Numerical modelling of electromagnetic turbulent transport of energetic ions in burning plasmas

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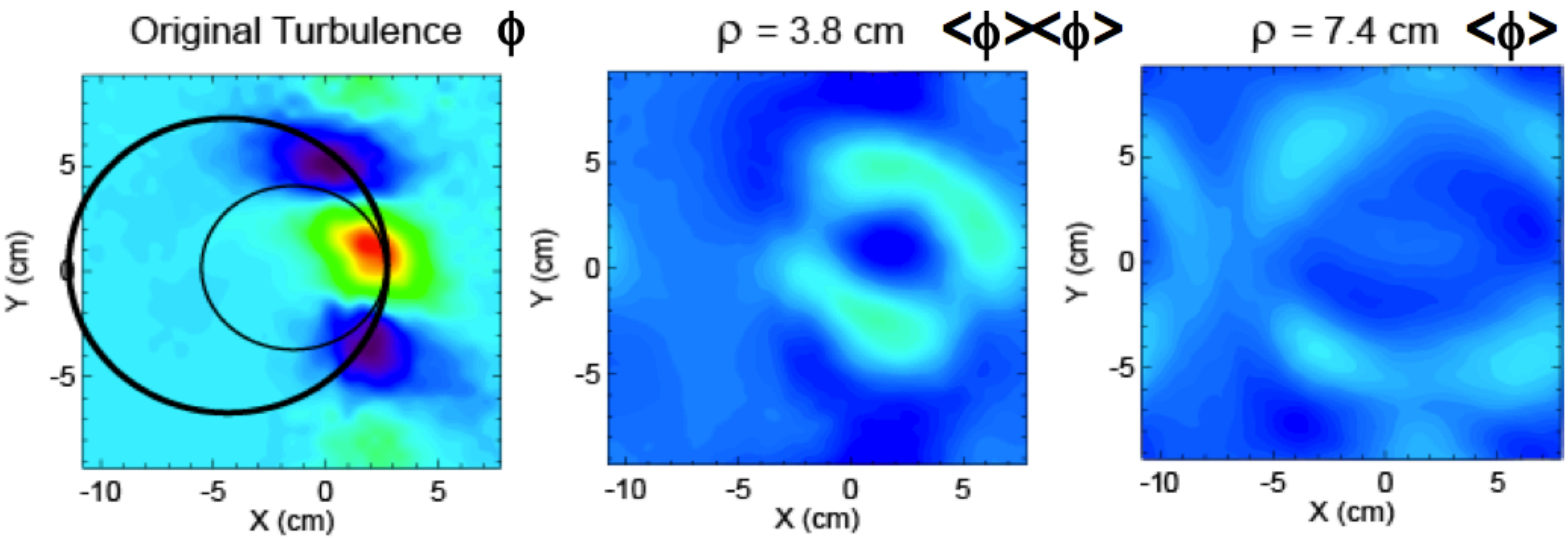
Motivation

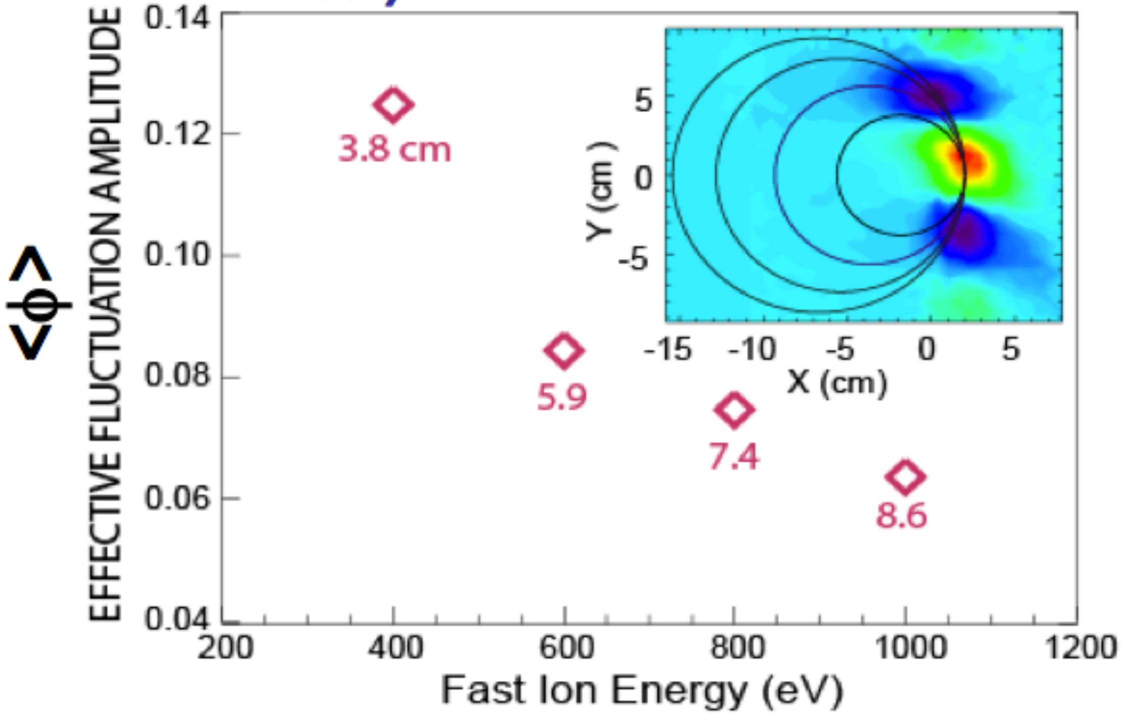


Larger energy
Larger gyroradius
Smaller effective field
Smaller transport

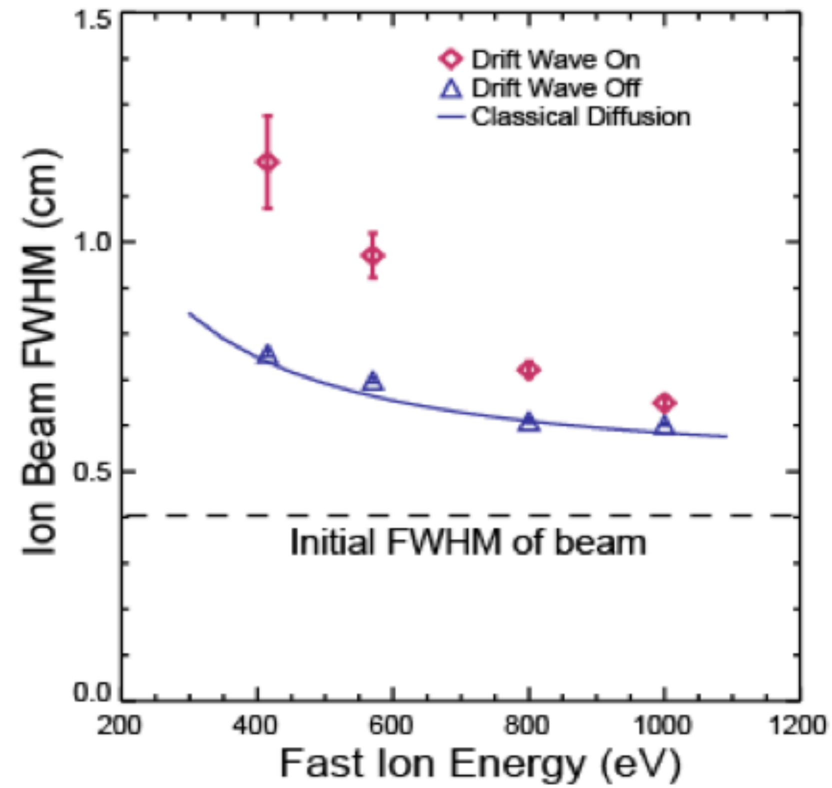
B. Heidbrink, GSEP Workshop (2010)

Motivation

Theory



Experiment



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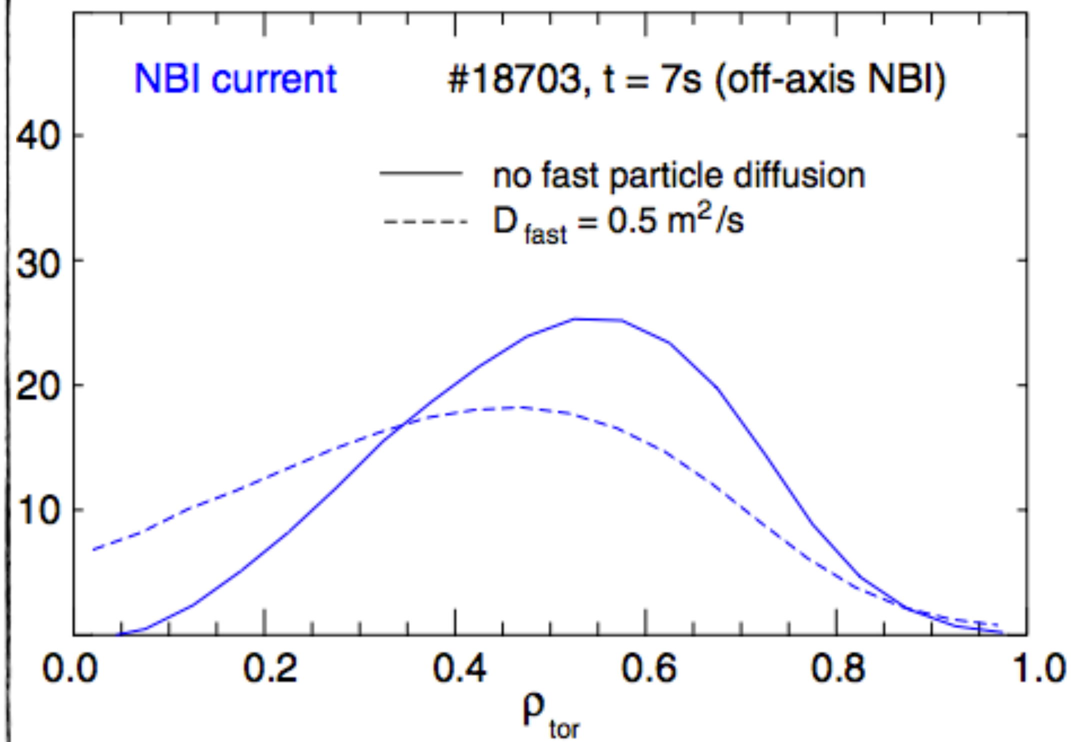
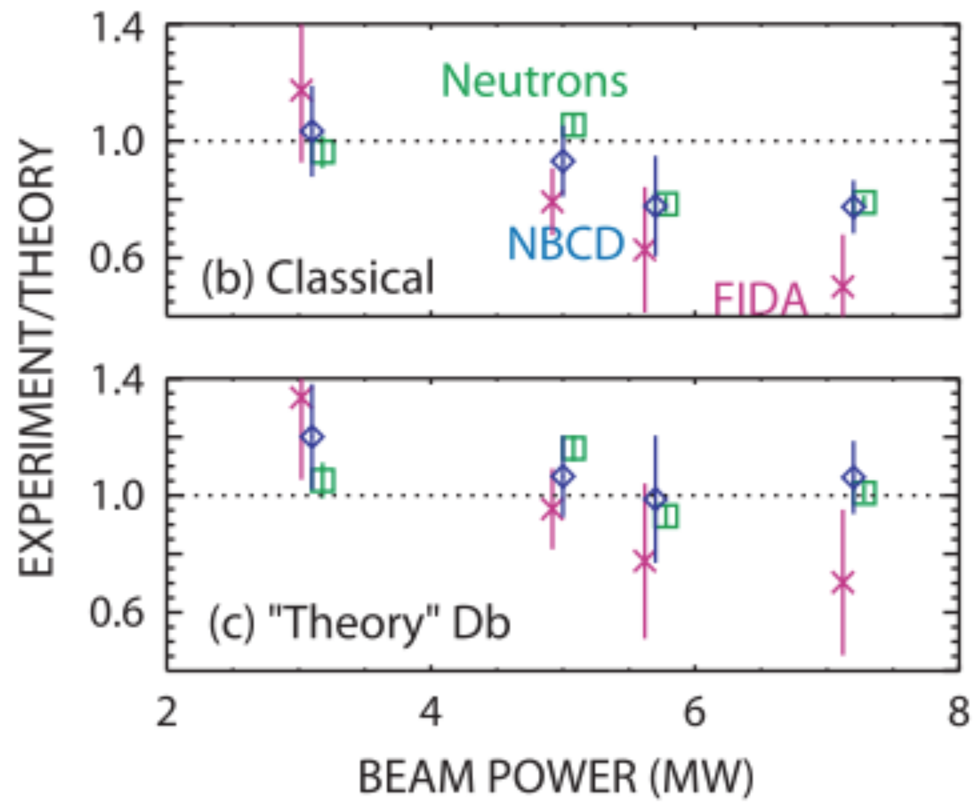
B. Heidbrink, GSEP Workshop (2010)

Motivation

ASDEX-U Experiments



DIII-D Experiments



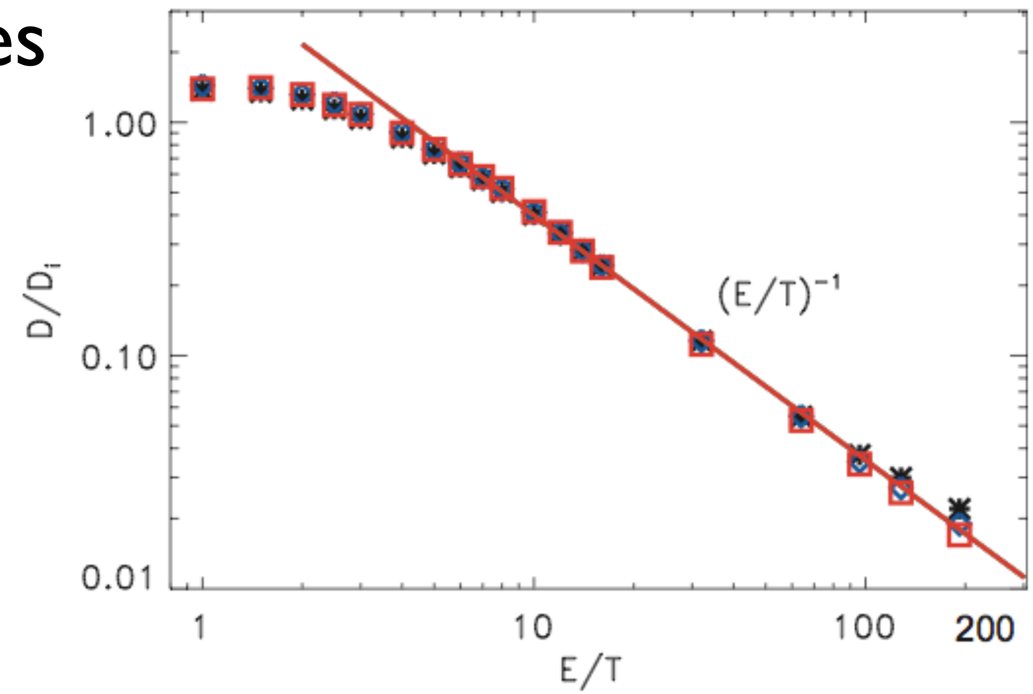
S. Günter, Nuclear Fusion (2007)

B. Heidbrink, Physical Review Letters (2010)

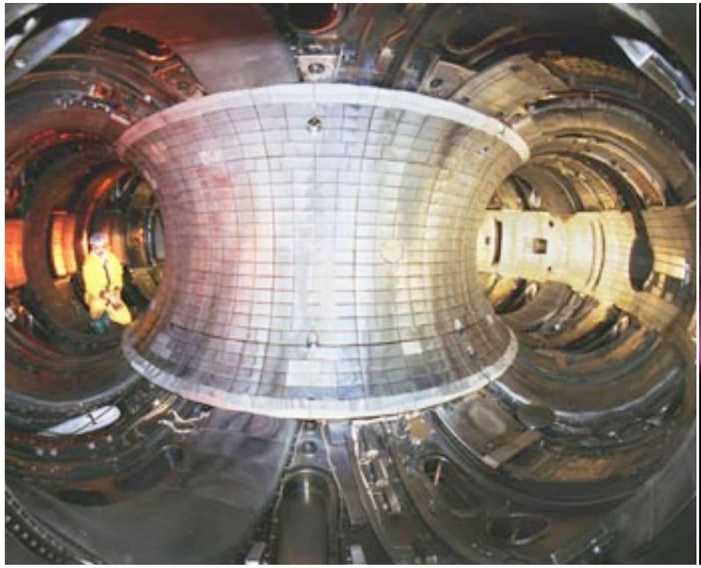
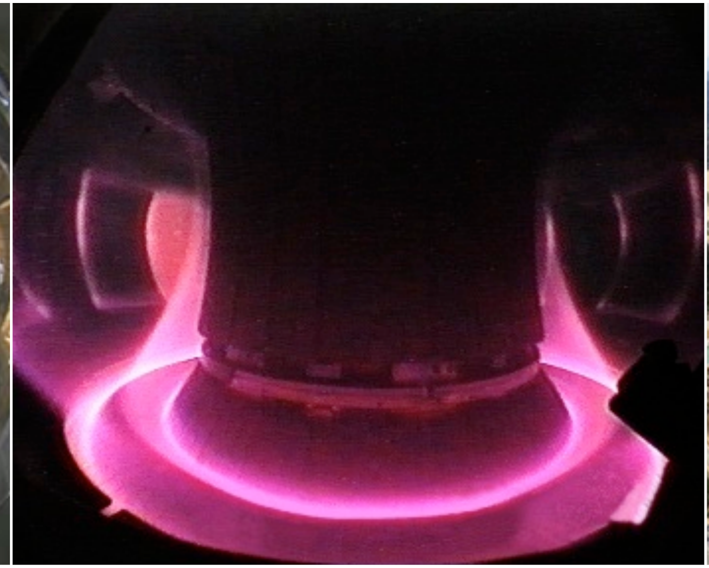
Motivation

- Anomalies in NBI particles
- Smaller E_{nbi}/T_e ratio
  - larger transport
- Beam energies unchanged in past years
- Plasma temperatures larger in present day experiments

W. Zhang, Physics of Plasmas (2010)



Motivation

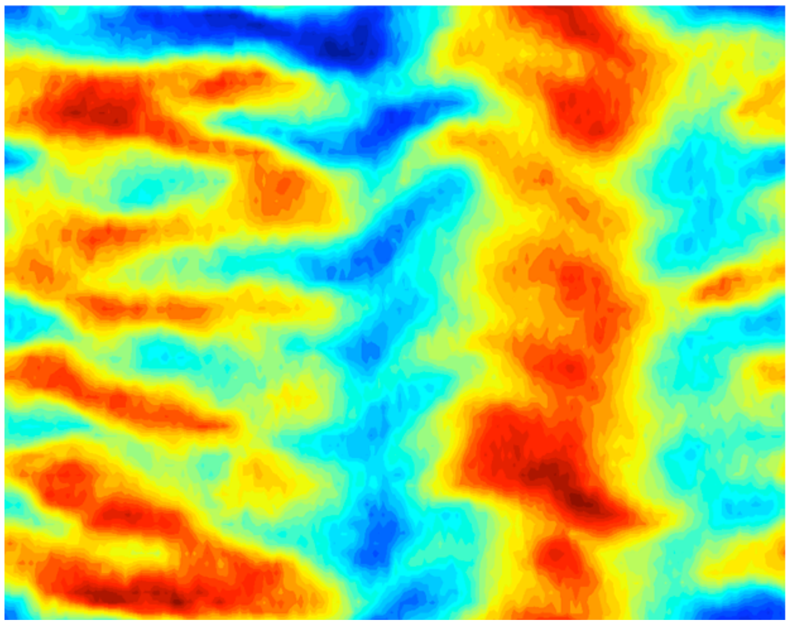




TFTR	ASDEX Upgrade/DIII-D	ITER
Early Experiments	Present day experiments	Future Experiments
$E_\alpha/T_e = 1000$ $E_{nbi}/T_e > 30$	$E_\alpha/T_e > 300$ $E_{nbi}/T_e \leq 20$	$E_\alpha/T_e > 100^*$ $E_{nbi}/T_e \cong 30$
Neoclassical behaviour	Presence of anomalies	What effect on the NBI?

*C. Angioni, Nuclear Fusion (2009)

Outline

Microturbulence

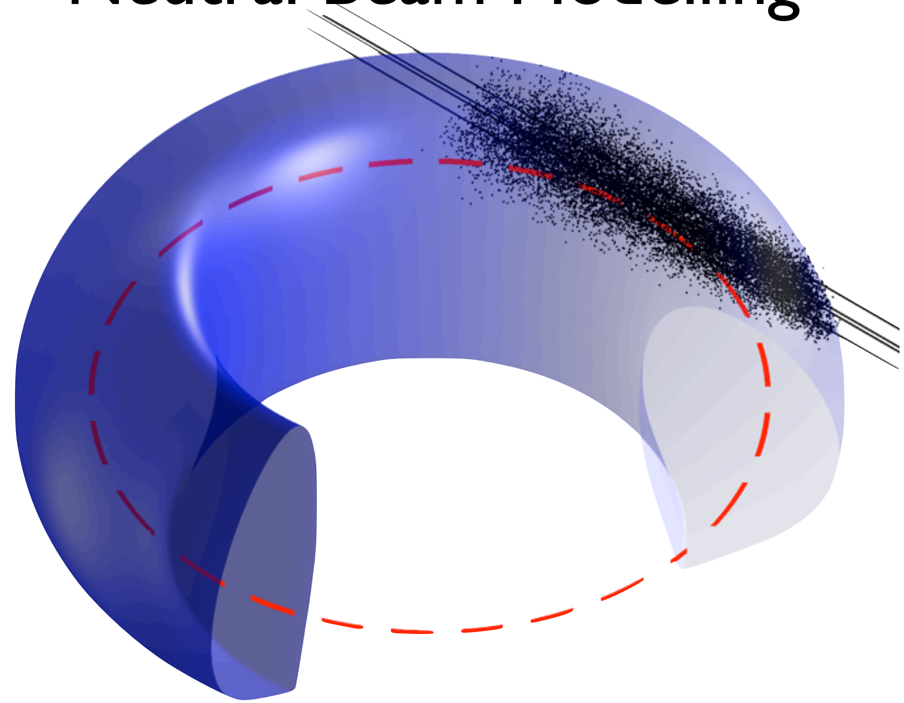


GENE code

ITER steady state

Energetic ion diffusivity

Neutral Beam Modelling



VENUS code

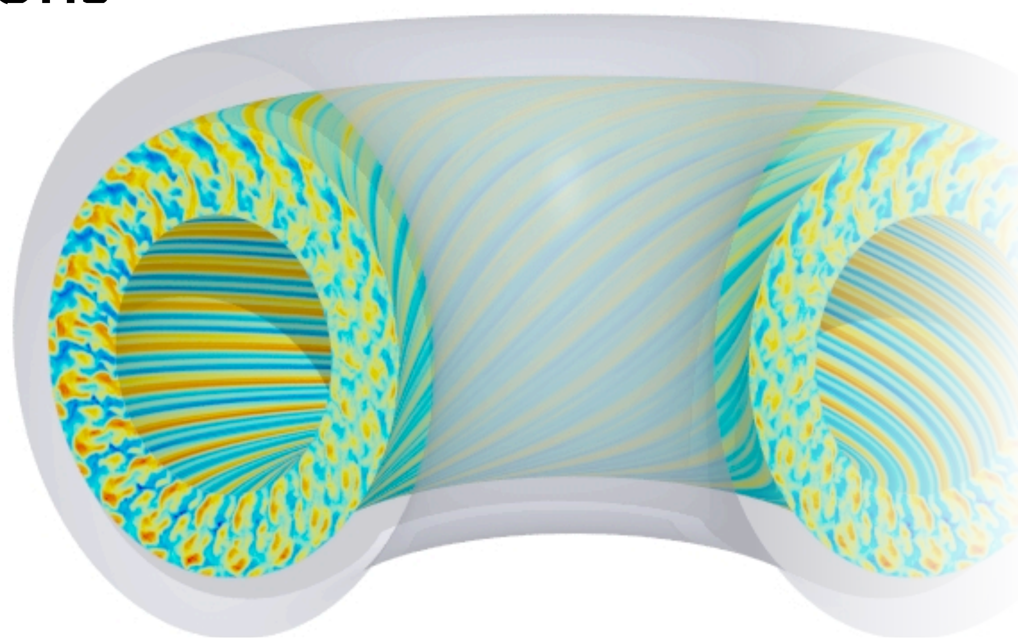
Collisional slowing down

<u>Anomalous transport</u>

Gyrokinetic simulations of turbulent transport

The numerical platform

- GENE[1] code
- Linear and nonlinear flux tube simulations
- Electromagnetic perturbations
- Multi-species
- Interface with MHD equilibrium code CHEASE[2]



[1]F. Jenko, Physics of Plasmas (2000)
[2]H. Lütjens, CPC (1996)

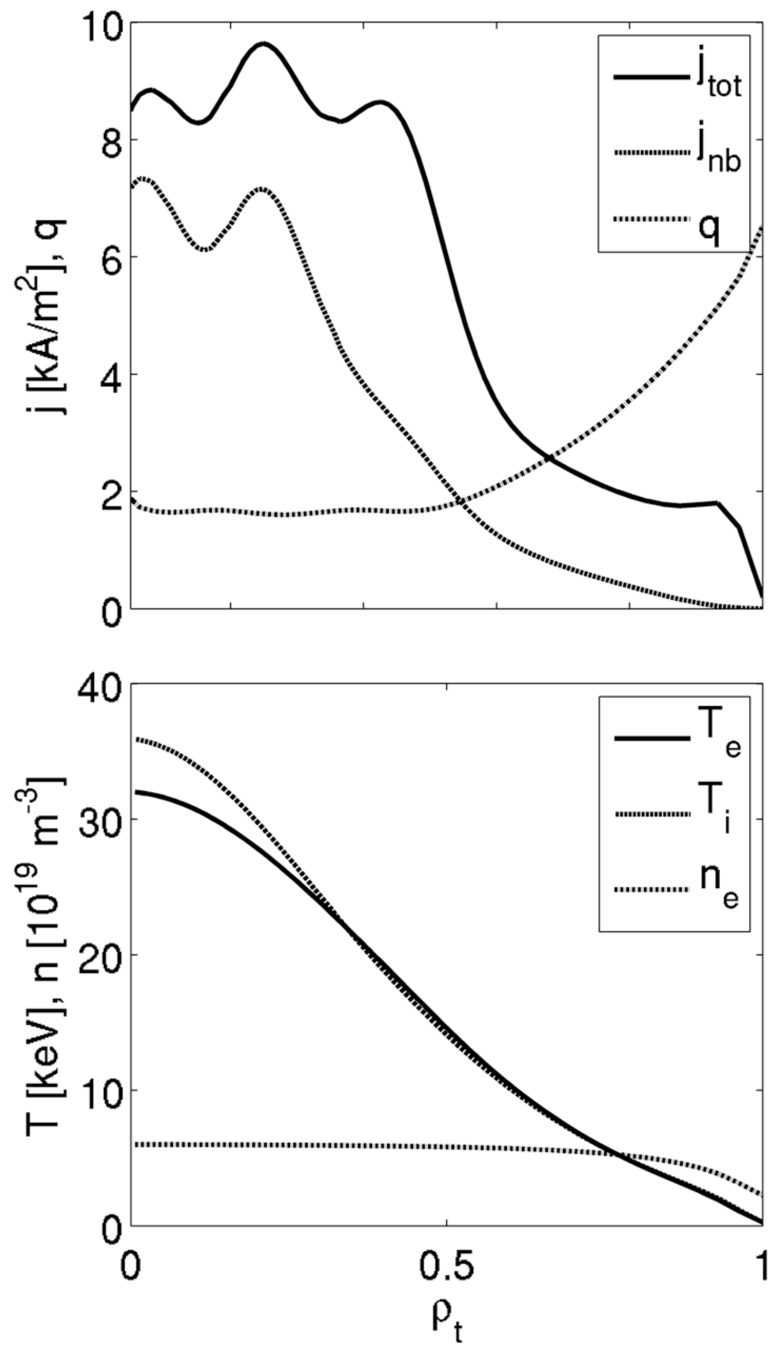
Linear analysis

- ITER steady state scenario (D + e^-)
- <u>Simulations near marginal stability (at *mid-radius*)</u>
- Temperature gradient

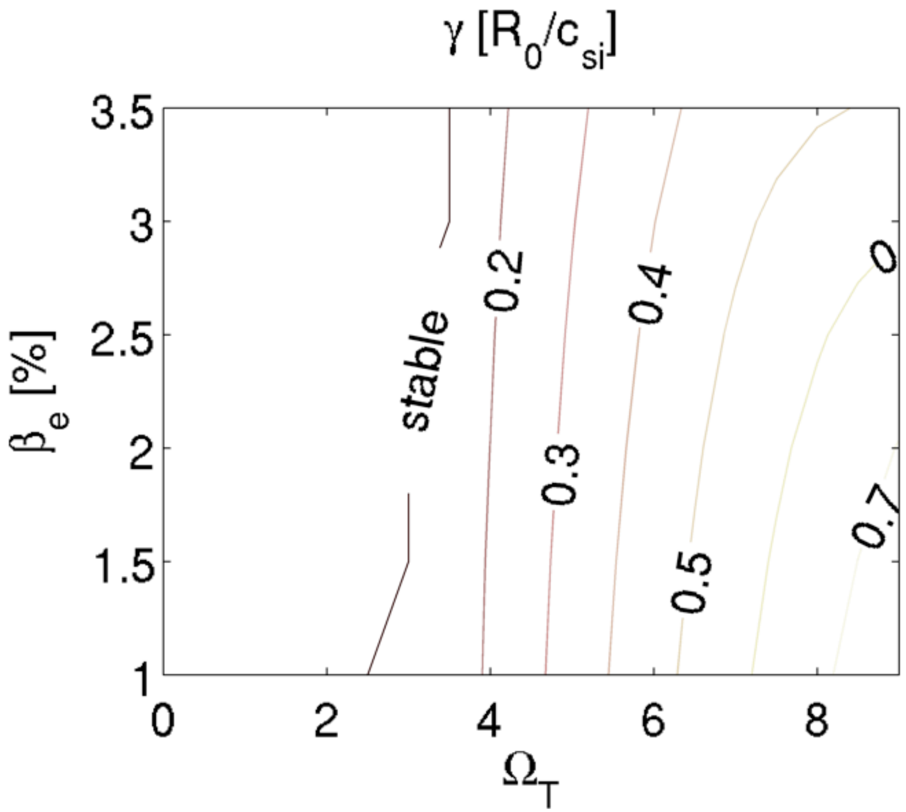
$$\Omega_T = -(R_0/a)\,\mathrm{d}\ln T/\mathrm{d}\rho_t$$

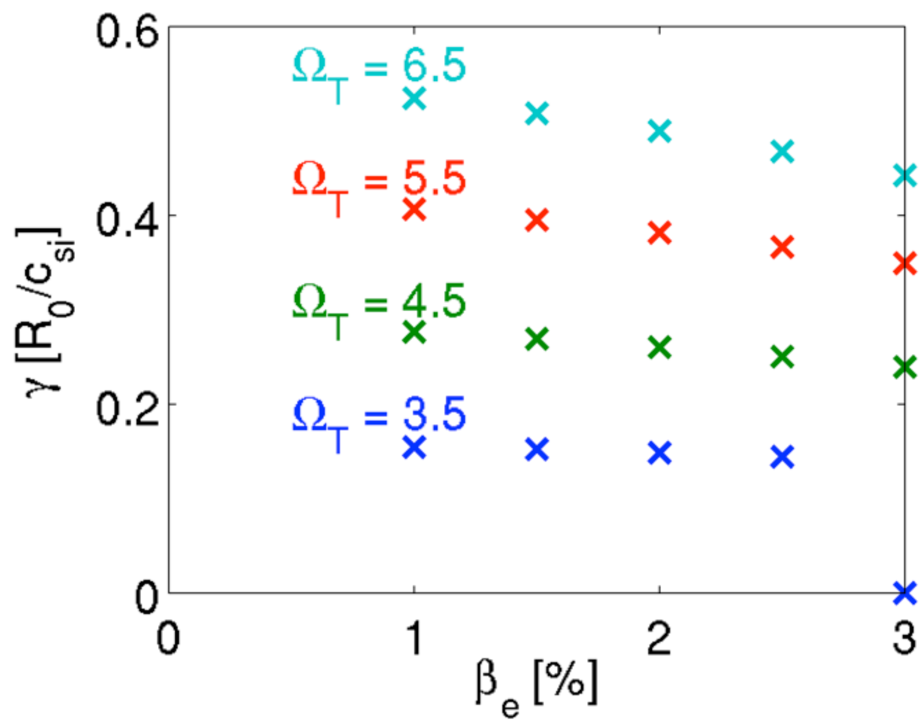
- Beta effects

$$\beta_e = n_e T_e/(B_0^2/2\mu_0)$$



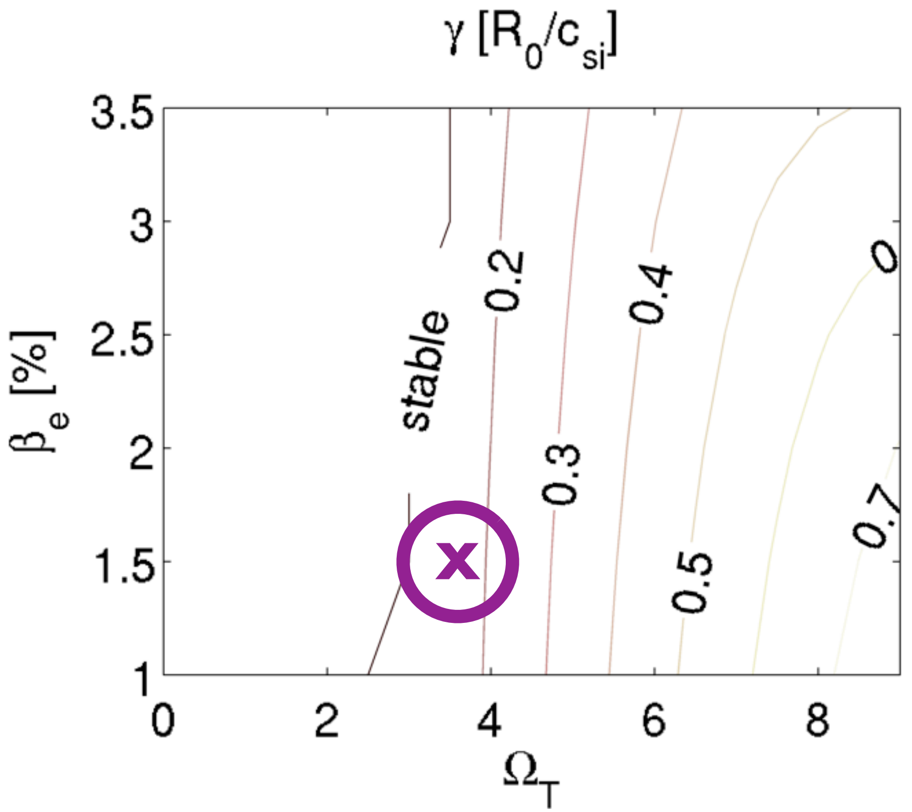
Linear Analysis

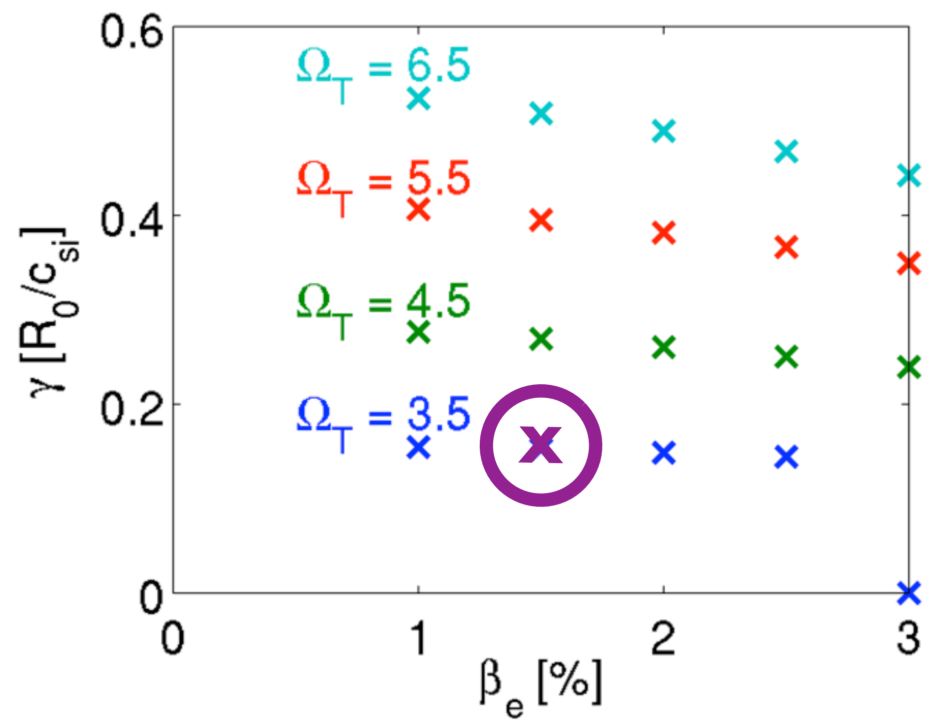




- ITG dominant instability
- Beta effects not exciting kinetic ballooning modes
- Subdominant modes <u>are present</u>
- Investigation for nonlinear simulation

Linear Analysis

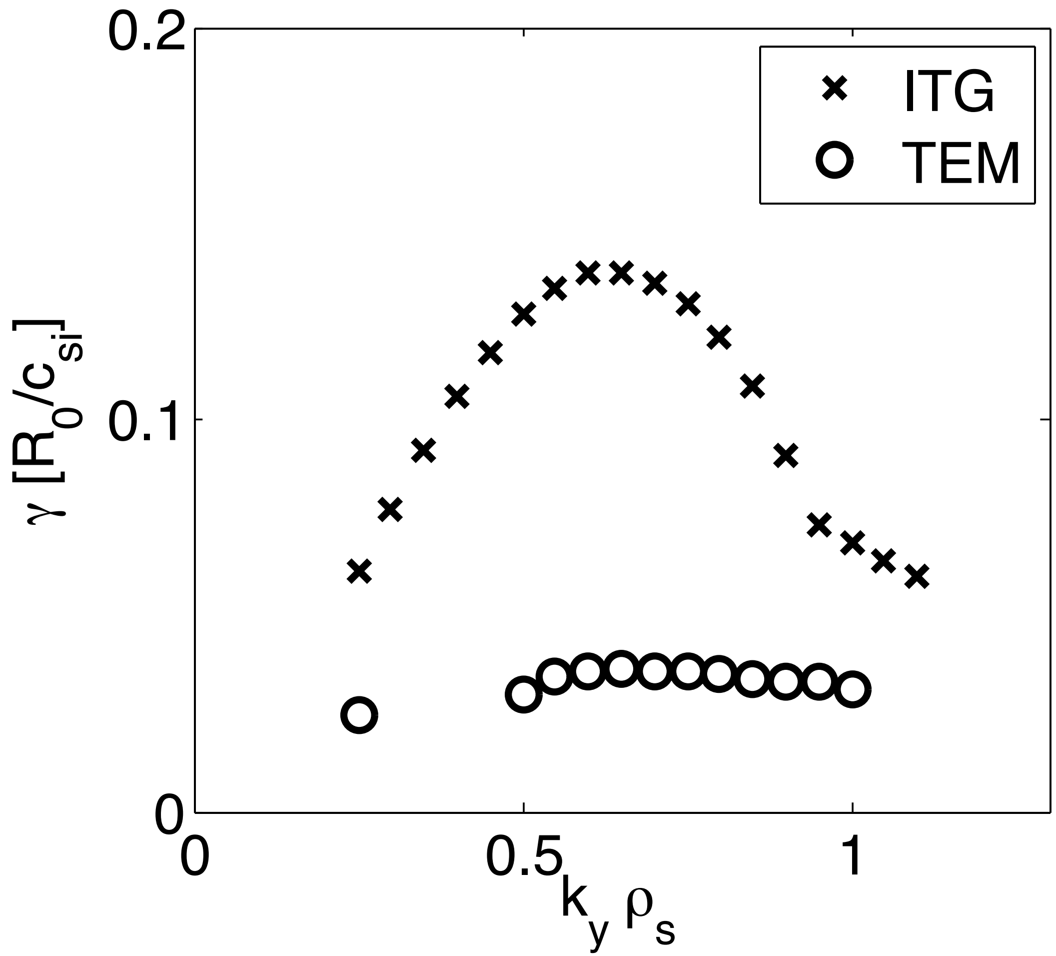




- ITG dominant instability
- Beta effects not exciting kinetic ballooning modes
- Subdominant modes are present
- Investigation for nonlinear simulation x

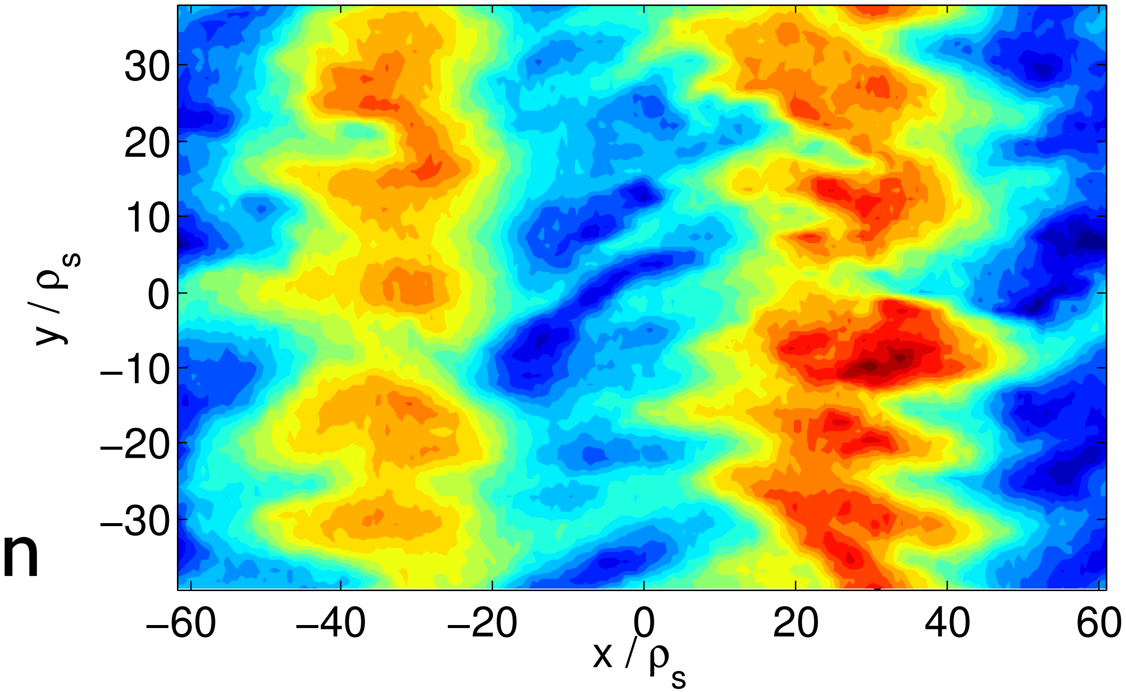
Linear Analysis

- Turbulence
  - Dominant ITGs
  - Subdominant TEMs
- Observation of ETGs
  - Negligible effect
- Nonlinear simulations can be performed



Nonlinear Analysis

- Mixture of ITG and TEM
- Magnetic perturbations
- Passive deuterium
  - Maxwellian distribution
  - Beam ions non-thermal



- What variables can describe the particle diffusivity?

The variables studied

- Energetic particle transport is a diffusive process*

- It <u>must be</u> consistent with Fick's law

$$D(\mathbf{x}) = -\frac{\Gamma(\mathbf{x})}{\nabla n(\mathbf{x})} = -\frac{1}{\nabla n(\mathbf{x})} \int \delta f(\mathbf{x}, \mathbf{v}) \delta u(\mathbf{x}, \mathbf{v}) d\mathbf{v}$$

- Allows for 'electrostatic' and 'magnetic' transport separation

$$\delta \mathbf{u}^{es} = -\frac{\nabla \delta \bar{\Phi} \times \mathbf{B}}{B^2} \qquad \delta \mathbf{u}^{em} = v_{\parallel} \frac{\nabla \delta \bar{A}_{\parallel} \times \mathbf{B}}{B^2}$$

*W. Zhang, Physical Review Letters (2008)

The variables studied

- Velocity space resolved diffusivity (gyroaveraged)

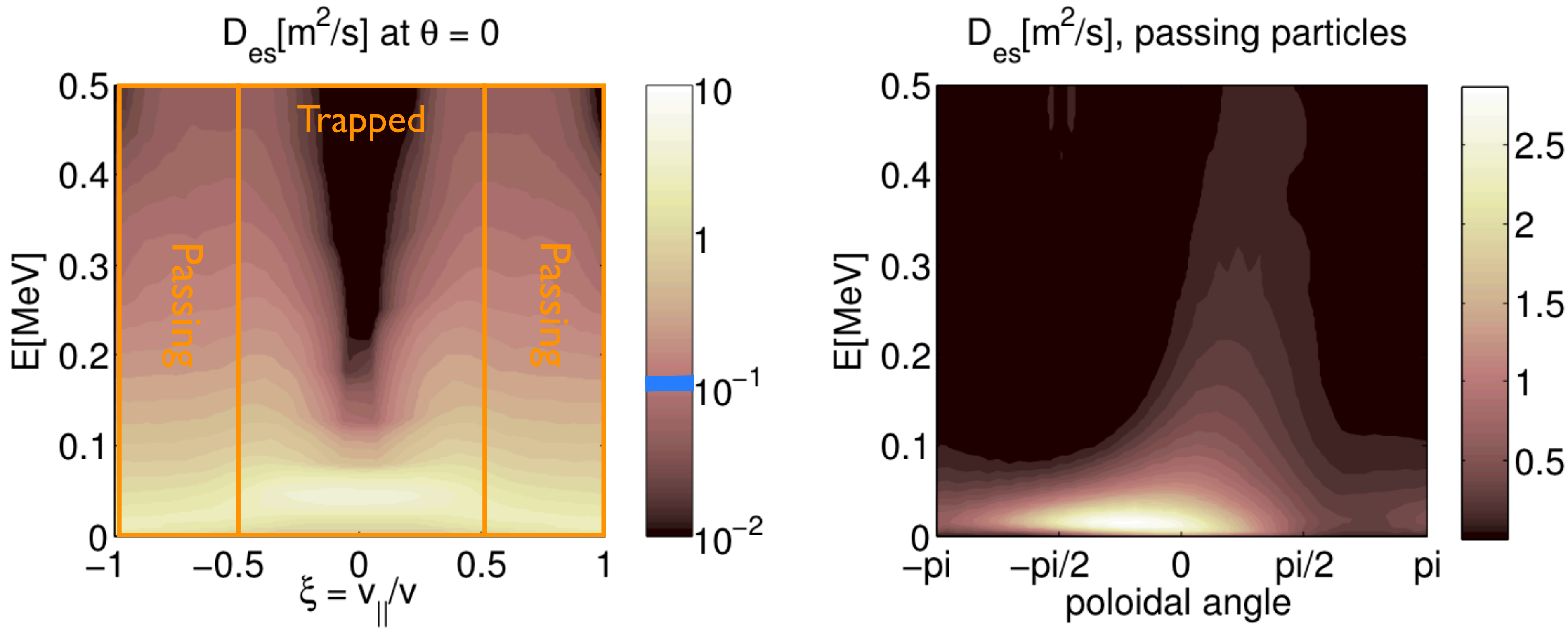
$$D_v(\mathbf{x},\mathbf{v}) = -\frac{1}{\nabla \ln n(\mathbf{x})}\frac{\delta f(\mathbf{x},\mathbf{v})}{f_0(\mathbf{x},\mathbf{v})}\delta\mathbf{u}(\mathbf{x},\mathbf{v})\cdot\hat{\mathbf{e}}_r$$

- Consistent with Fick's law

$$\langle D_v\rangle_{f_0} = \frac{\int d\mathbf{v}\, D_v(\mathbf{x},\mathbf{v}) f_0}{\int d\mathbf{v}\, f_0} = -\frac{\Gamma(\mathbf{x})}{\nabla n(\mathbf{x})} = D^{\mathrm{eff}}(\mathbf{x})$$

M. Albergante, Physics of Plasmas (2009)

Nonlinear results



- Trapped ions: orbit- and gyro-averaging
- Passing ions: no gyro-averaging, orbit-averaging?
- Above collisional estimates (——)

Transport Summary

- Potentially large electrostatic transport for beam ions
- Magnetic transport negligible
- What impact on the beam driven current?
- Can poloidal effects/collisions play a role?

Simulation of the neutral beam injection and slowing down

NBI Modelling

(1) 4 Injectors

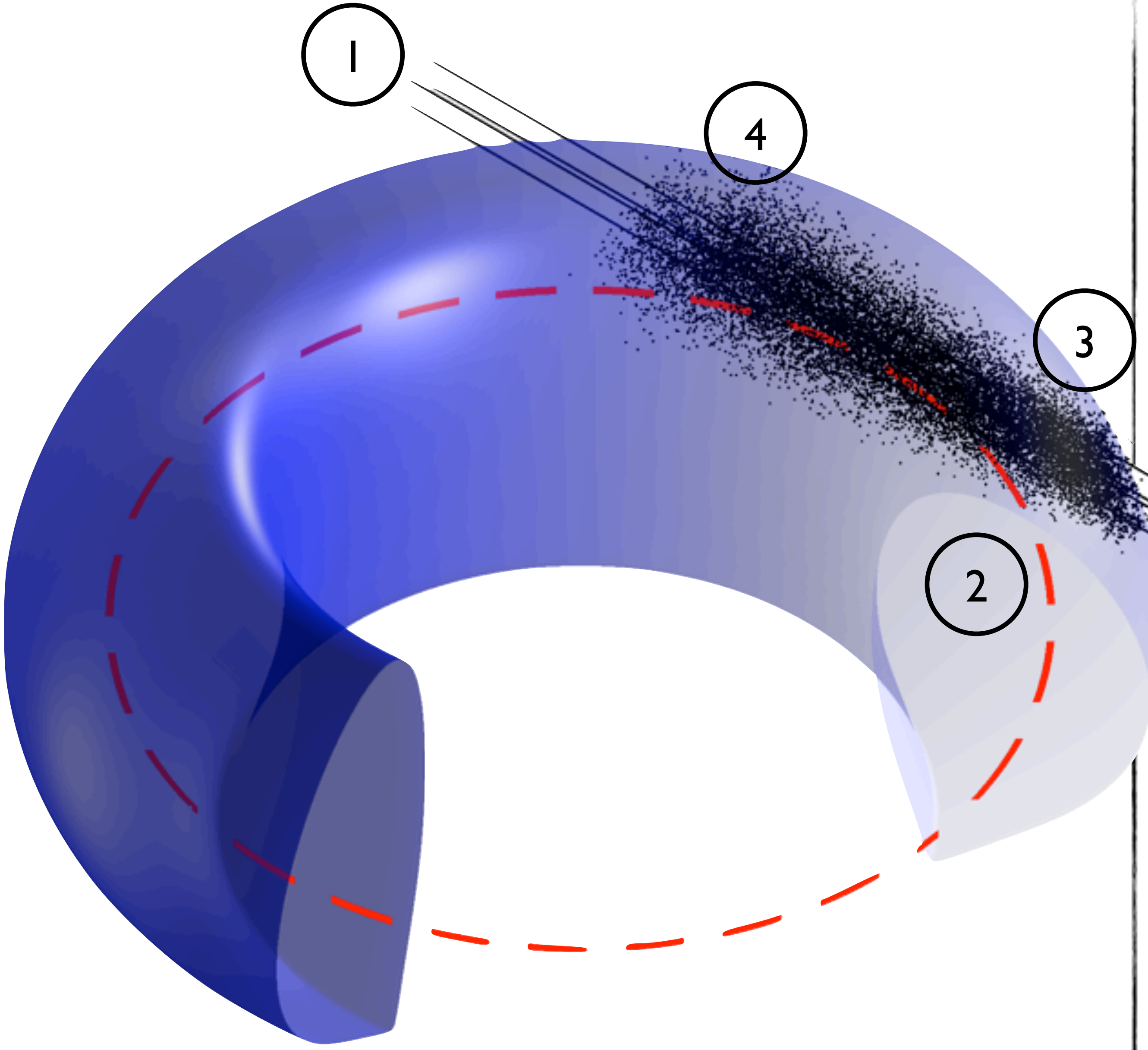
(2) Tangential

(3) Uniform number of particles

(4) Beam collimation reproduced

(5) Parallel velocity from CHEASE

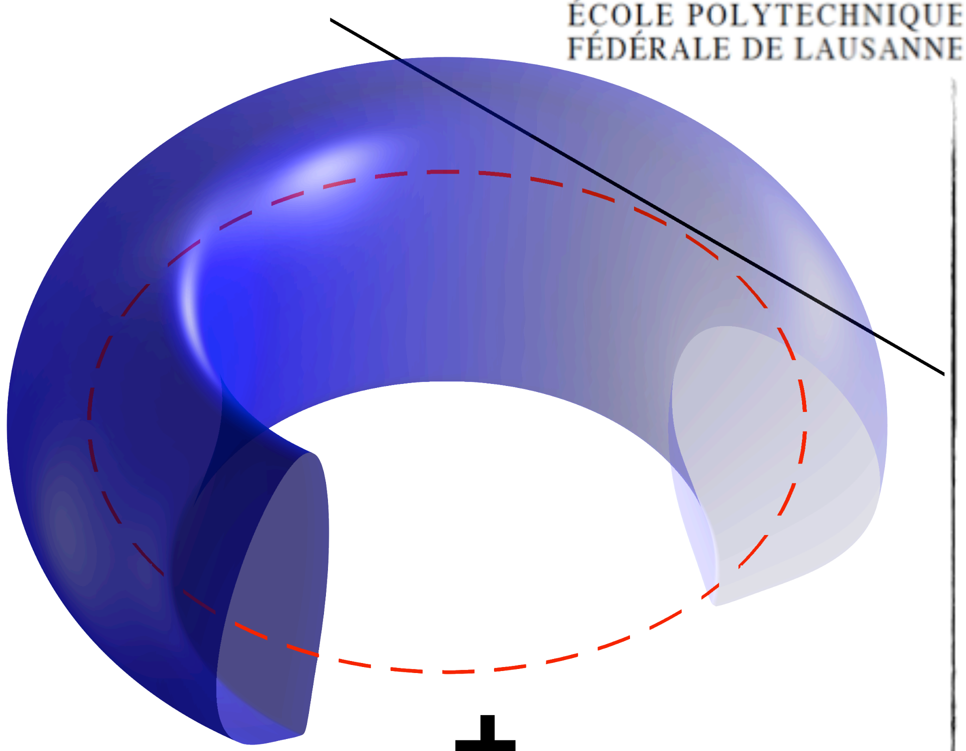
(6) What weight?



NBI Geometry

- Beam intensity

$$I(\ell) = I_0 e^{-\int_0^\ell n_e(\ell')\sigma_{\text{eff}}(\ell')d\ell'}$$



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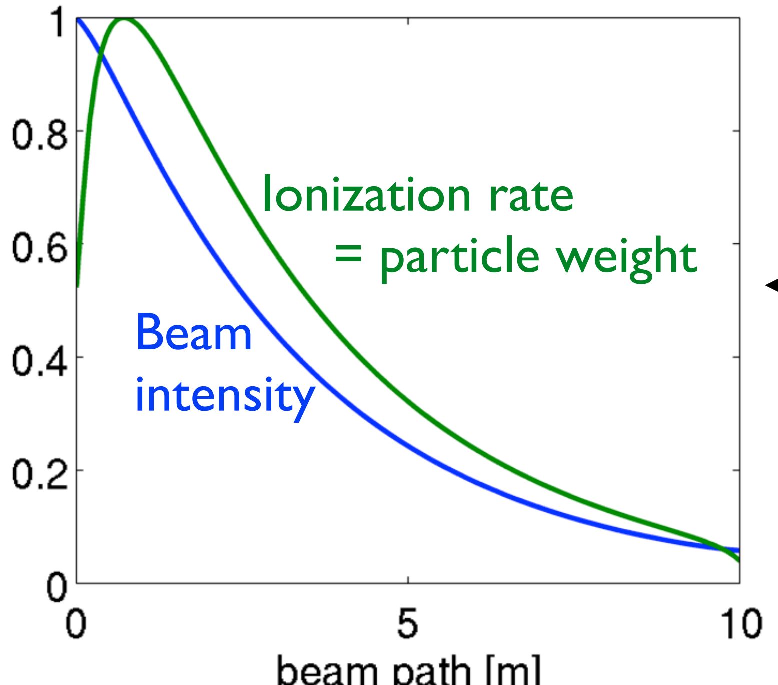

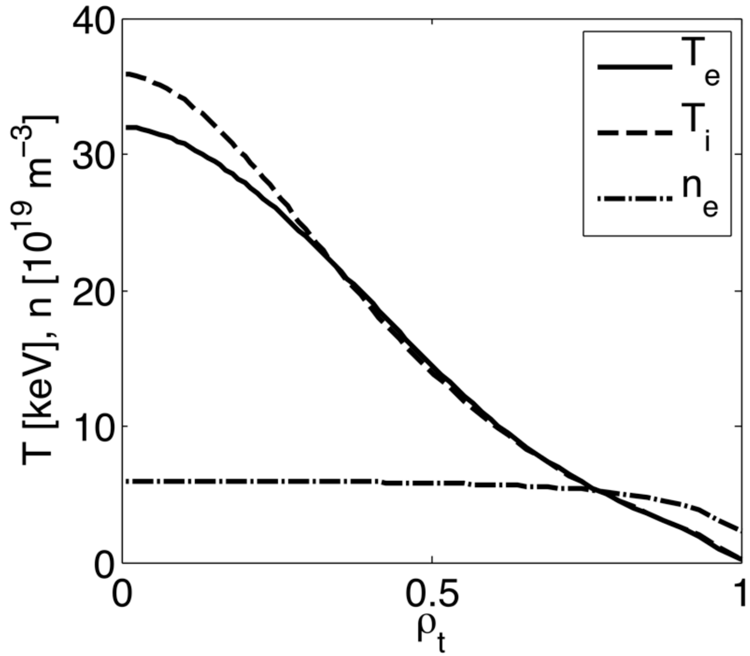

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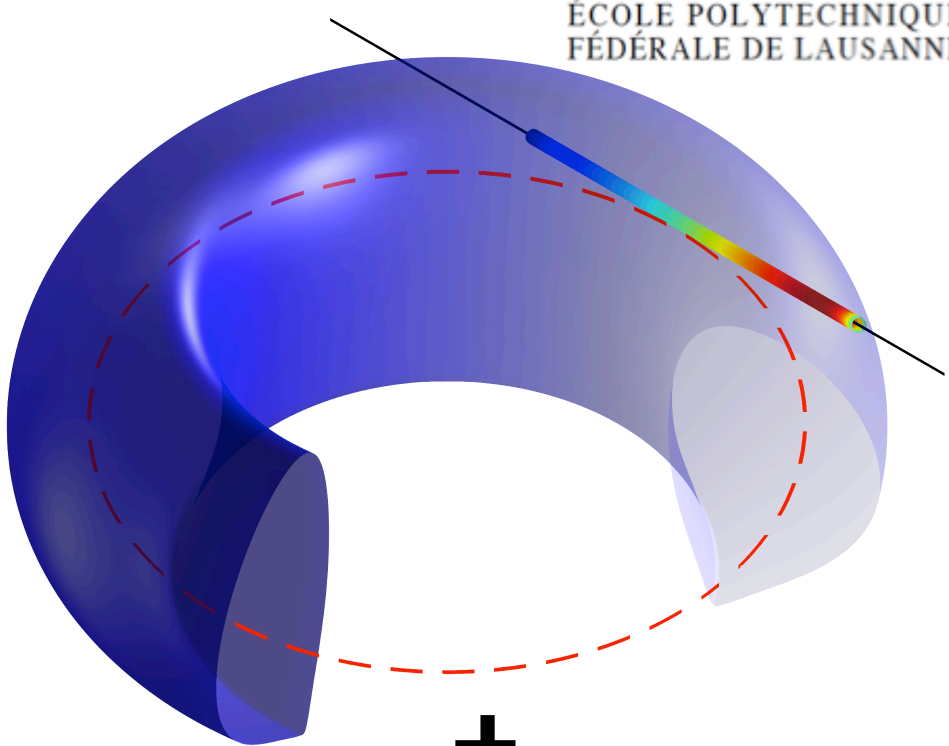

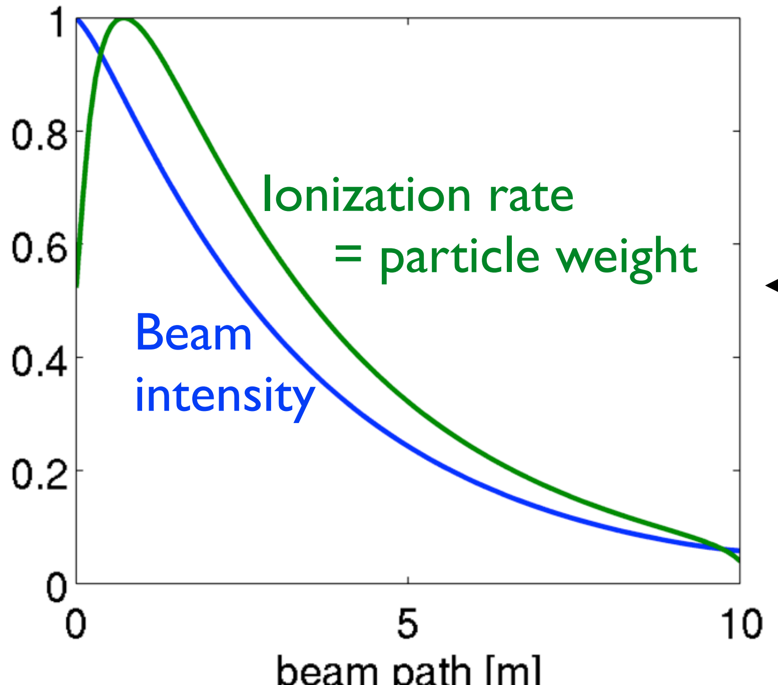

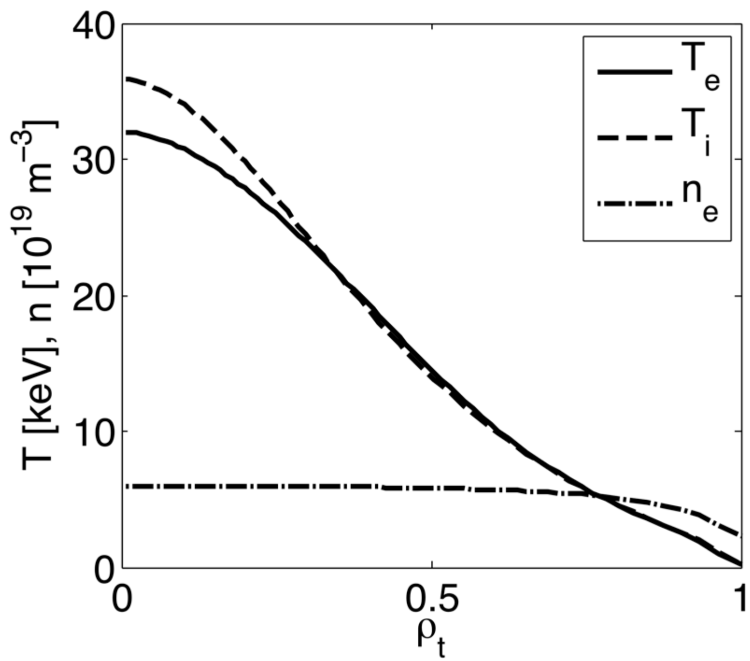

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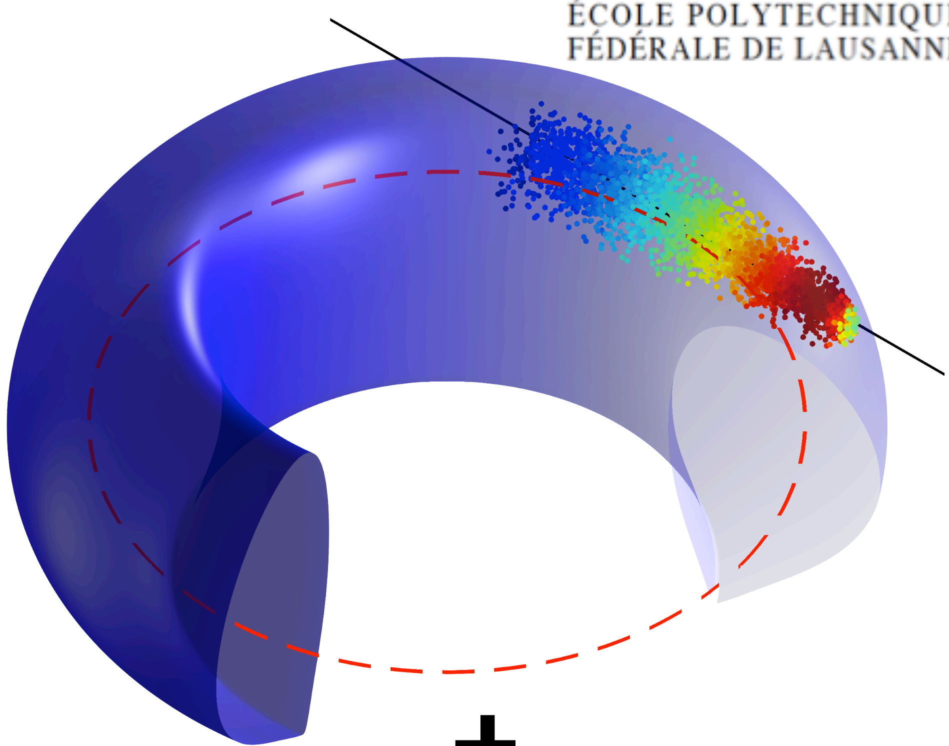
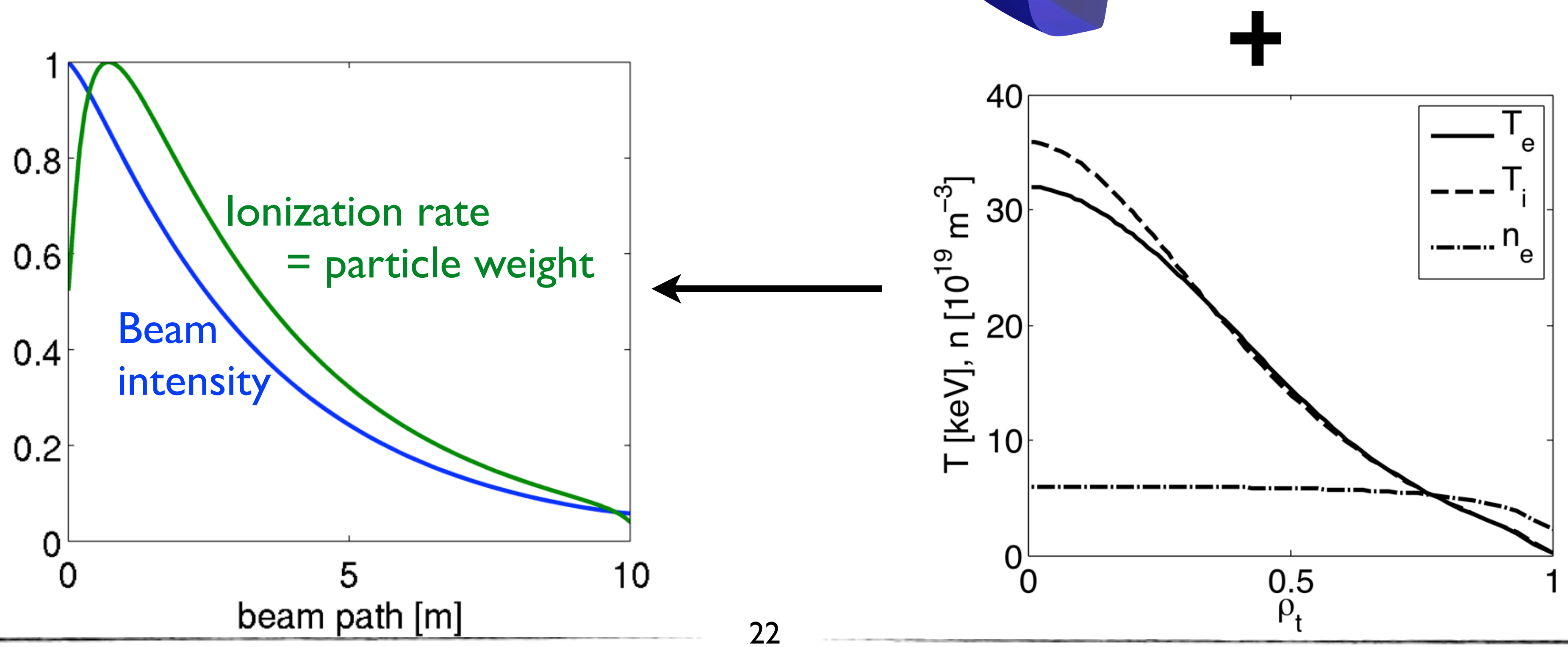
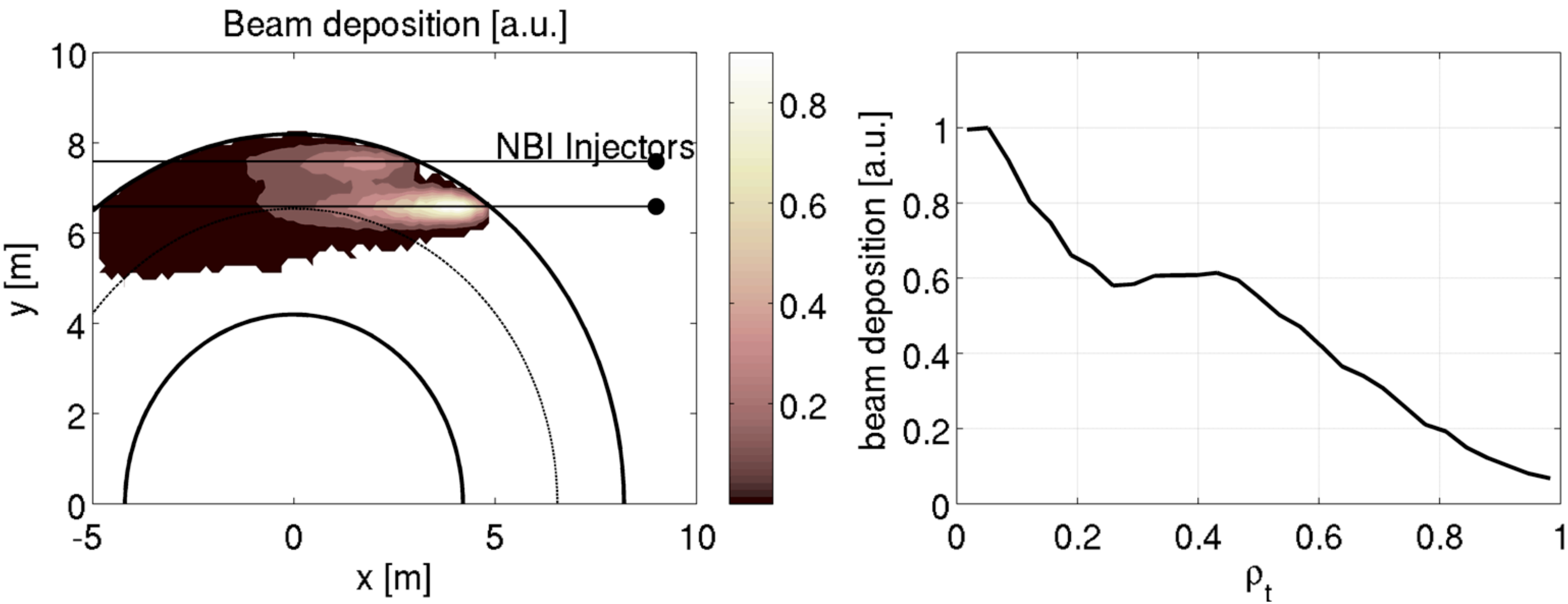




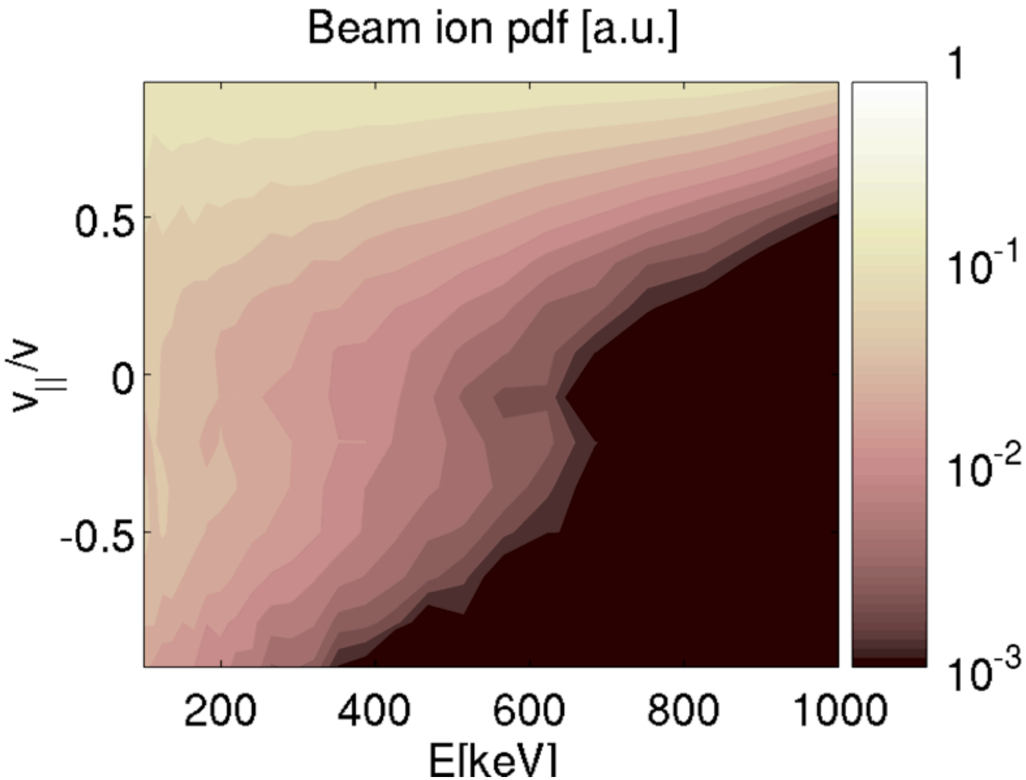
NBI Geometry

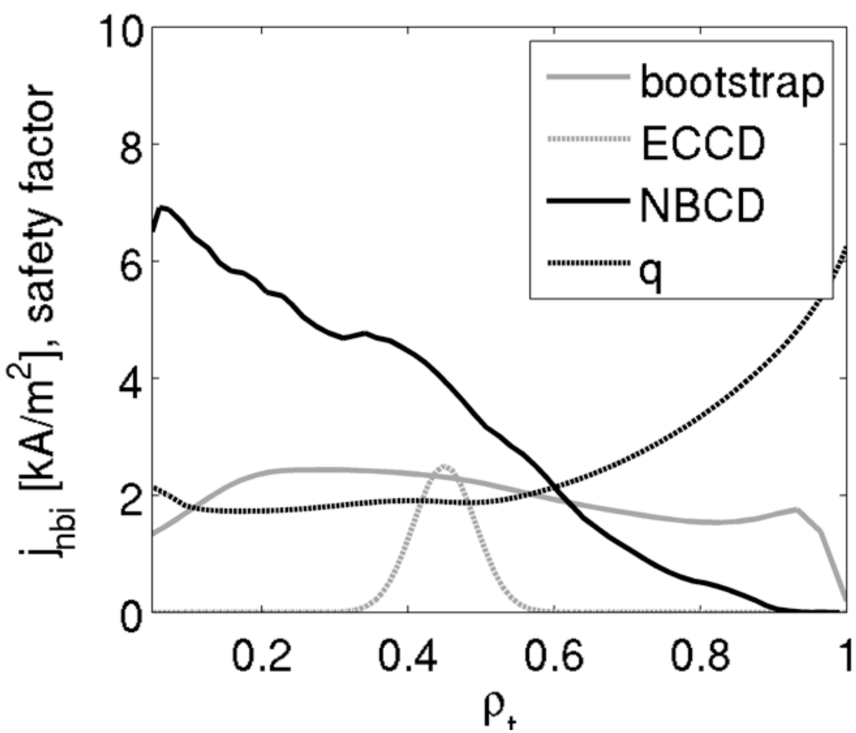


- Broad deposition, peaked profile
- Edge deposition: need for high energy NBI
- What time evolution?

The VENUS Code*

- Drift-kinetic particle pushing code
- Velocity space kicks for Coulomb collisions
- Inclusion of electron drag





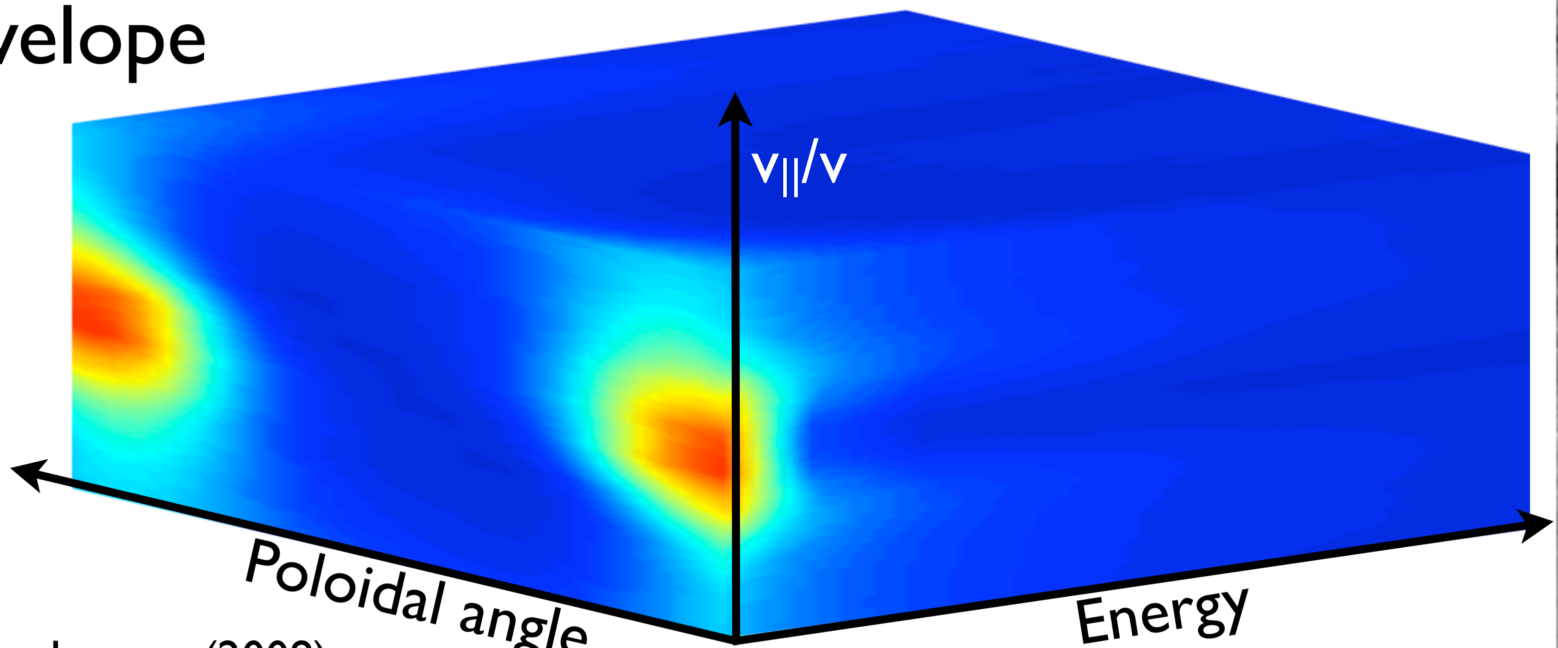
*See M. Jucker, this Friday

NBI summary

- Neutral beam model ready
- Collisional slowing down of NBI particles
- Anomalous transport must be implemented

Anomalous diffusivity module

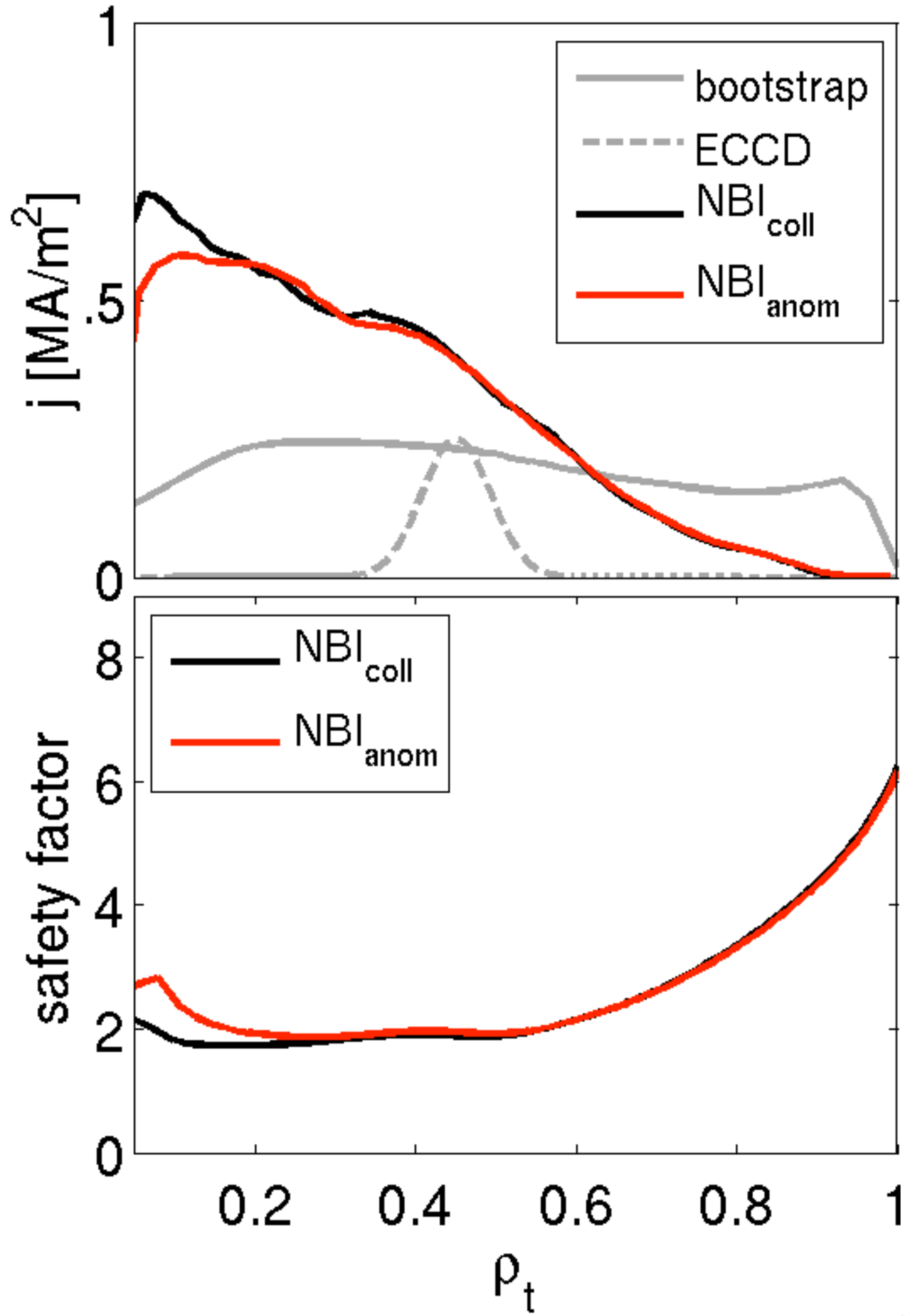
- Monte-Carlo diffusion
- Effective gyroaveraged diffusivity from GENE simulations
  - Interpolate at particle position
  - Radial envelope



*W. Zhang, Physical Review Letters (2008)

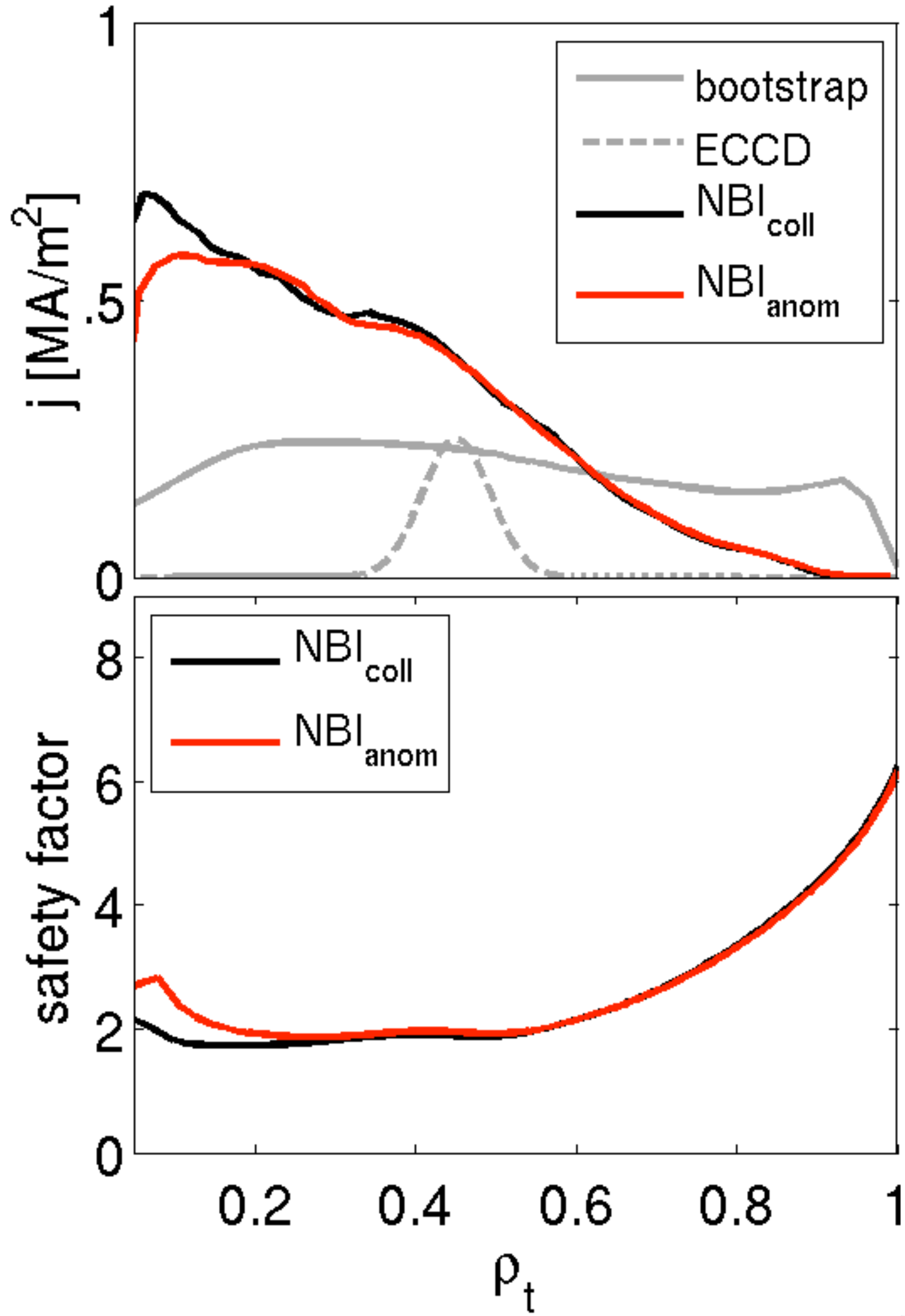
Results

- NBCD profile redistributed
- Small changes in the safety factor
- Moderate shear reversal
- ‘Averaged’ model is a good approximation



Results

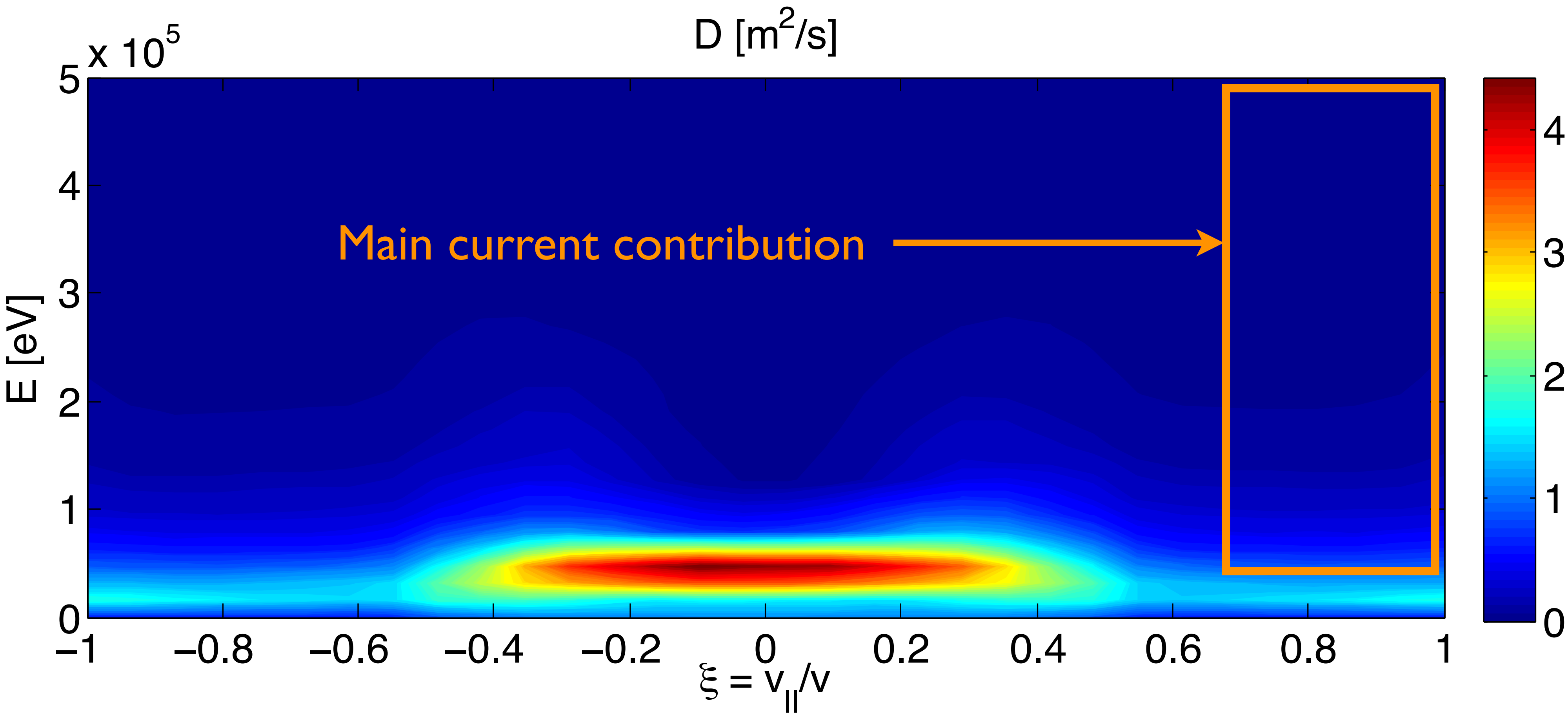
- Main disadvantage
  - Local approximation
- Solutions
  - Global version of GENE*
  - Multiple flux tube simulations+
- Low microturbulent impact. Why?



*T. Görler, tomorrow
+M. Barnes, Thursday

Results

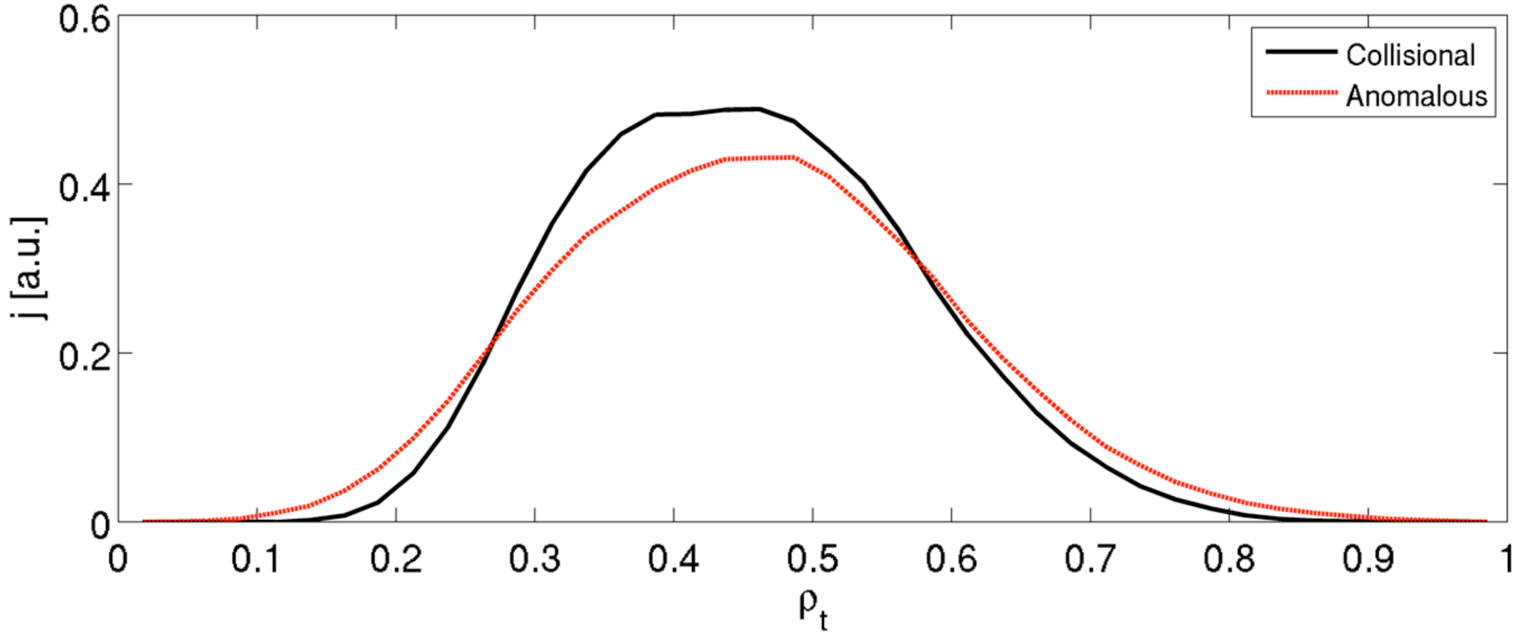
- Low diffusivity for particles contributing to the current



- High energy NBI at 1 MeV good choice

Lower energy NBI

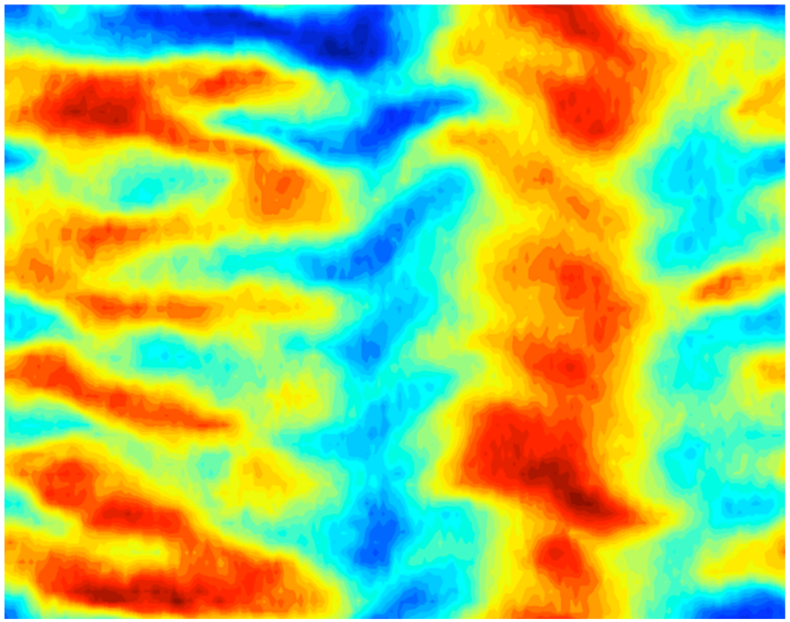
- E_{nbi} = 300 keV at mid-radius
- E_{nbi}/T_e = 20 (similar to ASDEX)
- Previous scenario $E_{nbi}/T_e > 50$ at mid-radius



- Beam redistribution more important

Conclusions

Microturbulence

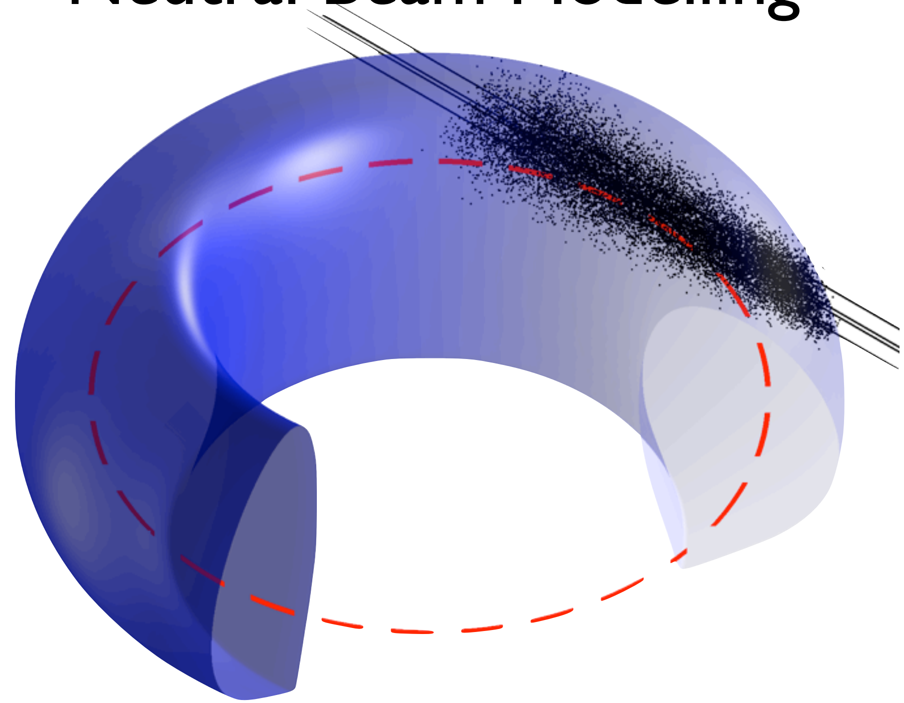


<u>GENE</u> code

Energetic ion diffusivity

Velocity space analysis

Neutral Beam Modelling



<u>VENUS</u> code

Collisional slowing down

<u>Anomalous transport</u>

Conclusions

- Modelling of the ITER steady state scenario
- Consequences for 1 MeV NBI
  - Small but potentially important NBCD redistribution
  - Transport and stability would change
- Consequences for low energy NBI
  - Larger transport, more redistribution
- Our model underestimate?
  - NBI model improvements ($E_{nbi}/2$ and $E_{nbi}/3$ fractions)
  - Background turbulence potentially stronger

Outlook

- DEMO reference scenarios more affected
  - Large beam current (1 MeV)
  - Plasma temperature two times ITER's goal
- More detailed and self consistent turbulence
  - very challenging
- Comparison with experimental data
  - even more challenging

CRPP

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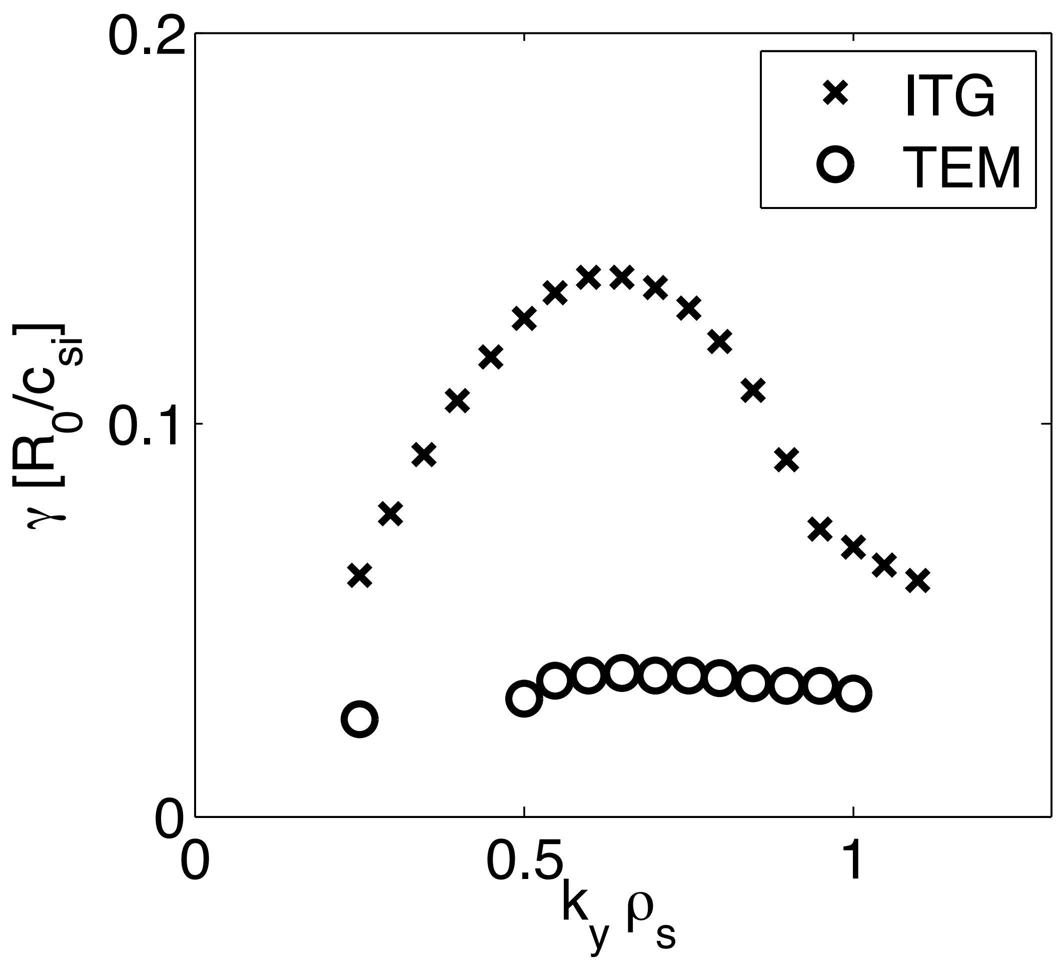
Linear Analysis

- Subdominant TEMs
- Also investigated ETG

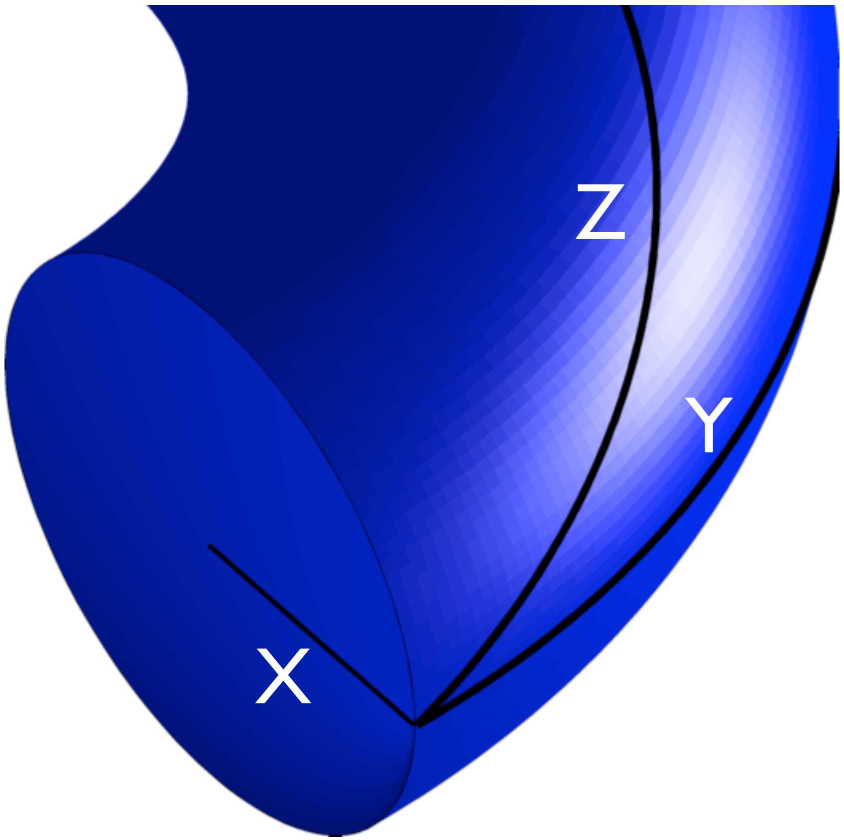
$$\frac{\gamma^{ETG}}{\gamma^{ITG}} \ll \sqrt{\frac{m_e}{m_i}}$$

- Hyperfine scale neglected



Nonlinear analysis

Parameters	
[nx nky nz]	[192 32 48]
[nvpar nmu]	[64 32]
$k_{y\text{-min}}$*rho_s	0.08
$\Omega_T = -(R_0/a)\,\mathrm{d}\ln T/\mathrm{d}\rho_t$	3.5
Electron beta	1.5%
q_{flux surface}	1.8
species	deuterium + e^-
$\hat{s} = \dfrac{\rho_t}{q}\dfrac{\mathrm{d}q}{\mathrm{d}\rho_t}$	1.0



NBI Geometry

- 4 Injectors
- Tangential geometry
- 5 coordinates
- Real space
- Velocity space

  ($v_{||}$, E)
- Weight = beam ionization