EMITTANCE DILUTION IN NLC MAIN LINAC (1 TeV CM): DISPERSION FREE STEERING

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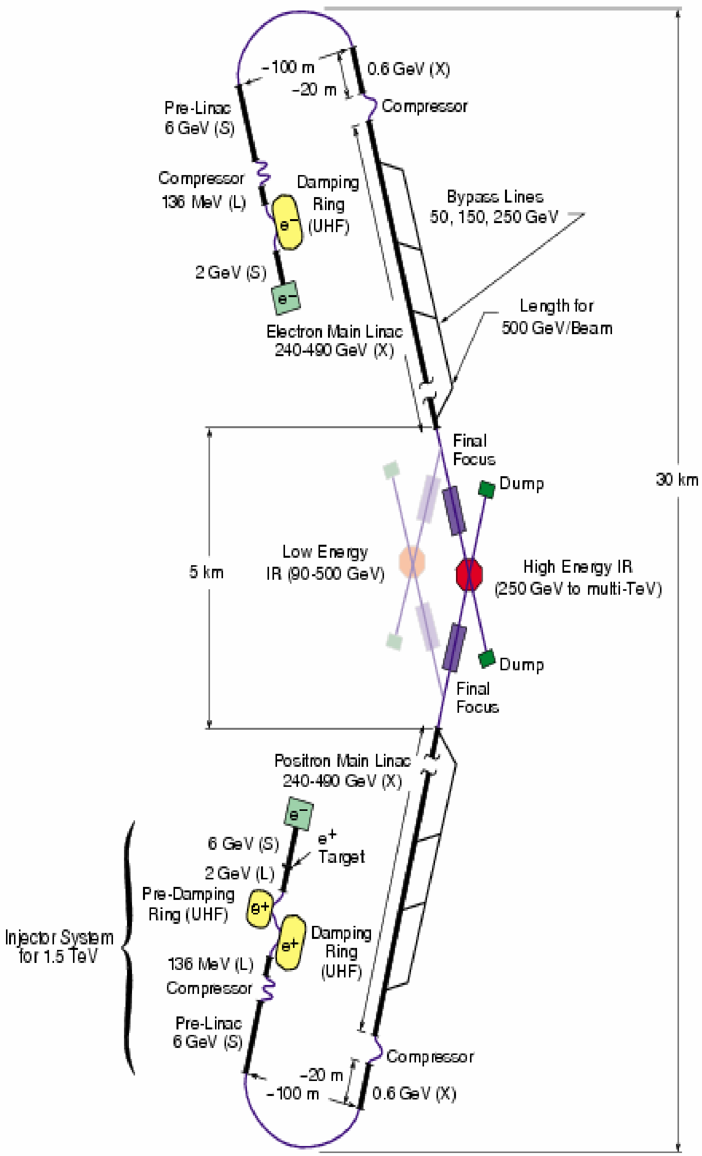
OVERVIEW

- Emittance Dilution in NLC Main Linac:
  - Single Bunch Beam Break Up
  - Incoherent sources
  - Beam Based Alignment
    - RF Structure Alignment
    - Quad Alignment
      - Dispersion Free Steering
- MATLIAR – Main Linac Simulation
- Results
- Conclusions / Plans

NEXT LINEAR COLLIDER (NLC)



NLC –Design Parameters

Parameter	NLC-500 GeV CM	NLC-1 TeV CM
Luminosity	2.0×10^{34}	3.0×10^{34}
Repetition rate	120 Hz	120 Hz
Bunch Charge	0.75×10^{10}	0.75×10^{10}
Bunch/train	192	192
Bunch separation	1.4 ns	1.4 n
Unloaded Gradient	65 MV/m	65 MV/m
Loaded Gradient	52 MV/m	52 MV/m
Inject $\gamma\varepsilon_x$	3.0 μm	3.0 μm
IP $\gamma\varepsilon_x$	3.6 μm	3.6 μm
Inject $\gamma\varepsilon_Y$	20 nm	20 nm
IP $\gamma\varepsilon_Y$	40 nm	40 nm
β_x*	8.0 mm	13.0 mm
β_Y *	110 μm	110 μm
σ_z	110 μm	110 μm
σ_x*	243 nm	219 nm
σ_y*	3.0 nm	2.3 nm
Pinch enhancement	1.51	1.47

NLC MAIN LINAC

- NLC Main linac will accelerate e^-/e^+ from ~10 GeV -> 250 GeV, (after Upgrade 500 GeV)

- There are two major design issues:
  - Efficient acceleration of the beams, and
  - Emittance preservation => Primary sources of Dilution:
    - Transverse Wakefields (Beam Break Up): Short and Long Range
    - Dispersive and Chromatic Effects
    - Transverse Jitter

- ***Vertical plane*** would be more challenging:
  - Large aspect ratio (x:y) in both spot size and emittance (~100:1)
  - 1 to 2 orders of magnitude more difficult

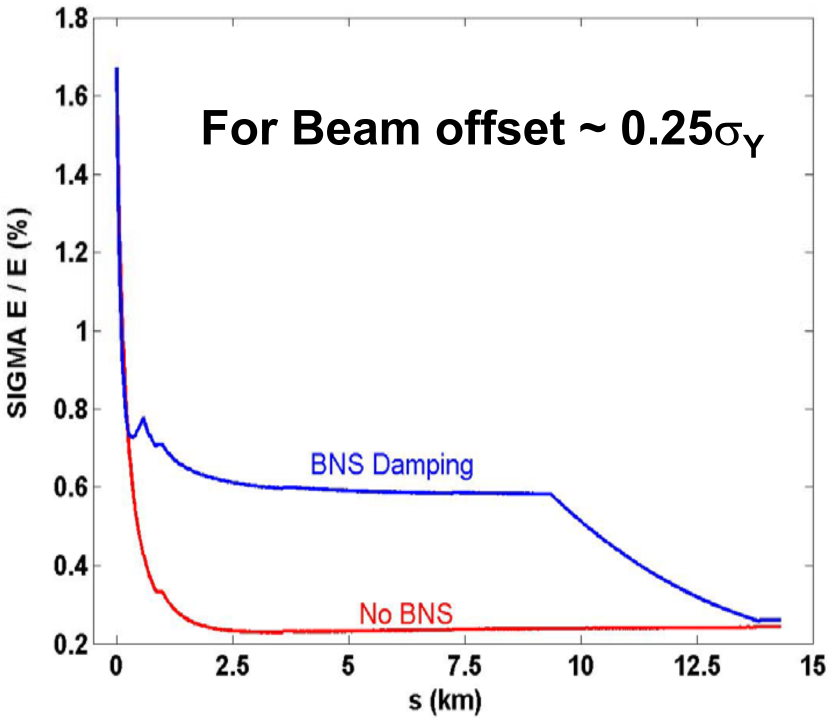
Normalized Emittance Dilution Budget in NLC Main Linac

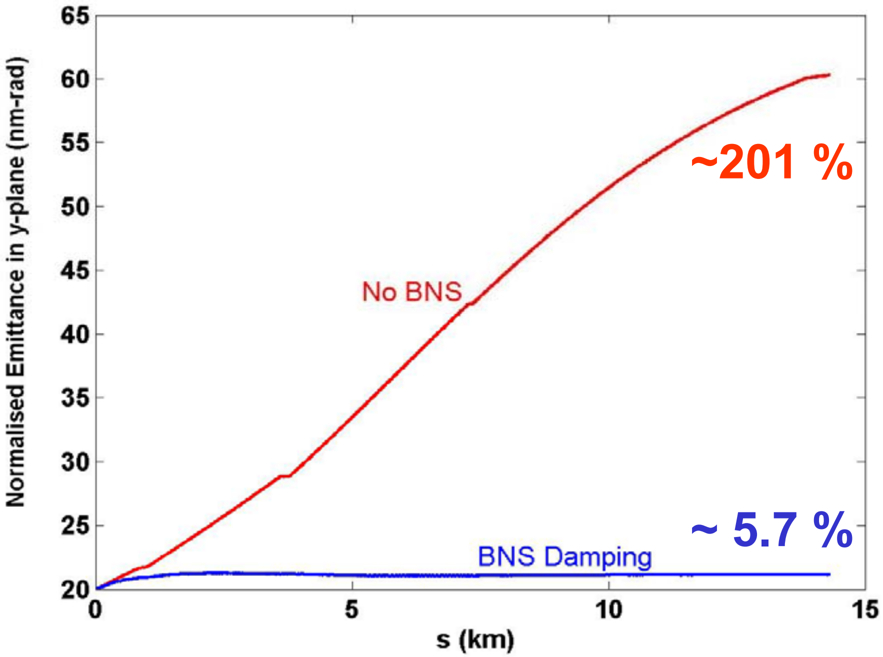
(both for 500 GeV / 1 TeV machine)

	DR Ext.	=>	ML Inject.	=>	ML Ext.	=>	IP
Hor. **(nm-rad):**	3000	=>	3200	=>	3300 (3.3%)	=>	3600
Vert. **(nm-rad):**	20	=>	24	=>	34 (50%)	=>	40

MAIN LINAC EMITTANCE DILUTION - BEAM BREAK UP (BBU)

- ☞ Occurs when beam undergoes betatron oscillation through Linac
- ➢ Single Bunch BBU
  - ☞ **Solution**: BNS Damping: Introduce ***correlated energy spread:***
    - ⇨ Bunch head higher in energy than bunch tail





- ➢ Multi Bunch BBU
  - ☞ Solution: Damped Detuned Structure

SINGLE BUNCH - WHAT's LEFT AFTER BBU?

- Chromatic and Dispersive Sources
  - Misalignments:
    - Beam-to-Quad offsets (most problematic)
    - Beam-to-RF Structure offsets
    - RF Structure pitch angles
  - Quad Roll Errors
  - Quad Strength

Misalignment Tolerances (Vertical plane) in NLC ML (500 GeV CM)

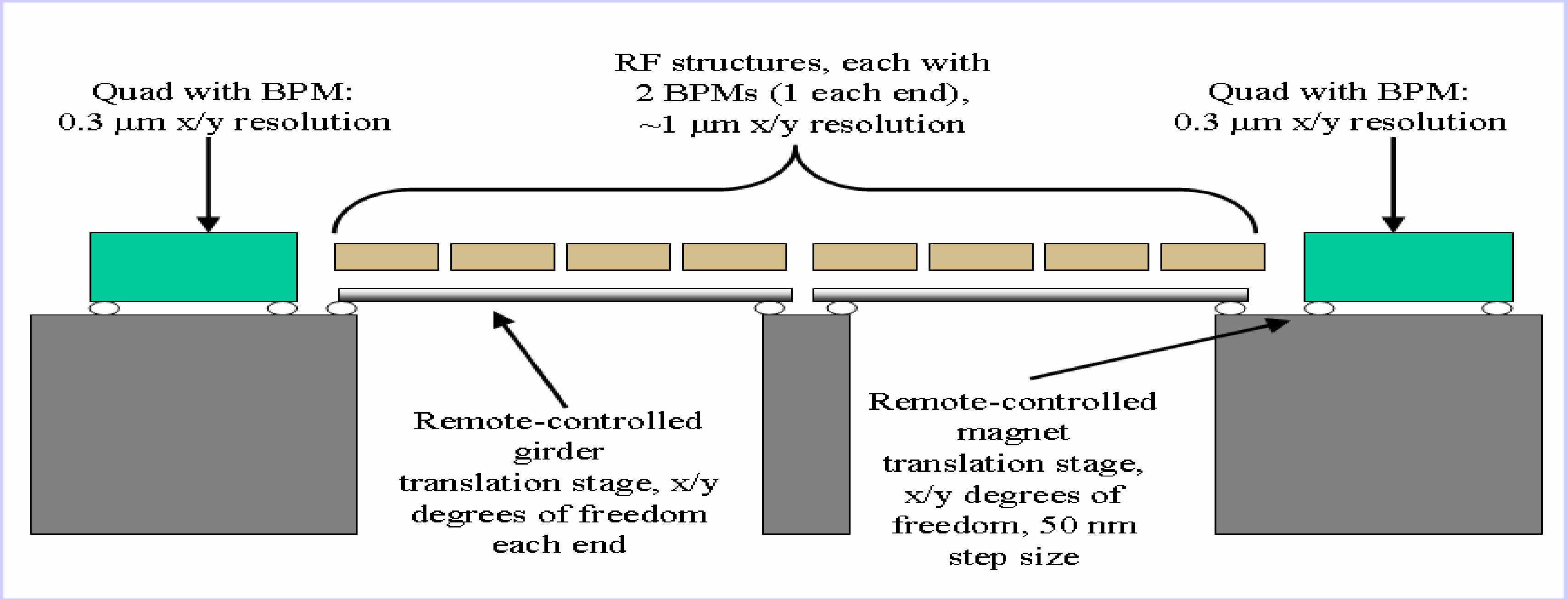
Misalignment	Tolerance	Emittance Growth (nm)
Beam-to-Quad	2.0 μm	2.2
Beam-to-RF-girder	3.0 μm	1.5
Quad rotation	300 μrad	1.4

- Transverse Jitter

BEAM BASED ALIGNMENT (BBA)

- Alignment tolerances can not be met by *ab initio* installation
- Quads and RF structures need to be aligned with beam-based measurements
- Set of all such techniques ⟺ "Beam Based Alignment (BBA)"

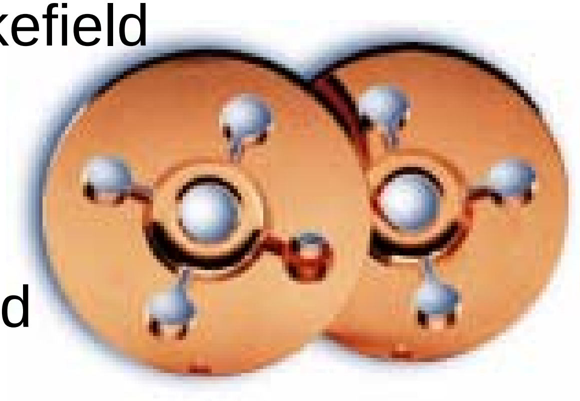
Instrumentation



- Remotely controlled *Girder* and *Magnet* Translation Stages
- High resolution BPMs in Quads and RF structures

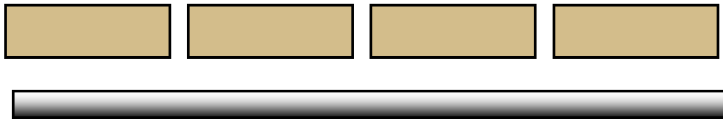
BBA - RF STRUCTURE ALIGNMENT

- S-BPMs: Beam position in RF structure is measured by the Amplitude and Phase of the Dipole Wakefield signal



- Structure Alignment: Nulling Technique.
  Zero on S-BPM => Nulling transverse wakefield

- "Simple" algorithm for RF alignment (to zero mean offset /angle on S-BPMs) works if:
  - No unexpected systematic offsets in S-BPM reading.
  - Structure stays "straight" between beam-based shape measurements
  - Structure-to-structure alignment on girder is okay
    - Loose tolerance (many tens of µm)



BBA - QUAD ALIGNMENT

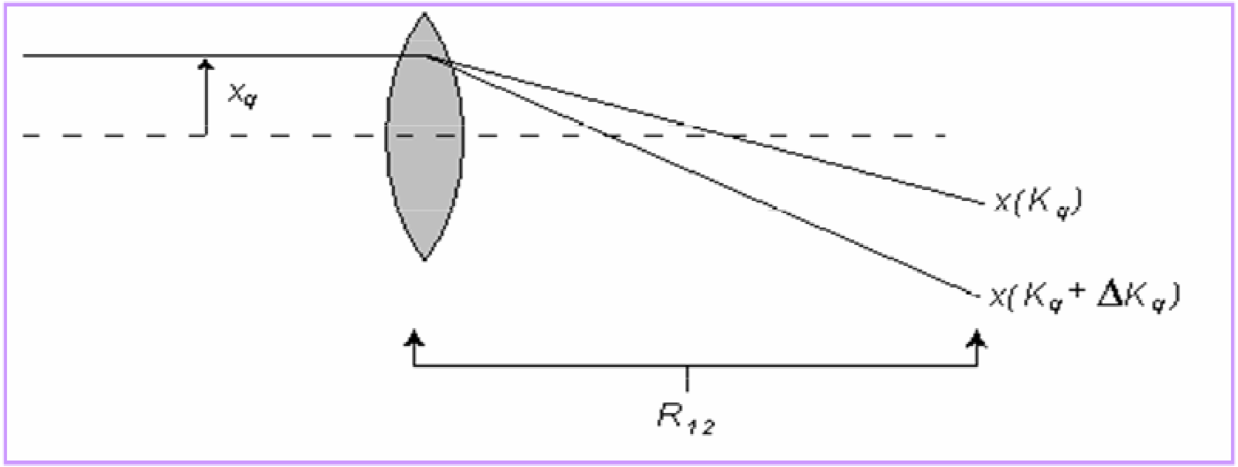
- Every linac quad contains a captured Q-BPM

- Quad alignment – How to do?
  - ☞ Find a set of BPM Readings for which beam should pass through the exact center of every quad
  - ☞ Move the quads until that set is achieved and Steer the beam

- Quad alignment is *relatively difficult*:
  - ☞ Moving a quad steers the beam
  - ☞ BPM Electrical Center ≠ Quad Magnetic Center
    - ⇨ RMS difference ~ 100 µm.
    - ⇨ Can't just "steer BPMs to Zero"
    - ⇨ Measure BPM-to-Quad offsets => ***Quad Shunting***.

BBA - QUAD ALIGNMENT

- **Quad Shunting**: Measure beam kick vs quad strength to determine BPM-to-Quad offset (prerequisite, routinely done)



- Not adequate to achieve micrometer-level accuracy.
  - ⇨ up to ~ 5µm BPM-to-Quad offset.

- Look for a technique which does not require the knowledge of the BPM-to-Quad offset ⟹ Dispersion Free Steering.

(Proposed by Raubenheimer/Ruth [NIM A302,191-208,1991])

DISPERSION FREE STEERING (DFS)

- DFS is a technique that aims to directly measure and correct dispersion in a beamline
- General principle:
  - ⇨ Measure dispersion (via mismatching the beam energy to the lattice)
  - ⇨ Calculate correction (via steering magnets or magnet movers) needed to zero dispersion
  - ⇨ Apply the correction
- Very successful in rings (LEP, PEP, others)
- Less successful at SLC (never reduced resulting emittance as much as predicted)

(Note: SLC varied magnet strengths (center motion?), others varied beam energy)

SIMULATION: MATLAB + LIAR (MATLIAR)

- LIAR (LInear Accelerator Research Code)
  - ⇨ General tool to study beam dynamics
  - ⇨ Simulate regions with accelerator structures
  - ⇨ Includes wakefield, dispersive and chromatic emittance dilution
  - ⇨ Includes diagnostic and correction devices, including beam position monitors, RF pickups, dipole correctors, magnet movers, beam-based feedbacks etc

- MATLAB drives the whole package allowing fast development of correction and feedback algorithms

- CPU Intensive: Two Dedicated Processors for the purpose

MATLIAR SIMULATION: NLC MAIN LINAC (1 TeV CM)

- Test the steering algorithm in simulation – ***100 seeds*** of misalign linac, steer to zero BPM readings, DFS

Nominal Conditions:

Tolerance	x	y	Comment
BPM-Quad Offset	5 μm	5 μm	From quad shunting systematics
Quad Misalign	150 μm	50 μm	Expected survey & alignment quality
Quad Rotation	300 μrad		Expected fiducialization quality
Quad Strength	0.25%		FFTB experience
RF-to-Girder	75 μm	25 μm	
Girder Offset	150 μm	50 μm	Similar problem to quad mechanical alignment
Structure Angle	100 μrad	33 μrad	
Girder Angle	45 μrad	15 μrad	
BPM Resolution	0.4 μm	0.4 μm	Achieved at FFTB

MATLIAR SIMULATION: NLC MAIN LINAC (1 TeV CM)

- Main Linac Design
  - ~14.3 km length
  - 17856 X-band RF (11.424GHz) structures, each ~0.6 m length
  - 4 structures per girder
  - 986 Quads
  - Injection energy = 7.87 GeV
  - Initial Energy spread = 1.48 %
  - Extracted beam energy = 500 GeV
- Beam Conditions
  - Bunch Charge: 0.75 x 10^{10} particles/bunch
  - Bunch length = 110 μm
  - Normalized injection emittance:
    - $\gamma\varepsilon_{X} =$ 3000 nm-rad
    - $\gamma\varepsilon_{Y}$ = 20 nm-rad
- Only Single bunch used
- No Jitter in position, angle etc.; No Ground Motion and Feedback

STEERING ALGORITHM
FRENCH CURVE (FC) vs. DFS

FC

Break linac into segments of ~ 50 quads
In each segment:

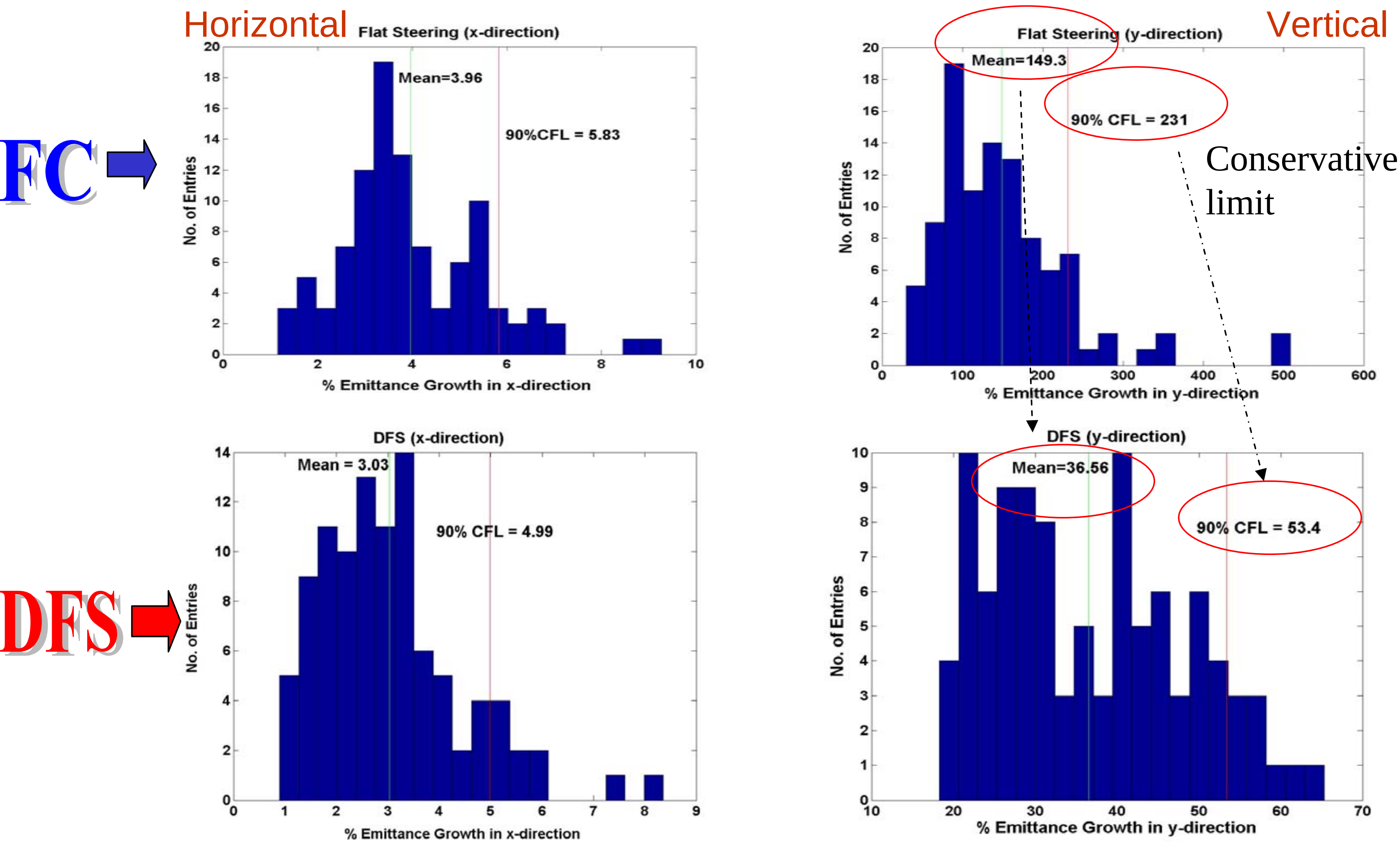
- Read all Q-BPMs in a single pulse
- Compute set of magnet moves and apply the correction
  - Constraint – simultaneously minimize RMS of the BPM readings and RMS magnet mover position change
- Align RF structures
- Iterate a few times and go on to next segment.
- *Next segment starts from the center quad of the previous segment (50% overlap)*
- Performed for 100 Seeds

DFS

Break linac into segments of ~50quads

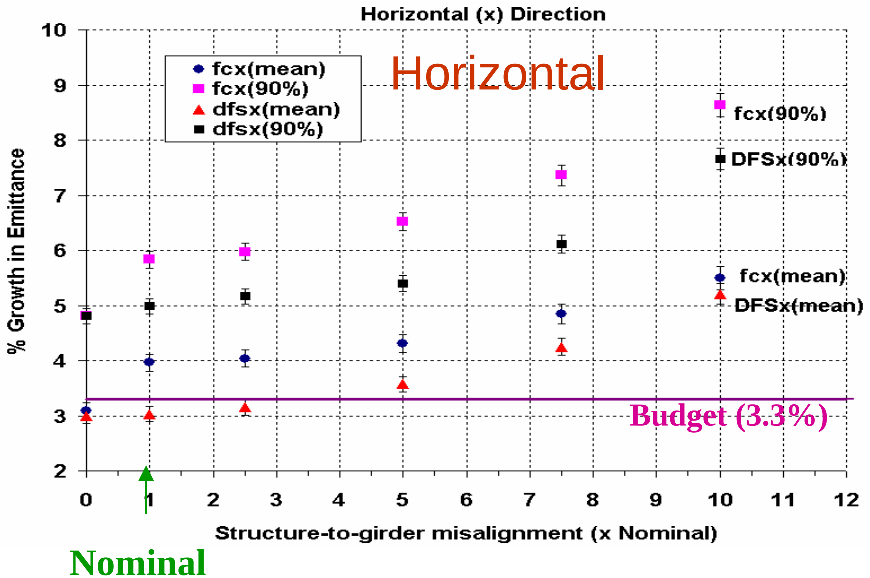
- Vary energy by switching off structures in front of a segment (no variation within segment)
- Measure change in orbit (fit out incoming orbit change from RF switch-off)
- Apply correction
  - Constraint – simultaneously minimize dispersion and RMS magnet mover position change
- Align RF structures
- Iterate a few times and go on to next segment
- Performed for 100 Seeds

FOR NLC NOMINAL CONDITIONS



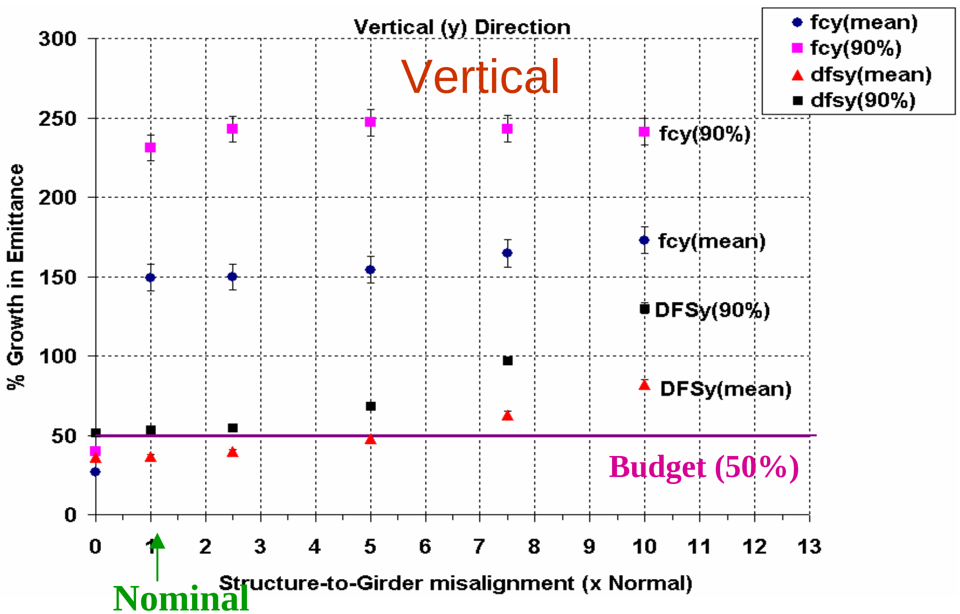
- DFS: Lower mean emittance growth than FC.
- DFS is More effective in vertical plane (which is good!)

STRUCTURE-to-GIRDER OFFSET



- $\gamma\varepsilon_x$ growth in DFS and FC:
  - DFS: mean (~ x2.5) within tolerance.
  - DFS: 90% CFL can create problem.
  - FC: both mean and 90% limit beyond tolerance even for nominal values.

Nominal Values
RMS offset in x /y plane : 75 μm / 25 μm
RMS yaw / pitch angle : 100 μrad / 33 μrad

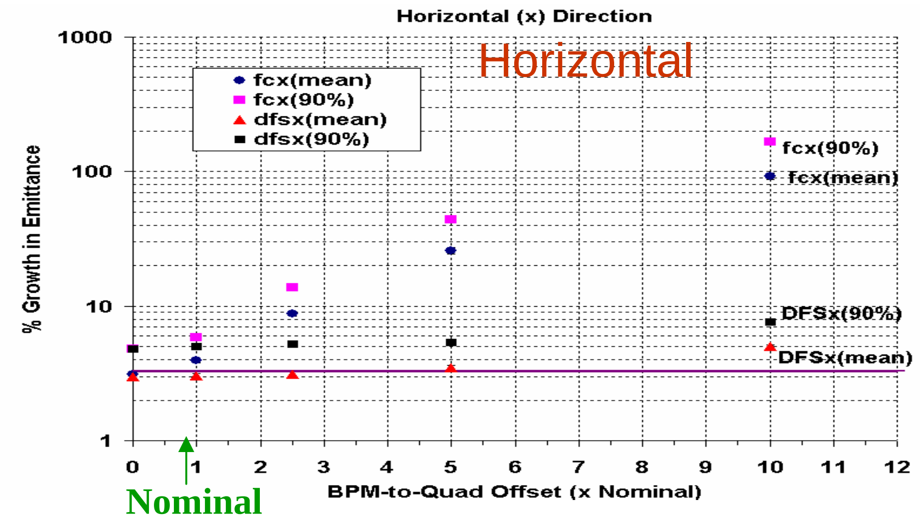


- $\gamma\varepsilon_y$ growth in FC:
  - remains almost constant (~ x5 nominal values), but
  - much above tolerance.

- $\gamma\varepsilon_y$ growth in DFS:
  - increases more rapidly.
  - mean within specs. (~x5 times)
  - 90% CFL can cause problem

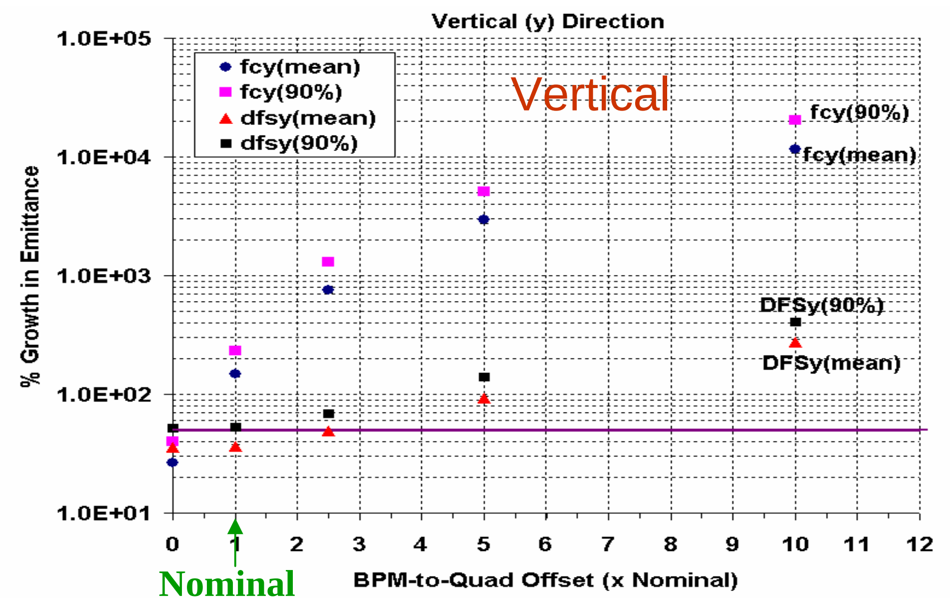
(machine should be "mean" seed !!)

BPM-to-QUAD OFFSET



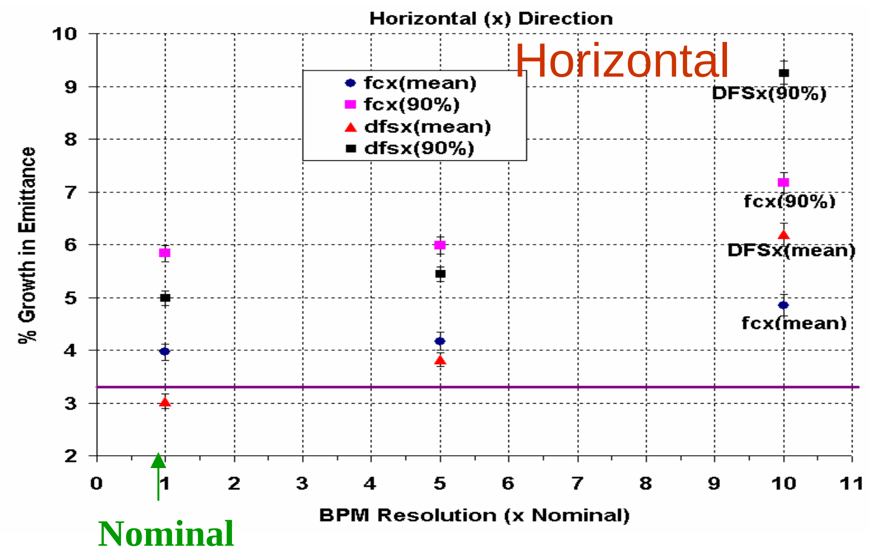
- $\gamma\varepsilon_y$ & $\gamma\varepsilon_x$ growth in FC:
  - ☞ Increases significantly
  - ☞ Much above tolerance.

Nominal Values
RMS offset in x / y-plane : 5 μm / 5 μm



- $\gamma\varepsilon_y$ & $\gamma\varepsilon_x$ growth in DFS:
  - ☞ Increases gradually due to soft constraints and initial beam condition.
  - ☞ Mean is within tolerance for ~ x 2.5 nominal values.

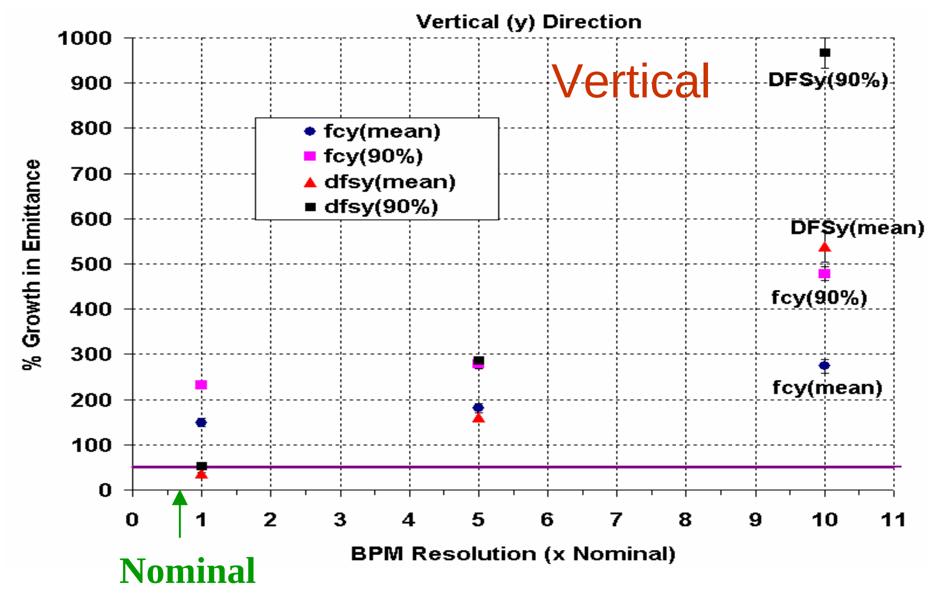
BPM RESOLUTION



- $\gamma\varepsilon_y$ & $\gamma\varepsilon_x$ growth in FC:
  - ☞ Lesser dependence, but,
  - ☞ much above tolerance.

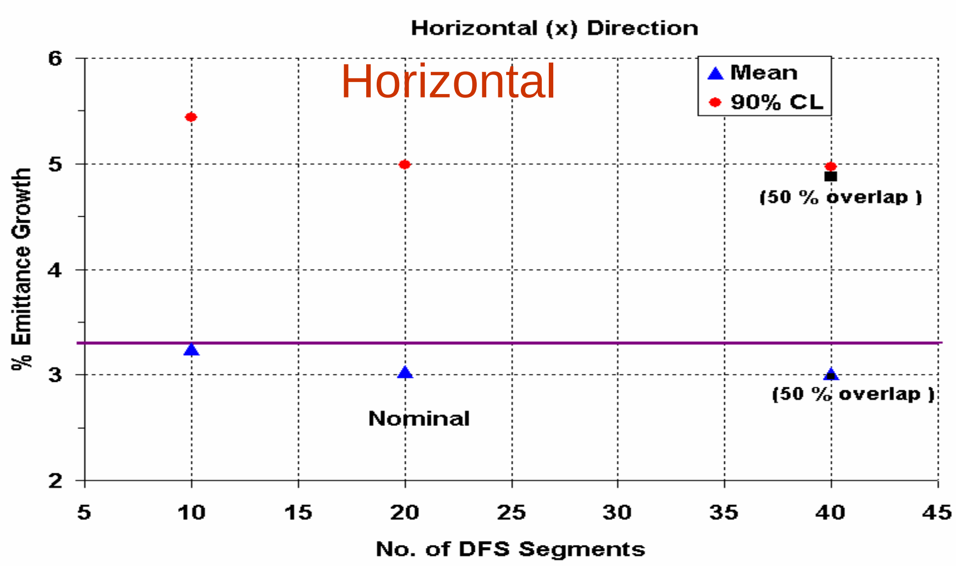
Nominal Values

RMS offset in x / y plane : 0.4 μm / 0.4 μm



- $\gamma\varepsilon_y$ & $\gamma\varepsilon_x$ growth in DFS:
  - ☞ Depends heavily on BPM resolution.
  - ☞ Should remain within nominal values.

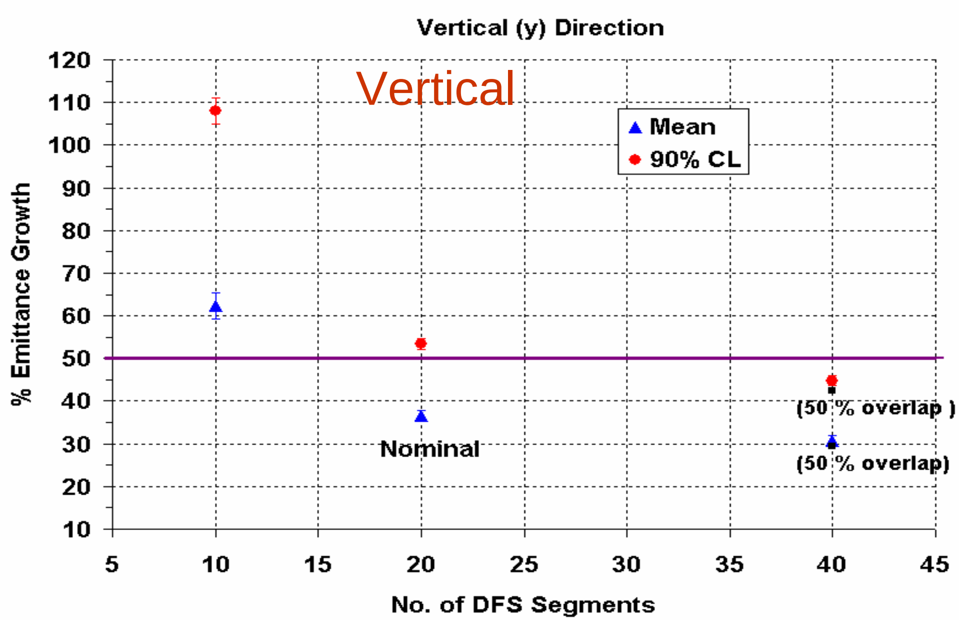
NUMBER OF DFS SEGMENTS



- $\gamma\varepsilon_x$ growth in DFS:
  - Doesn't depend much on the no. of segments .

Nominal Value

No. of DFS segments : 20 (No overlap)



- $\gamma\varepsilon_y$ growth in DFS:
  - Decreases significantly from 10-> 20, but then decreases gradually.
  - Nominal looks O.K.
  - Overlapping the segments (like in FC) doesn't affect much.

EFFECT OF PITCH ANGLE b/w STRUCTURE & GIRDER

Mean % Emittance Growth in vertical direction

	FC	DFS
Nominal	149.3	36.6
x10 Nominal structure-to-girder pitch angle only	160.3	57.7
x10 Nominal structure-to-girder all offsets*	172.8	82.0

* RMS horizontal and vertical misalignments, yaw and pitch angles of whole structure w.r.t. Girder.

- mean % $\gamma\varepsilon_y$ growth in DFS
  - ☞ significantly greater than that in FC.
  - ☞ structure-to-girder pitch angle alone accounts for ~ ½ the total growth.
    - ⇨ a serious limitation on the performance if not corrected.

SUMMARY / PLAN

- Normalized emittance growth (Single bunch) in Main Linac for 1 TeV CM NLC machine is simulated using MATLIAR
- DFS and FC steering algorithm are compared in terms of:
  - Structure-to-girder offsets
  - BPM-to-Quad offset
  - BPM resolution
  - Structure-to-girder pitch angle only
- DFS algorithm provides significantly better results than FC. DFS results are within emittance budget for mean seeds (for Nominal conditions)
- DFS algorithm is drastically affected by BPM resolution and structure-to-girder pitch angle – should remain within their nominal tolerances

PLAN

- *Include Transverse Jitter and Ground Motion*
- *Perform a Similar Study for TESLA LINAC*