BEAM DYNAMICS and ERROR SIMULATIONS

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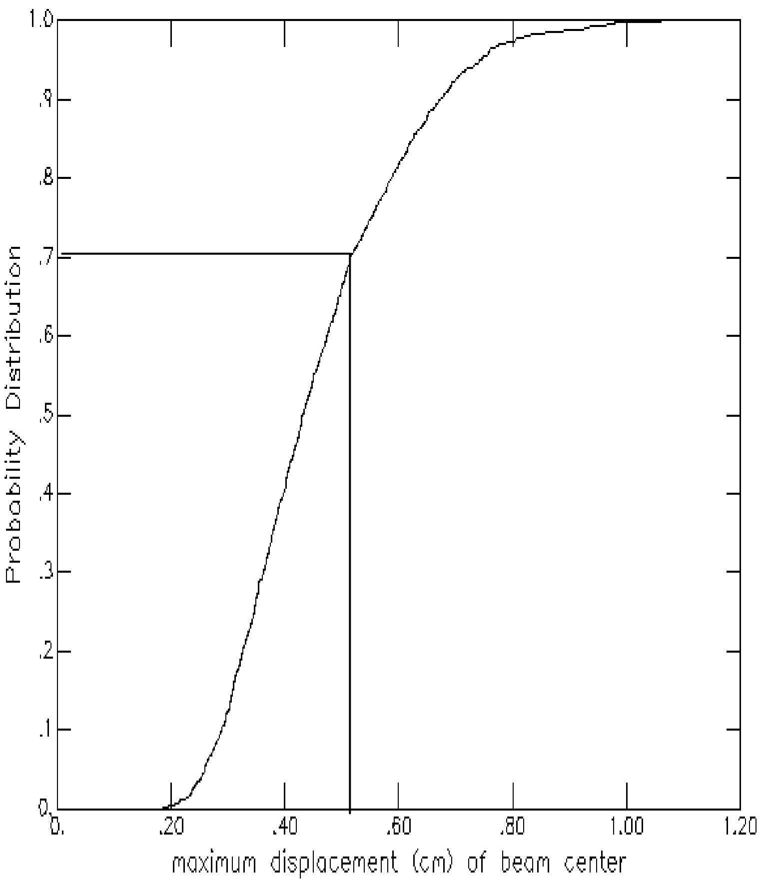
Outline

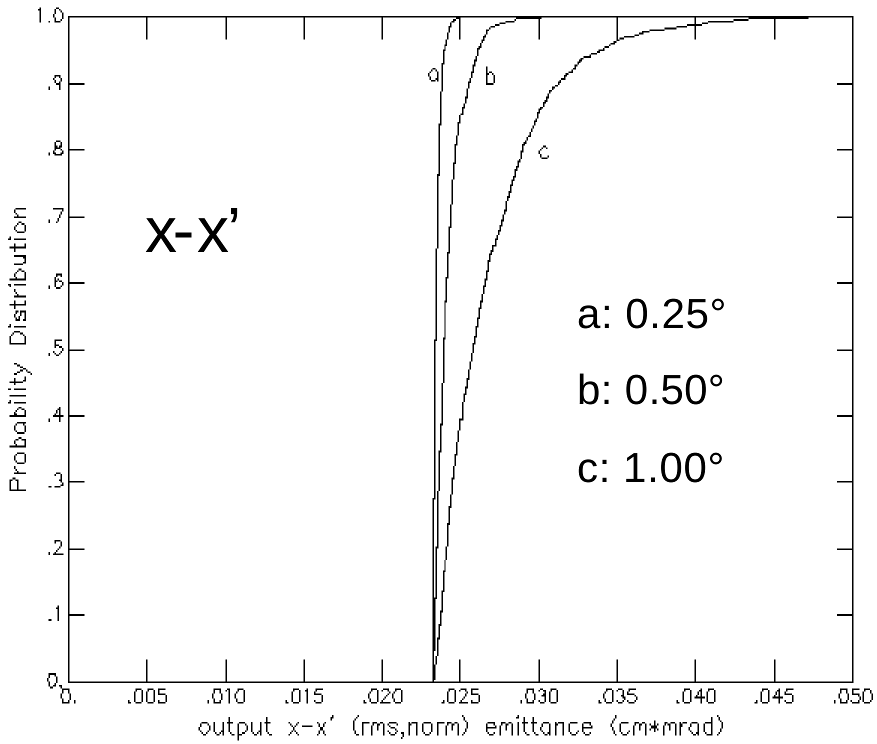
- DTL PMQ Study
- CCL Steering Study
- SRF Steering Study
- Space Charge Algorithm Comparison

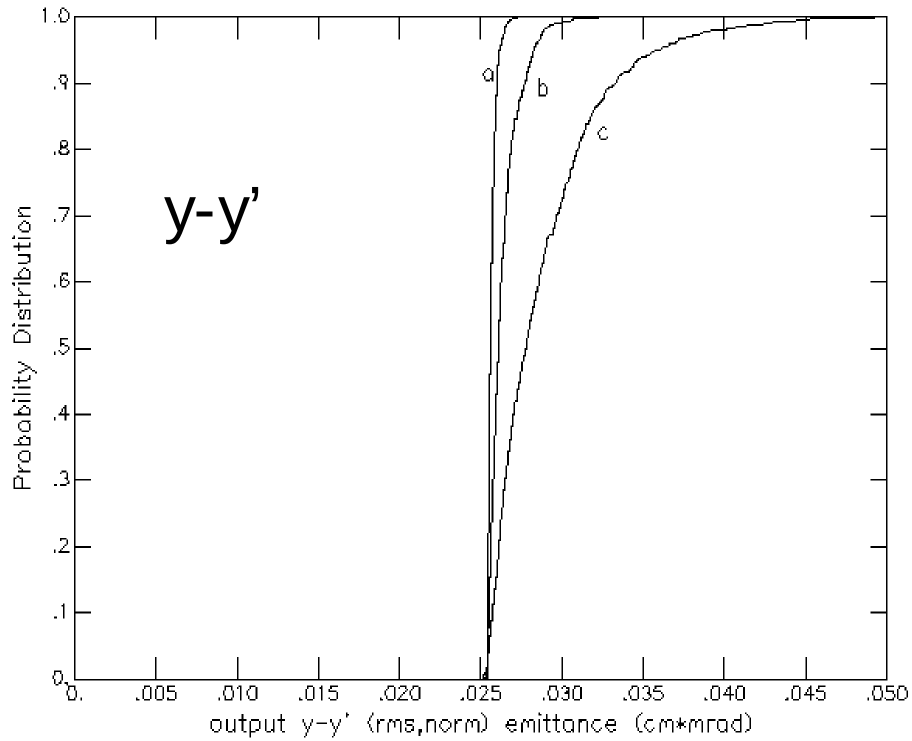
Probability Curve Generated by LTRACE Program

- LTRACE program - an envelope code
- Follows the beam-envelope and beam-center through linac
- Each run uses random errors within tolerance limits (e.g. ± 5 mil, uniform distribution)
- Largest radial excursion (r_{max}) saved for each run
- 1000 values of r_{max} sorted and plotted
- With 70% confidence level, $r_{max} < 0.52$ cm



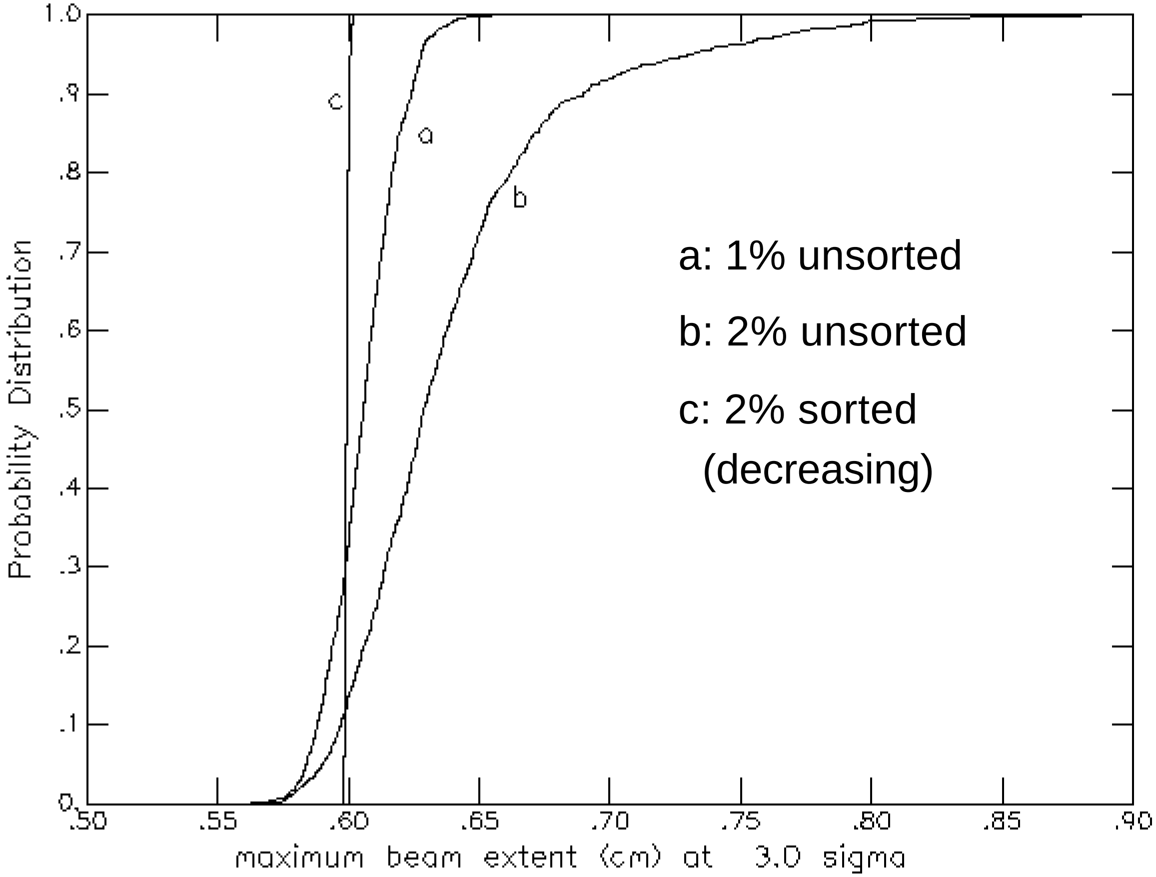
Effect of PMQ Rotation on Transverse Emittance





- With 95% confidence, emittance will grow < 10% with 0.5° error
- Low probability that emittance may double with 1.0° rotation error

Effect Of Gradient Error on Maximum Beam Extent (3 Sigma)



- 2% sorted is as good as no gradient error

CCL Alignment Errors Considered

- Alignment errors cause the beam to be displaced from the linac axis.
- Can magnify effects of nonlinear fields:

  - multipoles

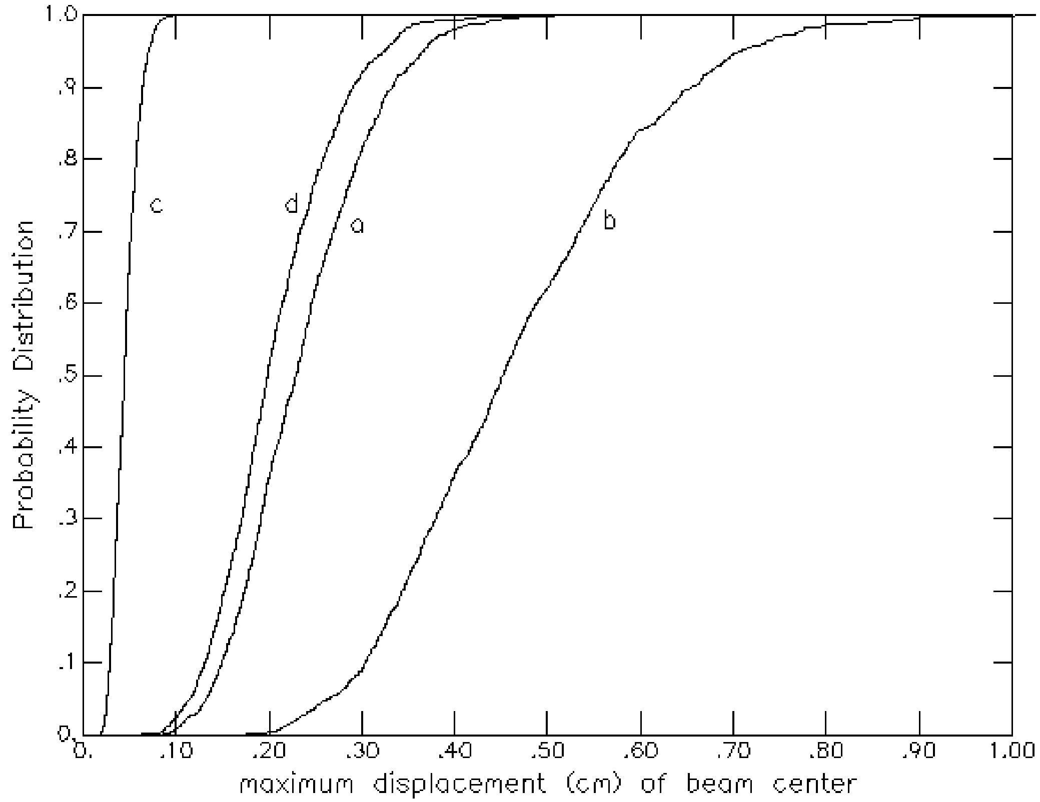
  - gap fields
- Alignment errors considered:

  --- quad displacements,

  --- quad tilts and

  --- tank (segment) displacements (and tilts).
- Studied with LTRACE
- Correction (Steering algorithm) not yet implemented in PARMILA

Maximum Beam-Center Displacement for Individual Alignment Errors



a: Quad Displacement 0.005”

b: Quad Displacement 0.010”

c: Quad Tilt 5.0°

(± 3.5 mm over 8 cm)

d: Tank Displacement 0.100”

- Most important is Quad displacement error

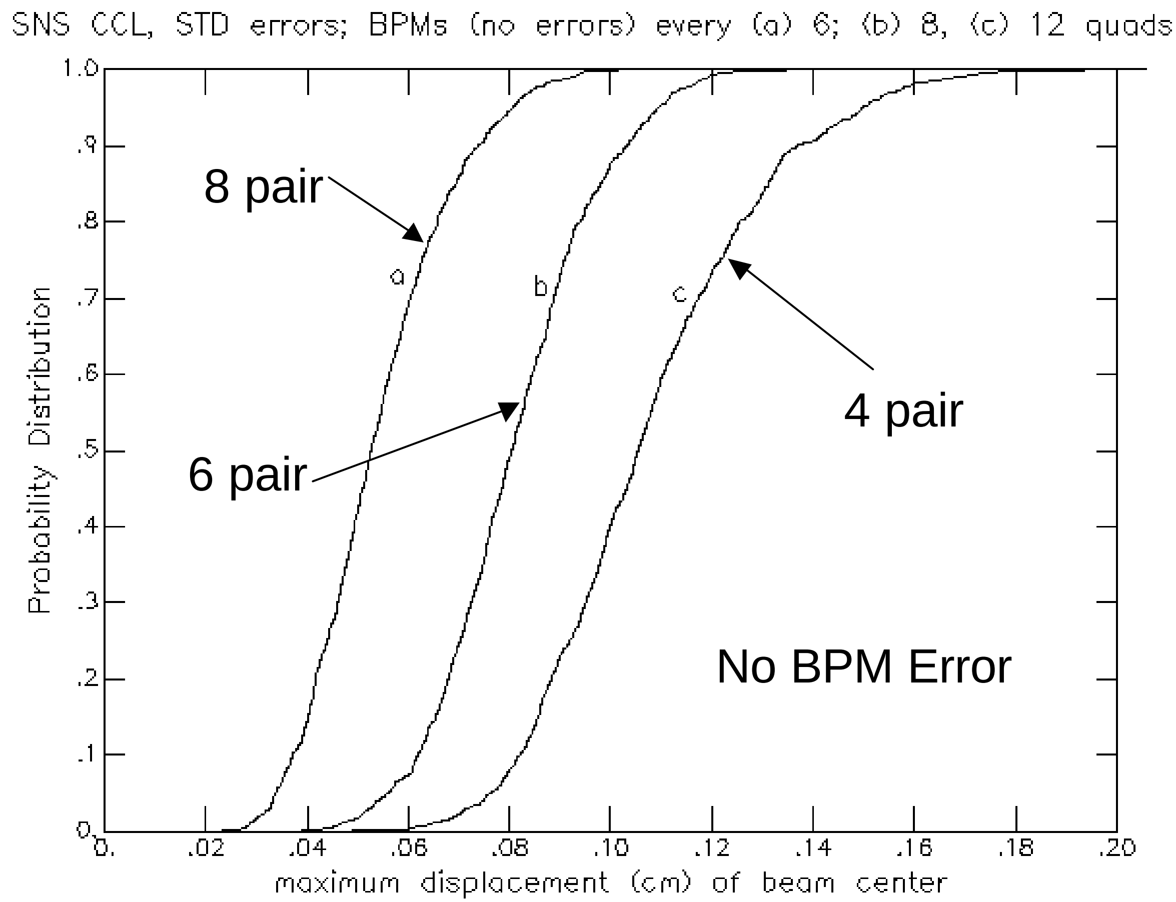
Relative Importance of Individual Alignment Errors -- Summary

- The most important by far is the quad displacement error.
- Beam displacement is really insensitive to quad tilts (pitch and yaw) - tilt tolerances are about a factor of 20 higher than quad displacements'.
- Tolerances of 0.100'' on independent random displacements of each end of a tank (segment) has slightly less effect than a 0.005" tolerance on quad displacements --segment misalignment is insensitive.

Beam Position Monitors -- At What Locations?

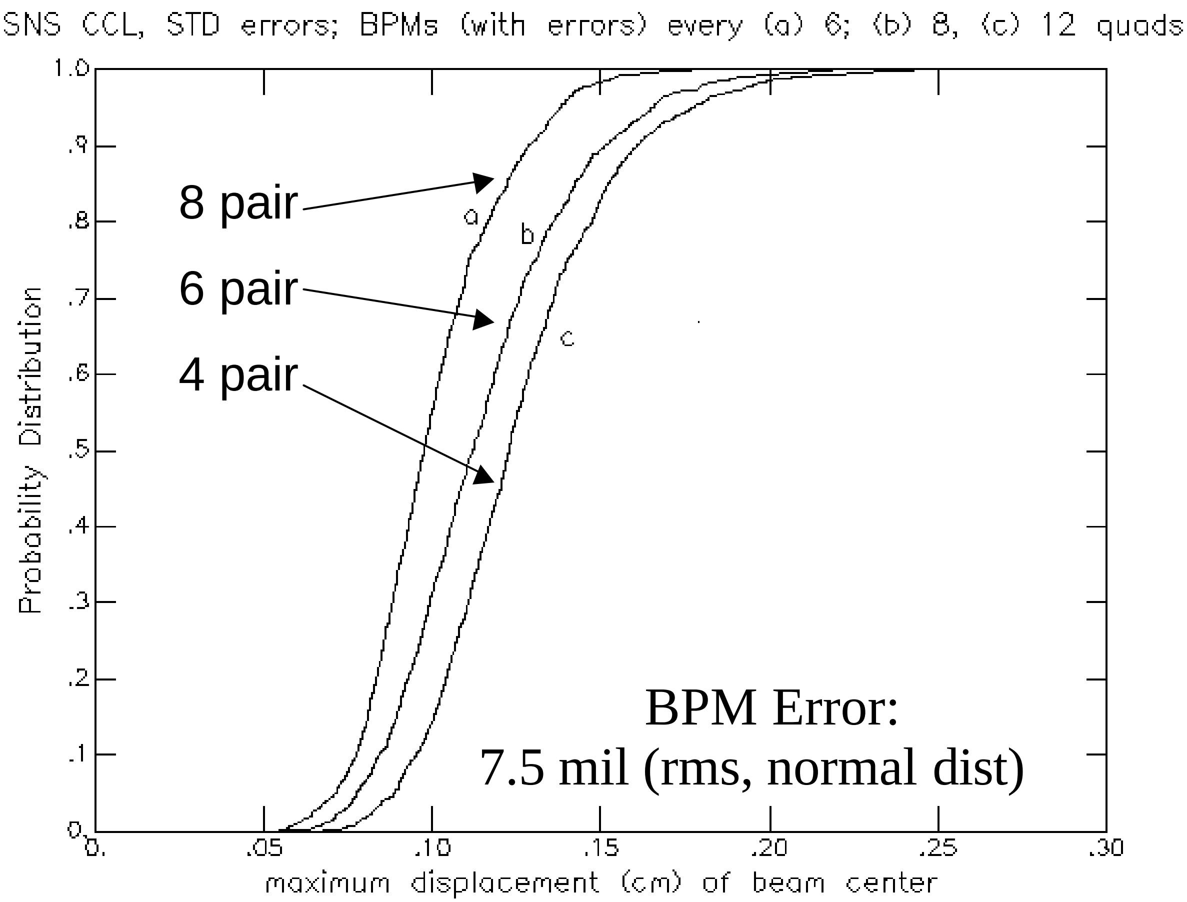
- Set of tolerances assumed :
  - Quad displacement = ± 0.005”
  - Quad Tilt = ± 1°
  - Segment displacement = ± 0.010”
- 48 quads and 48 tanks in the CCL. **Consider 3 cases**:
  a. BPM pairs at every 6 quads (8 BPM pairs) (e.g. 4 and 6; 10 and 12; etc)
  b. BPM pairs at every 8 quads (6 BPM pairs)
  c. BPM pairs at every 12 quads (4 BPM pairs)
- Efficient steering: Steer in x direction in x focusing quad; same for y
- Minimum required:
  4 dipoles - 2 horizontal and 2 vertical
- In All cases:
  4 dipoles in upstream quads nearest to BPMs (e.g. 1,2,3,4 for case “a”)

Results of 3 Cases of Different BPM Numbers



- More BPMs give smaller excursions

Results of 3 Cases with BPM errors included

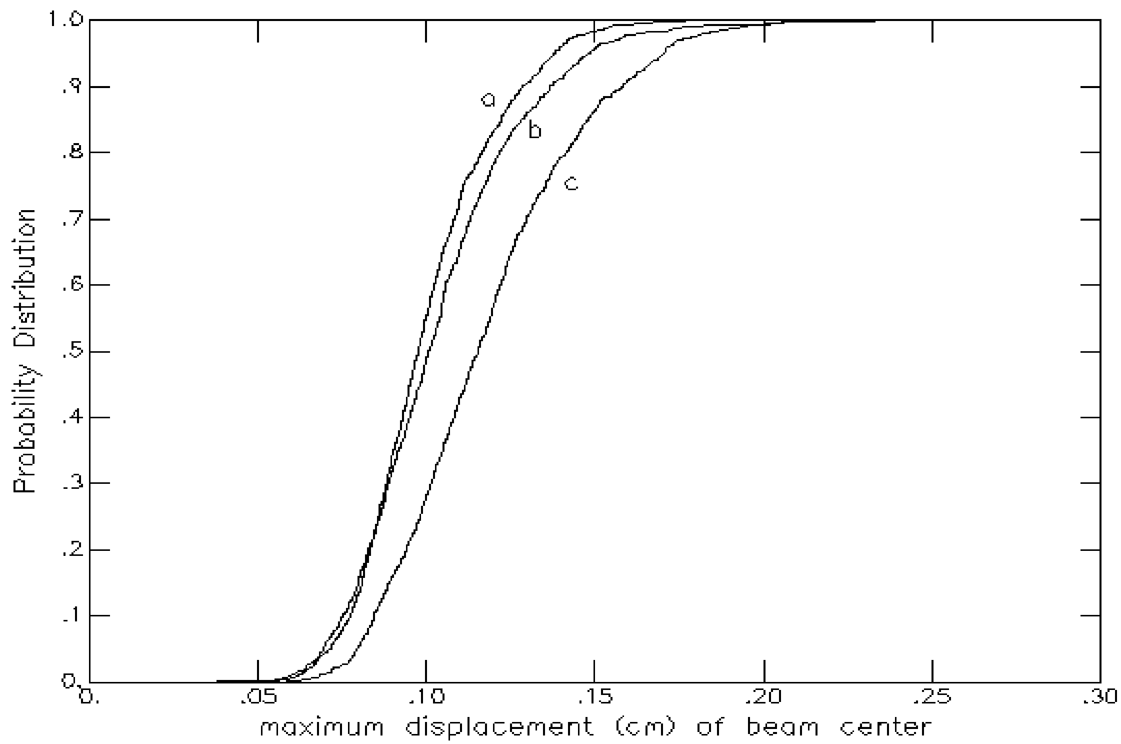


• With BPM errors, no pronounced dependence on the total number of BPMs

How About Fewer BPMs?

- Same Set of tolerances assumed
- **Consider 3 cases**: (All cases use 32 dipoles)
  a. 1 BPM pair at every 6 quads (8 BPM pairs) (e.g. (4,6), (10,12), etc)
     4 steerers in upstream quads for each BPM pair (e.g. 1,2,3,4)
     Total of 32 dipoles, 16 BPMs
  b. 1 BPM pair at every 12 quads (4 BPM pairs) (e.g. (10,12), (22,24),etc)
     8 steerers for each BPM pair (4 for each x,y direction)
     Total of 32 dipoles, 8 BPMs
  c. 1 BPM pair at every 24 quads (2 BPM pairs) (e.g. (22,24),(46,48))
     16 steerers for each BPM pair (8 for each x,y direction)
     Total of 32 dipoles, 4 BPMs
- ‘a’ assumes conventional steering
- ‘b’ and ‘c’ uses “**Strength Minimization**” technique.
  - Minimizes “sum of the square” of the dipole-strengths.

Results of 3 Cases with different Number of Steerers and BPMs



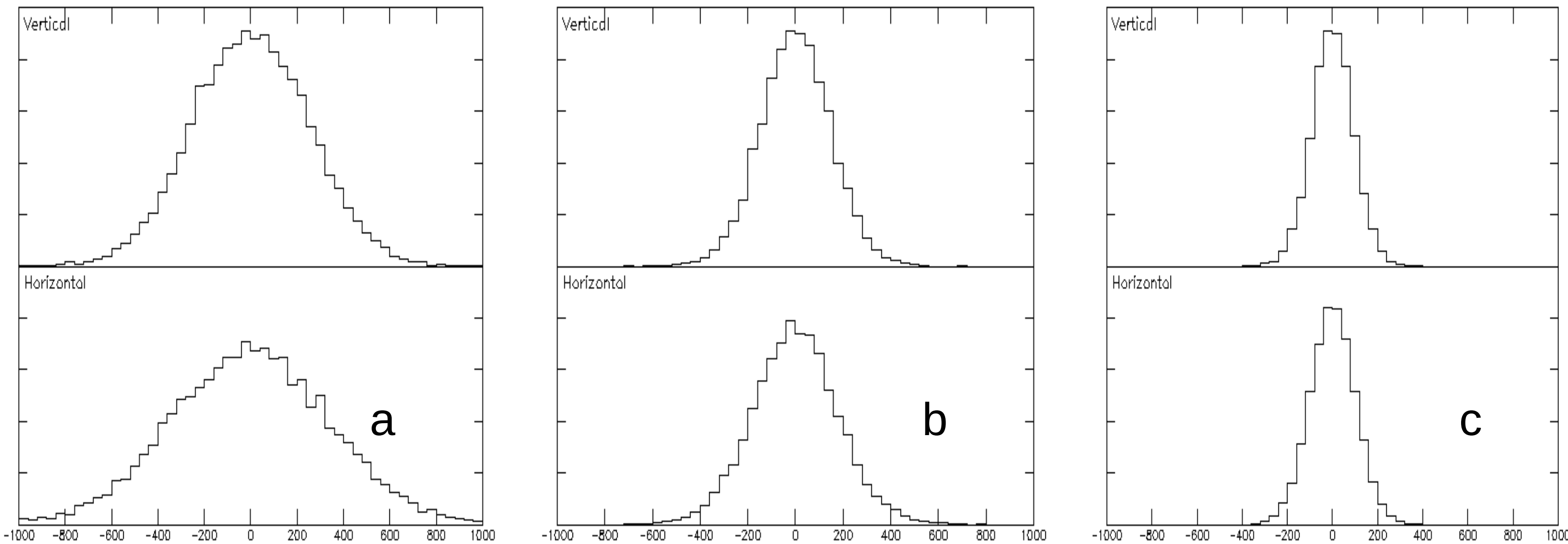
a. 8 BPM pairs (total)

b. 4 BPM pairs (total)

c. 2 BPM pairs (total)

- Essentially no difference between ‘a’ and ’b’
- “Strength minimization” technique reduces hardware counts for BPMs

Steering Strength needed for Case 3 is Least



(a) Steering Strengths required (G-cm), 8 BPM pairs

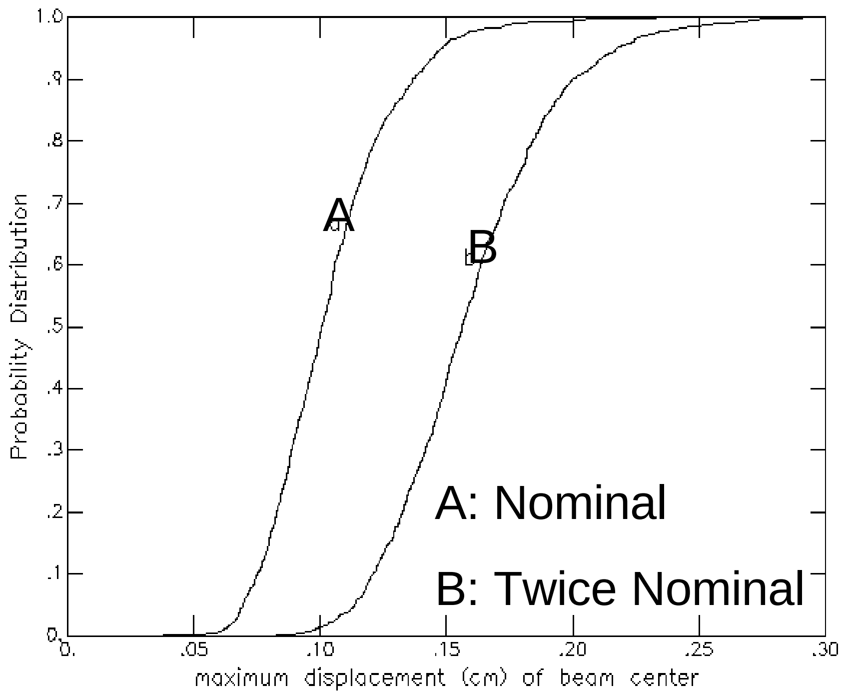
(b) Steering Strengths required (G-cm), 4 BPM pairs

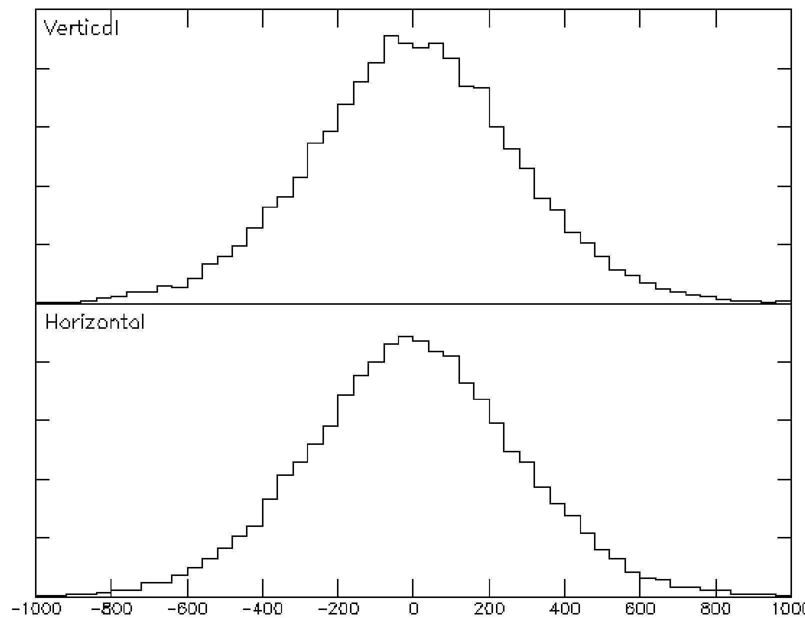
(c) Steering Strengths required (G-cm), 2 BPM pairs

BPMs	16	8	4
Dipoles	32	32	32

- 'Minimum Strength' technique (with fewer BPMs) greatly reduces dipole fields required
- Optimize -- Choose Case 'b' (4 BPM pairs, 8 dipoles for each BPM pair)

Results for Case 'b' with two sets of Errors





- With twice the nominal error tolerances, beam center displacement nominally doubles
- Steering strengths needed are also higher

SRF Linac Alignment Errors Considered

- Alignment errors cause the beam to be displaced from the linac axis.
- Alignment errors considered:

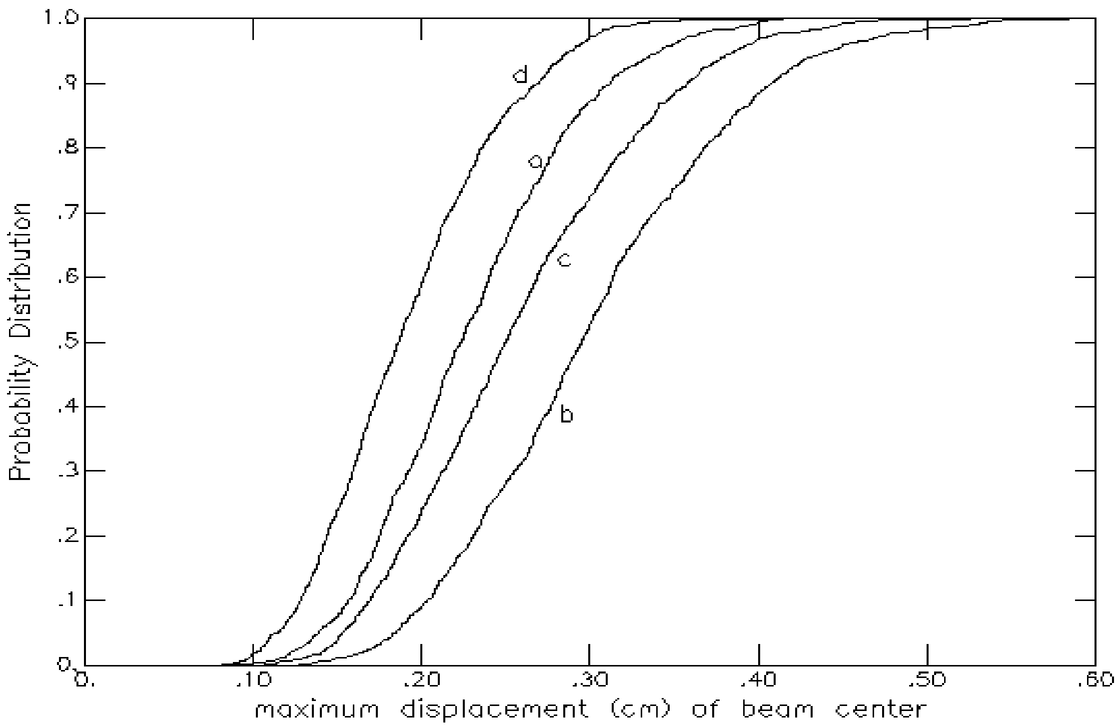
  - quad doublet displacement,

  - quad doublet tilt

  - quad tilt

  - cavity displacement
- Studied with LTRACE
- Correction (Steering) not yet implemented in PARMILA

Maximum Beam-Center Displacement for Individual Alignment Errors



a: Doublet Displacement 0.010”

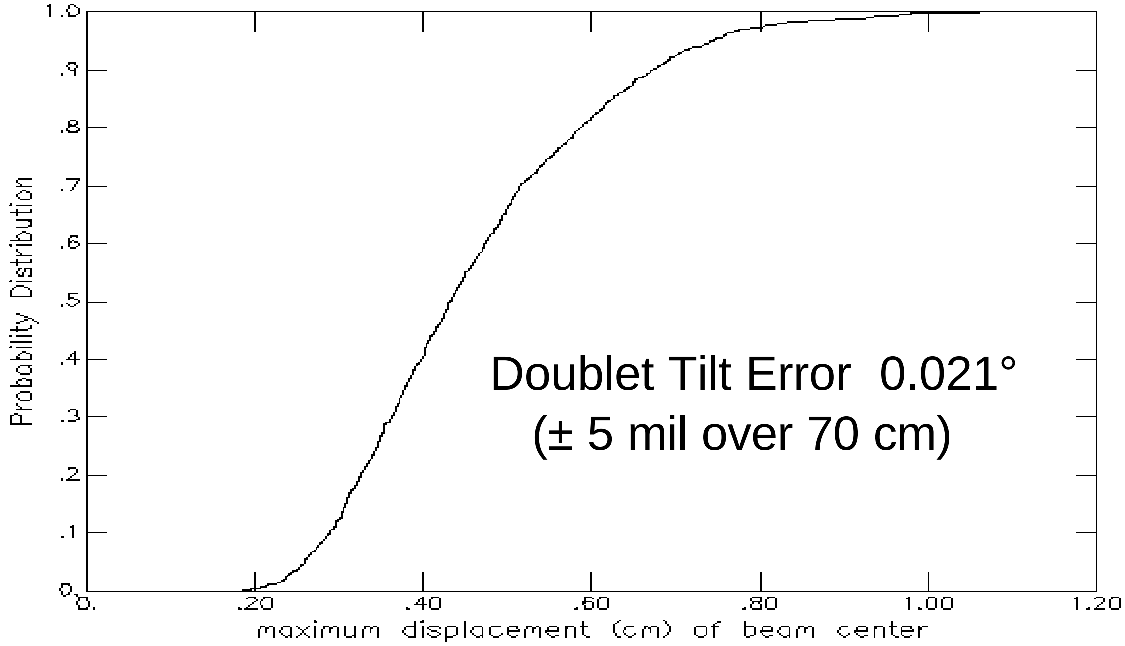
b: Doublet tilt 0.01°
(± 2.5 mil over 70 cm)

c: Quad Tilt (wrt doublet axis) 1.0°
(± 3.5 mm over 40 cm)

d: Cavity Displacement
0.050”

- Doublet tilt error is most important
- If we can achieve 'b' (too stringent), we can possibly get by without steering

Result for Twice the Doublet-Tilt Error

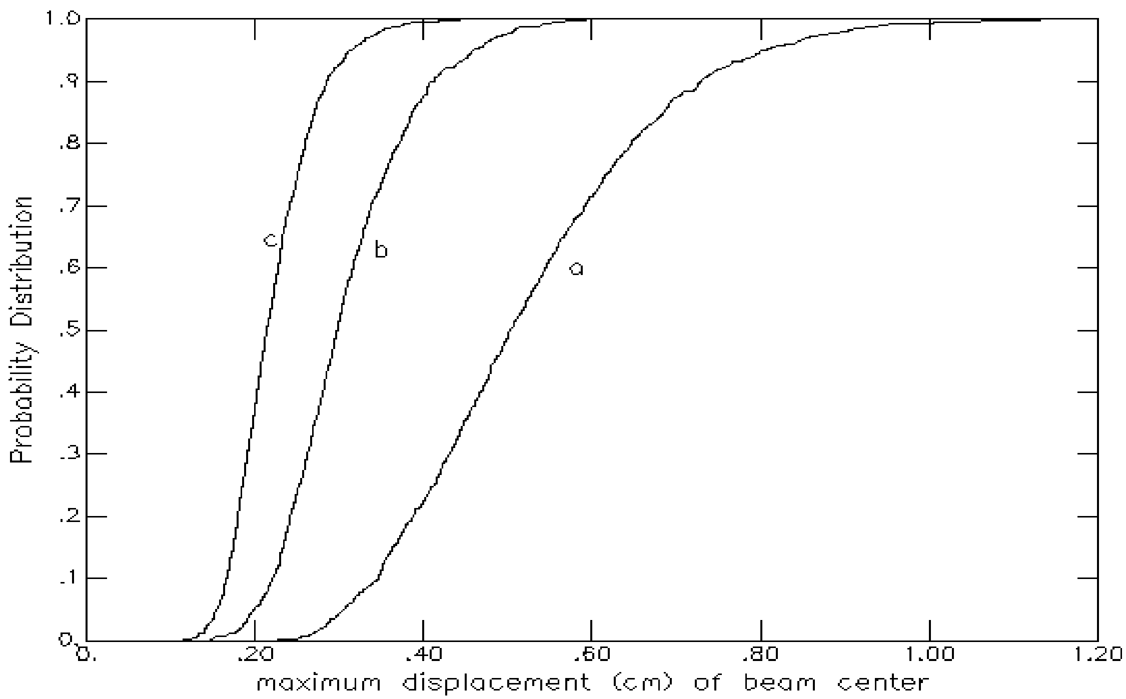


- Doublet tilt error may be the main reason for steering being necessary.

Steerers and BPMs -- At What Locations?

- Set of tolerances assumed:
  - Doublet displacement = ± 0.010”
  - Quad displacement = ± 0.005” (equivalent to 0.021° doublet tilt)
  - Quad tilt = ± 0.5°
  - Cavity displacement = ± 0.040”
  - BPM error = 0.5 mm (rms, normal)
- 32 quad doublets in the SRF linac. **Consider 3 cases**:
  a. No steering
  b. 4 pair of BPMs in 2nd of the doublet (i.e. {7,8}, {15,16}, {23,24}, {31,32})
     4 sets of steering (i.e. {6,7}, {14,15}, {22,23}, {30,31})
  c. 4 pair of BPMs in 2nd of the doublet (i.e. {7,8}, {15,16}, {23,24}, {31,32})
     8 sets of steering (i.e. {2,3}, {6,7}, {10,11}, {14,15}, etc)
     Use “Minimum Steering” technique
- Dipole : X Steering - 1st quad of the doublet
  Y Steering - 2nd quad of the doublet

Results of 3 Cases: Same BPMs but Different Number of Steerers



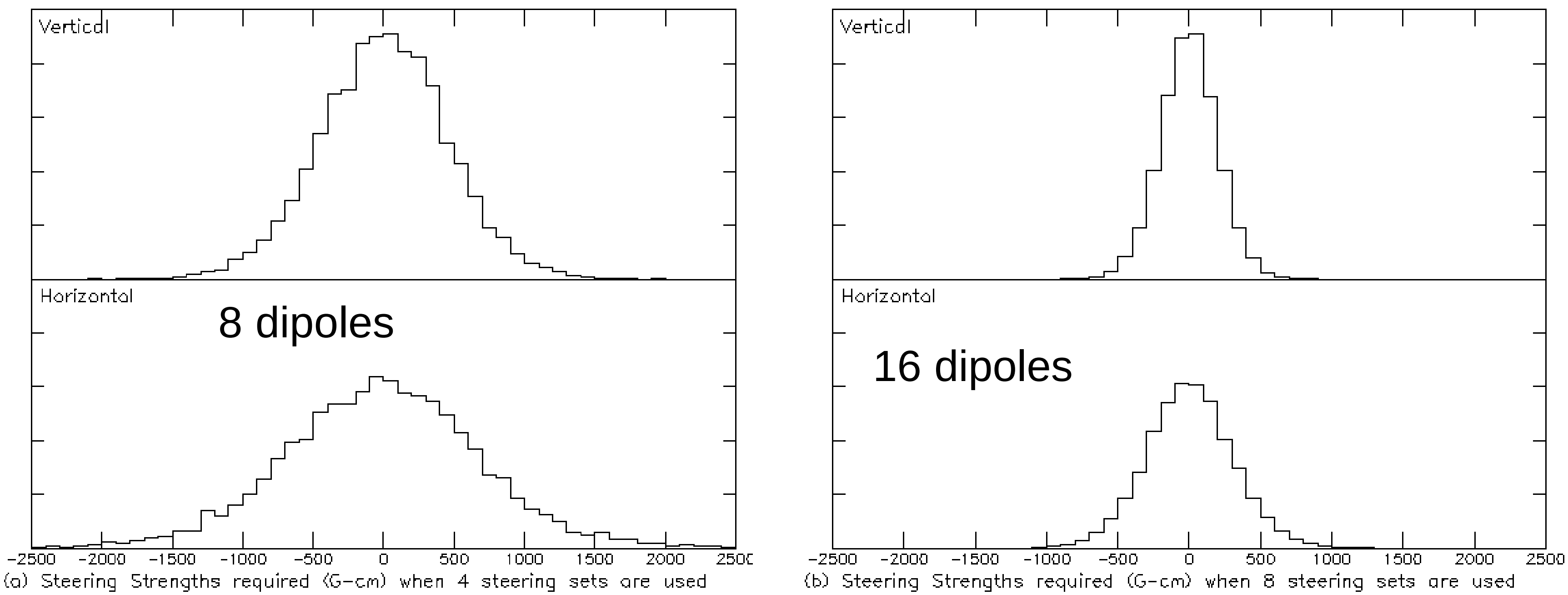
a: No Steering

b: 8 dipoles
8 BPMs

c: 16 dipoles
8 BPMs
(Min. Steering Method)

- With all other errors thrown in, ‘a’ is almost identical to the curve with only doublet tilt error, i.e., **Doublet tilt error dominates**

Dipole Strengths are Least for ‘c’



- 'Minimum Strength' method minimizes required dipole fields

Space Charge Codes

- SCHEFF (Space CHarge EFFect):

  - a 2D (r-z), particle-in-cell (PIC) code,

  - widely used (since ‘67) in almost all linac beam-dynamics codes.

- PICNIC (Particle In Cell Numerical Integration between Cube):

  - a full 3D (x,y,z), particle-in-cell (PIC) code,

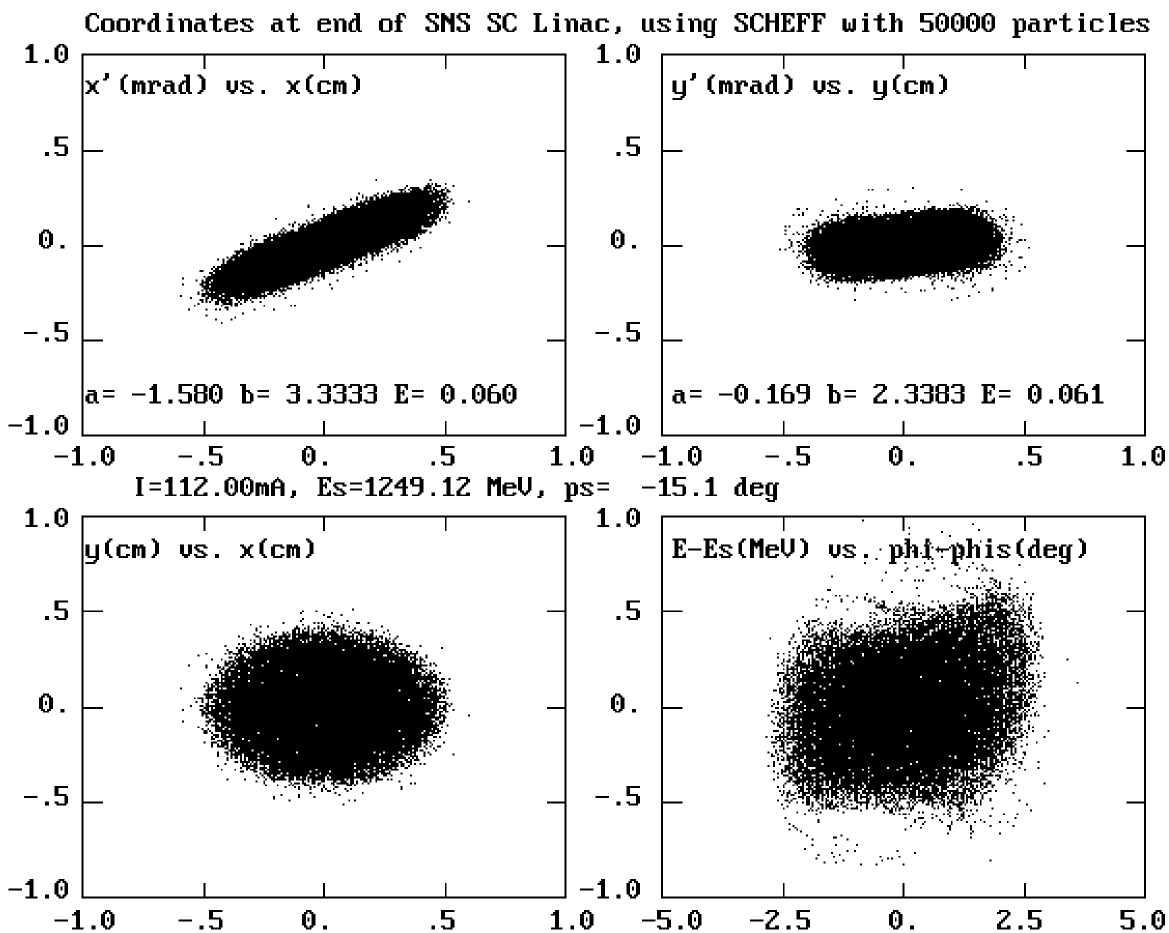
  - recently (‘98) introduced, being used in linac beam-dynamics codes.

- IMPACT (Integrated Map Particle ACcelerator Tracking):

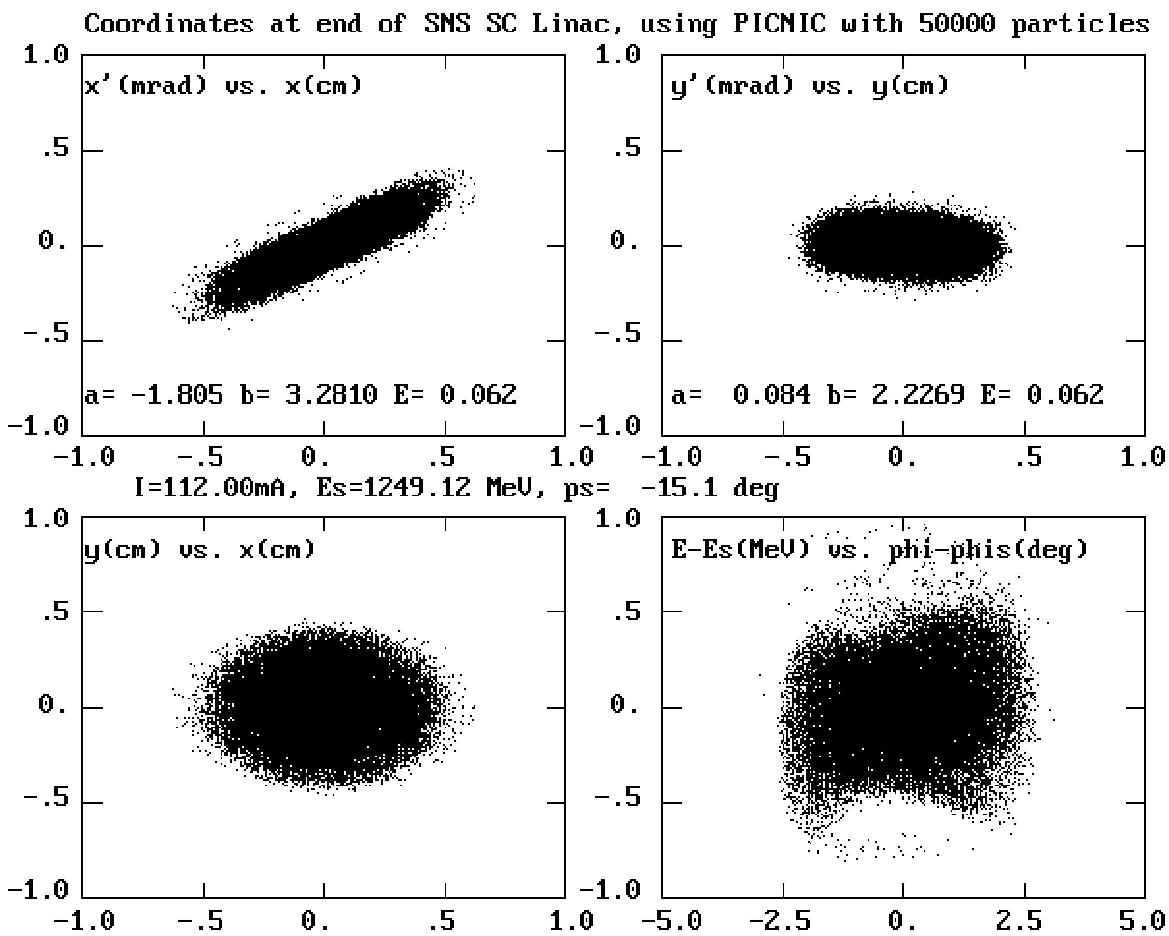
  - recently introduced (‘98), an integrated “parallel mode implementation” of particle-in-cell (PIC) code for linear accelerators,

  - space-charge calculation done using a 3D (x,y,z) “Poisson solver” with 6 types of boundary conditions.

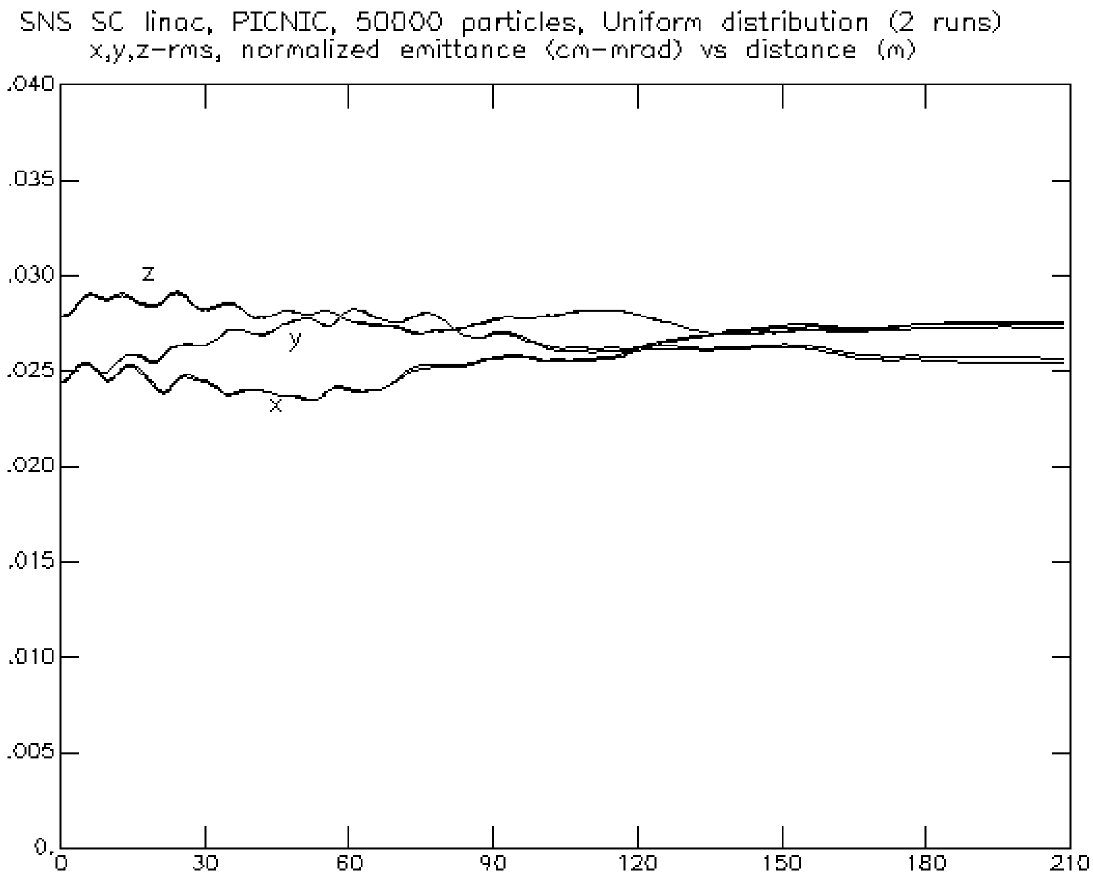
Phase Space at the end of SRF Linac Using SCHEFF



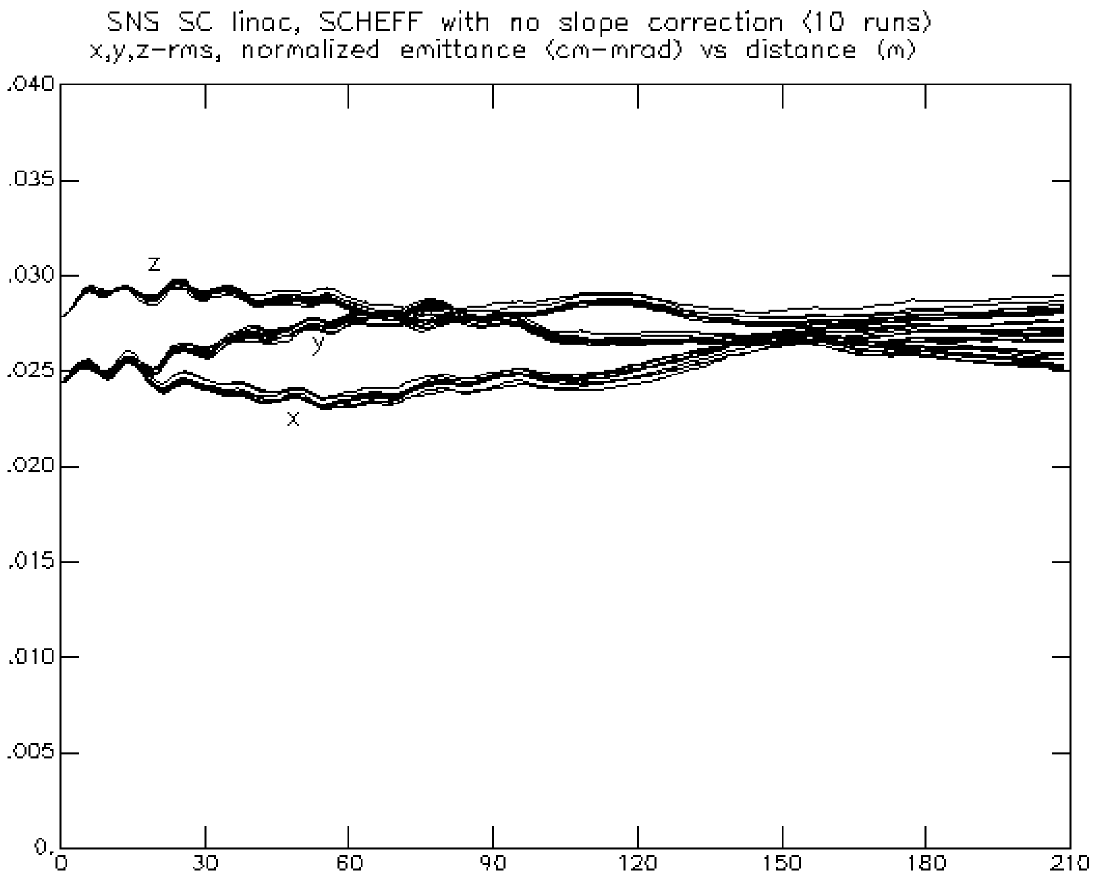
Phase Space at the end of SRF Linac Using PICNIC



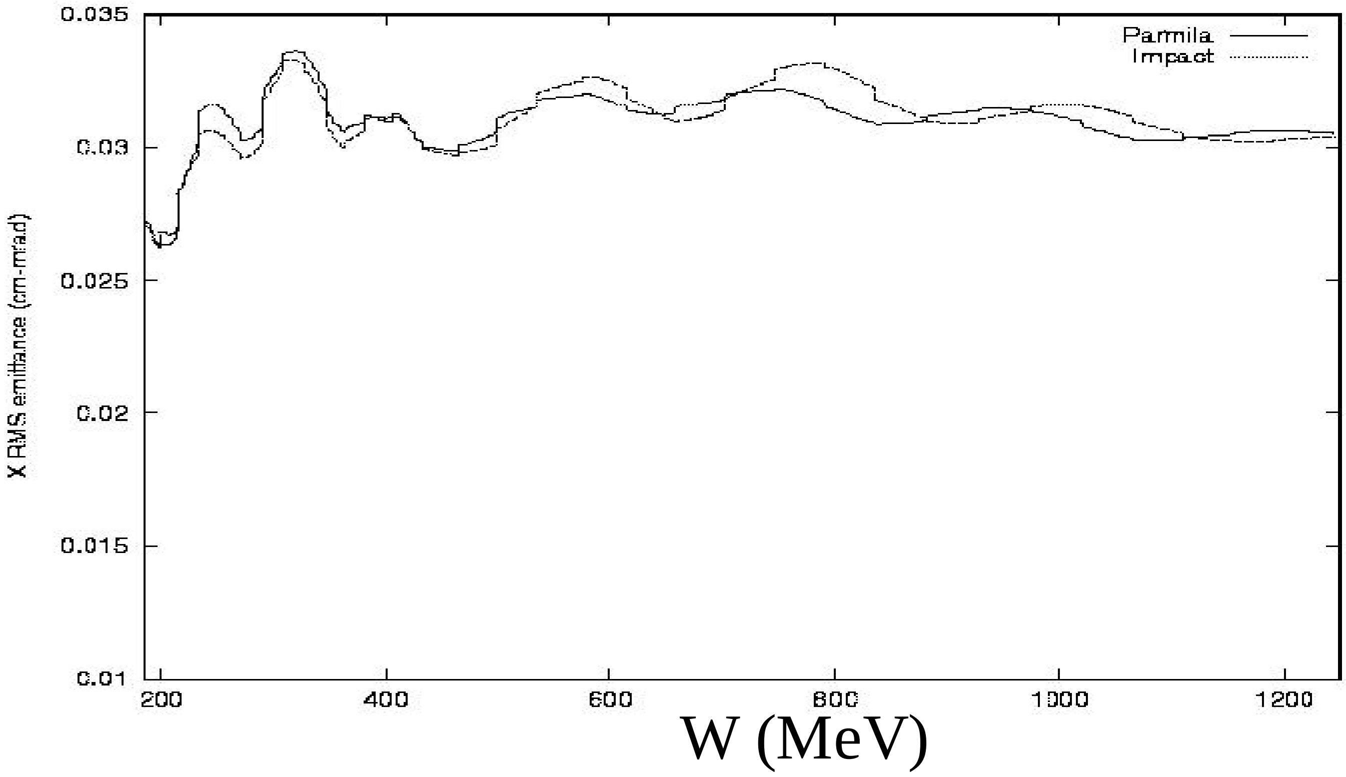
Emittance Profile through SRF Linac Using PICNIC



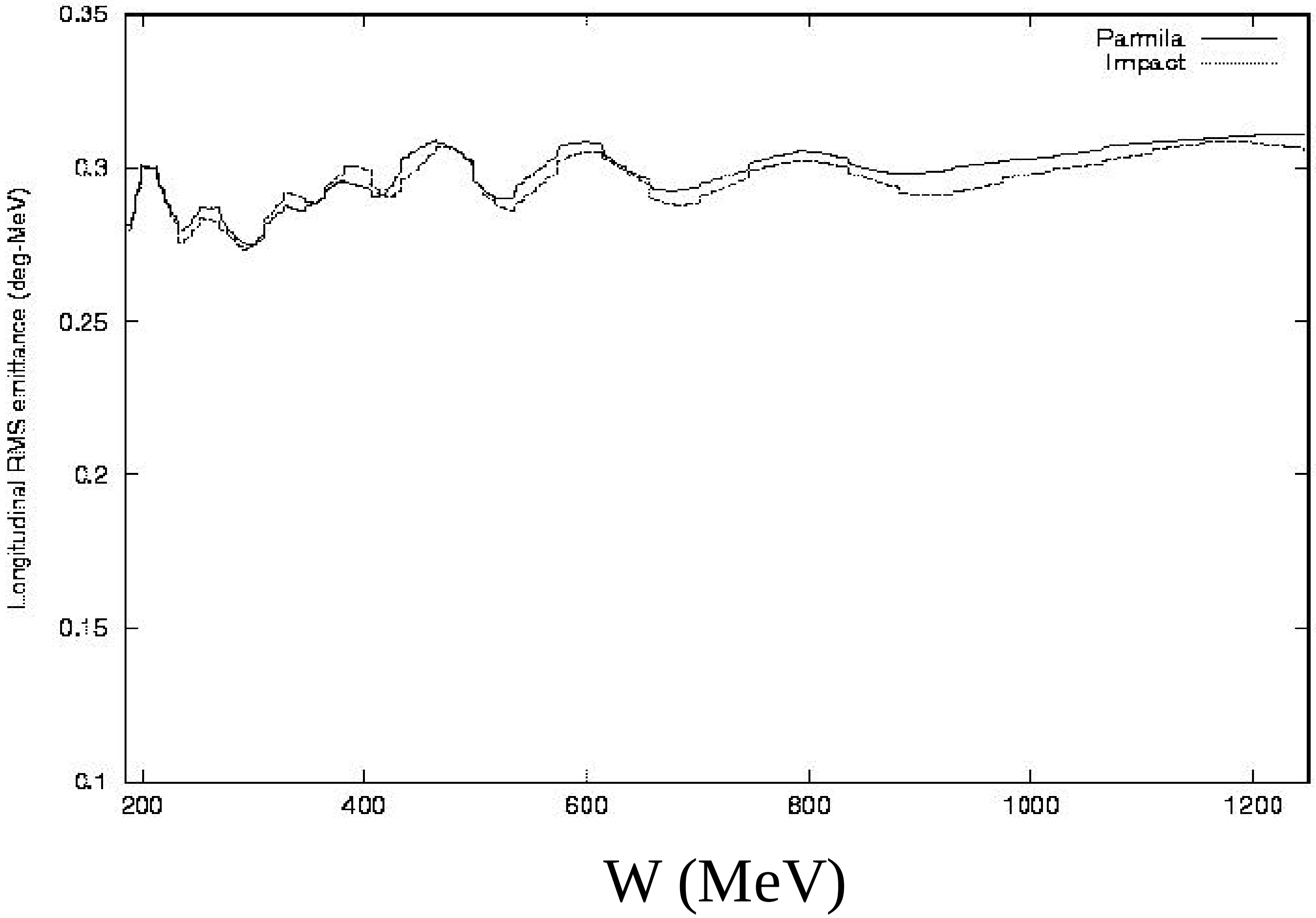
Emittance Profile through the SRF Linac Using SCHEFF



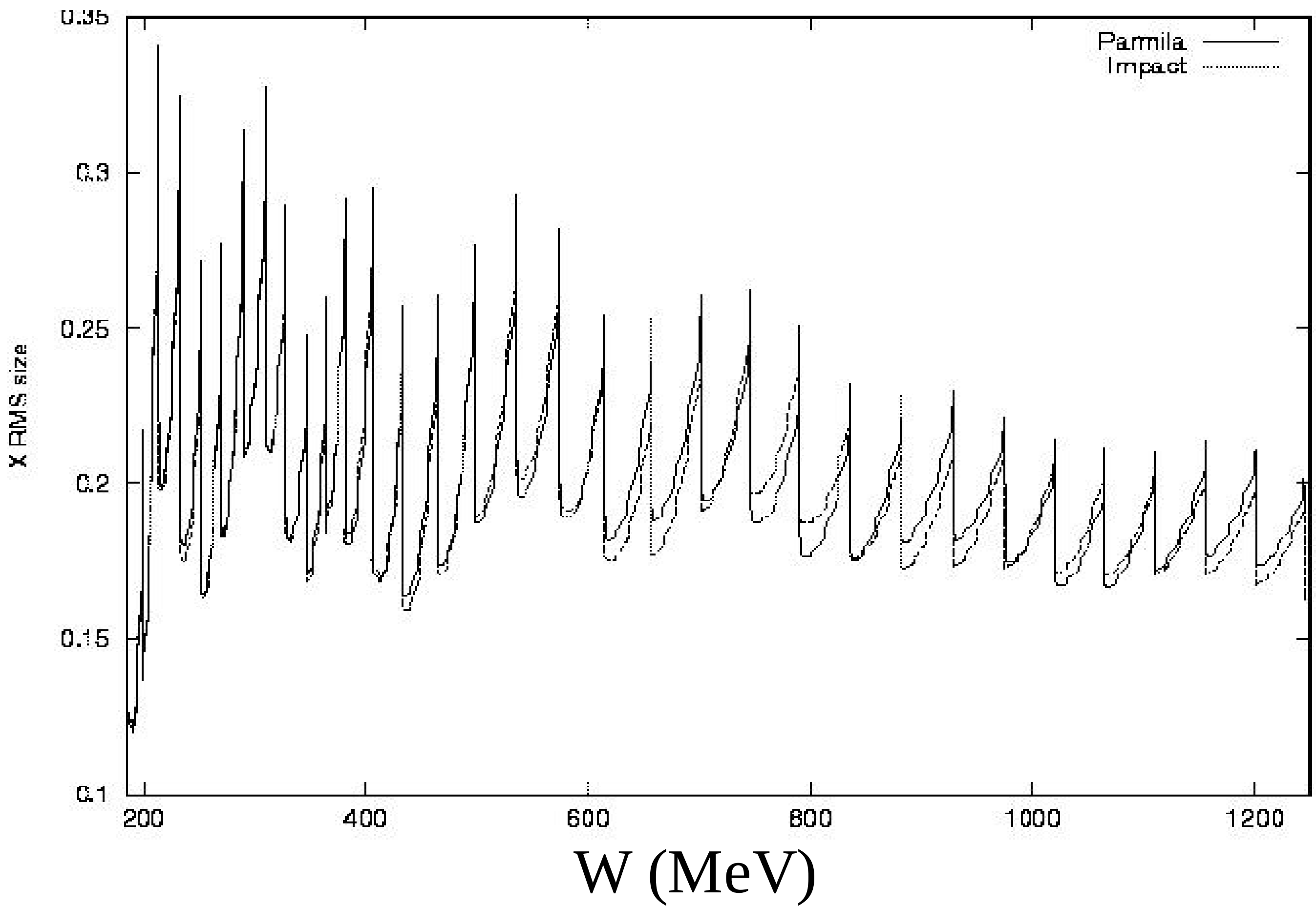
Emittance Profile in SRF Linac Using PARMILA (with SCHEFF) and IMPACT



Longitudinal RMS Emittance Profile in the SRF Linac Using PARMILA and IMPACT



RMS Beam-Size in the SRF Linac Using PARMILA (with SCHEFF) and IMPACT



Summary of Space-Charge Calculation Comparison

- RMS emittaces calculated with same beam dynamics code (LINAC) using 2D (SCHEFF) and full 3D (PICNIC) agree remarkably well.
- The same is true for Phase-space and Real-space (x-y) particle distributions .
- RMS emittances and beam-sizes calculated with PARMILA and SCHEFF, and IMPACT track each other very closely.
- SCHEFF is fast compared to full 3D codes.
- Details of halo comparison are continuing

Summary

- Total PMQ rotation error should be less than 0.5 degree
- 2% gradient error, when PMQs are sorted is equivalent to no error.
- In CCL, most important error is Quad displacement.
- “Minimum Steering” method requires fewer BPMs.
- Doublet tilt is dominant error in the SRF linac.
- SCHEFF is in remarkably good agreement with 3D codes at RMS level; it’s fast, thus well suited for studies of RMS behavior of the beam.

Appendix

Following pages contain description of the key features of the space charge codes referred to in the presentation.

SCHEFF

- The SCHEFF subroutine is widely used for applying space-charge impulses in many beam-dynamics codes.
- It is a particle-in-cell (PIC) code that calculates the electric field components, E_r and E_z, on a two-dimensional (2D) r-z grid, and interpolates these field components to get the force on each particle.
- For purposes of calculating the space-charge fields, each particle is considered to be a ring of charge. The elliptical cross section on the x-y plane is taken into account when calculating effective the radius of the rings of charge.

(Ref: K. Crandall, 1967, Private Communication)

SCHEFF (Continued)

- The amount of charge in each rectangular box of the grid is then determined. Using pre-calculated tables, E_r and E_z are calculated at every node in the vicinity of the beam.
- The ellipticity of the beam cross section is taken into account when applying to each particle the impulse due to E_r. The x', y' and longitudinal energy of each particle is changed by applying the E_r and E_z for a given time or distance interval.
- Relativistic corrections are made for transforming the beam coordinates from the lab frame to the beam frame and back again.

PICNIC

- The PICNIC (Particle In Cell Numerical Integration between Cube) is a full 3D code.
- As in SCEFFF, it applies the space charge impulses to a beam at a given z or time.
- Particles in each cube formed by the 3D grid are counted.
- The field is calculated at each node of the grid as the sum of the contributions from all the grid-cubes, each of which is assumed to be uniformly populated.
- The field at the position of the particle is interpolated from the neighboring nodes, allowing a calculation of space-charge impulse.

(Ref: N.Pichoff, S. Nath, J.-M. Lagniel, LINAC 98 Proc., 141-143)

PICNIC (Continued)

- The field acting on particles outside the mesh is the one of a Gaussian beam with the same RMS dimensions as the real beam.
- Relativistic corrections are made by transforming the beam-coordinates from the lab frame to the beam frame and back again.
- The mesh size is adjusted to ± 3.5 times the RMS beam-size in all directions.

IMPACT Code with 3D Space Charge Routine

- IMPACT is a “parallel mode implementation” of particle-in-cell (PIC) code for linear accelerator.
- Use of canonical variables (x, p_x, y, p_y, t, p_t); t is the tof wrt the reference particle.
- Beamline elements (drift, quads, rf gaps) treated as “transfer matrices”.
- Transfer matrix for an rf gap is found by integrating the equations of motion for the “real map” of the rf gap fields.
- A space-charge calculation using a 3D (x,y,z) “Poisson solver” with 6 types of boundary conditions.
- Electrostatic fields are calculated in bunch frame and Lorentz transformed back to the lab frame.

(Ref: J. Xiang et al, Jnl. Comp. Phys., 163, p1-18, 2000)