Error Model for the RF

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General Remarks

- The tolerance numbers given are only indicative
- Important to define the relevant values and procedures
- For actual numbers some decision remains to be taken

  - are they for the nominal parameters or for the worst case?

  - conventionally we quote 2% luminosity loss, but many small values add up
- I would suggest to define a table with the allowed luminosity loss for the different imperfections
- The RF is controlled by complex feedforward and feedback

  $\Rightarrow$ need to simplify

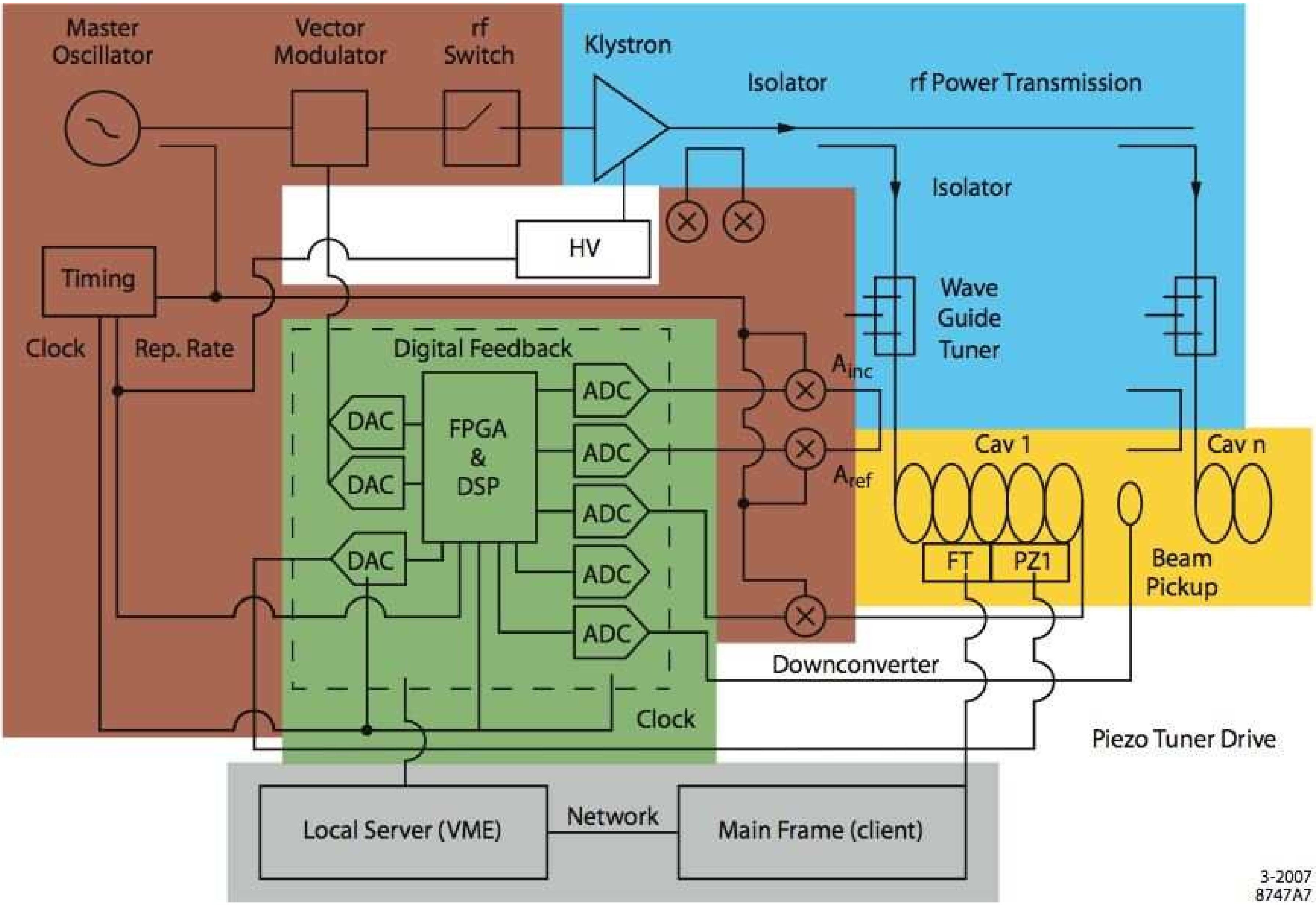
Main Linac RF Noise Sources

- Lorentz force detuning
  - systematic from pulse to pulse
  - is largely corrected using piezo tuners in feedforward
- Microphonics
  - unpredictable
  - corrected by klystron-based (or piezo-based) feedback
- Klystron amplitude and phase jitter
  - corrected by klystron based feedback
- Beam current variation
  - measure beam current at damping ring and use feedforward for klystrons
- Feedback noise
- Jitter of timing reference
  - need to find out size, but expected very small

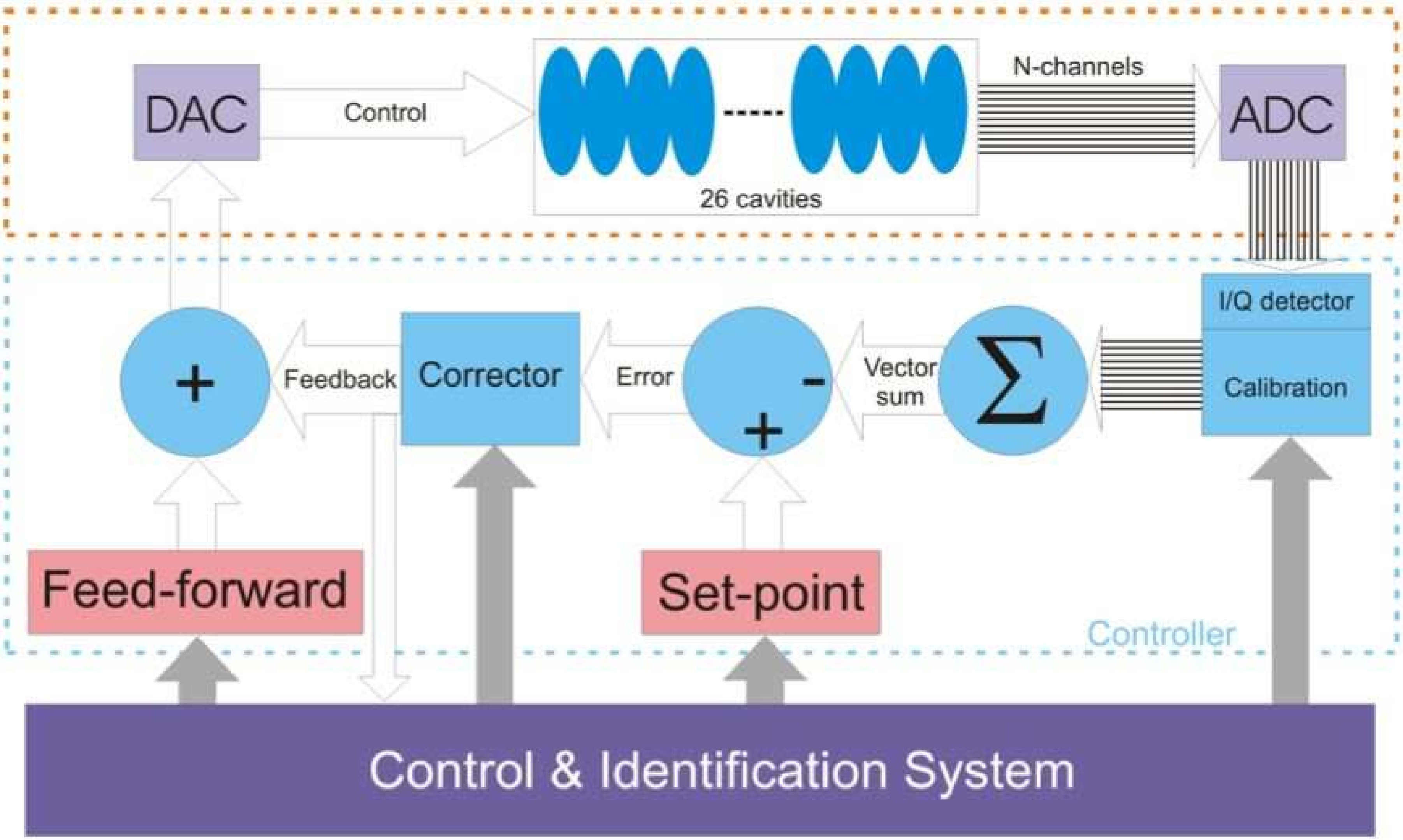
Low Level RF Controls

- The low level RF control ties the RF phase to a timing reference and adjusts the gradient
- For each cavity one measures
  - field amplitude and phase
  - input power
  - reflected power
- As correctors are used
  - piezo tuners in each cavity
  - stepping motors
  - klystron amplitude and phase
- One needs a beam timing feedback
- The klystron-based feedback acts on the vector sum of all cavity gradients in a unit
- The sensors are calibrated measuring the field with and without beam
  - the field induced by the beam can be calculated
- Input and reflected power per cavity is measured
- Beam current is measured at damping ring and used for feed-forward

Feedback Layout



Software Design



Beam Dynamics Constraints

- The final energy needs to be accurately known for physics
  - measurement
- The final energy needs to be stable for physics
  - large energy variations would also cause luminosity loss due to limited BDS bandwidth
  - need to control final energy
- The emittance needs to be preserved in presence of static imperfections
  - differences between the actual and the assumed lattice can cause emittance growth
  - need to control energy profile
- The emittance needs to be preserved in presence dynamic imperfections
  - the energy profile needs to be stable
  - kicks due to cavity tilts need to be controlled
- Beam timing errors lead to luminosity loss
  - need to control bunch compressor RF stability

Final Energy Static Error

- We can expect systematic errors in the acceleration along the main linac
  - coherent calibration errors of amplitude and phase measurement in all RF units
  - random calibration errors of amplitude and phase in each RF unit
- The beam energy will be measured with the spectrometer and the detector
  - very high precision (10^{-4}, actually it will be precisely the "relevant energy")
  - can remove coherent calibration errors
- We are left with random calibration errors

  $\Rightarrow$ they can cause emittance growth
- Typical parameters are accuracies of 1% and 1°

  $\Rightarrow$ should specify that this is acceptable (some work has been already done)

  for 1.5% random acceleration error per unit, DFS still works

  $\Rightarrow$ should identify our limit

Final Energy Stability

- This is fundamental physics requirement

  ⇒ has to be achieved by the control system

  ⇒ let us try to see if this is the tightest tolerance
- Aim for 0.07% energy stability (RDR)
  - but for four error sources, should be reviewed
- Tolerance for coherent errors along main linac are
  - $\sigma_\phi = 0.35°$
  - $\sigma_G = 0.07\%$
- Tolerance for independent errors per RF unit along main linac are
  - $\sigma_\phi = 5.6°$
  - $\sigma_G = 1\%$
- Phase tolerances depend on average RF phase used
- We would expect to have better stability but let us check if we do need it
- Check requirement of single cavity

Error of Individual Cavities

- The piezo feedback controls the frequency of each structure
- The RF feedback controls the vector sum of all cavities fed by one klystron
- Errors of RF units can cause dispersion
  - errors of individual cavities can be averaged
- But if cavities are tilted the errors lead to transverse kicks
- For 1% gradient error one finds $\Delta\epsilon_y \approx 0.4\,\mathrm{nm}$
- For the same bunch-to-bunch error one finds $\Delta\epsilon_y \approx 10\,\mathrm{nm}$

$\Rightarrow$ Errors of individual cavities are relevant

$\Rightarrow$ The timescale at which errors occur is relevant ($\approx 0.2\%$ for fast, $\approx 1\%$ for slow errors)

$\Rightarrow$ This needs to be included in the tolerance requirements

Considerations on Coherence

- The amplitude is regulated locally
  - no coherent error from the feedback measurement
  - but coherent noise could cause coherent effect

    e.g. klystron phase error until it is removed by the feedback

    e.g. beam loading

  $\Rightarrow$ will have some coherent error
- The phase is regulated with respect to timing reference
  - can have coherent error from feedback
  - can have coherent noise source giving a coherent effect

  $\Rightarrow$ need to consider coherence
- Eample: klystron jitter
  - phase jitter of a series of klystrons has some correlated and some uncorrelated contribution
  - both will be demagnified by the phase feedback which ties the klystron phase to the timing reference

  $\Rightarrow$ uncorrelated phase jitter will remain uncorrelated

Bunch Compressor

- RF gradient and phase error result in
  - timing error at IP
  - beam energy variation (mean and spread)
  - bunch length variation
- Acceptable timing error is given by the luminosity loss
  - assuming the detector people agree on longitudinal position jitter of their collisions
- Required simulation is simple
  - modify RF
  - run tracking
  - run beam-beam

$\Rightarrow$ According to RDR the phase and amplitude tolerances are

  - $0.24°$ for coherent and $0.48°$ for incoherent phase jitter
  - 0.5% for coherent and 1.6% for incoherent gradient jitter

- Calibration error will most likely be tuned out completely
- Need to specify limits for bunch length and energy spread, but should be less important

RF for the Crab Cavities

- The main constraint is luminosity loss from horizonal beam-beam offsets due to phase errors
- Offset is given by

$$\Delta x = \Delta\Phi \frac{\theta_c}{2} \frac{\lambda}{2\pi}$$

- Luminosity loss is given by

$$\frac{\Delta\mathcal{L}}{\mathcal{L}} = 1 - \exp\left(-\frac{\Delta x^2}{4\sigma_x^2}\right)$$

- Hence, $\sigma_\phi \leq 0.09^\circ$ at 3.9GHz (RDR quotes $\sigma_\phi \leq 0.015^\circ$)
- An amplitude error leads to a beam angle

$$\theta = \frac{\theta_0}{2} \frac{\Delta A}{A}$$

- $\approx 0.4\,\mathrm{mradian}$ is acceptable

  $\Rightarrow \sigma_/ A \leq 6\%$

First Proposal for a Model

- We can express all tolerances in amplitude and phase
  - it seems possible to treat them largely as independent
- Assume that RF phase and cavity error have a static and a dynamic contribution
- Assume that the static error is independent from RF unit to RF unit
  - coherent errors will be corrected to 10^{-4} using the end of linac energy measurement

  $\Rightarrow$ need to identify limit from static emittance preservation (1.5% per unit is OK)
- Assume for now that the dynamic contribution is independent from bunch to bunch
  - i.e. dominated by noise
  - this is a pessimistic model

  $\Rightarrow$ single bunch studies are sufficient
- Assume three contributions to dynamic errors
  - correlated along machine
  - independent for each RF unit
  - independent for each cavity (the vector sum is used for feedback)
- Particular problem are transverse kicks from tilted cavities

Conclusion

- The work has just started

  - more to come

- The requirements from the physics experiments put a strong constraint on the main linac energy stability

  ⇒ we can use these as simple tolerance

  - they could be the tightest dynamic tolerances for the main linac
    1% and 1° incoherent

- The requirements for the bunch compressor are only slightly tighter

- The cavity tilts put a constraint on the gradient/field stability in each cavity

  - better understanding required

  - feedback and error source are important (cavity act as a filter)

- Start to write this down in a document

  - perform some simulations to check numbers