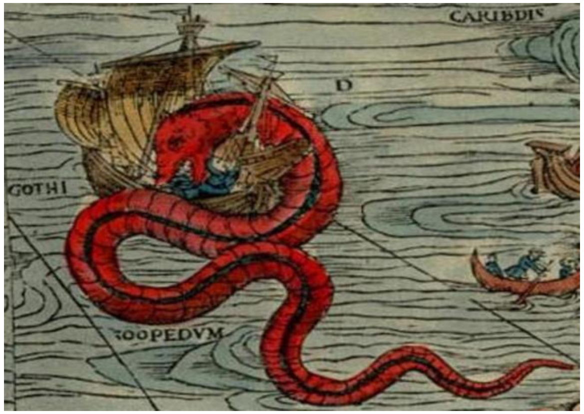


An accelerator-based surface diagnostic for plasma-wall interactions science on the Alcator C-Mod tokamak

Zach Hartwig
Harold Barnard, Brandon Sorbom, Pete Stahle, Dennis Whyte, Richard Lanza

Plasma Science and Fusion Center
Massachusetts Institute of Technology

Alcator C-Mod

PSFC @ MIT
Massachusetts Institute of Technology

Our map for the next twenty minutes ...

I. Prerequisites

Goal : Review magnetic confinement devices

II. Plasma-Wall Interactions (PWI)

Goal : Impart understanding of critical nature of PWI for fusion energy

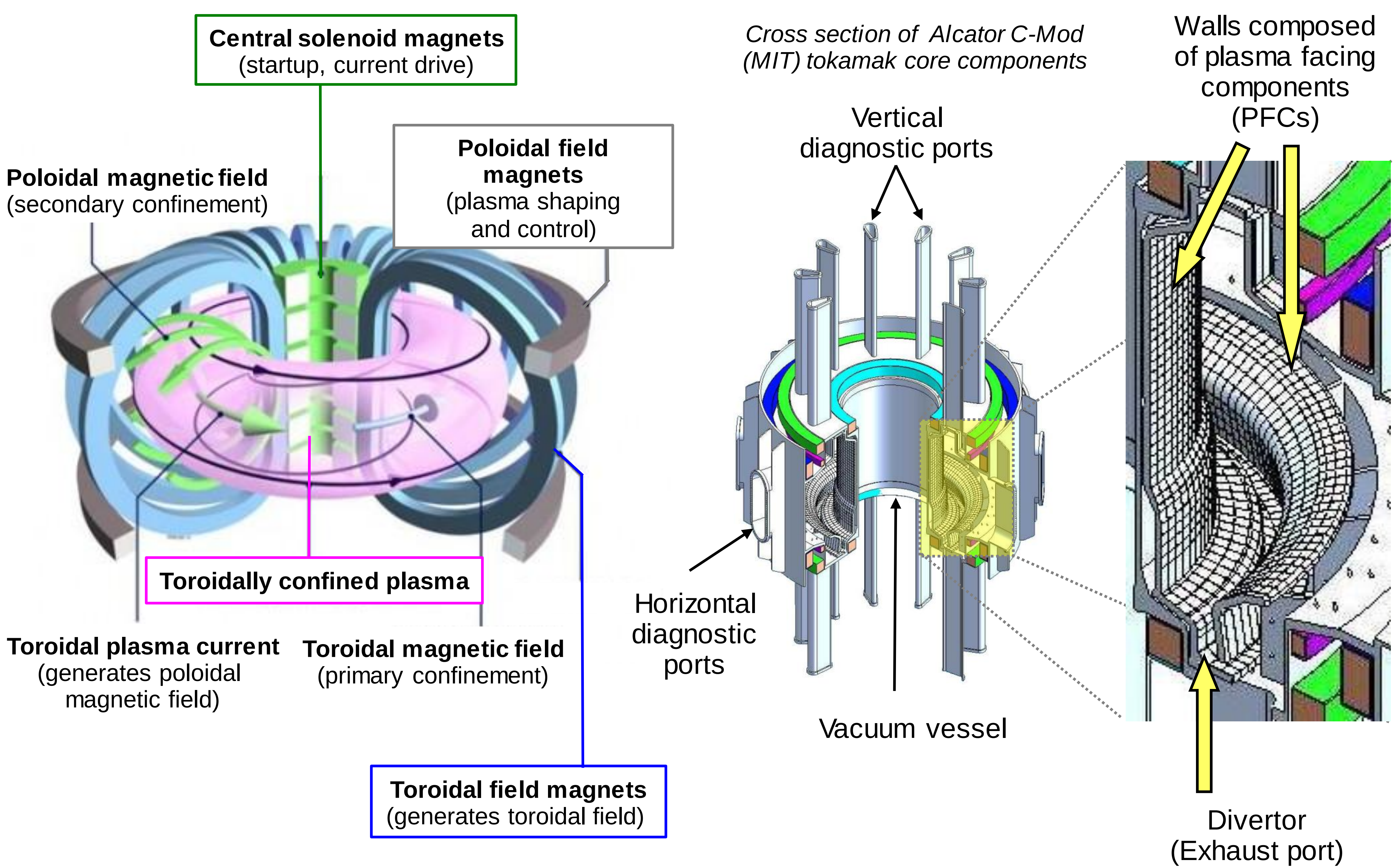
III. AGNOSTIC: advancing in-situ PWI diagnostics

Goal : Show the first diagnostic that will open up an understanding of PWI

Prerequisite #1: Thanks to all the people who have contributed their efforts to the success of this project

- **Diagnostic team**
  - Harold Barnard
  - Brandon Sorbom
  - Pete Stahle
  - Dennis Whyte
  - Richard Lanza
- **Alcator C-Mod team**
  - Earl Marmar
  - Mark Chilenski
  - Nathan Howard
  - Ian Faust
  - Matt Reinke
  - Bob Granetz
- **Alcator C-Mod engineering**
  - Dave Terry
  - Rui Vieira
  - Alan Binus
  - Henry Savelli
  - Gary Dekow
  - Jim Irby
  - C-Mod Machine Shop
  - ...rest of C-Mod staff

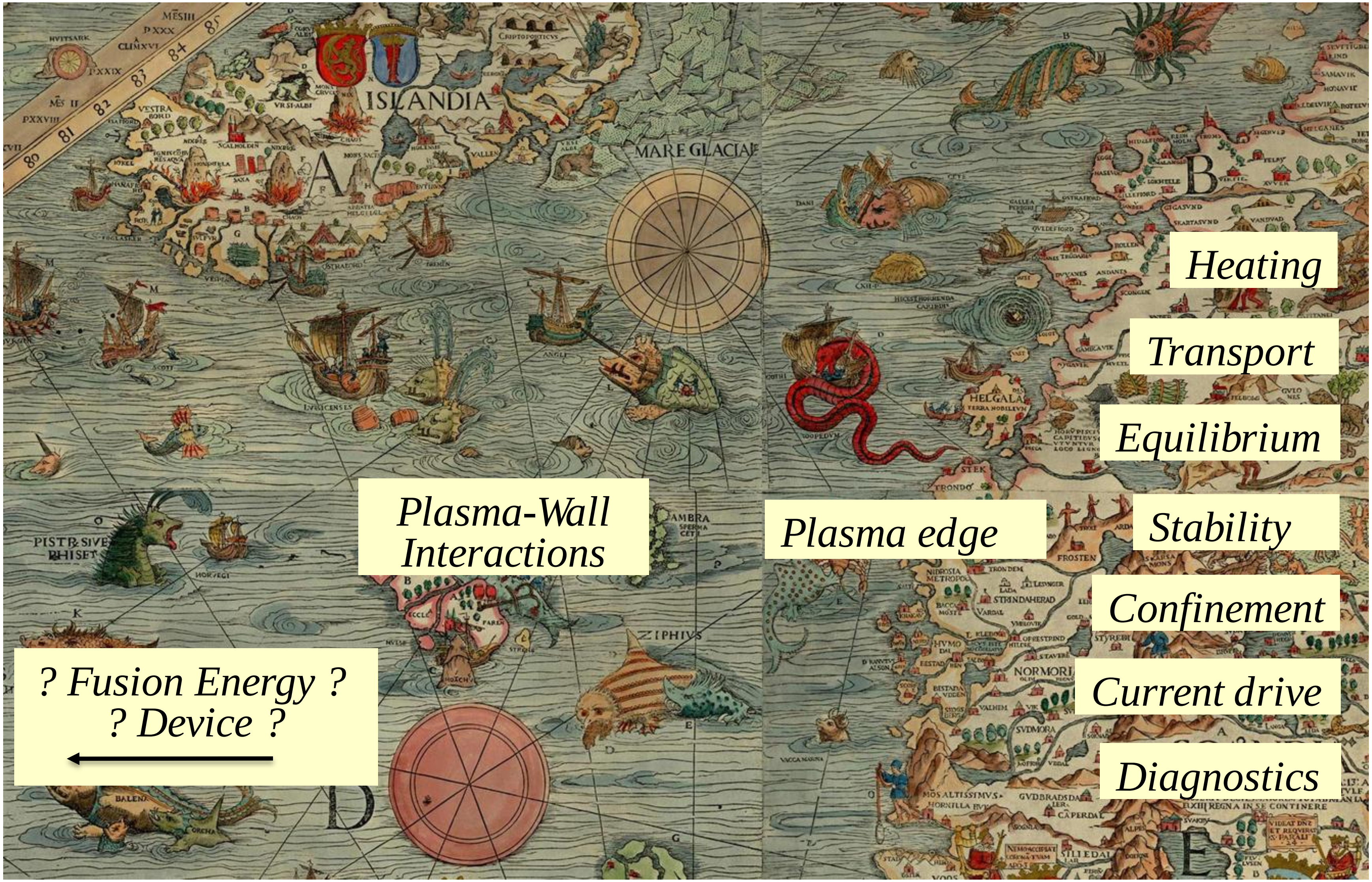
Prerequisite #2: Getting to know your magnetic fusion confinement device ...



Hic sunt dracones: a medieval cartographic practice of depicting monsters in place of the unknown

A portion of Carta Marina (Olaus Magnus, c. 1530 A.D.)

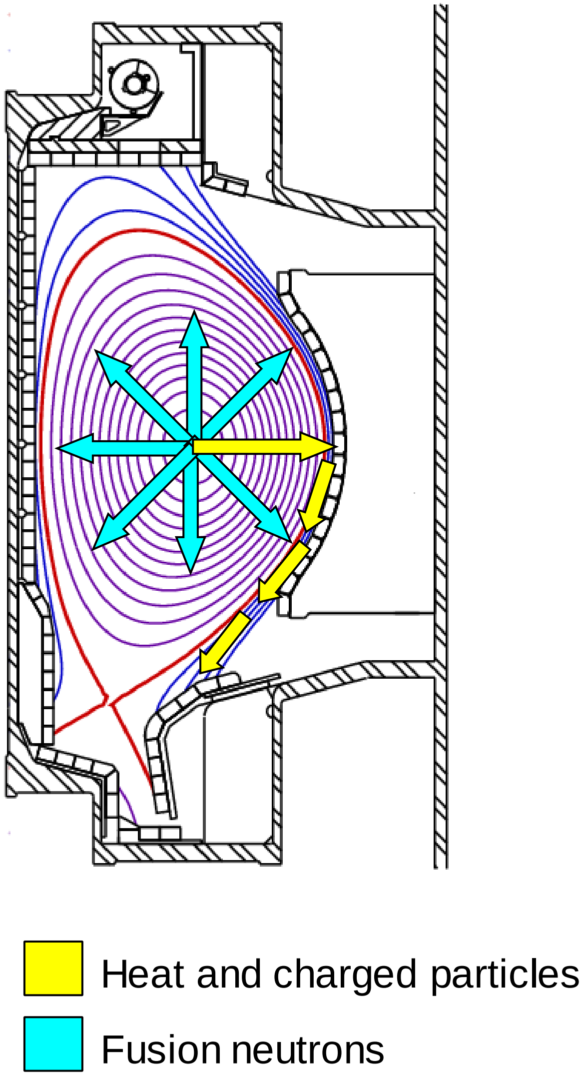
Hic sunt plasmae superficies interactionus: a modern fusion science practice of leaving PWI undiagnosed



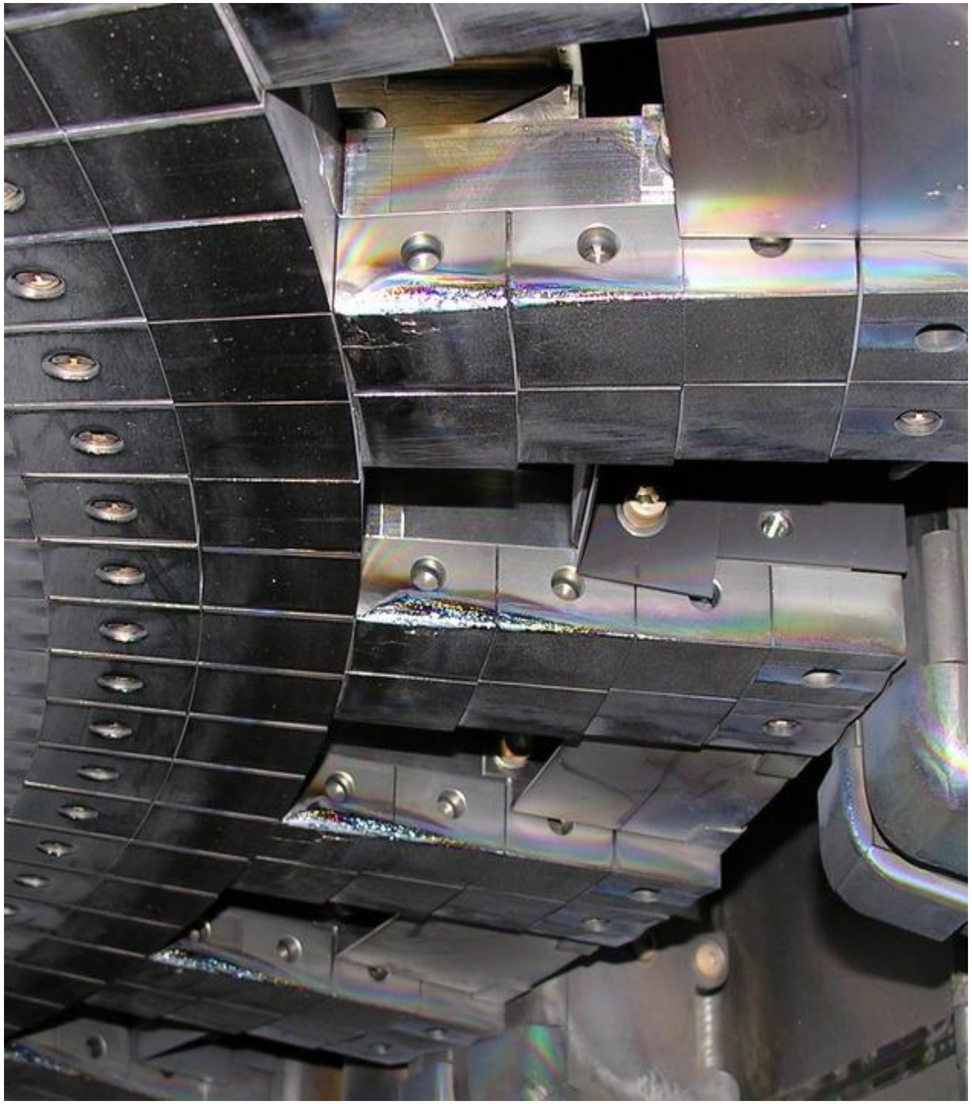
A portion of Carta Marina (Olaus Magnus, c. 1530 A.D.)

Plasma-boundary coupling results in modifications to core plasma and material surfaces in magnetic fusion devices

- Plasma-Wall Interactions (PWI) seeks to understand the coupled system that forms between magnetically confined plasmas and their physical boundary surfaces known as plasma facing components (PFC).
- PFCs are exposed to extremely hostile environments...
  - heat fluxes up to ~10^9 W/m^2
  - charged particle fluxes up to ~10^5 A/m^2
  - neutron fluxes and nuclear activation
- ...resulting in modifications to the PFC surfaces:
  - hydrogenic fuel retention (deuterium, tritium)
  - net erosion and redeposition
  - melting
  - isotope mixing
  - sputtering



Examples from Alcator C-Mod demonstrate the destructive potential of PWI issues



Upper divertor PFC tiles

Midplane limiter PFC tiles

Extrapolating to reactor-scale devices indicates the potential severity of PSI issues for fusion energy

Issue / Parameter	Present Tokamaks	ITER	DEMO
Quiescent energy exhaust *GJ / day*	~ 10	3,000	60,000
Transient energy exhaust from plasma instabilities $\Delta T \sim MJ / A_{wall}(m^2) / (1\ ms)^{1/2}$	~ 2	15	60
Yearly neutron damage in plasma-facing materials *displacements per atom*	~ 0	~ 0.5	20
Max. gross material removal rate with 1% erosion yield *(mm / operational-year)*	< 1	300	3000
Tritium consumption *(g / day)*	< 0.02	20	1000

Implications

- Unknown affect on core plasma
- Increased cost
- Increased maintenance shut down
- Operational limits
- Shortened device and component lifetimes
- *Feasibility of magnetic fusion energy*

New *in-situ* diagnostics are required to significantly advance PWI science in magnetic fusion devices

- *Ex-situ* diagnostics and "benchtop" PWI experiments are critically limited
  - Unable to replicate tokamak-relevant PWI conditions ("benchtop")
  - Limited PFC surfaces available for measurement (IBA)
  - "Archaeological" measurements lack dynamic PWI information (IBA)

- *In-situ* PWI surface diagnostics are severely limited in deployment and unable to meet all requirements

- The ideal PFC surface diagnostic would provide measurements:
  - in-situ without vacuum break
  - on a shot-to-shot frequency for time resolution and PWI dynamics
  - of large areas of PFC surfaces (poloidally and toroidally resolved)
  - of elemental/isotope discrimination to depths of ~10 microns

AGNOSTIC exploits intra-pulse capabilities of a tokamak and deuteron-induced reactions to investigate PWI

- AGNOSTIC (**A**ccelerator-based **G**amma and **N**eutron **O**bserving **S**urface-diagnosting **T**ool for **I**n-situ **C**omponents) derives from two key observations:

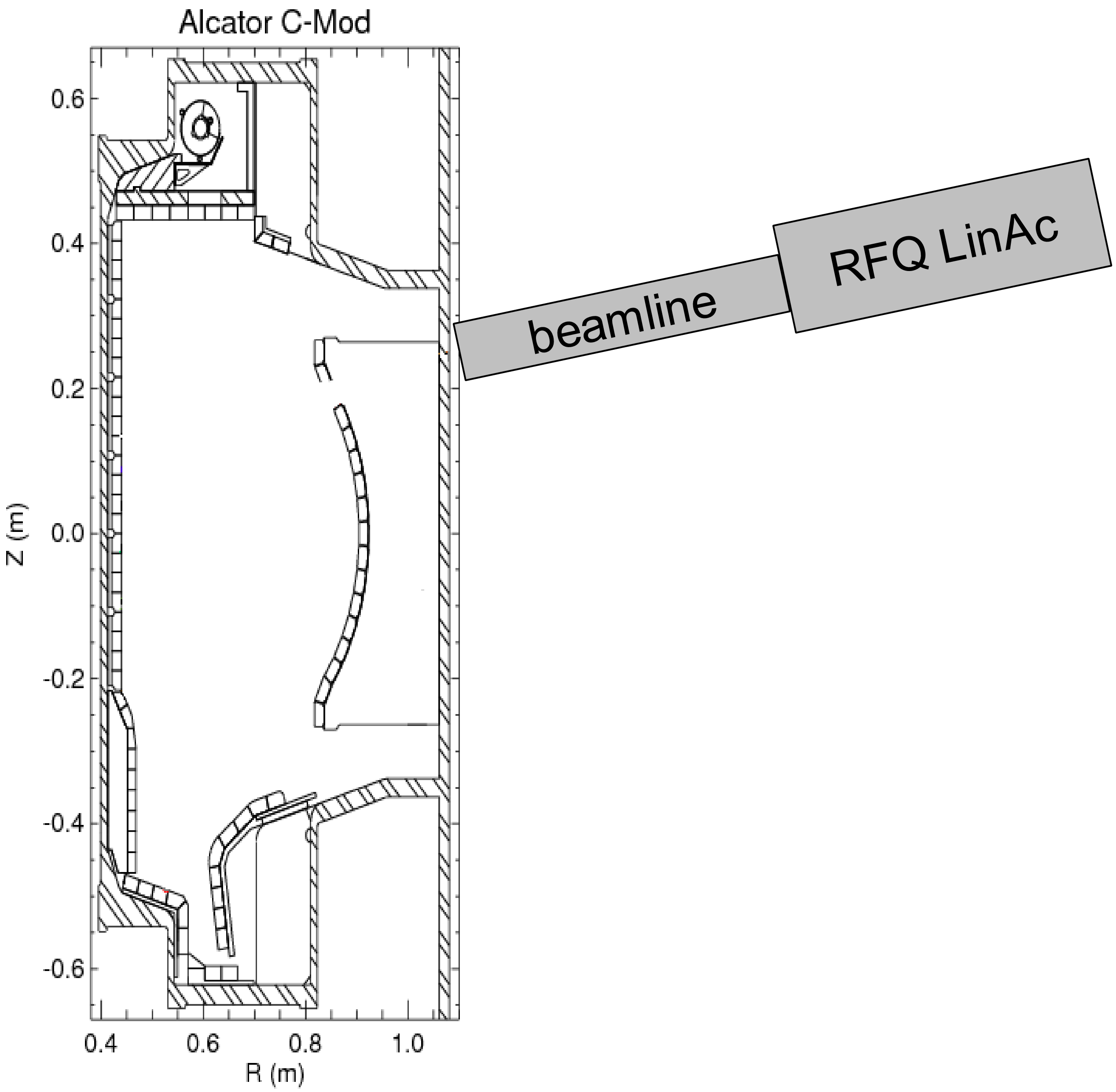
  1) The tokamak magnetic fields can be used between plasma shots to steer a charged particle beam to PFC surfaces of interest

  2) The gammas and neutrons produced by low-energy, deuteron-induced nuclear reactions provide a comprehensive diagnostic tool for PWI

PWI Issue	Nuclear reaction	Induced particle energy (MeV)
Fusion fuel retention	$^{2}H(d,n)^{3}He$ $^{3}H(d,n)^{4}He$	E_n = 2 – 4 MeV E_n = 17 – 19 MeV
Erosion / redeposition	$^{6}Li(d,p+g)^{7}Li$ $^{8}Be(d,p+g)^{9}Be$	E_g = 0.478 E_g = 0.718
Wall conditioning	$^{11}B(d,p+g)^{12}B$ $^{16}O(d,p+g)^{17}O$	E_g = 0.953, 1.674 E_g = 0.871
Impurity transport	Accessible Low-Z reactions	E_g <= 5 MeV

Basic principles for AGNOSTIC on Alcator C-Mod: *in-situ* ion beam analysis

(1) Radio Frequency Quadrupole (RFQ) linear accelerator injects 0.9 MeV D+ beam into vacuum vessel through a radial port



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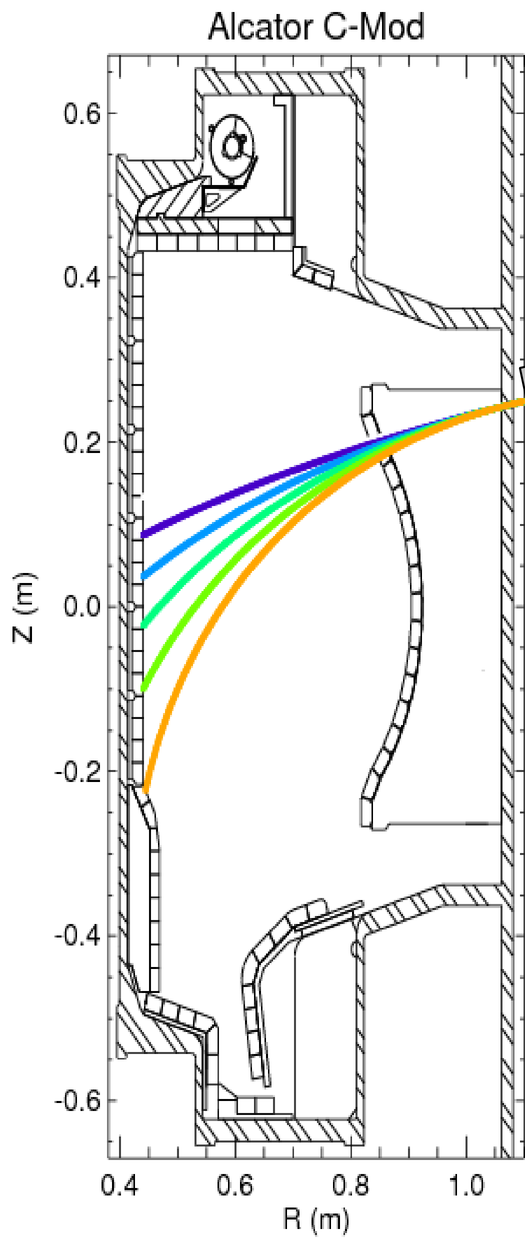
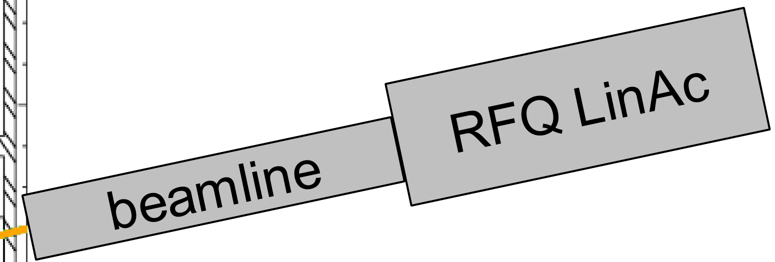
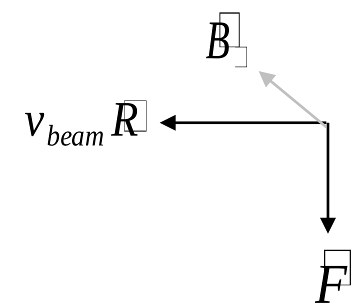
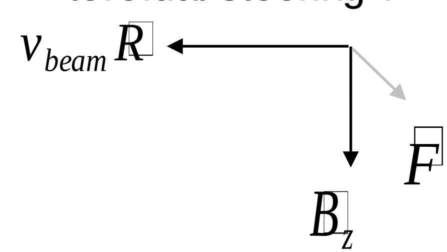




Toroidal field provides poloidal steering :



Vertical field provides toroidal steering :



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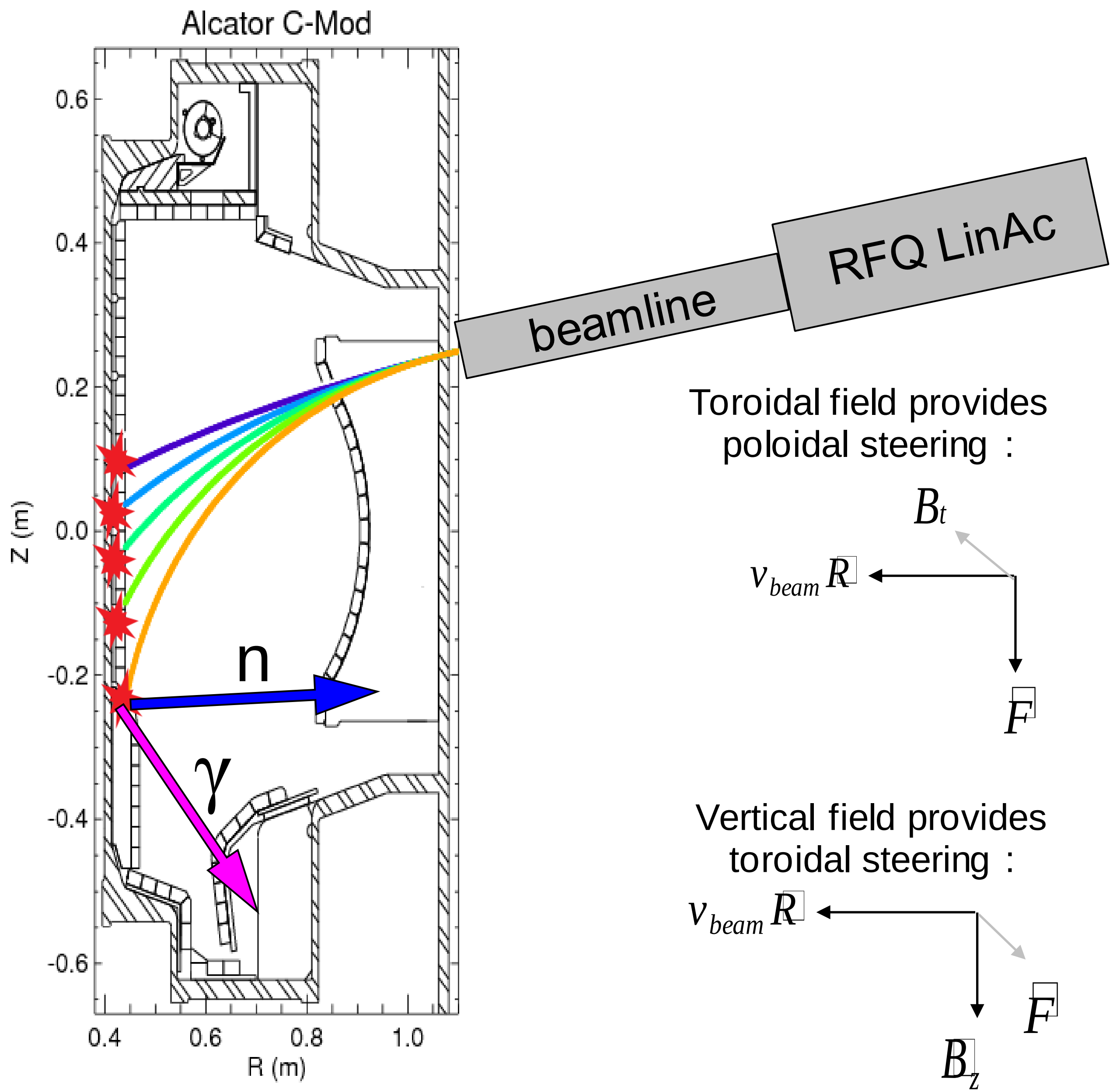

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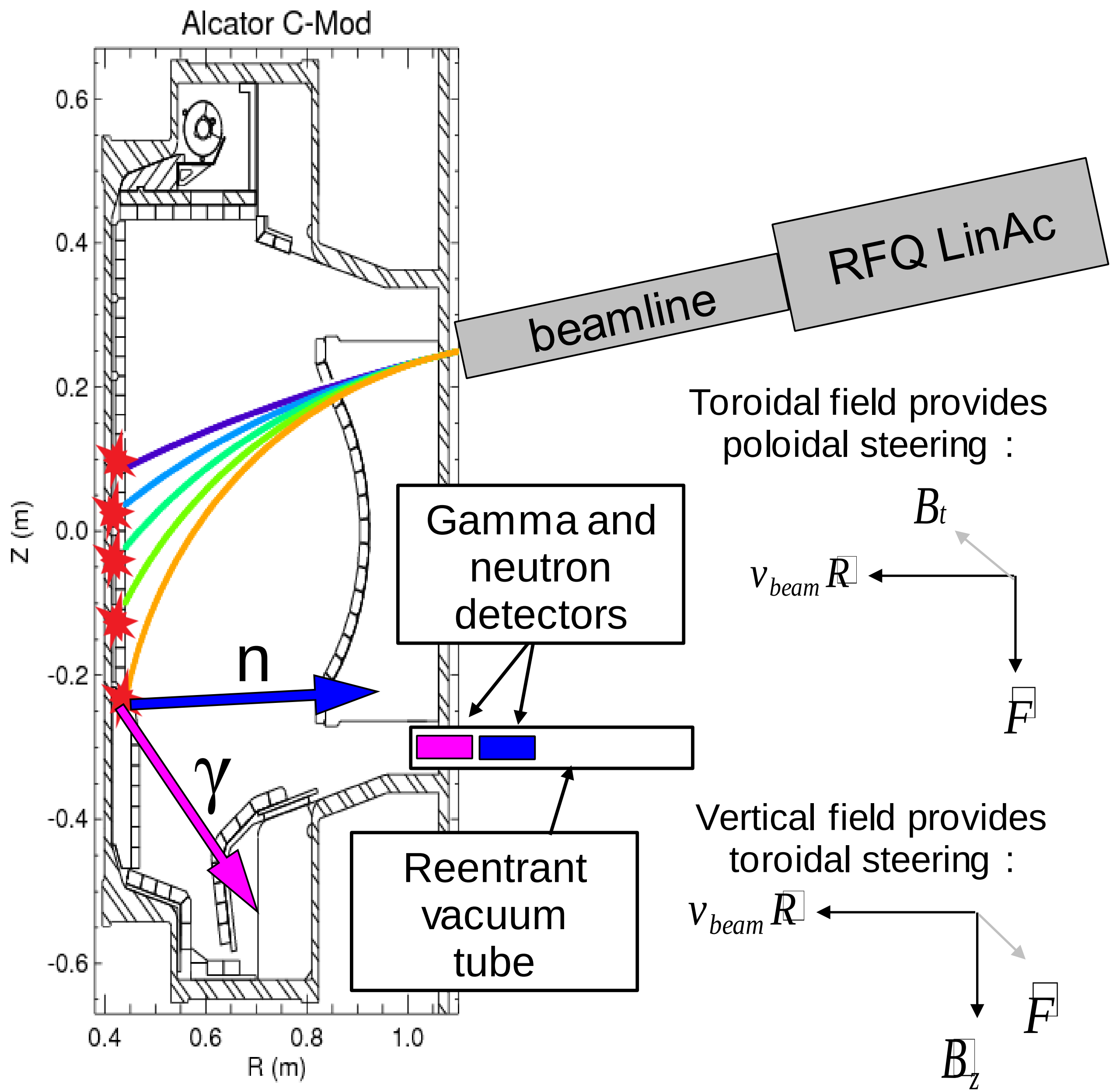
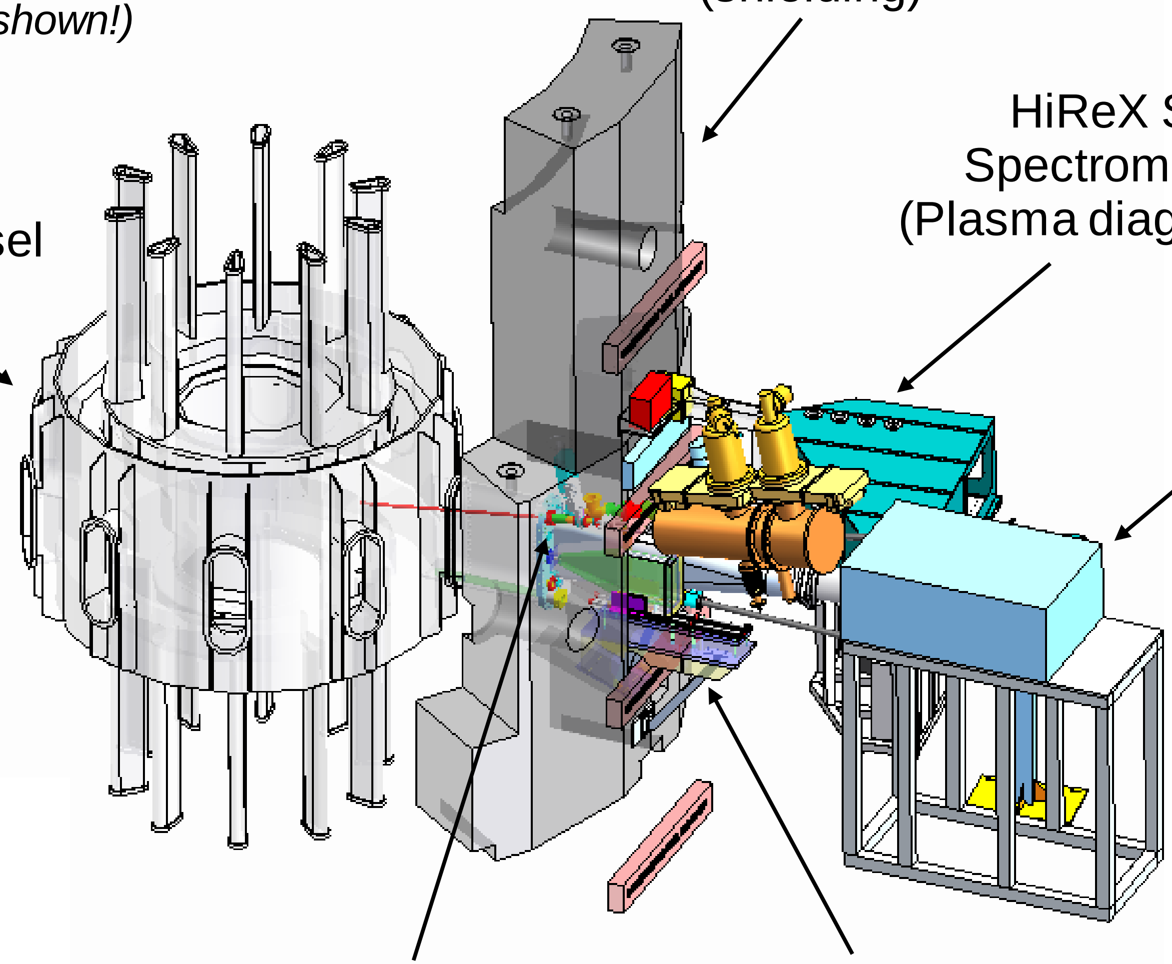
(4) In-vessel detection and energy spectroscopy provides a wealth of information on PFC surface composition and conditions



AGNOSTIC was designed to fit amidst the extremely crowded area around C-Mod's horizontal ports

A solid model with cutaways of the proposed installation location for AGNOSTIC on Alcator C-Mod. (Lots of stuff not shown!)



* **A**ccelerator-based
Gamma and
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Observant
Surface-diagnosing
Tool for
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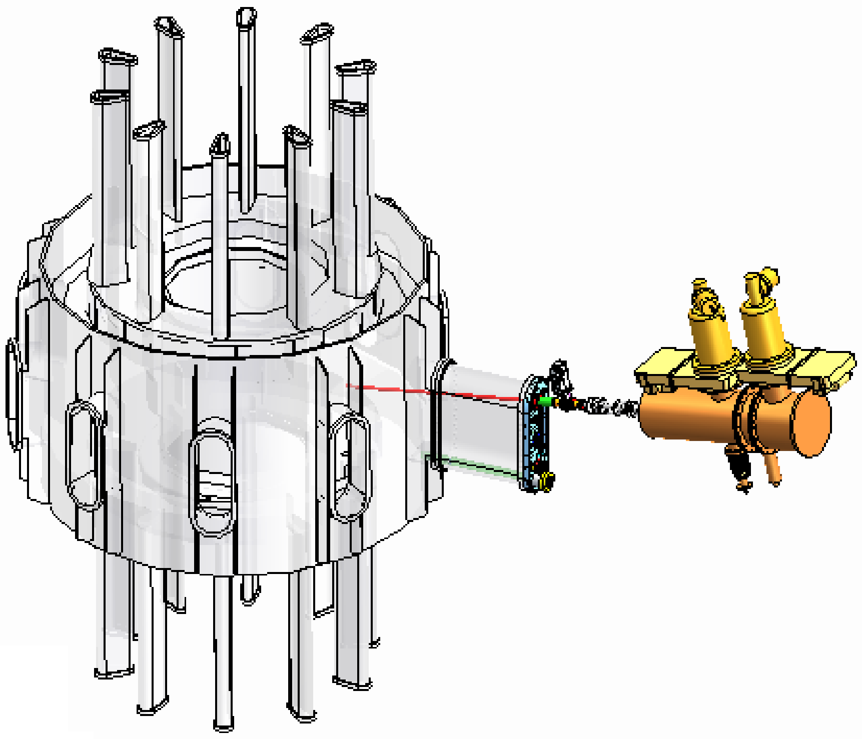
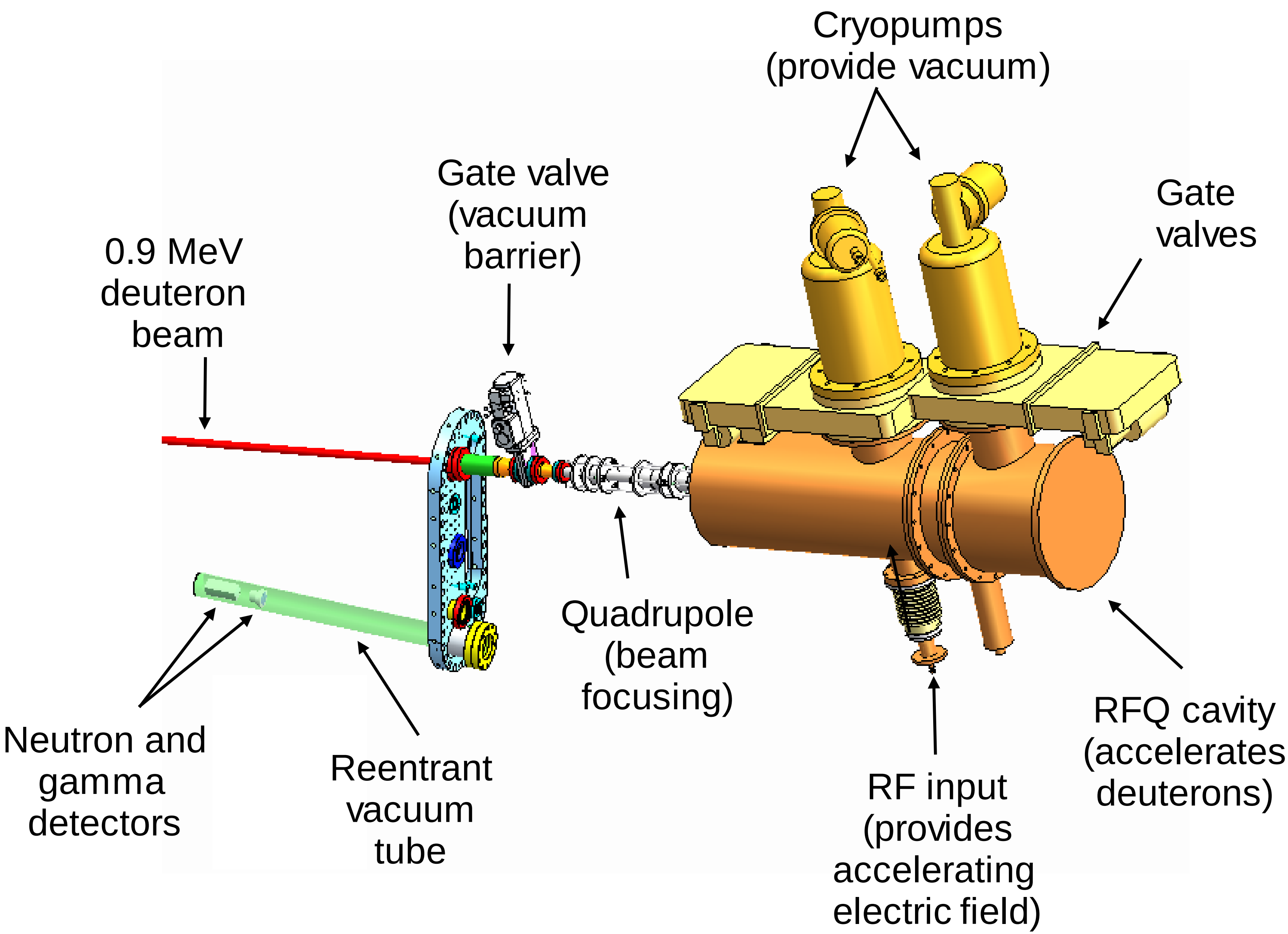


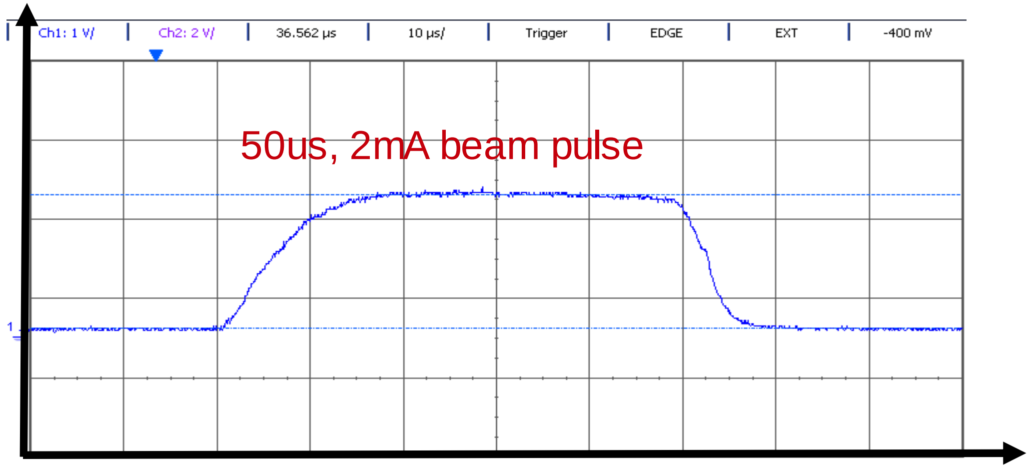
AGNOSTIC consists of the RFQ accelerator, focusing quadrupole beamline, reentrant tube, and particle detectors



An 0.9 MeV deuteron RFQ accelerator has been completely refurbished and upgraded

- ~25 year old prototype RFQ (radiofrequency quadrupole) accelerator from Accsys Inc has been completely refurbished and modernized
  - New RF tubes and coax; digital control systems; new vacuum system;
  - ~0.9 MeV deuterons, < 2% duty factor, ~2 mA peak current, ~50 uA avg current
  - Beam spot using permanent focusing quadru-pole magnets is ~1 cm at 2 m from RFQ exit

Voltage [1V/div]
(Calibration 1V/mA)



Time [10 us/div]

A compact $LaBr_3$:Ce scintillator coupled to an Si-APD provides high-resolution gamma spectroscopy

- AGNOSTIC particle detection must be performed in an extremely hostile environment
  - High neutron flux (~10^{13} m^{-2} s^{-1})
  - High magnetic fields (< 0.1 T)
  - Mechanical shock (~200 g)
  - Compact geometry (~cm)
  - High counts rates (<10^5 / s)

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A photo of the LS detector next to a pencil for scale (left) and within its reentrant cartridge (right)

- A 0.9 x 0.9 x 3.5 cm $LaBr_3$:Ce crystal coupled to a Hamamatsu silicon avalanche photodiode in a ruggedized stainless steel housing was fabricated by Saint-Gobain for AGNOSTIC

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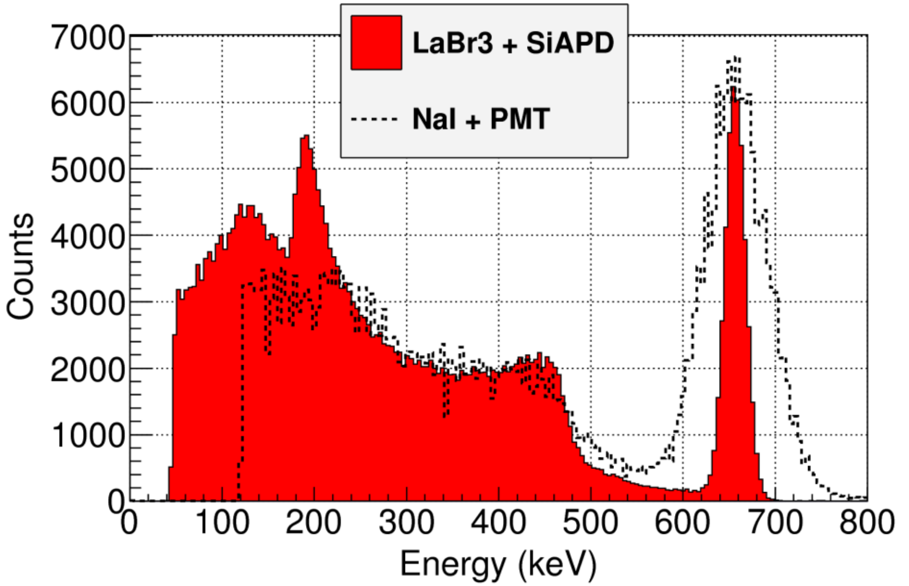
LS Detector response to 661.7 keV gammas



- Energy resolution typically a factor of 2 to 3 better than NaI(Tl) detector; photo-peak statistics excellent despite 30x smaller sensitive volume than NaI(Tl) detector

An EJ301 liquid scintillator with SiPM readout and very fast preamplifier provides high-energy neutron detection

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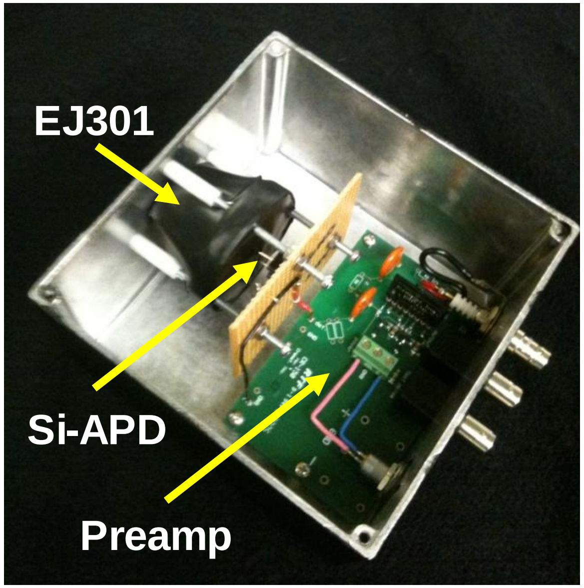
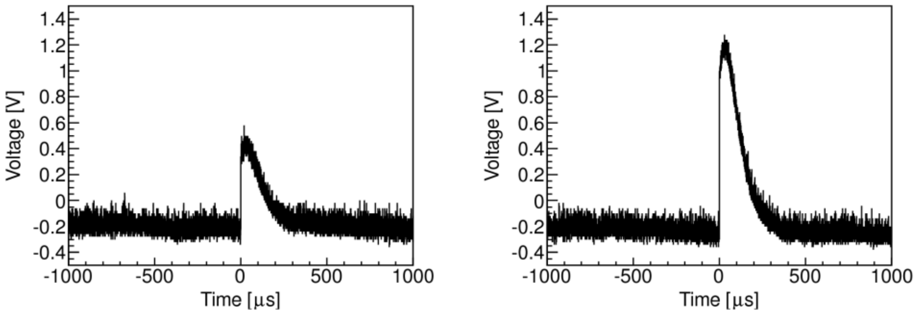
- A 2.5 x 2.5 cm EJ301 liquid organic coupled to an Si-APD was successful; however, no pulse shape discrimination (PSD) was possible
  - Neutrons and gammas indistinguishable

Prototype EJ301-SiAPD scintillator detector with charge-integrating preamplifier



ES detector waveforms



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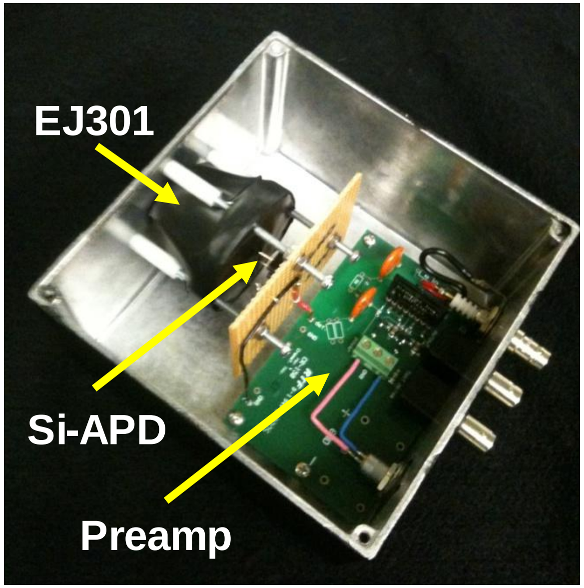
- A 2.5 x 2.5 cm EJ301 liquid organic coupled to an Si-APD was successful; however, no pulse shape discrimination (PSD) was possible
  - Neutrons and gammas indistinguishable
- Next generation EJ301 with silicon photo-multiplier and fast preamplifier provides ~nanosecond voltage following for PSD
  - Potentially the first detector of its kind
  - Applications in fusion, high energy physics, SNM detection, well logging

Prototype EJ301-SiAPD scintillator detector with charge-integrating preamplifier



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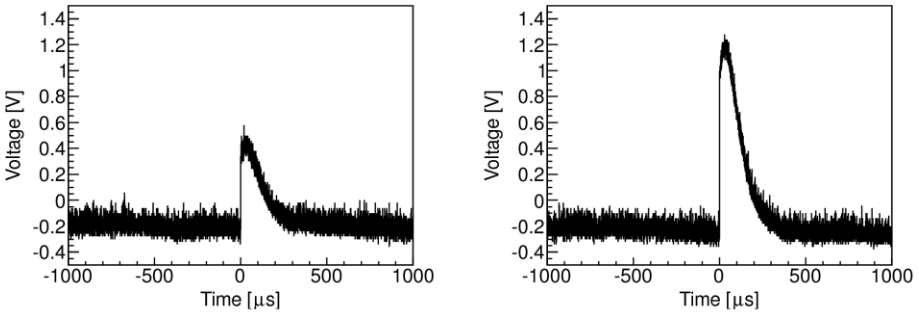
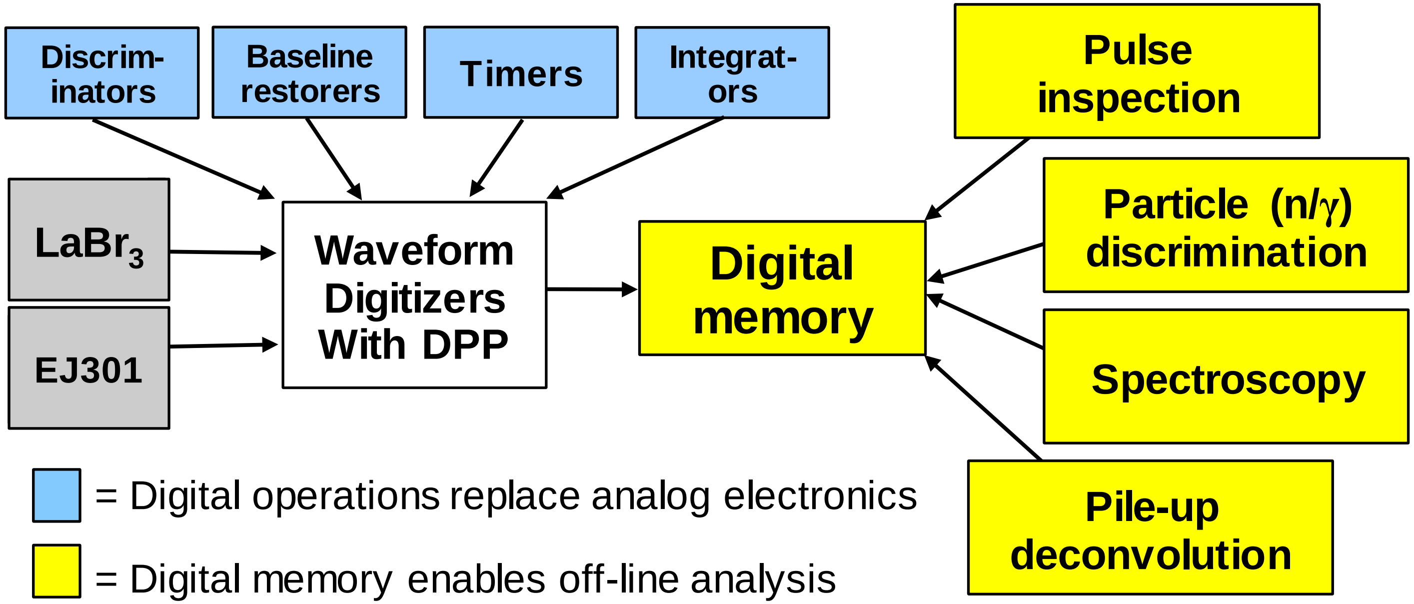


Digital detector waveform acquisition and post-processing enable AGNOSTIC particle detection



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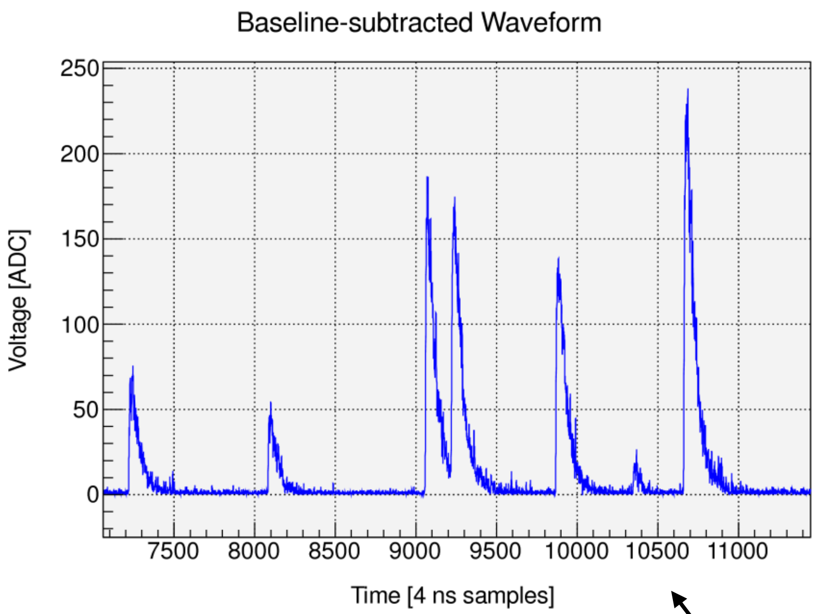
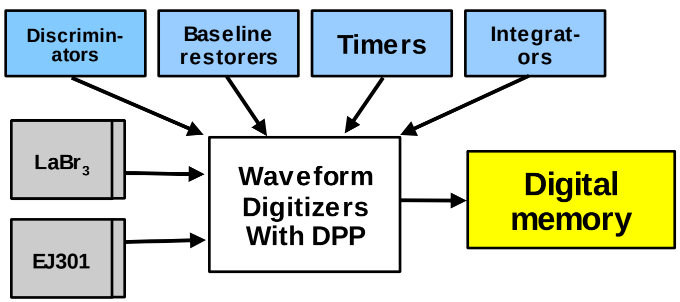


Pulse inspection

Particle (n/γ) discrimination

Spectroscopy

Pile-up deconvolution



= Digital operations replace analog electronics

= Digital memory enables off-line analysis

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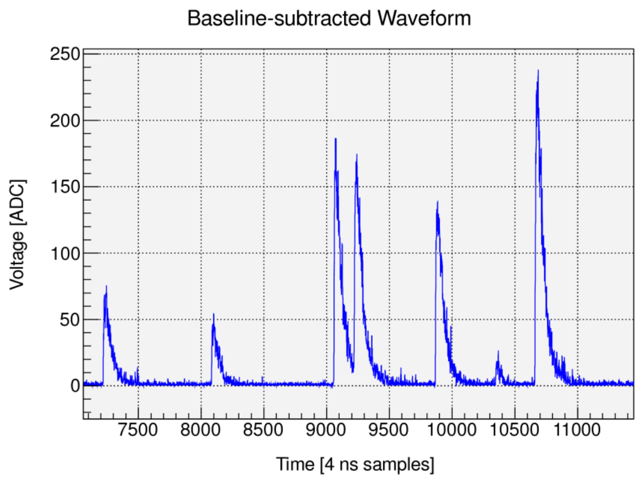

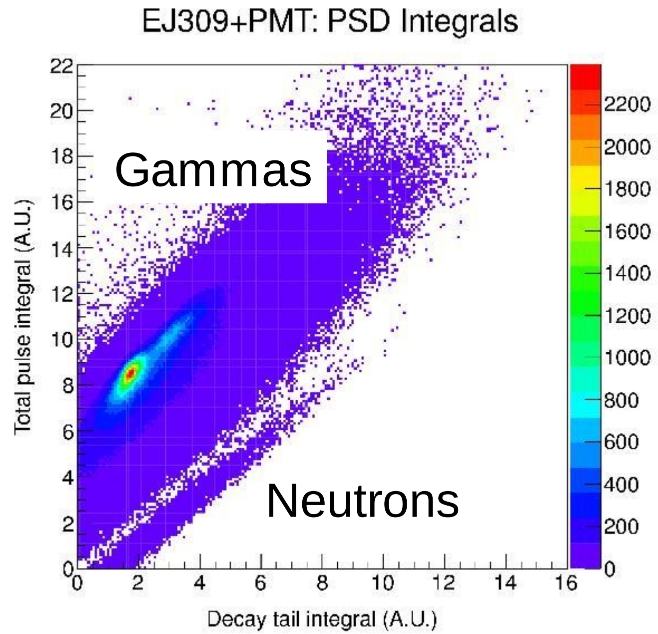

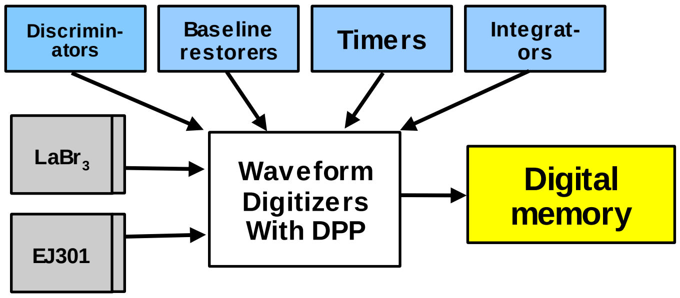

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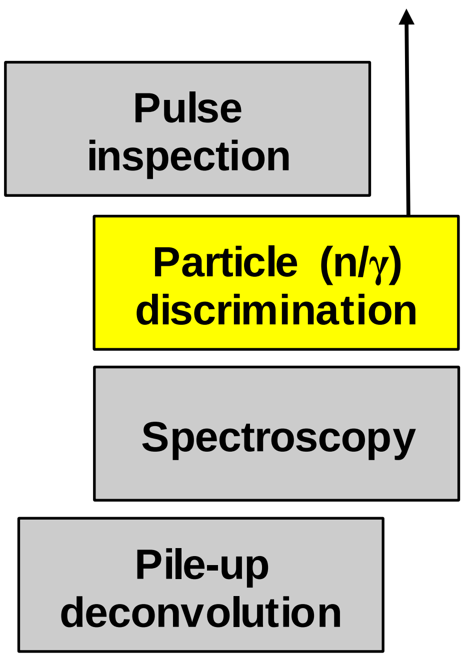

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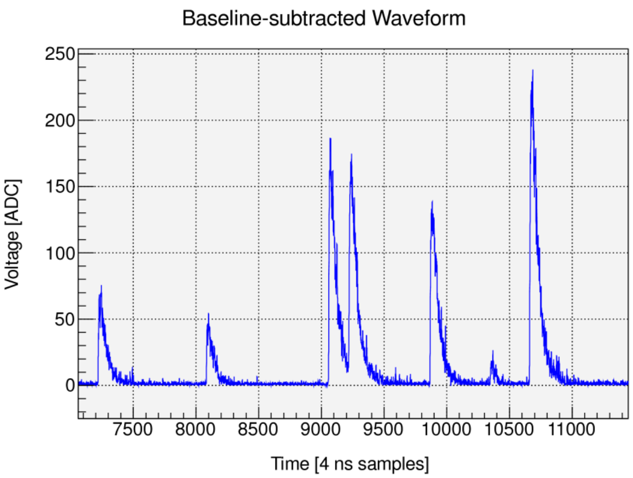

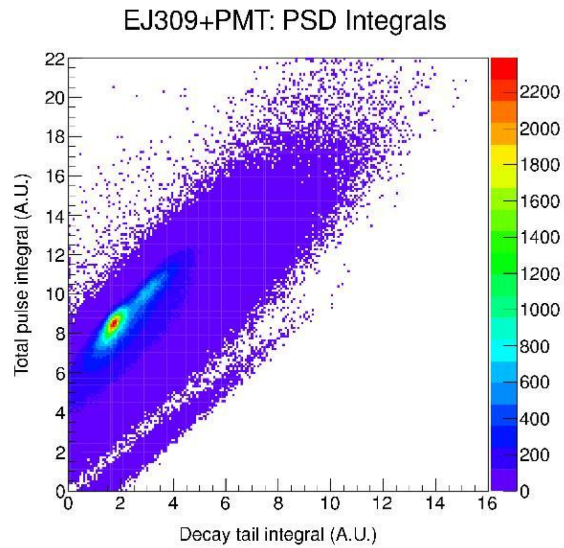

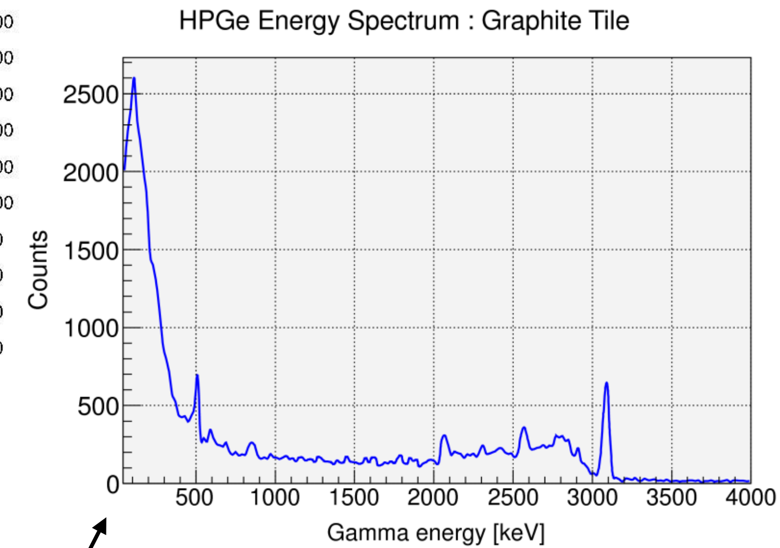

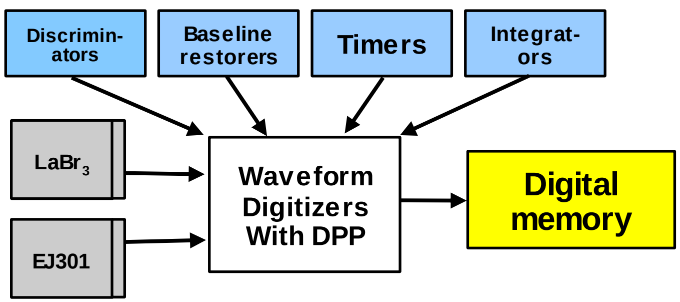

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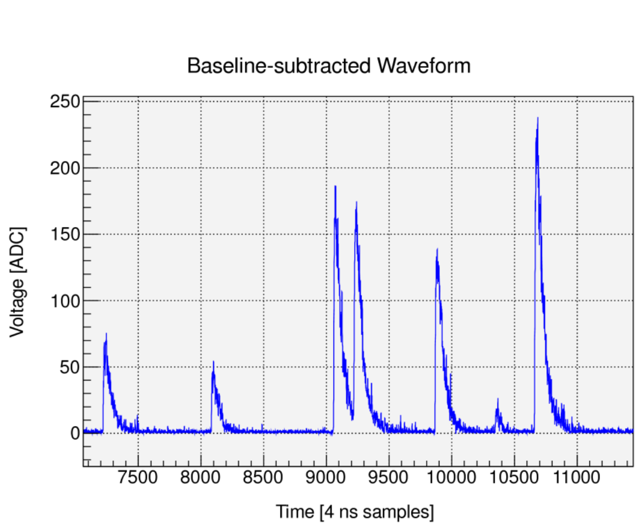

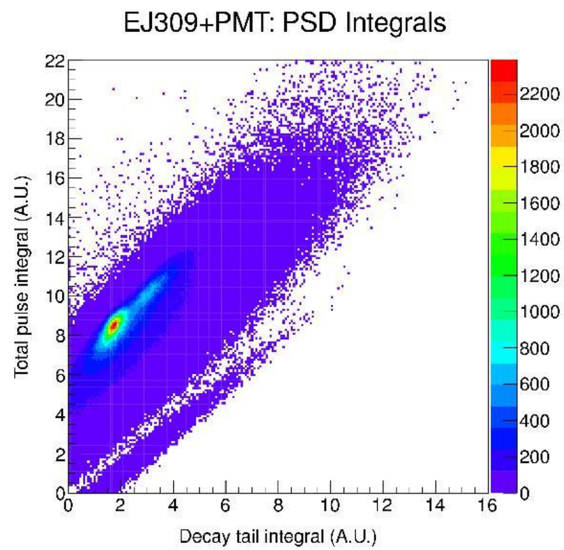

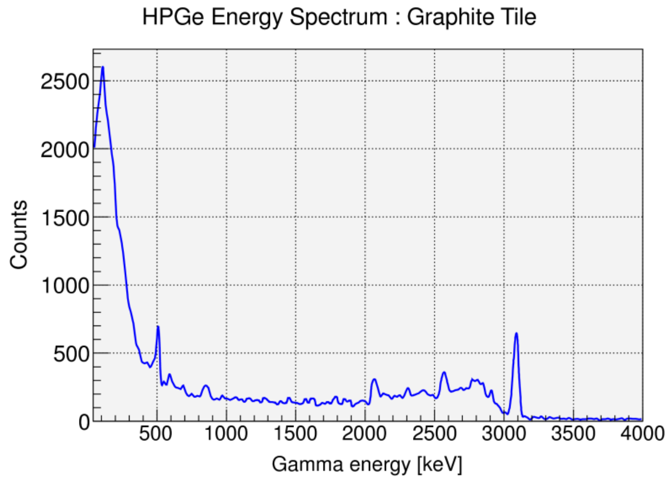

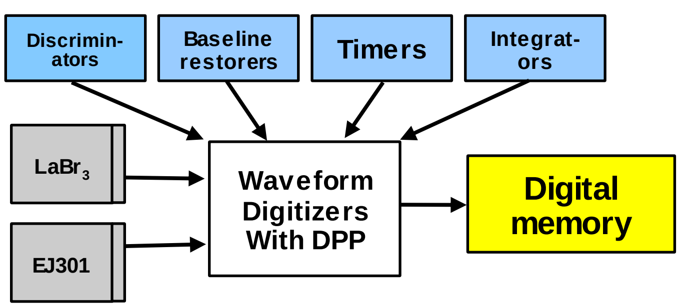

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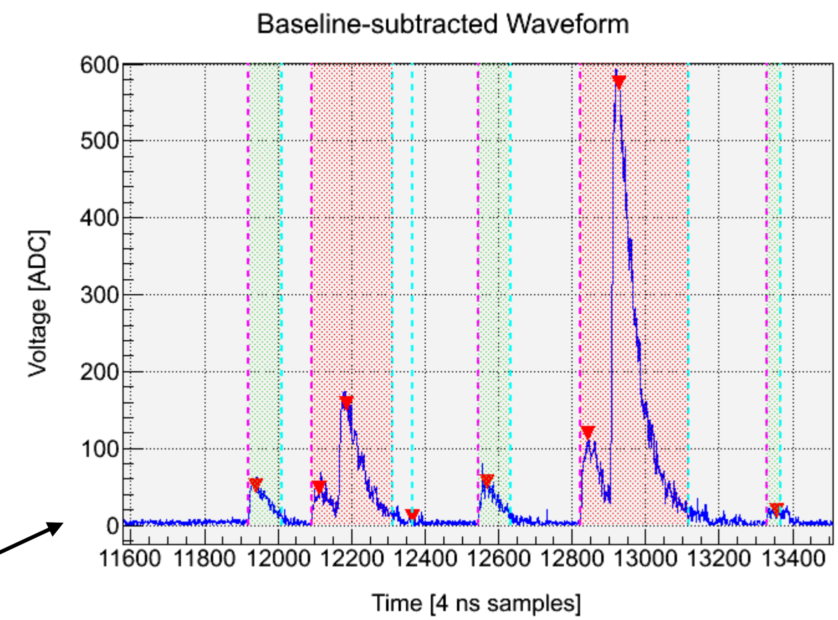


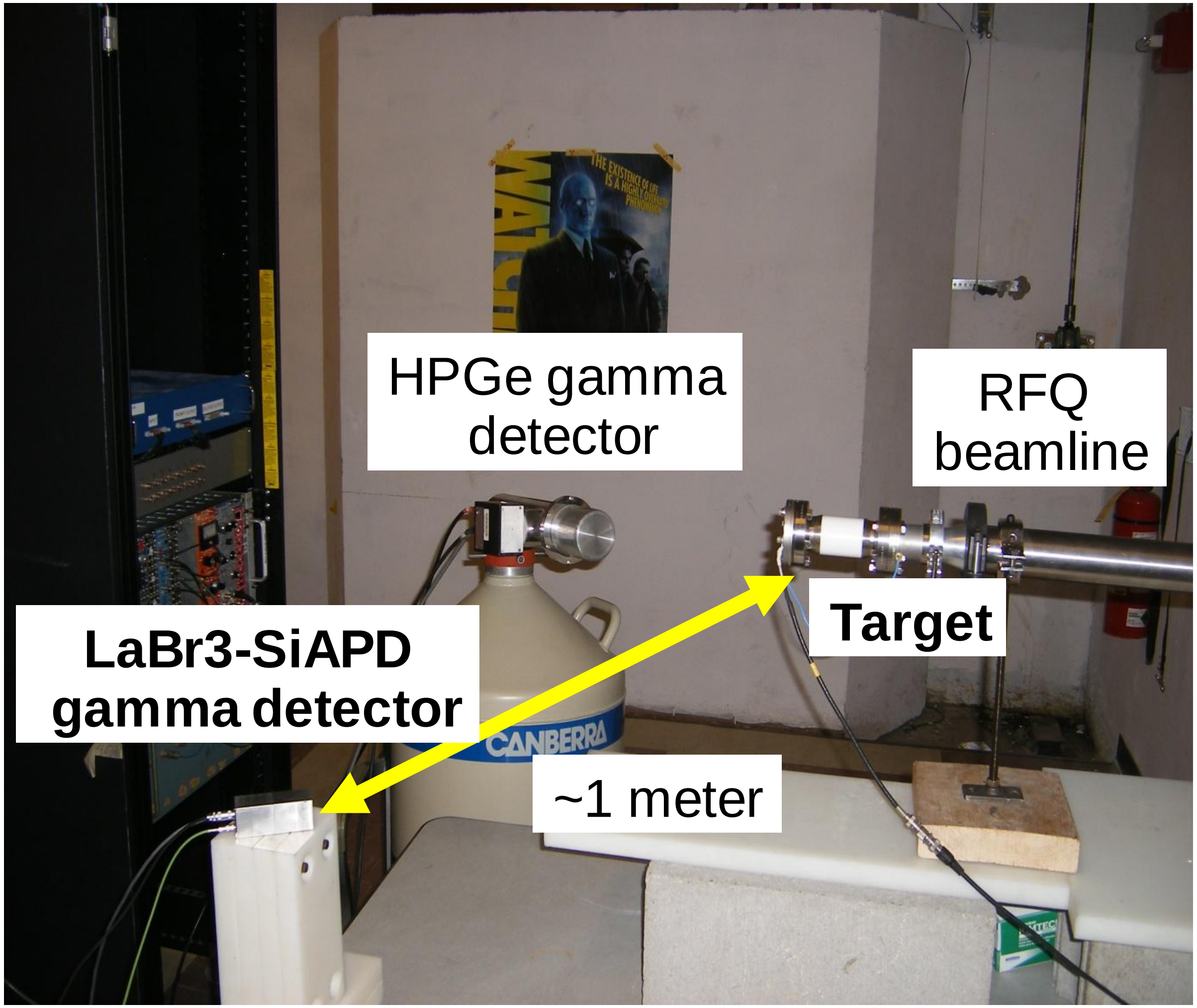
Mockup first-wall measurements were conducted with AGNOSTIC in the laboratory

- Experiments to simulate the actual PWI measurements on C-Mod were conducted *ex-situ* in the laboratory

- **Beam:** ~0.9 MeV Deuterons
  0.1% duty cycle
  50 us bunches
  30 Hz rep rate

- **Target:** C-Mod Molybdenum PFC Tiles from inner wall

- **Objective:** Validate ability to monitor wall conditions by quantifying boron and oxygen isotopes



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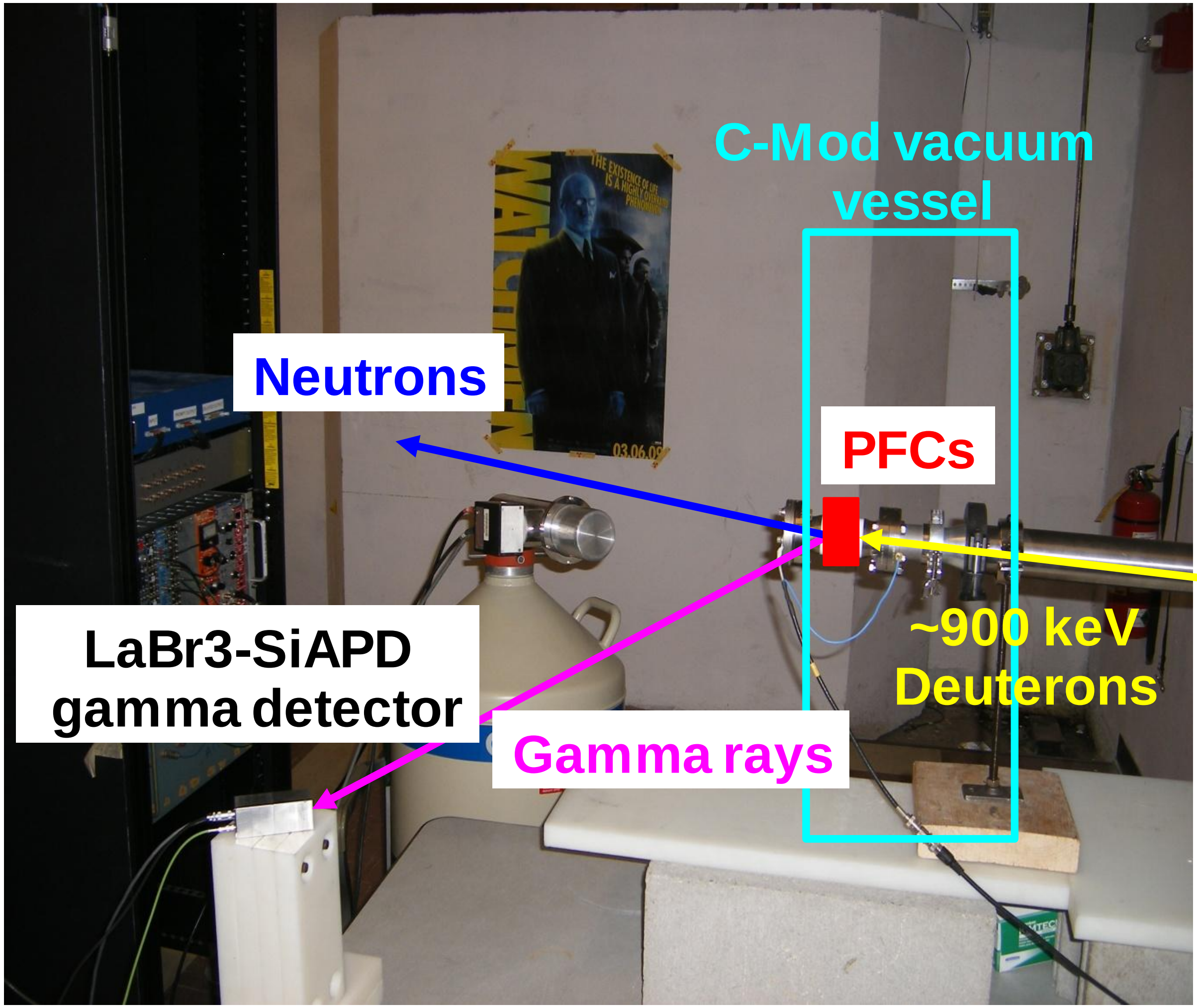
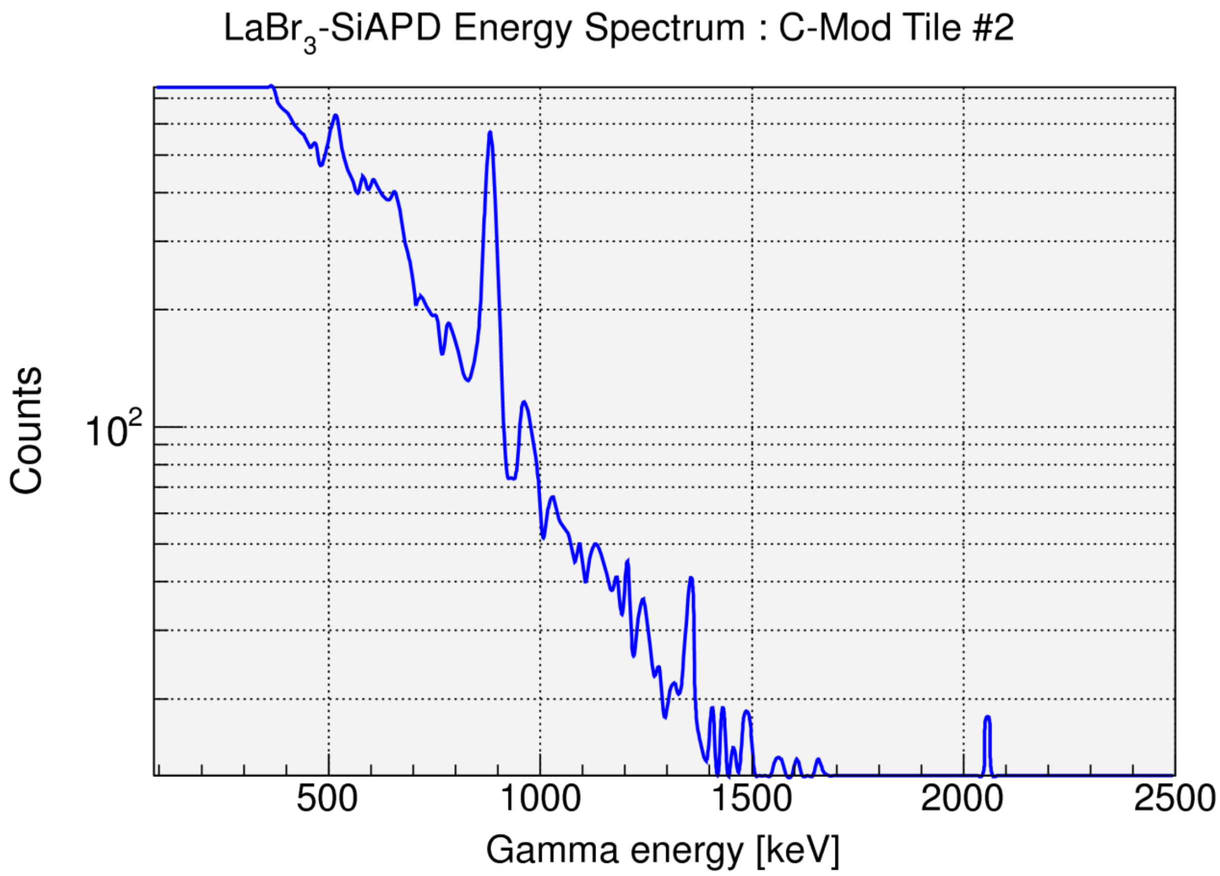


AGNOSTIC has successfully identified boron on molybdenum PFC tiles from Alcator C-Mod in the laboratory

Discrete gamma energies → Unique nuclear level spacing → Isotope identification



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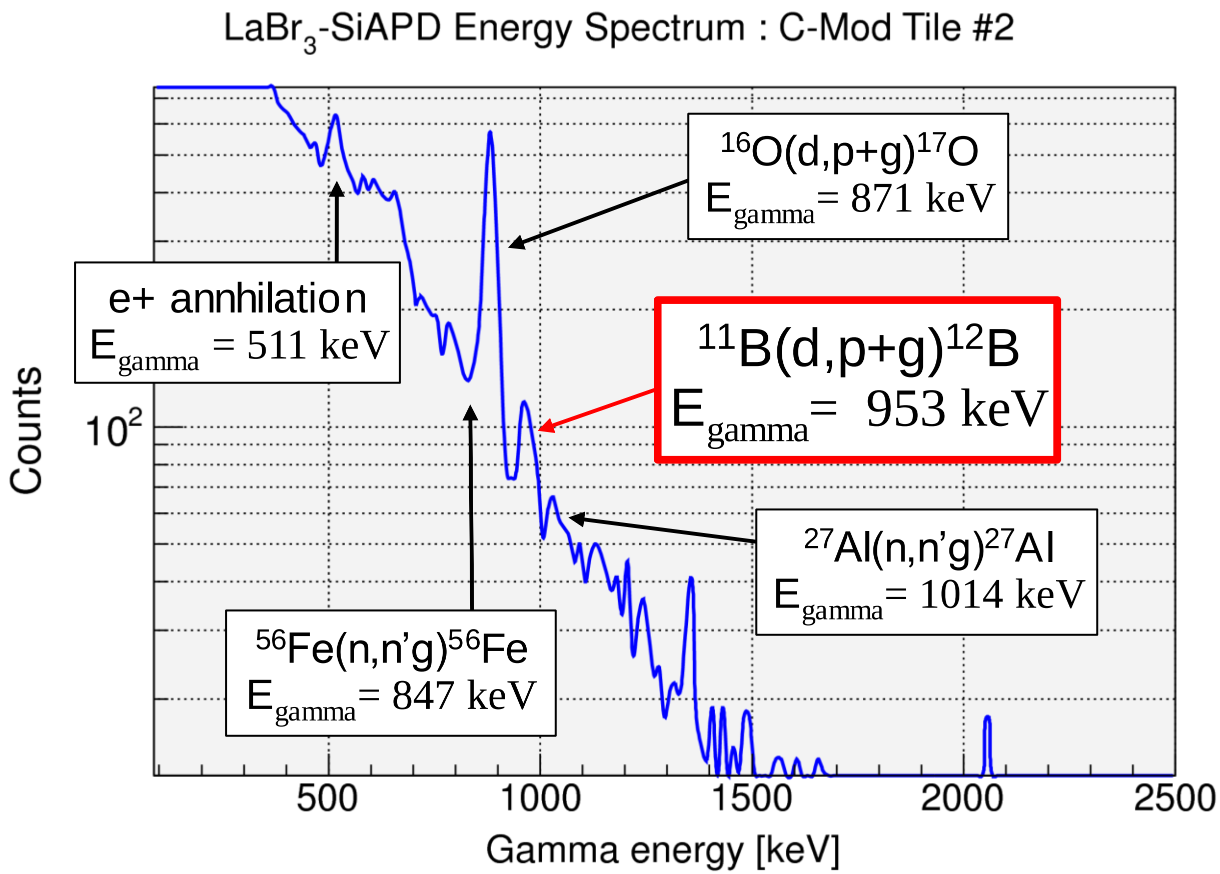

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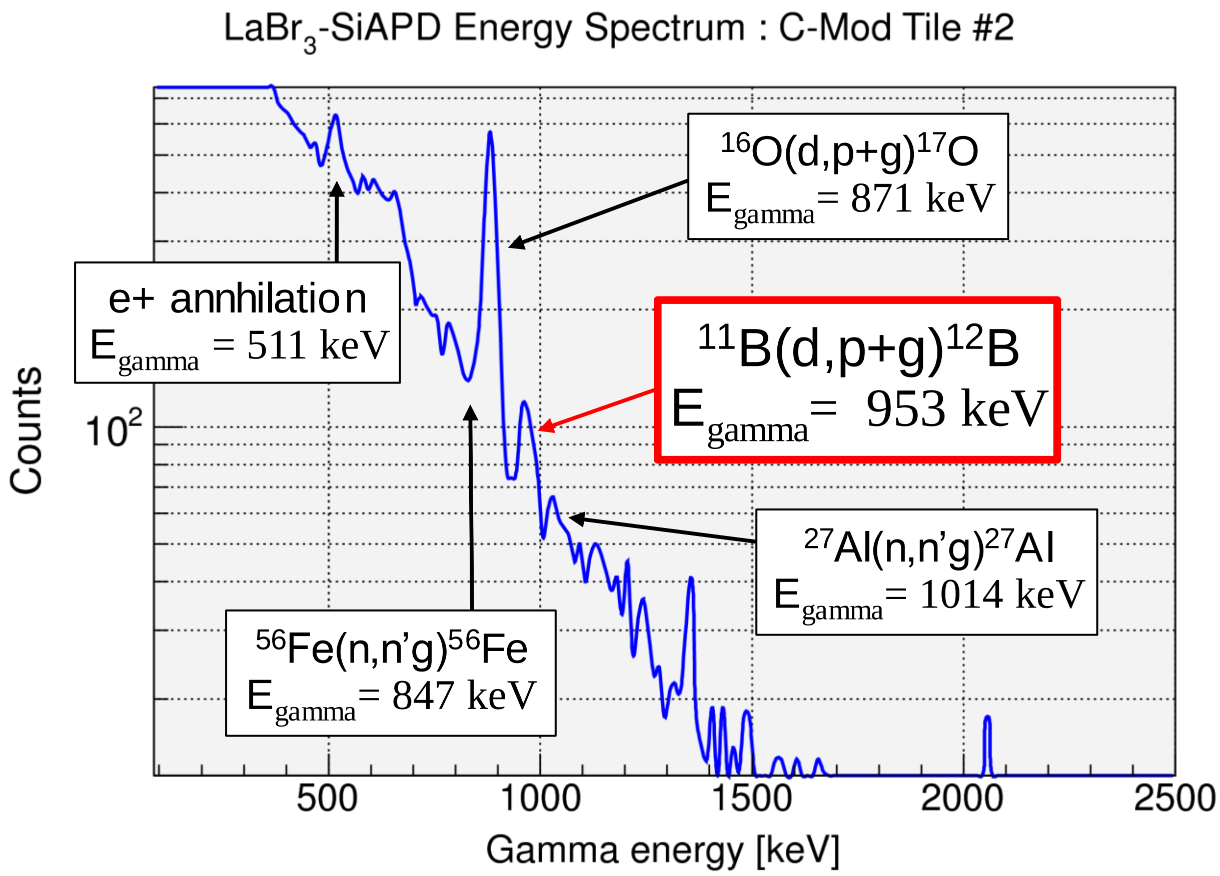
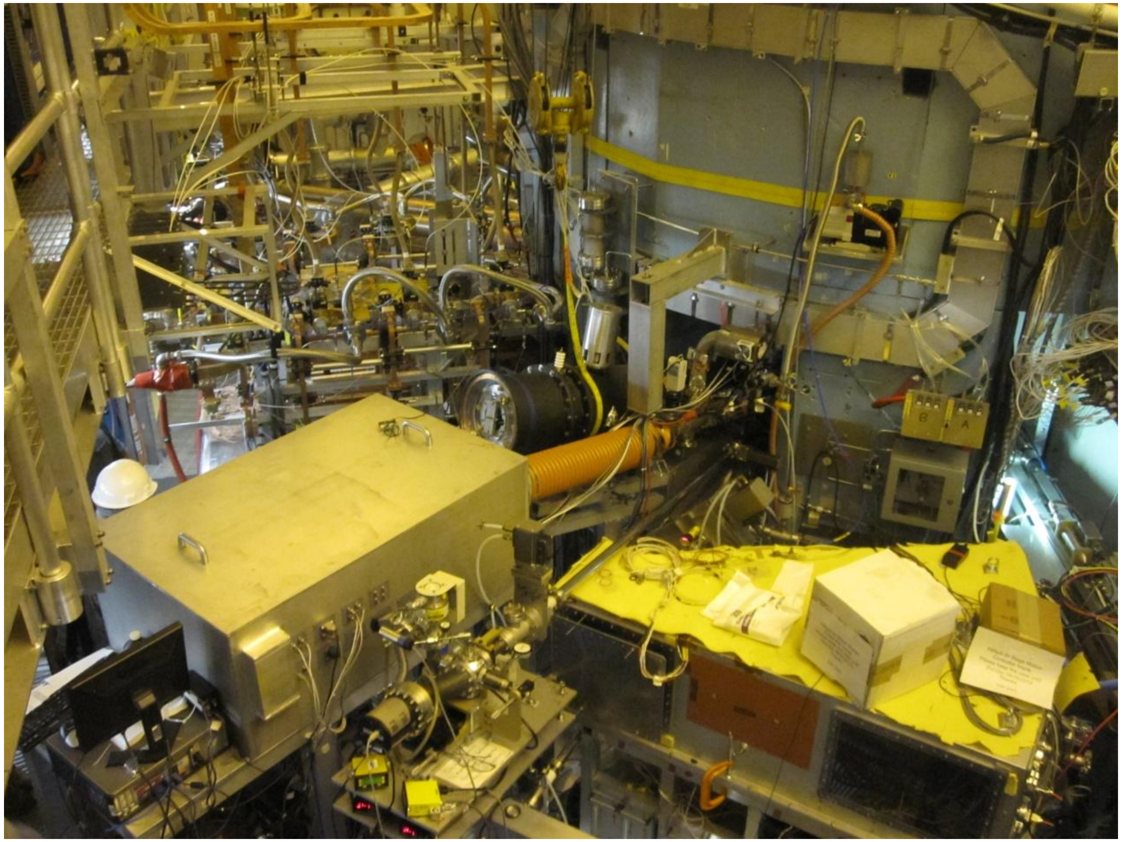
- *Ex-situ* validation of the proposed diagnostic technique
- Confirmation of AGNOSTIC components working together
- Validation that LS detector can resolve the peaks of interest from "background" peaks



AGNOSTIC was successfully installed on Alcator C-Mod last weekend; first results expected in next few days



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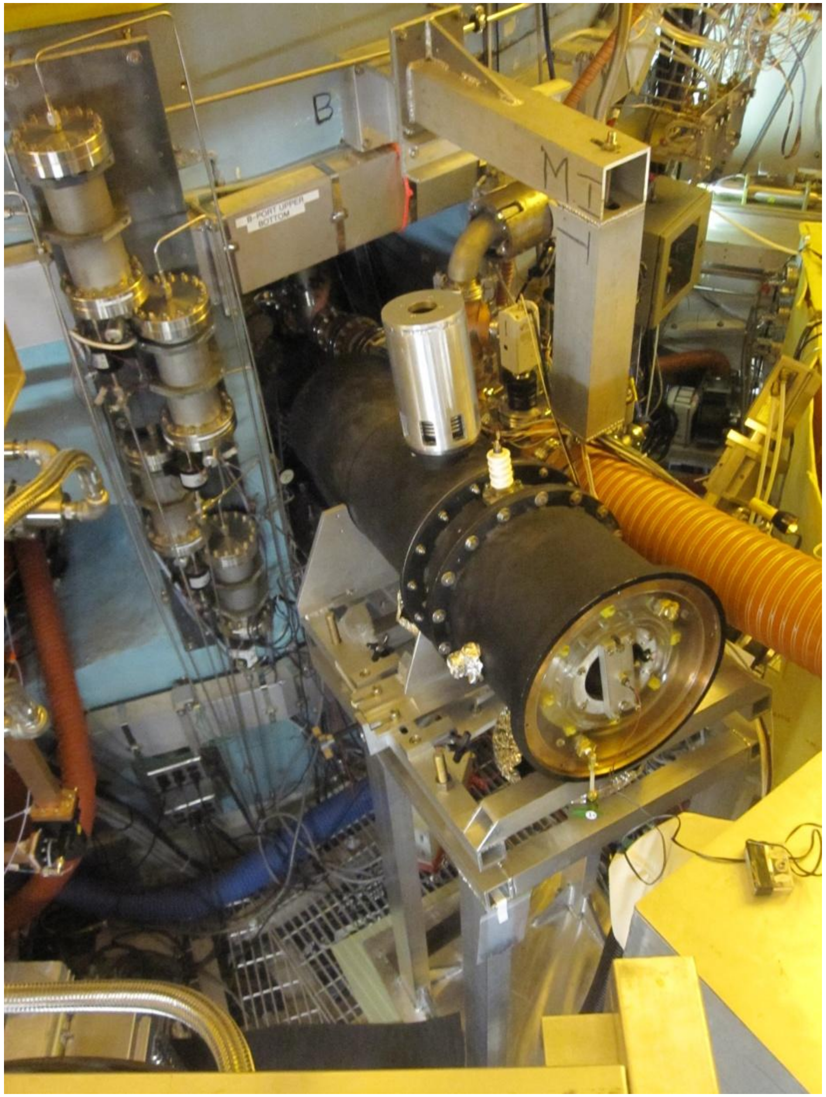
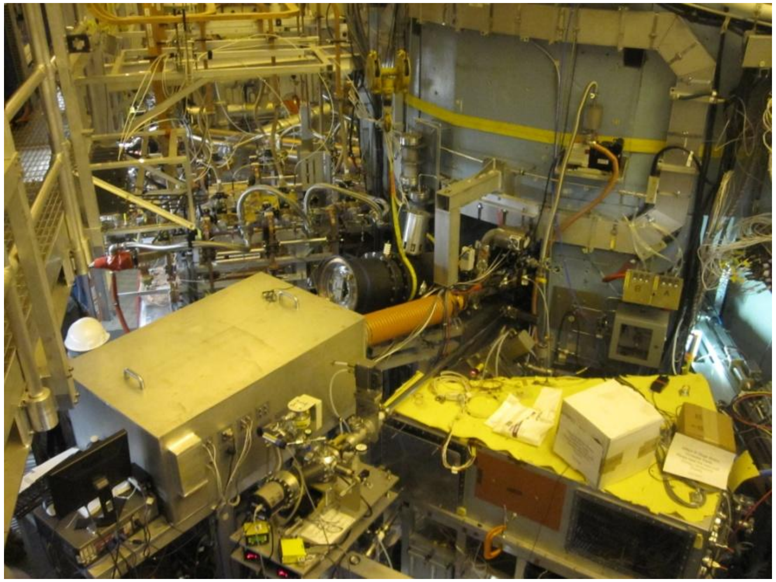
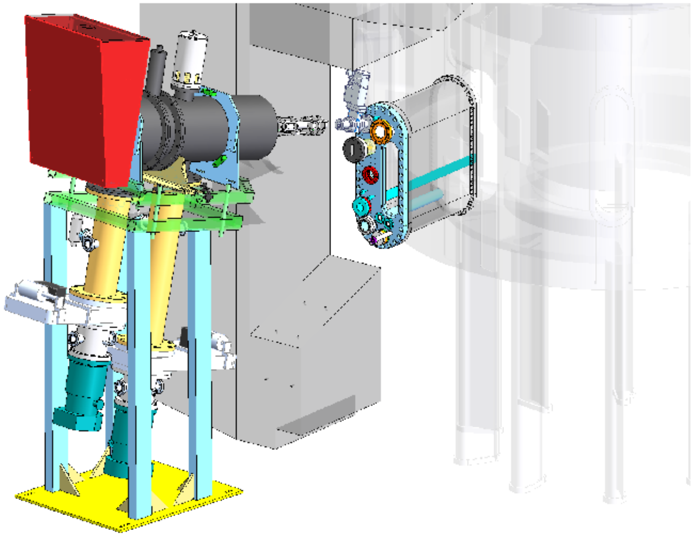
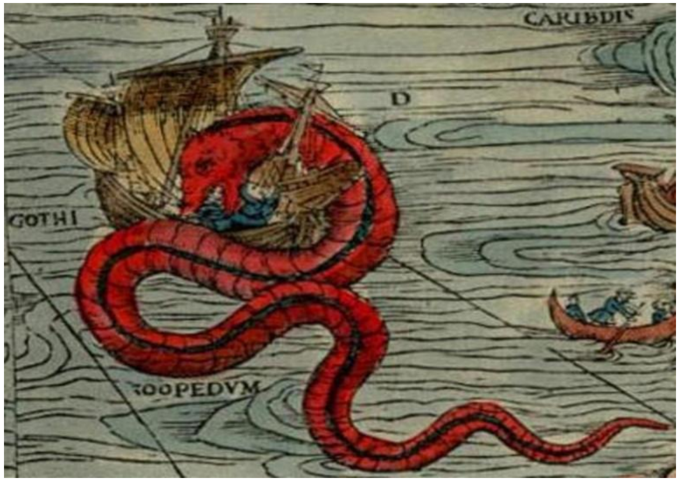


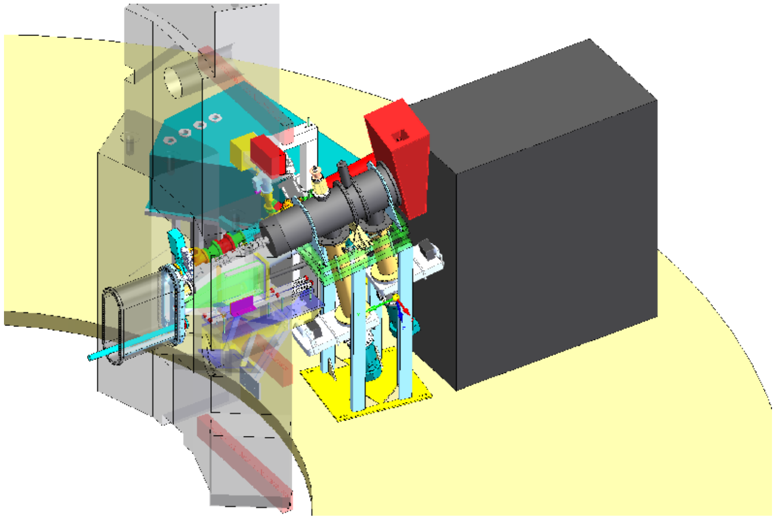






The future of PWI and magnetic fusion energy?

AGNOSTIC will begin the first *in-situ* exploration of PWI



The future of PWI and magnetic fusion energy!

- The understanding of plasma-wall interaction (PWI) science is essential to advance magnetic fusion energy and reactor-relevant confinement devices
- AGNOSTIC is a new generation of *in-situ* ion beam diagnostics capable of exploring the most fundamental issues of PWI, including fusion fuel retention, erosion/redeposition, wall conditioning, and isotope mixing