SNS Division Review Committee

Linac Physics

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Assignment: Physics Design of the Complete SNS Linac

- End-to-end beam physics design
  - from the MEBT to the HEBT
- Design all room-temperature cavities
  - SRF cavity design contracted to INFN, Milano
- Detailed beam performance simulations
- Define mechanical requirements & tolerances
- Define rf power & control requirements
- Define magnet & diagnostics requirements
- Develop commissioning scenarios
- Participate in beam commissioning (?)

Linac Performance Specs are Still a Moving Target

- Room temperature design — Oct 99
  - 2 MW, 1 GeV & 56 mA peak current
- Superconducting Design — March 00
  - 2 MW+, 1.3 GeV & 52 mA
- Reference Design — June 00
  - 950 MeV & 52 mA
- Cost Constrained Design — Dec 00
  - 600 kW, 840 MeV & 37-51 mA
- Design is converging to consistent upgradable scenario

Some Reference Design Constraints

- Frequency = 402.5 & 805 MHz
- Linac shall be predominately SRF
- I_{peak}= 1 - 52 mA
- W_{final} upgradable to 1.3 GeV
- Beam duty factor = 6%
- $\varepsilon_{initial} \approx 0.20\ \pi$ mm mrad (rms, norm) at 2.5 MeV

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
- Beam loss < 1 W/m

Reference Linac Architecture Summary

Structure	W final	Total Length	Cells per Cavity	Cavities per Module	Modules	No of Klystrons	Structure Length
	MeV	m					m
DTL	86.8	36.6	60 to 21		6	6	36.6
CCL	185.6	91.9	8	12	4	4	55.4
SRF I	378.8	157.7	6	3	11	33	64.2
SRF II	968.6	276.0	6	4	15	59	118.4
SRF upgrade	1248.4	323.4	6	4	6	25	47.3

Structure	HVPS	HVPS Power	Transmitters	Klystrons	Klystron Power
		MW			MW
RFQ & DTL	3	10	7	7	2.5
CCL & HEBT	5	10	6	6	5.0
SRF I & II	8	10	16	92	0.55
SRF upgrade	3	10	5	25	0.60

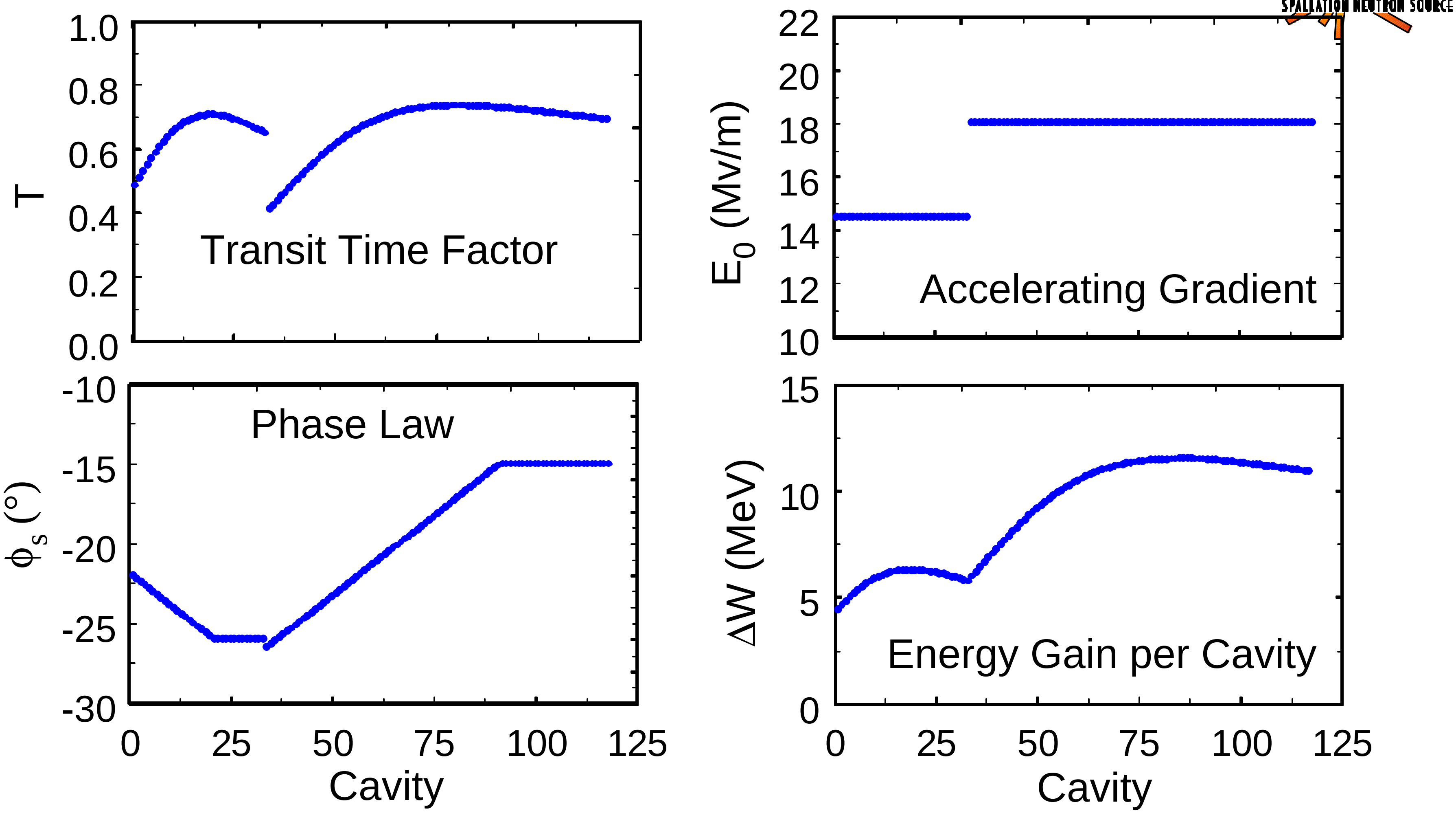
Some Normal Conducting Linac Design Features

- DTL at 402.5 MHz
  - All permanent magnet quadrupole focused, constant GL, sorted
  - 6 $\beta\lambda_{402.5}$ focusing period, FF0DD0 lattice
  - Steering dipoles & diagnostics in empty drift tubes
  - 1 $\beta\lambda$ between tanks to minimize mismatches
  - Beam is adiabatically matched longitudinally
    - E_0 ramped in tanks 1, 2 & 6
    - ϕ_s ramped down in tank 6
- CCL at 805 MHz
  - 13 $\beta\lambda_{805}$ focusing period matches phase advance in DTL
  - Quads are ramped down in module 4 to match phase advance in SRF + matching

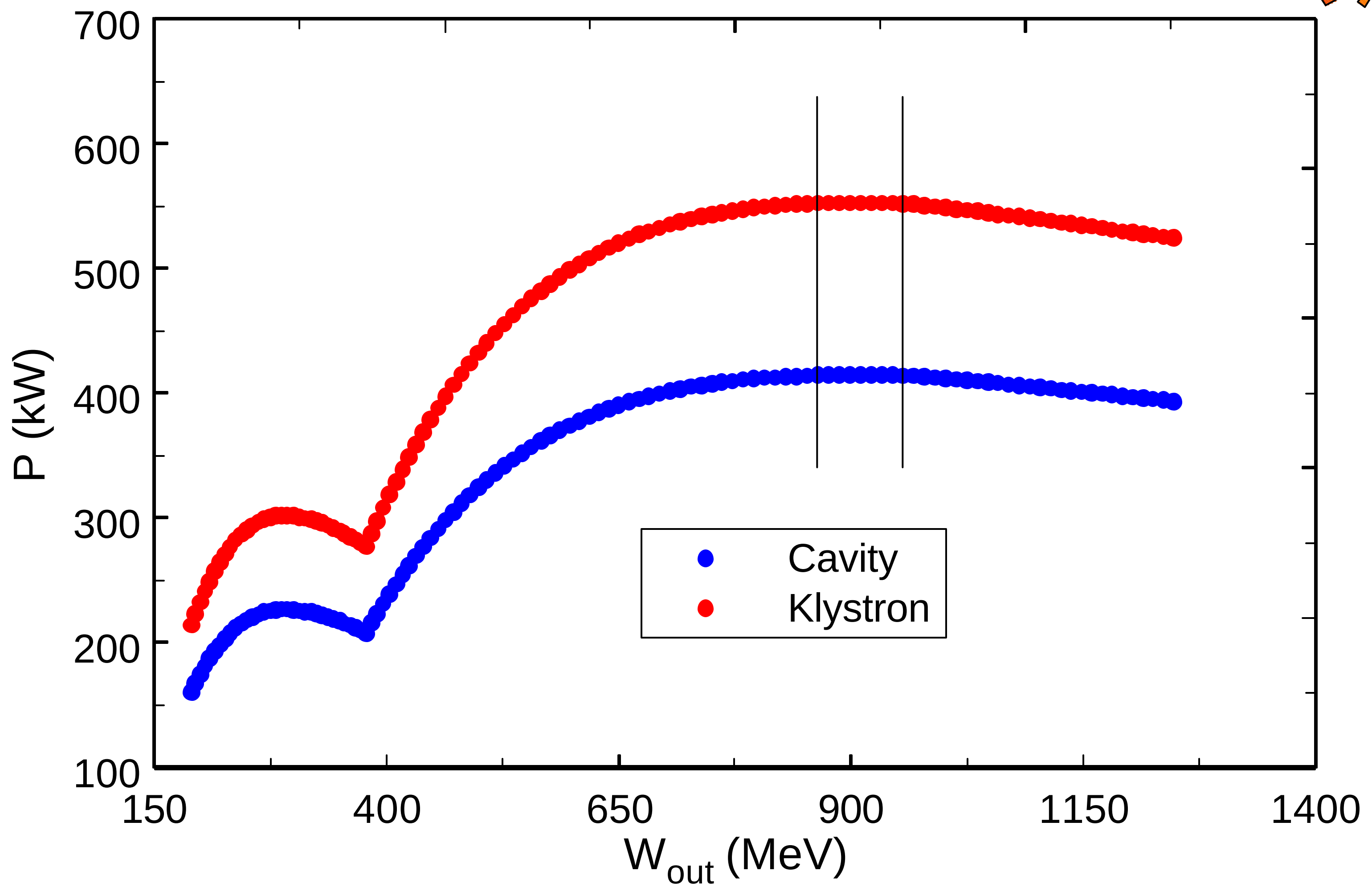
SRF Design is Based on 2 Cavity bs

- $E_{max} \leq 27.5$ MV/m, peak surface electric field
- Optimized for cost with 2 β cavities
  - 3rd lower-β cavity would be too numerous, inefficient & costly
- $\beta_1 \equiv 0.61$
  - based on earlier 2-cavity optimization studies by Wangler & Nath
  - 5 MW CCL modules coarsely quantize initial energy
- $0.74 \leq \beta_2 \leq 0.82$
  - higher β provides more efficient acceleration
    - i.e. higher E_0, T & L_{cav}
  - if $E_{max} > \langle E_{max} \rangle$, higher β supports a higher W_{final}
- Transition energy
  - maximized final energy for fixed cost machine

SRF Linac Reference Design Assumes E_{max}=27.5 MV/m



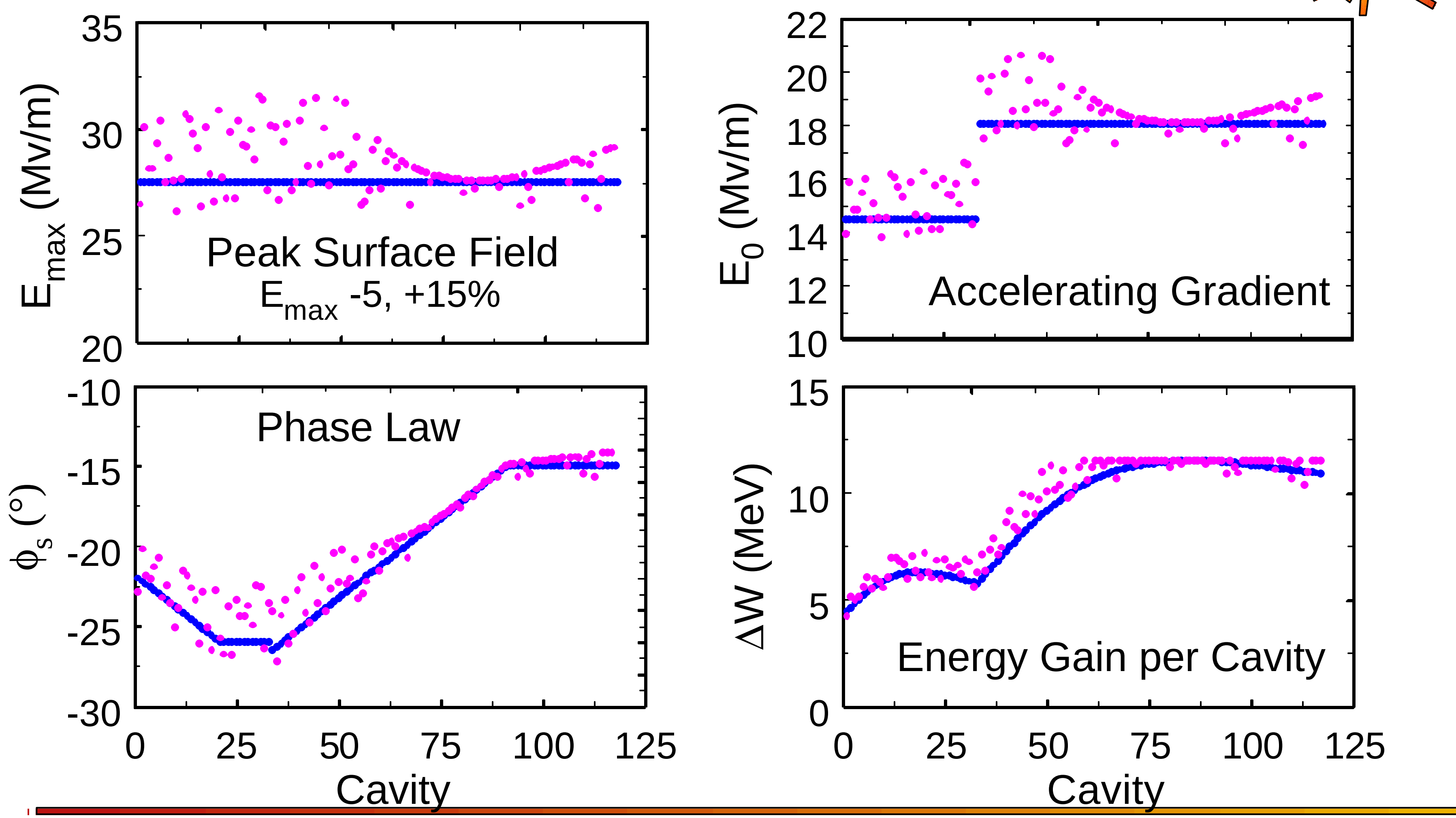
Beam Consumes 75% of Available rf Power



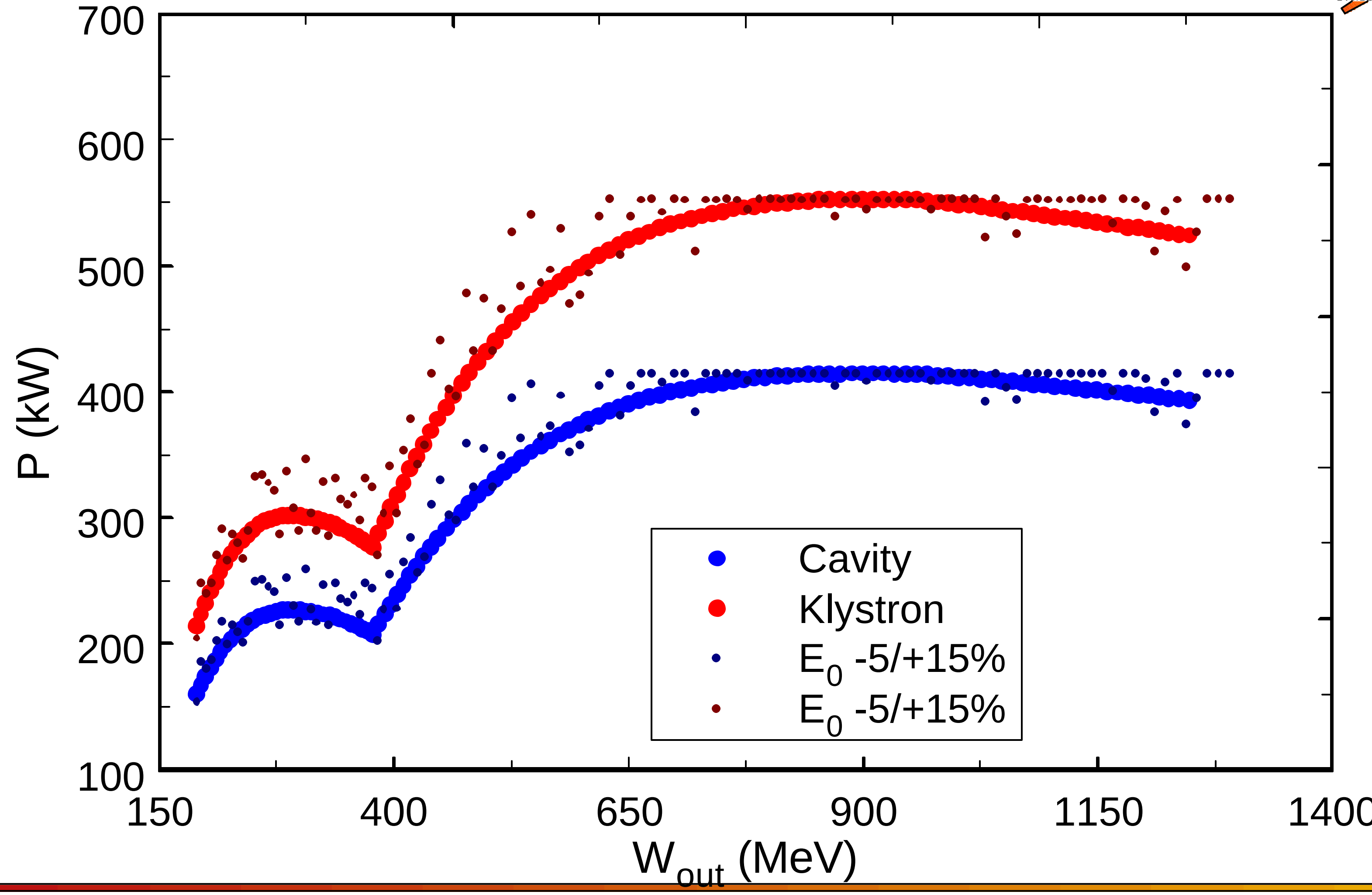
SRF Phase & Amplitude Set-Points Preserve Longitudinal Dynamics

- E_{max} determined at acceptance for each cavity
  - $\langle E_0 \rangle \approx E_{dsn} \pm 10\%$
- Calibrate cavity field probes
  - using drifting beam to excite cavities
- $E_{0,operating}$ established for each cavity
- Corresponding $\phi_{operating}$ derived for each cavity
  - preserving longitudinal dynamics
  - holding $k_{0,l}$ constant

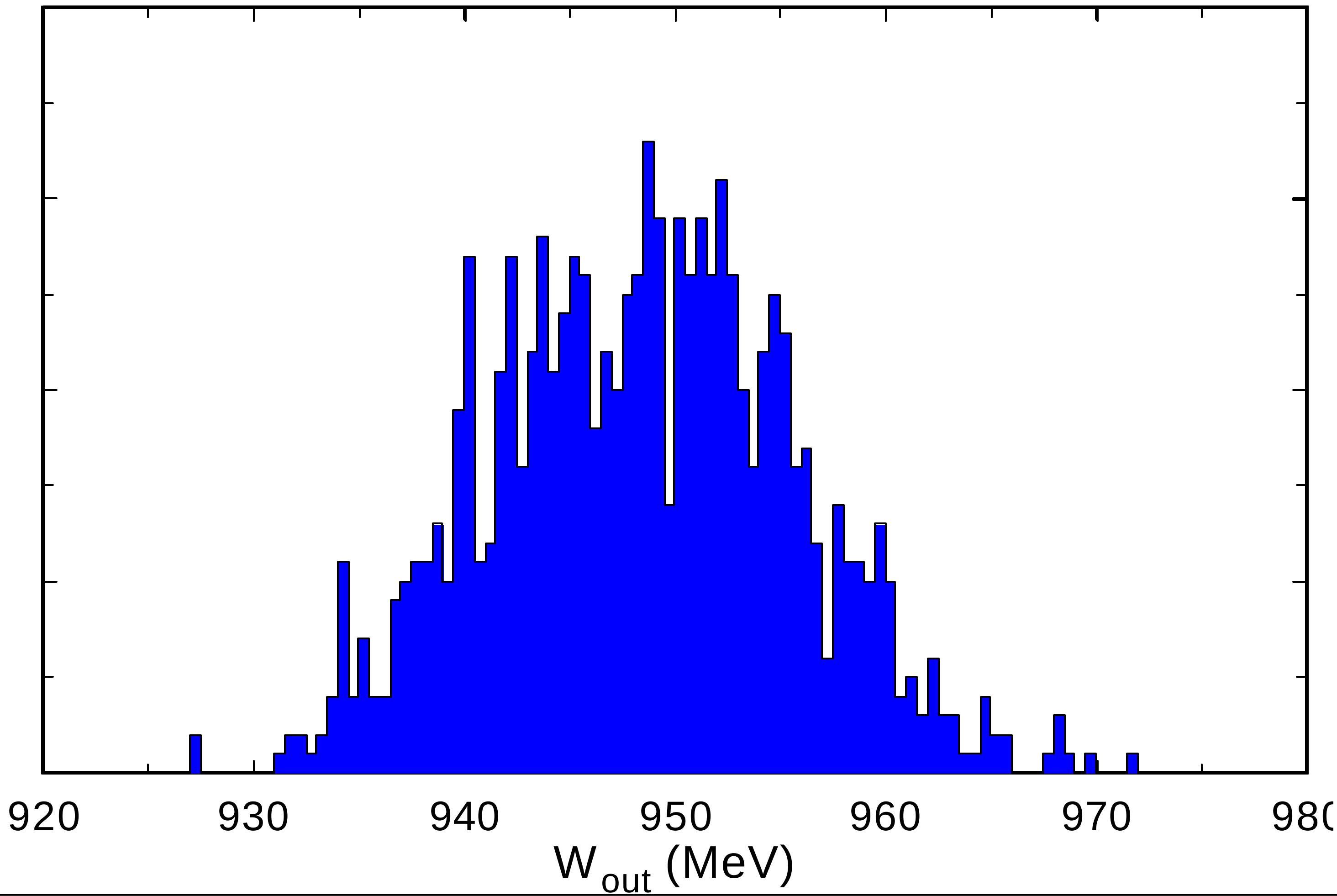
$\langle E_{max} \rangle = 27.5 \pm 10\%$
Cavities will not be Sorted



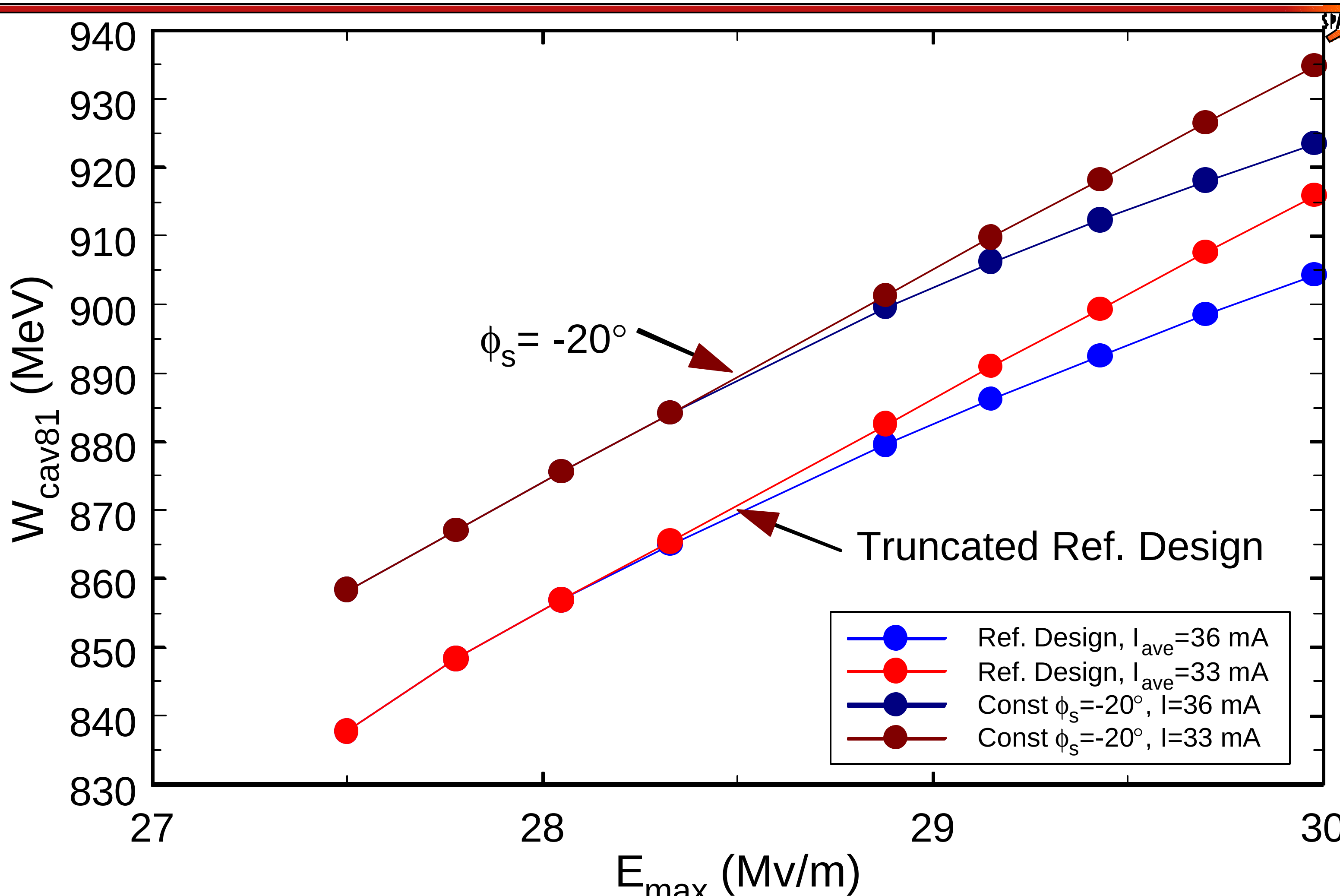
Most Efficient Part of the Linac is Limited by the Installed rf Power



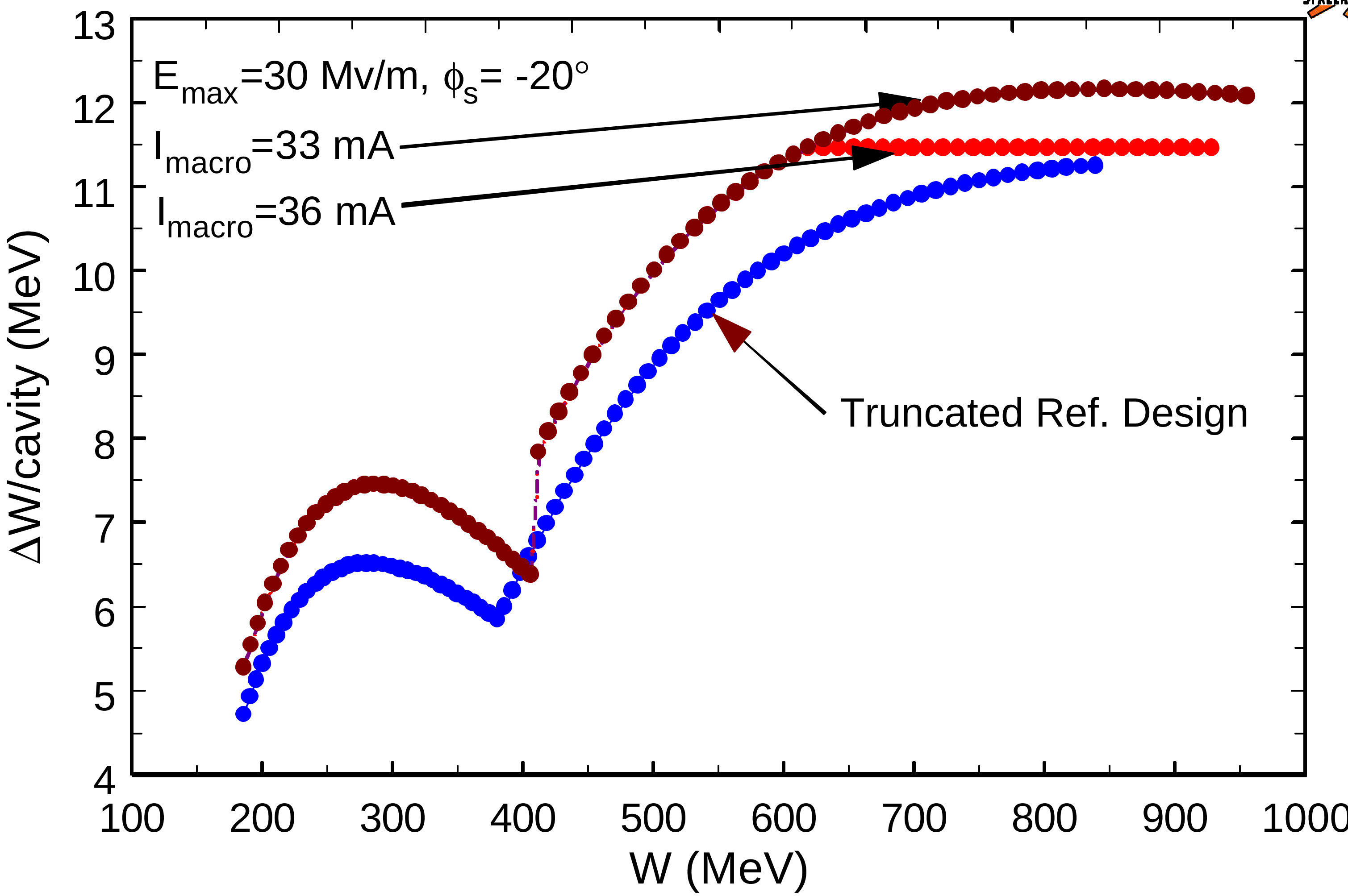
W_{final} is a Function of Cavity Quality



Better Cavities & Alternate Phase Laws May Improve Truncated Design



Energy is Limited by Beam Current at Higher Gradients



Some Reference Design Performance Criteria

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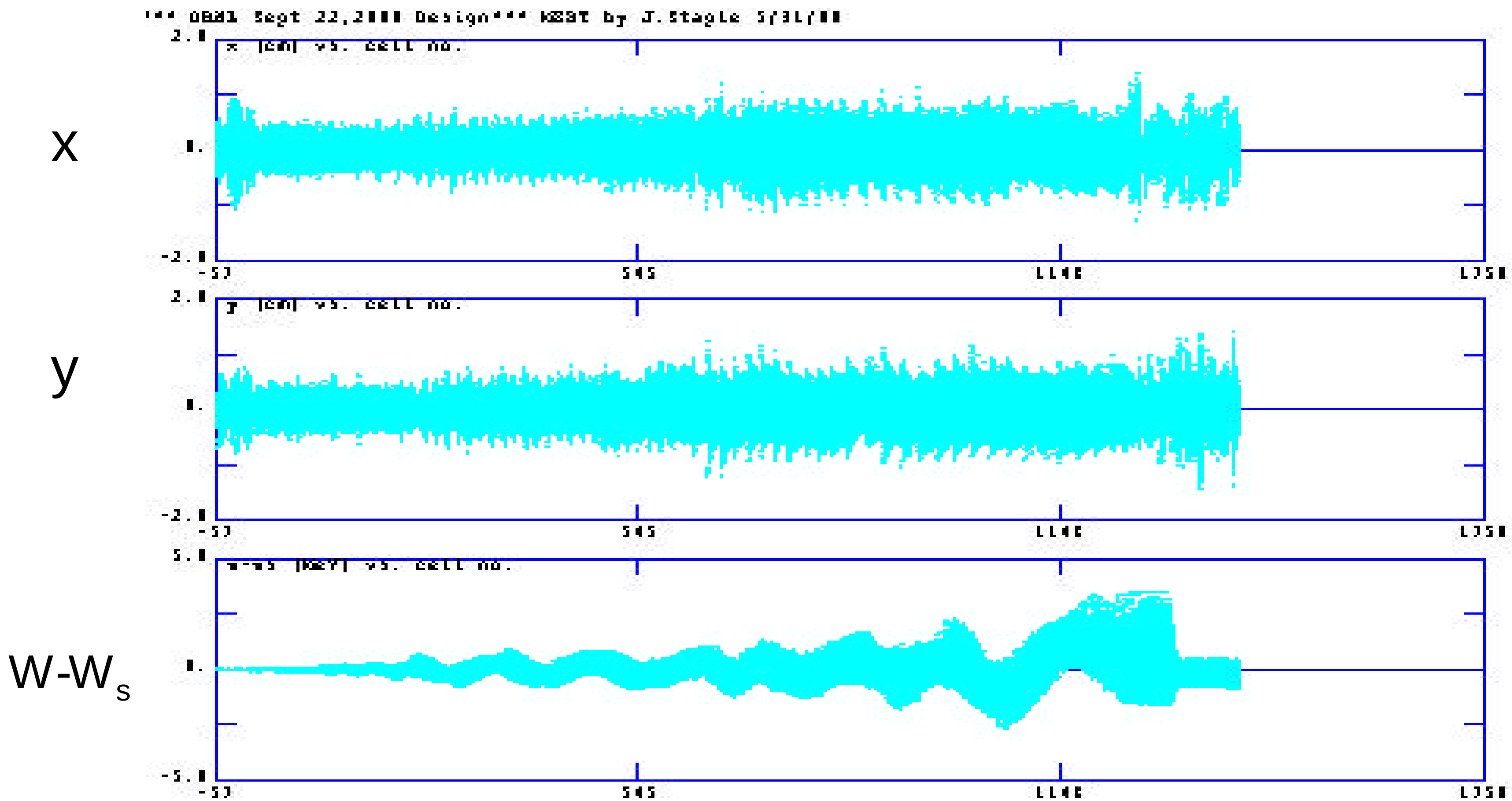
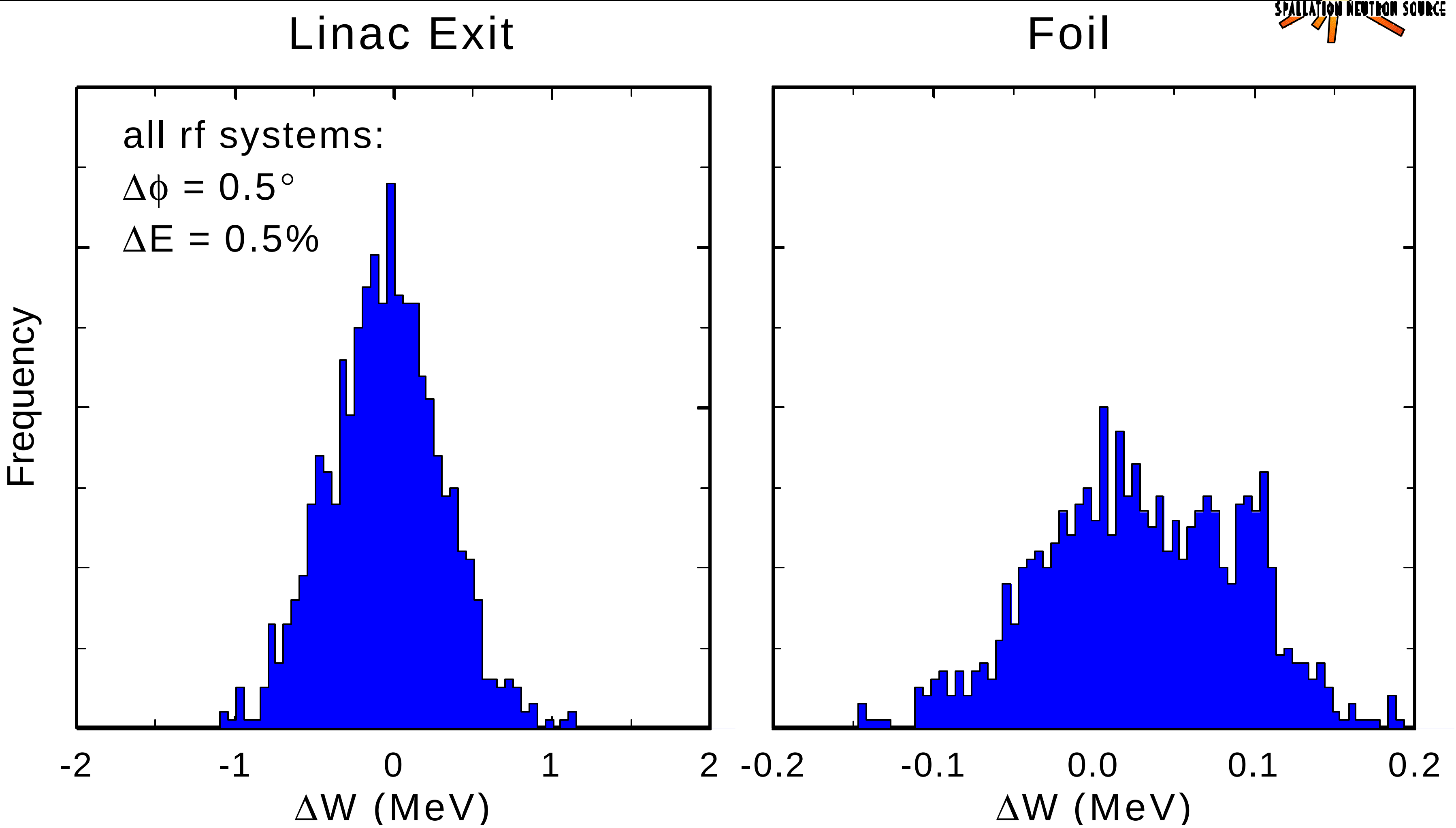
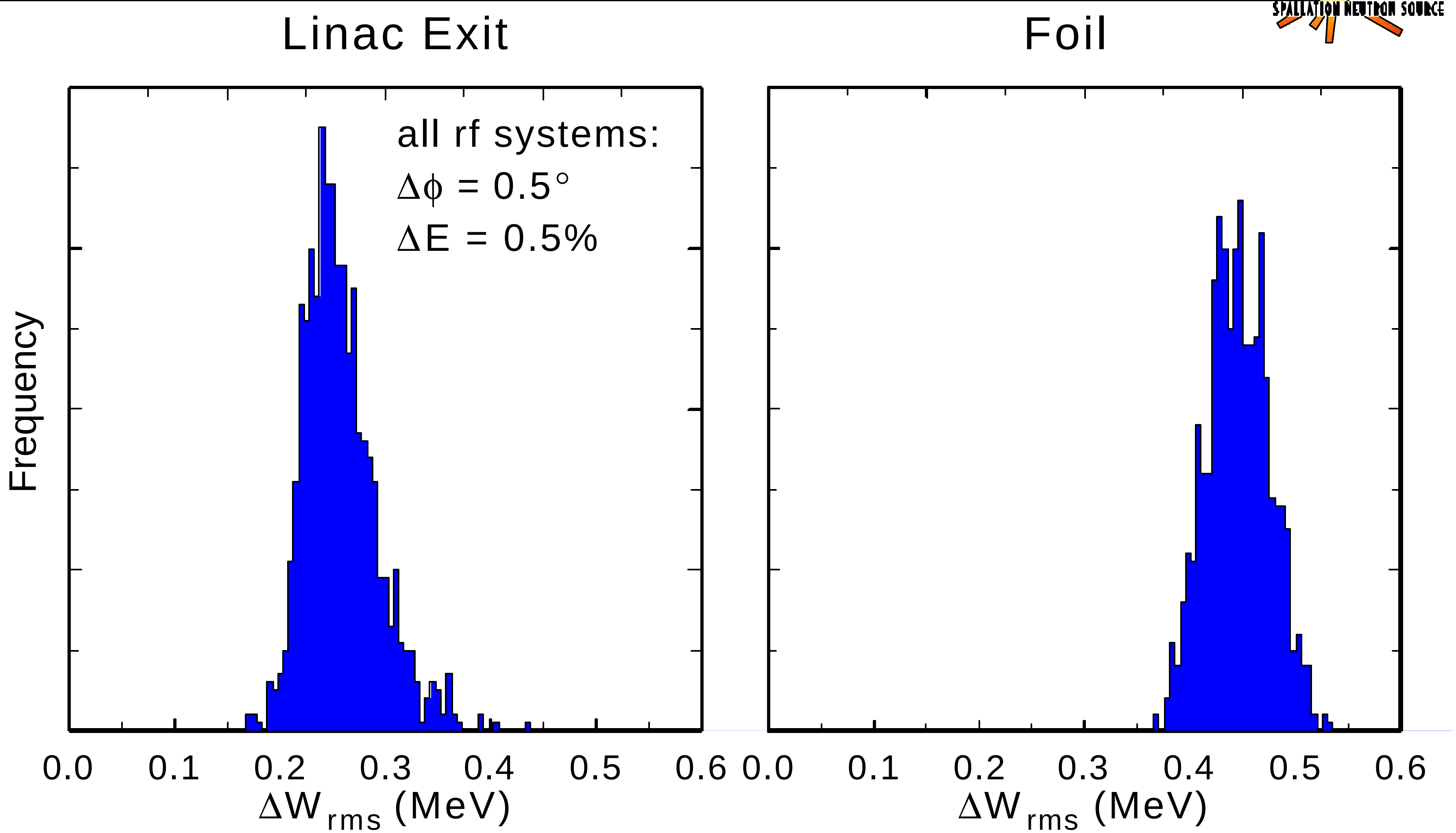
Typical Beam Profile, All Errors Except Quad Displacements



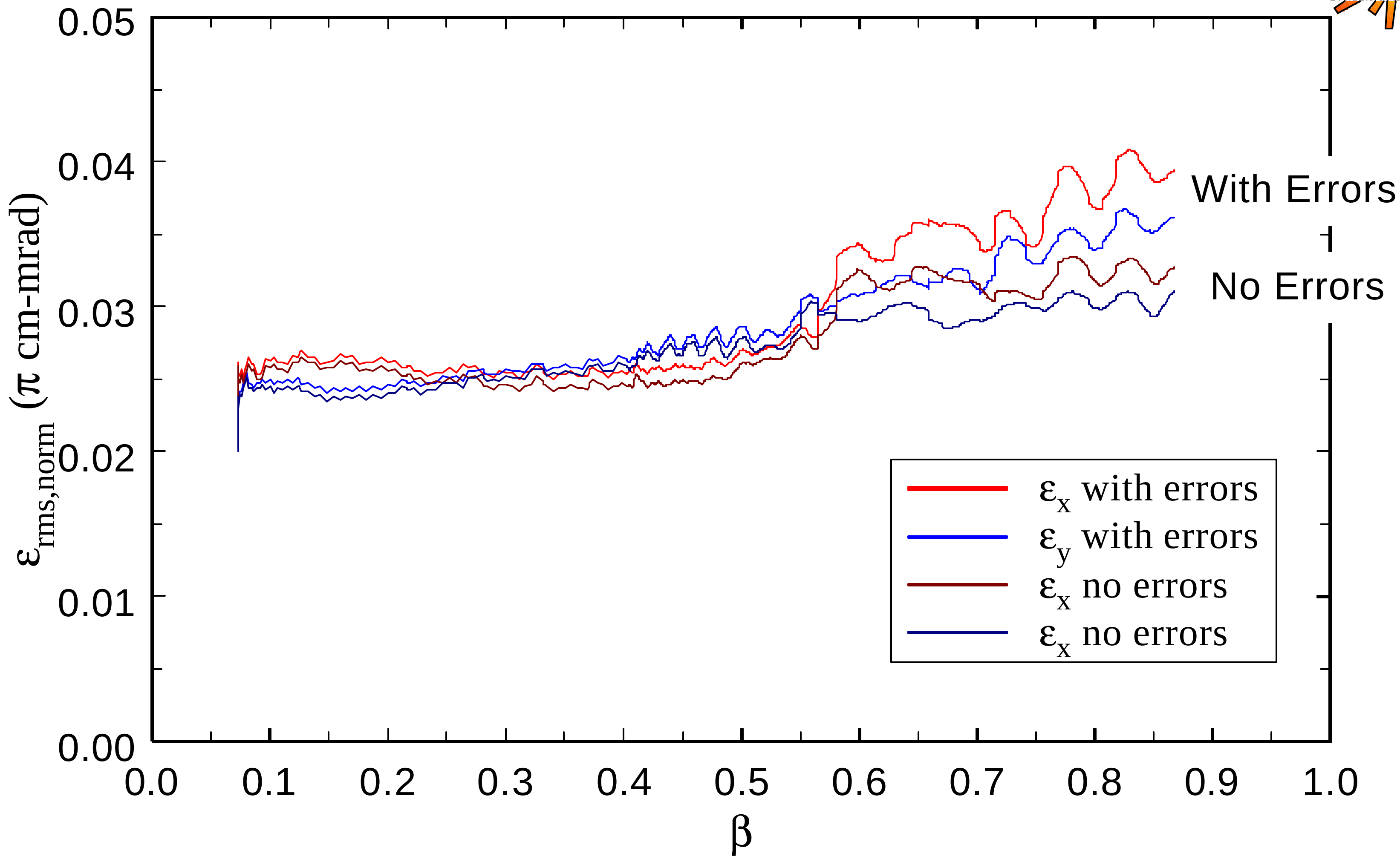
Energy Jitter is a Function of RF Control Tolerances & Meets Spec.



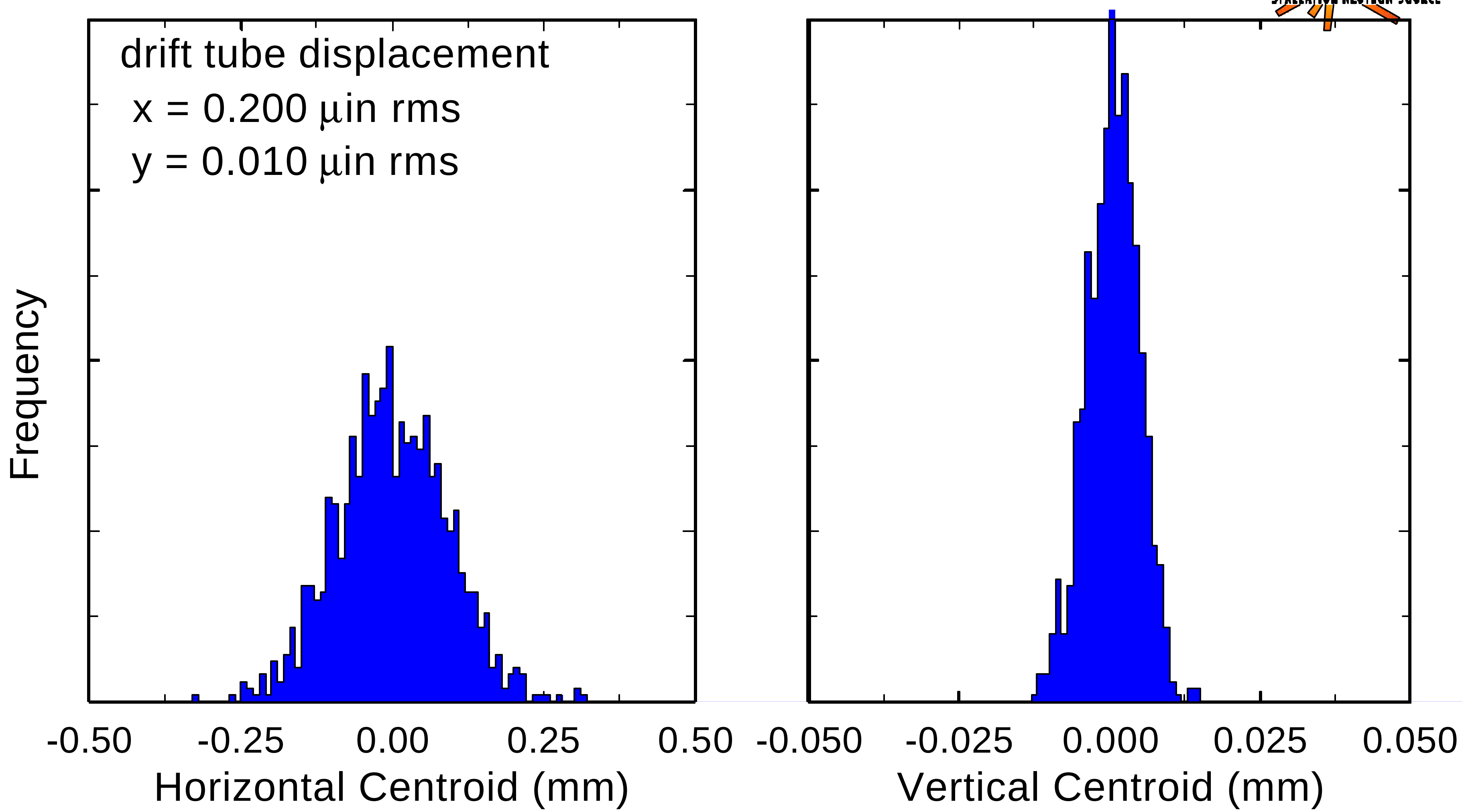
DW is a Function of Space Charge & Corrector Voltage & Meets Spec.



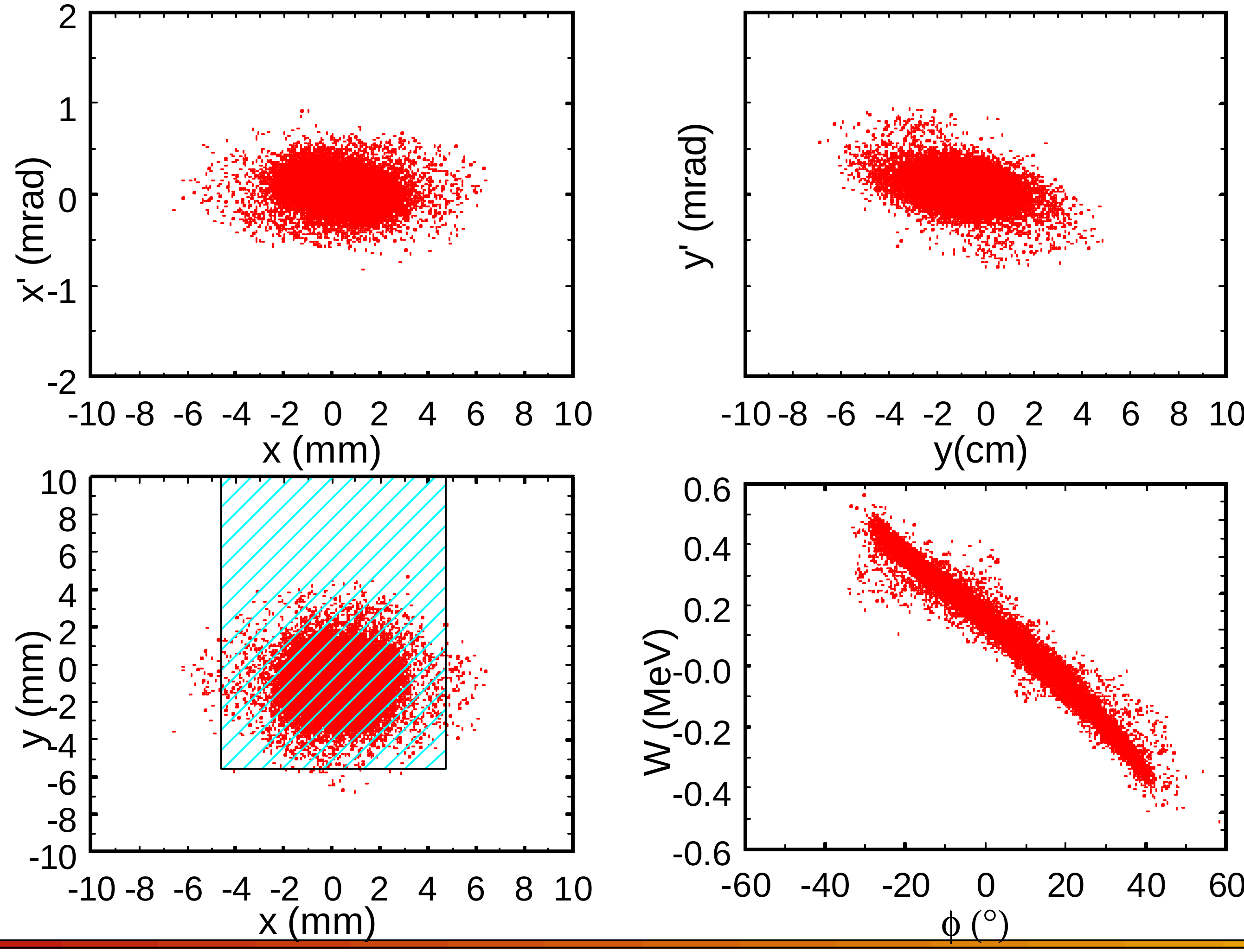
rms Emittance Profiles With & Without Errors, Excluding Misalignments



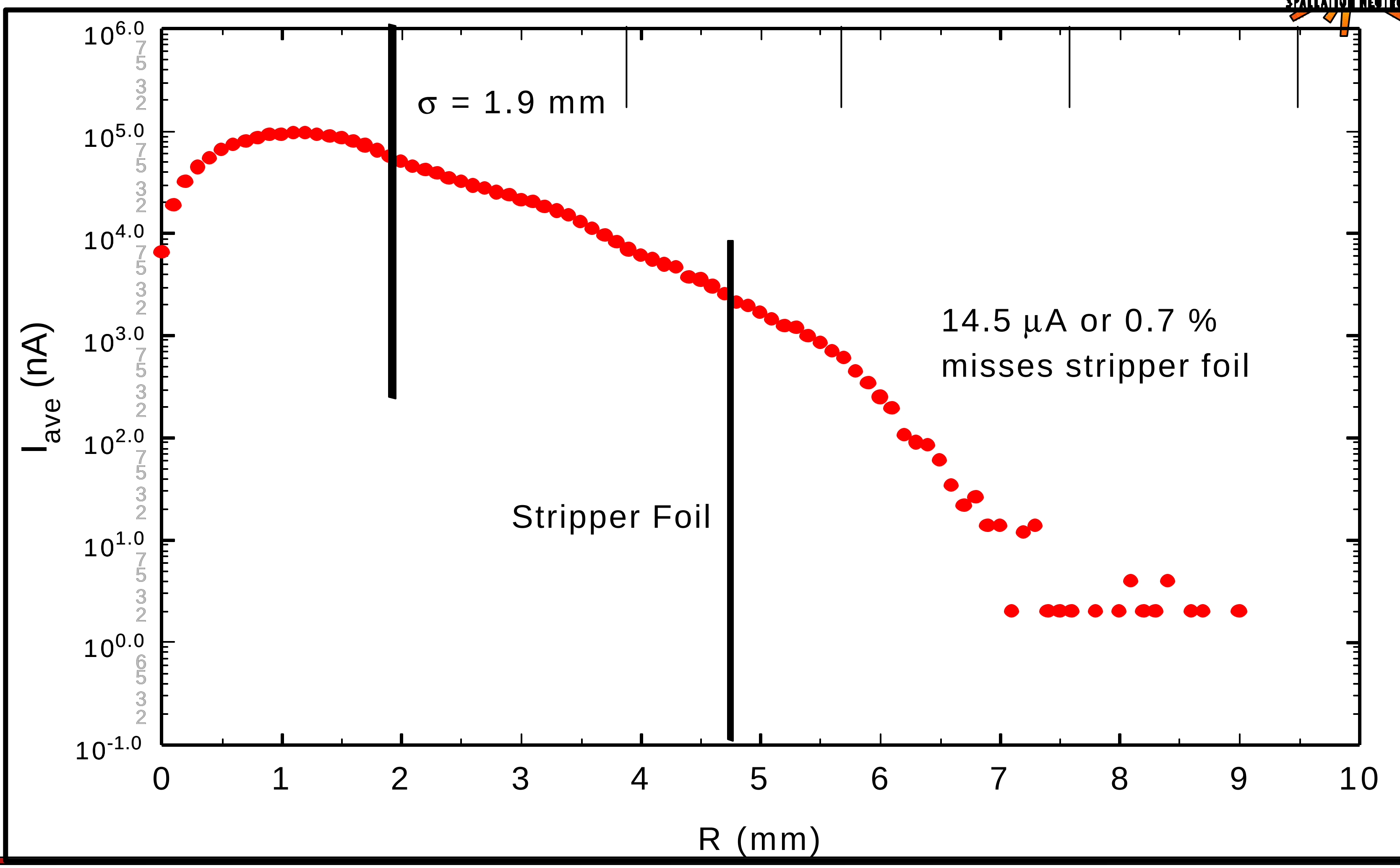
Transverse Jitter at the Foil is a Function of Quad Vibrations & Meets Spec.



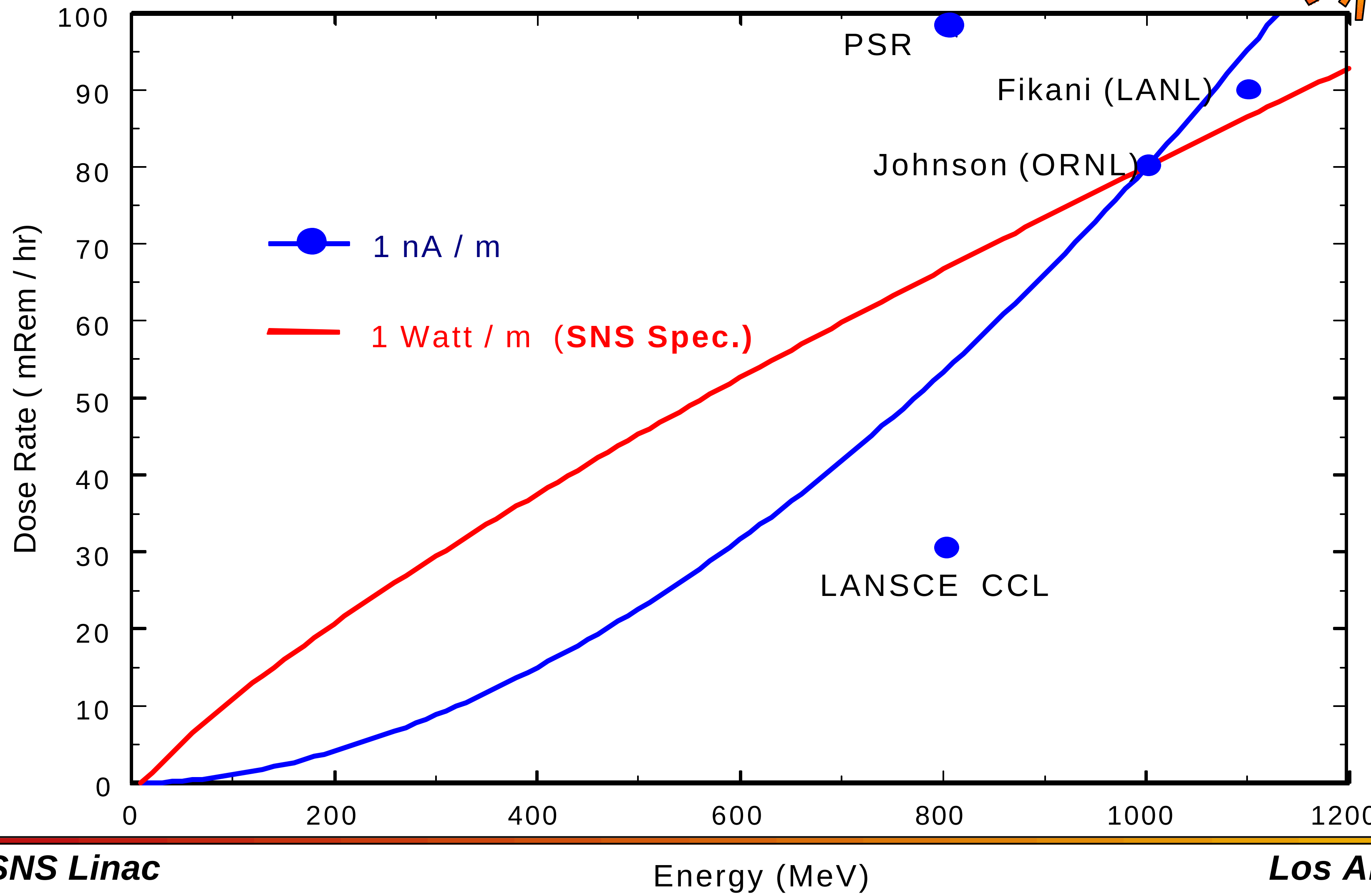
Beam Phase-Space Projections at the Foil



Radial Particle Distribution at the Foil with Errors



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



Beam Loss Mechanisms

- Gas Stripping
- Magnetic Stripping
- Longitudinal beam loss
  - **poor MEBT matching**
  - turn-on transients
  - dynamic phase & amplitude errors
  - static (mistuned) modules (ϕ & amp.)
- Transverse beam loss
  - misalignments & missteering
  - **halo**
    - **initial beam distribution**
    - **poor MEBT matching**
    - **other mismatches**

Issues of Concern to ASAC: SRF Cavity Tilts

- "Possibility of significant beam dynamics sensitivity to cavity tilt errors"
  - cavities fields will be tuned flat during fabrication
  - field tilts will result from squeezing the asymmetric cavities to correct their frequency at 2 K
- Mechanical analysis will predict the expected field tilts
- Drifting-beam field calibration can only detect E_0, the average axial cavity field
  - the tuning algorithm sets the average cavity phase
  - a tilt could result in a different final energy and effect the longitudinal focusing
- Typically cell-by-cell simulations with very large phase slips yield the same dynamics as cavity simulations using average field values
- This effect is expected to be small compared to the uncertainty in E_0

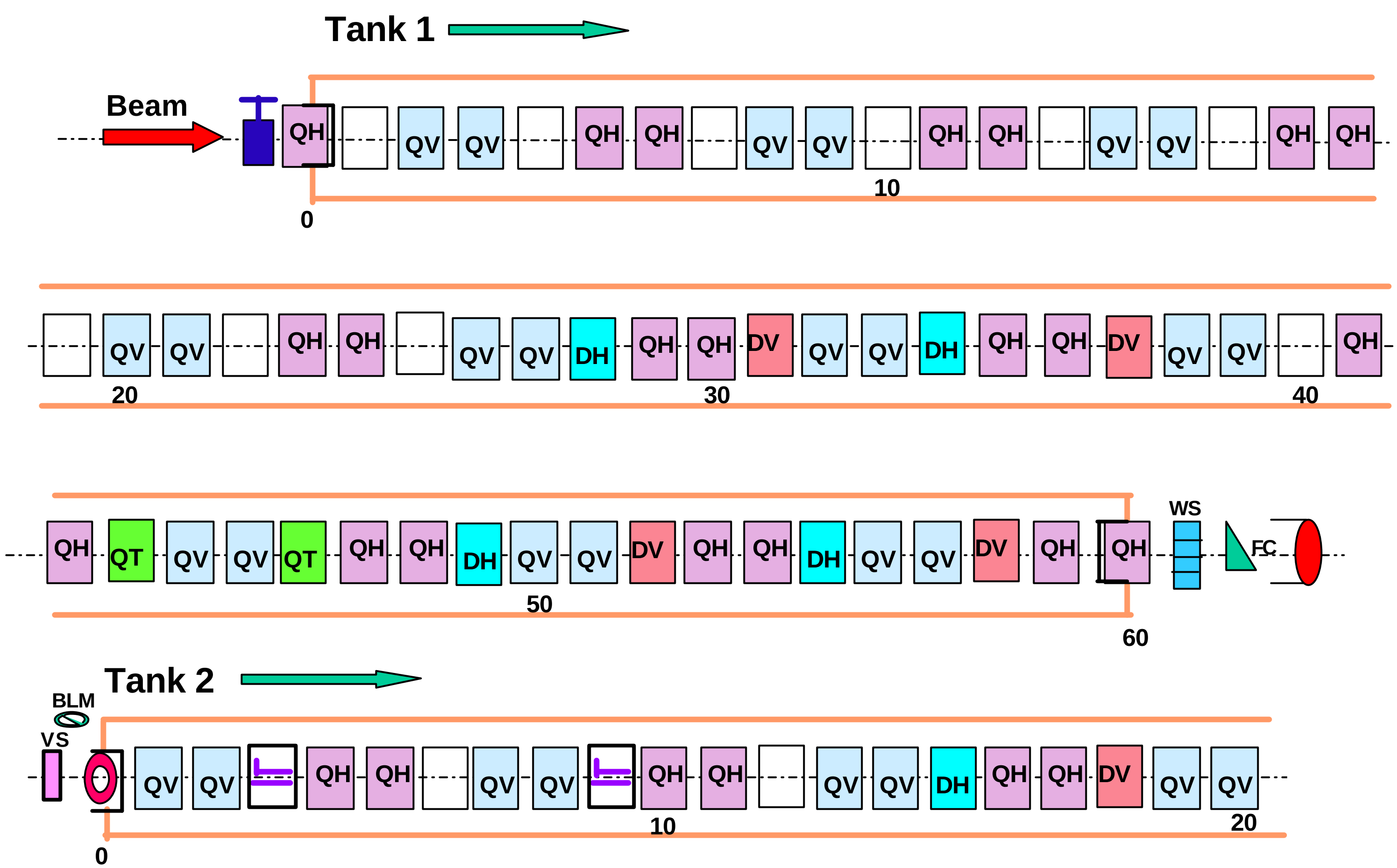
Issues of Concern to ASAC: DTL Adjustable Quadrupoles

- "… give serious consideration to incorporation of electromagnetic quadrupoles"
  - "PMQs are not conservative & don't provide tunability or flexibility"
  - Couldn't accommodate alternate quad laws developed later
  - Presumably couldn't correct mismatches
- This may be good advice coming too late
  - 400 MHz frequency choice precludes EMQs in the drift tubes
  - techniques for correcting mismatches are yet to be identified

Trim Quadrupole Proposal

- We have investigated a variety of variable quad designs
  - the liability of any of these designs could not justify any added flexibility
- DTL focusing lattice is FF0DD0
  - every 3rd drift tube is empty
  - most have been reserved for dipoles and diagnostics
- We propose to incorporate low gradient (~10% nom.) EMQs in some of the remaining empty drift tubes
  - lattice would become FFfDDd
  - two such periods would give us the flexibility to correct any mismatch if detectable
  - It would not accommodate alternate quad laws

SNS DTL Beam Diagnostics & Magnet Layout



We Plan to Submit a Project Change Request

- Design a trim quad & drift tube
- Prototype a trim quad
- Field map the prototype
  - ASAC has expressed concern over the field quality of short magnets
- Pursue studies to identify techniques for identifying and correcting mismatches in the DTL
- Assuming positive results we would either
  - shelve the design or
  - build ~16 drift tubes containing trim quads
- When the day comes that we believe we can improve the linac performance, they would be installed

Issues of Concern to ASAC: Simulation Codes

- “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.”

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 problem
- The physics from PARMILA has been incorporated into other codes
- We welcome and solicit its comparison of other codes
  - PARMILA has served as the reference against which many codes have been compared over the years
  - all comparisons to date support its accuracy
- There are presently no known "errors" in the distribution version

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, PARMELA, LINAC, PARWIN & IMPACT calculate multiparticle beam dynamics
  - LTRACE calculates envelope dynamics

PARMELA is Our Most Detailed Simulation Code

- PARMELA : Phase & Radial Motion in Electron Linacs
  - time step integration
  - composite E & H fields
  - 2.5-D & 3-D space charge
  - E_r, E_z & H_θ field map computed by SUPERFISH
  - <1M particle typical
- IMPACT
  - hybrid: integration + impulse approx.
  - 3-D space charge
  - assumes linear expansion for off-axis fields in the gap
  - 1-10M particle typical (could run 10^8)

PARMILA is Our Design and Primary Simulation Code

- PARMILA : Phase & Radial Motion in Ion Linacs
  - designs integrated linacs incl. DTLs, CCLs, CCDTLs & SRF
  - impulse approximation
  - 2.5-D & 3-D space charge
  - gap transformation includes transit time integrals T,T', S & S'
  - off-axis fields derived using Bessel-function expansions
  - 100k - 1M particle typical
- LINAC : a proprietary code similar to PARMILA
  - written for CCLs but extended to DTLs & SRF
  - Dynamics similar to PARMILA

PARWIN is the French Windows "Version" of PARMILA

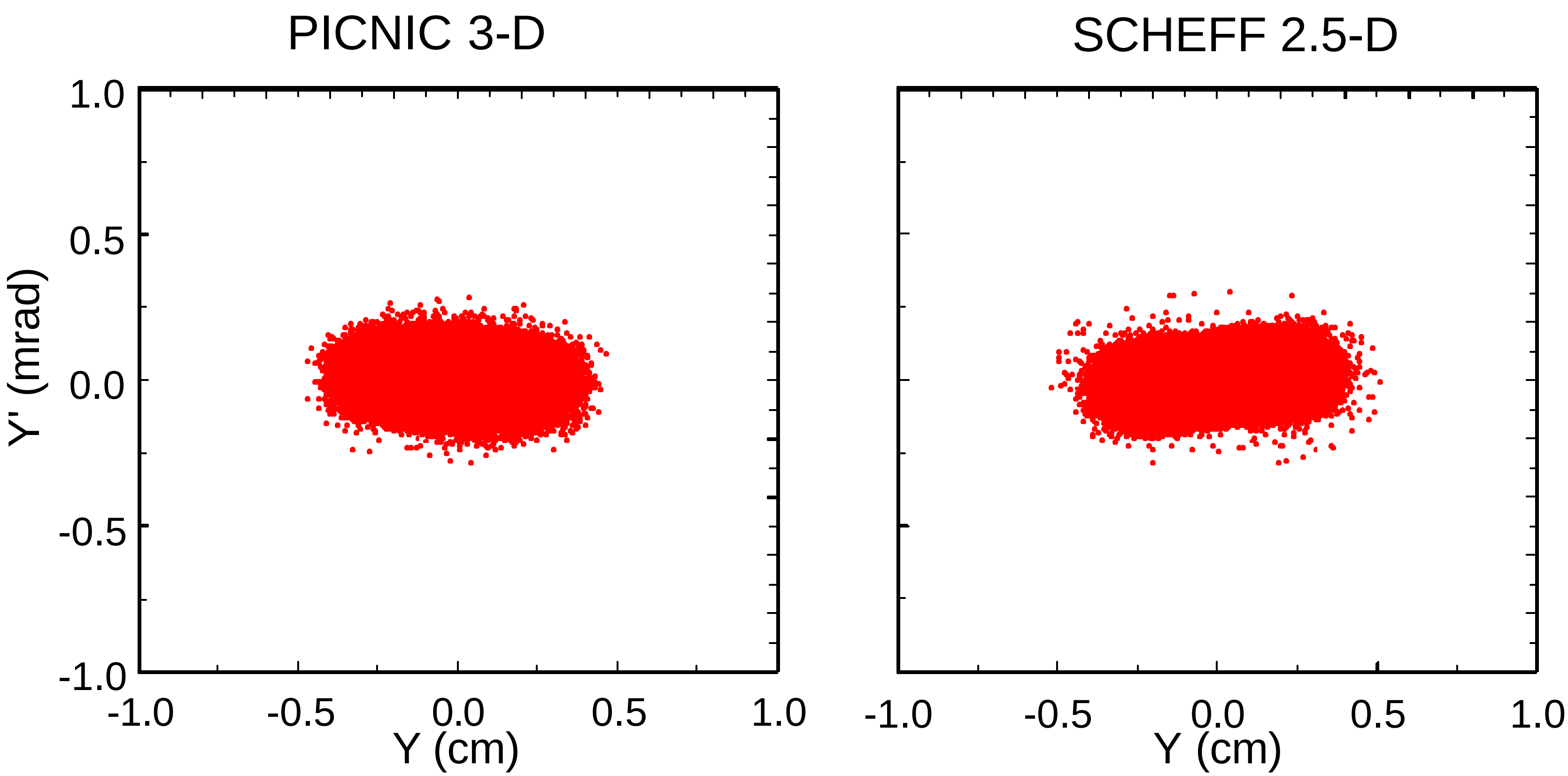
- PARWIN : PARMILA for Windows
  - design & simulation functions in separate codes
  - designed to be compatible with PARMILA
  - dynamics nominally copied from PARMILA
  - 2.5-D & 3-D space charge
  - 10k - 1M particle typical
  - assumes sinusoidal SRF cavity fields for design studies
  - now includes complete SRF cavity fields a la PARMILA
  - flexible and user friendly

Code comparisons: Preliminary Results

- All 5 codes can now simulate the entire SNS linac
- Differences between 2.5- & 3-D space charge are very small for the reference distributions (100k RFQ output)
- All but IMPACT agree on the emittance growth
  - IMPACT shows an extra ~10% growth in DTL Tank 1
- Primary differences between the 5 codes
  - speed of execution
  - 2.5 & 3-D space charge, minor differences in method of field calculation
  - time integration vs. impulse approximation
  - number of particles in the calculation
  - characterization of gap fields

"SCHEFF & PICNIC show significant difference in orientation of the Y-Y' phase plane"

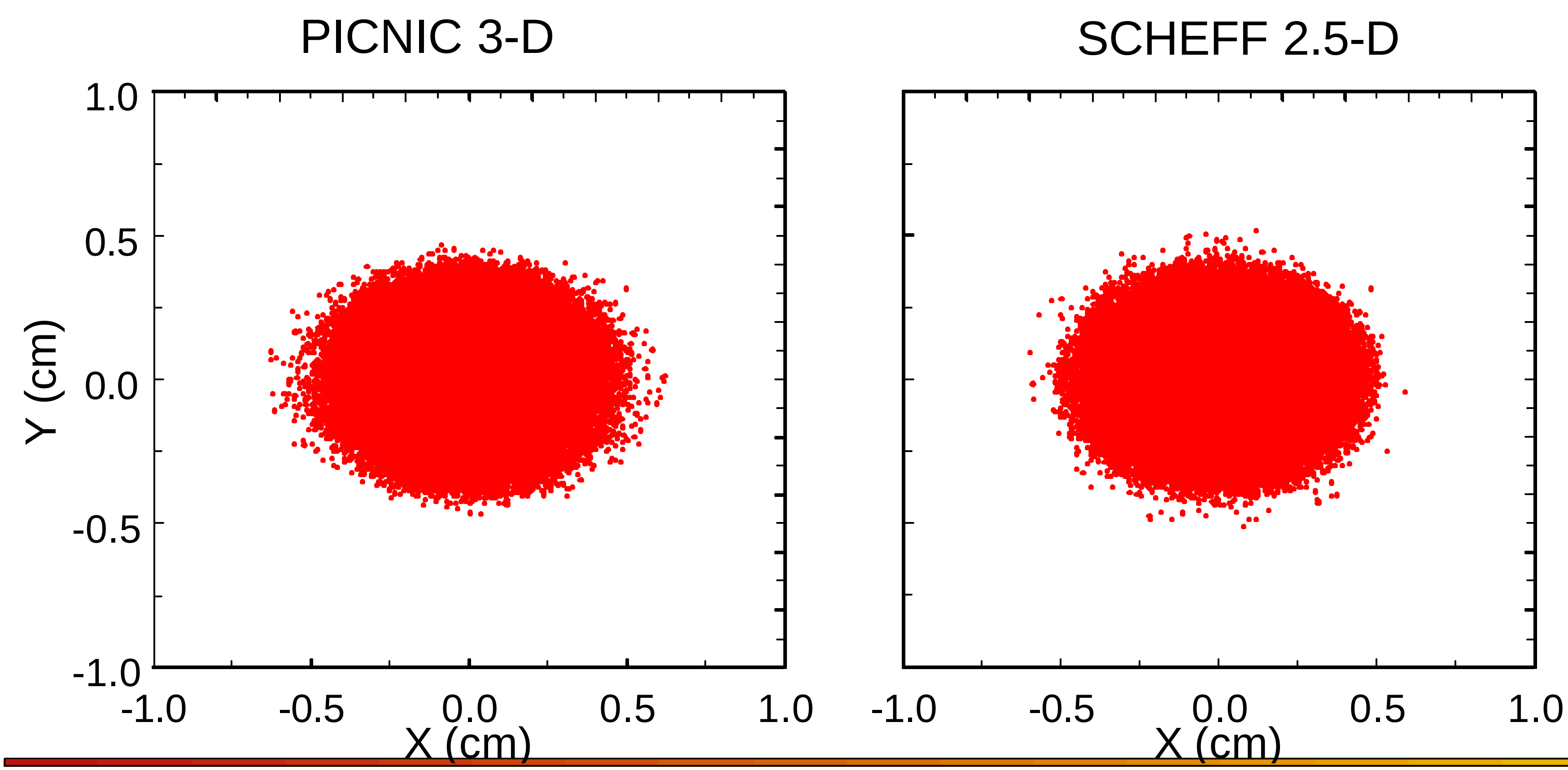
Phase Space Projections at 1.25 GeV
SRF Only, Waterbag Initial Distribution



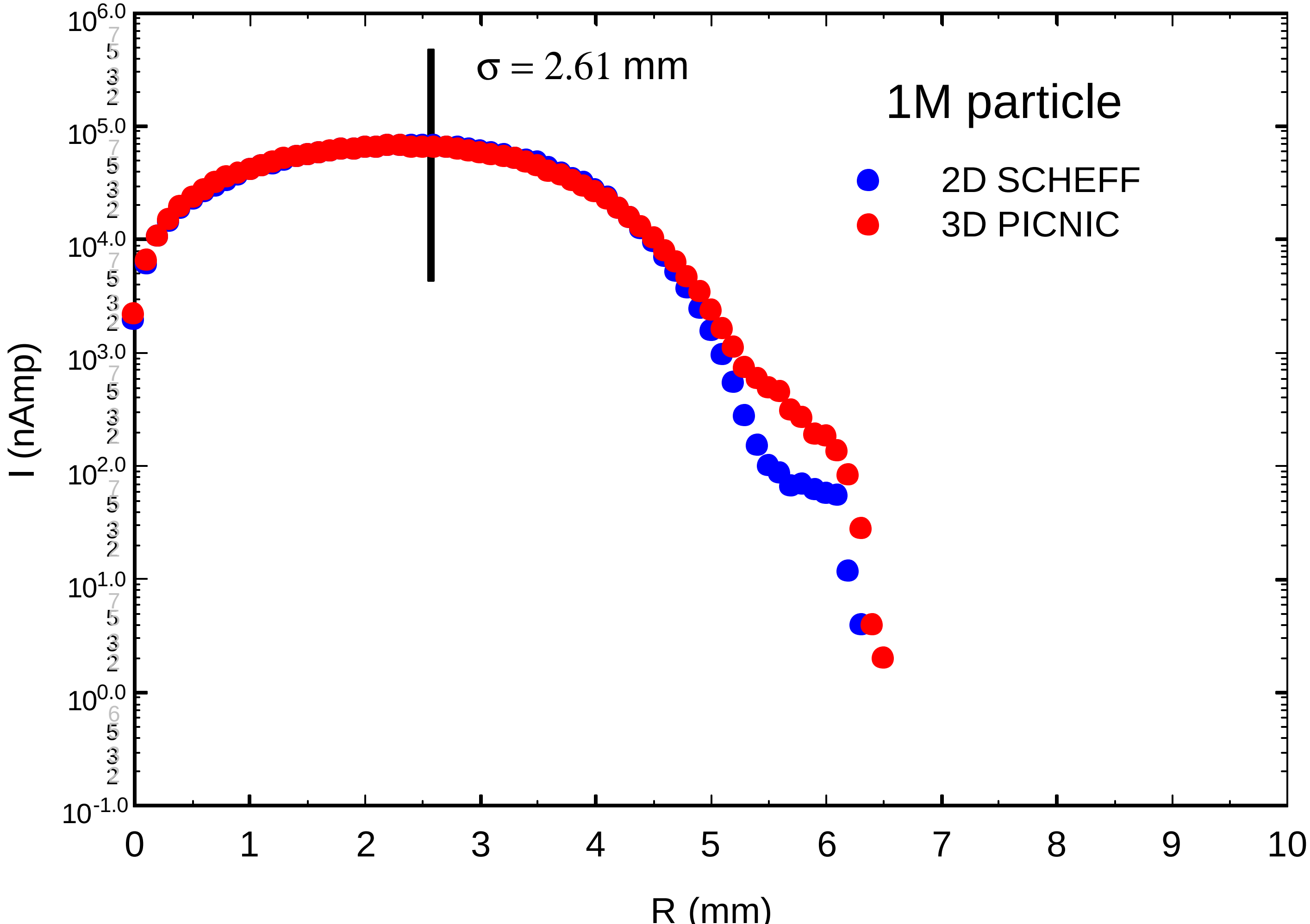
Our Primary Space Charge Concern is not Orientation but Halo

Real Space Projections at 1.25 GeV

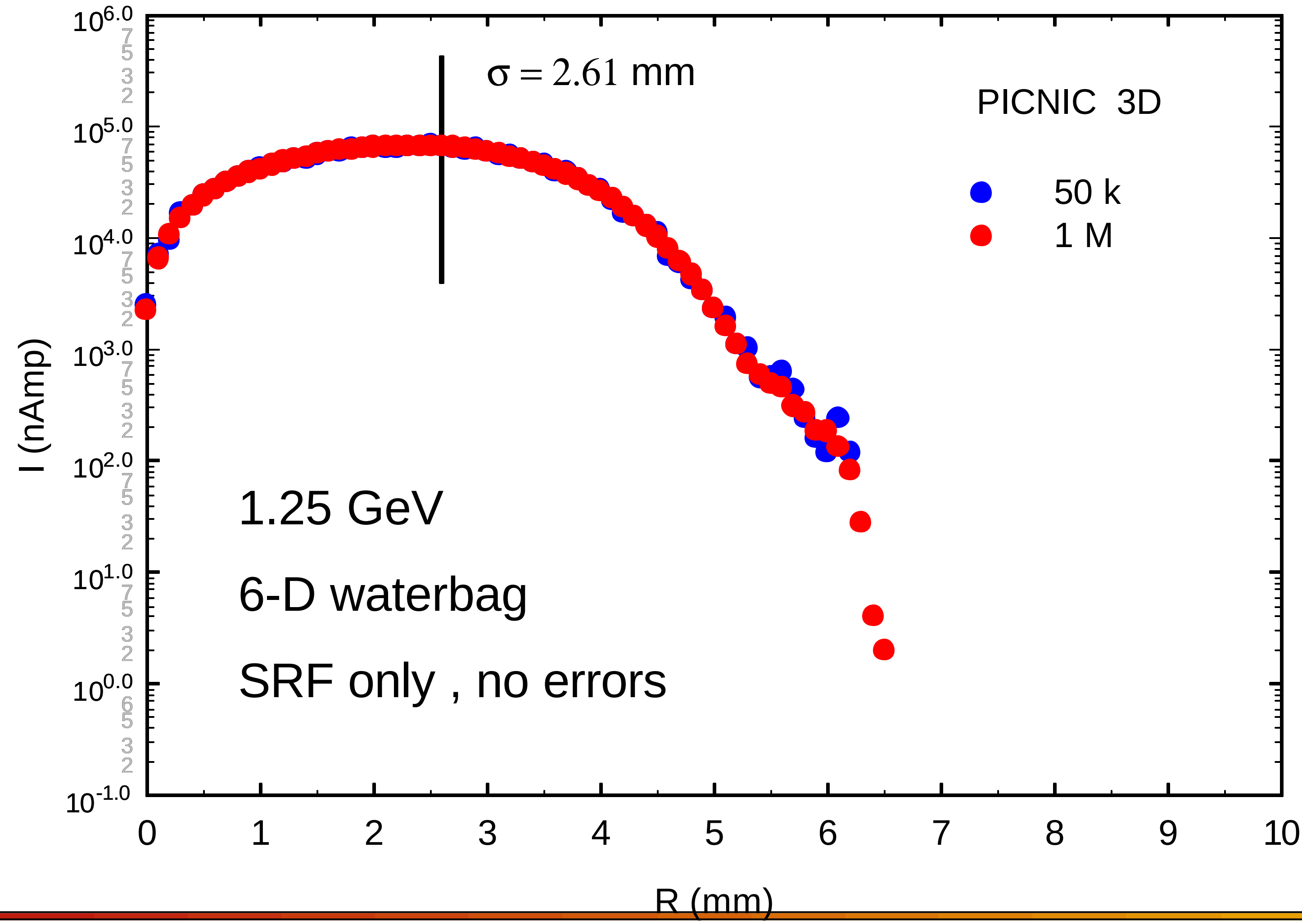
SRF Only, Waterbag Initial Distribution



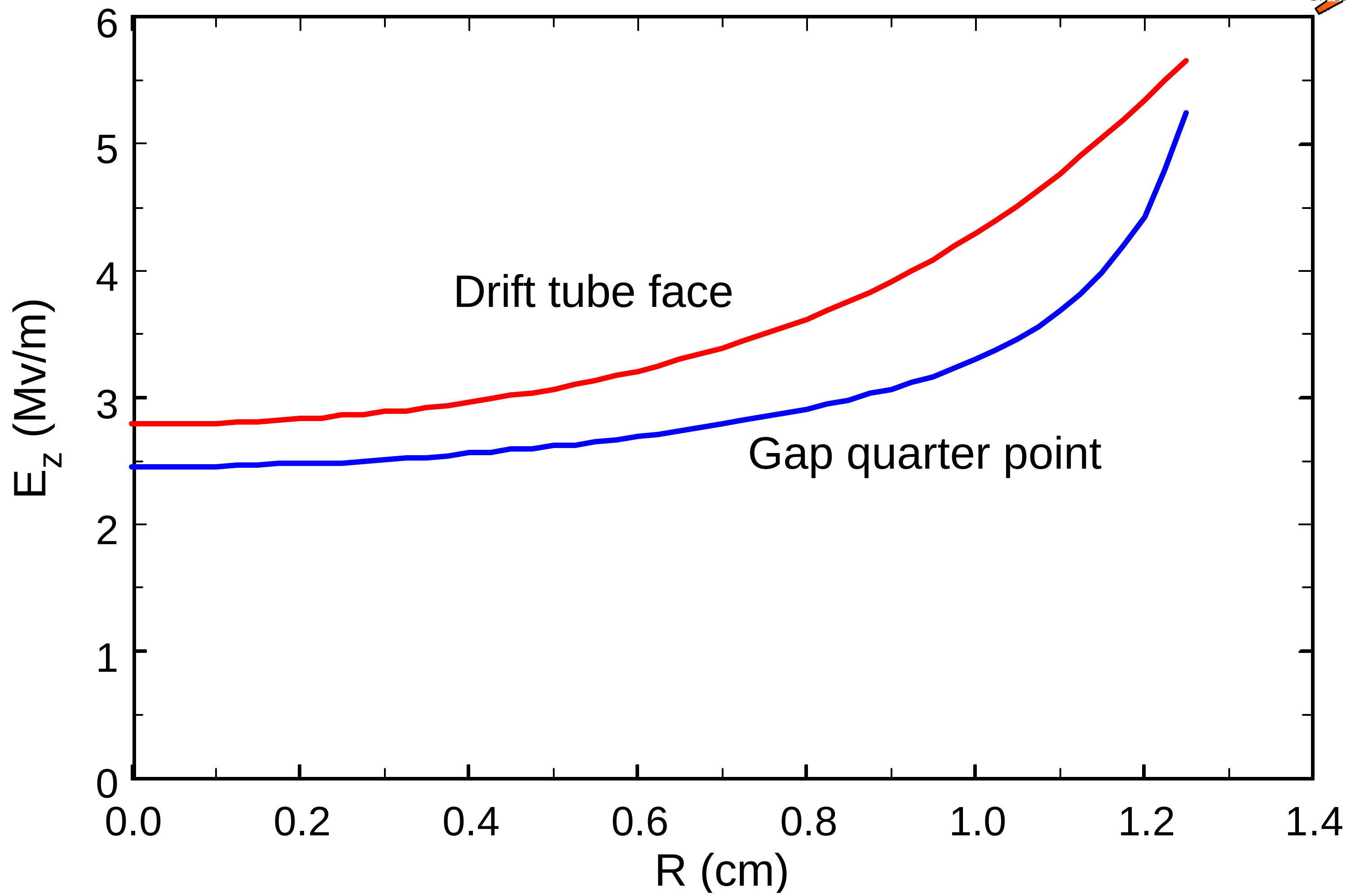
Simulations Differ at the 100 nA Level in the Distribution but not in the Extent



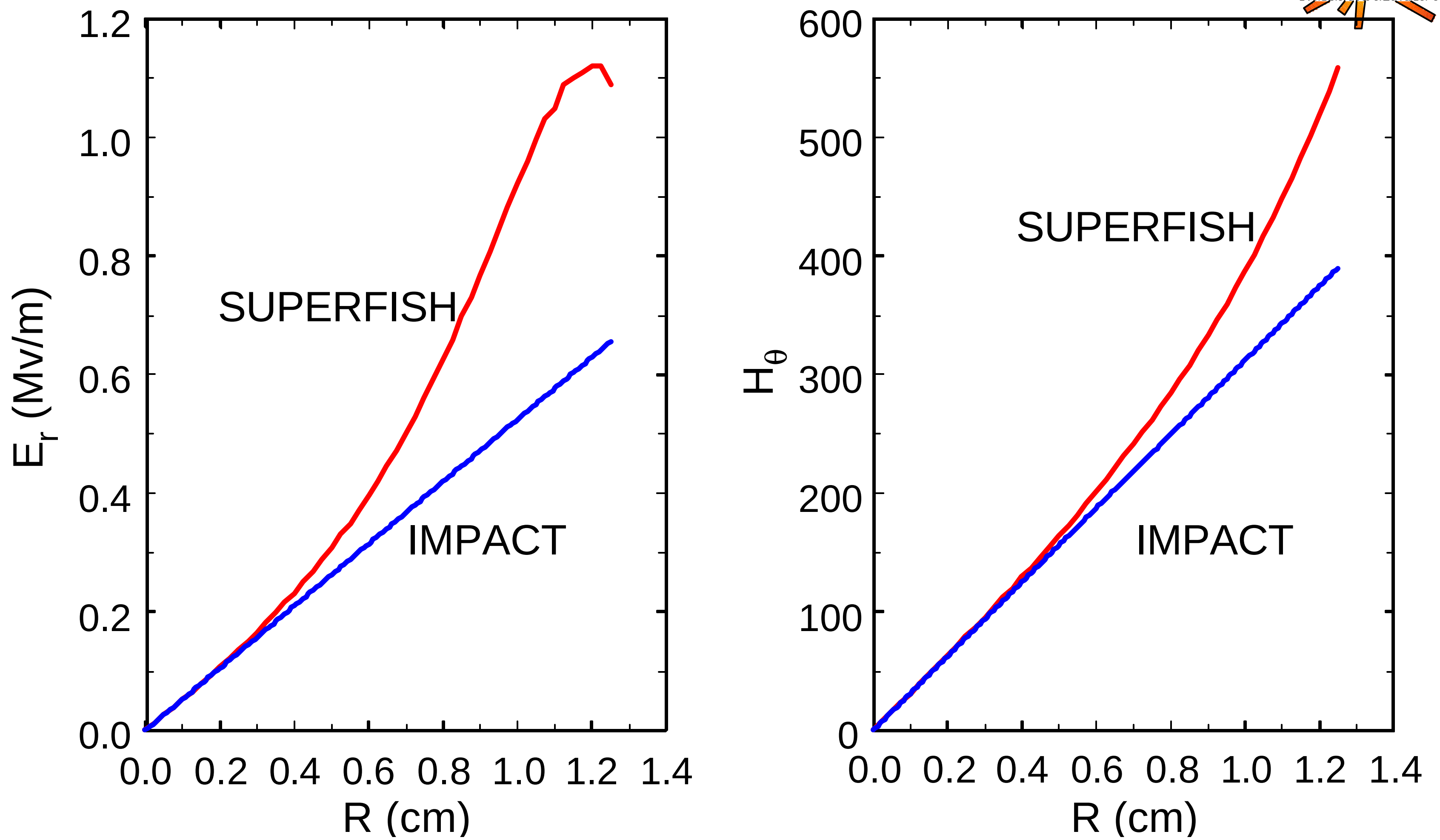
Small & Large Distributions Yield Consistent Results



IMPACT Assumption of Linear Fields May Not be Accurate Enough



Gap Fields in DTL Cell 1



Issues of Concern to ASAC

- "Physics design has not been presented in framework of space-charge physics."
  - i.e. "tunes" as a function of current and energy
- Presentations have not addressed "the behavior of the beam edges at the required levels of 10^{-4} - 10^{-8}"
  - "bring in new semi-analytical or simulation approaches to understand halo"
  - "brute force running of simulation codes and simplistic evaluation"
- Recommend
  - reaching out to partner labs for contributions
  - sponsor workshops
  - engage consultants
  - write about our work

Los Alamos Response to Recommendations

- Space-charge framework
  - tune space can be presented
  - "understanding halo" is still an open issue and beyond the scope of our assignment
- Required levels of 10^{-8}
  - impractical & unbelievable but see distribution plots
- Recommendations
  - hosted HEBT interface workshop
  - expanded existing collaboration with Saclay linac group
  - hosted beam dynamics workshop in November, next scheduled for Spring
  - involved ORNL staff in commissioning studies in mentoring role
  - developing consulting contracts with R. Jameson, JM. Lagniel & I.Hoffman
  - ~10 papers at PAC
  - teach "Introduction to Linear Accelerators" at the USPAC

Linac Design is Mature

- DTL Physics design is complete
  - Field stabilization scheme demonstrated
  - PCR to be submitted for EMQs
  - Design drawings in process
- CCL Physics design is complete
  - Cavity geometry finalized
    - details being incorporated into mechanical design
  - Bridge-coupler details under study
  - Hot-model in fabrication
- SRF Reference design is complete
  - Cavity layout is frozen
  - Investigating alternate phase & quad laws

Linac Interfaces are Mature

- MEBT-DTL: dimensions are frozen, matching is complete
- DTL-CCL: dimensions are frozen, matching is complete
- CCL-SRF: dimensions are frozen, have a matched solution
  – modified phase law under study
- SRF β_1-β_2: have a matched solution
- SRF-HEBT: overall length frozen
  – transport design defrosted & refrozen at 840 MeV
  – end-to-end simulations underway
  – energy corrector/spreader cavity-physics design complete

Status of Linac Design & Beam Simulation Studies

- Steering algorithms have been selected
- Dipole & BPM locations identified
- Algorithms incorporated into simulation codes
- Error studies underway
- DTL & CCL phase & amplitude set-point algorithms under study
- Code comparisons under study
- Mismatch studies pending
- Full error set pending rf tuning algorithms
- Next beam dynamics workshop scheduled in Spring