Final Design & Expected Beam Performance of the SNS Linac

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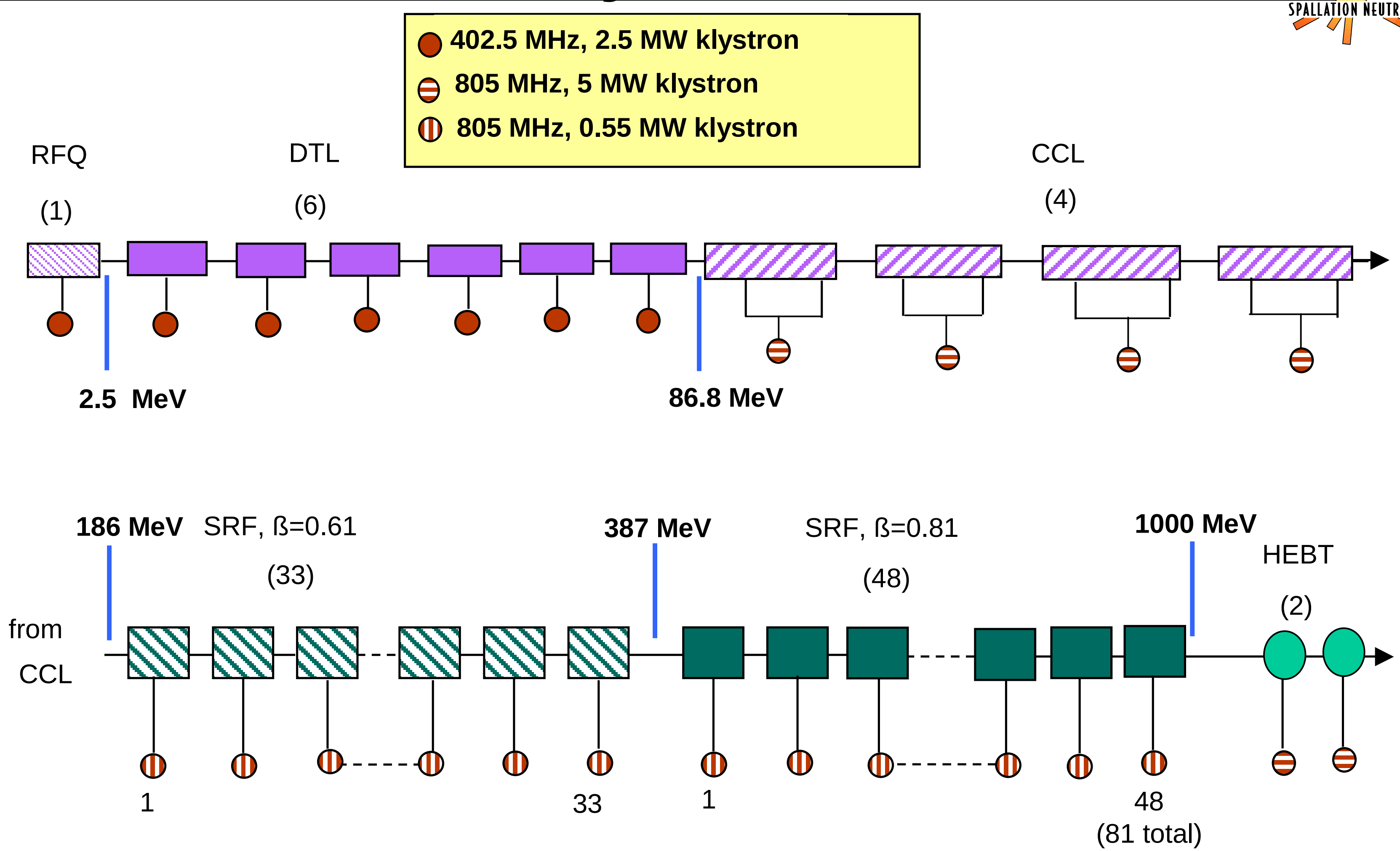
"The basic physics design & configuration … are essentially complete." ASAC 10/01

- W_{final} increased from 800 MeV to1 GeV
- Klystron power still ≤ 550 kW
- E_{max} increased for β_2 cavities from 27.5 to 35 MV/m nom.
- Klystron control margin increased to 40% for high β cavities
  - in anticipation of increased Lorentz force detuning
  - expected detuning is under study
- ϕ_{design} in SRF linac reduced to ~-20° to increase acceleration
- I_{ave} reduced from 2.0 to 1.55 mA to exploit increased cavity fields
  - I_{peak} = 38 mA, $I_{chopped}$=26 mA
- W_{final} , or I_{peak} may be increased by adding SRF modules
- Parametric resonances are avoided
- DTL inter-tank mismatches compensated

The SNS Linac has 5 Types of Accelerating Structures & 94 Klystrons

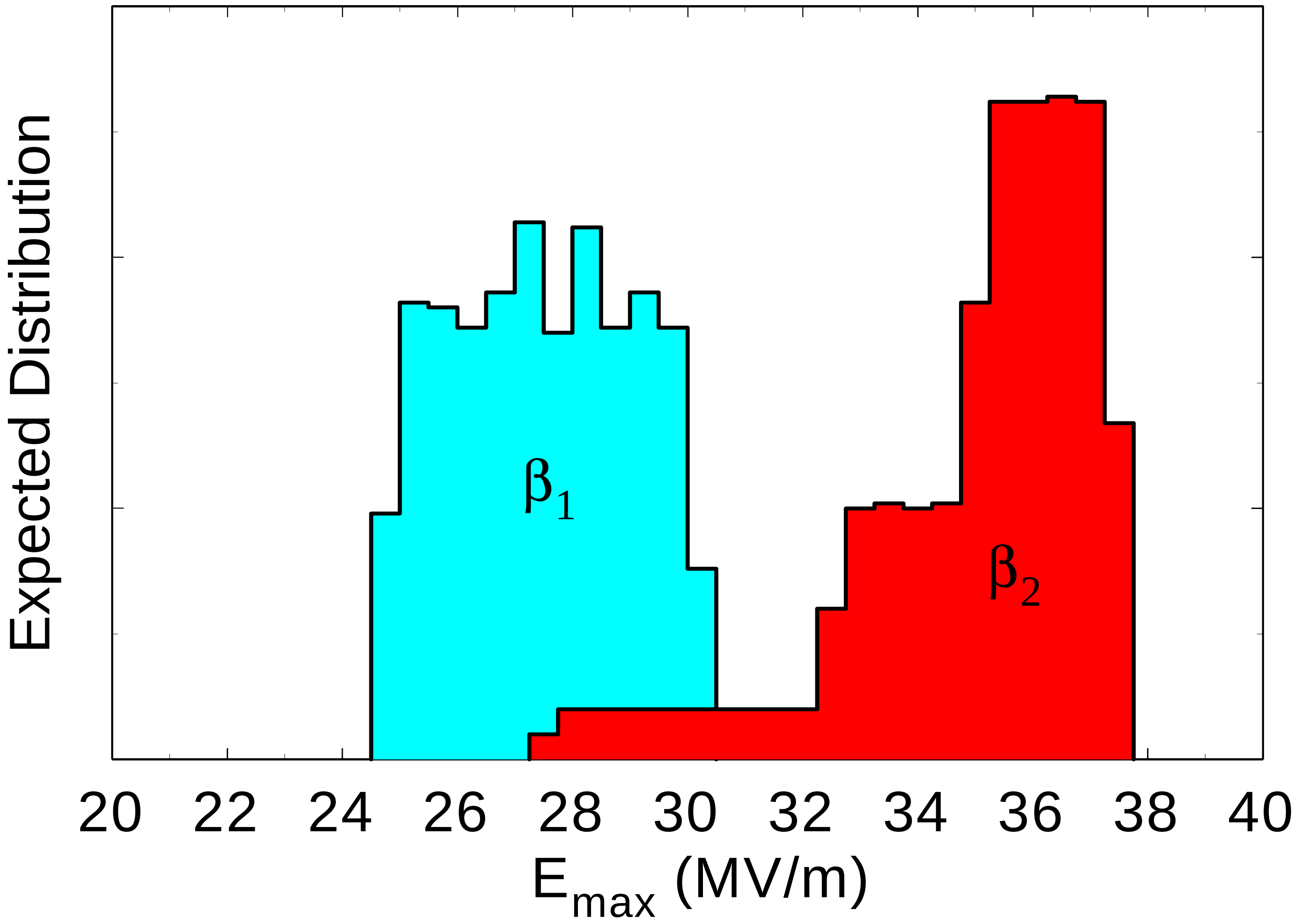


Available Power is Limited by High Voltage, Control Margin & Losses

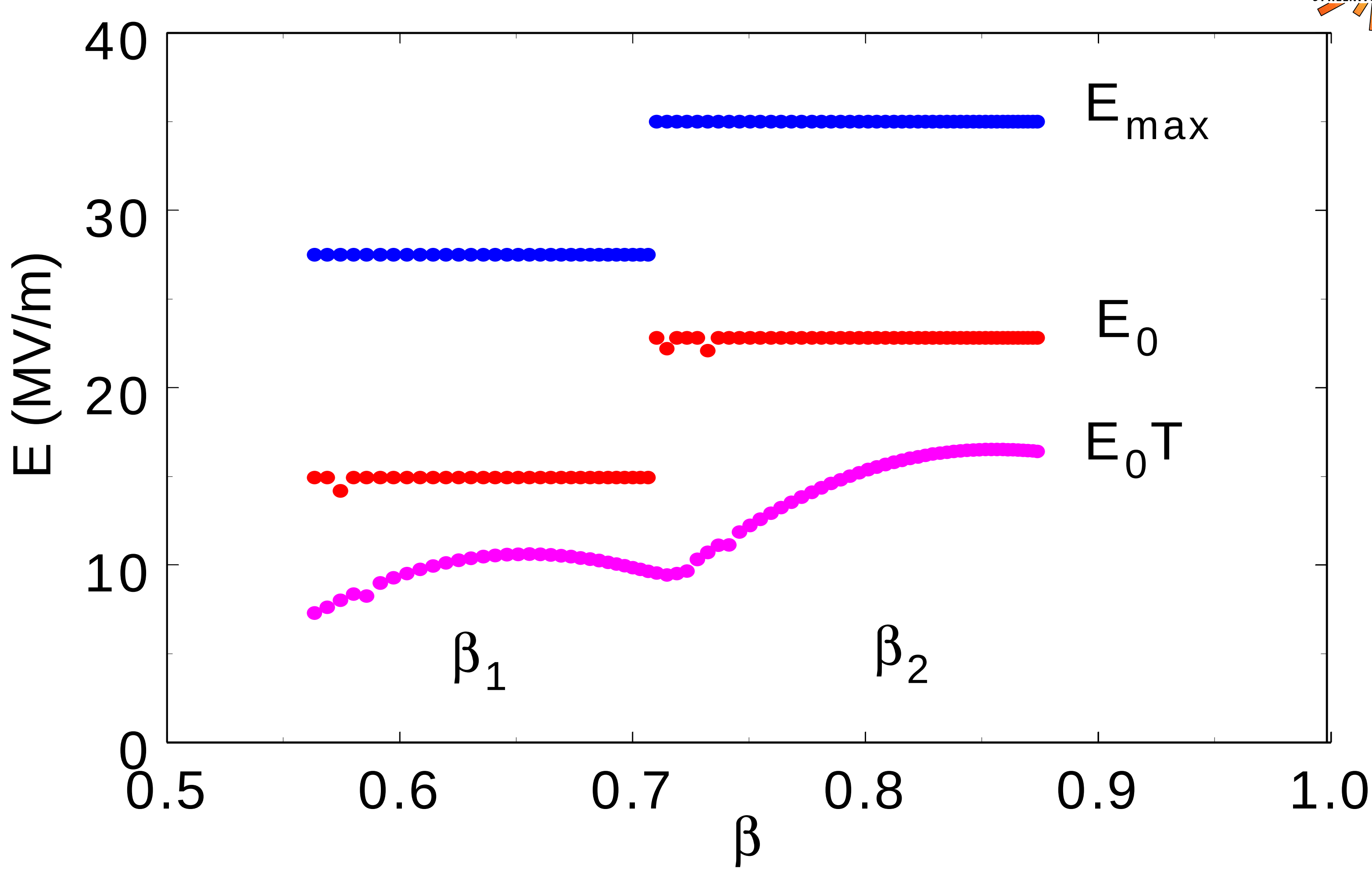
Structure	W_{gain}	Section Length	Maximum Cavity Power	Maximum Beam Power*	Control Margin + Losses	Maximum Power Demand	Power Available
	MeV	m	MW	MW	%	MW	MW
DTL	87	32	1.29	0.47	25	2.2	2.5
CCL	99	56	2.53	.73	25	4.1	5.00
SRF I	123	43	0	.191	33	.254	0.42
SRF II	692	150	0	.393	40	.550	0.55

* $I_{chopped}$ =26 mA

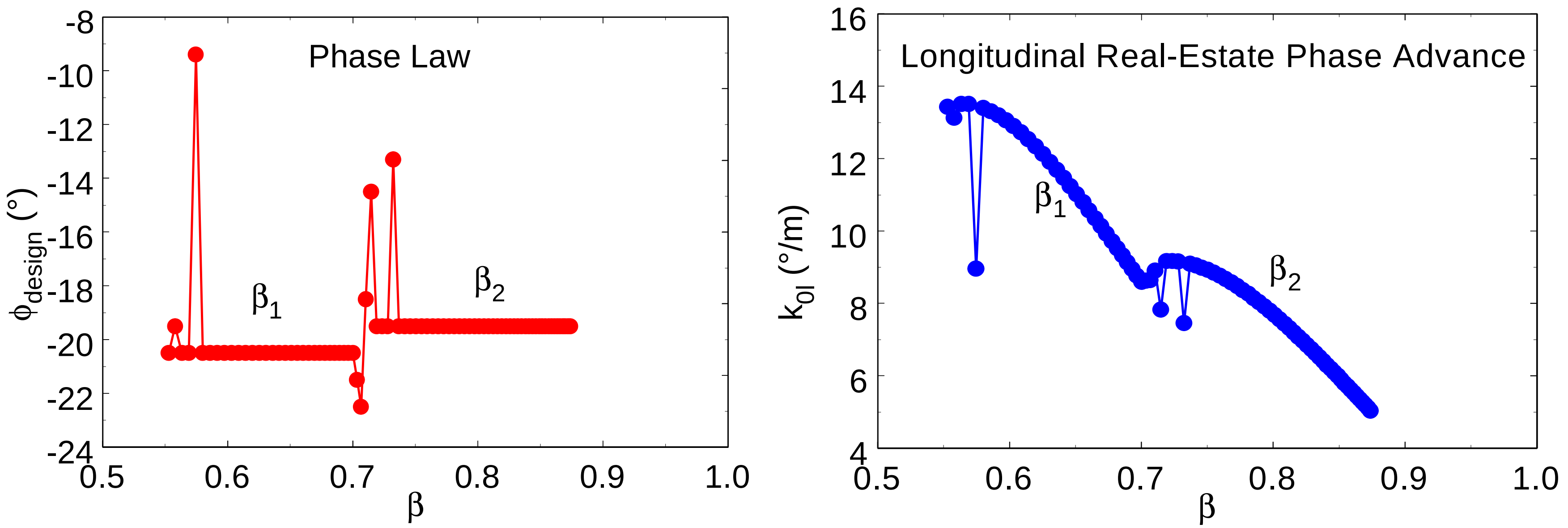
SRF Linac Performance will Depend on Success of Cavity R&D Program



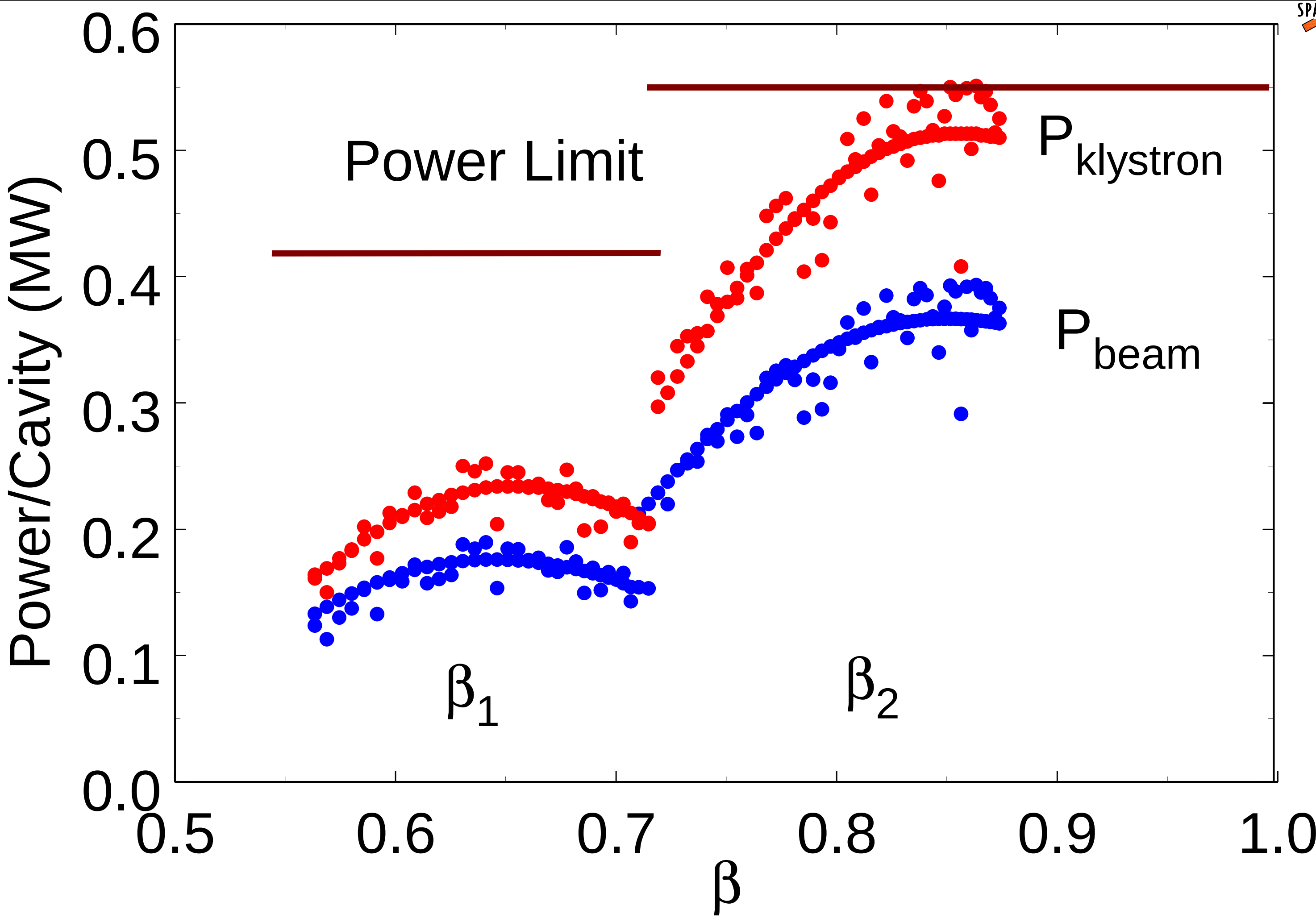
The SRF Reference Design Uses the Mean Values of the Predicted Cavity Fields



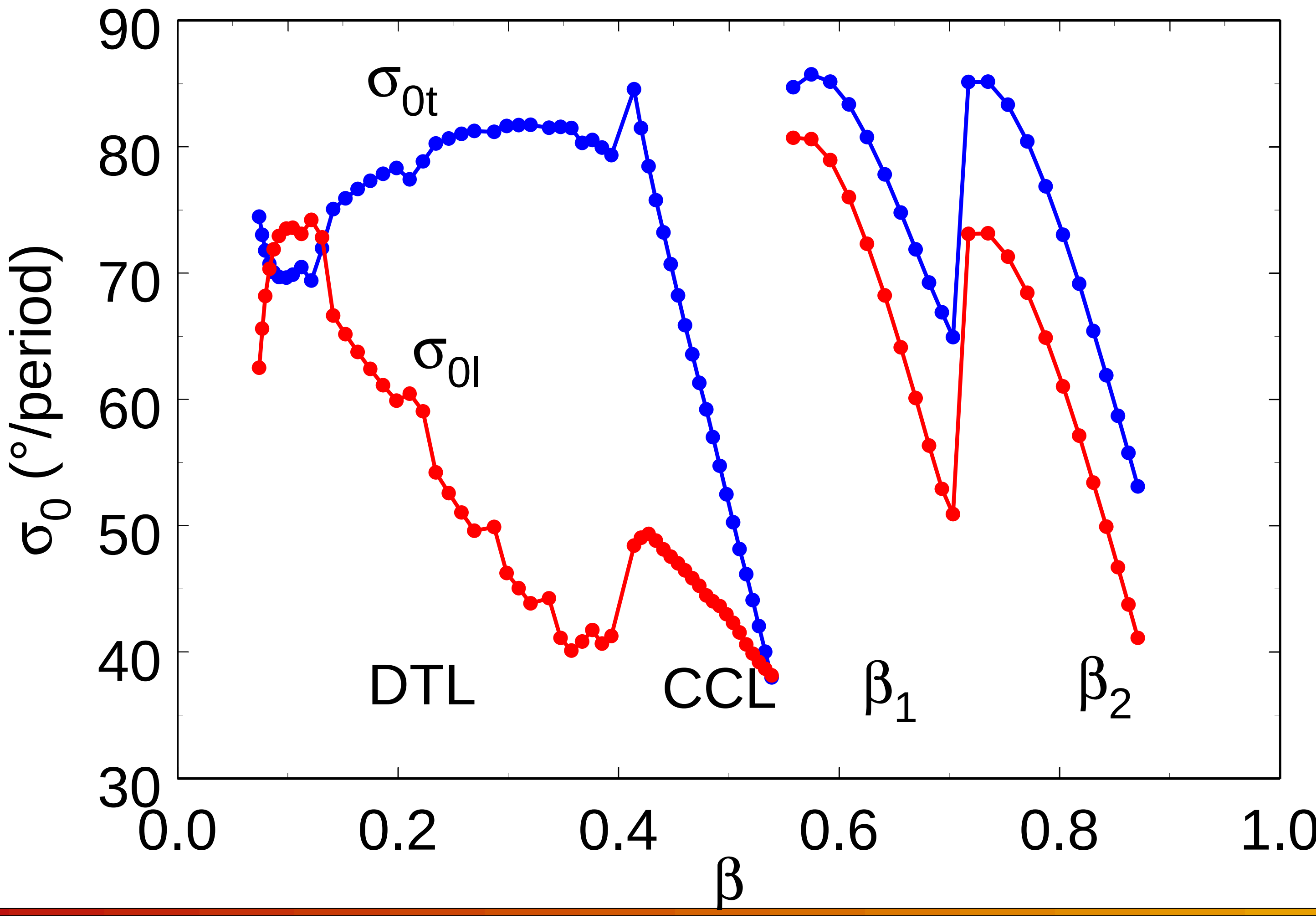
Phase Law Keeps $k_{0,l}$ Continuous but Reduces Longitudinal Acceptance



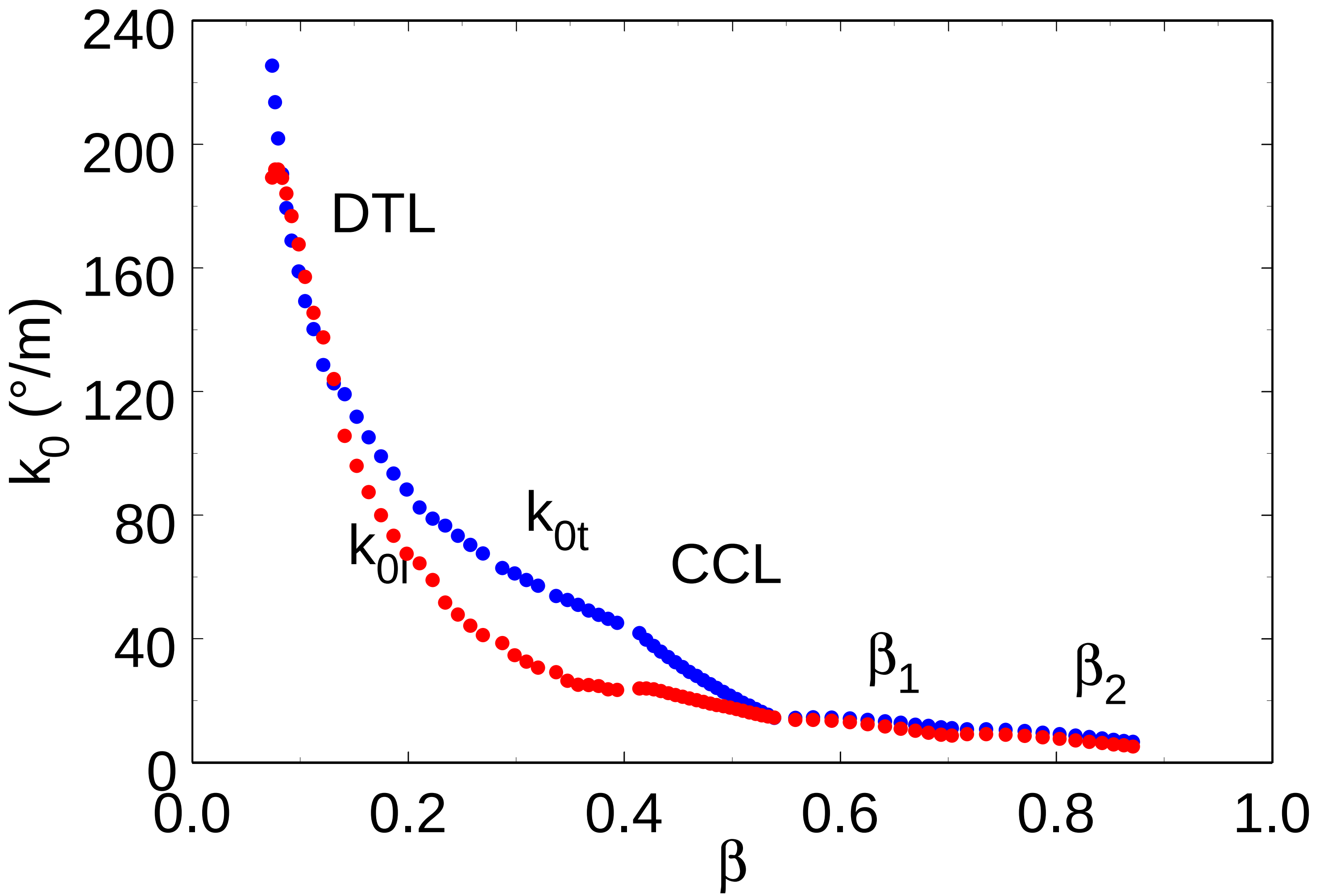
W_{final} is Limited by Cavity Quality, I_{beam} is Limited by Klystron Power



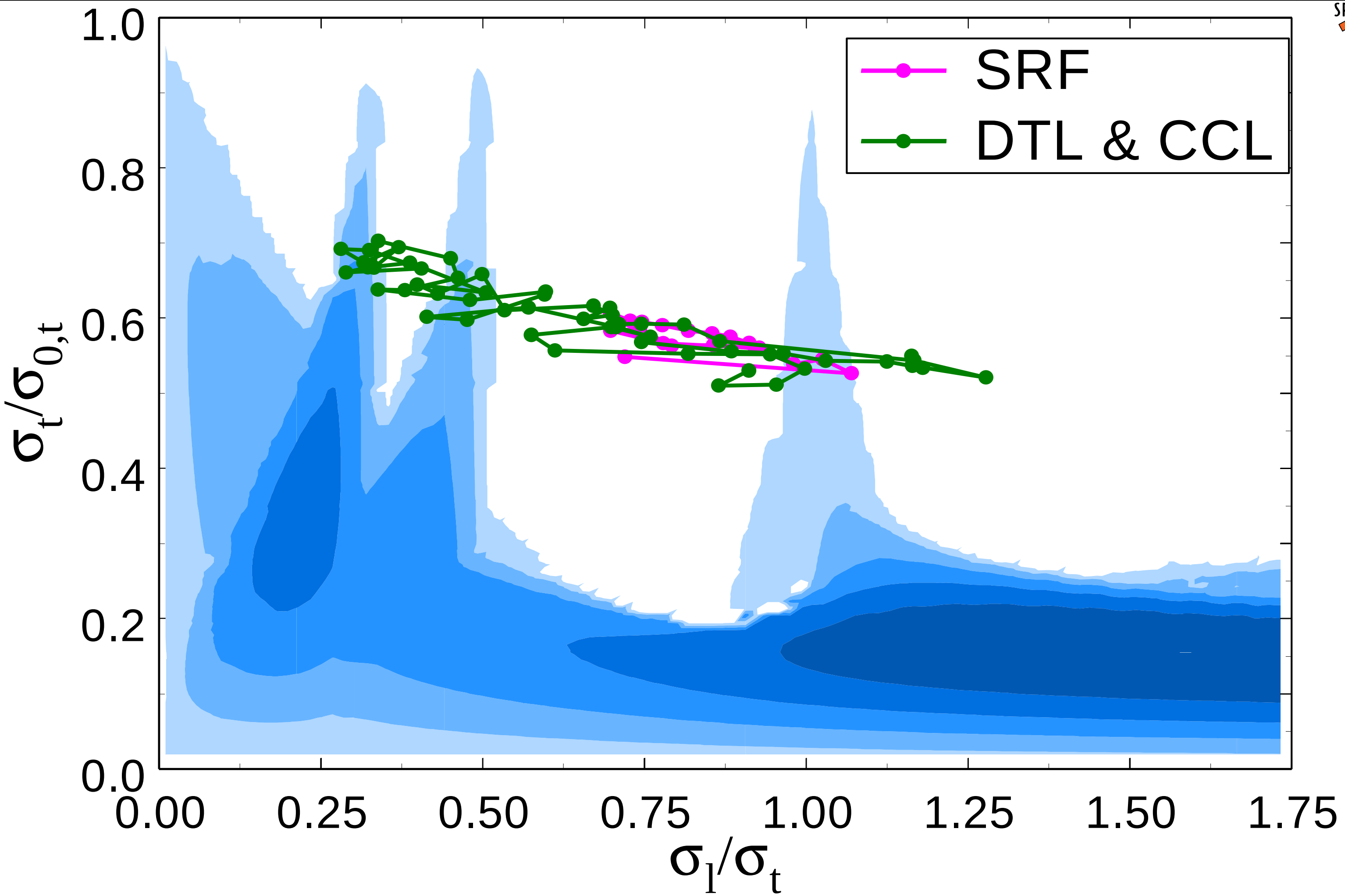
Phase & Quad Laws Avoid Structure & Parametric Resonances Throughout



Continuous Transverse Real-Estate Phase Advance Helps Current Independence



Coherent Resonances Pose Little Risk for Emittance Growth



Expected Linac Errors: Measured, Prototyped & Predicted

	Units	DTL	CCL	SRF
Quadrupoles				
static displacement (x & y)	±mils	5	5	5
dynamic displacement (x)	±mils	0.2	0.05	0.05
dynamic displacement (y)	±mils	0.05	0.01	0.01
pitch & yaw	±°	0.6	0.6	0.6
roll	±°	0.5	0.3	0.3
gradient	±%	measured	0.5	0.5
3rd order	on/off	on	on	on
harmonics	±%, °	measured	prototype	estimate
chromaticity	on/off	on	on	on
PMQ correction	on/off	on	-	-
Cavities & Cavity Fields				
static displacement (x & y)	±mils	5	12	80
static rf set point [1,2]				
amplitude	±%	1	1	[2,3]
phase	±°	1	1	[4]
Dynamic rf set point				
amplitude	±%	0.5	0.5	0.5
phase	±°	0.5	0.5	0.5
Beam Position Monitors				
uncertainty in electric axis	±mm rms	0.125	0.15	0.4
static displacement (x & y)	±mils	5	5	80

[2] set point errors are correlated & depend on tuning procedure

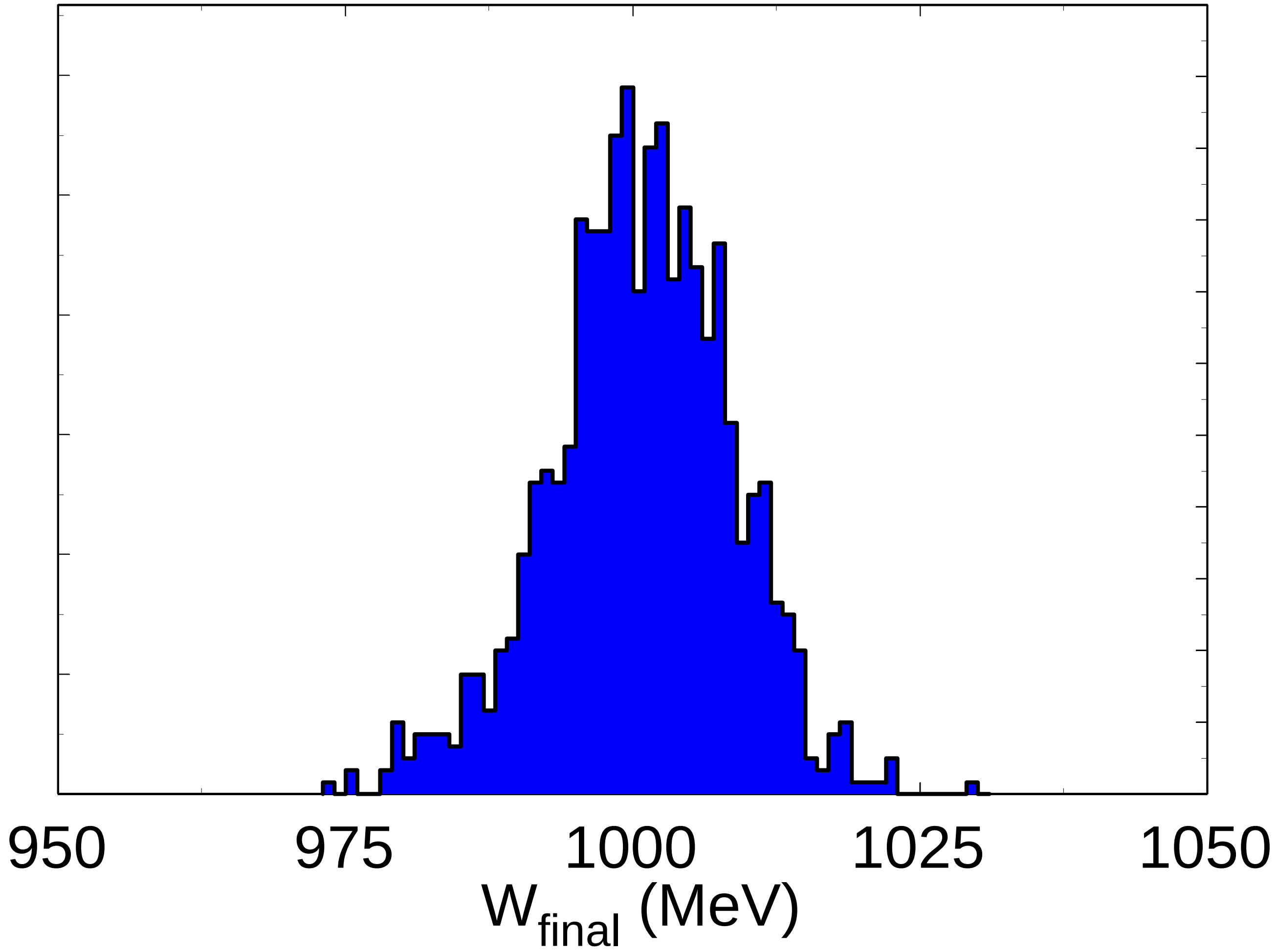
[3] β_1=±10, β_2=-21%, +7% per Sundelin distribution

[4] correlated with amplitude to preserve σ_l

Performance Criteria, Including Expected Errors, are Met

- W_{final}: 1 GeV ±15 MeV
- W_{final} stability: ± 0.2 MeV
- W_{final} spread: ± 0.85 MeV (rms)
- Transverse stability: ± 0.2 mm
- Protons missing foil: < 2%
- ε_{foil} : < 0.034 π cm-mrad (rms, norm)
- Beam loss: < 1 W/m

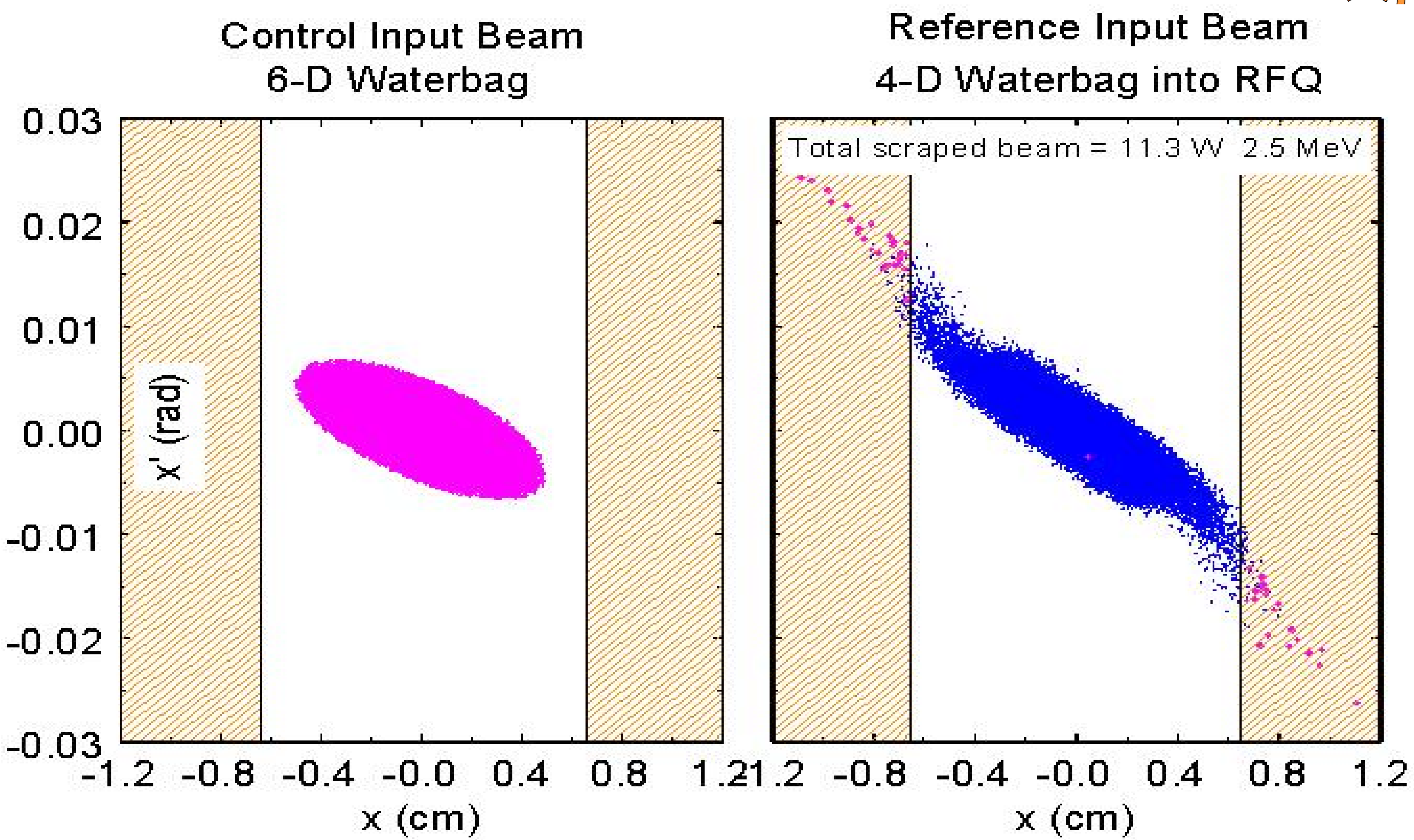
$\langle W_{final} \rangle$ = 1 GeV ±15 MeV (±2σ) and is a Function of SRF Cavity Quality



For Error Studies we Compare 2 Initial Beam Distributions

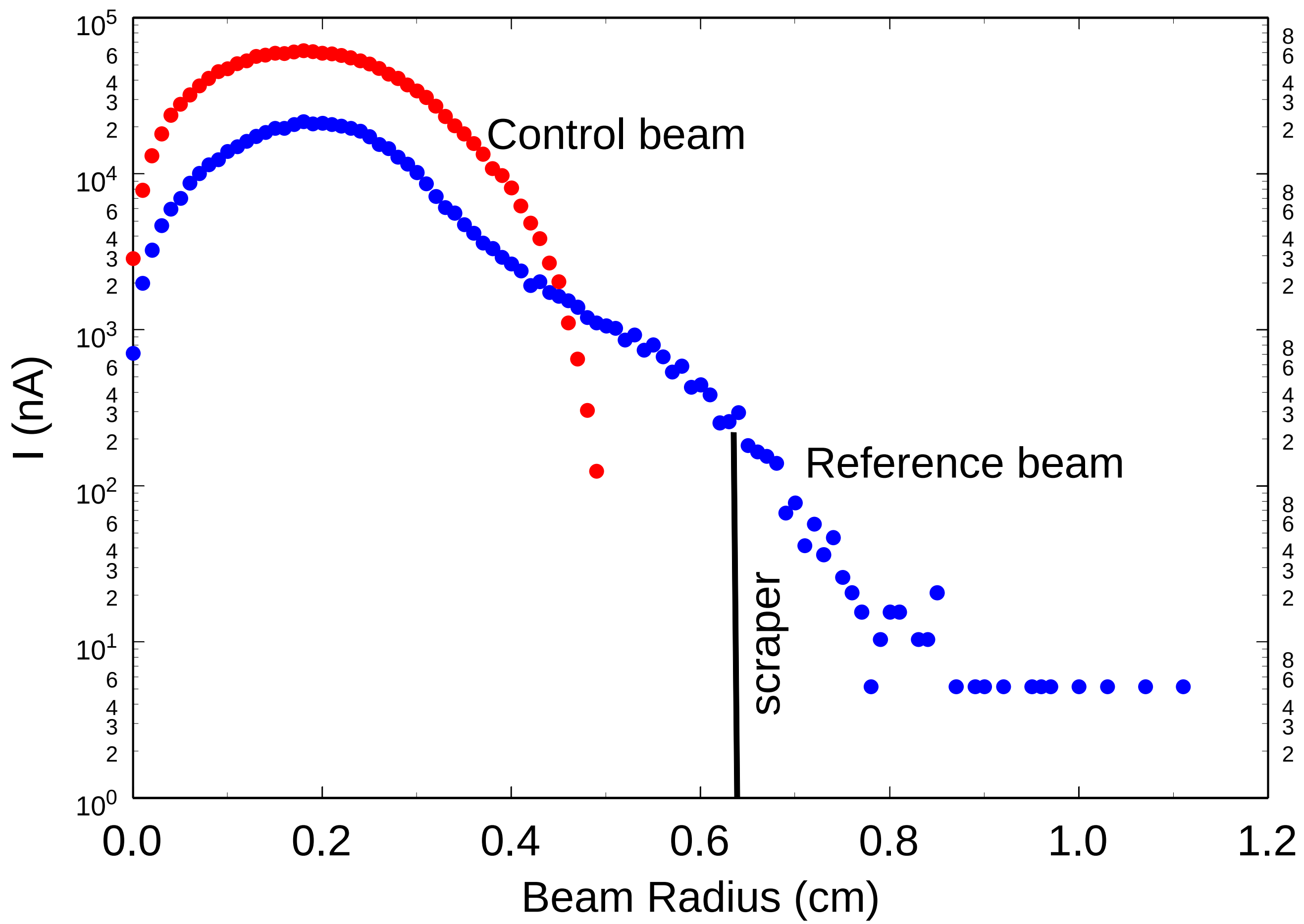
- Control beam: 6-D water-bag at DTL entrance
- Reference beam: 4-D water-bag at RFQ entrance
  - TOUTATIS transports beam through RFQ
  - 3-D PARMILA transports beam through MEBT
  - All low energy particles are deleted
  - All particles outside ±6.45 mm are deleted
    - Not to simulate scraping but to make sure error studies reflect properties of the linac not of the initial particle distribution
- Both beams have the same rms emittance and Twiss parameters

For Error Studies we Compare 2 Initial Beam Distributions

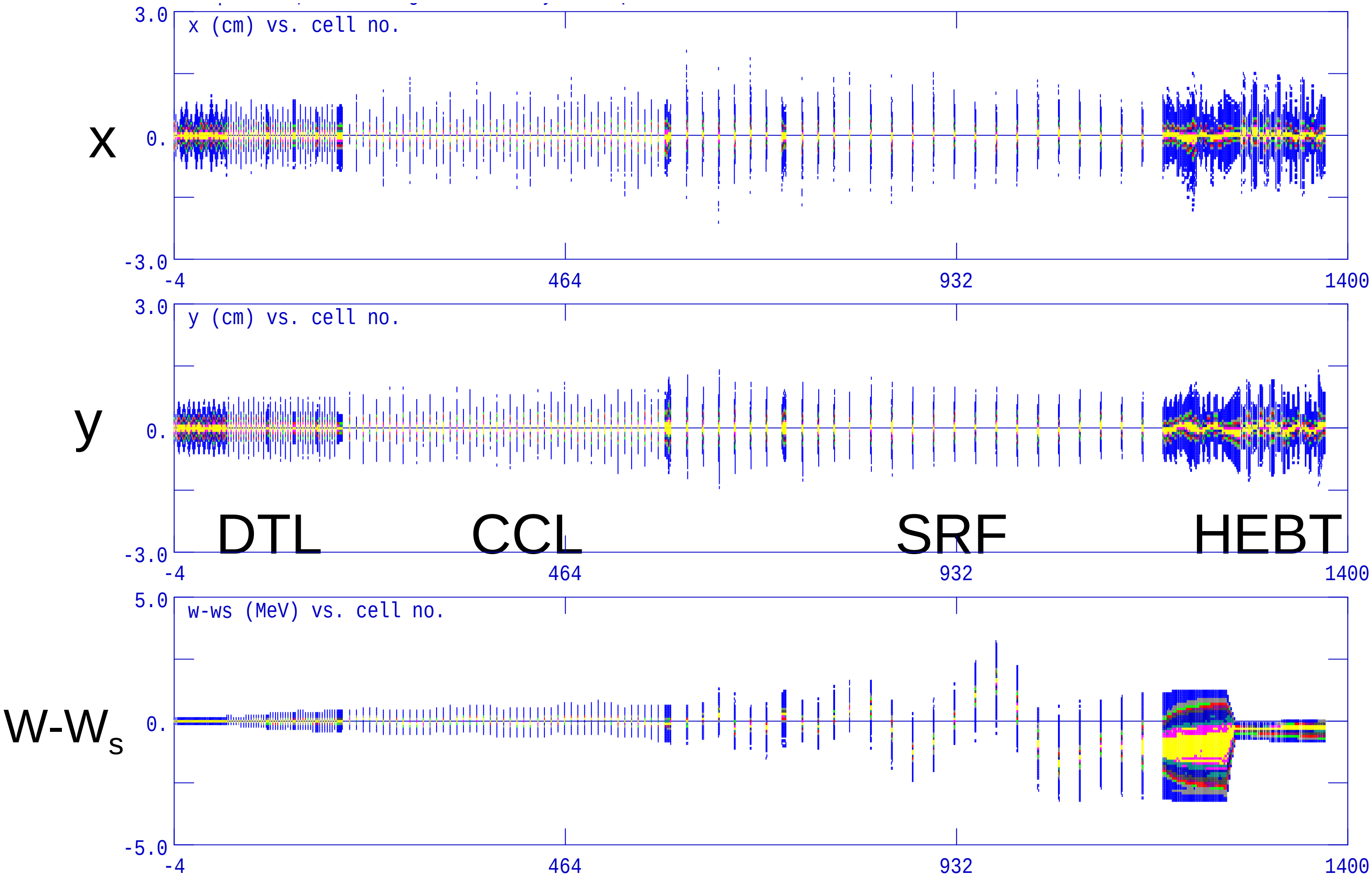


The Reference Beam Distribution Develops a Halo in the RFQ

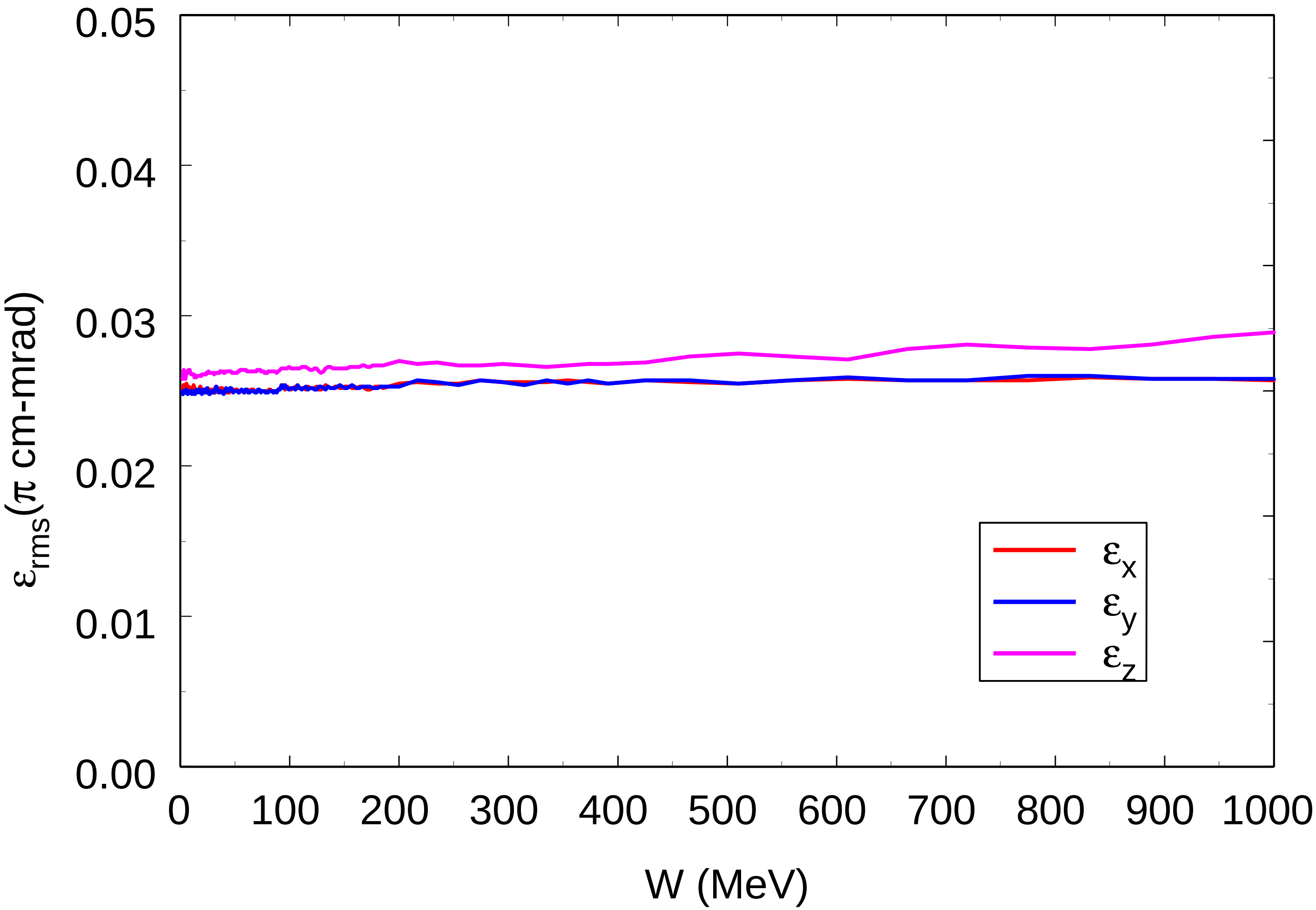
Radial Particle Distribution at the DTL



Reference Beam is Matched, Energy Corrector ϕ Feed-Forward Off

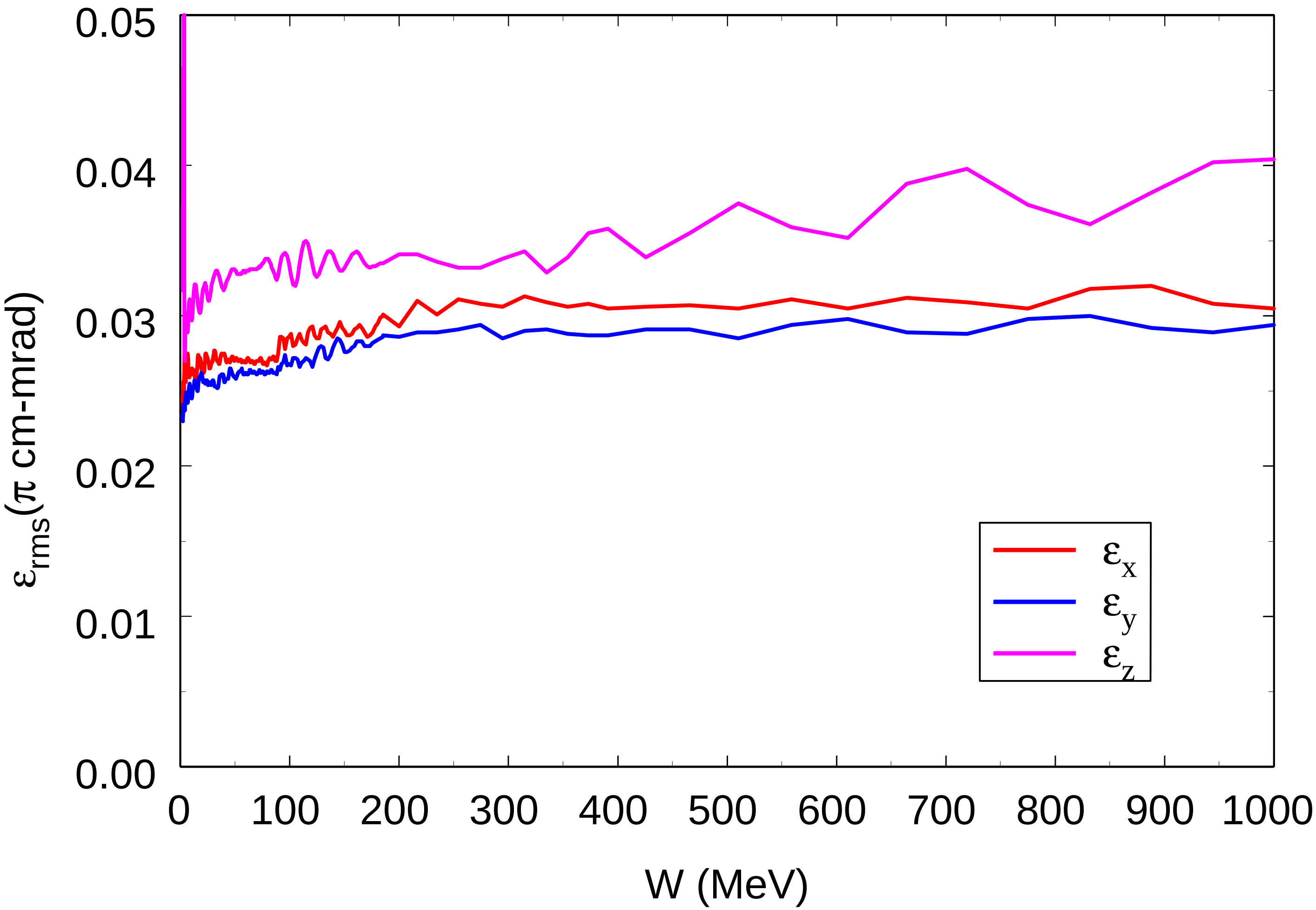


Control Beam:
$\varepsilon_{trans,\ rms}$ Grows 3%



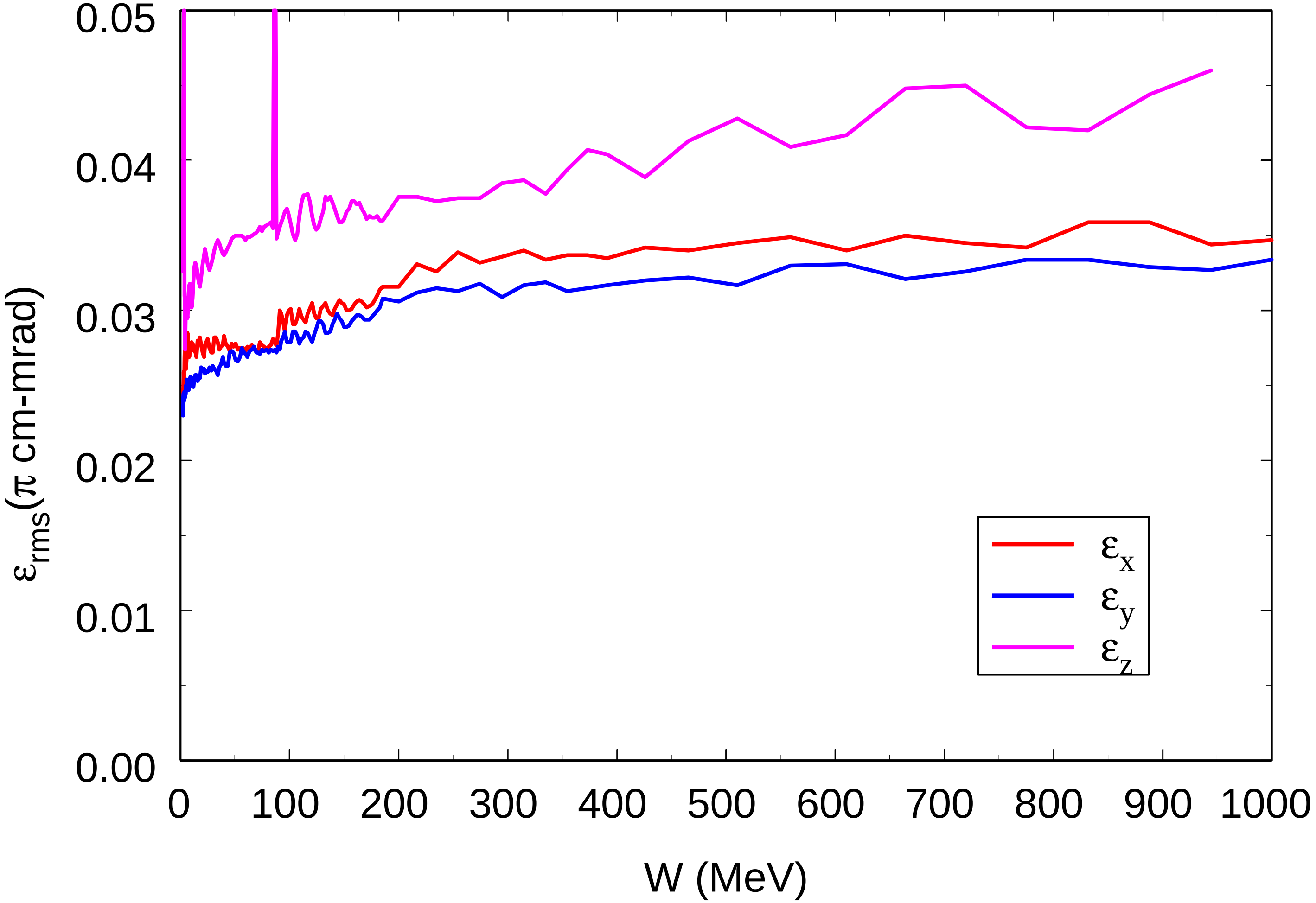
Reference Beam:

$\varepsilon_{trans, rms}$ Grows 26% Without Errors

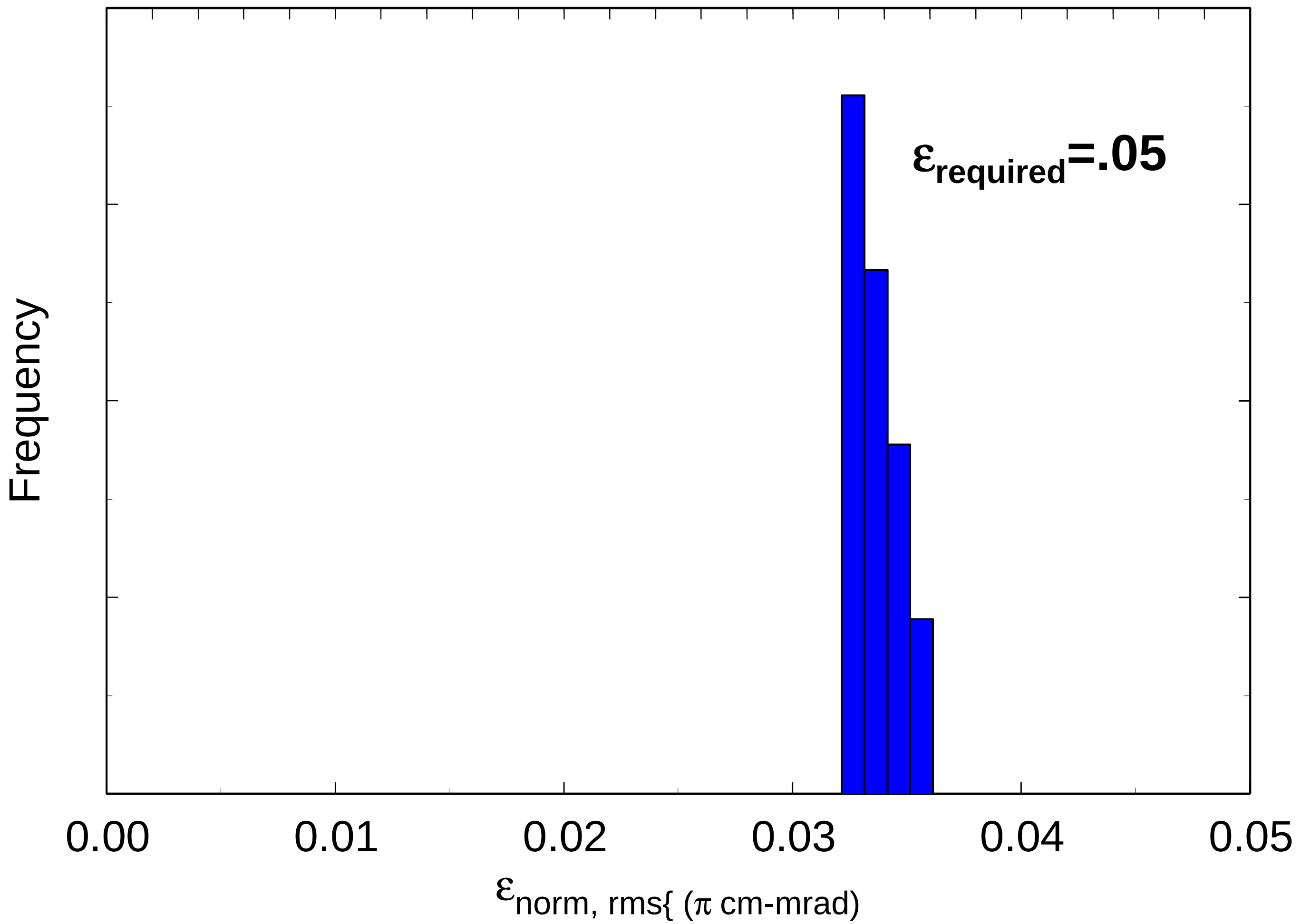


Reference Beam:

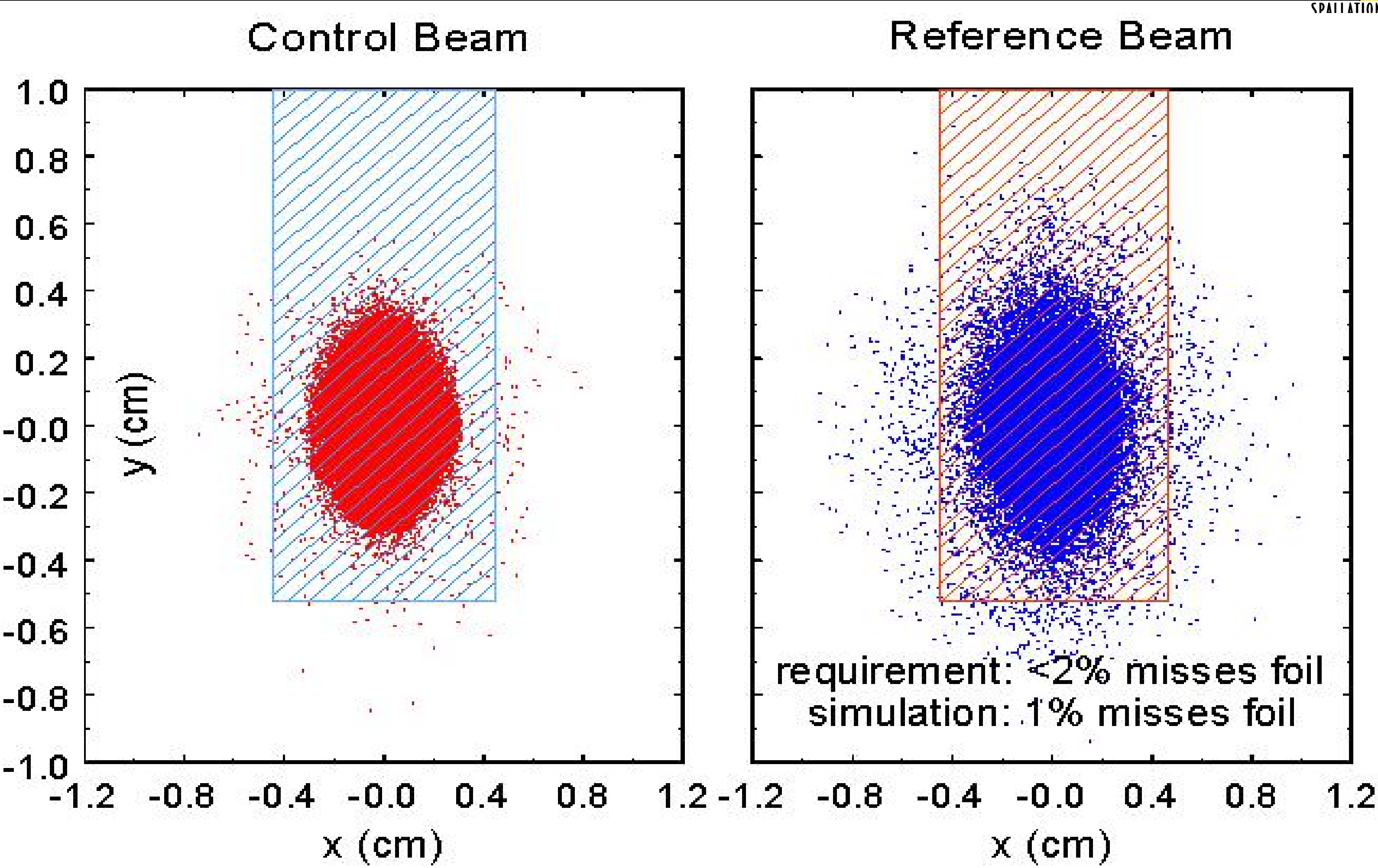
$\varepsilon_{\text{trans, rms}}$ Grows 37% With Errors



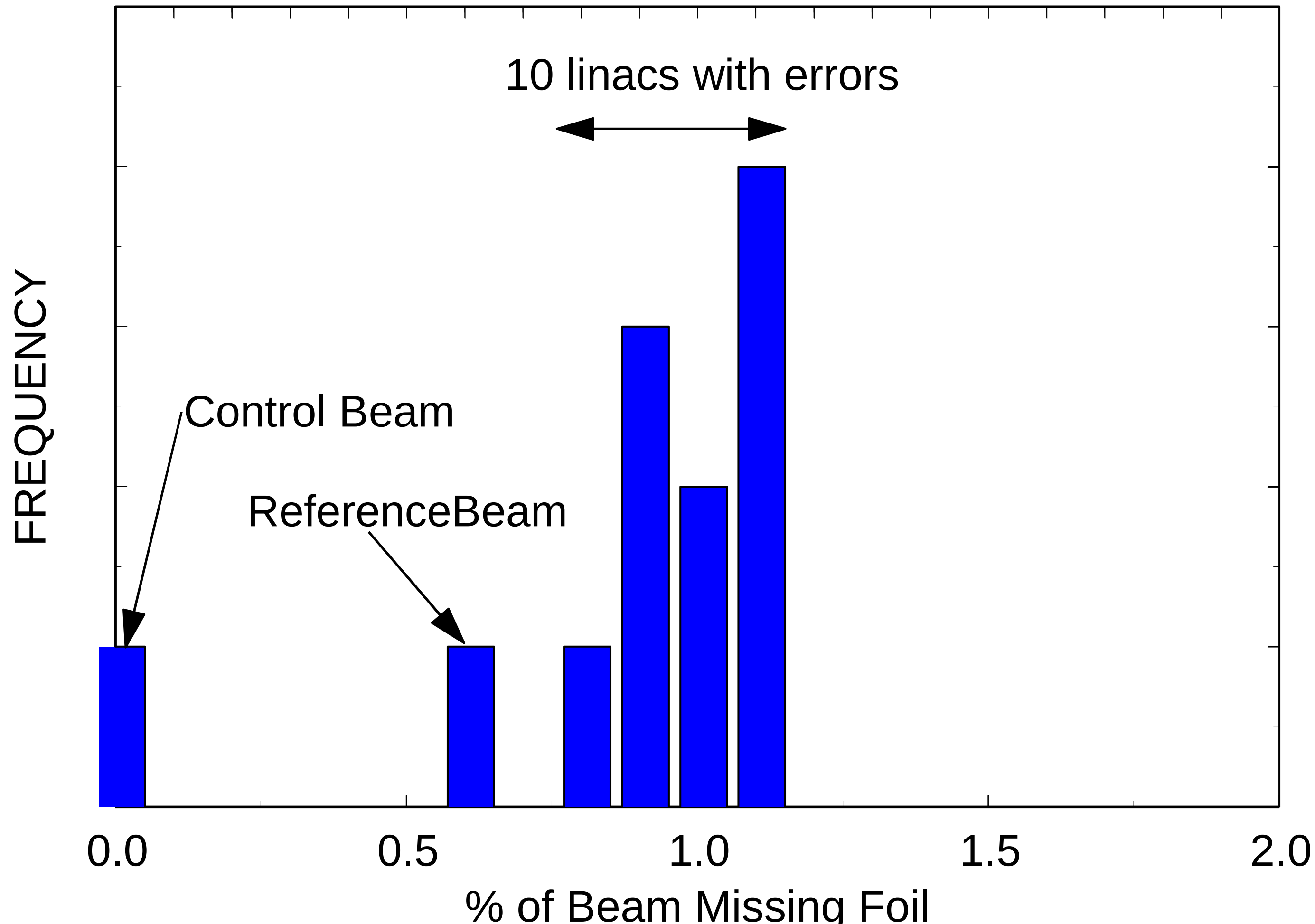
Expected $\varepsilon_{trans,\ rms}$ is Based on Ten 300k Particle Simulations Including all Errors



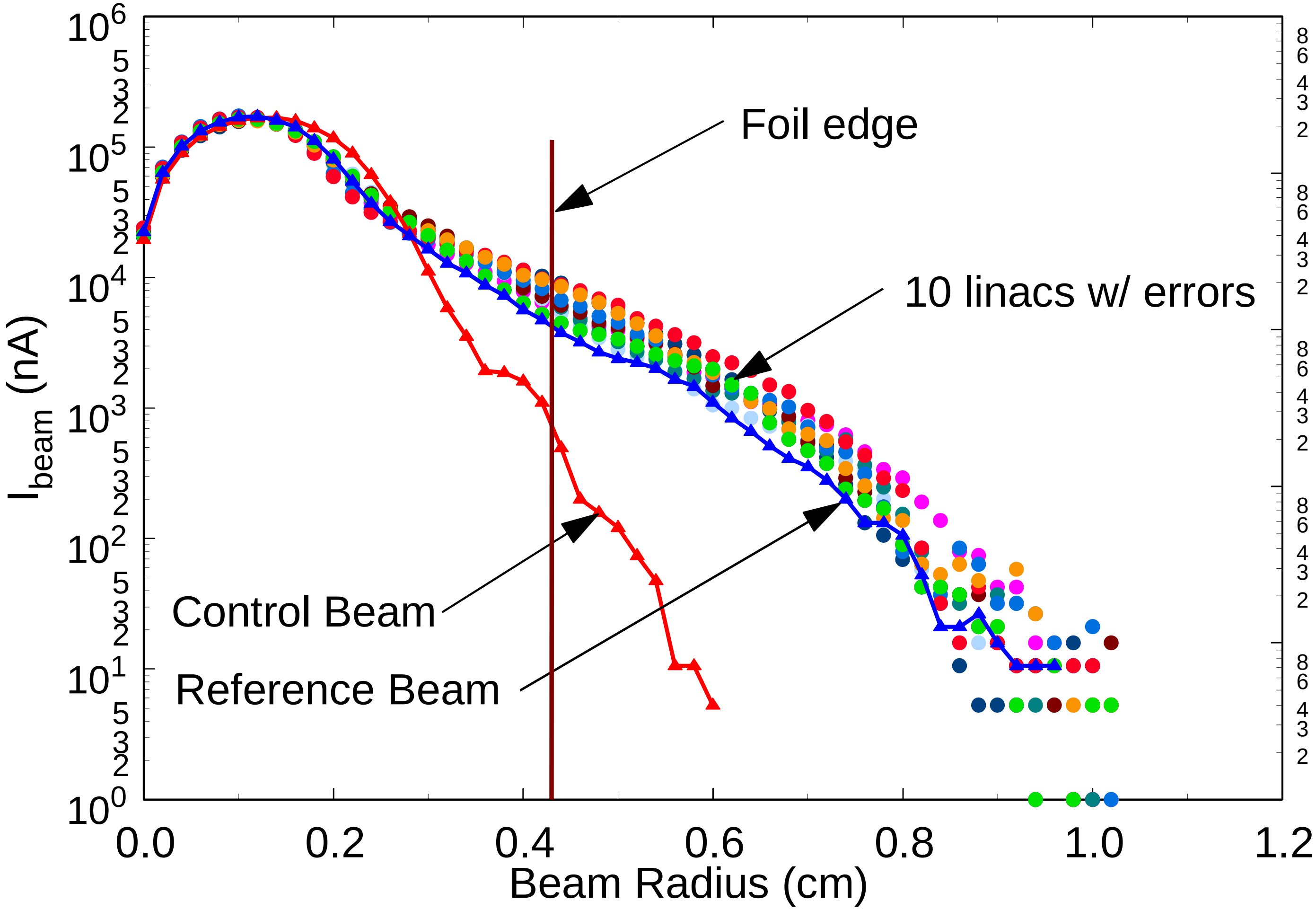
1% of the Reference Beam Misses the Injection Foil



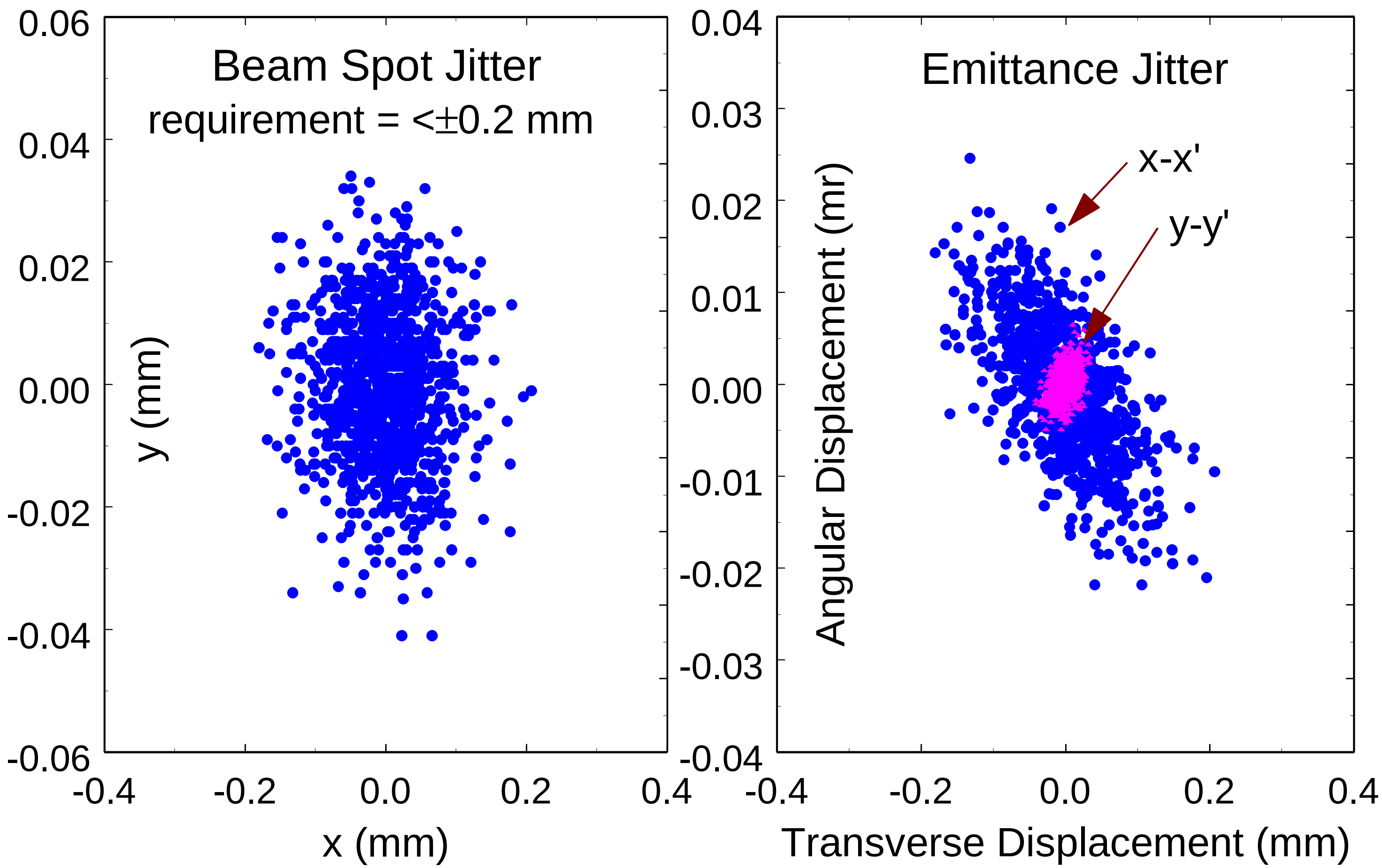
Expected Foil-Misses: Meets Requirement of 2%



Expected Errors Have Small Effect on the Beam Distributions at the Foil



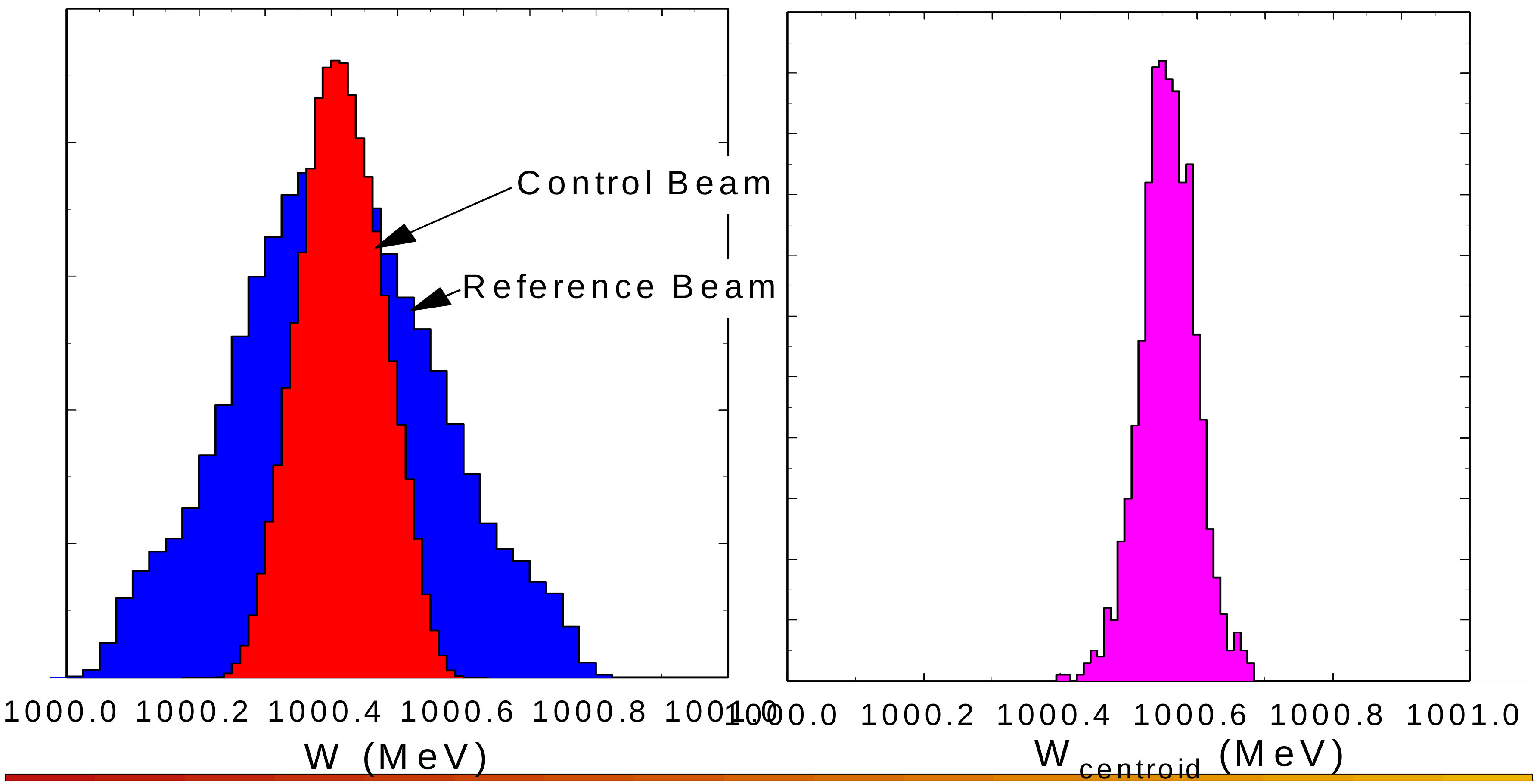
Transverse Jitter at the Foil is a Function of Quad Vibrations & Increases the Effective Emittance



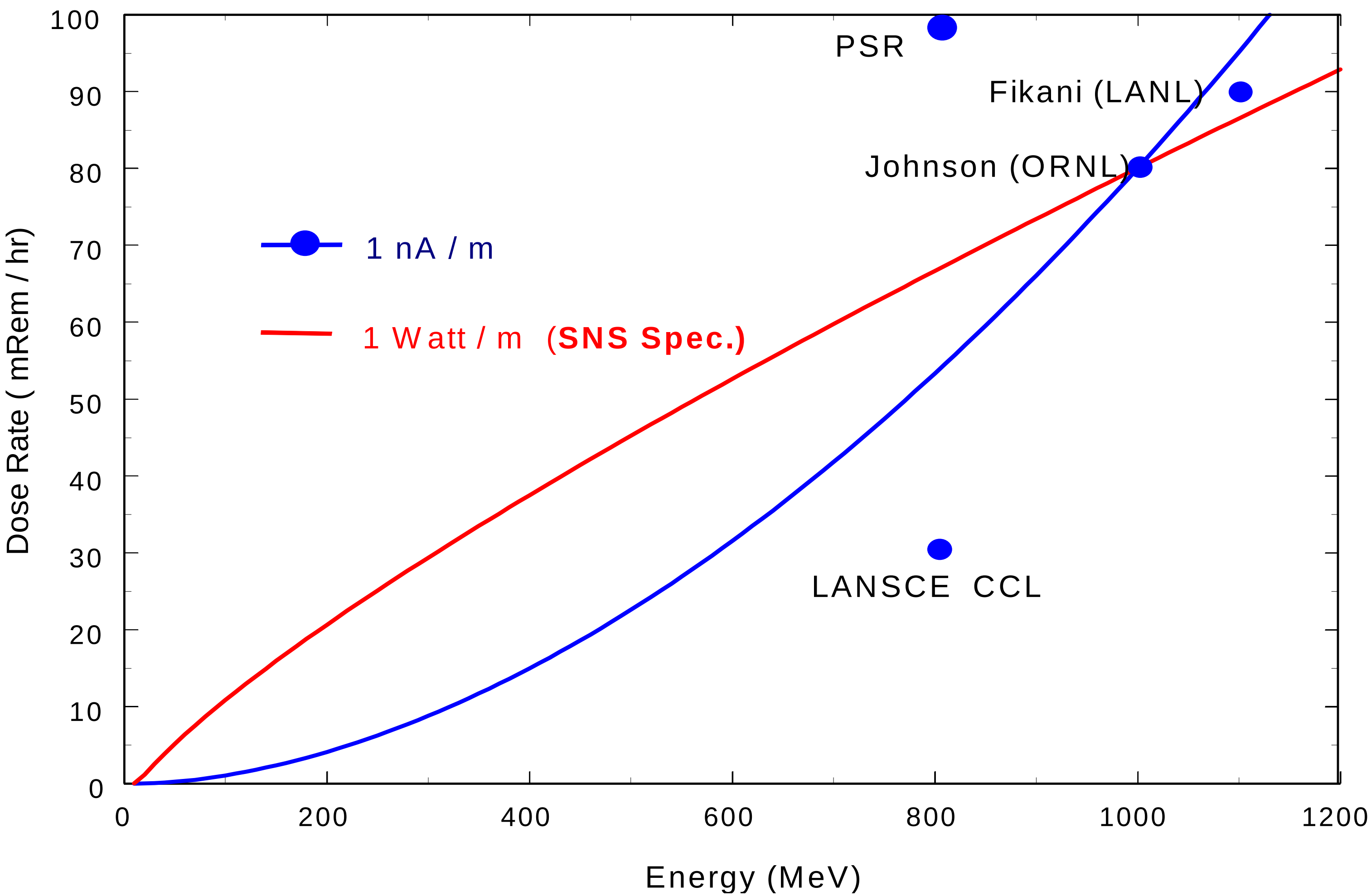
Energy Spread ∝ rf Tuning (ϕ & E_0), Jitter ∝ rf Control Tolerances (ϕ & E_0)

Energy Spectrum
spec=0.85 MeV rms

Energy Jitter
spec=0.2 MeV



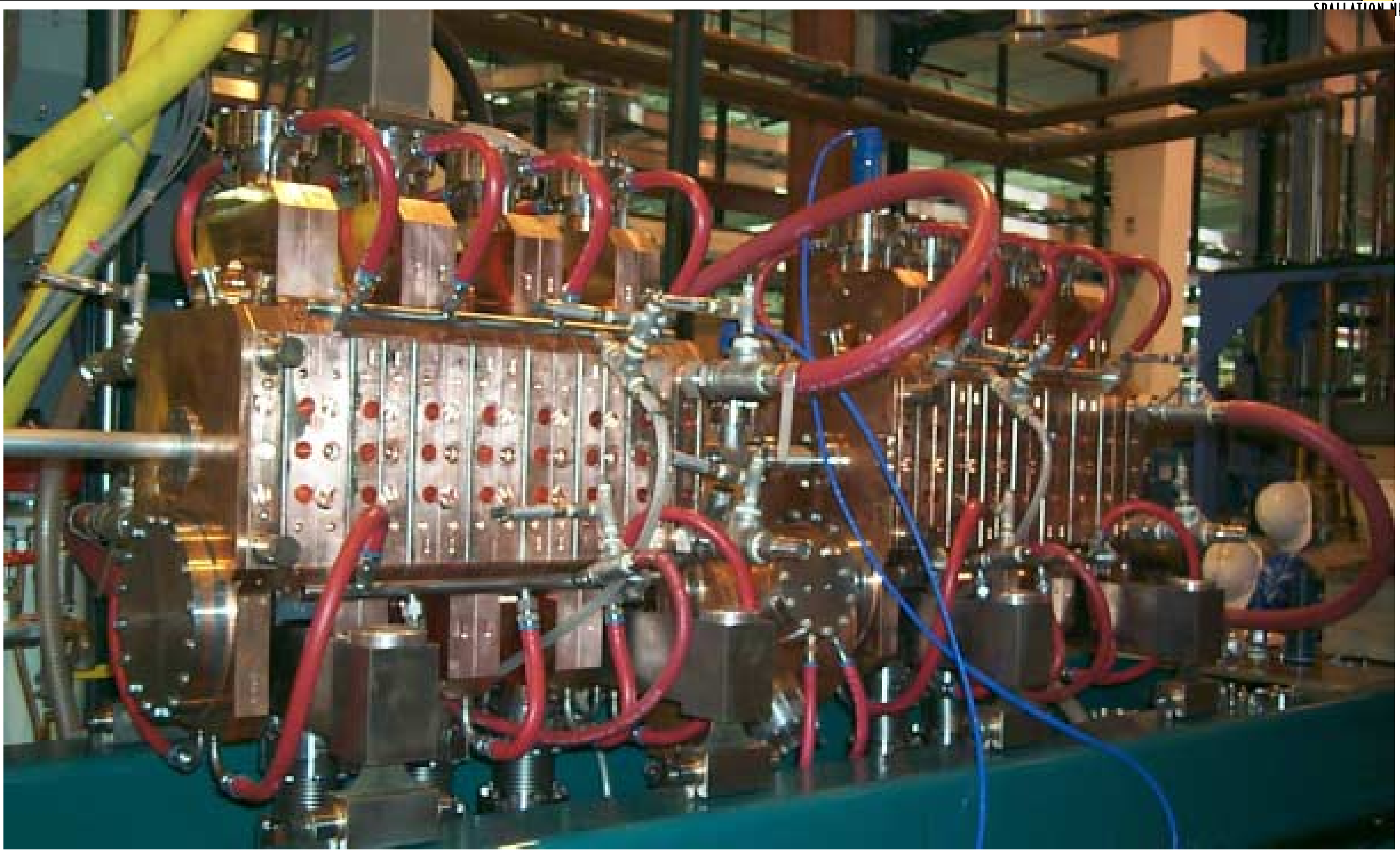
Permissible Activation ∝ W, Dose Rate at 1 ft, 4 Hours after Beam-Off



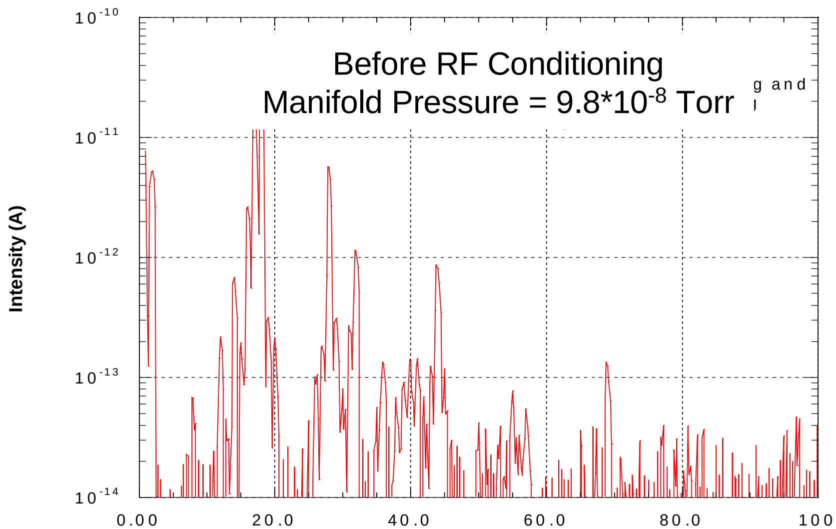
Beam Loss Mechanisms

- Gas Stripping — predicted from vacuum measurements
- Magnetic Stripping: — negligible
- Longitudinal beam loss
  - **poor MEBT matching** — will be derived from matching algorithms
  - turn-on transients: — minimized by beam current ramp
  - dynamic ϕ & E_0 errors: — no effect is observed
  - mistuned modules (ϕ & E_0): — no effect is observed
- Transverse beam loss
  - misalignments & missteering: simulated
  - **halo**
    - initial beam distribution: — simulated
    - poor MEBT matching: — will be derived from matching algorithms
- No beam loss is observed in the SRF linac

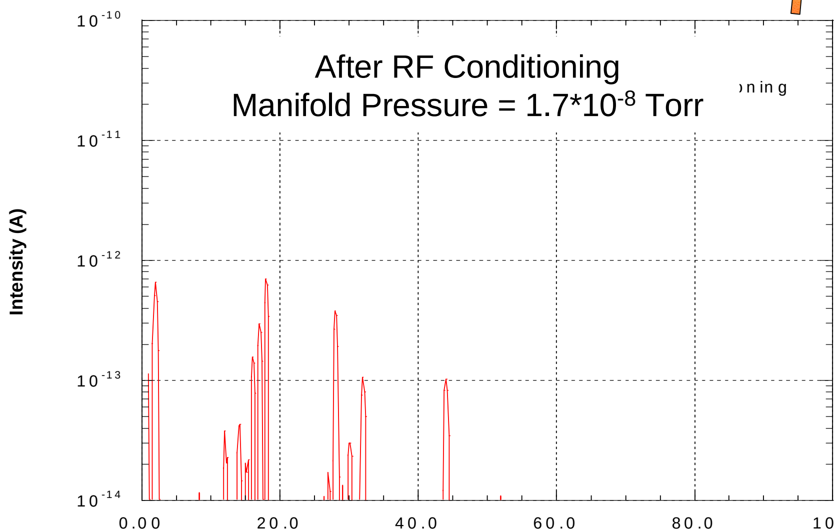
CCL Hot Model Vacuum Improved with Time & Conditioning



RGA Scans Show a reduction in all Heavy Gases With Time & Conditioning



Gas Species	Beamline Partial Pressure (Torr)	% Total Gas Composition
H2	3.10e-09	1.5
He	0.0	0.0
H2O	1.59e-07	79.4
N2 or CO	2.08e-08	10.4
O2	4.81e-09	2.4
Ar	6.18e-10	0.3
CO2	4.66e-09	2.3
Other	7.0e-09	3.7
Total	2.0e-07	100

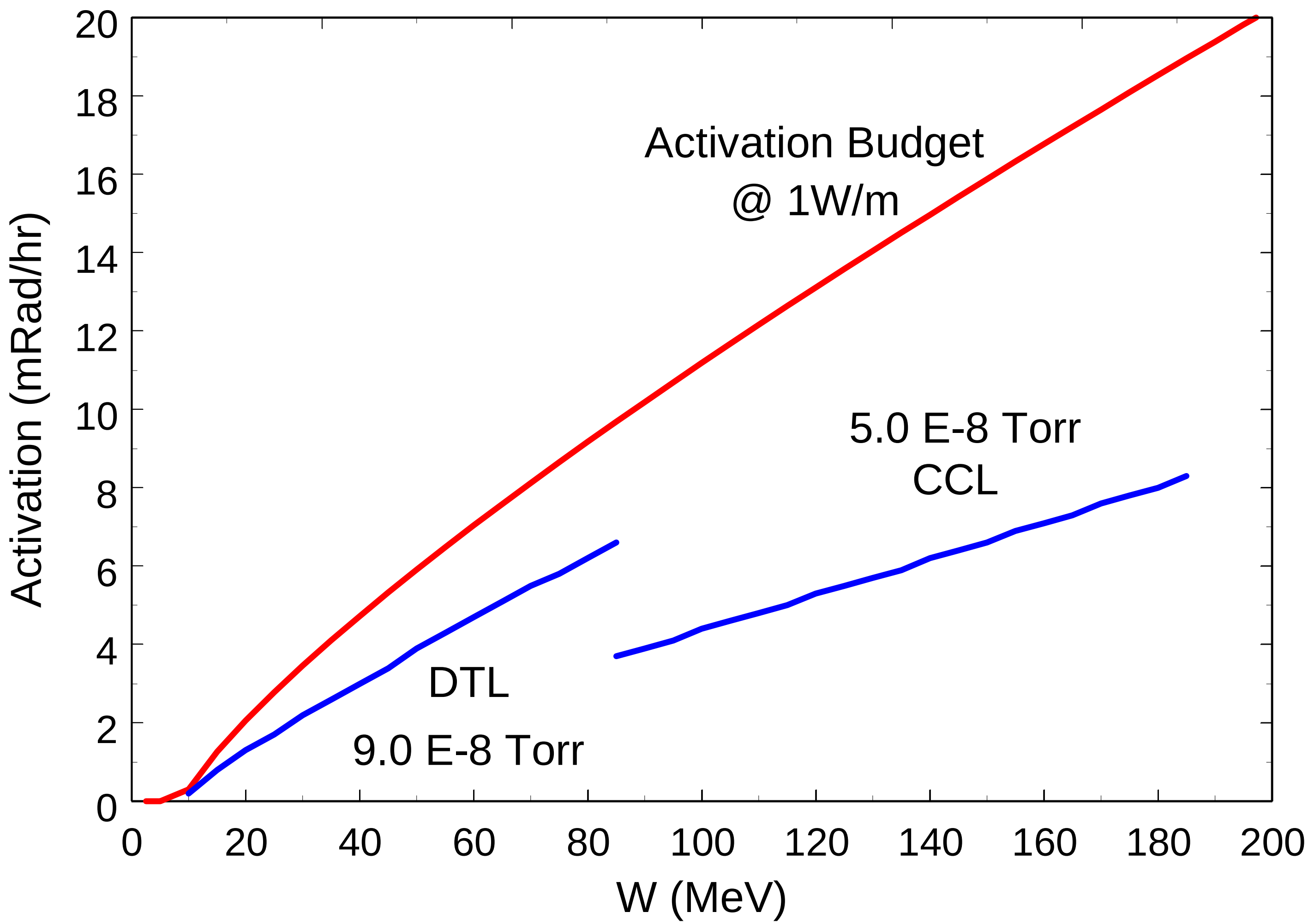


Gas Species	Beamline Partial Pressure (Torr)	% Total Gas Composition
H2	2.39e-09	6.9
He	0.0	0.0
H2O	1.35e-08	39.2
N2 or CO	8.63e-09	25.1
O2	2.90e-09	8.4
Ar	2.07e-10	0.6
CO2	3.73e-09	10.8
Other	3.06e-09	9.0
Total	3.4e-08	100

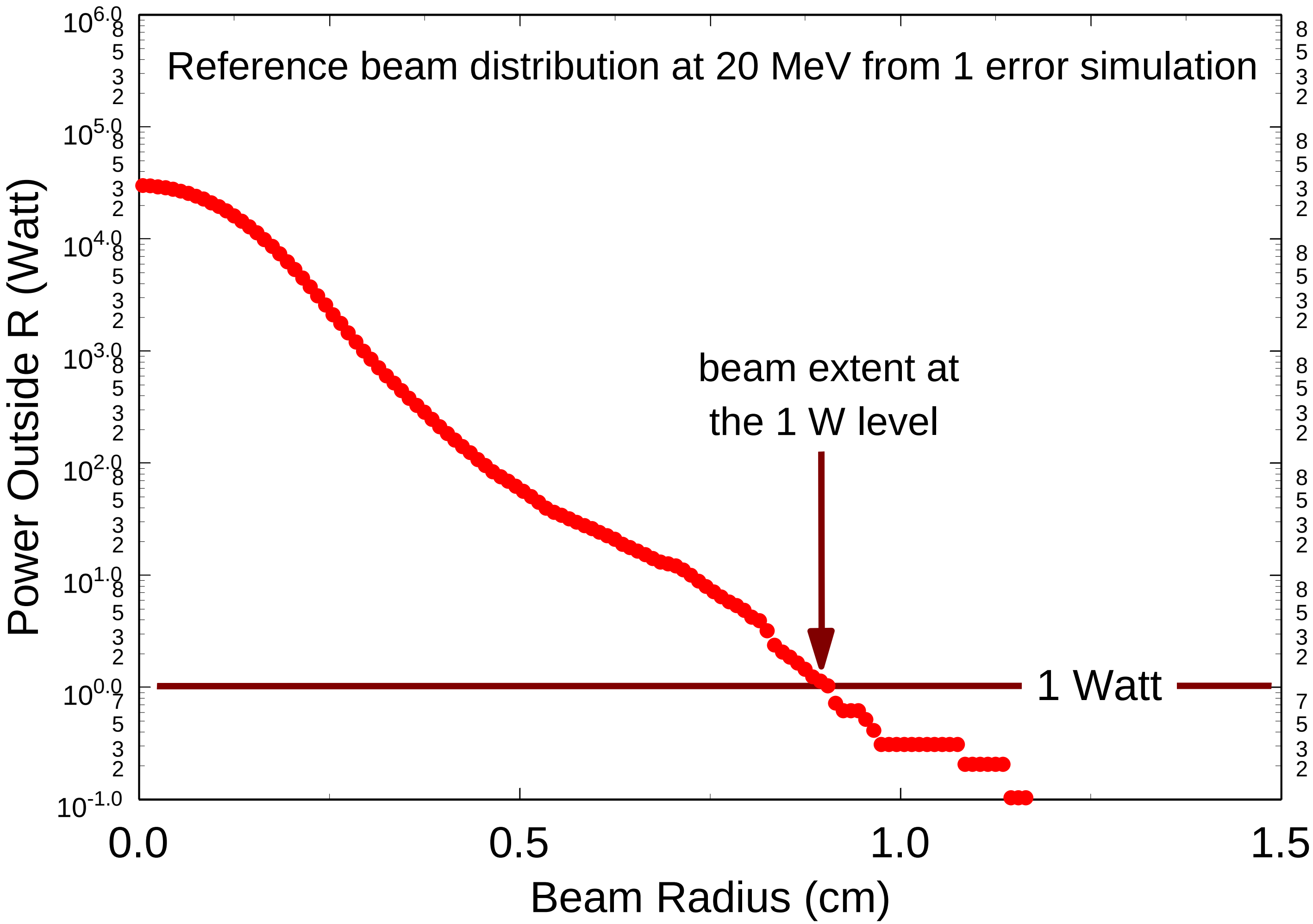
Expected Gas Stripping is Based on CCL Hot-Model RGA Measurements

Gas	Molecular weight	Partial pressure	Electrons per molecule	Estimated beam loss @185 MeV
		torr		watts/meter
H_2	2	3.5E-09	2	0.006
He	4	9.0E-12	2	0.000
?	12	3.0E-10	6	0.001
?	14	6.0E-10	7	0.003
?	15	4.0E-10	7	0.002
?	16	3.0E-09	8	0.019
H_2O	18	1.8E-08	10	0.144
N_2 + CO	28	8.7E-09	14	0.097
O_2	32	2.4E-09	16	0.031
Ar	40	4.3E-10	18	0.006
CO_2	44	2.1E-09	22	0.037
Total, rf off		3.9E-08		0.347
Total, rf on		5.0E-08		0.440
w/o H_2O, N_2 & CO		1.6E-08		0.134

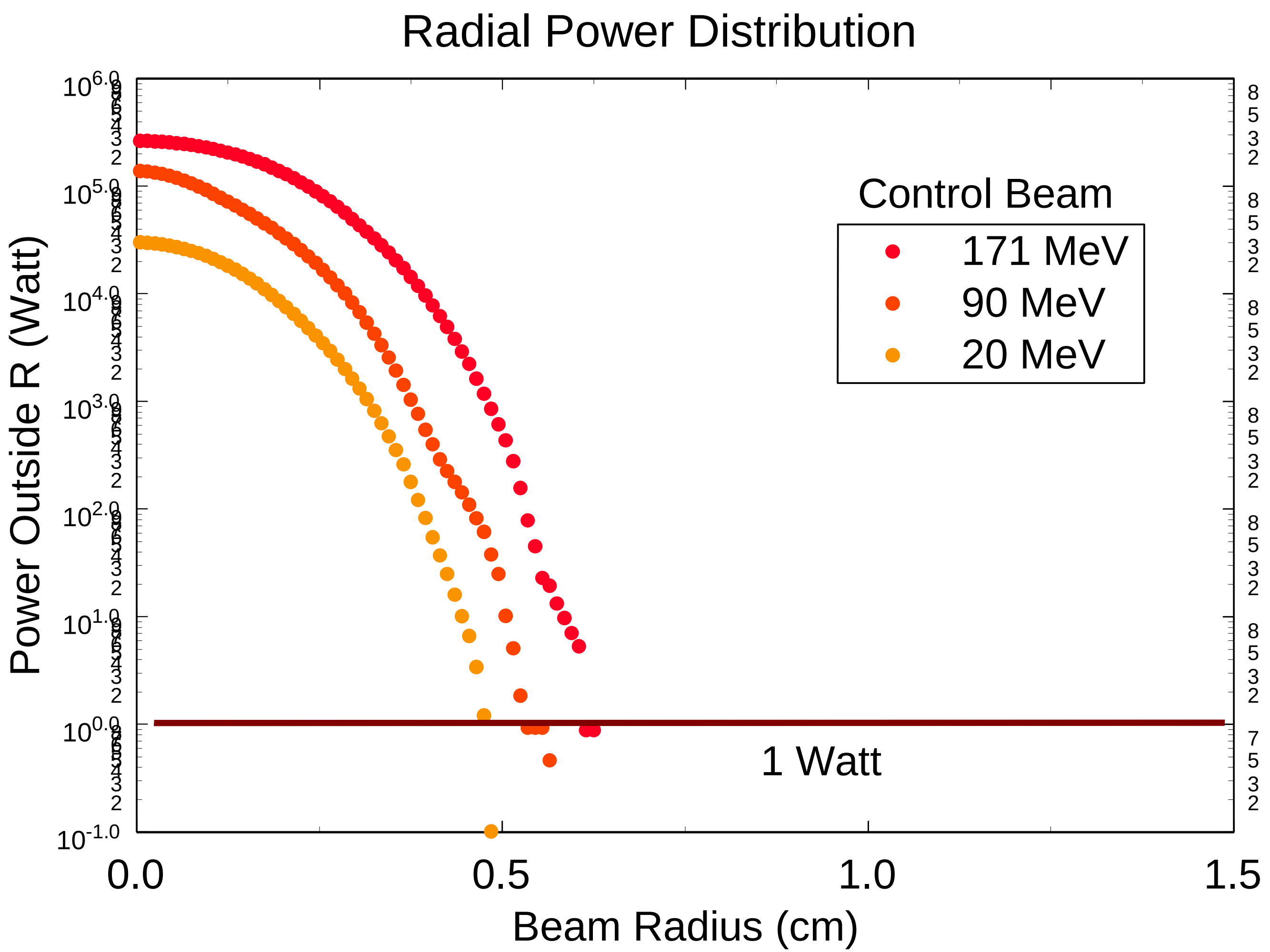
Gas Stripping in the DTL/CCL will Consume Part of the Beam Loss Budget



A Radial Power Distribution Identifies the Beam Edge at the 1 Watt Level

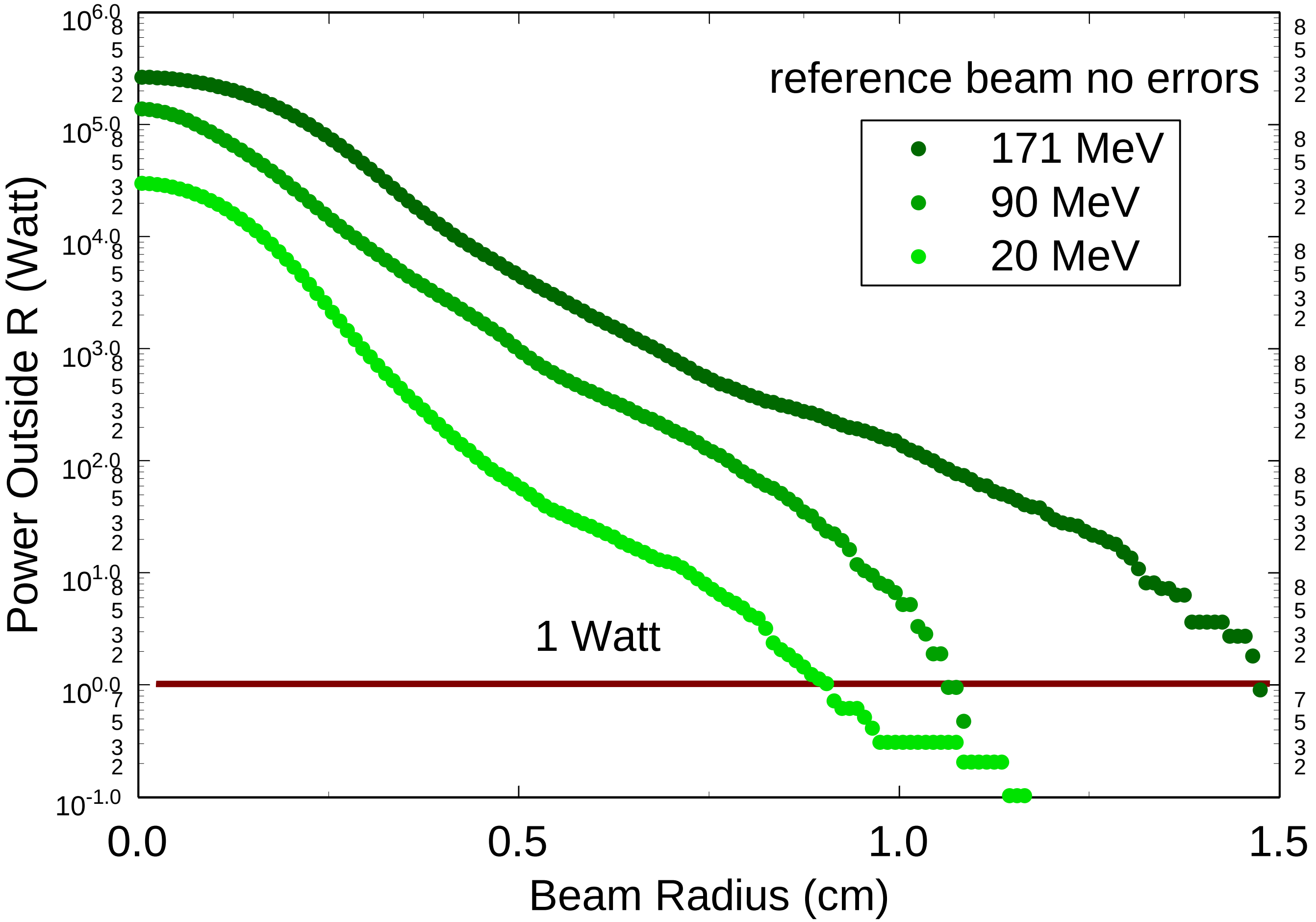


Control Beam Develops Very Little Halo in the Linac

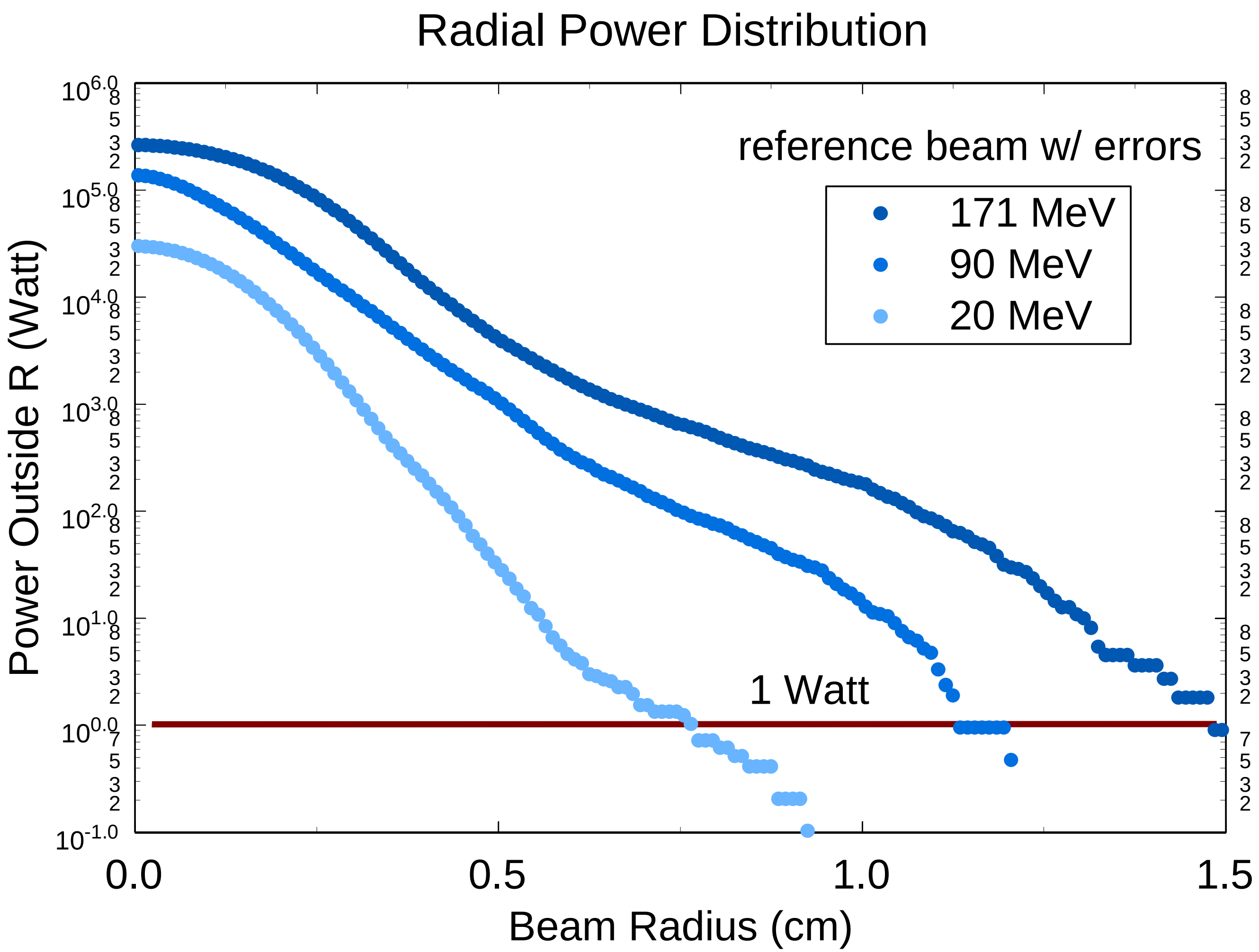


Reference Beam Without Errors Develops a Significant Halo

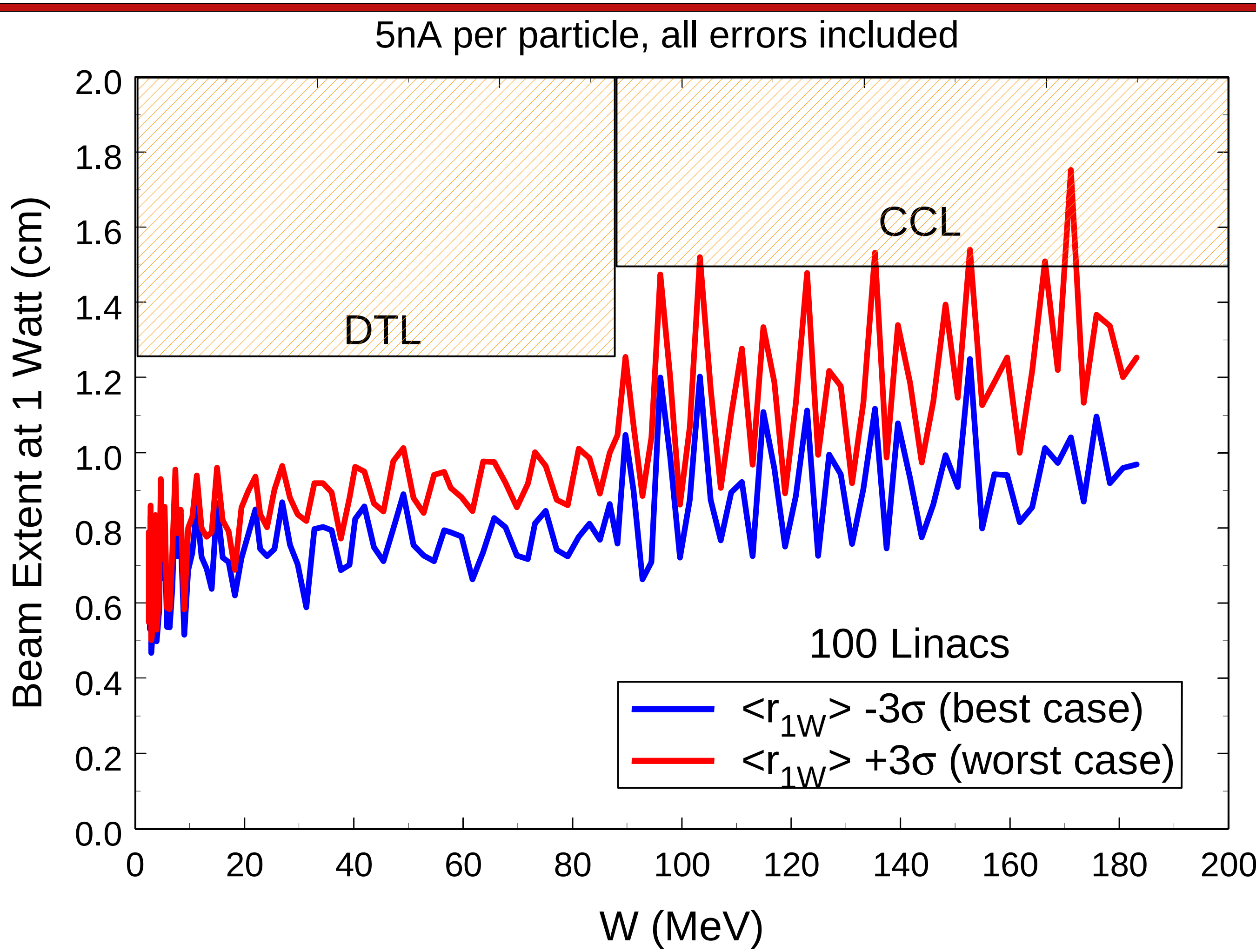
Radial Power Distribution



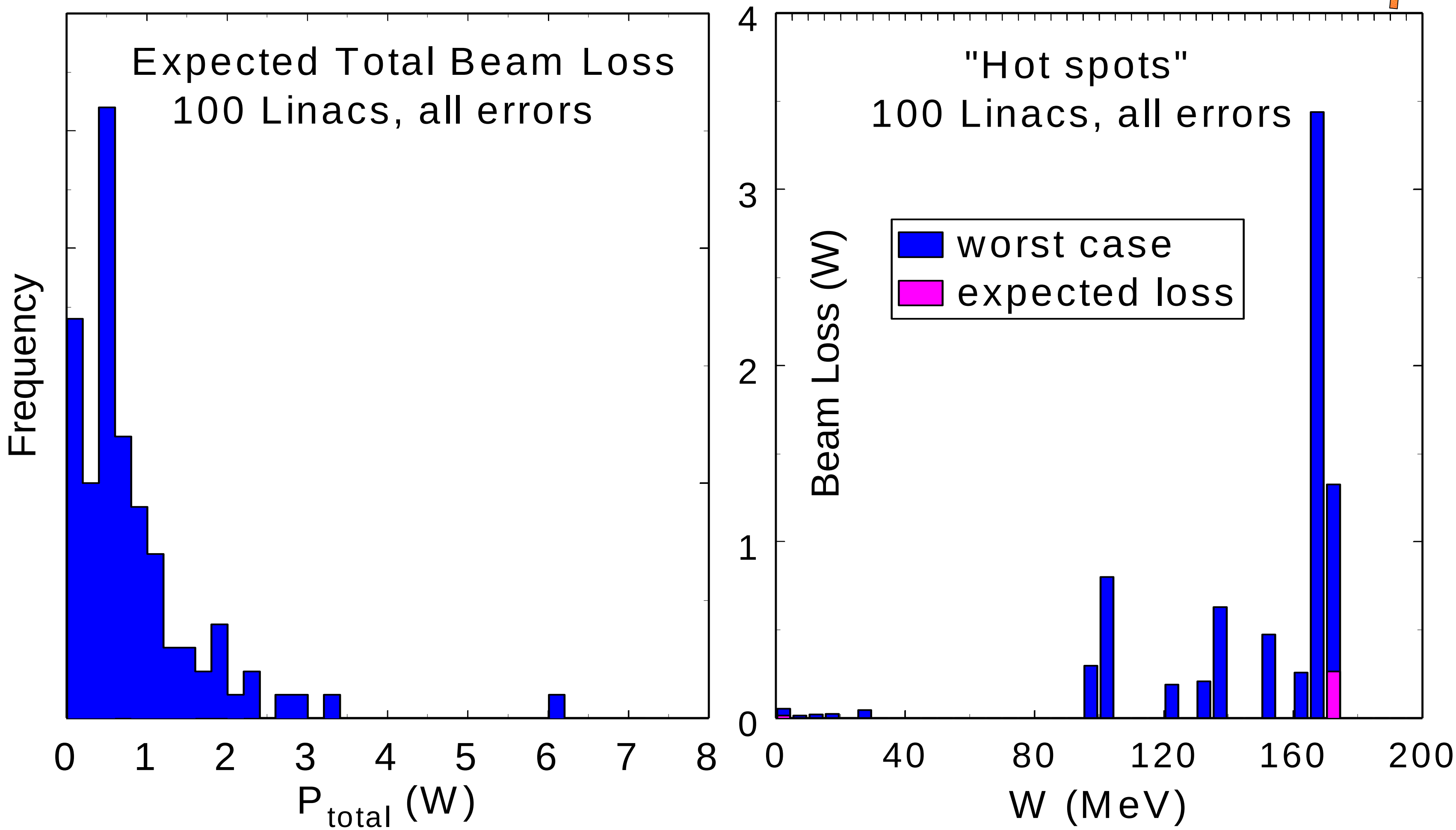
Inclusion of Errors Has Little Effect on Reference Beam Evolution



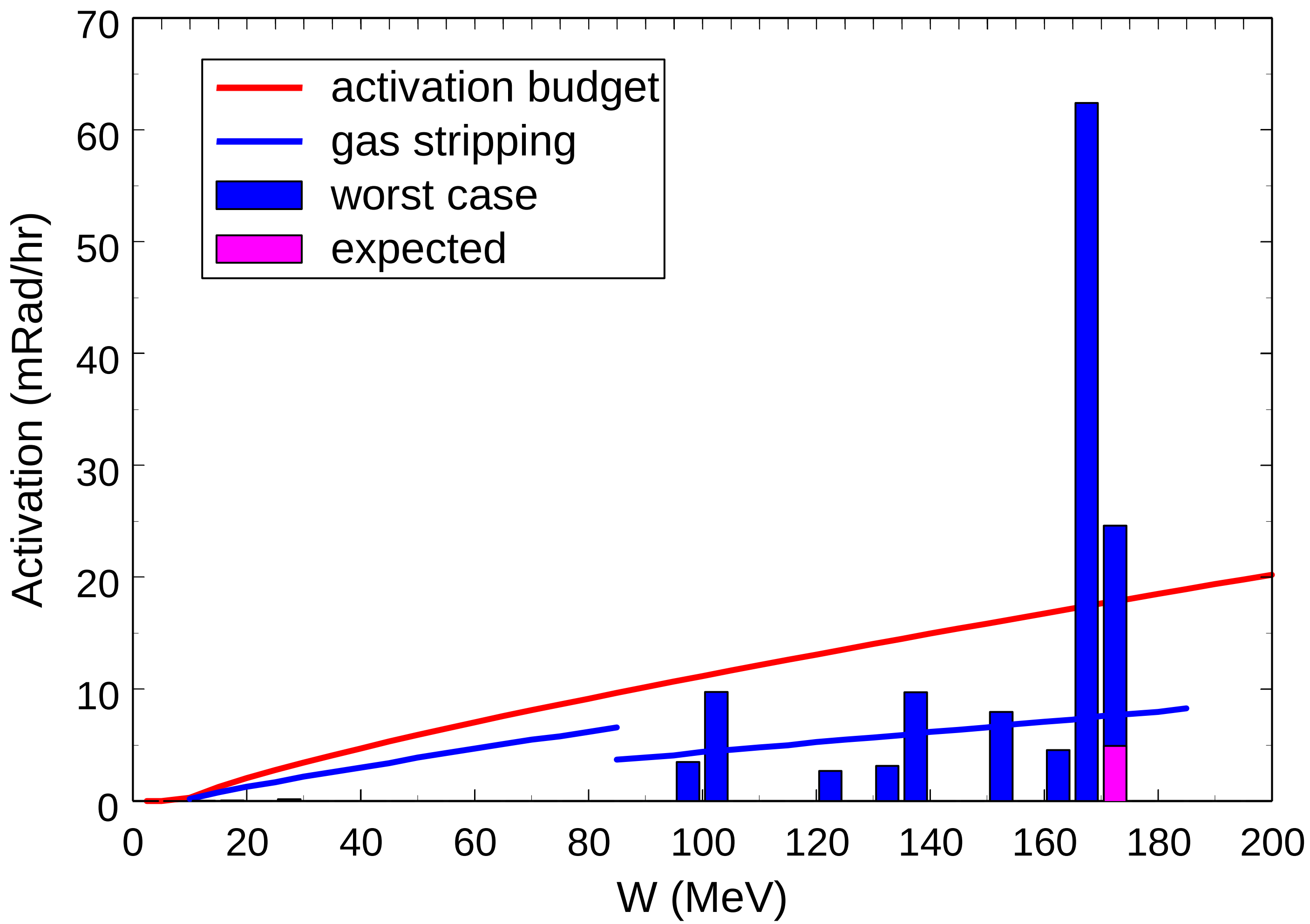
Maximum Expected Beam Extent at the 1 Watt Level Occurs in the CCL



Total Expected Beam Loss & Hottest Expected Spot Meet Requirement



Activation Expected to Meet 1 W/m Requirement



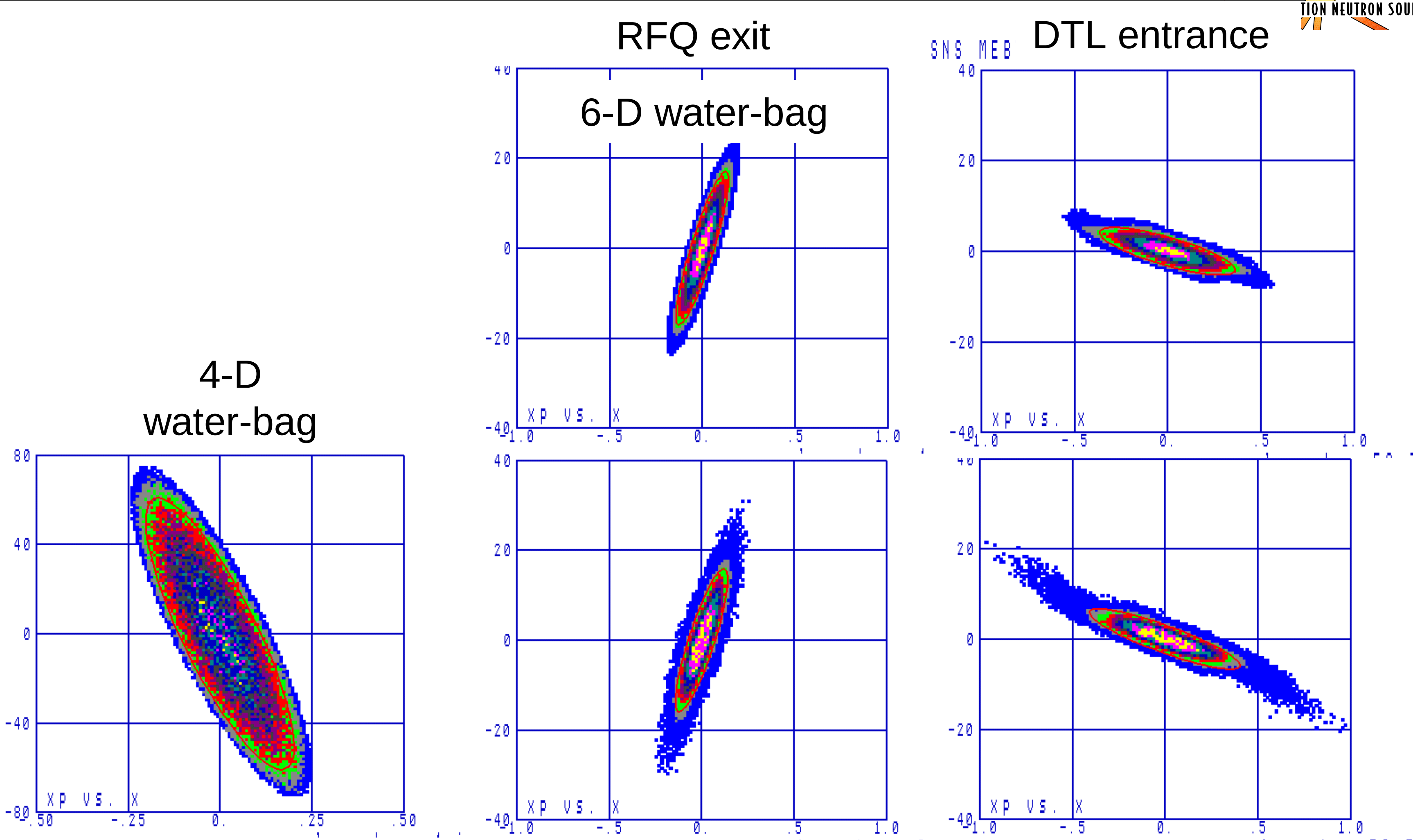
Simulations using a matched reference beam show …

- Linac is inherently stable
- Longitudinal stability in the SRF, at the design control level, is acceptable
- Linac errors degrade the beam quality a little
- Requirements are met for:
  - final rms emittance
  - injection foil coverage & spatial stability
  - energy spread & stability
  - beam loss induced machine activation

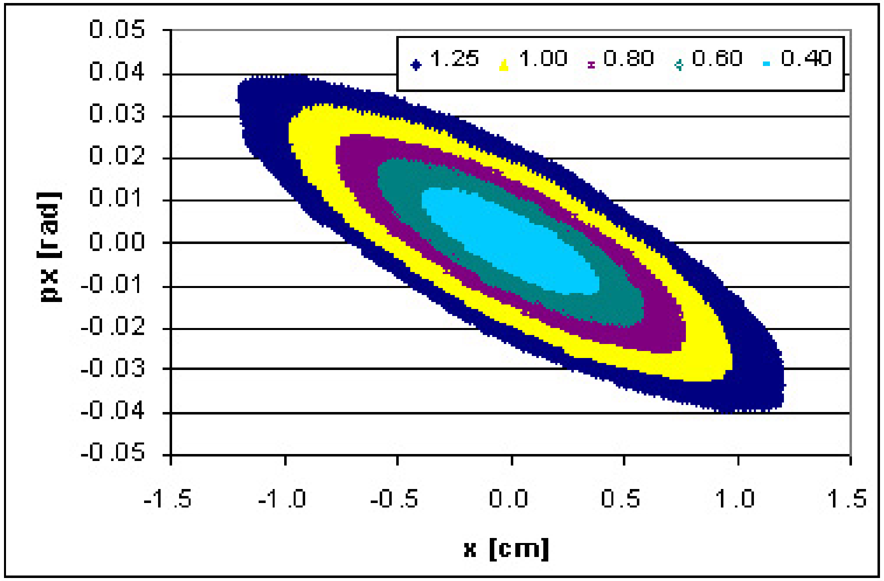
"Simulations have to be made more realistic …" ASAC 10/01

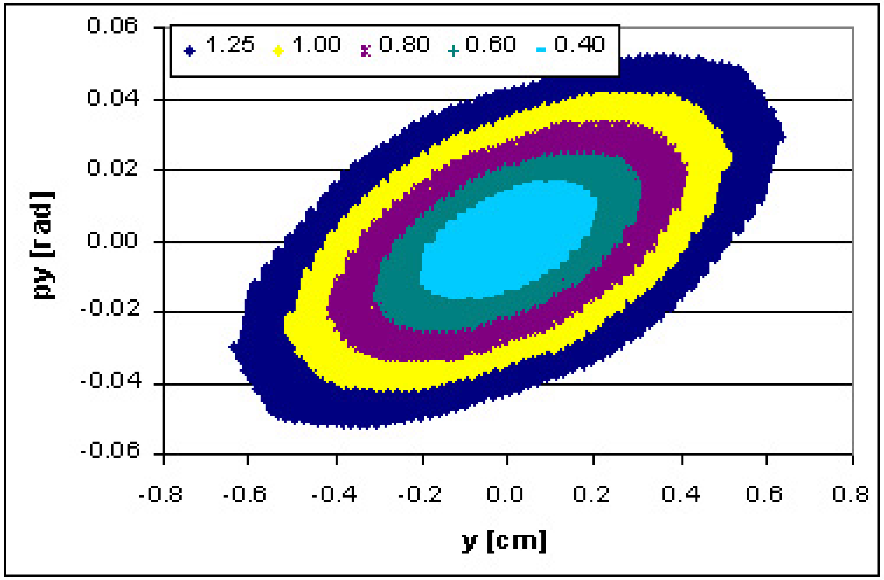
- Develop more realistic initial particle distributions
- Identify sources of initial beam emittance dilution
- Investigate options for improving or tailoring the initial beam distribution
- Develop realistic matching & tuning algorithms
- Carry out error studies based on
  - expected &/or measured beam distributions
  - mismatches derived from the planned tuning methodology
- Plan & simulate commissioning procedures

The Reference Beam Distribution Develops a Halo in the RFQ



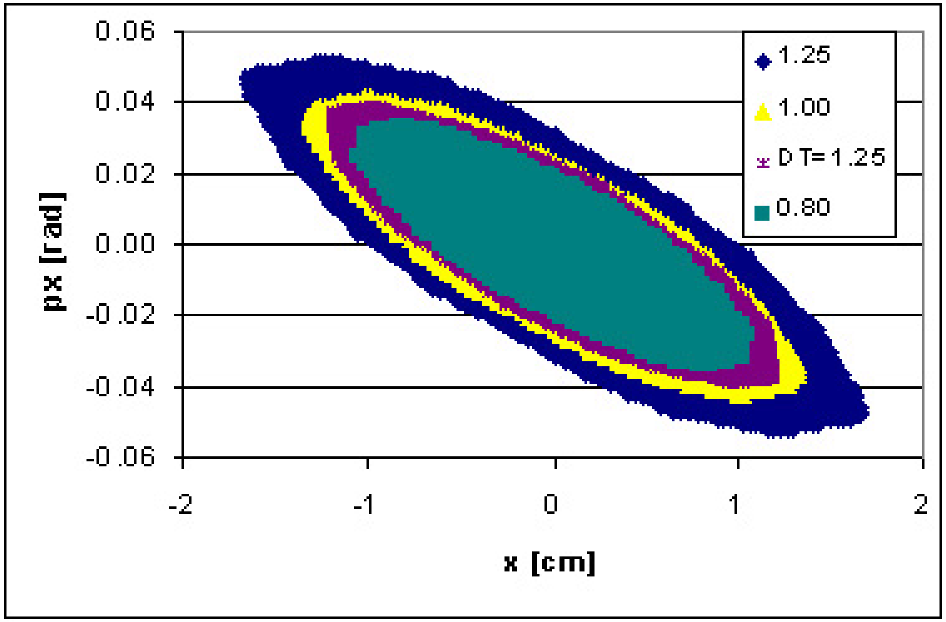
Reducing Drift-Tube Apertures has been Suggested to Trim the Halo



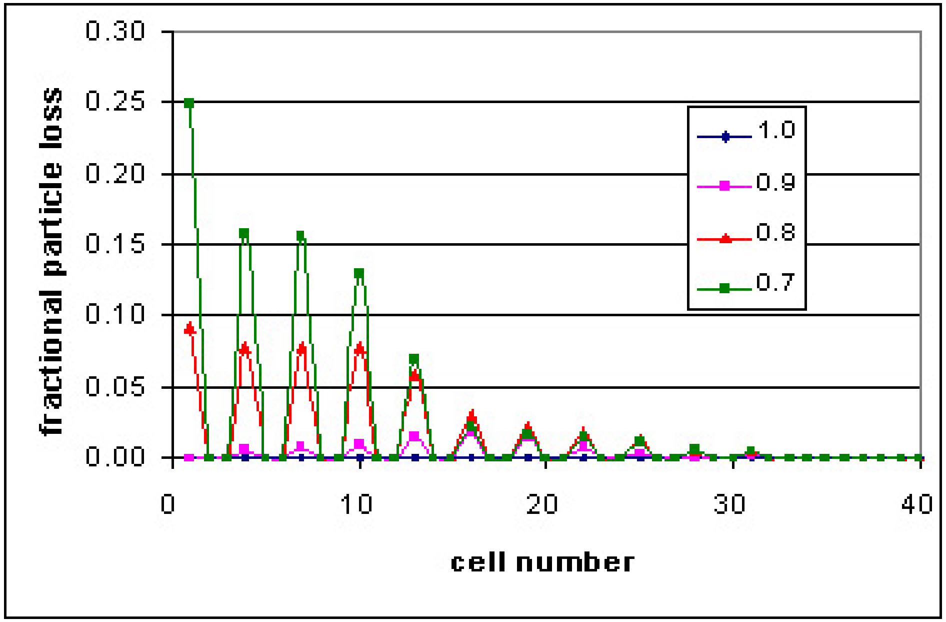


X & Y acceptance as a function of bore radius.

Empty Drift-Tubes in the FF 0 DD 0 Lattice Might be a Safe Place for Apertures

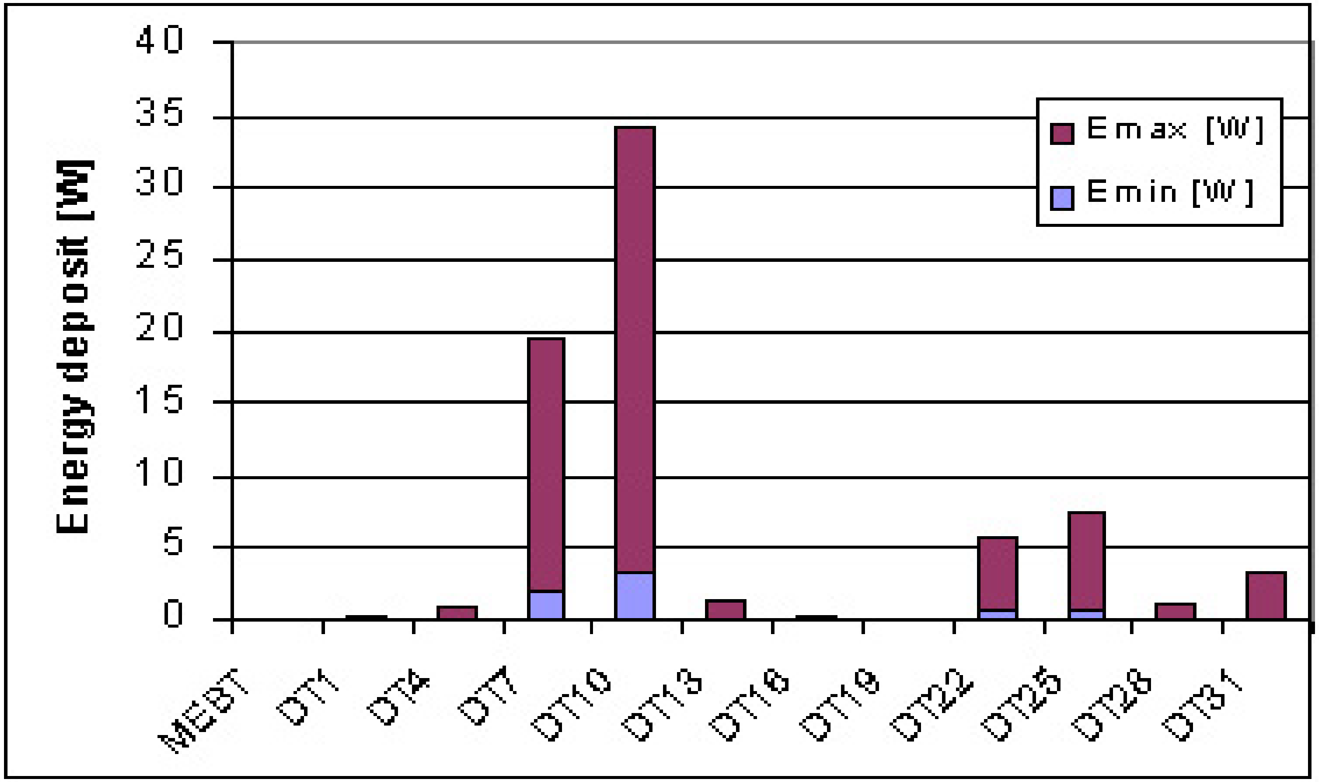


Acceptance defined by apertures at empty drift tubes



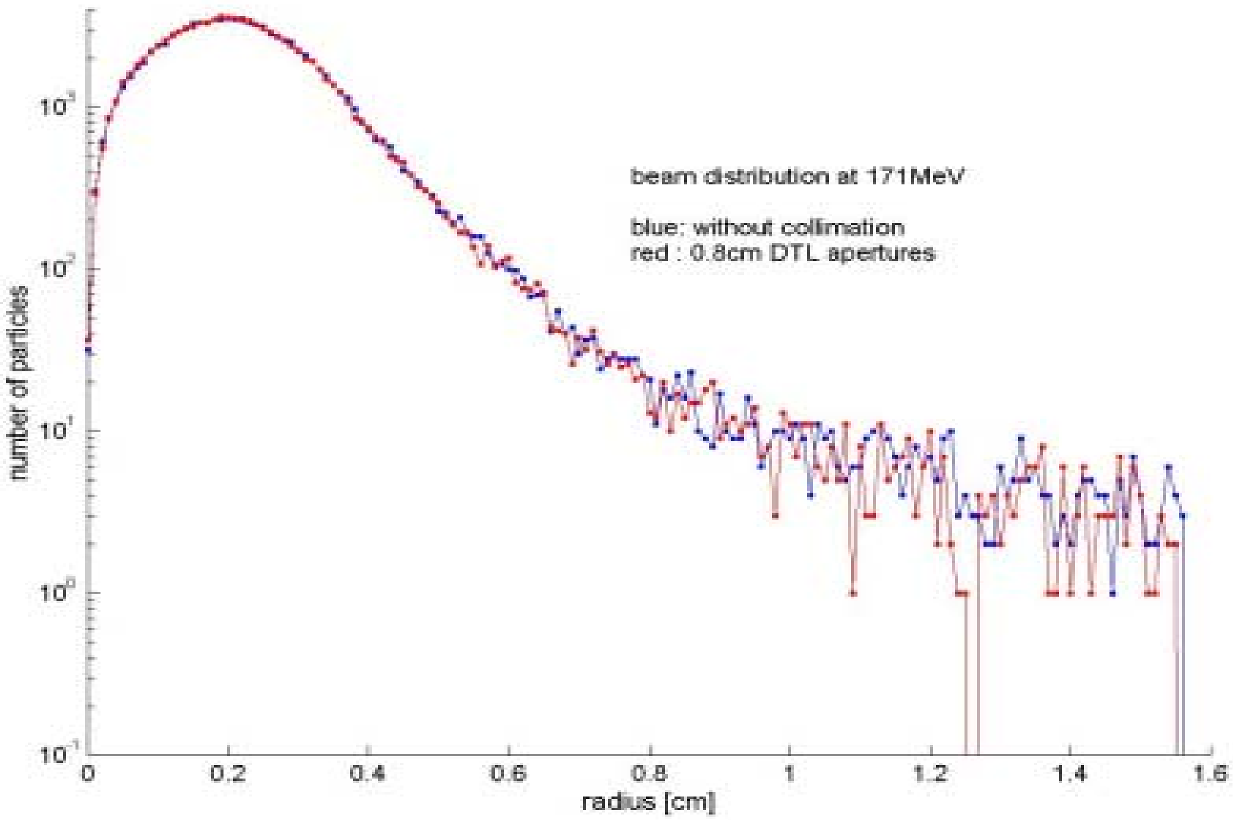
Fractional particle loss by scrapers in empty drift tubes

R=8 mm apertures in empty drift-tubes risk significant power dissipation



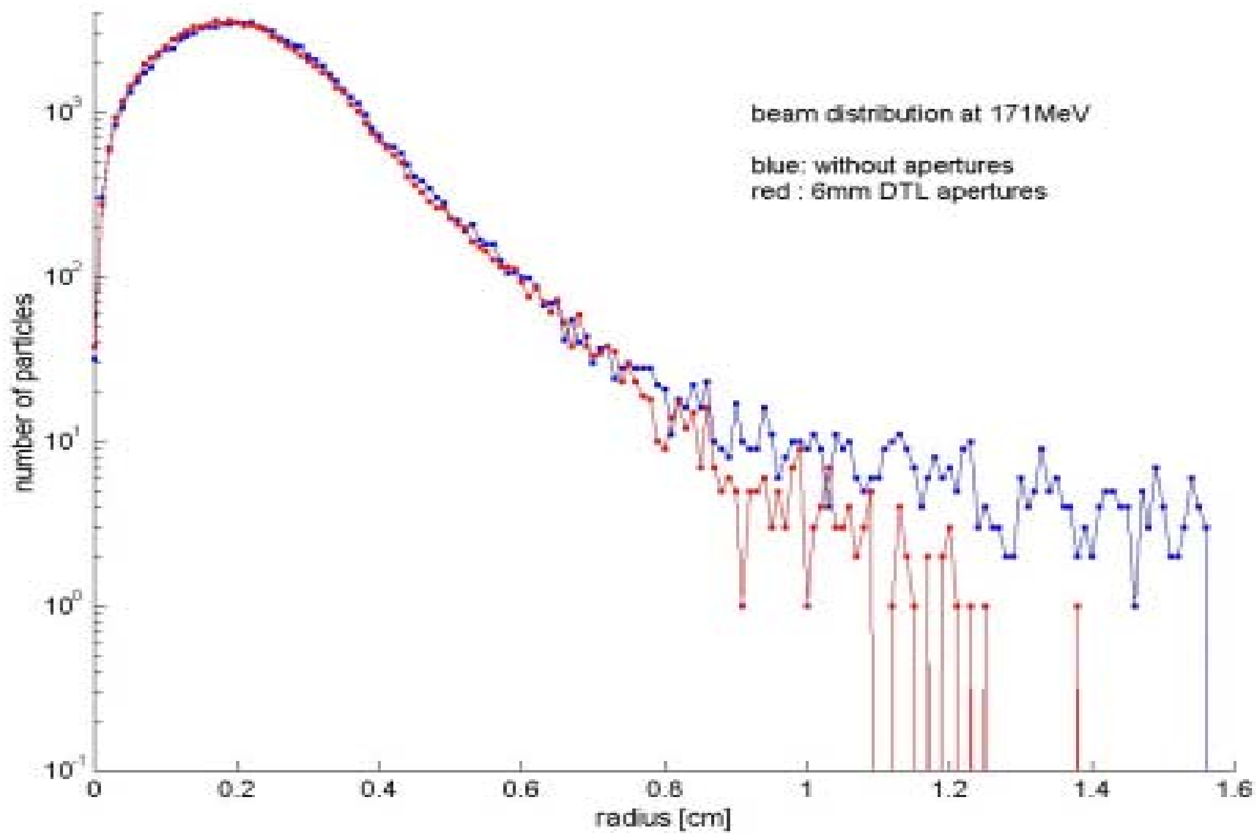
Expected power dissipated on apertures for 100 linacs including errors

R=8 mm apertures in empty drift-tubes don't reduce halo!



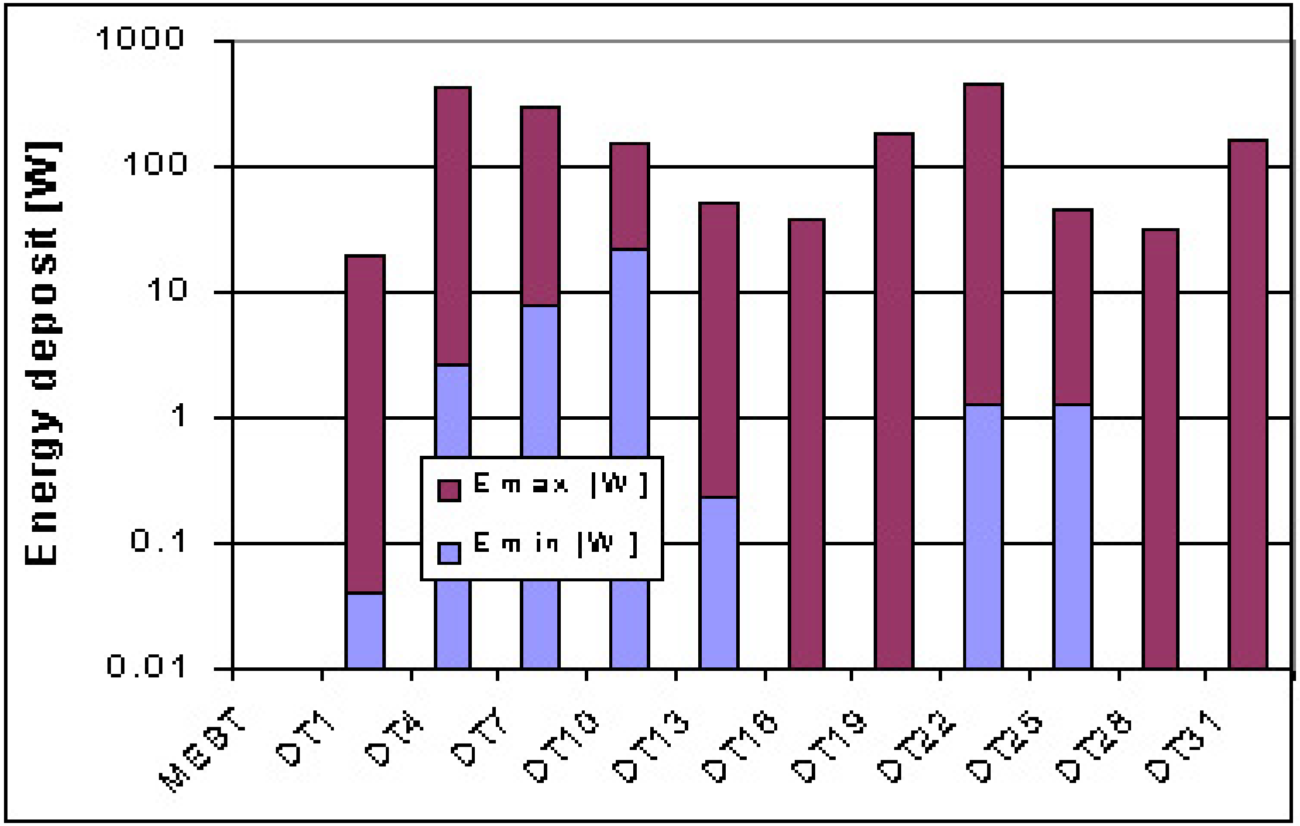
Radial particle distribution at 171MeV

R=6 mm apertures in empty drift-tubes do reduce halo



Radial particle distribution at 171MeV

R=6 mm apertures risk prohibitive power dissipation



Expected power dissipated on apertures for 100 linacs including errors

"LANL-SNS group should put together a prioritized list …" DRC 12/00

Task	LANL mmo	Priority
1. Halo Studies	7	High
2. Study of physics design basis	13	Medium
3. Design study	13	Complete
4. Comparison of codes	11	Medium
5. Diagnostics & Instrumentation physics	10	High
6. Commissioning	46	High
7. Error and tolerance studies	5	Medium
8. Professional	19	Medium
9. Accelerating structures development	19	Complete
10. Fabrication Support/tuning	19	High
11. Reliability/Failure Studies	2	Low
12. Code development/support	11	High
Total mmo	175	

Continuing physics effort will be dominated by tuning & commissioning