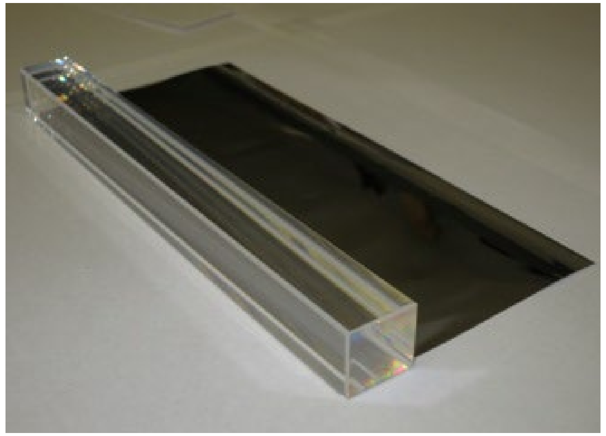
High-Density Glass with Tuned Scintillation/Cherenkov Response to Improve Hadron Energy Resolution in NP-Exp

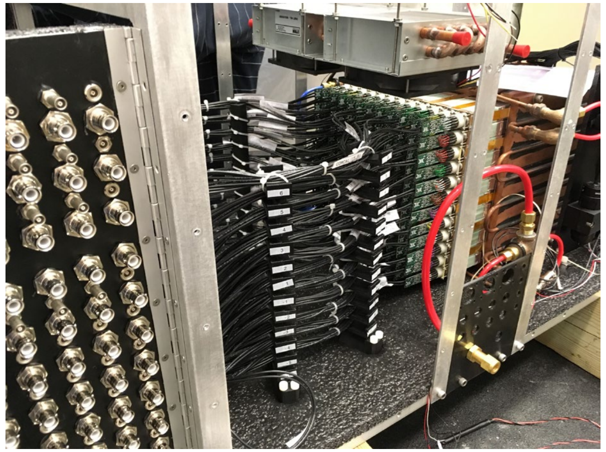
- ☐ Scintilex
- ☐ Dual-Readout Calorimeters
  - ➢ Example: Electron-Ion Collider
- ☐ Experiment Requirements and STTR goals
- ☐ Project Overview and results
- ☐ Outlook

Principal Investigator: Tanja Horn
Business Official: Ian L. Pegg
Award: DE-SC0021459

Scintilex Overview

- ❑ Main focus: design and construction of instrumentation based on Cherenkov and scintillation light using novel materials
  - ➢ Applications: particle detection in nuclear physics experiments and homeland security; also medical
- ❑ Activities and expertise
  - ➢ R&D new detector materials
  - ➢ Pilot testing and scale up; hardware
  - ➢ Software development and DAQ systems
- ❑ Activities related to scintillator material
  - ➢ Jefferson Lab (JLab): EM calorimeters detectors: TCS@NPS, Hy(F)CAL …
  - ➢ Electron-Ion Collider (EIC): EPIC Detector, EIC 2nd detector
  - ➢ Possibly CERN future colliders, e.g., FCC





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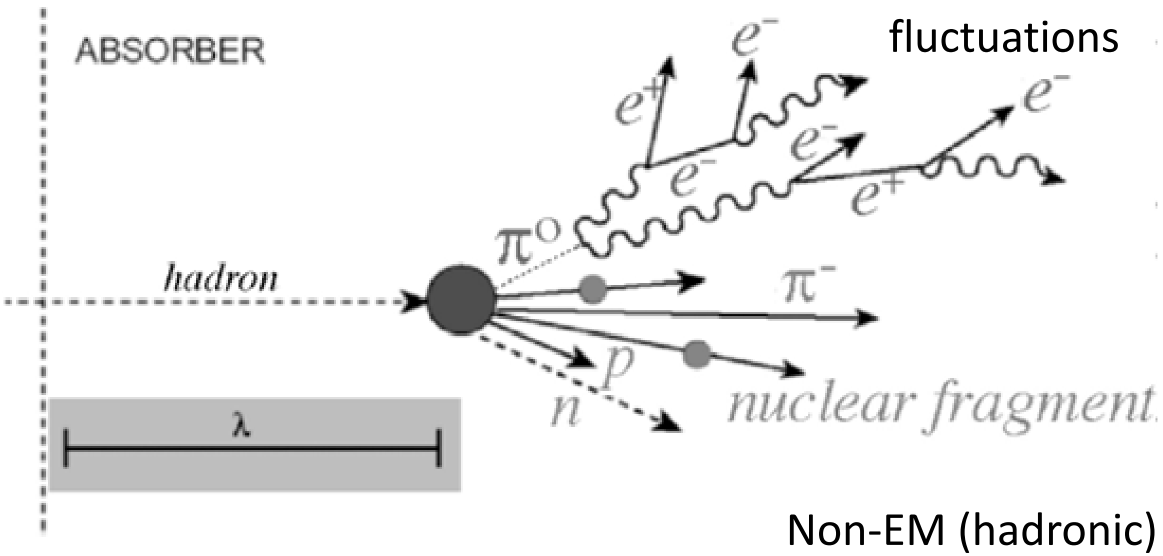
Dual Readout Calorimetry (DRC)

- ❑ Dual readout calorimetry is a principle to resolve the issue of poor hadronic energy resolution caused by the fluctuation of the electromagnetic (EM) shower component and the binding energy loss
- ❑ The EM component in the shower can be measured by implementing two different channels with different response (e.g., Cherenkov/Scintillation) in a calorimeter
- ❑ Excellent energy resolution for hadrons may then be achieved by correcting the measurement event-by-event

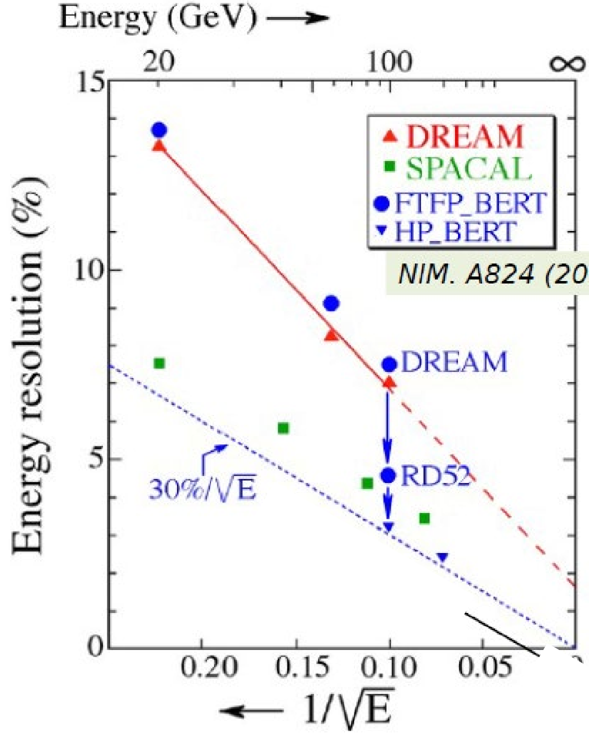
- ➢ The validity of this principle has been demonstrated with the DREAM fiber calorimeter
- ➢ Two factors impacting hadronic resolution remain: sampling fluctuations and fluctuations in the Cherenkov light yield.
- ➢ **Homogeneous materials such as crystals and glasses in which both S and C light are generated in the same optical volume have the potential to eliminate these two issues.**

Hadronic shower

EM component, non-Gaussian fluctuations



Non-EM (hadronic) component



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Hadronic Resolution with DREAM concept

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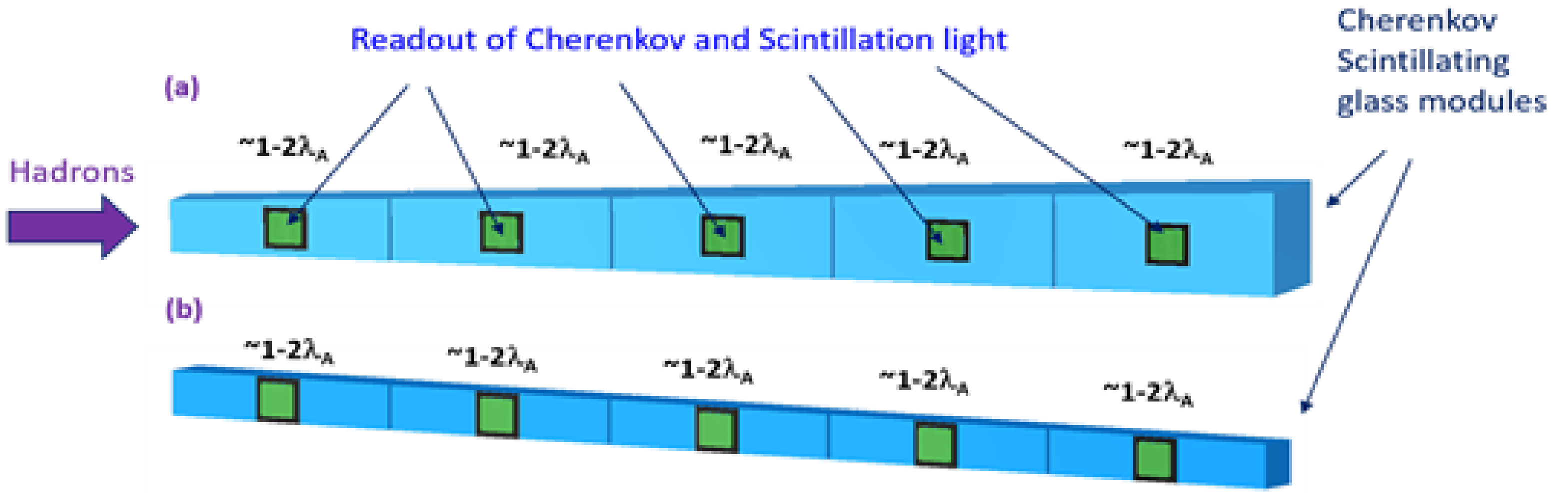
Dual Readout Calorimetry with homogeneous materials



- ☐ Schematic showing a possible cell (two configurations) for the hadron calorimeter dual readout concept.
- ☐ It removes the traditional boundary between EMCal and HCal, and thus eliminates the effect of dead materials in the middle of the hadronic shower development.
- ☐ It is similar to typical homogeneous EMCal cell, but has segments with a total length of 1-2λ_A. Readout devices could be mounted on the side faces.

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Requirements on homogeneous DR materials

- Conversion of energy into visible light – Scintillation Light Yield
  - **Scintillation light output that not too bright**
- Scintillation Response – emission intensity, decay kinetics
  - **Scintillation light slow and at around >500 nm for clear C/S discrimination**
- Emission spectrum matching between scintillator and photo detector – emission peak
  - **UV transparent to effectively collect the Cherenkov light – Good UV transmittance with UV cutoff < 350 nm**
- Chemical stability and radiation resistance – 100 Gy (EM) and 10^{15} n/cm^2
- High density to reduce volume of large hadron calorimeters – Interaction length and Moliere radius for lateral shower containment
- Temperature stability

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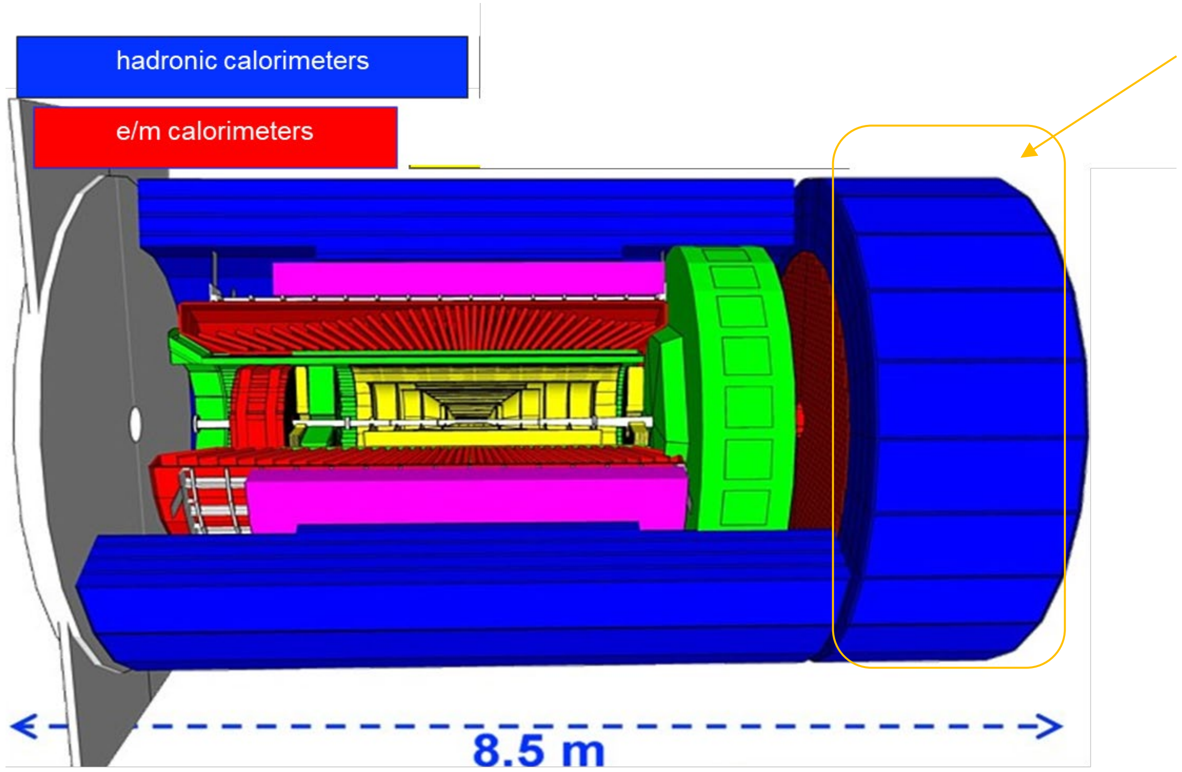
NP Examples: Hadron Calorimetry at EIC and Compton Polarimetry

Improve hadron energy resolution for forward hadron calorimeter and far forward calorimeters, e.g., zero-degree calorimeter (ZDC)

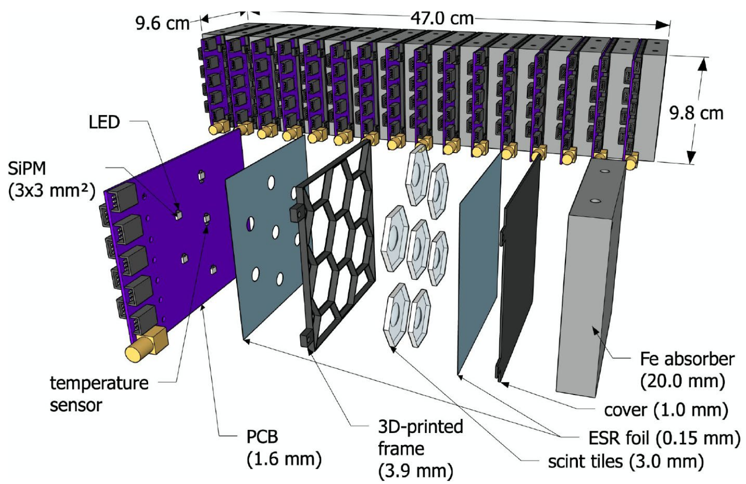


Auxiliary detectors not shown

For η > 3, a constant term of ~5% is needed as jet energies rapidly increase in this region while tracking resolution significantly degrades

- ➢ energy resolution is important
- ➢ energy resolution dominated by the constant term

Possible design for a Si-PM on tile detector for a ZDC



η	Energy resolution
3.0 : 3.5 (inner)	**$50\%/\sqrt{E} \oplus 10\%$**
1.0 :3.0 (outer)	**$35\%/\sqrt{E} \oplus 5\%$**

Another possible application: Compton Photon Detectors for beam polarization measurements – requires excellent timing properties (Cherenkov) and reasonable energy resolution

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Scintilex STTR Concept

- ❑ Demonstrate that the formulation and production techniques developed by Scintilex produce high-density C/S glass with sufficient Scintillation and Cherenkov response as well as optical characteristics suitable for nuclear physics experiments.

  - ➢ C/S glass is based on SciGlass – optimize formulation to meet specifications for DRC
  - ➢ Establish a measurement setup and algorithm for signal processing to determine the contribution of Cherenkov light. Optical filters can be used to select Cherenkov light with small or no scintillation contamination and vice versa
  - ➢ Develop a simulation to make projections of the contribution of the Cherenkov light of different glass formulations and optimize readout choice

- ❑ To demonstrate that high-density C/S glass coupled to state-of-the-art light sensors can meet the experimental specifications at GeV scale Scintilex will perform detailed studies of the performance of the high-density C/S glass using particle beams.

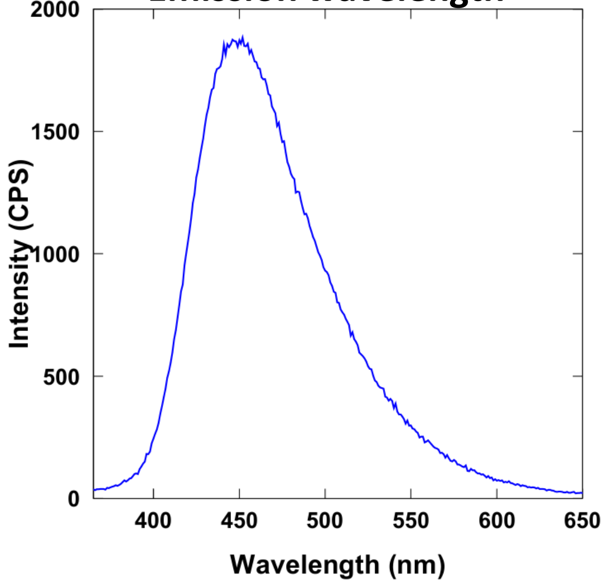
Glass Scintillator formulations

☑ Two glass formulations for homogeneous calorimeter application

VSL-Scintilex-G4 (nominal)

VSL-Scintilex-T1

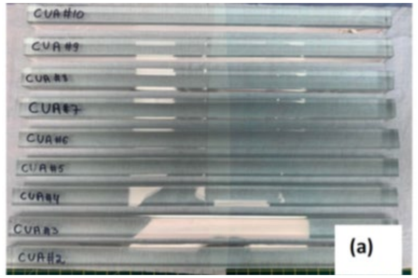
Emission wavelength



Scintillation light

- ➢ Nominal: optimized LY, timing, radiation hardness, etc. ✓
- ➢ Increased density compared to nominal, lower LY, but still higher than PWO

SciGlass

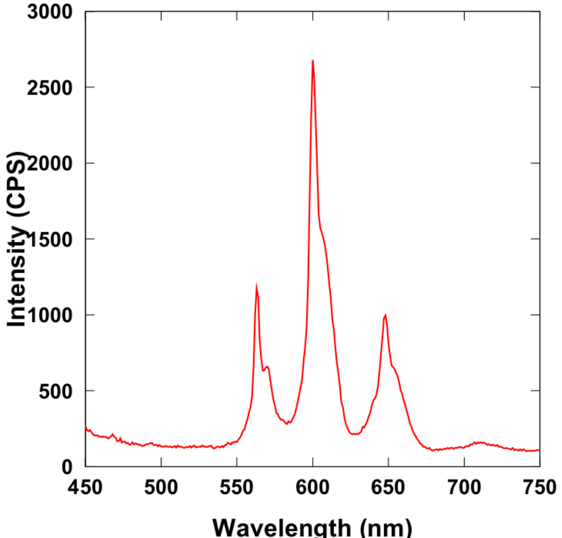


☑ Formulations with initial emission wavelength tuning

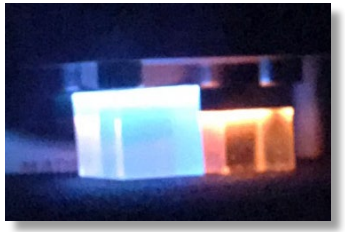
VSL-Scintilex-SC1

VSL-Scintilex-EC1

Emission wavelength

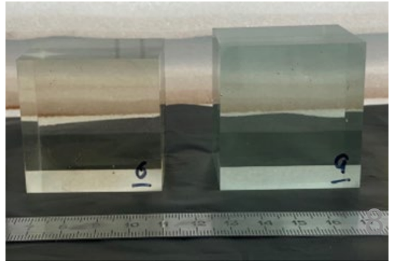


Scintillation light

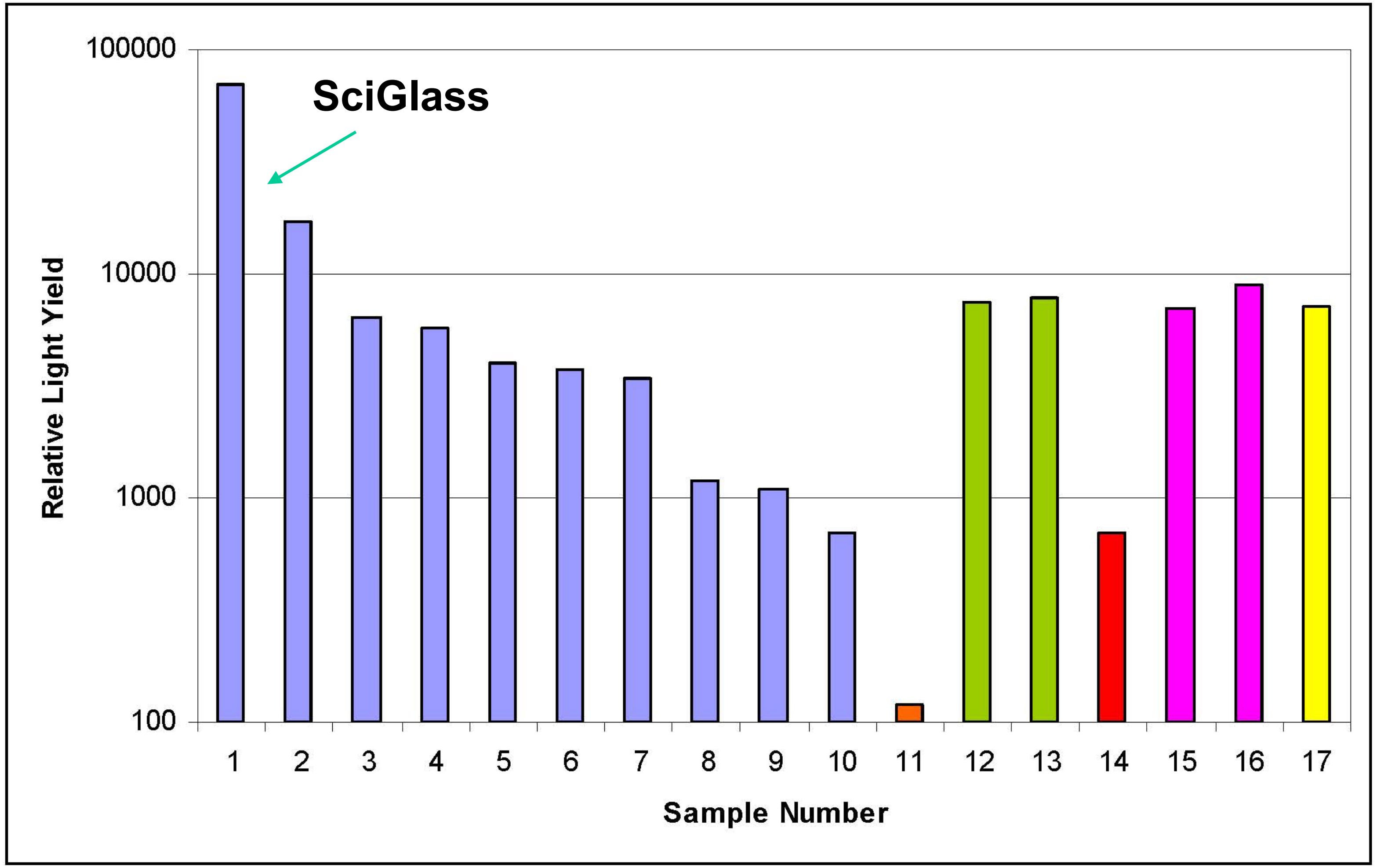


- ➢ Can have higher density compared to nominal, emits at >550nm, good LY

CSGlass (this talk)



Phase 1: Process optimization to control C/S light yield



Samples made at CUA/VSL/Scintilex with different relative C/S light yield

Demonstrated control of relative C/S light yield and identified candidates for scale up

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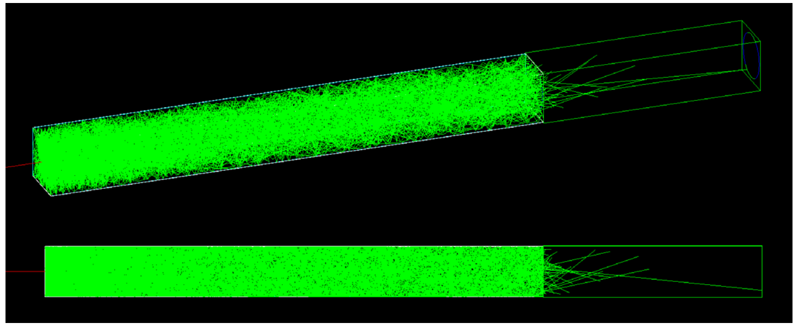
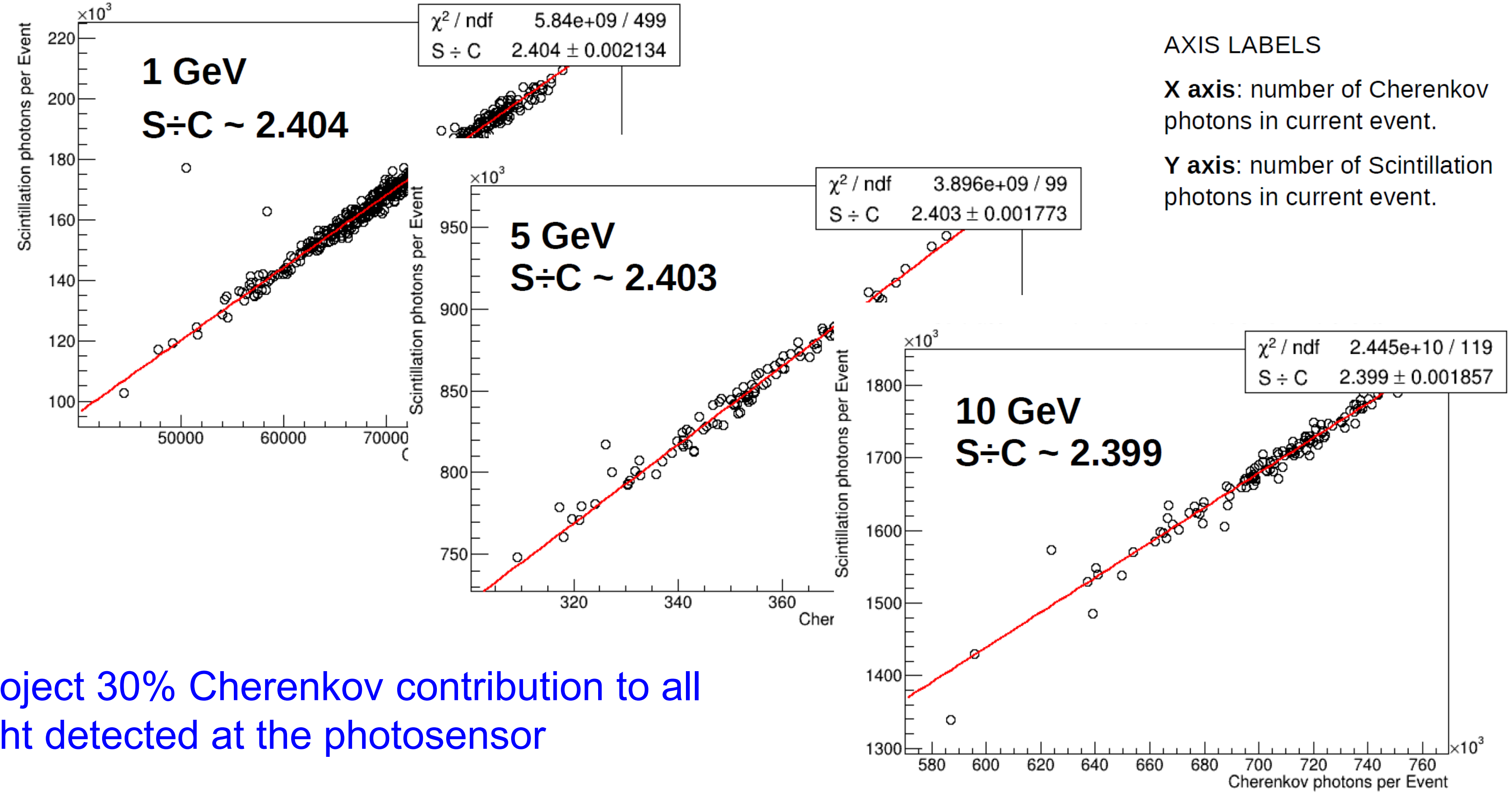
Scintillation to Cherenkov Ratio Projection

- Developed an optical photon simulation for CSGlass – includes a two step process to mitigate the dramatic increase in CPU cost for a full optical simulation
- Results shown for lepton/photon energies of 1 GeV, 5 GeV, and 10 GeV





AXIS LABELS

X axis: number of Cherenkov photons in current event.

Y axis: number of Scintillation photons in current event.

Project 30% Cherenkov contribution to all light detected at the photosensor

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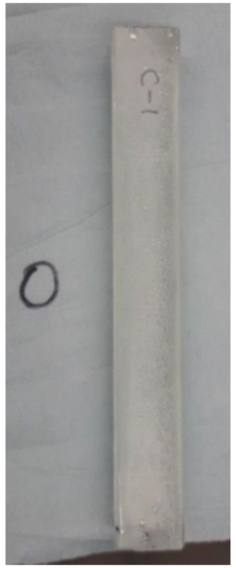
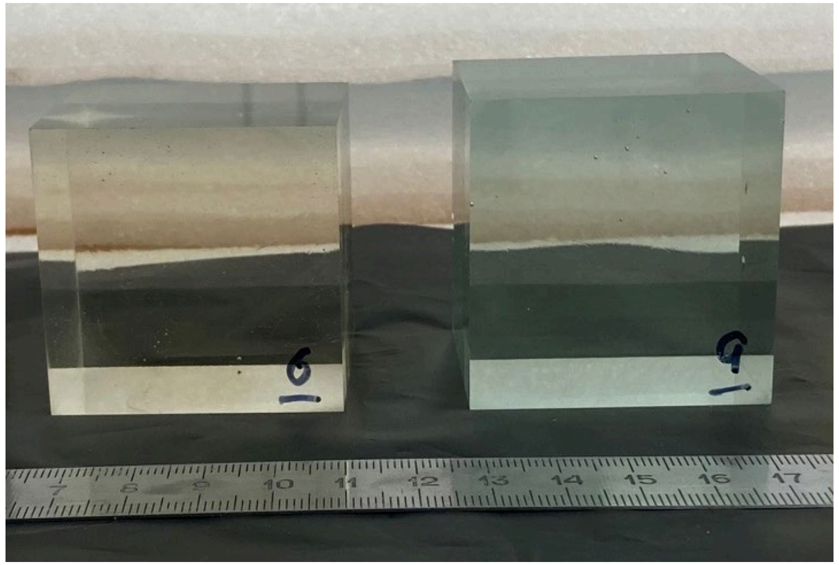
Phase 2: Scale-up and larger scale production

- ☐ Demonstrated a new formulation that further eliminates bubbles in the bulk, which is important for fabricating long or generally larger dimensions blocks
- ☐ Produced rectangular shapes (20cm long) and larger lateral dimension blocks (5 x 5 x 5 cm3)



Transparency before polishing the sides



CSGlass of length 20cm can be produced reliably and 40cm blocks can now be produced routinely – lab size batches (10-25 blocks)

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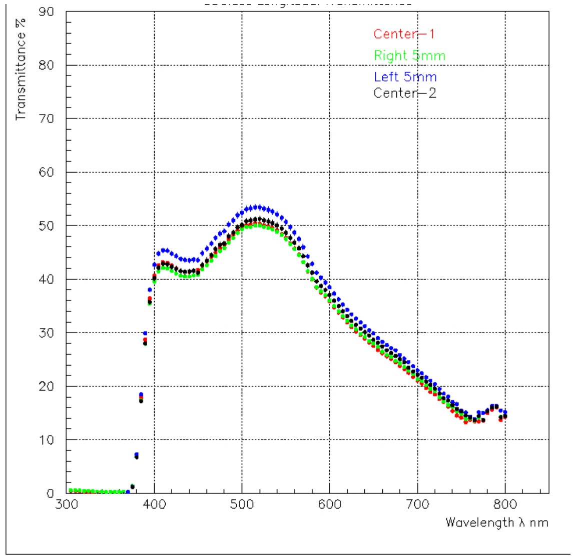
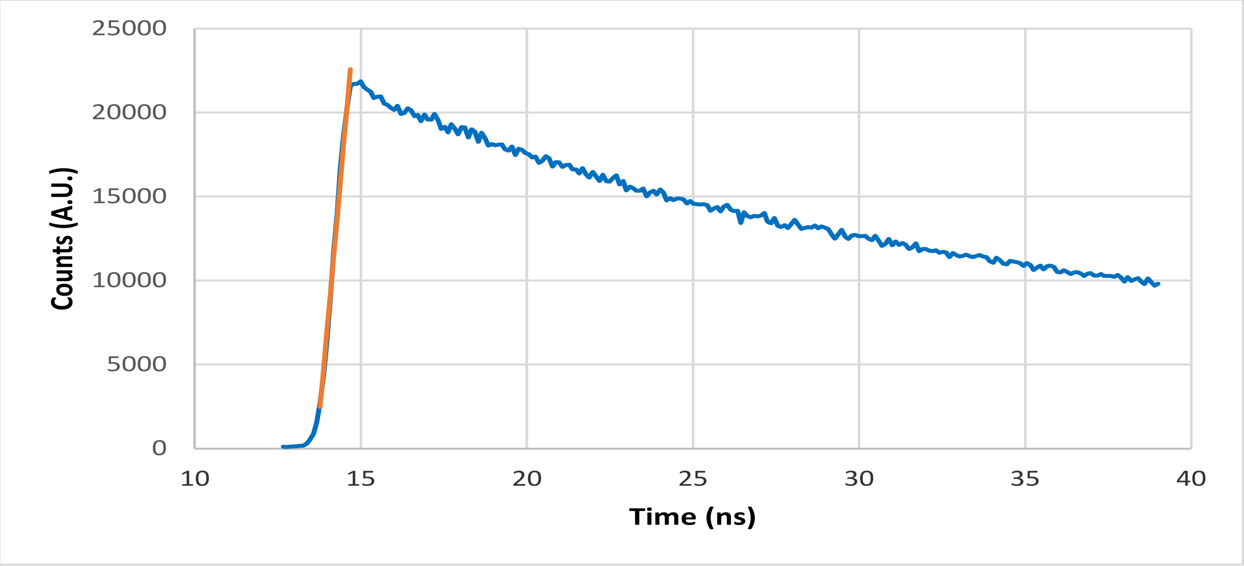
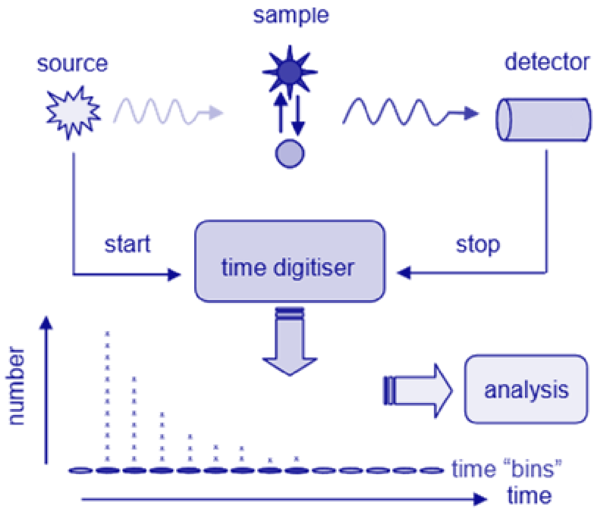
SciGlass Characterization

Longitudinal transmittance and kinetics







- ❑ With the recent optimizations in the glass matrix and the production process, the transmittance peaks around 500nm at 50% transmittance - wavelengths well matched to the photon detection of typical SiPMs.
- ❑ Further improvements in transmittance anticipated after new glass production method is implemented
- ❑ The scintillation kinetics were studied with the time-correlated single-photon counting method. A rise time with time constant ~1ns was observed – the effective decay time from a fit with a mono-exponential decay function is 46ns.

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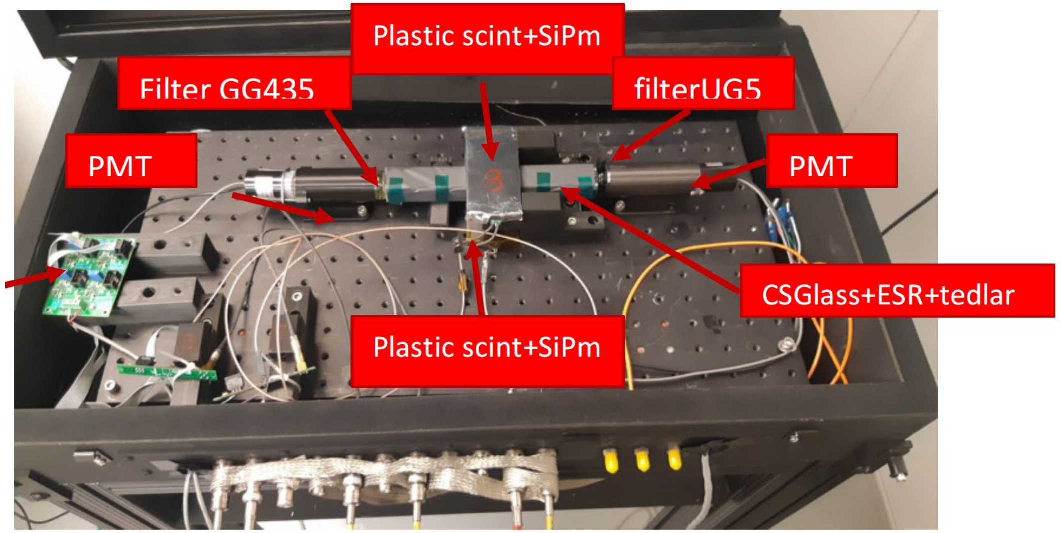
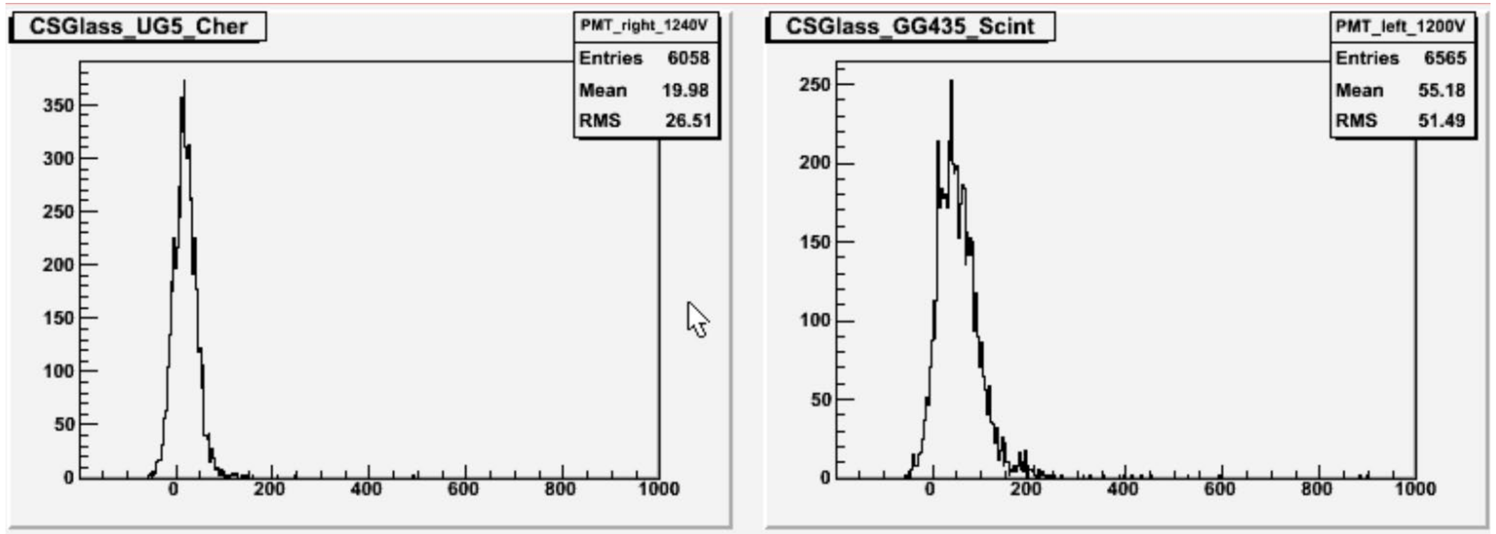
Separating Scintillation and Cherenkov Signals: Filters



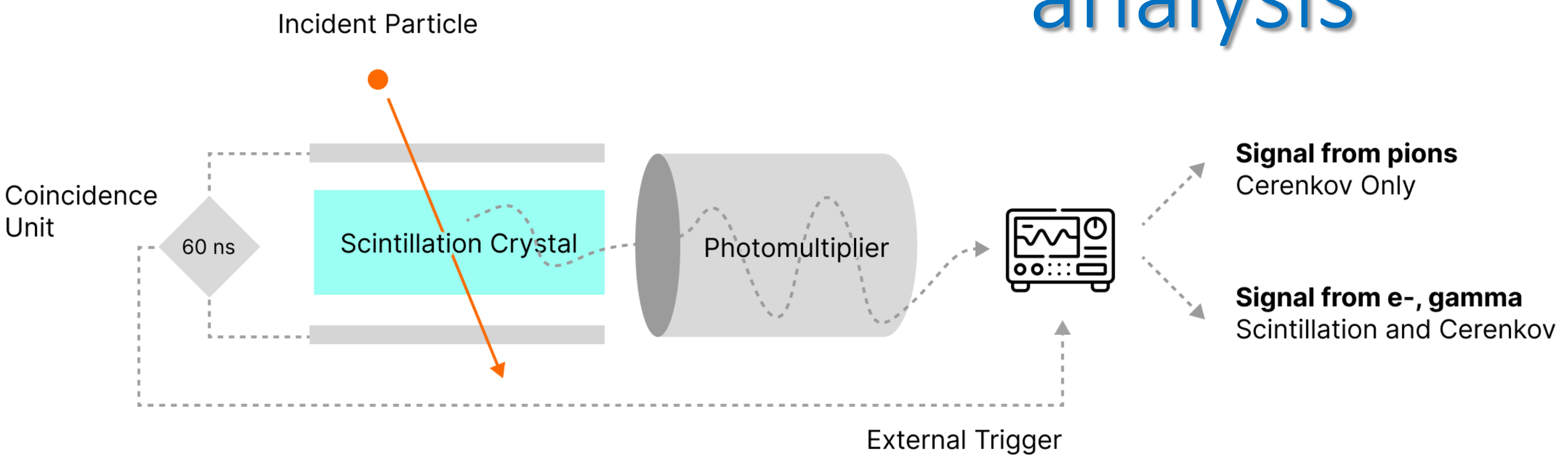


Digitized signals are noticeably different – the Cherenkov signal is narrow, while the scintillation signal is broader with a tail on the right

- Setup: testbench with optical filters: UV pass filter UG5 to select Cherenkov and low-pass band filter GG435 to select scintillation light
- Light output signals were measured with a cosmic ray trigger: plastic scintillator with SiPM readout featuring a custom designed PCB that includes bias voltage and signal
- Cherenkov and scintillation light were measured simultaneously by two fast PMTs (R6427, 28mm, 1.7ns rise time)

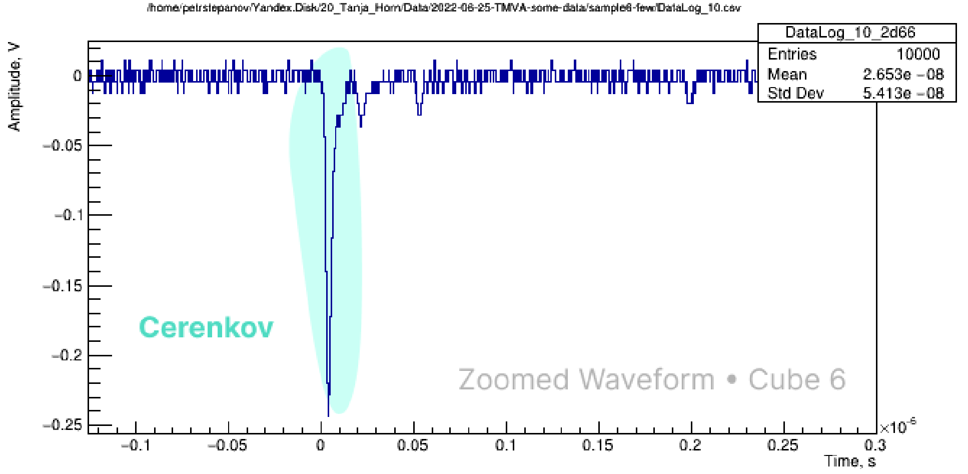
Cherenkov and scintillation light can be separated by time of arrival and analysis of the recorded waveform

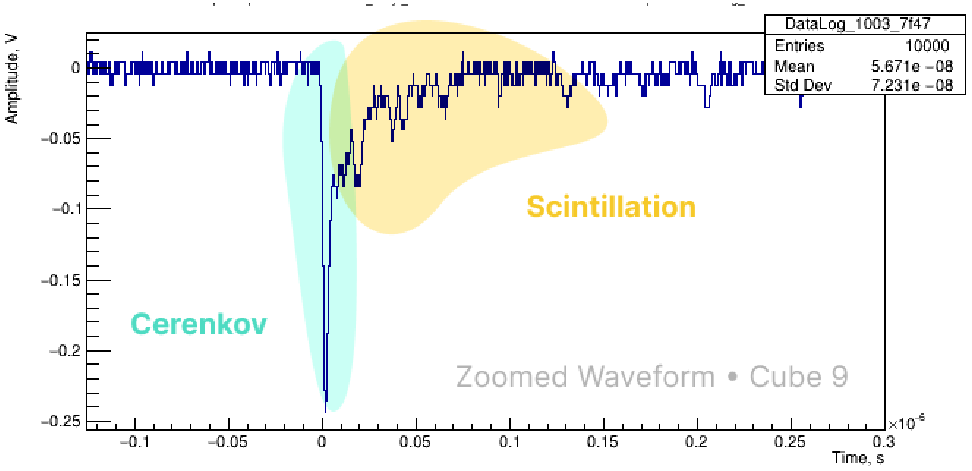
Separating Scintillation and Cherenkov Signals: waveform analysis



Signal from pions
Cerenkov Only

Signal from e-, gamma
Scintillation and Cerenkov





❑Setup: Tektronix oscilloscope MDO4034C with external trigger using the PyVisa library

❑Acquire Cherenkov-only and Cherenkov+Scintillation spectra – a few tens of thousand spectra for each

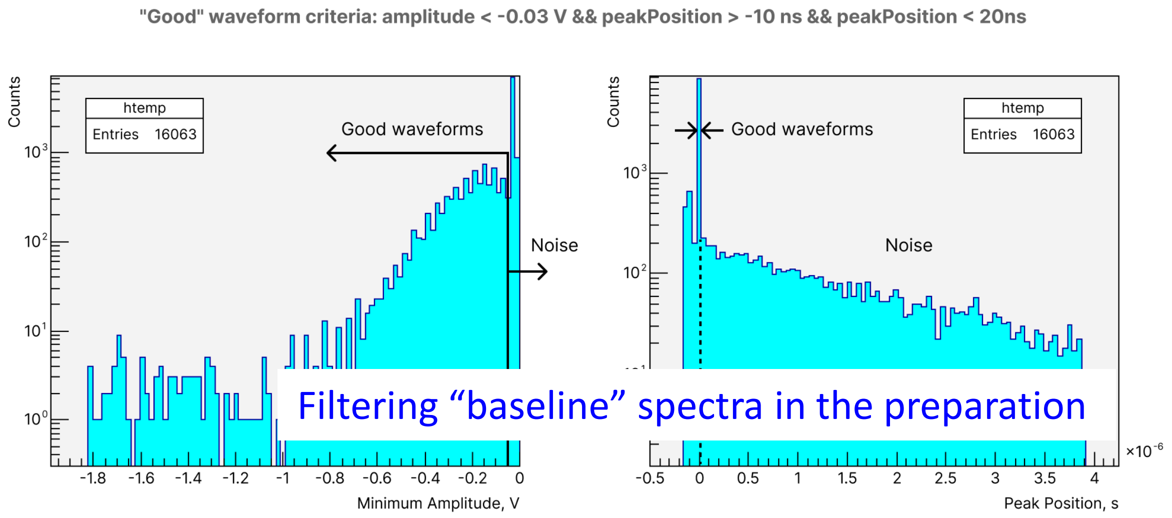
❑Use ML techniques to perform classification of “unknown” experimental spectra – CERN ROOT TMVA framework with Binary Decision Trees (BDT) and Deep Neural Networks (DNN)

Separating Scintillation and Cherenkov Signals: AI-assisted

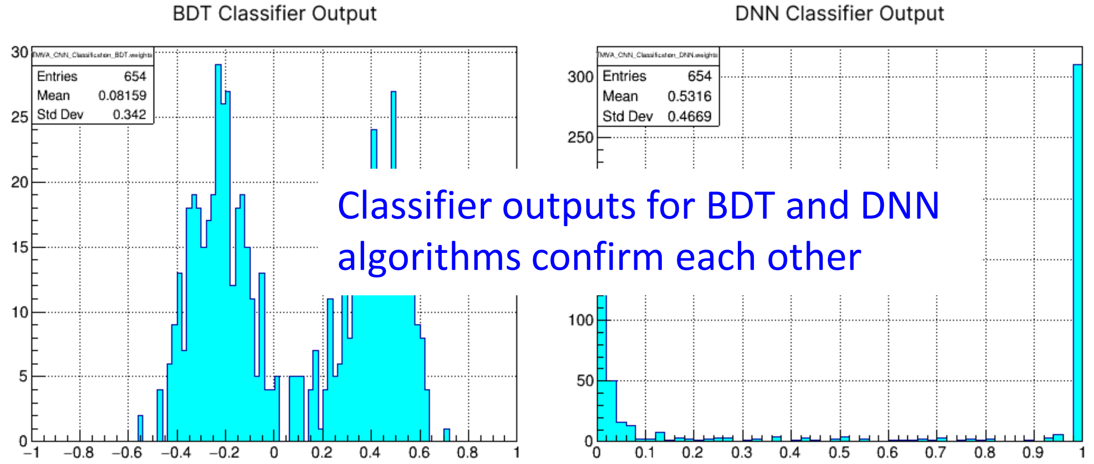
Overview of the ML algorithm used here:

- **Preparation.** Oscilloscope waveforms are processed and converted into a ROOT tree of a certain format to be loaded into the ML algorithm(s).
- **Training.** Known input data that corresponds to each classification group is given to the ML algorithm.
- **Classification (BDT, DNN).** Unknown spectra are analyzed by the trained algorithm and classified into groups.

ML technique can be used for differentiating between spectra shapes and the algorithm can be deployed in the particle analysis procedure



Filtering “baseline” spectra in the preparation



Classifier outputs for BDT and DNN algorithms confirm each other

Planned algorithm upgrades: implement multi-class classification → train the algorithm to recognize “baseline” spectra and attribute them to a third class of signals

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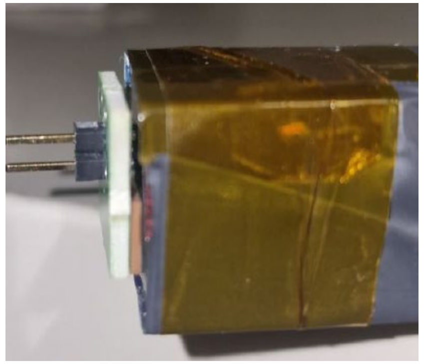
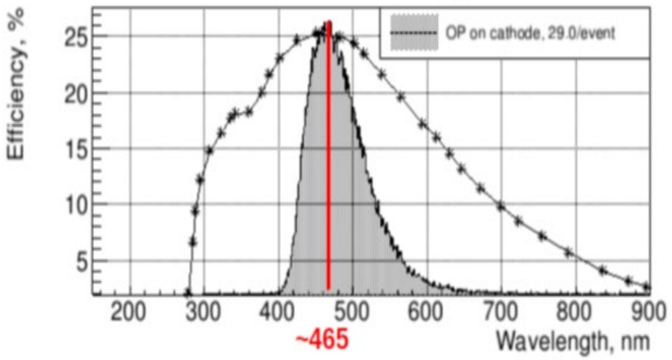
Prototype Beam Campaign to test performance at scale

Preparations for beam tests

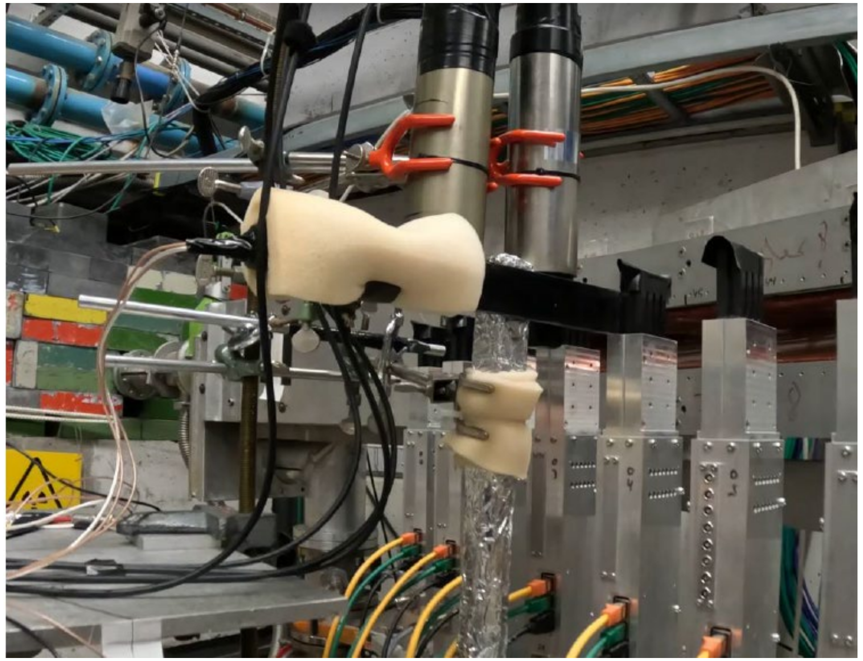
- Detector prototypes have been designed and built and are ready for beam test
- Readout chain based on PMT to baseline – difficulties with procurement
- Readout chain based on SiPM – based on our simulations expect ~30% increase in detected light compared to PMT as quantum efficiency fits the emission spectrum
- Investigating alternative beam facilities for the test campaigns
    - Test at GeV scale with clean photon beam similar to the tests carried out for SciGlass
    - Test at GeV scale with mixed electron/hadron beams
    - Test at MeV/GeV scale with hadron beams
    - Different setup at different luminosity, e.g., in the Compton Photon detector setup at JLab
    - Few hundred MeV regime instead of GeV scale to validate fundamental glass properties



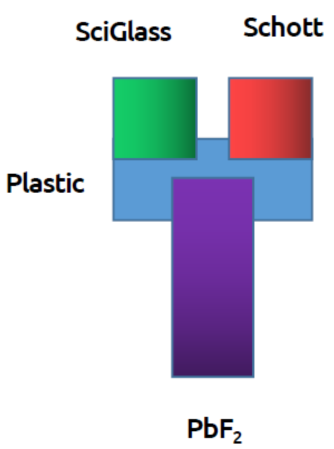


There was no opportunity to carry out a beam test campaign at GeV scale in 2023/24

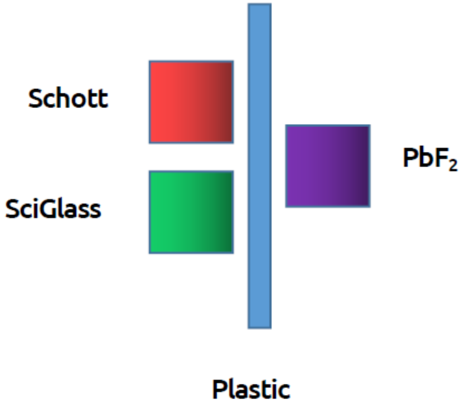
Beam Test Campaign at MeV Scale – electrons



Side view



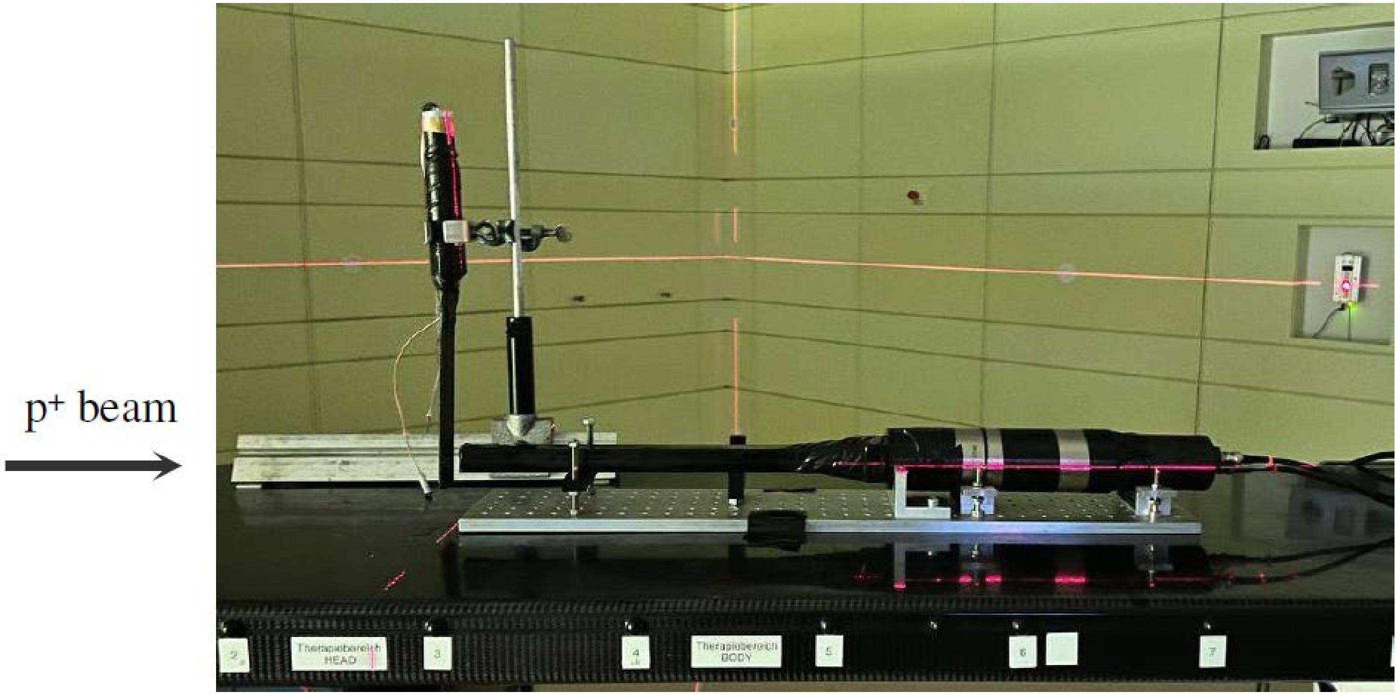
View from above

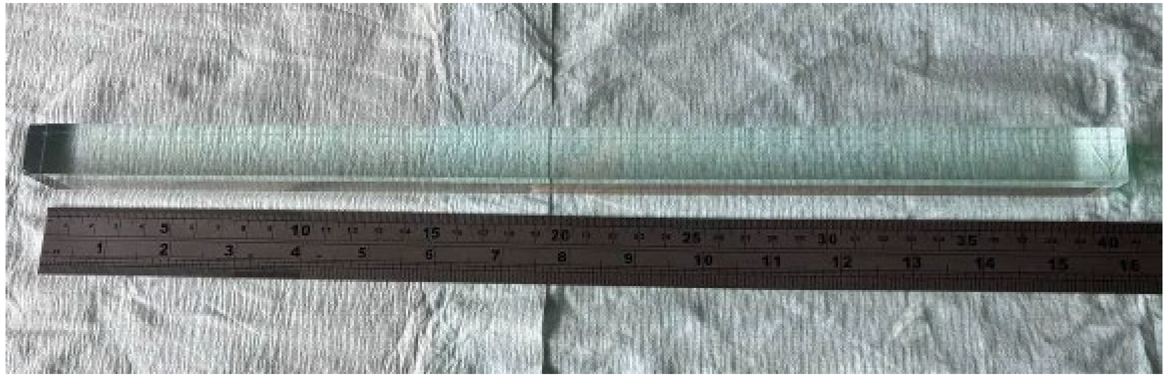


- Initial electron beam E = 855 MeV, I=25 pA
- 3 runs: different positions for different electron energy
- 4 channels: plastic, CSGlass, Schott, PbF$_2$

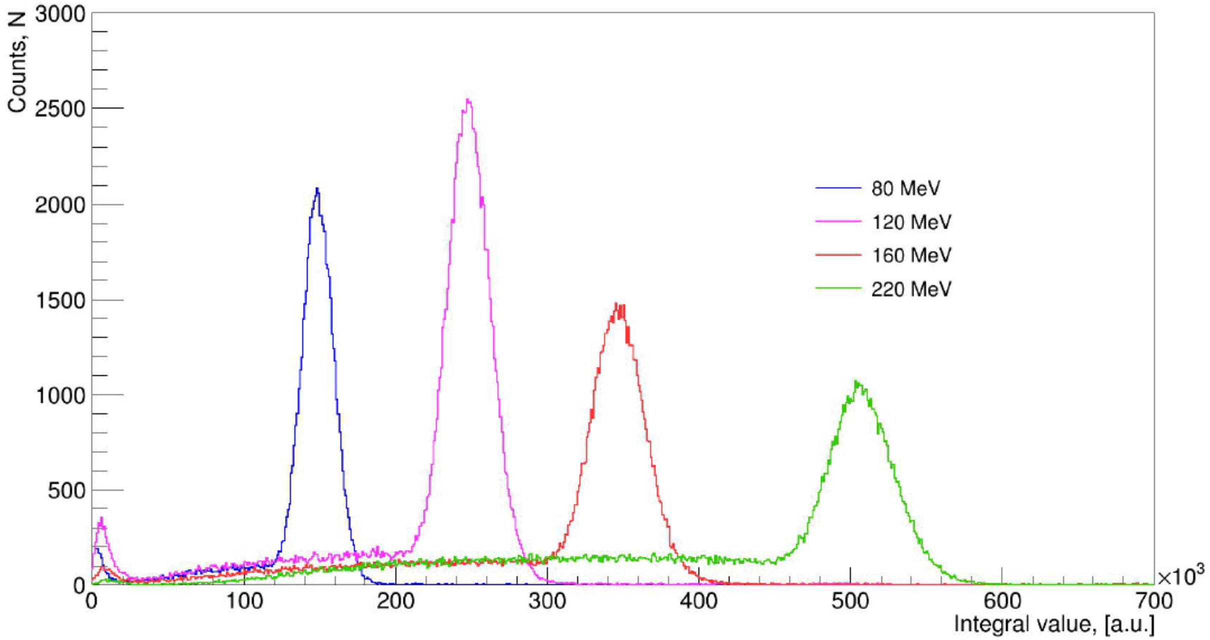
Detector	# in output file	mainz_beam1					mainz_beam2					mainz_beam3				
		HV, V	DAQ time, min	e-energy, MeV	threshold, lsb	Traces, N	HV, V	DAQ time, min	e-energy, MeV	threshold, lsb	Traces, N	HV, V	DAQ time, min	e-energy, MeV	threshold, lsb	Traces, N
Plastic	ch#0	1400	15	611-680	50	817274	1400	10	349-394.5	50	149215	1400	10	147-175	50	119007
CSGlass	ch#2	1600	15	611-631	50	355987	1600	10	349-363	50	107024	1800	10	147-155	100	75027
Schott	ch#3	1600	15	661-680	50	461471	1600	10	380-394.5	50	75352	1800	10	166-175	100	75901
PbF$_2$	ch#4	1300	15	634-655	50	817282	1300	10	365-378	50	179588	1300	10	156-165	50	142966

Beam Test Campaign at MeV Scale – protons





- Proton beam with 10 kHz count rate
- 4 runs: 80, 120, 160, 220 MeV proton energy
- Beam spots FWHM: 19.6, 13.3, 19.6, 8.1 mm
- 2 channels: plastic, CSGlass (2x2x40cm)
- Coincidence scheme: plastic AND CSGlass in 160 ns time window
- DAQ time: 5 min per run
- Trace length: 3.5 us



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Outlook

Acknowledgement: Award: DE-SC0021459

- ☐ Demonstrated an optimized glass formulation (CSGlass) to meet the general specifications for DRC
- ☐ Scaled up CSGlass blocks have been produced in lab size batches (10-20 blocks)
- ☐ Established a measurement setup and algorithm for signal processing to determine the contribution of Cherenkov light.
  - Optical filters were used to select Cherenkov light with small or no scintillation contamination and vice versa
  - Developed and tested a full waveform analysis algorithm using AI/ML techniques.
- ☐ Completed MeV scale beam test campaigns with protons and electrons
- ☐ For a complete performance evaluation with a prototype and suitable readout for NP experiments at scale need to carry out a beam test campaign at GeV scale when there is an opportunity