Photodetectors: PMTs/Bases for IceCube & Friends

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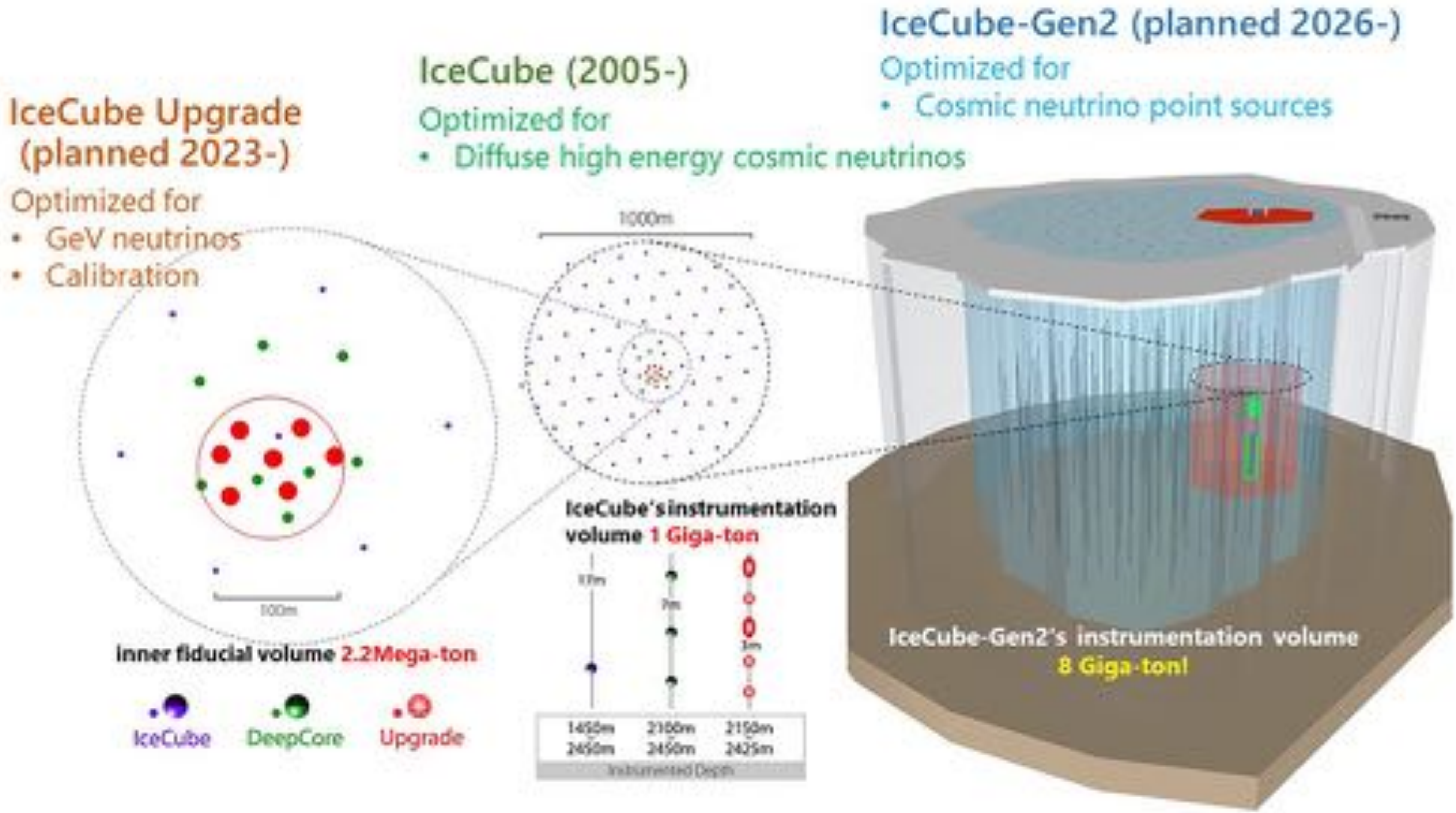
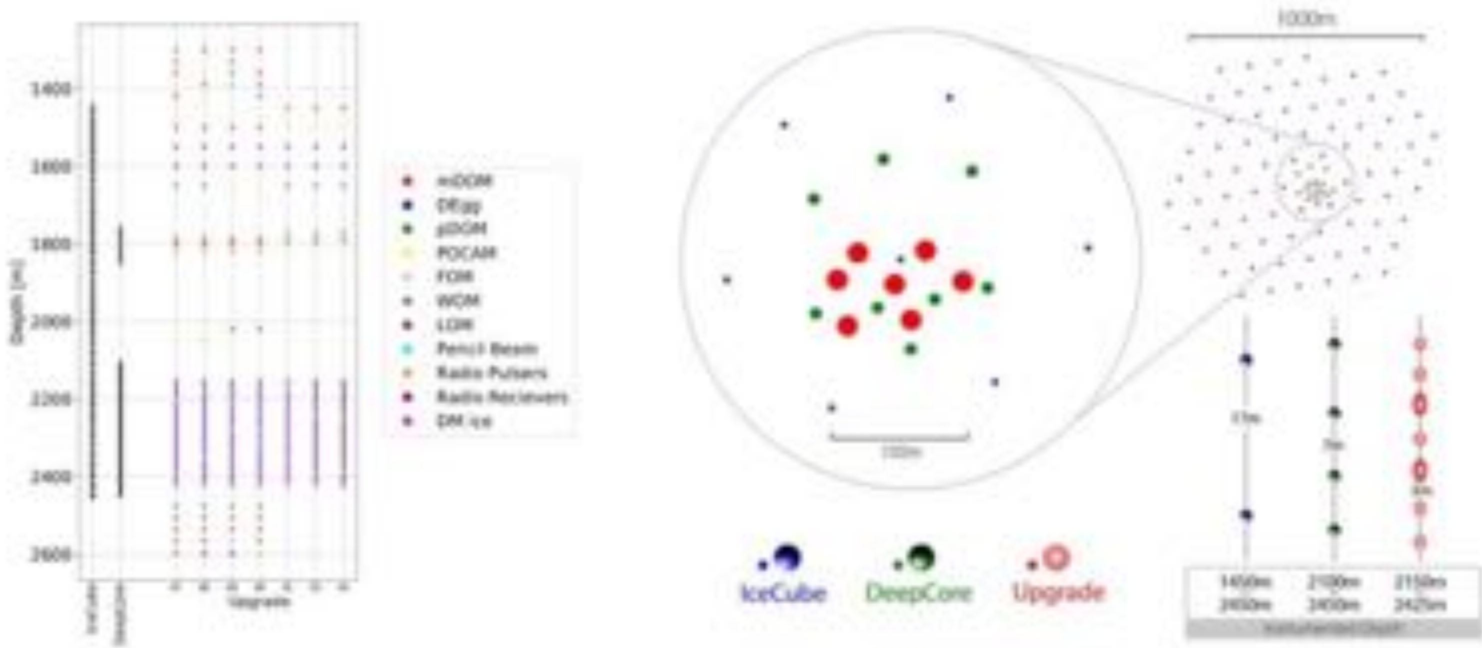
IceCube (Gen1) – Upgrade – Gen2

- Existing IceCube experiment, focused on astrophysics, with in-fill (DeepCore) focused on oscillations
- IceCube Upgrade is fully funded, would have installed this year at Pole, but three lost field seasons due to COVID, denser still, looking at oscillations, plus precision calibration of the ice (and some R&D for Gen2)
- IceCube Gen2 is a proposed, second generation, astrophysics instrument focused on higher energies, and on neutrino sources


IceCube-Gen2 (planned 2026-)
Optimized for
• Cosmic neutrino point sources
IceCube (2005-)
Optimized for
• Diffuse high energy cosmic neutrinos
IceCube Upgrade (planned 2023-)
Optimized for
• GeV neutrinos
• Calibration
1000m
100m
inner fiducial volume 2.2Mega-ton
IceCube
DeepCore
Upgrade
IceCube's instrumentation volume 1 Giga-ton
17m
7m
3m
1450m 2450m
2100m 2450m
2150m 2425m
Instrumented Depth
IceCube-Gen2's instrumentation volume
8 Giga-ton!



7 strings - 693 Optical sensors:

- 277 D-Eggs (2x 8" PMT)
- 402 mDOMs (24x 3" PMT)
- 14 PDOMs
- Calibration devices

2 Mton effective volume for LE neutrino events:

- trigger down to 1 GeV
- 90% efficient at 3 GeV

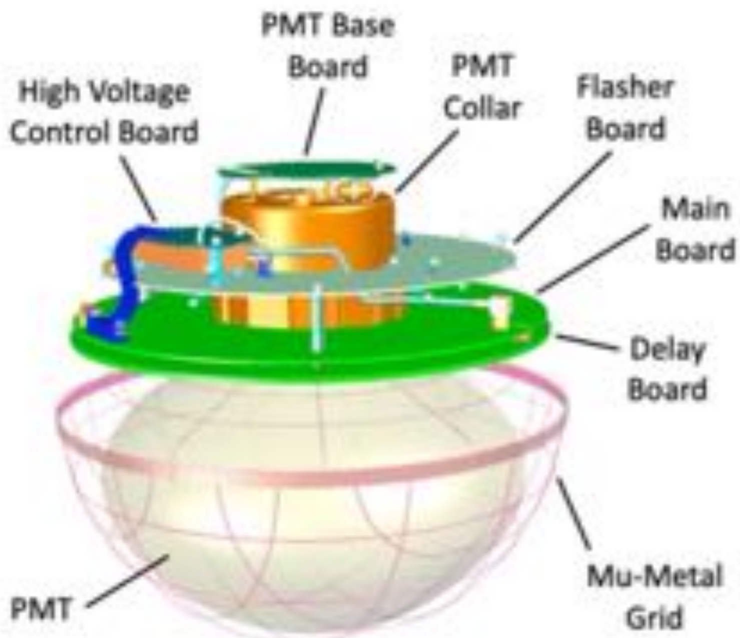
Single Drill / Install Season

1. **Neutrino Properties**
2. **Recalibration and Reanalysis of IceCube Data**
3. **IceCube-Gen2 Research and Development**

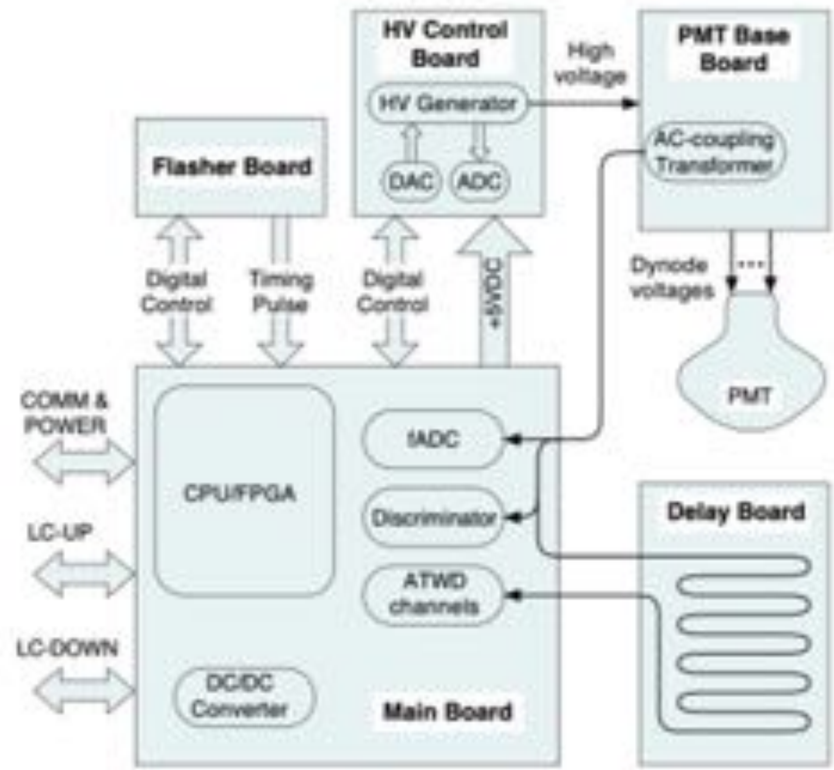
Optical Modules

- Gen1 IceCube used single 10” Hamamatsu PMT with base using custom EMCO HV supply, divider network, inductively coupled output
- IceCube Digital Optical Modules (DOMs) aim for spacecraft level reliability, only a handful of the >5000 modules have failed in the 10-14 years they have been deployed
- Upgrade has mix of D-Eggs (Chiba, Japan, 2x 8” HQE PMTs) and mDOMs (DESY-Zeuthen, 24x 3” HQE PMTs)
- These >10,000 PMT assemblies were built with custom active bases inside the Hamamatsu factory, a manufacturing approach we were very excited to explore
- Gen2 looking at going further into the integrated photodetector space with custom PMTs and bases (>100,000 units) with onboard digitization

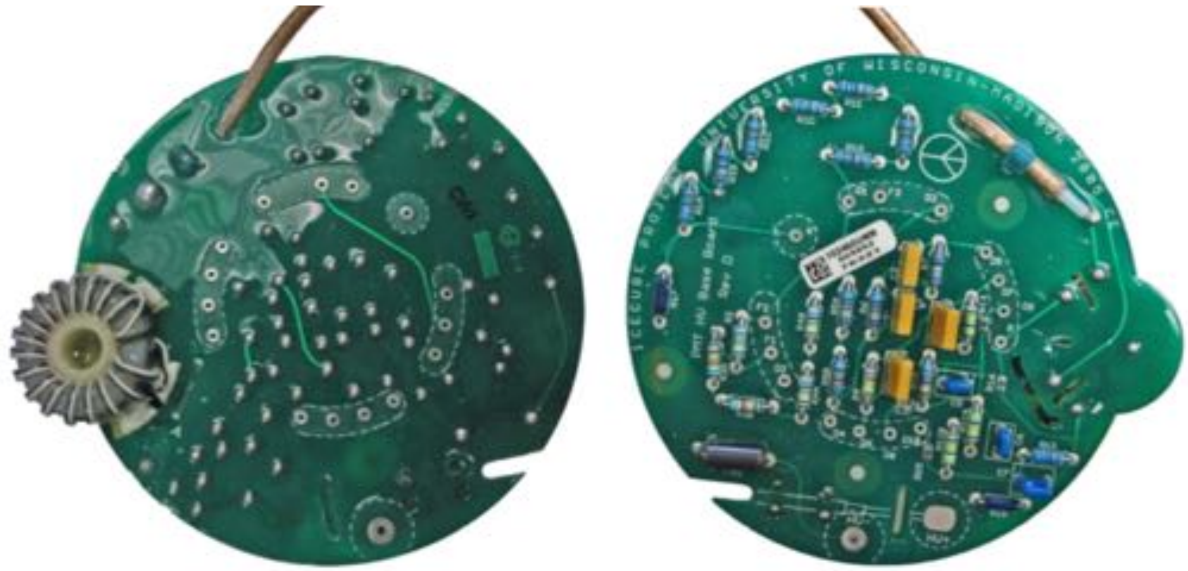
IceCube Gen1

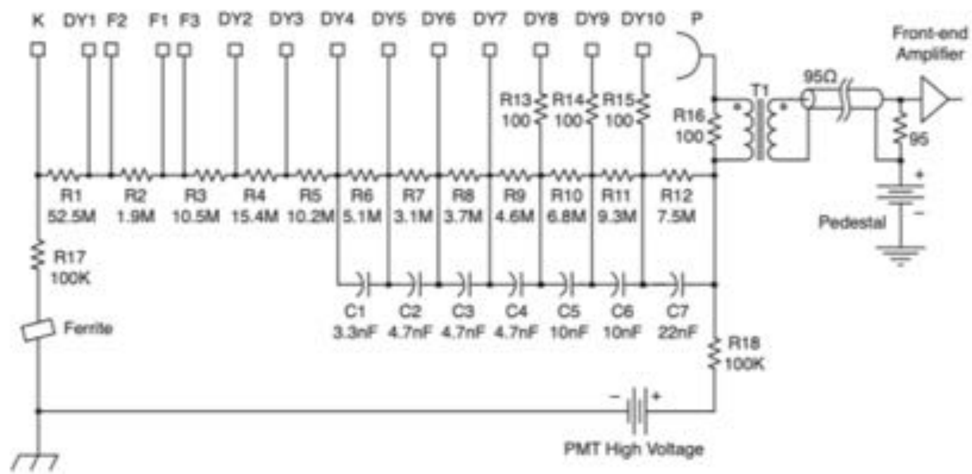


PMT Base Board
PMT Collar
High Voltage Control Board
Flasher Board
Main Board
Delay Board
Mu-Metal Grid
PMT

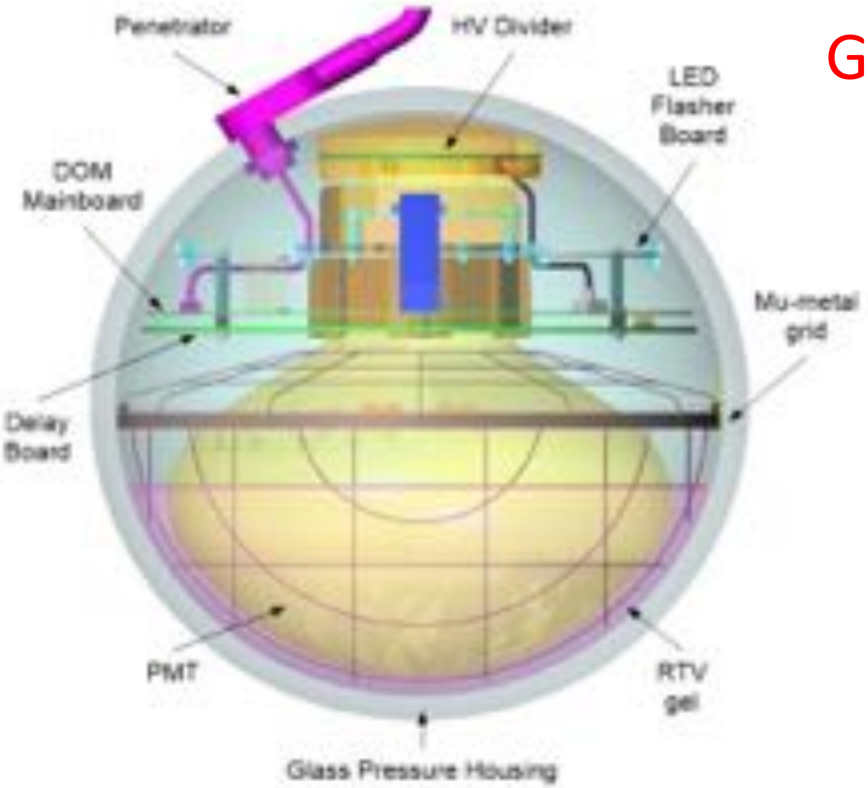


HV Control Board
HV Generator
DAC
ADC
High voltage
PMT Base Board
AC-coupling Transformer
Flasher Board
Digital Control
Timing Pulse
Digital Control
+5VDC
Dynode voltages
PMT
COMM & POWER
LC-UP
LC-DOWN
CPU/FPGA
fADC
Discriminator
ATWD channels
DC/DC Converter
Main Board
Delay Board

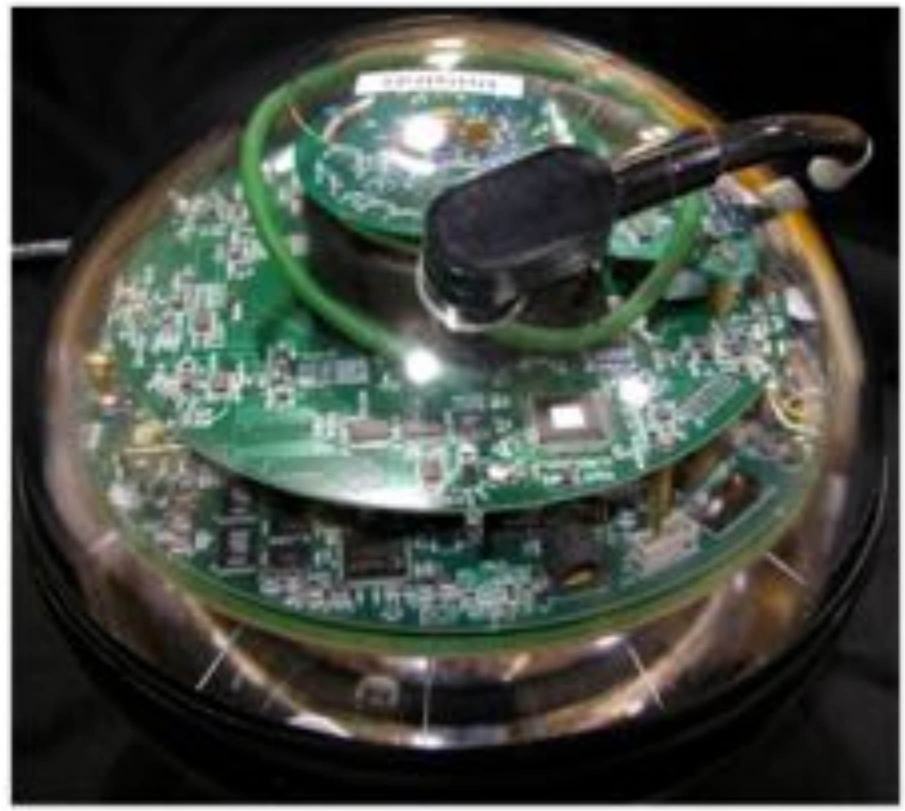



K
DY1
F2
F1
F3
DY2
DY3
DY4
DY5
DY6
DY7
DY8
DY9
DY10
P
Front-end Amplifier
95Ω
T1
R13 100
R14 100
R15 100
R16 100
95
R1 52.5M
R2 1.9M
R3 10.5M
R4 15.4M
R5 10.2M
R6 5.1M
R7 3.1M
R8 3.7M
R9 4.6M
R10 6.8M
R11 9.3M
R12 7.5M
Pedestal
R17 100K
Ferrite
C1 3.3nF
C2 4.7nF
C3 4.7nF
C4 4.7nF
C5 10nF
C6 10nF
C7 22nF
R18 100K
PMT High Voltage

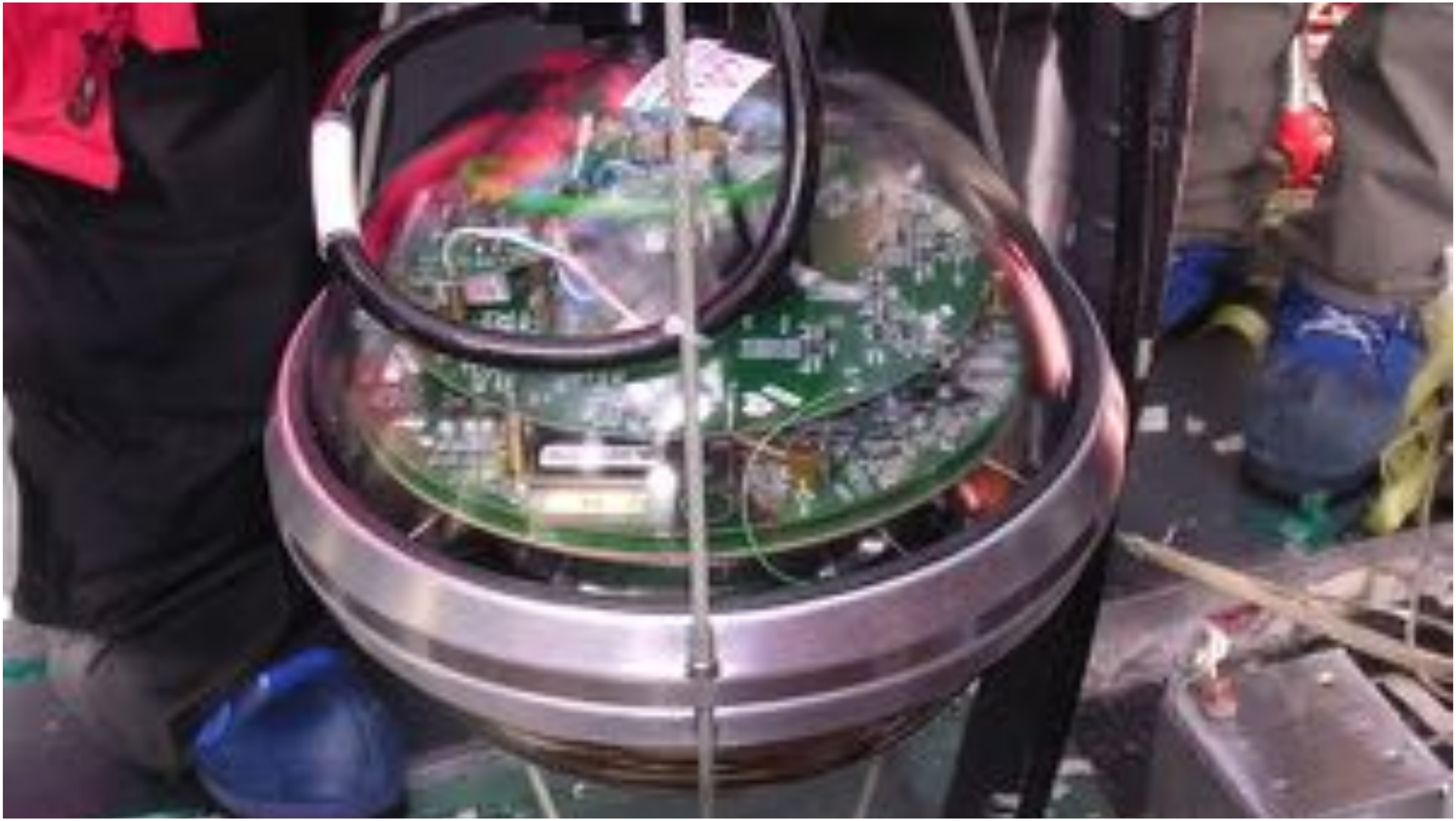
IceCube Detector Element: The Digital Optical Module



GEN1




EXIT
TOS 1
2



IceCube Upgrade

WBS 1.3.1
430 mDOMs

WBS 1.3.2
310 D-Eggs

WBS 1.3.4
900 Ice Comms Modules

WBS 1.3.3
20 Refurbished IceCube DOMs

WBS 1.3.5
Coordination of R&D Sensors

Base & production techniques

The Chicagoland Observatory Underground for Particle Physics Cosmic Ray Veto System

M. Crisler, J. Hall, S. Hansen, E Ramberg and T. Kiper
Fermi National Accelerator Laboratory Batavia, Illinois*

***Abstract*-A photomultiplier (PMT) readout system has been designed for use by the cosmic ray veto systems of two warm liquid bubble chambers built at Fermilab by the Chicagoland Observatory Underground for Particle Physics (COUPP) collaboration. The systems are designed to minimize the infrastructure necessary for installation. Up to five PMTs can be daisy-chained on a single data link using standard Category 5 network cable. The cables is also serve distribute to low voltage power. High voltage is generated locally on each PMT base. Analog and digital signal processing is also performed locally. The PMT base and system controller design and performance measurements are presented.**

bases over the links and has outputs for driving an LED flasher system. The data path from the controller to the DAQ is 100 Megabit Ethernet.

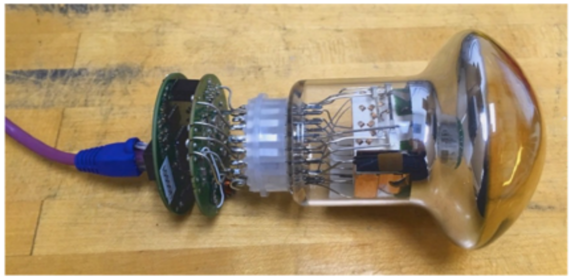
II. Motivation

A cosmic ray veto is commonly used in low background searches to aid the rejection of background events. Typically scintillator either solid or liquid is used. PMTs are the still the sensor of choice for these systems because of their large sensitive are. What is unusual in the case of COUPP is the time scale over which PMT signals must be stored pending a

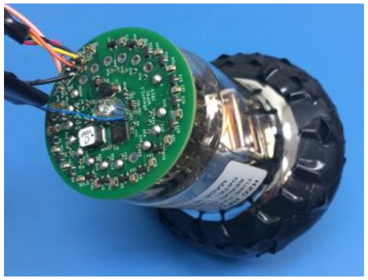
WIPAC MicroBase Summary, Background

- Cockcroft-Walton HV Base
- Resonant Generator Input Circuit
  - Inspired by COUPP PMT Base (FNAL) → CHIPS → IceCube
- On-board Microcontroller
- Optimized for Low Power, Noise, Cost, Compactness, mDOM Geometry
- Versions Developed for Hamamatsu R12199, HZC XP82B2F

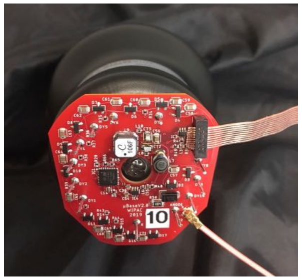
CHIPS MicroDAQ + CW-HV boards, rewired for HZC 3.5" (Daan Van Eijk)



MicroBase V1.1 with HZC XP82B20D



MicroBase V2.0 with Hamamatsu R12199



WIPAC MicroBase Summary, Background

- Cockcroft-Walton HV Base
- Resonant Generator Input Circuit
  - Resonant operation inspired by COUPP PMT Base (FNAL) → CHIPS → IceCube
  - MicroBase uses matching network instead of transformer to drive resonance
- On-board Microcontroller
- Optimized for Low Power, Noise, Cost, Compactness, mDOM Geometry
- Development for Hamamatsu R12199 from Feb. 2019 (V2.0) to Jan. 2020

MicroBase V2.4
December 2019

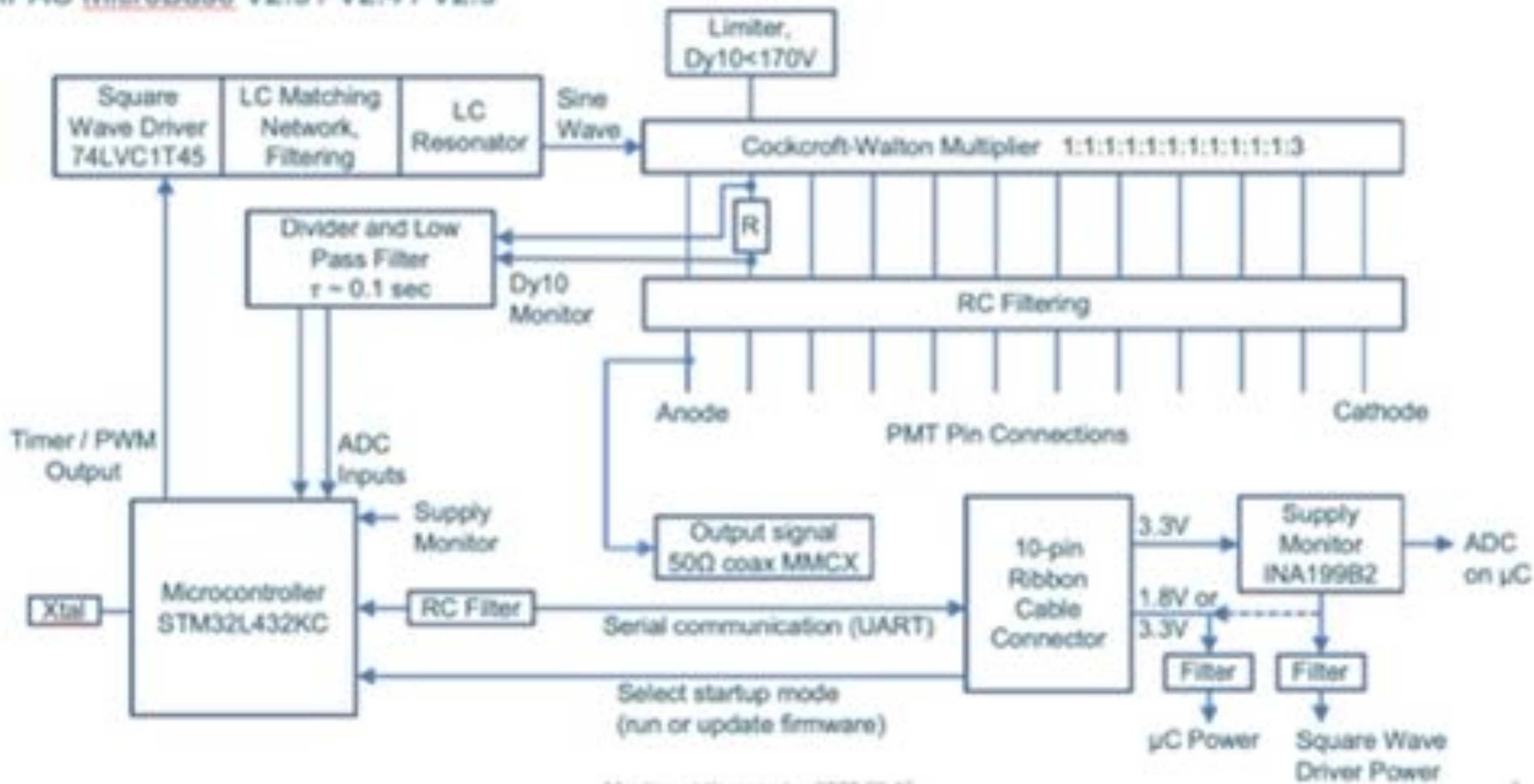
PMT "MicroBase" for 14" MDOM

- Cockcroft-Walton HV generator with ARM-Cortex micro controller
- Ribbon cable delivers 3.3V and 1.8V and serial communication link for control and status
- < 10mW power consumption per PMT
- 10000 units are being produced by Hamamatsu, our design, assembled to their 3" PMTs

We have shared these modules with a number of neutrino, CR, and gamma ray groups.

System Block Diagram

WIPAC MicroBase V2.3 / V2.4 / V2.5



Adding digitization, towards Gen2

Waveform capture, anode plus deep dynode, FPGA, memory, but very simple device (wuBASE)

Waveform MicroBase

ICECUBE GEN2

- Adds the following to original MicroBase:
  - Preamps, discriminator for precise leading edge time capture
  - ADC for full waveform capture (65 MSPS, 2 channels, 12-bit)
  - FPGA for time capture and buffering ADC output
  - Non-volatile flash memory 2Gb (optional)
  - Single ribbon cable interface to main board (power, communications, timing)

Recall PMT analog BW

SN DAQ
Plus lookback

MicroBase - mDOM version

DAQ Additions

140mW per PMT

$65 board

Though right now
FPGAs cannot be had
For love or money

12

9

C. Wendt,
Dec.. 2019

PMT MicroBase with HV and Waveform ADC Readout

Power and cost detail

- Including 2 channels / PMT to cover wide dynamic range

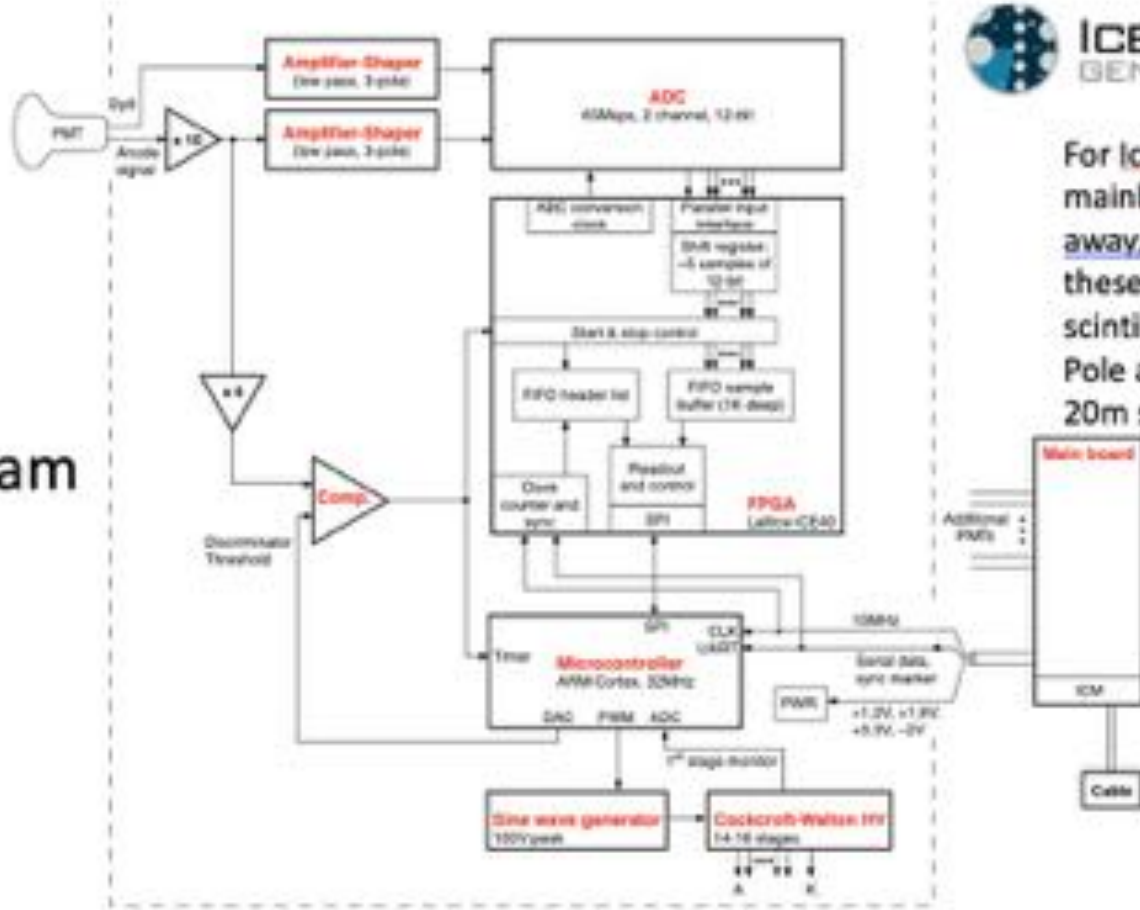
	Item	Description	Qty / Board	Power / Board	Cost / Board	Comment
	MicroBase-HV	Cockcroft-Walton HV with ARM-Cortex Microcontroller	1	10mW	$18	Assembled cost
Lattice	LTC2142-12	ADC, 65MSPS, 12 bit, 2 channel	1	92mW	$22	
	iCE5LP4K-SG48ITR	FPGA, 4K cells, 10kB RAM	1	3mW	$4	
	AD8014	Op-amp	2	12mW	$3	
	ADA4940-1	Differential ADC driver	2	12mW	$5	
Maxim,	MAX9010	Comparator	1	5mW	$1	
needs	TDC7201	TDC	1	8mW	$2	Option
thought	MT29F2G01	Flash memory 2Gb	1	5mW	$2	Option

Example 10-PMT module:

Waveform MicroBase, 10x => 1.5W
Main Board with ICM, DCDC => 0.6W

For Gen2, longer term, will make an ASIC for this

PMT Base Block Diagram



For IceCube this mainboard is 10cm away, but have built these for surface scintillators at South Pole as well at a 10-20m separation.

Bunch of little bits

- We do our own HALT testing for these board designs
- Vendor does the HASS for them
- Conformal coating is applied
- Design rules are employed for <1/2 atmosphere pressure over the HV
- Yield of bases at Hamamatsu was >99%
- Inexpensive cabling has been conceptually part of the design
  - Micro base uses CAT5e for power, comms, and signal
  - Wu base uses CAT6 for power, comms, and data

Gen2 DOMs

Optical Module for IceCube-Gen2?

Full operation since 2011

IceCube DOM

10" PMT & dia. 33 cm

>98% still in operation without problems after 10 years

Low-energy extension & ice calibration

Deployment scheduled in 2025/26 season

mDOM

24x 3" PMTs & dia. 36 cm

D-Egg

2x 8" HQE PMTs & dia. 30 cm

- First Multi-PMT In-Ice Optical Module designs
- Designs tuned for low-E events & ice measurements
- Major updates in essential elements (pressure vessels, optical gel, electronics, and etc)
- New production, testing facilities, and skilled R&D teams

High energy extension

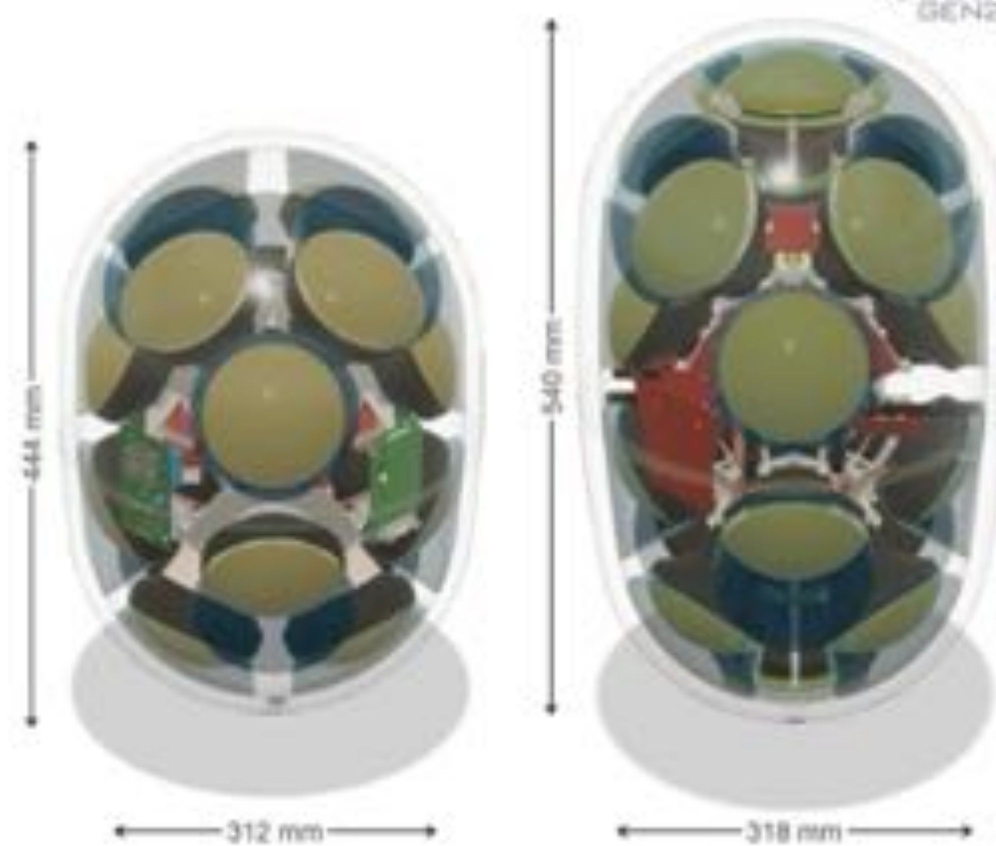
Design report in preparation

IceCube-Gen2 Optical Module development is built on

- Successful design from IceCube
- Updates through IceCube-Upgrade

Gen2 Optical Module Design Candidates

- Two design candidates; 16 and 18 PMT options
  - Custom non-spherical pressure vessels for both options
- 4" PMT is the best pick to maximize effective area
  - Back-to-back layout not feasible with > 4" PMTs
  - (*) Does not exist in the current lineups of PMT vendors
- PMTs are coupled to pressure vessels through "gel pads"
  - Cone shape enhances the effective area
  - Coupling PMTs and pressure vessel optically&mechanically
- Custom electronics designed for Gen2 needs
  - Tuned for high energy array (dynamic range)
  - Low power consumption (infrastructure)
  - In-module data buffering (bandwidth)

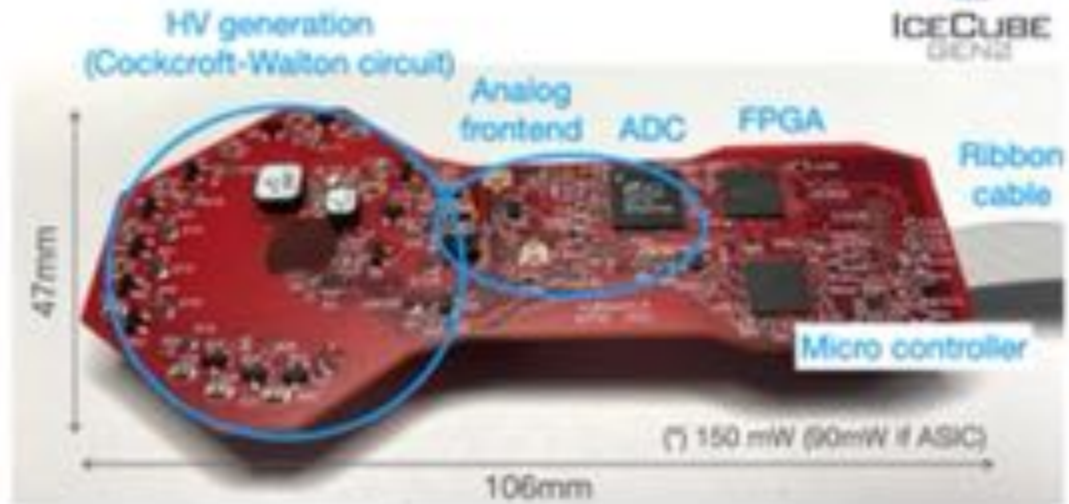


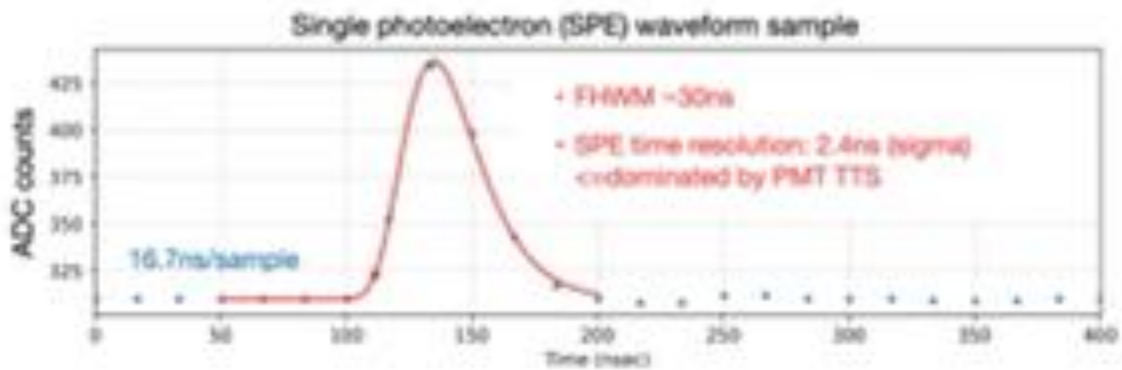
16 PMT option

18 PMT option

Waveform MicroBase

- Add DAQ feature to the existing custom HV base
  - HV base developed for the IceCube-Upgrade project
    - MicroBase (ref: PoS(ICRC2021) 1070)
  - Ribbon cable for controlling and data transfer
- DAQ functionalities
  - Continuous digitizing with 2-channel 12 bit ADC at 60MSPS and captured in a low-power consumption FPGA
  - Record Anode (high gain) and 8th Dynode (low gain) signals
  - Microcontroller manages control and regulation of HV, and buffering and low-level processing of digital waveform data

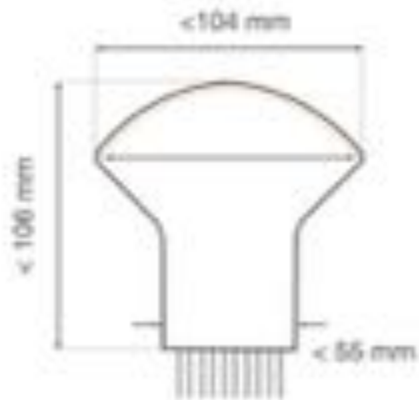




4 inch PMT

As short as possible accepting minimum compromise in performance

- Two vendors: Hamamatsu and North Night Vision Technology (NNVT)
  - Newly-designed 4inch box&line style dynode PMTs
  - NNVT has produced 15,000pcs 20" MCP-PMTs for JUNO
  - Keep multiple vendors for for Gen2!
- Very compact, 106mm (abs max.) long
  - (Potential) Caveat is moderate cathode uniformity (transit time and/or collection efficiency, for example)
- Confirmed prototypes from both vendors meet the requirements
  - No public plots/numbers yet
  - Development/Improvement still ongoing



Target numbers

Parameter	Target value
Gain	5e6 @ <1500V
Transit Time Spread	< 8ns (FWHM)
Peak/Valley	>2
QE	>25% @400nm
Pre/late/after pulses	Less than 1/5/10%

And Friends…

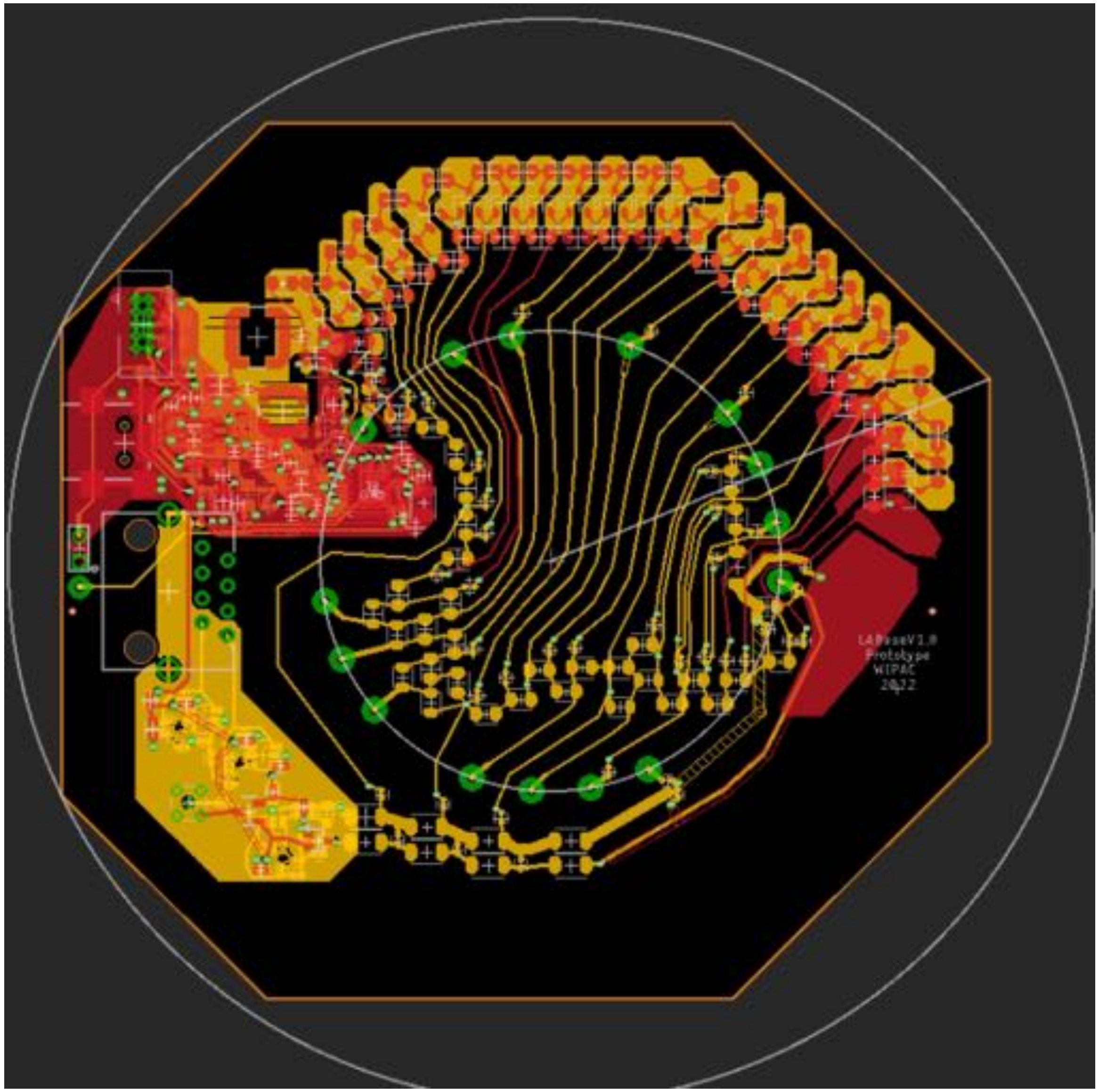
WIPAC LABase Project

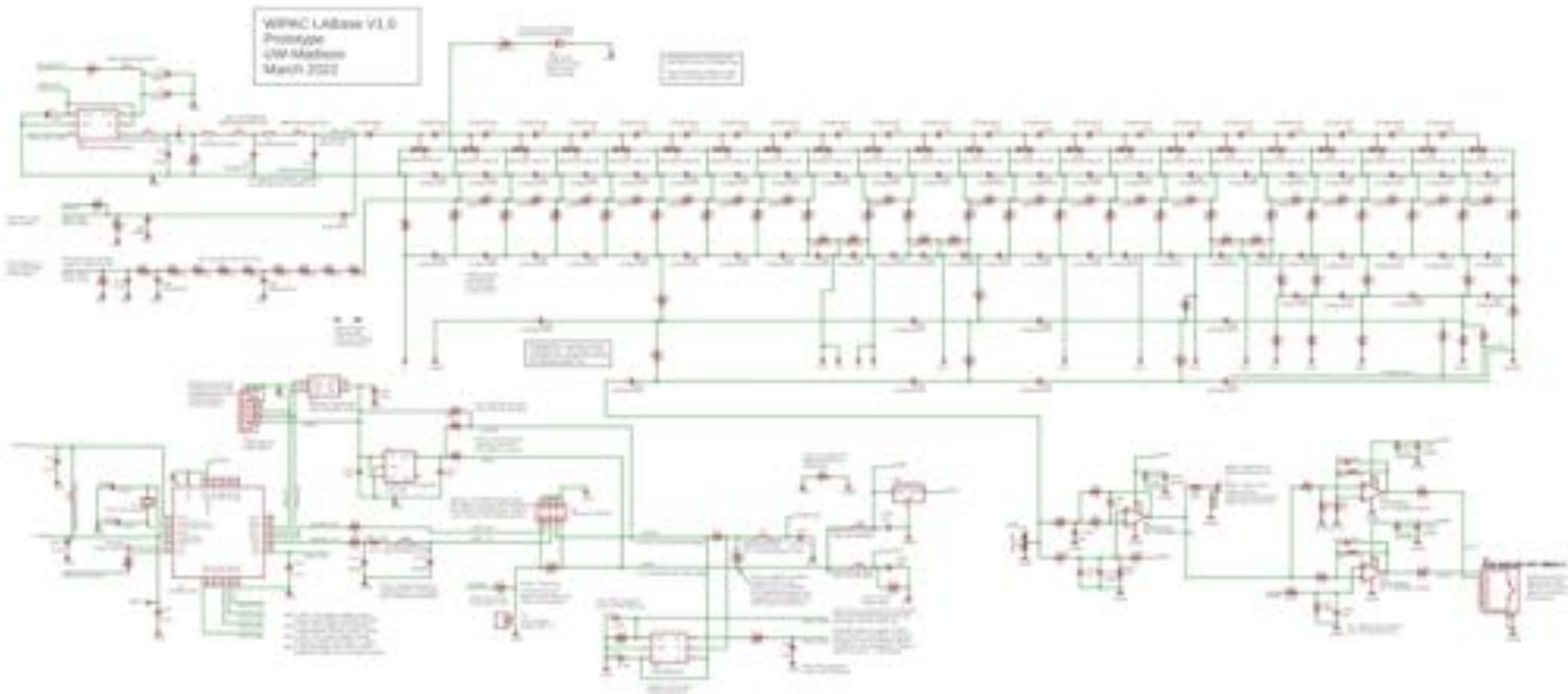
- Initiative is from Mike Duvernois
  - Intended for use in SWGO Experiment, 8" PMTs
  - Board design & programming by C. Wendt

- HV base fitting Hamamatsu large-area PMTs (10-stage)
  - Current version (V1.0) fits 8" R5912 or 10" R7081
  - Later version planned for R14688-100

- HV circuit adapted from MDOM MicroBase "uBase"
  - Change from grounded anode to grounded cathode, previously tested on 3" PMTs (IceCube LOM R&D)
  - Number of Cockcroft-Walton stages increased from 13 (uBase or wuBase) to 22 (LABase)
  - MCU and HV control firmware very close to MDOM uBase version

- Preamplifier outputs with coax and RJ45 connector options
  - wuBase DAQ not implemented on this version, only analog outputs


LABaseV1.0
Prototype
WIPAC
2022


WIPAC LABase V1.0
Prototype
UW-Madison
March 2022


27-May-22
11:17:16
1
10 ns
5.0mV
LeCroy
B:Harea(1)=
.1 nVs
100 #
←0%/→2%
===in 19472
D:M2=======
.1 nVs
0.50 k#
←0%/→1%
inside 7436
Peak to valley okay
4ns leading edge
Maybe a touch slower than desired
Undershoot with grounded cathode looks okay

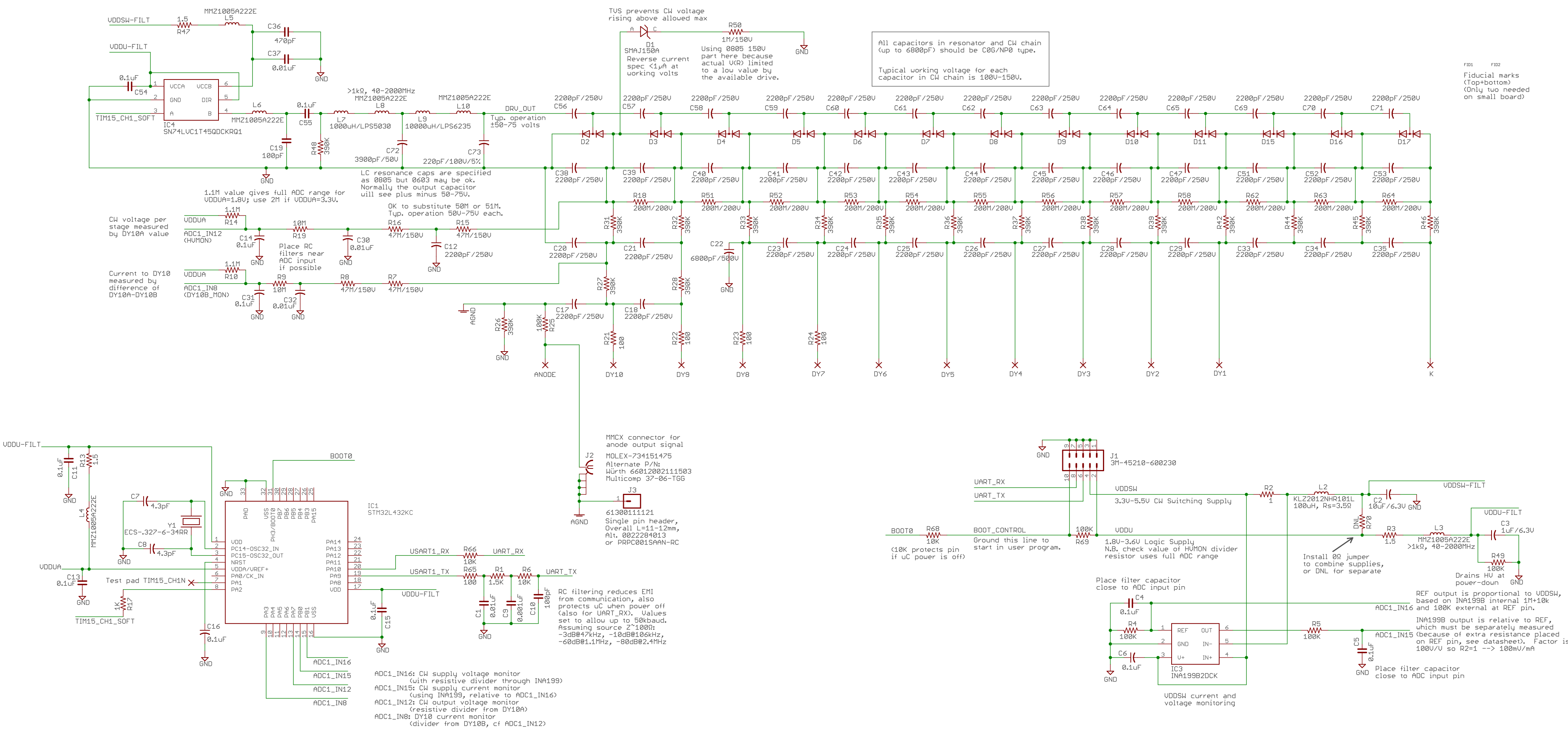
Thanks!

Backup Slides

WIPAC μBase V2.5
UW-Madison
January 2020

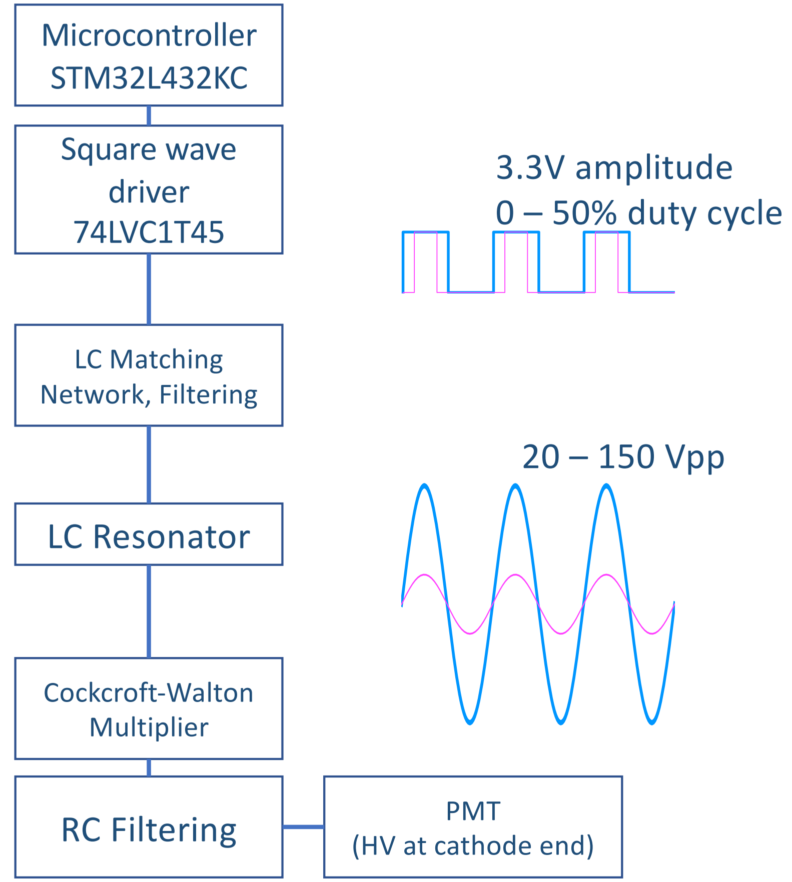
Schematic Diagram

ICECUBE UPGRADE



Design – HV Generation

- Microcontroller produces square wave with adjustable frequency ~100kHz, duty cycle 0%-50%
- Impedance matching network used between square wave driver and LC resonator
  - Minimize reactive current; load appears mostly resistive
  - Component values tuned in LTSpice simulation exercise and refined using bench tests on prototype boards
- LC resonator components chosen for low power loss at 100V – 150V (P-P) sine wave output
- Ferrite beads and capacitor inserted to reduce remaining switching transient noise on sine wave
- Cockcroft Walton multiplier generates voltages proportional to amplitude of ~100kHz sine wave
- RC filter network reduces ripple at dynodes



Cockcroft-Walton Output vs Dy10 Voltage

<u>MicroBase only looks at Dy10 voltage to regulate output</u>

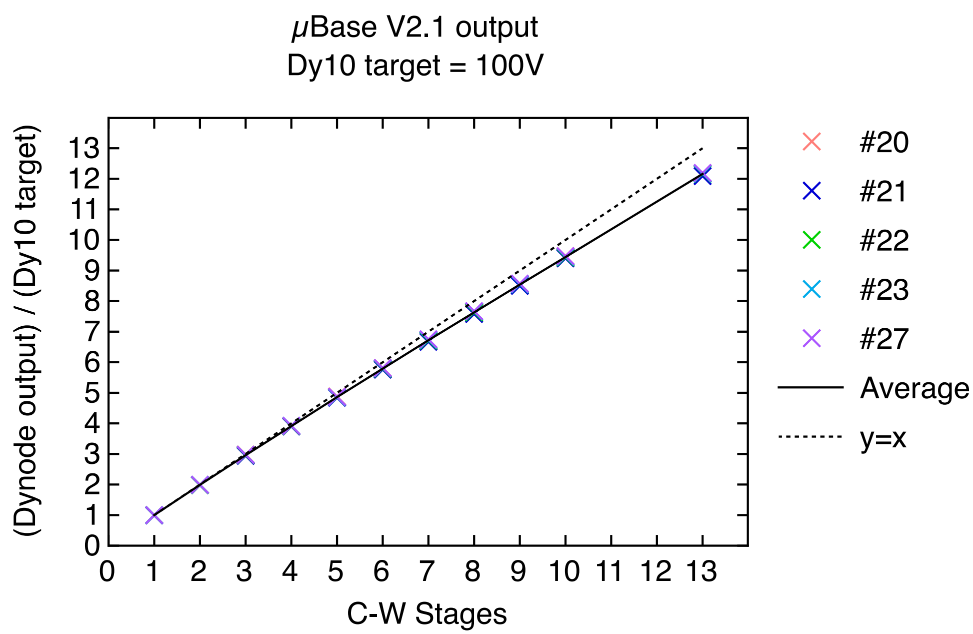
Other dynodes and cathode are at multiples of Dy10

- This is due to the same sine wave propagating through the capacitor chain and driving each stage DC value
- Small parasitic capacitances in the diodes, as well as other losses, cause the sine wave amplitude to be slightly lower towards the cathode end

  → not exactly 1:1:1:1:1:1:1:1:1:1:3 ratios

- IceCube plans to calibrate gain against Dy10 voltage, rather than actual cathode voltage
- Lab measurements show the ratio of cathode voltage to Dy10 voltage is typically 12.2

Lab measurements with 10GΩ load

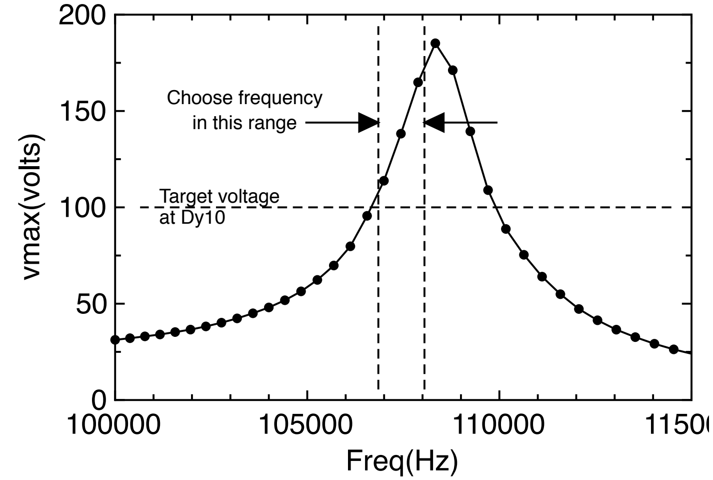


HV Control Parameters

Setting of frequency and duty cycle

Resonance curve gives maximum voltage achievable vs. frequency

- We choose square wave frequency to the left of resonance peak, and where resonance curve is at least 5 volts above the targeted output voltage, e.g. “Upwmfreq 107000”
- Periodic adjustment to chosen frequency may be necessary if conditions change (especially temperature)

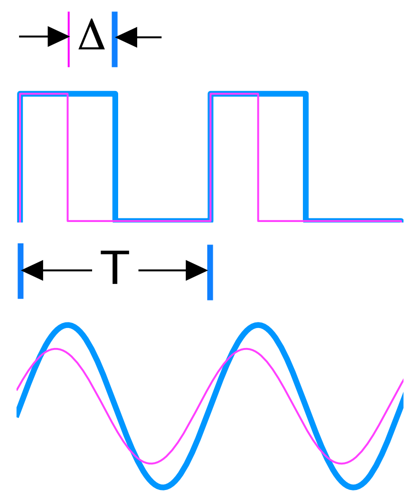


At fixed frequency, feedback controller varies duty cycle as needed

- LC resonator responds mainly to lowest sine wave component in Fourier decomposition of square wave, given by:

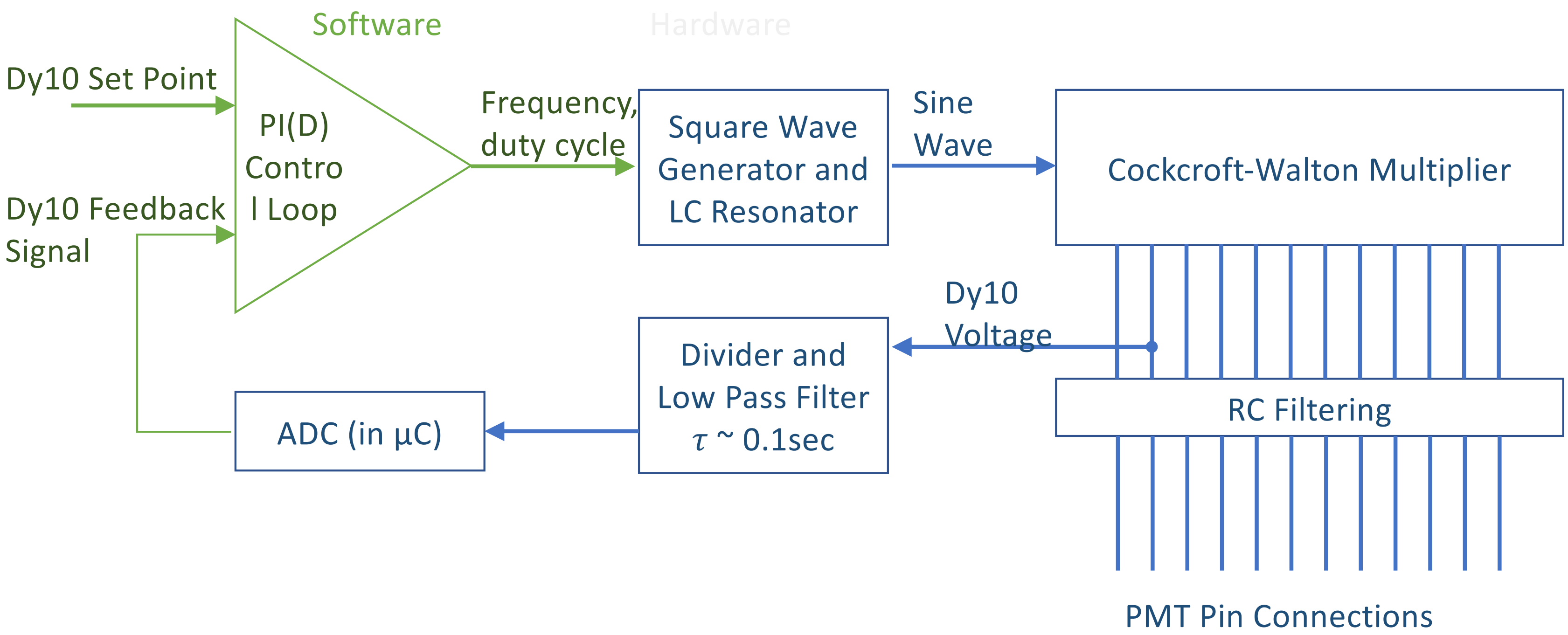
$$V_{out}=V_{max}\cos(\pi\Delta/T)$$

- The feedback algorithm monitors Dy10 voltage and adjusts Δ to maintain output at the target value, e.g. “Uvoltage 100”



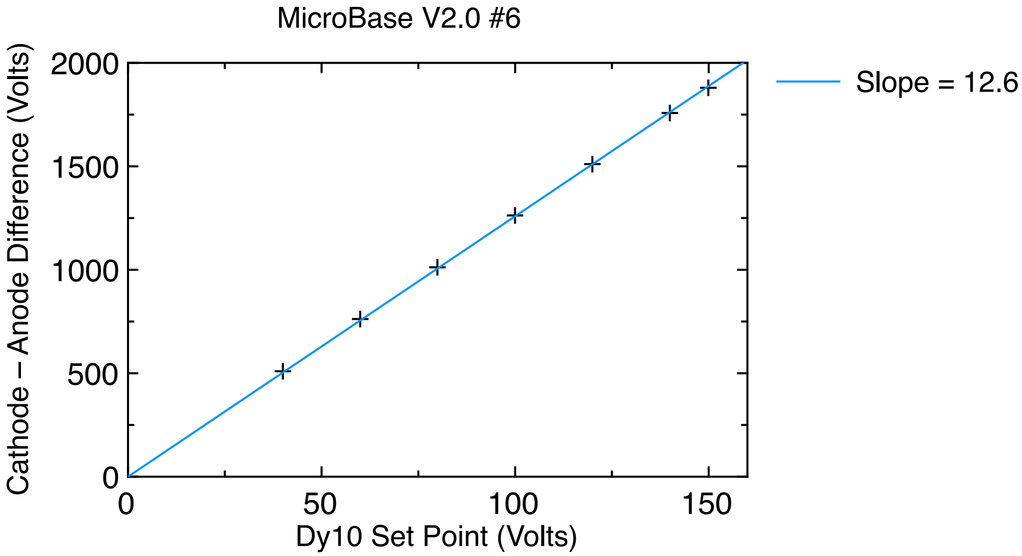
Design – HV Control Loop

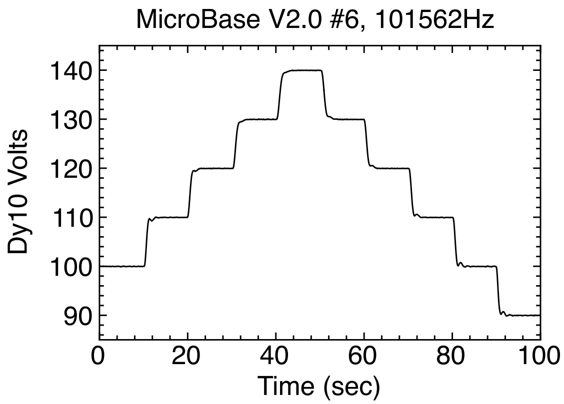
- Voltage at Dy10 (first C-W stage output) is measured at 10SPS
- Feedback controller (software) adjusts square wave to maintain set voltage
- Voltages at other dynodes constrained by Cockcroft Walton design

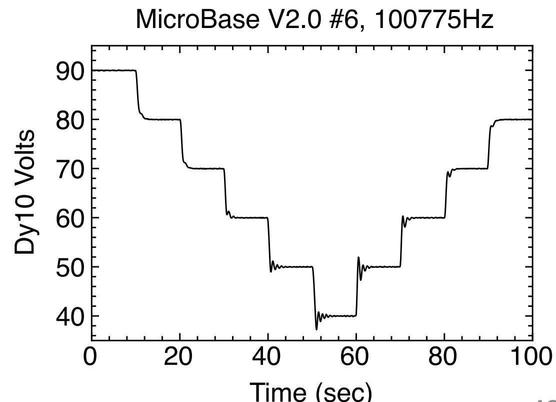


Output voltage range

- Output from 500V-1900V by setting Dy10 at 40 – 150V
  - Voltage measured with 10GΩ series resistor, DMM with 11.1MΩ input impedance

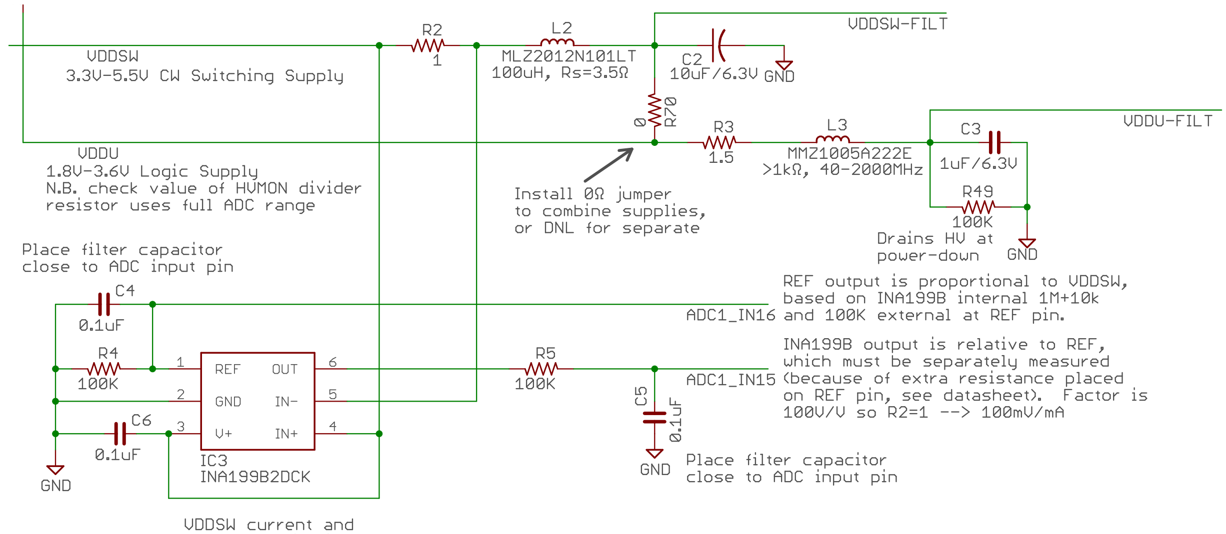






Power Consumption

- On-board input current monitor
  - Jumper selects option to combine supplies and measure sum
  - µC power measured with C-W generator turned off
  - Increase measured when C-W generator is turned on



- Microcontroller 4mW @ 1.8V or 7mW @ 3.3V
  - Running at 26MHz, power scales with clock rate up to 80MHz
  - Using CPU light sleep mode between events (saves factor two)

- Cockcroft-Walton Generator 5mW-12mW depending on HV