ART DOE Review

WBS x.8 RF System & Others

June 30, 2008

		ILC Costs (k$) w/o Indirects
Design		
	RF Design / Wakefields	150
R&D		
	Marx Modulator	277
	SBK + MBK/Int	370 + 490
	RF Distribution	341

R&D (cont)		
	Cavity Couplers	244 + 327 clean rm com
	NC e+ Capture Cavity	21
	SC Linac Quad & BPM	127
Infrastructure		
	L-band Operations	370

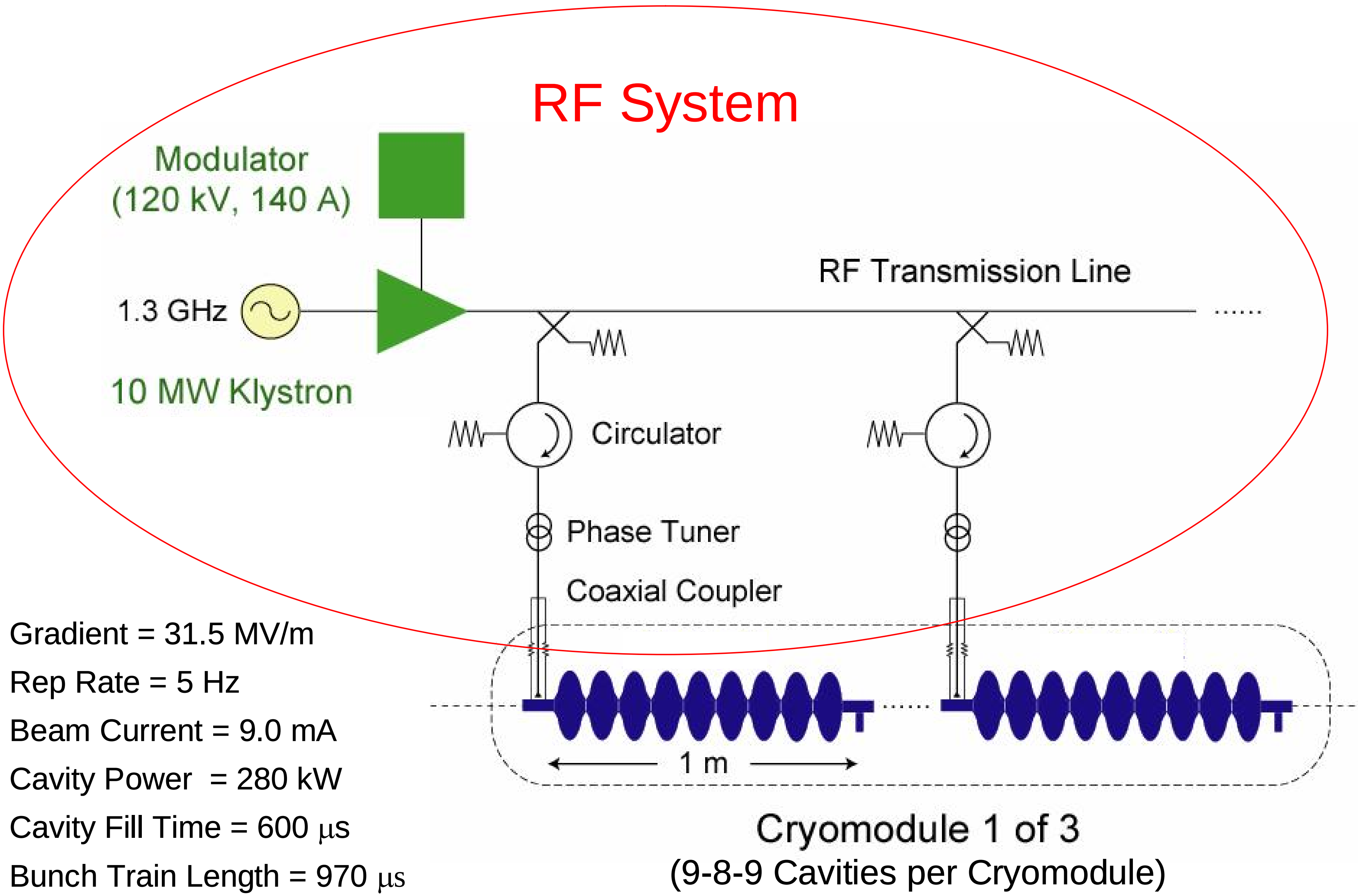
General Goals:

Develop more reliable and lower cost L-band RF source components for the ILC linacs.

Verify performance goals of the rf system

Chris Adolphsen

ILC Main Linac RF Unit (1 of 560)



Gradient = 31.5 MV/m

Rep Rate = 5 Hz

Beam Current = 9.0 mA

Cavity Power = 280 kW

Cavity Fill Time = 600 μs

Bunch Train Length = 970 μs

Wakefield and Cavity Studies

- Study kicks imparted to an on-axis beam due to the wakefields generated by the HOM and FM coupler antennae, which protrude past the irises, and by the transverse rf fields generated by the asymmetric power coupler.
- Modal analysis of cavity HOM signal data taken at the DESY TTF facility. Both broad and narrow band cavity HOM signal data are being analyzed to determine the properties of the lowest band dipole modes.
- Simulate multipacting in the cavity power couplers and compare to experimental results from the coupler test stand at SLAC ESB.
- Simulate the effectiveness of the cryomodule 70 K HOM absorbers in attenuating the high frequency wakefields before they are dissipated in the 2 K cryogenic system.

On-Axis Wake and RF Cavity Kicks

DESY-FNAL-SLAC collaboration to compute these kicks – final results show they are fairly benign in the ILC Main Linacs

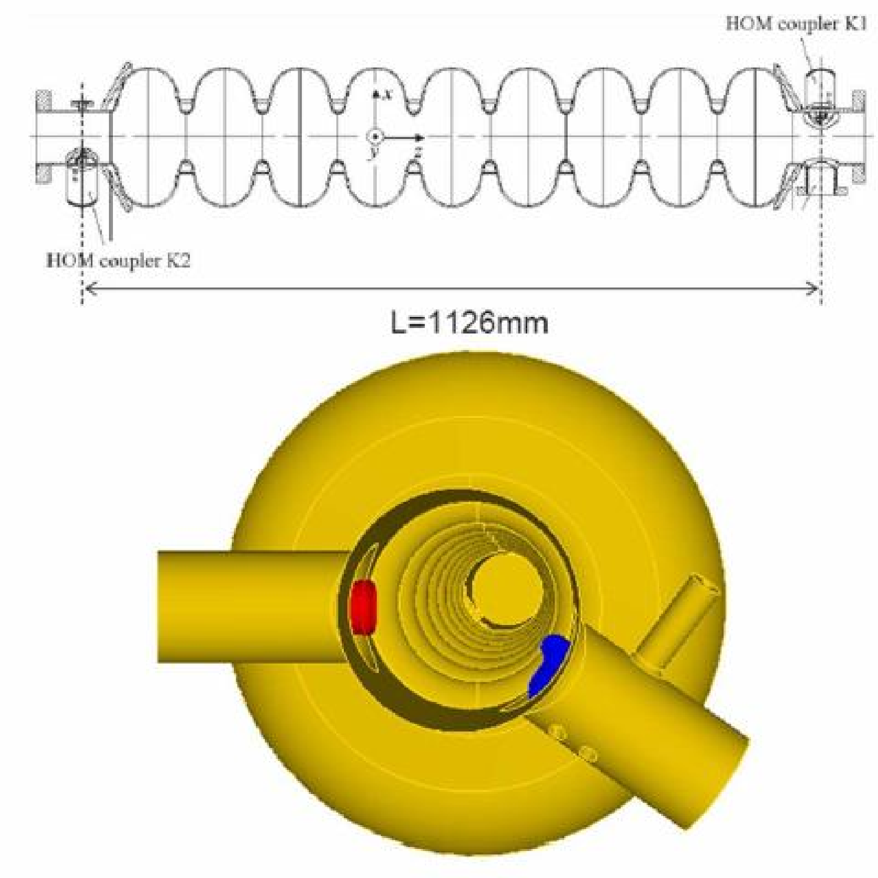


Table 1: Wake kick on-axis (k_{x0},k_{y0}) due to coupler asymmetry, for bunch length $\sigma_z = 1$ mm, in [V/nC] (ECHO).

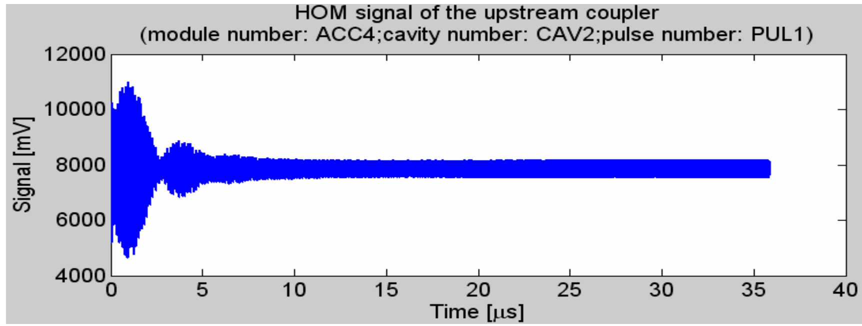
Case	Numerical	Analytical
Couplers in pipe	$(-21.2, -18.6)$	$(-20.8, -17.1)$
Couplers in cavity	$(-10.8, -10.0)$	$(-12.7, -7.0)$
Steady-state solution	$(-7.6, -6.8)$	

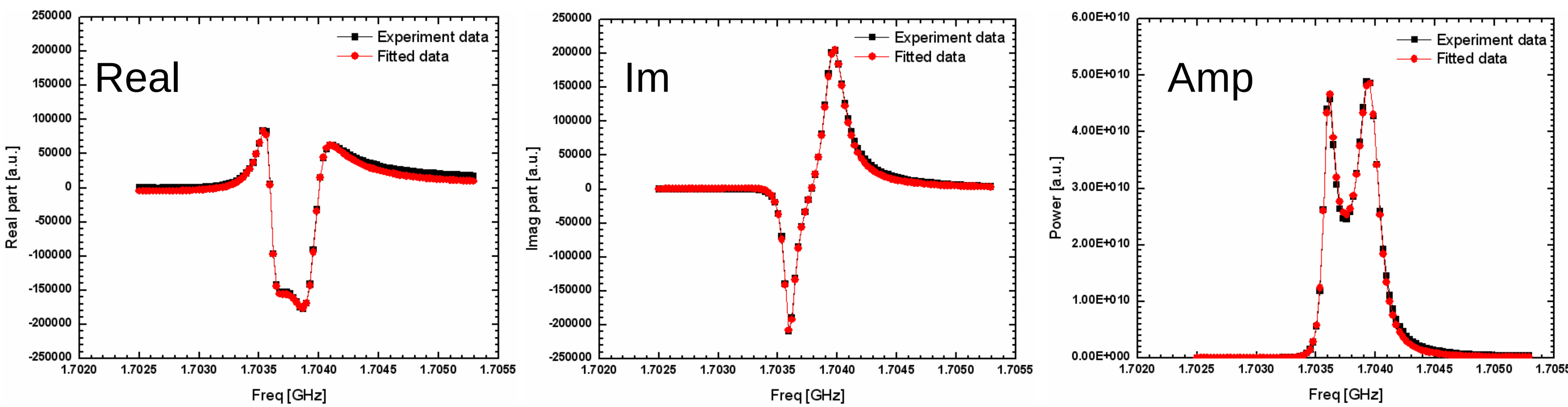
Table 2: RF kick on-axis due to coupler asymmetry in [kV]. Re(V) is the in-phase, Im(V) the out-of-phase kick.

Region	$\mathbf{V}_x$	$\mathbf{V}_y$
Upstream	$-1.82 + 0.22i$	$-1.29 - 0.11i$
Downstream	$-0.79 - 1.62i$	$+1.15 + 0.28i$
Total	$-2.61 - 1.40i$	$-0.13 + 0.17i$

From EPAC08 paper TUPP019

Modal Analysis of Cavity Dipole Signals



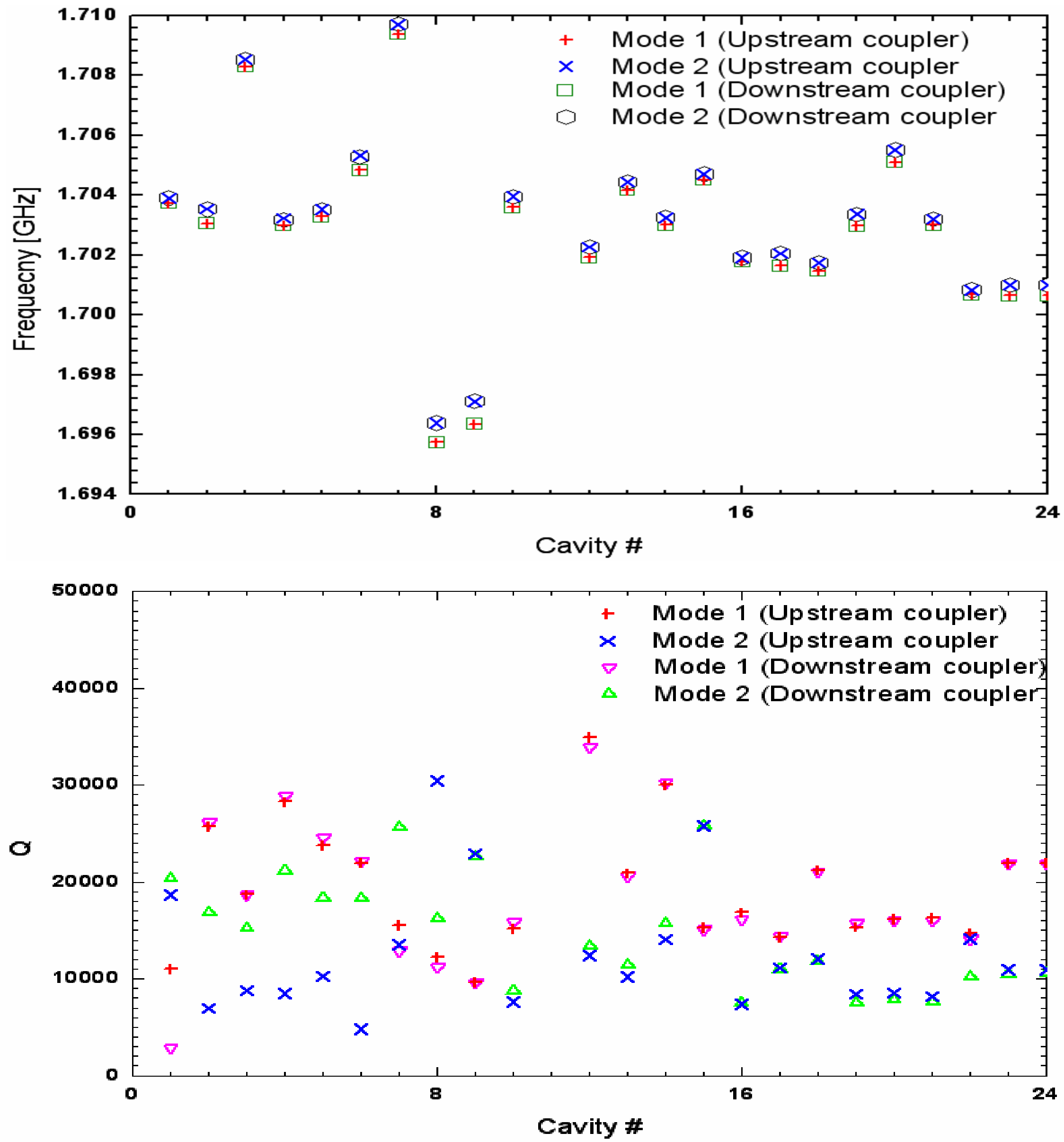


Fit frequency spectrum near 1.7 GHz
to sum of complex Lorentzians

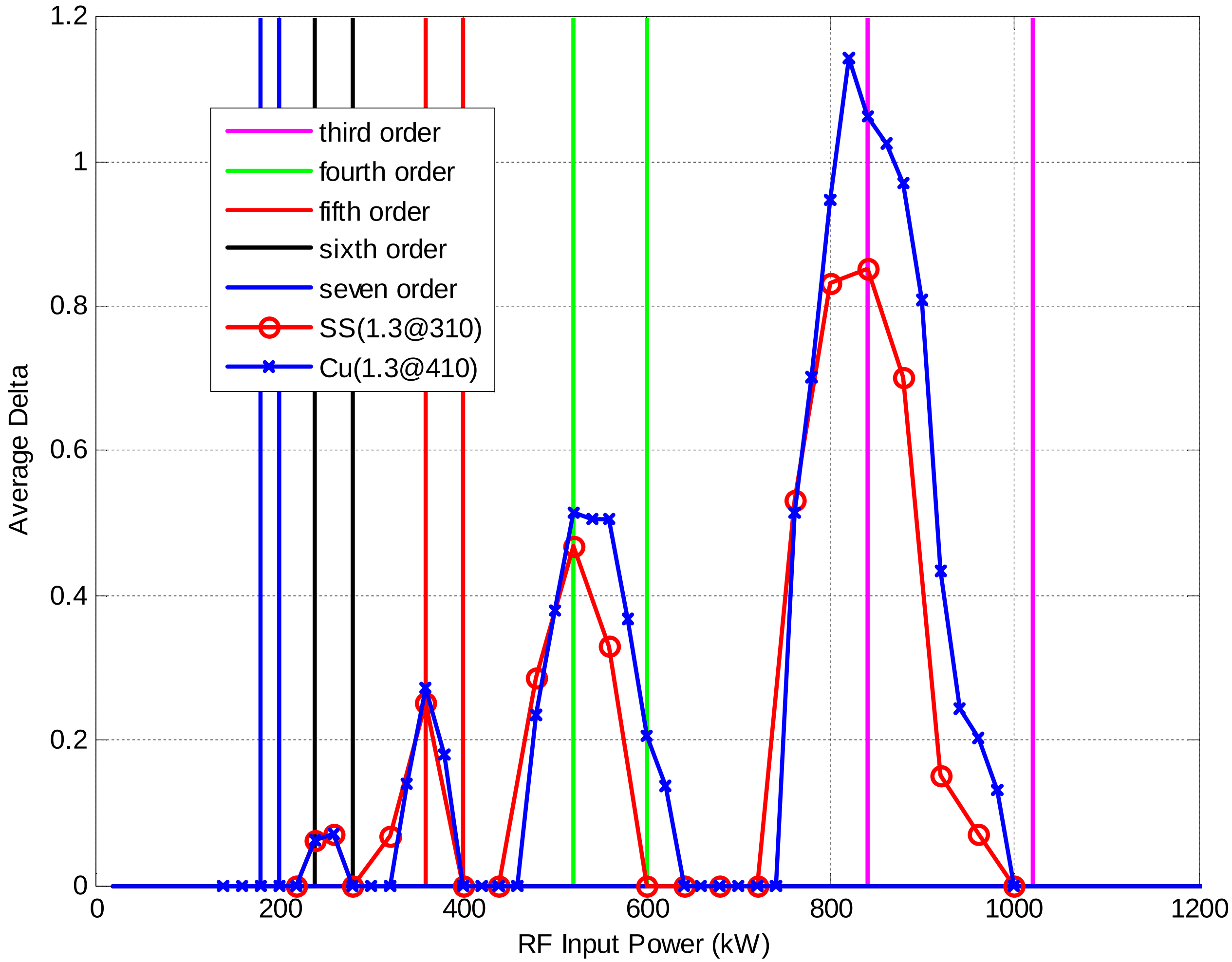
$$\frac{A_n}{\omega - \omega_{0\,n} + \Gamma i}$$

Derive frequency and Q of two polarizations from simultaneous fit to 36 orbits

TE111-6 Dipole Frequencies and Q's

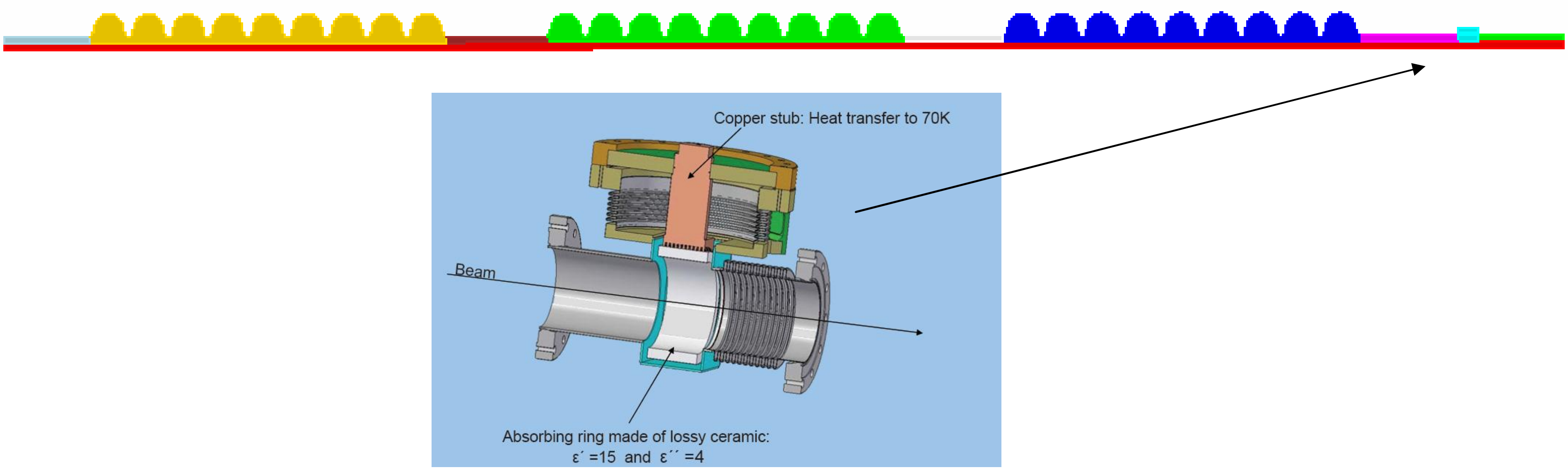


MAGIC Multipacting Simulation and ‘Resonant Finder’ Results for a 40 mm Coax Line



Beamline Absorber Study Using T3P

One bunch Q=3.2nc, bunch length=10mm Loss factor (V/pc)=9.96V/pc	**Lossy dielectric conductivity σ_{eff}=0.6(s/m)** **Dielectric constant ε_r=15, within 80ns**
Total Energy Generated by Beam (J)	10.208e-5
Energy propagated into beam pipe (J)	*4.44e-6*
Energy dissipated in the absorber (J)	*7.0e-7*
Energy loss on the Non SC beampipe wall (J) around absorber	9.3e-10
Energy loss in intersection between two cavities (J)	1.3e-9



SLAC Hosted Wake Fest 07 Workshop in December

"Wake Fest 07 - ILC wakefield workshop at SLAC"
chaired by Cho Ng (SLAC) , Roger Jones (Manchester) , Karl Bane (SLAC) , Nikolay Solyak (FNAL)

from **Tuesday 11 December 2007 (09:00)**
to **Thursday 13 December 2007 (18:45)**
at SLAC (***Kavli Conference Rooms***)

Description : Local Organization: Zenghai Li, Cho Ng, Chris Adolphsen (SLAC)

Place:
Dec 11: Kavli Conference room 222;
Dec 12: Kavli Conference room 305;
Dec 13: Orange room (central lab);
(SLAC Maps http://www2.slac.stanford.edu/maps/slacarea.html)

Material : WebEx connection info, practical information

Tuesday 11 December 2007 | Wednesday 12 December 2007 | Thursday 13 December 2007 |

Tuesday 11 December 2007

top

09:00->*12:20* Wakefield and Coupler RF Kicks (Location: Kavli Conf. Room 222)

09:00	Wakefield issues in the ILC main linacs (20') (Slides)	Chris Adolphsen (SLAC)
09:20	Coupler short-range wakefield kicks (30') (Slides)	Karl Bane (SLAC)
09:50	Coupler RF kick simulations (30') (Slides)	Slava Yakovlev (FNAL)
10:20	break	
10:50	Omega3P & S3P simulation of coupler RF kicks (30') (Slides)	Zenghai Li (SLAC)
11:20	Wakefield simulations for ILC cavity (30') (Slides)	Slava Yakovlev (*FNAL*)
11:50	Discussions (30')	
12:20	lunch break	

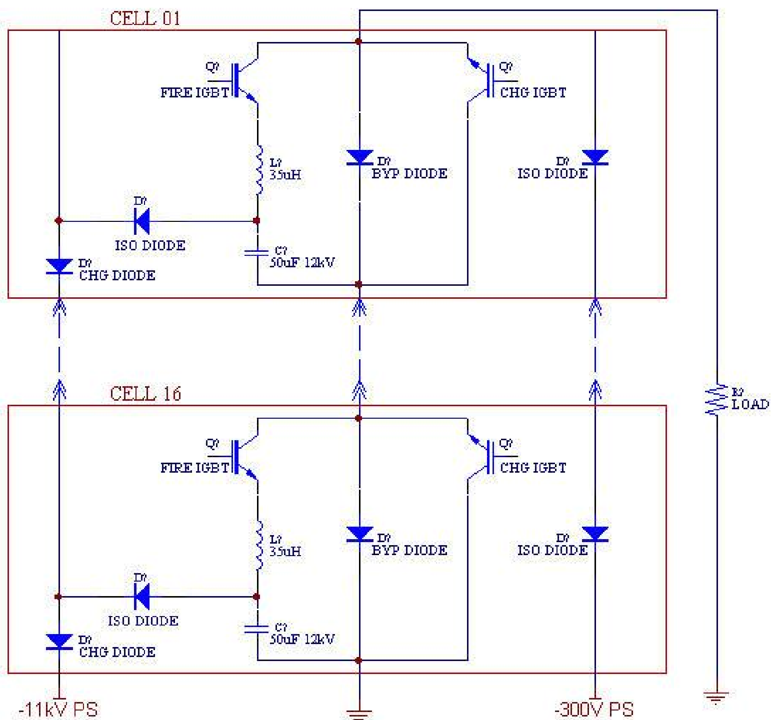
Marx Modulator

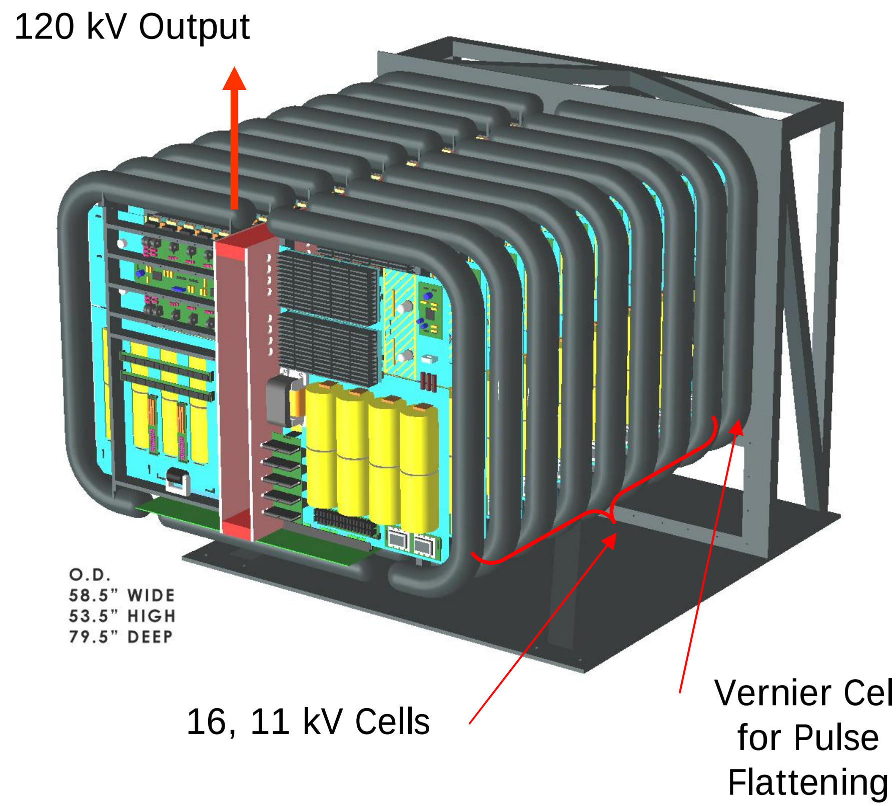
- **Goals:**
  - Develop Marx Modulator approach as an alternative to the ILC baseline Pulse Transformer Modulator with Bouncer.
  - Reduce cost, size and weight, improve efficiency and eliminate oil-filled transformers.
- **Project Status:**
  - Prototype built that has achieved peak power goals.
  - Spent last 18 months to make design more robust (i.e.. mitigate failures and problems). Currently doing ‘spark-down’ tests to verify that it survives klystron arcing.
  - In parallel, close to completing Vernier Cards (mini-Marx) to flatten pulse.
  - Will install tested unit in air cooled enclosure and move to End Station B (ESB) this Fall to drive a 10 MW Toshiba Multi-Beam Klystron.

ILC Modulator Specifications

Pulse Voltage	120 kV
Pulse Current	140 A
Pulse Length [flat-top]	1.6 mS
Pulse Flatness	+/- 0.5%
Total Pulse Charge	0.22 C
Total Pulse Energy	27 kJ
Repetition Rate	5 Hz
Average Output Power	135 kW

Marx Generator Modulator

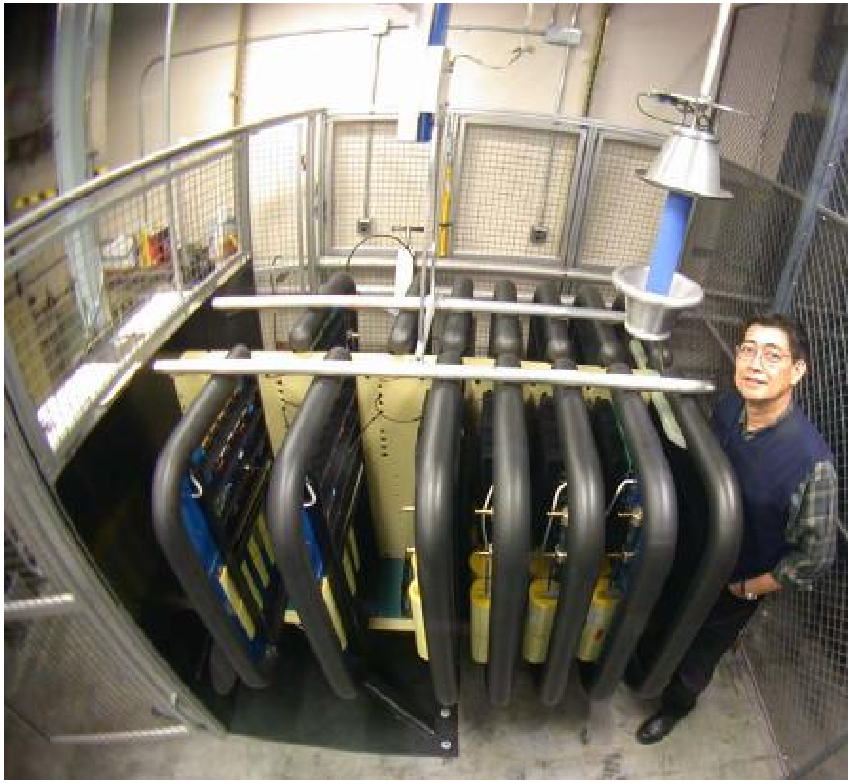




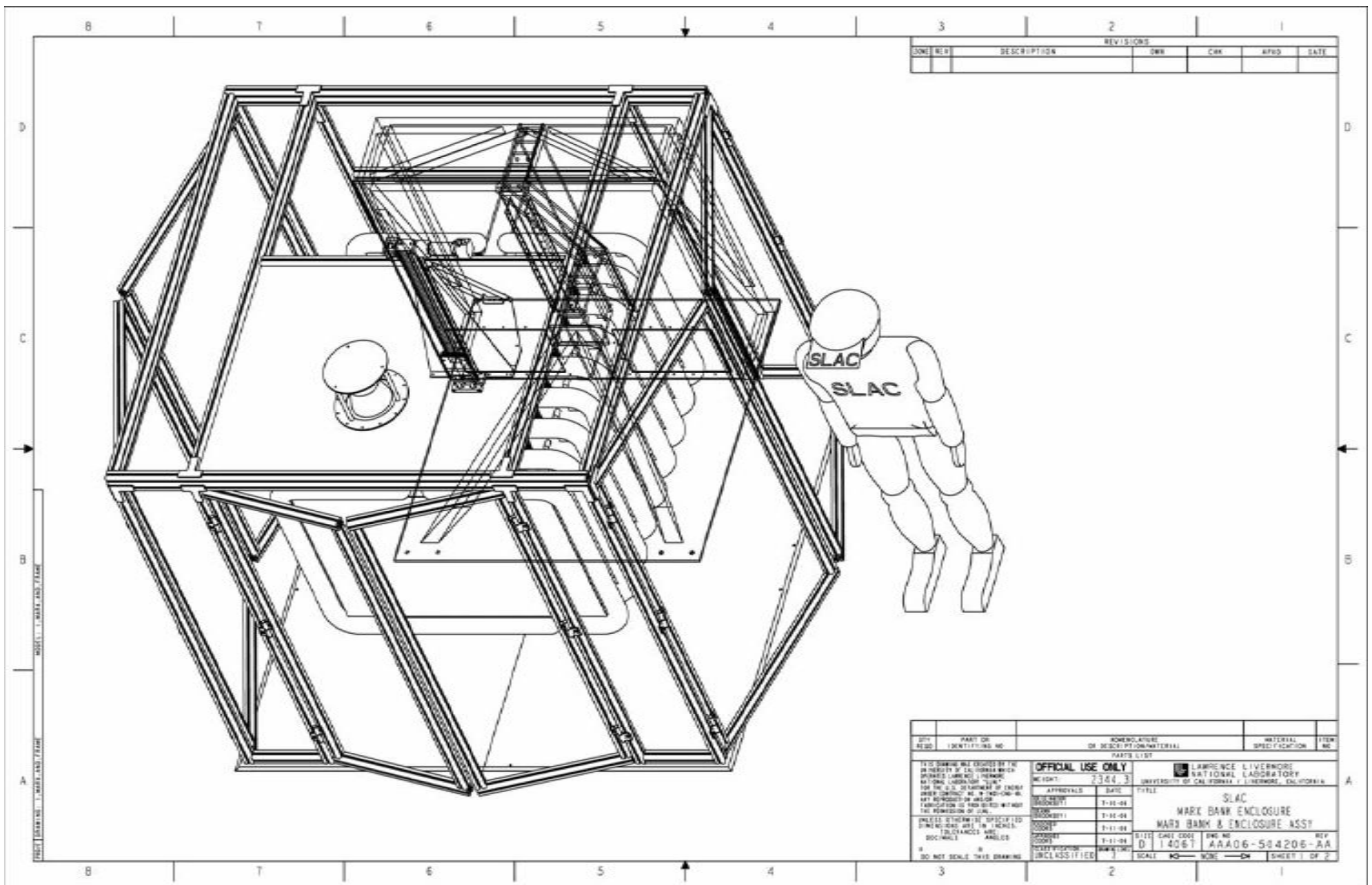
- 11kV per cell
- Switching devices per cell: two 3x5 IGBT arrays.
- Charge switch provides return path for 11kV and control sources
- Diode strings provide isolation between cells

MARX Prototype

Overall Size: 60” W x 55” H x 80” D



As Installed in an Air-Cooled Enclosure with a Heat Exchanger



11kV Marx Cell – Front & Rear Views

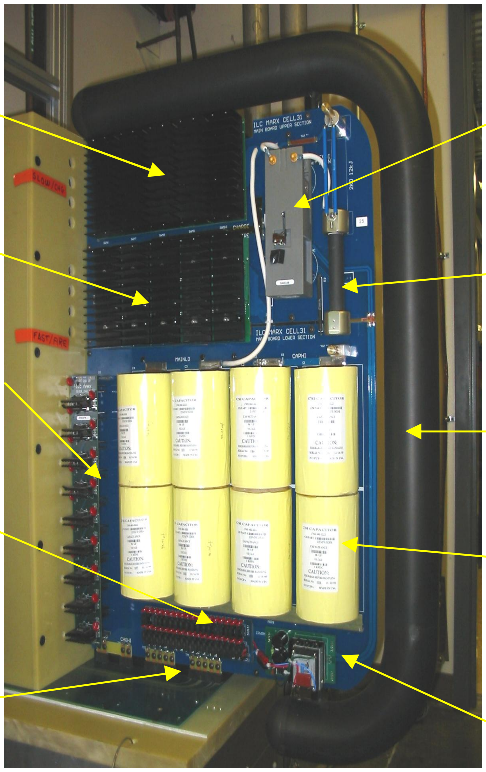
5 Charging SW Modules

5 Firing SW Modules

Charge Diode String

Bypass Diode String

Connector Group to Backplane



Cell Grounding Relay

Cap. Discharging Resistor

Equipotential Ring

Energy Storage Capacitors

Control Power Converters

11kV Isolated Power/Trigger Boards

Cell Control Module

dI/dt Limiting Inductor

Charge Isolation Diode String

Red text denotes modified components

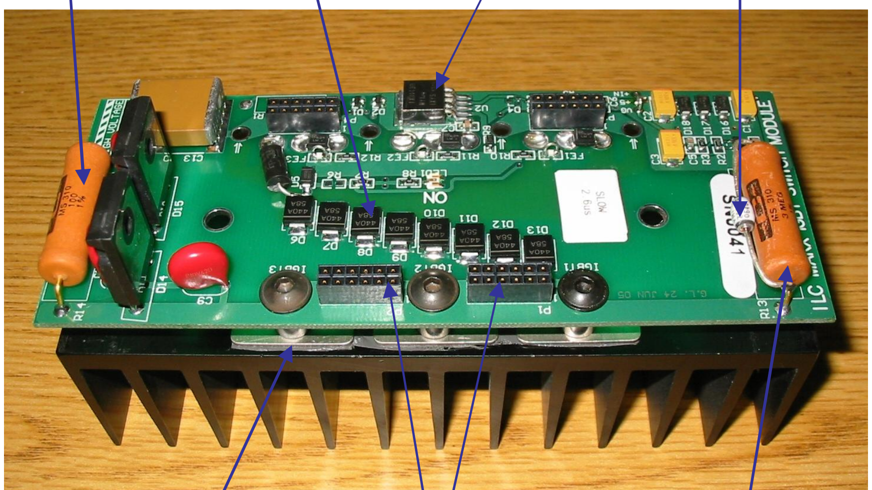
Firing/Charging IGBT Switch

RCD Snubber

C-E TVS String

Gate Driver

Anti-Parallel Diode

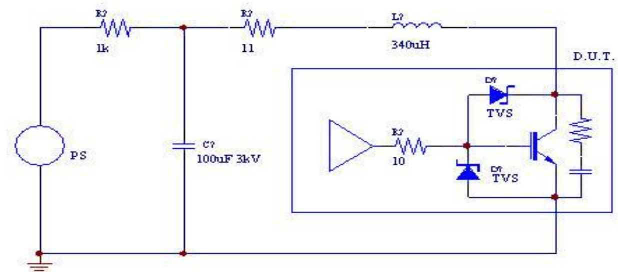


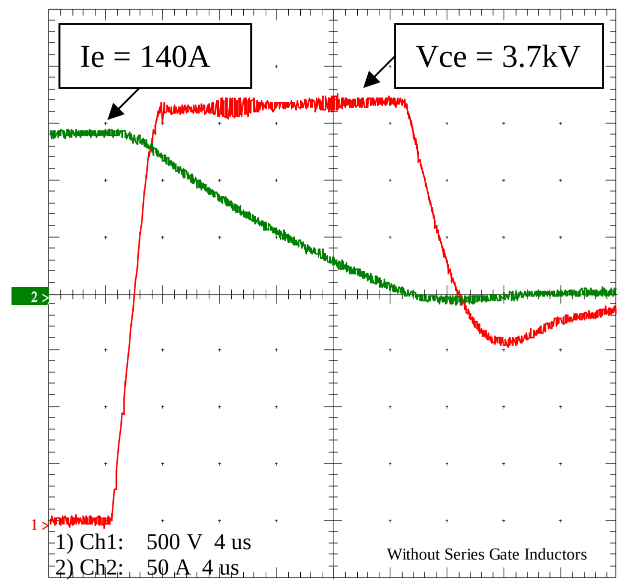
Matched IGBTs
4.5kV, 60A x 3 ea

Collector Connectors

Voltage Balancing Resistor

Over-Voltage Protection Test





Modified IGBT Switch Module Issues & Solutions

- Over voltage/current failure
  - Mismatched IGBT switching speed: removed, characterized, and matched devices (500+ IGBTs, time consuming process)
  - Existing TVS over-voltage protection works only if dV/dt is slower than IGBT turn-on delay: added another TVS between Gate & Emitter to close the C-E path
  - No snubber: implemented RCD snubber but capacitance is still too small to have much effect (capacitor size is restricted by current board layout)
- Improvements to prevent possible failure
  - No anti-parallel diode: added a small, fast recovery diode to conduct reverse current under fault conditions
  - Removed series gate inductors: caused parasitic oscillation that could potentially damage IGBT.
  - Added 15V TVS on each of IGBT G-E to clamp gate voltage, and limit emitter current under fault conditions

120 kV, 140 A Marx Output with Coarse Flattening

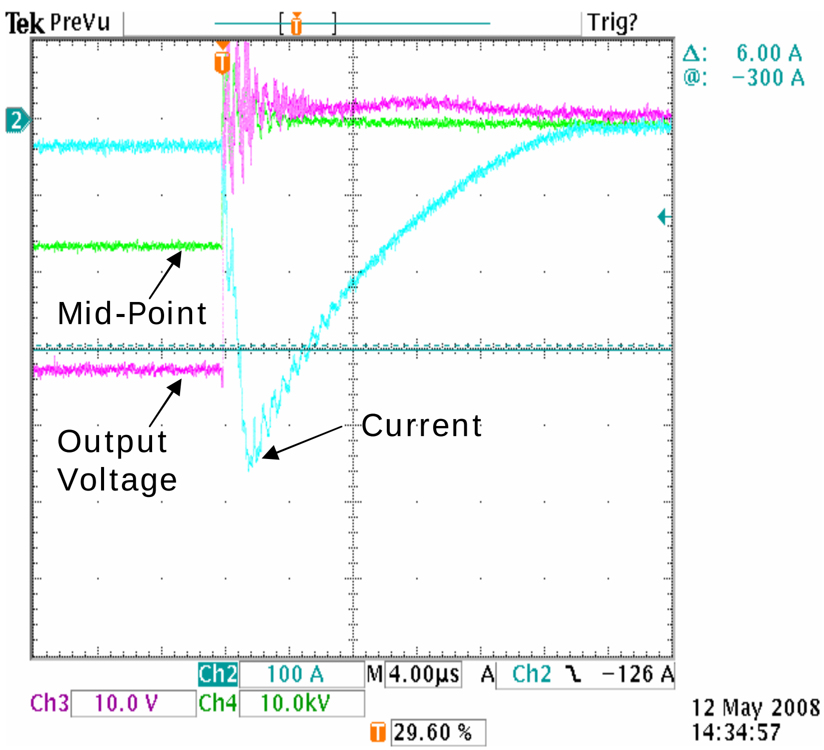
16 Cells at 11kV into Water Load (5 delayed to flatten pulse). Operate at 3 Hz due to facility cooling and charging PS limitations.

Efficiency

- Total energy (out/in) efficiency: 97%
- Usable (flattop) efficiency: 92%
- Usable efficiency can be increased by reducing the rise and fall times which are presently large (~ 130 us) to accommodate diagnostics

Marx Output 'Spark-Down'

Sparked-Down Voltage & Current Waveforms



- Two and Four Cells preliminary short circuit tests
- Cells were over-current protected by themselves
- Detection of load over-current to shut down the main Marx trigger has not yet implemented
- Two-cells were successfully tested to 24kV
- Four-cell test was up to 36kV but failed at 40 kV (however, has survived full voltage faults in load). Currently adding snubbers to cells.

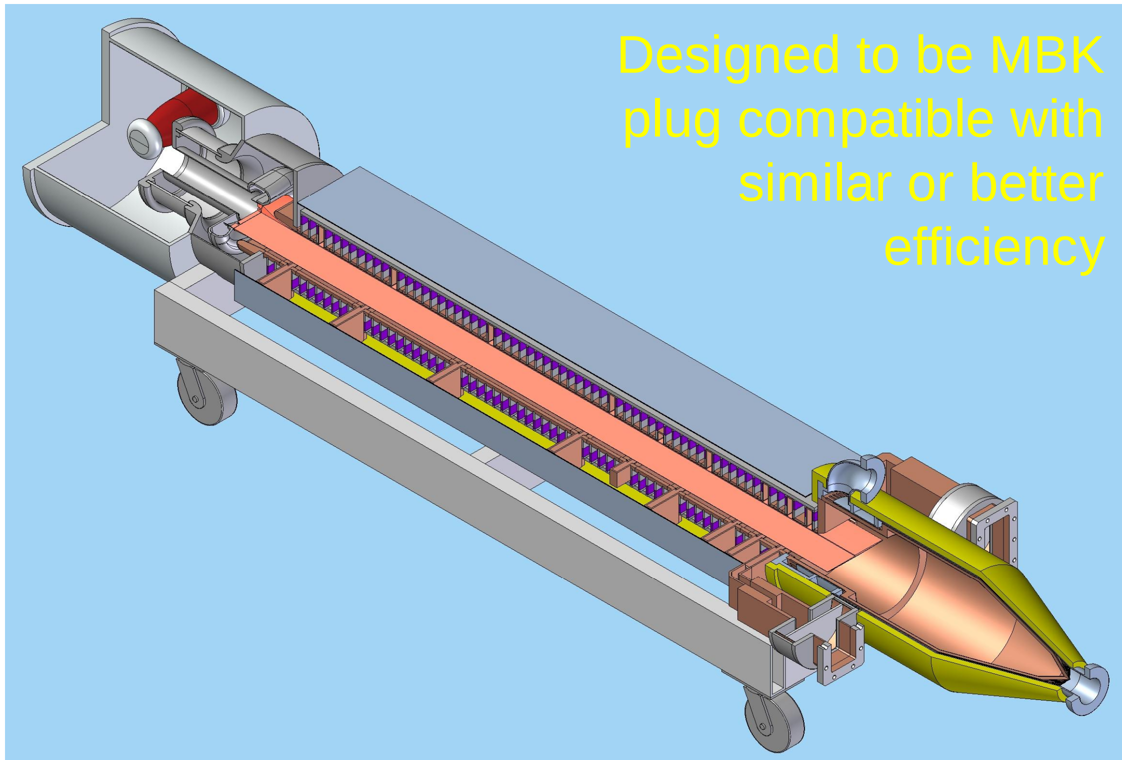
Sheet Beam Klystron Development

- **Goals:**
  - The Sheet Beam Klystron (SBK) has a 40:1 beam aspect ratio and utilizes permanent magnet focusing, making it smaller, much lighter and less expensive than the baseline Multi-Beam Klystron (MBK), for which it is plug-compatible (it also has similar efficiency).
  - Both a Beam Tester and full SBK are being built so the issues for beam transport and rf generation can be separately studied.
- **Project Status:**
  - Thus far, the Beam Tester design is complete (at least to the gun output) and fabrication is well along – expect testing this Winter.
  - The design of the full klystron is nearing completion - working to optimize the optics for 3D beam transport – expect testing in Spring, 2009

Sheet Beam Klystron Development at SLAC

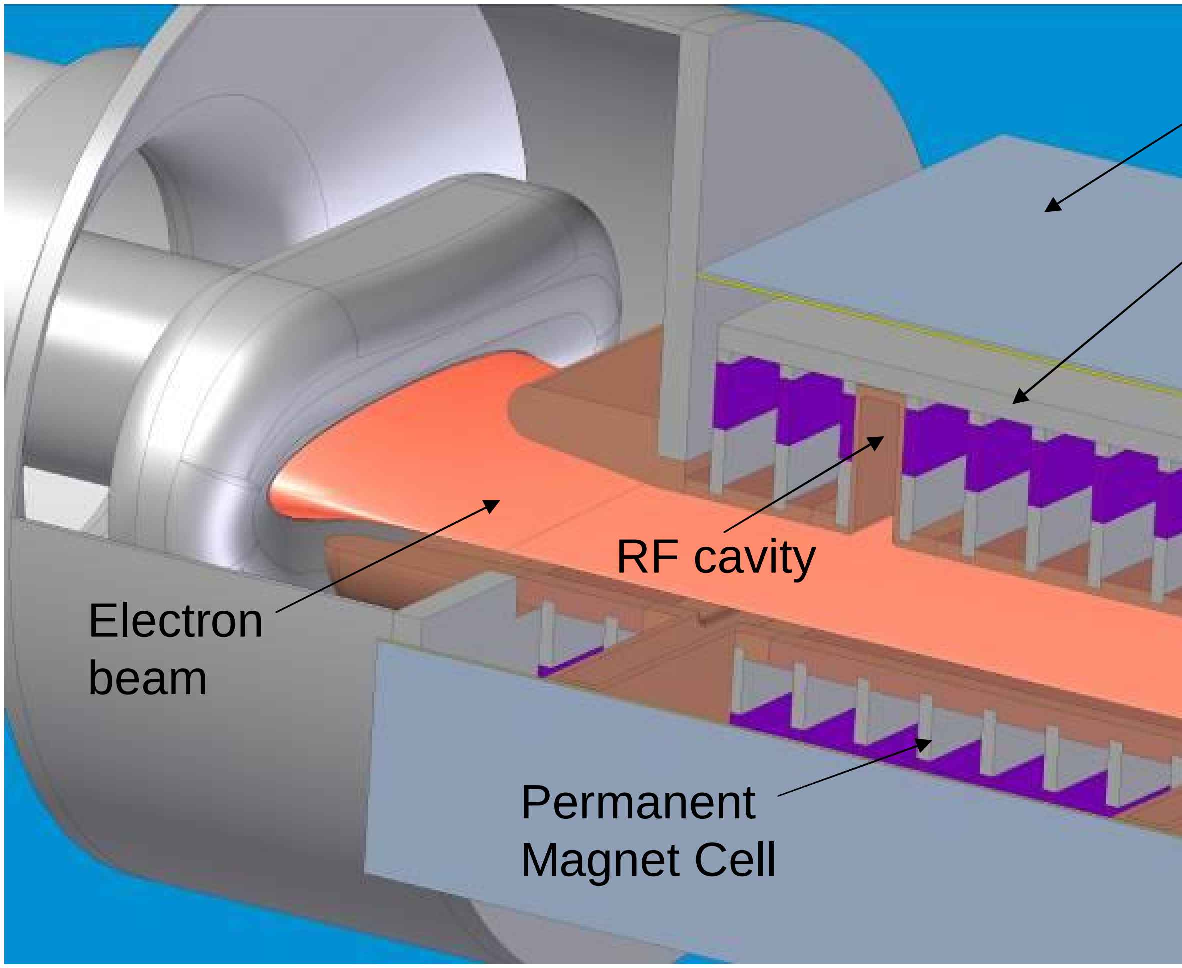
Why Sheet Beam ?

- Allows higher beam current (at a given beam voltage) while still maintaining low current density for efficiency
- Will be smaller and lighter than other options
- PPM focusing eliminates power required for solenoid



Beam Transport and RF

The elliptical beam is focused in a periodic permanent magnet stack that is interspersed with rf cavities



Lead shielding

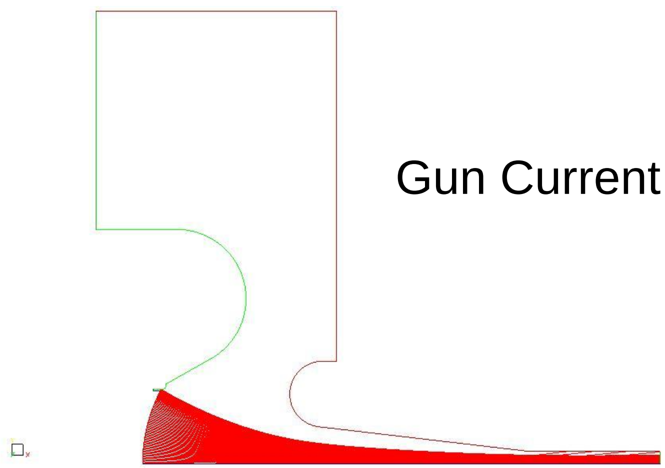
Magnetically shielded from outside world

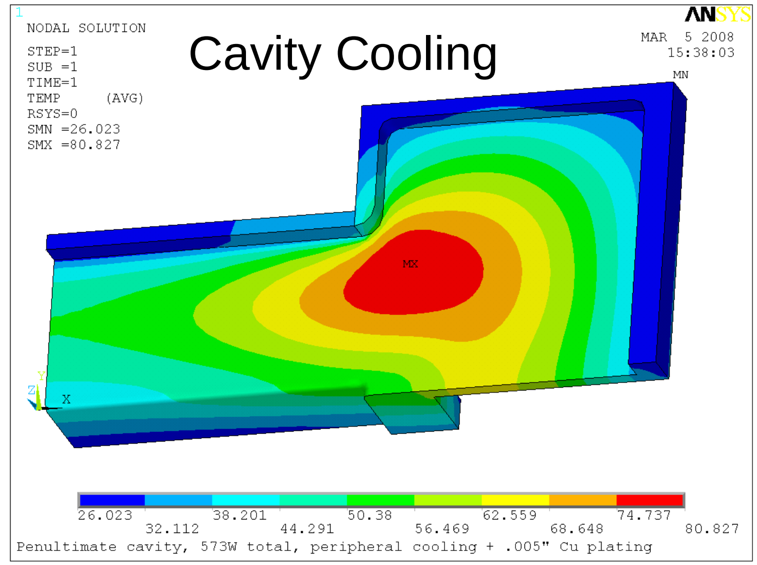
Have done:

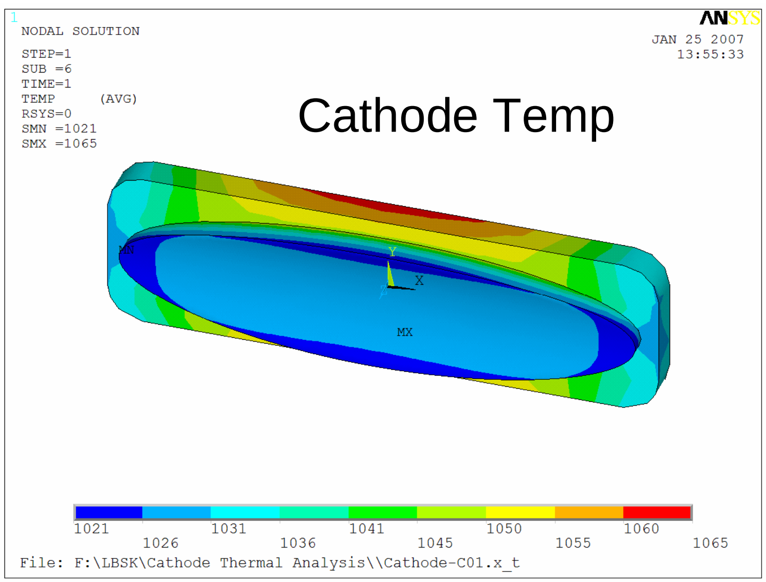
3D Gun simulations of a 130 A, 40:1 aspect ratio elliptical beam traversing 30 period structures.

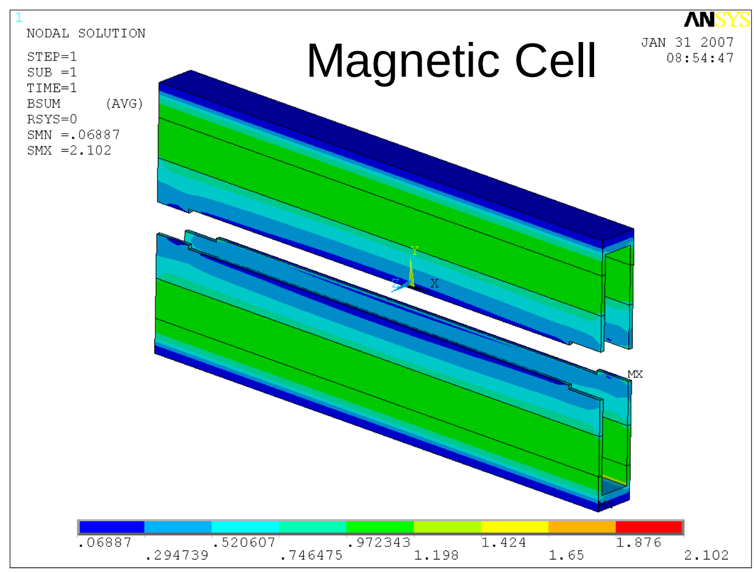
3D PIC Code simulations of rf interaction with the beam.

SBK Simulations

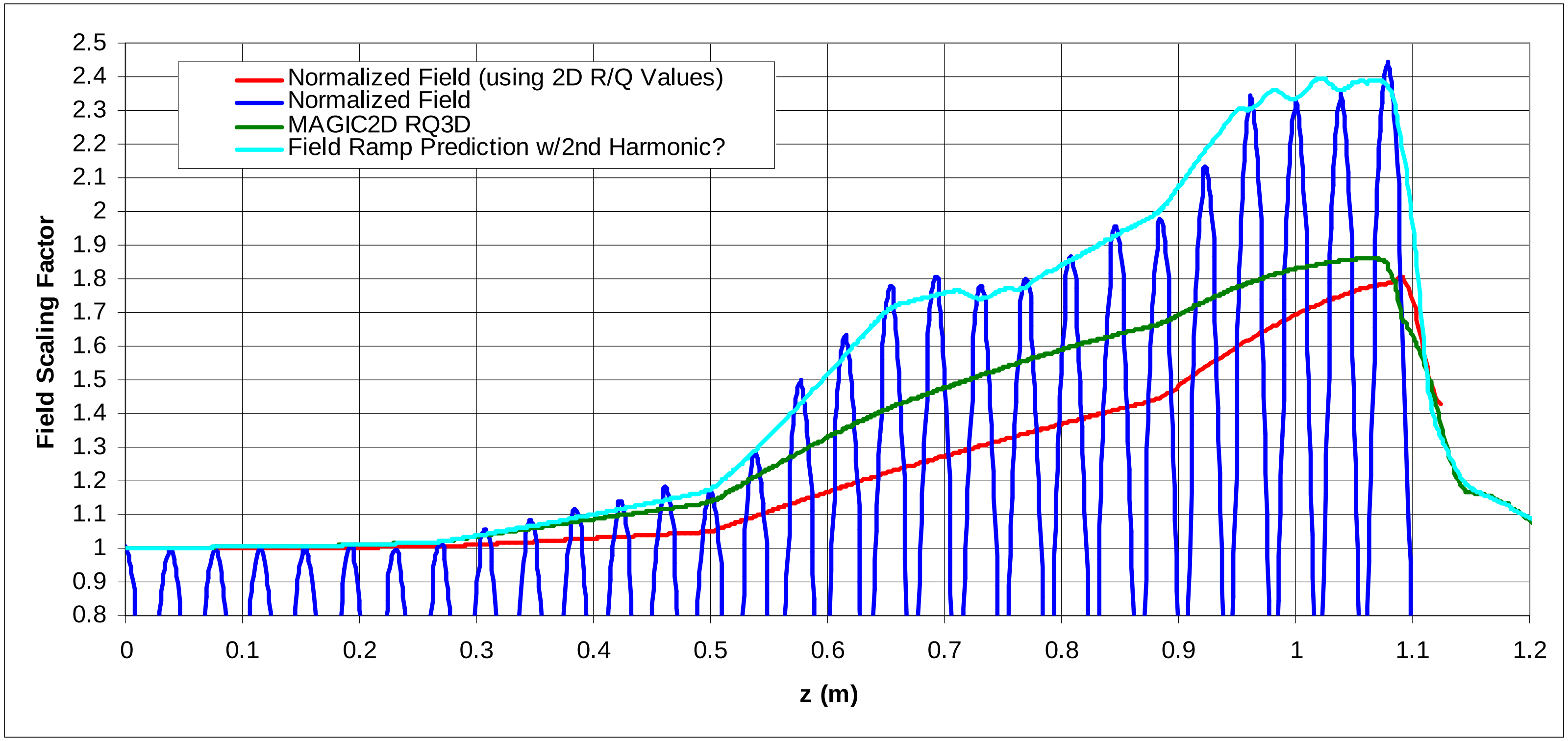


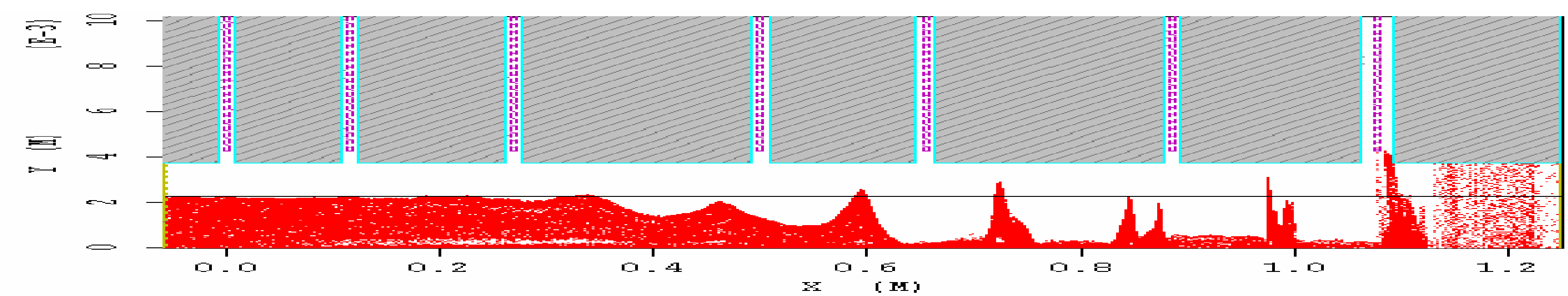




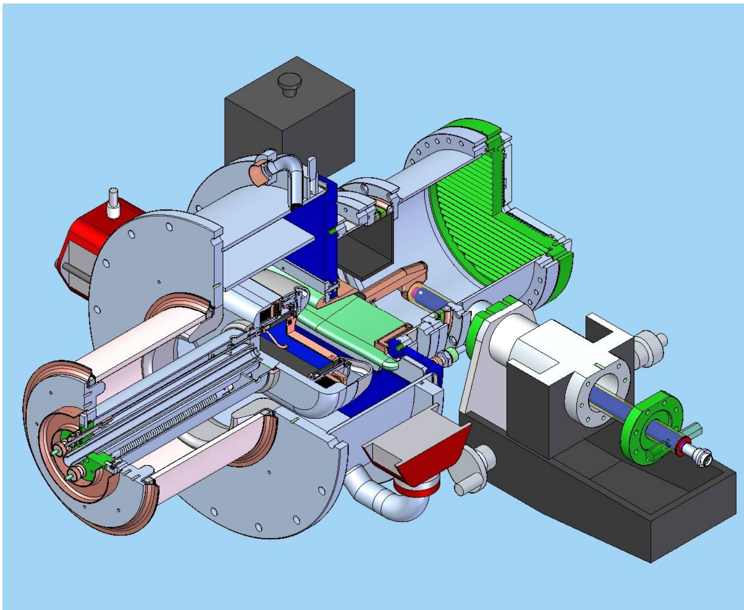


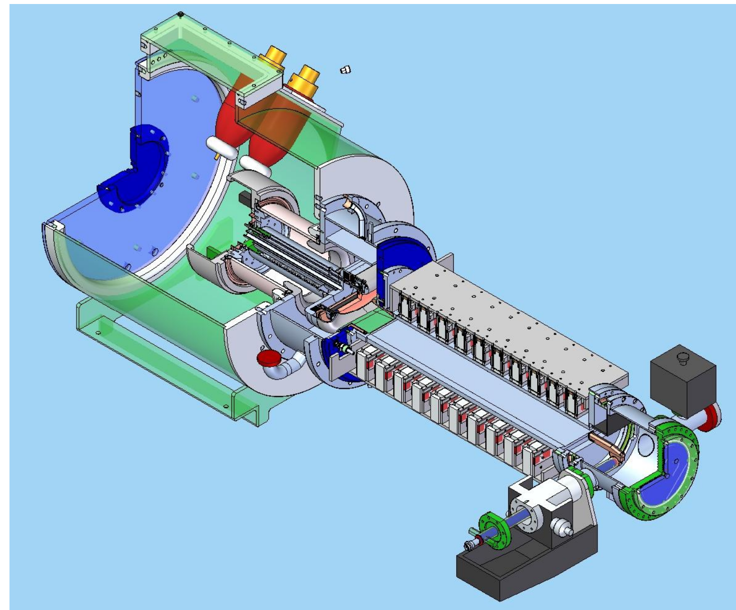
RF Simulations with Magic 2D





Design/Test Evolution





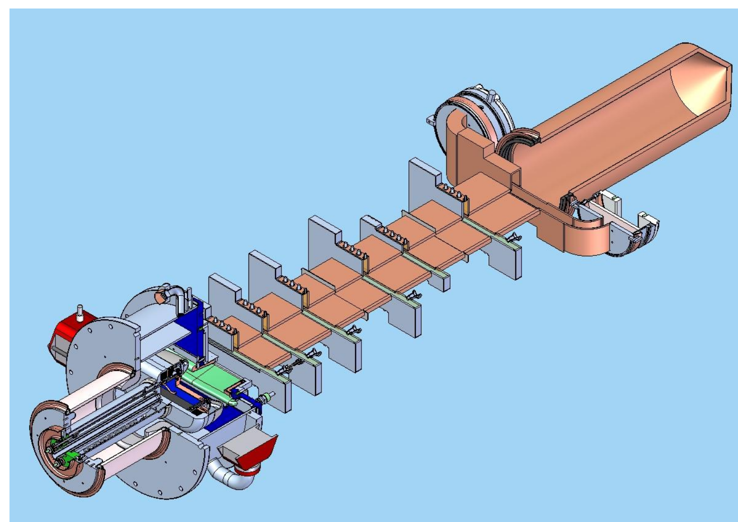
Measure Beam
From Gun

Winter 08

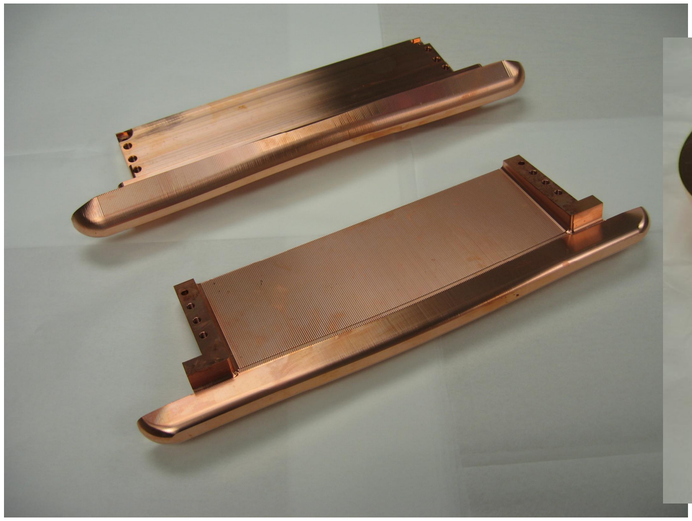
Measure Beam
after Transport
w/o RF

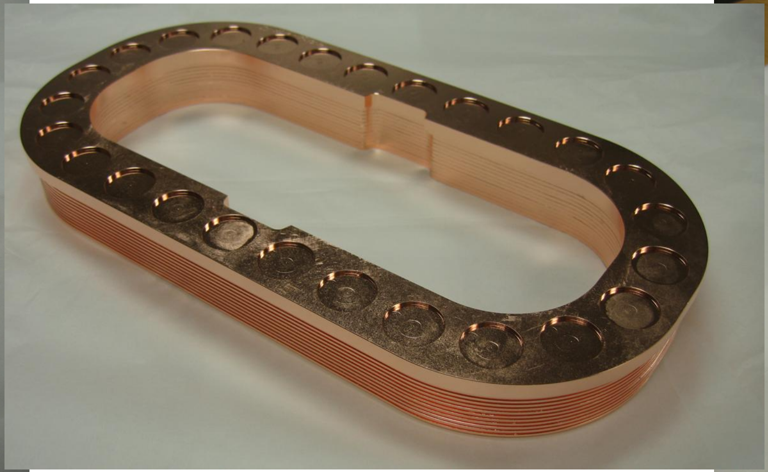
Spring 09

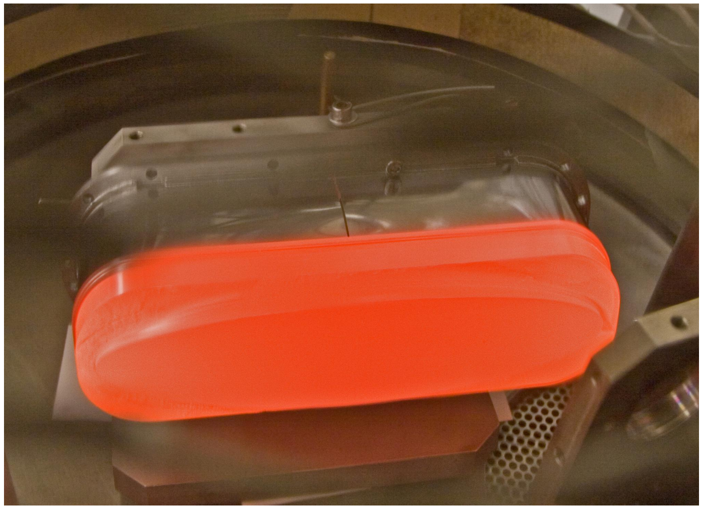
Measure RF
Generation

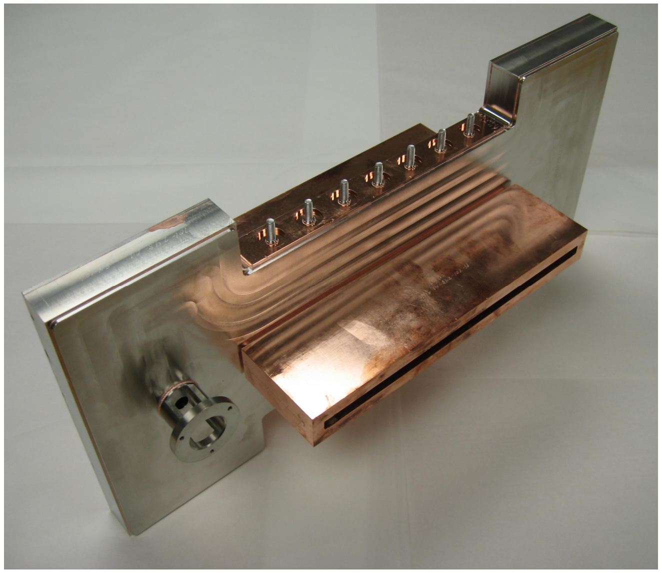


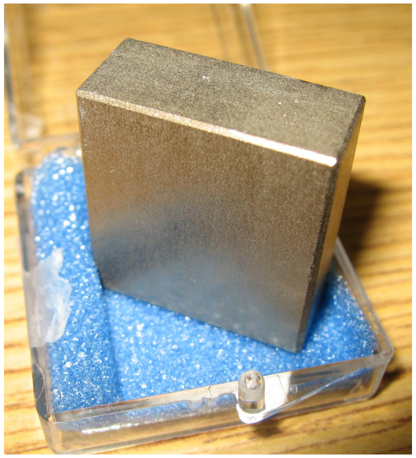
SBK Parts







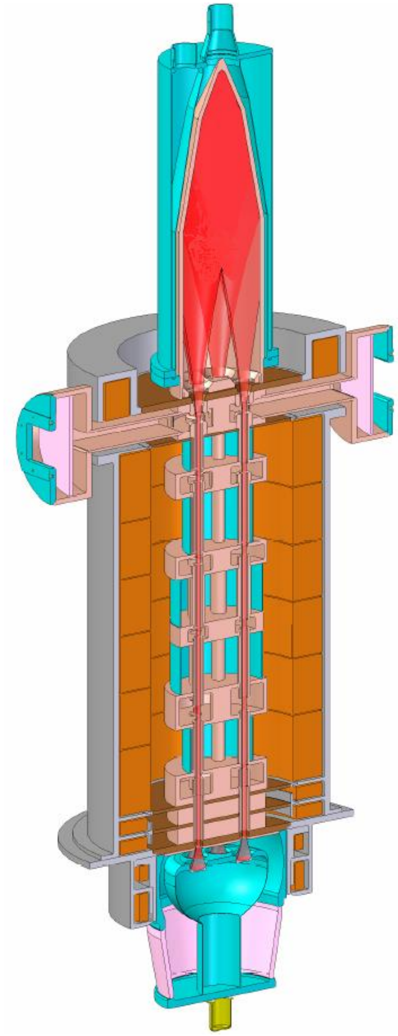




Multi-Beam Klystron Acquisition

- **Goals:**
  - Acquire 10 MW Multi-Beam Klystron (MBK) to do long term, full power testing.
  - DESY has lead the effort to develop these tubes but thus far has run them mostly at low power for cryomodule operation.
- **Project Status:**
  - In collaboration with KEK, contracted Toshiba to build a vertical MBK of the design developed for DESY (other MBK designs by CPI and Thales have not performed as well).
  - Delivered in Jan 2008 after testing at Toshiba were it performed very well (with 68% efficiency)
  - Installed in a oil tank at SLAC End Station B – waiting for the Marx modulator to power it.
  - Will eventually be shipped to FNAL to power the first full rf unit.

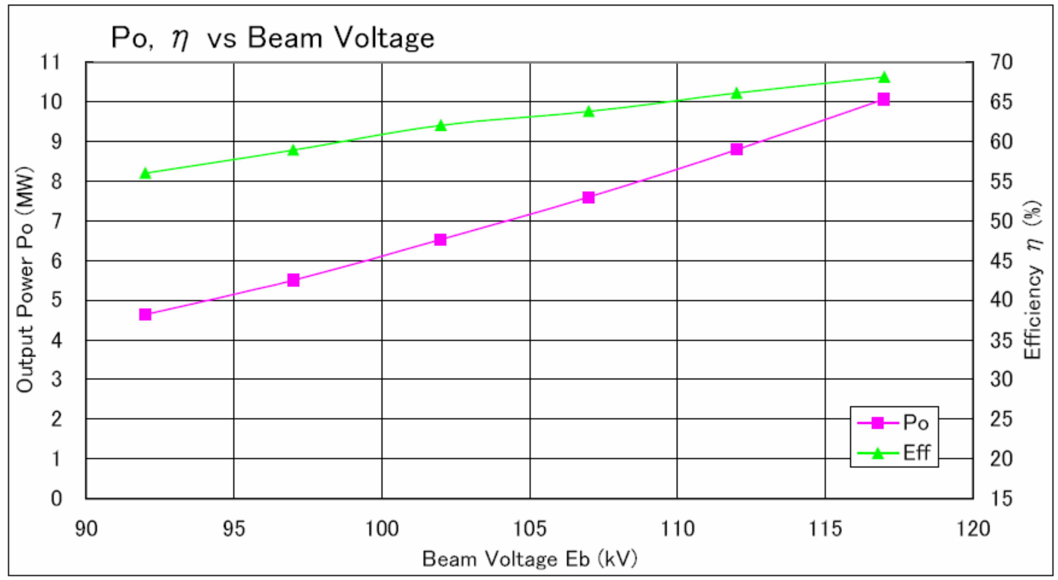
SLAC/KEK Toshiba 10 MW MBK

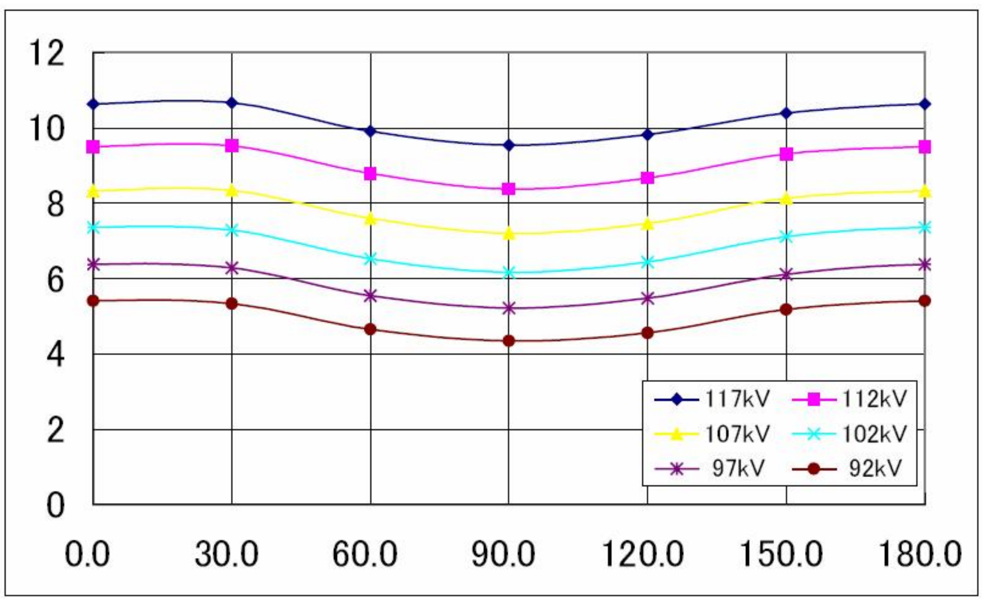


6-Beam
Gun

Test Results at Toshiba

Efficiency and Output Power -vs- Beam Voltage



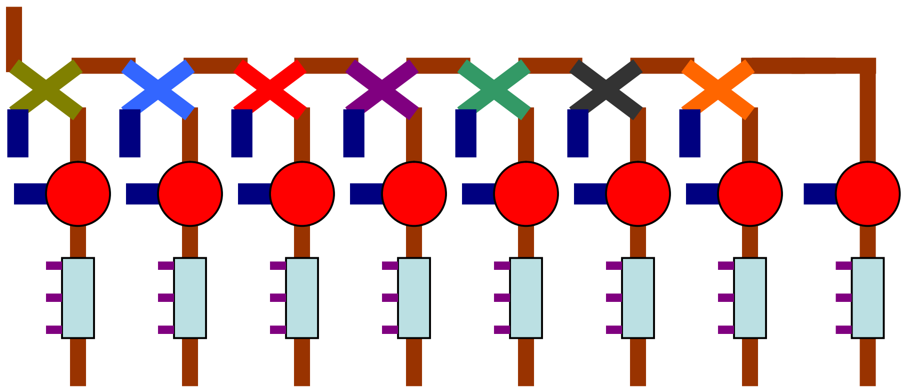


Effect of a Mismatch
(VSWR = 1.2):
Output Power -vs- Phase of Mismatch

Optimized RF Distribution System

- **Goals:**
  - Four changes to the baseline rf distribution design are being pursued to lower its cost and to control the relative power fed to each cavity, which will allow higher gradient operation when there is a large spread in cavity performance.
  - (1) Use hybrids instead of isolators (2) make the tap-offs adjustable to accommodate a large spread in cavity gradients (3) use simpler (or no) phase shifters instead of 3-stub tuners and (4) develop an in-situ waveguide welding technique to eliminate flanges. Build systems for FNAL cryomodules.
- **Project Status:**
  - A variable tap-off (VTO) and custom hybrid were built and high power tested successfully.
  - Four, 2-cavity modules are nearing completion for the first FNAL 8-cavity cryomodule – includes isolators for back-up and for beam operation.
  - Examining ways to further reduce cost of the system.

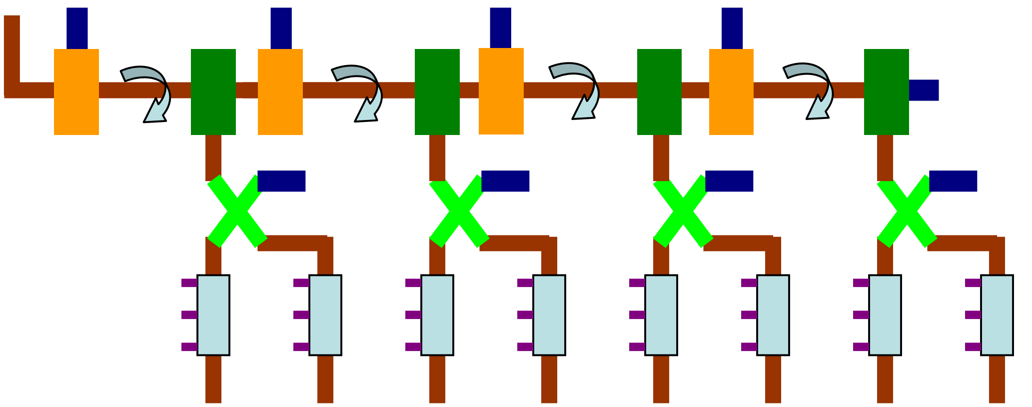
Baseline RF Distribution System



Fixed Tap-offs

Isolators

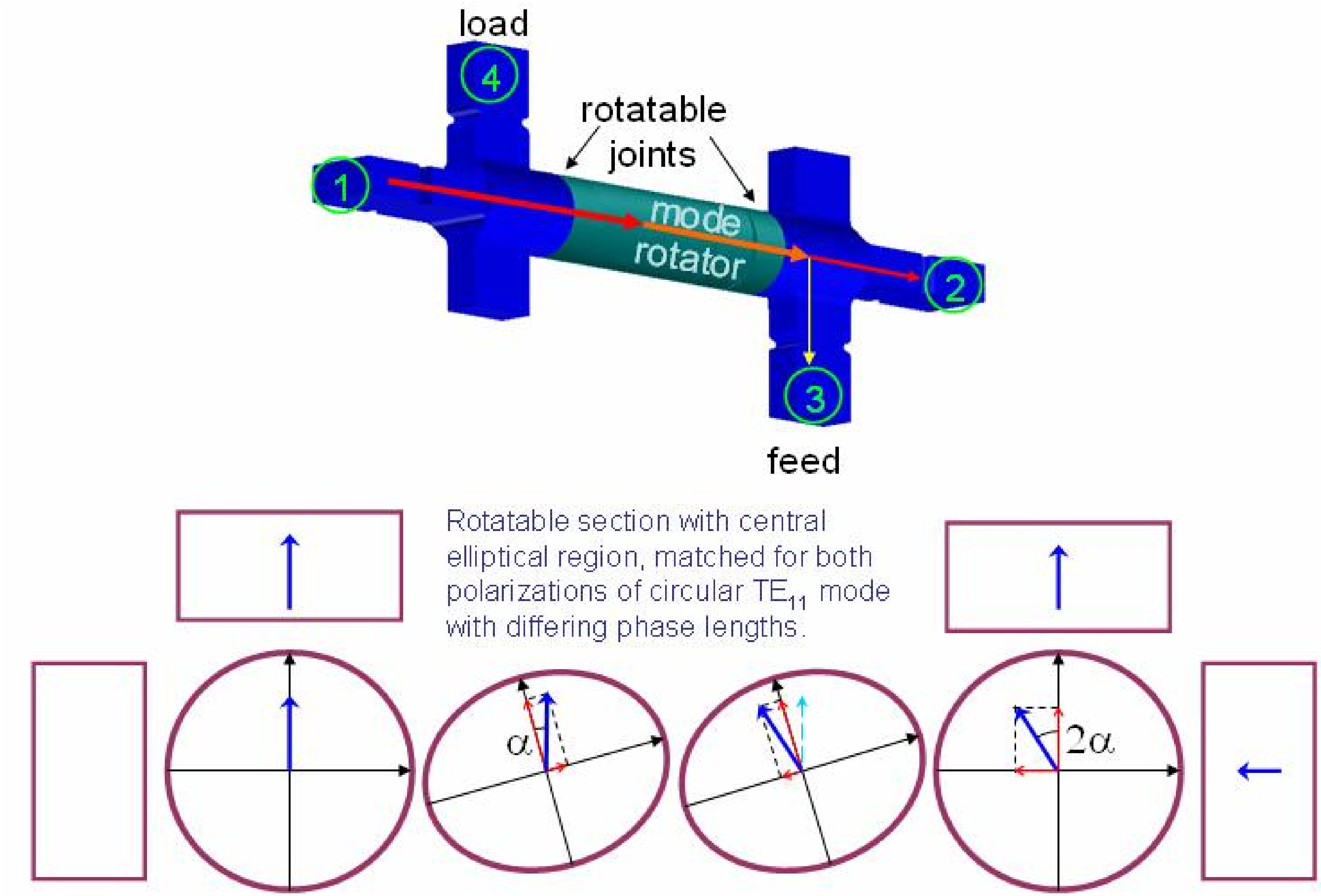
Alternative RF Distribution System



Variable Tap-offs (VTOs)

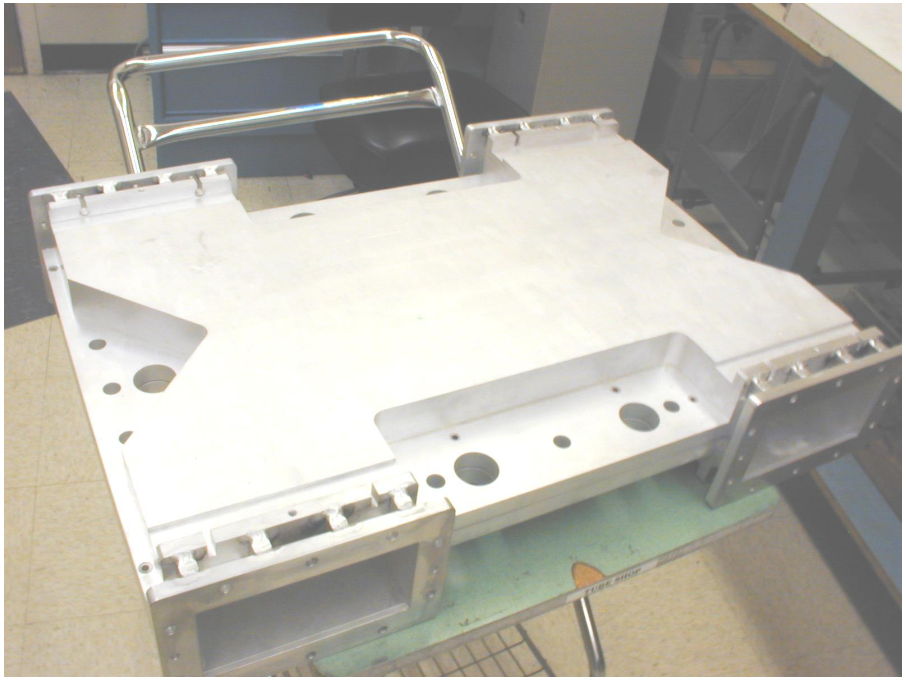
3 dB Hybrids

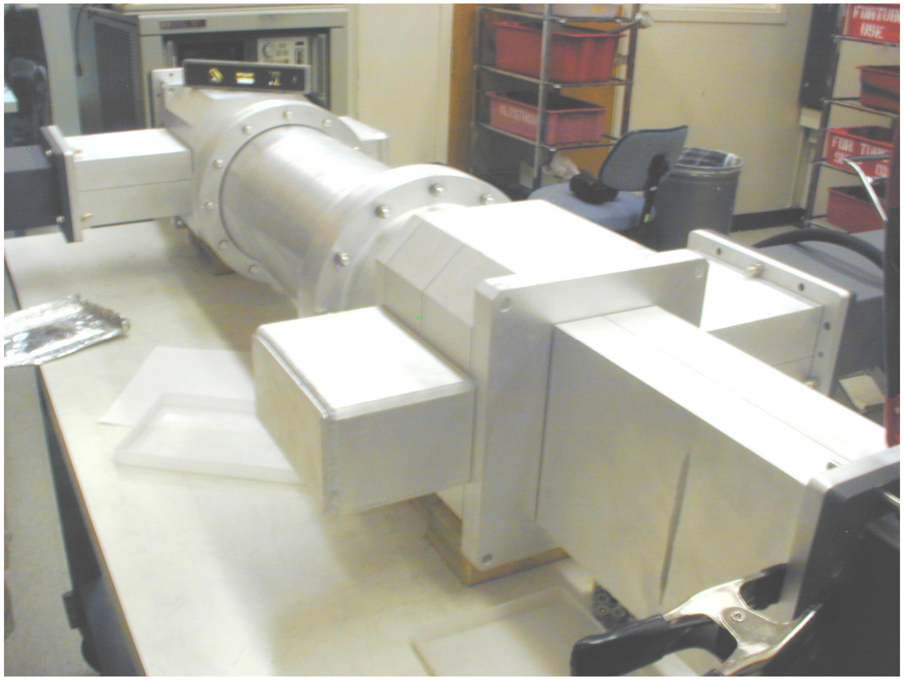
Variable Tap-Offs Using Mode Rotation

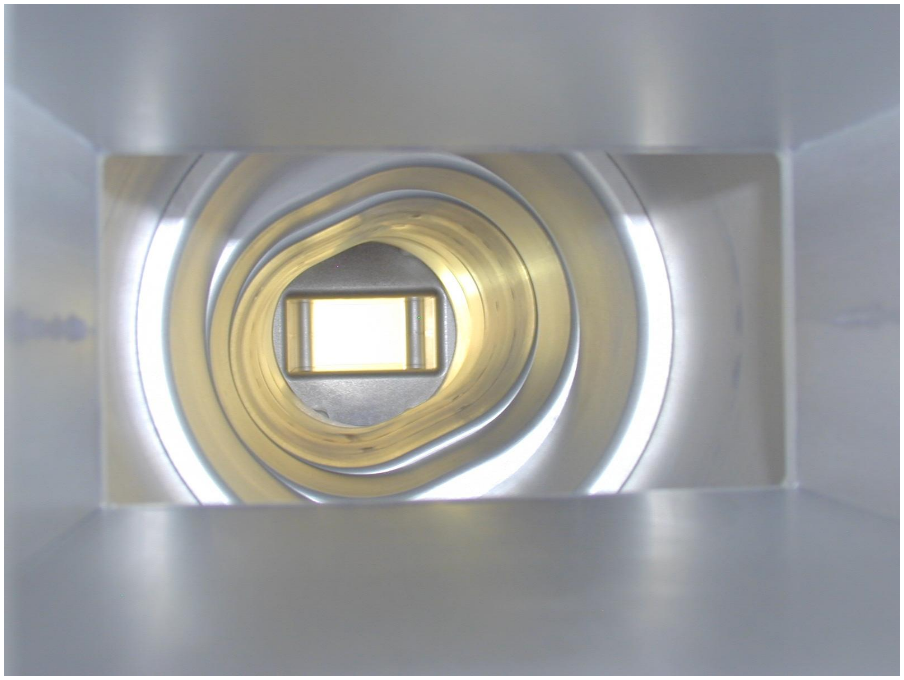


Prototype VTO (below) and Hybrid (right)

Have been individually powered, operating stably at 3 MW, 1.2 ms, 5 Hz at atmospheric pressure

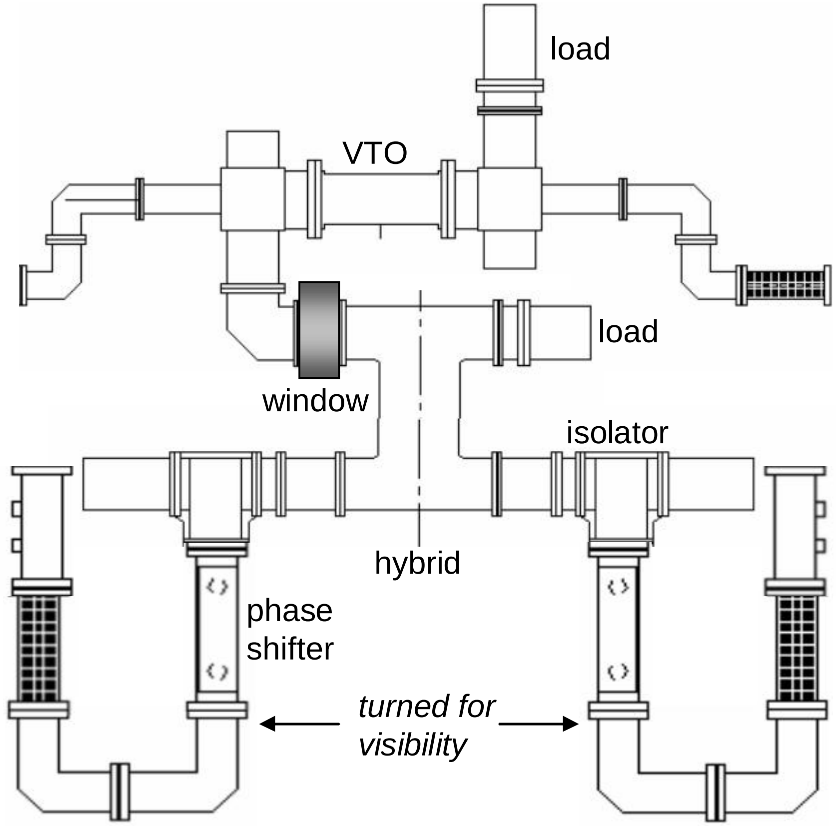


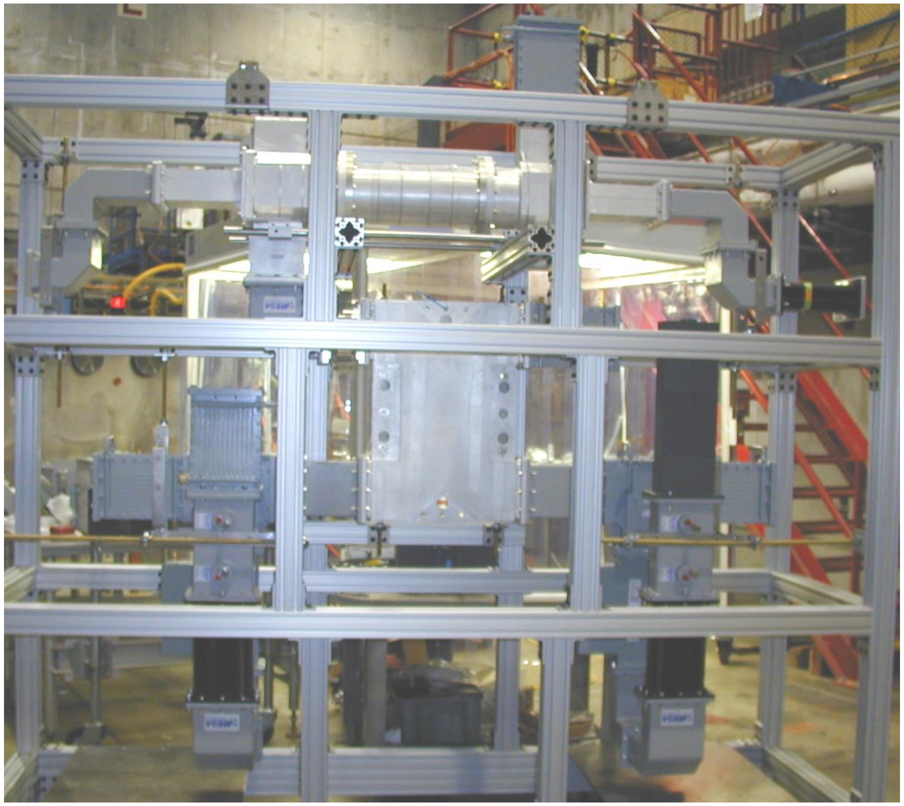




RF Distribution Modules

One (of 4) 2-cavity distribution modules that are being built to power FNAL's first cryomodule – expect to complete assembly and high power testing in the next few months

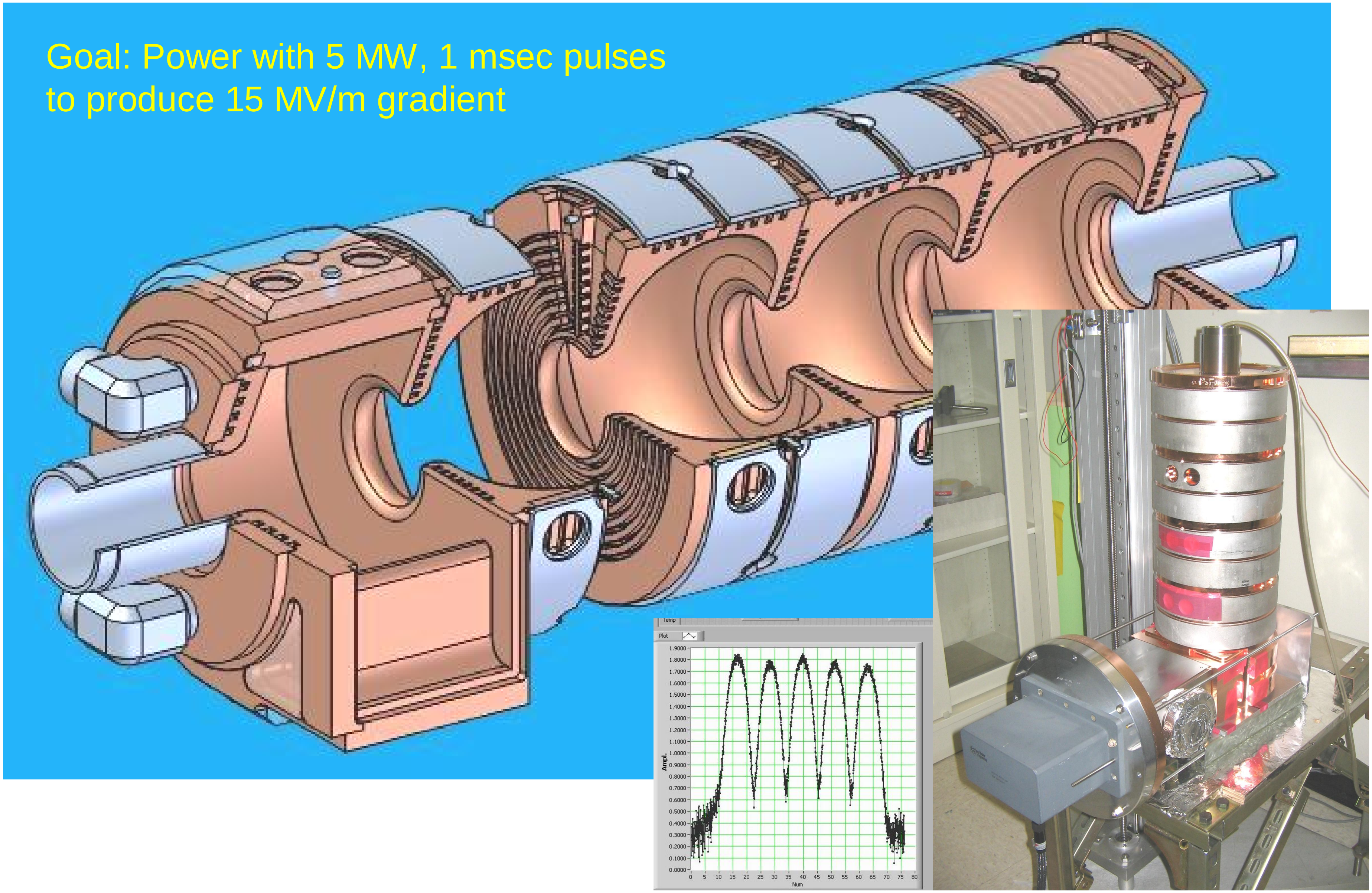




NC Positron Capture Structure

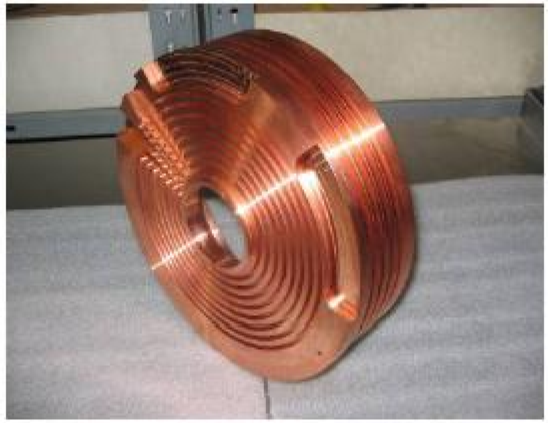
- **Goals:**
  - Test a prototype ILC normal-conducting, positron-capture cavity to verify that
    - The required 15 MV/m gradient can be achieved reliably in 1 ms long pulses
    - It can operate in a 0.5 T solenoidal field
    - The generated heat (25 kW) can be removed effectively to limit cavity detuning.
- **Project Status:**
  - The cavity has been installed in the NLCTA beamline in a 0.5 T solenoidal magnet, as would be the case in ILC.
  - The cavity has been processed to ~ 15 MV/m with 1 ms pulses (solenoid off) and operated with beam.
  - Still to do: complete processing with and without solenoid, and operate with beam at maximum gradient (were modulator limited for the last 5 months).

ILC Positron Capture Cavity Prototype



Some of Completed Sub-assemblies

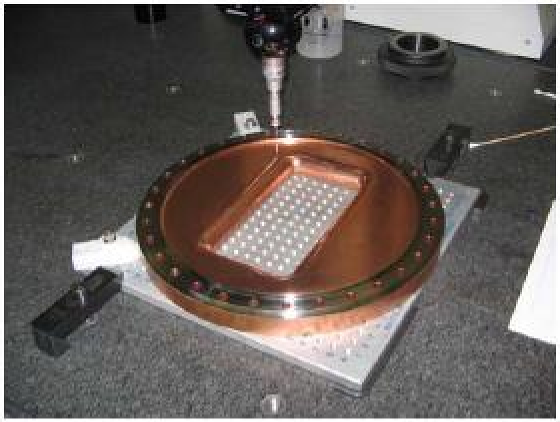
Input coupler cell



Half cell attached to coupler

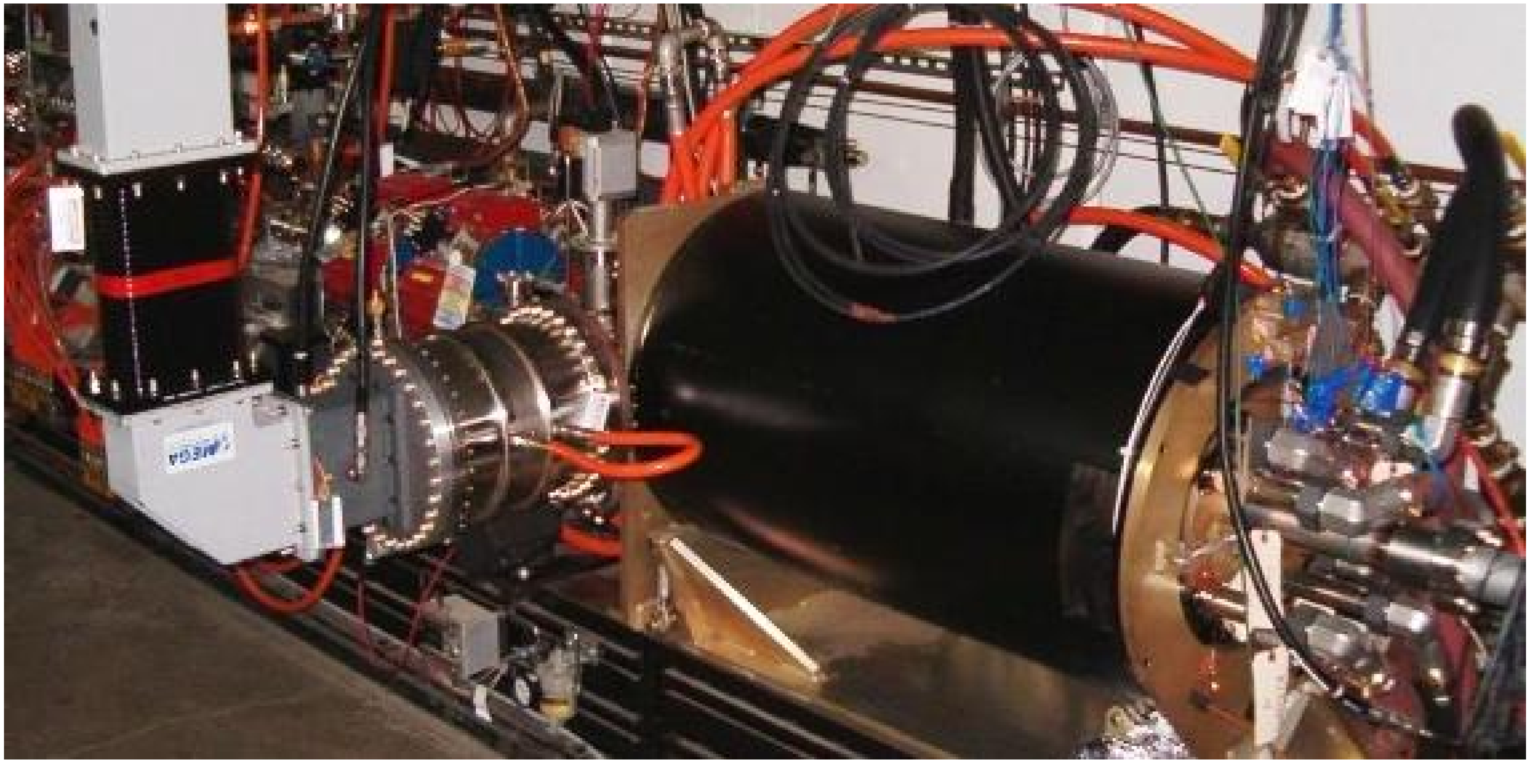
Completed unit cell

L-Band RF window



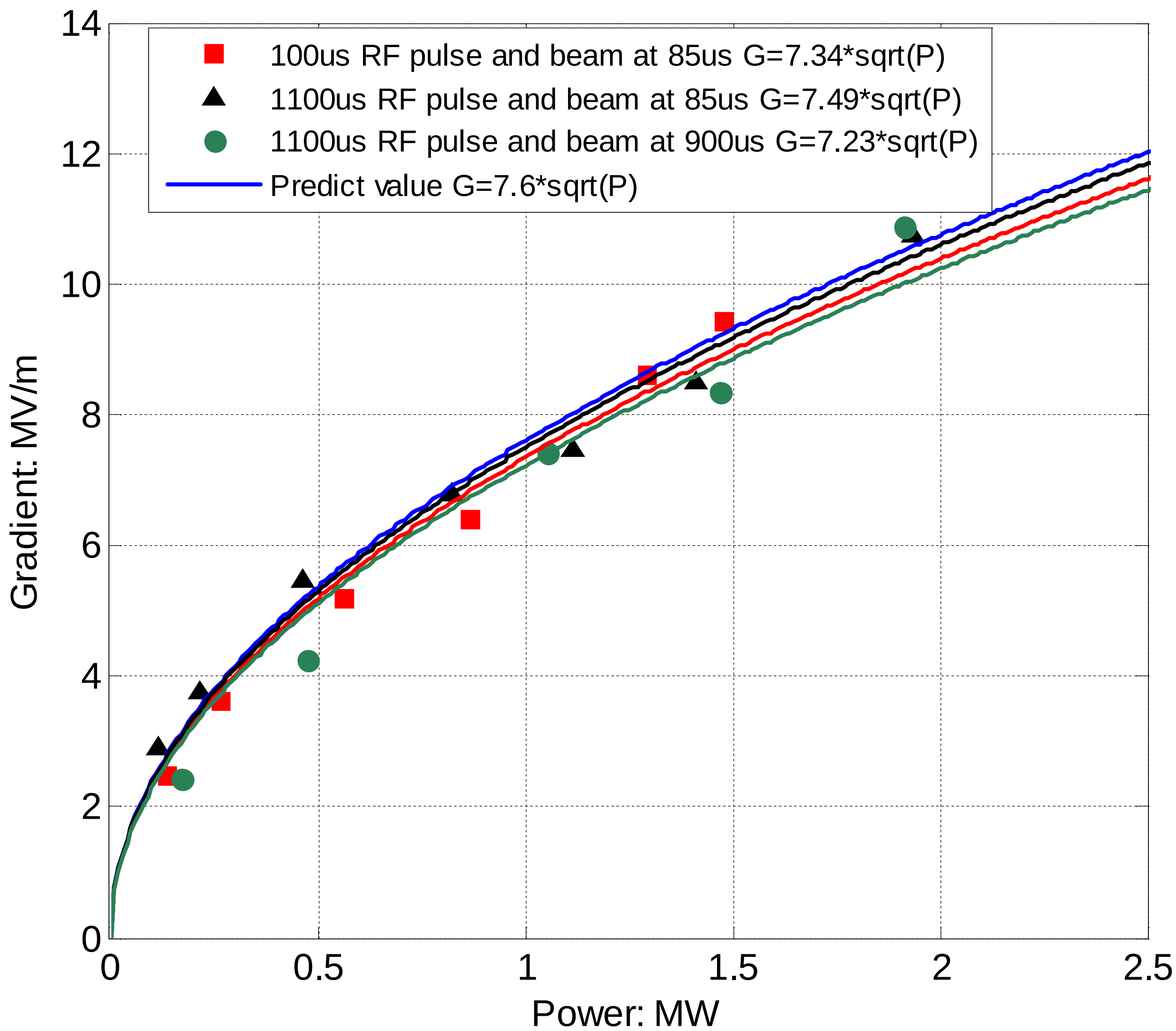
L-Band Vacuum Flange for Accelerator/Coupler

Cavity Installed in NLCTA in a 0.5 T Solenoid with 100 GPM Cooling



Cavity Gradient Measurements with Beam

(World's first L-band cavity operation in an X-band Linac)



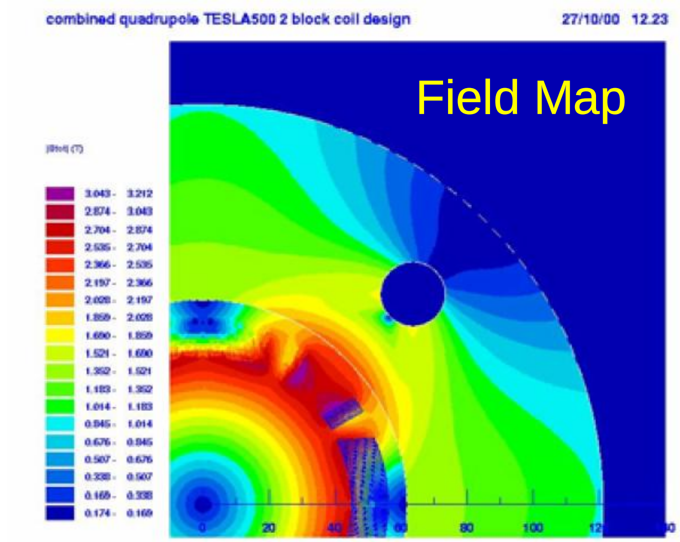
SC Linac Quad & BPM

- **Goals:**
  - Characterize field properties of a prototype linac SC quad.
  - Verify quad center moves < ~ 1 microns when the field strength is changed by 20% as required for beam based alignment.
  - Develop cavity BPMs with micron-scale resolution for multi-bunch (200 ns spacing) operation.
- **Project Status:**
  - In FY06, acquired a prototype SC linac quad from CIEMAT/DESY.
  - Construction of a warm-bore cryostat to operate this magnet at 4 K was completed after many problems.
  - A custom rotating coil system, originally developed for NLC, is being used to characterize the quad and dipole fields
  - The S-band rf cavity bpms were built and tested successfully with beam in End Station A (ESA). Data taken there the last few years is being analyzed to understand the stability of the relative bpm alignment.

ILC Linac SC Quad/BPM Evaluation

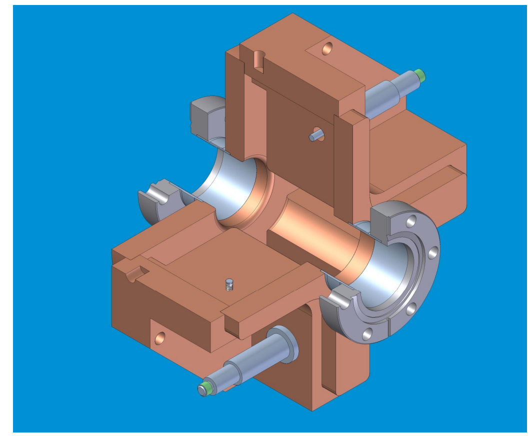
Cos(2Φ) SC Quad

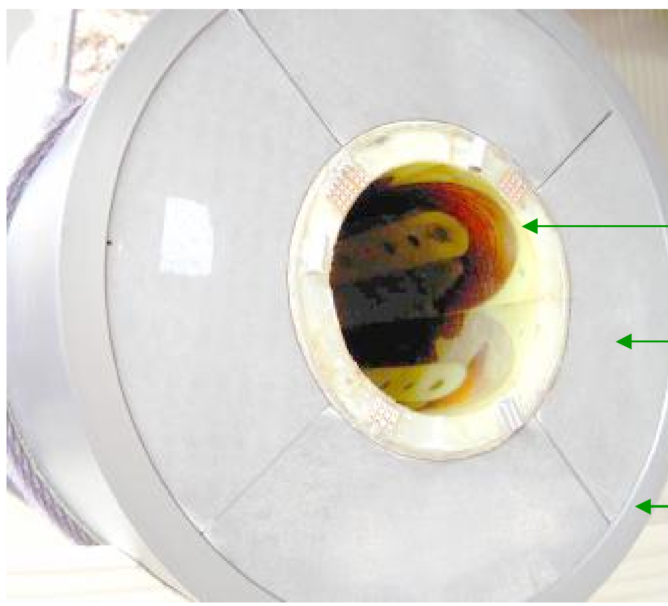
(~ 0.7 m long)



S-Band BPM Design

(36 mm ID, 126 mm OD)



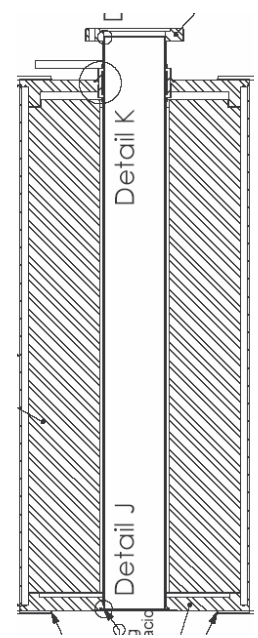


He Vessel

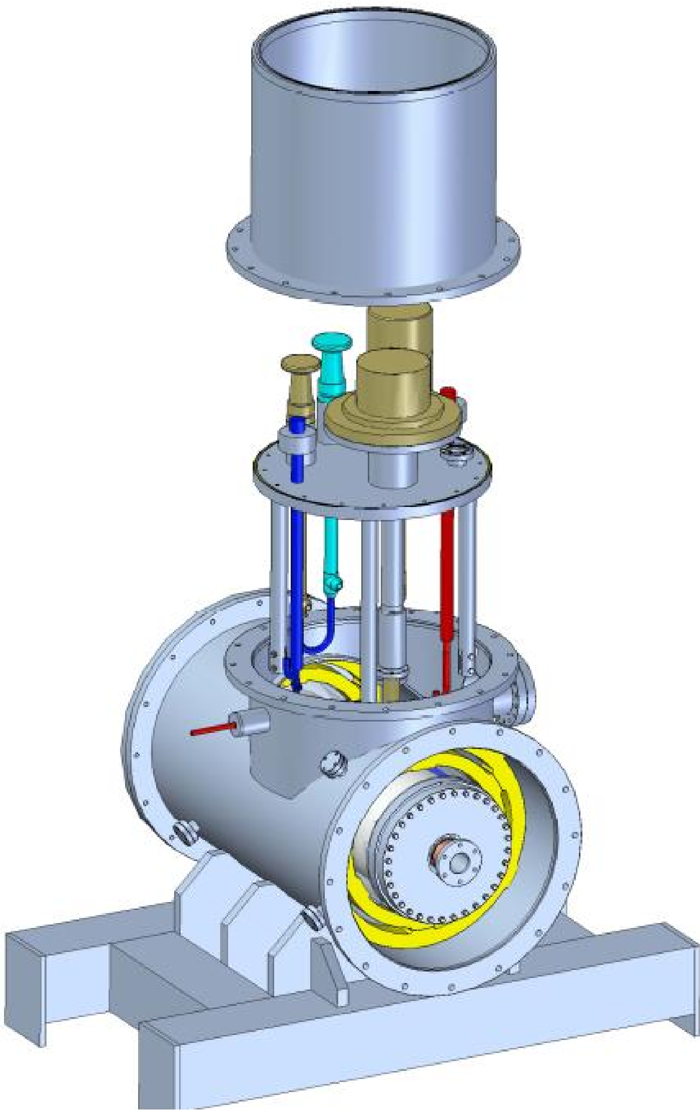
SC Coils

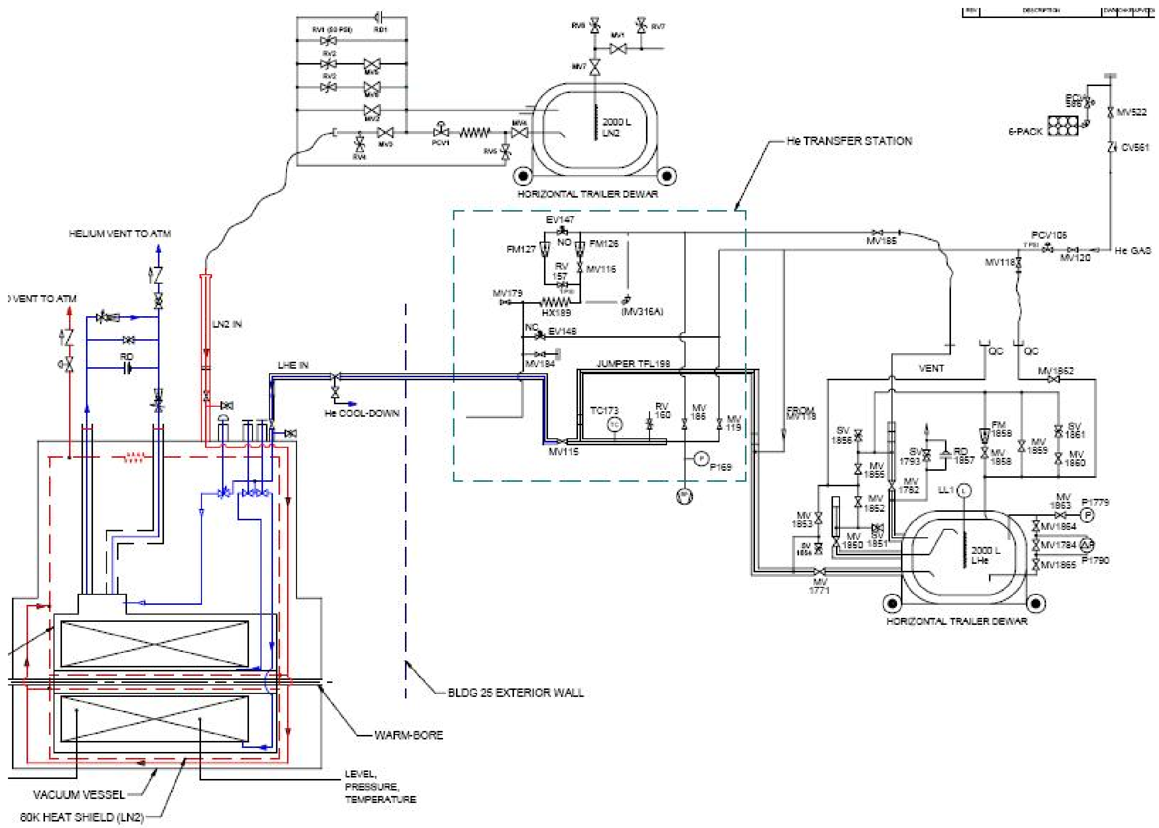
Iron Yoke Block

Al Cylinder



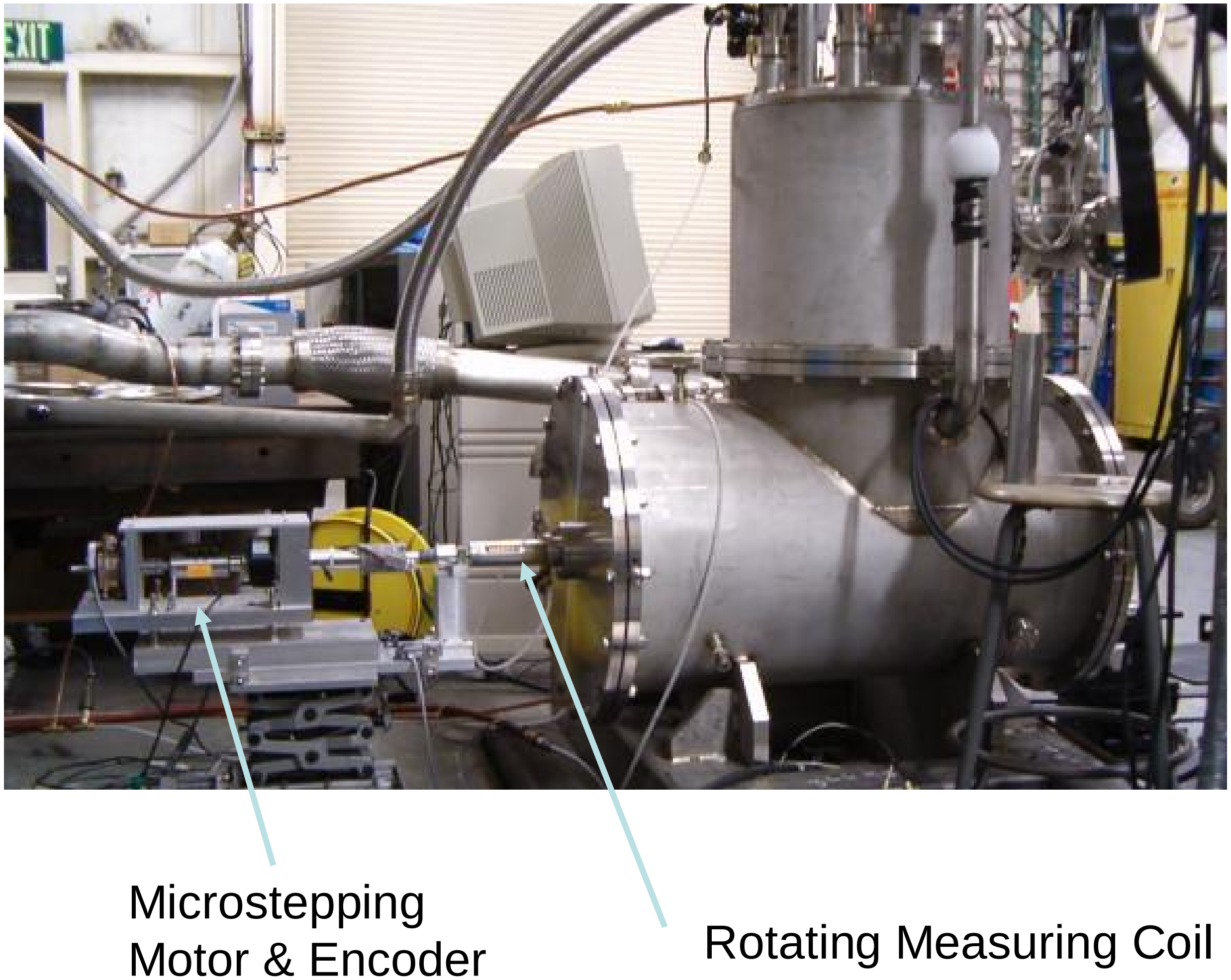
Cryostat and Cryogenic System





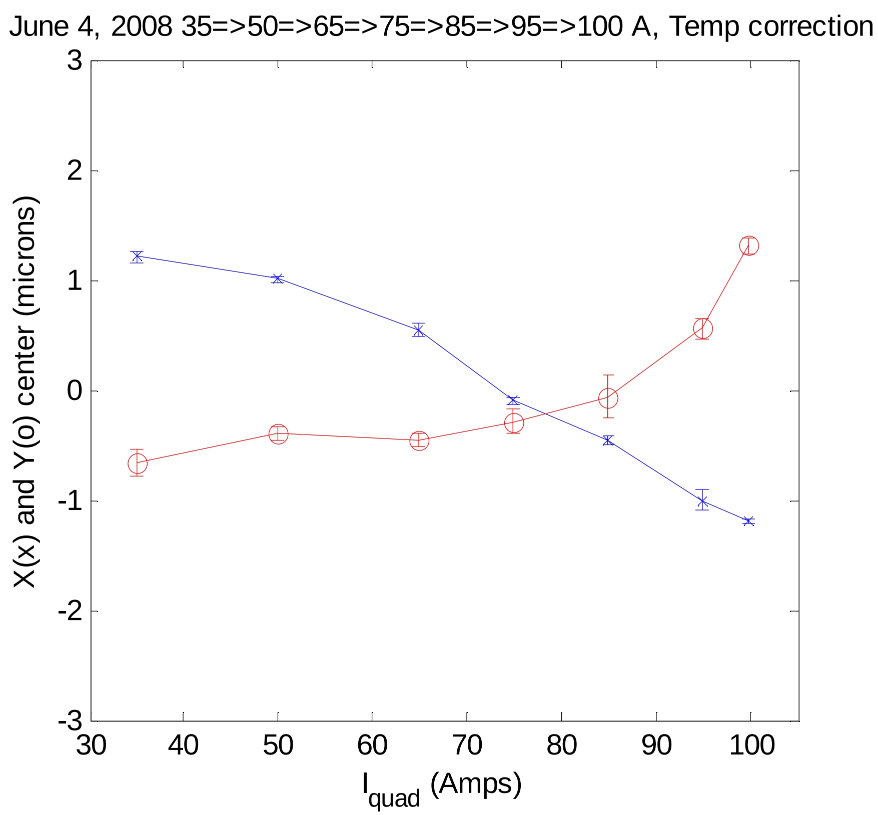
ILC SC QUAD CRYOSTAT

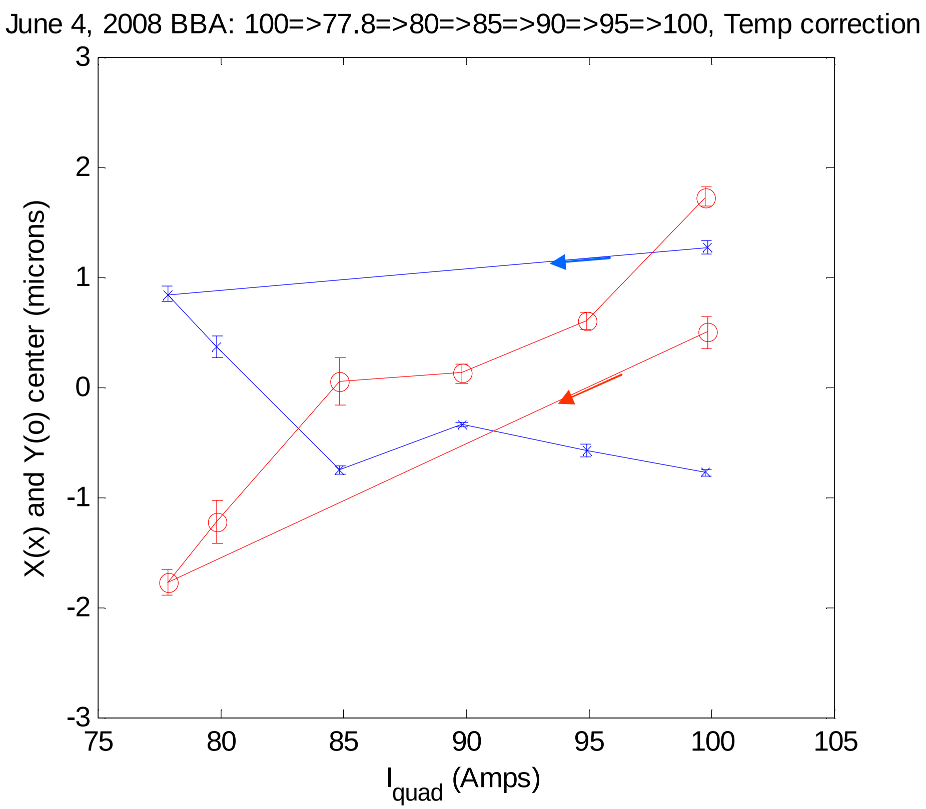
Cryostat and Quad/Corrector PS



World's First High Precision Measurement of the Magnet Center Stability of a SC Quad

Center Motion < ~ 2 microns with 20% Field Change – Close to ILC Requirement

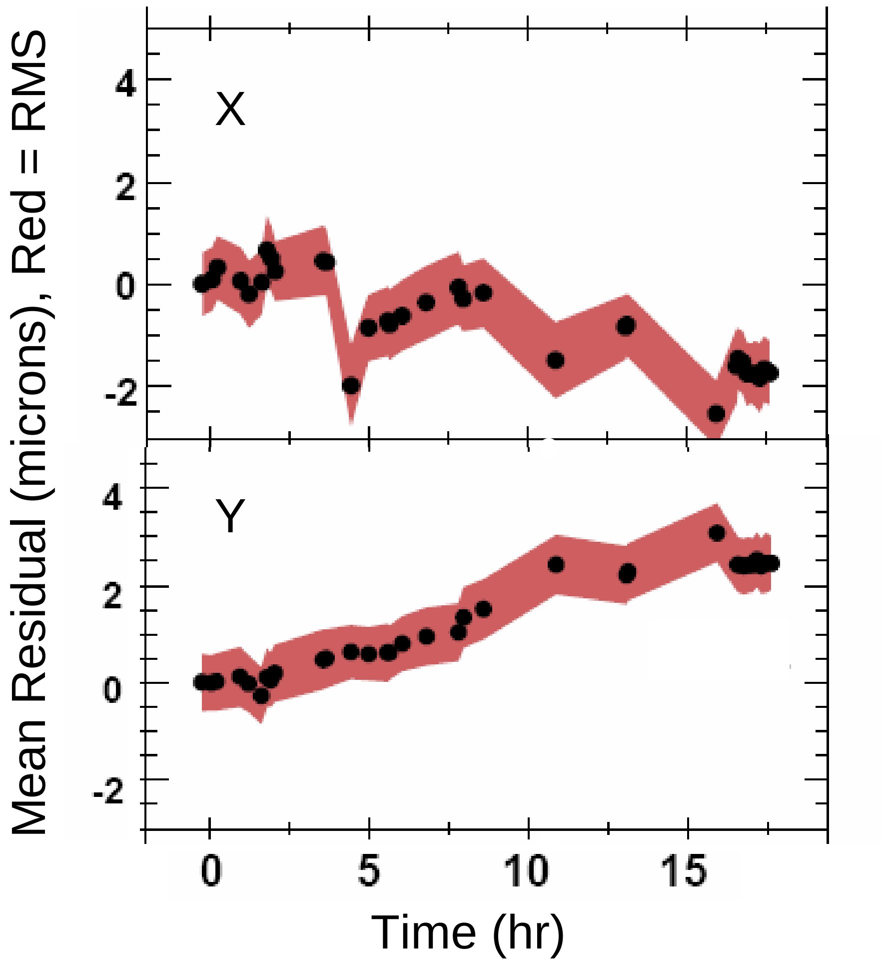


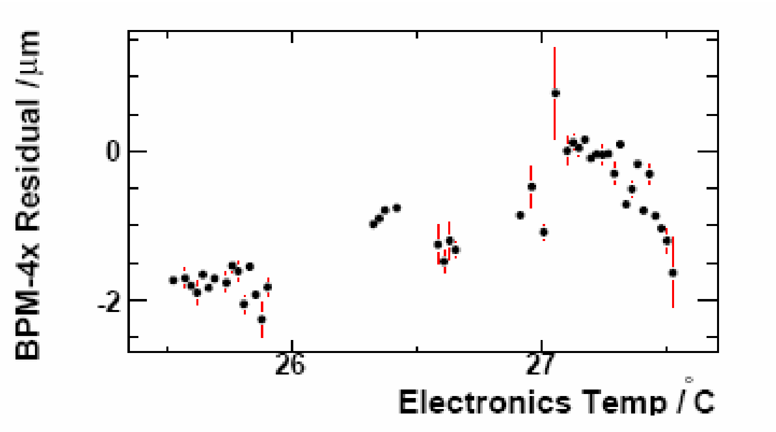


BPM Triplet Stability Results

(~ 0.5 micron resolution, 1.4e10 electrons, Q of 500 for clean bunch separation)

Final SLAC ESA Run Slated for June 2008 Canceled due to Budget Constraints





M. Slater, et al., Nucl. Instr. and Meth. A (2008), doi:10.1016/j.nima.2008.04.033

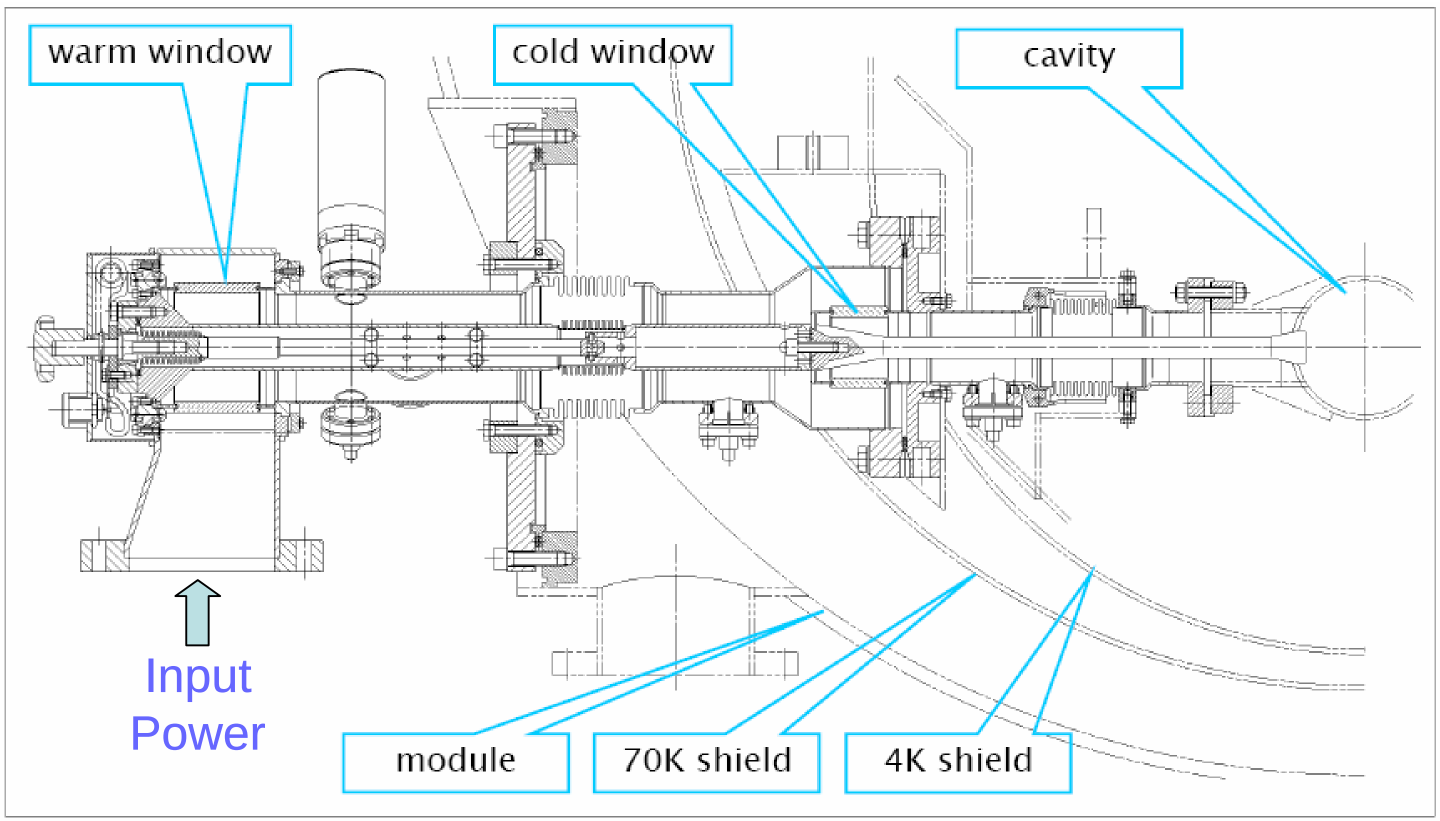
Coupler Assembly & Processing

- **Goals:**
  - Setup a class 10 clean room at SLAC to clean and assemble cavity couplers from parts built by CPI (no welding required). Similar to Orsay facilities used to supply couplers to DESY.
  - Once assembled, pairs of couplers will be rf processed at the L-Band test area at End Station B and then shipped to FNAL.
- **Project Status:**
  - Received 12 couplers ordered from CPI by FNAL – being Inspected to look for assembly errors/defects (history of poor QC by CPI)
  - Class 10 clean room being assembled
  - Developed a pizza-box-like connector to rf process a pair – recently processed first pair successfully (in 17 hours)
  - Expect to begin shipping couplers to FNAL is Fall

TTF-3 Coupler Design

Design complicated by need for tunablity (Qext), dual vacuum windows and bellows for thermal expansion.

Coaxial Power Coupler

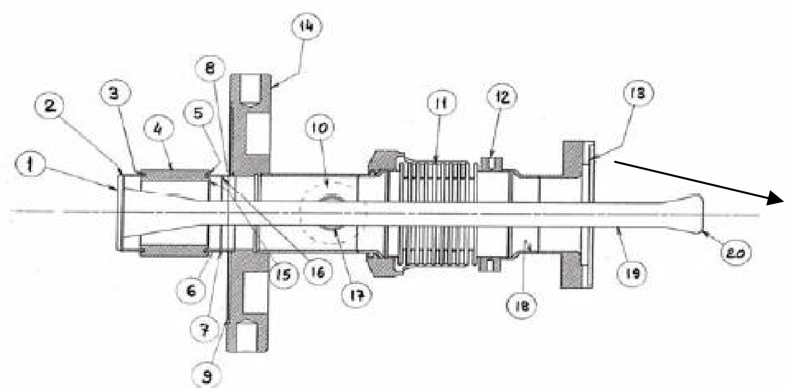


Received 12 Couplers Ordered from CPI by FNAL – Being Inspected

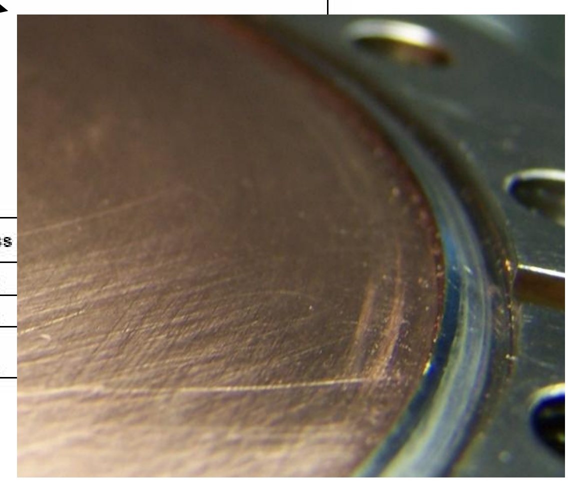
STANFORD LINEAR ACCELERATOR CENTER

TTF3 Coupler Metrology Report

Inspection of Cold Part 3964328/A.000					
Serial Number:	CP3C41	Inspector:	Keith Caban (CMM)	Date:	11/9/2007
Serial Number:	CP3C41	Inspector:	Tom Nakashima Video	Date:	11/14/2007

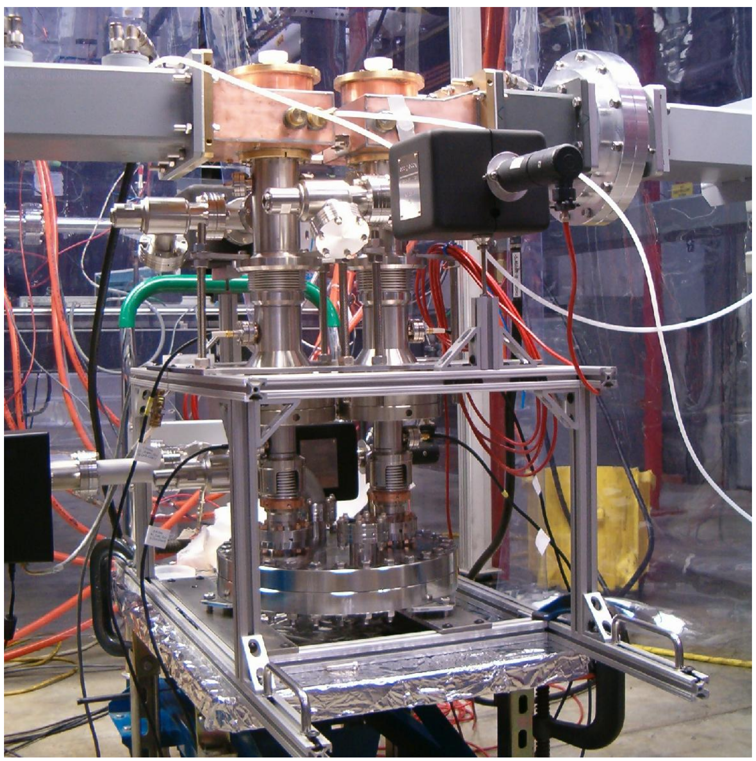


Item	Inspection Criteria	DESY Print Number	LAL Print Number	Findings	Pass
1	Visual: Nicks, scratches, proper edge chamfers	3964328/A.003	I65-3D-1250		X
2	Visual: Weld form, size, and porosity	3964328/A.000	I55-2E-1200		X
3	Visual: Brazing: Irregularities, centering of groove , buildup Ceramic: metallization borderline,coverage, chamfer	3964328/A.200	I65-3S-1260		X

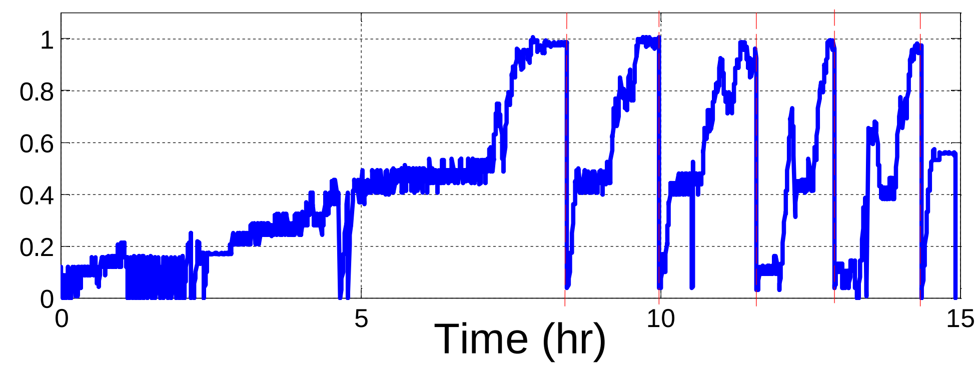


Coupler Sub-Assemblies and RF Processing Stand

Instrumented Coupler Test Stand at SLAC ESB



Processing of First Pair after a 150 °C Bake: Power (MW) -vs- Time for Pulse Widths of 50,100, 200, 400, 800, 1000 μs



Clean Room Being Constructed at SLAC

Storage Lockers

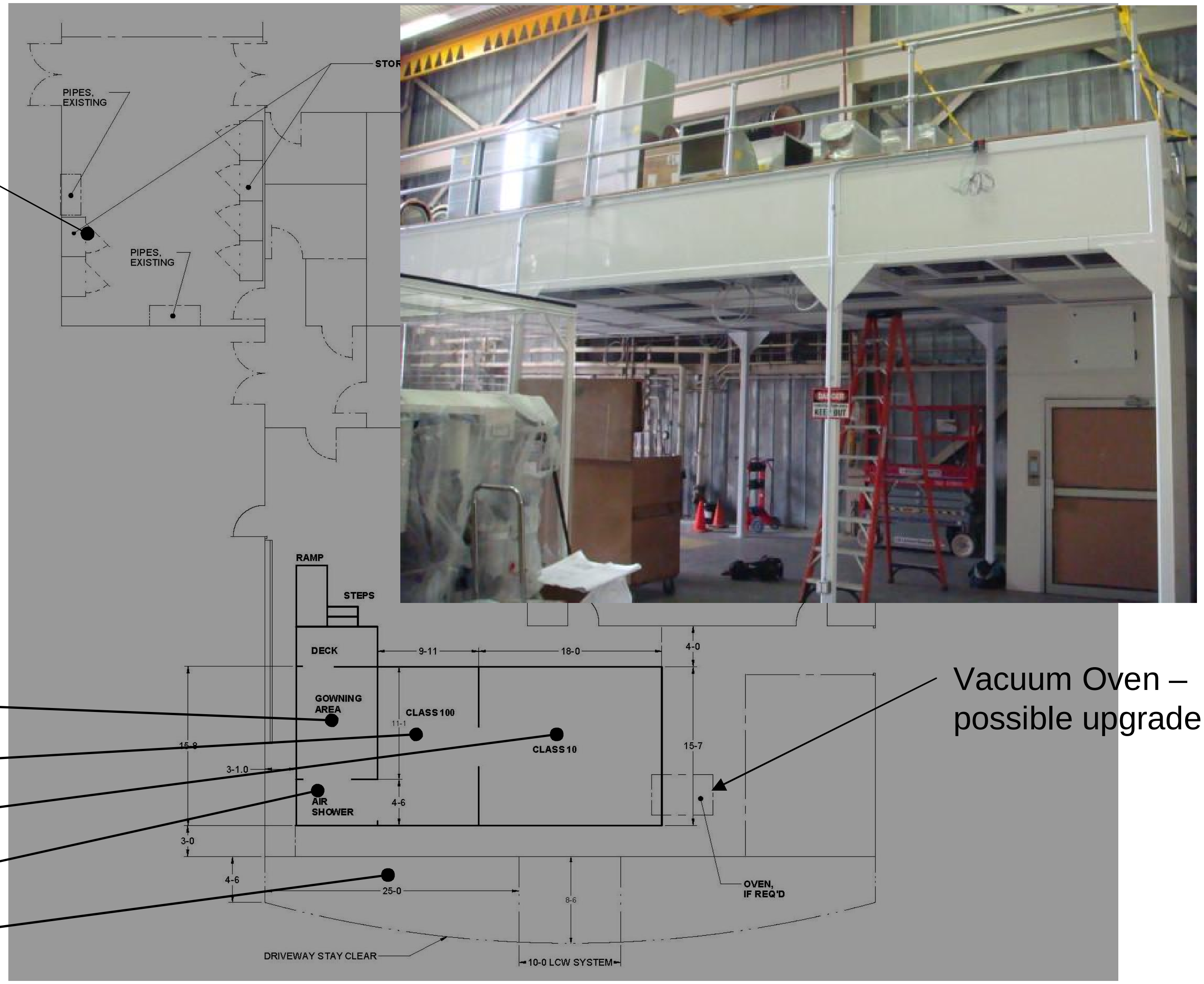
SLAC Modification to Orsay Design:

Eliminate separate material pass-through

More class 10 area

Class 1000 => 100

Remote vacuum bake



Gowning Area

Class 100

Class 10

Air Shower

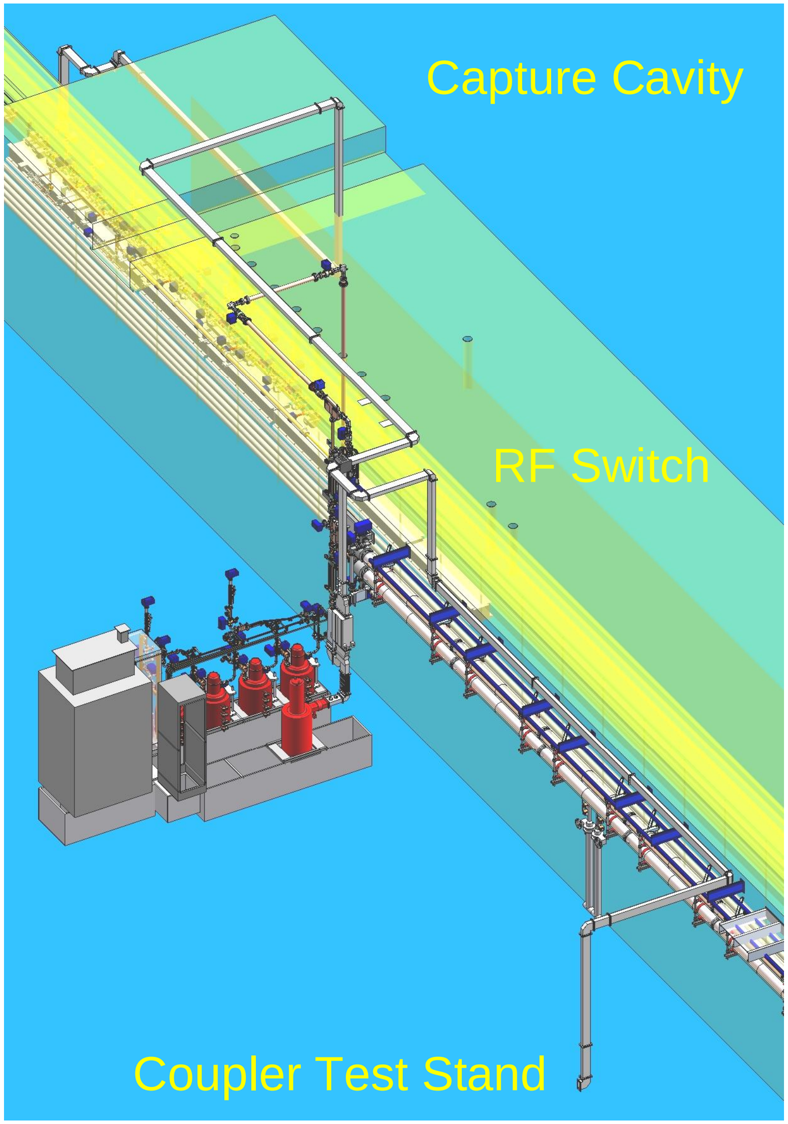
Air Handling System

Vacuum Oven – possible upgrade

L-Band Operations

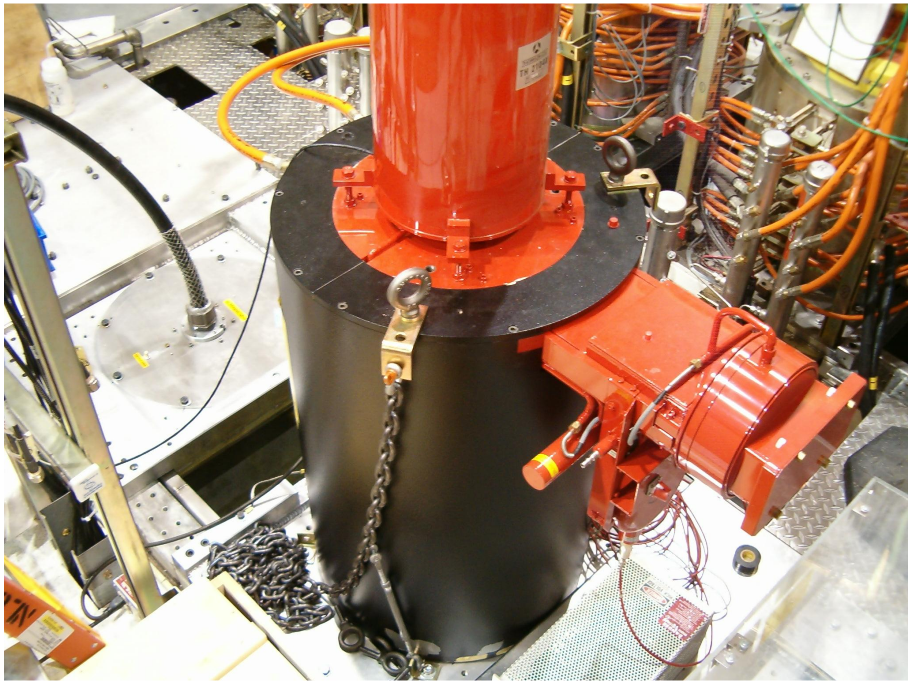
- **Goals:**
  - Maintain and complete construction of the test areas for the existing L-band station in End Station B
  - Complete infrastructure for a new station, which will be used initially to evaluate the Marx Modulator and the Toshiba 10 MW Multi-Beam Klystron.
- **Project Status:**
  - Tank that holds a vertical klystron, a water load, and a filament PS transformer is complete and the MBK has been installed.
  - Power and water connections will be installed in next few months.
  - New control system that features ‘Fast Fault Finder’ FPGA/VME boards is being assembled.

Current SLAC L-Band Test Stand

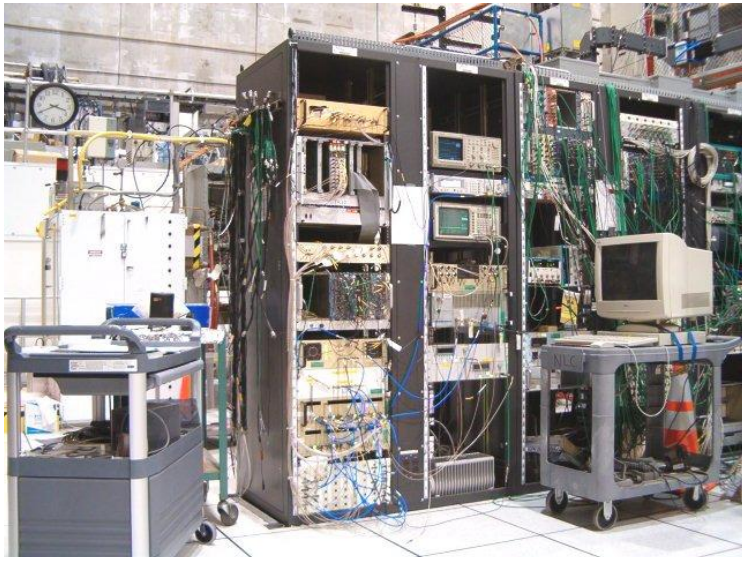


Produces 5 MW, 1.2 msec pulses at 5 Hz with a TH2104C klystron and a SNS-type modulator

Source powers a coupler test stand and a normal-conducting ILC e+ capture cavity

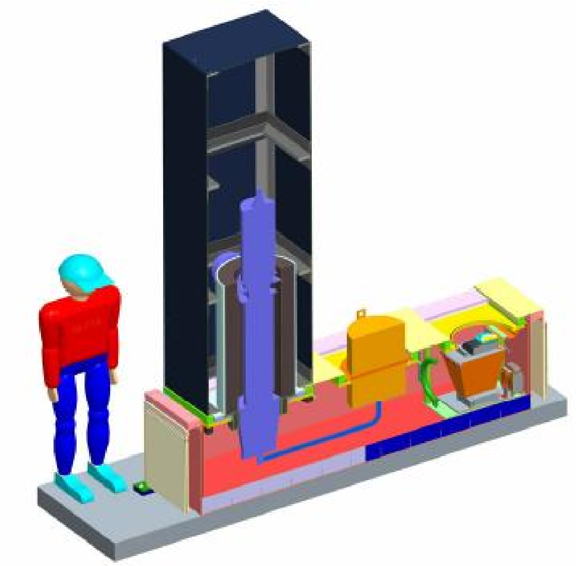


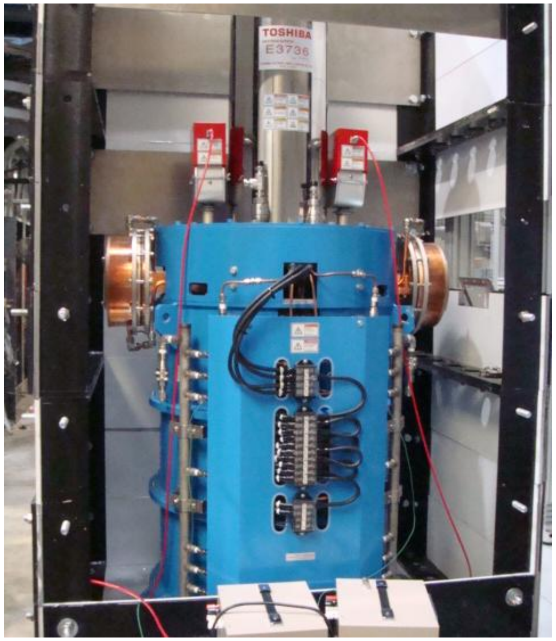
Current L-Band Test Stand in ESB



New Station Under Construction

- In FY09, the Marx Modulator will be used to power the 10 MW Toshiba MBK (and eventually the SBK) for long-term evaluation.
- Built oil tank to support the MBK, a water load, and a filament PS transformer.
- Water load can dissipate the full output power of the modulator in the absence of a klystron





Fast Fault Finder

- Replaces PLC and NIM logic to protect klystron (the modulator has its own interlock system)
- All signals, fast (e.g., rf or light) or slow (e.g., flow or PS current), are pre-conditioned to the same voltage range and sampled by a 20 MHz, 12 bit ADC and sent to a FPGA to generate fast (< 1 us) or slow (< 1 ms) fault signals based on high/low thresholds of individual channels or channel differences.
- Currently, four VME boards (4 fast, 10 slow channels each) are being tested.

FY09-12 Overarching Goals

- Demonstrate rf system performance at the level required for the TDP
  - Design approaches finalized
  - Industrial versions built
  - Reliability measured at the 10 khr level
  - Cost and path to mass production understood
  - Potential vendors identified
- Use ILC-like rf source in 'string test' to power an rf unit (3 cryomodules) at FNAL

RF Program in FY09 and Beyond

- Budget: 6.1 M$ requested in FY09 – flat in the following years.
- Start next generation Marx design in FY09 (likely with 3 kV cells to mitigate parallel switching problems). Continue prototype cycle every two years.
- Complete initial evaluation of SBK approach in FY09, and build next version in the subsequent two years, and then port to industry.
- Operate prototype Marx and MBK / SBK for at least several khours.
- Continue building and refining rf distribution systems for FNAL cryomodules (one in FY09 and three more by FY12).
- Work to develop a lower cost means of fabricating the TTF-3 couplers.
- Inspect, assemble and rf process couplers for FNAL cryomodules (up to 10 in FY09, and at least 36 by FY12).
- By FY12, deliver ILC-like charging supply, modulator and 10 MW klystron to FNAL for first full rf unit test.

Summary

- With funding cut-off, have continued generic L-band R&D at a slower pace.
- Gained much expertise in low-frequency, long-pulse rf sources, and beam related issues with SC quads and ‘cold’ BPMs.
- Future ILC focus at SLAC remains the same - develop the Marx and SBK as alternative sources, and to assemble/process couplers and develop an optimized rf distribution system for the FNAL cryomodules.
- Well positioned to provide rf sources for FNAL Project X in synergy with ILC L-band R&D