Project X RD&D Plan
High-Energy Linac

Mark Champion
AAC Meeting
February 3, 2009

Outline

- Description of the scope of the system
- Performance specification of the system
- Primary technical issues and the strategy to address them
- Goals of the plan by year
- Role of outside collaborators.

System Scope

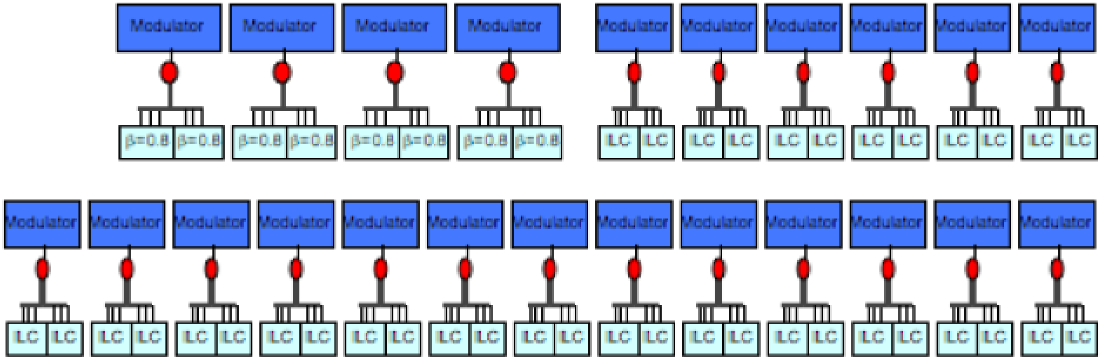
1300 MHz LINAC

1300 MHz 0.42-1.3 GeV

4 Klystrons (ILC 10 MW MBK)
64 Squeezed Cavities (β=0.81)
8 Cryomodules

1300 MHz 1.3-8.0 GeV

19 Klystrons (ILC 10 MW MBK)
304 ILC-identical Cavities
38 ILC-like Cryomodules



- Primary Elements
  - Cryomodules
  - RF Systems
- Related Systems (other WBS elements)
  - Controls, Vacuum Systems, Instrumentation, Cryogenics, Conventional Facilities

Breakdown of primary elements

- Cryomodules
  - Cavities
  - RF couplers
  - Magnets
  - Instrumentation
  - Mechanical & cryogenic design
- RF Systems
  - Modulators
  - Klystrons
  - RF distribution, including vector modulators
  - Low-level RF controls
  - Interlocks

Project X Requirements (from ICD 1.0)

Req. No.	Description	Req.	Unit
3.0	**1300 MHz Linac**		
3.1	Average Gradient (ILC portion)	25	MV/meter
3.2	Average Gradient (S-ILC portion)	23	MV/meter
3.3	Average Beam Current	20	mA
3.4	Pulse Length	1.25	mS
3.5	Repetition rate	5	Hz
3.6	1300 MHz Availability	88	%
3.7	Initial Energy	420	MeV
3.8	Length (approx.)	700	meters
3.9	Peak RF Current	31.9	mA
3.10	Linac Species	H-	
3.11	Energy Variation (rms)	1	%
3.12	Bunch Phase jitter (rms)	1	degree
3.13	Final Energy	8	GeV
3.14	Transverse Emittance (95% normalized)	2.5	π-mm-mrad
3.15	Macro Bunch Duty Factor	67	%
3.16	Macro Bunch Frequency	53	MHz
3.17	Micro Pulse Length	10.4	uS
3.18	Micro Pulse Period	11.1	uS

Technical Issues

- Lattice design optimization
- Cryomodule mechanical and cryogenic design
- Design of the beta=0.81 cavities and cryomodules
- Determination of need for HOM couplers
- Design of RF power coupler
- Choice of klystron: 5 MW single-beam vs 10 MW multi-beam
- Choice of modulator: Bouncer vs Marx
- RF distribution configuration and components
- Low-Level RF control system
- Impact of upgrade plans

Project X

Technical Strategy

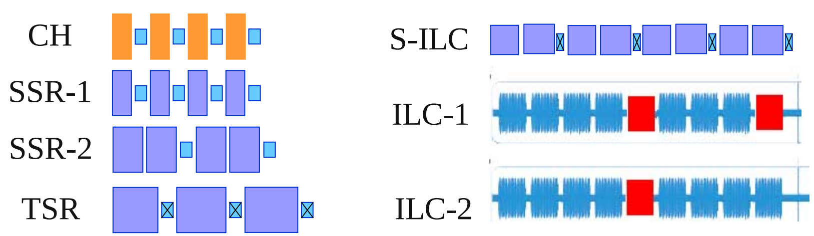
Lattice design optimization

- The Fermilab Accelerator Physics Center (APC), in collaboration with Argonne and Oak Ridge, will perform beam physics studies with the following objectives:
  - Meet overall system performance requirements
  - Minimize beam losses
  - Efficiently utilize cavities, RF systems and magnets
  - Provide operational flexibility in case of equipment failures
    - e.g., operations with offline cavities
  - In view of upgrade plans

Project X Lattice studies in progress

Cavity parameters and focusing lattice

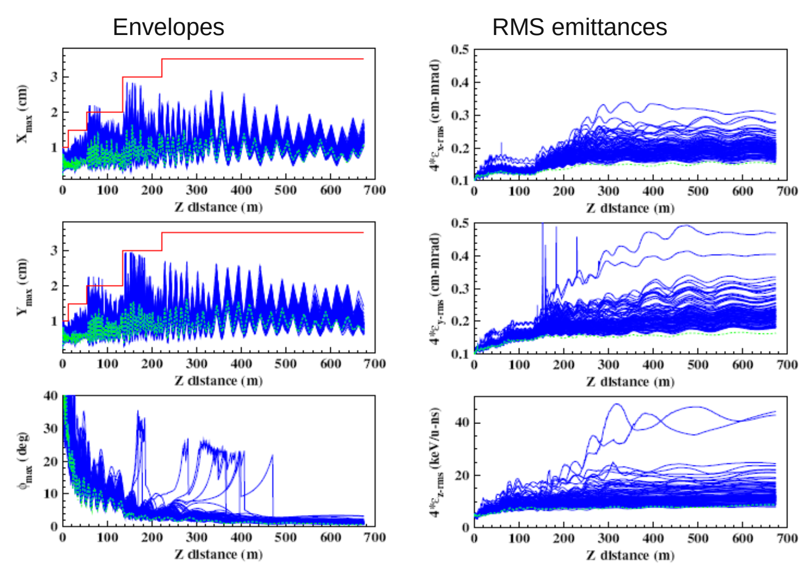
Section	CH	SSR-1	SSR-2	TSR	S-ILC	ILC-1	ILC-2
β_G	-	0.2	0.4	0.6	0.83	1.0	
# of res.	16	18	33	42	64	63	240
# of cells	4-5	2	2	4	8	9	9
# of cryostats	-	2	3	7	8	9	29
E_{PEAK} (MV/m)	-	30	28	30	50	50	
E_{ACC}(MV/m)	1.8-3.0	11.5	8.64	9.65	23	25	
L_F (m)	0.52-0.75	0.75	1.6	3.81	6.1	12.2	24.4



Conclusion and Outlook

- Accelerator physics is well advanced
- Iterate beam physics with engineering design, cost optimization
  - Cryomodule design
  - Alignment errors and tolerances
  - RF distribution system
  - RF errors, include realistic LLRF, transient analysis
  - Specs to beam diagnostics system
  - Beam losses
- Failure modeling
- Linac tuning, start-up

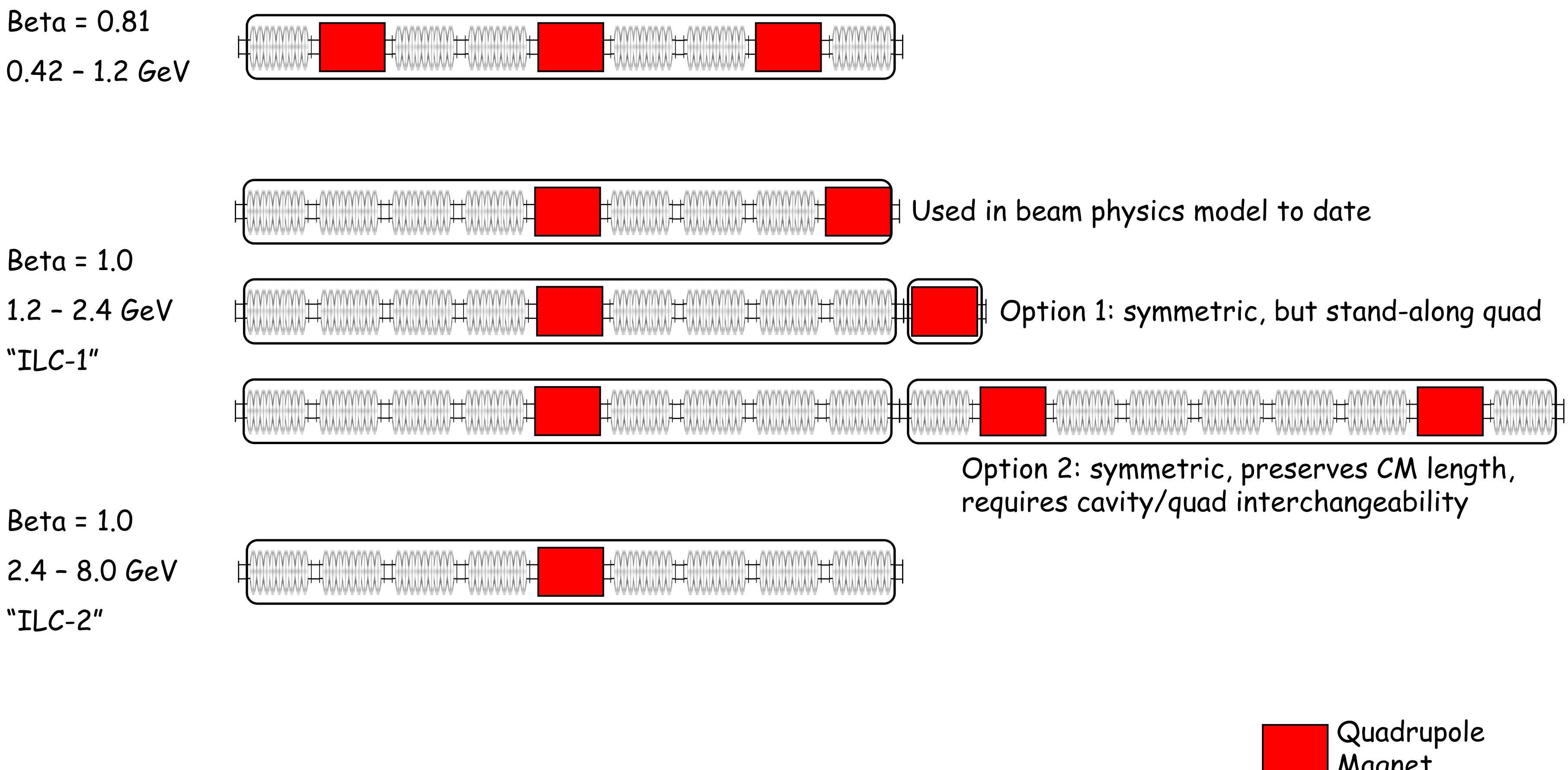
High statistics simulations for 8-GeV, 100 seeds with all errors



Peter Ostroumov
Project X Collaboration Meeting
Nov 2008

AAC, February 3, 2009 – Mark Champion

HE Linac Lattice



Technical Strategy

Cryomodule mechanical and cryogenic design

- Design basis is Fermilab Type-4 cryomodule
  - Derived from European XFEL (Type 3+) cryomodule design
  - 8 cavities plus center-mounted quadrupole & BPM
- Issues to be addressed
  - Retain 5K shield?
  - Retain piping sizes?
  - Cavity tuner type and position
  - Number of cavities and magnets; overall length
  - Cost optimization / compatibility between beta=0.81 and beta=1.0 cryomodules

Technical Strategy

Design of the beta=0.81 cavities and cryomodules

- Guiding principles:
  - The beta=0.81 cryomodule design will be based on the Fermilab Type-4 cryomodule
  - Strive to maintain compatibility and similarity between the beta=0.81 and beta=1.0 cryomodules
    - Sharing of components → reduced development and construction costs
- Start with the beta=0.81 cavity design that was prototyped at MSU
  - Carry on the processing & testing of the prototype cavities
- Optimize the cavity design with respect to:
  - Number of cells
  - Cell geometry and coupling
  - HOM spectrum and HOM damping requirements
  - Multipacting
  - Integration with Type-4 cryomodule design

Technical Strategy

Determination of need for HOM couplers

- Calculate mode spectra for cavities for range of variations on ideal cavity geometry
- Examine mode excitation based on baseline and upgrade beam parameters
- In case of mode excitation, determine damping requirements to avoid emittance degradation, beam loss, and cryogenic system loading
- Collaborate with Oak Ridge regarding SNS design and experience with HOM couplers
- Consult with DESY and Jefferson Lab colleagues

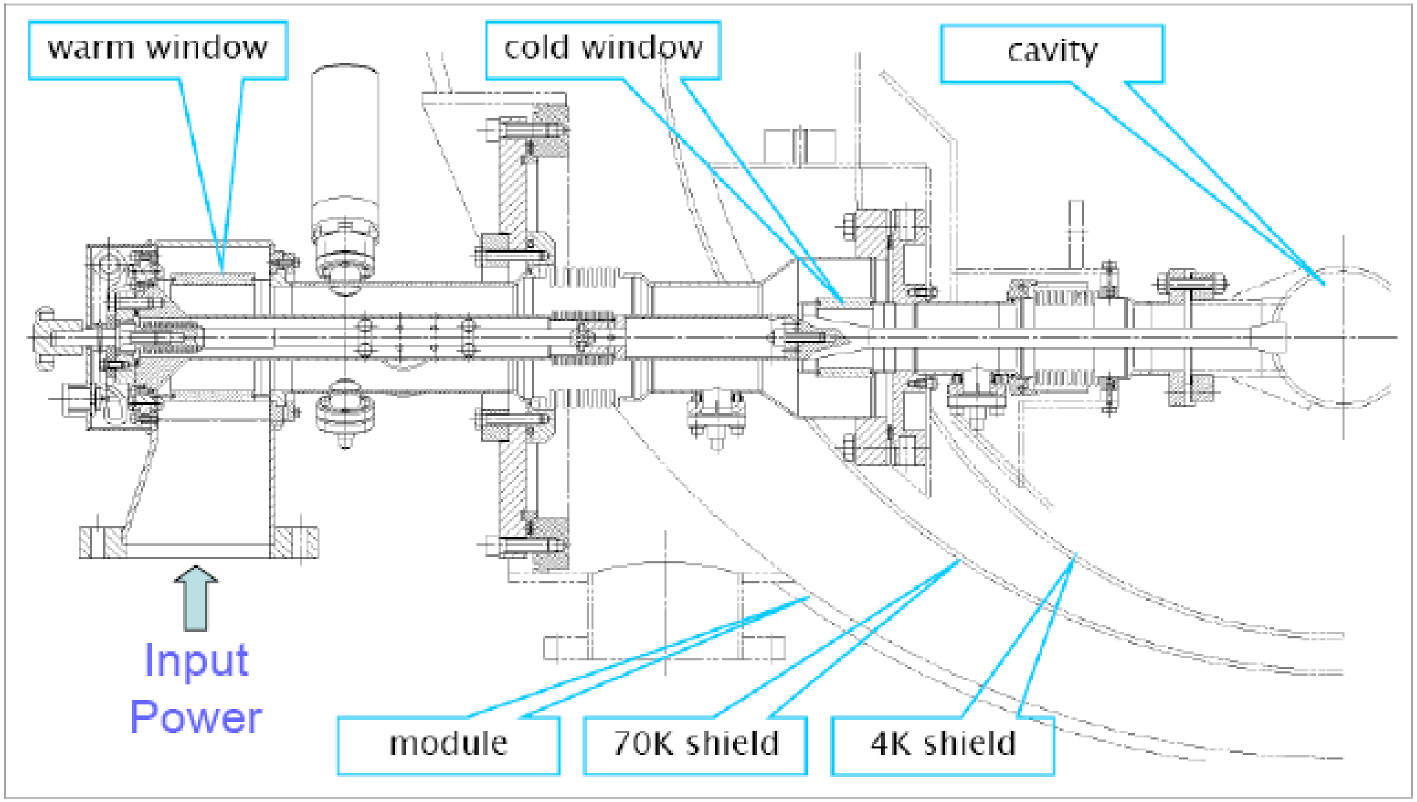
Technical Strategy
RF Couplers

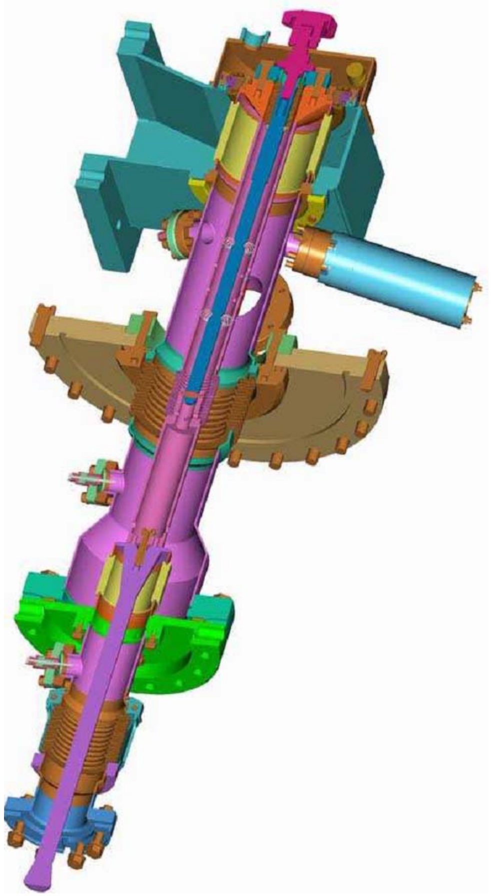
Parameters	Units	1 MW	2 MW Upgrade	4 MW Upgrade
Beam energy	GeV	8	8	8
Current	mA	20	20	20
Repetition rate	Hz	5	10	10
Acc. Gradient (beta=1)	MV/m	25	25	25
Q external	10^6	1.25	1.25	1.25
Filling time	ms	0.212	0.212	0.212
Pulse length (flat-top)	ms	1.25	1.25	2.5
Total RF pulse length	ms	1.465	1.465	2.712
Peak power / coupler	**kW**	**500**	**500**	**500**
Average power / coupler	**kW**	**3.7**	**7.3**	**13.6**

Primary challenge: Average power dissipation

Technical Strategy
RF Couplers

Starting Point: XFEL TTF-3 Coupler Design





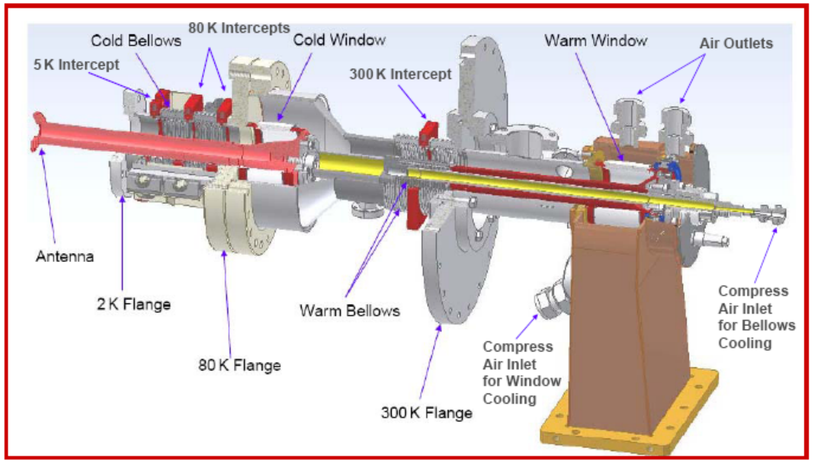
Cornell ERL Coupler

Cornell University
Laboratory for Elementary-Particle Physics

Cornell ERL injector input coupler

Design features:

- Design derived from the TTF-III coupler
- The cold part was completely redesigned using a 62 mm, 60 Ohm coaxial line for stronger coupling, better power handling and avoiding multipacting
- Antenna tip was enlarged and shaped for stronger coupling
- "Cold" window was enlarged to the size of "warm" window
- Outer conductor bellows design was improved for better cooling (added heat intercepts)
- Air cooling of the warm inner conductor bellows was added



October 15, 2007 S. Belomestnykh: SRF in SR Light Sources - SRF2007, Beijing

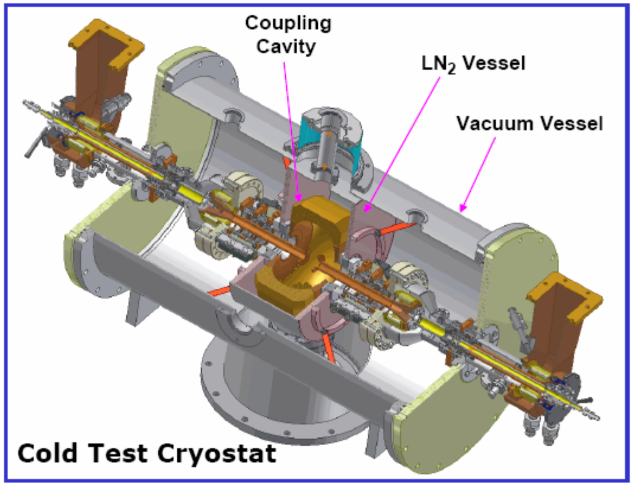
Cornell ERL Coupler

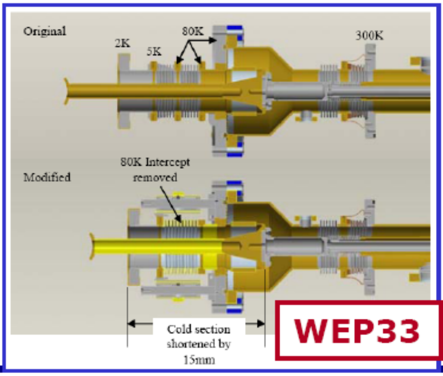
Cornell University
Laboratory for Elementary-Particle Physics

Sattus and test results

- Two prototype and eight production couplers have been manufactured by CPI to date. Two prototypes and two production couplers were tested.
- A special Cold Test Cryostat (CTC) was designed and built for input coupler testing.
- After testing prototype couplers some design changes were implemented to further improve cooling.
- *In situ* baking to 120° C was implemented to facilitate quicker processing.
- Production couplers reached 61 kW CW level after pulsed RF conditioning up to 85 kW (above 36 kW CW).
- Exposure of RF surfaces to room temperature air for 4 hours did not degrade performance: couplers "remember" processing!
- These couplers (slightly modified) will be used in the ERL cryomodule (collaboration Daresbury/Cornell/LBNL/Rossendorf/Stanford).

WEP26





WEP33

October 15, 2007 S. Belomestnykh: SRF in SR Light Sources - SRF2007, Beijing

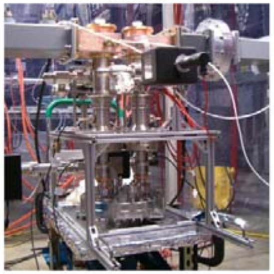
Technical Strategy
RF Couplers – SLAC Collaboration

40 vs 60 mm Diameter Cold Sections

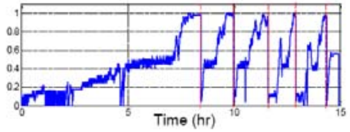
- Much experience with TTF3 40 mm cold sections although usually run below ILC input power level of 300 kW
- 40 mm design my be less lossy cryogenic wise but this should be checked since warm rf losses lower with 60 mm
- Strong multipactor bands from 300-600 kW in 40 mm tube although they process out – long term effect not clear
- 60 mm design likely increases power handling capability - see fairly gas-free operation of warm 60 mm sections – need to quantify
- 60 mm designs already developed at Orsay and KEK, and KEK has developed cavities with 60 mm ports (not difficult to adjust HOM accordingly). May need 60 mm coupler design for PX at FNAL
- As usual, ability to use either diameter is desirable, but regardless of diameter, should have adjustable Q

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



Power Coupler Assembly in SLAC Class 10 Cleanroom

Technical Strategy
RF Couplers

Conclusions

- Existing TTF-III coupler doesn't work at required average power of 7.5 kW (upgrade PrX to 1MW)
  - Limitation: overheating of the bellows of an internal conductor in warm vacuum part
  - Means used to cure the problem (in coupler for ERL):
    - *Increase of the inner conductor diameter and the coaxial impedance – helps up to 7.5 kW CW.*
    - *Air cooling of the warm part of the inner conductor – helps up to >10 kW CW.*
- A number of existing 1.3 GHz couplers provide needed average power, for peak power need tests.
  - KEK STF coupler,
  - KEK ERL coupler;
  - Cornell ERL coupler.
- **It is necessary to review these couplers in details in order to decide whether it is possible to use them as a prototype or to adapt directly.**

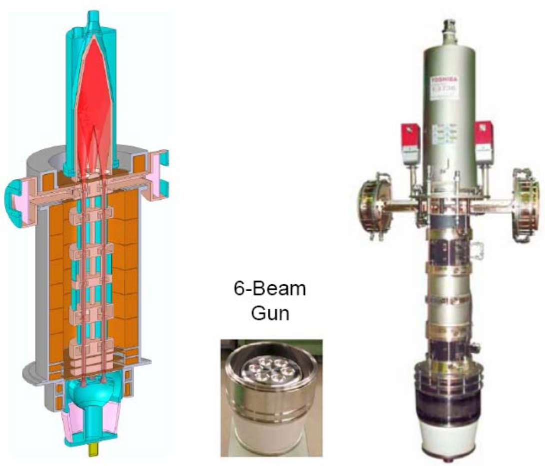
Solyak and Yakovlev
FNAL

Technical Strategy

Choice of klystron: 5 MW single-beam vs. 10 MW multi-beam

- Depends largely on economics and upgrade strategy
- Baseline configuration
  - One 10 MW klystron per two cryomodules
- ILC R&D plan supports long-term testing of MBK and development of sheet-beam klystron at SLAC
- Will also benefit from ongoing work at DESY (XFEL)

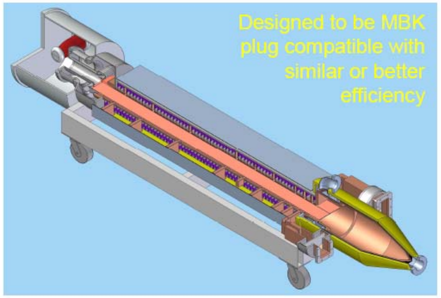
SLAC/KEK Toshiba 10 MW MBK



Sheet Beam Klystron Development at SLAC

Why Sheet Beam ?

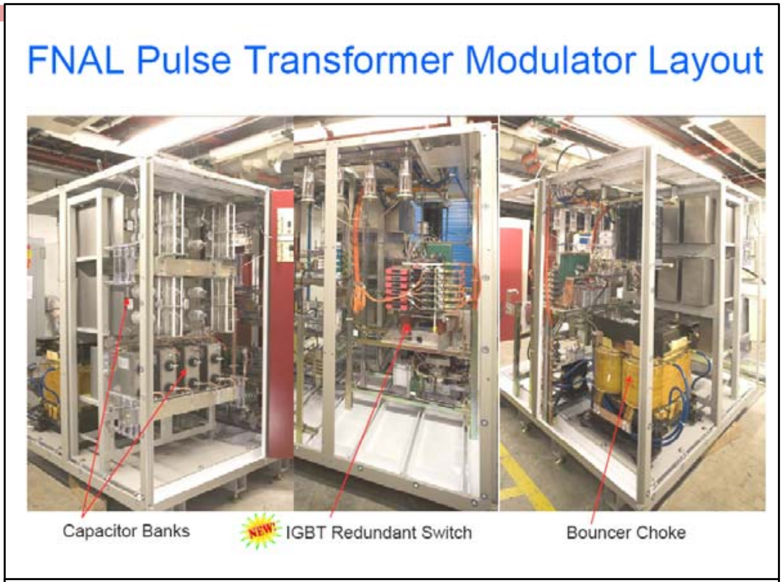
- Allows higher beam current (at a given beam voltage) while still maintaining low current density for efficiency
- Will be smaller and lighter than other options
- PPM focusing eliminates power required for solenoid

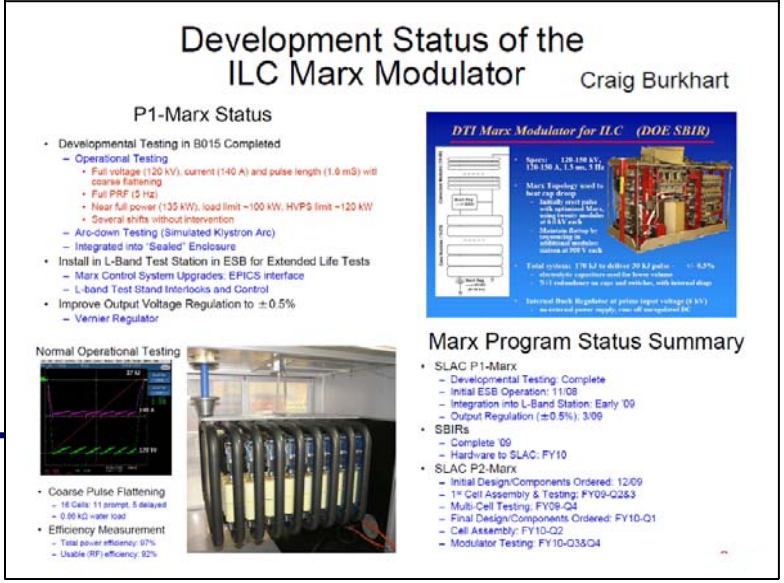


Technical Strategy

Choice of modulator: Bouncer vs. Marx

- Baseline design calls for proven Fermilab “bouncer” modulator
- SLAC Marx modulator will undergo continued development as part of ILC R&D program
  - Extensive testing planned in FY09-10
- Choice will be made based on performance, reliability and cost considerations



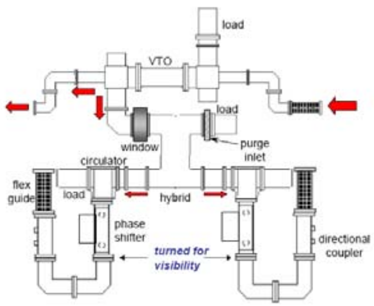


Project X

Technical Strategy

RF distribution configuration and components

Modular 2-Cavity PDS Unit for 1st FNAL CM

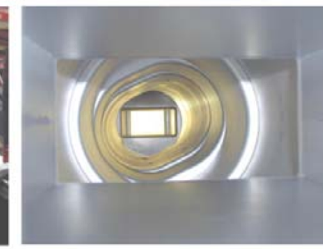


BENEFITS OVER LINEAR BCD:

- Fewer types of splitters (2 vs. 9)
- Power division adjustable by pairs with Variable Tap Off (VTO)
- Permits elimination of circulators by using a hybrid

Prototype VTO (below) and Hybrid (right)

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

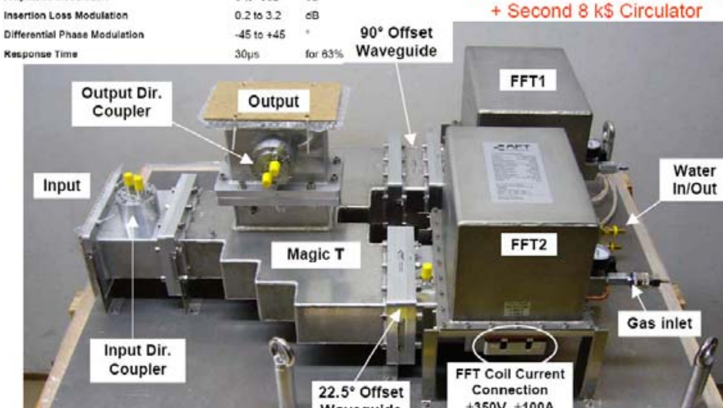


- ILC developments in support of NML over next few years
  - Select configuration and components based on experience and cost & performance considerations

AFT E/H Tuner Prototype

Minimum Insertion Loss	< 0.2	dB
Amplitude Modulation	0 to -3dB	dB
Insertion Loss Modulation	0.2 to 3.2	dB
Differential Phase Modulation	-45 to +45	°
Response Time	30μs	for 63%

Cost Each in Quantity Estimated to be 30 k$ (WG) + 15 k$ (PS) + Second 8 k$ Circulator



Technical Strategy

Low-Level RF control system

- DESY / Fermilab collaboration well established
  - LLRF control systems for A0 photo-injector, capture cavity II, and horizontal test system
- Single klystron / multiple cavity LLRF system being prepared for New Muon Lab (NML) at Fermilab
  - Will support testing of first cryomodule this year
- Ongoing development for NML will result in LLRF system for high-energy Linac of Project X

Technical Strategy

Impact of upgrade plans

- ICD 1.0 calls for 1 MW beam power at 8 GeV
  - 20 mA, 1.25 ms, 5 Hz
- Achieve 2 MW beam power by doubling rep rate to 10 Hz
- Achieve 4 MW beam power by doubling pulse length to 2.5 ms
- Issues:
  - RF coupler ratings
  - Heat load to cryogenic system
  - Modulator and klystron ratings
    - Number of RF systems
    - AC power and cooling water
    - Layout: floor space, penetrations, RF distribution

Goals and Timeline

- FY09
  - Lattice design optimization
  - RF coupler design, prototyping, testing
  - HOM studies
  - Modulator & klystron testing
  - Test cryomodule 1 at NML
  - LLRF for cryomodule 1 at NML
  - Beta=0.81 cavity design studies; test 7-cell prototypes at MSU
  - Complete Type 4 cryomodule design
- FY10
  - Ongoing design studies and optimization
  - Complete cryomodule 2 (Type 3+, aka XFEL)
  - Fabricate prototype beta=0.81 cavities
  - Modulator & klystron testing
- FY11
  - Test prototype beta=0.81 cavities
  - Complete cryomodule 3 (1st Type 4)
- FY12
  - RF Unit test at NML
  - Complete cryomodule 4 (2nd type 4)
  - Complete 1st beta=0.81 cryomodule

Collaborators

- Argonne and Oak Ridge
  - Linac beam physics studies
- Argonne and Jefferson Lab
  - Cavity processing; also testing at JLab
- Indian Institutions (RRCAT, BARC, VECC, IUAC, DU)
  - Design, prototyping and production of beta=0.81 cryomodules
- SLAC
  - High-Level RF System: Klystrons, modulators, RF distribution
  - RF couplers
- CERN
  - Power distribution, choppers
- LBNL
  - LLRF, timing and synchronization, beam physics
- MSU
  - Beta=0.81 cavities

Summary

High-Energy Linac issues are relatively clear

- Need to conduct detailed studies on several fronts
  - Lattice optimization, beam physics studies
  - HOM damping requirements
- Prototyping and testing required, especially for RF couplers and beta=0.81 cavities
- Cost/performance optimization needed; share components across range of cryomodules
- Take advantage of ongoing ILC/SRF R&D programs
  - Modulators, klystrons, RF distribution, LLRF
- Need to firm up RD&D plan details and collaborations
- Need to gain experience through cryomodule production and testing/operations at NML