Software Tools for Commissioning of the Spallation Neutron Source Linac

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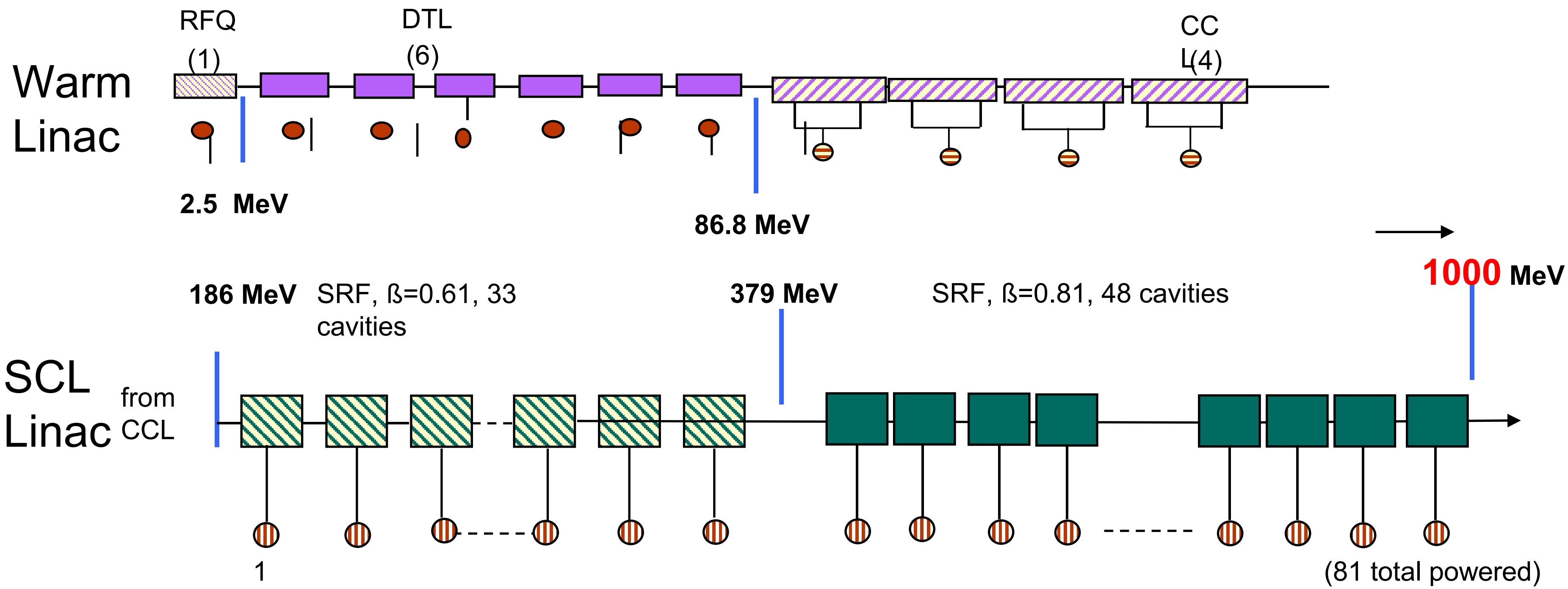
Challenges

- **SNS is the first application of pulsed, proton acceleration using a superconducting RF linac**
- **Aggressive commissioning schedule**
  - **Superconducting Linac in August 2005**
  - **Ring in Jan. 2006**
- **Needed reliable stable linac beam to commission the Ring**
- **SRF configuration is a moving target**
  - **Need flexible tools**

XAL Infrastructure

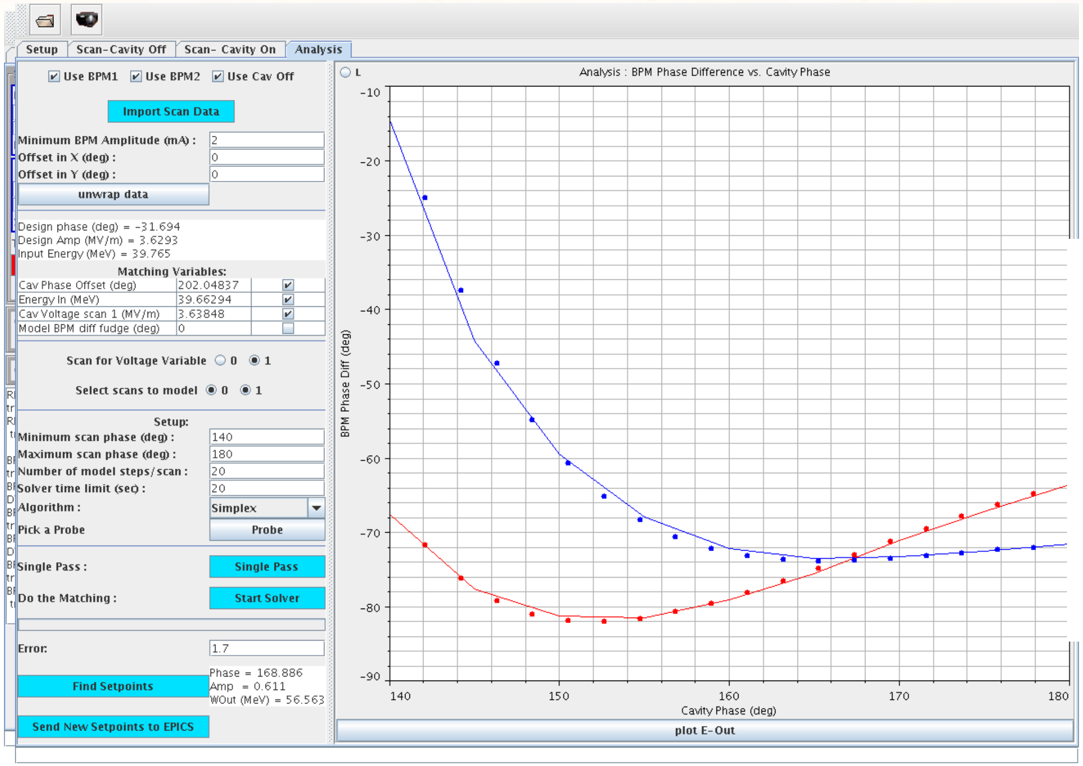
- Software tools use the Java based XAL infrastructure
- Accelerator class hierarchy
- Database configuration
- Beam Model
  - Transverse + longitudinal dynamics
  - Envelope and single particle tracking capabilities
- Lots of sharable tools
  - High level EPICS communication
  - Plotting
  - Database connection
  - …

Layout of the SNS Linac: Copper and Superconducting Modules



- SCL has 81 independently powered cavities
  - Many “parts” to keep running
  - Many values to set w.r.t. the beam

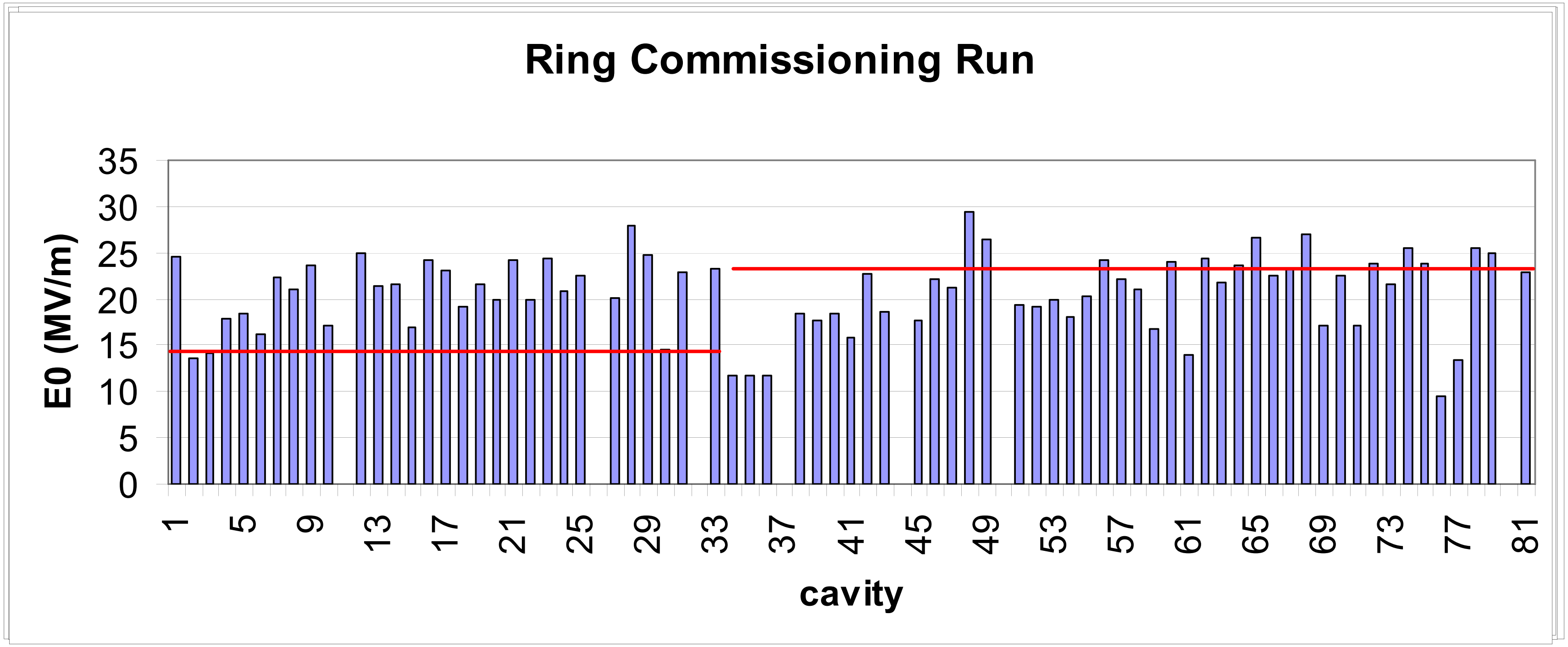
Warm Linac Tuning RF Phase and Amplitude Setting - PASTA



Analyze data with model comparison- gives RF gradient, phase offset, and beam energy

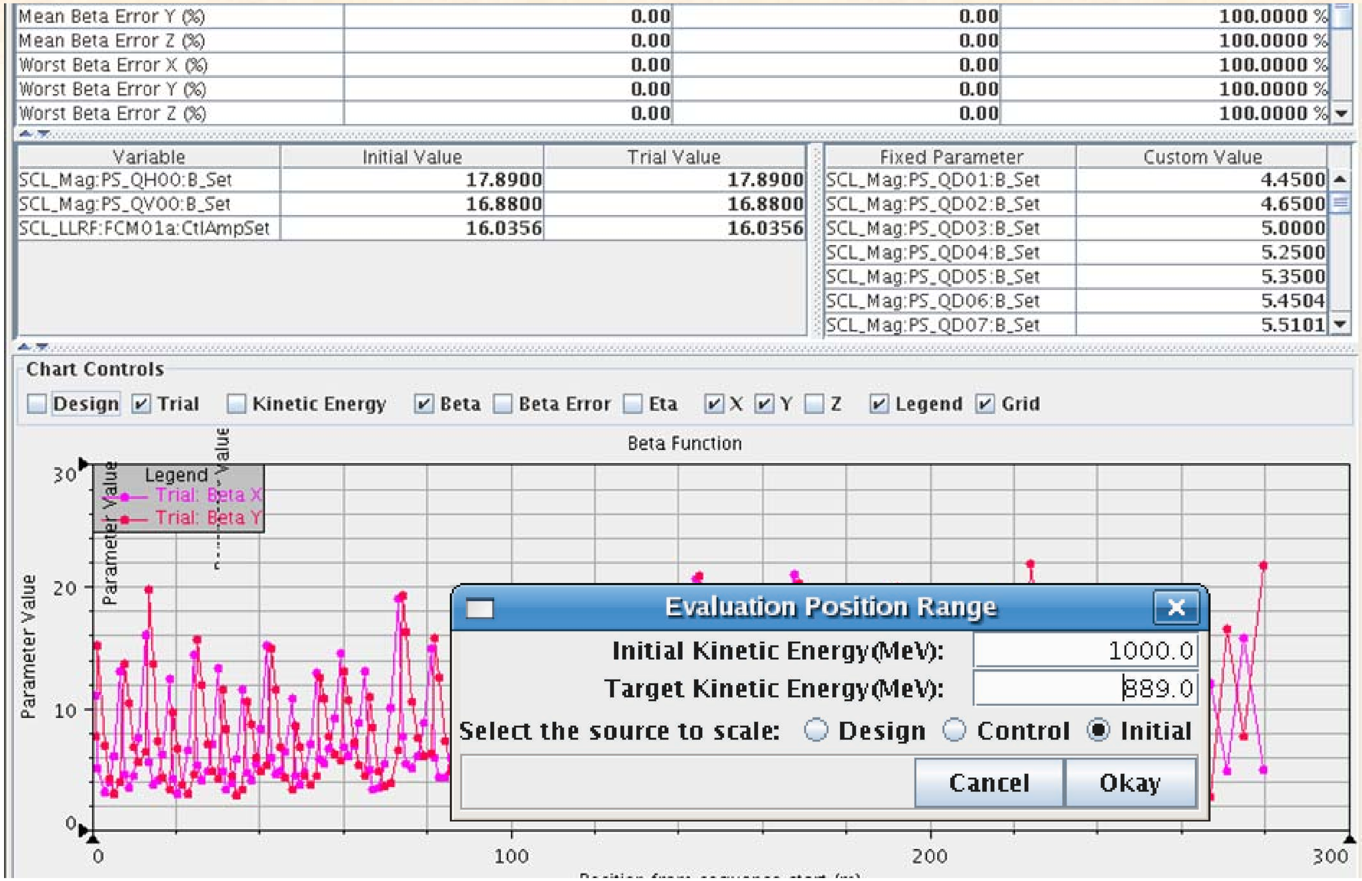
- **Previous technique used a linear approximation valid near the final setpoints.**
- **Phase signature scans involves running a longitudinal tracking model for many points along a scan, all within an optimization framework**

SCL Cavity Amplitudes



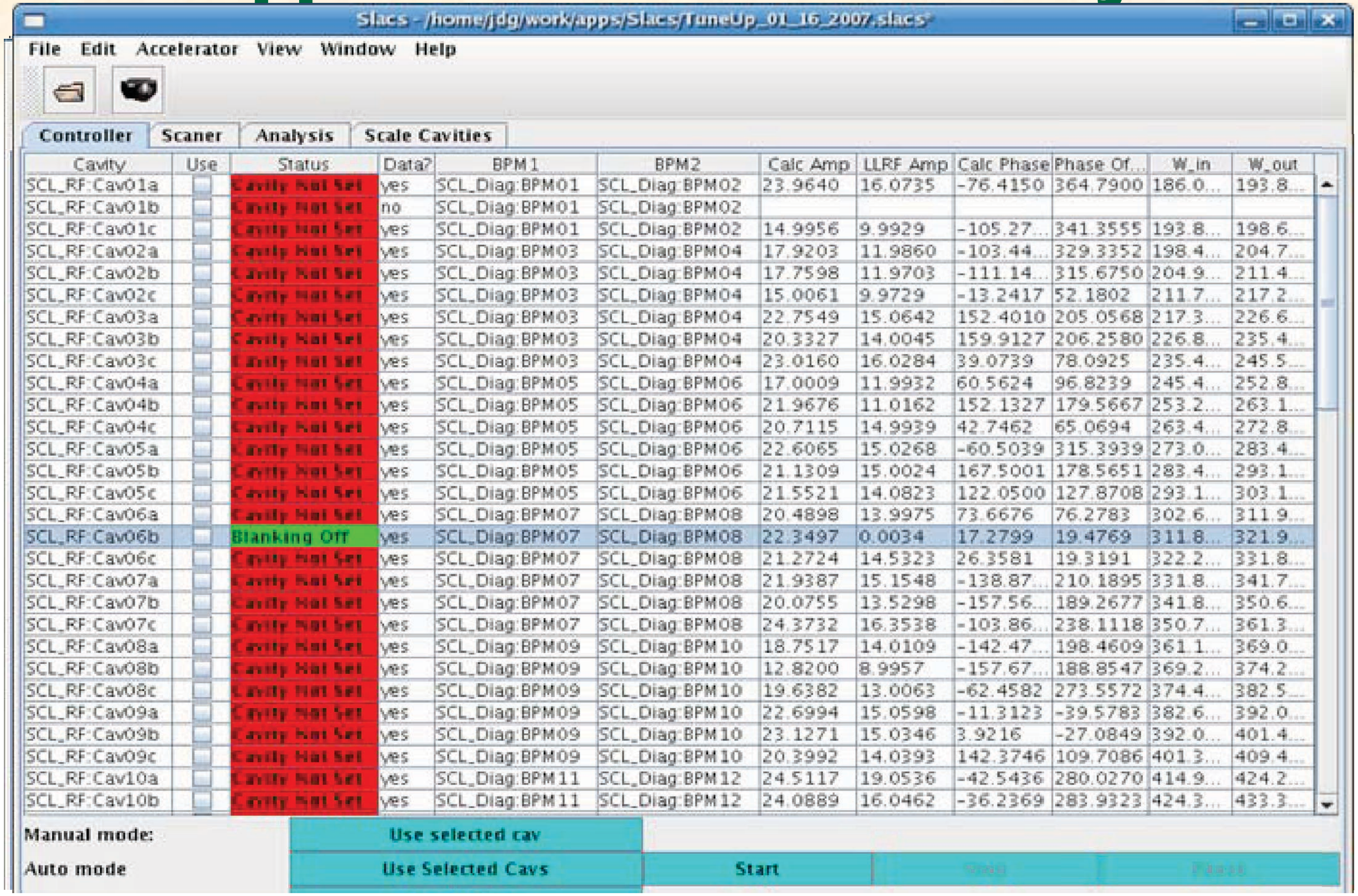
- **Strategy is to run cavities at their maximum safe amplitude limit**
- **Need to be *flexible* – SRF capabilities change, not near the design**
- **Linac output energy is a moving target**

Energy Manager Application



- **Need to find new quad lattice tune for different energies**
  - **Matching optimization, quad variables**
- **Scale magnet setpoints based on new energy**

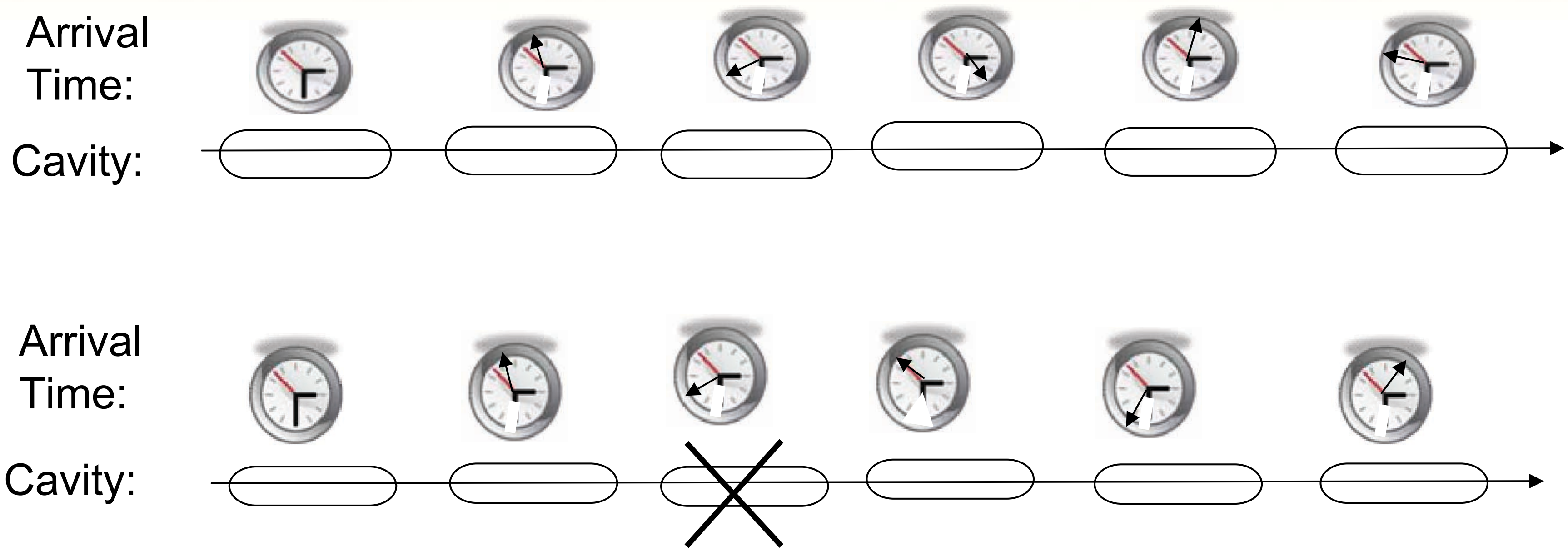
SLACS – App to Set the SCL Cavity Phase



Cavity	Use	Status	Data?	BPM1	BPM2	Calc Amp	LLRF Amp	Calc Phase	Phase Of...	W_in	W_out
SCL_RF:Cav01a		Cavity Not Set	yes	SCL_Diag:BPM01	SCL_Diag:BPM02	23.9640	16.0735	-76.4150	364.7900	186.0...	193.8...
SCL_RF:Cav01b		Cavity Not Set	no	SCL_Diag:BPM01	SCL_Diag:BPM02						
SCL_RF:Cav01c		Cavity Not Set	yes	SCL_Diag:BPM01	SCL_Diag:BPM02	14.9956	9.9929	-105.27...	341.3555	193.8...	198.6...
SCL_RF:Cav02a		Cavity Not Set	yes	SCL_Diag:BPM03	SCL_Diag:BPM04	17.9203	11.9860	-103.44...	329.3352	198.4...	204.7...
SCL_RF:Cav02b		Cavity Not Set	yes	SCL_Diag:BPM03	SCL_Diag:BPM04	17.7598	11.9703	-111.14...	315.6750	204.9...	211.4...
SCL_RF:Cav02c		Cavity Not Set	yes	SCL_Diag:BPM03	SCL_Diag:BPM04	15.0061	9.9729	-13.2417	52.1802	211.7...	217.2...
SCL_RF:Cav03a		Cavity Not Set	yes	SCL_Diag:BPM03	SCL_Diag:BPM04	22.7549	15.0642	152.4010	205.0568	217.3...	226.6...
SCL_RF:Cav03b		Cavity Not Set	yes	SCL_Diag:BPM03	SCL_Diag:BPM04	20.3327	14.0045	159.9127	206.2580	226.8...	235.4...
SCL_RF:Cav03c		Cavity Not Set	yes	SCL_Diag:BPM03	SCL_Diag:BPM04	23.0160	16.0284	39.0739	78.0925	235.4...	245.5...
SCL_RF:Cav04a		Cavity Not Set	yes	SCL_Diag:BPM05	SCL_Diag:BPM06	17.0009	11.9932	60.5624	96.8239	245.4...	252.8...
SCL_RF:Cav04b		Cavity Not Set	yes	SCL_Diag:BPM05	SCL_Diag:BPM06	21.9676	11.0162	152.1327	179.5667	253.2...	263.1...
SCL_RF:Cav04c		Cavity Not Set	yes	SCL_Diag:BPM05	SCL_Diag:BPM06	20.7115	14.9939	42.7462	65.0694	263.4...	272.8...
SCL_RF:Cav05a		Cavity Not Set	yes	SCL_Diag:BPM05	SCL_Diag:BPM06	22.6065	15.0268	-60.5039	315.3939	273.0...	283.4...
SCL_RF:Cav05b		Cavity Not Set	yes	SCL_Diag:BPM05	SCL_Diag:BPM06	21.1309	15.0024	167.5001	178.5651	283.4...	293.1...
SCL_RF:Cav05c		Cavity Not Set	yes	SCL_Diag:BPM05	SCL_Diag:BPM06	21.5521	14.0823	122.0500	127.8708	293.1...	303.1...
SCL_RF:Cav06a		Cavity Not Set	yes	SCL_Diag:BPM07	SCL_Diag:BPM08	20.4898	13.9975	73.6676	76.2783	302.6...	311.9...
SCL_RF:Cav06b		Blanking Off	yes	SCL_Diag:BPM07	SCL_Diag:BPM08	22.3497	0.0034	17.2799	19.4769	311.8...	321.9...
SCL_RF:Cav06c		Cavity Not Set	yes	SCL_Diag:BPM07	SCL_Diag:BPM08	21.2724	14.5323	26.3581	19.3191	322.2...	331.8...
SCL_RF:Cav07a		Cavity Not Set	yes	SCL_Diag:BPM07	SCL_Diag:BPM08	21.9387	15.1548	-138.87...	210.1895	331.8...	341.7...
SCL_RF:Cav07b		Cavity Not Set	yes	SCL_Diag:BPM07	SCL_Diag:BPM08	20.0755	13.5298	-157.56...	189.2677	341.8...	350.6...
SCL_RF:Cav07c		Cavity Not Set	yes	SCL_Diag:BPM07	SCL_Diag:BPM08	24.3732	16.3538	-103.86...	238.1118	350.7...	361.3...
SCL_RF:Cav08a		Cavity Not Set	yes	SCL_Diag:BPM09	SCL_Diag:BPM10	18.7517	14.0109	-142.47...	198.4609	361.1...	369.0...
SCL_RF:Cav08b		Cavity Not Set	yes	SCL_Diag:BPM09	SCL_Diag:BPM10	12.8200	8.9957	-157.67...	188.8547	369.2...	374.2...
SCL_RF:Cav08c		Cavity Not Set	yes	SCL_Diag:BPM09	SCL_Diag:BPM10	19.6382	13.0063	-62.4582	273.5572	374.4...	382.5...
SCL_RF:Cav09a		Cavity Not Set	yes	SCL_Diag:BPM09	SCL_Diag:BPM10	22.6994	15.0598	-11.3123	-39.5783	382.6...	392.0...
SCL_RF:Cav09b		Cavity Not Set	yes	SCL_Diag:BPM09	SCL_Diag:BPM10	23.1271	15.0346	3.9216	-27.0849	392.0...	401.4...
SCL_RF:Cav09c		Cavity Not Set	yes	SCL_Diag:BPM09	SCL_Diag:BPM10	20.3992	14.0393	142.3746	109.7086	401.3...	409.4...
SCL_RF:Cav10a		Cavity Not Set	yes	SCL_Diag:BPM11	SCL_Diag:BPM12	24.5117	19.0536	-42.5436	280.0270	414.9...	424.2...
SCL_RF:Cav10b		Cavity Not Set	yes	SCL_Diag:BPM11	SCL_Diag:BPM12	24.0889	16.0462	-36.2369	283.9323	424.3...	433.3...

Keep “spread-sheet” summary of tune-up information for all cavities

Cavity Fault Impact on Beam Arrival Times for a Proton Linac



- **Proton beams for high power applications (< 10 GeV) are not fully relativistic and the velocity is energy dependent**
- **If a cavity fails, the beam arrives at downstream cavities later**
- **For SNS if an upstream cavity fails, the arrival time at downstream cavities can be delayed up to 5 nsec**
  - **This is over 1000 degrees phase setting of an 805 MHz RF cavity**
  - **Our goal is to set the cavity to within ~ 1 degree**

Scaling Method for Cavity Fault Recovery

New cavity phases

New Beam Energy

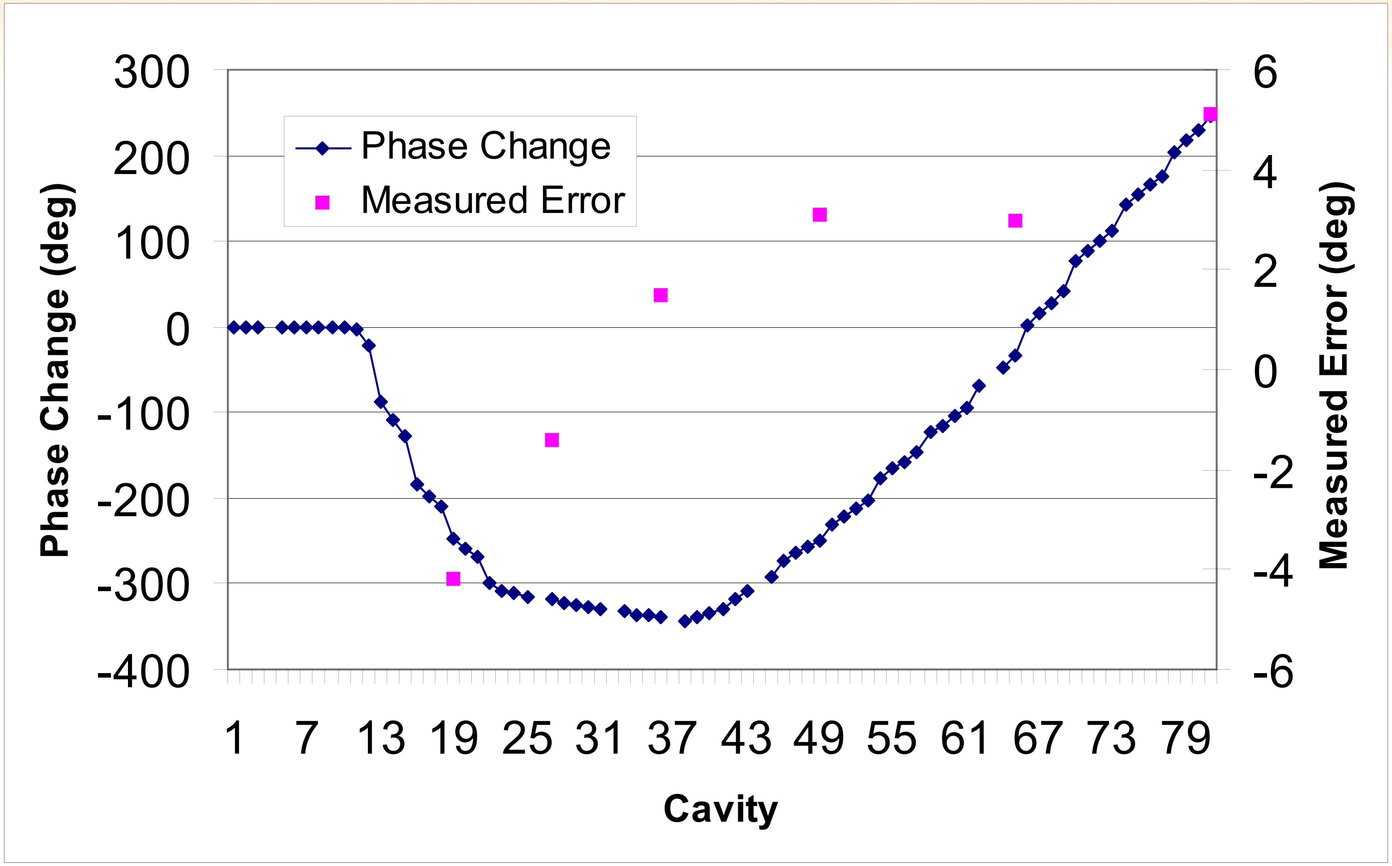
Controller | Scaner | Analysis | Scale Cavities

Cavity	Amplitude_0	Amplitude New	Avg Phase_0	Start Phase_0	Manual Pha...	Start Phase New	W_0 (MeV)	W_New
SCL_RF:Cav01a	23.964	23.964	-14.515	-76.415	0	-76.415	193.45	193.45
SCL_RF:Cav01b		0	60.856		0	0	193.45	193.45
SCL_RF:Cav01c	14.996	14.996	-26.571	-105.275	0	-105.275	198.258	198.258
SCL_RF:Cav02a	17.92	0	-17.871	-103.446	0	-104.893	204.671	198.258
SCL_RF:Cav02b	17.76	17.76	-17.784	-111.149	0	-135.016	211.339	204.617
SCL_RF:Cav02c	15.006	15.006	-21.789	-13.242	0	-60.455	217.048	210.09
SCL_RF:Cav03a	22.755	22.755	-14.711	152.401	0	36.423	226.421	219.126
SCL_RF:Cav03b	20.333	20.333	-15.452	159.913	0	20.046	235.093	227.539
SCL_RF:Cav03c	23.016	23.016	-14.742	39.074	0	-122.765	245.247	237.451
SCL_RF:Cav04a	17.001	17.001	-18.192	60.562	0	-164.214	252.779	244.844
SCL_RF:Cav04b	21.968	21.968	-14.723	152.133	0	-94.202	262.844	254.768
SCL_RF:Cav04c	20.711	20.711	-15.513	42.746	0	136.936	272.413	264.249
SCL_RF:Cav05a	22.606	22.606	-14.663	-60.504	0	-21.435	282.975	274.756
SCL_RF:Cav05b	21.131	21.131	-15.252	167.5	0	-171.876	292.846	284.611
SCL_RF:Cav05c	21.552	21.552	-14.931	122.05	0	126.191	302.914	294.696
SCL_RF:Cav06a	20.49	20.49	-16.316	73.668	0	31.585	312.38	304.202
SCL_RF:Cav06b	22.354	22.354	-15.147	24.257	0	-33.273	322.691	314.578
SCL_RF:Cav06c	21.272	21.272	-15.212	26.358	0	-44.889	332.404	324.372
SCL_RF:Cav07a	21.939	21.939	-15.2	-138.872	0	111.472	342.306	334.372
SCL_RF:Cav07b	20.075	20.075	-16.559	-157.57	0	80.007	351.192	343.356
SCL_RF:Cav07c	24.373	24.373	-15.168	-103.868	0	122.312	361.891	354.187
SCL_RF:Cav08a	18.752	18.752	-17.419	-142.479	0	51.973	369.906	362.306
SCL_RF:Cav08b	12.82	12.82	-25.25	-157.671	0	26.116	375.041	367.511
SCL_RF:Cav08c	19.638	19.638	-16.753	-62.458	0	111.589	383.268	375.852
SCL_RF:Cav09a	22.699	22.699	-15.159	-11.312	0	135.18	392.69	385.411
SCL_RF:Cav09b	23.127	23.127	-15.212	3.922	0	141.245	402.108	394.968
SCL_RF:Cav09c	20.399	20.399	-16.073	142.375	0	-88.467	410.232	403.215
SCL_RF:Cav10a	24.512	24.512	-13.701	-42.544	0	63.529	419.914	413.044

Initialize Model | Run Trial | Send New Phases | Restore Old Phases | Export Table

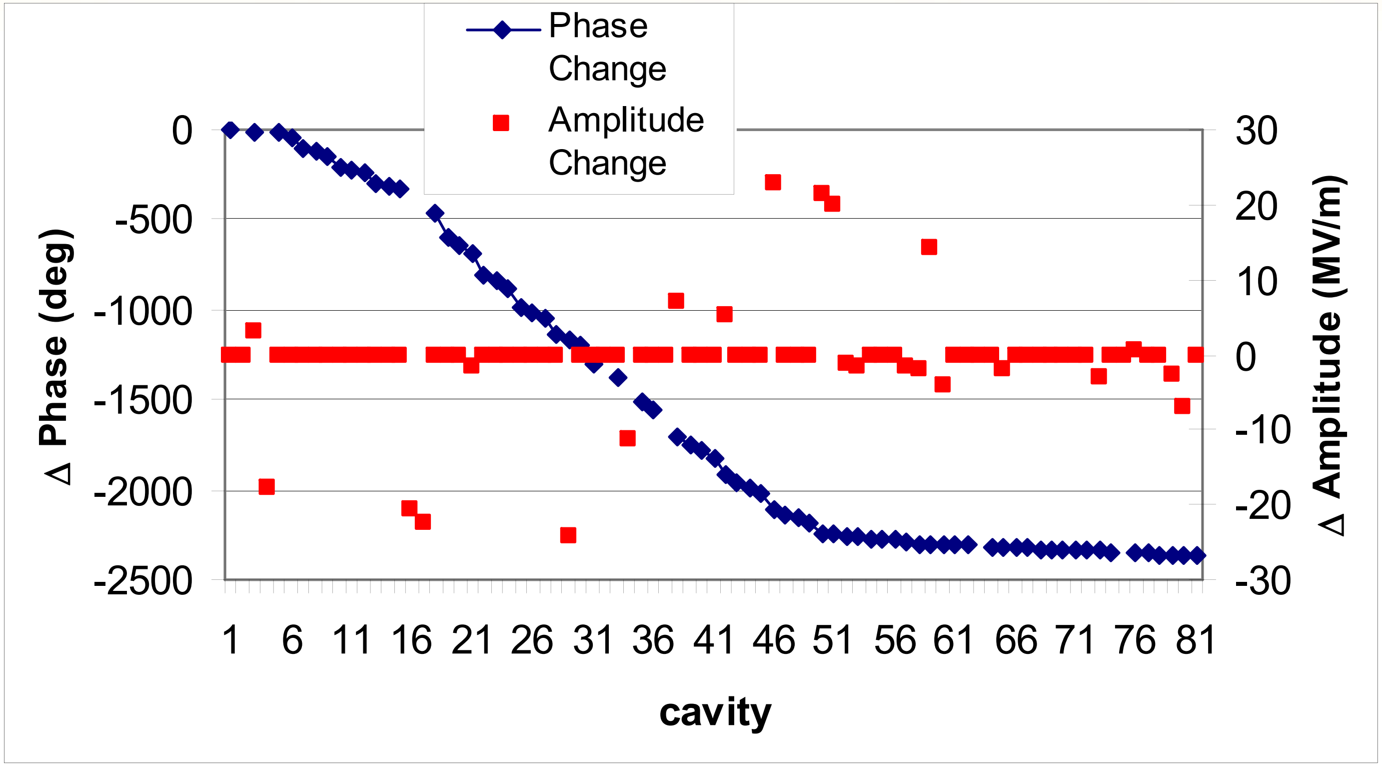
Read new Amplitudes

Fault Recovery Scheme Test



- **Tested in Spring 2006, when 11 cavity gradients were lowered, and one cavity restored to operations**
- **Spot checks done using phase scans indicate scaling works within a few degrees**

Application of the Cavity Fault Recovery Scheme



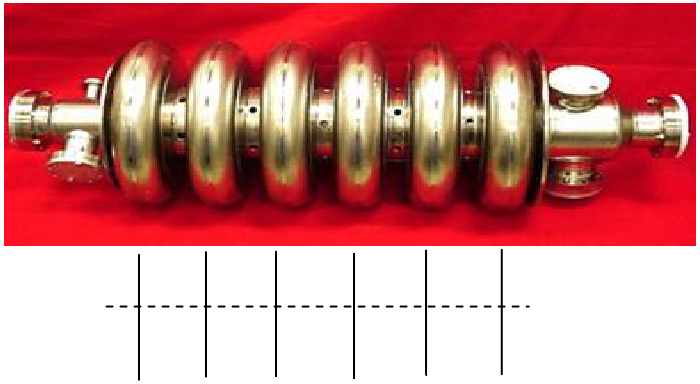
- **In April 2007 the SCL was lowered from 4.2K to 2 K to facilitate 30 Hz operation.**
- **About 20 cavity amplitudes changed.**
- **The fault recovery scheme restored beam to the previous loss state.**

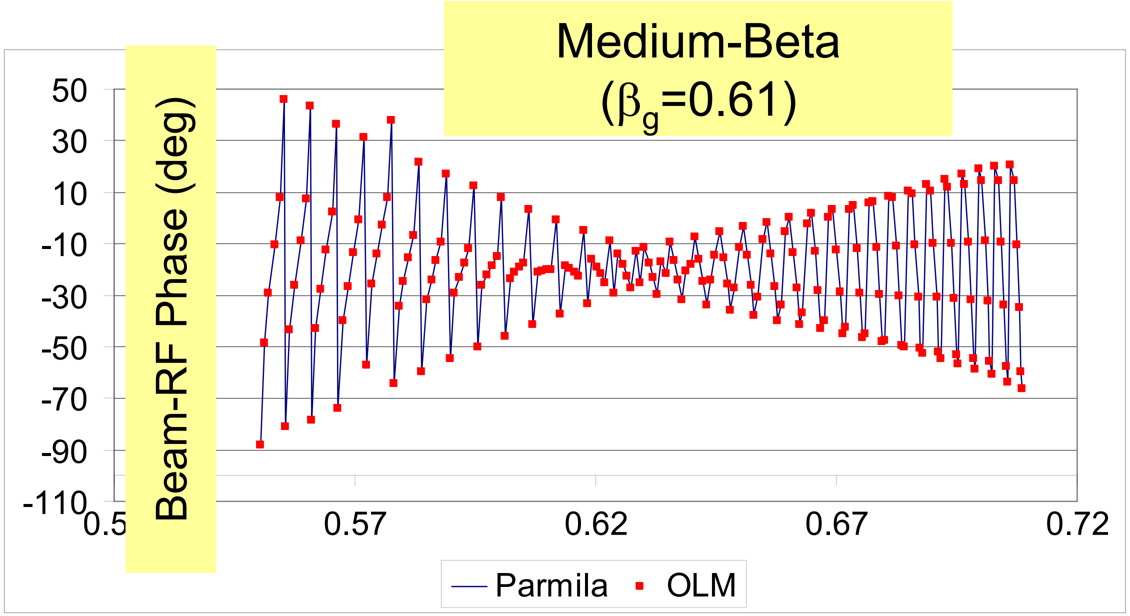
Summary

- The SNS Superconducting Linac is operated in a variety of configurations
  - We need flexible software to accommodate this.
- Using the XAL framework, a variety of tools are developed to set-up and rapidly reconfigure the linac
  - Cavity phase setting with signature matching
  - Transverse optics re-matching
  - Model based Cavity fault recovery method

Backups

Longitudinal Acceleration Modeling (Application Programs – Online Model)





- **Standard drift-kick-drift longitudinal tracking method**
- **Assume design field profiles throughout the cavity**
- **Transit Time Factor is calculated at each gap, based on a fit of Superfish calculations**
- **The beam sees a large phase slip from gap to gap as it traverses the cavity**

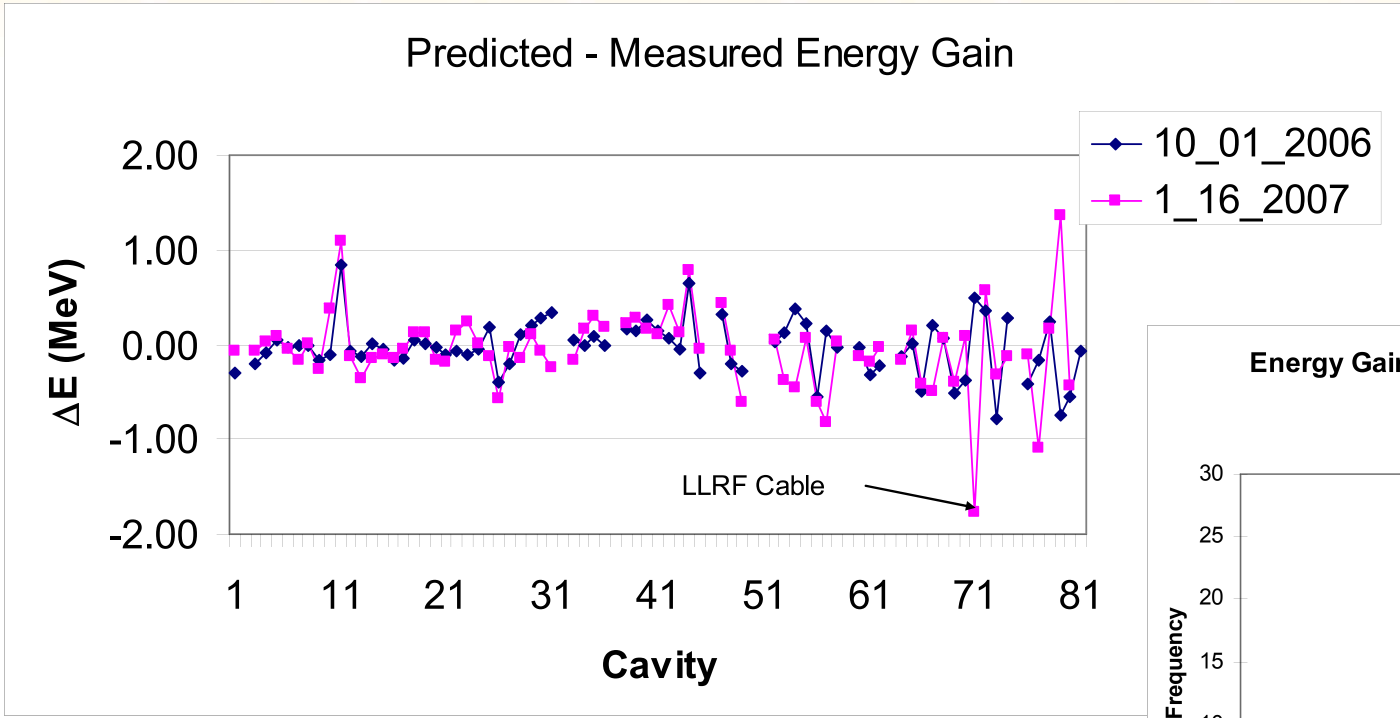
SCL Cavity Phase Setup Times are Getting Shorter

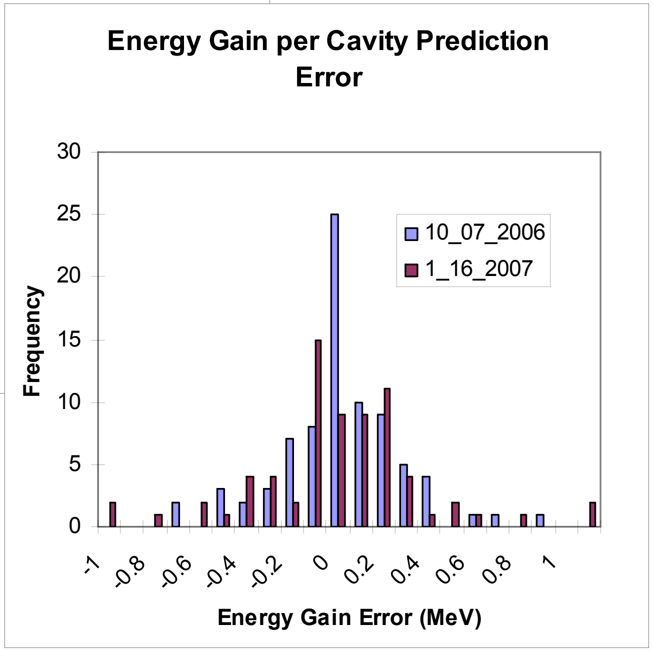
- **August 2005: 48 hrs**
  - **560 MeV, initial run, > 20 cavities off**
- **Dec. 2005: 101 hrs**
  - **925 MeV, turned on all planned cavities**
- **July 2006: 57 hrs**
  - **855 MeV**
- **Oct 2006: 30 hrs**
  - **905 MeV, used established cavity turn on procedure**

Power cavities on sequentially

- **Jan. 2007: 6 hrs**
  - **905 MeV, beam blanking used, which allowed all cavities to be on during the tuning process**
- ***The procedures used to setup the superconducting linac have matured, and the setup time is now minimal***
- ***Still exists a need for fast recovery from changes in the SCL setup***

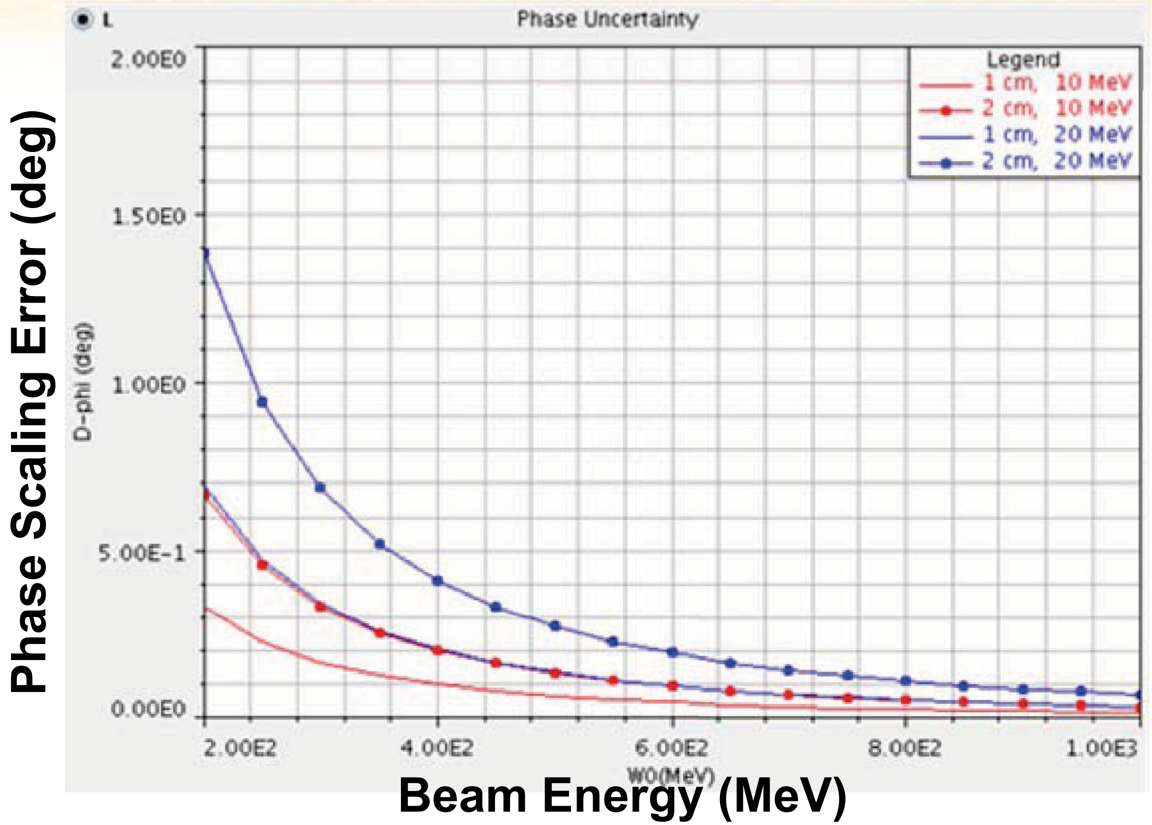
SCL Tune-up – Linac Energy Gain is Understood and Predictable





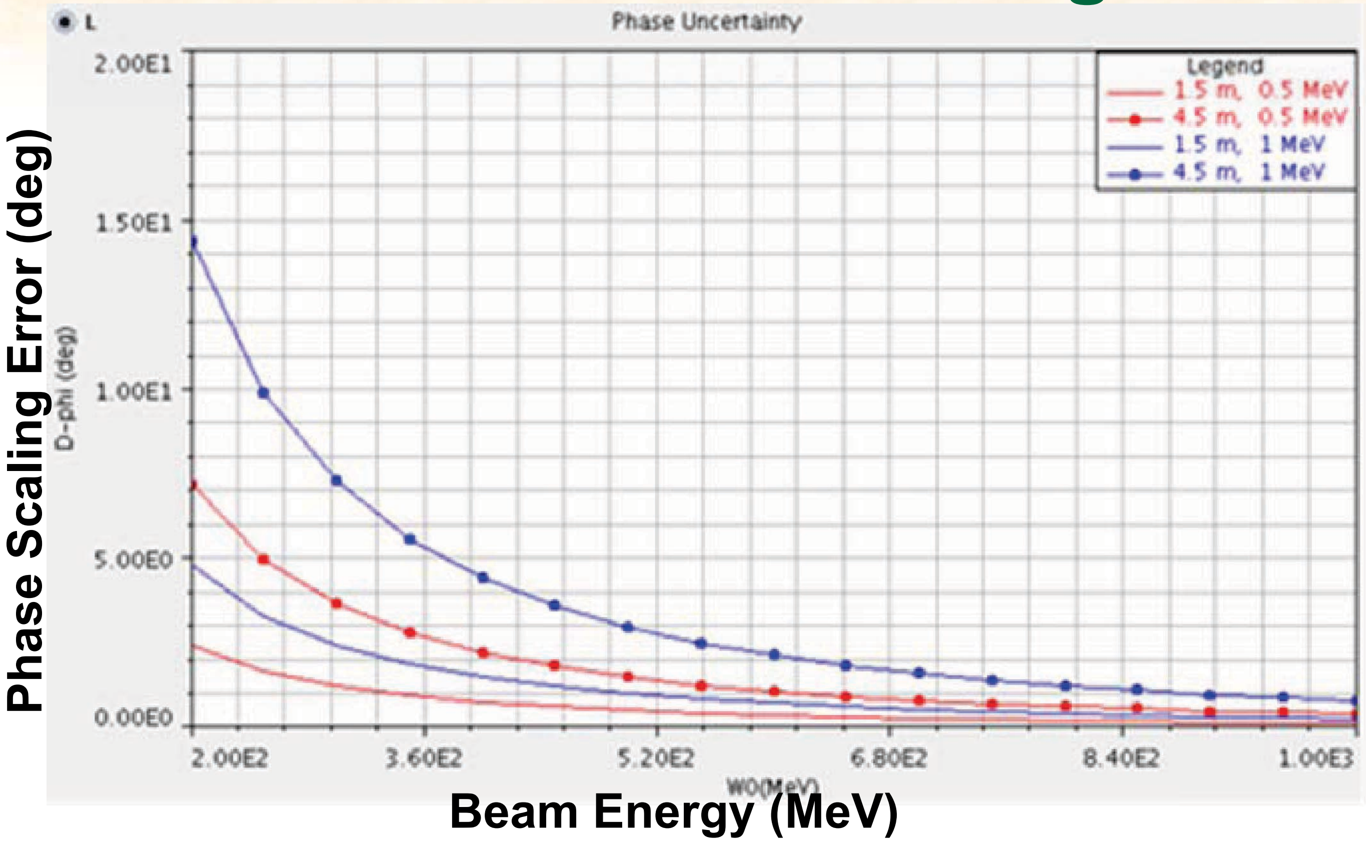
- **Energy gain per cavity is predictable to a few 100 keV and distributed about 0.**
- **Final energy is predictable to within a few MeV**

Expected Errors from the Scaling Method (I)



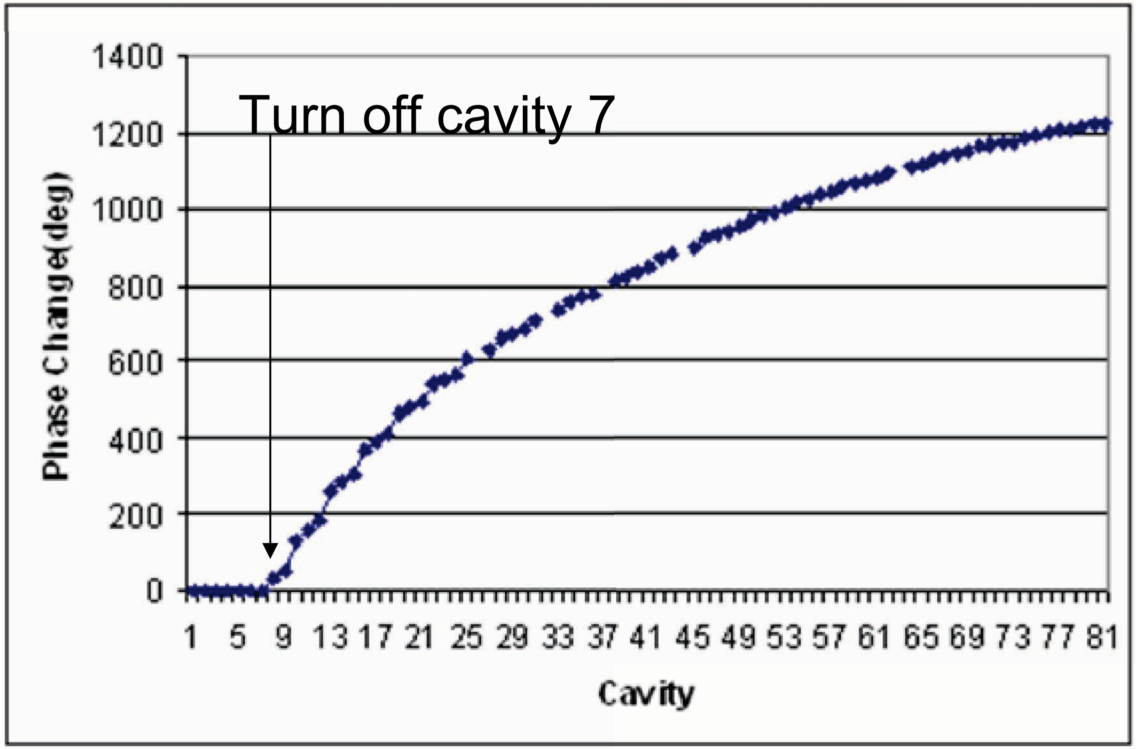
- Uncertainty in the cavity positions leads to errors in the predicted change in phase
- Relative cavity positions are known to a few mm, so < 1 degree error is expected from this uncertainty

Expected Errors from the Scaling Method (II)



- **Uncertainty in the energy gain/cavity results in errors in the predicted change in cavity phase**
- **Energy gain is known to within a few hundred keV, so the error from this uncertainty is 1-2 degrees**

Test of the Cavity Recovery Method – Single Cavity "Failure"



- Turned off cavity 7, rescaled the downstream cavity phase setpoints
- Downstream cavity phase setpoints changed > 1000 degrees
- A beam measurement check with the last cavity showed it was within 1 degree of the scaled prediction

Cavity Fault Recovery Scheme at SNS

- Additional applications of the cavity recovery scheme
  - Missing cryo-module tests to evaluate the impact on beam loss from removing entire cryo-modules from service for repairs.
  - Recovery from a control system failure that resulted in 3 broken cavity tuners.
- While intended for use in recovering from a single cavity failure, the scheme has been used more often to recover from more severe situations
  - Usually takes days to assess the situation, minutes to apply the recovery scheme
  - Previously took days to setup the cavities (now ~ 1 shift) with beam based measurement techniques
- This technique is considered a “standard practice” by now at SNS
  - Future improvements may include a more automated invocation