Measurement of fast ion losses from JET: preliminary results

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Outline

Introduction

- *Motivation*
- *Faraday Cups- energy, radial, poloidal, good time resolution*
- *Scintillator Probe - pitch angle, gyroradius, modest time resolution*

Analysis of losses in TF Ripple Experiments

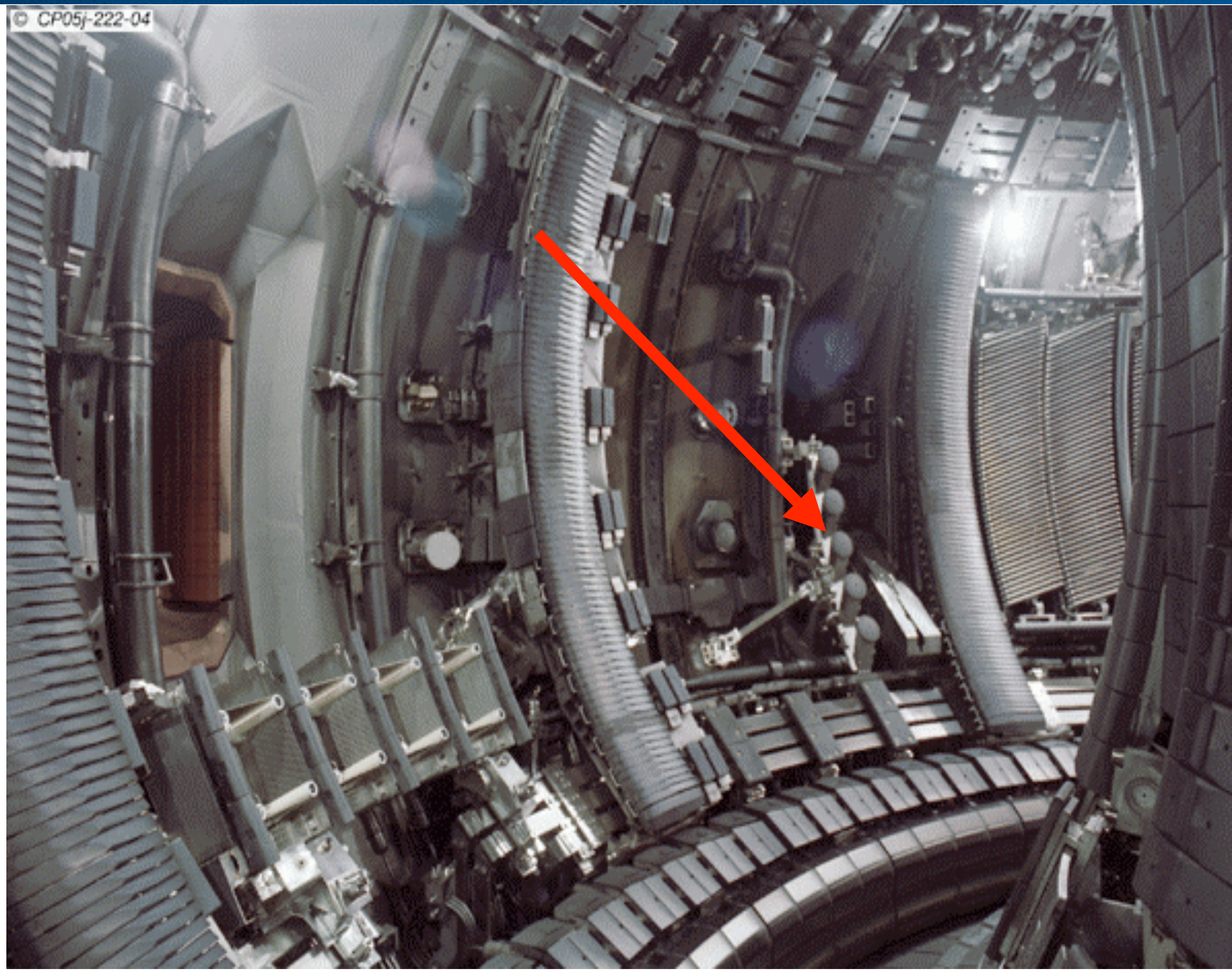
- *NB fast ion studies*
- *TF Ripple Plasma Commissioning*
- *H-mode Ripple studies*
- *TF Ripple in Advanced Tokamak scenarios*

Summary

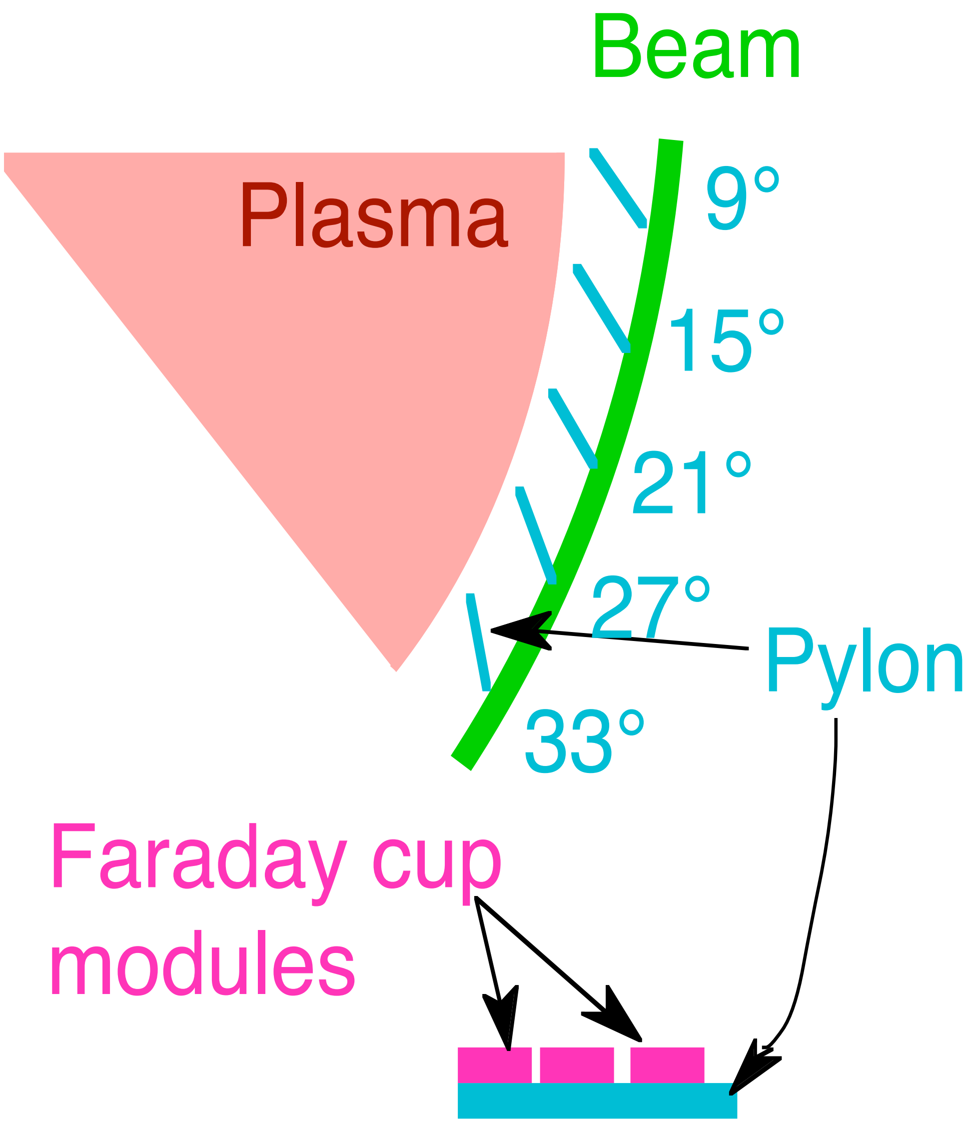
Fast ion loss measurements are important

- Most auxiliary heating involves fast ions
  - NBI: < 160 keV
  - ICH tail: < 5 MeV
  - α particles: 3.5 MeV
- Loss means inefficient heating
- Concentrated loss may damage first wall
- Features of loss reveal details of physics within plasma
- Important to measure losses in ITER -> Faraday cups
  - Bakeable
  - Radiation hard
  - Low radiation noise
  - Large dynamic range

A Faraday-Cup array was installed in JET (Octant 7)



Faraday cups are positioned poloidally and radially

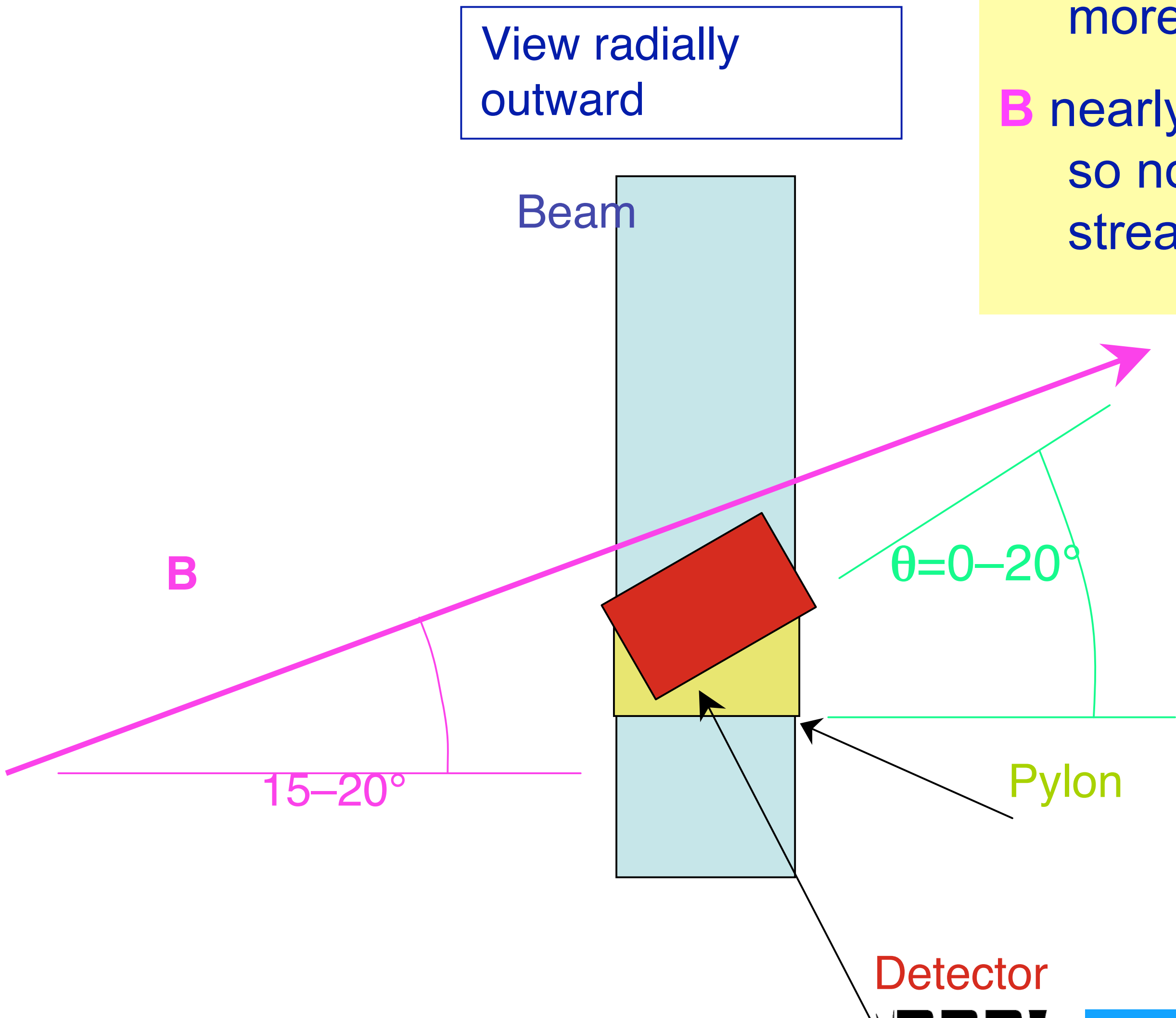


- Curved beam mounted on vessel wall below midplane
- 5 “Pylons” mounted on beam - poloidal resolution
- Each pylon contains up to 3 Faraday cup modules - radial resolution

FC detector orientation

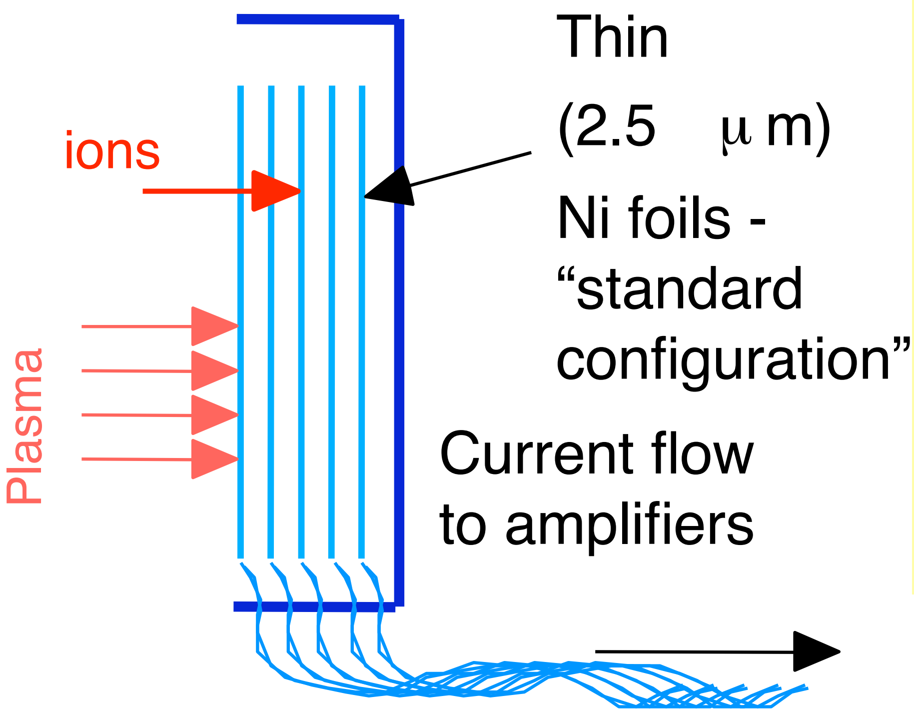
Plasma moves along **B** much more rapidly than normal to **B**

B nearly parallel to plane of foils, so no path exists for plasma streaming onto surface of foils



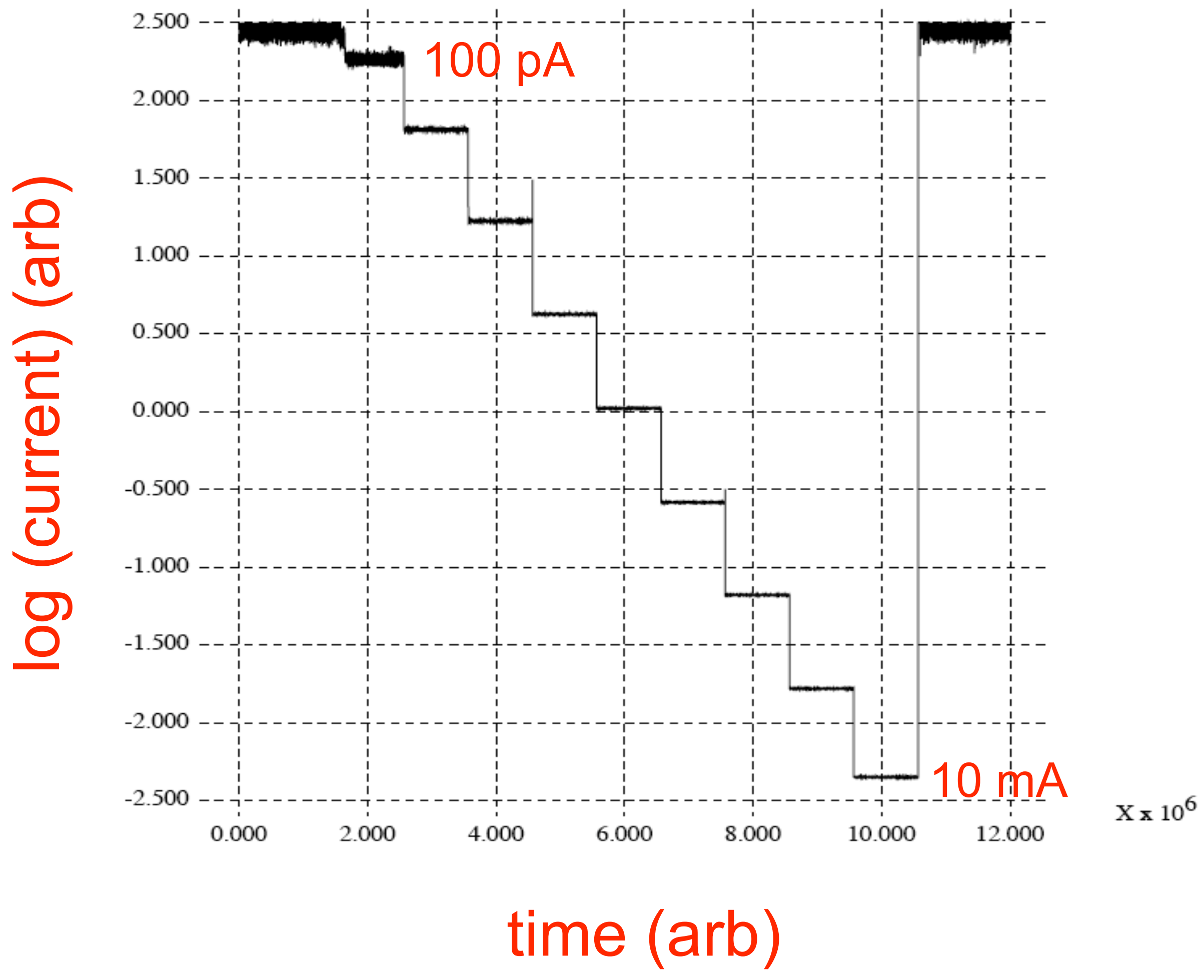
Thin foil Faraday cups allow energy resolution

Detector composed of multiple thin metal foils



- Metal foils separated by mica foils
- Ion energy determines deposition depth
- Ion current measured for each foil individually
- Current vs. depth gives energy distribution (ΔE~30–50%)

Log amplifiers allow 9-decade current-measurement 100 pA - 10 mA



• **Response of log amp to 9-decade calibration current source**

Deuterons with E < 0.78 MeV don't reach 2nd foil

Energy ranges (MeV) for Ions in JET KA-2 foils

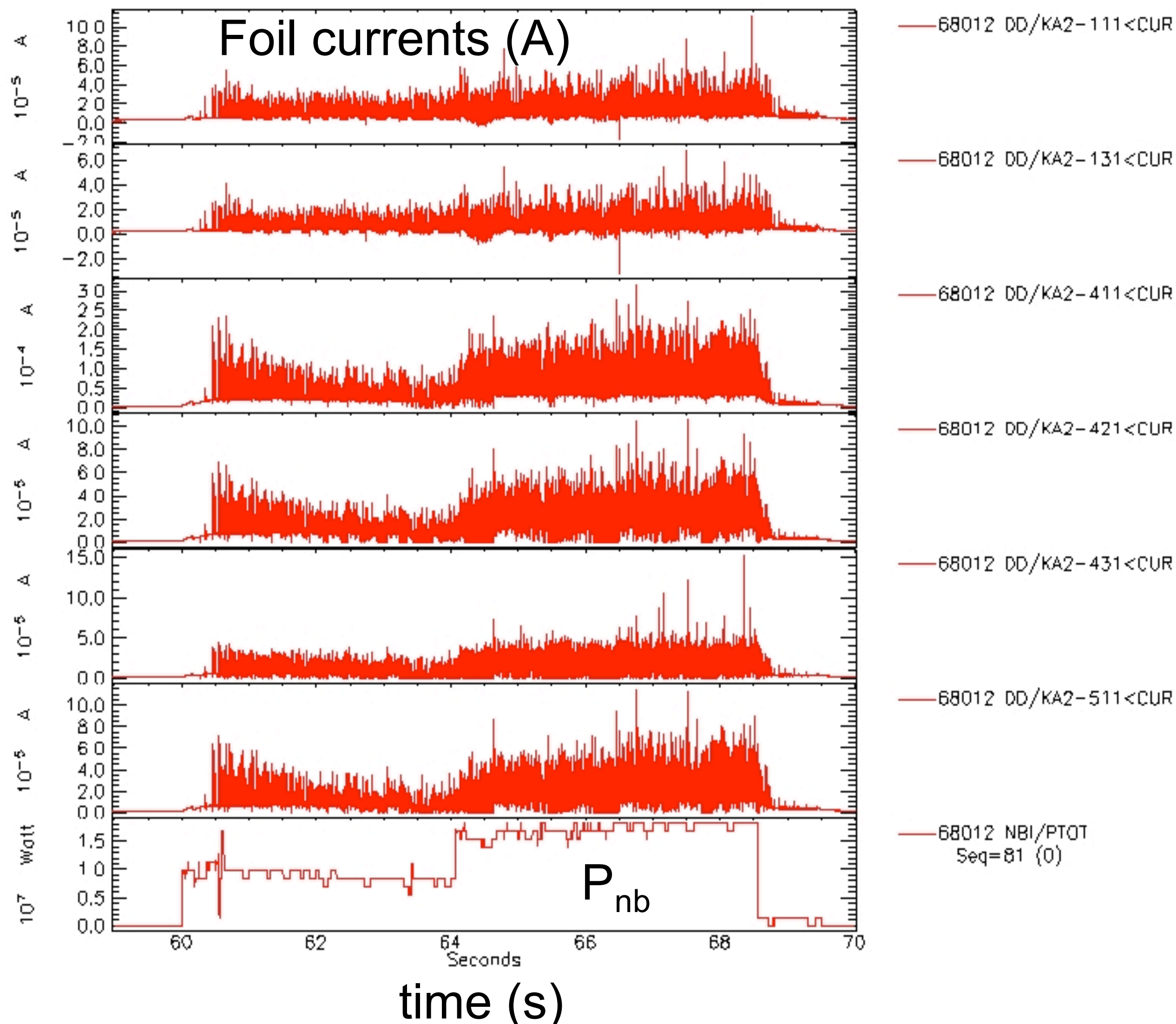
Ion	proton	deuteron	triton	Helium - 3	alpha
Standard detector					
1 (2.5 um)	0.0 - 0.50	0.0 - 0.54	0.0 - 0.53	0.0 - 1.58	0.0 - 1.58
2 (2.5 um)	0.68 - 0.98	0.78 - 1.18	0.78 - 1.25	2.26 - 3.49	2.35 - 3.68
3 (4.0) um	1.15 - 1.52	1.35 - 1.83	1.45 - 2.21	4.00 - 5.42	4.24 - 5.87
4 (2.5 um)	1.65 - 1.83	2.00 - 2.26	2.24 - 2.53	5.81 - 6.57	6.32 - 7.17
15 MeV p detector					
1 (2.5 um)	0.0 - 0.50	0.0 - 0.54	0.0 - 0.53	0.0 - 1.58	0.0 - 1.58
2 (2.5 um)	0.68 - 0.98	0.78 - 1.18	0.78 - 1.25	2.26 - 3.49	2.35 - 3.68
3 (4.0) um	1.15 - 1.52	1.35 - 1.83	1.45 - 2.21	4.00 - 5.42	4.24 - 5.87
4 (2.5 um)	1.65 - 1.83	2.00 - 2.26	2.24 - 2.53	5.81 - 6.57	6.32 - 7.17
5 (25 um)	1.94 - 3.51				
6 (75 um)	3.74 - 6.73				
7 (500 um)	6.76 - 17.83				
8 (100 um)	17.85 - 19.46				
Hi E res					
1 (1 um)	0.0 - .22				
2 (1 um)	0.46 - 0.67				
3 (1 um)	0.78 - 0.91				
4 (1 um)	1.05 - 1.15				
5 (1 um)	1.29 - 1.39				
6 (1 um)	1.50 - 1.59				
7 (1 um)	1.70 - 1.78				
8 (1 um)	1.87 - 1.95				

Some Faraday cups have special configurations

Θ_{pol} ,Z	Inner (R)	Middle (R)	Outer (R)
9° Z= 10 cm	standard configuration	standard	standard
15° Z= - 11 cm	standard	T/C*	
21° Z= - 31 cm	standard		
27° Z= - 50 cm	15-MeV protons	standard	standard
33° Z= - 68 cm	High E resolution		

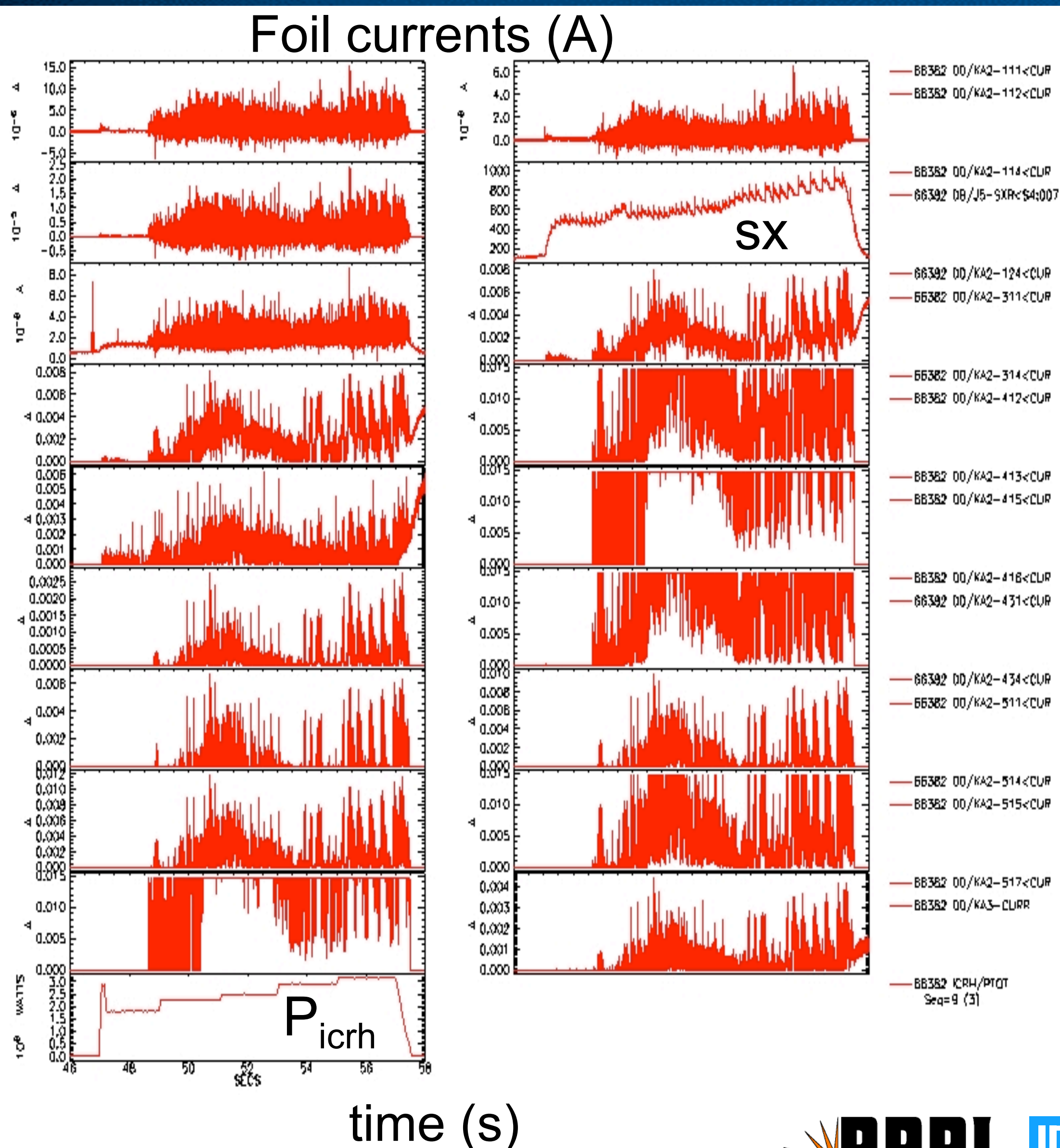
Total: 44 signals. Conduit can accommodate up to 46 wires. *T/C designates a position with a single foil and thermocouple

Only front foils respond to NBI ion loss



- NBI only
- Deeper foils respond at noise level
- Proton E>~0.7 MeV required to penetrate to 2nd foil
- Loss signal increases with P_{nbi}

Sawteeth modulate ICRH ion loss



- 3 MW ICRH
- Energetic ions penetrate to deeper foils
- Some log amplifiers saturated by large currents

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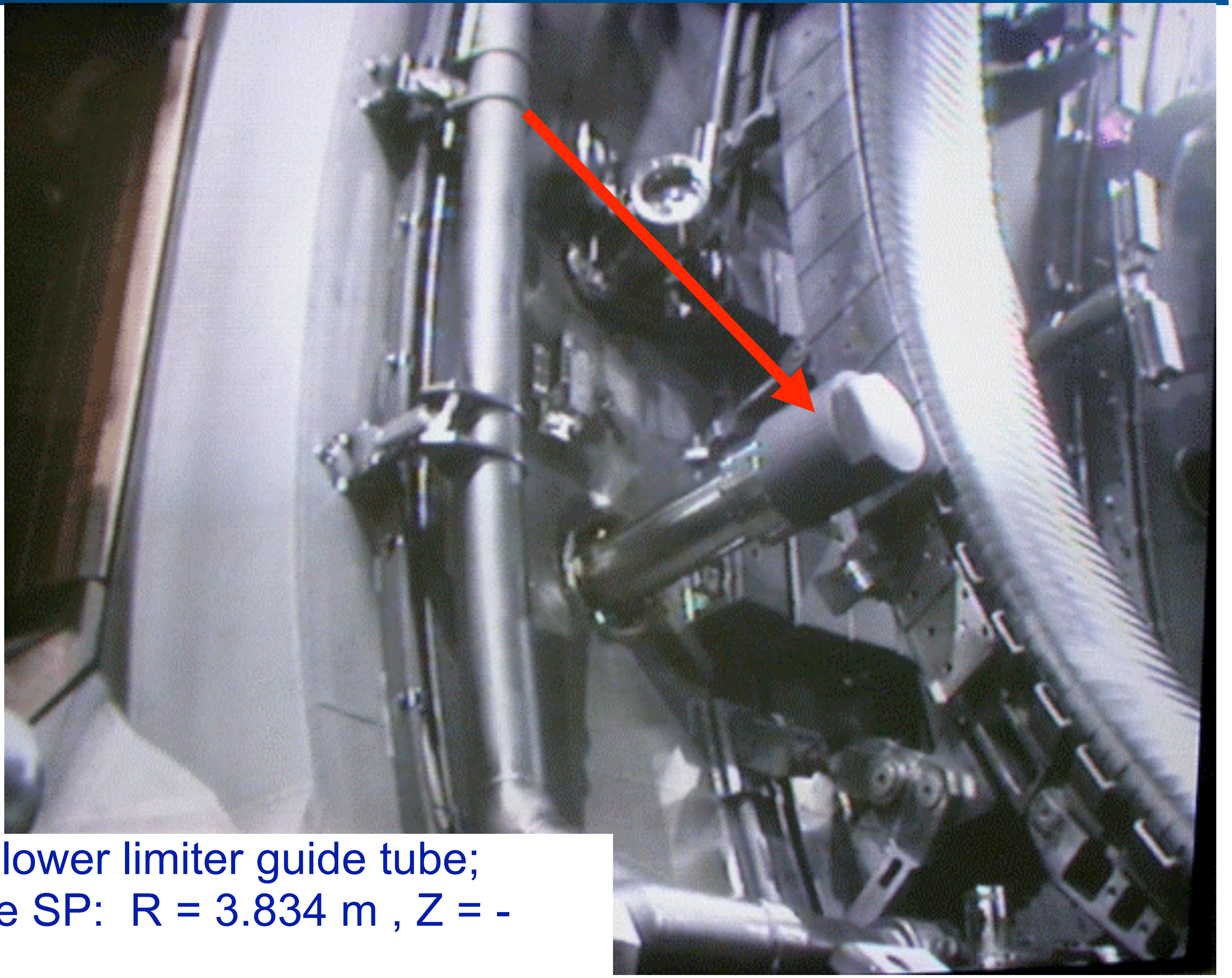
Scintillator Probe in JET (Oct.4)



SP located in the lower limiter guide tube; coordinates of the SP: R = 3.834 m , Z = -0.277 m

Scintillator probe provides pitch-angle and gyroradius resolution

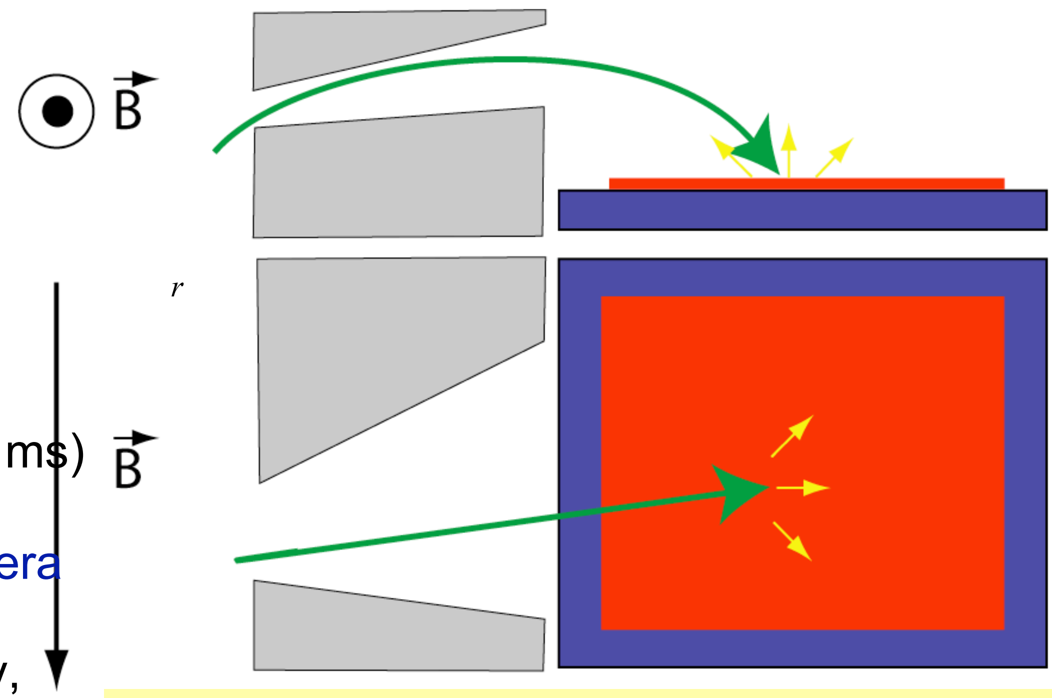
Ion selection is defined by the slit-geometry and magnetic field

- energy range selection
- pitch-angle range selection

KA3 detects particles with gyro-radius from *30 mm* to *140 mm*

Particle energy is linked to gyroradius of fast ions :

$$r \propto \sqrt{mE_\perp} / B_T Z$$



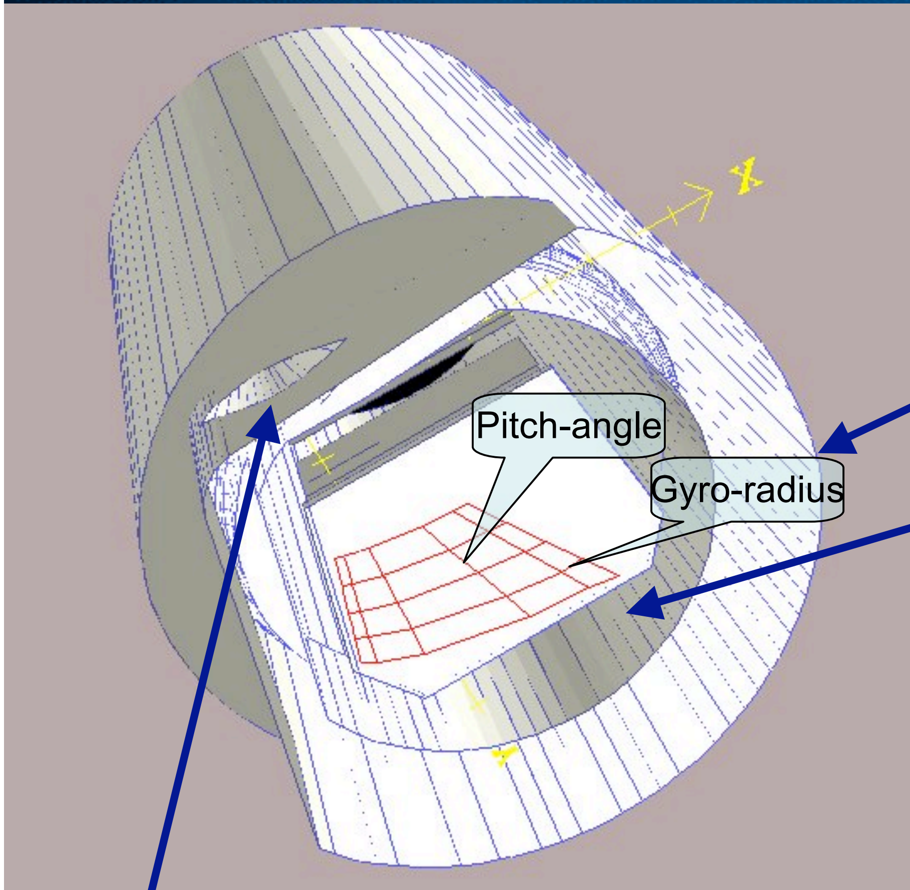
Observation of lost ions:

- particles hit surface of the scintillating material (P56, τ= 2 ms)
- light emission (611nm) allows to use conventional CCD camera (512x512 pixel, 10-50 Hz) and PMT detectors (4x4 PMT array, rate >1 kHz)

Entrance aperture 1-m Au foil stop slow-energy ions (e.g. NBI): H, D < 150 keV; He < 250 keV

Scintillator probe provides 2D lost-ion images (pitch-angle & gyroradius)

Grid lines indicate pitch angle and gyroradius



Scintillator probe

3D model

Gridlines indicate mesh of particle impact positions where they have constant pitch angle and gyro-radius respectively

Development of the software for data evaluation and PPF generation is almost finished. (M.Reich, IPP)

Collimator shape optimized in iterative process between CAD-design and orbit calculations using real model co-ordinates.
1-μ Au foil is installed to stop NBI-ions

Ion losses were analyzed in TF Ripple Experiments

- The 1st foil signals of the FC system were used for analysis of NBI and low-energy ion losses in the following experiments
  - TF Ripple Plasma Commissioning
  - TF Ripple effect on NB fast ions
  - H-mode Ripple studies in low triangularity plasmas

- The 1st foil currents were integrated over 1-s interval

- Fusion products and MeV-ion losses were analyzed with Scintillator Probe in experiments on ripple effects in Advanced Tokamak scenarios

Analysis of four experiments was done

Commissioning - Restart TF

t=57-58s

	delta I imbalance(kA)	
69178	42	
69179	42	63.8/22.1
69180	0	42.5/43
69181	27	
69186	27	
69187	0	
69198	0	
69197	27	
69199	0	
69200	27	

H-mode - S1

t=60-62s

	Imax/Imin	delta	
69625	42/42		42/42.5
69631	0.73	0.5	
69632	0.73	0.5	
69633	0.64	0.7	
69635	0.52	1	55.3/29.4

NB fast ions-H/M

t= 57-58s, 59.5-60.5s, 62.5-63.5s

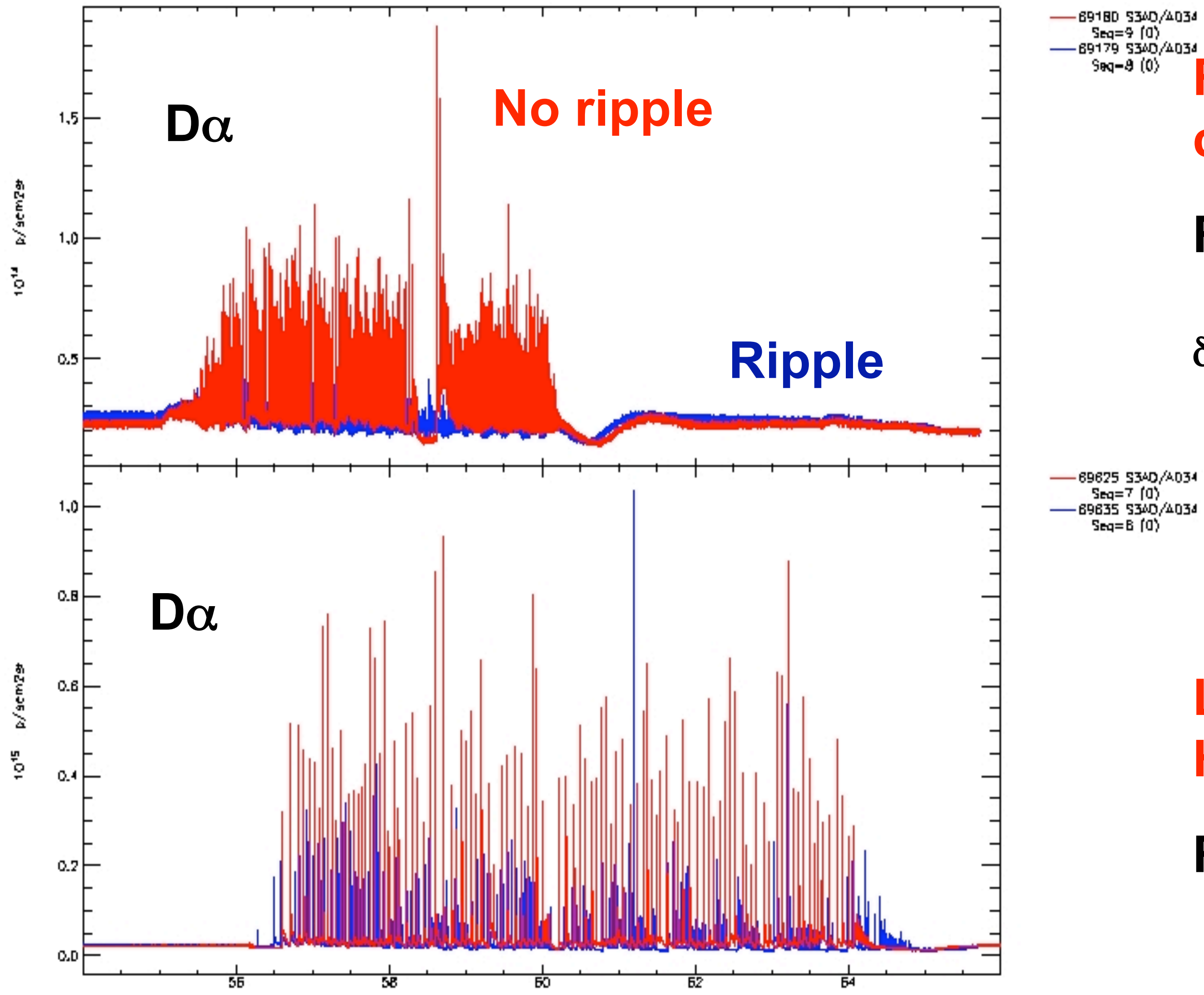
	Imax/Imin	delta	
69605	43/42	0.03	42.3/42.8
69606	47/38	0.4	47/38
69607	52/33	0.8	51.7/33.4
69608	56.6/29	1.1	
69610	61/24	1.5	61.4/24.2

AT scenarios - S2

t=45.025s

69685	1	0	no ripple	42.7/43.1
69687	0.5		ripple	56.7/43
69689	1	0	no ripple	42.7/43
69690	0.5		full ripple	56.7/43

ELM amplitude reduced by ripple



time (s)

Ripple plasma commissioning

Ripple δ=0,1.5%

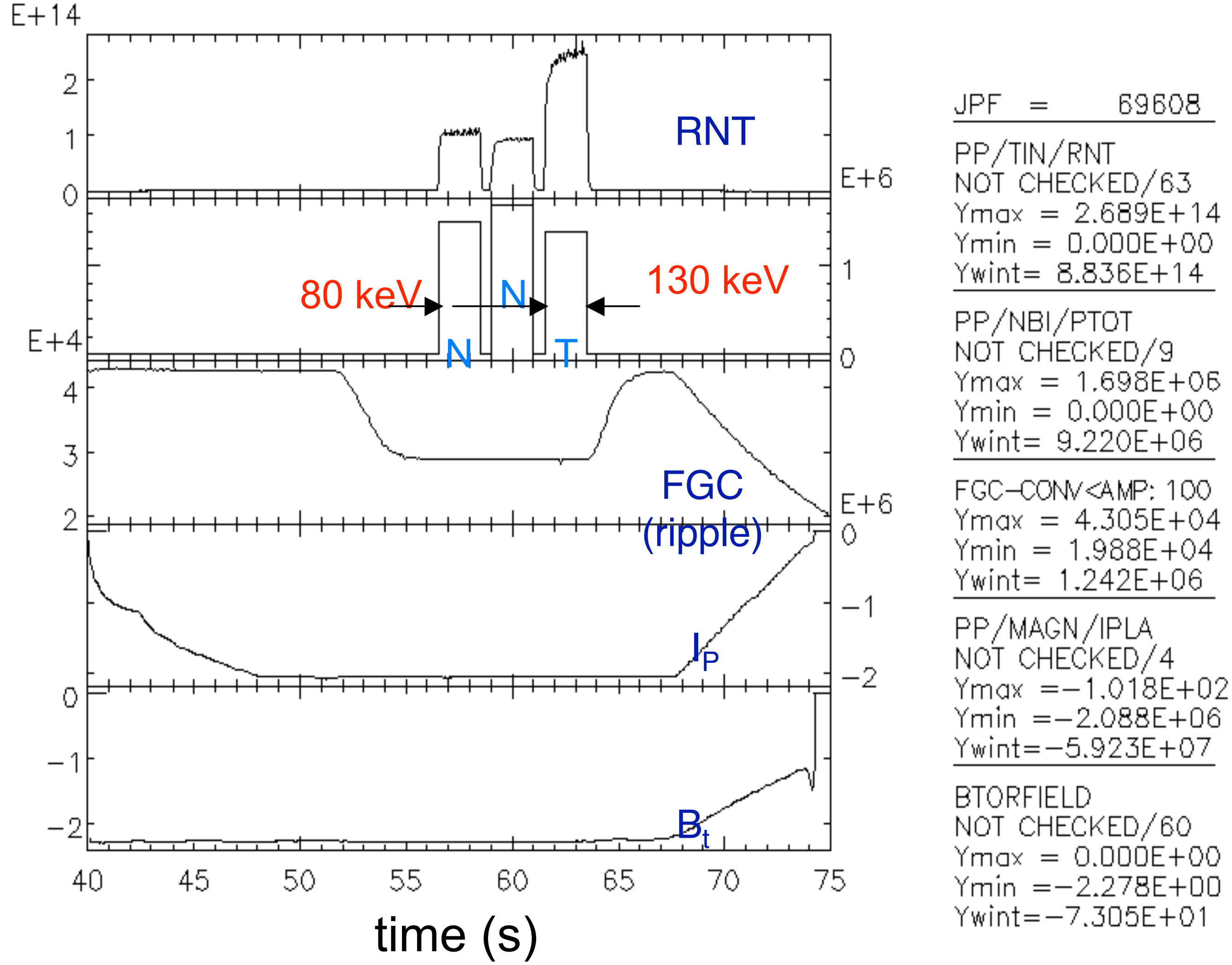
δ=(Bmax-Bmin)/(Bmax+Bmin)

Low triangularity H mode

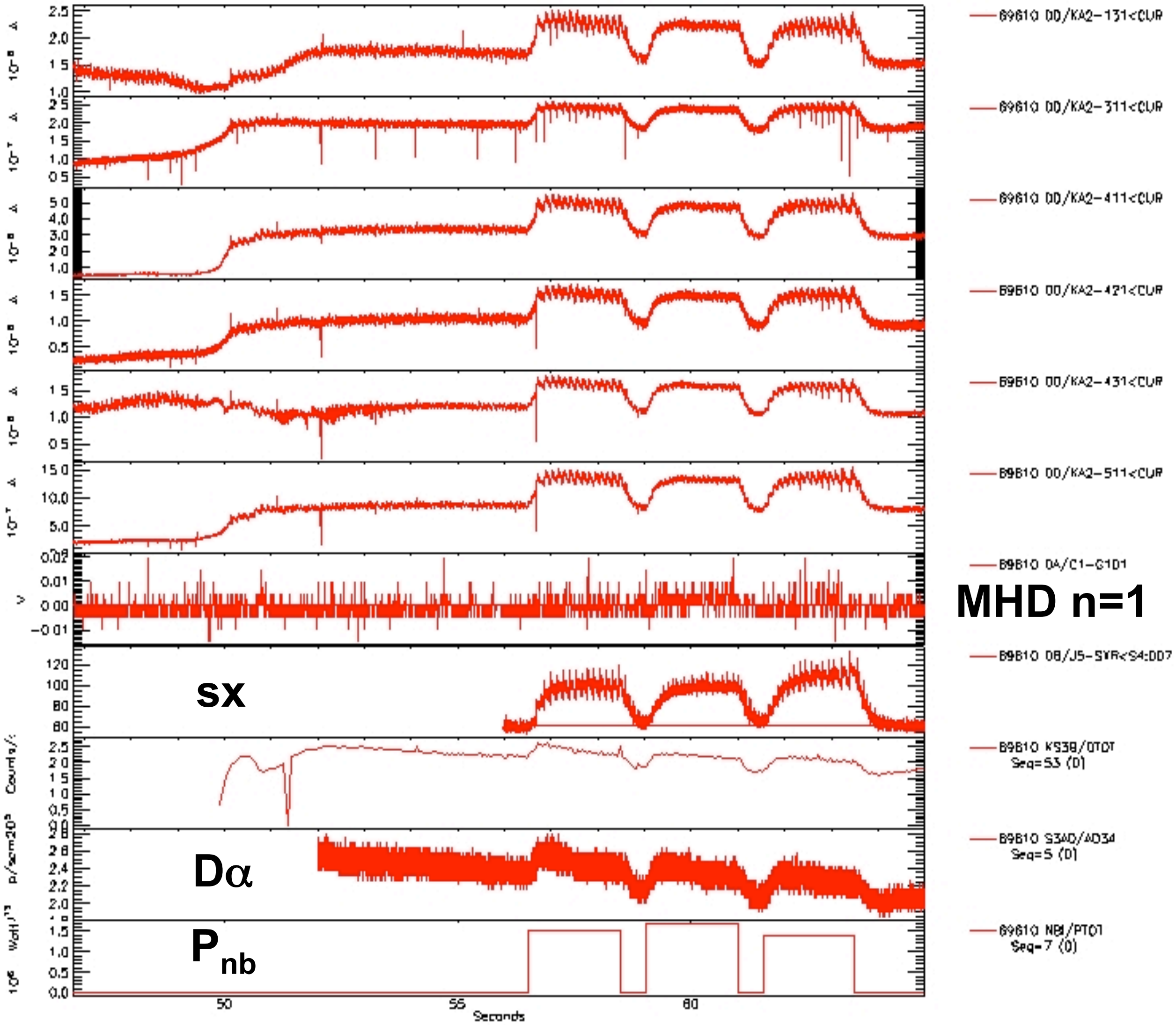
Ripple δ =0,1.0%

TF Ripple - NB fast ion studies (Ian Jenkins)

$B_t = 2.2$ T, $I_p = 2.1$ MA, $\delta = 0 - 1.5\%$



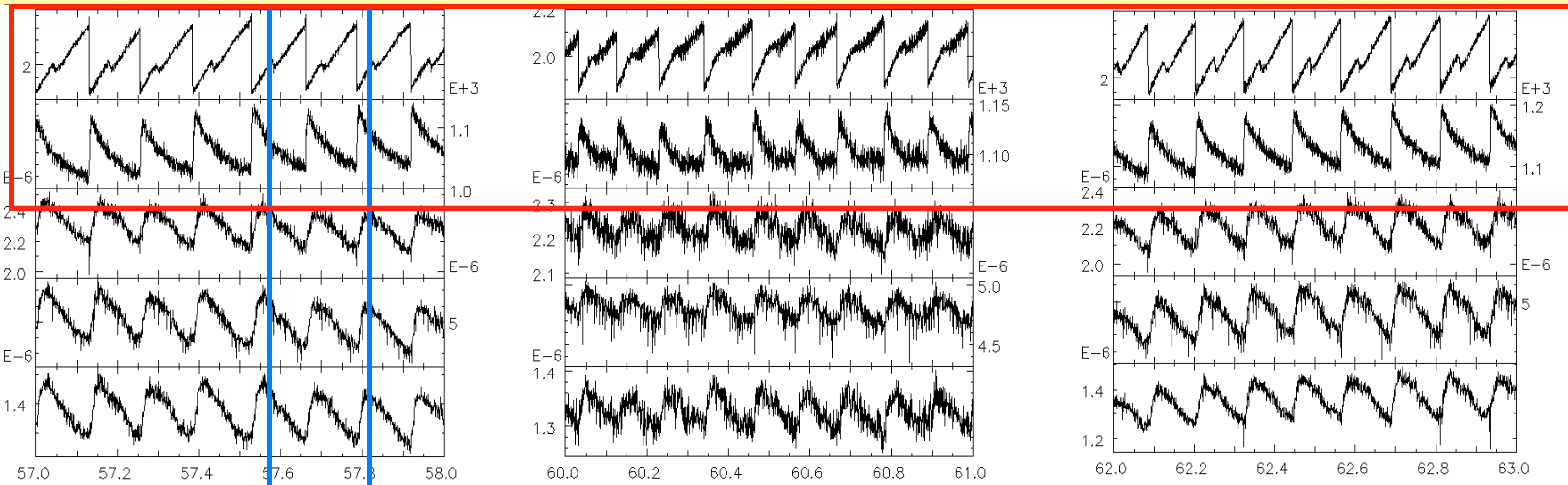
Front foils respond to NBI injection



- **NB-fast-ion loss experiments**
- **No ELMs**
- **Ripple δ = 1.5%**

TF Ripple - NB fast ion studies (2)

Delayed losses relative to sawtooth crashes



T_e :R=2.97 m

T_e : R=3.48 m

FC: Z = 4 cm

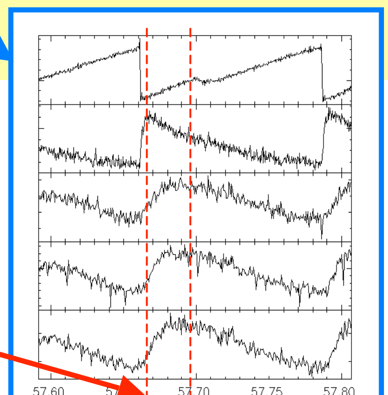
FC: Z = -50 cm

FC: Z = -68 cm

On-axis NBI
80-keV, normal bank
bank

Off-axis NBI
80-keV, normal bank

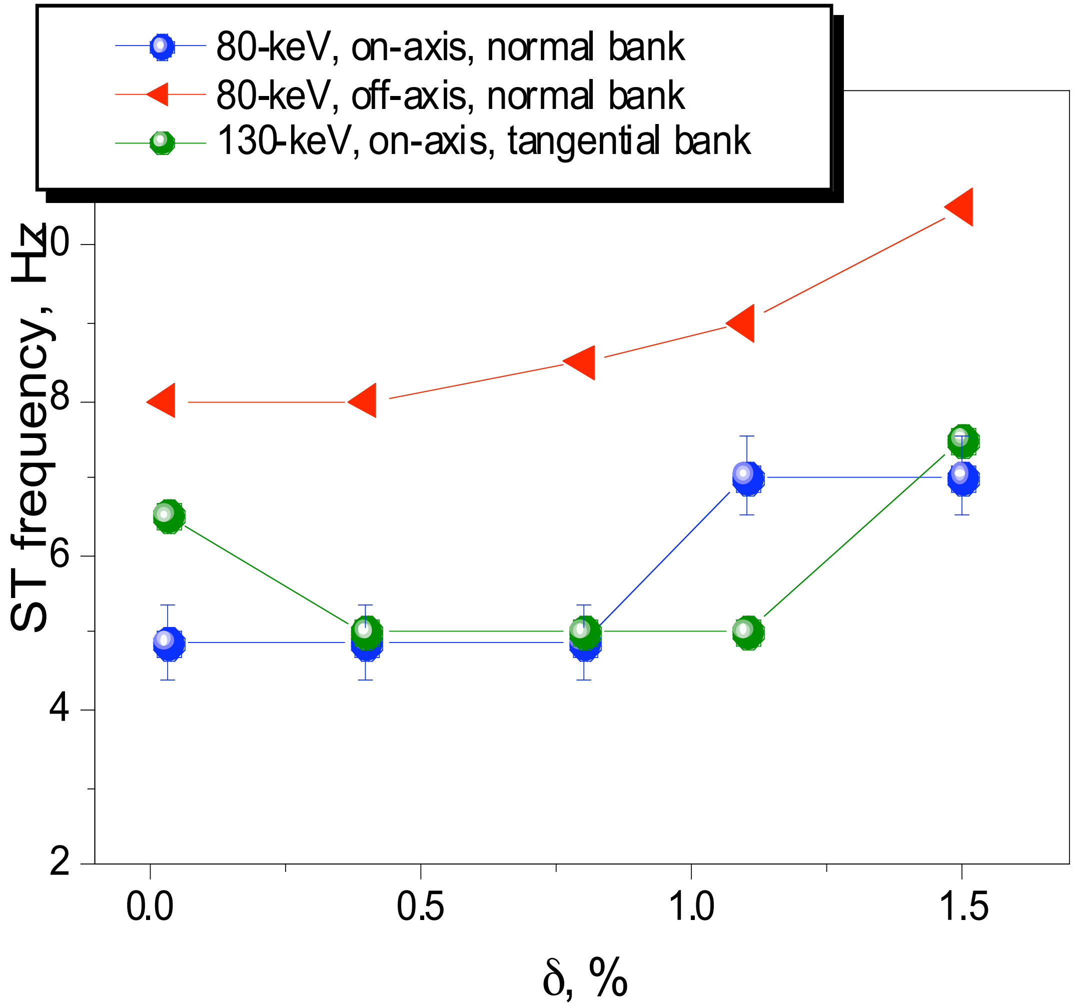
On-axis NBI
130-keV, tangential



The fast-ion signal peaks ≈20 ms after the sawtooth crash

TF Ripple - NB fast ion studies (3)

Sawtooth frequency varies with ripple value



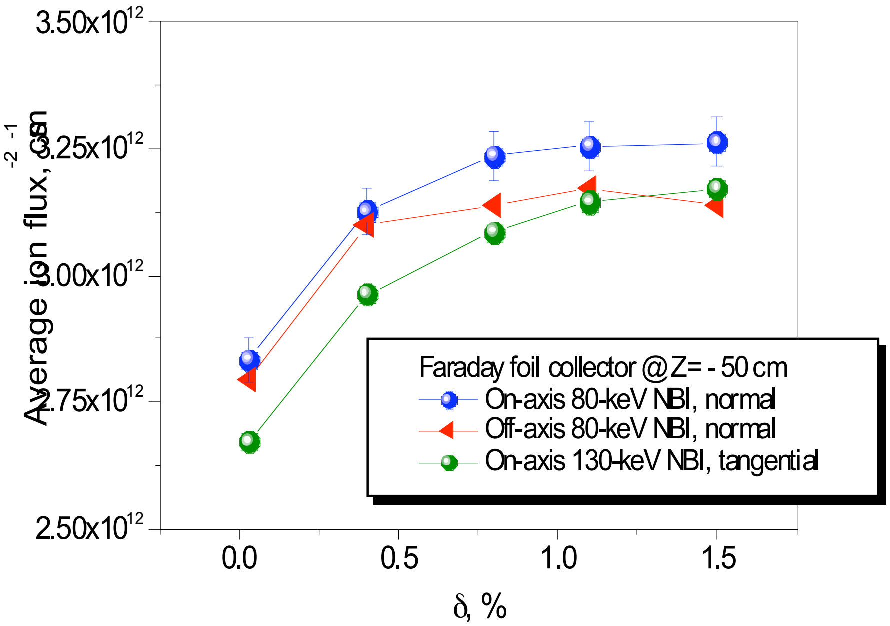
In the off-axis NBI the ST frequency monotonically increases with δ.

In the on-axis NBI (normal and tangential banks) that is not the case.

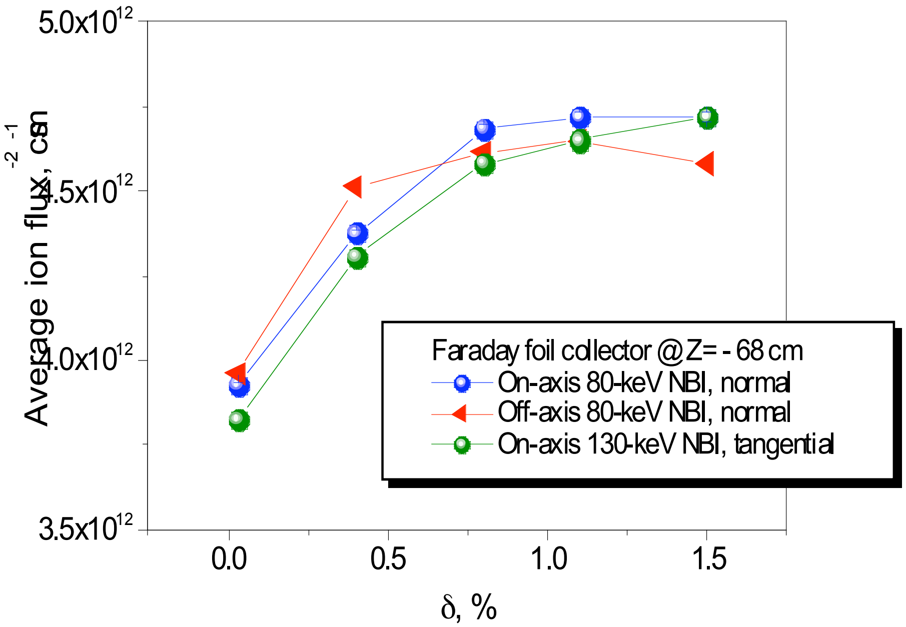
TF Ripple - NB fast ion studies (4)

NB ion losses depend on ripple value

27° below midplane



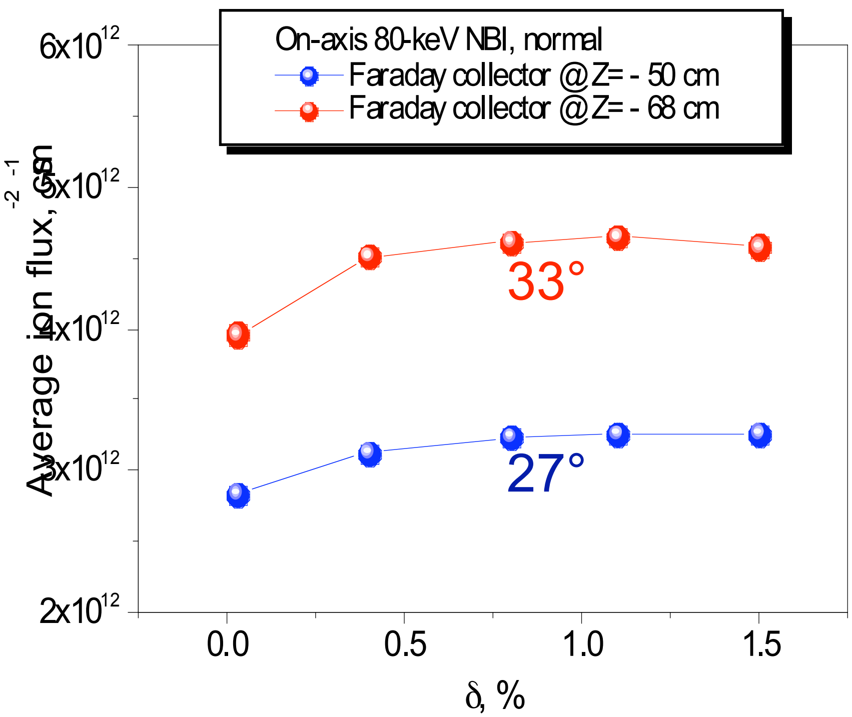
33° below midplane

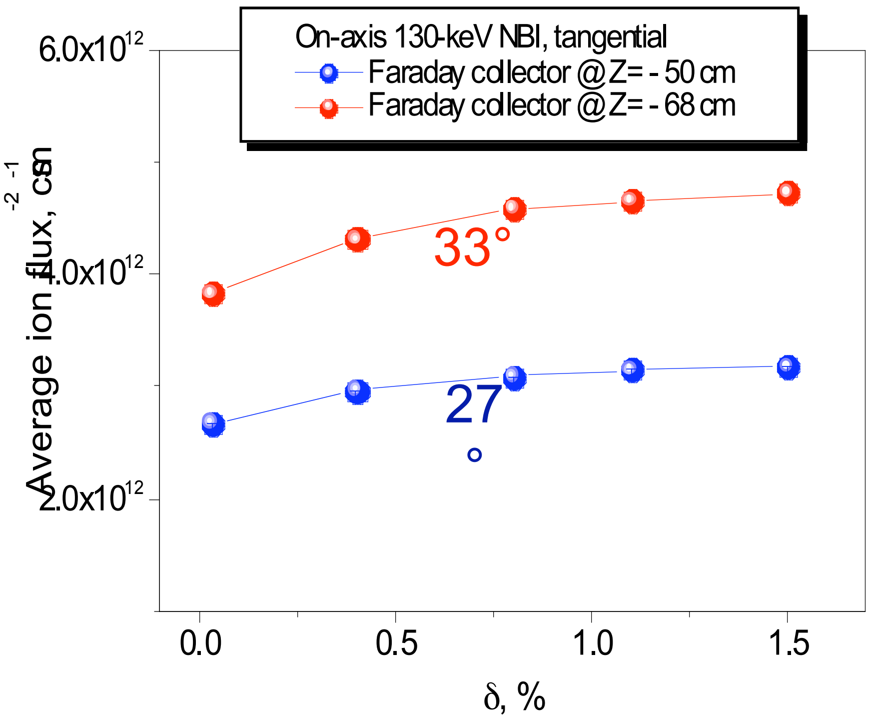


In the case of the normal bank 80-keV NBI the losses are a bit higher than for the tangential bank 130-keV NBI. In the off-axis case the losses are intermediate

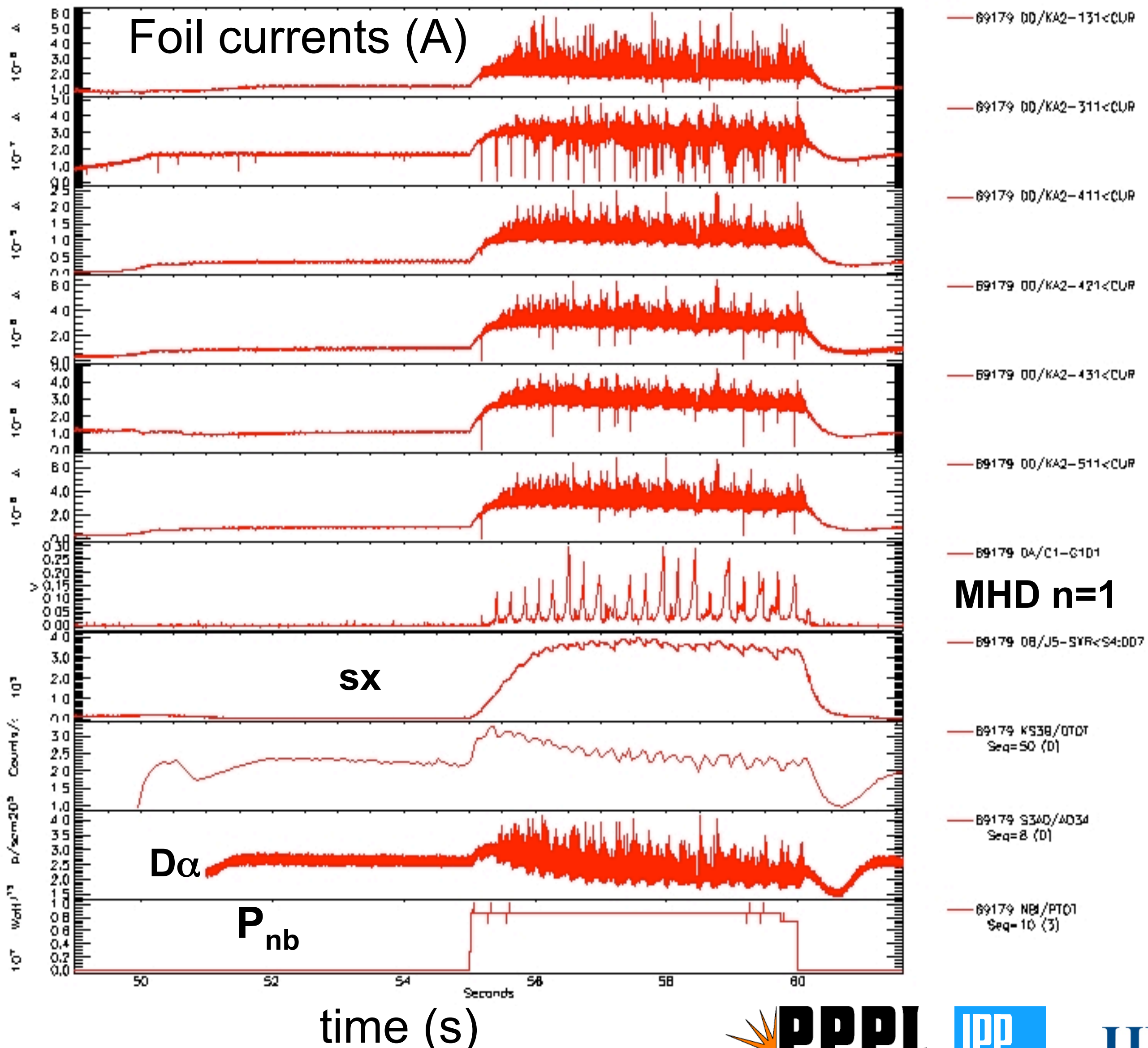
TF Ripple - NB fast ion studies (5)

Losses show a poloidal dependence





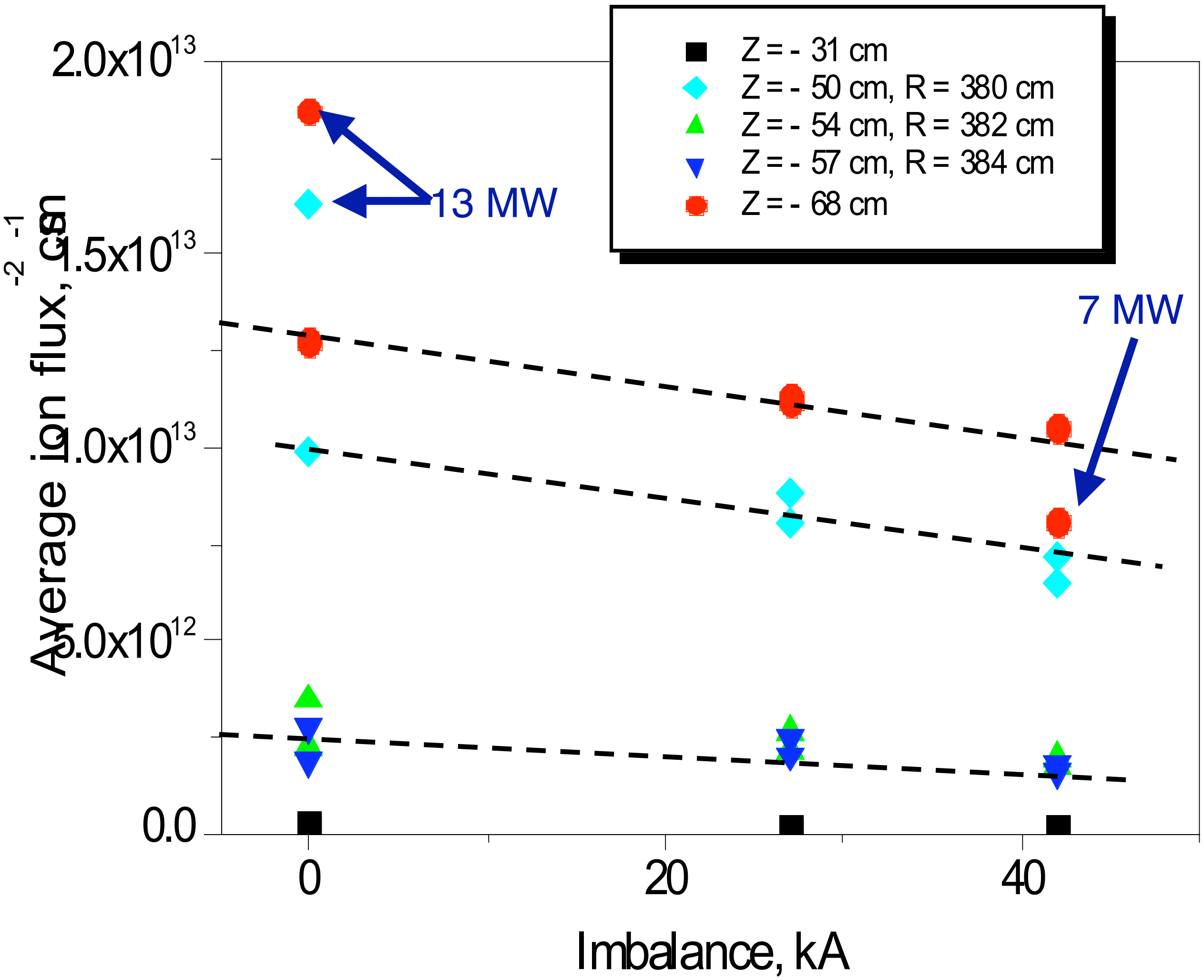
Marked front-foil signal and ELMS during NBI



- **Ripple plasma commissioning experiments**
- **ELMs**
- **Imax/Imin = 64/22 kA**
- **Ripple δ = 1.5%**

TF Ripple Plasma Commissioning (4)

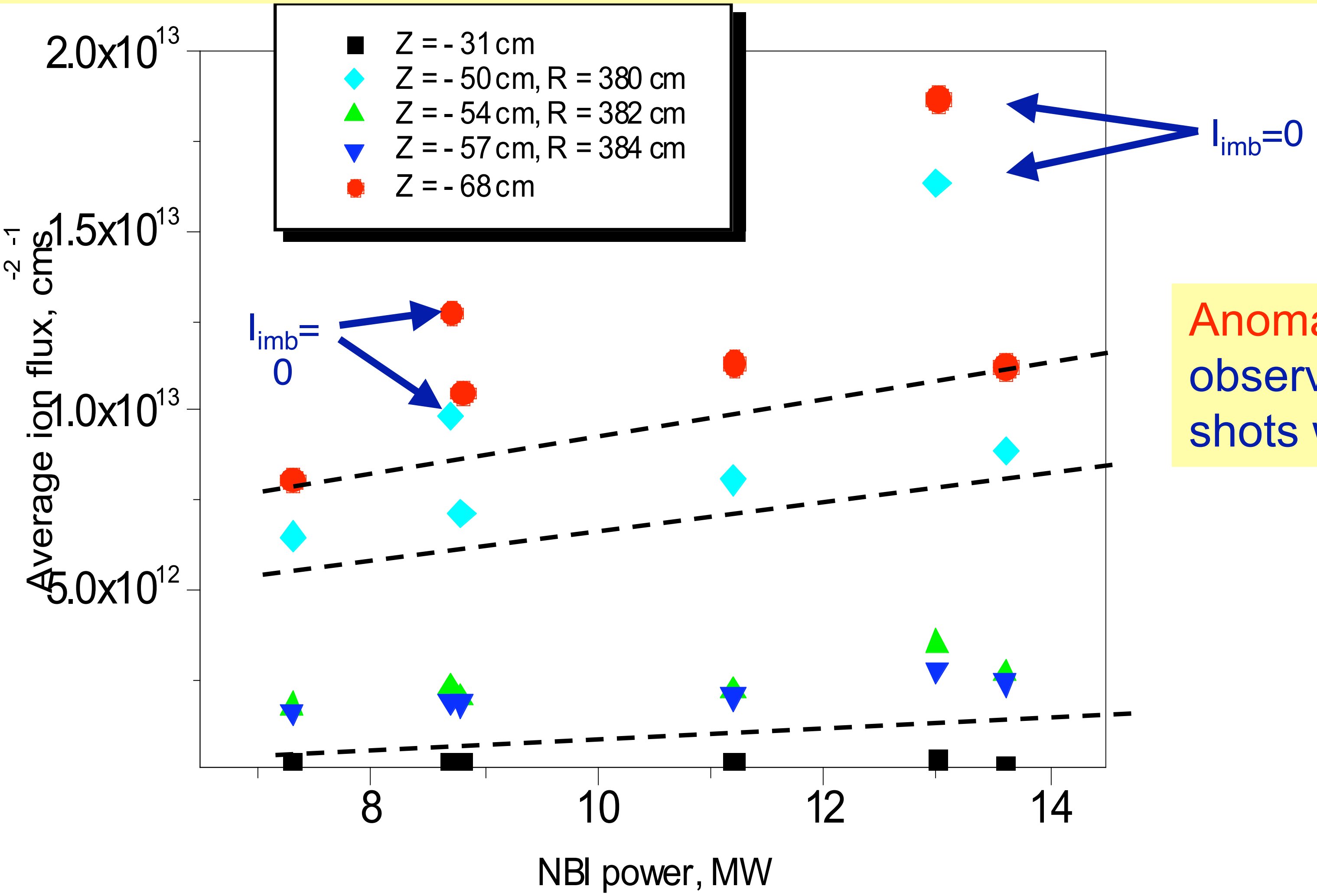
Losses monotonically decrease with ripple value



Anomalies were observed for the shots with max/min injected NBI power (ELMs vs. ripple-loss competition?)

TF Ripple Plasma Commissioning

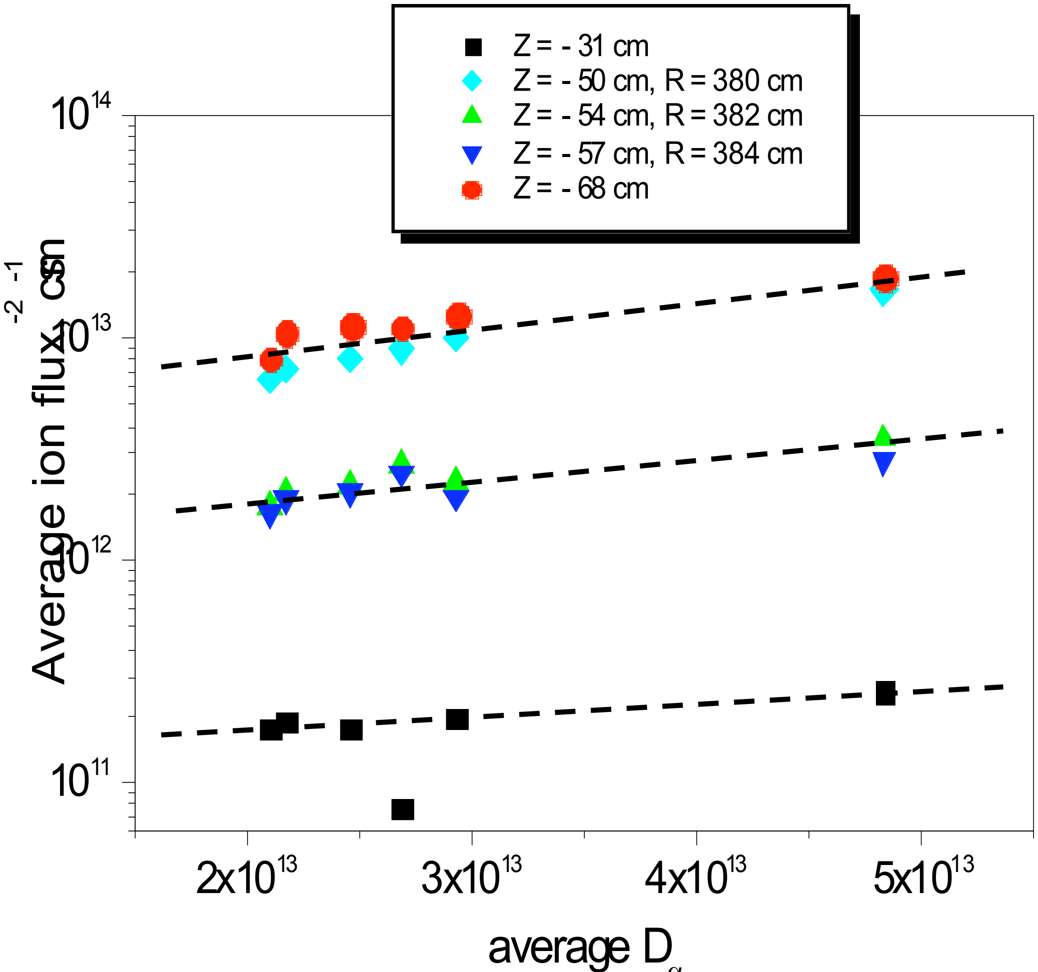
Losses monotonically increase with NBI power



Anomalies were observed for the shots with I_{imb}=0)

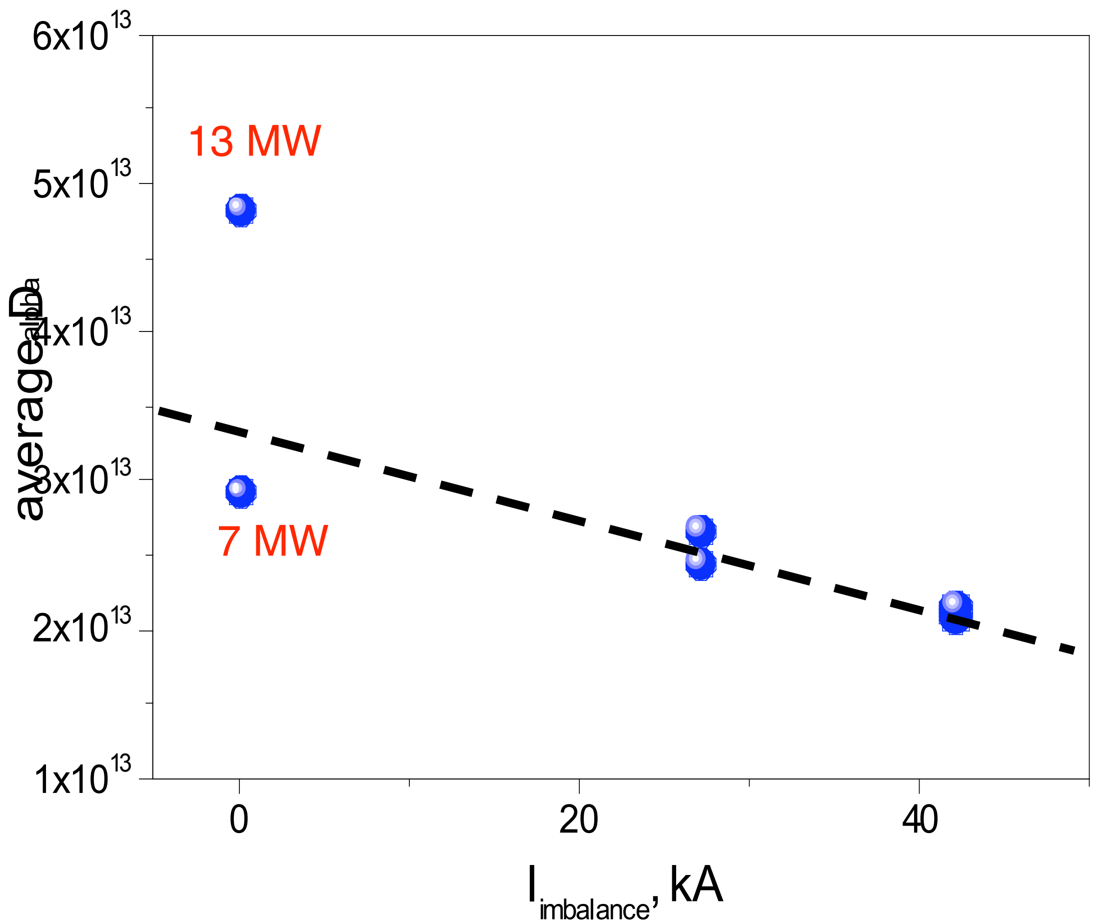
TF Ripple Plasma Commissioning (2)

Losses Increase with Dα



TF Ripple Plasma Commissioning (3)

Dα signal decreases with ripple amplitude



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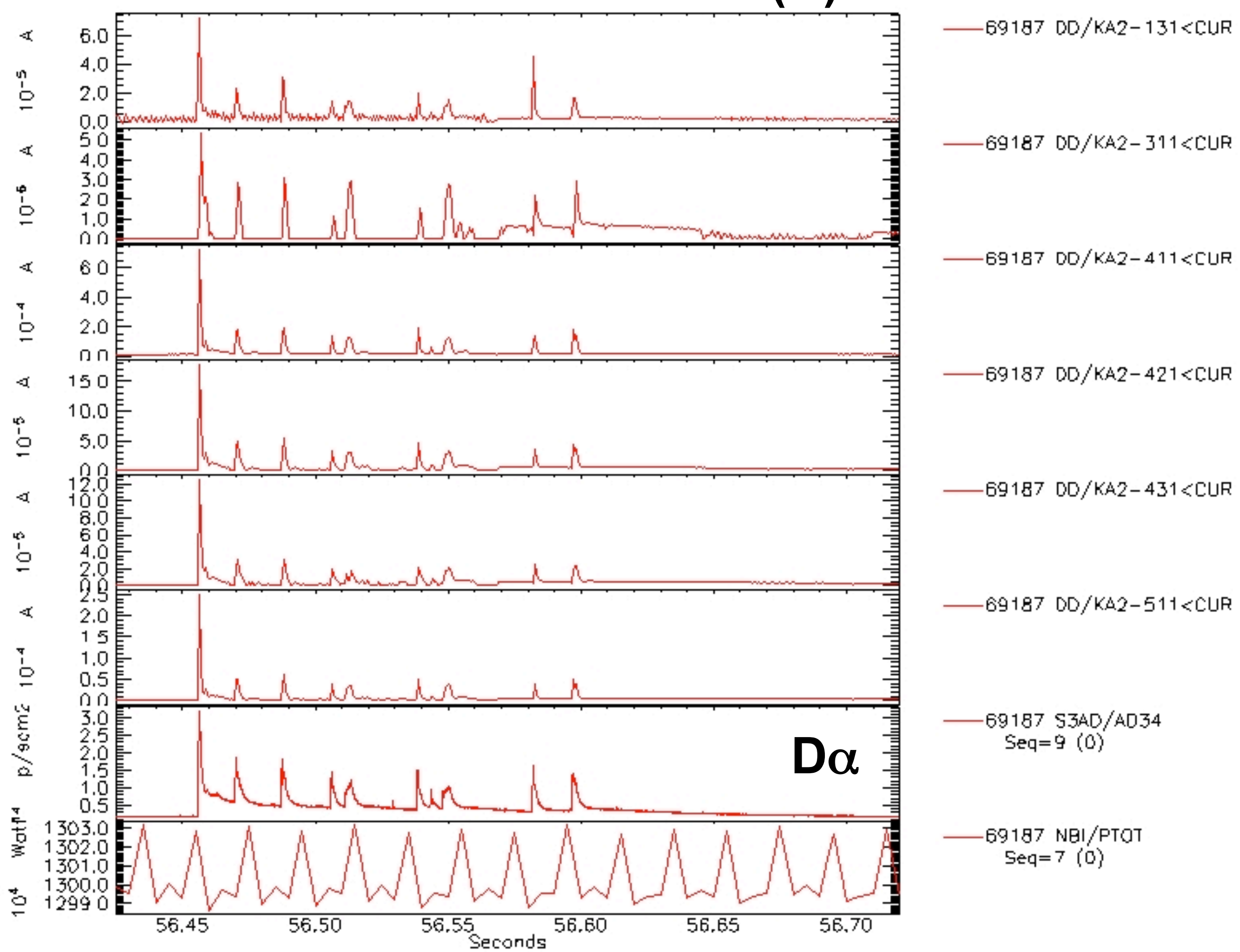
Ion losses higher during ELM event

Fast ion current (A)

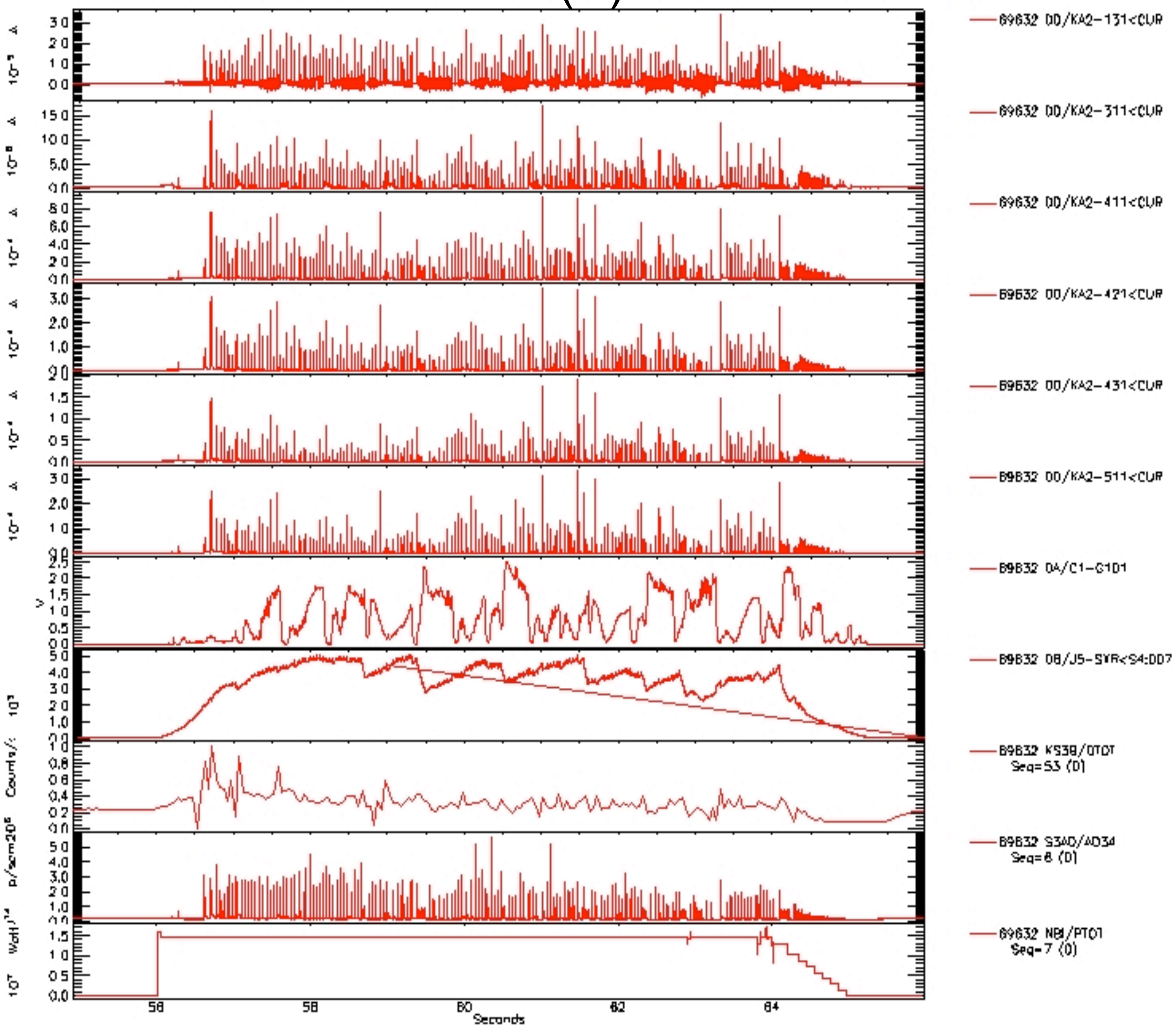


time (s)

- Analyze losses during vs between ELMs

Front foils respond to NBI and ELMs - H-mode

Foil currents (A)

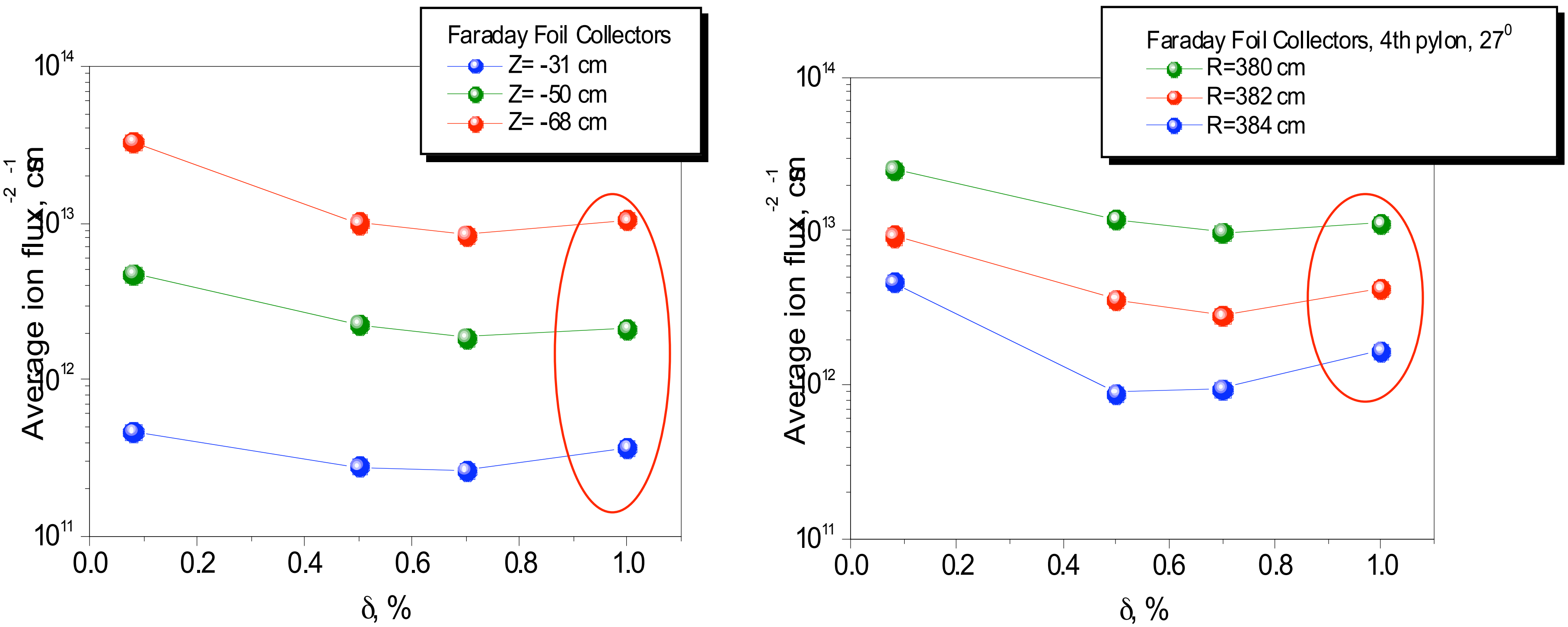


time (s)

- **Low triangularity H-mode studies**
- **ELMs**
- **Ripple δ=0.5%**

H-mode Ripple studies (low triangularity)

Poloidal and radial dependencies of losses

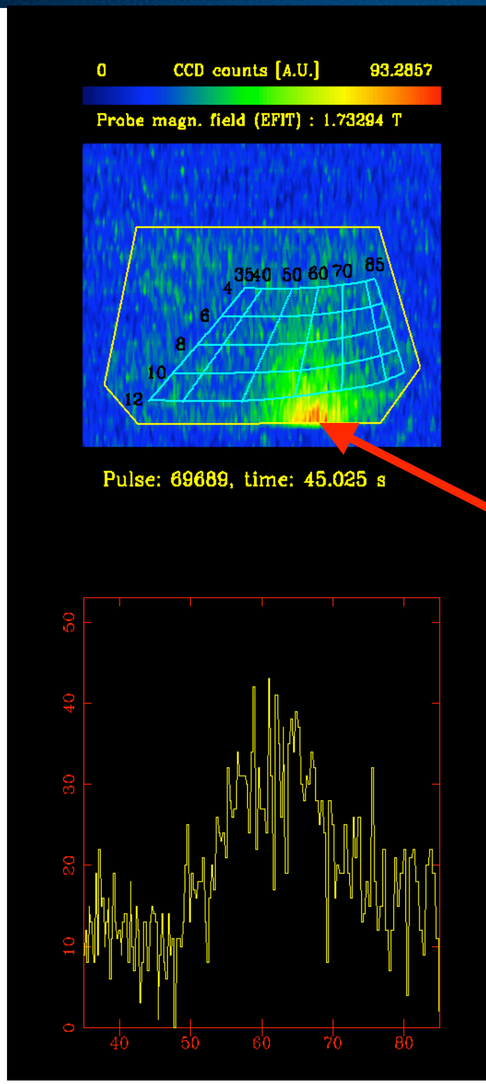


The losses decrease with ripple amplitude except for the measurements with largest ripple:

ELMs vs. Ripple loss(?)

TF Ripple in AT scenarios (4)

Scintillator Probe results



No ripple

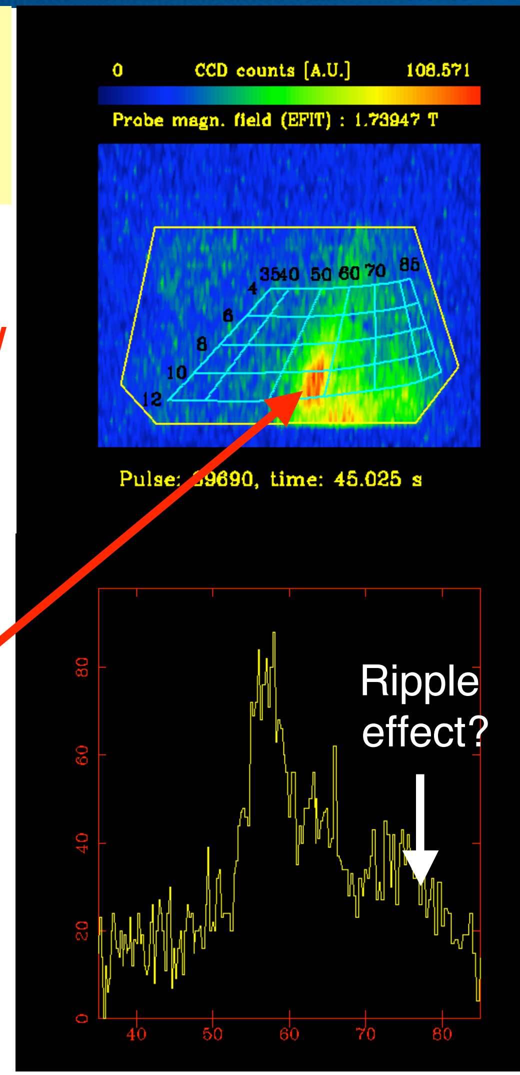
NBI on-axis

P_{NBI}= 8.4 MW & 13 MW

P_{ICRF}= 3.0 & 3.5 MW

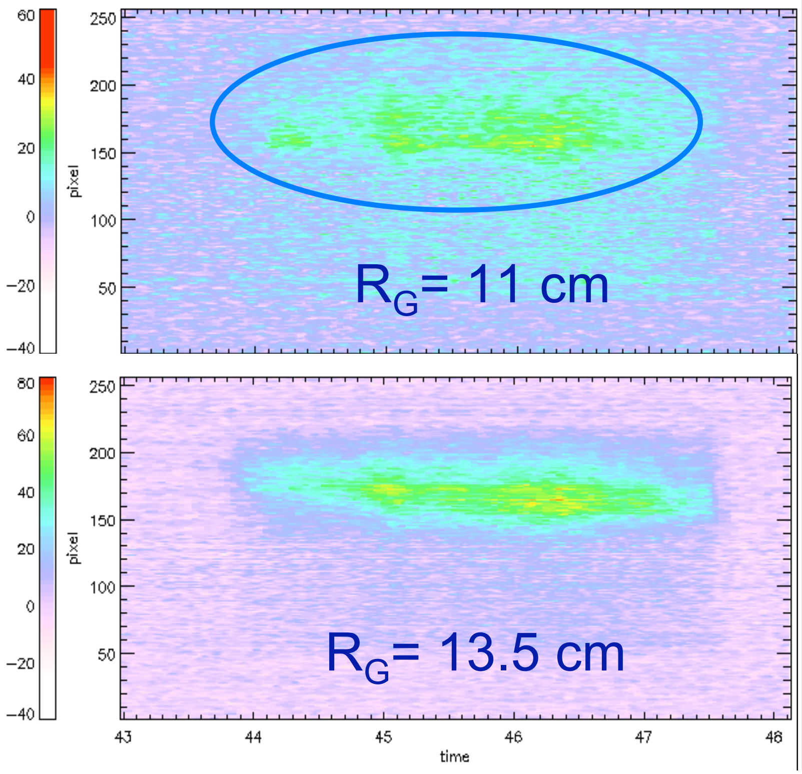
Fusion protons
$<E_p>$ ~ 2.8 MeV

Tail protons
$<E_p>$ ~ 1.6 MeV
and deuterons
$<E_d>$ ~ 0.8 MeV



Ripple: I_{min} / I_{max} = 0.5

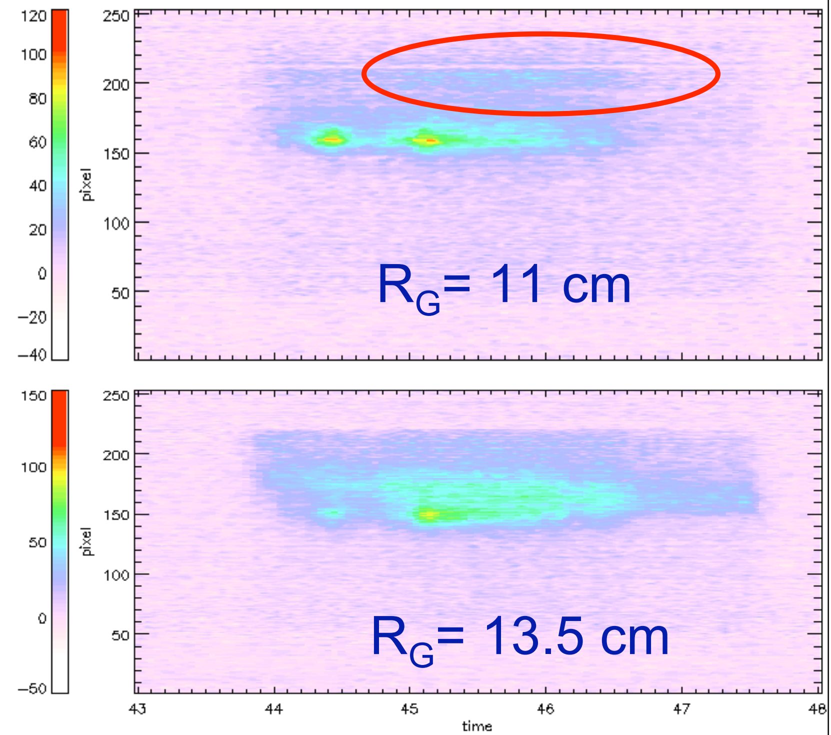
TF Ripple in AT scenarios (5)



Pulse No. 69689

No ripple

There are no losses with narrow pitch-angle distribution @ $\theta \approx 55^o$ (ICRF power is too low?)



Pulse No. 69688

Ripple: $I_{min} / I_{max} = 0.5$

A component with $\theta \approx 75^o$ was observed in the off-axis case as well

Summary (1)

- Faraday cup and scintillator probe were used for measurements of fast-ion losses of the keV and MeV-ranges in the JET ripple experiments
- A significant dependence of losses on Dα was found, suggesting that substantial ion losses may take place due to ELMs
- In the H-mode experiments
  - ion losses decrease with δ except at the largest ripple value, where the increase suggests a competition of loss mechanisms (ELMs vs. Ripple)
  - there are significant z- and R-dependencies of the losses
  - there is a monotonic increase of the losses with NBI power
  - losses with normal bank NBI are higher than in the tangential bank case

Summary (2)

- In the NB fast ion studies
  - the sawtooth frequency depends on the ripple value
  - delayed losses relative to the sawtooth crashes
  - there is an increase of losses with δ !
  - there is no strong link with the NB injection type
- In the AT scenarios
  - MeV-ion losses (fusion products and ICRF accelerated ions) were observed
  - there is evidence of MeV-ion redistribution due to the ripple

Future work

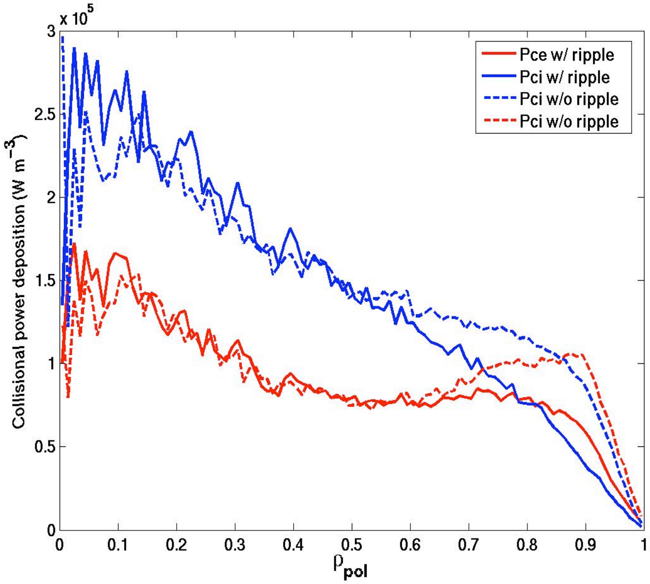
- Look at broader range of ion-loss data
  - MHD
  - TAEs
  - ELMs
- Compare ripple-experiment measurements with simulations from TRANSP/ORBIT, ASCOT - R. Budny, R. White, T. Johnson, A. Salmi, others
- Differentiate ELM vs ripple-loss contributions
- Correlate Faraday-Cup data with Scintillator-Probe data
- …

- Backup slides

#69649 w/ and w/o ripple - A. Salmi

Without ripple:

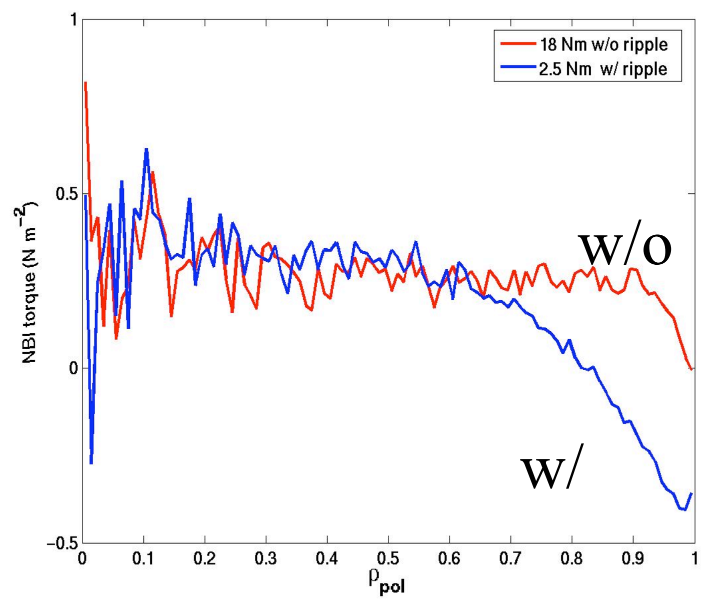
Initial torque of 18.4 Nm goes:
to *wall* 0.2 Nm
to plasma through *collisions* 4.8 Nm
to plasma through *JxB force* 13.6 Nm
to *coils* 0 Nm



1% of ripple induces ~20% of energy losses of NBI mostly outside rho_{pol} 0.7

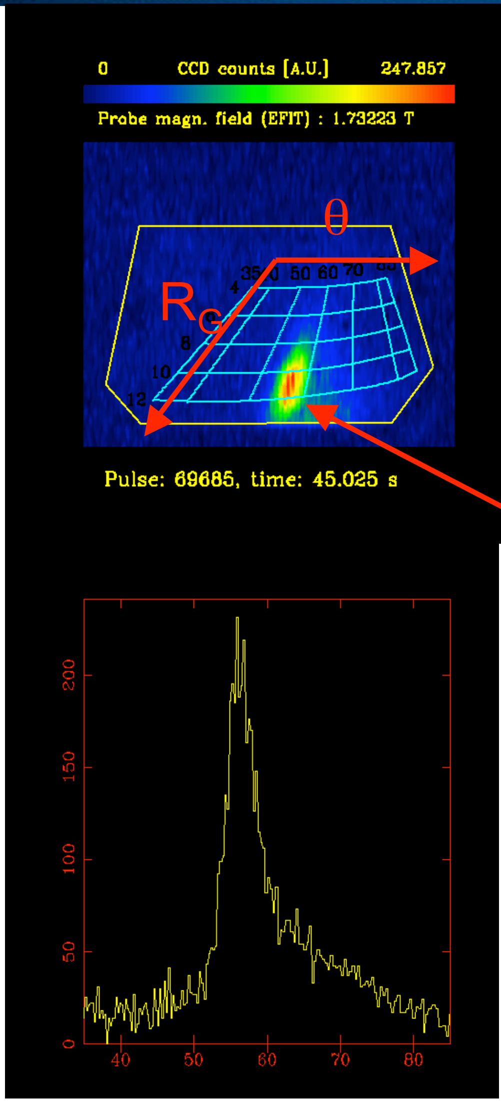
With ripple:

Initial torque of 18.4 Nm goes:
to *wall* 3.1 Nm
to plasma through *collisions* 4.6 Nm
to plasma through *JxB force* -2.1 Nm
to *coils* 12.8 Nm



1% of ripple reduces ~85% of the total torque from NBI

TF Ripple in AT scenarios (E. Joffrin)



Scintillator Probe results

NBI off-axis

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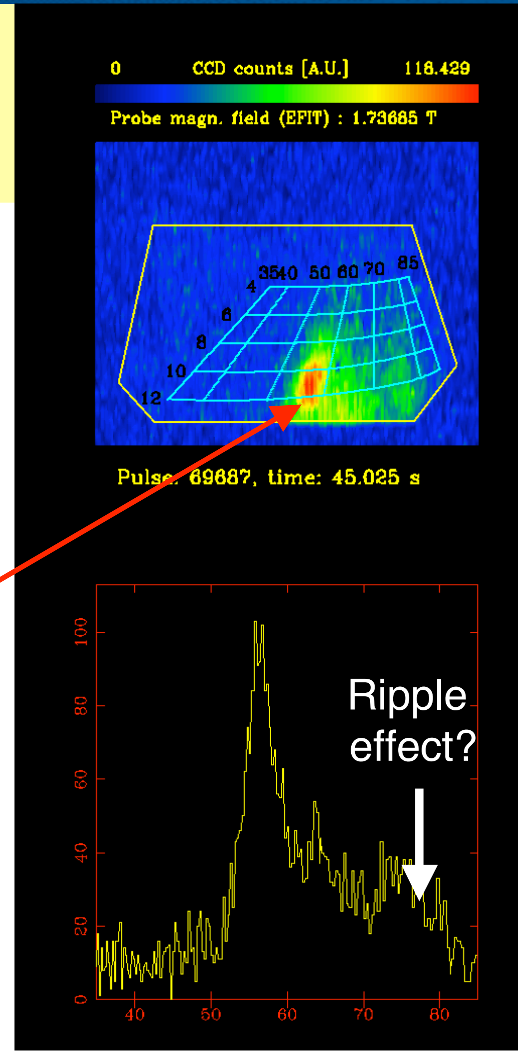
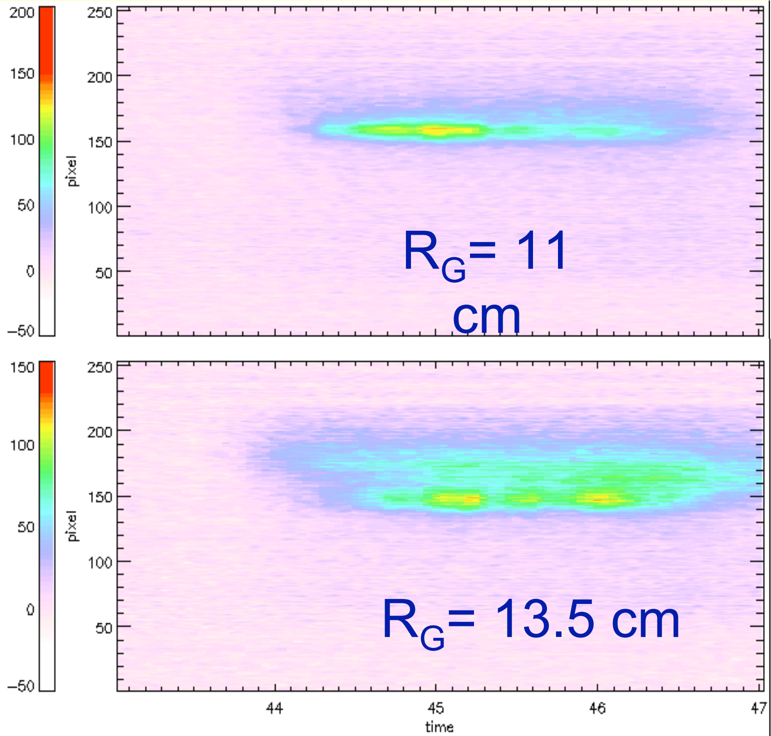


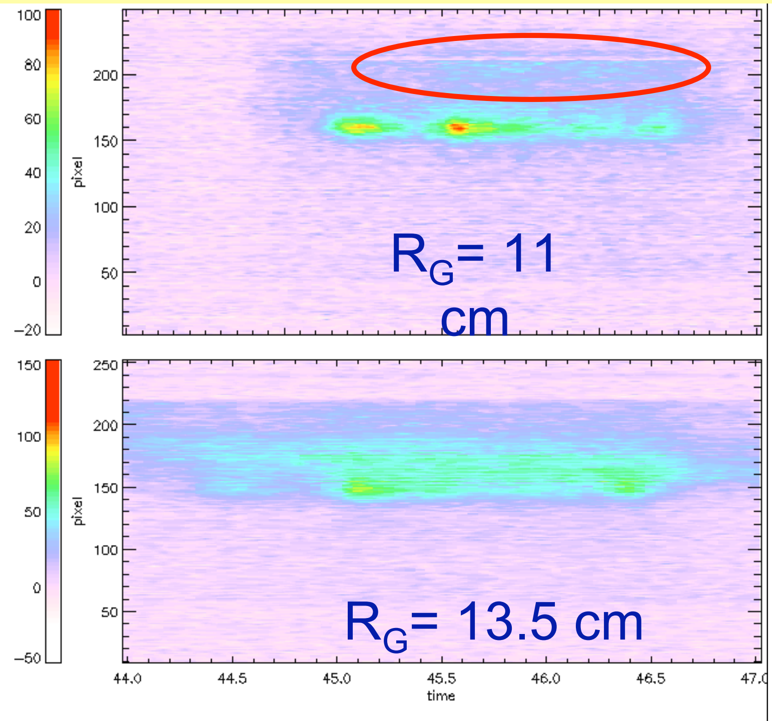
Ripple: I_{min} / I_{max} = 0.5

No ripple

TF Ripple in AT scenarios (3)

MeV-ion redistribution due to the ripple





Pulse No. 69685

No ripple

There are losses with narrow pitch-angle distribution @ $\theta \approx 55^o$ (deuterons?)

Pulse No. 69687

Ripple: $I_{min} / I_{max} = 0.5$

Pitch-angle distribution is broader, and a component with q » 75^o was observed