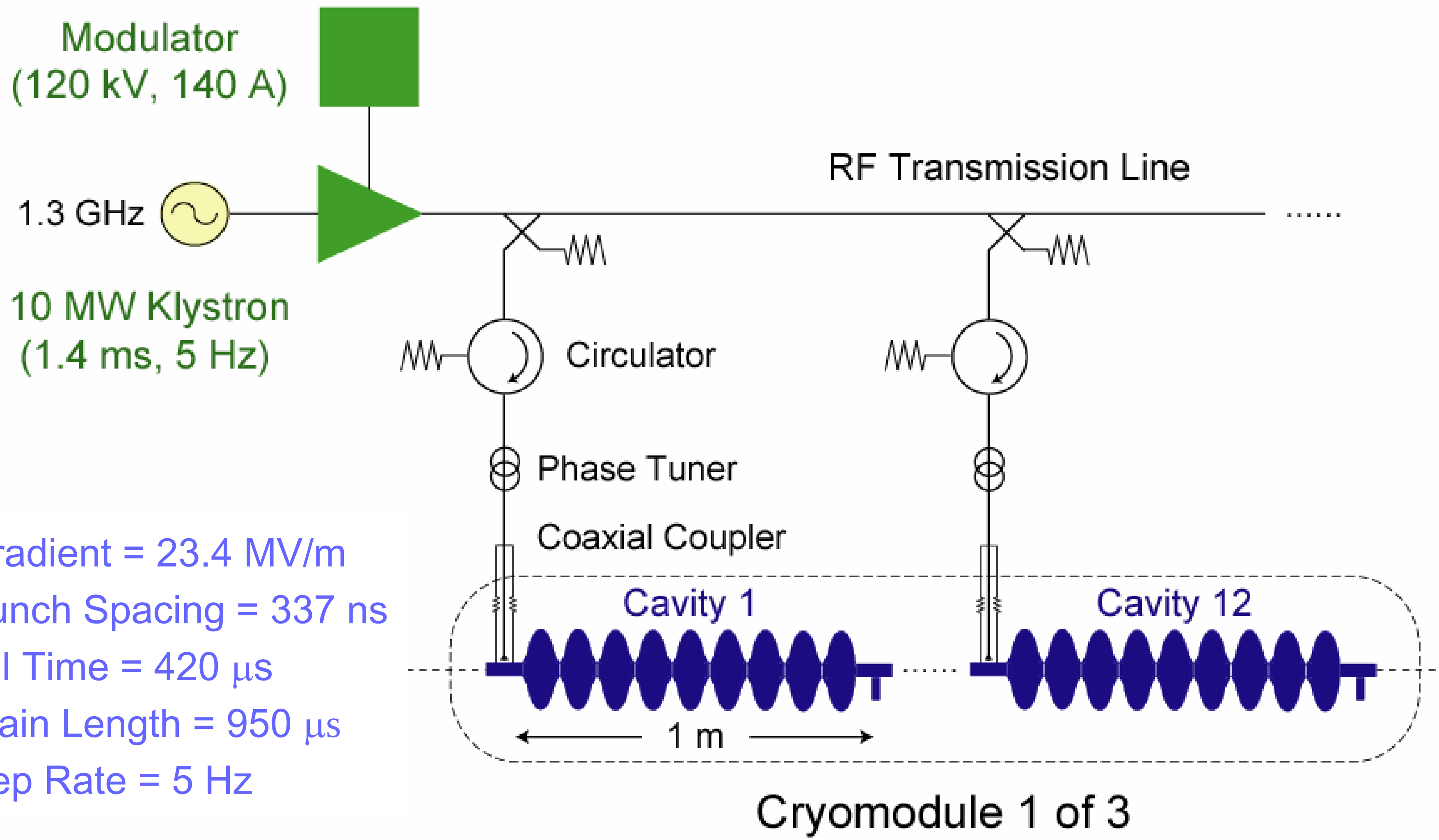
L-Band RF R&D

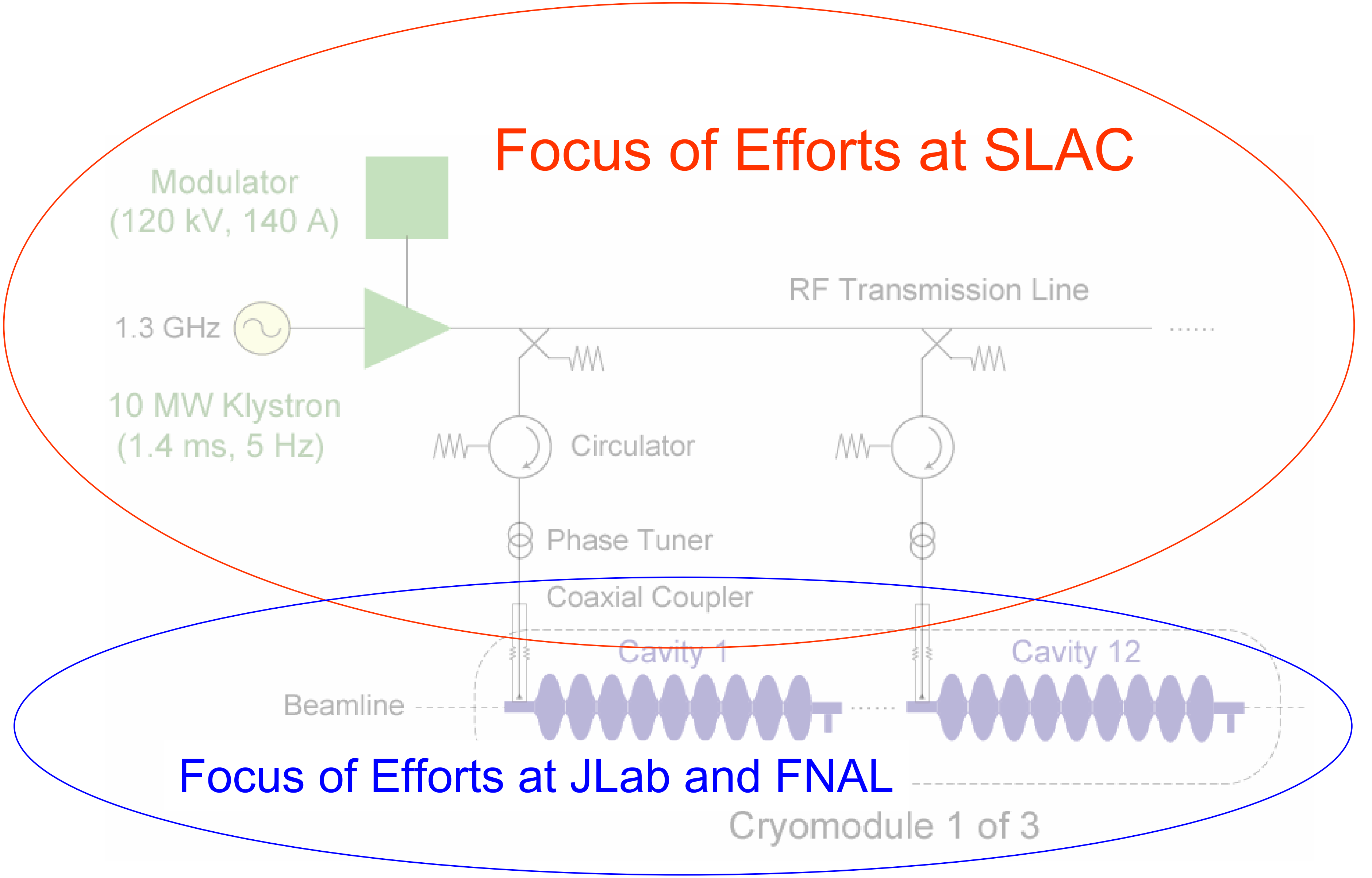
SLAC DOE Review
June 15th, 2005

Chris Adolphsen
SLAC

International Linear Collider (ILC) RF Unit
(TESLA TDR Layout)



Gradient = 23.4 MV/m
Bunch Spacing = 337 ns
Fill Time = 420 μs
Train Length = 950 μs
Rep Rate = 5 Hz



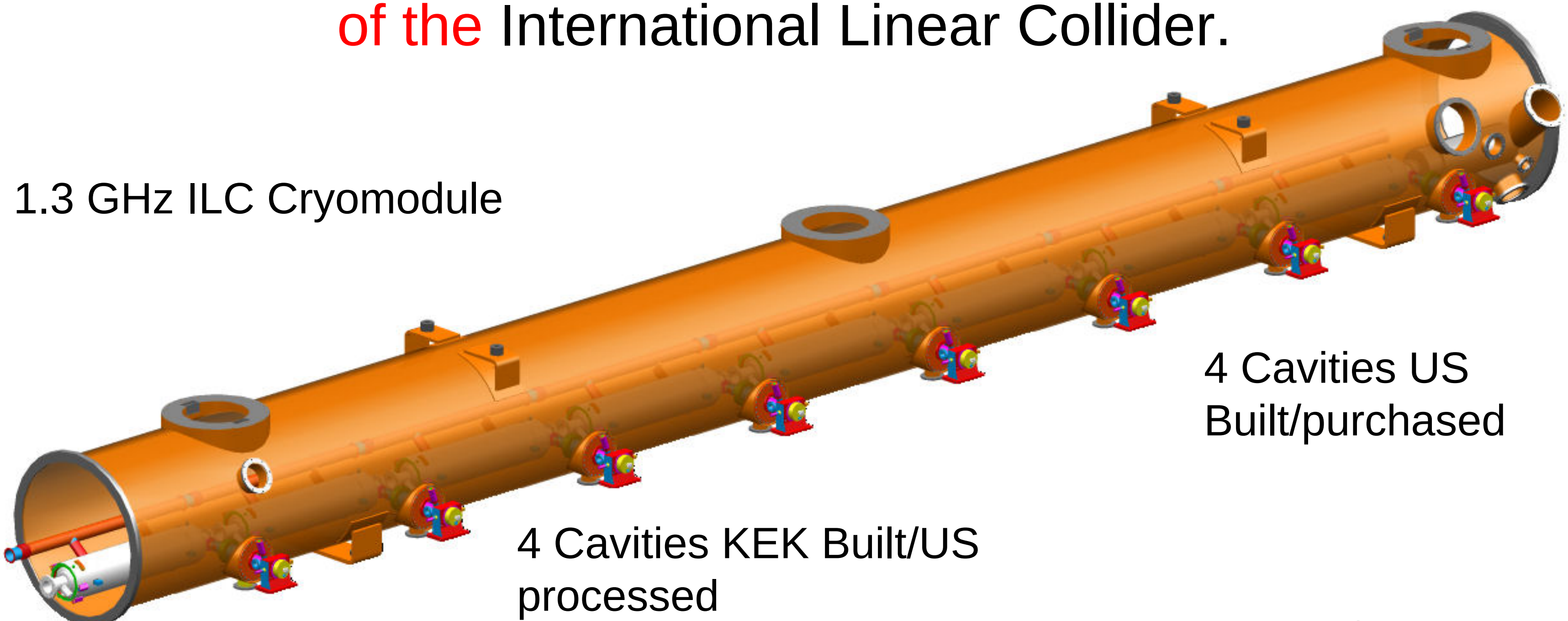
FNAL-Based SMTF Proposal: “It is anticipated that, with coordination from the ILC-Americas collaboration, SLAC will lead the ILC rf power source efforts ...

Superconducting Module Test Facility (SMTF) at FNAL

Main Goal: Develop U.S. Capabilities in fabricating and operating with Beam

High gradient (35 MV/m or Greater) and high Q (~0.5-1e10)

Superconducting accelerating cavities and cryomodule in support of the International Linear Collider.



1.3 GHz ILC Cryomodule

4 Cavities US Built/purchased

4 Cavities KEK Built/US processed

Shekhar Mishra

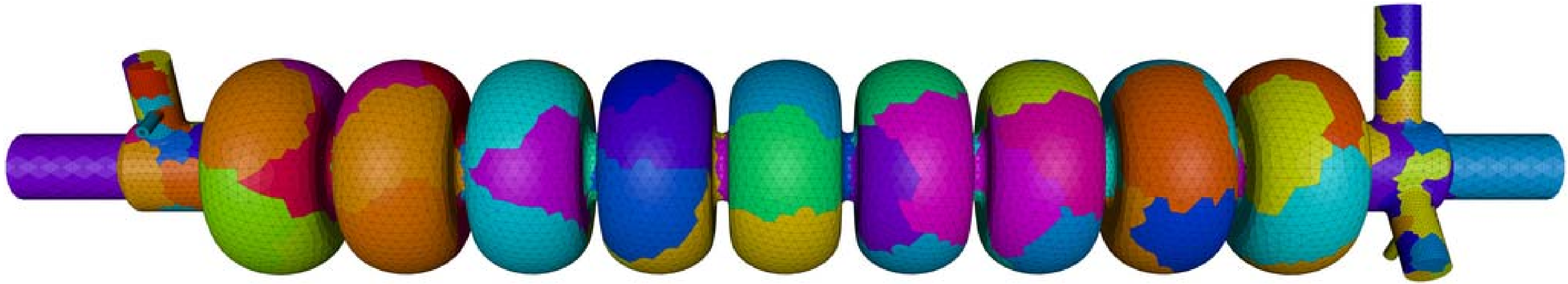
Electron Beam Welding Facility at SLAC

May collaborate with FNAL to electron beam weld niobium cavities with the 500 kW, 3 M$ SLAC EBW facility used for PEP-II components.

BR_008 E - Beam Welding of Equatorial Ports 8-19-97

Cavity Wakefields and Alignment

- Doing extensive 3-D wakefield modeling of the baseline cavity design and the proposed low-loss design.
  - Uses 768 processors and requires 300 GB memory.
  - Look for high Q modes trapped within and between 9 cell cavities.

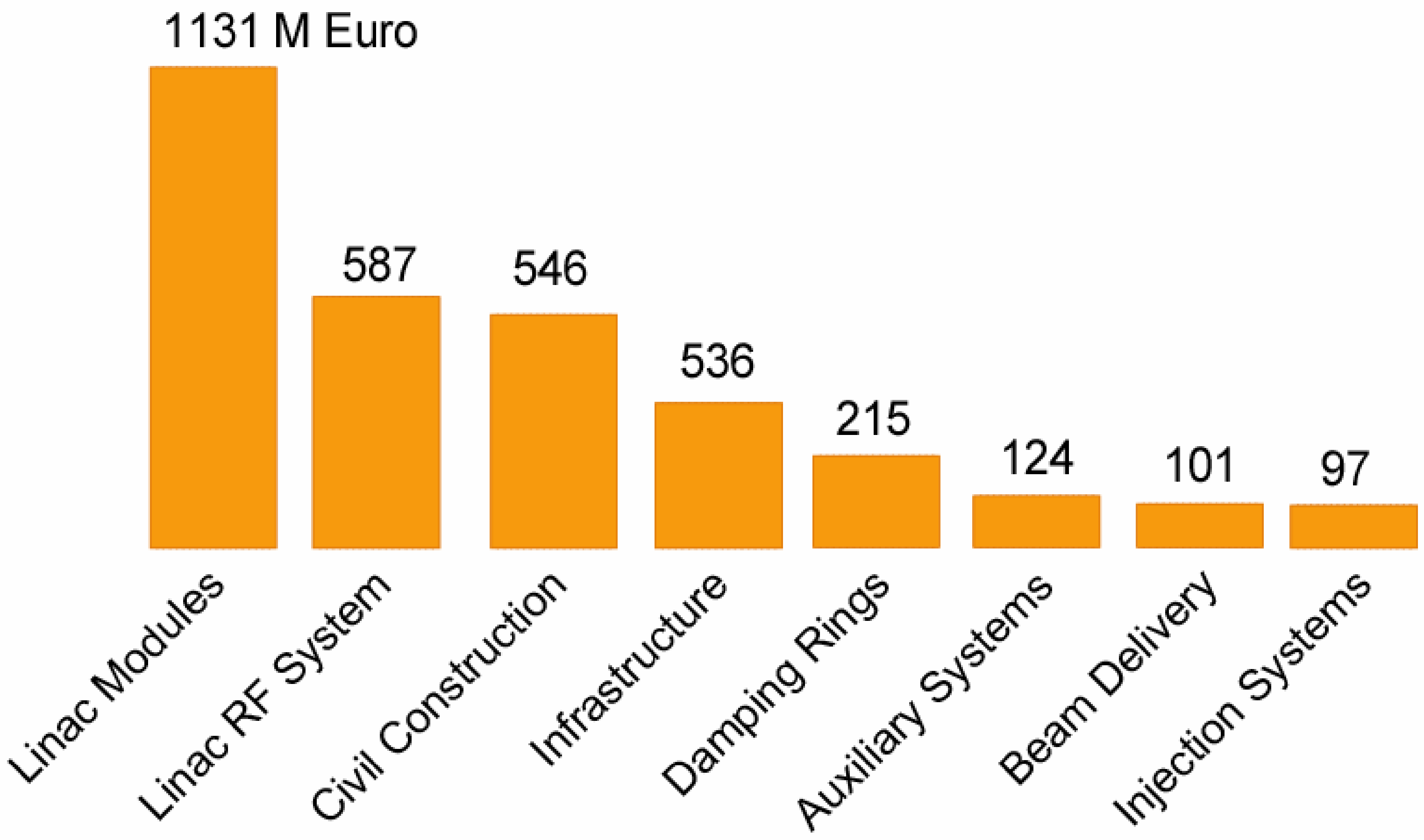


- Computing the effect of dipole mode polarizations on x-y jitter coupling in the ILC linacs.
- Using HOM signals to measure cavity-to-beam alignment (discussed in instrumentation talk).

ILC RF Sources Overview

- Industry built modulators and 5 MW and 10 MW klystrons are available although baseline 10 MW tube not fully proven. Would need about 600 rf units for the ILC.
- The SC linac for the X-ray FEL (XFEL) project at DESY requires 35 rf units but:
  - '10 MW' klystrons will be run at 5 MW and the modulator voltage will be reduced to yield 8 MW max klystron power (although at 10 Hz).
  - Not enough units to prompt significant cost reduction programs by industry: DESY needs to start soon, so will basically use current designs.
- Initial SLAC program will focus on:
  - Establishing a 1.3 GHz test stand to gain experience with L-band technology and to test NC structures and cavity power couplers.
  - Developing alternatives to the baseline modulator and klystron to reduce cost and improve efficiency and reliability.

TESLA TDR Cost Estimates
(RF Sources ~ 1/3 Linac Cost)



Modulators for ILC

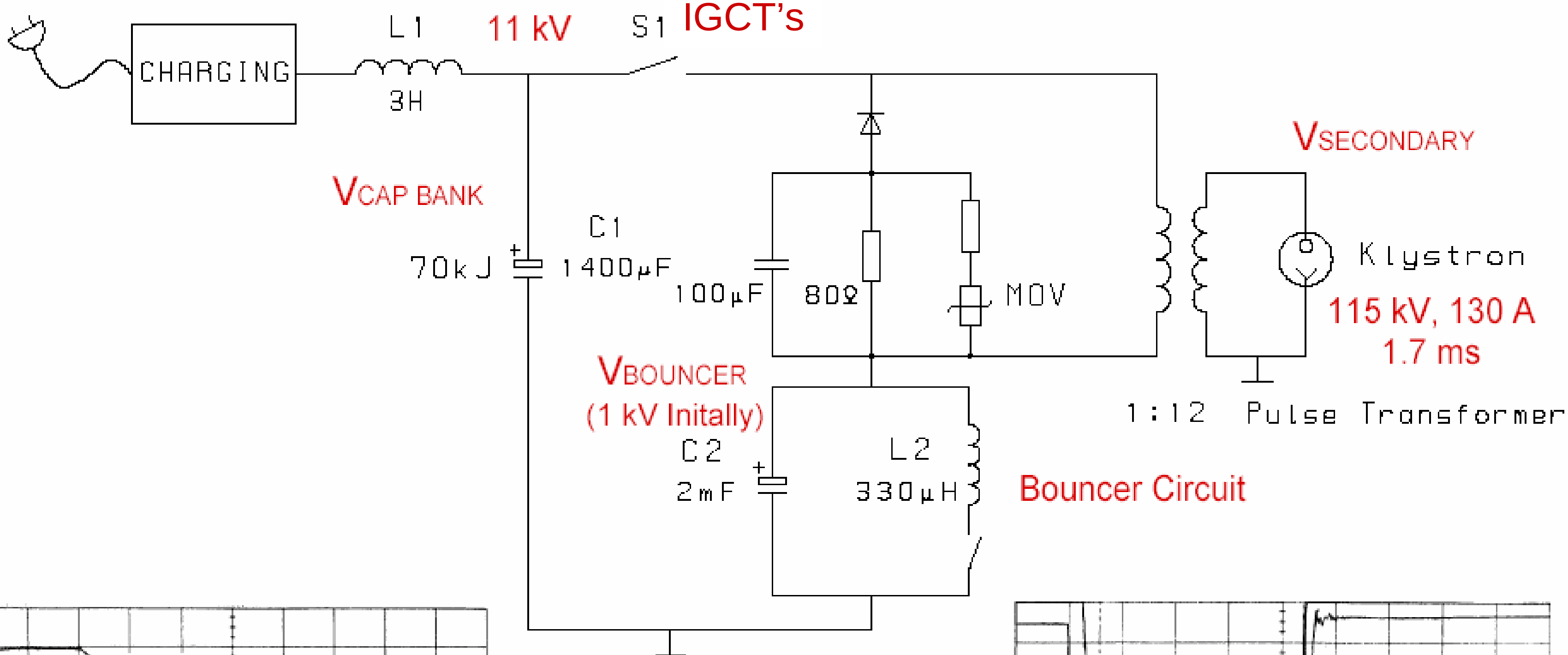
Requirements

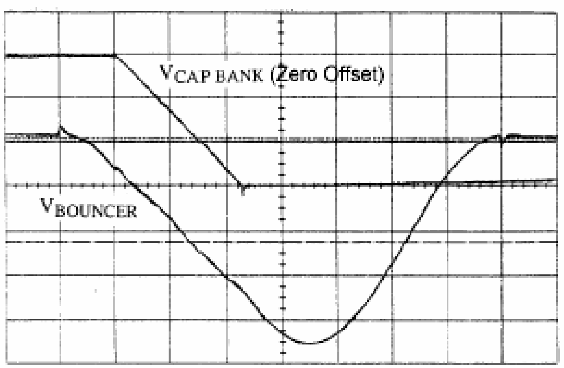
RF Pulse Length	1.37 ms
Modulator Rise/Fall Time	0.2 ms max
Modulator Pulse Length	1.7 ms max
Klystron Gun Voltage	120 kV max
Klystron Gun Current @120kV	140 A max
Pulse Flatness	+/- 0.5%
Total Energy per Pulse	25 kJ
Repetition Rate	5 Hz
Modulator Efficiency	85%
AC Power per RF Station	120 kW
Number of Modulators	~ 600

- ILC baseline choice is the FNAL/DESY/PPT ‘Pulse Transformer’ modulator.
- SLAC is evaluating alternative designs (SNS HVCM, DTI Series Switch and Marx Generator).

ILC Baseline Modulator

FNAL Design in Which a Bouncer Circuit Offsets the Voltage Droop (19%) During Discharge of a Capacitor Bank

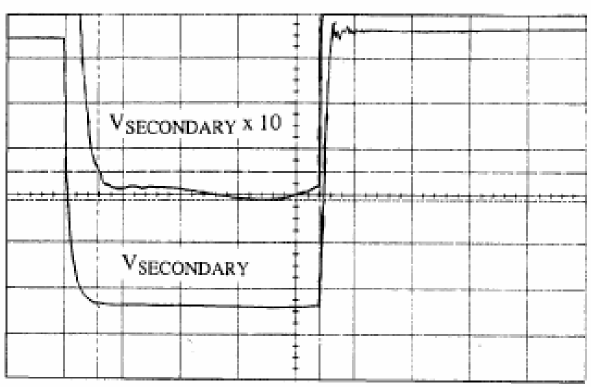




500 V/div

1 ms/div

2 kV/div (top)
20 kV/div (bottom)

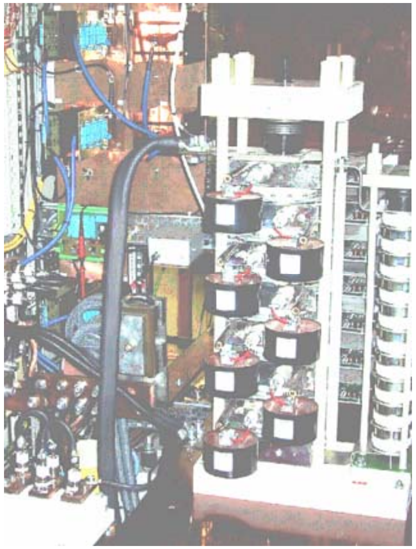


0.5 ms/div

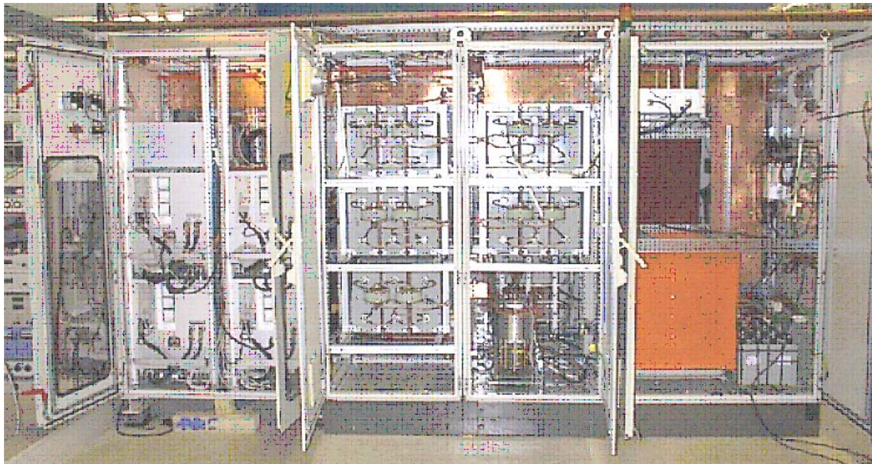
Pulse Transformer Modulator Status

- 10 units have been built, 3 by FNAL and 7 by industry (PPT with components from ABB, FUG, Poynting).
- 8 modulators are in operation.
- 10 years operation experience.
- Working towards a more cost efficient and compact design.
- FNAL will build two more, one each for ILC and Proton Driver programs – SLAC will provide switching circuits.

IGCT Stack



HVPS and Pulse Forming Unit

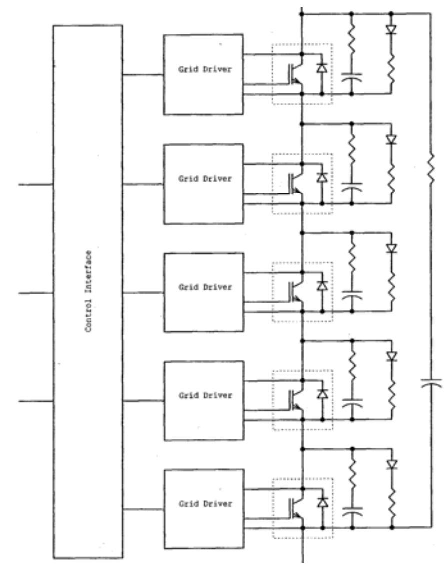


New Switch Design Provided by SLAC

Two IGBT's stacks similar to that above

- Light triggered
- Water cooled
- Snubbers not shown

- 10 kV Nominal operation
- >2.5 Voltage safety factor
- 1700 Amp pulsed current
- >2.4 Current safety factor
- 5.1 msec pulse @ 3 PPS
- IGBT's cycling life time $>10^9$ Pulses @ 99% confidence
- Redundant pulse input control
- Detection and opening of switch in case of a single fault
- Snubbers designed to prevent cascade failures during turn off



Switch Schematic

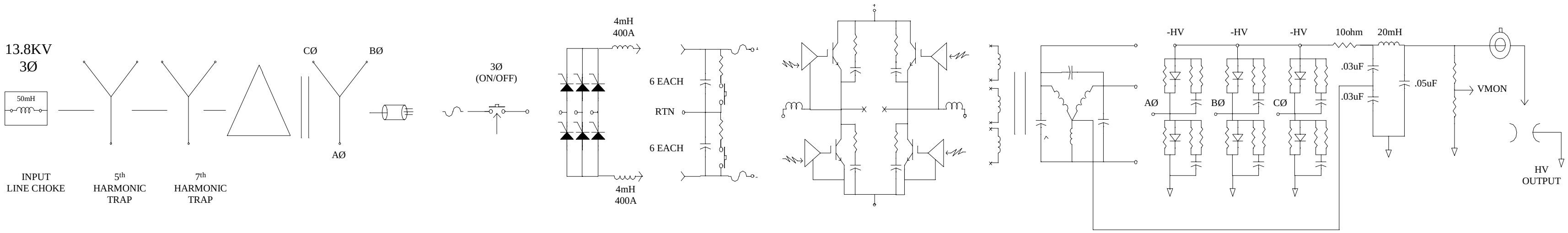
- Redundant drive
- Independent snubbers

Alternative ILC Modulators

SNS High Voltage Converter Modulator

(Recently Acquired a Production Unit from SNS)

RECTIFIER TRANSFORMER AND FILTERS | SCR REGULATOR | ENERGY STORAGE | SWITCHING | BOOST TRANS-FORMER | HV RECTIFIER AND FILTER NETWORK



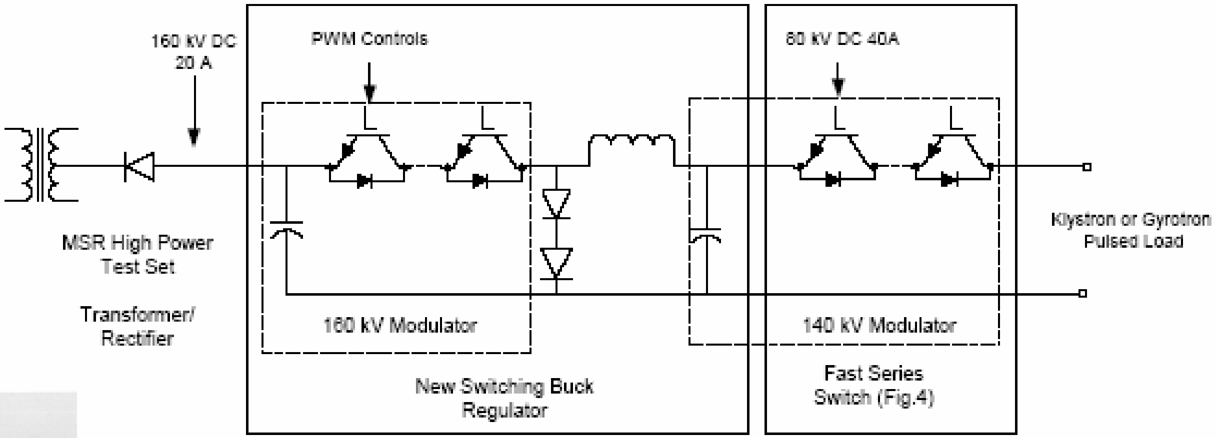
RECTIFIER TRANSFORMER AND FILTERS

SCR REGULATOR

HVCM

EQUIPMENT CONTROL RACK

Series Switch Modulator
(Diversified Technologies, Inc.)



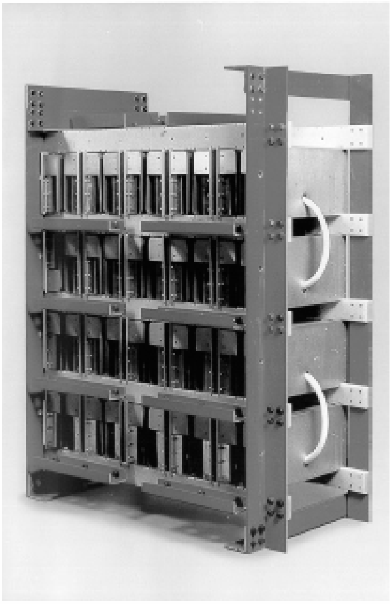


Figure 2. 140kV, 500A solid-state switch

- IGBT Series Switch
- 140kV, 500A switch shown at left in use at CPI
- As a Phase II SBIR, DTI will produce a 120 kV, 130 A version to be delivered to SLAC for the Klystron Program

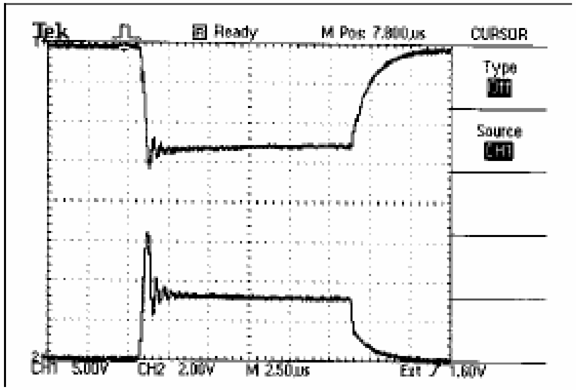
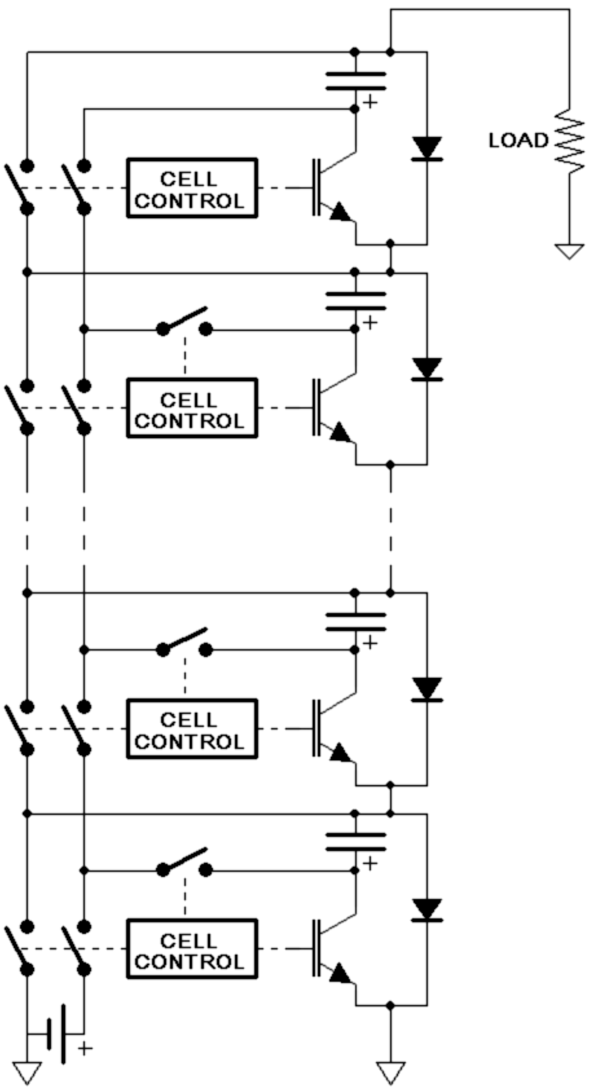
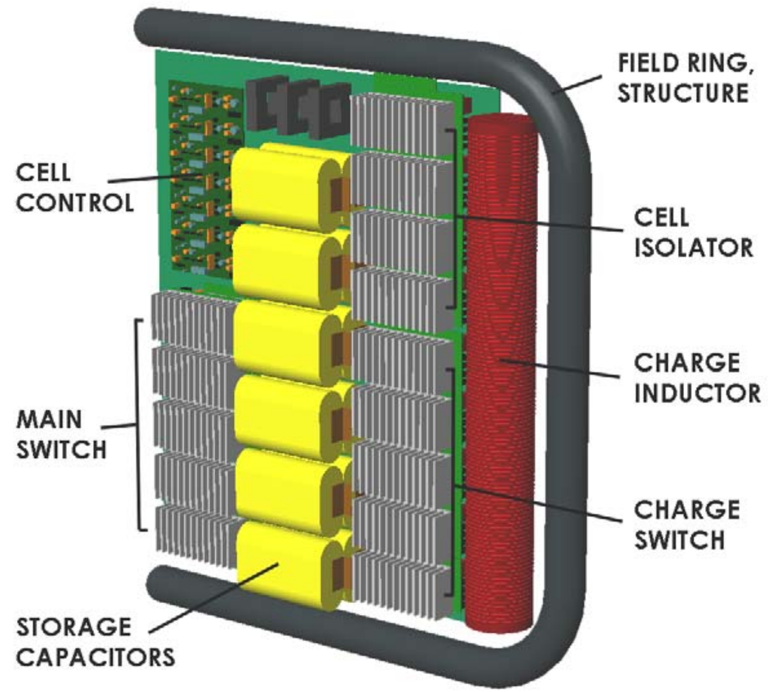


Figure 3: Test pulse (140 kV, 160 A, 13 µsec) of solid-state modulator. Upper trace is voltage at 63 kV/division. Lower trace is current at 100 A/division

SLAC Marx Generator Modulator



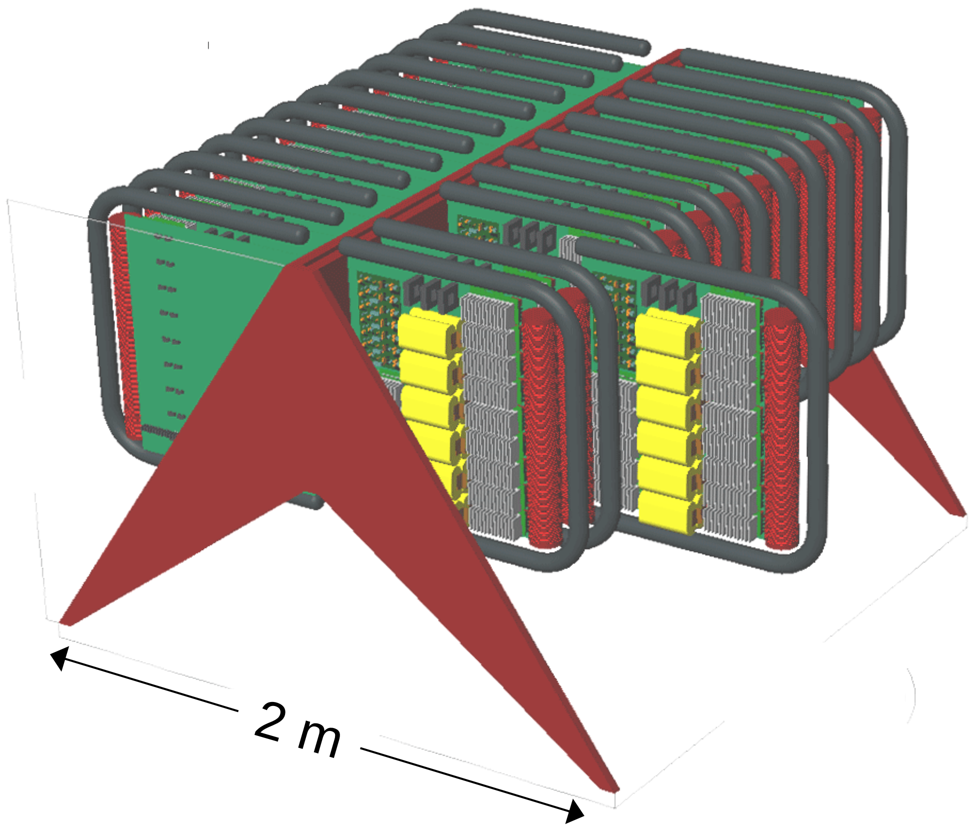


12 kV Marx Cell (1 of 24)

- IGBT switched
- No magnetic core
- Air cooled (no oil)
- Building prototype (2007)

Prototype Development Approach

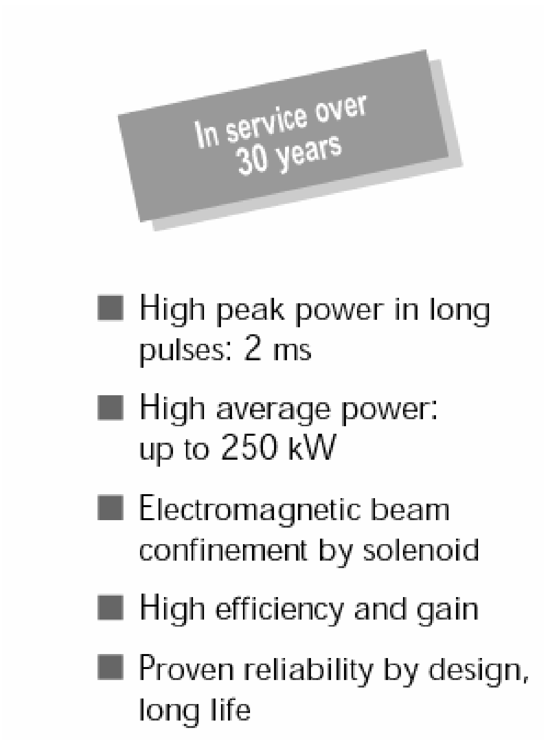
- Start with the highest technical risk items – 12kV switch, energy storage capacitors.
- Assemble, test, debug a complete cell.
- Work towards developing a ‘short stack.’
- Explore stack-level fault scenarios.
- Design, test the active regulation control loop.
- Develop complete modulator, control system, RF station. Integrate with L-Band klystron.

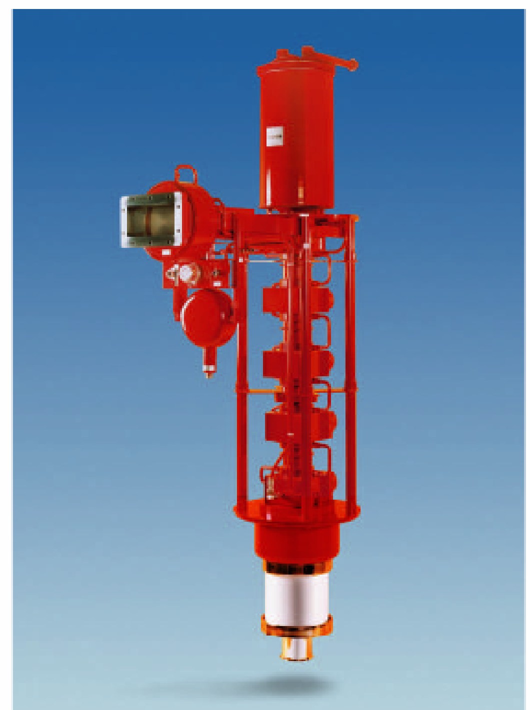


Greg Leyh

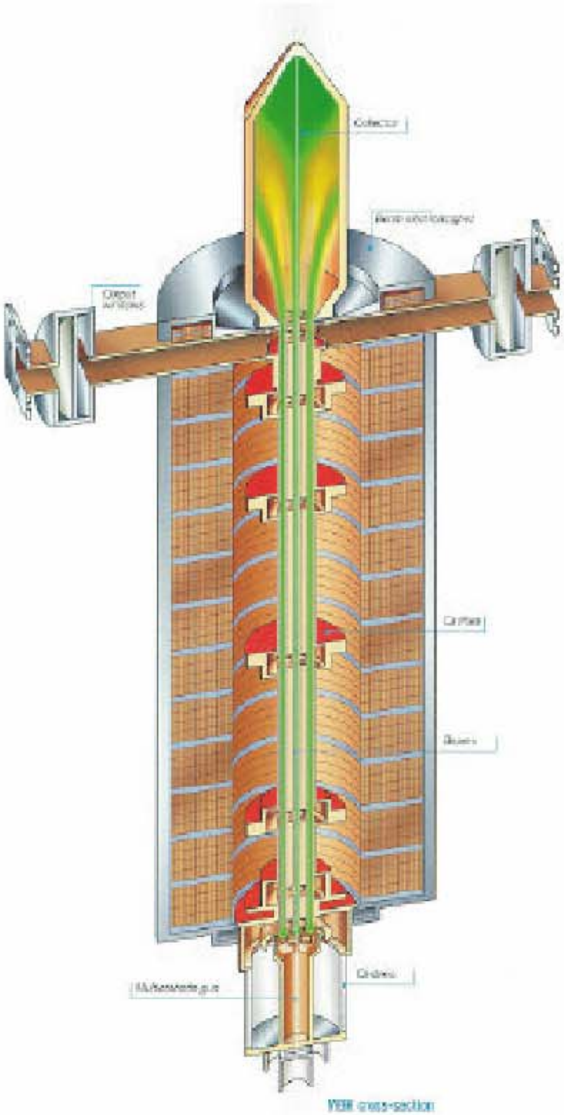
Klystrons

- The 1.3 GHz ‘workhorse’ tube for operation and testing at FNAL and DESY is the Thales 2104C single beam klystron. It produces 5 MW, 2 ms pulses at up to 10 Hz.
- Its 46% efficiency is low compared to that achievable (~ 70%) at lower perveance – it is not an ILC candidate.





ILC Klystron Development



GOAL

Reduce HV Requirements and Improve Efficiency (Lower Space Charge) with a Multiple Beam Klystron

Use Seven 19 A, 110 kV Beams to Produce 10 MW with a 70% Efficiency

Thales TH1801 MultiBeam Klystron

Spec's:
10 MW, 10 Hz, 1.5 ms with 4 kW Solenoid Power

First Tube Achieved 65% Efficiency at 1.5 ms, 5 Hz and Is Used in TTF

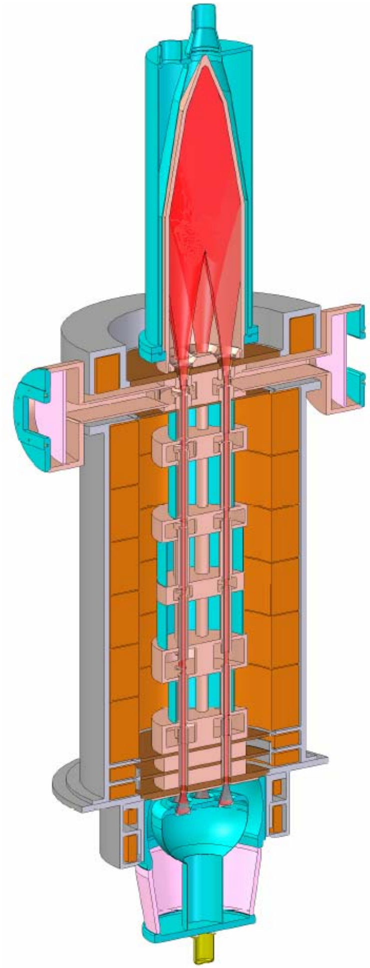
Photo of TH1801 Tube (top) and Cathode (bottom)

Other 10 MW Multi-Beam Klystrons Being Developed

TOSHIBA E3736
(Collaboration with KEK)

Features

- 6 beams
- Ring shaped cavities
- Cathode loading < 2.1 A/cm^2
- Expect ~ 100 khour cathode lifetime compared to ~ 40 khours for the Thales tube



VKL-8301

Features

- Six cathodes with six heater feed-throughs
  - can turn off individual cathodes
- Six cavities in each beam-line
  - three fundamental-mode with external tuners
  - one second-harmonic
  - two common HOM (input & output)
- Six isolated collectors
  - can measure intercepted current in each beam-line
  - one main collector water manifold
- Low cathode loading
  - Expect ~ 100 khour cathode lifetime

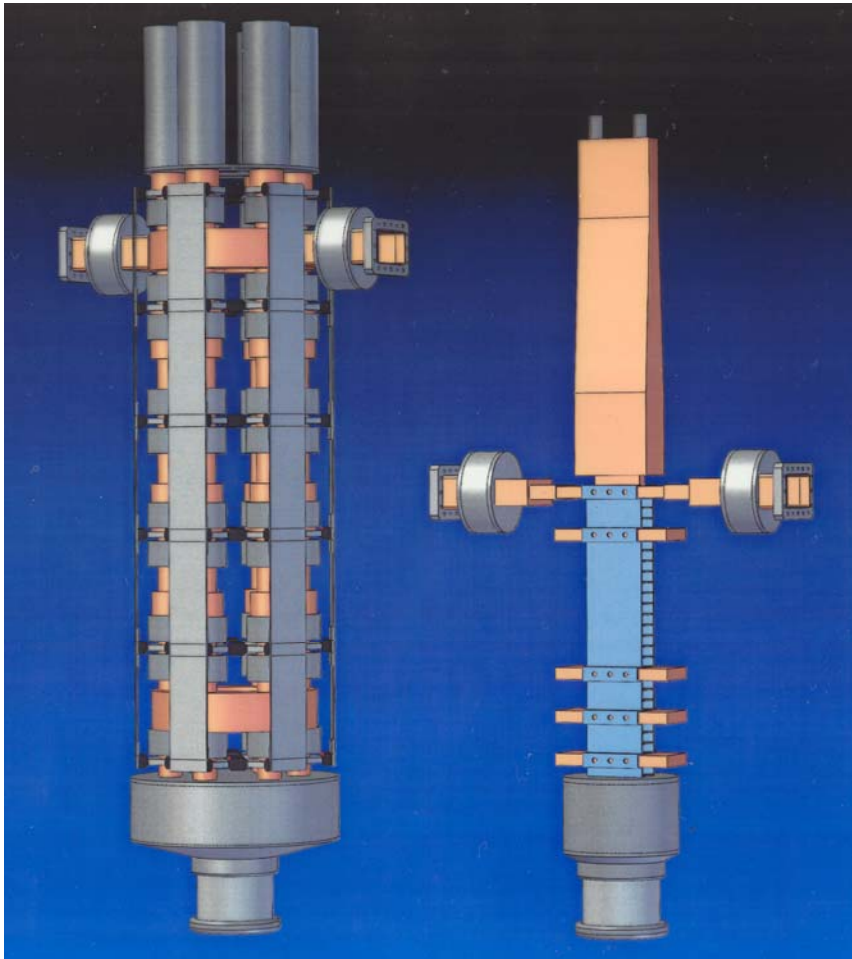
Klystron Status / Program

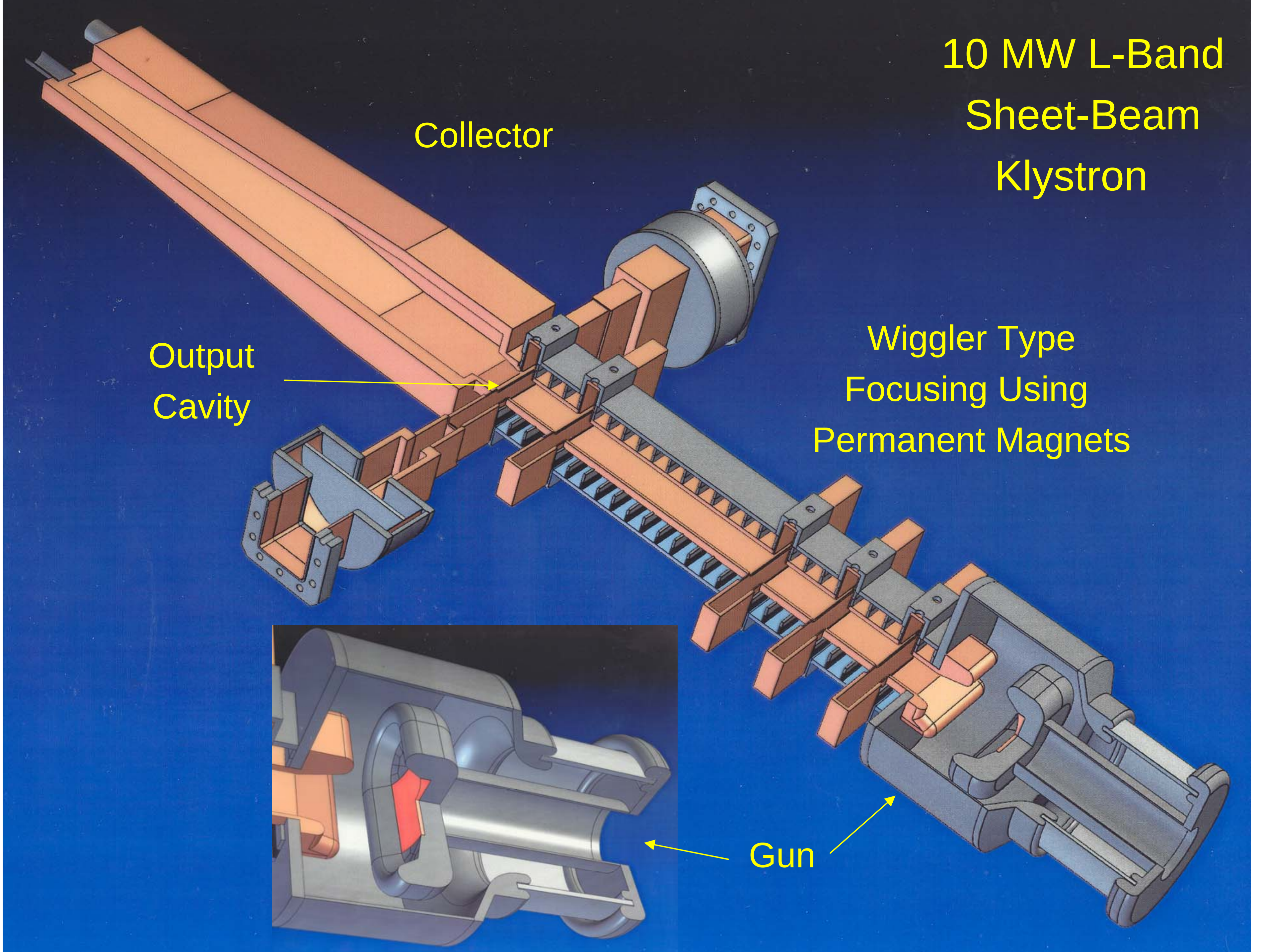
- DESY 10 MW Klystron Program
  - Three Thales tubes built, five more ordered – all 3 tubes developed gun arcing problems – two rebuilt to correct problem but not fully tested, the other has run for 18 khour at lower voltage (~ 95 kV).
  - One CPI tube built – achieved 10 MW at short pulse length, limited by CPI modulator - was accepted by DESY, may come to SLAC after testing at DESY.
  - One Toshiba tube built and under test – 10 MW, 1 ms achieved – longer pulses limited by modulator, which is being upgraded.
- SLAC Klystron Program
  - Developing a 10 MW L-band Sheet-Beam Klystron.
  - If multi-beam program falters, consider lower perveance, single beam, 5 MW tube, possibly with PPM focusing.
  - Buy commercial 5 MW tubes as needed for 1.3 GHz NC structure and coupler program.
  - Possibly collaborate with DESY and CPI on 10 MW tube.

SLAC Sheet-Beam Klystron

- Developing a 10 MW sheet beam klystron as an alternate to the multi-beam tubes to reduce cost
  - Uses flat beams instead of six beamlets to reduce space charge forces.
  - It is smaller with a planar geometry for easier construction.
  - No solenoid magnet (saves ~ 4 MW of power).
  - Would be plug compatible with baseline design and have similar efficiency.
  - W-band 'proof-of-principle' version in progress using external funding.

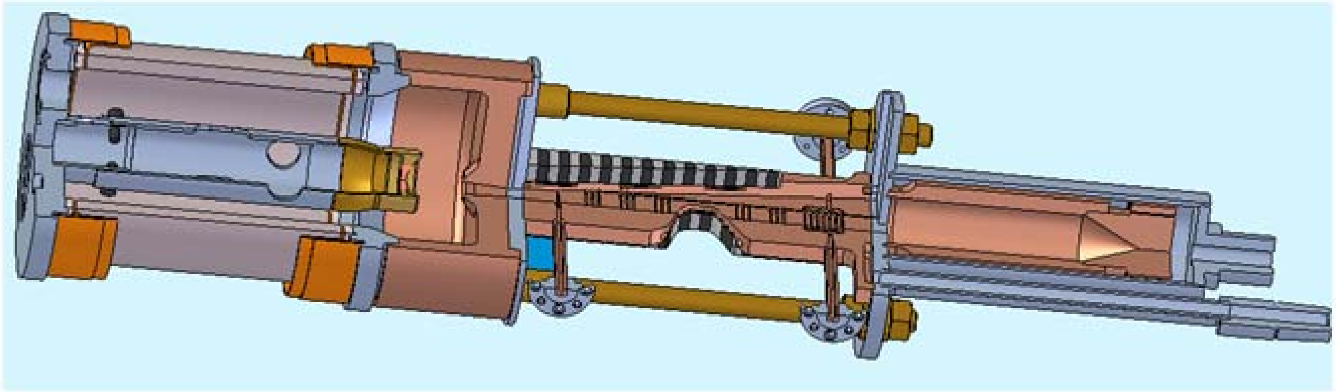
Multi-beam tube   Sheet-beam tube

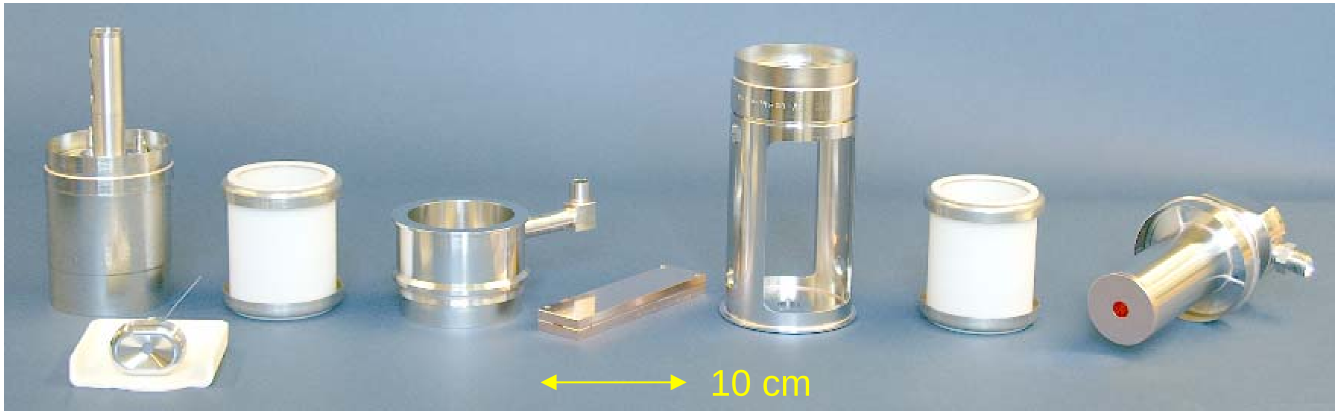



10 MW L-Band
Sheet-Beam
Klystron
Collector
Output
Cavity
Wiggler Type
Focusing Using
Permanent Magnets
Gun

W-Band Sheet Beam Klystron Program
(Not ILC funded)

A 91 GHz, 100 kW peak power sheet-beam klystron (74 kV, 3.6 A beam) has been designed and is being fabricated (plan to test this year).

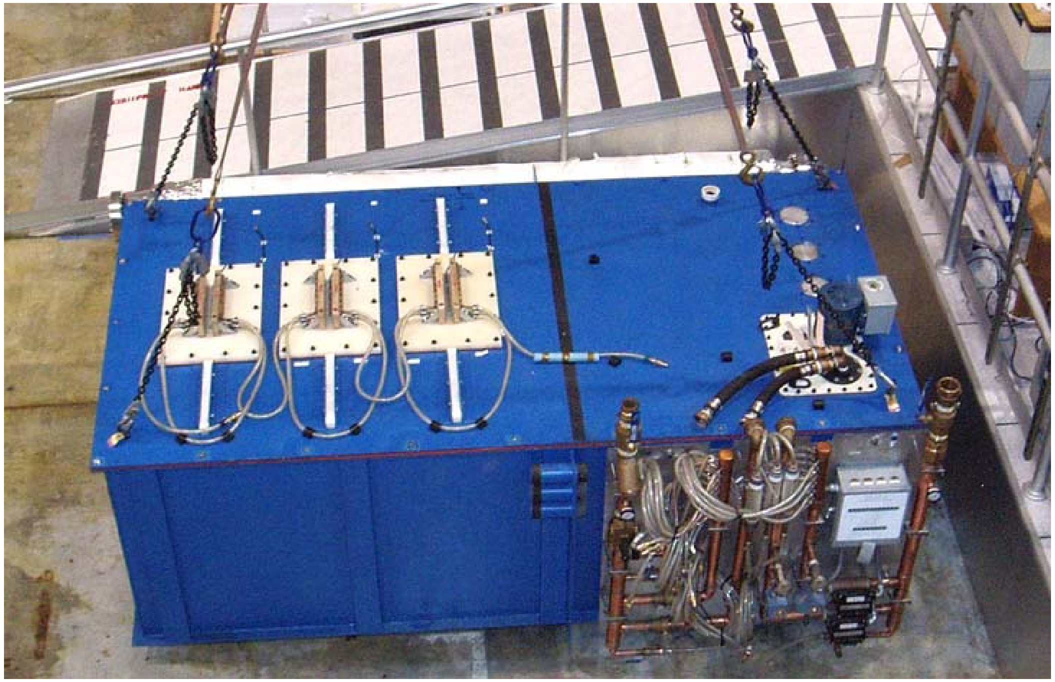




L-Band Test Facility at NLCTA

- Recently acquired a 10 MW HVCM Modulator from SNS.
- Buying a 5 MW TH2104C tube from Thales (1 year delivery).
  - In meantime use a SDI-Legacy tube from Titan (TH2104U).
- All major LLRF and waveguide components on order.

SNS Modulator Being Assembled at NLCTA

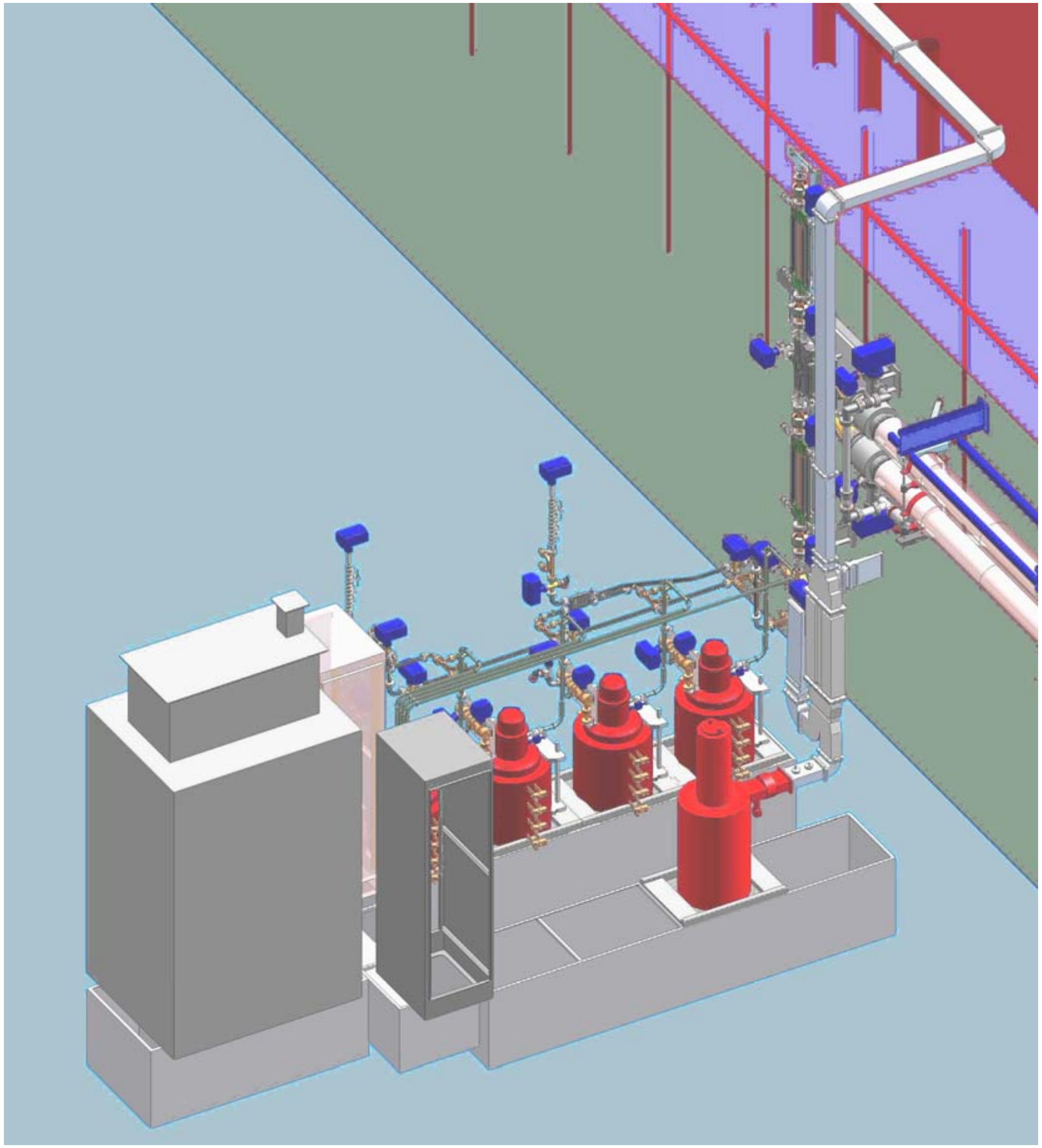


Thales 2104U Klystron

Klystron & WG Layout

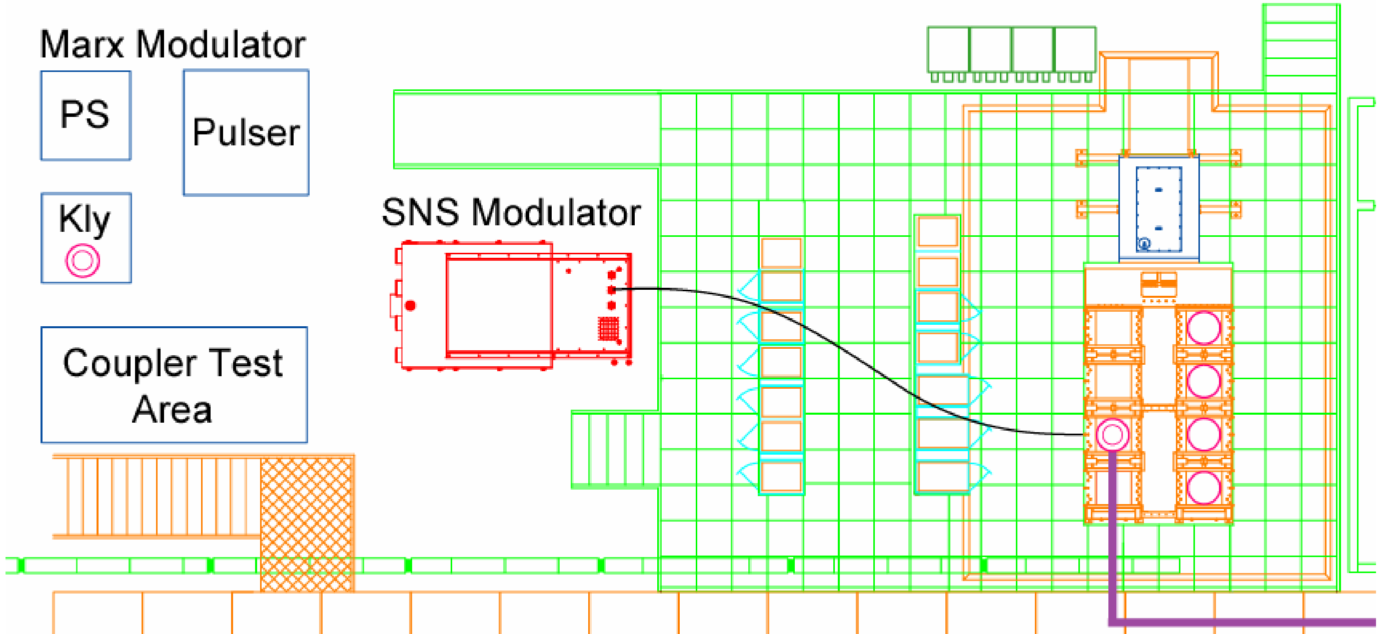
The klystron will be installed in the unused half of the Eight-Pack Modulator tank and waveguide will be run into the NLCTA beam enclosure.

Expect first power in Jan 2006.

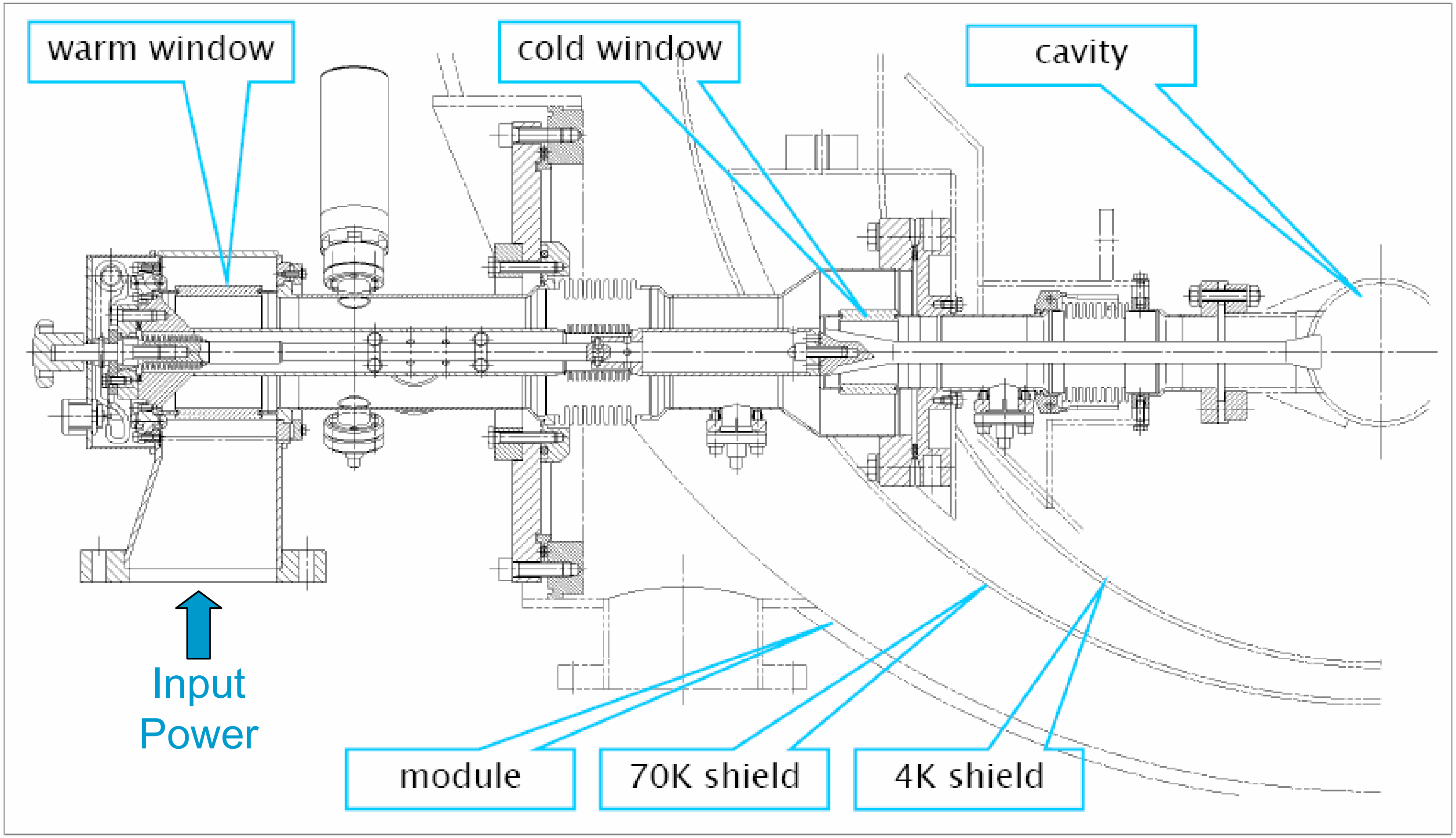


Test Facility Program in 2006

- Use 5 MW source for coupler and normal-conducting cavity tests (discussed below).
- Propose to add a second L-band station using ILC prototypes.
  - Based on progress, use Marx Generator, DTI Direct Switch or buy a baseline modulator from PPT.
  - Either buy are borrow a CPI or Toshiba 10 MW klystron from DESY.



Coaxial Power Couplers for the Superconducting Cavities

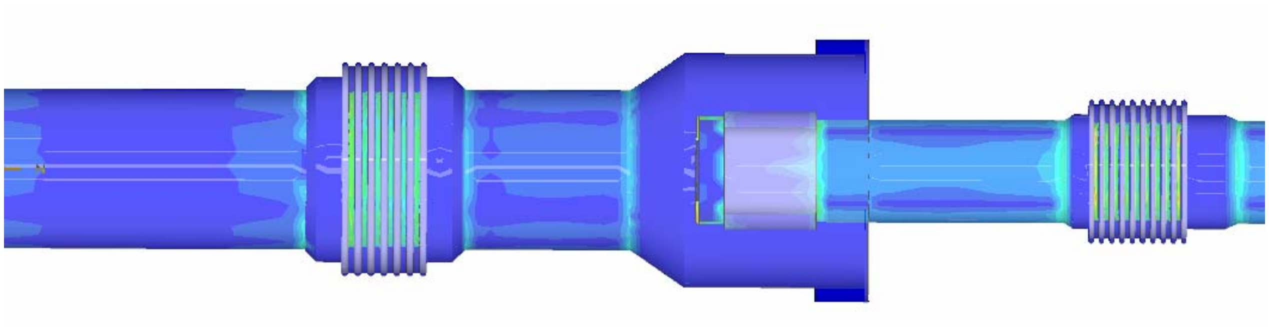


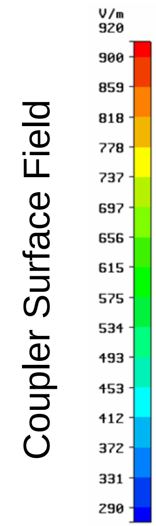
Coupler Overview

- Design challenging due to requirements of tunability, vacuum isolation and low heat loss.
- Extensive testing of TTF3 coupler at 20-25 MV/m but limited testing at 35 MV/m – performance acceptable but
  - RF processing is too slow (~ 100 hr, limited by outgassing; also require ~ 50 hr in-situ processing).
  - Cost too high (want 60% reduction from current cost of 25 k$ each for quantities of ~ 10).
- Main supplier is the US company CPI
  - Currently building 30 for XFEL cavity evaluation.
  - Will likely bid for at least 500 of the 1000 needed for the XFEL, whose cavities require ~ ½ the input power of those in the ILC.
  - Would need 20,000 for ILC.

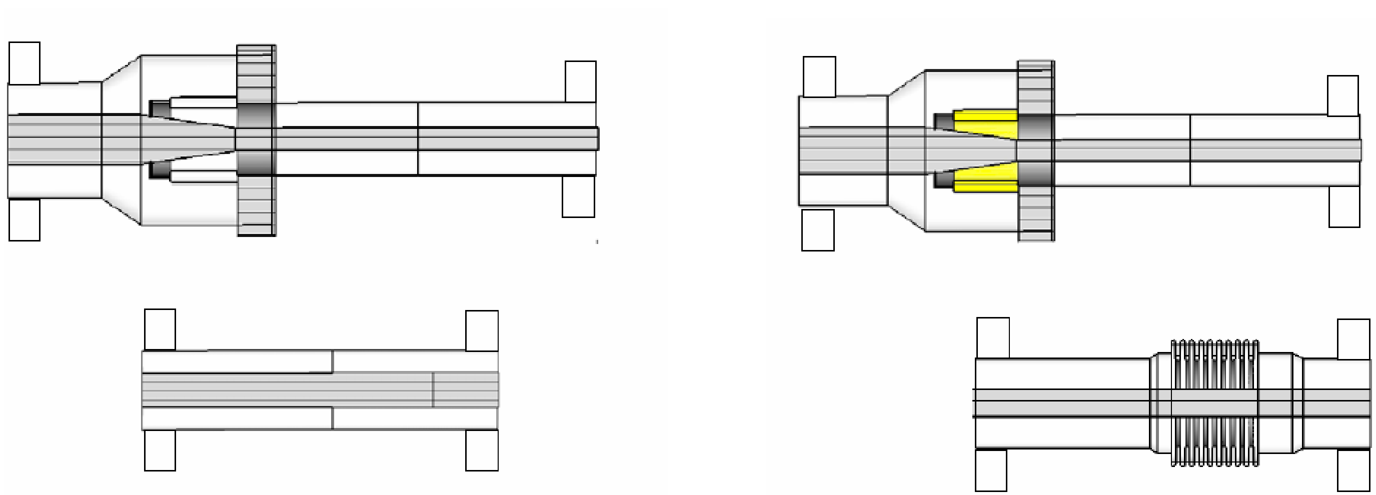
Coupler Processing Studies

One concern is that the surface field variations in the bellows and near the windows may lead to excessive mulitpacting.





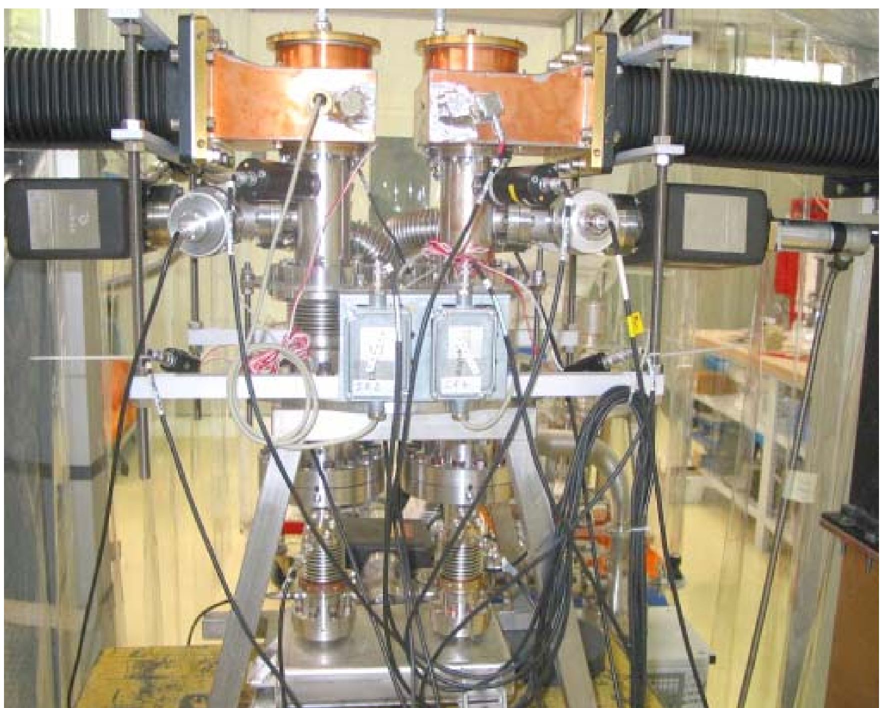
To understand processing limitations, plan in FY06 to process coupler components individually. In particular, determine if bellows or the windows are the source of the long processing time.

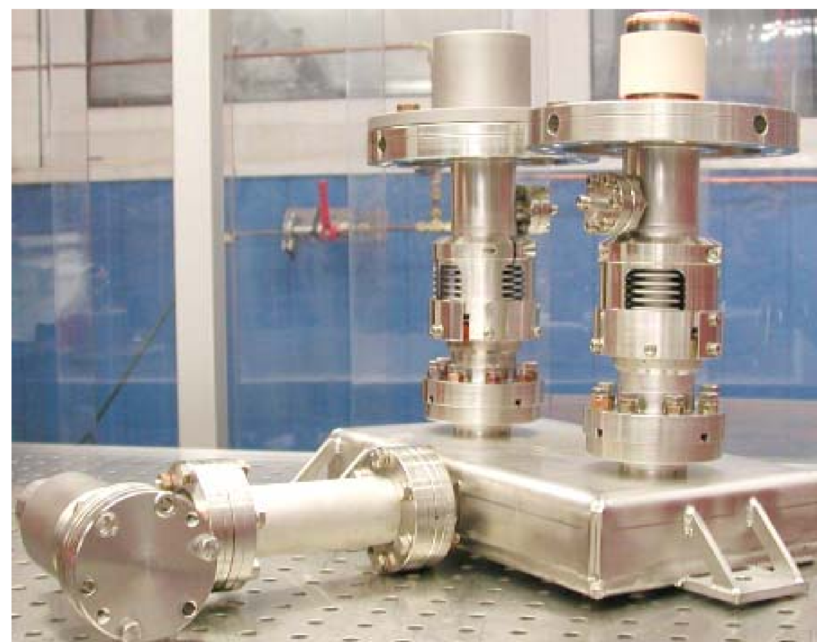


Brian Rusnak

In FY06, Propose to Setup a Coupler Test Stand at NLCTA to Process Couplers for SMTF Cavities

Instrumented Coupler Test Stand at Orsay

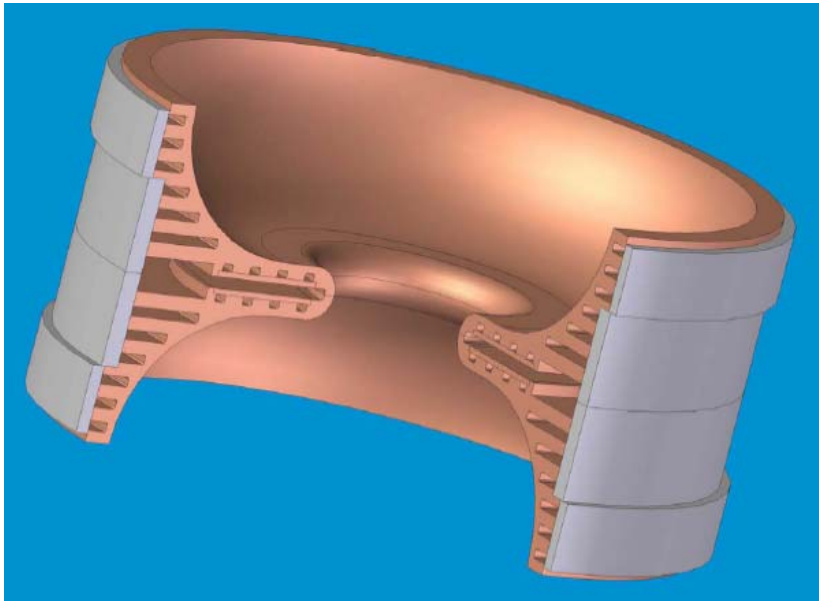


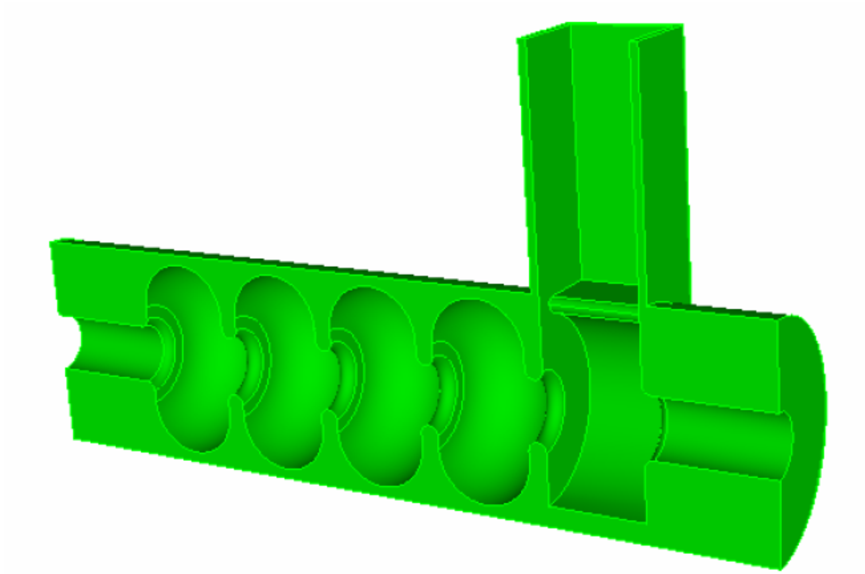


NC Structure for ILC Positron Capture Accelerator

- Goal: Build and test a 1.3 GHz, normal-conducting (NC) cavity of the type that would be used just downstream of the ILC positron target.
  - 60 mm aperture, 15 MV/m gradient, 1 msec pulses, 0.5 T magnetic field.
  - Average heating of 5 kW/cell from rf losses and 7.5 kW per cell from particle losses.
- Have chosen a π-mode SW design with extensive cooling channels versus DESY's more complex and harder to cool CDS $\pi/2$-mode design.
- Current plan to is build a 5 cell cavity and test at NLCTA in FY06 using the new 5 MW source. The cavity would be operated in a magnetic field and the gradient sustainability and detuning compensation would be evaluated.
- Status
  - Basic rf design complete and mechanical design started.
  - In process of finalizing coupler, window and flange choices.

SW Cavity Geometry and Heating Effects



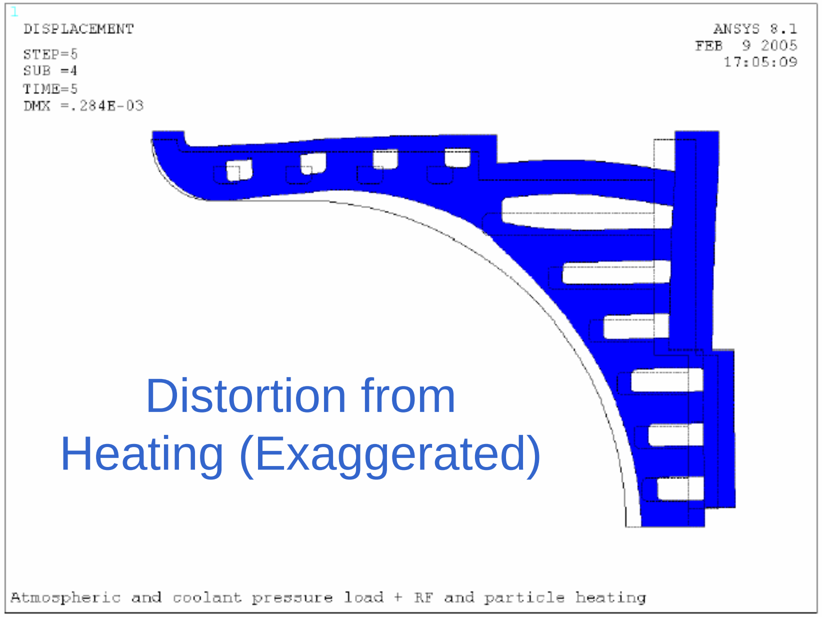


Pulse Temperature Rise < 20 deg C

Average Detuning = 69 kHz

Pulse Detuning = 17 kHz

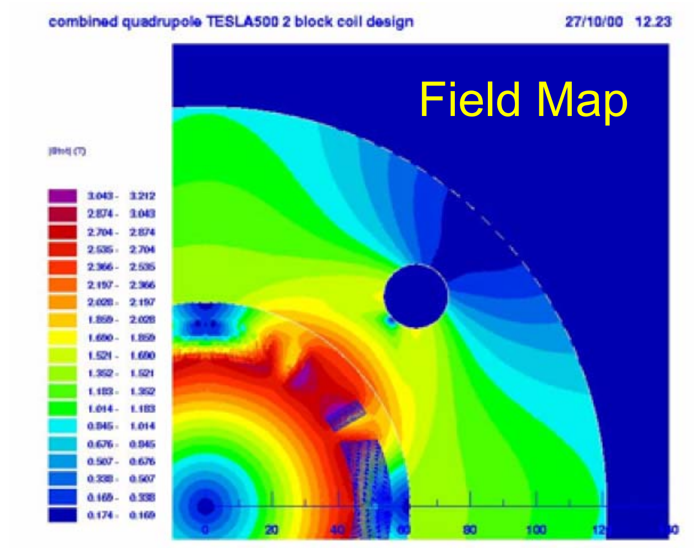
Will require a 5% power adjustment during pulse for detuning compensation.



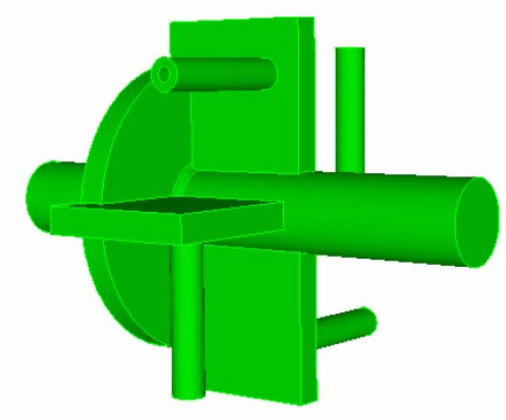
ILC Linac SC Quad/BPM Evaluation

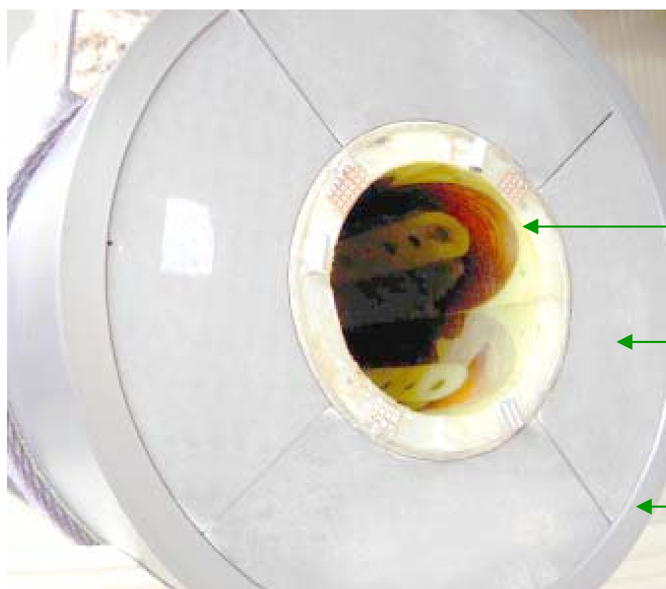
- Goal: Demonstrate Quad/BPM performance required for ILC beam-based alignment:
  - Verify < ~ 5 micron movement of Quad magnetic center with field change.
  - Show ~ 1 micron BPM resolution and < ~ 5 micron Quad-to-BPM stability with a compact, 35 mm aperture rf cavity BPM.
- For this program, we plan to
  - Acquire the ILC prototype Quad built by CIEMAT in Spain and build a warm-bore cryostat for it at SLAC.
  - Do quad center stability tests with a rotating coil at the SLAC Magnetic Measurements Lab.
  - Develop linac rf cavity BPMs and test with beam at ESA.
  - Integrate Quad and BPMs for a beam-based quad shunting test.
- Status
  - Quad nearly finished and cryostat and coil engineering underway – expect first magnet test in 2/06.
  - BPM design complete – test with beam in 2006.

Cos(2Φ) SC Quad
(~ 0.7 m long)



S-Band BPM Design
(36 mm ID, 126 mm OD)



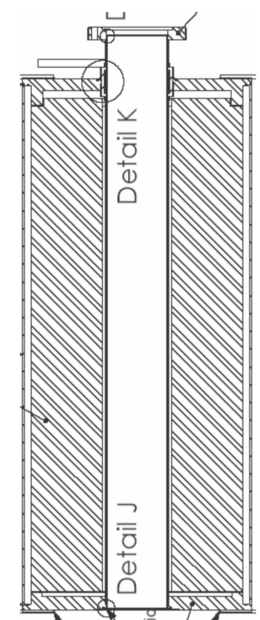


He Vessel

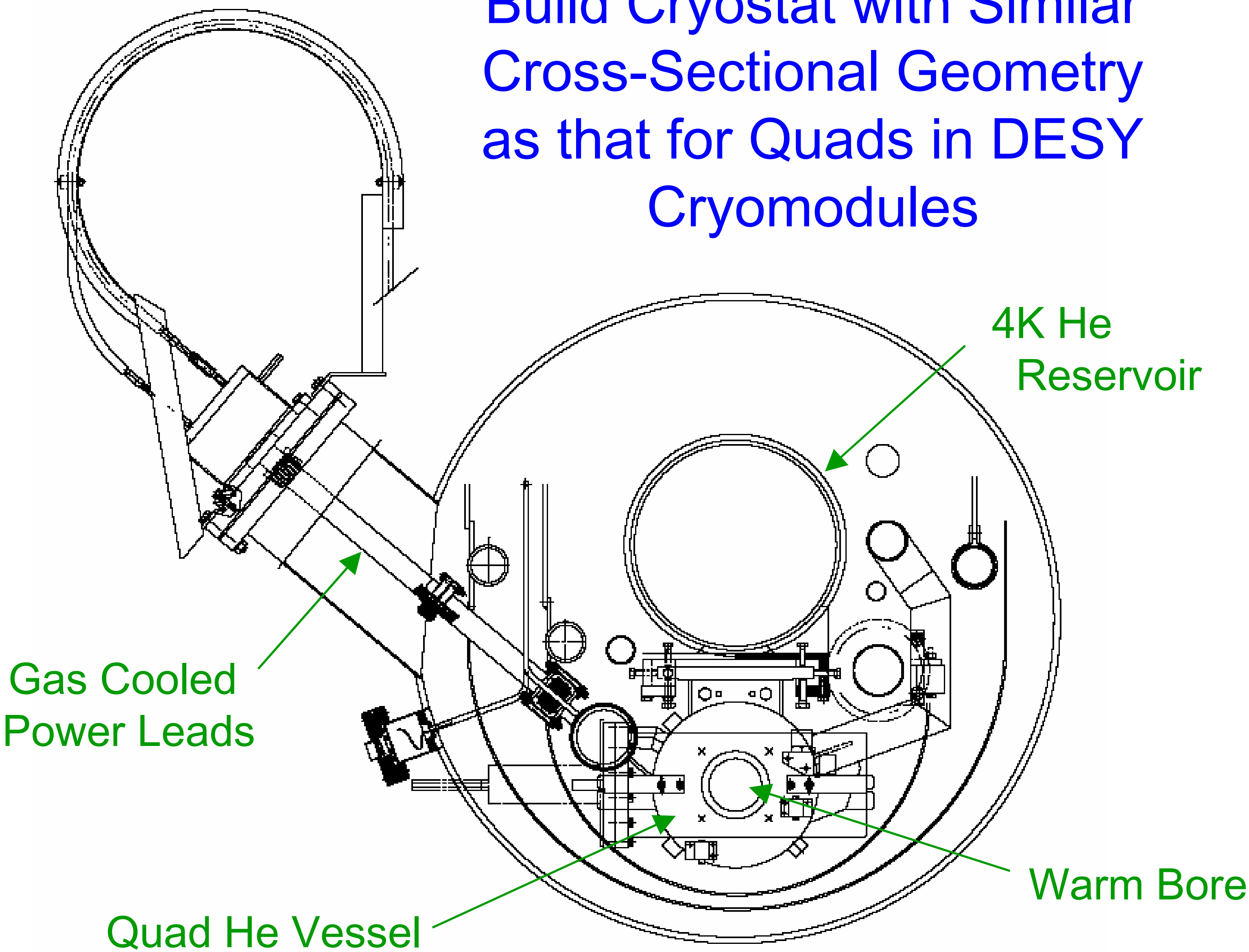
SC Coils

Iron Yoke Block

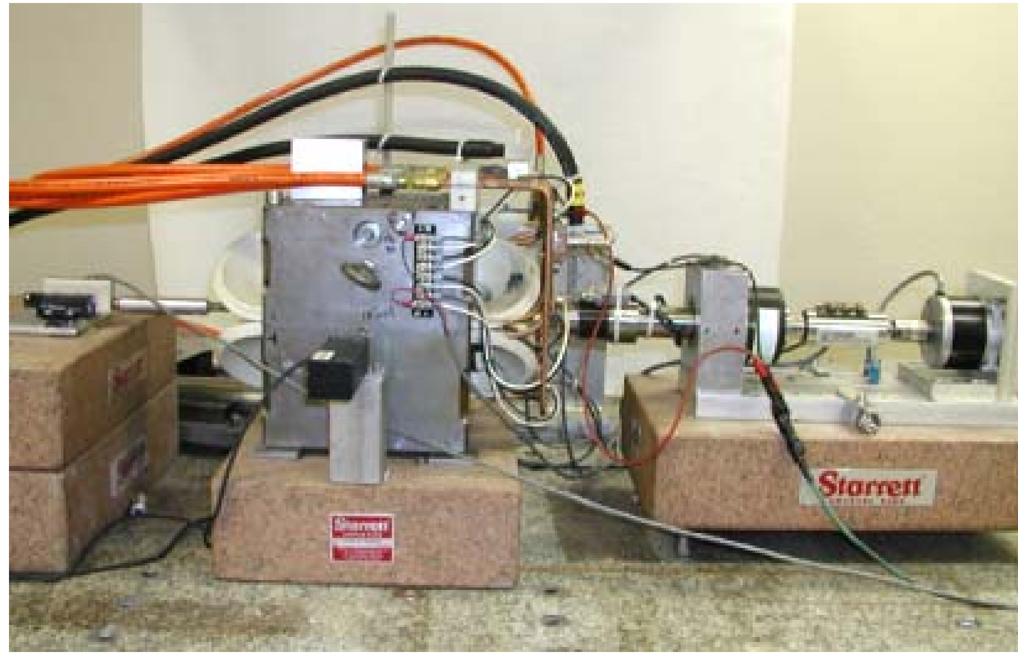
Al Cylinder

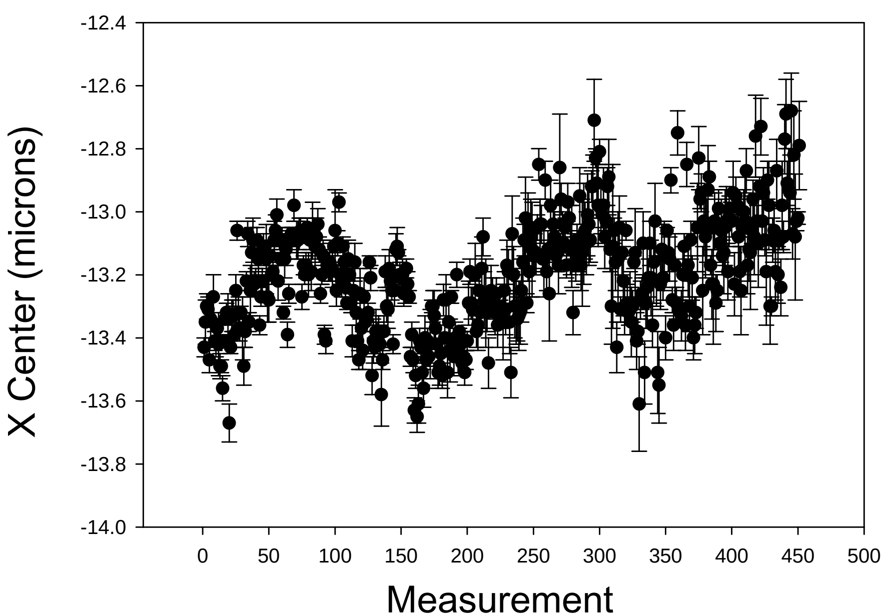


Build Cryostat with Similar Cross-Sectional Geometry as that for Quads in DESY Cryomodules



For Magnetic Center Measurements, Adapt Apparatus Developed for NLC NC Quads





Series of measurements (8 minutes each) of a 25 cm long NLC prototype quad - shows that sub-micron resolution is possible and systematics are controllable.

Currently designing longer, wider coil for SC Quad test – will qualify it first with a NC Quad.

Program Summary

- Programs started in FY05
  - Assemble an L-band rf station at NLCTA
  - Build IGBT switching circuits for two SMTF modulators
  - Develop a Marx-generator style modulator
  - Develop an L-band sheet-beam klystron
  - Build and test a 5 cell prototype positron capture cavity
  - Demonstrate linac quad and bpm performance for ILC beam-based alignment.
- Programs proposed for FY06
  - Build a second L-band station with ILC prototype modulator and klystron (collaborate with DESY).
  - Systematic study of coupler processing (with LLNL)
  - Assemble and process couplers for SMTF cavities (with FNAL)
  - E-beam weld SMTF cavities (with FNAL)

Summary

- Have reoriented SLAC rf program to match
  - ILC needs in view of other national and international programs.
  - Strengths of lab in developing high power HV and rf sources.
  - Experience in normal conducting accelerator design and operation.
  - Expertise in wakefield and alignment issues.
- Off to a good start.
  - Have quickly acquired components for an L-band source that will be used for structure and coupler testing.
  - Are at the forefront on design issues - will help lead program at Snowmass.
  - Well positioned to support the SMTF program and to collaborate with DESY on rf sources.
- Hope for strong GDE/DOE support to continue momentum from warm linear collider program.