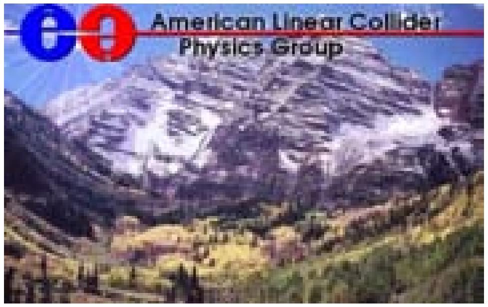
STUDY OF MAIN LINAC SINGLE BUNCH EMITTANCE PRSERVATION IN USColdLC DESIGN (500 GeV C.M.E.)

Kirti Ranjan
Fermilab and University of Delhi, India
&
Nikolay Solyak and Shekhar Mishra
Fermi National Accelerator Laboratory
&
Peter Tenenbaum
Stanford Linear Accelerator Center



2nd ILC Accelerator Workshop
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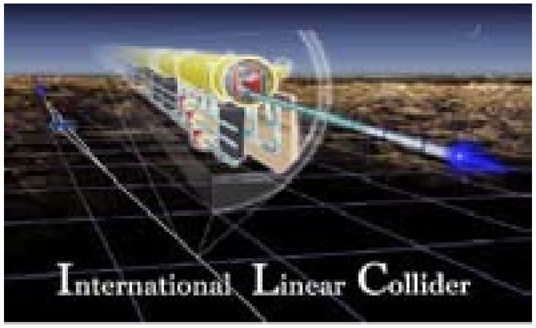


SINGLE BUNCH EMITTANCE DILUTION SIMULATION

Comparison of 1:1 vs. Dispersion Free Steering

Present talk

Lattice Configuration Studies

Nikolay Solyak's talk

OVERVIEW

GOALS OF THE PRESENT TALK

- **To study single-bunch emittance dilution in USColdLC Main Linac**
- **To compare the emittance dilution performance of two different steering algorithms : "1:1" and "Dispersion Free Steering" under nominal conditions**
- **To compare the sensitivity of the steering algorithms for conditions different from the nominal**

- USColdLC Main Linac Design
- Beam Based Alignments
  - ⇨ One-to-One (1:1) Steering
  - ⇨ Dispersion Free Steering
- MATLIAR – Main Linac Simulation
- Results
- Conclusions / Plans

USColdLC MAIN LINAC

- **"USColdLC" Main linac will accelerate e^-/e^+ from ~ 5 GeV → 250 GeV**
  - ⇨ Adaptation from the TESLA TDR

- **Two major design issues:**

  - ⇨ **Energy :** Efficient acceleration of the beams
  - ⇨ **Luminosity :** Emittance preservation

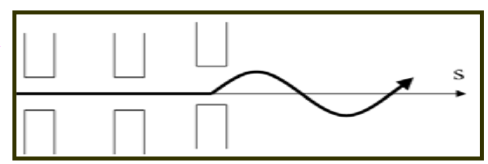
Normalized Emittance Dilution Budget

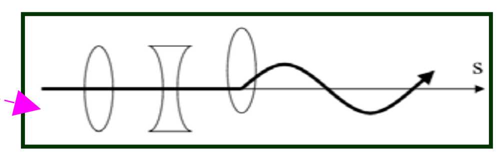
		DR Exit =>	ML Injection	=> ML Exit	=> IP
TESLA (TDR):	Hor./Vert (nm-rad):		8000 / 20		=> 10000 / 30
USColdLC:	Hor./Vert (nm-rad):	8000 / 20 =>	8800 / 24	=> 9200 / 34 =>	9600 / 40

10 nm (50%) Vertical emittance growth in USColdLC

- **Vertical plane would be more challenging:**
  - ⇨ Large aspect ratio (x:y) in both spot size and emittance (400:1)

- **Primary sources of Emittance Dilution:**
  - ⇨ Transverse Wakefields:
    - Short Range : misaligned structures or cryomodules
  - ⇨ Dispersion from Misaligned Quads or Pitched Structures
  - ⇨ XY-coupling from rotated Quads
  - ⇨ Transverse Jitter





USColdLC MAIN LINAC

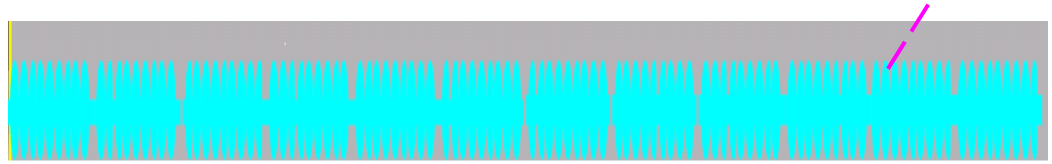
- USColdLC Main Linac Design
  - ⇨ Linac Cryogenic system is divided into Cryomodules(CM), with **12 RF structures / CM**
  - ⇨ **1 Quad / 2CM** : Superconducting Quads in alternate CM, **330 Quads** (165F,165D)
  - ⇨ Magnet Optics : FODO “constant beta” lattice, with β phase advance of **60^0** in each plane
  - ⇨ Each quad has a *Cavity style BPM* and a *Vertical Corrector* magnet; horizontally focusing quads also have a nearby *Horizontal Corrector* magnet.

(similar to the 1^{st} half of TESLA TDR main Linac)

- Main Linac Parameters
  - ⇨ ~**11.0 km** length
  - ⇨ **9 Cell** structures at **1.3 GHz** and **12 structures** per cryostat; Total structures : **7920**
  - ⇨ Loaded Gradient : **30 MV/m** (Original: 28 MV/m; *TESLA TDR: 23.5 MV/m*)
  - ⇨ Injection energy = **5.0 GeV** & Initial Energy spread = **2.5 %**
  - ⇨ Extracted beam energy = **250 GeV** (500 GeV CM)

- Beam Conditions
  - ⇨ Bunch Charge: **2.0×10^{10} particles/bunch**
  - ⇨ Bunch length = **300 μm**
  - ⇨ Normalized injection emittance:
    - ▪ **$\gamma\varepsilon_Y$ = 20 nm-rad**

TESLA SC 9-Cell Cavity



12 “9-Cell Cavity” CryoModule

USColdLC MAIN LINAC

ab initio (Nominal) Installation Conditions

Tolerance	Vertical (y) plane
BPM Offset w.r.t. Cryostat	300 µm
Quad offset w.r.t. Cryostat	300 µm
Quad Rotation w.r.t. Cryostat	300 µrad
Structure Offset w.r.t. Cryostat	300 µm
Cryostat Offset w.r.t. Survey Line	200 µm
Structure Pitch w.r.t. Cryostat	300 µrad
Cryostat Pitch w.r.t. Survey Line	20 µrad
BPM Resolution	1.0 µm

Not mentioned in TESLA TDR

10 µm in TDR

- BPM transverse position is fixed, and the BPM offset is w.r.t. Cryostat
- Only Single bunch used
- No Ground Motion and Feedback
- Steering is performed using Dipole Correctors

ALIGNMENT & STEERING ALGORITHMS

- Beam line elements are needed to be aligned with beam-based measurements
- "Beam Based Alignments (BBA)" refer to the techniques which provide information on beamline elements using measurements with the beam
  - Quad strength variation ← Estimate beam-to-quad offset
  - **"One-to-One" Correction**
  - **Dispersion Free Steering** ← Considered here
  - Ballistic Alignment
  - Kubo's method *and possibly others*….

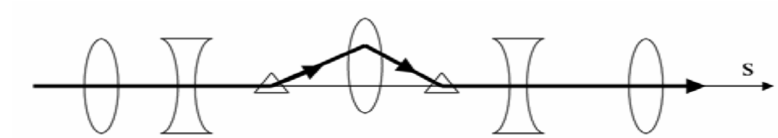
- ***Quad Shunting:*** Measure beam kick vs. quad strength to determine BPM-to-Quad offset (routinely done)

  - In USColdLC, it is not assumed that all quads would be shunted
    - Quads are Superconducting and shunting might take a very long time
    - No experimental basis for estimating the stability of the Magnetic center as a function of excitation current in SC magnets
    - In **Launch region** (1^{st} 7 Quads), we assume that offsets would be measured and corrected with greater accuracy (~30 μm)

BEAM BASED ALIGNMENT

1: 1 Steering

- Every linac quad contains a cavity Q-BPM (with fixed transverse position)
- Quad alignment – How to do?
  - **Find a set of BPM Readings for which beam should pass through the exact center of every quad (zero the BPMs)**
  - **Use the correctors to Steer the beam**



- One-to-One alignment generates *dispersion* which contributes to emittance dilution and is sensitive to the BPM-to-Quad offsets

Dispersion Free Steering (DFS)

- DFS is a technique that aims to directly measure and correct dispersion in a beamline **(proposed by Raubenheimer/Ruth, NIMA302, 191-208, 1991)**
- General principle:
  - ⇨ **Measure dispersion (via mismatching the beam energy to the lattice)**
  - ⇨ **Calculate correction needed to zero dispersion**
  - ⇨ **Apply the correction**
- Successful in rings (LEP, PEP, others) but less successful at SLC (Two-beam DFS achieved better results)

(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 BPMs, 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: Dedicated Processors for the purpose

BEAM BASED ALIGNMENT

➢ **Launch Region Steering (can not be aligned using DFS)**

⇨ **Emittance growth is very sensitive to the element alignment in this region, due to low beam energy and large energy spread**

⇨ **First, all RF structures in the launch region are switched OFF to eliminate RF kicks from pitched structures / cryostats**

⇨ **Beam is then transported through the Launch and BPM readings are extracted => estimation of Quad offsets w.r.t. survey Line**

⇨ **Corrector settings are then computed which ideally would result in a straight trajectory of the beam through the launch region**

⇨ **The orbit after steering the corrector magnets constitutes a reference or "gold" orbit for the launch**

⇨ **The RF units are then restored and the orbit is re-steered to the Gold Orbit. (This cancels the effect of RF kicks in the launch region)**

STEERING ALGORITHM : ONE-to-ONE vs. DFS

1:1

Divide linac into segments of ~50 quads in each segment:

- Read all Q-BPMs in a single pulse
- Compute set of corrector readings and apply the correction
  - ⇨ Constraint – minimize RMS of the BPM readings
- Iterate few times before going to the next segment.
- Performed for 100 Seeds

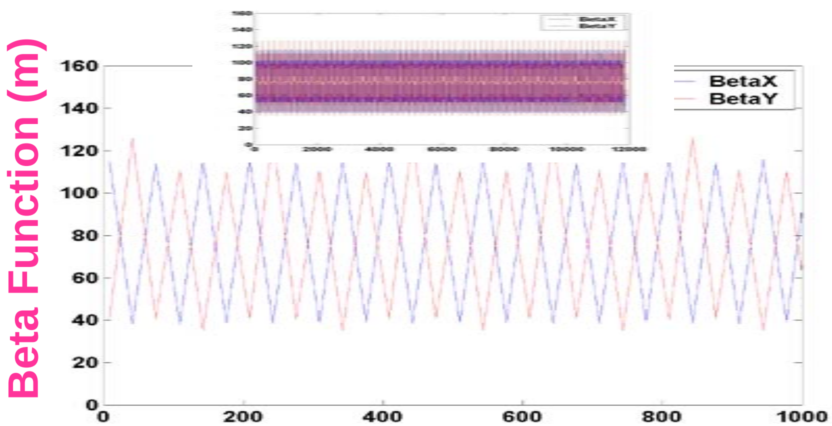
DFS

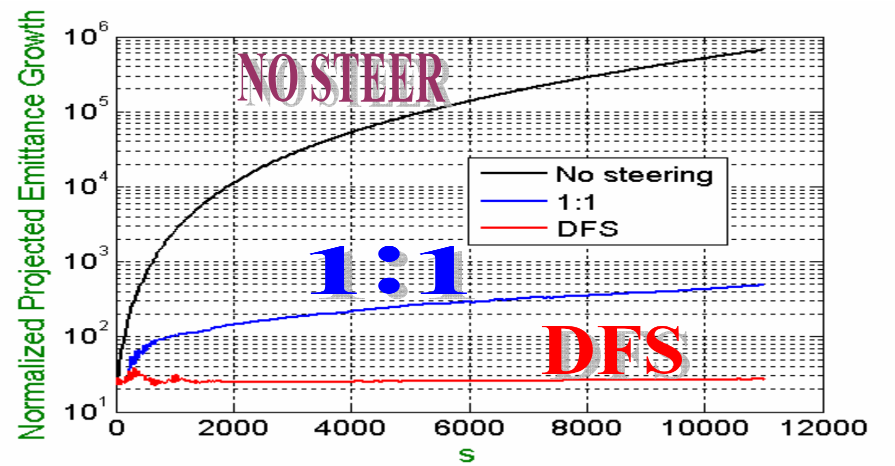
Divide linac into segments of ~40quads

- Two orbits are measured
- 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 of the BPM readings (weight ratio: $\sqrt{2} : 300$)
- Iterate twice before going to the next segment
- Performed for 100 Seeds

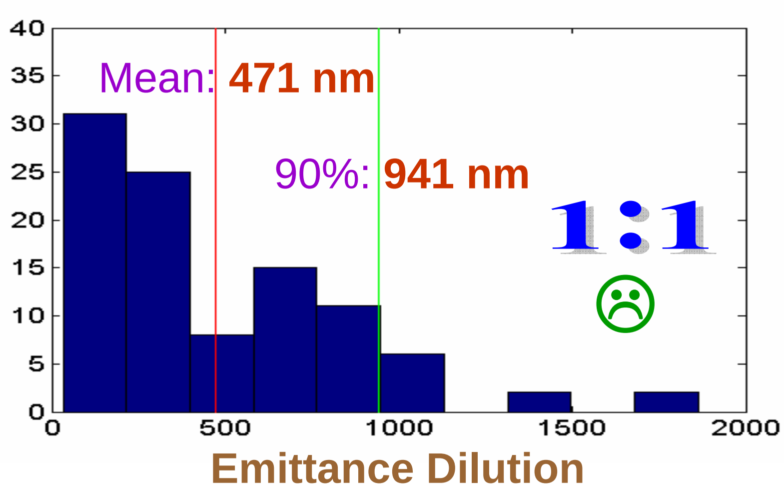
FOR USColdLC NOMINAL CONDITIONS

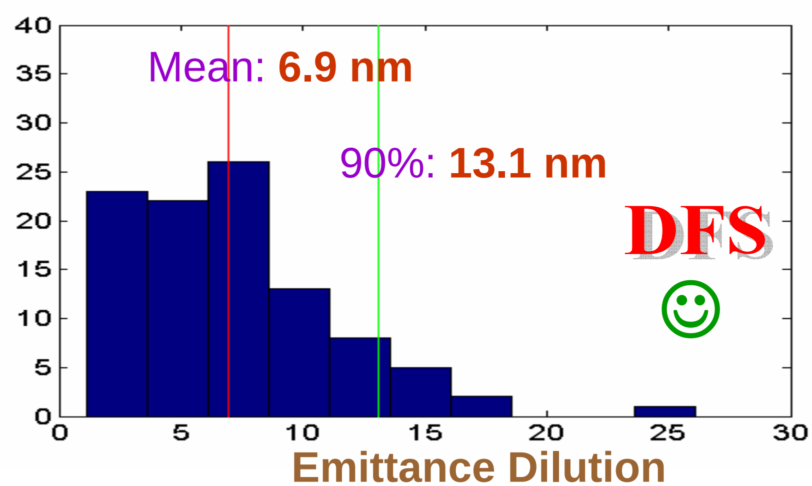
- Gradient : 30 MV/ m; No BNS Energy Spread ; 100 seeds





Projected Emittance Dilution = Emittance (Exit) – Emittance (Entrance)

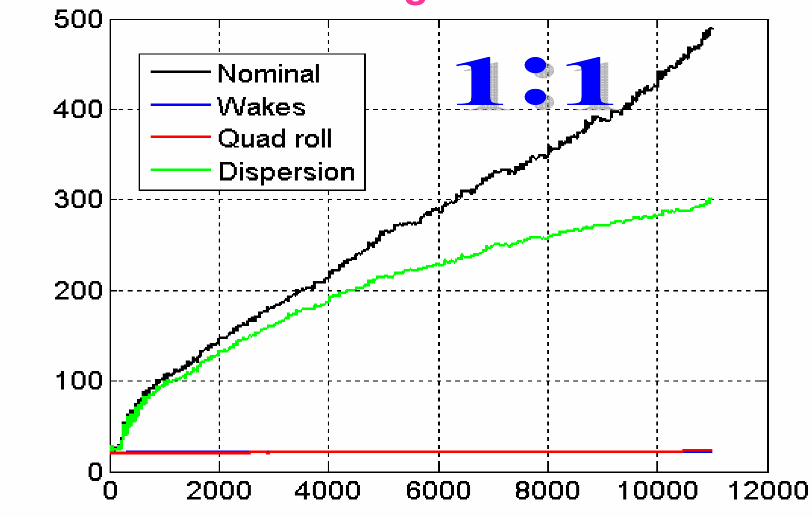


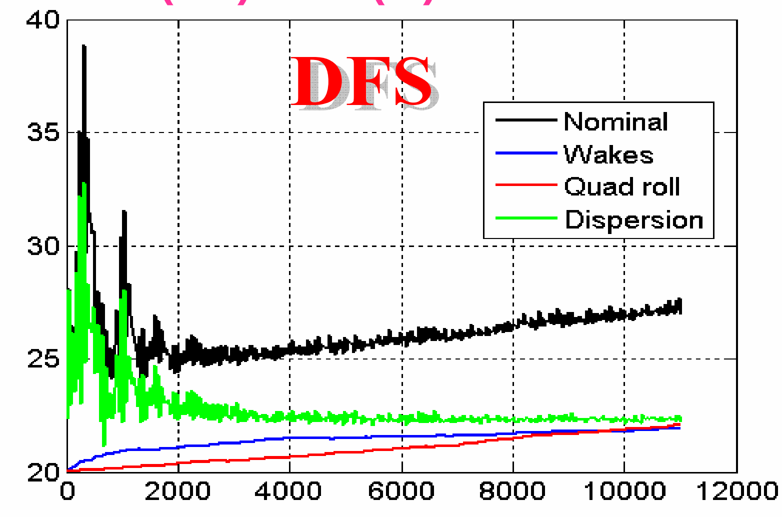


- ☞ Lower mean emittance growth for DFS than One-to-One
- ☺ Mean Growth under the Emittance dilution budget ⟵ No Jitter and No BNS energy spread!

FOR USColdLC NOMINAL CONDITIONS

Average Normalized Emittance Growth (nm) vs. s (m)





Average Normalized Emittance Dilution (nm)

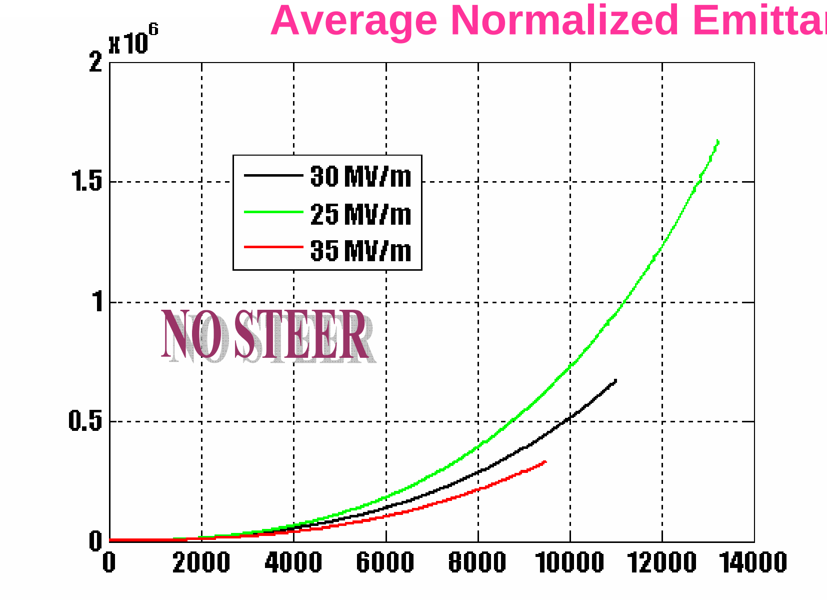
Tolerance	1:1	DFS
Nominal	470	6.9
Wakes only	1.9	1.9
Dispersion only	280	2.2
Quad roll only	2.1	2.1

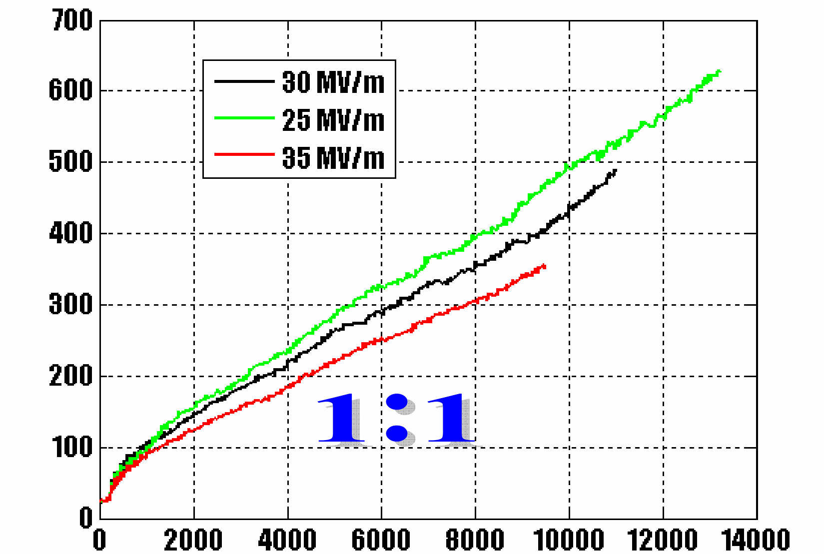
Almost equal contributions

- ☞ Wakes include only Cavity and CM offsets; Dispersion includes Quad / BPM Offsets & Cavity / CM pitches
- ☞ Nominal >Wakes+Dispersion+Quad roll (Why?– wakefields causing systematic errors ?)

Effect of GRADIENT

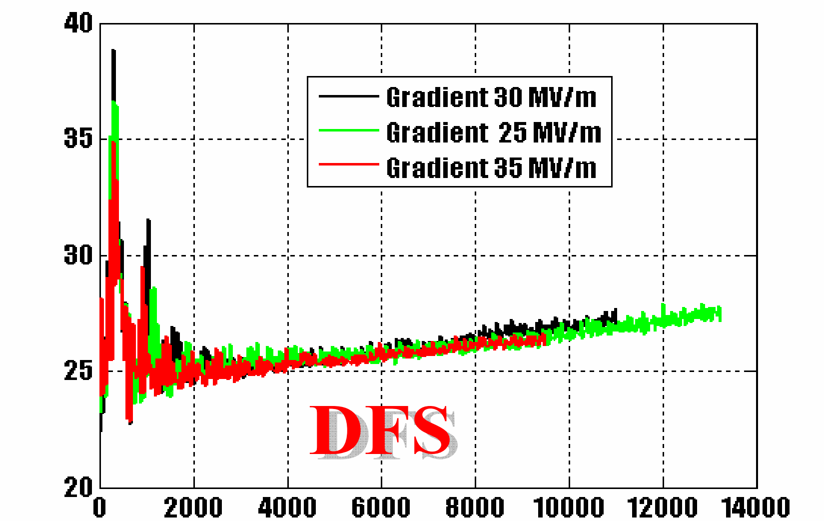
Average Normalized Emittance Growth (nm) vs. s (m)





- ☞ **Same wakefields used for all the gradients!**

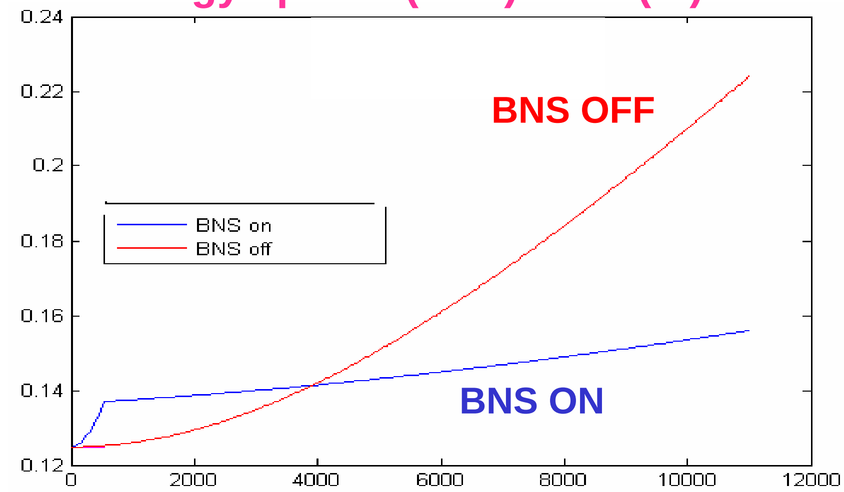
- ☞ **DFS is almost independent of the change in gradient whereas for 1:1, emittance dilution decreases with increasing gradient**



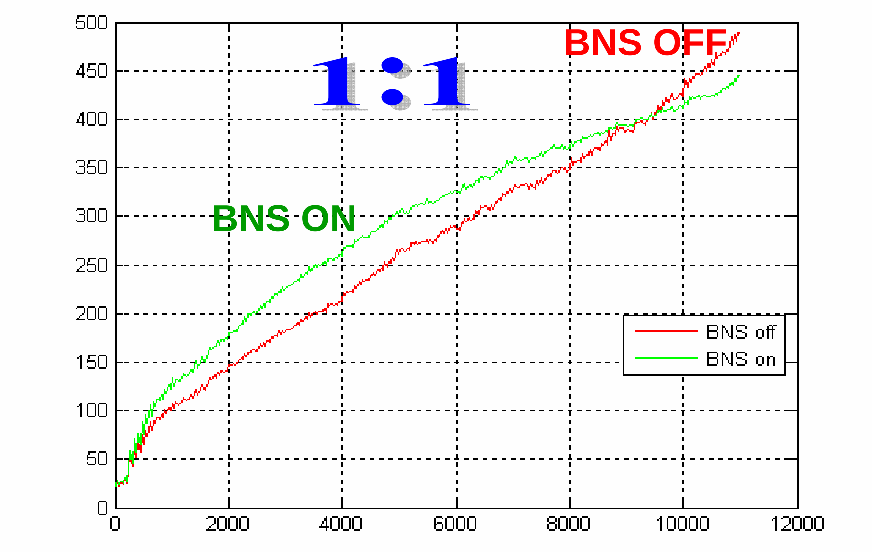
Effect of BNS ENERGY SPREAD

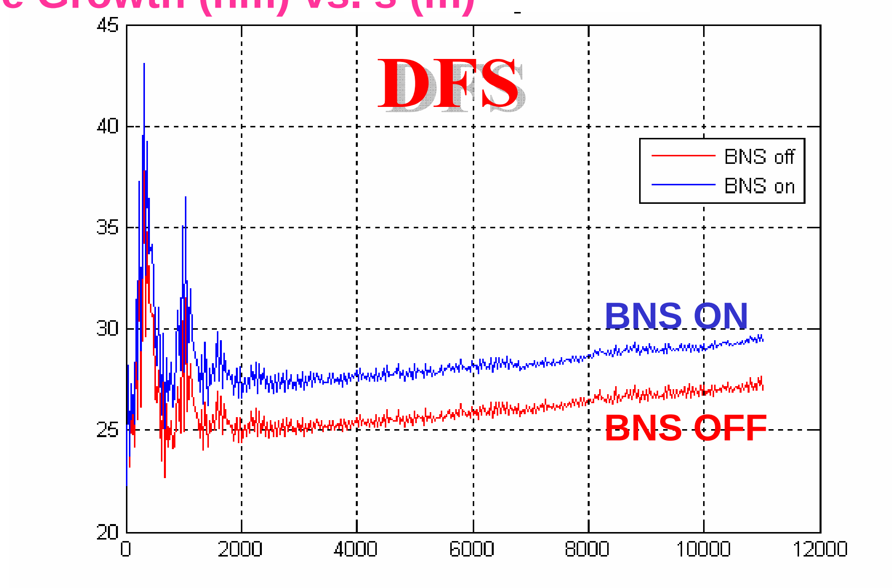
- Taken from 28 MV/m Lattice
- Bunch behind the crest by 29^0 in initial 14 CM; and 4.4^0 ahead in rest of the CM

Energy spread (GeV) vs. s (m)



Average Normalized Emittance Growth (nm) vs. s (m)

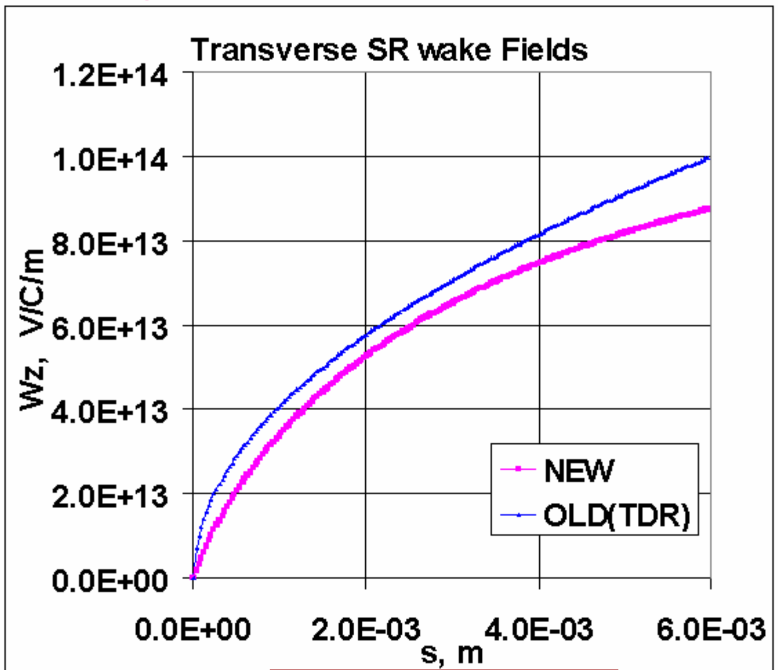




NEW vs. OLD WAKE FIELD

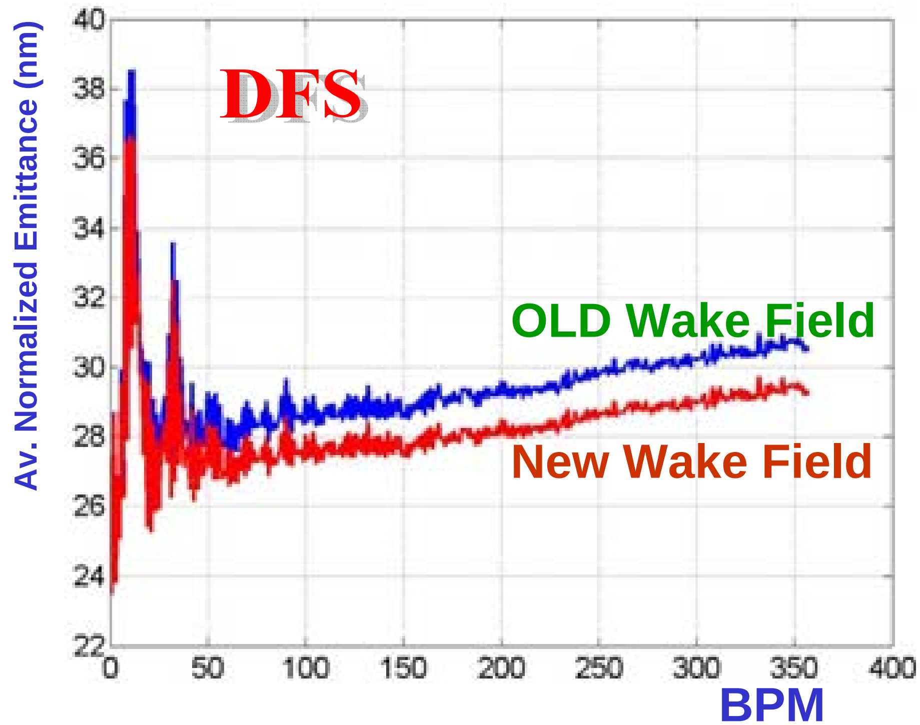
28 MV / m Gradient ; w/ BNS Energy Spread; Nominal misalignments

New Wakefield calculations from Zagorodnov & Weiland 2003



New tr. wakes ~ 30% less

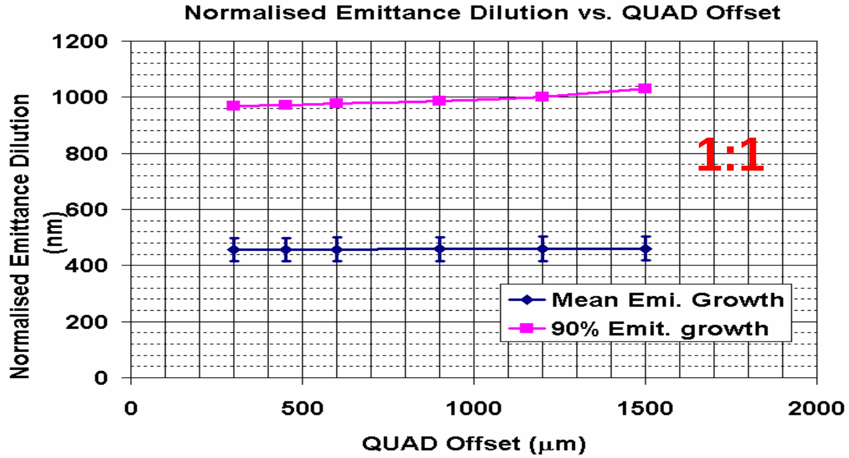
Average Emittance Dilution in the BPMs

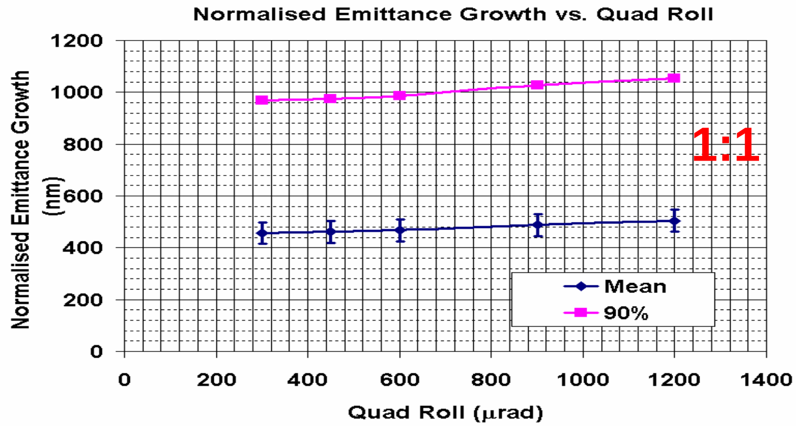


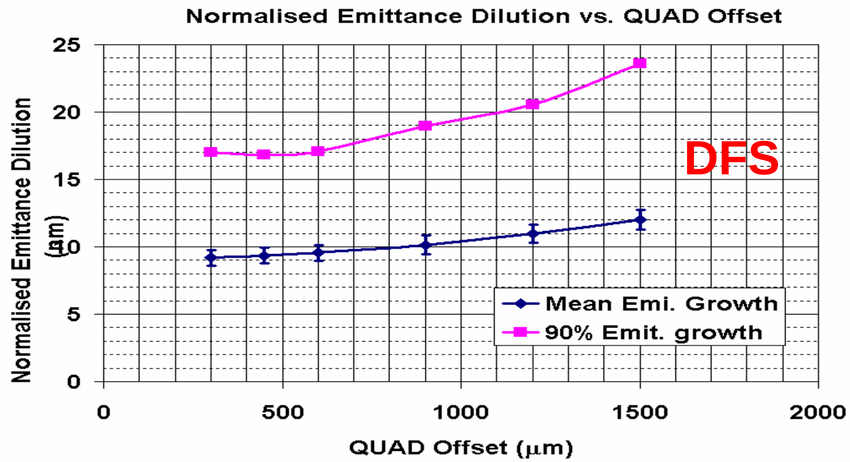
SENSITIVITY STUDIES
28 MV/m Lattice w/ Autophasing

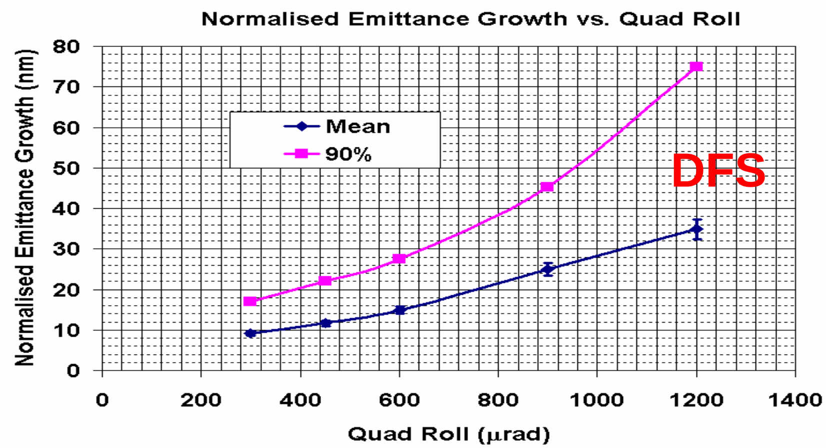
EFFECT OF *QUAD OFFSETS* / *QUAD ROLL* VARIATION

➢ Keeping all other misalignments at Nominal Values and varied only the Quad offsets / Quad roll



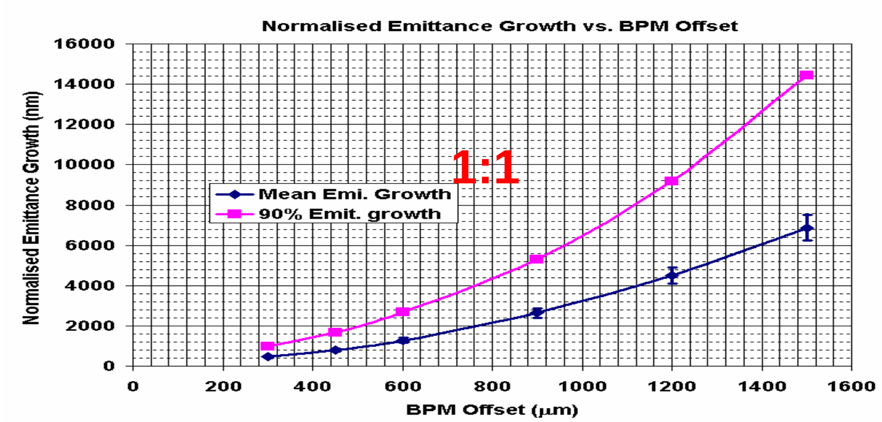


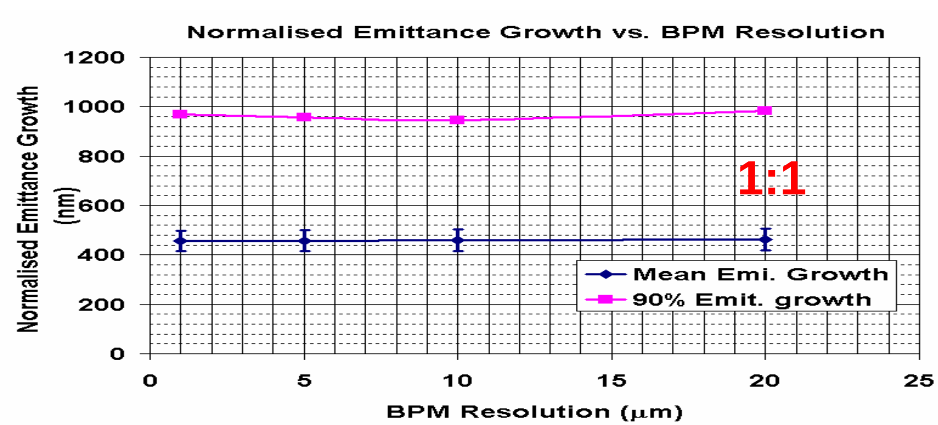


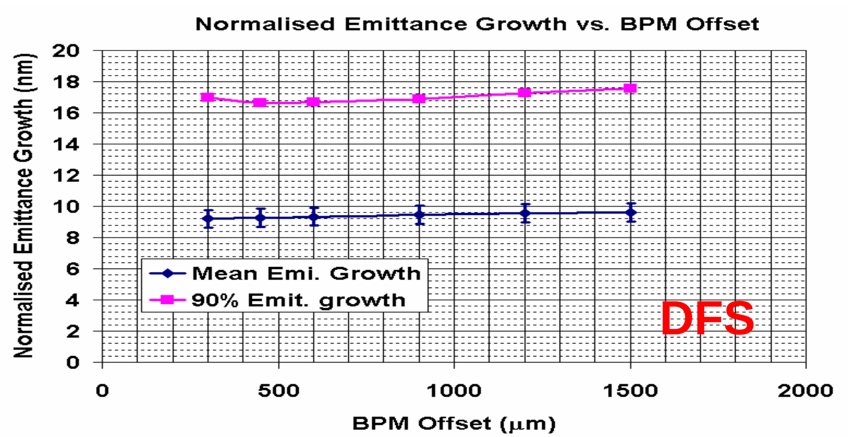


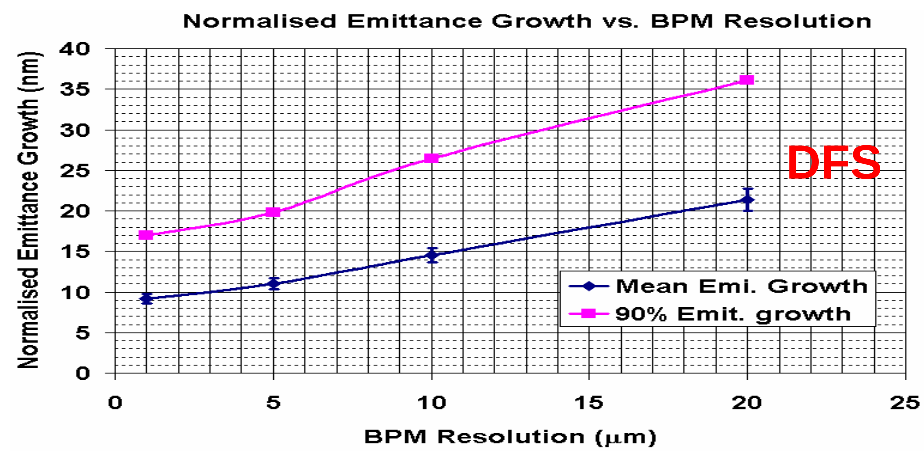
- **Emittance dilution increases slowly with increase in Quad Offsets**
- **DFS: Just under the budget for 2x nominal values**
- **DFS: Emittance dilution increases more rapidly with increase in Quad Roll**
- **DFS: Goes Over the budget even for 1.5x nominal values**

EFFECT OF *BPM OFFSETS / RESOLUTION* VARIATION



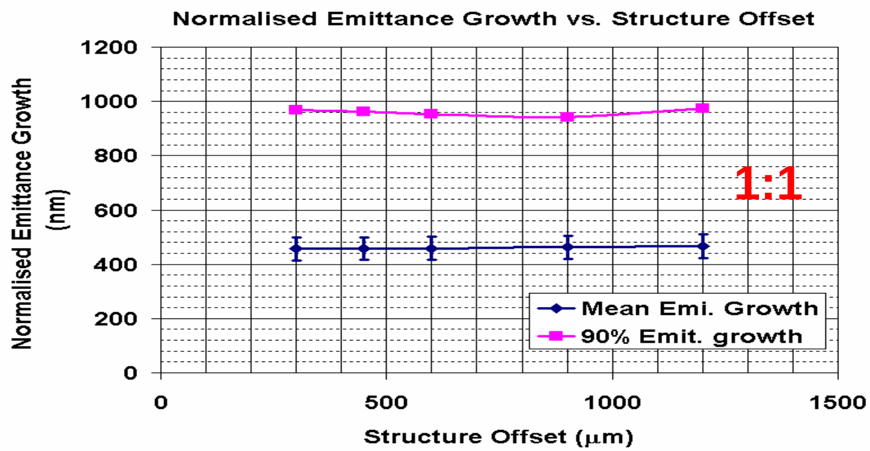


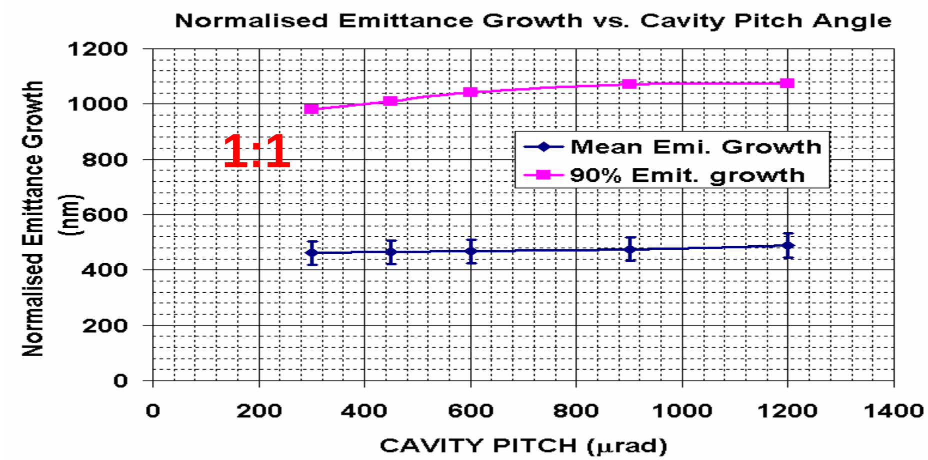


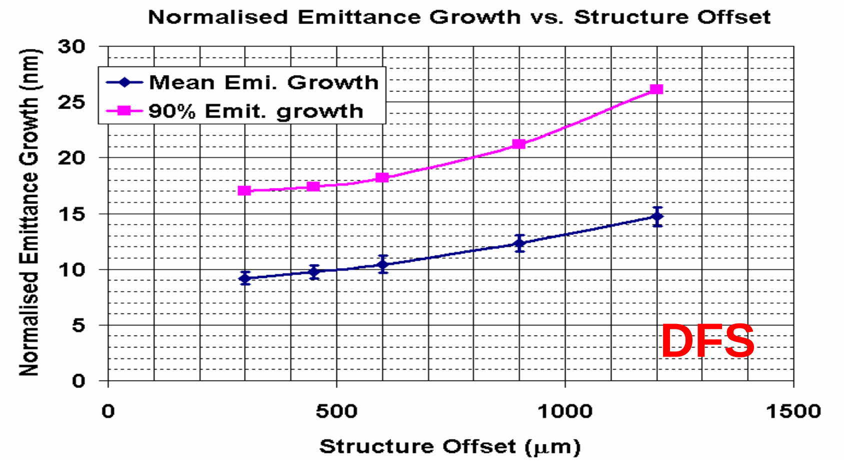


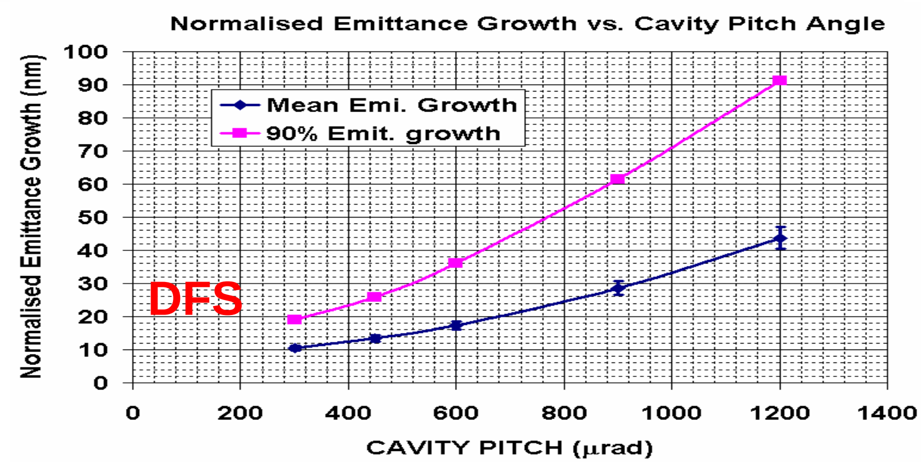
- ***Advantage of DFS:*** **Emittance dilution for 1:1 increases very sharply with BPM offsets**
- **DFS: Emittance dilution is almost independent of BPM offset**
- **DFS: Remains within the budget even for 5x nominal**
- **Emittance dilution for 1:1 is almost independent of the BPM resolution**
- **DFS: Emittance dilution is sensitive to BPM resolution**
- **DFS: Goes Over the budget even for 5x nominal values**

EFFECT OF *STRUCTURE OFFSET / PITCH* VARIATION



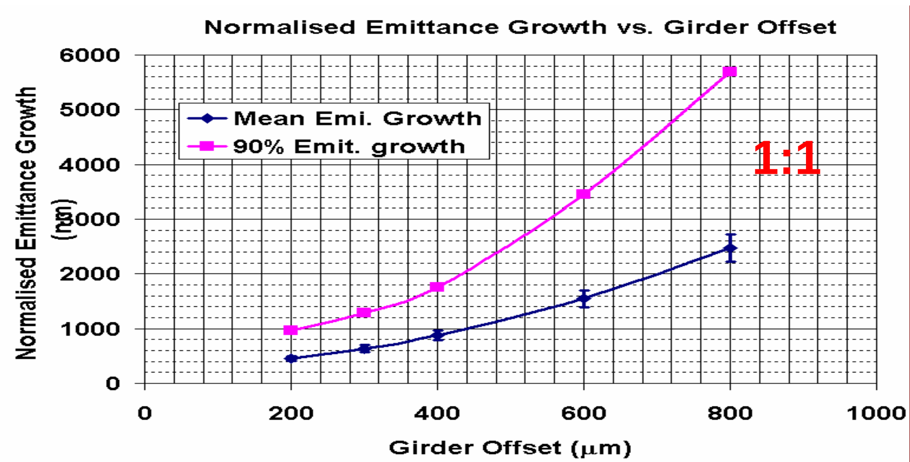


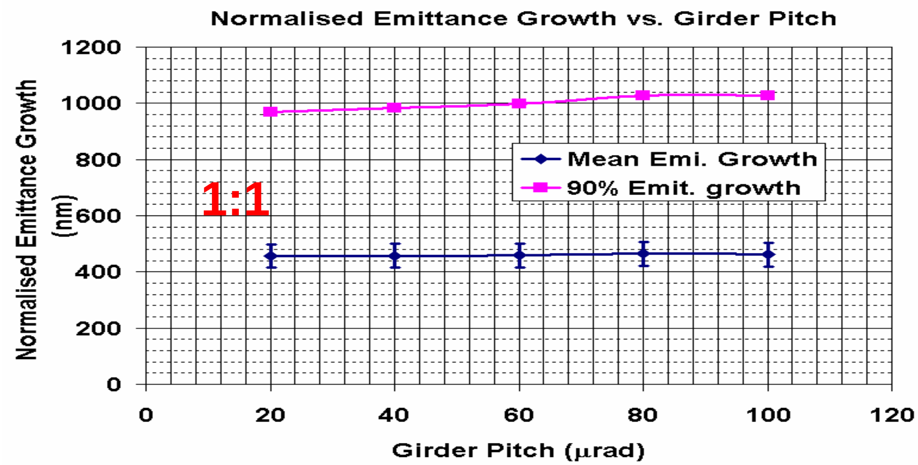


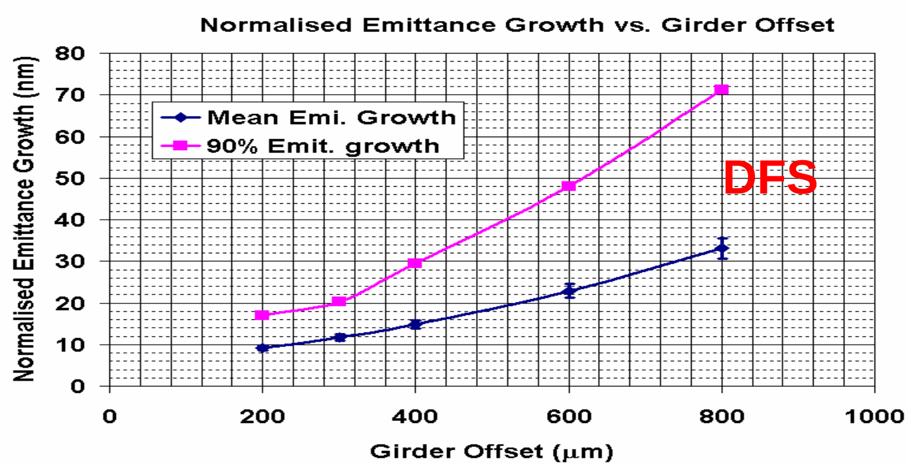


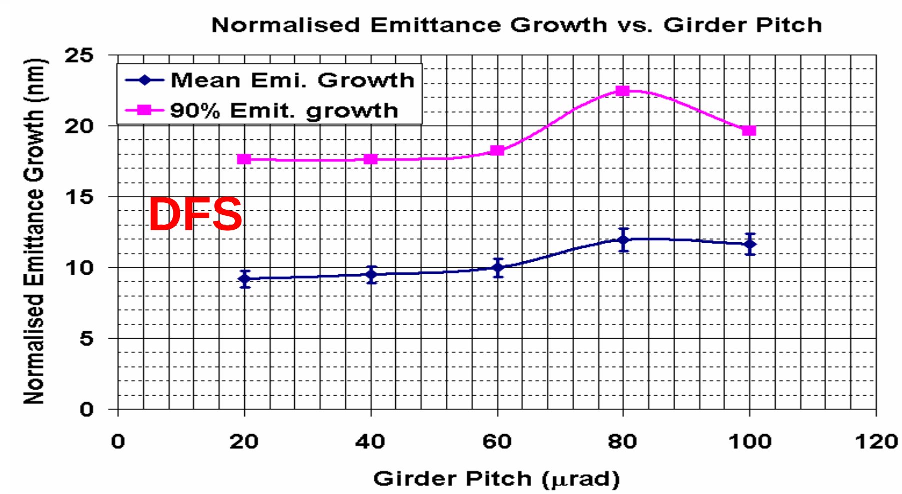
- **Emittance dilution for 1:1 is almost independent of the structure offset**
- **DFS: Emittance dilution grows slowly with structure offsets**
- **DFS: Goes Over the budget for 2.0x nominal values**
- DFS: Emittance dilution is sensitive to Cavity pitch
- DFS: Goes Over the budget even for 1.5x nominal values

EFFECT OF *CRYOMODULE OFFSET/ PITCH* VARIATION





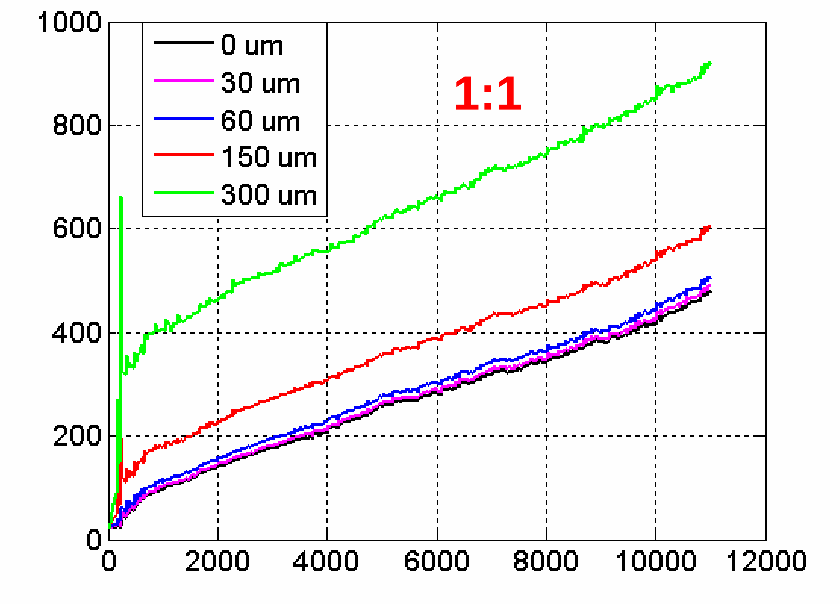


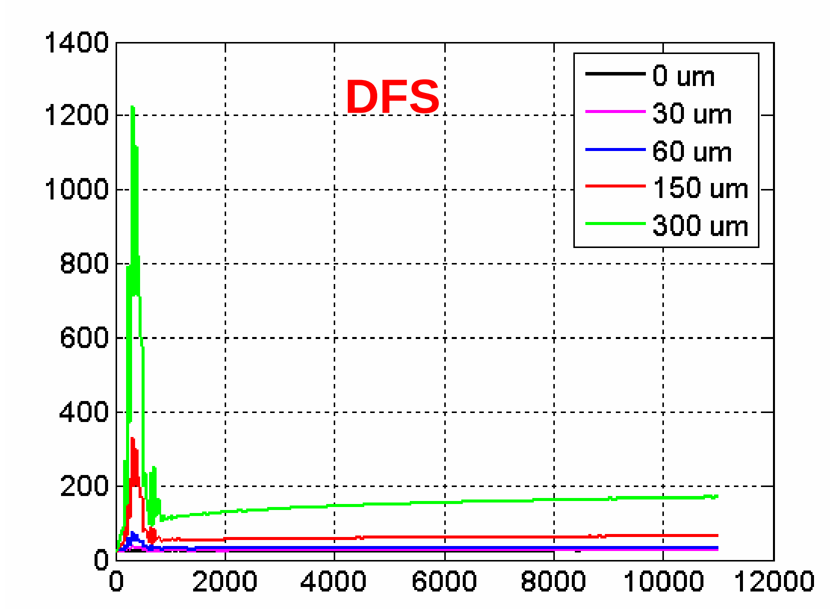


- DFS and 1:1: Emittance dilution grows sharply with CM offset
- DFS: Goes Over the budget even for 1.5x nominal values
- DFS and 1:1: Emittance dilution is almost independent of the CM pitch
- DFS: Remains within the budget for 3x nominal

EFFECT OF *LAUNCH BPM OFFSETS* VARIATION

30 MV / m; No BNS Energy Spread; 1Q/2CM Lattice





Average Emittance Dilution (nm)

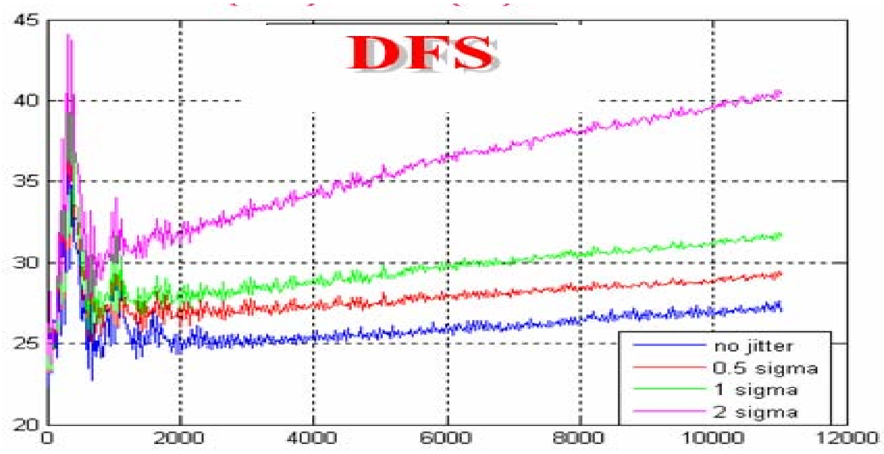
	1:1	DFS
0 um :	4.617e+002	5.165e+000
Nominal → 30 um:	4.709e+002	6.932e+000
60 um :	4.876e+002	1.181e+001
150 um :	5.835e+002	4.282e+001
300 um:	8.956e+002	1.484e+002

- DFS and 1:1: Emittance dilution is very sensitive to the Launch BPM offsets

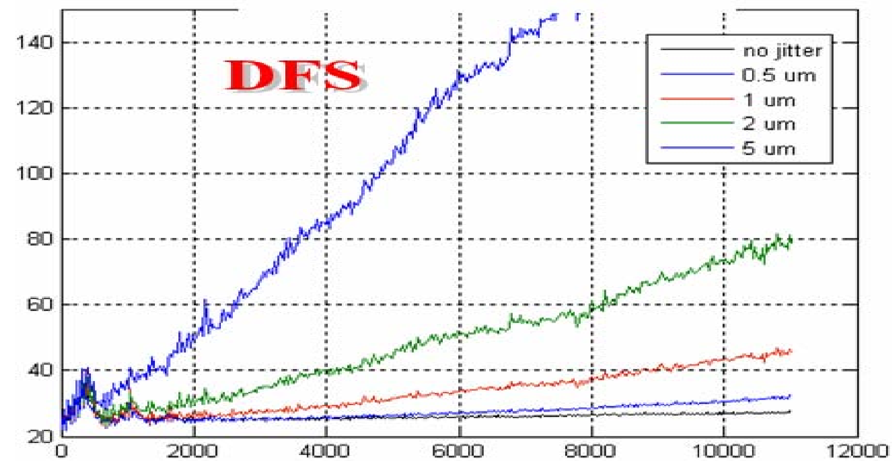
JITTER

Average Normalized Emittance Growth (nm) vs. s (m)

Beam – Beam

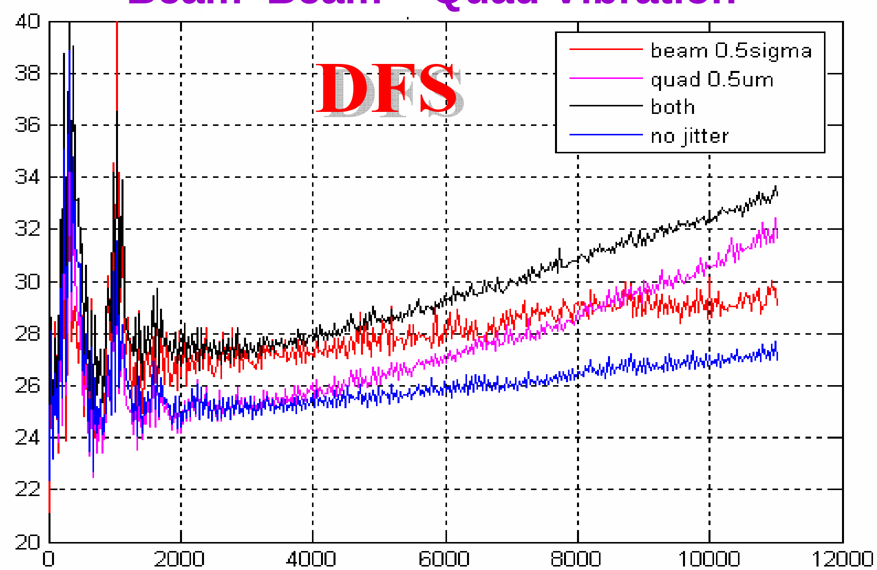


Quad Vibration



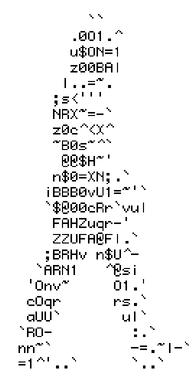
30 MV / m; No BNS
Energy Spread;
1Q/2CM Lattice

Beam–Beam + Quad Vibration



SUMMARY / PLAN

- ➢ Normalized vertical emittance growth (Single bunch) in Main Linac for 500 GeV C.M. USColdLC machine is simulated using MATLIAR
- ☺ DFS algorithm provides significantly better results than One-to-One
- ➢ Important considerations for DFS algorithm
  - ☹ **Spike in the launch region is not understood**
  - ☺ **Average emittance dilution w/ new wake fields and w/o BNS energy spread for 30 MV/m Gradient is within the dilution budget for the nominal misalignments (6.9 nm)**
  - 😐 **Emittance dilution remains within the budget w/ 0.5 sigma beam-beam Jitter (~9.2 nm) but inclusion of quad jitter of 0.5 μm makes it go beyond the budget (~13 nm)**
  - ☹ **90% emittance dilution is beyond the dilution budget**
  - ☞ **Important tolerances to meet**
    - ⇨ **Structure Pitch; CM offset; Quad roll (within the nominal tolerances)**
    - ⇨ **BPM resolution (for 10 μm: 6.9 nm → 13.9 nm)**
    - ⇨ **Quad / beam-beam Jitter**
    - ⇨ **rather insensitive to Quad / BPM offsets; structure offset and CM pitch**
  - ☞ **Launch BPM offsets are needed to be ~ 30 μm or less.**



PLAN

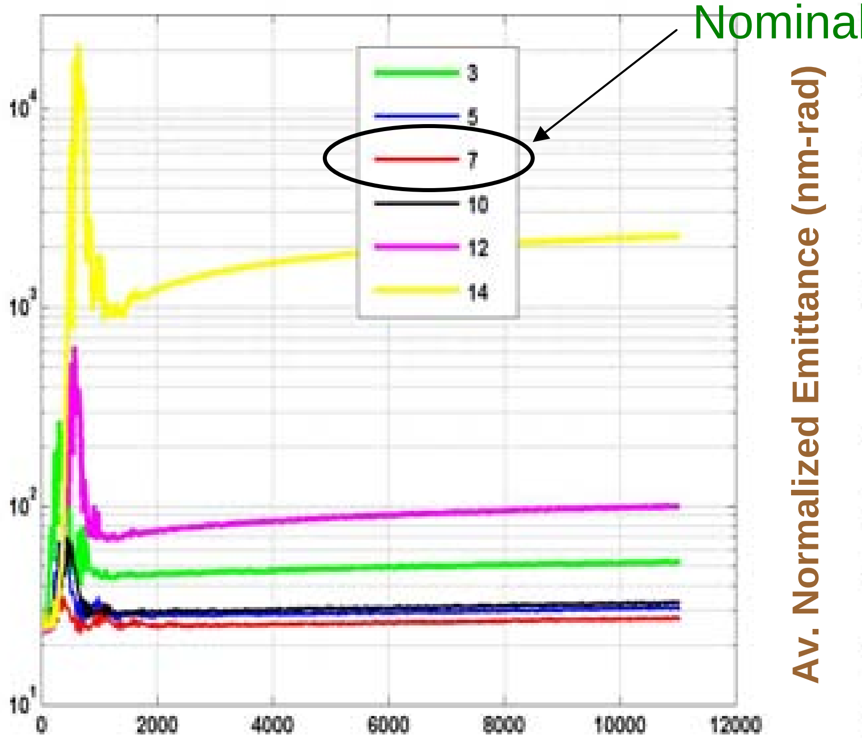
- ➢ Include Ground Motion; Include bumps
- ➢ Comparison w/ Other Alignment techniques
- ➢ Effect of earth curvature
- ➢ Bad seeds study

Further Studies related with DFS Implementation

30 MV/m, USColdLC 1Q/2CM lattice ; Nominal Misalignments

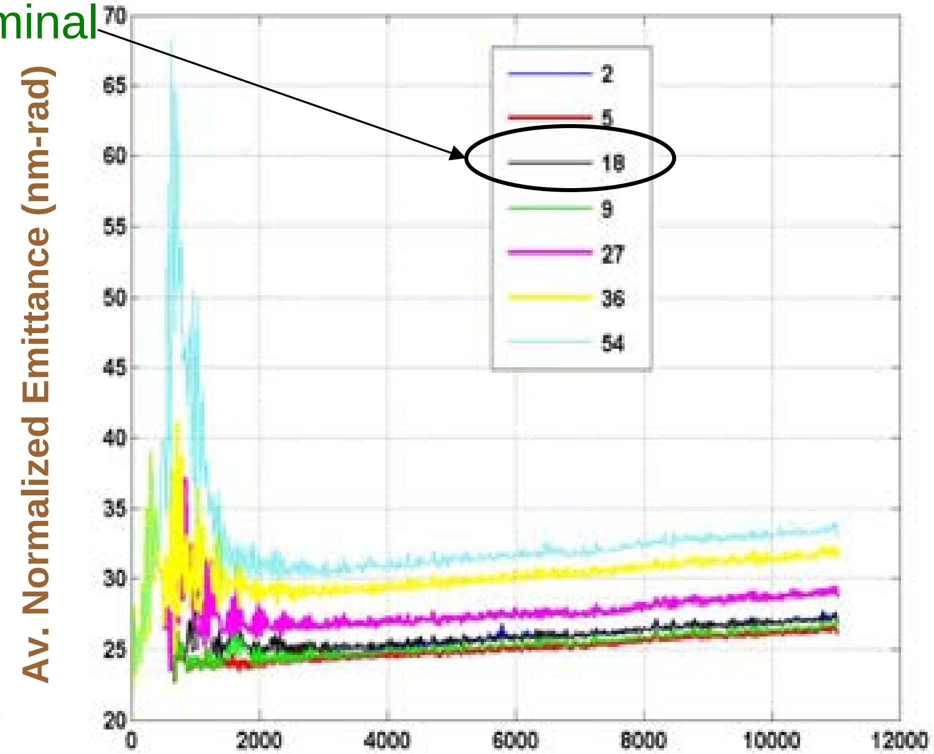
BACK UP – 2

Effect of No. of BPMs in Launch region
(DFS Segments = 18)



Length (m)

Effect of No. of quads per DFS segment
(BPMs in Launch region = 7)

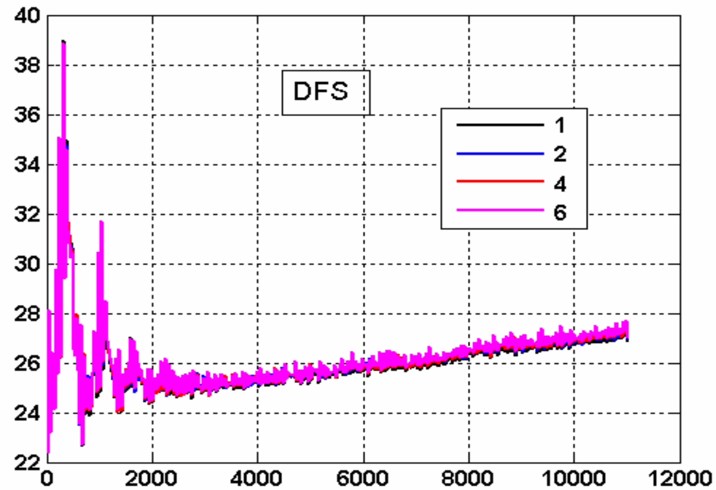


Length (m)

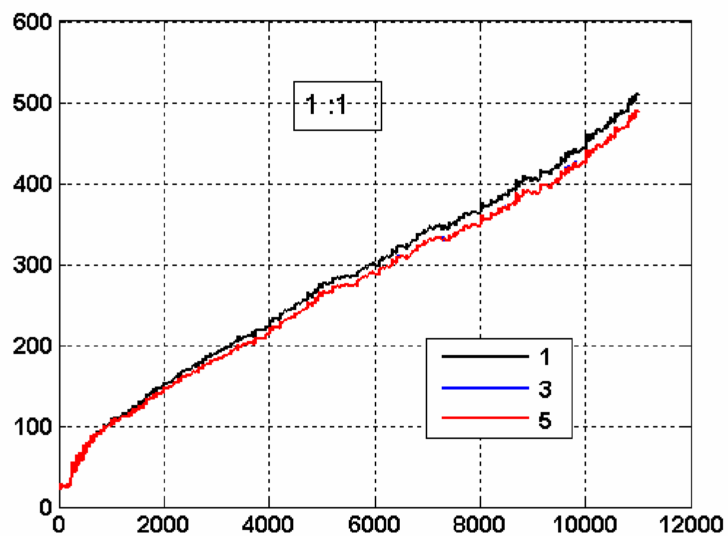
- Tuned for 7 BPMs in Launch Region for 1Q/2CM (5,7,10 give almost similar results
- Better for larger number of quads per DFS segment (2,5,9,18 give almost comparable results)

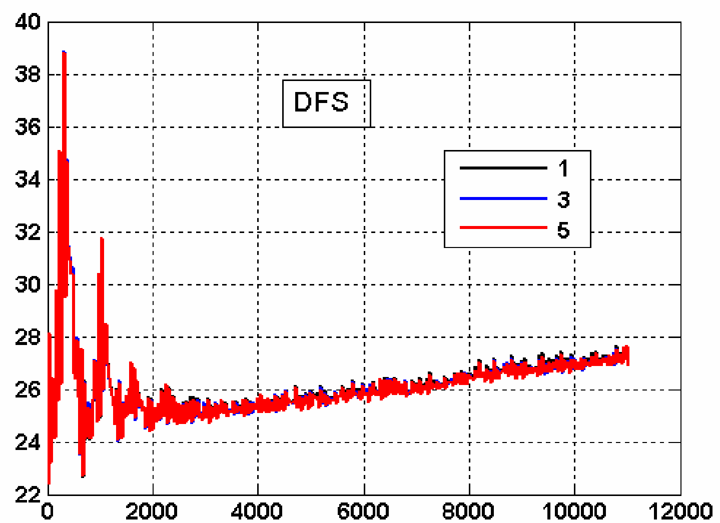
BACK UP – 3

Varying No. of DFS iterations only



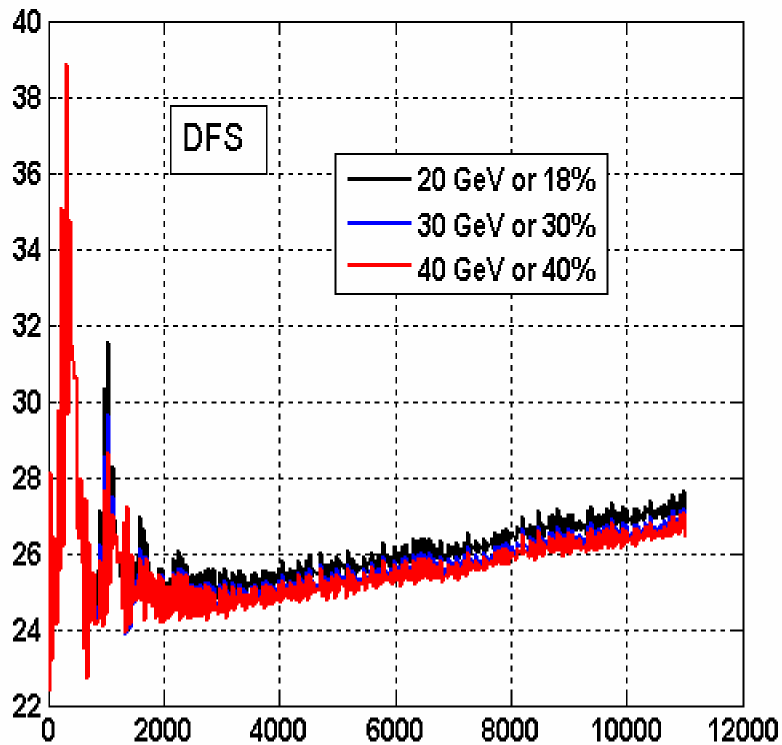
Varying No. of 1:1 iterations only



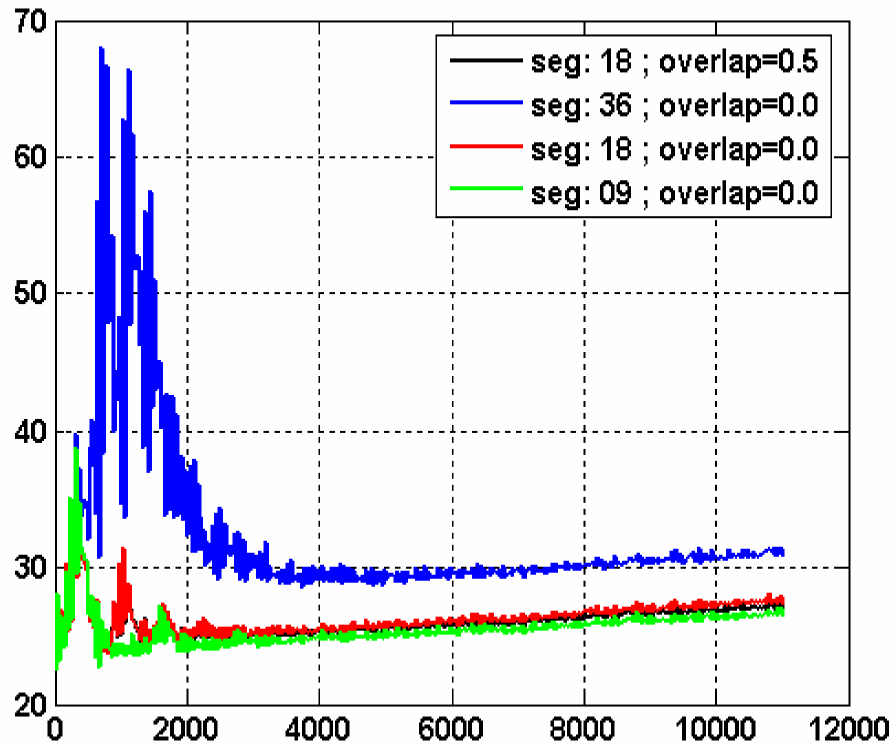


BACK UP – 4

**Varying DFS energy only;
Max. relative energy change and
Max. absolute energy change**

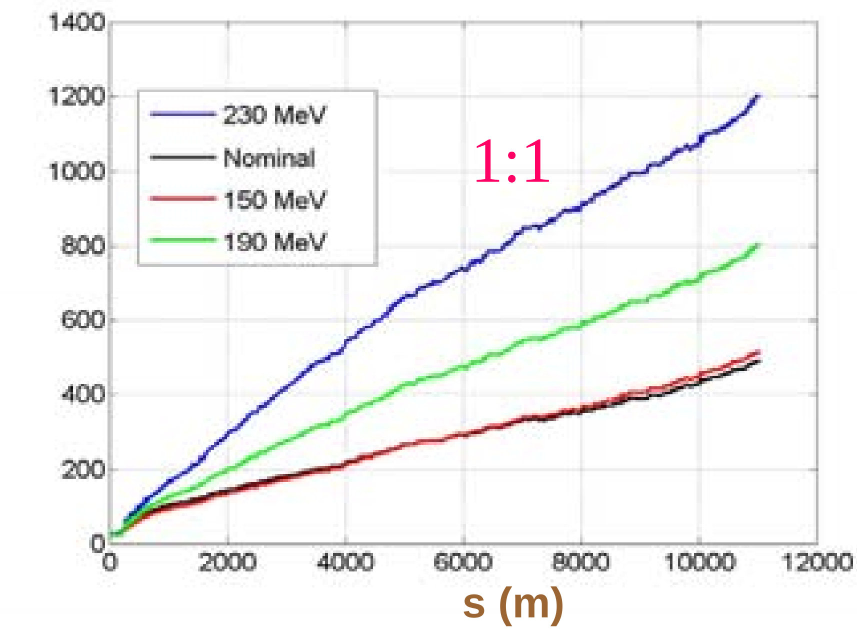


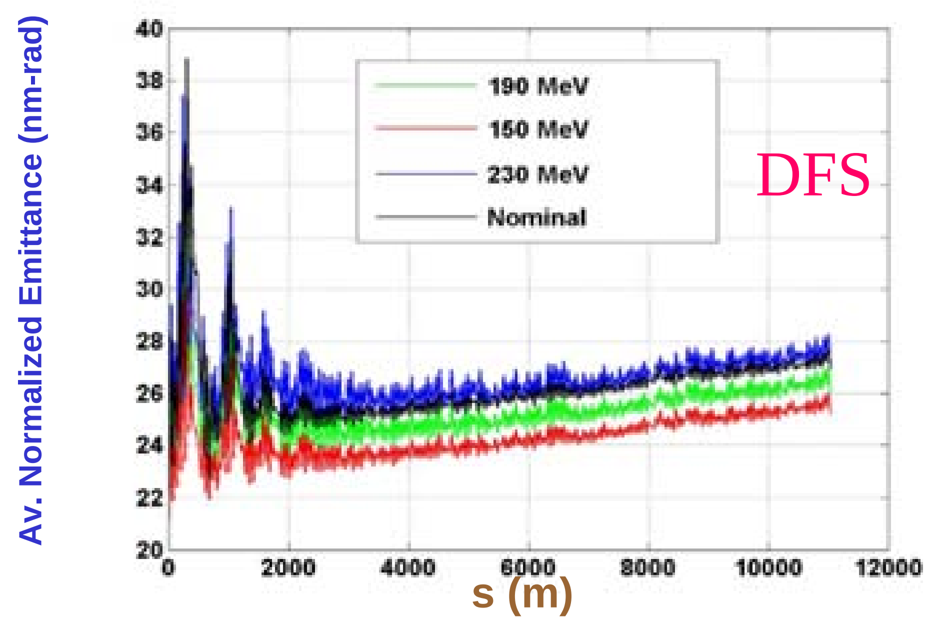
Varying DFS overlap only;



Variation in Injected Energy / Uncorrelated Energy Spread

⇨ **1Q/2CM; 30 MV/m; No Autophasing considered; Nominal Misalignment conditions**





	Mean dilution (nm)		90% (nm)	
	1:1	DFS	1:1	DFS
Nominal Inj. Energy = 5 GeV; espread = 125 MeV	471±38	6.9±0.4	940	13.1
Nominal Inj. Energy =13.5 GeV; espread 150 MeV	496±40	5.2±0.3	992	10.0
Nominal Inj. Energy = 13.5 GeV; espread 190 MeV	782±66	5.9±0.4	1657	11.0
Nominal Inj. Energy =13.5 GeV; espread 230 MeV	1179±104	7.0±0.4	2590	12.9