Neutral Beam Injection

Principles: A Physics Overview

Neutral beams in fusion plasmas · Beam–plasma interaction physics
The neutral beam injector · NUBEAM & NuBDeC modeling · Application to CPD

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01

NBI in Fusion Plasmas

What a beam of fast neutrals does inside a tokamak

- Why we need auxiliary heating
- Atomic physics of beam stopping & penetration
- Fast-ion orbits, slowing down, and the critical energy
- Current drive, rotation, fueling — and how fast ions get lost

Ohmic heating alone cannot reach fusion temperatures

- **Ohmic heating density $P = \eta\, j^2$ is built into every tokamaks:**
  - –Spitzer resistivity $\eta \propto Z_{eff} / T_e^{3/2}$ → the hotter the plasma, the weaker the heating
  - –current density j is capped by MHD stability (safety factor $q \gtrsim 2$)
- Result: T_e saturates at ~2–3 keV — far below the 10–20 keV needed for D–T fusion.
- In an ignited reactor ($V \approx 2000\ m^3$, T = 10 keV): ohmic power ≈ 6 MW — negligible.
- Two workhorse solutions: neutral beam injection (this lecture) and RF waves.

Neutral Beam Injection

Fast neutral atoms carry energy across the magnetic field, ionize, and heat the plasma by Coulomb collisions. Also drives current, torque, and fueling.

RF heating (for contrast)

Electromagnetic waves at resonant frequencies (ECH / ICH / LHCD). Complementary physics — covered in a separate lecture.

What NBI provides a tokamak

Heating

Both electrons and ions — the split is set by E_b / E_c (coming up).

Current drive

Tangential injection → circulating fast-ion current (NBCD); enables steady state & profile control.

Torque & rotation

Momentum input drives toroidal rotation → E×B shear, RWM and error-field resilience.

Core fueling

Each captured neutral is also a particle source deep in the core.

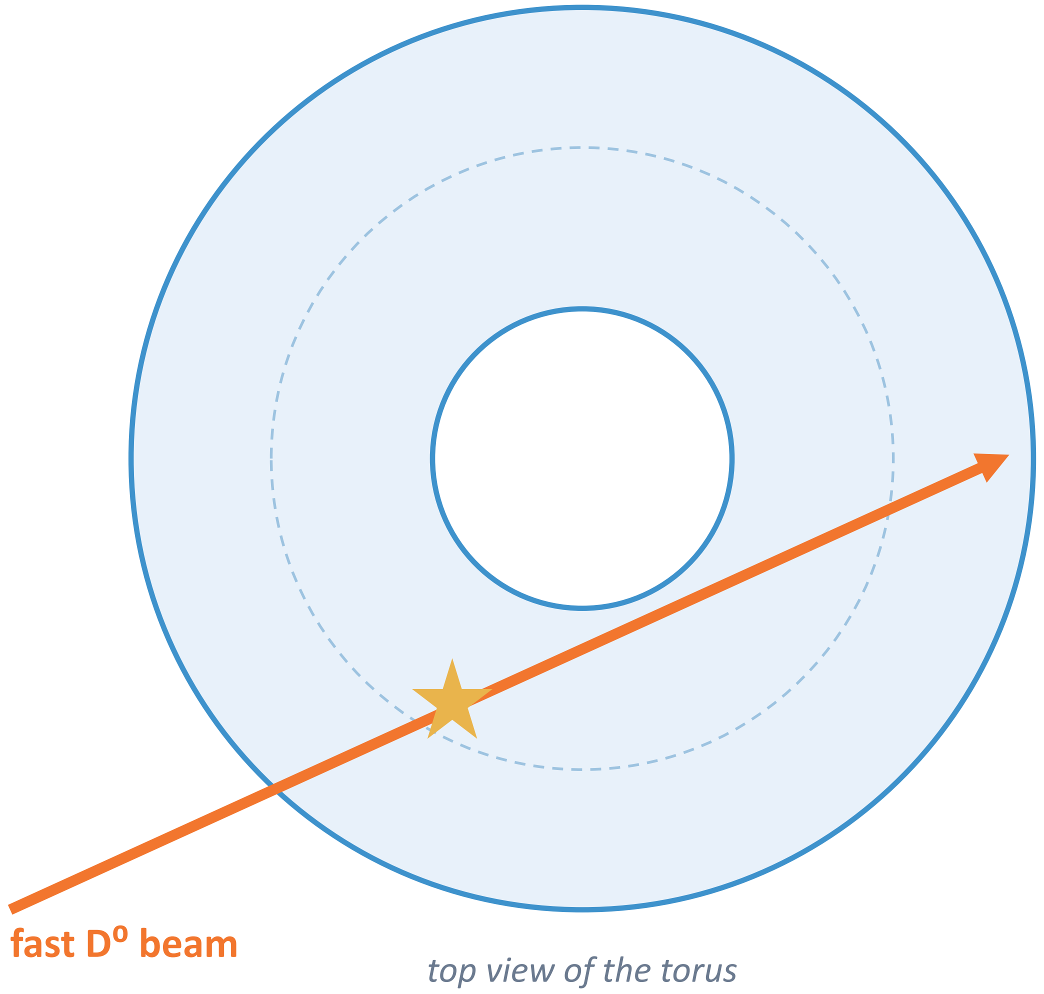
Diagnostics & fast-ion physics

CXRS, MSE, FIDA ride on the beam; beam ions are a test bed for alpha-particle physics.

Design tension

All roles share one set of NBI: beam energy, power, species, and injection geometry. Optimizing one role constrains the others — that is why we model.

NBI in one picture: from neutral atom to plasma heat



1. **Inject fast neutral atoms**

   Unaffected by B — they fly in straight lines across the confining field.

2. **Ionization in the plasma**

   Charge exchange & impact ionization strip the electron → energetic ion, now magnetically confined.

3. **Fast-ion orbit**

   Set by energy, pitch angle, and birth point: passing or trapped (banana) orbits.

4. **Coulomb slowing down**

   Drag transfers the energy to plasma electrons and ions → heating, current, torque, particles.

How the plasma captures the beam: three atomic processes

Charge exchange

$$D_b^0 + D_p^+ \rightarrow D_b^+ + D_p^0$$

fast neutral steals nothing — it hands its electron duty over; dominant for D below ~90 keV

Ionization by ions

$$D_b^0 + D_p^+ \rightarrow D_b^+ + D_p^+ + e^-$$

hard collision knocks the electron off; dominant above ~90 keV

Ionization by electrons

$$D_b^0 + e^- \rightarrow D_b^+ + 2e^-$$

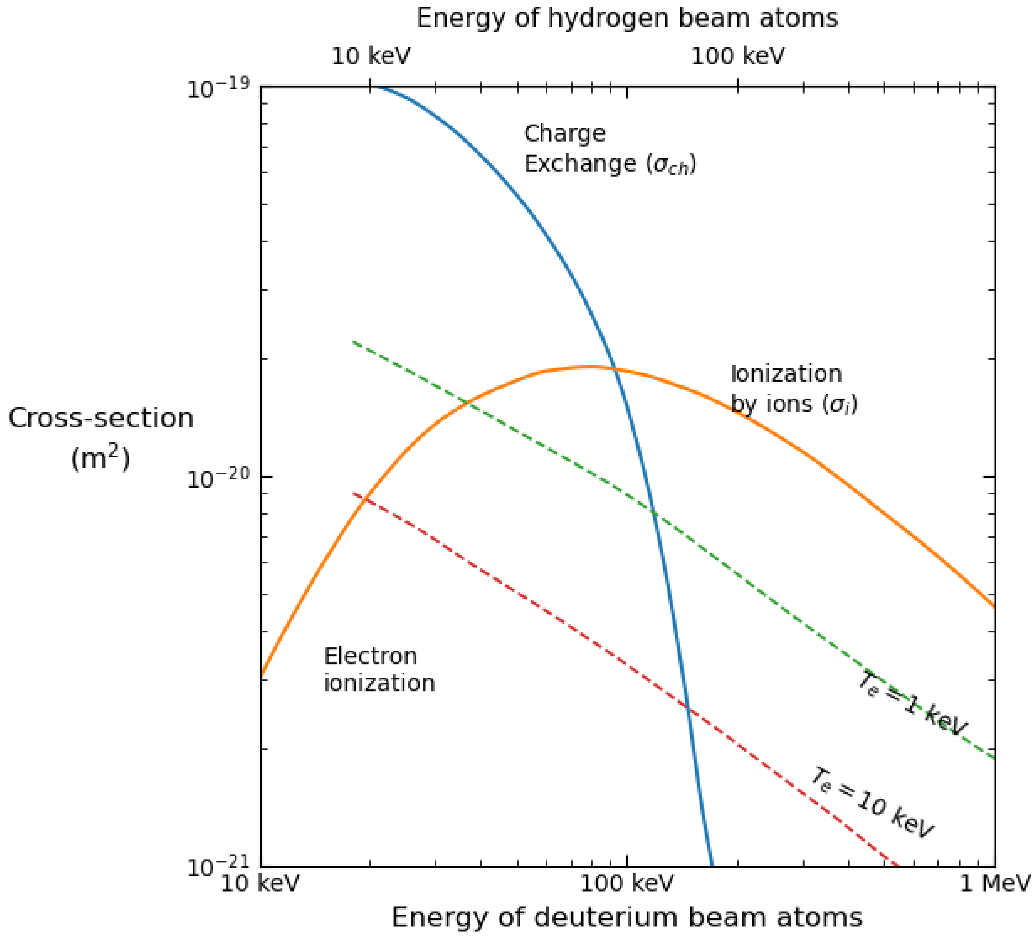
enters as $\langle\sigma_e v_e\rangle / v_b$ since $v_e \gg v_b$; smallest of the three

$$d\Gamma/dx = -n_e \left(\sigma_{cx} + \sigma_i + \langle\sigma_e v_e\rangle/v_b \right) \Gamma$$

beam flux $\Gamma = n_b v_b$ decays exponentially — the total cross section sets the decay length λ

- **In a real plasma:**
  - stopping on impurities (Z-scaled data)
  - CX / ionization on other slowing-down fast ions — matters when $n_b / n_e \gtrsim 10\,\%$
  - multi-step (excited-state) ionization at high n_e — "beam-stopping enhancement"
- Beam species note: H curves = D curves at twice the energy (same velocity).

Stopping cross sections



Recreated from analytic fits; after Wesson, Tokamaks Fig. 5.3.1

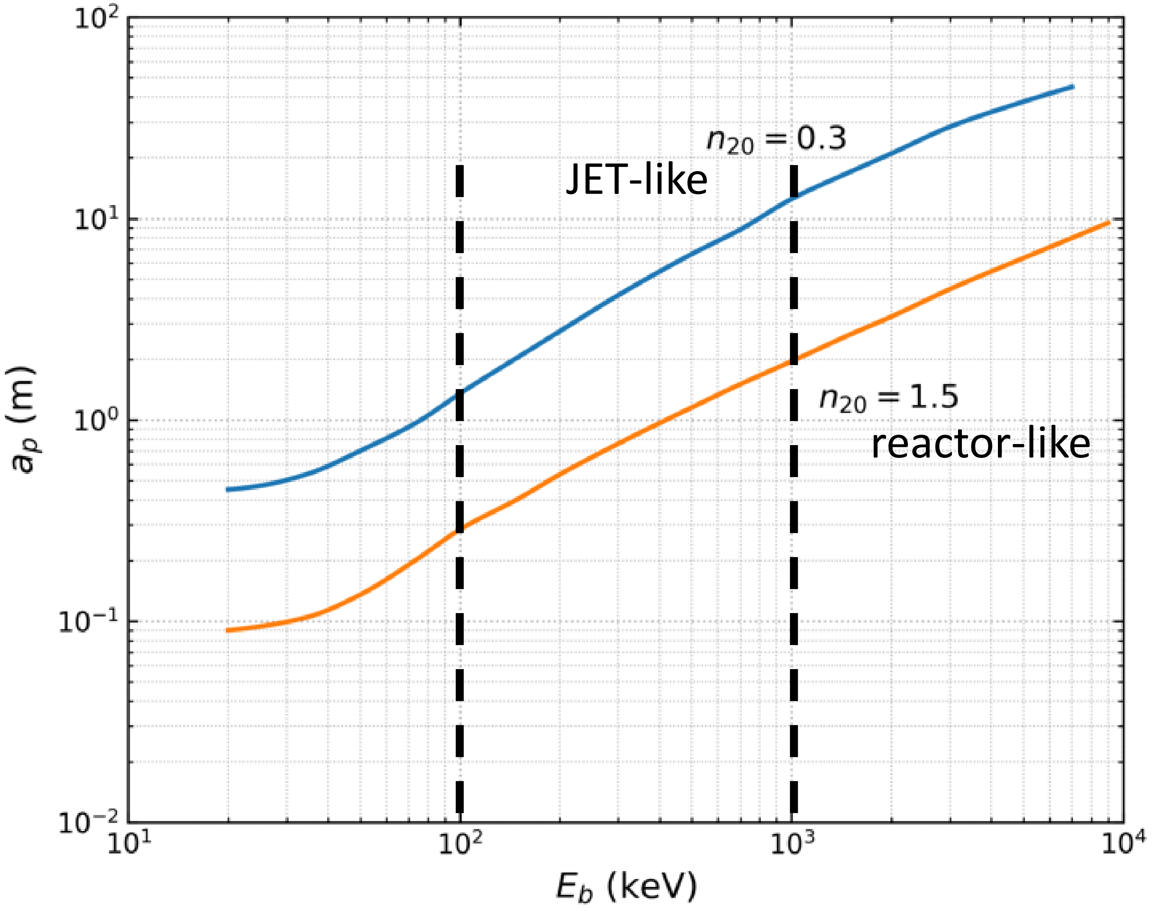
- Charge exchange rules below ~90 keV (D); ion impact takes over above.
- All processes weaken as E_b grows → faster beams fly further before capture.
- **Worked number (reactor-grade density):**

$$\lambda = 1 / (n_e \sigma) \approx 1 / (10^{20} \cdot 3\times10^{-20}) \approx 0.3\ m$$

at Eb = 100 keV, $n_e = 10^{20}\ m^{-3}$ — compare to a reactor minor radius a ≈ 2 m

A 100 keV beam is absorbed in the first 30 cm of a reactor plasma → edge heating only.

Penetration sets the beam energy: Eb = Eb(a, n)

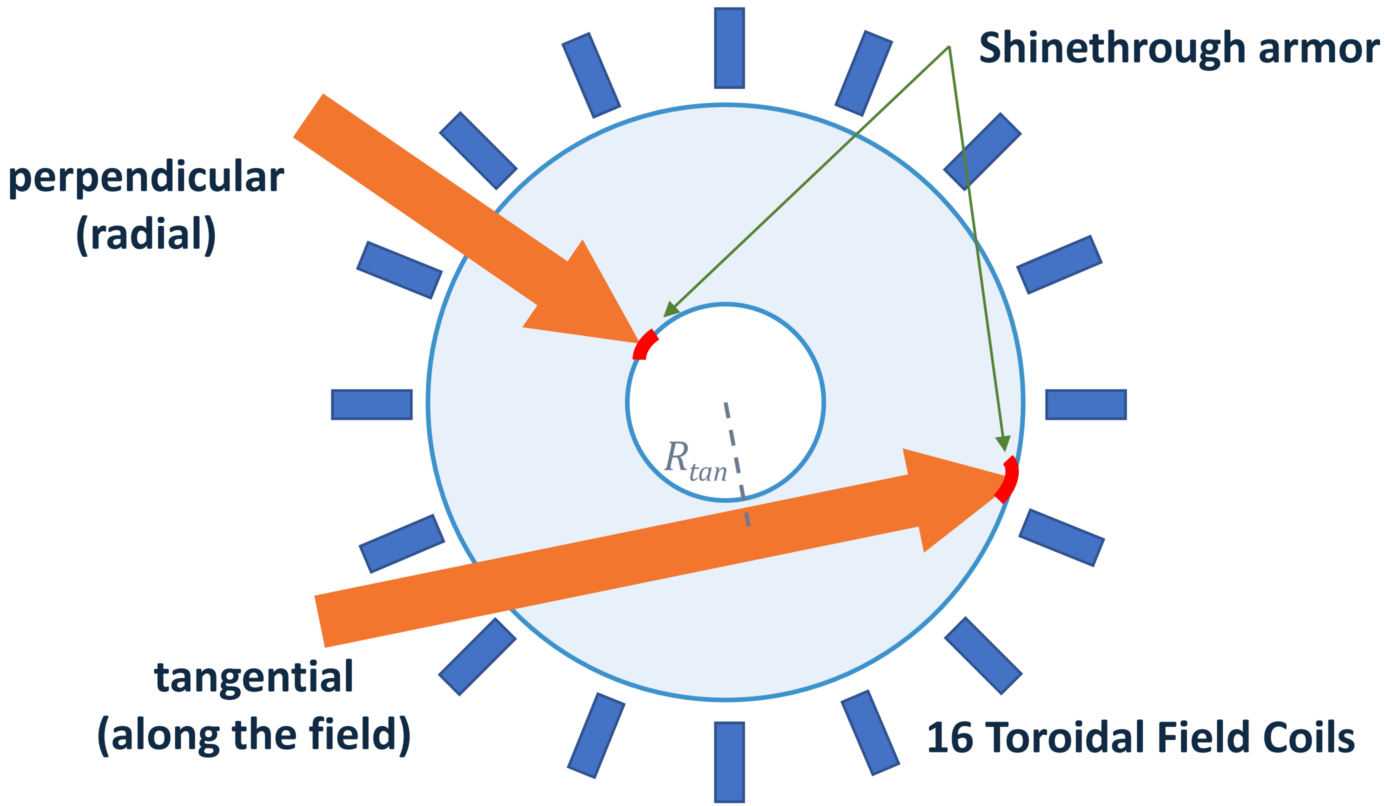


Perpendicular injection, $\sigma_{cx} + \sigma_i$ model; after Freidberg Fig. 15.4

- Too weak absorption → shine-through: beam power hits the far wall.
- Too strong absorption → all the power be absorbed at the edge.

- JET-like (n_{20} = 0.3, a = 1 m): ~100 keV suffices → positive-ion NBI
- Reactor (n_{20} = 1.5, a = 2 m): ~0.8–1 MeV → negative-ion NBI (Part II).
- Tangential path is ~2.4× longer at R/a = 2.5 → even higher E_b.

Perpendicular or tangential? The injection-angle compromise



R_{tan} = distance of closest approach of the beam line to the machine axis → sets the birth pitch angle

Perpendicular

- + short path, simple port access
- – mostly $v_\perp$ at birth → ripple-trapped loss
- – shine-through risk in small / thin plasmas

Tangential

- + long absorption path, large $v_\parallel$ → current drive, fewer trapped ions
- – tight access between TF coils, long ducts → pumping load
- Real systems: a compromise angle; co- vs counter-injection w.r.t. I_p

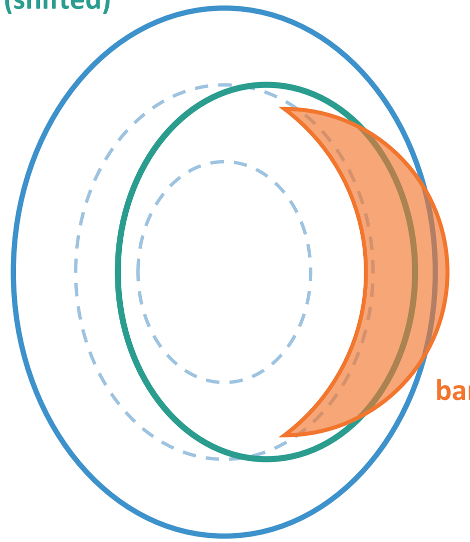
The moment of ionization fixes the fast ion's orbit

- **At ionization, the ion follows the neutral velocity vector exactly**
- Birth pitch: $v_{\parallel} / v = R_{tan} / R_{ion}$ — pure geometry.
- (E, pitch, birth point) → the entire collisionless orbit is determined.
- One beam = three beams: full, half, and third energy components (E_0, $E_0/2$, $E_0/3$) from D^+, D_2^+, D_3^+ in the source — the lower energies deposit further out.
- Toroidal rotation matters: deposition and slowing down happen in the rotating plasma frame

$$\textit{pitch at birth:} \quad v_{\parallel} / v = R_{tan} / R_{ion}$$

- shine-through — beam crossing the whole plasma unabsorbed
- deposition / birth profile H(ρ) — where fast ions are created
- pitch (angle) — $v_{\parallel}/v$, the orbit-defining ratio
- full / half / third energy — the three species-mix components
- co- / counter-injection — beam parallel / antiparallel to I_p

Passing and trapped fast ions



poloidal cross-section (schematic)

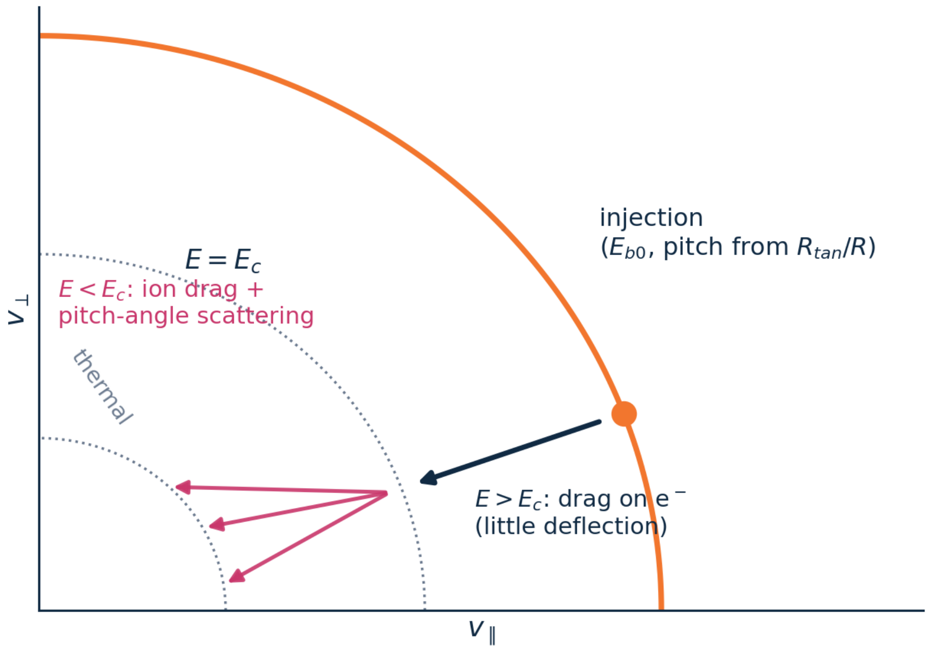
- Trapped if $v_\parallel/v$ is small: $|v_\parallel/v| \lesssim \sqrt{(2\varepsilon)}$, $\varepsilon = r/R$ — mirror force of the 1/R field.
- Orbits drift off the flux surface; banana width $\Delta_b \sim q\,\rho_L / \sqrt{\varepsilon}$ — tens of cm for a 100 keV D ion in a medium tokamak.
- Wide edge orbits can cross the last closed flux surface → prompt (first-orbit) loss onto plasma-facing components

$$E, \qquad \mu = \frac{1}{2}\frac{mv_\perp^2}{B}, \qquad P_\varphi = mRv_\varphi - q\psi$$

Energy, magnetic moment, canonical toroidal momentum
the collisionless invariants — axisymmetry ⇒ P_ϕ conserved: orbit and loss criteria

Coulomb collisions: energy transfer

- **Velocity ordering for a beam ion: $v_{Ti} \ll v_b \ll v_{T_e}$**
- Collisions with electrons — a viscous background:
  - pure drag, negligible deflection ($m_e \ll m_b$); energy flows to electrons
- Collisions with plasma ions — billiard balls:
  - drag and pitch-angle scattering (comparable masses); energy flows to ions
- Described by a Fokker–Planck collision operator: drag + pitch-angle scattering + energy diffusion



Life in velocity space: drag first, scattering later (below E_c)

Ec — critical beam energy

$$E_c = 19 - 20\mathrm{T_e} \qquad D_b \to Dp,$$

- $E_b > E_c$: electron drag wins → energy flows to electrons (little scattering).
- $E_b < E_c$: ion drag wins → energy flows to ions + pitch-angle scattering.

$$P_i \propto \frac{1}{m_i}\sqrt{\frac{m_b}{E_b}},\ P_e \propto \frac{E_b}{T_e^{3/2}},\ P_i(E_c) = P_e(E_c)$$

$$\frac{dE_b}{dt} = \sum P = -\frac{2E_b}{\tau_{se}}\left(1 + \frac{E_c}{E_b}\right)^{3/2}$$

one ODE describes the whole slowing-down history (Wesson eqn 5.4.10)

KSTAR-like

$E_b = 100$ keV, $T_e = 3$ keV

$E_c \approx 56$ keV → $E_b \approx 1.8\ E_c$: mixed electron/ion heating

ITER HNB

$E_b = 1$ MeV, $T_e = 20$ keV

$E_c \approx 370$ keV → electron-dominated heating

CPD (Part IV!)

$T_e = 25$ keV → $E_c \approx 500$ keV

120 & 400 keV beams are both below E_c → ion heating dominates

The slowing-down time: how long a fast ion lives

$$\tau_{se} \propto \frac{T_e^{3/2}}{n_e} \approx 0.023s \frac{(T_e[keV])^{3/2}}{n_{20}} \quad \text{, D beam}$$

Spitzer slowing-down time: e-folding of the energy against electron drag — hotter plasma → weaker drag

$$\tau_{th} = \left(\frac{\tau_{se}}{3}\right) \ln\left[1 + \left(\frac{E_{b0}}{E_c}\right)^{3/2}\right]$$

Characteristic time for thermalization:
integrate $dE/dt = -(2E/\tau_{se})[1+(E_c/E)^{3/2}]$ from E_{b0} down to thermal (Wesson eqn 5.4.12)

- $W_{fast} \sim P_{NB}\,\tau_{se}$ → the slowing time sets the fast-ion inventory, stored energy, and beam–target neutron rate.
- NBCD efficiency inherits the same scaling: each fast ion drives current for ~ τ_{se} → $\eta_{CD} \propto T_e^{3/2}/n_e$

KSTAR-like

T_e = 3 keV, n_e = 5×10^{19} m^{-3}, E_{b0} = 100 keV

$\tau_{se} \approx 0.24$ s; $E_{b0} \approx 1.8\,E_c$ → $\tau_{th} = (\tau_{se}/3)\ln(3.4) \approx 0.10$ s

CPD-like

T_e = 25 keV, n_e = 2.4×10^{20} m^{-3}, E_{b0} = 400 keV

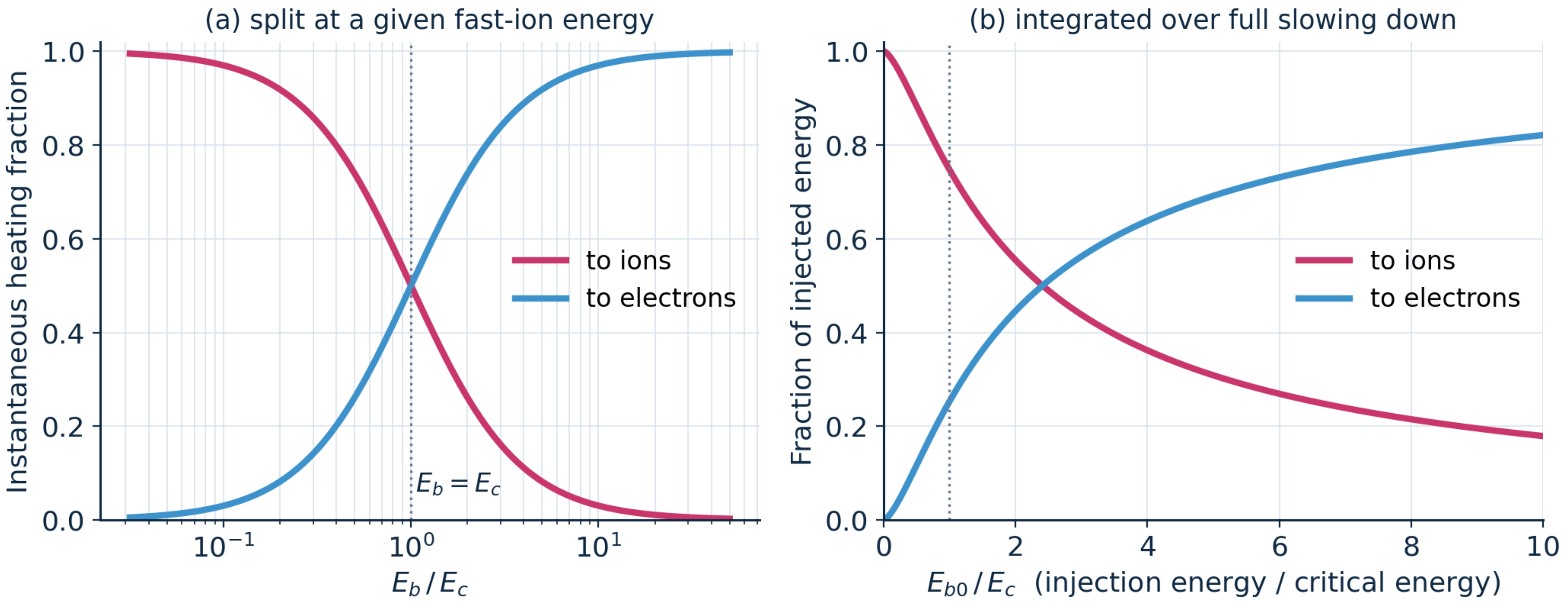
$\tau_{se} \approx 0.023\text{x}125/2.4 \approx 1.2$ s; $E_{b0}/E_c \approx 0.8$ → $\tau_{th} \approx 0.22$ s

The pattern

T_e^(3/2) beats n_e

reactor-grade plasmas hold their fast ions longer → large W_fast, strong NBCD

Who gets the energy? Electrons vs ions, quantitatively



Electron first

well above E_c → electrons first, ions late in the slowing down

After Wesson Figs. 5.4.1–5.4.2: $P_i/P \propto [1 + (E/E_c)^{3/2}]^{-1}$ and its slowing-down integral $\varphi(E_{b0}/E_c)$

Neutral beam current drive: stacking ions, shielding electrons

- Why: inductive current is pulsed → steady state needs non-inductive drive; tangential NBI gives heating + torque + current in one system
- Stacking: injected ion current accumulates lap after lap, until buildup = loss (slowing down on e⁻/ions, or charge exchange). Each ion contributes to the plasma current for one τ_{se}

$$J_f = SeZ_f\tau_{se}v_{b0}F(u_c)$$

F from the 2-D slowing-down distribution (Fokker–Planck / Monte Carlo → NUBEAM); $\tau_s \propto T_e^{3/2}/n_e$ enters here

$$\frac{I}{I_f} = 1 - \frac{Z_f}{Z_{eff}} + 1.46A(Z_{eff})\sqrt{\epsilon}\,\frac{Z_f}{Z_{eff}}$$

Wesson eqn 3.14.1 (banana regime, $v_b \ll v_{T_e}$): A = 1.67 (Z_{eff} = 1) → 1.18 (Z_{eff} = 4)

Fast ion current

- 1 — the bare fast-ion current.
- – Z_f/Z_{eff} — reverse electron current: dragged electrons drift with the beam; $Z_f = Z_{eff}$ → complete cancellation (Ohkawa).
- + $1.46 A\sqrt{\varepsilon} Z_f/Z_{eff}$ — trapped electrons cannot carry the back-current → shielding incomplete; net current recovers toward the edge ($\sqrt{\varepsilon}$ grows).
- **Near-cancellation is possible → compute the electron response accurately, surface by surface.**

NBCD efficiency — and the experimental results

$$\eta = \frac{J_f}{P_d},\ P_d = \frac{1}{2} m_f v_{b0}^2 S$$

evaluate → maximize τ_{se} (high T_e, low n_e) and pick E_b near E_c ($u_c \approx 1$) (Wesson §3.14)

- Maximize $\tau_{se} \propto T_e^{3/2}/n_e$: hot, low-density plasmas drive current best.
- Inject near E_c … but in practice E_b is set by penetration, not by CD efficiency
- Profile control: driven-current profile = beam energy + deposition profile + injection angle; typical net efficiency: tens of kA/MW.
- **Experiments agree well with the theory — and the CPD scan (Part IV) shows ~35 kA/MW**

TFTR

0.34 MA driven @ 11.5 MW

+0.5 MA bootstrap of 0.9 MA total → predominantly non-inductive

DIII-D · JT-60U · JET

0.35 / 0.5 MA fully non-inductive; JET 0.25 MA

bootstrap + NBCD sustained the entire current at low density

JT-60U N-NBI

1 MA @ 3.75 MW, 360 keV

negative-ion beam → reactor-relevant efficiency; the bridge to Part II and to CPD

Torque, fueling, and active diagnostics

Torque → rotation

Momentum source Σ S $m_b v_b$ = (collisional + J×B) Rotation shear suppresses turbulence; stabilizes RWMs and error fields. Often the only torque source

Core fueling

Each captured neutral = one core electron–ion pair. A calibrated, localized particle source — visible in density evolution.

Beam–target fusion

Fast ions on thermal fuel dominate neutron rates in beam-heated D / D–T plasmas

Active diagnostics

CXRS: T_i & rotation profiles. MSE: internal q-profile. FIDA / NPA: fast-ion distribution. BES: turbulence imaging. No beam → no measurement.

Where fast ions go (other than heating plasma)

Shine-through

Unabsorbed beam strikes the far wall. Sets the minimum target density for beam operation.

Prompt (first-orbit) loss

Wide birth orbits cross the LCFS and hit PFCs within one transit → localized heat loads. (NuBDeC, Part III)

TF ripple loss

Field ripple from discrete coils traps / stochastically ejects ions — δ_s criterion, modeled in NUBEAM.

Charge-exchange loss

Fast ion re-neutralizes and escapes across the field. Recapture also possible.

MHD-induced

Sawteeth mix the core population (Kadomtsev); fishbones expel bursts; Alfvén eigenmodes transport fast ions.

Why it matters

Lost power = lost heating and CD efficiency + MW/m^2-scale loads on plasma-facing components.

Five decades of NBI: from 50 eV to burning-plasma scale

1973

First beam heating

ATC · CLEO · ORMAK — tens of kW, ΔT ≈ 50 eV

1979

PLT breakthrough

2.4 MW D^0 → T_i : 1 → 6.5 keV

1990s

TFTR / JET D–T

10s of MW; JET: T_i ≈ 19 keV, P_fus ≈ 1.5 MW

1996

JT-60U N-NBI

first negative-ion beams 350–500 keV

2020s

JT-60SA → ITER

500 keV N-NBI; ITER HNB: 2 × 16.5 MW at 1 MeV D^-

02

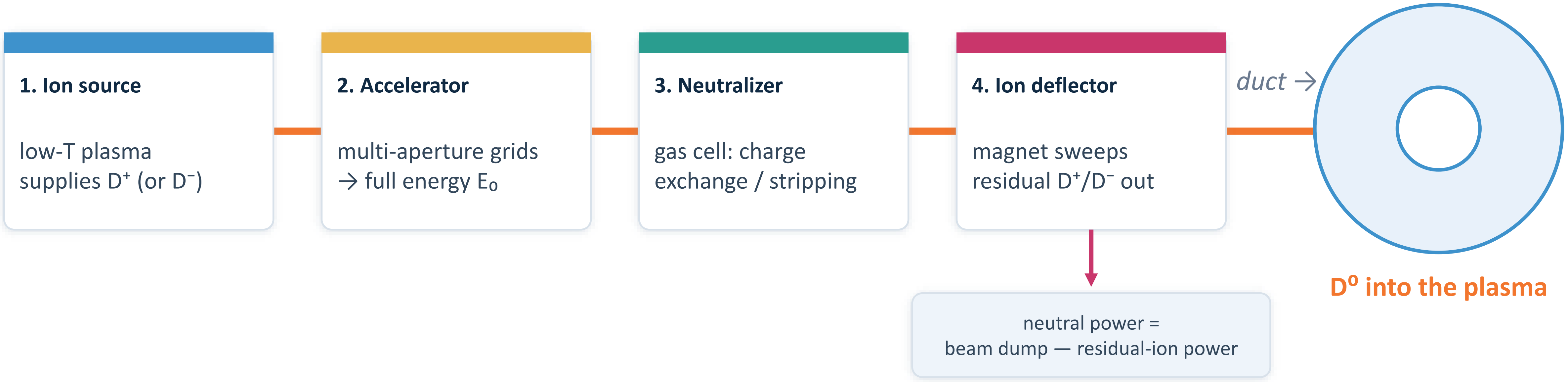
The Neutral Beam Injector

How to transfer a megawatt flow of fast neutral atoms

- Beamline anatomy: source → accelerator → neutralizer → deflector
- Ion source physics and the species mix
- Why positive-ion neutralization collapses above ~100 keV
- Negative ions: the route to 1 MeV

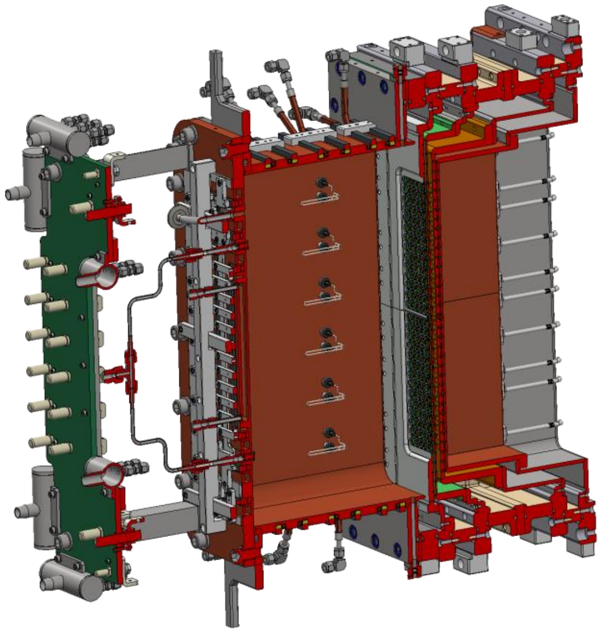
PART II · ANATOMY

Anatomy of a beamline: four stages plus a duct

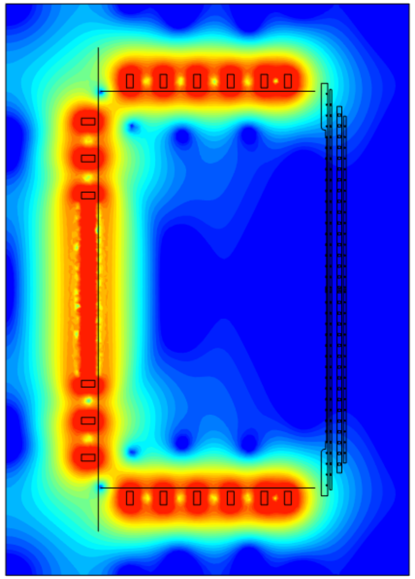


- “Beamline” = everything outside the main vessel: source, grids, neutralizer, deflector + dump, valves, duct.
- The accelerator is where the electrical power is spent; the neutralizer is where the efficiency is decided.

The ion source: a plasma to feed the accelerator

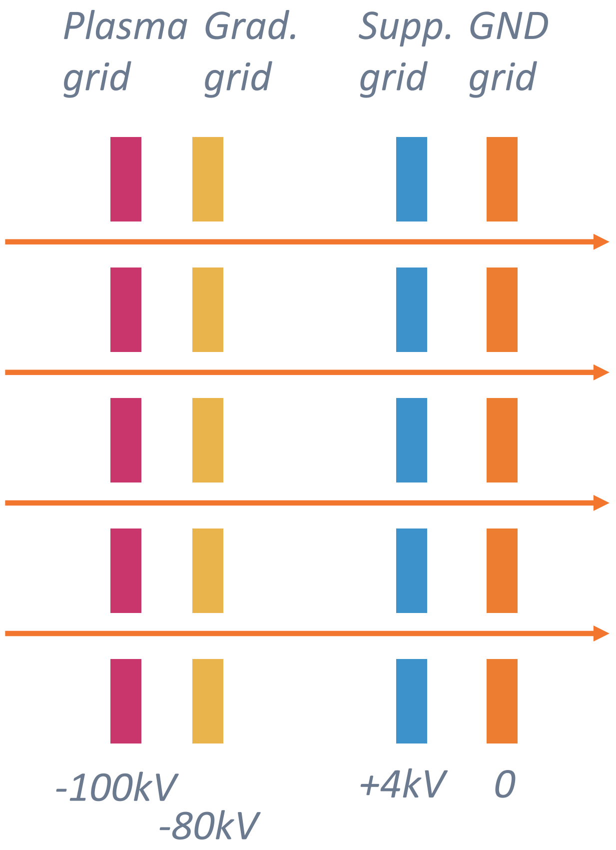


- Bucket / multicusp source: permanent-magnet cusp field confines a low-temperature plasma; the central extraction region stays nearly field-free.
- Driven by hot filaments — or RF excitation for long-pulse / steady state (ITER's choice).
- **The species-mix problem – Positive:**
  - the source makes D^+, D_2^+, D_3^+ — all fall through the same voltage
  - molecules dissociate in the neutralizer → neutrals at $E_0/2$ and $E_0/3$
  - lower-energy components penetrate poorly → edge heating
  - Good sources reach 80–90 % atomic (full-energy) fraction
- **Electron co-extraction – Negative:**



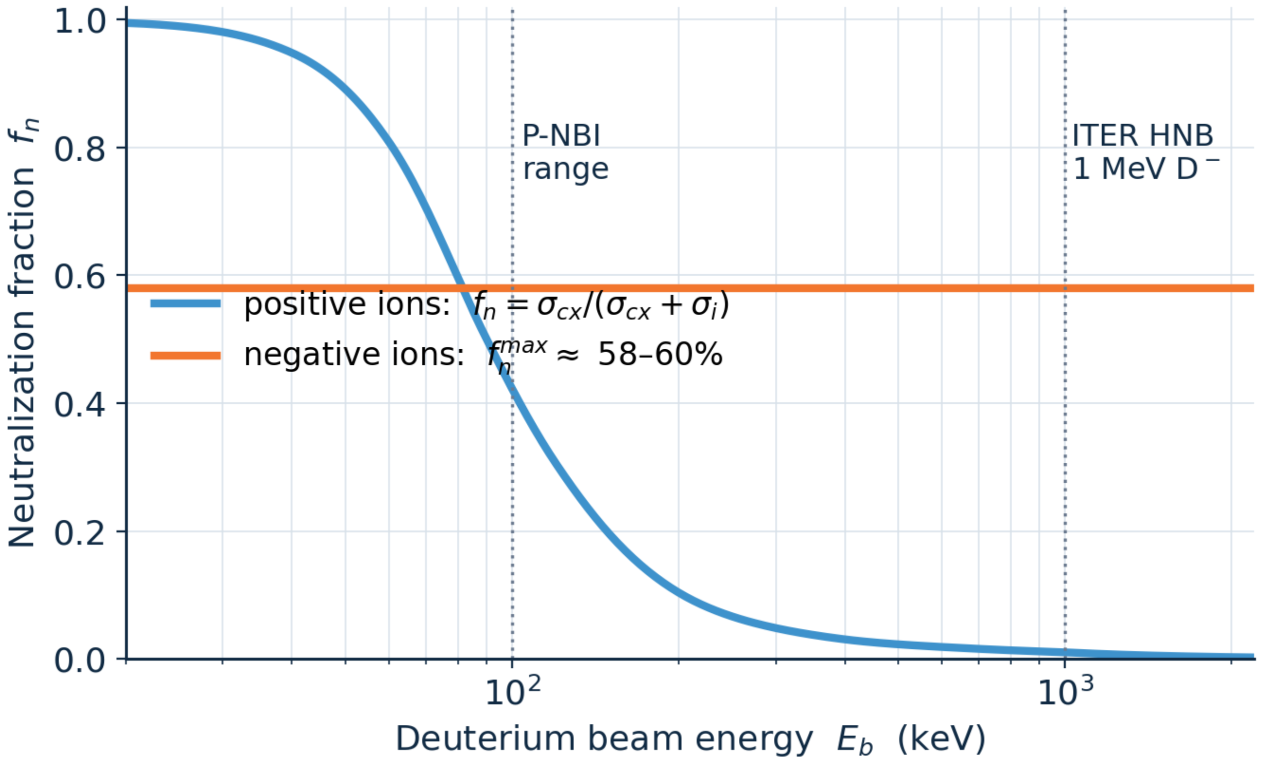
The accelerator: electrostatic optics for a megawatt beam

- Multi-aperture grids (slots or circular holes) at graded potentials accelerate the ions to E_0; this stage consumes most of the wall-plug power.
- Each aperture → one beamlet, divergence as low as ~0.5°; hundreds of beamlets form the beam.
- Steering & focusing: aperture offsets between grids and geometric grid shaping aim every beamlet down the long duct.
- Space charge (perveance) limits the current per aperture — off-optimum operation increases beam divergence.
- Grids intercept beam power → embedded cooling channels between apertures.
- At 1 MV (ITER HNB), holding the voltage is hard: vacuum insulation, breakdown conditioning.



graded-potential grids → parallel beamlets

Positive-ion neutralization: an equilibrium



After Wesson Fig. 5.5.3 / Freidberg Fig. 15.5

- **Two competing reactions in the gas cell:**
  - $D^+ + D_2 \rightarrow D^0 + D_2^+$ (charge exchange, σ_{cx})
  - $D^0 + D_2 \rightarrow D^+ + D_2 + e^-$ (re-ionization, σ_i)
- Thick target → charge-state equilibrium:

$$f_n = \sigma_{cx} / (\sigma_{cx} + \sigma_i)$$

a pure ratio of cross sections — no engineering can improve it

- σ_{cx} collapses above ~100 keV/amu → $f_n < 1$ % at 1 MeV.
- **Positive-ion NBI is therefore capped near $E_0 \approx$ 100–120 keV (D)**

Negative ions: the weakly bound electron

- D^- binds its extra electron by just 0.75 eV → "stripping" $D^- \to D^0$ stays efficient at any energy.
- But neutrals keep being ionized ($D^0 \to D^+$) and nothing replenishes D^- → the neutral yield rises, peaks, then decays along the cell:

$$\frac{dN^-}{dx} = -n\sigma_{-10}N^-, \qquad \frac{dN^0}{dx} = n(\sigma_{10}N^- - \sigma_{01}N^0)$$

N: neutral density, σ_{-10}: stripping, σ_{01}: ionization
solve → optimum target thickness nx_{opt} and peak fraction $f_n^{max} = \delta^{\{\delta/(1-\delta)\}}$, $\delta = \sigma_{01}/\sigma_{-10}$

- Measured fits (0.5–1 MeV): $\sigma_{-10} \approx 1.04$, $\sigma_{01} \approx 0.34 \times 10^{-20}/E(\text{MeV})\ \text{m}^2$ → $\delta \approx ⅓$, independent of E.
- **⇒ peak neutral fraction ≈ 58–60 % — flat all the way to 1 MeV**
- The hard part moves to the source: volume + caesiated-surface D^- production, co-extracted electrons, Cs management, 1 MV holding.

P-NBI vs N-NBI

Species	D^+	D^-
Energy	≤ ~120 keV	0.2 – 1 MeV
f_n @ 1 MeV	< 1 %	~60 %
Source	bucket / RF	Cs surface-plasma
Deployed	most tokamaks (KSTAR…)	JT-60U/SA, LHD → ITER

The neutral beam injector

A beamline is a factory	plasma source → grids (E_0) → gas cell (D^0) → residual ion dump
Energy of positive ions limited	$f_n = \sigma_{cx}/(\sigma_{cx}+\sigma_i)$ is a fixed ratio → collapses above ~100 keV
Negative ions scale	0.75 eV binding → ~60 % neutral yield even at 1 MeV → the reactor route (ITER HNB, JT-60SA …).

Next: putting it all together in silicon — NUBEAM and NuBDeC.

03

Modeling: NUBEAM & NuBDeC

Monte-Carlo fast ions — from beamline blueprint to heating profiles and wall loads

- Why NBI analysis needs a Monte-Carlo code
- NUBEAM: deposition → orbits → collisions → profiles (Pankin et al. 2004)
- NuBDeC: prompt loss on real 3-D walls at KSTAR (Rhee et al. 2019)
- How the two codes complement each other

Monte-Carlo code

- **What the analytic Part-I picture ignored:**
  - –real beamline geometry: tangency radius, source shape, divergence, focusing
  - –three energy components × several beamlines
  - –full atomic physics: impurities, beam–beam stopping, excited states
  - –finite orbit width: deposition is orbit-averaged, not local
  - –collisions evaluated along the orbit, in the rotating-plasma frame
  - –time-dependent equilibrium and profiles

What we need out (→ transport analysis)

- $P_e(\rho)$, $P_i(\rho)$ — heating profiles
- $J_{NB}(\rho)$ — driven current
- torque density (ρ) — rotation source
- $S_b(\rho)$ — particle / fueling source
- n_{fast}, W_{fast}, $f(E, v_{\parallel}/v, \rho, \theta)$ — fast-ion content
- beam–target & beam–beam neutron rates
- shine-through, orbit, CX, ripple losses

NUBEAM: (Pankin et al., CPC 2004)

- Monte-Carlo fast-ion module of TRANSP (PPPL), modularized to the NTCC library — callable from any transport code
- Handles beam ions and fusion products (α, T, ^3He) with the same machinery
- Fast ions = a few 10^3–10^4 weighted markers per species; ions below 3/2 T_i are handed to the thermal plasma as a source.
- Validated for decades — e.g. reproduces JET's measured D–T neutron emission profiles.

Beamline input
geometry, R_tan, divergence, E_0 mix

→ **MC deposition**
neutral tracks; $P(L)=\exp(-\int dl/v\tau_{fl})$; shine-through

→ **FLR step**
particle → guiding center (gyro-phase randomized)

→ **GC orbiting**
drift equations in numerical equilibrium; E, μ, P_ϕ checked

→ **Collisions + CX**
drag, pitch scattering, E-diffusion each half-bounce; losses; fusion

→ **Thermalize**
below 3/2 T_i → source profiles to transport equations

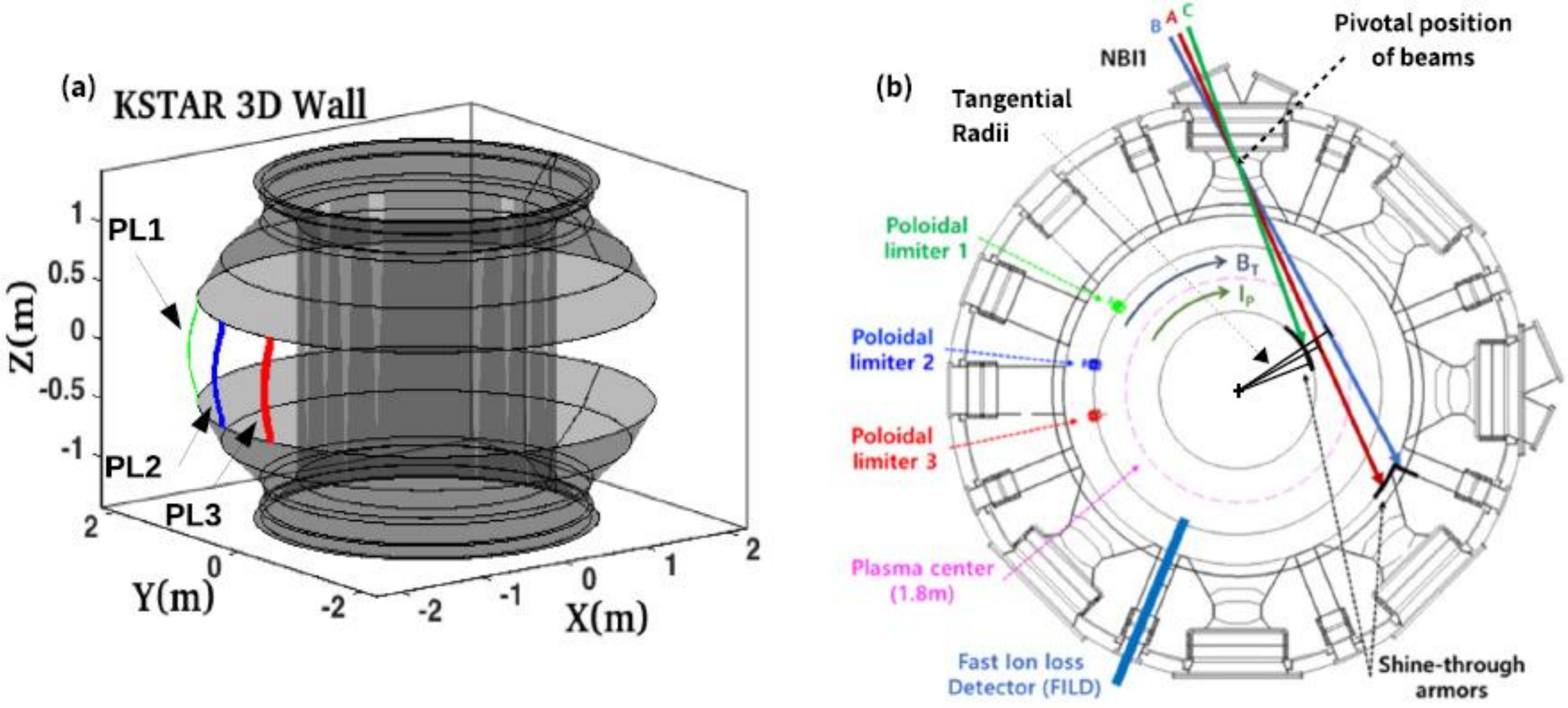
one NUBEAM timestep — repeated self-consistently as the plasma evolves

Deposition uses the full stopping physics of Part I: e-impact, thermal-ion CX & impact, impurities, other fast ions, excited-state correction.

NuBDeC: when the interesting physics is outside the LCFS

- The problem (KSTAR, high-β_p long pulse, $I_p \approx 400$ kA): poloidal limiters on the LFS midplane overheat — suspected NBI prompt orbit loss.
- **But NUBEAM / ORBIT stop at the LCFS → they cannot say where lost ions land.**
- NuBDeC = deposition + orbit following out to the real 3-D wall:
  - ① ionization module: Gaussian-beamlet sampling; ionize when $\exp(-\int n\sigma\, ds) \le$ random k; Janev–Suzuki stopping fits; benchmarked vs OFMC
  - ② orbit module: guiding-center drift eqs. (∇B, curvature, $E\times B$), RK4 in (R, ϕ, Z); $\psi(R,Z)$ cubic splines; wall-strike test vs PFC model incl. 3 poloidal limiters + FILD
- Quality: E and P_ϕ conserved to < 1 % over 10 ms; collisionless 1 ms runs ($\ll \tau_{se}$) capture prompt loss.

NuBDeC: KSTAR case

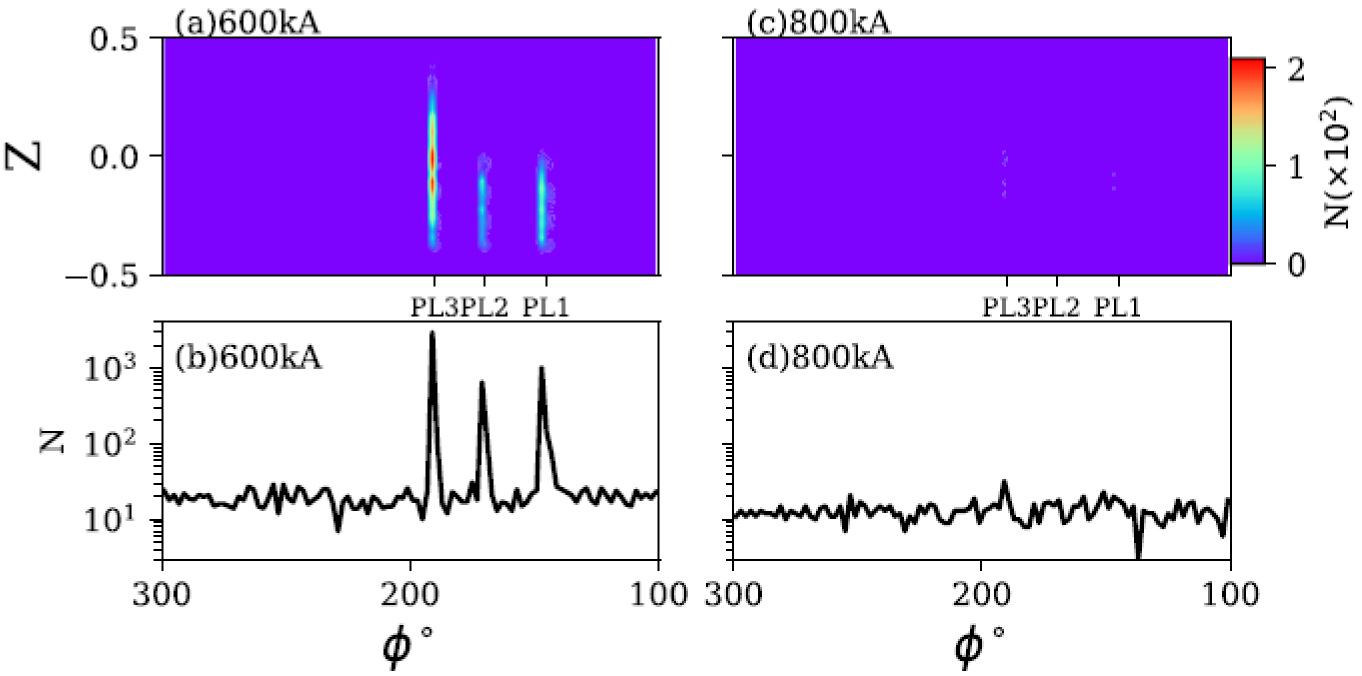


after Rhee et al. 2019, Fig. 1

Run at a glance

- E_b = 95 keV (full energy only)
- 3 sources: NBI1-A/B/C, R_{tan} = 1.486 / 1.72 / 1.245 m
- 6×10^5 markers, 1 ms, collisionless
- H-mode-like n_e, T_e profiles for stopping
- wall: full KSTAR PFC set + PL1–PL3

Prompt loss decoded: HFS birth + curvature drift → limiter strike



after Rhee et al. 2019, Fig. 13

- 2.6 % of injected ions strike the poloidal limiters — 85 % of that on PL3 alone.
- 65 % come from NBI1-C, the most perpendicular source (R_tan = 1.245 m) — geometry from Part I at work.
- Mechanism: born deep on the HFS → curvature drift downward → exit at the LFS midplane → limiter strike.
- **Mitigation, read off the diagram: raise I_p or shift the outer boundary inward → L_{PFC} closes. Verified by scans.**

NUBEAM and NuBDeC answer different questions — use both

	NUBEAM	NuBDeC
Question answered	How much heat / current / torque, where, and when?	Which ions are promptly lost, and where do they land?
Domain	inside the LCFS (magnetic coordinates)	out to the real 3-D wall, incl. limiters & probes
Collisions	full: drag, scattering, E-diffusion, CX, fusion	collisionless ($t \ll \tau_{se}$) — prompt physics only
Time base	time-dependent, follows the discharge (TRANSP)	snapshot: ~1 ms after injection
Typical use	interpretive & predictive transport analysis	PFC heat-load design, loss mitigation, FILD analysis

Same Part-I physics in both; complementary missions. Now let's use NUBEAM on a real design question.

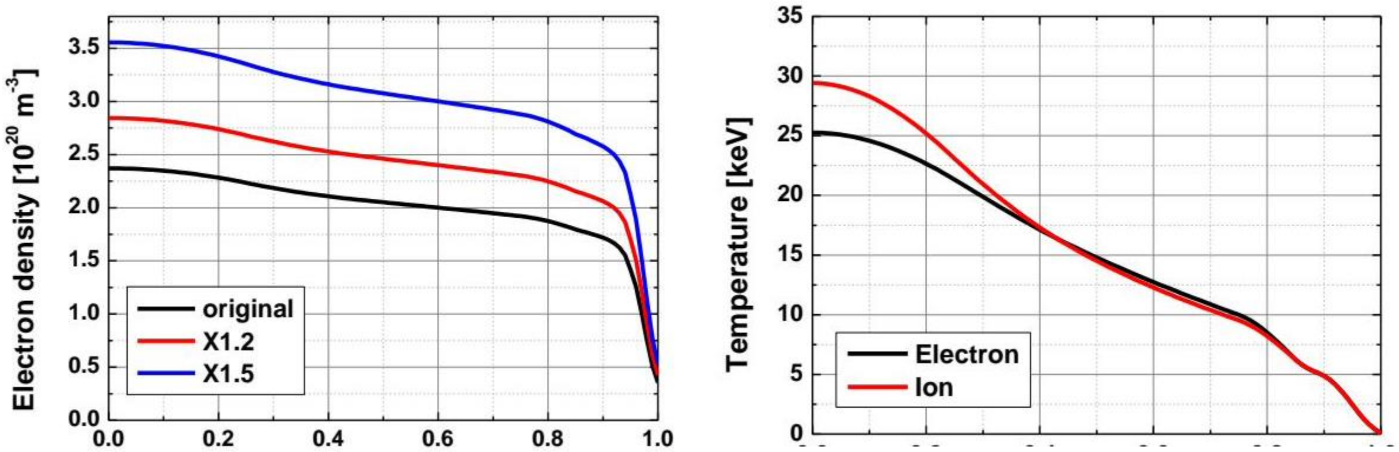
04

Application: NBI for CPD

A NUBEAM design scan — 120 keV vs 400 keV at 100 MW

- The CPD target plasma (FUSE, P_{fus} = 500 MW class)
- Tangency-radius scan from perpendicular to tangential
- Heating split and driven current

The CPD target plasma: a penetration challenge



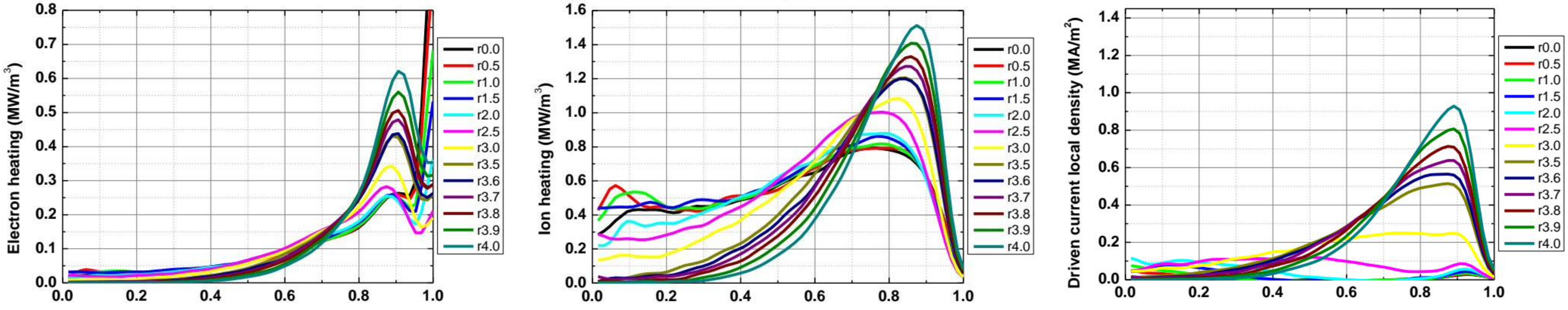
CPD reference profiles: n_e and T_e, T_i (FUSE-generated target; KFE NUBEAM CPD study, 2025)

- R ≈ 3.5 m compact pilot device, 16 TF coils.
- FUSE-generated target plasma for P_{fus} = 500 MW class.
- **n_{e0} = 2.4×10^{20} m^{-3}**
- **T_{e0} = 25 keV, T_{i0} = 29 keV**
- Density and temperature both reactor-grade — this is the hardest kind of plasma for a beam to enter.
- NUBEAM scan: R_{tan} = 0 → 4.0 m (perpendicular → tangential), P_{inj} = 100 MW fixed.
- Two beam energies: 120 keV (P-NBI class) vs 400 keV (N-NBI class).

Part-I predictions — before we look at the results

- penetration: reactor-class *na* → 120 keV gives λ ~ 10 cm → edge deposition
- heating split: E_c ≈ 20 T_e ≈ 500 keV → both beams below E_c → ion-dominated heating

120 keV: the beam never reaches the core



120 keV, 100 MW — electron heating, ion heating, and driven current density vs ρ across the R_t scan (KFE, 2025)

Pinned at the edge

All deposition sits at ρ ≈ 0.8–0.9 — for every tangency radius in the scan.

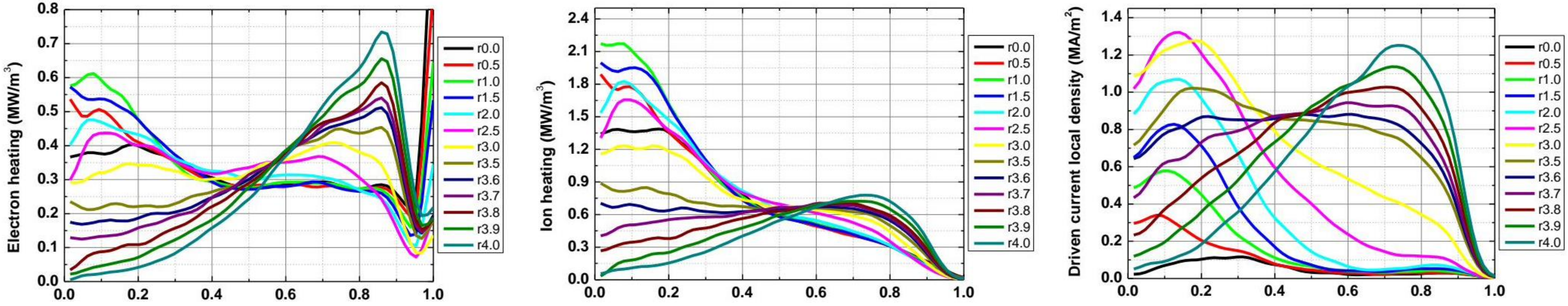
Part I, verified

λ(120 keV, 2.4×10^{20} m^{-3}) ~ cm-scale: the edge eats the beam, exactly as estimated.

No current-profile control

Driven current is small and edge-localized. Geometry cannot rescue an under-energized beam.

400 keV: penetration restored — geometry starts to matter



400 keV, 100 MW — electron heating, ion heating, and driven current density vs ρ across the R_t scan (KFE, 2025)

Core unlocked

Heating profiles now fill 0 ≤ ρ ≤ 1; ion heating core-peaked (E_b < E_c ≈ 500 keV — as predicted).

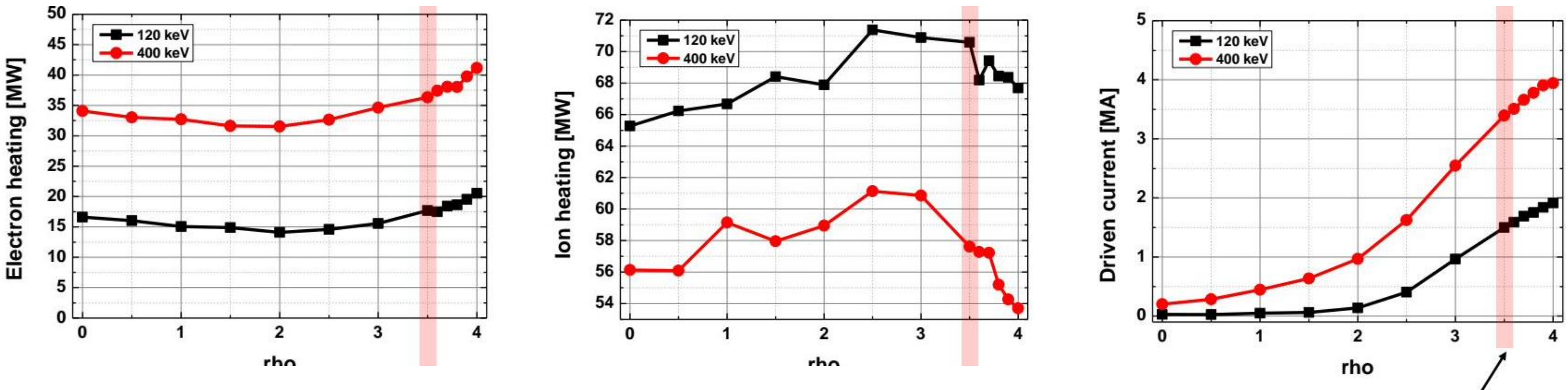
R_{tan} is now a knob

Deposition location responds to the tangency radius → a genuine profile-control actuator.

Serious current drive

Driven current density reaches ~MA/m² scale, steerable from core to mid-radius.

The bottom line: ~35 kA/MW



Volume-integrated electron heating, ion heating, and driven current vs R_t; NBCD efficiency ≈ 35 kA/MW at the marked point (KFE, 2025)

- Ion heating dominates at both energies (≈55–72 MW of 100 MW): $E_b < E_c \approx 500$ keV — the Part-I critical-energy prediction, confirmed.
- **Driven current: 120 keV drives ~2 MA ; 400 keV climbs to ~4 MA-class at large R_{tan} → NBCD efficiency ≈ 35 kA/MW at the design point, squarely in the Part-I range.**
- **Design answer: CPD needs N-NBI-class energy + tangential injection**

WRAP-UP

NBI

Atomic reactions

$\sigma(E)$ sets $\lambda = 1/(n\sigma)$: where the beam is captured

→

Coulomb collisions

E_c ≈ 20 T_e decides who is heated — and drives NBCD

→

Technology

neutralization physics caps D^+ at ~100 keV → D^- for ~MeV

→

Computation

NUBEAM / NuBDeC integrate orbits, collisions, walls

→

Design

CPD: 400 keV tangential, ~35 kA/MW — physics verified

References and further reading

J. Wesson, Tokamaks, 3rd ed., Oxford (2004) — §§5.3–5.5

Beam stopping, heating, slowing-down distribution, beam production.

J. Freidberg, Plasma Physics and Fusion Energy, Cambridge (2007) — §15.3

Penetration Eb(a) and positive/negative-ion neutralization, worked simply.

A. Pankin, D. McCune, R. Andre, G. Bateman, A. Kritz, Comput. Phys. Commun. 159 (2004) 157

The NUBEAM module: physics content, Monte-Carlo methods, NTCC modularization.

T. Rhee et al., Phys. Plasmas 26, 112504 (2019)

NuBDeC: NBI prompt loss at KSTAR poloidal limiters; (P_ϕ, μ) loss criterion.

S. Hong (KFE), NUBEAM CPD study: 120 vs 400 keV, 2025 (internal)

Part-IV figures: R_t scan, heating split, NBCD efficiency ≈ 35 kA/MW.

Further: R. Janev et al. (atomic data); S. Suzuki et al., PPCF 40 (1998) — beam-stopping fits

The stopping cross-section fits used inside NUBEAM / NuBDeC.

감사합니다 — 谢谢大家 — *thank you*