L-Band RF System & Main Linac Integration Programs

April 29-30, 2009 ART Review

Chris Adolphsen, SLAC

General Goals:

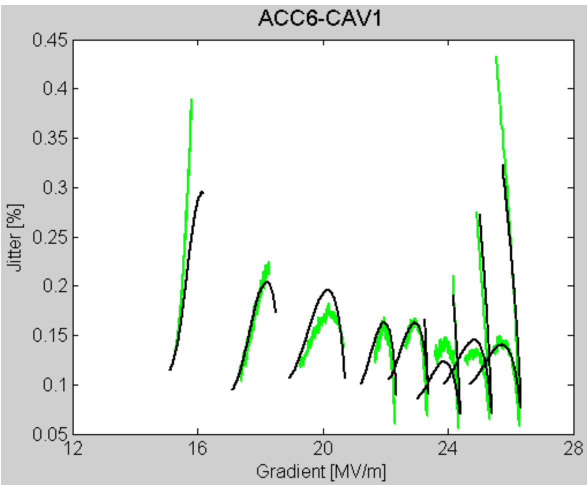
- Develop more reliable and lower cost L-band RF source components for the ILC linacs.
- Verify performance goals of the rf system
- Address linac issues that span subsystem boundaries

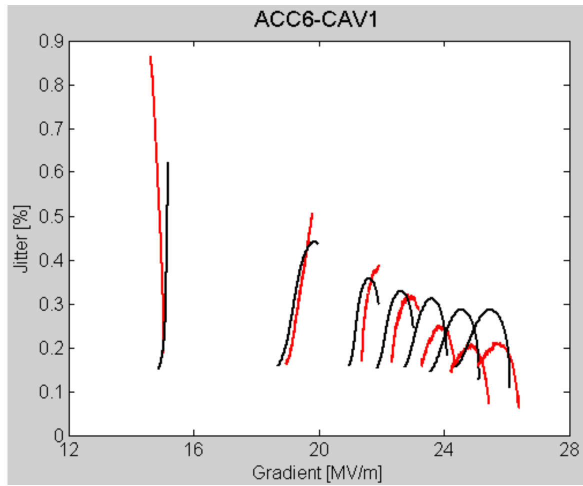
Main Linac Integration

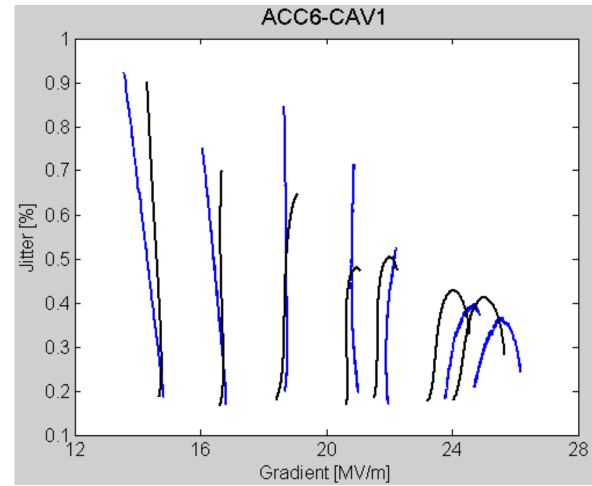
- Study pulse-to-pulse gradient stability in the FLASH cavities at DESY to evaluate rf overhead and model gradient control
- Evaluate the effectiveness of the cryomodule 70 K HOM absorbers in preventing a significant fraction of the beam induced, high frequency (above cavity cutoff) wakefield energy from being dissipated in the 2 K accelerator
- Design a 60 mm cold coupler section that is plug compatible with the TTF3 warm coupler section. Could allow mix of 40 mm (DESY and FNAL) and 60 mm (KEK) cavity/couplers in ILC

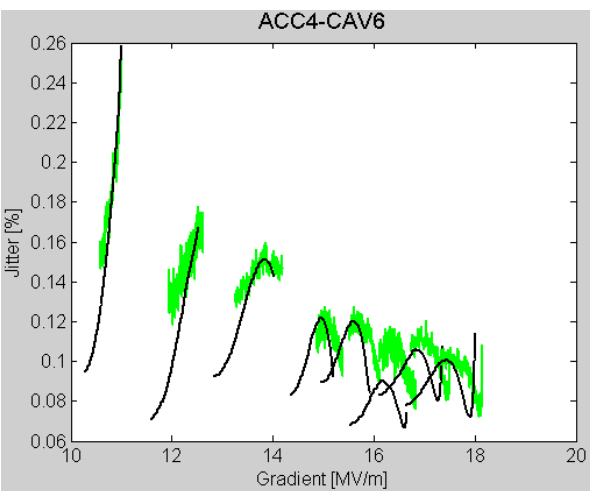
FLASH Cavity Gradient Stability

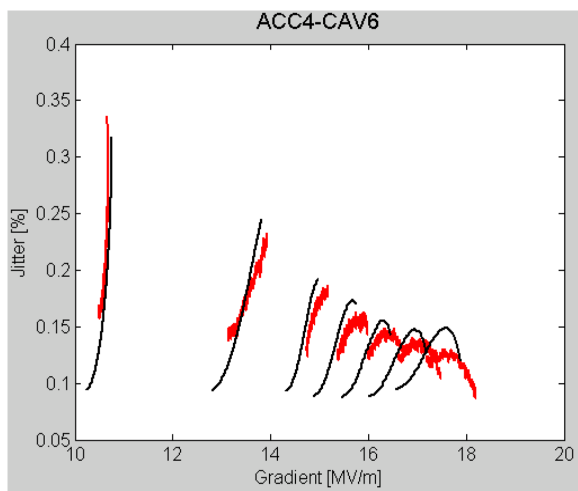
Comparison of beam-off measurements of pulse-to-pulse cavity gradient jitter during the flattop period for different gradients and initial cavity detuning (green, red and blue lines) to a cavity fill model including Lorentz force detuning (black lines) with two degrees of freedom (initial and initial rms detuning)

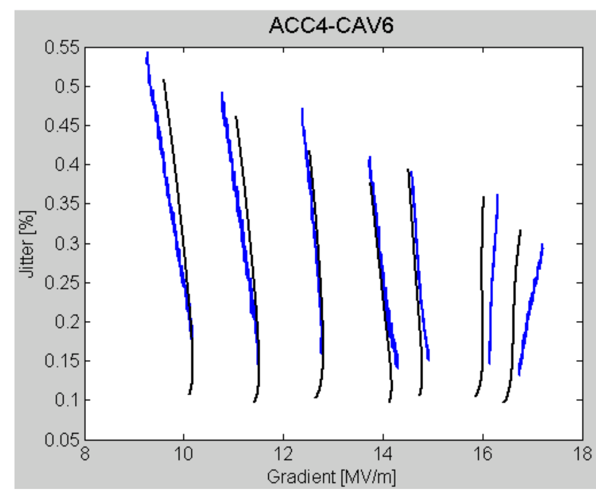










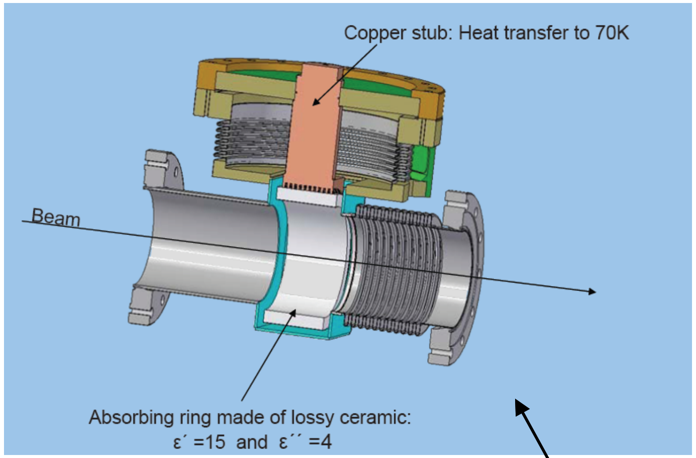


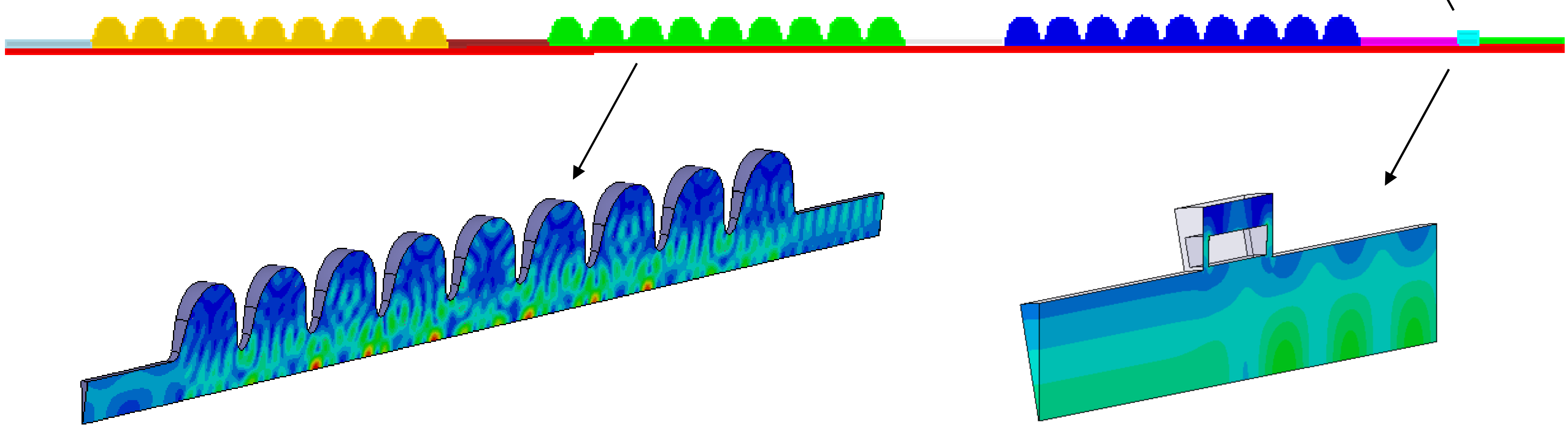
Effectiveness of Beamline HOM Absorber

Compute S-Matrixes for 4-20 GHz TM0n mode propagation through cavities and absorber

Cascade results to compute power loss profile in 8 cavity + 1 absorber strings

Goal: verify that beam pipe losses at 2K are small compared to losses in 70 K absorbers



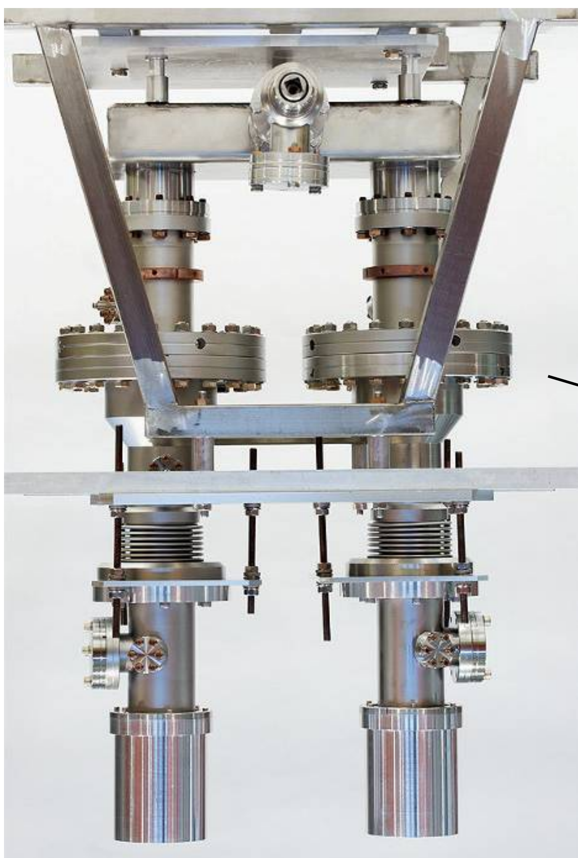


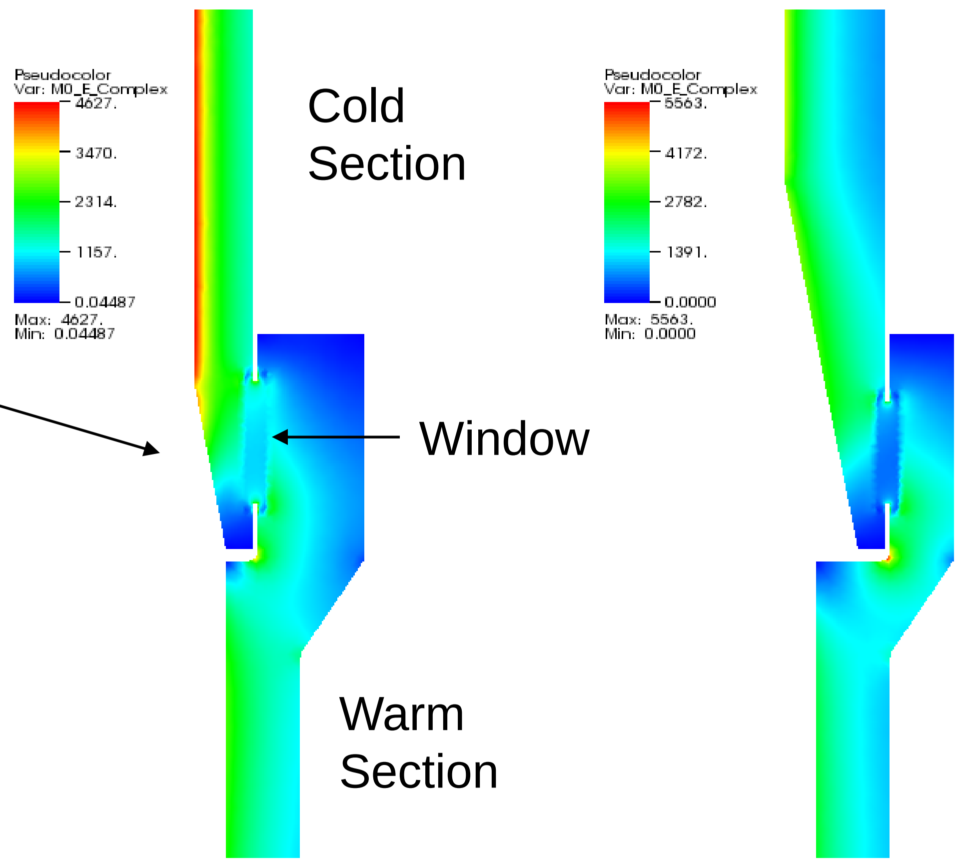
Designing a 60 mm Diameter Plug Compatible Coupler Cold Section

Like Orsay's TTF5 60 mm coupler shown on left, but warm section unchanged

TTF3 40 mm

60 mm Design

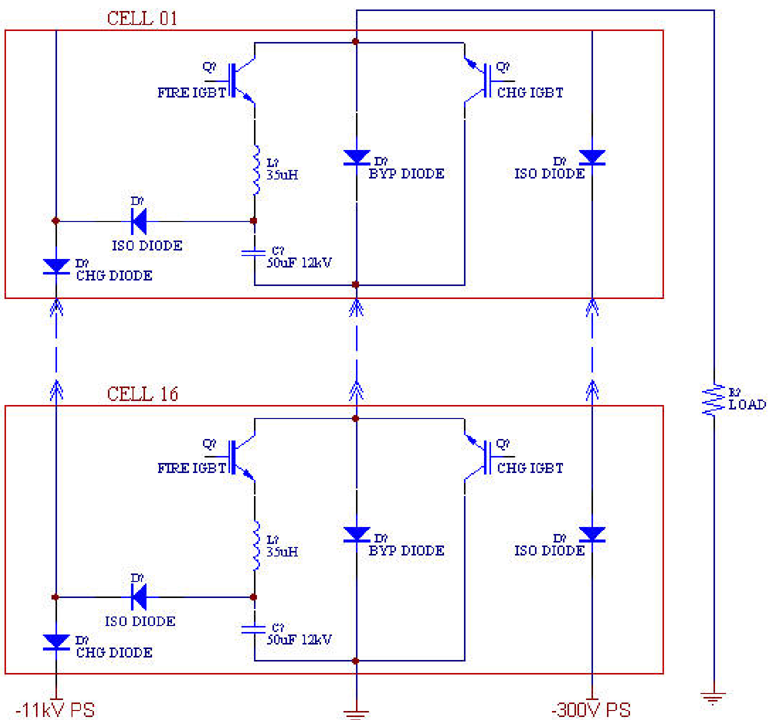


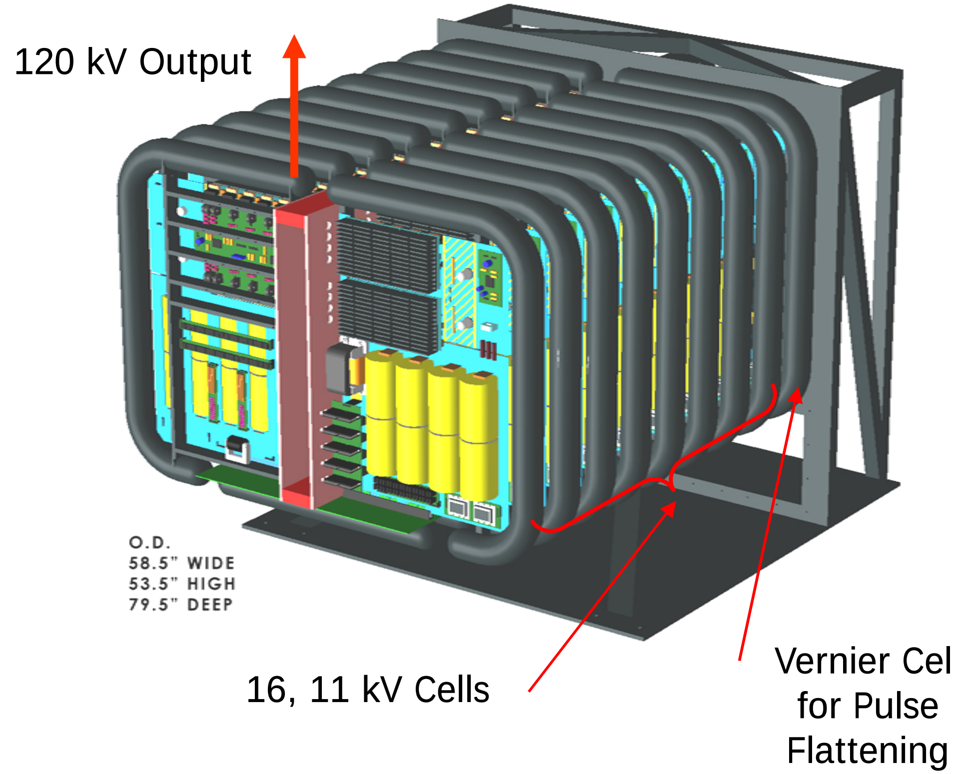


Marx Modulator

- **Goals:**
  - Develop Marx Modulator approach as an alternative to the ILC baseline Pulse Transformer Modulator with Bouncer
    - Reduces cost, size and weight, improves efficiency and eliminates oil-filled transformers
- **Project Status:**
  - Prototype (P1) built that has achieved peak power goals – moved to ESB in early 2009 where it has run 250 hr into a water load and is now undergoing control system upgrades to power a 10 MW Toshiba MBK
  - Vernier Cell (mini-Marx) to flatten pulse will be installed soon
  - Started design of next Marx version with ~ 3 kV cards and droop compensation on each card

P1 Marx Modulator
(120 kV, 140 A, 1.6 ms, 5Hz)

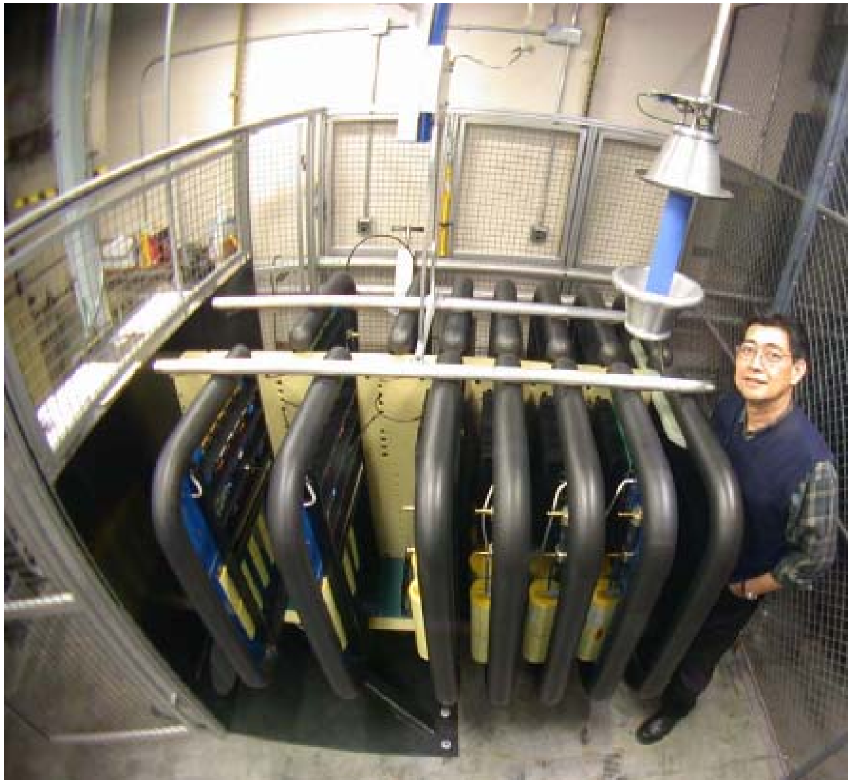




- 11kV per cell
- Switching devices per cell: two 3x5 IGBT arrays
- Charge switch provides return path for 11 kV and control sources
- Diode strings provide isolation between cells

Initial Testing at the Power Conversion Department

Overall Size: 60” W x 55” H x 80” D



11 kV Marx Cell

Front & Rear Views

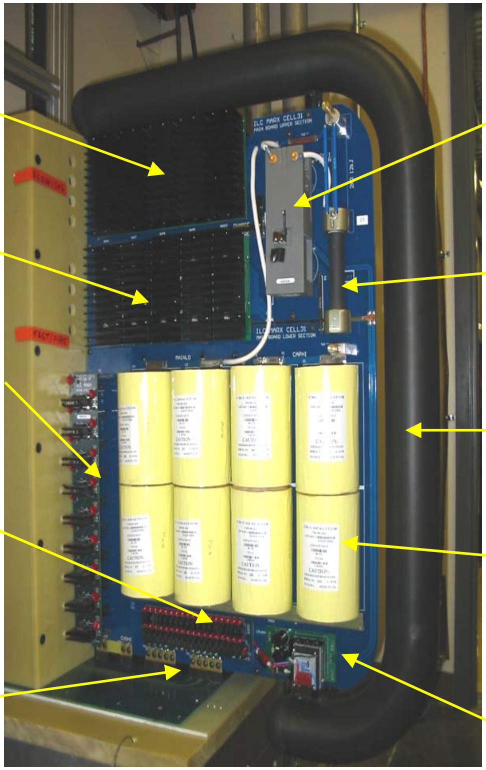
5 Charging SW Modules

5 Firing SW Modules

Charge Diode String

Bypass Diode String

Connector Group to Backplane



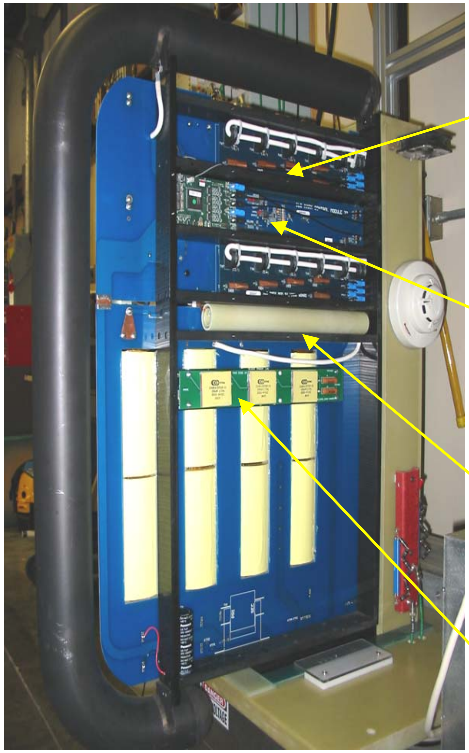
Cell Grounding Relay

Cap. Discharging Resistor

Equipotential Ring

Energy Storage Capacitors

Control Power Converters



11kV Isolated Power/Trig ger Boards

Cell Control Module

dI/dt Limiting Inductor

Charge Isolation Diode String

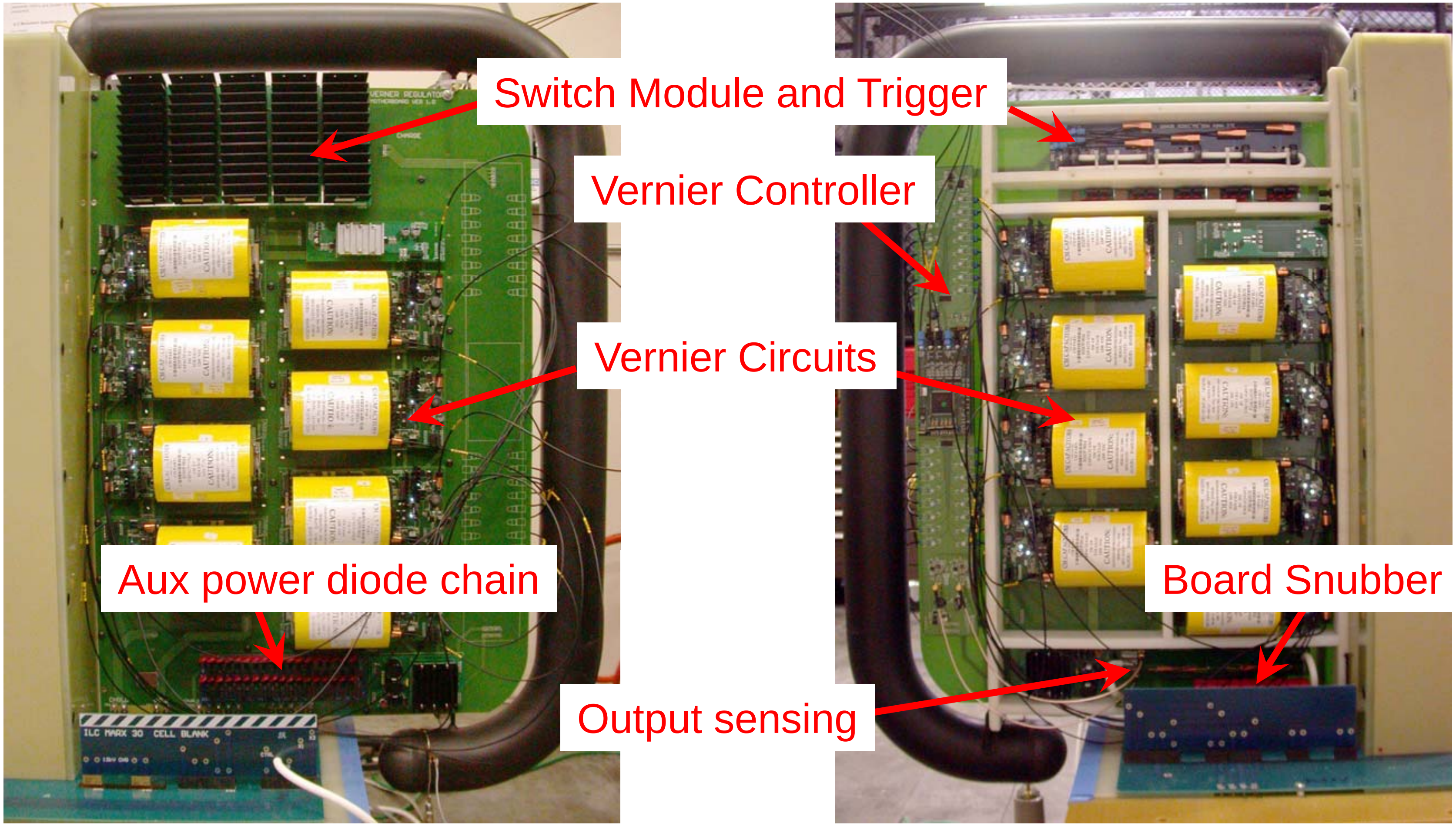
120 kV, 140 A Marx Output with Coarse Flattening

16 Cells at 11 kV into Water Load (5 delayed to flatten pulse). Operate at 4 Hz due to 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

Vernier Cell

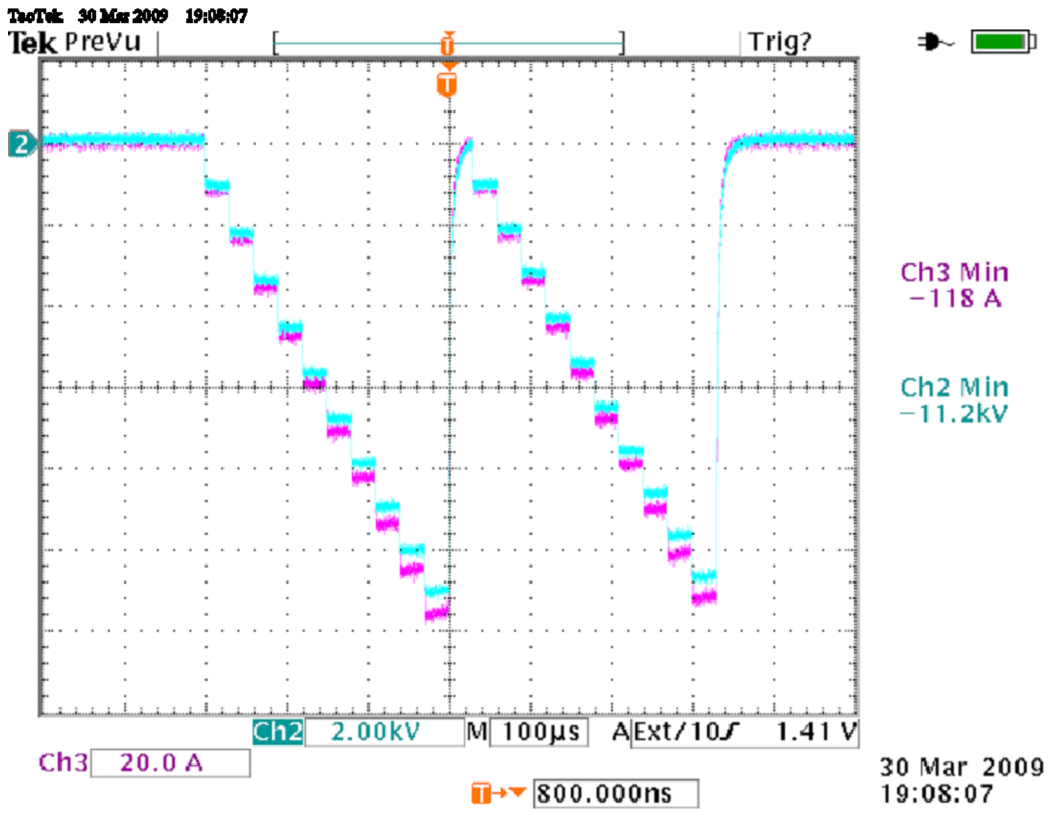


Front Side

Back Side

Independent Vernier Cell Testing

- Vernier is tested with resistive load
- Different turn on sequences are tried



Load impedance: 100 ohm
First cycle fire sequence: cell 0 to cell 9
Second cycle: cell 15 to cell 6

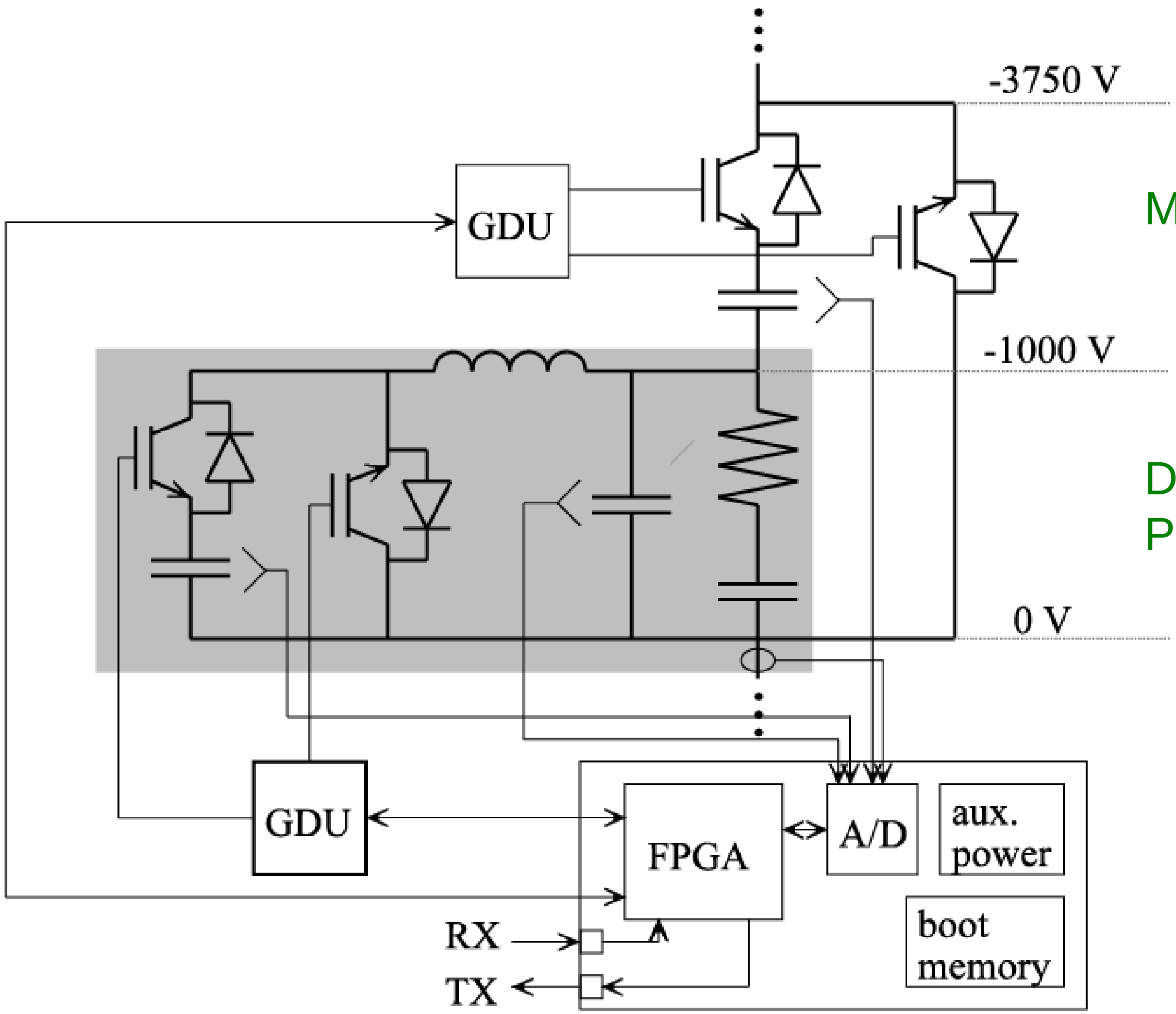
New L-Band Station at ESB: Marx Modulator and 10 MW Toshiba Multi-Beam Klystron

See Next Talk

P1 Deficiencies

- Footprint
  - Low density, due to poor field grading
  - Inefficient, short and squat
  - Incompatible with RDR tunnel
- Manufacturability
  - PCB-based construction inappropriate for power components
  - IGBT
    - Single-source
    - Device-device variations
- No redundancy
  - Lost “spare” cells to reduced operating voltage (12 to 11 kV)
  - Vernier Cell has numerous single-point failure elements
- Control system limitations (for high availability operation)
  - Diagnostic access is limited by wide potential variations in cell
  - Limited bandwidth: processing and transmission

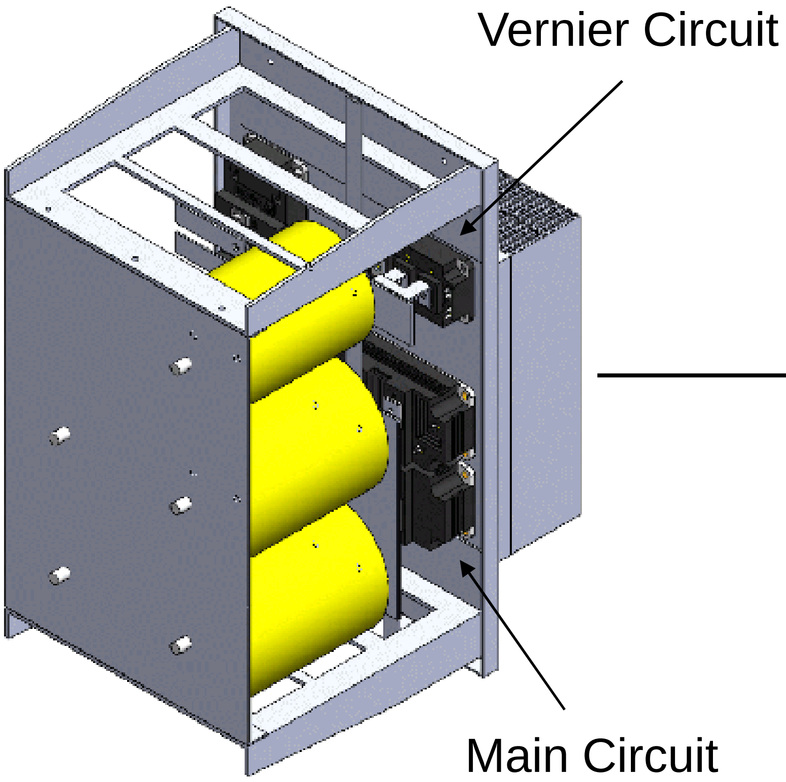
P2 Marx Cell

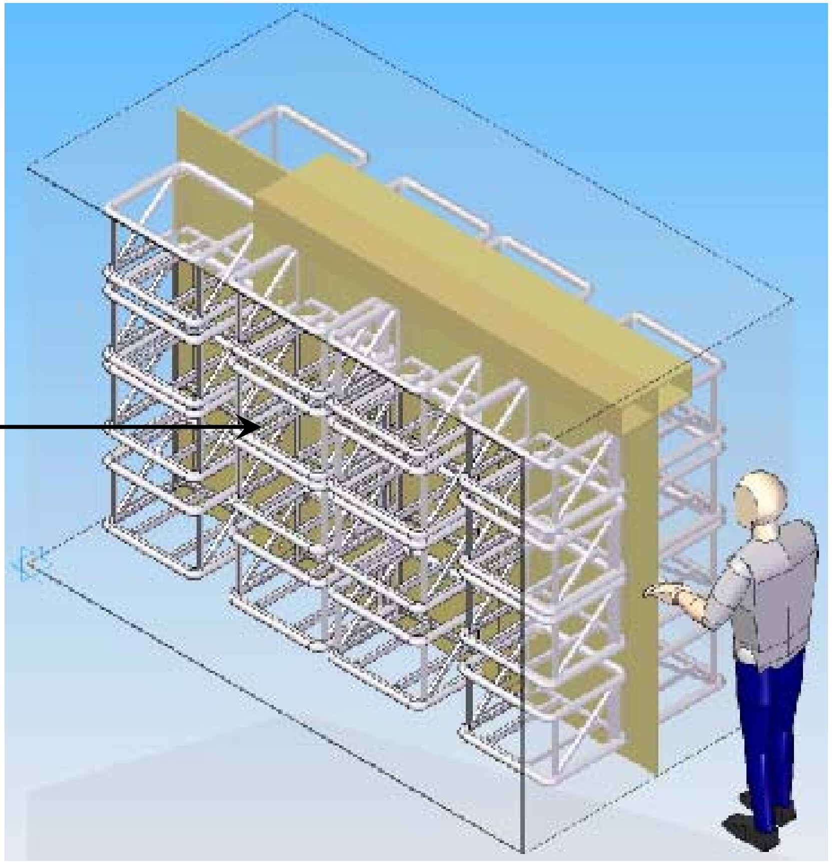


Main Voltage Step-up

Droop Compensation using Pulse Width Modulation

One Concept for P2 Layout



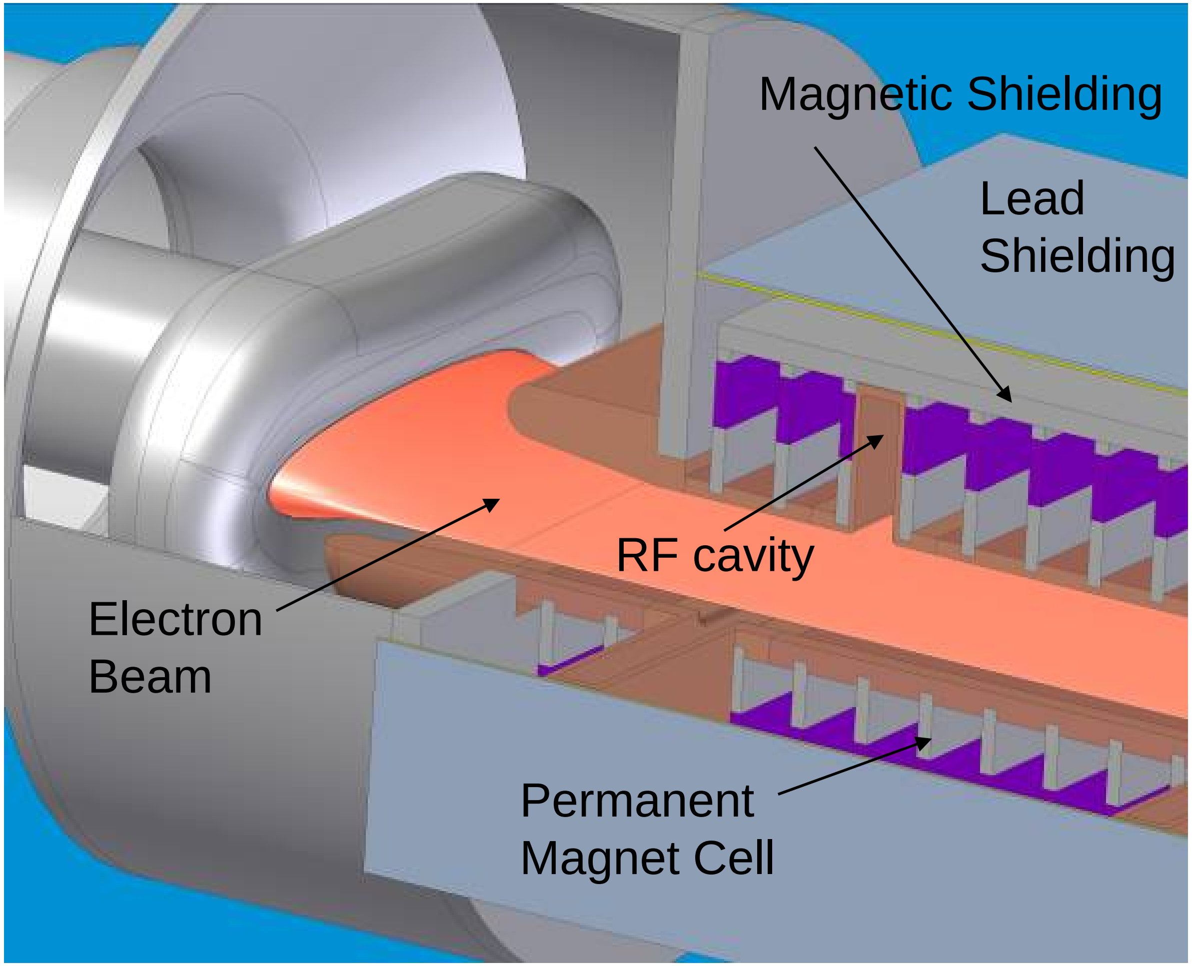


Sheet Beam Klystron Development

- **Goals:**
  - The Sheet Beam Klystron (SBK) originally envisioned has a 40:1 beam aspect ratio and utilizes permanent magnet focusing, making it smaller, lighter and less expensive than the baseline Multi-Beam Klystron (MBK)
  - SBK would be plug-compatible and have similar efficiency as the MBK
  - Both a Beam Tester and full SBK would be built so the issues of beam generation, transport and rf operation can be studied separately
- **Project Status:**
  - After some machining delays, Beam Tester about to be operated with short pulses
  - In designing the SBK, discovered strong beam induced transverse modes in the beam tube that would drive the beam into the wall in 10's of ns. No easy fixes, but have a plan to salvage the initial concept

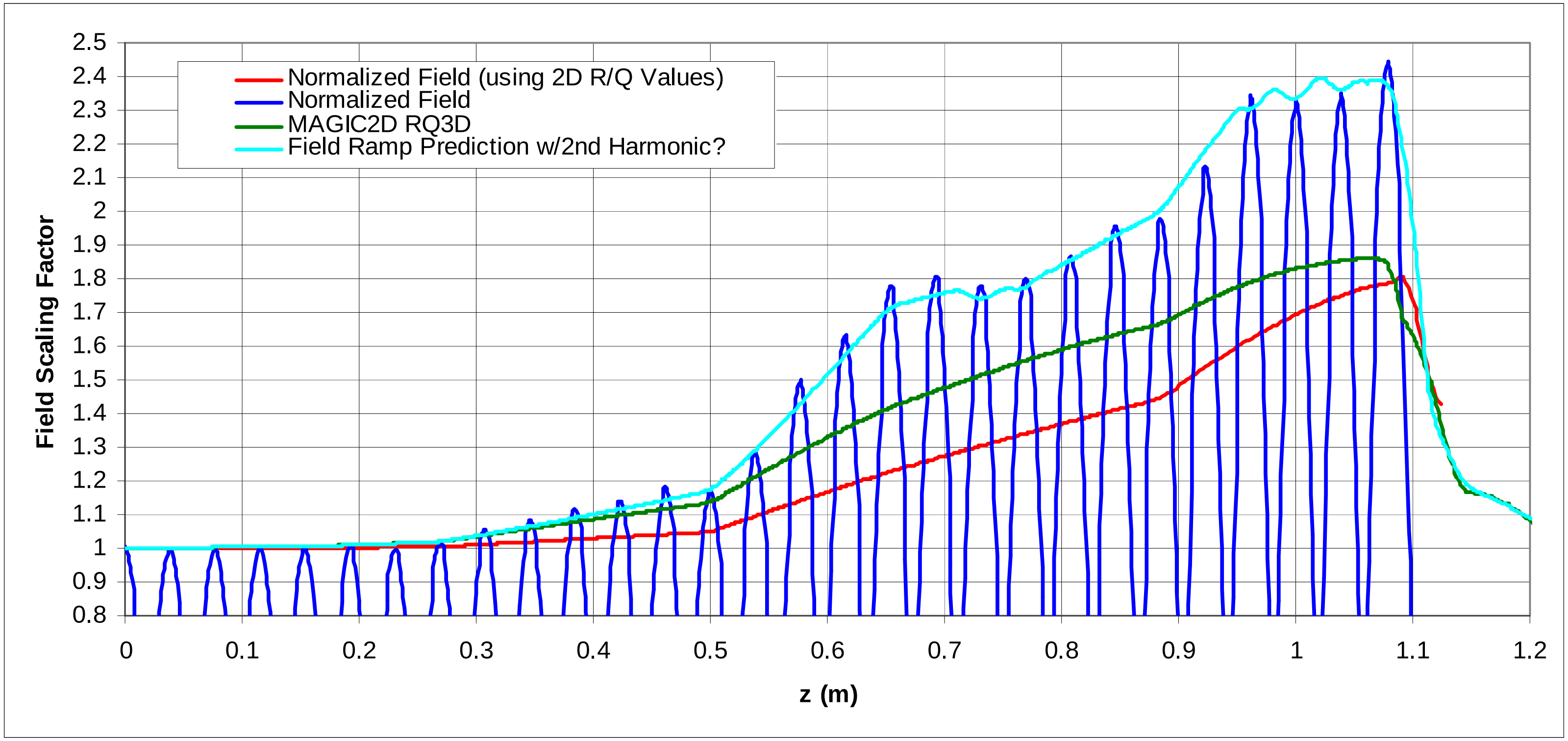
Beam Transport and RF

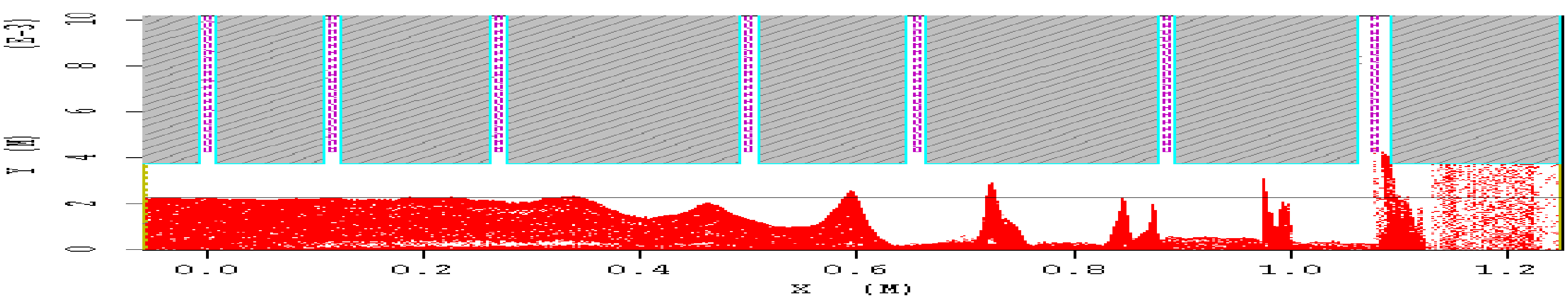
An elliptical beam is focused in a periodic permanent magnet stack that is interspersed with rf cavities



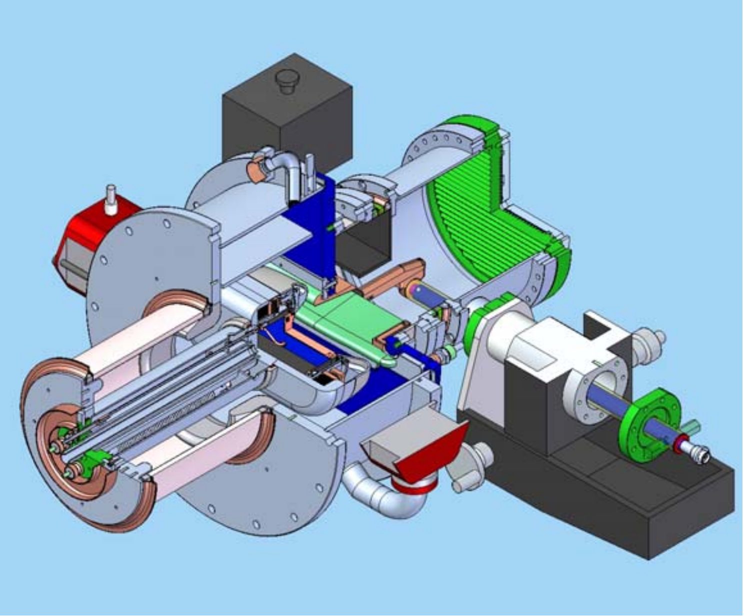
RF Simulations with Magic 2D

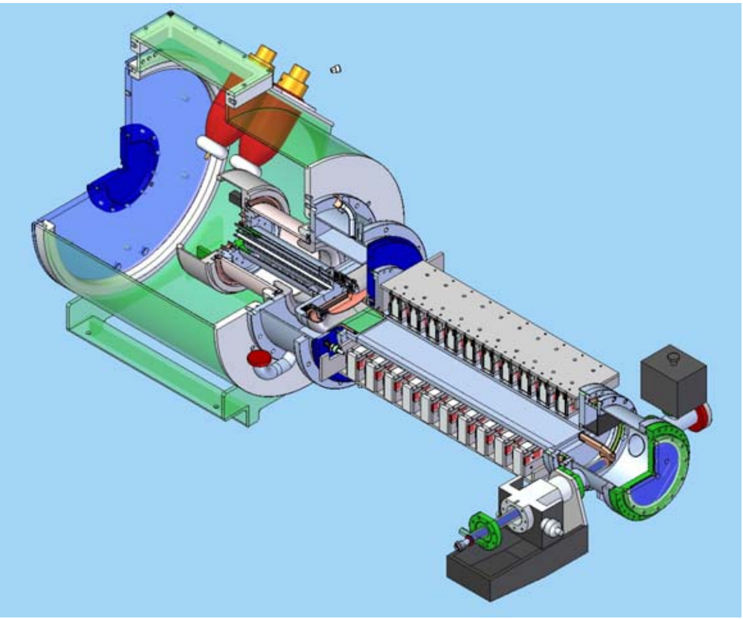
(Assuming Up-Down Symmetry)





Design/Test Evolution



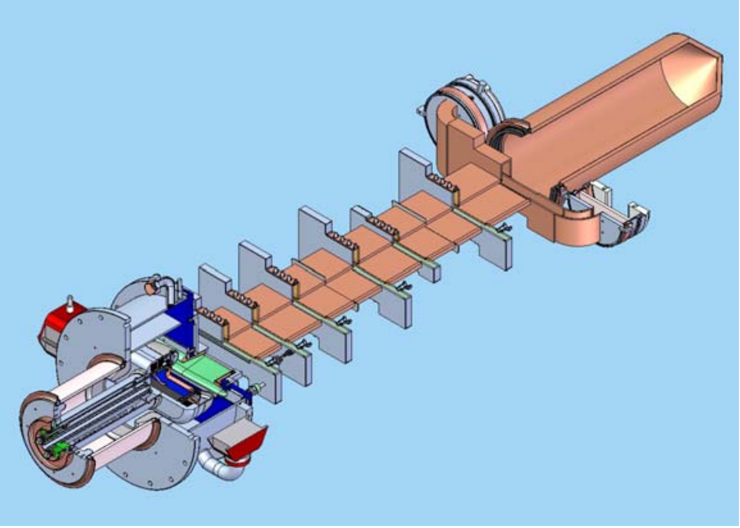


Measure Beam
From Gun

Measure Beam
after Transport
w/o RF

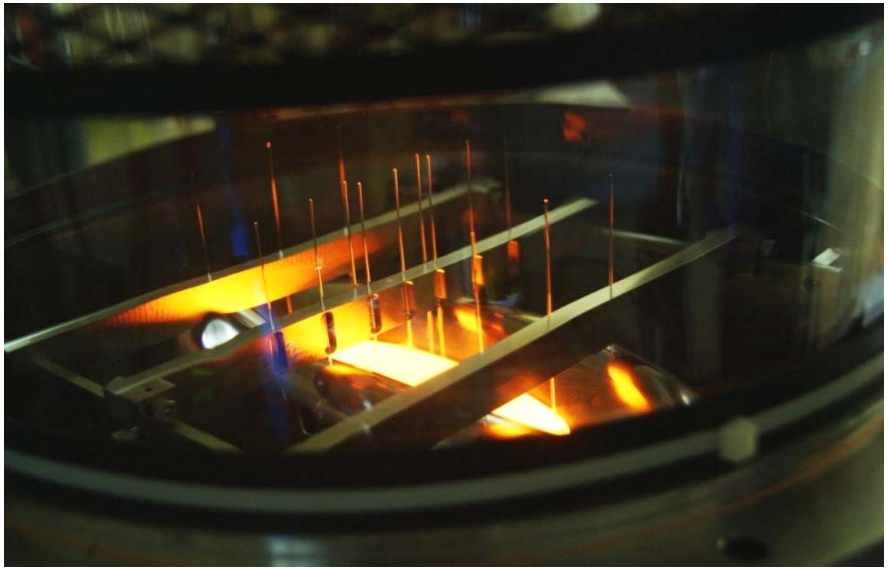
Original Plan

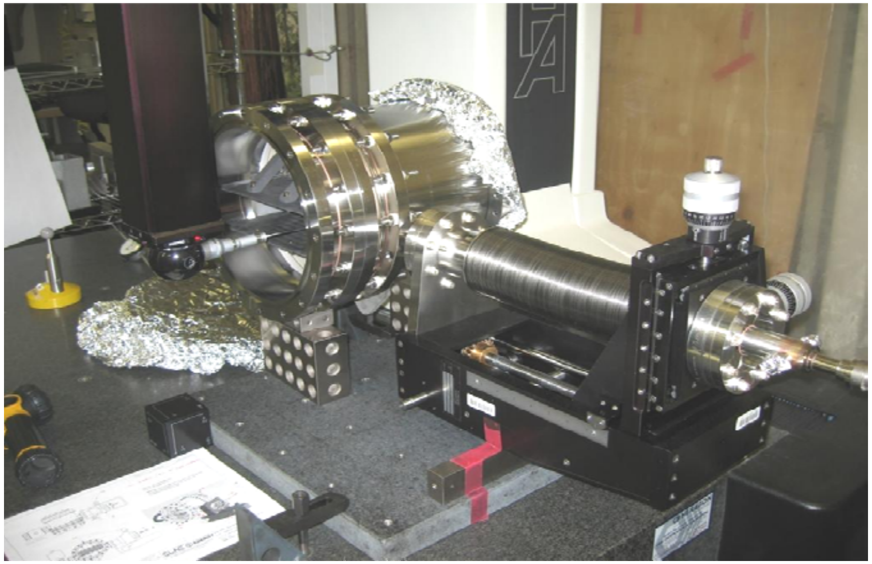
Measure RF
Generation

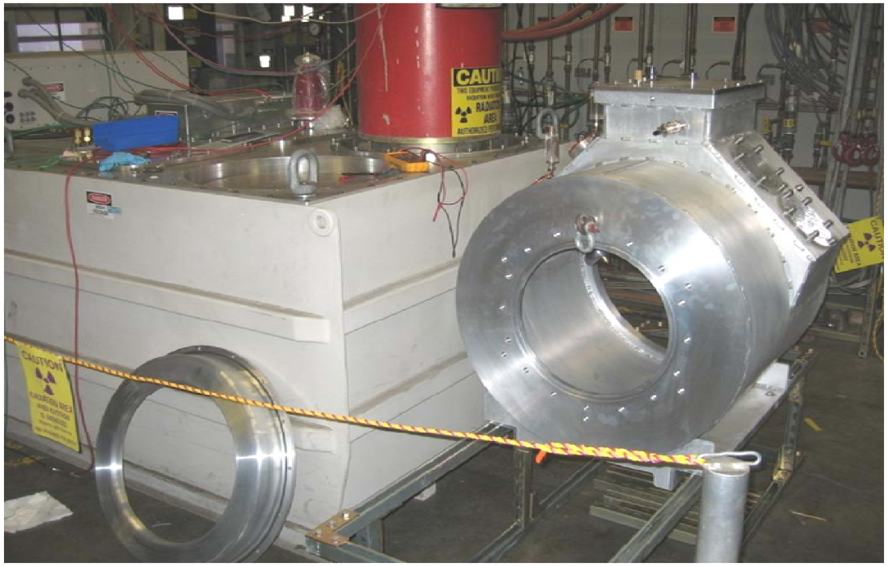


Rotational Alignment of Gun Stem

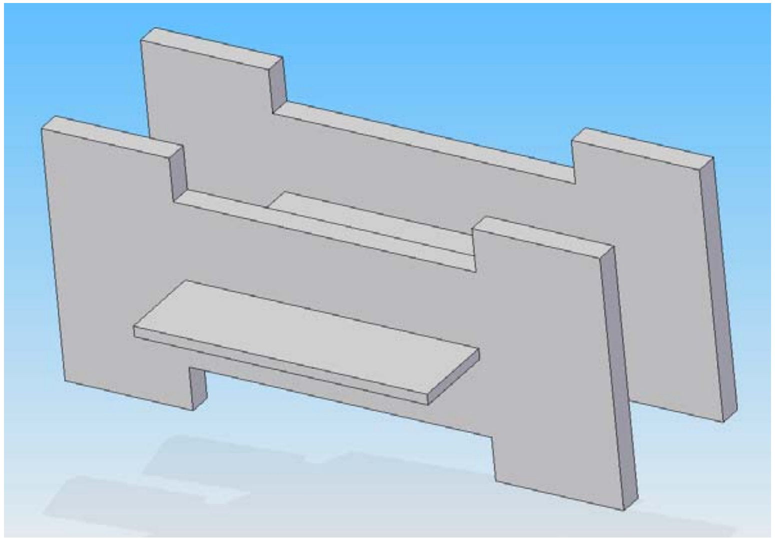
Photos of Gun Preparation



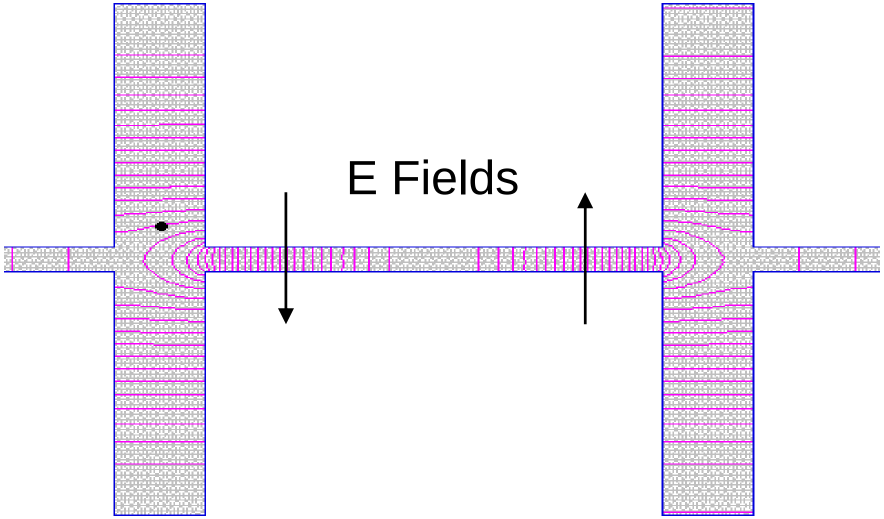




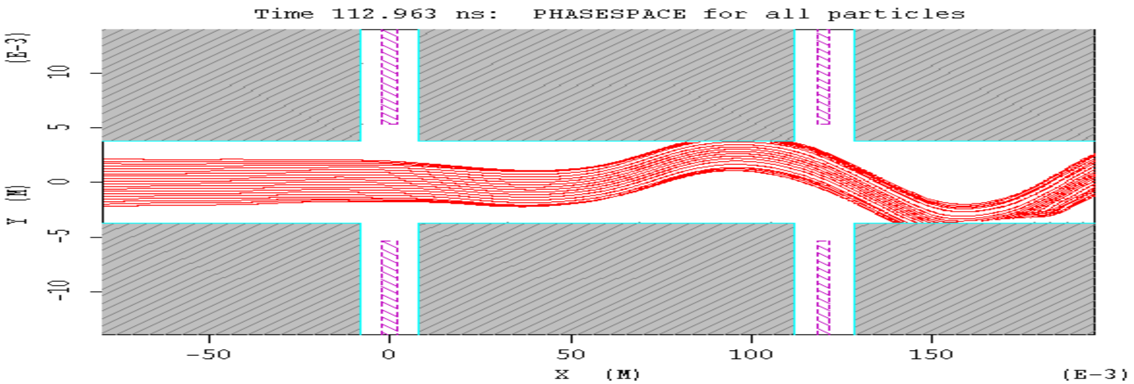
Trapped Modes Between Cavities



Two Cavity Geometry



Two Cavity Trapped Mode



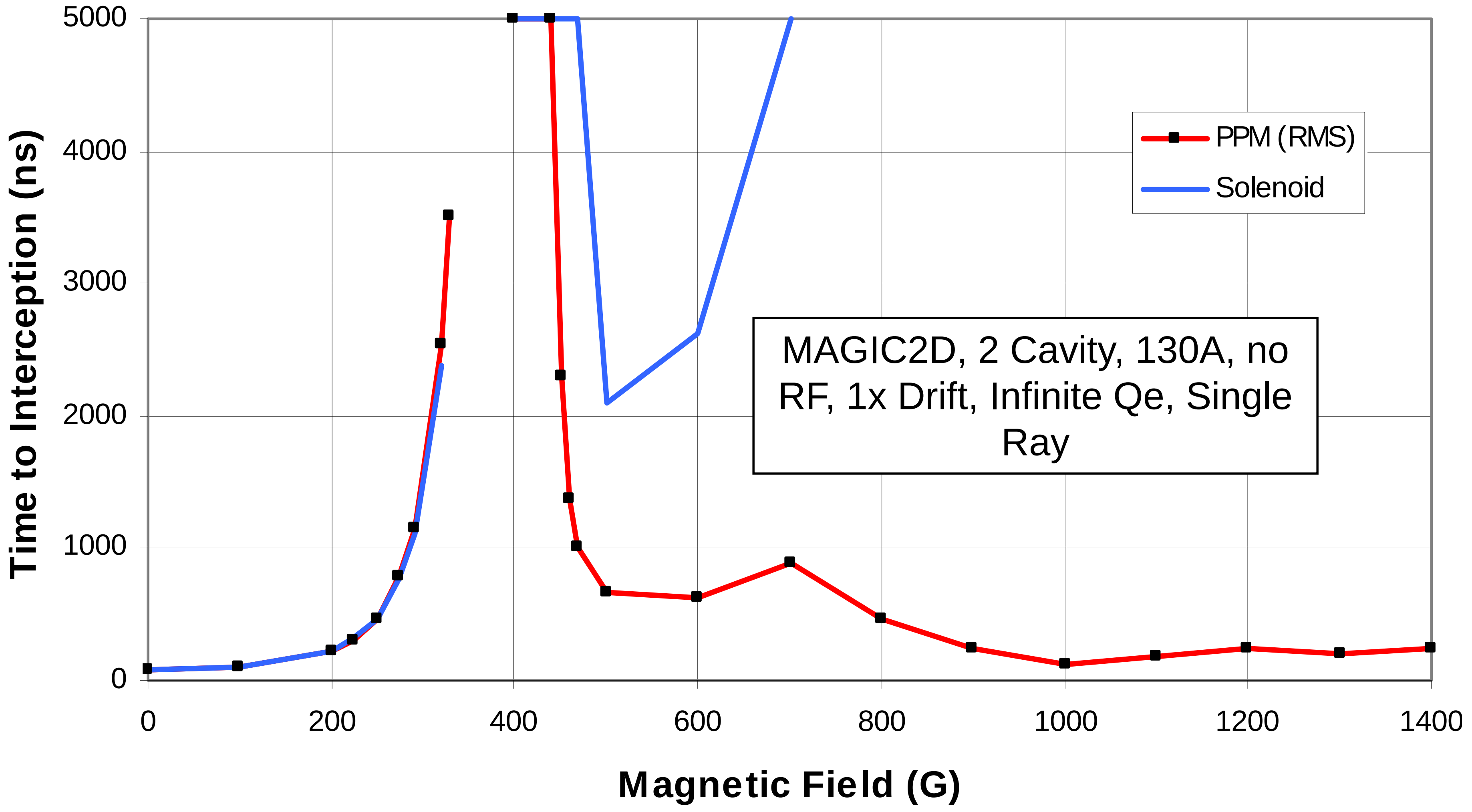
Trapped Mode Interaction with Beam (MAGIC2D)

A collaboration of Linear Collider, Beam Physics, Advanced Computations and Klystron Department physicists has been aggressively studying this problem by for past six months

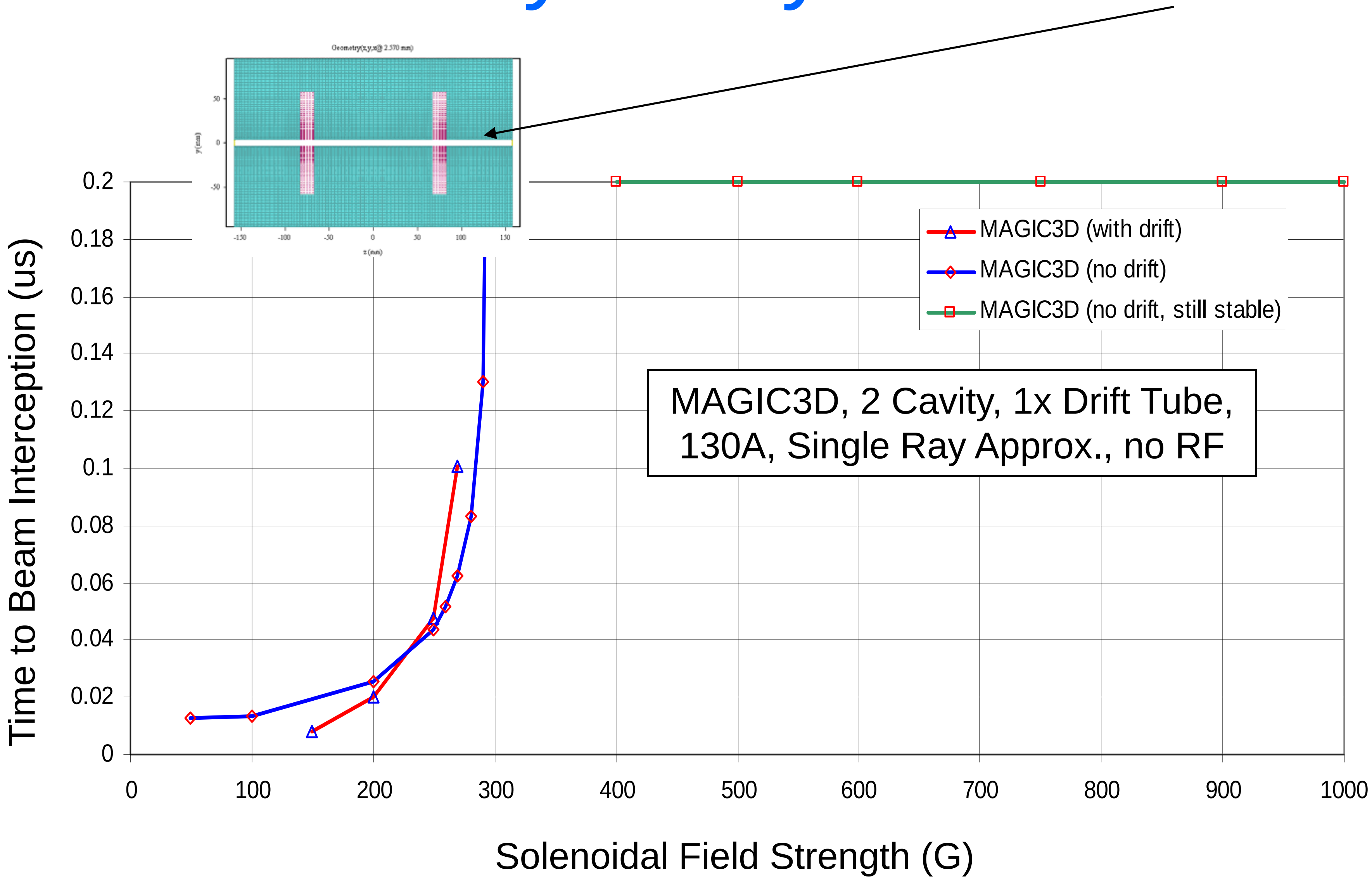
Road to a SBK

- Simulation codes: Analytic 2D (very fast), Numeric 2D and 3D (fast), MAGIC 2D (slow) and MAGIC 3D (very slow)
- Cases: 2 or 7 cavities, low or high current, 2D or 3D, rf on or off, Soln or PPM focusing, 1X or 2X beam tube height, current ramp or no ramp, drift or no drift region, ….
- For no rf, low current, 2D, 2 cavity, 1X height and soln focusing: Analytic 2D, Numeric 2D and MAGIC 2D (seeded) generally agree, and going to 3D with rf and high current does not change MAGIC results significantly.
- Plan to verify predicted regions of stability by running Beam Tester with two cavities and 'matched' solenoid or PPM (complete by end of 2009)
- In meantime, use Numeric 3D code to design 7 cavity klystron with PPM focusing or low power soln focusing, and check with MAGIC 3D running on SLAC processing clusters. So far, > 600 G solenoid focusing with 2X height works in 2D at high current with rf
- If above successful, start SBK engineering design in FY10 Q2

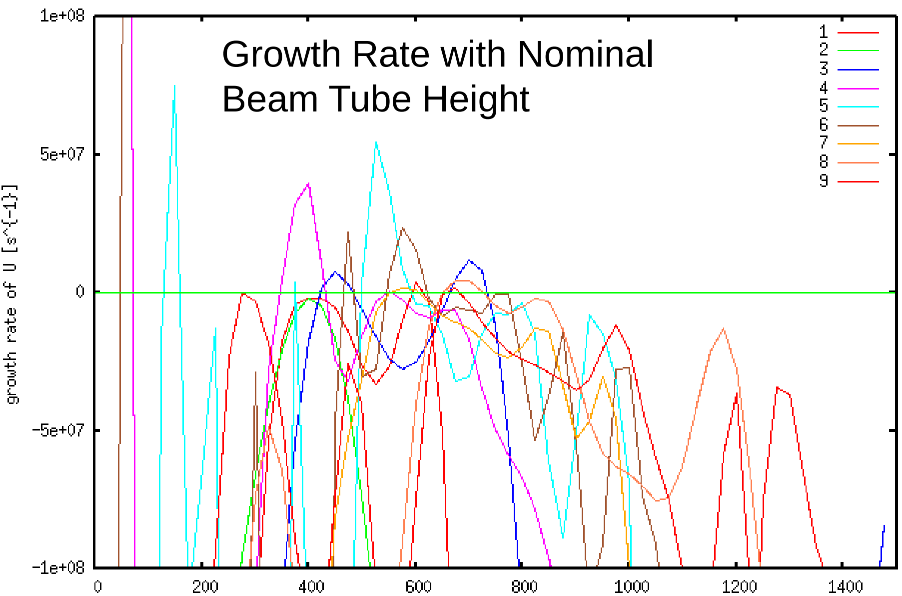
2D Stability Study: PPM vs Soln

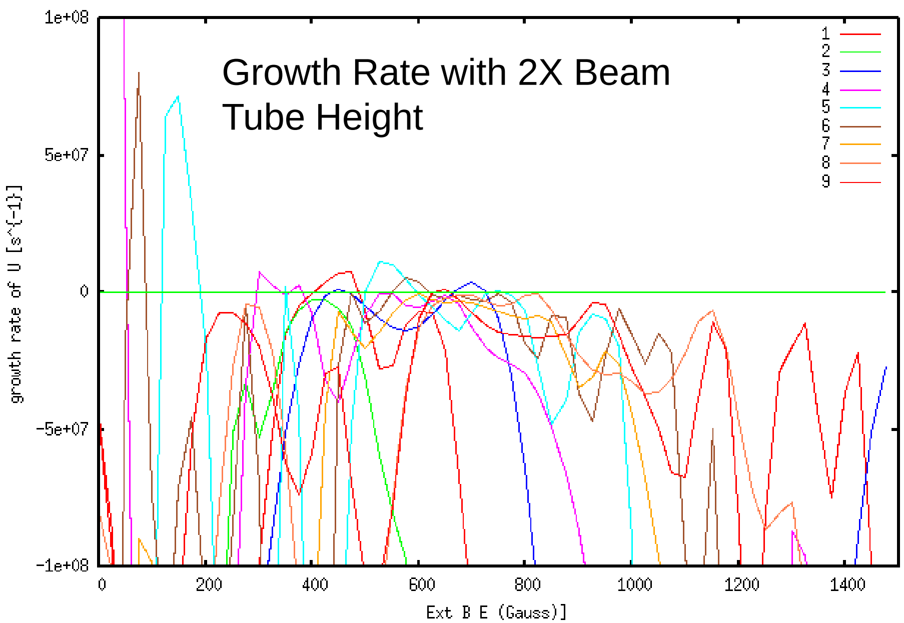


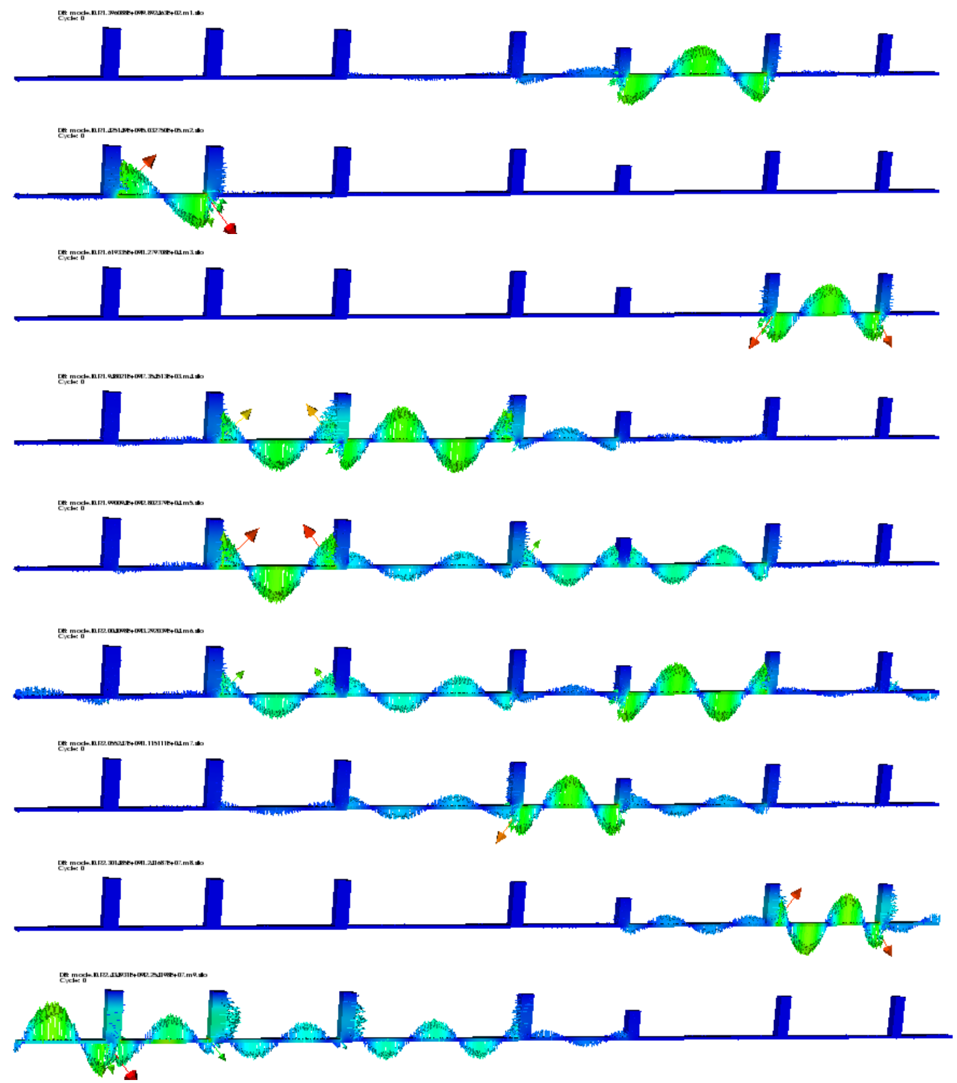
3D Stability Study: w/wo Drift



Modes with 7 Cavities: 1.4-2.4 GHz





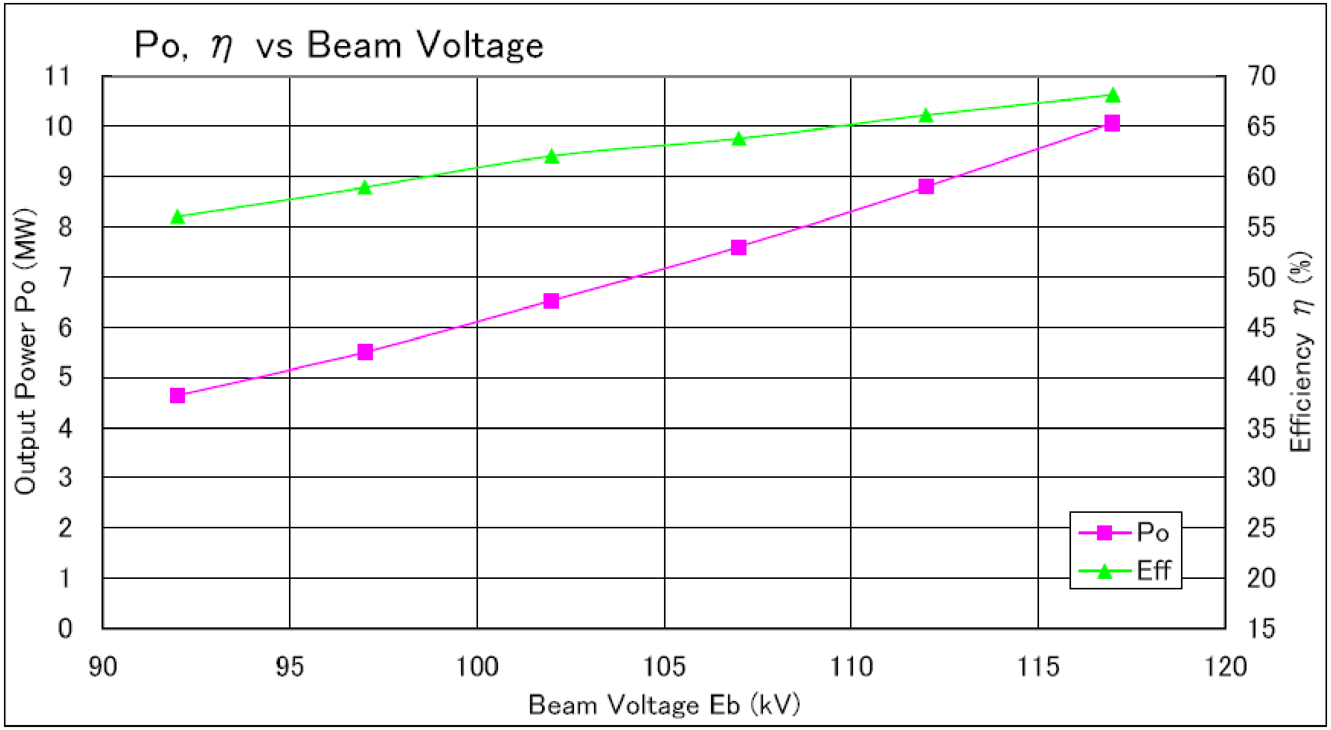


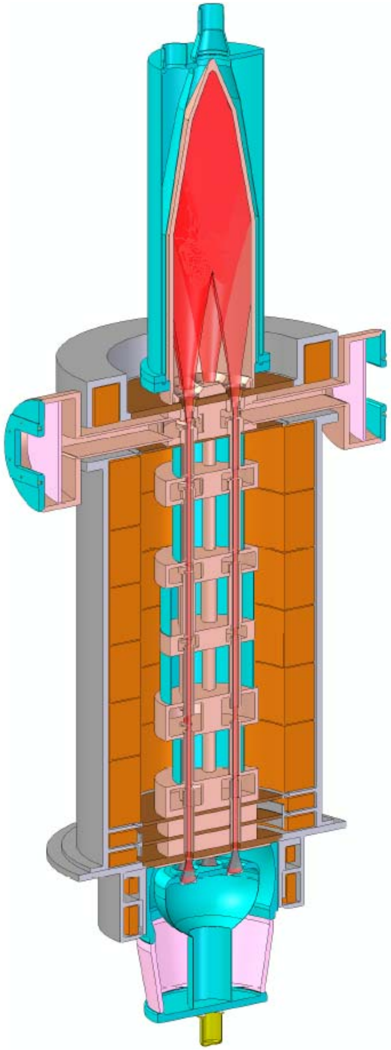
Multi-Beam Klystron Acquisition

- **Goals:**
  - Acquire 10 MW Multi-Beam Klystron (MBK) to do long term, full power testing.
  - DESY has led 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
  - 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 where it will be powered soon with the P1 Marx modulator – see next talk
  - Will eventually be shipped to FNAL to power the first full ILC rf unit

SLAC/KEK Toshiba 10 MW MBK

Toshiba Measurements of Efficiency and Output Power -vs- Beam Voltage

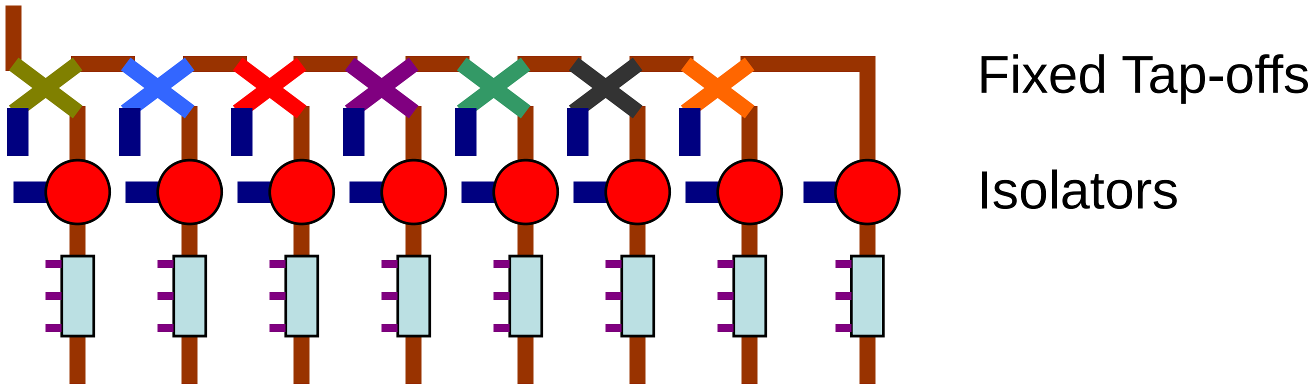




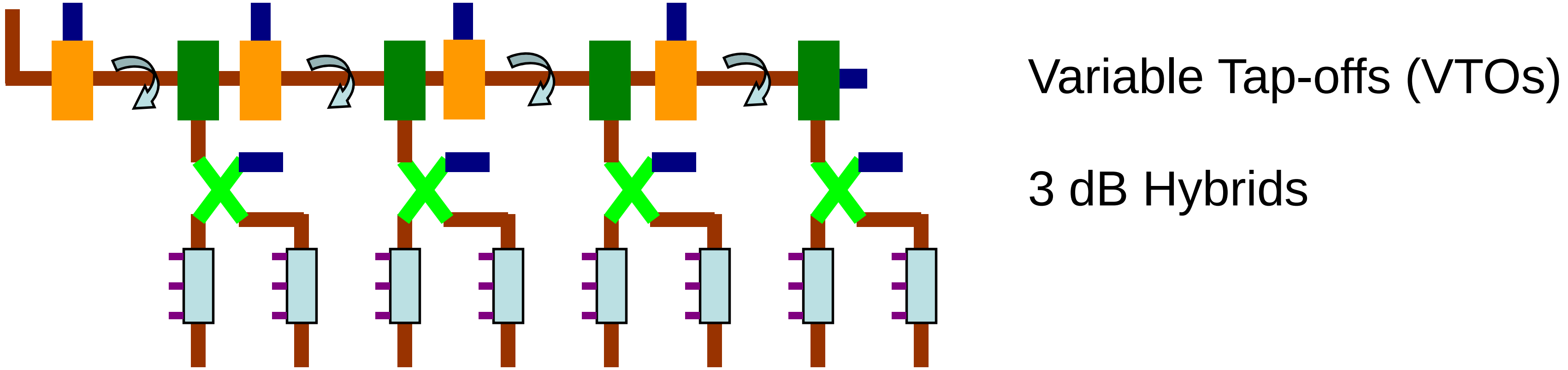
Optimized RF Distribution System

- **Goals:**
  - Pursuing two changes to the baseline distribution scheme to lower its cost: (1) Use hybrids instead of isolators and (2) Variable Tap-Offs (VTOs) instead of fixed tap-offs to accommodate the large spread in cavity gradients
  - Build such systems for FNAL cryomodules (CMs)
  - Develop a Klystron Cluster distribution scheme that would move rf sources to surface buildings, eliminating the need for a service tunnel
- **Project Status:**
  - An 8-cavity distribution system was built and sent to FNAL in FY09 Q2 to power their first CM (later this year) – includes isolators for back-up, which are also required for beam operation
  - Currently developing a lower cost, remotely controlled VTO for next CM
  - For Klystron Cluster scheme, have rf design for taps and an R&D plan to demonstrate basic performance – hope to have funding soon

ILC Baseline RF Distribution System

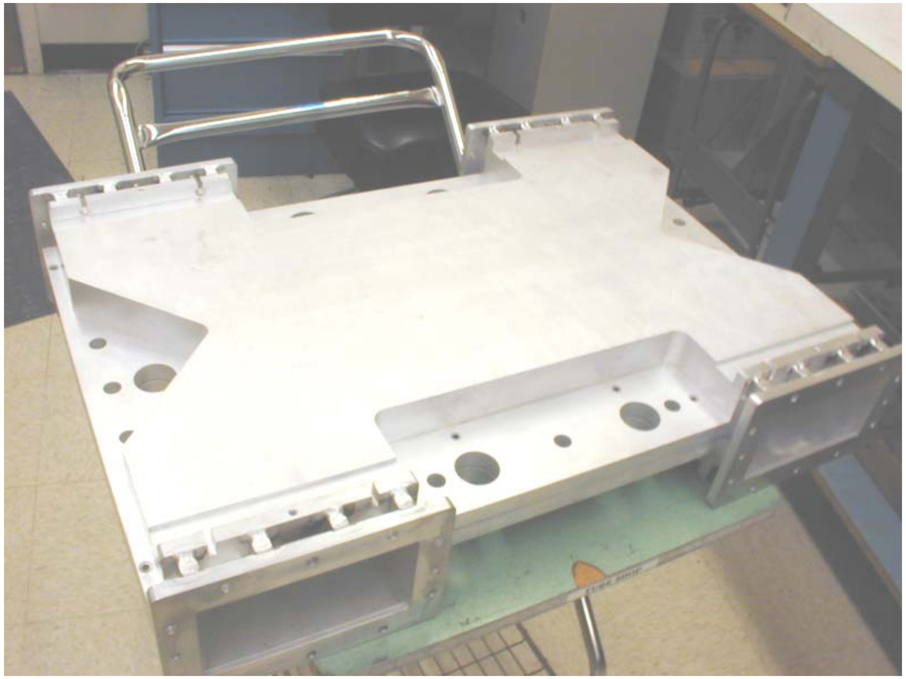


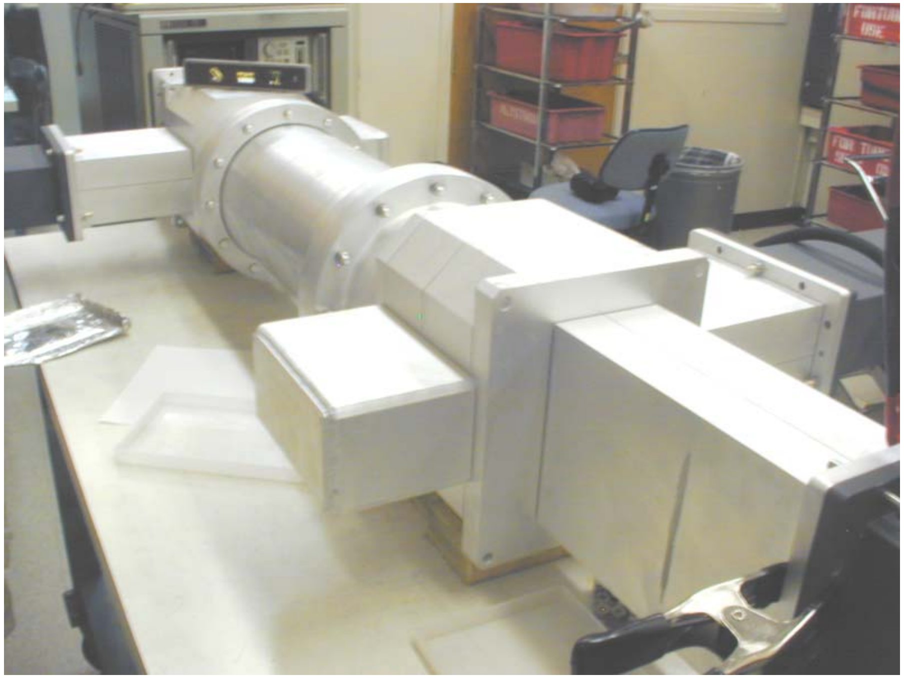
Alternative RF Distribution System

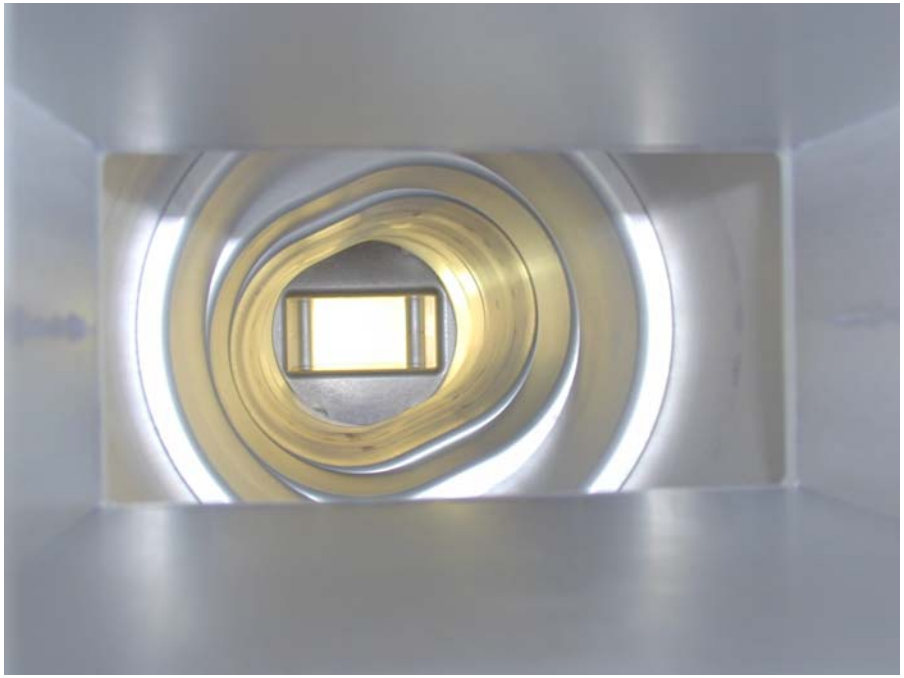


Prototype VTO (below) and Hybrid (right)

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

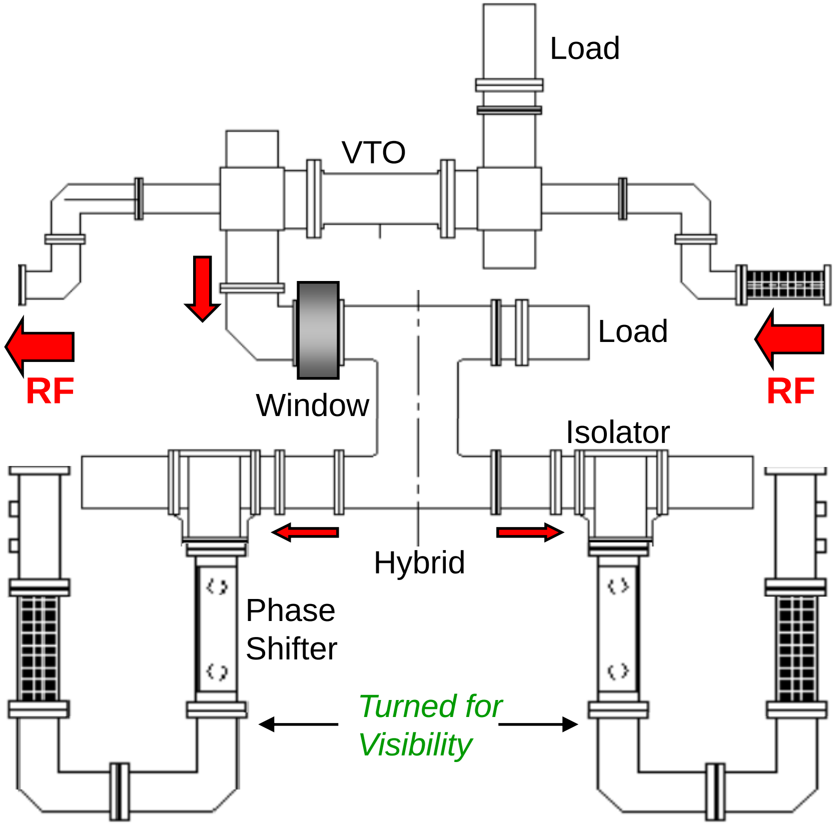


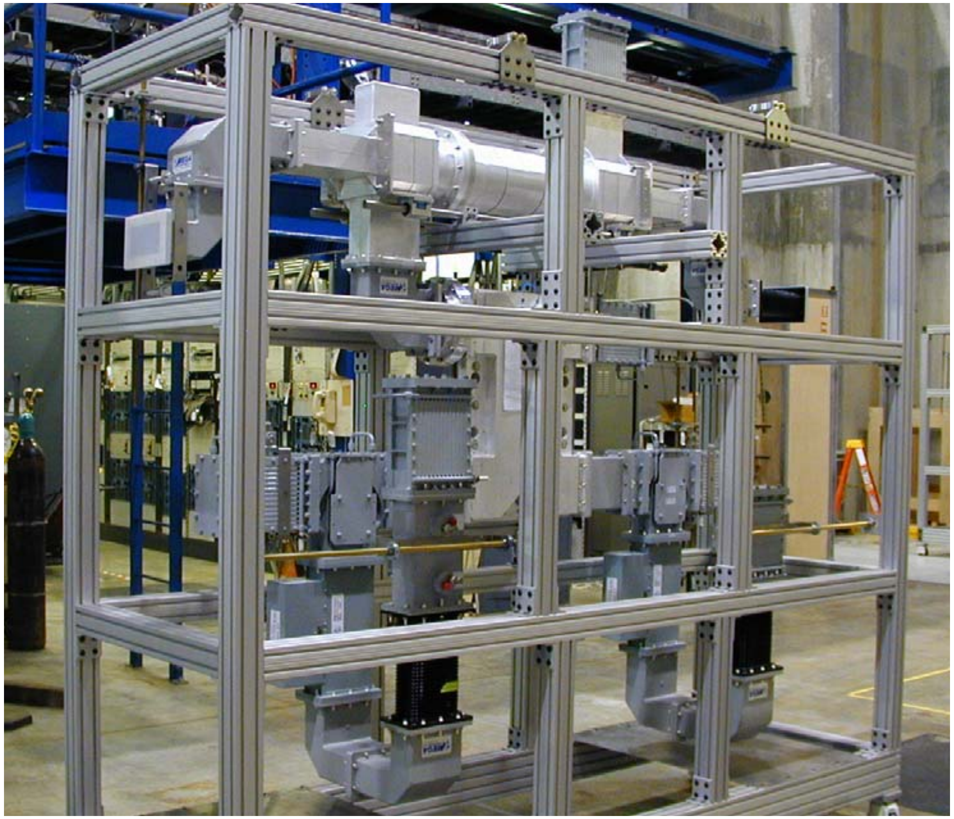




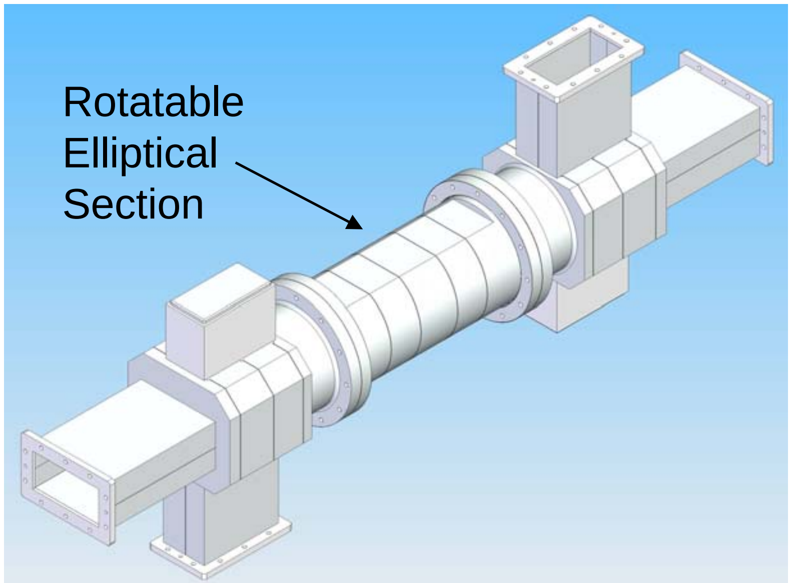
RF Distribution Modules

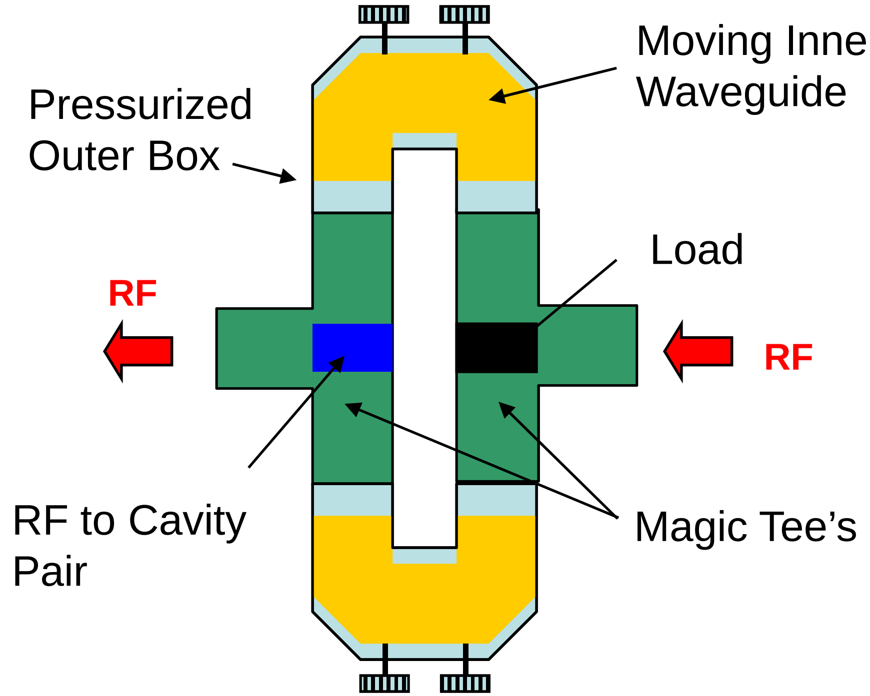
Four, two-cavity distribution modules were individually high power tested and then shipped to FNAL

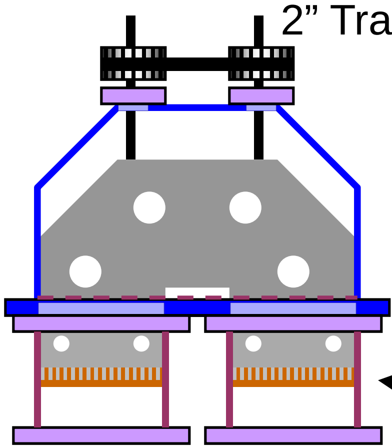




Developing Simpler VTO For Next CM







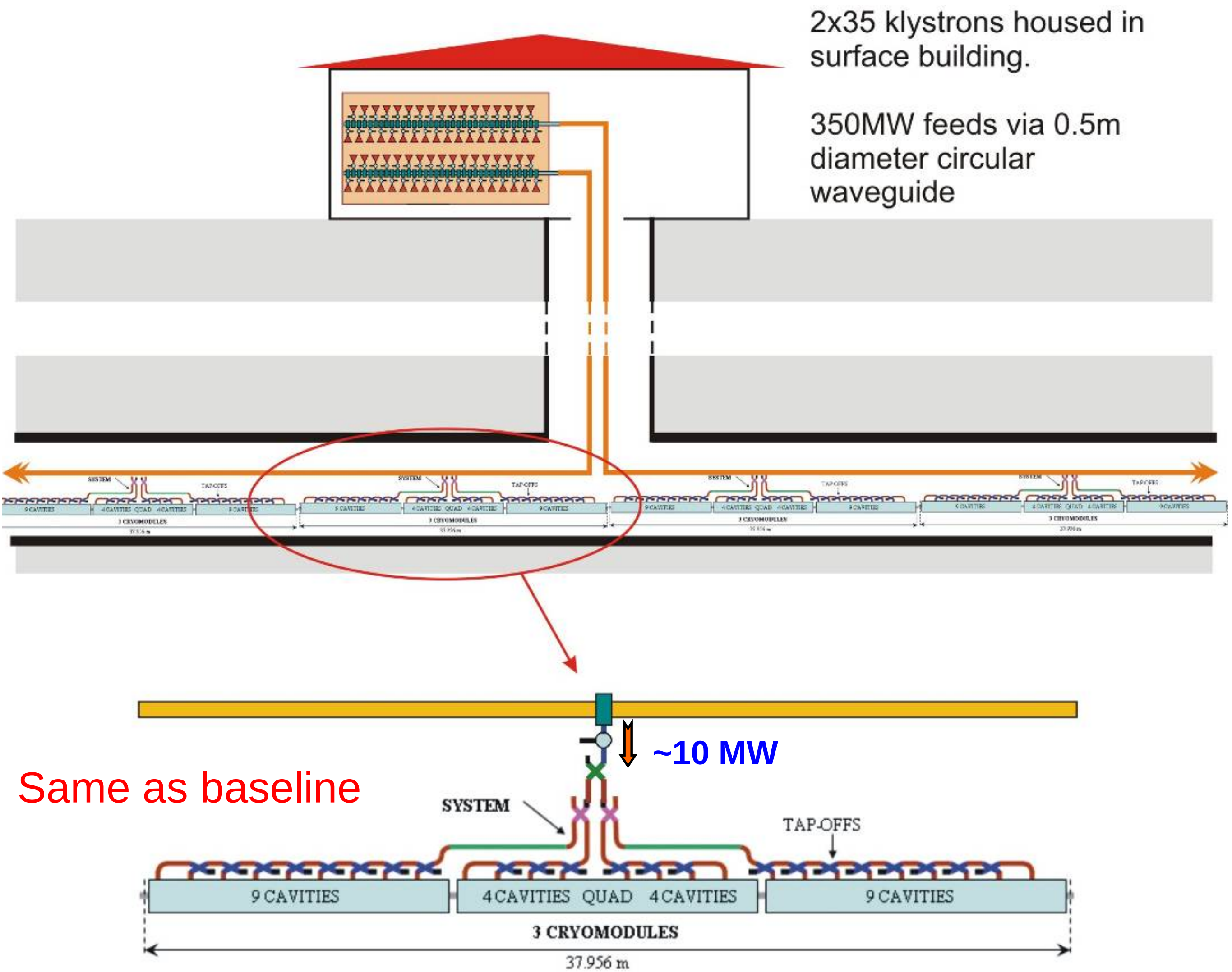
Use commercial Magic Tee's

Put remotely controllable phase shifters into U-bends – relative phase controls power split

Match ideally unaffected by position

No bellows but need 'finger' stock to cut off RF

Klystron Cluster Concept



Each tap-off from the main waveguide feeds 10 MW through a high power window and probably a circulator or switch to a local PDS for a 3 cryomodule, 26 cavity RF unit (RDR baseline).

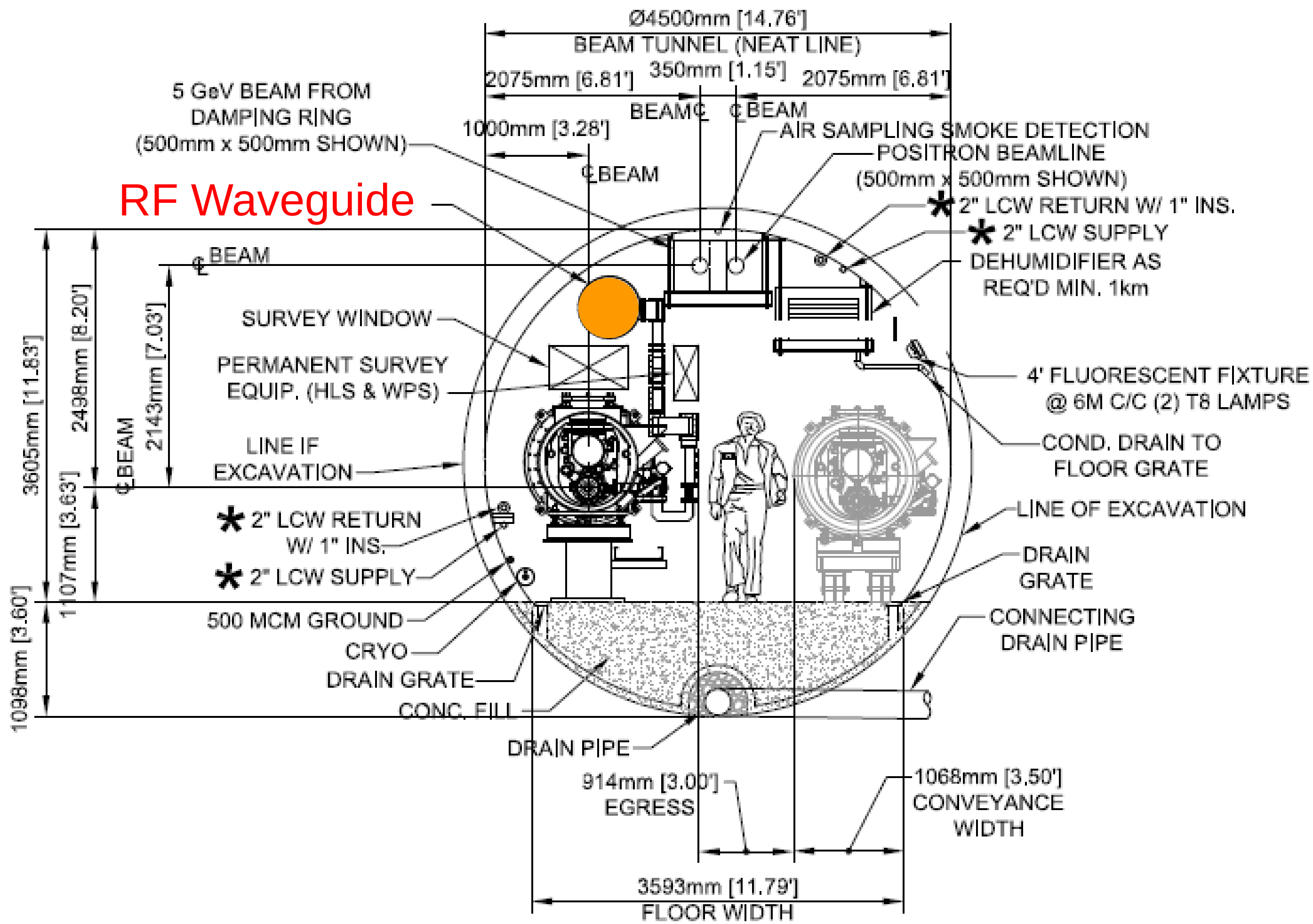
RF power "piped" into accelerator tunnel every 2.5 km

Service tunnel eliminated

Electrical and cooling systems simplified

Concerns: power handling, LLRF control coarseness

First Pass at New Tunnel Layout

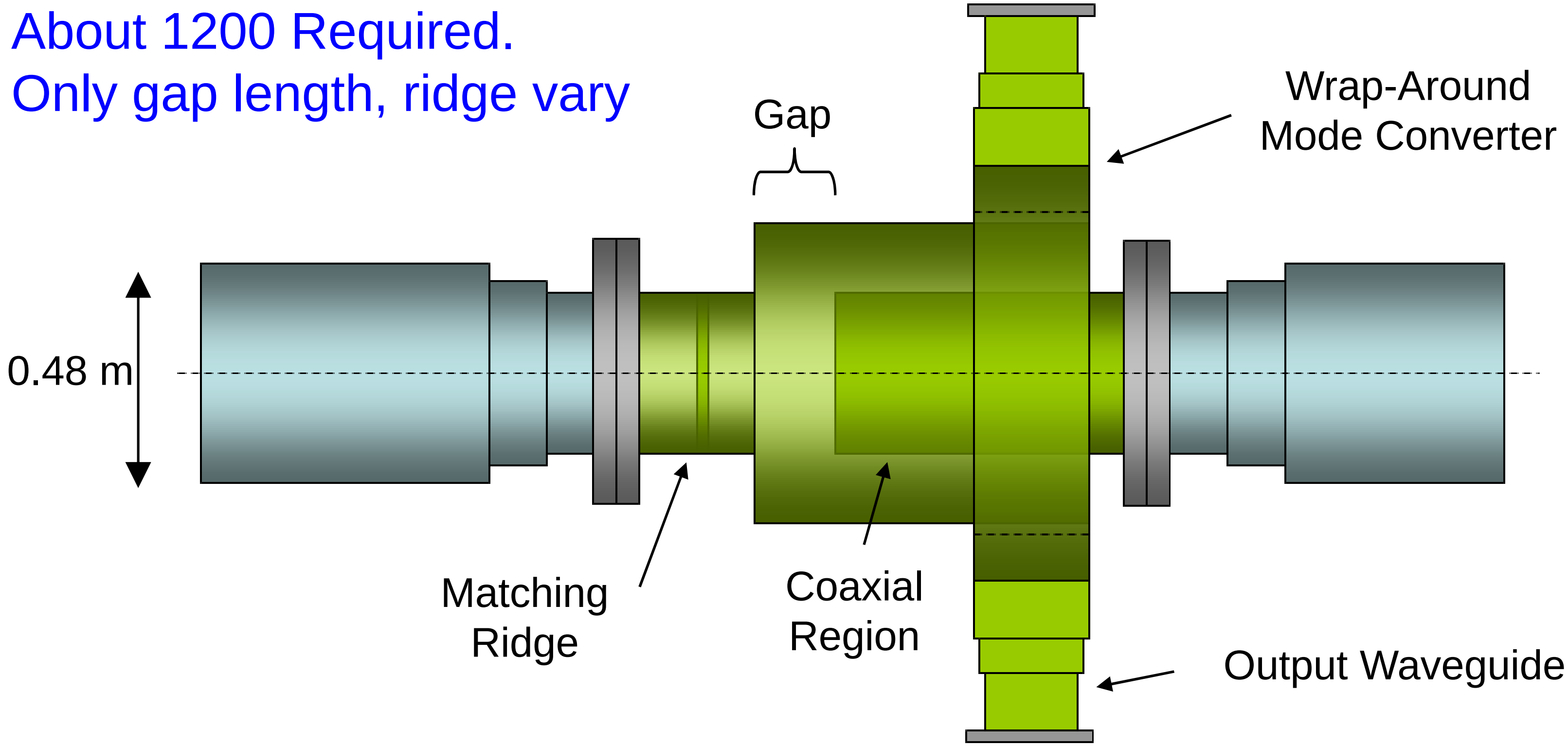


TYPICAL MAIN LINAC SECTION

DRAFT FOR REVIEW

Coaxial Tap Off (CTO)

About 1200 Required.
Only gap length, ridge vary



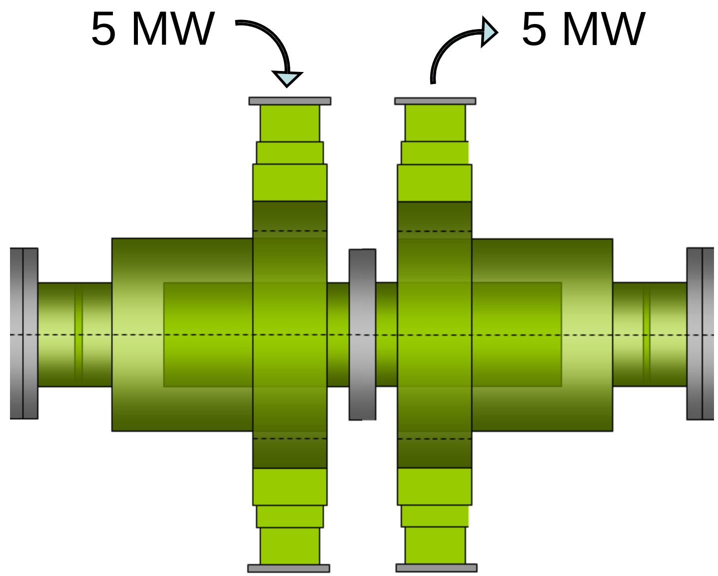
Power is tapped off from the circular TE_{01} mode, in 10 MW increments, into a coaxial region, without breaking azimuthal symmetry (no surface E fields)

A wrap-around mode converter extracts this power from the coaxial TE_{01} mode into two output waveguides (5 MW each), analogous to klystron output arms

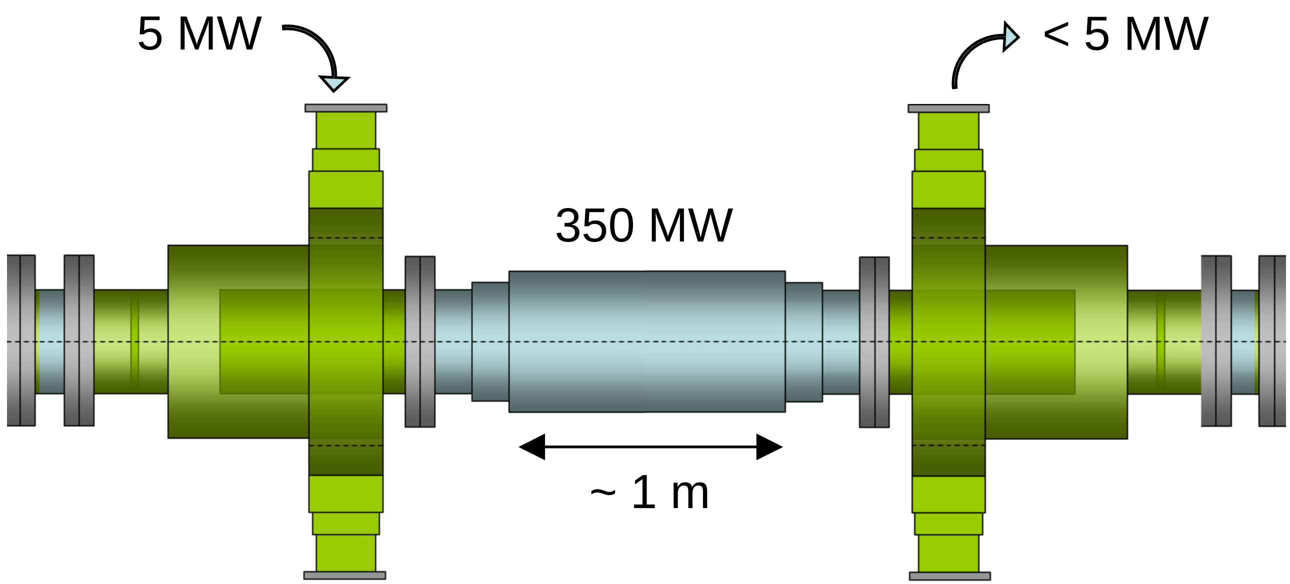
The same devices are used in reverse for launching power into the pipe

Klystron Cluster Development Steps

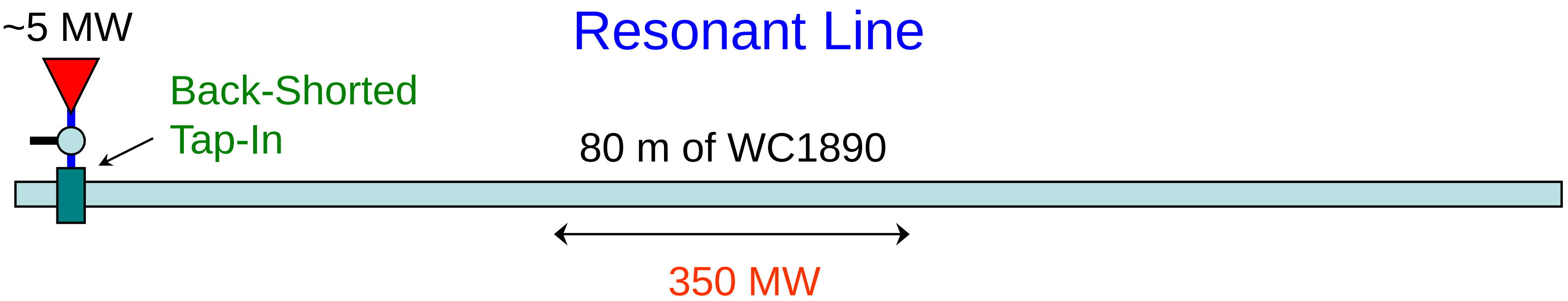
Step 1: Run 10 MW through back-to-back, blanked-off CTOs w/o pipe step up: no resonant rf build up



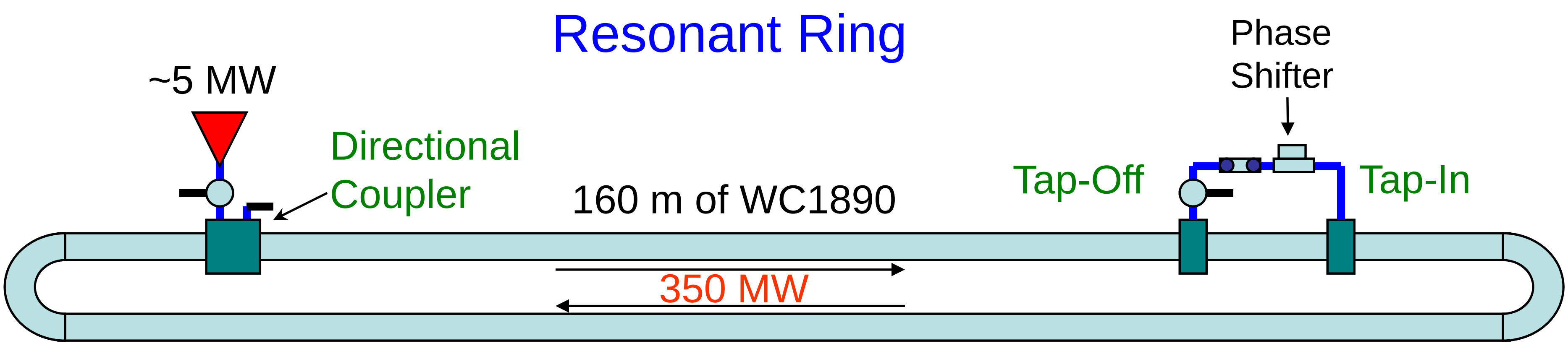
Step 2: Add pipe step up, adjust shorts to resonantly produce 350 MW SW



Step 3: Use resonant waveguide to build up the stored energy equivalent to 350 MW traveling waves - provides more realistic rf turn-off time if have a breakdown



Step 4: Use resonant ring to test bends and 'final design' tap-in/off



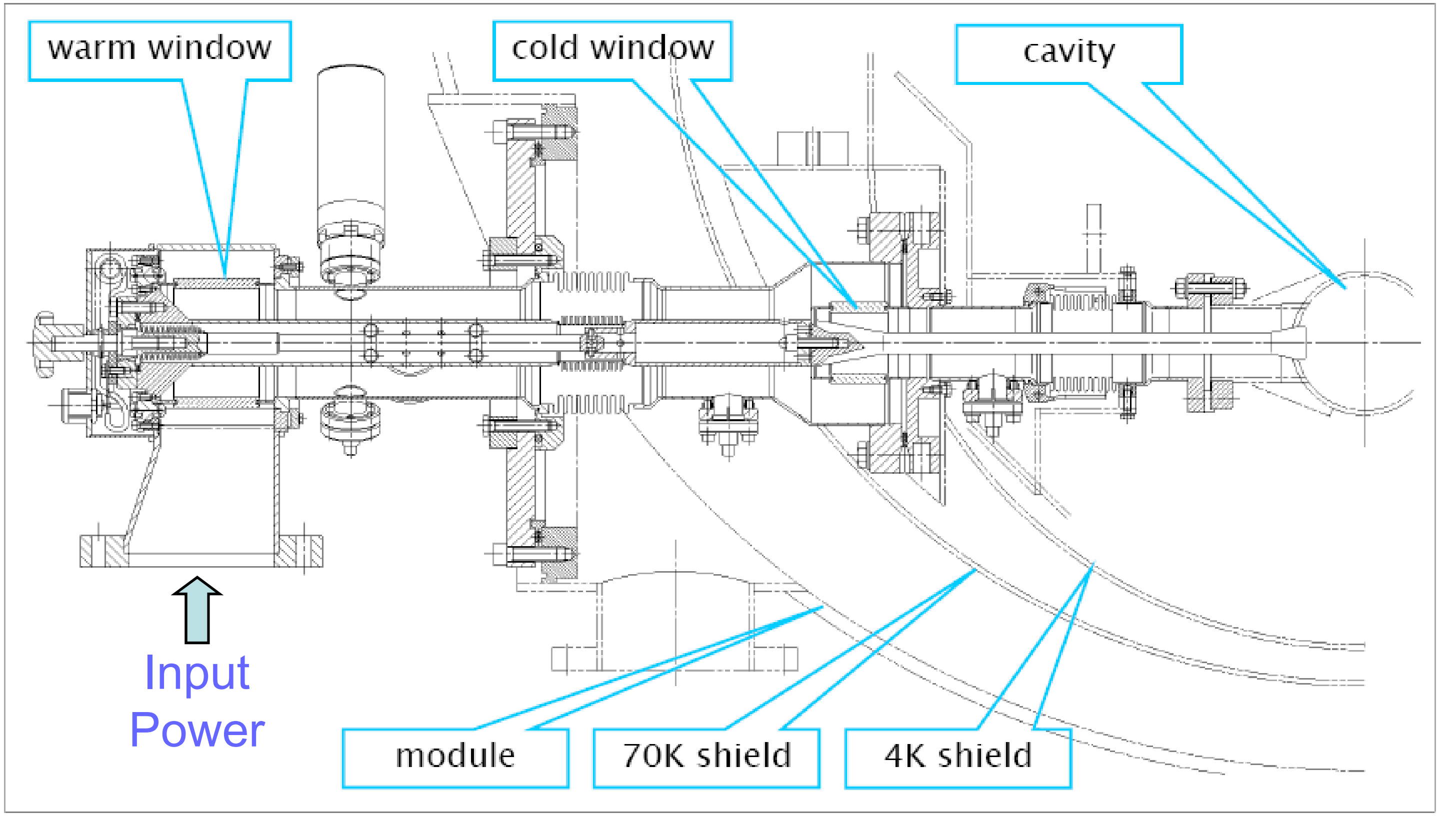
Coupler Assembly & Processing

- **Goals:**
  - Setup a class 10 clean room at SLAC to clean and assemble cavity couplers from parts built by CPI (no welding required).
  - Once assembled, pairs of couplers are rf processed at the L-Band test area at End Station B and then shipped to FNAL.
  - Develop less expensive means of producing couplers
- **Project Status:**
  - Received 12 couplers ordered from CPI by FNAL – have been inspected: three sent back to CPI where they have been repaired/replaced
  - Class 10 clean room facility completed in FY09 Q2
  - First coupler pair assembled in clean room, baked (150 degC for a day) and rf processed (in < 10 hours) - have been sent to FNAL
  - Started program to build coupler cold section with induction brazing or TIG welding

TTF-3 Coupler Design

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

Coaxial Power Coupler

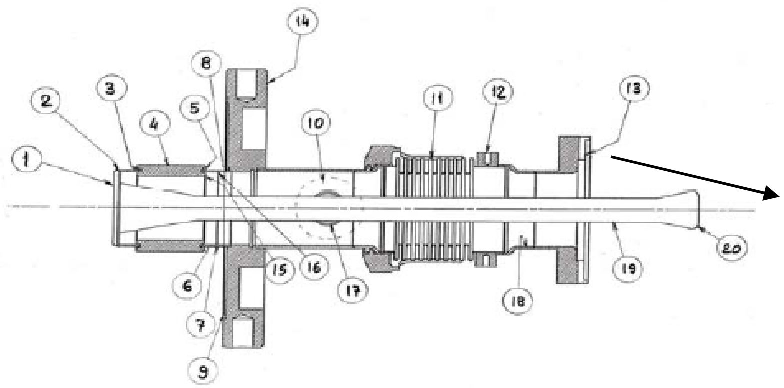


12 Couplers Ordered from CPI by FNAL Have Been Inspected/Repaired

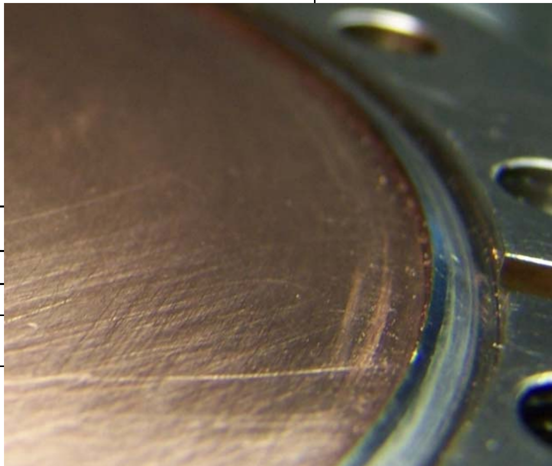
STANFORD LINEAR ACCELERATOR CENTER

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

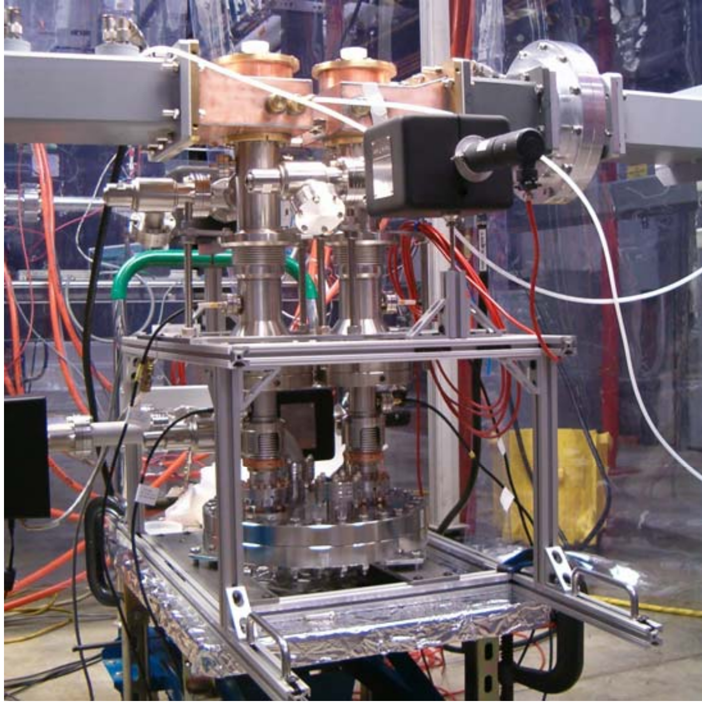


Item	Inspection Criteria	DESY Print Number	LAL Print Number	Findings	Pass
1	Visual: Nicks, scratches, proper edge chamfers	3964328/A.003	I65-3D-1250		X
2	Visual: Weld form, size, and porosity	3964328/A.000	I65-2E-1200		X
3	Visual: Brazing: Irregularities, centering of groove , buildup Ceramic: metallization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



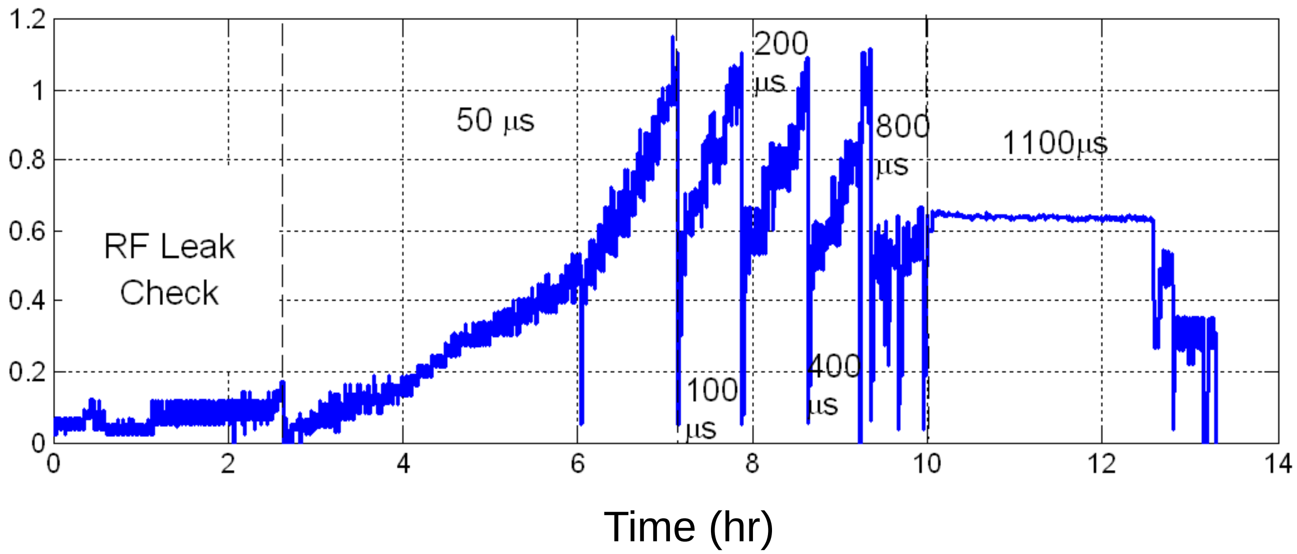
Coupler Assembly in SLAC Class 10 Cleanroom

RF Processing of Coupler Pairs

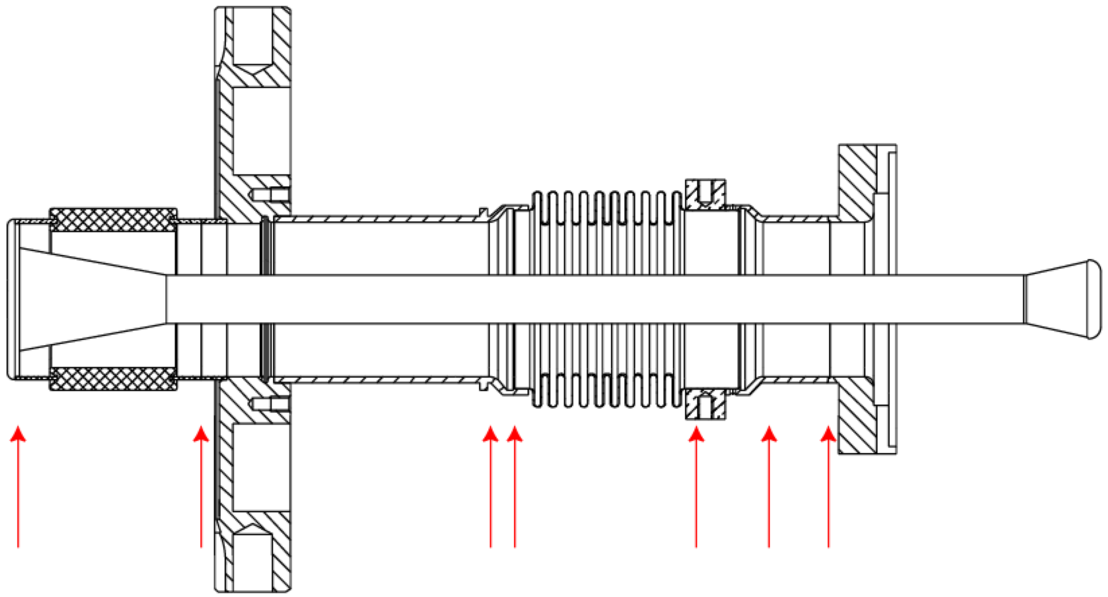


Processing of first pair sent to FNAL:
Power (MW) -vs- Time for Pulse Widths of
50,100, 200, 400, 800, 1100 μs

Processed Fast by Historical Standards



Fabrication Simplification



Many of the above joints e-beam welded so bellows and windows not heated – looking at using induction brazing or TIG welding in many places

Mid-FY09 Direct Costs (k$) & Budgets

	Cost+Commits YTD (3/31)			FY09 Budget			% Spent
	Non-Shop	Shop	M&S	Non-Shop	Shop	M&S	
ML Design	81.9	0.0	0.0	358.4	0.0	15.0	22
Wakefields	101.8	0.0	0.0	196.9	0.0	0.0	52
Marx Modulator	342.7	0.6	87.9	597.7	0.0	300.0	48
SBK	320.4	296.0	65.7	594.2	114.7	300.0	68
RF Distribution	98.9	11.0	139.5	237.7	0.0	415.0	38
Couplers	177.0	27.5	83.7	230.6	0.0	314.0	53
L-Band at ESB	312.8	8.0	18.6	474.5	0.0	100.0	59
Total	2174.0			4248.7			51

FY09 and FY10 Milestones
(with ARRA funds)

Milestones	FY09 Forecast	Actual	Revised	New for FY10	Comment
2nd generation Marx design (P2)	Q4				Full conceptual design + high current test of cell design
Second iteration of cell design				Q2	
Run P2 with several cells				Q4	P2 complete in Q2 of FY11
Sheet beam klystron beam tester	Q3				
2 Cavity Instability Test				Q1	Beam tester + 2 cells + collector running at long pulse
Decide whether to proceed with Klystron				Q2	Klystron complete in Q2 of FY11
Fabricate RF distribution system for FNAL CM1	Q2	Q2			
Fab Lower cost version with remote power control				Q2	May replace current CM1 system in Q4 when CM2 installed
Parts on hand for next system for Type4 CM				Q4	Use to run three CMs in mid FY11
RF test stand - Marx/MBK 1500 hrs	Q4				
Additional 3000 hrs of operation				Q3	Depends on type of problems found in FY09
Test of DTI Marx into a Water Load				Q4	Depends on successful completion of SBIR
Klystron Cluster POP - Phase 1+2	Q4		Q1 FY10		Delay in funding
Decide whether to proceed to Phase III				Q2	
Phase III complete (100 m of pipe at 350 MW)				Q4	Phase IV in Q3 of FY11
10 couplers to Fermilab	Q3				Shipped two to FNAL in Q2
Develop induction brazed cold section				Q1	Have some made in industry with ARRA funds by Q3
22 more couplers to FNAL				Q4	

L-Band RF Program in FY10
(with ARRA funds)

- Assume FY10 Budget of 6.1 M$ (4.2 M$ Direct) + 3.0 M$ ARRA funds in 5/09
- ML Design and Wakefields: continue support of ILC GDE in evaluating cavity and coupler performance and linac integration (0.3 M$).
- Complete Marx P2 second round of cell development by mid year and have partial stack running by the end of year (1.0 M$).
- Do two-cavity instability test and determine best SBK design from simulation and experimental results (0.3 M$). If competitive, begin klystron design/construction (0.6 M$)
- Complete distribution system for CM2 with remotely controlled power splitters and start construction of a third system (ARRA funds plus some ILC carryover).
- Operate Marx and Toshiba MBK for least 3 khr and maintain the L-band systems at ESB (0.3 M$). Install and test Marx from DTI if they deliver (0.5 M$)
- Complete Phase I+II of Klystron Cluster R&D (0.2 M$), and if successful, complete Phase III and start Phase IV (1.0 M$ plus request an additional 0.3 M$)
- Complete processing of 22 couplers ordered in FY09, order up to 16 more for FY11, develop lower cost means of fabricating TTF-3 couplers and build a few in industry (ARRA funds plus some ILC carryover).

L-Band RF Program in FY10

(without ARRA funds – changes in red)

- Assume FY10 Budget of 6.1 M$ (4.2 M$ Direct) + ~~3.0 M$ ARRA funds in 5/09~~
- ML Design and Wakefields: continue support of ILC GDE in evaluating cavity and coupler performance and linac integration (0.3 M$).
- Complete Marx P2 second round of cell development by mid year and have partial stack running by the end of year (1.0 M$).
- Do two-cavity instability test and determine best SBK design from simulation and experimental results (0.3 M$). If competitive, begin klystron design/construction (0.6 M$)
- Complete distribution system for CM2 with remotely controlled power splitters and start construction of a third system (0.4 M$ plus some ILC carryover).
- Operate Marx and Toshiba MBK for least 3 khr and maintain the L-band systems at ESB (0.3 M$). ~~Install and test Marx from DTI if they deliver (0.5 M$)~~
- Complete Phase I+II of Klystron Cluster R&D (0.2 M$), and if successful, complete Phase III and start Phase IV (0.5 M$ plus request an additional 0.8 M$)
- Complete processing of 10 couplers ordered in FY09, order up to 10 more for FY11, develop lower cost means of fabricating TTF-3 couplers at low level ~~and build a few in industry~~ (0.6M$).

Summary

- Making good progress on Marx/MBK, rf distribution and couplers – on track to meet goals and are continuing to improve designs
- Hit a bump in the SBK program – have a plan to reassess viability of approach at beginning of 2010
- Stimulus funds will expand coupler effort
- Hope to get started on Klystron Cluster R&D soon (400 k$ requested in FY09) in support of a less expensive ILC (big bang for the buck)