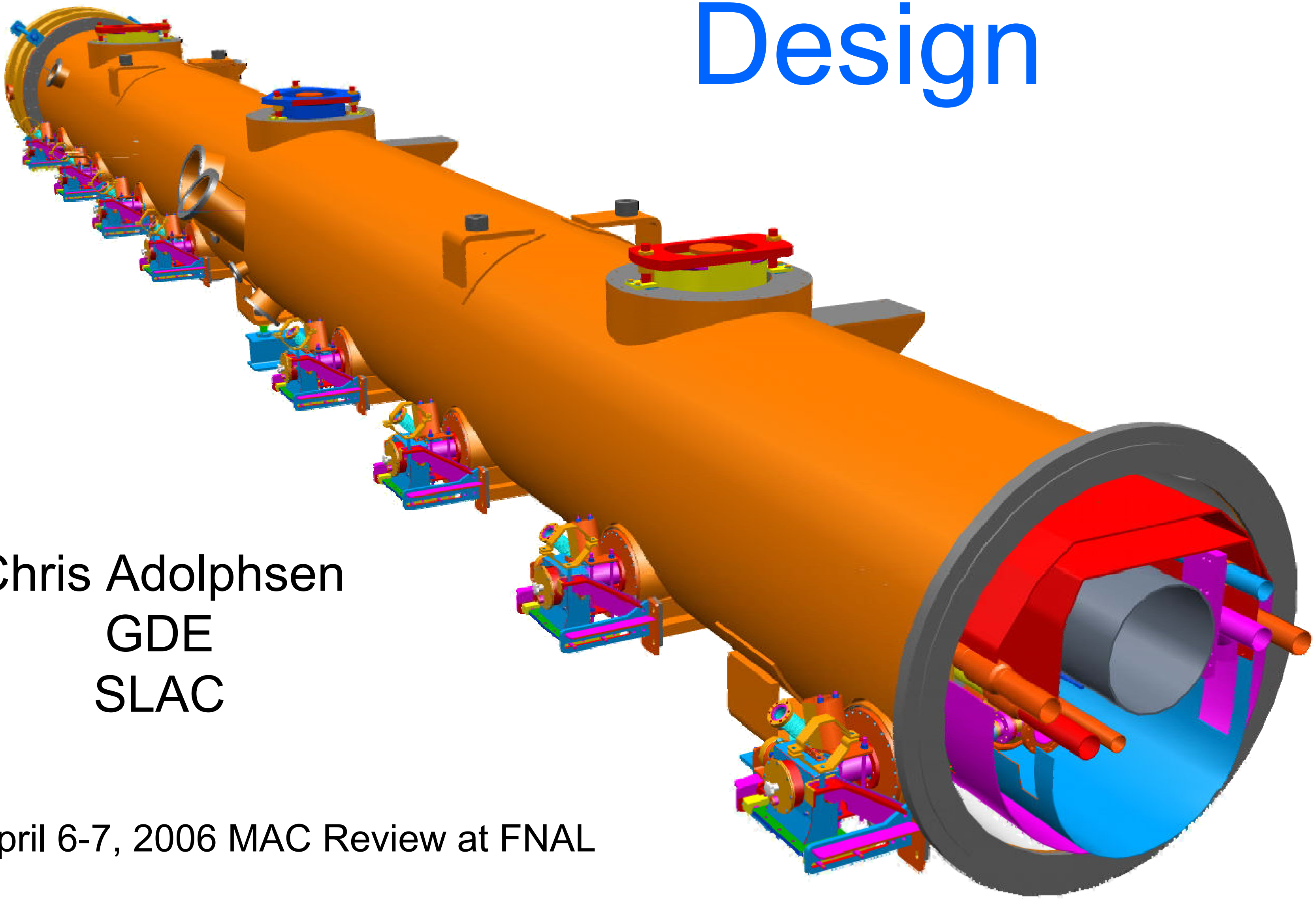
Main Linac Design



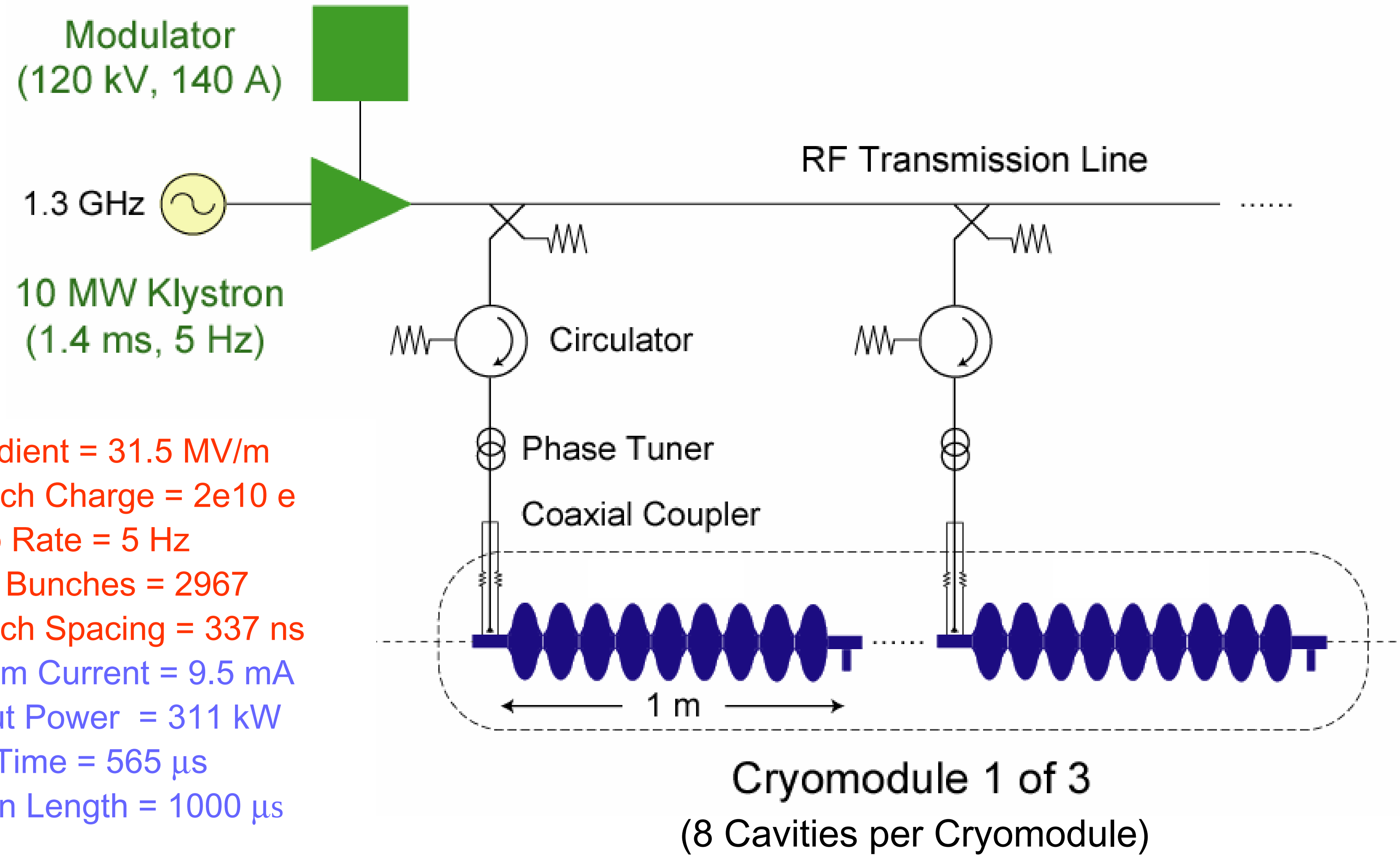
Chris Adolphsen
GDE
SLAC

April 6-7, 2006 MAC Review at FNAL

Main Linac Design

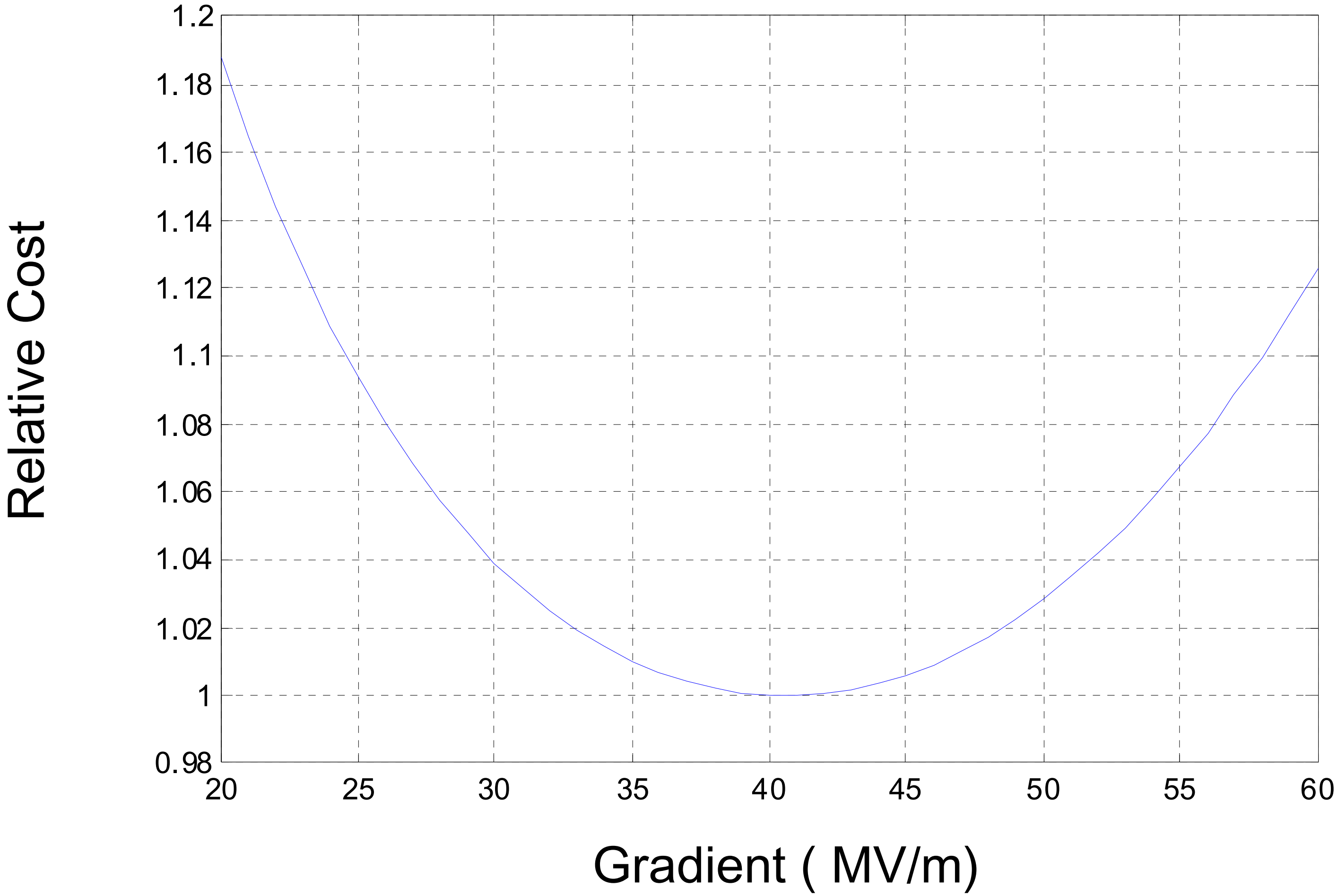
- BCD distilled from Snowmass Working Group recommendations.
  - WG5 for the cavity package and cryomodule
  - WG2 for the rf system and cryomodule
- Major differences from 2001 Tesla TDR 500 GeV Design.
  - Higher gradient (31.5 MV/m instead of 23.4 MV/m) for cost savings.
  - Two tunnels (service and beam) instead of one for improved availability.
- GDE Linac Area Group is continuing to evolve design.

ILC Linac RF Unit (1 of ~ 600)



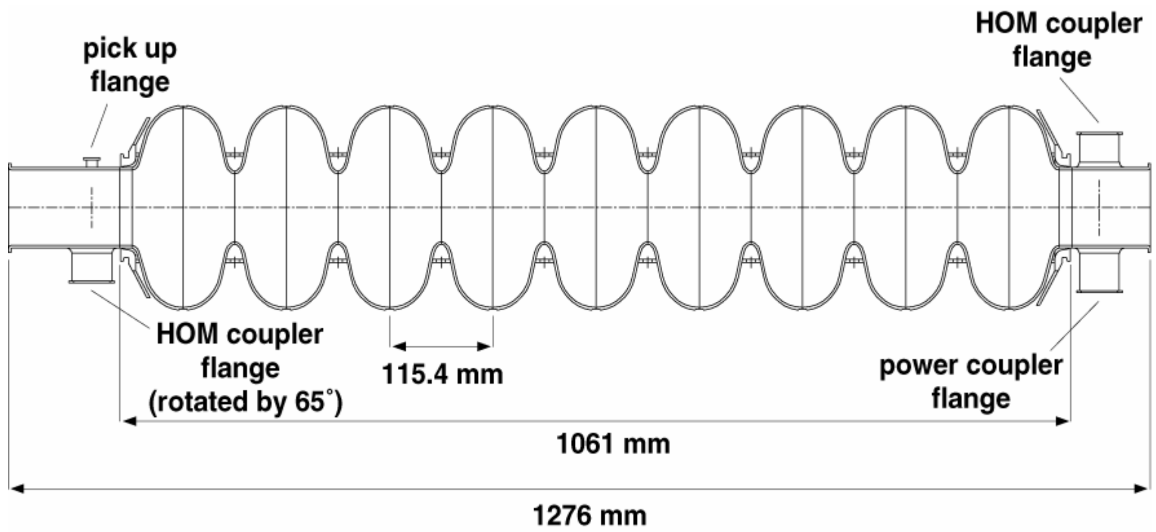
Gradient = 31.5 MV/m
Bunch Charge = 2e10 e
Rep Rate = 5 Hz
# of Bunches = 2967
Bunch Spacing = 337 ns
Beam Current = 9.5 mA
Input Power = 311 kW
Fill Time = 565 μs
Train Length = 1000 μs

Relative Total Project Cost* (TPC)
-vs-
Linac Gradient



* TPC is for 500 GeV machine in US Options Study.

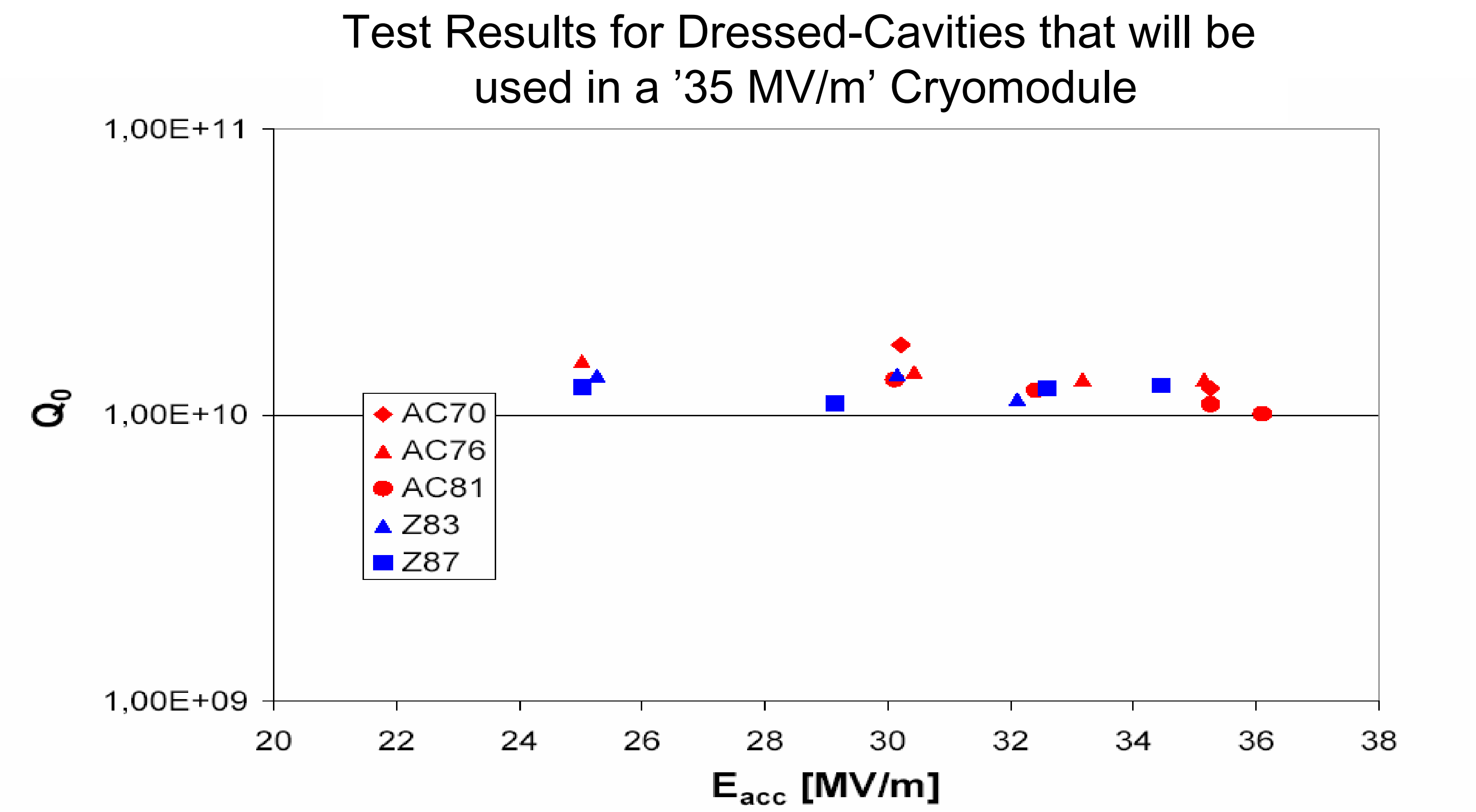
1.3 GHz TESLA Cavities



- For ILC, would accept only ‘vertically’ tested cavities (using CW rf without high power couplers) that achieve gradients > 35 MV/m and Q > 8e9 (discard or reprocess rejects).
- When installed in 8 cavity cryomodules, expect stable operation at an average gradient of 31.5 MV/m and Q = 1e10 (rf system designed for 35 MV/m).
- Derating due to desire for overhead from quench limit, lower installed performance and limitations from using a common rf source.
- For a 1 TeV upgrade, expect average gradient = 36 MV/m, Q = 1e10 for new cavities (the TDR 800 GeV design assumed 35 MV/m and Q > 5e9).

Achieved Gradients in Single and 9-Cell Cavities

- In recent years, single-cell cavity gradients approached fundamental limit: Bc * (Grad / B surface) ~ 1800/41.5 ~ 43 MV/m for Tesla-shape cavities.
- During past 2.5 years, DESY has produced 6 fully-dressed cavities with Gradients > 35 MV/m and Q > 8e9. Yield for such cavities < 30%.

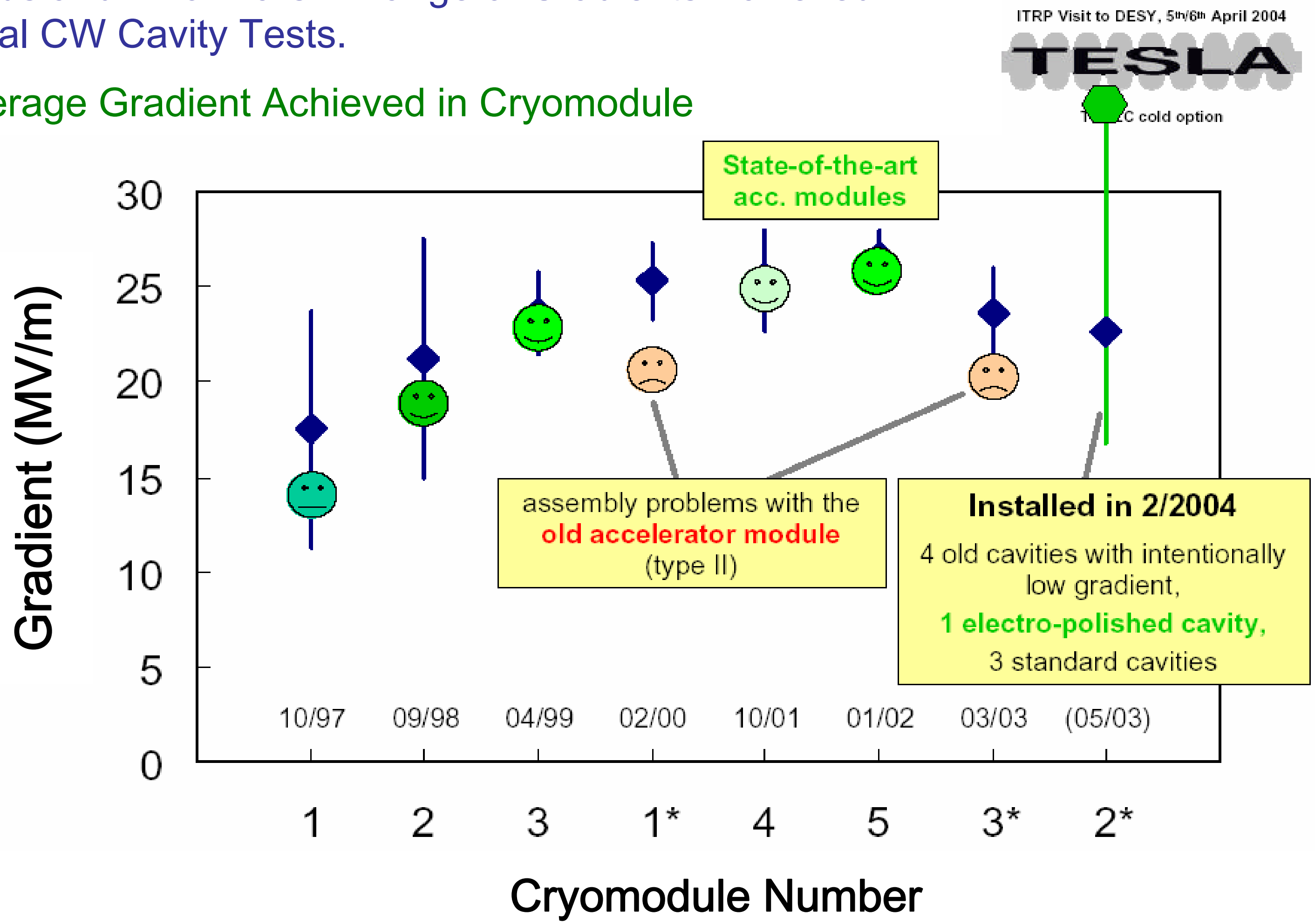


Achieved Gradients in Tesla Test Facility (TTF) 8-Cavity Cryomodules

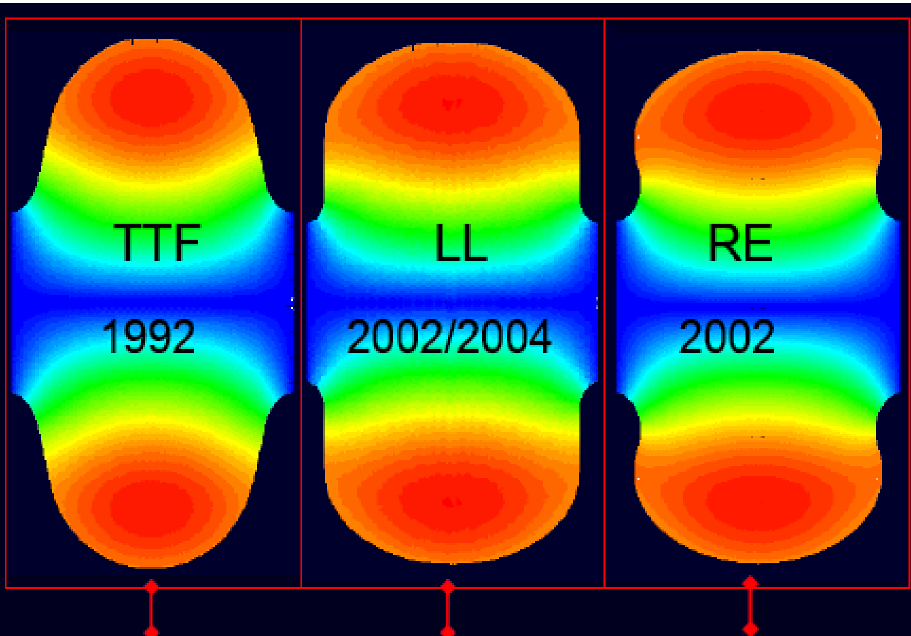
(Cavities not Electro-Polished)

Diamonds and Error Bars = Range of Gradients Achieved in Individual CW Cavity Tests.

☺ = Average Gradient Achieved in Cryomodule

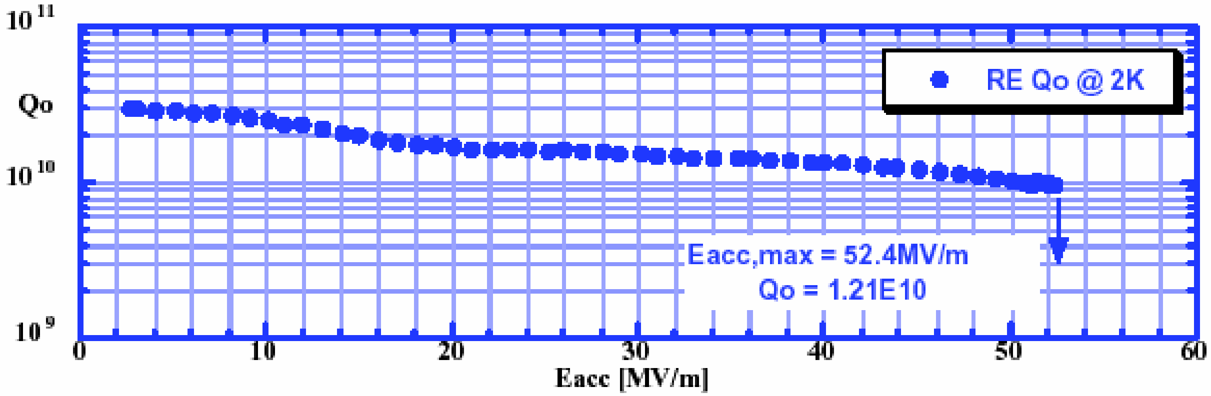


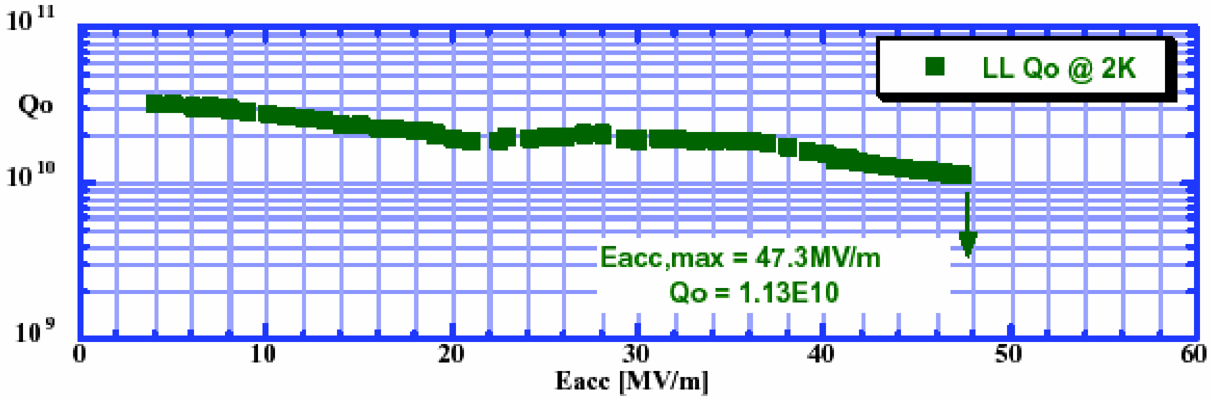
High Gradient R&D: Low Loss (LL) and Re-Entrant (RE) Cells with a Lower Bpeak/Eacc Ratio

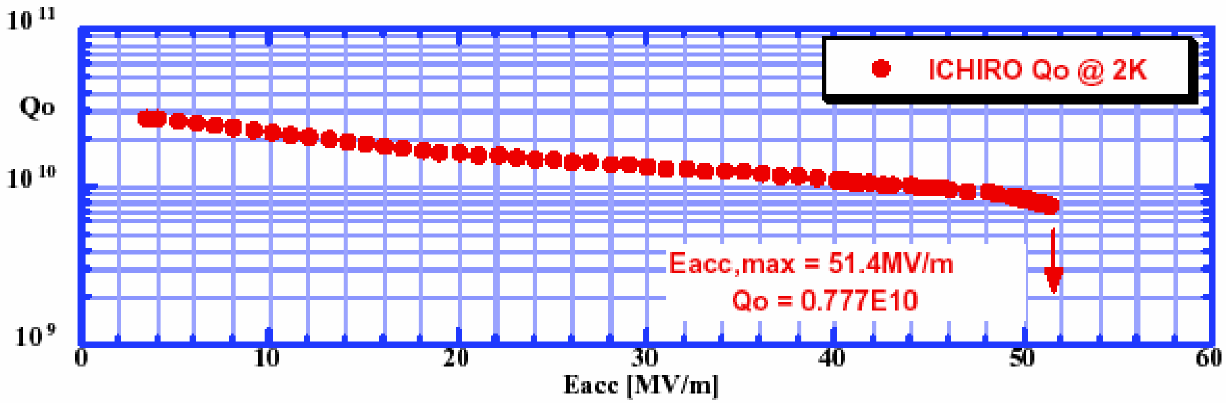


		TTF	LL	RE	
r_{irisb}	[mm]	35	30	33	
k_{cc}	[%]	1.9	1.52	1.8	field flatness
E_{peak}/E_{acc}	-	1.98	2.36	2.21	max gradient (E limit)
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.61	3.76	max gradient (B limit)
R/Q	[Ω]	113.8	133.7	126.8	stored energy
G	[Ω]	271	284	277	dissipation
R/Q*G	[Ω*Ω]	30840	37970	35123	dissipation (Cryo limit)

Single Cell Results: Eacc = 47 - 52 MV/m





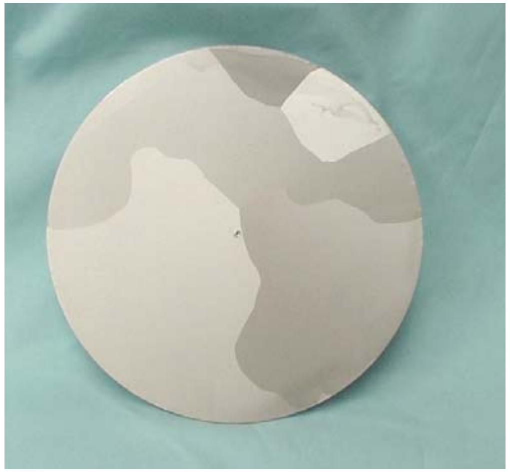


Re-entrant

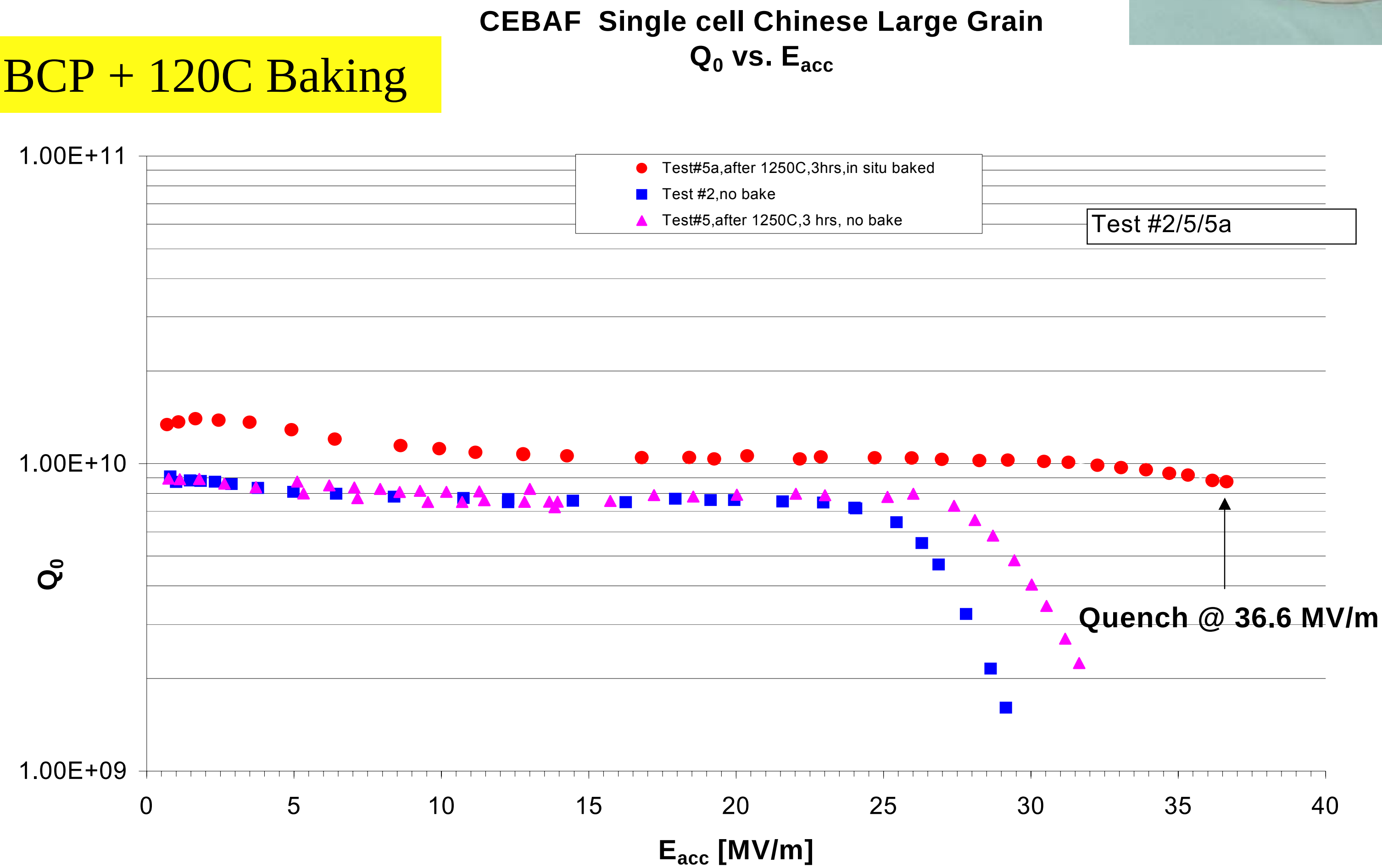
Fabricated
at Cornell

Low-Loss /Ichiro

Studies also underway using single or large grain Nb – could eliminate need for Electro-Polishing (EP)

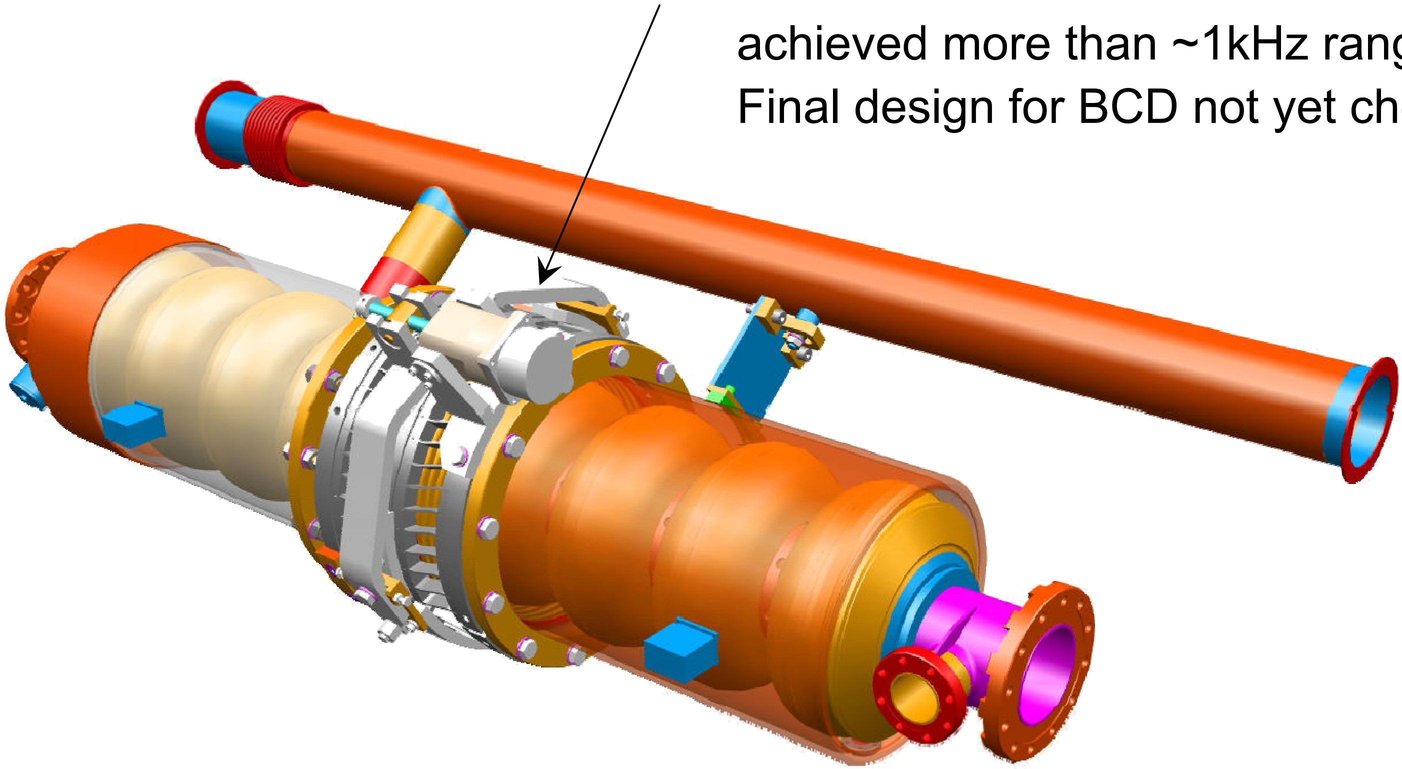


BCP + 120C Baking



Tuning the Cavities

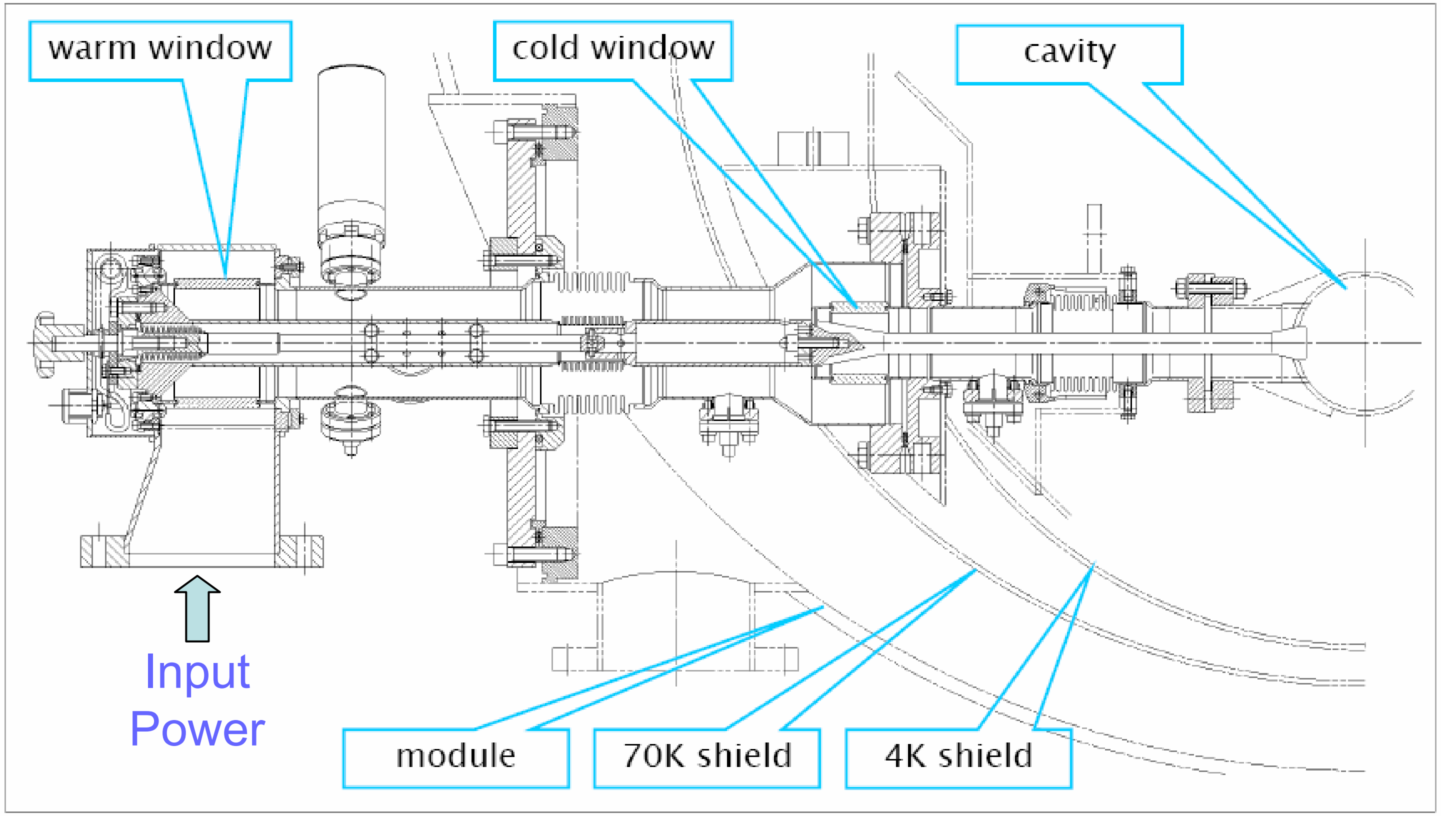
- Both slow (500 kHz over minutes) and fast (2.5 kHz during the 1.6 ms pulse) tuning required – achieve by compressing the cavity (~ 1 micron per 300 Hz).
- Want tuners located away from cavity ends to minimize cavity spacing.
- ‘Blade Tuner’ shown below. To date, have not achieved more than ~1kHz range of fast tuning. Final design for BCD not yet chosen.



Powering the Cavities

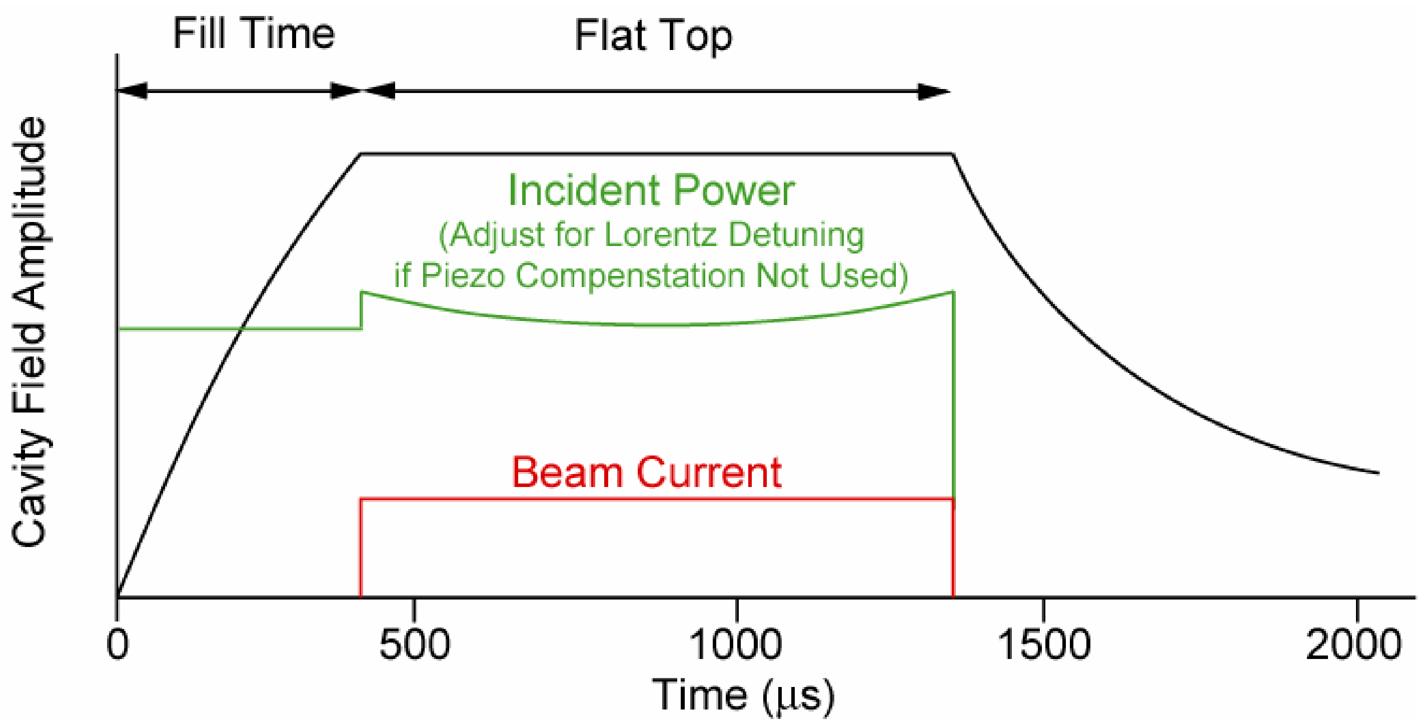
- Power coupler design complicated by need for tunablity (Qext), windows and bellows.
- Baseline TTF3 design processed to 1 MW and tested up to 600 kW for 35 MV/m operation (1000 hours): long term reliability for required operation at 350 kW not known.

Coaxial Power Coupler



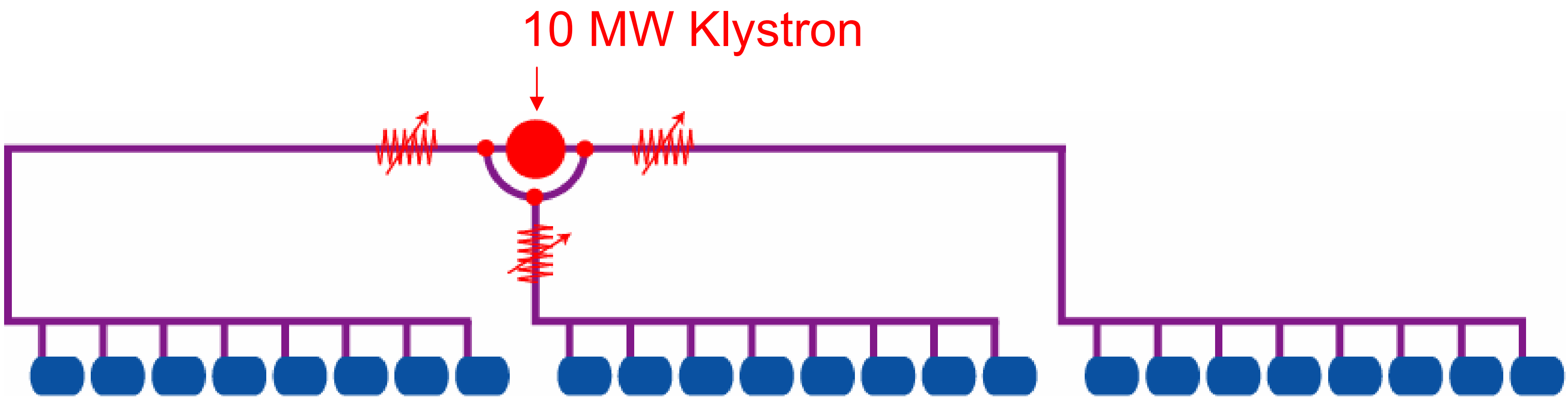
RF Fill Dynamics

- Adjust Qext to match cavity impedance (R/Qo * Qext) to the beam impedance (Gradient / Current) so zero reflected power during fill.
- For ILC, Qext = 4e6 so cavity BW = 325 Hz (ΔL = 1 micron).
- Need to achieve < 0.1% energy gain uniformity with LLRF system
  - Feedback to maintain constant 'sum of fields' in 24 cavities



RF Distribution Math

(for 35 MV/m Max Operation)



35 MV/m * 9.5 mA * 1.038 m = 345 kW (Cavity Input Power)

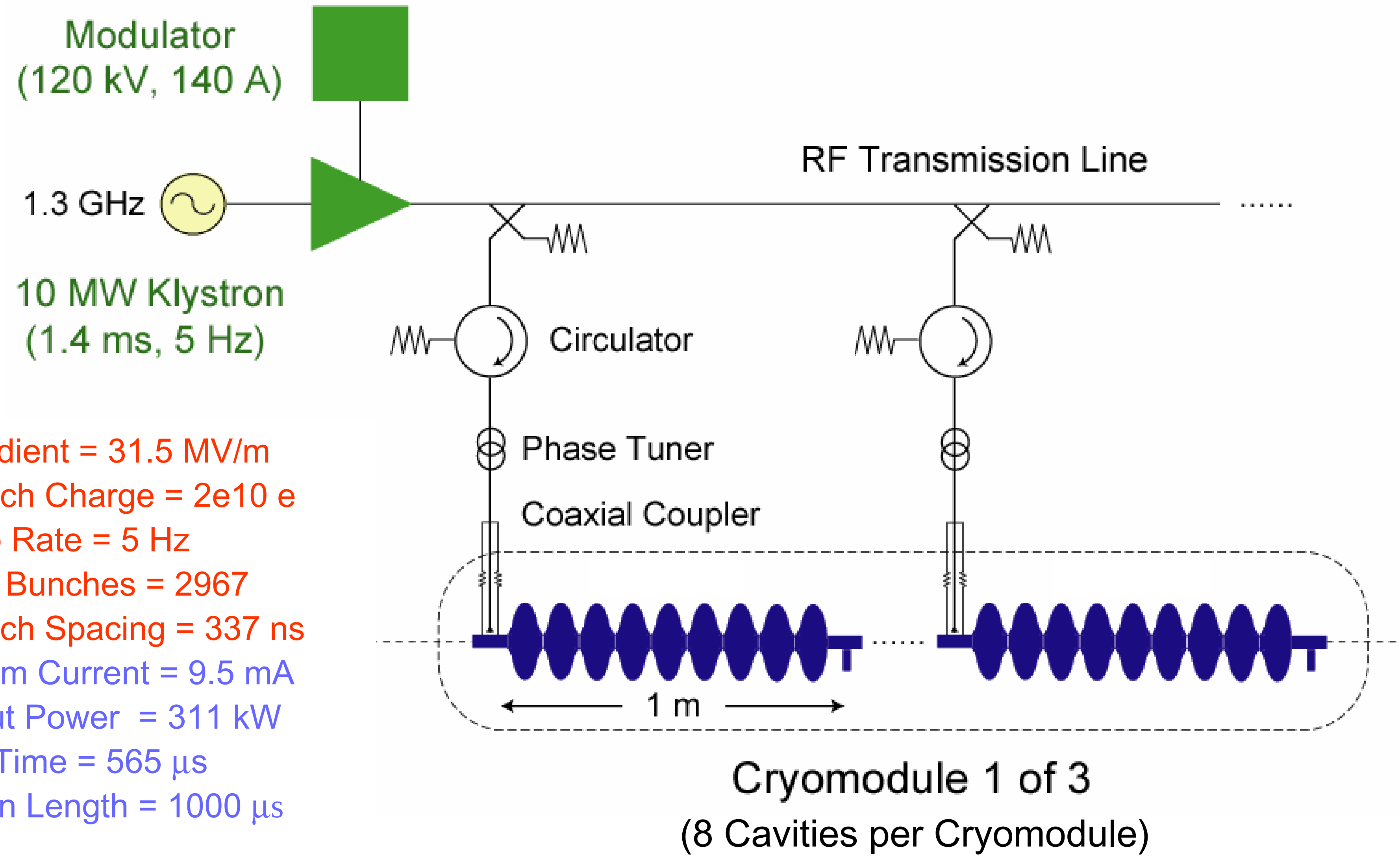
× 24 Cavities

× 1/.93 (Distribution Losses)

× 1/.89 (Tuning Overhead)

= 10.0 MW

ILC Linac RF Unit (1 of ~ 600)



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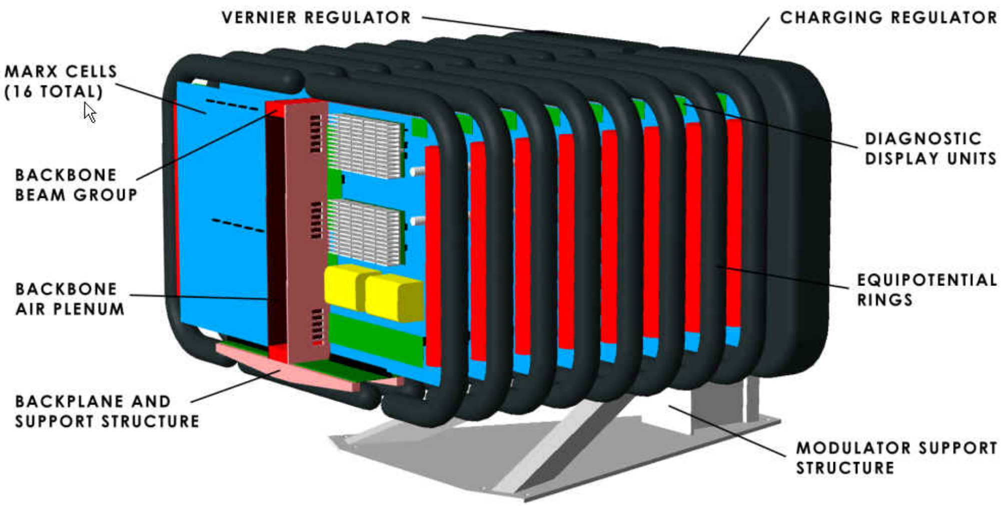
Rep Rate = 5 Hz
# of Bunches = 2967
Bunch Spacing = 337 ns
Beam Current = 9.5 mA
Input Power = 311 kW
Fill Time = 565 μs
Train Length = 1000 μs

Modulators

- Baseline: Pulse Transformer
  - 10 units have been built over 10 years, 3 by FNAL and 7 by industry.
  - 8 modulators in operation – no major reliability problems (DESY continuing to work with industry on improvements).
  - FNAL working on a more cost efficient and compact design, SLAC building new dual IGBT switch.
- Alternative: Marx Generator
  - Solid state, 1/n redundant modular design for inherent high availability, reliability.
  - Highly repetitive IGBT modules (90,000) cheap to manufacture.
  - Eliminating transformer saves size, weight and cost, improves energy efficiency.

Modulators (115 kV, 135 A, 1.5 ms, 5 Hz)

Pulse Transformer Style

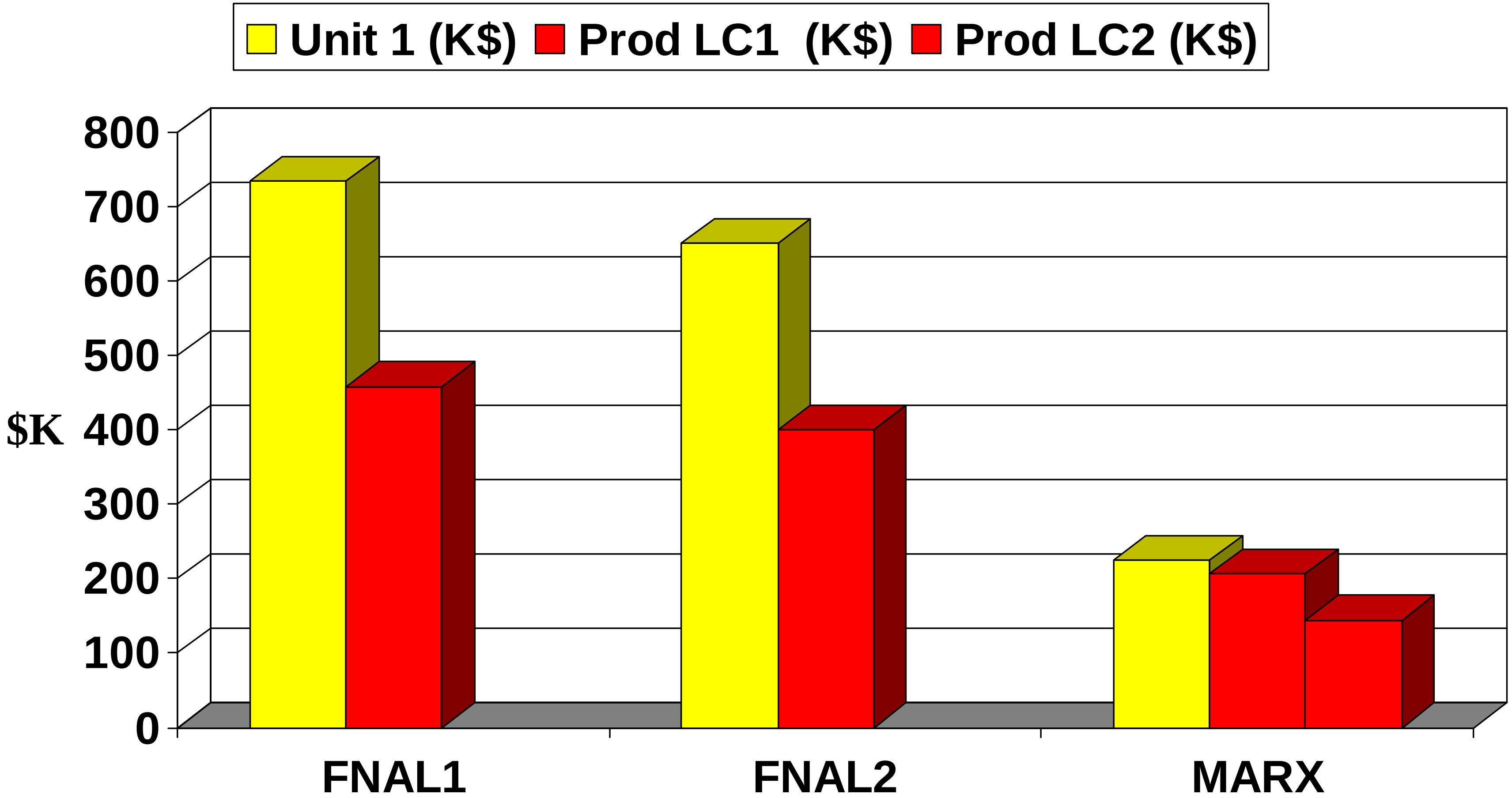


(~ 2 m Long)

To generate pulse, an array of capacitors is slowly charged in parallel and then discharged in series using IGBT switches.

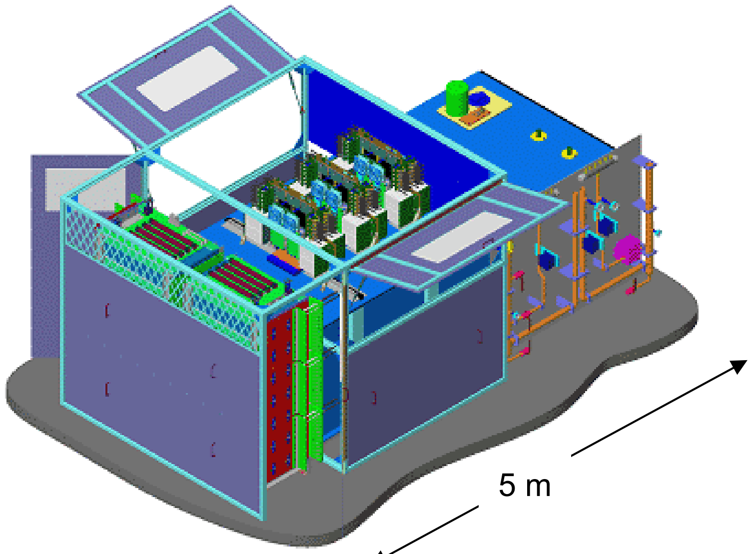
Will test full prototype in 2006

Modulator Unit 1 vs. 600 Unit Avg. Production Cost Estimates

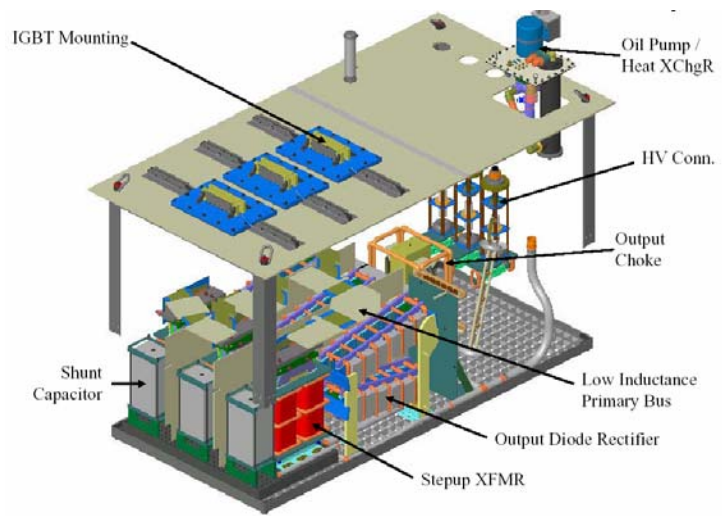


Other Modulator R&D

- Three Marx SBIR Phase I proposals awarded in US.
- DTI Direct Switch due at end of 2006 for evaluation at SLAC.
- SNS High Voltage Converter Modulator being operated, optimized, evaluated at SLAC L-Band Test Facility.



SNS High voltage power conditioning converter/modulator assembly



Low Level RF

Proposal for Baseline Design

- LLRF systems for VUV-FEL and X-FEL should serve as baseline for LLRF for ILC. Same architecture is used as SNS, J-PARC, Cornell and others with smaller number of channels.

- Performance (Luminosity !) of ILC is strongly coupled to performance (field stab. and availability) of LLRF
  - Need high degree of automation
  - Beam based feedbacks
  - Build-in diagnostics
  - Extensive exception handling

  } Most of the work just started

- Requires assembly of several strong teams from regions

Klystrons

Baseline: 10 MW Multi-Beam Klystrons (MBKs) developed by three tube companies in collaboration with DESY

Thales

CPI

Toshiba

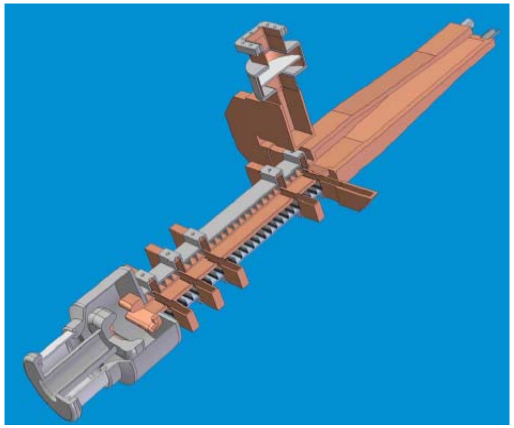
Status of the 10 MW MBKs

- Thales: Four tubes produced, gun arcing problem occured and seemed to be corrected in last two tubes after fixes applied (met spec). However, tubes recently developed other arcing problems above 8 MW. Thales to build two more without changes and two with changes after problem is better diagnosed.
- CPI: One tube built and factory tested to 10 MW at short pulse. At DESY with full pulse testing, it developed vacuum leak after 8.3 MW achieved – has been repaired and will be tested again.
- Toshiba: One tube built and achieved operation spec but developed arcing problems above 8 MW – being shipped to DESY for further evaluation.
- These are vertically mounted tubes – DESY will soon ask for bids on horizontally mounted tubes for XFEL (also needed for ILC).

Alternative Tube Designs

10 MW Sheet Beam Klystron (SBK)

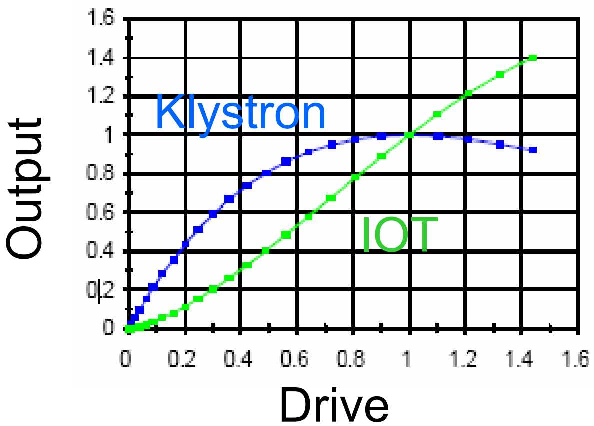
Parameters similar to 10 MW MBK



SLAC

5 MW Inductive Output Tube (IOT)

Peak Output Power	5	MW (min)
Average Output Power	75	kW (min)
Beam Voltage	115	kV (nom)
Beam Current	62	A (nom)
Current per Beam	5.17	A (nom)
Number of Beams	12	---
Frequency	1300	MHz
1dB Bandwidth	4	MHz (min)
Gain	22	dB (min)
Efficiency	70	% (nom)



CPI

Low Voltage 10 MW MBK

Voltage 65 kV
Current 238A
More beams

Perhaps use a Direct Switch Modulator

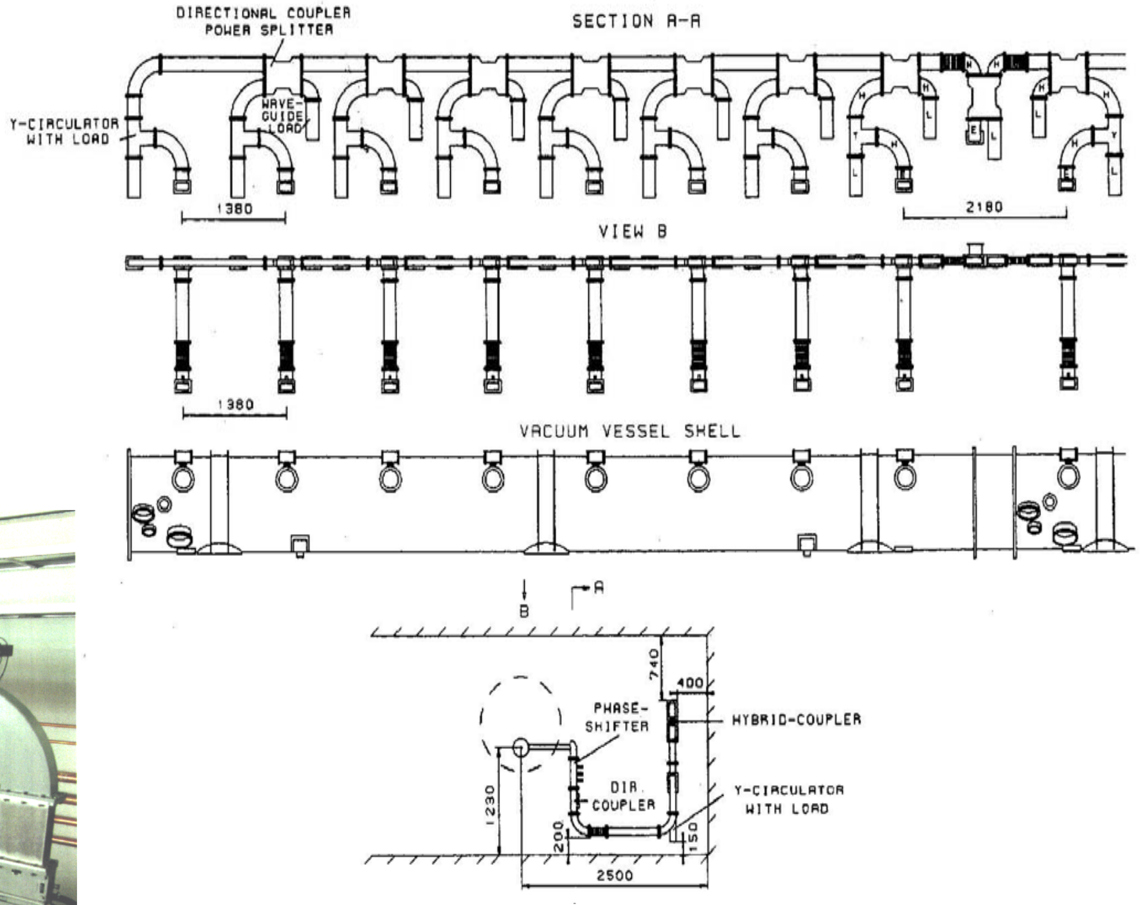
KEK

Klystron Summary

- The 10 MW MBK is the baseline choice – continue to support tube companies to make them robust (DESY needs 35 for XFEL although will run at 5 MW).
- SLAC funding design of a 10 MW sheet-beam klystron (will take several years to develop).
- Backup 1: Thales 2104C 5 MW tube used at DESY and FNAL for testing – it appear reliable (in service for 30 years) but has lower effiency compared to MBKs (42% vs 65%).
- Backup 2: With increased DOE funding next year, propose to contract tube companies to develop high efficiency, single-beam, 5 MW klystron.

RF Distribution

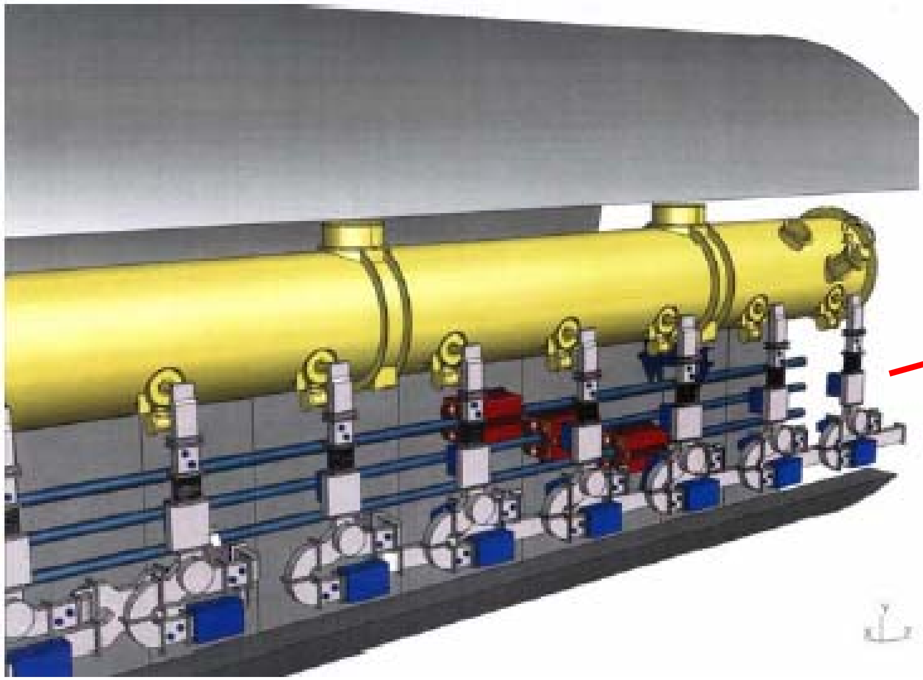
Baseline choice is the waveguide system used at TTF, which includes off-the-shelf couplers, circulators and 3-stub tuners (phase control).

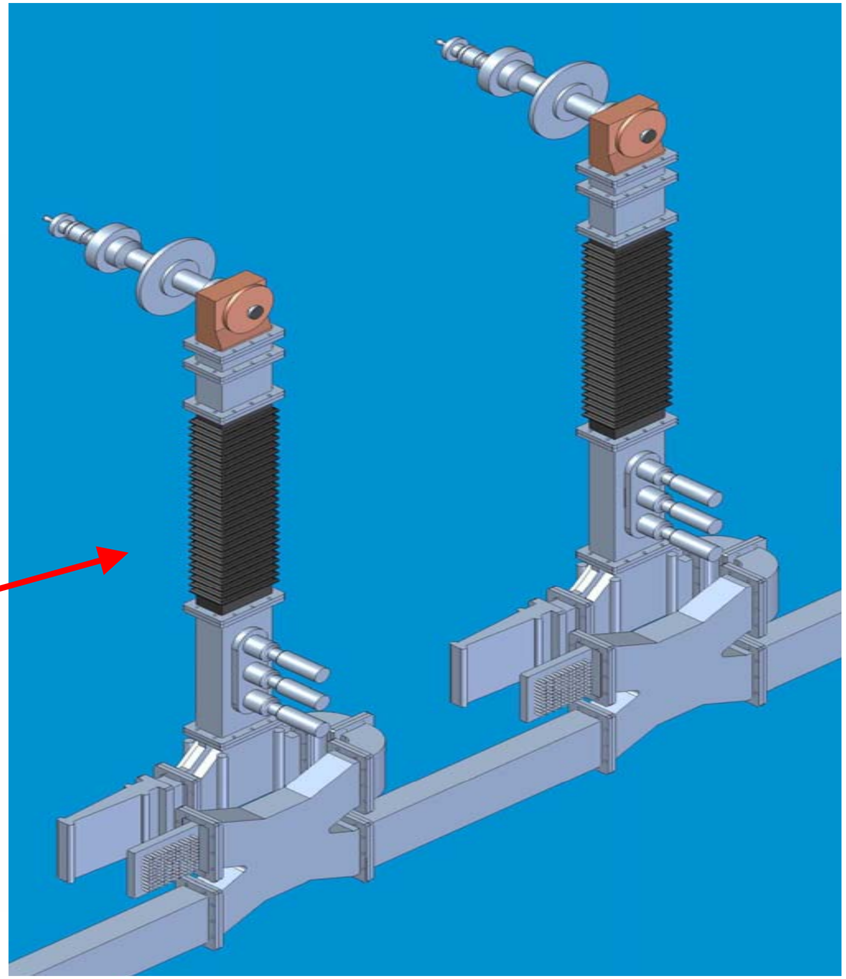


Need more compact design

(Each Cavity Fed 350 kW, 1.5 msec Pulses at 5 Hz)

Two of ~ 16,000 Feeds

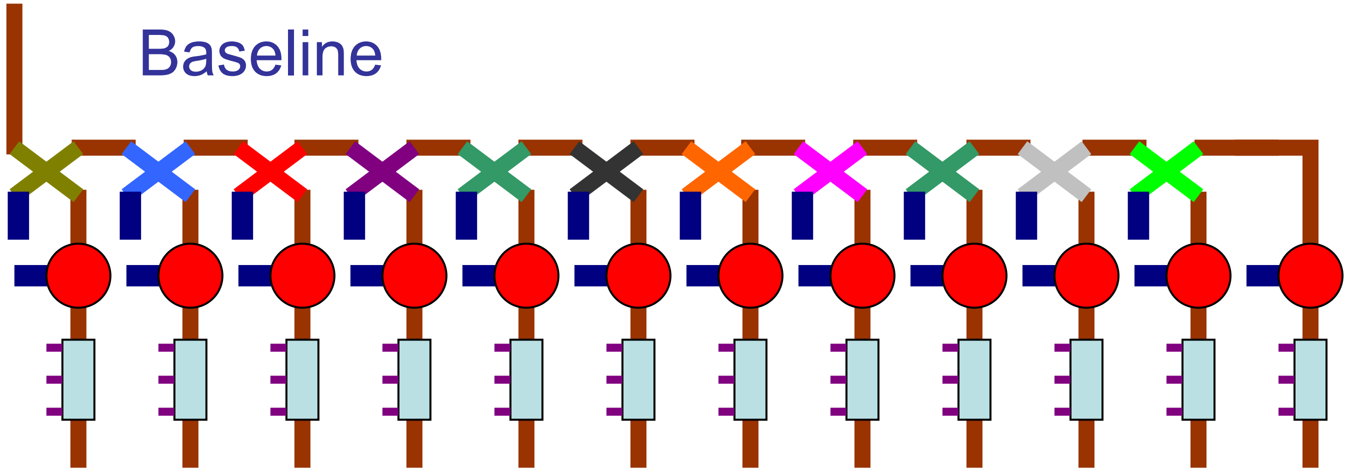




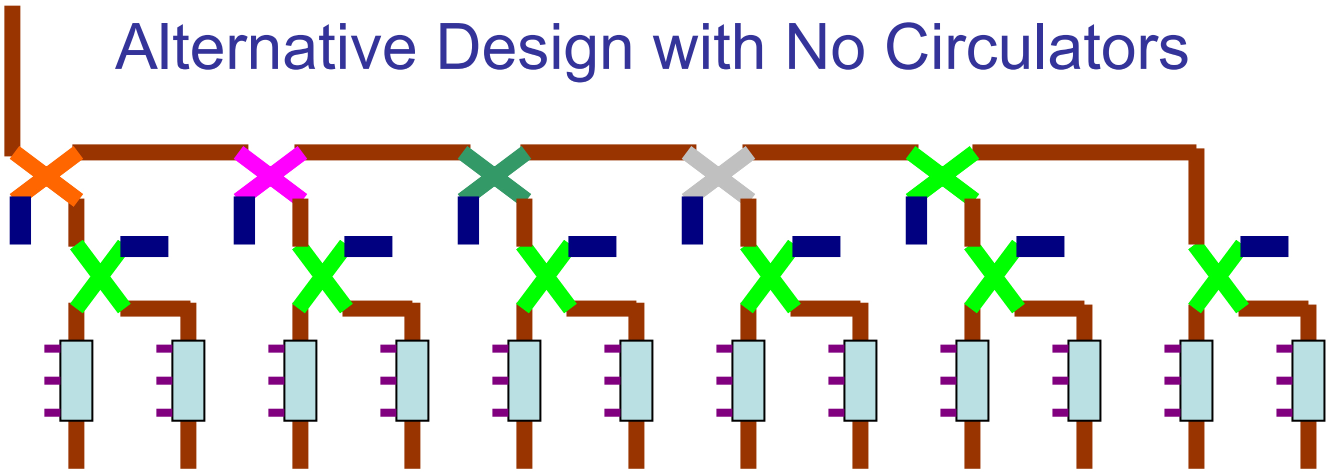
And should consider simplifications

(circulators are ~ 1/3 of cost)

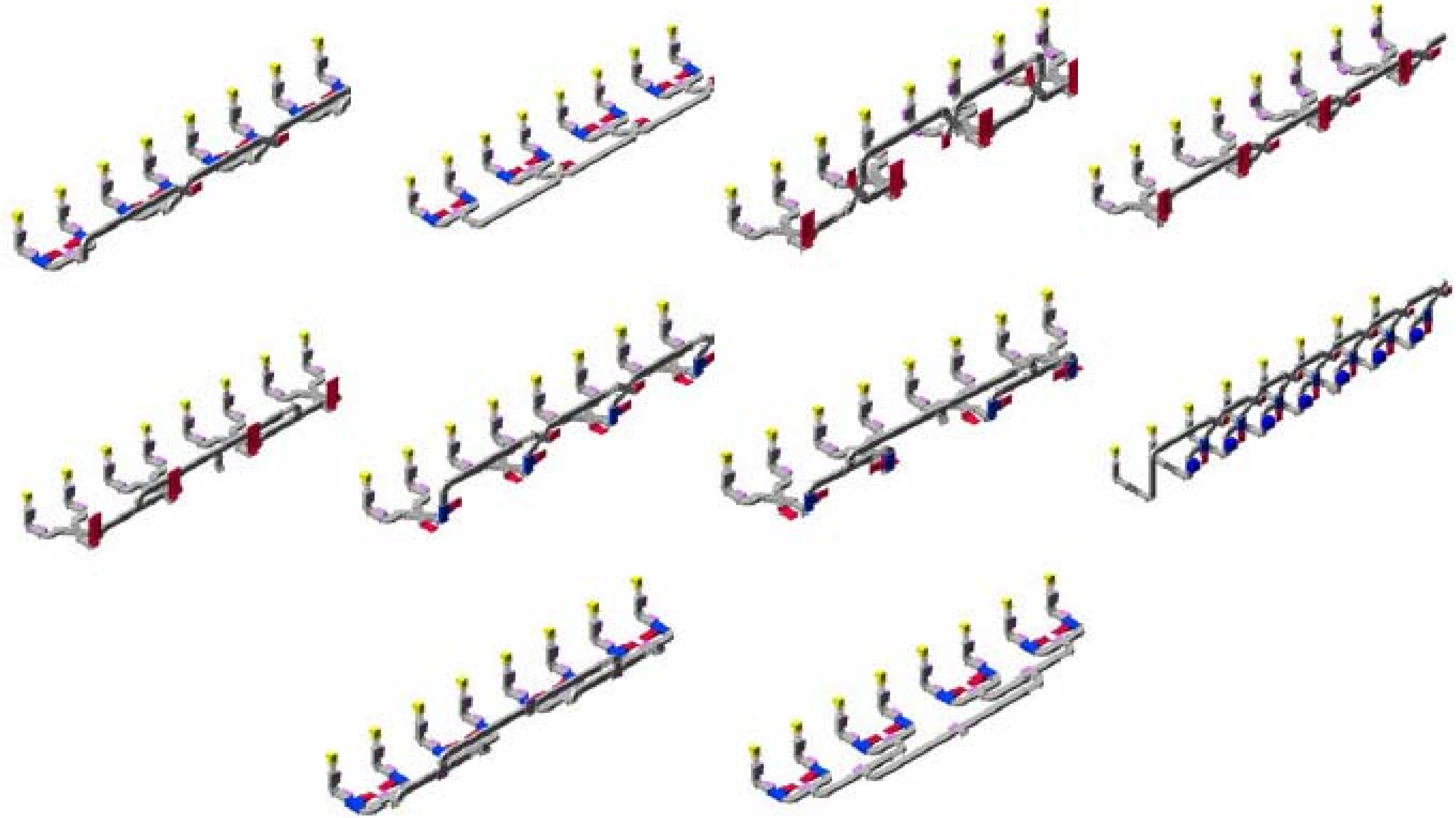
Baseline



Alternative Design with No Circulators

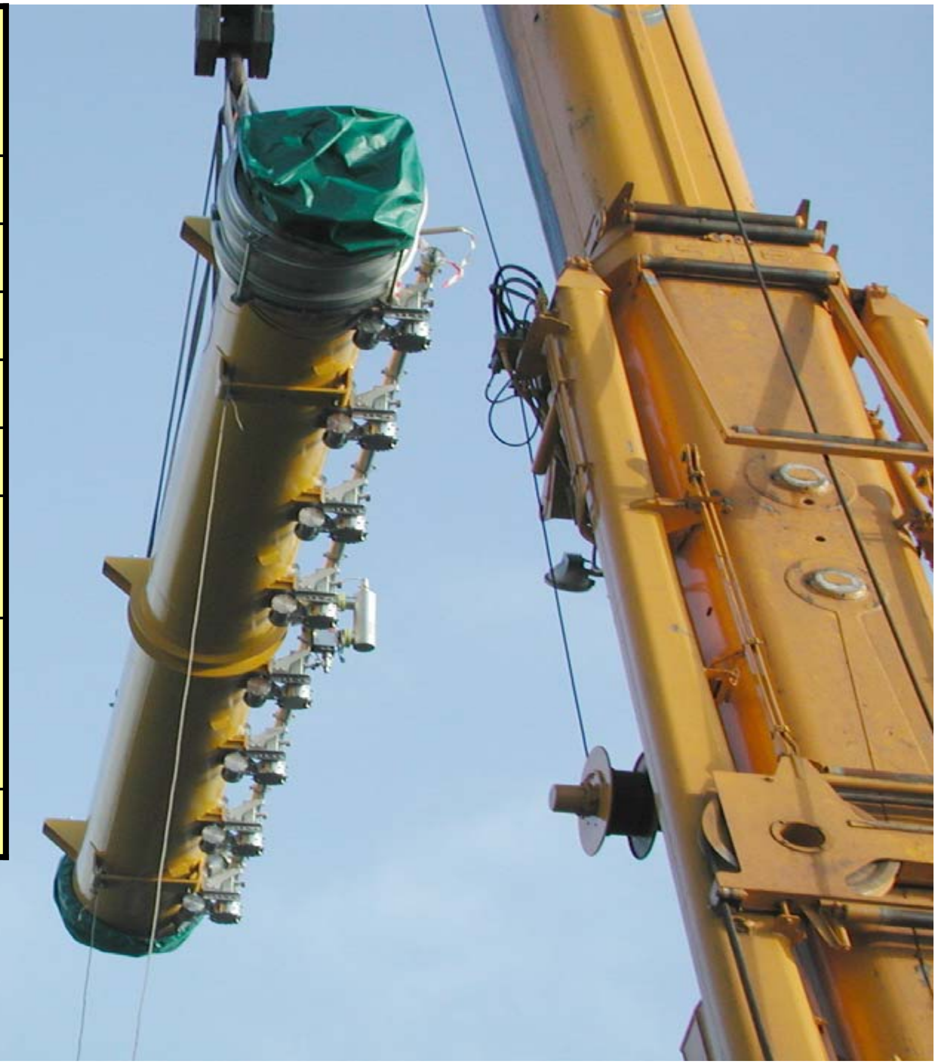


Alternative Waveguide Distribution Schemes Being Considered by DESY



Cryomodules

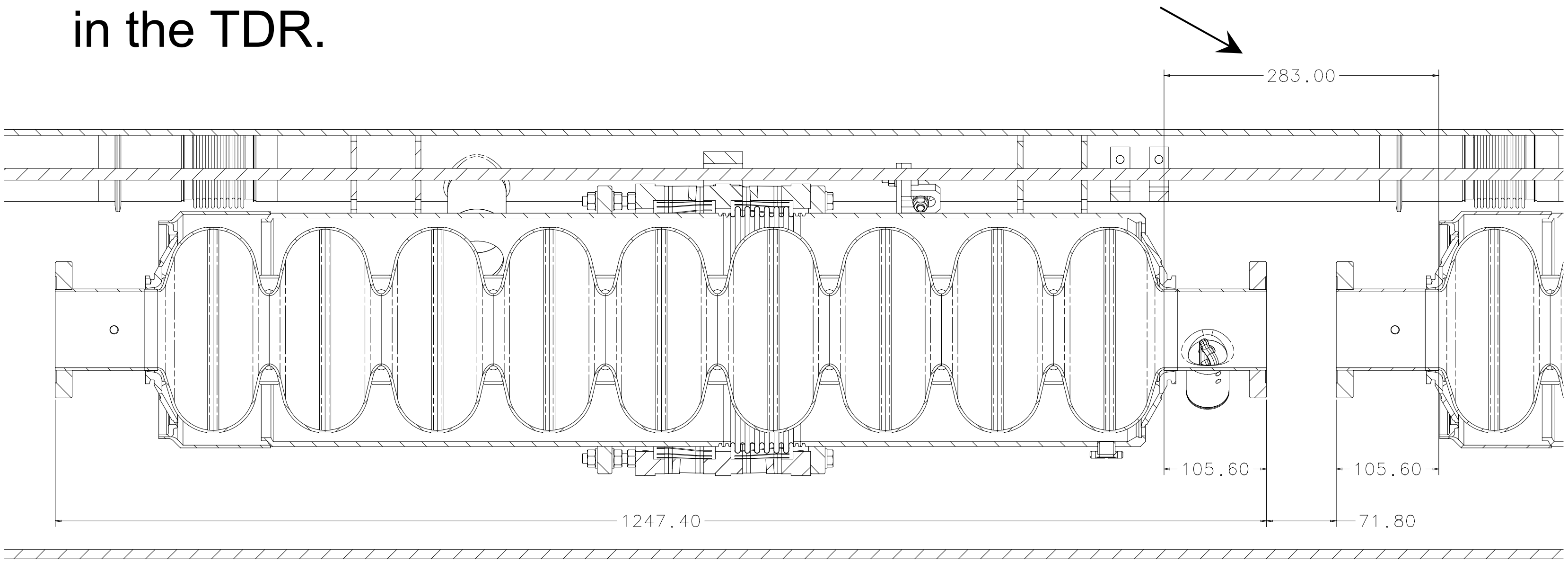
TTF Module	Installation date	Cold time [months]
CryoCap	Oct 96	50
M1	Mar 97	5
M1 rep.	Jan 98	12
M2	Sep 98	44
M3	Jun 99	35
M1* MSS	Jun 02	30 8
M3* M4 M5	Apr 03	19 19 19
M2*	Feb 04	16



Cryomodule Design

Relative to the TTF cryomodules

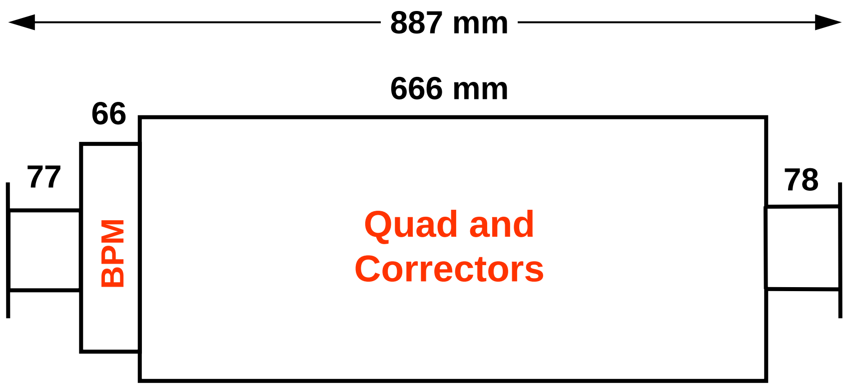
- Continue with 8 cavities per cryomodule based on experience and minimal cost savings if number increased (12 in TDR).
- Move quad / corrector / bpm package to center (from end) to improve stability.
- Increase some of cryogenic pipe sizes (similar to that proposed for the XFEL).
- Decrease cavity separation from 344 mm to 283 mm as proposed in the TDR.



Beam-Related Design Issues

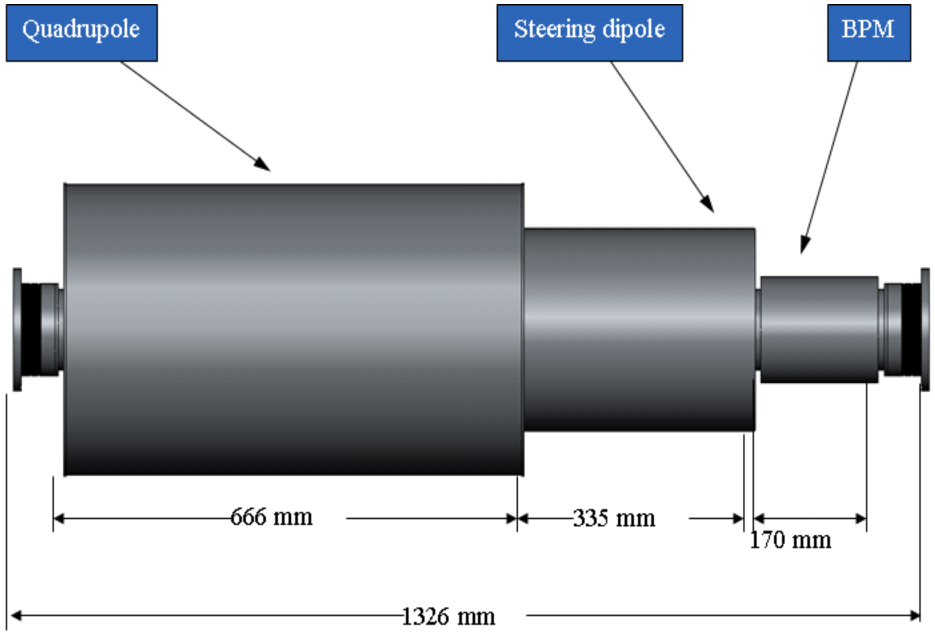
- Optics / Tolerances / Operation similar to that in TDR:
  - One quad per rf unit (three, 8-cavity cryomodules).
  - Few hundred micron installation tolerances for cavity, quad and BPM (demonstrated with TTF cryomodules).
  - Cavity BPM resolution of a few μm (should be achievable).
  - Use quad shunting and DFS tuning algorithms for dispersion control (need to better understanding systematic effects).
  - Assume beamline will follow Earth's curvature.
  - XFEL will serve as a benchmark although emittance much larger.
- Alternatives for cost savings.
  - Larger quad spacing at high energy end of the linac where wake and dispersion effects smaller.
  - Halve quad and bpm aperture to allow superferric quad and higher resolution BPMs (increases wakes by 10%).

Quad / Corrector / BPM Package



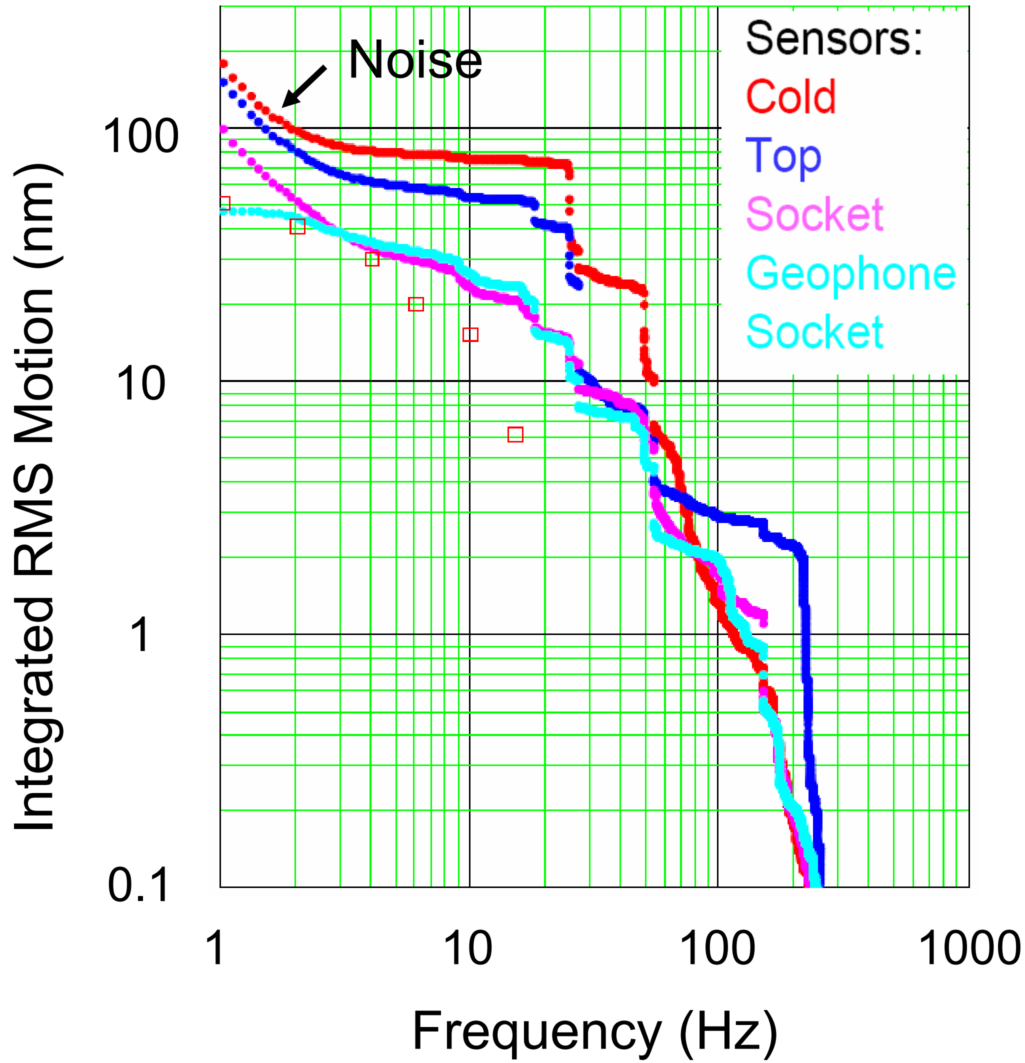
TDR

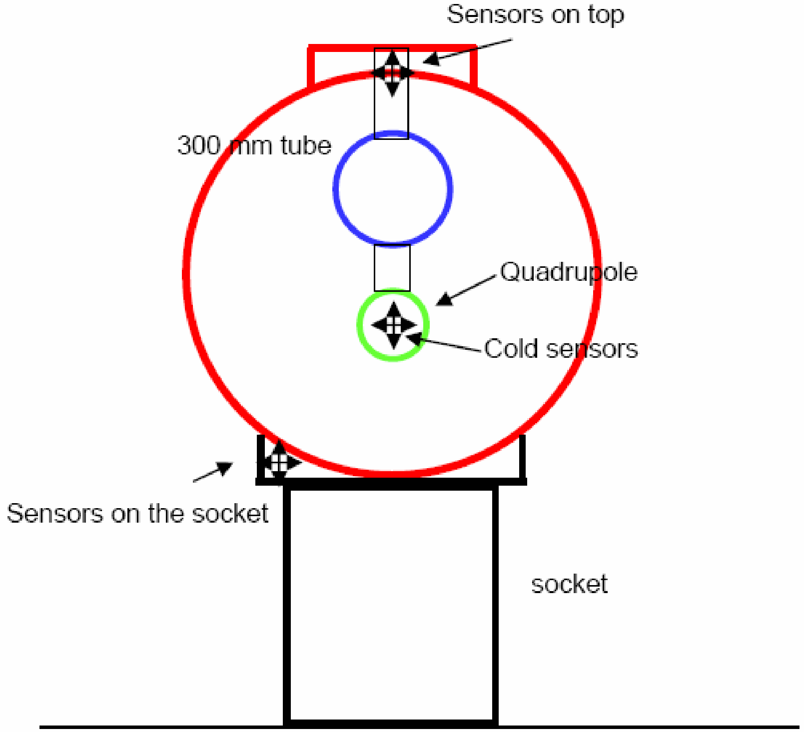
ILC
Proposal



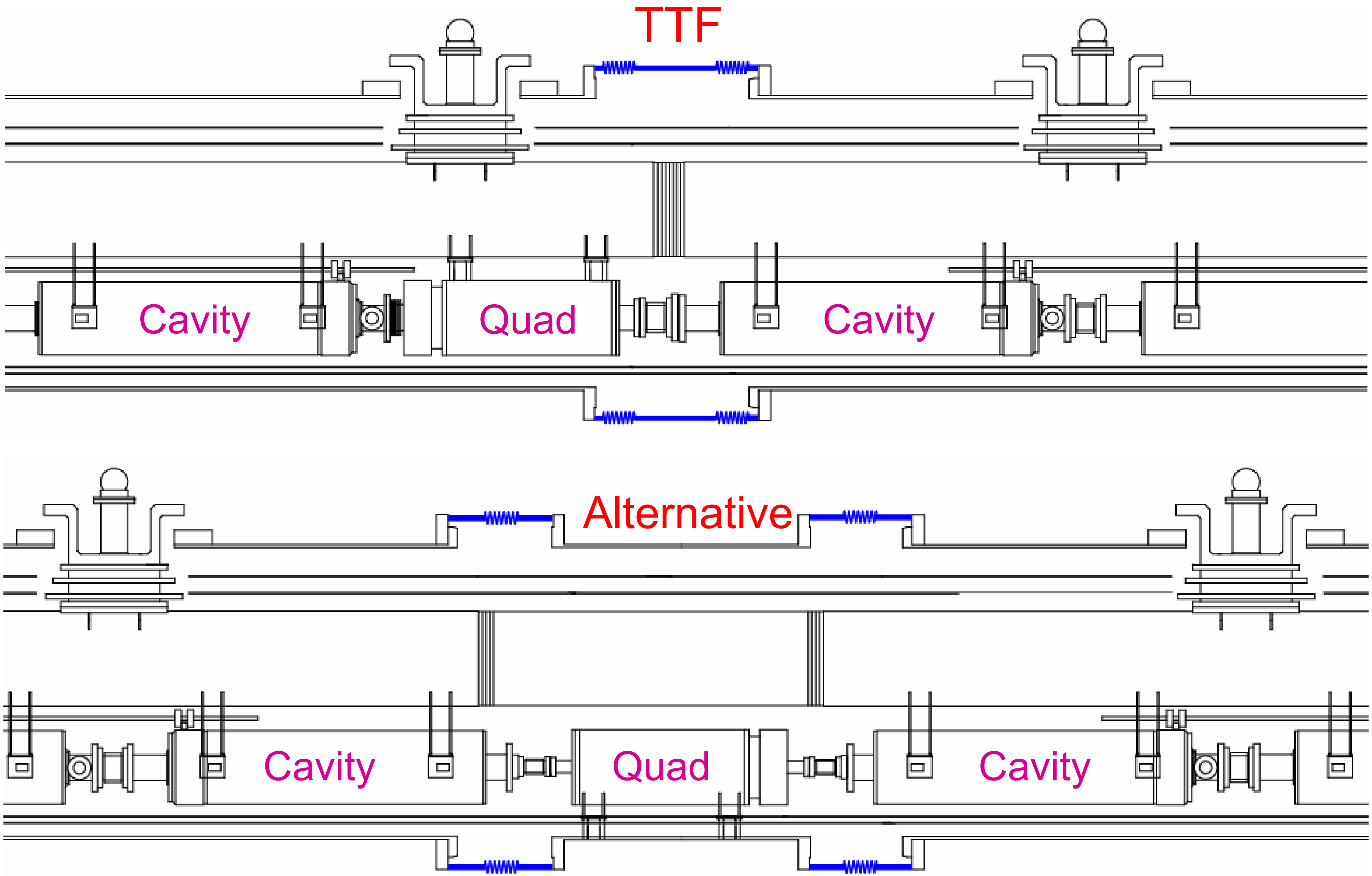
Vertical Quad Vibration at TTF

(ILC Goal: < 100 nm uncorrelated rms motion > ~ 0.2 Hz)





Alternative Quad Location



Cryogenic System

Assume static heat leaks based on TTF measurements instead of the smaller values assumed in the TDR

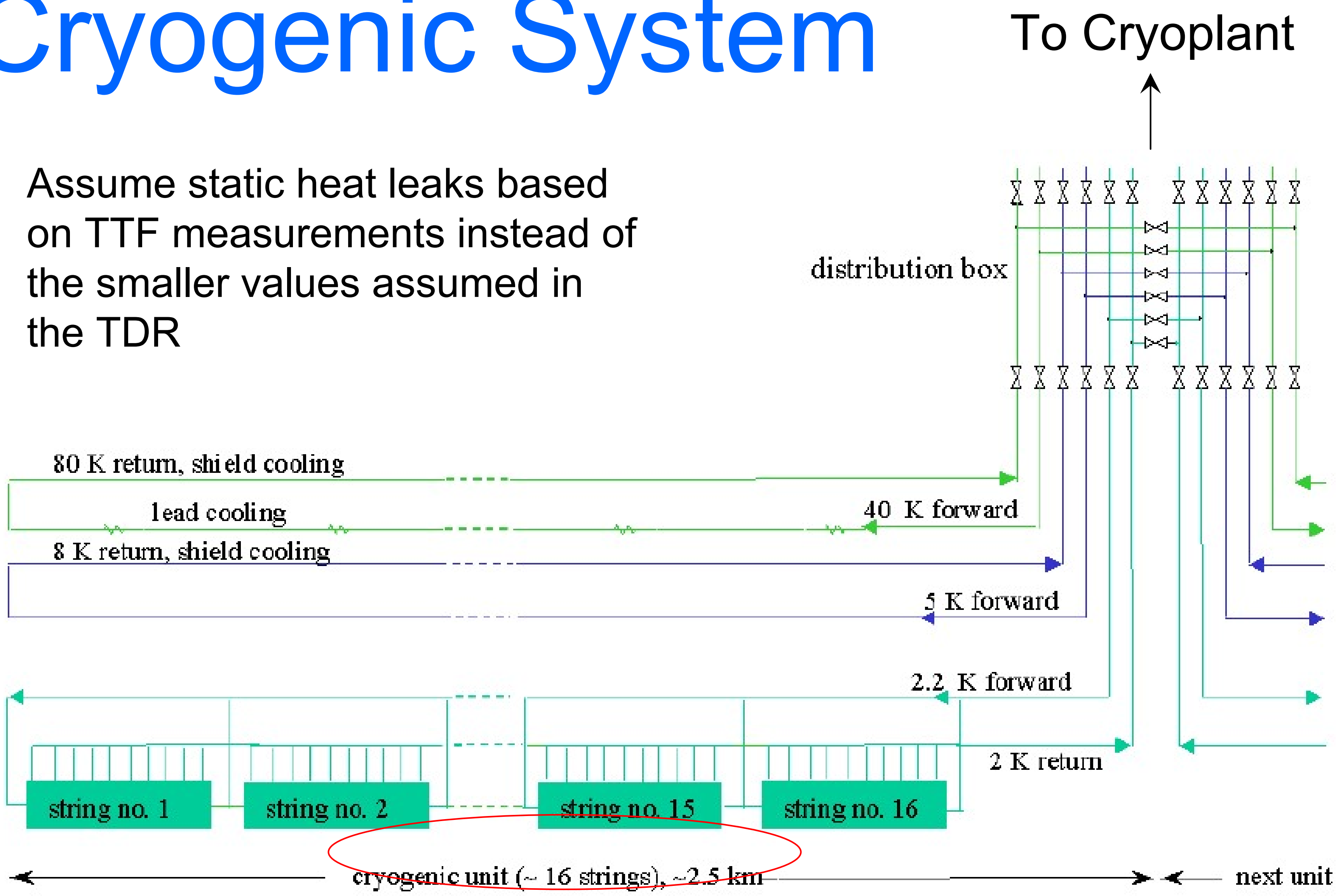
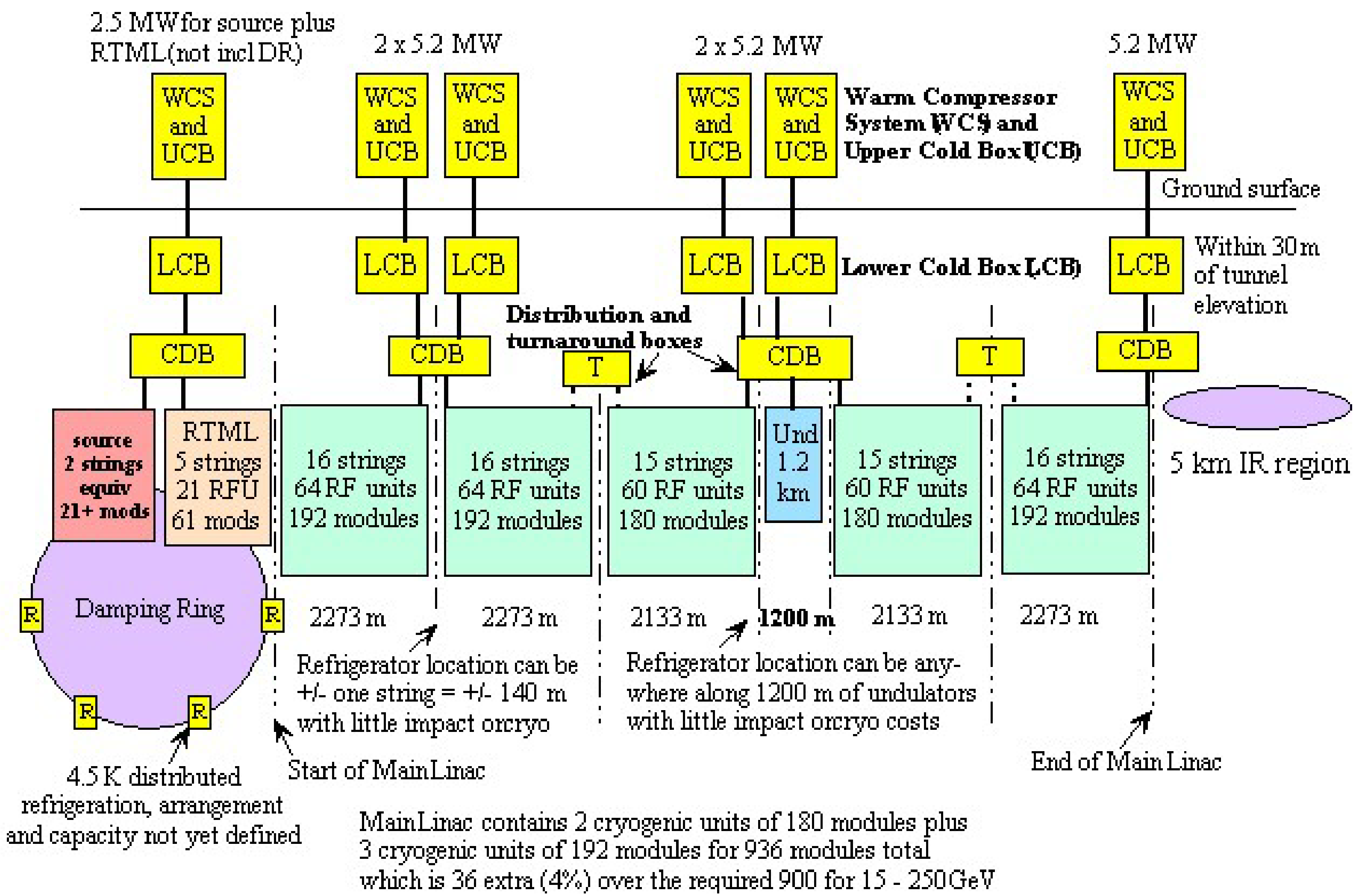


Figure 8.7.2: *Cryogenic unit.*

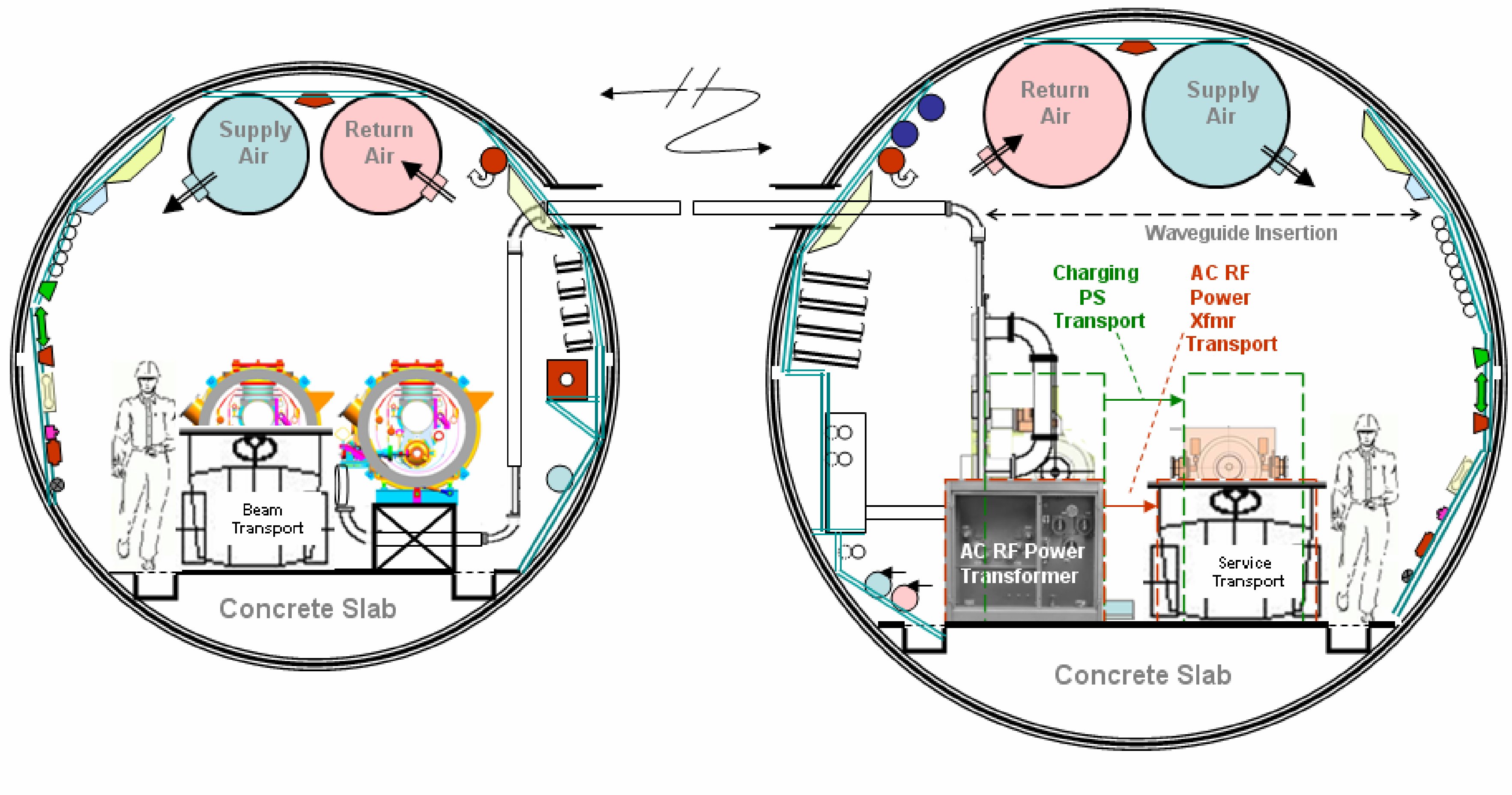
Cryoplant Layout

For ILC 500, require 57 MW of AC power for Cryoplants



Tunnel Layout

For baseline, developing deep underground (~100 m) layout with 4-5 m diameter tunnels spaced by 5 m.



Summary

- Basic linac design complete: converging on details
  - Tradeoffs of operability, availability and cost.
- Major cost and technical risks
  - Producing cryomodules that meet design gradient at a reasonable cost (cost model still in development, XFEL will provide a reference, and will get new industry-based estimates).
  - Producing a robust 10 MW klystron.
- Potential Cost Savings
  - Adopt Marx Modulator
  - Use simpler rf distribution scheme
  - Have one tunnel although 'the additional cost is marginal when considering the necessary overhead and equipment improvements to comply with reliability and safety issues.'
  - Reduce cavity aperture to 60 mm for 21% reduction in dynamic cryo-loading and 16% reduction in cavity fill time.