Diagnostic of fast-ion energy spectra and densities in magnetized plasmas

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Main message of this talk

- Alpha particle density and energy spectrum measurements at ITER will be possible by solution of inverse problems: velocity-space tomography, energy spectrum inference, model fitting

Outline

- **ITER measurement requirements**
- High-resolution fast-ion measurements
- Velocity-space coverage of fast-ion measurements
- Velocity-space tomography at JET and ASDEX Upgrade
- Prospects for alpha diagnostic at ITER: Velocity-space tomography, energy spectrum inference, model fitting
- Conclusions

ITER measurement requirements

Donne et al. (2007) *NF.* Progress in the ITER Physics Base, Ch.7: Diagnostics

Measurement	Parameter	Condition	Range or Coverage	Resolution: Time or Freq.	Resolution: Spatial or Wave No.	Accuracy
30. Confined alphas	Energy spectrum	Energy resolution TBD	(0.1–3.5) MeV	100 ms	$a/10$	20%
	Density profile		$(0.1–2) \times 10^{18}\ \mathrm{m}^{-3}$	100 ms	$a/10$	20%

Now in the ITER measurement requirements database

Title	Range Value Coverage	Condition	Time Res.	Spatial Res.	Accuracy
30. Confined alphas and fast ions - alpha density profile	(0.1 - 2) E^{18} m^{-3}	(blank)	100ms	a/10	20%
30. Confined alphas and fast ions - alpha energy spectrum	0.1 - 3.5 MeV,	Energy res. 10 %	100ms	a/10	20%
30. Confined alphas and fast ions - D, T, H, He3 energy spectrum	0.1 - 1 MeV	Energy res. 10 %	100ms	a/20	20%

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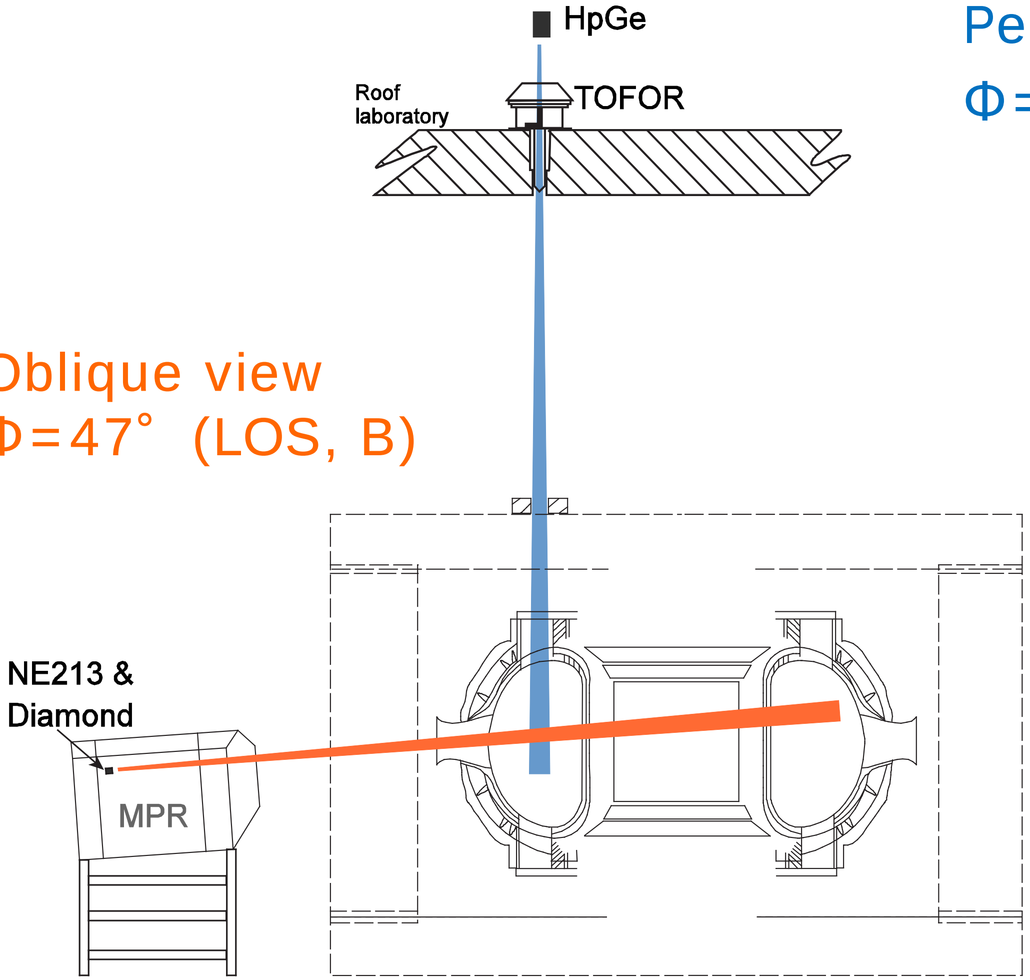
Neutron emission and gamma-ray spectrometry at JET

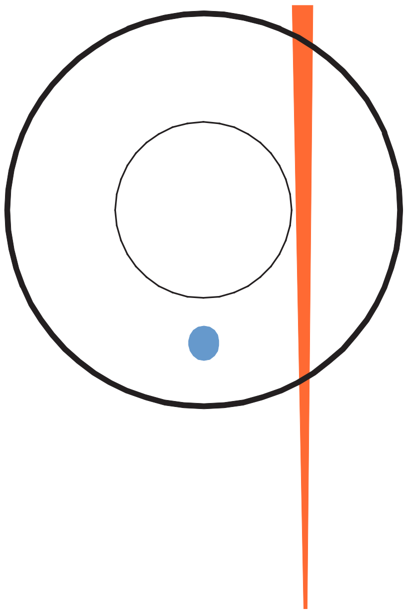
Perpendicular view

Φ=90° (LOS, B)

Oblique view

Φ=47° (LOS, B)

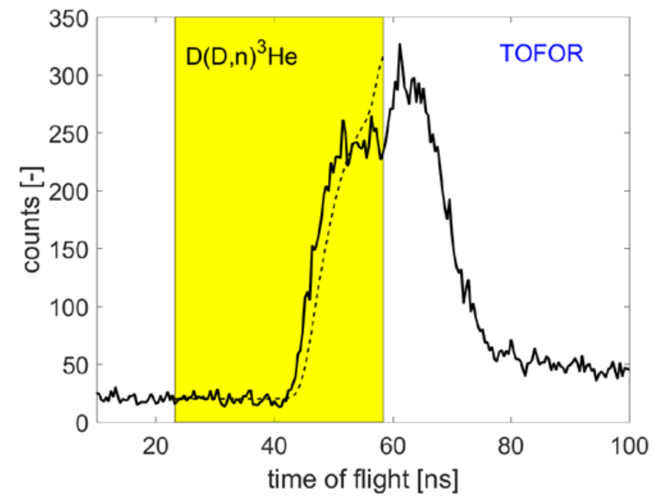


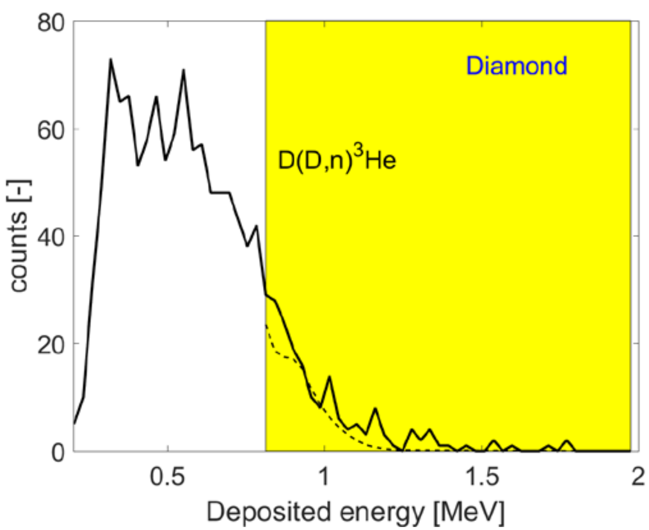


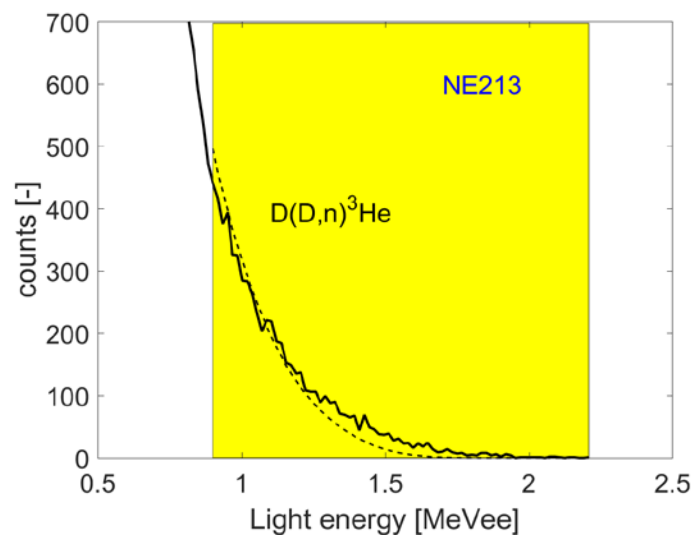
Eriksson et al (2015) *NF*

NES measurements

- 3 simultaneously measured spectra in JET #86459
- 4.5 MW NBI + 3 MW 3rd harmonic ICRF-heating
- Yellow: Used for inversion
- Measure spectra of various quantities



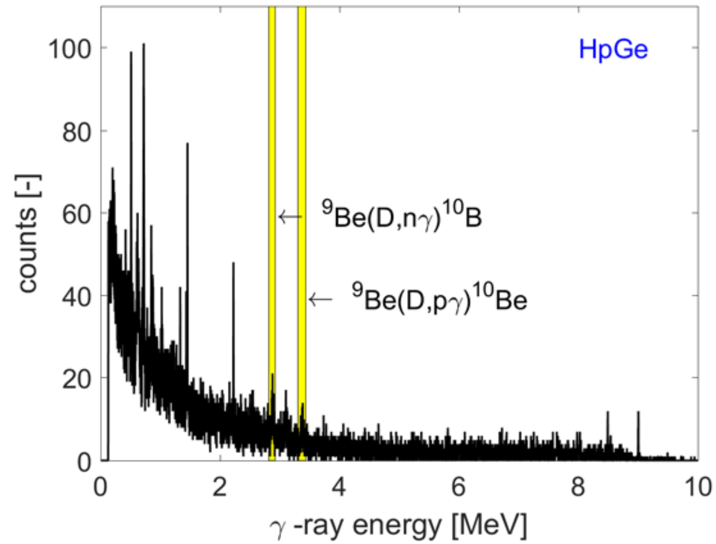


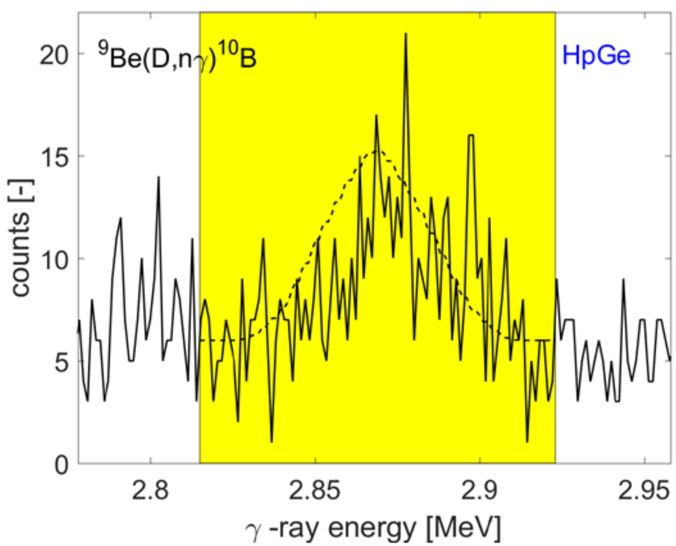


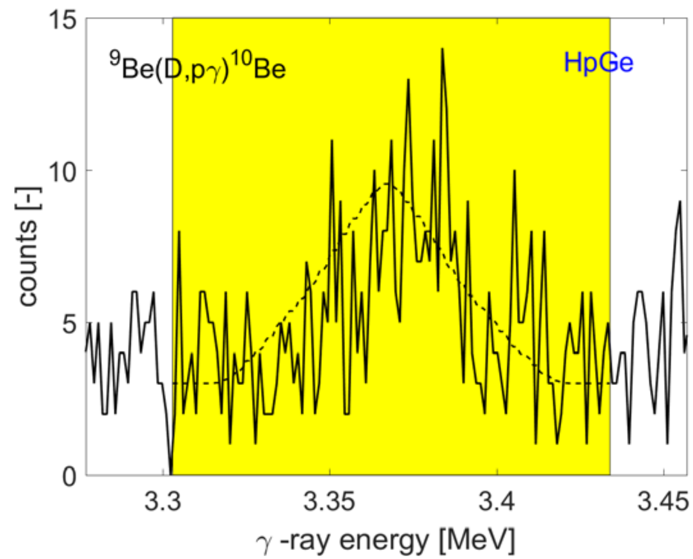
Salewski et al (2017) *NF*

GRS measurements

- 2 GRS spectra in JET #86459
- High-resolution High-purity Germanium detector (1keV over 10 MeV)
- Two competing reactions
- Measure gamma-ray energies



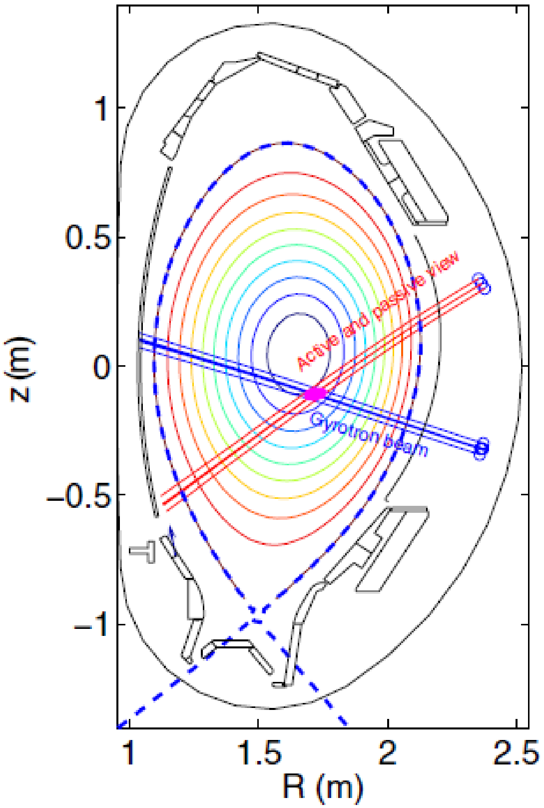


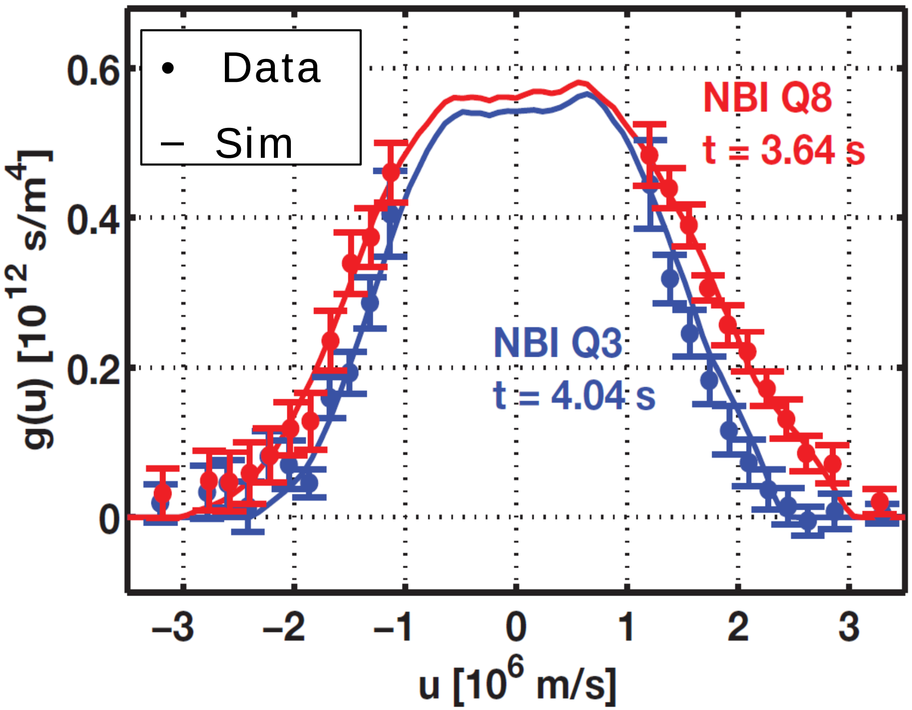


Salewski et al (2017) *NF*

Collective Thomson scattering measurement at ASDEX Upgrade

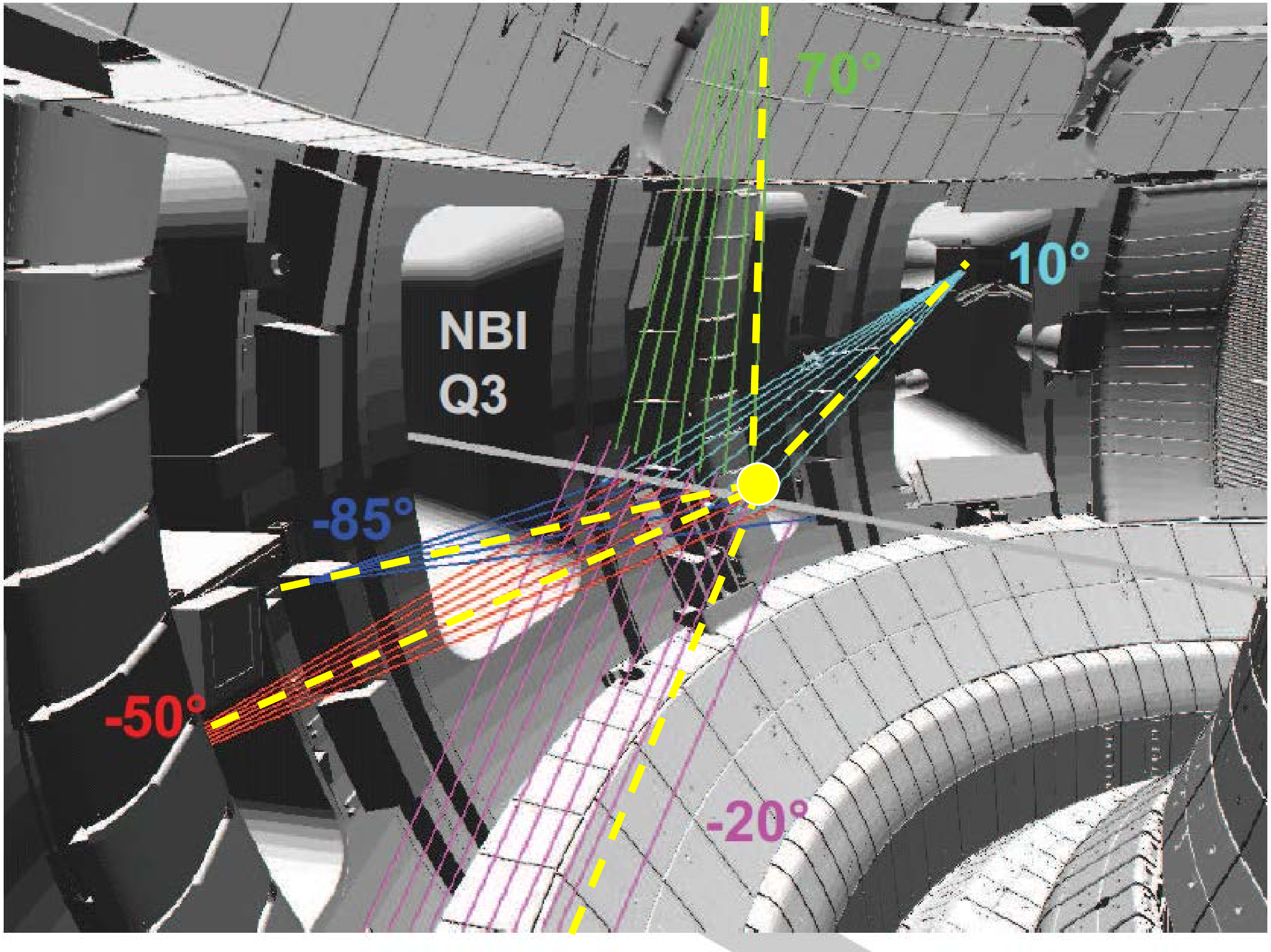
- CTS measures velocities projected along a resolved direction u.

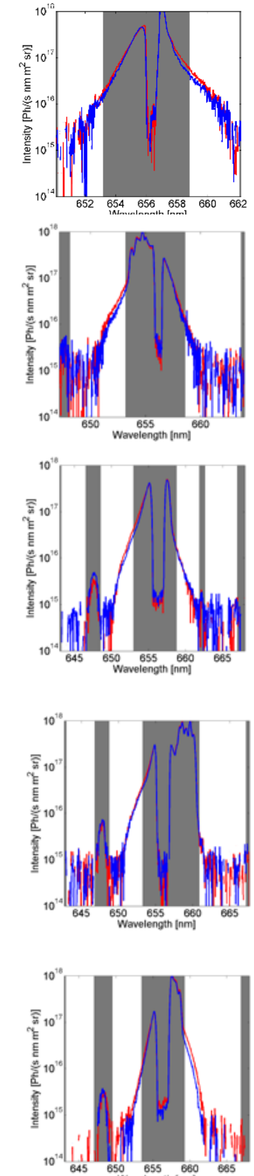




Rasmussen et al. (2015) *PPCF*

Fast-ion D-alpha spectroscopy at ASDEX Upgrade





Weiland et al (2016) *PPCF*

Outline

- ITER measurement requirements
- High-resolution fast-ion measurements
- **Velocity-space coverage of fast-ion measurements**
- Velocity-space tomography at JET and ASDEX Upgrade
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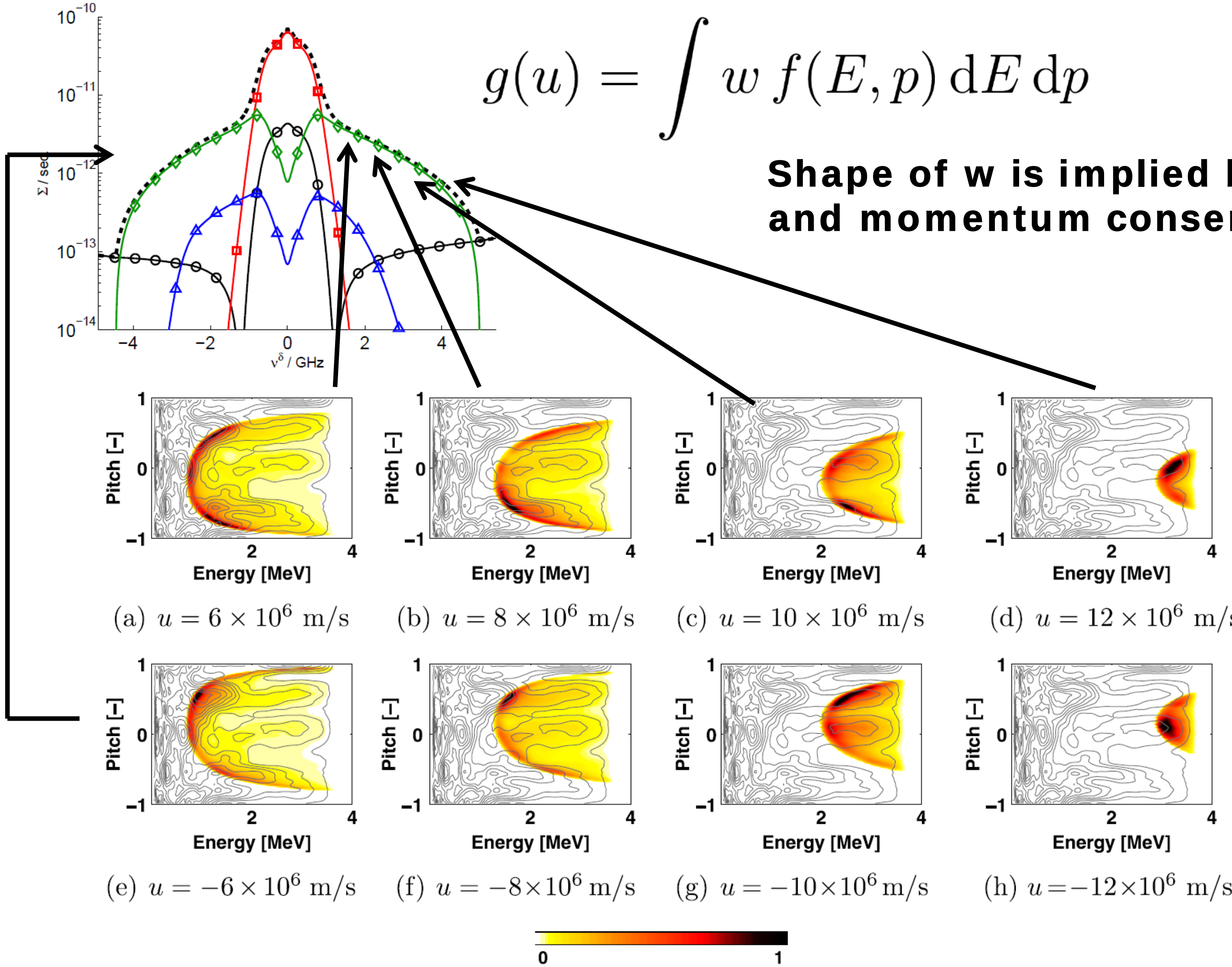
Velocity-space origin of the CTS signal

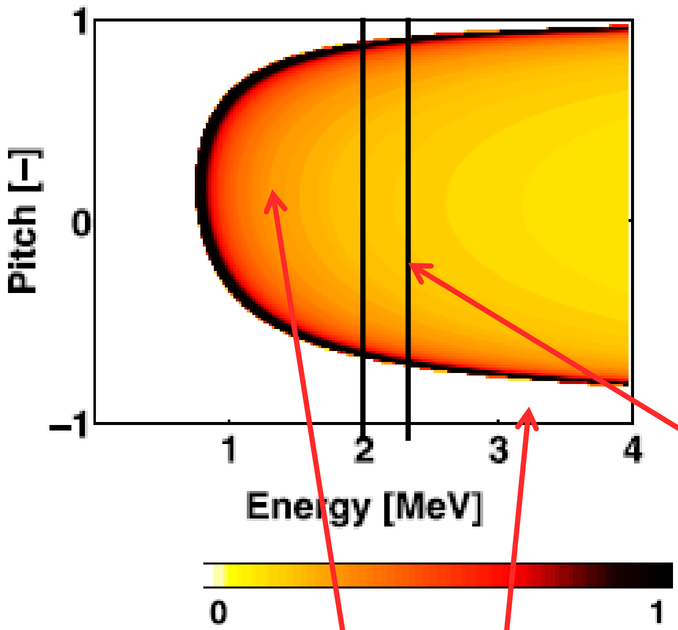
$$g(u) = \int w\, f(E,p)\, \mathrm{d}E\, \mathrm{d}p$$

Shape of w is implied by energy and momentum conservation



Salewski et al. (2011) *NF*

Alpha densities and energy spectrum



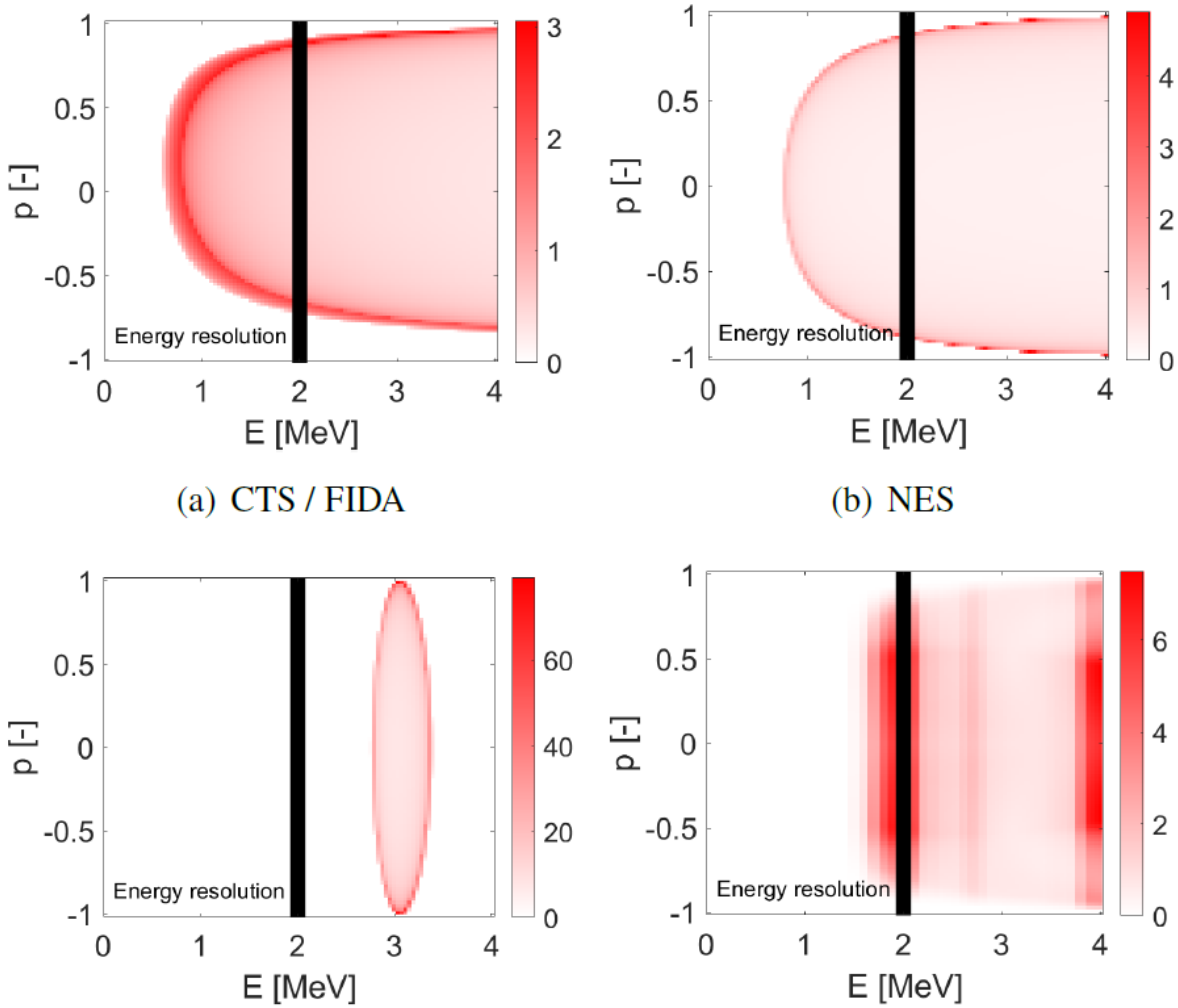
$$g(u) = \int w\, f(E,p)\, \mathrm{d}E\, \mathrm{d}p$$

Weight function suggests incomplete velocity-space coverage and no energy resolution.

- no direct densities
- Signal/ion varies
- f(E,p) is incompletely diagnosed

- no direct energy resolution
- Signal from $E>E_{min}$ for given u

Alpha energy spectra and densities cannot be determined directly by CTS, GRS or NES



(a) CTS / FIDA

(b) NES

(c) GRS-1

(d) GRS-2

Options for alpha-particle energy spectrum and density measurements

1. Measure 2D velocity distribution function by velocity-space tomography
   - Integrate to get energy spectrum
   - Integrate again to get density
2. Measure 1D energy spectrum by velocity-space tomography with prior: isotropy
   - Integrate to get density
3. Fit a model, e.g. slowing-down distributions
   - Spectrum is assumed, not measured.

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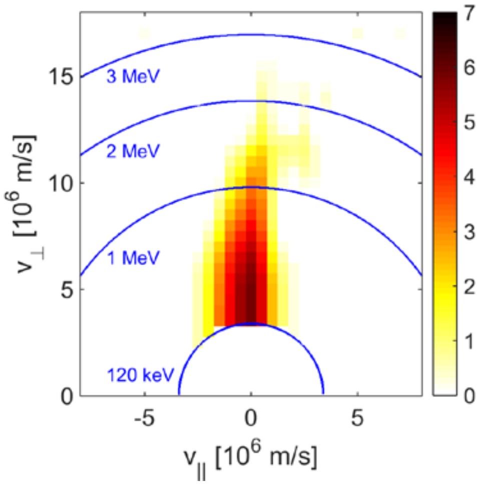
Introduction to velocity-space tomography

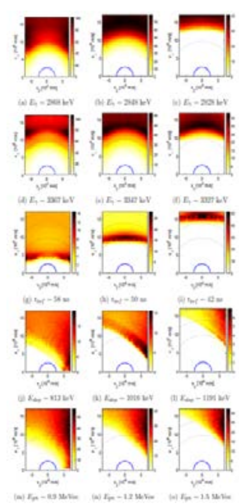
Forward problem

$$WF = S$$

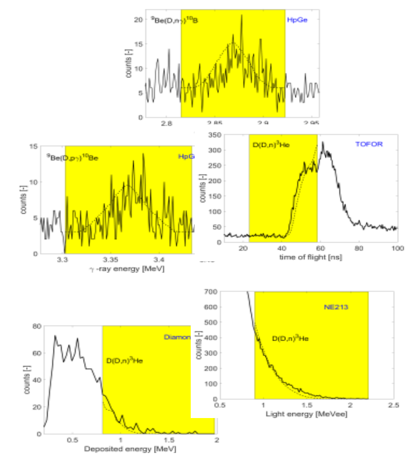
Distribution function F



Matrix W



Measurements S



$$\text{minimize} \left\| \begin{pmatrix} W \\ \lambda L \end{pmatrix} F - \begin{pmatrix} S \\ 0 \end{pmatrix} \right\|_2 \quad \text{subject to} \quad F \geq 0$$

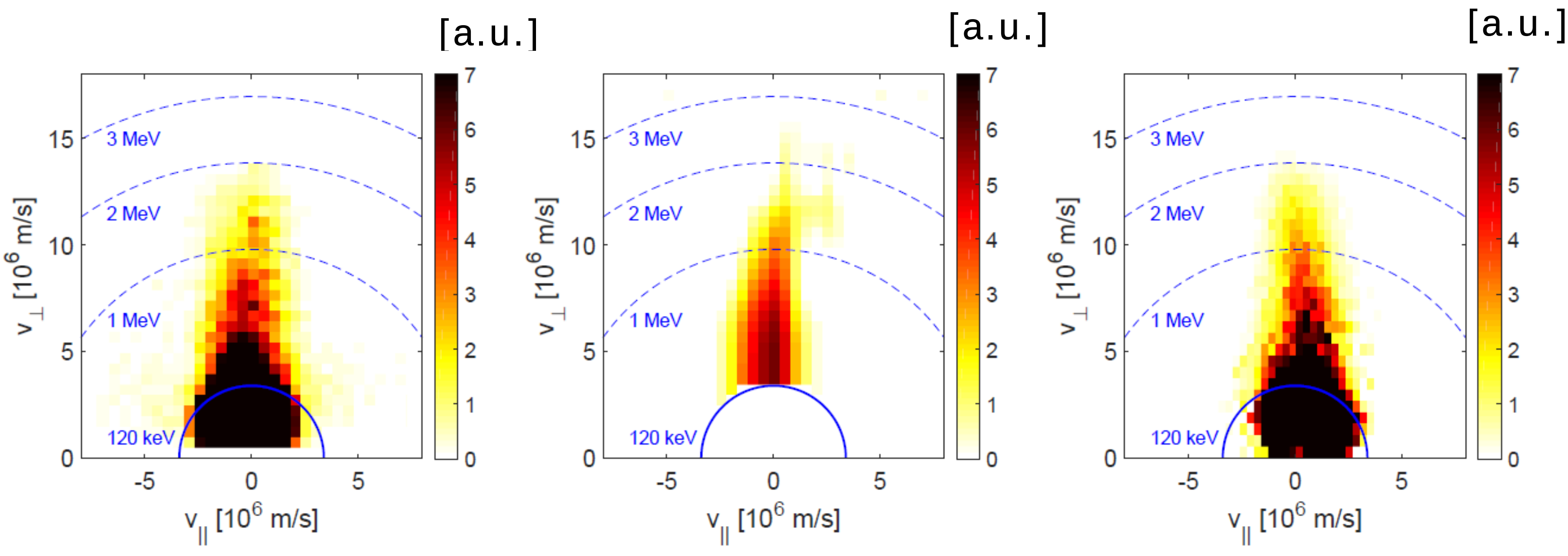
Salewski et al

(2011,12,13,14,15,16,17,18) *NF*

Inverse problem

Velocity-space tomography vs. Simulation at JET

- 4.5 MW NBI + 3 MW 3rd harmonic ICRF measured by GRS/NES
- Basic features agree: Tail length, tail width.
- Barrier region suggests low densities above 2 MeV.
- Velocity-space tomography confirms the barrier experimentally.



(a) SPOT-RFOF (b) Measurement (c) ASCOT-RFOF

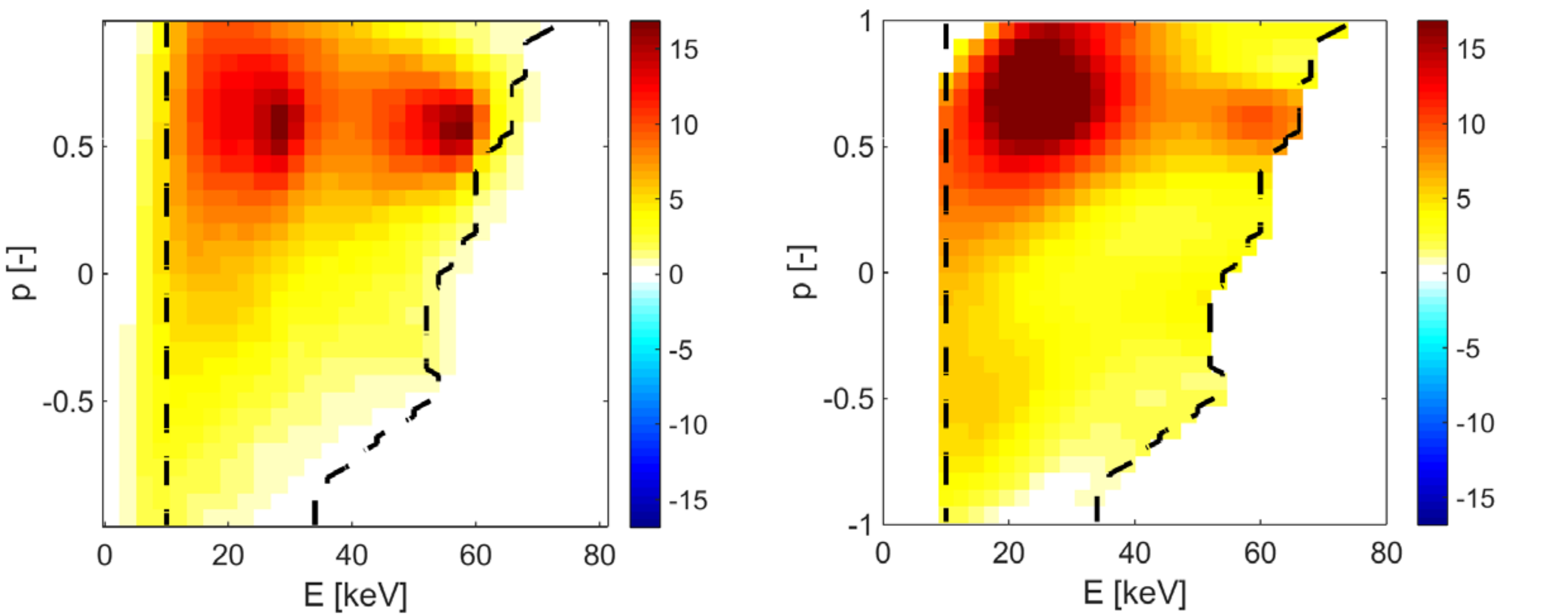
Salewski et al (2017) *NF*

Velocity-space tomography vs. simulation at ASDEX Upgrade

- 2.5 MW NBI measured by 5-view fast-ion D-alpha spectroscopy

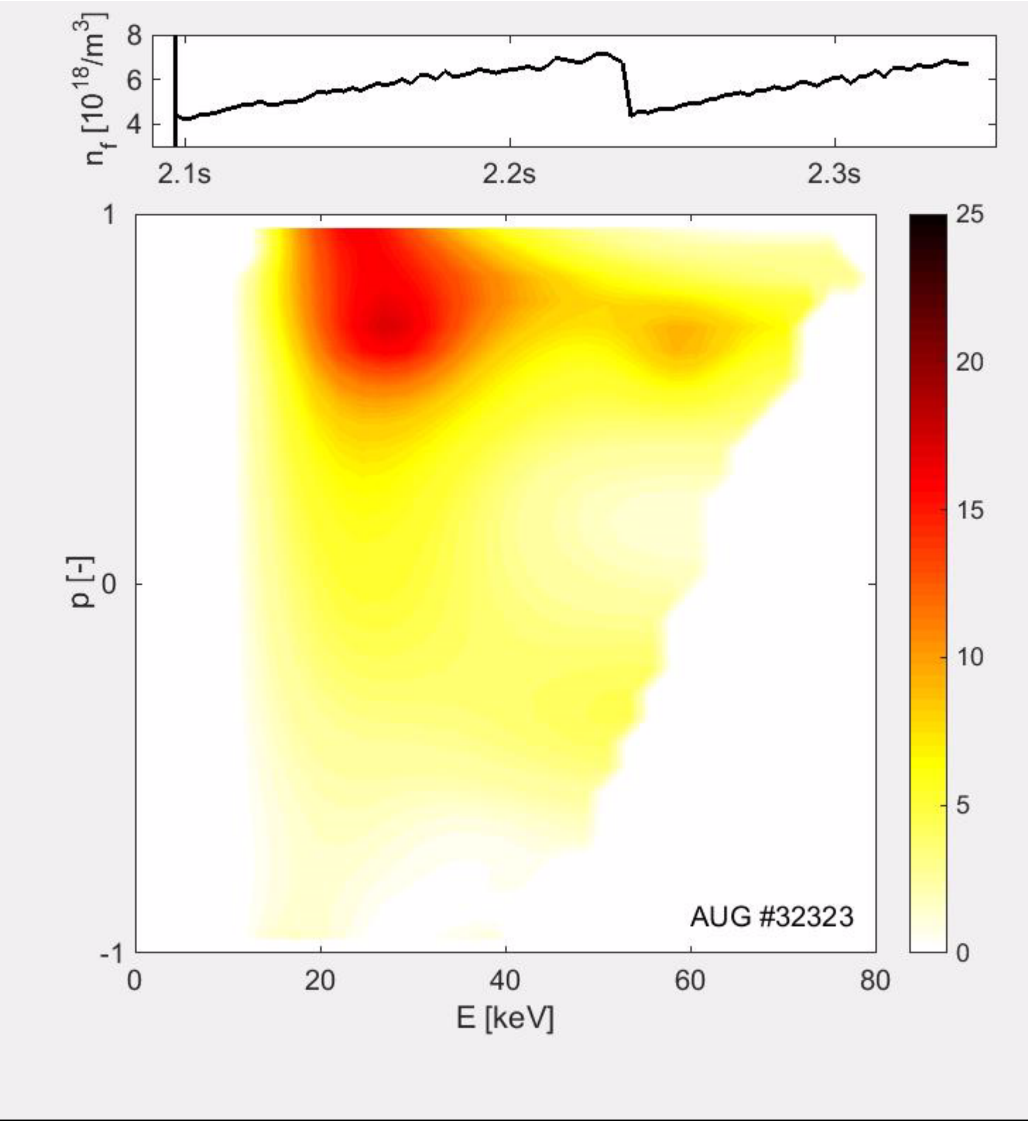
$$F^* = \arg\min_F \left\| \begin{pmatrix} W \\ \lambda\kappa(E,p)L \end{pmatrix} F - \begin{pmatrix} S \\ 0 \end{pmatrix} \right\|_2 \quad \text{subject to} \quad \begin{cases} F^*(E_0, p_0) = 0 \\ F^* \geq 0 \end{cases}$$

Simulation   Measurement



Salewski et al (2016b) NF

Tomography movie of a sawtooth crash



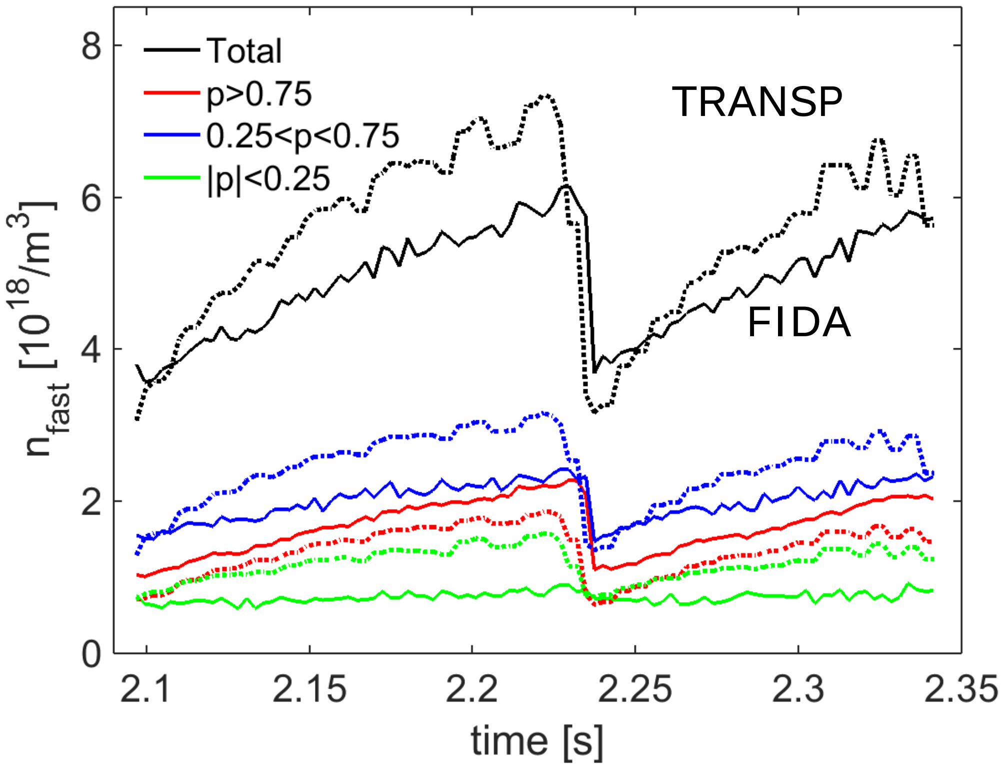
- Upper panel: Measurement of fast ion density

$$n_f = \iint f dE dp$$

- Lower panel: tomographic inversion movie
- fit to 50.000 data points
  - 100 frames
  - 5 spectra per frame
  - 100 data points per spectrum

Salewski et al (2016b) NF

Sawteeth: FIDA tomography vs. TRANSP



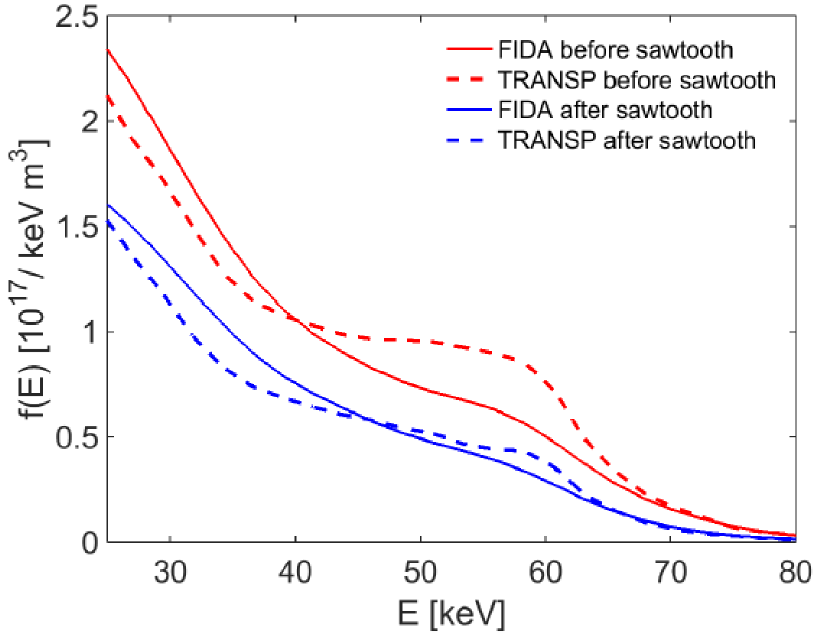
AUG #32323

- Fairly good agreement
- Measured crashes smaller than simulated crashes.
- No measured crashes for |p|<0.25 in agreement with Kolesnichenko (1996) NF and disagreement with TRANSP.

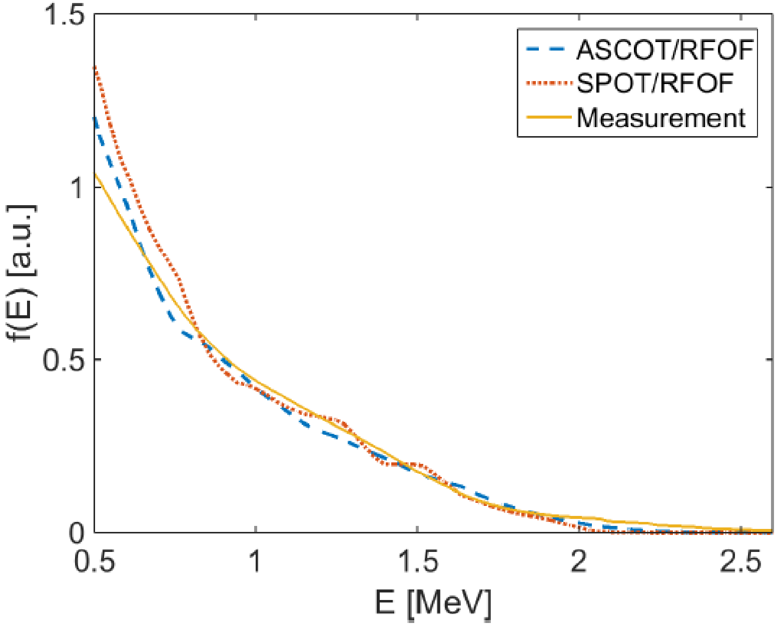
Salewski et al (2016b) NF

Energy spectrum measurements at JET and ASDEX Upgrade

ASDEX Upgrade



JET



- Fast-ion density and energy spectrum measurements are now demonstrated at current machines.

Outline

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- **Prospects for alpha diagnostic at ITER: Velocity-space tomography, energy spectrum inference, model fitting**
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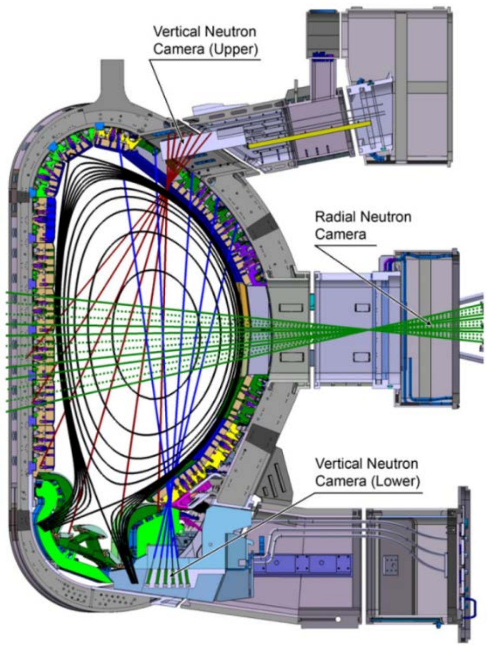
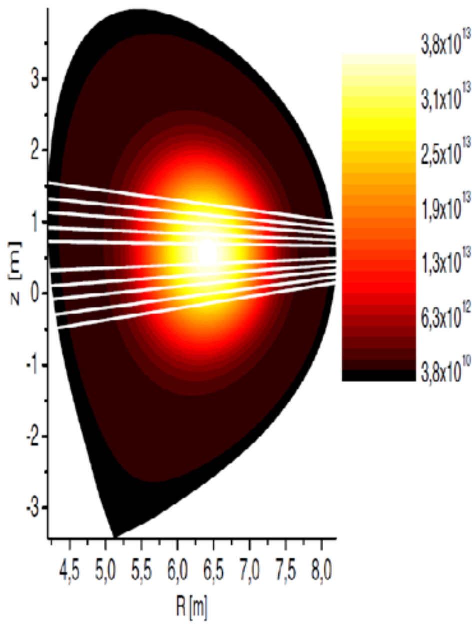
Alpha velocity-space diagnostic at ITER

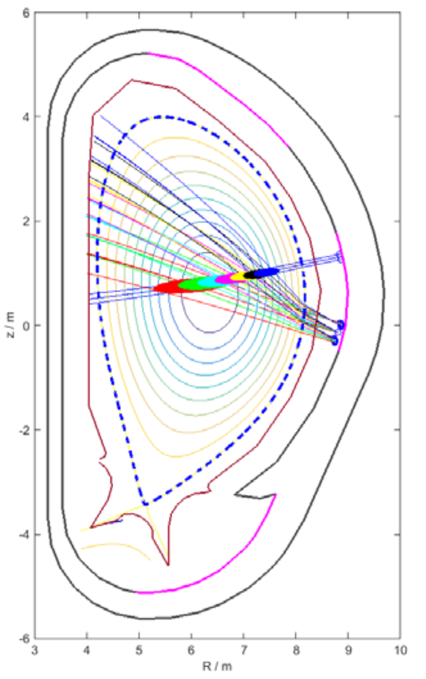
- 2 gamma-ray views and 1 CTS view in the center
- All lines-of-sight almost perpendicular to **B**.
- GRS: 90° , CTS: 97°



Shevelev et al. (2013) NF



Nocente et al. (2017) NF



Salewski et al. (2016) ITPA-EP

E>1.7 MeV: Velocity-space tomography

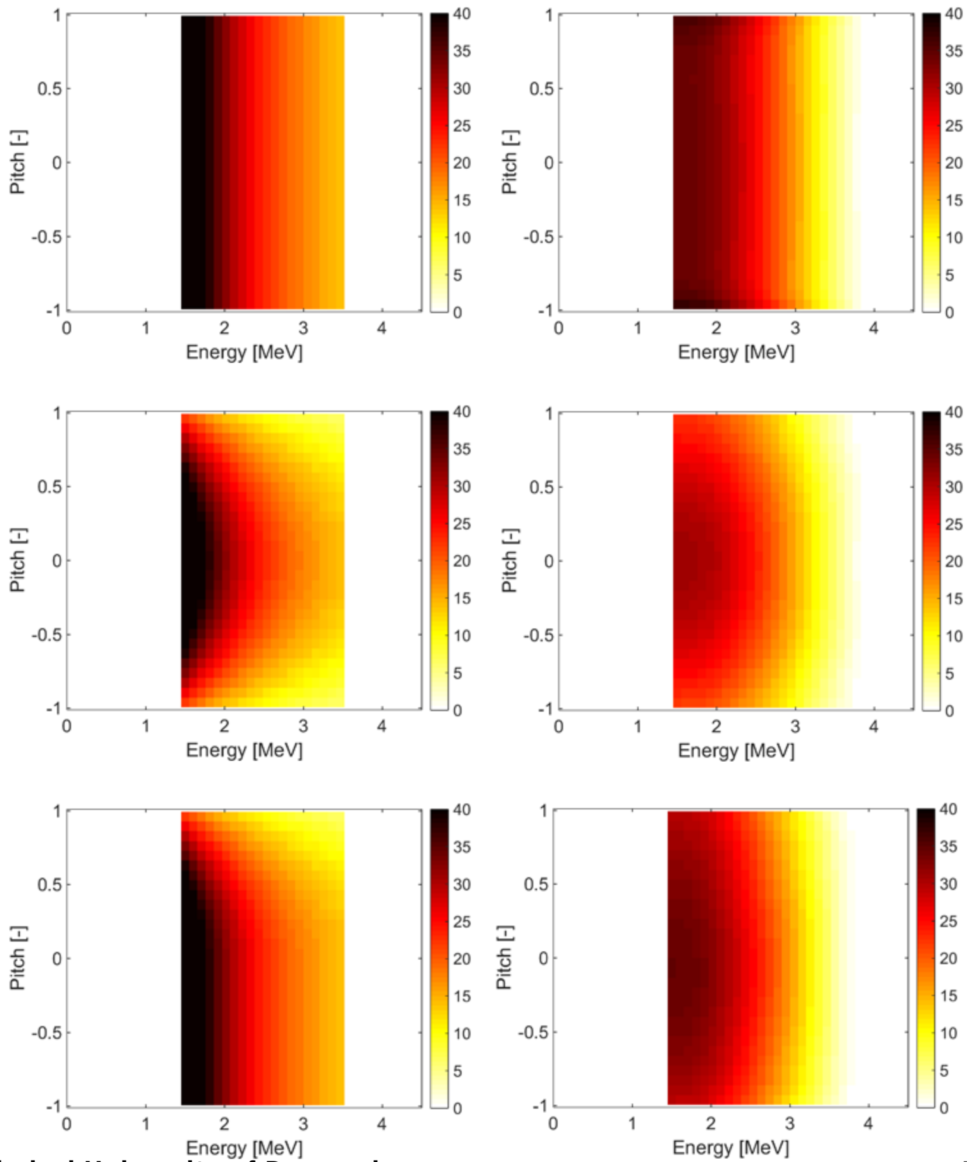
Ground truth

Tomography

Alpha slowing-down

Co- and counter-passing ejected, but not trapped

Co-passing ejected, but not trapped and counter-passing

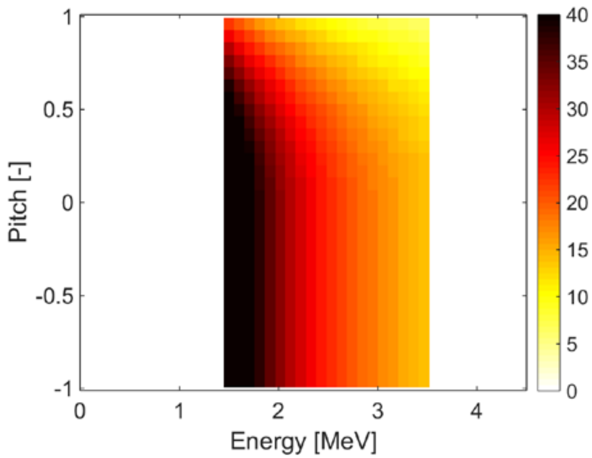


Can’t tell co- and counter-going ions apart!

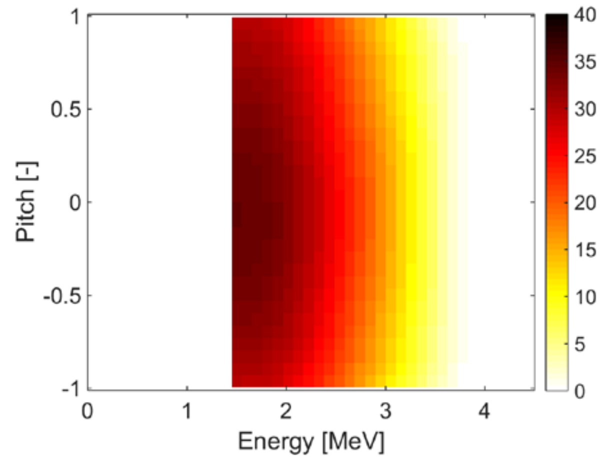
(E,|p|)-coordinates

Oblique views tell co- / counter-going ions apart

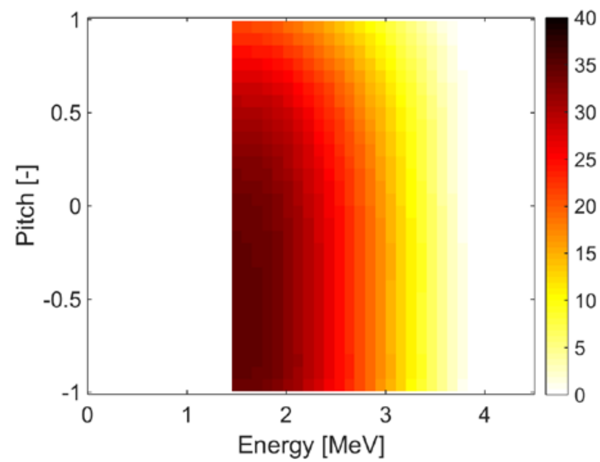
Ground truth



GRS 2x90+ CTS



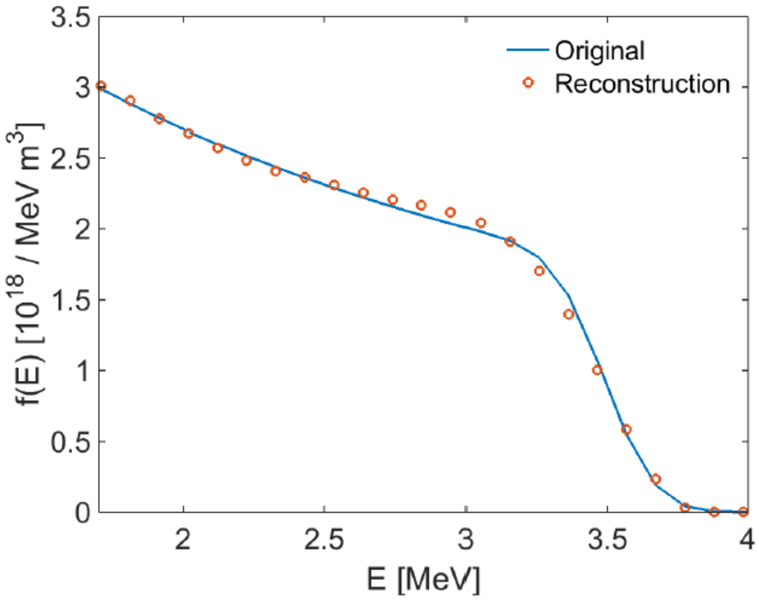
- Inversion with an additional 30° GRS detector
- **Anisotropy could then be tracked.**



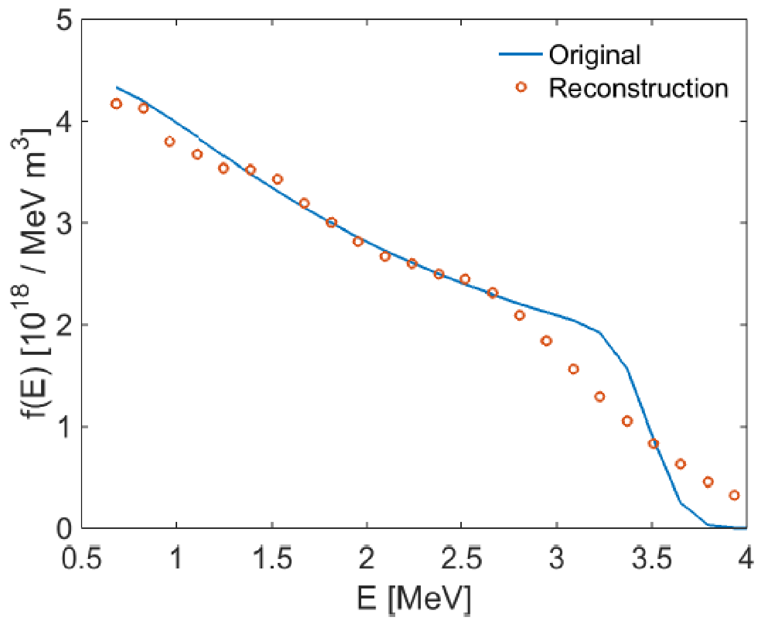
E<1.7 MeV: Energy spectrum inference assuming isotropy

$$\text{minimize} \quad \left\| \begin{pmatrix} W \\ \lambda_E L_E \\ \lambda_p L_p \end{pmatrix} F - \begin{pmatrix} S \\ 0 \\ 0 \end{pmatrix} \right\|_2 \quad \text{subject to} \quad \begin{matrix} F \geq 0 \\ \lambda_p \gg \lambda_E \end{matrix}$$

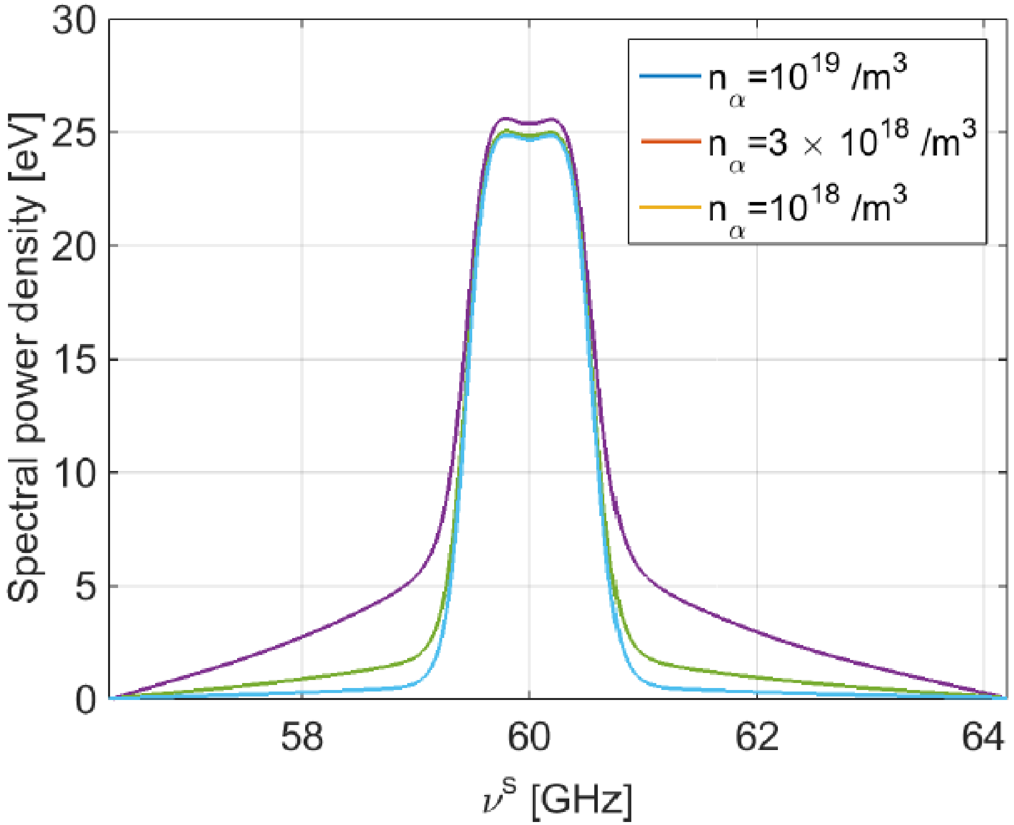
- Combined gamma-ray spectroscopy and collective Thomson scattering (>1.7 MeV)



- Collective Thomson scattering only (>0.5 MeV)



Alpha densities by fitting a model to the data



- Compute expected spectrum for various alpha densities of an alpha-particle slowing down distribution

Conclusions

- ITER measurement requirements on alpha energy spectra and densities can be fulfilled by solving inverse problems.
- 2D velocity-distribution functions by velocity-space tomography
  - E>1.7 MeV in (E,|p|), requires oblique GRS detector to get (E,p)
- Energy spectra
  - Integrate 2D velocity distribution function over pitch
  - Velocity-space tomography assuming isotropy
- Alpha densities
  - Integration of energy spectra above
  - Fit a model to the measurements, e.g. isotropic slowing-down distribution
- Velocity-space tomography experimentally demonstrated on JET and ASDEX Upgrade.

Thank you for your attention!