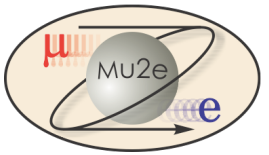
Fermilab

U.S. DEPARTMENT OF ENERGY Office of Science

Delivery Ring RF 475.02.06
Mu2e CD-2 Review



Joseph E. Dey
L3 Manager
7/8/2014

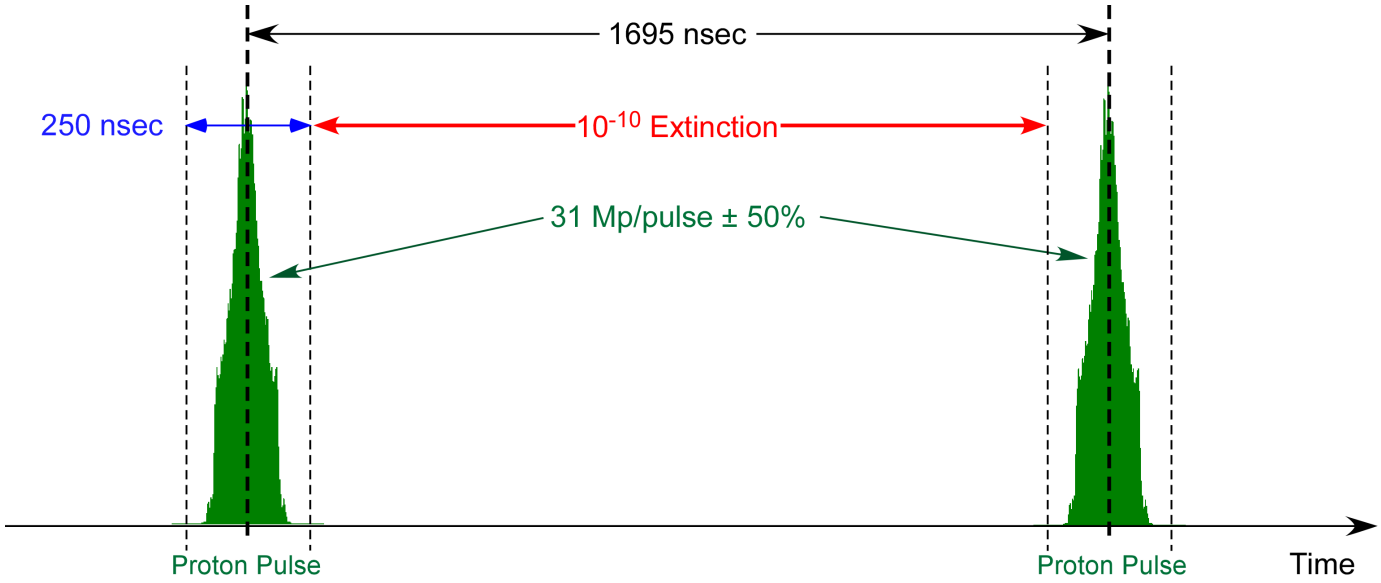
WBS 475.02.06 Delivery Ring RF

- The Delivery Ring's 2.4 MHz RF systems purpose is to produce an efficient transfer of beam from Recycler and to preserve a 250 ns bunch structure in the Delivery Ring.

Proton Beam Requirements

The bunch length requirement is primarily accomplished by the Recycler Ring 2.5 MHz RF system (Recycler AIP).

The function of the Delivery Ring 2.4 MHz RF system is to preserve the narrow bunch width received from the Recycler.



The g-2 experiment uses the same Recycler 2.5 MHz system for their bunch formation.

Since the g-2 requirements are more severe than those of Mu2e, the system will meet the needs of Mu2e.

Bunch Length Requirements Full width	
Mu2e	g-2
250 nsec	149 nsec

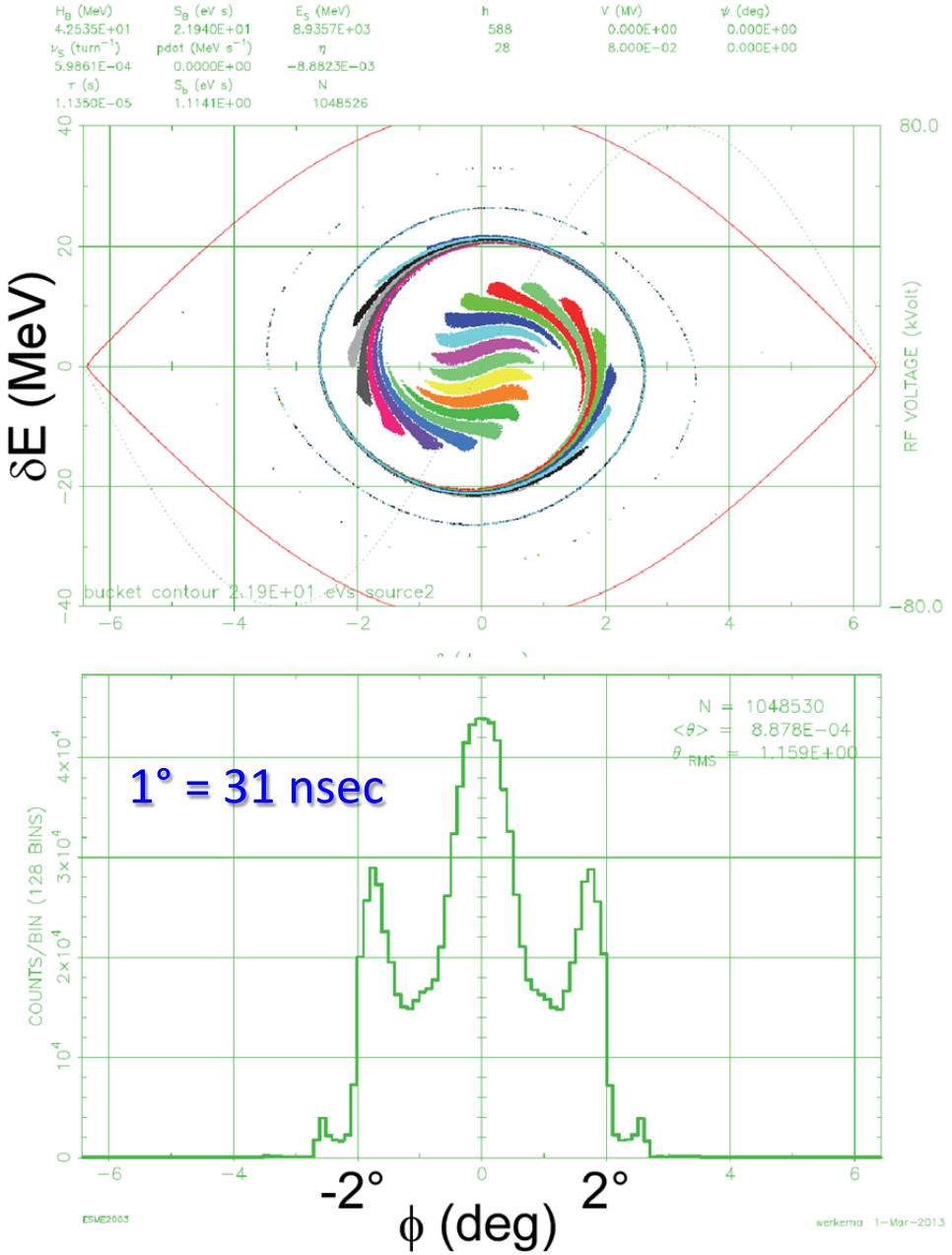
Recycler Bunch Formation

Recycler bunch shape

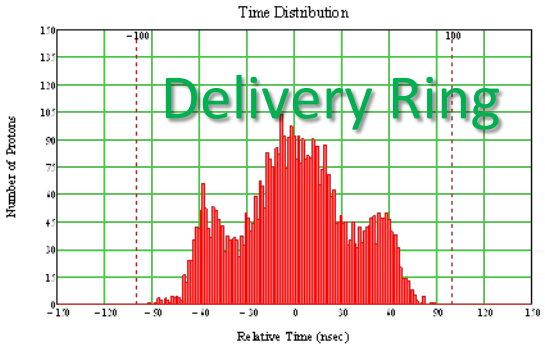
The 53 MHz bunched beam from the Booster Synchrotron is re-bunched with the 2.5 MHz RF system in the Recycler.

This re-bunching cycle requires 90 msec. At the end of this time, the Recycler beam consists of four bunches that occupy 1/7 of the circumference of the Recycler Ring.

This beam is extracted one bunch at a time to the Delivery Ring.

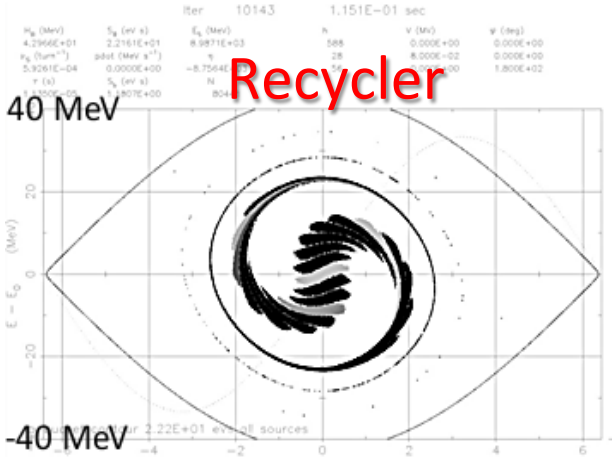


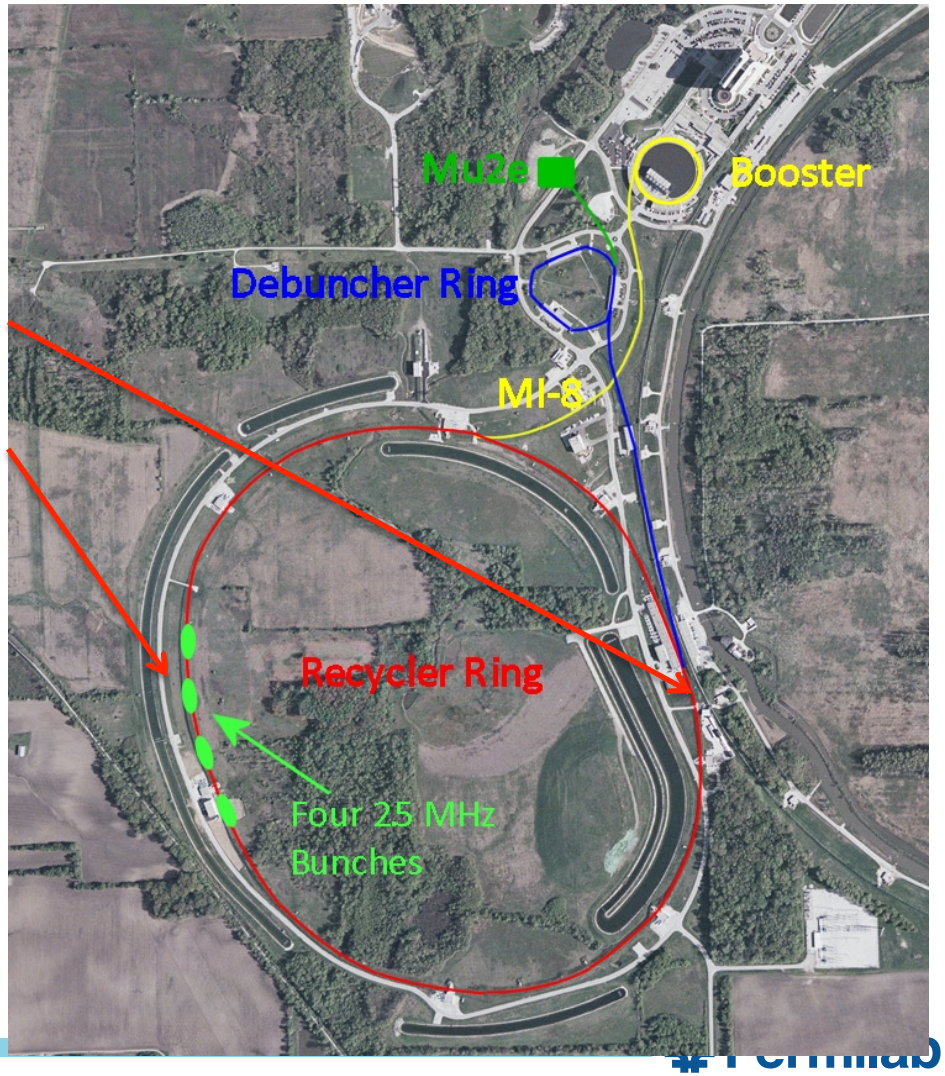
Big Picture Conceptual Design



Single bunch extraction

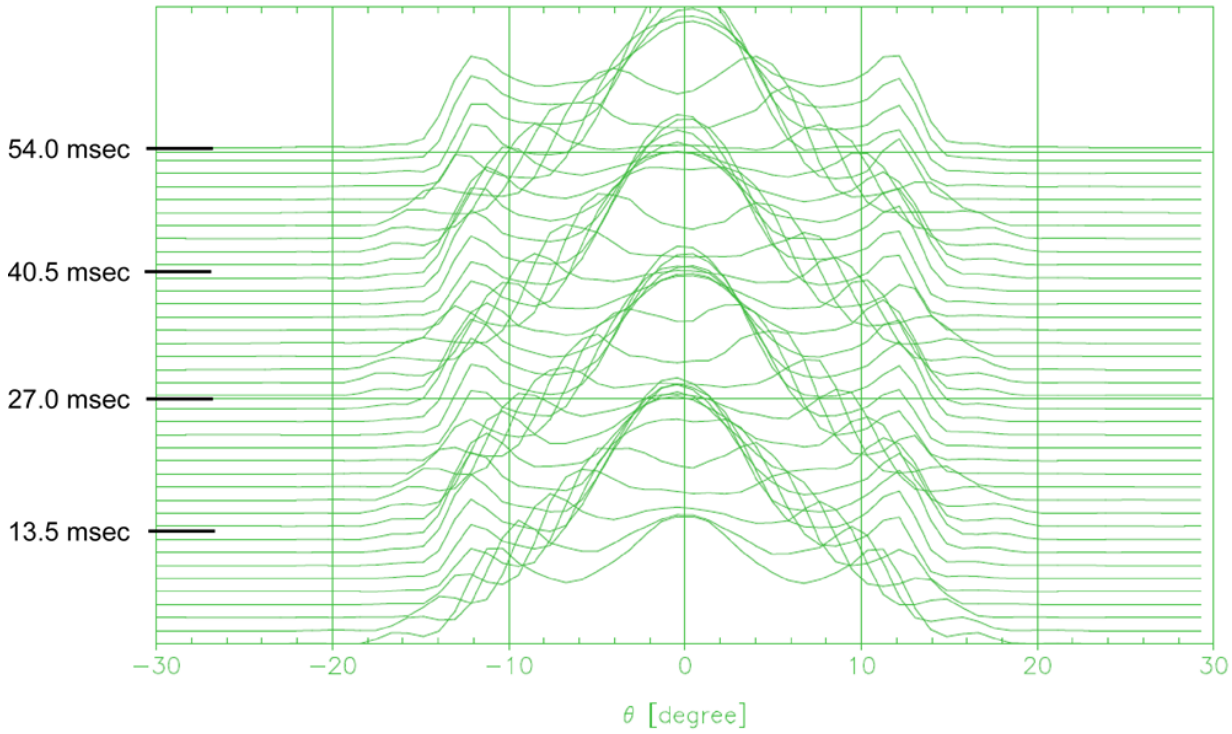
After bunch formation
(Δt_{FW} < 200 nsec)





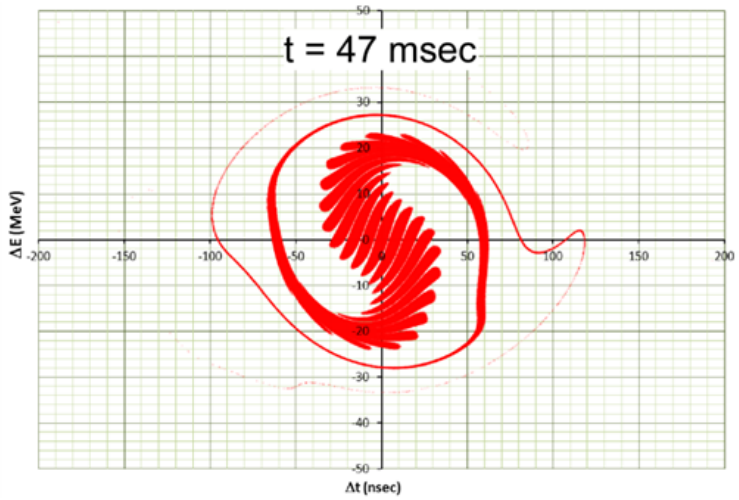
Bunch Shape Time Variation

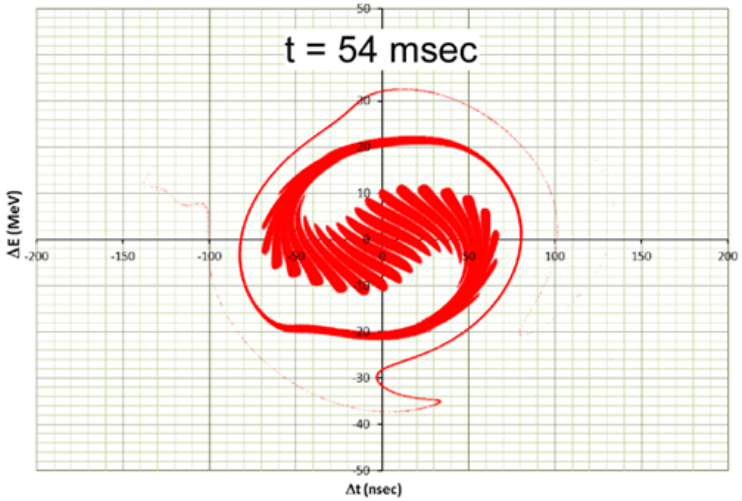
The re-bunched beam from the Recycler is poorly matched to the 2.4 MHz RF bucket in the Delivery Ring. Thus, the beam tumbles in the bucket. The bunch shape changes at twice the synchrotron frequency (T_{synch} = 25.6 msec).



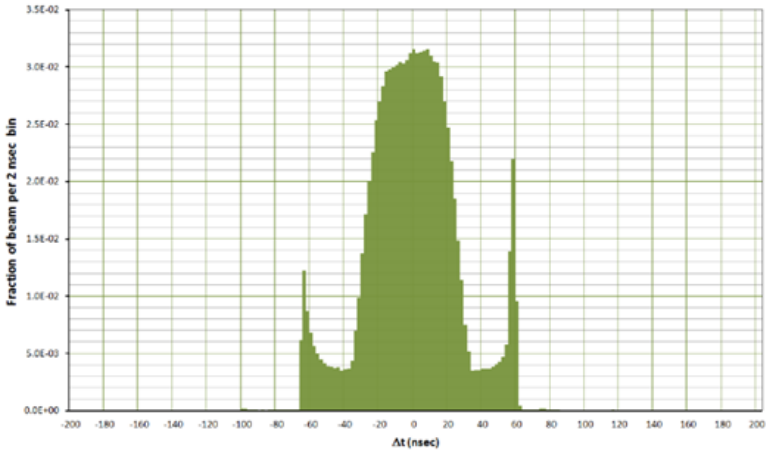
Waterfall display of the variation of the proton bunch time profile as the bunch rotates in the 2.4 MHz RF bucket. A trace is plotted every 1.35 msec over the course of the spill. The vertical axis is time relative to the start of the spill. The horizontal axis is Delivery Ring phase (1° = 4.708 nsec).

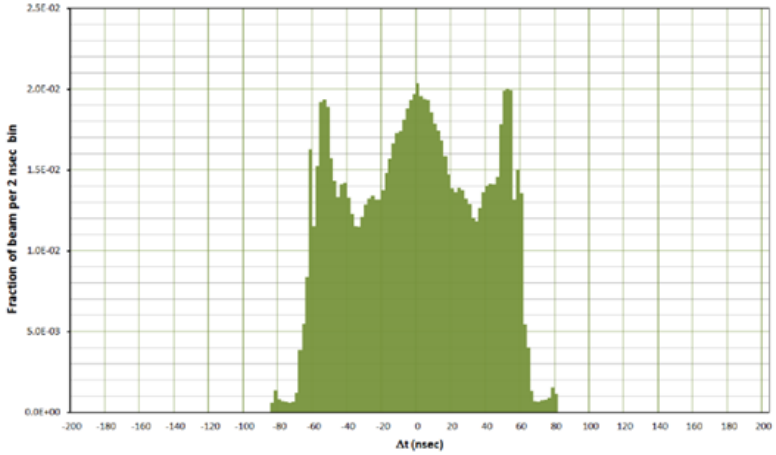
Bunch Shape Time Variation





ΔE vs. Δt



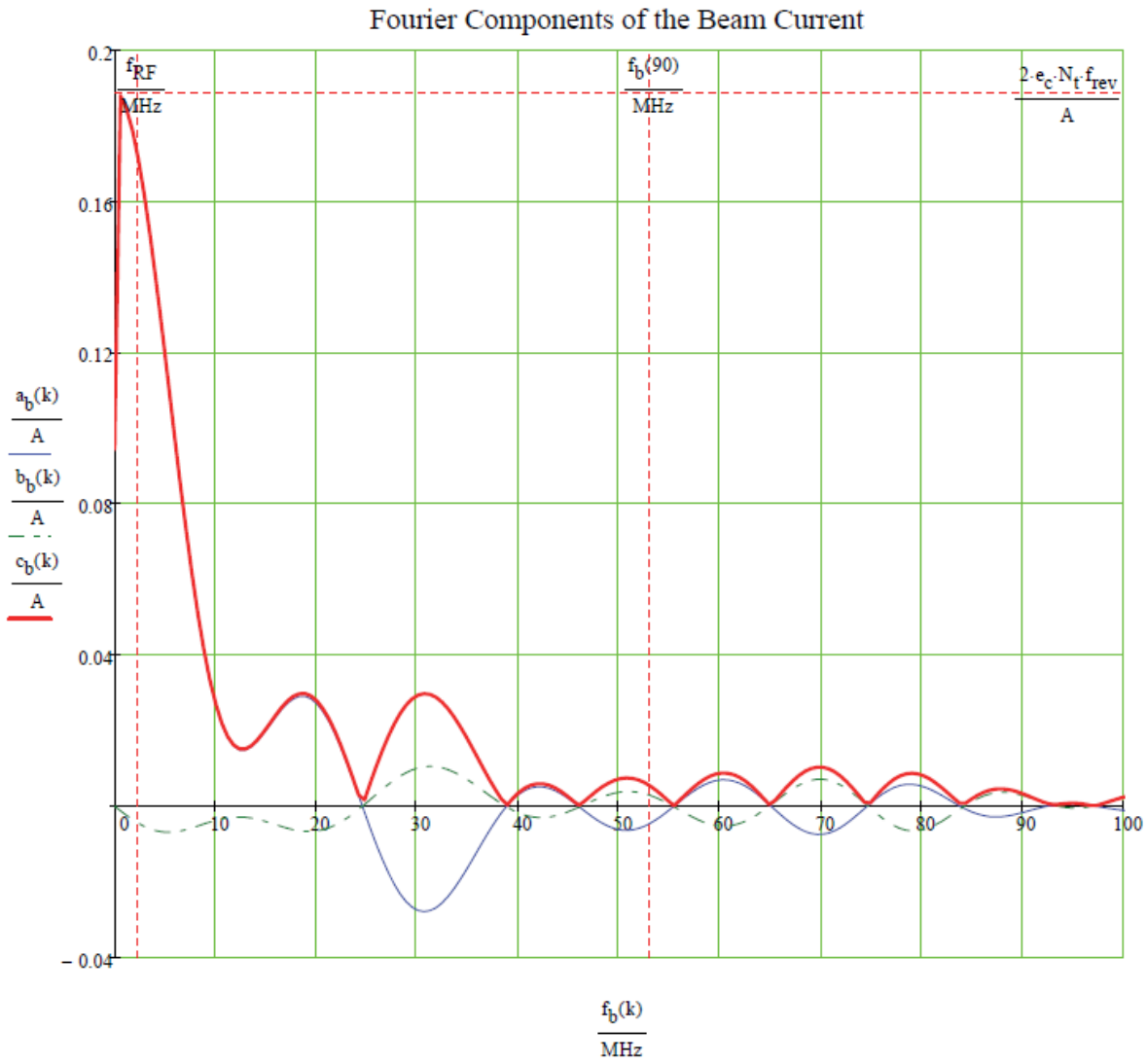


Bunch time distribution

Fourier Components of the Beam

1×10^{12} protons
Single Bunch
ESME Simulation

$a_b(k)$ = cosine amplitudes
$b_b(k)$ = sine amplitudes
$c_b(k)$ = overall magnitude



Requirements

Parameter	Value	Units
Harmonic Number	4	
Frequency	2.360	MHz
Peak Total Voltage	10	kV
Number of Cavities	1	
R/Q	400	Ω
Q	125	
Duty Factor	100	%

Requirements

Beam Current (Ip) = 178.564×10^{-3} A

Number of Cavities = 1

R/Q = 400 Ω

Q = 125

Cavity Voltage = 10.0 kV

Cavity Power Loss per Cavity = $1. \times 10^{3}$ W

Total Apparent Power = 1.04858×10^{3} VA ∠ 17.5089 degrees

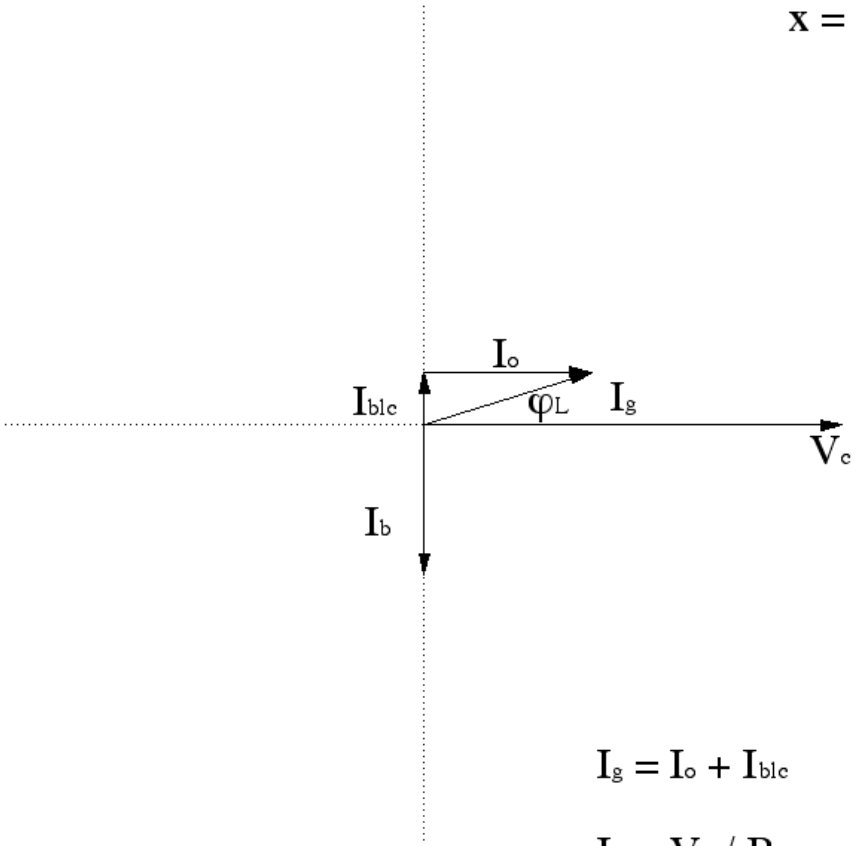
Total Current = 209.716×10^{-3} A ∠ 17.5089 degrees

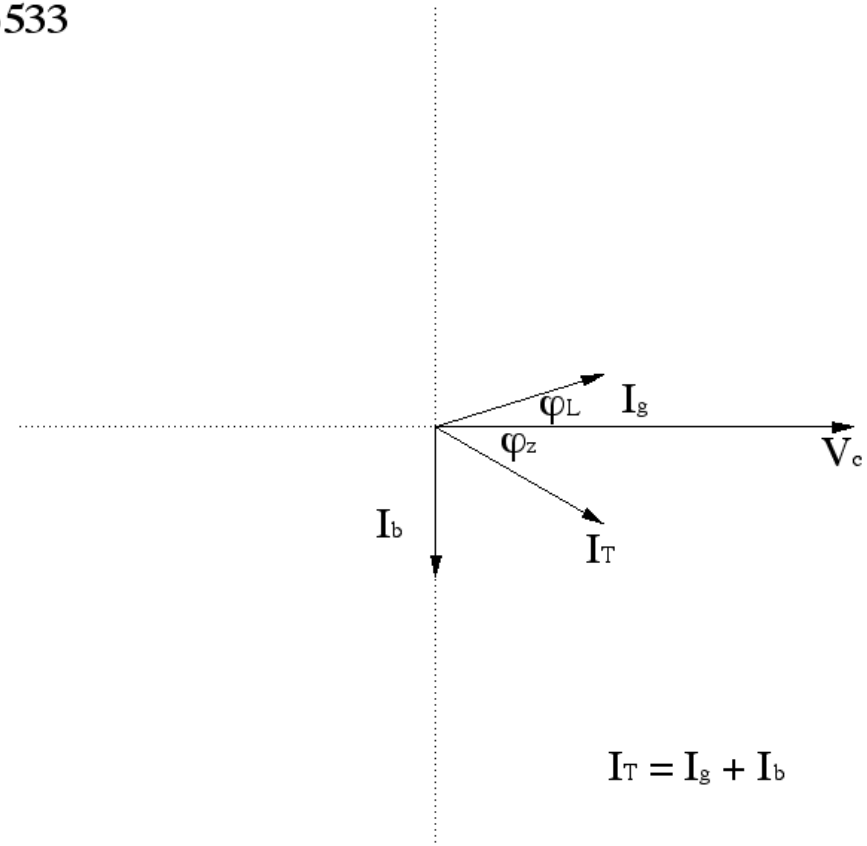
Percent of Induced Mode Compensated = 3.78649 dB = 35.3341 %

Robinson Stable = 4.

Requirements

Robinson Stable = 4.00
35.33% Beam Loading Compensation
x = 0.3533





$I_g = I_o + I_{blc}$

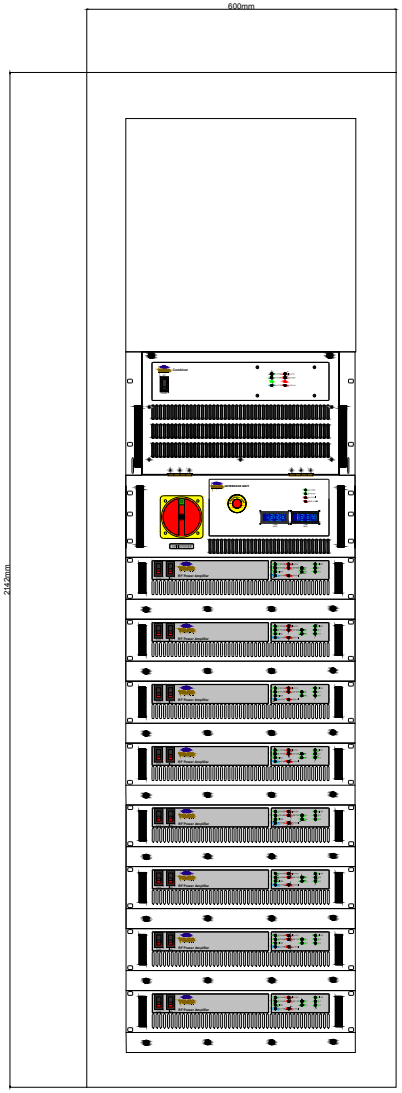
$I_o = V_c / R$

$I_{blc} = j \times I_b$

$I_T = I_g + I_b$

Design - Delivery Ring 2.4 MHz RF

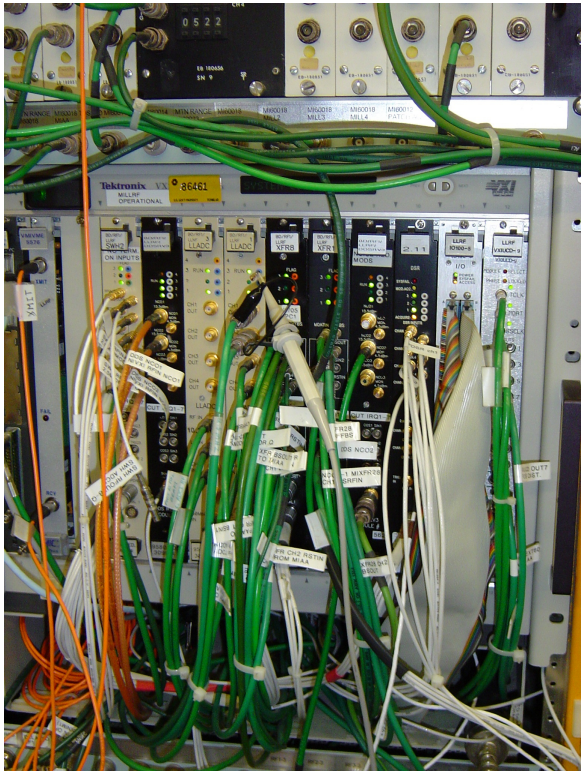
Purchase an
8 kW 2.5 MHz
Solid State Amplifier
to Drive the Cavity
Provided by the
Recycler RF AIP



Performance – Delivery Ring 2.4 MHz RF

- An 8 kW Solid State Amplifier will leave plenty of overhead for operation.
- We will be able to easily accomplish Direct RF Feedback and Feedforward Beam Loading Compensation using a Solid State Amplifier.
- Water Cooling is key to overall reliability of operation.

Design – Low Level RF System



Main Injector VXI Controlled
Low Level RF

Design – Low Level RF System

I6 VXI LLRF Novice Mode (most restrictive) 27-MAR-12 14:06:53 ◆Pgm_Tools◆

SEQUENCE TABLE VIEWER | CURVES | ARRAYS | required data

Sequence Table View

HrdwrID: [MILLRF] *Send To Hardware *Refresh *Save To Database

MI State: [4 150 GEV Collider Protons to Tevatron (operational)] Current state: 13

ROW	TYPE	SIGNAL	MESSAGE	DATUM1	DATUM2	DATUM3	DATUM4
0	Event	AnyReset	EnergyStepToFset	52811400			
1	Continue		XfrSyncMItoBooster	2	14	-37	
2	Continue		SetPhisFrontEndAtten	24	18		
3	Continue		EnergyArmATC	0	3047700		
4	Continue		V588 Feedback	ON	10	10	
5	Continue		QdotfbOn			0	8Gev LPF
6	Continue		SetRposGain	0 db			
7	EventX3	BooPInject	XfrSyncBoosterToMI	◆Popup List◆	◆Popup List◆	◆Popup List◆	
10	Delay	0.4508999884	EnergyQrpfb	-15	-30000	.255	All DSR
11	Continue		AlignH28RF2	16.865			
12	Delay	1.5400099754	EnergyQrpfb	-2	-3000	.08	All DSR
13	Delay	1.5700000525	QdotfbOn			0	120Gev LPF
14	Delay	1.5980000496	QdotFbOff				
15	Continue		QcpFwa	1	Tev Control		
16	Continue						
17	Delay	1.6152998209					
18	Continue		V28sbcSet	0	50.5	0	
19	Continue		Delay	usec	1		
20	Continue		Delay	usec	1		
21	Continue		V588Set	All Off	0	0	Tev Control
22	Delay	1.6599999666	V588Apg(t)Curve	All On		.001	Tev Control
23	Delay	1.6699999571	V28sbcSet	0	0	.0014	
24	Continue		QdotfbOn			.5	120Gev LPF
25	Delay	1.7549999952	SetLogReports	Minimum			
26	Continue						
27	Delay	1.9000098705	QscpUpdate	550			
28	Continue		QscpPlay	550	.42	0	adiabatic
29	Continue		XfrCogToTevatron			-40	
30	Event	EndCycle					
31							

Main Injector VXI Low Level RF Console Application

Performance – Low Level RF System

- In using an embedded system LLRF, we will be able easily accommodate studies and modify operations as needed.
- The LLRF system will be very similar to the existing Main Injector and Recycler LLRF systems.
- In using a Console Application, one will be able to access the Delivery Ring RF from any Console onsite.
- State of the art embedded systems hardware will be used for this design.

Changes since CD-1

- The 8 kW Solid State Driver was switched from an in-house design to an outside vendor's product.

Value Engineering since CD-1

- A budgetary quote was completed for the procurement of the 2.4 MHz 8 kW Solid State Amplifiers.
- In doing this we were able to lower the overall cost of the Solid State Amplifiers by going from an in-house design to purchasing from a vendor.
- M&S went up from $183,400 (30%) to $334,600 (10%), but labor went down from 3,441 hours (25%) to 320 hours (25%.)

Organizational Breakdown

- Low Level RF System – 475.02.06.01
  Engineers – Brian Chase, Ed Cullerton, Philip Varghes
  Technician – Dan Klepec

- Delivery Ring RF Studies & Tuning – 475.02.06.02
  Steve Werkema, Dave Peterson,
  Dave Vander Meulen and Joe Dey

- Delivery Ring RF System Cooling – 475.02.06.03
  Engineers – Maurice Ball and Dave Hixson
  Technicians – Mechanical Support Water Technicians

Organizational Breakdown

- Delivery Ring 2.4 MHz RF -475.02.06.04

  Engineers – Joe Dey, Dave Peterson and Christine Ader

  Technicians – Pete Seifrid, and Wes Mueller

Quality Assurance

- Delivery Ring 2.4 MHz RF – Testing of the 8 kW 2.4 MHz Solid State Driver (47502.06.04.001320) against the Delivery Ring 8 kW 2.4 MHz Solid State Driver Electrical Specifications (Mu2e-doc-4333) will be done.
- Low Level RF System – Will have been completely bench tested and documented before being released to the project.

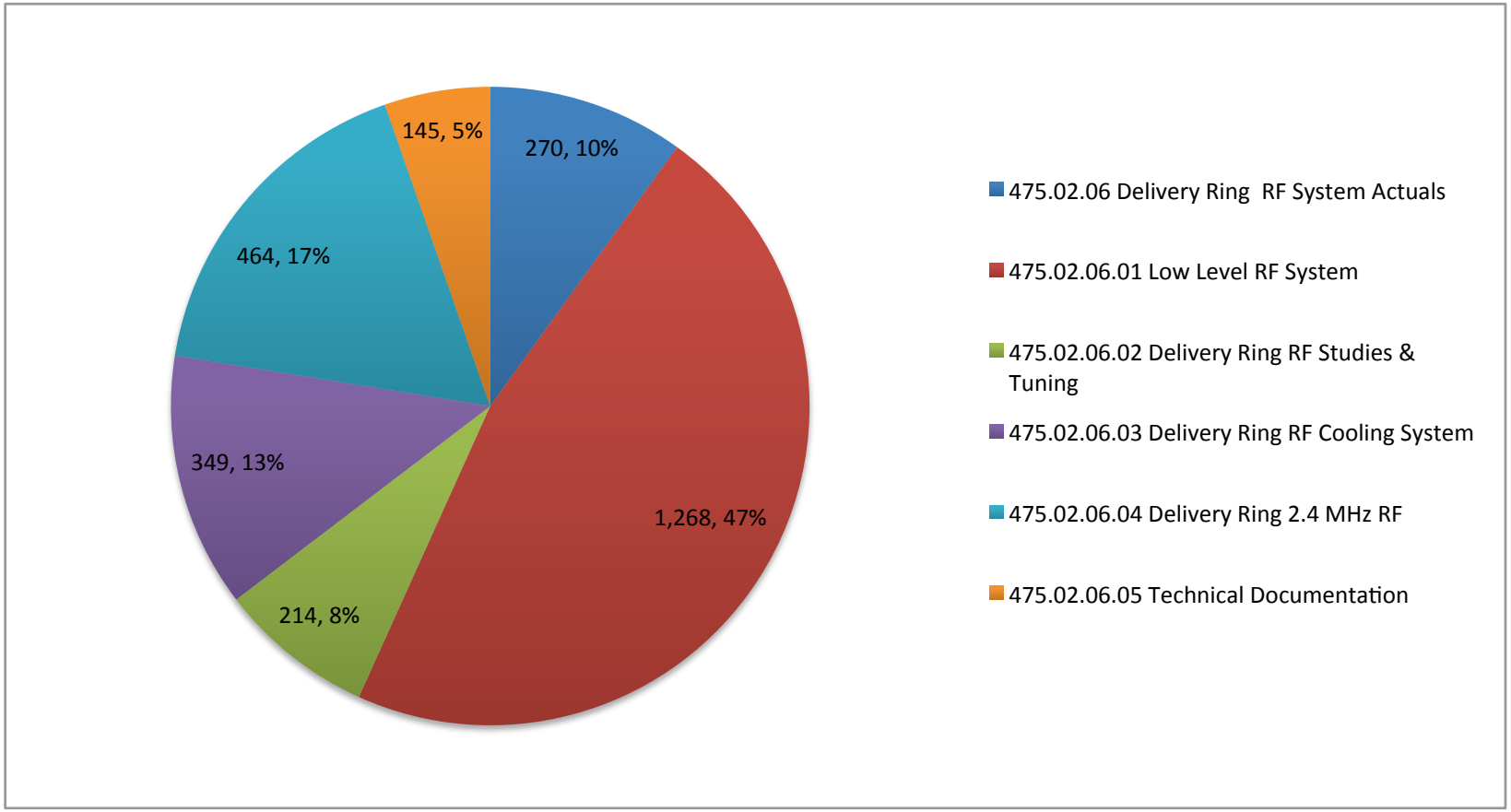
Risks

- Risks from TDR
- Low Level RF System – The risk here will be in how much of the existing LLRF software code can be repurposed for the Delivery Ring's new Hardware.
- Delivery Ring RF Studies & Tuning – No risks are noted here.
- Delivery Ring RF Cooling System – A nearly identical RF cooling system will be implemented for Recycler well in advance of the Delivery Ring's. No risks are noted here.
- **Additional Risk that we are considering because of Budgetary Quote.**
- **Delivery Ring 2.4 MHz RF – The risk here is if the vendor of the 8 kW Solid State Driver can deliver their product within the time frame quoted.**

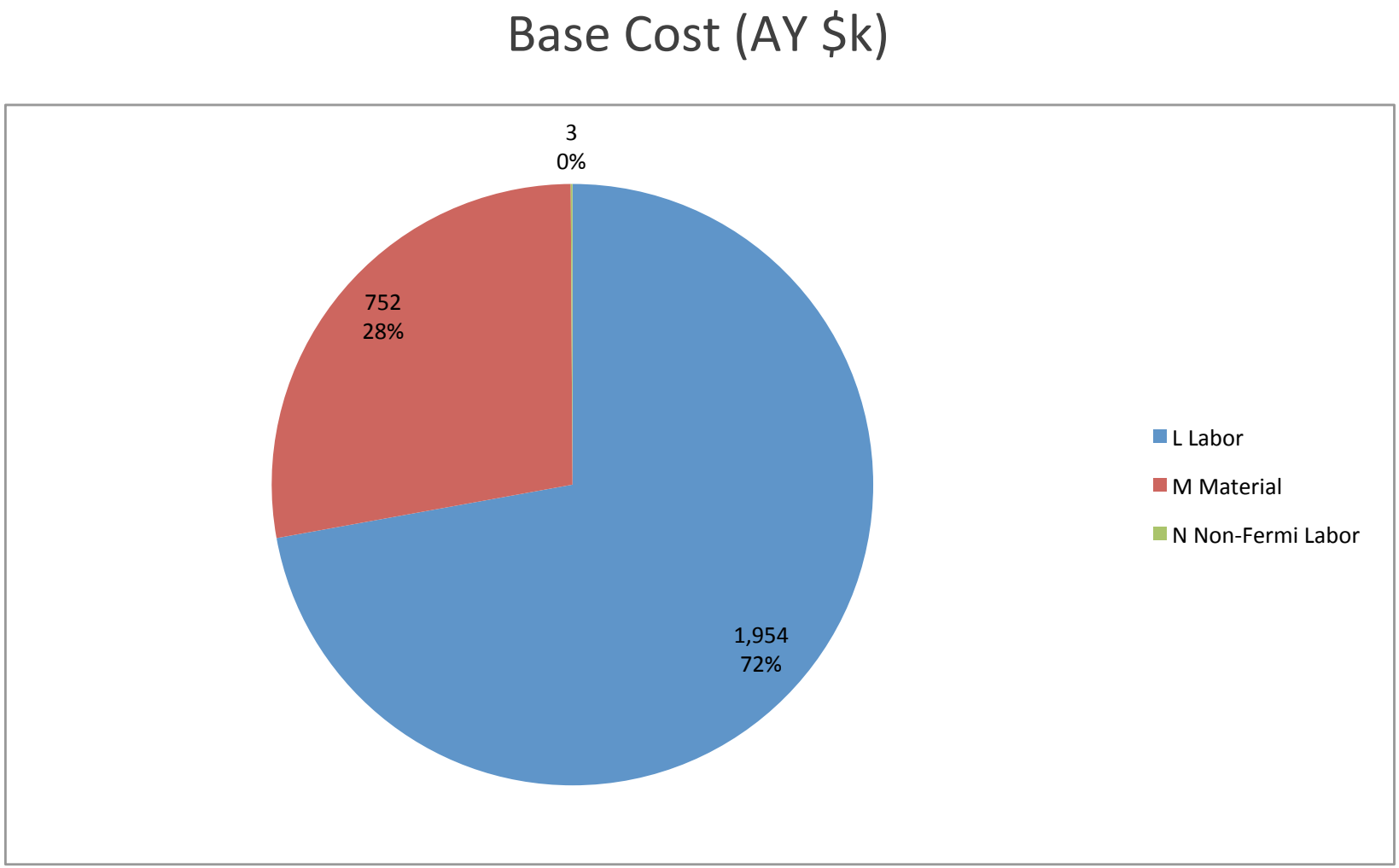
ES&H

- LOTO procedures will be written for the Operation of the Delivery Ring High Level RF and for the Delivery Ring RF Cooling System.

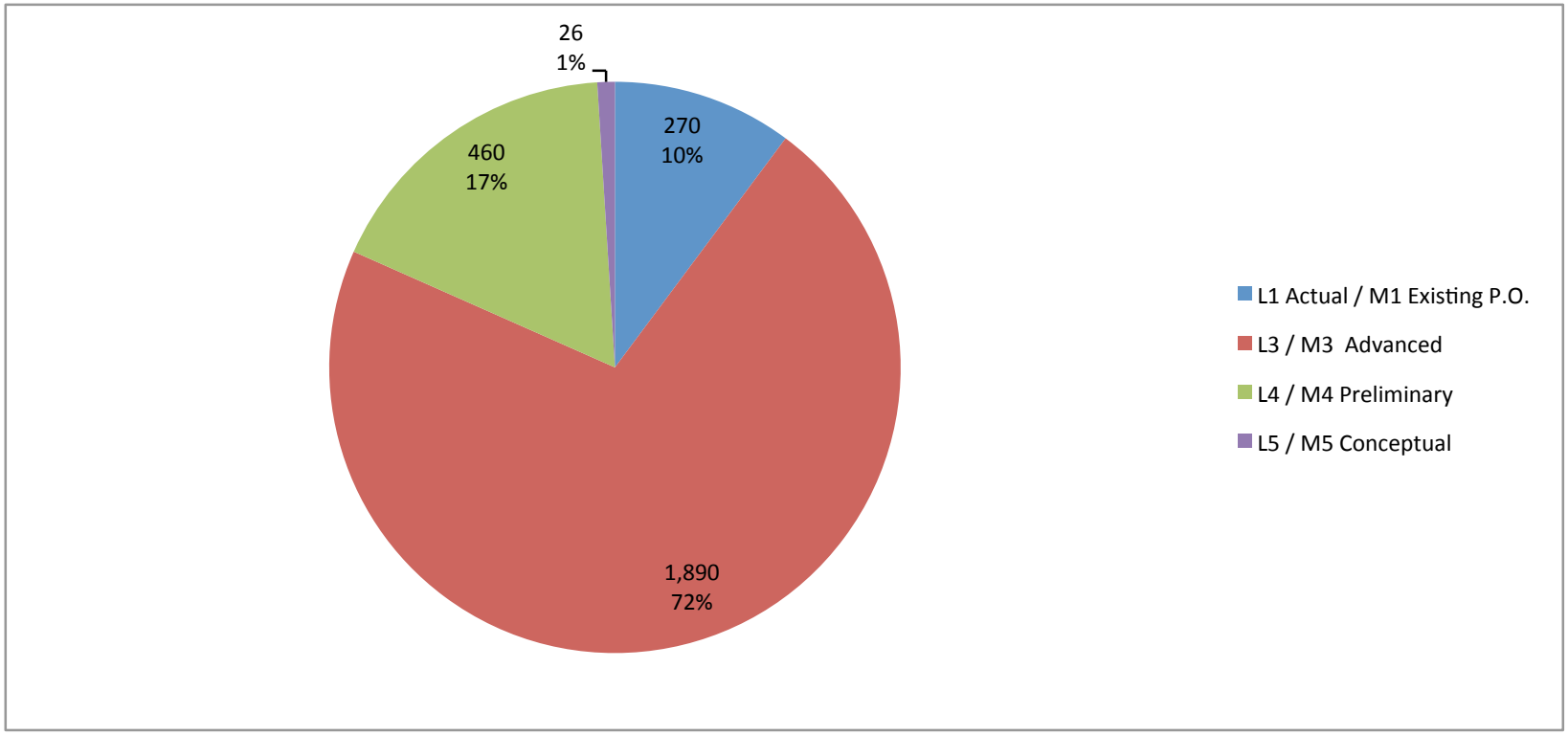
Cost Distribution by L4



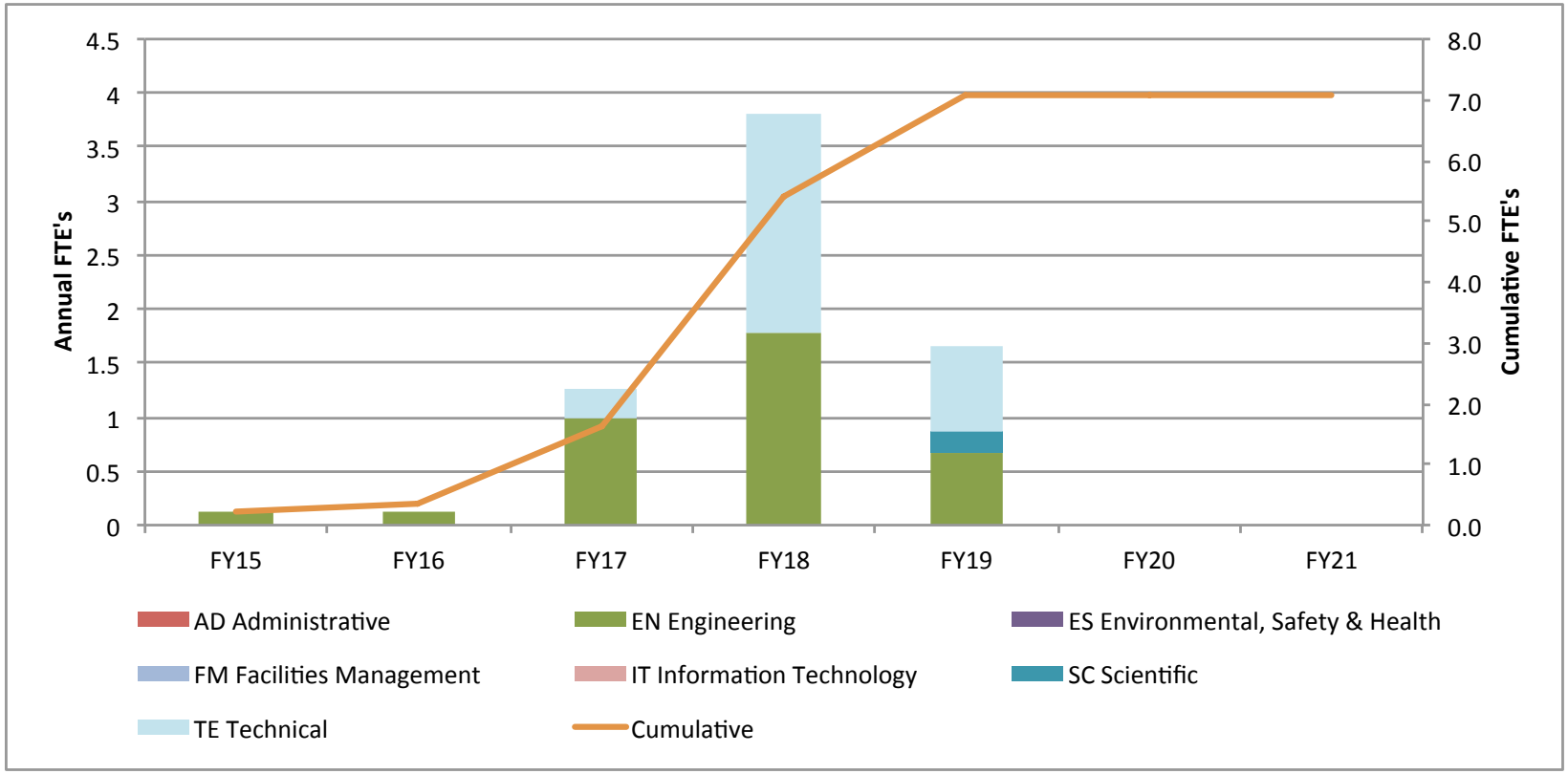
Cost Distribution by Resource Type



Quality of Estimate



Labor Resources



Cost Table

WBS 2.6 Delivery Ring RF

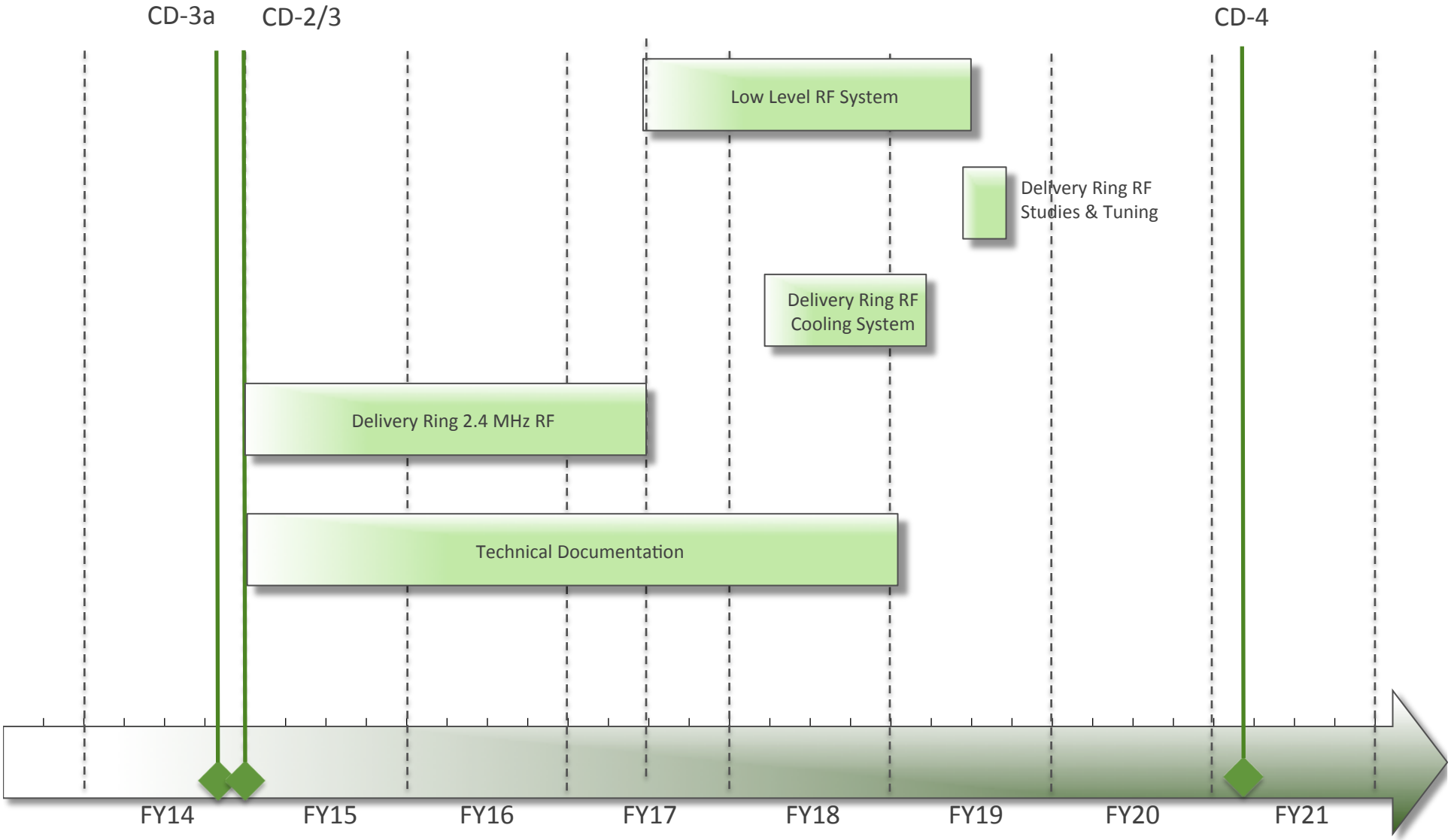
Costs are fully burdened in AY $k

	M&S	Labor	BAC	Estimate Uncertainty	% contingency on ETC	Total
475.02.06 Actuals		270	270			270
475.02.06.01 Low Level RF System	88	1,180	1,268	322	25%	1,590
475.02.06.02 Delivery Ring RF Studies & Tuning		214	214	53	25%	267
475.02.06.03 Delivery Ring RF Cooling System	185	164	349	105	30%	454
475.02.06.04 Delivery Ring 2.4 MHz RF	335	128	464	55	12%	519
475.02.06.05 Technical Documentation		145	145	29	21%	174
Grand Total	**609**	**2,100**	**2,709**	**565**	**23%**	**3,273**

Major Milestones

Activity ID	Milestone Name	Milestone Description	Milestone Date
47502.06.04.001440	Delivery Ring 8kW 2.4 MHz solid state driver RF testing complete	Post-installation testing and commissioning of the Delivery Ring 2.4 MHz RF high level system complete.	October 13,2015
47502.06.04.001230	Delivery Ring 2.4 MHz RF Installation Complete	Procurement, assembly and installation of the Delivery Ring 2.4 MHz RF high level system complete.	November 3, 2016
47502.06.03.001060	Delivery Ring RF Cooling Systems Complete	Fabrication and installation of the cooling system for Delivery Ring 2.4 MHz RF complete	October 12, 2018
47502.06.1020	Delivery Ring RF System Complete	Fabrication and installation complete for all of the deliverables specified for the Delivery Ring 2.4 MHz RF System.	March 28, 2019
47502.06.02.001040	Delivery Ring RF Studies Complete	Implementation of the RF studies capabilities of Delivery Ring RF complete.	June 21, 2019

Schedule


CD-3a
CD-2/3
CD-4
Low Level RF System
Delivery Ring RF Studies & Tuning
Delivery Ring RF Cooling System
Delivery Ring 2.4 MHz RF
Technical Documentation
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

Summary

- A Budgetary Quote was conducted and the 8 kW Solid State Driver was switched from an in-house design to purchasing from a vendor.
- Our Final Design is complete and we are ready to Baseline the schedule.