ILC Machine Protection System (MPS)

MPS ≡ collection of devices intended to keep the beam from damaging machine components.

- **both from damage caused by a**
  - single bunch and the residual radiation or
  - heating caused by small (fractional) losses of a many bunches

ILC:

- **average beam power of 20 MW,**
- **consisting of 14000 bunches of 2e10 ppb each per second,**
- **beam sizes near 10 x 1 micron,**

The MPS consists of:

1) a single bunch damage mitigation system,
2) an average beam loss limiting system,
3) a series of abort kickers and low power dumps,
4) a restart ramp sequence,
5) a beam permit system,
6) a fault analysis recorder system,
7) a strategy for limiting the rate with which magnetic fields (and insert-able device positions) can change,
8) a sequencing system that provides for the appropriate level of protection depending on machine mode or state, and
9) a protection collimator system.

Single Pulse Damage:

1. **will be mitigated by systems that check the preparedness before each pulse.**
2. **is only necessary in the 'damped-beam' section of the ILC, where the beam area is less than 50 micron^2 (2e10).**
3. **mitigation will be done using two basic subsystems:**
    1) a leading benign pilot bunch and
    2) a beam permit system that surveys all appropriate devices before damping ring beam extraction begins and provides a permit if each device is in the proper state.

In addition, some exceptional devices will need fast monitoring systems and redundancy.

(damping ring RF and extraction kickers for example)

Single Pulse Damage in 1.4 mm Cu

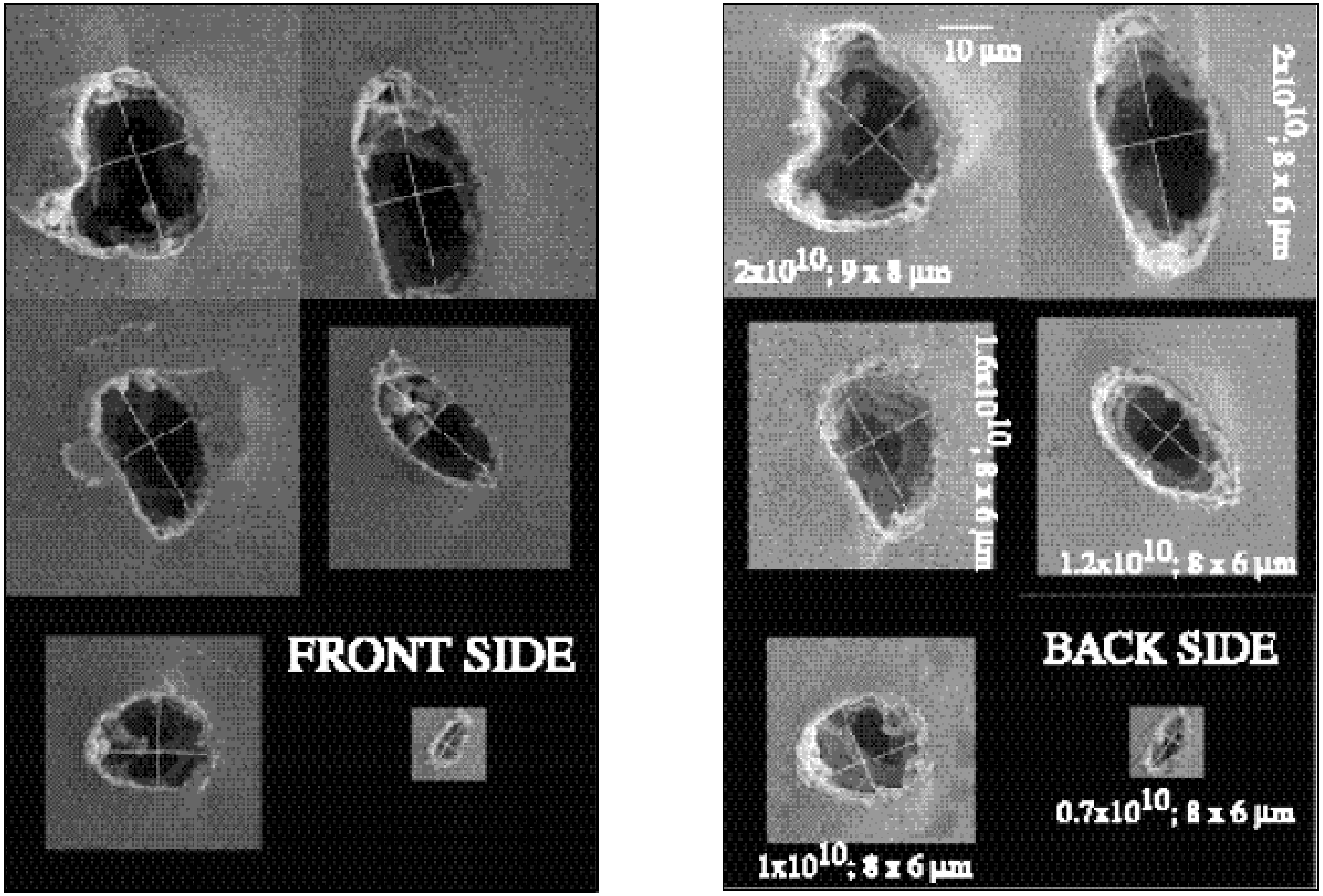
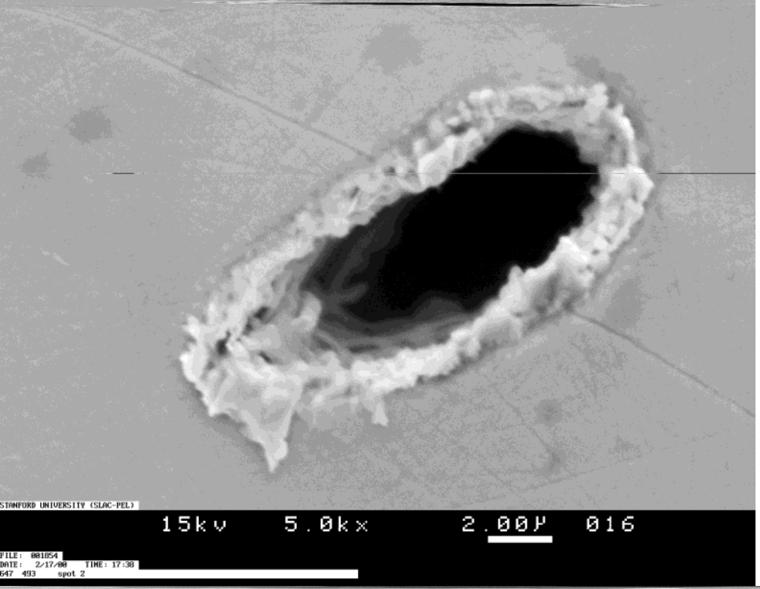
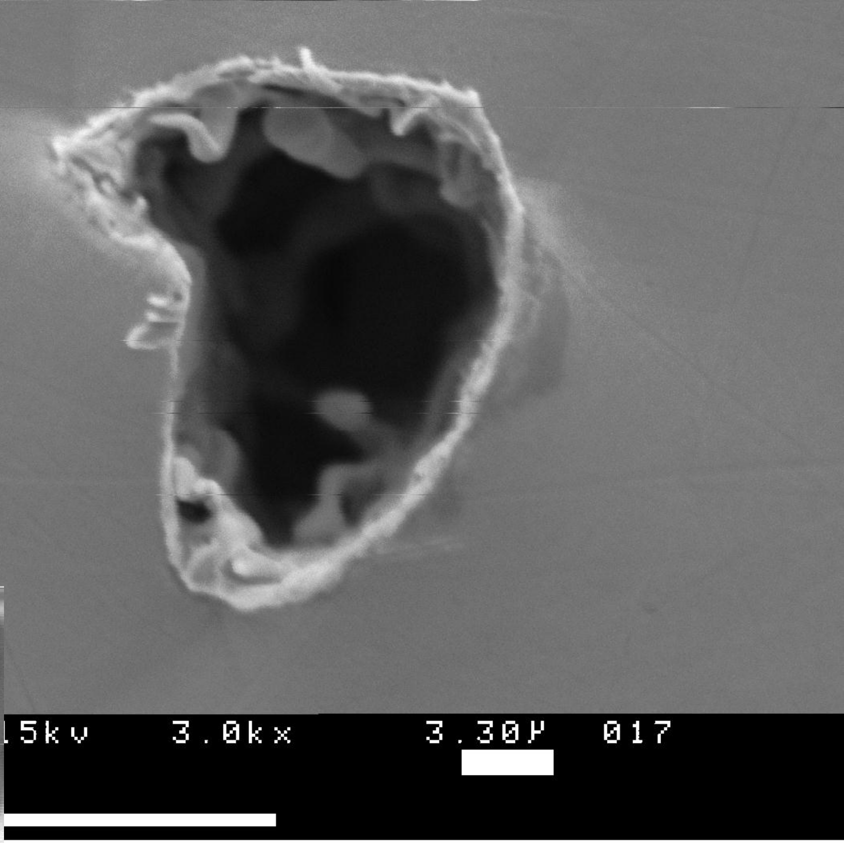
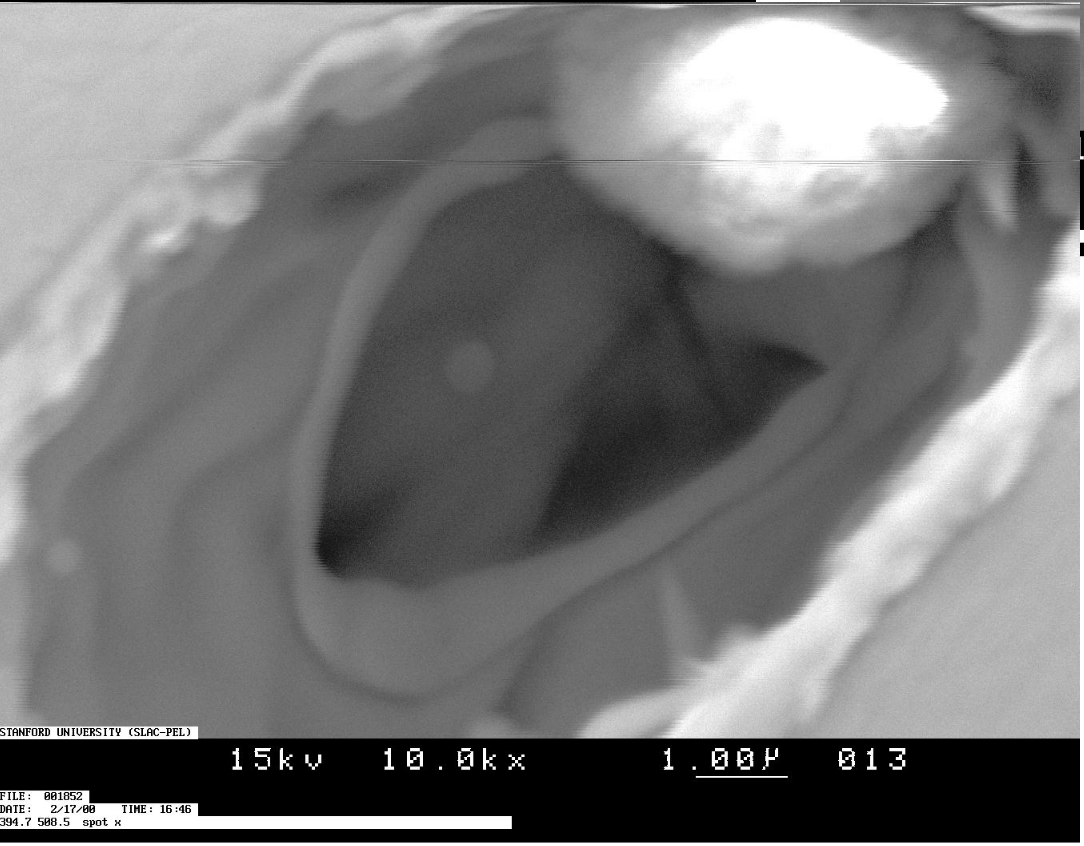


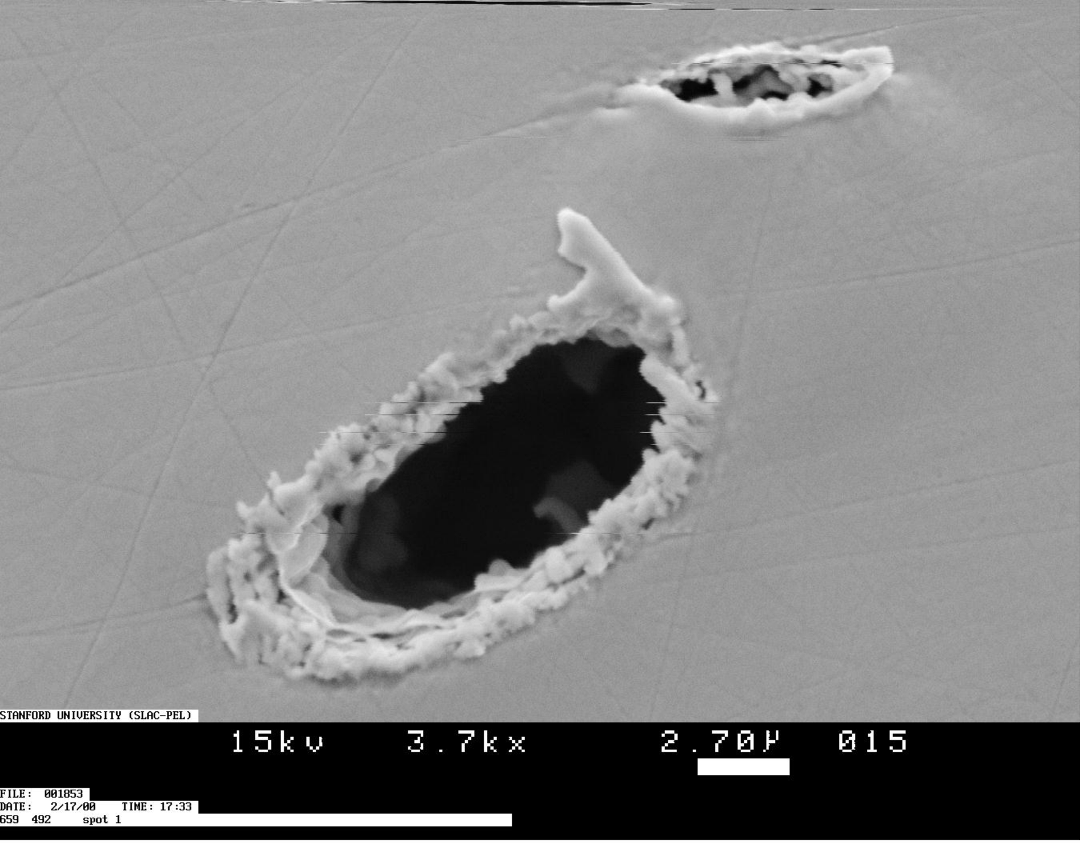
Figure 1: Scanning electron microscope (SEM) images of the entrance (left) and exit (right) points on the copper coupon. The faint lines drawn in the figure were used to estimate the impact point size. All of the images in the montage have the same scale.







Single Pulse Damage in 1.4 mm Cu (2)



Single Pulse Damage in 1.4 mm Cu (3)

Single Pulse Damage in Cu Summary

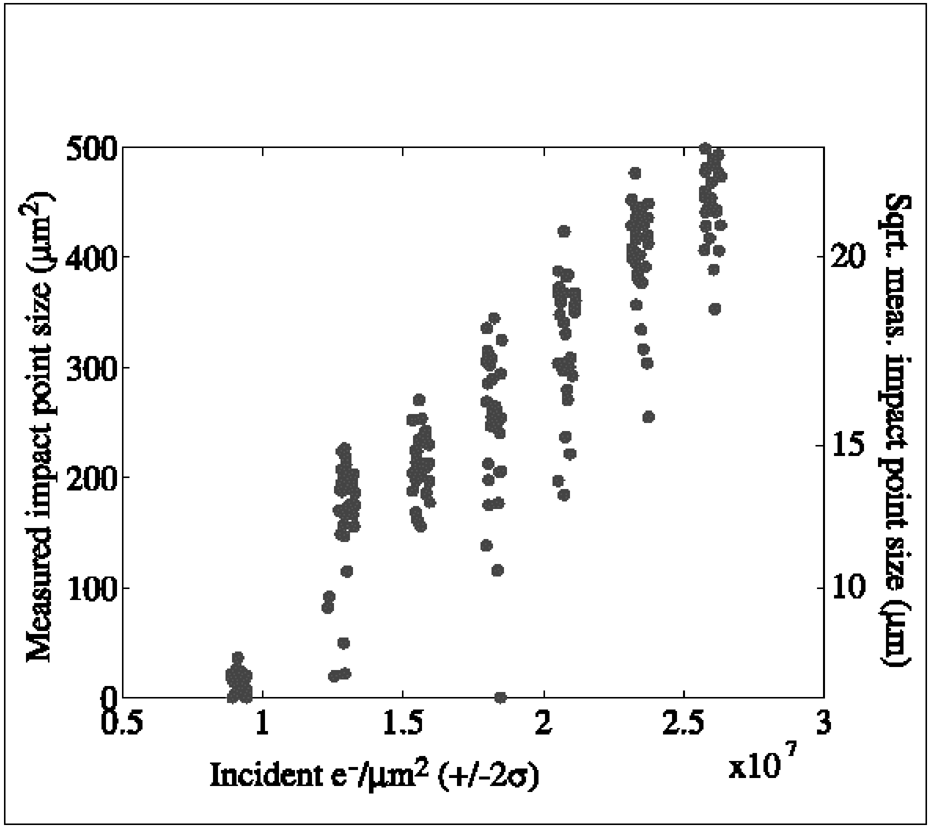


Figure 3: Measured impact point sizes vs beam density.

Figure 2: Sketch of a section of the copper coupon showing beam impact points (IPs) and associated parameters. The coupon size is 34 x 15 mm.

pilot bunch

- **1% nominal current, spaced 10 usec ahead of the start of the nominal train.**
- **must traverse the machine properly before the rest of the train is allowed to pass.**
- **Proper passage is sensed using the beam position monitors and beam intensity monitors**
- **If an errant trajectory is sensed, the nearest upstream abort system is triggered.**
- **Assuming the latency for detecting the fault is 500 ns, the upstream signal effective propagation speed is 0.7 c, and the abort kicker latency time is 1 us, the maximum kicker spacing should be 1000m.**

pilot bunch (2)

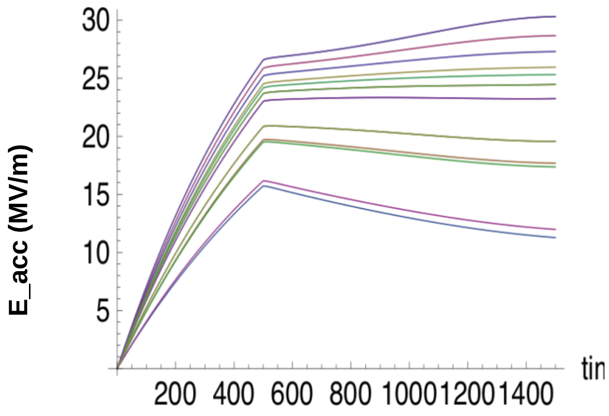
- Only those bunches extracted from the damping ring before the abort signal is sensed and received at the ring need to be dumped and the damping ring extraction sequence will be terminated, leaving what is left of the partially extracted beam train stored.
- Given that the time needed for the beam to go from the damping ring to the main beam dump is 67 us, in the worst case, (when the downstream most sensor detects a fault condition from the pilot), and the signal return time to the damping ring is another 100 us, roughly 450 bunches need to be dumped. Since there is more than one dump line, not all of these need to be dumped in one place.
- The injector complex must include systems that reliably generate the pilot bunch.
- Extraction from the ring should not begin unless the pilot is within allowed limits; its intensity should be high enough for the trajectory sensors to read and respond reliably yet below the single damage threshold, expected to be around 1% for bunches which are intended for the whole machine. There may also be a need for a benign pilot bunch of nominal intensity but much larger emittance.

Methodology for ramping to maximum gradient and full beam loading (16 cavities FLASH ACC6/7)

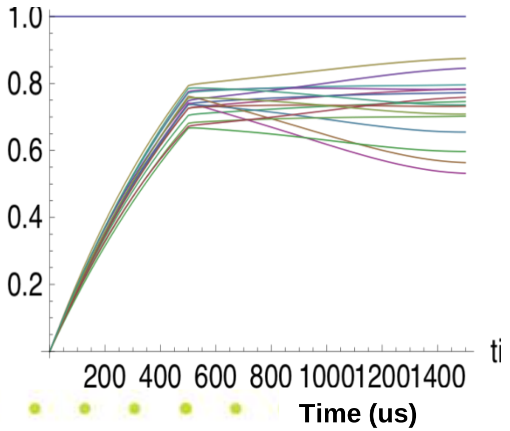
Step 1

Adjust Q_l

Cavity Voltages: 6mA
Default Qexts, 3.5MW



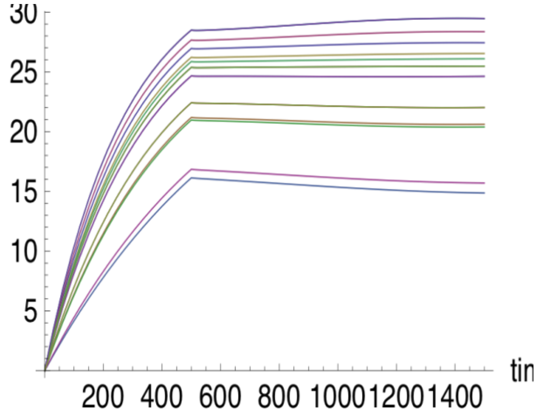
Fraction of quench limit



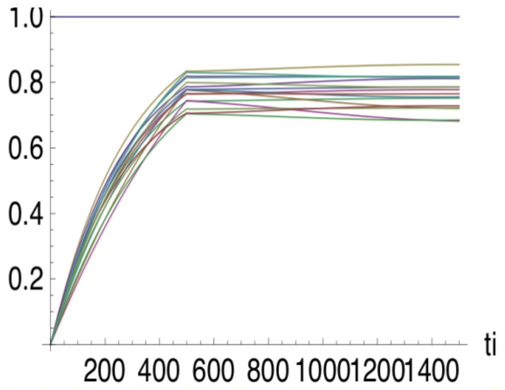
Step 2

Raise Power

Cavity Voltages: 6mA
Shin's Qexts, 3.5MW

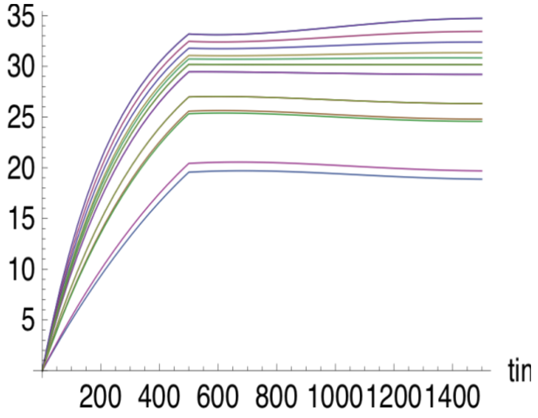


Fraction of quench limit

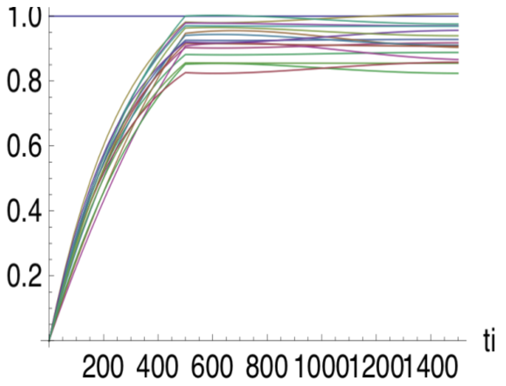


Step 3

avity Voltages: 6mA
Shin's Qexts, 5.1MW



Fraction of quench limit

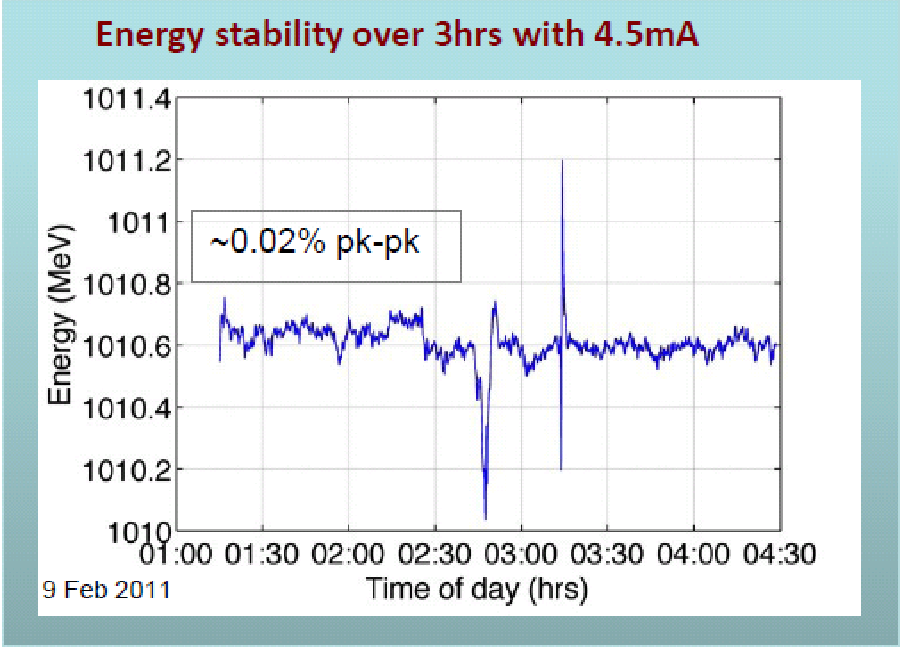


J. Branlard, Fermilab/DESY

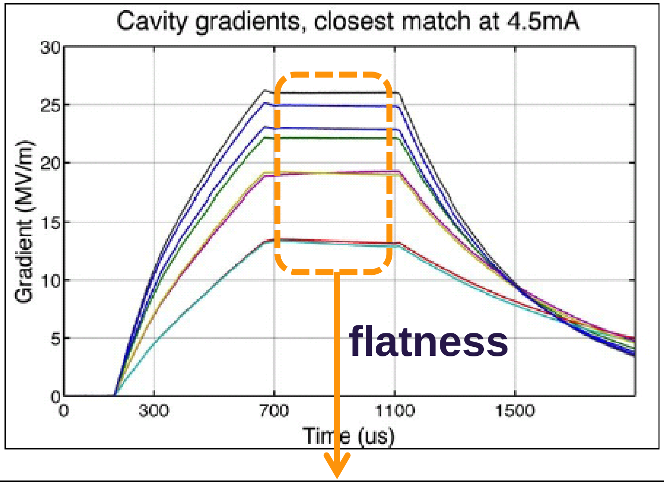
Performance of LLRF system after upgrade

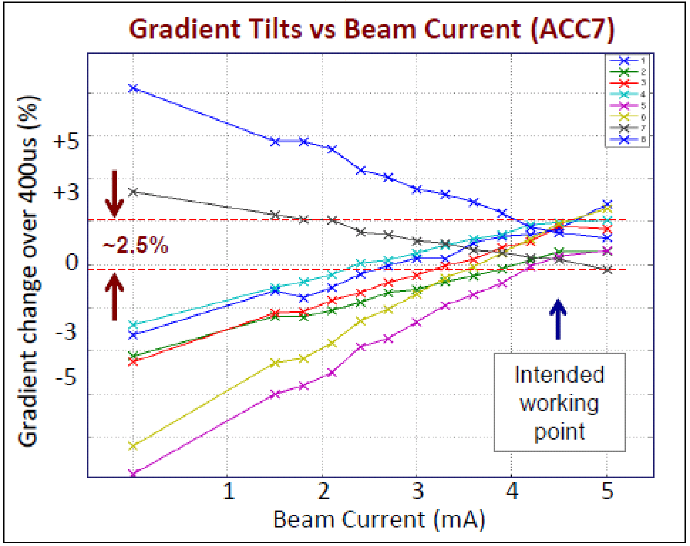
ILC studies: energy stability / gradient flatness / gradient limit

Energy stability exit of accelerator



Minimizing slopes by QL tuning



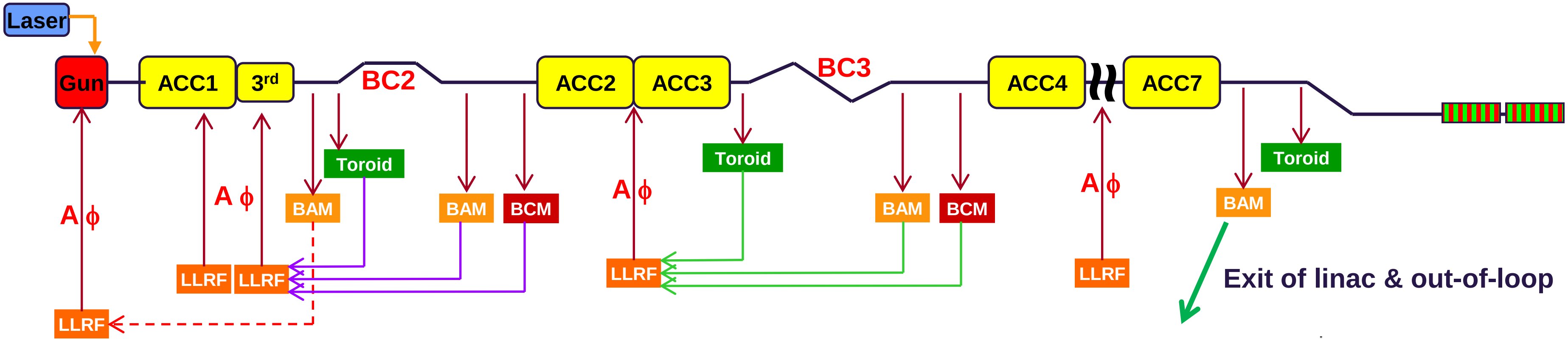


Important studies for FLASH & XFEL

- Impacts orbit variation and orbit slopes
- Achievable energy gain

ILC study results → Poster J. Branlard

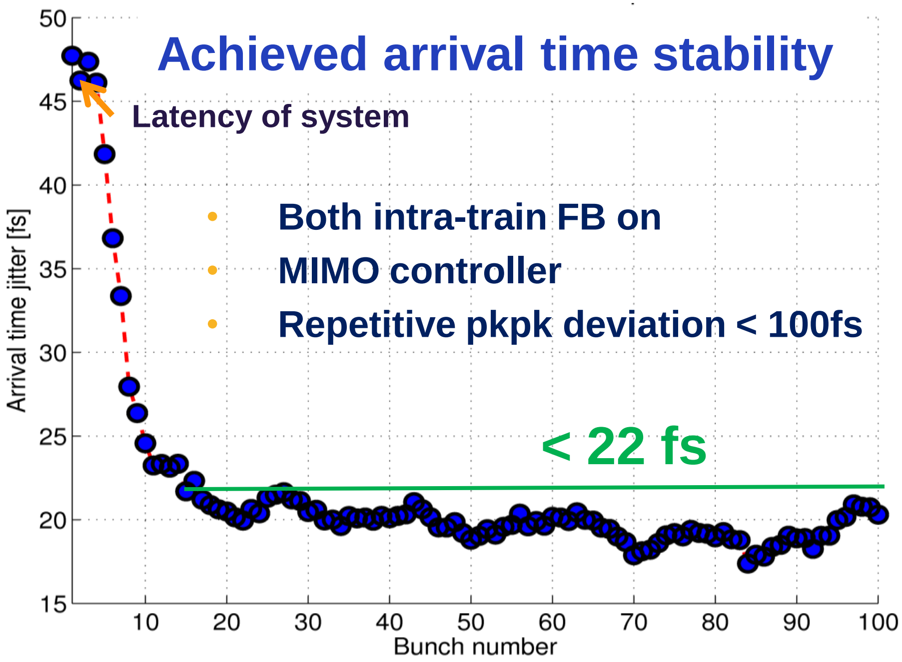
Performance of LLRF system after upgrade



Exit of linac & out-of-loop

Beam Based Feedbacks:

- BAM before BC2 corrects phase in RF-Gun
- BAM and BCM after BC2 simultaneously correct amplitude and phase in ACC1 and 3rd harmonic
- BAM and BCM after BC3 correct amplitude and phase in ACC23



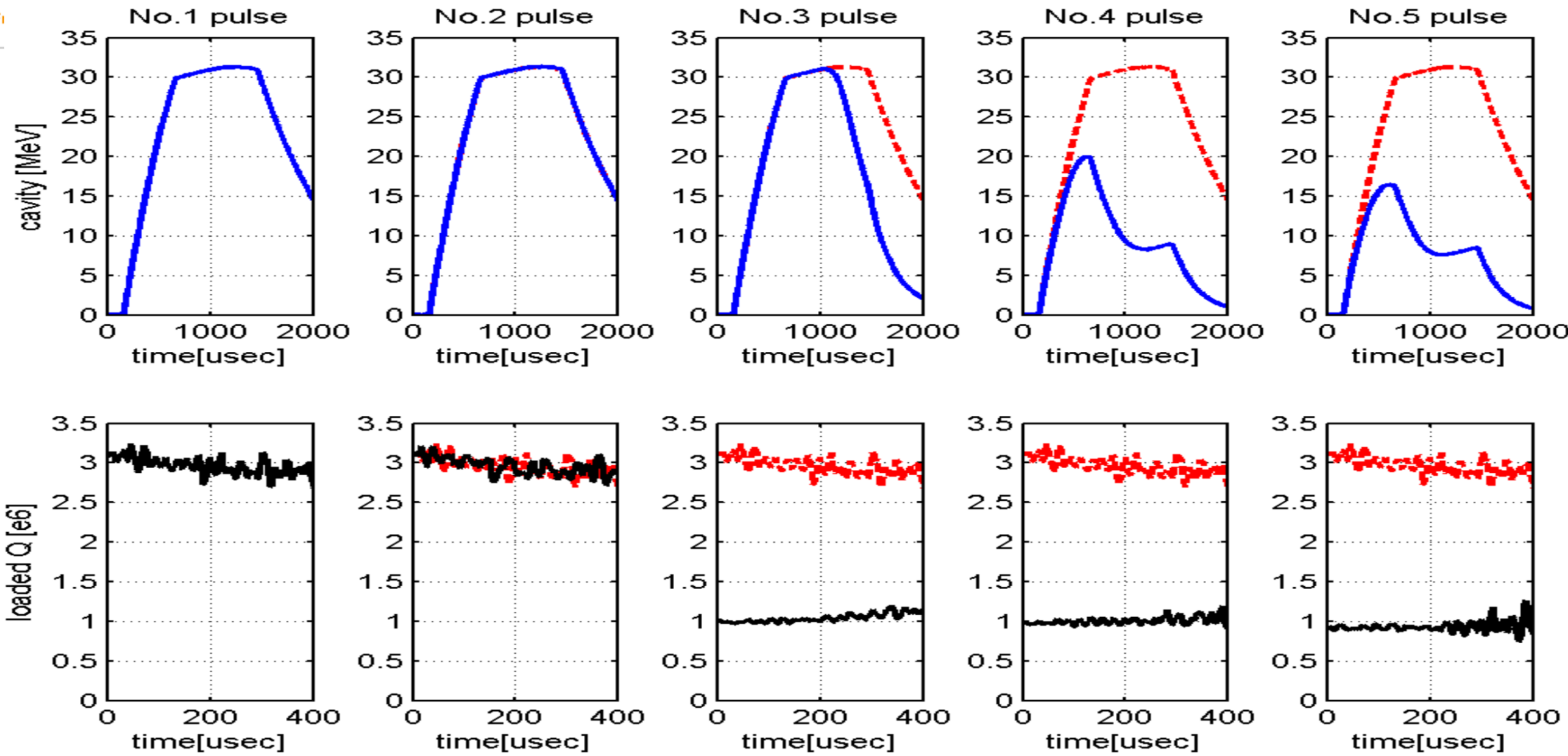
Achieved arrival time stability

Latency of system

- Both intra-train FB on
- MIMO controller
- Repetitive pkpk deviation < 100fs

< 22 fs

Quenches during 800us RF pulses, no beam



- At longer pulse (~800 us flattop), "quasi-quenches" were not observed.
- Once a quench took place, there was not a quick recovery, probably due to the larger energy deposited in the quenched area.

Average beam loss

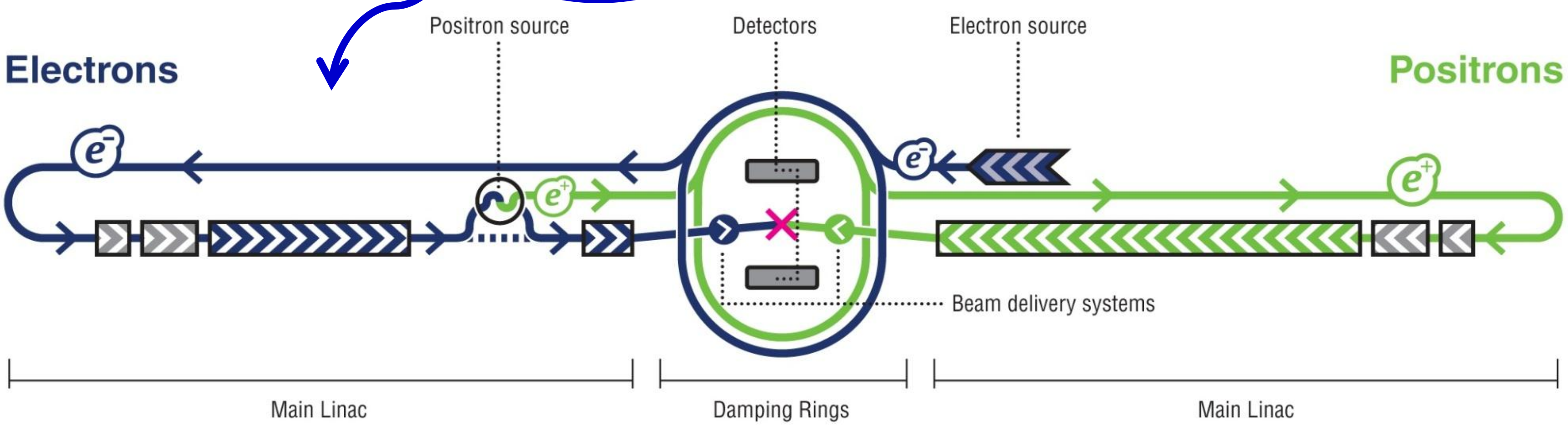
- limited using a combination of radiation, thermal, beam intensity and other special sensors.
- similar to other machines, such as SLC, LHC, SNS and Tevatron.
- exceeded exposure limits during the passage of the train, ring extraction or source production (e+/e-) is stopped.
- For stability, it is important to keep as much of the machine operating at a nominal power level.
- Done by segmenting into MPS regions.
- Since the fault response can (and will) occur during the train, and since there will be 9 full power shut-off points, each with an extraction system and a full capacity dump,
- The average beam loss MPS will be applied throughout the complex, including the source, damping ring injector and the damping ring itself.
-

beam shut-off points

	Region name	Begin	End
1	e- injector	Source (gun)	e- Damping ring injection (before)
2	e- damping ring	Ring injection	e- Ring extraction (after)
3	e- RTML	Ring extraction	e- Linac injection (before)
4	e- linac	Linac injection	Undulator (before)
5	Undulator	Undulator	BD; e+ target
6	e- BDS	BD start	e- Main dump
7	e+ target	e+ target	e+ damping ring injection
8	e+ damping ring	Ring injection	e+ ring extraction
9	e+ RTML	ring extraction	e+ linac injection
10	e+ linac	linac injection	e+ BDS
11	e+ BDS	e+ BDS	e+ main dump

Table 1: beam shut off points. Each of these segmentation points is capable of handling the full beam power, i.e. both a kicker and dump are required. These systems also serve as fast abort locations for single bunch damage mitigation.

ILC and CLIC



- **Main Linac Technology**
  - ILC Superconducting RF cavities and global industrialization
  - CLIC copper accelerating structures and drive system
- **Common Technology**
  - Damping Ring
  - Beam Delivery

Abort Systems

- Abort systems are needed to protect machine components, especially the superconducting cavities, from single bunch damage.
- It is expected that a single bunch impact on a niobium iris will leave a small hole, roughly the diameter of the beam, through which the helium will flow.
- The minimal abort system consists of a spoiler / collimator / absorber block (copper) and a kicker.
- The kicker rise time should be fast enough to produce a guaranteed displacement of more than the pipe radius in an inter-bunch interval.

Abort Systems (2)

- **In any given fault, at most 450 bunches would then strike the copper block. It is expected that the upstream block surface would be marred with a sequence of small impact holes, but that the block would not fracture and would not require cooling.**
- **If the block is thick enough to absorb the full shower, the energy associated with 450 bunches should be less than 400kJ (250 GeV) and the block temperature will rise about 4 degrees.**
- **Since each abort precedes a cool down interval, the average power on the block should be very low.**
- **In the baseline configuration five abort systems are needed on the electron side (four on the e+ side): 2 upstream of the linac, one upstream of the undulator and 2 in the beam delivery.**
- **The required kicker deflection is 10 mm, for the radius, and a relatively small additional amount for margin. With a kicker volume of 20 * 20 mm, about 25 MW of peak power would be required for a 50 m long kicker system [1]. RD is needed to reduce this requirement and to make a system with an appropriate safety factor.**
- **The total length associated with abort systems is 200 m per side.**
- **In the beam delivery and the RTML, 2 of the abort system can be integrated with the tune up dumps.**
- **The abort system can also be triggered during the train, if a serious trajectory distortion is detected. The kickers must be triggered as close as possible to the preceding bunch so that no bunch is kicked incompletely.**

restart sequence

- **Depending on the beam dynamics of the long trains, it may be advisable to program short trains into a restart sequence.**
- **There may also be single bunch, intensity dependent effects that require an intensity ramp.**
- **In order to avoid relaxation oscillator performance of the average beam loss MPS, the system will be able to determine in advance if the beam loss expected at the next stage in the ramp sequence is acceptable.**
- **Given the number of stages and regions, the sequence controller must distribute its intentions so that all subsidiary controls can respond appropriately and data acquisition systems are properly aligned.**
- **The sequence may need to generate a ‘benign’ bunch sequence with the nominal intensity but large emittance.**
- **The initial stages of the sequence will be used to produce ‘diagnostic’ pulses to be used during commissioning, setup and testing.**

‘NLC’ restart sequence

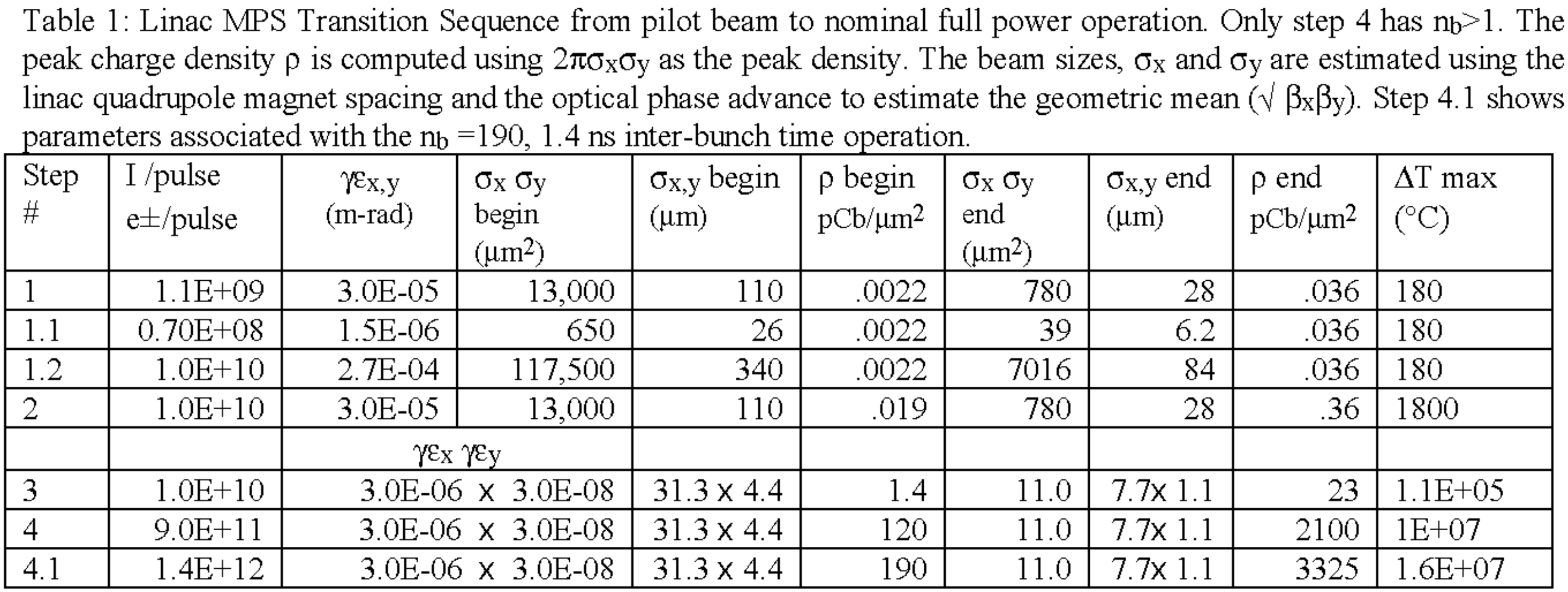


Table 1: Linac MPS Transition Sequence from pilot beam to nominal full power operation. Only step 4 has $n_b>1$. The peak charge density ρ is computed using $2\pi\sigma_x\sigma_y$ as the peak density. The beam sizes, σ_x and σ_y are estimated using the linac quadrupole magnet spacing and the optical phase advance to estimate the geometric mean ($\sqrt{\beta_x\beta_y}$). Step 4.1 shows parameters associated with the n_b =190, 1.4 ns inter-bunch time operation.

Step #	I /pulse e±/pulse	$\gamma\varepsilon_{x,y}$ (m-rad)	σ_x σ_y begin (μm^2)	$\sigma_{x,y}$ begin (μm)	ρ begin pCb/μm^2	σ_x σ_y end (μm^2)	$\sigma_{x,y}$ end (μm)	ρ end pCb/μm^2	ΔT max (°C)
1	1.1E+09	3.0E-05	13,000	110	.0022	780	28	.036	180
1.1	0.70E+08	1.5E-06	650	26	.0022	39	6.2	.036	180
1.2	1.0E+10	2.7E-04	117,500	340	.0022	7016	84	.036	180
2	1.0E+10	3.0E-05	13,000	110	.019	780	28	.36	1800
		$\gamma\varepsilon_x$ $\gamma\varepsilon_y$							
3	1.0E+10	3.0E-06 x 3.0E-08		31.3 x 4.4	1.4	11.0	7.7x 1.1	23	1.1E+05
4	9.0E+11	3.0E-06 x 3.0E-08		31.3 x 4.4	120	11.0	7.7x 1.1	2100	1E+07
4.1	1.4E+12	3.0E-06 x 3.0E-08		31.3 x 4.4	190	11.0	7.7x 1.1	3325	1.6E+07

rapidly changing fields / devices – slew rate limits and locks

- **there are critical devices whose fields (or positions) can change quickly, perhaps during the pulse, or (more likely) between pulses.**
- **These devices need 1) special controls protocols, 2) redundancy or 3) external stabilization and verification systems.**
- **1) Depending on the state of the machine, there should be programmed (perhaps at a very low level) ramp rate limits that keep critical components from changing too quickly. For example, a dipole magnet should not be allowed to change its kick by more than a small fraction of the aperture (few percent) between beam pulses during full power operation. This may have an impact on the speed of beam based feedback. Some devices, such as collimators should be effectively frozen in position at the highest beam power level. There may be several different modes, basically defined by beam power, that indicate different ramp rate limits.**

High speed device redundancy

- 2) There are a few critical, high power, high speed devices (damping ring kicker, RF, linac front end RF, bunch compressor RF and dump magnets) which will need some level of redundancy in order to reduce the consequence of failure. In the case of the extraction kicker, this will be done by having a sequence of independent power supplies and stripline magnets that have minimal common mode failure mechanisms. In the case of the front end and bunch compressor RF, there will be more than one klystron / modulator system powering a given cavity through a tee. The LLRF feedback will be used to stabilize the RF in the event that one of sources fails ‘mid-pulse’. There are alternate methods of doing this, for example using a sequence of modestly powered devices controlled completely in parallel, as in the case of the critical damping ring extraction system.

Common mode failures

- **3) There are several serious common mode failures in the timing and phase distribution system that need specially engineered controls. This is necessary so that, for example, the bunch compressor or linac common phase cannot change drastically compared to some previously defined reference, even if commanded to do so by the controls, unless the system is in the benign – beam tune up mode.**
-

some MPS ‘rules’

- **starting from the hardest**

  1) Critical component control through high level software should be 'keyed' through MPS modes, so that various controls are severely limited or disabled. Feedback must also be subject to these controls.
  2) An assessment is needed to balance the beamline design and MPS response. e.g. it is foolish to place a large number of small apertures in the linac and then expect a omniscient MPS to keep them all happy and safe. This assessment must be made numerical for very expensive choices, like the one in the example.
  3) parallel beam diagnostic and device monitoring MPS paths are needed.

some MPS ‘rules’ (2)

- 4) Every attempt should be made to make individual components as robust as possible.
5) Device controller responsibilities should have as much responsibility as possible. This includes reporting field changes (even if requested) and OOT. This will have the effect of de-centralizing the MPS - see LHC abort kicker set-point monitor threshold controls
6) MPS itself must include routine test procedures, some with beam.
7) beam dynamics - related failures deserve additional consideration and controls. These are especially important for the DR.
8) generic design rules controlling rate/bunch number transitions, management of diagnostic bunches, integration.