Beam-Simulation Code Comparisons

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Simulation Codes are of Specific Concern to ASAC

- “A detailed comparison of codes, including interpretation of results in a physics framework, must be done.”
- “Committee members are aware of issues in most extant versions of PARMILA that is used extensively.”
- “Concerns with PARMILA have led other groups to write their own codes.”

End-to-End Beam Dynamics Simulations are Confirmed by Multiple Codes

- 4-D "Waterbag" distribution enters the RFQ
- RFQ beam dynamics calculated by:
  - PARMTEQ: multiparticle space-based &
  - TOUTATIS: multiparticle time-based
- Linac beam dynamics
  - MEBT, DTL, CCL, SRF & HEBT
  - PARMILA is the design code
  - PARMILA, PARM<u>E</u>LA, LINAC, PARTRANS & IMPACT calculate multiparticle beam dynamics
  - LTRACE and TRACEWIN calculate envelope dynamics

PARMELA is Our Most Detailed Simulation Code

- PARMELA : Phase & Radial Motion in Electron Linacs
- Originally written to simulate electron beam dynamics
  - now extended to simulate ion dynamics
- It does not design linacs
  - the linac is described as a sequence of elements and field maps
- Main features
  - time step integration
  - composite E & H fields
  - 2.5-D & 3-D space charge
    - note that 3-D space-charge requires ≥100k particles
  - E_r, E_z & H_θ field maps computed by SUPERFISH

PARMILA is Our Design and Primary Simulation Code

- PARMILA : Phase & Radial Motion in Ion Linacs
- Initially written to design DTLs and simulate their dynamics
  - can now design integrated linacs incl. DTLs, CCLs, CCDTLs , SRFs & transport systens
  - includes large variety of design & simulation options
    - special quad & phase laws, errors, phase advance, steering, ...
- Main features
  - z-based with impulse approximations
  - presently uses 2.5-D space charge (3-D pending)
  - gap transformation includes transit time integrals T, T', S & S'
  - off-axis fields derived using Bessel-function expansions
  - 100k - 1M particle typical
- Main disadvantage is that it contains ~37k lines of code

PARMILA is a Very Well Established Design & Simulation Code

- It has benefited from close scrutiny by many experts for many years
- It has been used to design many successful linacs
- There are indeed extant flawed versions in the community
  - its distribution is now controlled in an attempt to correct this
- Physics from PARMILA has been incorporated into other codes
- We welcome and solicit its comparison of any other codes
  - PARMILA has served as the reference against which many codes have been compared
  - all comparisons to date support its accuracy
- We have been unable to verify the existence of any issues, concerns or errors in the distribution version

LINAC is a Commercial Code Similar to PARMILA

- Initially written to for CCLs and CCDTLs only
- Now extended to integrated linacs including DTL, CCL, CCDTL & SRF
- Does not design linacs
- Dynamics similar but simpler than PARMILA
  - uses T only in CCL & SRF
- Can use either 2.5-D or 3-D space charge
- Includes large variety of simulation options including errors and steering

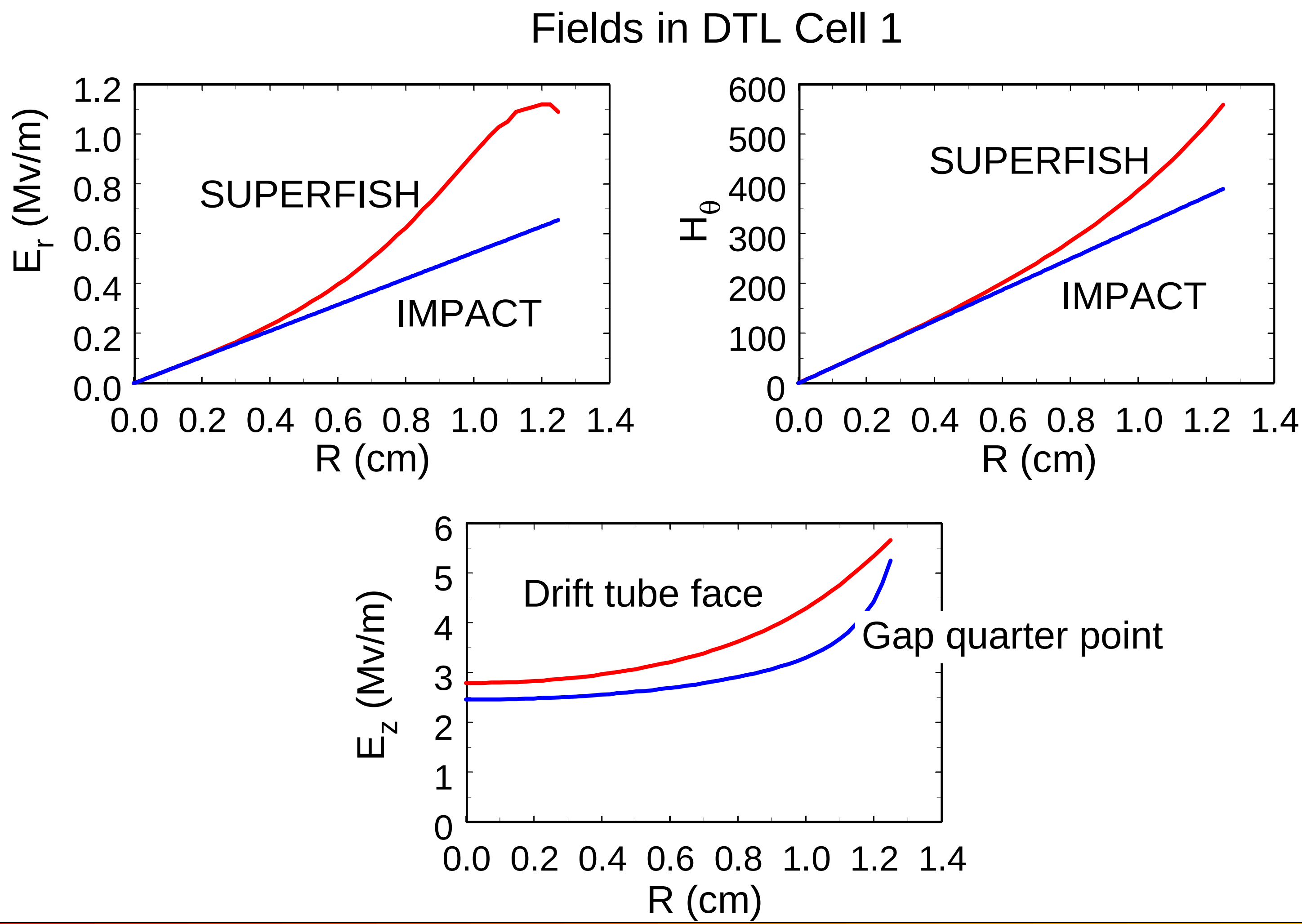
ParTrans is the French "Version" of PARMILA

- Design & simulation functions are handled separately
- Written to be compatible with PARMILA
- Dynamics i.e., gap transformation, transport through other elements are treated as in PARMILA
- Can use either 2.5-D & 3-D space charge
- 3 options for SRF linacs
  - field per cavity, per cell or assume a sinusoidal field
  - step integration (z) through SRF axial field from SUPERFISH;
    - radial field treated via Bessel function expansion
- More flexible and user friendly graphics than PARMILA
- E_r, E_z & H_θ field map (from SUPERFISH) integration Pending

IMPACT Uses Parallel Computation

- IMPACT is a “parallel mode implementation” of particle-in-cell (PIC) code for linear accelerators
  - used for simulations only, no design
- Uses canonical variables: x, p_x, y, p_y, t, p_t
- Calculates gap field integrals including acceleration
  - assumes linear expansion for off-axis fields in the gap
- Drifts, quads & gaps treated via “transfer matrices”
- Uses 3D space charge applied impulsively multiple times per element
- Can run very large particle arrays (could run 10^8)

IMPACT Gap Fields:
E_r & H_θ are Linear in r, E_z is Quadratic in r



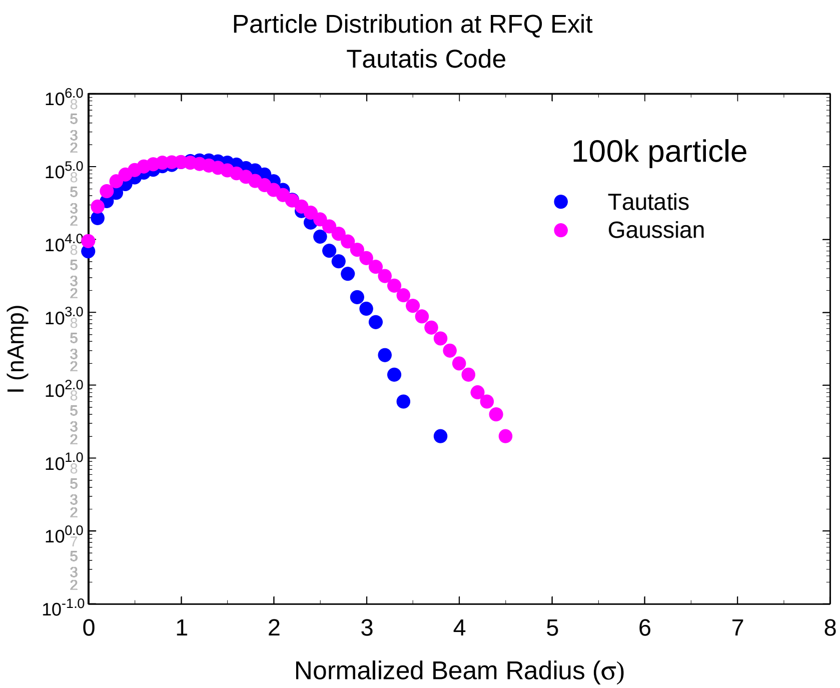
All 5 Codes Can Now Simulate the Entire SNS Linac

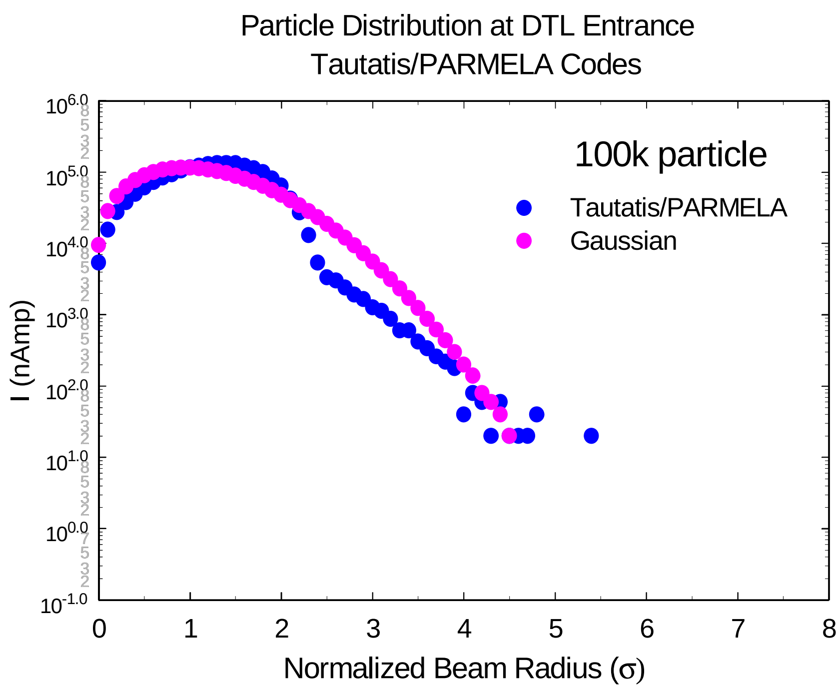
- Primary differences between the 5 codes
  - speed of execution
  - 2.5 & 3-D space charge, minor differences in method of field calculation
    - frequency of impulse application
  - time integration vs. impulse approximation
  - number of particles in the calculation
  - characterization of gap fields
- Main problems
  - describing exactly the same linac to each code in its unique input format
  - calculating the resultant beam properties in exactly the same way at the same locations

Basis of Comparison

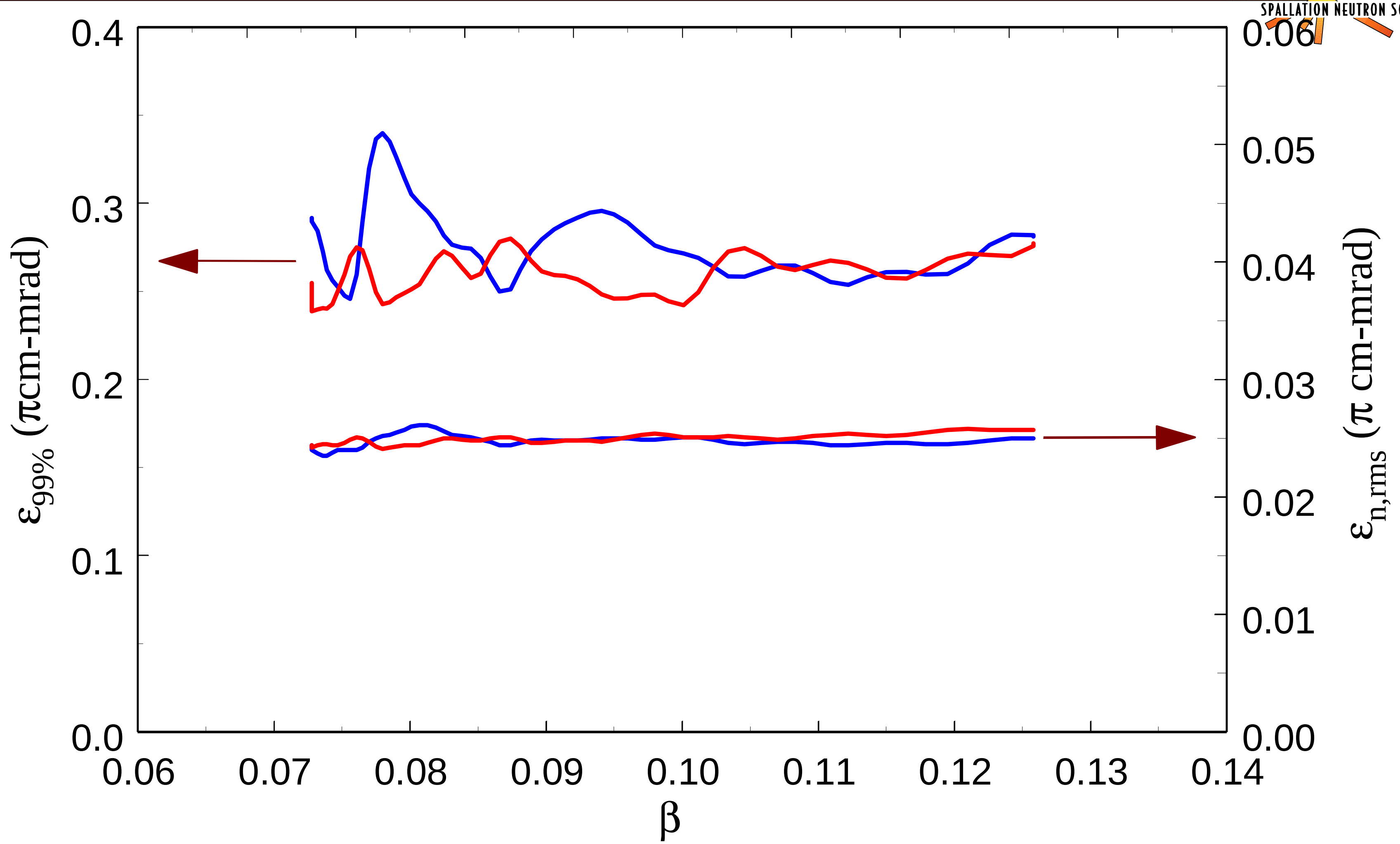
- Of primary interest to SNS is transverse emittance & beam size
- For DTL tank 1 only, we calculate
  - rms emittance profile
  - 99% emittance profile
  - normalized radial particle distribution at the exit
- All codes used the same input particle distribution
  - matched, 4-D waterbag, 1M particle distribution at RFQ entrance
  - RFQ dynamics computed using Toutatis with 3-D space-charge
  - MEBT dynamics computed using PARMELA with 3-D space-charge

The Particle Distribution Develops a Halo in the MEBT

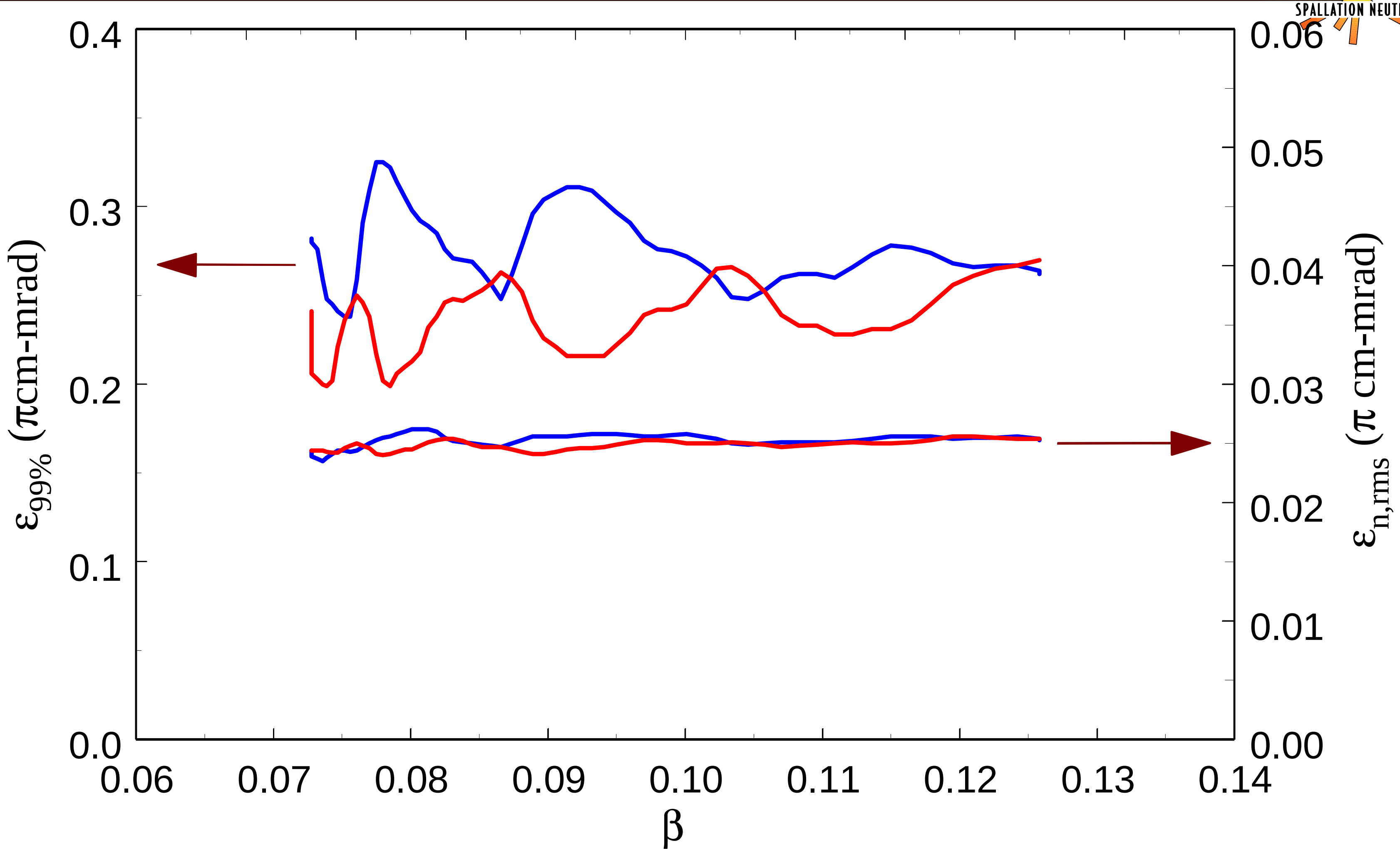




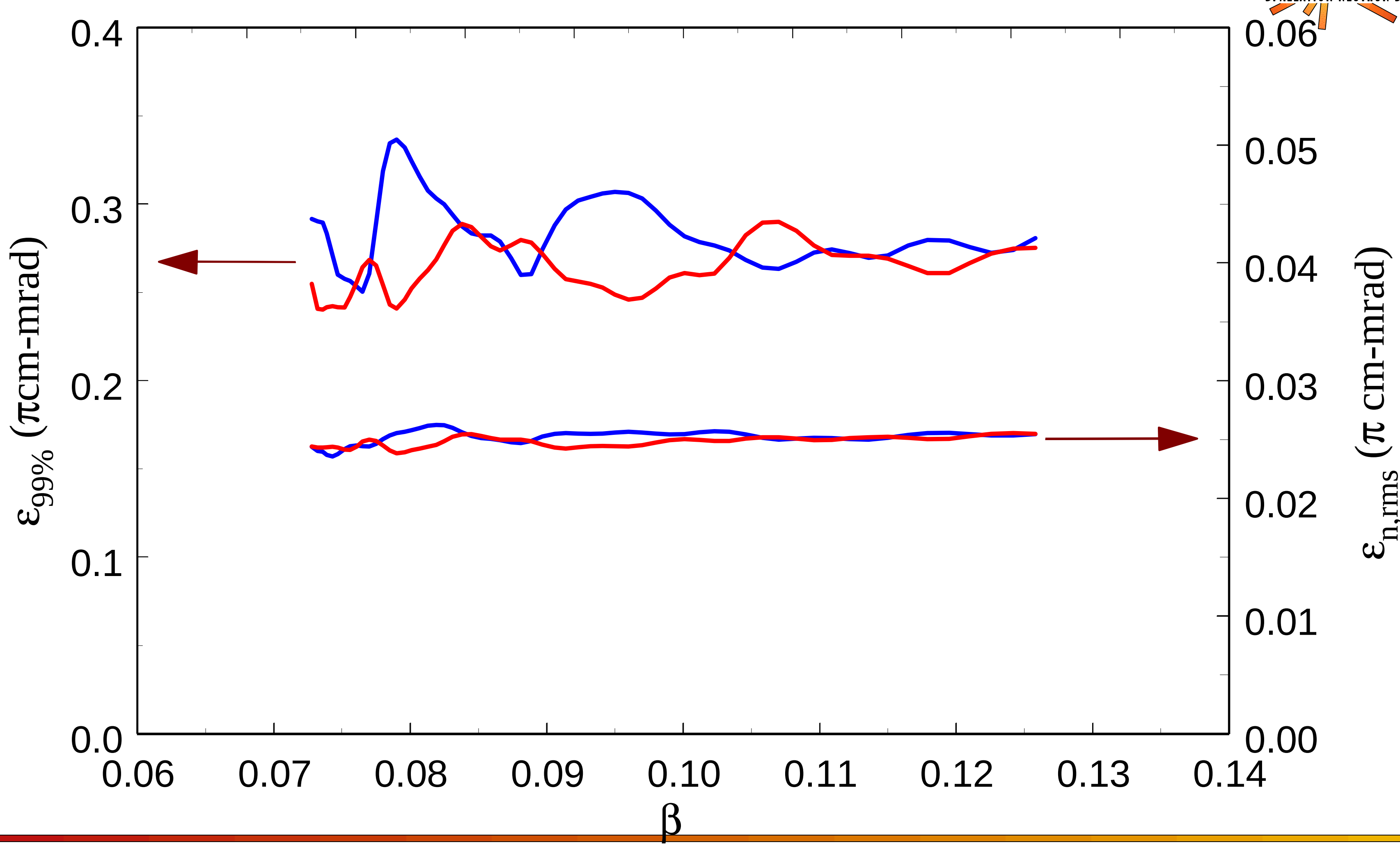
DTL Emittance Profiles
PARMILA Code



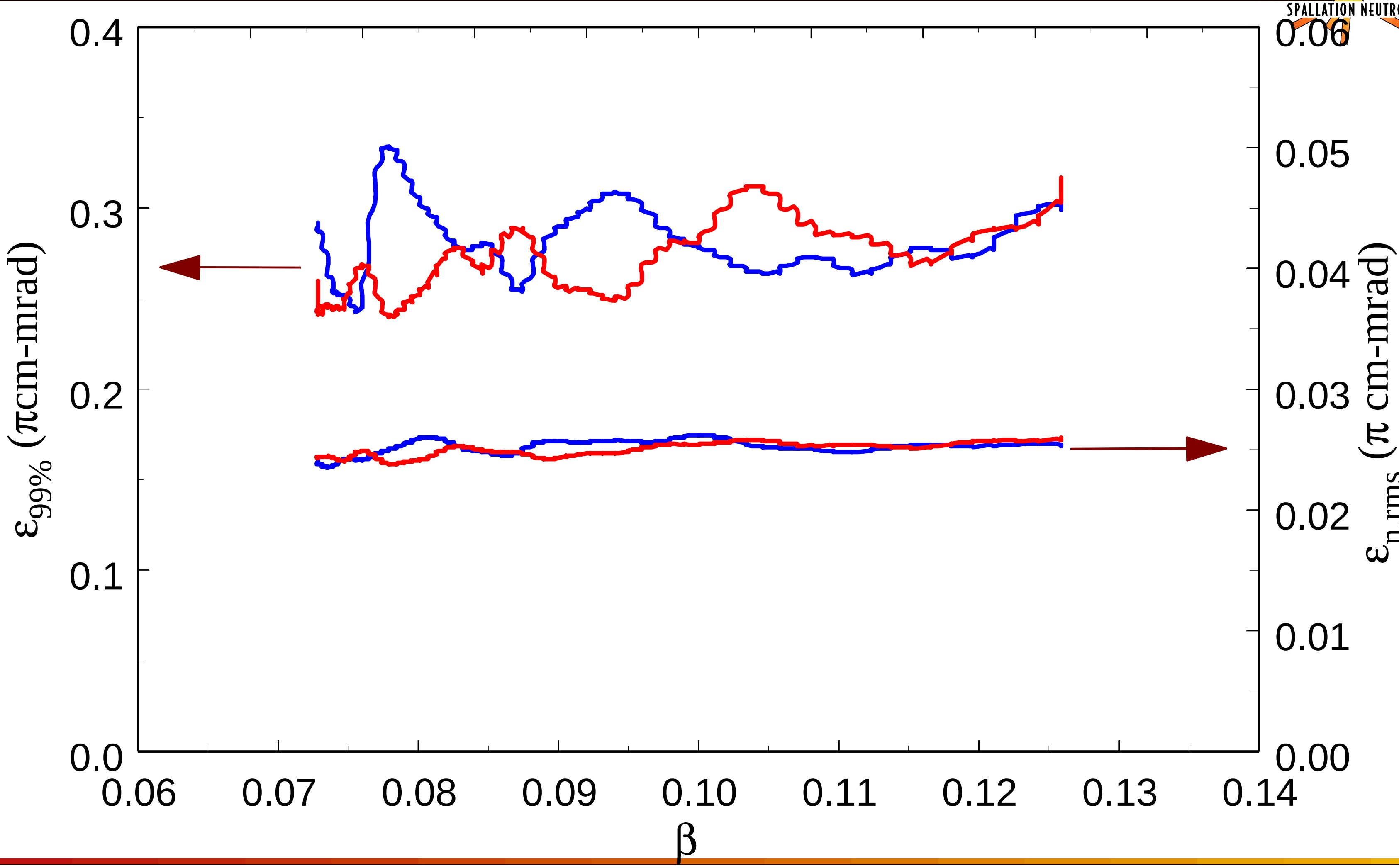
DTL Emittance Profiles
LINAC Code



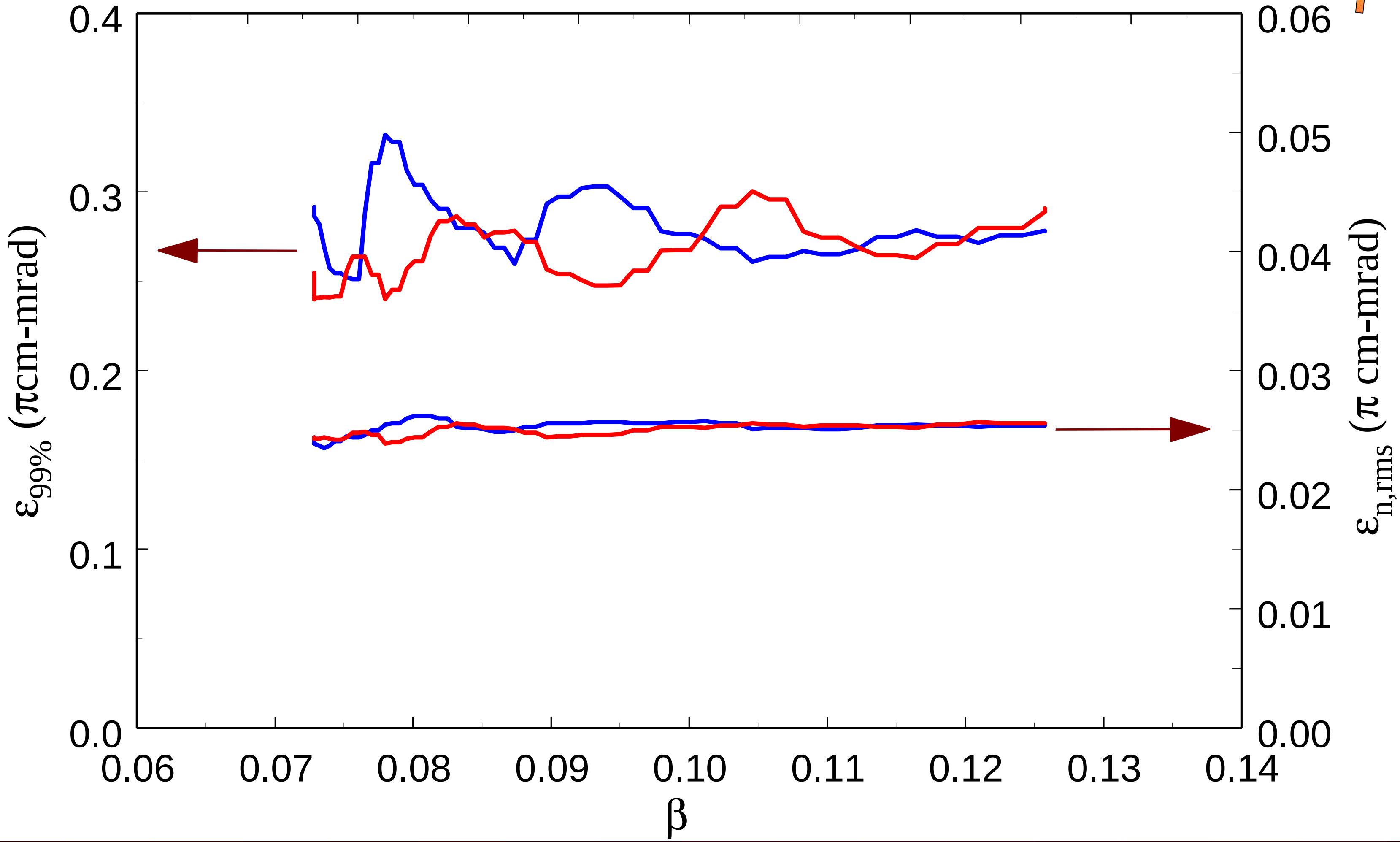
DTL Emittance Profiles
ParTrans Code



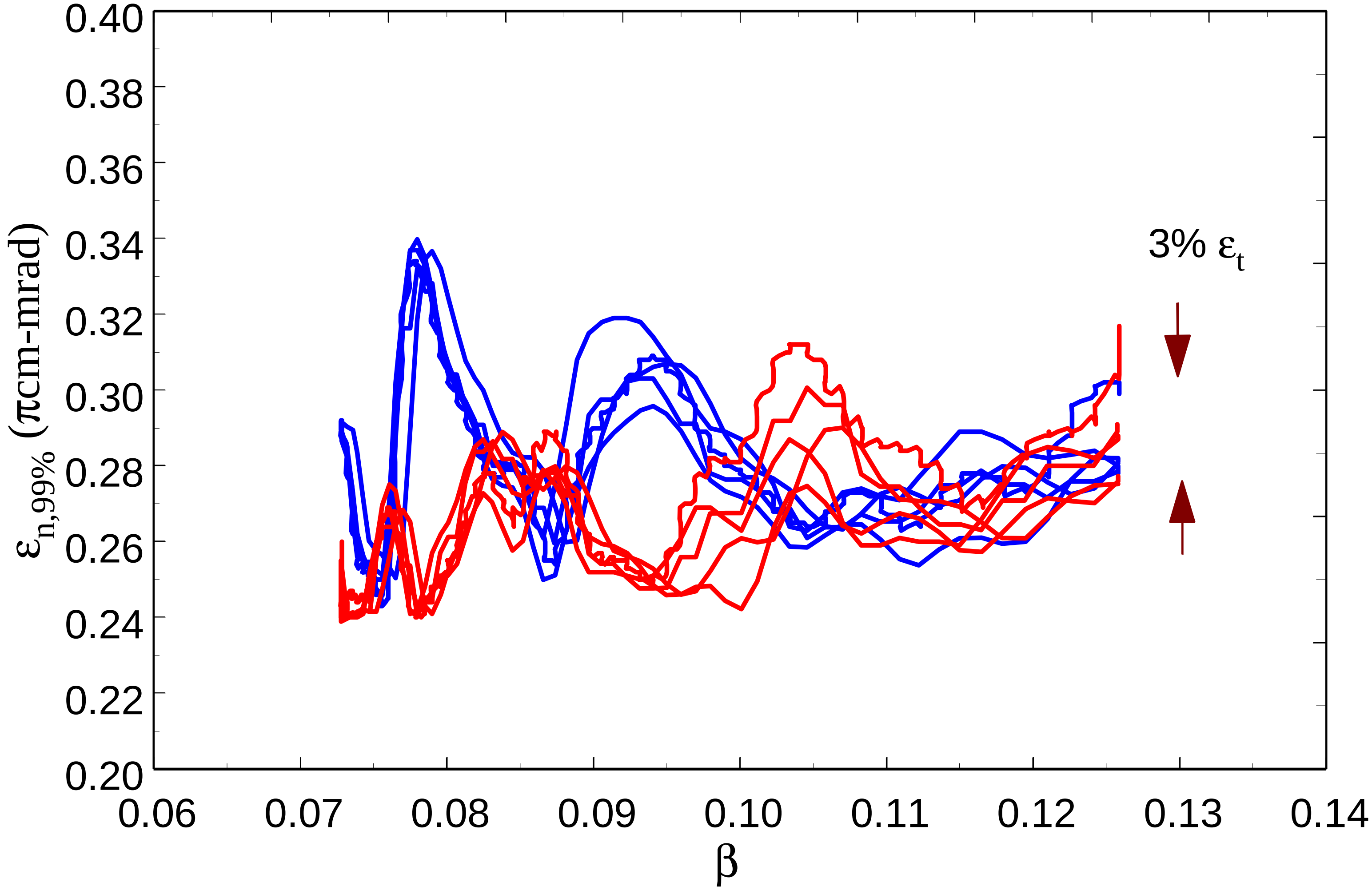
DTL Emittance Profiles
IMPACT Code



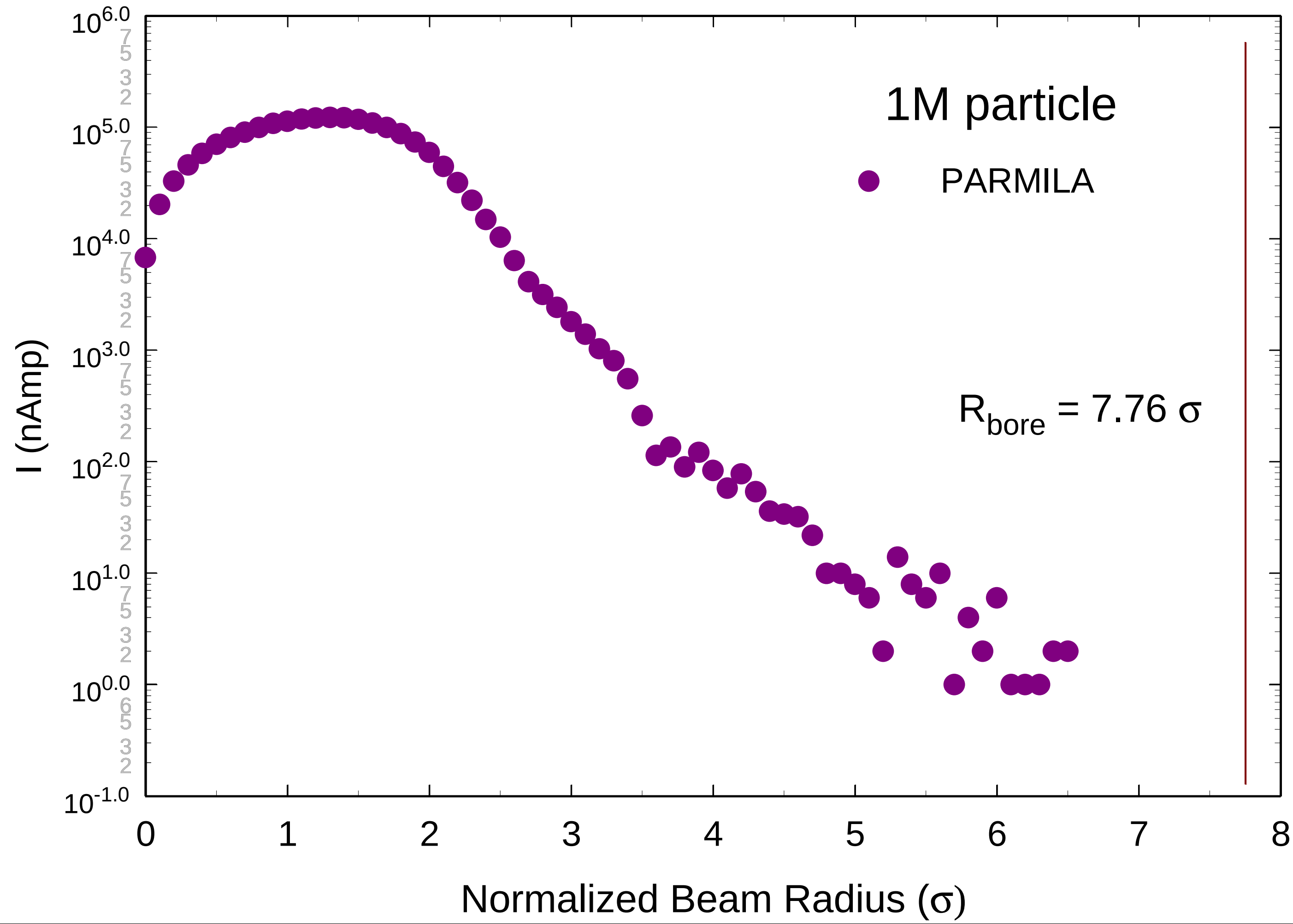
DTL Emittance Profiles
PARMELA Code



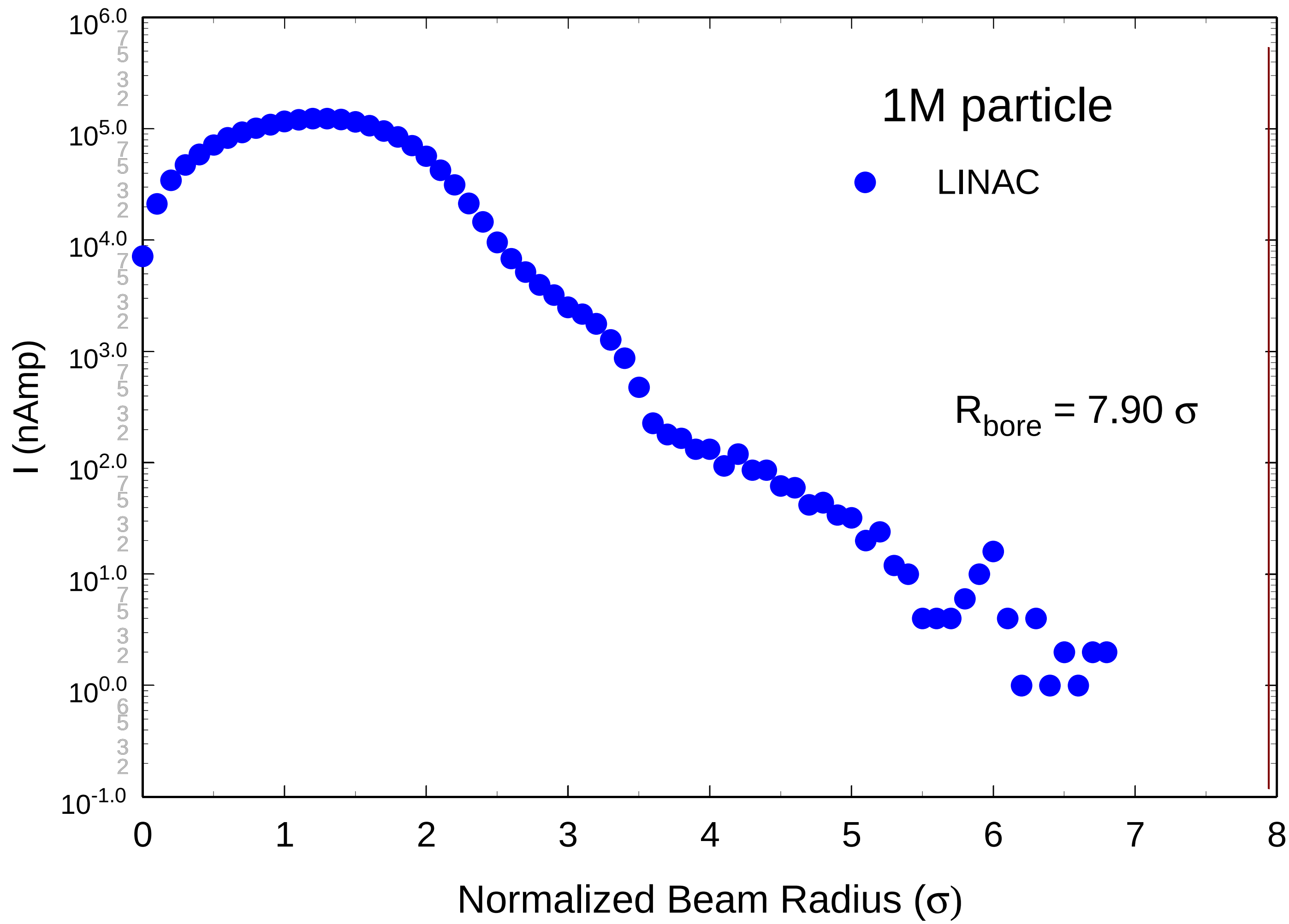
DTL 99% Emittance Profiles
5 Codes



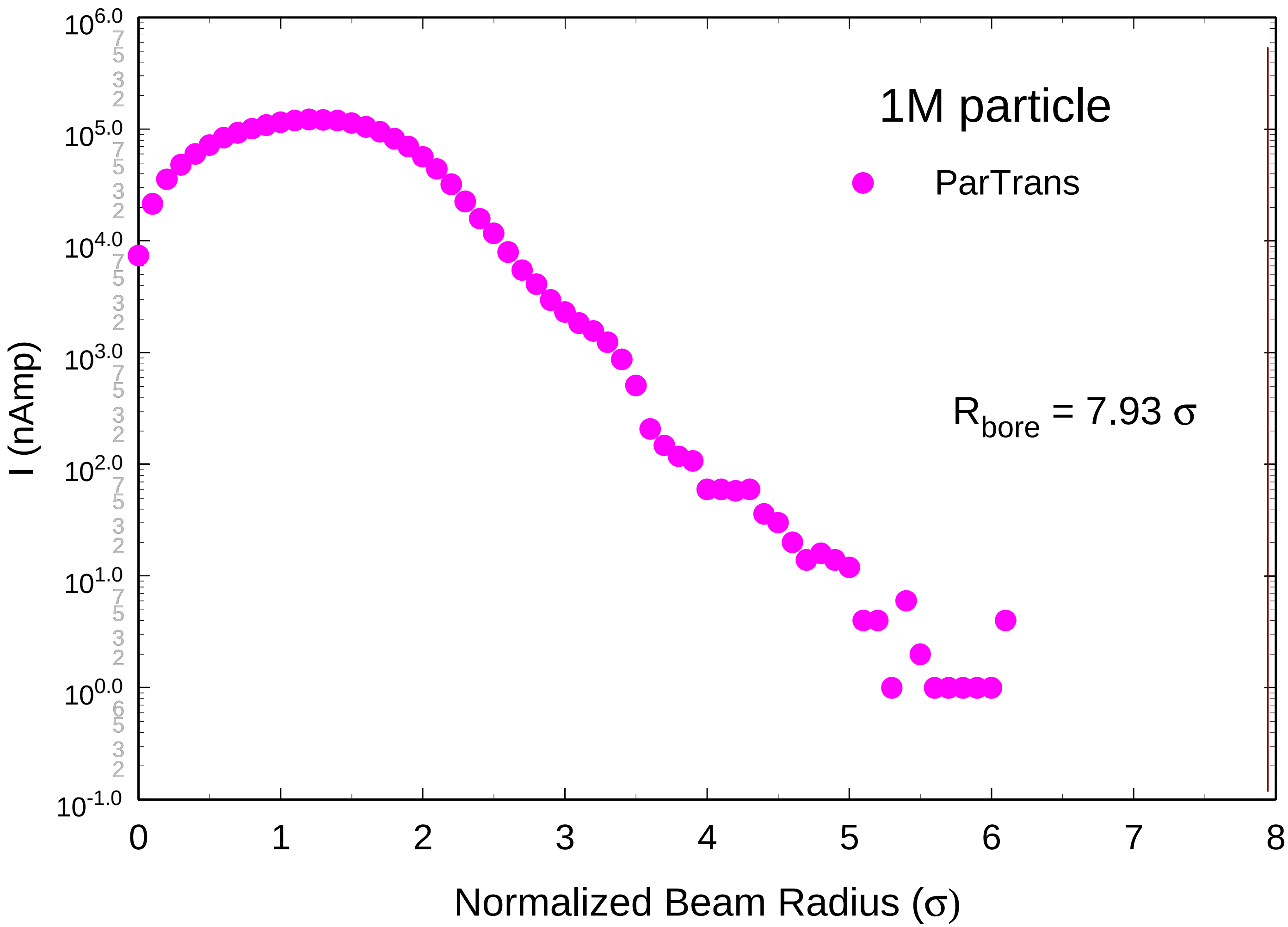
Radial Distribution at Tank 1 Exit
PARMILA Code



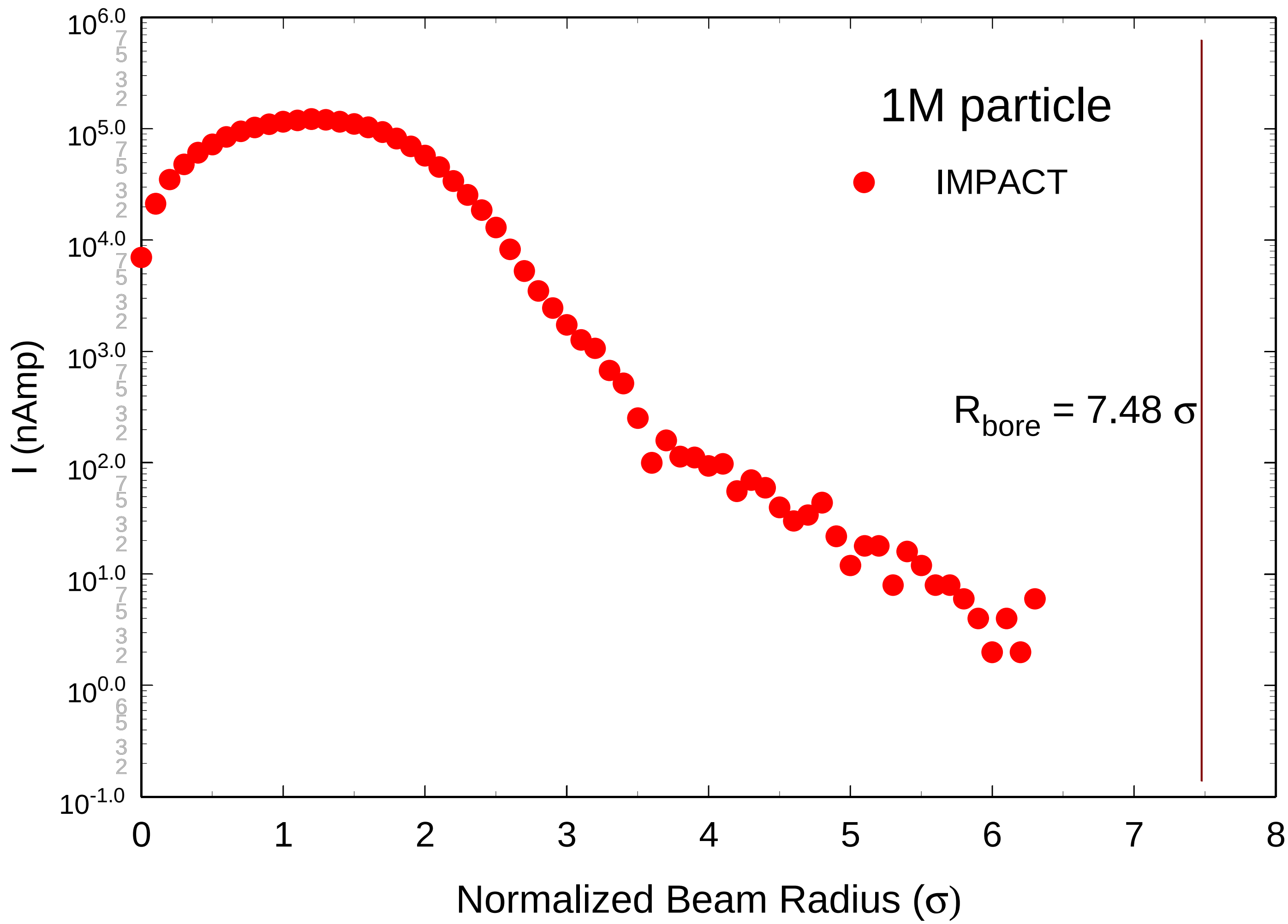
Radial Distribution at Tank 1 Exit
LINAC Code



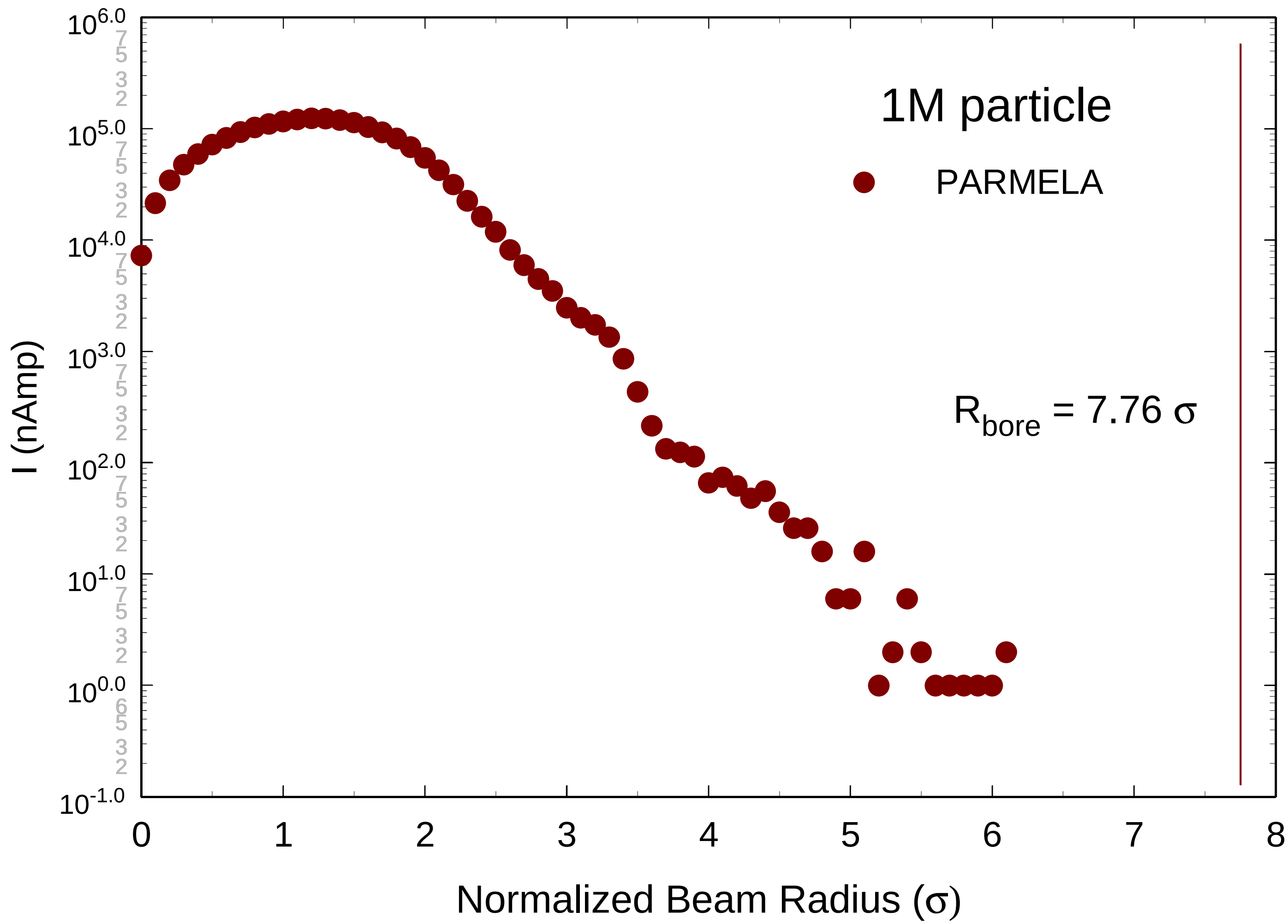
Radial Distribution at Tank 1 Exit
ParTrans Code



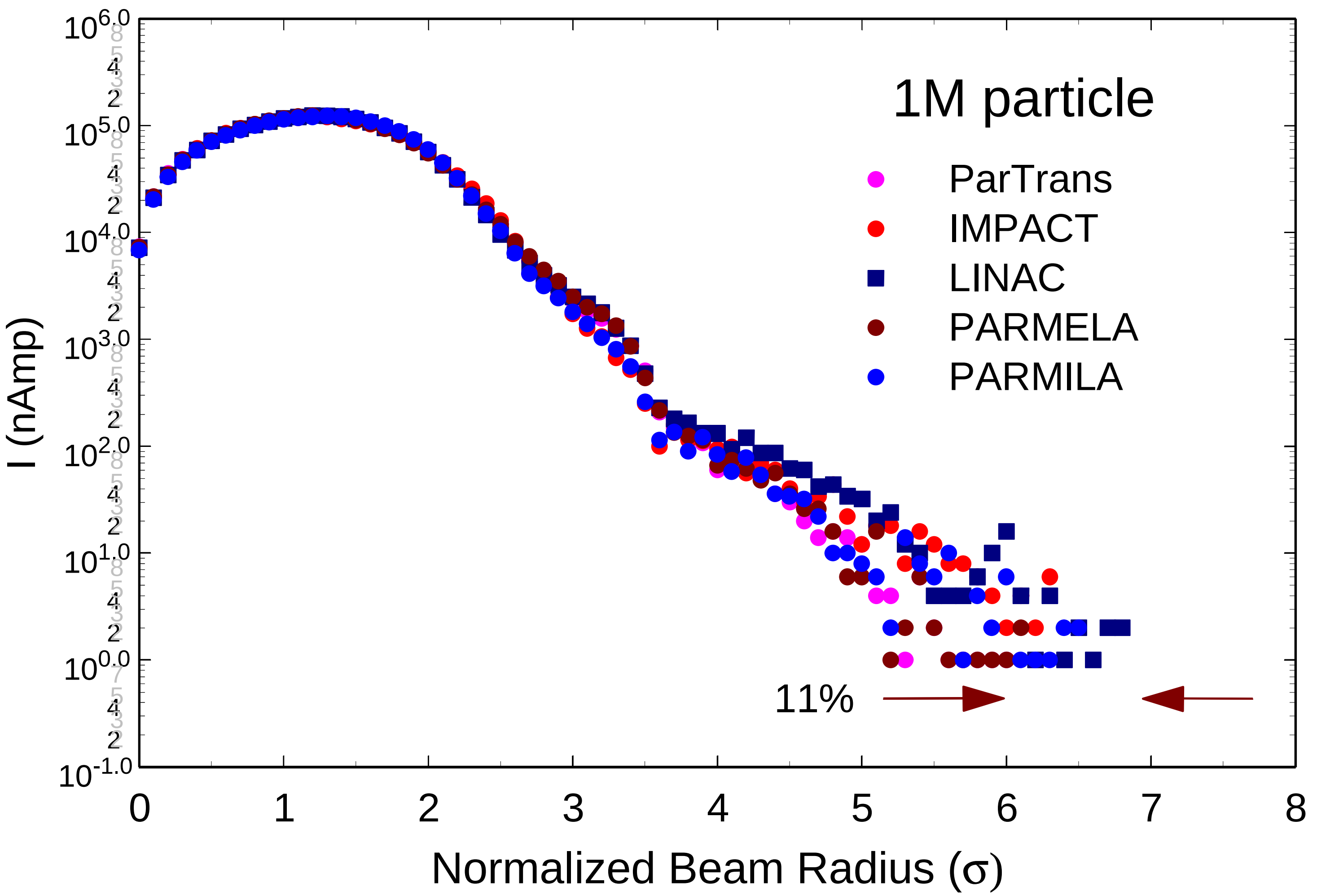
Radial Distribution at Tank 1 Exit
IMPACT Code



Radial Distribution at Tank 1 Exit
PARMELA Code



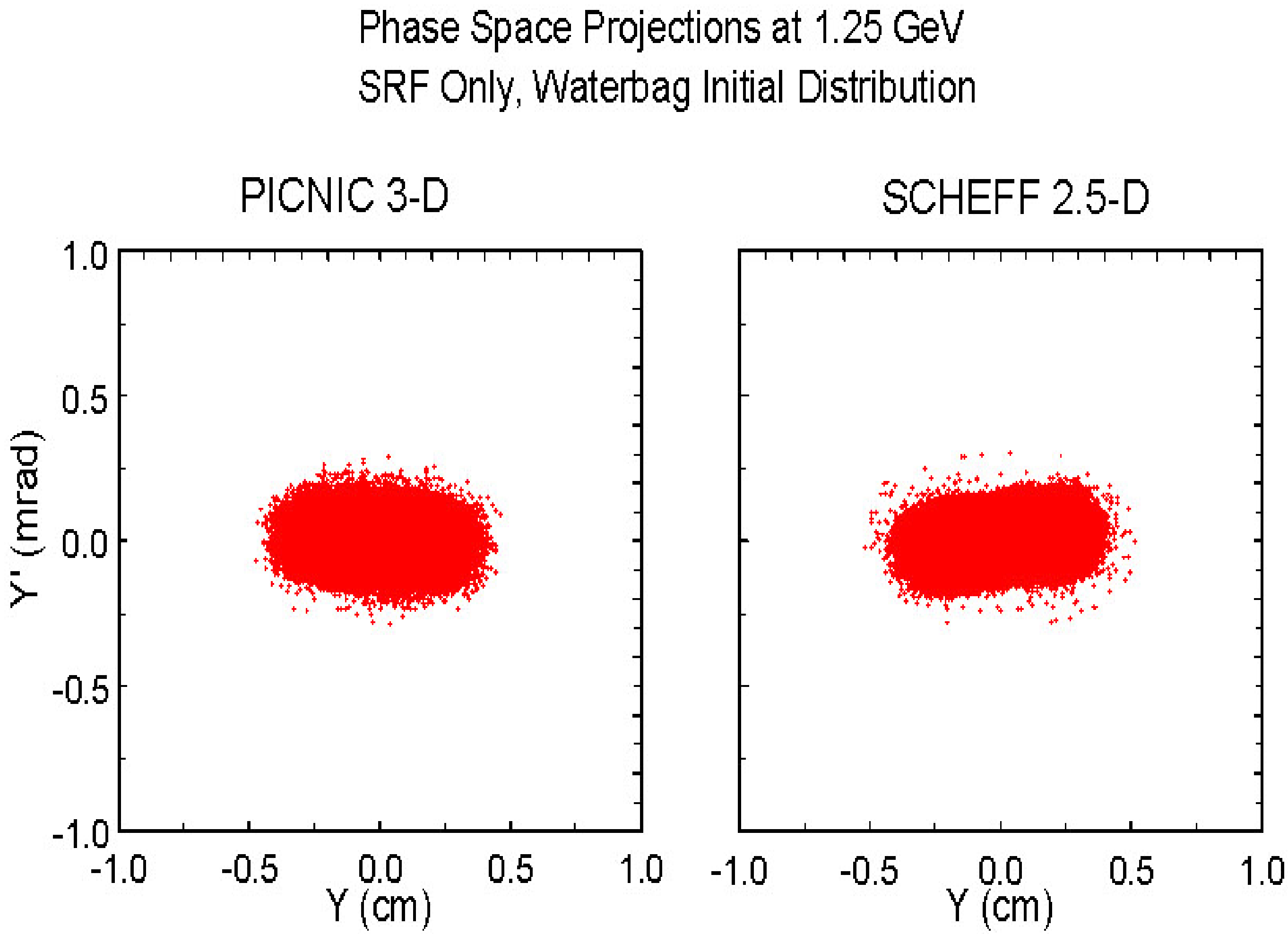
Radial Distribution at Tank 1 Exit
All Codes



Code Comparisons are Ongoing

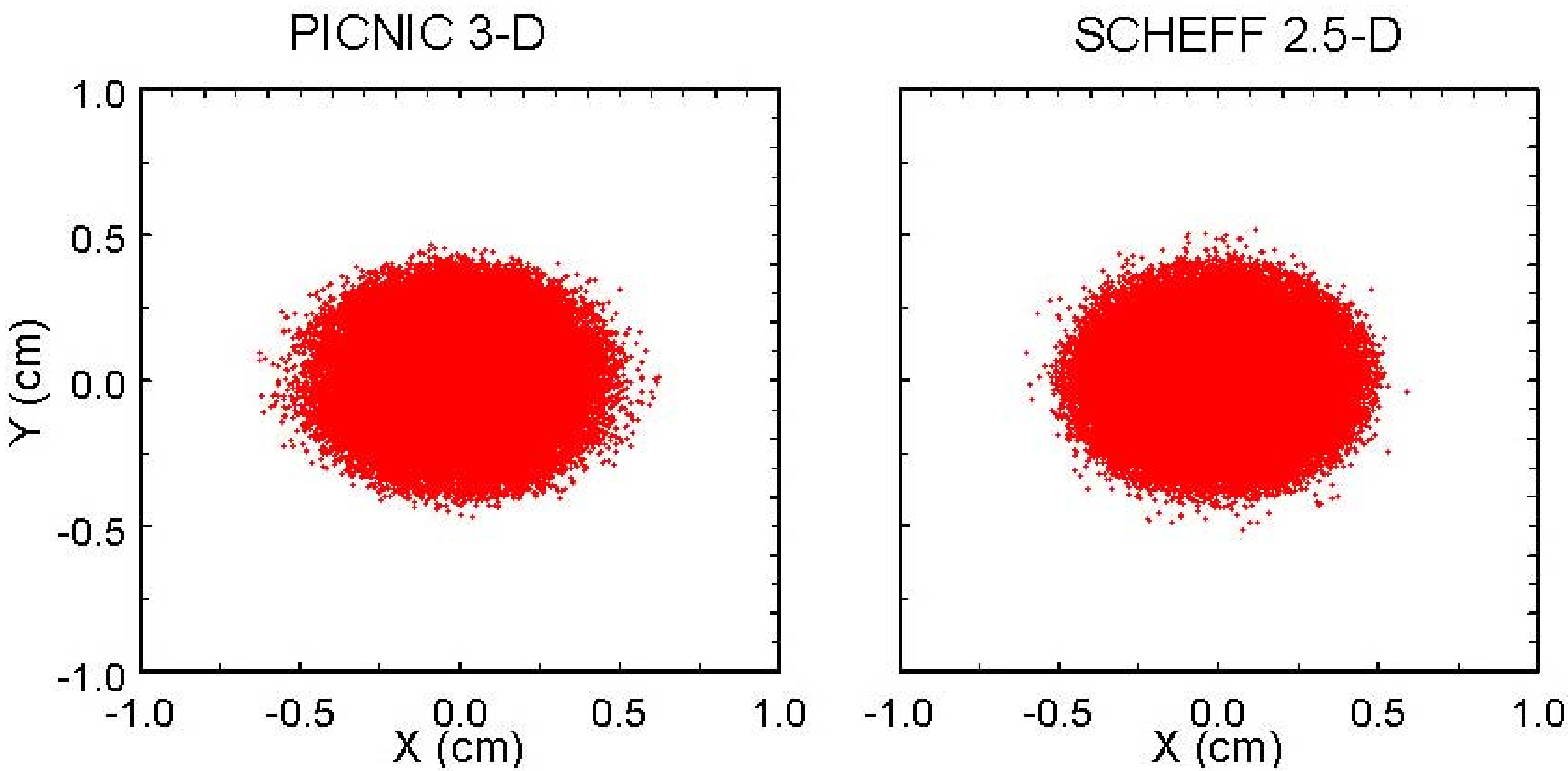
- Tank 1 results should be most sensitive at detecting differences
  - results are in good qualitative and quantitative agreement
- All codes are being modified to accept a common input format that describes the entire linac
  - PARMILA will generate the linac description
- End-to-end simulations of the SNS linac are underway using 100k distributions

“SCHEFF & PICNIC show significant difference in orientation of the Y-Y’ phase plane”

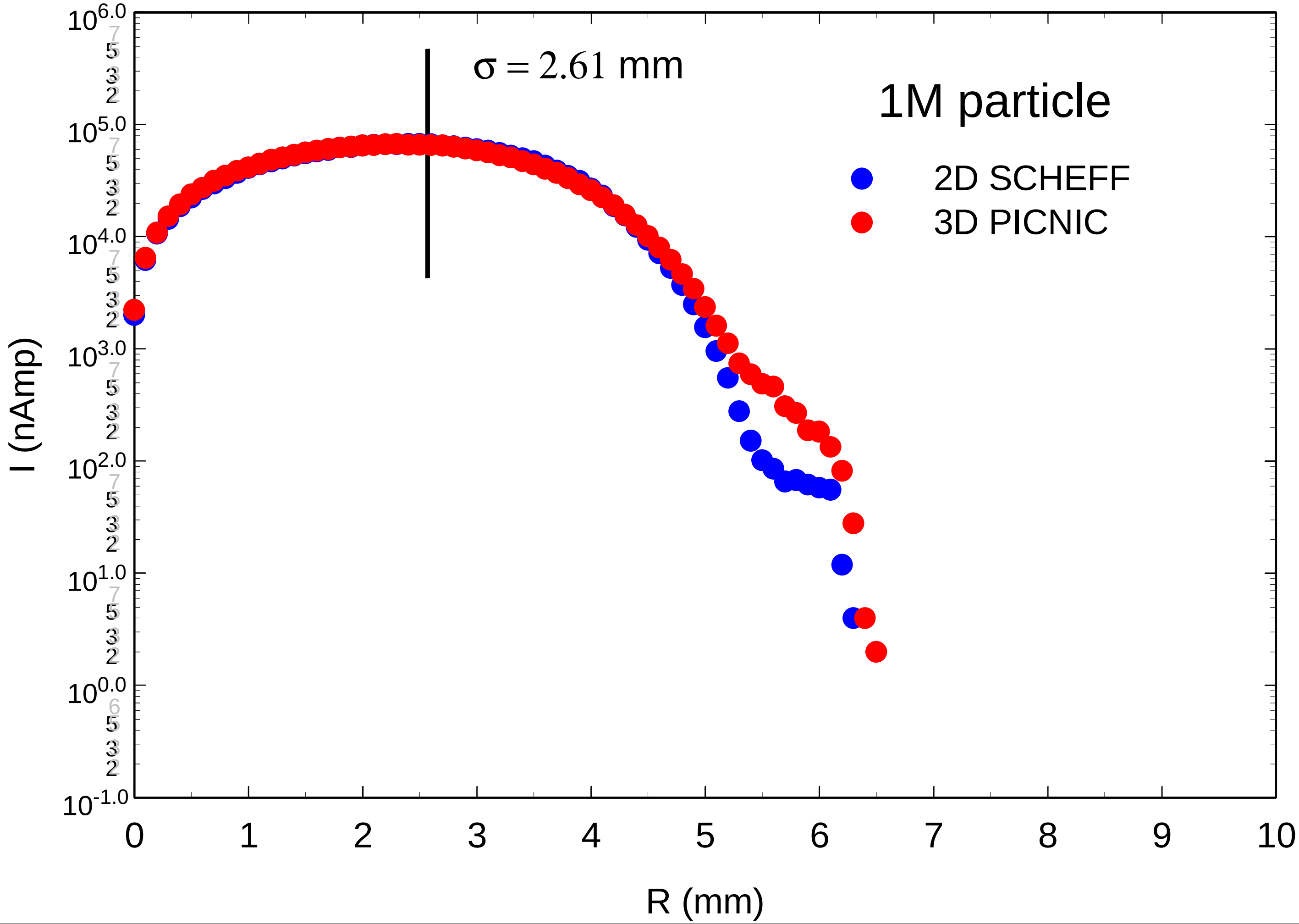


Our Primary Space-Charge Concern is not Orientation but Halo

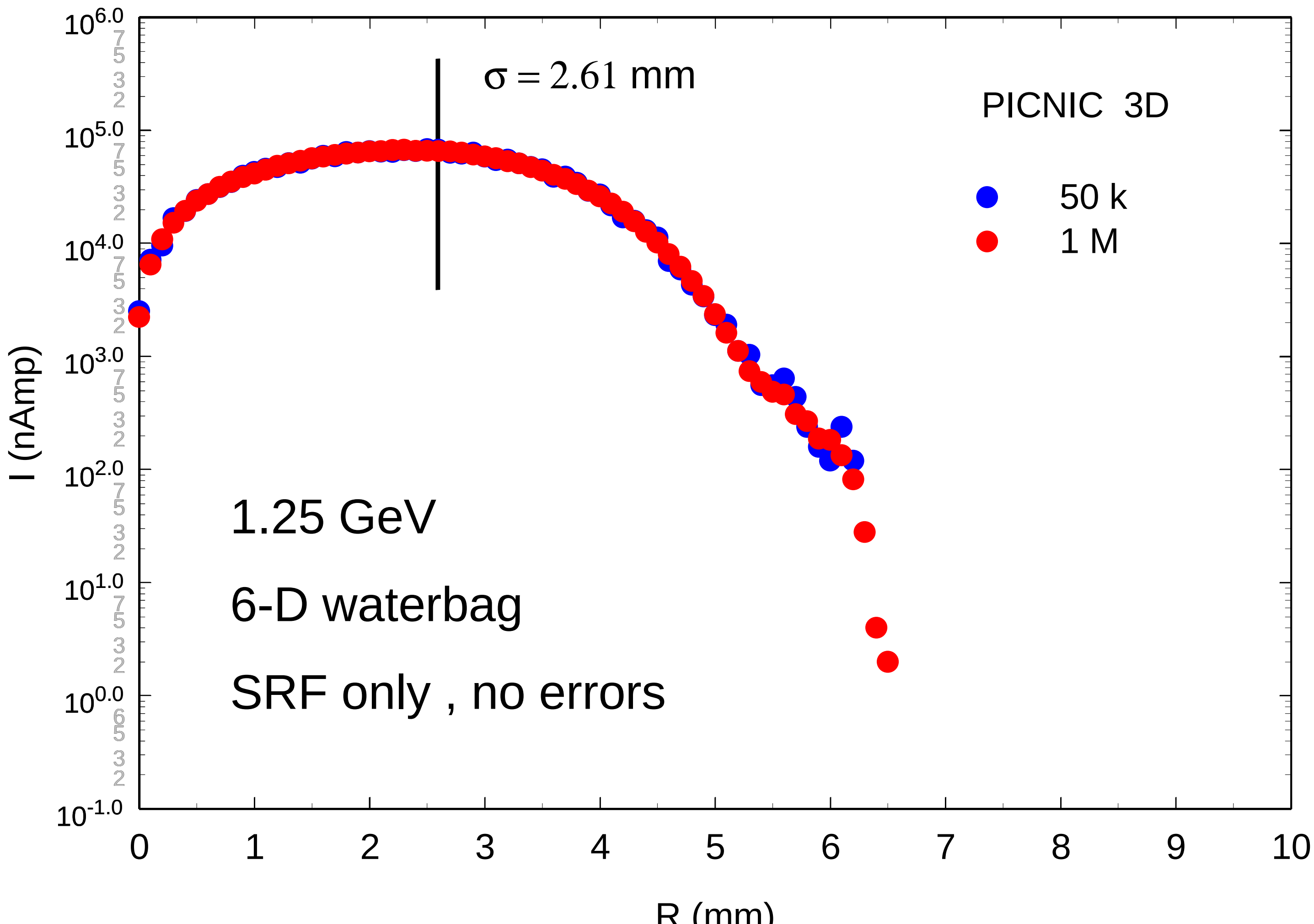
Real Space Projections at 1.25 GeV
SRF Only, Waterbag Initial Distribution



Simulations Differ at the 100 nA Level in the Distribution but Not in the Extent



Small & Large Distributions Yield Consistent Results



Linac Beam Dynamics Studies

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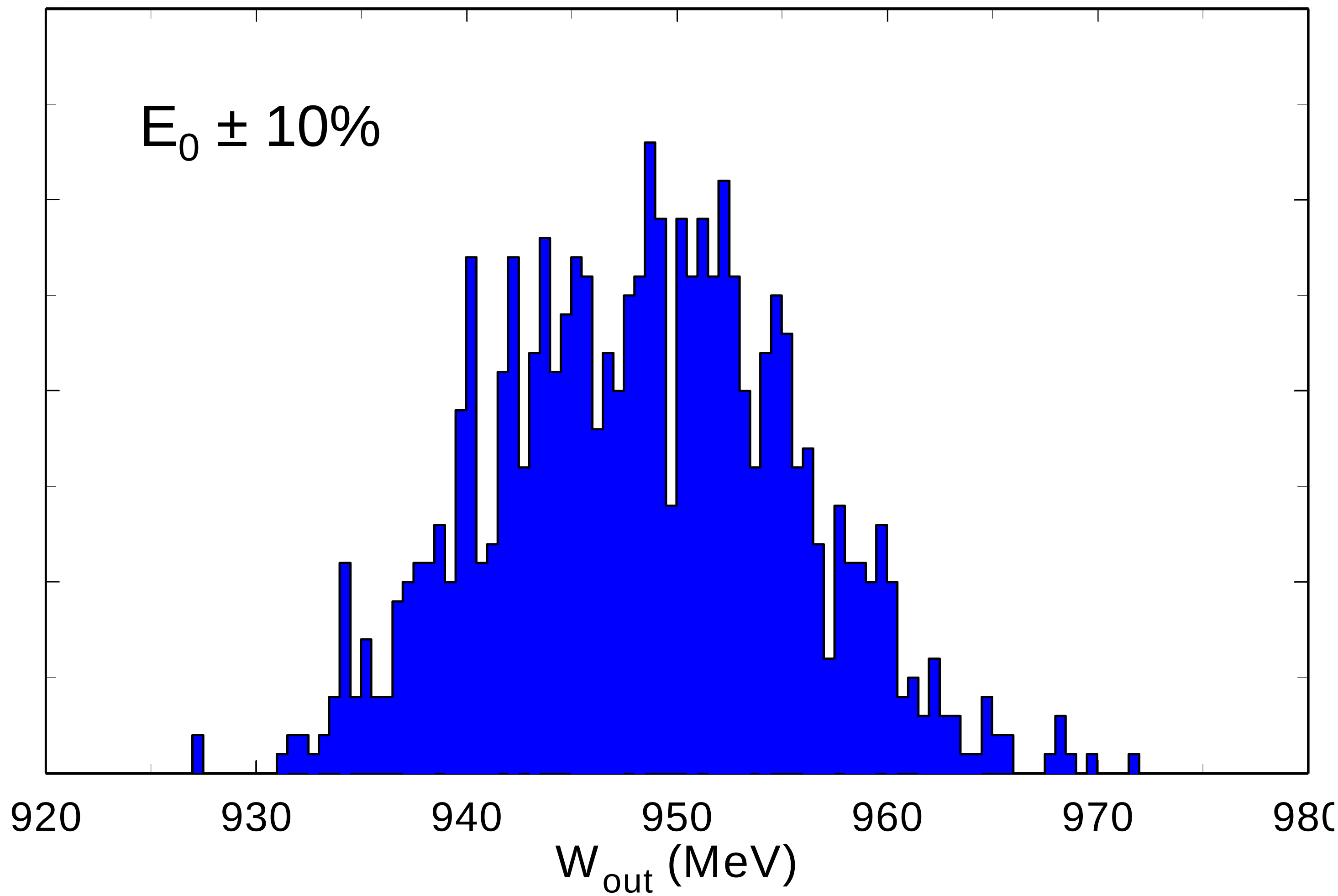
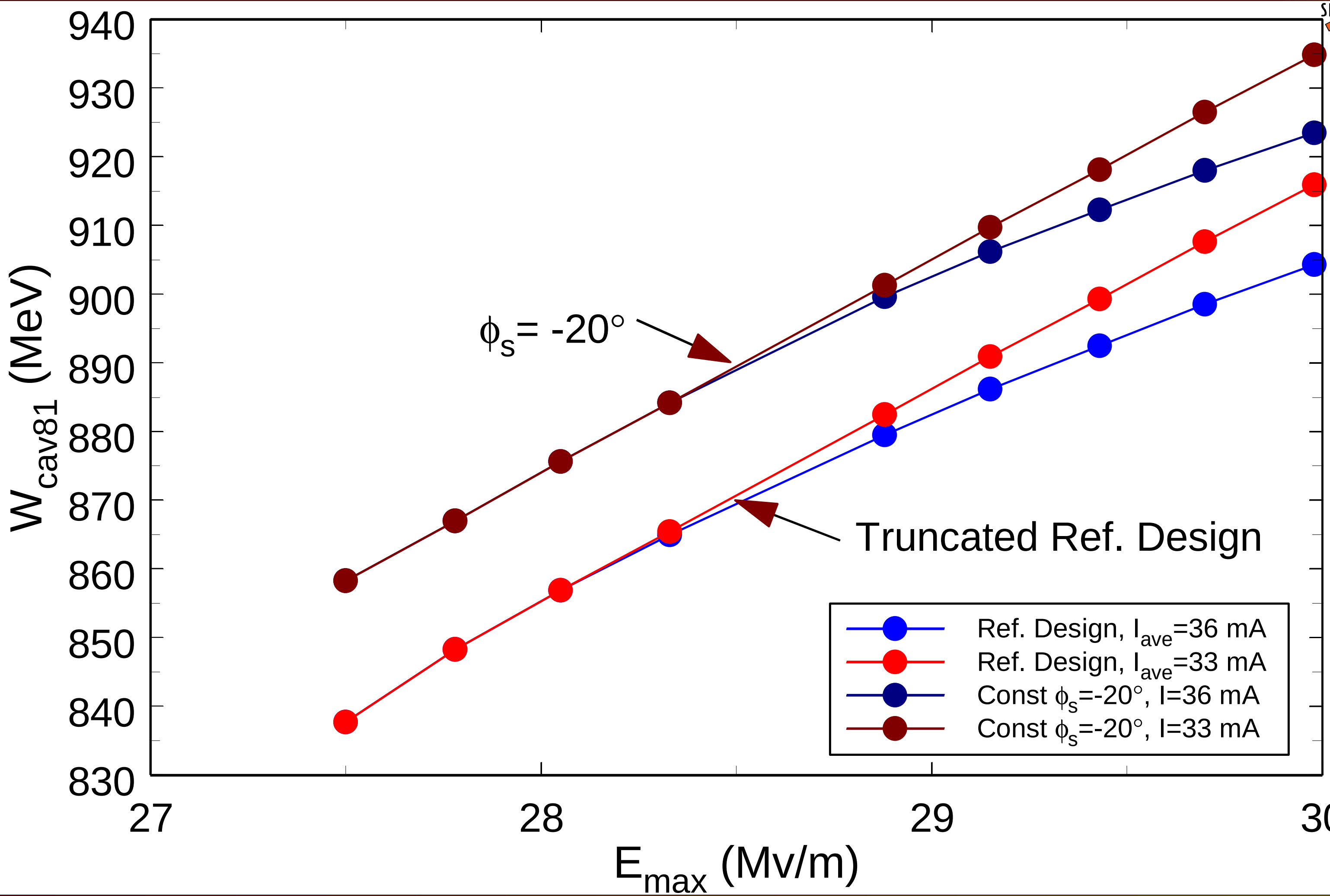
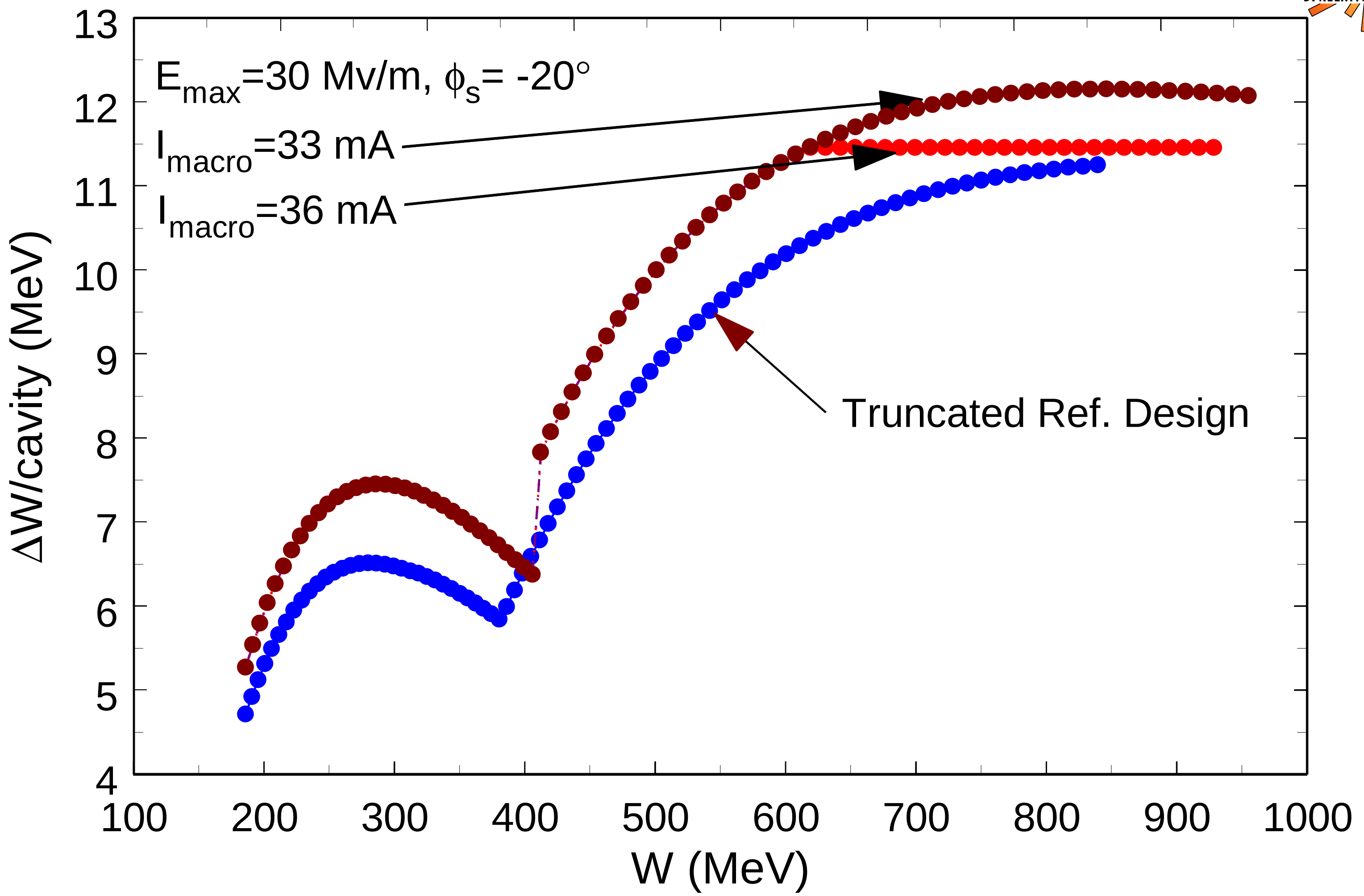
The Expected W_{final} is a Function of SRF Cavity Quality



Better Cavities & Alternate Phase Laws May Improve the Truncated Design



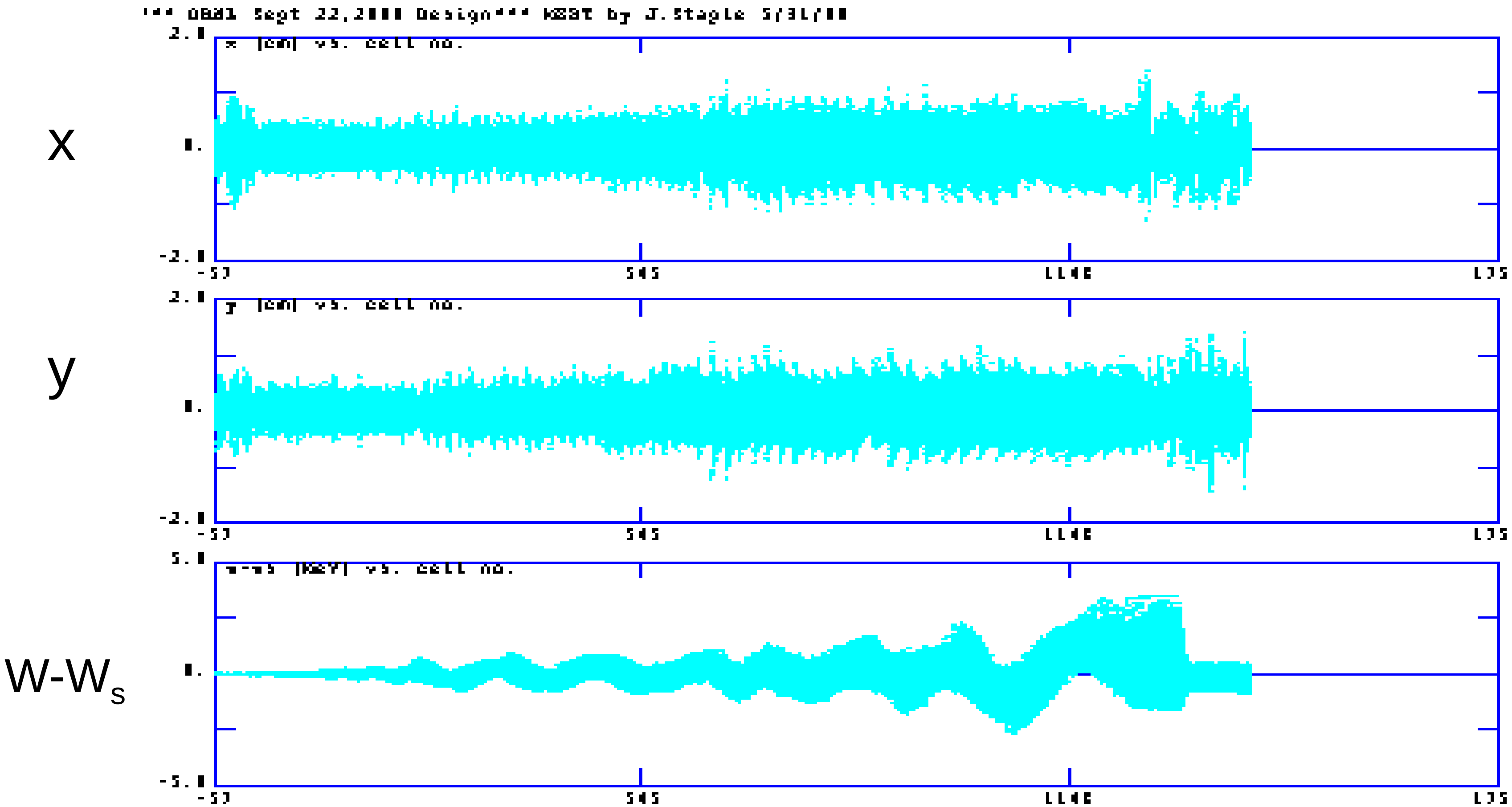
Energy is Limited by Beam Current at Higher Gradients



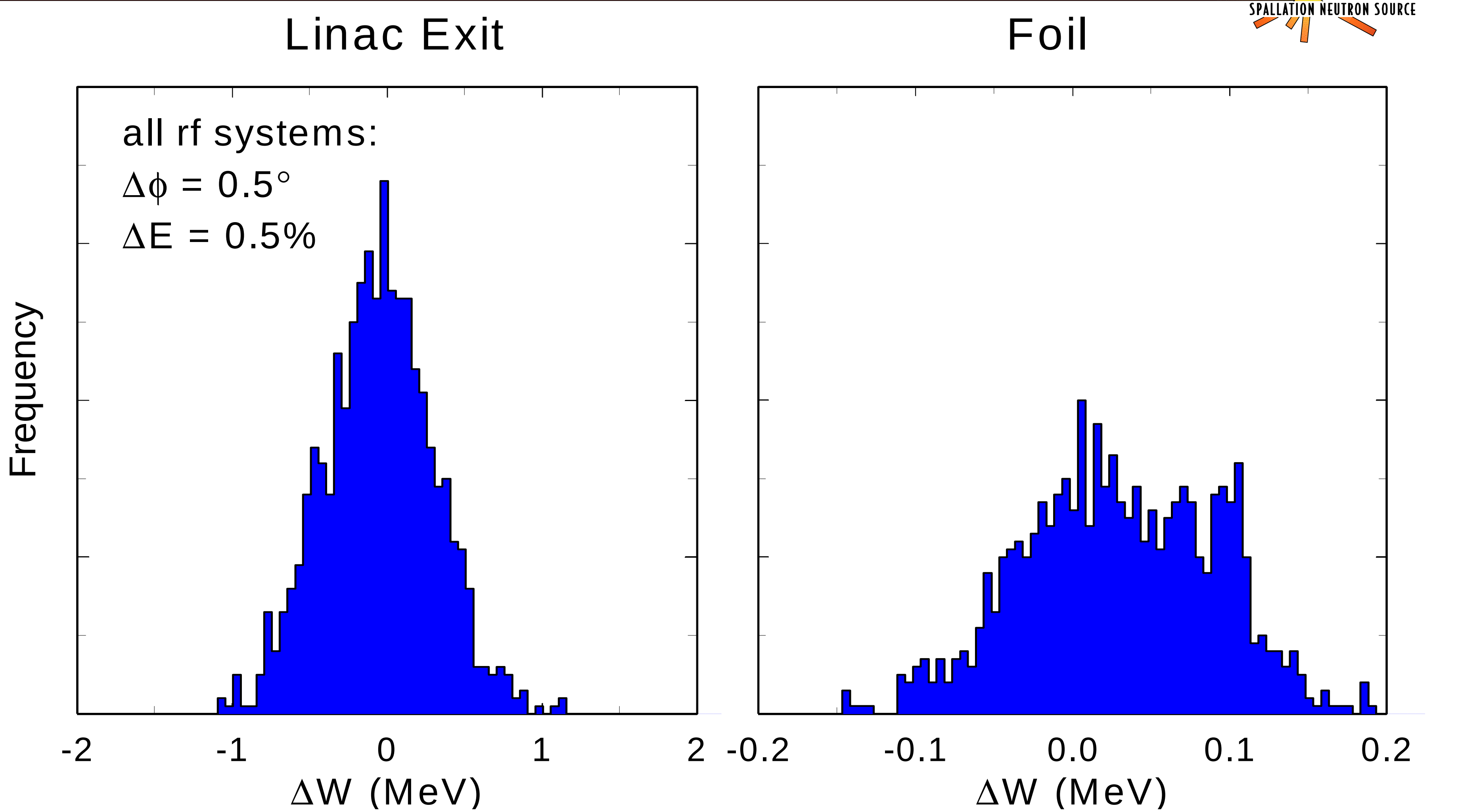
Some Reference Design Performance Criteria

- W_{final} = 840 - 1300 MeV
- W_{final} stability < ±2.2 MeV
- W_{final} spread < ±0.33 MeV (rms)
- ε_{foil} < 0.50 π mm mrad (rms, norm)
- Beam centroid stability at foil < ±0.2 mm
- Protons missing foil < 2%
- Beam loss < 1 W/m

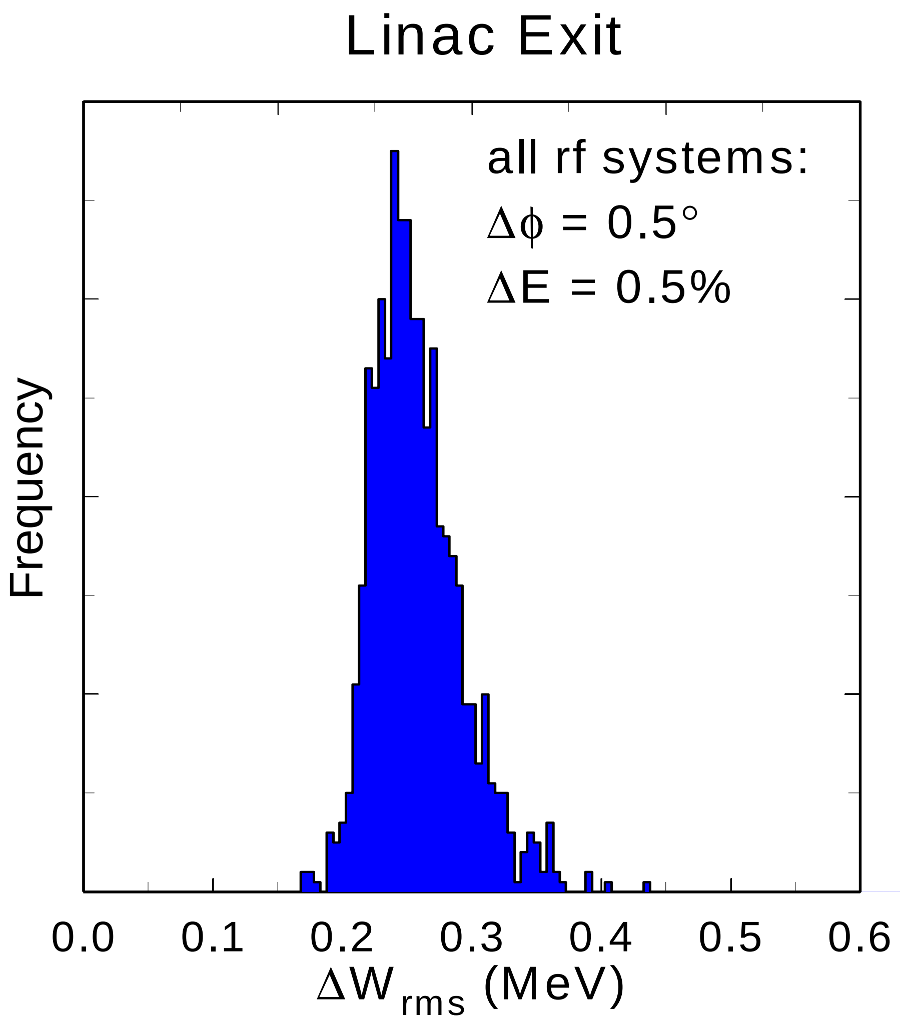
Typical Beam Profile, All Errors Except Quad Displacements

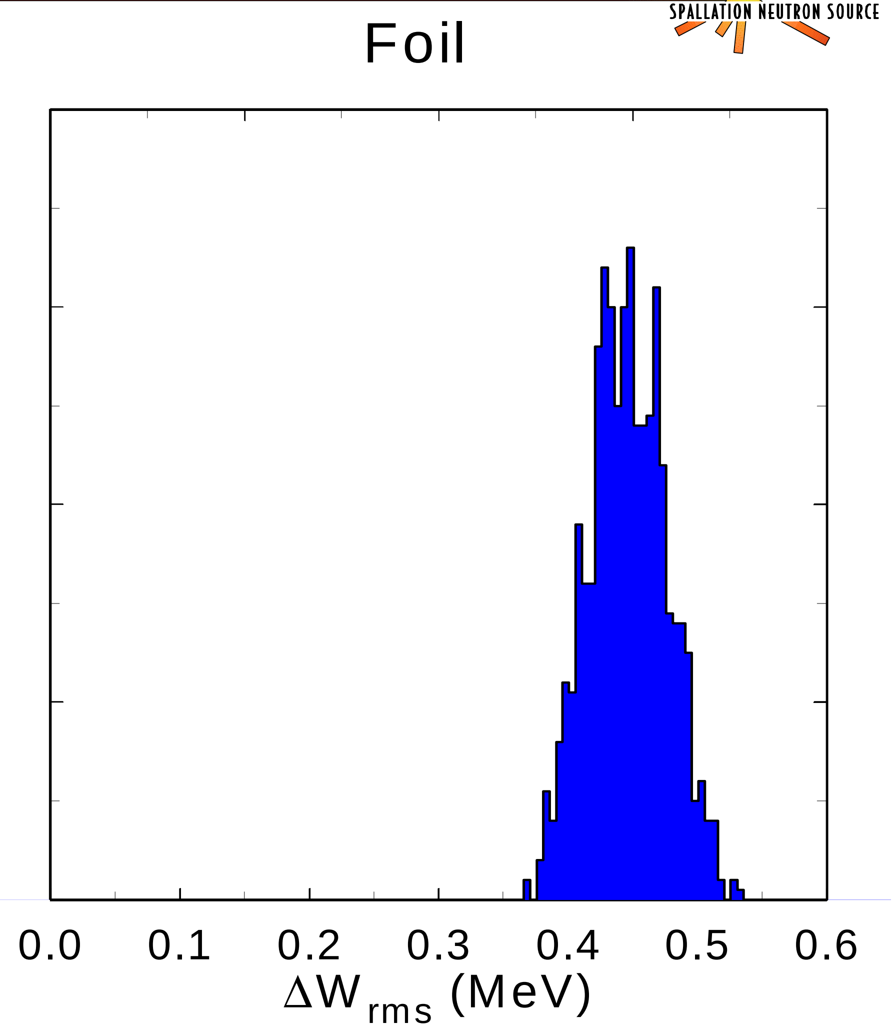


Energy Jitter is a Function of RF Control Tolerances & Meets Spec.

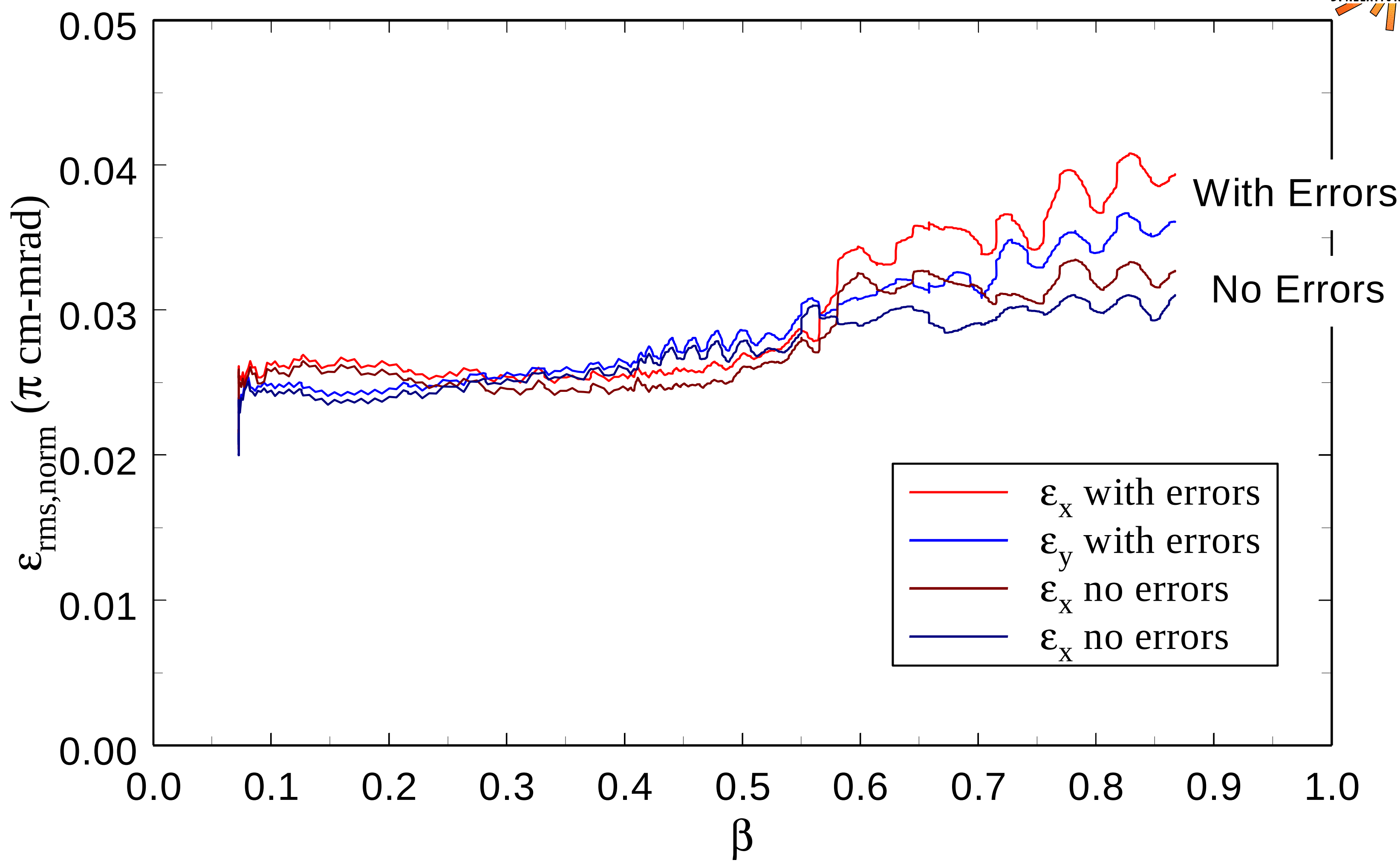


The Expected Energy Spread Meets Spec.

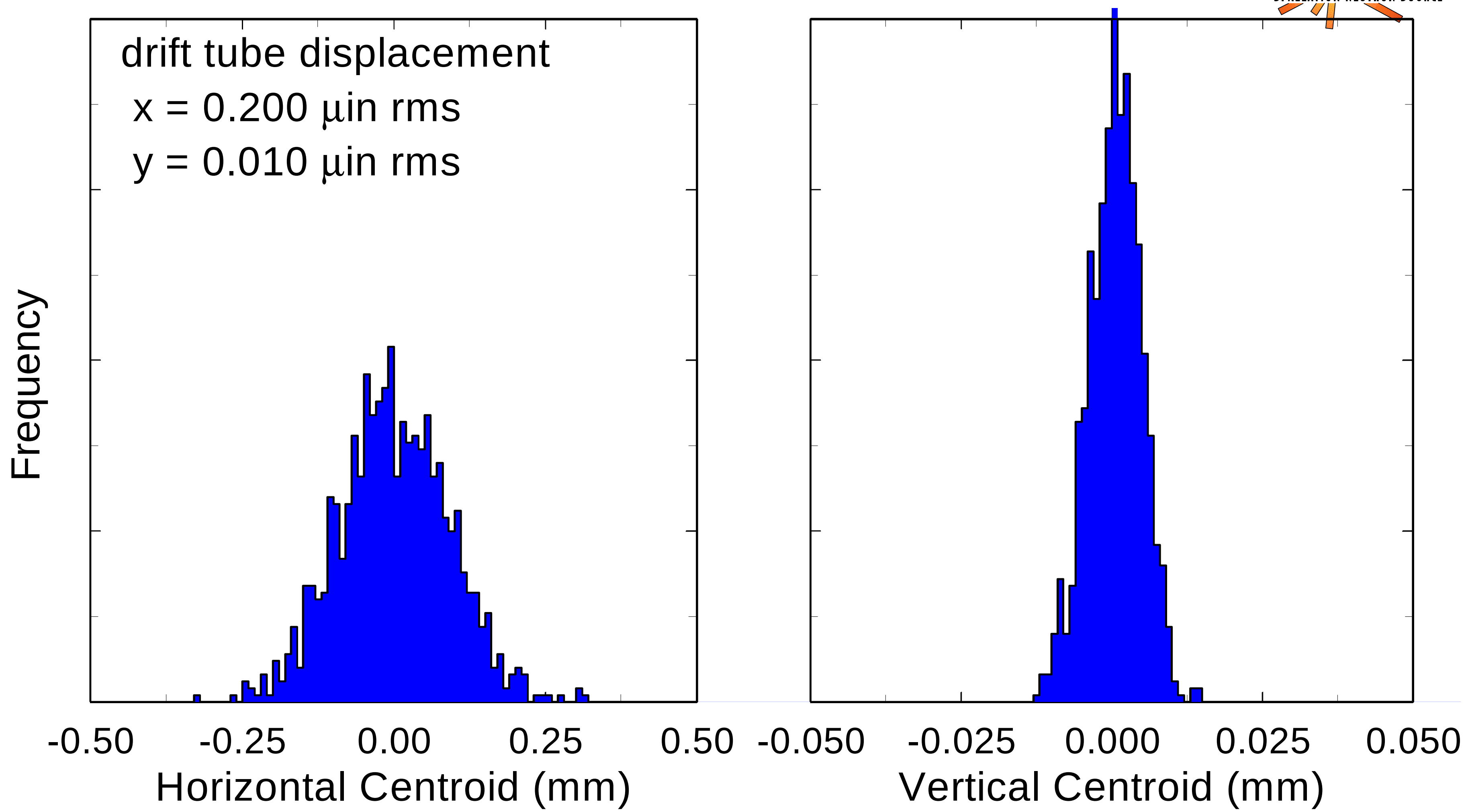




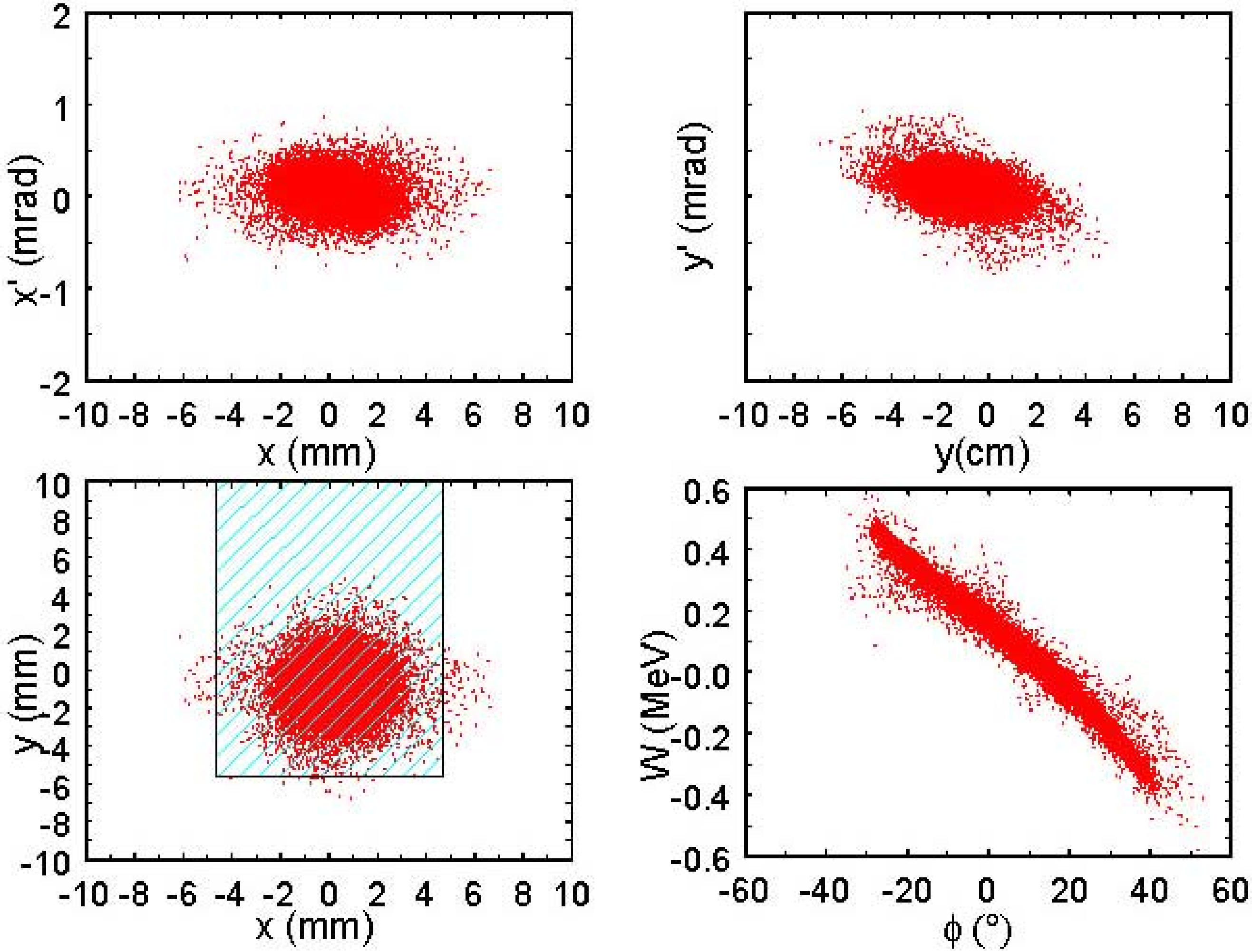
rms Emittance Profiles With & Without Errors, Excluding Misalignments



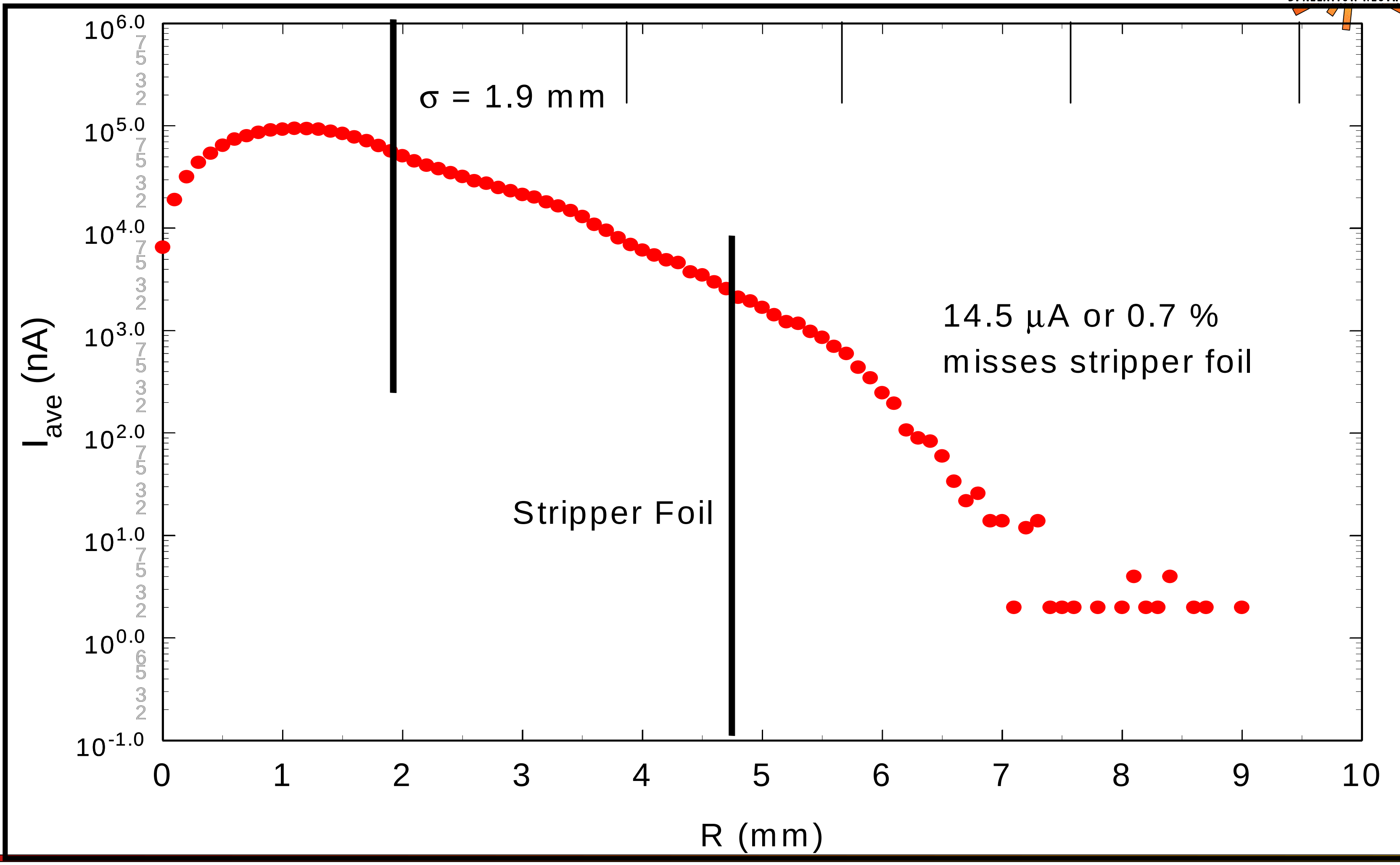
Transverse Jitter at the Foil is a Function of Drift Tube Vibrations & Meets Spec.



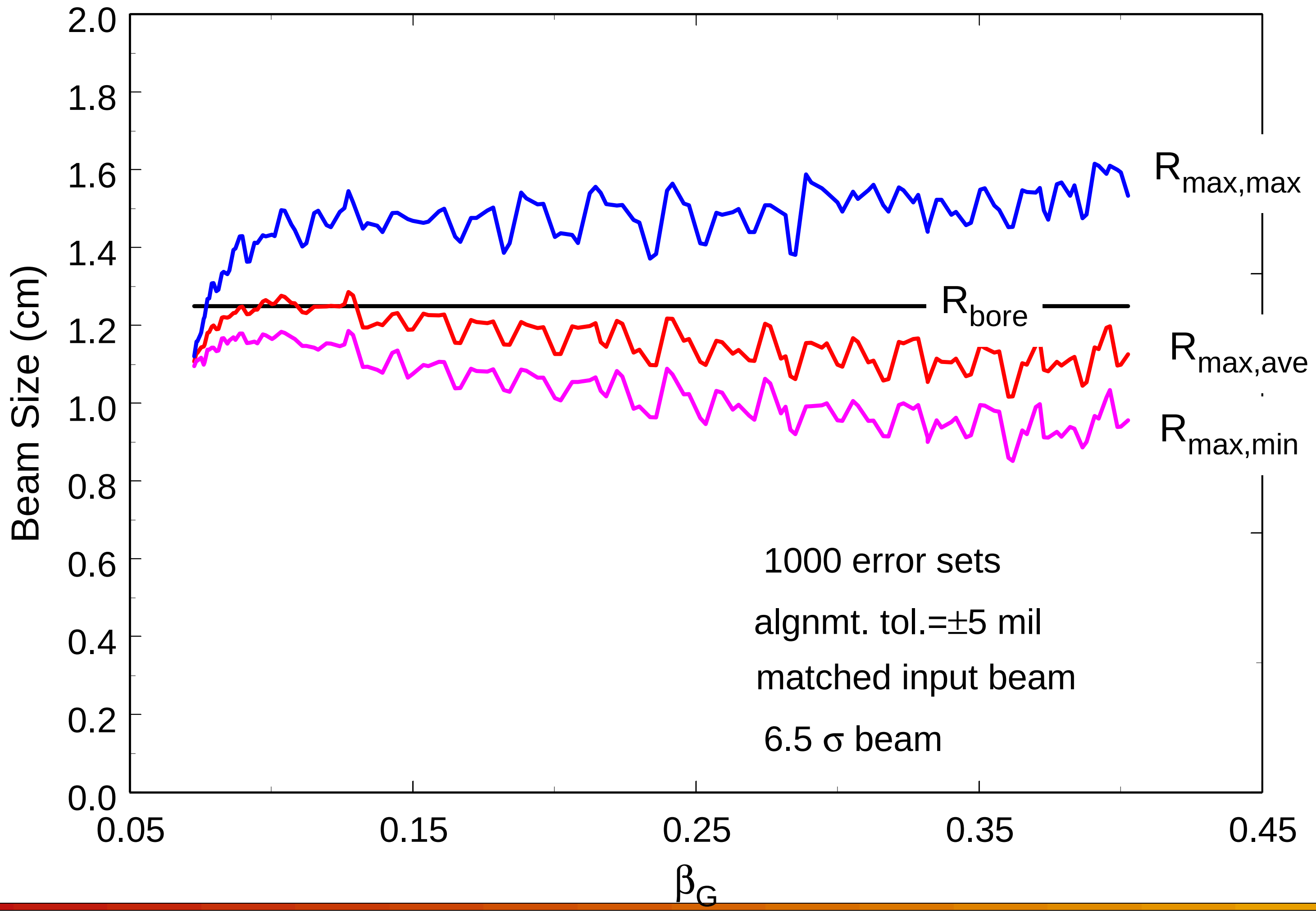
Beam Phase-Space Projections at the Foil



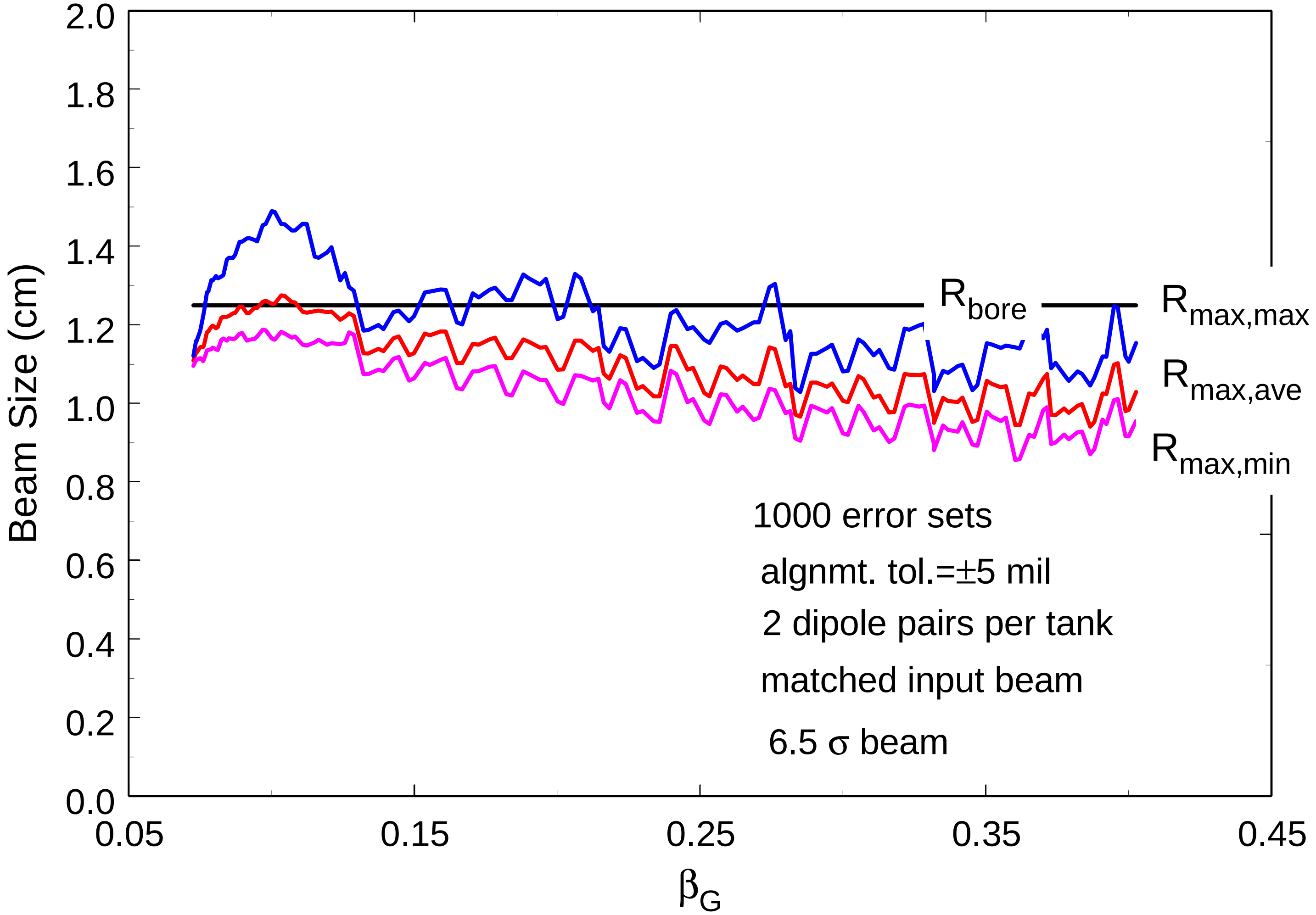
Expected Proton Fraction Missing the Foil (with Errors) Meets Spec.



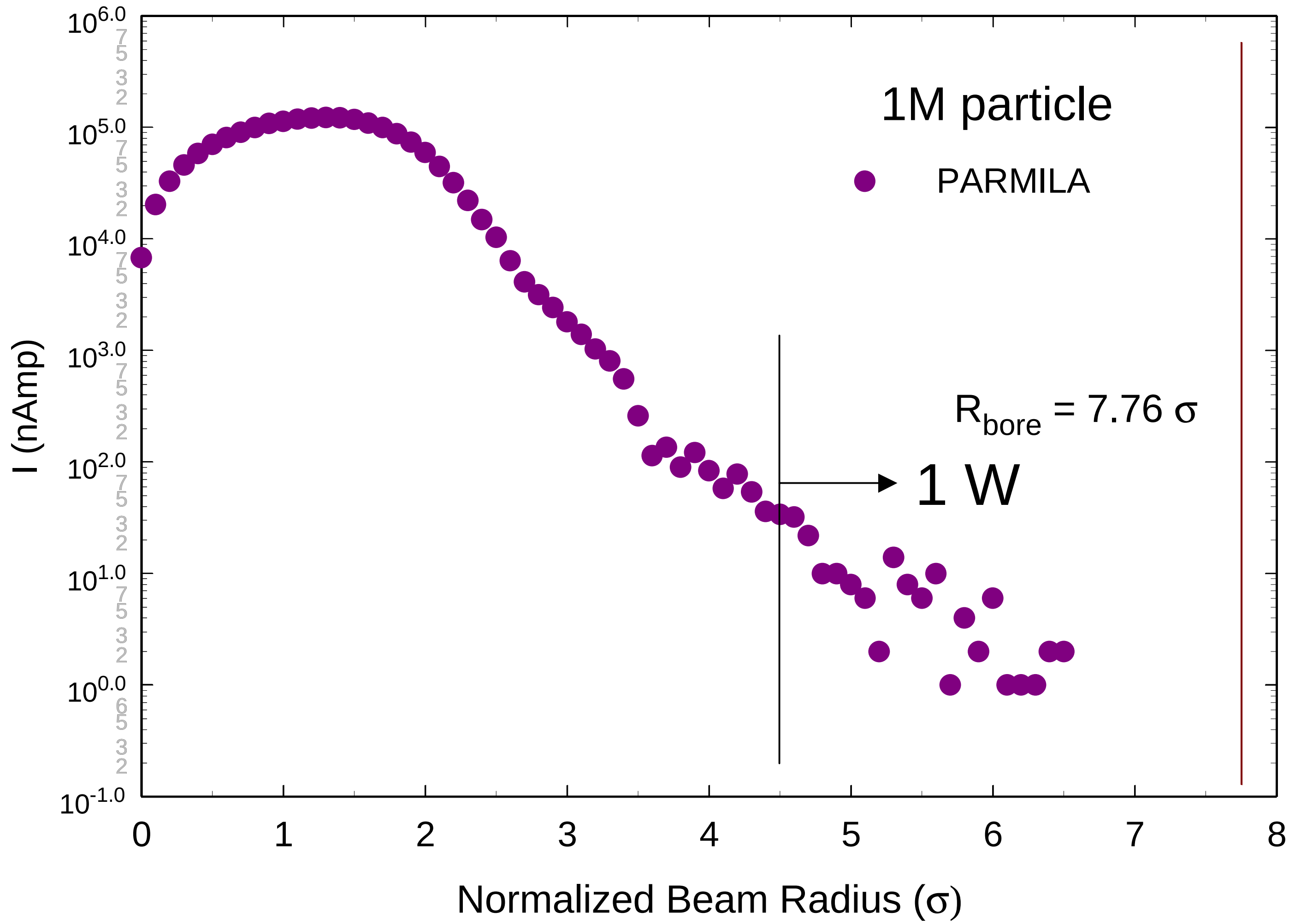
Maximum Beam Excursions are a Function of Drift Tube Alignment



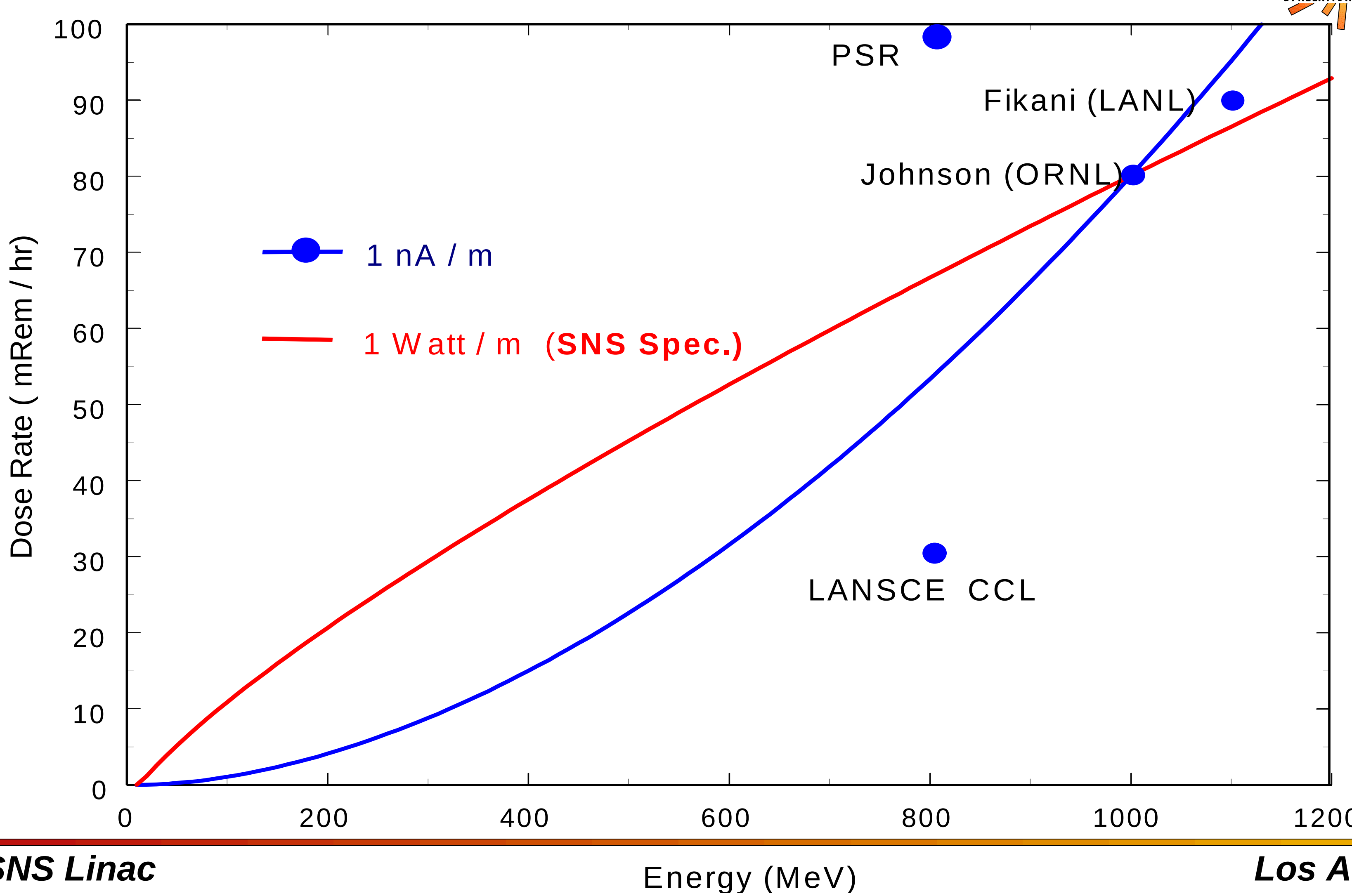
Beam Steering Uses 4 Dipoles & 2 BPMs in Each Tank



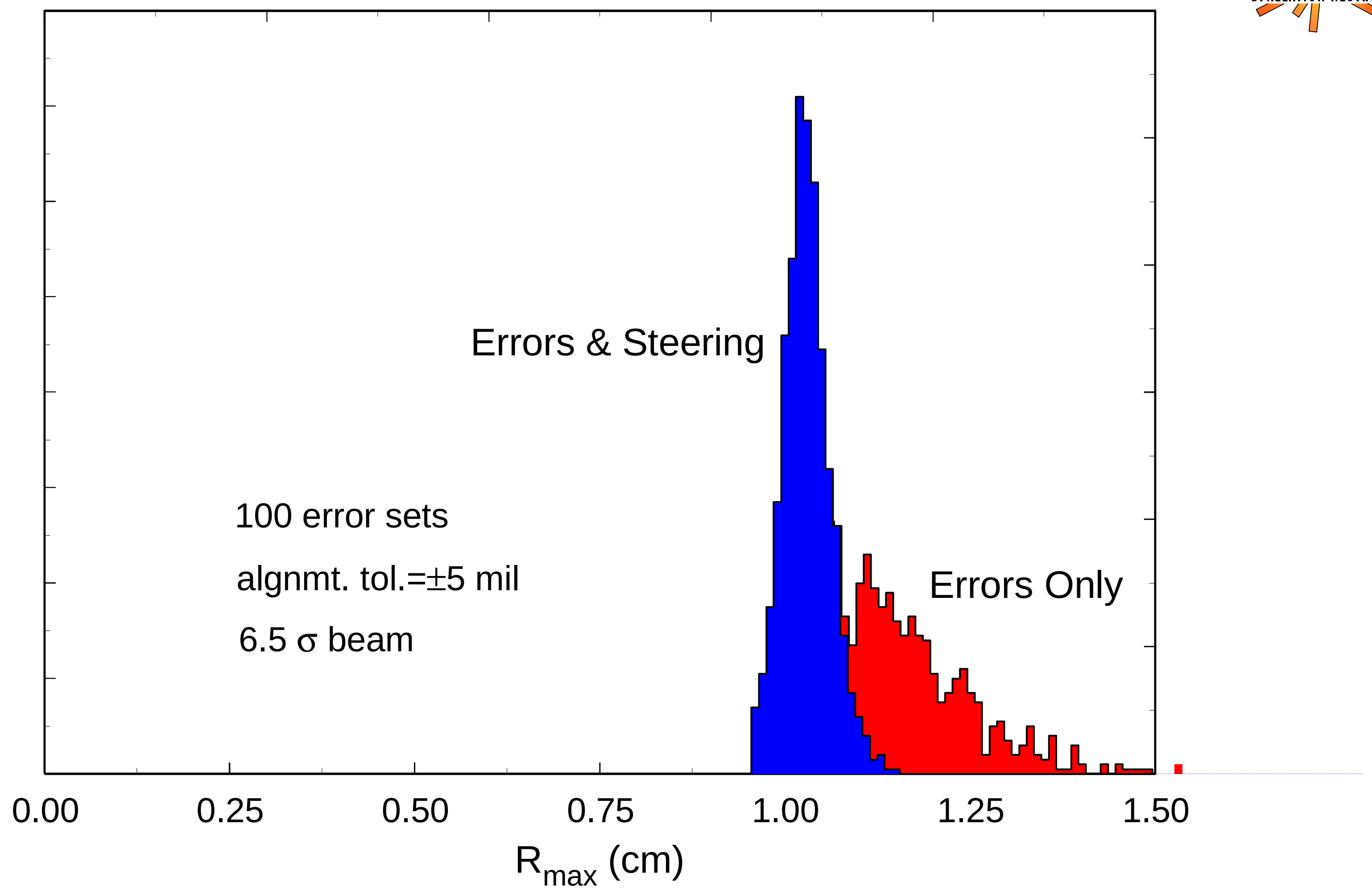
We Can Scrape Beam at the 4.5 σ Level and Still Meet the Loss Criteria



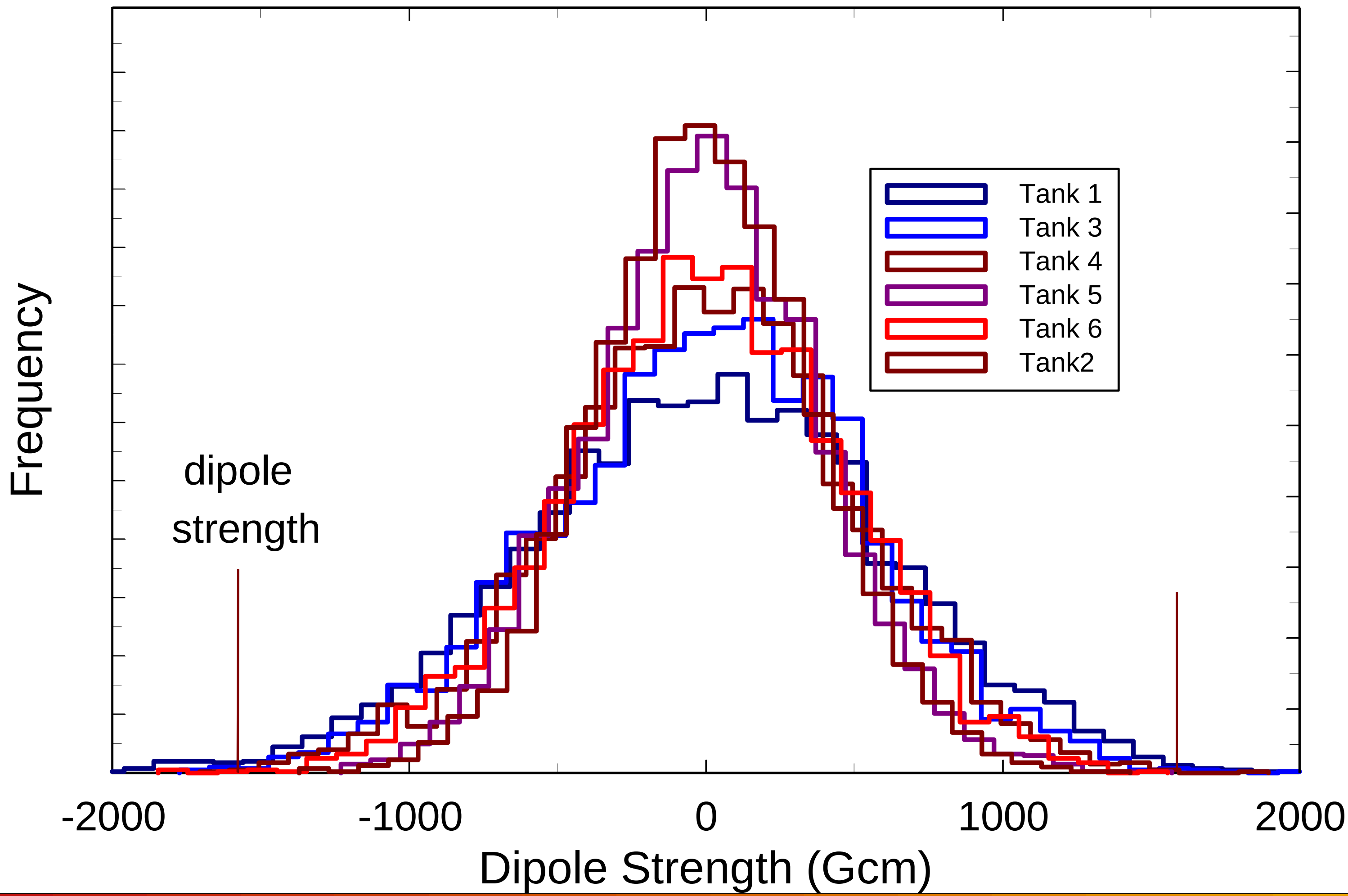
Beam Spill Induced Activation: Dose Rate at 1 ft after 4 Hours



Expected R_{max} at the DTL Exit



Expected Distribution of Dipole Strengths



Status of Linac Design & Beam Simulation Studies

- The linac design is mature
- Many performance requirements can be met
- Suitable steering algorithms have been selected and incorporated into simulation codes
- Error studies with steering are underway
  - full error set pending rf tuning algorithms
- DTL & CCL phase & amplitude set-point algorithms under study
- Alternate SRF parameters under study
- Improved interface matching & mismatch studies pending
- Beam dynamics workshops scheduled in Spring & Summer
- Addressing commissioning issues is high priority