Fusion plasma velocity-space tomography

Mirko Salewski
Technical University of Denmark
Department of Physics

DTU Physics
Department of Physics

Outline

1) Introduction to fusion energy, fast ions and velocity distribution functions

2) Introduction to tomography in position and velocity space - The Lucky-Luke-Doppler experiment

3) How is Per Christian helping fusion plasma physics?

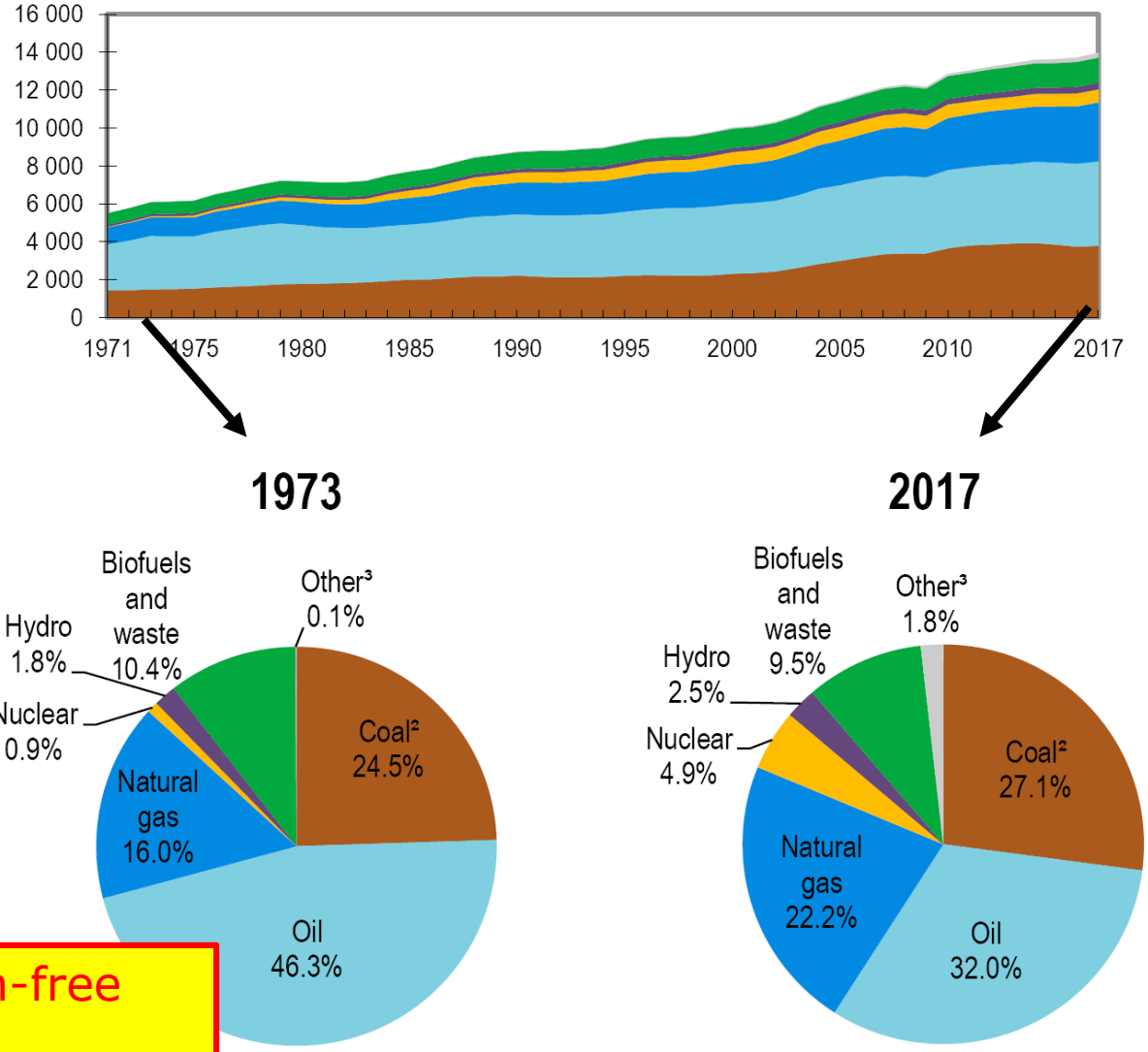
4) A closing riddle

The energy problem

- Annual worldwide primary energy supply (Mtoe)

2017

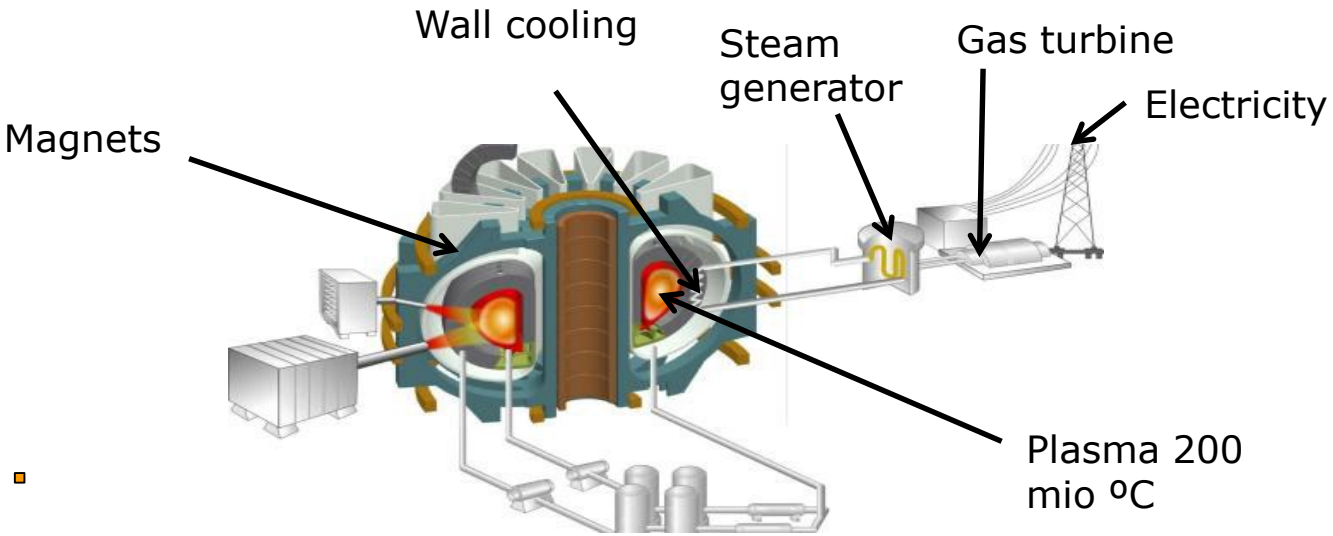
- Fossil fuels >80%
- Biofuels 10%
- Fission 5%
- Hydro, wind, solar, tidal, geo <5%



World energy outlook (2019), IAE

We must switch to emission-free energy sources!

A fusion power plant

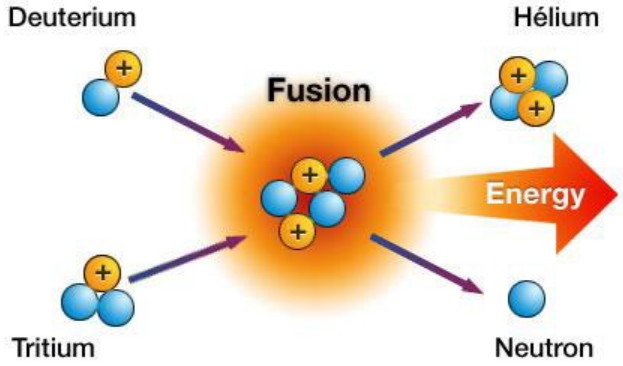


Sun core:
15 mio ºC

Fusion power plant:
150-200 mio ºC

D + T → n + He + energy

Li + n → T + He + energy



+No greenhouse gases
+Safe, no risk of meltdown
+Abundant fuels

+No long-lived radioactive waste
+Reliable, steady power

Energy from water and lithium

- Average EU citizen energy consumption over a life

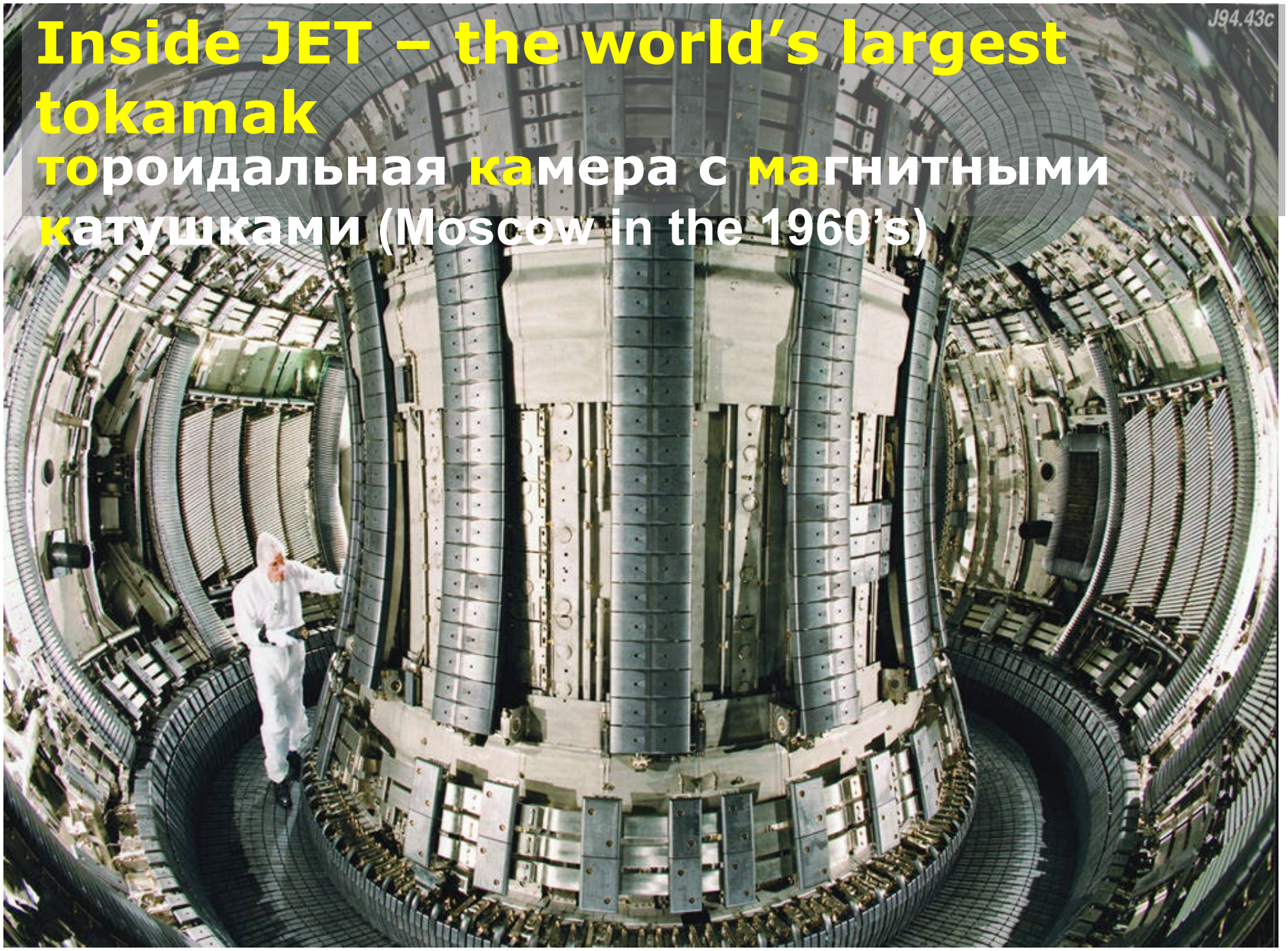
500 t coal	300 t oil	20g deuterium and 60g lithium
5 train wagons	*1/10th swimming pool*	*10 bath tubs of water and 10 laptop batteries*

- Fuel consumption of 1 GW electric power over 1 year

2.500.000 t coal
250 2km trains

1.400.000 t oil
4 400m tankers

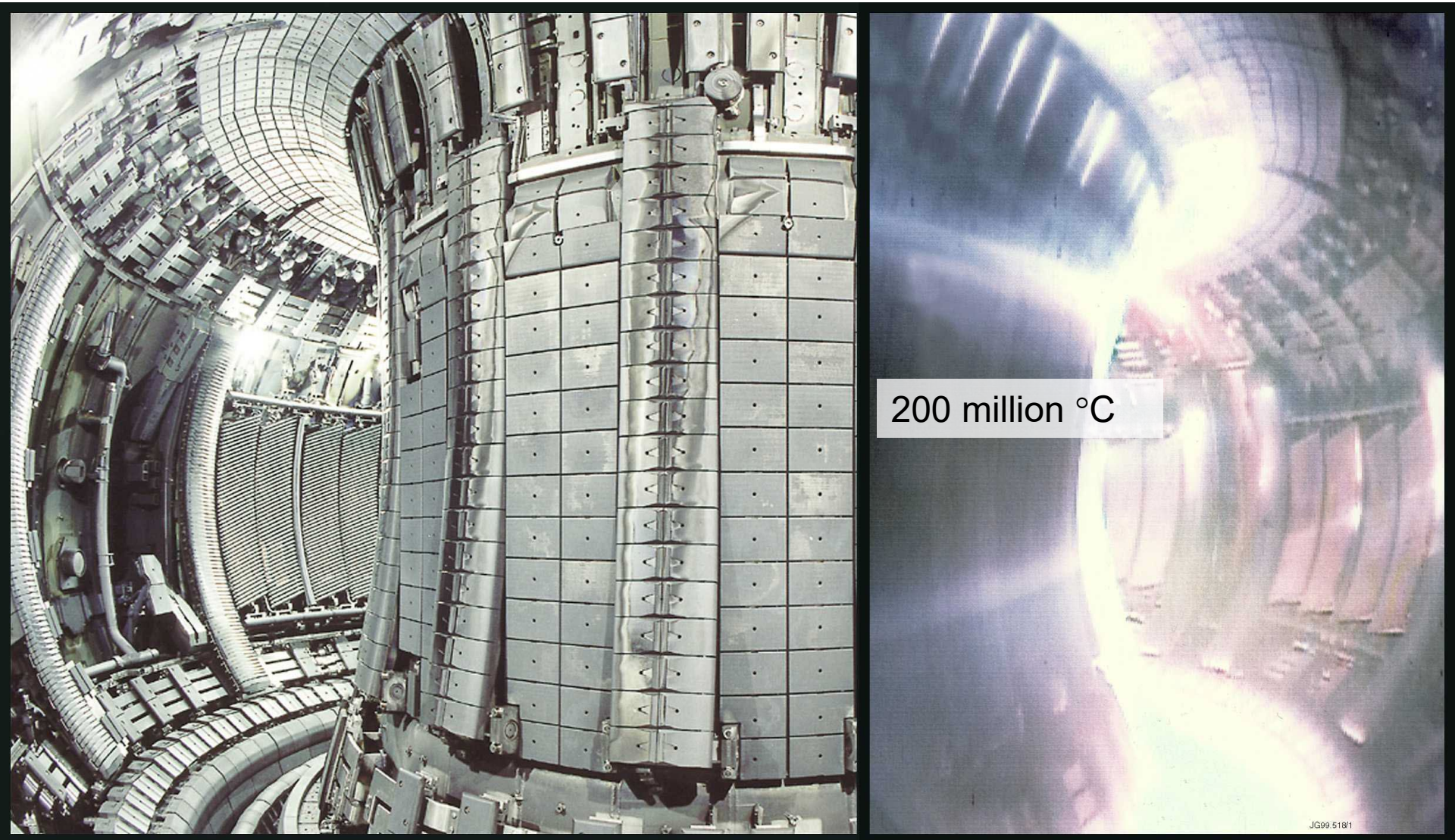
100kg D + 300kg Li
(5000t water + 10t Li ore)
1 swimming pool + 1 truck load



Inside JET – the world's largest tokamak

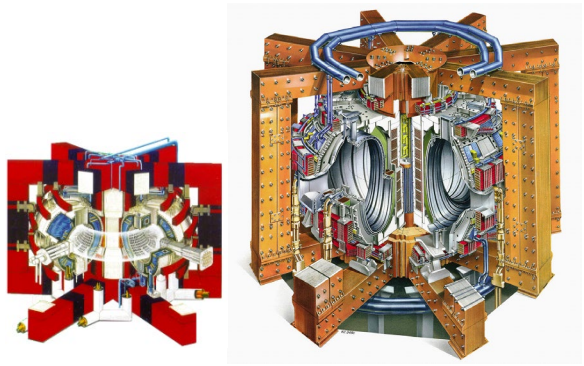
тороидальная камера с магнитными катушками (Moscow in the 1960's)

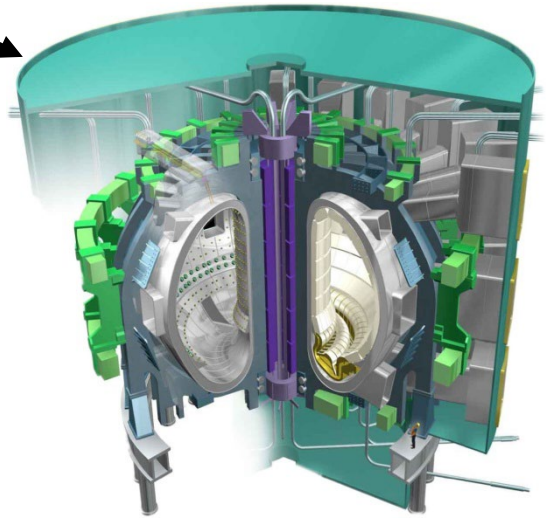
Fusion plasma in the JET tokamak

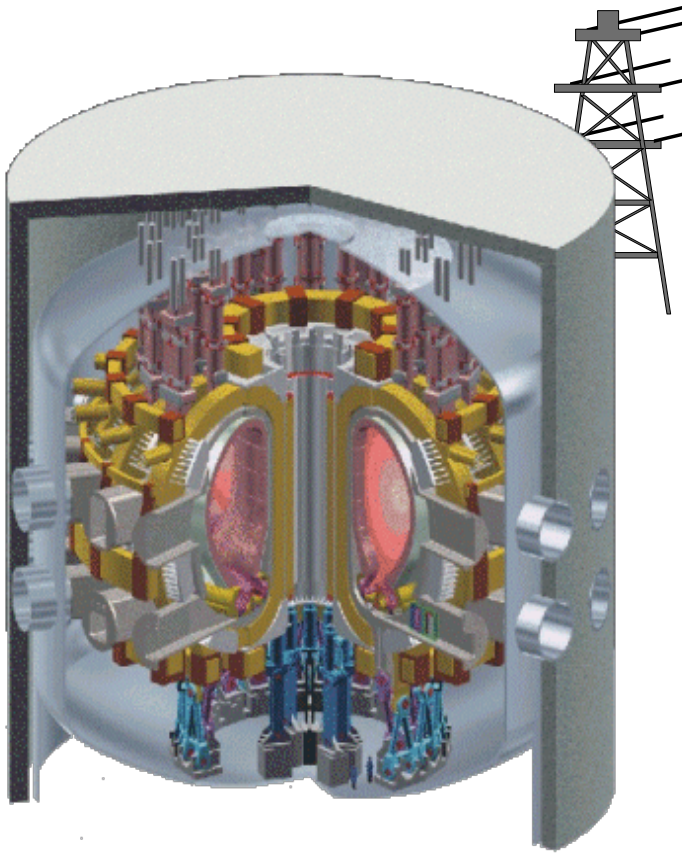


The ITER tokamak and future fusion reactor sizes

ITER will amplify the injected power by a factor 10.

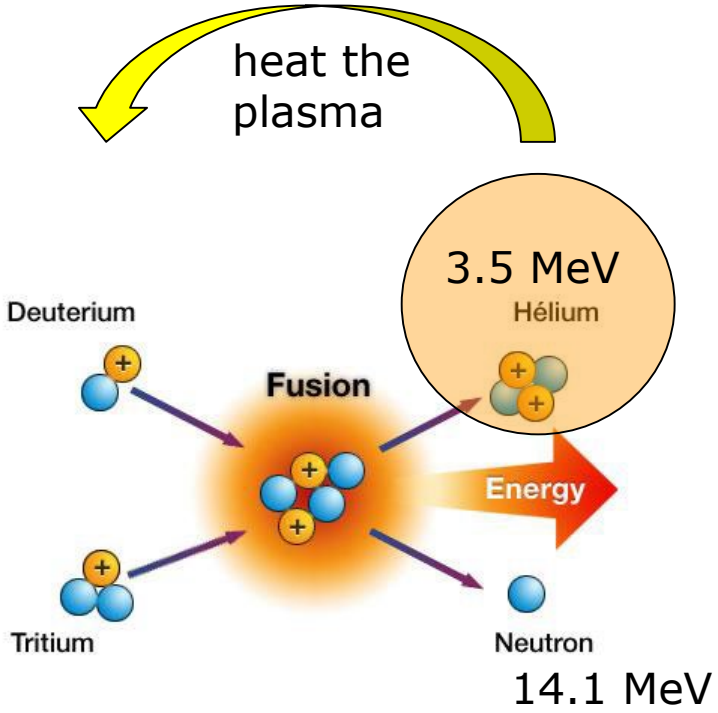


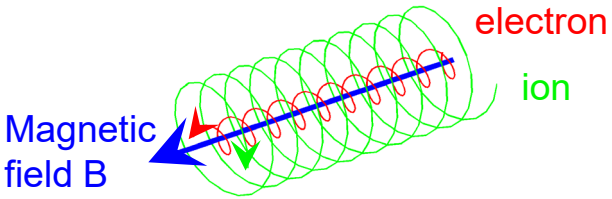




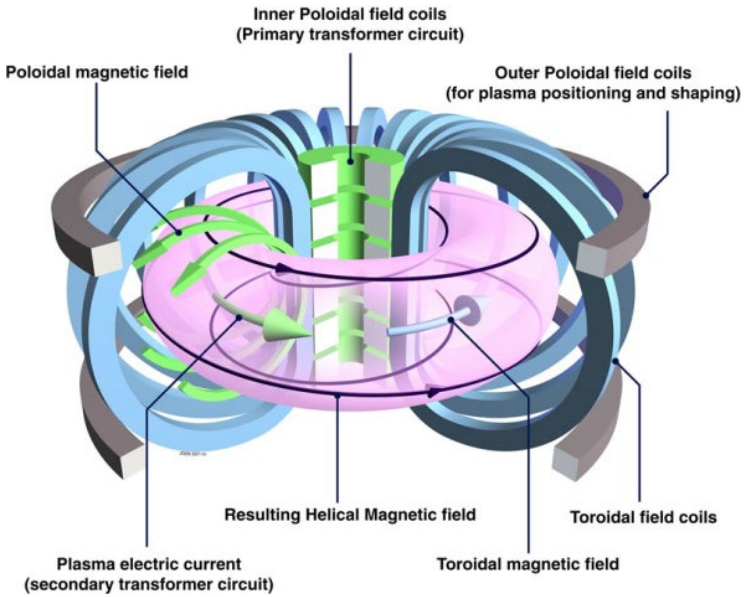
Tore Supra	*JET*	*ITER*	*Reactor*
25 m^3	*80 m^3*	*830 m^3*	*~ 1500 - 2000 m^3*
~ 0 MW	*~16 MW_{th}*	*~ 500 MW_{th}*	*~ 4 500 MW_{th}*
	Q=0.64	*Q=10*	*Q~50*

Fast ions in a tokamak fusion plasma

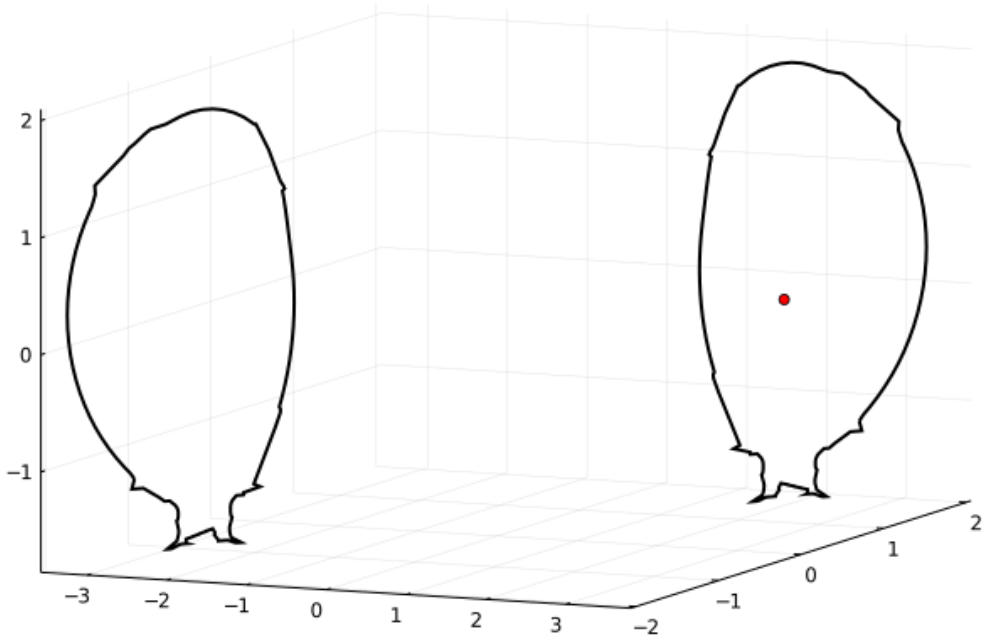




- Helium is born at 9,000,000 m/s ~ 3% of the speed of light
- Caught by a donut-shaped magnetic field

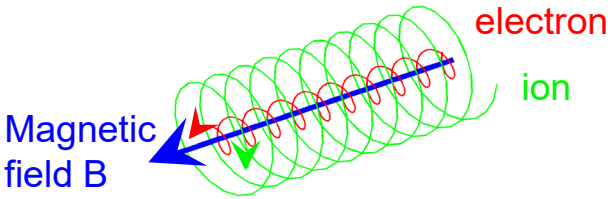


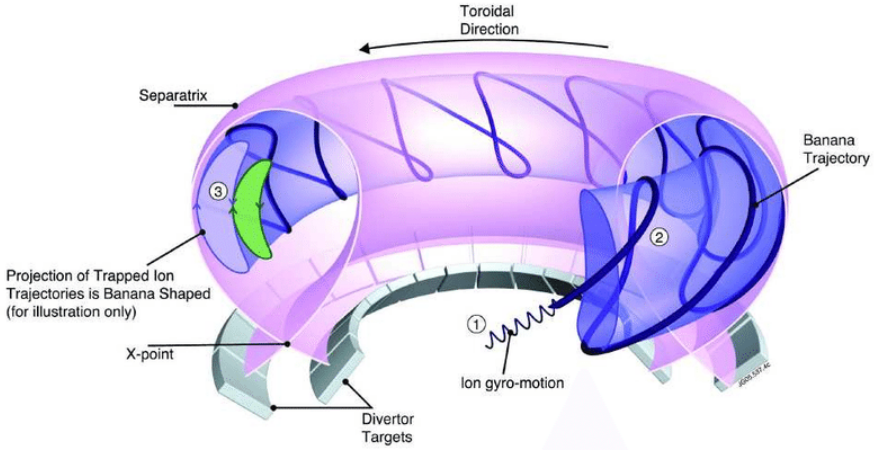
Fast ions in a tokamak fusion plasma



- Fast ions stay on surfaces in the donut.

Järleblad et al. (2022) Nucl. Fusion

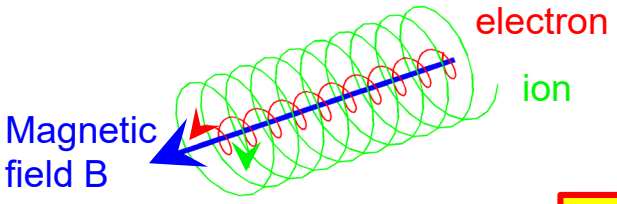




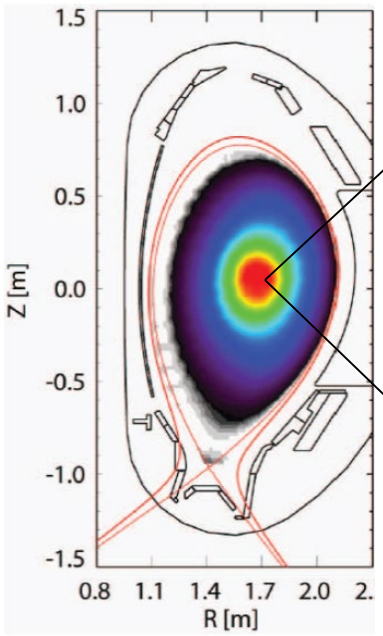
Fast ions in a tokamak fusion plasma

Fast ions

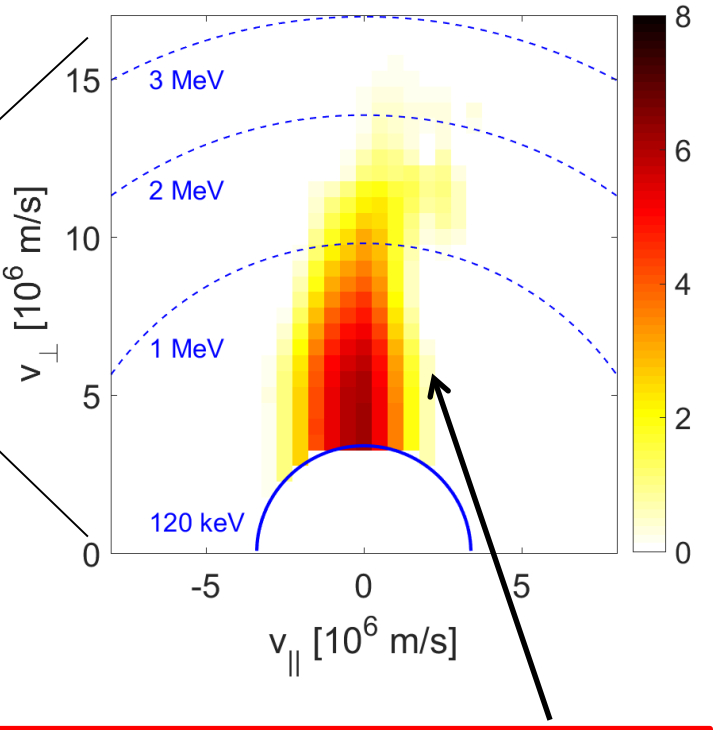
- heat the plasma
- drive instabilities
- transported by instabilities



2D position distribution



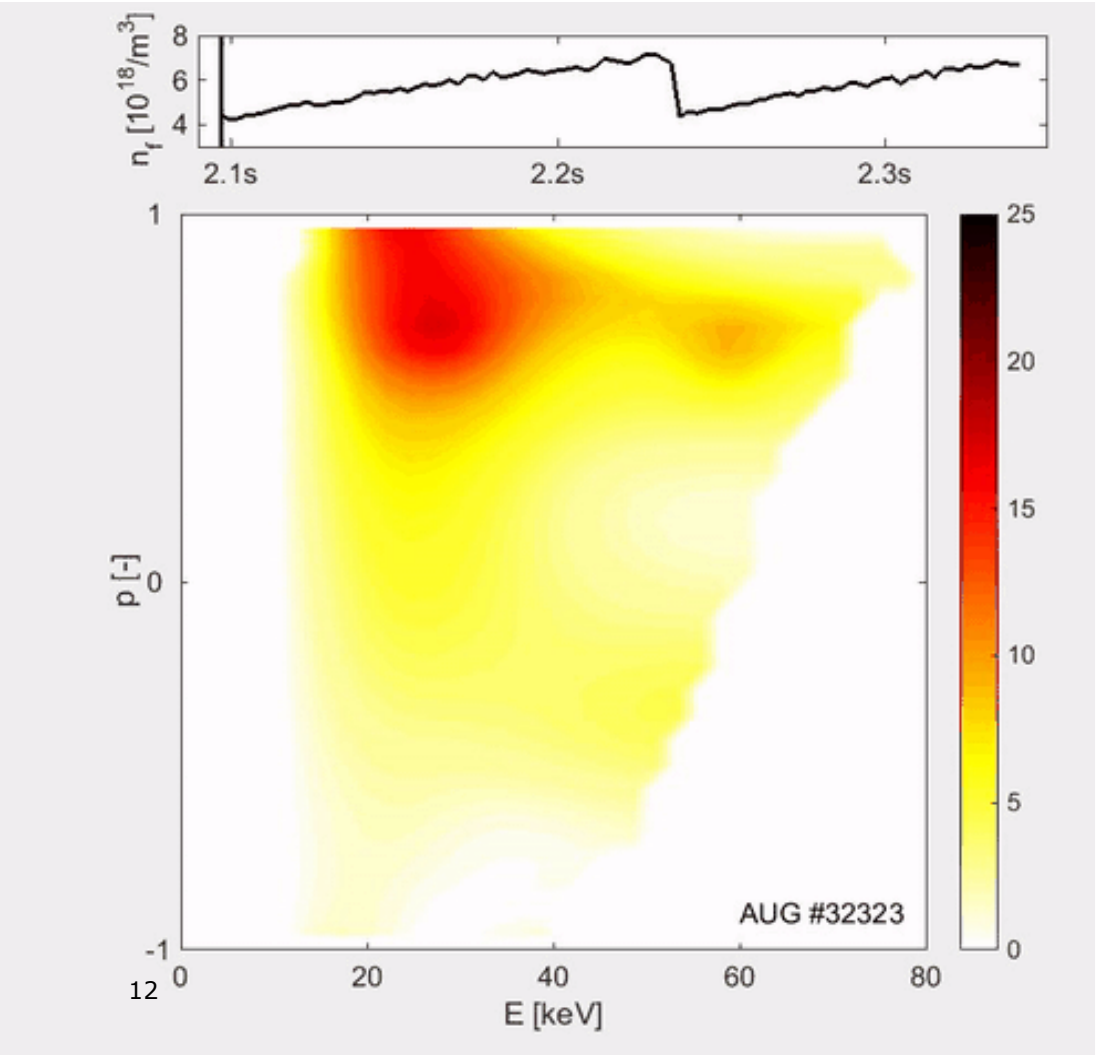
2D velocity distribution in the center



Velocity-space tomography: Measure this

Fast ions can be transported by instabilities

- Sawteeth instability, sawtooth pattern in time traces of *T*, *n*, *p*
- Measurement of *f(E,p)* in a sawtoothing plasma at ASDEX Upgrade



- Upper panel: Measurement of fast ion density (integral of the lower panel)
- Lower panel: Velocity-space tomogaphy movie (100 frames)

Salewski et al (2016b) NF

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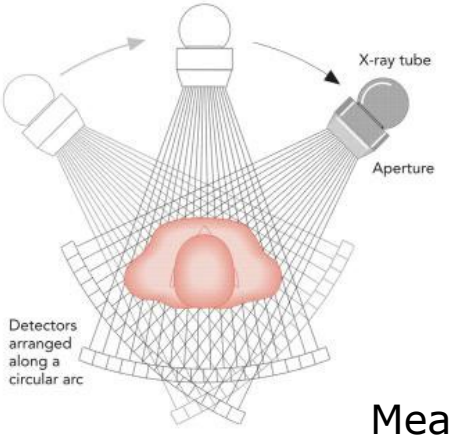
Every-day tomography: CAT scanner



- Red spot in sample traces S-curve in data

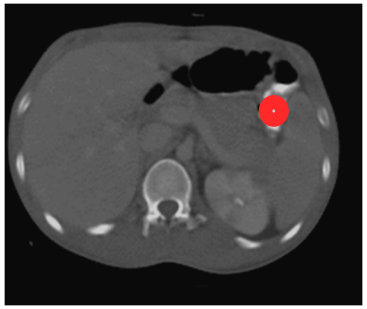
- Cormack 1963, 64
- Hounsfield 1968-73

Nobel Prize Medicine 1979

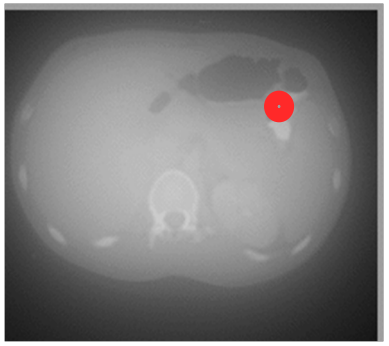
$$WF = S$$

Measurement data

Slice through patient



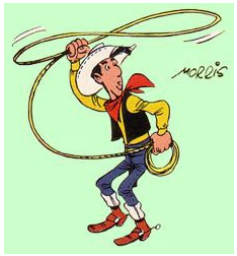
Image



Other medical examples:

- PET – positron emission tomography
- MRI – magnetic resonance imaging
- Ultrasound imaging
- Breast mammography
- …

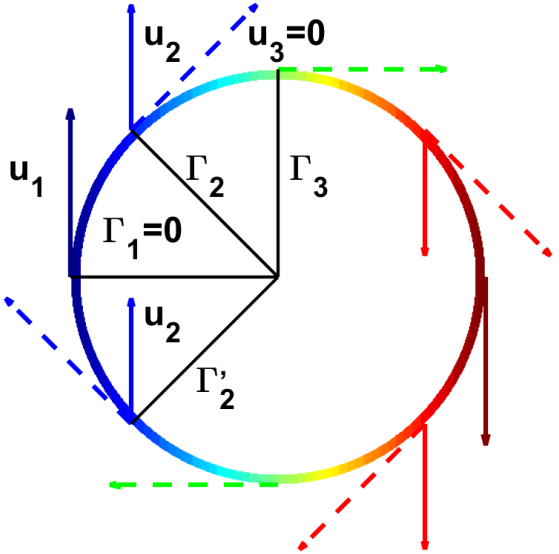
The Lucky-Luke-Doppler experiment

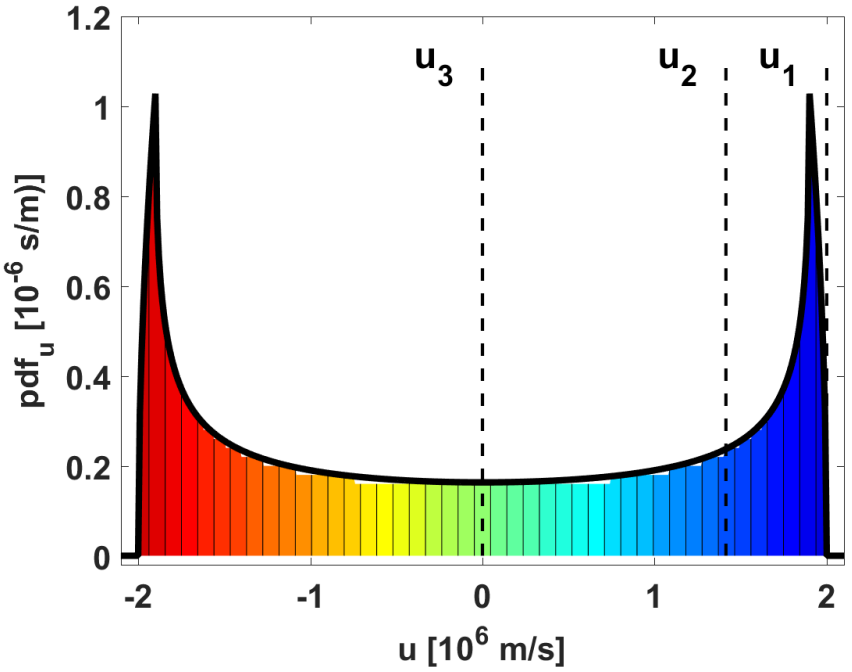


- Doppler-shifted sound from a gyrating pitchfork at 258 Hz.
- Doppler shift:

$$u = c\,\frac{\Delta f}{f}$$

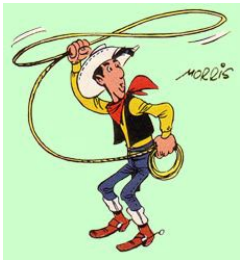
- Fast ions generate Doppler shifted radiation: light, gamma-rays and similar Doppler-shifted signals

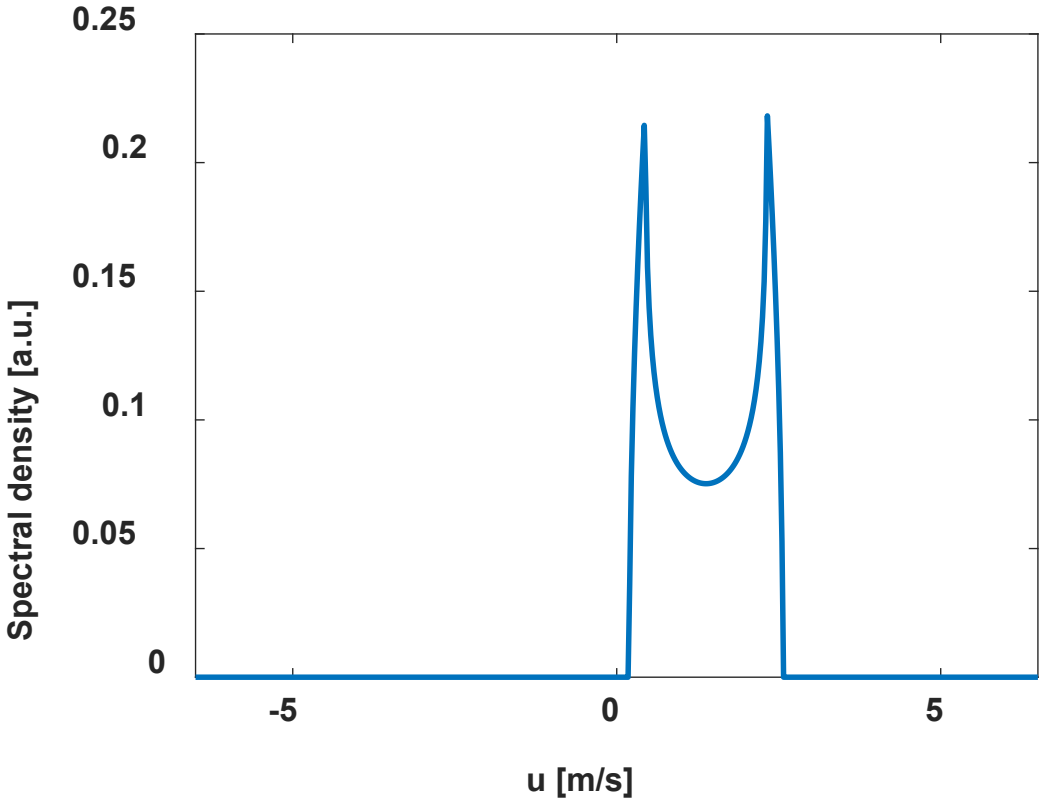




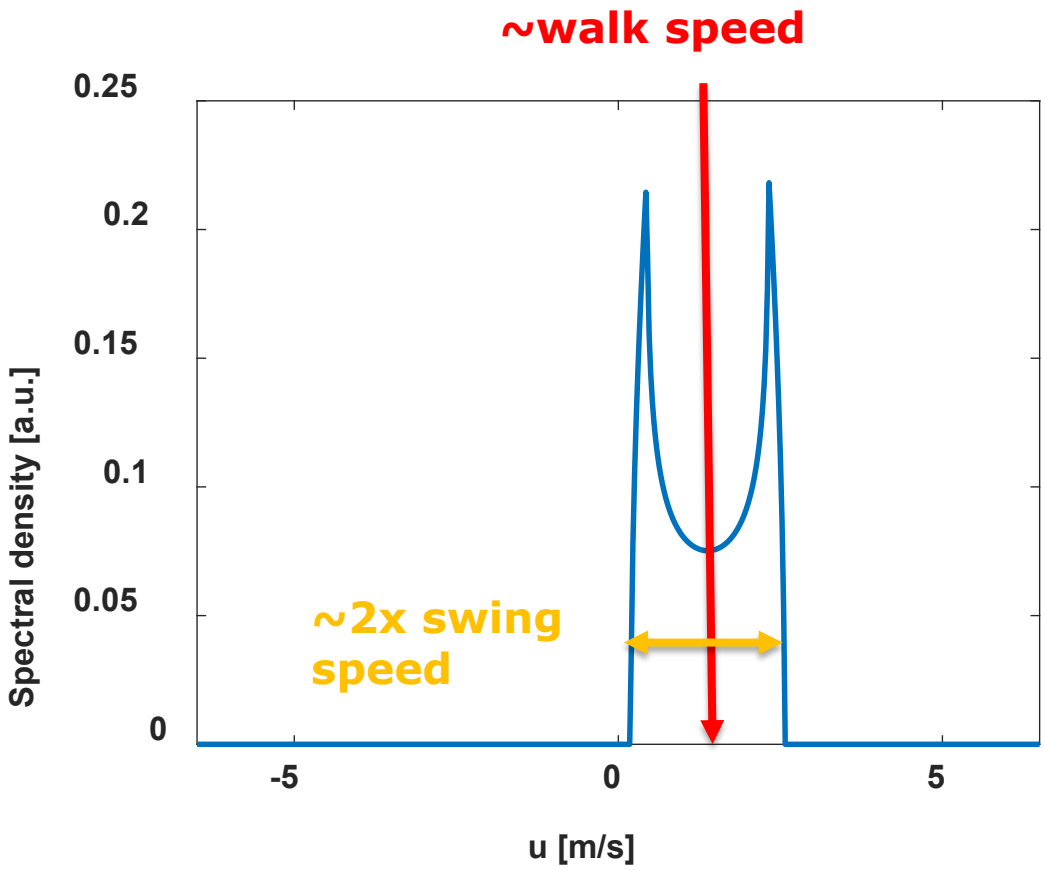
Spectrum for one walking person with gyrating emitter

How fast am I walking and swinging the pitch fork?



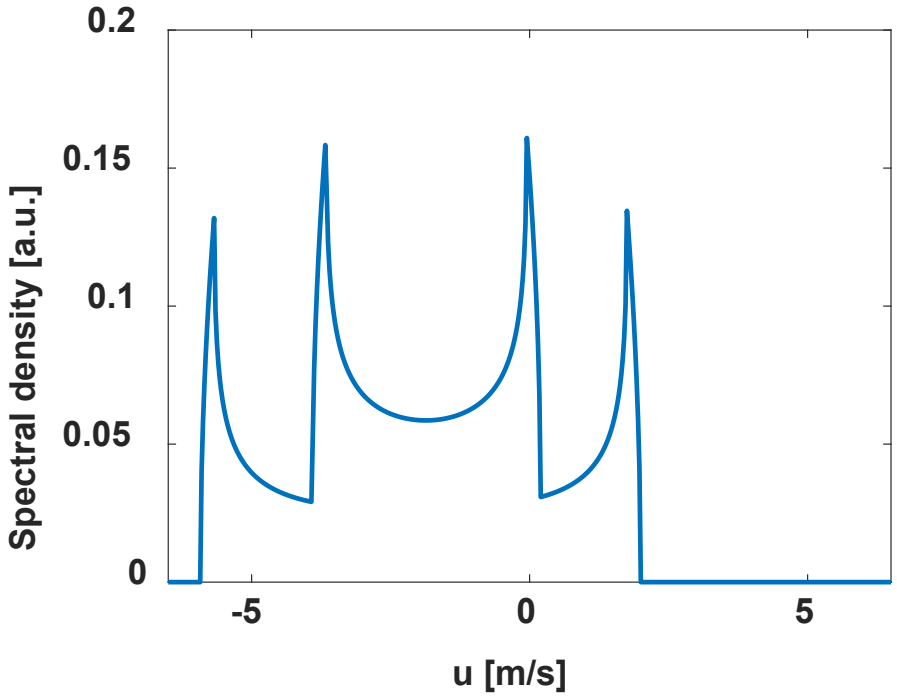


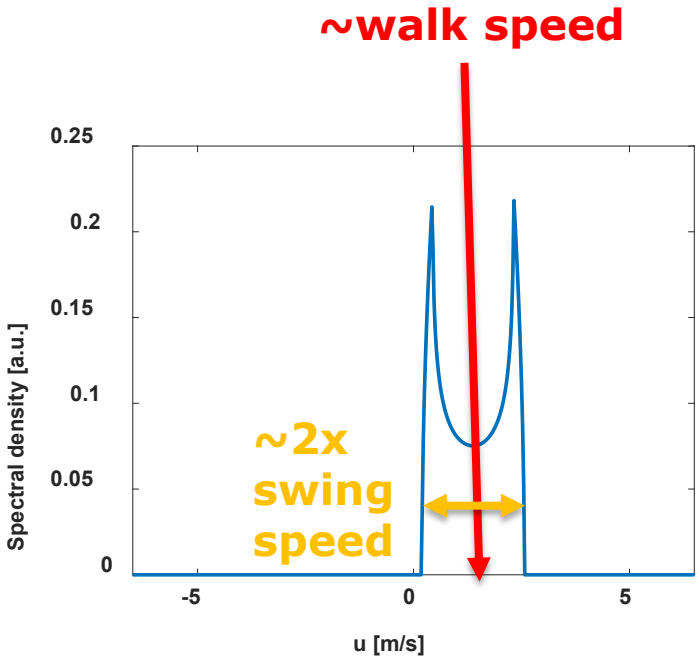
Spectrum for one walking peorson with a gyrating emitter

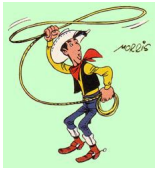


Spectrum for two walking people with gyrating emitters

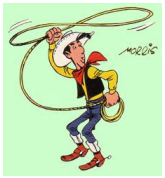
How fast are the two people walking and swinging?

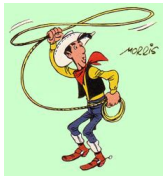


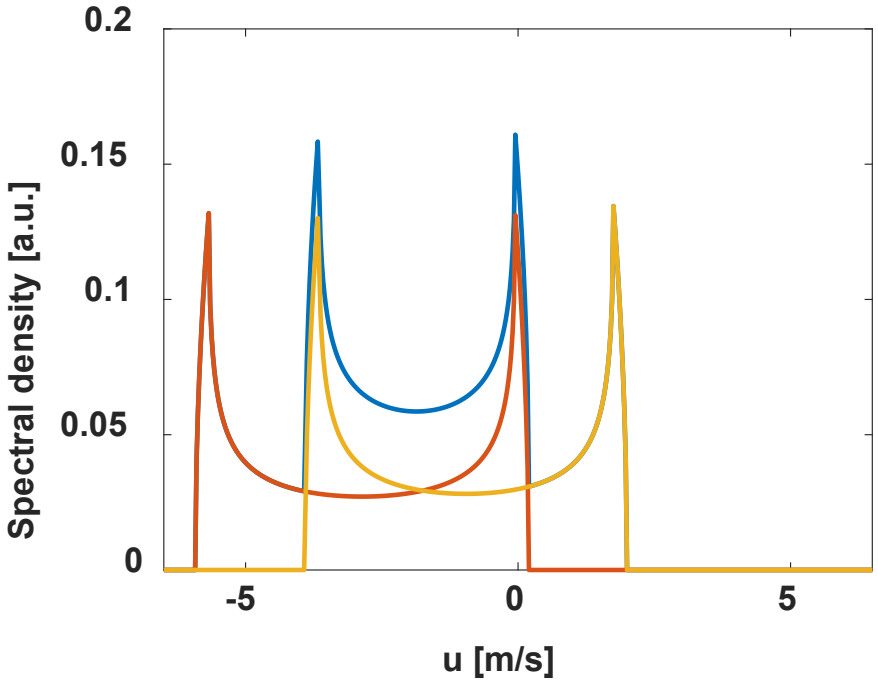




Spectrum for two walking people with gyrating emitters





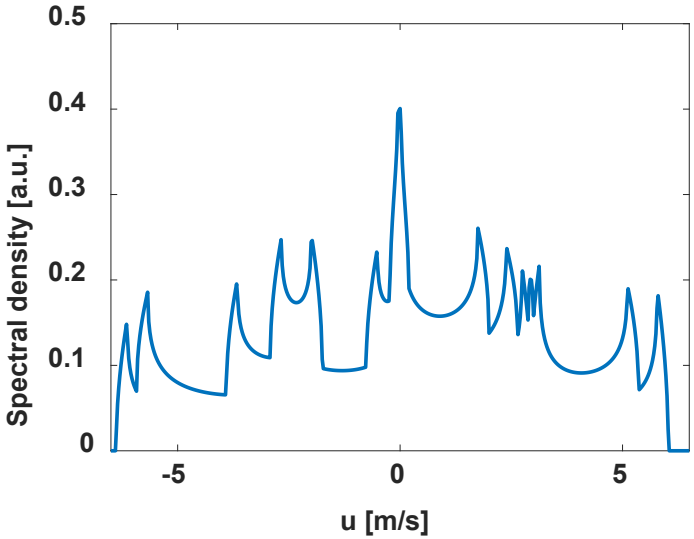


- Both: Swing about 3m/s (width/2)
- Red: Walks at -3m/s (center)
- Yellow: Walks at -1m/s (center)

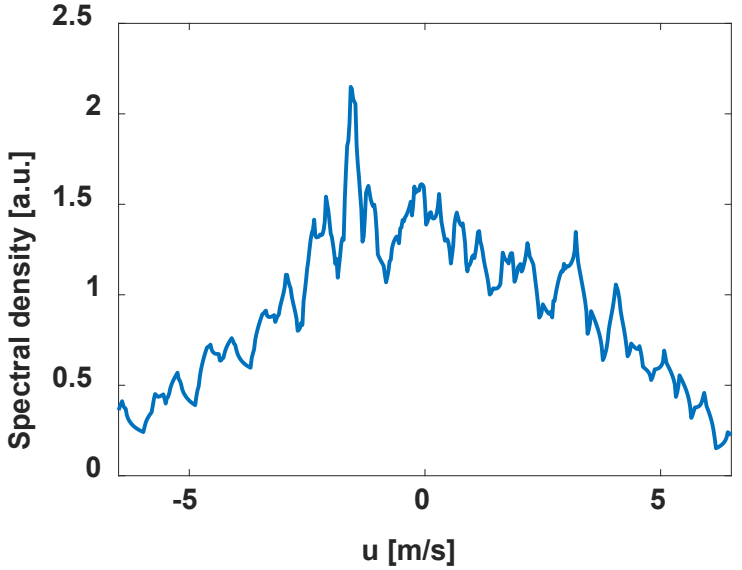
- Both: Walk at about -2m/s (centers)
- Person 1 swings at 2m/s (width/2)
- Person 2 swings at 4m/s (width/2)

Spectrum for many walking people with gyrating emitters

7 people



50 people

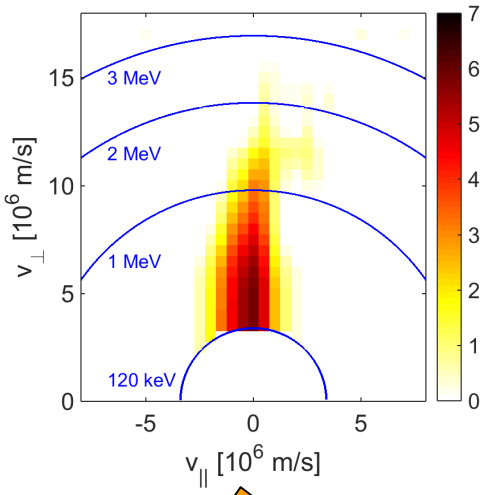


Velocity-space tomography

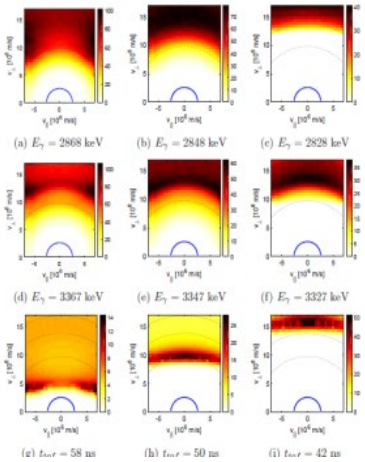
Forward problem

$$WF = S$$

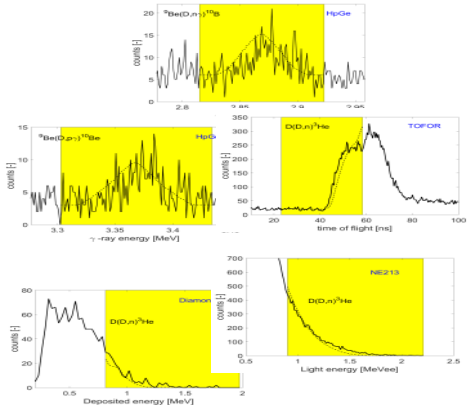
Distribution function *F*



Matrix *W*

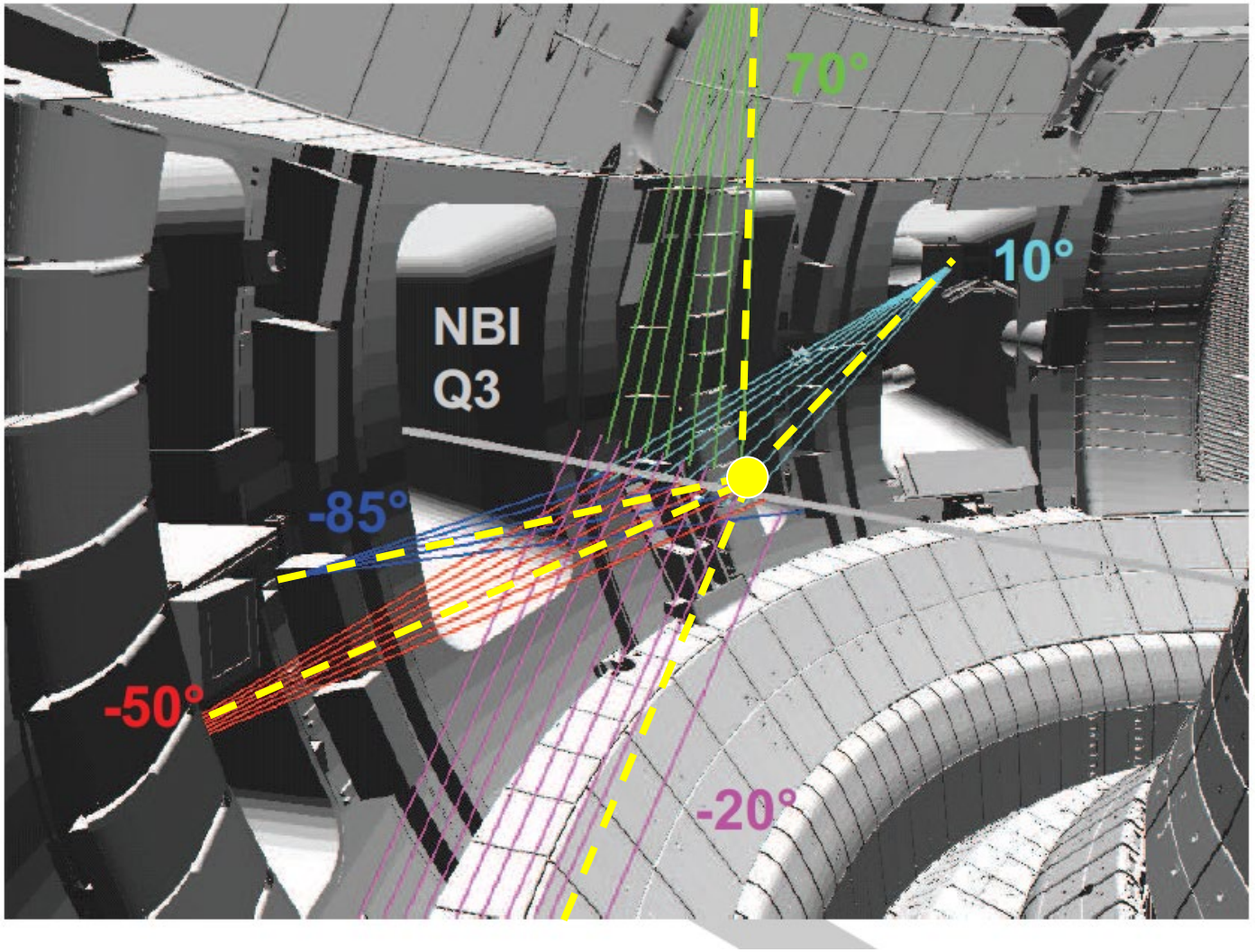


Measurements *S*



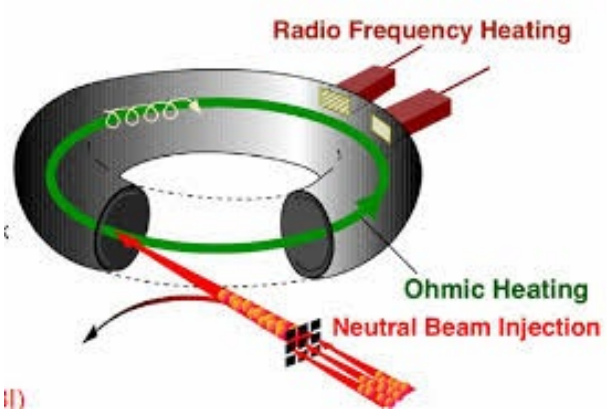
Inverse problem

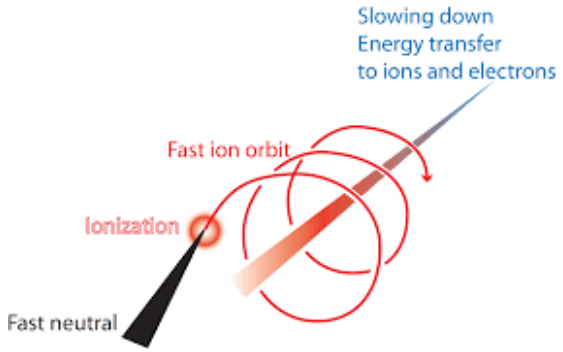
Fast ion D-alpha spectroscopy at ASDEX Upgrade



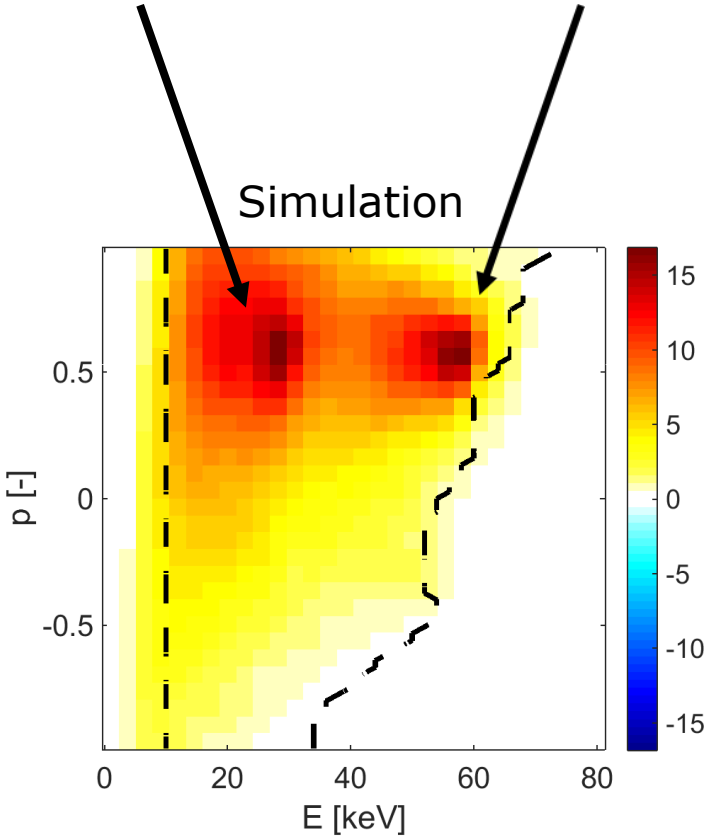
Weiland et al (2016) *PPCF*

Energetic particle injection at ASDEX Upgrade



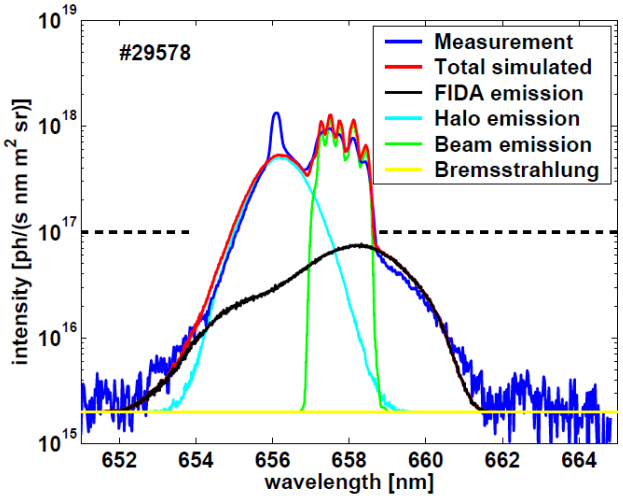


We know well at what energies and direction particles are born



Salewski et al (2016b) NF

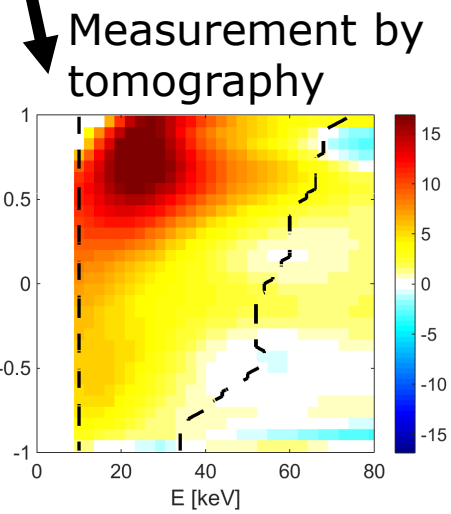
Velocity tomography without extra prior information

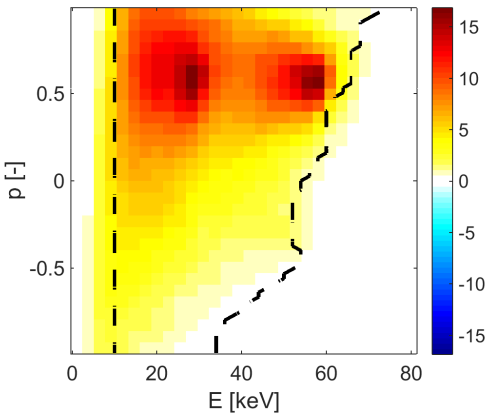


- 5 measured spectra like this
- Truncated singular value decomposition
- Standard Tikhonov regularization

Artifacts appear when no further prior information is used

1) Negative values!
2) Particles at too large energies
3) Not good at finding peaks





Salewski et al (2016b) NF

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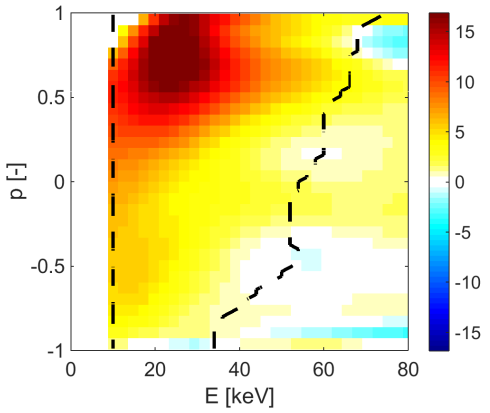
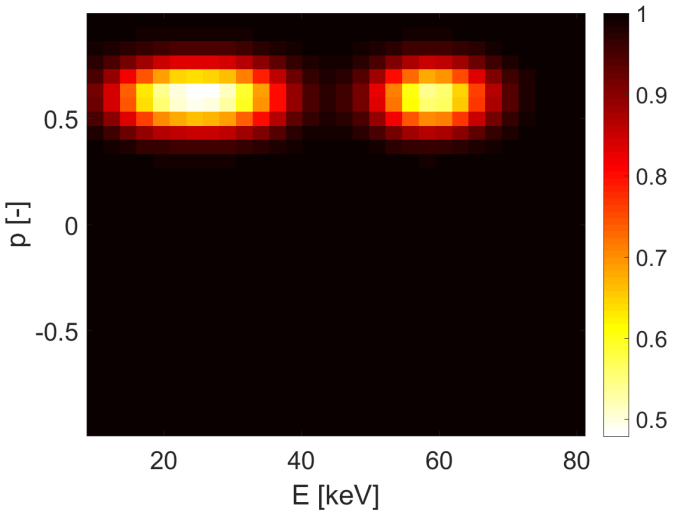
Prior information: What do we know?

- The number of particles in a box is non-negative.
- Energies and direction of injected high-energy particles are known.

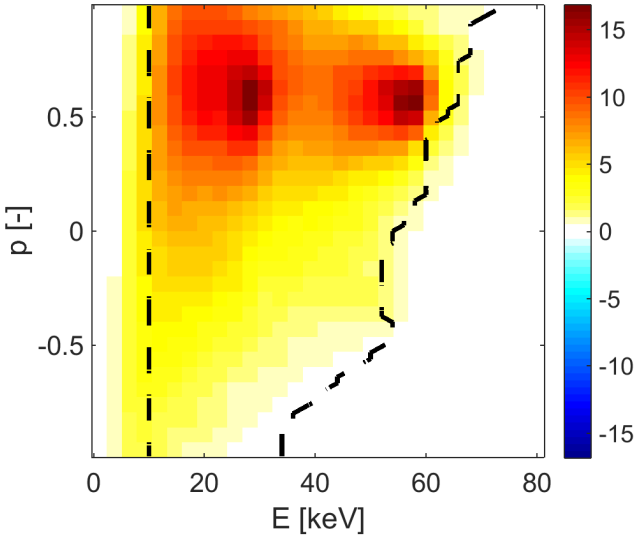
Measurement



$\kappa(E, p)$

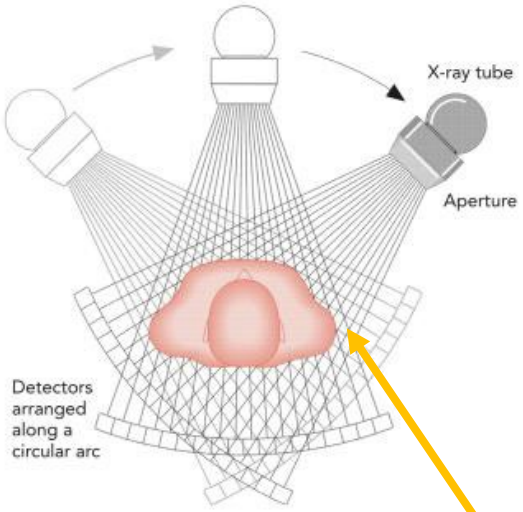


Simulation

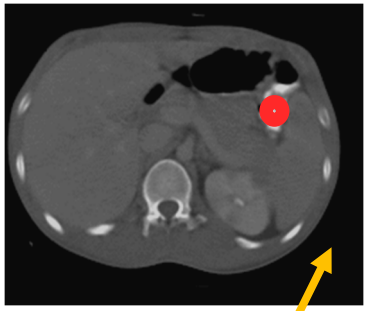


Salewski et al (2016b) NF

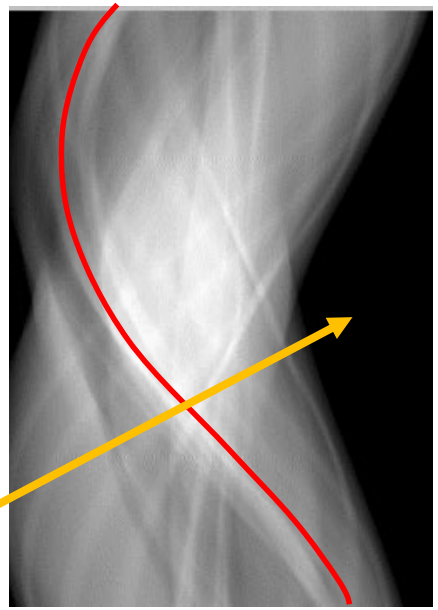
Null measurements in a CAT scanner



Slice through patient



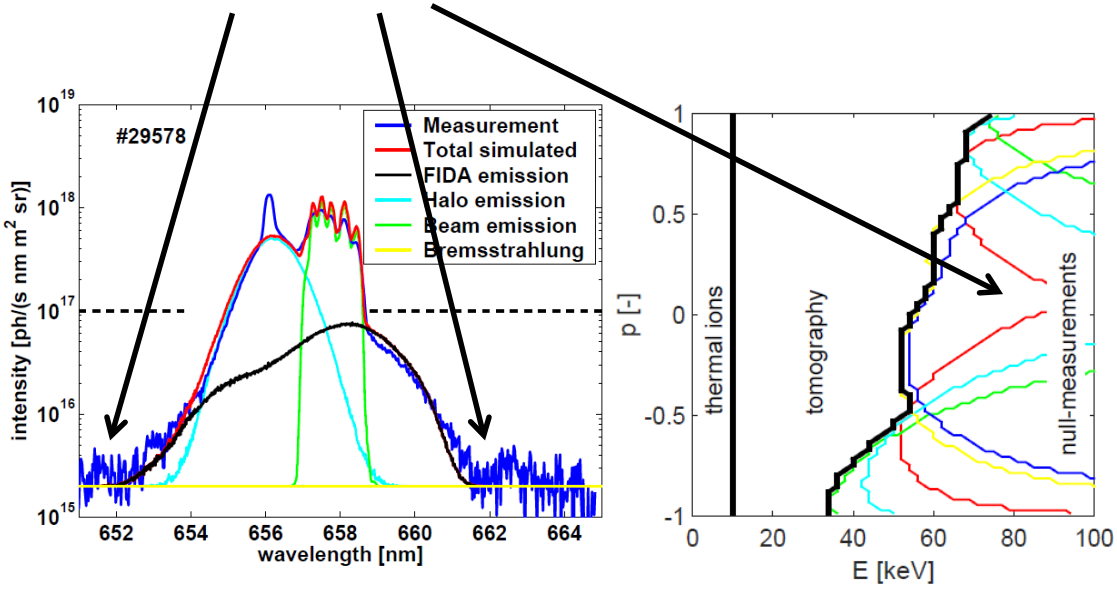
Measurement data



The outer beams measure the absence of the patient!

Prior information: What do we know?

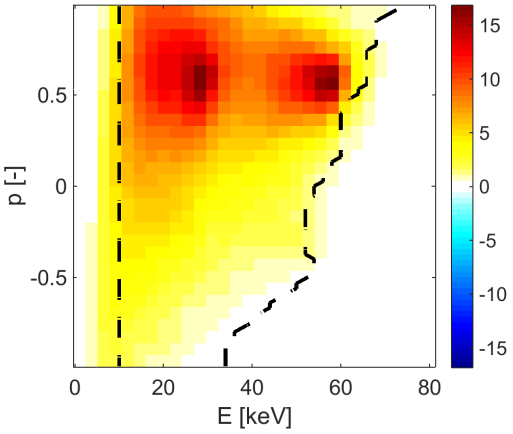
- Null-measurements: no ions here

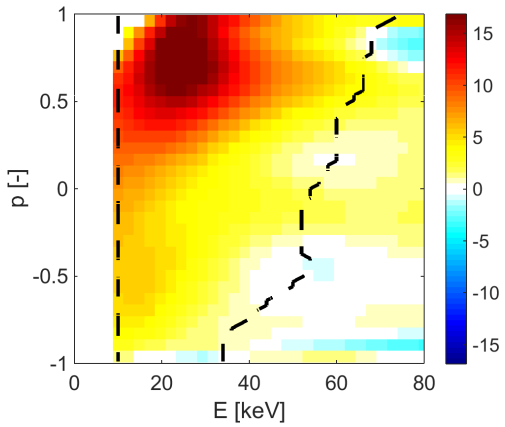


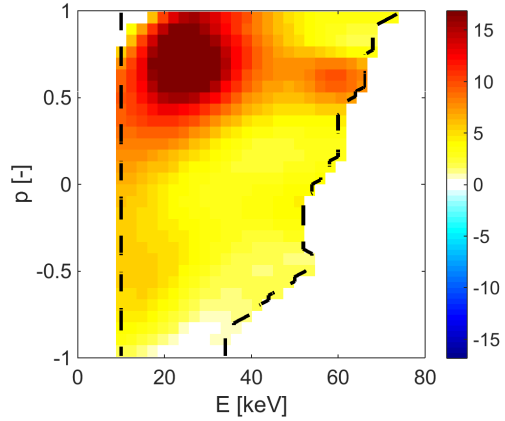
$$F^* = \arg\min_F \left\| \begin{pmatrix} W \\ \lambda\kappa(E,p)L \end{pmatrix} F - \begin{pmatrix} S \\ 0 \end{pmatrix} \right\|_2 \quad \text{subject to} \quad \begin{cases} F^*(E_0,p_0) = 0 \\ F^* \geq 0 \end{cases}$$

High-definition tomography: Prior information

Simulation







Truncated SVD
Standard Tikhonov
Without prior information:
Artifacts

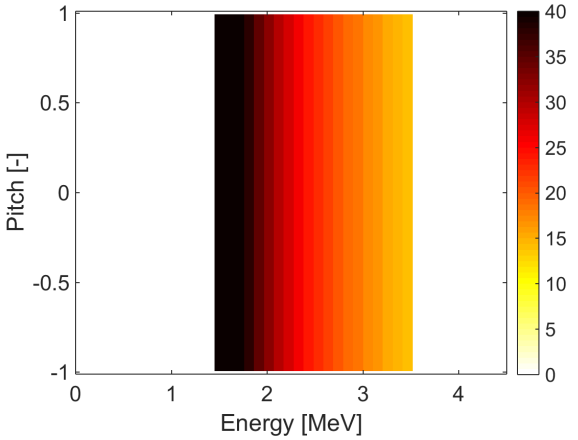
With prior information:
No visible artifacts

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

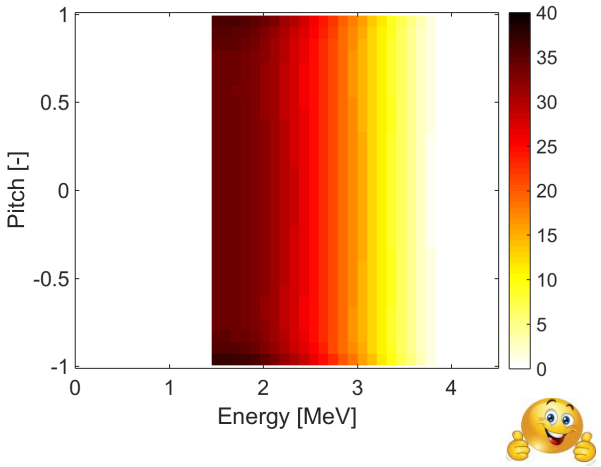
Salewski et al (2016b) NF

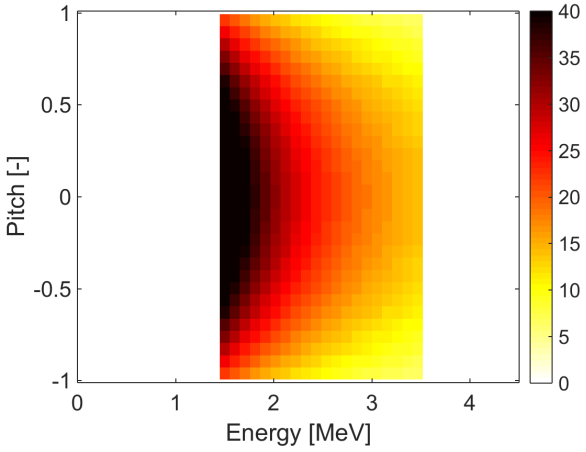
Velocity-space tomography at the ITER tokamak

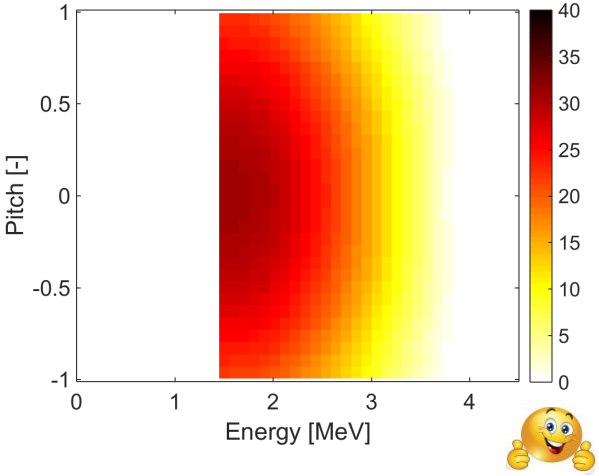
Ground truth



Tomography





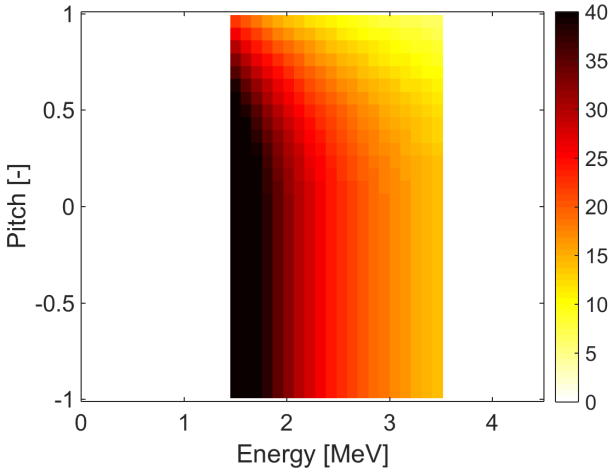


- First plasmas in ITER in >2025
- Fusion plasmas in ITER in >2035
- We can reconstruct up-down symmetric functions

Salewski et al (2018) *NF*

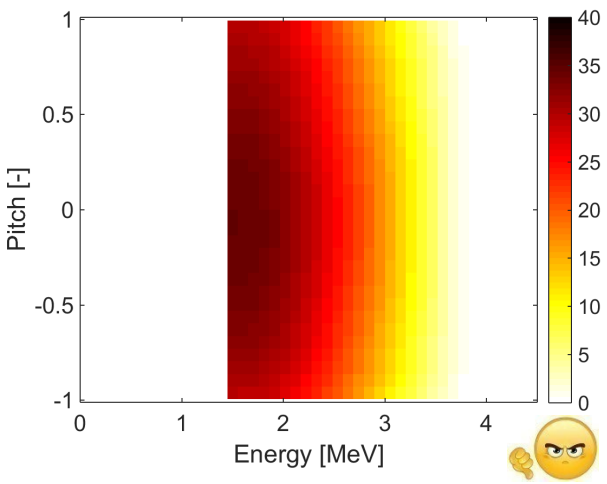
Velocity-space tomography at ITER

Ground truth



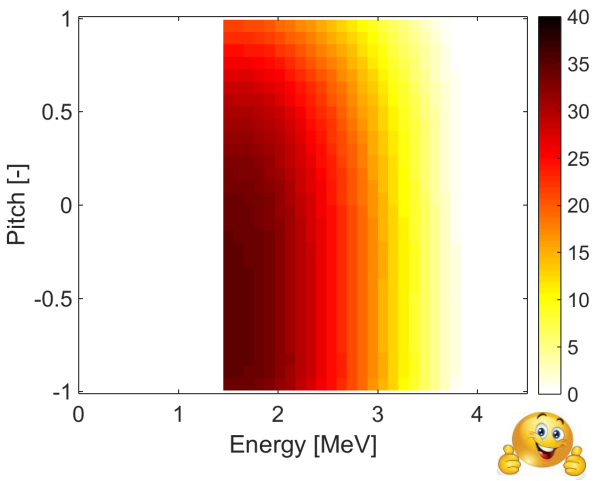
Up-down asymmetric

Tomography with currently foreseen diagnostics



Up-down symmetric

Tomography with an additional gamma-ray detector



Up-down asymmetric

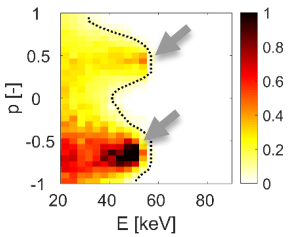
- For asymmetric ground truth, we get symmetric solutions
- Found reason through maths tools: singular value decomposition

We need an additional oblique gamma-ray detector at ITER!

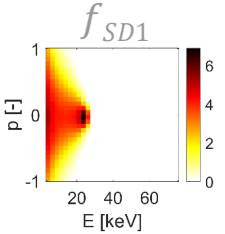
Salewski et al (2018) *NF*

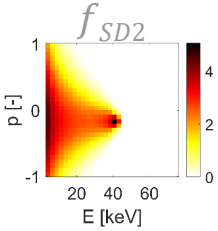
Collision physics-based basis functions
Prior information: Collisions in plasmas

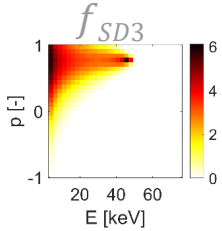
EAST distribution



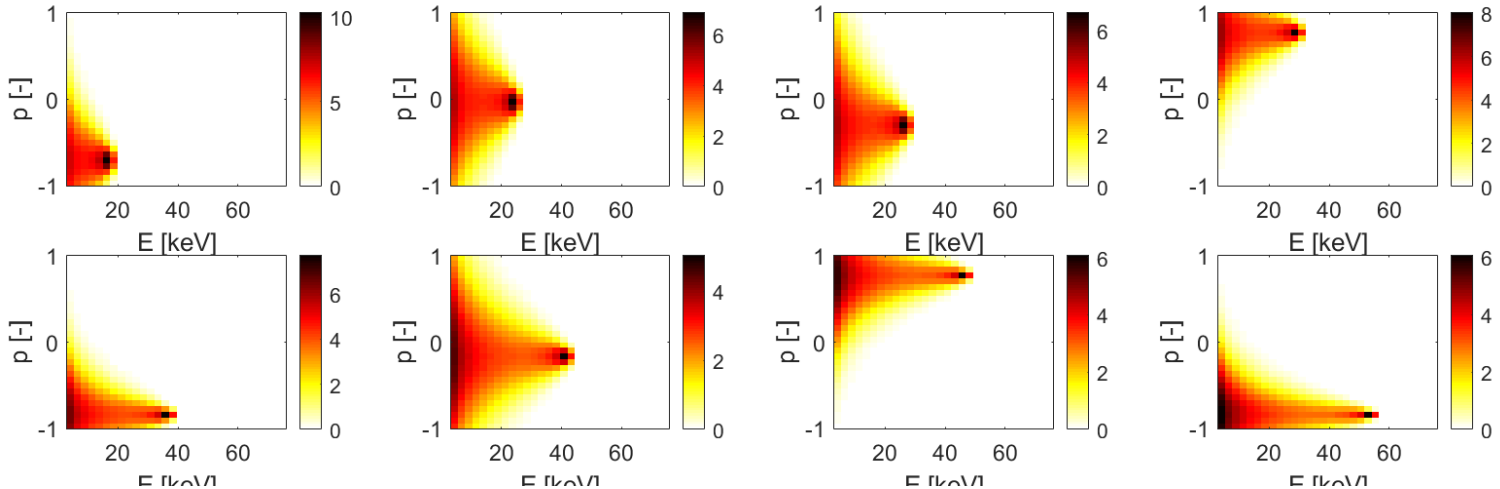
$= a_1 \times f_{SD1} + a_2 \times f_{SD2} + a_3 \times f_{SD3} + \ldots$







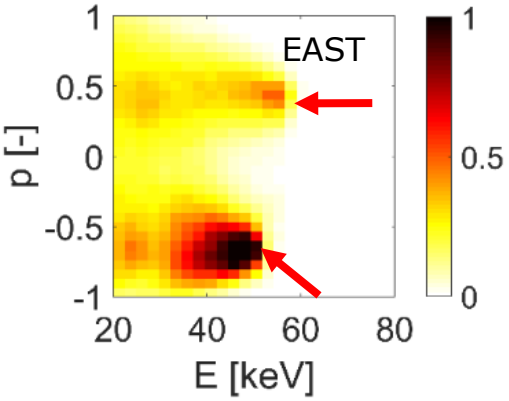
$$f = \sum_i a_i f_{SD,i}$$



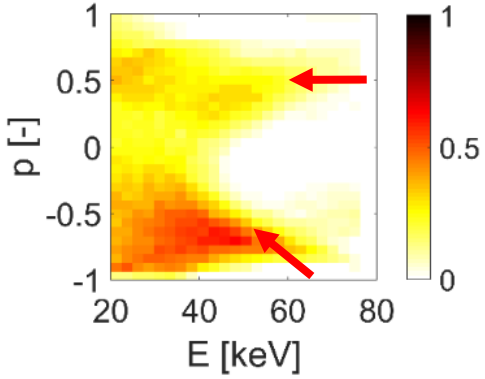
Madsen et al. 2020 ppcf

Collision physics-based basis functions
Prior information: Collisions in plasmas

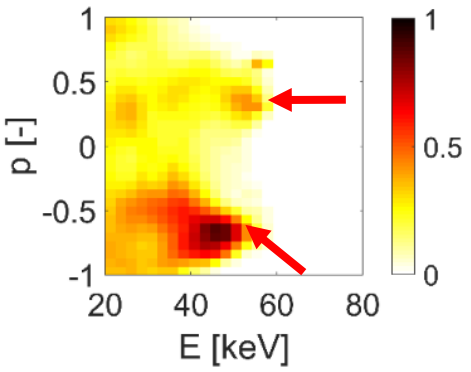
Ground truth



Pixel basis reconstruction



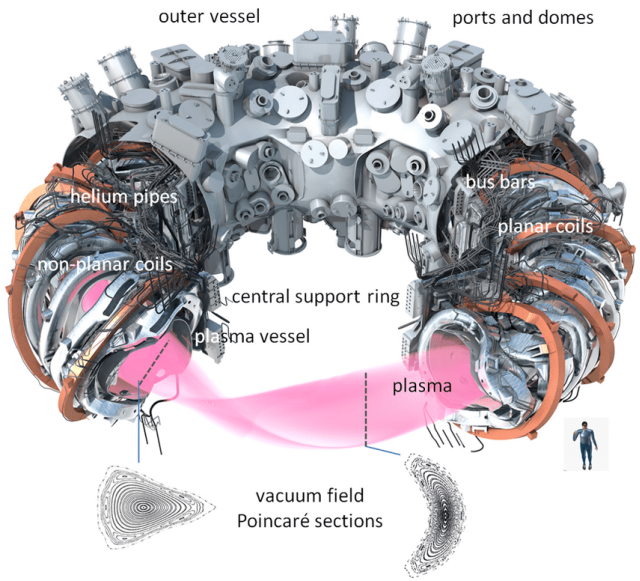
Collision-physics basis reconstruction

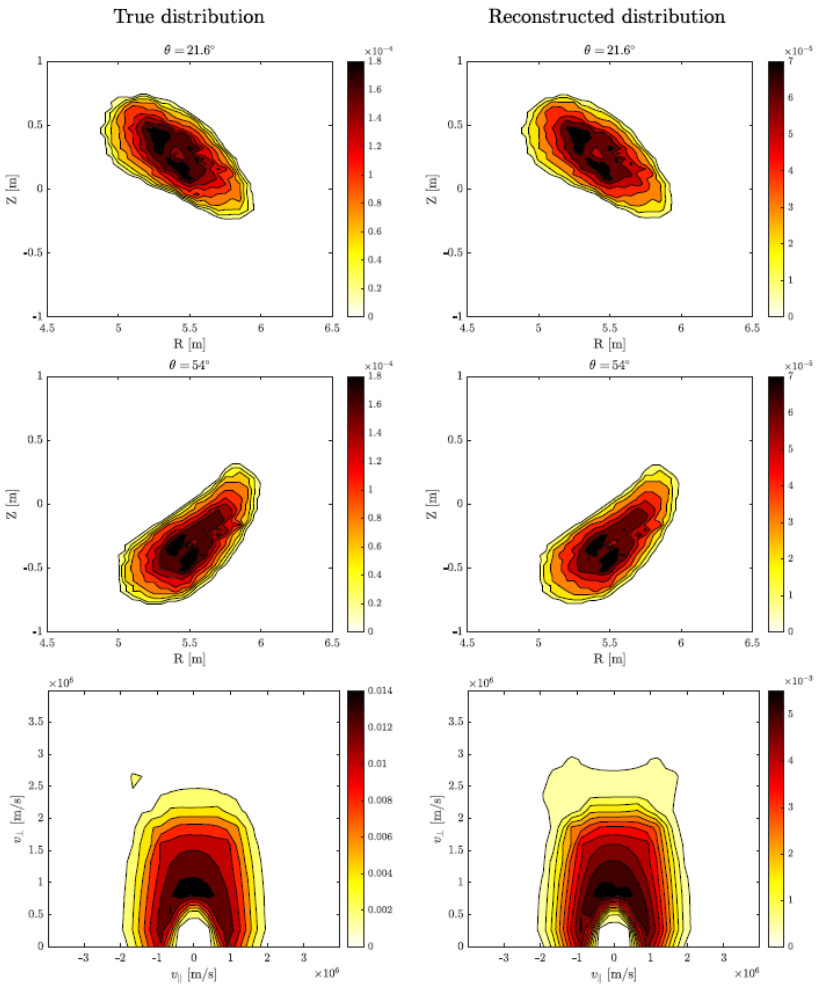


- Collision physics is very strong prior information
- This approach can be extended to 3D, 4D, and 5D tomography

Madsen et al. 2020 ppcf

The 4D/5D tomography problem





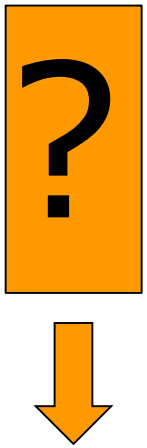
- At each point in 3D position space, there is a 2D velocity distribution function.
- Our first baby steps: inference based on 24 base functions

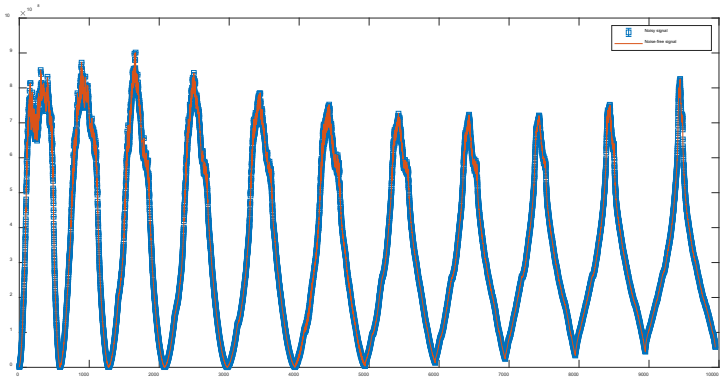
Simmendefeldt et al. (to be submitted)

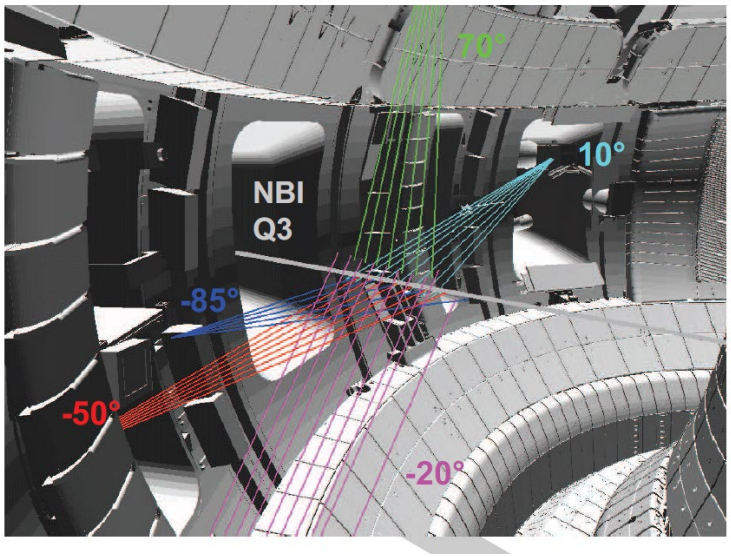
Outline

1) Introduction to fusion energy, fast ions and velocity distribution functions
2) Introduction to tomography in position and velocity space - The Lucky-Luke-Doppler experiment
3) How is Per Christian helping fusion plasma physics?
4) A closing riddle

What velocity distribution function in a fusion plasma produces these 11 spectra of projected velocities ?

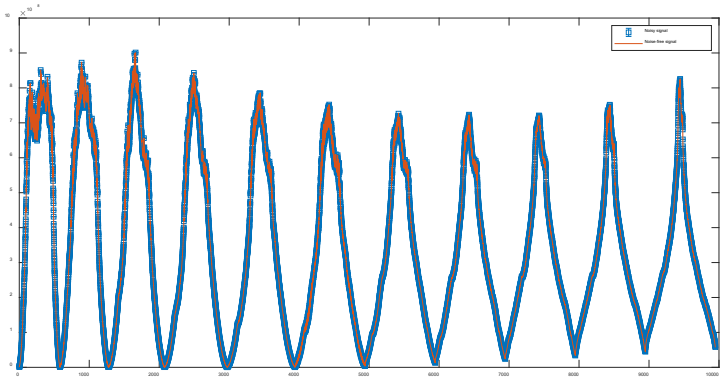


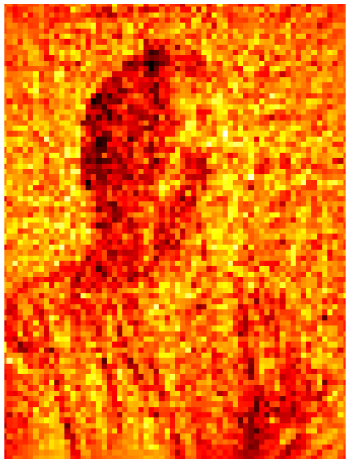




First two trials of velocity-space tomography

?

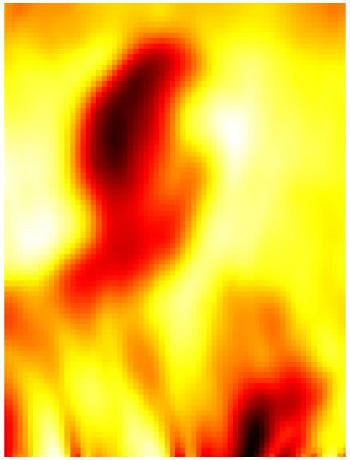




Too spiky / jittery.

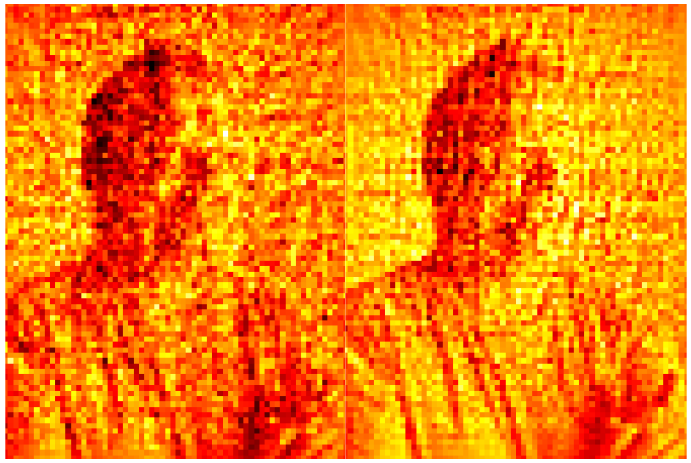
Need more smoothing.

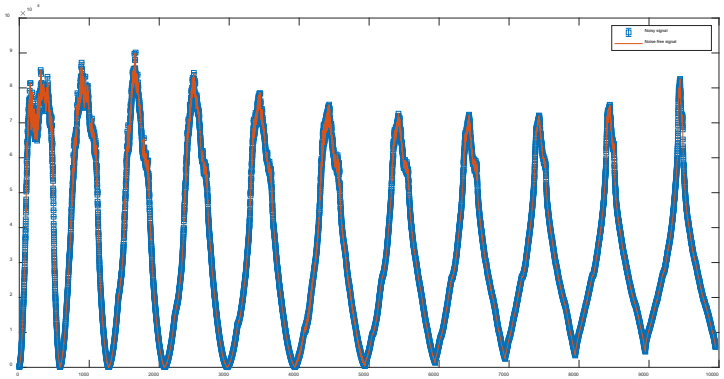
Too smooth / blobby.
Need less smoothing.

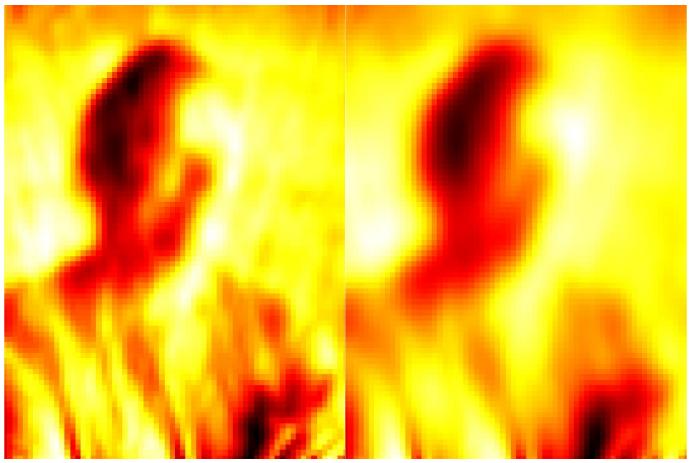


Next two trials of velocity-space tomography

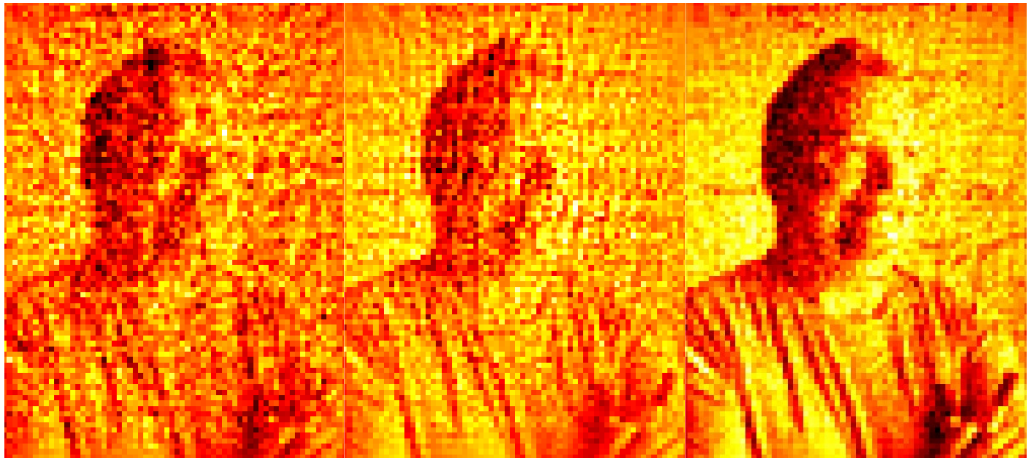
?

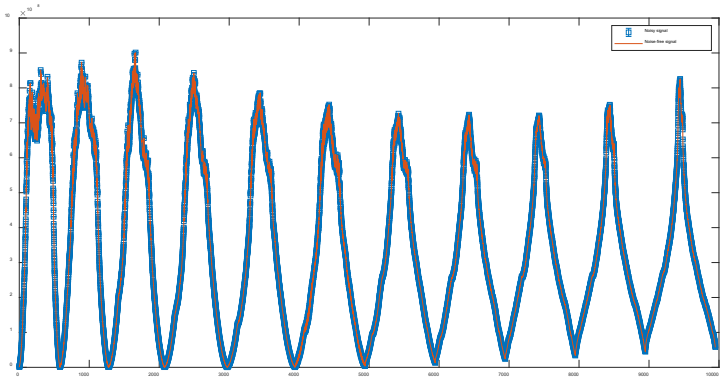


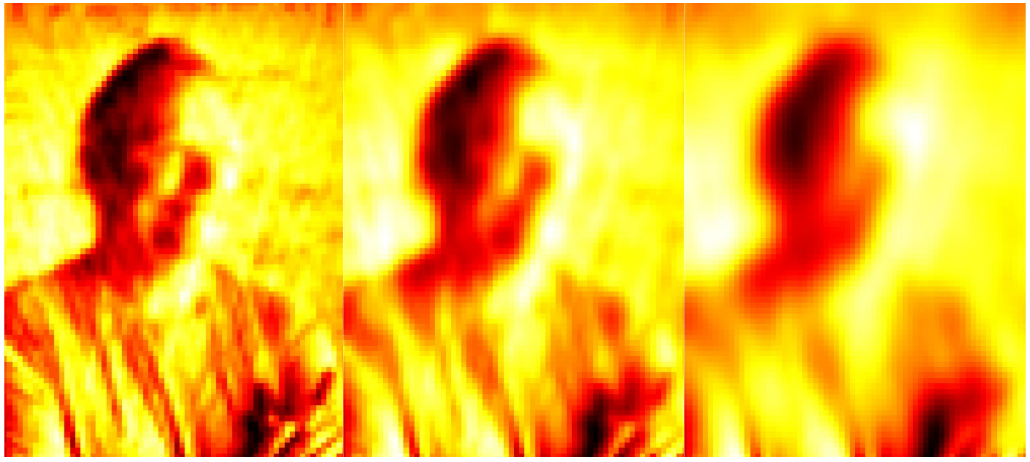




Next two trials of velocity-space tomography

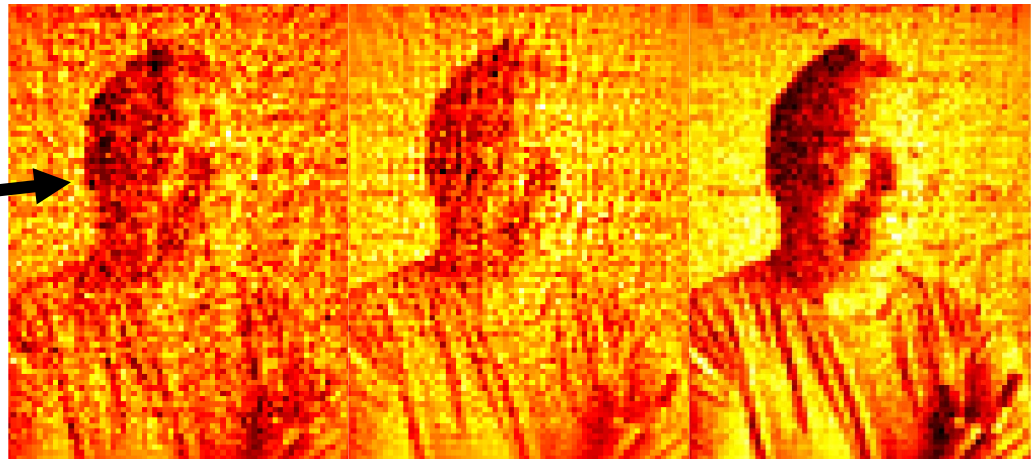






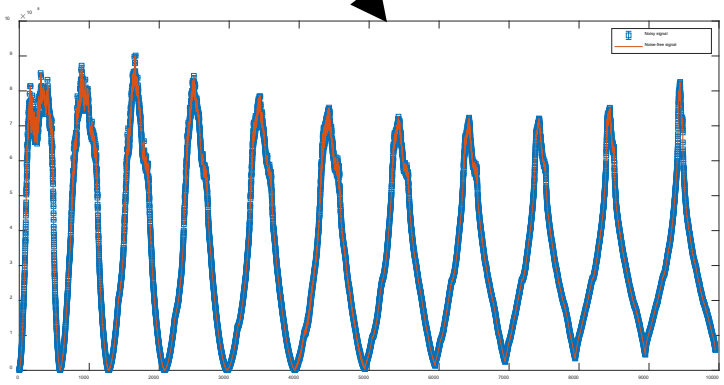
Exploded Per Christian:

Too spiky



Per Christian projected on 11 spectrometers

Very hard to tell!



Now find the *right* amount of smoothing, e.g. by the "L-curve"

Hansen 1992, 1993, 2000

Blobby Per Christian:

Too smooth

Congratulations on 40 years at DTU!