Computational Study of Cr-SPD for Neutron Flux Measurements in HCPB TBM of ITER

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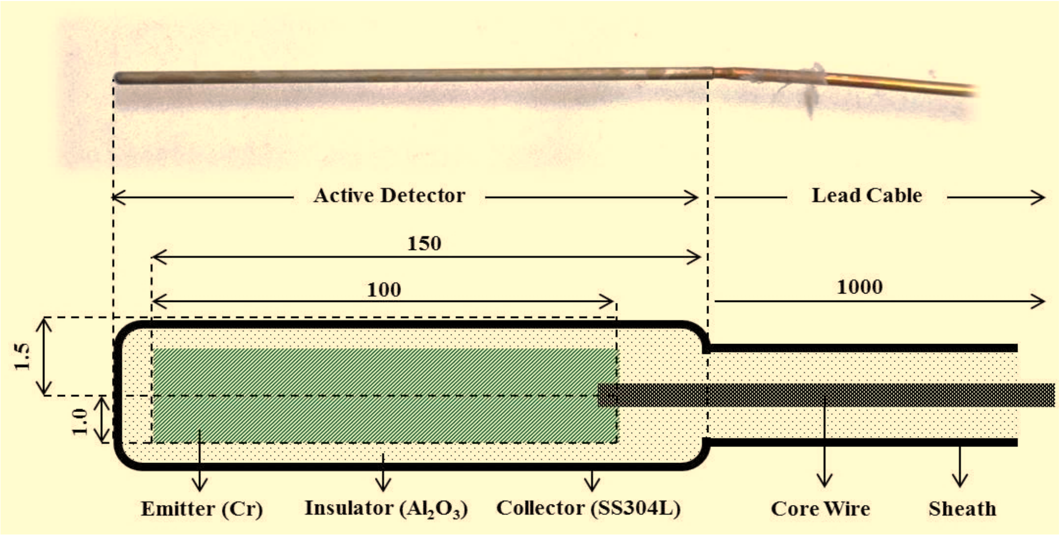


OUTLINE

1a. ITER Test Blanket Modules (TBM)

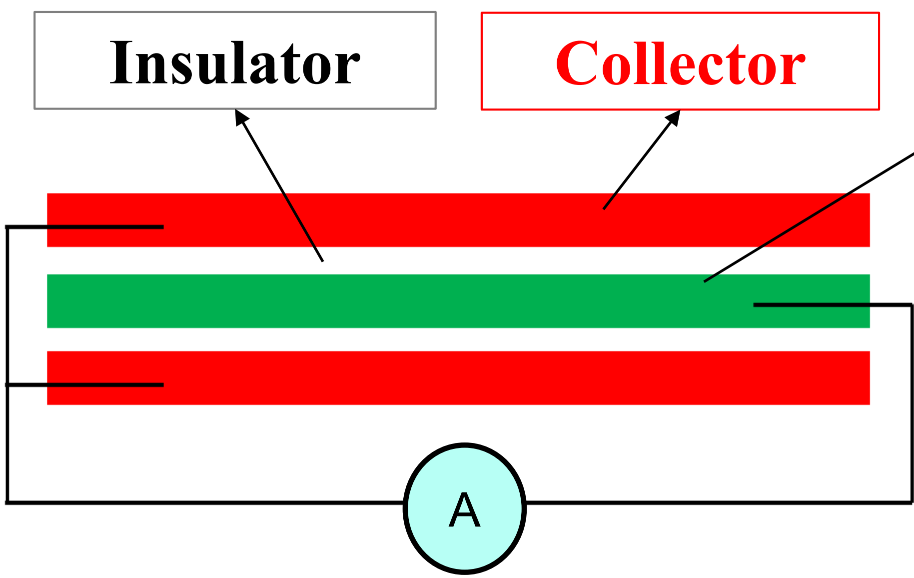
- **ITER** is a Tokamak Fusion Reactor being built in St. Paul lez Durance

$$ {}_{1}^{2}D + {}_{1}^{3}T \rightarrow {}_{2}^{4}He + {}_{0}^{1}n + Energy\ (18\ MeV) $$

- To test tritium breeding concepts → **Test Blanket Modules (TBM)**
- To validate neutronic modelling tools, viz.- particle transport/ activation codes, nuclear cross-section data → neutronic experiments in TBM
- **Neutron and Gamma Flux Measurements** important → indirect measures for tritium production, material activation
- Harsh conditions: E_n- 14 MeV, Φ_n-10^{14} cm^{-2} s^{-1}, B - 4 T, T - 500 ℃
- Do we have detectors?? Activation system, fission chambers, diamond

1b. Self-Powered Detectors (SPD)

- **Self-Powered Detectors (SPD)** are common instruments for neutron and gamma flux monitoring in fission reactor cores



Emitter

"High Interaction Cross Section"

Neutrons

Self-Powered Neutron Detector (SPND)

[redacted]

$n + X \rightarrow Y + \gamma \rightarrow e$

[redacted]

$n + X \rightarrow Y \rightarrow Z + \beta$

Gamma

Self-Powered Gamma Detector (SPGD)

$\gamma \longrightarrow e$

- Direct Current (DC) signal → incident flux
- No bias voltage required!
- Compact, robust and reliable!

1c. SPD Design and Interactions

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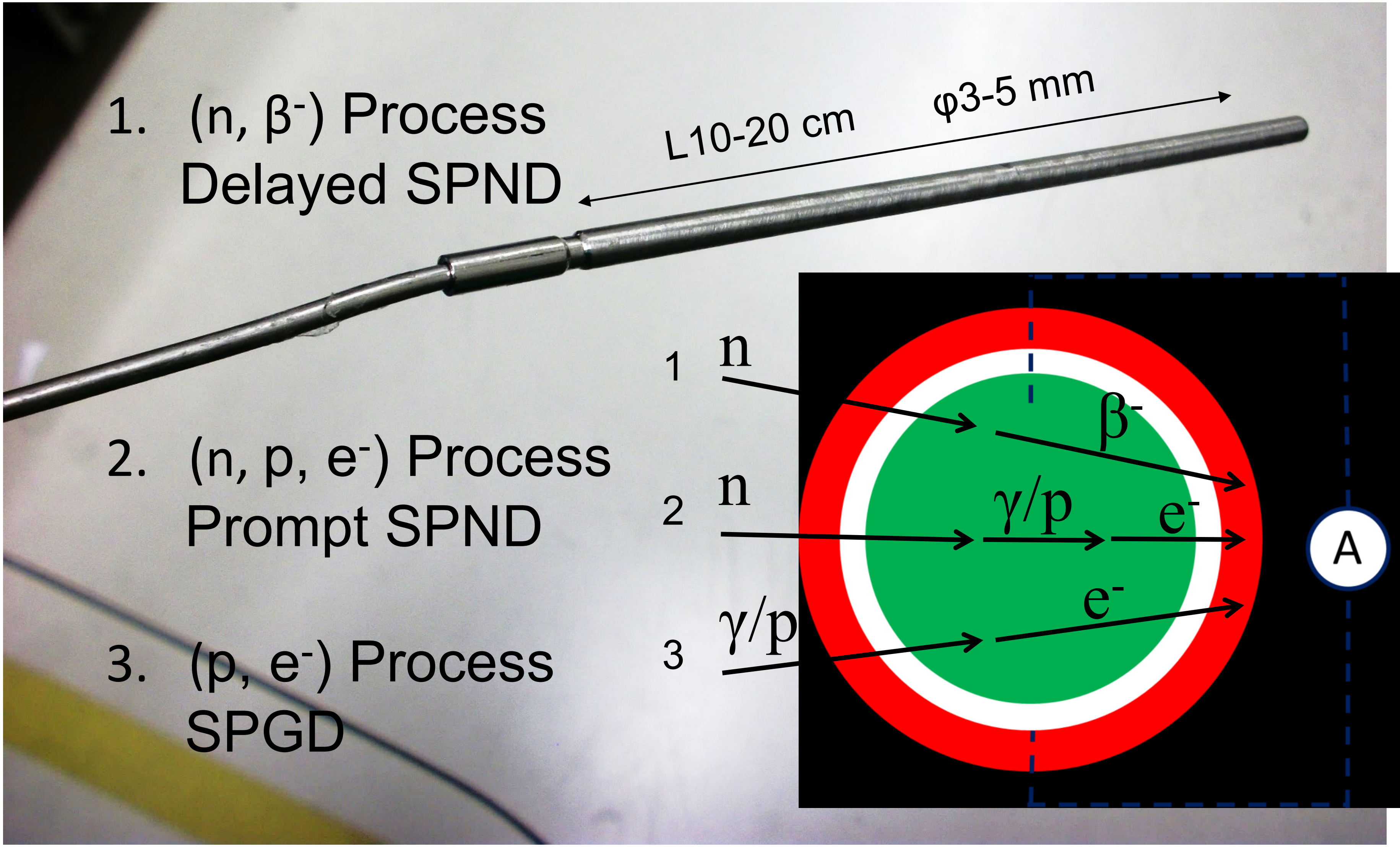
1. (n, β^-) Process
   Delayed SPND
2. (n, p, e^-) Process
   Prompt SPND
3. (p, e^-) Process
   SPGD

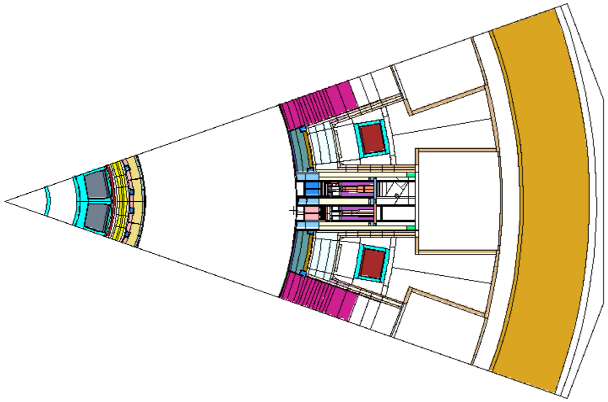


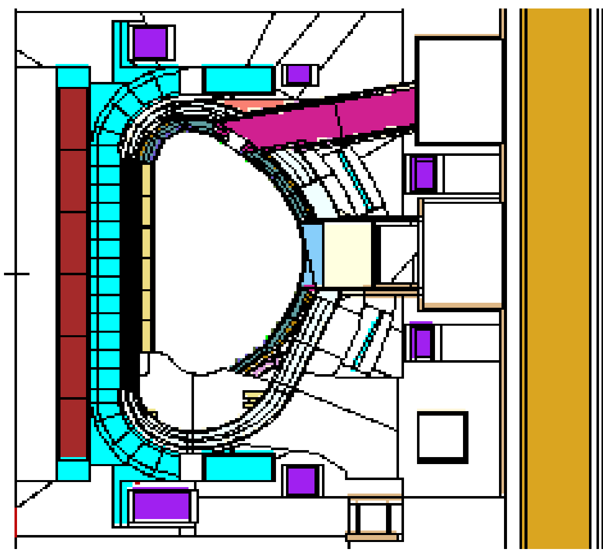
1d. Chromium Fast Neutron SND

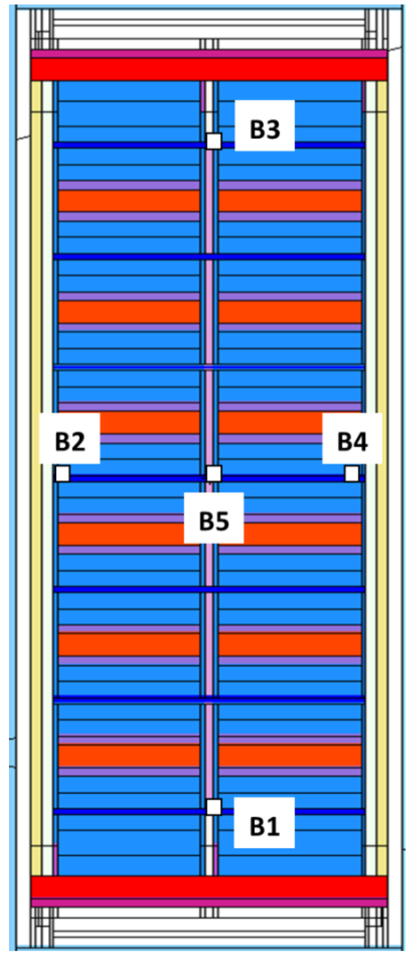
- Fast Neutrons very low cross-section for (n, β^-) processes: 0.01-100 mb
- Many new (threshold) reactions: (n, p), (n, α) etc. apart from (n, γ)
- Delayed SPND- similar cross-sections (for all materials), competing effects → sophisticated response mechanism
- Prompt SPND- comparable photon production probabilities and therefore, response
- Emitter materials shortlisted for study: **$^{52}Cr(n,p)^{52}V$, $^{9}Be(n,\alpha)^{6}He$**
- **ENEA + KIT Cr-SPD**: with typical dimensions, designed & constructed

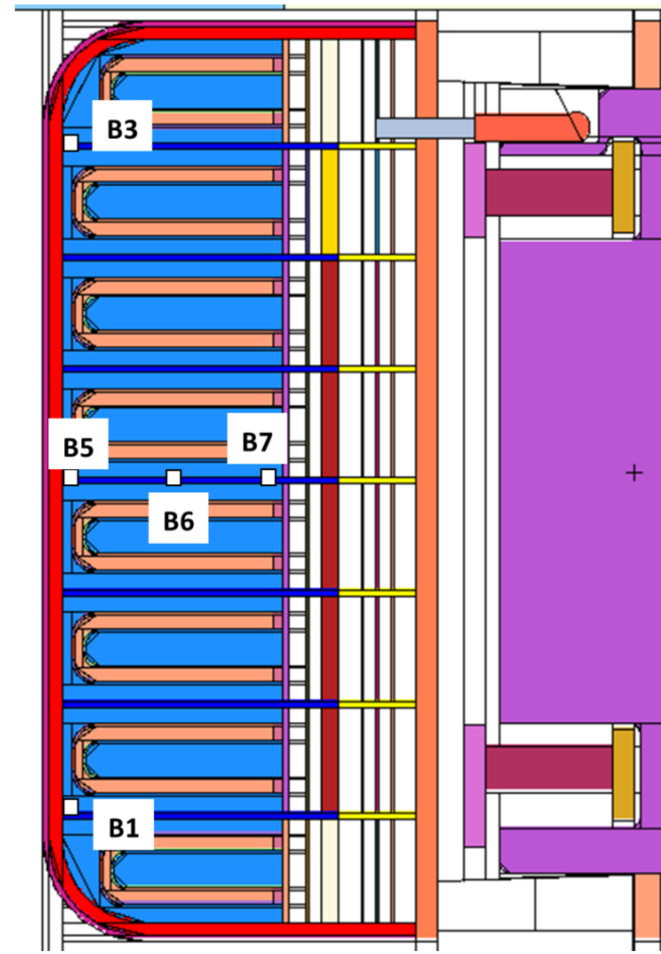
  Cr-emitter, Al_2O_3- insulator, SS304L-collector

2a. A-lite MCNP Model & HCPB TBM

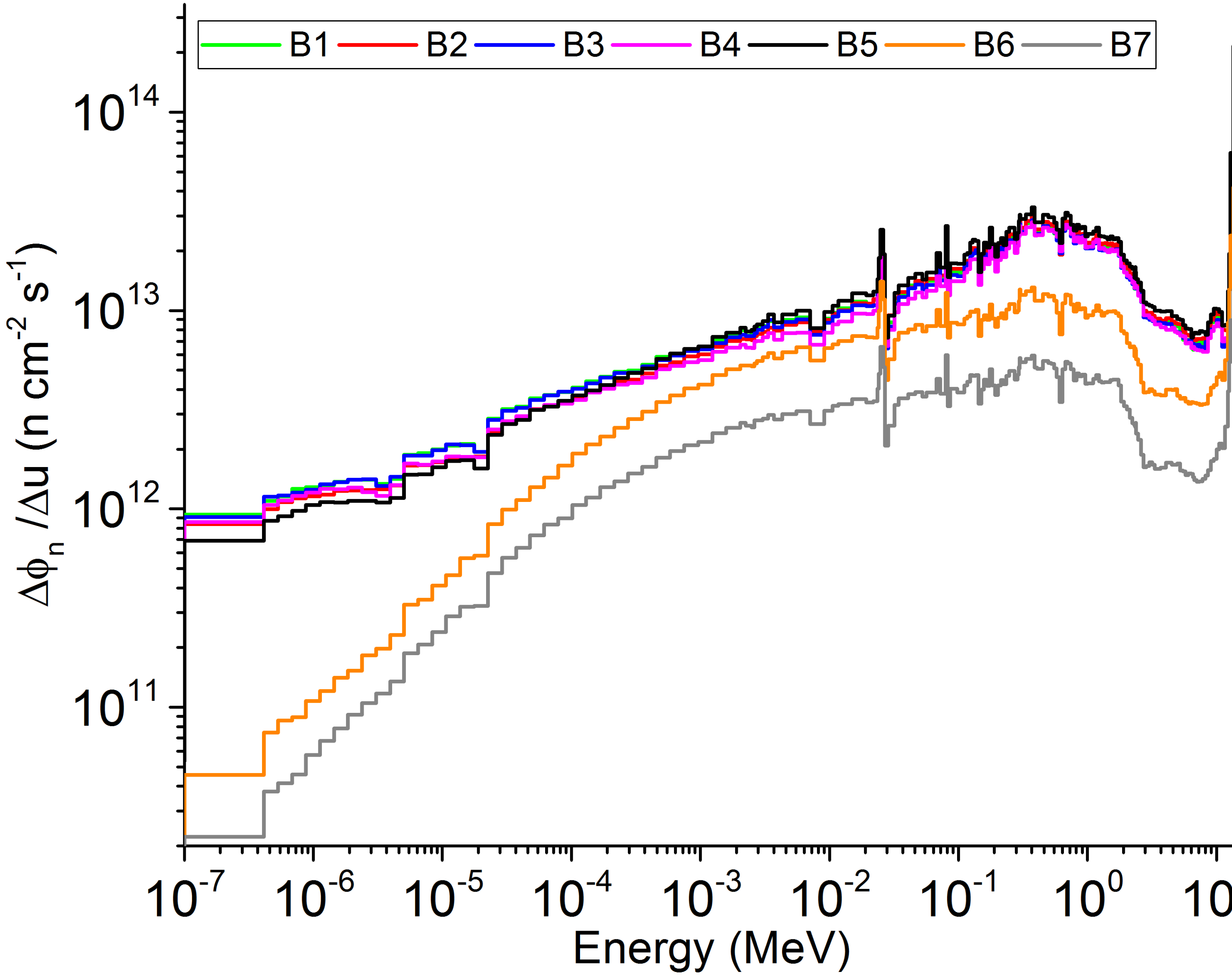




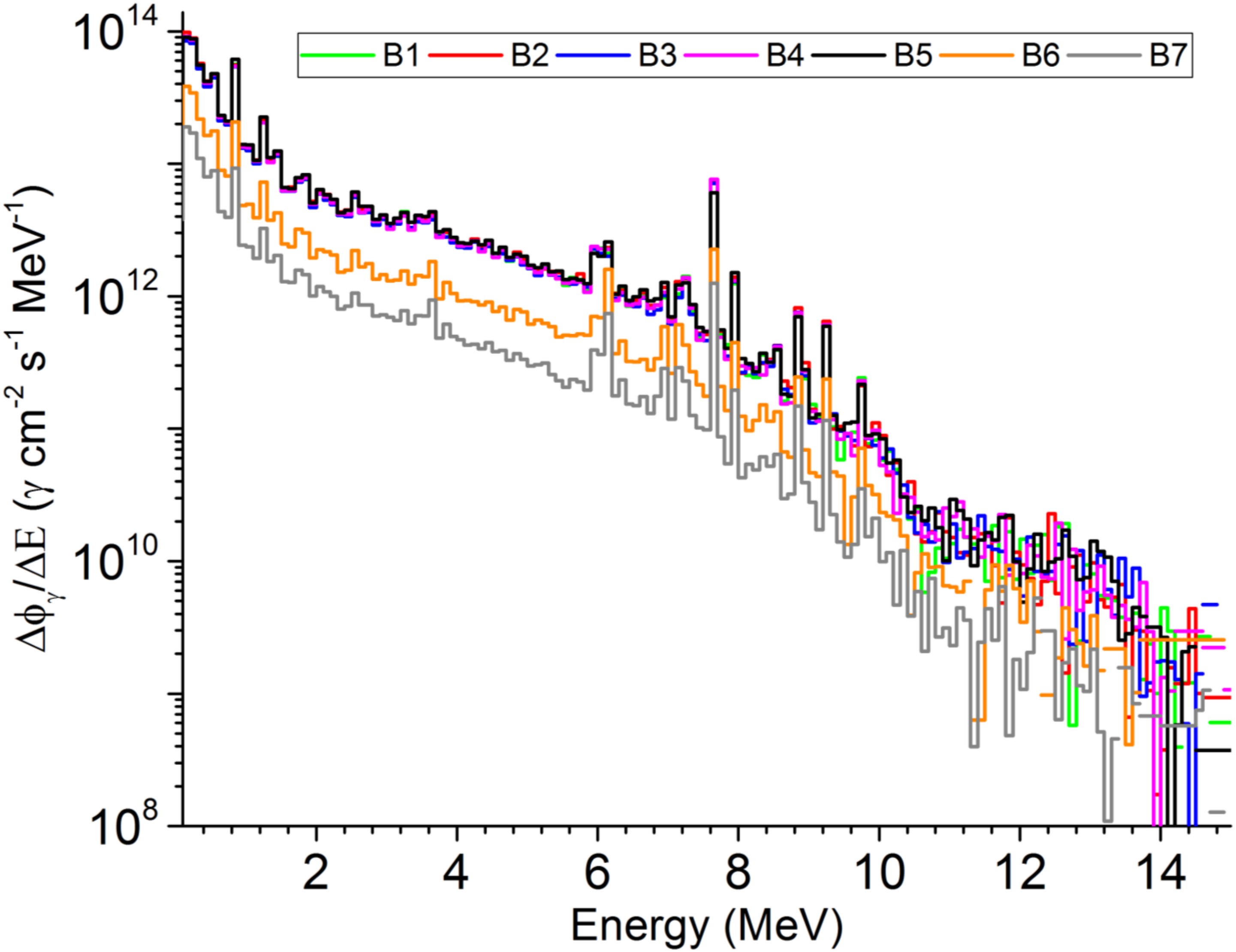




2b. HCPB Neutron Spectrum



2c. HCPB Photon Spectrum



2d. SPD Sensitivity Theory and Model

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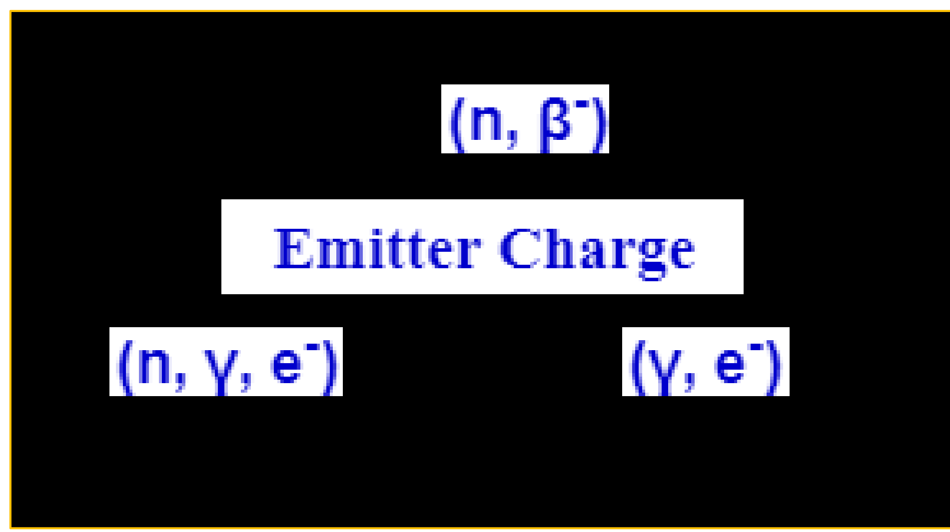
$$I_\beta = \frac{eV}{L} \int_0^{E_{max}} \Sigma(E_n)\, \varphi(E_n)\, f(E_n)\, dE_n \times \int_{E_{MIN}}^{E_\beta} \left(\frac{-dE}{dx}\right)_E^{-1} dE \times \int_E^{E_\beta} N[R(E') - R(E)]\, B(E')\, dE'$$

- Neutron Capture Rate (Emitter)
- Stopping (Insulator)
- Beta emission and transport

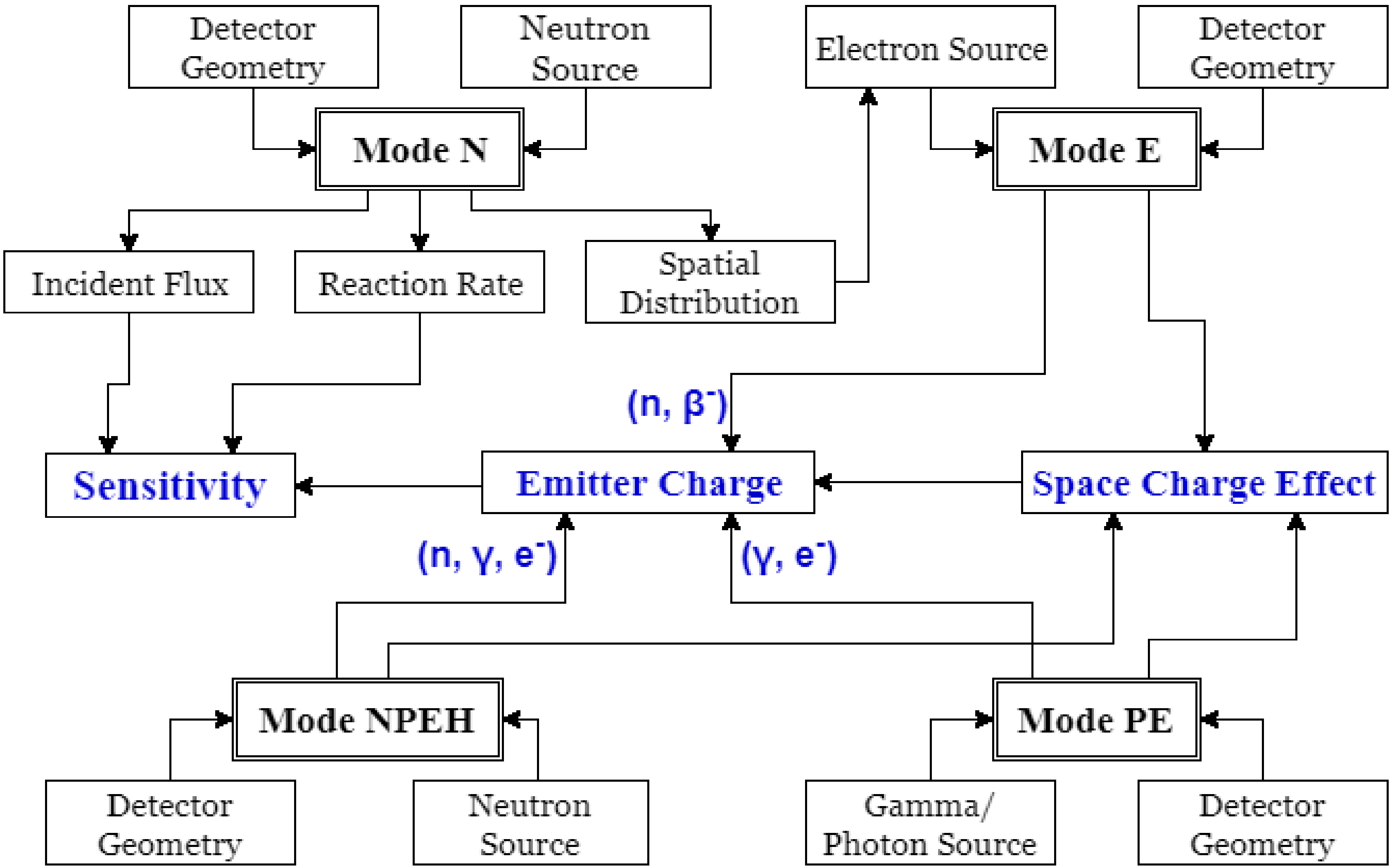
$$S = \frac{Q_e}{\varphi}$$

<u>Monte-Carlo (MCNP) Model</u>

- Coupled n-γ-e transports
- Activation products modelled in multiple steps, normalized to 1 source neutron
- Insulator charge accumulation affects included separately



2e. Model Development in MCNP



2f. Sensitivity of SPD

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Sensitivity	Emitter Charge	Space Charge Effect

Emitter charge: $\boldsymbol{Q_{eTOT}} = RR \times Q_{eE} + \varphi_{G/N} \times Q_{ePE} + Q_{eNPE}$

Insulator charge: $\boldsymbol{Q_{iTOT}} = RR \times Q_{iE} + \varphi_{G/N} \times Q_{iPE} + Q_{iNPE}$

Insulator charge density: $\boldsymbol{\rho_{iTOT}} = RR \times \rho_{iE} + \varphi_{G/N} \times \rho_{iPE} + \rho_{iNPE}$

- $\boldsymbol{\rho_{iTOT}}$ used in Poisson's equation to solve for Space-Charge Field
- **F:** Returning Fraction, pseudo-analysis

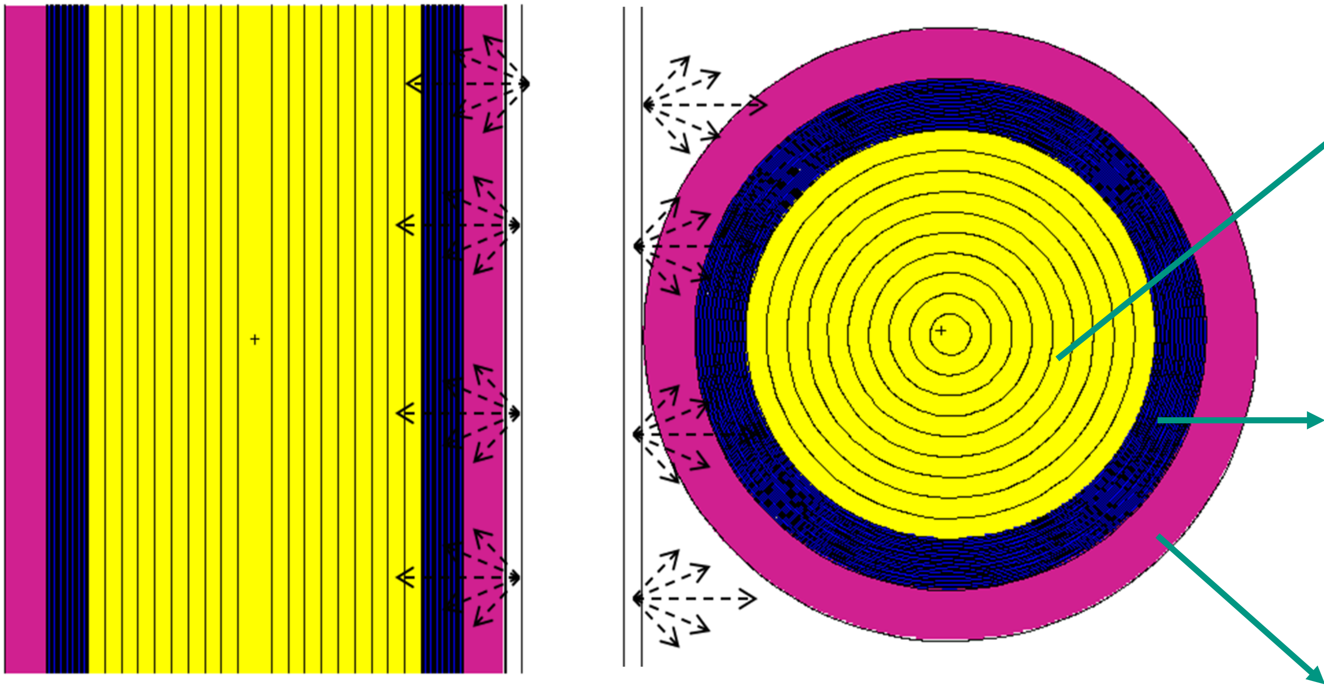
- Net Emitter Charge (per neutron)

$$\boldsymbol{Q_e} = Q_{eTOT} + F \times Q_{iTOT}$$

- Sensitivity:

$$\boldsymbol{S} = \frac{\boldsymbol{Q_e}}{\boldsymbol{\varphi}}$$

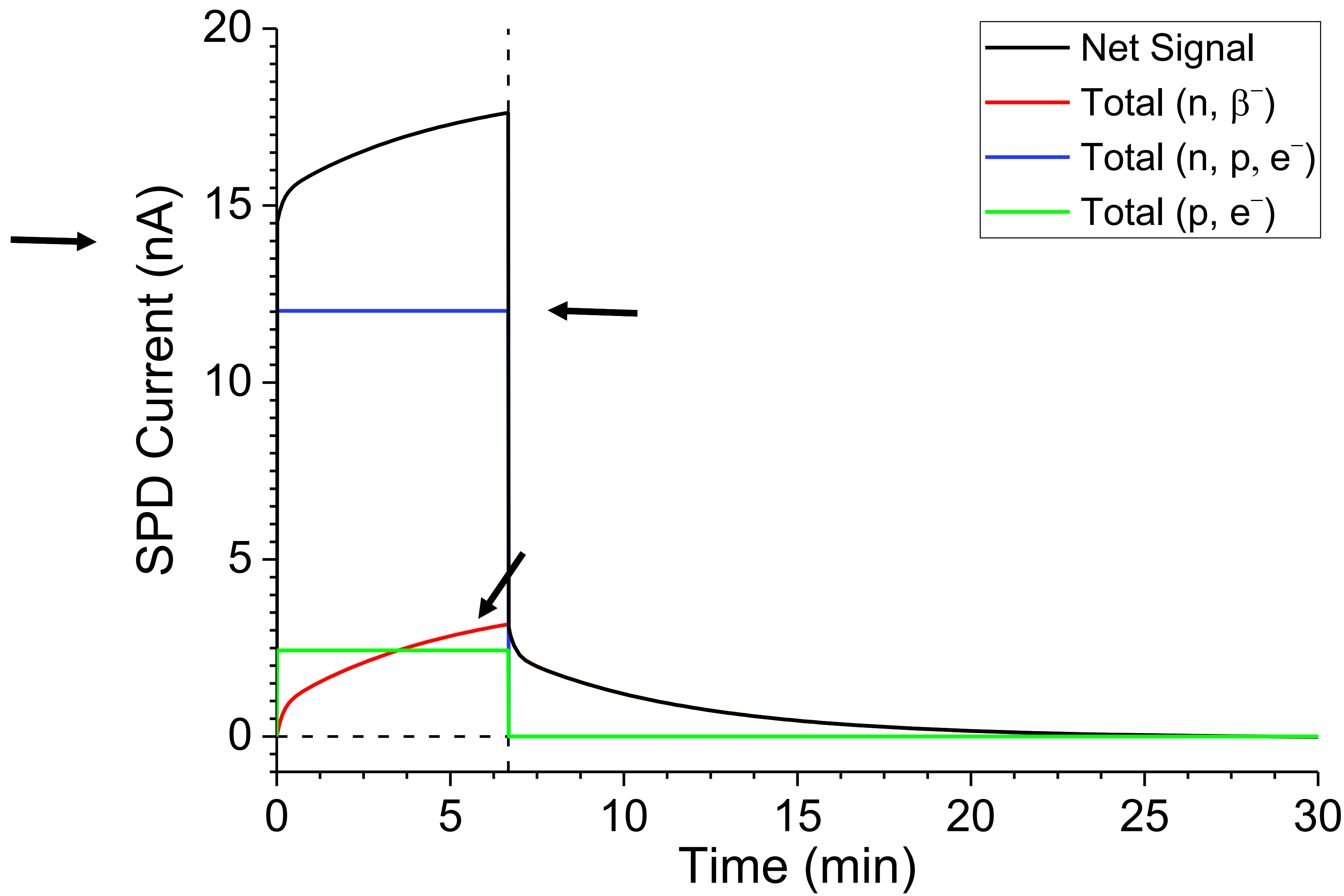
2g. Case of Cr-SPD in HCPB TBM of ITER



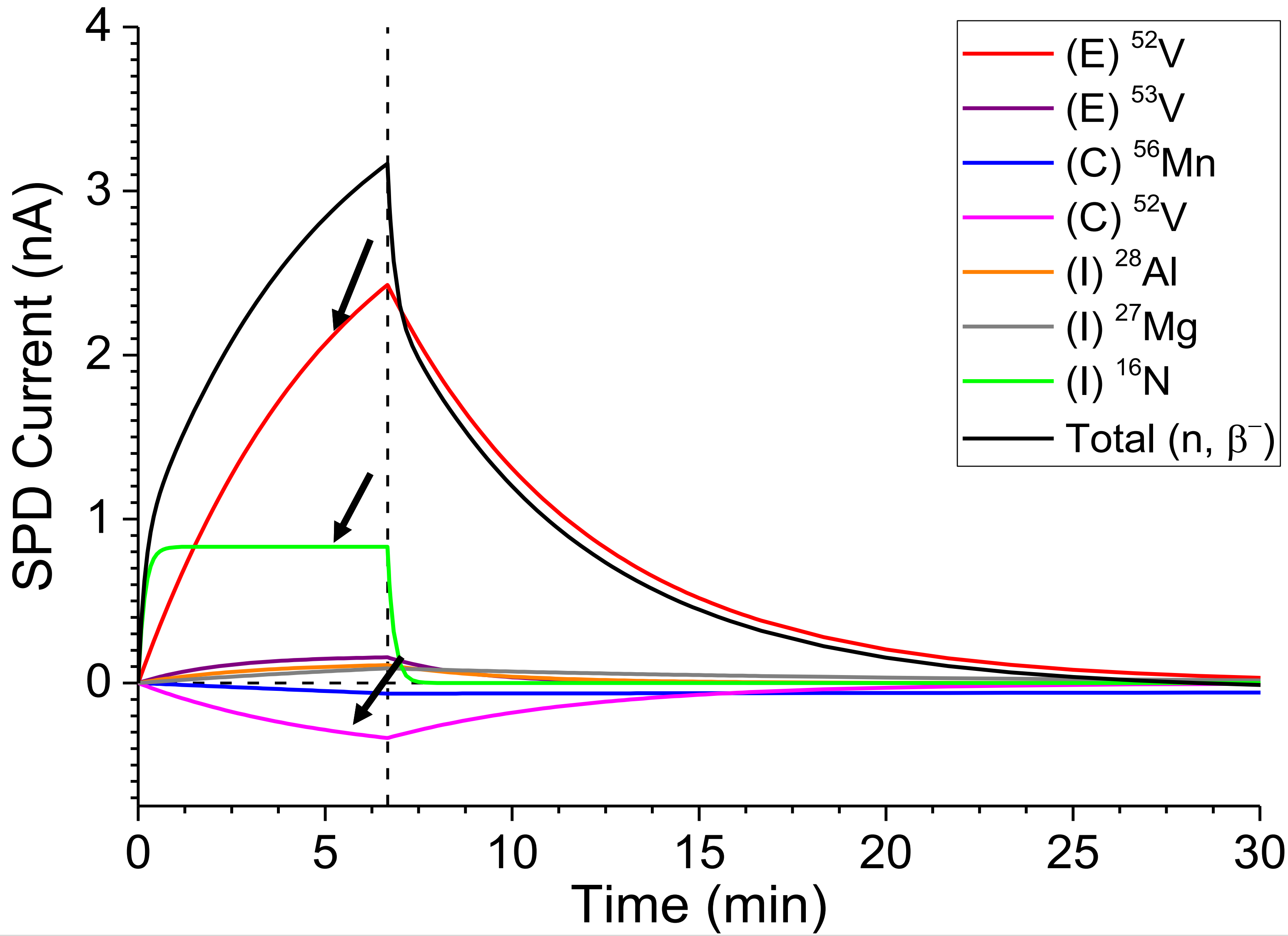
- Emitter (Cr)
  0 to 0.1 cm
  10 cells
- Insulator (Al_2O_3)
  0.1 to 0.125 cm
  25 cells
- Collector (SS304L)
  0.125 to 0.150 cm
  1 cell

- A flat source on surface, forward direction
- Flux densities: N- 7 x 10^{14}, P- 2 x 10^{13} cm^{-2} s^{-1}
- Two representative ITER Pulses: 400s and 3000s
- Signal Profiles and their Interpretation

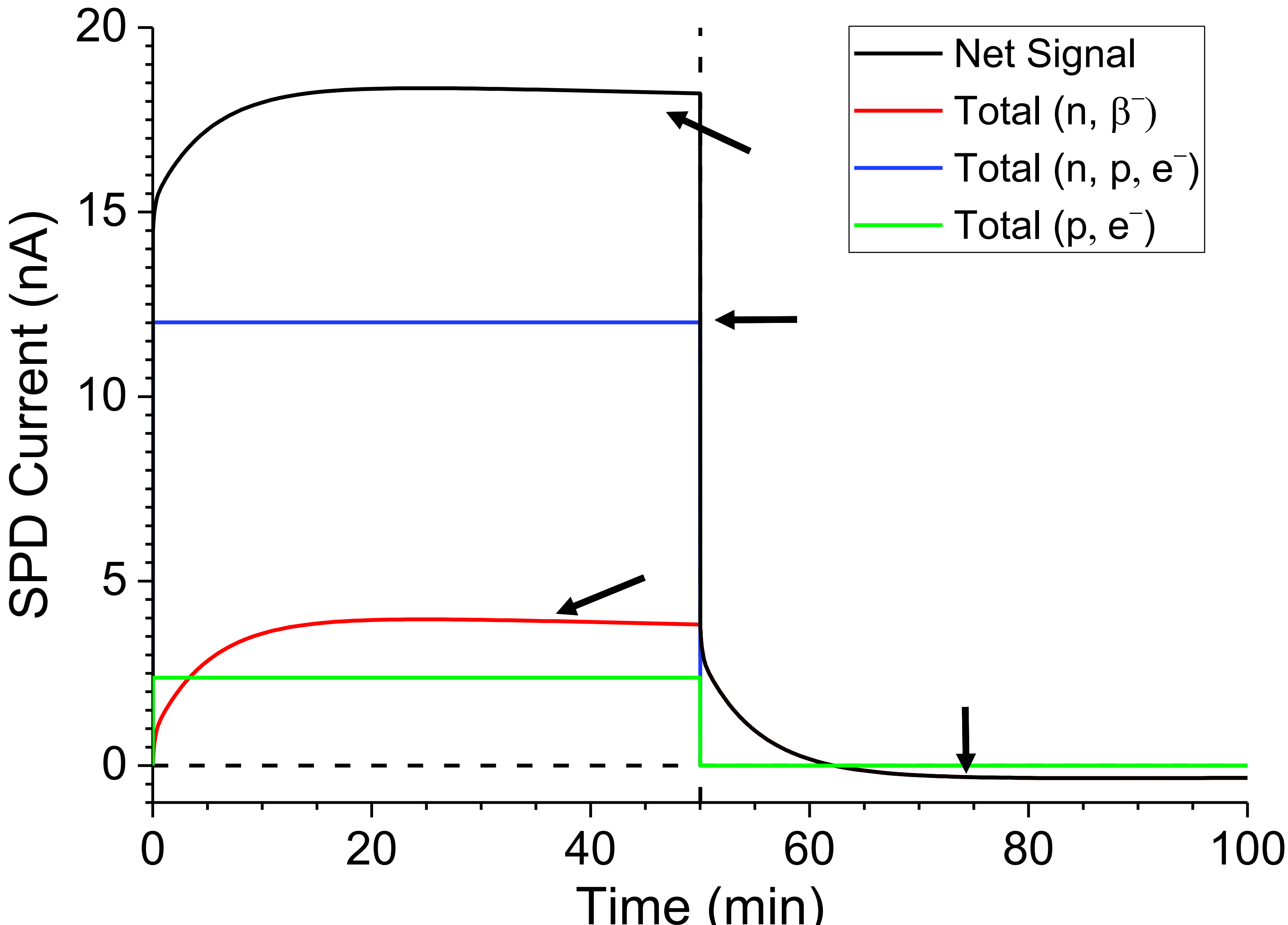
3a. Signal Profile and Breakup (400 s)



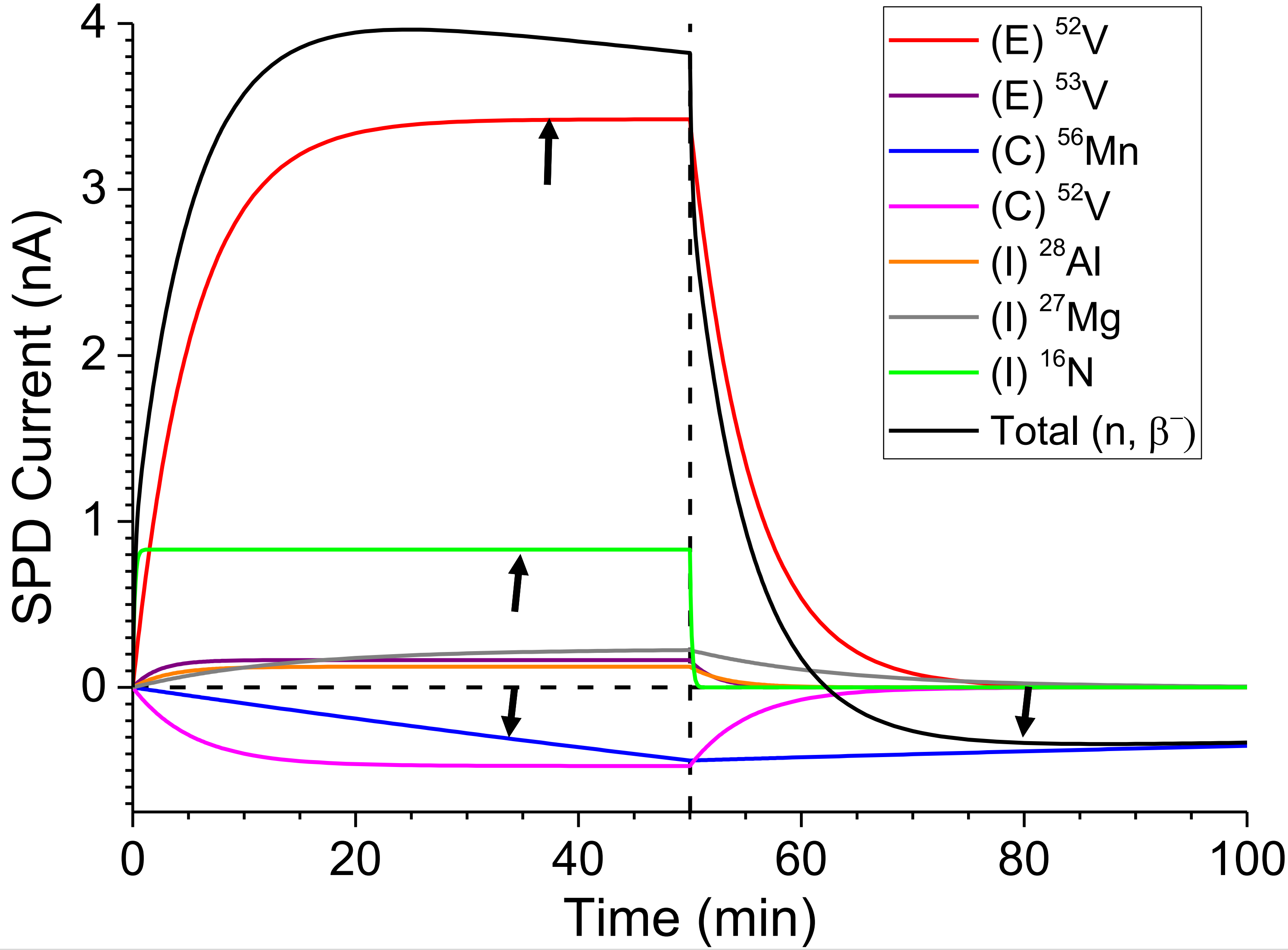
3b. Delayed Signal Components (400 s)



3c. Signal Profile and Breakup (3000 s)



3d. Delayed Signal Components (3000 s)



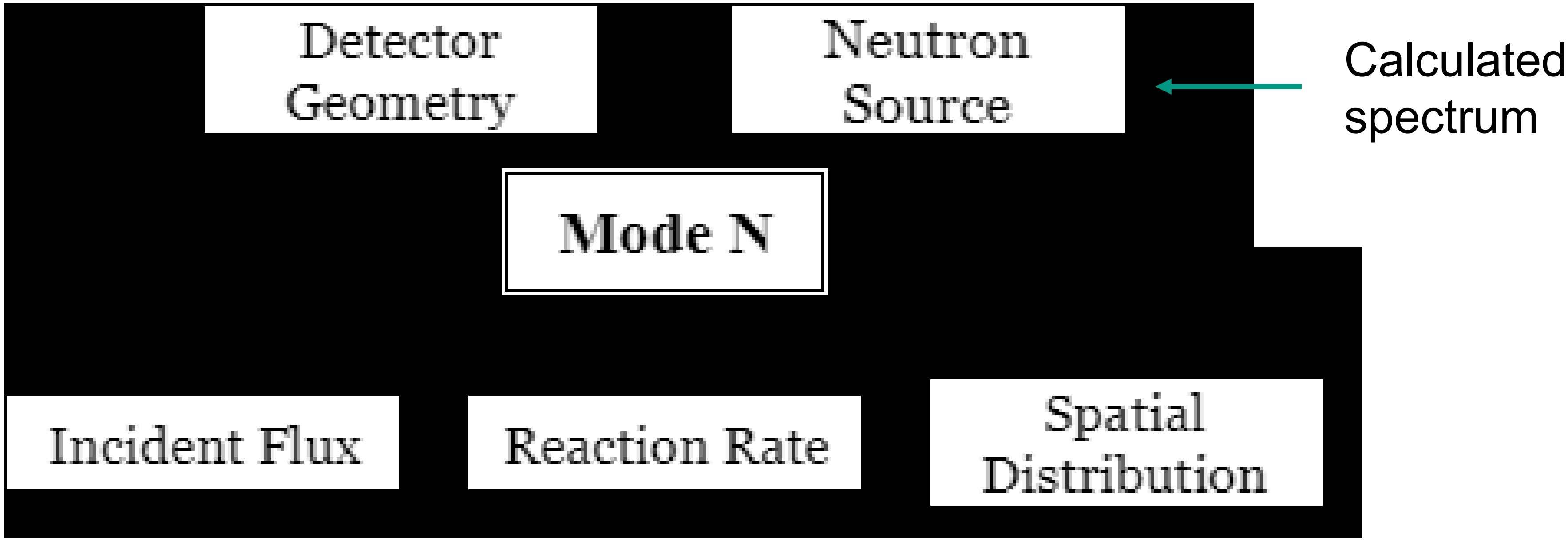
4. Conclusions & Outlook

- **Cr-SPD: Not Delayed but Prompt –SPND** (80% prompt, due to neutrons)
- Fast neutron signal needs to be carefully extracted from delayed part. Need for **online signal interpretation** software.
- Negligible thermal neutron signal expected. Decay gamma (1%) and external electron (difficult) contributions to be included!
- Observable prompt photon signal (spinoff: **SPGD feasible**)
- **Nanoamperes** with present design: difficulties in measurement expected. With geometrical optimization- ten-folds or more
- **Need of verification with experiments** (lab-based signals very small)

The work leading to this publication has been funded partially by Fusion for Energy under the Specific Grant Agreement F4E-FPA-395-2. This publication reflects the views only of the author, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

1extra. Chromium Fast Neutron SND

2extra. Neutron Only Calculations



- F2-Surface Flux
- Comp. w/ Expt.
- **Φ_n (neutron/ cm^2)**

- F4-Cell Flux
- All (n, β^-) reactions
- **RR**: (ρ/M), all cells

- F4-Cell Flux
- **RR(r)**: electron emission in cells

2extra. Electron Only Calculation

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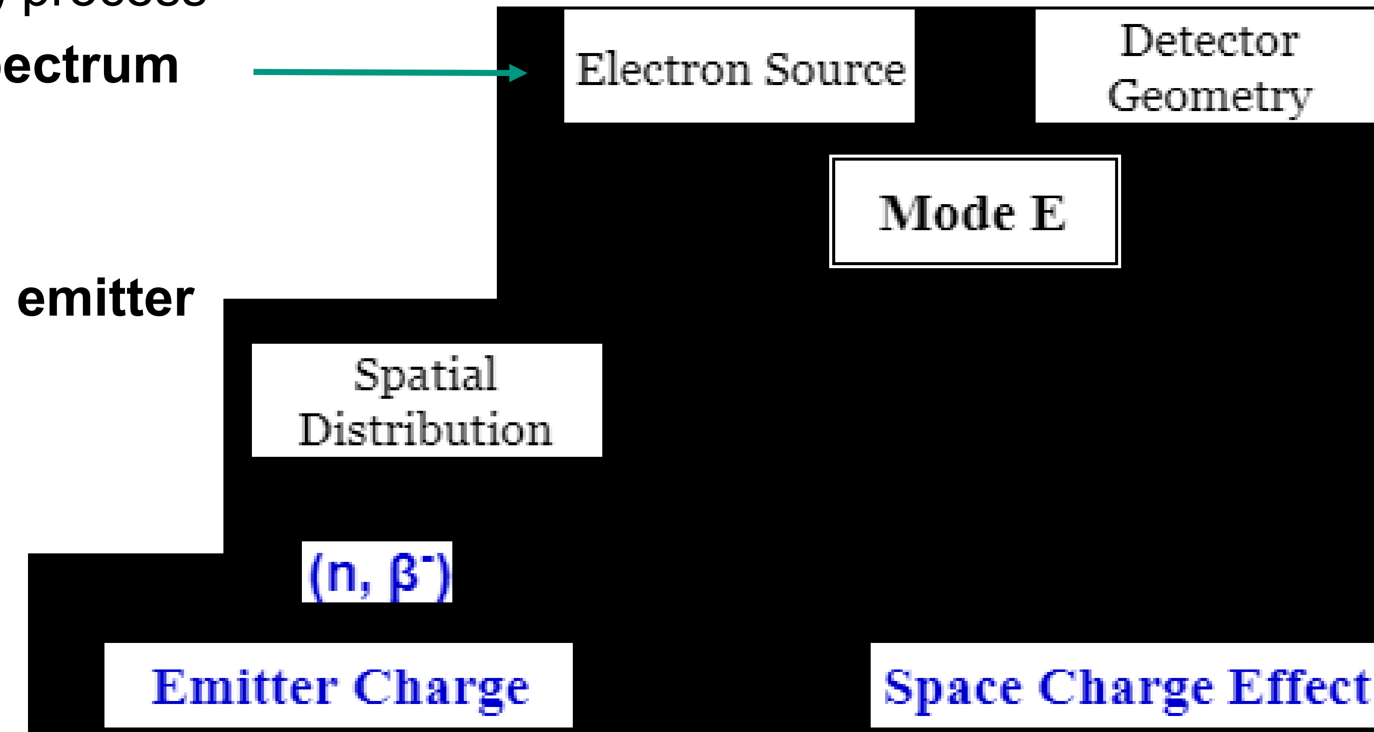
- For each (n, β^-) process
- **Fermi Beta Spectrum** (JEFF)
- **RR (r) in emitter**



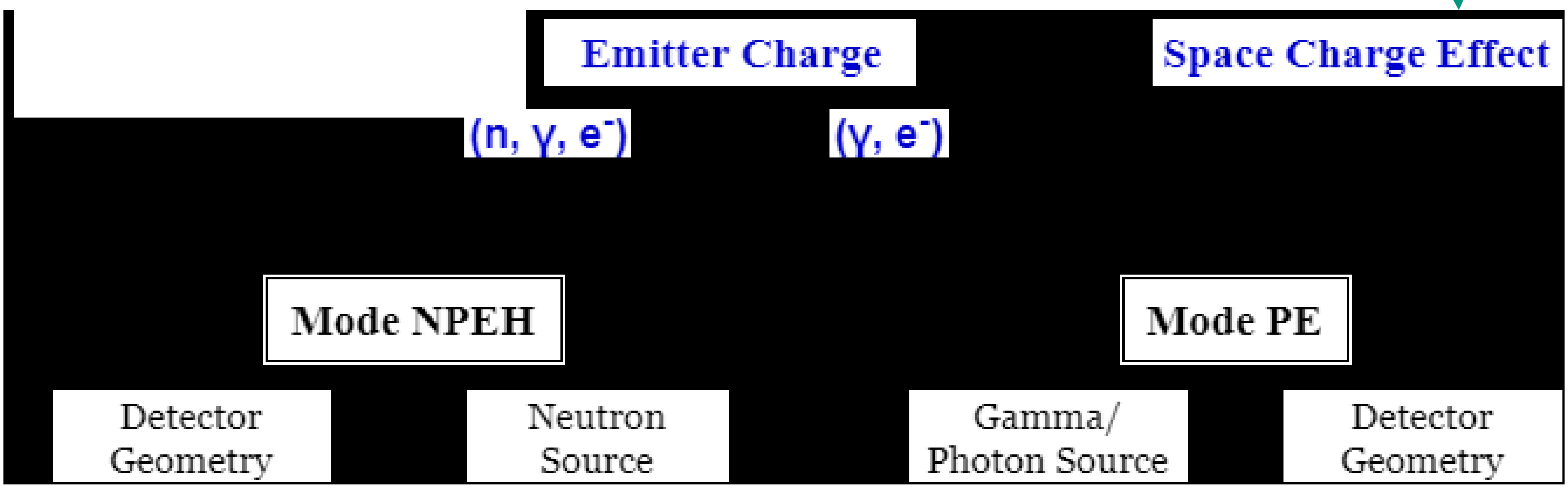
- F1- Surface Current or +F8- Cell Charge
- **Q_{eE} (emitter), Q_{iE} (insulator)**

ρ_{iE}(r)

2extra. Coupled Calculations

- F1- Surface Current or +F8- Cell Charge
- **Q_{eNPE} (emitter), Q_{iNPE} (insulator)**
- **Q_{ePE} (emitter), Q_{iPE} (insulator)**

$\rho_{iNPE}(r)$
$\rho_{iPE}(r)$



Calculated neutron/ photon spectra