IHEP-CLIC Collaboration

（Beam Dynamics）

J. Gao

IHEP

Nov. 3, 2011

Collaboration members from IHEP
(beam dynamics)

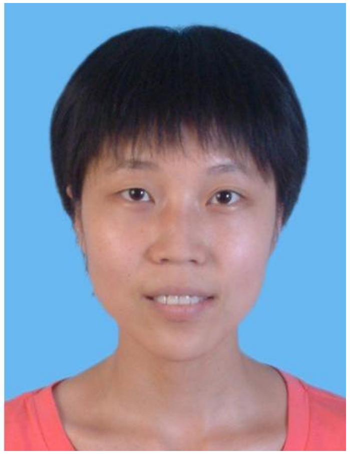
Prof. Jie Gao

IHEP LC group leader

Asia Linear Collider Steering Committee Chairman

ICFA Beam Dynamics

Panel Member



Dr. Dou Wang

IHEP LC Group member

LC beam dynamics

Mr. Yiwei Wang

Ph.D student of IHEP

CLIC beam dynamics

Mr. Ming Xiao

Ph.D student of IHEP

LC beam dynamics

Students' visiting CERN (CLIC group)

- WANG Dou's visit: Oct. 1st, 2008～Dec. 31th, 2008 (three months)

  topic: CLIC Booster Linac dynamics

Ph.D. Tutor: Prof. J. Gao

Collaborating tutor: Dr. D. Schulte

Supported by Dr. Jean-Pierre Delahaye

- WANG Yi Wei's visit: Nov. 1st, 2010～Oct. 31th, 2011 (one year)

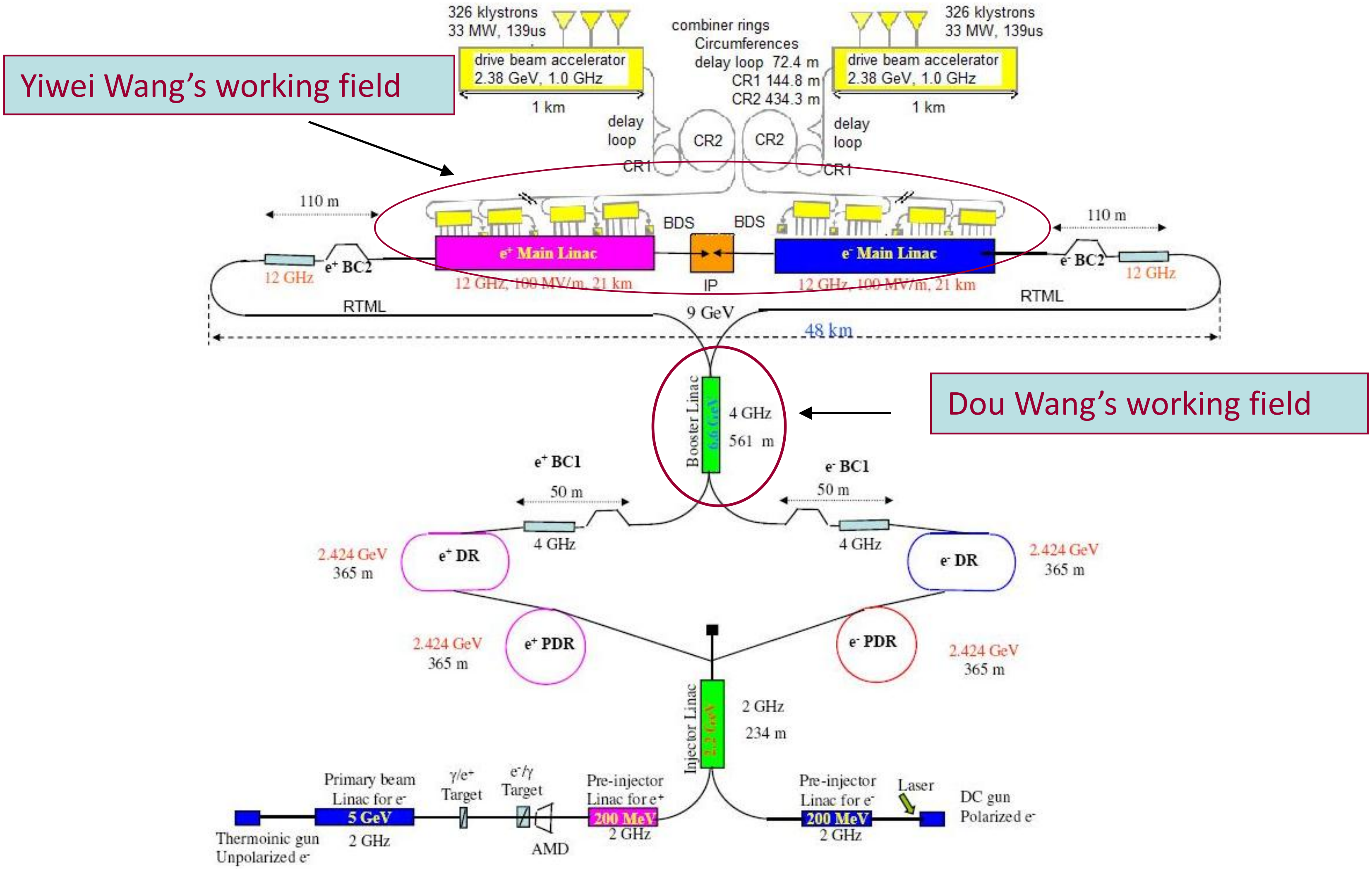
  topic: CLIC Main Linac dynamics

Ph.D. Tutor: Prof. J. Gao

Collaborating tutor: Dr. D. Schulte

Supported by Dr. Jean-Pierre Delahaye and Dr. Steinar Stapnes

IHEP working fields



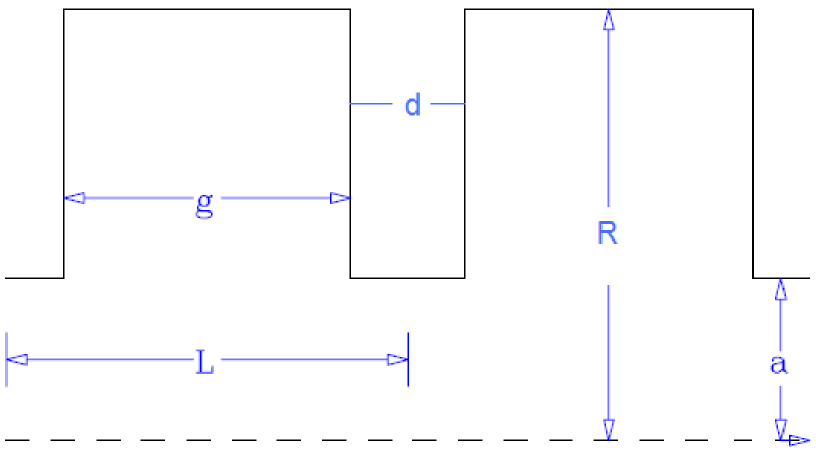
CLIC Booster Linac Design and Beam Dynamics Study

(2008.10-2008.12)

Booster main parameters

Initial Beam energy (GeV)	2.42
Final Beam energy (GeV)	9
Initial Normalized horizontal emittance (nm.rad)	500
Initial Normalized vertical emittance (nm.rad)	5
Initial Enery spread (MeV)	29
Bunch length (μm)	175
Bunch spacing (cm)	15
Number of electrons per bunch	3.72×10^9
Number of bunches per train	312
Accelerating gradient (MV/m)	30
RF frequency (GHz)	4
Structure length (m)	3

Accelerating structure scaled from NLC



a (mm)	11
R (mm)	32
g (mm)	21
L (mm)	25

- Short-range wake model

$$\begin{cases} W_L(s) = \dfrac{Z_0 c}{\pi a^2} H(s) e^{-\sqrt{s/s_0}} \\ W_\perp(s) = \dfrac{4 Z_0 c s_0}{\pi a^4} H(s)\left[1-\left(1+\sqrt{\dfrac{s}{s_0}}\right) e^{-\sqrt{s/s_0}}\right] \end{cases}$$

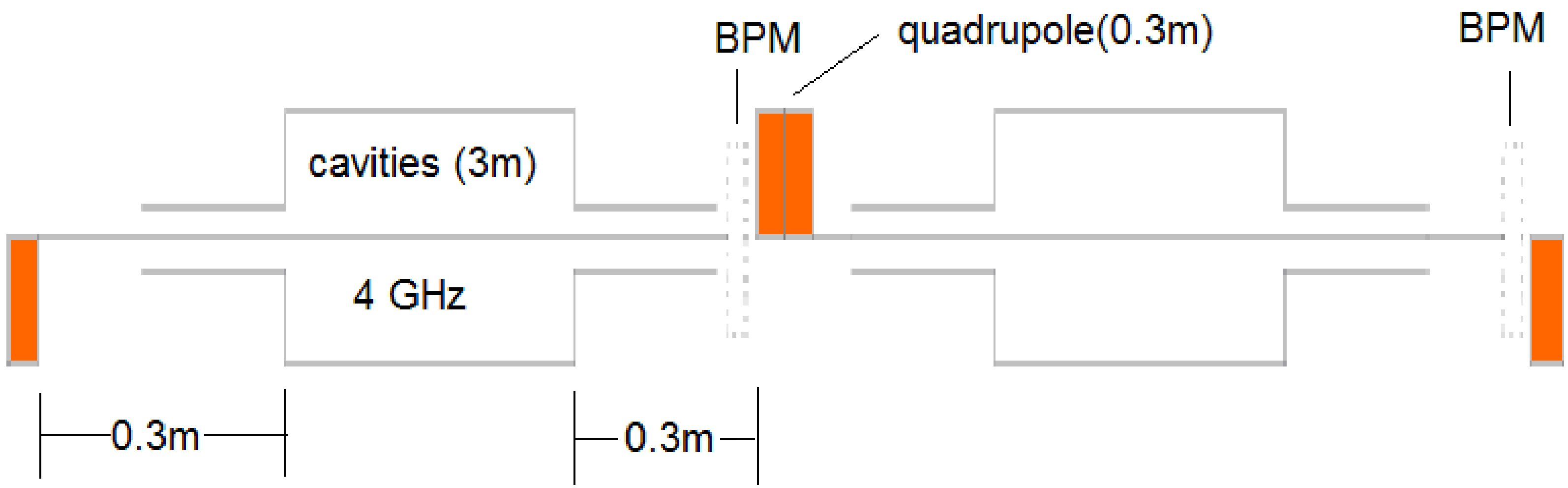
$$s_0 = \frac{g}{8}\left(\frac{a}{\alpha(\frac{g}{L})L}\right)^2, \alpha(x) = 1 - 0.4648\sqrt{x} - (1-0.9296)x$$

$W_L \sim f^2$

$W_T \sim f^3$

→ the wakefield effects in the 4GHz Booster linac may not be small.

Lattice cell

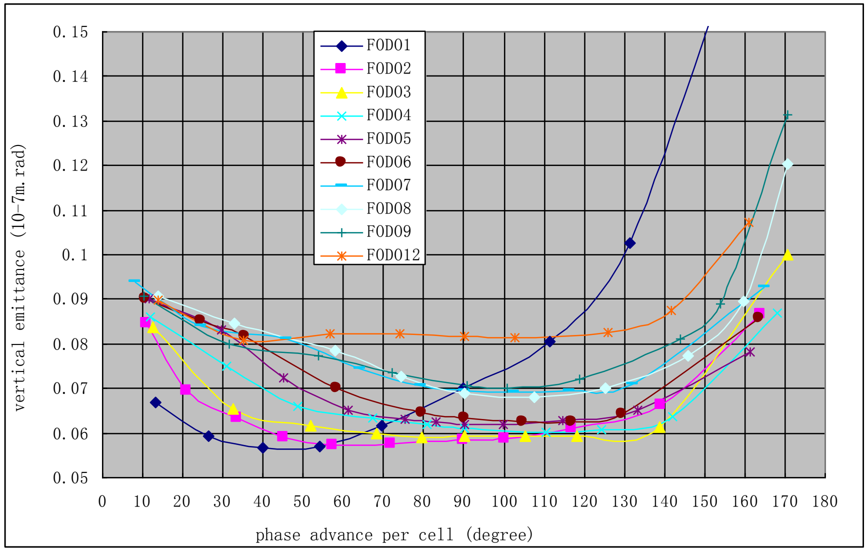


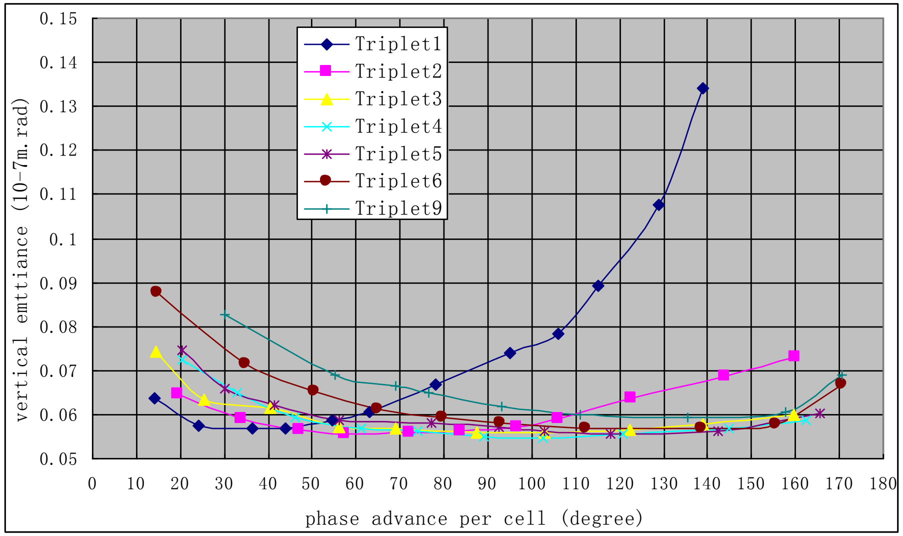
Two main sources of emittance dilution:

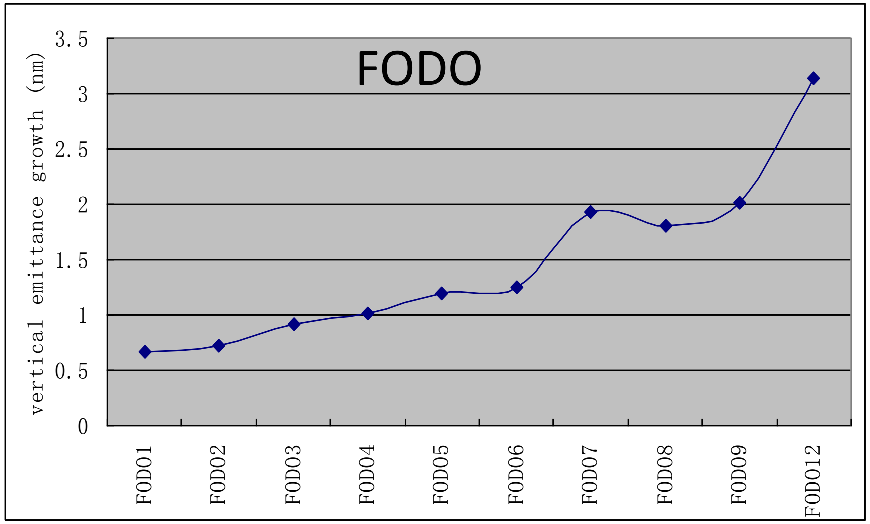
- transverse wakefields
- dispersion

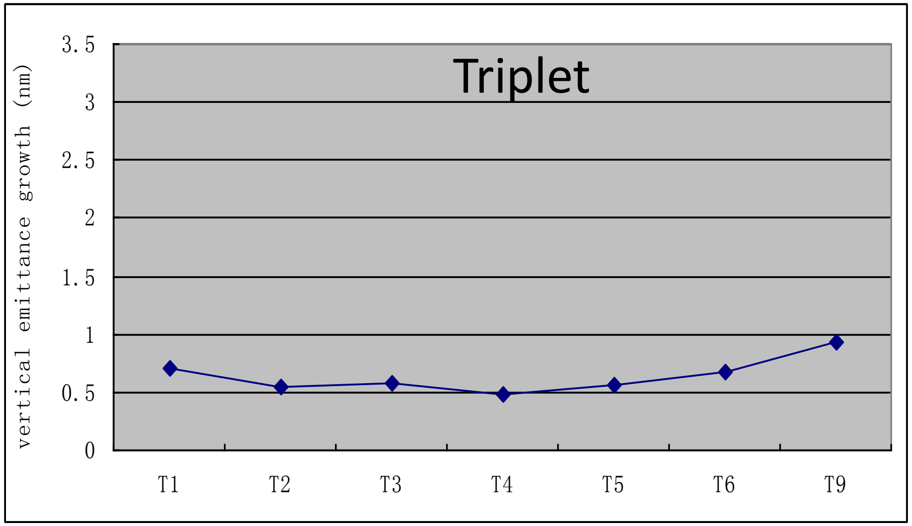
Make a balance between wakefiels and dispersion effects !

Single-bunch emittance-1









Only cavity misalignment: δy_c=100μm , random seeds=100

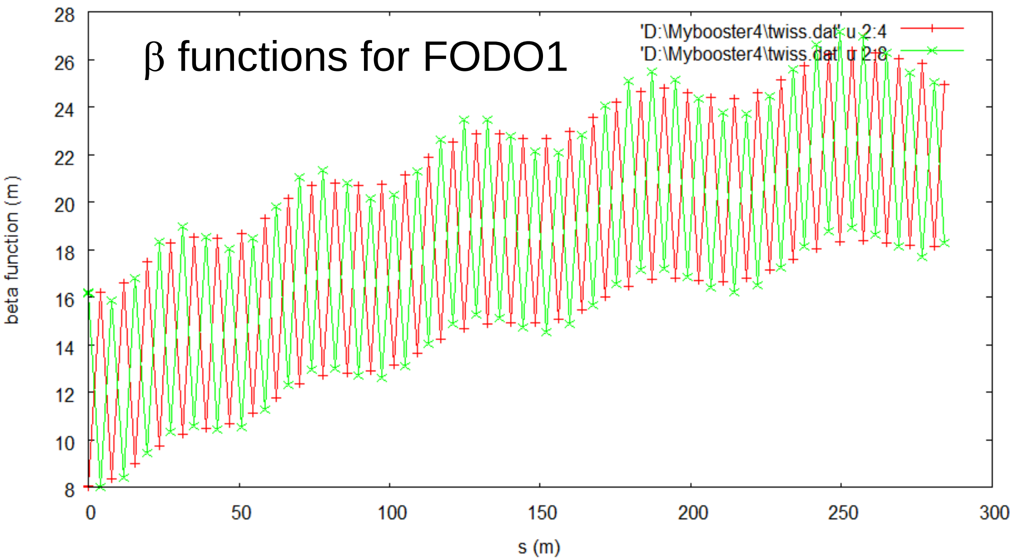
Single-bunch emittance-2

• Emittance growth decreases with decreasing number of quadrupoles first (dispersive effects dominate) and then increases again after Triplet3 (wakefield effects dominate).

• Roughly, T3 is equal to FODO1, T6 is equal to FODO2, T9 is equal to FODO3 and so on.

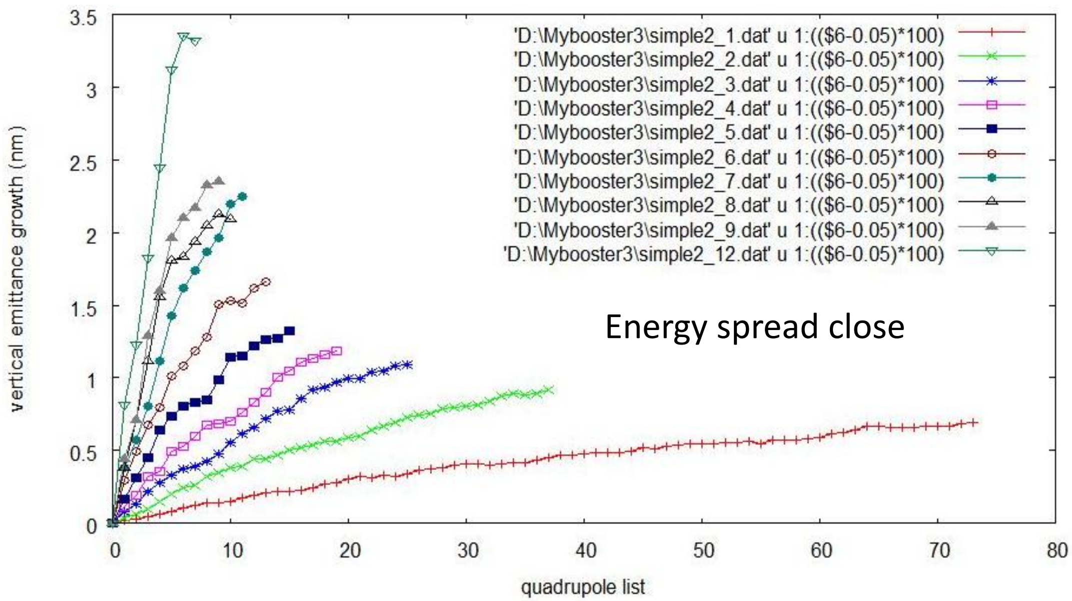
• There is no significant advantage for Triplet lattice, so we chose FODO lattice for its facility.

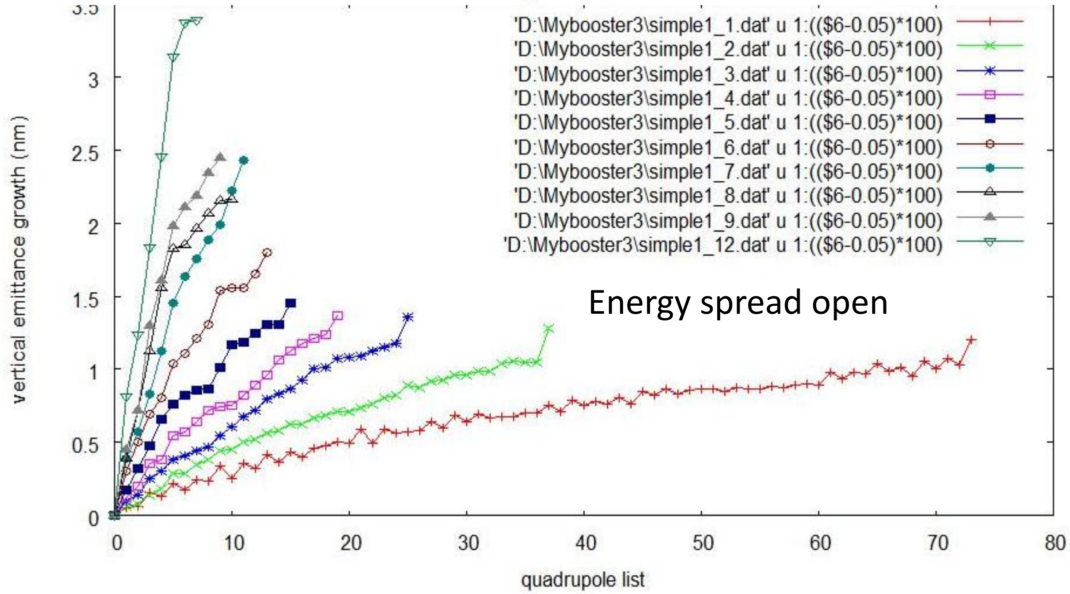
• FODO7, FODO8, FODO9 and FODO12 result too high emittance growth because of the weak focusing. They will not be choose.



Single-bunch emittance-3

- Cavity misalignment: 100 um
- Quadrupole misalignment: 100um
- BPM resolution: 10 um
- One-to-one correction
- Random seeds=100

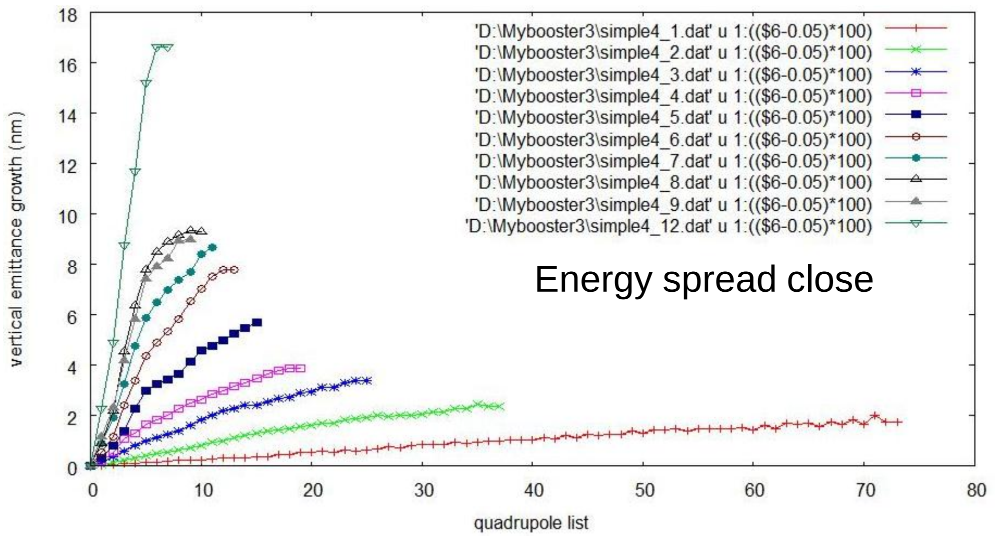


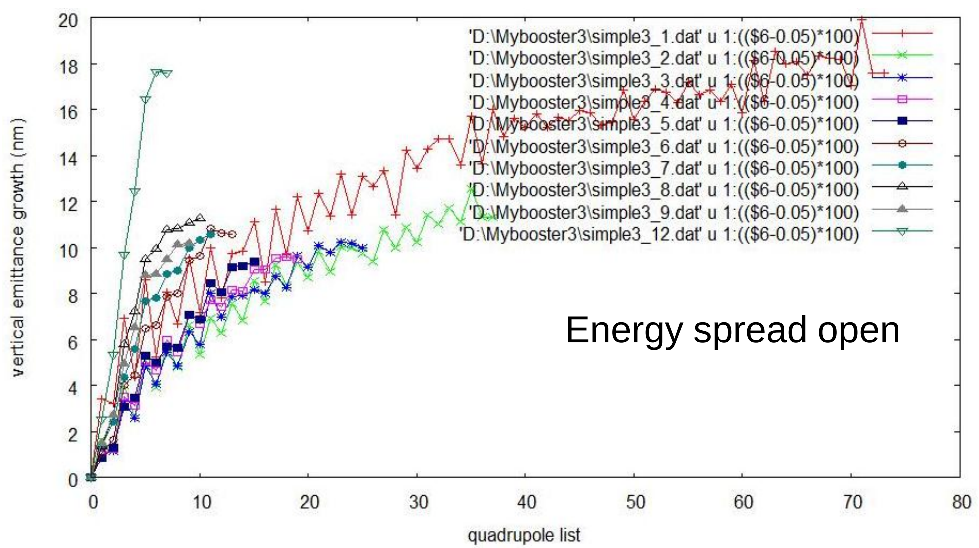


- FODO1 and FODO2 have emittance osillations when energy spread was included - stronger dispersive effect!

Single-bunch emittance-4

- Cavity misalignment: 100 um
- BPM misalignment: 100um
- BPM resolution: 10 um
- One-to-one correction
- Random seeds=100

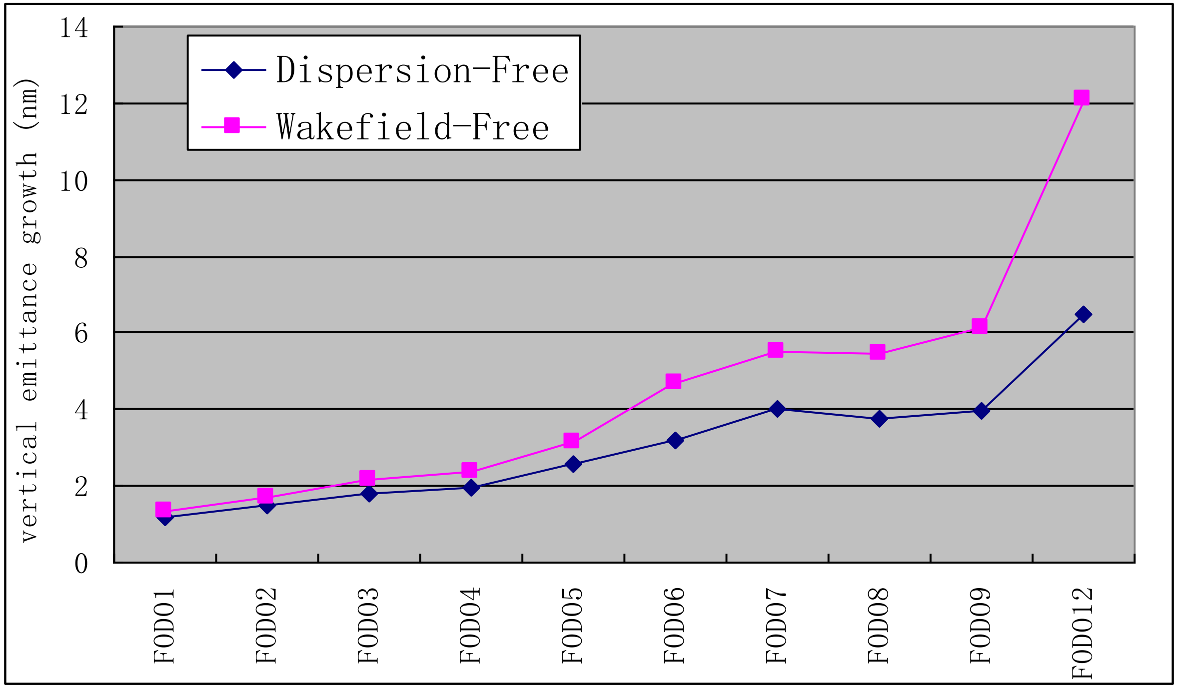




- Large emittance osillations came from energy spread - dispersive effect!
- emittance growth is more sensitive to BPM misalignment.

Wakefield-free steering and dispersion-free steering

- Cavity misalignment: 100 um
- Quadrupole misalignment: 100 um
- BPM misalignment: 100um
- BPM resolution: 10 um
- Energy spread open
- Random seeds=100



The average emittance growth can be controlled to 1.2 nm for FODO1 after dispersion-free steering.

Analytical long-range wakefield for the fundamental mode

Gao theory for fundamental mode:

References:

J. Gao, "Analytical approach and scaling laws in the design of disk-loaded traveling wave accelerating structures", Particle Accelerators, Vol. 43(4) (1994), pp. 235-257.

J. Gao, "Analytical formulae and the scaling laws for the loss factors and wake-fields in disk-loaded periodic structures", Nucl. Instr. and Method, A381 (1996), p.174.

$$f_{010} = \frac{c}{2\pi} \cdot \frac{u_{01}}{R} = 3.59GHz, \; f_{\pi/2,010}^2 = f_{010}^2 \left(1 + \frac{4a^3}{3\pi g R^2 J_1^2(u_{01})}\right)$$

Coupling coefficient :

$$K_{010} = -\frac{4a^3}{3\pi g R^2 J_1^2(u_{01})} \cdot e^{-\alpha_{010} d} = -0.043$$

$$f_{\theta_{010}}^2 = f_{\pi/2,010}^2 [1 + K_{010} \cos(\theta_{010})] \longrightarrow$$

$\theta_{010} \approx 2\pi/3$

$f_{\theta 010} = 3.8$ GHz

Loss factor :

$$k_{010} = \frac{g u_{01}^2 J_0^2(\frac{u_{01}}{R} a)}{\left(\frac{u_{01}}{R}\right)^2 \varepsilon_0 L \pi R^4 J_1^2(u_{01})} \left(\frac{\sin^2 x_1}{4x_1^2} + \frac{\sin^2 x_2}{4x_2^2}\right) = 30.6V/pc/m \quad \left(x_1 = x_2 = \frac{g}{2} \cdot \frac{u_{01}}{R} = 0.79\right)$$

Longitudinal wakefield:

$$W_{L,010}(s) = 2k_{010} \cos\left(\frac{\omega_{\theta_{010}}}{c} \cdot s\right)$$

Analytical long-range wakefield for the first dipole mode

Gao theory for dipole mode:

$$f_{110} = \frac{c}{2\pi}\cdot\frac{u_{11}}{R} = 5.7GHz,\ f_{\pi/2,110}^{2} = f_{110}^{2}\left(1-\frac{4a^{3}}{3\pi g R^{2} J_{2}^{2}(u_{11})}\right)$$

coupling coefficient:

$$K_{110} = \frac{4a^{3}}{3\pi g R^{2} J_{2}^{2}(u_{11})}\cdot e^{-\alpha_{110} d} = 0.103$$

$$f_{\theta_{110}}^{2} = f_{\pi/2,110}^{2}[1+K_{110}\cos(\theta_{110})] \longrightarrow$$

$\theta_{110} \approx 5\pi/6$

$f_{\theta 110} = 5.03$ GHz

Loss factor :

$$k_{110} = \frac{2 g u_{11}^{2} J_{1}^{2}(\frac{u_{11}}{R}a)}{\left(\frac{u_{11}}{R}\right)^{2}\varepsilon_{0} L \pi R^{4} J_{2}^{2}(u_{11})}\left(\frac{\sin^{2} x_{1}}{4x_{1}^{2}}+\frac{\sin^{2} x_{2}}{4x_{2}^{2}}\right) = 29.06V/pc/m \quad (x_{1} = x_{2} = \frac{g}{2}\cdot\frac{u_{11}}{R} = 1.26)$$

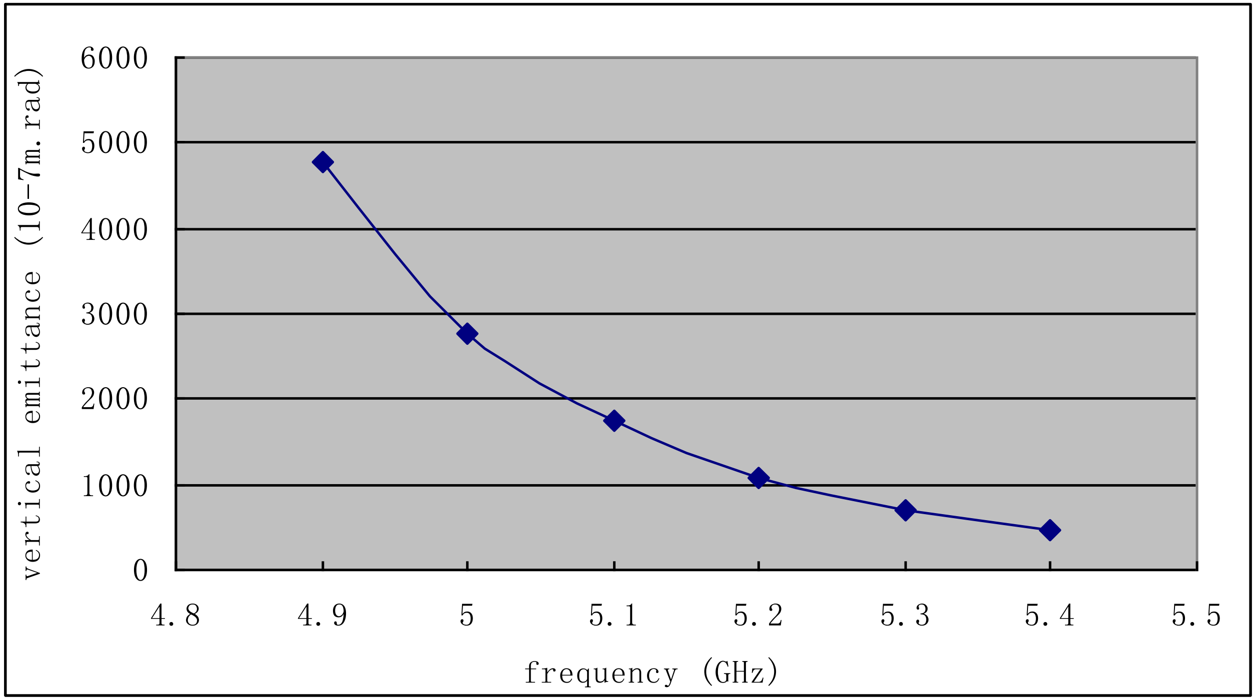
Transverse wakefield:

$$W_{T,110}(s) = \frac{2ck_{110} r_{0}}{\omega_{\theta_{110}} a^{2}}\cdot\sin\left(\frac{\omega_{\theta_{110}}}{c}\cdot s\right)\cdot e^{-\frac{\omega_{\theta_{110}}\cdot s}{2cQ_{\theta_{110}}}}\cdot(\vec{r}\cos\phi - \vec{\phi}\sin\phi)$$

So, the amplitude of transverse wakefield needed in PLACET is

$$A_{110} = \frac{2ck_{110}}{\omega_{\theta_{110}} a^{2}} = 4560V/pc/m^{2}$$

Muli-bunch emittance growth



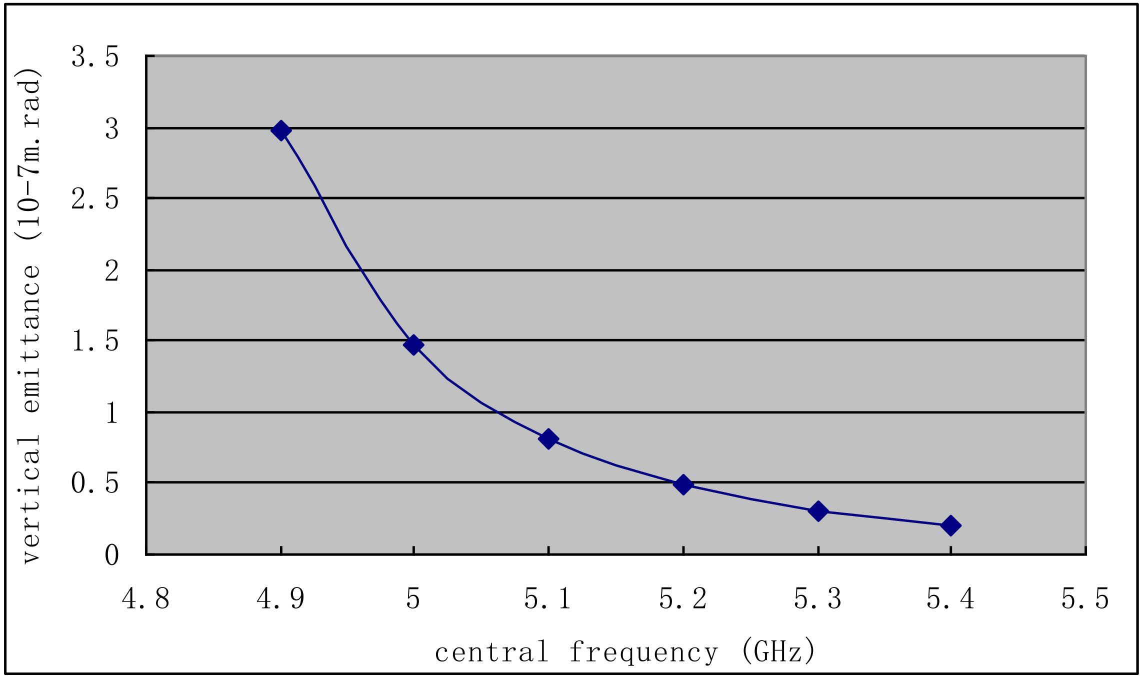
- Perfect alignment
- Initial injection error: δ_{y0}=10μm
- Bunch number per train: n_b=312

The first dipole mode alone can lead to a large multi-bunch emittance growth !

Long-range wakefield detuning

Two-frequency detuning

$$A\sin(\omega_1 t) + A\sin(\omega_2 t) = 2A\sin(\frac{\omega_1 + \omega_2}{2} \cdot t) \cdot \cos(\frac{\Delta\omega}{2} \cdot t)$$

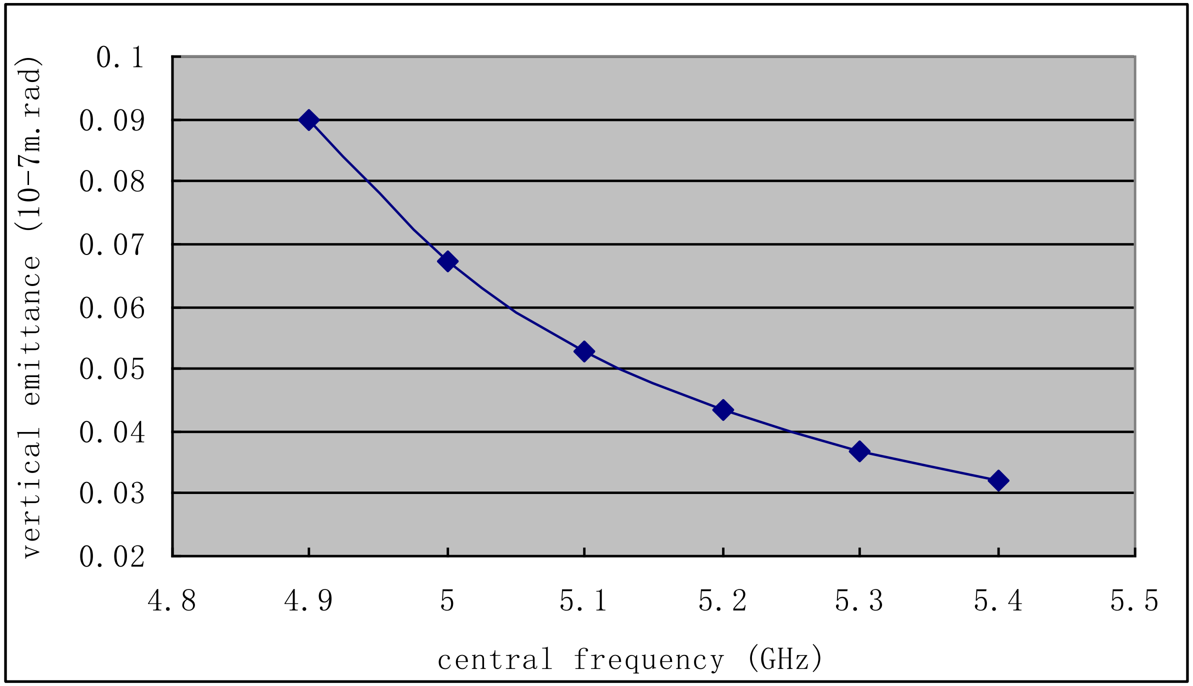


$f = f_0 \pm 0.5$ GHz

Obviously, the emittance is controlled after detuning.

Gaussian frequency detuning

- frequency spread σ_f: 0.2GHz
- cut of the frequency spread : 3 σ_f

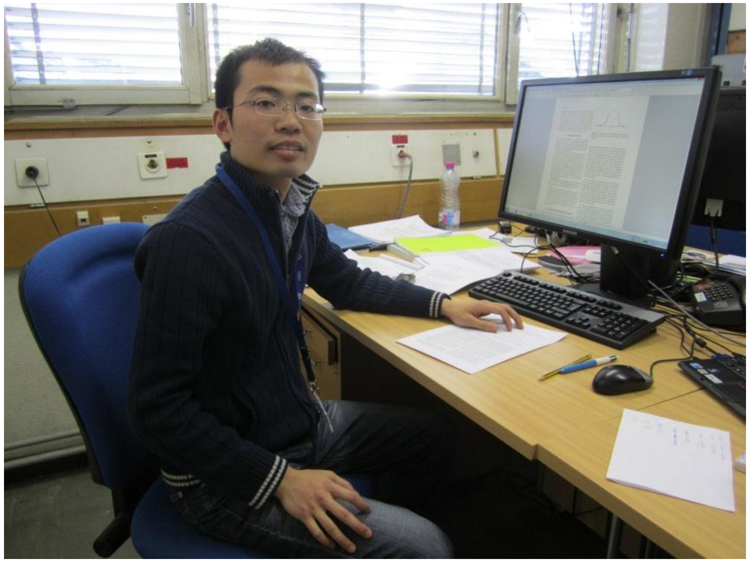


- *The transverse wakefield can be reduced apparently by the Gauss frequency spread!*
- *The random cavity fabrication errors are helpful to the view of multi-bunch beam dynamics.*

Beam dynamics of CLIC main linac

(2010.11-2011.10)

- IHEP Ph.D student Yiwei Wang worked with Daniel Schulte on beam dynamics of CLIC main linac from Nov. 2010 to Oct. 2012.



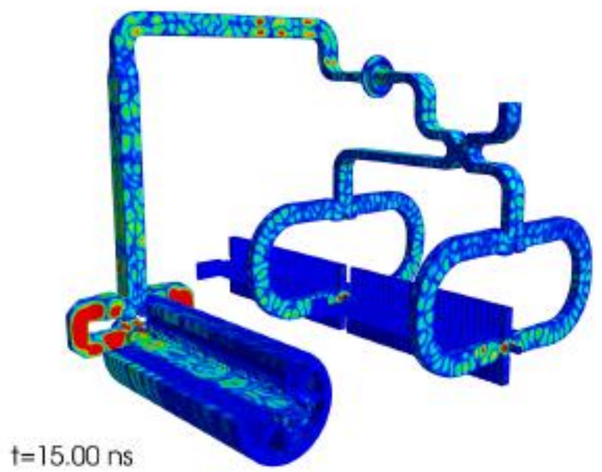
The effects of the external wakefield from the PETS (3TeV CLIC)

- We study the beam qualities degradation due to the external wakefield from the PETS.

  - Left figure shows the plot of wakefield feeded from PETS.

  - Right one shows the wakefield experenced by main beam.

$$W_x = 276.7V/bunch/mm/2AS, W_y = 5.5V/bunch/mm/2AS$$



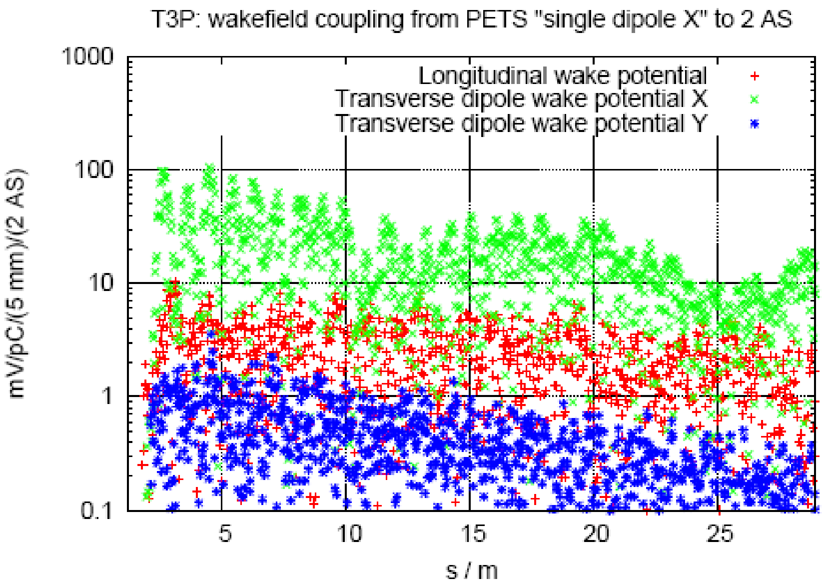


Fig. 1: The external wakefield from PETS*

* SLAC-PUB-14439, A. Candel et.al

The effects of the external wakefield from the PETS (3TeV CLIC)

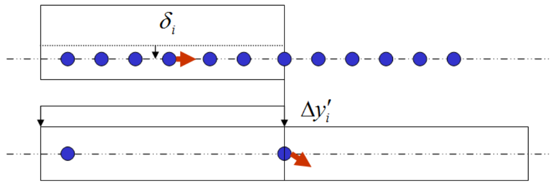
- Consider misaligned PETS (0.1mm) and consecutive drive beam

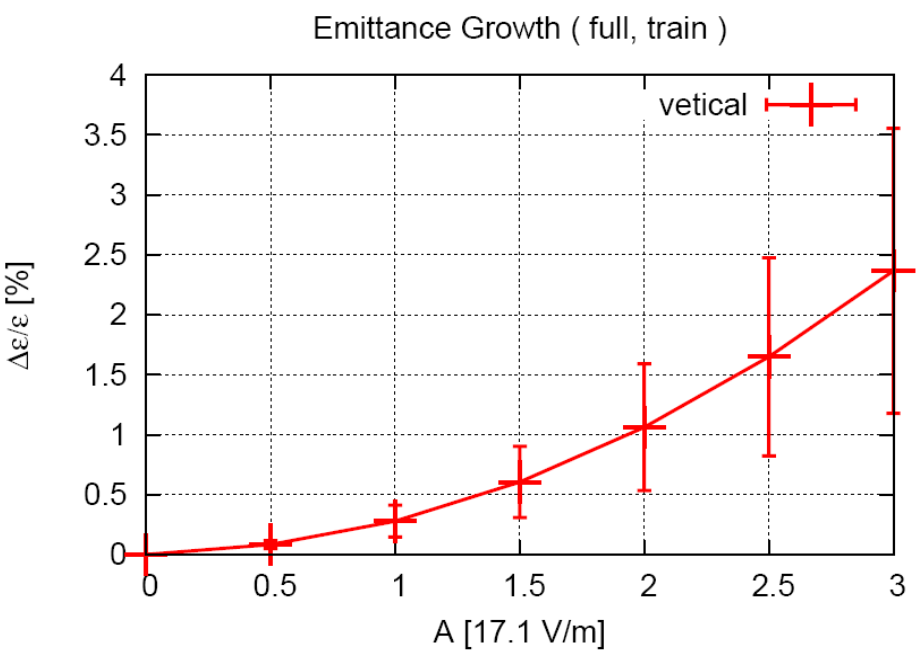
  - We simulate the kicks on main beam and find the tolerances of the external wakefield from a consecutive drive beam:

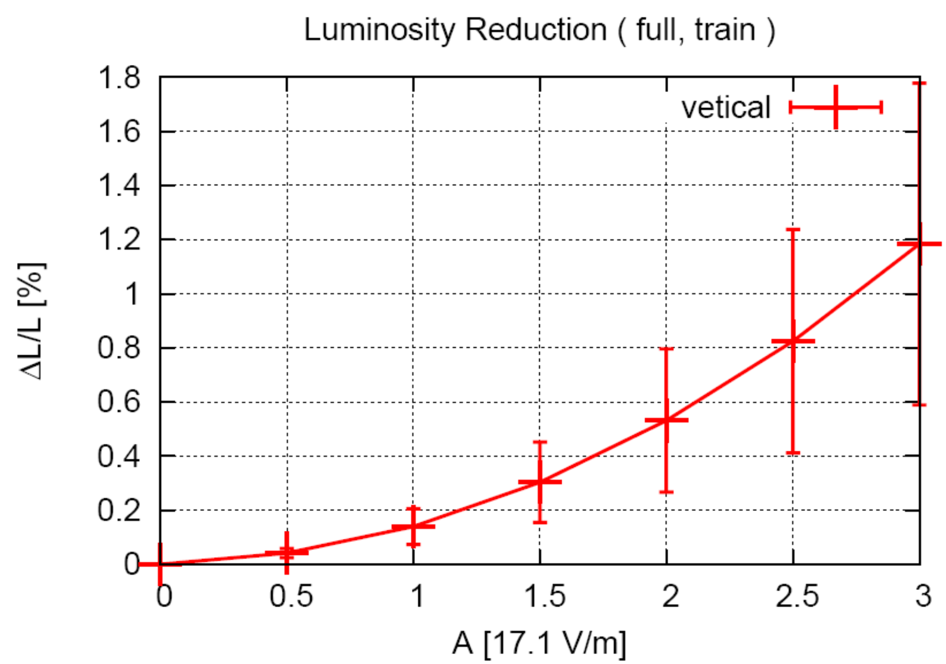
  $A_y \le 47V/m,\ A_x \le 364V/m,$ if constraint $\Delta L/L \le 1\%$

  - quite loose for current RF design

  - but the actual drive beam for the compensation of beam loading might not give so loose tolerances.







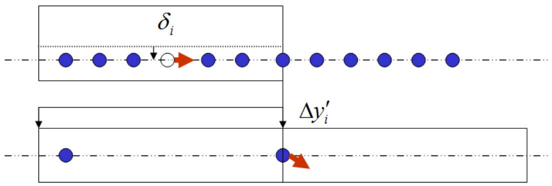
The effects of the external wakefield from the PETS (3TeV CLIC)

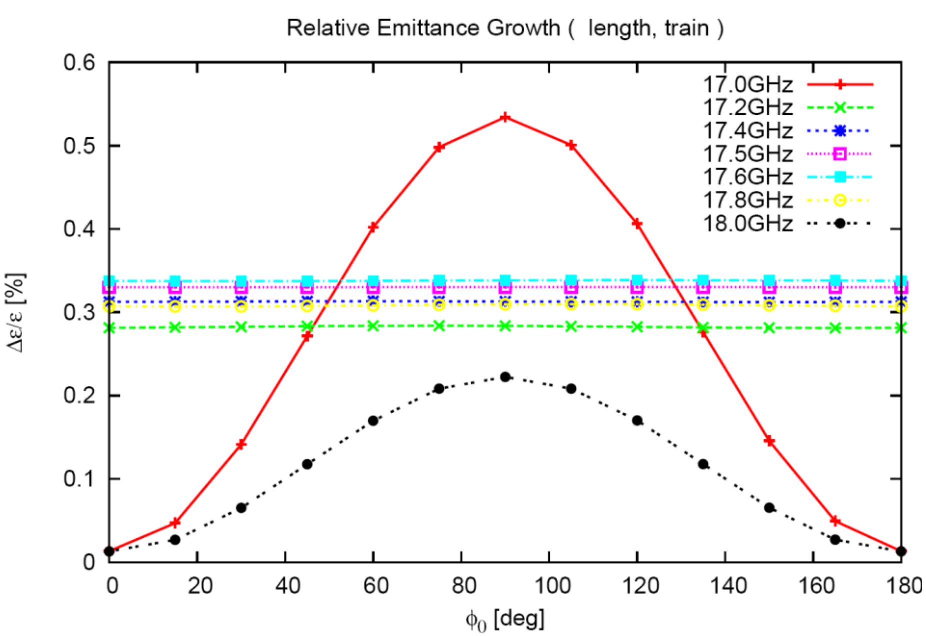
- Consider misaligned PETS (0.1mm) and drive beam with compensation of transient beam loading

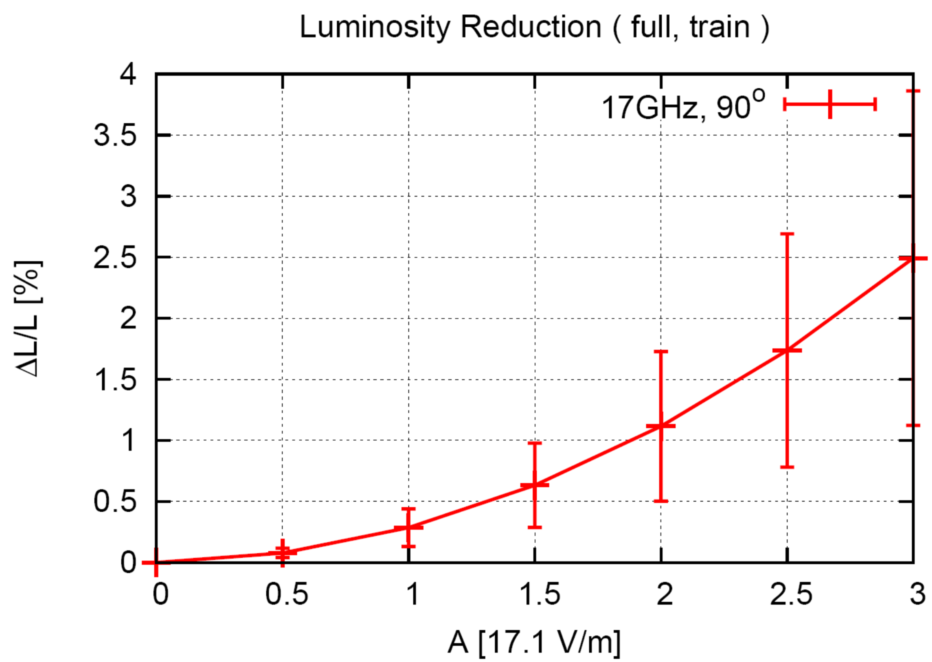
  - We estimate the additional kick with single drive beam and find the tolerances of the external wakefield:

  $A_y \le 31\, V/m,\ A_x \le 240\, V/m,$ if constraint $\Delta L/L \le 1\%.$

  - works for more accurate result are under going







Design and optimization of 1TeV CLIC main linac

- We design a new 1TeV CLIC main linac different from the low energy running of 3TeV one.

  - use CLIC_G accelerating structure (100MV/m)

  - same parameters constrain with 3TeV design (Table 1)

  - vertical emittance growth less than 10nm*rad and horizontal one 60nm*rad; budget for vertical and horizontal are both 50%

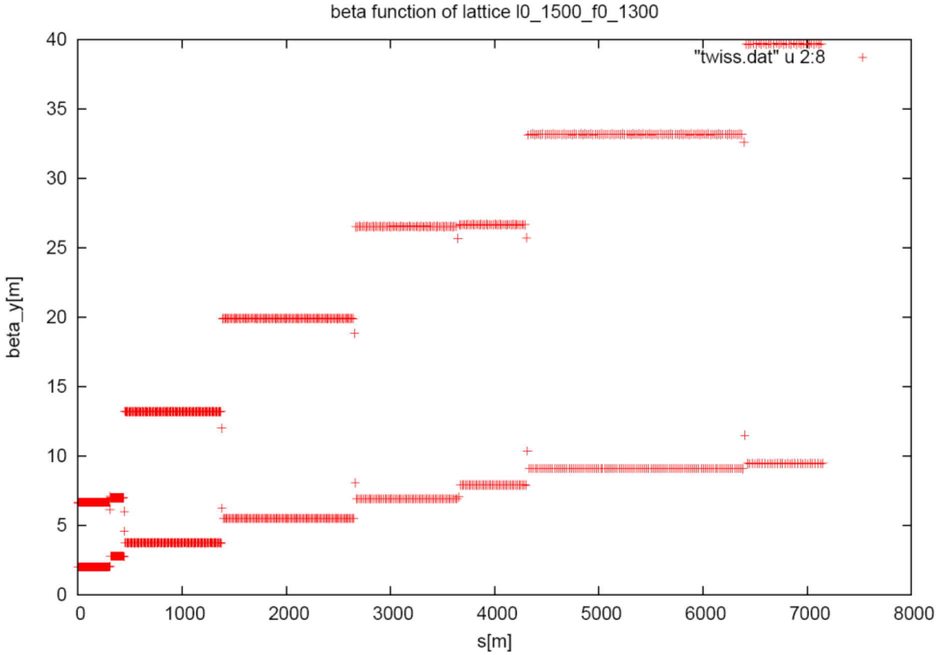
  - same module with 3TeV design

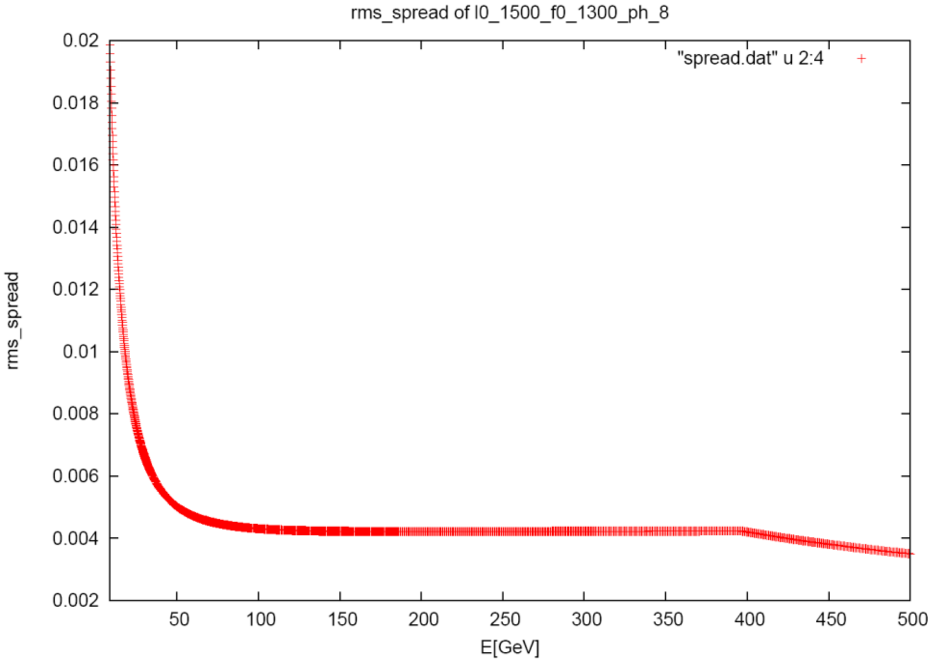
initial energy	9GeV	final energy	500GeV
bunch charge	3.72 e9	bunch number	312
bunch spacing	15cm	bunch length	44 μ m
rms initial espread	⩽2%	rms final espread	⩽ 0.35%
ini. emitt.x	⩽ 600 nm*rad	final emitt.x	⩽ 660 nm*rad
ini. emitt.y	⩽ 10 nm*rad	final emitt.y	⩽ 20 nm*rad

Table1： 1TeV CLIC main linac parameters

Design and optimization of 1TeV CLIC main linac

- We designed the 1TeV lattice.
  - The figures show the vertical beta function and energy spread for the lattice similar to 3TeV design. (l0=1.5m, f0=1.3m)

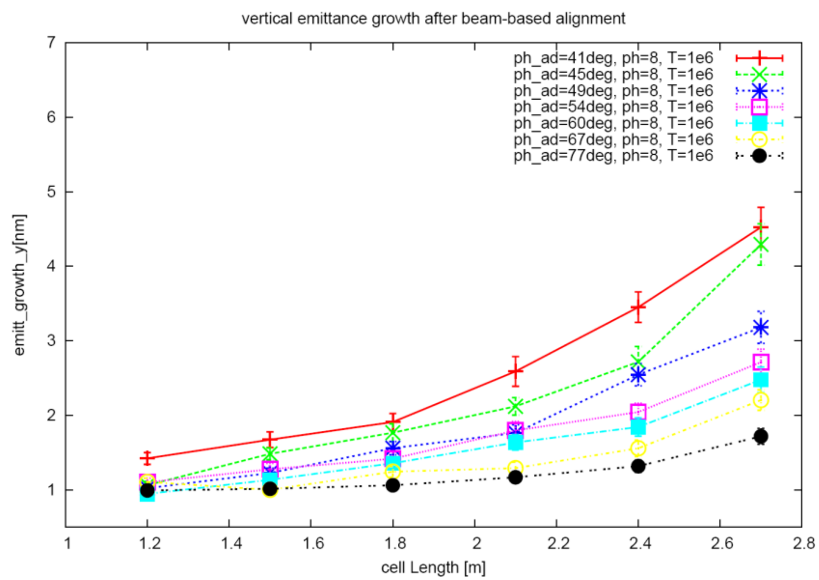




Design and optimization of 1TeV CLIC main linac

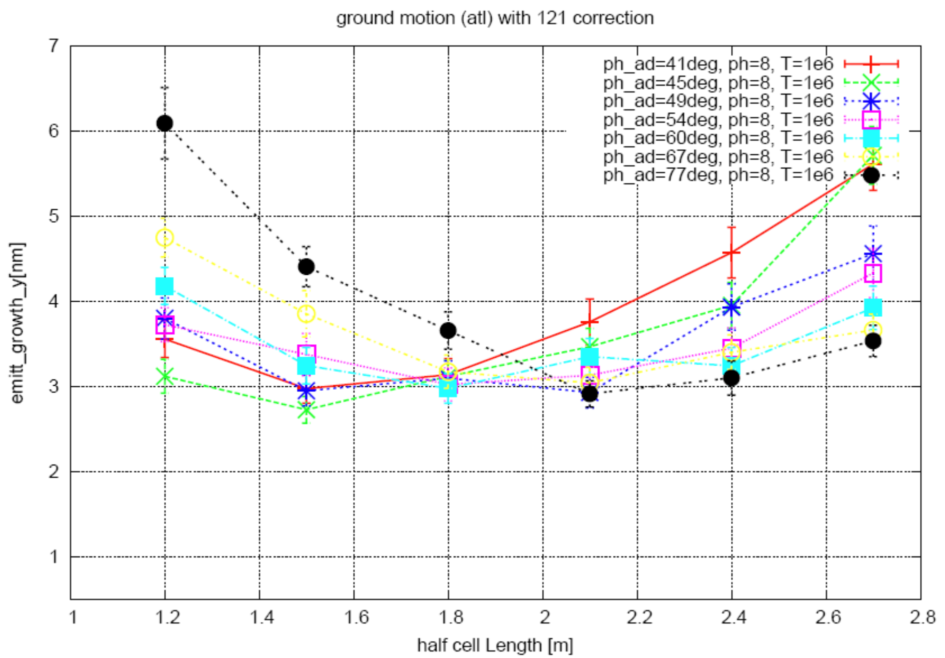
- We study the effect of static imperfections and beam-based alignment.
  - same prealignment tolerances for the static imperfections with 3TeV design
  - We implement 1-2-1, DFS and WFS correction.
  - The figure show that the lattices with initial half cell length 1.2m-2.7m and phase advance 41degree-77degree all meet the requirement on static emittance growth(5nm*rad) .

imperfection	with respect to	symbol	target value
BPM offset	wire reference	σ_{BPM}	14 μm
BPM resolution		σ_{res}	0.1 μm
accelerating structure offset	girder axis	σ_4	10 μm
accelerating structure tilt	girder axis	σ_t	200 μradian
articulation point offset	wire reference	σ_5	12 μm
girder end point	articulation point	σ_6	5 μm
wake monitor	structure centre	σ_7	5 μm
quadrupole roll	longitudinal axis	σ_r	100 μradian



Design and optimization of 1TeV CLIC main linac

- We also study the effect of dynamic imperfections.
  - For ground motion, we get primary results with simple ATL model.
  - The figure shows the vertical emittace growth after 1-2-1 corretion for about 12 days ground motion. The static emittance growth after BBA have been considered.
  - We could find a roughly same minimum emittance (3nm*rad)for each phase advance (41deg-77deg).



Documentations and presentations

- Dou Wang, D. Schulte, J. Gao and F. Stulle, Design Study of the CLIC Booster Linac with FODO Lattice, EUROTeV Report 2008-092 or pac09.
- Wang Dou's Ph.D thesis, May, 2011, IHEP.
- Yiwei Wang, Andrea Latina and Daniel Schulte " The Effects of the External Dipole Modes from the PETS ", LCWS11, Madrid, 2011.

Funds obtained

- Started from 2012.1.1 IHEP LC group obtained a fund from National Sceince Fundation of China (NSFC) on future linear collider beam dynamics, in which, IHEP-CLIC Collaboration on beam dynamics is included as one of the research items
- A new Ph. D student of Prof. J. Gao, Mr. Ming QIAO will come back to IHEP after Master degree course studies, and join the LC beam dynamics studies.

Future plan

- Together with the progress of linear collider study (ILC +CLIC), the synergy of beam dynamics efforts in both projects will speed up.
- IHEP LC beam dynamics group members will work both on ILC and CLIC.
- Exchange visiting scholars hope keep going as in previous years.
- Visitors from CLIC to IHEP are welcome.
- Regular Webex working meeting between IHEP and CLIC is proposed to establish (Prof. J. Gao would coordinate both beam dynamics and rf hardware from IHEP side, beam dynamics: Prof. J. Gao, and rf hardware: Prof. Feng Li Zhao).
- It is proposed to have a LC beam dynamics workshop in late 2012 at IHEP (if as ICFA beam dynamics panel workshop, we could start to apply)

Thanks

-Many thanks to Jean Pierre Delahaye, with whom we initiated the collaboration on beam dynamics between IHEP and CERN on CLIC at Dubna, Russia, in 2008.

-Many thanks to Daniel Schulte, under whom two IHEP Ph. D students works at CERN on CLIC with his guidance.

-Many thanks to Steinar Stapnes, with his support the collaboration will keep going…