Versatile, Long-Lifetime, Wide Dynamic Range Detector for TOF Applications

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TOF Detector Performance

- TOF detector specifications are a major factor in tool performance. Key criteria are:
  - Timing: faster detector and electronics → Improved Mass Resolution
  - Output range: high saturation values, better linearity → Wider dynamic range, single gain working point
  - Gain: → unambiguous detection of single ion over background noise
  - Stability/Lifetime: Longer lifetime → Reduced cost of ownership, more stable and simple operation
- El-Mul offers a range of solutions by integrating its ScintiFast™ technology, fast light sensors and proprietary fast amplifiers into the patented MTOF™ detector concept

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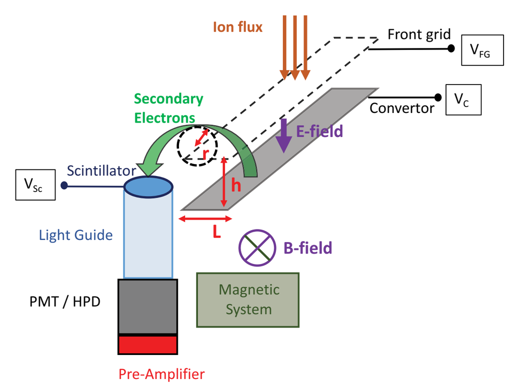
MTOF™ (Magnetic Time of Flight) Concept

- Ions converted to Secondary Electrons (SE) using conversion plate
- Electrons directed to ScintiFast™ scintillator by ExB fields
- Sensor collects photons from scintillator and provides analog signal
- HPD or fast PMT light sensor allows for sub-ns time resolution
- Switchable polarity
- Proprietary fast amplifiers (if needed)
- Nearly 100% detection efficiency
- Flexibility in design to meet space constraints



See also Thermo Fisher Scientific's poster "Characterization of a detection system with high sensitivity and dynamic range for a novel HRAM mass spectrometer" by Johannes Petzoldt *et.al.*.

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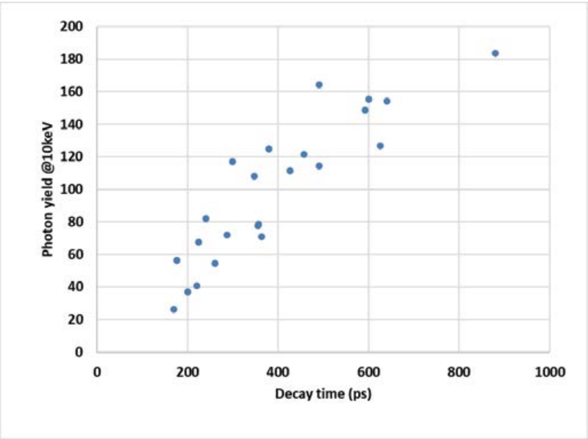
Scintillator Selection

- ScintiFast™ scintillators can be produced with a range of response times, but there is a tradeoff between decay times and photon yield
- Each TOF system may require a different set of response time and photon yield
- Selection of ScintiFast properties may affect dynamic range
- Selection of ScintiFast™ properties does not affect short- and long-term stability



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Sensor Selection

- Sensor is selected by identifying the properties needed for the detector
  - Response time / Mass resolution
  - Dynamic range
  - Gain / noise floor
  - Cost
  - Available space
- Hybrid Photo Diode (HPD) and Photo-Multiplier Tubes (PMTs) are compact, low-noise, vacuum-sealed sensors that are suitable for use in MTOF™ detectors

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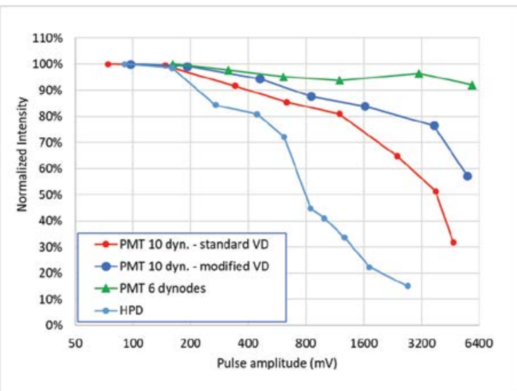
Sensor Performance

	FWHM (ns)	Max Gain	Operating Voltage
HPD	0.6	1.2E5	8kV
PMT 6-dynodes	0.8	2.5E5	1kV
PMT 10-dynodes	1.1	5E6	1kV

- Dynamic range is determined by linearity of the output pulse
- 6-dynode PMT are linear up to >6V
- 10-dynode PMT range can be extended by using modified dynode voltage arrangement
- HPD has the lower range, regardless of gain
- Actual dynamic range can be extended using calibration algorithms



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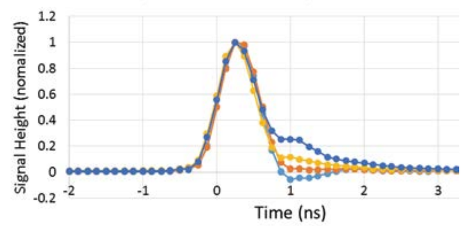
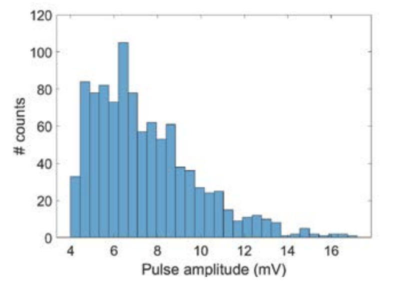
MTOF with HPD: Pulse Width and Height

- **Traces** from MTOF detector with HPD including pre-Amplifier operated at maximal gain
- FWHM = 0.63 ns (averaged over of 1000 single pulses)
- Pulse can be shaped by optimizing output impedance
- Smooth decay without undershoot or significant "ringing" can be achieved without compromising mass resolution



- **Pulse Height Distribution** measured with single electrons on subassembly (ScintiFast + Light-guide + HPD)
- Single electron pulse height = 7.4 ± 2.3 mV
- Ion signal is typically 2-4 electrons = 15-30mV
- Reliable Single Ion detection above noise level
- Allows to work at lower gain and increase dynamic range



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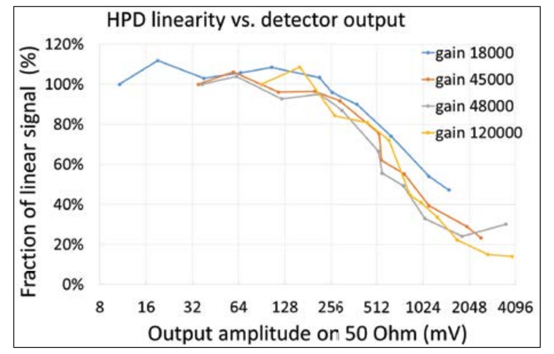
MTOF with HPD: Linearity and Dynamic Range

- Measurements performed on HPD using 80-ps pulse laser
- Linearity is output-limited
- Pulse output linear up to ~200 mV, then monotonic sublinear without pulse distortion up to ~4V
- No dependence on gain
- Overall dynamic range of ~3 orders of magnitude with non-linearity corrections



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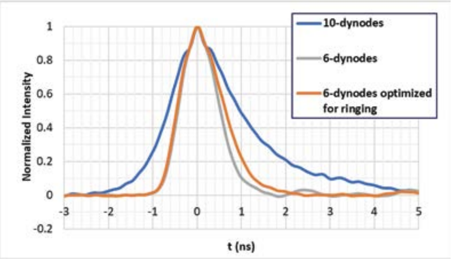
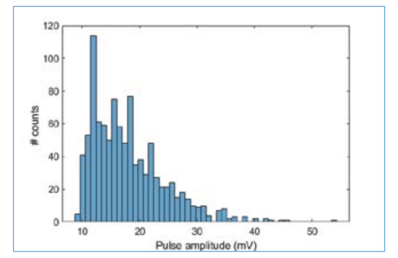
MTOF with PMT: Pulse Width and Height

- **Traces** from MTOF detector with two PMT types
- FWHM between 1ns for 6-dynodes PMT to 1.8 ns for 10-dynodes PMT
- Smooth decay without undershoot or significant "ringing" can be achieved by electronics optimization but pulse is slightly broadened



- **Pulse Height Distribution** measured with single electrons on subassembly (ScintiFast + Light-guide + PMT)
- Single electron pulse for 6-dynode PMT= 12.4 ± 5.3 mV
- Ion signal is typically 2-4 electrons = 25-50mV
- As with HPD, it allows reliable Single Ion detection above noise level or to decrease gain and increase dynamic range



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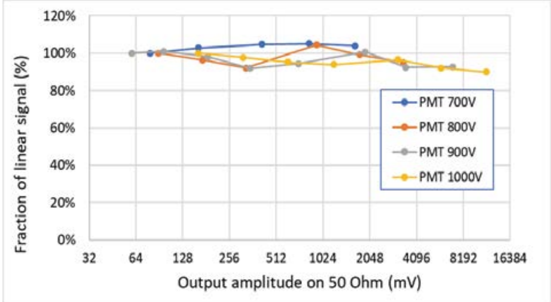
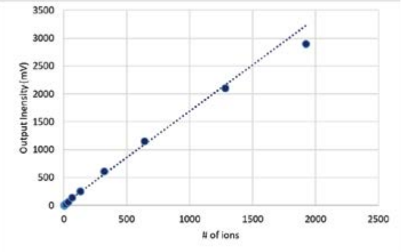
MTOF with PMT: Linearity and Dynamic Range

- Measurements performed on PMT using 80-ps pulse laser
  - Minor deviation from linearity over ~4 orders of magnitude
  - No dependence on PMT voltage
- MTOF Detector in TOF system shows at least 3 orders of magnitude linearity





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MTOF Detectors Configurations

- Few examples of TOF detectors based on MTOF technology are shown below
- For each detector, selection of scintillator and sensor, together with the limitations of space and cost were taken into account in the design

Detector	Scintillator	Sensor	Pulse width	Dynamic range
1	Fast	HPD	<0.7ns	Up to 100
2	Semi-fast	6-dynodes PMT	1	2,000
3	Semi-fast	10-dynodes PMT	1.7	2,000
4	"Standard"	10-dynodes PMT	2	>10,000

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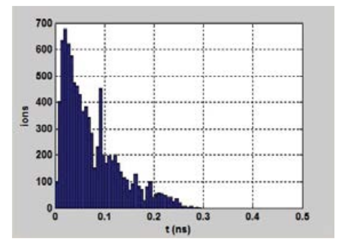
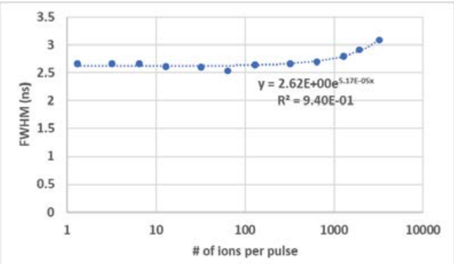
Multi-ion Timing

- Ion time-spread is mostly due to electric field non-uniformity between entrance grid and convertor, and to convertor non-planarity
  - Spread will be larger for larger ion-beam dimensions
- In the upper example, of fast detector (fast scintillator, HPD) ions are uniformly distributed over active area of 15*25 mm (worst case scenario)
- Calculation for 10,000 ions with M = 3 kDa and energy 20keV show that FWHM ~ 0.10 ns, and ~90% of positive ions arrive within 0.15 ns, ~100% arrive within 0.25 ns
- The lower figure, an experiment with a slower detector (10-dynode PMT), shows ~10% broadening above 1k ions/pulse
- For several detectors over the parameters range shown, multi-ion signal broadening is typically 10-20%





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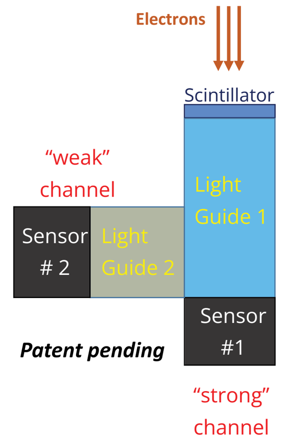
Light Splitting for Enhanced Dynamic Range

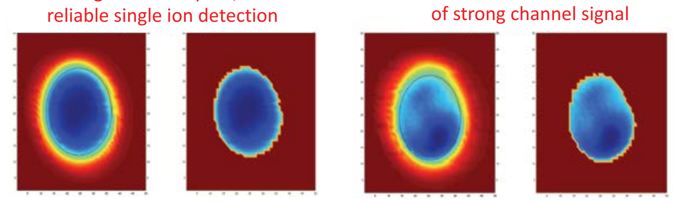
- Modification of the optical system of the MTOF detector enables a wider dynamic range, using a single scintillator and splitting the photons into two channels, where the weak channel collects only a few % of the signal:
  - Use the weak channel to collect signals with a large number of ions
  - Use the strong channel to collect signals with a small number of ions
- Each channel includes its own light sensor (HPD or PMT) and electronics
- Ratio between channels can be determined by design – dynamic range can be chosen
- Demo unit was scanned with electron beam showing uniform collection in both channels from all scintillator area



Patent pending

Strong channel: 5ph-e/e → reliable single ion detection

Weak channel collects 3% of strong channel signal



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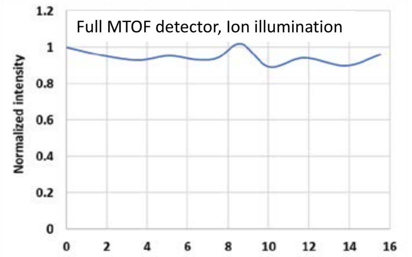
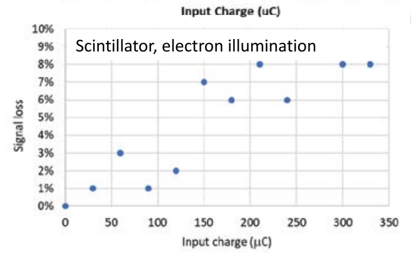
Stability and Lifetime

- Full detector, with semi-fast scintillator, and 10-dynodes PMT was measured on El-Mul Benchtop TOF system, PFTBA gaseous source
- Input current $2x10^7$ ion/sec → 3 pA → 0.01µC/H
- Detector operated continuously over 1000H showing no significant degradation
- Accumulated to 16 µC input charge (equivalent to ~16 C output charge in "standard" detector)
- Scintillator degradation was also tested using e-beam up to 350 µC input current and seen to be <10%.





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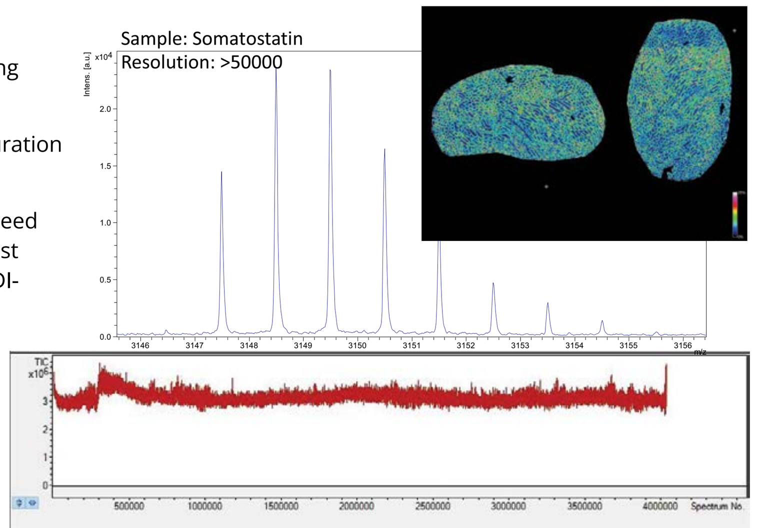
Detector Stability

- Data from Bruker Daltonics Rapiflex™ MALDI-TOF, utilizing MTOF detector
- Fast scintillator, HPD configuration
- The data demonstrate the successful combination of speed and signal stability in this most demanding high speed MALDI-Imaging application

Measurement and data with courtesy of Dr. Sebastian Bohm, Bruker Daltonics



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Summary

- Variety of TOF detectors based on El-Mul's patented MTOF ™ concept, incorporating El-Mul's fast ScintiFast™ scintillators are presented
- Selection of the scintillator and sensor types enables detector design for specific performance over wide range of parameters: mass resolution, dynamic range, beam dimensions, available space, cost
- FHWM between <0.7 to 2 ns for single ion pulse was demonstrated
  - Broadening for multi-ion signal is typically 10-20% and depends on system parameters
- Dynamic range between 10^2 of 10^4 was demonstrated and can be further enhanced by using split optical channels
- Stability and long-lifetime was proven for both fast, narrow dynamic range and for slower, wide dynamic range detectors
- This ultrafast, high gain, wide dynamic range and long lifetime detector represents a significant performance improvement over traditional MCP-based and electron multiplier-based high resolution TOF detectors