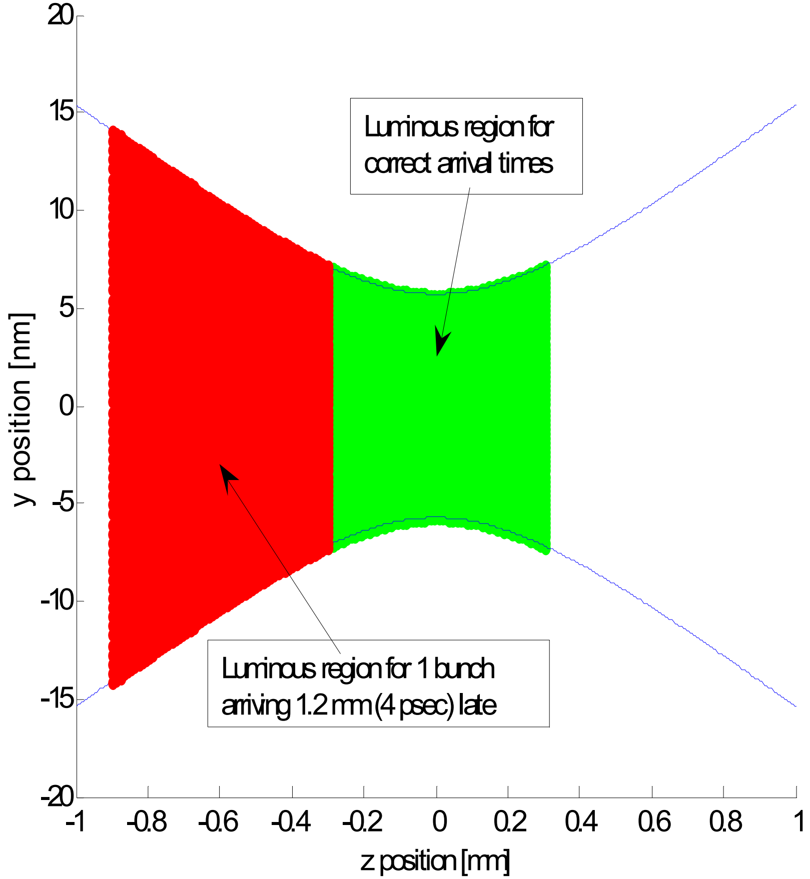
ILC RF phase stability requirements and how can we demonstrate them

Sergei Nagaitsev

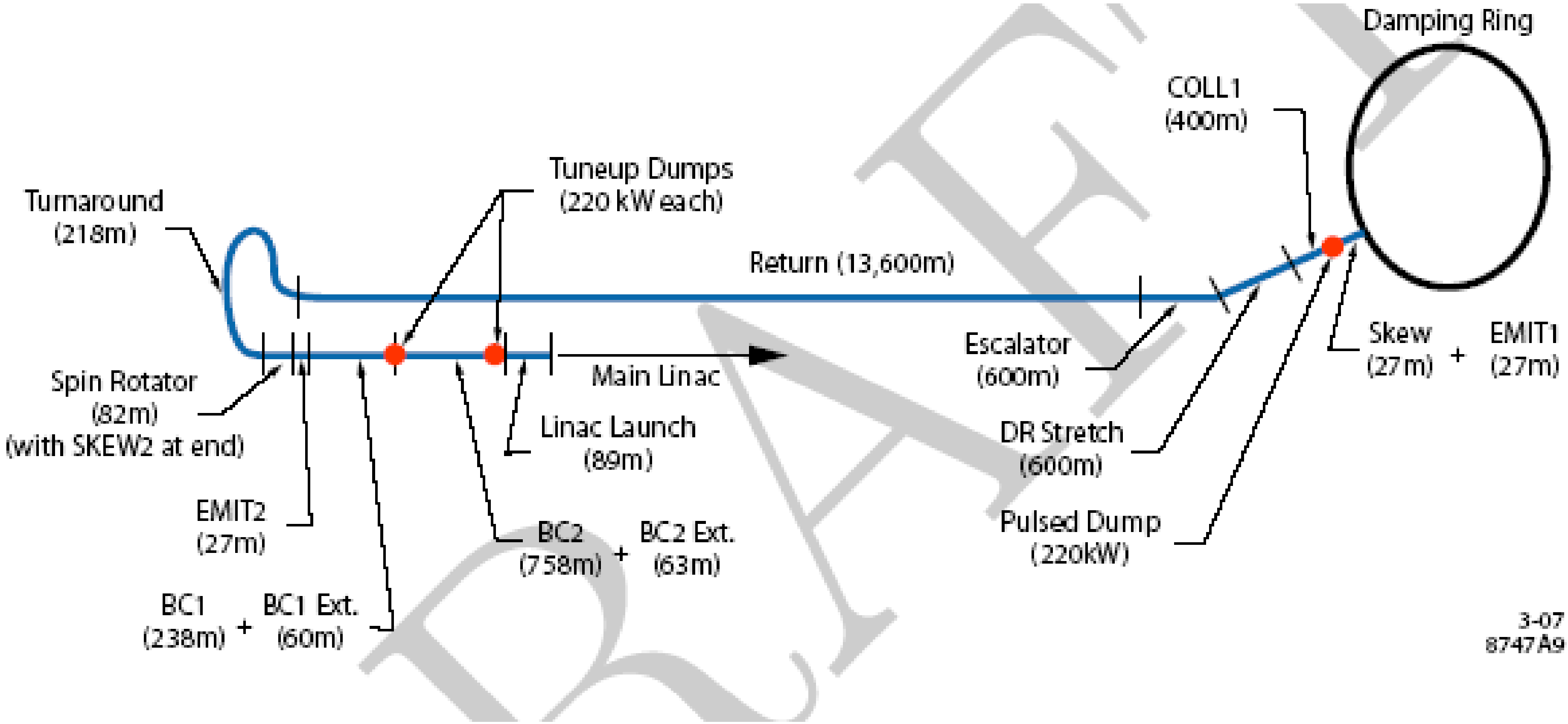
Oct 24, 2007

IP arrival time stability

- The *relative* arrival time of the 2 beams at the IP (e+ and e-) must be *stable*
  - If one beam is late wrt the other, lumi is lost due to the "hourglass effect"
  - Stability requirement – the arrival time can be tuned and set, but don't want to have to tune it every second (or every train, or every pulse)
- What does it have to do with rf phase???
  - Very little in the linac: time=length/c (if the length stays constant)
  - Bunch compressor stability is essential



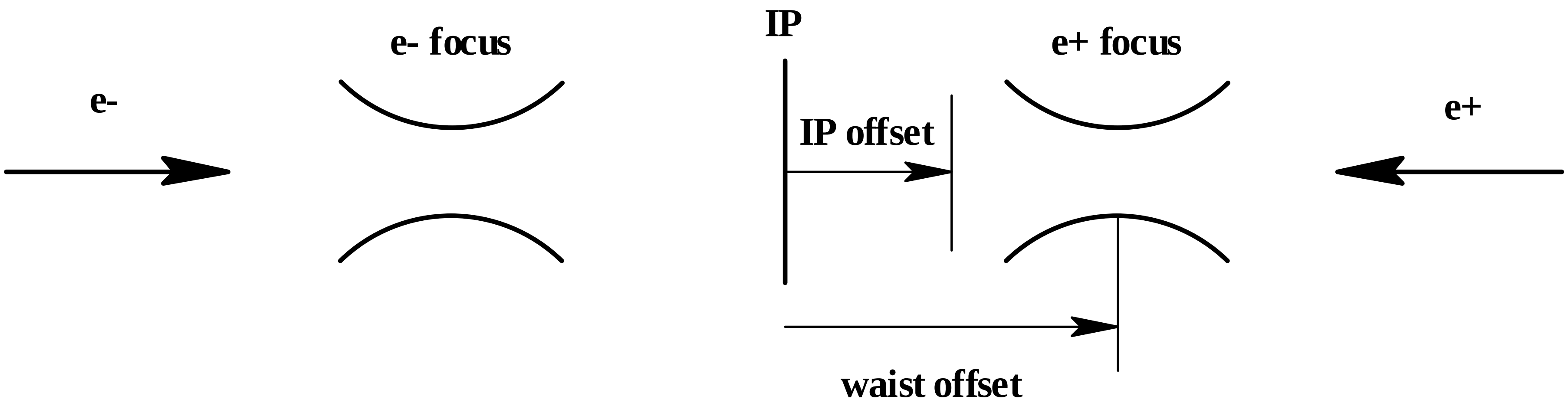
Ring to Main Linac (RTML)

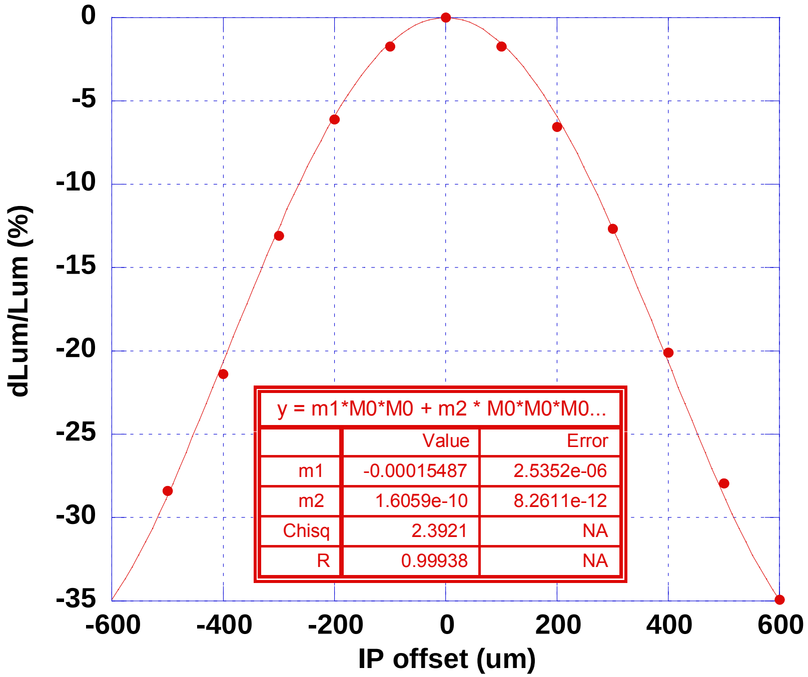


RTML bunch compressor (key parameters)

Parameter	Nominal BC1 Value	Nominal BC2 Value
Initial energy	5 GeV	4.88 GeV
Initial energy spread	0.15%	2.5%
Initial bunch length	9 mm	1.0 mm
RF voltage	448 MV	11.4 GV
RF phase	-105°	-27.6°
Wiggler R_{56}	-376 mm	-54 mm
Final energy	4.88 GeV	15.0 GeV
Final energy spread	2.5%	1.5%
Final bunch length	1.0 mm	0.3 mm

IP offset defines the time jitter of the collision point



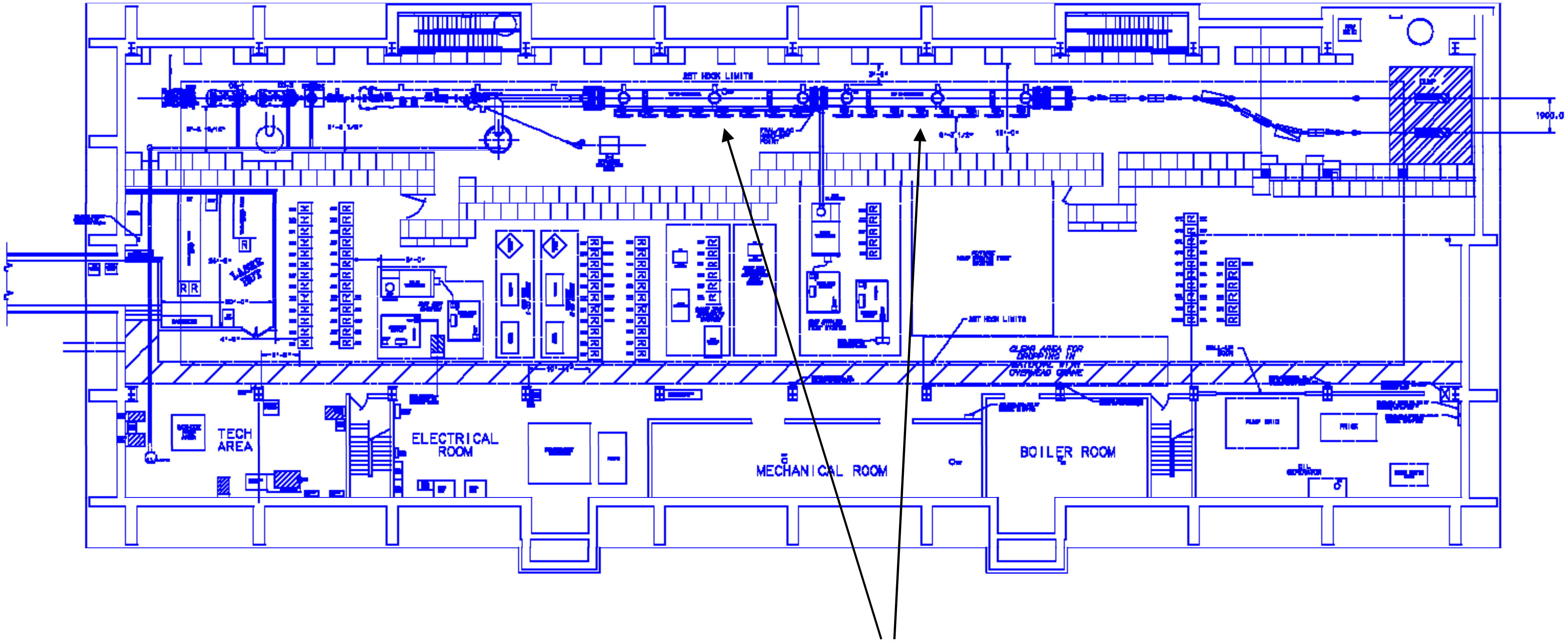


1 ps ≈ 0.3 mm ≈ 0.5°

Phase stability specs from RTML RDR:

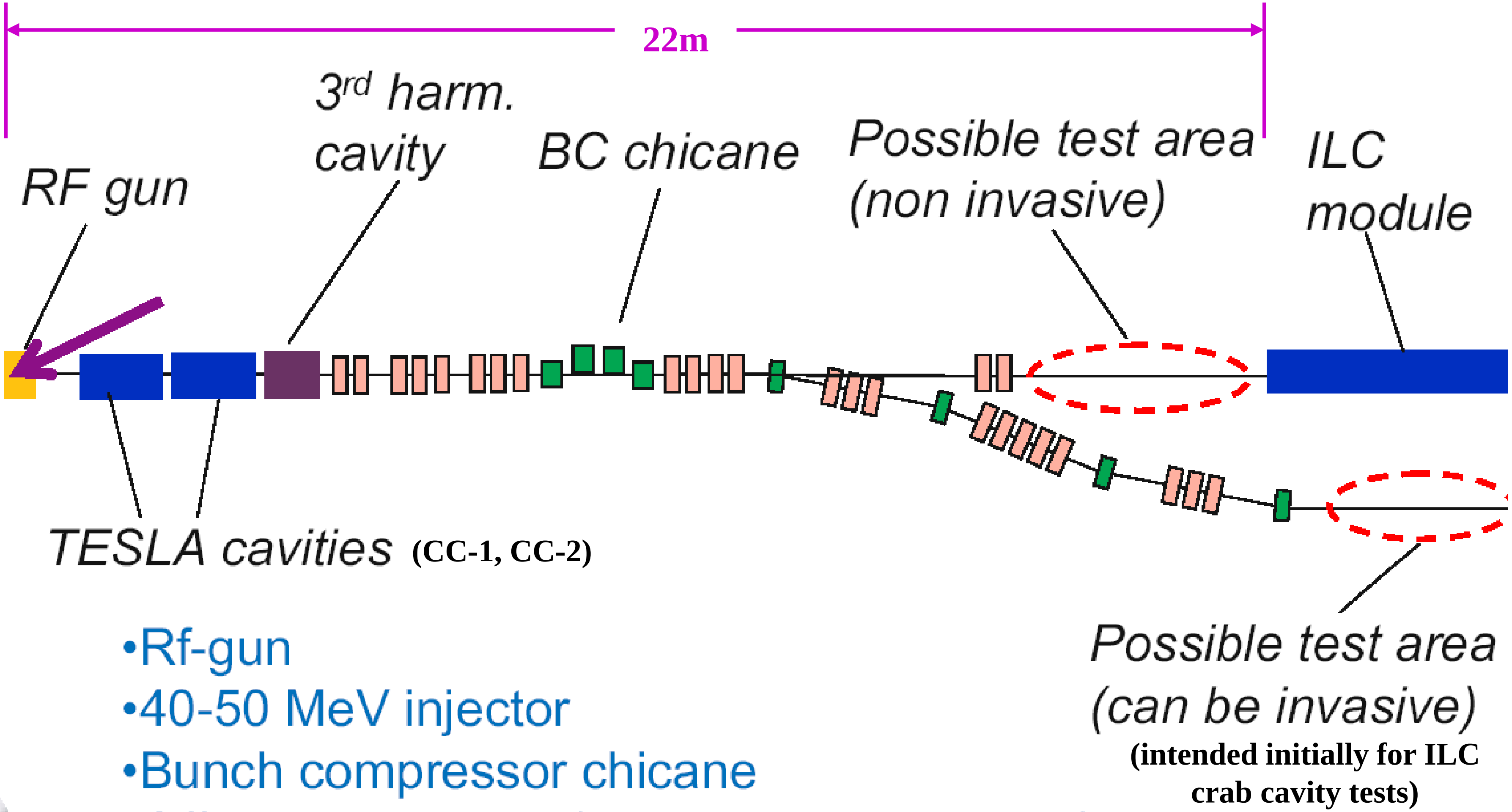
- Bunch compressor RF phase and amplitude stability tolerances are more stringent than the that for the Main Linac
- Phase stability tolerance: 0.25 degrees rms at 1.3 GHz
  - The tolerance is on timing jitter between electron and positron sides.
- Amplitude stability tolerance: 0.5% rms
- Bunch compressor rf cavities operate close to zero-crossing:
  - -100-degrees off-crest (first stage), beam decelerates
  - -20 to -40-degrees off-crest (second stage)
  - Gradient: typ. 25 MeV/m

Two CMs with beam



Two ILC cryomodules (12 m each).

Proposed NML Injector Layout



- Rf-gun
- 40-50 MeV injector
- Bunch compressor chicane
- Off-axis beam line (dogleg w tunable R56)

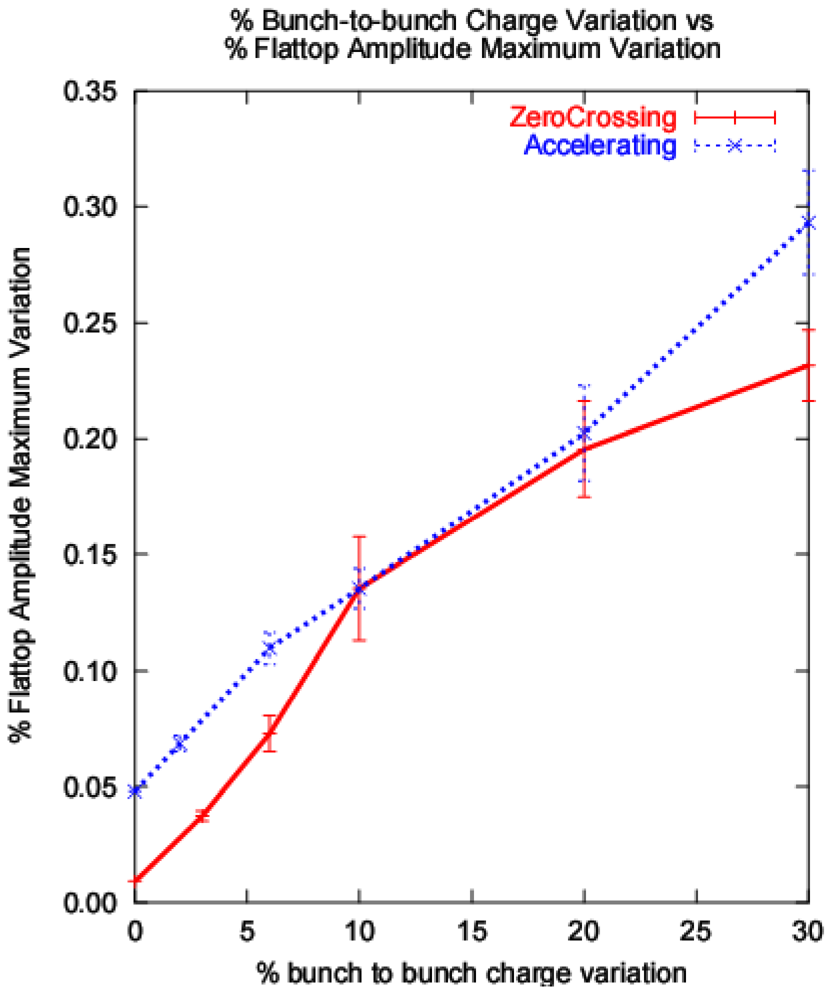
P. Piot

LLRF system is the key component

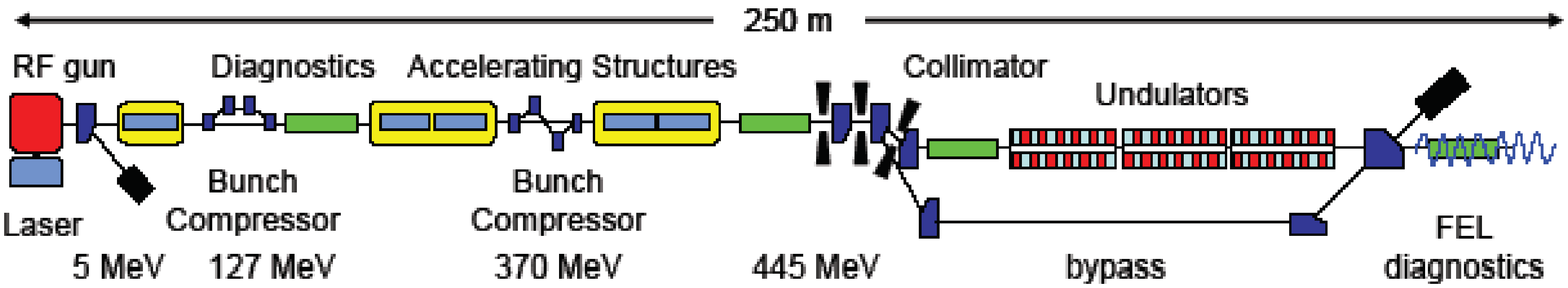
- Bunch compressor requirements drive the LLRF system design:
  - Beam loading is at 90-degrees w.r.t cavity rf
  - For a Tesla cavity R/Q=1kOhm and bunch charge q=3.2 nC the bunch will excite 14 kV/m decel. gradient at 1.3 GHz. At zero crossing (90-degrees off-crest), this will cause a 0.03-degree phase shift.
  - Missing bunches have the same effect (opposite sign)
  - Consecutive bunches (or missing bunches) add up in phase. If there are 100 bunches with charge 10% lower than nominal, the phase will shift outside the tolerance limit.
  - Need both feed-back and feed-forward

LLRF simulation example (Upenn)

- Described at PAC07
- Includes FB and FF

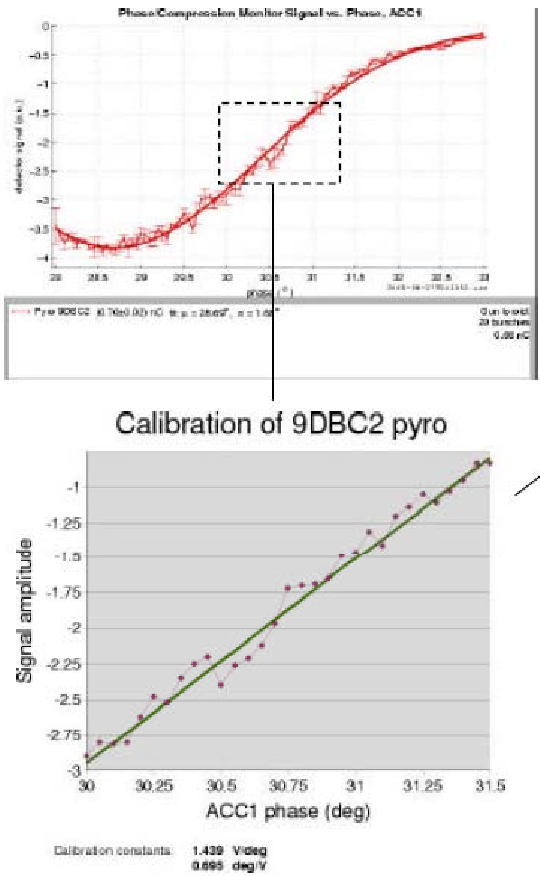


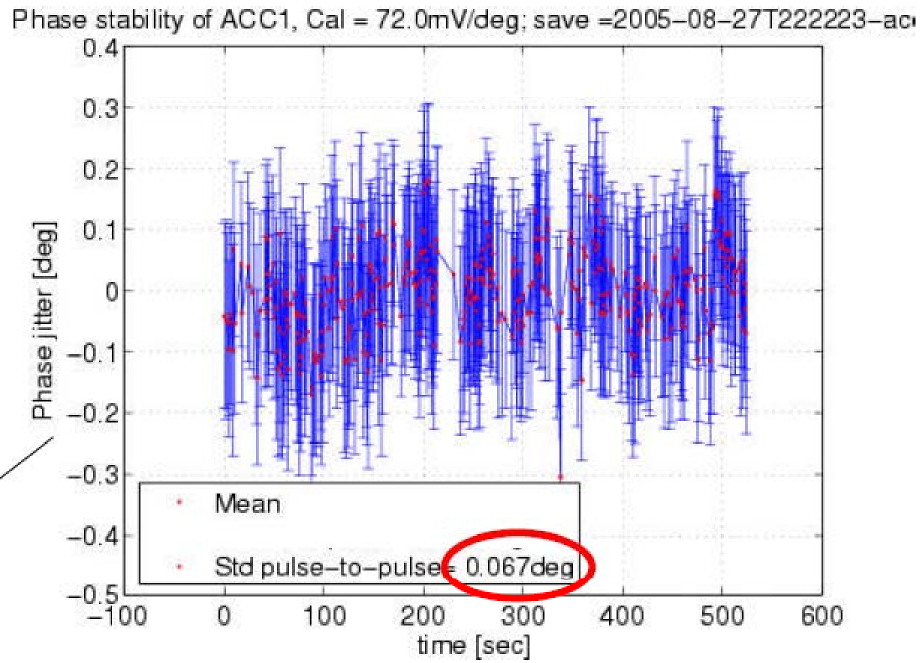
TTF/FLASH at DESY



Single bunch phase stability measurements at TTF
(from S. Simrock)

Phase stability with pyro-detector





But! This is the phase stability between the beam arrival into the acceleration module relative to the RF phase!!!

=> Major contribution is likely from laser

10/31/2005

What can we measure at NML?

- Required (for ILC) phase stability (rms):
  0.25-degrees = 0.5 ps (0.16mm)
  - The stability is with respect to an ideal master oscillator
  - Preferably, this stability should be demonstrated independently of the LLRF system error signal, since the LLRF system is only a portion of the RF system we are trying to evaluate.
- The stability evaluation scheme depends on how many rf units (or rf systems) we have

For a single RF system

- The suggested stability evaluation scheme has two parts
  1. The bunch arrival stability. First, the bunch arrival phase (for each bunch) is measured separately w.r.t. the master oscillator. It would be good to make the bunch time jitter lower than 100 fs. This would exclude the bunch jitter from the tests we are trying to do.
  2. Beam energy. The beam phase is set far off-crest. The bunch-by-bunch energy is measured as the beam position after a spectrometer magnet. This measurement is independent of the master oscillator stability and the LLRF error signal.

Cont'd

- For bunch time-of-arrival method would like to have a resolution of at least 100 fs
  - This is possible with electro-optical sampling technique (either by directly coupling of a probe laser beam to the E-field of the e- beam, or by using an electrical pick-up and sampling the generated signal via optical method)
- Similarly, for energy measurements, the energy spread should not be much higher than the energy jitter one is trying to measure. Bunch energy spread is entirely due to bunch length and rf slope
  - Possible for a 0.3mm bunch, impossible for a 3mm bunch

Additional constraints

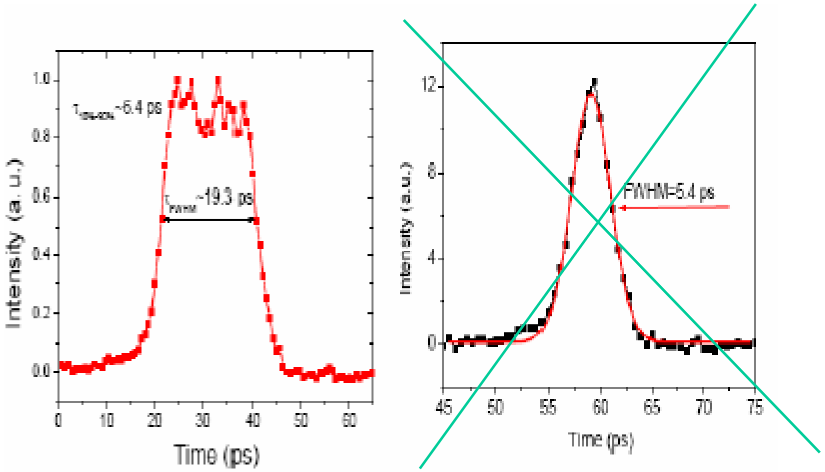
- Tests need to be done as close to zero crossing as possible. My definition of being close enough: 60 to 90-degrees of crest.
- After the bunch passing the rf unit the overall energy spread should not exceed 1% for optics reasons.

Bunch launch jitter because of laser

- At Fermilab A0: laser timing jitter WRT master oscillator is 200 fs rms (0.1 degree @ 1.3 GHz)
- At TTF (probably) 100 fs rms
- Bunch compressor would help to reduce the bunch time jitter.

Beam parameters after gun

- DESY PITZ-type gun
- For 4-stacked laser pulses at 40 MV/m @ cathode
  - 3.2 nC per bunch
  - 4.2 MeV kinetic energy at gun exit
  - 4-μm rms norm emittance
  - 2.4 mm rms bunch length (3.7° rms at 1.3 GHz)
  - 1.2% rms momentum spread
- Undesirable to run with a single laser pulse.



Energy spread due to bunch length

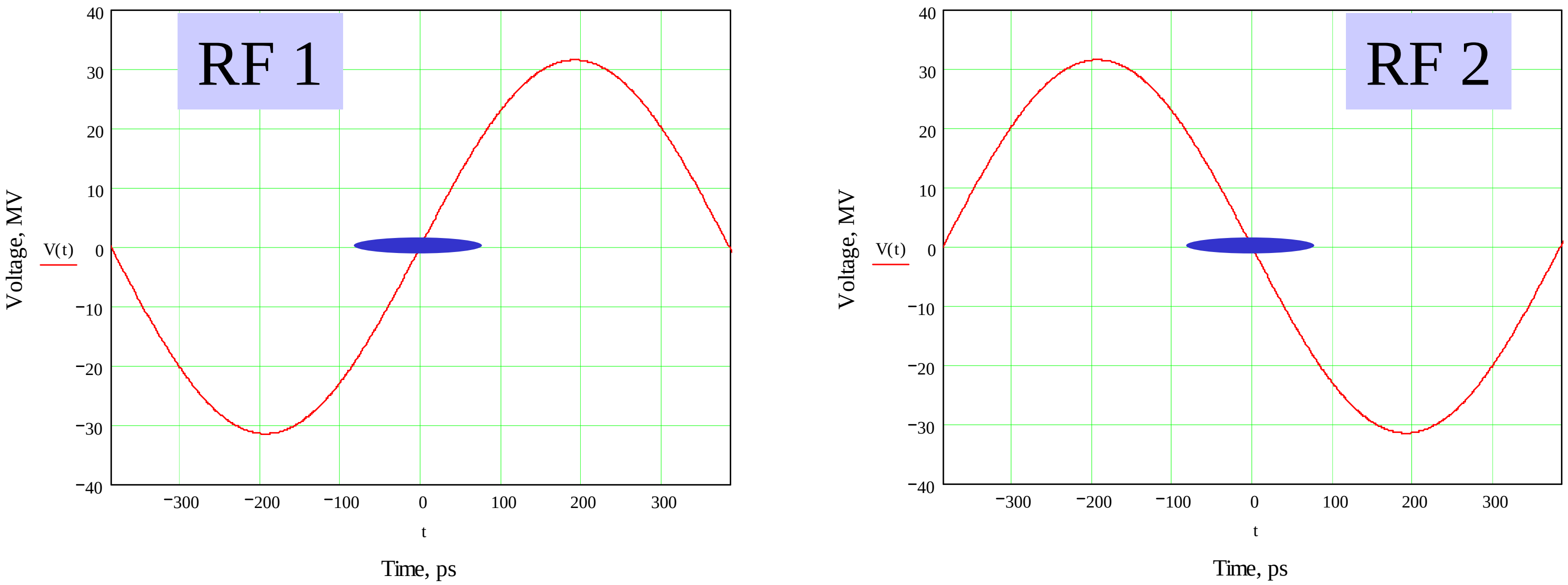
- Beam parameters at CM entrance (Fermilab NML plan):
  - Beam energy – 40 MeV
  - Bunch length – 0.3 mm rms
- If one limits $\Delta E/E$ to 1%, the beam can not be run at phases greater than 55-degrees off-crest for 31 MV/m
  - The effect of phase jitter is 0.1% energy variation – easily measurable with a bpm and Dx=50 cm or so.

Running at zero-crossing

- Impossible with a 40 MeV injector; energy spread more than 10%

Two rf systems

- Allows to evaluate two systems with respect to each other – just like we need for the electron and positron BC's
- Relaxes the bunch arrival requirements
- The idea is – to run two system 180 degrees apart
- Suggested by Tom Himel and PT



Two rf systems (cont'd)

- If both systems are run at equal amplitudes, the correlated energy spread is canceled
- The phase jitter of one system with respect to another will show up as the energy jitter of the beam.
- Use energy spectrometer to evaluate the beam energy

Conclusions

- For a single RF unit:
  - Need a bunch compressor to resolve 0.05-degrees or 100-fs. Bunch length of 1-ps should work, 10-ps will not.
  - Can not run beam close to zero-crossing because of energy spread induced by rf slope and low injection energy.
  - Need also to measured the incoming bunch-to-bunch energy jitter so this calls for dispersive section (a compressor) before the CM
- For two RF units:
  - Need two rf units or, at least, two rf systems powering two cryomodules
  - Does not require bunch arrival jitter measurements.
  - Can run beam at zero-crossing