STUDY OF MAIN LINAC SINGLE BUNCH EMITTANCE PRSERVATION IN USColdLC DESIGN (500 GeV CM)

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

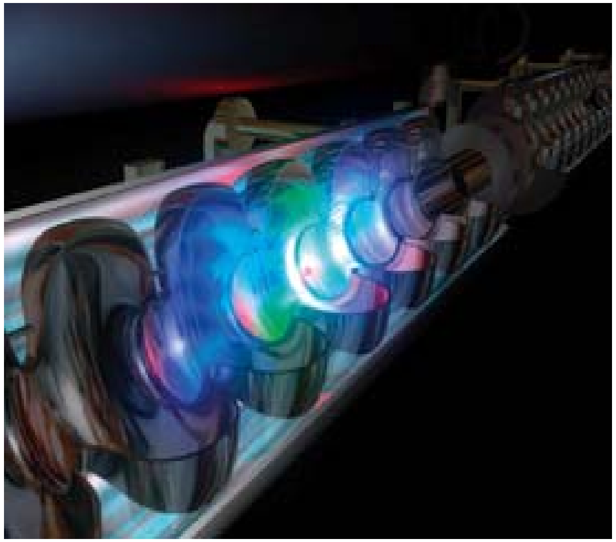
OVERVIEW

Goal:

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

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

Similar work on the NLC MAIN LINAC was performed Last Year



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

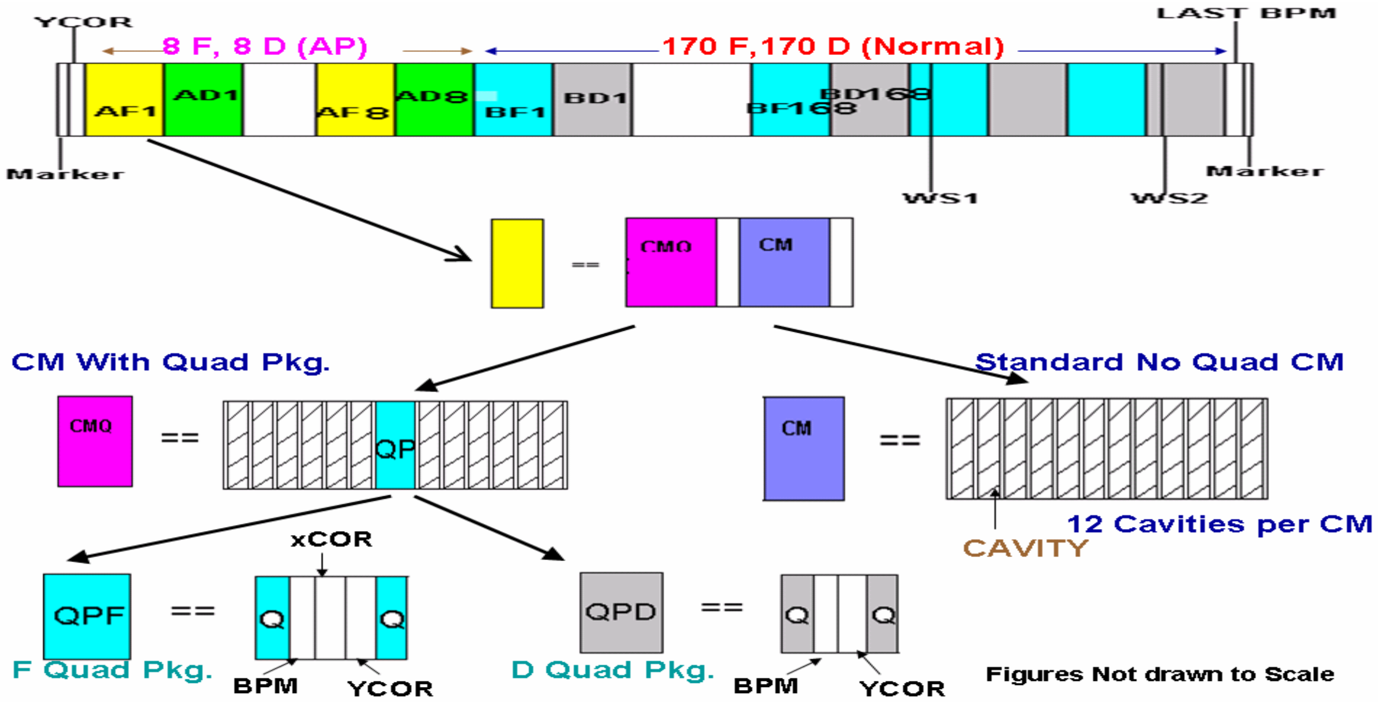
	DR Exit =>	ML Injection =>	ML Exit =>	IP
TESLA (TDR): Hor./Vert **(nm-rad):**		**8000 /20**		**=> 10000 / 30**
USColdLC: Hor./Vert **(nm-rad):**	**8000 / 20 =>**	**8800 / 24**	**=> 9200 / 34 =>**	**9600 / 40**

- *Vertical plane* would be more challenging:
  - Large aspect ratio (x:y) in both spot size and emittance (400:1)
  - ~ 2-3 orders of magnitude more difficult

10 nm (50%)
Vertical emit. Growth in USColdLC

- Primary sources of Emittance Dilution:
  - Transverse Wakefields (Beam Break Up):
    - Short Range : misaligned structures or cryomodules
    - Long Range : as above, and also beam jitter
  - Dispersion from Misaligned Quads or Pitched Structures
  - XY-coupling from rotated Quads
  - Transverse Jitter driven by Quad vibration

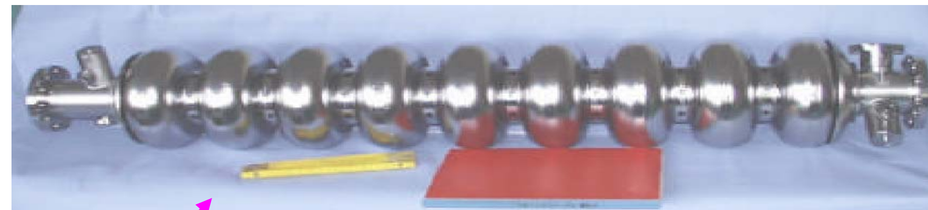
USColdLC MAIN LINAC



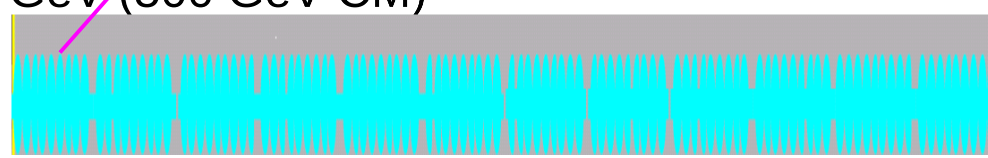
- US Cold LC Main Linac Design
  - Linac Cryogenic system is divided into Cryomodules(CM), with 12 structures / CM
  - Superconducting Quads in alternate cryostats, 356 Quads (178 F, 178 D)
  - Magnet Optics : FODO lattice, with β phase advance of 60^0 in each plane
  - Initial 32 CM are provided with Autophased cavities for BNS damping
  - Each quad has a *Cavity style BPM* and a *Vertical Corrector* magnet; horizontally focusing quads also have a nearby *Horizontal Corrector* magnet.

USColdLC MAIN LINAC

- Main Linac Design
  - ~11.9 km length (similar to the 1st half of TESLA TDR main Linac, but longer)
  - 9 Cell structures at 1.3 GHz and 12 structures per cryostat
  - Total structures : 8544
  - Loaded Gradient : 28 MeV/m
    (*TESLA TDR: 23.5 MeV/m*)
  - Injection energy = 5.0 GeV
  - Initial Energy spread = 2.5 %
  - Extracted beam energy = 250 GeV (500 GeV CM)



TESLA SC 9-Cell Cavity

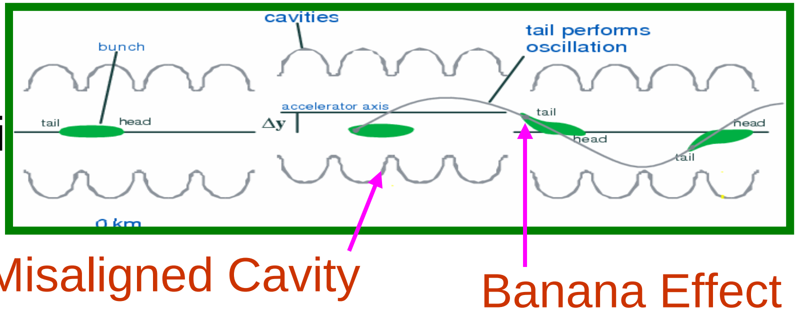


12 "9-Cell Cavity" CryoModule

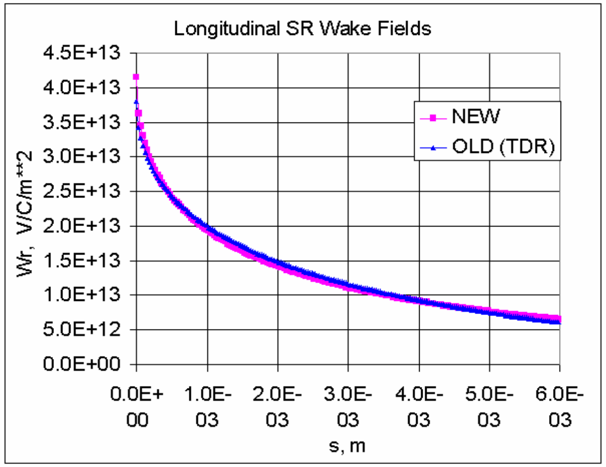
- Beam Conditions
  - Bunch Charge: 2.0×10^{10} particles/bunch
  - Bunch length = 300 μm
  - Normalized injection emittance:
    - $\gamma\varepsilon_Y$ = 20 nm-rad

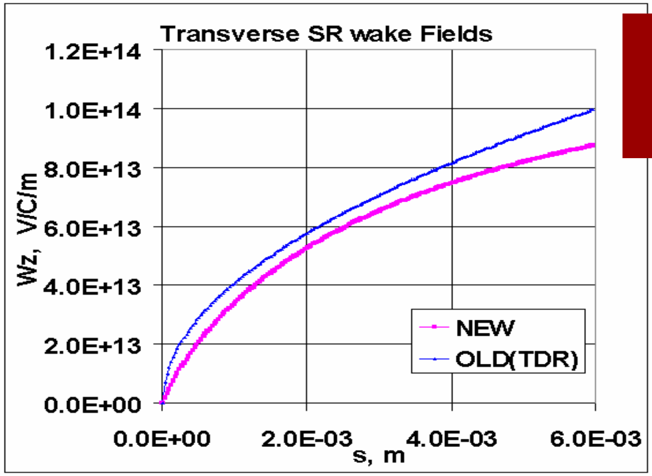
EMITTANCE DILUTION - BEAM BREAK UP (BBU)

- EM field of a charged particle beam interacts with the surroundings
  - ⇨ Act back on the beam itself
  - ⇨ Transverse and Longitudinal
  - ⇨ Short (single bunch) & Long range (multi
  - ⇨ SC advantage : small wakes



- Single Bunch BBU
  - ⇨ BNS Damping: Introduce ***correlated energy spread:***
    - Bunch head higher in energy than bunch tail
    - Transverse wakefield effect compensated by Quad chromaticity





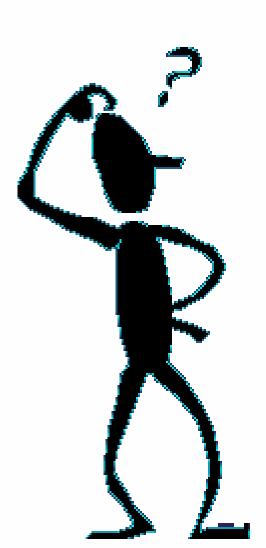
New trans. wakes ~ 30% less

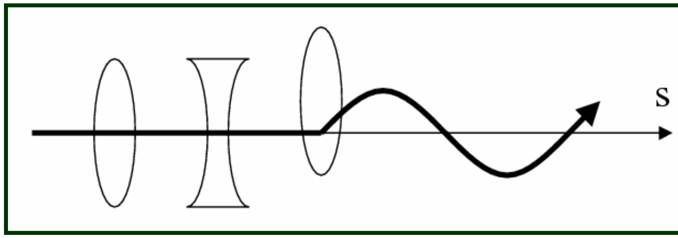
New wake calculations from Zagorodnov & Weiland 2003

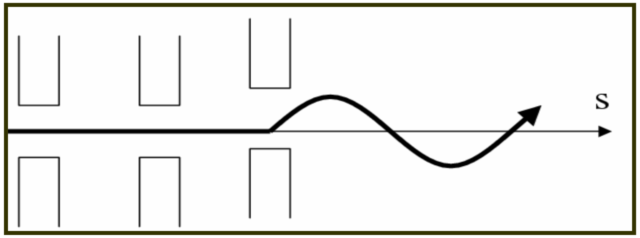
- Multi Bunch BBU
  - ⇨ HOM Dampers : at both end of the TESLA Cavity

SINGLE BUNCH - WHAT's LEFT AFTER BBU?

- Chromatic and Dispersive Sources
  - ☞ Misalignments:
    - ⇨ Beam-to-Quad offsets
    - ⇨ Beam-to-RF Structure offsets
    - ⇨ RF Structure pitch angles
  - ☞ Quad Roll Errors







- Transverse Jitter

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 (Structure Pitch w.r.t. Cryostat; Cryostat Pitch w.r.t. Survey Line)

10 μm in TDR, expect improved results using NLC X-band Cavity BPM R&D (BPM Resolution)

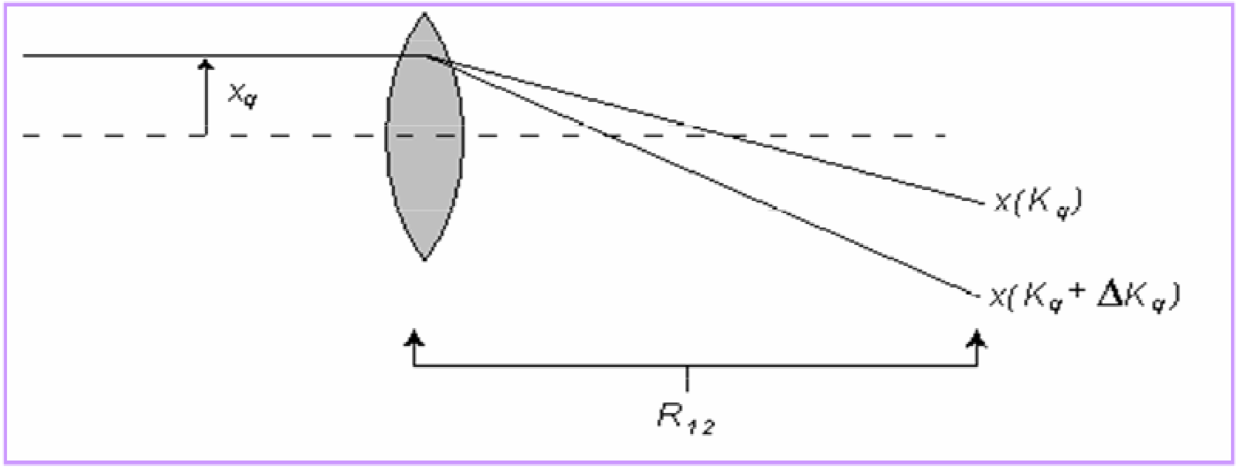
- BPM transverse position is fixed, and the BPM offset is w.r.t. Cryostat
- Only Single bunch used
- No Jitter in position, angle etc.; No Ground Motion and Feedback
- No Quad Movers, Steering is performed using Dipole Correctors.

ALIGNMENT & STEERING ALGORITHMS

- Alignment tolerances can not be met by *ab initio* installation
- 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 ← Considered here
  - Dispersion Free Steering ← Considered here
  - Dispersion bumps
  - Ballistic Alignment
  - Others….

BEAM BASED ALIGNMENT

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

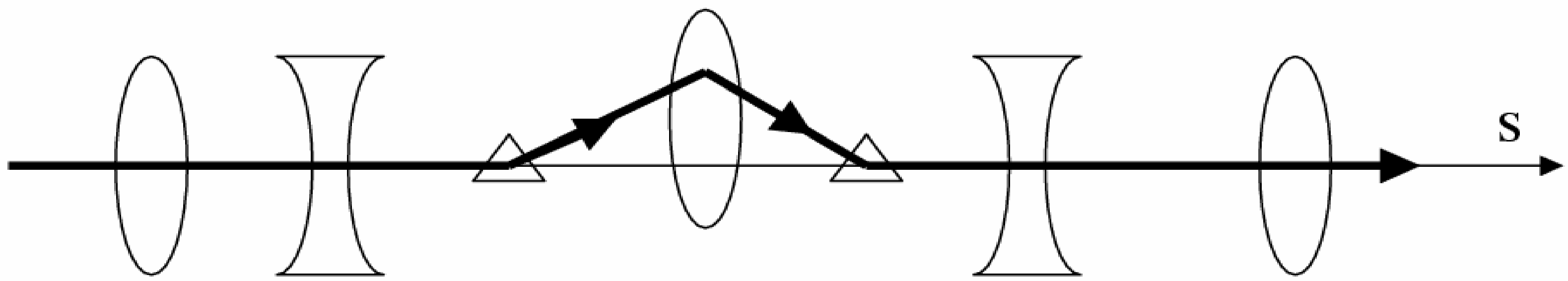


- Allows estimation of beam-to-quad offset
- In USColdLC, it is not assumed that all quads would be shunted
  - ⇨ Quads are Superconducting and shunting might take a very long time
  - ⇨ No experimental basis for estimating the stability of the Magnetic center as a function of excitation current in SC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

BBA : ONE-TO-ONE CORRECTION

- 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
  - ☞ 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

BBA: 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 (via steering magnets) 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: Dedicated Processors for the purpose

➢ Launch Region Steering

⇨ 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

One-to-One

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

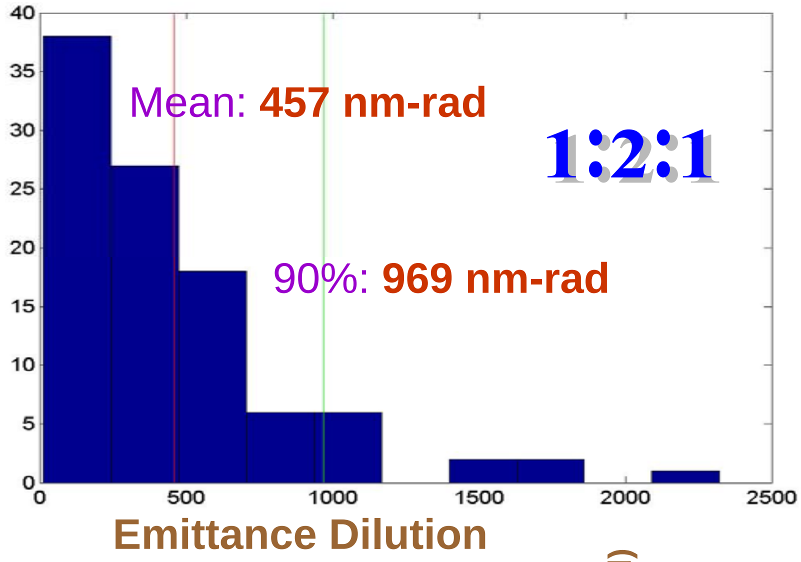
- Read all Q-BPMs in a single pulse
- Compute set of corrector readings and apply the correction
  - Constraint – minimize RMS of the BPM readings
- Iterate few times before going to the next segment.
- Performed for 100 Seeds

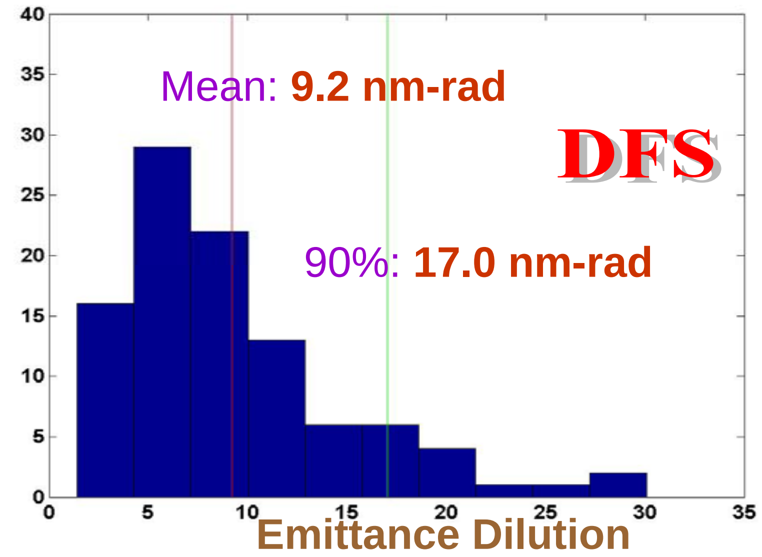
DFS

Divide linac into segments of ~40quads

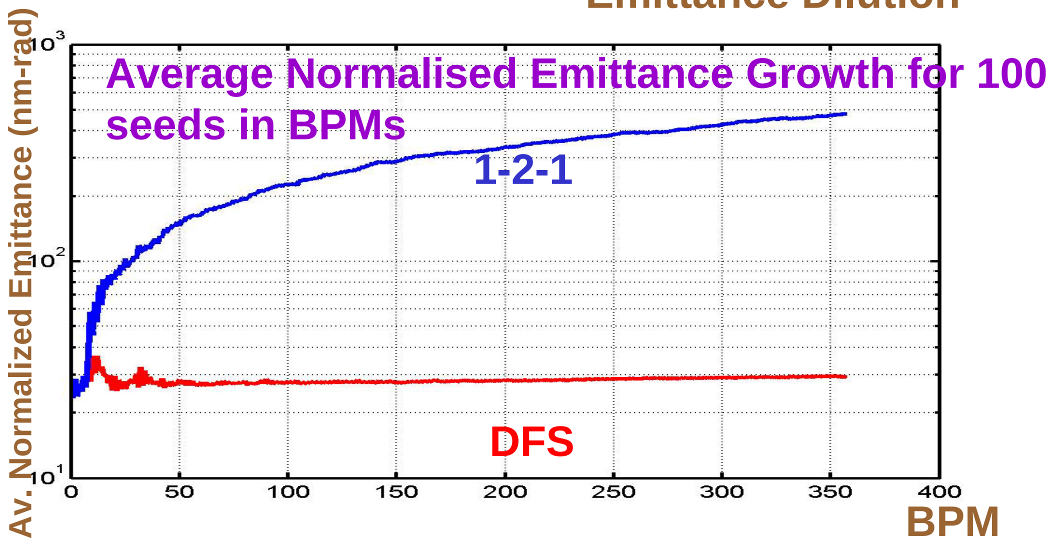
- Two orbits are measured
- Vary energy by switching off structures in front of a segment (no variation within segment)
- Measure change in orbit (fit out incoming orbit change from RF switch-off)
- Apply correction
  - Constraint – simultaneously minimize dispersion and RMS of the BPM readings (weight ratio: $\sqrt{2}:300$)
- Iterate twice before going to the next segment
- Performed for 100 Seeds

FOR USColdLC NOMINAL CONDITIONS





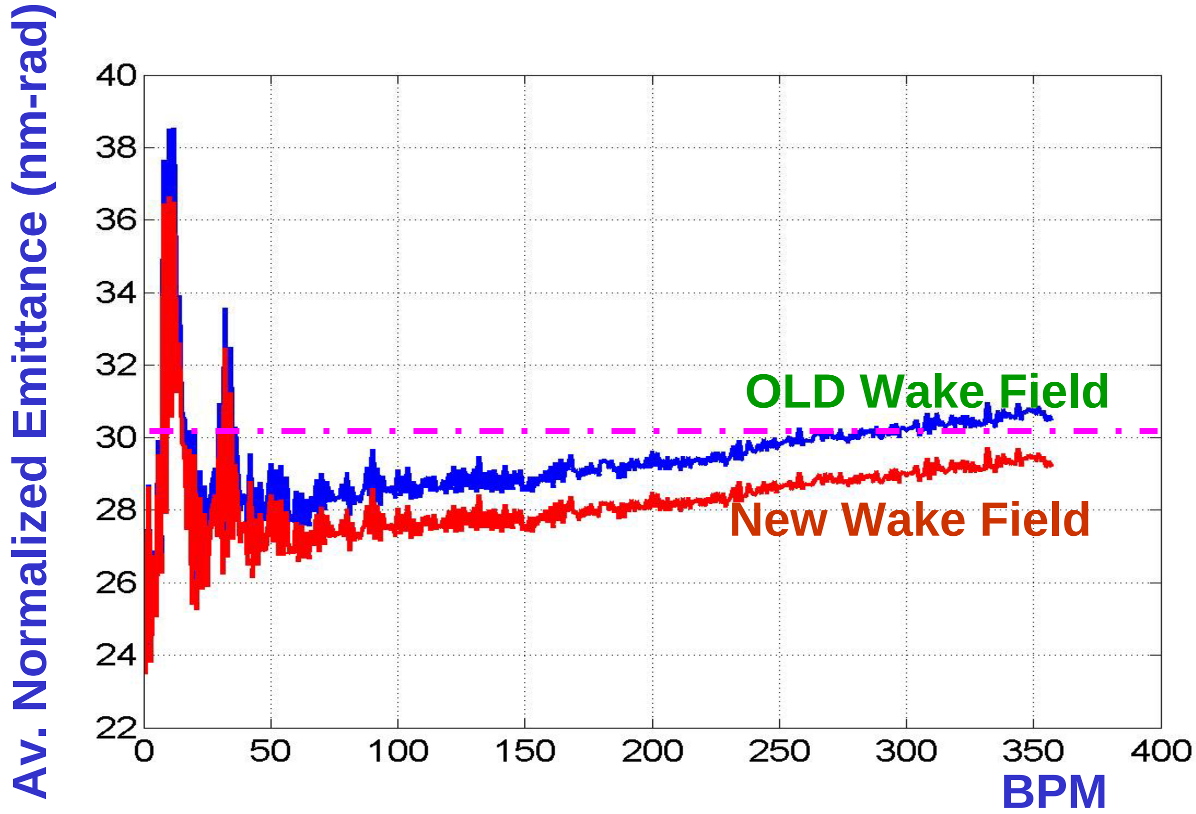
Emittance Dilution = Emit. (Exit) – Emit.(Entrance)



- Lower mean emittance growth for DFS than One-to-One
- Mean Growth just under the Emittance dilution budget ← No Jitter !

NEW vs. OLD WAKE FIELD

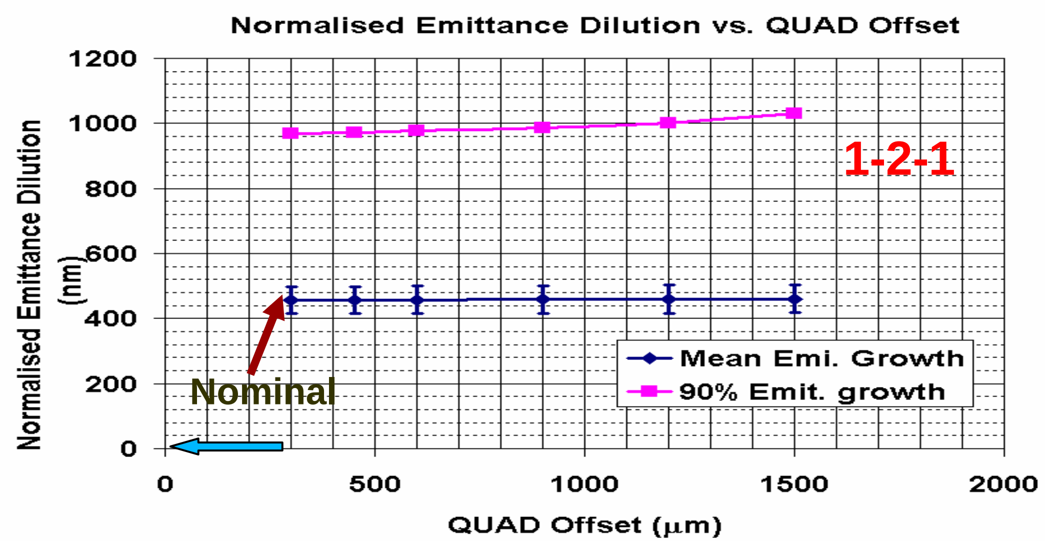
Average Emittance Dilution in the BPMs for 100 seeds for DFS

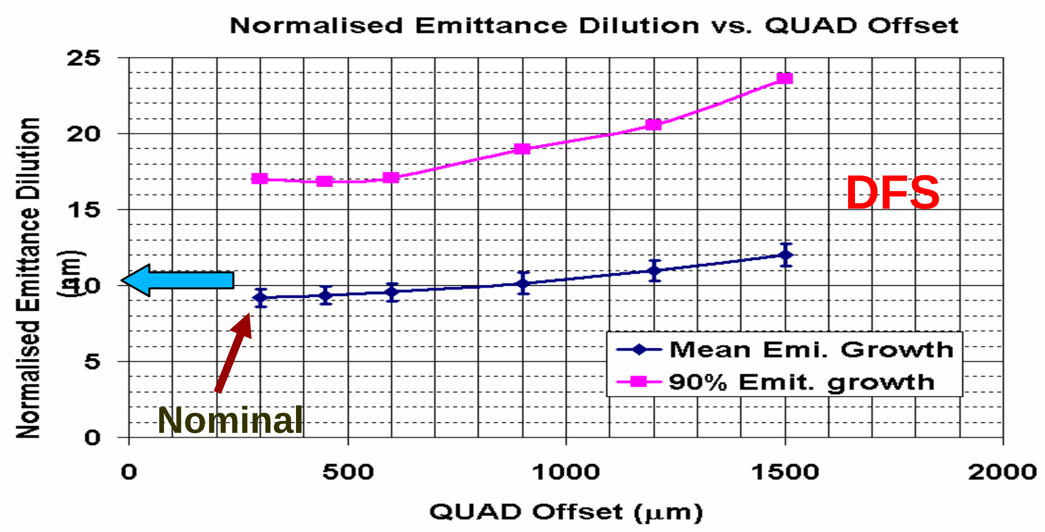


Emittance Dilution for OLD WakeField
Mean : 10.5 nm-rad
90% : 19.0 nm-rad

Emittance Dilution for New Wake Field
Mean : 9.2 nm-rad
90% : 17.0 nm-rad

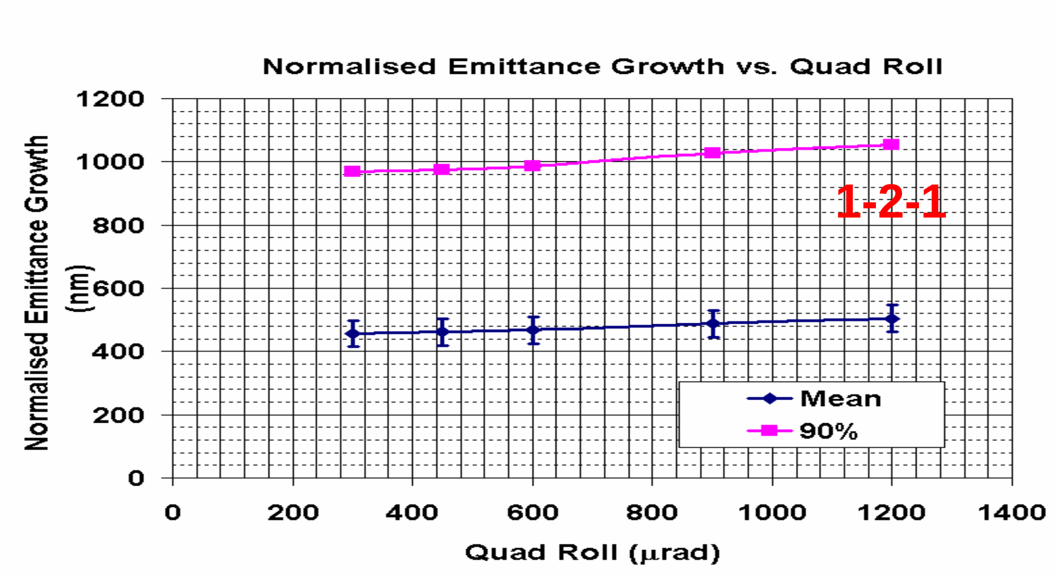
EFFECT OF *QUAD OFFSETS* VARIATION

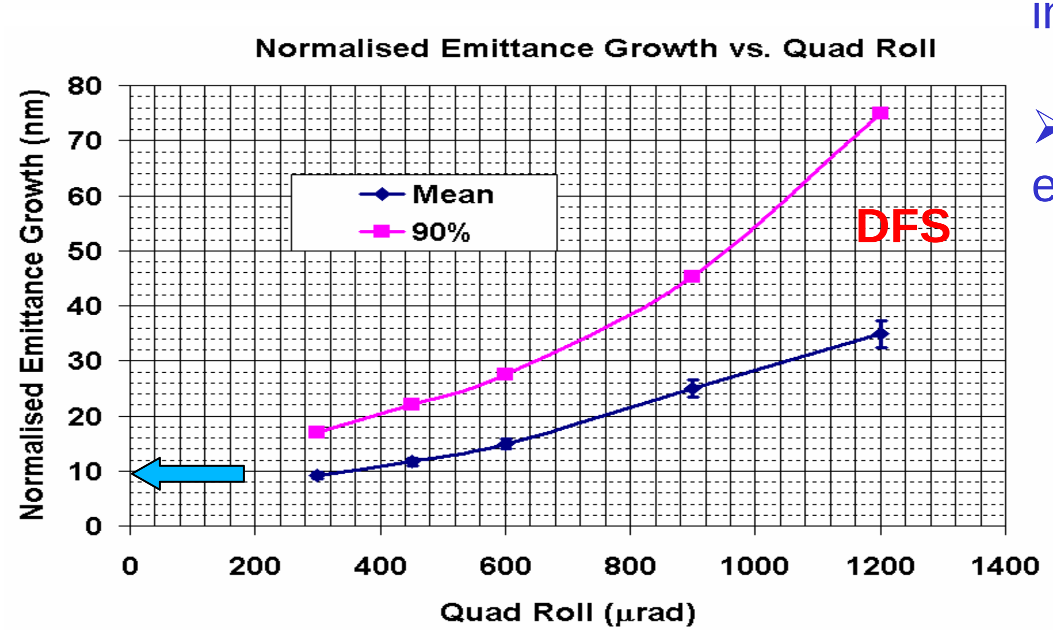




- Keeping all other misalignments at Nominal Values, we have varied only the quad offsets
- Emittance dilution increases slowly with increase in Quad Offsets
- DFS: Just under the budget for 2x nominal values

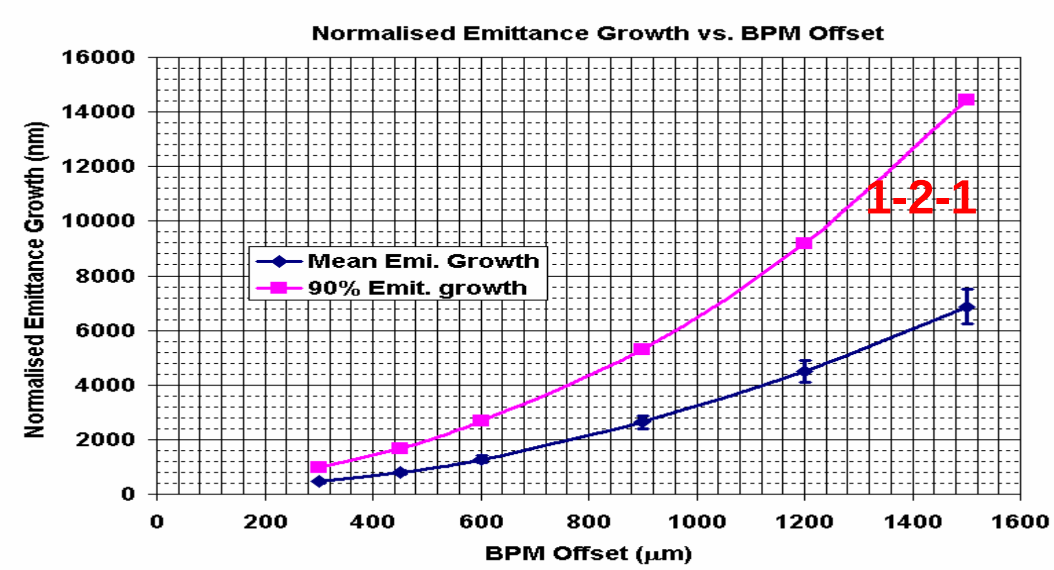
EFFECT OF *QUAD ROLL* VARIATION

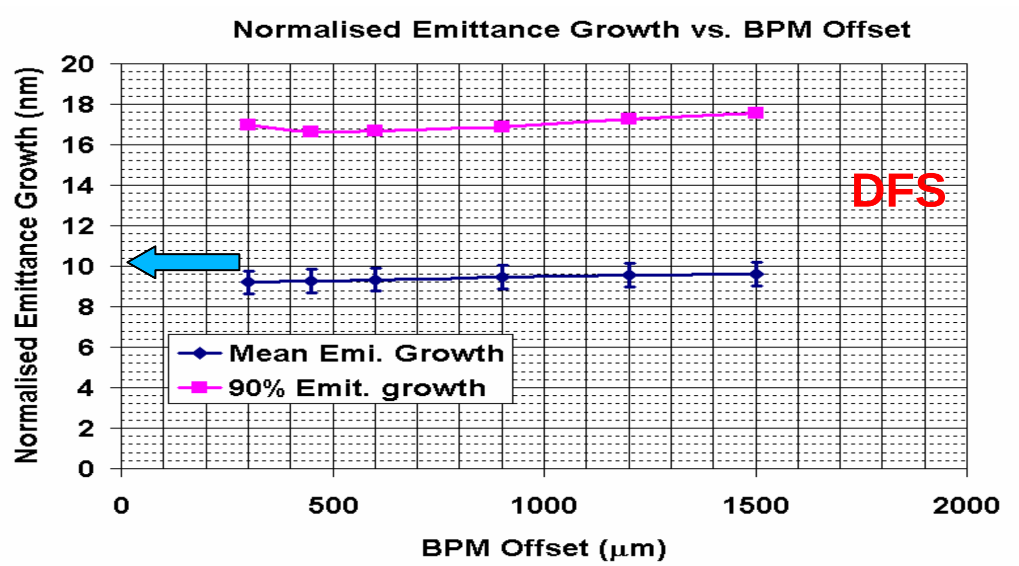




- Keeping all other misalignments at Nominal Values, vary only the quad roll
- DFS: Emittance dilution increases more rapidly with increase in Quad Roll
- DFS: Goes Over the budget even for 1.5x nominal values

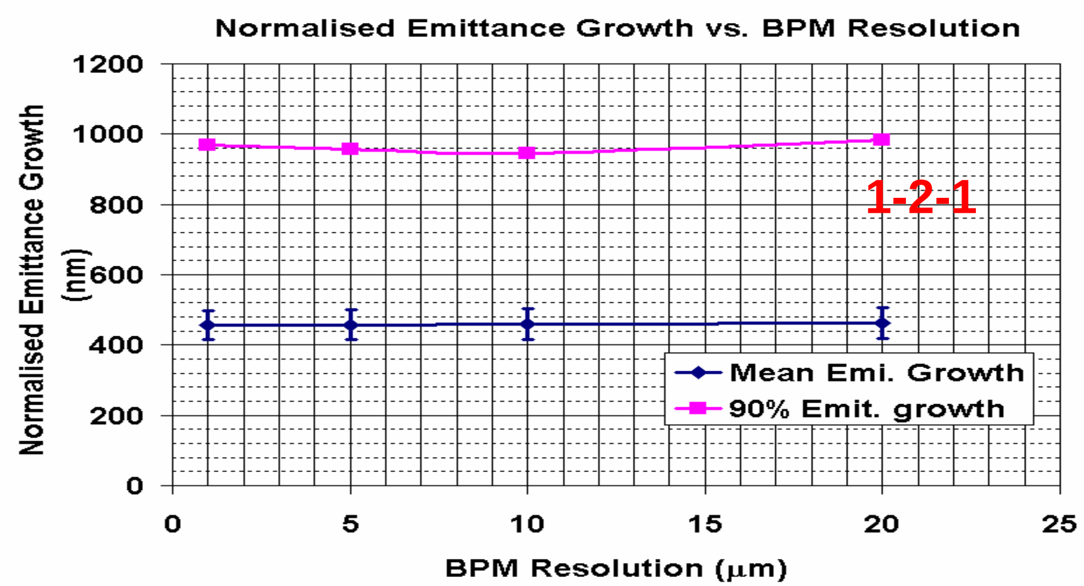
EFFECT OF *BPM OFFSET* VARIATION

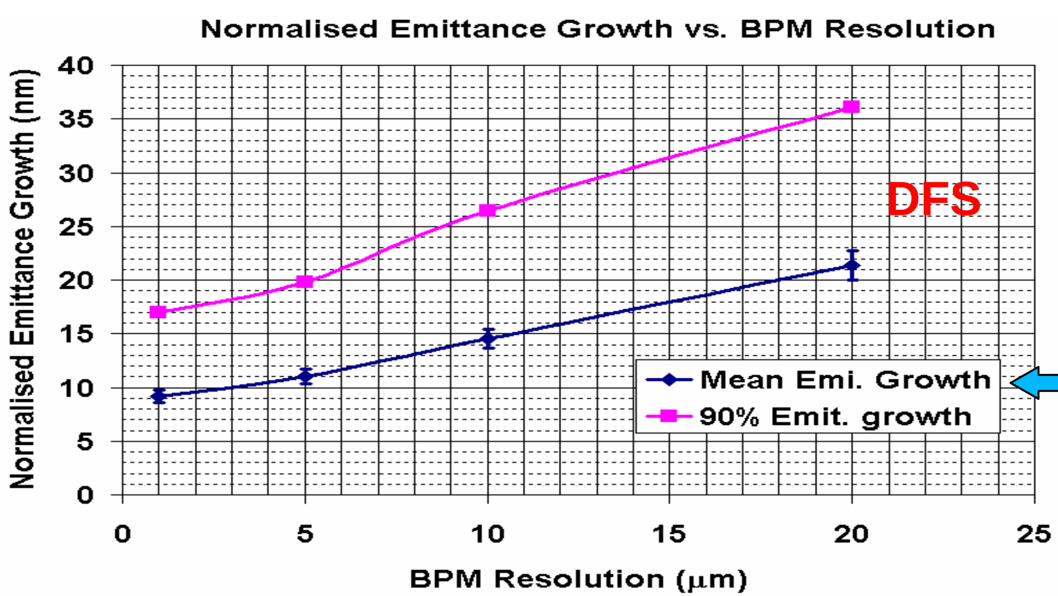




- Keeping all other misalignments at Nominal Values, vary only the BPM Offset
- *Advantage of DFS:* Emittance dilution for 1-2-1 increases very sharply with BPM offsets
- DFS: Emittance dilution is almost independent of BPM offset
- DFS: Remains within the budget even for 5x nominal

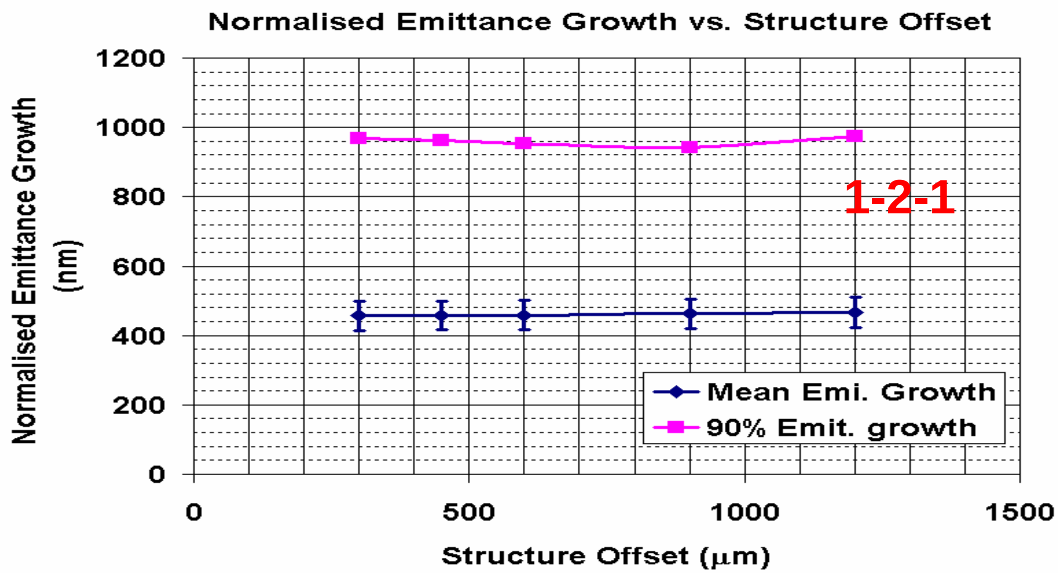
EFFECT OF *BPM RESOLUTION* VARIATION

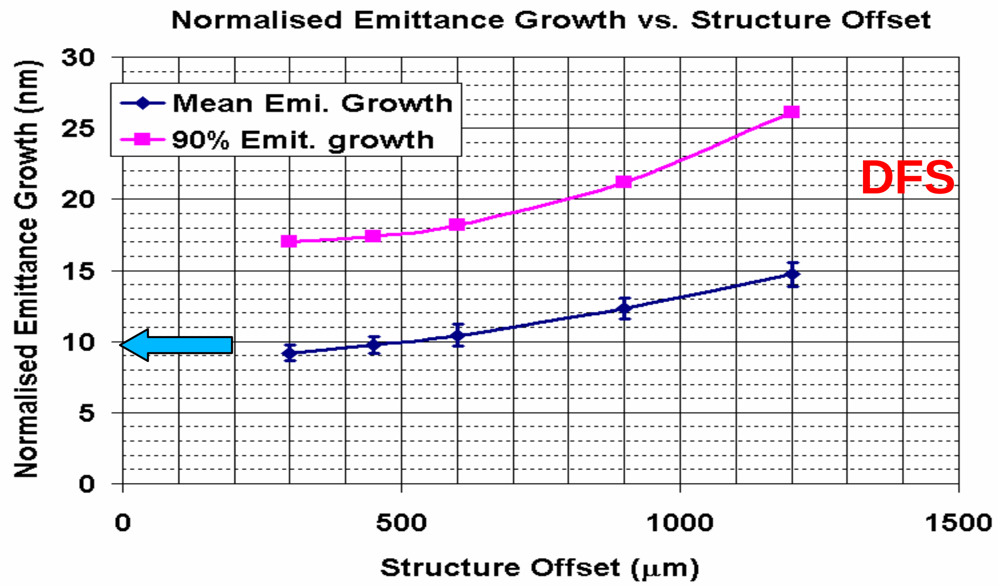




- Keeping all other misalignments at Nominal Values, vary only the BPM resolution
- Emittance dilution for 1-2-1 is almost independent of the BPM resolution
- DFS: Emittance dilution is sensitive to BPM resolution
- DFS: Goes Over the budget even for 5x nominal values

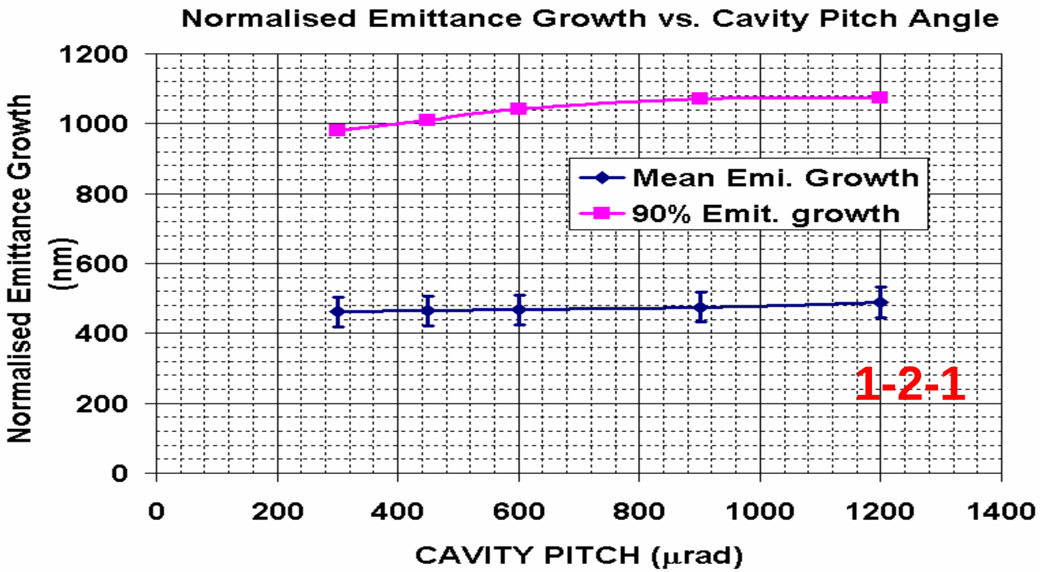
EFFECT OF *STRUCTURE OFFSET* VARIATION

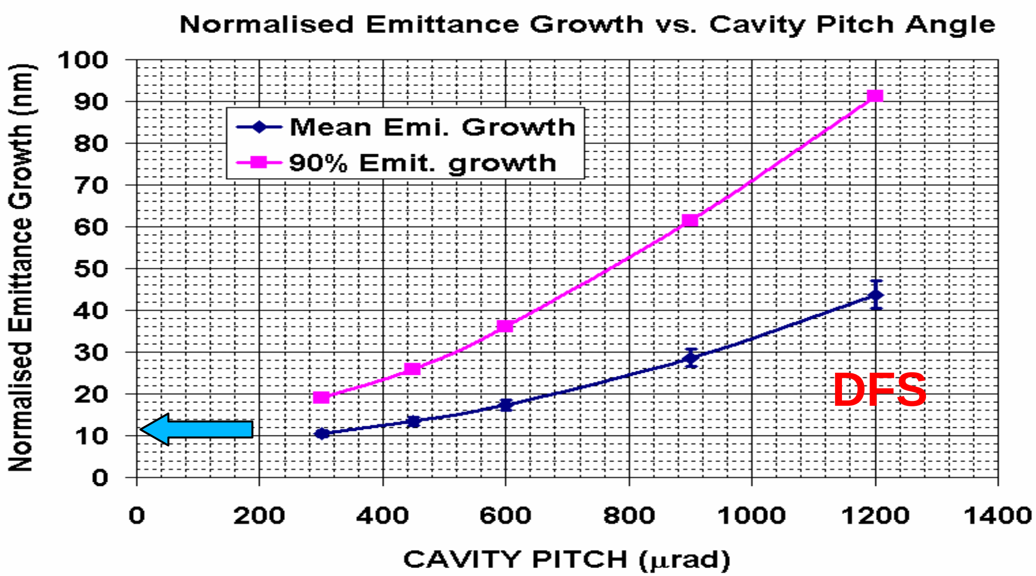




- Keeping all other misalignments at Nominal Values, vary only the Structure Offset
- Emittance dilution for 1-2-1 is almost independent of the structure offset
- DFS: Emittance dilution grows slowly with structure offsets
- DFS: Goes Over the budget for 1.5x nominal values

EFFECT OF *STRUCTURE PITCH* VARIATION

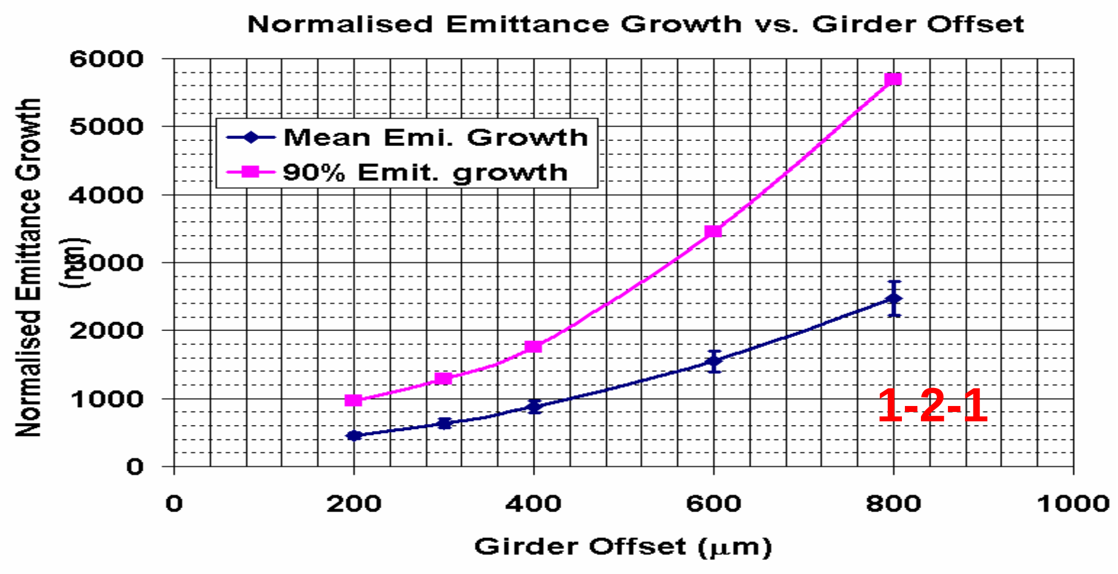


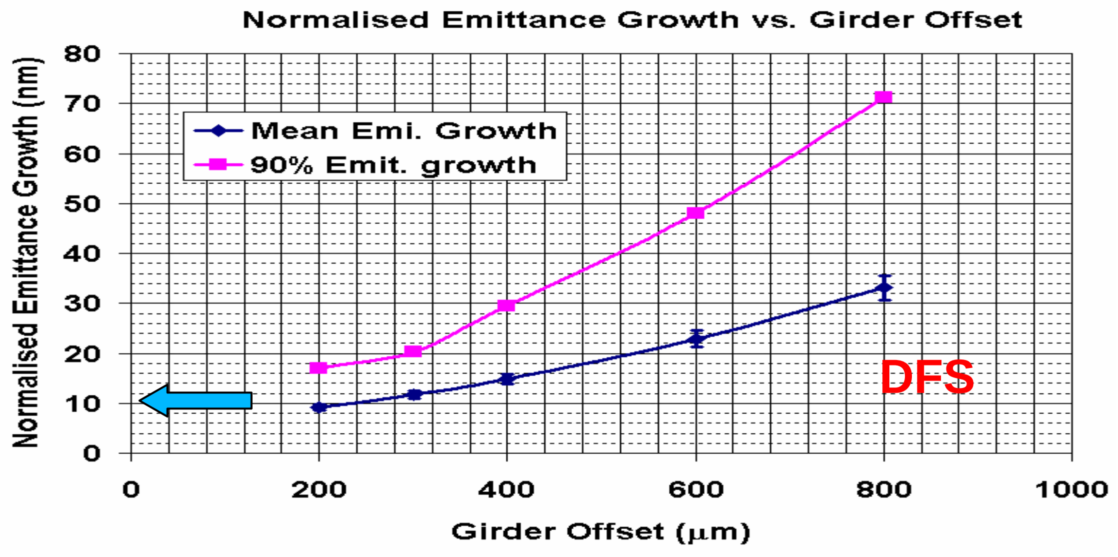


- Keeping all other misalignments at Nominal Values, vary only the Cavity Pitch
- DFS: Emittance dilution is sensitive to Cavity pitch
- DFS: Goes Over the budget even for 1.5x nominal values

OLD WF USED

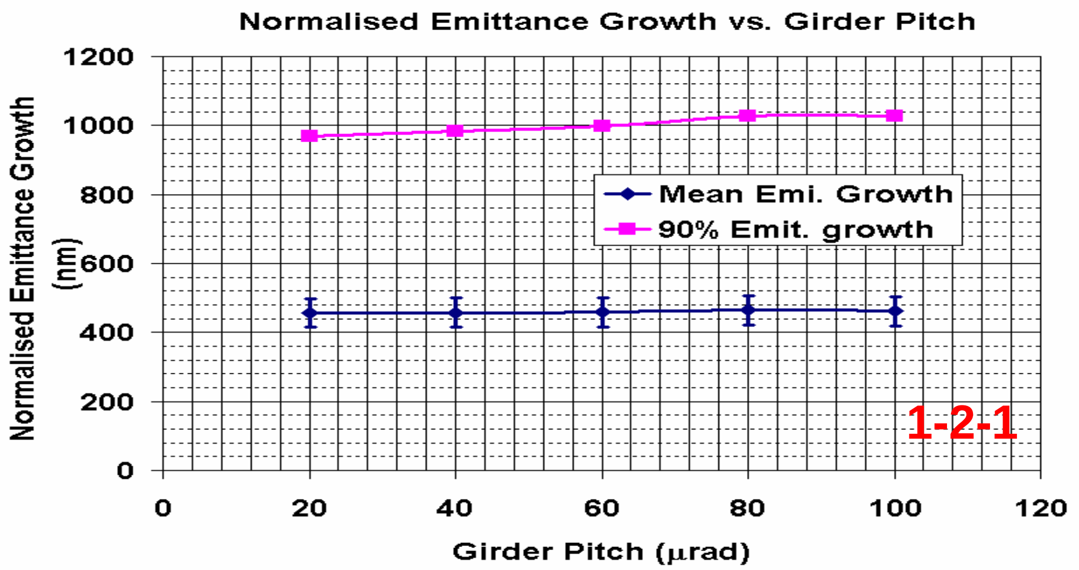
EFFECT OF *CRYOMODULE OFFSET* VARIATION

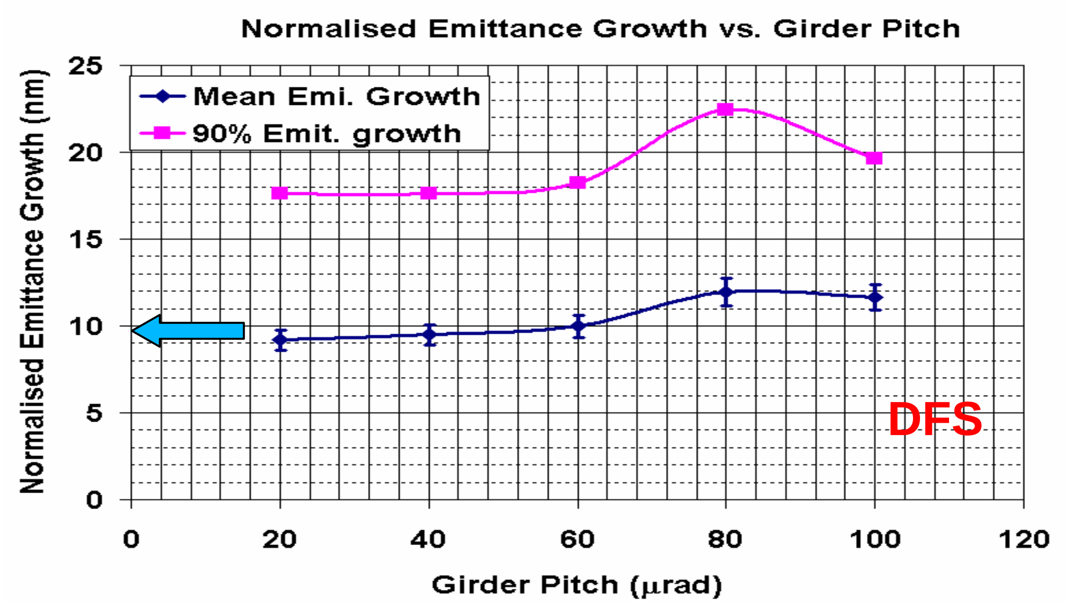




- Keeping all other misalignments at Nominal Values, vary only the CM offset
- DFS and 1-2-1: Emittance dilution grows very sharply with CM offset.
- DFS: Goes Over the budget even for 1.5x nominal values

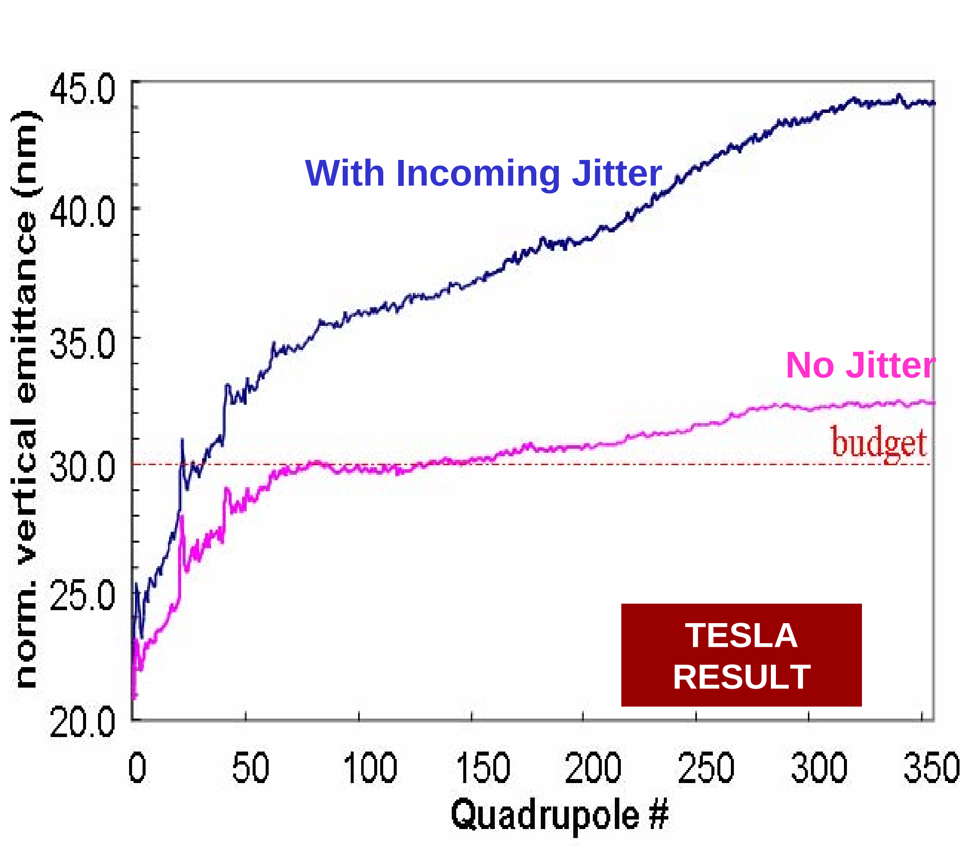
EFFECT OF *CRYOMODULE PITCH* VARIATION





- Keeping all other misalignments at Nominal Values, vary only the CM Pitch
- DFS and 1-2-1: Emittance dilution is almost independent of the CM pitch
- DFS: Remains within the budget for 3x nominal

DISPERSION FREE STEERING : ISSUES



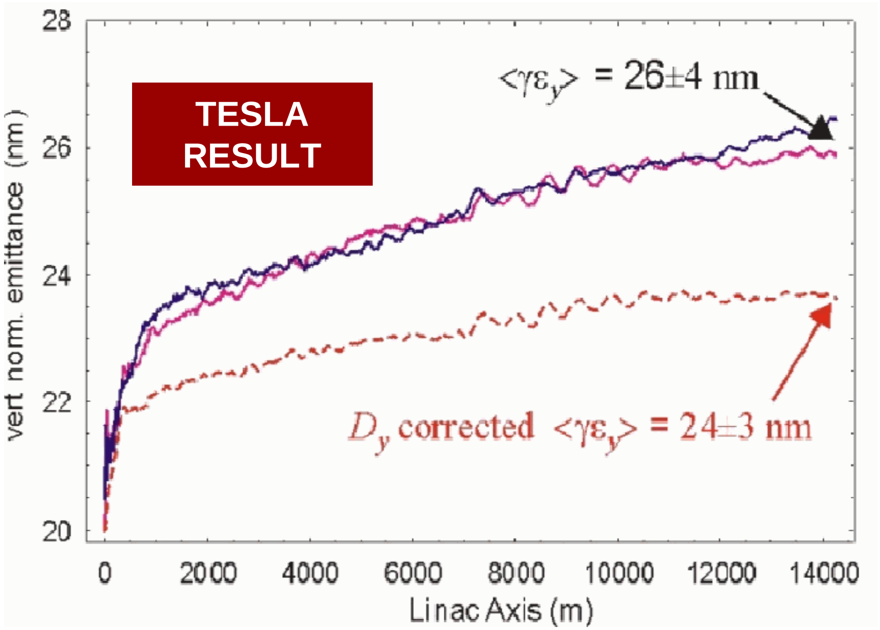
- The effect of upstream beam jitter on DFS simulations for the TESLA linac
  - ⇨ 1 σ_y initial jitter
  - ⇨ 10 μm BPM noise

average over 100 random machines

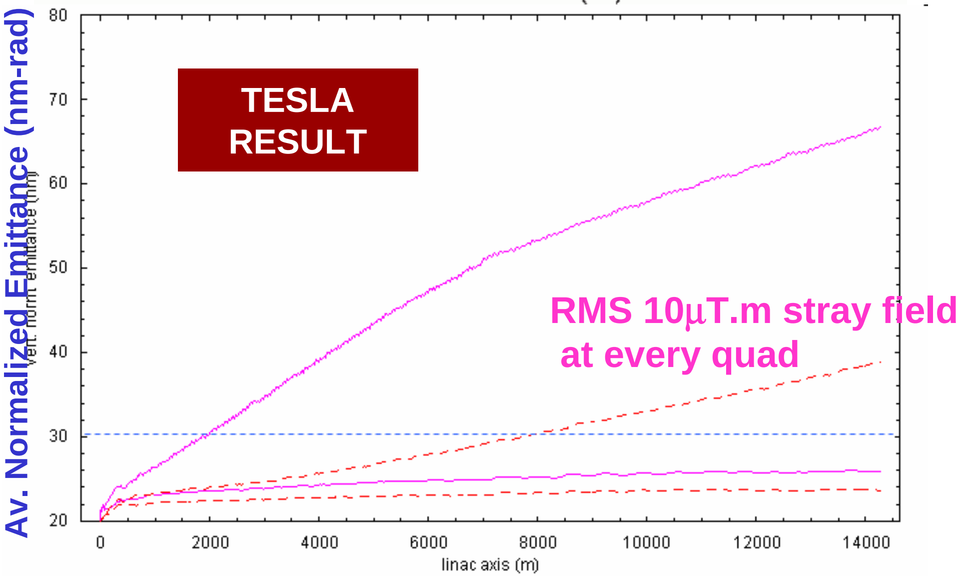
- DFS Fitting algorithm confuses when the RF structures are pitched

TO DO…INCLUDE *BALLISTIC ALIGNMENT*

- Divide Linac into segments
- Turn off RF + Quads and measure BPM Orbit
  - Steer beam in a straight line from first to last BPM
- Turn back ON, resteer to "all-off" Line
- Results look good in simulation

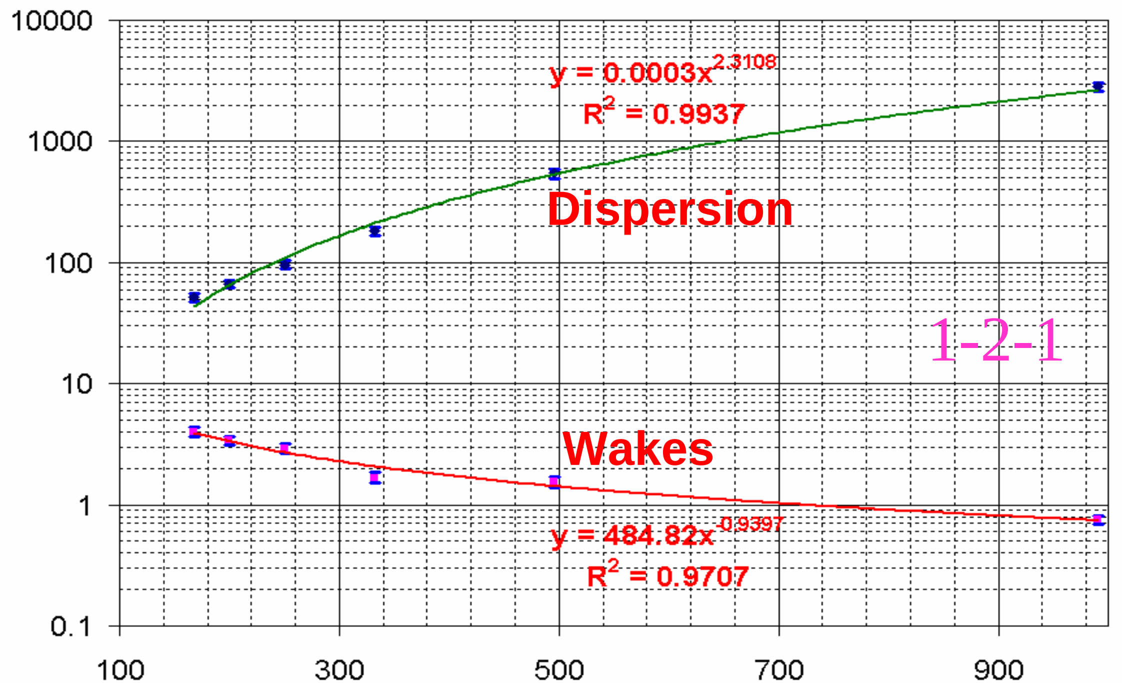


- ISSUES:
  - Turning OFF Quad => Limit on stray / residual quad fields
  - Effect scales as B_{res}^2
  - Tolerance: 2.5 mT.m RMS



DISPERSION vs. WAKEFIELD

- Effect of varying quad spacing – 6 different configurations with diff. quad spacing (varies from Quad / 1 CM to Quad / 6 CM)
  - Dispersion Case – Quad, BPM Offsets and Structure, CM Pitch
  - Wake Case – Structure, CM offset, wakefields
- Dispersion scales as $\mathbf{N_Q^{2.3}}$ (b/w 1 for filamentation and 3 for short Linacs)
- Wake scales as $\mathbf{N_Q^{-0.94}}$ (close to -1)



SUMMARY / PLAN

- Normalized vertical emittance growth (Single bunch) in Main Linac for 500 GeV CM USColdLC machine is simulated using MATLIAR
- DFS and 1-2-1 steering algorithm are compared in terms of:
  - Structure-to-CM and CM-to-Survey Line offsets
  - BPM, Quad offsets
  - BPM resolution
  - Structure-to-CM, CM to Survey line pitch angle
- DFS algorithm provides significantly better results than One-to-One.
- DFS algorithm is significantly affected by BPM resolution, Pitched RF structure and Incoming beam Jitter.

PLAN

- *Include Transverse Jitter and Ground Motion in DFS*
- *Include Dispersion bumps*
- *Study of Ballistic Alignment*