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


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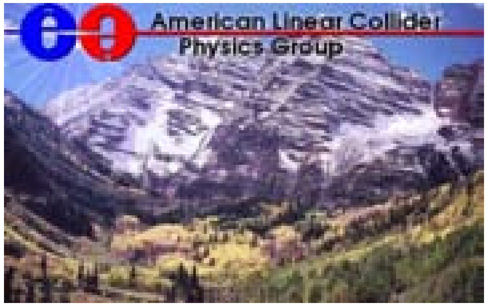


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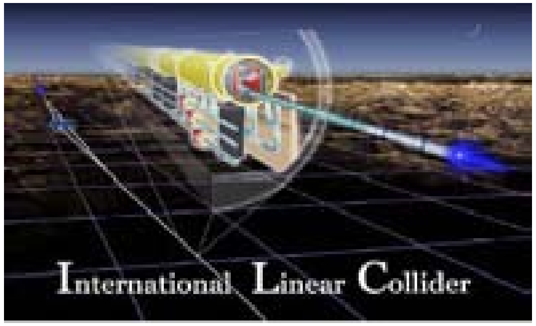
**Aug.14-27, 2005**



# 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

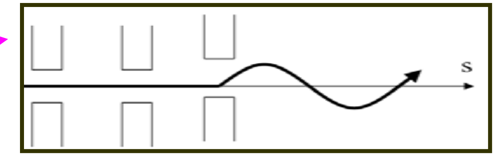
**Normalized Emittance Dilution Budget**

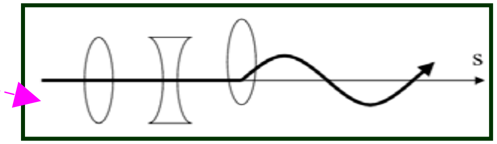
| | | DR Exit => | ML Injection | => ML Exit | => IP |
|---|---|---|---|---|---|
| **TESLA (TDR):** | Hor./Vert (nm-rad): | | 8000 / 20 | | => 10000 / 30 |
| **USColdLC:** | Hor./Vert (nm-rad): | 8000 / 20 => | 8800 / 24 | => 9200 / 34 | => 9600 / 40 |

**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 1st half of TESLA TDR main Linac)**

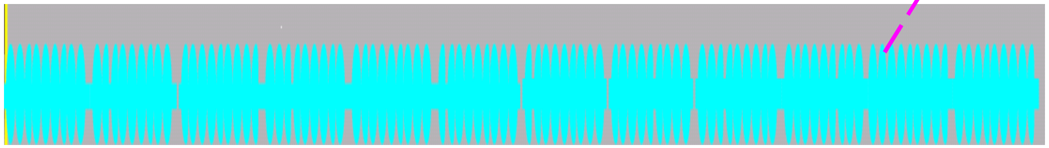
## ➢ Main Linac Parameters

- ⇨ ~**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)

**TESLA SC 9-Cell Cavity**

## ➢ Beam Conditions

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



**12 "9-Cell Cavity" CryoModule**

## *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

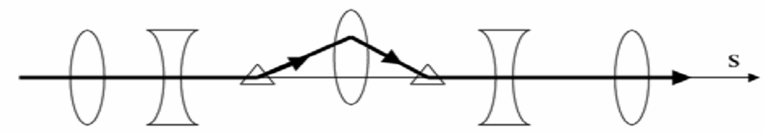
- Beam line elements are needed to be aligned with beam-based measurements
- "Beam Based Alignments (BBA)" refer to the techniques which provide information on beamline elements using measurements with the beam
  - Quad strength variation ← Estimate beam-to-quad offset
  - **"One-to-One" Correction**
  - **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)

## 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

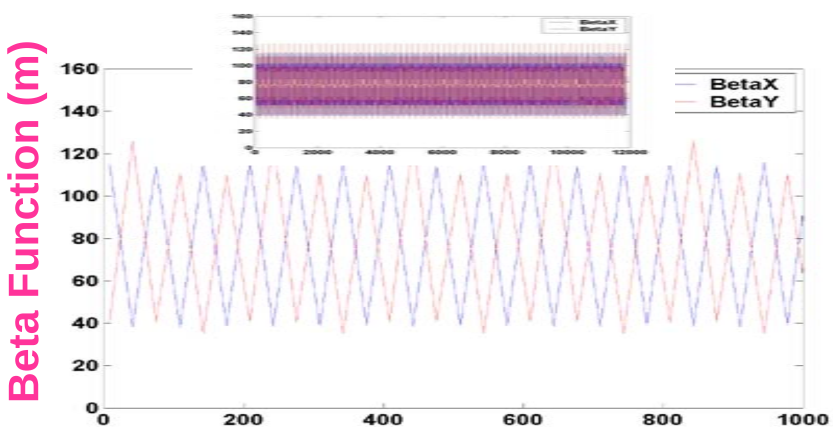
## DFS

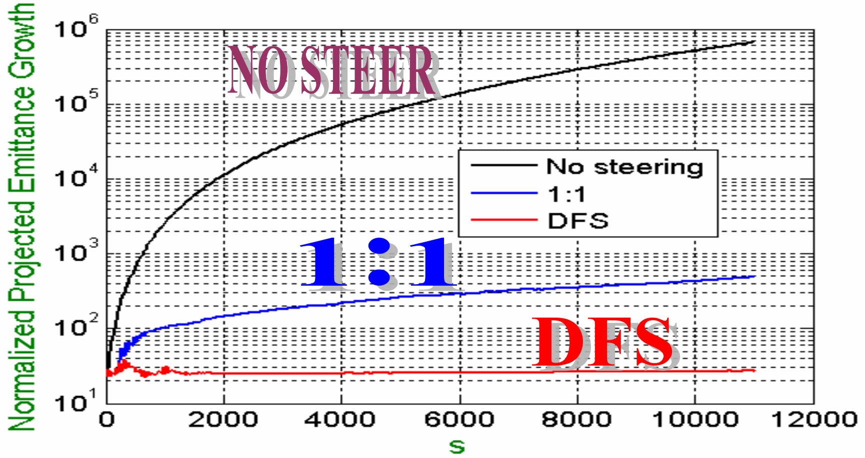
Divide linac into segments of ~40quads

- 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

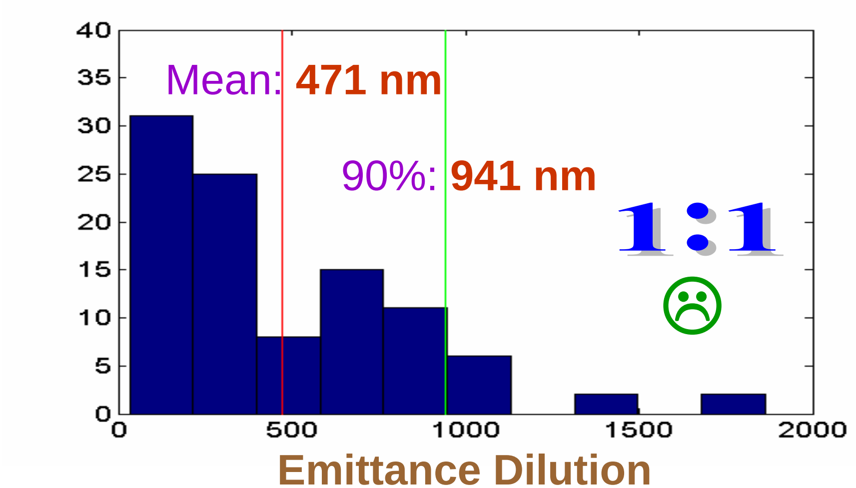
# FOR USColdLC NOMINAL CONDITIONS

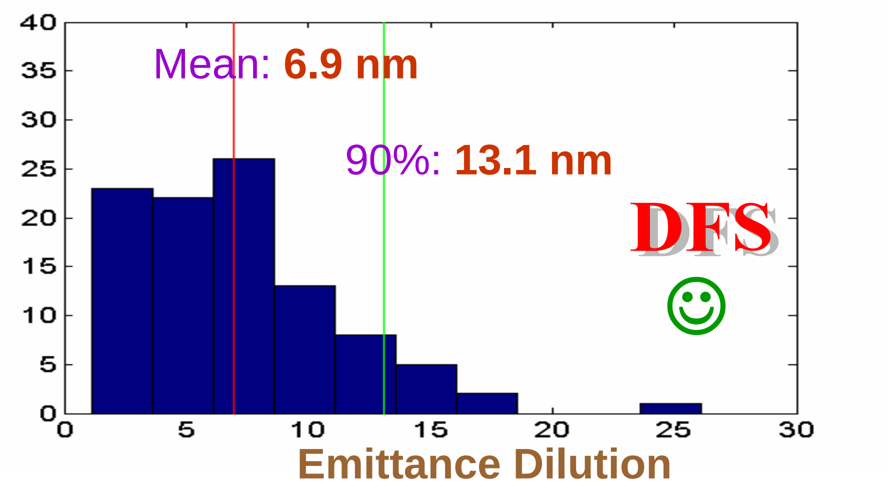
- Gradient : 30 MV/ m; No BNS Energy Spread ; 100 seeds




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



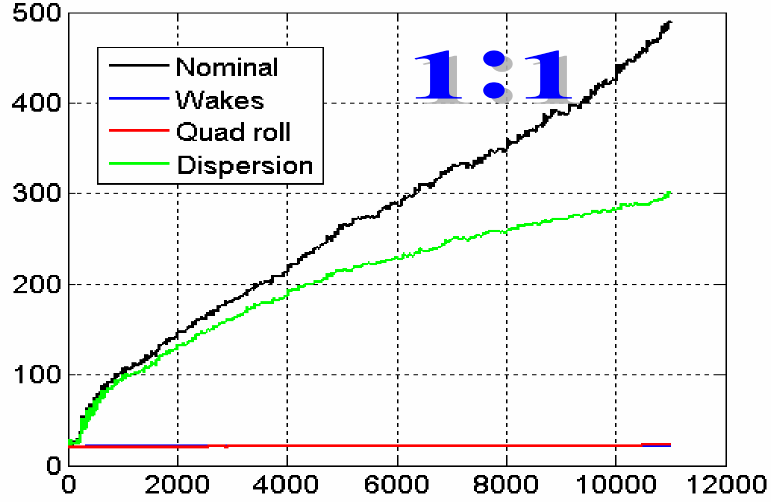



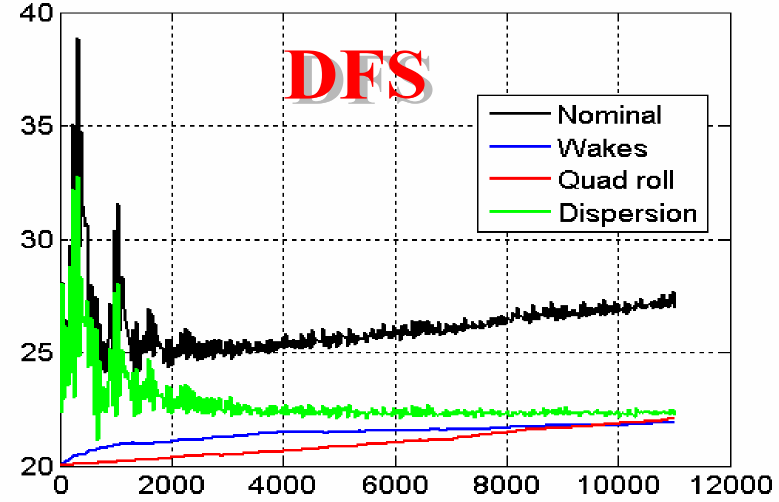

☞ Lower mean emittance growth for DFS than One-to-One

☺ 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)

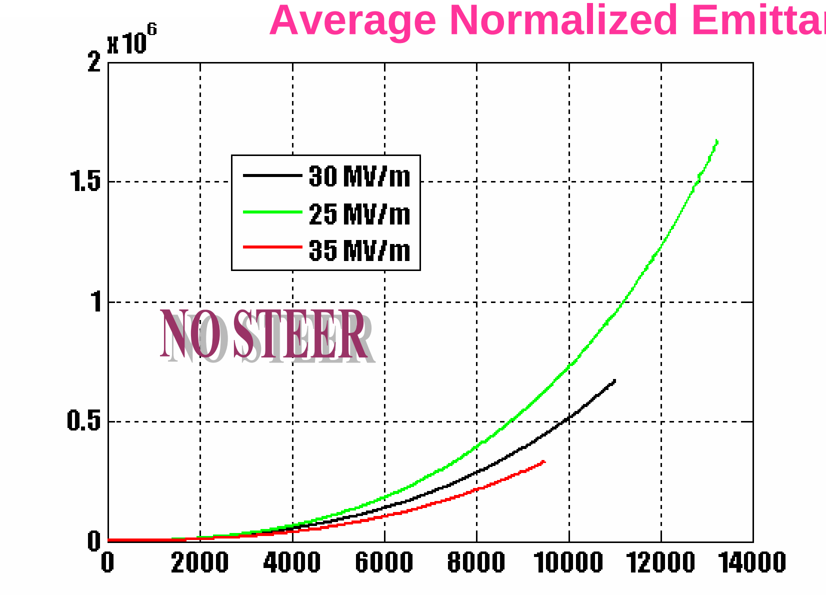
| Tolerance | 1:1 | DFS |
|---|---|---|
| Nominal | 470 | 6.9 |
| Wakes only | 1.9 | 1.9 |
| Dispersion only | 280 | 2.2 |
| Quad roll only | 2.1 | 2.1 |

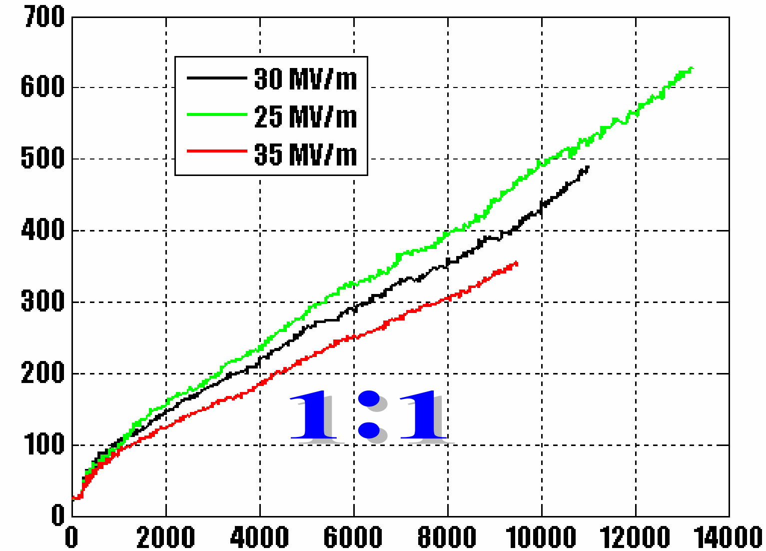
Almost equal contributions

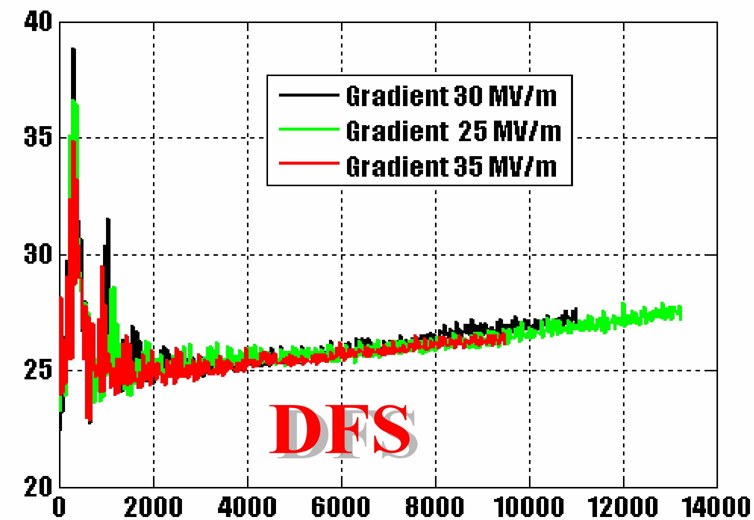
- Wakes include only Cavity and CM offsets; Dispersion includes Quad / BPM Offsets & Cavity / CM pitches
- Nominal >Wakes+Dispersion+Quad roll (Why?– wakefields causing systematic errors ?)

# Effect of GRADIENT

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



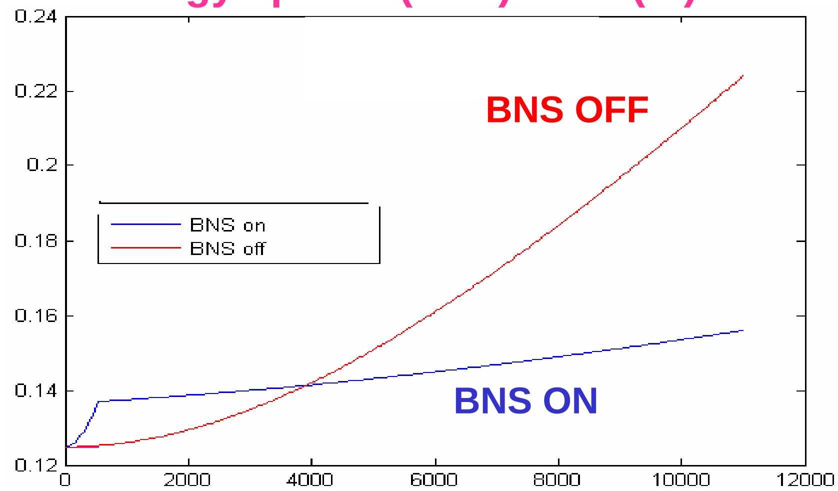



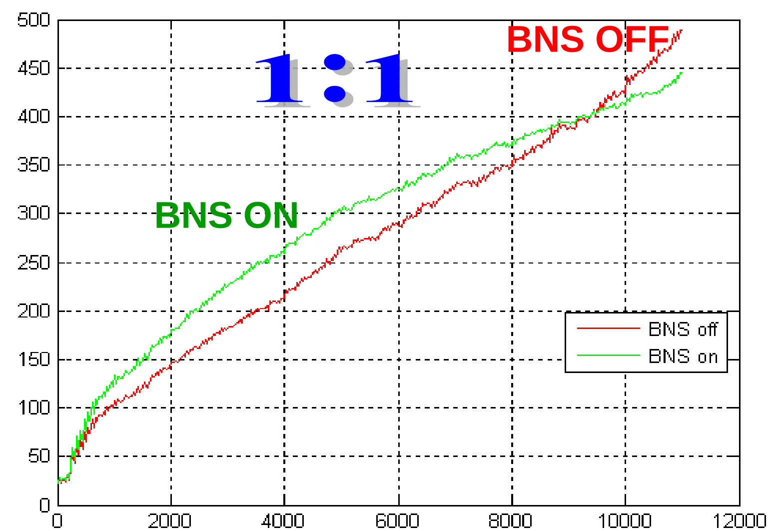

- ☞ **Same wakefields used for all the gradients!**
- ☞ **DFS is almost independent of the change in gradient whereas for 1:1, emittance dilution decreases with increasing gradient**

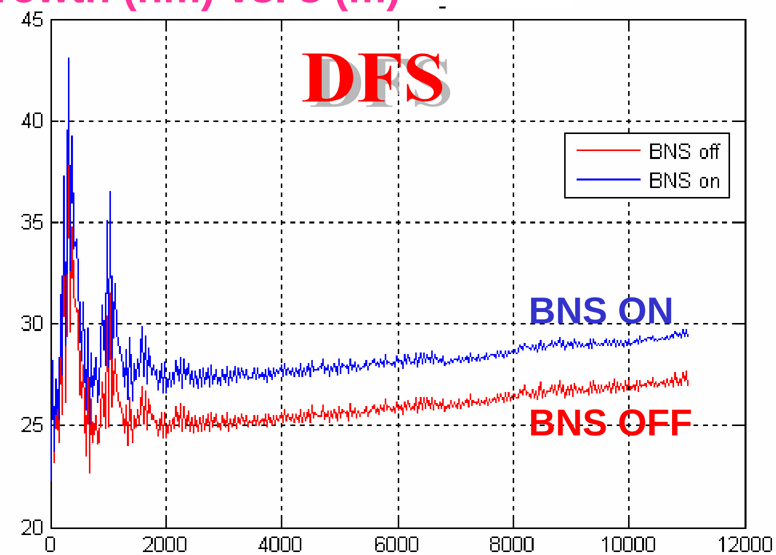
# Effect of BNS ENERGY SPREAD

- ➢ 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




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

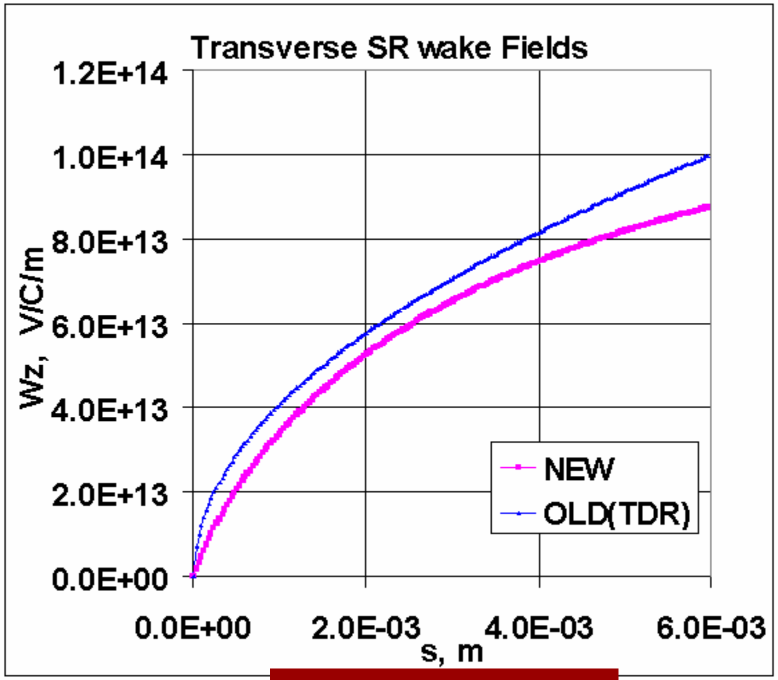


# NEW vs. OLD WAKE FIELD

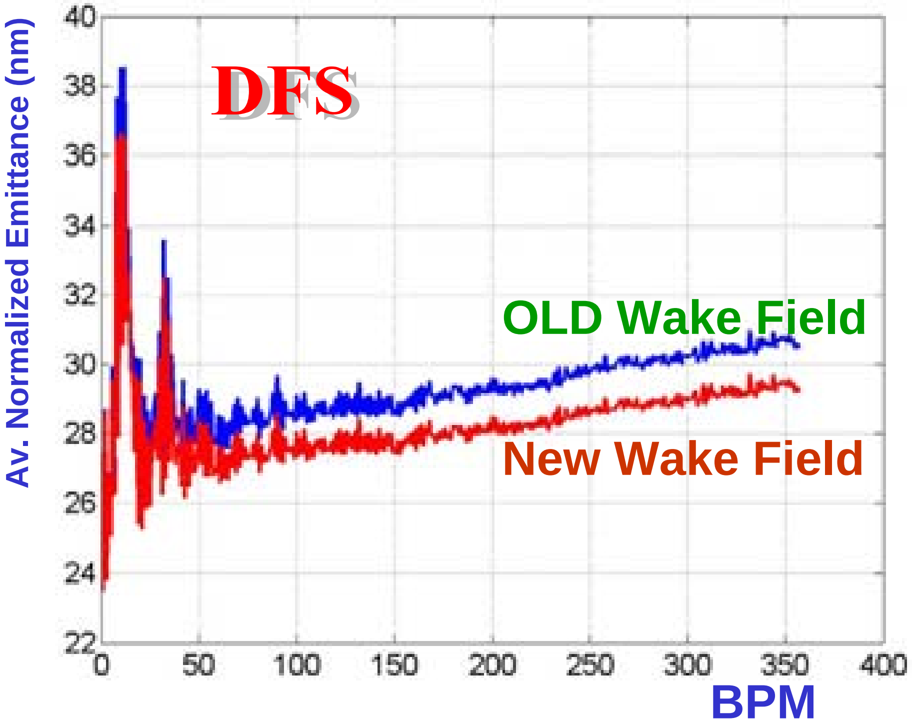
## 28 MV / m Gradient ; w/ BNS Energy Spread; Nominal misalignments

New Wakefield calculations from Zagorodnov & Weiland 2003




New tr. wakes ~ 30% less

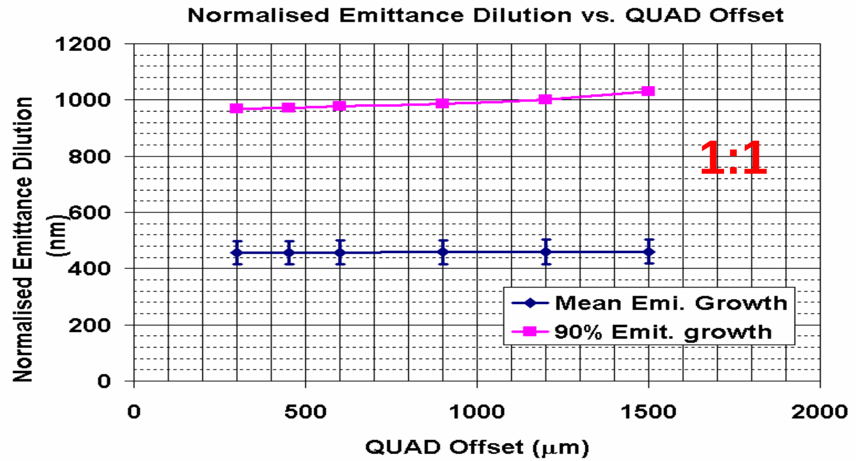
Average Emittance Dilution in the BPMs

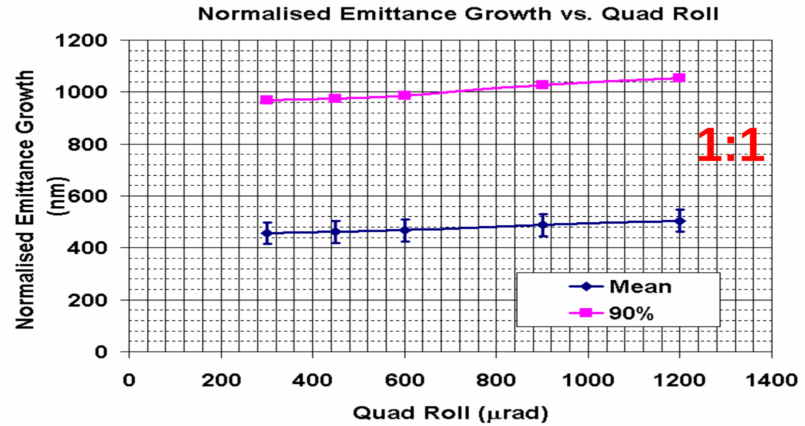


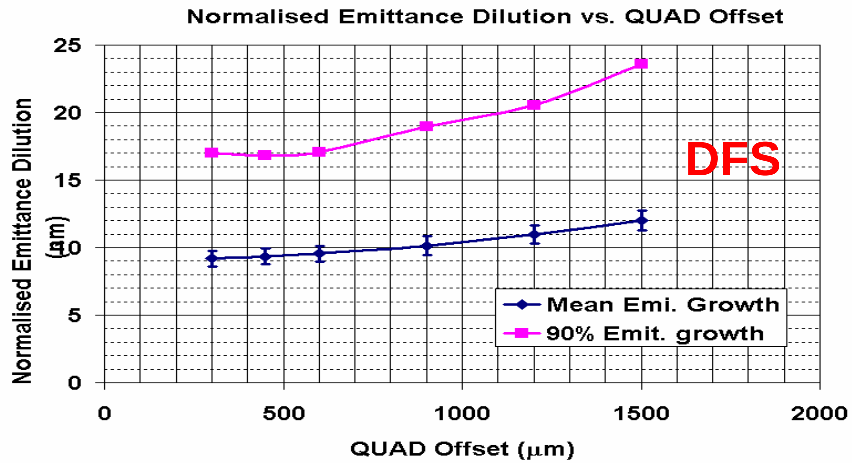
# SENSITIVITY STUDIES
# 28 MV/m Lattice w/ Autophasing

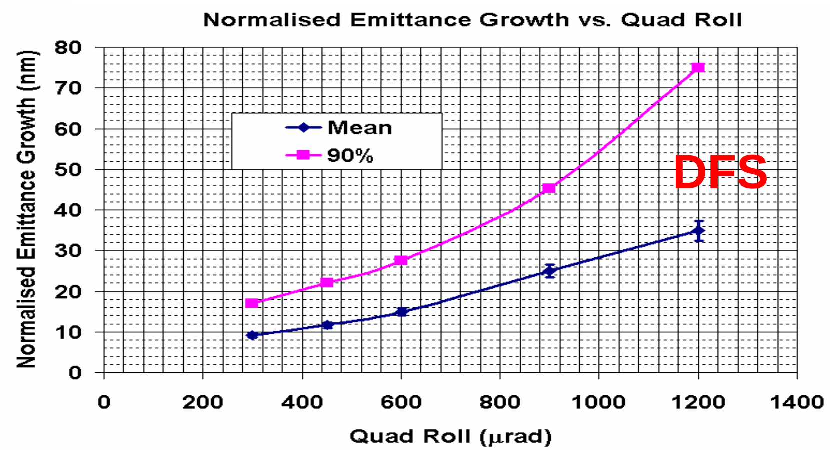
# EFFECT OF *QUAD OFFSETS* / *QUAD ROLL* VARIATION

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



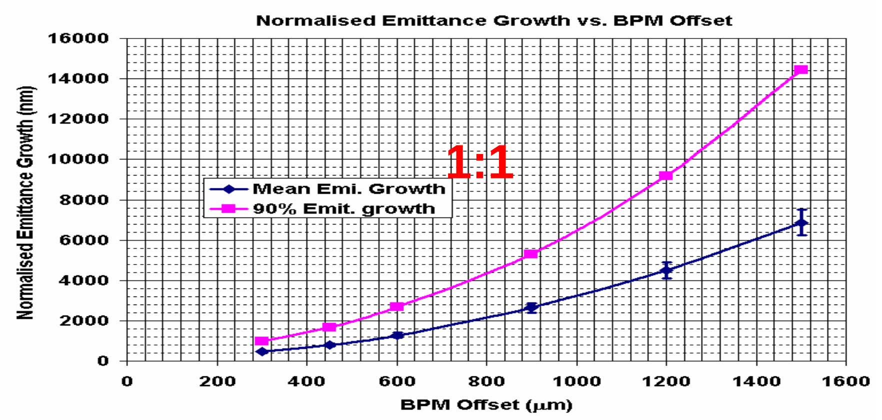



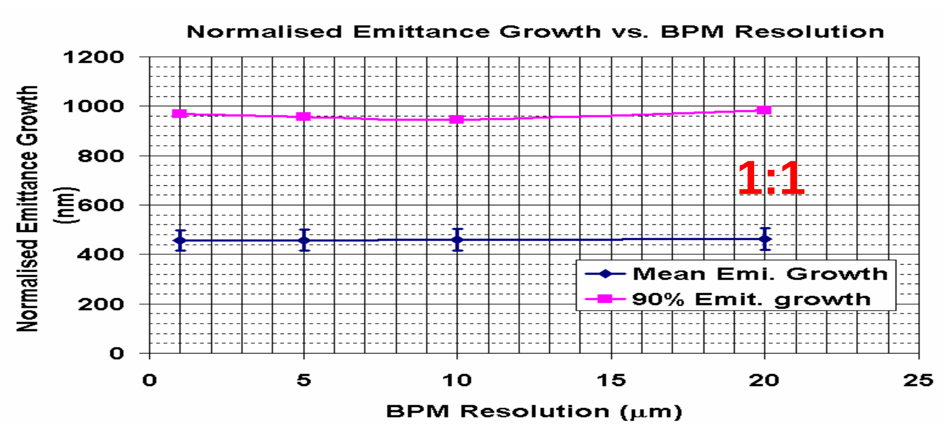



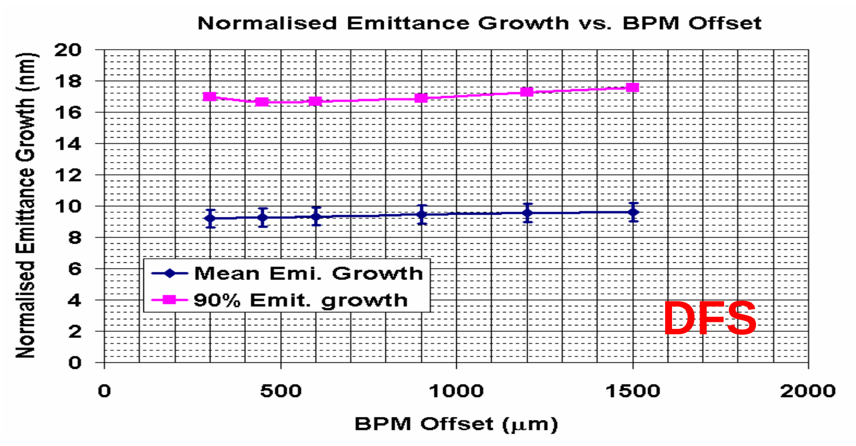



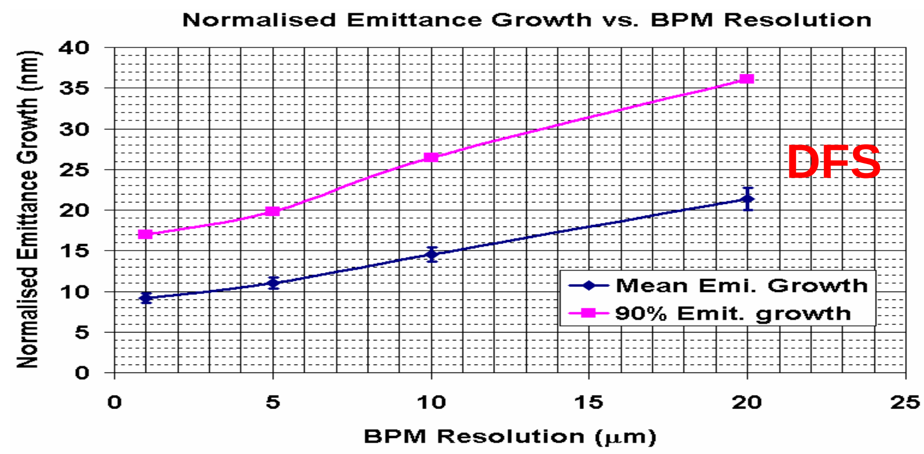

- **Emittance dilution increases slowly with increase in Quad Offsets**
- **DFS: Just under the budget for 2x nominal values**
- **DFS: Emittance dilution increases more rapidly with increase in Quad Roll**
- **DFS: Goes Over the budget even for 1.5x nominal values**

# EFFECT OF *BPM OFFSETS / RESOLUTION* VARIATION



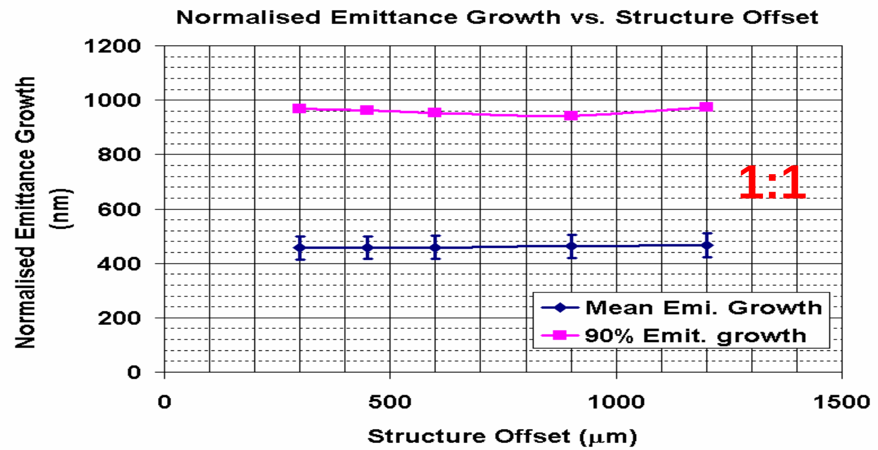



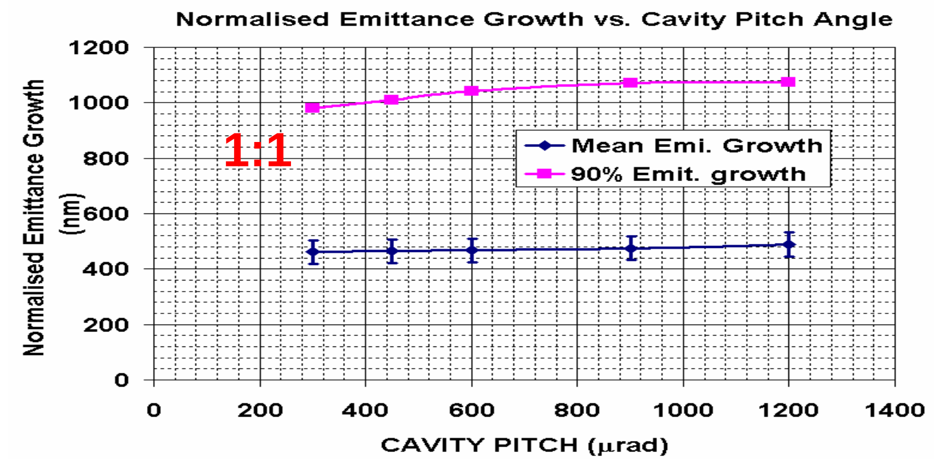



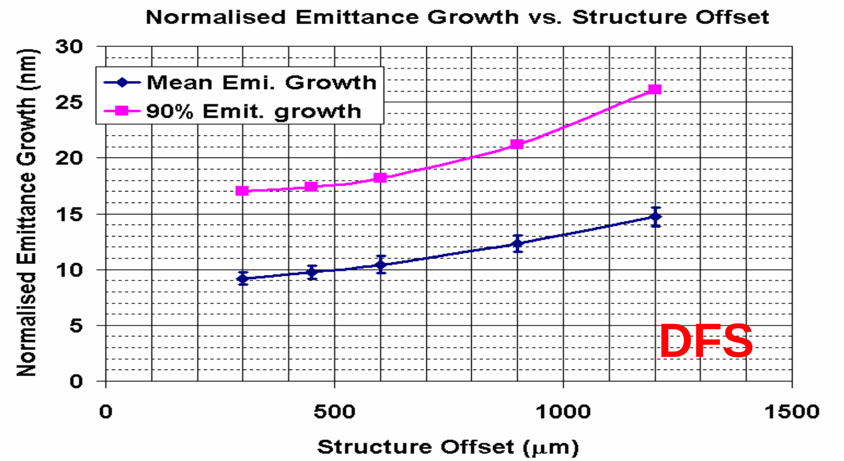



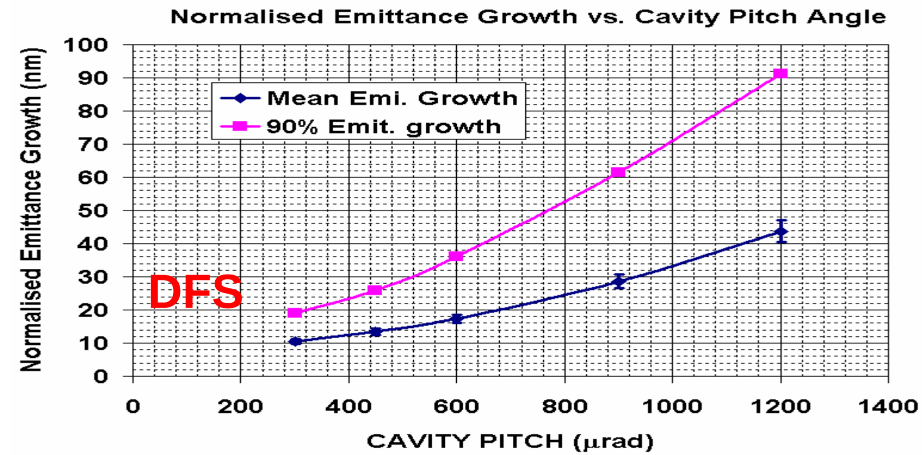

- ***Advantage of DFS:*** **Emittance dilution for 1:1 increases very sharply with BPM offsets**
- **DFS: Emittance dilution is almost independent of BPM offset**
- **DFS: Remains within the budget even for 5x nominal**
- **Emittance dilution for 1:1 is almost independent of the BPM resolution**
- **DFS: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

# EFFECT OF *STRUCTURE OFFSET / PITCH* VARIATION



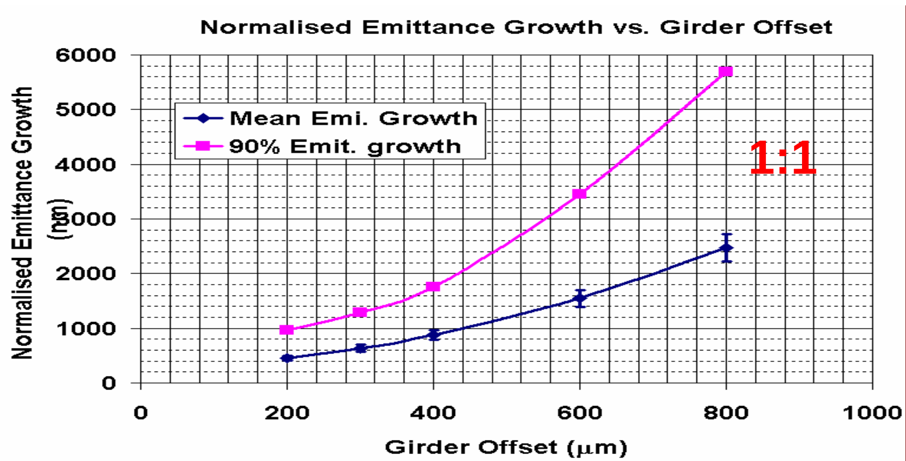



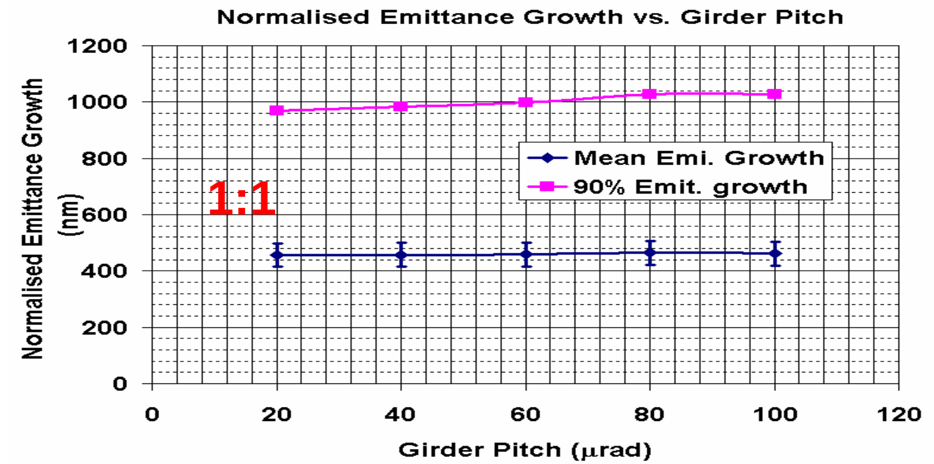



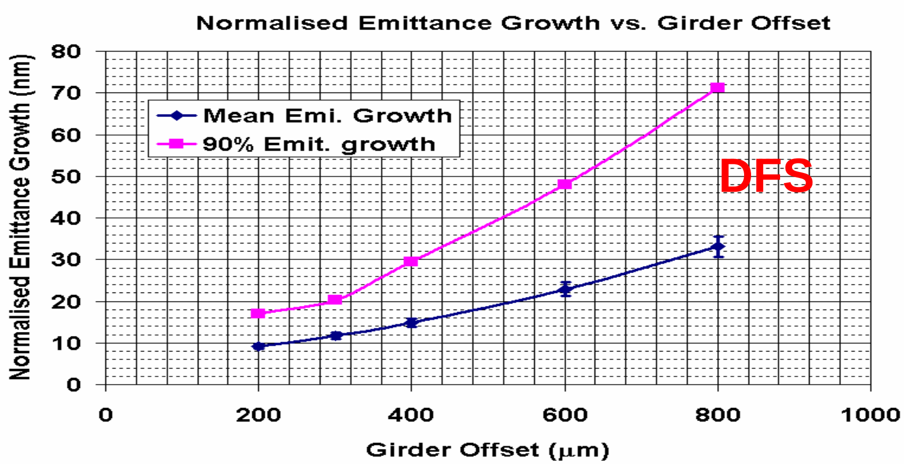



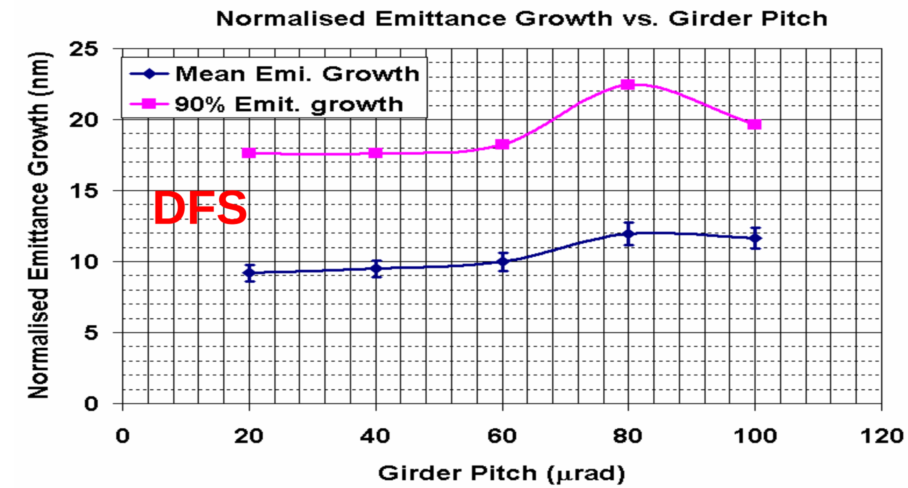

- **Emittance dilution for 1:1 is almost independent of the structure offset**
- **DFS: Emittance dilution grows slowly with structure offsets**
- **DFS: Goes Over the budget for 2.0x nominal values**
- DFS: Emittance dilution is sensitive to Cavity pitch
- DFS: Goes Over the budget even for 1.5x nominal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

# EFFECT OF *CRYOMODULE OFFSET/ PITCH* VARIATION



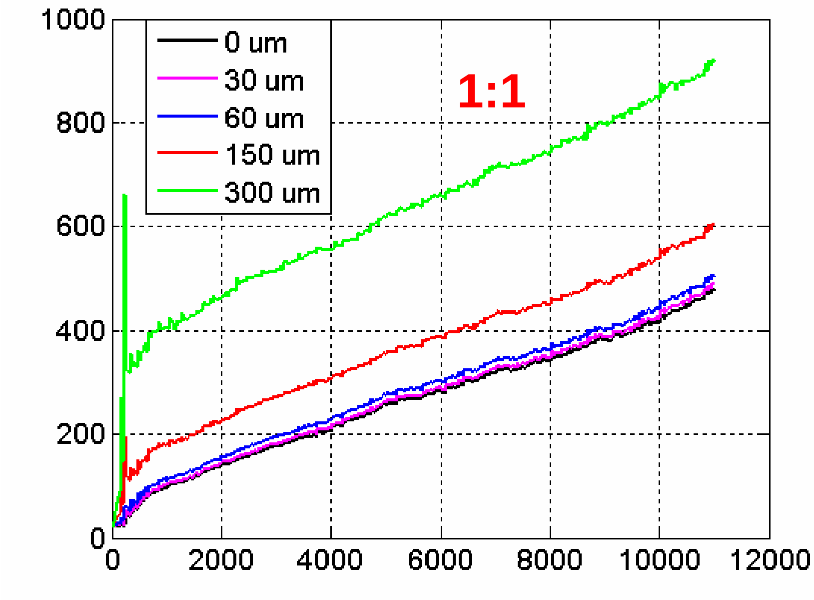



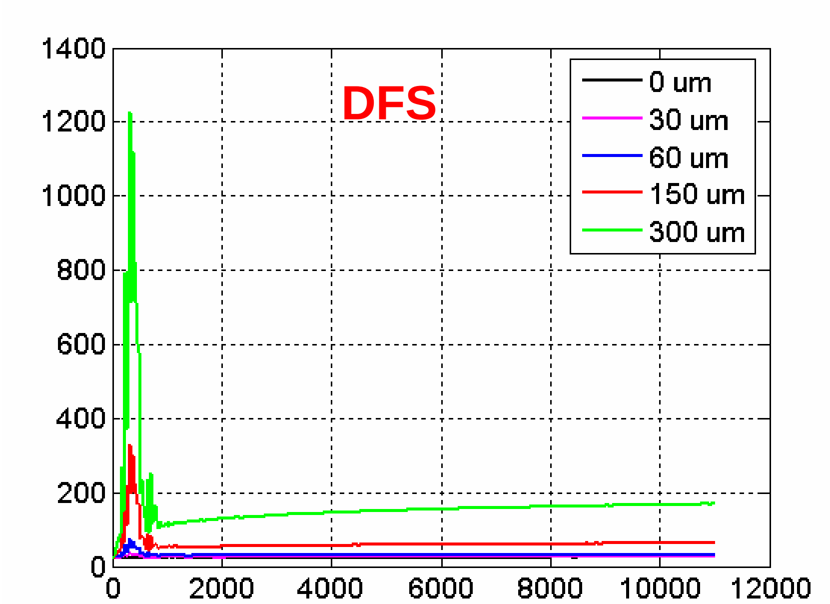




- DFS and 1:1: Emittance dilution grows sharply with CM offset
- DFS: Goes Over the budget even for 1.5x nominal values
- DFS and 1:1: Emittance dilution is almost independent of the CM pitch
- DFS: Remains within the budget for 3x nominal

# EFFECT OF *LAUNCH BPM OFFSETS* VARIATION

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




### Average Emittance Dilution (nm)

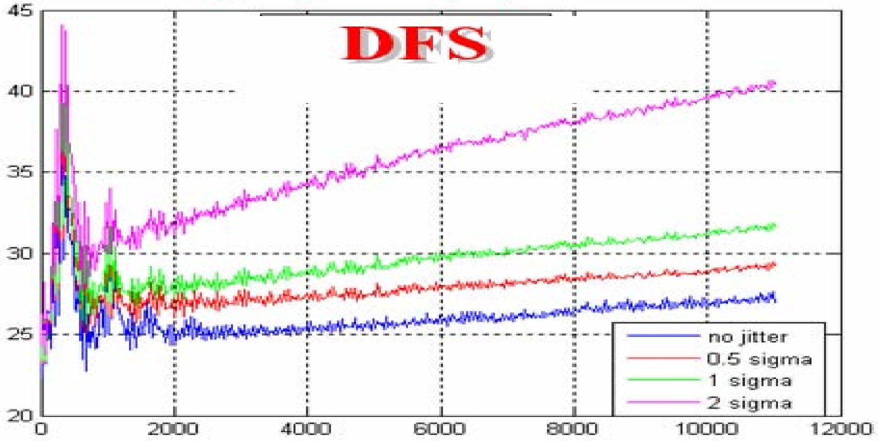
| | 1:1 | DFS |
|---|---|---|
| 0 um : | 4.617e+002 | 5.165e+000 |
| Nominal → 30 um: | 4.709e+002 | 6.932e+000 |
| 60 um : | 4.876e+002 | 1.181e+001 |
| 150 um : | 5.835e+002 | 4.282e+001 |
| 300 um: | 8.956e+002 | 1.484e+002 |

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

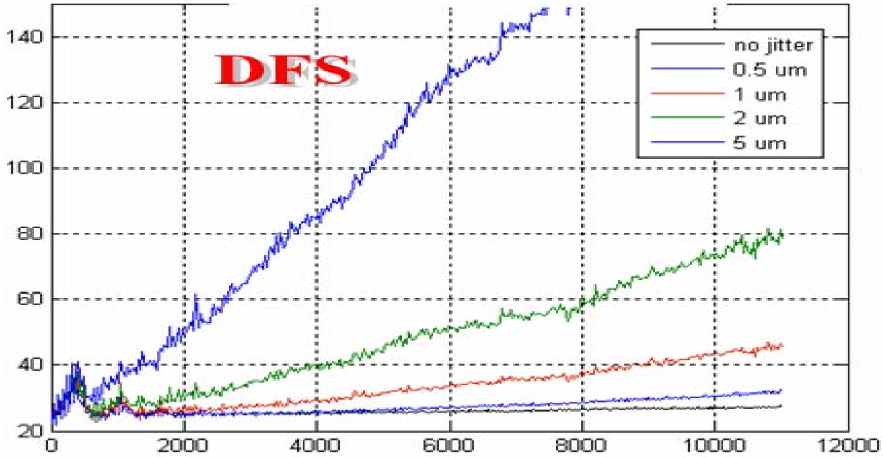
## JITTER

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

**Beam – Beam**

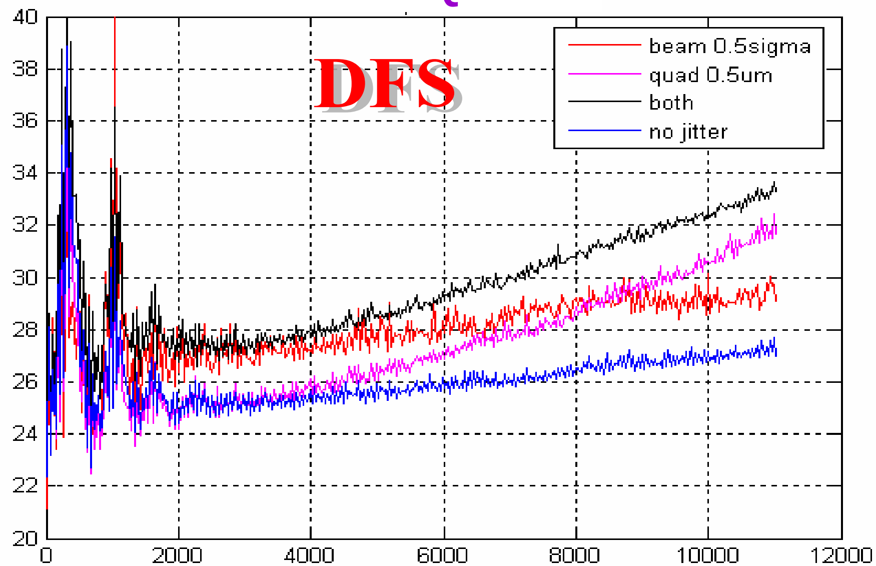



**Quad Vibration**



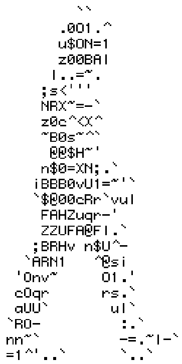

**Beam–Beam + Quad Vibration**

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



# 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

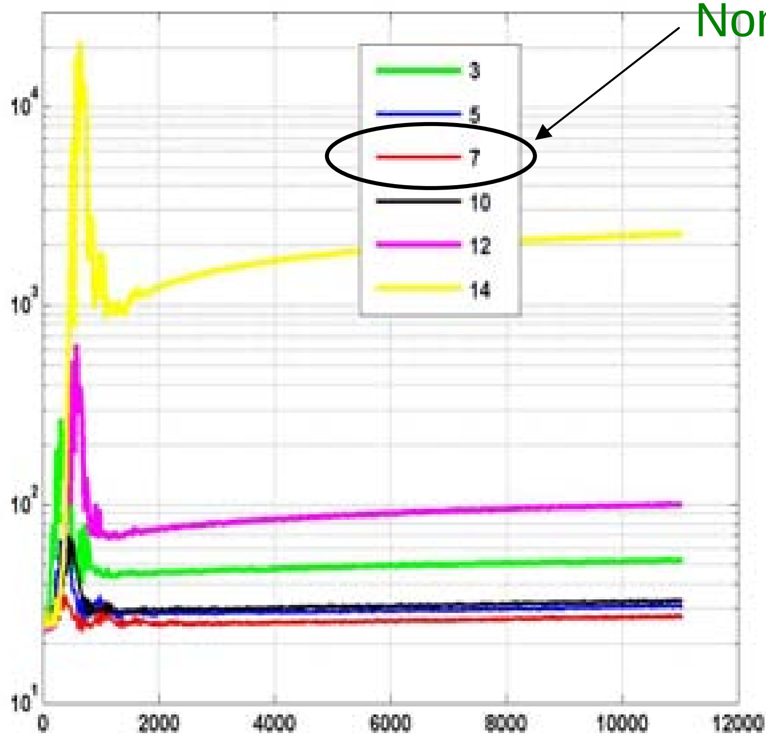
# BACK UP – 1

## Further Studies related with DFS Implementation

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

# BACK UP – 2

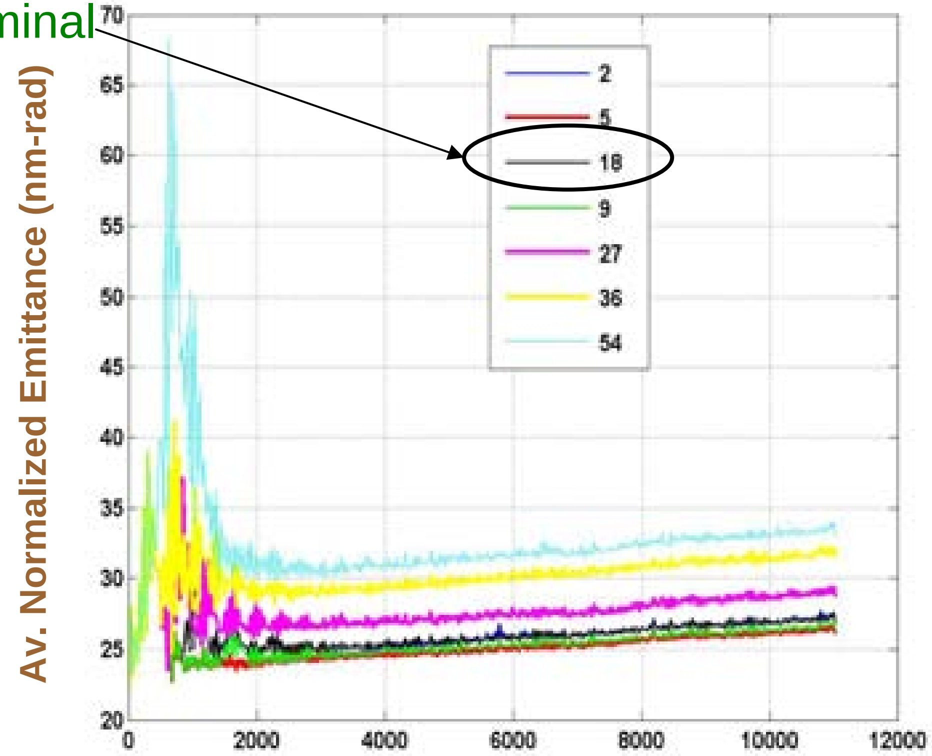
Effect of No. of BPMs in Launch region (DFS Segments = 18)




Length (m)

Nominal

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

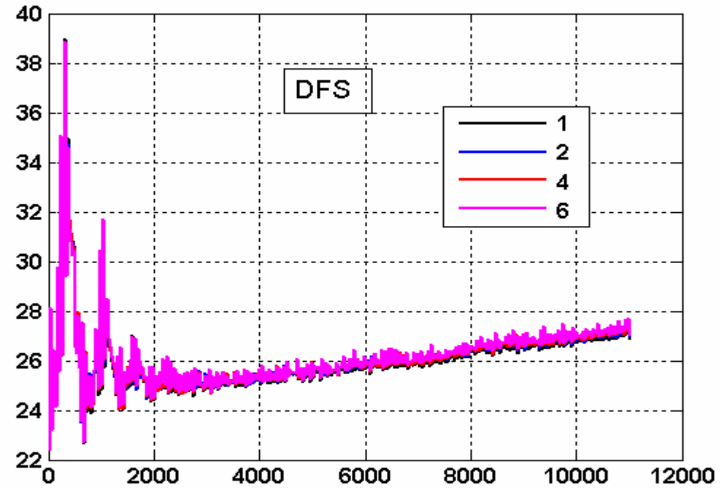



Length (m)

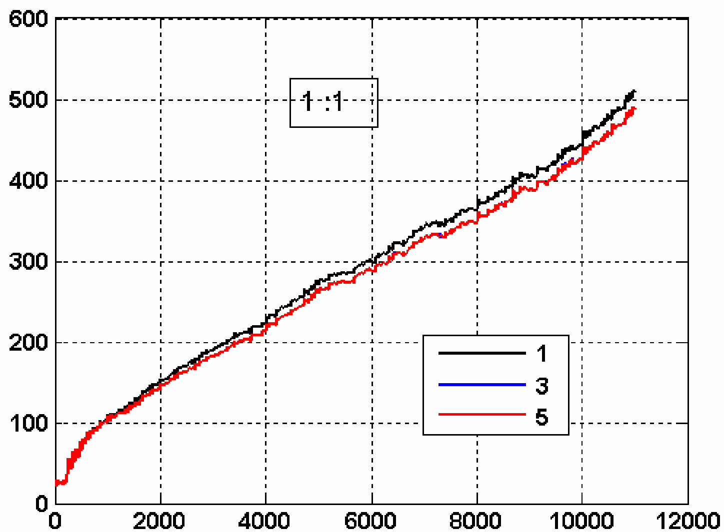
- ➢ Tuned for 7 BPMs in Launch Region for 1Q/2CM (5,7,10 give almost similar results
- ➢ Better for larger number of quads per DFS segment (2,5,9,18 give almost comparable results)

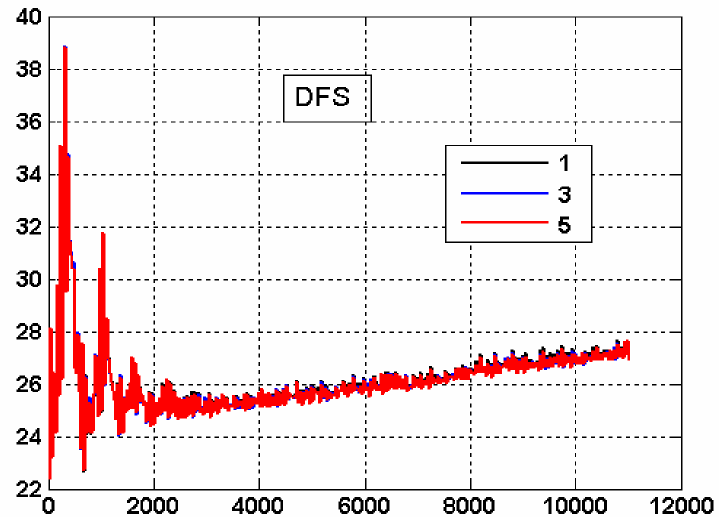
# BACK UP – 3

## Varying No. of DFS iterations only



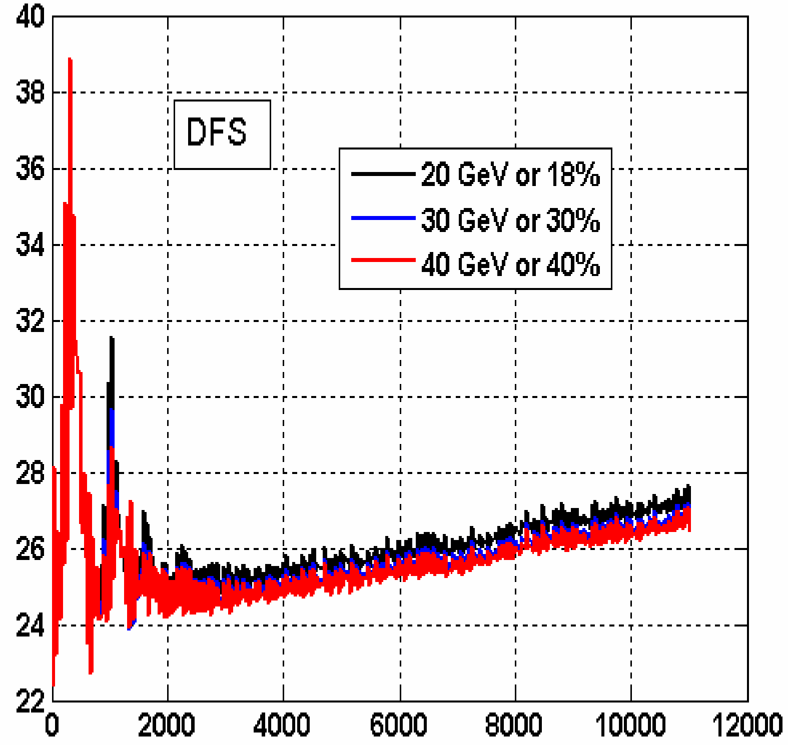

## Varying No. of 1:1 iterations only



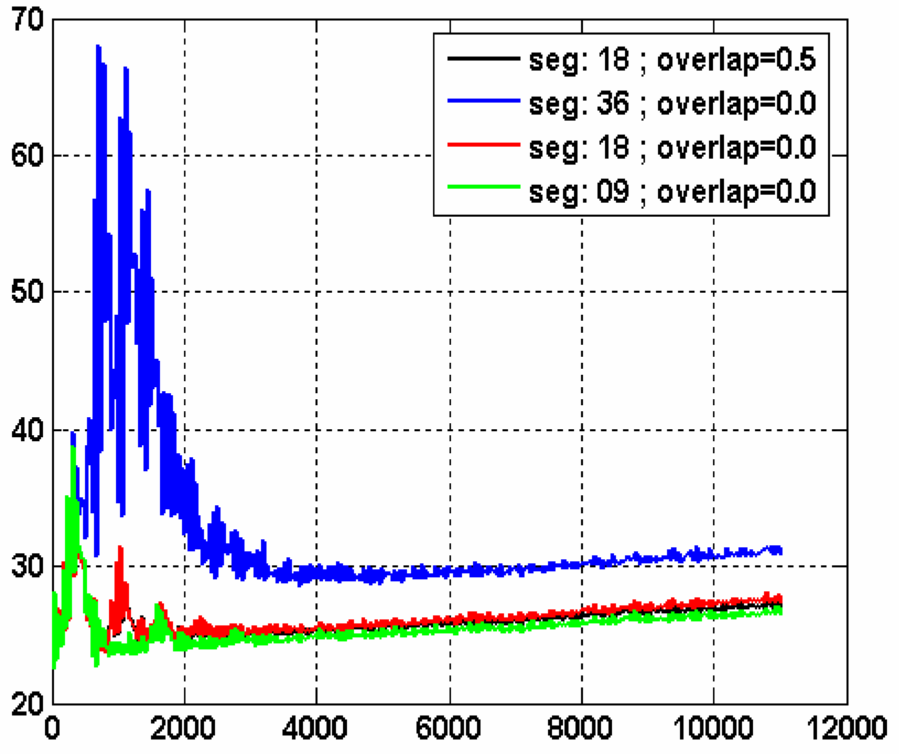



# BACK UP – 4

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

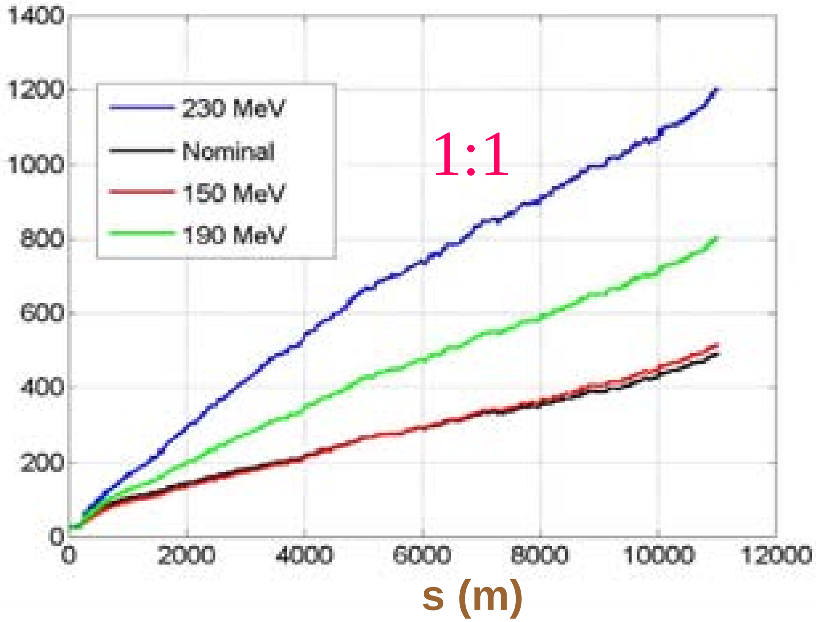


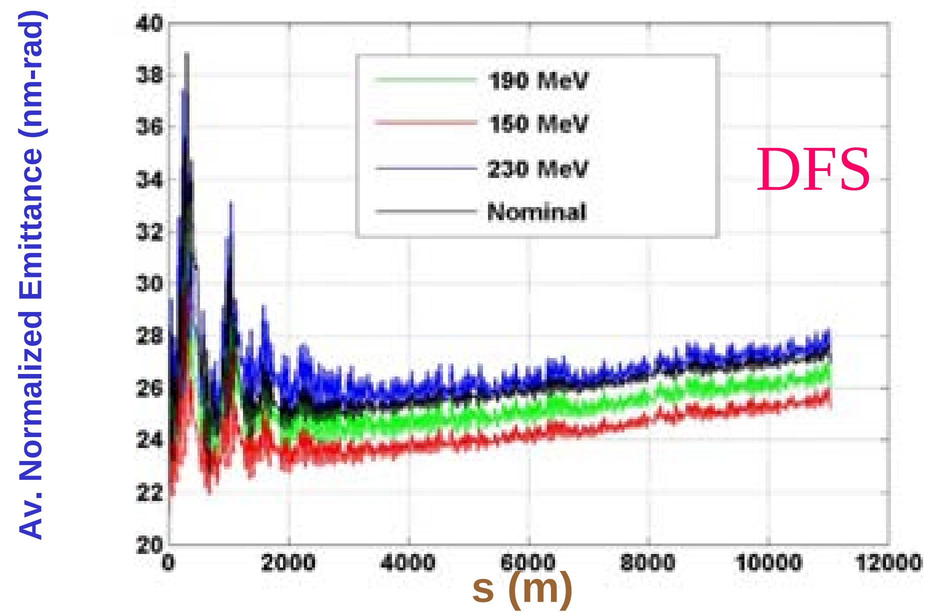

Varying DFS overlap only;



# 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 |