Alignment model for ILC Main Linac beam dynamics simulations

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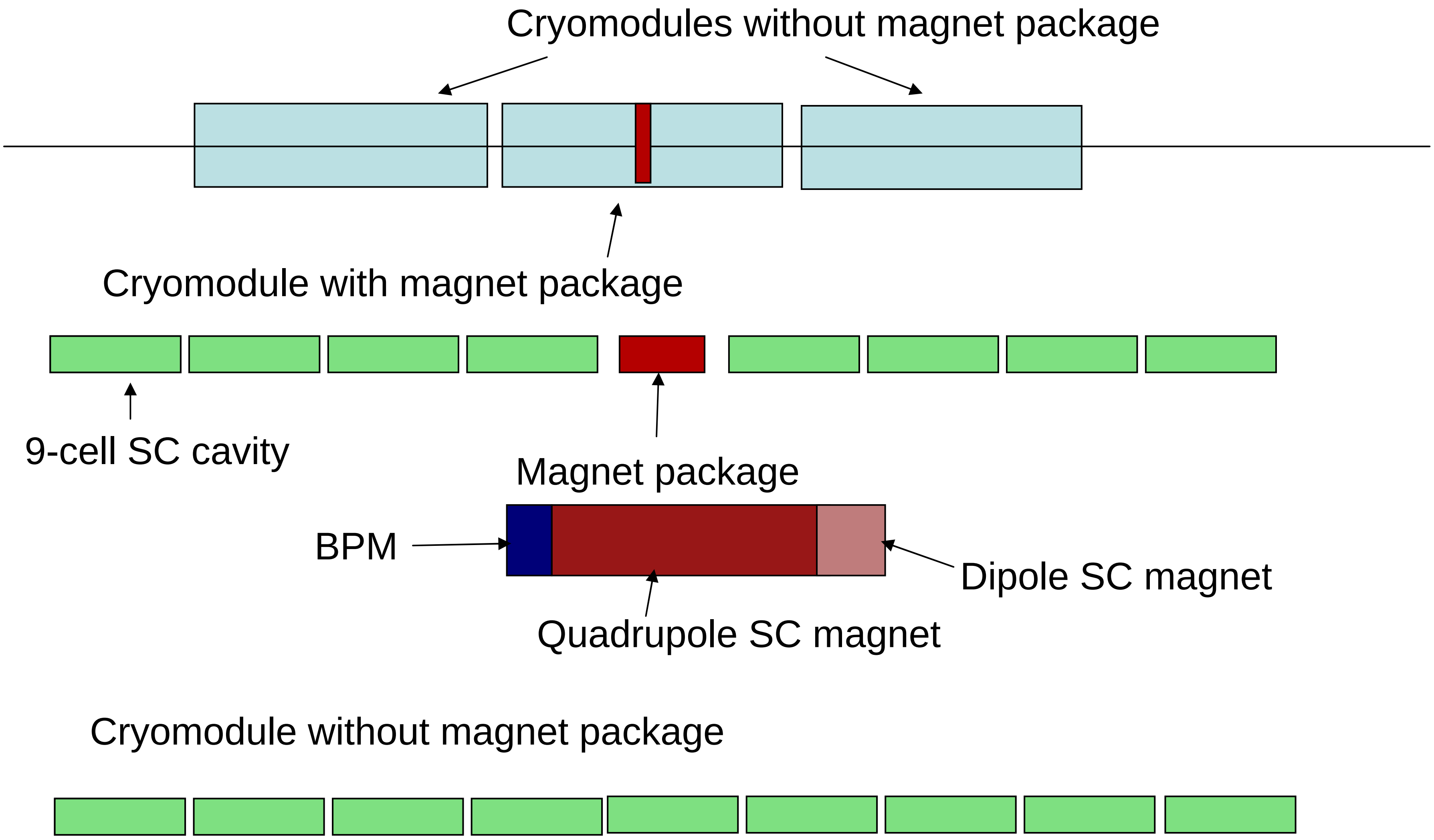
From Beam Dynamics Point of View

1. Introduction
2. Local independent misalignment
    - Review of beam dynamics simulation studies
3. Model of Survey Line
    - Some results of beam dynamics simulations

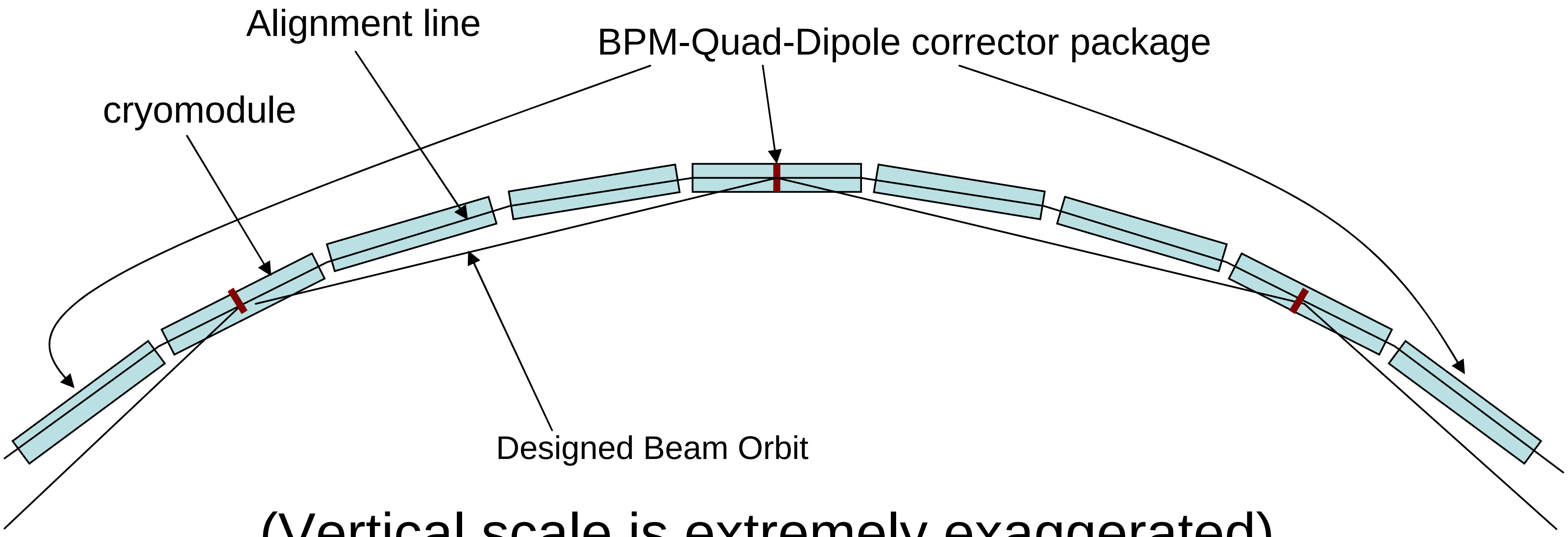
ILC Main Linac

- About 11 km long
- Beam energy 15 GeV to 250 GeV
- Following earth's curvature
- Consists of iterations of units (about 280 units),
  - 3 cryomodules
    - 1 module, quad magnet and 8 cavities
    - 2 modules, each has 9 cavities
  - One klystron feed power to one unit
- Emittance: $\gamma\varepsilon_x$=10 μrad, $\gamma\varepsilon_y$=20 ~ 30 nm

Unit of main linac, about 280 units/linac



Alignment and Beam Orbit in Curved Linac, Following earth curvature



(Vertical scale is extremely exaggerated)

This difference between the designed alignment line and the designed beam orbit has no significant effect in beam dynamics.

Alignment models in past LC beam dynamics simulations

- Most simulations assume
  - Random and independent misalignment of every component with respect to perfect design lines.
    - For Main Linac, random cryomodule misalignment + component misalignment with respect to cryomodule
  - Error of survey line has not been included.
- Some studies included long range misalignment
  - Alignment along sinusoidal lines for estimating relevant alignment length
  - Ground motion model.
    - ATL like misalignment
    - Wave

Long range alignmenthas not been well studied by beam dynamics point of view. Because:

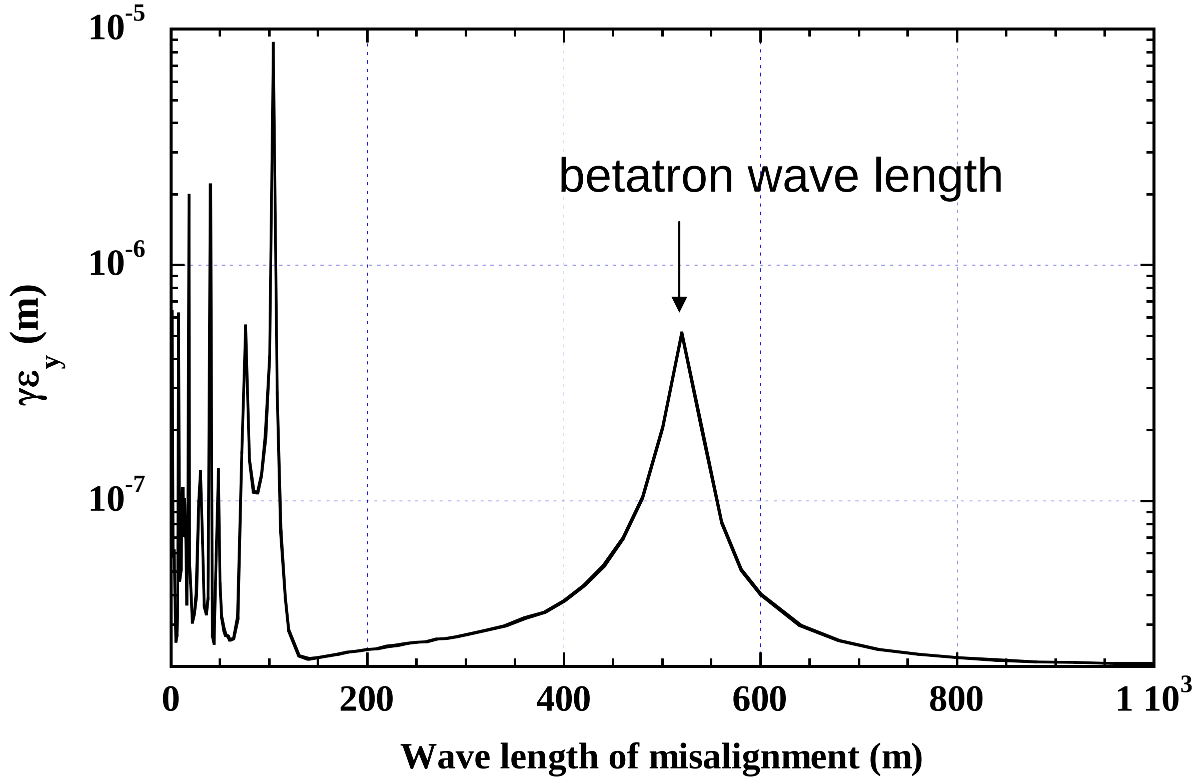
- Believed not to be a problem. (?)
  - Long range misalignment, longer than beta-function, should not be important in beam dynamics.
  - Survey line will be smooth enough in such range.
  - Is this correct?
  - How smooth is smooth enough?
    - I can not answer now.
    - Survey/alignment people and beam dynamics people need to work together to answer to this question.
- No realistic models available. (?)
- Trial of Long range alignment model will be presented here

Relevant length of misalignment

Final emittance vs. wave length of sinusoidal offset.

Components are placed along sinusoidal line. Amplitude 1 mm.

One to one steering: beam goes through center of every BMP.



Misalignment in length >> betatron wave length does not matter.

Corrections in ILC Main Linac

- Initial alignment will never be accurate enough for low emittance preservation.
- Beam based corrections (steering or re-alignment based on measurement of beam orbit and/or beam size) is necessary.
- Here, DFS (Dispersion Free Steering) is assumed for estimating tolerances, etc..
  - Measure orbits with different accelerating voltages. Then, set steering magnets to make the differences as designed (zero in laser straight linac, but non-zero in curved linac).
  - DFS has been well established technique (in simulations). There are some variations and possible choices of parameters.
  - DFS in various simulation codes were cross checked.
  - Following simulation results assume one of DFS algorithms with a certain set of parameters.

First part of this talk

- Review of past beam dynamics simulation works of ILC Main Linac
  - Tolerances (or assumptions, standard misalignment) of component alignment in ILC Main Linac
  - Assuming Random and independent misalignment

“Nominal” errors in ILC Main Linac (RMS)

Quad offset w.r.t. Cryomodule (μm)	300
Cavity offset w.r.t. Cryomodule (μm)	300
BPM offset w.r.t. Cryomodule (μm)	300
Quad roll w.r.t. design (μrad)	300
Cavity pitch w.r.t. Cryomodule (μrad)	300
Cryomodule offset w.r.t. survey line (μm)	200
Cryomodule pitch w.r.t. survey line (μrad)	20
BPM resolution (μm)	1

“survey line” is “design line” in most cases.
Realistic enough for “local” alignment. (?)

“Standard” Independent errors translated from the “Nominal” errors (RMS)

	Vertical	Horizontal
Quad Offset (μm)	360	1080
Quad Roll (μrad)	300	
Cavity Offset (μm)	640	1920
Cavity Pitch and Yaw (μrad)	300 (pitch)	900 (yaw)
BPM Offset (μm)	360	1080
BPM Roll (μrad)	0	
BPM resolution (μm)	1	1
BPM scale error	0	0

Horizontal errors are chosen to be three times of vertical errors.

Calculation of “Independent errors” equivalent to “Nominal” errors

Effects of misalignment of RF cavities:

Transverse kick due to

- Offset error with Wakefield
- Tilt error with accelerating field

Total effect of cavities in one cryomodule depends on only:

Average offset and average tilt

(Because length of cryomodule << beta function)

Calculation of “Independent errors” equivalent to “Nominal” errors

Error of components installed in cryomodules.

$$\sigma_{c,i}^2 = \sigma_c^2 + n_c \sigma_{cryo}^2$$

$\sigma_{c,i}$: Error of component with respect to survey line

σ_c : Error of component with respect to cryomodule

σ_{cryo} : Error of cryomodule with respect to survey line

n_c : Number of components installed in a cryomodule

E.g., if 9 cavities are in a cryomodule,
“Cryomodule pitch 20 μrad, Cavity pitch 300 μrad” and
“Cryomodule pitch 180 μrad, Cavity pitch 250 μrad” have the same effect.

This is an approximation, which is good if
length of the cryomodule << beta-function and
Beam energy change in a cryomodule << beam energy

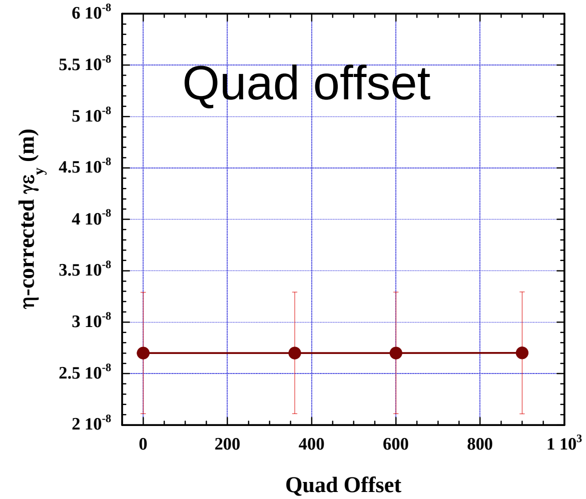
Sensitivity of final emittance to each item of errors

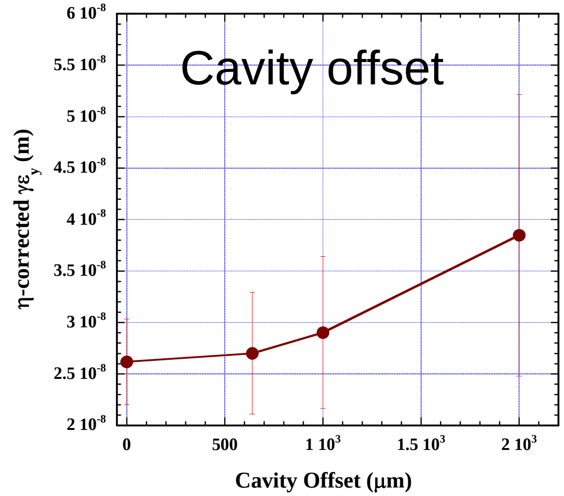
- Tracking simulation of single bunch beam
- Assuming DFS correction
- Change RMS of one item, keeping RMS of other errors constant
- 40 random seeds for one setting

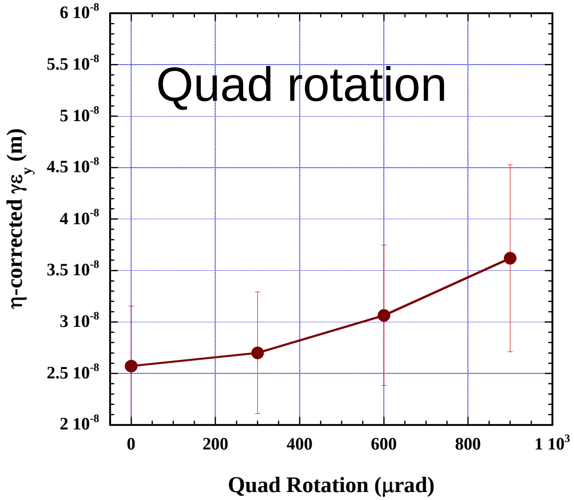
Sensitivity to each error-1 (emittance vs. error)

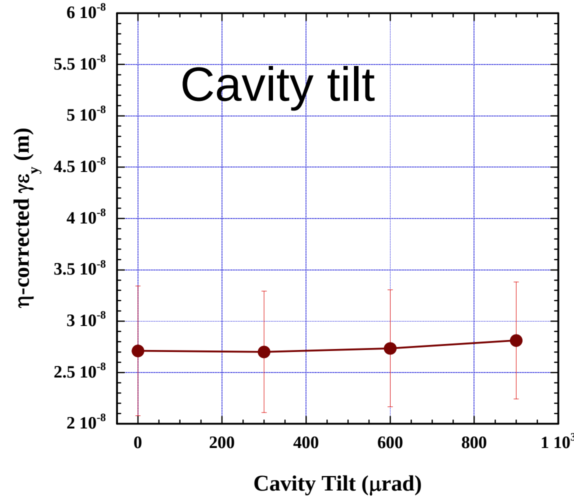
Other errors are kept as “standard”. Initial $\gamma\varepsilon$=2E-8 m.

Average of 40 random seeds. Error bars indicate standard deviations.





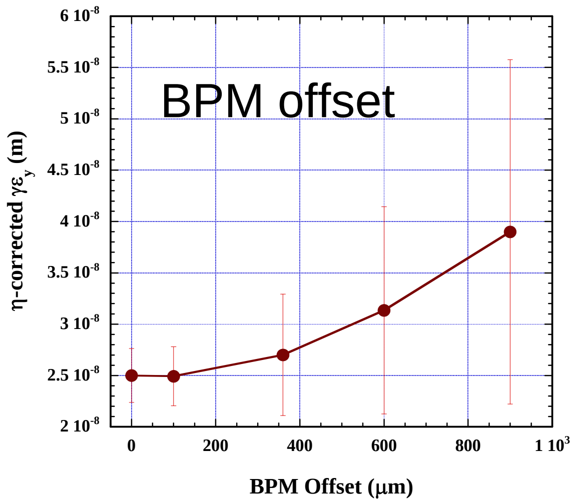


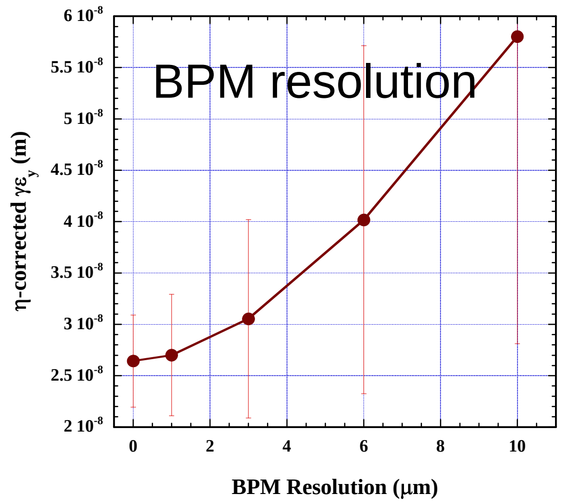


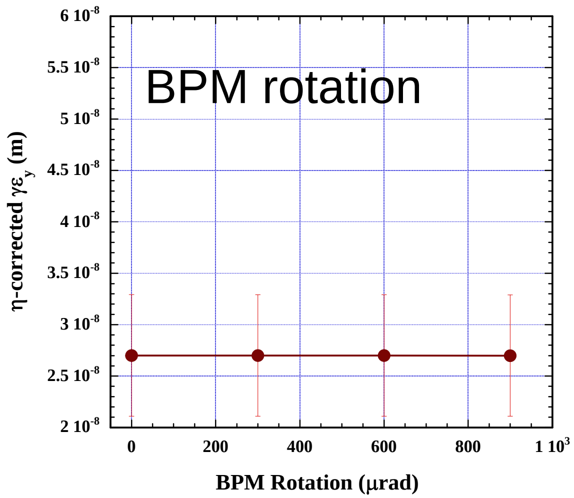
Sensitivity to each error-2

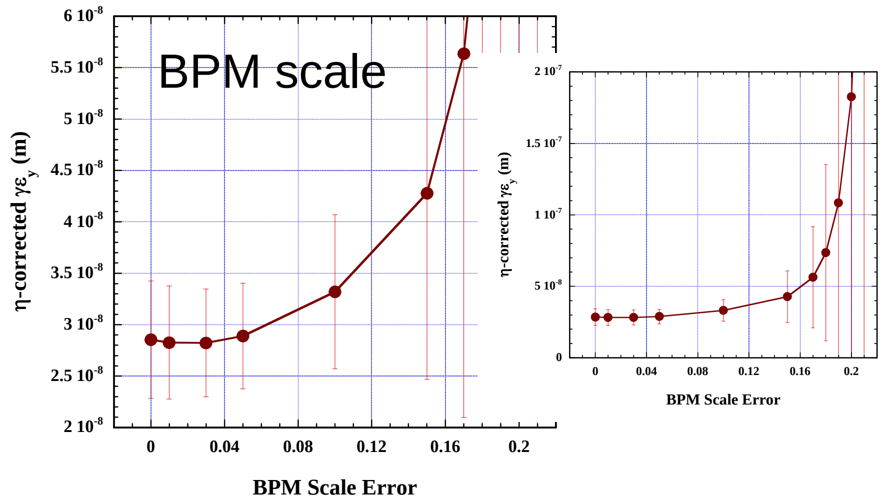
Other errors are kept as “standard”. Initial $\gamma\varepsilon$=2E-8 m.

Average of 40 random seeds. Error bars indicate standard deviations.









Sensitivity to each alignment error

- Very little sensitivity to Quad offset
  - up to 900 micron
- Very little sensitivity to Cavity tilt
  - up to 900 micro radian

- Some sensitivity to Cavity offset and BPM offset
  - DFS does not correct effects of cavity wake fields.
- Some sensitivity to Quad rotation
  - DFS does not cure the x-y coupling.
- Additional corrections may be possible to cure them, if necessary.

As Conclusion,

the “Nominal” set of alignment error is good enough !!!

Part 2: Including long range alignment, or survey line

- We are trying to make a realistic model of survey and alignment
  - Realistic enough for beam dynamics, but
  - As simple as possible.
- Started in summer of last year.
- Test model and some simulation results will be shown here.
- Need your (survey/alignment experts’) help !!

Alignment (offset and tilt) model

1. Mark primary reference point, every 2.5 km.
   - Error will be random, independent Gaussian. (~mm or cm ?)
   - 2.5 km corresponds to distance between shafts

2. Between them, mark reference point every ? (5~250) m
   - Survey from one primary point to the next one.
   - Error will be from random walk (random angle and offset)
   - One step length depends on method of survey

3. Girders, cryomodules and other independent components will be placed w.r.t. the nearest reference.
   - Error will be random, independent Gaussian, w.r.t. survey line.

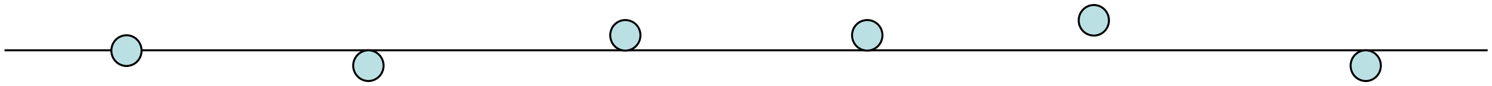
4. Most components are placed on girders or cryomodules
   - Error will be random, independent Gaussian, w.r.t. girders/cryomodules

Comment on alignment model

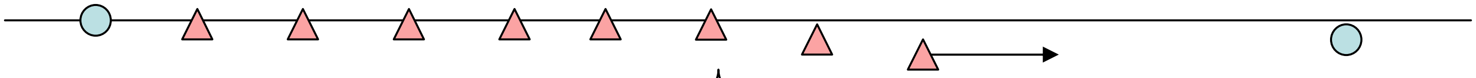
- Alignment model in beam dynamics simulation is not necessarily simulate actual alignment process.
- But it have to reproduce the result of alignment.
- , , , , ,?

Alignment procedure

Every 2.5 km, primary references,
? using GPS? Random error.

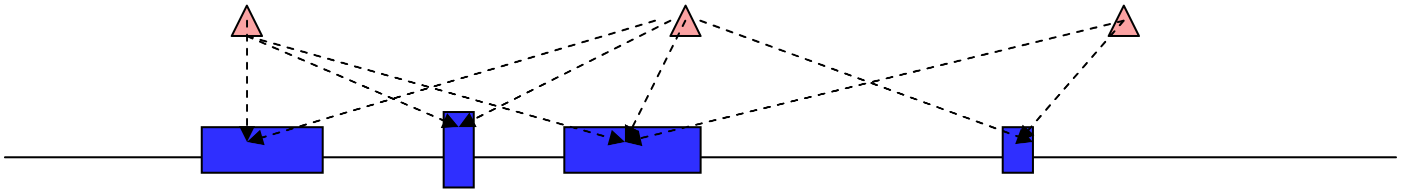


Survey from one primary reference to the next.
Every about 5~50 m, mark reference point



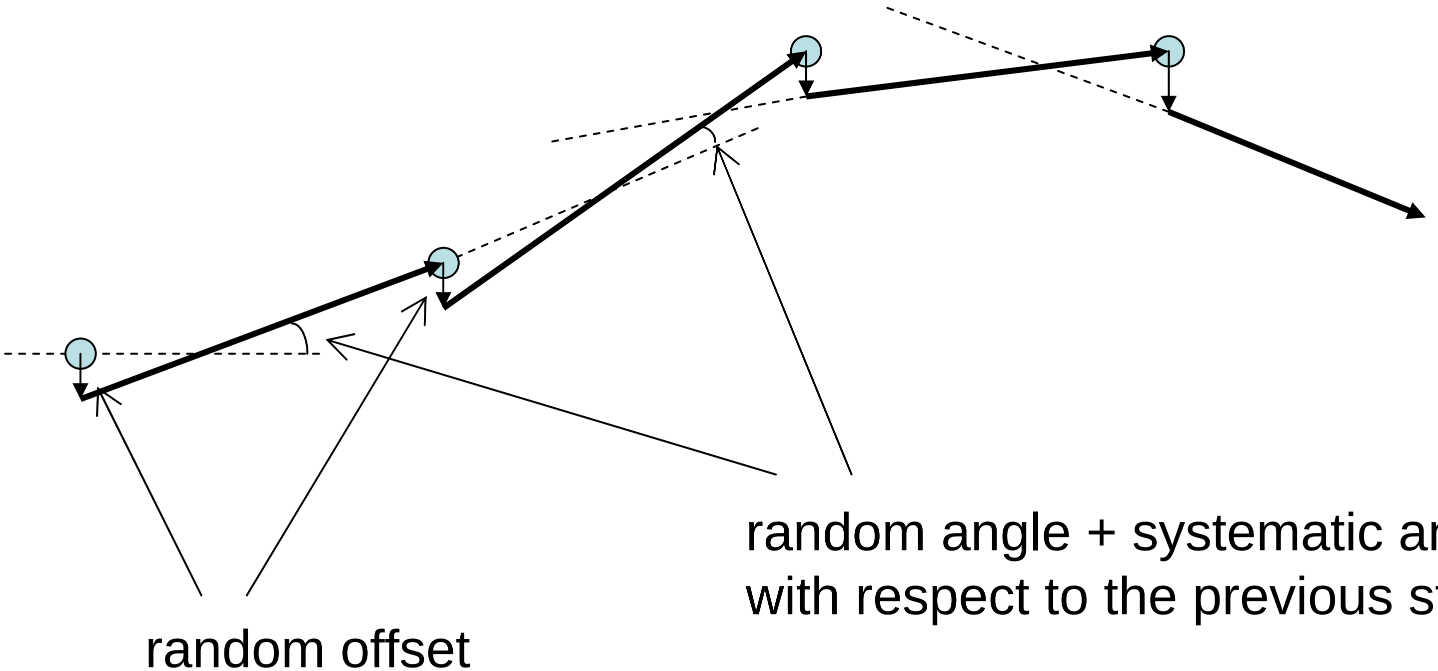
Applied to tracking simulation

Girders, cryomodules, etc. are aligned w.r.t. the reference.



Not yet applied to simulation

Step by step survey:
Random Walk + systematic angle error



Parameters: l_{step} : length of one step

a_y : random offset/step

a_θ : random angle error/step

θ_O : systematic angle error

Expressed by equations

reference point). Let $y_{0,j,n}$ denote the offset at the n-th step in the j-th region and $\theta_{j,n}$ the angel of the n-th step in the j-th region, the effect of the one step can be expressed as:

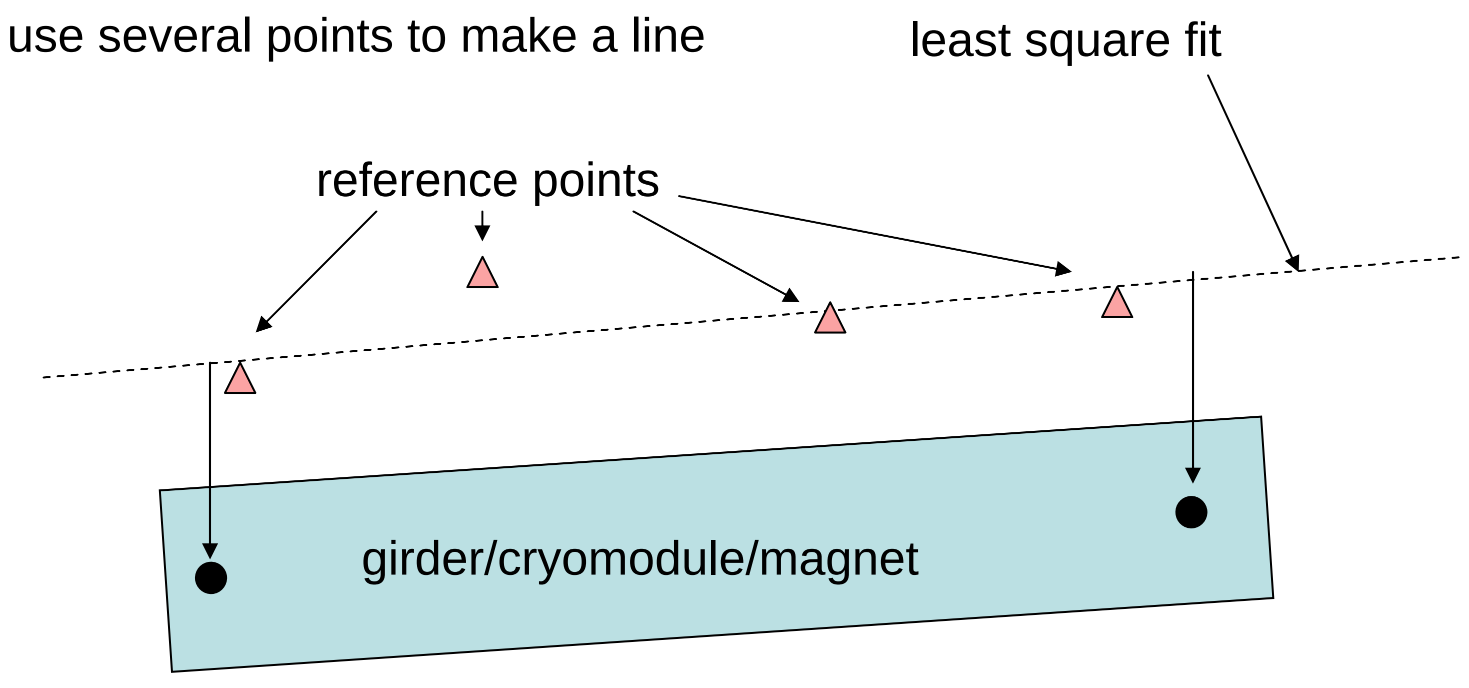
$$\begin{aligned} \theta_{j,n+1} &= \theta_{j,n} + G(a_\theta, t_\theta) + \theta_O \\ y_{0,j,n+1} &= y_{0,j,n} + G(a_y, t_y) + l_{step}\theta_{j,n+1} \qquad (0 \le n \le N-1) \quad \text{(1-2)} \\ y_{0,j,0} &= y_{P,j} \end{aligned}$$

where a_y, t_y, a_θ and t_θ are parameters for the random walk and θ_O represents systematic error. (See reference [1].)

N is the number of steps in the j-th region, $n=0$ corresponds to the j-th primary reference point and $n=N$ corresponds the $j+1$-th primary reference point. It is natural to make L_r / l_{step} integer.

From reference [1], tentative parameters can be $a_y = 0.5\ \mu\text{m}$, $a_\theta = 0.1\ \mu\text{rad}$ and $l_{step} = 4.5\ \text{m}$.

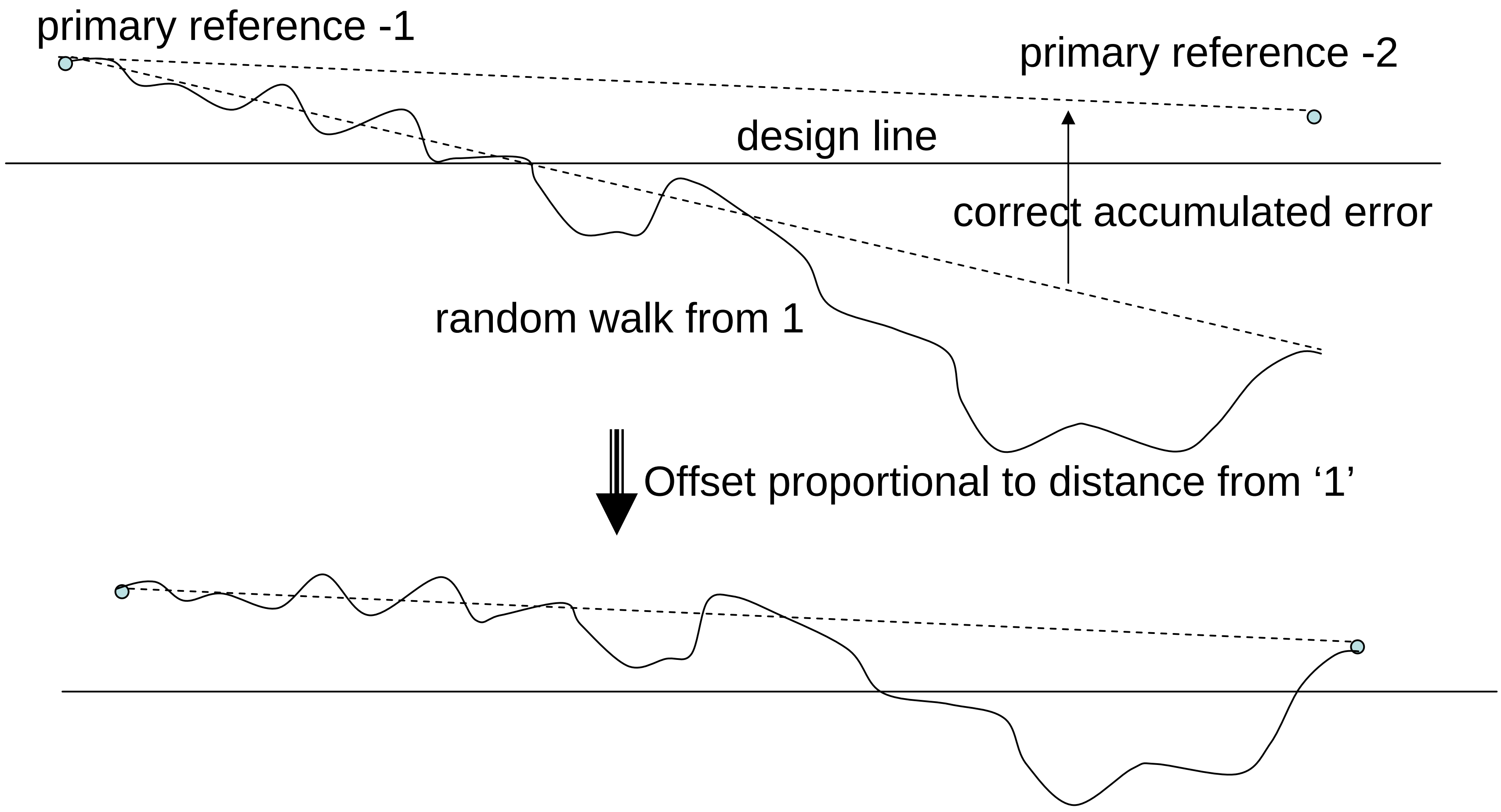
Survey line to component alignment, Alignment model w.r.t. reference points (example)



Rotation error model

- Rotation is adjusted w.r.t. gravity
  - Independent of survey line
  - Can variation of gravity be ignored?
- Every warm magnet has independent random error
- Every cryomodule has independent random error
  - Cold magnet and cold BPM has random error w.r.t. cryomodule

Correction of accumulated error in Random Walk using primary reference



This simple correction makes kinks at primary references and may not be good choice. (see beam simulation results later.)
There must be better methods? Still under study.

Correction of accumulated survey line error using primary references

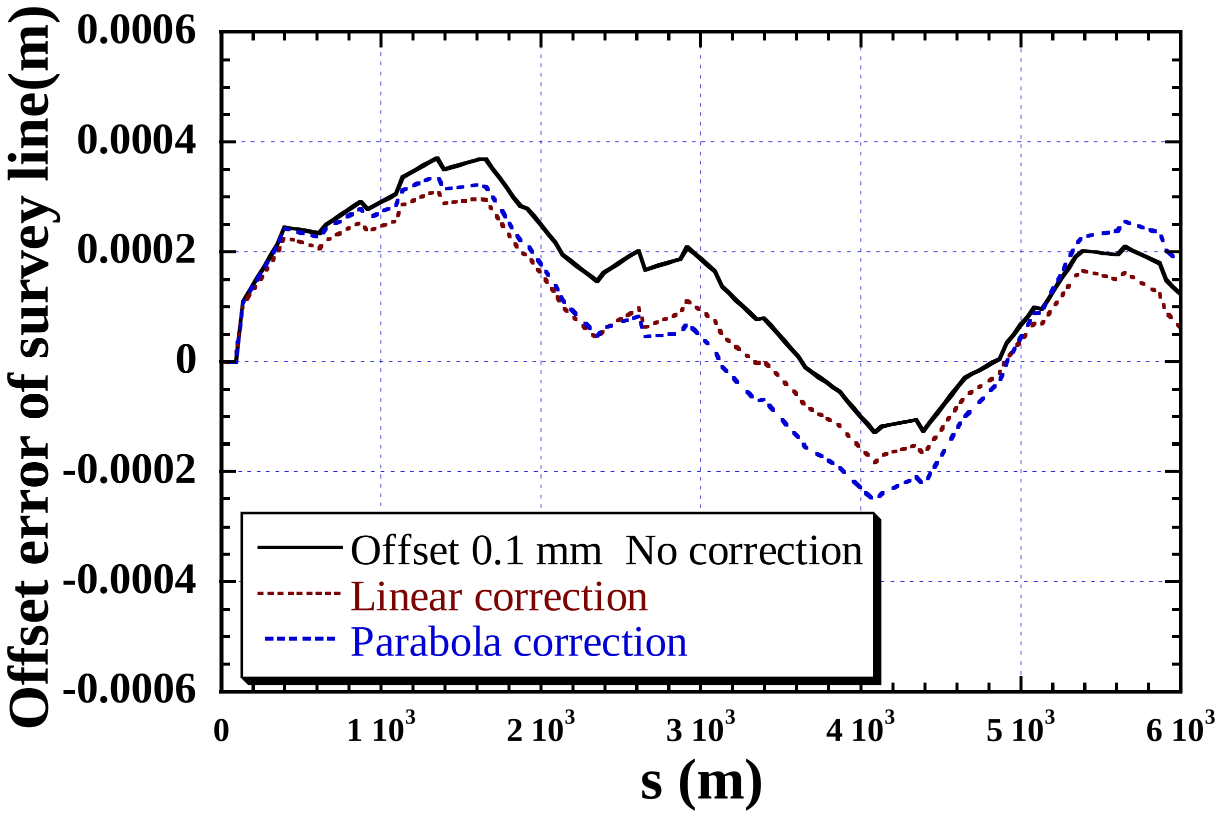
- Linear correction
  - Correction proportional to distance from the start point.
  - Angle error of first step is canceled.
  - Causes kinks at primary reference. (Problem?)
- Parabola correction
  - Correction proportional to square of distance from the start point.
  - Angle error of first step is not canceled. (How to treat the initial angle error is not clear.)
  - No kinks.
- Other methods
- Optimum method will depend on expected range of errors. (?)

Three cases (No correction, linear correction and parabola correction) were compared in tracking simulations.

Example: Comparison of correction of accumulated error 1

Spacing of primary references: 2500 m, Error of primary reference: 0
Step length of survey (random walk): 50 m

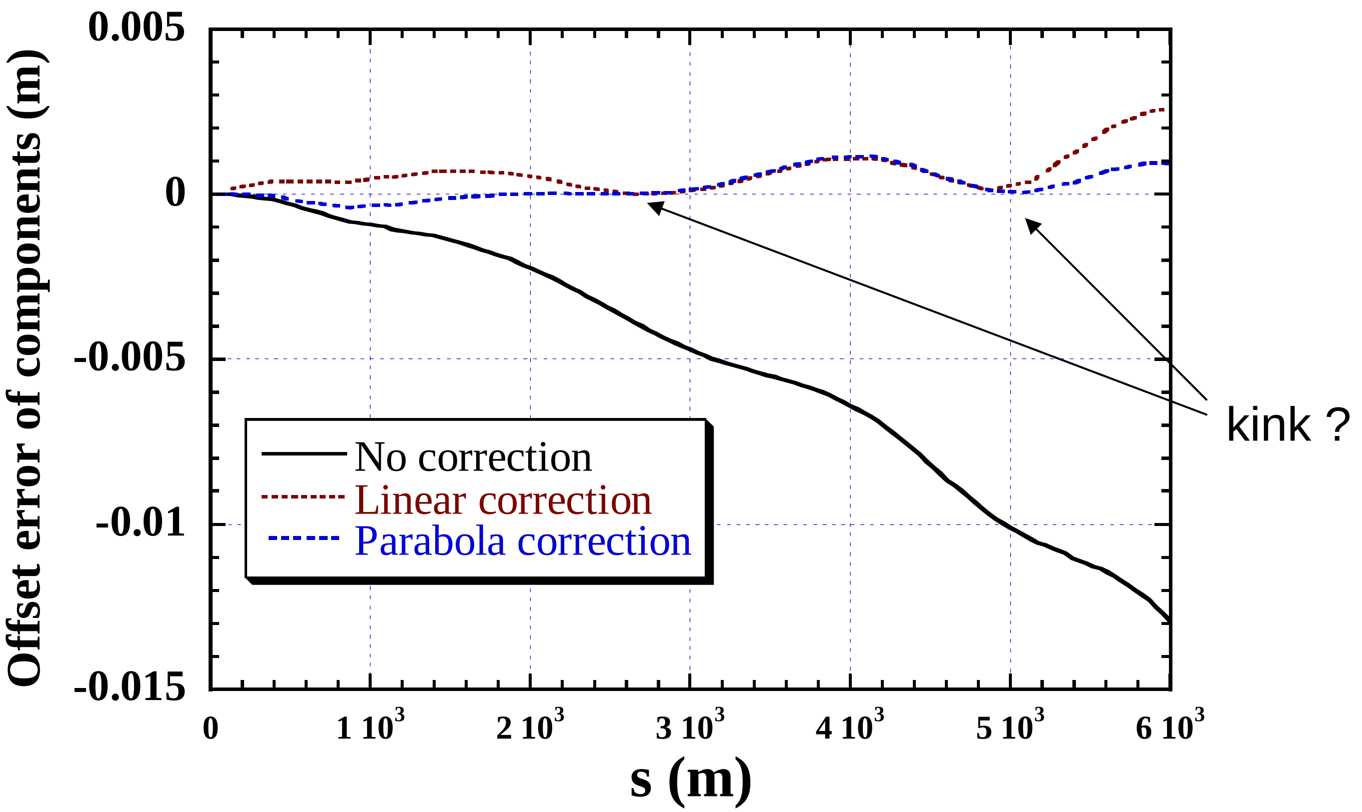
Offset error /step, a_y = *100 μm*, Angle error/step, a_θ = *0*



Example: Comparison of correction of accumulated error 2

Spacing of primary references: 2500 m, Error of primary reference: 0
Step length of survey (random walk): 50 m

Offset error /step, $a_y = 0$, Angle error/step, $a_\theta = 1\ \mu rad$



Survey model was applied to tracking simulations

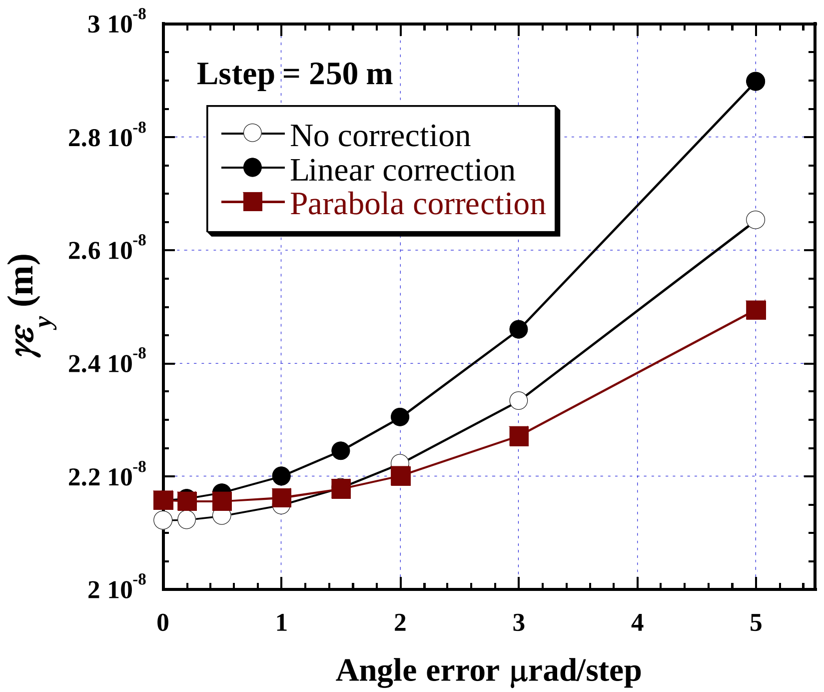
First trial: Using simplified model

- Every component (quad, cavity or BPM) is aligned perfectly along the survey line
  - For each component, use the three closest reference points to make a reference line (least square fitting)
  - The component is placed along this line perfectly.

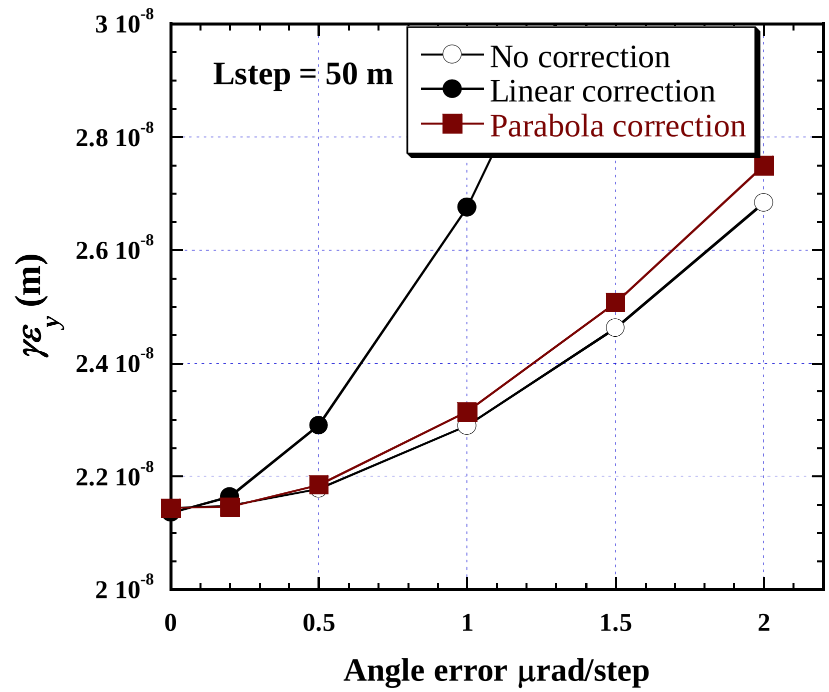
This model can be applied also to most of RTML(Ring to Main Linac) and BDS (Beam Delivery Sytem). But here, only Main Linac was studied.

Angle error of random walk vs. Final emittance after DFS correction

Step length 250 m



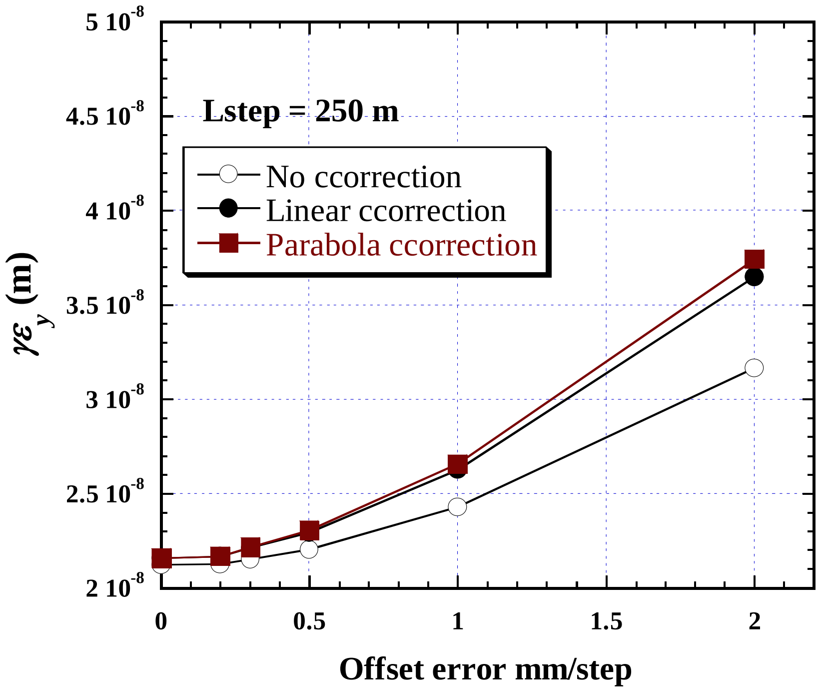
Step length 50 m



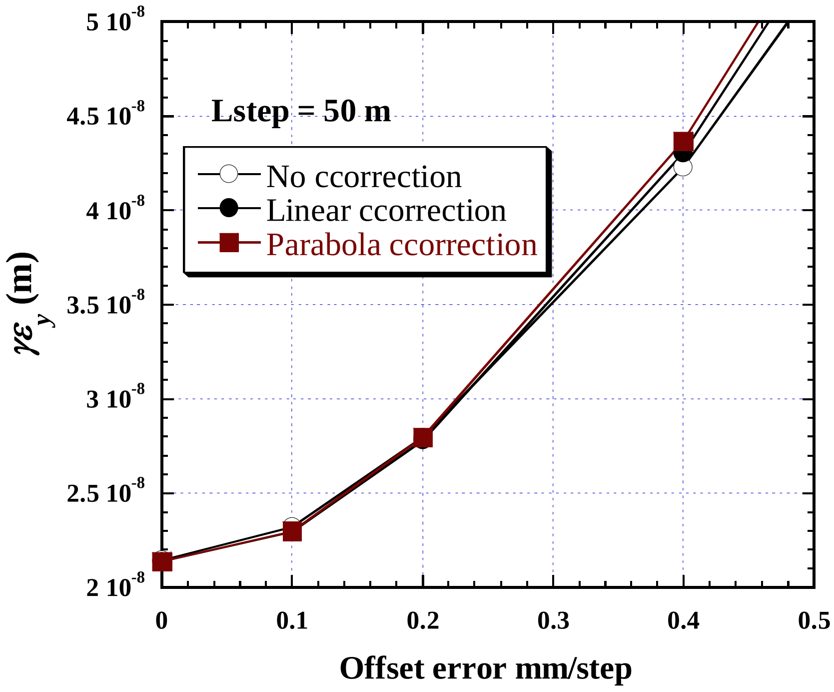
No other errors, except BPM resolution 1 μm

Offset error of random walk vs. Final emittance after DFS correction

Step length 250 m



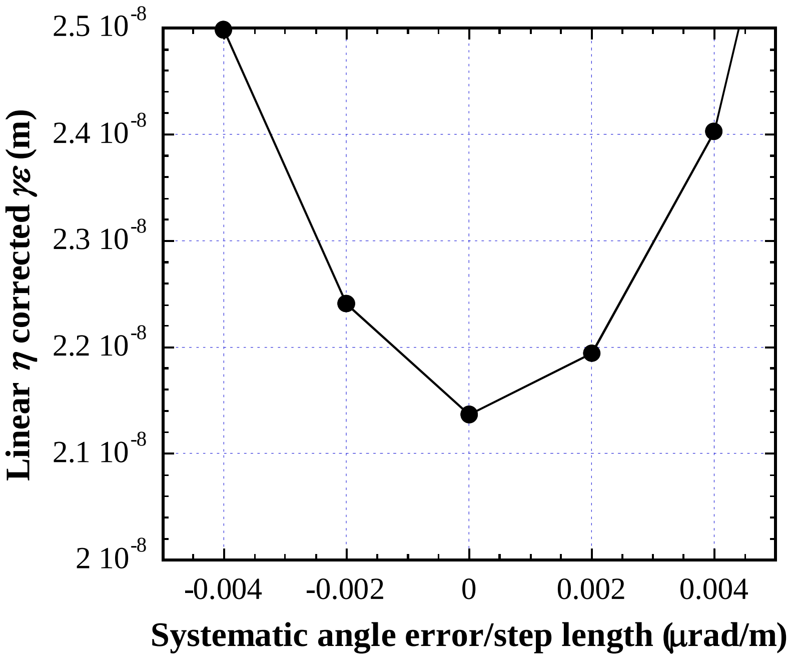
Step length 50 m



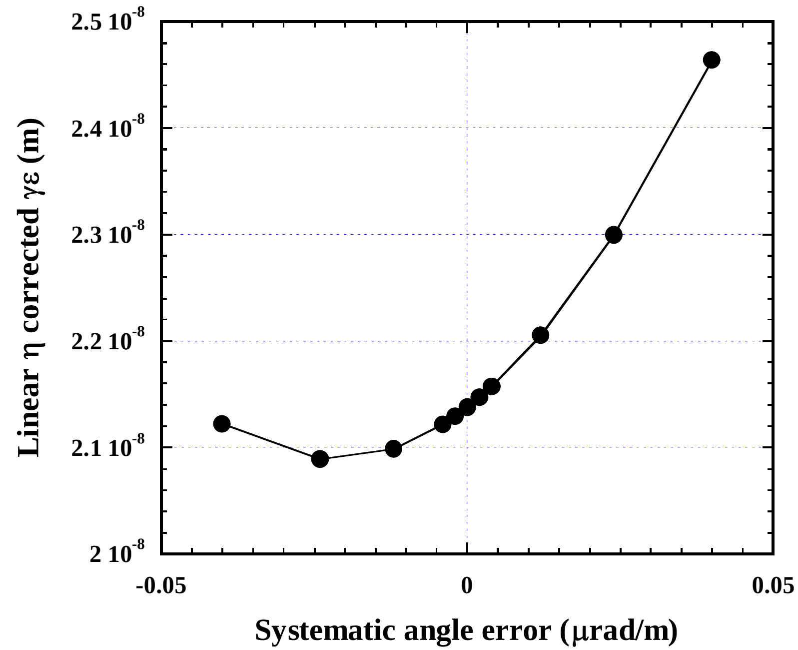
No other errors, except BPM resolution 1 μm

Systematic angle error/step vs. Final emittance after DFS correction

Linear Correction of accumulated error



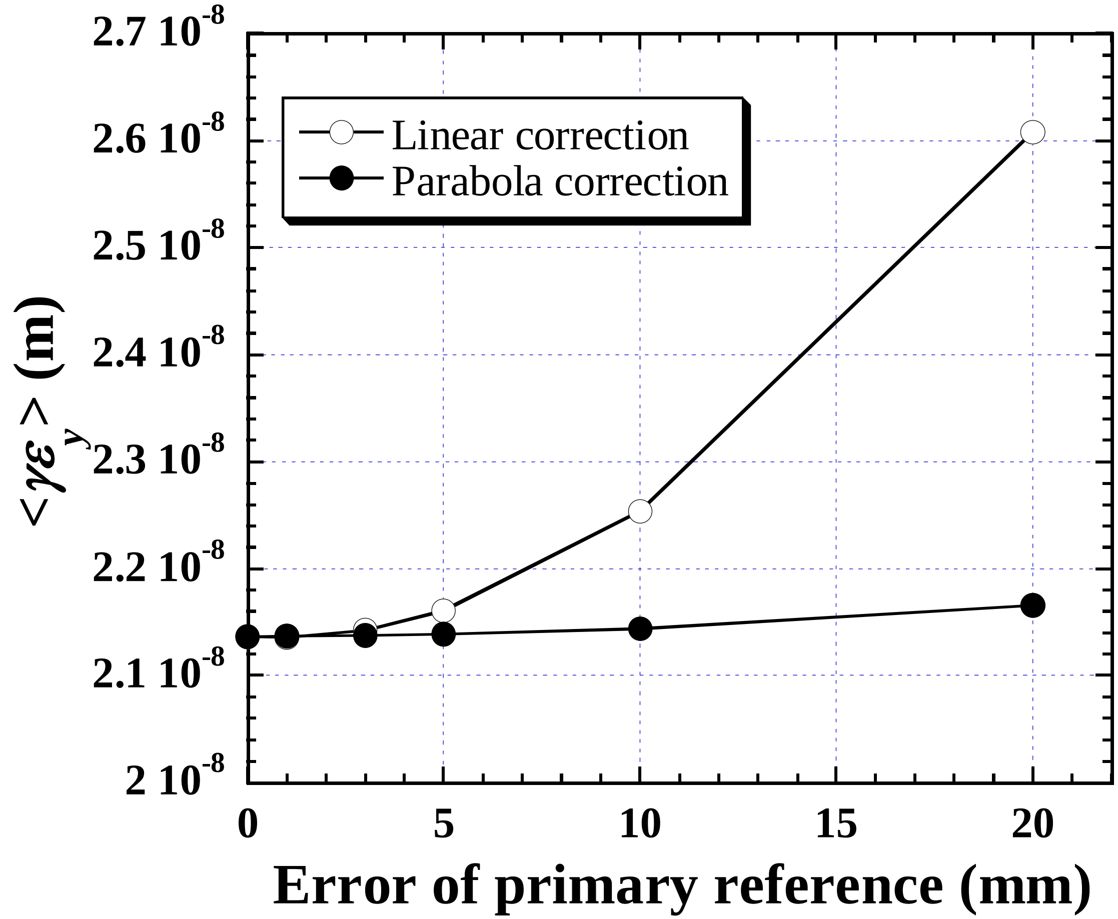
No Correction of accumulated error



(Earth's curvature = 0.16 μrad/m)

No other errors, except BPM resolution 1 μm

Offset error of primary reference (2.5 km spacing) vs. Final emittance after DFS correction

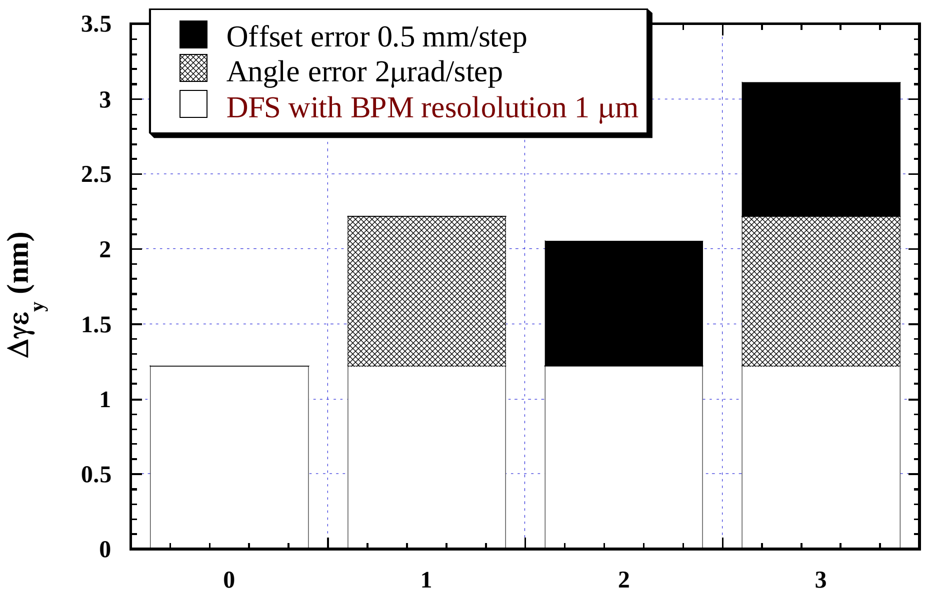


No other errors, except BPM resolution 1 μm

Contribution of each error to emittance growth is additive

Lstep=250 m, No accumulated error correction

BPM resolution (μm)	1	1	1	1
Angle error/step (μrad)	0	2	0	2
Offset error/step (mm)	0	0	0.5	0.5
Emittance growth (nm)	1.22	2.22	2.05	3.11



Parameters and “tolerances” for Survey

	Suggested numbers
Distance between primary references	2.5 km
Step length of survey	5 ~ 250 m (?)

Roughly estimated tolerances (Preliminary) $\langle \Delta\gamma\varepsilon \rangle / \gamma\varepsilon_0 \sim 5\%$		
Step length of survey	50 m	250 m
Error of primary reference	8 mm (Linear correction) 30 mm (Parabola correction)	
Random Angle error of one step	0.8 μrad	2 μrad
Random Offset error of one step	0.08 mm	0.5 mm
Systematic angle error (error of vertical curvature)	~15 % of the Earth’s curvature (~25 nrad/m)	

Summary of long range alignment

Model of Survey Line (reference points)

- Setting primary reference
- Random walk between primary reference
  - Linear correction of accumulated error may not be good.

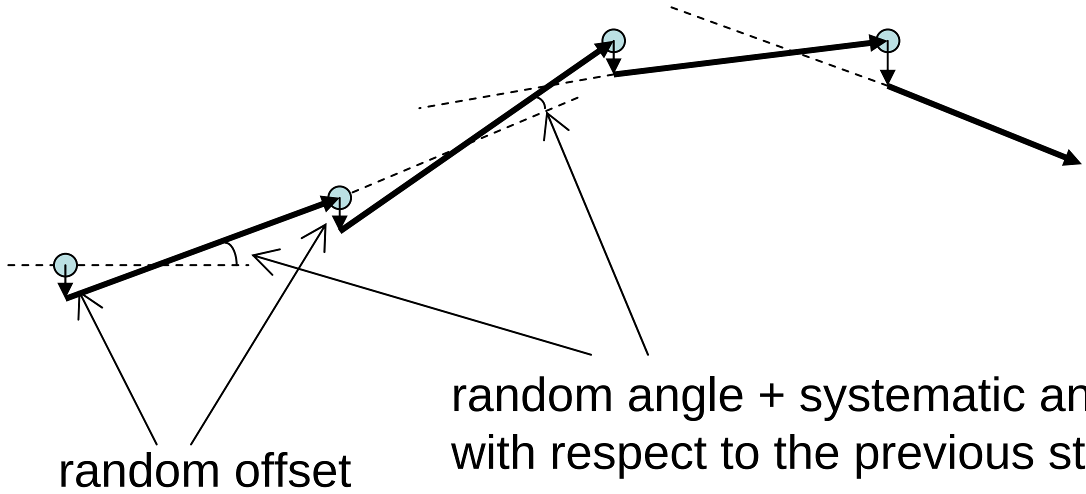
Survey line to component alignment

- Least square fit using several references
- Plus random, independent errors

Some results of tracking simulations

- Simulate error of survey line
- Assume perfect “survey line-to-component” alignment
- Perform DFS
- Tolerances look tight ?

Final Questions on Long Range Alignement



Parameters:

l_{step} : length of one step

a_y : random ofset

a_θ : random angle error

θ_O : systematic angle error

Is this model realistic enough?

If so, can you give numbers for the parameters?

If not, can you give a good model?

SUMMARY

- Short range misalignment (component by component independent misalignment) has been well studied.
  - "Standard set" of errors is good enough, assuming Dispersion Free Steering
- Long range misalignment (survey) has not.
  - Test model of survey line was constructed.
    - Realistic enough or not?
  - Applied to tracking simulations.
    - "Tolerances" were roughly estimated. Look tight (?)
  - Results have not been well understood. Need more studies.
  - We (beam dynamics workers) need help from Survey/alignment experts to make a good alignment model.

References

Document of this model:
"DRAFT: Alignment model of ILC LET components – for beam dynamics simulations"
https://lists.desy.de/sympa/arc/ilc-metapy/2007-10/pdfSdh4G1uubO.pdf

Communications:
Join mailing list ilc-metapy@desy.de
 ref: https://lists.desy.de/sympa/info/ilc-metapy
 archive of past mails: https://lists.desy.de/sympa/arc/ilc-metapy

Reports in LCWS (ILC-GDE meeting) at DESY, May-June 2007.
http://ilcagenda.linearcollider.org/sessionDisplay.py?sessionId=90&slotId=0&confId=1296 #2007-06-01
Reports in ILC-GDE meeting at FNAL, Oct. 2007.
 http://ilcagenda.linearcollider.org/conferenceDisplay.py?confId=2319
Reports in ILC-LET workshop at SLAC, Dec. 2007.
 http://ilcagenda.linearcollider.org/conferenceDisplay.py?confId=2364