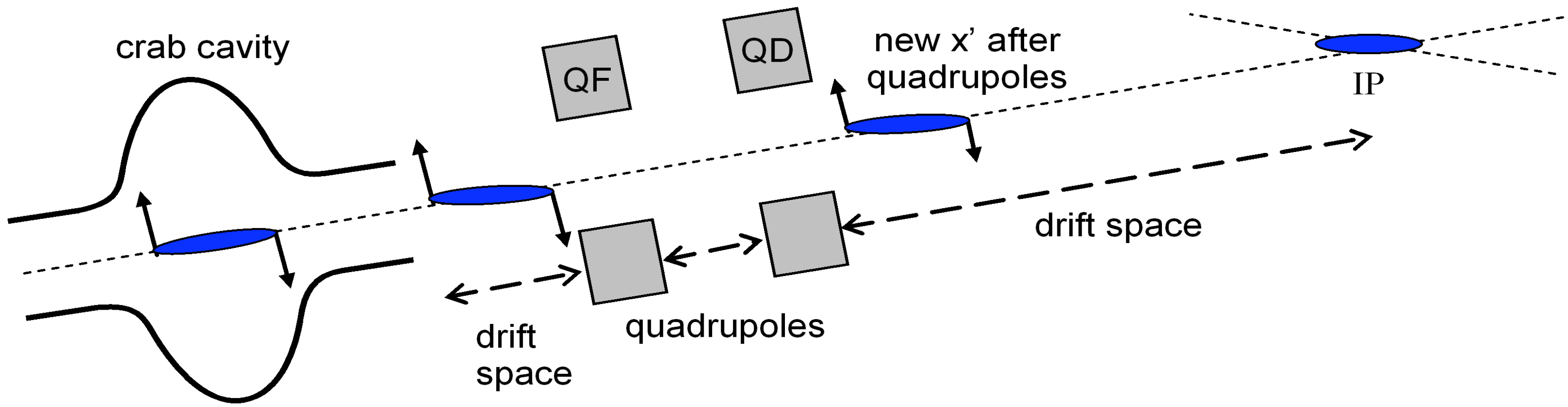
ILC Crab Cavity: RDR Completeness

Technical: ***EuroTev Report 2007-010***

Introduction / system requirements
Cavity shape and interaction w/ beam
LLRF and phase control
Cryovessel and cryogenics

Costing

Introduction



- Simple geometric effect at IP to improve luminosity by factor ~4
- But if kick at head of (short!) bunch is not exactly equal to kick at tail, net effect is to displace bunch transversely at IP
- Bunch dimensions at IP are $\mathcal{O}$[nm], effective throw arm is $\mathcal{O}$[m] $\Rightarrow$ uncorrelated phase jitter between e^+ and e^- arms must be very well controlled.

Introduction / Requirements

- MAD/Guinea Pig simulation sets phase & amplitude specs:

	timing(phase) tolerance limiting luminosity loss to < 2%	amplitude tolerance limiting luminosity loss to <2% (%)
RMS beam timing jitter	0.68ps = 0.95°	
RMS beam energy jitter		0.33
RMS cavity timing jitter (uncorrelated)	0.067ps = 0.094°	
RMS cavity timing jitter(anticorrelated)	0.047ps = 0.066°	
RMS cavity amplitude jitter		6.6

But you can get the same result with relatively simple geometric calculation

- Required deflection $V = cE\,\theta_C \,/\, (4\pi f R_{12})$ = 2.64MV in 1 TeV case, + control overhead

Introduction / Requirements

- Beam aperture must be ≥ 30mm diameter in horizontal plane, because of beam-associated γ's
- From short-range wake considerations, would not want to go much below 30mm in vertical direction
- If frequency is multiple of 1.3GHz, can operate at any beam operating parameters that could ever occur
- Return arm of other spent beam passes only ~18cm away ⇒ need ≥ 1.3GHz structure

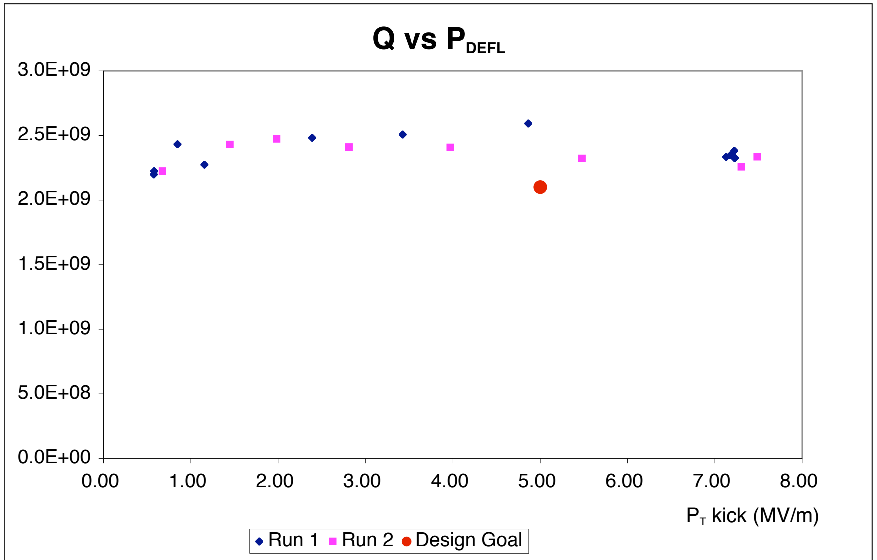
Introduction / Requirements

- Long fill times (1msec) and long intertrain spacing (200msec) strongly suggest SC technology to circumvent thermal cycling issues & their impact on phase control - $\mathcal{O}$ [≤10msec] "quasi-CW" running
- ERL efforts are developing very precise phase control systems that we can learn from
- SCRF requires less power ⇒ more cells/cavity and fewer klystrons ⇒ fewer elements in phase control system ⇒ reduces cost
- But Nb manufacturing limits you to $f \leq$ 3.9GHz

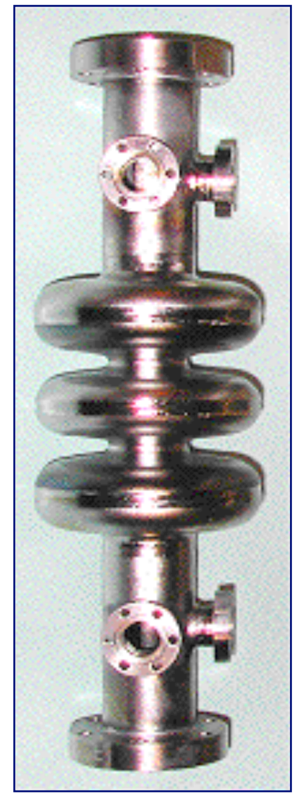
Introduction / Requirements

- Build upon work done for SCRF TM_{110} π mode cavity for K^+ separator at FNAL
- Pair of 9-cell versions per beamline meets all specs for 1 TeV case
- But damping couplers for non-operating modes are needed

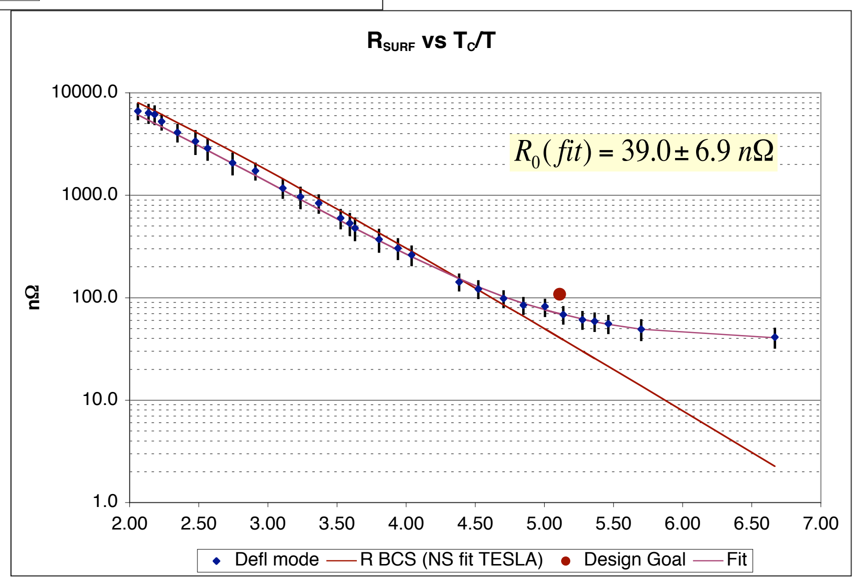
Introduction / Requirements



7.5 MV/m ⇔120mT B_{MAX}
A good & reasonable
result for BCP
processed cavities



R_0 = 39nΩ consistent
with literature, a
little higher than
3rd Harmonic results
in the same test stand



ILC Crab Cavity Collaboration

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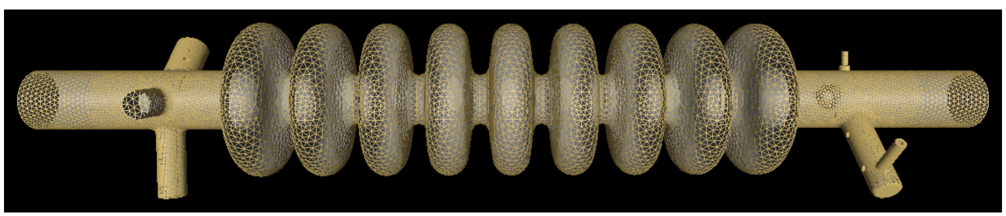
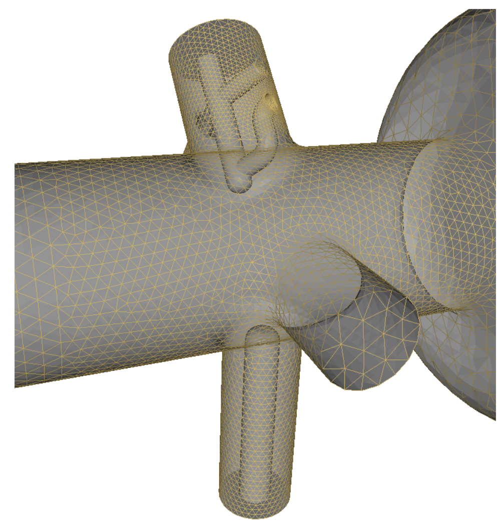
RDR Status: cavity & beam

- Cavity requirements and cavity-beam interactions seem to be well understood - this has been a major focus of our work to date. See e.g.
  - Wakefield analysis at EPAC06
  - FNAL Workshop May 2006
  - EuroTev 2007-003 - cell shape review
  - Large scale computing available via SciDAC



Caveat - we have not yet addressed manufacturing imperfections and want to study so-called "odd-even" effects as well



RDR Status: cavity & beam

- Damping of dipole modes is important to prevent unwanted beam deflections. TM_{010} mode has large coupling to beam, need to keep $Q_{\mathrm{EXT}} \sim 10^4$ so as to keep peak power through coupler at 1kW or less

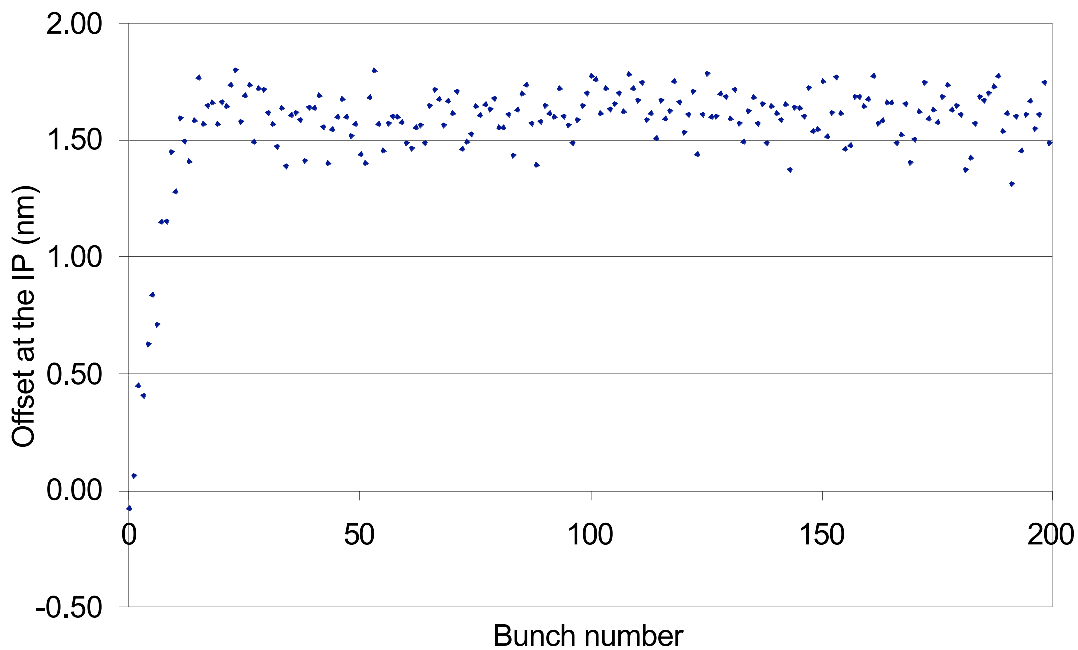
- Issues involve coupler manufacturability, peak surface current, tunability, power capacity; we can draw heavily on the 3rd Harmonic work at FNAL/DESY

- Higher, lower and same-order-other polarization coupler designs are going into Cu prototypes

- 3rd Harmonic power coupler with small modifications should suffice; has been tested up to ~50kW for 1.3msec pulses and we need ~3kW for $\mathcal{O}$ [≤10msec]

RDR Status: cavity & beam

- The damping spec for the dipole modes, is based on a worst case deflection including manufacturing tolerances. Correction for beam feedback has not yet been included in our calculations.
- ***Key spec is amount of transverse beam position jitter at the cavity***



RDR status: Low Level RF

- LLRF requirements are well understood and challenging but at state of the art

Simulation with MAD8.23 and Guinea Pig (M.Church) says 67fsec uncorrelated per station

Simple geometric argument gives the same result

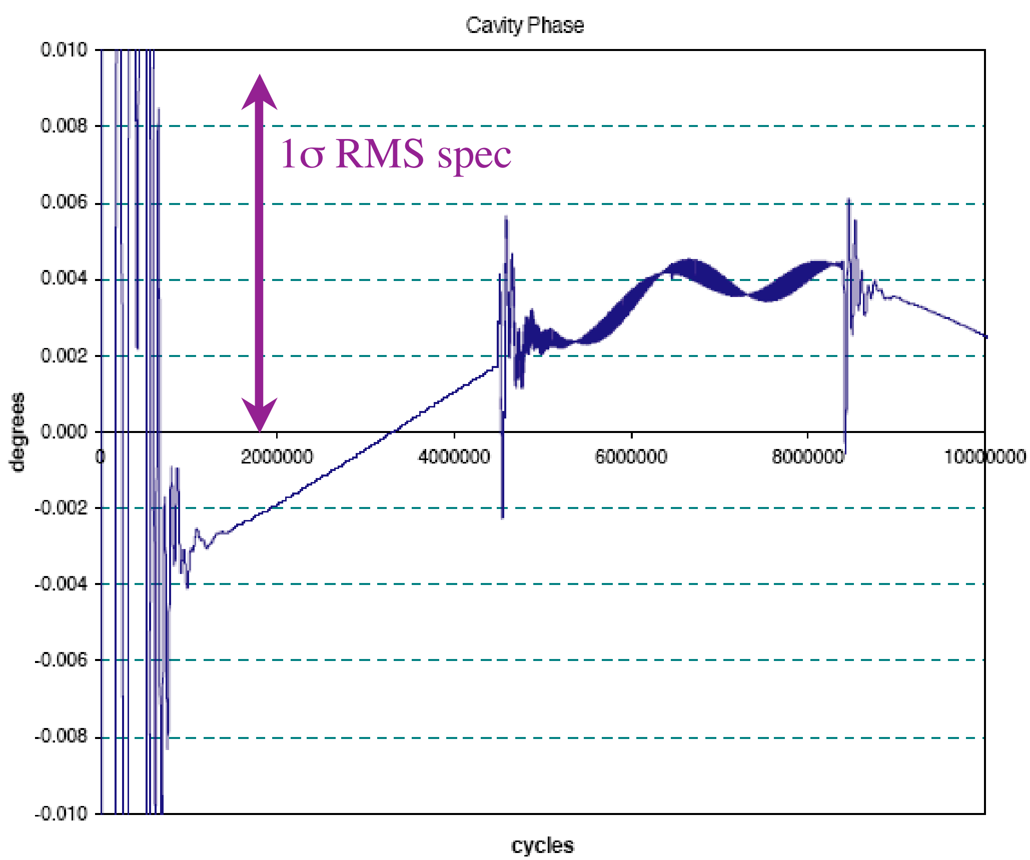
The MC also sets beam energy jitter spec at 0.33% RMS and cavity deflecting amplitude jitter spec at 6.6% RMS - we do not see these as problems.

Timing of beam relative to the cavity 1 order of magnitude easier - 680fsec - as this only causes the bunches to collide at different place in *z*.

Liepe et. al. achieved 0.02 degrees @1.5GHz, 37fs in CW operation at Q of 4×10^7
4GLS spec is 0.01 degrees @ 1.3GHz, 21fs

RDR status: Low Level RF

- LLRF simulation validates Q_{EXT} / P_{IN} / microphonics / beam loading / phase stability feasibility with PI algorithm



Q_{EXT} 3×10^6

Beam offset ±1mm oscillating at 2kHz

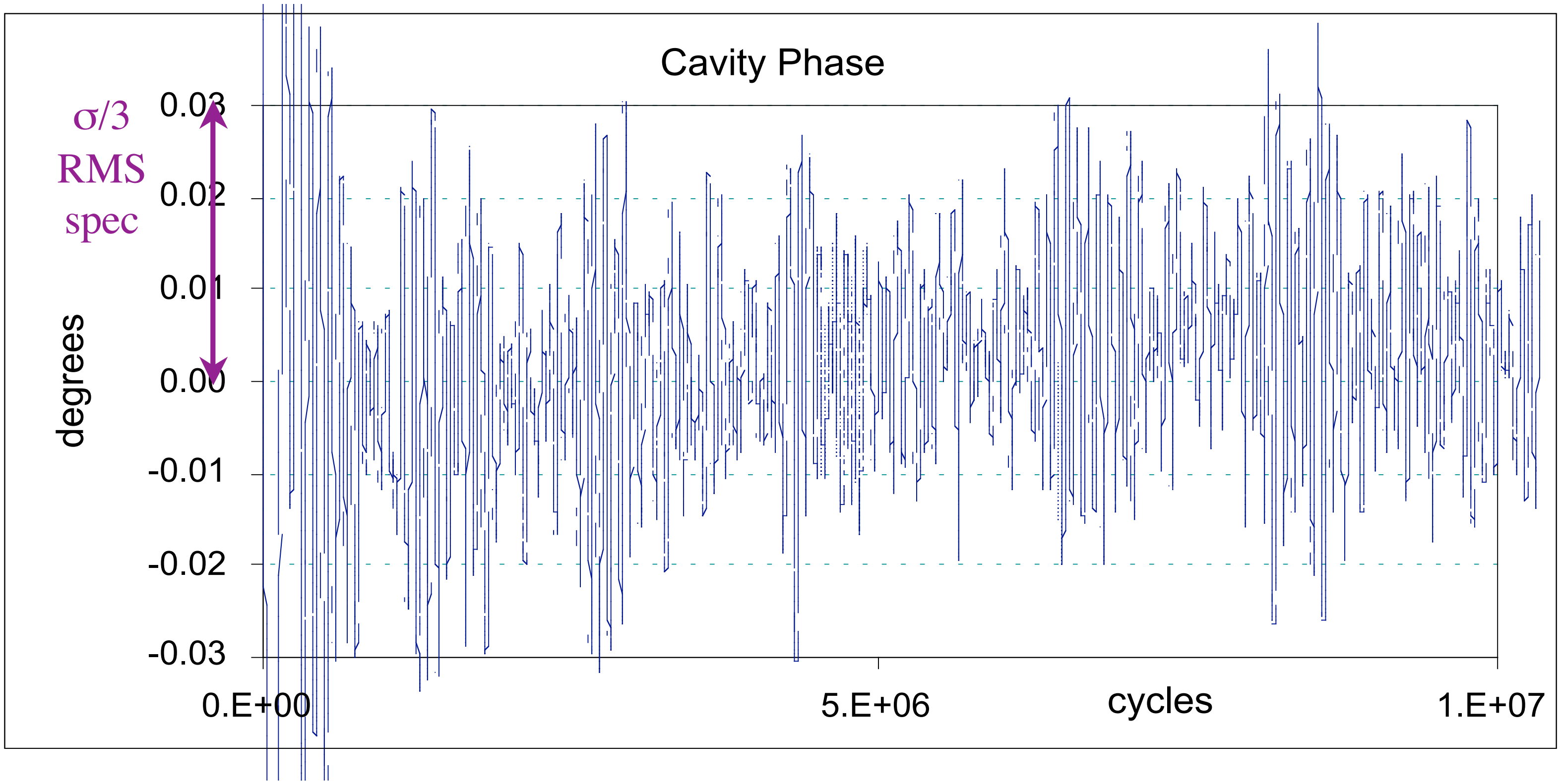
Microphonic FM modulation ±600Hz at 230Hz resonance

Bunch arrival time scatter 3° @1.3GHz

But no phase measurement errors or interferometer simulation yet

RDR status: Low Level RF

- After including phase measurement errors of ±0.015 degrees

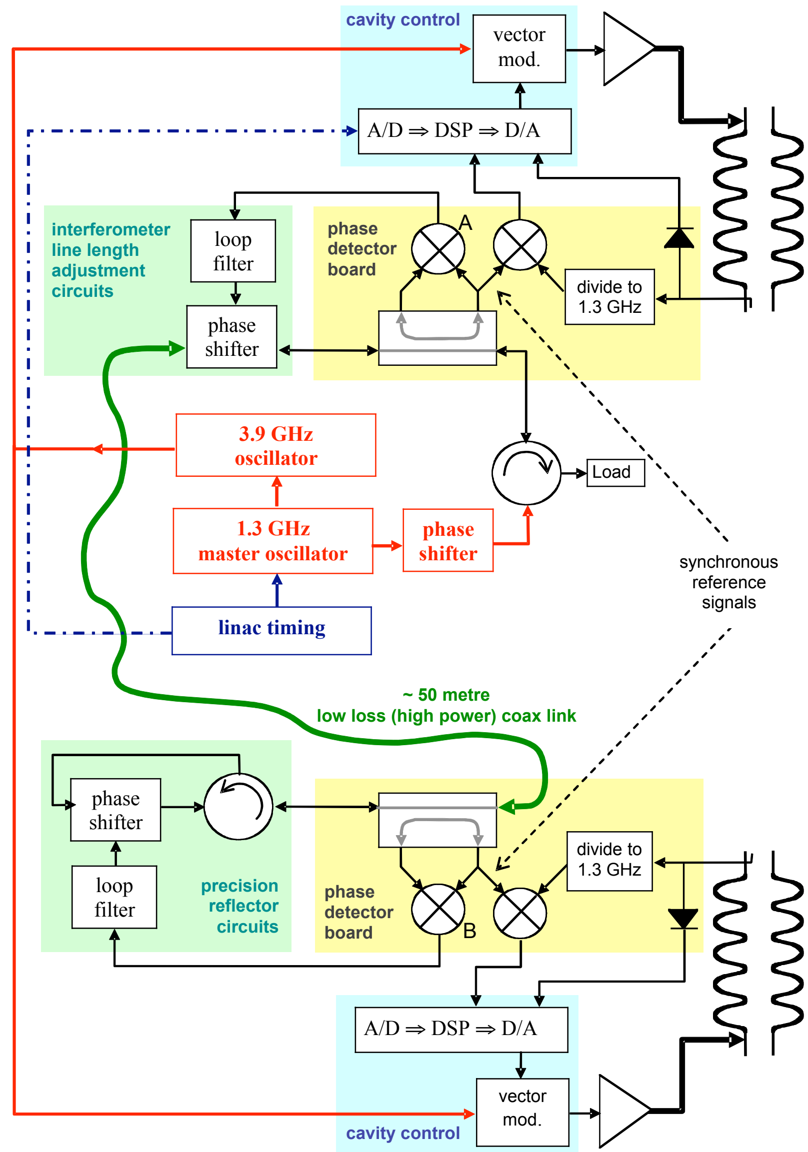


For a system latency of 1 μs, measurement errors dominate phase performance.

RDR status: Low Level RF

- Low Level RF control system is a digital FPGA based control system.
- e^+ to e^- synchronisation tighter than timing specification for main linac ⇒ synchronise one crab to one linac and then synchronise the second crab to the first with an interferometer.
- 1.3 GHz RF interferometer is planned, sparing us the task of converting RF to laser frequencies; but a fiber optic interferometer might have fewer reflection problems.
- 1° C over ~50m interferometer is ~170fs presumably at very low frequency
- A-priori error budget: 3 equal & correlated terms for 2 stations + interfereometer

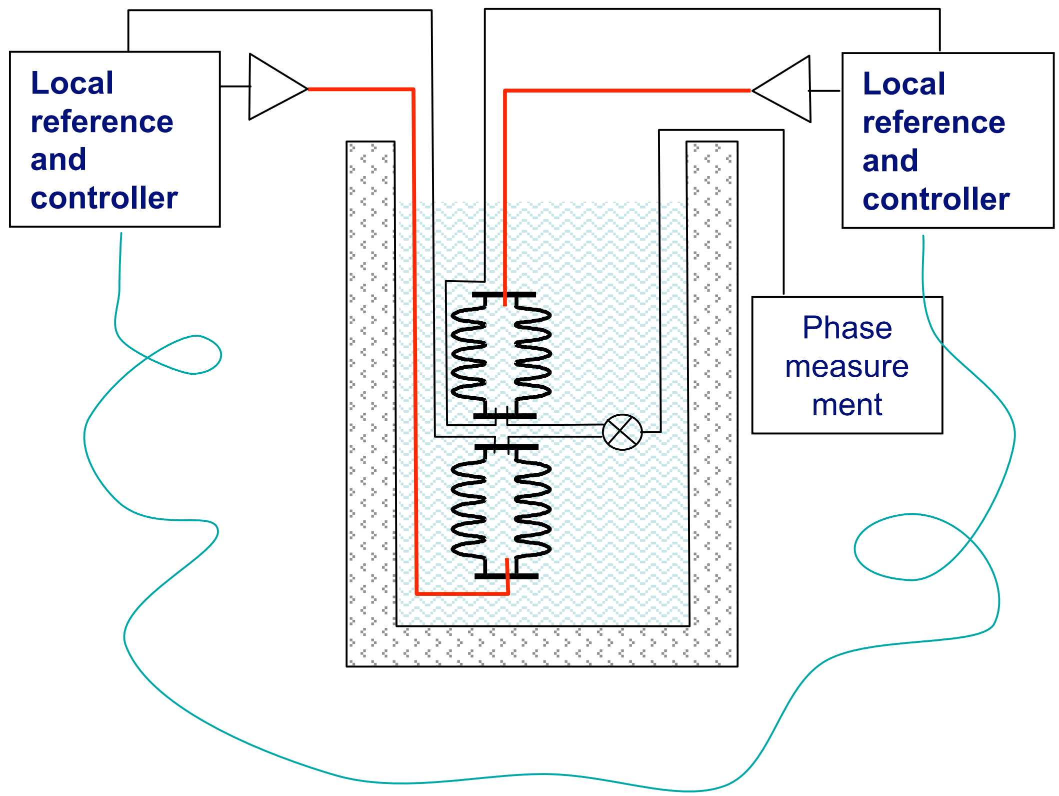
(newer version, P.MacIntosh's talk)



RDR status: Low Level RF

• Now working to test first-pass prototype of LLRF system with 2 cavities in a single vertical Dewar at low power

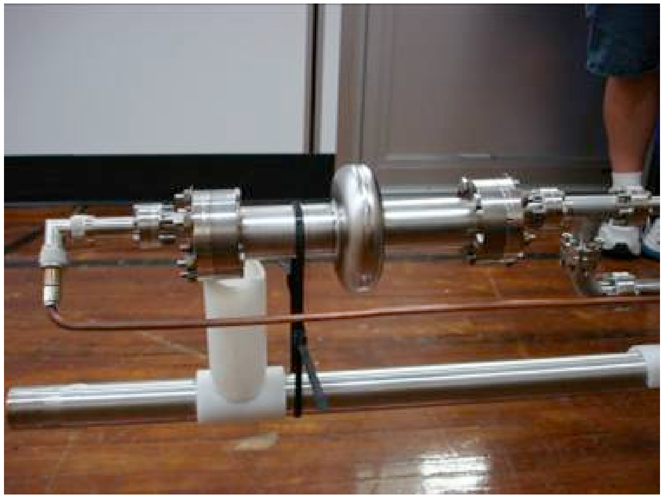
• Have cryostat, top plate, the 3.9GHz drive amps and the radiation enclosure. Work is ongoing to develop the cryo system and controls.

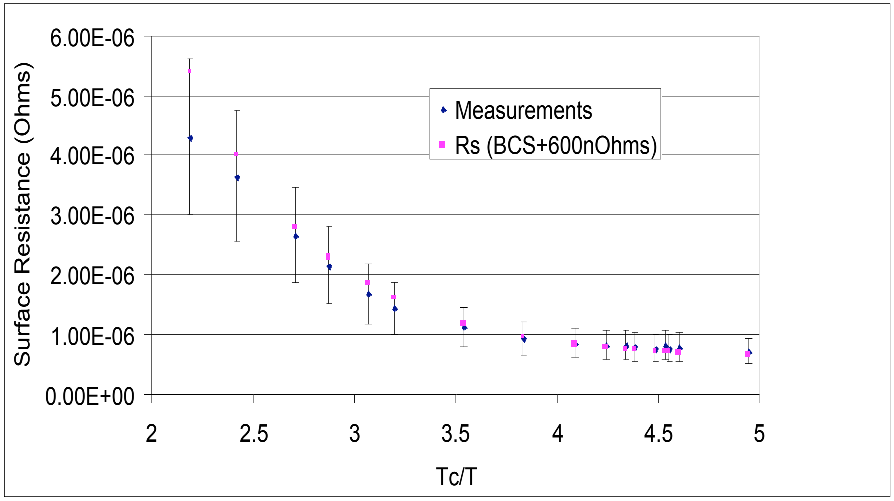


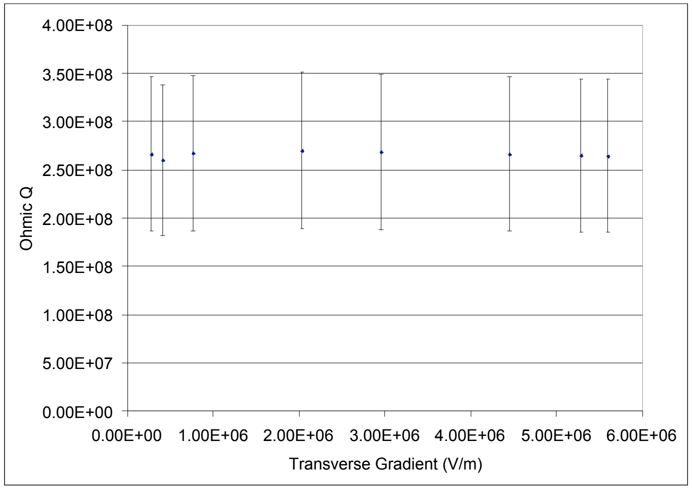
RDR status: Low Level RF

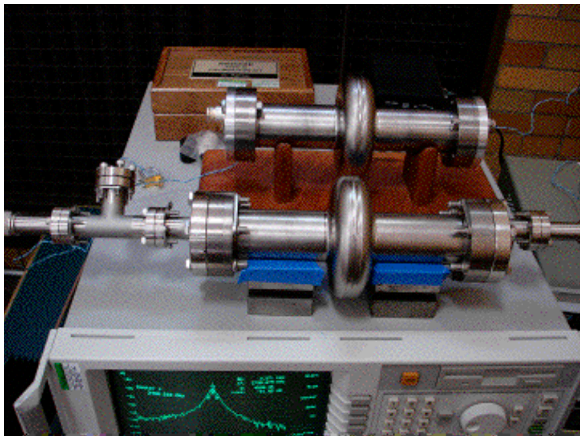
- 3 single-cell SCRF cavities were constructed, BCP'd and HP rinsed at Niowave
- Cold test results showed high surface resistance, perhaps in SS flanges. Quite OK for phase control tests.
- The cavities achieved required gradient without quench

RDR status: Low Level RF









RDR status: Low Level RF

- Double balanced mixers alongside digital phase detectors. The digital phase detectors give us 360º of calibration and the mixers give ultimately best resolution. Digital control allows the system to choose the best measurement at any instant.

- 16 bit accuracy improves the measurement range whilst still allowing us to resolve a couple of milli-degrees. To get the initial lock we will need a range of 360º hence the phase information must have two levels of amplification: fine which resolves 2 milli-degrees and coarse which resolves 45 milli-degrees.

- 3.9 GHz signal is downconverted to 1.3 GHz to allow the use of the Main Linac Timing. Down conversion to 1.3 GHz is necessary if we are to use currently commercially available digital phase detectors. The cable will be specified to 3.9 GHz so we can also run the interferometer at 3.9 GHz.

RDR Status: Cryovessel etc.

- Cryovessel requirements are challenging: roll alignment to $\leq$1mrad, transverse alignment to ~15μm, nearby return line for spent other beam, 50 gauss (!) stray field

- Cold tuner developed for FNAL/DESY 3rd Harmonic effort should suffice, along with similar LHe vessel; is probably a better choice than the CKM design (shown in EuroTeV 2007-010) because there will be more operating experience and better documentation

- Cryogenic load probably not large:
  - Dynamic load is ~4.5W x (duty factor) @ 1.8K
  - Static load of CKM cryovessel was 3.5 ±0.5 W
  - Additional load of alignment devices not known but for scale, 8 rods made of G10 with 1cm^2 cross-section and 20cm length add ~1/2 W @ 1.8K
  - Need also operating overhead
  - For now, saying 20W per 2-cavity vessel @ 1.8K, with 4.5K shield

RDR Status: Cryovessel etc

- Vacuum:
  - FNAL operates a 1.3GHz SCRF cavity at a few nTorr
  - Beam-gas interactions seem to suggest 1 nTorr requirement within 200m of the IP (Keller, Maruyama, Markiewicz, ILC-Note-2007-016
  - We allowed for additional joints off to ion pumps in our initial length estimate

- Other considerations:
  - Low vibration area will help the microphonics issue
  - Klystron close to cavity reduces control system latency - "survey gallery"

Cryovessel, magnetic shielding, vacuum design etc. have not been advanced very much to date due to resource limits and we do not yet have a solution for this situation

RDR Status: Costing

- Technical rather than cost minimization issues have been the primary focus to date
- Cryogen plant costs for crab cavities were listed in cryo-plant costs rather than crab cavity costs.
- LLRF for crab cavities were listed in LLRF costs rather than crab cavity costs

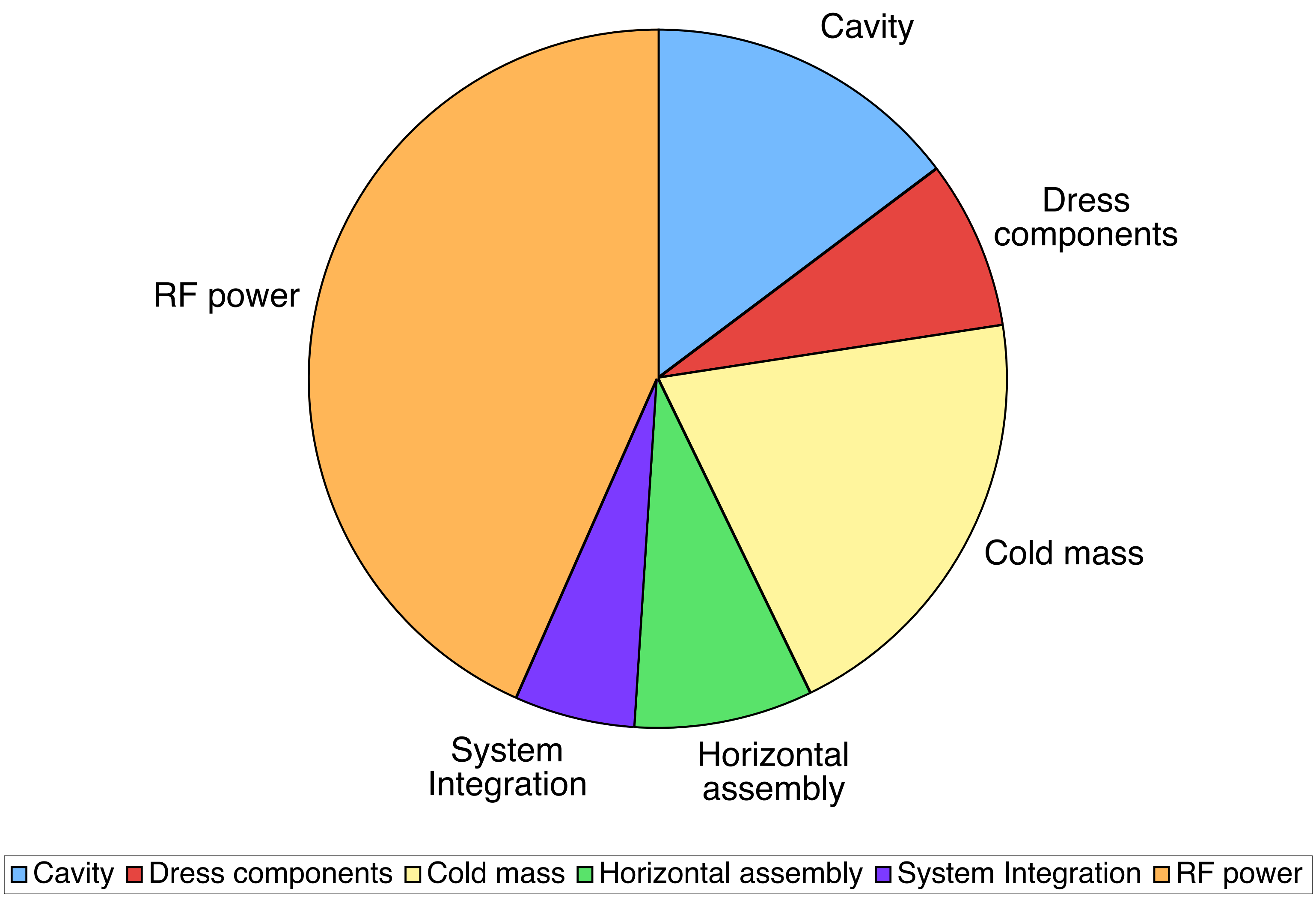
RDR Status: Costing

- Cavity and coldmass M&S estimates based heavily on the very similar-scale 3rd Harmonic project. Subsequent developments: (1) Coupler design harder than anticipated (R&D cost, not a build-time cost) (2) More oversight than was originally anticipated was required with certain vendors *ahem*

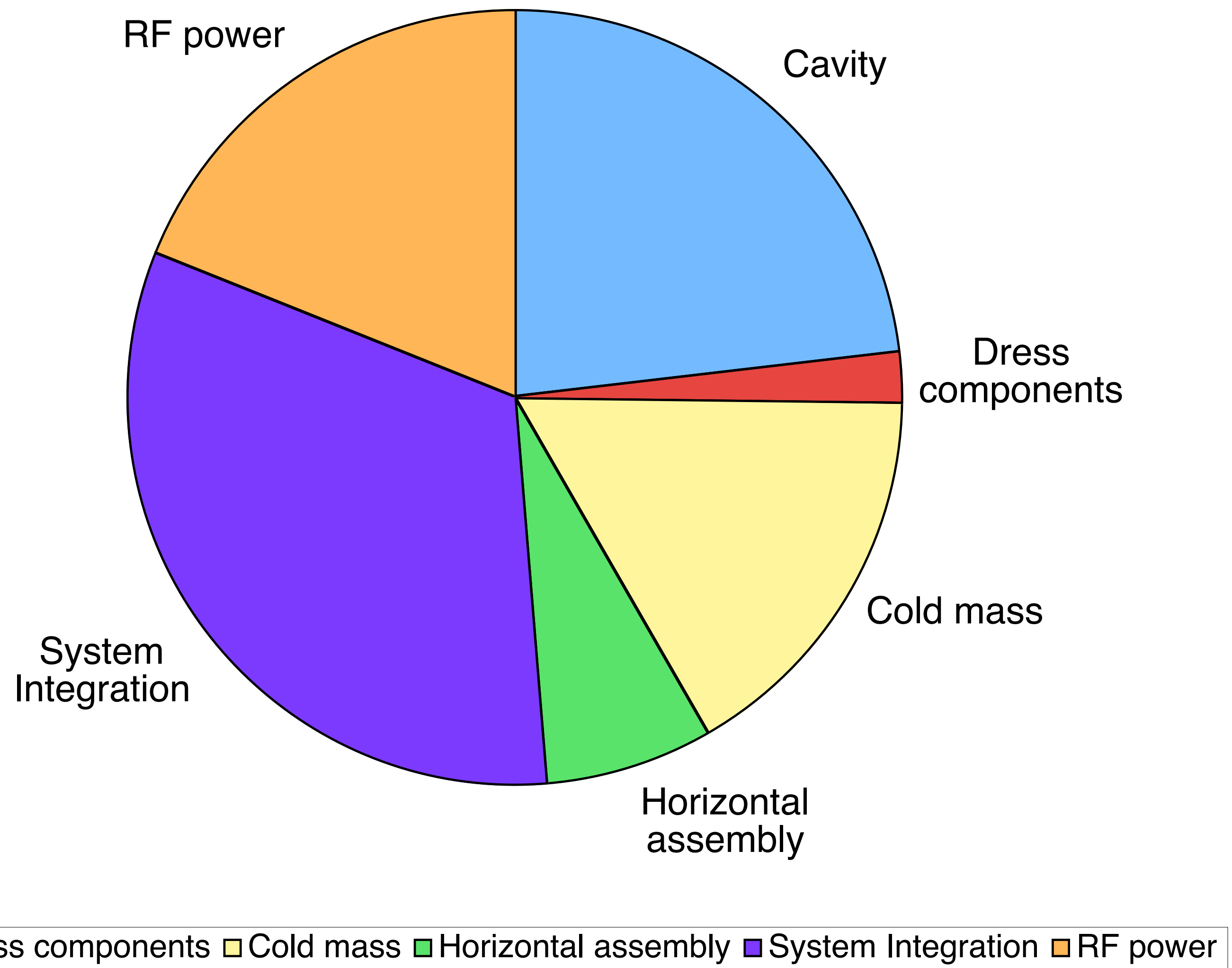
- HLRF cost based on existing commercial klystrons and assumption that we will need to design & build our own modulators. Solid-state class-C amps may well exist by the time we go to build.

- Cost in RDR estimate for 3 cryovessels, each with 2 cavities (100% redundancy for 500GeV); one cryovessel with klystron etc. is a cold spare.

RDR Status: Costing



RDR Status: Costing



Conclusion

Although the crab cavity subsystem has a challenging set of specifications to meet, there is an extensively studied cavity design based on existing prototypes and there is an active program for RF field control at a state-of-the-art level.