A “Polywell” p+^{11}B Power Reactor

Joel G. Rogers, Ph.D.
rogersjg@telus.net

Aneutronic fusion is the holy grail of fusion power research. A new method of operating Polywell was developed which maintains a non-Maxwellian plasma energy distribution. The method extracts down-scattered electrons and replaces them with electrons of a unique higher energy. The confined electrons create a stable electrostatic potential well which accelerates and confines ions at the optimum fusion energy, shown in the graph below. Particle-in-cell(PIC) simulations proceeded in two steps; 1) operational parameters were varied to maximize power balance(Q) in a small-scale steady-state reactor; and 2) the small scale simulation results were scaled up to predict how big a reactor would need to be to generate net power. Q was simulated as the ratio of fusion-power-output to drive-power-input. Fusion-power was computed from simulated ion density and ion velocity. Power-input was simulated as the power required to balance non-fusing ion losses. The predicted break-even reactor size was 13m diameter. Bremsstrahlung losses were also simulated and found manageable.

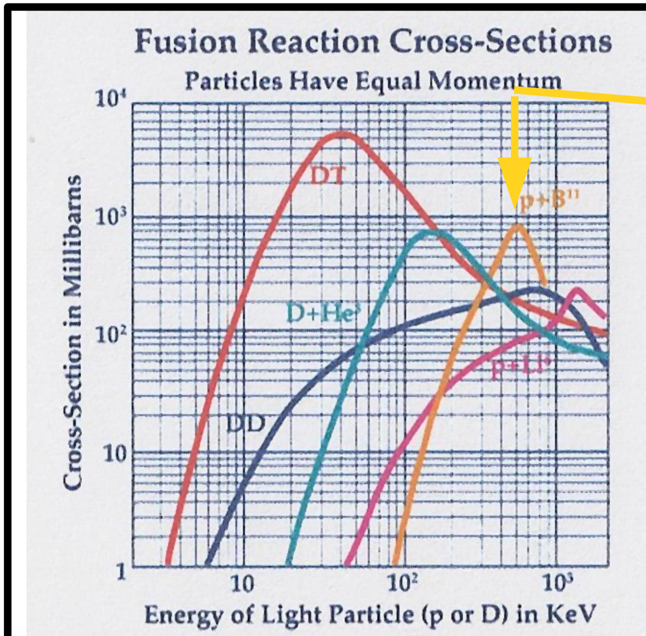


Figure 5 — Typical Fusion Reaction Cross Sections

The yellow line is for the cross section of p + ^{11}B aneutronic fusion, whose peak cross section is at 560 KV. It is impossible to achieve this energy with a plasma having with a Maxwellian energy distribution since most of its electrons and ions are emitting Bremsstrahlung radiation. *(This radiation is caused by the acceleration of a charged particle, such as an electron, when deflected by another charged particle, such as an atomic nucleus.)*

Robert W. Bussard, “Should Google Go Nuclear”, http://askmar.com/Fusion.html, November, 2006

Fig. 2 - “Polywell” Patent Pending

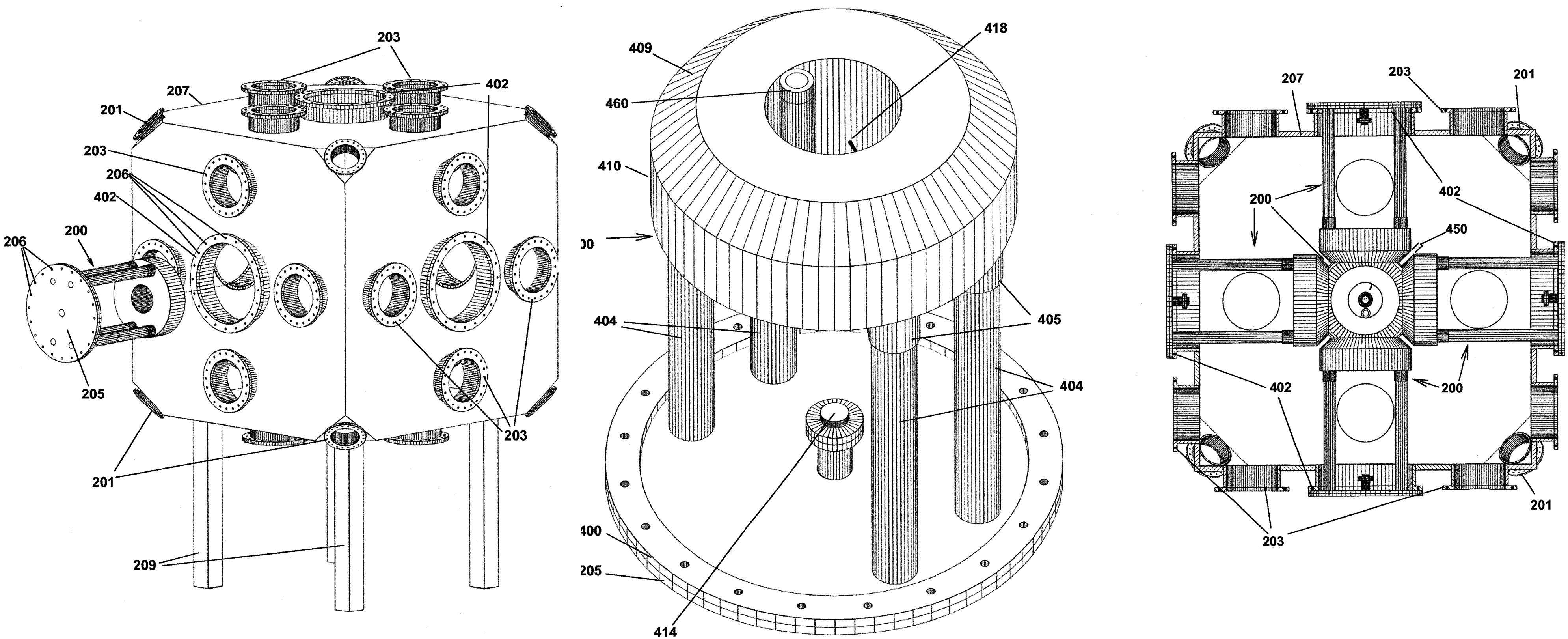


Fig. 3 - PIC Simulation Flowchart

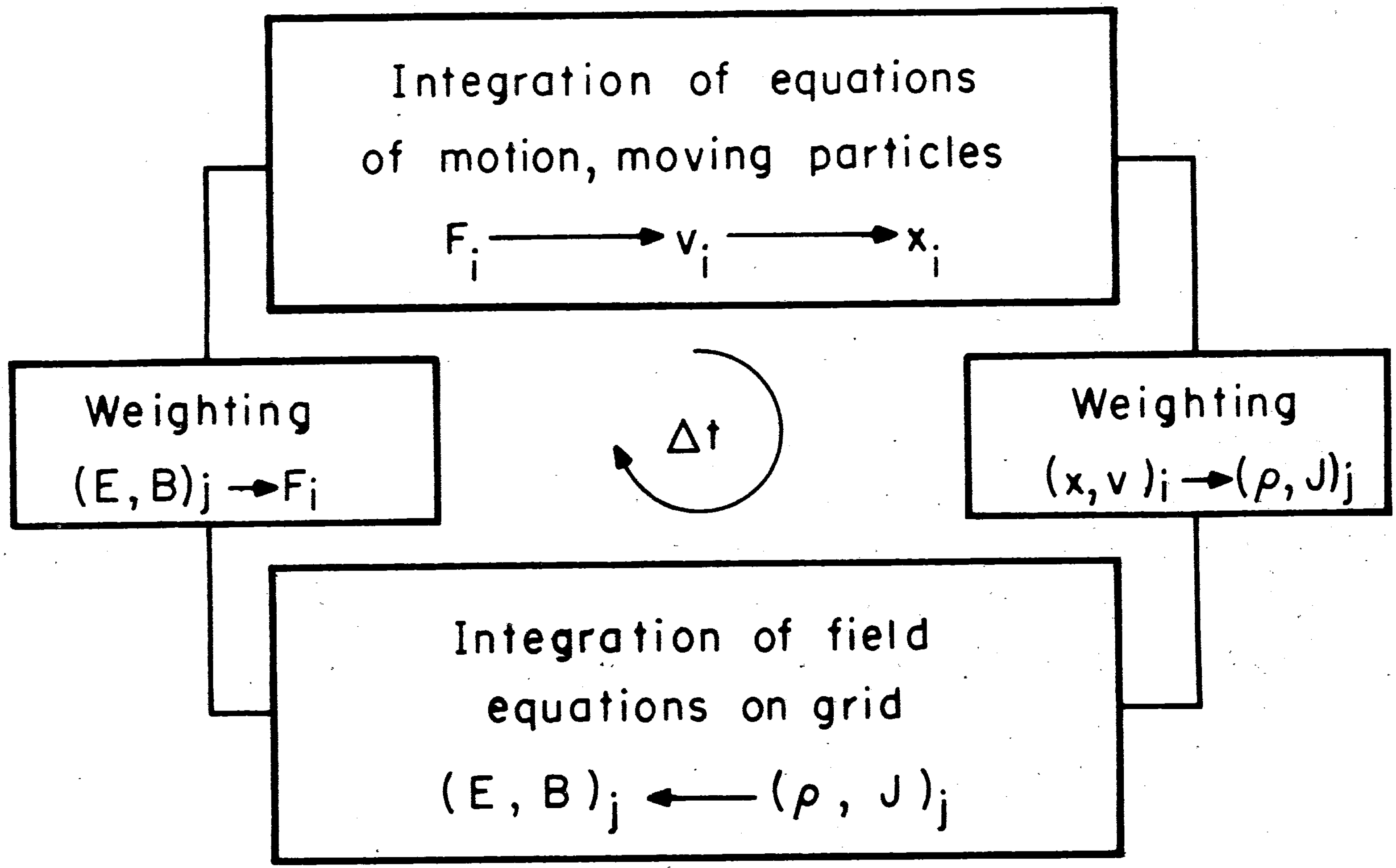


Figure 2-3a A typical cycle, one time step, in a particle simulation program. The particles are numbered $i = 1, 2, \ldots,$ NP; the grid indices are j, which become vectors in 2 and 3 dimensions.

The Figure(above) and caption were scanned from the textbook, Birdsall and Langdon, “Plasma Physics via Computer Simulation”, McGraw Hill, New York, 1985, pg. 11.

Fig. 4 - Electrons' 2D Positions

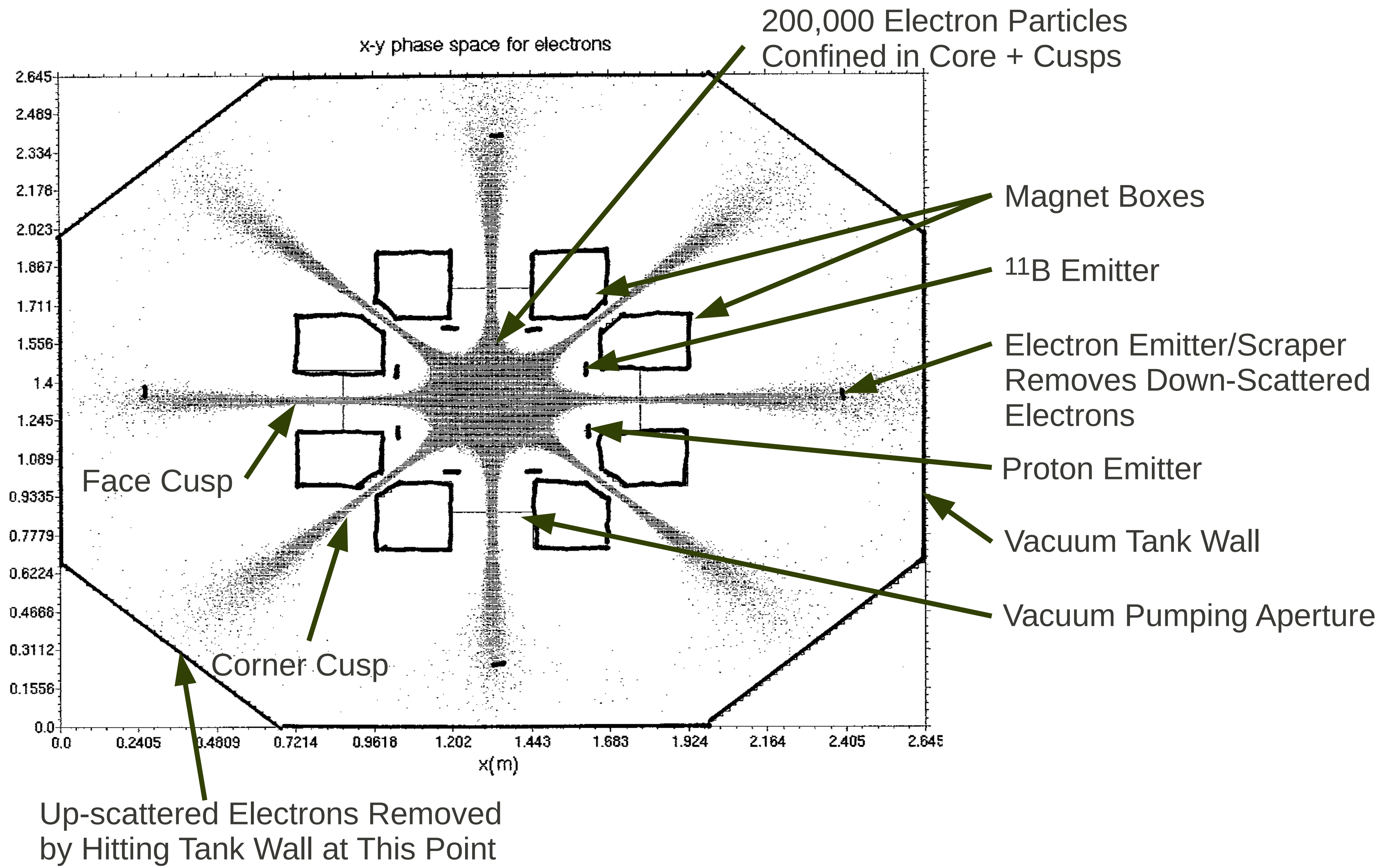


Fig. 5 - Confining Electrostatic Potential

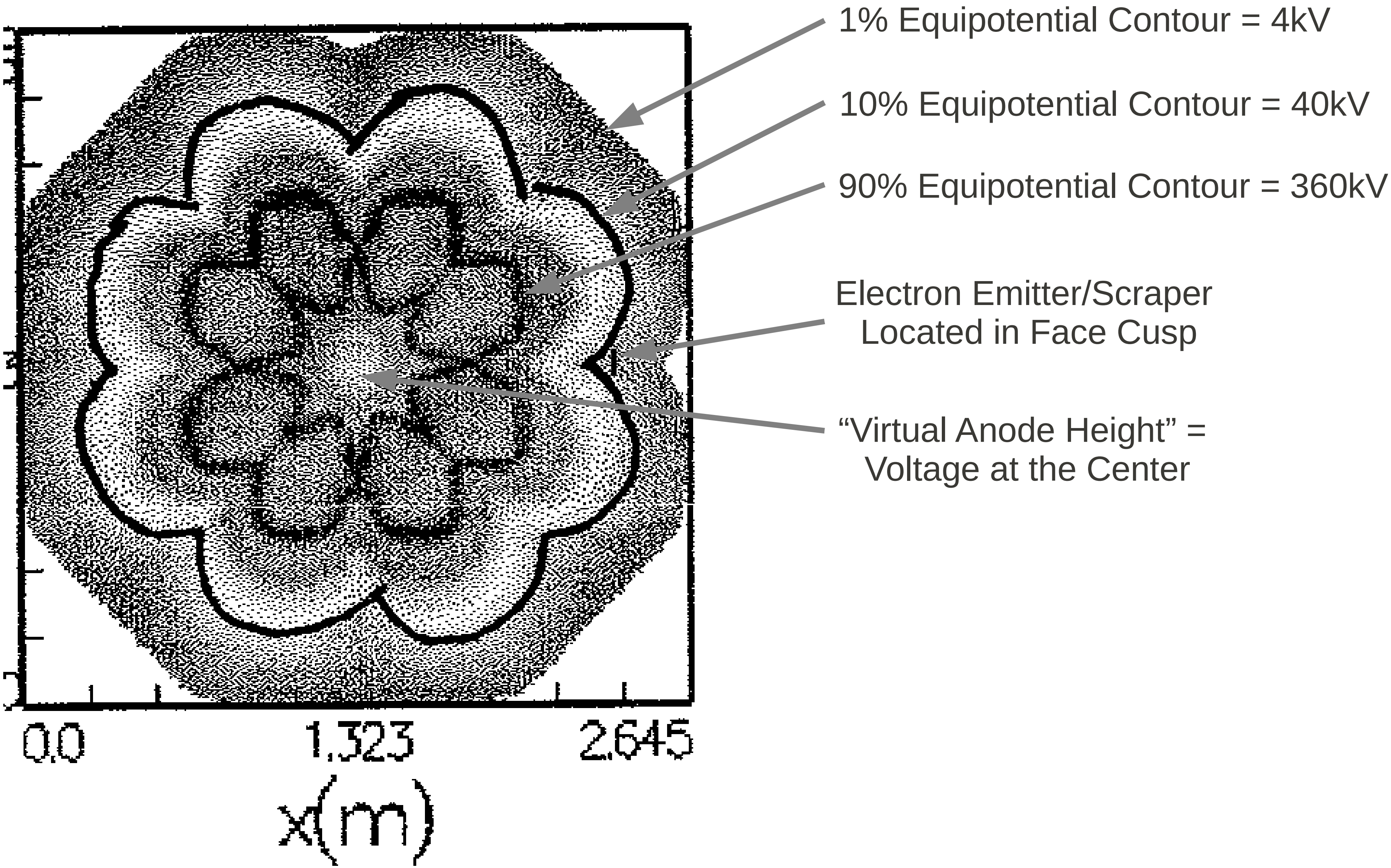


Fig 6 - Rider's 2005 Analysis of IEC

Required Power to Maintain Nonequilibrium Plasma

$$P_{\mathrm{recirc}} \equiv \int_0^\infty (dv\, 4\pi v^2)\left(\frac{1}{2}mv^2\right)\left(\frac{\partial f}{\partial t}\right)_{\mathrm{col}} \Theta[J(v)], \qquad (14)$$

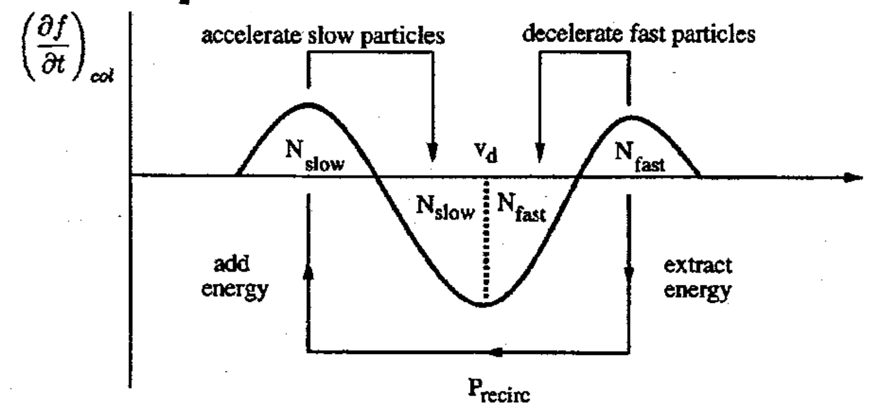
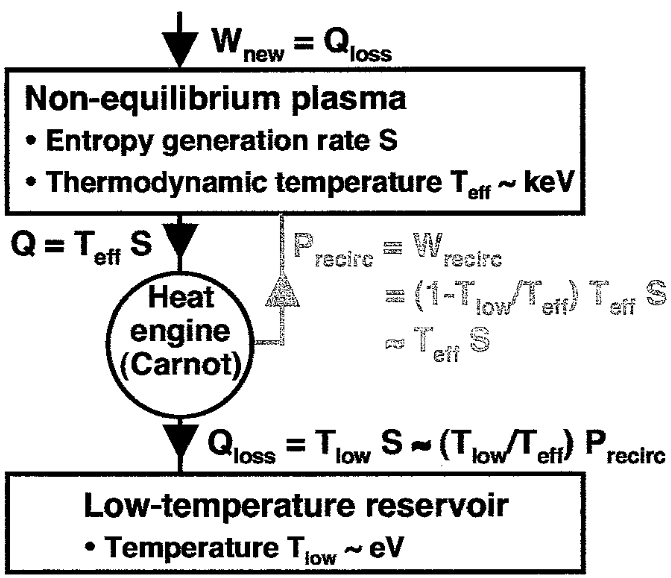


FIG. 2. A schematic diagram showing how to calculate the minimum recirculating power required to maintain a given non-Maxwellian isotropic velocity distribution shape. This particular example shows the recirculating power needed to sustain a distribution qualitatively similar to that in Fig. 1(b), but this general method may be extended to any isotropic but otherwise arbitrary velocity distribution, as described in Eq. (14).

Idealized System for Recirculating Power to Maintain a Nonequilibrium Plasma



THR-16
4/1/05

- P_{recirc}/P_{fus} ~ 5-50 for most interesting cases
- Direct electric converters, resonant heating, etc. would lose too much power during recirculation
- Need novel approaches (e.g., nonlinear wave-particle interactions) that
  - Are >95% efficient
  - Recirculate the power *inside the plasma* without running $P_{recirc} >> P_{fus}$ through external hardware
  - Are resistant to instabilities

T. H. Rider, *Phys. Plasmas* 4, 1039 (1997) and Ph.D. thesis, MIT (1995)—don't overlook Appendix E

Slide-16 from Rider's 2005 talk: http://www.longwood.edu/assets/chemphys/FusionRoute.pdf

Fig. 7 - Scraping Down-Scattered e's

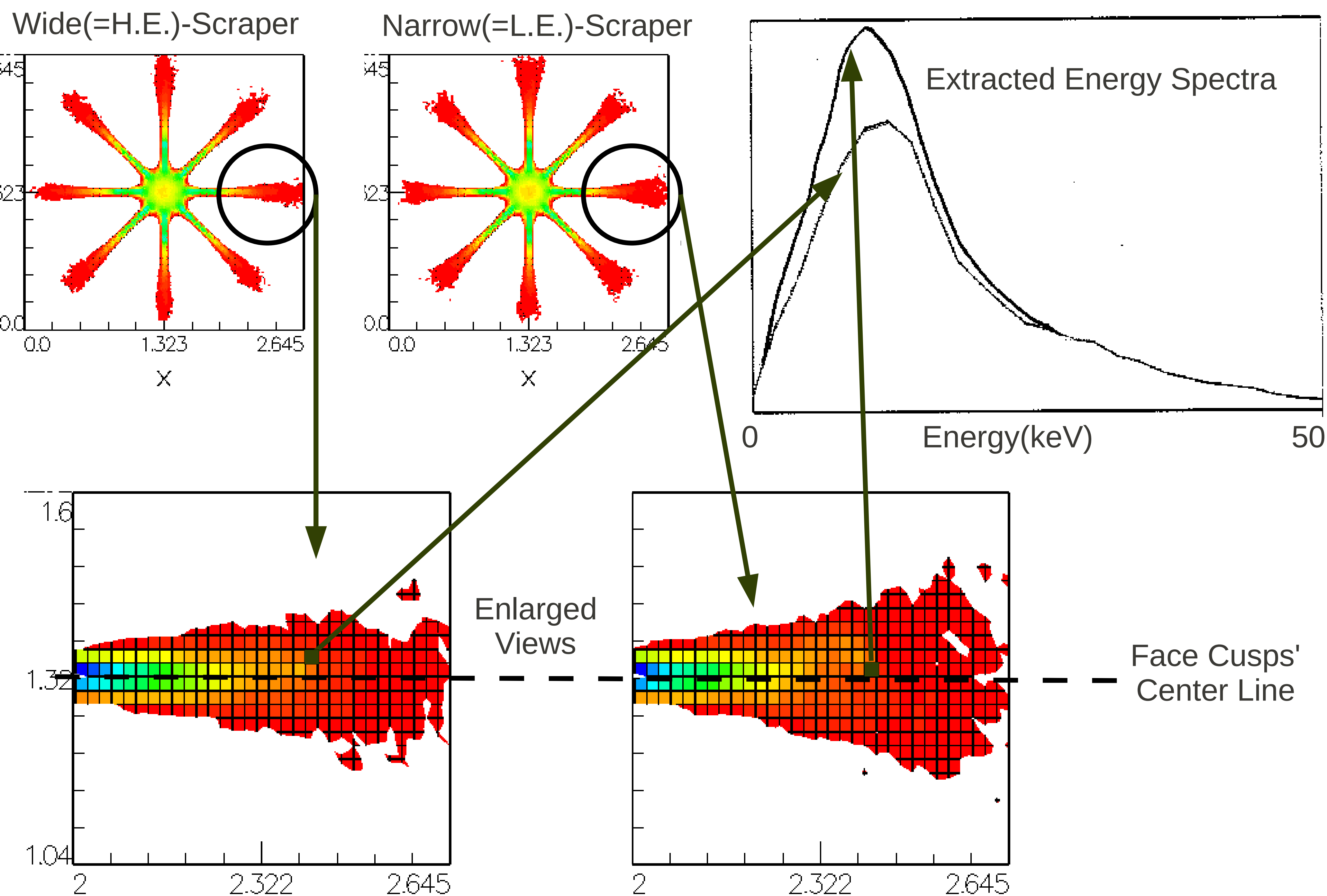


Fig. 8 - Ion Loss Power Calculation

- $P_{in} \equiv$ proton energy-loss-rate + boron energy-loss-rate (through corner cusps)

  $= (\text{\# slabs/cube})\ (\text{\# cusps/slab})\ \{\Sigma[\text{Particle Loss-energy})][\text{Particle loss-rate}]\}$

  $= (L/\lambda_D)\ (4)\ \{[\tfrac{1}{2}(956\text{MeV})(8e6)^2/c^2][\tfrac{1}{2}(114-110)(9e10)/(11e\text{-}6s)]$

  $\quad +[\tfrac{1}{2}(11)(931\text{MeV})(5.4e6)^2/c^2][\tfrac{1}{2}(114-110)(1.2e10)]/[(11e\text{-}6s)]\}$

  $= (30)(4)\{[(340\text{keV})(1.6e16/s)]+[(1700\text{keV})(2.2e15/s)]\} = 6.5e23 + 4.5e23$

- P_{in} = 1.1e24 eV/s

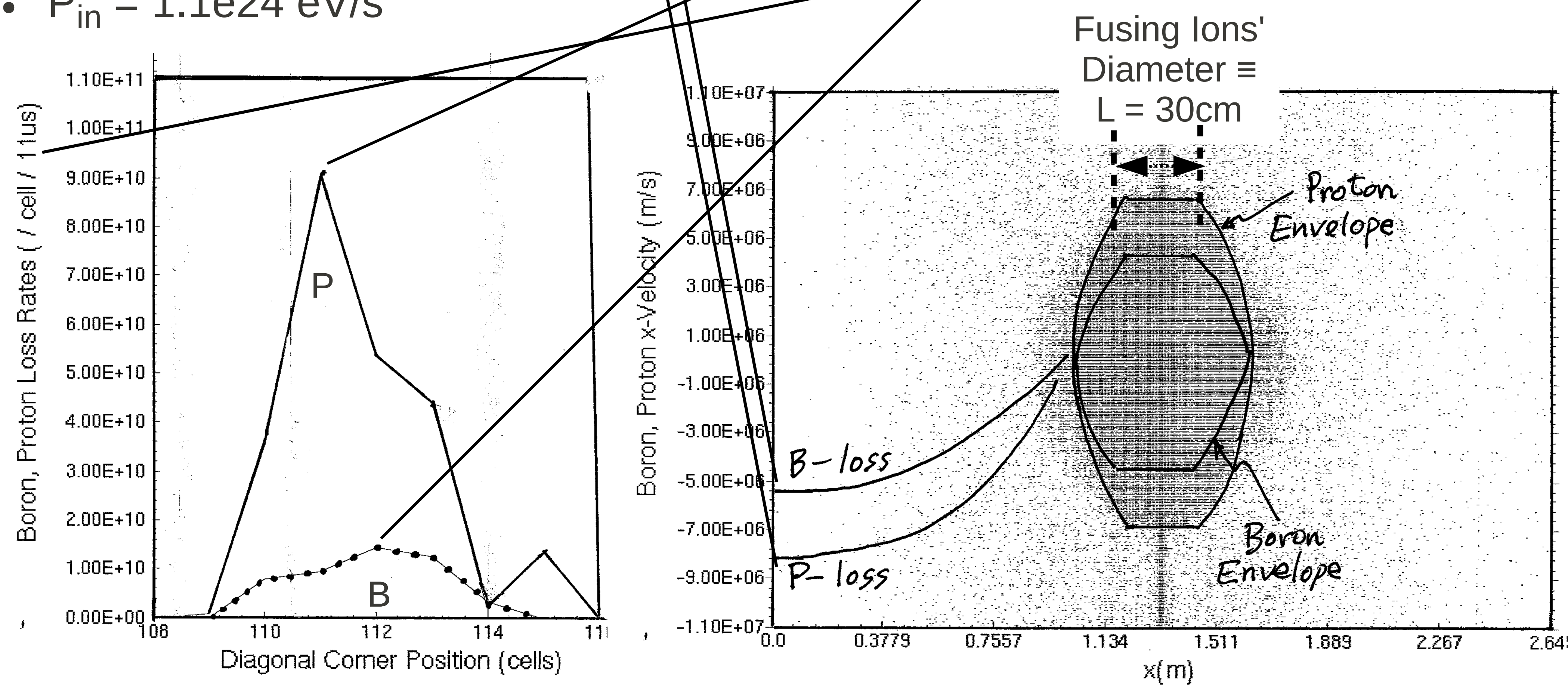


Fig. 9 - Power Balance Q

- Simulated (R = 35cm) power balance: $Q(R) \equiv P_{fus} / P_{in}$ where:
  - $P_{fus} = n_p\, n_b \langle\sigma_f\, v\rangle\, L^3\, E_f$ eV/s [6]
    - n_p = proton 3D density $\equiv N_p / \lambda_D$ = 1.1e17/m^3
    - n_b = boron 3D density = n_p / Z (Proton and boron partial pressures are made equal.)
    - Z = boron charge state from ion gun = 5
    - N_p = simulated (2D) proton density = 1.1e15/m^2 (Fig. 10)
    - λ_D = Debye length = 7.43e2 $E_e^{1/2}\, n_e^{-1/2}$ cm = 0.01m (Fig.10 & Formulary pg. 28 [7])
    - E_e = maximum electron energy inside well = 400keV (Fig. 10)
    - $n_e = 2n_p$ (Plasma quasi-neutrality is an inherent property of the simulation.)
    - <> = fusion x.c. times c.m. velocity = 8e-29m^2 x 1e7m/s = 8e-22m^3/s (Title page)
    - L = ion plasma cube dimension in meters = 0.3m (from previous slide)
    - E_f = fusing ion pair energy release in eV = 8.7 MeV (Formulary pg. 44 [7])
  - P_{fus} = (1.1e17) (2.2e16) (8e-22) (0.3^3) (8.7e6) eV/s = 4.5e17 eV/s
- $Q(R{=}35cm) = P_{fus} / P_{in}$ = 4.5e17 / 1.1e24 = 4.1e-7 (P_{in} from Fig. 8)

[6] Glasstone and Lovberg, “Controlled Thermonuclear Reactions”, van Nostrand, 1960, eq. 2.10
[7] NRL Plasma Formulary, http://wwwppd.nrl.navy.mil/nrlformulary/NRL_FORMULARY_11.pdf

Fig. 10 - Diagnostics Determining P_{fus}

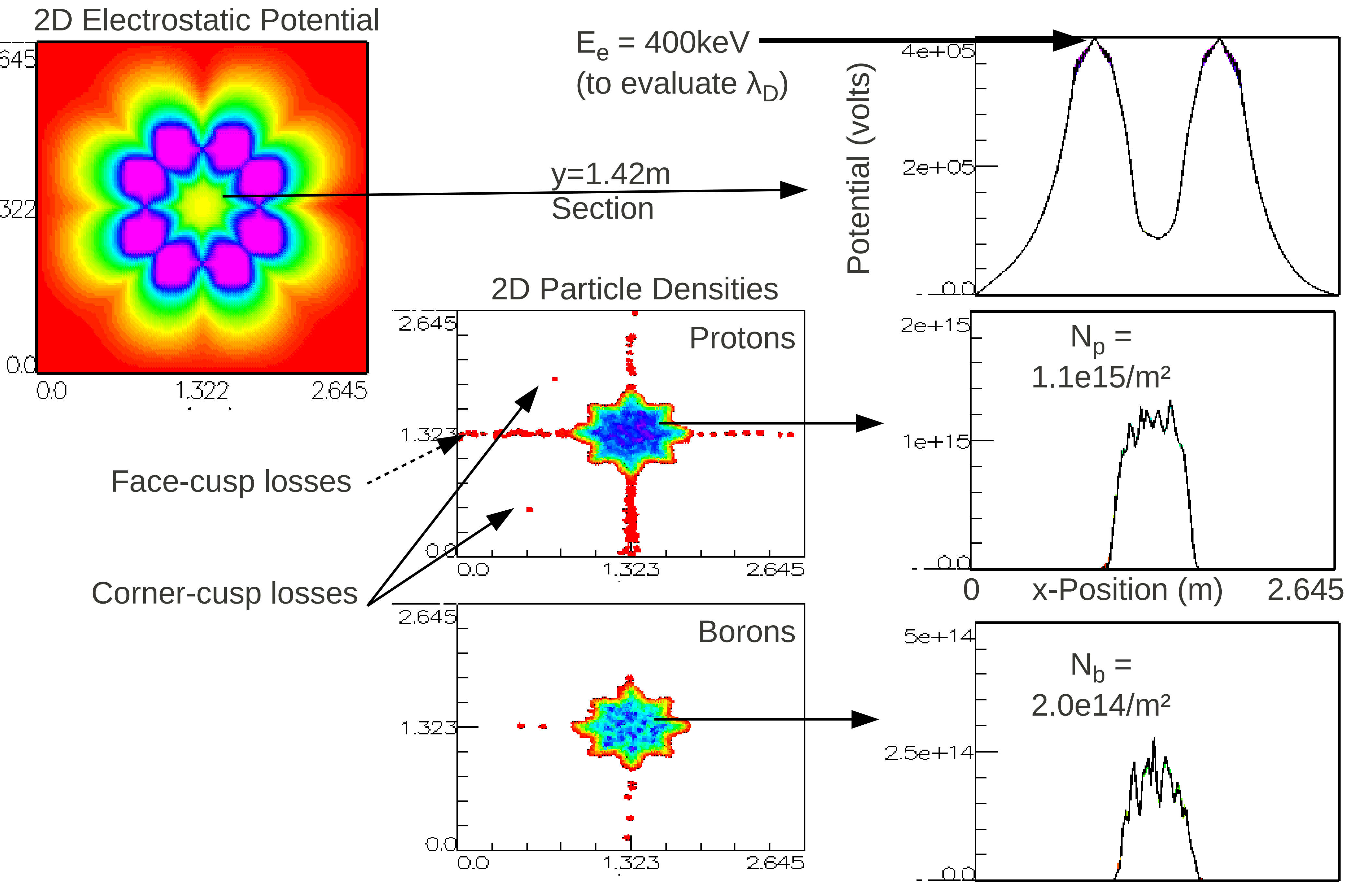
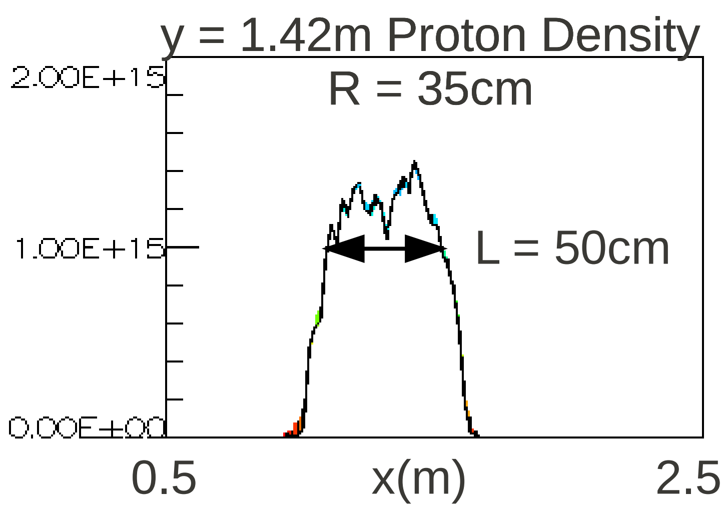


Fig. 11 - Reactor Break-Even Radius

- Bussard's Scaling Formula: $Q_1/Q_2 = (R_1/R_2)^5$ [8]
- Break-Even Formula: $Q(R=35cm)/Q(R_b) = (R/R_b)^5$
  - $Q(R_b) \equiv 1$
- Solving for Break-Even Radius: $R_b = R/Q^{1/5}$
- $R_b = 0.35m/(4.1e\text{-}7)^{0.2} = 6.6m$ = smaller than **ITER**



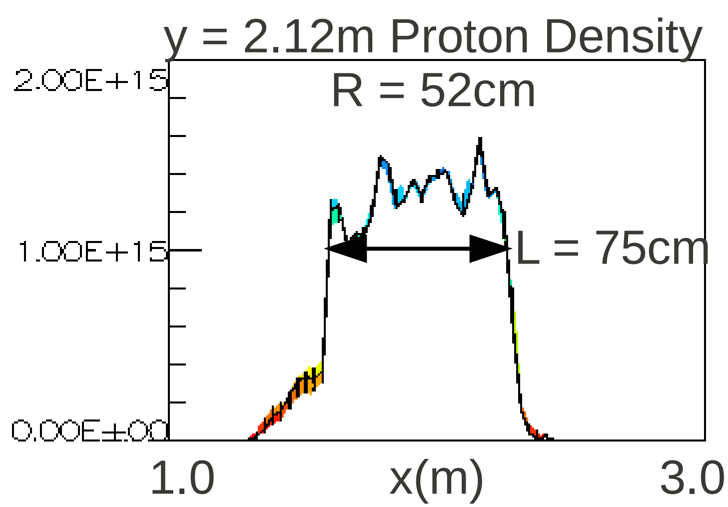
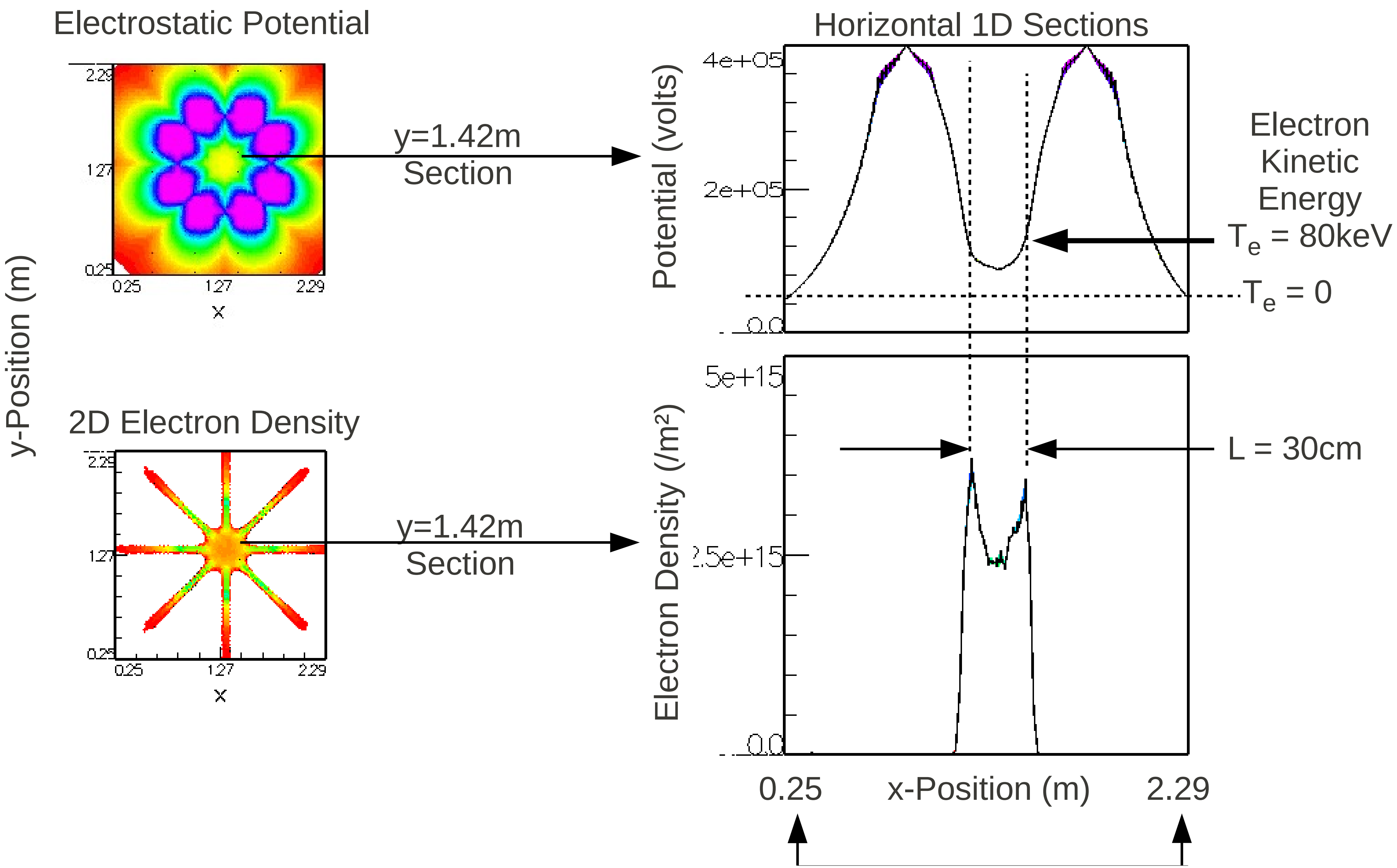


Fig. 12 - Bremsstrahlung Power Loss

- $P_b = 1.69e\text{-}32\ n_e\ T_e^{1/2}\ [n_p + Z^2 n_b]\ L^3$ W [Formulary p.58]
- $P_b = 1.1e\text{-}13\ n_e^2\ T_e^{1/2}\ [0.5 + (25)(0.1)]\ L^3$ eV/s
  - n_e = electron density in cm^{-3} = 2.2e11/cm^3 (Fig. 9)
  - T_e = electron kinetic energy in eV = 80keV (Fig 13)
  - L = electron core edge dimension in cm = 30cm (Fig. 13)
- $P_b = 1.1e\text{-}13\ (2.2e11)^2\ (8e4)^{1/2}\ [3.0]\ (30)^3$ eV/s
- P_b = 1.3e17 eV/s
- $P_b \approx$ 30% P_{fus} (Fig. 9)
- Bremsstrahlung losses ≈ 1/3 fusion output power

Fig. 13 - Diagnostics Determining P_b



These arrows mark chosen electron-emitter positions.
Electrons have ~zero kinetic energy at these points.

Fig. 14 - How to Reduce P_b Losses

- $P_b \sim T_e^{1/2}\ [1 + 25\ (n_b/n_p)\ ]$
- To reduce P_b the reactor design can change:
  - Reducing T_e to 1% E_e would reduce P_b by 4.5X. [4]
  - Boron fraction n_b/n_p 20 -> 10% would reduce P_b by ~2X.
- Reducing T_e might increase reactor size (R_b).
  - Not yet tested in simulation.
- Radiation might be reduced to 5% of fusion power.

Fig. 15 - p + ^{11}B Power; Conclusions

- New method efficiently recycles electron energy.
- Simulation predicts break-even R_b = 6.6m
- Additional design issues still need attention:
  - Electron power drain must be reduced.
  - Bremsstrahlung power drain must be reduced.
- A 3D simulation is needed for more realistic P_{in}.
- The future of aneutronic fusion power is bright.