9mA studies: proposal development for January 2011 accelerator studies period

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FLASH operations schedule (as of 23 Aug 2010)

	29	19.Jul - 25.Jul	2	FEL studies		school holidays HH/SH	
	30	26.Jul - 1.Aug	2			school holidays HH/SH	
	31	2.Aug - 8.Aug	3		preparation user run	school holidays HH/SH	
	32	9.Aug - 15.Aug	3			school holidays HH/SH	
	33	16.Aug - 22.Aug	3			school holidays HH/SH	pho
	34	23.Aug - 29.Aug	1	User Run		**FEL Malmö**	Sta
	35	30.Aug - 5.Sep	1			**Linac Tsukuba**	
	36	6.Sep - 12.Sep	1				
	37	13.Sep - 19.Sep	2	FEL studies			
	38	20.Sep - 26.Sep	2				
	39	27.Sep - 3.Oct	3		preparation user run		
	40	4.Oct - 10.Oct	1	User Run			
	41	11.Oct - 17.Oct	1				
	42	18.Oct - 24.Oct	1				
	43	25.Oct - 31.Oct	1				
	44	1.Nov - 7.Nov	2	FEL studies			
	45	8.Nov - 14.Nov	2				
	46	15.Nov - 21.Nov	3		preparation user run		
	47	22.Nov - 28.Nov	1	User Run			
	48	29.Nov - 5.Dec	1				
	49	6.Dec - 12.Dec	1				
	50	13.Dec - 19.Dec	1				
	51	20.Dec - 26.Dec	5	Maintenance			
January	52	27.Dec - 2.Jan	5				
2011	1	3.Jan - 9.Jan	4		preparation accelerator studies		
	2	10.Jan - 16.Jan	4	Accelerator studies			
	3	17.Jan - 23.Jan	4				
	4	24.Jan - 30.Jan	2	FEL studies			
	5	31.Jan - 6.Feb	2				
	6	7.Feb - 13.Feb	3		preparation user run		
	7	14.Feb - 20.Feb	1	User Run			
	8	21.Feb - 27.Feb	1				
	9	28.Feb - 6.Mar	1				
	10	7.Mar - 13.Mar	1				
	11	14.Mar - 20.Mar	2	FEL studies	test personnel interlock		
	12	21.Mar - 27.Mar	3		preparation user run		
	13	28.Mar - 3.Apr	1	User Run		**PAC New York**	
	14	4.Apr - 10.Apr	1				
	15	11.Apr - 17.Apr	1				
	16	18.Apr - 24.Apr	1				
	17	25.Apr - 1.May	2	FEL studies			
	18	2.May - 8.May	2				
	19	9.May - 15.May	3		preparation user run		
	20	16.May - 22.May	1	User Run			
	21	23.May - 29.May	1				
	22	30.May - 5.Jun	1				
	23	6.Jun - 12.Jun	1				
	24	13.Jun - 19.Jun	2	FEL studies			
	25	20.Jun - 26.Jun	3		preparation user run		
	26	27.Jun - 3.Jul	1	User Run		school holidays HH	
	27	4.Jul - 10.Jul	1			school holidays HH/SH	
	28	11.Jul - 17.Jul	1			school holidays HH/SH	
	29	18.Jul - 24.Jul	1			school holidays HH/SH	
	30	25.Jul - 31.Jul	2	FEL studies		school holidays HH/SH	
	31	1.Aug - 7.Aug	2			school holidays HH/SH	
	32	8.Aug - 14.Aug	3		preparation user run	school holidays HH/SH	
	33	15.Aug - 21.Aug	1	User Run			
	34	22.Aug - 28.Aug	1				
	35	29.Aug - 4.Sep	1				
	36	5.Sep - 11.Sep	1			**IPAC Valencia**	
	37	12.Sep - 18.Sep	4	Accelerator studies			
	38	19.Sep - 25.Sep	4				
	39	26.Sep - 2.Oct	4				En

- Call for proposals is expected soon for FEL studies in Nov and for accelerator studies in January
  - Need to submit a 9mA studies proposal
- A week of 9mA studies is penciled in for week of ~10th Jan (includes setup time)
- After January studies, there is only one other accelerator studies period before 2012 (three weeks in Sept)
- Impact of gun rf window on the accelerator studies schedule is not yet clear…
  - One possibility is that the gun is worked on during the Xmas break.

Machine conditions in Jan 2011…?

- Open question (gun rf window conditioning)
  - Will the gun be available for beam studies?
  - If so, what maximum gun rf pulse length might we expect?

- Possible scenarios for January
  - Full 800us bunch trains (unlikely)
  - Shorter bunch trains
  - RF only, no beam (the gun is being worked on)

- *How to make use of scenarios 1 & 2 for 9mA studies…?*

Reflecting on the top-level goals…

Specific objectives for the 9mA study

- Long bunch-train high beam loading (9mA) demonstration
  - 800μs pulse with 2400 bunches at 3MHz, 3nC per bunch
  - Vector Sum control of up to 24 cavities
  - +/- 0.1% energy stability
  - Cavity gradients approaching quench limits
  - Beam energy 700-1000MeV

Demonstrate ILC-like beams

- Characterize operational limits
  - Energy stability limitations and trade-offs
  - Cavity gradient overhead needed for LLRF control
  - Klystron power overhead needed for LLRF control
  - HOM absorber studies (cryo-load)

Studies requiring ILC-like beams

- Operation close to limits, eg
  - Robust automation of tuning, etc
  - Quench detection/recovery, exception handling
  - Beam-based adjustments/optimization

Operational challenge for FLASH
(well beyond typical beam parameters for photon users)

Scenario #1: 800us pulses and 9mA possible (ie no limitations from gun)

- **Main objectives for the studies:**
  - Gradient overhead characterization studies
  - Demonstrate operation of many cavities close to quench and with heavy beam loading

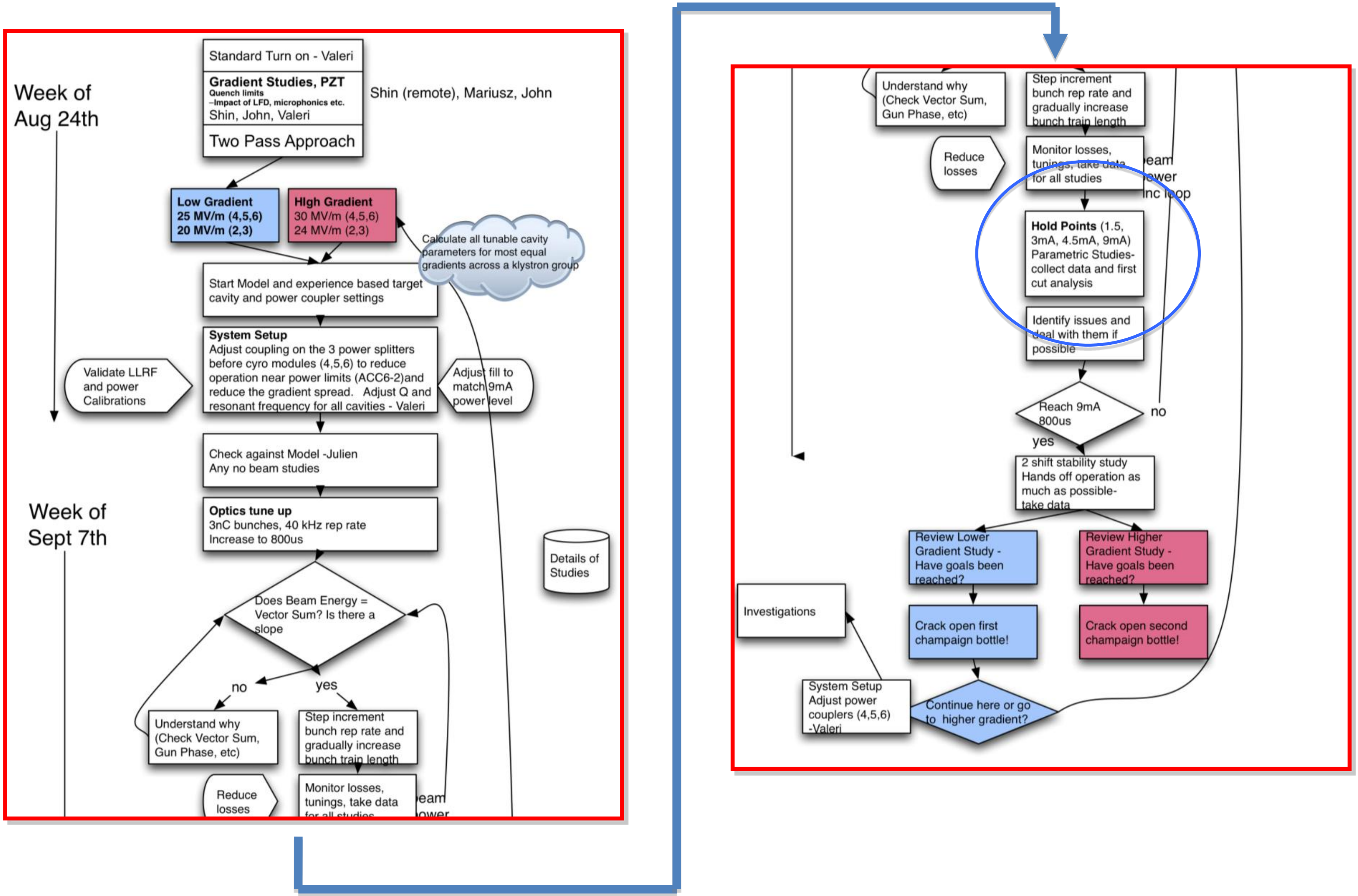
- First, we must re-establish operation with long bunch-trains and heavy beam loading (stable and reliable)
  - Many technical improvements since Sept 2009 (esp. LLRF), but still must anticipate a long setup time
    - Much easier at 3mA than at 6mA than at 9mA
  - There are new things to deal with, eg ACC39 operation

Some questions…

- How to apportion the week of studies time
  - Machine setup & tuning for 800us bunch trains at desired current
  - Main studies objectives (gradient overhead studies)
  - Broader scope LLRF studies with long bunch trains (none in Sept ’09)
- Which of the full list of studies topics to propose for January, which to delay until a later time
- What beam current to plan to use
  - Definitely less than 9mA if we want to be sure of doing any studies!
- *JC proposal: try to come up with a nominal required machine state(s) we think can be set up reliably using less than 50% of the allocated study time*

Last year's study plan flowchart…

(A nice balance of machine tuning, parametric studies, achieving milestones)



What beam current to plan for?

- Laser rep rate, assuming 3nC bunches
  - 0mA to 3mA: laser operates at 1MHz (normal configuration)
  - >3mA, laser must operate at 3MHz (requires setup time and tuning)

- Last time, we only ever operated with a nominal 3nC bunch charge to save setting up the injector multiple times
  - …but space-charge is a problem at 3nC -> larger bunch -> more losses per bunch
- Alternative: switch the laser to 3MHz at the beginning, then set up injector for bunches with 1-2nC

Proposed studies from WG3

- Machine / LLRF
  - Understand coupling between longitudinal and transverse effects and with LLRF
- LLRF
  - Vector Sum calibration
  - Long-term energy stability
  - Performance regulations at high gradient and high current
- Gradient overhead studies (ACC67)

- Optimization of Qext, prove concept for at least 3mA
- Microphonics and LFD, can be done w/o beam

- Klystron Overhead
  - Need high current, at 3mA need retune Qext
- ILC Bunch compressor stability studies
  - 2 RF units ACC45 & ACC67 to demonstrate 0.25 deg phase stability
- HOM studies

Beam requirements:

- Most studies are require high current regime > 3mA
  - 1.5 nC, 3 MHz, 800 bunches: (XFEL goal 4.5mA)

Characterize operating gradient margins

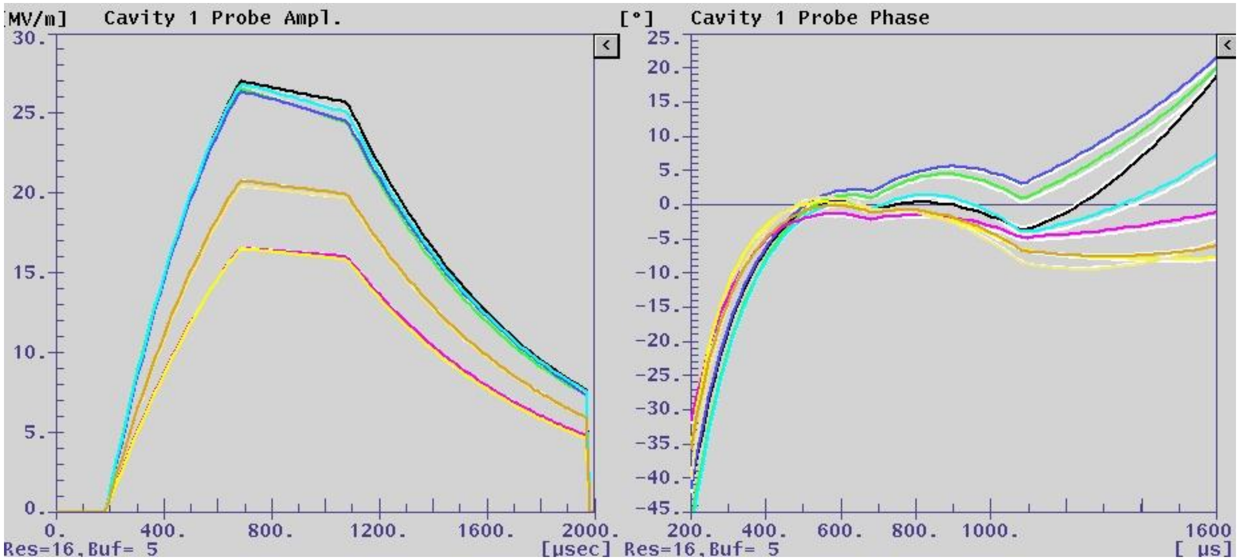
- **Demonstrate operation with gradient tilts of better than ~% on all cavities over 800us pulse with spread of gradients and 9mA beam**

- Pk/Qext studies (although we'll only be adjusting Qexts)
- Piezo LFD compensation optimization studies
- Test procedure for reaching full current, pulse length, maximum gradients
- Characterize and understand operating margins needed for, eg…
  - Random pulse to pulse fluctuations, eg microphonics
  - Residual uncorrected LFD
  - LLRF tuning – initial turn-on transients,…
  - Calibration errors
- Behavior of cavities when operating close to quench for long period… eg
  - Stability, shapness of the quench 'knee'
  - Do all cavities behave the same?
  - Does beam loading change anything?

Cavity gradient tilt studies

- Flattening cavity field amplitudes and phases without beam is not trivial
  - Optimization of mechanical tuners, Qext, piezo feedforward,…
- Even rf-only studies could be used to make meaningful progress towards understanding how to obtain flat gradient tilts

- Random example from the 9mA studies (25 Aug 2009, ACC6 probes, no beam)



Prioritization… (800us bunch trains possible)

- Machine / LLRF
  - Understand coupling between longitudinal and transverse effects and with LLRF
- LLRF
  - Vector Sum calibration
  - Long-term energy stability
  - Performance regulations at high gradient and high current
- **Gradient overhead studies (ACC67)**

- Optimization of Qext, prove concept for at least 3mA

- Microphonics and LFD, can be done w/o beam

- Klystron Overhead
  - Need high current, at 3mA need retune Qext
- ILC Bunch compressor stability studies
  - 2 RF units ACC45 & ACC67 to demonstrate 0.25 deg phase stability
- HOM studies (parasitic studies)

Beam requirements:

- Most studies are require high current regime > 3mA
  - 1.5 nC, 3 MHz, 800 bunches: (XFEL goal 4.5mA)

Scenarios #2 and #3
(short bunch trains or rf only)

- Reminder: after January, there is only one more accelerator studies period scheduled before 2012

- Main objectives:
  - Make as much progress as practical on the gradient overhead study
  - LLRF parametric studies, machine tuning studies
  - Preparation for future 9mA studies: practise tuning & setup, practical experience using available knobs, understand limitations,…

  - Optics / machine physics studies of bypass – better understanding of machine for future 9mA studies

  - Note: 200us with 9mA is still significant in terms of beam loading studies

Some questions….

- How much time to ask for
  - We will require a strong case to get significant beam time (compared with the scenario where long bunch trains were possible)
- Apportioning study time across different objectives
  - Machine setup & tuning for 800us bunch trains at desired current
  - Main studies objectives (gradient overhead studies)
  - Broader scope LLRF studies with long bunch trains (none in Sept '09)
- The same or a different subset of the studies list…?
- In case of shorter bunch trains, how much current to ask for
  - Maybe even 9mA…?

Characterize operating gradient margins

Incremental (limited) progress is possible on all these topics without long bunch trains

- **Demonstrate operation with gradient tilts of better than ~% on all cavities over 800us pulse with spread of gradients and 9mA beam**

- Pk/Qext studies (although we'll only be adjusting Qexts)
- Piezo LFD compensation optimization studies
- Test procedure for reaching full current, pulse length, maximum gradients
- Characterize and understand operating margins needed for, eg…
  - Random pulse to pulse fluctuations, eg microphonics
  - Residual uncorrected LFD
  - LLRF tuning – initial turn-on transients,…
  - Calibration errors
- Behavior of cavities when operating close to quench for long period… eg
  - Stability, shapness of the quench 'knee'
  - Do all cavities behave the same?
  - Does beam loading change anything?

LLRF parametric studies…

- [Compile a list]

Prioritization… (shorter bunch trains or rf only)

- Machine / LLRF
  - Understand coupling between longitudinal and transverse effects and with LLRF
- LLRF
  - Vector Sum calibration
  - Long-term energy stability
  - Performance regulations at high gradient and high current
- Gradient overhead studies (ACC67)

- Optimization of Qext, prove concept for at least 3mA
- Microphonics and LFD, can be done w/o beam

- Klystron Overhead
  - Need high current, at 3mA need retune Qext
- ILC Bunch compressor stability studies
  - 2 RF units ACC45 & ACC67 to demonstrate 0.25 deg phase stability
- HOM studies (parasitic studies)

<u>Beam requirements:</u>

- Most studies are require high current regime > 3mA
  - 1.5 nC, 3 MHz, 800 bunches: (XFEL goal 4.5mA)

Needed…

- Outline set of LLRF parametric studies + optics etc studies
- Modified outline plan for gradient overhead studies for scenarios #2 and #3 (short bunch trains, rf-only)
- Outline plan for piezo LFD optimization (to integrate with the gradient overhead study plan)
- …
- What about proposals that fit with the FEL studies program?

For reference: detailed 9mA studies proposals from WG3

List of 9mA studies proposals (WG3)
(Details are on the next few slides)

- Decoupling sources of error, both transverse and longitudinal
- Vector Sum calibration
- Energy Stability
- Ql and Pk tuning strategy for optimal operation with high gradient and heavy beam loading
- Study of LLRF regulation at the start of flattop with high beam current present
- Study of klystron power overhead
- Study of stability requirements for the ILC Bunch Compressor
- Beam Line Absorber tests at FLASH (HOM damping studies)

Decoupling sources of error, both transverse and longitudinal

Motivations:

- Except for the period of time during stable 3mA operation, the study did not converge on a stable tuning state for the machine. One of the reasons for this was the difficulty of localizing errors and drifts and the apparent coupling present between the transverse and longitudinal planes. Analysis of longitudinal data shows drifts and other errors, which are to some degree understood, however we don't understand transverse stability, or the couplings between longitudinal and transverse planes. These possible transverse errors or couplings may be present within the pulse, pulse to pulse, or over periods of hours or days. Within a pulse, power supply ripple may change magnetic fields. Heating of the gun during the pulse may also create phase or amplitude errors that difficult to isolate.

Decoupling sources of error, both transverse and longitudinal (2)

Test procedure:

- The concept of this test is to slide one or more systems at a time relative to the rest of the accelerator and analyze the results of this convolution. We expect that there is little coupling of the line phase to RF performance and we can therefore use the RF systems to scan the lattice over a fraction of a line cycle. Each RF system can be isolated by the same method of scanning its start time relative to the rest of the machine.
- **Transverse lattice:**
  - March the start time of all RF systems and laser over a 50 Hz line cycle - should decouple transverse & longitudinal planes
  - Can be done with small number of bunches (~30)
  - Look for jitter and drift in transverse space
  - Look for beam spot size with streak camera
  - Look for BPM and BLM
  - Can we identify a correlation with ripples in the magnets power supply?
  - Note that this can be done at commissioning
- **RF station and VS calibration:**
  - Hold the gun and laser starting time, but walk each RF station start time
    - One RF station at a time
    - Look for variations in beam energy and phase while the RF system is flat
    - Any errors in vector sum calibration should be detected
  - Gun vector calibration:
    - Hold RF and beam start time constant and walk the gun start time
    - As with the other stations this test will show errors in the gun vector

Vector Sum calibration

Motivations:

- There is evidence that the vector sums were not well calibrated during the study period. There are many possible contributions to this, however it is clear that operations with long pulses requires high quality calibrations that are quick, easy accurate and repeatable.

- **Understand and evaluate current calibration scheme**
  - Accuracy of the beam loading measurement (impact of receiver noise)
  - Accuracy of the beam current amplitude and phase measurement
  - Accuracy of the loaded Q measurement
  - Determine repeatability of the current calibration procedure
  - Run a cavity off crest to increase sensitivity to phase calibration

- **Propose alternate calibration scheme**
  - Provide a beam structure with a 10kHz square wave structure across the flat top
  - Perform an FFT and analyze the fundamental and sidebands
  - Repeat these experiments while changing the cavity tuners (i.e. changing cavity impedance) cf. Cornell approach
  - This work will require a fair simulation effort

Energy Stability

Motivations:

- Study analysis has shown that beam energy and phase regulation did not meet specification on many time scales.
  1. The energy stability should be studied for a single RF pulse, pulse to pulse and in the long term (i.e. hours, weeks)
  2. A single pulse will allow us to look at disturbances such as LFD, beam fluctuations during the bunch train, and some LLRF noise.
  3. The pulse to pulse study will allow us to look at slower disturbances such as pulse to pulse beam jitter, LLRF noise introduced by upstream stations, and microphonics.
  4. Long term stability will allow us to look at LLRF and injector drifts. Any machine settings during this time will need to be recorded and included in the analysis.
  5. Most of these studies can be done during normal FLASH operations. They should be performed at different points of the machine state space, such as different gradients, beam loading conditions.
  6. Question: what are the possible beam conditions? 1nC, 3MHz?

Qext and Pk tuning strategy for optimal operation with high gradient and heavy beam loading

Motivations:

- During the September study, cavity gradients in ACC456 had to be reduced when the beam current was raised pass 3mA. The purpose is to continue the previous work to optimize the coupling with high gradient operation and to align with simulation work.
  1. Change tuning strategy (individual QL)
  2. Simulation work with ACC6 and 7 (available knobs are individual motorized couplers and phase shifters and the power splitter between ACC6 and ACC7)

Study of LLRF regulation at the start of flattop with high beam current present

Motivations:

- During the study it was found that low beam loss could not be obtained if the beam pulse started at the beginning of flattop. This effect is not understood.
  1. Observe the first 20 usec of beam. Long bunch trains are not required. More current (i.e. more charge and bunch repetition rate) is desired.
  2. Understand and try to eliminate overshoot/undershoot in the energy due to LLRF settings.
  3. Correlate with cavity detuning and vectorsum calibration.
  4. This work should be backed-up with simulations

Study of klystron overhead

Motivations:

- Since the klystron is a non-linear device, operation point of the klystron input is a key-issue for llrf feedback system. Operational output power proposed in RDR is about 10%-15% below the saturation point, corresponding to the 5%-7.5% lower amplitude from klystron's saturation amplitude. This is quite higher than the present llrf feedback system, typically operated around 40% below the saturation power at SNS, J-PARC and FLASH. The focus of this study is to evaluate the performance of the klystron operation near its saturation.

Preparation:

- Due to the limitation of the input power to the cavities, the high voltage of the klystron was decreased. The calibration of input-output power is required. Protection system so as not to overdrive the klystron will be essential for the klystron. Software development for klystron linearization will be necessary to operate near the saturation point. High beam loading (9mA) is preferable. If this is not available, cavity filling pattern should be modified in order to operate the flattop region near saturation. It will be also necessary to change the Qe values if the filling-time requires longer period to accomplish this process.

1. Information of the klystron input-output characteristics at different klystron applied voltages (HV) (Fig.1) will be necessary.
2. Based on these characteristics, we have to select the operation HV. (The candidate of the operation point of the klystron should be 10%, 20%, 30% below the saturation power.)
3. Protection system for preventing the overdrive
4. Calibration of the input power
5. Linearization of the klystron output
6. Simulation work of the cavity filling pattern will be necessary in advance if the full beam loading is not available.

Study of klystron overhead (2)

Test procedure:

- **Without beam**
  1. Measure the vector sum amplitude and phase for the reference without beam.
  2. Decrease HV to operate 30% power margin point and measure the stability with and without linearization program. (compare the filling region)
  3. Decrease HV to operate 20% power margin point and measure the stability with and without linearization program. (compare the filling region)
  4. Decrease HV to operate 10% power margin point and measure the stability with and without linearization program. (compare the filling region)

- **With beam**
  1. Measure the vector sum amplitude and phase for the reference with beam. If the beam current is not matched to the loaded Q values, we should change Qext or the cavity filling pattern.
  2. Decrease HV to operate 30% power margin point and measure the stability with and without linearization program. (compare the flattop stability)
  3. Decrease HV to operate 20% power margin point and measure the stability with and without linearization program. (compare the flattop stability)
  4. Decrease HV to operate 10% power margin point and measure the stability with and without linearization program. (compare the flattop stability)

Study of stability requirements for the ILC BC

Motivations:

- For RTML bunch compressor amplitude and phase jitter in the SC cavities causes jitter in longitudinal position of the bunch in the collision point, jitter in the bunch length and in energy spread. To escape degradation of luminosity the requirements are the following:
  - Phase stability < 0.25° rms
  - Amplitude stability < 0.5% rms
- Bunch compressor RF cavities will operate close to zero-crossing (RDR baseline):
  - 105° off-crest (first stage), beam decelerates
  - 27.6° off-crest (second stage)
- For current studies we propose to operate FLASH in a regime with ACC45 at 90° off-crest and ACC67 at -90° off-crest. The Vector Sum of the both pairs of cryomodules should be equal to cancel out the beam arrival jitter and correlated energy spread due to bunch length. Each pairs is excited by separate klystrons. The goal is to study intra-train and pulse-to-pulse amplitude and phase stability in the ACC45 and ACC67 by measuring VS and energy jitter at the energy server. Understanding and improving of the LLRF system performance in regime with the beam off-crest operation are the part of these studies.

Required conditions:

- Maximum of 500-2400 bunches per pulse: 1-3nC/bunch at 500kHz-3MHz spacing
- Long RF flat tops (800us)
- Optics is tuned to the beam energy after ACC23 (420-500 MeV)
- Normally operate into the bypass line, energy measurements are essential.
- Precise measurements of the beam arrival time (phase) by BAM, installed before and after ACC456 modules (~40fs or 0.02 degrees). This is complementary information needed to study correlations between beam arrival jitter and energy jitter.

Study of stability requirements for the ILC BC

Test procedure:

- In this regime (off-crest) we can expect than performance of LLRF systems will not be the same as for 9mA studies. In studies we will measure phase and amplitude stability in each individual cavity, vector-sum in ACC23 and AC45 ACC67, energy (bunch-by-bunch and pulse–to-pulse). Jitter in bunch arriving time will be measured by two BAMs (bunch arriving monitors) before ACC45 and after AC67 and will study correlations. Probably 2-3 shifts will be enough in the first available run to understand performances of LLRF system and collect data for analysis. Further studies will continue in the next available run in the frame of 9mA studies.
  - Tune optics to ~440-500 MeV (after ACC23) with 90 degrees RF on ACC45 and -90 degrees in ACC67, RF amplitudes of both pairs of CM is equal (VS). Start with shorter train and 1nC charge, and 100-500 bunches.
  - For energy spectroscopy calibration, change the beam energy by RF phase in ACC45 and measure in energy server and possibly in downstream BPMs in DUMP area.
  - Increase current to nominal parameters and collect data
  - For understanding of the drift (in phase and amplitude before ACC45) will be useful to have klystrons, feeding ACC45 and ACC67 off every second pulse. Comparison with klystrons ON and OFF will provide additional information about system stability, which will be sort out in the data analysis

Preparation for the test:

- Understand BYPASS and DUMP optics for low energy beam
- Dynamic range of the energy server and FLASH downstream beamline
- Calibration of the cavity signals and VS.
- Setting for the klystron phase and amplitude during filling time and flat-top. This work should be backed-up with simulations

Beam Line Absorber tests at FLASH (HOM damping studies)

Motivations:

- Beam Line Absorber is designed to absorb the major propagating part of the HOM power in broad frequency range (up-to ~1 TGz), generated by the beam in SRF cavities (except the first few bands, trapped in cavity).
- In the 2008 and 2009 runs it was measured HOM power dissipation on BLA for long bunch length (>1mm). Simulations and measurements are in a reasonably good agreement. In new FLASH configuration BLA are placed between two cryomodules ACC6 and ACC7 which allow absorb HOM power from both cryomodules. The goal of next studies is to measure HOM dissipation for shorter bunch length.
  - These studies will require long bunch trains (3-9 mA) and stable long time operation (typical time constant for thermal equilibrium is ~3 hours).
  - These studies not require special dedicated shifts. Stable operation regime with long bunch trains (3nC per bunch) and short bunch length is essential for HOM damping studies.