

# FENDL-2.1 Benchmark Analyses

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# Background

- FENDL-2.1
  - Revision to FENDL-2.0 (1995/96)
  - Compiled November 2003, see report INDC(NDS)-451
  - Working libraries prepared by IAEA/NDS, see INDC(NDS)-467 (2004)
  - New reference data library for ITER neutronics calculations
  - ITER nuclear analyses service – enabling activities (CAD – MCNP benchmark)
  - QA specification document for ITER neutronic analyses
- Need for
  - Qualification  $\Rightarrow$  benchmark analyses
  - Validation  $\Rightarrow$  fusion benchmark experiments
- Approach
  1. Computational ITER benchmark, EFF-DOC-975 (May 2006)
  2. Re-analyses of FNG benchmark experiments

# FNG Fusion Benchmark Experiments

- ITER bulk shield experiment (EFF-DOC-405)
  - *Measurement of neutron/photon flux spectra by TUD (EFF-DOC-483)*
- ITER streaming experiment (EFF-DOC-626)
  - *Measurement of neutron/photon flux spectra by TUD (EFF-DOC-640)*
- W bulk shield experiment (EFF-DOC-863)
  - *Measurement of neutron/ photon flux spectra by TUD (EFF-DOC-857)*
- HCPB breeder mock-up experiment (EFF-DOC-938)
  - *Measurement of Tritium generated in  $\text{Li}_2\text{CO}_3$  pellets (EFF-DOC-956)*
  - *Measurement of neutron/photon flux spectra in back of assembly by TUD (EFF-DOC-972)*

⇒ *ENEA measurements of activation rates & T production already analysed by P. Batistoni et al. (EFF-DOC-964, May 2006)*

# Procedure for Benchmark Analyses

- Re-calculate FNG fusion benchmark experiments
  - Using MCNP4C and FENDL-2.1 ACE data
  - Using available MCNP input deck & FNG neutron source
- Compare to experimental data
- Compare to results obtained with FENDL-2.0 and EFF-3.0/JEFF-3.1

# FENDL Data Evaluations

## FENDL/E-1.0

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|           |   |
|-----------|---|
| ENDF/B-VI | $^1,^3\text{H}, ^6,^7\text{Li}, ^9\text{Be}, ^{10,11}\text{B}, \text{C}, ^{16}\text{O}, ^{19}\text{F}, ^{31}\text{P}, \text{S}, \text{Cl}, \text{K}, \text{V},$<br>$^{50}, ^{52-54}\text{Cr}, ^{55}\text{Mn}, ^{54, 56-58}\text{Fe}, ^{59}\text{Co}, ^{58, 60-62, 64}\text{Ni},$<br>$^{63, 65}\text{Cu}, ^{134-138}\text{Ba}, ^{182-184, 186}\text{W}, ^{206-208}\text{Pb}$ |
| JENDL-3   | $^{23}\text{Na}, \text{Mg}, ^{27}\text{Al}, \text{Ca}, \text{Ti}, \text{Mo}, ^{181}\text{Ta}, ^{209}\text{Bi}$  |
| BROND-2   | $^2\text{H}, ^{14, 15}\text{N}, \text{Si}, ^{90-92, 94, 96}\text{Zr}, ^{93}\text{Nb}, \text{Sn}$  |

## FENDL/E-2.0

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|           |  |
|-----------|--|
| JENDL-FF  | $^9\text{Be}, ^{12}\text{C}, ^{14}\text{N}, ^{16}\text{O}, ^{51}\text{V}, ^{\text{nat}}\text{Zr}, ^{93}\text{Nb}, ^{\text{nat}}\text{Mo}, ^{\text{nat}}\text{W}$ |
| EFF-3     | $^{27}\text{Al}, ^{56}\text{Fe}$   |
| ENDF/B-VI | $^{28, 29, 30}\text{Si}$   |
| BROND-2   | $^2\text{H}, ^{\text{nat}}\text{Sn}$   |

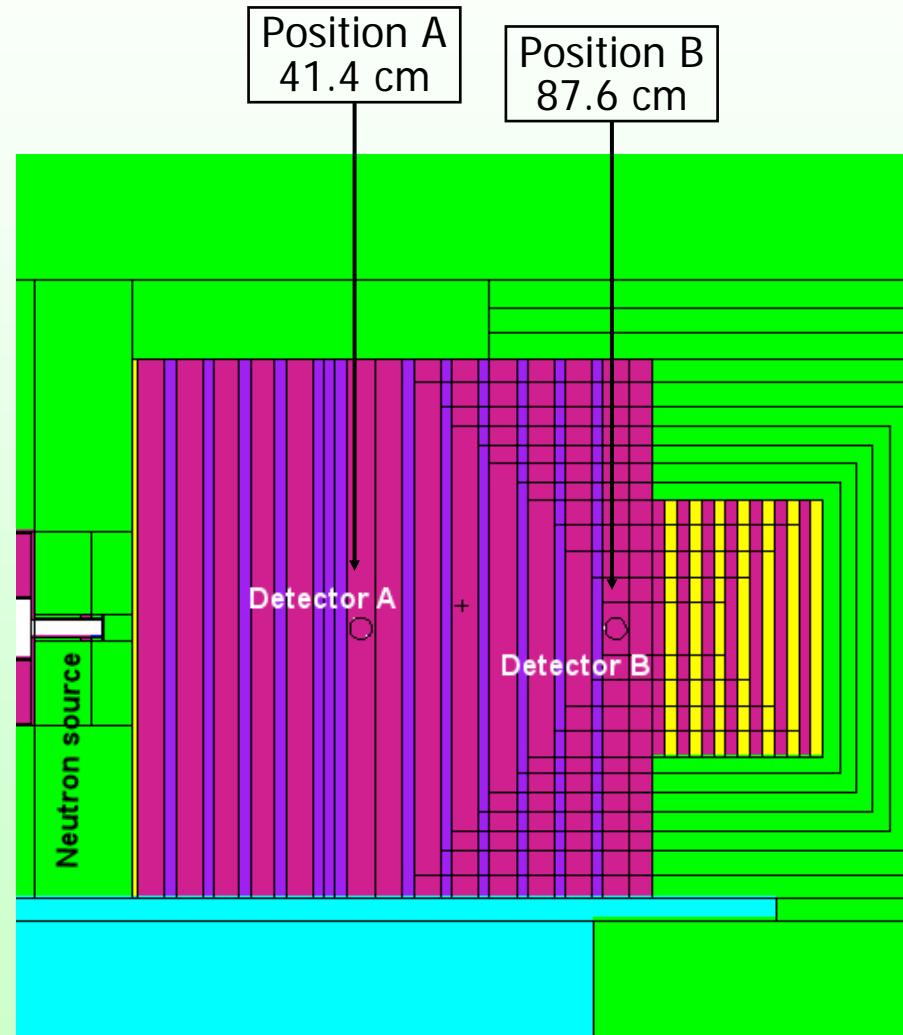
# FENDL-2.1 Original Data Sources

| No. | Library               | NMAT | Materials   |
|-----|-----------------------|------|---|
| 1   | ENDF/B-VI.8<br>(E6)   | 40   | <sup>2</sup> H, <sup>3</sup> H, <sup>4</sup> He, <sup>6</sup> Li, <sup>7</sup> Li, <sup>9</sup> Be, <sup>10</sup> B, <sup>11</sup> B, <sup>16</sup> O, <sup>19</sup> F, <sup>28-30</sup> Si, <sup>31</sup> P, S, <sup>35,37</sup> Cl, K, <sup>50,52-54</sup> Cr, <sup>54,57,58</sup> Fe, <sup>59</sup> Co, <sup>61,62,64</sup> Ni, <sup>63,65</sup> Cu, <sup>197</sup> Au, <sup>206-208</sup> Pb, <sup>209</sup> Bi, <sup>182-184,186</sup> W |
| 2   | JENDL-3.3<br>(J33)    | 18   | <sup>1</sup> H, <sup>3</sup> He, <sup>23</sup> Na, <sup>46-50</sup> Ti, <sup>55</sup> Mn, <sup>92,94-98,100</sup> Mo, <sup>181</sup> Ta, V  |
| 3   | JENDL-3.2<br>(J32)    | 3    | Mg, Ca, Ga  |
| 4   | JENDL-FF<br>(JFF)     | 4    | <sup>12</sup> C, <sup>14</sup> N, Zr, <sup>93</sup> Nb  |
| 5   | JEFF-3 (EFF)<br>JEFF3 | 4    | <sup>27</sup> Al, <sup>56</sup> Fe, <sup>58</sup> Ni, <sup>60</sup> Ni  |
| 6   | BROND-2.1<br>(BR2)    | 2    | <sup>15</sup> N, Sn   |

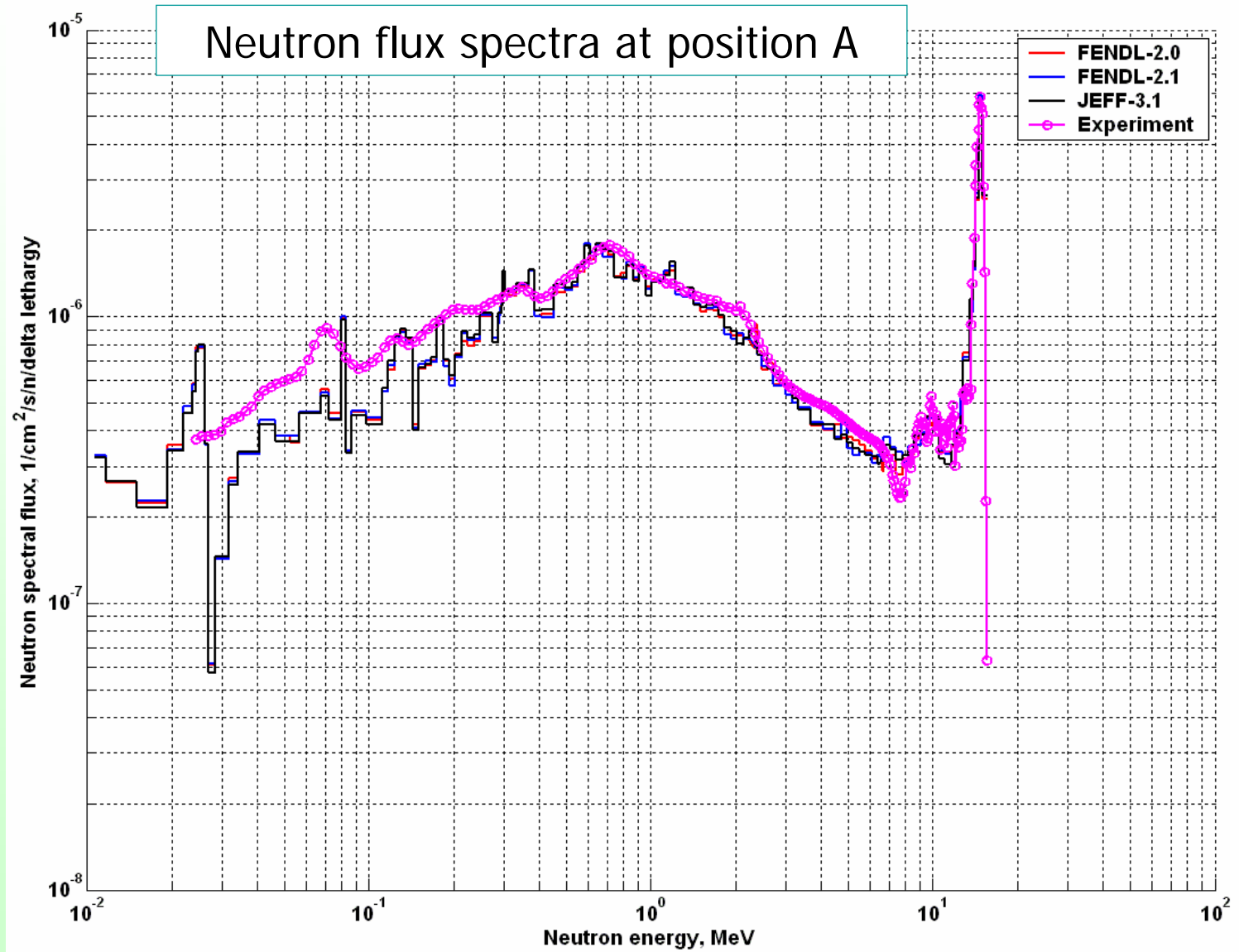
# ITER Bulk Shield Mock-up Experiment at FNG

Measurements of neutron/photon flux spectra by TUD (K. Seidel et al.)

- Mock-up of ITER inboard blanket/shield system with thickness of 94 cm (alternating plates of SS-316 and of Perspex).
- Backed by 30 cm thick block of alternating SS-316 and Cu plates simulating TF-coil.
- Neutron and photon flux spectra measured at positions A (41.4 cm) and B (87.6 cm)
- Neutron spectra measured in the energy range between about 20 keV and 15 MeV.
  - A set of gas-filled proportional counters and a stilbene scintillation spectrometer used in the energy range up to 3 MeV.
  - NE-213 scintillation spectrometer for energy range 1 to 15 MeV.
- Photon flux spectra measured with NE-213 spectrometer above 0.2 MeV.

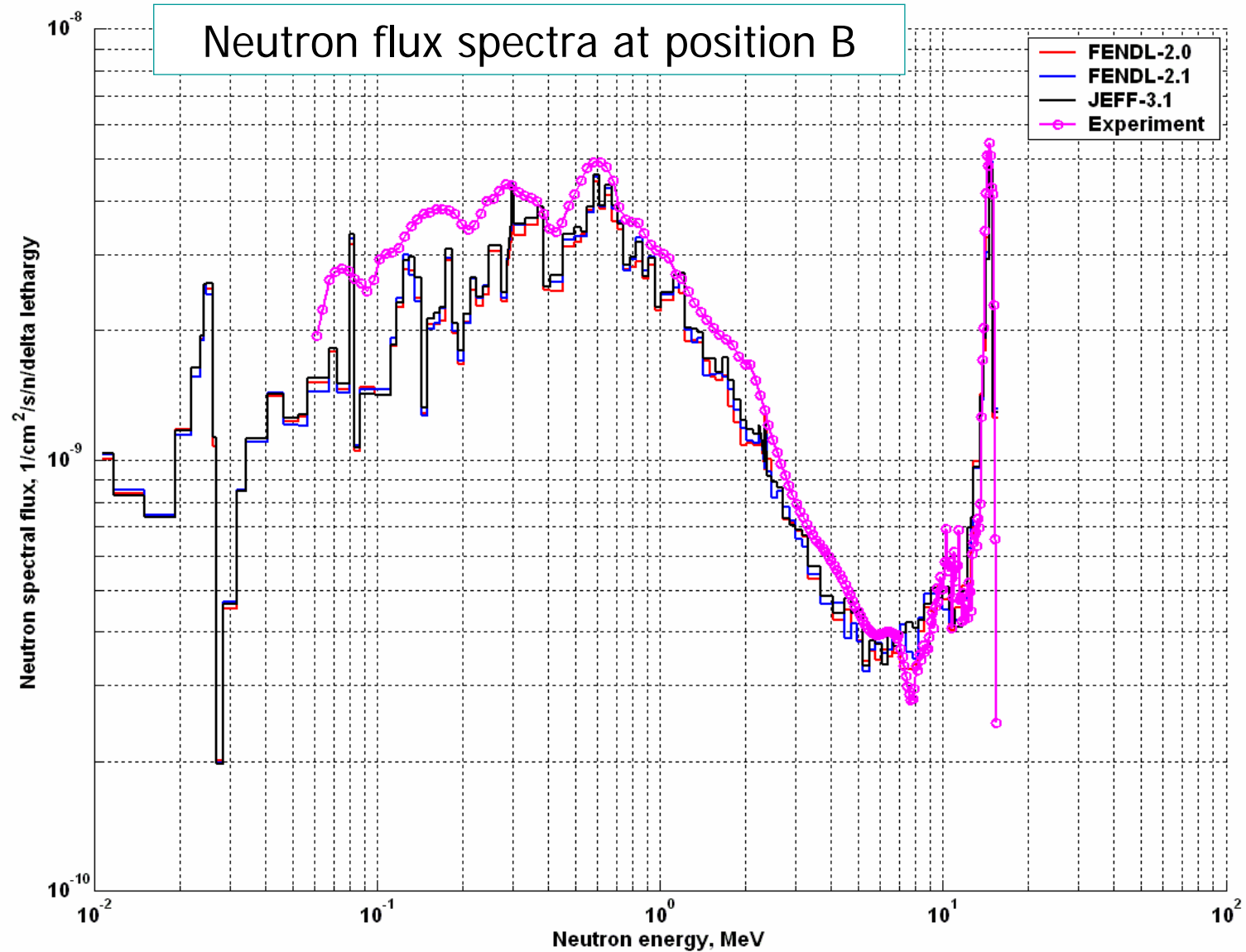


# ITER Bulk Shield Mock-up Experiment

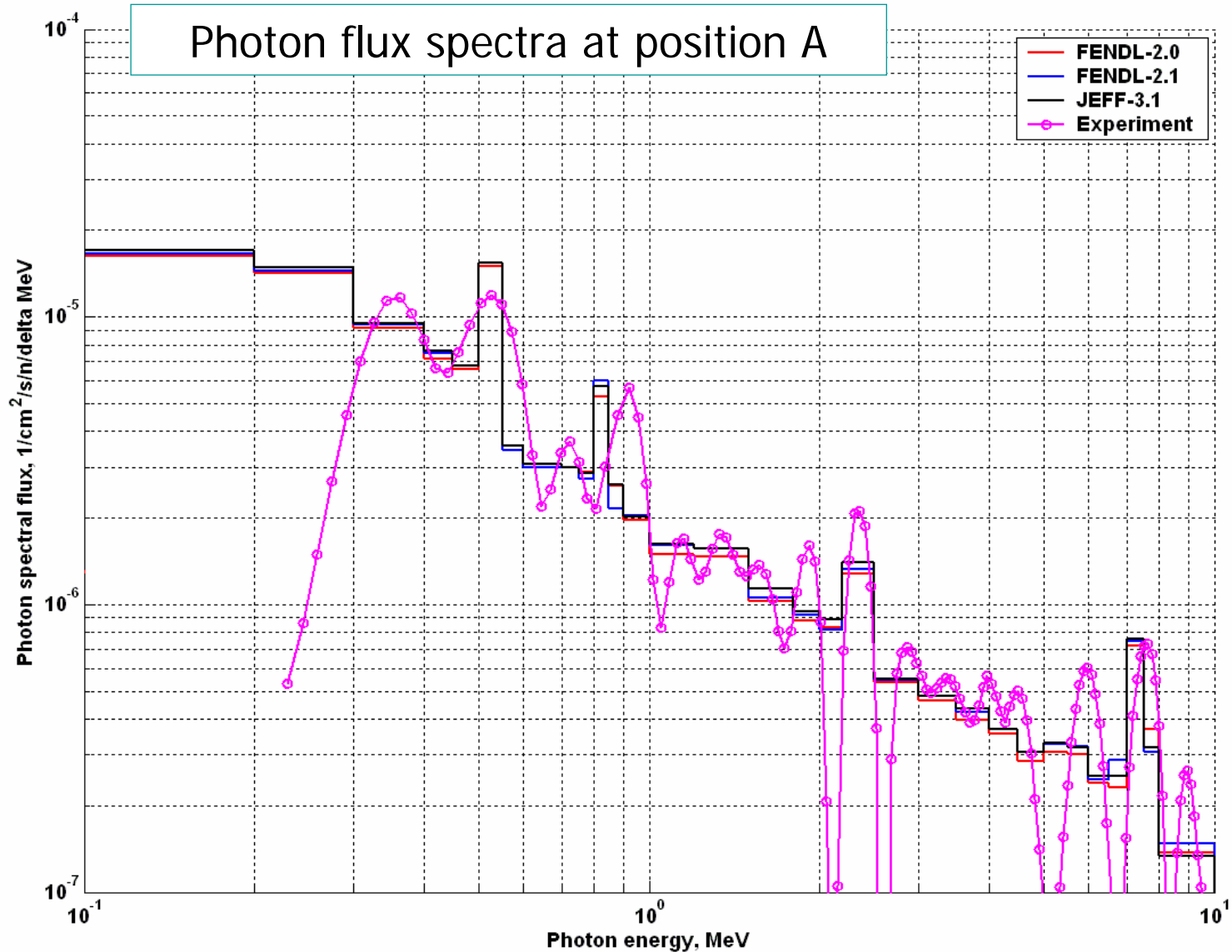




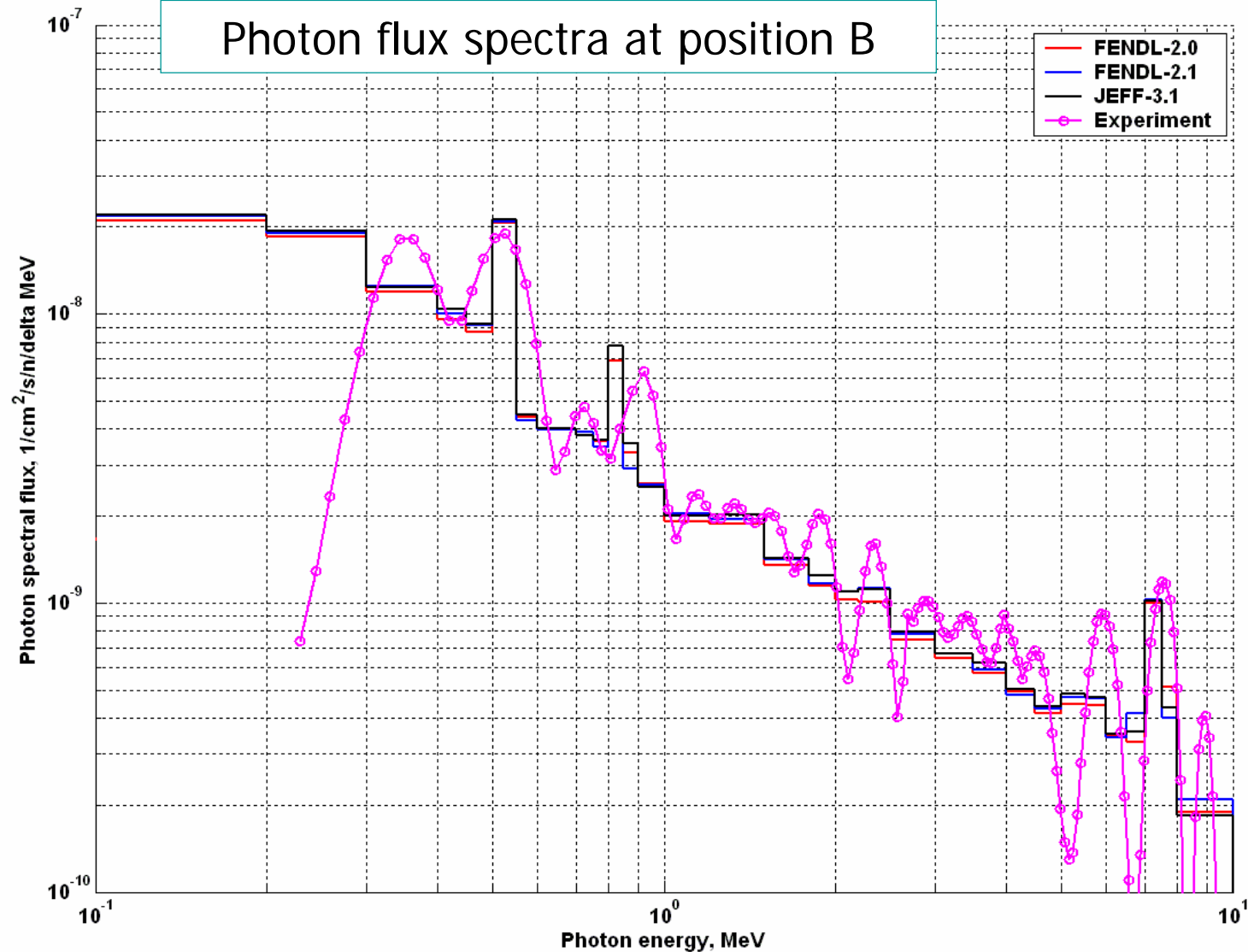
# ITER Bulk Shield Mock-up Experiment



# ITER Bulk Shield Mock-up Experiment



# ITER Bulk Shield Mock-up Experiment



# ITER Bulk Shield Mock-up Experiment

## C/E comparison for neutron flux integrals

| Energy, MeV | Position A |           |          | Statistical error (fsd): |           |          |
|-------------|------------|-----------|----------|--------------------------|-----------|----------|
|             | FENDL-2.0  | FENDL-2.1 | JEFF-3.1 | FENDL-2.0                | FENDL-2.1 | JEFF-3.1 |
| 0.1 - 1.0   | 0.89       | 0.90      | 0.91     | 0.35%                    | 0.43%     | 0.40%    |
| 1.0 - 5.0   | 0.93       | 0.93      | 0.94     | 0.48%                    | 0.59%     | 0.55%    |
| 5.0 - 10.0  | 0.97       | 0.98      | 0.99     | 1.14%                    | 1.40%     | 1.32%    |
| E > 10.0    | 0.82       | 0.81      | 0.80     | 1.14%                    | 1.43%     | 1.34%    |
| E > 0.1     | 0.90       | 0.90      | 0.91     | 0.27%                    | 0.33%     | 0.31%    |
| Energy, MeV | Position B |           |          | Statistical error (fsd): |           |          |
|             | FENDL-2.0  | FENDL-2.1 | JEFF-3.1 | FENDL-2.0                | FENDL-2.1 | JEFF-3.1 |
| 0.1 - 1.0   | 0.72       | 0.75      | 0.76     | 0.40%                    | 0.48%     | 0.45%    |
| 1.0 - 5.0   | 0.80       | 0.82      | 0.85     | 0.65%                    | 0.79%     | 0.74%    |
| 5.0 - 10.0  | 0.98       | 1.03      | 1.06     | 1.63%                    | 2.00%     | 1.85%    |
| E > 10.0    | 0.81       | 0.81      | 0.82     | 1.63%                    | 2.00%     | 1.90%    |
| E > 0.1     | 0.75       | 0.77      | 0.79     | 0.33%                    | 0.40%     | 0.37%    |

⇒ *No significant differences between FENDL-2.0, -2.1 and JEFF-3.1*

# ITER Bulk Shield Mock-up Experiment

## C/E comparison for photon flux integrals

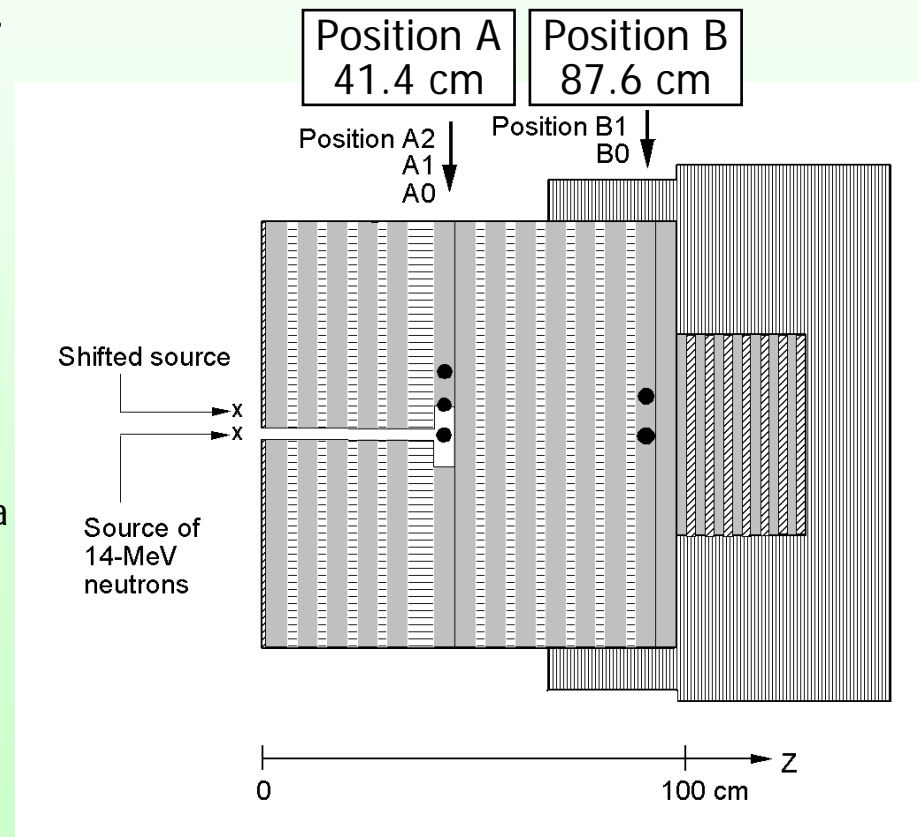
| Energy, MeV | Position A |           |          | Statistical error (fsd): |           |          |
|-------------|------------|-----------|----------|--------------------------|-----------|----------|
|             | FENDL-2.0  | FENDL-2.1 | JEFF-3.1 | FENDL-2.0                | FENDL-2.1 | JEFF-3.1 |
| 0.4 - 1.0   | 0.88       | 0.90      | 0.91     | 0.31%                    | 0.37%     | 0.35%    |
| 1.0 - 10.5  | 0.97       | 1.01      | 1.02     | 0.30%                    | 0.36%     | 0.34%    |
| E > 0.4     | 0.93       | 0.96      | 0.97     | 0.22%                    | 0.26%     | 0.25%    |
| Energy, MeV | Position B |           |          | Statistical error (fsd): |           |          |
|             | FENDL-2.0  | FENDL-2.1 | JEFF-3.1 | FENDL-2.0                | FENDL-2.1 | JEFF-3.1 |
| 0.4 - 1.0   | 0.82       | 0.84      | 0.86     | 0.46%                    | 0.56%     | 0.52%    |
| 1.0 - 10.5  | 0.88       | 0.91      | 0.92     | 0.41%                    | 0.51%     | 0.48%    |
| E > 0.4     | 0.85       | 0.88      | 0.89     | 0.31%                    | 0.38%     | 0.36%    |

⇒ *No significant differences between FENDL-2.0, -2.1 and JEFF-3.1*

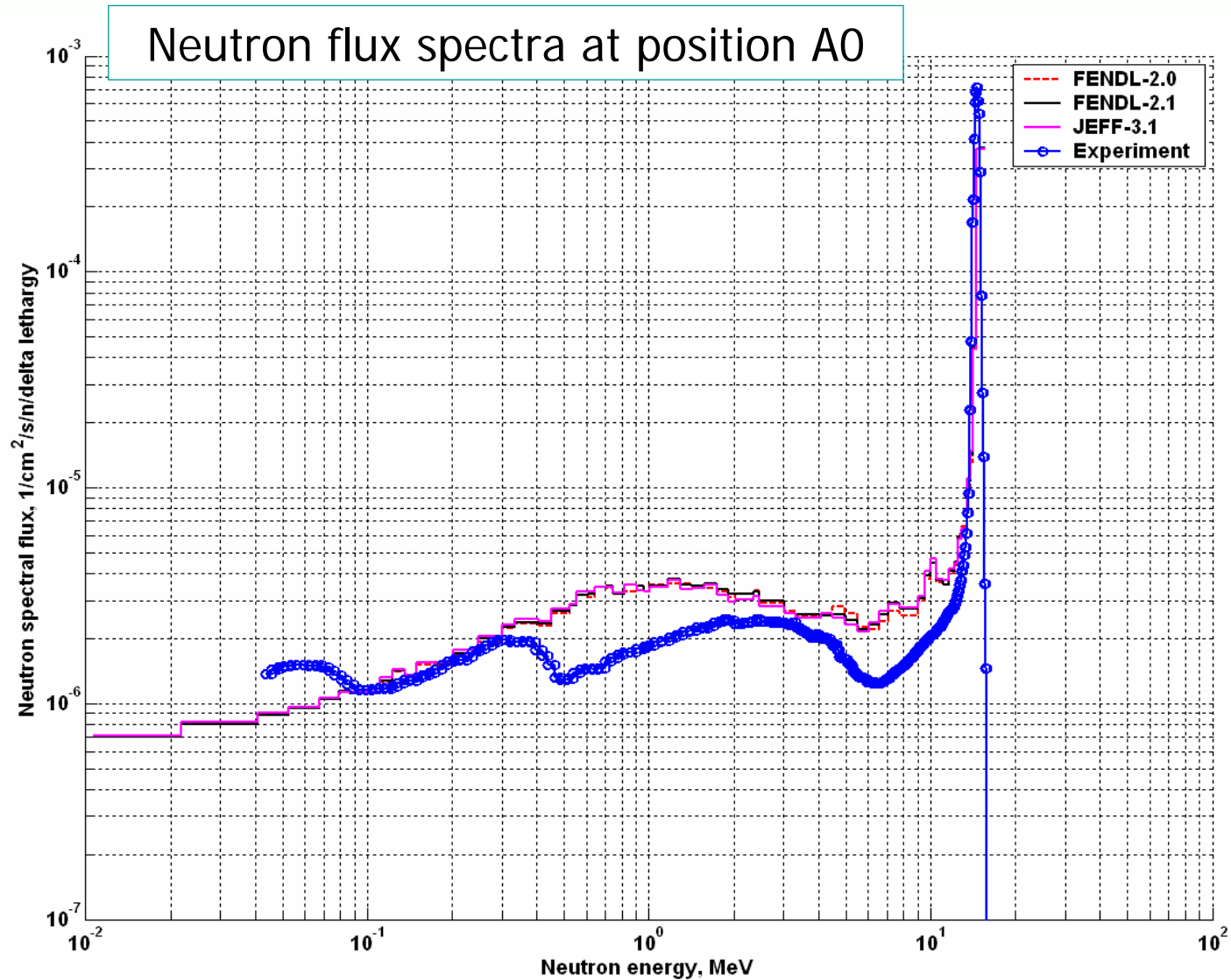
# ITER Streaming Experiment at FNG

Measurements of neutron/photon flux spectra by TUD (K. Seidel et al.)

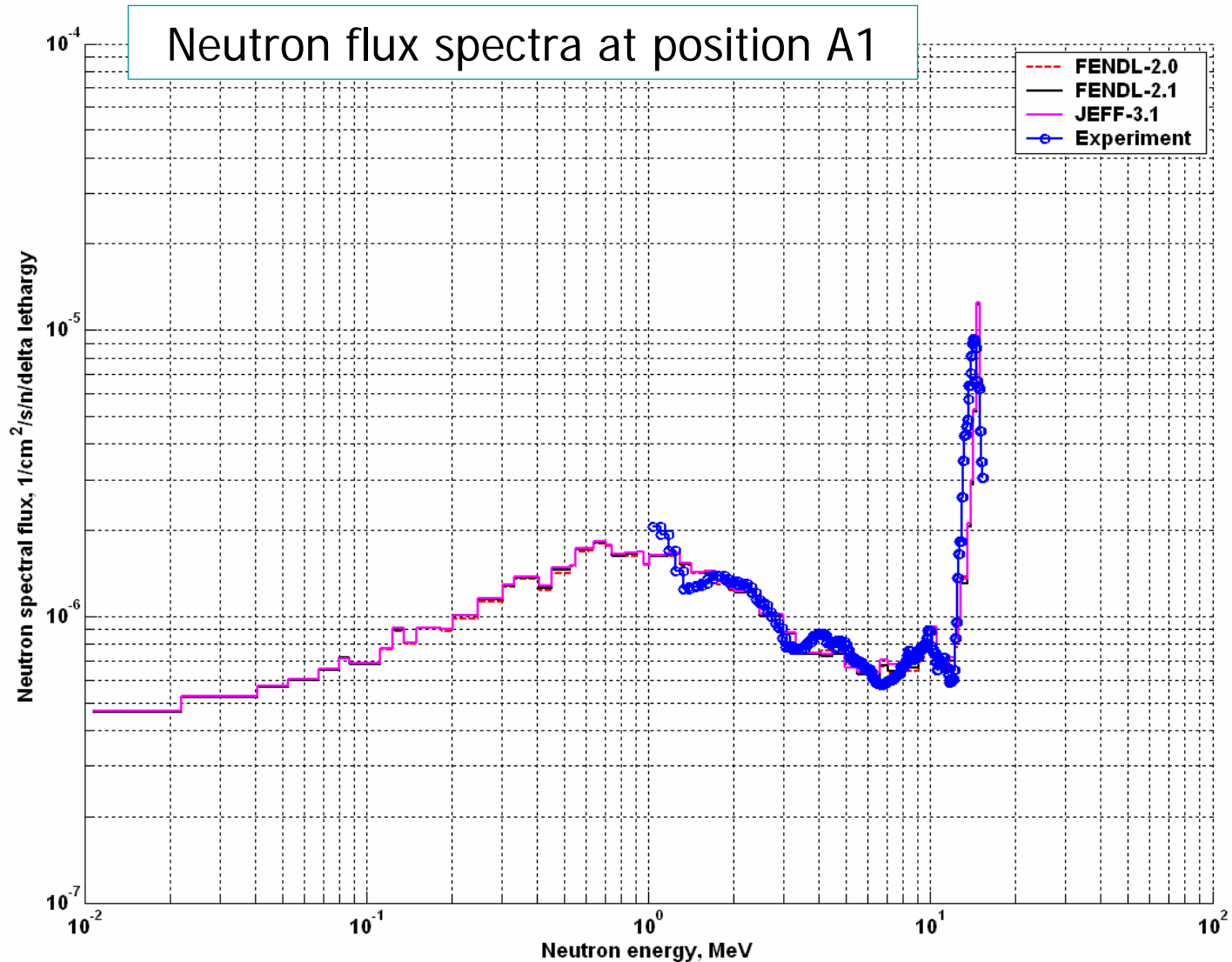
- Mock-up of ITER inboard blanket/shield system with streaming channel in the blanket and cavity at the bottom of channel.
- Neutron and photon flux spectra measured at positions A (41.4 cm) and B (87.6 cm) with source on and off axis (A0, B0).
- Additional measurements with detectors shifted off the axis by 7.5 cm, 15.0 and 9.0 cm (A1, A2 and B1).
- Neutron spectra measured in the energy range between about 20 keV and 15 MeV.
  - A set of gas-filled proportional counters and a stilbene scintillation spectrometer used in the energy range up to 3 MeV.
  - NE-213 scintillation spectrometer for energy range 1 to 15 MeV.
- Photon flux spectra measured with NE-213 spectrometer above 0.2 MeV.



# ITER Streaming Experiment

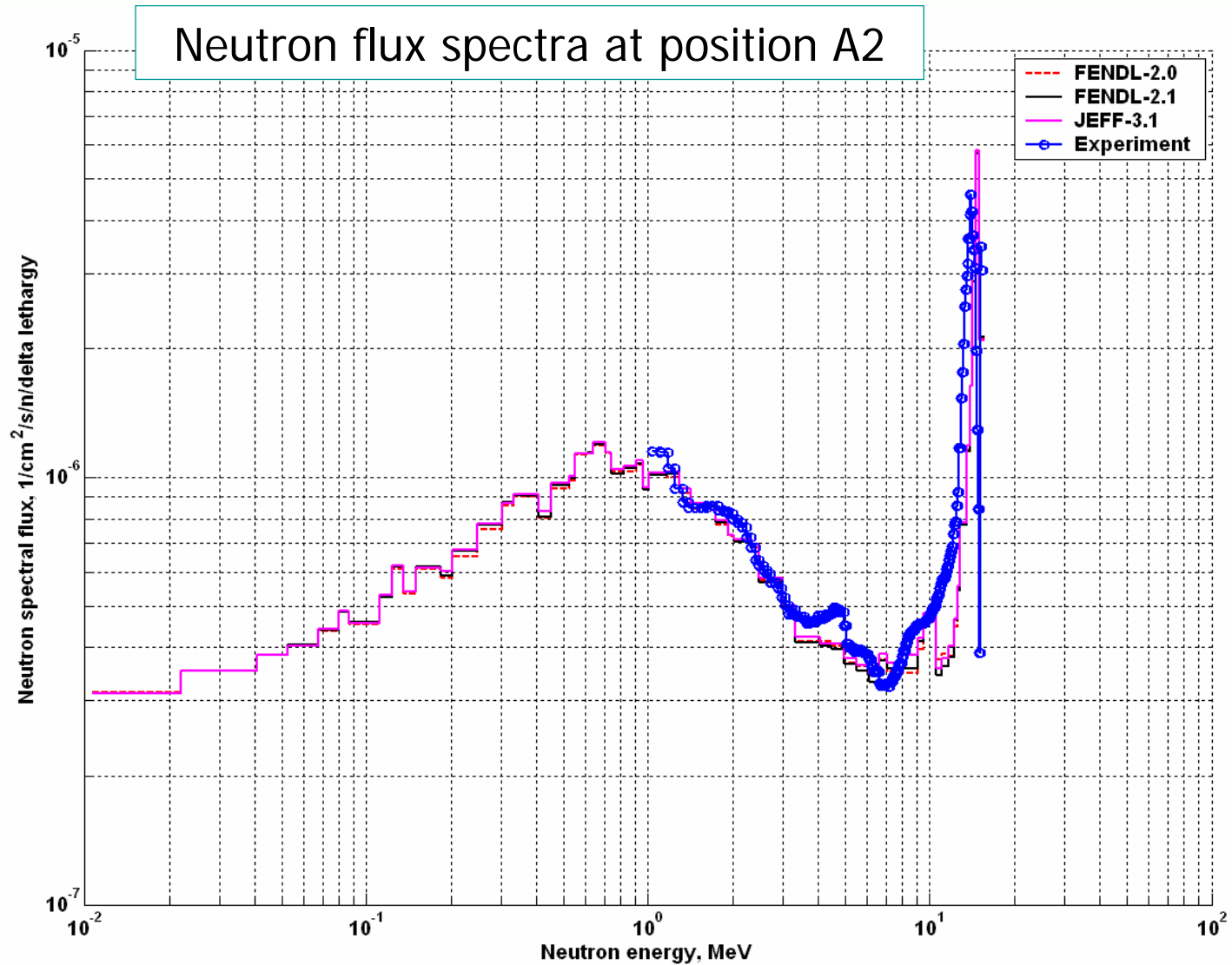


# ITER Streaming Experiment

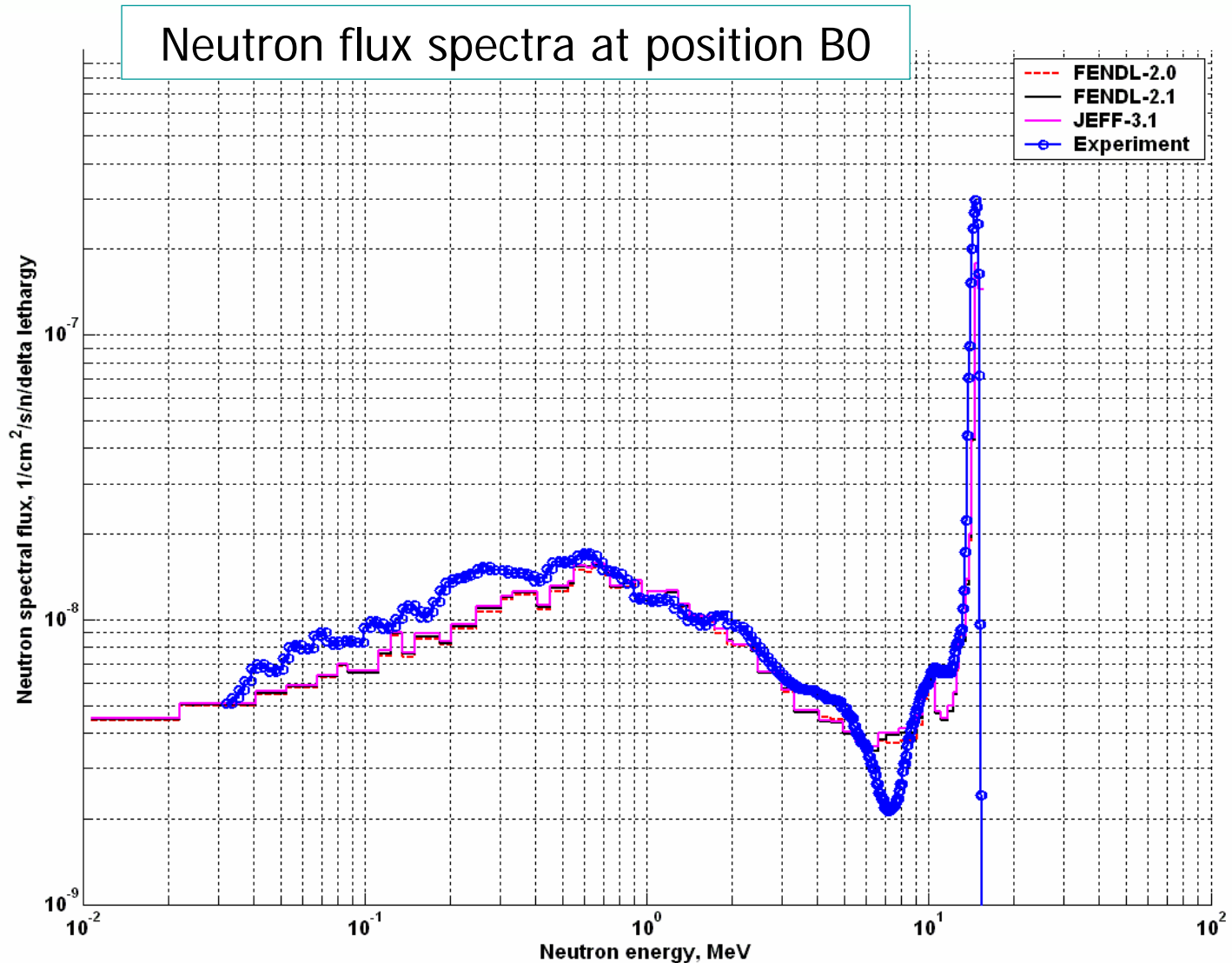




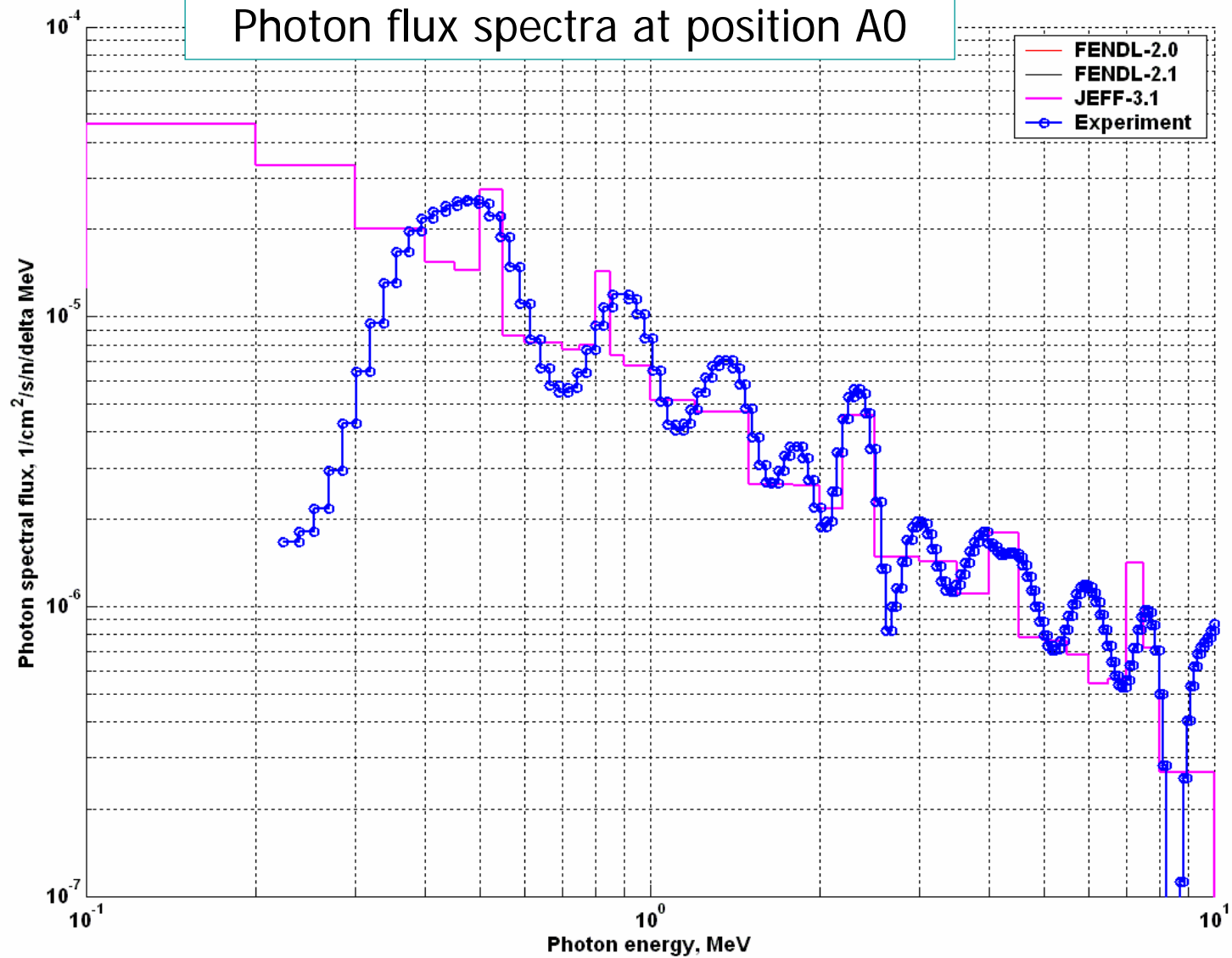
# ITER Streaming Experiment



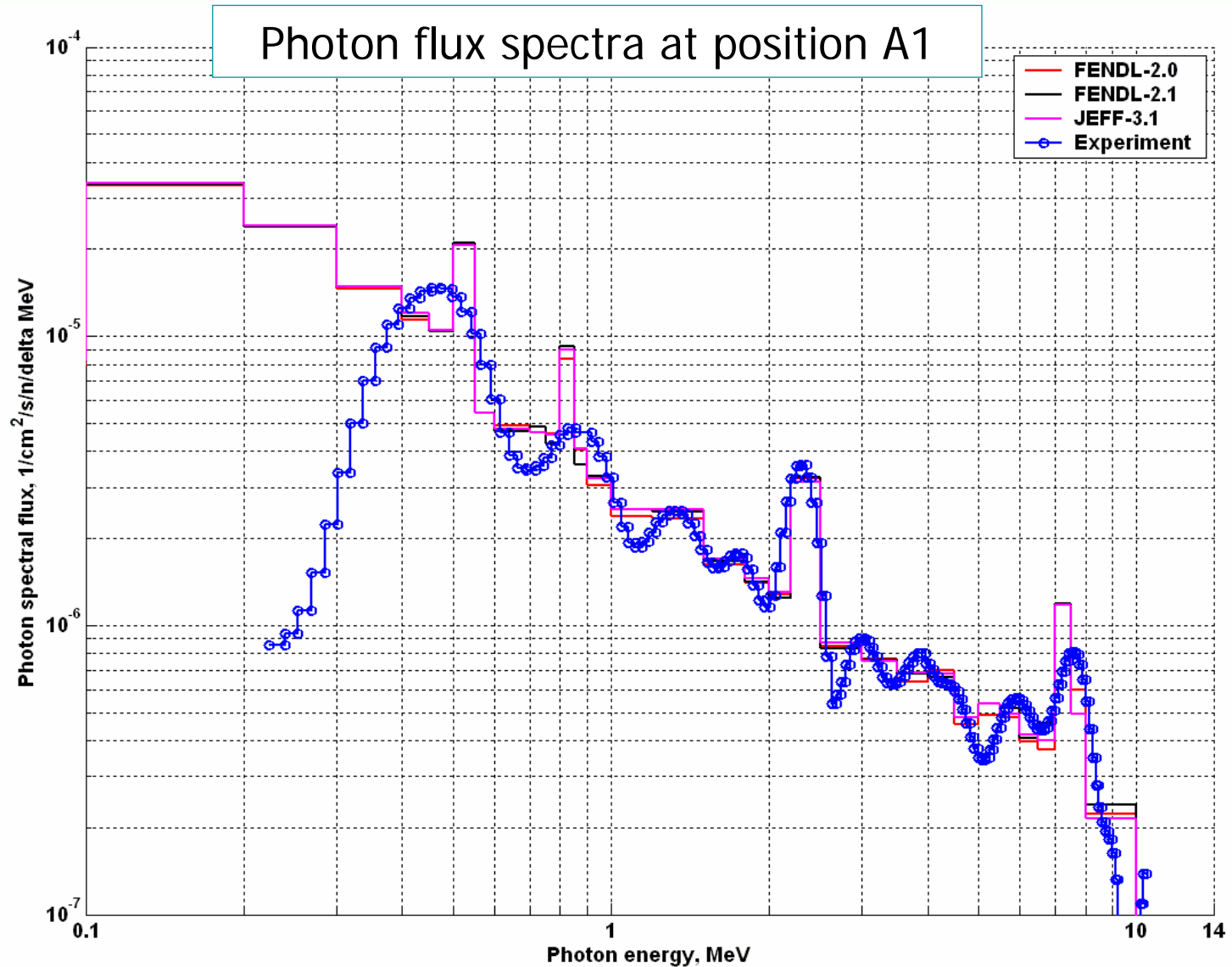
# ITER Streaming Experiment



# ITER Streaming Experiment

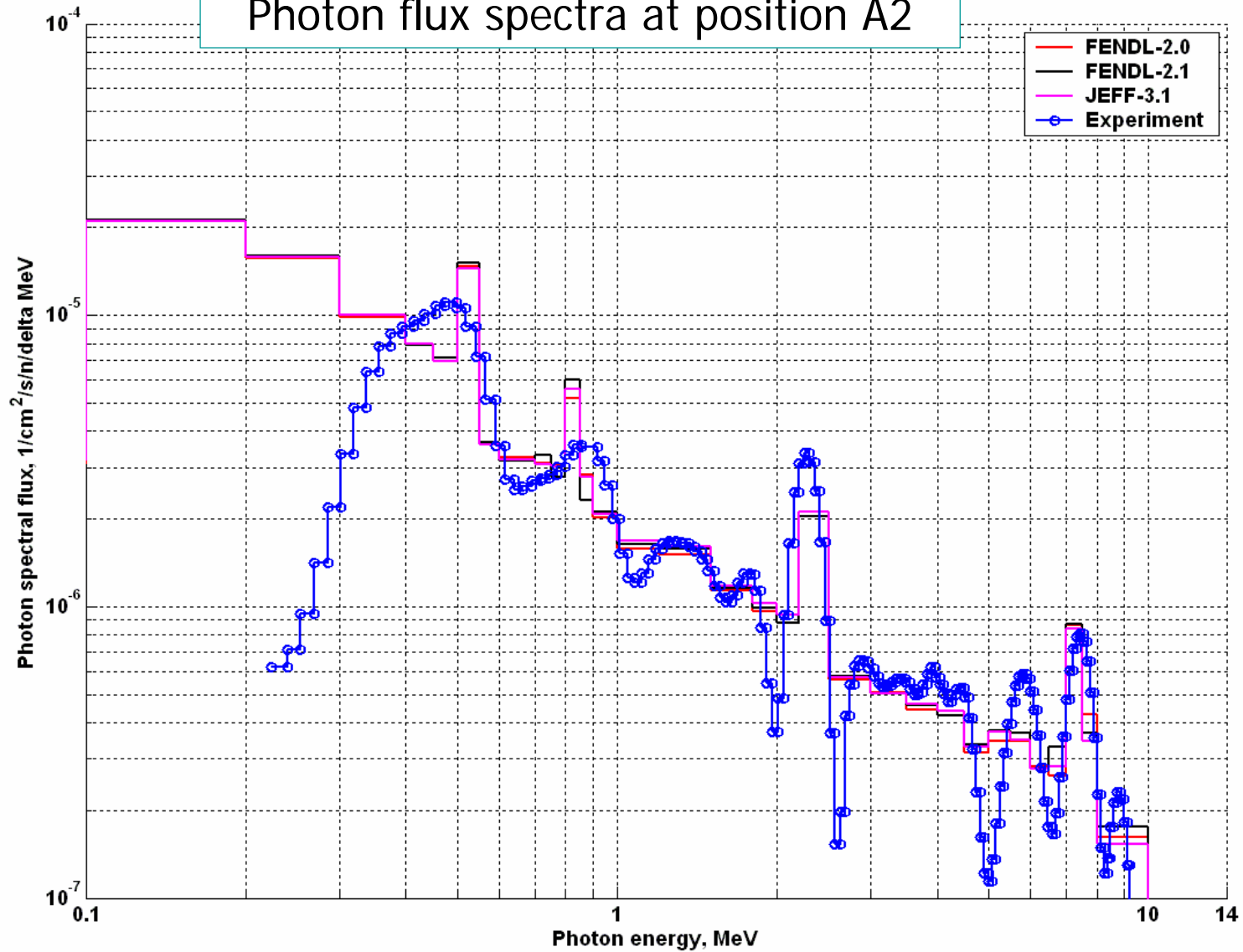


# ITER Streaming Experiment



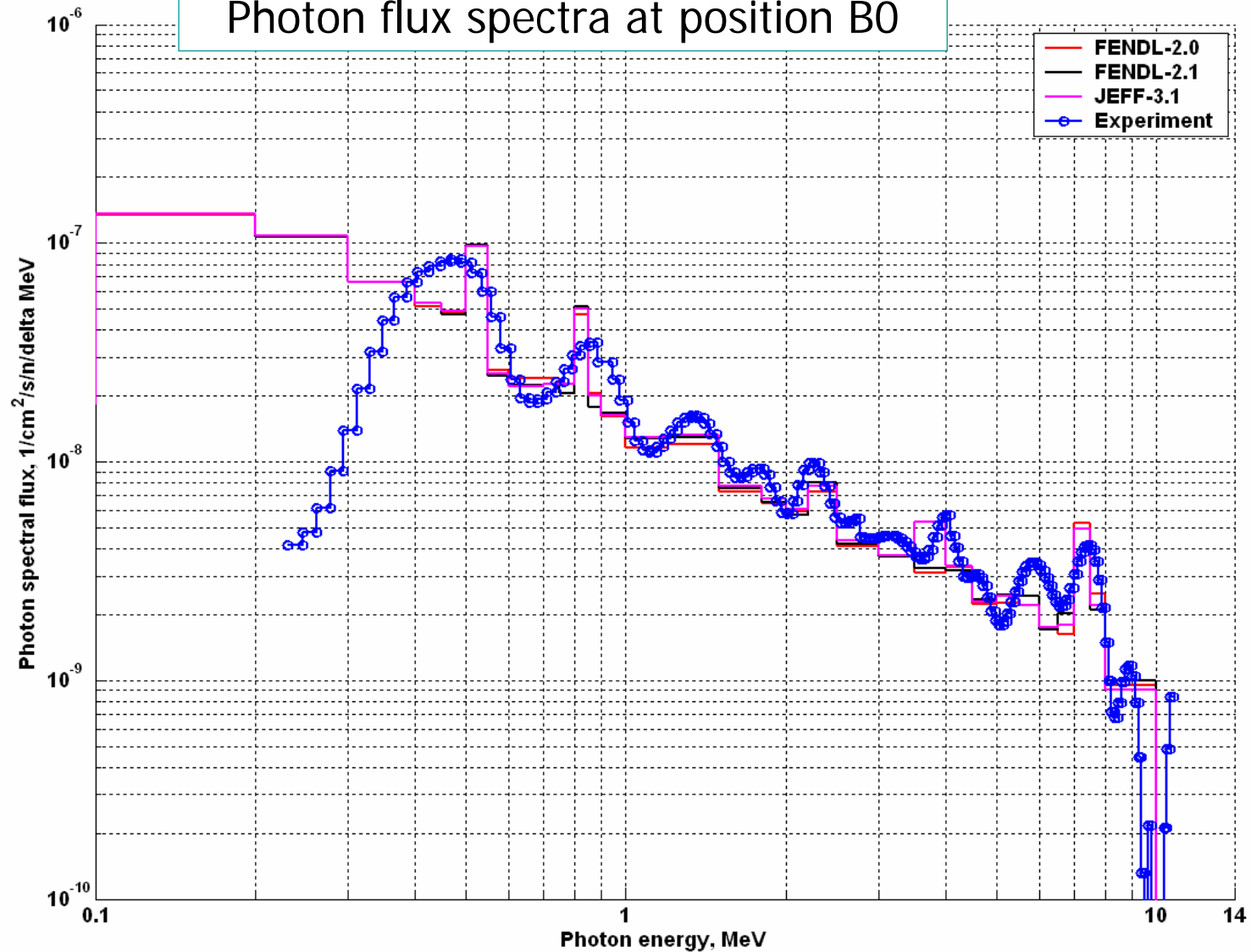
# ITER Streaming Experiment

Photon flux spectra at position A2

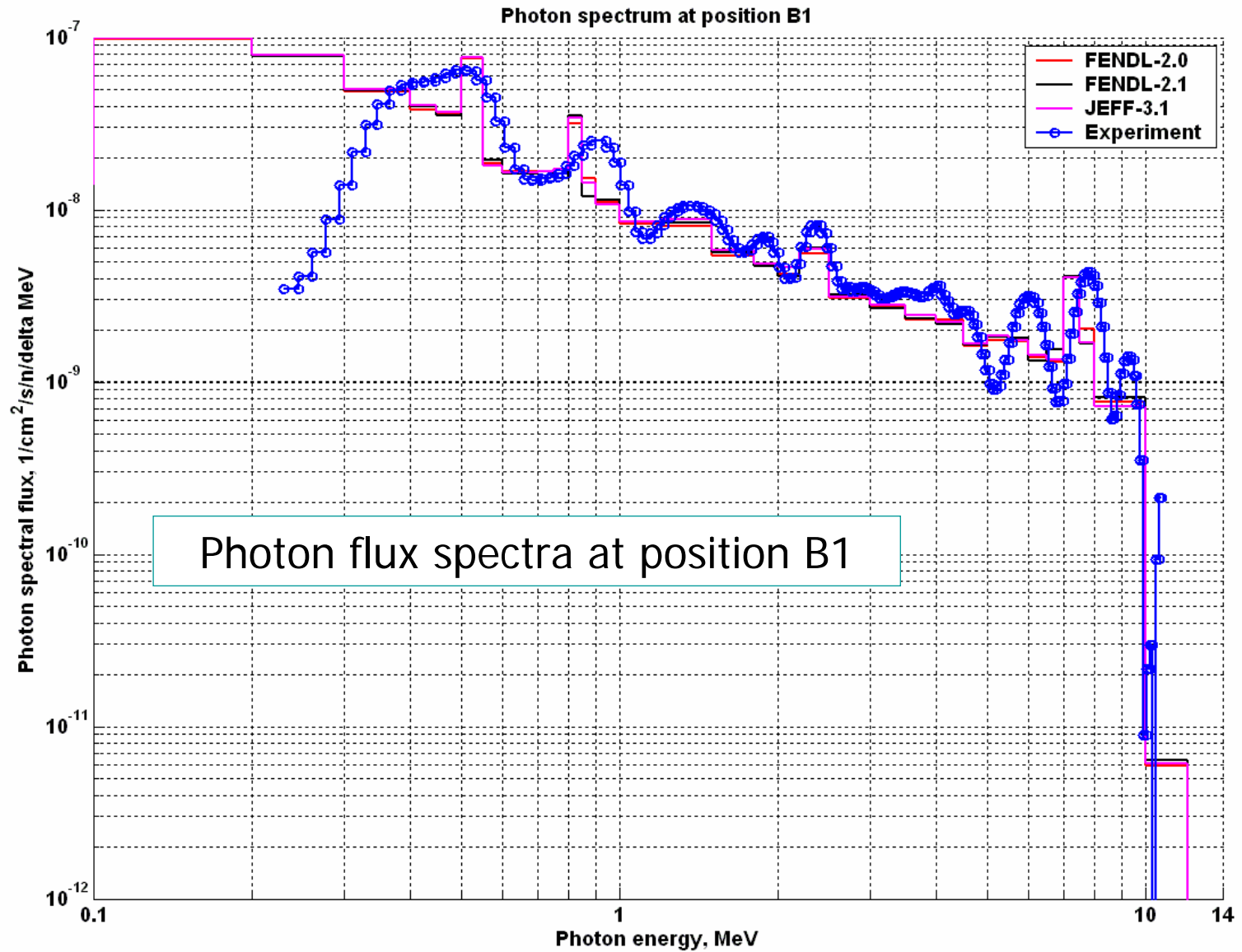


# ITER Streaming Experiment

Photon flux spectra at position B0



# ITER Streaming Experiment



# ITER Streaming Experiment

## C/E comparison for neutron flux integrals

| Position A0 |           |           |          | Statistical error (fsd) in A0-position: |           |          |
|-------------|-----------|-----------|----------|---|-----------|----------|
| Energy, MeV | FENDL-2.0 | FENDL-2.1 | JEFF-3.1 | FENDL-2.0                               | FENDL-2.1 | JEFF-3.1 |
| 0.1 - 1.0   | 1.37      | 1.39      | 1.42     | 0.59%                                   | 0.57%     | 0.63%    |
| 1.0 - 5.0   | 1.37      | 1.38      | 1.34     | 0.81%                                   | 0.80%     | 0.90%    |
| 5.0 - 10.0  | 1.73      | 1.79      | 1.80     | 1.22%                                   | 1.20%     | 1.26%    |
| E > 10.0    | 0.78      | 0.78      | 0.78     | 0.70%                                   | 0.69%     | 0.75%    |
| Position A1 |           |           |          | Statistical error (fsd) in A1-position: |           |          |
| Energy, MeV | FENDL-2.0 | FENDL-2.1 | JEFF-3.1 | FENDL-2.0                               | FENDL-2.1 | JEFF-3.1 |
| 0.1 - 1.0   | Inf       | Inf       | Inf      | 0.17%                                   | 0.17%     | 0.19%    |
| 1.0 - 5.0   | 0.89      | 0.89      | 0.90     | 0.21%                                   | 0.21%     | 0.23%    |
| 5.0 - 10.0  | 0.96      | 0.97      | 1.00     | 0.42%                                   | 0.42%     | 0.47%    |
| E > 10.0    | 0.90      | 0.89      | 0.91     | 0.40%                                   | 0.41%     | 0.45%    |
| Position A2 |           |           |          | Statistical error (fsd) in A2-position: |           |          |
| Energy, MeV | FENDL-2.0 | FENDL-2.1 | JEFF-3.1 | FENDL-2.0                               | FENDL-2.1 | JEFF-3.1 |
| 0.1 - 1.0   | Inf       | Inf       | Inf      | 0.16%                                   | 0.15%     | 0.17%    |
| 1.0 - 5.0   | 0.88      | 0.89      | 0.90     | 0.22%                                   | 0.21%     | 0.22%    |
| 5.0 - 10.0  | 0.92      | 0.93      | 0.96     | 0.49%                                   | 0.47%     | 0.51%    |
| E > 10.0    | 0.90      | 0.89      | 0.90     | 0.49%                                   | 0.47%     | 0.50%    |
| Position B0 |           |           |          | Statistical error (fsd) in B0-position: |           |          |
| Energy, MeV | FENDL-2.0 | FENDL-2.1 | JEFF-3.1 | FENDL-2.0                               | FENDL-2.1 | JEFF-3.1 |
| 0.1 - 1.0   | 0.77      | 0.79      | 0.80     | 0.56%                                   | 0.61%     | 0.59%    |
| 1.0 - 5.0   | 0.88      | 0.90      | 0.90     | 0.65%                                   | 0.71%     | 0.69%    |
| 5.0 - 10.0  | 1.03      | 1.06      | 1.10     | 0.76%                                   | 0.83%     | 0.81%    |
| E > 10.0    | 0.70      | 0.70      | 0.70     | 1.01%                                   | 1.11%     | 1.08%    |
| Position B1 |           |           |          | Statistical error (fsd) in B1-position: |           |          |
| Energy, MeV | FENDL-2.0 | FENDL-2.1 | JEFF-3.1 | FENDL-2.0                               | FENDL-2.1 | JEFF-3.1 |
| 0.1 - 1.0   | Inf       | Inf       | Inf      | 0.51%                                   | 0.56%     | 0.51%    |
| 1.0 - 5.0   | 0.71      | 0.72      | 0.73     | 0.58%                                   | 0.63%     | 0.58%    |
| 5.0 - 10.0  | 0.84      | 0.86      | 0.90     | 0.73%                                   | 0.79%     | 0.72%    |
| E > 10.0    | 0.69      | 0.68      | 0.70     | 0.73%                                   | 0.80%     | 0.74%    |



# ITER Streaming Experiment

## C/E comparison for photon flux integrals

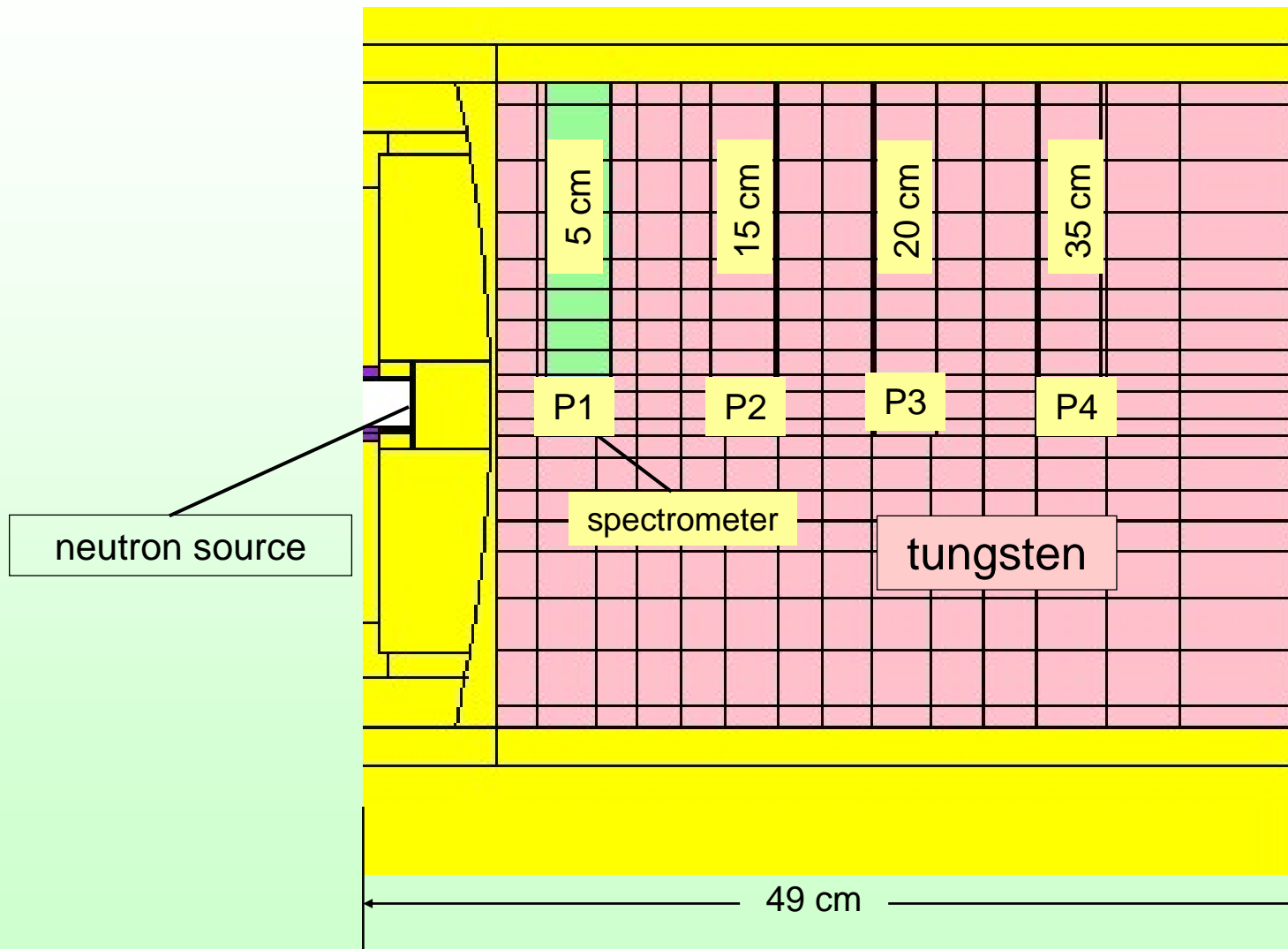
|             |           | Position A0 |          |           | Statistical error (fsd) in A0-position: |          |  |
|-------------|-----------|-------------|----------|-----------|---|----------|--|
| Energy, MeV | FENDL-2.0 | FENDL-2.1   | JEFF-3.1 | FENDL-2.0 | FENDL-2.1                               | JEFF-3.1 |  |
| 0.4 - 1.0   | 0.82      | 0.80        | 0.80     | 0.73%     | 0.68%                                   | 0.76%    |  |
| E > 1.0     | 0.82      | 0.84        | 0.83     | 0.62%     | 0.59%                                   | 0.64%    |  |
|             |           | Position A1 |          |           | Statistical error (fsd) in A1-position: |          |  |
| Energy, MeV | FENDL-2.0 | FENDL-2.1   | JEFF-3.1 | FENDL-2.0 | FENDL-2.1                               | JEFF-3.1 |  |
| 0.4 - 1.0   | 0.99      | 1.00        | 1.01     | 0.31%     | 0.32%                                   | 0.36%    |  |
| E > 1.0     | 0.99      | 1.01        | 1.00     | 0.24%     | 0.23%                                   | 0.25%    |  |
|             |           | Position A2 |          |           | Statistical error (fsd) in A2-position: |          |  |
| Energy, MeV | FENDL-2.0 | FENDL-2.1   | JEFF-3.1 | FENDL-2.0 | FENDL-2.1                               | JEFF-3.1 |  |
| 0.4 - 1.0   | 0.93      | 0.94        | 0.93     | 0.33%     | 0.32%                                   | 0.34%    |  |
| E > 1.0     | 0.93      | 0.96        | 0.95     | 0.25%     | 0.24%                                   | 0.27%    |  |
|             |           | Position B0 |          |           | Statistical error (fsd) in B0-position: |          |  |
| Energy, MeV | FENDL-2.0 | FENDL-2.1   | JEFF-3.1 | FENDL-2.0 | FENDL-2.1                               | JEFF-3.1 |  |
| 0.4 - 1.0   | 0.83      | 0.82        | 0.82     | 0.68%     | 0.67%                                   | 0.65%    |  |
| E > 1.0     | 0.84      | 0.87        | 0.90     | 0.50%     | 0.49%                                   | 3.03%    |  |
|             |           | Position B1 |          |           | Statistical error (fsd) in B1-position: |          |  |
| Energy, MeV | FENDL-2.0 | FENDL-2.1   | JEFF-3.1 | FENDL-2.0 | FENDL-2.1                               | JEFF-3.1 |  |
| 0.4 - 1.0   | 0.77      | 0.77        | 0.78     | 0.69%     | 0.83%                                   | 1.19%    |  |
| E > 1.0     | 0.78      | 0.80        | 0.80     | 0.52%     | 0.50%                                   | 0.54%    |  |

# FNG Tungsten Benchmark Experiment

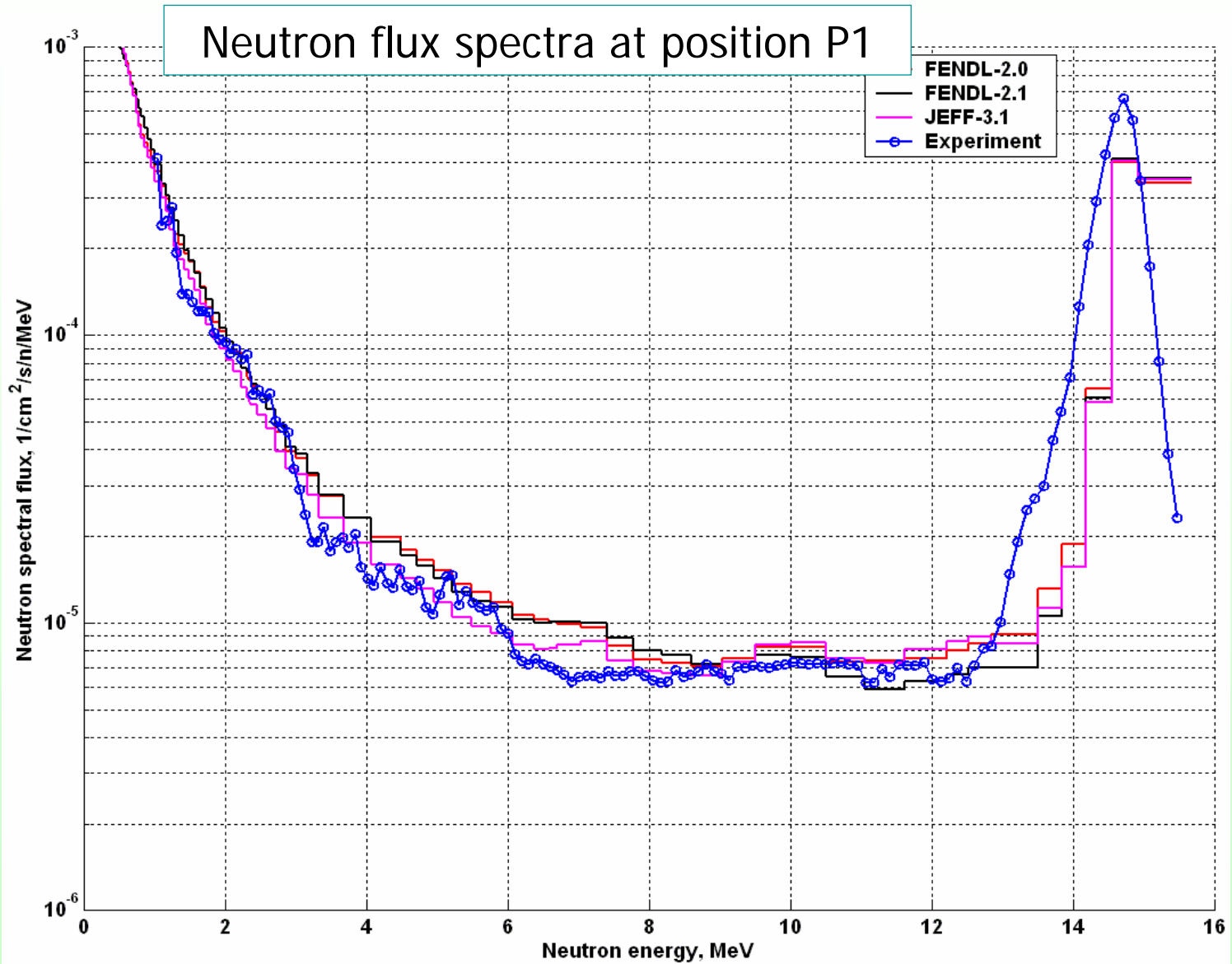
- Measurement of neutron & photon flux spectra in W assembly using a NE 213 liquid-scintillation spectrometer (*K. Seidel et al., EFF-DOC-857*)
  - Spectra measured in four positions in W assembly
- Previous analyses (*U. Fischer et al, EFF-DOC-860, EFF-DOC-897, EFF-DOC -931*)
  - MCNP4C calculations for 3D model of W assembly & rack, spectrometer, neutron generator and experimental hall (FNG)
  - W data: EFF-2.4 (=JENDL-3.0), FENDL-1(=ENDF/B-VI.0), FENDL-2 (=JENDL-FF), JENDL-3.3  
New EFF evaluation (P. Pereslavstev et al, EFF-DOC-912)

FENDL-2.1 = ENDF/B-VI.8

# FNG Tungsten Assembly Model

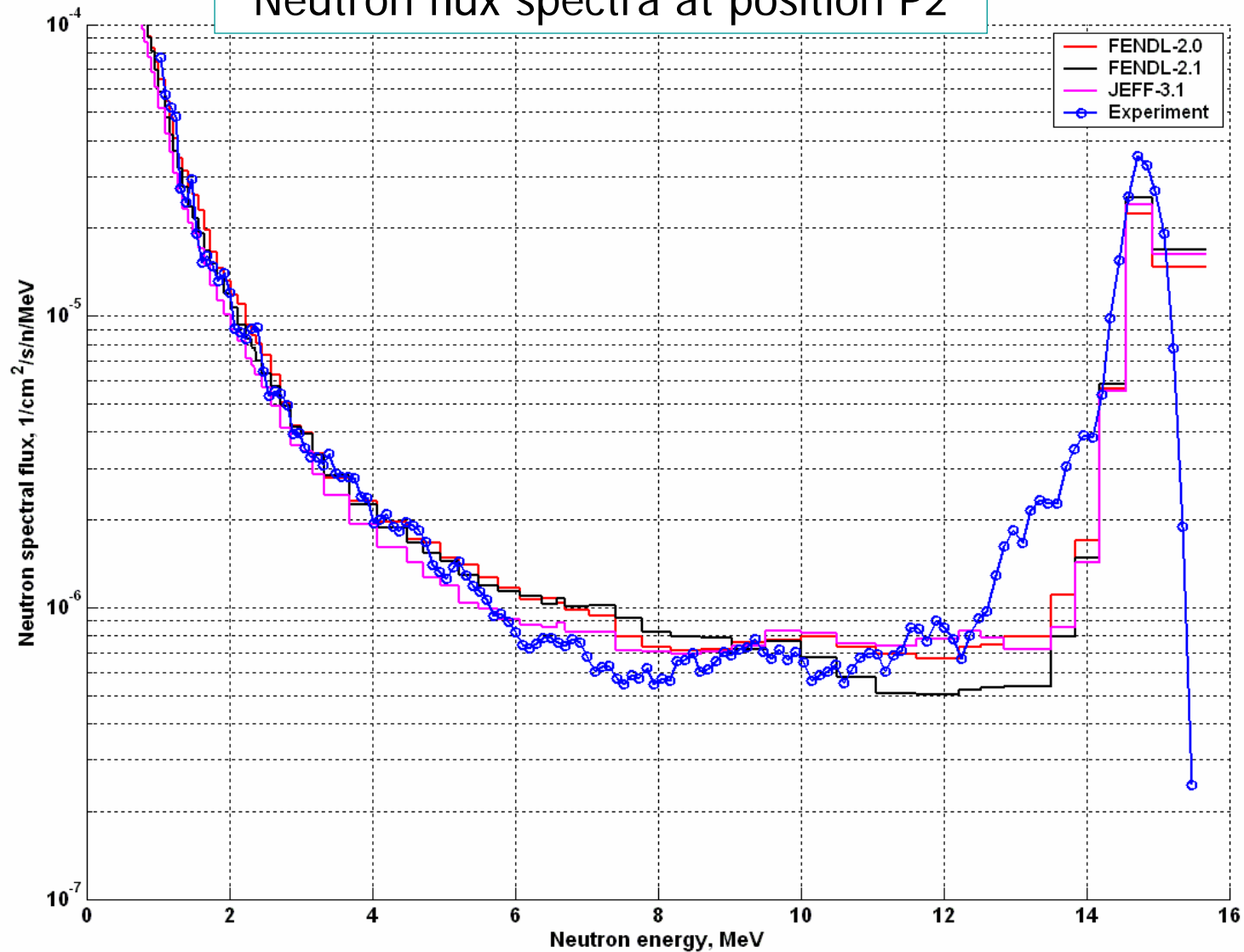


# FNG Tungsten Benchmark Experiment

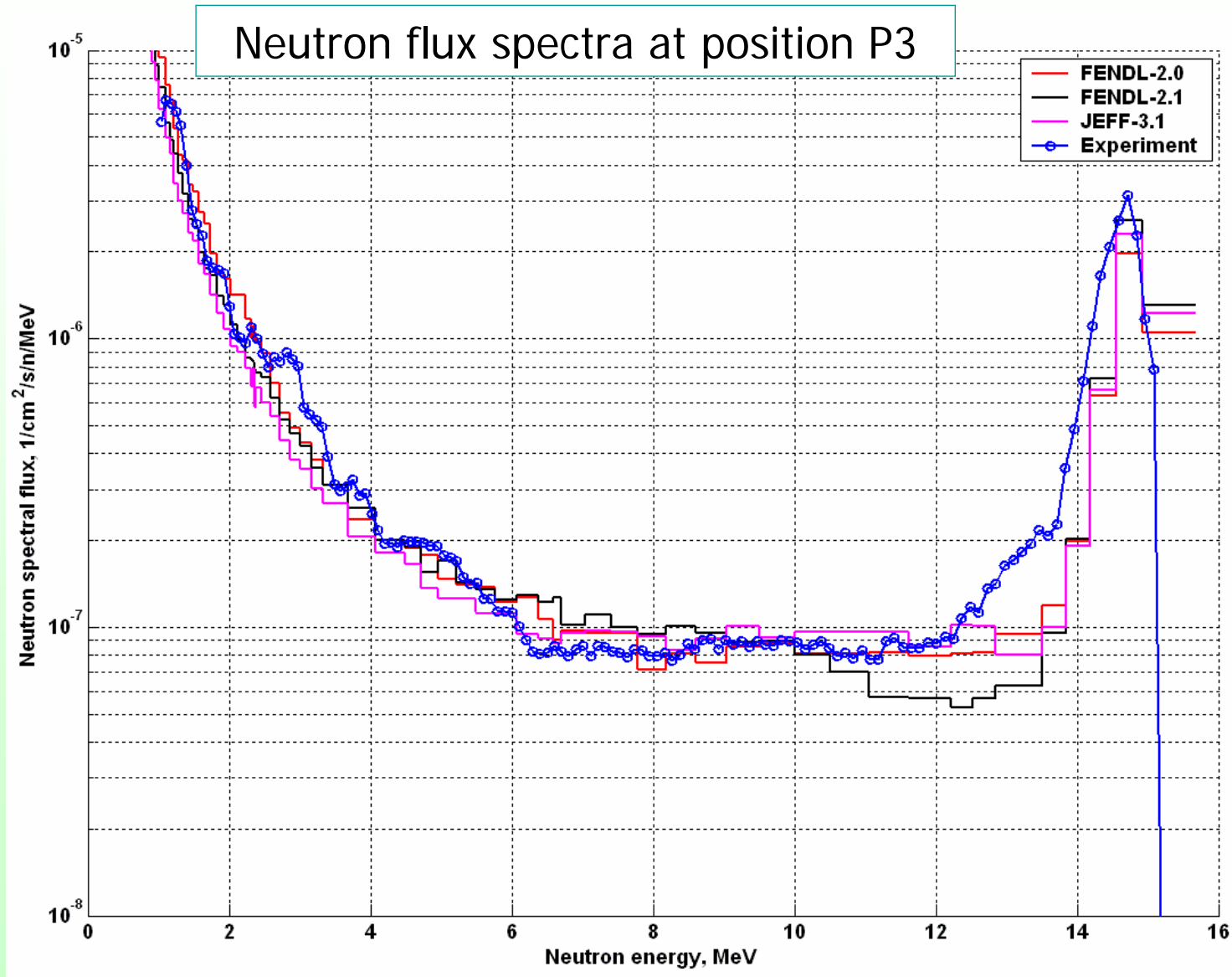


# FNG Tungsten Benchmark Experiment

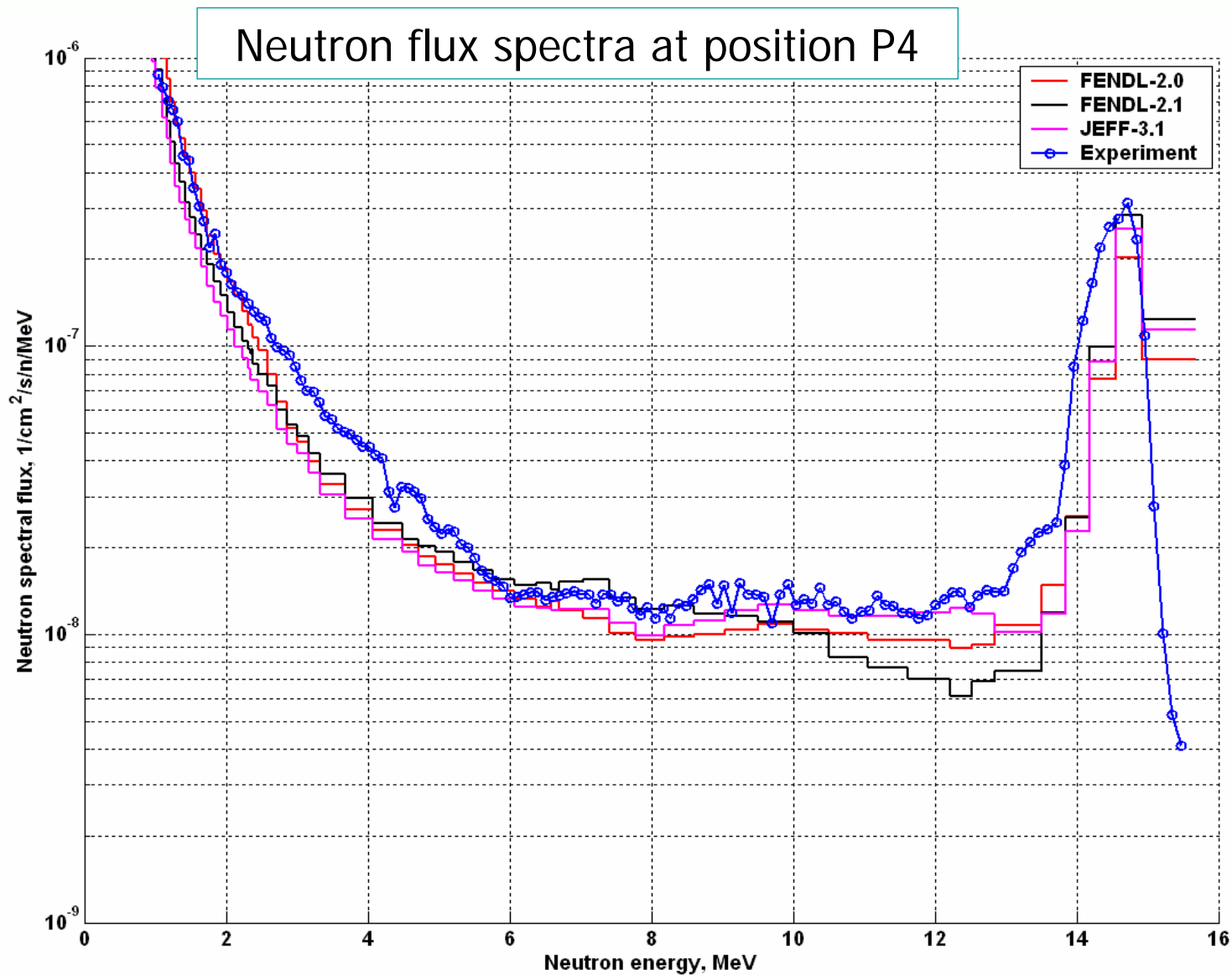
Neutron flux spectra at position P2



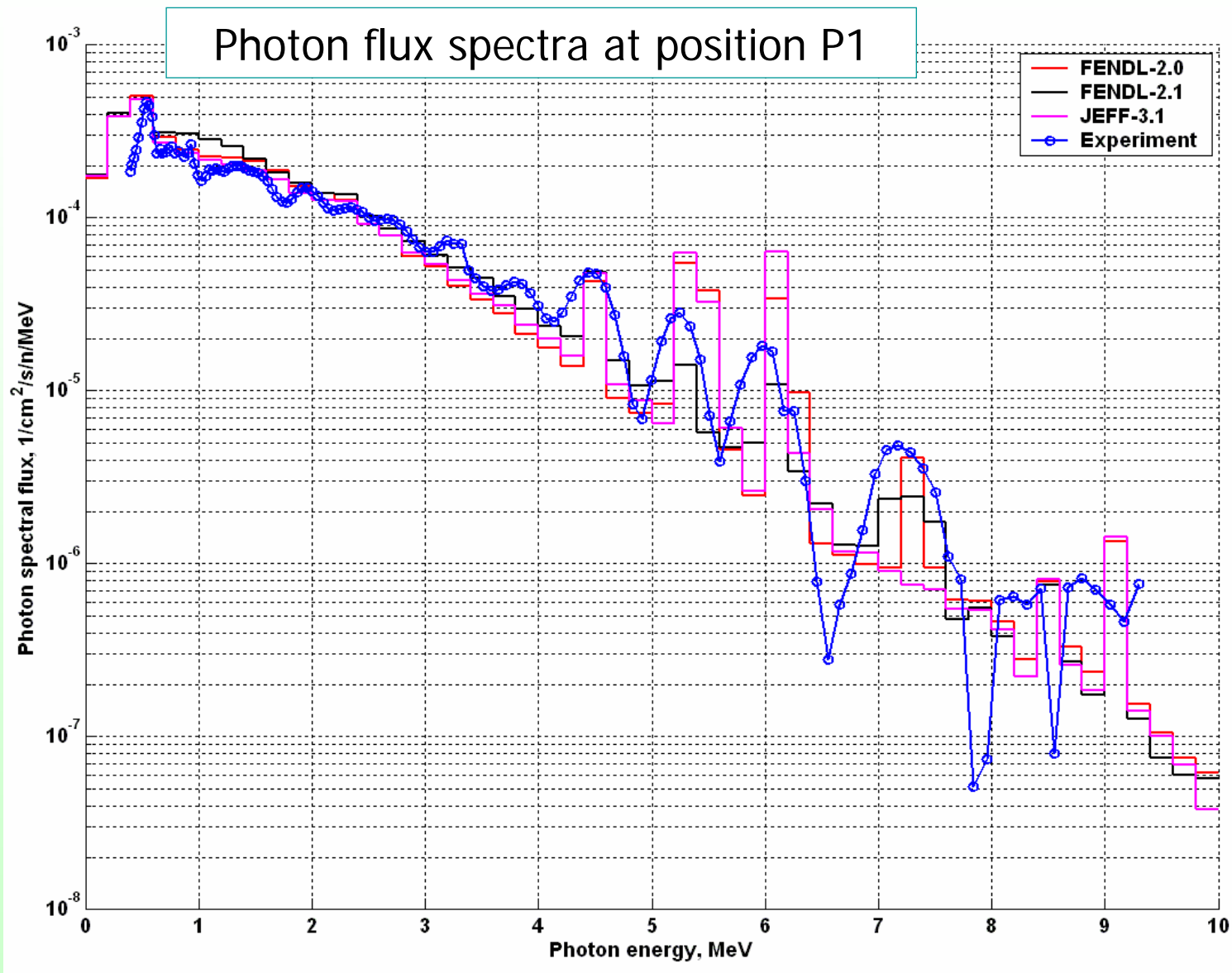
# FNG Tungsten Benchmark Experiment



# FNG Tungsten Benchmark Experiment

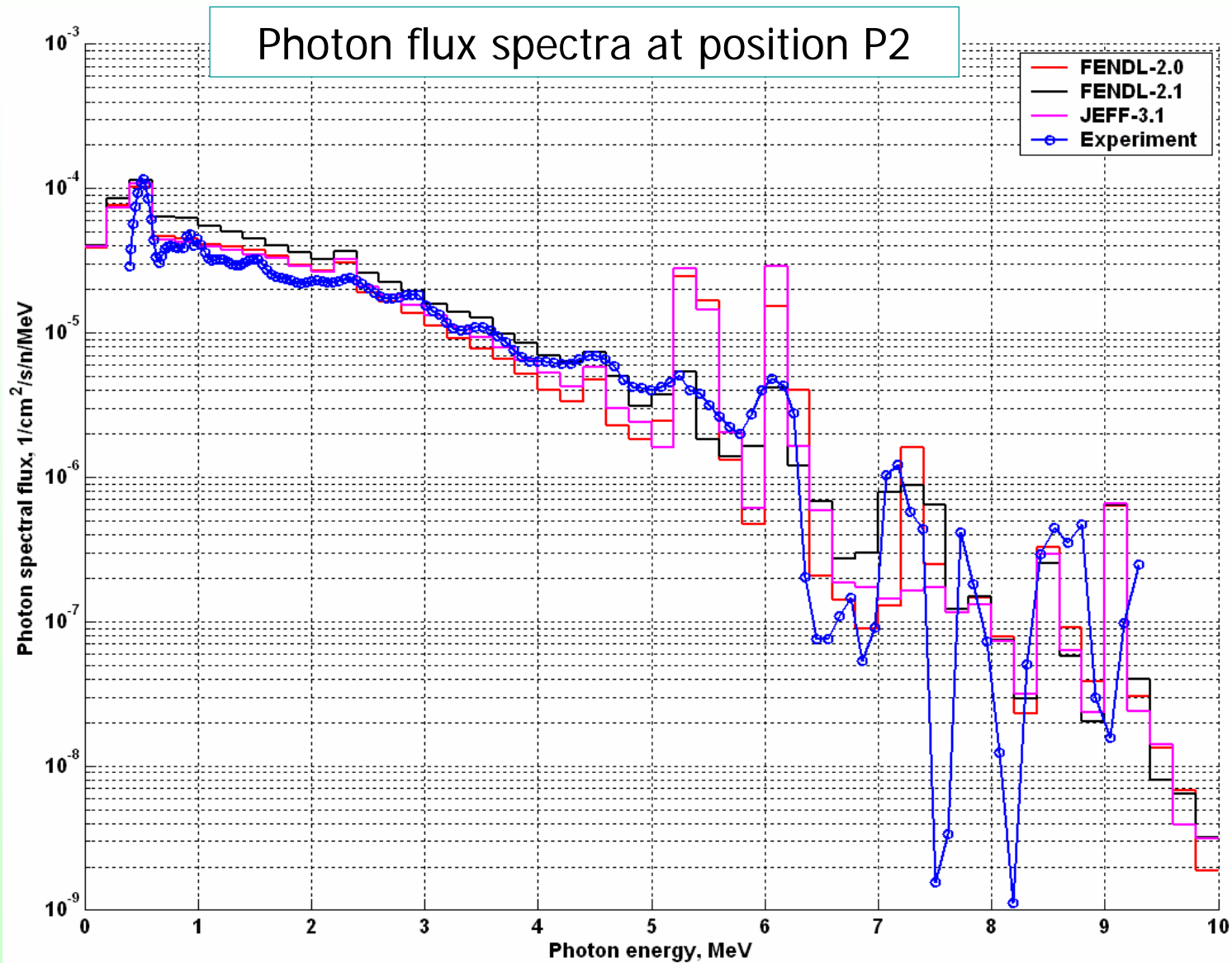


# FNG Tungsten Benchmark Experiment

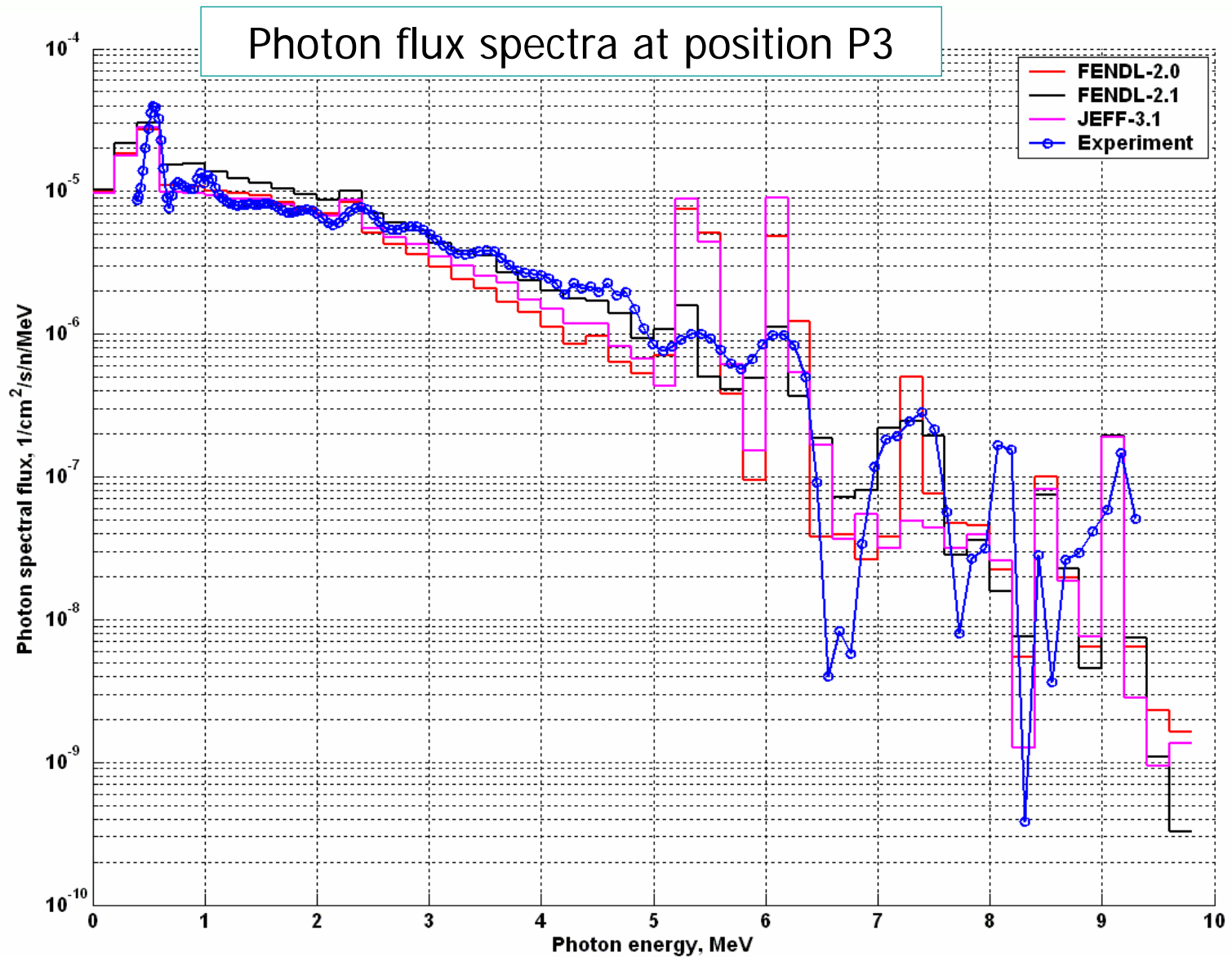




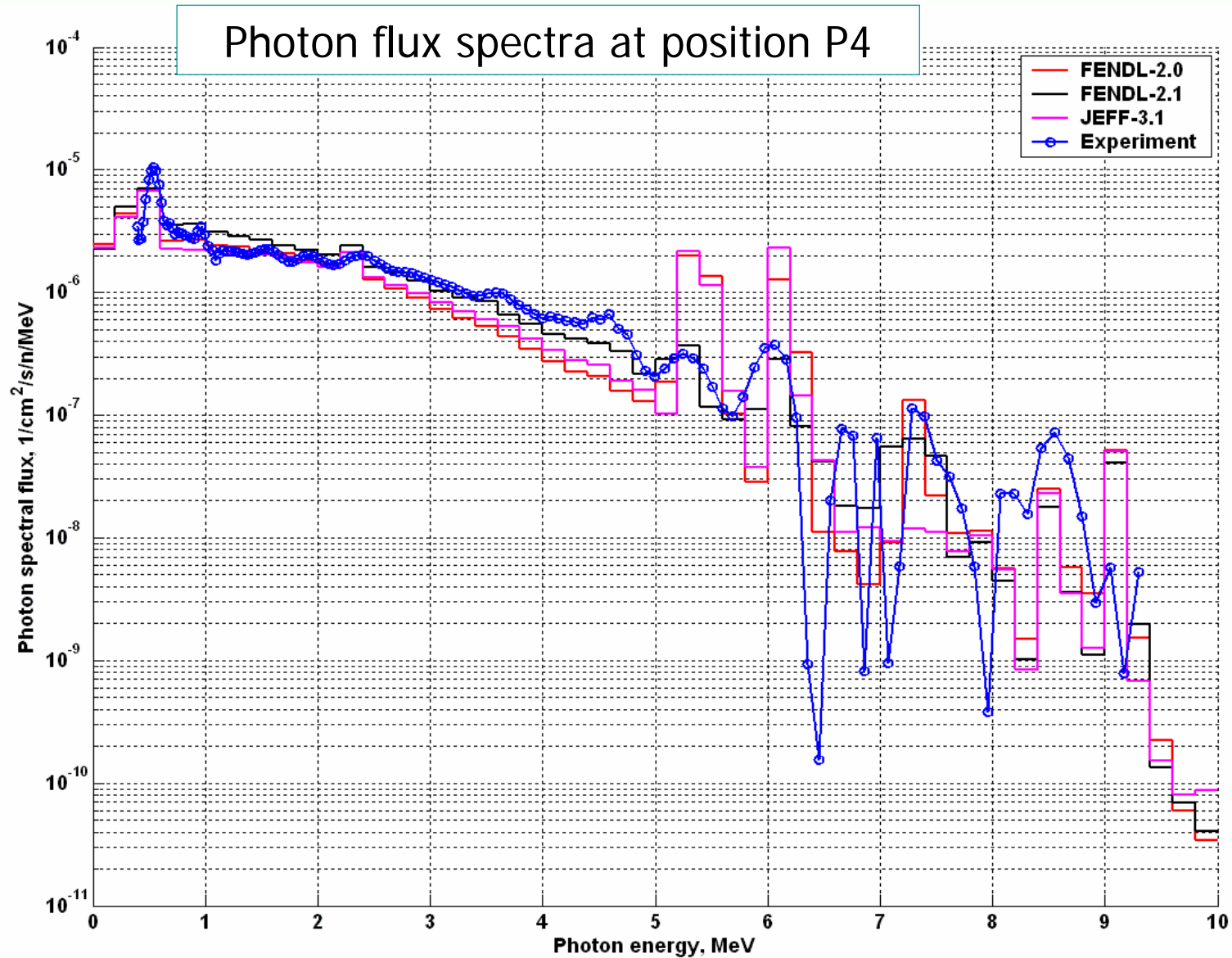
# FNG Tungsten Benchmark Experiment



# FNG Tungsten Benchmark Experiment

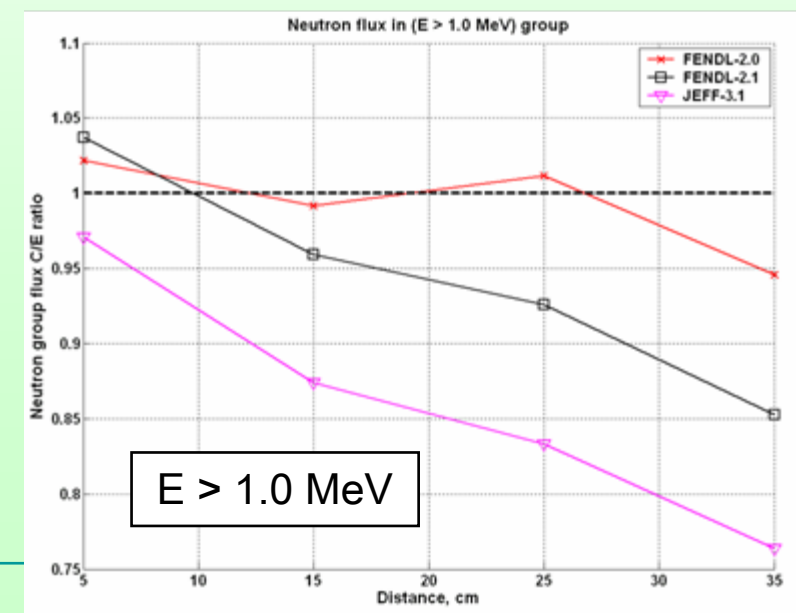
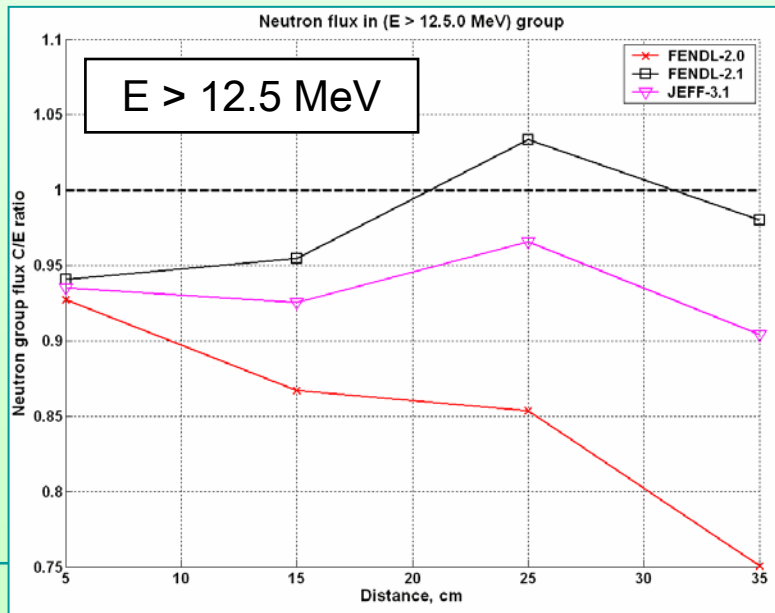
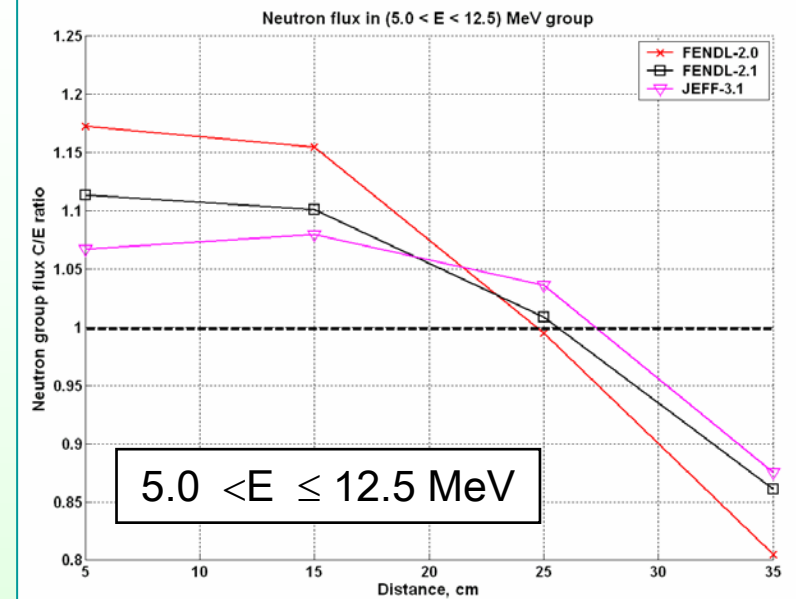
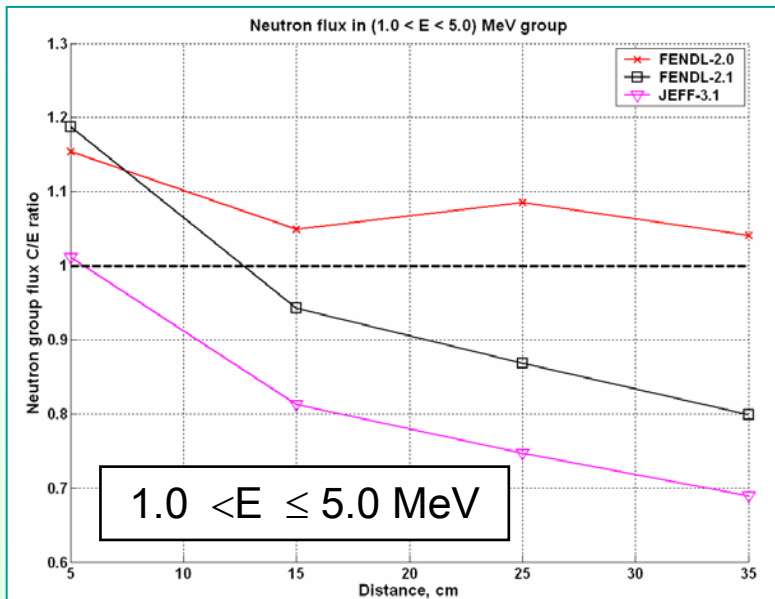


# FNG Tungsten Benchmark Experiment



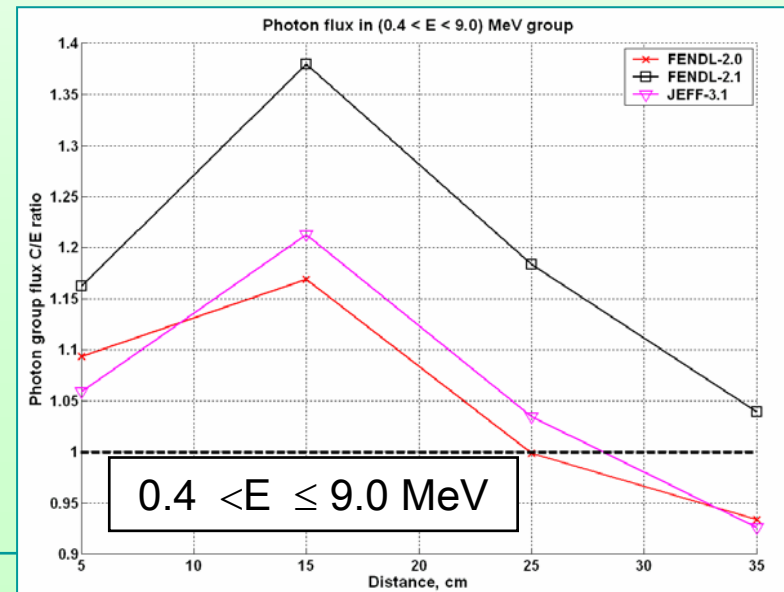
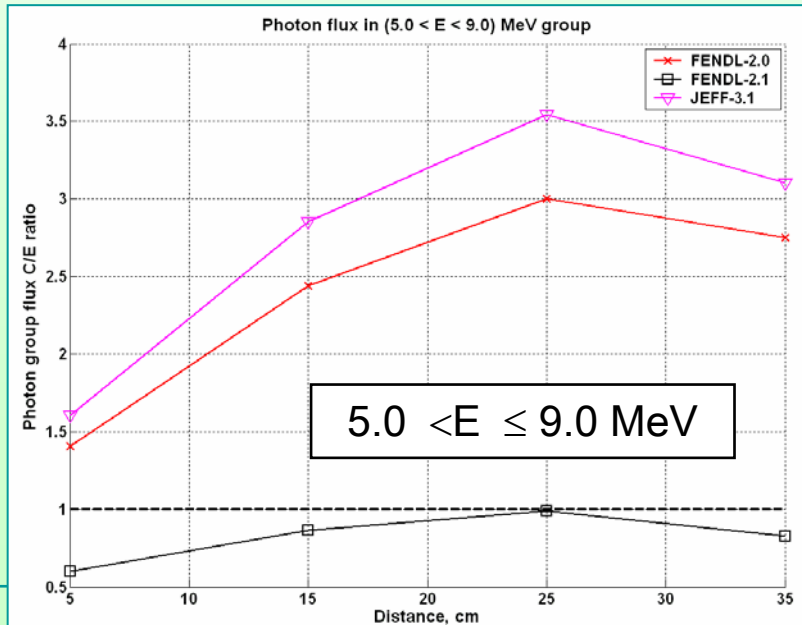
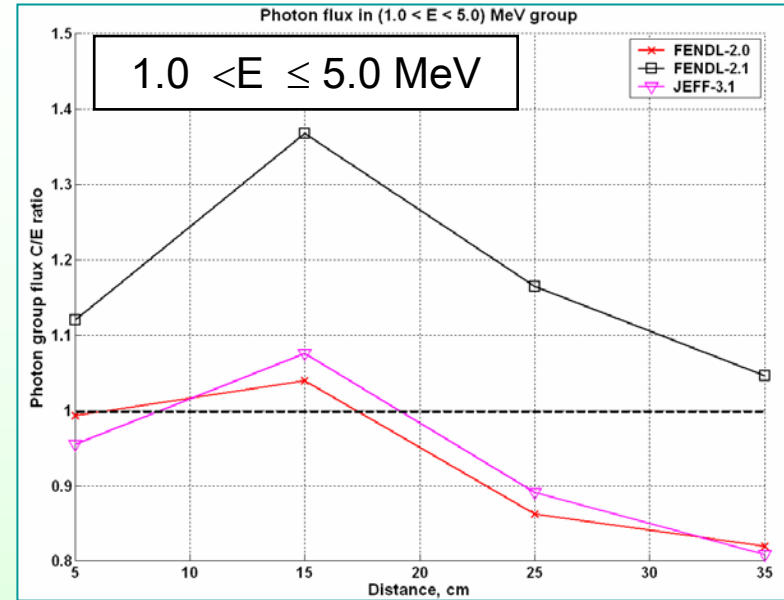
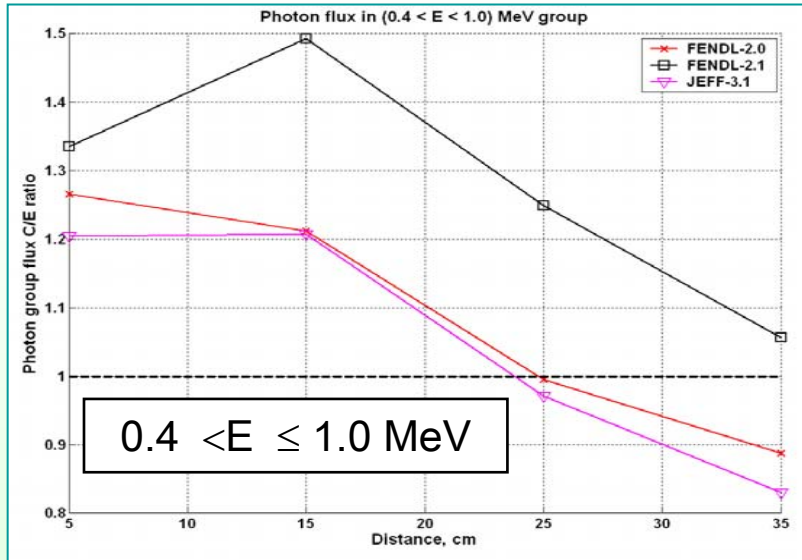
# FNG Tungsten Benchmark Experiment

## - C/E comparison of neutron flux integrals -



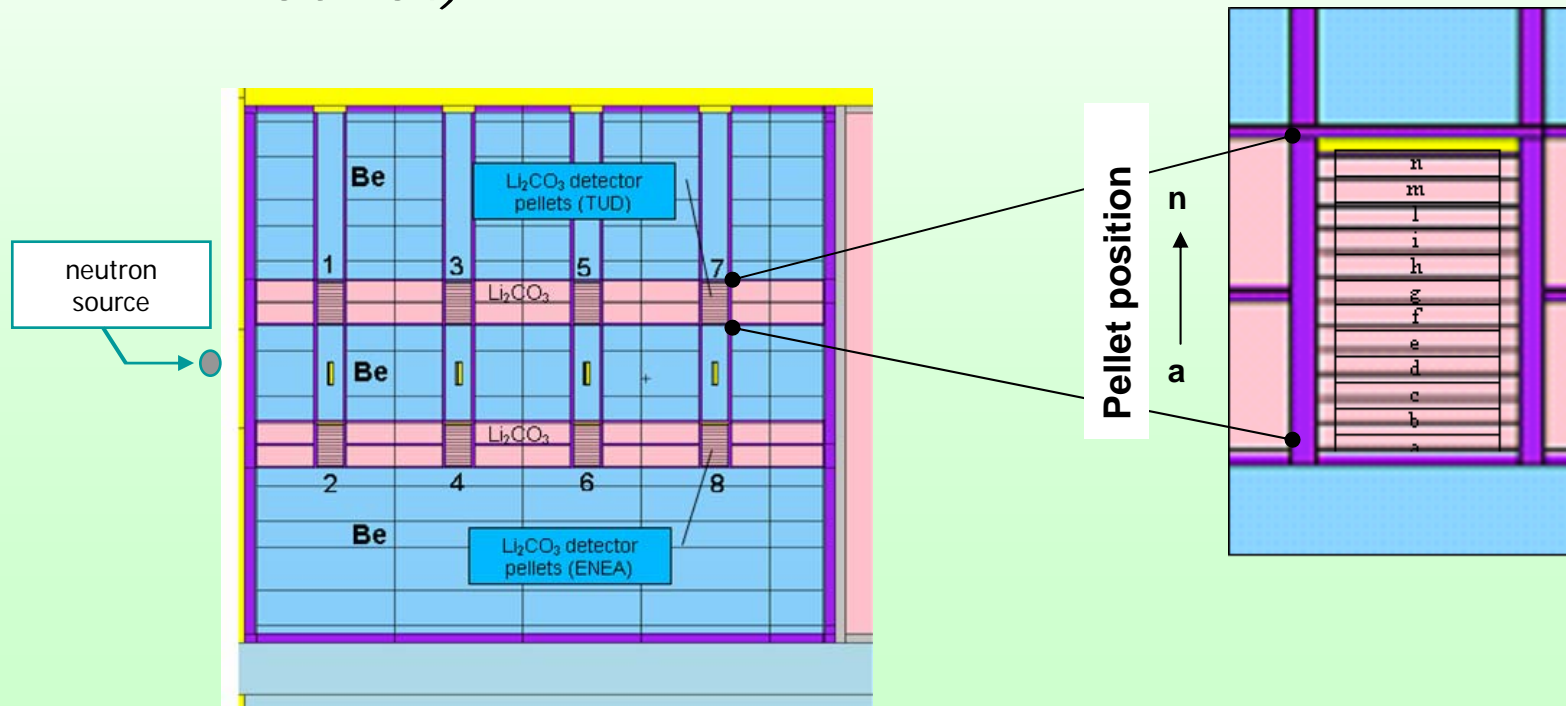
# FNG Tungsten Benchmark Experiment

## - C/E comparison of photon flux integrals -



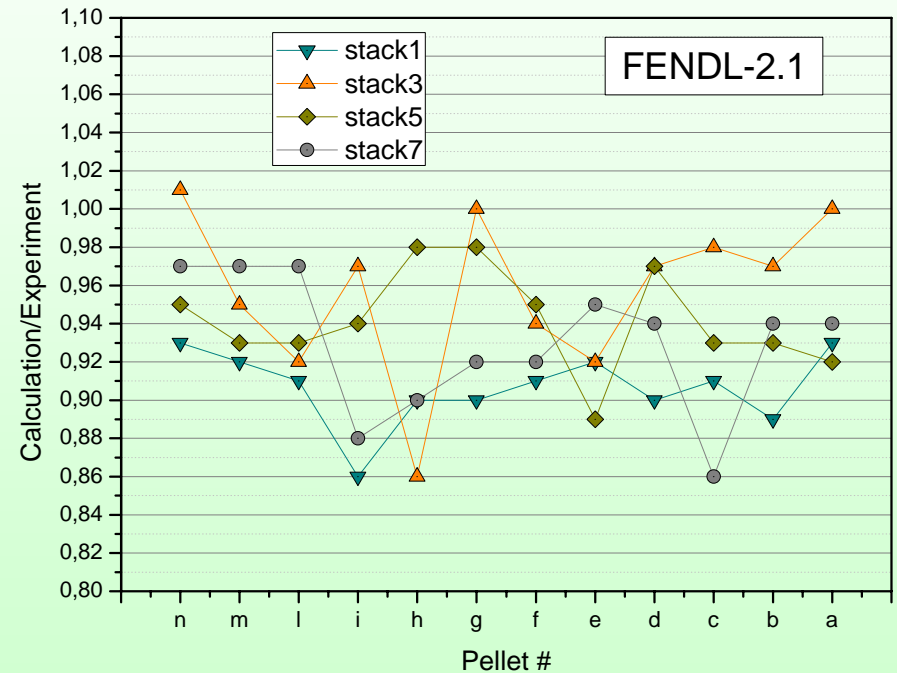
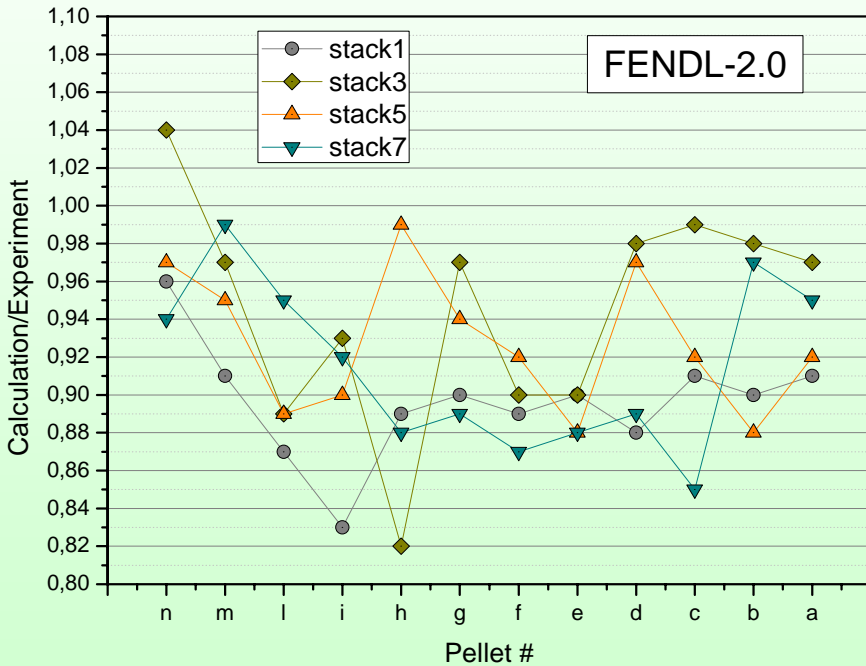
# HCPB Breeder Blanket Mock-up Experiment

- Benchmark experiment to validate prediction of Tritium production rate in mock-up of HCPB Test Blanket Module
- Performed at FNG by experiental groups of ENEA, TUID and JAEA, (*P. Batistoni et al., EFF-DOC-938; K. Seidel et al., EFF-DOC-956*)
- MC based analyses using EFF-3, FENDL-2.0, 2.1 (*U. Fischer et al., EFF-DOC-954*)



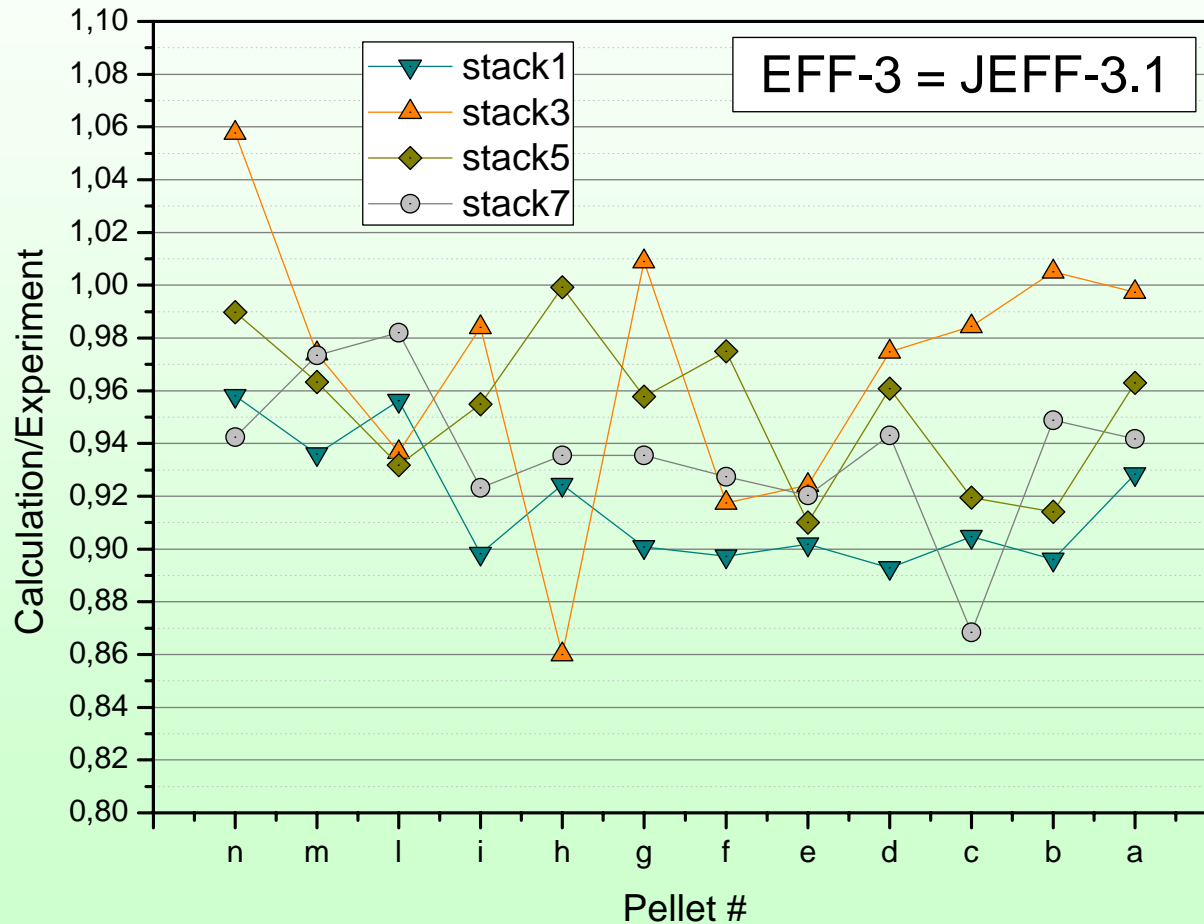
# HCPB Breeder Blanket Mock-up Experiment

*C/E comparison for Tritium production rates measured in pellets of stacks 1, 3, 5, and 7 (FENDL-2.0, -2.1 data)*



# HCPB Breeder Blanket Mock-up Experiment

*C/E comparison for Tritium production rates measured in pellets of stacks 1, 3, 5, and 7 (EFF-3 = JEFF-3.1 data)*





# Conclusions

- ITER shielding/streaming experiments
  - No significant differences between FENDL-2.0/2.1 and JEFF-3.1
- Tungsten benchmark experiment
  - FENDL-2.1 (ENDF-B/VI-8) performs better than FENDL-2.0 (=JENDL-FF) & JEFF-3.1 (=JENDL-3.3)
- Breeder blanket mock-up experiment
  - No significant differences between FENDL-2.0/2.1 and JEFF-3.1

⇒ *FENDL-2.1 data library suitable for fusion design applications calculations.*

⇒ *JEFF-3.1: W data need to be updated.*