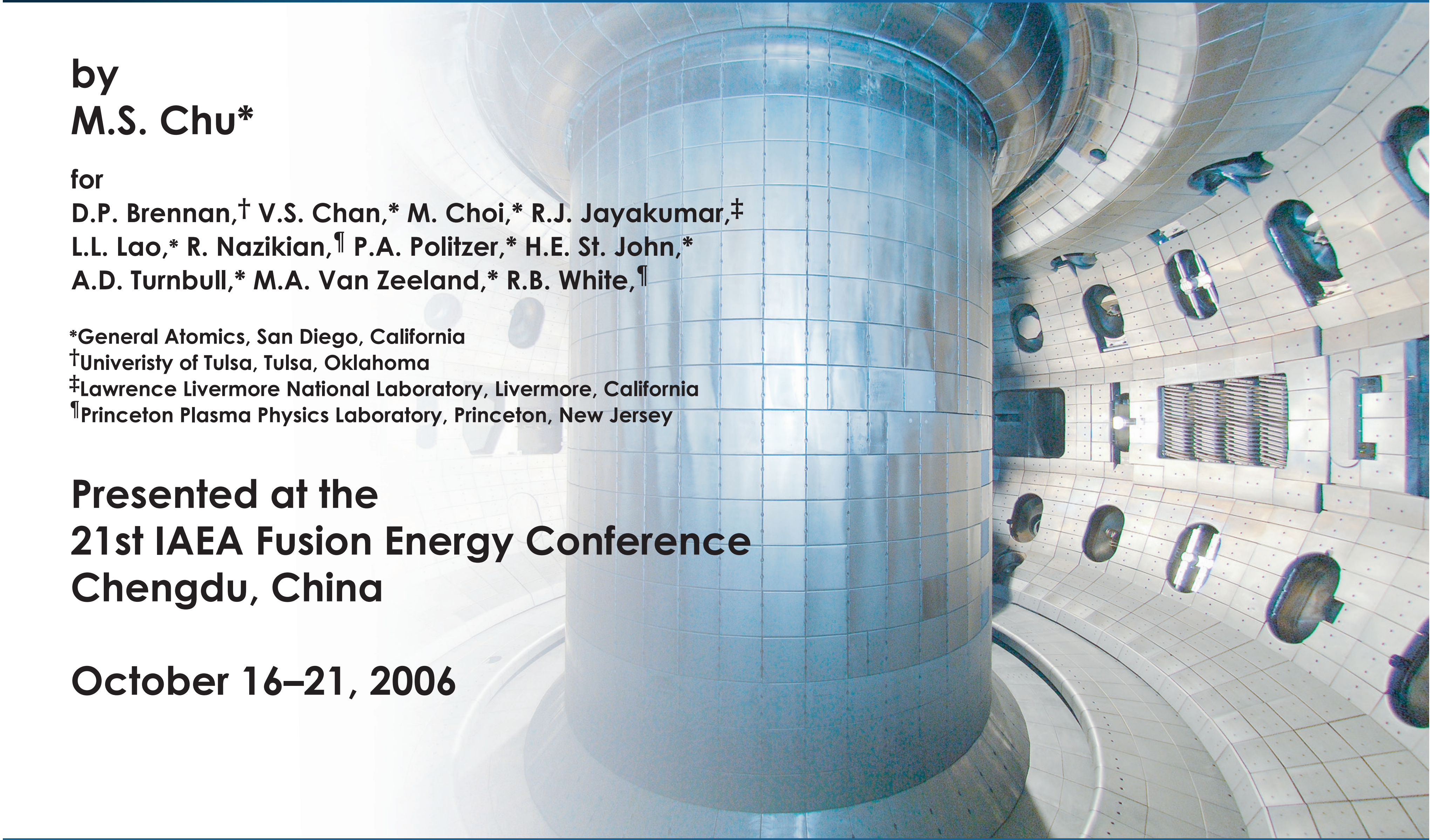
Maintaining the Quasi-steady State Central Current Density Profile in Hybrid Discharges



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GENERAL ATOMICS
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The Hybrid Scenario is an Attractive Option for ITER Operation

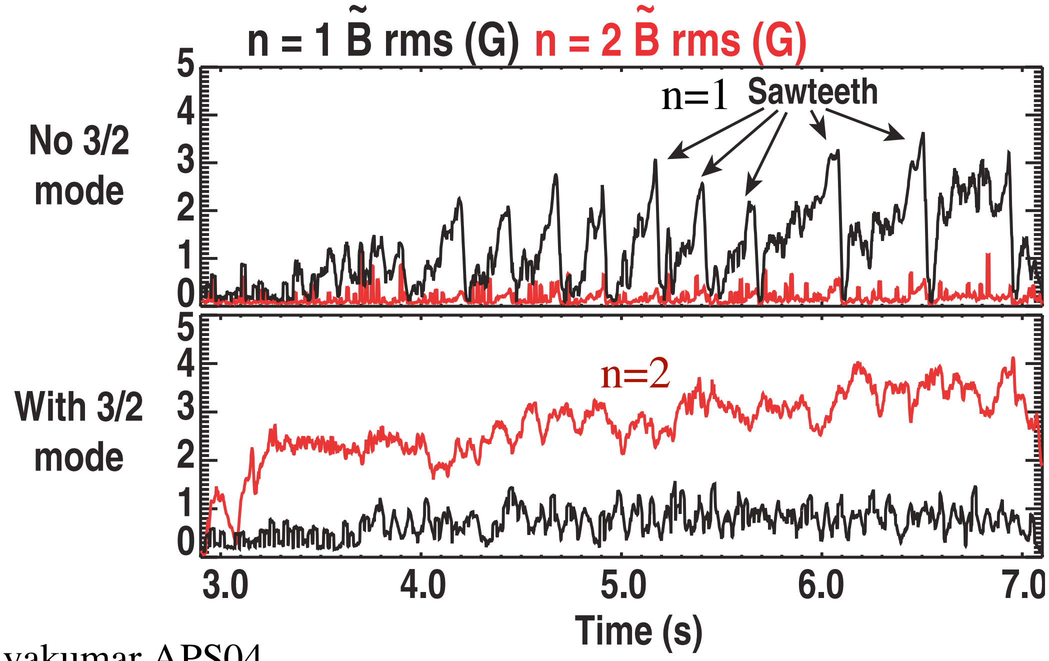
- Good confinement, nearly steady state
- Projected ITER performance at or above $Q_{fusion}=10$
- Robustly achievable over wide range of discharge parameters
- Compatible with sustained ignition scenario in ITER
- Can operate near the high β stability limit
- Reduced or eliminated occurrence of sawtooth

Hybrid Discharge Parameters

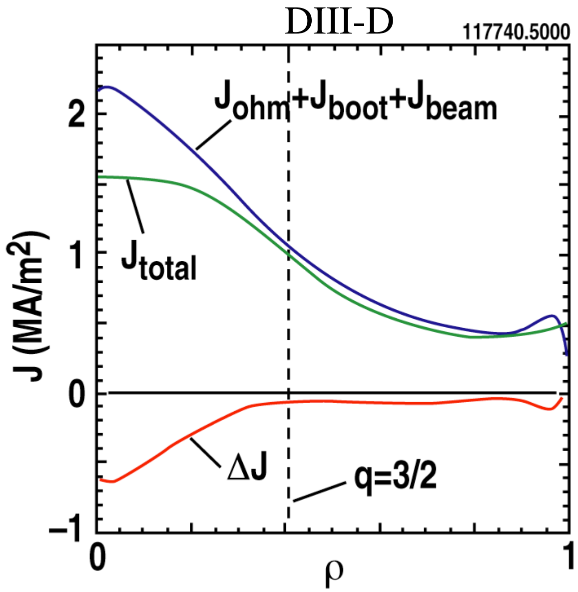
	DIII-D	ITER
I_p	1.2 MA	13.9 MA
B_T	1.1-1.9 T	5.3 T
R	1.75 m	6.2 m
q_{95}	2.8-4.7	3.2
β_N	2.6-3.3	2.8
H_{89p}	2.3-2.7	2.4
a	0.6 m	2.0 m
Q	N/A	12.9
T_{dur}	9.5 s	1500 s

Wade Nuclear Fusion 2005

NTM-MHD Mode is Key to Maintaining $q_0 \geq 1$ and Avoiding Sawteeth



Jayakumar APS04



ΔI≈-50 kA

Politzer EPS05

- In DIII-D hybrids, rotating 3/2 or 4/3 NTM islands observed.
- Magnetic islands prevent development of sawteeth - $q_0 \sim 1+\varepsilon$
- There is a current deficit – possibility of negative current drive inside neoclassical island surface

→ Explore the Relation of NTM Island and Current Deficit

Outline

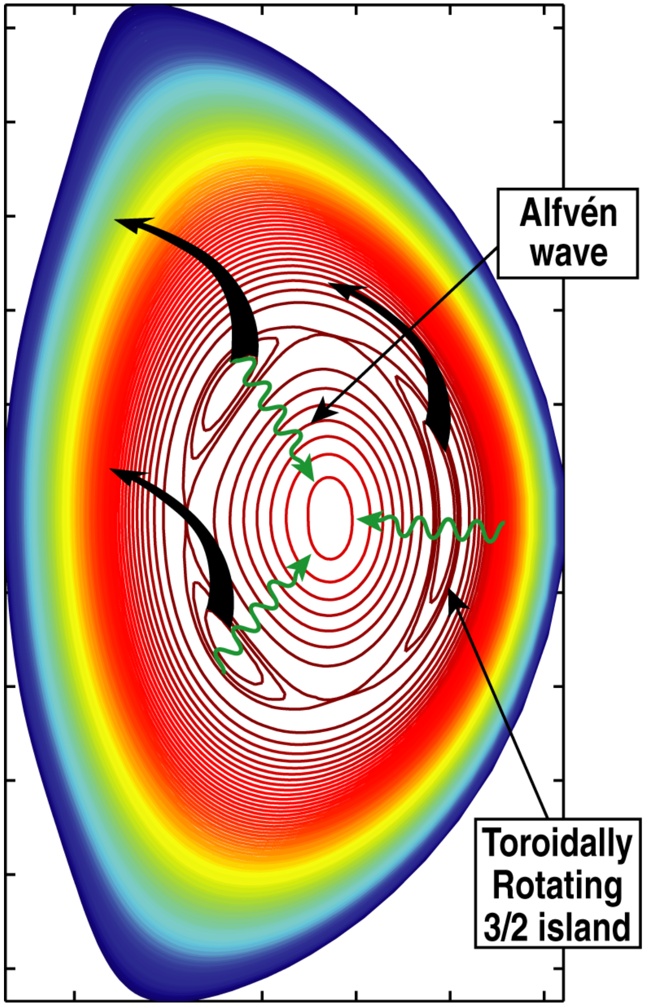
- **Rotating island provides rotating magnetic perturbation and acts as antenna, emitting Alfvén waves into the surrounding plasma**

- **Particle drifts due to Alfvén waves produce charge separation and effectively drive counter current**
  - Polarization drift could give rise to mode conversion
  - Curvature drift produces side band electric fields

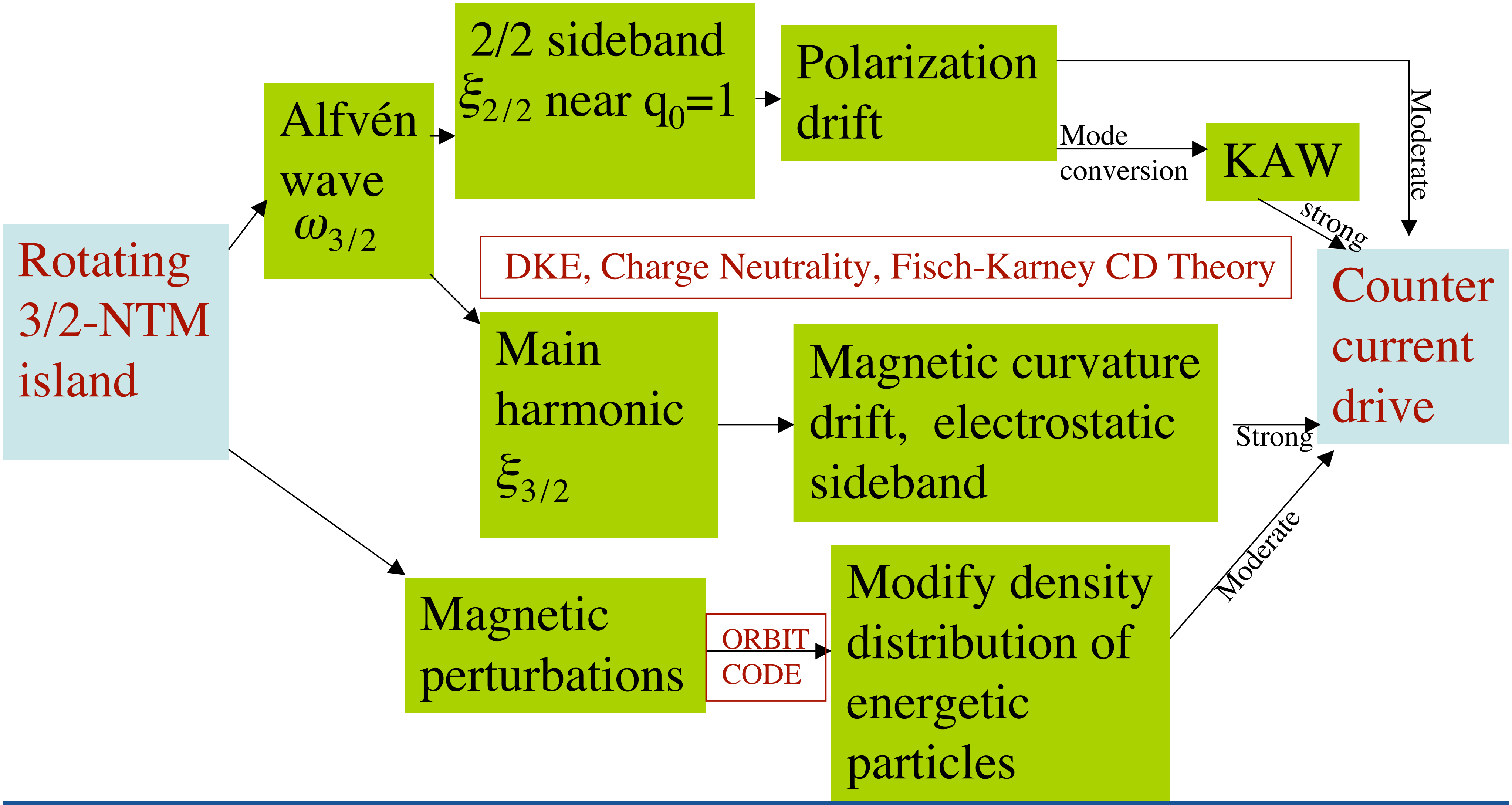
- **The wave can scatter NBI ions and reduce efficiency of NBI current drive**

Rotating Magnetic Island Emits Alfvén Wave and Redistributes Fast Ions

- **Alfvén waves drive current through modification of plasma drifts and excitation of $E_{\|}$**
  - Polarization drift and subsequent mode conversion to kinetic Alfven wave(kAW) excites $E_{\|}$
  - Magnetic curvature drift causes charge accumulation and drives $E_{\|}$
- **Magnetic field perturbation from NTM island can redistribute density of energetic ions and reduce NBI central current drive**



Current Drive by Alfvén Wave Is Strong Candidate to Explain Counter Current Drive



Rotating 3/2-NTM island

Alfvén wave $\omega_{3/2}$

2/2 sideband $\xi_{2/2}$ near $q_0=1$

Polarization drift

Mode conversion

KAW

Moderate

strong

DKE, Charge Neutrality, Fisch-Karney CD Theory

Main harmonic $\xi_{3/2}$

Magnetic curvature drift, electrostatic sideband

Strong

Counter current drive

Magnetic perturbations

ORBIT CODE

Modify density distribution of energetic particles

Moderate

Current Drive by Alfvén Wave Is Strong Candidate to Explain Counter Current Drive

Rotating
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Modify density
distribution of
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KAW

Counter
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Established F-K Current Drive Theory Requires Parallel Electric Field to Drive Current

- **Phase velocity important for current drive**

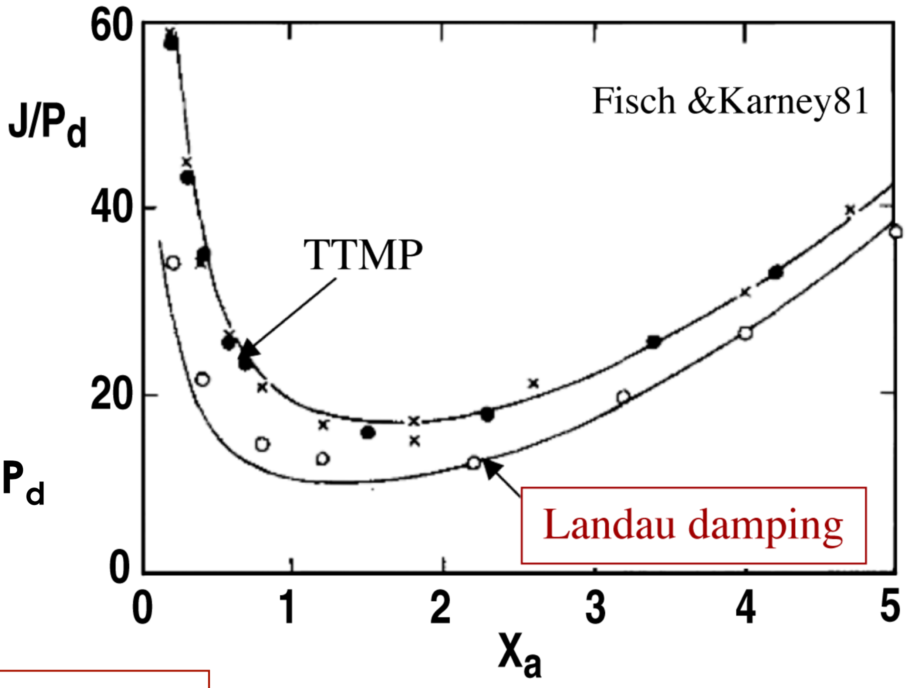
Current density

Power dissipation

$$\frac{J/en_0 v_{te}}{P_d/m_e n_0 \nu_e v_{te}^2} = \frac{8}{x_a} + 2 + 1.4(x_a)^2$$

Phase velocity

$$x_a = \frac{\omega^e_{3/2}}{k_\parallel v_{te}}$$



Landau damping

- **Electrons Landau damp on $E_\parallel$ therefore P$_d$ depends on $E_\parallel$**

- **$E_\parallel$ required to drive J**

Parallel electric field

$$J = \frac{n_0 \pi e^3}{(2\pi)^{1/2} m_e^2} \frac{\omega_{3/2}}{v_{te}^3 \nu_e} \frac{\langle E_\parallel^2 \rangle}{k_\parallel^2} \exp(-\frac{x_a^2}{2})\left[8 + 2x_a + 1.4x_a^3\right]$$

Perpendicular Electric Field Excites Parallel Electric Field through Particle Drifts

- **Kinetic theory determines electron and ion density responses to perturbing electric fields**

Electric field →

$$\vec{E} = -\vec{\nabla}_{\parallel}\,\psi - \vec{\nabla}_{\perp}\,\phi$$

Parallel potential

Perpendicular potential

- **Quasineutrality condition then determines the relationship between the electric fields,**

$$\boxed{\sum_s \frac{T_e}{T_s}\left[1+\varsigma_s Z\left(\varsigma_s^0\right)\right]\left(1-\frac{\vec{\omega}_s^{\,*}}{\omega_{3/2}^i}\right)\psi = -\sum_s \frac{T_e Z\left(\varsigma_s^0\right)}{T_s\sqrt{2}k_{\parallel}v_{ts}}\left[\omega_{3/2}^i\,\rho_s^2\nabla_\perp^2 + \left\langle \vec{\omega}_D^{\,s}\right\rangle\right]\left(1-\frac{\vec{\omega}_s^{\,*}}{\omega_{3/2}^i}\right)\phi}$$

Polarization drift

FLR

curvature drift

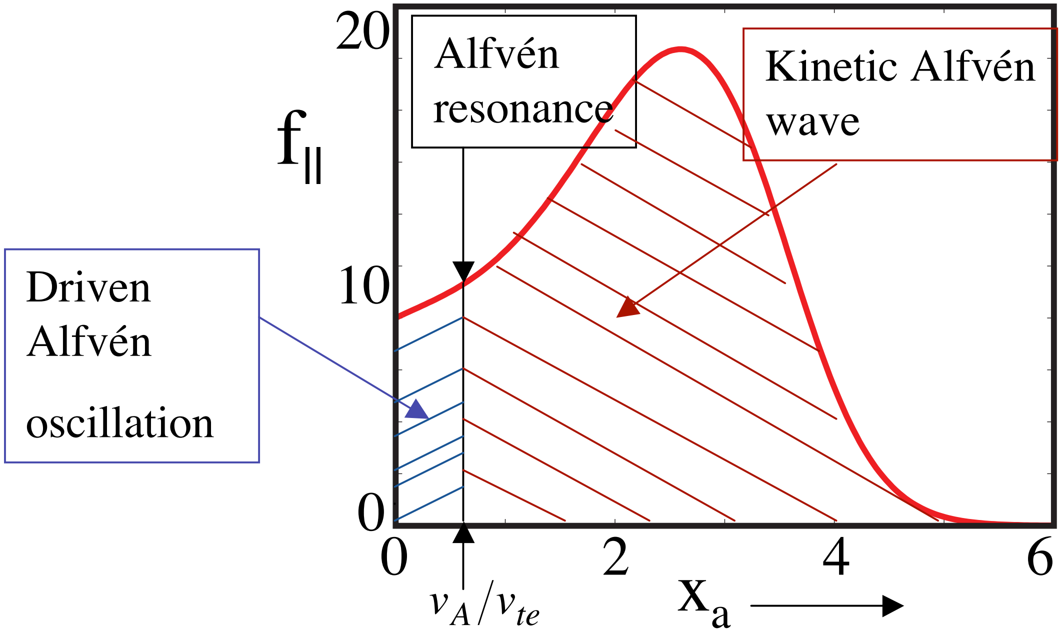
$\omega_{3/2}^i(r)$ is rotation frequency of 3/2 island w.r.t. local thermal ions

Total Alfvén Wave Driven Current Depends on Details of Electron and Ion Dynamics

$$J = J_{MHD} f_\perp f_\parallel$$

$$J_{MHD} = \frac{\sqrt{2}\pi^{3/2}\varepsilon_0^2}{e\ln\Lambda}\left[\frac{\omega^e_{3/2}(\omega^i_{3/2})^2 B^2 \xi_\psi^2}{k_\perp^2}\right]$$

Electron dynamics determines $f_\parallel$, ion dynamics determines $f_\perp$

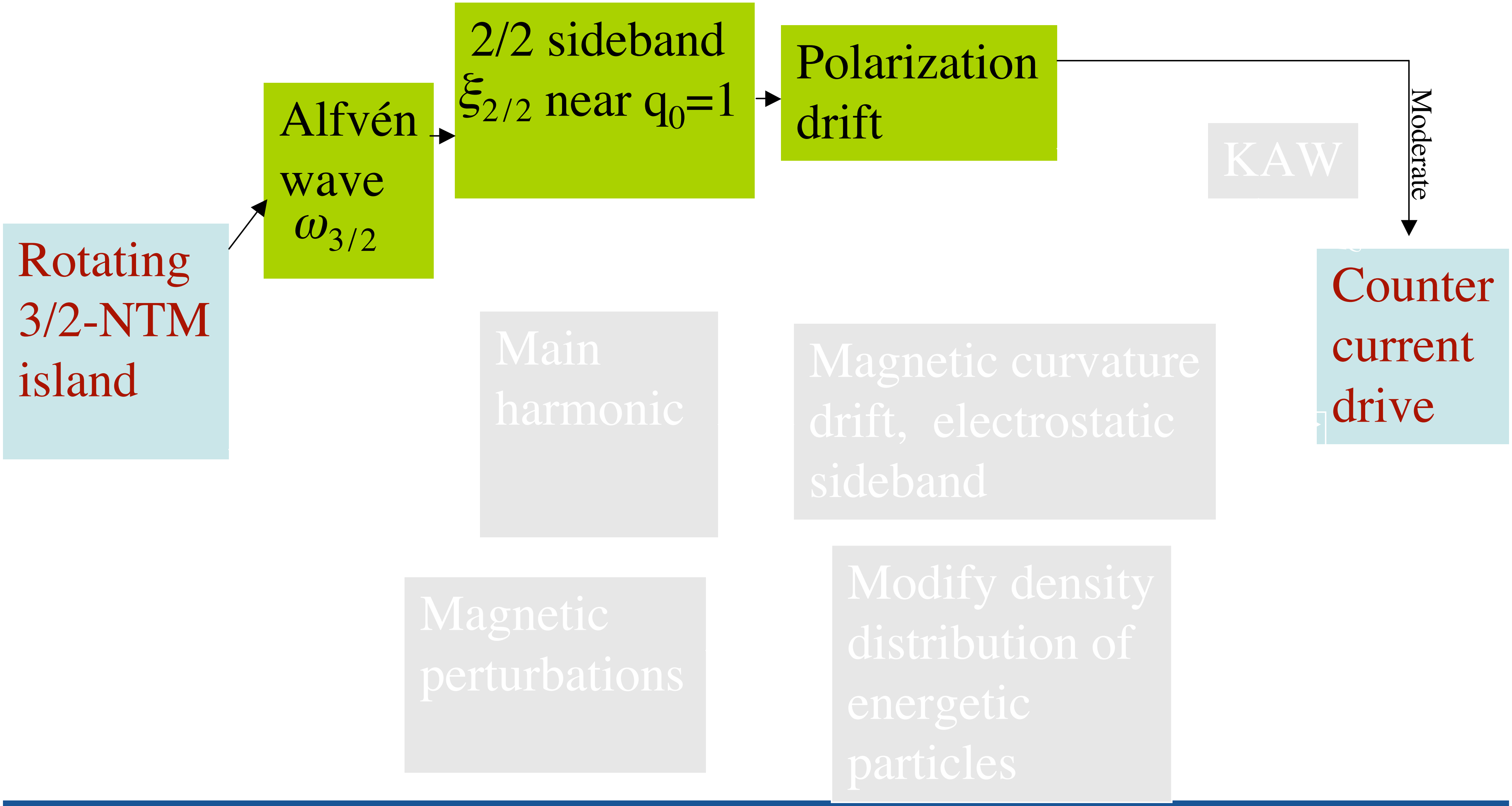


$$x_a = \frac{\omega^e_{3/2}}{k_\parallel v_{te}}$$

Parallel phase speed of perturbation relative to electron thermal speed

Changing the wave speed relative to the electron thermal speed does not grossly modify the current drive efficiency so long as x_a is less than 3

Polarization Drift Due to Alfvén Wave Contributes to Current Drive



Rotating 3/2-NTM island

Alfvén wave $\omega_{3/2}$

2/2 sideband $\xi_{2/2}$ near $q_0=1$

Polarization drift

Moderate

Counter current drive

KAW

Main harmonic

Magnetic curvature drift, electrostatic sideband

Magnetic perturbations

Modify density distribution of energetic particles

Without Mode Conversion or Sideband Coupling Total Driven Current is Small = 0.3 - 3.0 kA

- **Polarization drift induced $f_\perp = f_{\perp 1}$**

$$\boxed{f_{\perp 1} = \rho_i^4 \left(\frac{T_e}{T_i} k_\perp^2 \left(1 - \frac{\omega_i^*}{\omega_{3/2}^i}\right) \right)^2}$$

- **Estimate based on typical DIII-D hybrid discharge parameters**

$$q = q_0 + (q_{3/2} - q_0)\bar{r}^2 \qquad \omega_{3/2} = 1.05 \bullet 10^5 / s$$

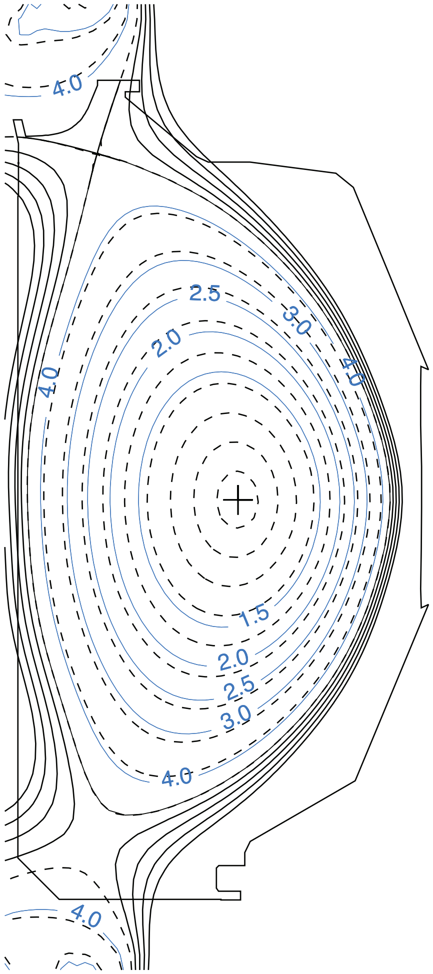
$$\bar{r} = r / r_{3/2} \qquad \rho_i = 4.2 \bullet 10^{-3} m$$

$$r_{3/2} = 0.3 \ \ m$$

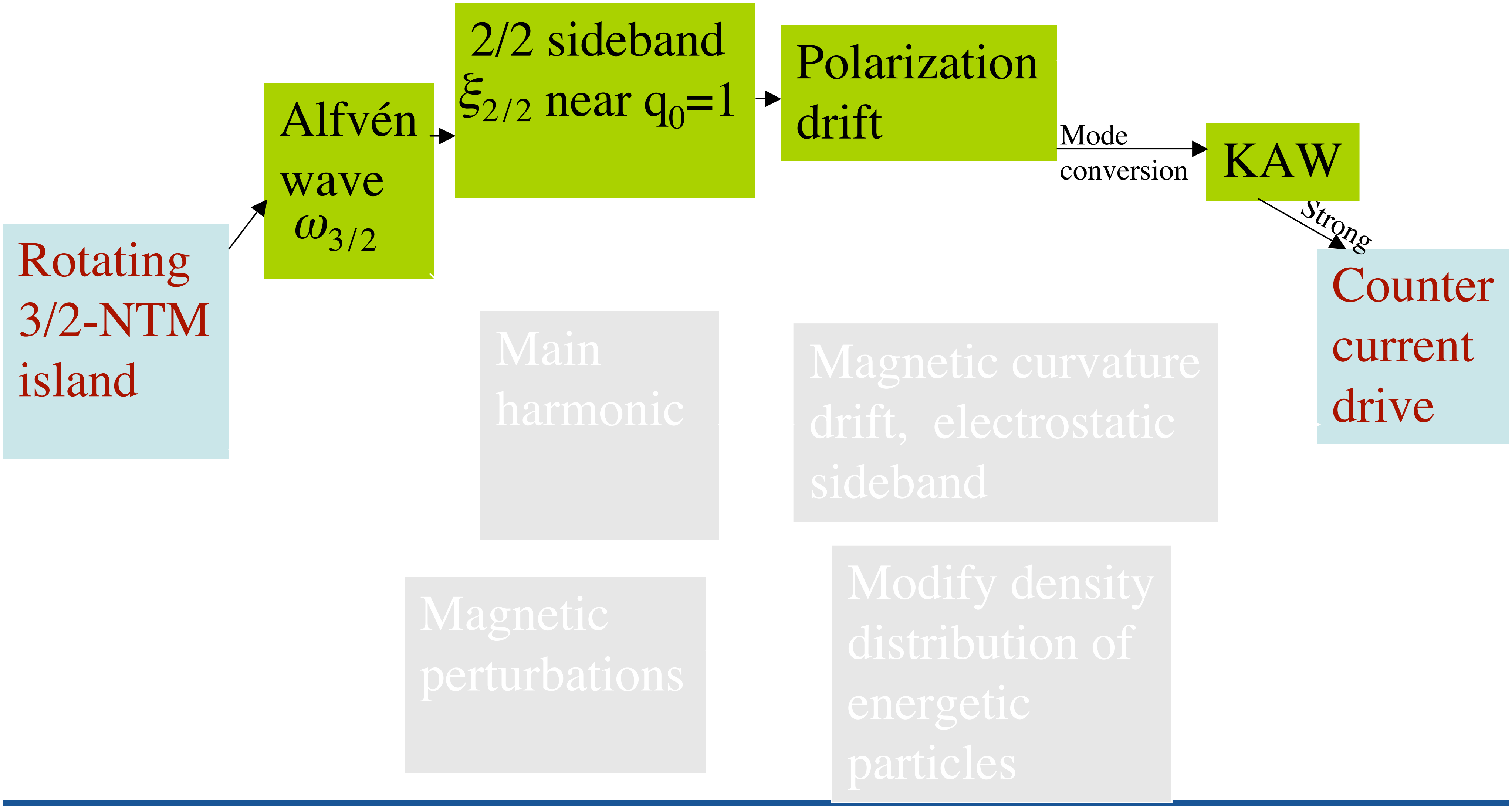
- **Assume central current drive region to cover only 0.10 m radius**

$$\xi_\psi = .1 \ \ m, \qquad J_{MHD} = 3.56 \bullet 10^7 A/m^2, \qquad f_{\|} = 13,$$

$$f_\perp = 1.5 \bullet 10^{-5}, \qquad Area = .044 \ \ m^2, \qquad I = Area \bullet J = .3kA$$



Mode Conversion to KAW Can Amplify Driven Current



Rotating 3/2-NTM island

Alfvén wave $\omega_{3/2}$

2/2 sideband $\xi_{2/2}$ near $q_0=1$

Polarization drift

Mode conversion

KAW

Strong

Counter current drive

Main harmonic

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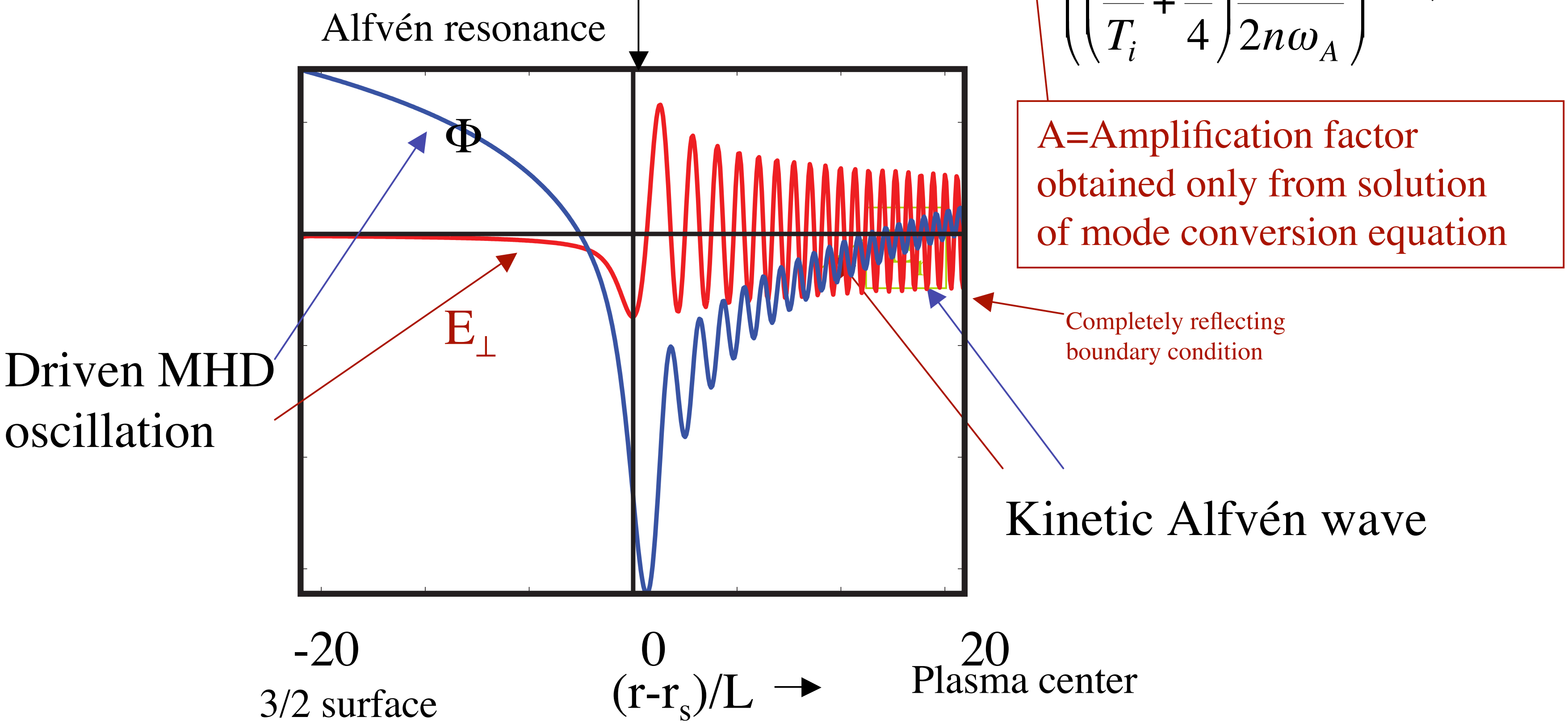
Modify density distribution of energetic particles

Mode Conversion to Kinetic Alfvén Wave Facilitated by Polarization Drift (FLR Effect)

$$f_{\perp 1} = \rho_i^4 \left(\frac{T_e}{T_i} k_\perp^2 \left(1 - \frac{\omega_i^*}{\omega_{3/2}^i}\right) \right)^2 \xrightarrow{\text{Mode conversion}} f_{\perp 1} = \rho_i^{4/3} A^2 \left(\frac{\dfrac{dq}{dr}}{\left(\dfrac{T_e}{T_i} + \dfrac{3}{4} \right) \dfrac{\omega_{3/2}^i}{2n\omega_A}} \right)^{4/3} \left(\frac{T_e}{T_i} \left(1 - \frac{\omega_i^*}{\omega_{3/2}^i}\right) \right)^2$$



A=Amplification factor obtained only from solution of mode conversion equation

Completely reflecting boundary condition

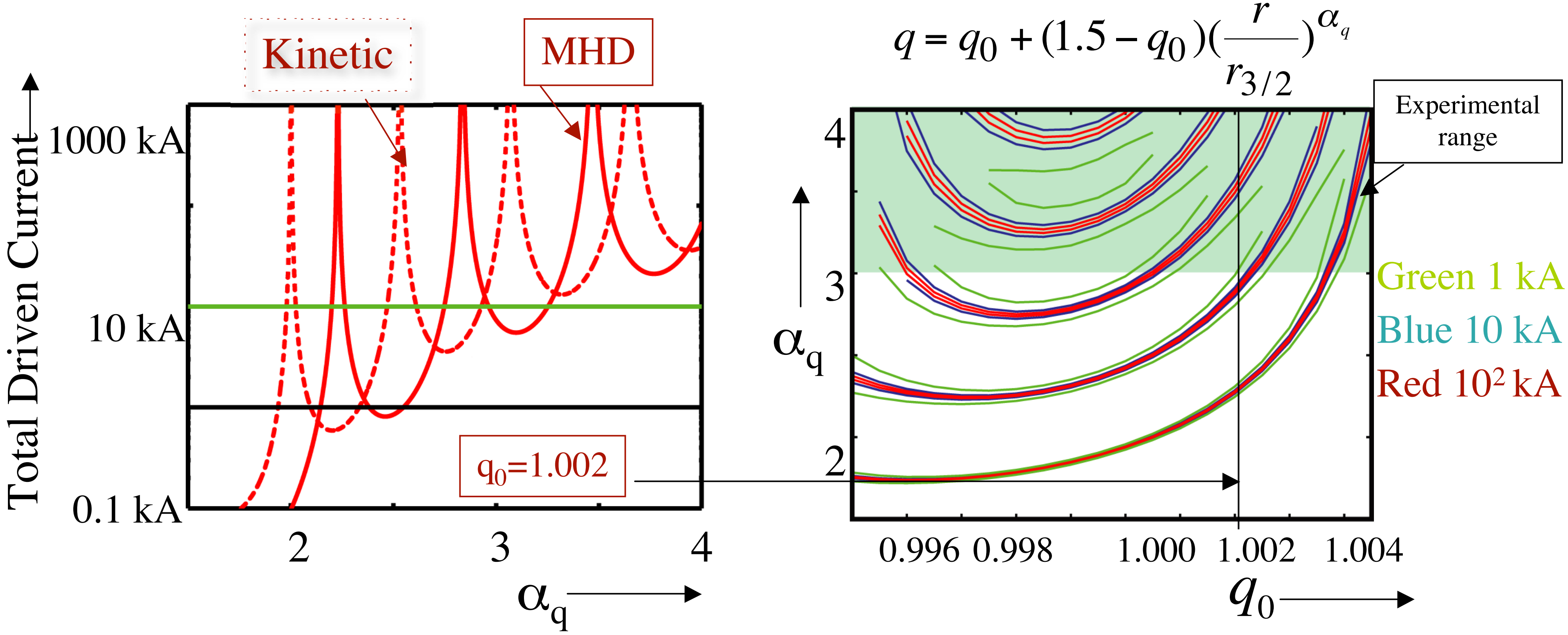
Driven MHD oscillation

Kinetic Alfvén wave

Mode conversion greatly shortens perpendicular wave length and increases $f_{\perp 1}$

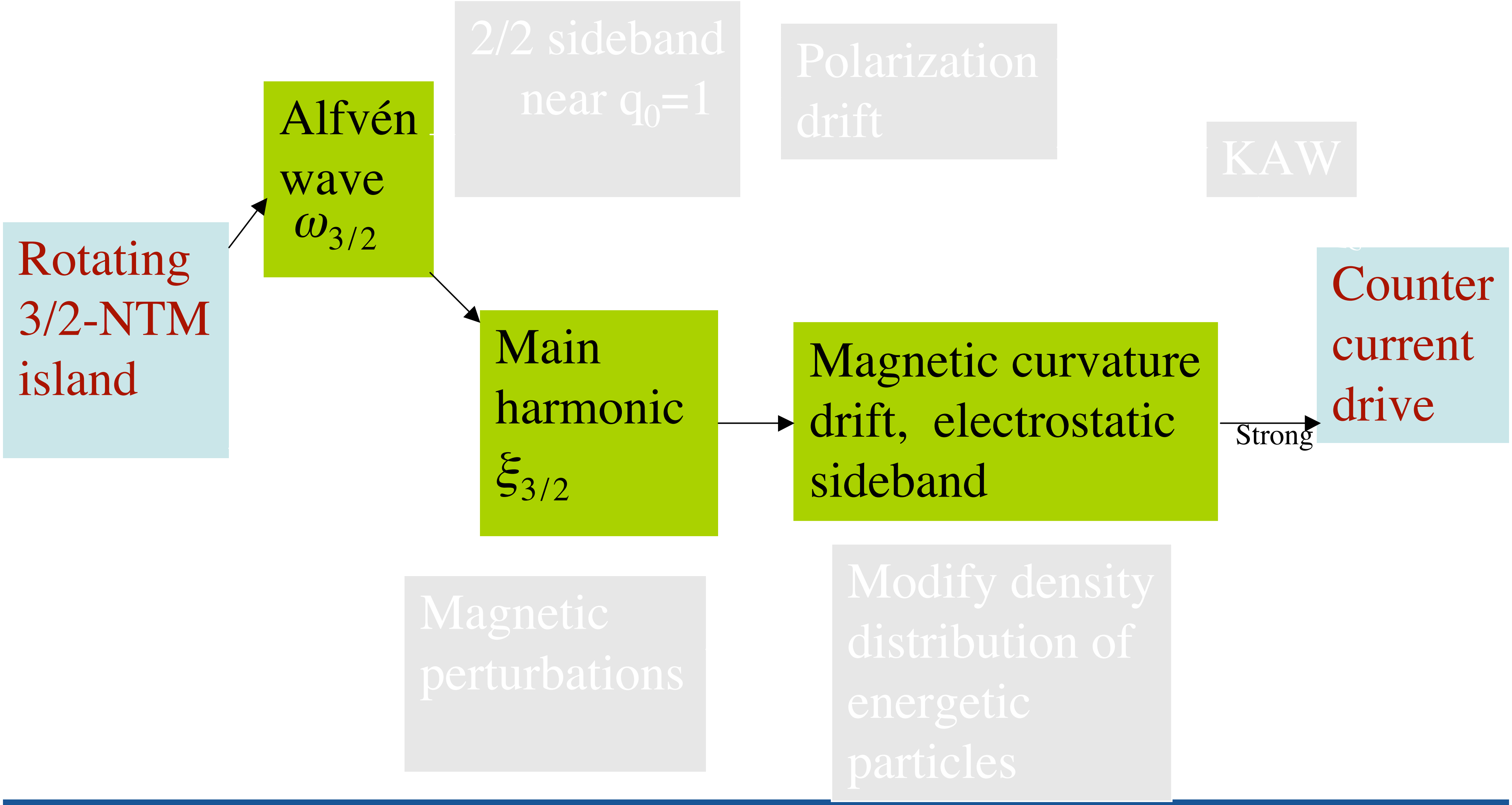
Total Driven Current Large at Resonances Due to Large Amplification Factor

$$q = q_0 + (1.5 - q_0)(\frac{r}{r_{3/2}})^{\alpha_q}$$



- Normalized to $\xi_{2/2} = 1\ cm$ at $r_{3/2}$
- Large current drive equilibria are associated with special solutions of the mode conversion equation which are the KAW eigenstates!!

Magnetic Curvature Drift Produces Sideband Electric Fields and Drives Current Effectively



Rotating 3/2-NTM island

Alfvén wave $\omega_{3/2}$

2/2 sideband near $q_0=1$

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Magnetic Curvature Drift due to Alfvén Wave Induces Electrostatic Sidebands

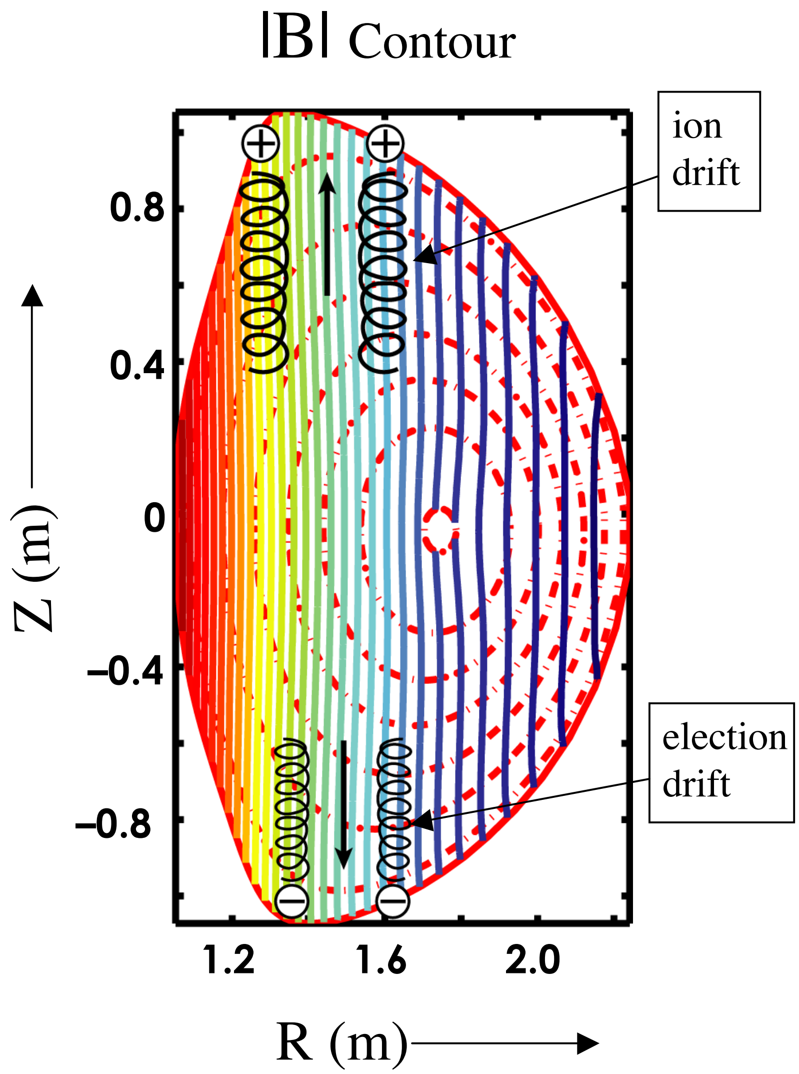
$$\psi_{\pm} = i\left[\frac{\sum_s \frac{1}{e_s BR}\left(1-\frac{\omega_s^*}{\omega_{Is}^i}\right)\frac{1}{\sqrt{2}k_{\|\pm}v_{ts}}Z(\varsigma_{s\pm})\left(\frac{m\pm 1}{r}\phi \mp \frac{\partial\phi}{\partial r}\right)}{\sum_s \frac{1}{T_s}\left[1+\varsigma_{s\pm}Z(\varsigma_{s\pm})\right]\left(1-\frac{\omega_{s\pm}^*}{\omega_{Is}^i}\right)}\right]$$

Induced parallel potential

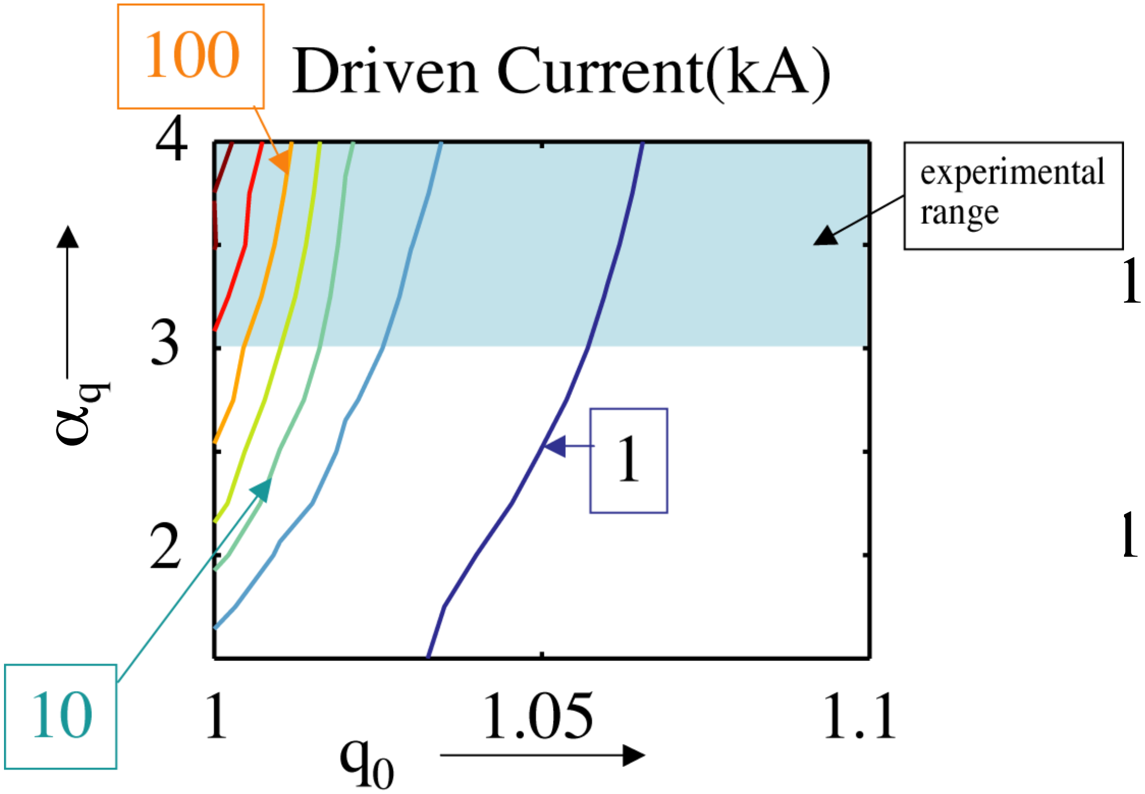
Perpendicular potential of Alfvén wave (MHD)

$$f_{\perp 2} = \left\langle \omega_D^i \right\rangle^2 \left(\frac{T_e}{T_i\omega_{3/2}^i}(1-\frac{\omega_i^*}{\omega_{3/2}^i})\right)^2$$

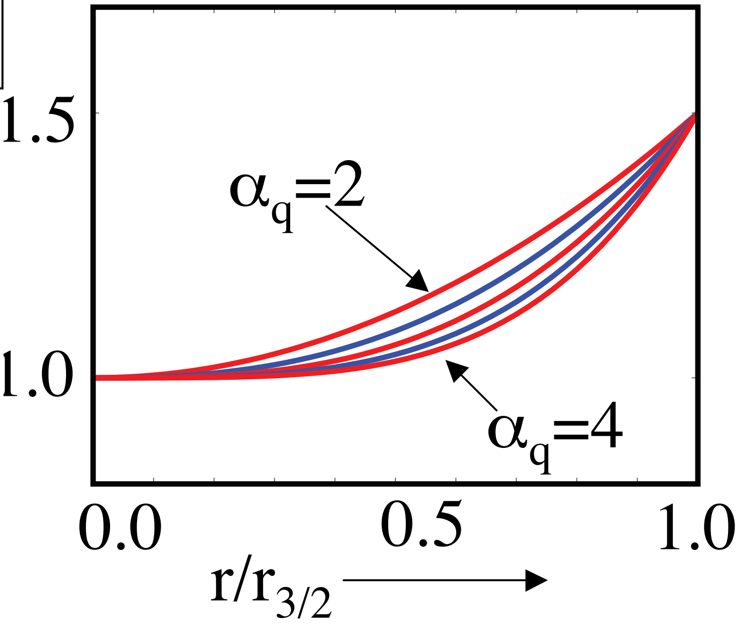
- + upper sideband, - lower sideband
- Scales with as $\left\langle \omega_D^i \right\rangle^2$ or $(\rho/R)^2$,
- purely toroidal effect



Electrostatic Sidebands Due to Magnetic Curvature Drift Drive Significant Amount of Current

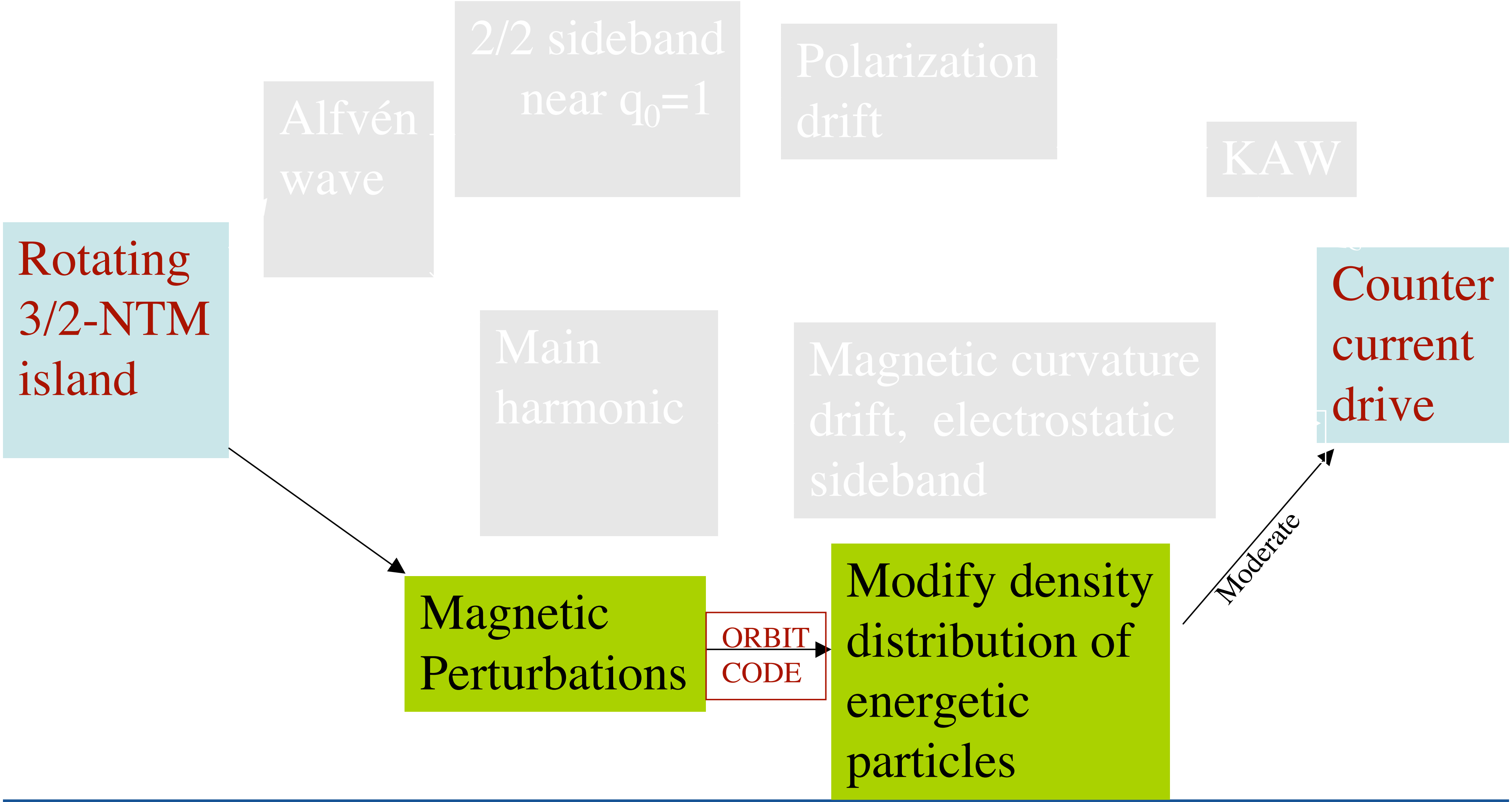


$$q = q_0 + (1.5 - q_0)(\frac{r}{r_{3/2}})^{\alpha_q}$$



- Purely toroidal effect
- Current driven mainly by lower sideband

Magnetic Perturbation Due to NTM Island Modifies Distribution of NBI Current Drive



Rotating 3/2-NTM island

Alfvén wave

2/2 sideband near $q_0=1$

Polarization drift

KAW

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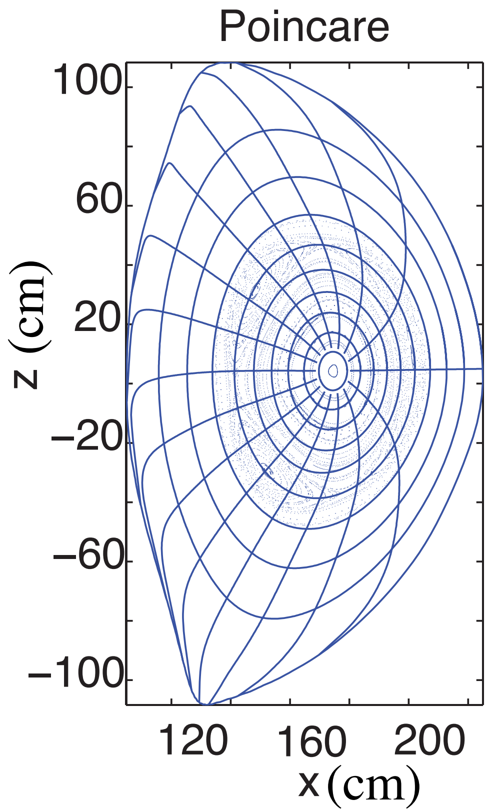
Magnetic Perturbations

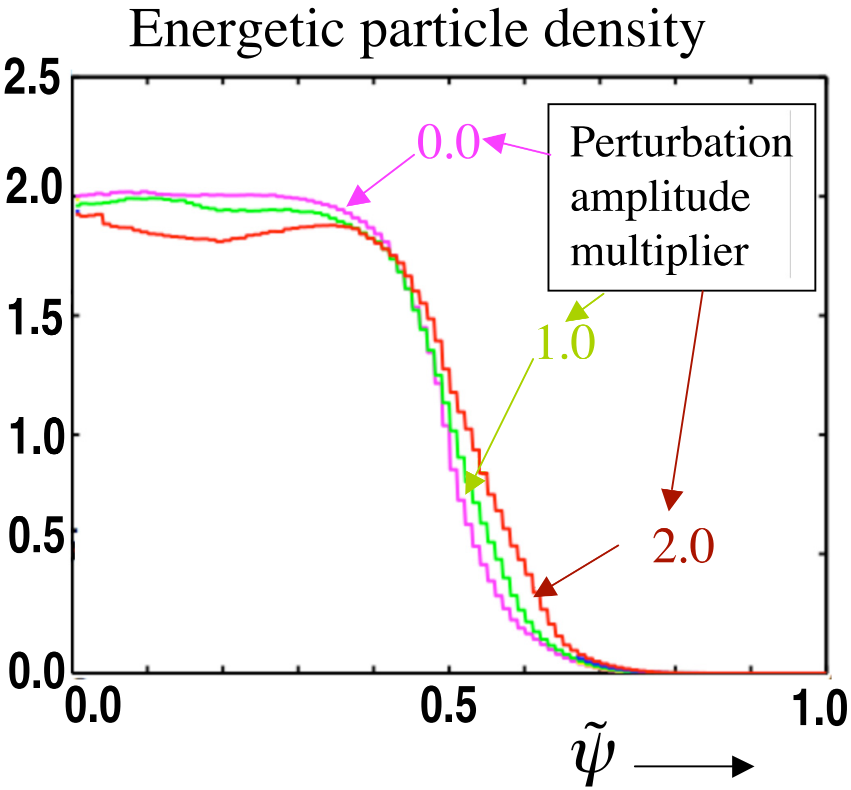
ORBIT CODE

Modify density distribution of energetic particles

Moderate

ORBIT Code Results Show Energetic Particle Density Modified Moderately by NTM Island





- New equilibrium reached within a few particle transit times
- Independent of energetic particles energy
- Account for 10%-20% of missing current

Discussion: Possible Tests of Theory and Extensions

Mechanism	Variables	Possible observations
KAW mode conversion current drive	1. Rotation shear of island w.r.t. central plasma 2. q(0) ~1	1. More current deficit if rotation is higher 2. a) low q(0) less accessible b) less current deficit if q(0) higher c) evolution path to low q(0) has intermittent hesitation
curvature drift current drive	1. rotation shear of island w.r.t central plasma 2. q(0) ~ 1 3. aspect ratio A	1. Same as above 2 a) b) Same as above 3. less effective at larger A
energetic particle redistribution	Excites other mode(s) (TAEs, ELMs?) to work synergistically with NTM	1. Current deficit independent of plasma rotation 2. Broadening of energetic particle density profile

Conclusion: Magnetic Curvature Drift and KAW Mode Conversion Can Explain Observed Current Deficit

Three mechanisms for driving negative current by the rotating NTM are investigated:

- **Polarization drift gives rise to mode conversion which effectively drives counter current**
- **Magnetic curvature drift produces sideband electric fields which effectively drives counter current**
- **The wave scatters NBI ions and reduces efficiency of NBI current drive to account for 10-20% of negative current**