Crab Cavities
Contribution from the U.S.

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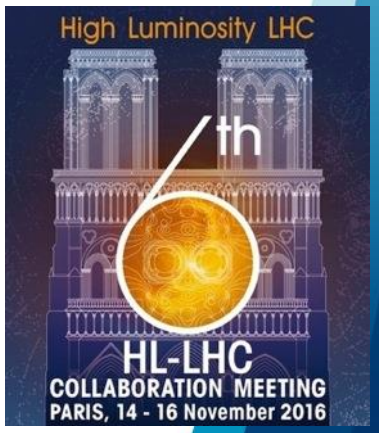
U.S. HL-LHC Accelerator Upgrade Project

HL-LHC Collaboration Meeting
Paris, 14-16 November 2016



Outline

- Soft Landing for Prototypes Circulating in the U.S.
- Scope of U.S. Contribution for HL-LHC
  - A Fresh Start for Prototypes and Production
- Strategy for Fabrication and Qualification
- Schedules
- Facilities
- QA & Risk
- Conclusions

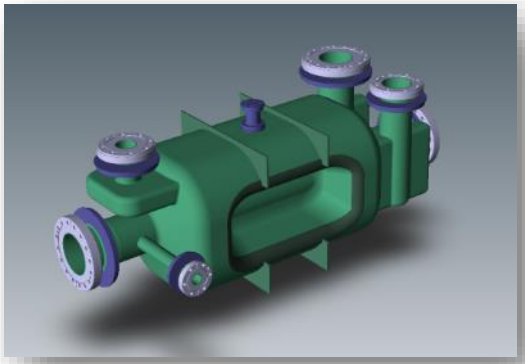
U.S. SPS Prototypes – Soft Landing

- None of the four U.S. SPS prototypes can be used in the SPS tunnel
  - Several CERN Certification Requirements could not be met within the framework of a U.S. SBIR grant. LARP requested the cavities to be handed off in parts to regain control of the process.

- Nevertheless, these 4 prototypes are providing valuable input for the production of HL-LHC DQW and RFD cavities
  - Completion of these 4 cavities is currently undertaken by Jlab/ODU/BNL
  - Final welding and cold tests will provide valuable input for HL-LHC production
- CERN is fabricating DQW prototypes for the SPS test, and will fabricate the production DQW cavities for HL-LHC installation
- A fresh start on solid ground was necessary also for the RFD cavities, this is undertaken by US LARP → soon to be known as HL-LHC AUP

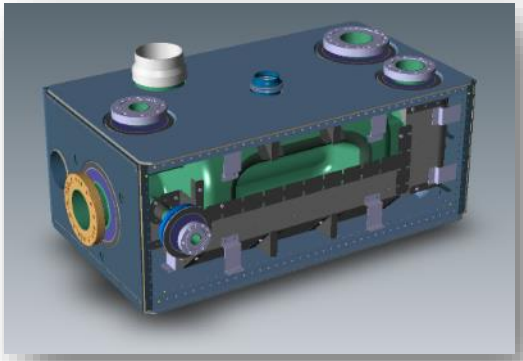
U.S. Crab Cavities Scope for HL-LHC

- **Two Dressed and Tested RFD Crab Cavities (prototypes)**
- **Ten Dressed and <u>Qualified</u> RFD Crab Cavities** (8 for tunnel + 2 spares)
  - In order to qualify 10 cavities, a production of 12 cavities will be launched (assume 80% yield)



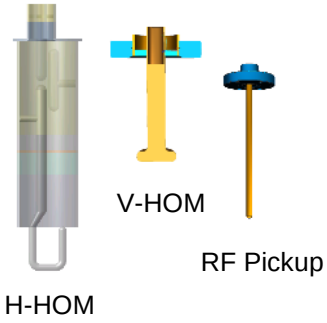
Bare RFD Cavity

Includes:
- Nb Cavity
- Brazed joints to SS flanges
- NbTi Adapter Rings



Jacketed RFD Cavity
(front wall removed to show internal components)

Includes:
- Bare Cavity
- Magnetic Shield
- Helium Tank



RF Ancillaries

Dressed RFD Cavity

Includes:
- Jacketed Cavity
- RF Ancillaries (H and V HOMs, RF Pick-up, tuner interface)

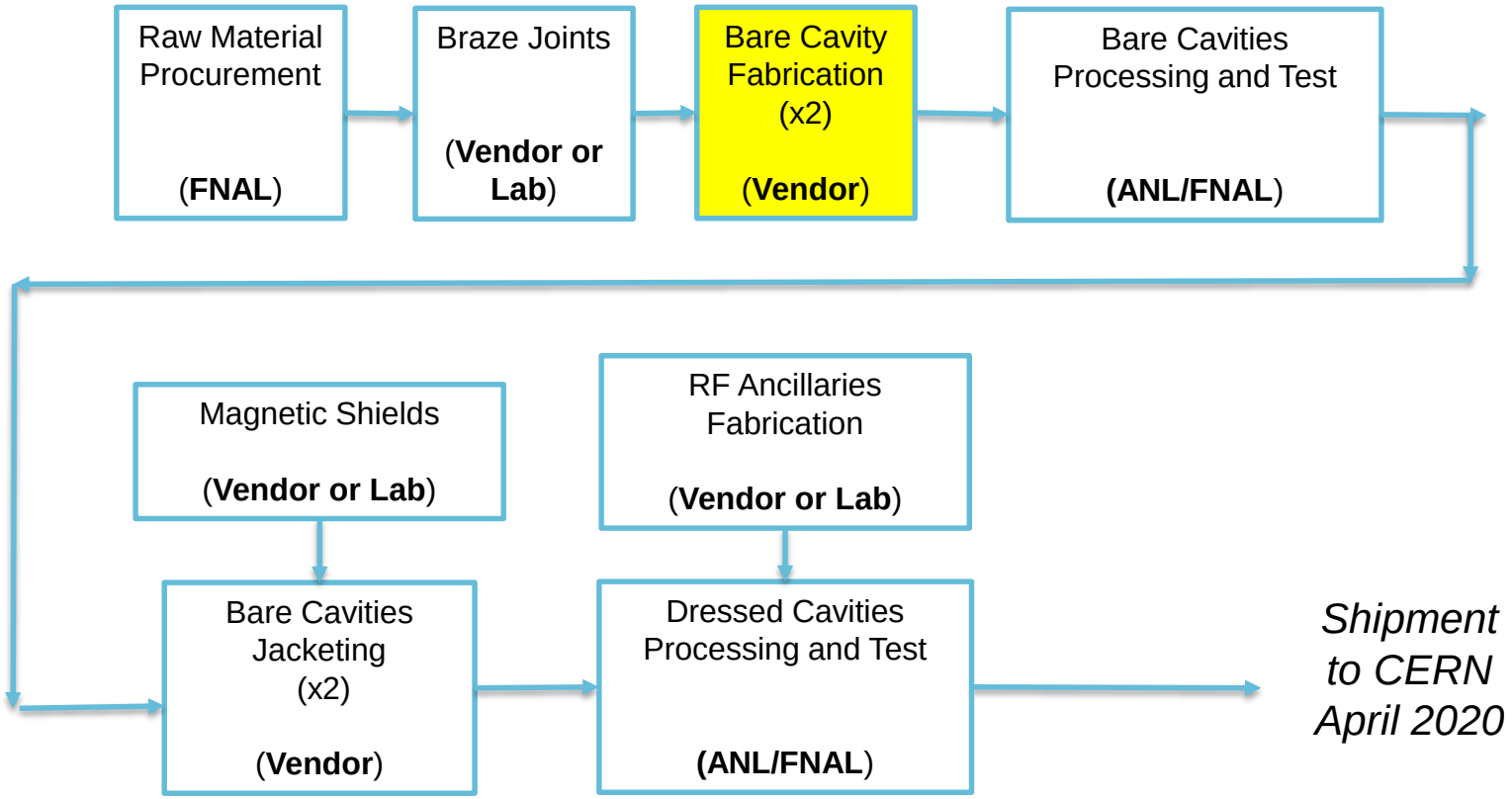
General Strategy – A Fresh Start

- The same model adopted for projects such as XFEL, LCLS-II, FRIB... will be followed.
  - Contracts managed by a laboratory, raw material inspected by laboratory, cavities built in industry (more in next slides) with heavy supervision, processing/testing in laboratory
  - The key aspect is: maximize direct control by the laboratory by placing direct contracts with industry
- Effort will be centralized at Fermilab
  - Leverage Fermilab SRF infrastructure and experience with other SRF cavity projects (ILC, LCLS-II, PIP-II, etc.)
  - All contracts (with industry and with other laboratories) will be managed through Fermilab procurement

Cavity Fabrication Strategy – Maximize Success

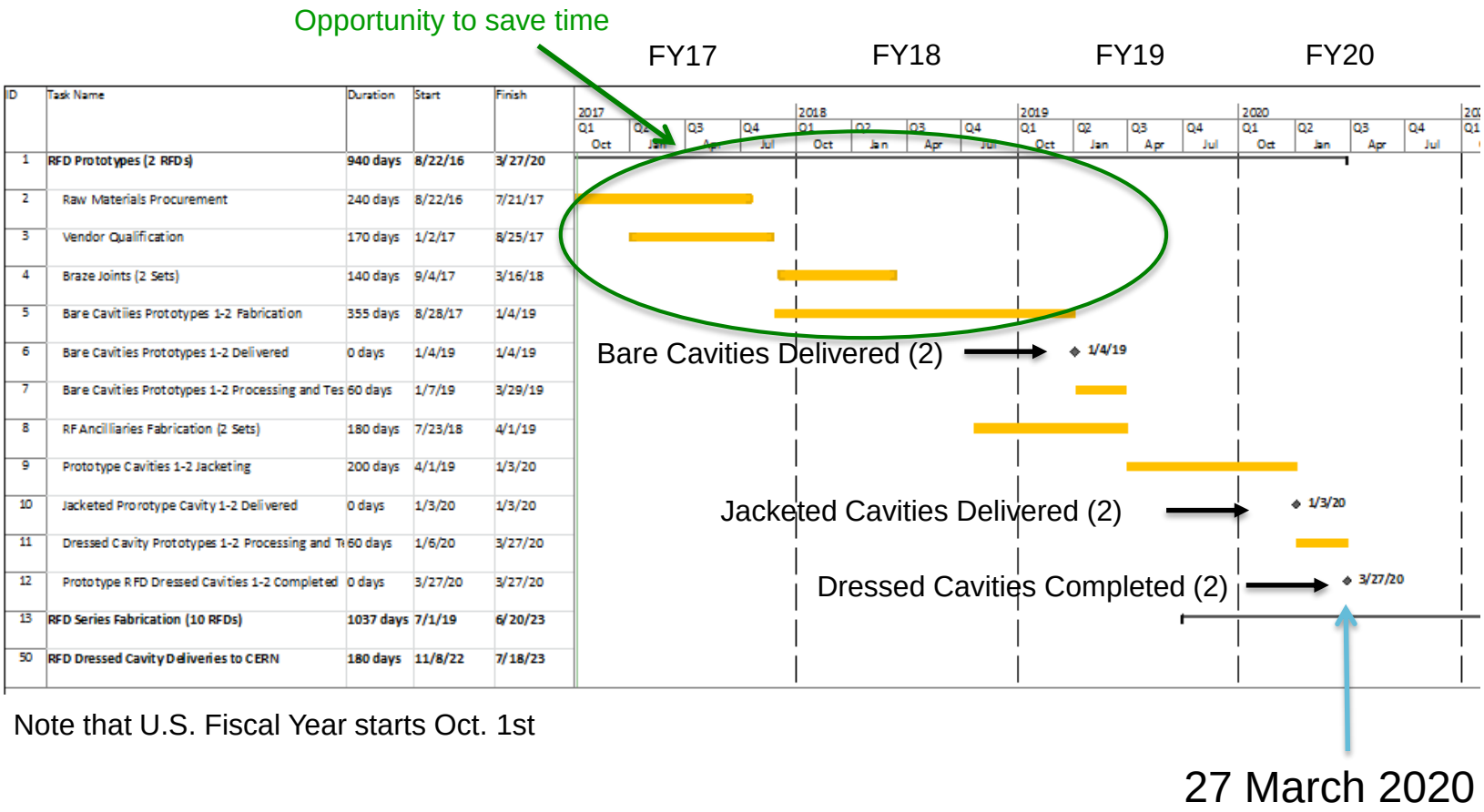
- Phases of Fabrication contracts:
  - Evaluate proposals and award (2, ideally 3) contracts only to suppliers meeting minimum requirements (**extensive and successful SRF experience**, existance of quality assurance system, acceptable proposal,....)
  - Fund initial development of representative samples for electron-beam welded joints of RFD cavity (qualification phase)
  - Down-select (1, ideally 2) based on quality of samples, quality of documentation, communications, and adherence to promised schedule
    - (CERN input is key in this phase, especially regarding quality assurance)
  - Fund fabrication of 1 cavity at each of 2 suppliers (ideal), or 2 cavities at one supplier.

RFD Prototypes Manufacturing Flow Plan



Although these cavities are considered HL-LHC prototypes, if the shipment can be anticipated, there would be an opportunity for installation in SPS (huge gain).

RFD HL-LHC Prototype Schedule



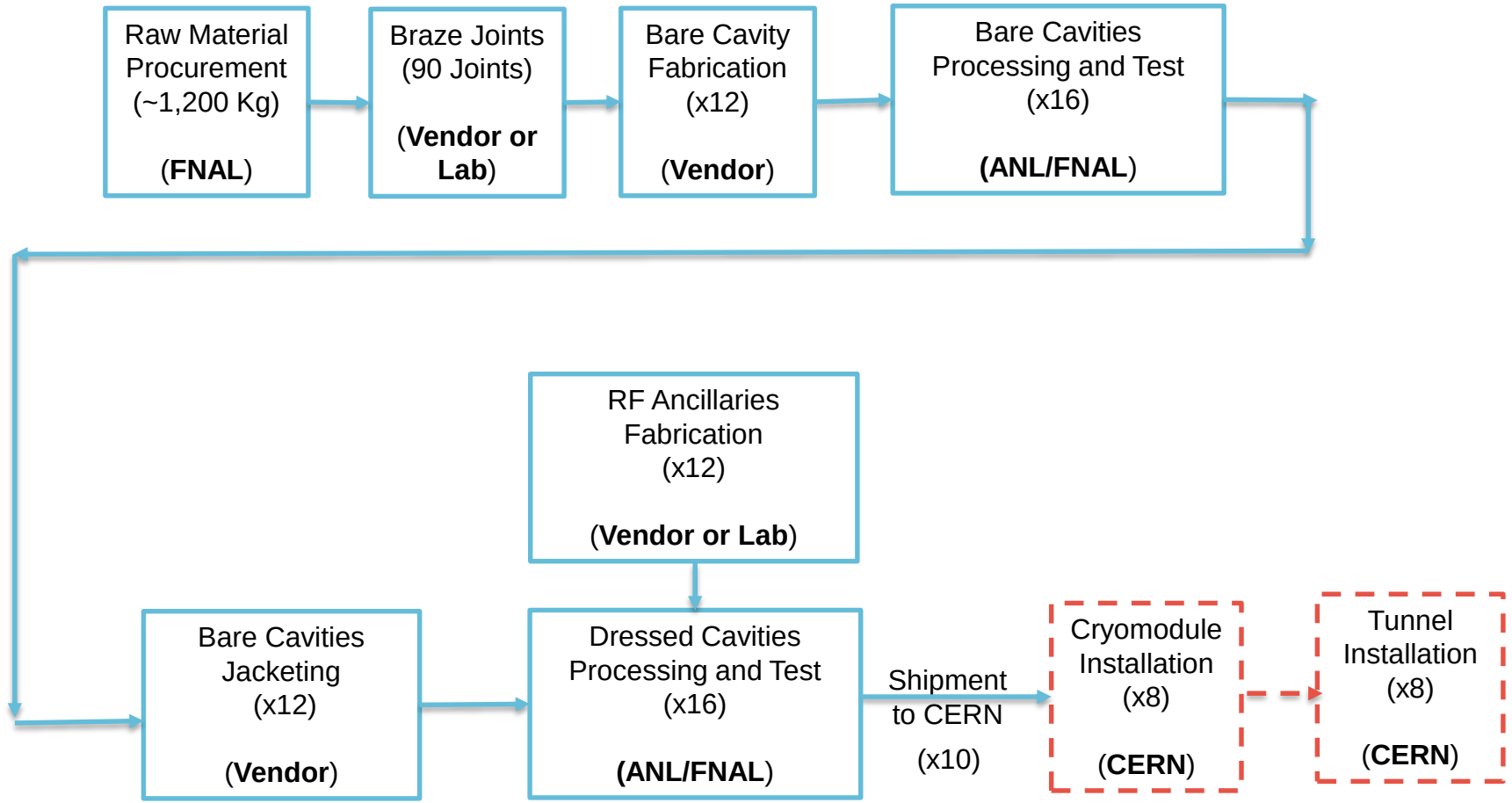
ID	Task Name	Duration	Start	Finish
1	**RFD Prototypes (2 RFDs)**	**940 days**	**8/22/16**	**3/27/20**
2	Raw Materials Procurement	240 days	8/22/16	7/21/17
3	Vendor Qualification	170 days	1/2/17	8/25/17
4	Braze Joints (2 Sets)	140 days	9/4/17	3/16/18
5	Bare Cavities Prototypes 1-2 Fabrication	355 days	8/28/17	1/4/19
6	Bare Cavities Prototypes 1-2 Delivered	0 days	1/4/19	1/4/19
7	Bare Cavities Prototypes 1-2 Processing and Tes	60 days	1/7/19	3/29/19
8	RF Ancilliaries Fabrication (2 Sets)	180 days	7/23/18	4/1/19
9	Prototype Cavities 1-2 Jacketing	200 days	4/1/19	1/3/20
10	Jacketed Prorotype Cavity 1-2 Delivered	0 days	1/3/20	1/3/20
11	Dressed Cavity Prototypes 1-2 Processing and Te	60 days	1/6/20	3/27/20
12	Prototype RFD Dressed Cavities 1-2 Completed	0 days	3/27/20	3/27/20
13	**RFD Series Fabrication (10 RFDs)**	**1037 days**	**7/1/19**	**6/20/23**
50	**RFD Dressed Cavity Deliveries to CERN**	**180 days**	**11/8/22**	**7/18/23**

Note that U.S. Fiscal Year starts Oct. 1st

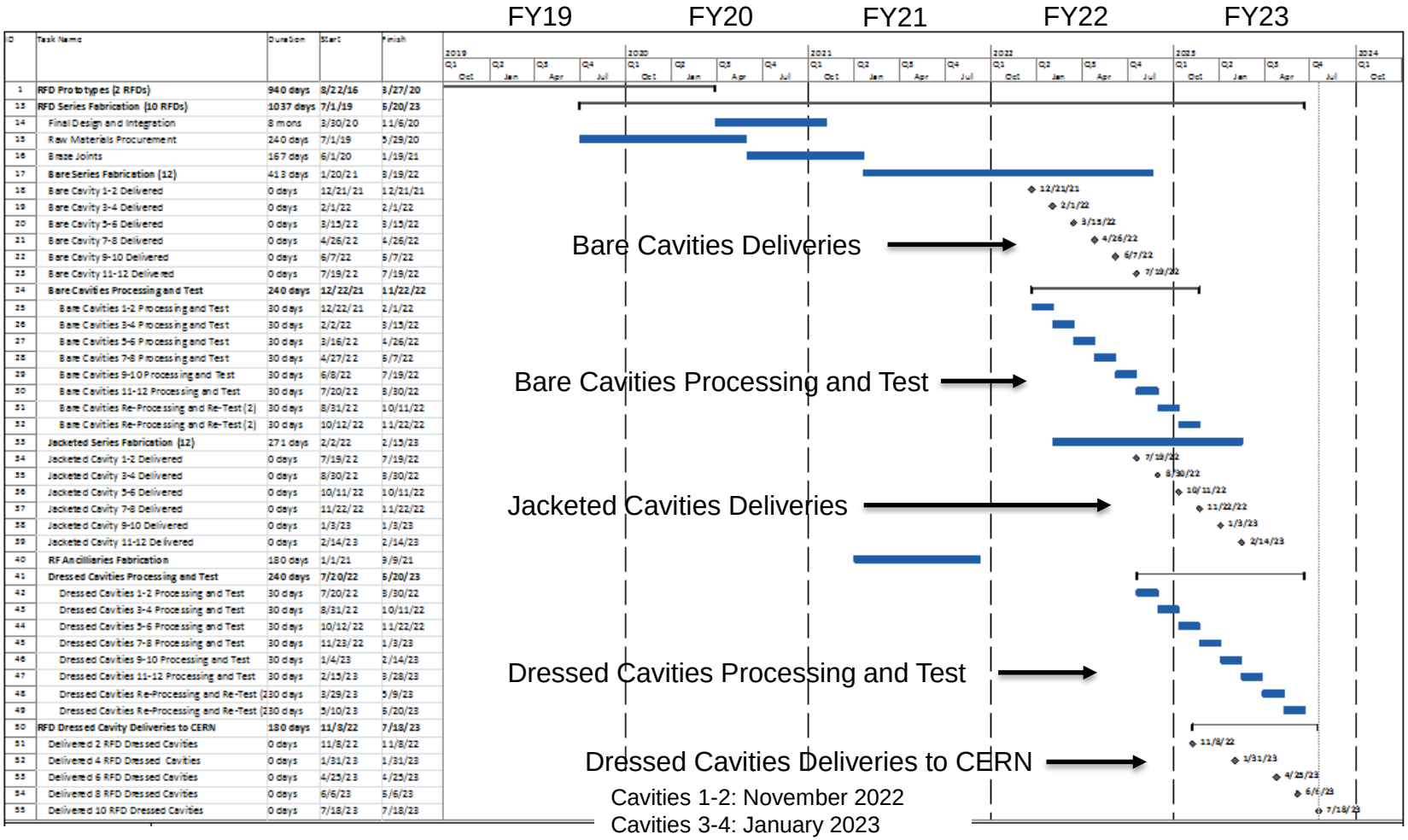
RFD HL-LHC Series Production

- To be funded entirely by the HL-LHC Accelerator Upgrade Project (AUP), an approved (CD-0) DOE 413.3b project with a Total Project Cost (TPC) budget of $200M (magnets + cavities).
- Vendor performance risk mitigated by prior vendor qualification steps and successful delivery of HL-LHC RFD bare and jacketed prototypes.
  - Same suppliers as prototypes
- Bare cavity production starts several months after HL-LHC RFD prototypes completion to allow feedback into final design.
- Assumptions on cavity ultimate yield (80%) and reprocessing rate (40%) included in project baseline plan.
  - 12 cavities will be manufactured to aim at qualification and shipment of 10 (8 + 2 spare)
- 8 RFD dressed cavities delivered to CERN by June-2023
  - 2 Spares to follow July 2023
  - This is the base schedule with no schedule contingency (float) added

RFD Production Manufacturing Flow Plan



HI-LHC RFD Series Production Schedule



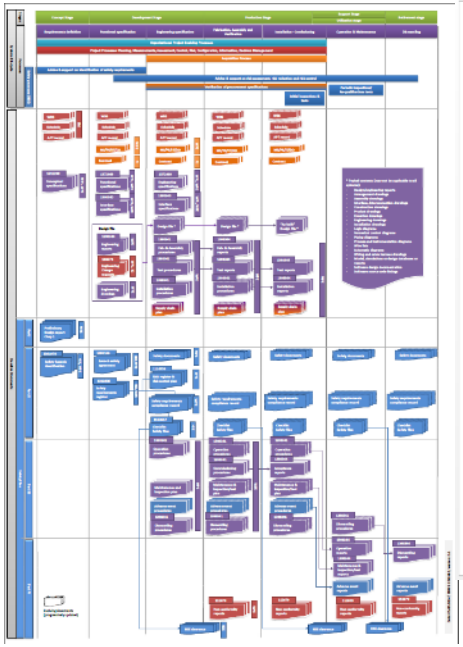
ID	Task Name	Duration	Start	Finish
1	**RFD Prototypes (2 RFDs)**	**940 days**	**8/22/16**	**3/27/20**
13	**RFD Series Fabrication (10 RFDs)**	**1037 days**	**7/1/19**	**5/20/23**
14	Final Design and Integration	8 mons	3/30/20	11/6/20
15	Raw Materials Procurement	240 days	7/1/19	5/29/20
16	Braze Joints	167 days	6/1/20	1/19/21
17	**Bare Series Fabrication (12)**	413 days	1/20/21	9/19/22
18	Bare Cavity 1-2 Delivered	0 days	12/21/21	12/21/21
19	Bare Cavity 3-4 Delivered	0 days	2/1/22	2/1/22
20	Bare Cavity 5-6 Delivered	0 days	3/15/22	3/15/22
21	Bare Cavity 7-8 Delivered	0 days	4/26/22	4/26/22
22	Bare Cavity 9-10 Delivered	0 days	6/7/22	6/7/22
23	Bare Cavity 11-12 Delivered	0 days	7/19/22	7/19/22
24	**Bare Cavities Processing and Test**	**240 days**	**12/22/21**	**11/22/22**
25	Bare Cavities 1-2 Processing and Test	30 days	12/22/21	2/1/22
26	Bare Cavities 3-4 Processing and Test	30 days	2/2/22	3/15/22
27	Bare Cavities 5-6 Processing and Test	30 days	3/16/22	4/26/22
28	Bare Cavities 7-8 Processing and Test	30 days	4/27/22	6/7/22
29	Bare Cavities 9-10 Processing and Test	30 days	6/8/22	7/19/22
30	Bare Cavities 11-12 Processing and Test	30 days	7/20/22	8/30/22
31	Bare Cavities Re-Processing and Re-Test (2)	30 days	8/31/22	10/11/22
32	Bare Cavities Re-Processing and Re-Test (2)	30 days	10/12/22	11/22/22
33	**Jacketed Series Fabrication (12)**	271 days	2/2/22	2/15/23
34	Jacketed Cavity 1-2 Delivered	0 days	7/19/22	7/19/22
35	Jacketed Cavity 3-4 Delivered	0 days	8/30/22	8/30/22
36	Jacketed Cavity 5-6 Delivered	0 days	10/11/22	10/11/22
37	Jacketed Cavity 7-8 Delivered	0 days	11/22/22	11/22/22
38	Jacketed Cavity 9-10 Delivered	0 days	1/3/23	1/3/23
39	Jacketed Cavity 11-12 Delivered	0 days	2/14/23	2/14/23
40	**RF Ancilliaries Fabrication**	180 days	1/1/21	9/9/21
41	**Dressed Cavities Processing and Test**	240 days	**7/20/22**	**6/20/23**
42	Dressed Cavities 1-2 Processing and Test	30 days	7/20/22	8/30/22
43	Dressed Cavities 3-4 Processing and Test	30 days	8/31/22	10/11/22
44	Dressed Cavities 5-6 Processing and Test	30 days	10/12/22	11/22/22
45	Dressed Cavities 7-8 Processing and Test	30 days	11/23/22	1/3/23
46	Dressed Cavities 9-10 Processing and Test	30 days	1/4/23	2/14/23
47	Dressed Cavities 11-12 Processing and Test	30 days	2/15/23	3/28/23
48	Dressed Cavities Re-Processing and Re-Test (2	30 days	3/29/23	5/9/23
49	Dressed Cavities Re-Processing and Re-Test (2	30 days	5/10/23	6/20/23
50	**RFD Dressed Cavity Deliveries to CERN**	**180 days**	**11/8/22**	**7/18/23**
51	Delivered 2 RFD Dressed Cavities	0 days	11/8/22	11/8/22
52	Delivered 4 RFD Dressed Cavities	0 days	1/31/23	1/31/23
53	Delivered 6 RFD Dressed Cavities	0 days	4/25/23	4/25/23
54	Delivered 8 RFD Dressed Cavities	0 days	6/6/23	6/6/23
55	Delivered 10 RFD Dressed Cavities	0 days	7/18/23	7/18/23

Cavities 1-2: November 2022
Cavities 3-4: January 2023
Cavities 5-6: April 2023
Cavities 7-8: June 2023
Cavities 9-10: July 2023

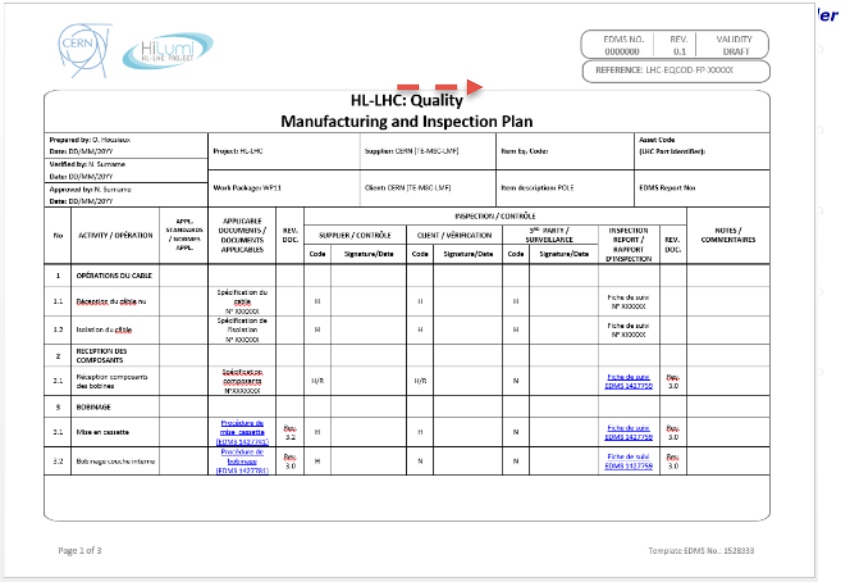
Quality Assurance

- U.S. RFD HL-LHC Cavity Deliverables will comply with CERN QA requirements
  - “Items” Baseline documentation in EDMS
  - “Assets” manufacturing data entered in MTF during manufacturing processes
    - Based on agreement (with WPL and WPE) of the “Manufacturing and Inspection Plan” (MIP), which includes major steps, associated procedures, and QC measurements

EDMS



MIP



HL-LHC: Quality
Manufacturing and Inspection Plan

MTF

er : Main Info

Equipment Identifier: HCMQXFC013-FL000001
Other Identifier: None
Description: Bare Coil

Main | Made of | Equipment data | Manufacturing | Operation | Documents | History | Map

Actions : Edit | View summary

Physical			
Manufacturer	FERMILAB		
Resp. Technique			
Status	Manufacturing		
Other Identifier			
Parent Equipment			
Parent Slot			
Location			
State	Good	MRC	M01
Safety			
RP Classification			
Comments			
Design			
Item in ARS	Bare Coil (ver.0)		
Audit			
Created on	2015-05-18	by	PAALVARE
Last modified on	2016-05-17	by	PAALVARE
EDMS owner	PAALVARE	EDMS group	HL-LHC-BARECOIL-MTF

Risk Management Plan

- Risk Management Plan Document (US-HiLumi DocDB #89) describes procedures for main processes:
  - Plan Risk Management
  - Identify Risks
  - Perform Qualitative Risk Analysis
  - Perform Quantitative Risk Analysis
  - Plan Risk Responses
  - Monitor and Control Risks
- Risk mitigation actions are part of the project baseline (scope, schedule, and cost)

	Negligible impact	Low impact	Medium impact	High impact
Technical	• Quality not affected	• Quality slightly below the required standard	• Quality moderately below the required standard	• Quality significantly below the required standard, or • KPP in jeopardy
Cost If Project TPC < 100M$	• 0.05% of TPC	• 0.05% – 0.5% of TPC	• 0.5% – 5% of TPC	• > 5% of TPC, or • Lack of funds halts Project
If Project TPC > 100M$	• < 50k$	• 50k$ – 500k$	• 500k$ – 5 M$, or	• > 5M$, or • Lack of funds halts Project
Schedule	• No schedule impact	• Critical path change of < 2 months, or • Tier-4 milestone (Project -owned) moves by > 1 month	• Crit 2-6 • Tie (FP mo	

Risk ID	Risk Owner	Risk Type	Risk Title	Risk Description	Detailed Risk Cause	Detailed Risk Effect	Initial Response Plan	Comments
		Threat	Cable loss	Cable loss due to LSNF, cabling machine failure during a cable run	The main concern for loss of a cable during a run is failure of a magnetic brake, or a mandrel to break.	Up to 1 RL of strand may be lost, resulting in a loss of up to TBD	failure of a magnetic brake has not happened recently at LBNL. The plan is to inspect magnetic brakes after every 8 runs (it takes two techs 2 days to remove the brakes from the spools, open the housings, inspect the permanent magnets inside, and re-mount them in the spools), and if necessary re-use magnetic brakes that have been used before and have been restacked to be of good quality. New brakes have been problematic in the past (cracked during operation because they were not sintered properly, producing free particles that would cause the brake to stop rotating). A 2nd mandrel will be fabricated and ready to install when the present mandrel has too much wear for access to check effects of fatigue. It takes 1-2 weeks to fabricate a mandrel by LSNL staff.	

Probability		Negligible impact	Low impact	Medium impact	High impact
Very High	64 - 100%	No rank	Medium rank	High rank	High rank
High	39 - 64%	No rank	Medium rank	High rank	High rank
Medium	21 - 39%	No rank	Low rank	Medium rank	High rank
Low	9 - 21%	No rank	Low rank	Medium rank	Medium rank
Very low	0 - 9%	No rank	Low rank	Low rank	Medium rank

Risk Mitigation Examples

- Cavity Vendor Performance: mitigated by funding type, vendor qualification-downselection process, and fabrication of cavity prototypes
- Technical Performance: assumes 12 dressed cavities will have to be fabricated to produce 10 acceptable products (~ 80% yield). Reprocessing rate is assumed to be 40%.
- Other Risks and their response plan are being identified in the project Risk Registry

If during project execution the yield turns out higher than assumed and adequate contingency is earned back, additional RFD spares could be delivered to CERN

Conclusions

- The scope of the U.S. contribution for HL-LHC Crab Cavities has been agreed: 10 “dressed” RFD Cavities
  - Preliminary U.S. bottoms-up cost estimate shows this scope would fit within the U.S. HL-LHC Accelerator Upgrade Project total budget
  - Funding profile matching is in progress (needs coordination with Q1/Q3 magnet scope, the major U.S. contribution for HL-LHC)
- Construction of four U.S. RFD and DQW SPS prototypes will be completed by mid-2017, but these cavities are not expected to go into the SPS tunnel
  - Nonconformities within the framework of an SBIR-funded work
  - Provide useful experience and “lessons learned” for HL-LHC cavities
- The U.S. is planning to fabricate 2 RFD HL-LHC prototypes by mid-2020, funded by LARP and managed at Fermilab
  - Vendor qualification-downselection is fundamental aspect
- The U.S. is planning to fabricate 12 RFD HL-LHC series production and deliver 10 qualified cavities to CERN by mid-2023, funded by the approved DOE 413.3b project “HL-LHC Accelerator Upgrade” and managed at Fermilab