Electron cloud effects in intense, ion beam linacs & theory and experimental planning for HIF

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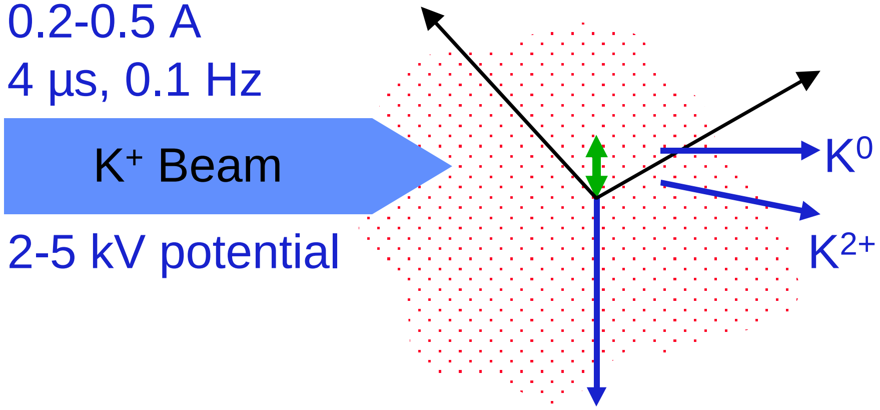
Beam interactions with gas and walls

Beam interactions produce electron cloud effects but also provide opportunities for diagnostics

Beam on gas, I_b

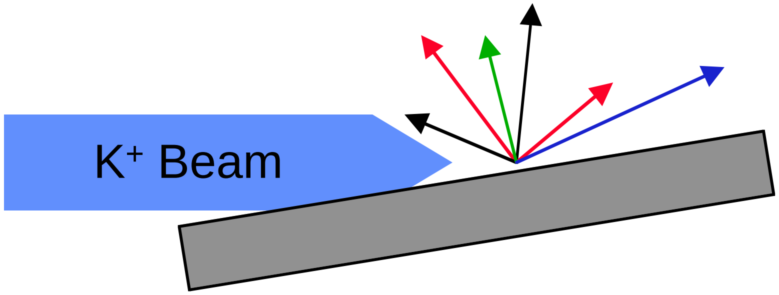
1.0-1.8 MeV
0.2-0.5 A
4 µs, 0.1 Hz



2-5 kV potential

Electrons - trapped (major source expected)
Ions - expelled radially (0-5 keV, ~0.2 µs)
Photons (excitation of gas or beam, 0.01 µs delay)
Some beam ions neutralized or doubly ionized

Beam loss to walls, I_{bw}

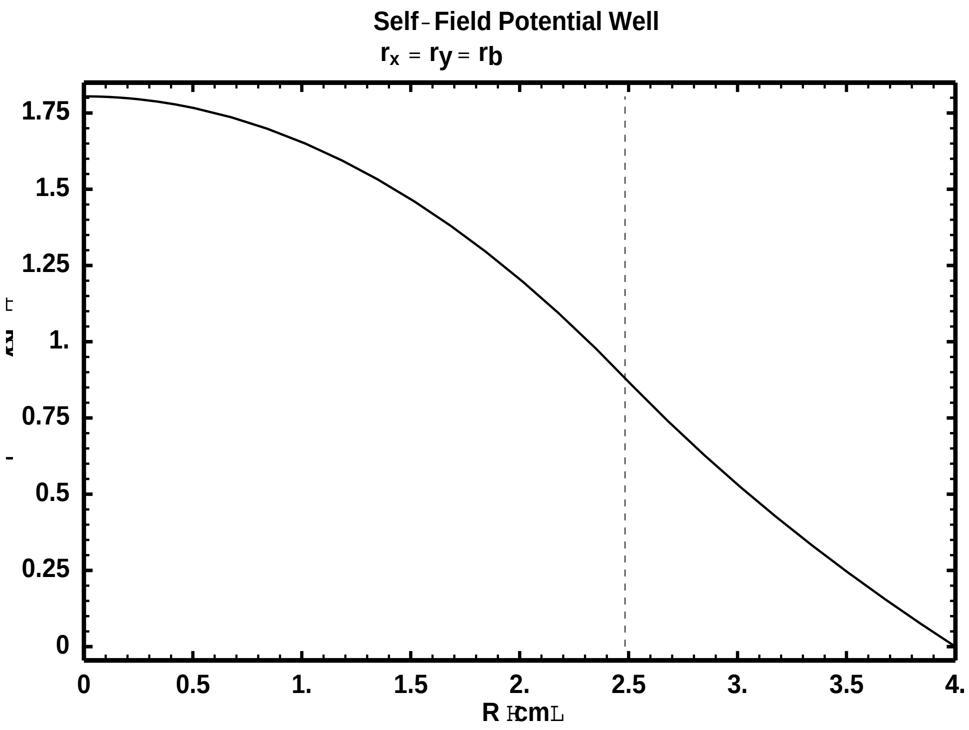


Secondary electrons (I_{se} ~20 I_{bw})
Scattered K^+ ions (≤0.7 I_{bw} - TRIM)
Sputtered metal (≤25 - TRIM)
Desorbed gas (~10^4 I_{bw} Extrapolated)
Photons I_ν(ramp up in time from beam on desorbed gas?)

Positive beam potential confines electrons and expels ions (from gas ionization)

Beam potential (kV) for beam of 0.2 A at 1.0 MeV

- Electrons from ionization of gas are born deeply trapped (confined until end-of-pulse)
- Electrons from the wall are untrapped or weakly trapped
- By varying beam radius we can vary potential at beam edge
- Dashed line indicates beam edge
- Beam potential scales linearly with beam energy



At end-of-pulse, beam potential decreases with beam current. First weakly trapped and then deeply trapped electrons are lost to wall.

Approximate cross section for background and desorbed gas in vacuum system

Present experiments: expect $n_e / n_b \sim 0.1$ for 4 µs pulses at 1-2 MeV in 10^{-7} Torr

- Actual cross section is for ionization of hydrogen atoms by protons*.
- For approximate heavy-ion impact cross sections, normalize beam energy to energy per nucleon.

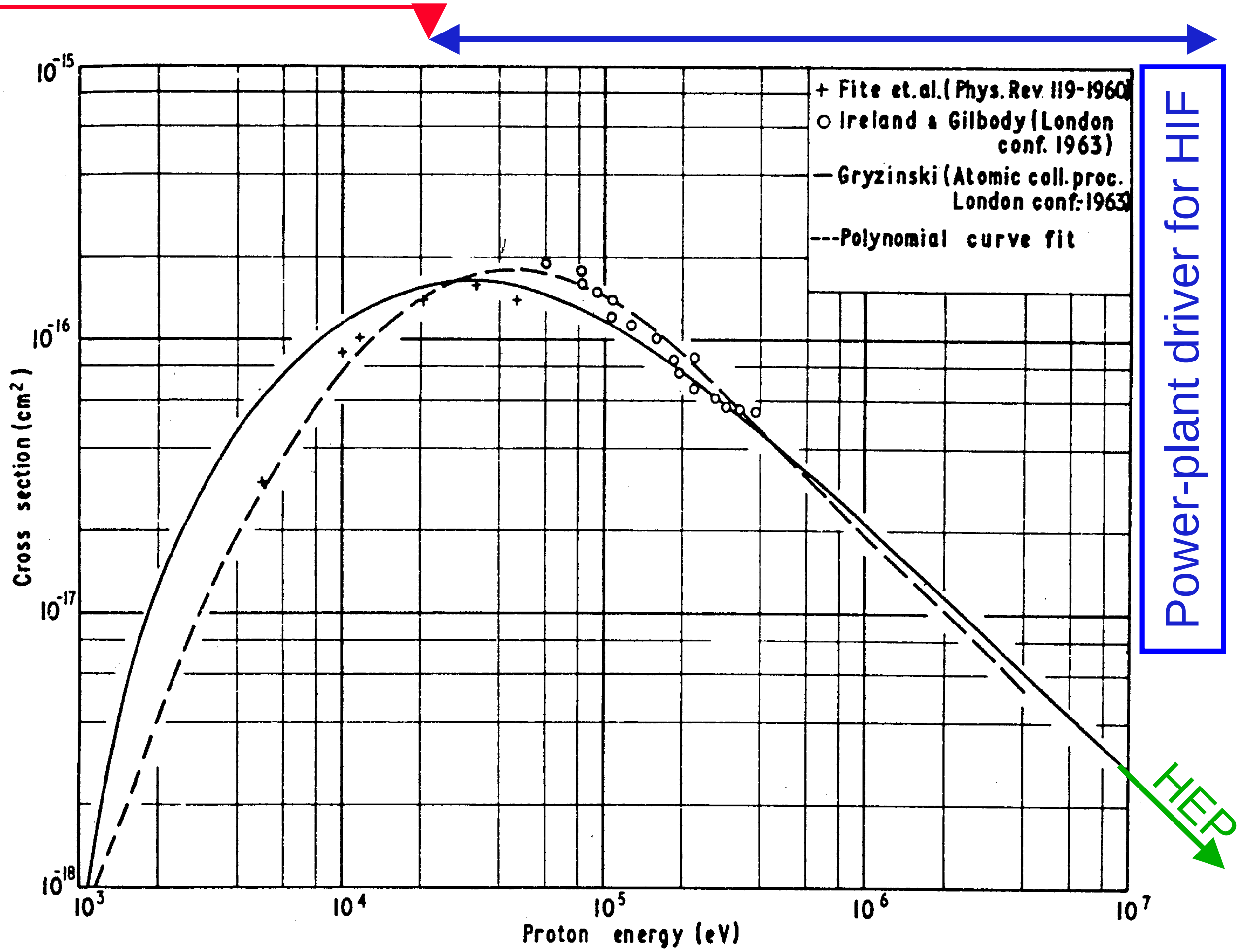


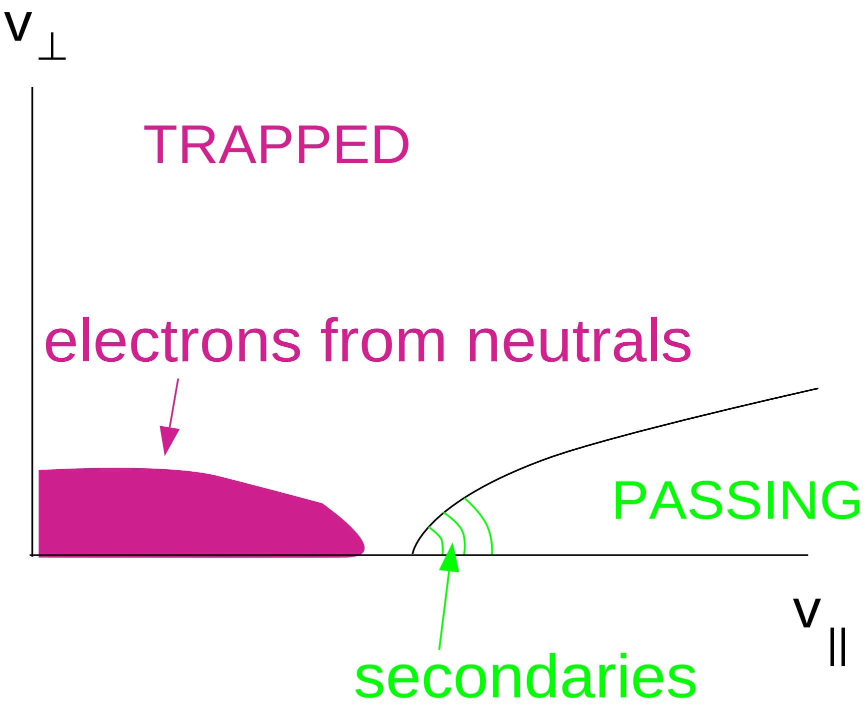
Fig.15 Ionisation of atomic hydrogen by protons

* R. L. Freeman and E. M. Jones, Tech. Report CLM-R-137, Culham Laboratory, UK (1974).

Electron confinement in magnetic quadrupoles

Velocity distribution of electrons on beam axis

Magnetic moment: $\mu = E_{\perp}/B$ is constant for an electron unless B changes significantly across electron orbit.



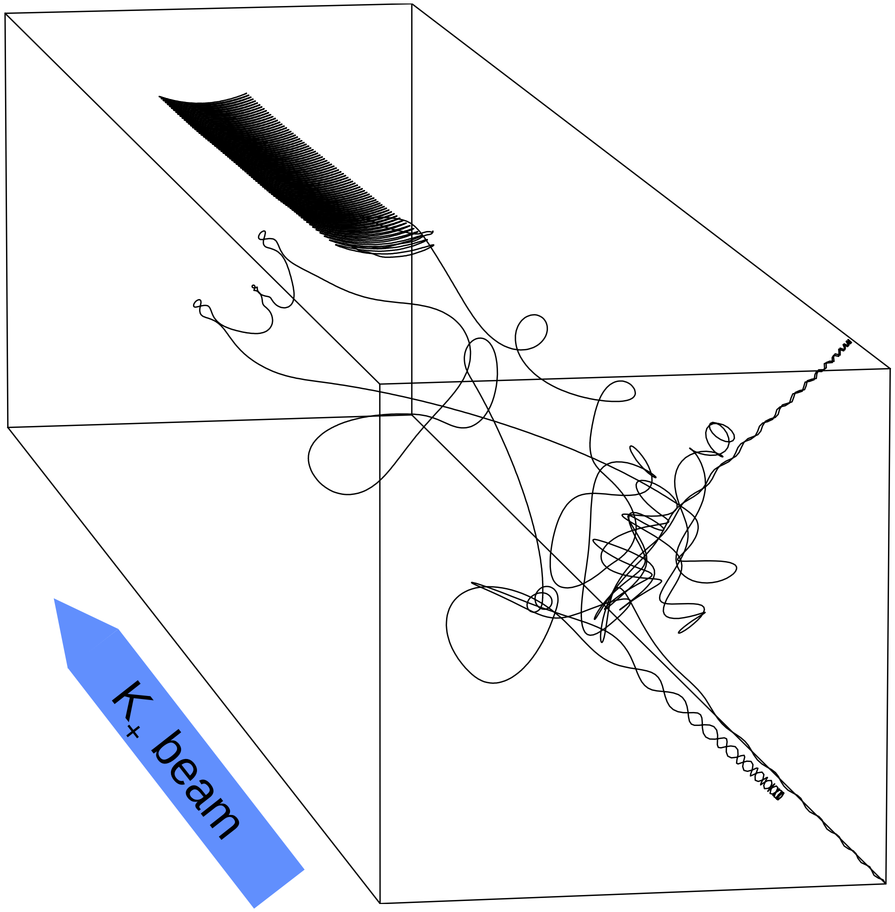
- Ionization by beam creates deeply trapped electrons.
- Secondary electrons off wall are untrapped, unless high instability level or while beam potential is rising at beam head.
- When beam pulse passes, its potential decreases. The loss boundary moves inwards: so first weakly trapped, then more deeply trapped electrons escape to the wall. Measurement of beam potential and electron current to wall VS time yield the trapped electron potential energy distribution (modified by trapping from jumps in magnetic moment).

Acceleration gap can detrap electrons

- Electron in magnetic field constrained – radially and azimuthally to follow field lines, axially to drift at sum of E x B and ∇B velocities.

- Electron, accelerated to energy greater than beam potential, is lost to wall.

- Then electron lifetime ~ drift time in magnetic quadrupole between acceleration gaps



Diagnostic goal – measure each term in electron particle balance

I. Electrons from ionization of neutral gas molecules

a. $dn_e/dt = n_n\, n_b \,\langle \sigma v_b \rangle - n_e/\tau_e$

b. $n_n = (2/r_w) \,\langle n_{wb}\, v_{\perp w}\, \kappa_n \rangle\, (t-\tau_{TOF})$ for $t \geq \tau_{TOF}$

2. Secondary electrons (in beam) from wall at r_w

$$dn_e/dt = (n_{wb}/\, n_b)(v_{\perp w}/v_b)\, n_b \,\langle \Lambda \rangle\, (v_b/r_w)\, \kappa_e - n_e / \langle \Lambda \tau_{ew} \rangle$$

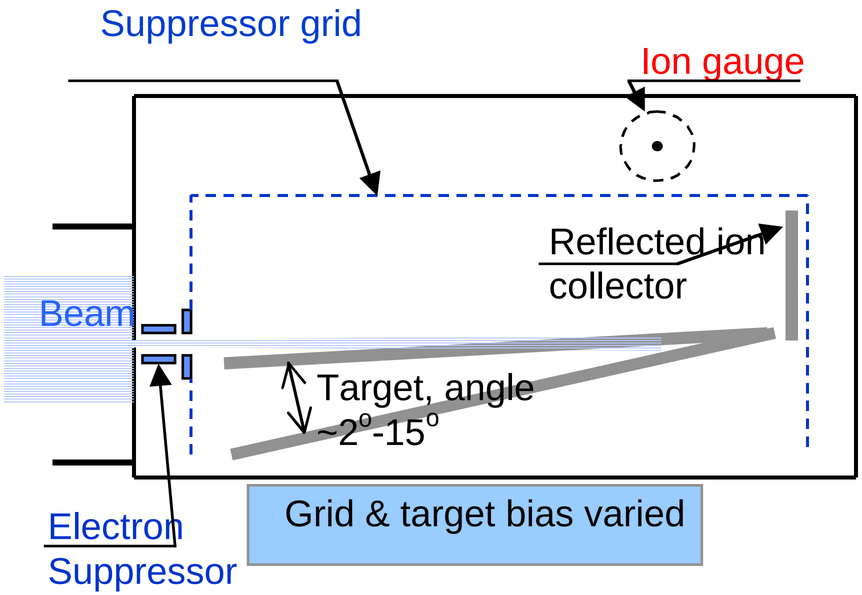
where the first 2 factors give the fraction of beam current hitting the wall; Λ is the multiplier due to trapping of electrons; κ_e is the secondary emission coefficient; τ_{ew} is the electron wall-to-wall transit time, and $\Lambda\tau_{ew}$ is the electron confinement time.

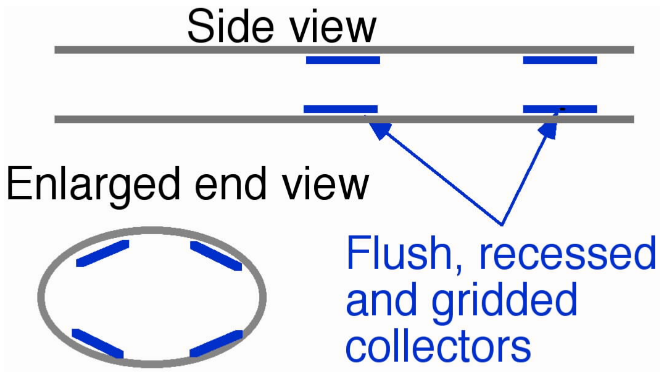
Color indicates: measure directly, infer from equations

Initial diagnostics will quantify electron issues for HCX

Gas, electron source diagnostic, **GESD**

- Will measure number and energy of electrons and gas molecules per incident K^+ ion (1.0-1.8 MeV)
- Calibrate secondary electron measurements in terms of beam loss
- Can evaluate mitigation techniques





Collectors in quadrupole magnets

- Flush probe – measure secondary electron current, with GESD data infer beam loss, gas reflux, $n_e(t)$, $n_0(t)$
- 2-grid probe – measure expelled ion current from gas in beam, calibrate for $n_0(t)$, infer one component of $n_e(t)$.
- 1-grid probe – measures ion + electron current, infer untrapped electrons; at end-of-pulse infer number and trapping-energy of electrons
- Capacitive probe – E-field implies peak beam potential

Array of simple diagnostics quantitatively distinguish beam-interaction products

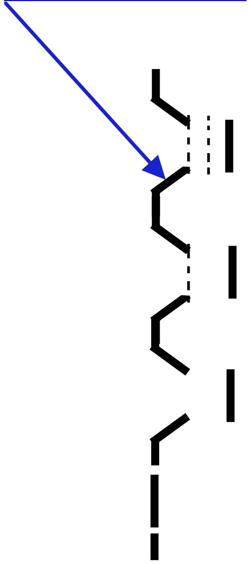
I_{in}, n_{in} Expelled ionized gas
I_{en}, n_{en} Electrons from gas
I_{es}, n_{es} Secondary electrons
n_n Gas density in beam

I_b Beam current
I_{wb} Beam to wall
I_{sb} Scattered beam
n_{wn} Gas near wall

E_b Beam electric field
$I_{e\nu}$, $n_{e\nu}$ Photo-electrons
I_e, n_e Trapped electrons
Φ_b (r) Beam potential

Suppress I_b,most I_{sb}

Diagnostics located in radial magnetic field to control secondary electrons and allow electrons escaping beam to reach collector



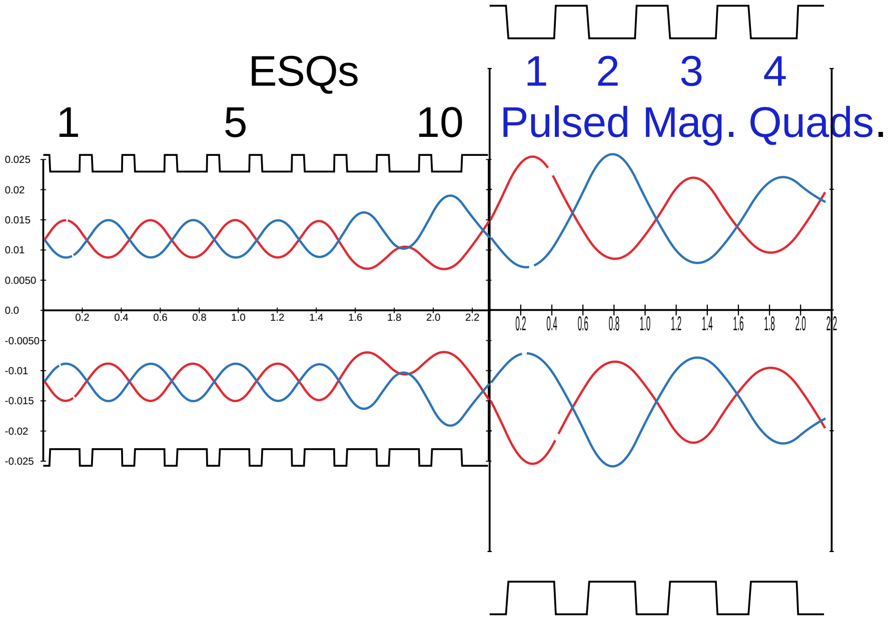
Diagnostic	Suppresses	Measures	Infers
2-grid analyzer	I_e, I_{es}, $I_{e\nu}$, I_b, I_{sb}, E_b	I_{in} = Beam-gas ionization	I_{en}, n_n
1-grid analyzer	$I_{e\nu}$, I_b, I_{sb} E_b	$I_{in} + I_e$	I_e, I_{es}, $n_e=\int I_e dt$
Capacitive probe	I_b, I_{sb}, (I_{es}-by deeper recess of collector)	E_b perturbed by I_{in}	Φ_b, & $(n_b - n_e)$
Flush probe	Nothing	$I_{es} + I_{e\nu}$	I_{wb}, n_n
3-grid analyzer	I_e, I_{es}, $I_{e\nu}$, I_b, I_{sb}, E_b	I_{in}, ion energy, or $I_{e\nu}$	$\Phi_b(r)$, $(n_b - n_e)$

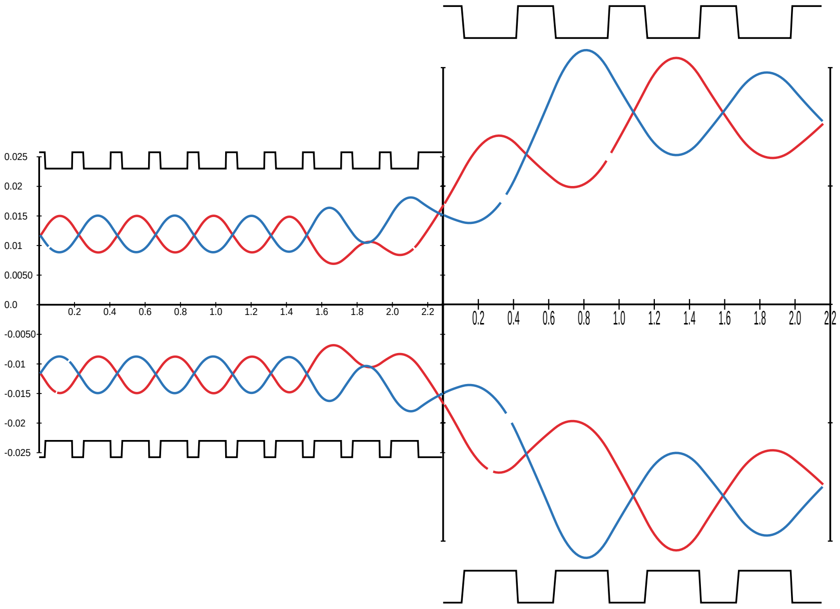
Vary envelope size – where do we run into trouble with e-cloud?

- HCX pulsed magnetic quadrupoles provide flexible operating range
- Find “e-cloud trouble,” try mitigation techniques

Minimize e-clouds with minimum fill factor

- Large fill factors achieved with lower B’. Expand beam until electron density is large.





Summary - We expect exciting results from E-Cloud Experiments for Heavy-Ion Fusion

- Interactions of beams with gas and walls provide both opportunities and difficulties for e-cloud diagnostics.

- For HIF parameters, we expect beam-gas interactions to dominate, producing deeply trapped electrons.

- Defined array of initial diagnostics to measure interaction products
  - Determine quantitative electron particle balance
  - Minimize errors from other interaction products.

- Theoretical studies show the importance of E x B and ∇B drifts
  - Constraining electron flows in magnetic quadrupoles
  - Acceleration gaps provide loss mechanism for trapped electrons

- A large operating window for HCX experiment provides range from minor to major e-cloud problems.

- We have good experimental access for additional diagnostics and for testing mitigation techniques.