Consultancy Meeting on
The Comparison of Modelling Codes Used in Simulations of Neutral Beam Penetration and Photoemission for Fusion Energy Reactors
18 (Wed) – 21 (Fri) May 2022, IAEA Headquarters, Vienna, Austria

Progress on the KSTAR beam emission spectra research

Under the CRP on

Experimental validation of atomic data for motional Stark effect diagnostics

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[4]Seoul National University, Seoul, Kore
[5]Commonwealth Fusion Systems, Cambridge, MA, USA

Scope of the project

Progress on the KSTAR beam emission spectra research

Under the CRP on

Experimental validation of atomic data for motional Stark effect diagnostics

- **High-precision measurements of beam-emission spectra from KSTAR discharges**
- **Development of a spectra analysis tool with a modulated interface for atomic data**

Outline of the CRP activities

High-resolution spectrum measurements ($\Delta\lambda \leq 0.05$ nm)

Mirror reflections

Faraday rotation

Polarized background

Multi-ion-source injection

Spectral analysis

Atomic models (NOMAD, ADAS etc)

Existing (conventional) MSE

- Input for model validation

- Comparison with spectral analyses

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Main ion CX (Prelim.)

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Year 3 and beyond (2019 -)

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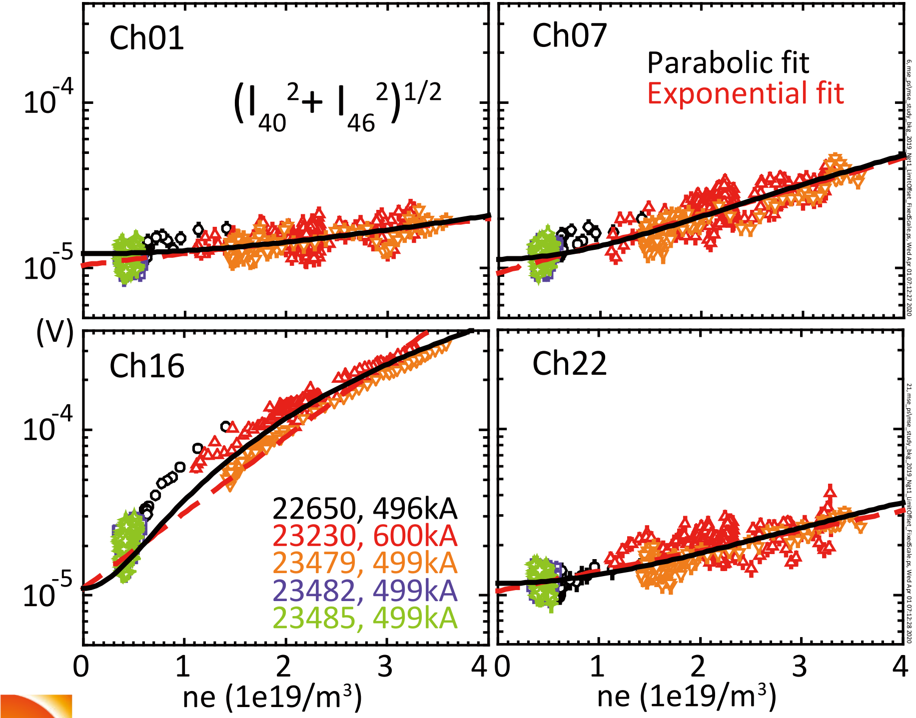
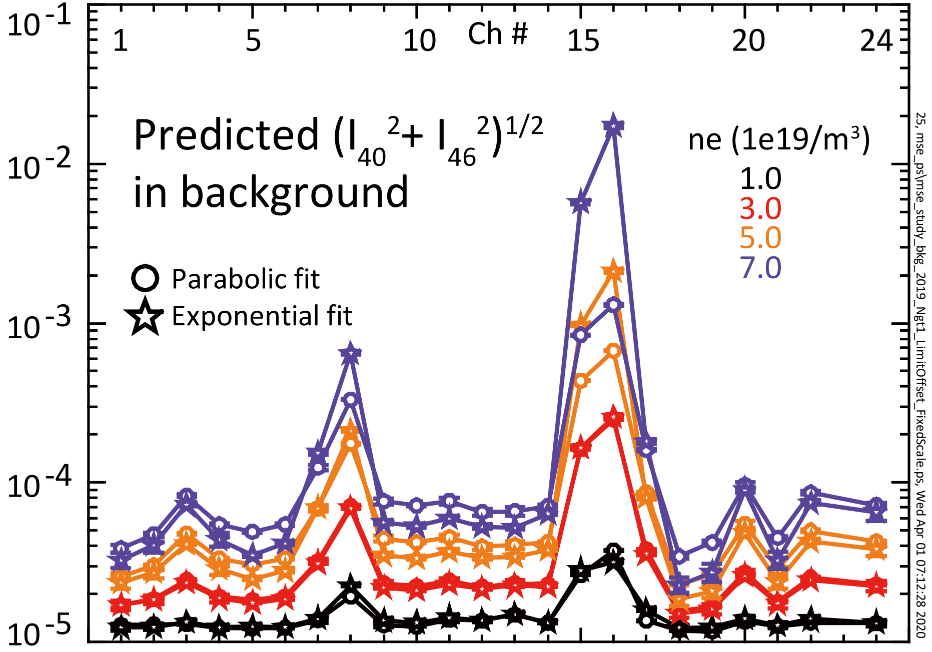
Main ion CX

Year 2 (2018)

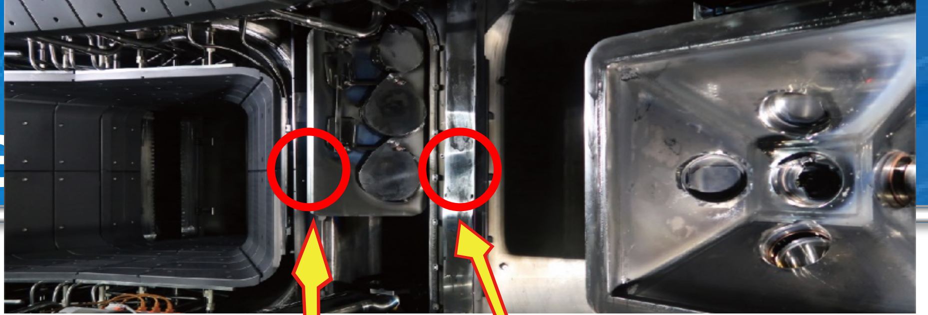
Year 3 and beyond (2019 -)

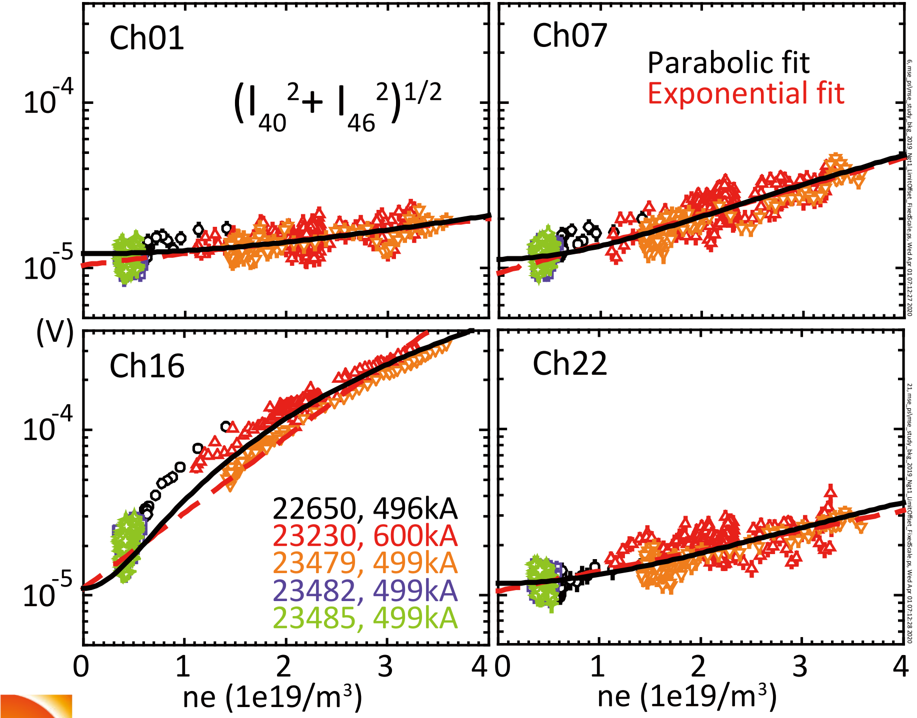
Origins and characteristics of polarized background light were identified

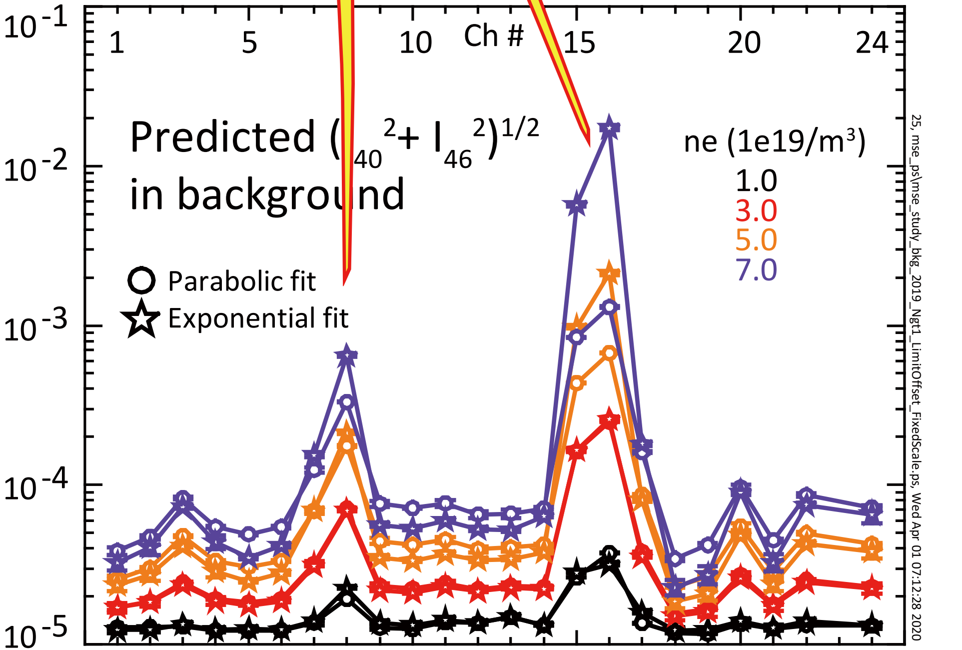




Origins and characteri
background light were



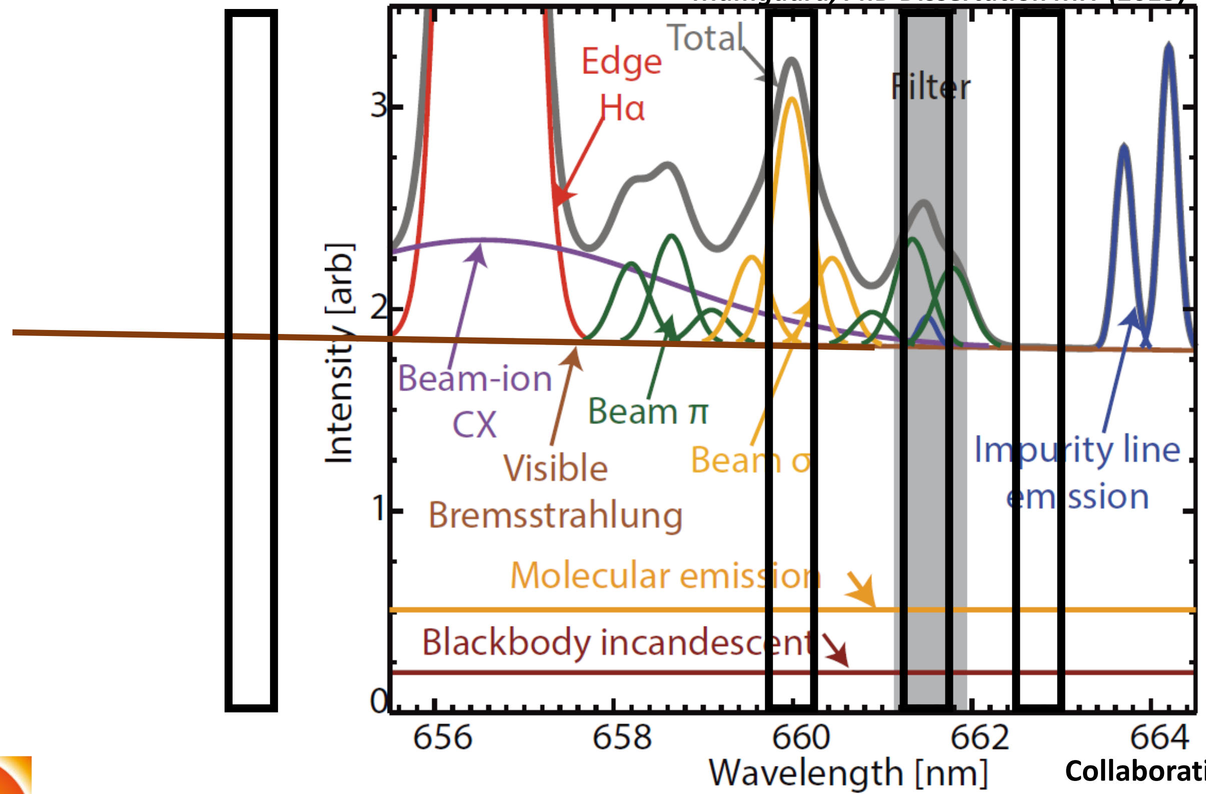


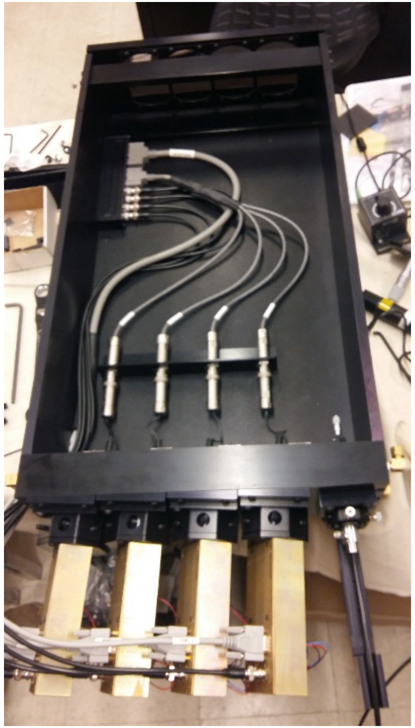


Ko et al. Rev. Sci. Instrum. 92 (2021) 033513

KSTAR now has an addition MSE system to simultaneously measure background

Mumgaard, PhD Dissertation MIT (2015)





Collaboration under MIT/PPPL US DoE project

Cross-check for both systems gives reasonable agreements

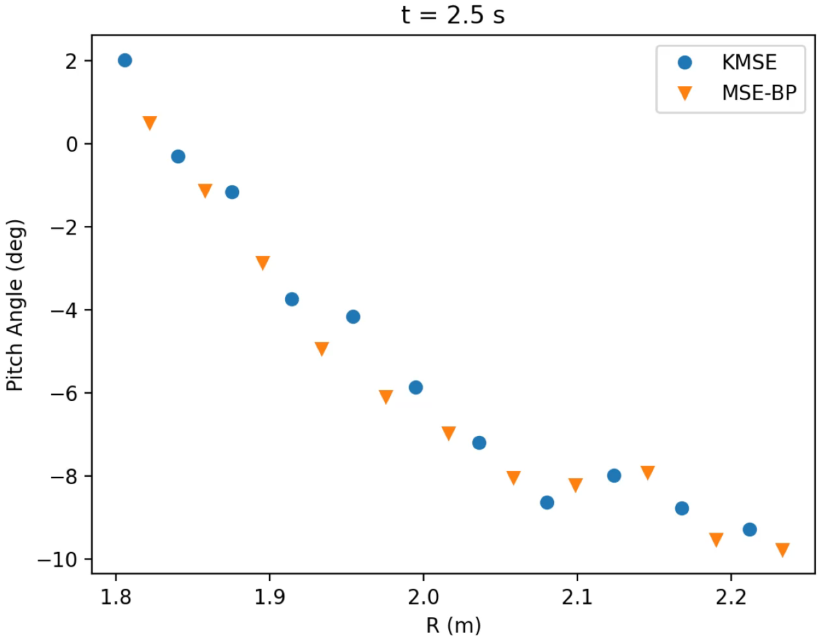
KSTAR MSE
Single-detector type
(Conventional)

KOREA INSTITUTE OF FUSION ENERGY
UST

MSE-Background polychrometer (BP)

MIT PSFC
PPPL
COMMONWEALTH FUSION SYSTEMS

- Odd channel fibers to K-MSE
- Even channel fibers to MSE-BP



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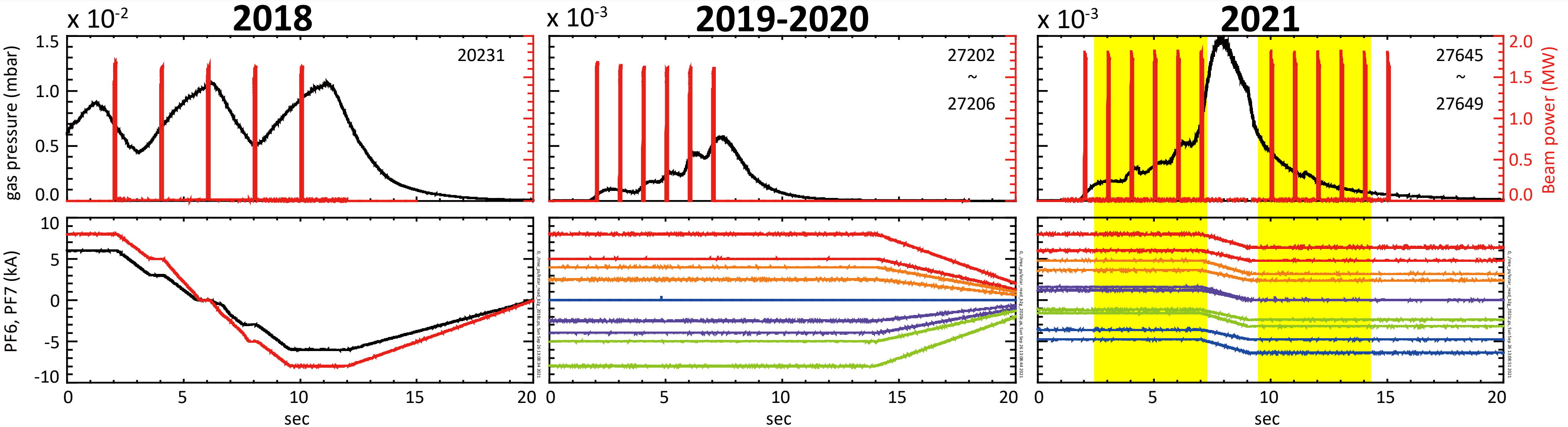
Beam-into-gas calibration that gets around the secondary neutral effects

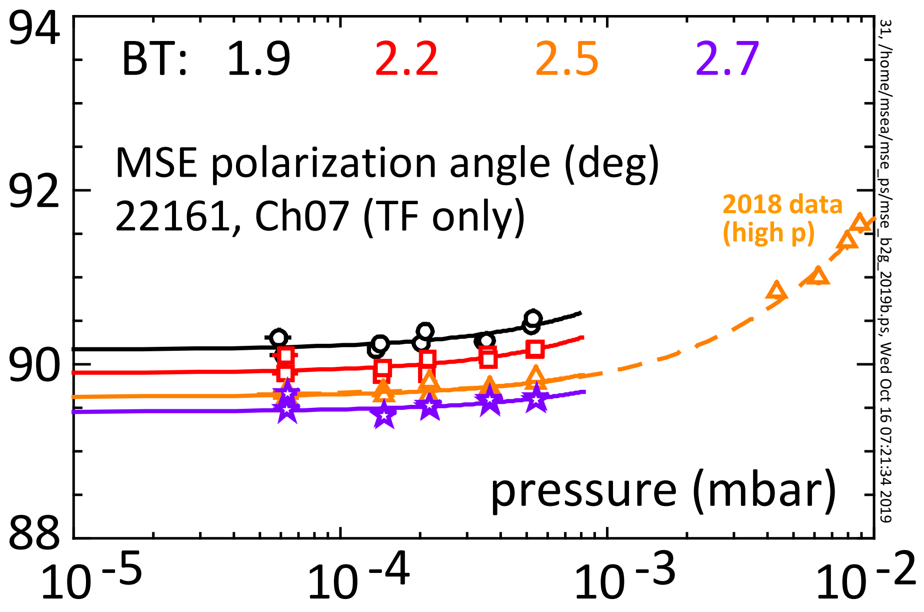


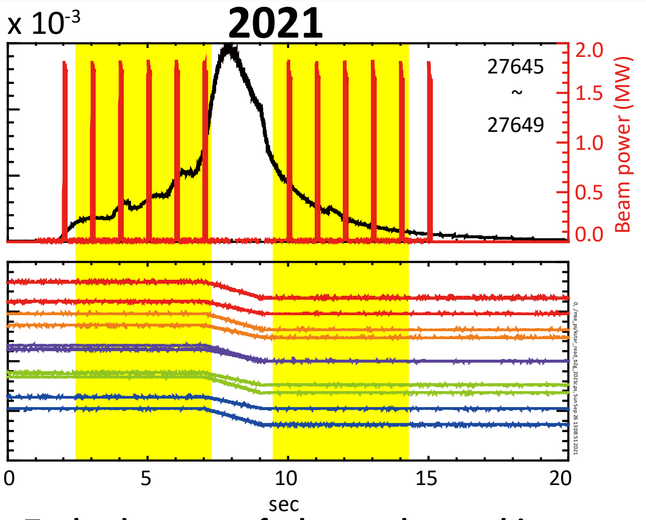
- Intra-shot pitch angle scan (vacuum field scan) without careful pressure control !).
- Suffered from spurious drift in the measured angle due to the secondary neutral emissions [Yuh et al. Rev. Sci. Instrum. 79 (2008) 10F523]
- This limit was addressed in the 2nd IAEA-CRP meeting.

- Intra-shot pressure scan at constant pitch angle profile (vacuum field profile).
- Did this at only a single vacuum-field profile in 2019 → not enough for calibration.
- Multiple vacuum-field profiles in 2020 → too much machine time (5 hrs per MSE).

- Took advantage of a long-pulse machine;
- Extended the pressure scan, utilizing its 'falling' phase (and a new vacuum field profile is formed meanwhile).
- Can cover two sets of vacuum field profiles within a shot → run time reduced by a factor of two.

Pressure dependence (2ndary neutrals) is clearly demonstrated.





- **Took advantage of a long-pulse machine;**
- **Extended the pressure scan, utilizing its 'falling' phase (and a new vacuum field profile is formed meanwhile).**
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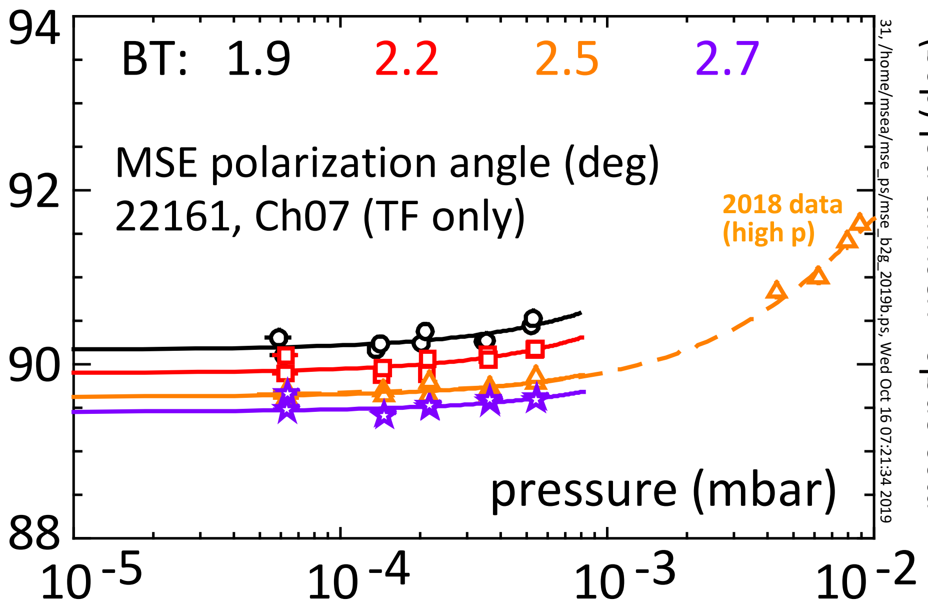
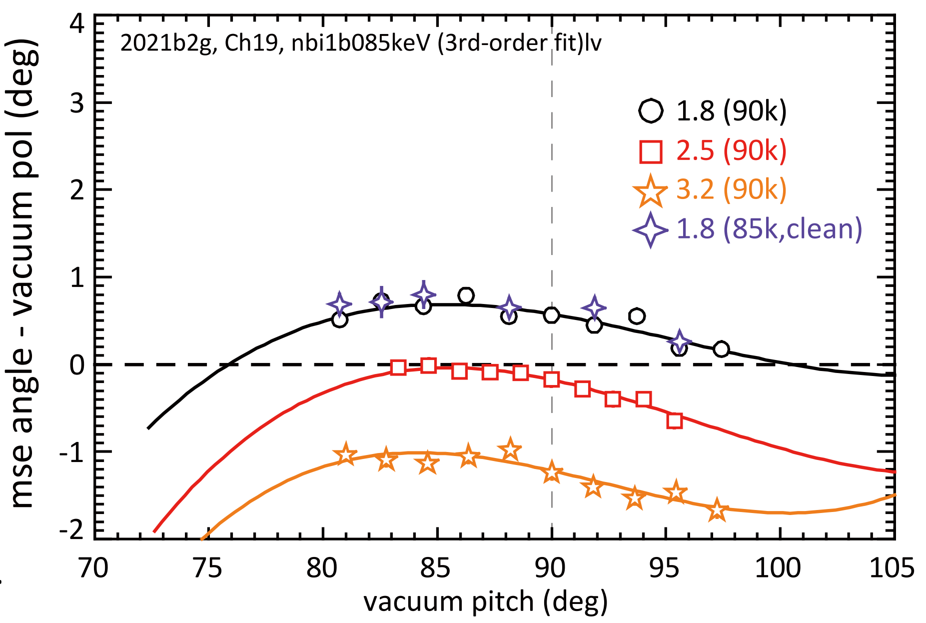
Faraday effect is dominant. Filter system works fine.





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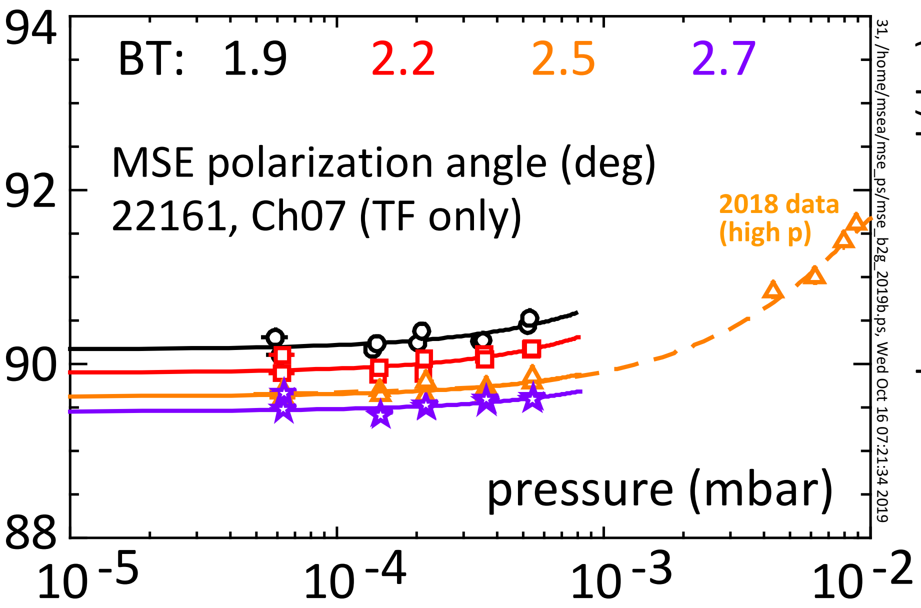
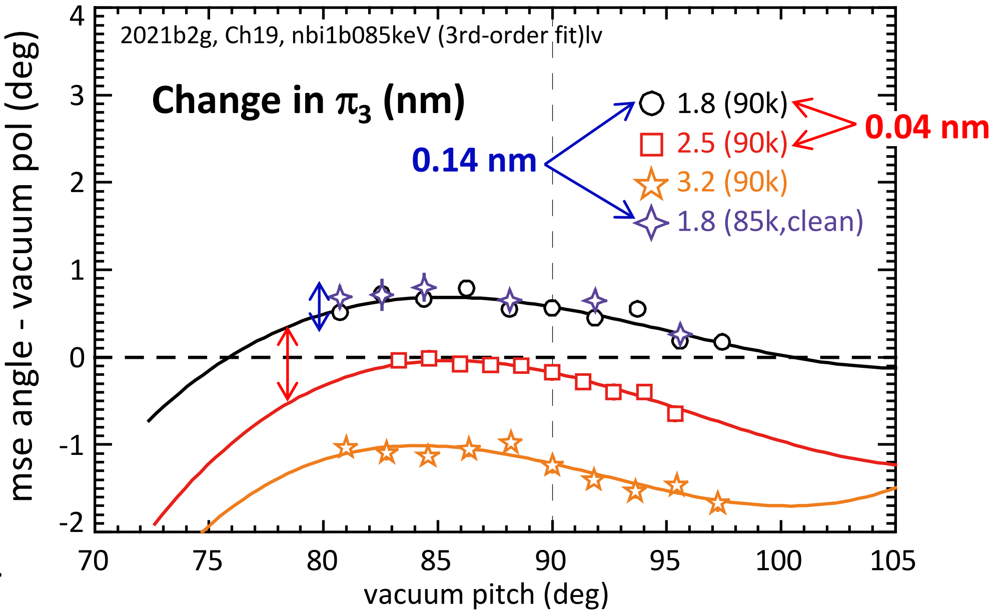
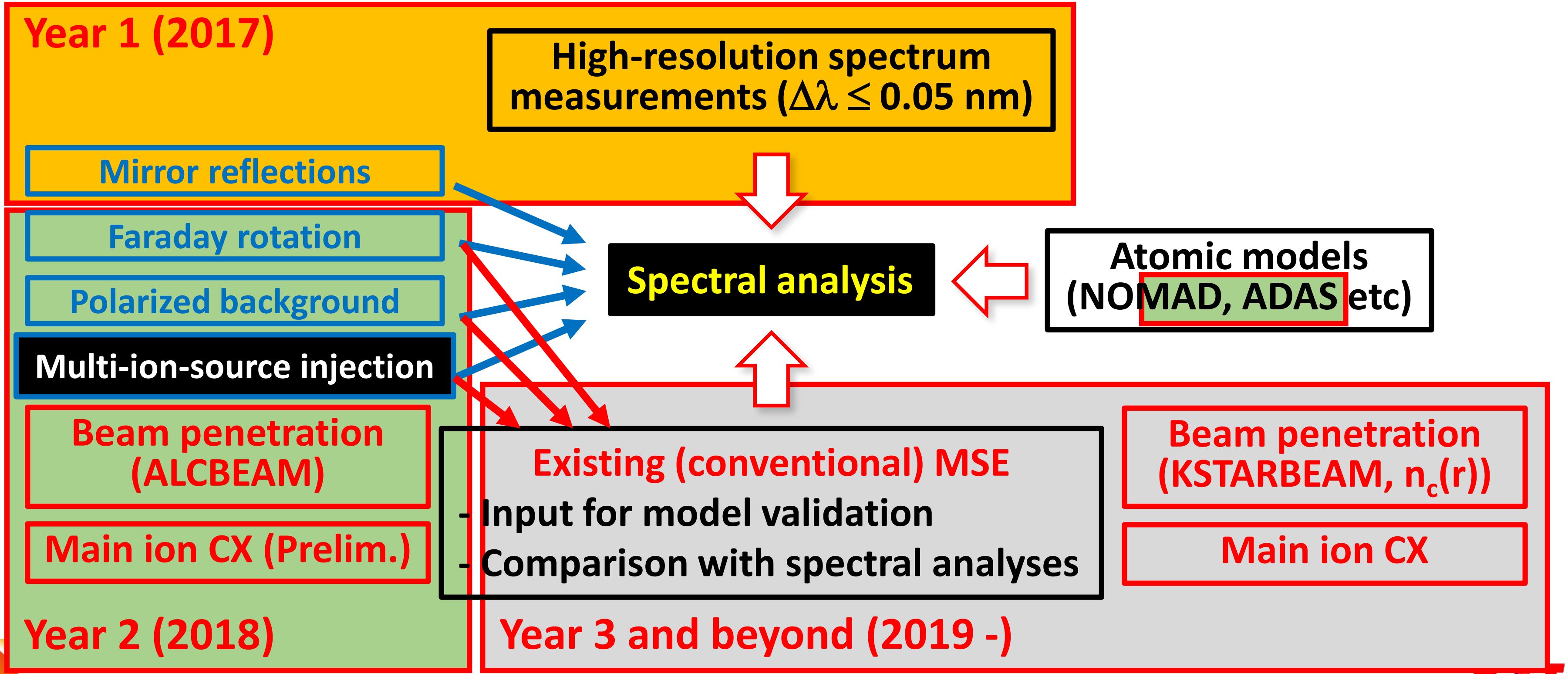
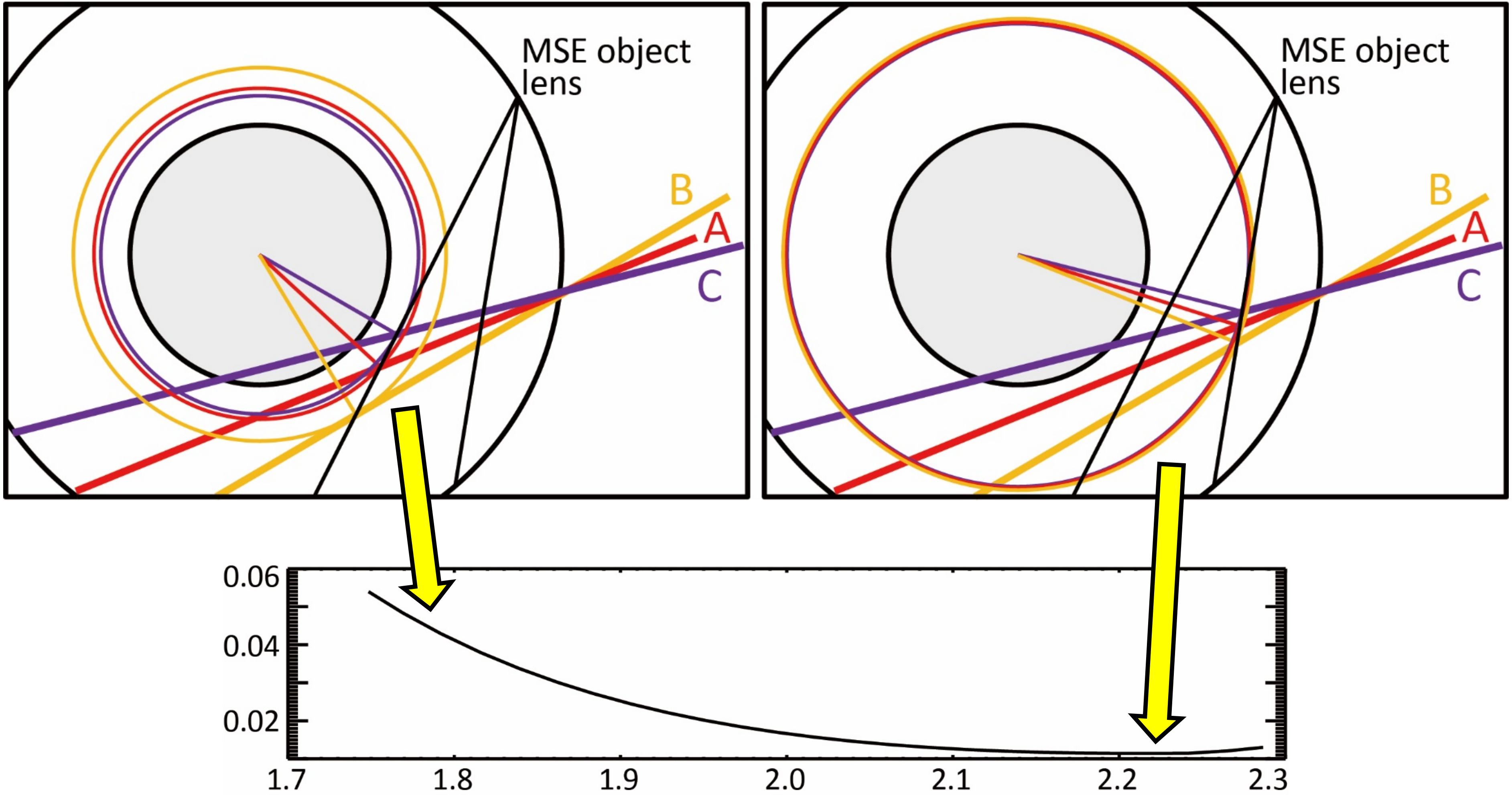




Outline of the CRP activities




MSE object lens
B
A
C
MSE object lens
B
A
C
0.06
0.04
0.02
1.7
1.8
1.9
2.0
2.1
2.2
2.3

Per sightline
MSE signal source: NBI1-A

B_T, V_A, V_B

Filter functions

$f_A(\lambda)$

$$I^A_{\pi,A} = \int \sum_i \sum_C I^{A,C}_{i\pi} f_A(\lambda) d\lambda$$
$$I^A_{\sigma,A} = \int \sum_j \sum_C I^{A,C}_{j\sigma} f_A(\lambda) d\lambda$$
$$I^B_{\pi,A} = \int \sum_i \sum_C I^{B,C}_{i\pi} f_A(\lambda) d\lambda$$
$$I^B_{\sigma,A} = \int \sum_j \sum_C I^{B,C}_{j\sigma} f_A(\lambda) d\lambda$$

MSE spectra

$I^{S,C}_{i\pi}$, $I^{S,C}_{j\sigma}$

$i = \pm 2, \pm 3, \pm 4$
$j = 0, \pm 1$
S = A or B
C = full, half, or third

Pitch angle profiles

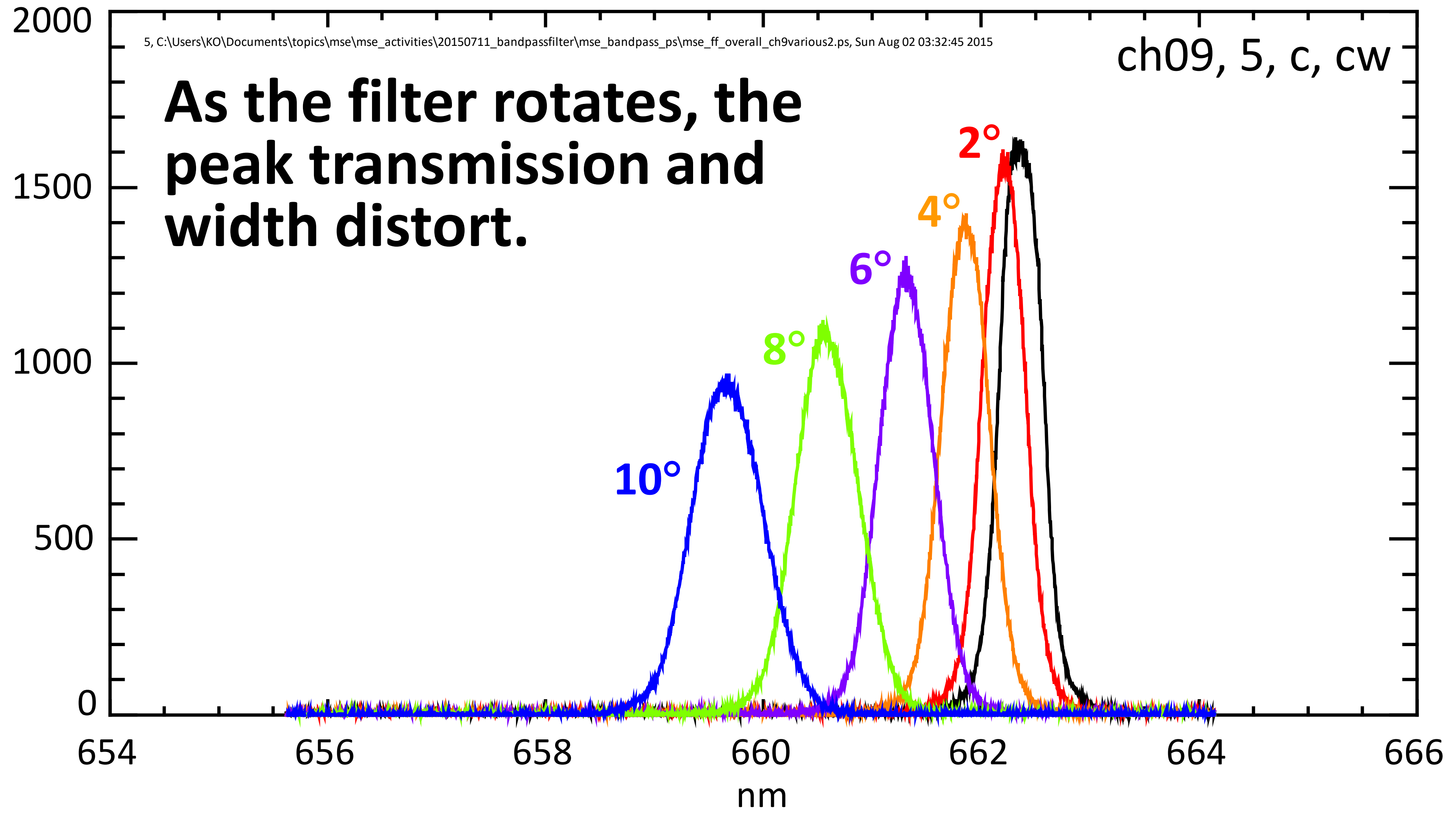
γ_A, γ_B

2nd and 3rd elements of the Stokes vector

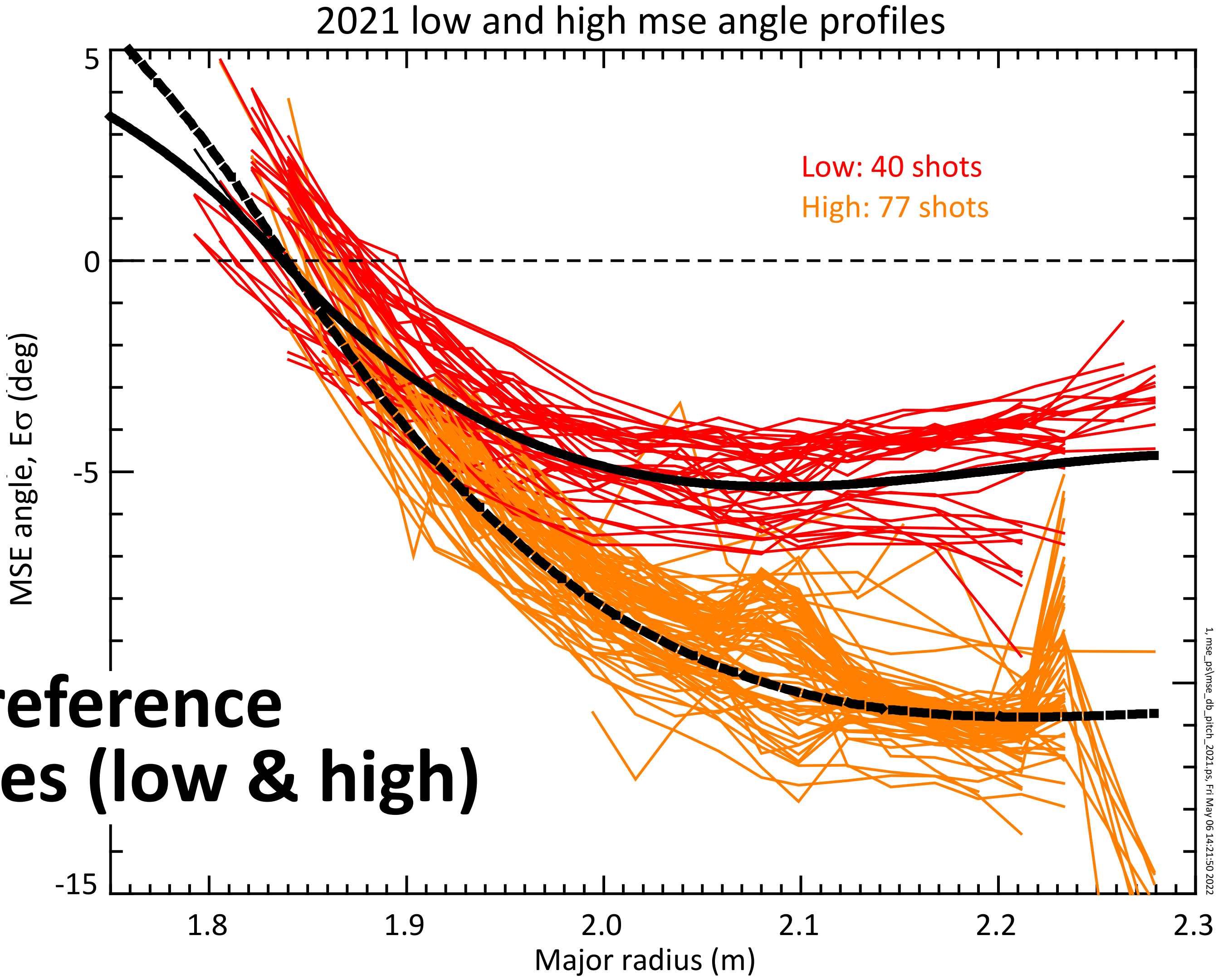
$$Q_A = I^A_{\pi,A}\cos(2\gamma_A) + I^A_{\sigma,A}\cos(2\gamma_A + \pi) + I^B_{\pi,A}\cos(2\gamma_B) + I^B_{\sigma,A}\cos(2\gamma_B + \pi)$$
$$U_A = I^A_{\pi,A}\sin(2\gamma_A) + I^A_{\sigma,A}\sin(2\gamma_A + \pi) + I^B_{\pi,A}\sin(2\gamma_B) + I^B_{\sigma,A}\sin(2\gamma_B + \pi)$$

$$\gamma^m_A = 0.5\,\mathrm{atan}\left(\frac{U_A}{Q_A}\right)$$

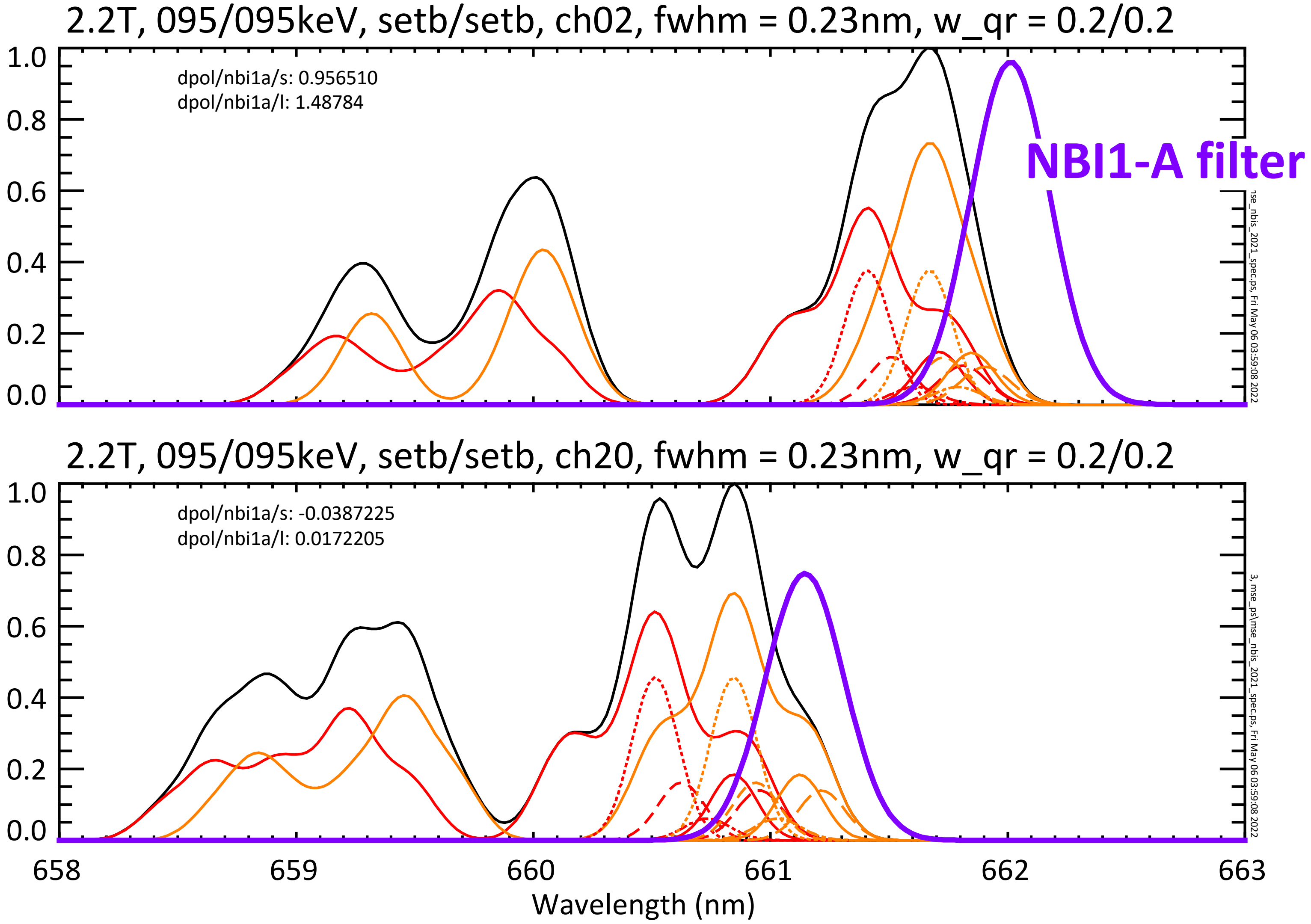
$$\Delta\gamma_A = \gamma_A - \gamma^m_A$$

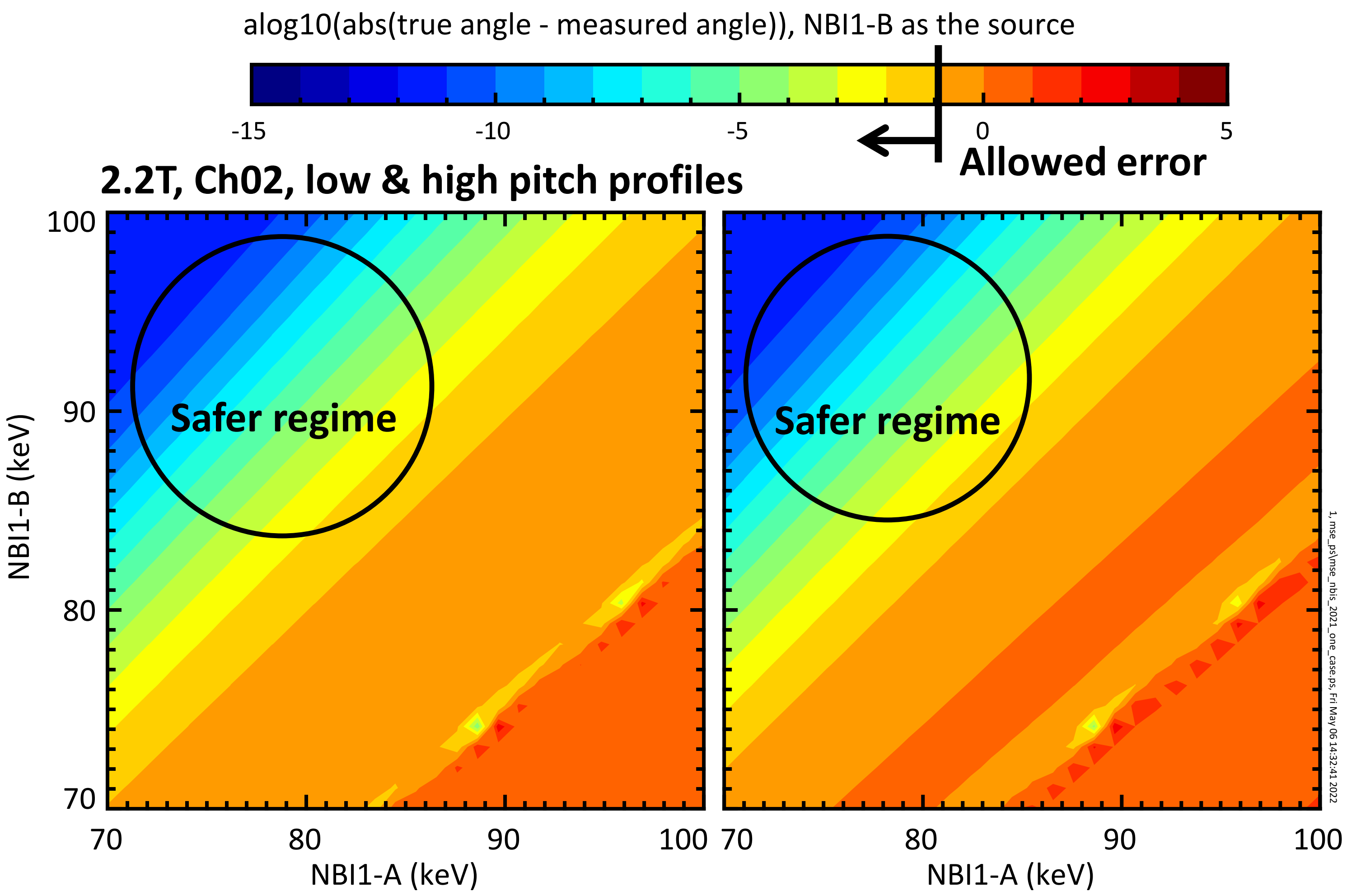


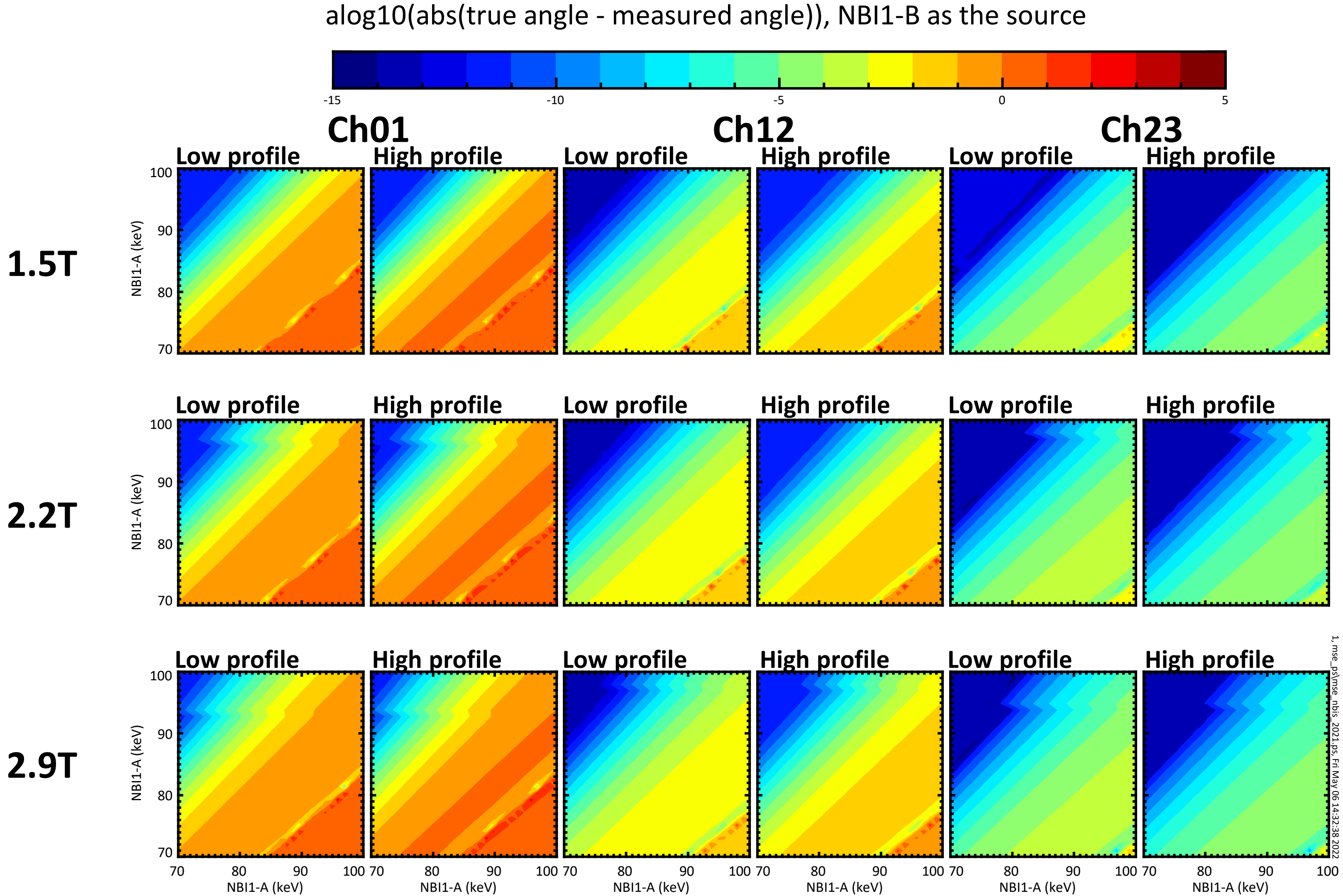
5, C:\Users\KO\Documents\topics\mse\mse_activities\20150711_bandpassfilter\mse_bandpass_ps\mse_ff_overall_ch9various2.ps, Sun Aug 02 03:32:45 2015
ch09, 5, c, cw
As the filter rotates, the peak transmission and width distort.
2°
4°
6°
8°
10°
2000
1500
1000
500
0
654
656
658
660
662
664
666
nm



Two reference profiles (low & high)


2.2T, 095/095keV, setb/setb, ch02, fwhm = 0.23nm, w_qr = 0.2/0.2
dpol/nbi1a/s: 0.956510
dpol/nbi1a/l: 1.48784
NBI1-A filter
2.2T, 095/095keV, setb/setb, ch20, fwhm = 0.23nm, w_qr = 0.2/0.2
dpol/nbi1a/s: -0.0387225
dpol/nbi1a/l: 0.0172205
1.0
0.8
0.6
0.4
0.2
0.0
658
659
660
661
662
663
Wavelength (nm)


alog10(abs(true angle - measured angle)), NBI1-B as the source
-15
-10
-5
0
5
Allowed error
2.2T, Ch02, low & high pitch profiles
100
90
80
70
NBI1-B (keV)
Safer regime
Safer regime
70
80
90
100
NBI1-A (keV)
70
80
90
100
NBI1-A (keV)
1, mse_ps\mse_nbis_2021_one_case.ps, Fri May 06 14:32:41 2022


alog10(abs(true angle - measured angle)), NBI1-B as the source
-15
-10
-5
0
5
Ch01
Ch12
Ch23
Low profile
High profile
1.5T
2.2T
2.9T
NBI1-A (keV)
100
90
80
70
NBI1-A (keV)
1, mse_ps\mse_nbis_2021.ps, Fri May 06 14:32:38 2022

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Year 3 and beyond (2019 -)

KSTAR run time dedicated to atomic data benchamark study during 2020 campaign

Proposed by

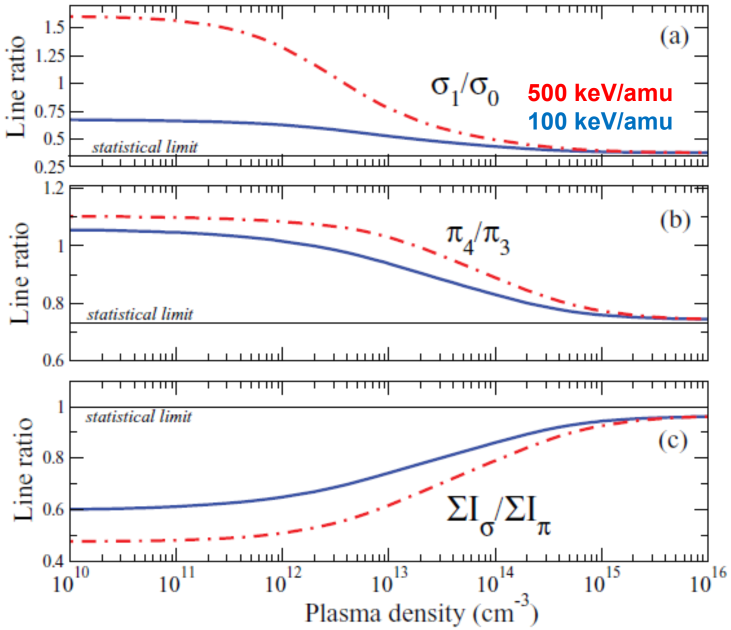
O. Marchuk, Yu. Ralchenko, D. R. Schultz, Ph. Mertens

<u>Motivation:</u>

- **Deviation of statistical populations in MSE atomic levels and line intensities still observed in many machines (JET, Alcator C-Mod etc).**
- **No experimental data of MSE intensities in helium plasmas – No predictions and studies available for initial ITER plasmas.**

<u>Approach:</u>

- **Utilizing the KSTAR's capability to measure high-resolution MSE spectra, obtain good-quality MSE spectra in helium and D plasmas.**
- **Comparison with polarimetric MSE results**



Marchuk et al, Plasma Phys. Control. Fusion 54 (2012) 095010
Ralchenko et al, Rev. Sci. Instrum. 83 (2012) 10D504

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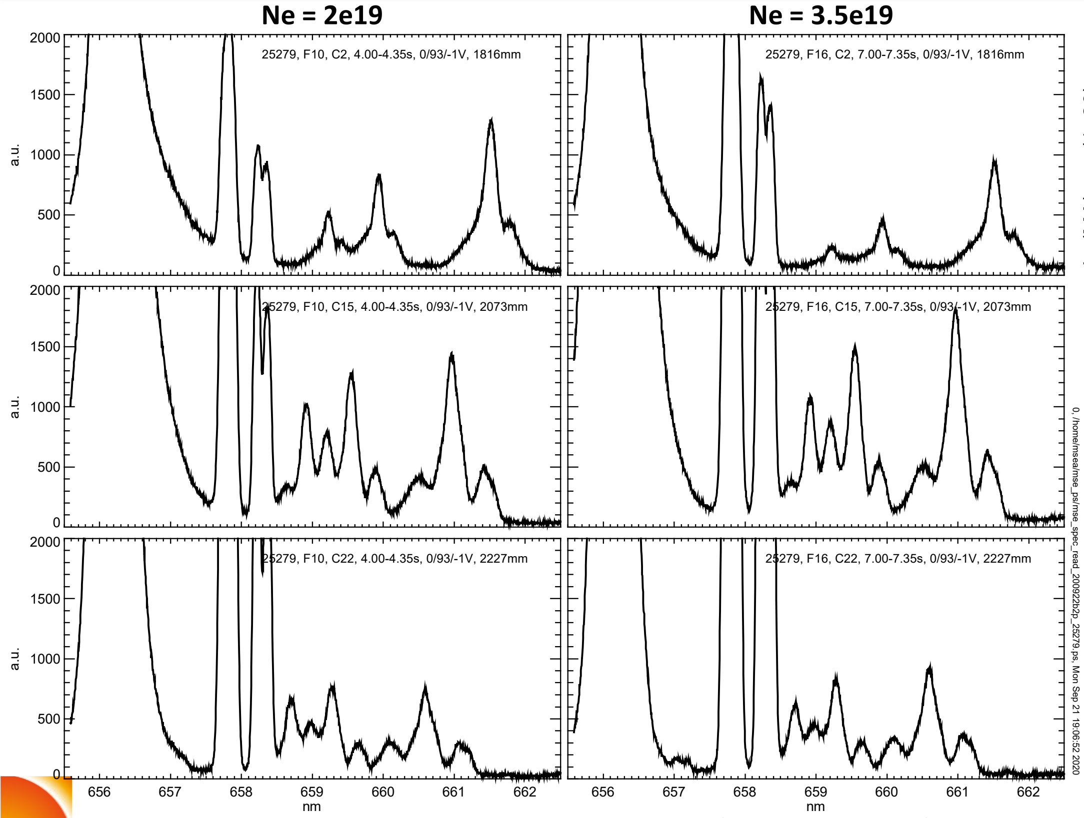
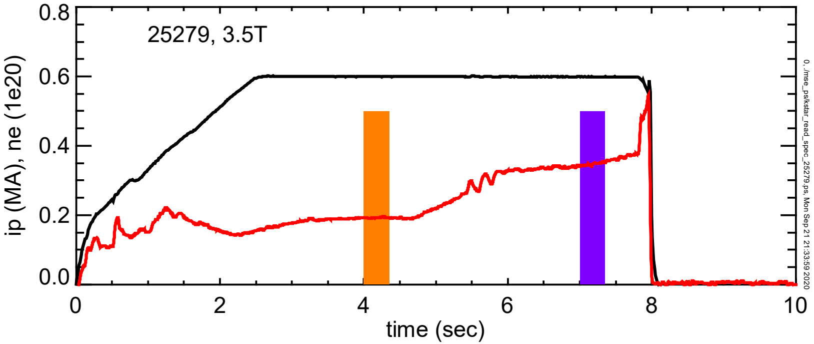
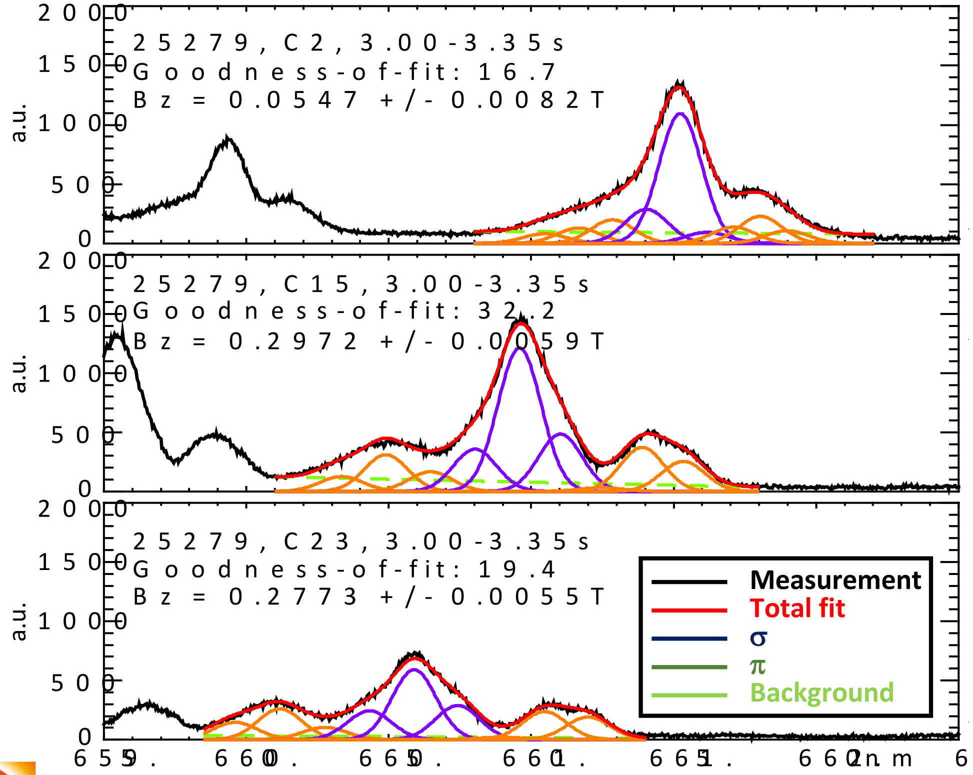




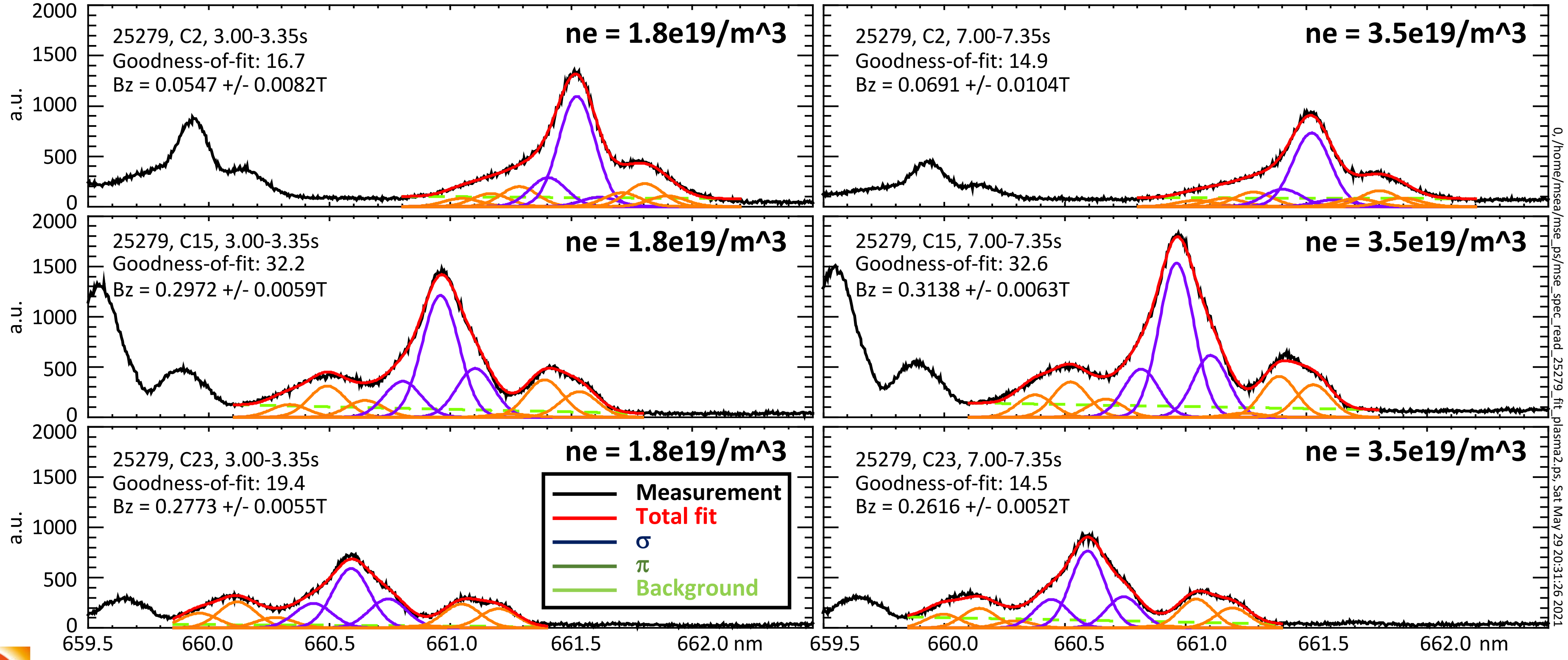
- **3 out of 25 conventional MSE channels connected to spectrometer (Core / Mid-minor / Edge).**
- **One shot with density scan at 3.5T, 90 keV deuterium beam (Originally 4 shots given).**
- **No Te & ne measurements! (Apology to Sascha)**

Spectral fit on MSE emission to infer vertical field at KSTAR

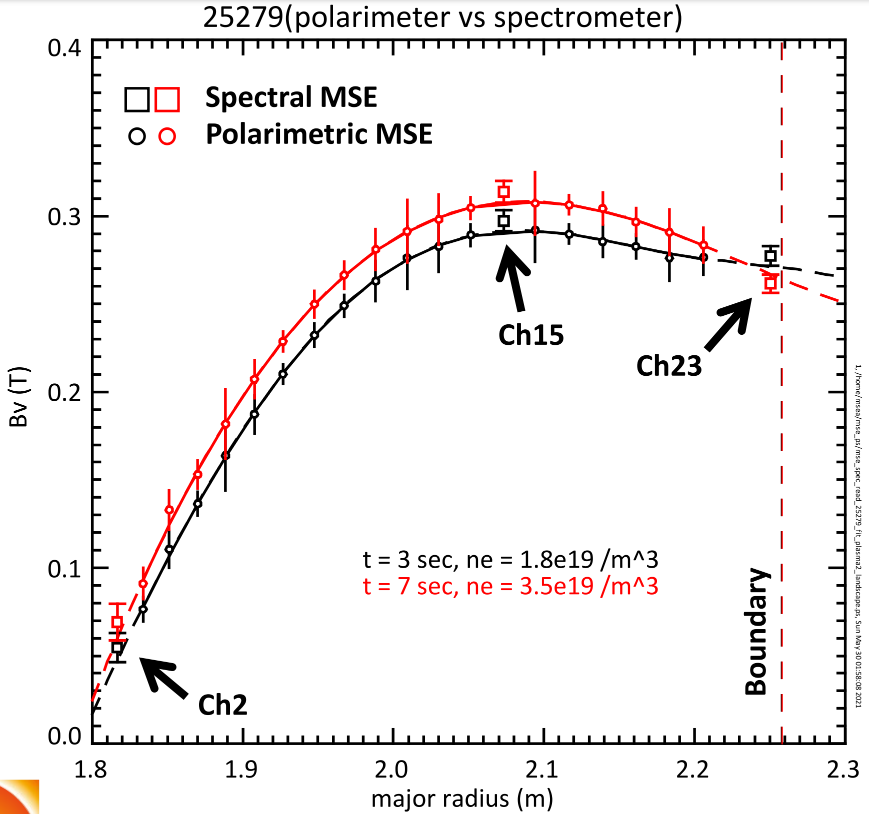


- **Multi-Gaussian fit model on full energy component of MSE spectrum includes:**
  - Asymmetry around σ0 dependent of channel position.
  - Free parameters with constraints: relative intensities of MSE multiplets, Stark splitting, line broadening.
  - Fixed parameters: Bt, beam energy, viewing angle.
  - Linear background (including FIDA).
  - 'Forward' initialization
- **Inferred Bv's are compared with that from polarimetric MSE.**

Spectral fit on MSE emission to infer vertical field at KSTAR at two ne values



Reasonable agreement between polarimetric and spectral MSE's



- **Bv's inferred from spectral MSE are overplotted with those from polarimetric MSE**
- **With slight offsets, Bv's from spectral MSE exhibit similar sensitivity as those from polarimetric MSE over two different Bv profiles.**
- **Next steps:**
  - **Stabilize (automate) establishing initial conditions.**
  - **Increase the number of 'spectral' channels.**
  - **Apply and test more various plasma discharges (ITB etc).**
  - **Cases of multiple ion-source injections? Will be very challenging.**

Zoletnik et al. Nucl. Fusion, To be submitted

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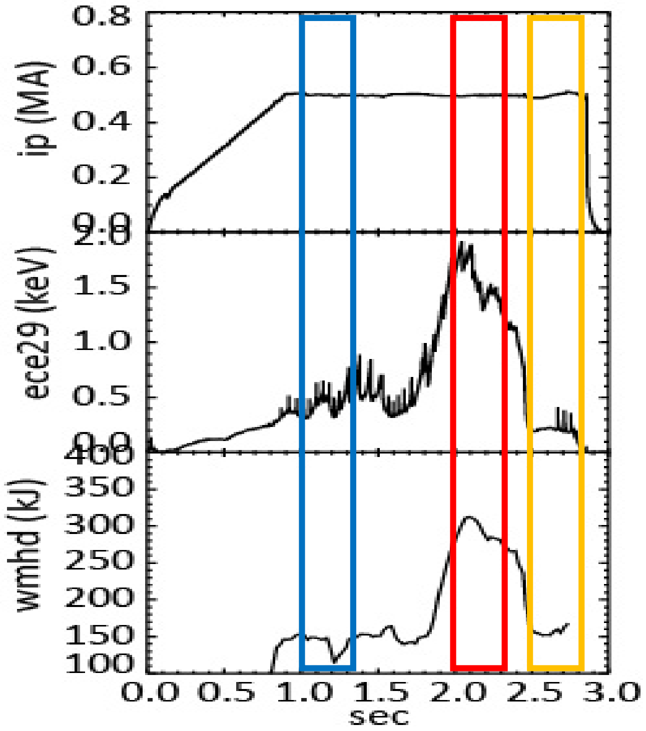
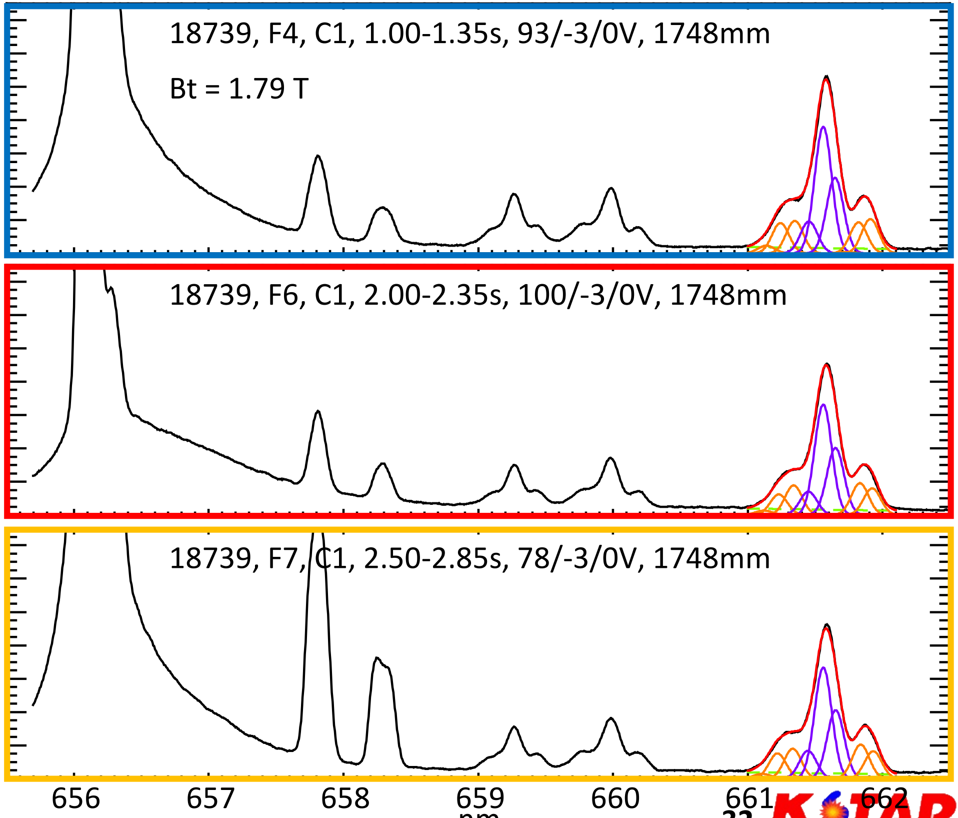
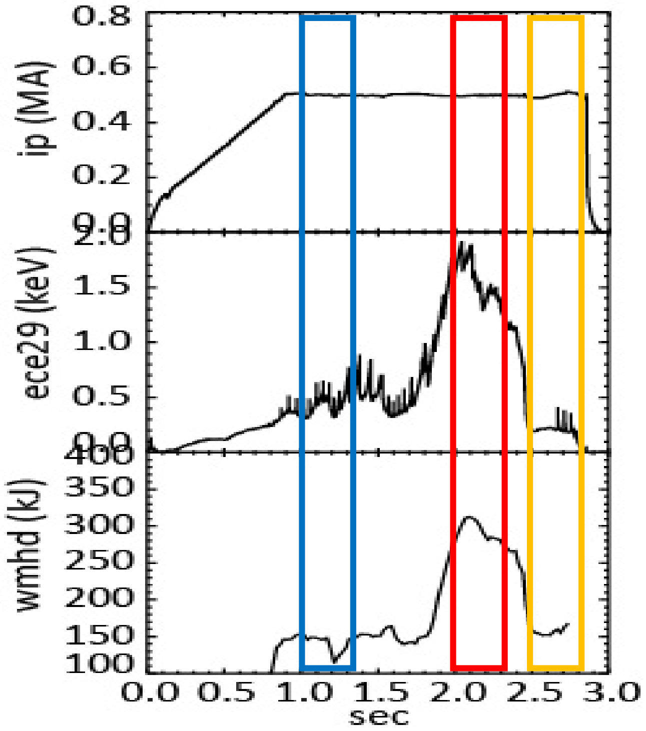
Year 3 and beyond (2019 -)

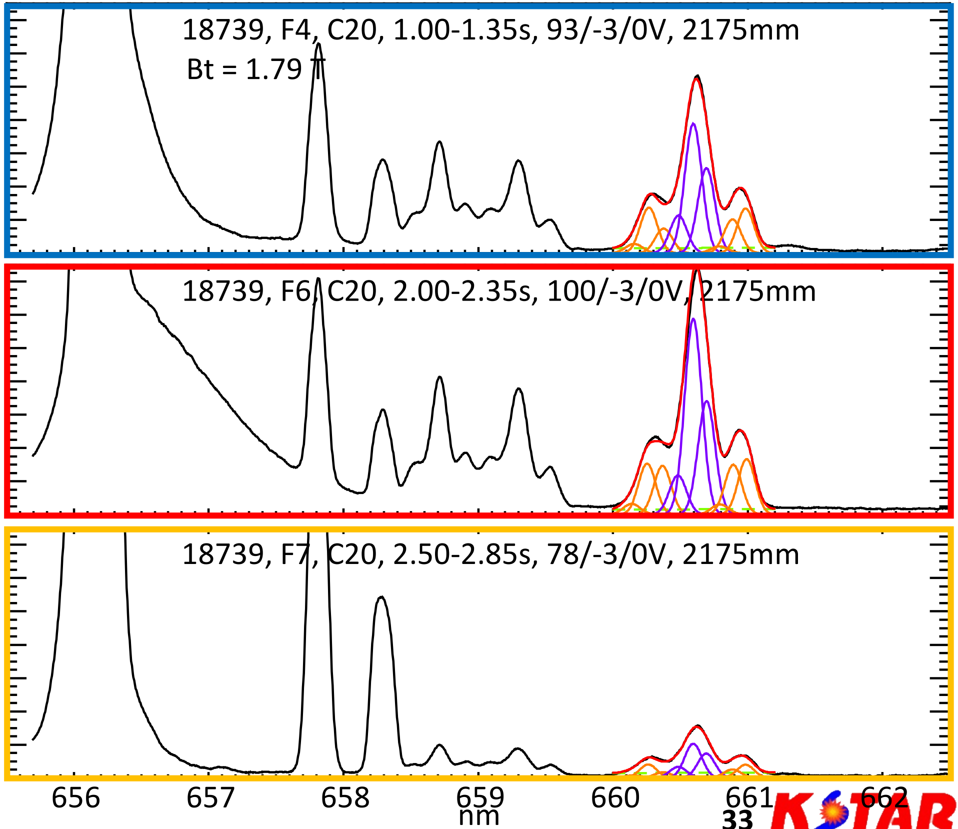
Last time, we mentioned the observation of main-ion CX components



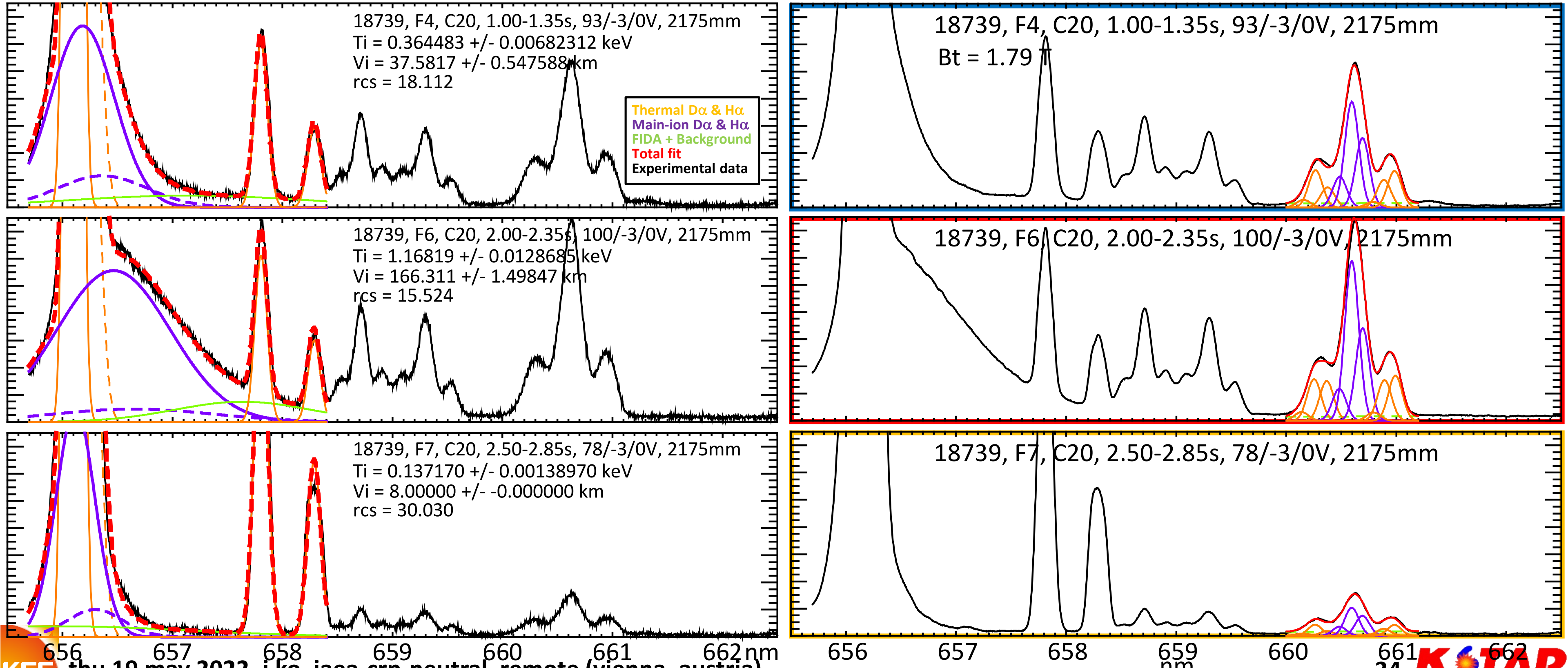


…which qualitatively broaden during high confinement regimes





Multi-Gaussian fit for main-ion CX interpretation done in addition to MSE fits



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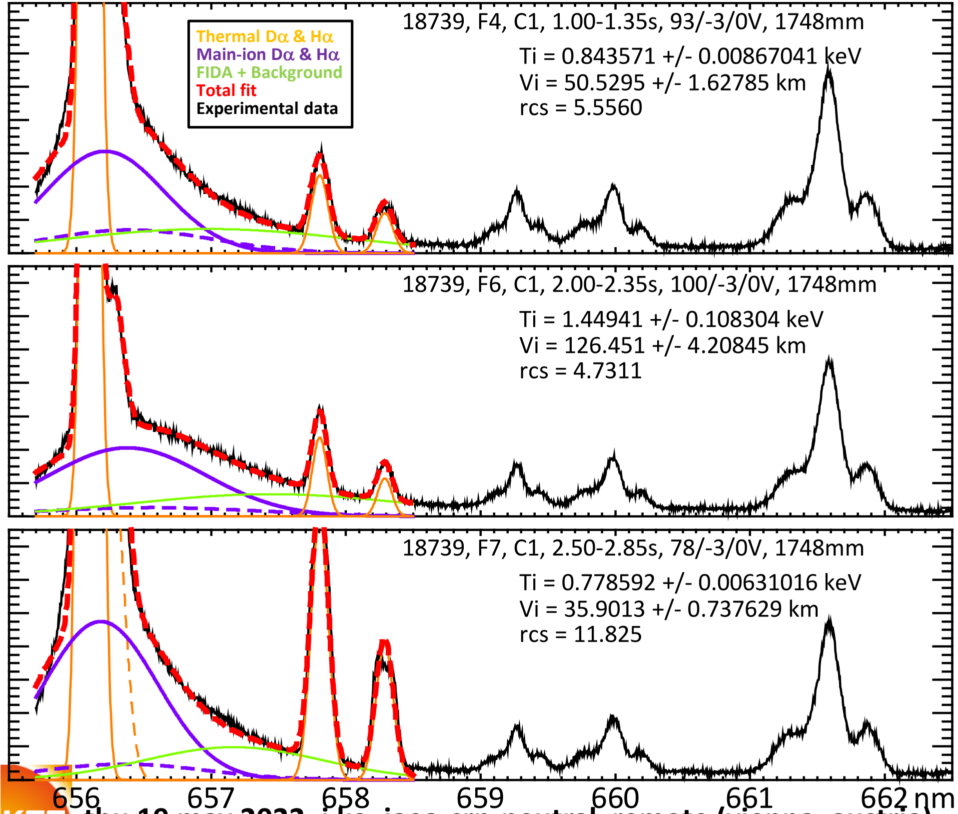

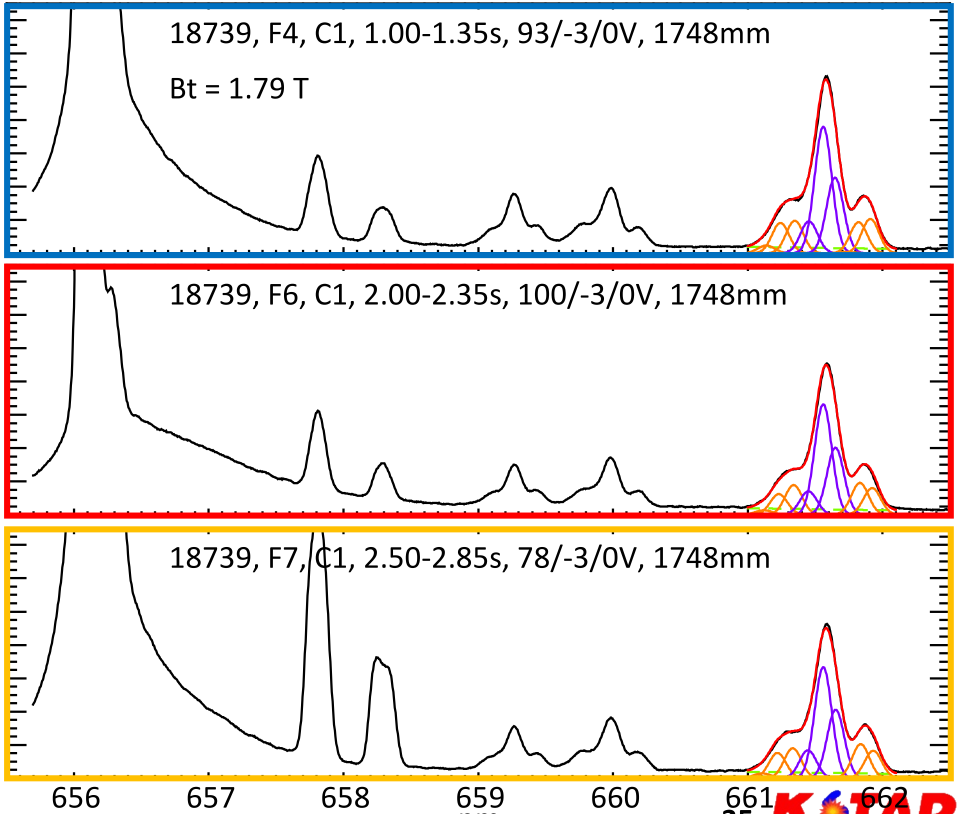

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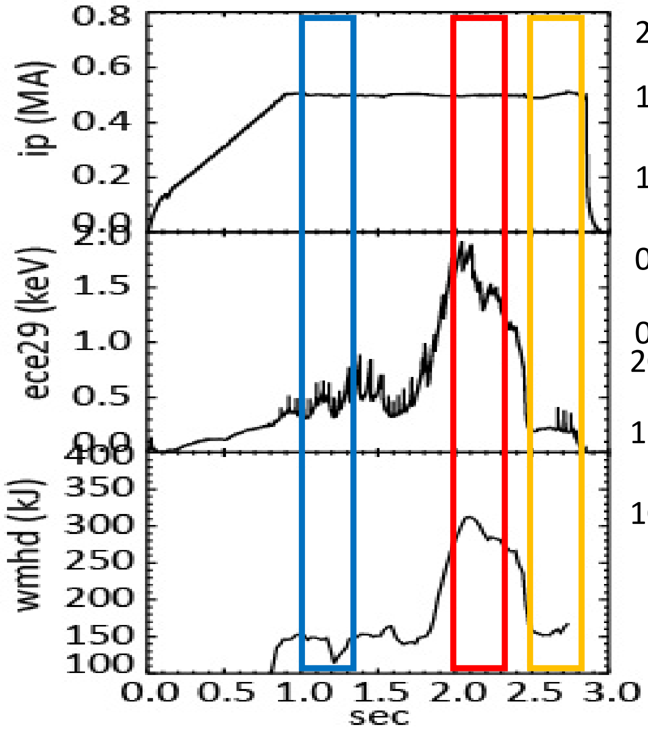
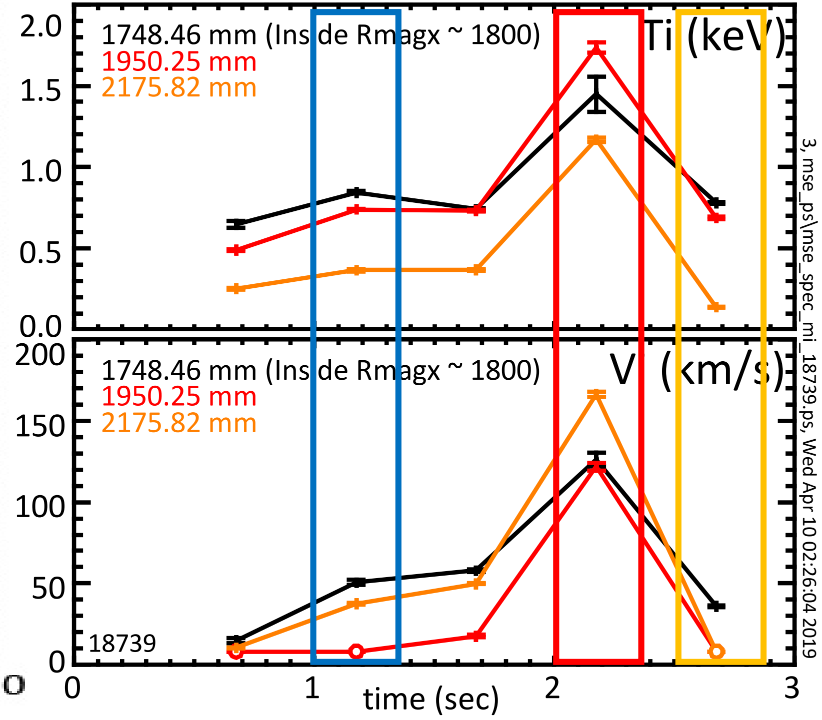
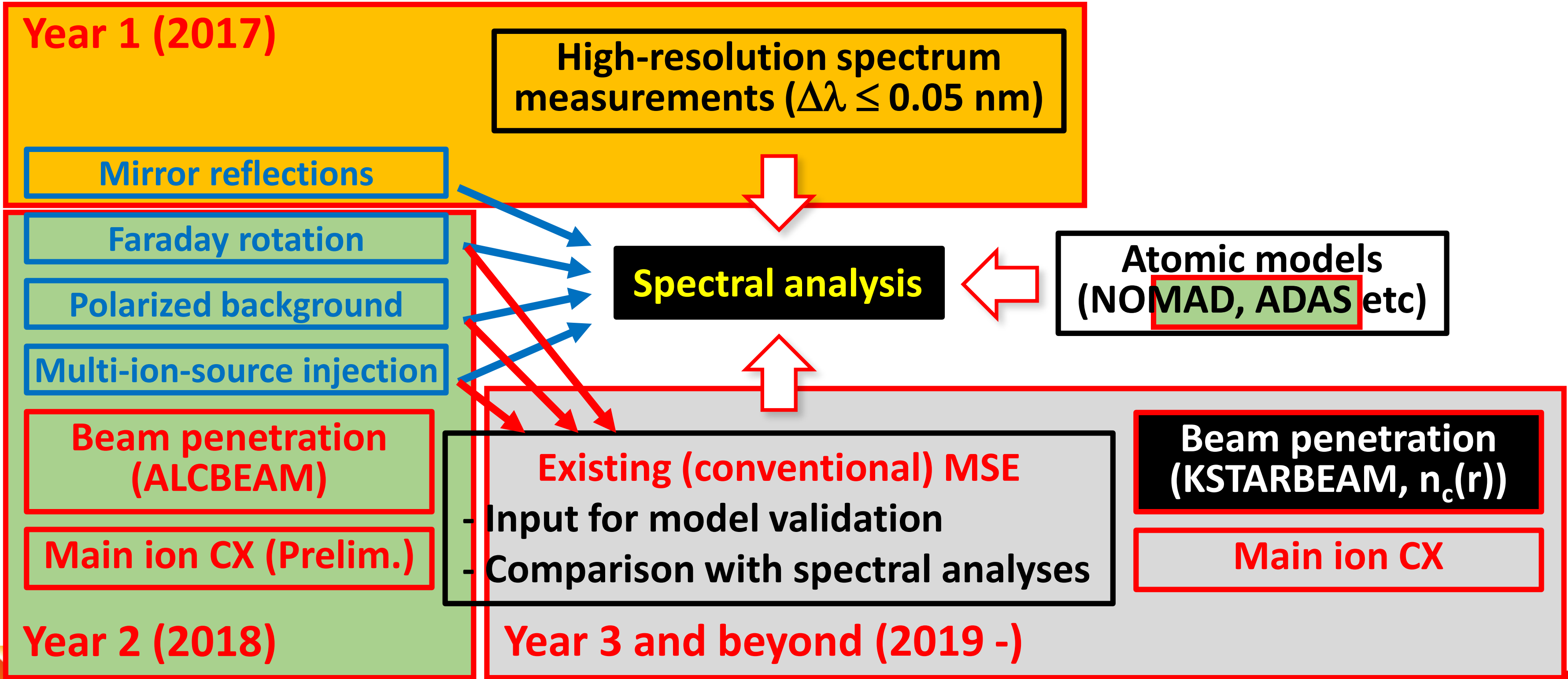




- **Rather challenging fit because the beam-off thermal components are included.**
- **Cross-section distortion and halo not included.**
- **Impurity-based CX data can be used as initial conditions.**
- **Full-channel measurements planned to confirm pedestal structures etc.**

Outline of the CRP activities



Carbon density profiles obtained for the first time in KSTAR

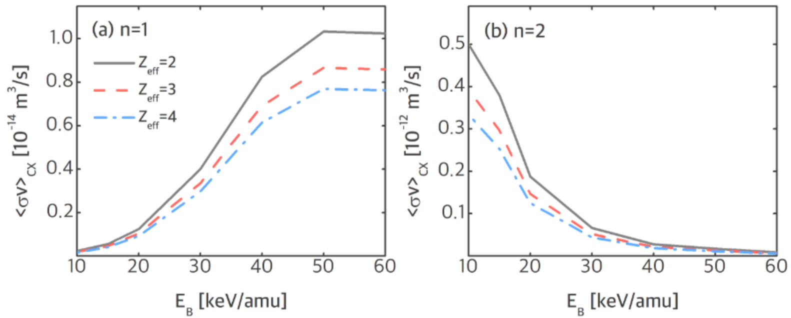
- **Last time, a brief introduction was made on the application of the ALCBEAM* code to KSTAR**
- **ALCBEAM has been modified (and renamed as KSTARBEAM) for the KSTAR beam configs.**

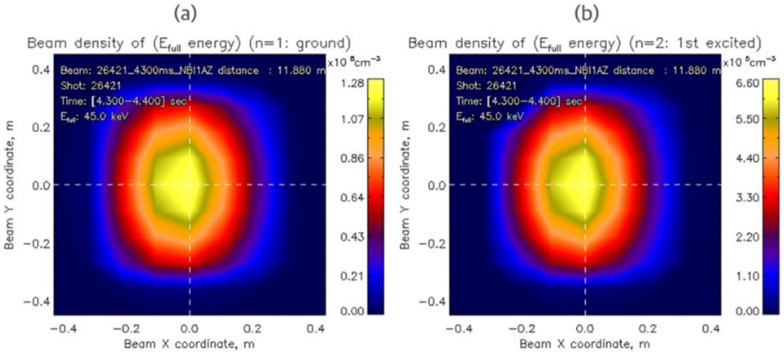
$$n_C = \frac{4\pi\epsilon_{CX}^{\lambda}}{\sum_k \sum_j < \sigma v >_{j,k}^{\lambda} \int n_{b_{j,k}}(l)dl}$$

ϵ_{CX}^{λ} : the charge exchange brightness at wavelength λ
j : beam energy components $(E, E/2, E/3)$
k : beam atoms excited levels
$< \sigma v >_{j,k}^{\lambda}$: the effective cross-section rate (from ADAS)
dl : the path length of diagnostic's line of sight through the beam

$$n_{b_j}(z) = n_{b_j}(0) \exp\left(- \int \left(n_e(z)\sigma_{S_j} \right) dz \right)$$

z : distance along the beam trajectory
$n_{b_j}(0)$: the initial neutral beam density at the plasma boundary
σ_{S_j} : the effective beam stopping cross-section





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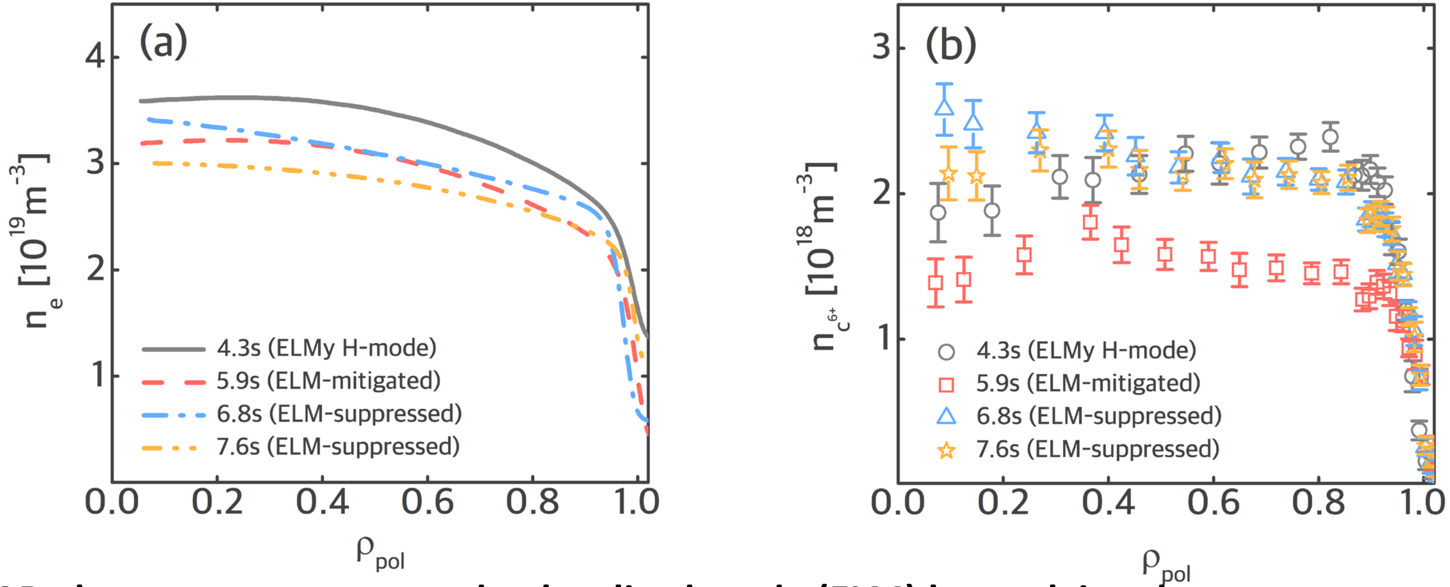
Impurity accumulation during ELM-free phase has been observed



- **KSTAR plasmas can suppress edge-localized mode (ELM) by applying the resonant magnetic perturbation.**
- **Carbon density profiles confirm the impurity accumulation during ELM-free while electrons are pumped out.**

J K Lee et al. AIP Advanced, 2022

Future plans

- Retry the MSE spectrum measurements in 2022 KSTAR campagin with Te and ne measurements, and narrow slits (lots of nlm-resolved data!) – Dedicated run time allocated in July

- Apply the main-ion CX fit to recent (and upcoming) high-Ti KSTAR plasmas

- Reliable initialization in the MSE and main-ion CX fits

- Extend the spectral MSE to various advanced operation regimes (ITB etc) and the multi-ion-source injection cases and compare it with polarimetric MSE

- Revist the spectrum measurements from the gas with the beam and the field (for atomic physics data collections)

- Utilization of (Comparison with) NOMAD

O Marchuk, J Ko, Yu. Ralchenko, J Y Ko, J W Juhn, D R Schultz, Ph. Mertens, J Chung

Shot plan*: 7 shots with NB1A, NB2B, SMBI

- **Ref: #29449****
  - ✓ Obtained by J W Juhn in 2021
  - ✓ 0.7 MA with SMBI, NB1A/B = 80/85 keV
  - ✓ Record high f_{GW} & ne (80% & 8.5e19)
- **Initial modifications**
  - ✓ NB1A = 90 keV
  - ✓ NB2B replaces NB1B to avoid beam spectral overlap
  - ✓ Keep the fueling scheme
- **MSE and other hardware**
  - ✓ MSE 3 channels to spectrometer/CCD
  - ✓ Te and ne profiles necessary (TS, ECE)
  - ✓ SMBI

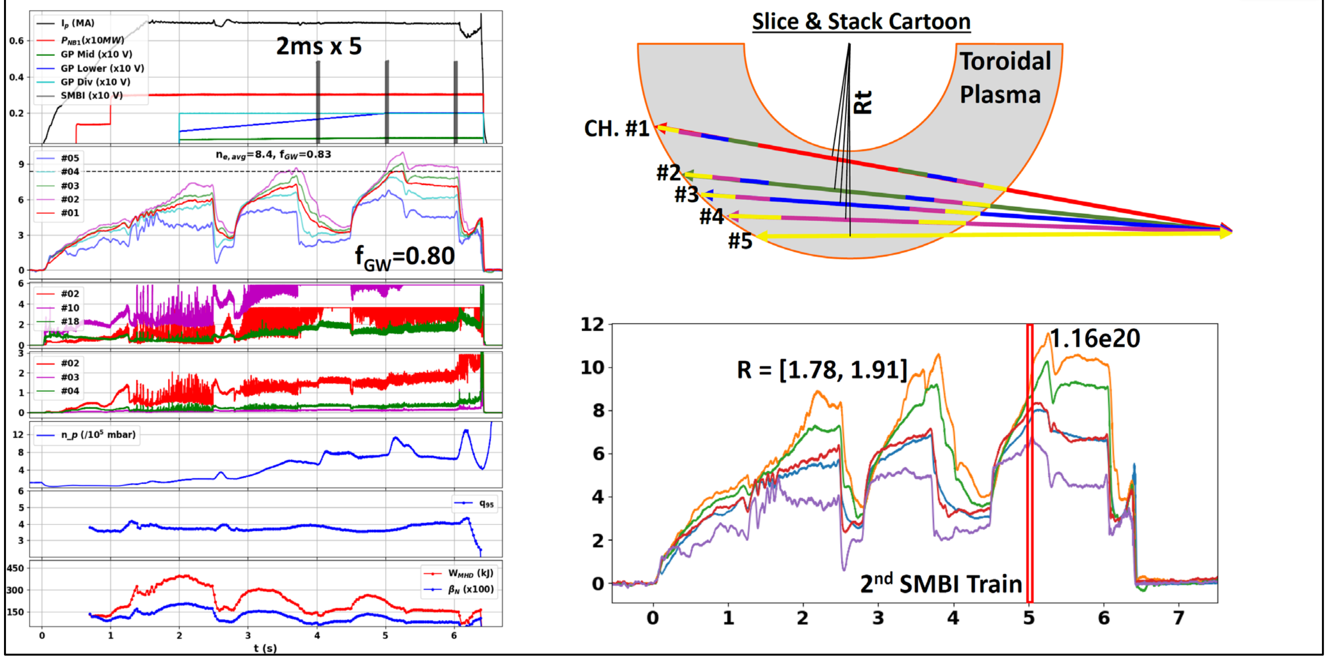
- Shot 1: Re-achieve #29449
- Shot 2 / 3: NB1A = 90 keV / 60 keV
- Shot 4 / 5: NB1A = 90 keV / 60 keV with Ar 1% (Challenge to even higher f_{GW})
- Shot 6: Ip = 1 MA, NB1A = 90 keV
- Shot 7: Ip = 1 MA, NB1A = 90 keV, Bt = 3.5T

**Alternative in case of no SMBI: #28844 (NB1A/B/C, NB2C, f_{GW} = 74%)

- **Expectations if successful:**
  - ✓ Obtain unique atomic physics data (main purpose)
  - ✓ Obtain dataset for spectral MSE for ITER application
  - ✓ Pursue record ne/n_{GW} in KSTAR

29449

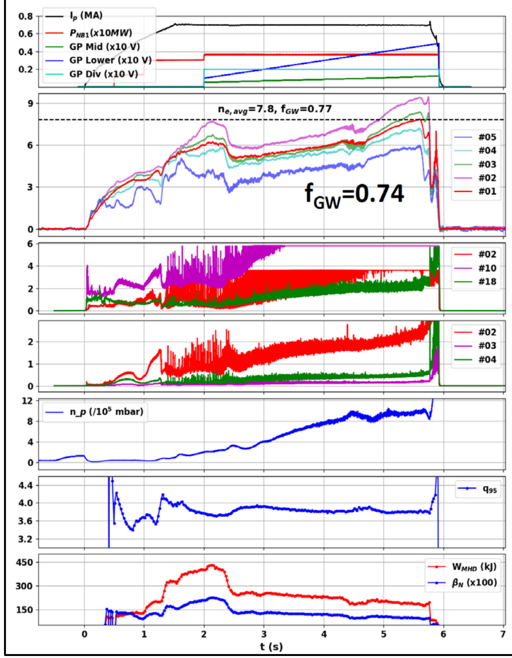
SMBI Injection Test (#29449)

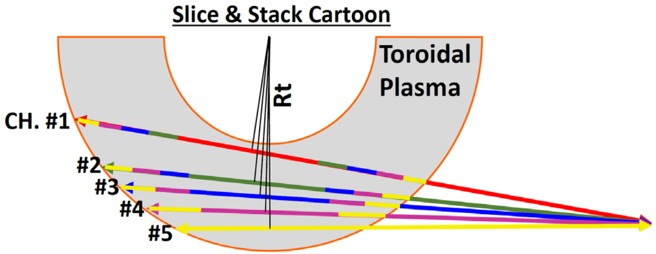


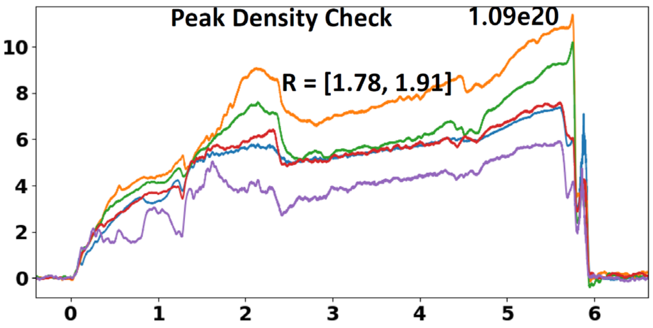
From 2021 KSTAR Summary
by J W Juhn

28844

0.7 MA Discharge (#28844)







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