High Level RF Power (HLRF) Cost Estimate

Prepared for

HLRF EDR Kickoff Meeting

October 1-3, 2007, SLAC Webex

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For the ILC HLRF Collaboration

HLRF Collaboration

- Team Leaders for Cost Estimating
  - *S. Fukuda, KEK, Asia, Spokesperson*
  - *R. Larsen, SLAC, Americas*
- Participants:
  - *KEK: T. Shidara, M. Akemoto*
  - *SLAC: M. Neubauer, C. Nantista, C. Adolphsen, R. Cassel, C. Corvin*
  - *FNAL: C. Jensen, B. Chase, O. Nezhevenko, J. Reid, M. Champion, P. Garbincius*
  - *DESY: W. Bialowons*

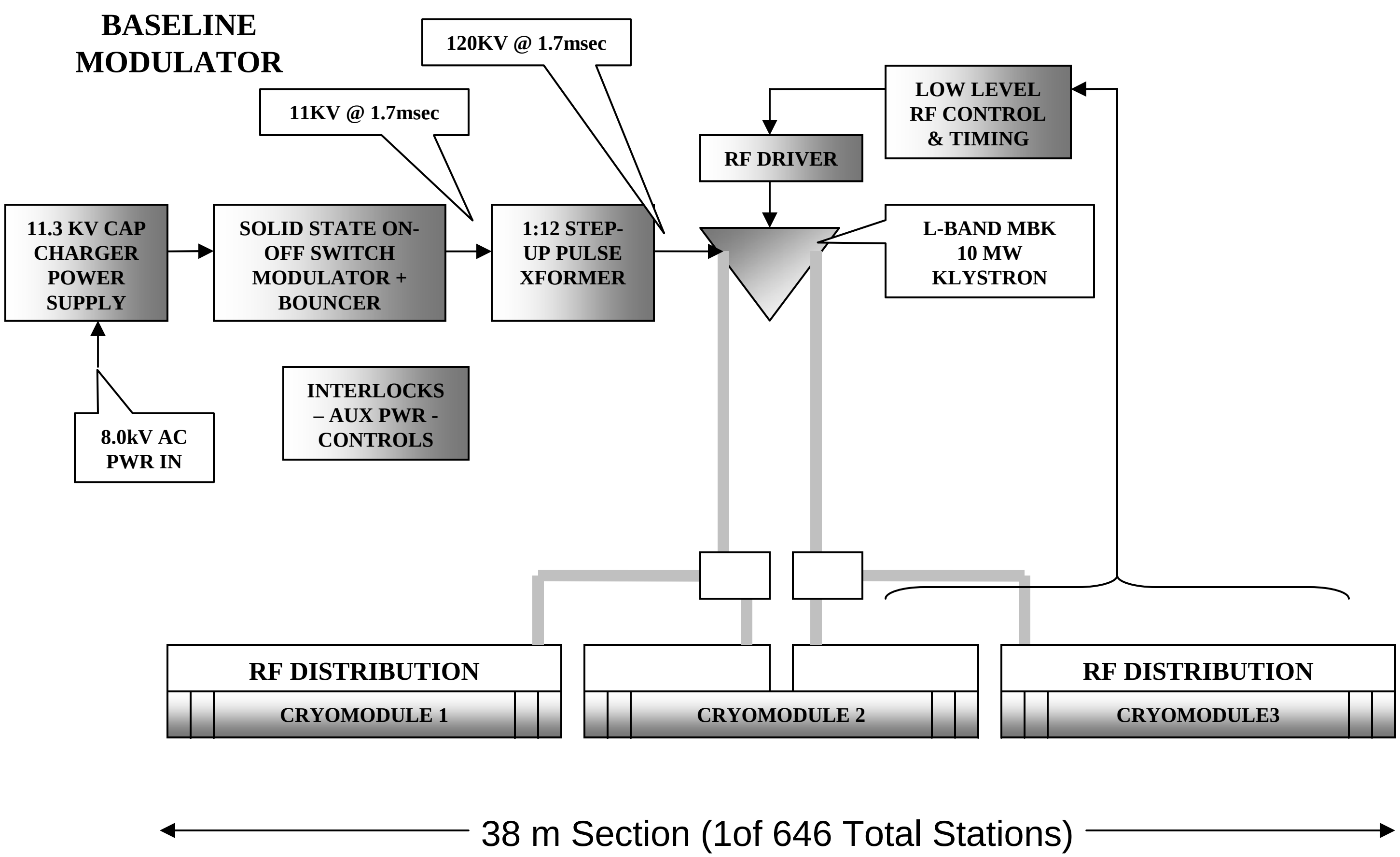
Outline

I. Summary Paris Cost Presentation
II. Cost Results
III. ACD Cost Estimates
IV. Conclusions
- Appendix: Cost Estimate Details

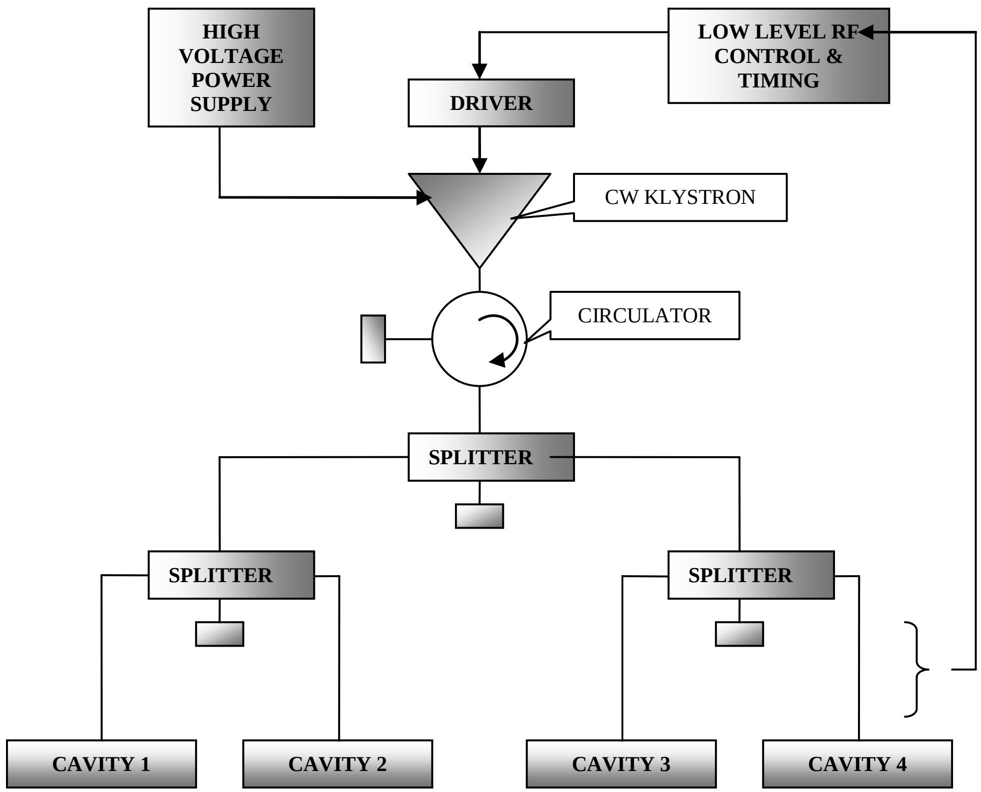
1. System Overview

- HLRF Station Types
  - *Main Linac, Sources & RTML (646)*
  - *Damping Rings (20)*
- Details will focus on ML Station since over 90% of total HLRF cost
- All of RF comprises ~12% of Total Project Cost (TPC)

Main Linac Block Diagram



Damping Ring Block Diagram



1 of 20 Stations

Baseline Modulator

Capacitor Banks

IGBT Redundant Switch

Bouncer Choke

Courtesy C. Jensen, FNAL

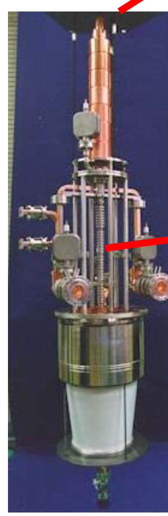
Klystron Model Basis

Scaled from Cornuelle NLC factory model

Size/volume → raw mat'l + labor + equip.

# of beams → drift tube mat'l count + labor

Caryotakis Difficulty factor → yields

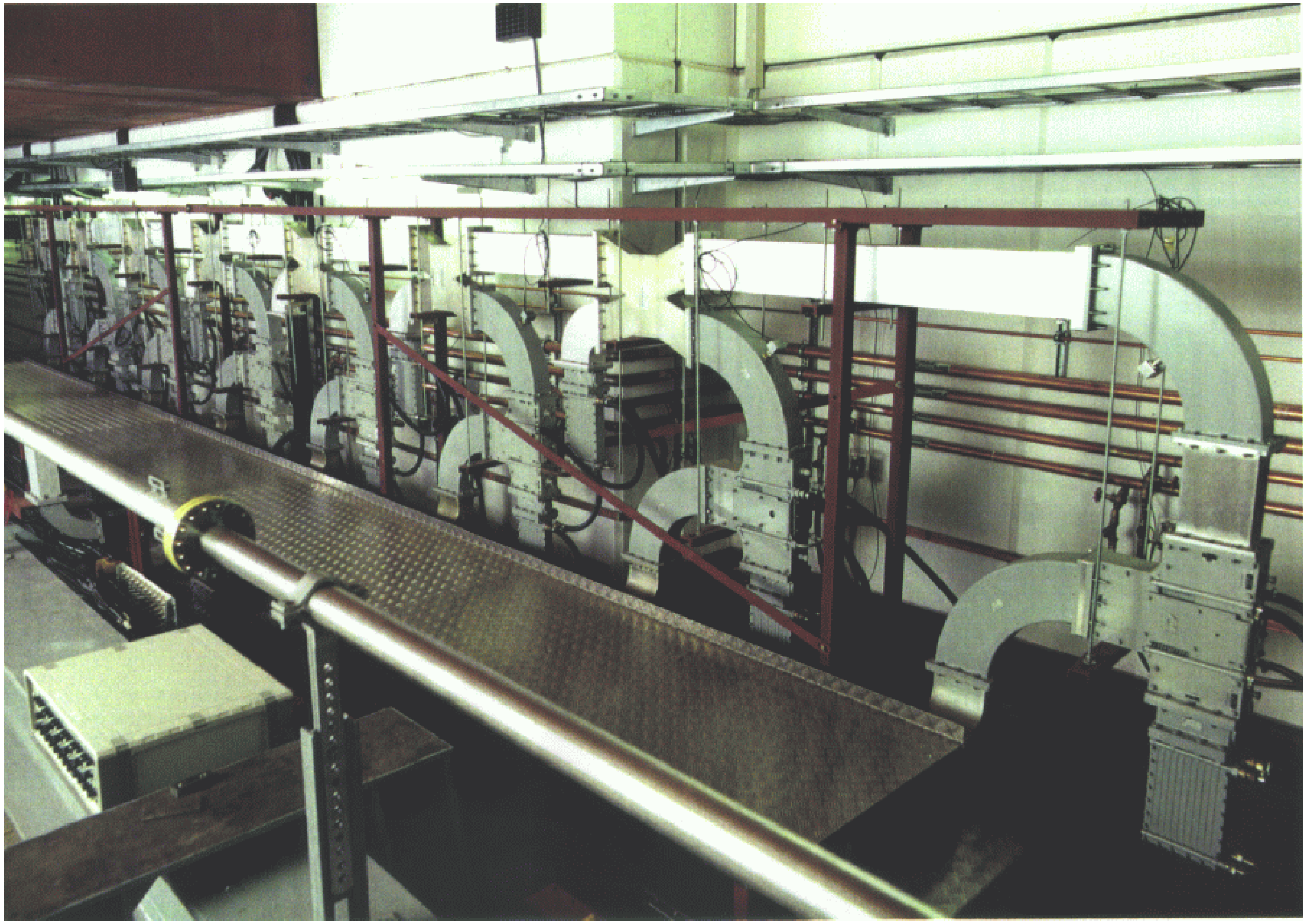


X-Band Single Beam

L-Band MBK

Courtesy M. Neubauer

Waveguide Distribution



Courtesy S. Choroba, DESY

Schedule Assumptions

- *7 Year Construction Period*
- *2.5 Years Pre-production, 4.5 Years Production*
- *HLRF Manufacturing Models stress JIT delivery with minimum on-site storage prior to Installation*
- *Described in HLRF TN 2006-1,* Factory, Staging & Installation Models*, and HLRF TN 2006-2:* ILC High Level RF Cost Assumptions, Rev. *July 7 2006*
- Modulators & Klystrons *delivered tested, ready to inspect, prep and install*
- Distribution *delivered as complete subassembly, ready to inspect, mount on cryomodule in staging area, pre-tune and install*
- *Two vendors for each component w/ multiple production lines, extra capacity strategy to maintain schedule (e.g. extra line, extra shifts)*

Cost Methodologies

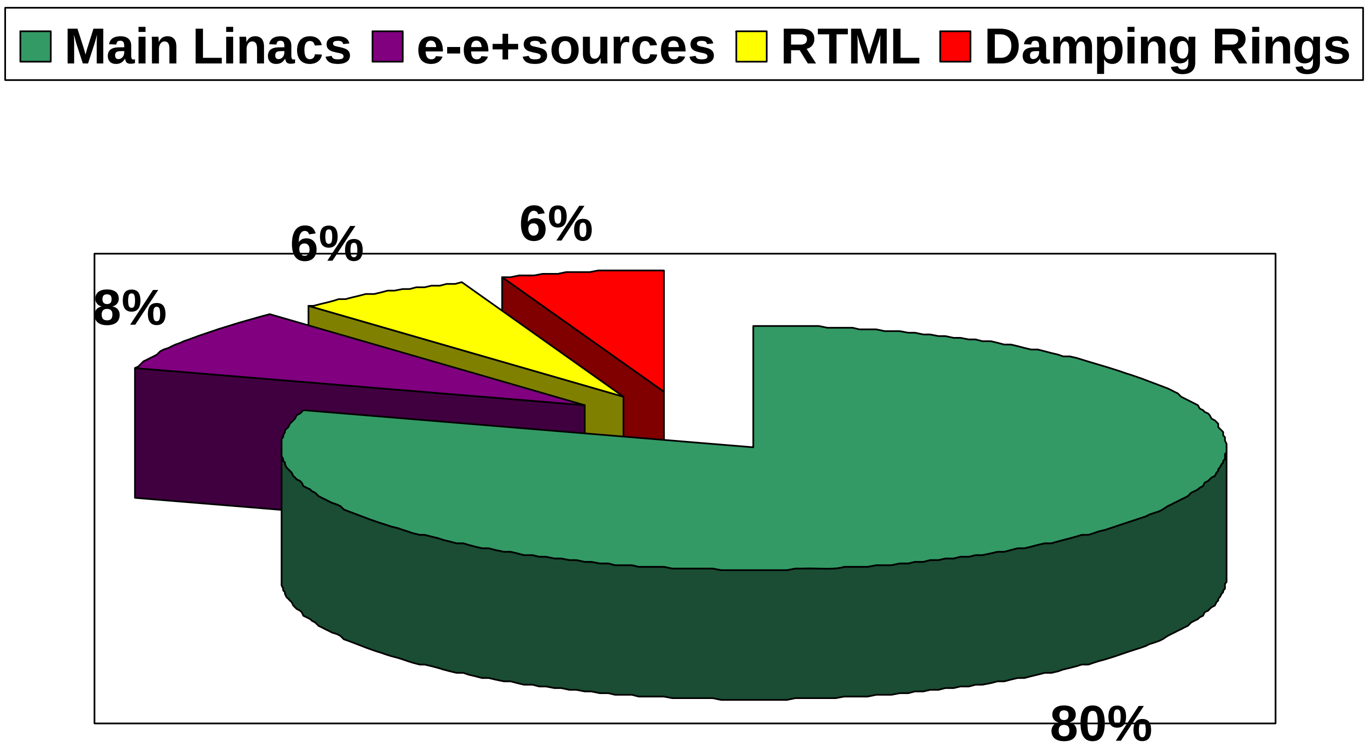
- Modulator
  - *First Unit basis: Engineering bottom-up from existing advanced prototypes*
  - *Production basis: Estimates from (a) Engineering “Rules of Thumb” (FNAL), (b) Learning curves from first article cost (SLAC); Industry quotes from DESY, KEK*
- Klystron
  - *First unit basis: Bottom-up estimates of materials, labor to fabricate by resident former industry expert (M. Neubauer)*
  - *Production basis: Full cost recovery plus profit, sustaining follow-on business Factory model developed from NLC study by SLAC klystron industry experts (J. Cornuelle, G. Caryotakis, M. Neubauer*
  - *Learning curves using published factory experience to select ratios, rates for materials, labor*
  - *Industry quotes from DESY, KEK*

Methodologies 2

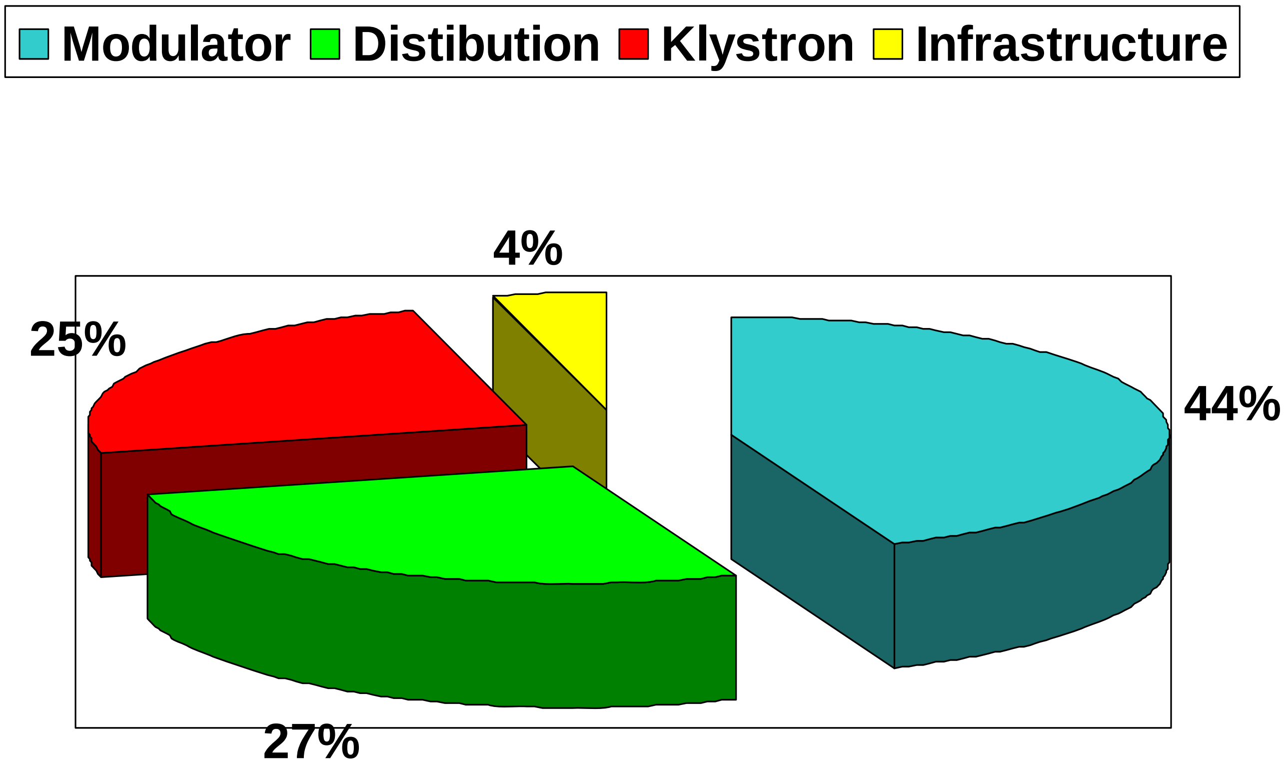
- Waveguide Distribution
  - *First unit basis: (a) Engineering bottom-up estimate by (former industry) expert based on materials and labor models (b) Manufacturer quotations (2-3 small suppliers)*
  - *Production basis: (a) Engineering bottom-up material, labor estimates from basic engineering models, discussions with vendors in other regions, (b) Learning curves based on models of automated machining and hand-machining processes for relative labor content, costs (c) industry quotes from KEK, DESY*

II. Cost Results

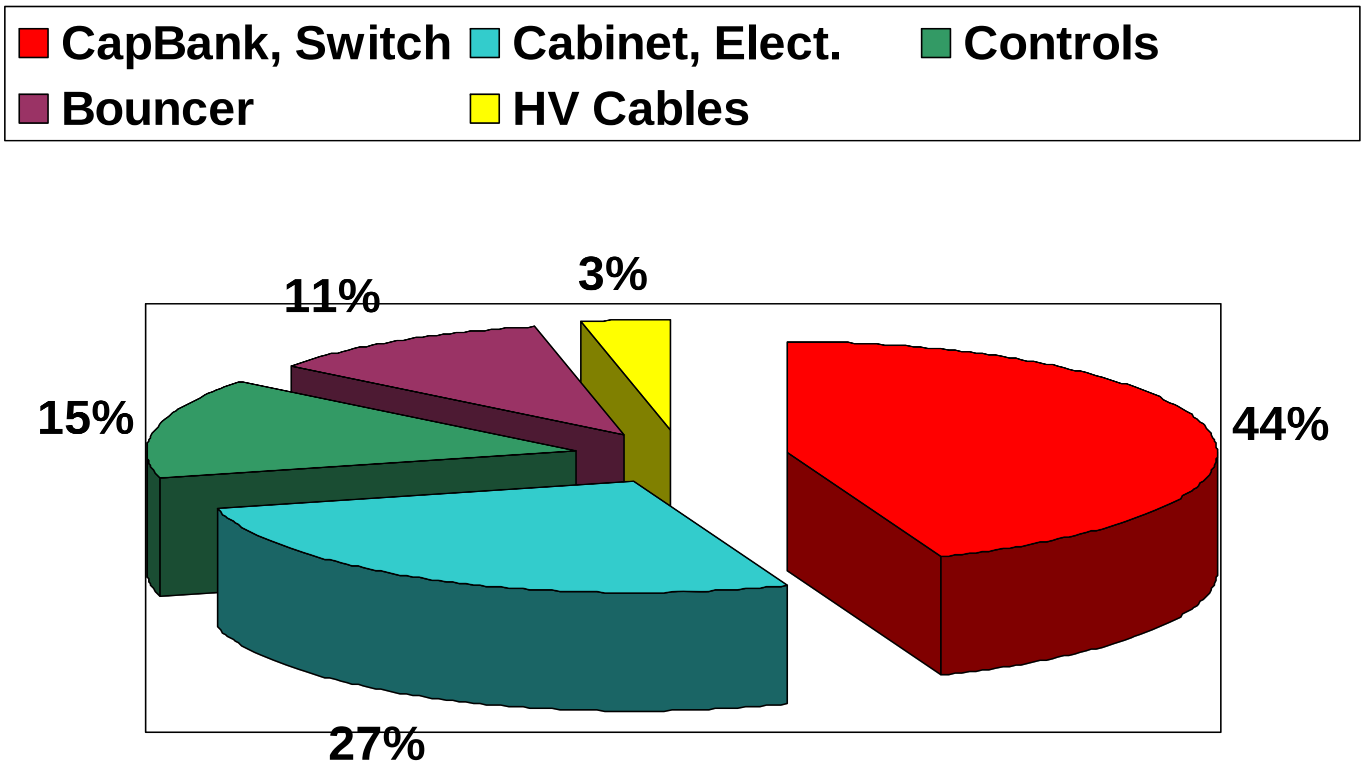
ML RF System Costs by Area



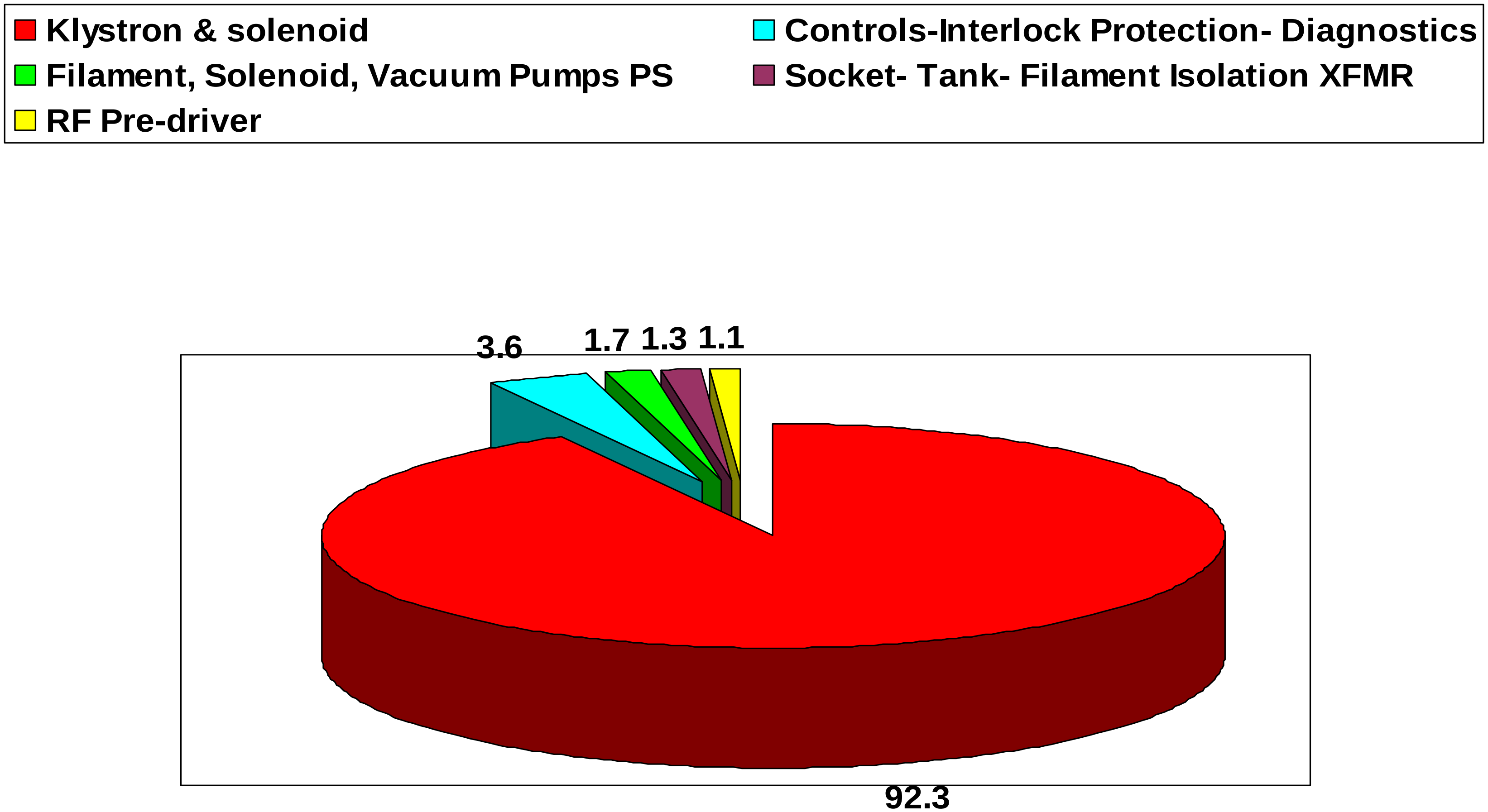
RF Subsystem Cost Breakdown



Modulator Subsystem

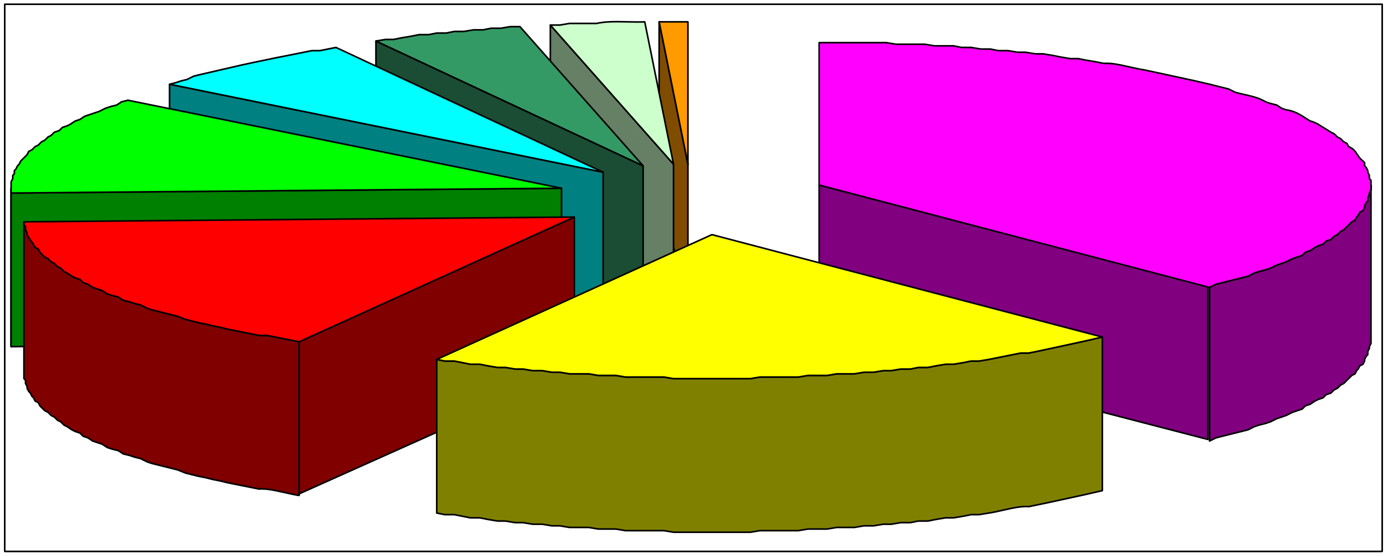


Klystron Subsystem

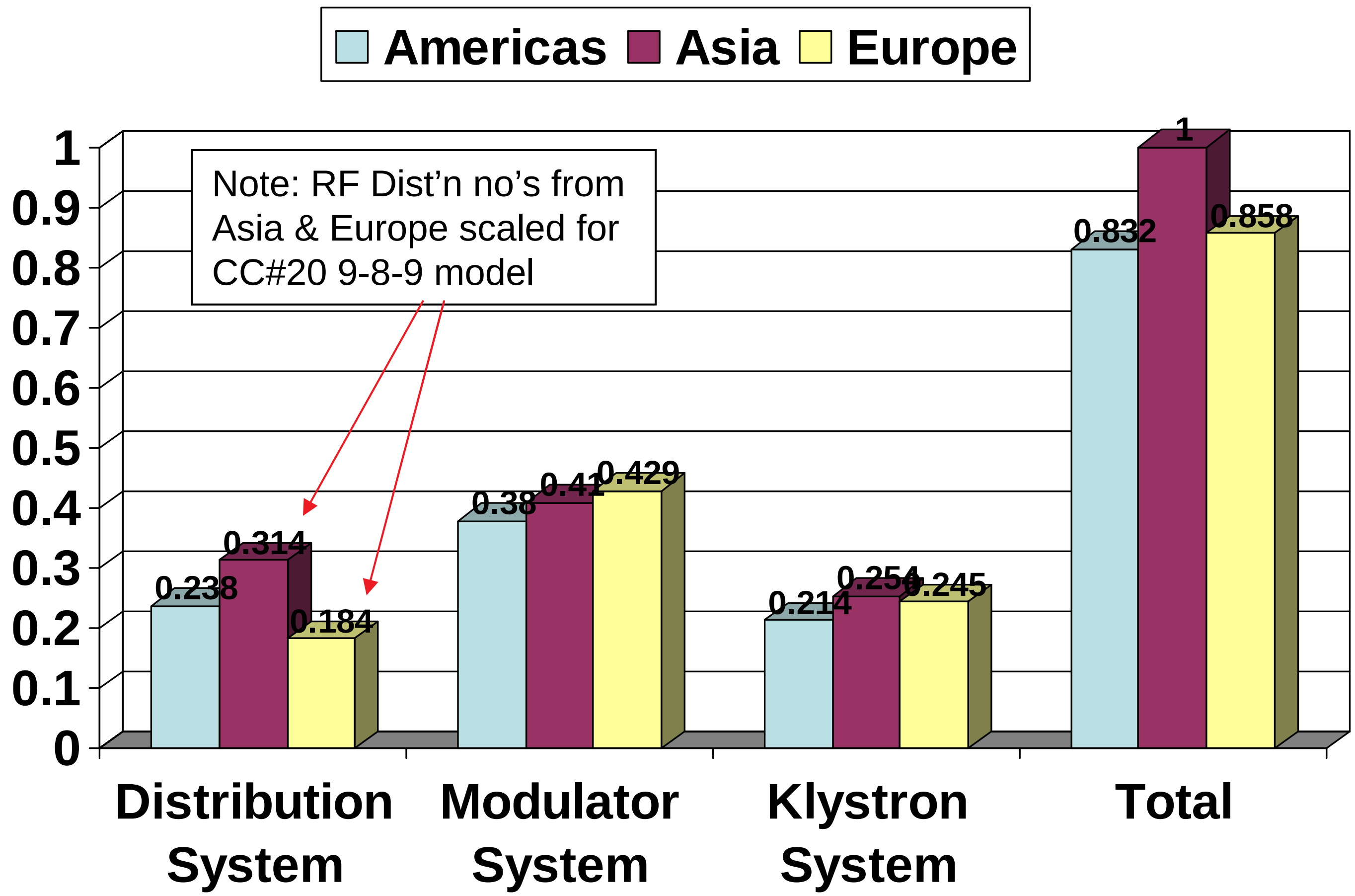


Distribution Subsystem

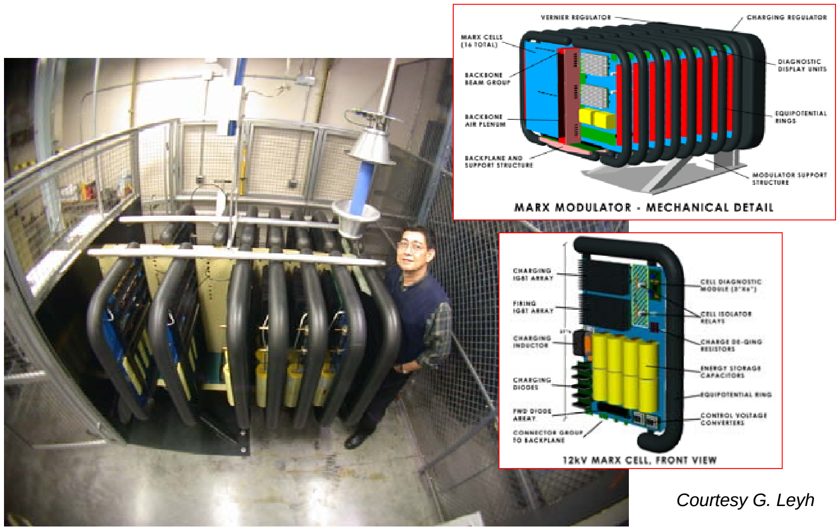
Circulator | 3-stub tuner | Circulator Load | Hybrid Loads | WR650 WG | H-plane Bend | E-plane Bend | Directional Coupler



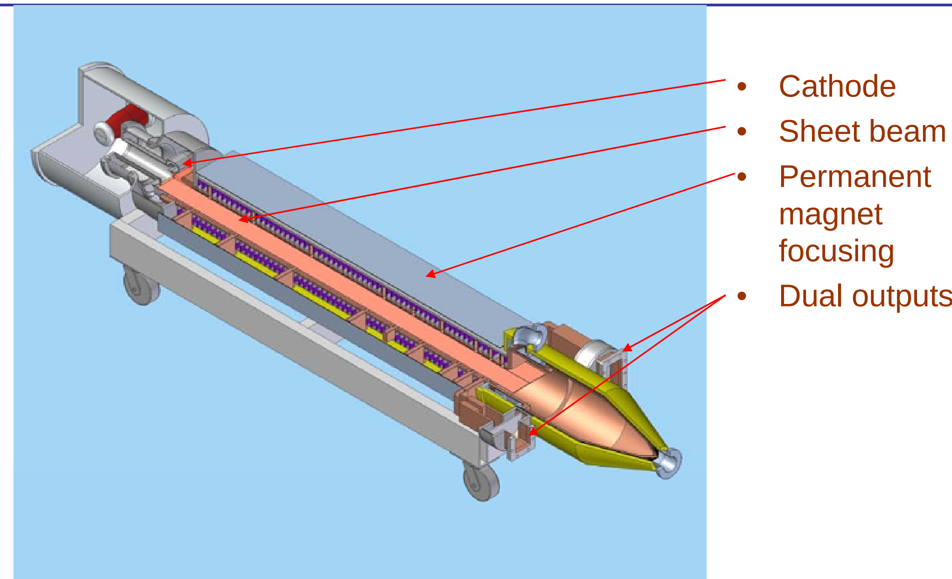
Regional Cost Estimates



III. ACD Cost Estimates

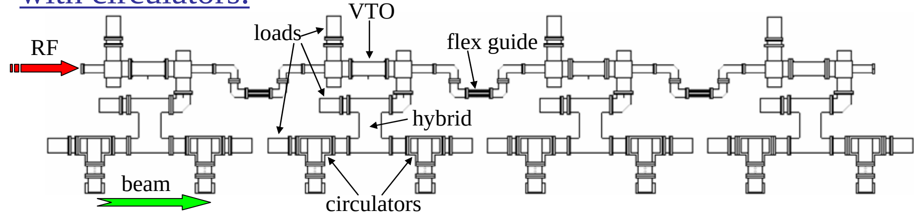


Courtesy G. Leyh



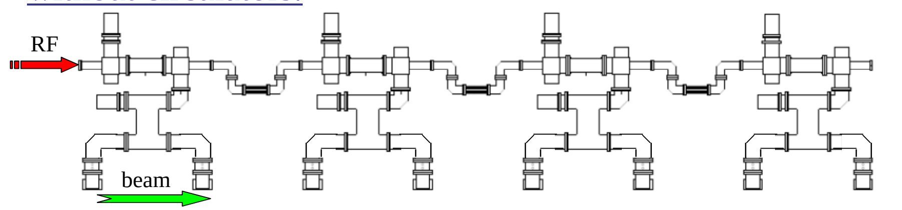
- Other ACD's
  - *6-Pack HA Charger*
  - *Interlocks & Controls HA FPGA based*

with circulators:



VTO's allow pair-wise adjustment of power distribution.

without circulators:



Hybrid feeding of equal-Q cavity pairs directs reflected power into hybrid loads.

HLRF ACD Justification

- Must demonstrate significant cost savings, needed performance improvements or both
  - *Marx modulator, SBK klystron and circulator-less integrated Power Distribution all promise potential cost reductions ~2x as well as technical benefits (e.g. smaller, lighter, higher efficiency, availability)*
- ACD estimates not yet verified through complete prototypes or industry quotes
  - *Marx estimate based on first prototype parts count; needs re-verification since becoming near-operational*
  - *Marx entering DFM phase in order to fit into tunnel; new cost estimate needed when initial design complete*
  - *SBK based on SLAC KD bottom-up estimate before first prototype*
  - *Distribution estimated by considering parts eliminated from BCD by redesign; needs new bottom-up*

Other ACD Initiatives

- Modulator Charger System
  - *Proposed new 6-Pack high availability system (R. Cassel)*
  - *Solves important technical issue of pulse loading harmonic interference on power mains*
  - *Bottom-up cost estimate shows modest reduction*
  - *Proposed to build prototype in FY09 for L-Band TF*
- M-K Interlocks & Controls
  - *Proposed new I&C system based on HA architecture, FPGA fail-safe design*
  - *Significant reduction of hardware cost; can coexist within ATCA-like modular control system*
  - *Proposed to demonstrate initial prototype in FY08 for TF*

IV. Conclusions

- HLRF BCD cost estimates comprehensive, satisfied Paris review team
  - *Review team endorsed strong ACD efforts as main opportunity for significant cost reductions*
- Initial ACD estimates promising but immature
  - *Need operational prototypes to prove anticipated performance, improvements, develop more reliable cost models*
  - *Modified DFM designs will need new estimates*
  - *Until demonstrated and re-estimated, cost risk of all ACD estimates remains high.*
- ACD demonstrations time-critical to meet down-select goals by or shortly after EDR period

End of Slides

Appendix: Cost Estimate Details

Cost Estimating Rules

- Estimates include:
  - *Engineering, Design & Inspection person-power (Py) estimates for Pre- and Construction periods*
  - *No monetary value assigned to Labor*
  - *Materials and labor costs for industrial production*
  - *Monetary value assigned based on estimates from Americas, Asia & Europe*
- Not included: Contingency or escalation
  - *Applied globally by Cost Engineering Group*

Factory, Staging & Installation Models

*Document HLRF TN 2006-1: *Factory, Staging & Installation Models*

* *Factory Models all RF components*
* *Main Linacs, Sources, RTML & Damping Ring RF Stations*

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Pre- & Constr'n Period Support, Costs

- Document HLRF TN 2006-2: *High Level RF Cost Assumptions*

** Assumptions for schedule, estimates ED&I** Labor (Py), Workspace (m sq), cost of test systems for factory support, Pre- Construction & Construction Phases*

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***ED&I=Engineering, Design & Inspection*

Comprehensive Cost Details

- Engineering, Design & Inspection (ED&I) Py from end EDR R&D period forward to final commissioning
  - *Documentation, supervision of bid packages for delivery of tested klystrons, modulators and integrated distribution assemblies*
  - *Support of factory testing, test systems*
  - *Factory verification of testing, acceptance to ship*
  - *Onsite final assembly area development, supervision, management*
  - *Systems engineering & documentation for production, final assembly,*
  - *Engineering team development, support of final integration & commissioning in tunnels*
  - *Sustaining Engineering, tech maintenance of tested systems during commissioning*

Cost Details 2

- M&S
  - *Purchase tested major components (Klystrons, Modulators, Distribution Controls and Protection)*
  - *Purchase infrastructure electrical, cables, plumbing & rack materials)*
  - *Purchase, develop factory test stations for major assemblies*
  - *Handling and test equipment for on-site assembly areas, commissioning in tunnels*
- Other
  - *Administrative support for management teams (Py)*
  - *Floor space estimates for on-site assembly, staging (sq m)*

Factory Model Details - Klystron

- Klystron
  - *Assumed Factory Model is that new capacity must be funded as part of construction cost of ILC quantities*
  - *Model based on work by J. Cornuelle for USLCTOS but refined by M. Neubauer based on recent design experience of vendors*
  - *Cornuelle and Neubauer have many years engineering and management experience in klystron industry*
  - *Factory model assumes higher early unit costs to recover investment costs of factory capacity, with unit costs decreasing as recovery completed*
  - *Profit and labor overheads fully included based on current vendor practice*
  - *Model yields fully loaded average Acquisition cost per unit*
- On-Site Costs
  - *Model assumes pre-testing at factory and on-site inspections for shipping damage prior to installation in tunnels*
  - *FTE's etc. for 5 Horsemen estimated separately*

Klystron Tube Model Details

Parts and Labor

VACUUM ENVELOPE ASSEMBLY:
RAW MATERIALS
BRAZE ALLOY
ELECTRON GUN ASSEMBLY
BODY ASSEMBLY
WAVEGUIDES/WINDOWS
COLLECTOR
PARTS AND MATERIAL SUBTOTAL
LABOR HRS
LABOR COST SUBTOTAL
EXHAUST:
LABOR HRS
LABOR COST SUBTOTAL
FINAL ASSEMBLY:
MAGNET ASSEMBLIES
LABOR HRS
LABOR COST SUBTOTAL
TEST:
LABOR HRS
LABOR COST SUBTOTAL
YIELDED PARTS AND MATERIALS
YIELDED LABOR HOURS
YIELDED LABOR COST
ENGINEERING FTE'S
ENGINEERING LABOR HOURS PER TUBE
ENGINEERING LABOR COST PER TUBE

Equipment

PLANT COSTS
SQ FT PER EXHAUST STATION
SQ FT PER TEST STATION
BASE CRANE SPACE
SQ FT OF CLEAN RM /100 TUBES/YR
BASE GENERAL SPACE
SQ FT OF GEN SPACE /100 TUBES/YR
GEN'L SPACE SQ. FT.
CLEAN-RM SQ. FT.
CRANE SPACE SQ. FT.
TOTAL SQ. FT.
GEN'L SPACE COST PER SQ. FT.
CLEAN-RM COST PER SQ. FT.
CRANE SPACE COST PER SQ. FT.
TOTAL PLANT COST
TOTAL COST, PLANT AND EQUIPMENT
ANNUAL LEASE COST

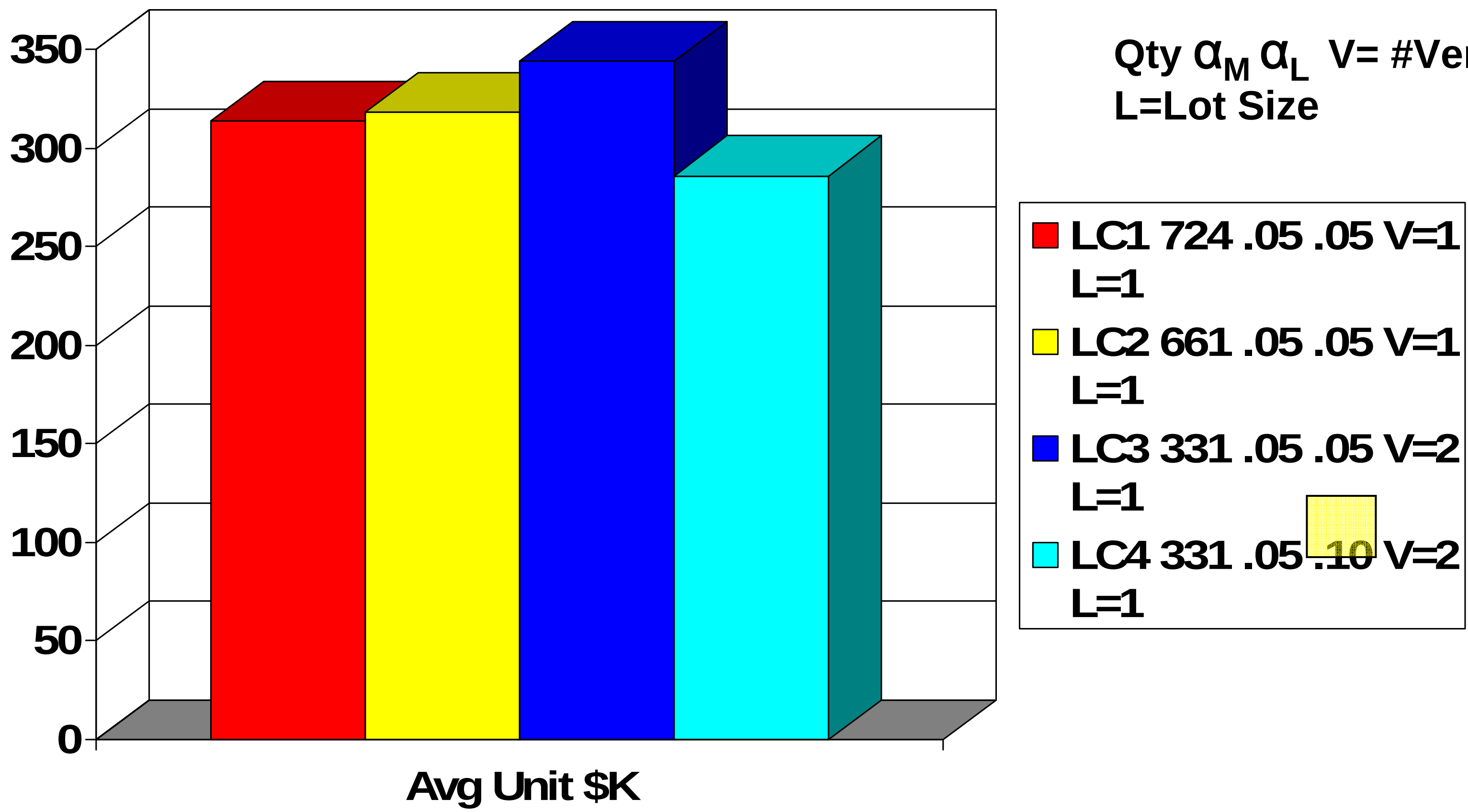
Difficulty Factors

COST/LEARNING FACTORS
RAW MATERIALS
PURCHASED PARTS
LABOR
COSTING QUANTITY
YIELD FACTORS
VACUUM ASSEMBLY
BAKEOUT
TEST
TOTAL
EQUIPMENT UTILIZATION
EXHAUST TIME (HRS)
TUBES/STATION
TEST TIME (HRS)

RF Distribution Model Details

- Waveguide, Hybrids, Circulators, 3-Stub Tuners
  - *Pre-Snowmass estimates done very roughly from incomplete set of vendor catalog costs*
  - *New estimates made by Neubauer in bottom-up models*
  - *Circulator for every cavity is most expensive item*
  - *Cost model includes materials cost estimates, machining and brazing or welding costs*
  - *Other units optimized to minimize numbers of flanges*
  - *Unit costs and learning curves applied to get totals*
- Vendor Comparables
  - *Where possible vendor quotes obtained for similar units from two companies in US and two companies in Japan.*

Modulator Learning Curve Sensitivity Variable Qty, #Vendors, Alpha Labor



Qty α_M α_L V= #Vendors, L=Lot Size

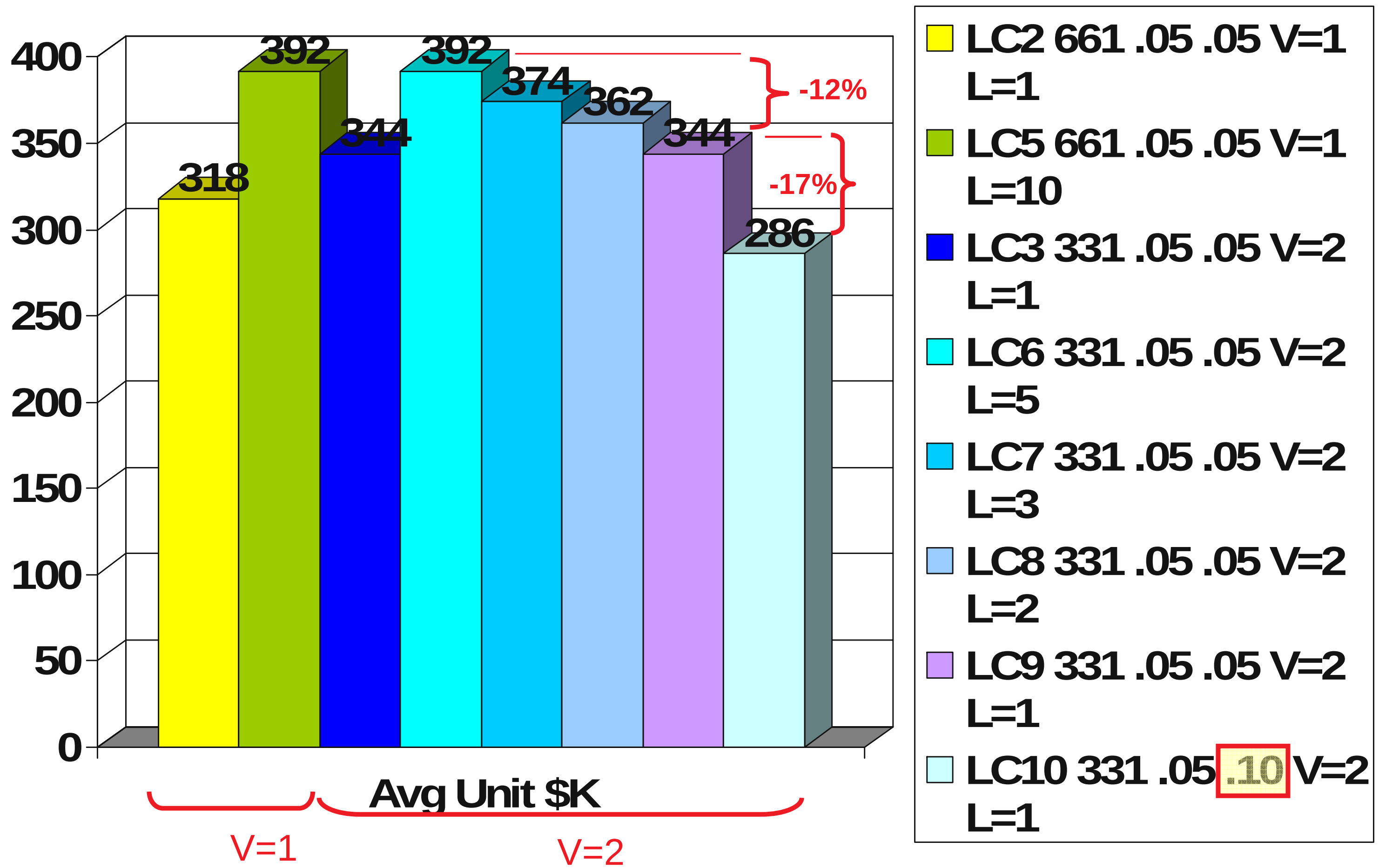
REF. 0

+1.3%

+9.6%

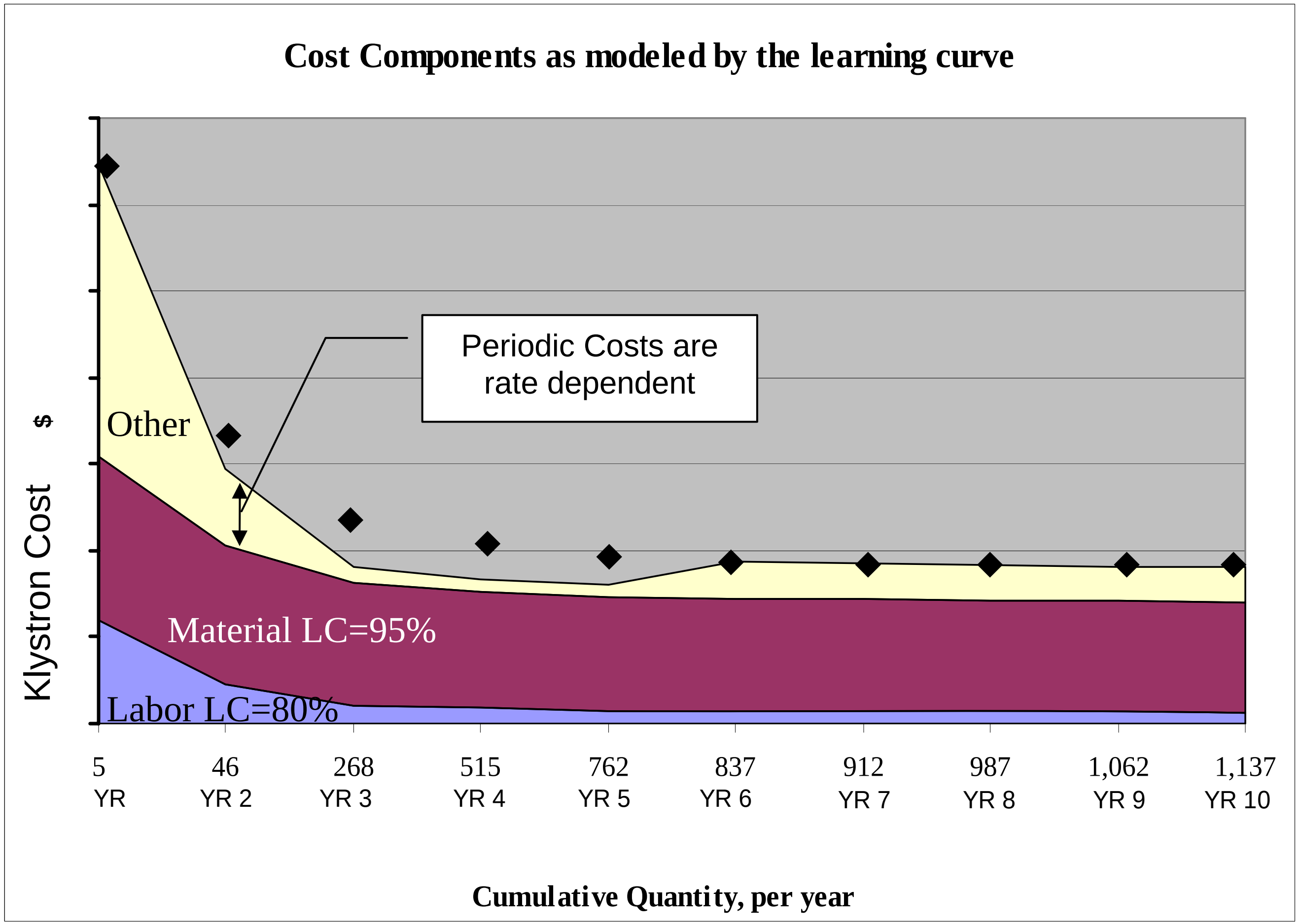
-8.9%

Modulator LC Sensitivity
Variable Lot Size, 1 or 2 Vendors



Klystron LC *c.f.* Industry

"Learning Curve Components" for an 88% curve fit to the Klystron Factory Model



- Other Periodic Costs
  - Tooling
  - Fixturing
  - Automation
  - Indirect Labor
  - Cleaning
  - Plating
  - Supplies
  - Utilities
  - Leasing

CPI Communications & Power Industries

High Volume Manufacturing

VKS-7964M: breaking the Exhaust bottleneck

Example

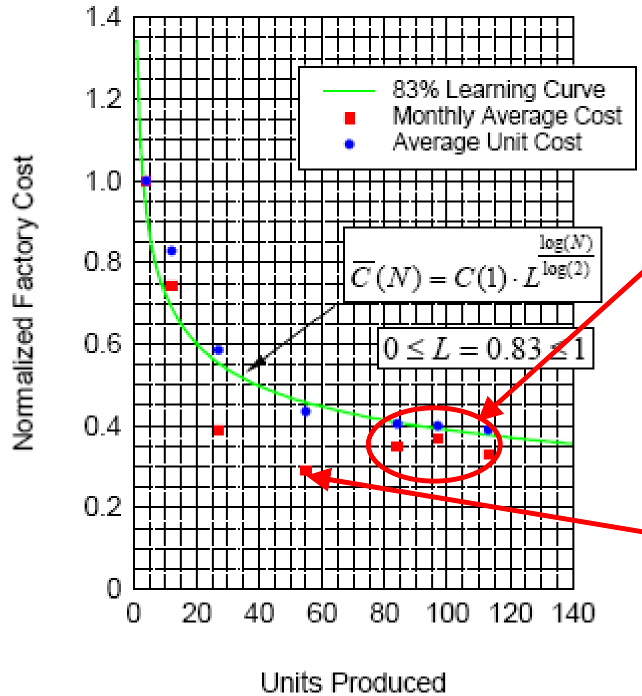
Snowmass 2005 "RF source selection for the ILC" Wright, Bohlen, Lenci, Balkcum

A multi-port exhaust manifold was used

DFA/DFM methodology critical to our success; 83% learning curve realized

Delivery was as high as 12 per week, however we were asked to reduce to 10 per week due to Amplifier manufacturing constraints

250 units produced



Costs increased when rate was reduced

Lowest cost at max production rate

Insist on the original...

Pre-Construction & Construction Period Onsite Engineering & Labor

Area	Area Fraction	Engineer Project/ Supervisory	Engineer- Elect, RF	Engineer- SWE	Engineer- QA Testing	Tech- Elec/RF/ Rigger	Tech Drafting/ Layout	Tech Admin	Pre-Production Period P-yrs by Area
Pre-Production Period Totals (FTE)		6	20	8	0	13	12	12	71
2.5 Year Totals		15	50	20		32.5	30	30	177.5
Main Linacs	0.83	12.5	41.7	16.7		27.1	25.0	25.0	148.0
e- Source	0.02	0.3	1.0	0.4	0.0	0.7	0.6	0.6	3.6
e+ Source	0.05	0.8	2.5	1.0	0.0	1.6	1.5	1.5	8.9
RTML	0.06	1.0	3.2	1.3	0.0	2.1	1.9	1.9	11.4
Damping Rings	0.03	0.5	1.6	0.6	0.0	1.0	1.0	1.0	5.7
									Pre-Production Period P-yrs by Area
Production Period Totals (FTE)		14	17	9	17	37		15	109
4.5 Year Totals		63	76.5	40.5	76.5	166.5	0	67.5	490.5
Main Linacs	0.83	52.3	63.5	33.6	63.5	138.2	0.0	56.0	407.1
e- Source	0.02	1.3	1.5	0.8	1.5	3.3	0.0	1.4	9.8
e+ Source	0.05	3.2	3.8	2.0	3.8	8.3	0.0	3.4	24.5
RTML	0.06	3.8	4.6	2.4	4.6	10.0	0.0	4.1	29.4
Damping Rings	0.03	1.9	2.3	1.2	2.3	5.0	0.0	2.0	14.7
Total P-Yrs									668

Pre-Production 2.5 Yrs				Production 4.5 Yrs				Totals	Py	7 Yrs
Area	Engineers Py Total	Techs Py Total	Admins Py Total	Area	Engineers Py Total	Techs Py Total	Admins Py Total	Engrs	Techs	Admins
Main Linacs	70.9	52.1	25.0	Main Linacs	212.9	138.2	56.0	283.8	190.3	81.0
e- Source	1.7	1.3	0.6	e- Source	5.1	3.3	1.4	6.8	4.6	2.0
e+ Source	4.3	3.1	1.5	e+ Source	12.8	8.3	3.4	17.1	11.5	4.9
RTML	5.4	4.0	1.9	RTML	15.4	10.0	4.1	20.8	14.0	6.0
Damping Rings	2.7	2.0	1.0	Damping Rings	7.7	5.0	2.0	10.4	7.0	3.0

Cost Risk Table

	A	B	C	D	E	F	G	H	I	J	K	L
2	**HLRF % RISK ASSESSMENT SUMMARY**											
3												
4			**DESIGN**		**TECHNICAL**		**COST**		**SCHEDULE**		**TOTALS**	
5			**min**	**max**	**min**	**max**	**min**	**max**	**min**	**max**	**min**	**max**
6	**ITEM**											
7												
8	**ML 10 MW KLYSTRON**		**0**	**0**	**40**	**80**	**8**	**16**	**8**	**8**	**56**	**104**
9												
10	**ML RF DISTRIBUTION**		**0**	**0**	**2**	**4**	**3**	**6**	**8**	**8**	**13**	**18**
11												
12	**ML MODULATOR**		**0**	**0**	**4**	**8**	**4**	**8**	**8**	**8**	**16**	**24**
13												
14	**DR KLYSTRON**		**0**	**0**	**4**	**8**	**3**	**6**	**8**	**8**	**15**	**22**
15												
16	**DR HV POWER SUPPLY**		**0**	**0**	**4**	**8**	**4**	**8**	**8**	**8**	**16**	**24**
17												
18												

Pre & Production Total ED&I, Admin

Task	Engineer Project/ Supervisory	Engineer-Elect, RF	Engineer-SWE	Engineer-QA Testing	Tech-Elec/RF/ Rigger	Tech Drafting/ Layout	Tech Admin	Total
4a.	6	3					6	15
4b.		10	3		7	7	4	31
4c.		7	5		6	5	2	25
Pre-Production Period Totals	**6**	**20**	**8**		**13**	**12**	**12**	**71**
4a.	6	3					6	15
5a.				6	3			9
5b.	5	7	7	8	10/6		6	49
5c.	3	7	2	3	18		3	36
Production Period Totals	**14**	**17**	**9**	**17**	**37**		**15**	**109**

ED&I Labor Area Allocation

Area	No. Stations (755 All Types)	Fraction Total
Main Linacs	630	0.834
e- Source	15	0.02
e+ Source	38	0.05
RTML	48	0.064
Damping Rings	24	0.032

Area Totals by Py & Type

Area	Area Fraction	Engineer Project/ Supervisory	Engineer-Elect, RF	Engineer-SWE	Engineer-QA Testing	Tech-Elec/RF/ Rigger	Tech Drafting/ Layout	Tech Admin	Pre-Production Period P-yrs by Area
Pre-Production Period Totals (FTE)		6	20	8	0	13	12	12	71
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Damping Rings	0.03	1.9	2.3	1.2	2.3	5.0	0.0	2.0	14.7
Total P-Yrs									668

Table 3: Py by Area and Type

Pre & Construction Period Py Totals by Area & Category

Pre-Production 2.5 Yrs				Production 4.5 Yrs			
Area	**Engineers Py Total**	**Techs Py Total**	**Admins Py Total**	**Area**	**Engineers Py Total**	**Techs Py Total**	**Admins Py Total**
Main Linacs	**70.9**	**52.1**	**25.0**	**Main Linacs**	**212.9**	**138.2**	**56.0**
e- Source	**1.7**	**1.3**	**0.6**	**e- Source**	**5.1**	**3.3**	**1.4**
e+ Source	**4.3**	**3.1**	**1.5**	**e+ Source**	**12.8**	**8.3**	**3.4**
RTML	**5.4**	**4.0**	**1.9**	**RTML**	**15.4**	**10.0**	**4.1**
Damping Rings	**2.7**	**2.0**	**1.0**	**Damping Rings**	**7.7**	**5.0**	**2.0**

Table 4: Py by Generic Categories