Operational Experience of a Superconducting Cavity Fault Recovery System At the Spallation Neutron Source

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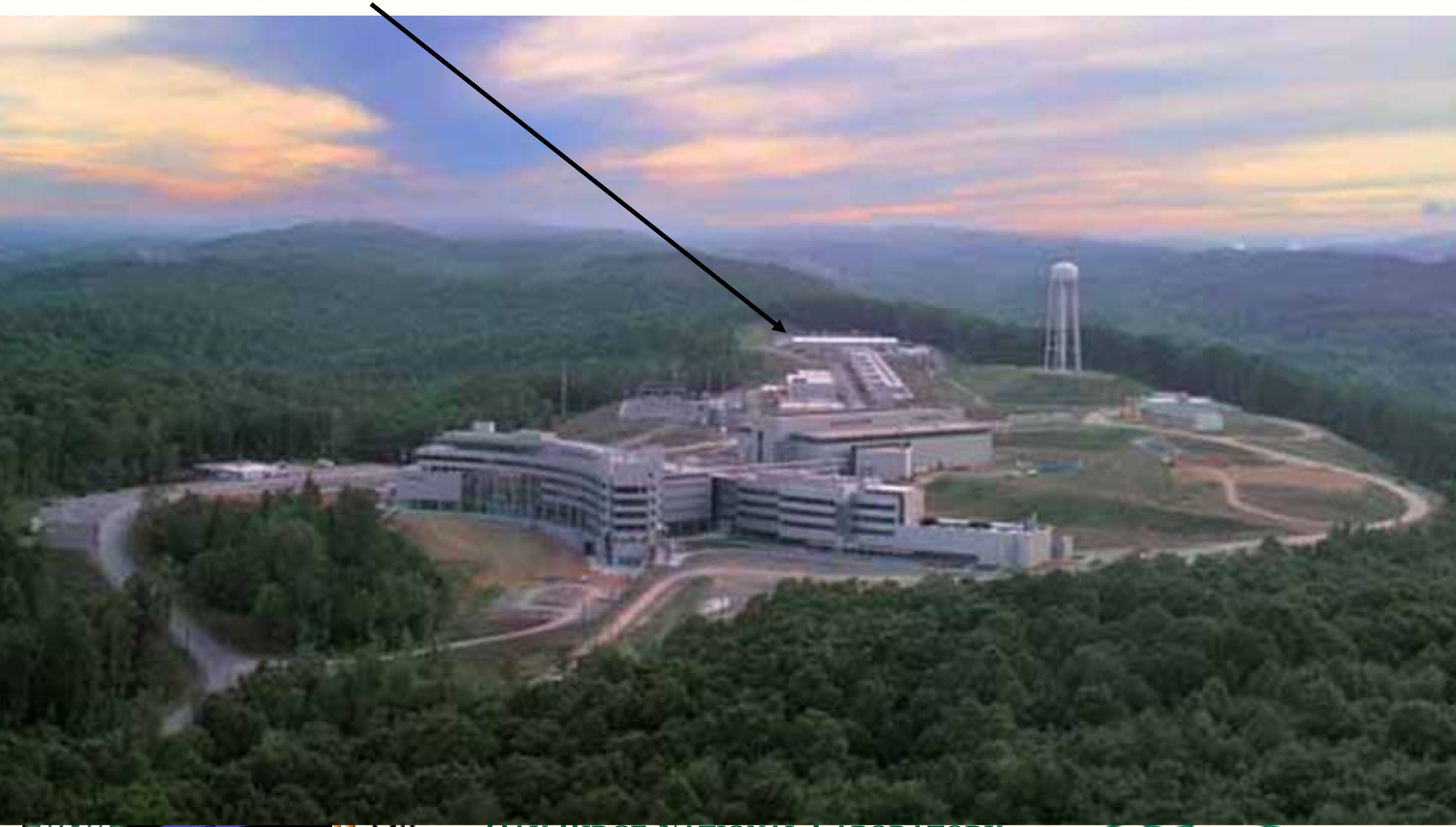
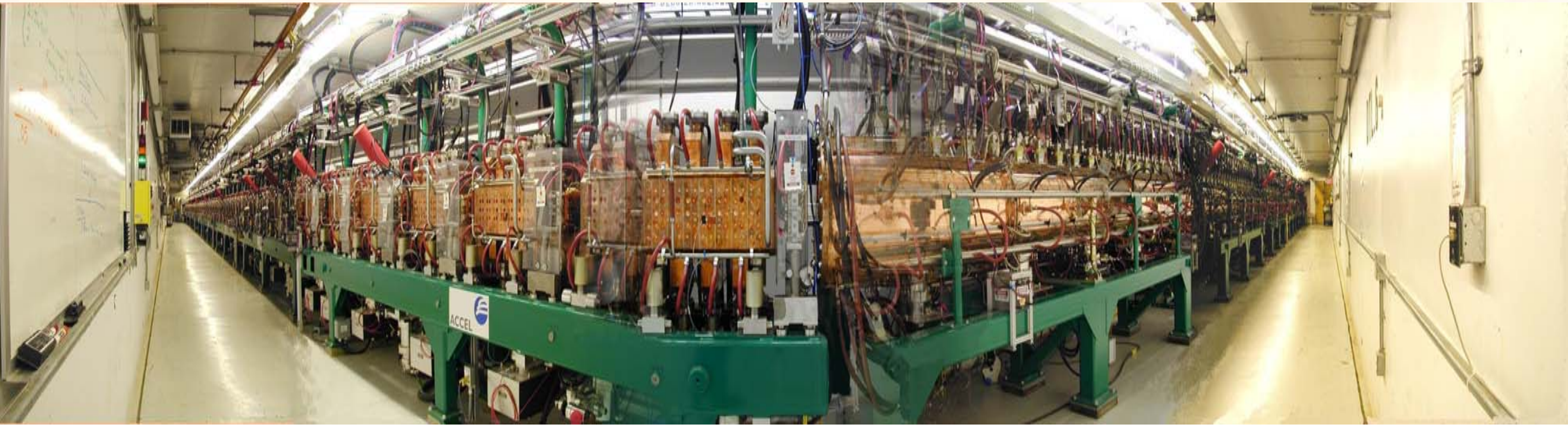
Outline

- The SNS Linac
- Commissioning and Operational experience With the SCL Linac
- Why does SNS need a cavity fault recovery system?
- A Cavity Fault Recovery System and Use Cases

The SNS Linac



Normal Conducting Linac



- **CCL Systems designed and built by Los Alamos**
- **805 MHz CCL accelerates beam to 186 MeV**
- **System consists of 48 accelerating segments, 48 quadrupoles, 32 steering magnets and diagnostics**
- **402.5 MHz DTL was designed and built by Los Alamos**
- **Six tanks accelerate beam to 87 MeV**
- **System includes 210 drift tubes, transverse focusing via PM quads, 24 dipole correctors, and associated beam diagnostics**

Superconducting Linac

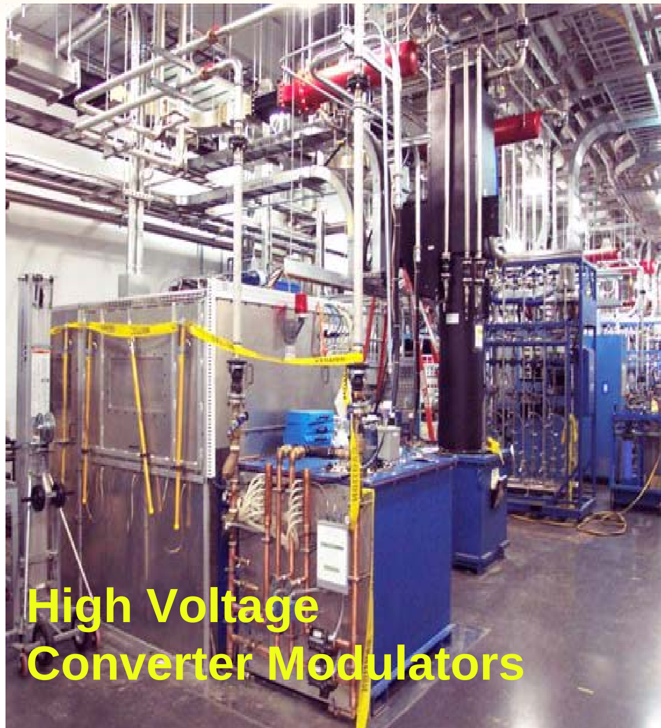
- **Designed an built by Jefferson Laboratory**
- **SCL accelerates beam from 186 to 1000 MeV**
- **SCL consists of 81 cavities in 23 cryomodules**
- **Two cavities geometries are used to cover broad range in particle velocities**
- **Cavities are operated at 2.1 K with He supplied by Cryogenic Plant**
- **Most operation has been at 4.2 K**

Medium beta cavity

High beta cavity

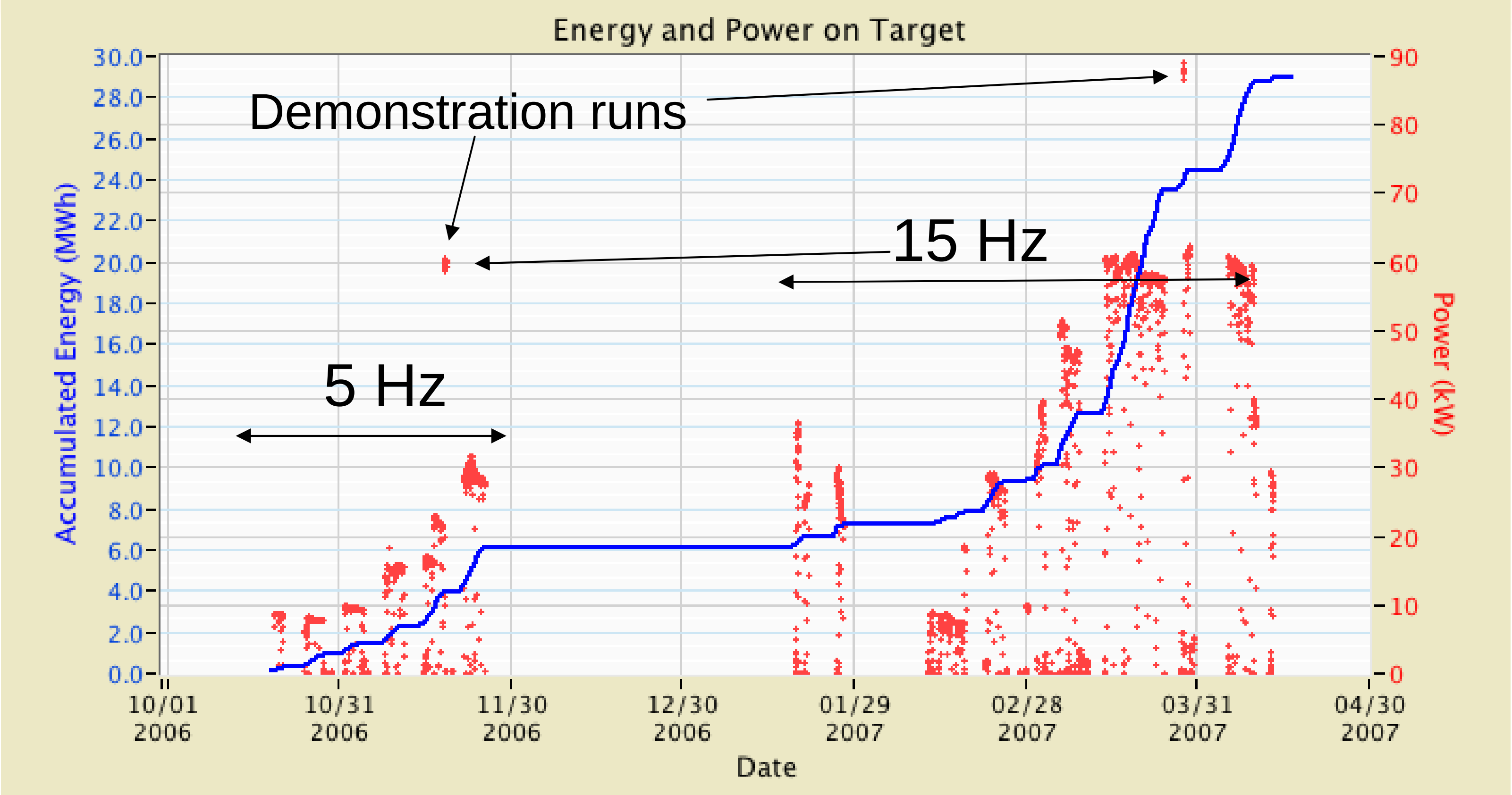
Linac RF Systems

- **Designed and procured by LANL**
- **All systems 8% duty factor: 1.3 ms, 60 Hz**
- **7 DTL Klystrons: 2.5 MW 402.5 MHz**
- **4 CCL Klystrons: 5 MW 805 MHz**
- **81 SCL Klystrons: 550 kW, 805 MHz**
- **14 IGBT-based modulators**



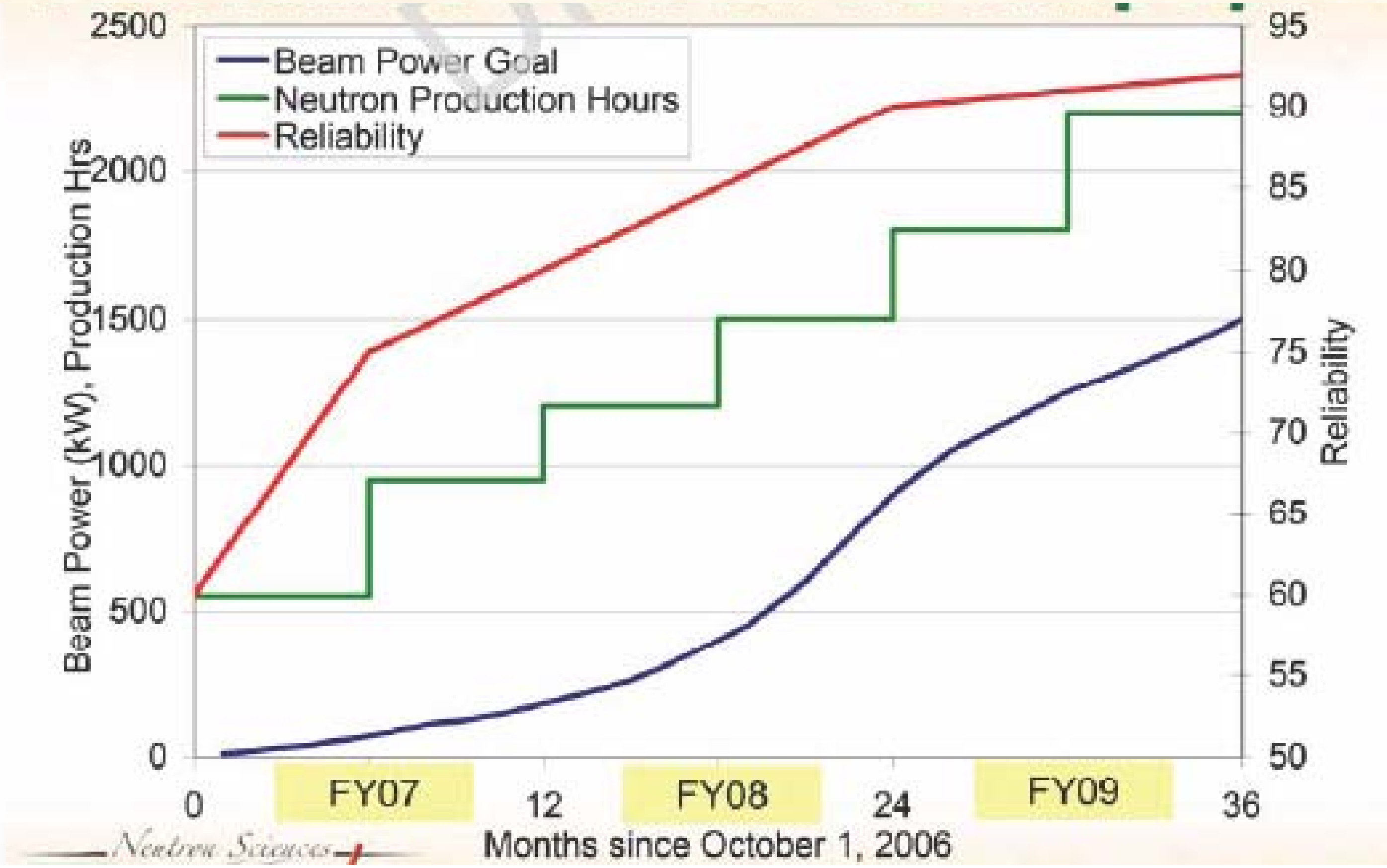
- **2nd largest klystron and modulator installation in the world!**

Beam Power Progress



- **Power has ramped up from 8 kW to 60 kW over the last two run periods (since Oct. 2006)**
- **Machine setup and beam state recovery is more repeatable**

The Beam Power Ramp Up Goal



- **We need to ramp to full design power, at full final reliability with decreasing beam study time by Oct. 2009**

SNS Availability Is Important

PSI Availability (ICFA High Brightness Workshop, 2006)

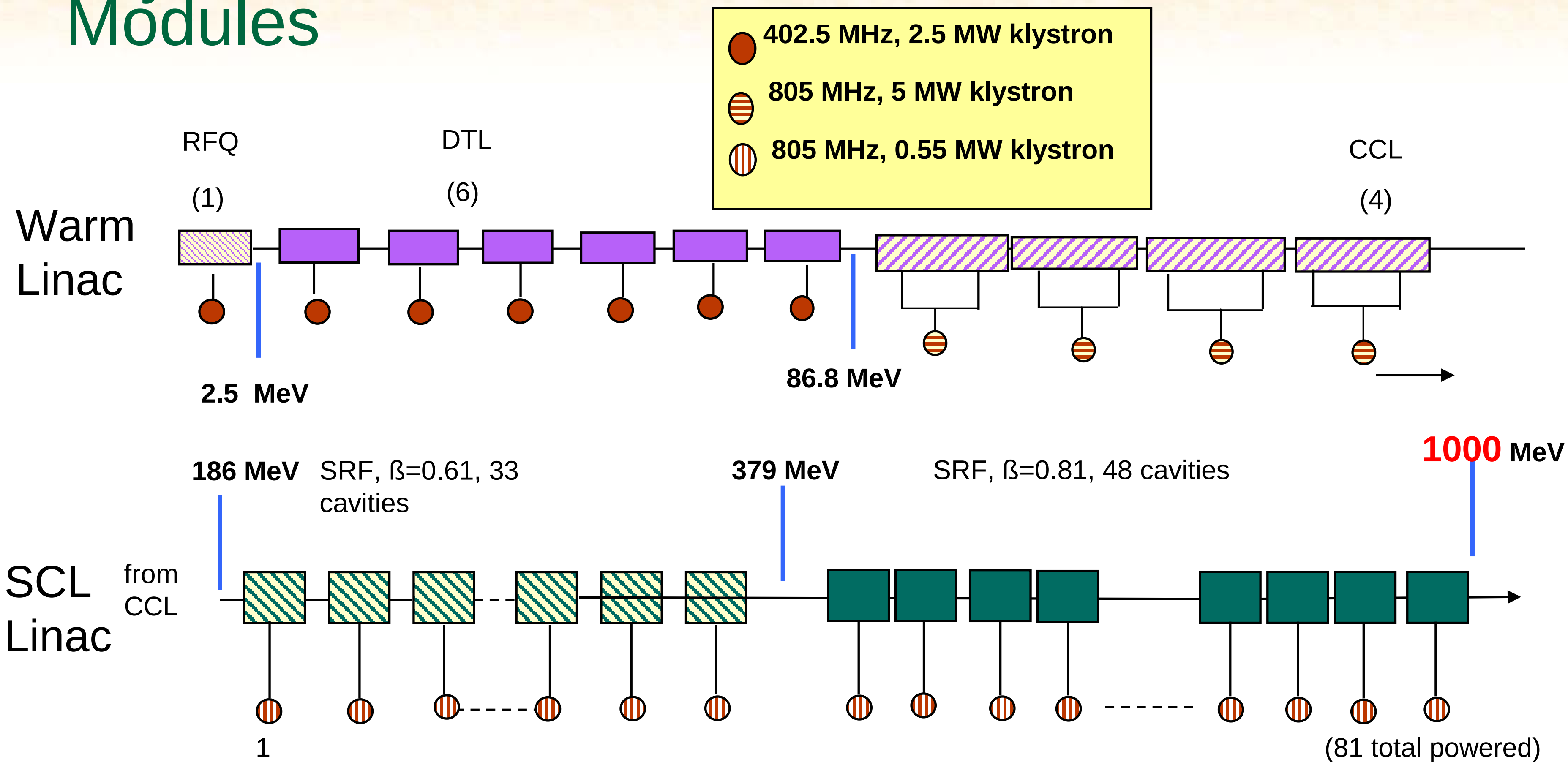
A short overview over the last 8 years shows that it is very hard to achieve availability values above the magic limit of 90 %.

Year	1999	2000	2001	2002	2003	2004	2005	2006
Hours with beam on target	5700	5200	4250	5030	4790	4710	5420	5520
Availability	91	86	86	88.6	89.2	84.2	83.9	86.0
Min avail./week	52	30	27.3	53.5	71.1	29.3	0.2	11.6
Max avail./week	98	97.8	97.5	97.7	97.8	96.4	97.8	98.7

End date of cycle

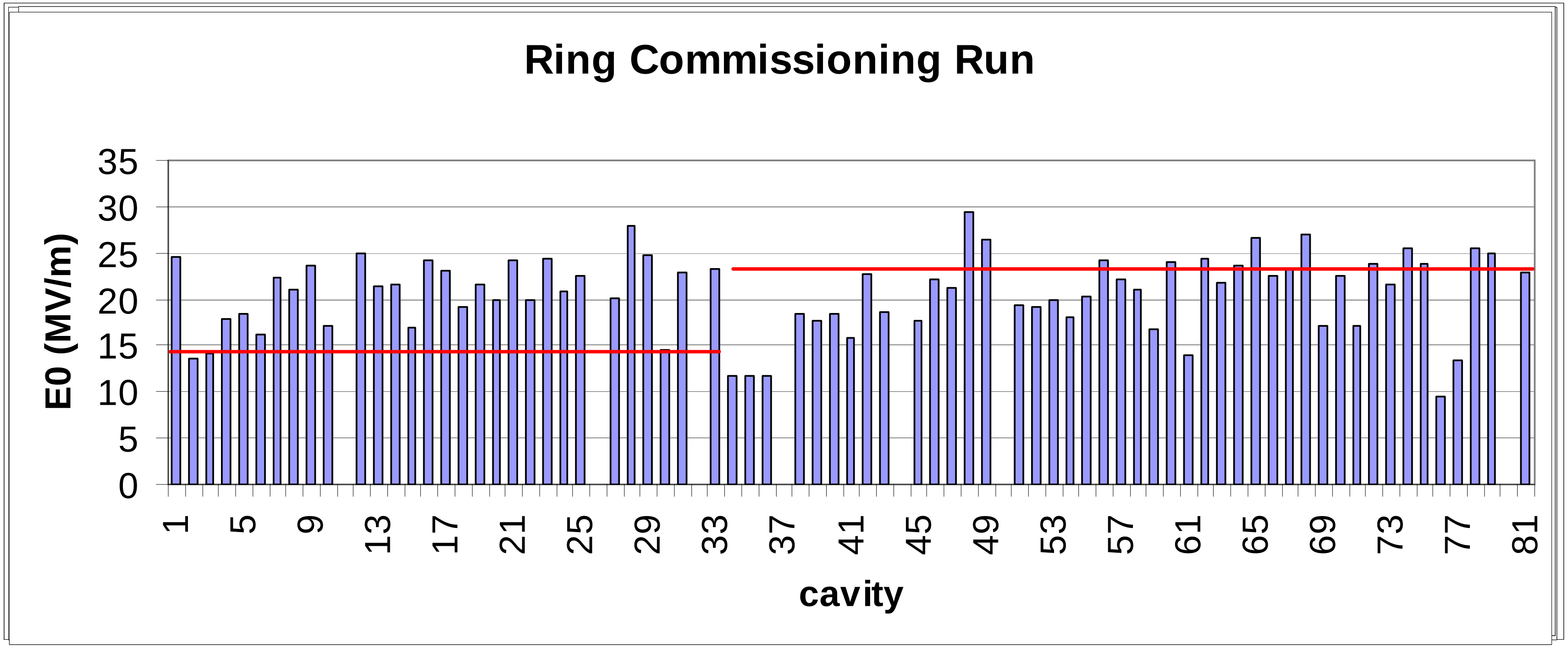
- **SNS is a user facility – many users only scheduled for a few days**
- **Target availability is 95%**
- **RF systems are a major focus of availability**

Layout of Linac RF with NC and SRF Modules



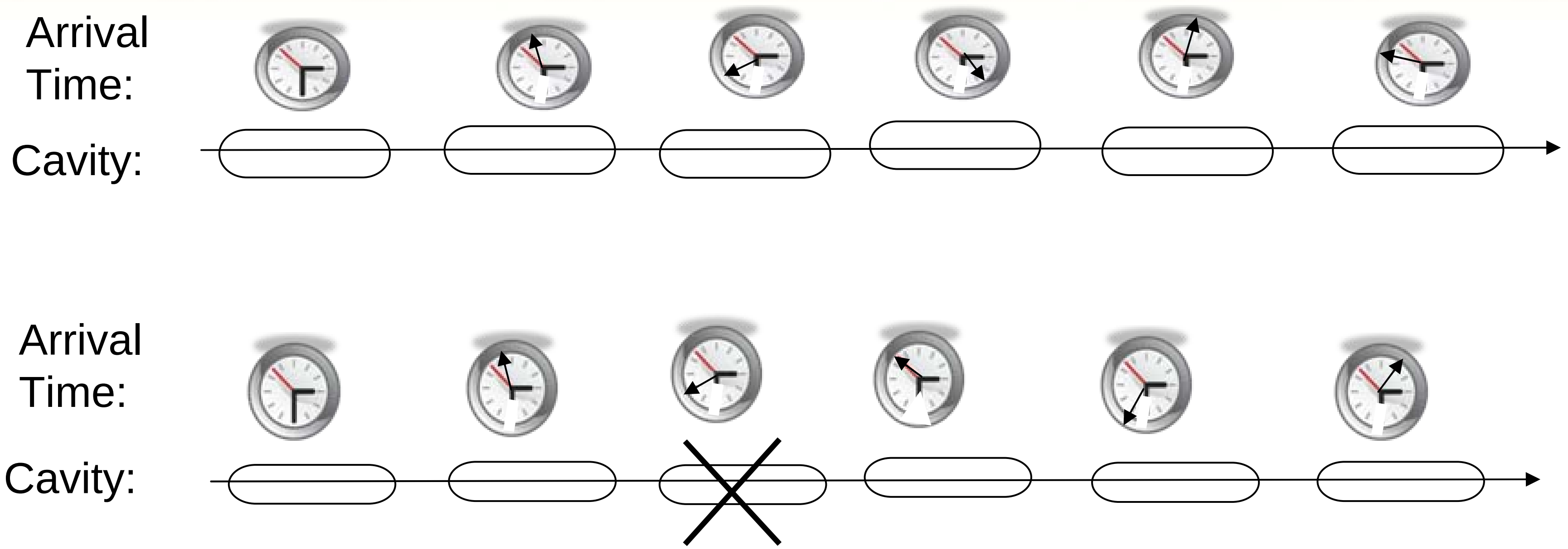
- SCL has 81 independently powered cavities
  - Many parts to keep running
  - [illegible]es to set w.r.t. the beam

SCL Cavity Amplitudes



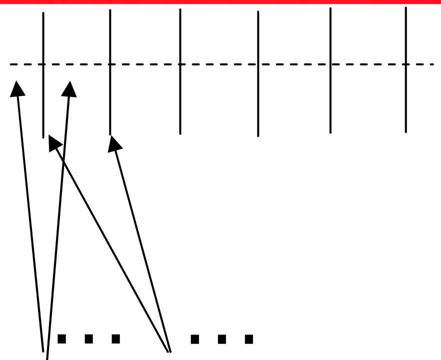
- **Strategy is to run cavities at their maximum safe amplitude limit**
- **Need to be *flexible* – SRF capabilities change, not near the design**
- **Linac output energy is a moving target**

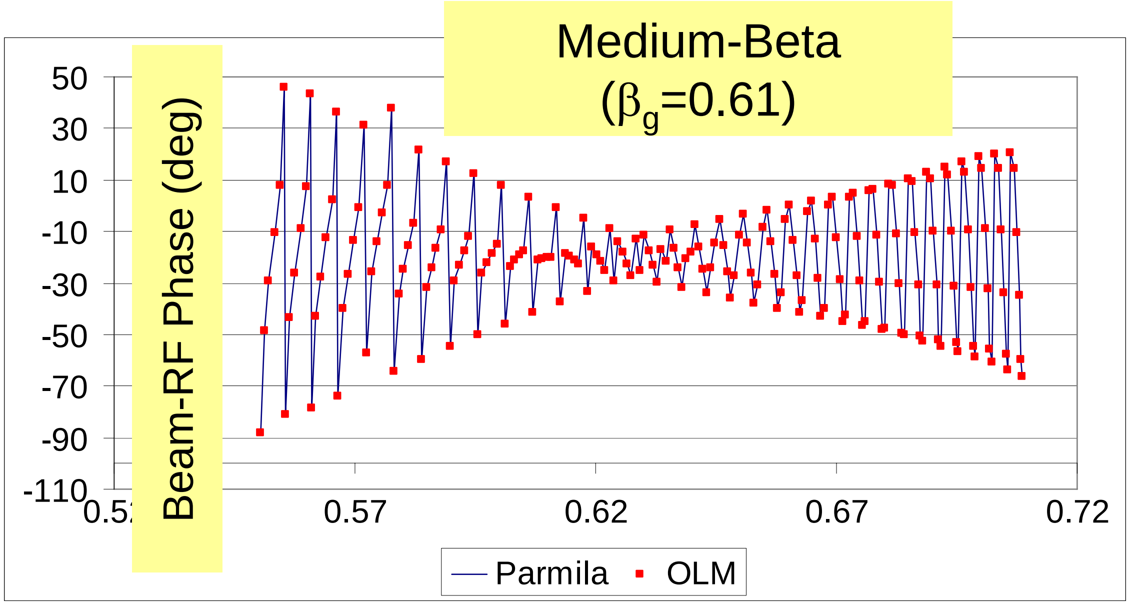
Cavity Fault Impact on Beam Arrival Times for a Proton Linac



- **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**

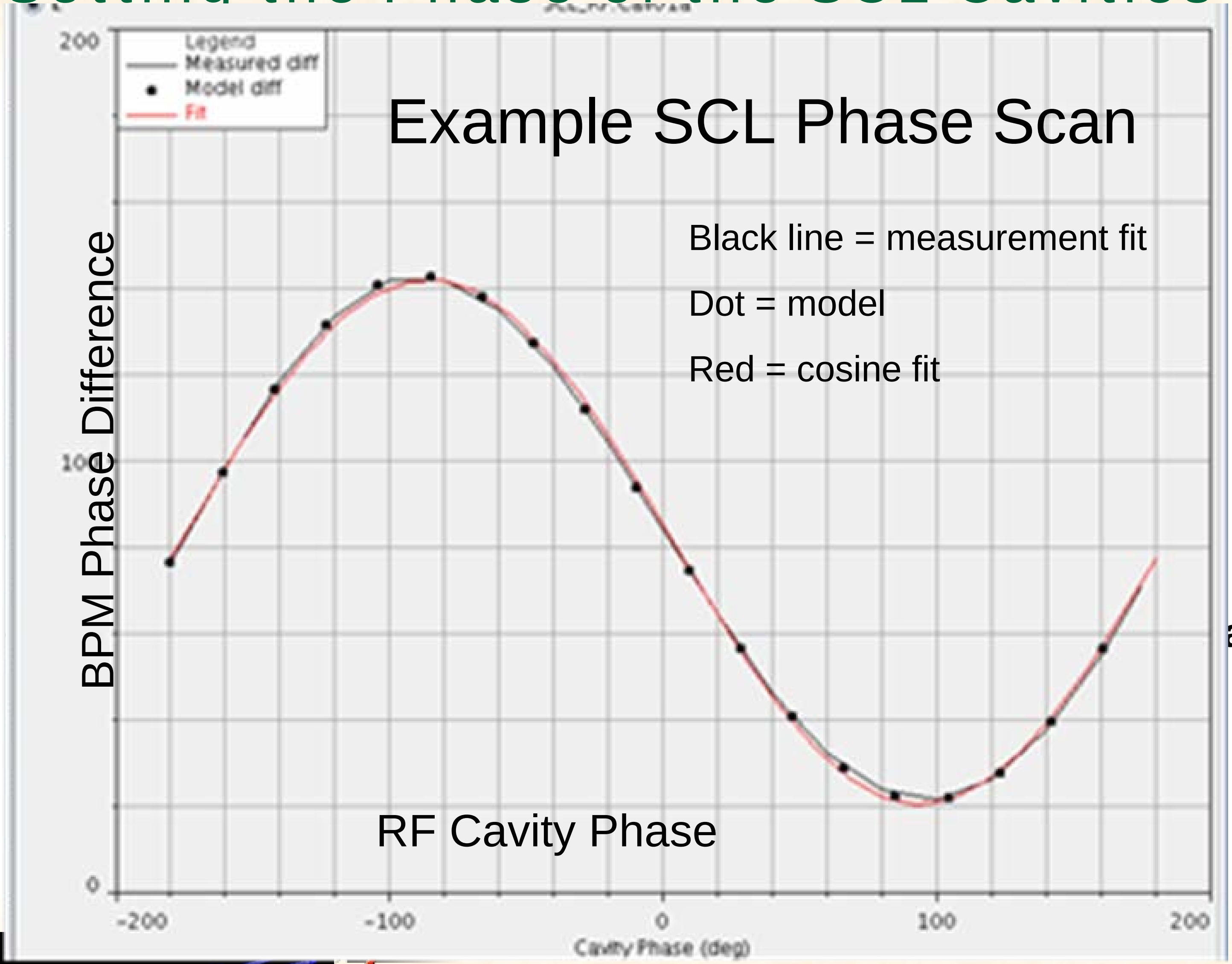
Longitudinal Acceleration Modeling (Application Programs – Online Model)





- **Drift-kick-drift 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**

Setting the Phase of the SCL Cavities



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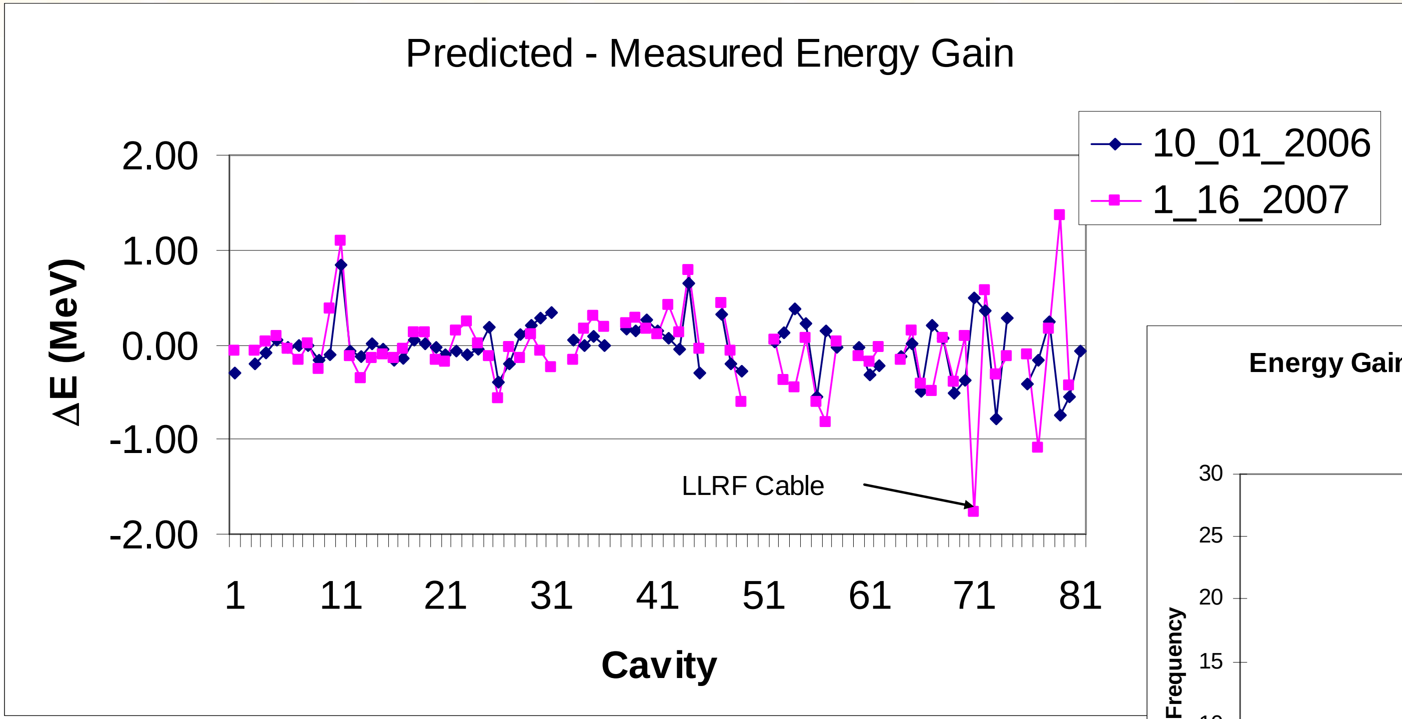
SCL Cavity Phase Setup Times are Getting Shorter

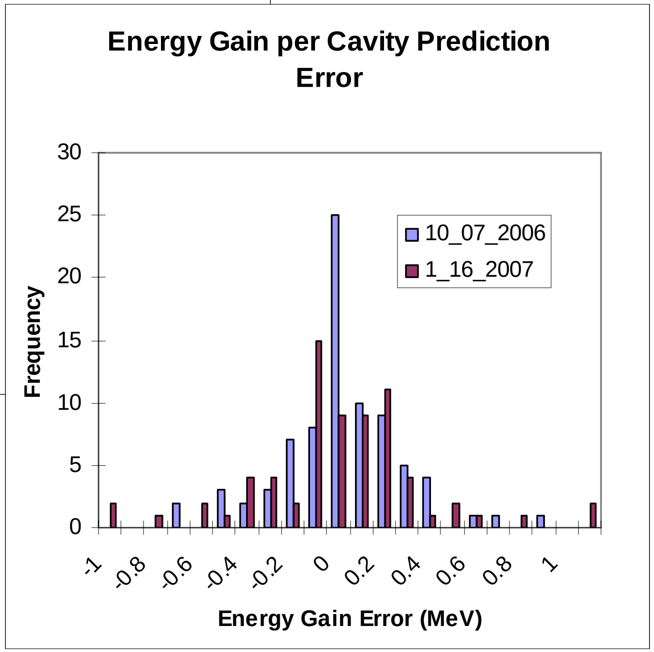
- **August 2005: 48 hrs**
  - **560 MeV, initial run, > 20 cavities off**
- **Dec. 2005: 101 hrs**
  - **925 MeV, turned on all planned cavities**
- **July 2006: 57 hrs**
  - **855 MeV**
- **Oct 2006: 30 hrs**
  - **905 MeV, used established cavity turn on procedure**

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**

Scaling Method for Cavity Fault Recovery

New cavity phases

New Beam Energy

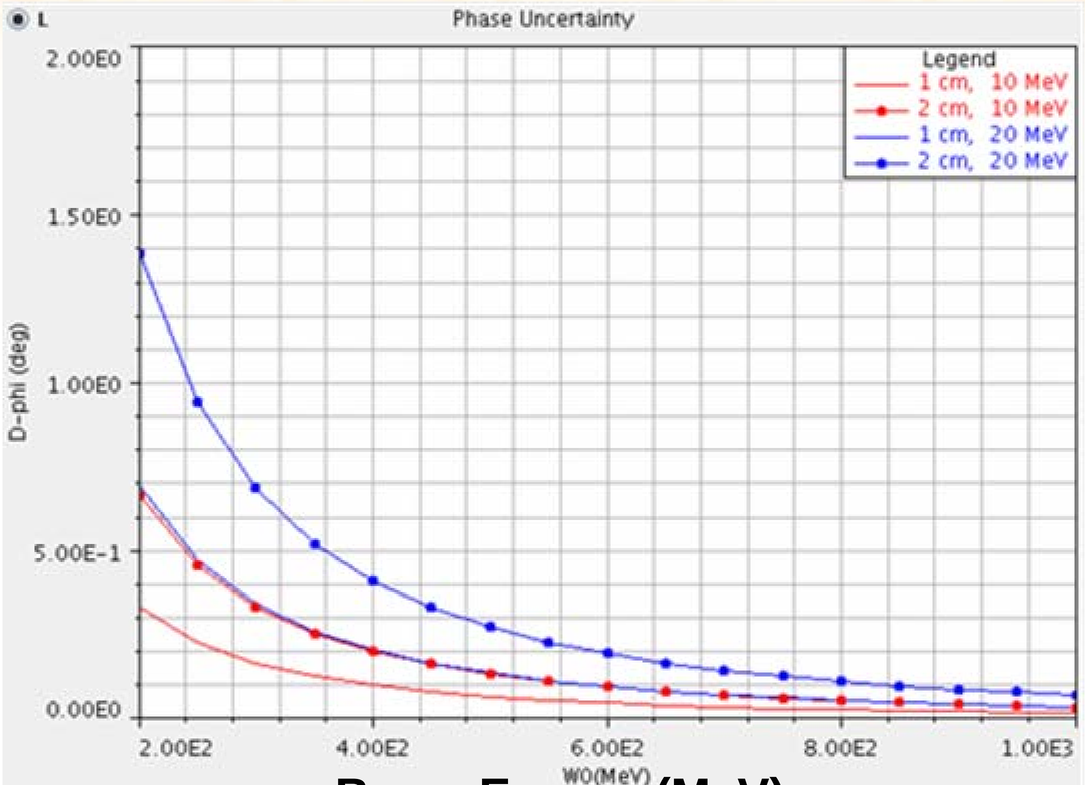
Controller | Scaner | Analysis | Scale Cavities

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

Expected Errors from the Scaling Method (I)

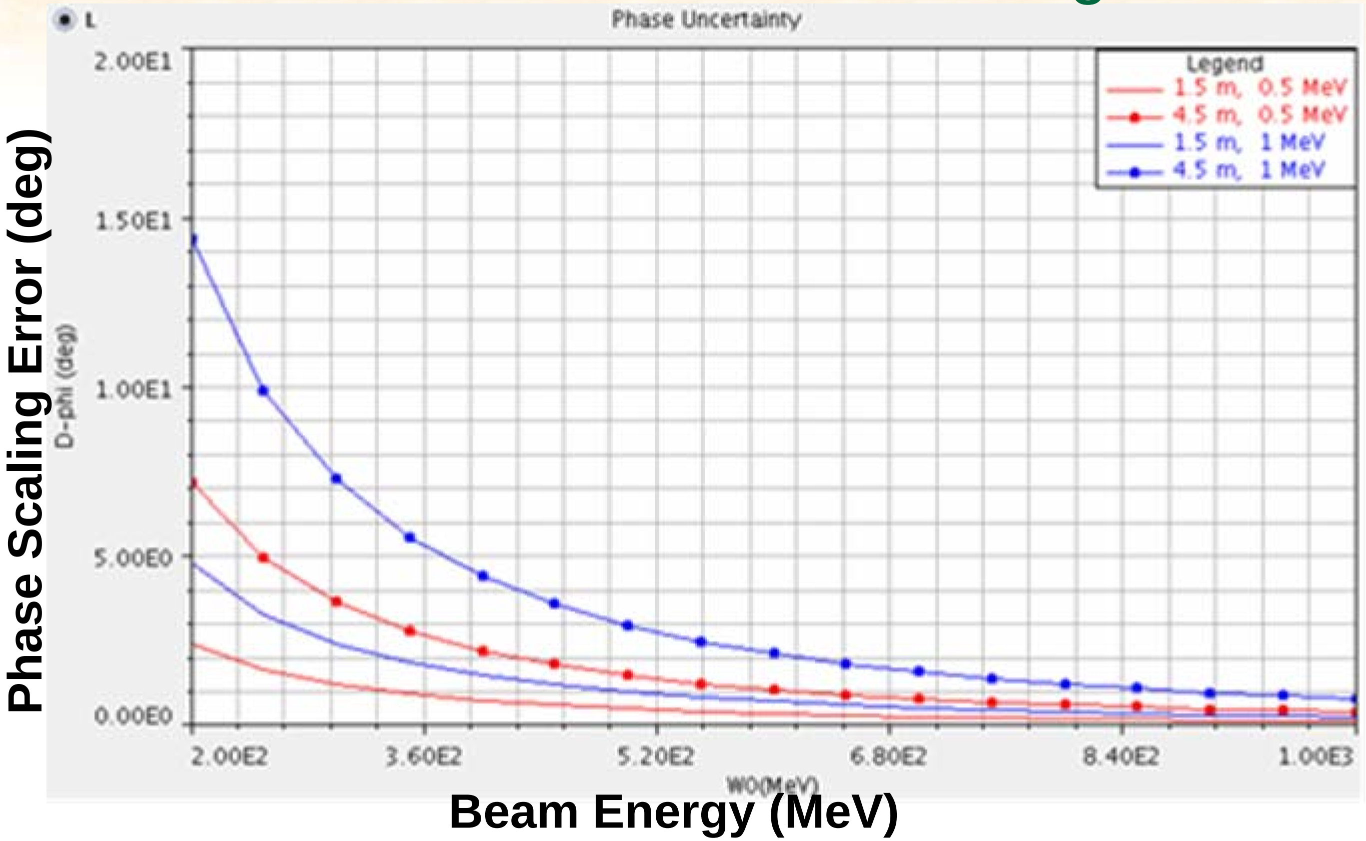


Phase Scaling Error (deg)

Beam Energy (MeV)

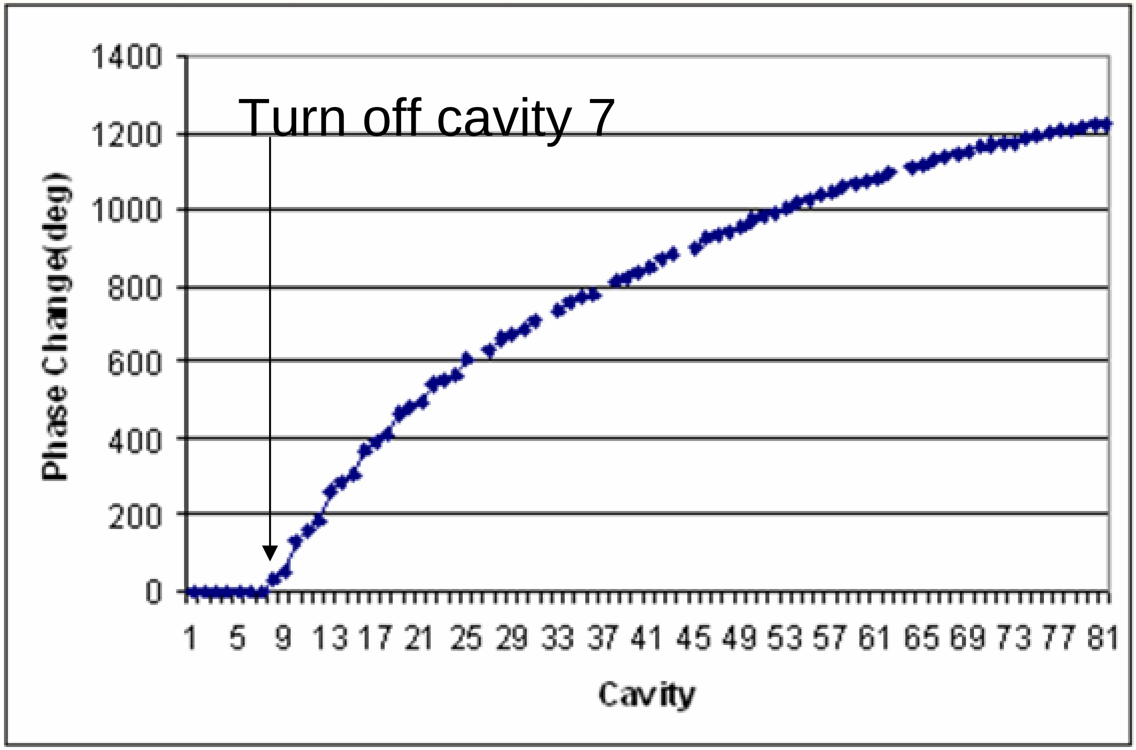
- **Uncertainty in the cavity positions leads to errors in the predicted change in phase**
- **Relative cavity positions are known to a few mm, so < 1 degree error is expected from this uncertainty**

Expected Errors from the Scaling Method (II)



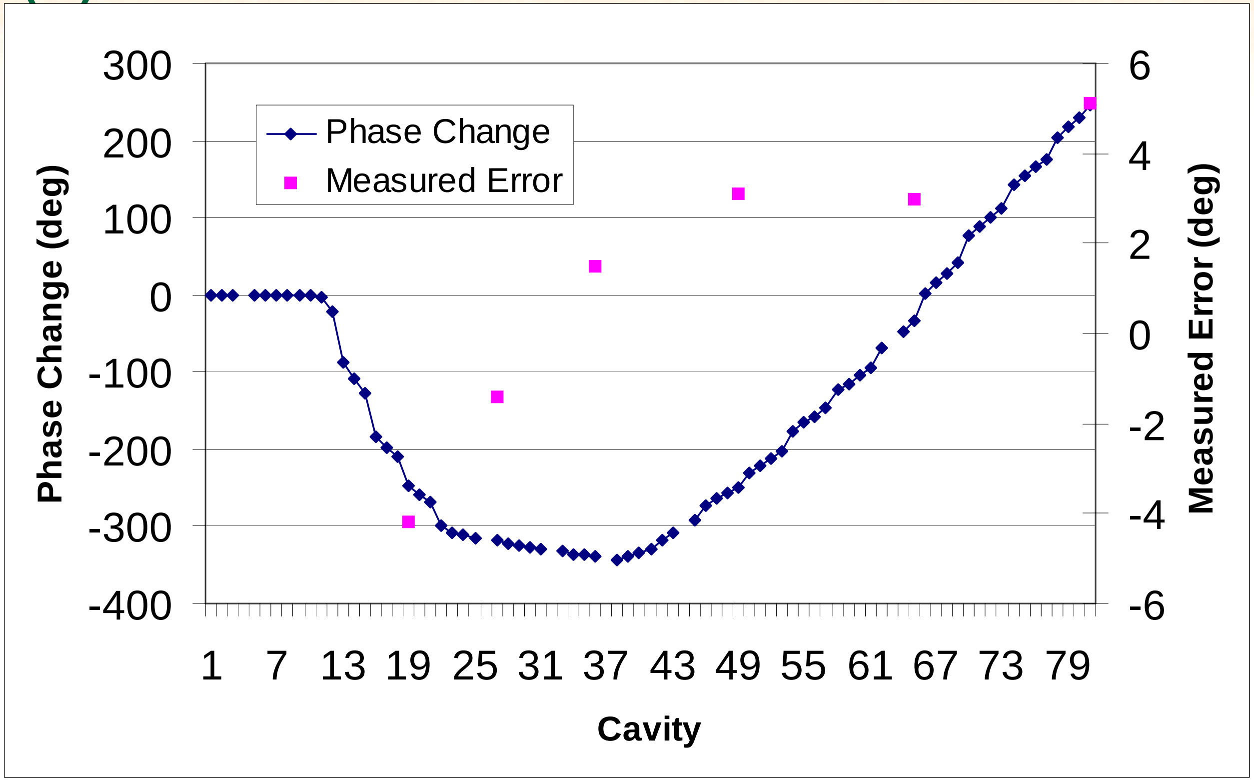
- **Uncertainty in the energy gain/cavity results in errors in the predicted change in cavity phase**
- **Energy gain is known to within a few hundred keV, so the error from this uncertainty is 1-2 degrees**

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



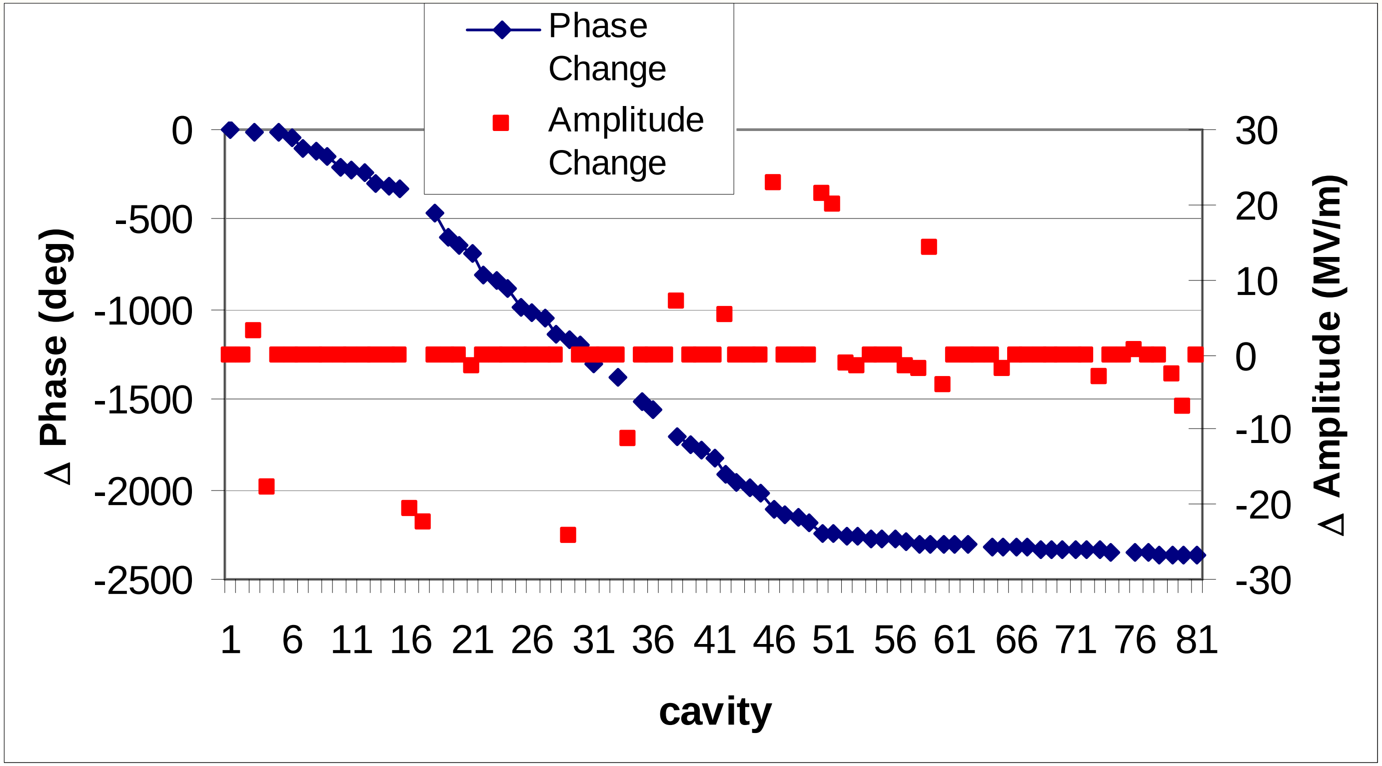
- Turned off cavity 7, rescaled the downstream cavity phase setpoints
- Downstream cavity phase setpoints changed > 1000 degrees
- A beam measurement check with the last cavity showed it was within 1 degree of the scaled prediction

Application of the Cavity Fault Recovery Scheme (I)



- In the spring 2006, 11 cavities had to be either turned off or have their amplitudes reduced for safe operation, 1 cavity was returned to operation
- The fault recovery scheme was applied "all at once"
- Phase scan spot checks indicate the scaling was within 4 degrees
- No detectable change in beam loss

Application of the Cavity Fault Recovery Scheme (II)



- **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.**

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

Summary

- High availability will be a strong driver at SNS
- A fault recovery scheme for superconducting cavity failure has been developed
- To date, its primary application has been for quick recovery from events involving multiple cavities
- It works !