SNS Linac Physics Studies

J. Stovall, J. Billen, S. Nath,
H. Takeda, L. Young, R. Shafer,
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SNS ASAC Review

7 March 2000

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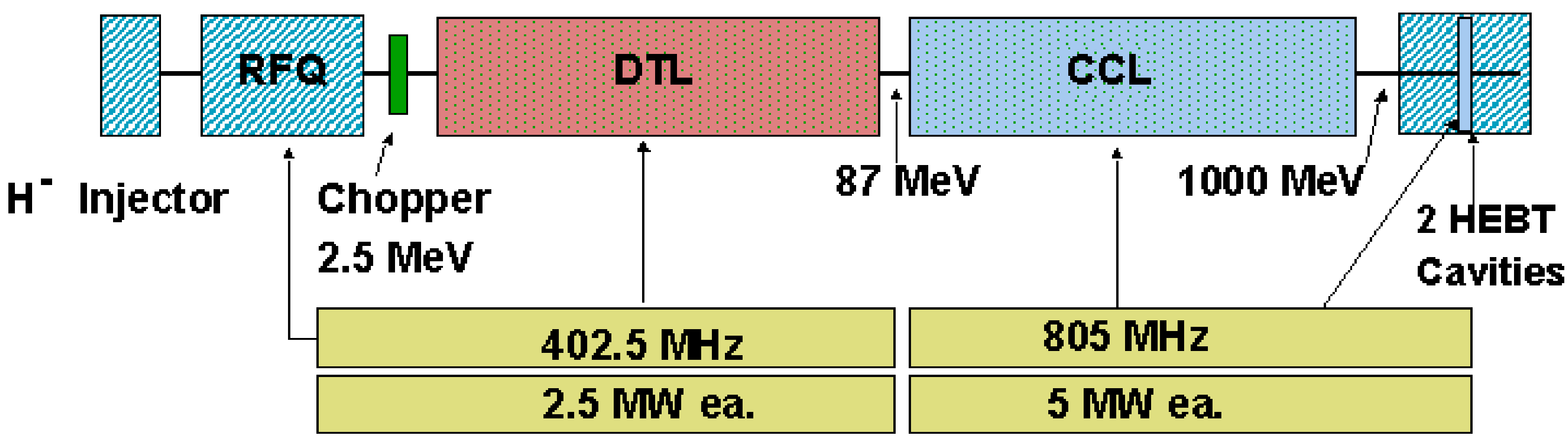
SNS DOE Lehman Review

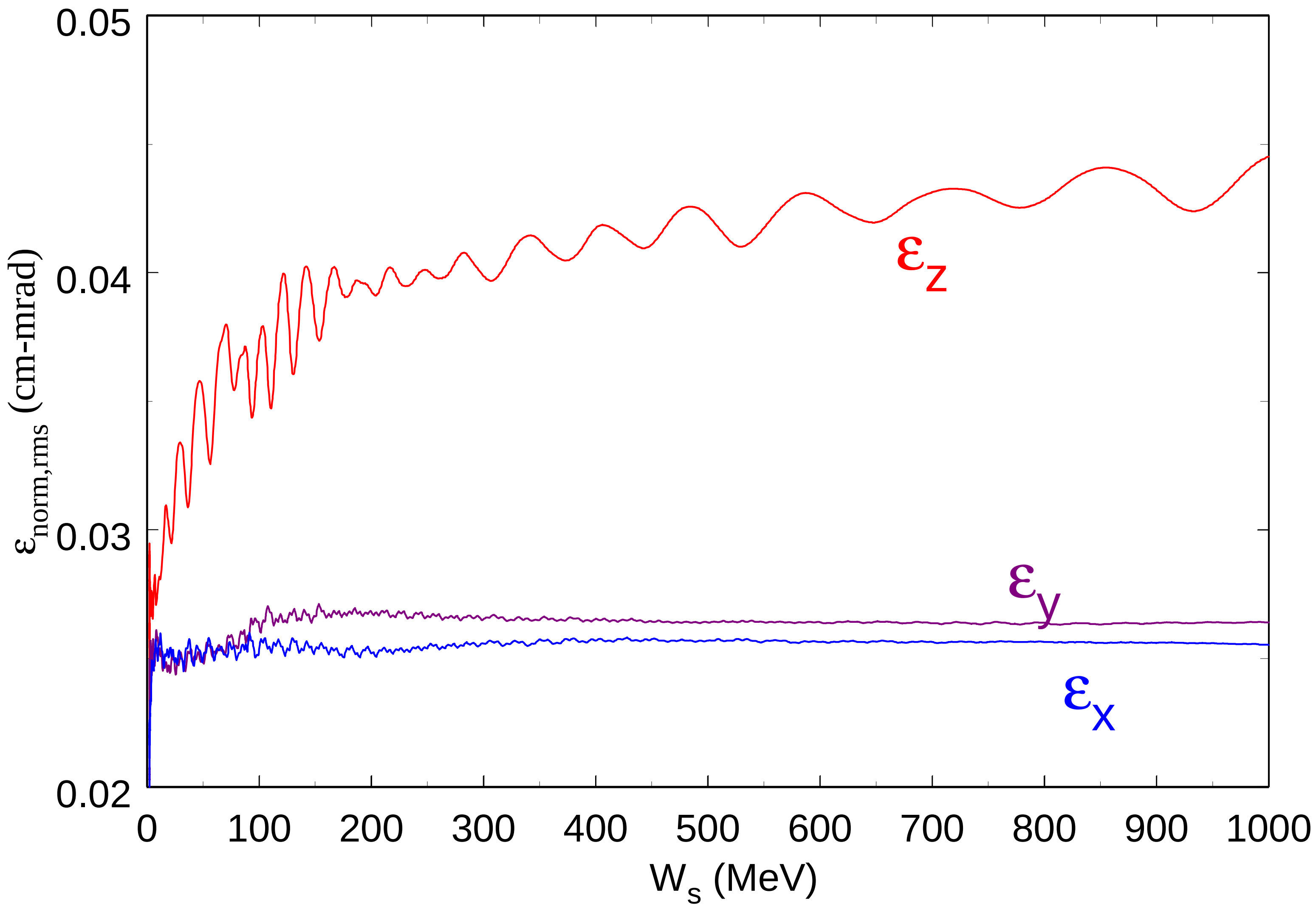
14-15 March 2000

Baseline Architecture

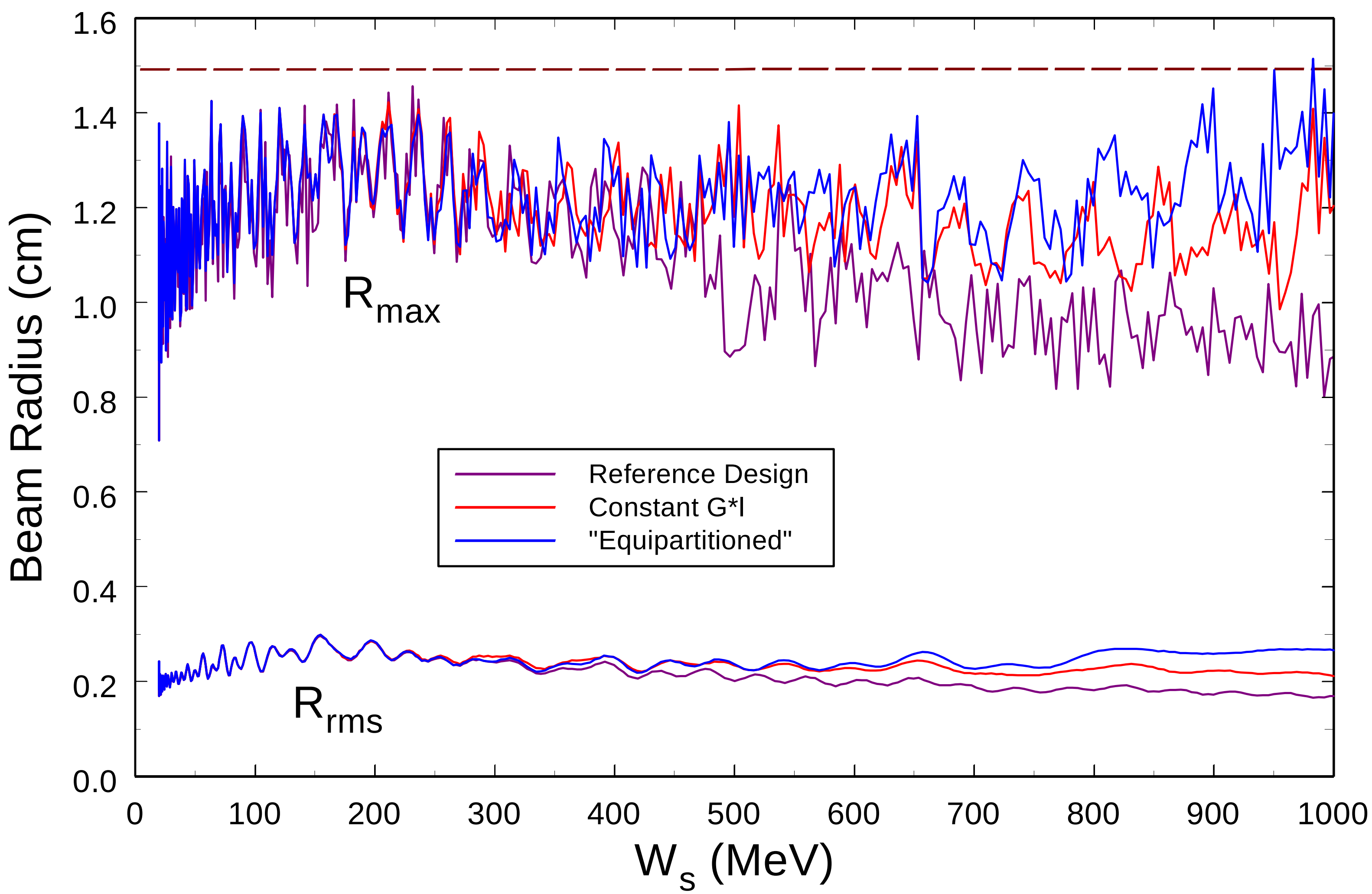


	No of Tanks/Segments		
	DTL	**CCDTL**	**CCL**
Reference Design	1	84	261
Proposed Design	6	0	257

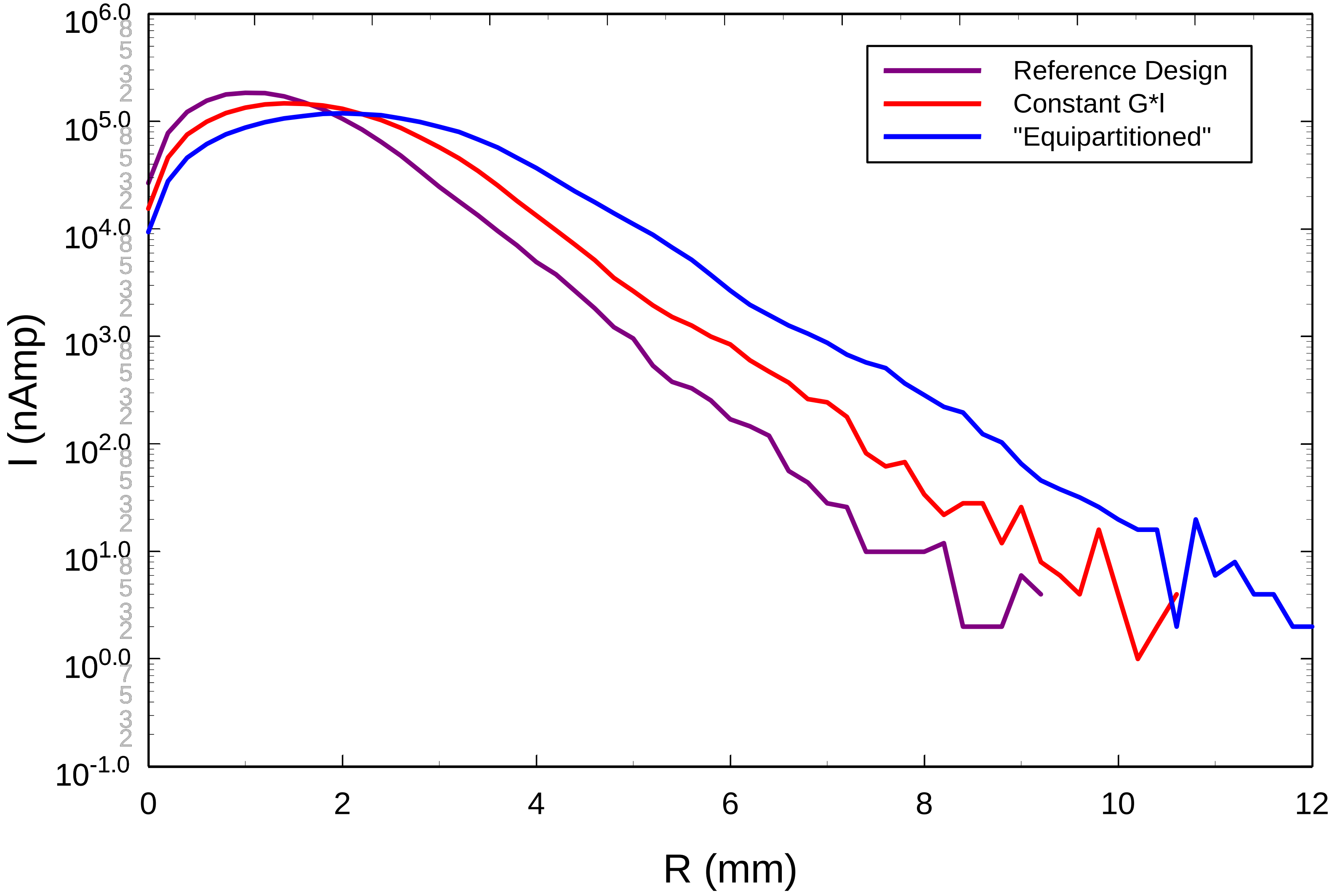
Emittance Profiles
Room Temperature Design



Beam Size for 3 Quad Laws Including Errors, No Mismatch



for 3 Quad Laws, Errors Included



SCRF Investigations to Date

- Alternate cavity designs
- Alternate linac configurations
- Alternate cavity/klystron scenarios
- Various field control Schemes
- Transient field analysis
- Error studies for some cases

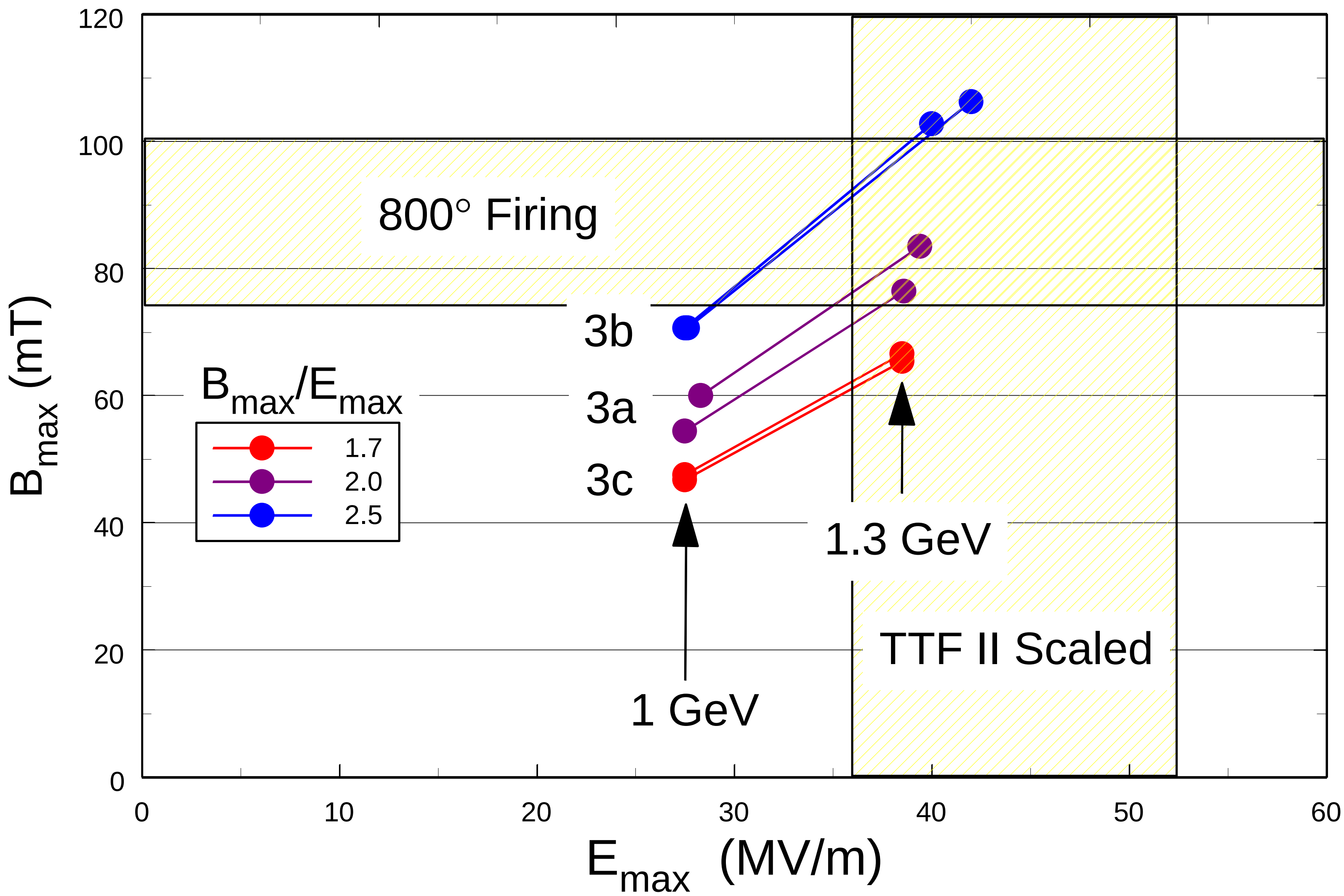
Initial SCRF Linac Design Constraints

- $P_{max} \leq 350$ kW
- $E_{max} = 27.5$ MV/m
  - » all cavities assumed to meet or exceed
  - » no cavity sorting
- One klystron per cavity
- 6 cells per cavity
  - » meets both P_{max} & E_{max} constraints

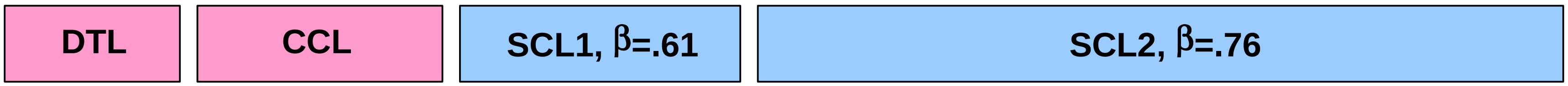
Cavity Assumptions

- TTF cavities represent the state-of-the-art to which we should aspire
- Cavities will not be heat treated above 800° C
- E_{max} derated by empirically observed scaling law $\propto A^{1/4}$
- Balance risk of quench & field emission
  - » $B_{max}/E_{max} \approx 2.0$

Cavity Design Options



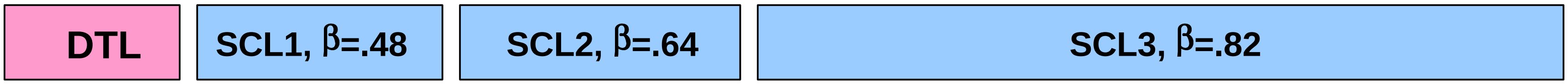
January Reference Design



	DTL	CCL	SCL1	SCL2	Total
W_{final} (MeV)	86	185	320	1000	
Klystrons	6	8	27	80	121
Cryostats	-	-	9	20	29
Length (m)	36.5	56.5	52.5	154.0	299.5

- very conservative cavity fields
- transverse & longitudinal lattice discontinuities are separated
  - » frequency changes at the CCL
- matching is tractable

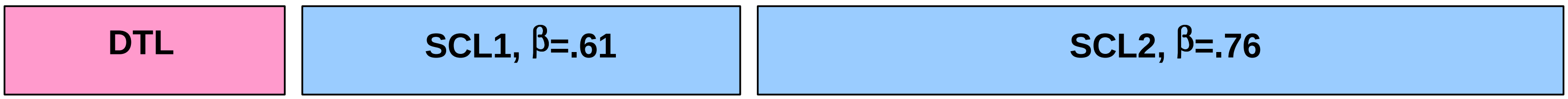
Design Option No. 1



	DTL	SCL1	SCL2	SCL3	Total
W_{final} (MeV)	86	214	492	1000	
Klystrons	6	51	57	60	174
Cryostats	-	17	19	20	56
Length (m)	36.5	91.5	113.0	119.5	360.5

- no CCL
- 3 β SCL sections
- simultaneous transverse & longitudinal lattice discontinuities
- difficult matching problem
- most expensive

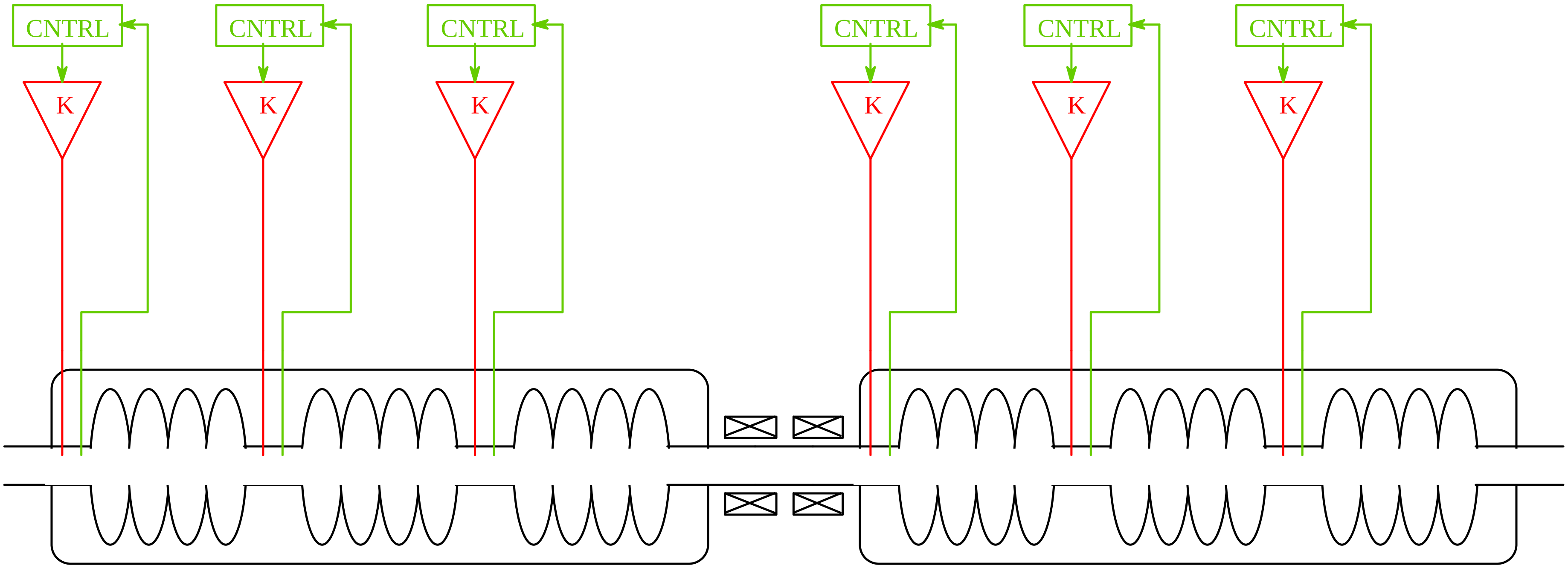
Design Option No. 2



	DTL	CCL	SCL1	SCL2	Total
W_{final} (MeV)	150	-	307	1000	
Klystrons	8	-	45	112	165
Cryostats	-	-	15	28	43
Length (m)	66.5	-	85.0	210.5	362

- high energy DTL
- no CCL
- 2 β SC sections
- simultaneous transverse & longitudinal lattice discontinuities
- difficult matching problem
- very expensive

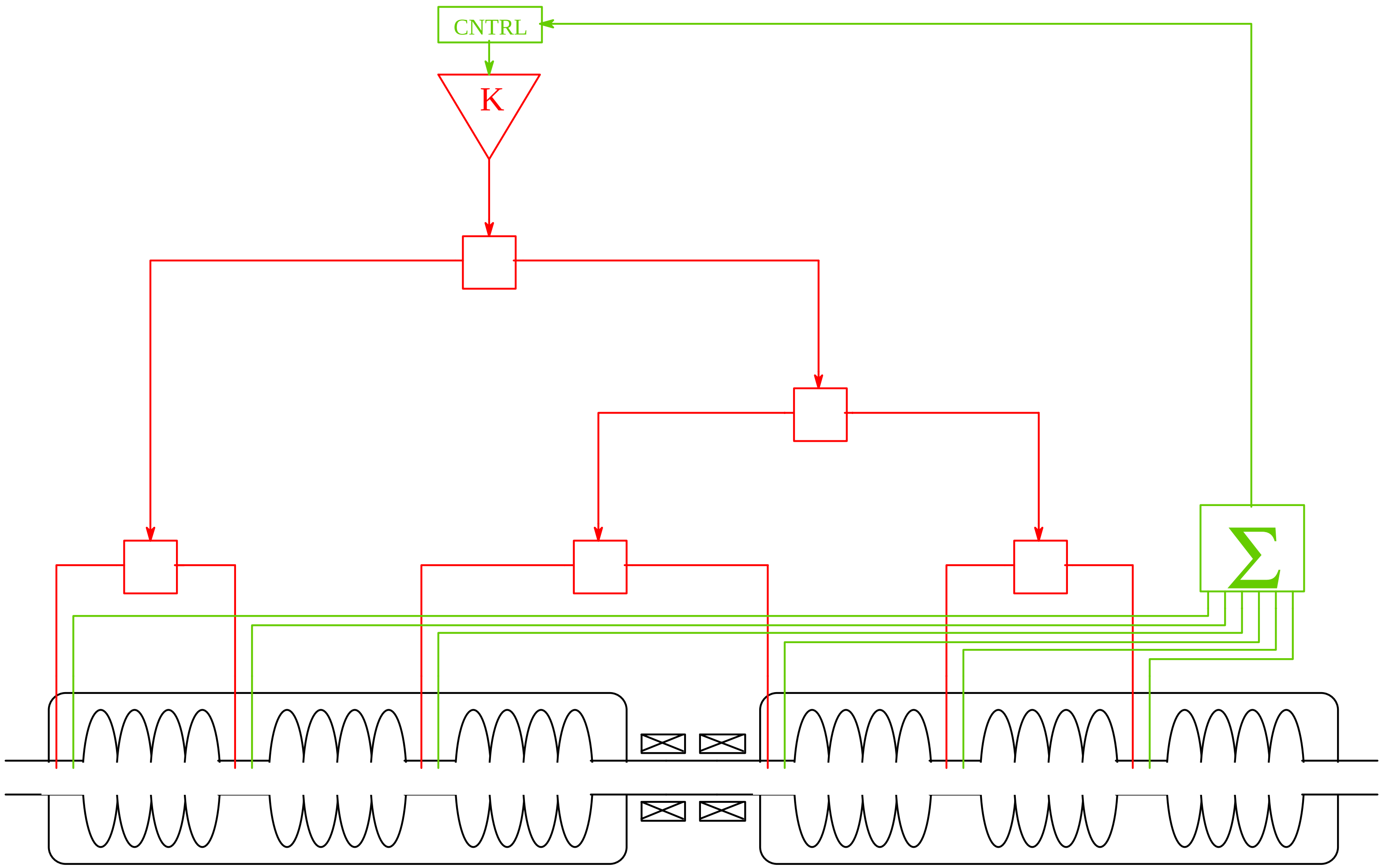
CDR: 1 Cavity/Klystron
Individual Cavity Control



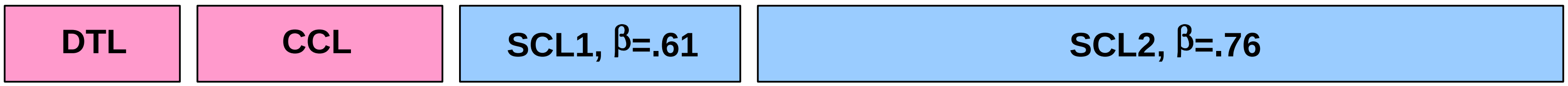
January Status Summary

- Confirmed modified CDR design
- Major cost impact of +$80M
- Initiated search for cheaper topologies

6 Cavities/Klystron
Vector Sum Control



Next Reference Design



	DTL	CCL	SCL1	SCL2	Total
W_{final} (MeV)	86	185	308	1000	
Klystrons	6	8	6	14	34
Cryostats	-	-	8	21	29
Length (m)	36.5	56.5	46.6	161.7	301.3

- 6 cavities per Klystron
- Linac repartitioned
- Assume vector sum control of 6 cavities
- Programmed E_0
- Long inter-cryostat drifts cause transient energy slew
- Uncorrected cavity-to-cavity field errors

Trial Error Budget

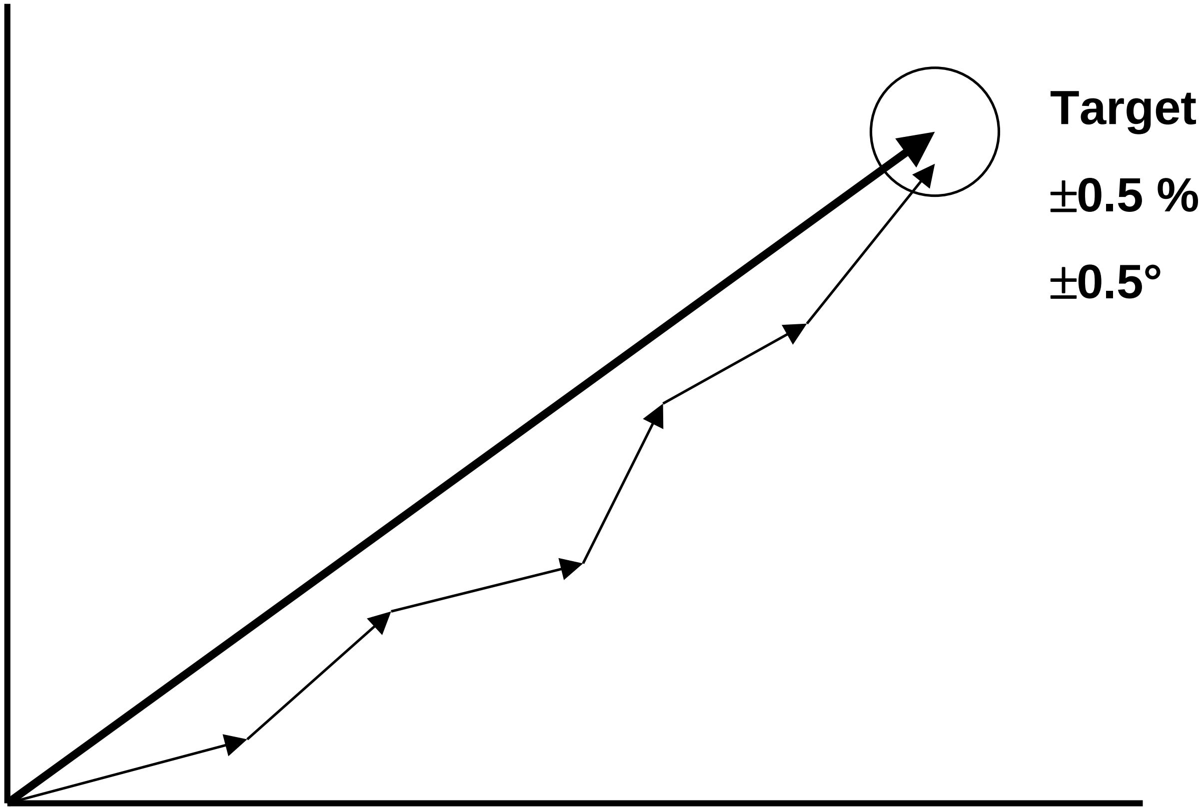
Static Errors

		$\Delta\phi$	ΔE_0
		$\pm$°	$\pm$%
Determine setpoints		2	2
Cavity-to cavity			
Loop Calibration		1	1
Power split	$\pm$0.1 db	-	2
Power coupling	$\pm$20%	-	10

Dynamic Errors

		$\Delta\phi$	ΔE_0
		$\pm$°	$\pm$%
Uncertainty in control response		0.5	0.5
Cavity-to cavity			
Microphonics	$\Delta f=\pm 50$ Hz	2.6	3
Lorentz detuning	$\Delta K=1$ $\Delta f=\pm 140$ Hz	9	7
Beam Loading	$\pm$1%	0.4	0.6

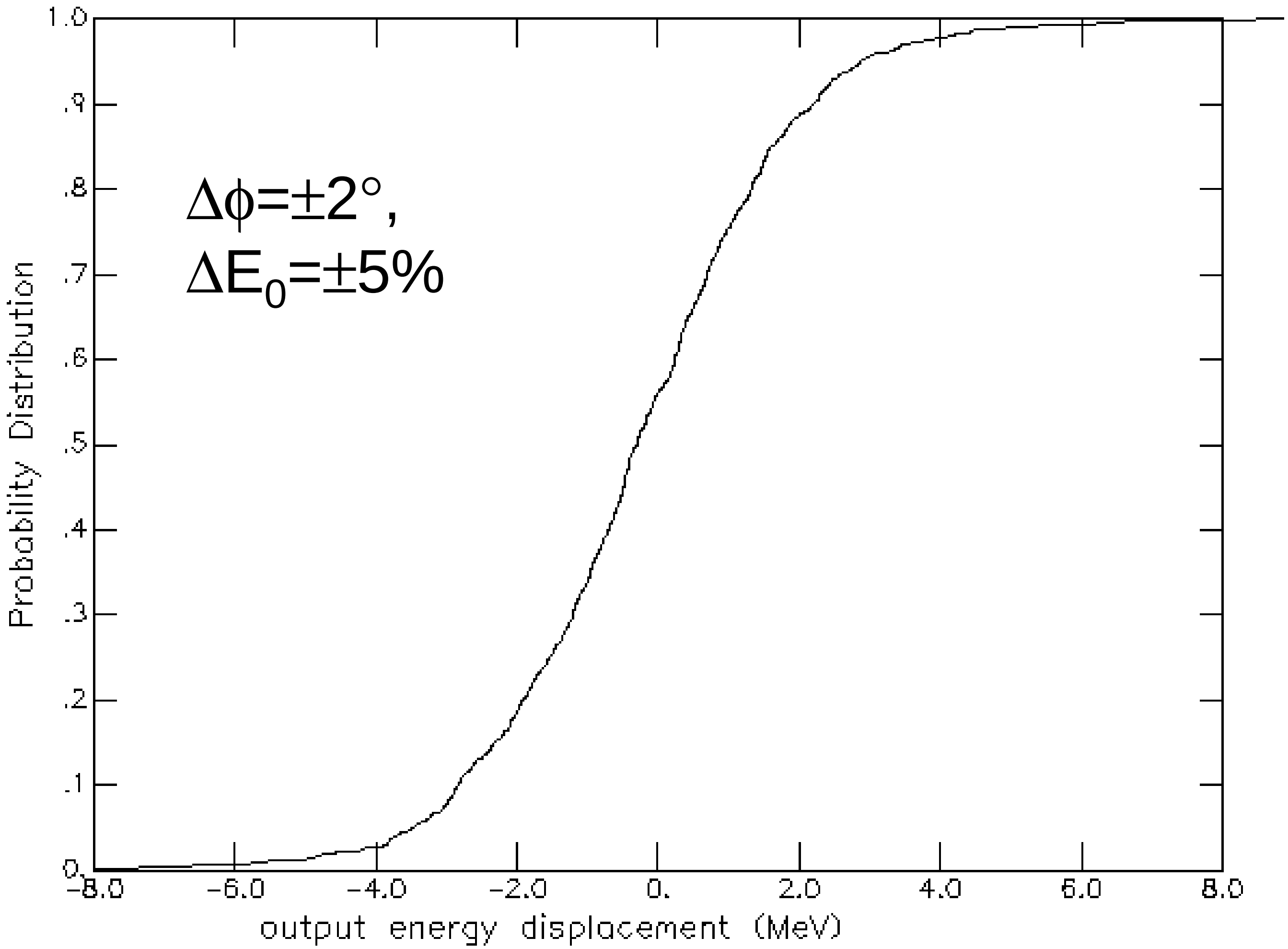
Vector Sum Control



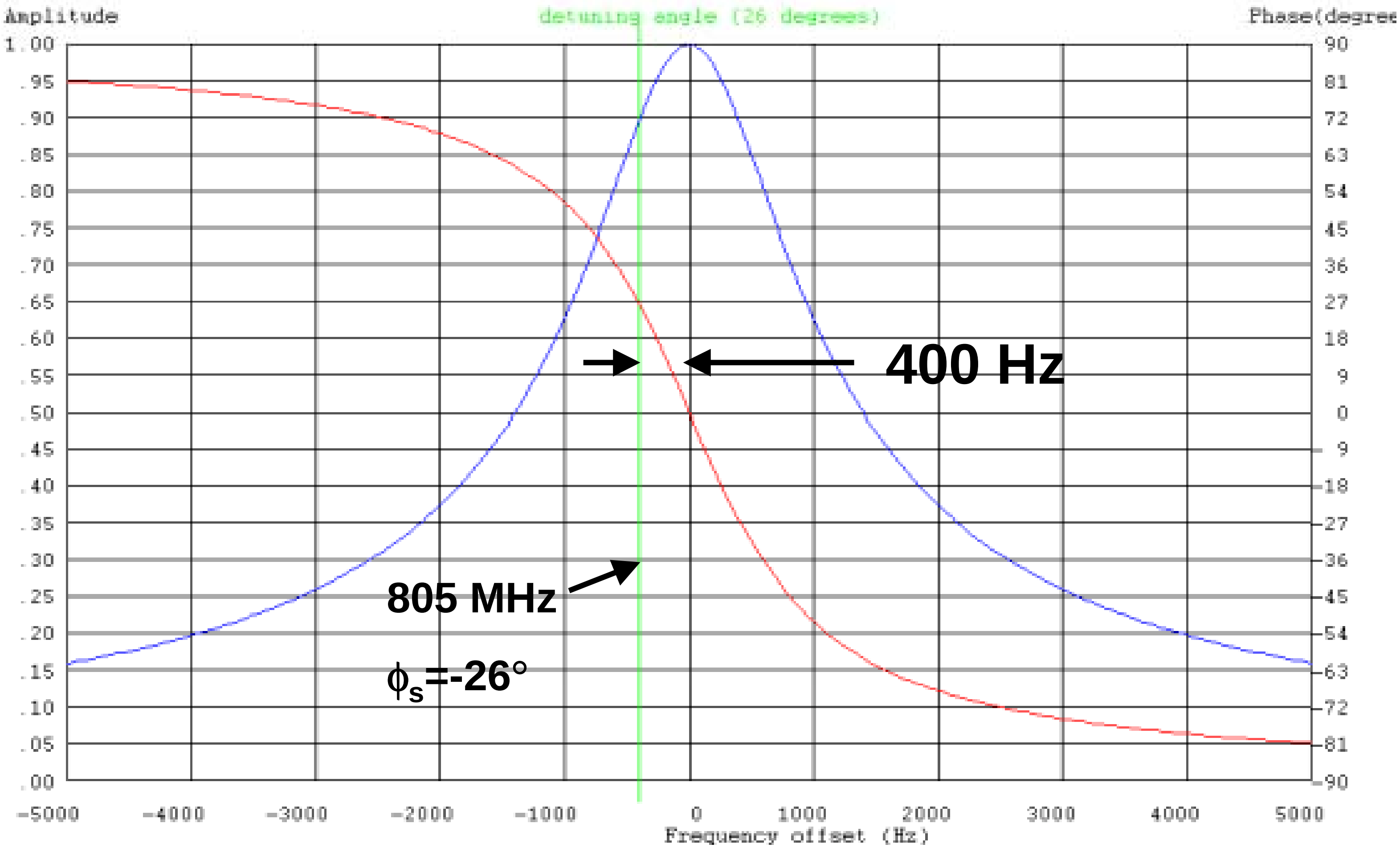
Dynamic Errors

- Lorentz Detuning
  - » $\Delta f = KE_a^2$
    - – for β=0.61, K=2, Δf =170 Hz
    - – for β=0.76, K=1, Δf =140 Hz
    - – for all cavities ΔK=1, $\Delta f \approx \pm 140$ Hz
  - » Collective effect is correctable via adaptive feed-forword
  - » cavity-to-cavity difference is uncorrectable via collective control
- Microphonics
  - » ±50 Hz cause final energy jitter to exceed spec.
- Both are uncorrectable via collective control

ΔW_{out}, Static Errors Only

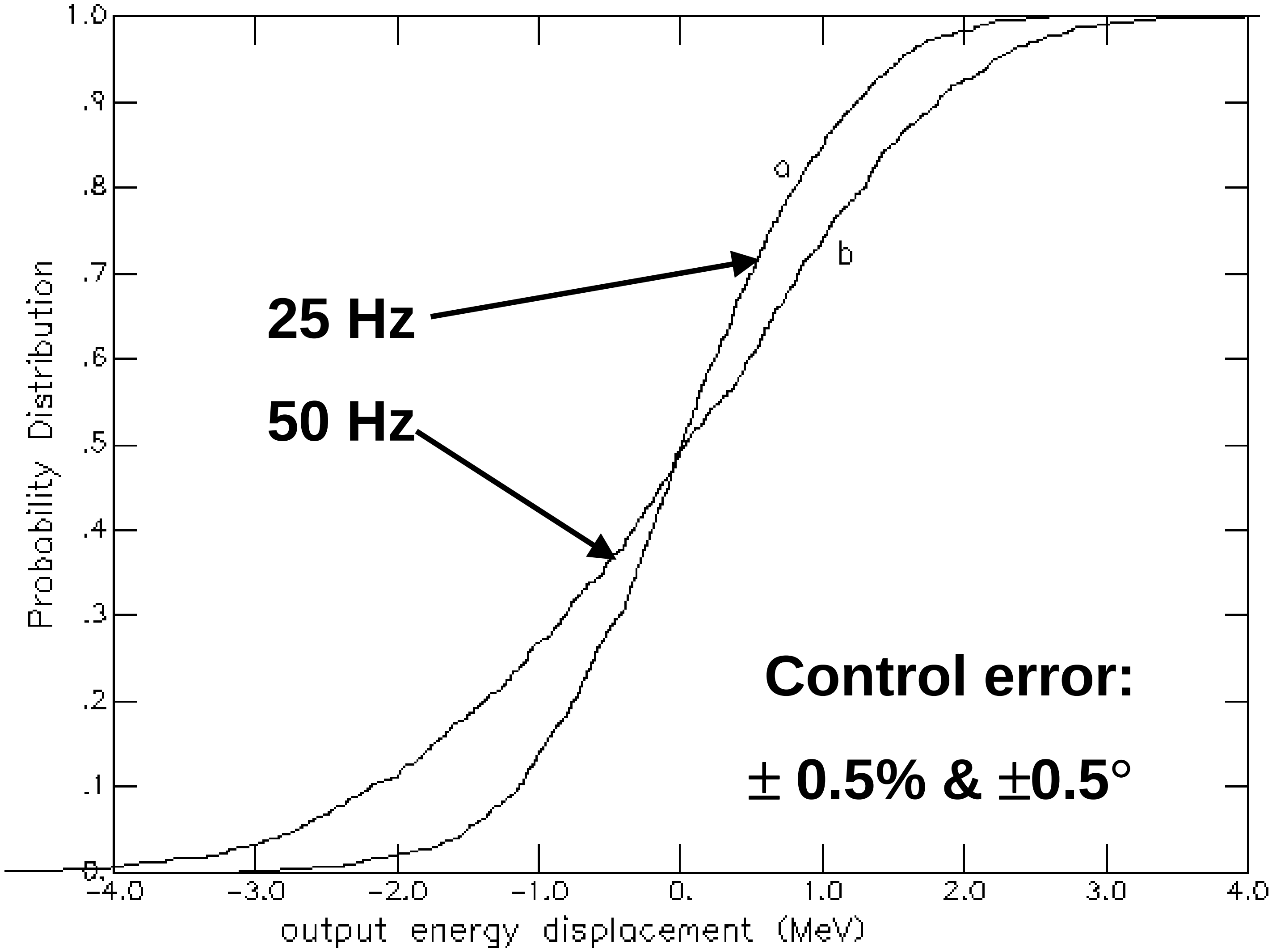


Cavity Resonance Curve



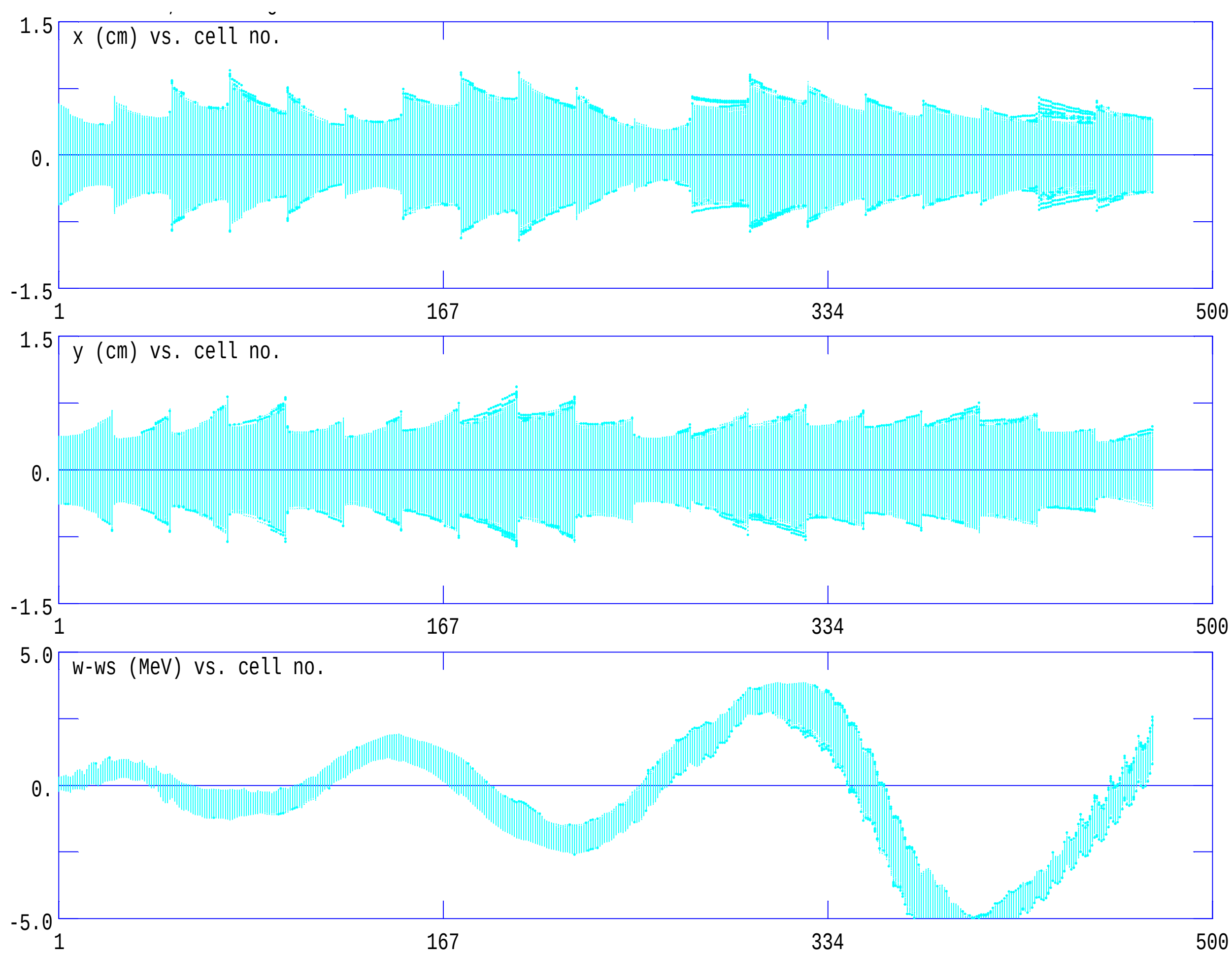
Correlated Field Errors

ΔW (jitter), Microphonics Corrected by Linear Averaging



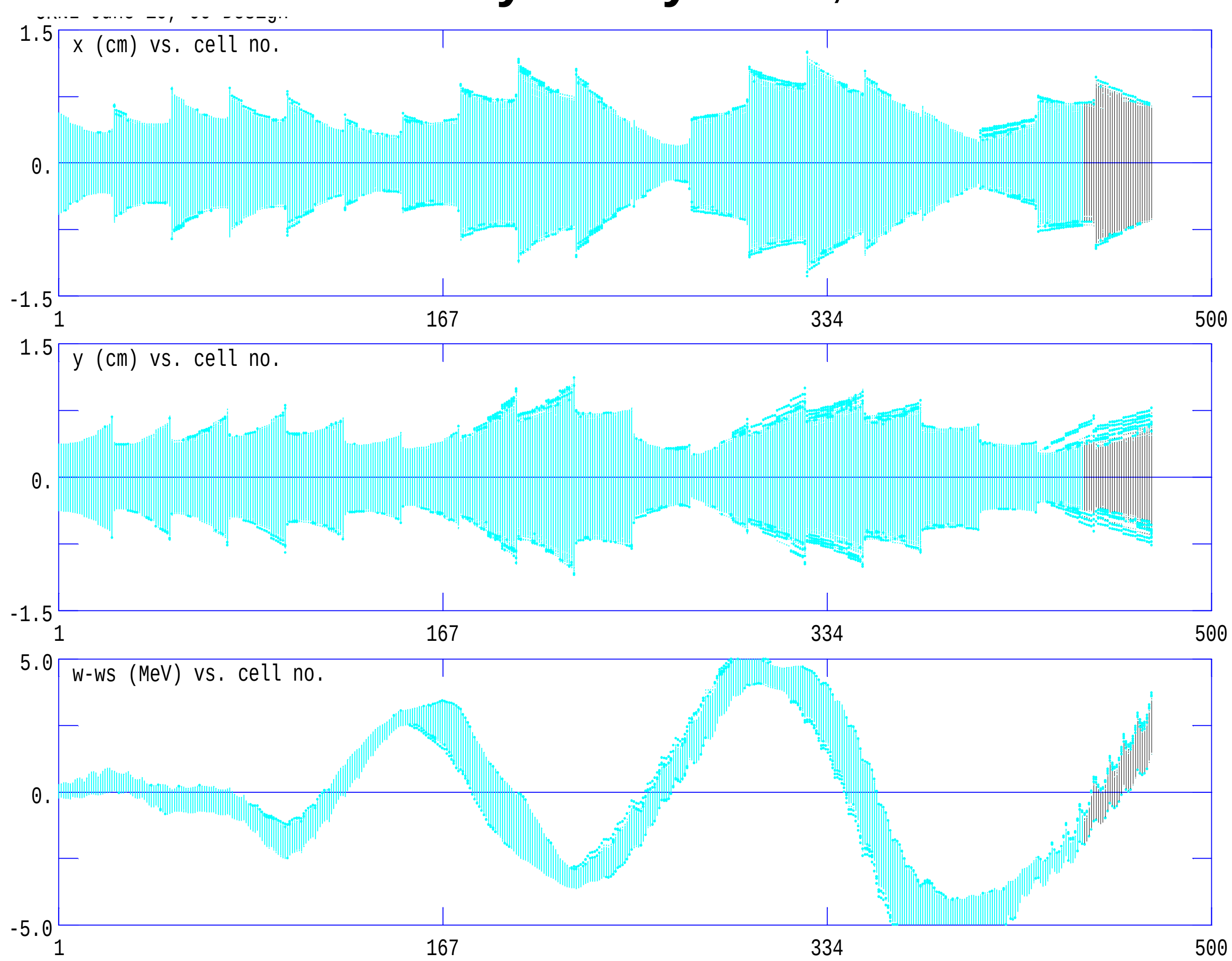
Beam Profile in 2nd β Section Vector Sum Control (±0.5°, ±0.5%)

Cavity-cavity = ±3°, ±3%

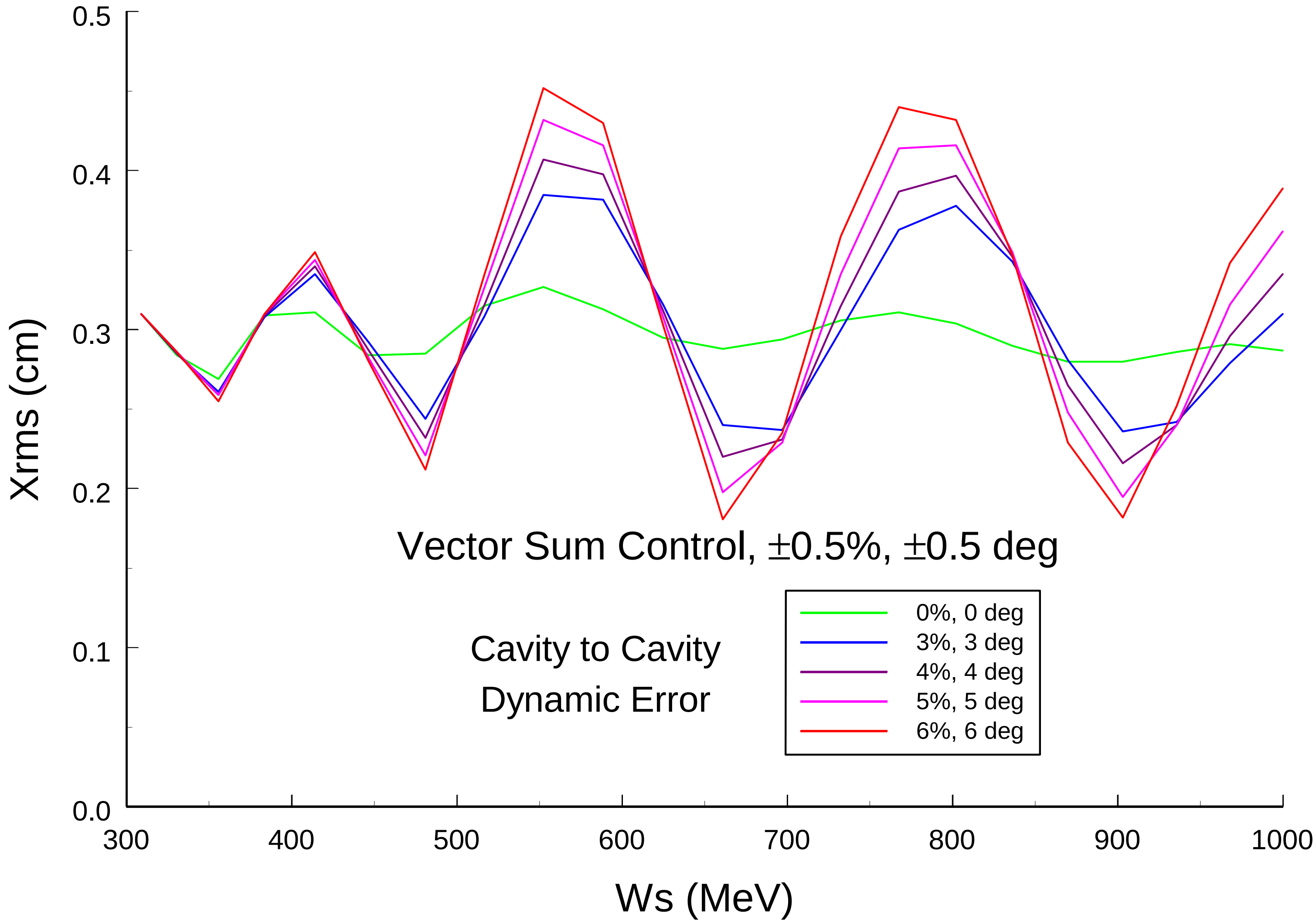


Beam Profile in 2nd β Section Vector Sum Control (±0.5°, ±0.5%)

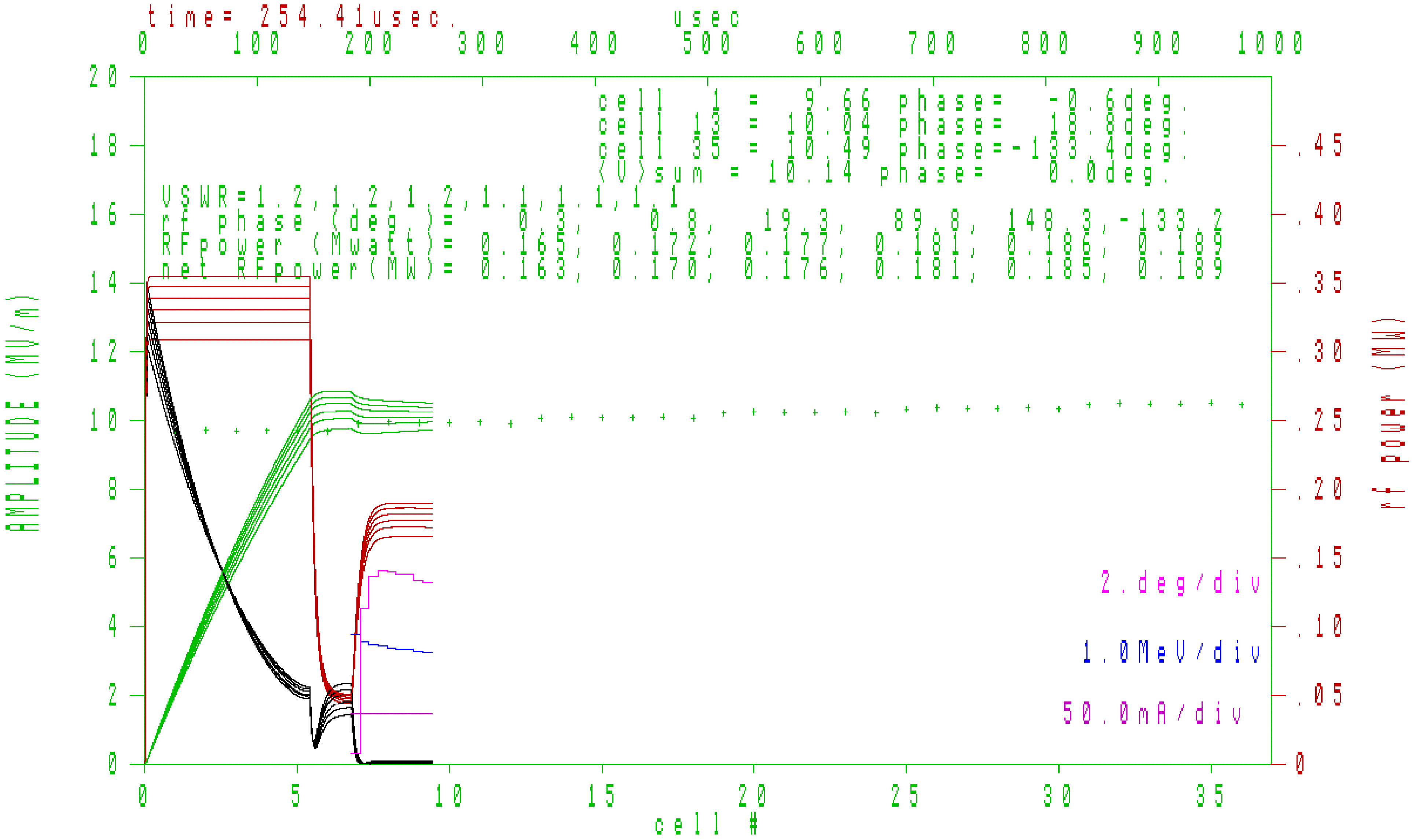
Cavity-cavity = ±4°, ±4%



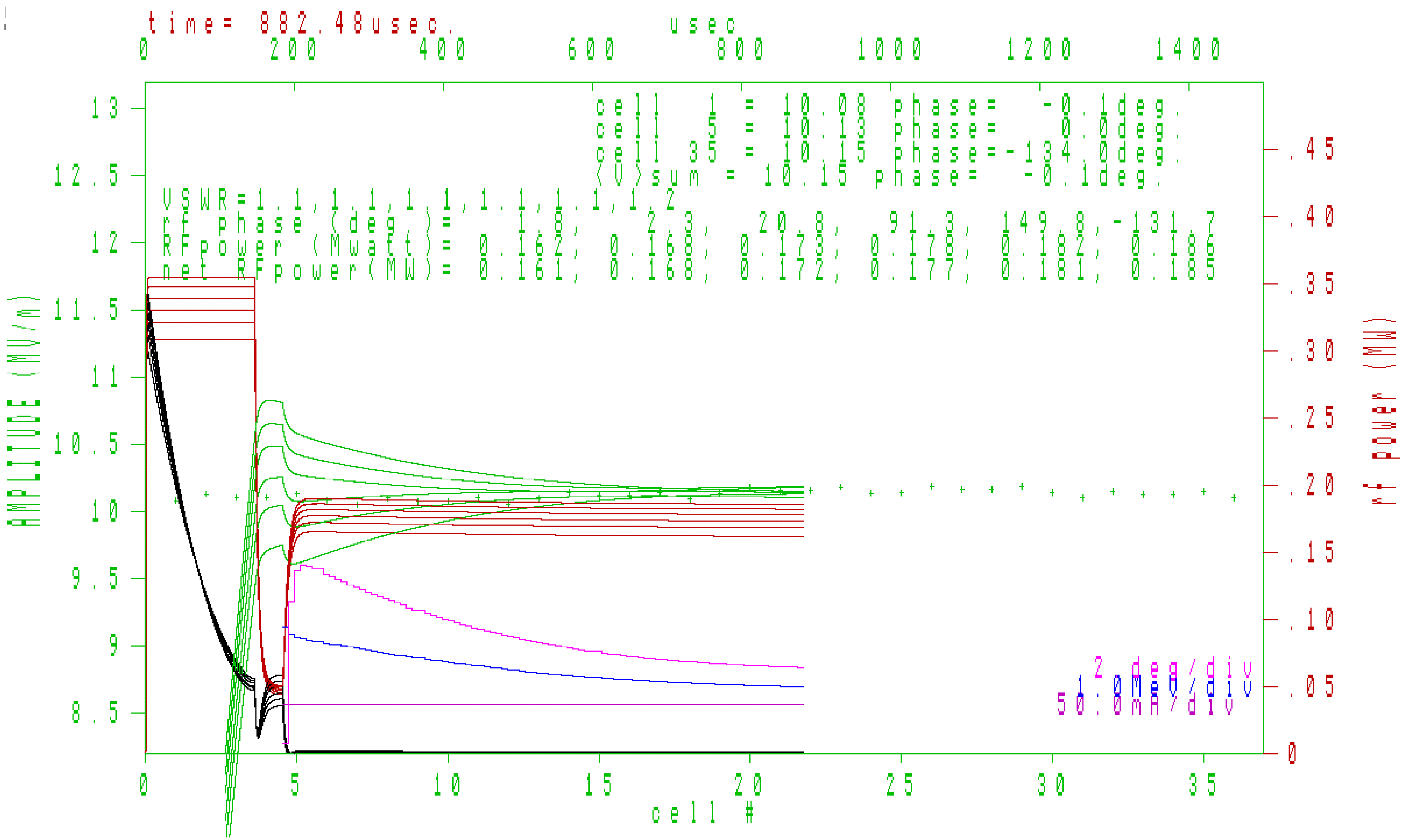
Beam Profile in 2nd β Section Vector Sum Control



Vector Sum Control
First 250 μsec



Vector Sum Control
Full Macropulse

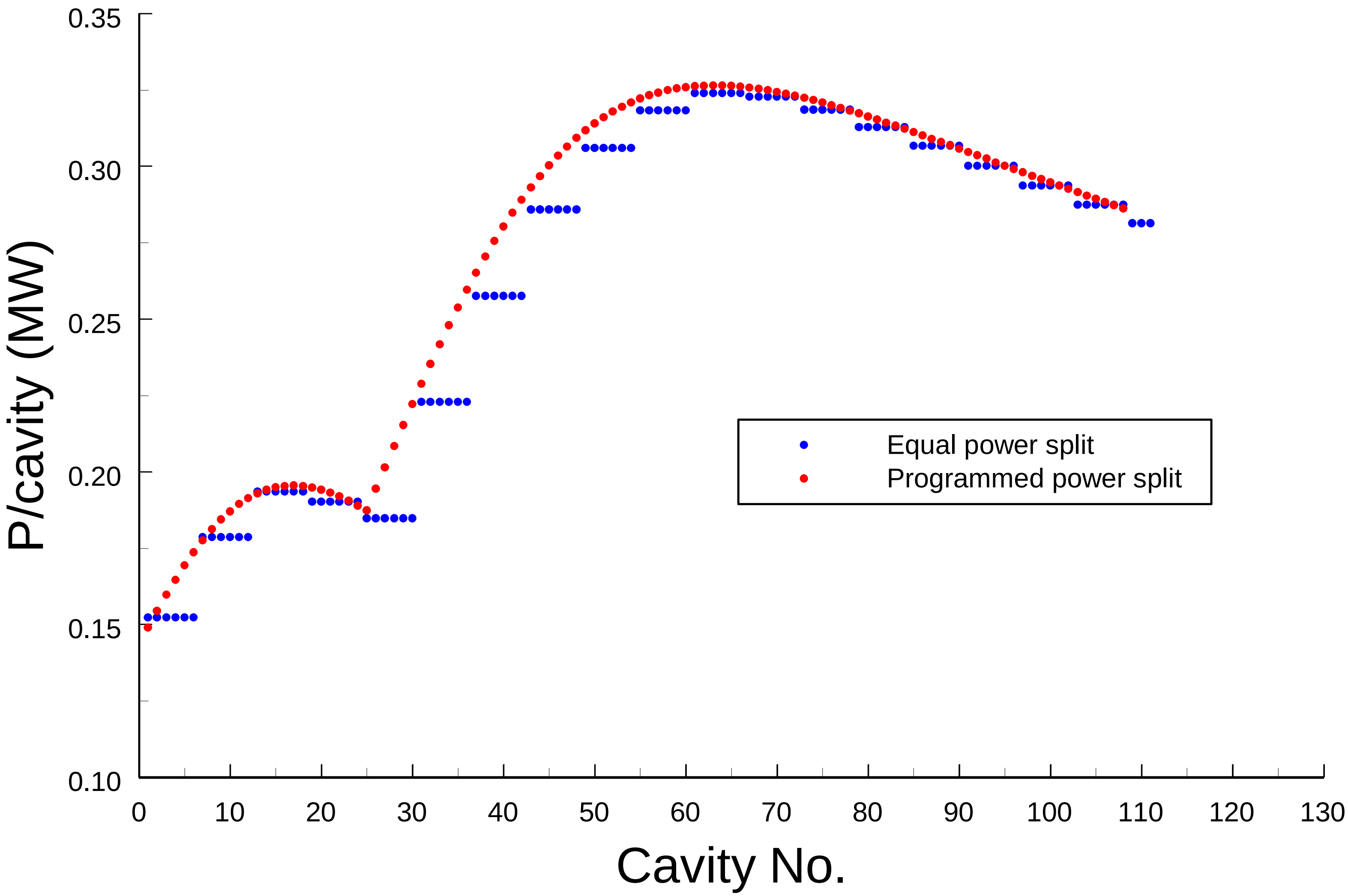


Notes: 6 cavities/klystron Vector Sum Control

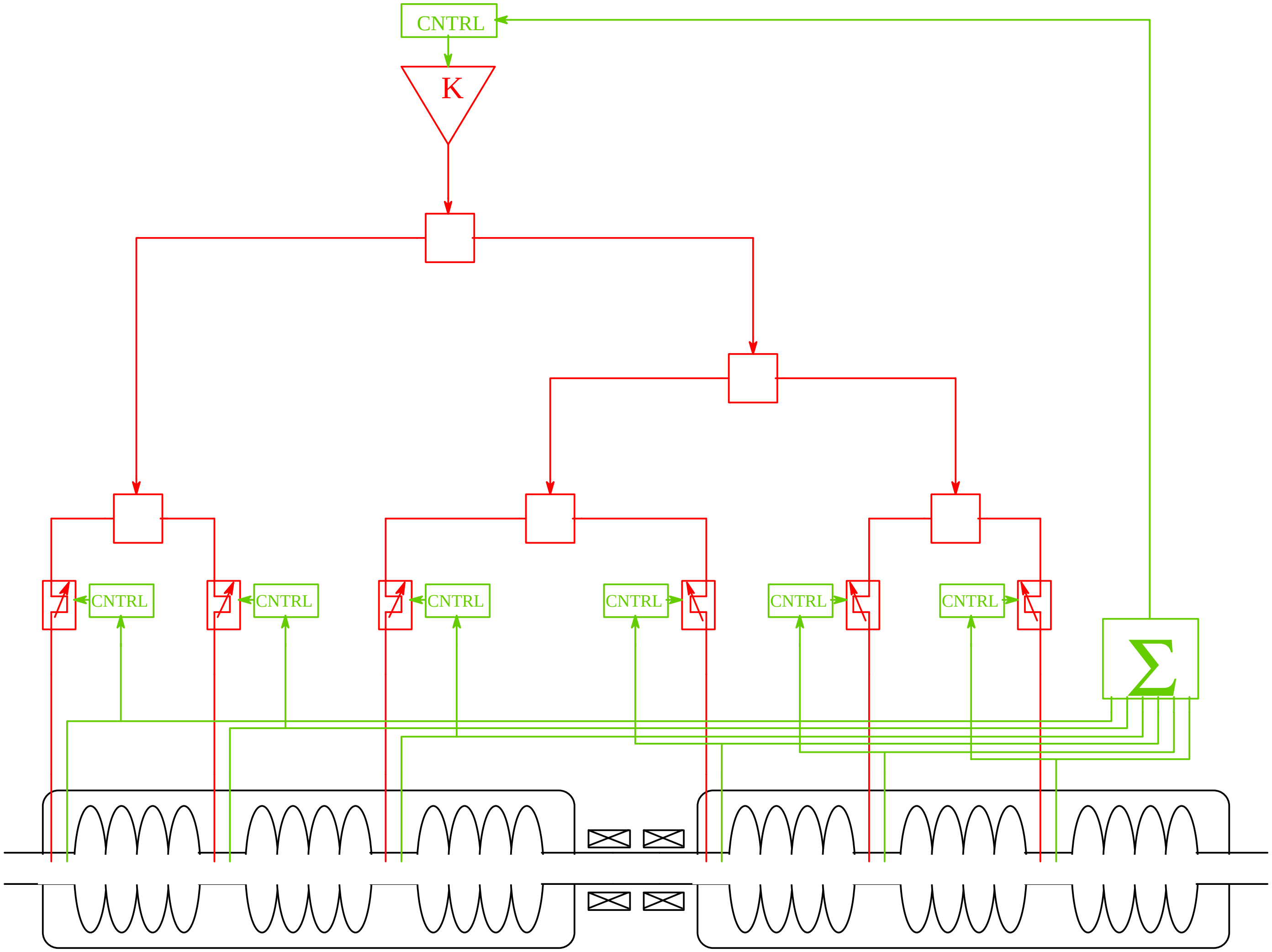
- No errors in simulation
  - » power split delivers correct power to each cavity
  - » no error in couplers
  - » Q is same for all cavities, minimum reflected power at full current
  - » All cavities de-tuned 190 Hz to account for synchronous of –23 degrees
- Amplitude and phase feedback on vector sum
- Because power is over-coupled (?) in first 3 cavities, initial field is low
  - » Beam gains too little energy in first 3 cavities and arrives late at the 4th cavity
  - » second 3 cavities are under coupled (?) so fields are too high
  - » because of the long inter-cryostat drift beam arrives even later
  - » The fields in the 2nd 3 cavities are initially too high and the energy gain is over-compensated
  - » the beam energy from the first module is initially about 750 keV too high!
- Beam energy stabilizes after about 800 usec

- This 'ideal" situation would be cured by having equal power splits and each cavity in a module designed to operate at the same field

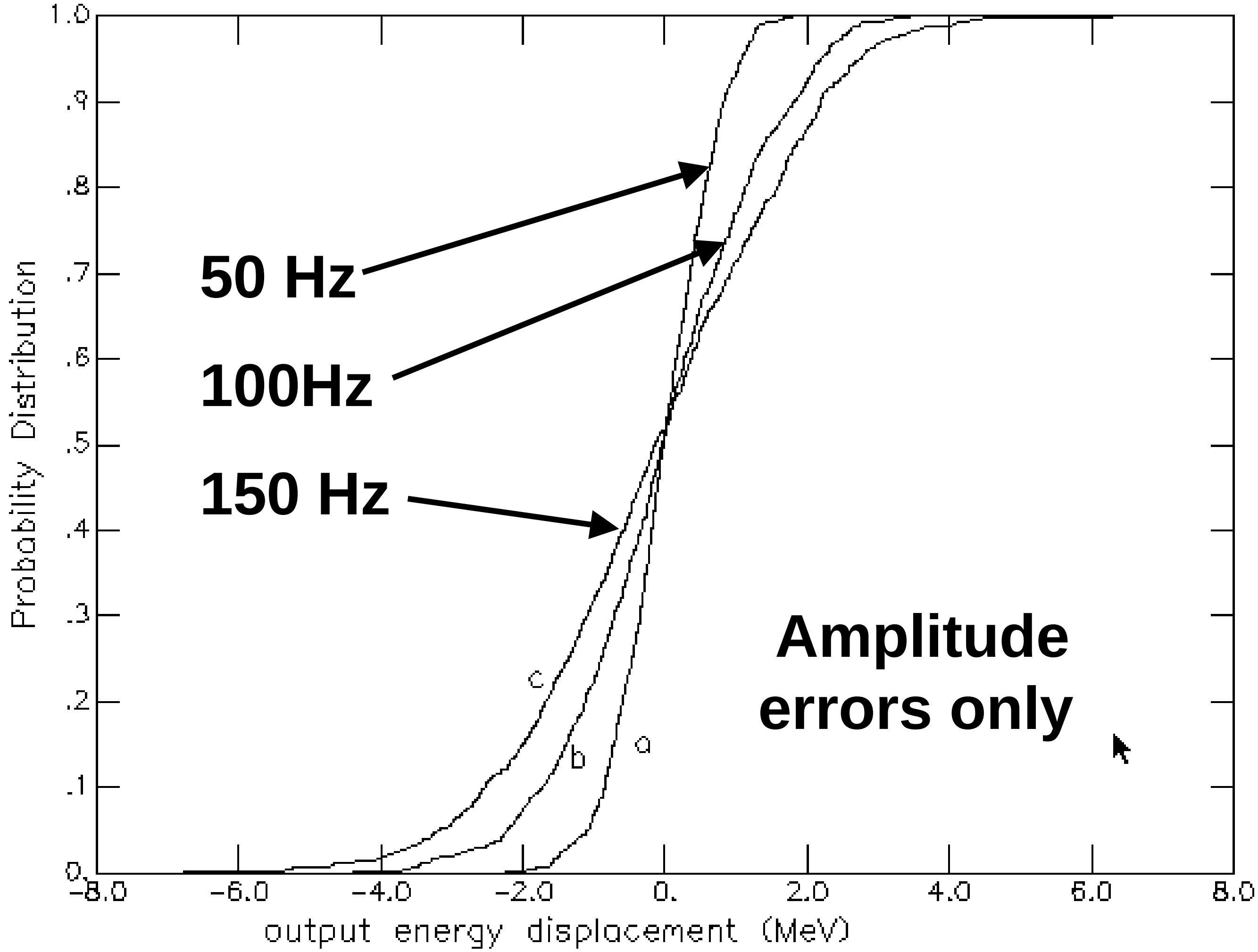
Programmed vs. Equal Power Split



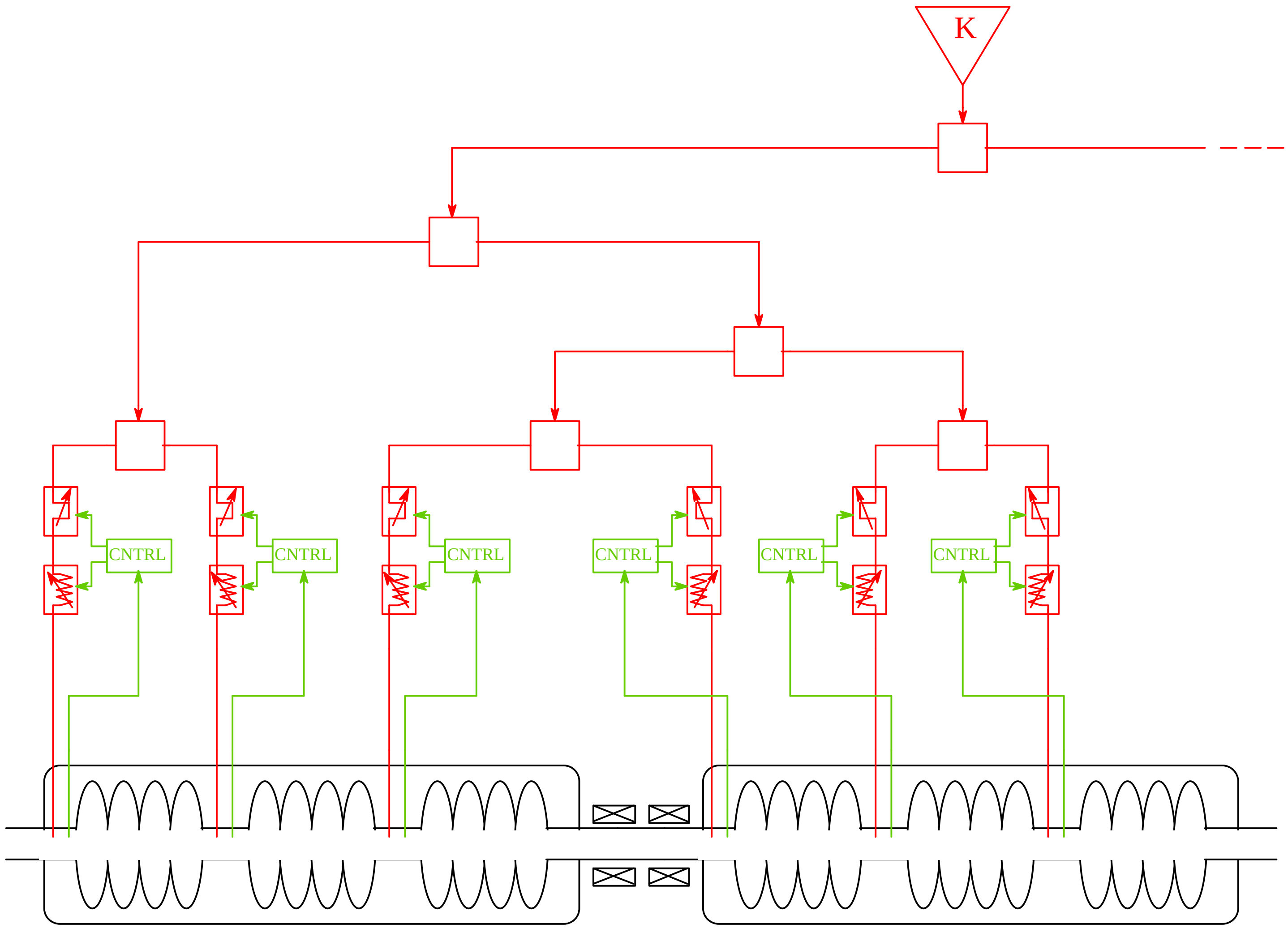
Vector Sum + Individual Cavity Phase Control



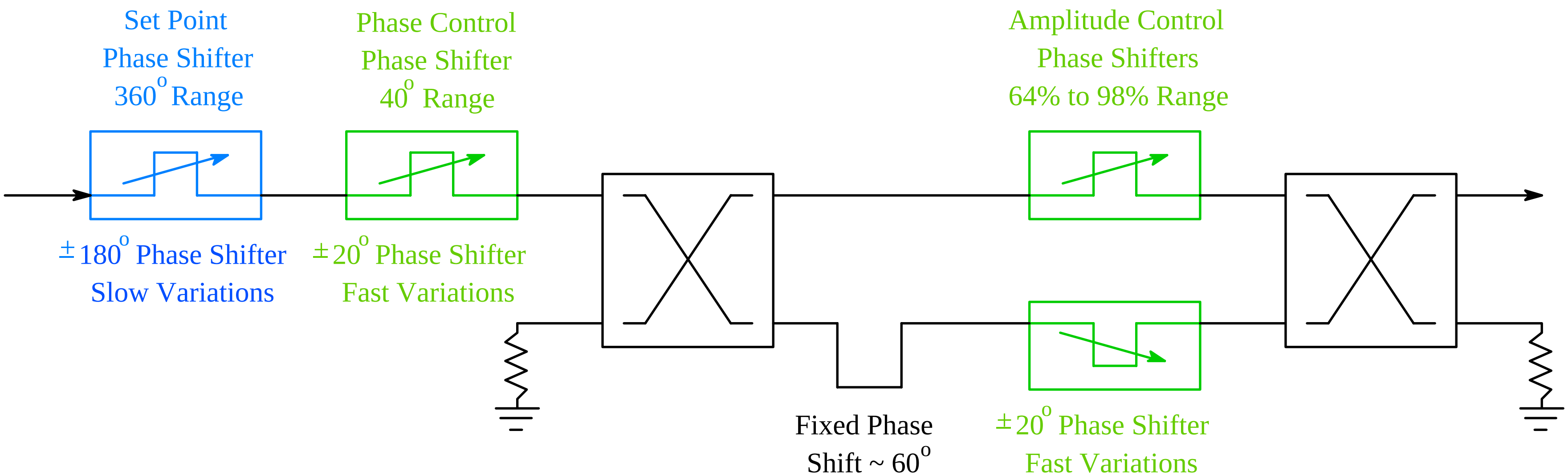
ΔW, Microphonics Corrected by Linear Averaging + Individual Cavity Phase Control



12 Cavities/Klystron
Individual Cavity Control

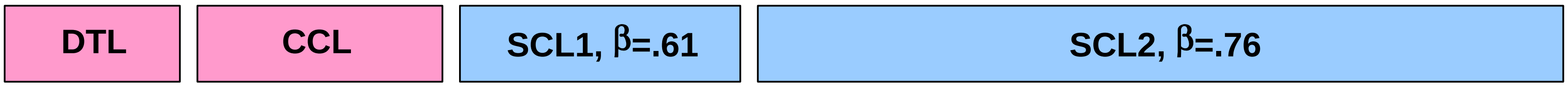


Dual Fast Phase Shifter Scheme



- $\Delta P = 33\text{-}93\%$
- $\Delta\phi = \pm 20°$
- Slew rate ≈ 0.4°/μsec

“Final” Reference Design



	DTL	CCL	SCL1	SCL2	Total
W_{final} (MeV)	86	185	308	1000	
Klystrons	6	4	2	7	19
Cryostats	-	-	8	21	29
Length (m)	36.5	56.5	46.6	161.7	301.3

- 12 cavities per Klystron
- Repartitioning not required
- Assume vector sum control of “common mode” for 12 cavities
- Individual cavity field control via dual-phase-shifter scheme
- Very complex control algorithm

Transient Performance
First 6 Cavities, No Errors

- No errors
- klystron power held constant
  - all control provided via “Suny” gizmos on each cavity
  - dual phase shifter assemblies act as an attenuators for amplitude
  - series phase shifters for phase
  - 0.4 deg/usec slew rate
- phase is corrected for Lorentz detuning throughout pulse
- less power is delivered to first 3 cavites, somewhat more to second 3
- beam is turned on just as cavity fields approach design level at 225 usec (top)
- individual cavity fields converge after another 150 usec
  - beam energy is stable
  - delay caused primarily by slew rate of phase shifters (?)
  - something about constraining magnitude of control vectors

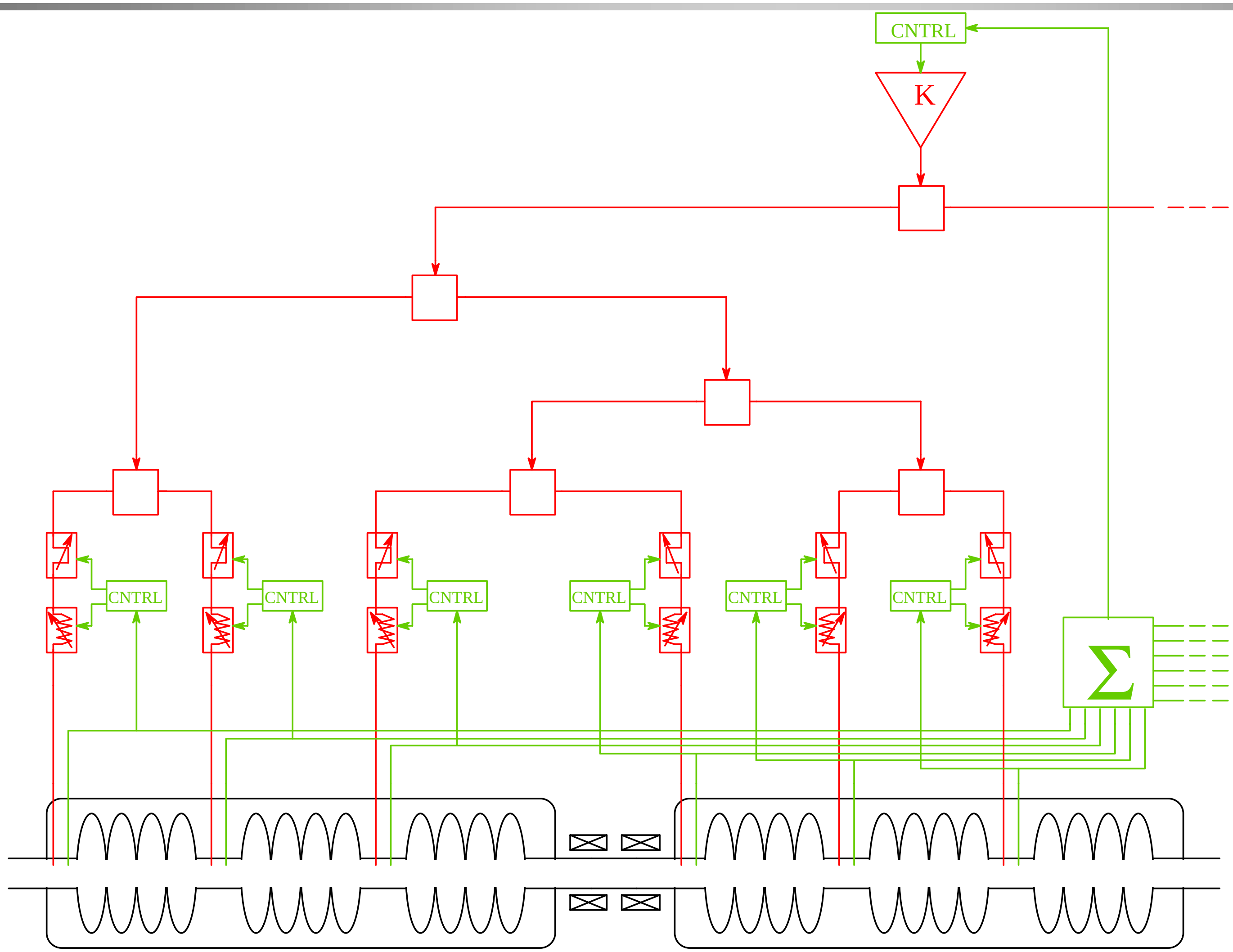
Transient Performance First 6 Cavities, With Errors

- Microphonics added 2 ea @ +/-100 Hz, others ~=/- 30 Hz
  - » Qexternal +/-20%
  - » same power split
- cavities now take 300 usec to converge after beam is turned on
- something about realistic magnitude for control vector

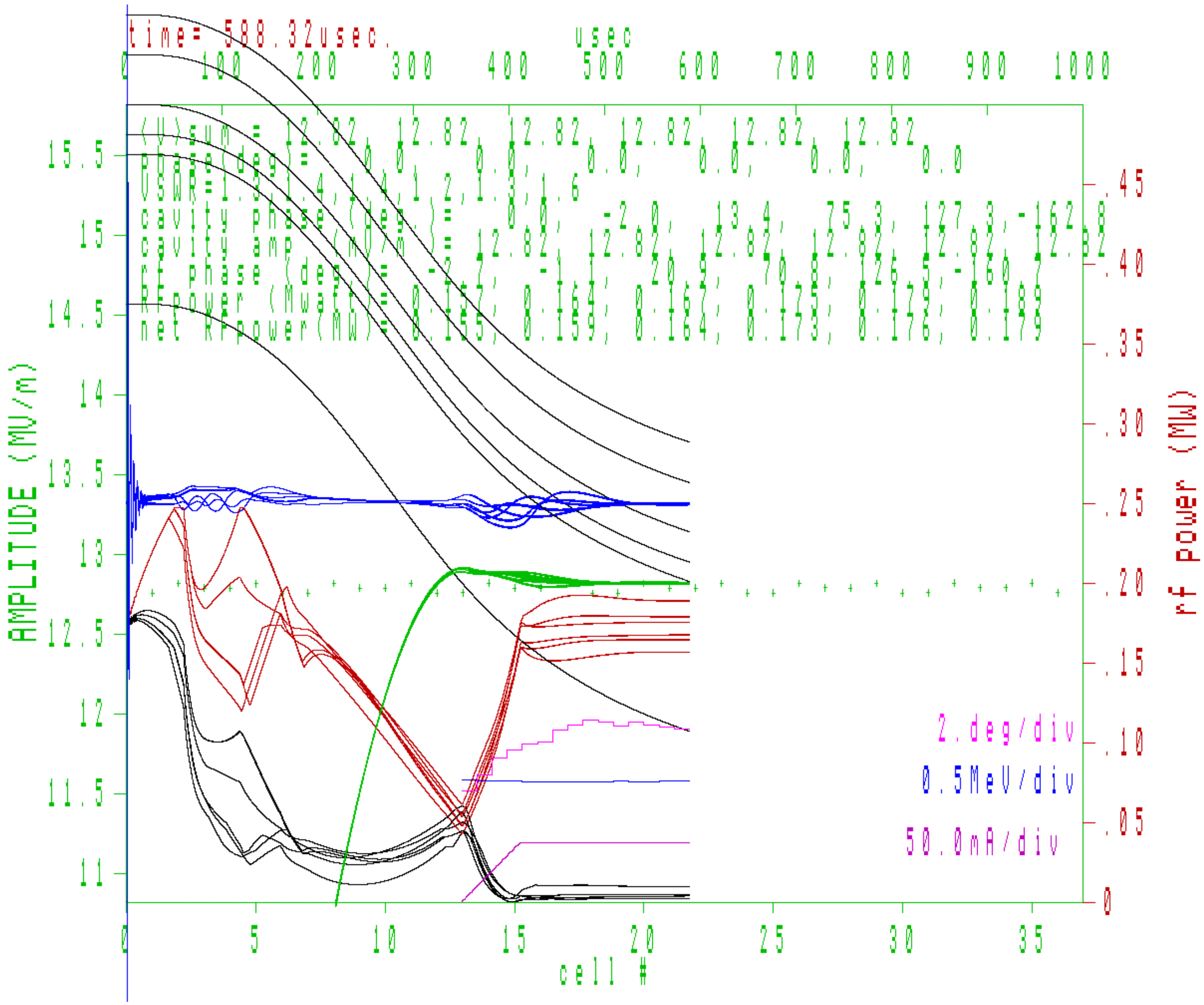
Transient Performance
First 6 Cavities, Fast ϕ-Shifters

- Slew rate increased to 4 deg/usec **Slew = 4°/μsec**
  - » independent but limited control on phase & amplitude
- beam delayed for 350 usec for fields to stabilize
  - » can't control phase at reduced forward power
  - » fields converge in 150 usec

12 Cavities/Klystron
Individual + Collective Cavity Control



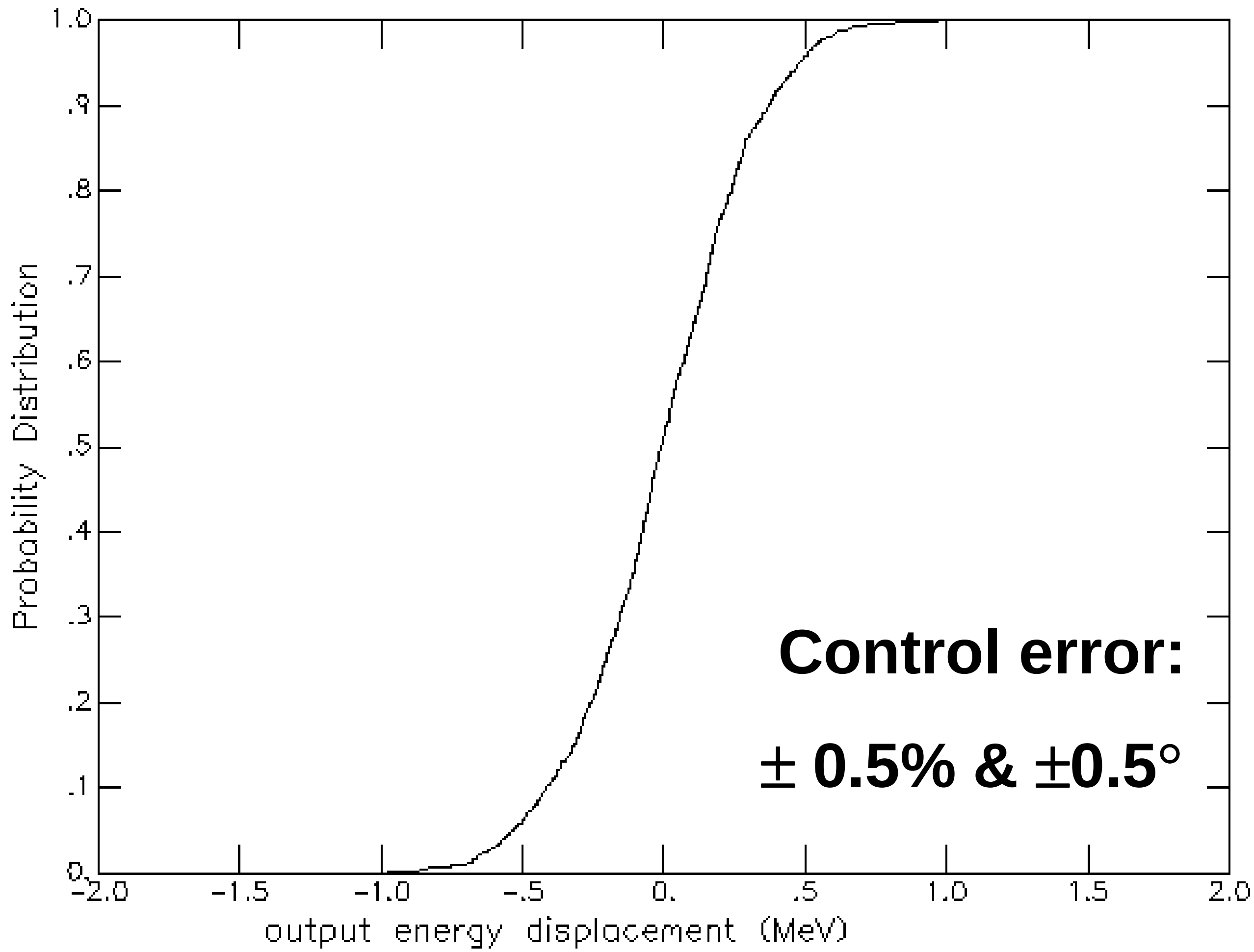
Transient Performance
Individual + Collective Cavity Control



Transient Performance
Individual + Collective Cavity Control

- average beam current is ramped by pulsing over the first 50 usec.
- phase shifters +- 20 deg
- Q external error= +- 15%
- The simulation has perfect phase shifters and klystrons without noise.
- This system has an extremely complex rf control system.

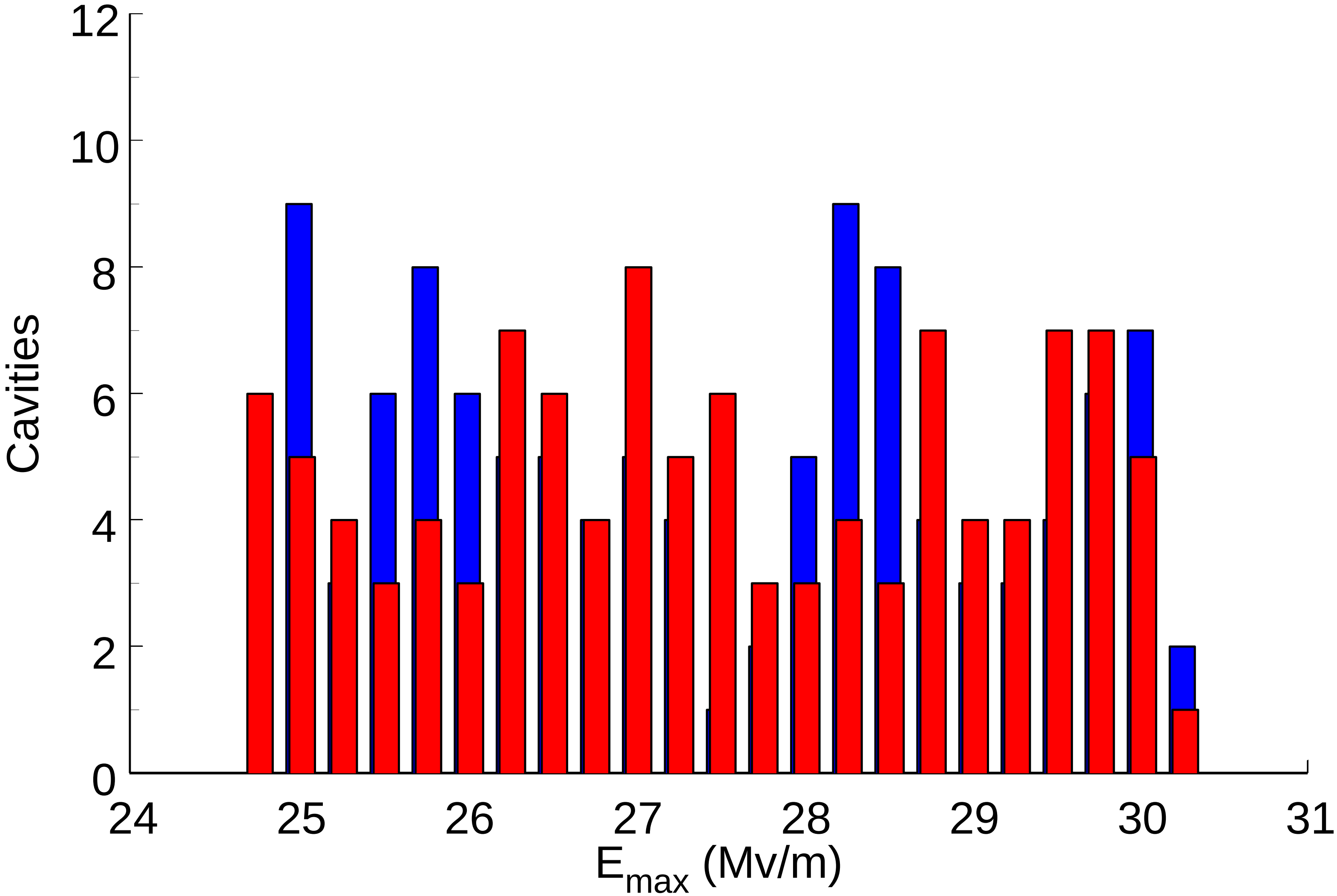
Energy Stability
Individual + Collective Cavity Control



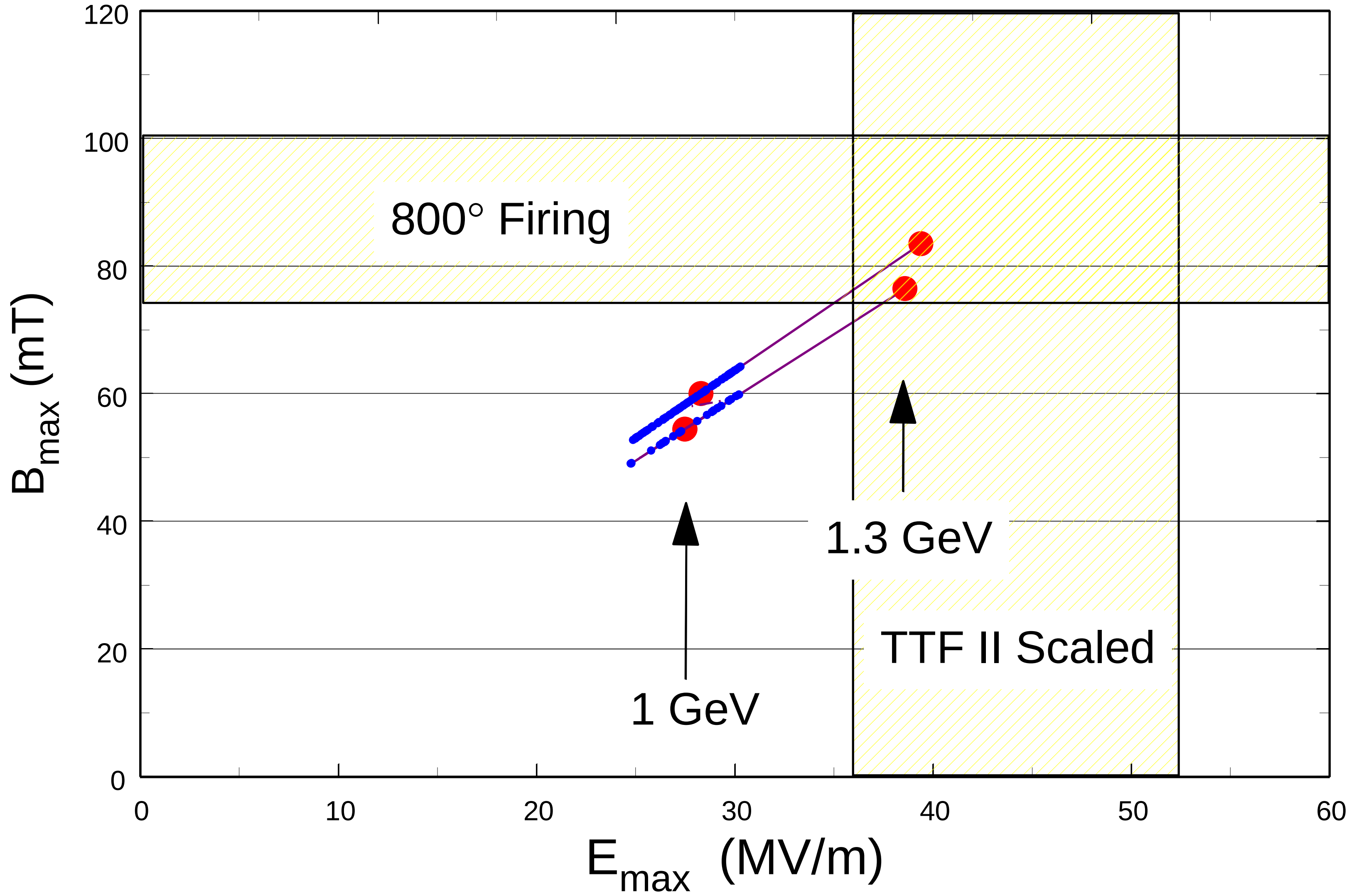
New SCRF Linac Design Constraints

- $P_{max,coupler} \leq$ 500 kW pulsed
  - » $\pm$ 20% coupling tol.
- E_{max} = 27.5 MV/m $\pm$ 10% cavity perf.
  - » actual operating points to be determined at installation
  - » no sorting
- 12 cavities per klystron
- Individual cavity control
  - » collective feedback for klystron control of "common mode"

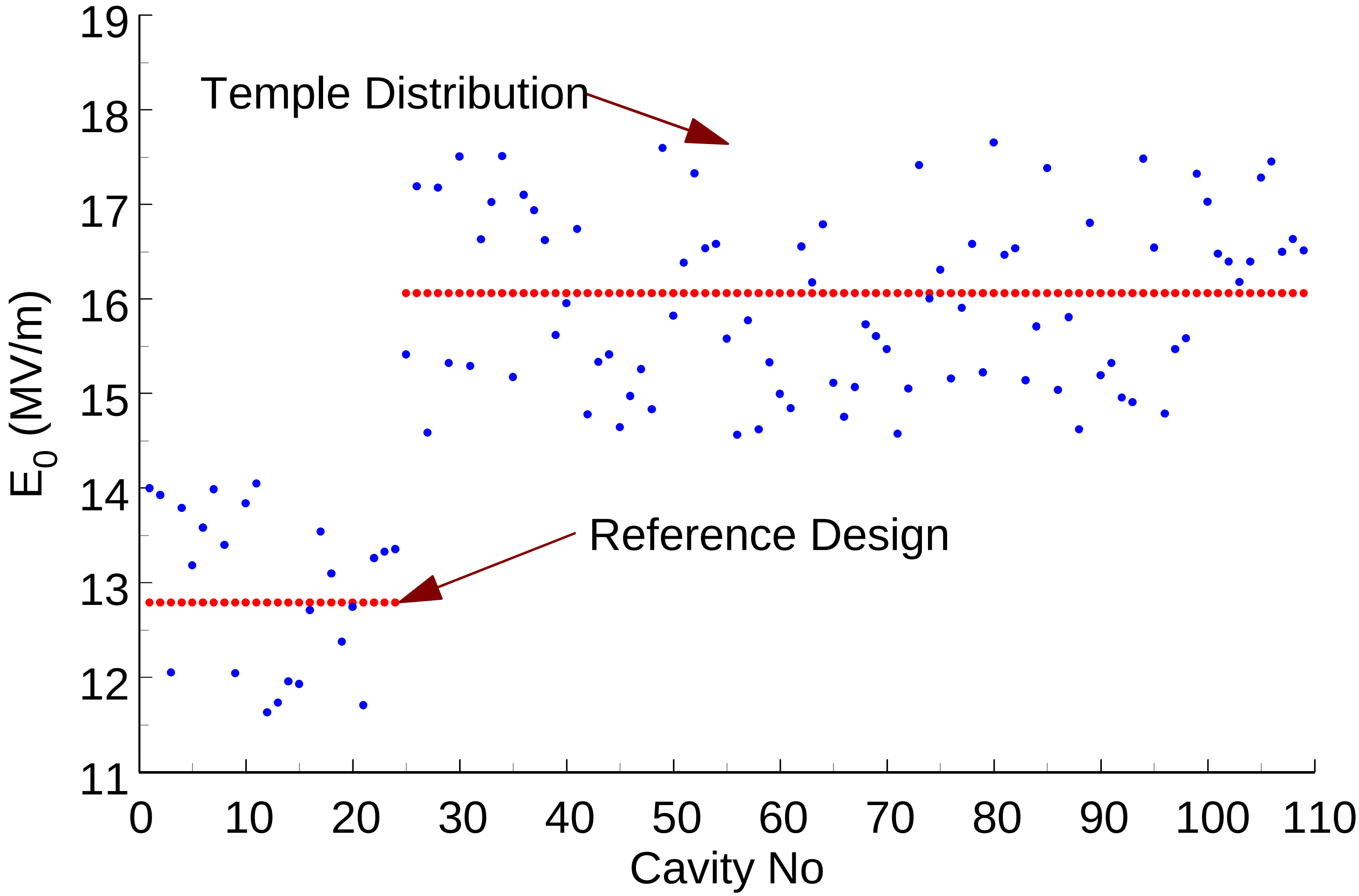
Random Sampling of Cavities From Temple Distribution



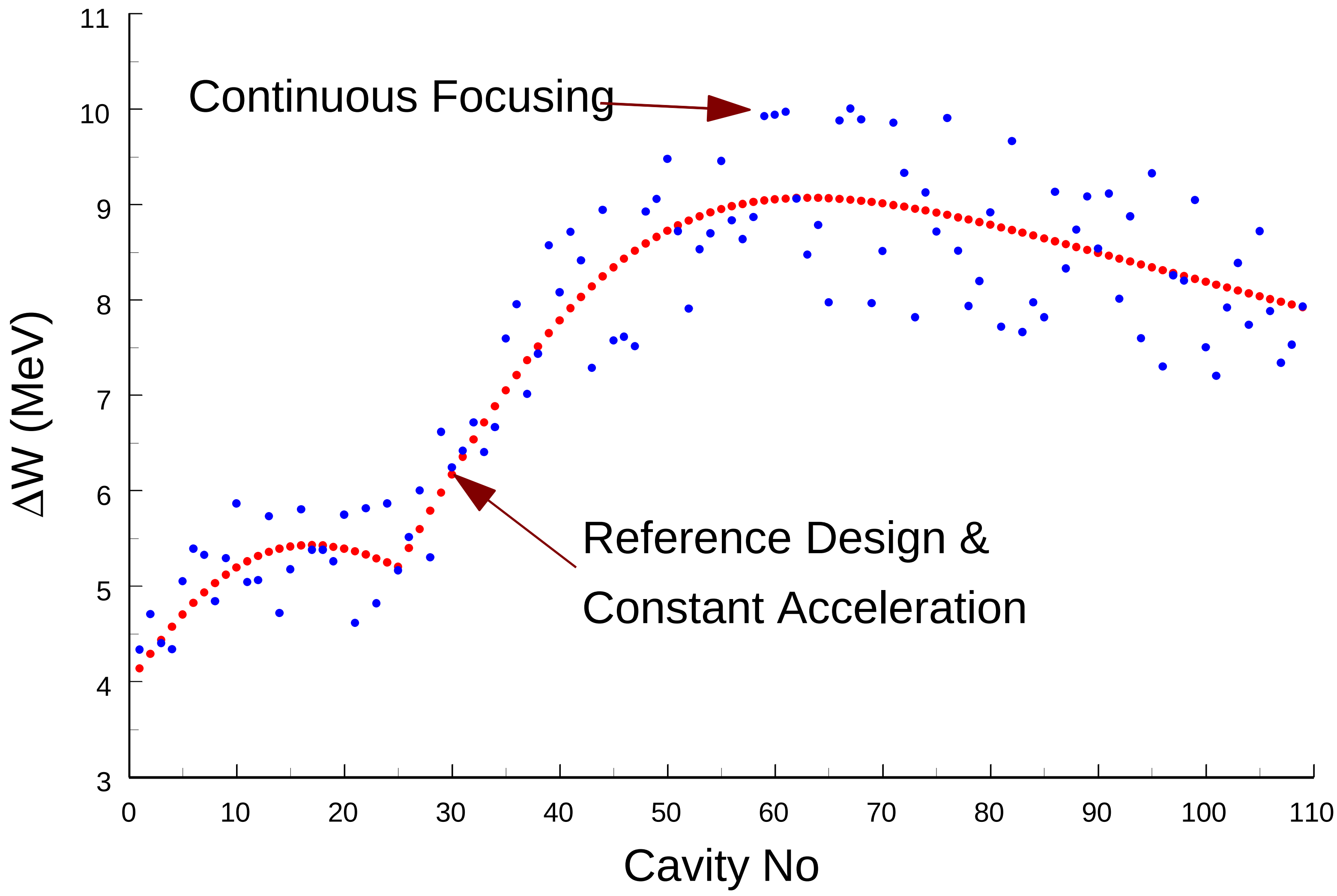
Expected Performance of SNS Cavities



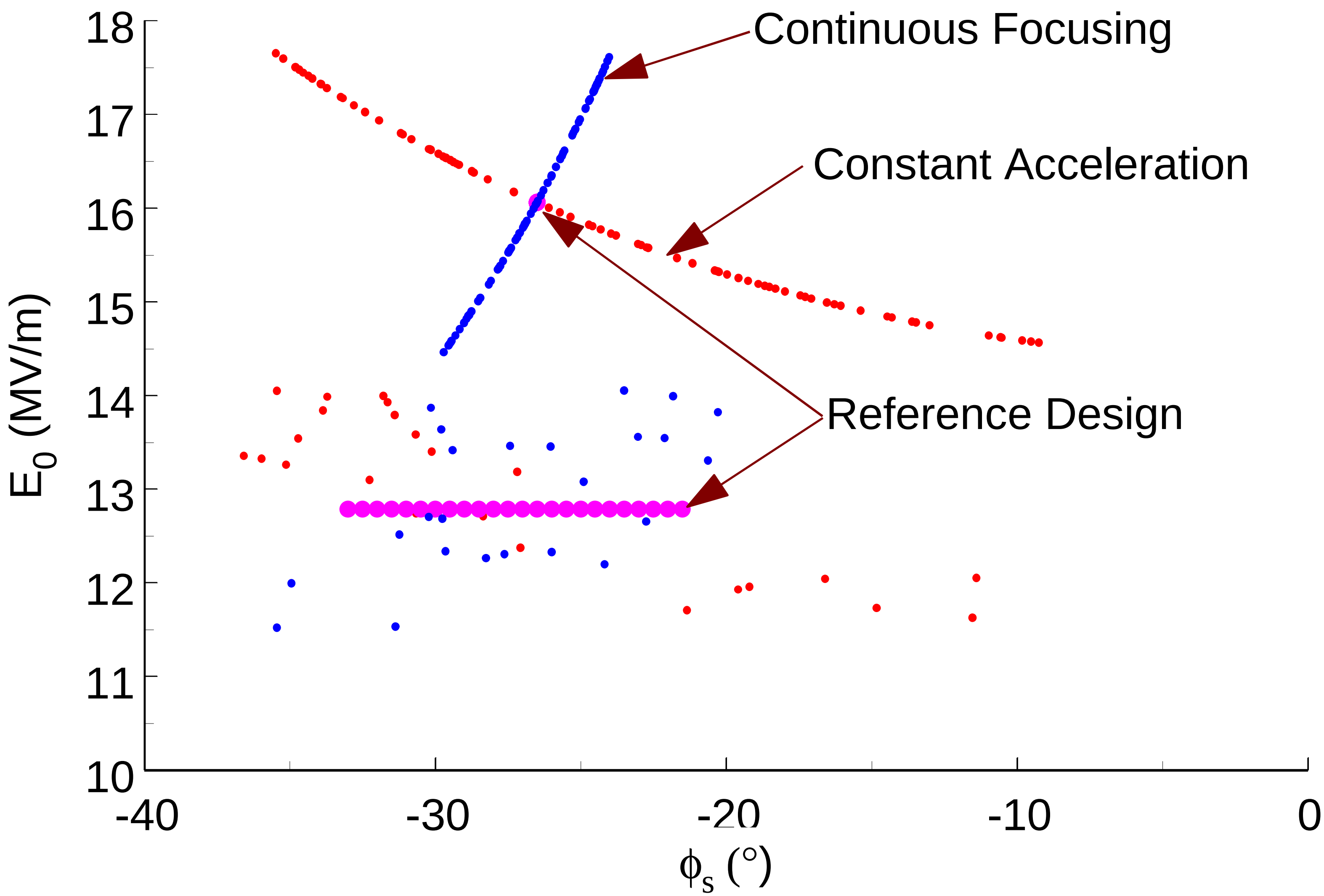
Gradient Distribution for Temple Distribution



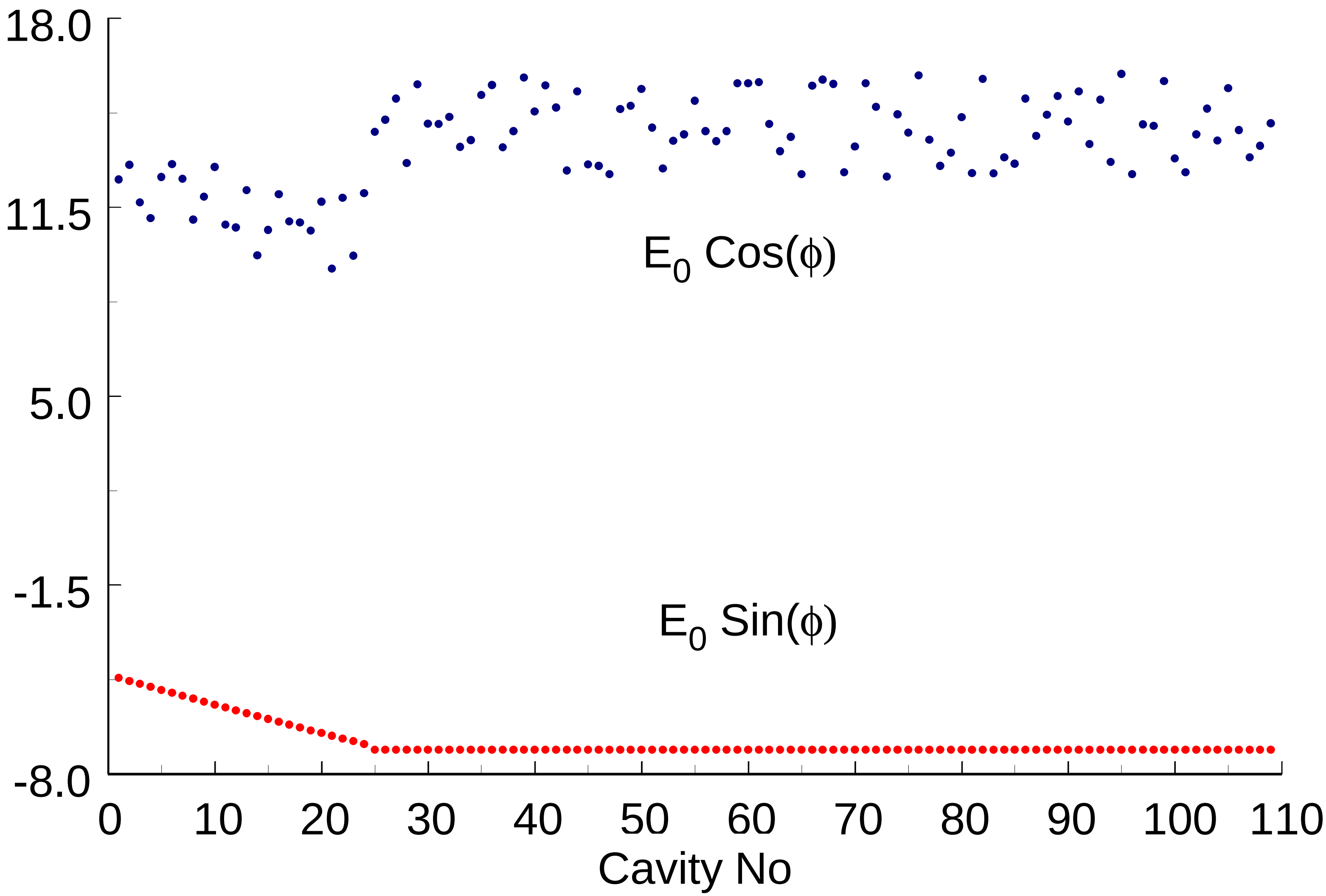
Energy Gain Profile for Two Design Options



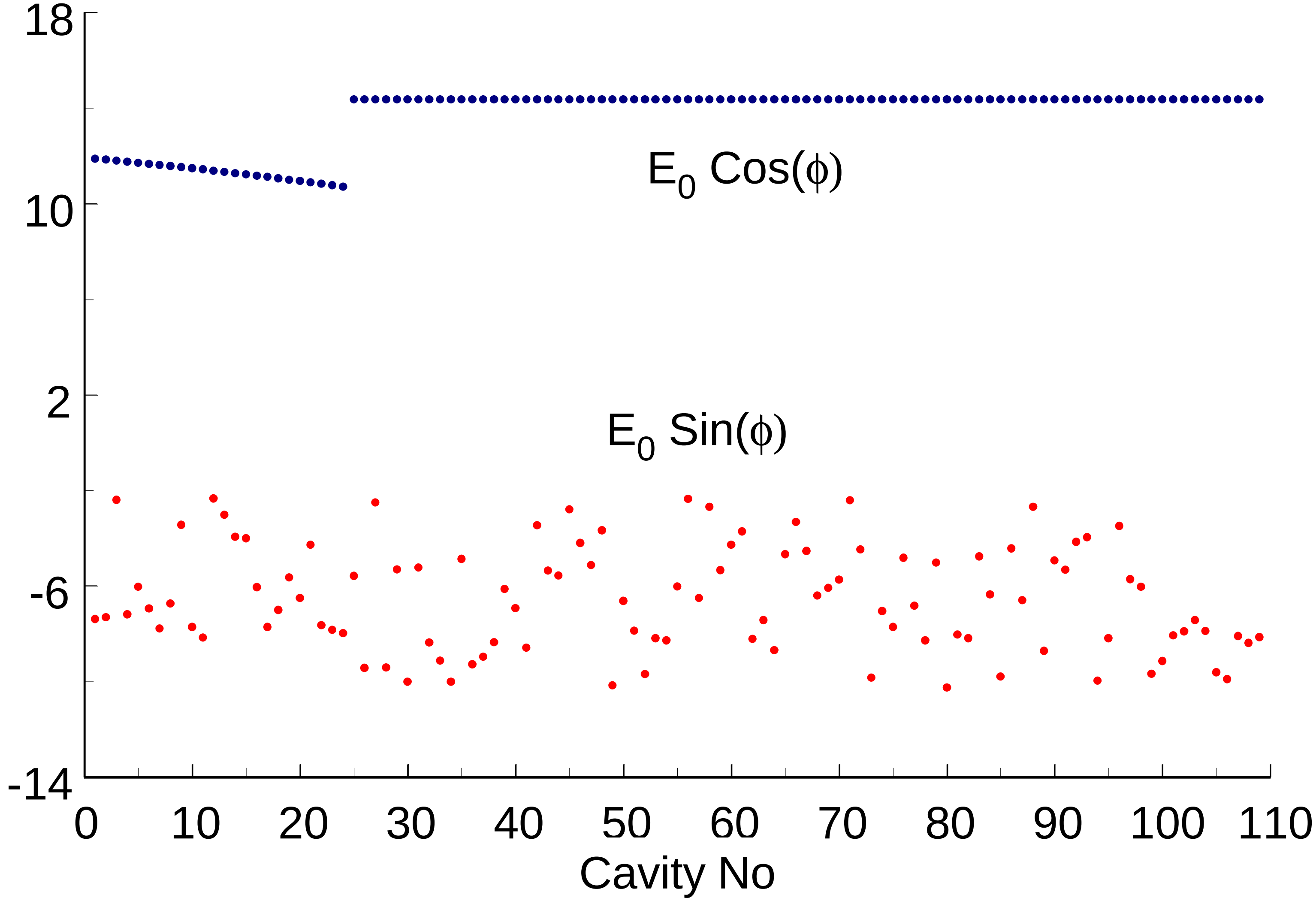
Phase-Energy Laws for Two Design Options



Continuous Focusing Scheme



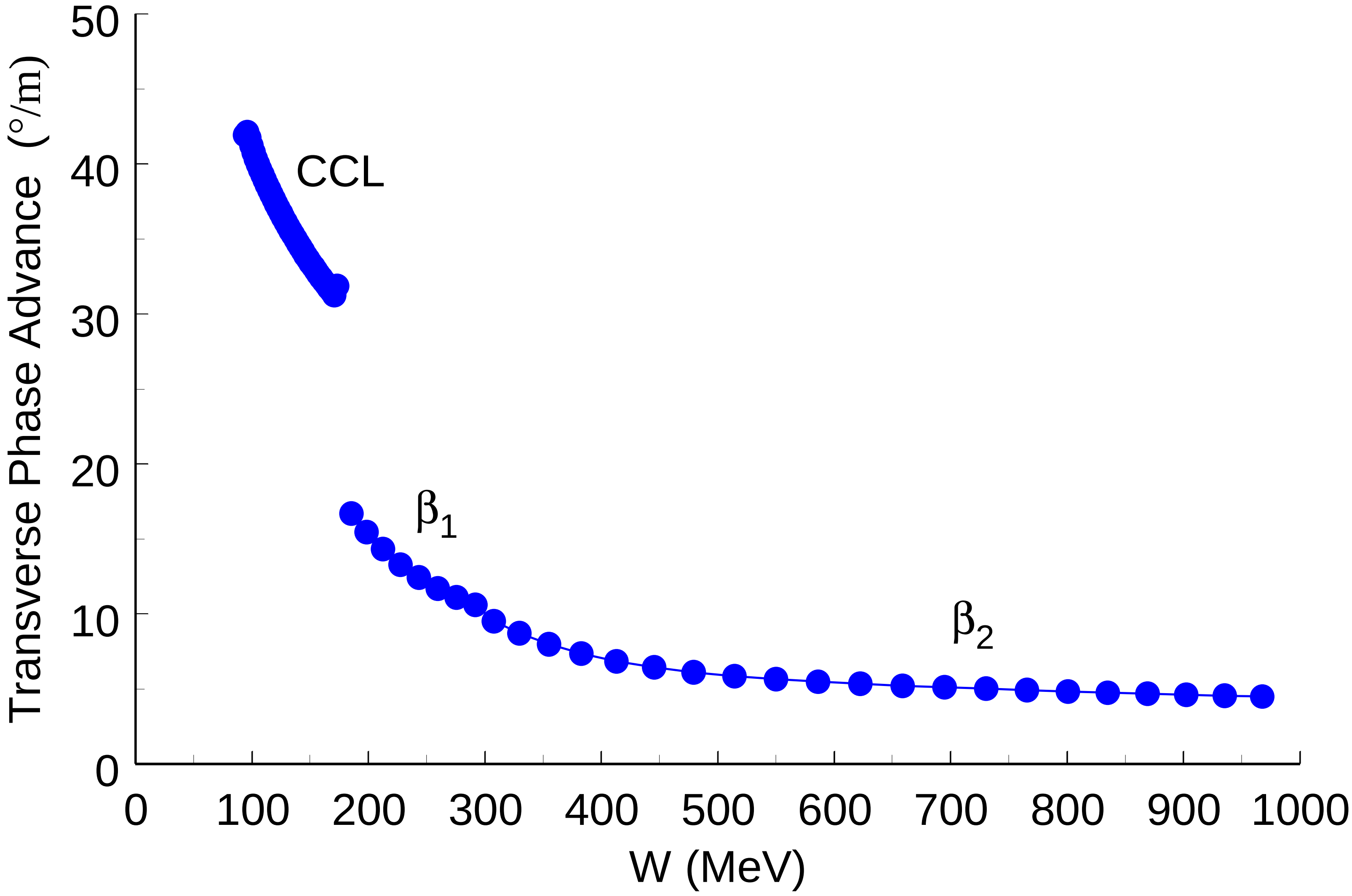
Constant Acceleration Option



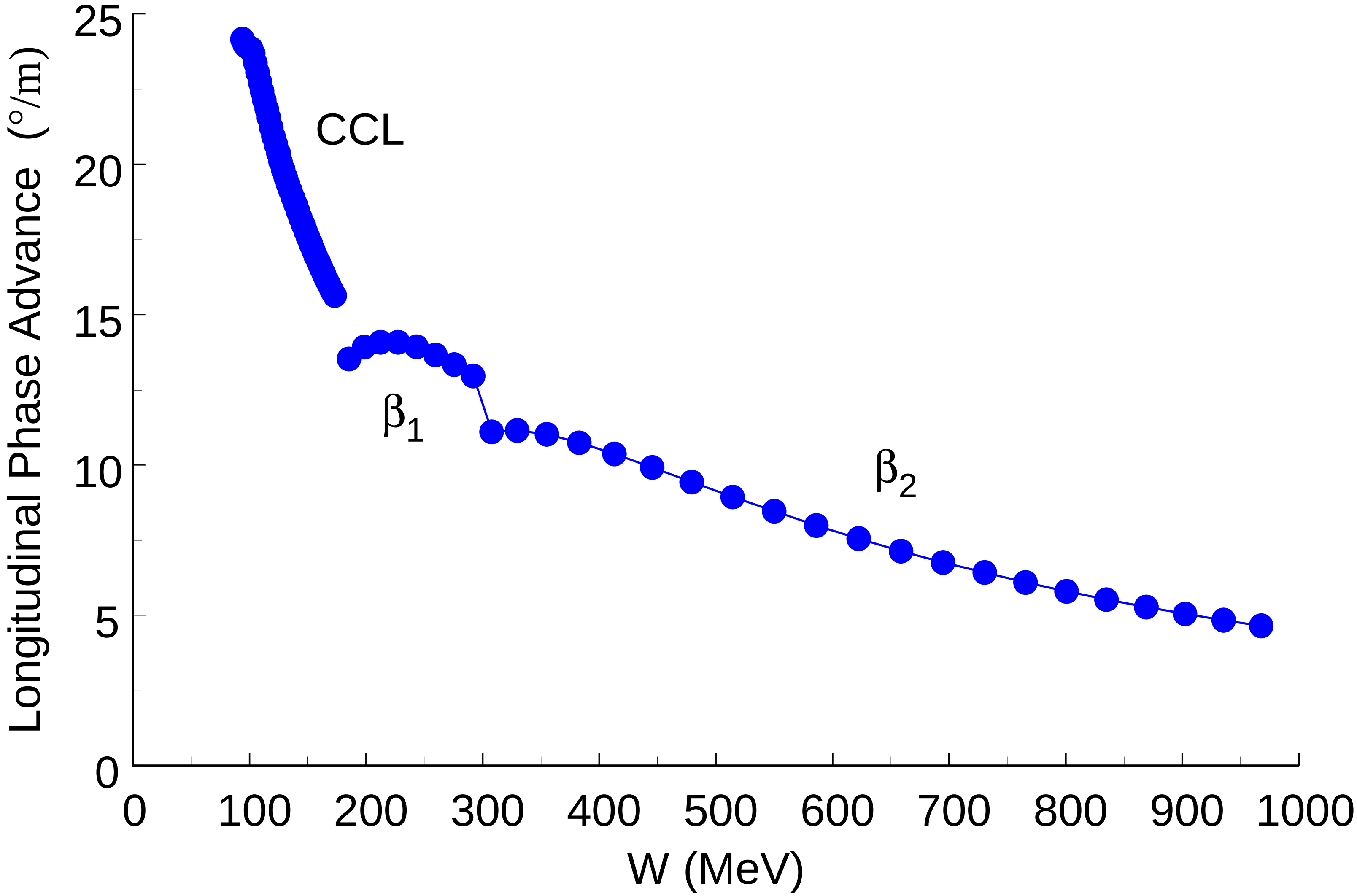
Design Studies Pending

- Cavity optimization
  - » β_g & cavity shape
- Linac design
  - » optimize phase law for constant E_0
  - » Implications of E_0Temple distribution
  - » ϕ_s, constant acceleration vs. focusing
  - » quad laws
- Matching, current independent
  - » transverse & longitudinal
- Transient field effects
- Error studies
- End-to-end linac performance
- Commissioning scenarios

Reference Design
Transverse Phase Advance



Reference Design
Longitudinal Phase Advance



Error Studies

- Define realistic error budget, static & dynamic
- Beam properties as a function errors:
  - » Uncertainty in final energy centroid
  - » Stability of final energy centroid
  - » Emittance dilution & stability, trans. & long.
  - » Halo formation
  - » Expected beam loss
  - » Missmatches
- Detection & Correction schemes for the above