ID: 1097

# Effect of partially ionized high-Z atoms on fast dynamics electron tokamak plasmas

Y. Peysson[1]*, D.Mazon[1], A. Jardin[2], K. Kroll[2], J. Bielecki[2], D.Dworak[2], M. Scholz[2], O. Embreus[3], L. Hesslow[3], T. Fülop[3], M. Hoppe[3], J. Decker[4] and WEST TEAM
[1]CEA/IRFM, F-13108, Saint-Paul-lez-Durance, France
[2]Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland
[3]Chalmers University, Göteborg, Sweden
[4]EPFL, Swiss Plasma Center, CH-1015 Lausanne, Switzerland
yves.peysson@cea.fr

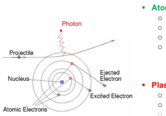
## Context

Growing interest for studying the impact of partially ionized high-Z atoms on fast electron dynamics in magnetized plasmas

- ***Passive source*** *: plasma-wall interaction*
  - Tungsten-based plasma-facing components to reduce tritium retention
  - Metallic objects like rf antennas in contact with the scrape-off layer (Copper, Iron,…)
- ***Active source*** *: massive gas injection* of Argon or Neon to mitigate the formation of a runaway electron beam after a major disruption.



## Impact of partially ionized atoms on fast electron dynamics and bremsstrahlung




Consistent description of screening effects for electron-ion scattering and bremsstrahlung in the Born approximation

- **Atomic physics** : screening effect → F(**q**)
  - Distribution of ionization states (Open-ADAS)
  - Simple models (Thomas-Fermi, Yukawa)
  - Exact models (DFT calculations)
  - Form factor F(**q**) for any ionized state of any relevant high-Z atom in plasma physic (Ar, Ne, Cu, Fe, W,…) in the Born approximation.
- **Plasma physics** : elastic scattering
  - Z → Z – F(**q**) (atomic physic: *form factor* F)
  - Coulomb logarithm lnΛ(p,ψ)
  - Validity of Fokker-Planck approximation
  - Cut-off approximation in collision integrals
- **Plasma physics** : Inelastic scattering
  - e-i bremsstrahlung: Z → Z – F(**q**)
  - e-e bremsstrahlung: $n_e \rightarrow n_e + \Sigma_s n_s N_s$
  - Ion excitation: $\hbar<\omega_s>/E_c$
  - Enhanced ionisation by fast electrons



## Extended work of atomic physics in hot plasmas

- Generalize screening effects to partially ionized high-Z atoms in hot plasmas (*Copper, Iron, Tungsten,…*)
- Calculate a Fokker-Planck collision operator (elastic + inelastic terms) in presence of partially ionized high-Z atoms with screening effects for **LUKE code**.
- Consider screening effects for the quantum relativistic bremsstrahlung cross-section *differential in photon energy and angle* in **R5-X2 code**.



## Elastic scattering by partially ionized atoms

- Weak perturbation theory (Fermi's Golden rules) for the transition probability

$$W=\frac{2\pi}{\hbar}\left|\left\langle f\mid\tilde{H}\mid i\right\rangle\right|^2\rho_f \quad \Rightarrow \quad \frac{d\sigma}{d\Omega}=\left|\left\langle f\mid\tilde{H}\mid i\right\rangle\right|^2\frac{V^2m_e^2}{(2\pi)^2\hbar^4}$$

- 1st Born approximation (plane wave functions for the scattered free electron)

$$|i\rangle=\frac{1}{\sqrt{V}}\exp(i\mathbf{k}_i\cdot\mathbf{r}) \qquad |f\rangle=\frac{1}{\sqrt{V}}\exp(f\mathbf{k}_i\cdot\mathbf{r})$$

$$\left\langle f\mid\tilde{H}\mid i\right\rangle=\frac{1}{V}\int_V\exp(-i\mathbf{q}\cdot\mathbf{r}/\hbar)\,\tilde{H}d\mathbf{r}$$

$\mathbf{p}_{i[f]}=\hbar\mathbf{k}_{i[f]}$

Transferred momentum : $\mathbf{q}=\mathbf{p}_f-\mathbf{p}_i\simeq 2\mathbf{p}\sin(\theta/2)$



## Elastic scattering by partially ionized atoms

- Perturbed Hamiltonian : $\tilde{H}=eU_{Z_s}+eU_{N_s}$
- Bare nucleus potential : $U_{Z_s}=-\frac{Z_se}{4\pi\epsilon_0|\mathbf{r}|}$
- Bound electrons potential : $\nabla^2U_{N_s}=-\rho_{Z_{0,s}}e/\epsilon_0$ $\qquad \int_V\rho_{Z_{0,s}}d\mathbf{r}=N_s=Z_s-Z_{0,s}$

$$\langle f\mid U\mid i\rangle=-\frac{\hbar^2e^2}{\epsilon_0|\mathbf{q}|^2}\frac{1}{V}\left(Z_s-F_{Z_{0,s}}(\mathbf{q})\right)$$

**Atomic form factor** : $F_{Z_{0,s}}(\mathbf{q})\equiv\int_V\exp(-i\mathbf{q}\cdot\mathbf{r}/\hbar)\,\rho_{Z_{0,s}}d\mathbf{r}$ — Fourier transform of the *bound electron density*

Rutherford scattering cross-section : *(spinless electron)* $\frac{d\sigma}{d\Omega}=\frac{r_e^2}{4\bar{p}^4\sin^4(\theta/2)}\left(Z_s-F_{Z_{0,s}}(\mathbf{q})\right)^2$ $\qquad \bar{p}=p/(m_ec)$

↳ Pitch-angle scattering in Fokker-Planck collision operator



## Inelastic scattering by partially ionized atoms : e-i bremstrahlung

- e-i bremsstrahlung (classical limit) : $d^2\sigma=d\sigma_{Rutherford}\times dW_k$ — Photon emission probability
- Fully quantum relativistic differential cross-section (Bethe-Heitler, 1st Born approx.) :

$$\frac{d^5\sigma_{Z_{0,s}}}{d\bar{k}d\Omega_kd\Omega_p}=\alpha\left(\frac{r_e}{2\pi}\right)^2\left(Z_s-F_{Z_{0,s}}(\bar{q})\right)^2\frac{\bar{p}}{\bar{k}\bar{p}_0\bar{q}^4}\sum_{k=1}^{k=4}B_k$$

$$\bar{q}^2=\bar{p}^2+\bar{p}_0^2+\bar{k}^2-2\bar{p}_0\bar{k}\cos\theta_0+2\bar{p}\bar{k}\cos\theta-2\bar{p}\bar{p}_0(\cos\theta\cos\theta_0+\sin\theta\sin\theta_0\cos\phi)$$

$$B_1=\frac{\bar{p}^2\sin^2\theta}{(\bar{E}-\bar{p}\cos\theta)^2}\left(4\bar{E}_0^2-\bar{q}^2\right) \qquad B_3=-\frac{2\bar{p}\bar{p}_0\sin\theta\sin\theta_0\cos\phi}{(\bar{E}-\bar{p}\cos\theta)(\bar{E}_0-\bar{p}_0\cos\theta_0)}\left(4\bar{E}\bar{E}_0-\bar{q}^2\right)$$

$$B_2=\frac{\bar{p}_0^2\sin^2\theta_0}{(\bar{E}_0-\bar{p}_0\cos\theta_0)^2}\left(4\bar{E}^2-\bar{q}^2\right) \qquad B_4=\frac{2\bar{k}^2\left(\bar{p}^2\sin^2\theta+\bar{p}_0^2\sin^2\theta_0-2\bar{p}\bar{p}_0\sin\theta\sin\theta_0\cos\phi\right)}{(\bar{E}-\bar{p}\cos\theta)(\bar{E}_0-\bar{p}_0\cos\theta_0)}$$

$$\Rightarrow \frac{d^3\sigma_{Z_{0,s}}}{d\bar{k}d\Omega_k}=\int_0^\pi\sin\theta d\theta\int_0^{2\pi}d\phi\frac{d^5\sigma_{Z_{0,s}}}{d\bar{k}d\Omega_kd\Omega_p}$$

Radiation intensity is large but Abraham-Lorentz-Dirac reaction force is small



## Atomic physics

Calculation of the bound electron density averaged over solid angle (*form factor*).

- Approximate models : Thomas-Fermi or Yukawa simplified atomic models.
- Exact models : numerical quantum calculations based on Density Functional Theory (DFT). *Relativistic calculations must be carried out for high-Z elements using the Douglas-Kroll-Hess second order scalar relativistic Hamiltonian and the natural orbital-relativistic correlation basic set.*
  - Virial theorem : $\frac{mv^2}{2}=\frac{Z_se^2}{4\pi\epsilon_0r}$ → $\frac{v}{c}=\alpha Z_s\ll 1$
  - Quantum uncertainty principle : $mv=\hbar/r$
  - Ne (10) : 0.07, Ar (18) : 0.131, Cu (29) : 0.212, W (74) : 0.54



## Atomic physics: Thomas-Fermi model

- Poisson's equation : $\nabla^2\left(\mu_{Z_{0,s}}-V_{Z_{0,s}}(r)\right)=4\pi e^2\rho_{Z_{0,s}}(r)$
- Energy variational principle : $\rho_{Z_{0,s}}(r)=\left(\frac{5}{3}C_{kin}\right)^{-3/2}\left(\mu_{Z_{0,s}}-V_{Z_{0,s}}(r)\right)^{3/2}$ $\qquad C_{kin}=\frac{3^{5/3}e^2\pi^{1/3}}{10}a_0$
- **Thomas-Fermi equation** : $\frac{d^2\phi}{d\chi_s^2}=\frac{\phi^{3/2}}{\sqrt{\chi_s}}$ $\qquad \mu_{Z_{0,s}}-V_{Z_{0,s}}(r)=\frac{Z_se^2}{r}\phi(\chi_s)$ $\qquad \chi_s=r/b_s$, $b_s=\bar{b}_sa_0$
- Normalized Thomas-Fermi neutral atom radius [$a_0$] : $\bar{b}_s=\frac{1}{4}\left[\frac{9\pi^2}{2Z_s}\right]^{1/3}$
- Ion ($N_s<Z_s$) : $\phi(\chi_{0,s})=0$ $\qquad -\chi_{0,s}\phi'(\chi_{0,s})=1-N_s/Z_s$ $\qquad \chi_{0,s}=r_{0,s}/\left(\bar{b}_sa_0\right)$
- Form factor (*numerical integration*) : $F_{Z_{0,s}}(\bar{q})=4\pi\int_0^\infty\rho_{Z_{0,s}}(r)\frac{a_0r}{\hat{q}}\sin\left(\frac{\hat{q}r}{a_0}\right)dr$

$$\hat{q}=2\bar{p}\sin(\theta/2)/\alpha=\bar{q}/\alpha$$



## Atomic physics: Thomas-Fermi-Kirillov model

- Approximate formulation of the form factor (Kirillov, Trubnikov et al, 1975)

$$F_{Z_{0,s}}^{TFK}(\xi_s)=Z_s\int_0^{\chi_{0,s}}\phi(\chi)^{3/2}\chi^{1/2}\frac{\sin(\xi_s\chi)}{\xi_s\chi}d\chi \qquad \xi_s=\hat{q}\bar{b}_s$$

Used for runaway electron physics

- Two limits : $\xi_s\chi_{0,s}\ll 1 \rightarrow F_{Z_{0,s}}^{TFK}(\xi_s)=N_s$; $\quad \xi_s\chi_{0,s}\gg 1 \rightarrow F_{Z_{0,s}}^{TFK}(\xi_s)\simeq Z_s\sqrt{\frac{\pi}{2\xi_s^3}}$

$$F_{Z_{0,s}}^{TFK}(\bar{q})\simeq\frac{N_s}{1+\left(\bar{q}\bar{a}_{Z_{0,s}}^{TFK}/2\right)^{3/2}} \qquad \bar{a}_{Z_{0,s}}^{TFK}\equiv 2a_{Z_{0,s}}^{TFK}/\alpha$$

- Approximate neutral atom radius : $N_s=Z_s$

$$a_{Z_{0,s}=0}^{TFK}\simeq\frac{3}{4}Z_s^{-1/3} \qquad a_{Z_{0,s}=0}^{TF}=\frac{1}{4}\left[\frac{9\pi^2}{2}\right]^{1/3}Z_s^{-1/3}$$

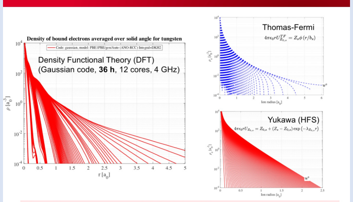


## Atomic physics: Yukawa (Tseng-Pratt) model

- Yukawa type model : $4\pi\epsilon_0rU_{Z_{0,s}}=Z_{0,s}+(Z_s-Z_{0,s})\exp\left(-\lambda_{Z_{0,s}}r\right)+\dots$
- By definition, $\lambda_{0,s}^{-1}$ is considered as the neutral atom radius :
  - *Thomas-Fermi* : $\lambda_{0,s}^{TF}=Z_s^{1/3}a_0^{-1}/\alpha^{TF}=1.13Z_s^{1/3}a_0^{-1}$
  - **Botto** *(fit of Hartree-Fock-Slater (HFS) potentials)* : $\lambda_{0,s}^{B}\simeq 0.9Z_s^{0.42}a_0^{-1}$
- Partially ionized atoms :
  - $\lambda_{Z_{0,s}}^2/\lambda_{0,s}^2=f_s\left(Z_{0,s}/Z_s\right)$ with $f_s(x)=\frac{1-x^{n_s+1}}{(1-x)^2}$ — Best $Z_{0,s}$ dependence as compared to DFT
  - $n_s=Z_s(1/3-0.0020\times Z_s)$
- Bound electron density : $\rho_{Z_{0,s}}=\frac{\lambda_{Z_{0,s}}^2}{4\pi r}(Z_s-Z_{0,s})\exp\left(-\lambda_{Z_{0,s}}r\right)$
- Form factor : $F_{Z_{0,s}}^{TP}(\bar{q})=\frac{N_s}{1+\left(\bar{q}\bar{a}_{Z_{0,s}}^{TP}/2\right)^2}$ $\qquad \bar{a}_{Z_{0,s}}^{TP}\equiv 2a_{Z_{0,s}}^{TP}/\alpha$ $\qquad a_{Z_{0,s}}^{TP}=\left(\lambda_{Z_{0,s}}a_0\right)^{-1}$



## Atomic physics : bound electrons density






## Atomic physics : the form factor F(q)

$$F_{Z_{0,s}}(\mathbf{q})\equiv\int_V\exp(-i\mathbf{q}\cdot\mathbf{r}/\hbar)\,\rho_{Z_{0,s}}d\mathbf{r}$$

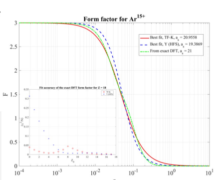
$$F_{Z_{0,s}}(\bar{q})=\frac{N_s}{1+\left(\bar{q}\bar{a}_{Z_{0,s}}/2\right)^m}$$

$m=(3/2,\ 2)$

$N_s=Z_s-Z_{0,s}$

$\bar{a}_{Z_{0,s}}\equiv 2a_{Z_{0,s}}/\alpha$

- **Thomas-Fermi model** → *cold plasma, ~10 eV (post-disruptive runaway electrons)*
- **Yukawa-type model** → *hot plasma, > 100 eV (RF current drive)*






## Plasma physics : elastic scattering

- Modified Rosenbluth potentials by screening effect

$$\mathbf{A}_s=\int d^3\mathbf{p}_sf_s(t,\mathbf{x},\mathbf{p}_s)\int d\Omega\frac{d\sigma_{es}}{d\Omega}u_s\Delta\mathbf{p}\equiv\{\Delta\mathbf{p}\}_s$$

$$\mathbb{D}_s=\frac{1}{2}\int d^3\mathbf{p}_sf_s(t,\mathbf{x},\mathbf{p}_s)\int d\Omega\frac{d\sigma_{es}}{d\Omega}u_s\Delta\mathbf{p}\Delta\mathbf{p}\equiv\frac{1}{2}\{\Delta\mathbf{p}\Delta\mathbf{p}^T\}_s$$

- Rutherford scattering cross-section: $\frac{d\sigma}{d\Omega}=\frac{r_e^2}{4\bar{p}^4\sin^4(\theta/2)}\left(Z_s-F_{Z_{0,s}}(\mathbf{q})\right)^2$

$$\int_{1/\Lambda_s}^1\frac{dx}{x}Z_s^2\rightarrow\int_{1/\Lambda_s}^1\left|Z_s-F_{Z_{0,s}}(q)\right|^2\frac{dx}{x}=Z_{0,s}^2\ln\Lambda_s+g_{Z_{0,s}}(p)$$

Screening effect

Fully screening ion ~ $F_{Z0,s}(q)=N_s$



## Fokker-Planck collision operator with partially ionized atoms

Fokker-Planck screening function → $\int_{1/\Lambda}^1\left|Z_s-F_{Z_{0,s}}(\bar{q})\right|^2\frac{dx}{x}=Z_{0,s}^2\ln\Lambda_s+g_{Z_{0,s}}(\bar{p})$

$$g_{Z_{0,s}}(\bar{p})=\int_{1/\Lambda}^1\left(\left|Z_s-F_{Z_{0,s}}(\bar{q})\right|^2-Z_{0,s}^2\right)\frac{dx}{x}$$

which reduces to

$$g_{Z_{0,s}}(\bar{p})=\frac{Z_s^2}{n}\left(\ln\left(1+\left(\bar{p}\bar{a}_{Z_{0,s}}\right)^n\right)-\frac{\left(\bar{p}\bar{a}_{Z_{0,s}}\right)^n}{1+\left(\bar{p}\bar{a}_{Z_{0,s}}\right)^n}\right)$$

for simplified atomic models with n = 3/2 for Thomas-Fermi-Kirillov model or n = 2 for Yukawa (Tseng-Pratt) model. *Condition of validity always fullfiled:*

$$\bar{p}\ll\Lambda_s/\bar{a}_{Z_{0,s}}$$



## Fokker-Planck collision operator with partially ionized atoms

Exact DFT calculations with $N_s=Z_s-Z_{0,s}$

$$g_{Z_{0,s}}(\bar{p})=\left(Z_s^2-Z_{0,s}^2\right)\left(\ln(2\bar{p}/\alpha)+\gamma_{EM}-1\right)+2Z_sN_s\hat{I}_{1,Z_{0,s}}+N_s^2\left(\frac{1}{2}-\hat{I}_{2,Z_{0,s}}\right)$$

$$\hat{I}_{1,Z_{0,s}}\equiv\frac{4\pi}{N_s}\int_0^\infty\bar{\rho}_{Z_{0,s}}(\bar{r}_1)\bar{r}_1^2\ln\bar{r}_1d\bar{r}_1$$

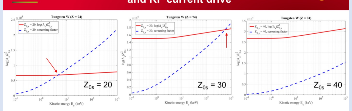
$$\hat{I}_{2,Z_{0,s}}=\frac{4\pi^2}{N_s^2}\int_0^\infty\bar{\rho}_{Z_{0,s}}(\bar{r}_1)\bar{r}_1d\bar{r}_1\int_0^\infty\bar{\rho}_{Z_{0,s}}(\bar{r}_2)\bar{r}_2d\bar{r}_2\left((\bar{r}_1+\bar{r}_2)^2\ln(\bar{r}_1+\bar{r}_2)-(\bar{r}_1-\bar{r}_2)^2\ln|\bar{r}_1-\bar{r}_2|\right)$$

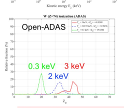
In the high velocity limit : $\bar{a}_{Z_{0,s}}=\frac{2}{\alpha}\exp\left[\gamma_{EM}-1+\frac{2Z_s\hat{I}_{1,Z_{0,s}}+N_s\left(m-\hat{I}_{2,Z_{0,s}}\right)}{Z_s+Z_{0,s}}\right]$

may be obtained from DFT for simplified atomic models with m = 7/6 for Thomas-Fermi-Kirillov model or m = 1 for Yukawa (Tseng-Pratt) model. (Consistent with direct fit of the form factor).



## Partial screening of high-Z elements and RF current drive




- The Coulomb logarithm term predominates over the screening term except for weakly ionized Tungsten ($Z_{0,s}$ < 20, $T_e$ < 0.3 keV, electrons lower than 50 keV)
- Partially ionized high-Z impurities may be considered as almost fully screened for RF current drive calculations → standard Fokker-Planck calculations holds for RF-driven discharge (50-500 keV, $T_e$ > 1.0 keV)



## Inelastic scattering by partially ionized atoms : ion excitation

The energy loss by excitation of ions over a distance Δx is equivalent of the work of an effective force $F^{ei}$ over that distance

$$\int_{\Delta x}\left.\frac{dE}{dx}\right|_{Z_{0,s}}dx=\int_{\Delta x}F^{ei}dx=\int_{\Delta x}\frac{p}{2}\nu_{sd}^{e-i}$$

Modified Fokker-Planck term : $\bar{F}_p^{ee}\rightarrow\bar{F}_p^{ee}+\bar{F}_p^{ei}=\frac{\bar{p}}{2}\left(\bar{\nu}_{sd}^{e-e}+\bar{\nu}_{sd}^{e-i}\right)$

$$\bar{F}_p^{ei}=\frac{\bar{n}_sN_s}{\ln\Lambda_{ee}^\dagger}\frac{\gamma^2}{\bar{p}^2}\left[\ln I_{Z_{0,s}}-\bar{\beta}^2\beta_{th}^{\dagger 2}\right]$$

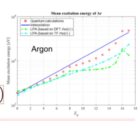
$$I_{Z_{0,s}}=\frac{\sqrt{2}\gamma\beta\sqrt{\gamma-1}}{\hbar\left\langle\omega_{Z_{0,s}}\right\rangle/m_ec^2}$$

Neutral atoms : $\hbar\left\langle\omega_{Z_{0,s}}\right\rangle\simeq 10Z_s\,eV$

Hydrogenoid ion : $\hbar\left\langle\omega_{Z_{0,s}}\right\rangle\simeq 13.6Z_s^2\,eV$

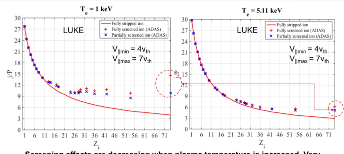
All ionization states : $\hbar\left\langle\omega_{Z_{0,s}}\right\rangle\simeq\exp\left(a\frac{Z_{0,s}}{Z_s-1}+b\right)$

*Local Plasma Approximation (DFT or TF)* → $I_{Z_{0,s}}$






## LH current drive efficiency

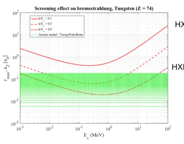



**Screening effects are decreasing when plasma temperature is increased. Very small impact of screening effects for partially ionized high-Z impurities for LH current drive, confirmed by simulation of WEST LH discharges. Fully screened ions (Open-ADAS) can be used for RF calculations.**



## Partial screening for e-i bremstrahlung

- Screening effects significant when $r_{max}/a_{Z_{0,s}}\gg 1$ where $r_{max}=\frac{\alpha a_0}{\bar{q}_{min}}$ (max. impact parameter)
- Equivalent to Bethe estimate (using Thomas-Fermi model) : $\frac{E_0\bar{E}}{\bar{k}}=\frac{1}{2}\frac{0.885}{\alpha}Z_s^{-1/3}$






## Partial screening for e-i bremstrahlung

Three methods (matlab script for R5-X2 code) for integrating the five differential bremsstrahlung cross-section (1BS Koch& Motz formula) on the scattered electron emission angles to obtain 2BN formula with screening effects

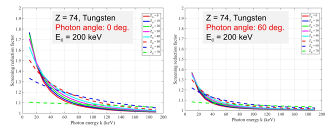
$$\frac{d^5\sigma_{Z_{0,s}}}{d\bar{k}d\Omega_kd\Omega_p}=\alpha\left(\frac{r_e}{2\pi}\right)^2\left(Z_s-F_{Z_{0,s}}(\bar{q})\right)^2\frac{\bar{p}}{\bar{k}\bar{p}_0\bar{q}^4}\sum_{k=1}^{k=4}B_k$$

$$\bar{q}^2=\bar{p}^2+\bar{p}_0^2+\bar{k}^2-2\bar{p}_0\bar{k}\cos\theta_0+2\bar{p}\bar{k}\cos\theta-2\bar{p}\bar{p}_0(\cos\theta\cos\theta_0+\sin\theta\sin\theta_0\cos\phi)$$

- Integration of full 5-D blocks (k,$\theta_0$,p,θ,φ) → (k,$\theta_0$) : arbitrary form factor, fast but very memory demanding.
- Integration of full 4-D blocks (k,$\theta_0$,p,φ) + loop for θ integration : arbitrary form factor, slow but accurate.
- Integration of full 4-D blocks (k,$\theta_0$,p,θ) : analytical integration in azimuthal angle φ, Tseng-Pratt-Botto form factor only, fast and accurate (*12 complex integrals to evaluate analytically*) → *Table of Legendre polynomials cross-section for each element and ionization state with electron kinetic energy interpolation in R5-X2 code.*



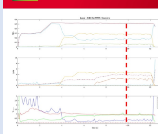
## Partial screening for e-i bremstrahlung




- Screening effect reduces progressively bremsstrahlung as compared to the fully stripped ion ($Z_s\rightarrow Z_{0,s}$).
- Screening decreases with kinetic electron energy.
- Screening are large for forward emission only and at low photo energies



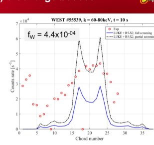
## WEST LH (+ICRH) discharge #55539



$P_{LH}$ = 4.8 MW

$n_{||0}\approx 2$

$J_{||METIS}$(@10s) = 0.45 MA




Large effect of partially ionized tungsten on bremsstrahlung level as compared to the fully screened approximation



## Summary

- Screening effects of partially ionized high-Z impurities are fully implemented in LUKE kinetic solver and the quantum relativistic bremsstrahlung code R5-X2.
- These rules may be used for slide-away (RF-driven) and runaway electrons (disruption) in very cold or hot plasmas.
- Very small impact screening of partially ionized high-Z impurities on LH current drive efficiency confirmed by WEST discharge simulations → *fully screened ion can be considered in RF calculations.*
- Large effect of screening on bremsstrahlung at low photon energies → *decoupling between the current density and bremsstrahlung profiles.*



## References

- L. HESSLOW, et al., Phys. Rev. Letter, 118 (2017) 255001
- Y. PEYSSON and J. DECKER, Fusion Science and Technology, 65 (2014) 22
- Y. PEYSSON and J. DECKER, Phys. Plasmas, 15 (2008) 092509
- R. PRATER, et al., Nucl. Fusion, 48 (2008) 035006
- P. T. BONOLI, et al., Phys. Plasma, 21 (2014) 061508.
- D. VAN HOUTTE et al. Nucl. Fusion, 2004, 44 , 5, pp. L11-L15
- C. BOURDELLE, et al., Nucl. Fusion, 55 (2015) 063017
- P. HOHENBERG and W. KOHN, Phys. Rev. 136, (1964) B864
- M. J. FRISCH, et al., Gaussian 09, Revision E.01, Gaussian, Inc., Wallingford CT, 2016.
- S. LUNDQVIST and N. H. MARCH, in Theory of the Inhomogeneous Electron Gas, Springer Science+Business Media, LLC (1983).
- V. D. KIRILLOV, et al., Fizika Plazmy, 1 (1975) 218-237
- D. J. BOTTO, et al., Phys. Rev. A, 18, 2 (1978) 580
- M. LAMOUREUX and N. AVDONINA, Phys. Rev. E, 55, 1 (1997) 912-926
- L. HESSLOW, et al., J. Plasma Phys., 84, 6 (2018) 905840605
- M. N. ROSENBLUTH, et al., Phys. Rev., 107, 1 (1957) 1-6
- H. P. SUMMERS, the ADAS User Manual, version 2.6 http://www.adas.ac.uk (2004)
- J. D. JACKSON, in Classical Electrodynamics, New York:Wiley (1999)
- S. SAUER, et al., Adv. Quant. Chem., 71 (2015) 29
- X. GARBET, et al., J. of Applied Physics, 61 (1987) 907
- J. LINDHARD and M. SCHARFF, Dan. Mat. Fys. Medd., 27, 15 (1953)
- H. A. BETHE, Proc. Roy. Soc. London, 30, 4 (1934) 524-539
- H. W. KOCH and J. W. MOTZ, Rev. Mod. Phys., , 31, 4 (1959) 920
- G. ELWERT and E. HAUG, Phys. Rev.,183,1 (1969) 90-105
- N. J. FISCH, Rev. Mod. Phys., 59, 1 (1987) 175-234
- J.F. ARTAUD, et al., Nuc. Fusion 58 (2018) 105001