VLT RF Technology Development
and
ITER Ion Cyclotron Heating and Current Drive Project

VLT Program Advisory Committee Meeting
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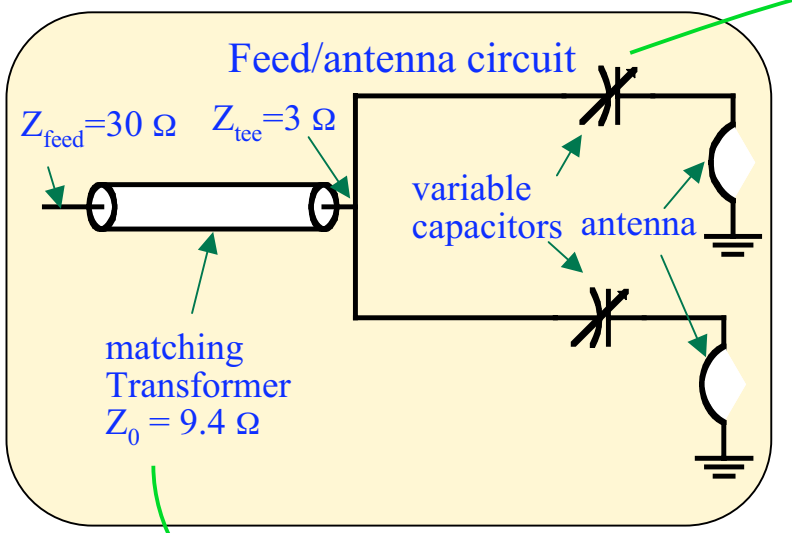
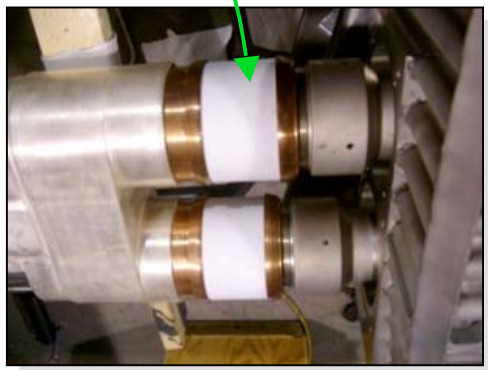
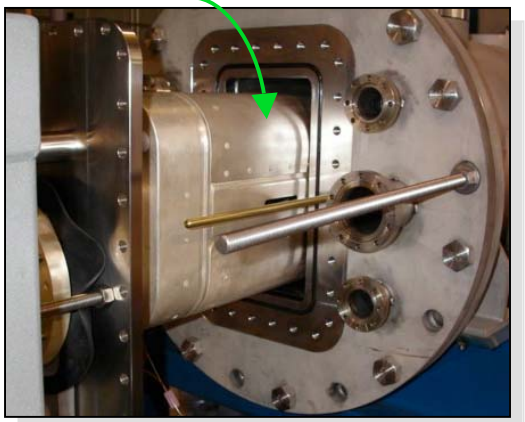
The long-term objectives are to develop reliable, advanced ICRF heating & current drive systems that:

- Operate routinely at their design power and voltage.
- Reduce the required port size - high power density launchers.
- Are robust - tolerant of rapidly varying plasma loads.
- Are flexible
  - Operate over a wide range of density and magnetic fields.
  - Heat either ions or electrons
  - Control plasma conditions via heating and current profile.
- Support long pulses - essentially steady-state.
- Work reliably in a reactor environment.

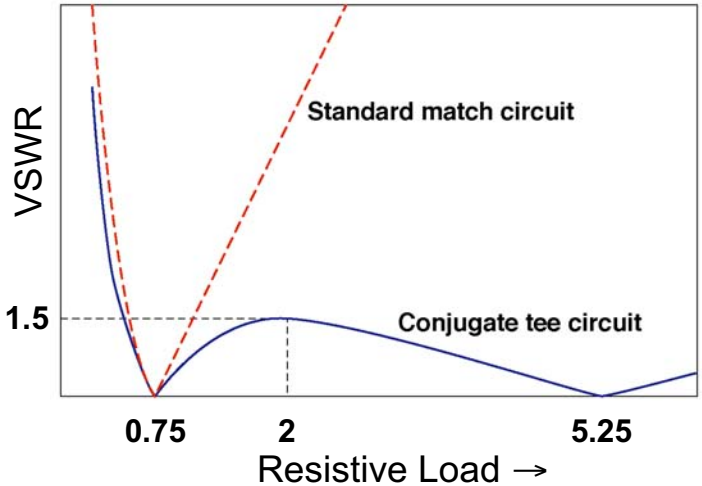
Load-tolerant antenna designs address the long standing plasma edge variability issue but also introduce some design challenges







RF match behavior with increasing resistive load



Load Tolerant Antennas:

Test

- Tore Supra
- JET-A2
- JET-HPP
- C-Mod external

Fabrication

- JET-EP

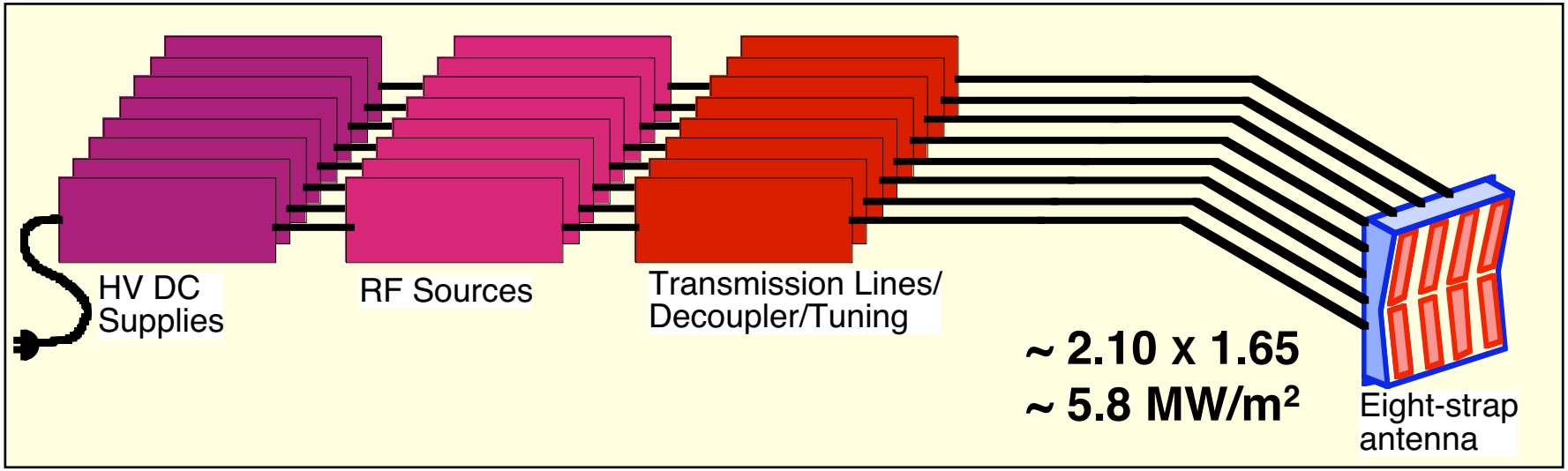
Design

- DIII-D replacement
- C-Mod replacement
- ITER

What is the ITER IC system and what does it do?

- **What it is:**
  - One antenna, eight current straps
  - Eight rf sources, each feeding one strap in the antenna
  - 35-65 MHz
  - 20 MW total power to the plasma
  - Variable phasing between straps
- **What it can be used for:**
  - Tritium ion heating during DT ops.
  - Minority ion heating during initial ops.
  - Current drive near center for AT operation
  - Minority ion current drive at sawtooth inversion radius

ITER ion cyclotron system block diagram



FY05 RF development tasks

ITER specific milestones	
Complete evaluation of alternative ITER antenna designs	03/05
Report on load tolerant matching with mutually coupled antennas for C-Mod and ITER	06/05
Participate in PDR for ITER Ion Cyclotron system	06/06
ITER specific R&D tasks (subtotal)	$960 K
1) ITER RF system design and evaluation (ORNL, PPPL)	$210 K
2) Dual -tube transmitter tests (PPPL)	$100 K
3) Neutron irradiation of ceramic RF insulators (with materials program)	$150 K
4) High power density antenna tests	$300 K
JET-HPP -> JET-EP "ITER-like" antenna comissioning	
C-Mod external load tolerant tuning	
5) ITER IC antenna component R&D (capacitors, stub tuners, fabrication techniques)	$200 K
Generic R&D - Multiple collaboration milestones and move (subtotoal)	$600 K
1) RF/edge interaction measurements and modeling (NSTX, C-Mod, DIII-D, Theory)	$150 K
2) High voltage RF breakdown studies (UIUC, ASDEX-U)	$250 K
3) Improved control and reliability (NSTX, DIII-D, …)	$100 K
4) Innovative approaches to advanced heating and current drive (MST, QPS, EBW)	$100 K
Base total	$1560K
FY05 Task increments in priority order	
1) Component testing and Faraday shield fab development (Materials and PFC)	$100 K
2) ITER RF system design and evaluation (ORNL, PPPL)	$100 K
ITER increment total	$200 K

Dual-tube ITER transmitter configuration test at PPPL

In order to meet the power and VSWR requirements for ITER, the:
US Baseline design is to combine the output of two CPI final amplifiers
EU alternative is to develop a “fusion” diacrode

A near term test using RF sources at PPPL could help resolve the issue:
FY05 (100 K)

- Design and analyze the combiner
- Perform the combined two-source stability test in early FY05 with existing equipment at PPPL.

FY06 RF development tasks

ITER specific milestones

Participate in PDR for ITER Ion Cyclotron system 06/06

	-10%	Flat	Flat+incr
ITER specific R&D tasks	$805 K	$960 K	$1550 K
1) ITER RF system design and evaluation (ORNL, PPPL)	$405 K	$510 K	$ 650 K
2) Neutron irradiation of ceramic RF insulators (matls. program)	$ 0 K	$ 50 K	$ 50 K
3) ITER IC antenna component R&D	$300 K	$300 K	$ 700 K
4) High power density antenna tests	$100 K	$100 K	$ 150 K
JET-HPP -> JET-EP "ITER-like" antenna comissioning			
C-Mod external load tolerant tuning			
Generic R&D - Multiple collaboration milestones	$600 K	$600 K	$600 K
1) RF/edge meas. & modeling (NSTX, C-Mod, DIII-D, Theory)	$150 K	$150 K	$150 K
2) High voltage RF breakdown studies (UIUC, ASDEX-U)	$250 K	$250 K	$250 K
3) Improved control and reliability (NSTX, DIII-D, …)	$100 K	$100 K	$100 K
4) Innovative approaches to advanced H&CD (MST, QPS, EBW)	$100 K	$100 K	$100 K
Total	$1405K	$1560K	$2150K

FY06 Task increments in priority order

1) ITER IC antenna component R&D	$400 K
2) ITER RF system design and evaluation (ORNL, PPPL)	$140 K
3) High power density antenna tests	$ 50 K
ITER increment total	$590 K

FY05 and FY06 ITER project funded tasks

- **ICH ITER IT support:** Provide research staff to act as Responsible Officer for the ITER Ion Cyclotron System on behalf of the International Team, and to coordinate design and R&D activities among the IT and the EU and US Participants.
  FY04 0.4 FTE
  FY05 0.8 FTE
  FY06 0.8 FTE

- **US team Engineering support:** Provide the capability to translate ITER drawing packages between CATIA (the drawing program used by the ITER IT) and ProEngineer (used by most US participants in the ITER work), in order to facilitate transfer between engineers on the IT and on the US Home Team.
  FY04 0.3 FTE
  FY05 0.8 FTE
  FY06 0.8 FTE

ICH Funding profile

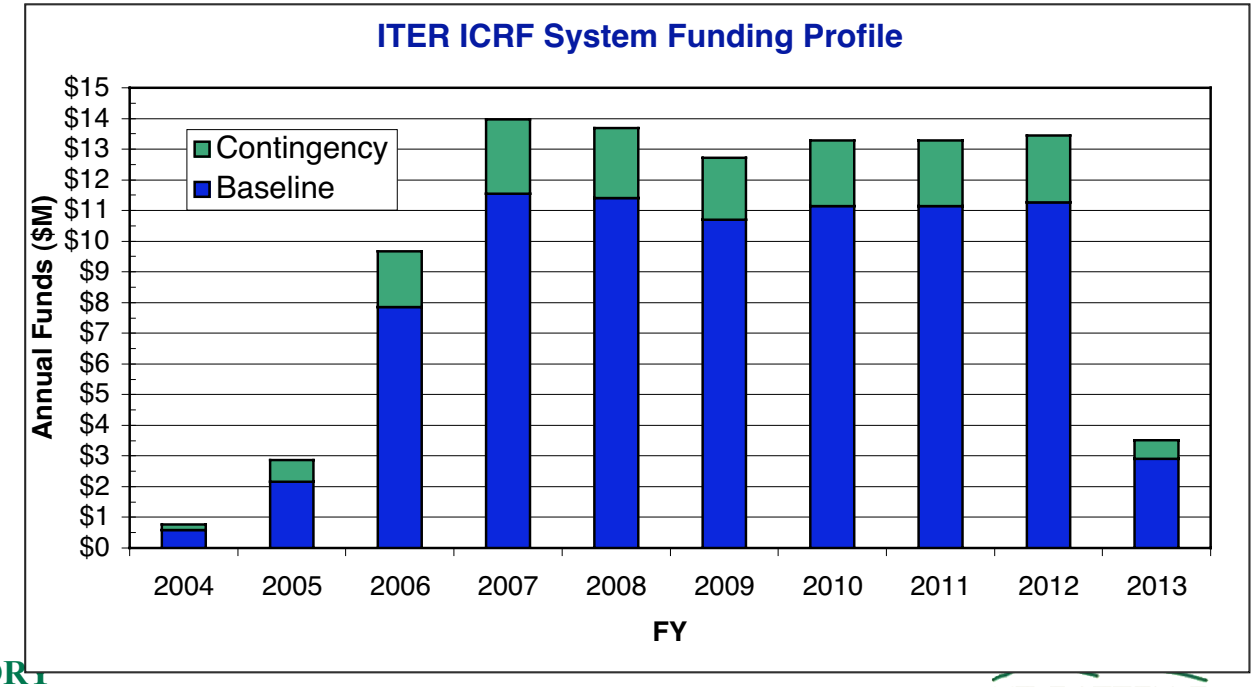
Antenna: R&D and prelim. design must start early

Source and DC supplies: this schedule was based on 2005 start

<u>Schedule should slide 1 year based on 2006 start</u>

Funding profile is dominated by source schedule – need to iterate with vendor.

Base Costs	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Antenna										
R&D	5%	30%	40%	25%						
Design	5%	10%	15%	30%	40%					
Procurement						20%	30%	30%	20%	
Follow-on						10%	10%	10%	35%	35%
Trans. Line										
Procurement			8%	14%	15%	15%	15%	15%	15%	3%
Follow-on	5%	12%	12%	11%	10%	10%	10%	10%	10%	10%
RF Sources										
Procurement			8%	14%	15%	15%	15%	15%	15%	3%
Follow-on	5%	12%	12%	11%	10%	10%	10%	10%	10%	10%
DC Supplies										
Procurement			8%	14%	15%	15%	15%	15%	15%	3%
Follow-on	5%	12%	12%	11%	10%	10%	10%	10%	10%	10%



Key concerns and issues

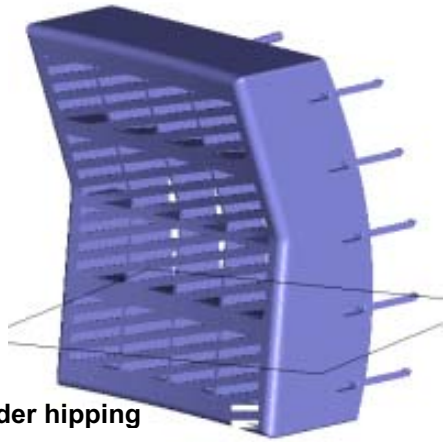
- Negotiation of US and EU roles and responsibilities
  - Site choice drives subsequent decisions
    - Identification of the EU IC project leader after site decision
    - How to split design, R&D, fabrication and testing of ITER antenna
- Antenna concept decisions
  - ITER antenna workshop planned at ORNL
  - Tuner concept (Sliding stubs or ceramic capacitors)
  - Tests required to permit use of ceramics for capacitors and insulators
- Transmitter design
  - Dual-tube - US baseline - Test at PPPL could resolve issues
  - Diacrode - EU alternative
- Test facilities need to be upgraded

FY03/04 Technical Highlights/Accomplishments

- JET-HPP
  - Identified high voltage and long pulse limits
- ITER
  - Costing study
  - Interaction with the ITER IT
- DIII-D - restart of FW systems and transmitter improvements
- NSTX
  - HHFW power dep profiles
  - Improved operation flexibility for power handling, phasing and power modulation
  - AORSA code CD pred matches experiment
  - Augmented RF/edge diagnostics
- HV breakdown - U of I
- EBW - modeling for NSTX, MST, QPS - measurements on NSTX
- C-Mod - improved antenna concept including LT matching
- MST - LH antenna field pattern measurements and modeling
- FIRE - innovative antenna design

Example: Analysis of Faraday shield fabrication

- Faraday shield is plasma-facing component, made of CuCrZr, s. steel cooling tubes, Be coating on the front.
- Lots of unknowns in design *and* fabrication.



Details from Nelson's spreadsheet

Model analysis

VOLUME	=	3.33E+08	MM^3
SURFACE AREA	=	1.95E+07	MM^2
DENSITY	=	8.00E+00	gm/cc
MASS	=	2.67E+06	gm
		2.67E+00	tonnes

material	CuCrZr, Be, sst
fabrication method	forming and welding bars hot isostatic powder pressing of body

overall dimensions		
height	2.1	m
width	1.65	m
depth	0.73	m
height	82.7	in
width	65.0	in
depth	28.7	in

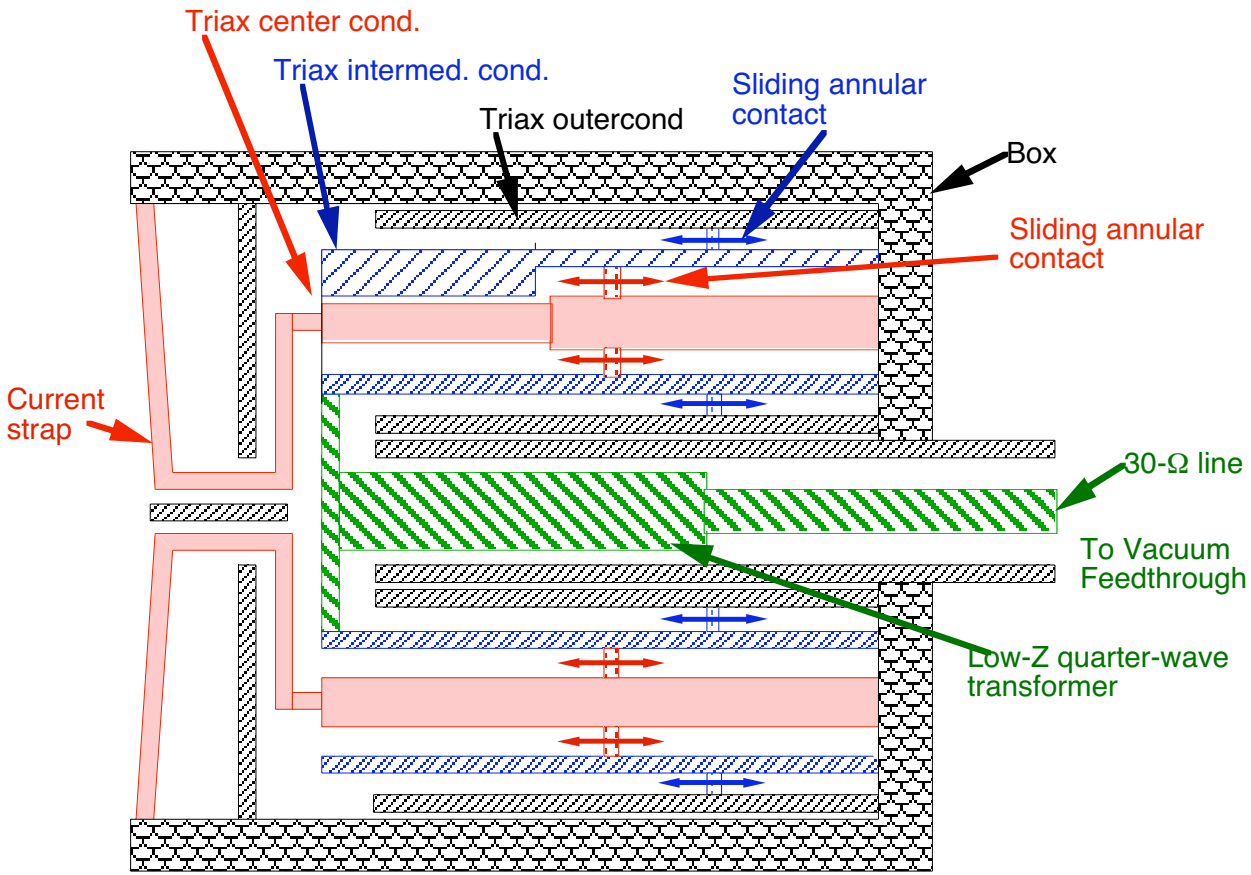
Symmetry: none, each of 8 pieces are different

Hardware cost based on forming and powder hipping

	no.	amount	unit	unit cost	total
material - Be	1	127	lbs	1500	190,302
material - copper	1	5.87E+03	lbs	20	117,308
Forming-bars	21	16	hours	50	16,800
pressing - tooling	1	1	ea	100000	100,000
pressing setup and sst cooling line fab.	1	320	hours	100	32,000
pressing - body	1	160	hours	100	16,000
machining - body	1	160	hours	50	8,000
machining - bars	21	16	hours	50	16,800
welding bars	21	24	hours	50	25,200
finish machining	8	40	hours	50	16,000
Be coating	1	5371	in^2	50	268,537
leak checking, hydro test, thermal cycling	1	160	hours	100	16,000
dimensional inspection	1	80	hours	100	8,000
plating/flame spray subtotal					830,946
rework	1	20%	each	166189	166,189
total hardware					997,136
calculated $/lb		1.70E+02			

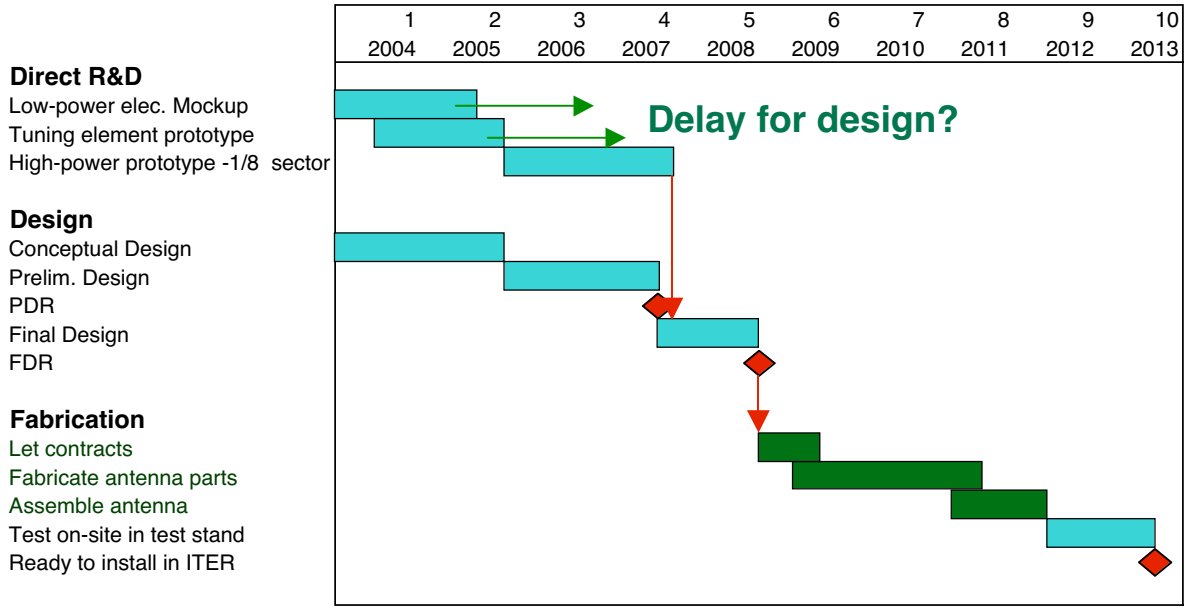
Antenna design and R&D estimate is tricky

- "Baseline design" exists in cartoon form, with several open questions:
  - How to make the tuners?
  - Will machine vacuum allow high rf voltages to be held off?

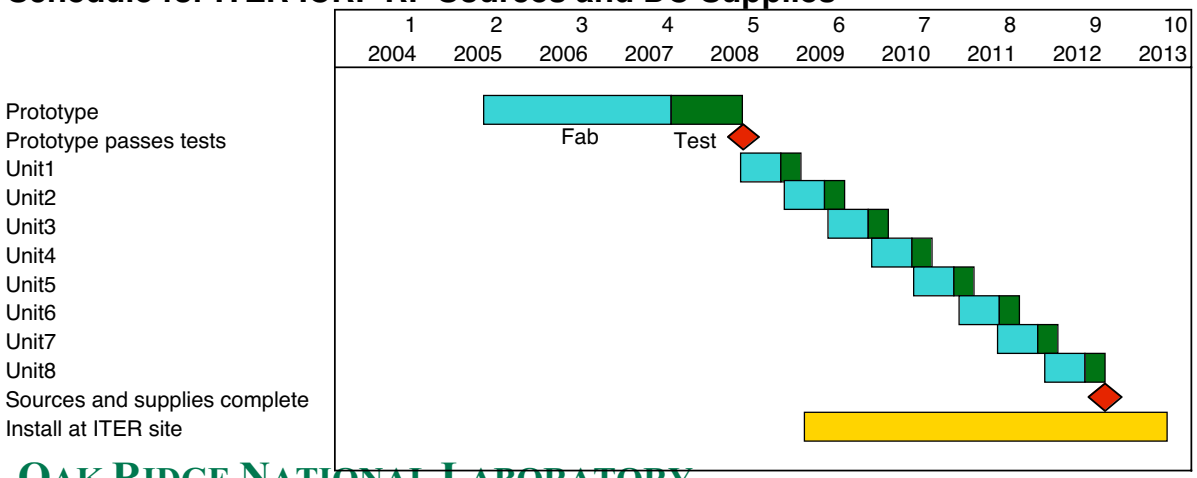


Antenna and source/supply schedules

Schedule for ITER ICRF Antenna



Schedule for ITER ICRF RF Sources and DC Supplies



Preliminary schedules

Antenna R&D and prelim. design must start early. We don't have a viable design.

Source and DC supplies:

- 3 years to build and test prototype
- 1 source delivered every 6 months
- Must start in 2005 to be installed by mid-2013