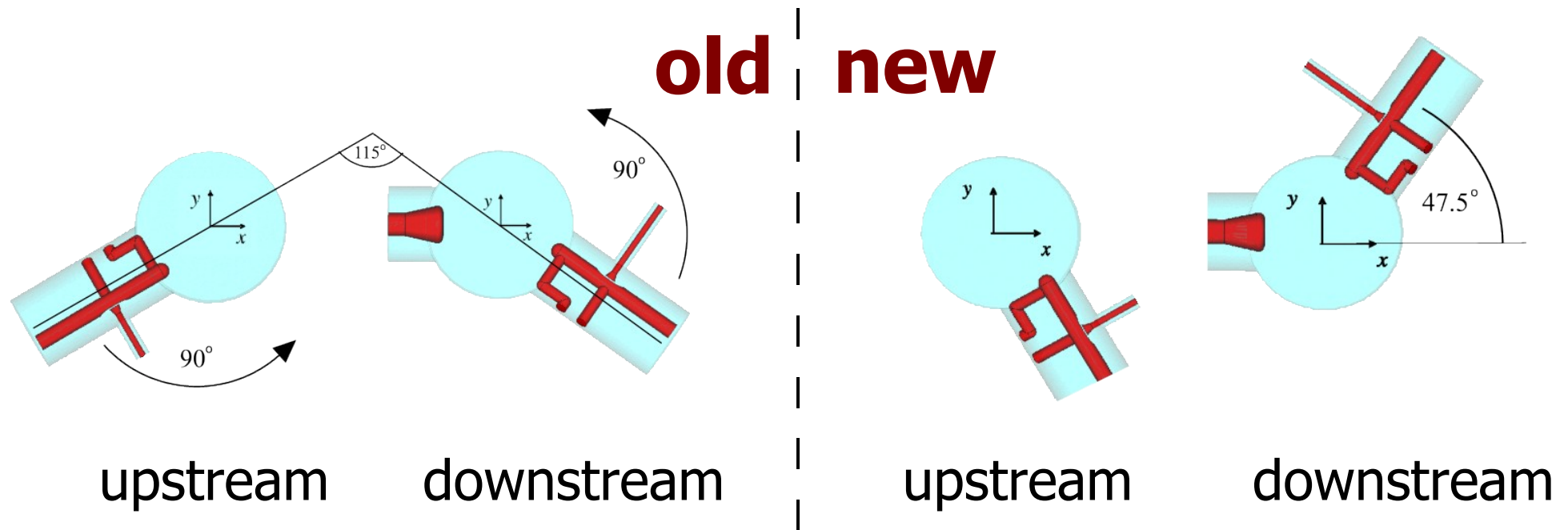
Dirk Krücker  - DESY
LCWS 08, Chicago, November 18, 2008

# Reminder on Cavity Couplers

- There are 3 couplers
    - 1 RF or power coupler
    - 2 HOM couplers
- Couplers destroy the rotational symmetry and introduce transverse field components
    - RF fields
    - Wakefields

HOM coupler

HOM coupler

RF coupler

upstream coupler

downstream coupler

TESLA cavity

# Reminder on Cavity Couplers



**old** | **new**

upstream      downstream      upstream      downstream

- A design change had been considered* to reduce the potentially strong transverse coupler wakefields

  – Rotate HOM couplers relative to RF coupler by 90° to minimise the sum of transverse wakefields

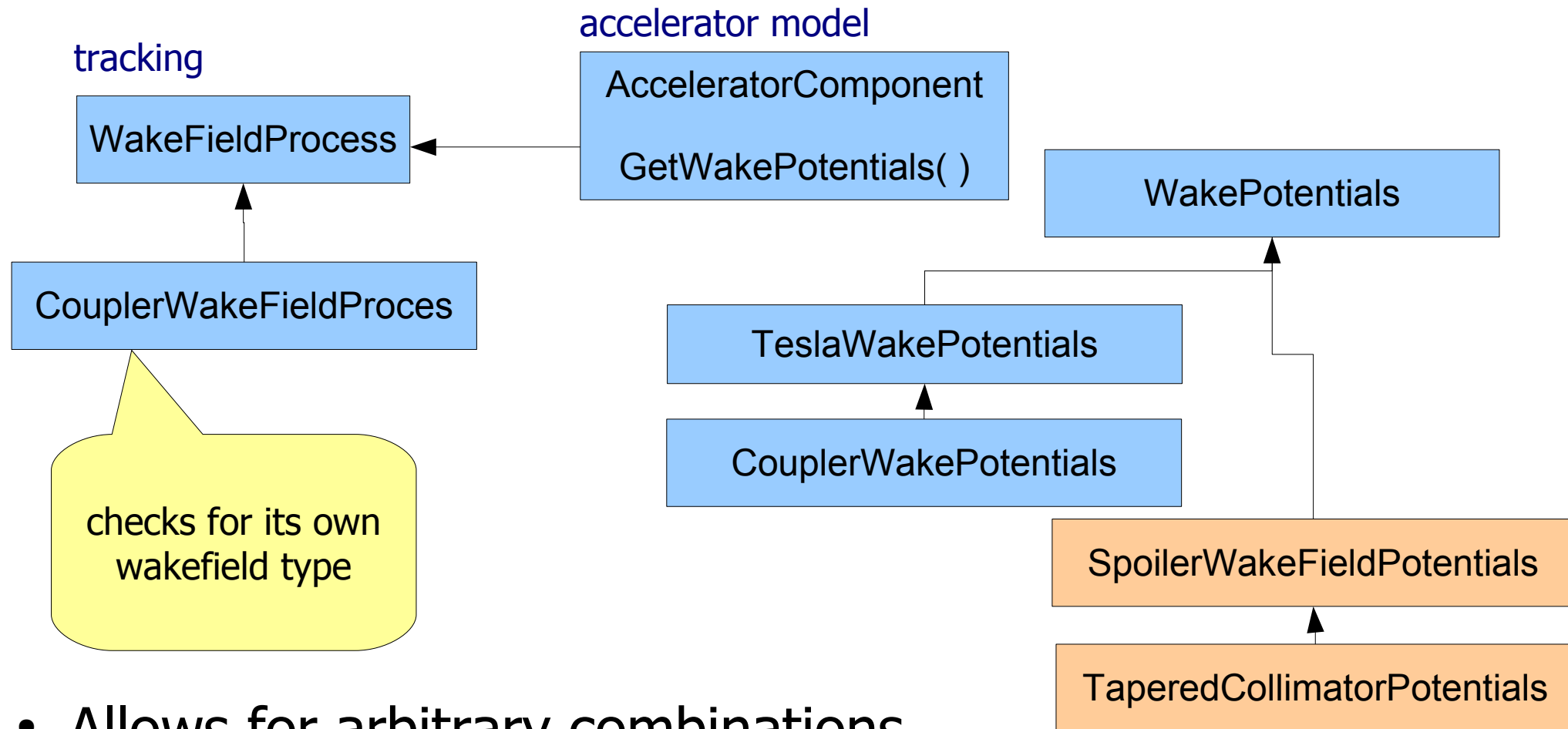- Alternatively just rotate one of the coupler by 180°

# Merlin

- A C++ class library for performing charged particle accelerator simulations
  `http://www.desy.de/~merlin`

- The physics considered for tracking can be extended by adding *processes*

  - Merlin knows about cavity wakefields

  - extended recently to include other types wakefield processes e.g. collimator or coupler wakes and RF kicks

- The accelerator consists of a list of accelerator components

  - with geometry, magnetic fields and wakefields

  + coupler wakefields + RF kicks

# `WakeFielProcess` and `WakePotential` in MERLIN

**accelerator model**

**tracking**

WakeFieldProcess

AcceleratorComponent

GetWakePotentials( )

WakePotentials

CouplerWakeFieldProces

TeslaWakePotentials

CouplerWakePotentials

checks for its own wakefield type

SpoilerWakeFieldPotentials

TaperedCollimatorPotentials

- Allows for arbitrary combinations
  e.g. cavity wakefield + coupler wakefield + RF kick

- Results of EM field calculations can be plugged in

# History of Merlin Simulations

Different Merlin implementations according to the changing numerical input

- My talk at SLAC, Wakefest 07 based on
    - I. Zagorodnov and M. Dohlus, LCWS/ILC Hamburg 2007, paper (sign errors in RF kicks!)
        - Reduced wakefield and (wrong!) RF kicks in new design
- Our paper at Genoa, EPAC08, TUPP047 (corrected) = EUROTeV-Report-2008-003
        - The RF kick is larger in the new design
- This meeting: steady state solution for coupler wakefields about 1/10!

# Coupler RF kick – MERLIN Implementation

- RF kick is given as a complex ratio wrt the accelerating voltage

$$\mathbf{v} = (v_x, v_y) := 10^6 \cdot \mathbf{V}/V_{\parallel} \qquad\qquad x, y\,[\mathrm{cm}]$$

$$\mathbf{v}_{old}(x, y) = \begin{bmatrix} -82+58\mathrm{i} \\ -9.2+1.8\mathrm{i} \end{bmatrix} + \begin{bmatrix} -29-27\mathrm{i} & 63+5.1\mathrm{i} \\ 63+7.0\mathrm{i} & 28+24\mathrm{i} \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}$$

- The kick is given by for example

$$\mathbf{v}_{new}(x, y) = \begin{bmatrix} -82+58\mathrm{i} \\ -74-8.7\mathrm{i} \end{bmatrix} + \begin{bmatrix} -29-27\mathrm{i} & 63+5.1\mathrm{i} \\ 4.9+2.9\mathrm{i} & -48-12\mathrm{i} \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}$$

MAFIA calculation by M.Dohlus

$$\Delta y' = \frac{\Delta E}{E}|v_y|\,\Re\left\{\mathrm{e}^{i(\phi_c - \varphi - k\Delta z)}\right\}, \qquad v_y = |v_y|\mathrm{e}^{i\phi_c}$$

$\Delta z = -\Delta ct$, longitudinal position for a particle at $\varphi$

$\varphi = 5.3^o$ RF phase, $k = 2\pi f/c$, $L = 1.036$ m

$\Delta E = 31.5$ GeV/m·L, $E = 15 \cdots 250$ GeV

# Coupler RF kick - Approximation for New Design

- There is no MAFIA field calculation for the modified design. Approximated in MERLIN by $v_y \rightarrow -v_y$ (downstream coupler)

- In this case the angle between HOM coupler and x-axis is only 42.5° instead of 47.5°.



HOM couplers are rotated relative to power coupler
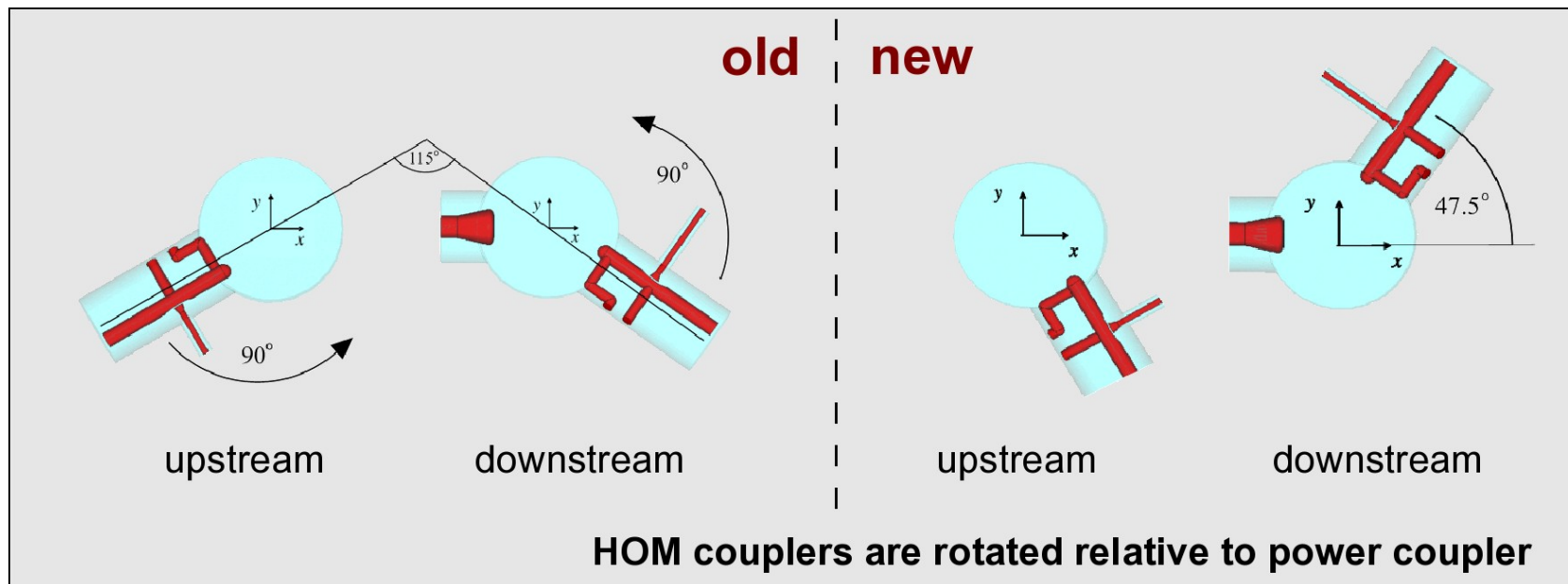
# Coupler RF kick – Differences between Codes

- There are different numerical calculations / different codes for electromagnetic field calculations

  - Omega3P, MAFIA, HFSS

- The numerical result is sensitive

  - cancelation between upstream and downstream coupler

  - the transverse fields are a small effect, about 5 orders of magnitude smaller than the longitudinal fields

  - depends on different assumptions e.g.

    - input coupler pen depth ~ $Q_{ext}$

# kick of main coupler

### scaled for TTF 9 cell cavity
problem: field asym. caused by asym. MWS mesh

$$\frac{Q_{ext}}{10^6}$$

$$\frac{10^6 \cdot V_x}{V_z}$$



x

z

shift

pen
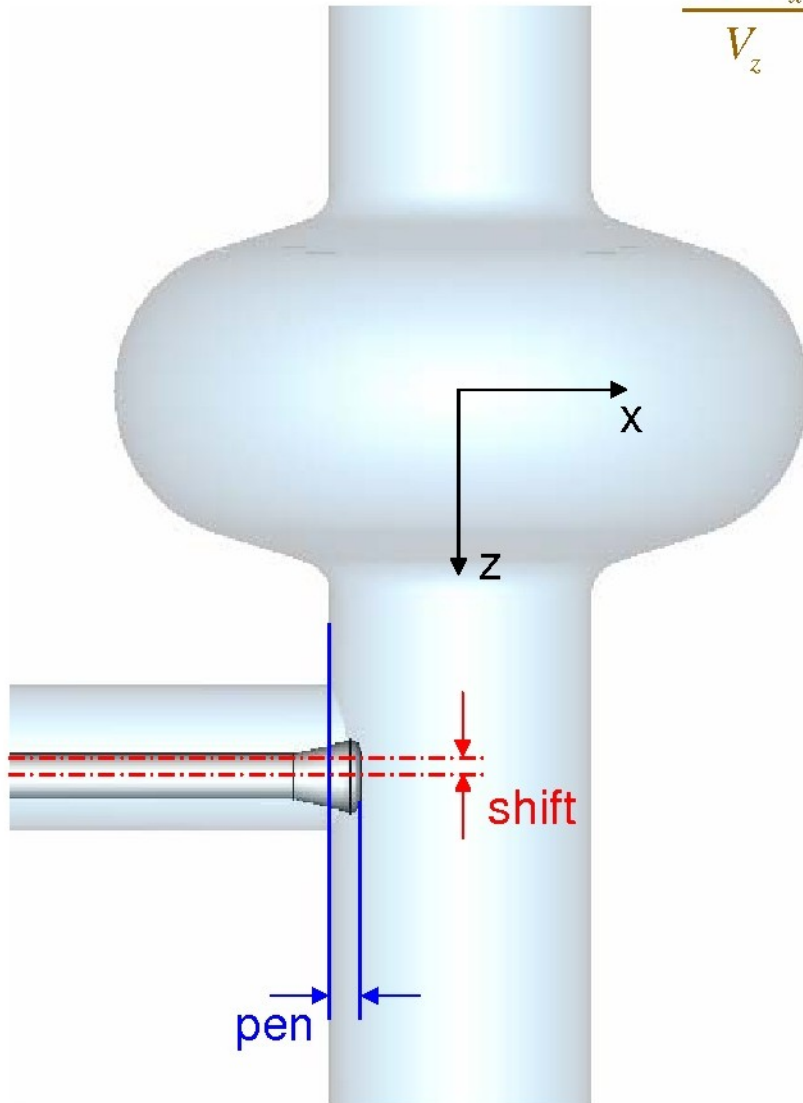
MWS-discretization: 30lines@2GHz

| pen/mm \ shift/mm | -5 | 0 | 5 |
|---|---|---|---|
| 4.5 | 3.347<br>19.9+j35.9 | 4.490 | |
| 6 | 2.466<br>47.6+j40.9 | 3.384<br>30.6+j54.3 | |
| 7.5 | 1.781<br>84.5+j50.0 | 2.4482<br>58.7+j65.0 | 3.987<br>37.4+j68.1 |
| 9 | 1.272<br>130.3+j56.9 | 1.940<br>93.4+j83.3 | 3.464<br>65.1+j88.9 |
| 10.5 | 0.9662 | 1.663 | 2.583<br>100.9+j86.5 |
| 12 | | 1.351 | 2.099<br>141.1+j65.0 |

MWS-discretization: 50lines@2GHz

| pen/mm \ shift/mm | -5 | 0 | 5 |
|---|---|---|---|
| 4.5 | 3.405 | | |
| 6 | 2.488 | 3.423 | |
| 7.5 | 1.857<br>83.7+j14.2 | 2.623<br>59.1+j31.7 | 4.242<br>37.1+j35.5 |
| 9 | | 2.008 | 3.237 |
| 10.5 | | 1.570 | 2.542 |
| 12 | | | |

*old values!*

# Coupler RF kick – Differences between Codes

| $|V_y|$ on axis for 31.5 GeV | Code and $Q_{ext}$ | |
|---|---|---|
| old        284 V <br> new       2350 V | MAFIA     $2.5 \cdot 10^6$ | used for MERLIN simulations |
| TDR(=old) 785 V <br> TDRM*     2621 V | Omega3P   $3.4 \cdot 10^6$ | Zenghai Li's talk, Wakefest 07 |
| TDR          130 V | Omega3P    $3.5 \cdot 10^6$ | Bane et al., EPAC08, TUPP019 |

*TDRM = downstream coupler rotated by 180º

For comparison *a* 100 *μ rad* cavity tilt

$$V_y = \frac{1}{2} \alpha V_\| = 1600 \ V$$

but RF kick is not random

Table 2: RF kick on-axis due to coupler asymmetry in [kV]. $\mathrm{Re}(V)$ is the in-phase, $\mathrm{Im}(V)$ the out-of-phase kick.

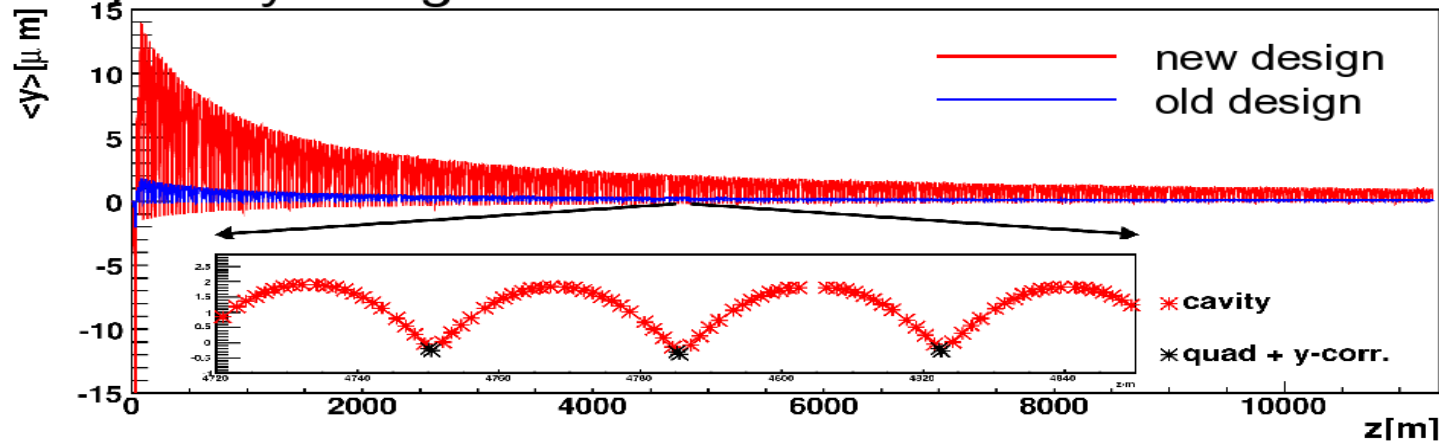| **Region** | $\mathbf{V}_x$ | $\mathbf{V}_y$ |
|---|---|---|
| Upstream | $-1.82 + 0.22i$ | $-1.29 - 0.11i$ |
| Downstream | $-0.79 - 1.62i$ | $+1.15 + 0.28i$ |
| Total | $-2.61 - 1.40i$ | $-0.13 + 0.17i$ |

cancelation between upstream and downstream coupler    11
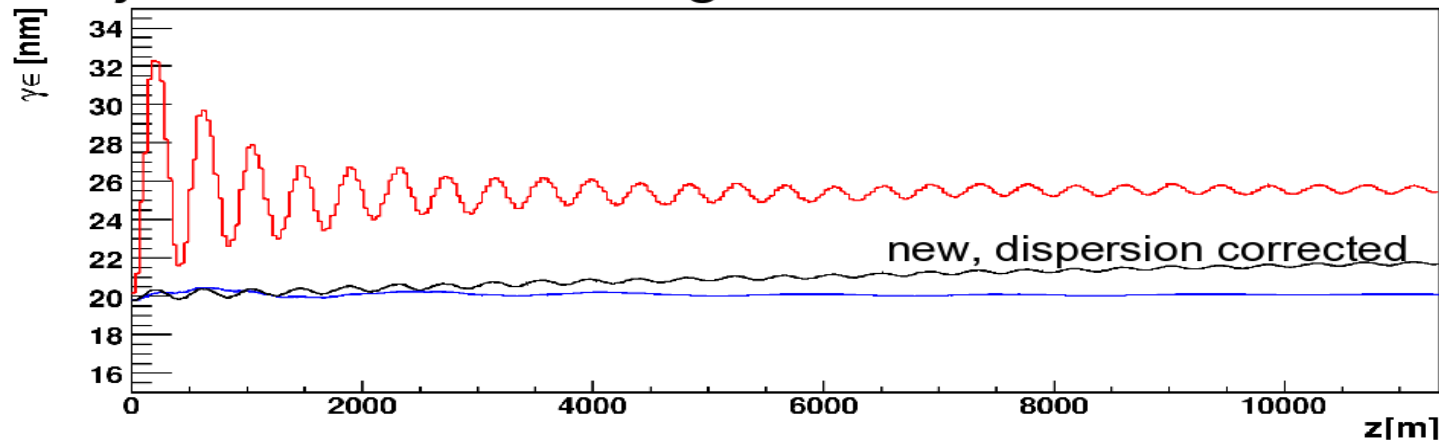
# Simulation Results - RF Kicks

D. Krücker et al., EPAC08, TUPP047, EUROTeV-Report-2008-003
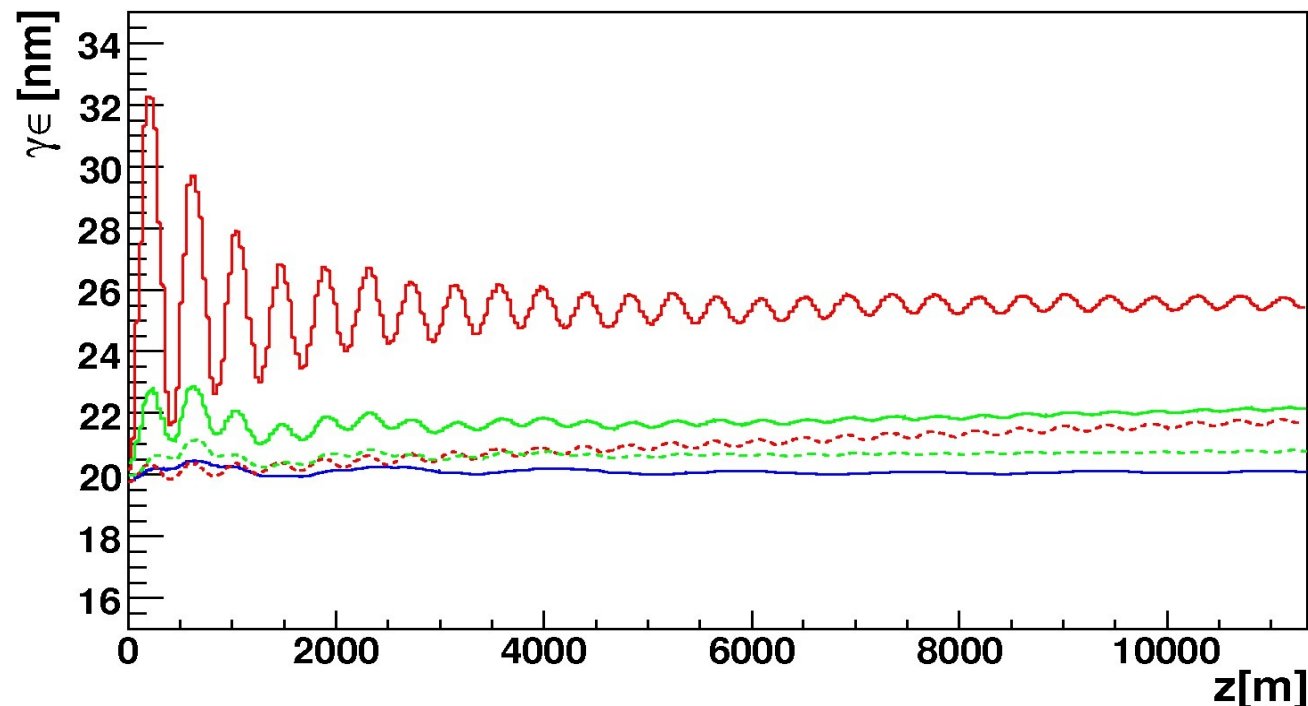


Trajectory along the main linac



Projected emittance along the main linac.

8-8-8 lattice, no undulator

- Perfect linac

- 20 nm initial emittance in y

- 1-2-1 steering to compensate kicks

- old design negligible

- new design
  $$\gamma \epsilon_y = 25.1\,\text{nm}$$

- dispersion corrected
  $$\gamma \epsilon_y^c = 21.8\,\text{nm}$$

12

# Simulation Results - RF Kicks



$$\gamma \epsilon_y^c = 20.8 \, \text{nm}$$

new, 2350V
old, 284V
800V

Dispersion corrected

- Only a small emittance increase even at 800V

Does the RF kick increased the sensitivity to Voltage instabilities?

- Random Klystron errors (24 cavities) applied to the steered system

| $\gamma\,\epsilon_y\,(\gamma\,\epsilon_y^c)\,[\mathrm{nm}]$ | 0% | 0.1%* | 1% |
|---|---|---|---|
| old design | 20.3 (20.3) | 20.3 (20.3) | 20.4 (20.3) |
| new design | 25.1 (21.8) | 25.1 (21.8) | 28.3 (22.1) |

*RDR value

- New design is slightly more sensitive to voltage errors

# Coupler Wakefields – MERLIN Implementation

- Calculation by I.Z. gives transverse kick not the wake potential

- We assume a purely capacitive wakefield (worst case)

  - A particle in a bunch with distribution $\lambda(s)$ experiences a transverse potential:

  $$W(s) = 2\mathrm{k} \int_{-\infty}^{0} \lambda(\tilde{s}) \, d\tilde{s}$$

  - In MERLIN numerically calculated

  $$w = 2k$$

$$k_{old}(x,y) = \begin{bmatrix} -21 \\ -19 \end{bmatrix} + \begin{bmatrix} 43 & 0.7 \\ 0.3 & -9 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$
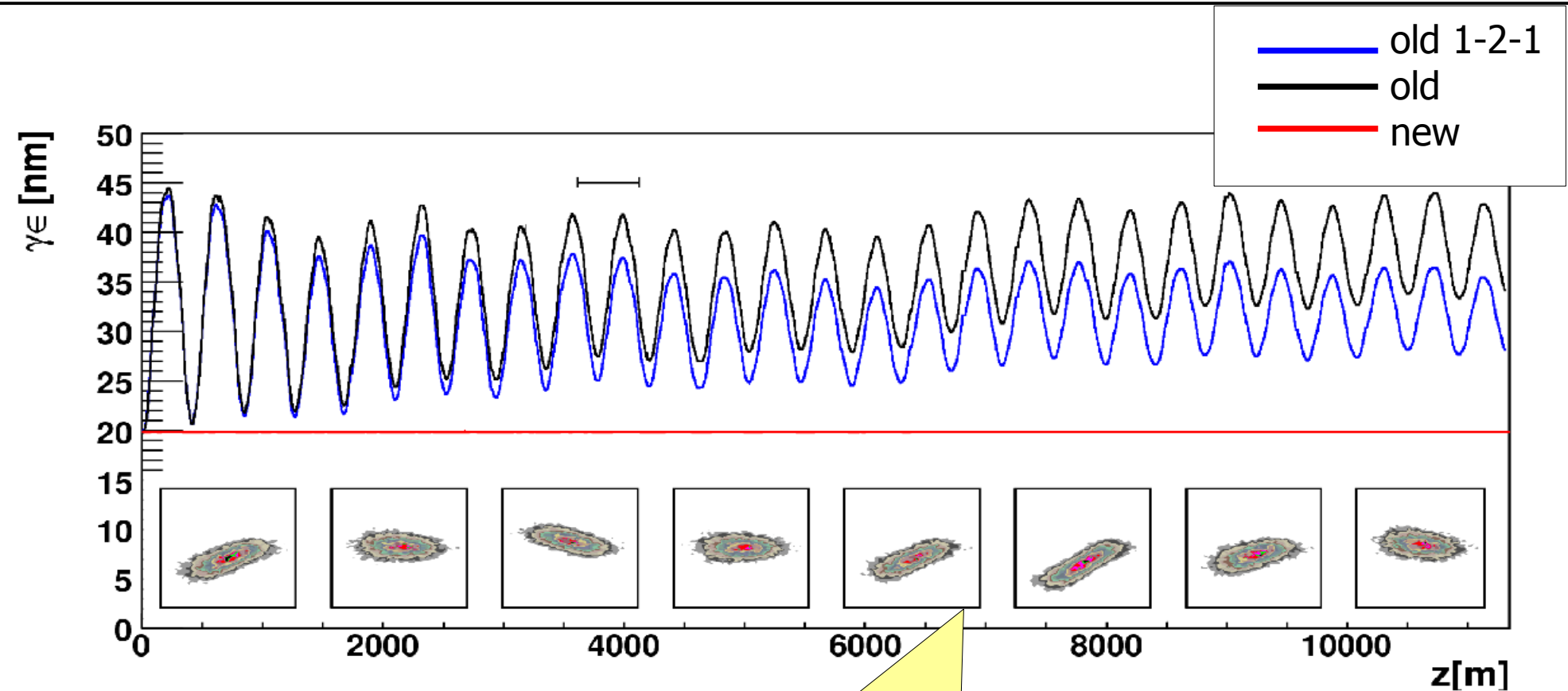
significantly smaller on axis

$$k_{new}(x,y) = \begin{bmatrix} 2.5 \\ -0.2 \end{bmatrix} + \begin{bmatrix} 23.3 & 0.4 \\ -0.2 & 11 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

I. Zagorodnov and M. Dohlus,
**LCWS/ILC, Hamburg 2007**

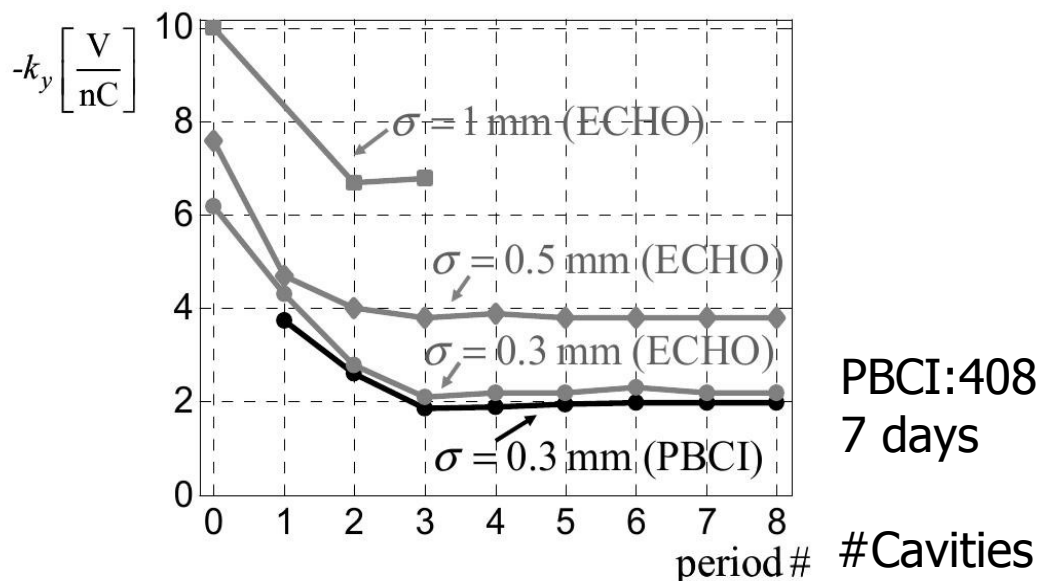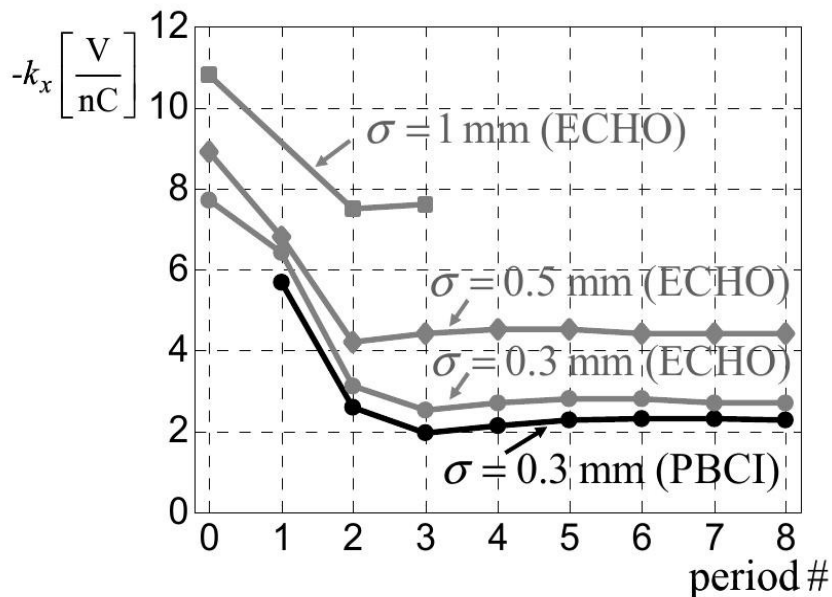$$x, y \, [\mathrm{cm}]; \quad k \, [\mathrm{V/nC}]$$

# Simulation Results -Wake Kicks (old Results)



old design
Snashots of the bunch profile (y-ct-plane, at quads 102,104...114). The bunch tail oscillates strongly driven by coupler wakefield.

DK et al., EPAC08 - TUPP047

# Coupler Wakefields – Steady state solution



PBCI:408 CPUs
7 days

#Cavities

M. Dohlus, I. Zagorodnov, DESY; E. Gjonaj, T. Weiland, TEMF, TU-Darmstadt;
EPAC08, MOPP013

*Self Induced Coupler Kick (Wake)*

It can be seen that the kick factor at both coordinate plans for $\sigma = 0.3$ mm is about 2 V/nC, that is an order of magnitude lower than a preliminary estimation of Ref. [5]. This is a consequence of a shadowing effect of the cavity and of a linear decrease of the steady-state wake with the decrease of the bunch length [6, 9].

$$k_{rescaled}(x, y) = 0.11 \cdot k_{old}(x, y);$$

to approximate the steady state solution

# Simulation Results – Wake Kicks, Steady State Results



Plot by Fabian Gross
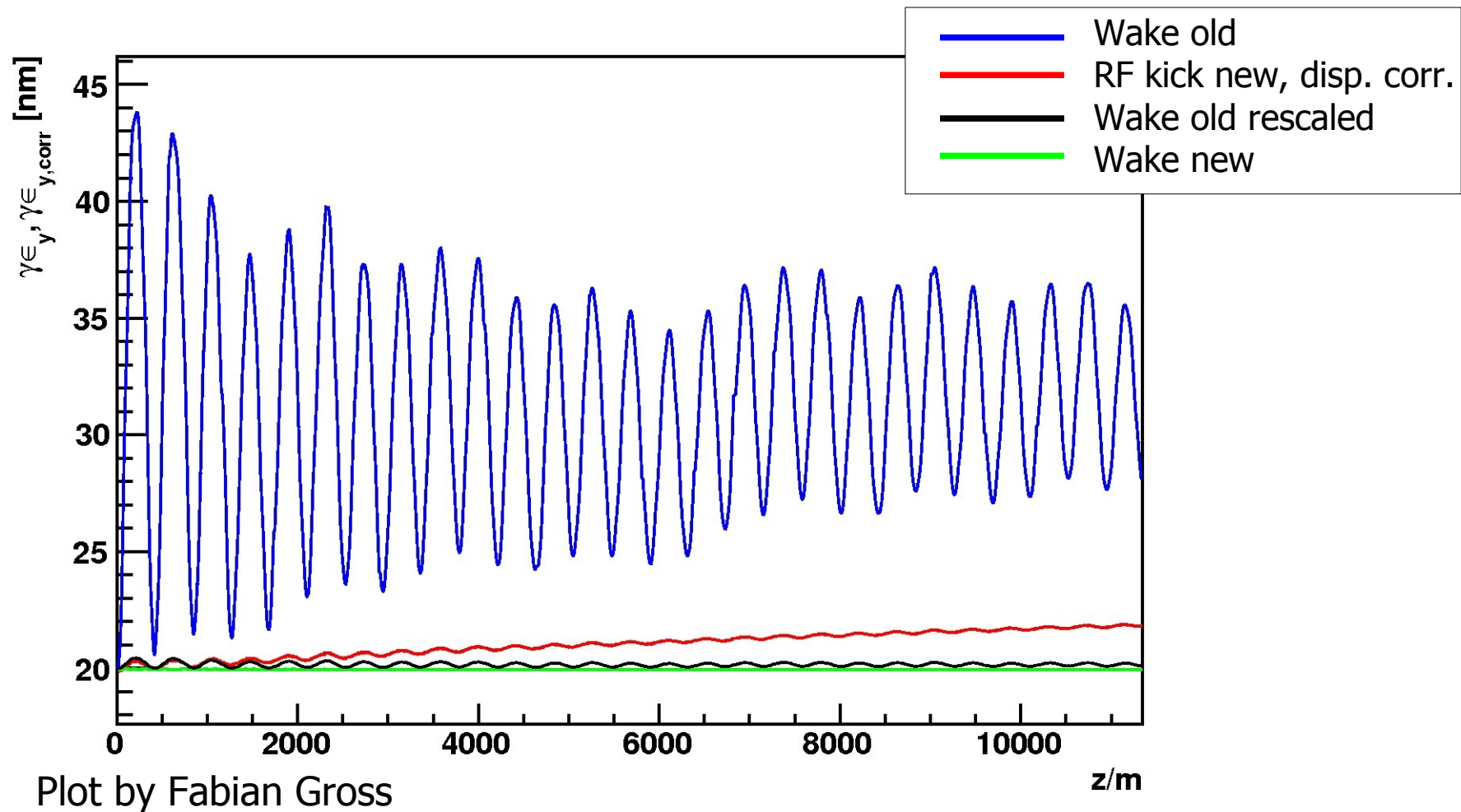
- Steady state result gives negligible emittance increase
- A large RF kick is more problematic than the coupler wakefield kick

# Conclusions

- The numerical input for the simulation:
  Chasing a moving target – consistent now(?)

- Effect of coupler wakefields on the emittance is
  negligible for the steady state solution

  - Is it preserved throughout the linac?

- A modification of the relative coupler position to reduce the
  wakefields will increases the RF kick $\Delta \gamma \epsilon_y^c = 1.8 \, \mathrm{nm}$
  - worse than the steady state wakefields

- Smallness of the RF kick is a result of a cancellation between
  up- and downstream couplers. The precise numerical value
  sensitively depends on assumptions but even for

  - Kick <800V : $\Delta \gamma \epsilon_y^c = 0.8 \, \mathrm{nm}$