Electron-beam based Neutron Sources

Roadmap for Future Accelerators- iFAST WP5.2 Workshop
3rd of September, 2024

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Is an electron linac a suitable driver for neutron production?

To answer this question, I will discuss:

I. The **necessity** for neutron sources (Introduction)

II. Neutron production **mechanism** with electrons

III. Unmoderated neutron **spectrum characterization**

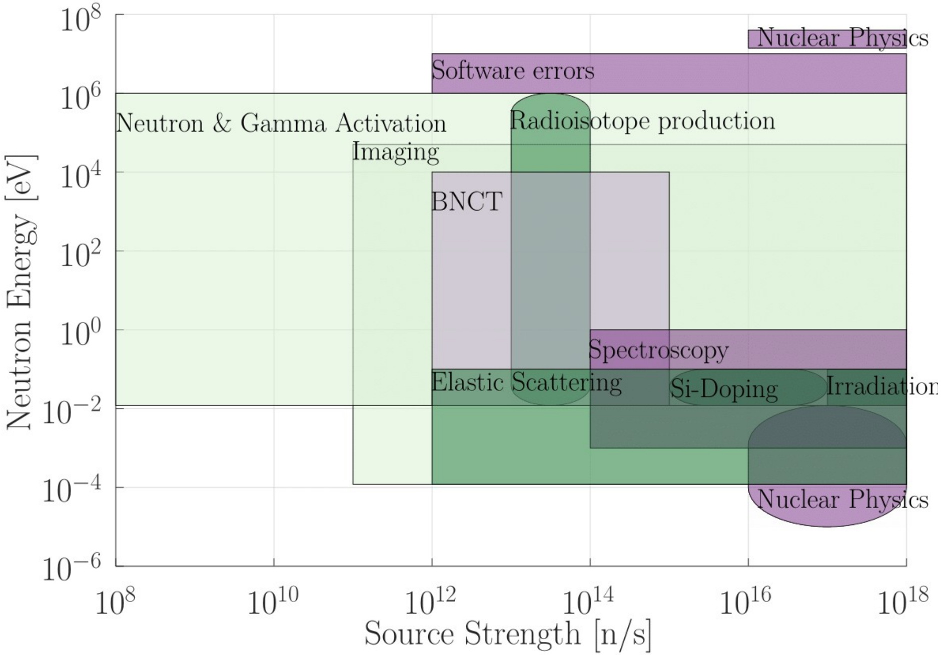
IV. Comparison with the **state-of-the-art**

V. Neutron moderation and **brightness/brilliance** discussion

VI. **VULCAN** neutron source

I. Necessity for neutron sources

- **Uprising demand**: Wide variety of research areas make use of neutrons
  - Not only research: Industrial and medical applications! [1, 2]



II. Neutron production with accelerators

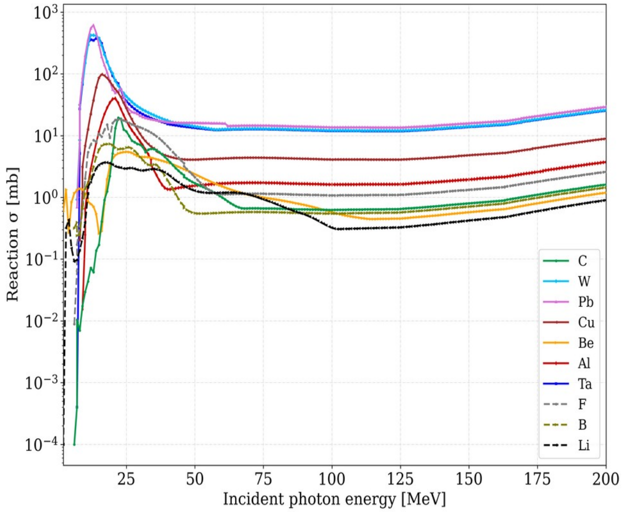
- Neutron sources migrating from nuclear reactors to **accelerator-based facilities** [3]
- **Hadron**-based machines. **Direct** processes:
  - Spallation
  - Controlled nuclear reaction:

$$\mathrm{p} + {}^{7}\mathrm{Li} \rightarrow \mathrm{n} + {}^{7}\mathrm{Be}$$

- **Electron**-based machines. Indirect process:
  - Bremmstrahlung + Photonuclear reaction

High Z

High σ



ENDF-v.VIII Photonuclear cross sections.

II. Neutron production with accelerators

- Neutron sources migrating from nuclear reactors to **accelerator-based facilities** [3]
- **Hadron**-based machines. **Direct** processes:
  - Spallation
  - Controlled nuclear reaction:

$$\mathrm{p} + {}^{7}\mathrm{Li} \rightarrow \mathrm{n} + {}^{7}\,\mathrm{Be}$$

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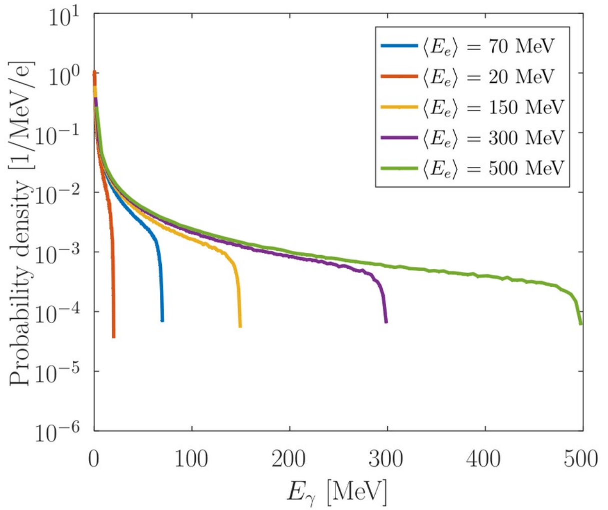
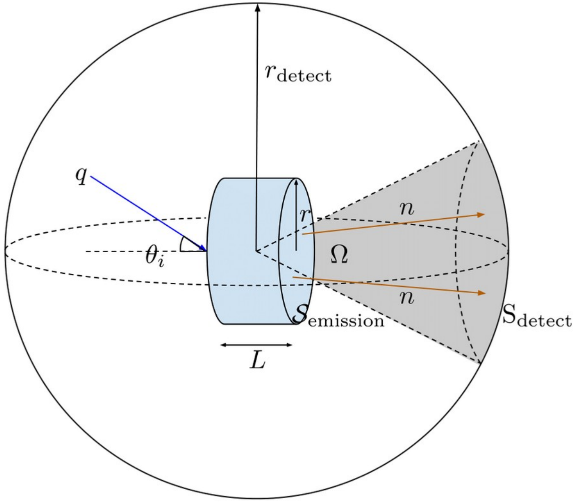


Bremmstrahlung spectrum for different electron beams against tungsten.

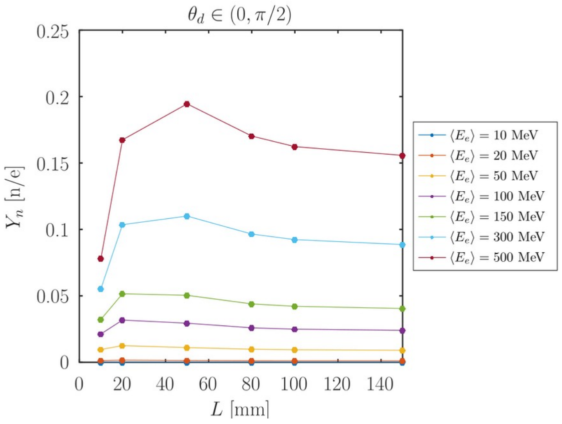
II. Neutron production with electrons

- Single tungsten target where **both** processes occur
- G4beamlines simulations **[4]**
  - Optimal dimensions: r = 50mm; L = 80 mm

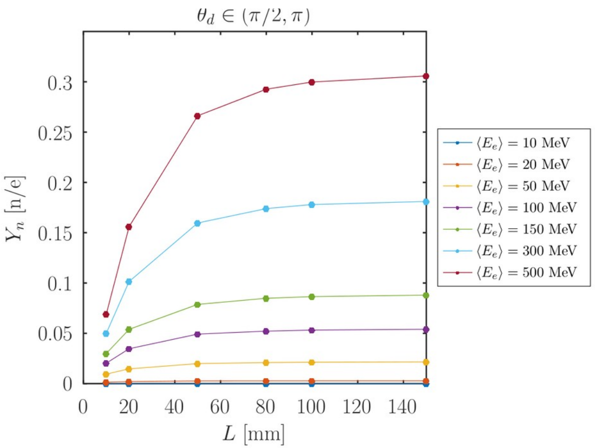
$$Y_n(E_e) \equiv \frac{N_n(E_e)}{N_e}$$



Neutron production setup



Forward neutron yield at r = 50 mm.
Θi = 0 deg



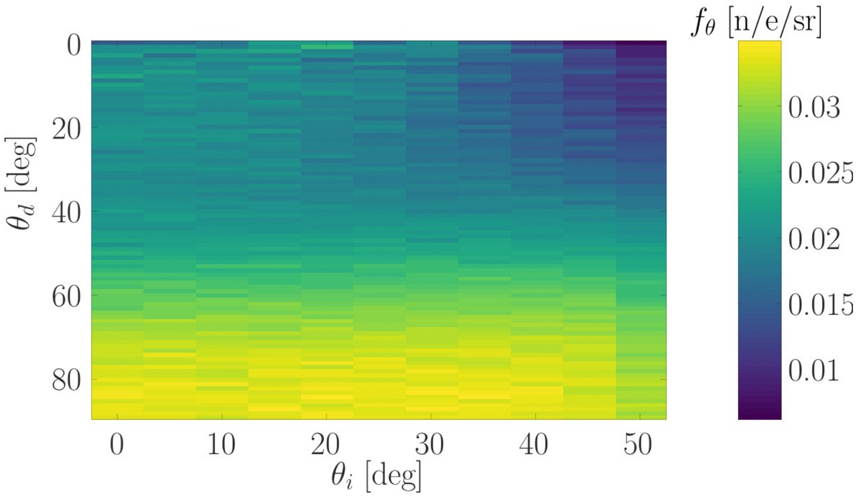
Backward neutron yield at r = 50 mm.
Θi = 0 deg

III. Unmoderated neutron spectrum

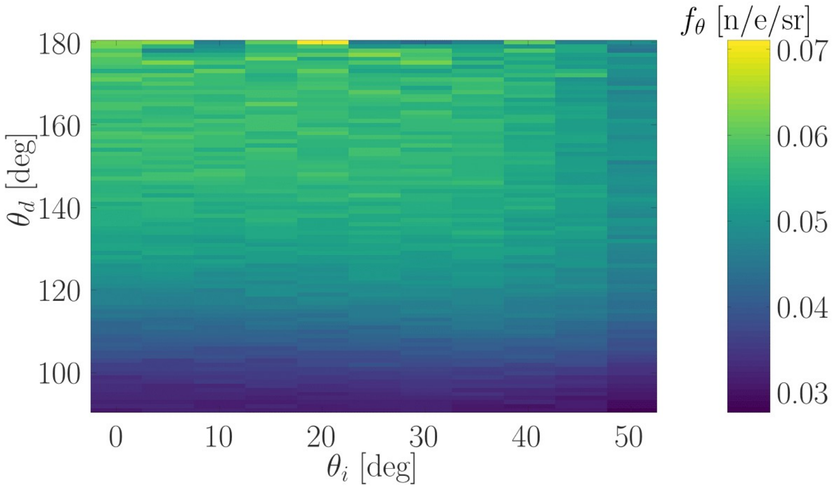
- For the optimized W target, we note:
  - Isotropy in incidence direction θ_i

$$f_\Omega(\varphi, \theta_d; E_e) \equiv \frac{\mathrm{d}^2 Y_n}{\mathrm{d}\Omega}(\varphi, \theta_d)$$

$$f_\theta(\theta_d; E_e) \equiv 2\pi \int_0^{2\pi} f_\Omega(\theta_d, \varphi)\mathrm{d}\varphi$$



Forward neutron detection dependency with incidence angle and <Ee> = 500 MeV



Backward neutron detection dependency with incidence angle and <Ee> = 500 MeV

III. Unmoderated neutron spectrum

- For the optimized W target, we note:
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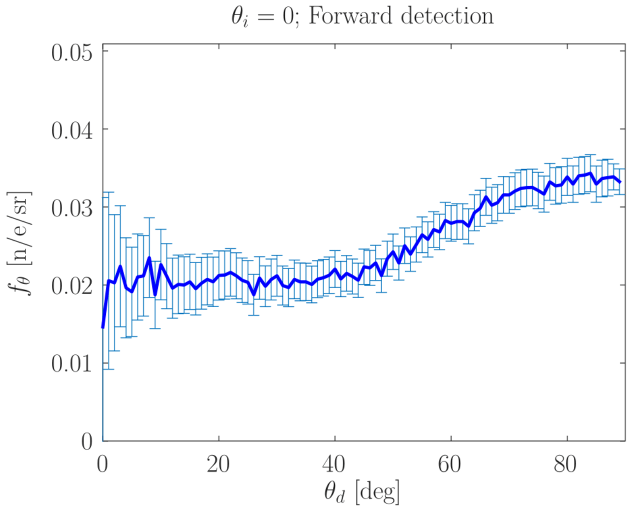
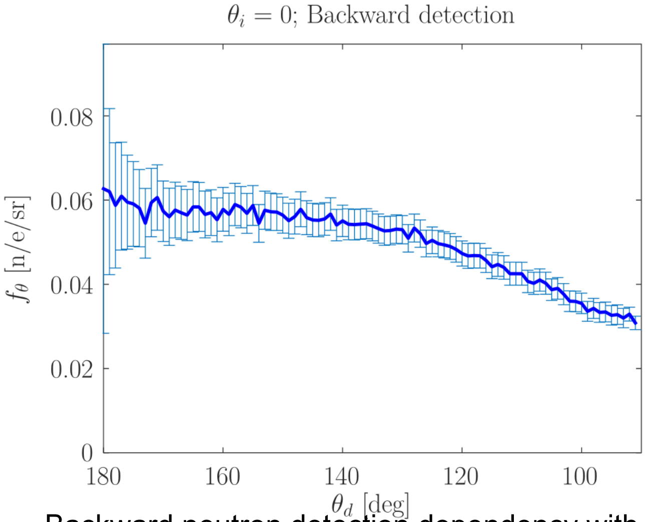
  - Isotropy in polar detecting angle: Up to 40 deg





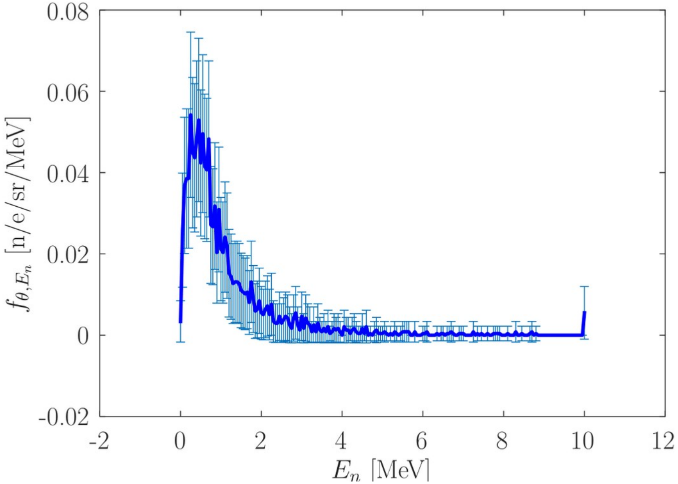
Forward neutron detection dependency with incidence angle and <Ee> = 500 MeV and θ_i = 0 deg.

Backward neutron detection dependency with incidence angle and <Ee> = 500 MeV and θ_i = 0 deg.

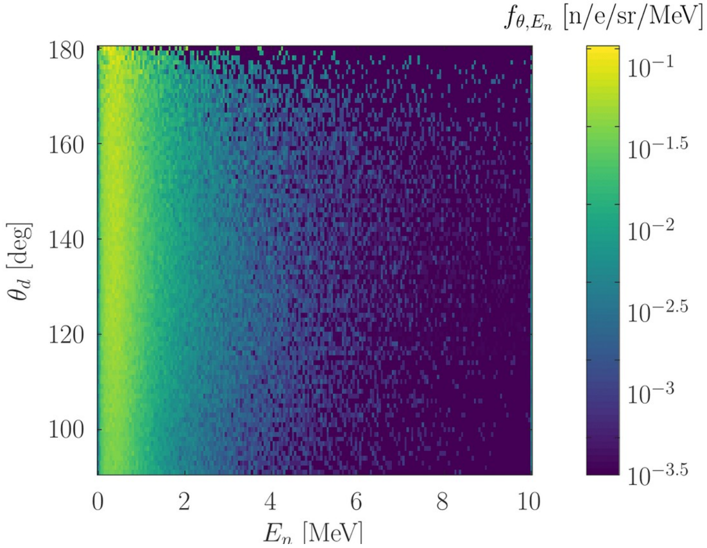
III. Unmoderated neutron spectrum

- For the optimized W target, we note:
  - Isotropy in incidence direction θ_i
  - Isotropy in polar detecting angle: Up to 40 deg
  - Maxwellian neutron emission with $\langle E_n \rangle \sim 1$ MeV

$$f_{\theta,E_n}(\theta_d, E_n; E_e) \equiv \frac{\mathrm{d}f_\theta}{\mathrm{d}E_n}$$



Energy distribution for different detecting angles.
$\langle E_e \rangle$ = 500 MeV and θi = 0 deg; θd = 165 deg.



Energy distribution for different detecting angles.
$\langle E_e \rangle$ = 500 MeV and θi = 0 deg.

III. Unmoderated neutron spectrum

- For the optimized W target, we note:
  - Isotropy in incidence direction θ_i
  - Isotropy in polar detecting angle: Up to 40 deg.
  - Maxwellian neutron emission with $\langle E_n \rangle \sim 1$ MeV
  - **Increase of σ_{E_n}** due to high E_n neutrons; **little change in $\langle E_n \rangle$**

$\langle \boldsymbol{E_e} \rangle$ [MeV]	$\boldsymbol{f_\theta}$ [10^{-2} n/e/sr]	$\langle \boldsymbol{E_n} \rangle$ [MeV]	$\boldsymbol{\sigma_{E_n}}$ [MeV]
20	0.056 ± 0.009	0.776	0.625
50	0.41 ± 0.04	0.859	0.741
100	1.02 ± 0.09	0.986	0.973
300	3.4 ± 0.3	1.08	1.15
500	5.8 ± 0.5	1.08	1.17

Energy neutron spectrum details detected at $\theta_d = 165$ deg

IV. High intensity e-linac proposal

- Targeted figure of merit: **Source strength**

$$I_n \equiv I_{e,\text{av}} Y_n$$

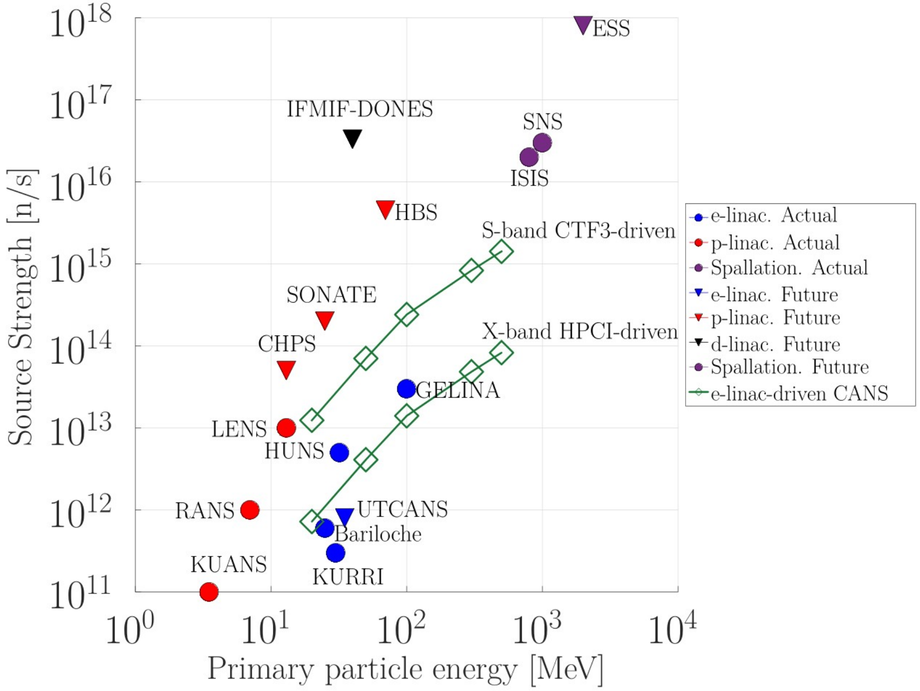
- Two normal-conducting high-intensity linacs are considered
  - **HPCI – linac**: S-band Photoinjector + X-band TW structures [5]
  - **CTF3 drive-beam linac**: S-band Thermoionic gun + S-band TW structures [6]

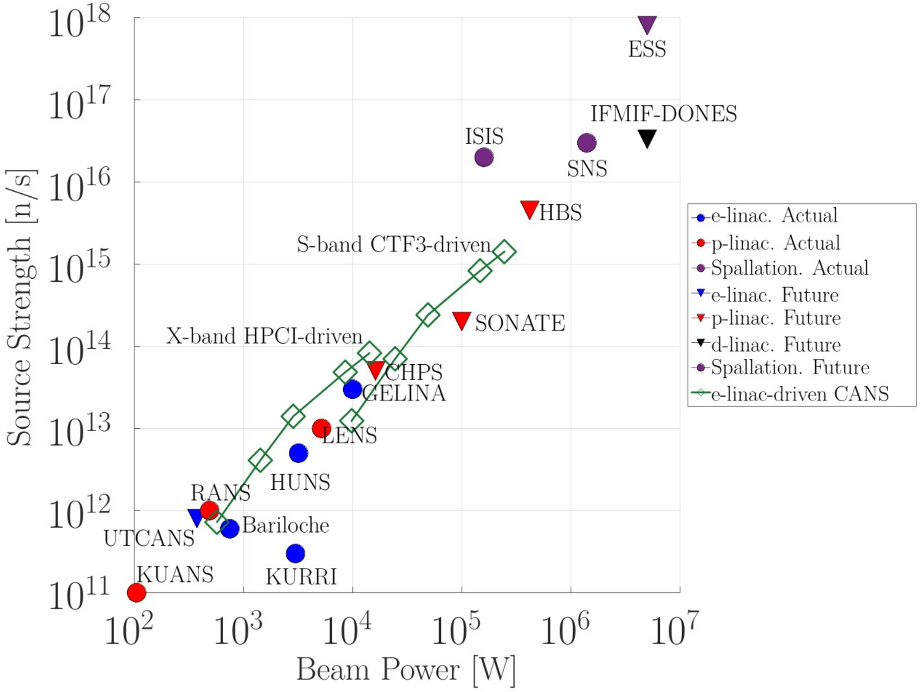
Magnitude	Units	HPCI-linac	CTF3 drive beam linac
f	GHz	12.00	3.00
Q_{bunch}	nC	0.285	2.33
N_{bunches}		1000	2100
$f_{\text{RF-cycle}}$	Hz	100	100
$I_{e,\text{av}}$	μA	28.50	489.3

High-intensity compact linac specifications [5, 6]

IV. State-of-the-art comparison

[7]





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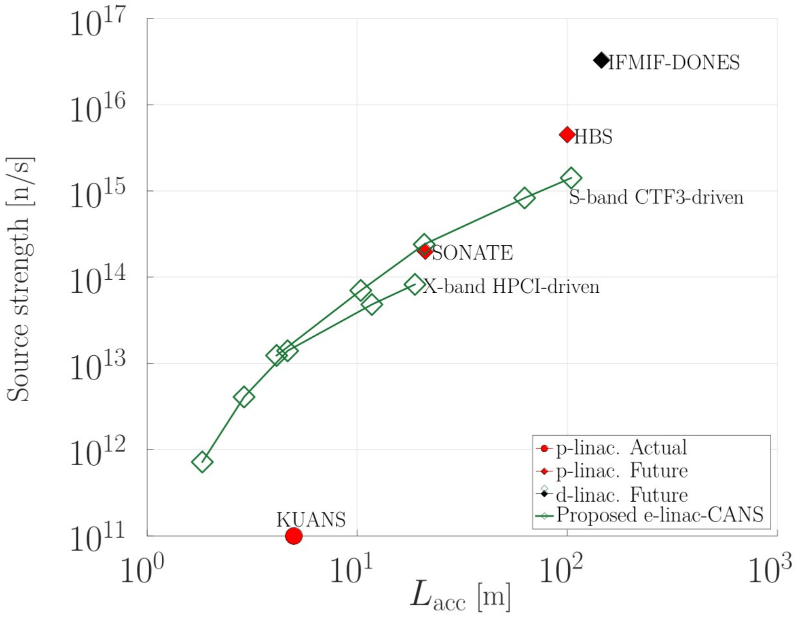
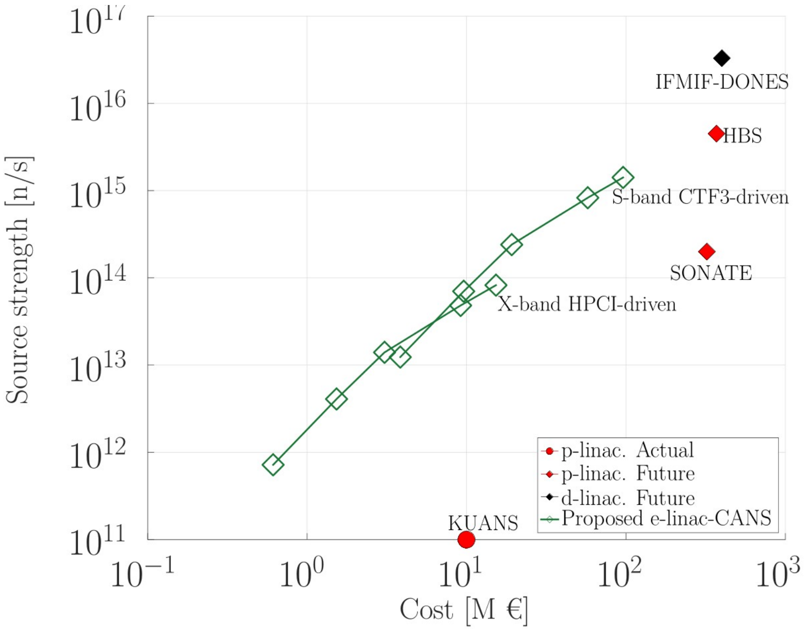
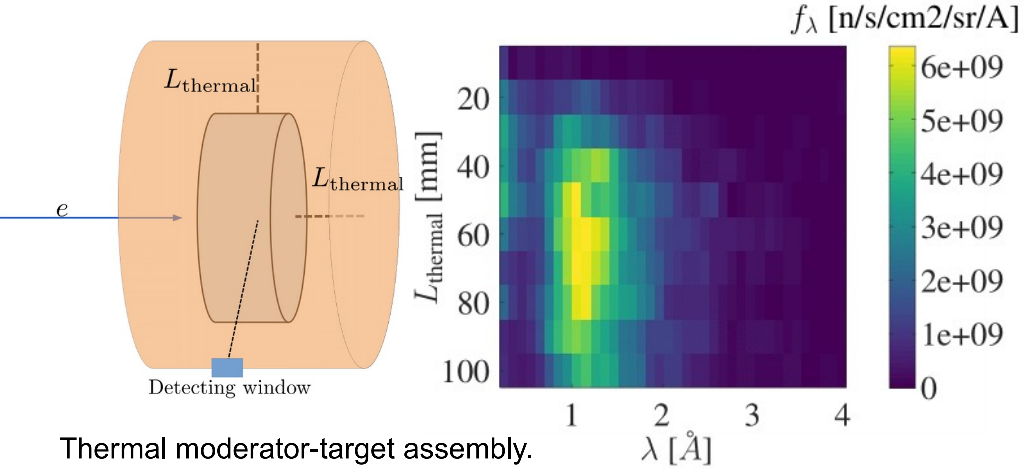




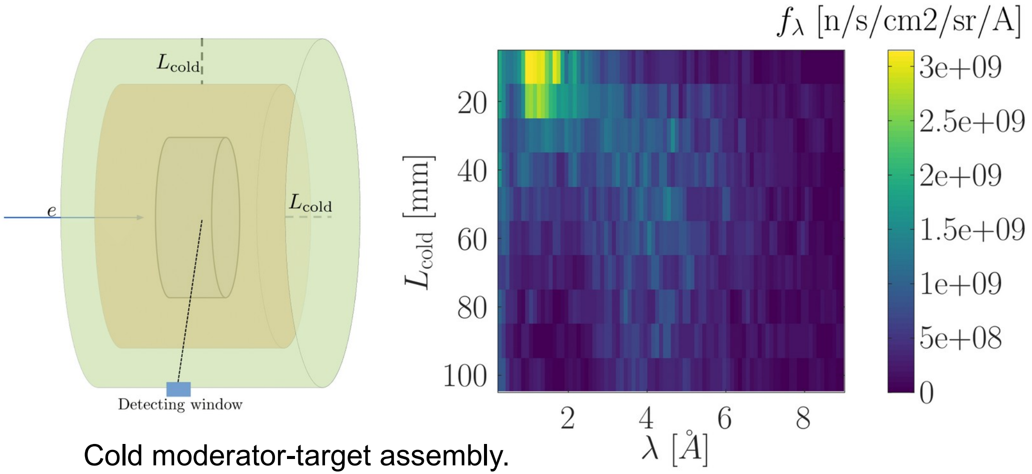
V. Thermal and cold neutron moderation

- Material science: **Diffractrometry** and **imaging** experiments
  - Require moderated neutrons – rich **H compounds**
- Targeted figure of merit: **Average brightness**

$$f_\lambda(\theta, \lambda; E_e) \equiv \frac{d^3 I_{n,\ av}}{dS_{emission}\, d\Omega\, d\lambda}$$



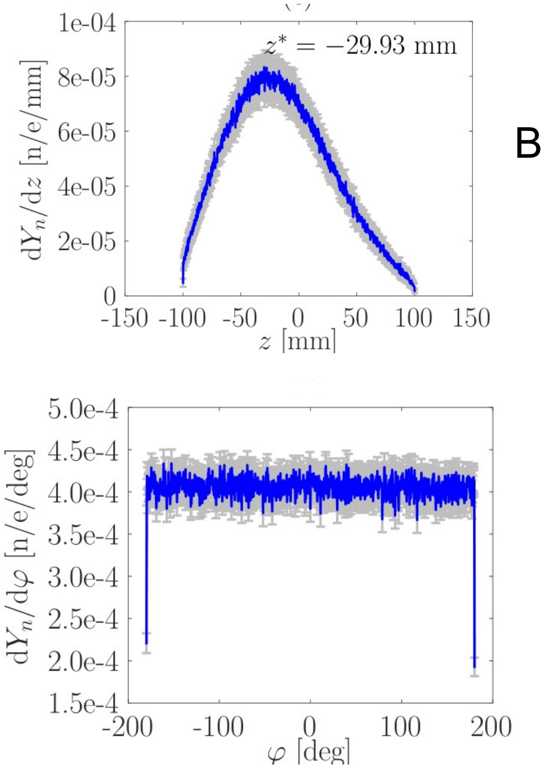
Thermal moderator-target assembly. **CH_4** layer



Cold moderator-target assembly. **Liquid H_2** (20K) layer

- **Optimal dimensions:** $L_{thermal}$ = 60 mm; L_{cold} = 25 mm.

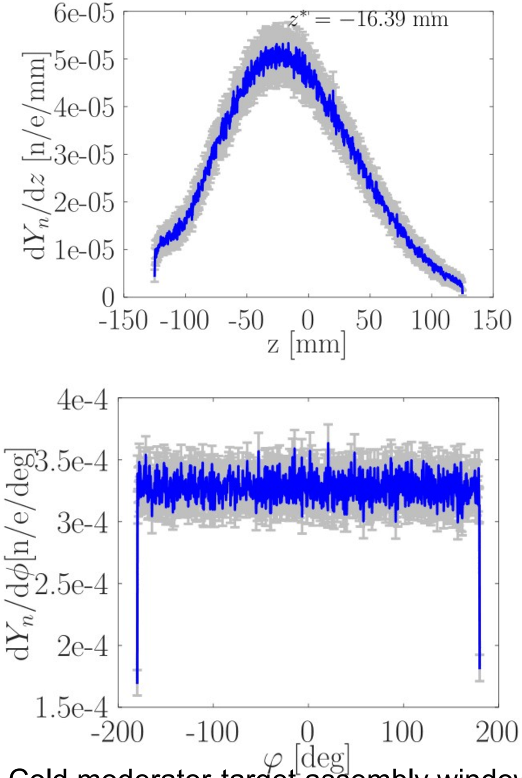
V. Thermal and cold neutron detection



Thermal moderator-target assembly window location (up)
and azimutal dependency of the yield (down)

Backward/Lateral maximum emission

Azimutal isotropy

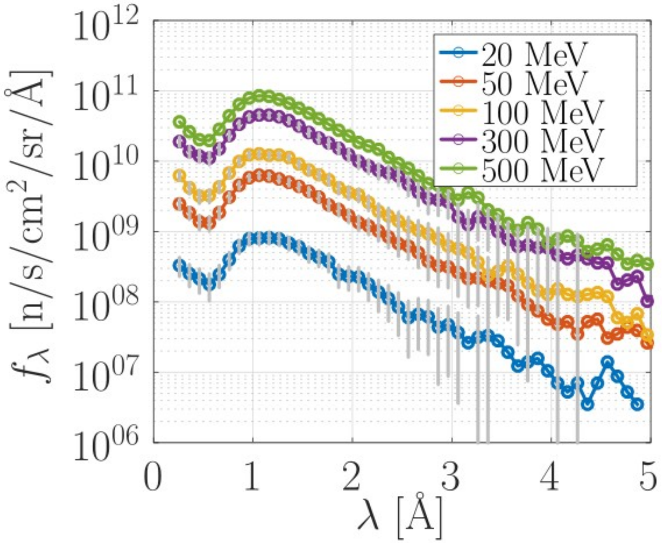


Cold moderator-target assembly window location (up)
and azimutal dependency of the yield (down)

V. Average Brightness

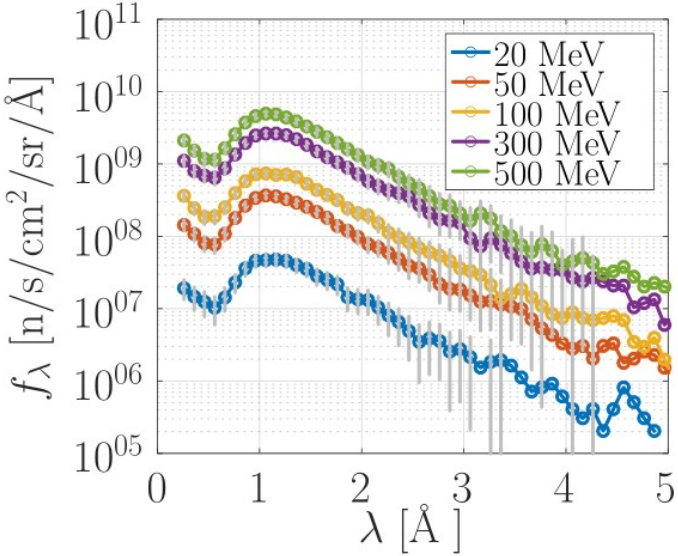
- Proportional to electron intensity (CTF3 > HPCI)

CTF3 d.b - thermal



Thermal moderator-target average brightness for different electron energies for CTF3 drive beam linac.

HPCI - thermal

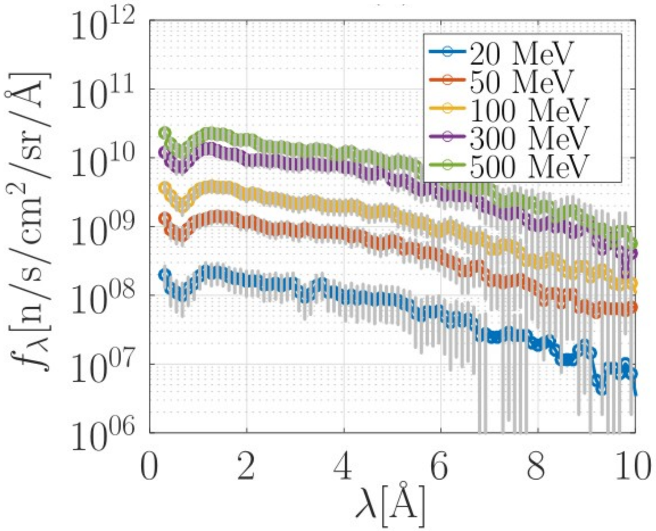


Thermal moderator-target average brightness for different electron energies for HPCI linac.

V. Average Brightness

- Proportional to electron intensity (CTF3 > HPCI)

CTF3 d.b - Cold



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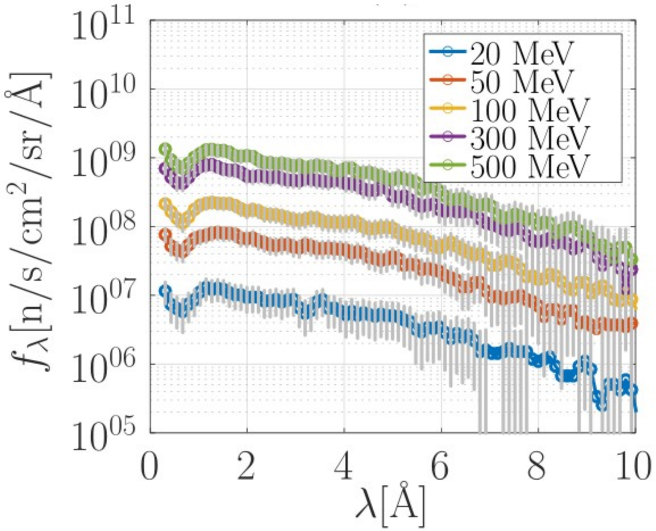


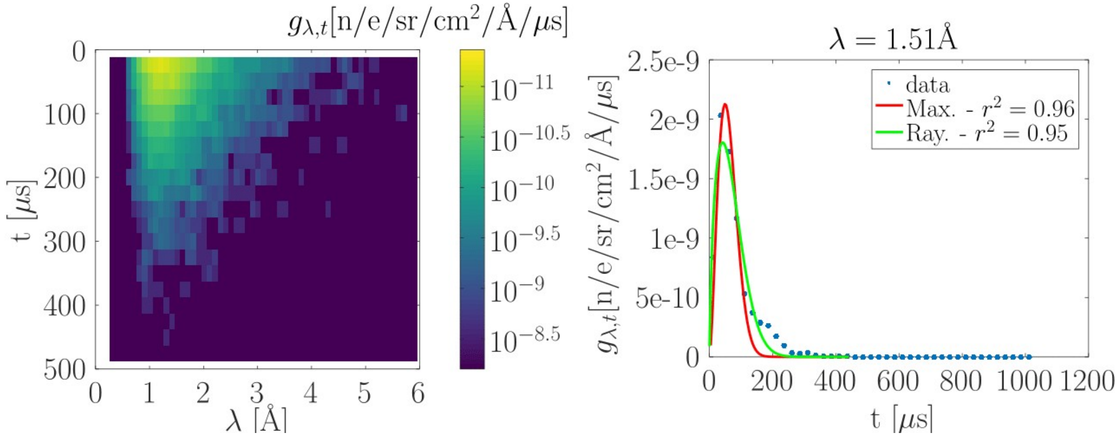
Cold moderator-target average brightness for different electron energies for HPCI linac.

V. Peak brightness

- Time-resolution of the brightness spectrum
  - Convolves electron pulse with neutron response

$$f_{\lambda,\ \mathrm{peak}} \equiv \max_{t>0}\left(\frac{\mathrm{d}q_e}{\mathrm{d}t} \otimes g_{\lambda,t}\right) \qquad g_{\lambda,t} \equiv \frac{{}^4Y_n}{\mathrm{d}S_{\mathrm{emission}}\mathrm{d}\Omega\mathrm{d}\lambda\mathrm{d}t}$$

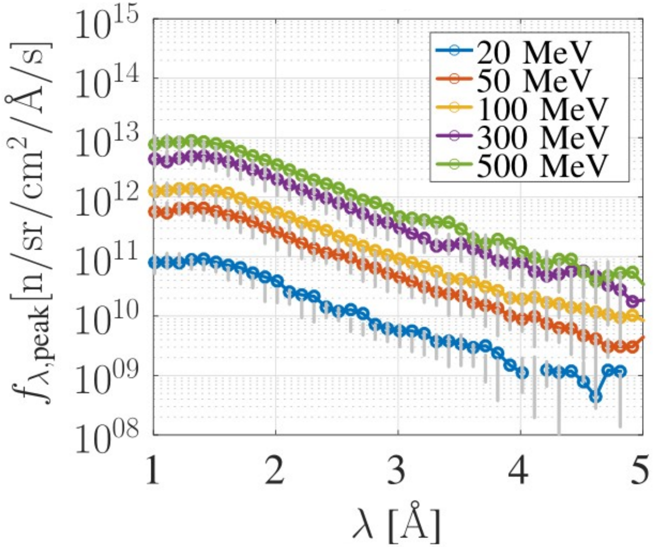
- Cold and thermal **neutron** responses extend **several μs.** GHz **electron** pulses extend **few ns**



V. Peak brightness

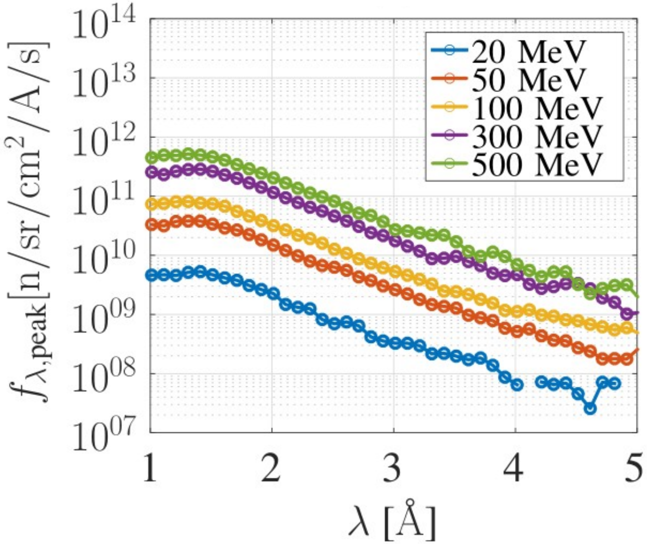
- For the case of electron trains (few ns), the peak brightness is just the normalization of g_λ to the total train charge.

CTF3 d.b - thermal



Thermal moderator-target peak brightness for different electron energies for CTF3 drive beam linac.

HPCI - thermal



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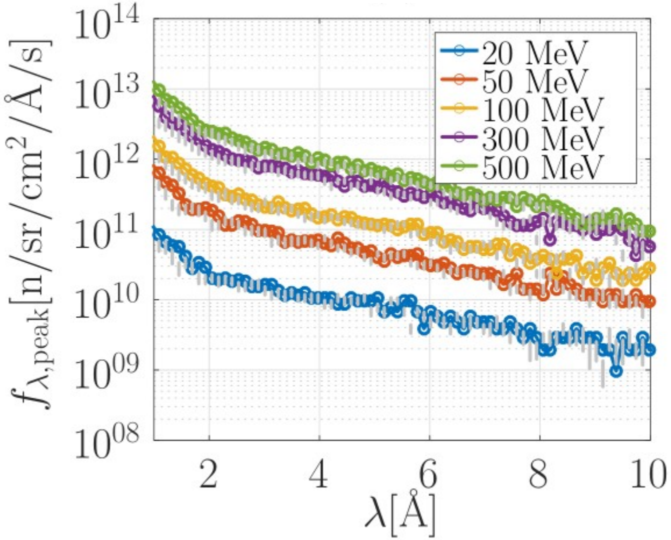
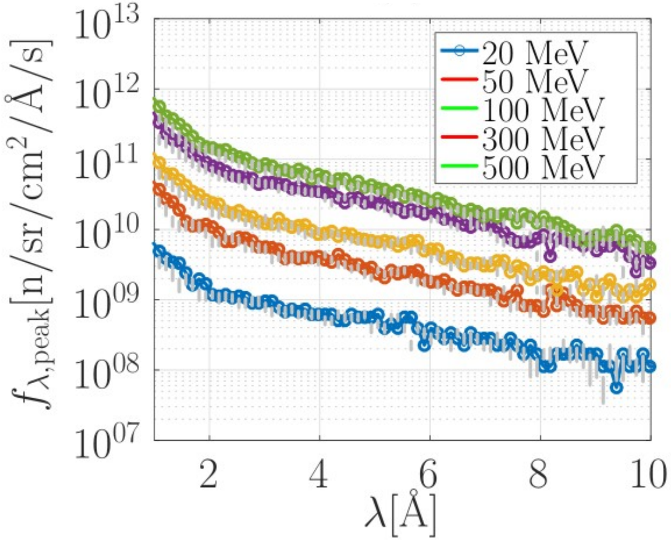


Cold moderator-target peak brightness for different electron energies for CTF3 drive beam linac.

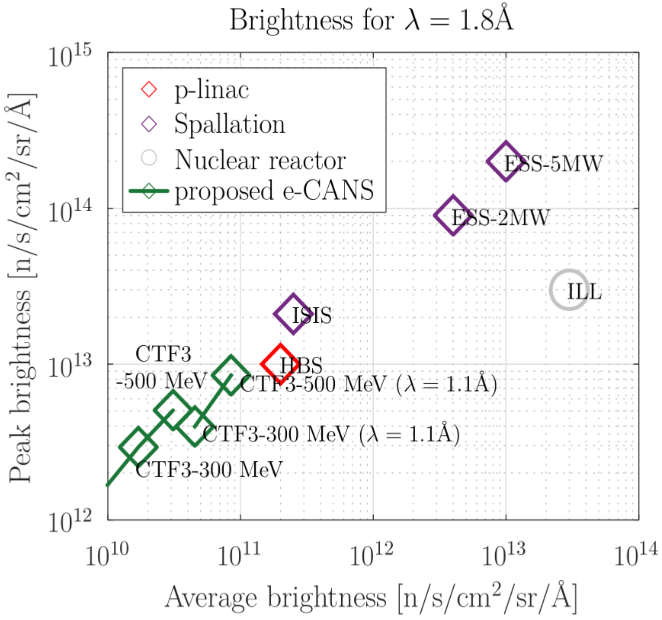
HPCI - Cold



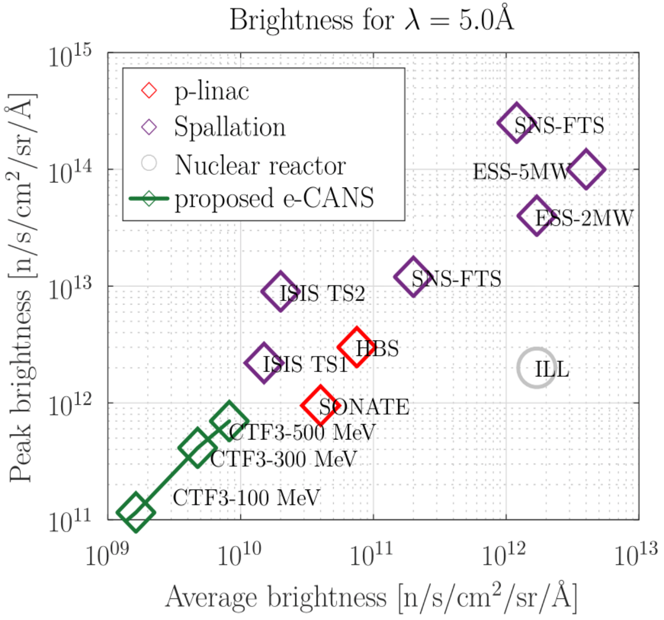
Cold moderator-target peak brightness for different electron energies for HPCI linac.

V. Brightness State-of-the-art comparison

- [7] [8] [9]



Thermal neutron brightness state-of-the-art.



Cold neutron brightness state-of-the-art.

VI. VULCAN

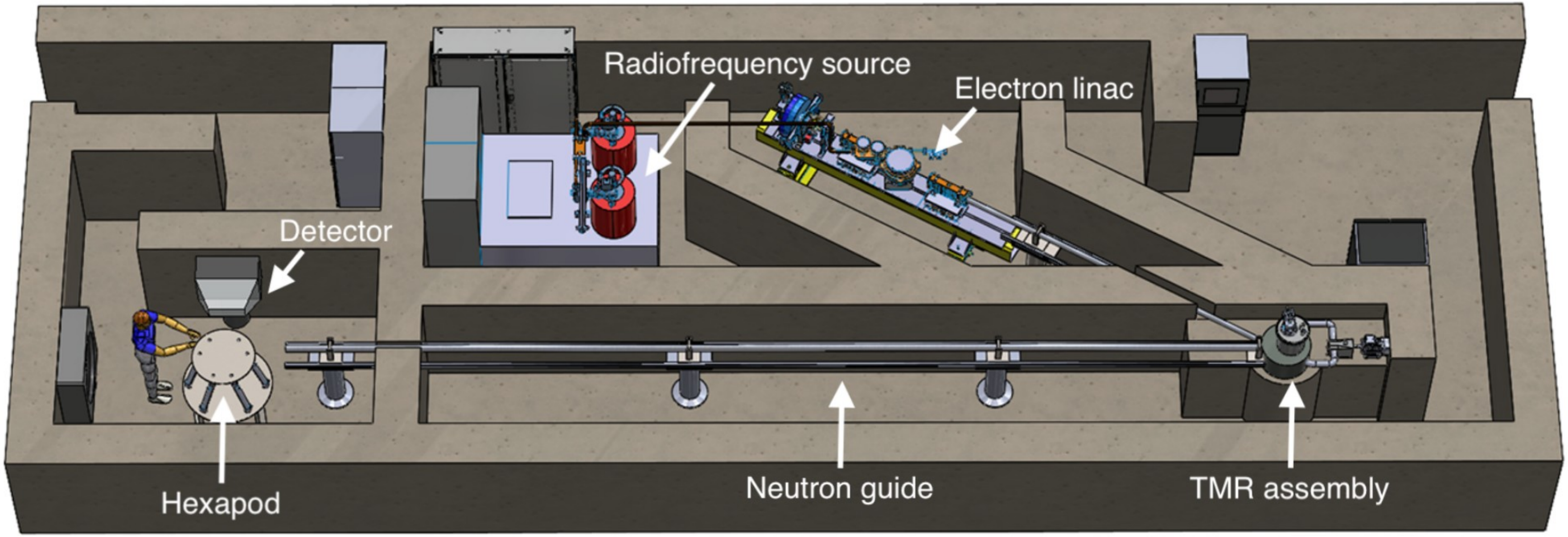
- **Commercial off-the-shelf** CANS (compact accelerator-based neutron source) **[10]**
- **VULCAN** = **V**ersatile **UL**tra **C**ompact **A**ccelerator-based **N**eutron source
- Collaboration between DAES SA and CERN → Industrial implementation

- Targeted applications:
  - In-situ **analysis** of **battery** and fuel cell **electrodes**
  - **Measurements** of internal **stresses** of **metallic** and **ceramic** components

VI. VULCAN

Parameter	Unit	Value
Energy	MeV	35
Energy spread	MeV	<5
Transverse size	mm	< 5
Transverse Jitter	mm	< 2
Train length	μs	<1
Train frequency	Hz	100-200

Electron beam requirements.



VI. VULCAN

REQUIREMENTS

- Beam power: > 1 kW
  - Average beam current > 29 μA
- Peak beam Current > 290 mA
- Length: < 10 m
- Cost: < 5 M€

ACCELERATOR DESIGN CHOICES

- **Thermoionic** gun
  - High average intensities
- High gradient RF cavities **(3-12 GHz**)
  - TW: Compatible with pulse compressor
- RF power source: **klystron**
  - Peak power in 5-50 MW

Conclusions

- Neutrons are produced from electron beams by **Bremsstrahlung** + **Photonuclear excitation**
- Neutron production is a trade off between beam power, cost and length. Electron-linac-based neutron sources serve as **affordable** and middle-flux options
  - Eg: VULCAN – **compact**, suited for **industrial** purposes
- Electron linacs are suitable for **multi-purpose facilities** since the unmoderated energy spectrum does not vary strongly with the initial electron energy
  - Dfferent intensities can be achieved while keeping the same moderating scheme can be adopted for different values of ⟨Ee⟩.
- High-energy and high-intensity electron linacs (like CTF3 drive beam linac at 300, 500 MeV) can provide **bright neutron beams comparable** to proton-linac-based and spallation sources.

Further work

- Experimental verification of simulations- that is currently in progress at CLEAR.
- Specific target-moderator design to meet the requirements of a particular application
  - Further engineering aspects to be considered
- VULCAN: Beam dynamics and EM simulations ongoing
  - CDR in writing phase.

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Thanks for your attention

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