Precision Neutron Time-of-flight for ICF and HED Experiments

ICF Diagnostics Workshop, 6-8 October 2015

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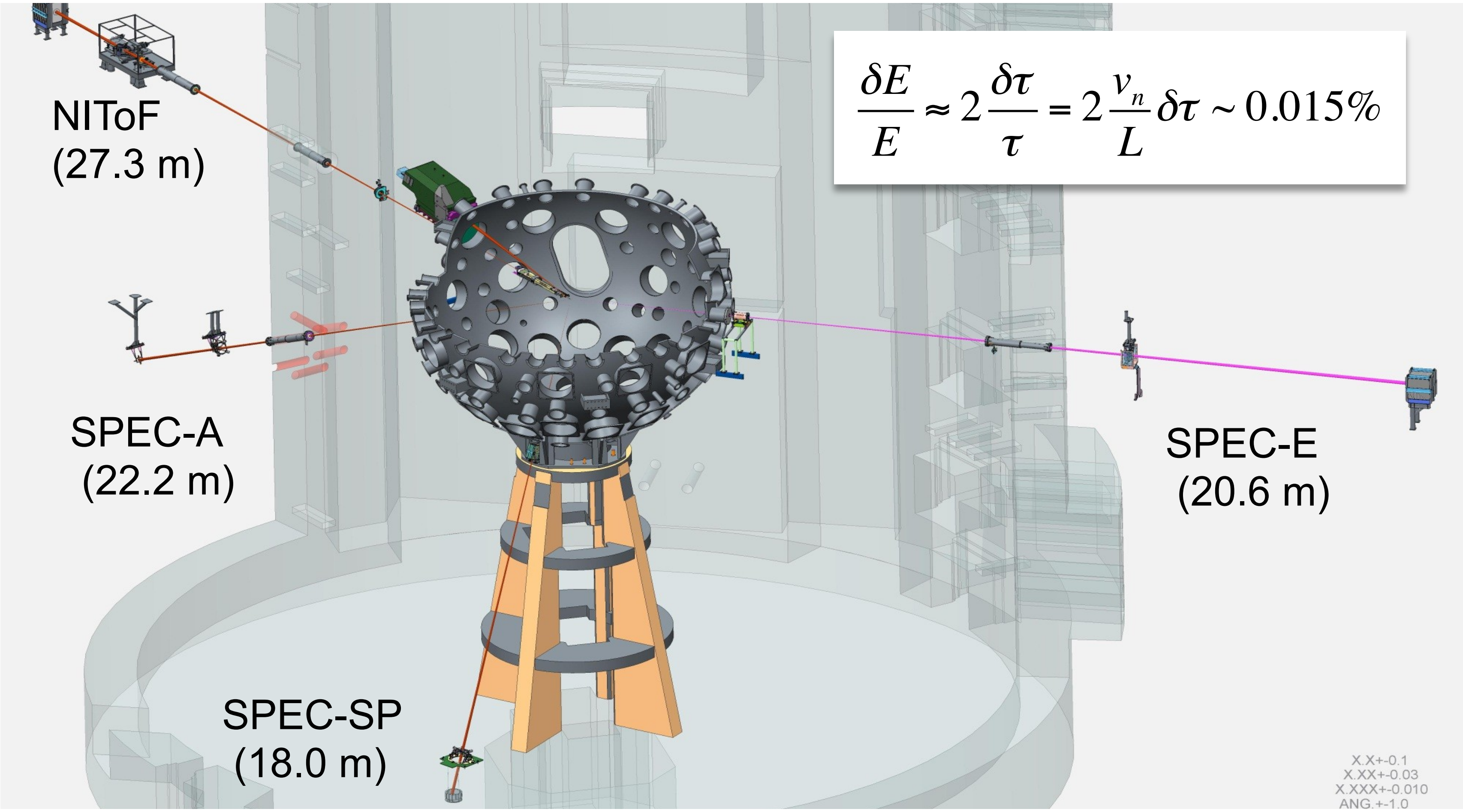
Summary

- The NIF is currently making unprecedented neutron time-of-flight measurements of both DD and DT neutrons including:
  - Unscattered Yield, Mean K.E., and variance, or "apparent ion temperature."
- These measurements have generated a number of surprises in layered implosions namely:
  - TDD ~ TDT – 0.75 keV,
  - Y_{DD} / Y_{DT} > expected equimolar reactivity
- Current systematic uncertainties don't allow strong statistical statements on important physics questions, thus…
- The Precision nToF project was created to better quantify the sources of current systematic uncertainty and to point the way to improved nToF precision.
- Since this scope is cuts across all ICF/HED facilities, it is a national project with engagement from NIF, Omega, and Z.

National ICF/HED Precision nToF Charter

- **Determine requirements for next generation of neutron time-of-flight diagnostics at HED facilities.**
- **Assess and down-select prospective technologies that address these requirements**
- **Create a 3-5 year plan to develop and implement selected technologies in facilities such as Omega, the NIF, and Z.**
- ***The balance of this talk will focus on NIF nToF issues.***
  - ***For details on Omega see talk by J. Knauer a bit later***
  - ***For the Z facility B. Jones yesterday…***

Principal nToF systems under discussion today…

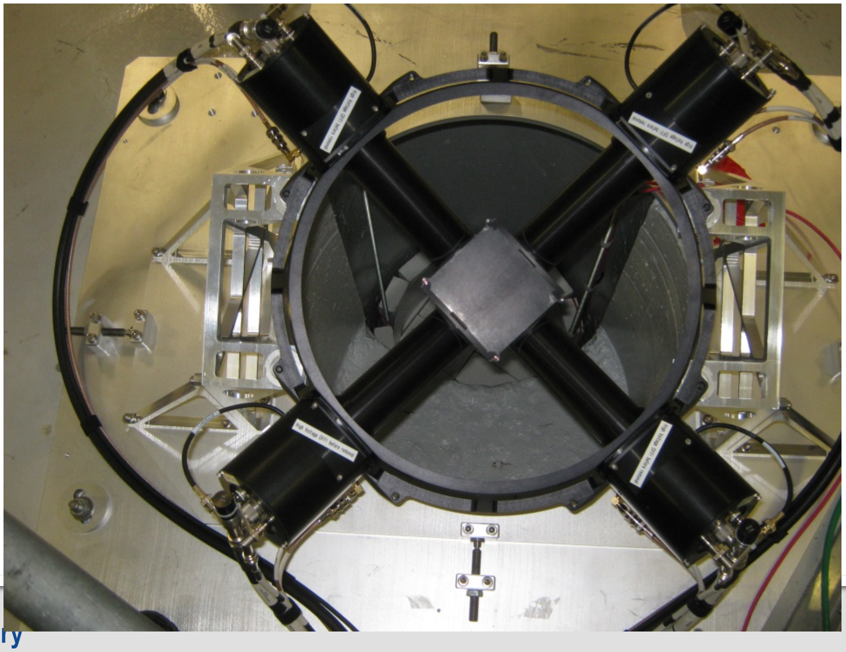


$$\frac{\delta E}{E} \approx 2\frac{\delta\tau}{\tau} = 2\frac{v_n}{L}\delta\tau \sim 0.015\%$$

NTOF Spec detectors all have fast scintillator with low afterglow, low mass housing, and 4 light detectors

- Bibenzyl/Stilbene scintillator provides good signal strength with low afterglow after peak for improved background in downscattered neutron region
- Low mass housing reduces local scattering further reducing scattering background in down scattered neutron region
- Four light detectors provide flexibility to measure many different quantities on a single shot (DD, DT, TT, RIF neutrons - customizable)

NTOF Spec SP:

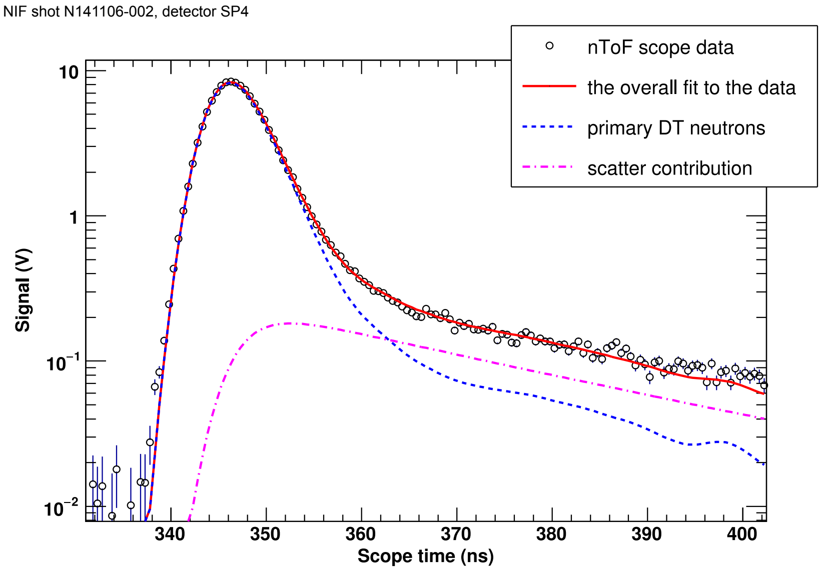


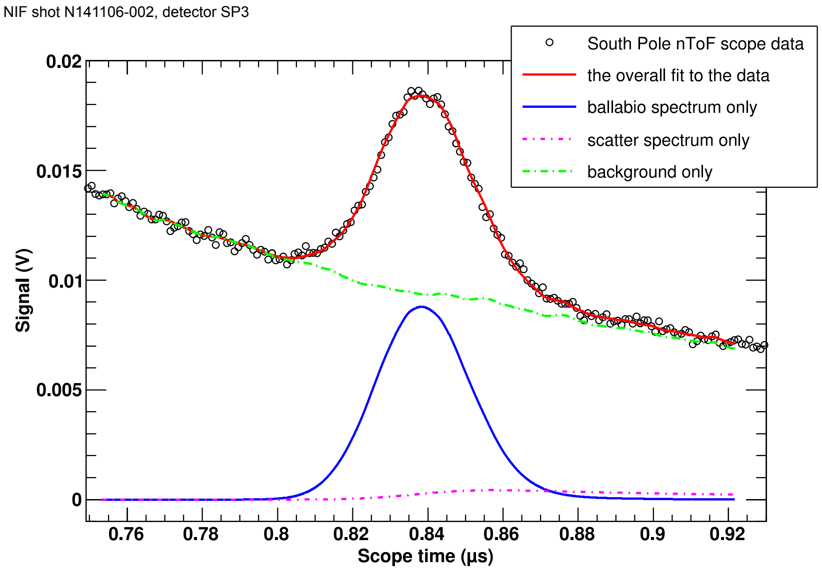
Four tubes looking at the same bibenzyl scintillator

Current NIF nToF systems report the 0th - 2nd moments spanning a dynamic range of ~300.

$Y_{unsc} = 2.8 \pm 0.04 \times 10^{15}$
$V_{DT} = 39.3 \pm 15$ km/s
$T_{ion} = 4.43 \pm 0.14$ keV

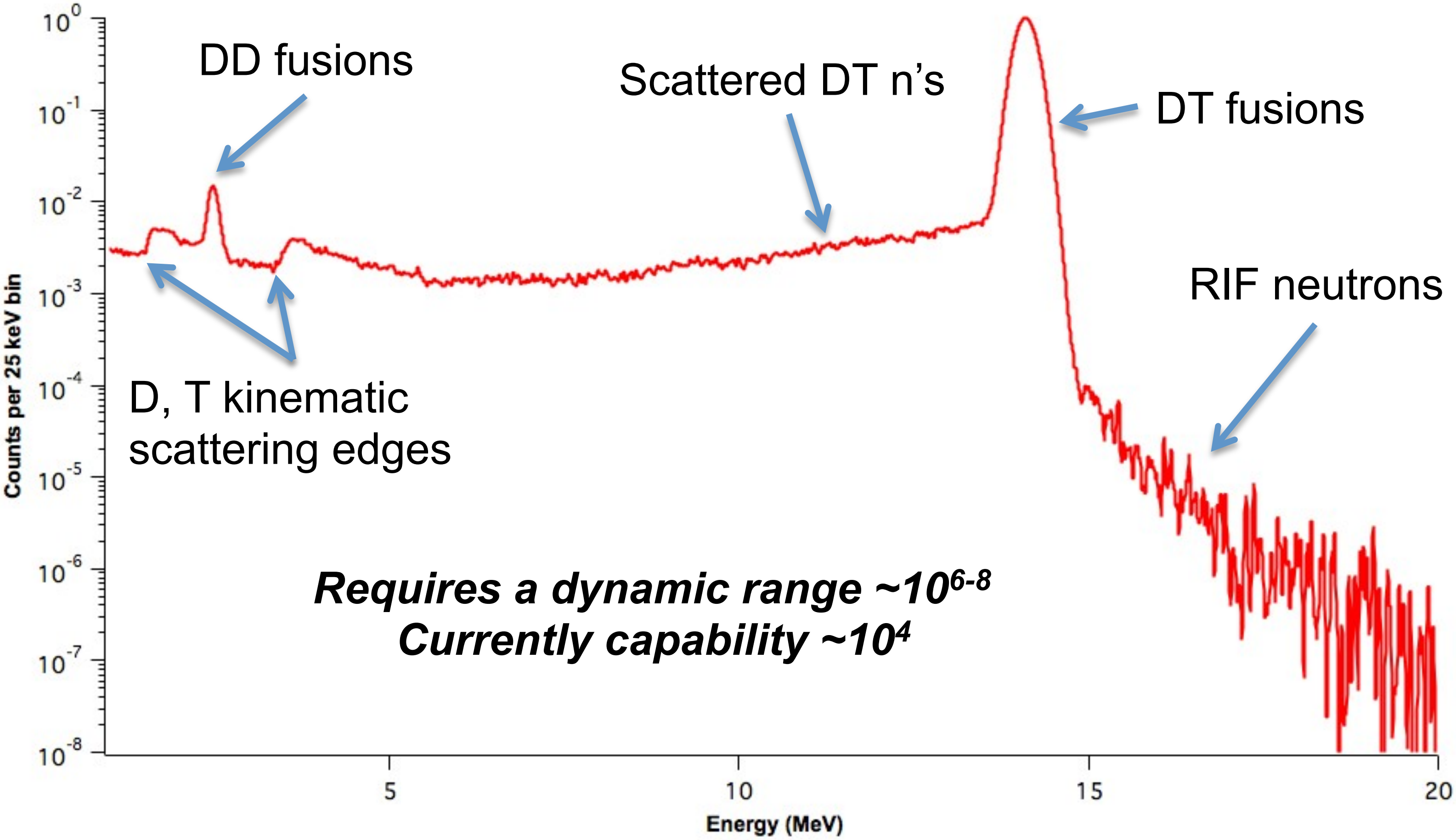
$Y_{unsc} = 1.02 \pm 0.09 \times 10^{13}$
$V_{DT} = 40 \pm 15$ km/s
$T_{ion} = 4.04 \pm 0.17$ keV


NIF shot N141106-002, detector SP4


NIF shot N141106-002, detector SP3

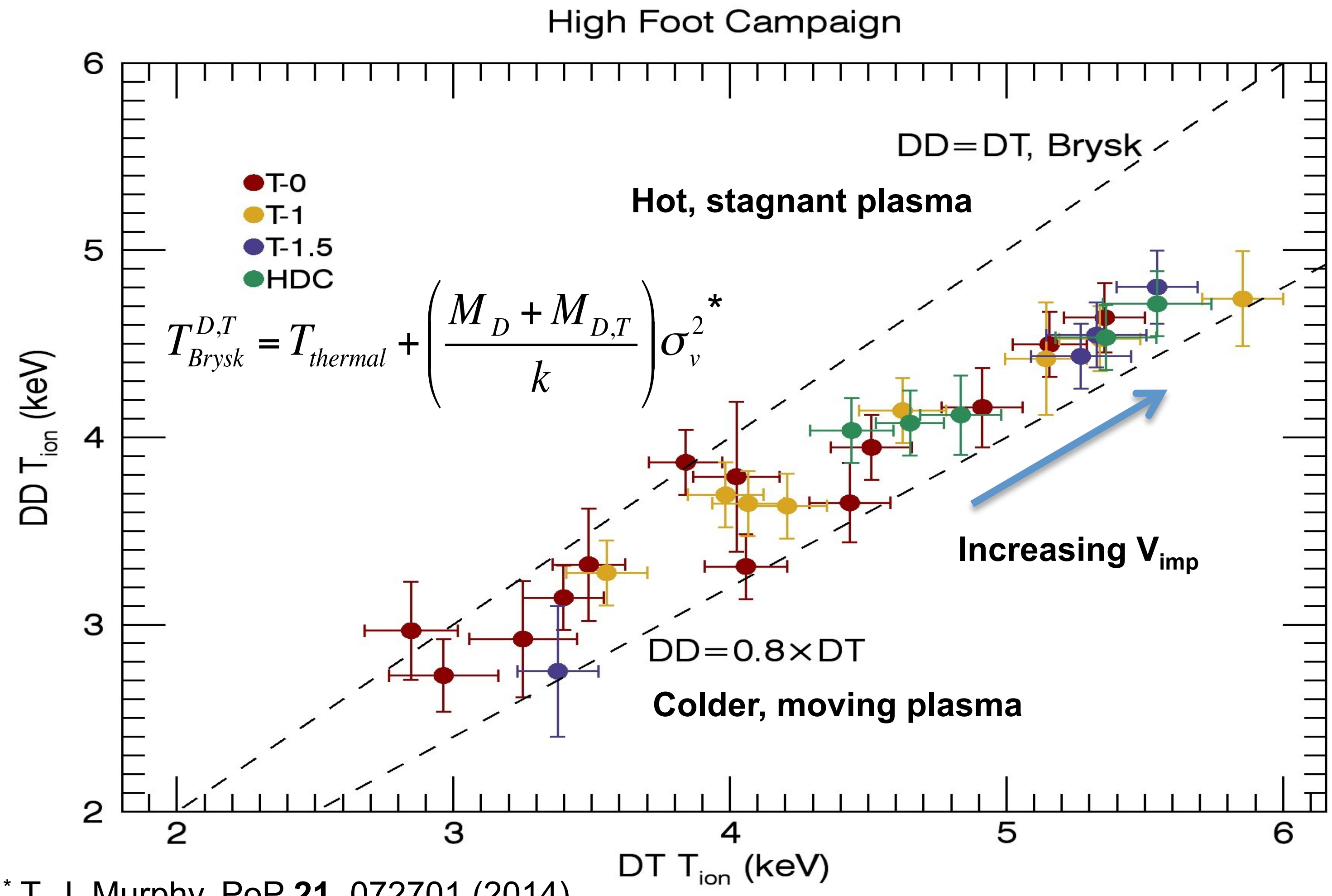
DT and DD fusion neutron peak moments are measured with % level accuracy.

Ultimately precision nToF should measure the full neutron spectrum in HED experiments…



Requires a dynamic range ~$10^{6\text{-}8}$
Currently capability ~10^4

On recent layered implosions nToF measurements show a ~0.75 keV difference in the apparent DD and DT ion temperatures



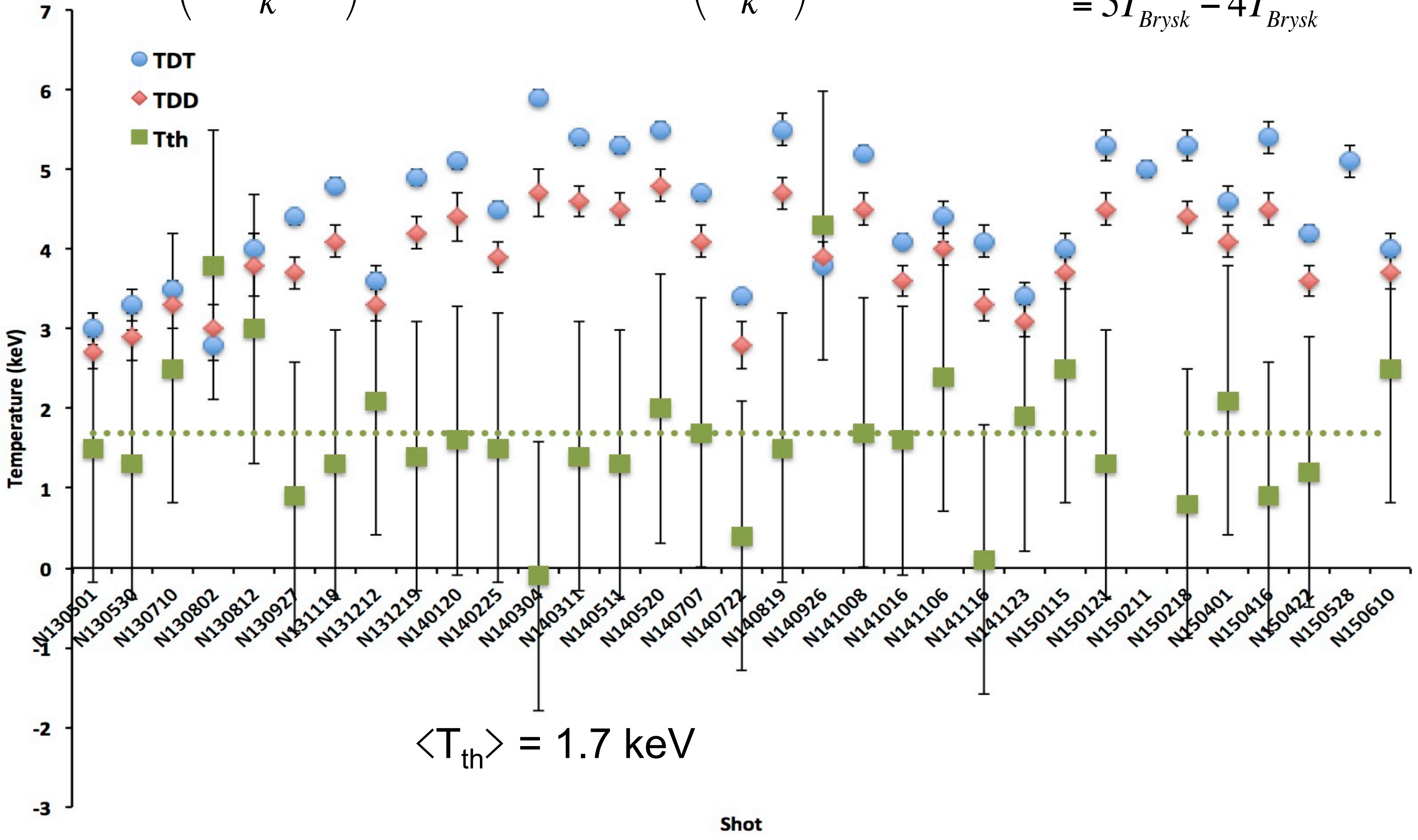
$$T_{Brysk}^{D,T} = T_{thermal} + \left(\frac{M_D + M_{D,T}}{k} \right) \sigma_v^2 {}^*$$

[*] T. J. Murphy, PoP **21**, 072701 (2014)

Blind application of error propagation leads to poor sensitivity to T_{th} via Murphy's formalism..

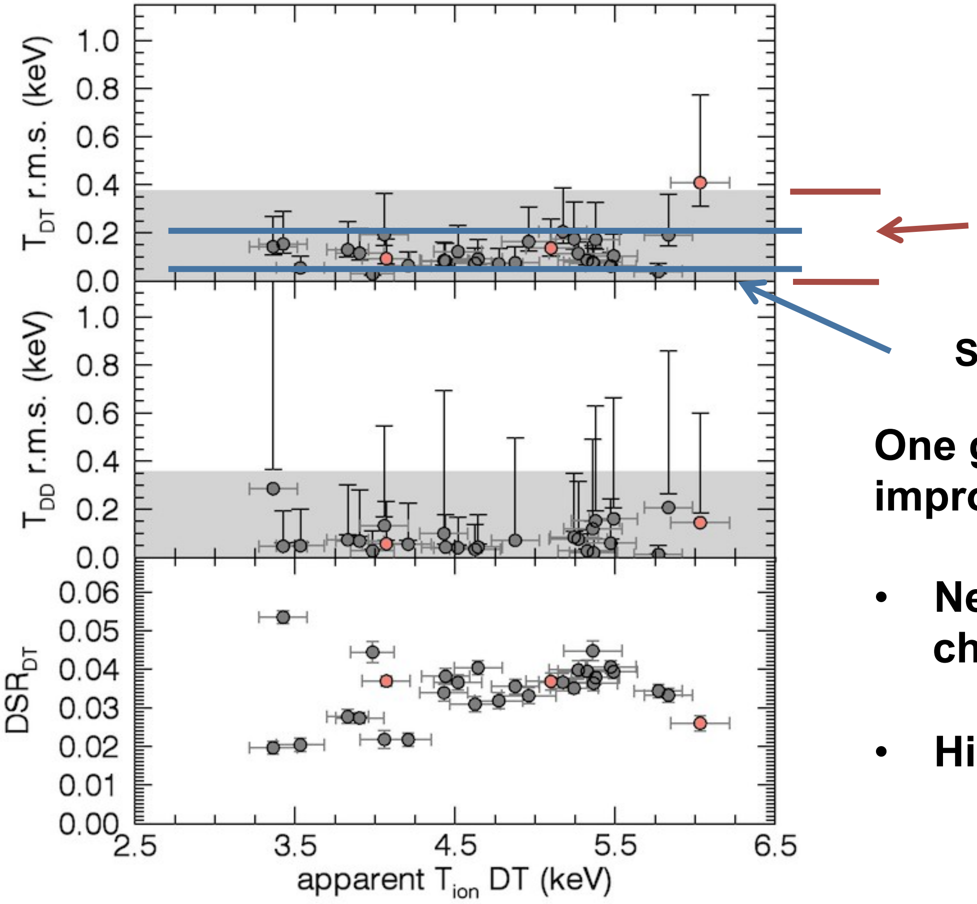
$$T^{DT}_{Brysk} = T_{thermal} + \left(\frac{M_D + M_T}{k}\right)\sigma_v^2 \;\; \& \;\; T^{DD}_{Brysk} = T_{thermal} + \left(\frac{2M_D}{k}\right)\sigma_v^2$$

$$\begin{aligned} T_{thermal} &= \left(M_D + M_T\right)T^{DD}_{Brysk} - 2M_D T^{DT}_{Brysk} \\ &= 5T^{DD}_{Brysk} - 4T^{DT}_{Brysk} \end{aligned}$$



$\langle T_{th} \rangle = 1.7$ keV

Further, detector systematic uncertainties dominate LoS variability measurements



Magnitude of systematic unc.

Shot-to-shot variability of T_{ion} RMS

One goal of the Precision nToF project is to improve systematic uncertainties through:

- **New detector systems with improved characteristics**
- **Higher sensitivity digital recording**

Finally, pursuing higher moment analysis of the fusion spectrum requires, precise knowledge of the system IRF

Physical Quantities

$\langle u_\Omega \rangle$ ➔ **LoS projected mean fluid velocity**

$\langle \kappa \rangle$ ➔ **Reactants CoM KE shift**

$\langle \tau \rangle$ ➔ **T_{ion}**

$\langle \tau^2 \rangle$ ➔ **T_{ion} variance**

Spectral moments (fit pars) required

Current

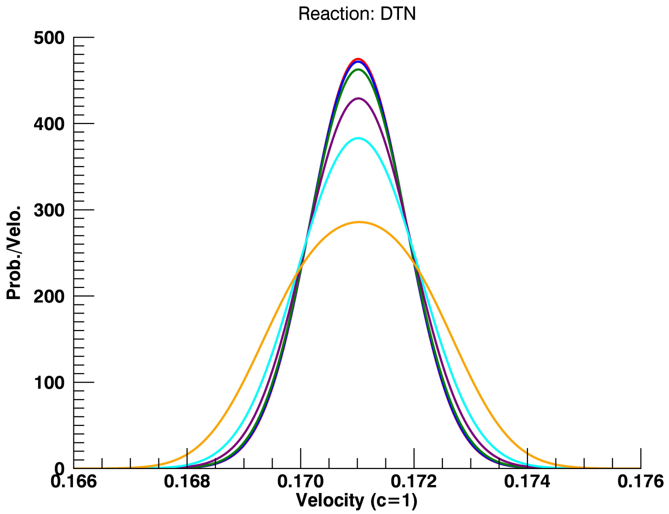
$$\langle \omega^1 \rangle = \langle u_\Omega \rangle + \langle \kappa \rangle + (1 + \tfrac{1}{2} v_0^2) \langle \tau \rangle / v_0 +$$

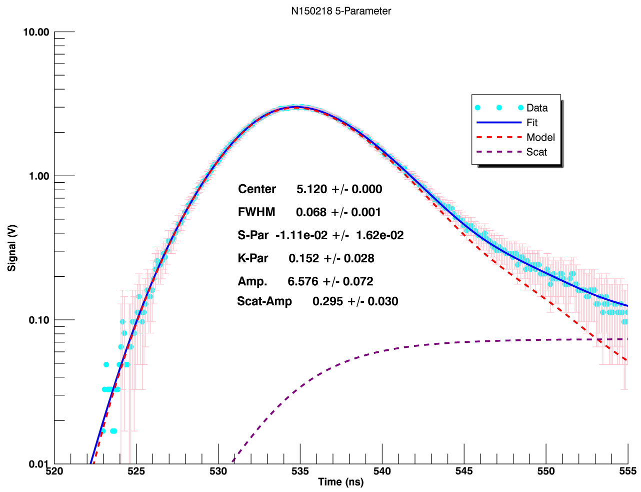
$$\langle \omega^2 \rangle = \langle \tau \rangle + \langle u_\Omega^2 \rangle + 2 \langle \kappa u_\Omega \rangle + \ldots$$

New

$$\langle \omega^3 \rangle = 3 \langle \tau u_\Omega \rangle + \langle u_\Omega^3 \rangle + \ldots$$

$$\langle \omega^4 \rangle = 3 \langle \tau^2 \rangle + 6 \langle \tau u_\Omega^2 \rangle + \langle u_\Omega^4 \rangle + \ldots$$





Current (Fall 2015)Precision nTof Performance Goals

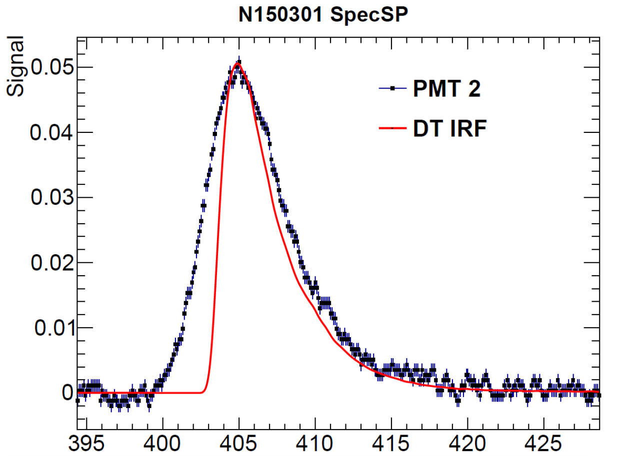
- Operate at fusion yields as high as 1 x 10^{16} to 1.2 x 10^{19} (33 kJ to 40 MJ).
- Produce a linear output signal over this yield range to better than 1% accuracy.
- Measure the absolute neutron fluence at the detector to better than 0.5%.
- Measure the first 4 central moments of the DT and DD neutron peaks to the following accuracy:

Moment	Precision
1st	0.02%
2nd	100 eV
3rd	0.3%
4th	1%

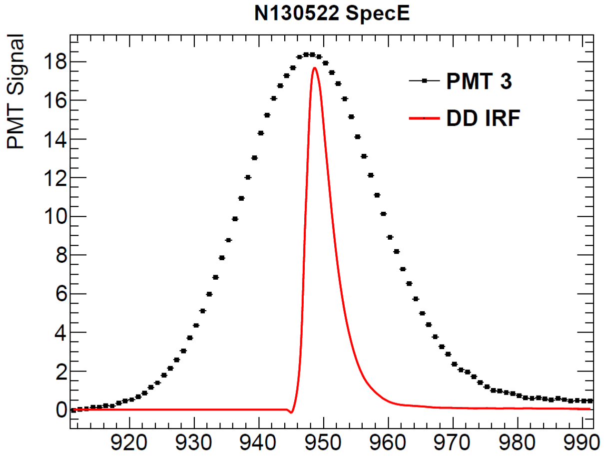
High Level Plan

- Define physics requirements for next generation of nToF diagnostics at HED facilities. (c.f. previous talk by Spears)
- Assess current detector performance in context of new requirements.
- Assess and down-select prospective technologies
- Create a 3-5 year plan to develop and implement selected technologies in facilities such as Omega, the NIF, and Z.

Status of 2nd moment systematic uncertainty understanding…



PMT#	SpecSP	SpecE	SpecA
1	2.11	2.38	2.13
2	2.04	2.25	2.05
3	2.37	2.07	2.04
σ	0.17	0.16	0.05



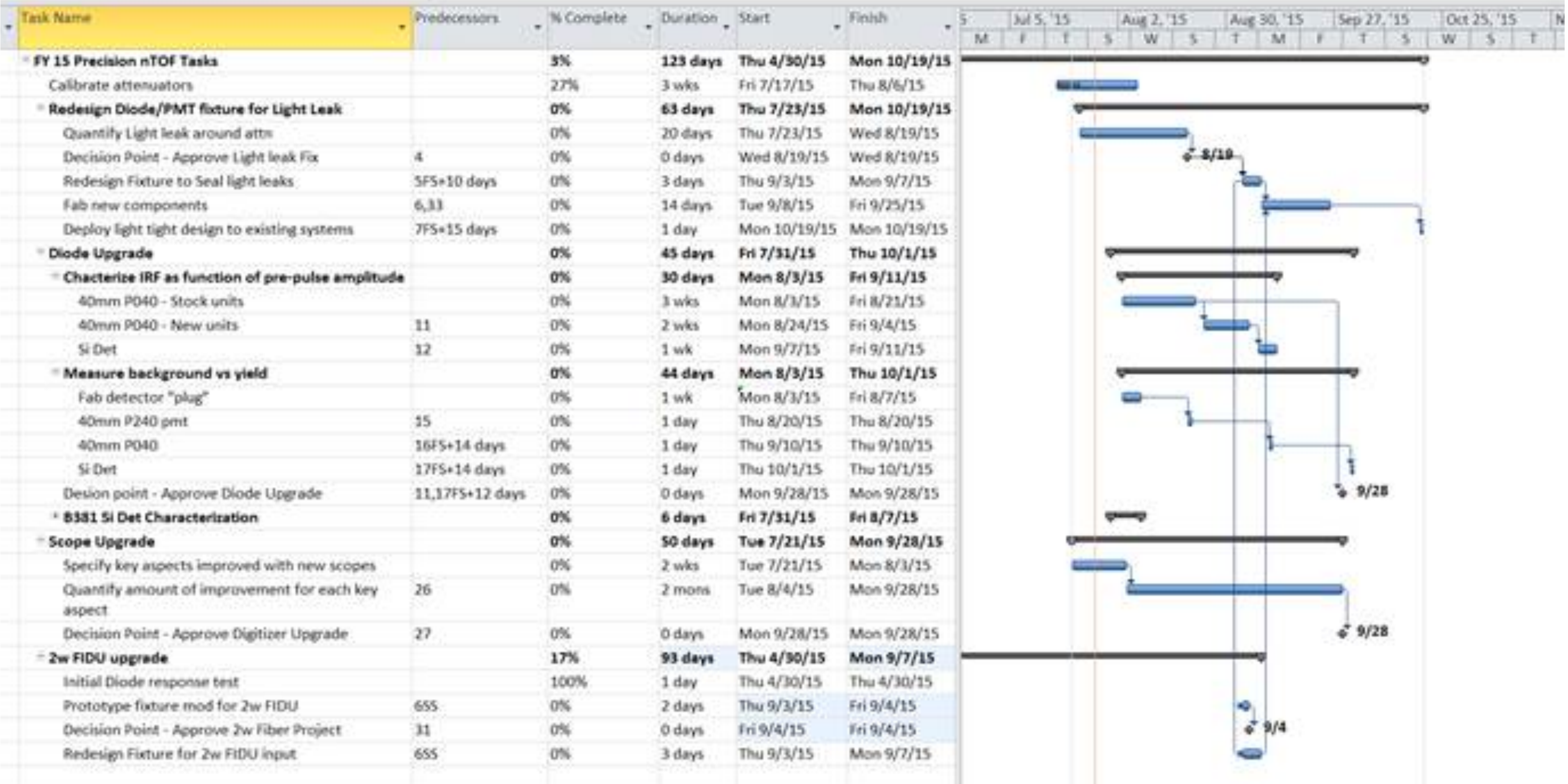
PMT#	SpecSP	SpecE	SpecA
2	2.32	2.30	2.32
3	2.35	2.29	2.33
σ	0.01	0.01	0.01

Source	Unc. (eV)
IRF (Relative)	120
Scattering	50
Fit Type	100
Fit Results	50-100
Timing Shot	?
IRF Global	?
Current	~240

Both detector IRF knowledge and effective bit depth are major contributors to this budget

Precision nToF will initially focus on assessing these issues.

The Precision nToF plan is managed through the NIF Diagnostics Engineering Team…



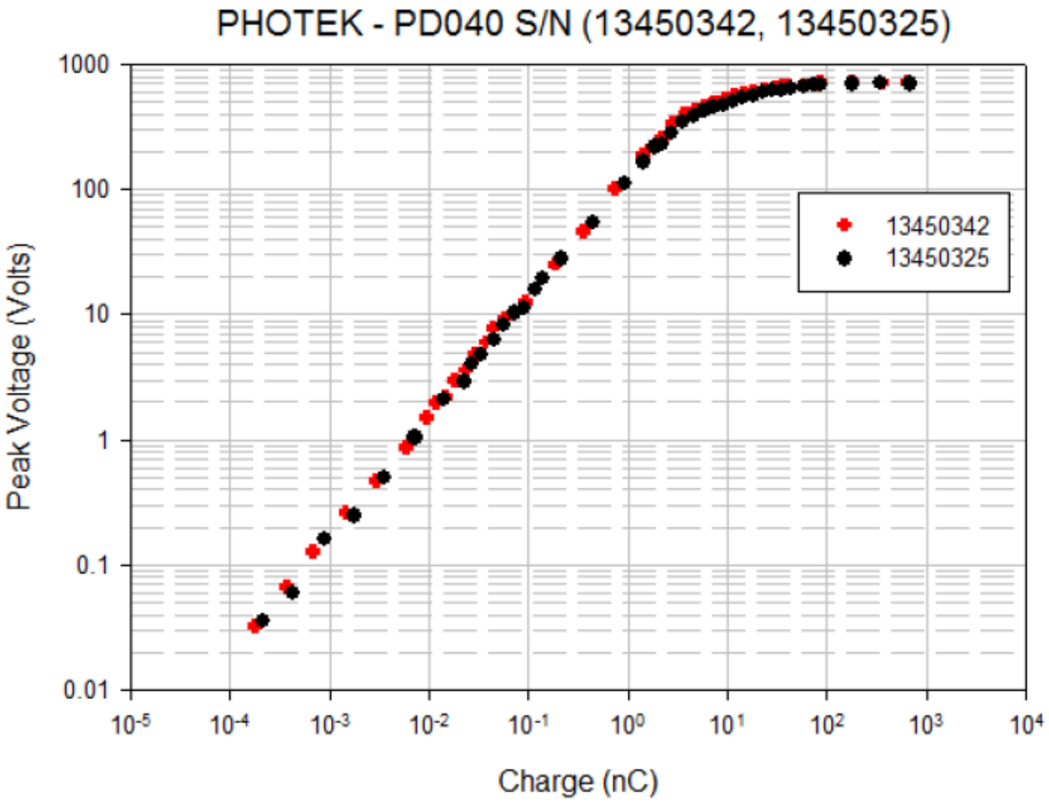
Task Name	Predecessors	% Complete	Duration	Start	Finish
FY 15 Precision nTOF Tasks		**3%**	**123 days**	**Thu 4/30/15**	**Mon 10/19/15**
Calibrate attenuators		27%	3 wks	Fri 7/17/15	Thu 8/6/15
Redesign Diode/PMT fixture for Light Leak		**0%**	**63 days**	**Thu 7/23/15**	**Mon 10/19/15**
Quantify Light leak around attn		0%	20 days	Thu 7/23/15	Wed 8/19/15
Decision Point - Approve Light leak Fix	4	0%	0 days	Wed 8/19/15	Wed 8/19/15
Redesign Fixture to Seal light leaks	5FS+10 days	0%	3 days	Thu 9/3/15	Mon 9/7/15
Fab new components	6,33	0%	14 days	Tue 9/8/15	Fri 9/25/15
Deploy light tight design to existing systems	7FS+15 days	0%	1 day	Mon 10/19/15	Mon 10/19/15
Diode Upgrade		**0%**	**45 days**	**Fri 7/31/15**	**Thu 10/1/15**
Chacterize IRF as function of pre-pulse amplitude		**0%**	**30 days**	**Mon 8/3/15**	**Fri 9/11/15**
40mm P040 - Stock units		0%	3 wks	Mon 8/3/15	Fri 8/21/15
40mm P040 - New units	11	0%	2 wks	Mon 8/24/15	Fri 9/4/15
Si Det	12	0%	1 wk	Mon 9/7/15	Fri 9/11/15
Measure background vs yield		**0%**	**44 days**	**Mon 8/3/15**	**Thu 10/1/15**
Fab detector "plug"		0%	1 wk	Mon 8/3/15	Fri 8/7/15
40mm P240 pmt	15	0%	1 day	Thu 8/20/15	Thu 8/20/15
40mm P040	16FS+14 days	0%	1 day	Thu 9/10/15	Thu 9/10/15
Si Det	17FS+14 days	0%	1 day	Thu 10/1/15	Thu 10/1/15
Desion point - Approve Diode Upgrade	11,17FS+12 days	0%	0 days	Mon 9/28/15	Mon 9/28/15
B381 Si Det Characterization		**0%**	**6 days**	**Fri 7/31/15**	**Fri 8/7/15**
Scope Upgrade		**0%**	**50 days**	**Tue 7/21/15**	**Mon 9/28/15**
Specify key aspects improved with new scopes		0%	2 wks	Tue 7/21/15	Mon 8/3/15
Quantify amount of improvement for each key aspect	26	0%	2 mons	Tue 8/4/15	Mon 9/28/15
Decision Point - Approve Digitizer Upgrade	27	0%	0 days	Mon 9/28/15	Mon 9/28/15
2w FIDU upgrade		**17%**	**93 days**	**Thu 4/30/15**	**Mon 9/7/15**
Initial Diode response test		100%	1 day	Thu 4/30/15	Thu 4/30/15
Prototype fixture mod for 2w FIDU	65S	0%	2 days	Thu 9/3/15	Fri 9/4/15
Decision Point - Approve 2w Fiber Project	31	0%	0 days	Fri 9/4/15	Fri 9/4/15
Redesign Fixture for 2w FIDU input	65S	0%	3 days	Thu 9/3/15	Mon 9/7/15

With the following major technical elements…

- Assessment of photo-detector impacts on system IRF
  - Linearity
  - Shift invariance
- Scope strategies to mitigate a non shift invariant IRF.
  - See A. Moore talk next
- Study the practicability of in-situ IRF generation via 2-ω fidu.
- Assessment of detector backgrounds from scattered radiation in the scintillator
  - Determine the cross over point where optical filtering cannot accommodate increased yields
- Scope new photo-detector designs to produce a shift invariant IRF.

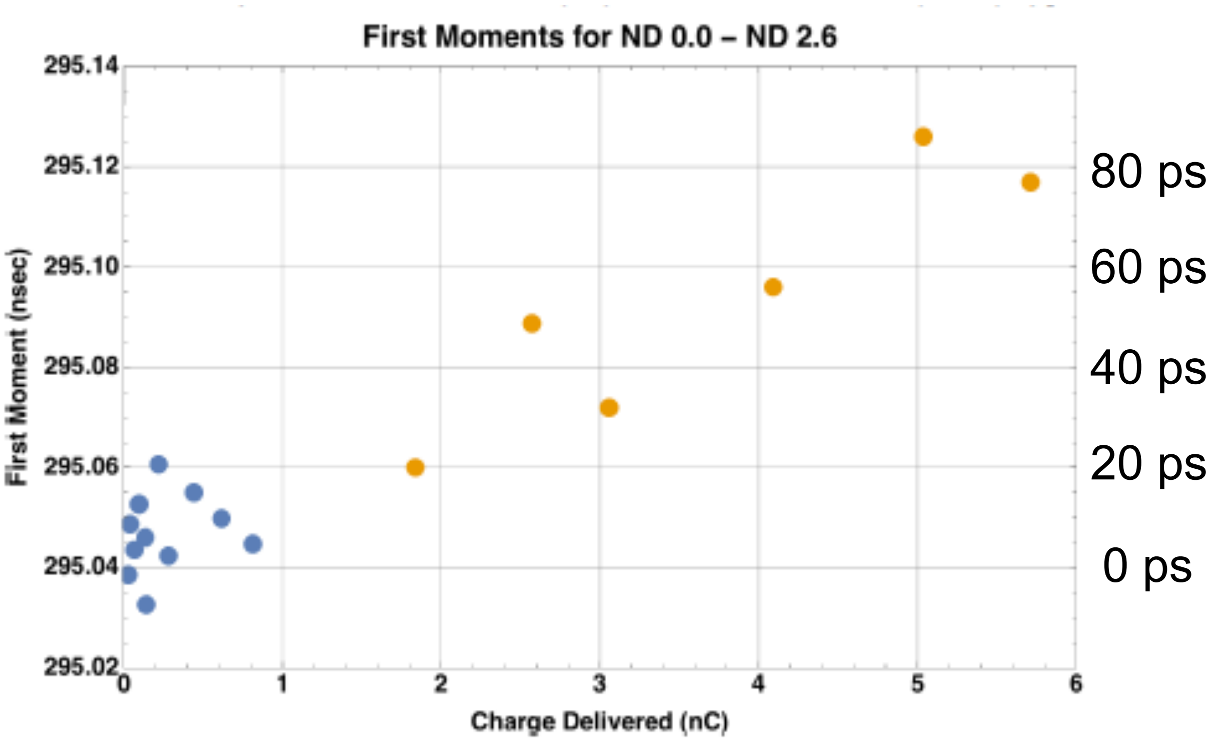
What follows is a snapshot status report on the above plan.

Impulse measurments show that the PD-040 appears to being saturating around 4 nC



Typical NIF shots result in ~2 nC being drawn from the tube

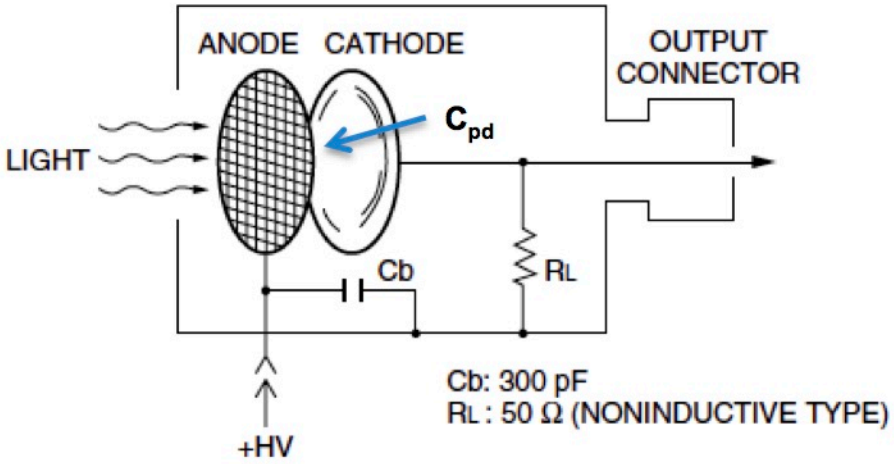
Impulse measurements also show a 1st moment shift show of ~15 ps/nC walk..



At 18 m 80 ps corresponds to ~12 km/s

Performance consistent with high resistivity cathode

Behavior appears consistent with a simple capacitor model of the detector



Cb: 300 pF
RL : 50 Ω (NONINDUCTIVE TYPE)

Where: $C_{pd} = \frac{A}{\Delta}\varepsilon_o = \frac{\pi D^2}{4\Delta}\cdot 8.8\frac{\text{pf}}{\text{m}}$

A = photocathode area
Δ = anode-cathode separation

If a bias voltage V_b is used, then the stored charge $Q_{stor} = C_{pd} \bullet V_b$.

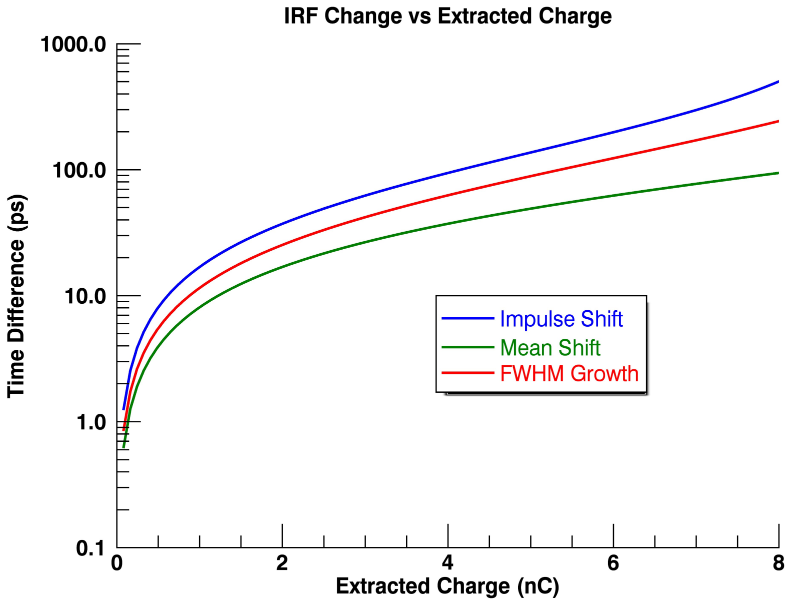
If charge Q_{ex} is extracted from the photo-cathode, the gap bias is reduced by Q_{ex} / C_{pd} resulting in a subsequent transit time of:

$$\tau_{trans} = \frac{\Delta}{v_{avg}} = \frac{2\cdot\Delta}{v_{pk}} = \Delta\sqrt{\frac{2m_e}{V_b - \frac{Q_{ex}}{C_{pd}}}} = 33.72\frac{\text{nsV}^{1/2}}{\text{cm}}\cdot\frac{\Delta}{\sqrt{V_b - \frac{Q_{ex}}{C_{pd}}}}$$

Key assumption here is that the charge line storage is unavailable…

This model provides estimates of IRF 1st and 2nd moment shifts due to extracted charge from a Gaussian signal…

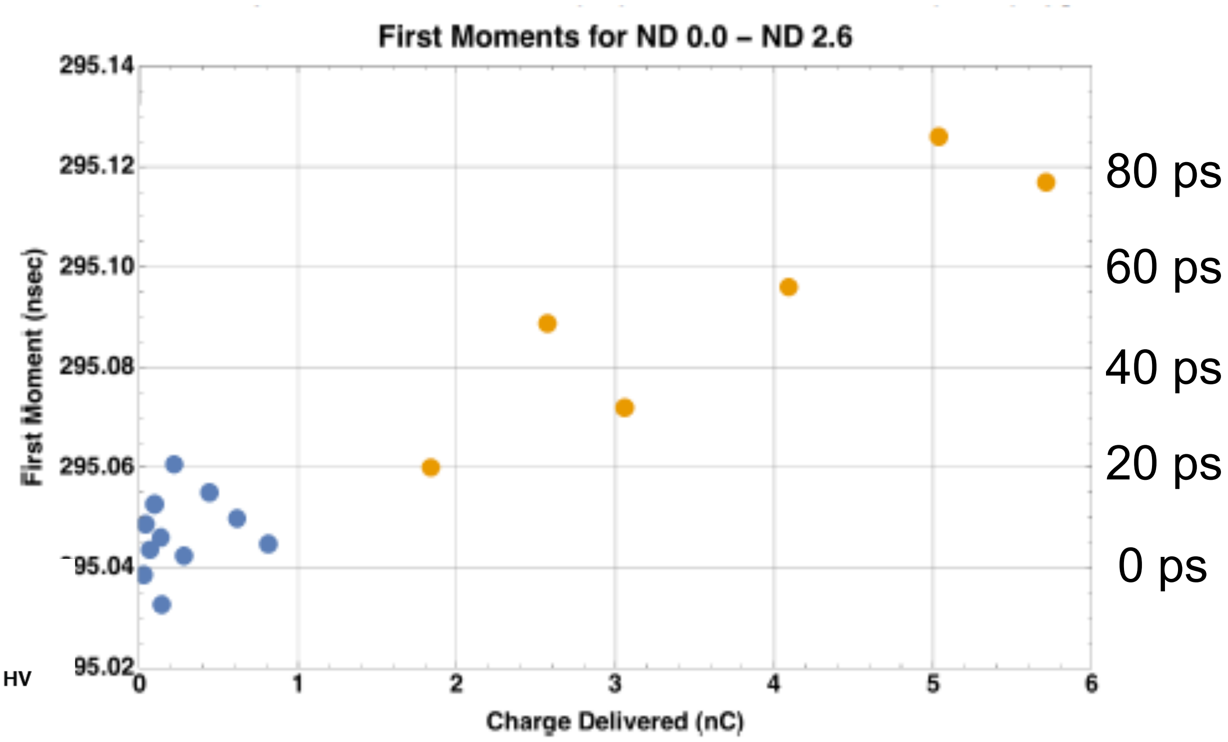
Q_{ext} (nc)	Impulse (ps)	1st Mom (ps)	FWHM (ps)
1	16.9	8.1	11.5
2	37.2	16.9	25.3
3	62.3	26.6	42.0
4	94.2	37.2	62.6
5	136.9	49.0	88.8



NB - Typical values for the FWHM of a system IRF ~1-2 ns.

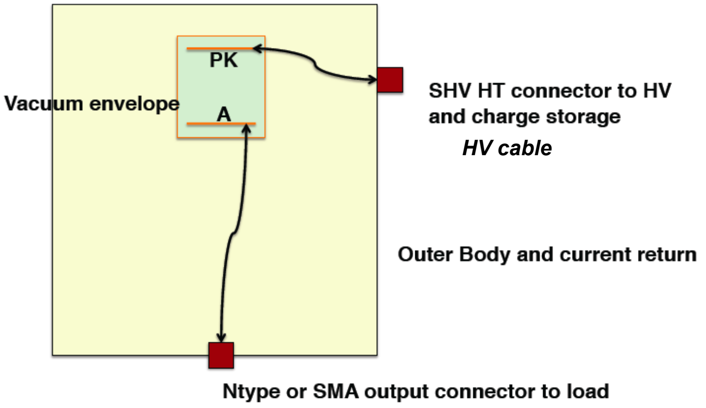
PD 040 1st moment shift from an impulse are consistent with charge depletion of the PK gap

Q_{ext} (nc)	Impulse (ps)
1	16.9
2	37.2
3	62.3
4	94.2
5	136.9

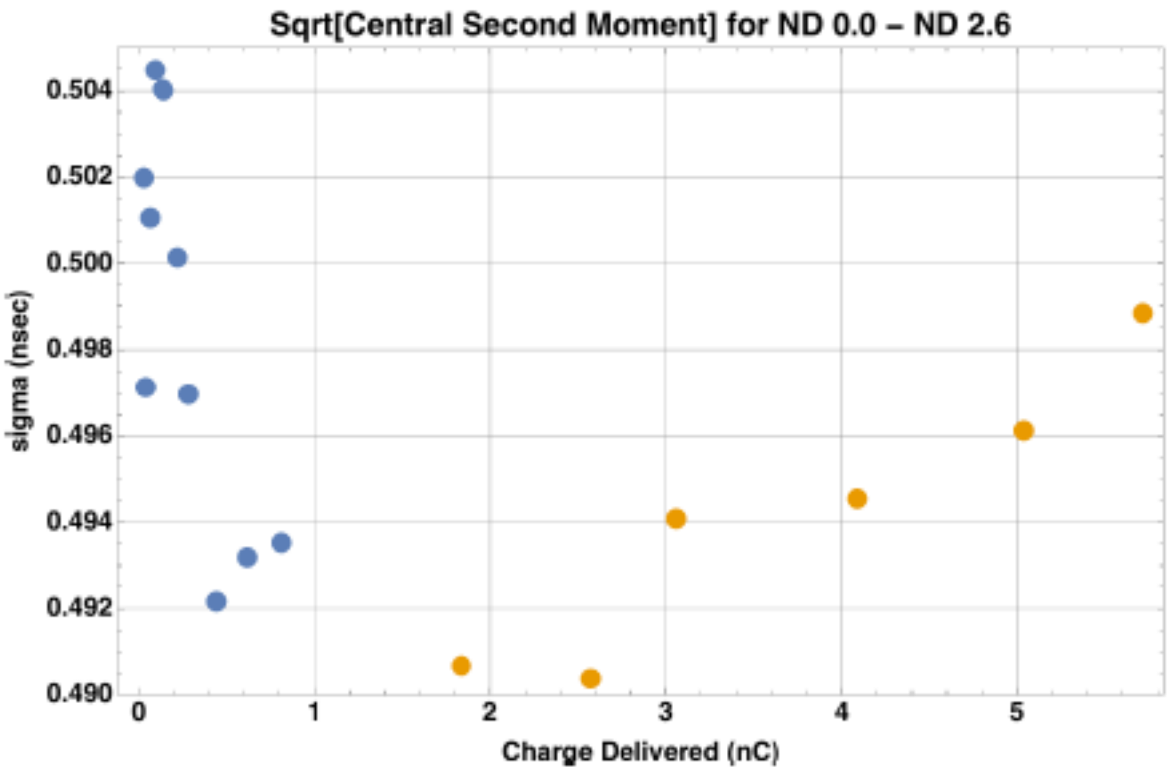


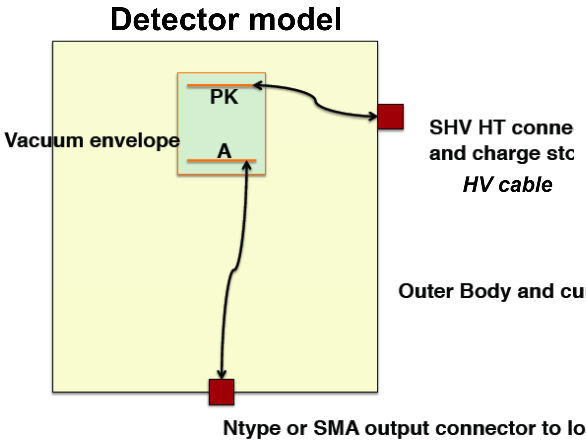
Performance consistent with high resistivity cathode

Detector model



As expected, the FWHM shift is small in comparison to the system FWHM





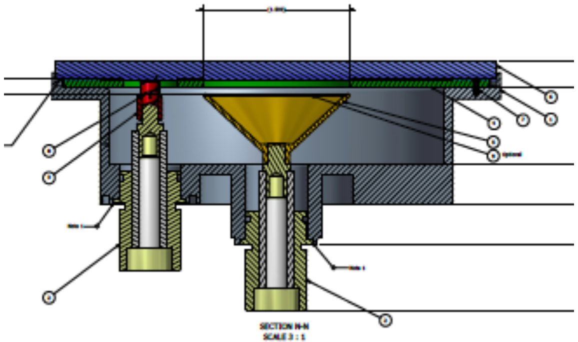
The expected growth of a 490 ps standard deviation Gaussian after 5 nC of extracted charge is ~8 ps.

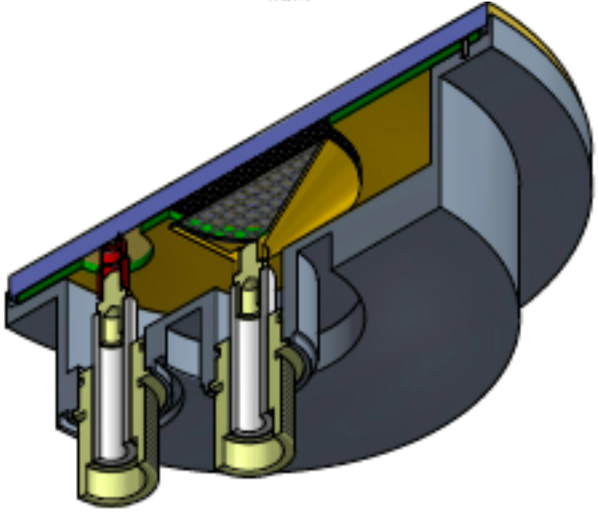
Known limitations of currently used photo-diodes…

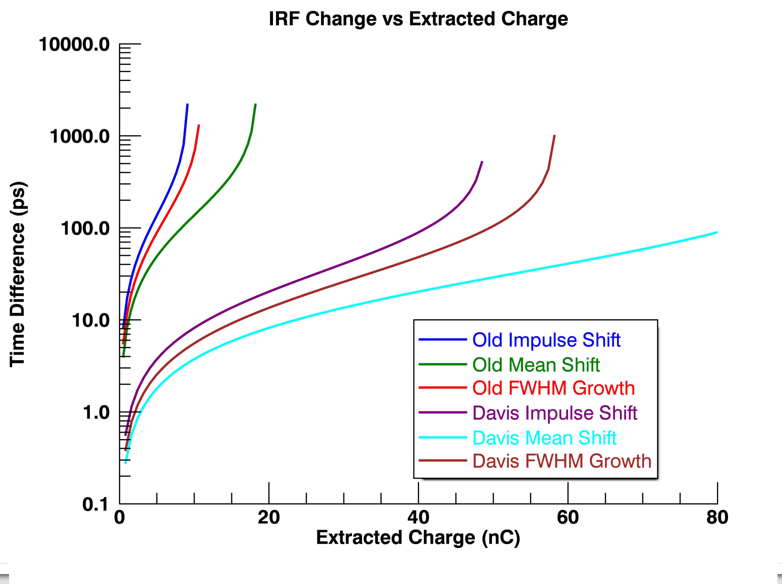
- Signal path impedance (not 50 Ohms)
- Conductivity of window deposited photo-cathode
- Small well capacitance

Prospective diode design by NSTec NVO (B. Davis) mitigates the charge dependent IRF.

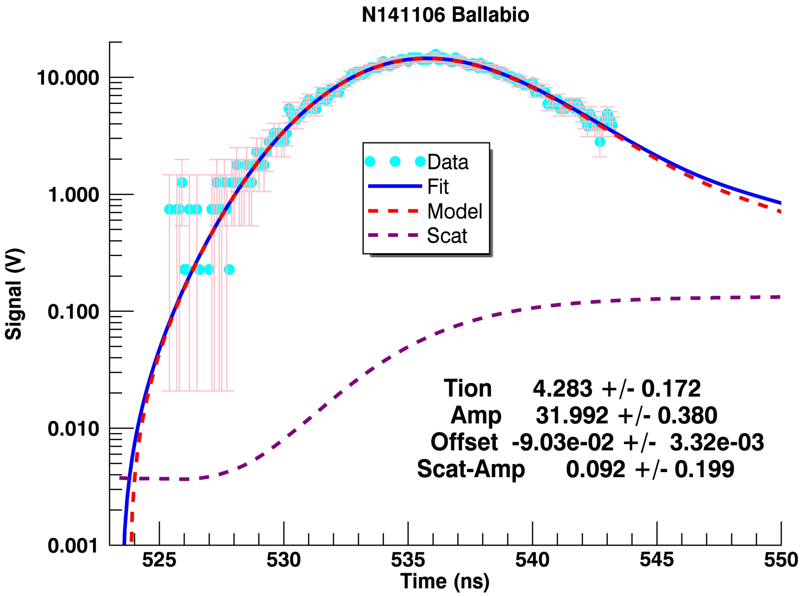
- Dual port design
- Conductive mesh underlayment between cathode and window
- Ring capacitance for increased stored charge – (1000x over PD040 design)
- 50 Ohm design to signal path

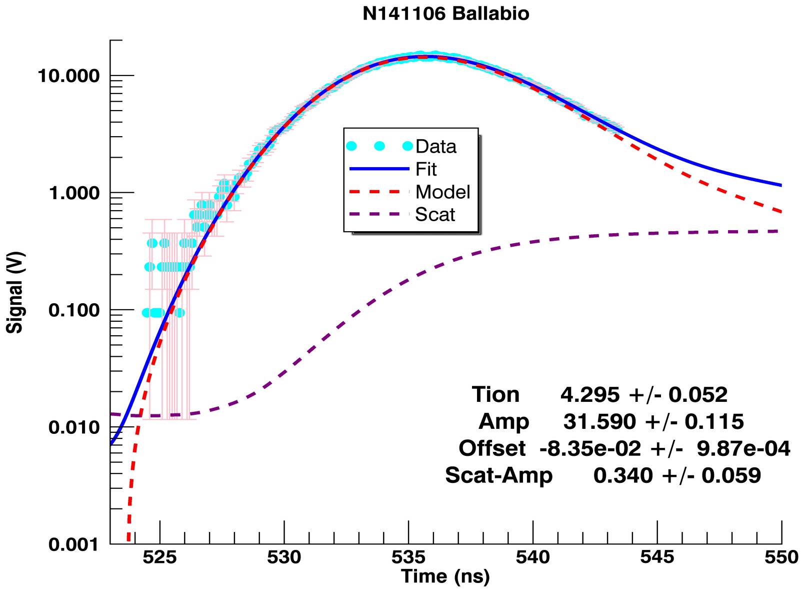






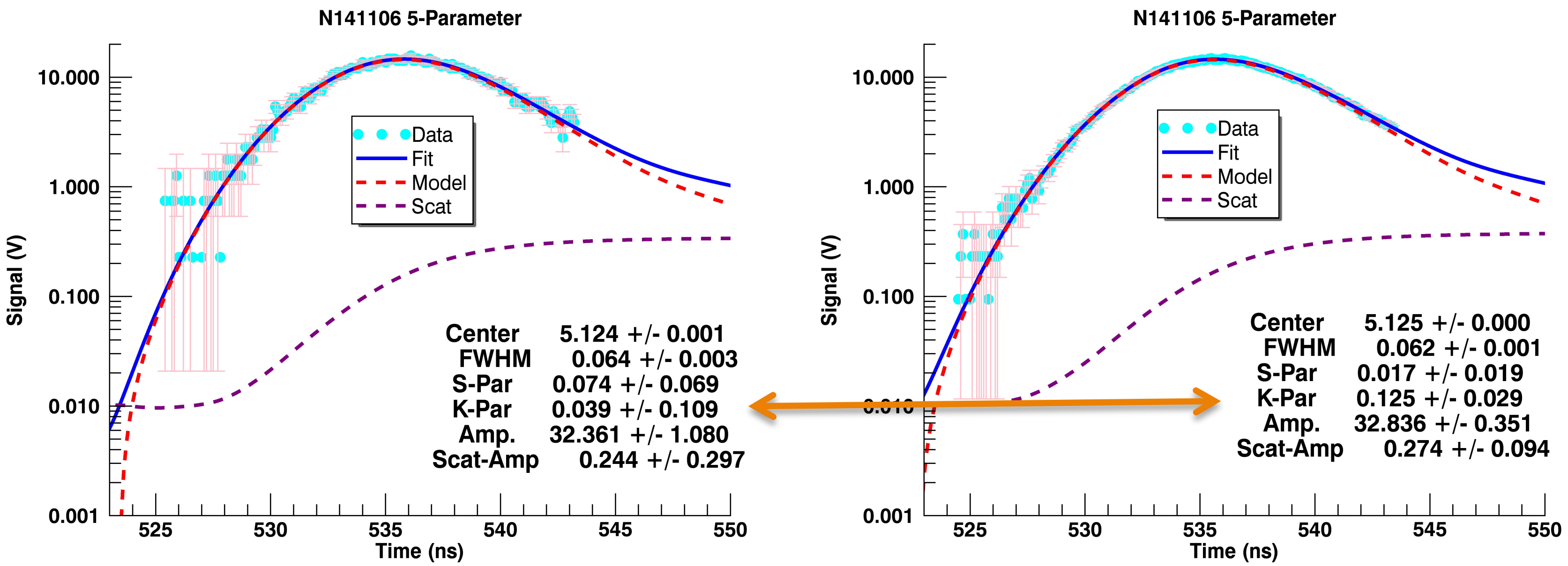
Digital recording ENoB plays a significant role in moment analysis…





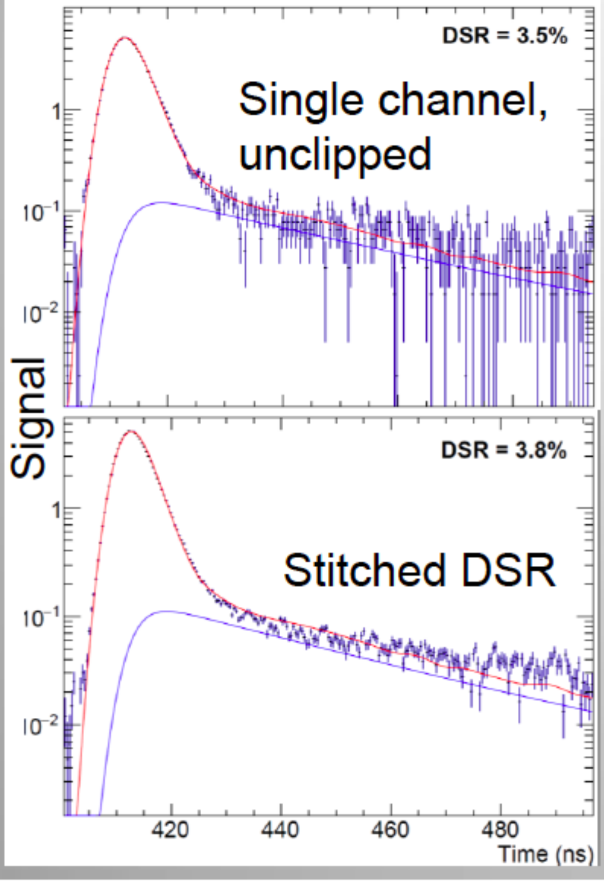
A factor of 4 increase in ENoB reduces fits uncertainties by 3x and dramatically improves the significance of the fit to the scattered flux.

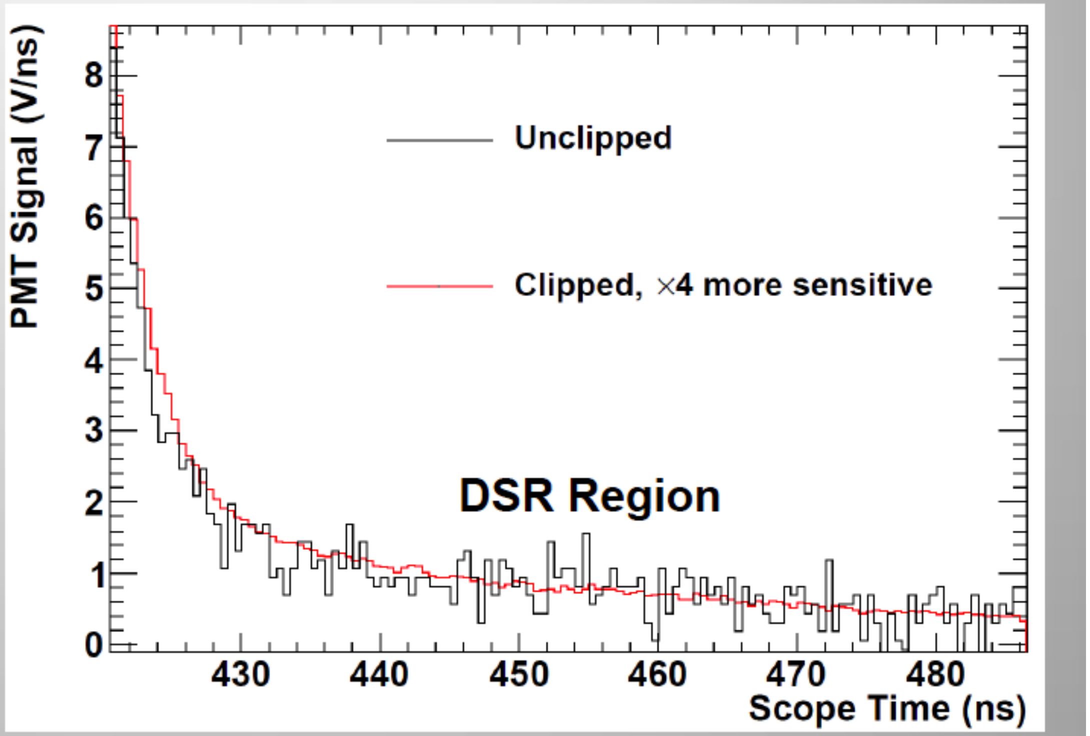
This is also reflected in higher moment sensitivity…



Increased ENoB also improves fit sensitivity to higher moments…

Stitching higher sensitivity channels to recover ENoB introduces systematic bias into DSR measurements





Overdriven channel recovers slowly and gives a DSR that is higher by ~10%

Summary

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- These measurements have generated a number of surprises in layered implosions namely:
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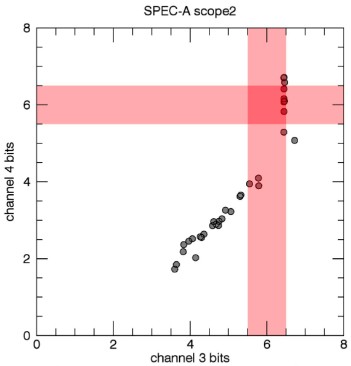
- Current systematic uncertainties don't allow strong statistical statements on important physics questions, thus…
- The Precision nToF project was created to better quantify the sources of current systematic uncertainty and to point the way to improved nToF precision.
- Since this scope is cuts across all ICF/HED facilities, it is a national project with engagement from NIF, Omega, and Z.

Current recording uses 4-5 bits, but new higher ENoB digitizers are available



PMT

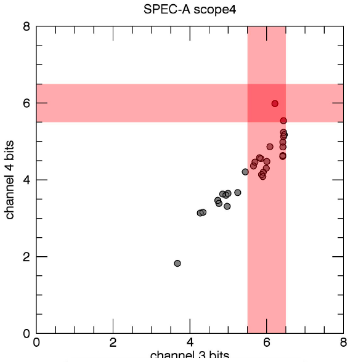
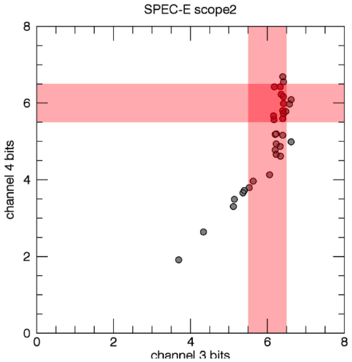


Photo-diode



PMT

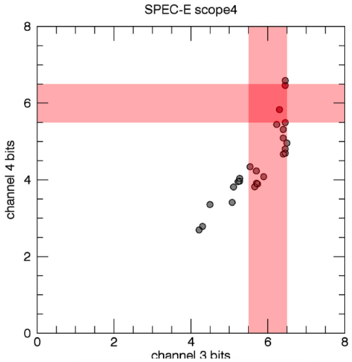
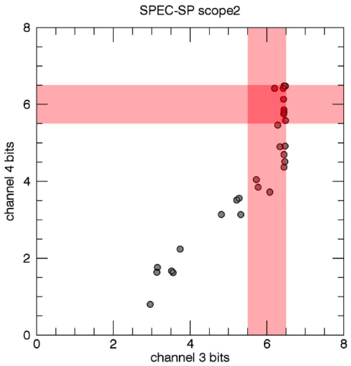


Photo-diode

New 10-bit Scopes/Digitizers are being studied to provide an improvement from 6 to 8 ENoBs which will significantly improve Tion and DSR precision.



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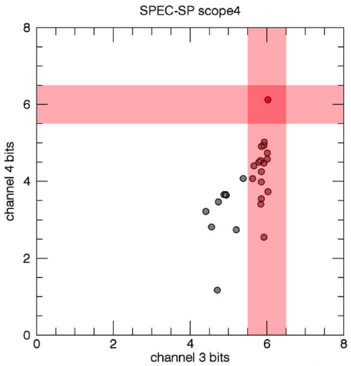


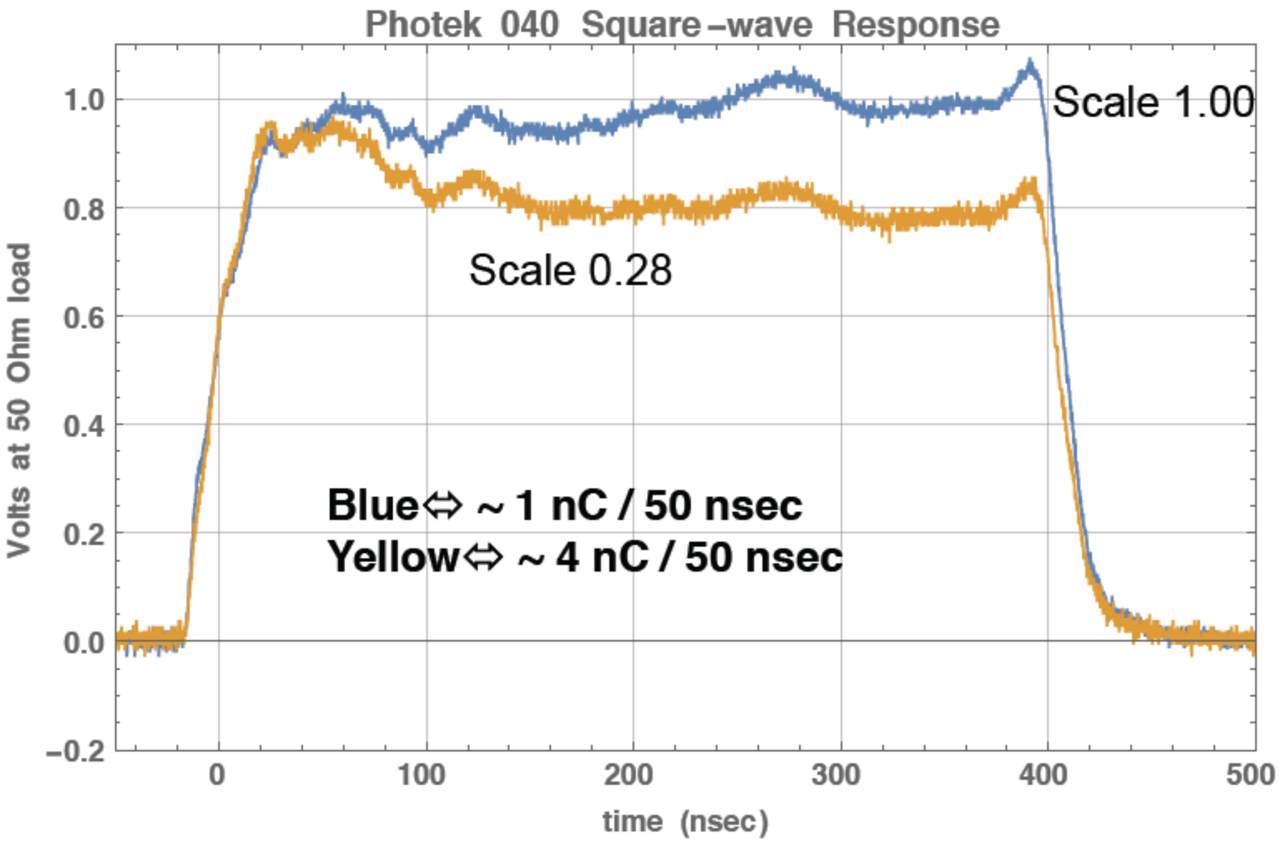
Photo-diode

Summary

- The Precision nToF project is focused on developing the requirements and technologies to advance nToF capability for future HED/ICF experiments.
- The Precision nToF Working Group is working to assess the performance of currently deployed nToF technologies on the physics goals of the future.
- Significant issues have been found with detector impulse response functions and digital recording systems that impact future precision capability
- Solutions too these issues are being explored through new detector designs and new recording equipment.

BACKUP

The finite capacitor storage also limits

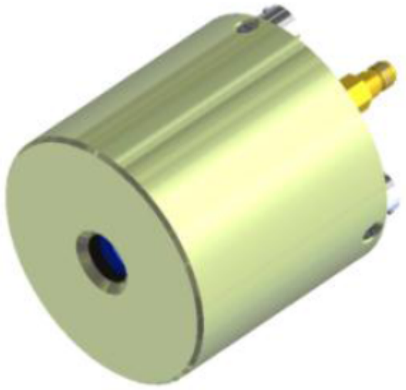


Blue⇔ ~ 1 nC / 50 nsec
Yellow⇔ ~ 4 nC / 50 nsec

Monitor data supports no change in excitation between these runs

The NIF relies heavily on 40 mm Photek photo-detectors locate ~20 m from the source

Photomultipliers & Photodiodes



Features: Photomultipliers

Yields $< 1\times10^{15}$

- 10 mm, 25 mm and 40 mm
- Single, chevron or z-stack MCP options with gain up to 3×10^7
- UV, Solar Blind, Visible and NIR responses
- Rise time to 60 ps (model dependant)
- FWHM to 100 ps (model dependant)
- Single photon jitter to 28 ps
- Multi-photon jitter below 10 ps
- Fast pulse output linear up to 1 A
- Fast gating to 2 ns
- Integral 50 ohm output

Features: Photodiodes

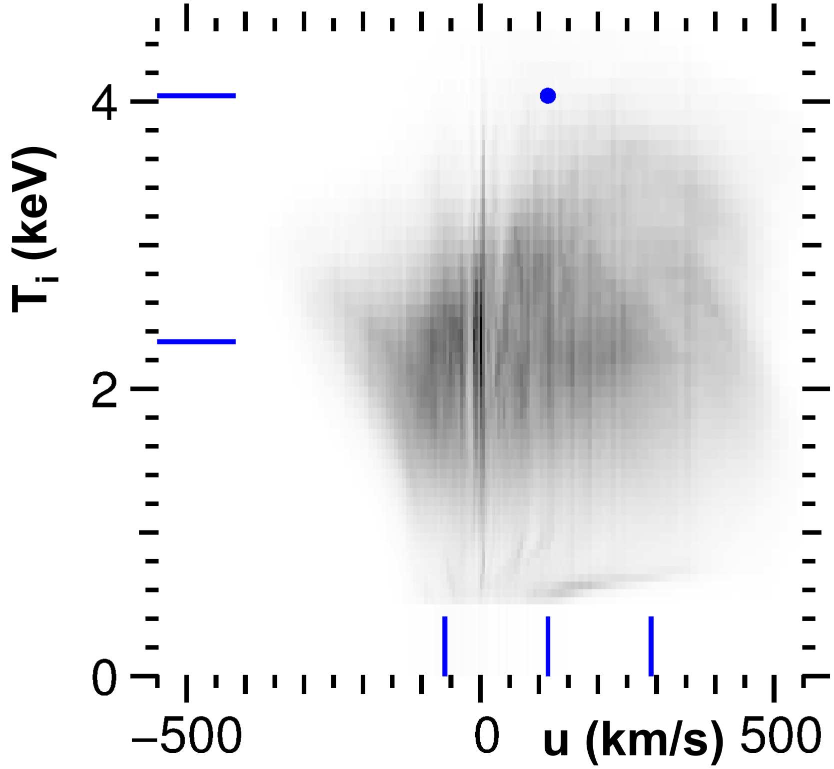
Yields $\geq 1\times10^{15}$

- 10 mm, 25 mm and 40 mm
- Unity gain
- UV, Solar Blind, Visible and NIR responses
- High dynamic range
- Linear response measured up to TBD amps per square centimetre
- Rise time < 100 ps
- Integral 50 ohm output

3-D simulations[*] of implosions produce neutrons from ensembles of fluid velocities and ion temperatures

Keep an eye out for coming paper by D. Munro on the details of this methodology.

burn T-u distribution (3D simulation)



u = fluid velocity component along LOS

Previous descriptions of the neutron spectrum based simply on T_{ion}, and σ_u are incomplete.

First and second moments of the birth spectrum only provide info on:

1. **<u>**
2. **T_{ion}**
3. σ_u

Higher moments of the spectral peak (skew and kurtosis, are required to provide info about T_{ion}-u correlations and *T_{ion} variance.*

[*] **Material provide by D. Munro and B. Spears**

Example of a Main Title and Content [Calibri Font]

Use 24-pt "Regular" (no bold) subtitles to provide additional detail

- Laboratory budgets over the last 15 years
- How does this affect my program?
- What are the relative values of our investments? (Discussion)
- Three critical issues to be decided:
  - Size of effort
  - Organization and R2A2
  - Funding mechanisms
- Wrap-up

Summary box has a full-width bleed.
Delete if not needed.

Title-only layout. Font size can be reduced for longer titles.

Summary box has a full-width bleed.
Delete if not needed.

Title for Text and Tables

- Select table and then click on Design tab to change table colors and attributes.
- All table fonts are Arial.

Heading 1	Heading 2	Heading 3	Heading 4
Body text item 1	100	200	300
Body text item 2	100	200	300
Body text item 3	100	200	300
Body text item 4	100	200	300
Body text item 5	100	200	300

Summary box has a full-width bleed.
Delete if not needed.

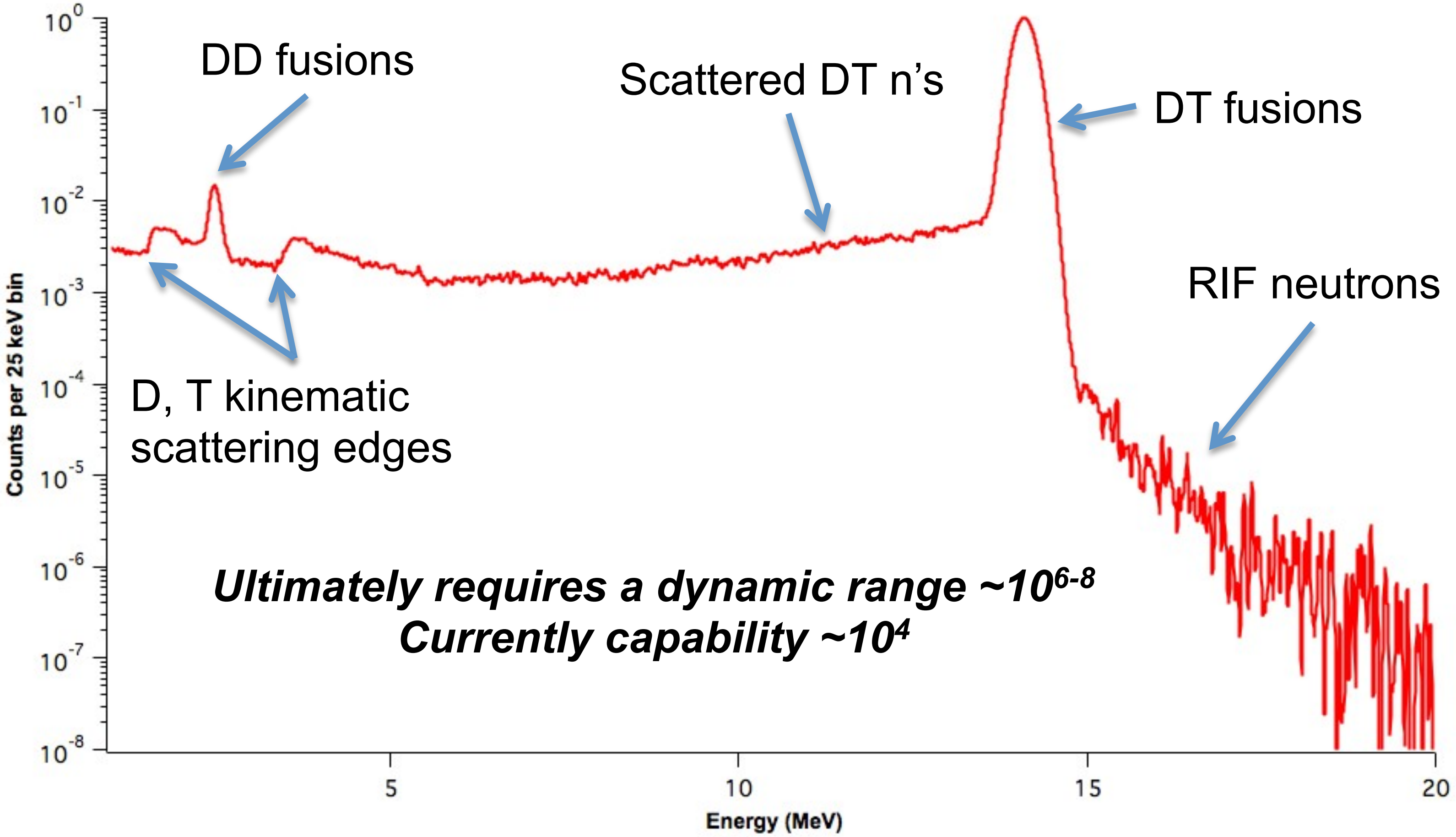
Title for bulleted text with left column

- Begin list of bullets here
  - Sub bullet
    - Sub bullet

Title for bulleted text with right column

- Begin list of bullets here
  - — Sub bullet
    - Sub bullet

Precision nToF must accurately measure the full neutron spectrum in HED experiments…



DD fusions

Scattered DT n's

DT fusions

RIF neutrons

D, T kinematic scattering edges

Ultimately requires a dynamic range ~$10^{6\text{-}8}$

Currently capability ~10^{4}