EUROPEAN FUSION DEVELOPMENT AGREEMENT

Effect of equilibrium reconstruction on pedestal analysis

(work in progress)

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Combined effort of a large group of people:

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+ITM/IMP-1 Equilibrium Reconstruction group:

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Topics

- Introduction to equilibrium reconstruction

- How to do equilibrium reconstruction?
- How to improve it
- Some examples
- Can we do better?
- Future plans

Tokamak plasma equilibrium

axisymmetric force balance:

$\partial/\partial t=0,\ \partial/\partial\zeta=0$

Force balance: $\vec{j}\times\vec{B}=\nabla p$

Ampere's Law: $\nabla\times\vec{B}=\mu_0\vec{j}$

$$\nabla.\vec{B}=0$$

$$\nabla.\vec{j}=0$$

Representation of variables and functions

$$\vec{B} = F\nabla\zeta + \nabla\zeta \times \nabla\Psi$$
$$= \vec{B}_{\text{toroidal}} + \vec{B}_{\text{poloidal}}$$

$$\Psi = (\text{Poloidal Flux})/2\pi$$
$$F = RB_{toroidal}$$

p and F are flux functions, $\overline{\Psi}$ is normalised flux

$$p = p(\overline{\Psi}),\ F = F(\overline{\Psi}), \quad \overline{\Psi} = (\Psi - \Psi_{axis})/(\Psi_{LCFS} - \Psi_{axis})$$

p' and FF' are modelled as polynomial functions (or splines) of the normalised poloidal flux, $\overline{\Psi}$

Representation of variables and functions

The toroidal plasma current is represented as

$$j_{toroidal} = R\, p' + \frac{1}{R}\frac{FF'}{\mu_0}$$

Notice R and 1/R local dependencies!

Diamagnetism: FF' has opposite sign to p'

Locally, $j_{toroidal}<0$ if gradients are steep

The poloidal plasma current is

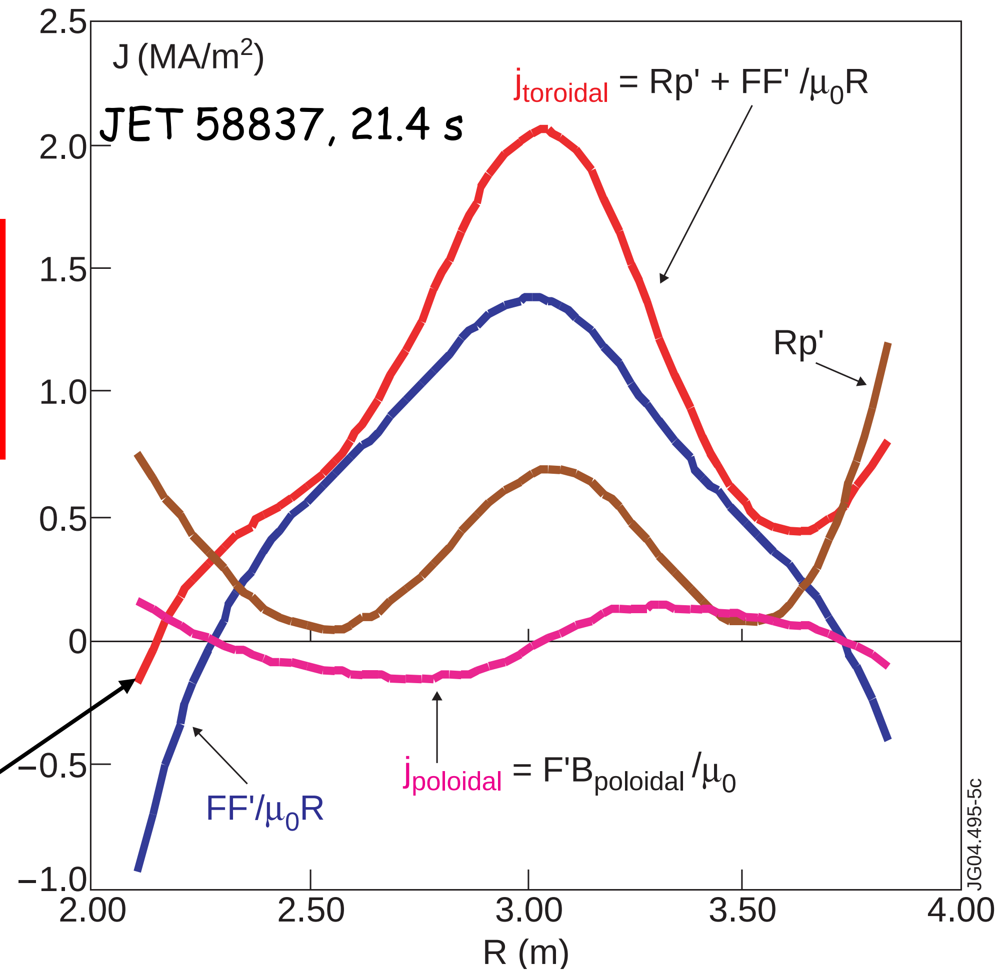
$$j_{poloidal} = -F' B_{poloidal} / \mu_0$$

Current density profiles just before an ELM

Edge diamagnetism

$$j_{toroidal} = R\,p' + \frac{1}{R}\frac{FF'}{\mu_0}$$

due to 1/R, $j_{toroidal}$ can be negative inboard



Reconstruction of equilibrium just before ELM (tricky!!!)

Introduction to equilibrium reconstruction

Find an equilibrium that minimizes χ^2

$$\chi^2 = \underbrace{\sum \mathrm{fwt} \frac{[\Psi_{meas}(k) - \Psi_{calc}(k)]^2}{\sigma(k)^2}}_{\text{measurements}} + \underbrace{\sum \mathrm{fwt}[C_{desired}(k) - C_{calc}(k)]^2}_{\text{constraints}}$$

- Measurements and constraints are calculated, or approximated , with Green functions

$$\Psi = \sum_{k'} G(k,k')I(k') + \Psi_{external}$$

G's are like mutual inductances: the flux at k produced by a current at k'

Fitting and equilibrium iterations

fitting: invert G matrix to compute I's, profiles, minimize χ^2

$$\begin{pmatrix} & G & \end{pmatrix} \begin{pmatrix} I \\ p' \\ FF' \end{pmatrix} = \begin{pmatrix} M \\ C \end{pmatrix}$$

equilibrium: solve Grad-Shafranov equation,

$$L(\Psi)=Rp'(\overline{\Psi})+FF'(\overline{\Psi})/R/\mu_0$$

Typically

- fitting iterations update coil currents & profiles
- equilibrium Picard iterations compute $j(\overline{\psi})$, update $\psi(j)$,

find boundary, recompute $\overline{\psi}$

Usual pedestal analysis in JET

- external magnetic and current measurements: magnetic probes, flux loops, saddle loops, currents in coils
- How much freedom does the current profile representation have? Very little

  2^{nd} order polynomials for p' and FF':

$$p'(\Psi) \approx a_0 + a_1\overline{\Psi} + a_2\overline{\Psi}^2$$

  + a regularising constraint to minimise $p'' \sim 2a_2$

- Can this represent pressure profiles with a pedestal?
  Not really: parabolic $p(\Psi) \approx p_0 + p_1\overline{\Psi} + p_2\overline{\Psi}^2$

Reconstruction of equilibrium for pedestal studies

What is being done now at JET:

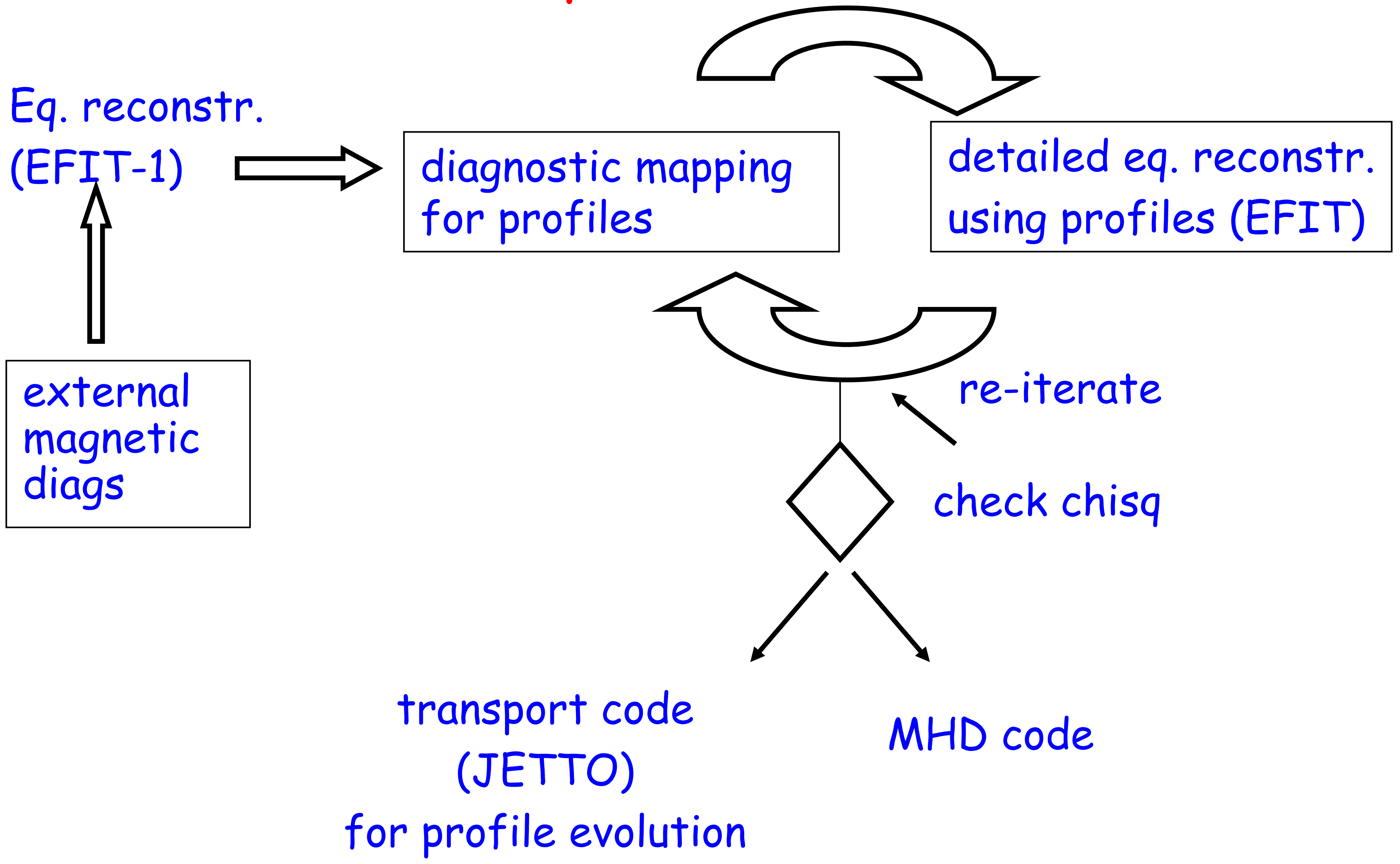
external magnetic diags ⇒ Eq. reconstr. (EFIT-1) ⇒ q(✡), Boundary, p′, FF′

⇒ diagnostic mapping for profiles

⇒ transport code (JETTO)

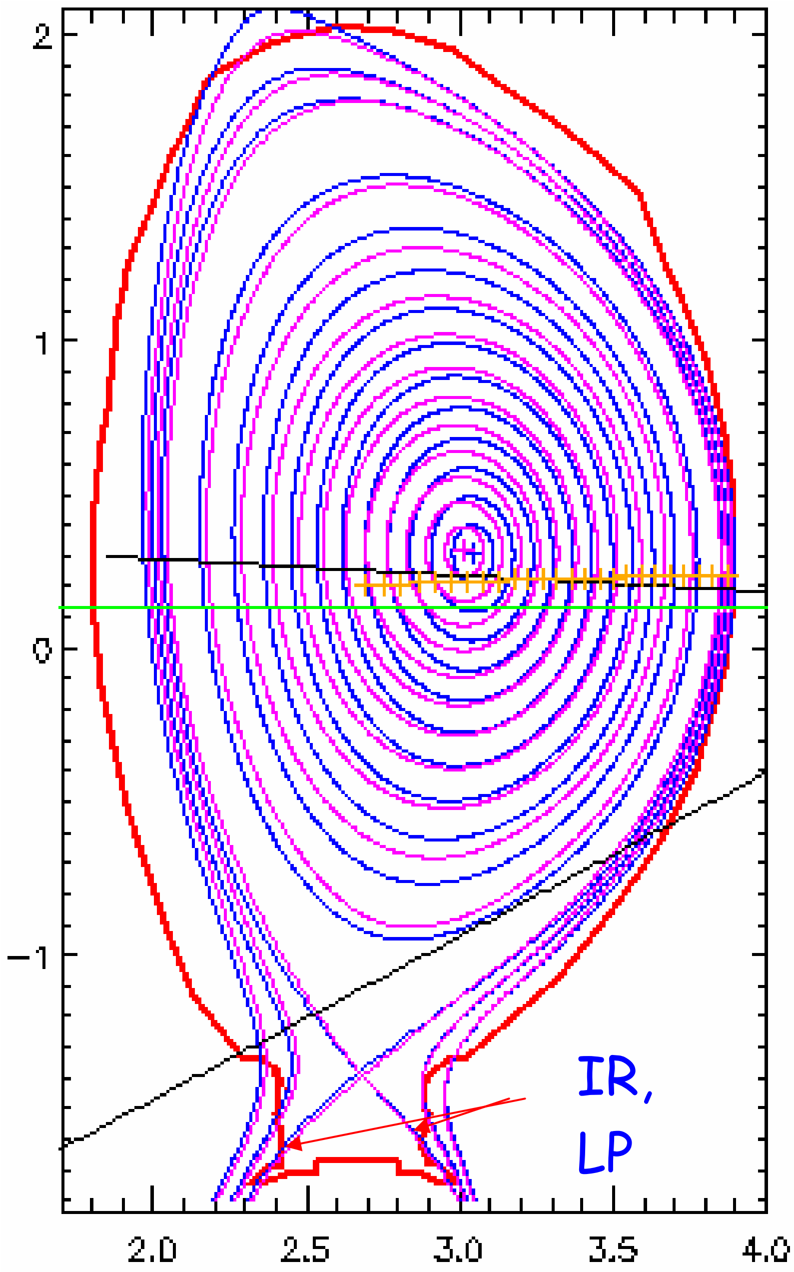
- Profile evolution (n, T, p, E_r).
- Refine/Update equilibrium as needed
- Refine equilibrium (HELENA)
- Test MHD (MISHKA?)

Better: equilibrium iteration



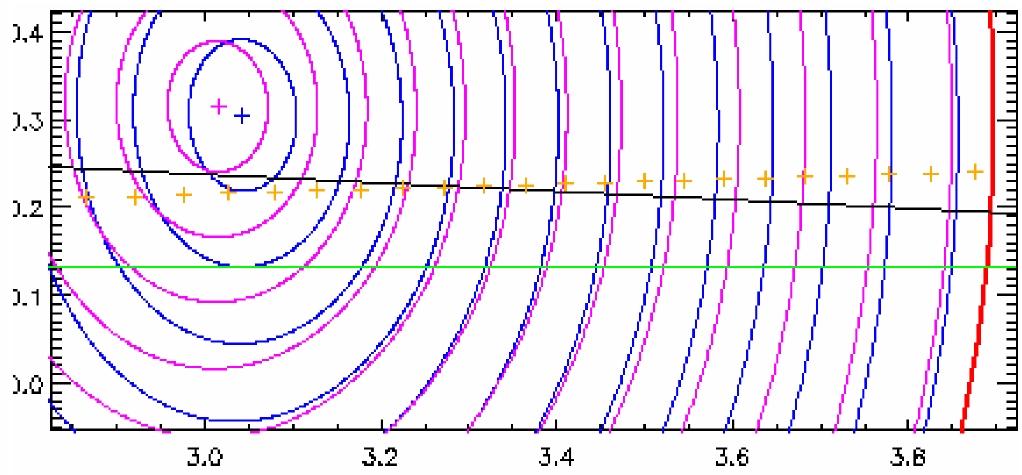
Art of detailed equilibrium reconstruction

- Mutually incompatible measurements and constraints: many diagnostics => many answers
- Results depend on diagnostic choices, constraint fitting weights, estimated error bars
- Integral quantities (q, shear) are not as sensitive as local measurements: many very different equilibria can produce barely distinguisheable q profiles
- If many measurements are available, more structure can be found in p and j.



Some useful diagnostics for equilibrium reconstruction

Electron Cyclotron Emission: ECE



Lines of sight:

Thomson Scaterring:

LIDAR, edge LIDAR, HRTS

Motional Stark Effect: MSE

+ Polarimetry line integrals

Can we do better? On the equilibrium side

EFIT can also be given more information from

- MSE: local measurements of B_{pol}, may be poluted by large electric fields
- Polarimetry: line integral of n_e B_{pol}
- LIDAR + "treated" T_i info: local measurement of pressure profile
- ECE can provide information on B, if T_e(B) is known
- Core measurements realy help pedestal reconstruction!

When many measurements are available

➡ high order polynomials (or splines) can be used to represent p' and FF'

➡ higher grid resolution can be exploited

➡ Details of p and j can be captured

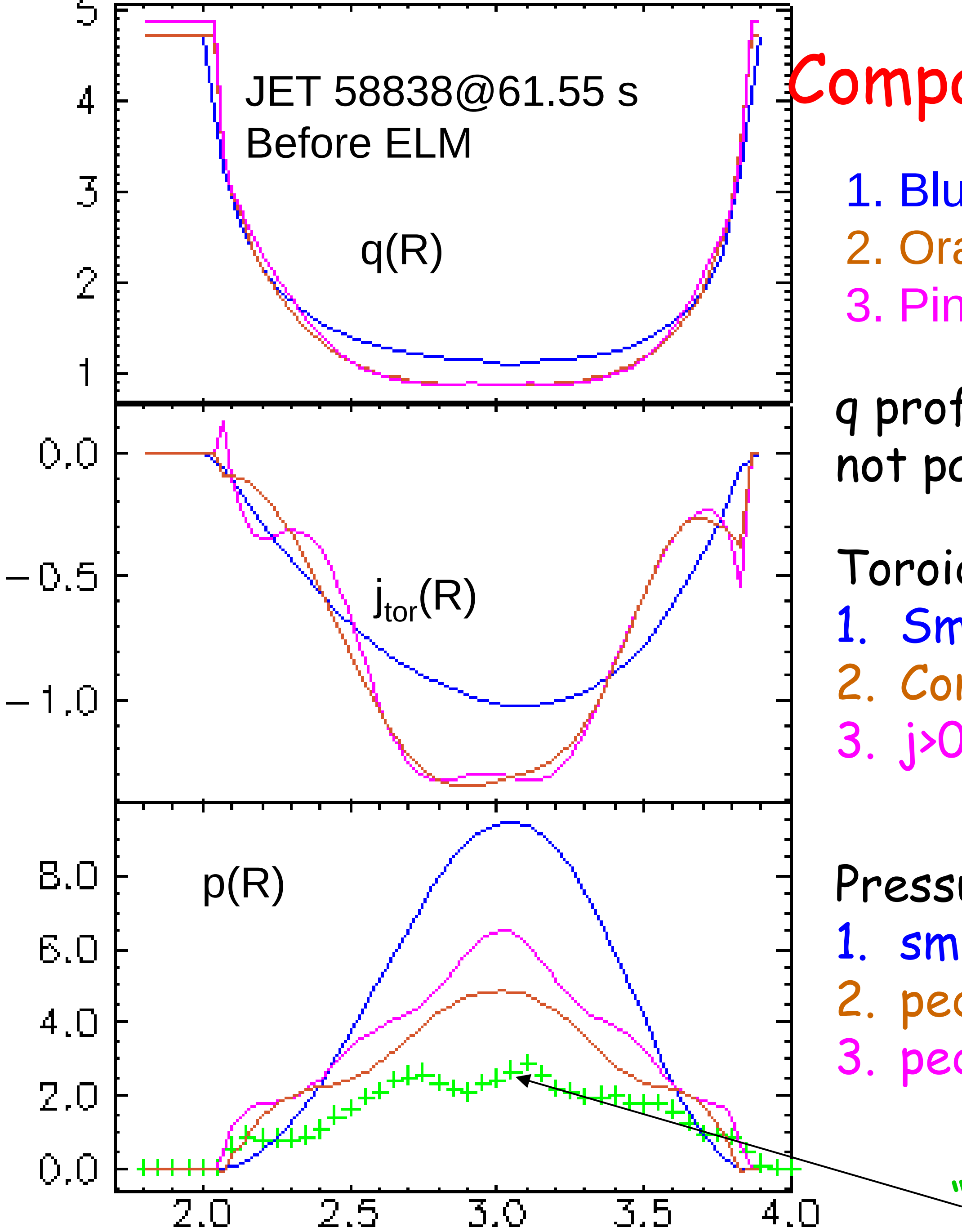
What do we get then?

- I am still dissatisfied with the equilibrium reconstructions I have: so far it has not been possible to properly fit the various available measurements.
- Slow work: manual adjustments of data and mapping are needed, by many diagnosticians, and models should be tested, validated and optimised further (iron, coil connections)

Let´s compare results for some examples so far:

1. External magnetics , 2 p′ and 2 FF′ coefs.
2. +MSE, polarimetry, 5 p(R,Z) points (3.0-3.77 m, LIDAR and edge LIDAR), Ti(CX), 5 p´, 5 FF´coefs
3. +MSE, polarimetry, 9 p(R,Z) points (2.5-3.65 m), Ti=Te, 5 p´, 5 FF´coefs, reduced fwt for position feedback coils, extra shift of LIDAR.

Comparing reconstructions



1. Blue: chain1 EFIT
2. Orange: + MSE, polarimetry, pressure
3. Pink: + extra-in-shifted pressure

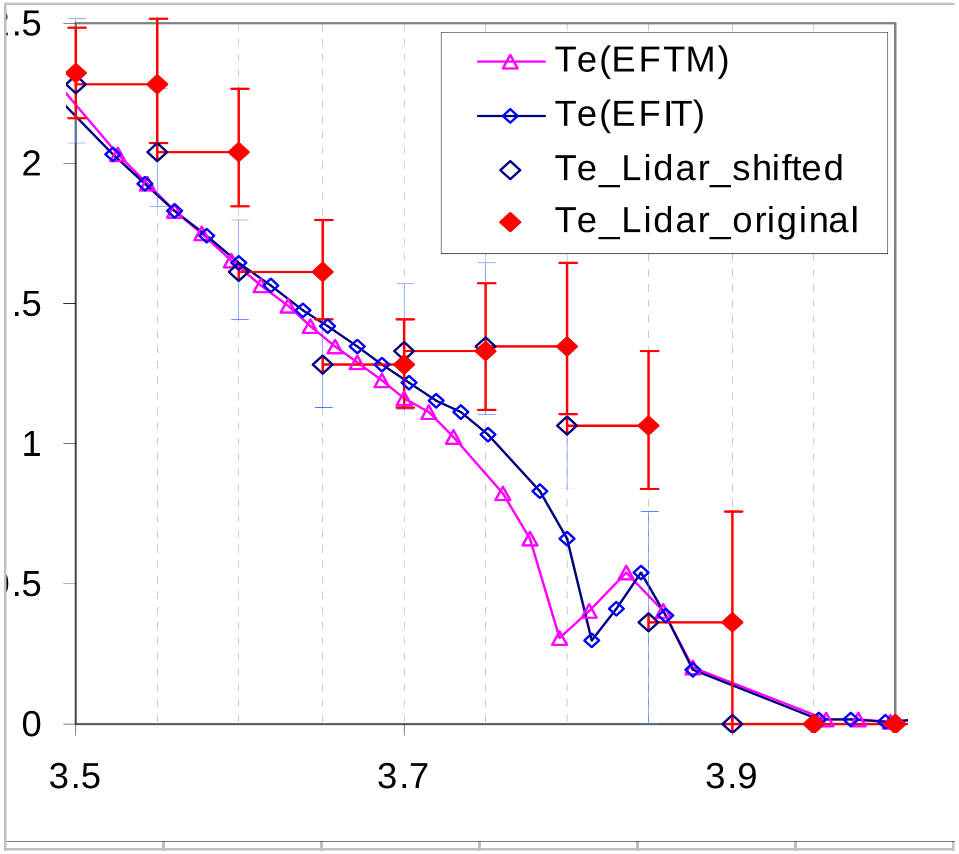
q profile:
not particularly different at pedestal

Toroidal current density
1. Smooth, small at edge
2. Considerable j>0 at edges
3. j>0 outer edge, j<0 inner edge

Pressure
1. smooth pressure, no pedestal
2. pedestal, but p<0 at edge
3. pedestal, shifted inwards

Comparing reconstructions: pedestal

Blue: TeECE with chain1 EFIT
Pink: TeECE with reconstruction 3
(E. de la Luna)



Red points: original LIDAR

Blue points: 5 cm shifted LIDAR

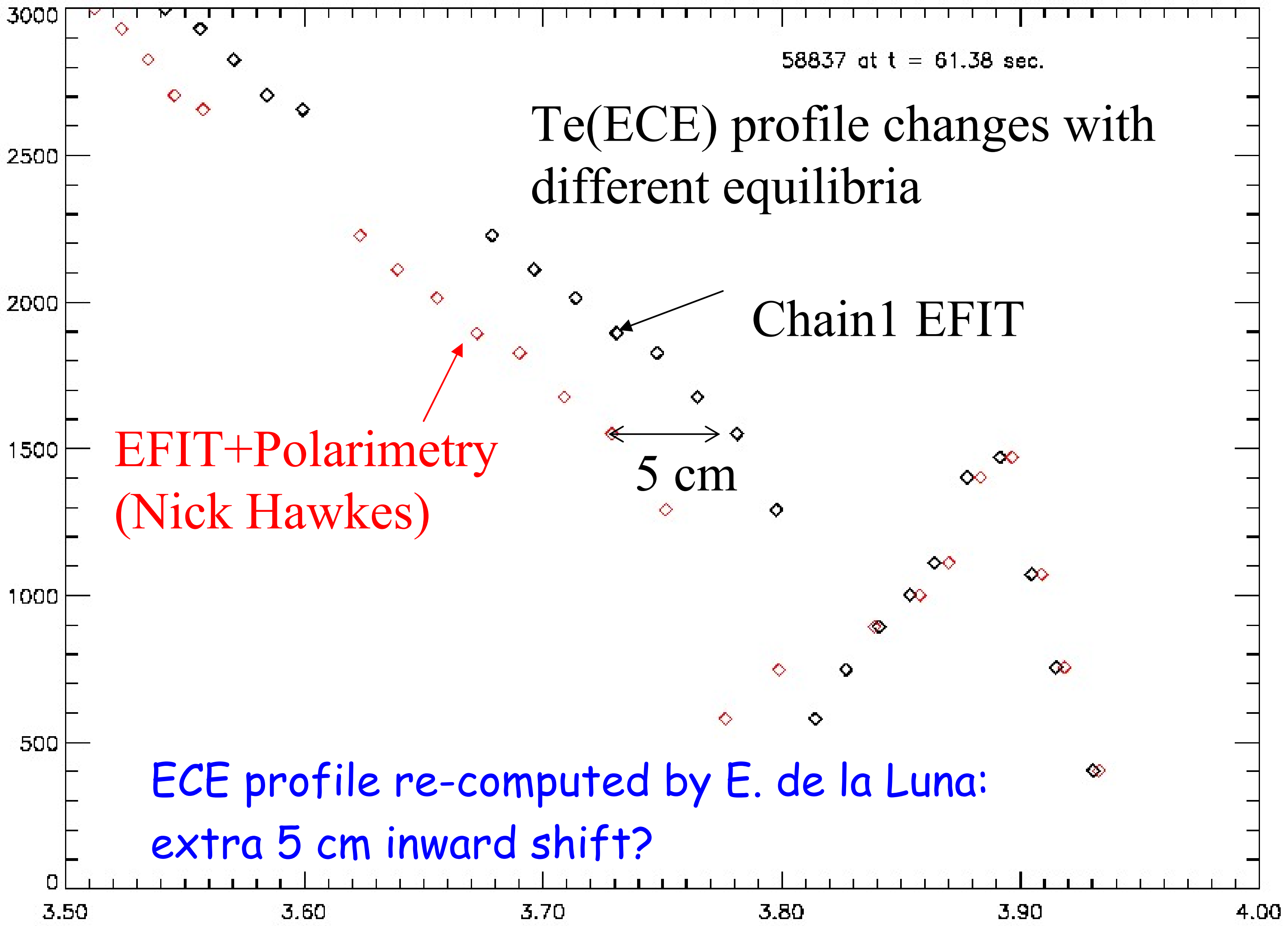
In 2000 LIDAR was shifted inward 5 cm “to match Te_ECE”.

Te_ECE profile depends on equilibrium reconstructed B_{tot}.

But, my best reconstruction so far requires an extra 2 cm shift?

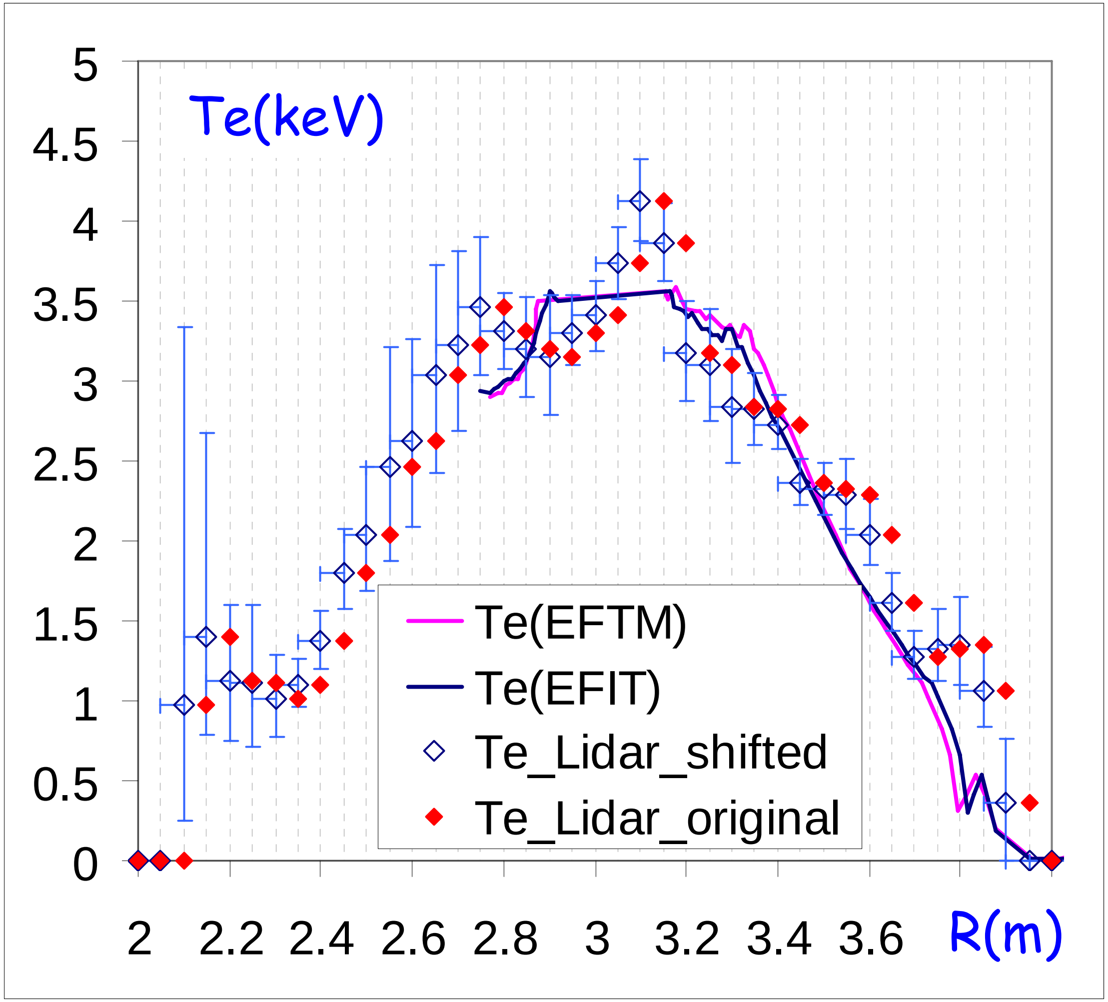
Similar effects for reflectometry.

Also, wrong strike locations in all cases!



3000
2500
2000
1500
1000
500
0
3.50
3.60
3.70
3.80
3.90
4.00
58837 at t = 61.38 sec.
Te(ECE) profile changes with different equilibria
Chain1 EFIT
EFIT+Polarimetry (Nick Hawkes)
5 cm
ECE profile re-computed by E. de la Luna:
extra 5 cm inward shift?

Overall profile: Not just a simple shift



In the edge, an "extra" shift?

Core original LIDAR position better match to ECE

Conclusion:

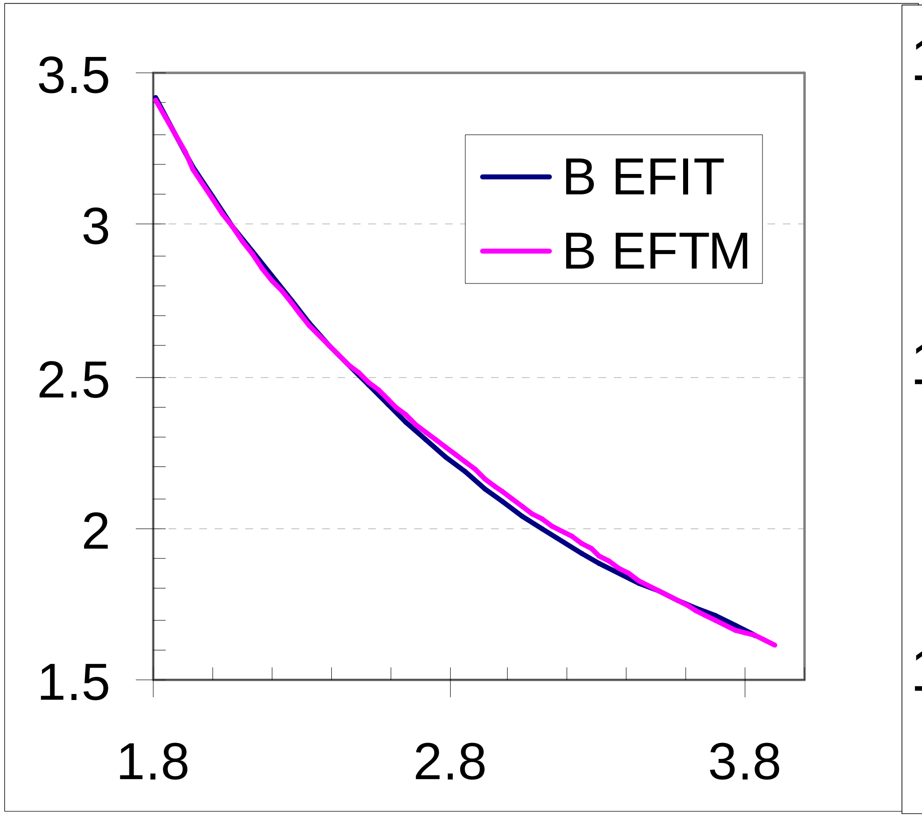
I still don´t trust the recosntructions.

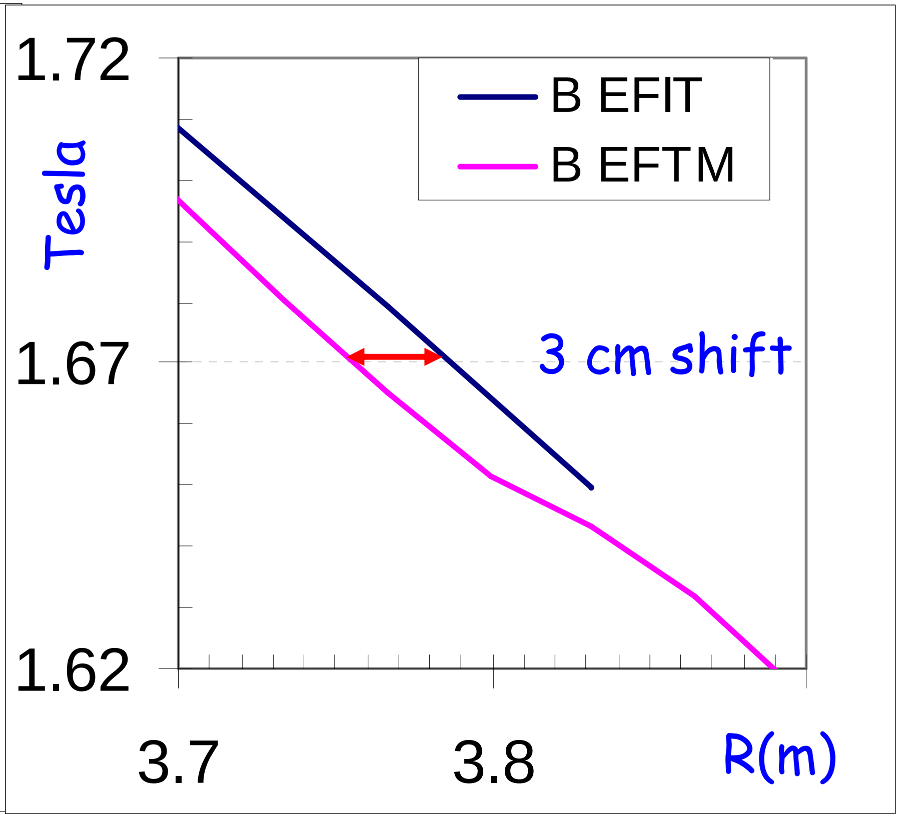
Probably need to find another shot, w/o MHD, but with many diags.

Diagnostic mapping

value of B for ECE and reflectometry

Here, plot B from EFIT along equator





Diagnostic mapping

value of B for ECE and reflectometry

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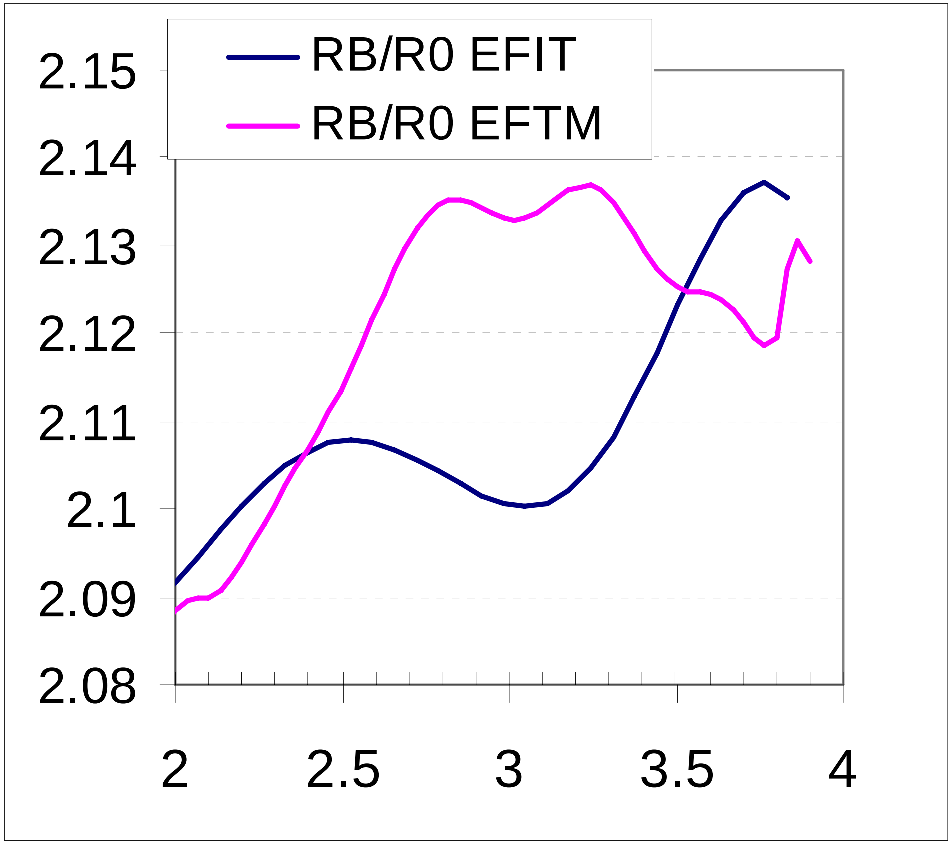


More to do? In EFIT

- Refine mesh: chain1 efit has grid mesh of 7x12 cm (65x65) or 14x24 cm (33x33): this must be improved for detailed reconstruction!

  MSE resolves 5 cm, pedestal widths are a few cm, current density profile can be even sharper.

- V&V iron core geometry model, iron permeability model (with dry runs, comparison with FE codes).
- Reorganize coil connections in code, to take into account real systems for position and shape control.
- Add diagnostics and constraints.
- Treat time and spatial averages consistently.

More to do? In transport codes, JETTO?

Recap: q, p′ and FF′ are taken from EFIT and used by JETTO, via HELENA, then evolved.

A proposal:

- read out the eventual JETTO-produced equilibrium
- compute with it χ^2 of the available data, as in EFIT.
- if χ^2 is reasonable, proceed.
  If not, iterate detailed equilibrium reconstruction with more diagnostic information, more structure in p′, FF′. Then get back to JETTO

Summary

Work is underway to improve detailed equilibrium reconstruction at JET

Flux-mapping of diagnostics is far from trivial

Core diagnostics can help pedestal mapping

Propose evaluating χ^2 in JETTO before proceeding to MHD analysis.

PS:

ITM IMP-1 project is equilibrium reconstruction.

If there is interest in it, I can say a few words about it.

Equilibrium reconstruction at JET

- Up until now EFITJ: from original EFIT by Lang Lao code, changed for JET by Dennis O´Brien, Wolfgang Zwingman and Vladimir Drozdov.
- A re-write of EFIT into fortran90 (mostly) was done in Culham by Lynton Appel.
- Lynton, Vladimir and myself working on unification for chain1 use

ITM/IMP-1 Project

Project Leader: Guido Huysmans

Deputy Project Leader: Lynton Appel

Aims:

- define input-output interfaces for equilibrium codes
- unify EFIT
- V&V ITM equilibrium reconstruction codes

Equilibrium reconstruction at JET

- Where are we now? *In the middle of it.*
- Data read from EFITJ/K-file, translated to different formats.
- Code now works and agrees exactly with JET for external magnetic measurements without saddles.

- Ongoing work: PPF I/O, more diagnostics, merging of various development versions, refine grid, iron model, circuit descriptions,...

Equilibrium reconstruction: ITM and CREATE

- In parallel, Wolfgang Zwingman is developing EFIT-ITM in Matlab.
- Paddy McCarthy has various codes for ASDEX, with great capabilities (SOL currents, regularised high order polynomials, q constraints, etc)
- The CREATE group has a suite of finite element equilibrium codes, with detailed treatment of the iron core (geometry and magnetization), now improving internal magnetic diagnostics.

- ITM-Equilibrium reconstruction:

    A meeting is planned sometime this spring

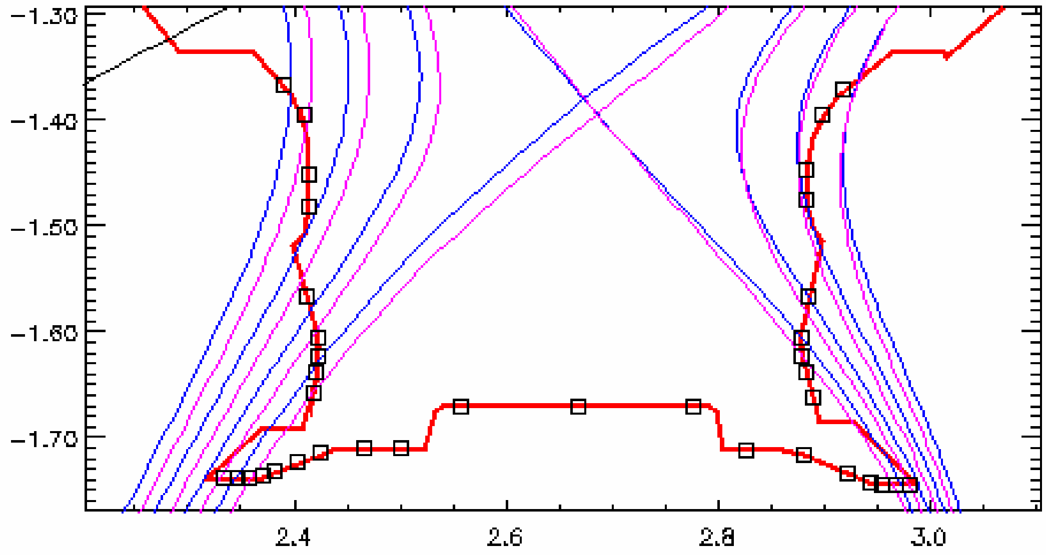
Introduction to equilibrium reconstruction

What measurements could be used for the fits?

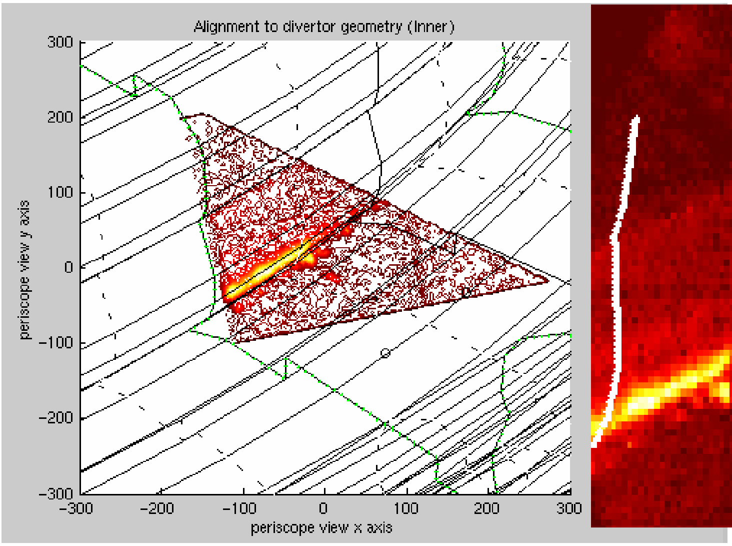
- External magnetic measurements: magnetic probes, flux loops, saddle loops, currents in coils
- Kinetic measurements: $p_e(R,Z)$ (made of ne, T_e, T_i, Z), including iso-surface information.
- Internal magnetic measurements: $B_R(R,Z)$, $B_Z(R,Z)$
- MHD information: location of modes
- Strike points, boundary clues

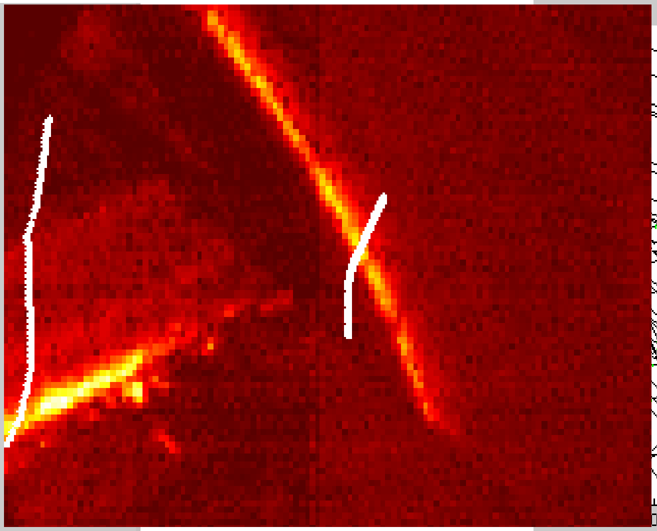
More information: position of strike points

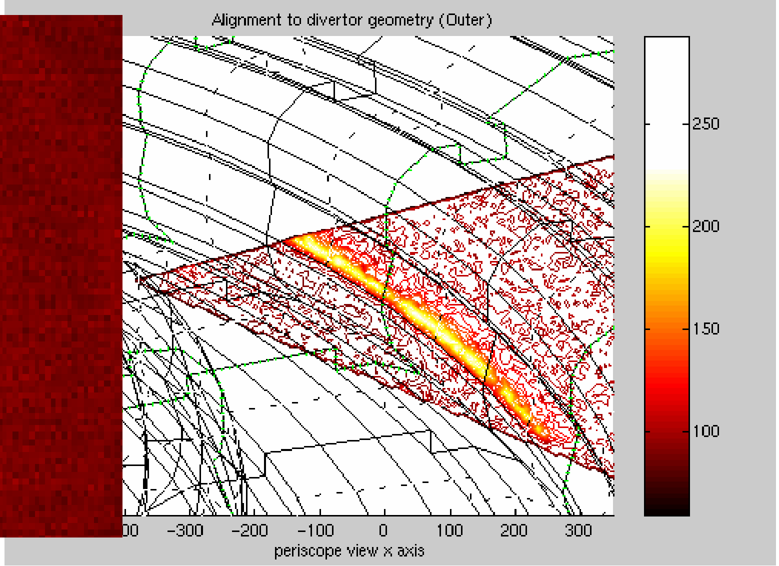
Target Langmuir Probes



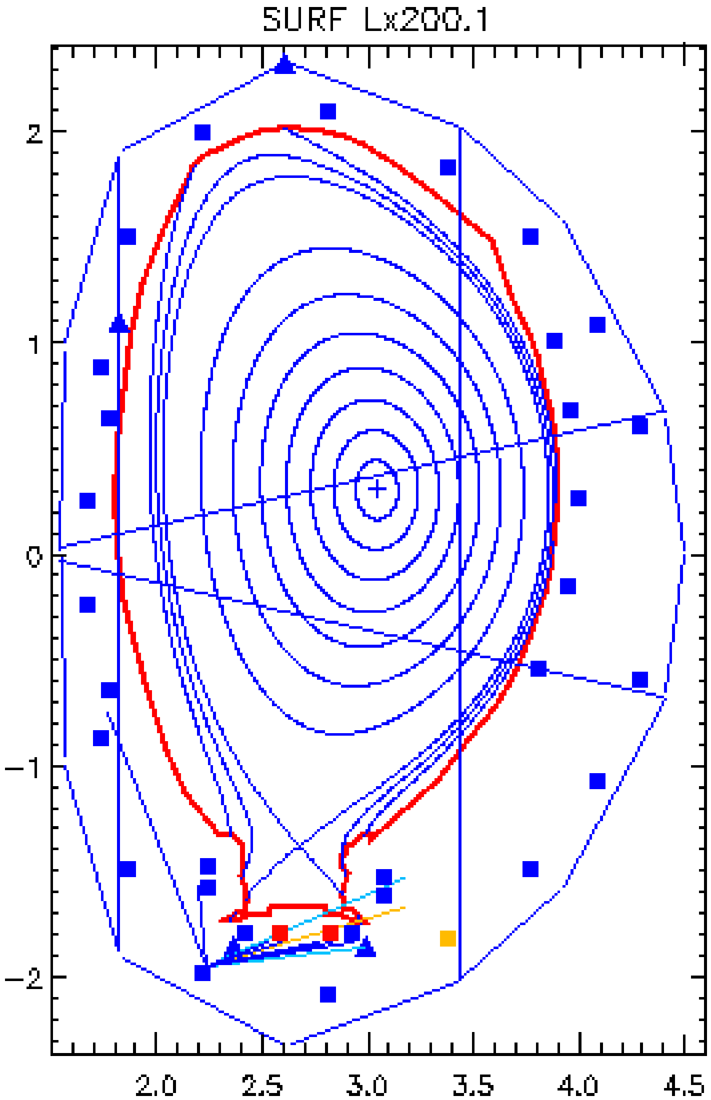
Divertor Infrared Camera







External magnetic measurements in JET



- magnetic probes, flux loops, saddle loops, currents in coils
- Probes are far appart, saddles produce very integral measurements, there are very few flux loops.

  (to be improved with JET-EP)

Representation of variables and functions

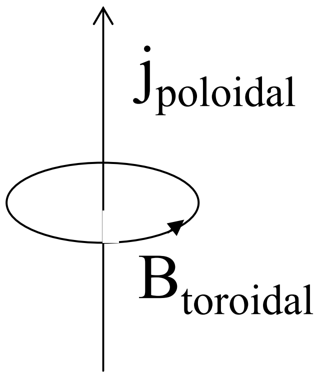
$$\vec{B} = F\nabla\zeta + \nabla\zeta \times \nabla\Psi$$
$$= \vec{B}_{toroidal} + \vec{B}_{poloidal}$$

$$\Psi = (\text{Poloidal Flux})/2\pi$$
$$F = RB_{toroidal}$$

p and F are flux functions, $\bar{\Psi}$ is normalised flux

$$p = p(\bar{\Psi}),\ F = F(\bar{\Psi}),\quad \bar{\Psi} = (\Psi - \Psi_{axis})/(\Psi_{LCFS} - \Psi_{axis})$$

$F(\bar{\Psi})$ is related to the poloidal current density:



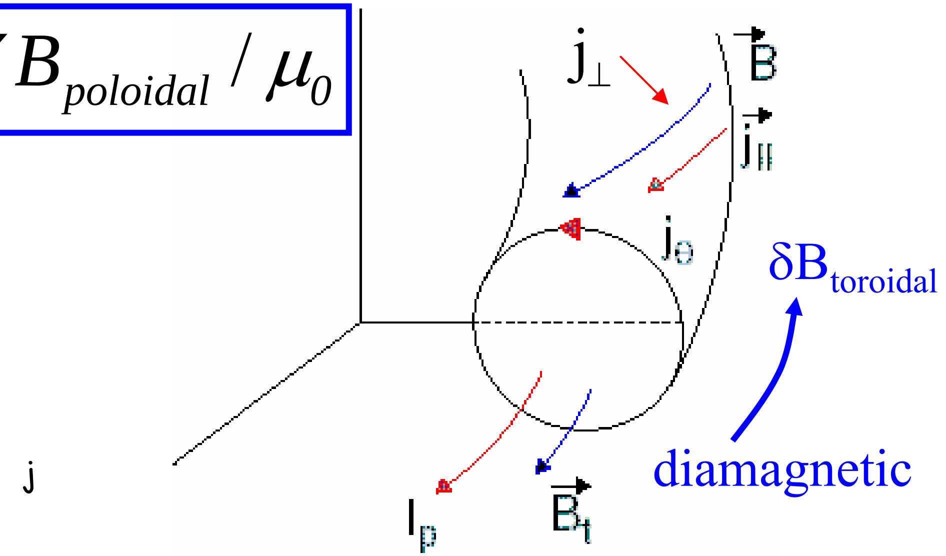
$$\oint B_{toroidal} R d\zeta = \mu_0 \int j_{poloidal} dS$$
$$\underbrace{2\pi\, RB_{toroidal}}_{2\pi F} = \mu_0 I_{poloidal}$$

Para and diamagnetism in tokamak plasma equilibrium

$$\vec{j} \times \vec{B} = \nabla p$$

$$j_{poloidal} = -F' B_{poloidal} / \mu_0$$

$$j_{toroidal} = R\, p' + \frac{1}{R} \frac{FF'}{\mu_0}$$



Diamagnetism:

j_{pol} from j_{perp} creates $\delta B_{toroidal}$ that opposes $B_{toroidal\ vacuum}$

Paramagnetism :

j_{pol} from $j_{parallel}$ creates $\delta B_{toroidal}$ that increases $B_{toroidal\ vacuum}$

Note: bootstrap is parallel and paramagnetic in tokamaks!

$\vec{j}_{bootstrap} \times \vec{B} = 0$, bootstrap alone can not hold ∇p

How are the reconstructed equilibria used at JET?

1. Chain1 EFIT output is used by most diagnostics for flux-surface mapping
2. Then

   Plasma boundary, q profile and current density representation are fed to another equilibrium code (HELENA)

   Flux surfaces outside of xpsi=95% or 99% are removed (X-point is difficult for codes like HELENA)

   The new equilibrium is fed to a transport code, which will re-calculate current profile evolution based on energy and poloidal field diffusion (JETTO, TRANSP)

Improving equilibrium reconstruction

- Central profile measurements (p, Bpol) for magnetic axis position and current and pressure peaking.
- Confinement region Te for iso-surfaces
- Edge p for pedestal structure (inboard???)
- Strike points for boundary information
- Pedestal and edge Bp (MSE, Li beam?) for pedestal j profile. (Note: MSE is often difficult to use before ELMs, as it is poluted by Er)
- Stationary plasmas: large MHD modes introduce poloidal and toroidal asymmetries, hard to deal with.
- MHD modes for q locations