MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

NBI for W7-X: A Four-Operational Campaign Overview

P. McNeely, Y. Drider, D.A. Hartmann, R. Kairys, O. Raths, P. Rong, C. Semrau, N. Rust, R. Schroeder, L. van Ham and the W7-X Team

(Newest team member: A. Hogberg)

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Introduction

- ***NBI Basics***
- ***Campaign overview of (mainly) the ion source performance:***
  - **OP1.2b**
  - **OP2.1**
  - **OP2.2&2.3**
- ***The Unexpected:***
  - **Ion Source**
    - Matching
    - Faraday Screen
  - **Ion Beam**
    - Magnetic Field of W7-X

Neutral Beam Injection on W7-X

Stellarator Wendelstein 7-X

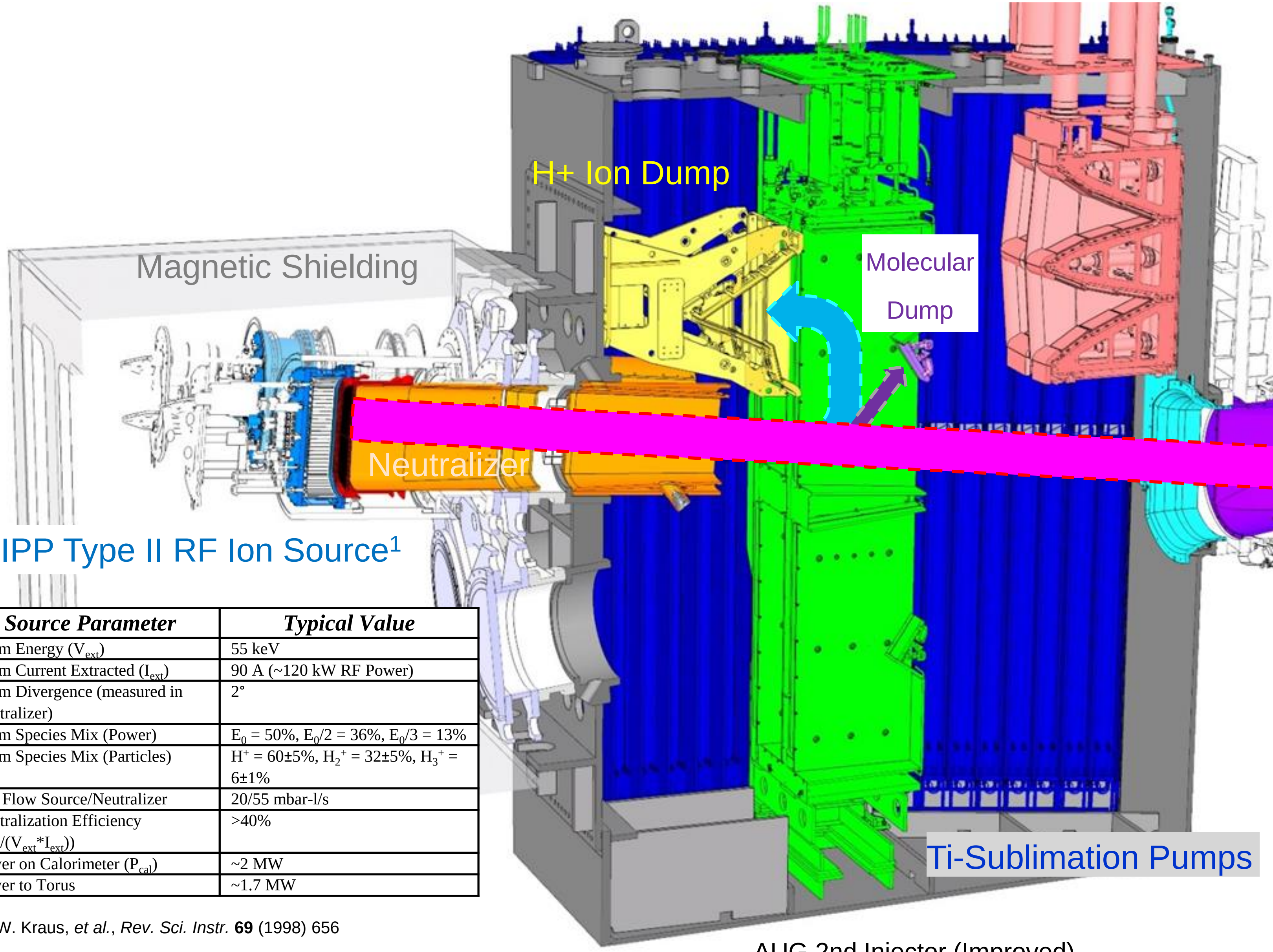
Major Radius: 5.5 m

Minor Radius: 0.53 m

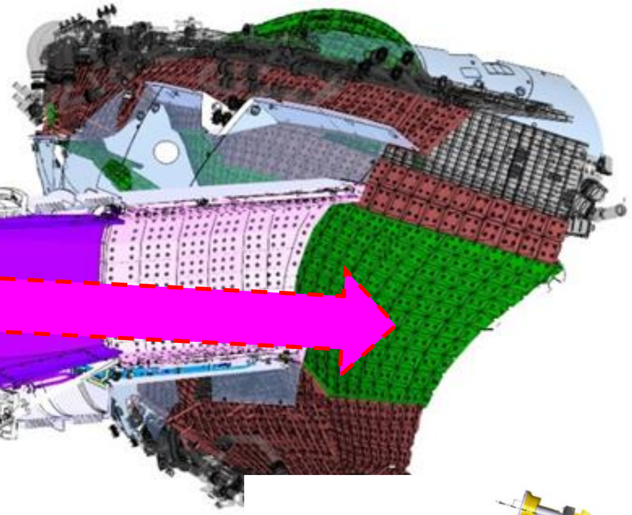
Magnetic Field on Axis: 3T

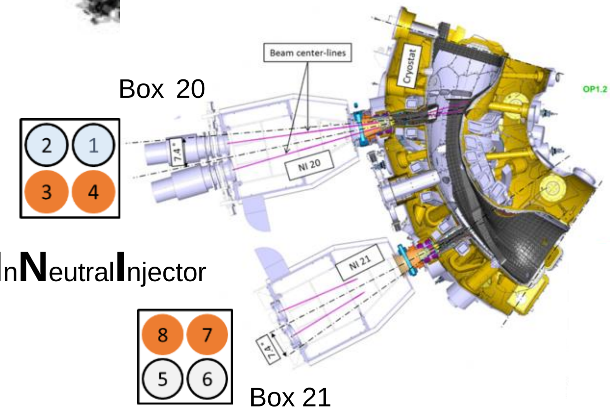
ECRH: 140 GHz (8.5 MW)

ICRH: 25 or 37.5 MHz (0.8 MW)



AUG 2nd Injector (Improved)



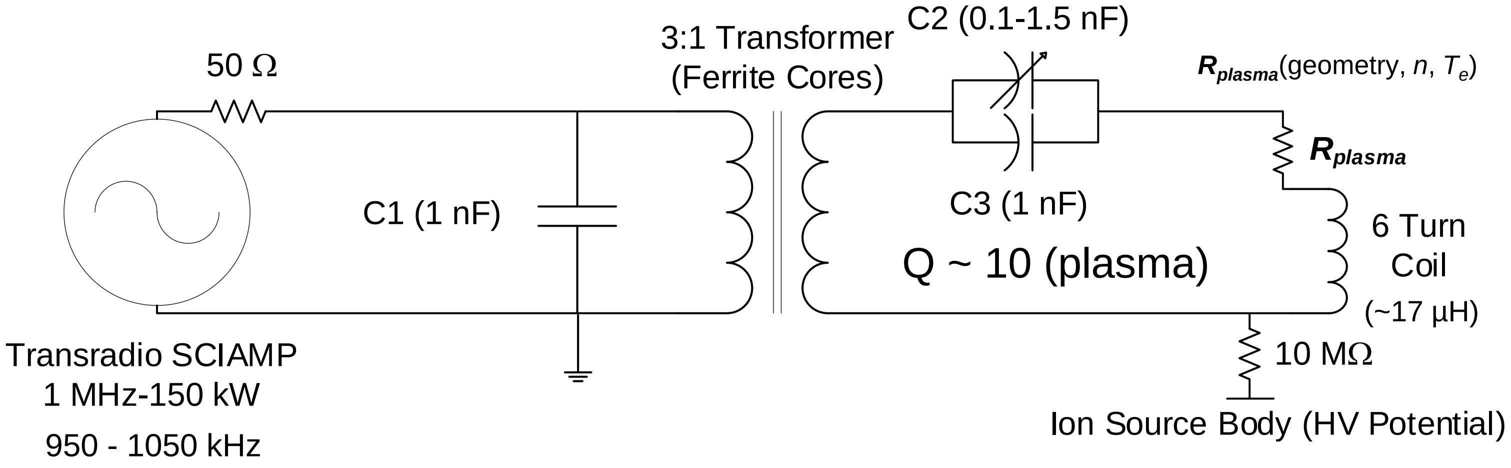


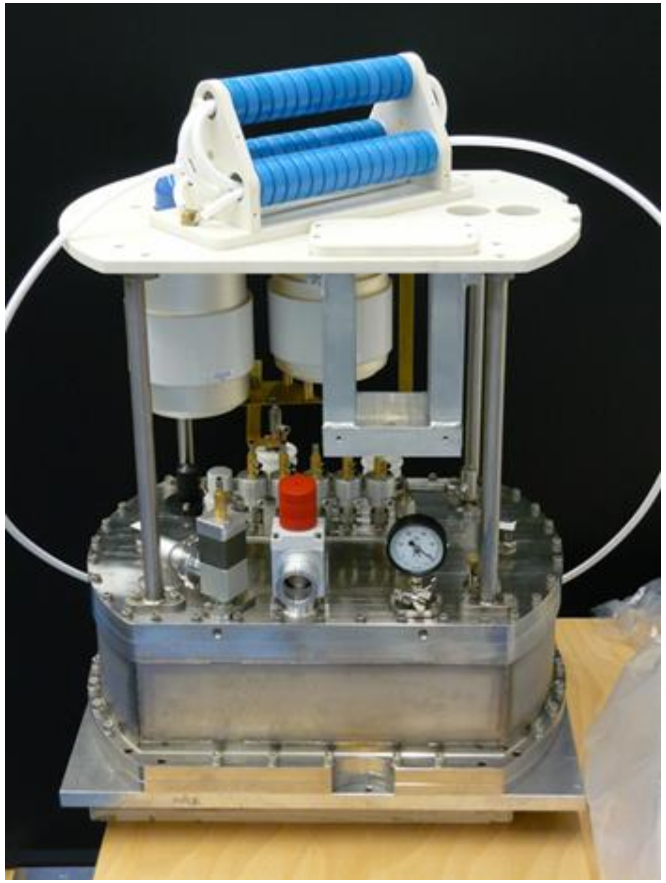
Source Parameter	*Typical Value*
Beam Energy (V_{ext})	55 keV
Beam Current Extracted (I_{ext})	90 A (~120 kW RF Power)
Beam Divergence (measured in Neutralizer)	2°
Beam Species Mix (Power)	E_0 = 50%, $E_0/2$ = 36%, $E_0/3$ = 13%
Beam Species Mix (Particles)	H^+ = 60±5%, H_2^+ = 32±5%, H_3^+ = 6±1%
Gas Flow Source/Neutralizer	20/55 mbar-l/s
Neutralization Efficiency ($P_{cal}/(V_{ext}*I_{ext})$)	>40%
Power on Calorimeter (P_{cal})	~2 MW
Power to Torus	~1.7 MW

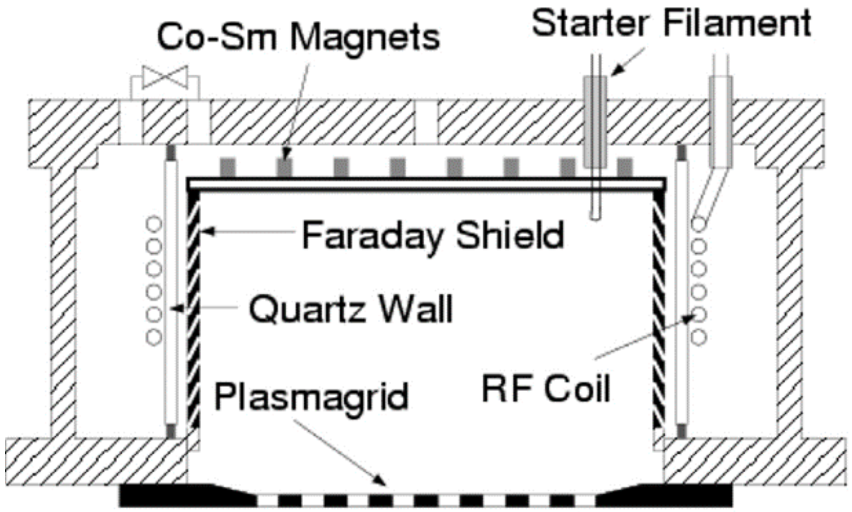
[1]W. Kraus, *et al.*, *Rev. Sci. Instr.* **69** (1998) 656

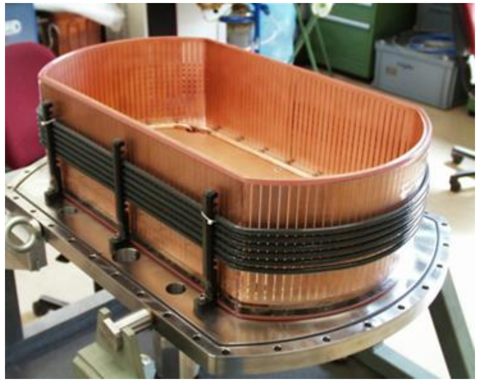
IPP Type II Ion Source

(Type II-X?)









Operational Points for Source 8 with W7-X

55 keV/90 A

Heating: Flow: 20/55 mbar-l/s; P_{RF}: 40/125 kW – 1000/1010 kHz

CXRS blips: Flow: 20/25 mbar-l/s; P_{RF}: 40/130 kW –1000/1006 kHz

20 ms, 5 Hz, 55 keV/~76 A

Campaign Overview I – OP1.2b (July to October 2018)

(The Bad, The Good, and The Reliability)

The Bad	• Late start due to source matching ➢ C1 value too high • Only PINI 8 fully ready, PINI 7 started at 42 kV • Overheating of the ferrites in transformer observed
The Good	• PINI 7&8 commissioned at full power (55 kV, 90 A) on W7-X • NBI only plasmas (highest density of W7-X) • First use of CXRS on W7-X
The Reliability	Very Good (87% of 302 shots successful) – only 5 were failures of the NBI system the other 33 failed shots were due to the shot programming

Campaign Overview II – OP2.1 (September 2022 to March 2023)

(The Bad, The Good, and The Reliability)

The Bad	• Very late start with only Box 21 ➢ Ignition NOT possible at C1 = 1 nF ?!? ➢ Ignition found at C1 = 0.5 nF ➢ Ignition now possible at C1 = 1 nF ??!!?? ➢ Very bad matching of all sources • Very unstable source operation ➢ Random premature RF termination • Damage to all source Faraday Screens
The Good	• Improved air cooling of ferrites successful • Considerable experience with source operation gained • PINI 4 commissioned on W7-X; PINI 3 operated at full power • Box 20 and Box 21 operated simultaneously (PINI 7, 8, 4) – new density record • Demonstrated enhanced CXRS (15 s long)
The Reliability	• Poor (est. 50-60% of shots worked as programmed)

Campaign Overview III – OP2.2 (September to December 2024)

(The Bad, The Good, and The Reliability)

The Bad	• Lack of trained operators • Operational frequency shift of Source 4: 1000 → 1005 kHz

The Good	• NBI available before start of W7-X plasma operation
	    • Premature termination solved
	    • All sources newly matched
	    • Operational points established
	    • Power maps
	• Routine Long pulse CXRS (20 s): PINI 8 operation point for CXRS
	• Development Low Field Start-up
	• Routine NBI Monitor Program (N. Rust)

The Reliability	• Good (est. 80% of shots worked) • Over OP2.2 fixed all 2nd Order failures

Campaign Overview IV – OP2.3 (February to May 2025)

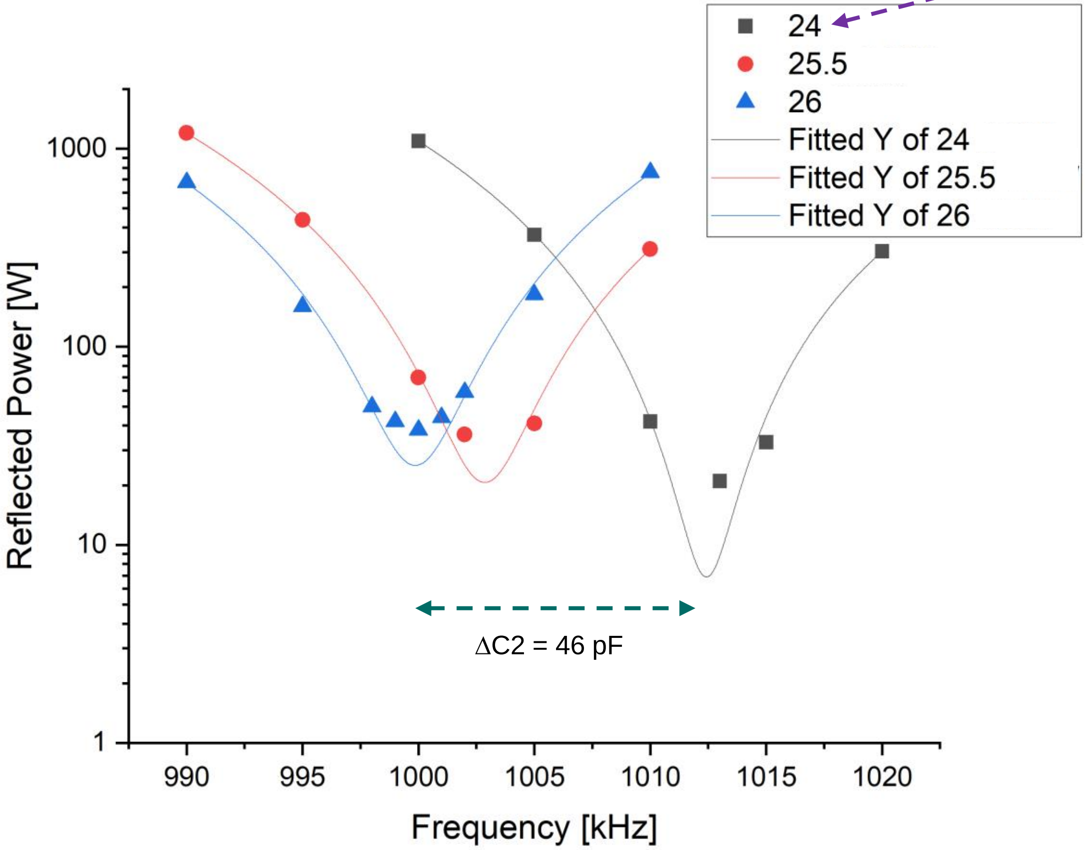
(The Bad, The Good, and The Reliability)

The Bad	• 3^{rd} Order failures • Operational frequency shift of source 8: 1000 → 998 kHz
The Good	• All sources were operating! • Routine Low Field start-up • High Performance studies (NBI plus ECRH or ECRH & Pellets) • CICERS on Box 20 → PINI 4 operation point for CXRS • He Beam from PINI 4 commissioned on W7-X
The Reliability	Extremely Good (est. 90-95% of shots worked as programmed)

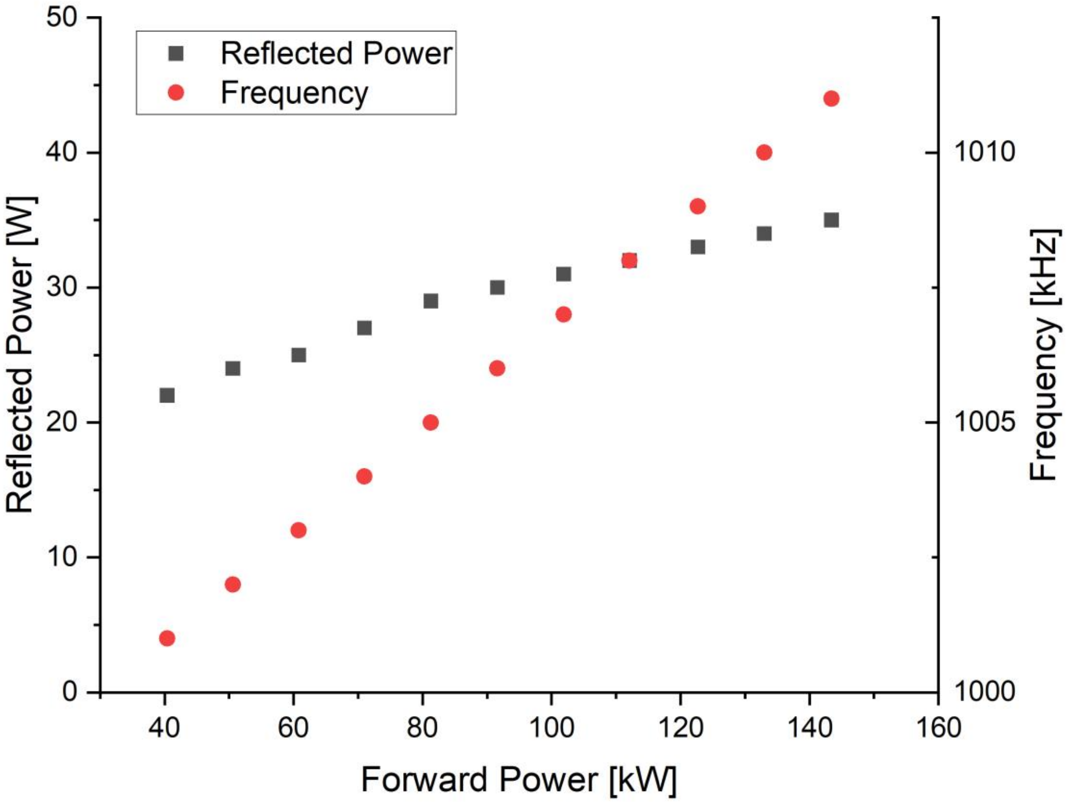
The Unexpected I (RF Matching)

Turns of C2

Source 3: $\boldsymbol{P_{RF}}(f)$ = 30 kW; C1 = 1.5 nF



Source 3: C1 = 1.5 nF; C2 = 26



Source Gas Flow = 25 mbar-l/s

SCIAMP Frequency range: 950-1050 kHz

The Unexpected I (RF Matching)

Source 3 By Eye

Source 3 5s „beam“ and ~8 s RF total

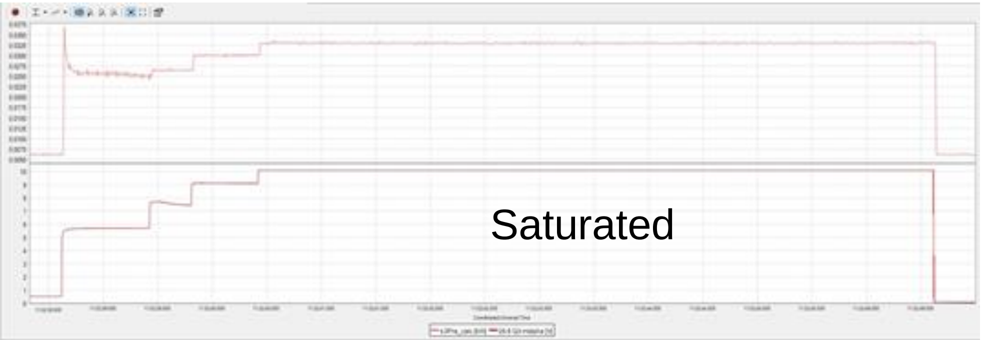
Pure RF

Flow: 25/0 mbar-l/s

P_{RF}(f): 40/120 kW – 1001/1009 kHz

$P_{RF}(r)$

Hα (a.u.)



Saturated

33 W

28.05.24

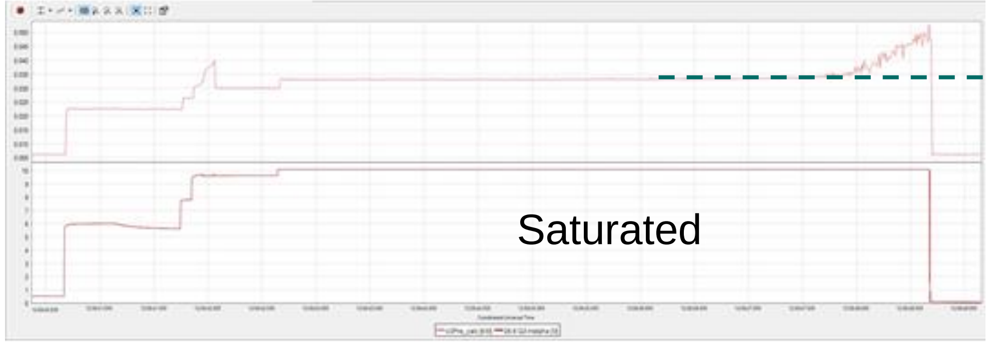
Pure RF

Flow: 20/55 mbar-l/s

P_{RF}(f): 40/120 kW – 1001/1012 kHz

$P_{RF}(r)$

Hα (a.u.)



Saturated

50 W

33 W

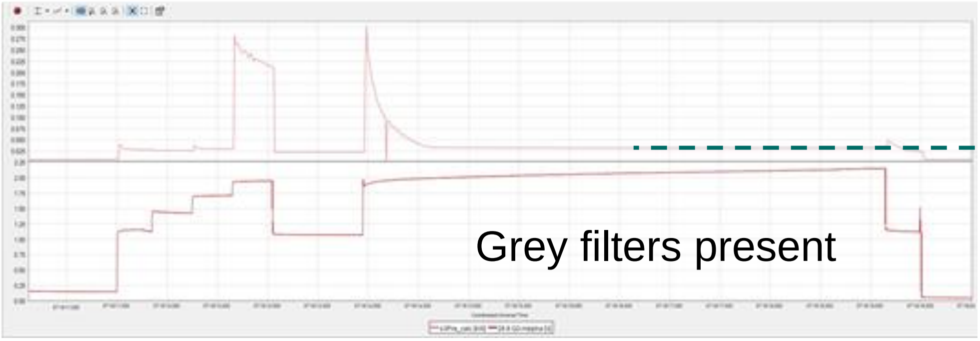
Beam into W7-X

Flow: 20/55 mbar-l/s

P_{RF}(f): 40/110 kW – 1001/1012 kHz

$P_{RF}(r)$

Hα (a.u.)



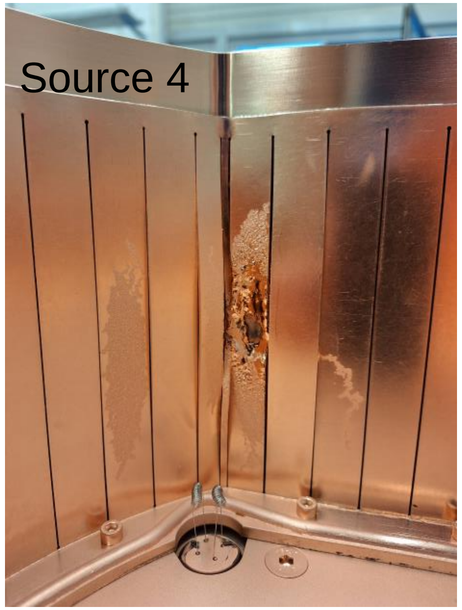
Grey filters present

300 W

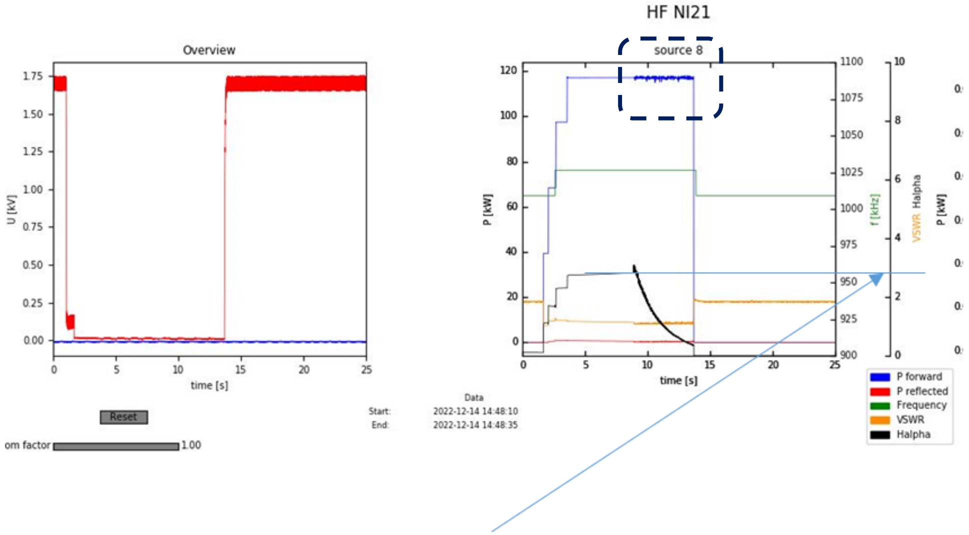
25 W

15.05.25

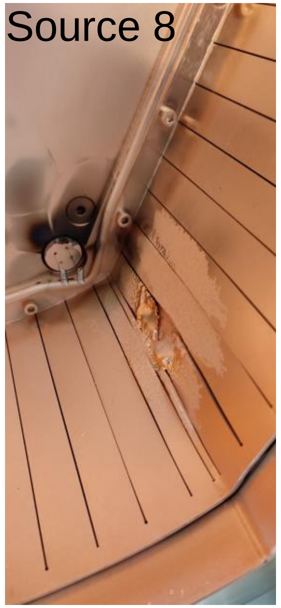
The Unexpected II (Damage to Faraday Screen)



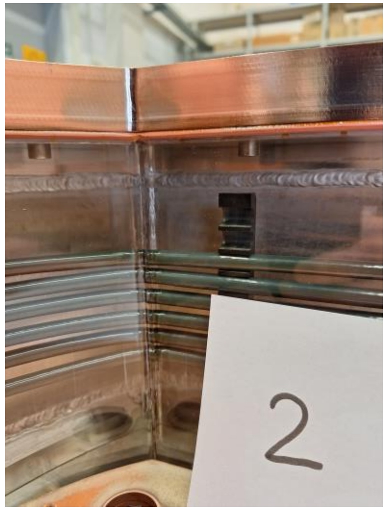
Source 4



Light level starts at the level from the end of the last shot.
Window is already partially coated.



Source 8

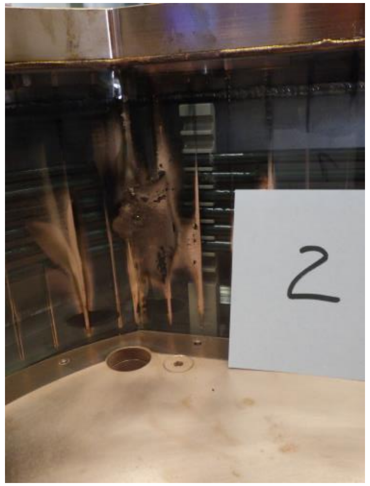


Source 3

Reason:

- Design Failure
- Stray Magnetic Field

Source 7



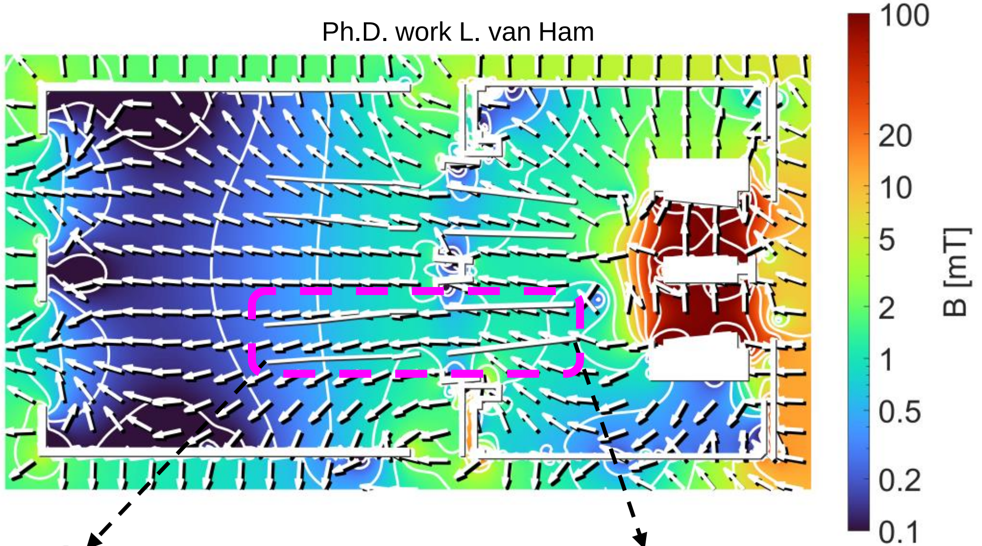
The Unexpected III (Beam Distortion from W7-X Stray Field)

W7-X Standard Field Configuration

Ph.D. work L. van Ham

PINI8

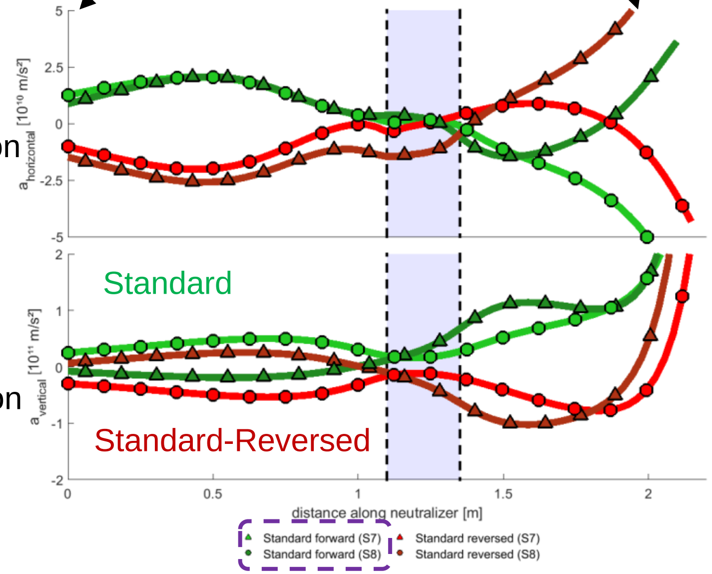
PINI7

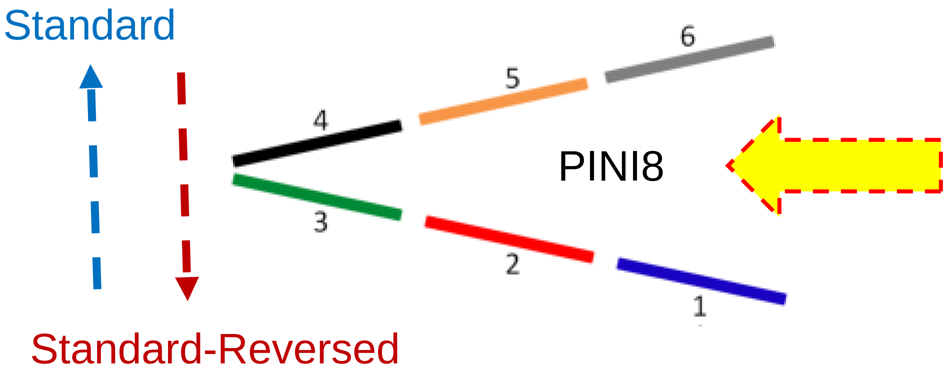


Horizontal Acceleration

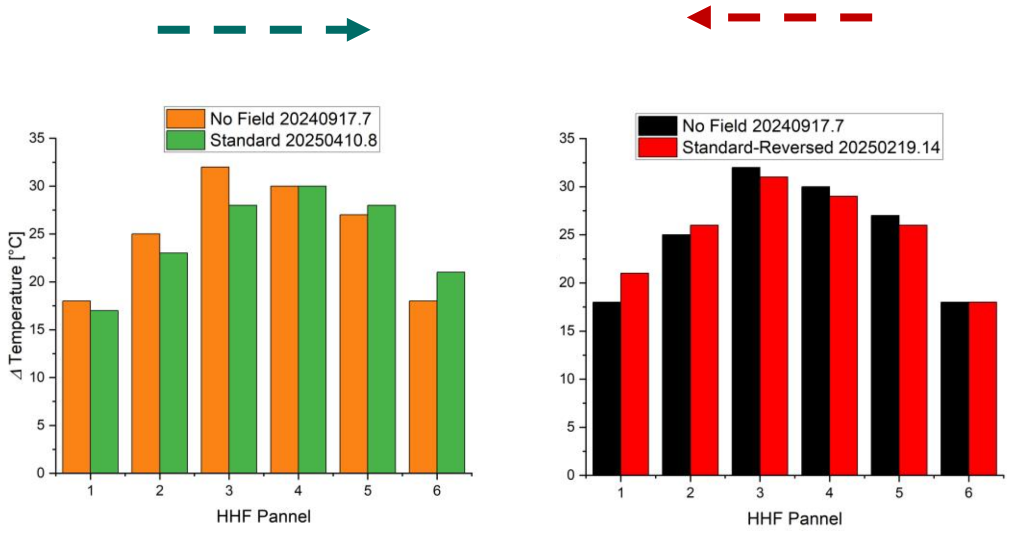
Vertical Acceleration

Beams3D





Beam on Calorimeter



Beamlet:

Gaussian → Binomial?

No Code Exists

Future Plans/Summary

- **Future Plans:**
  - Short Term:
    - Current Control
    - 10+ s injection into W7-X
  - Long Term:
    - More PINIs
    - Longer Beams and higher repetition rate

- **Summary:**
  - NBI on W7-X is now a reliable heating system
  - Sources are in a good state
  - The Unexpected strikes!
    - Matching – behavior of the SCIAMP: new learning curve
    - Faraday Screen – has survived 30 years on AUG, even with a design defect; we killed it
    - Magnetic Field – see the effect but lack the tools to describe it quantitatively

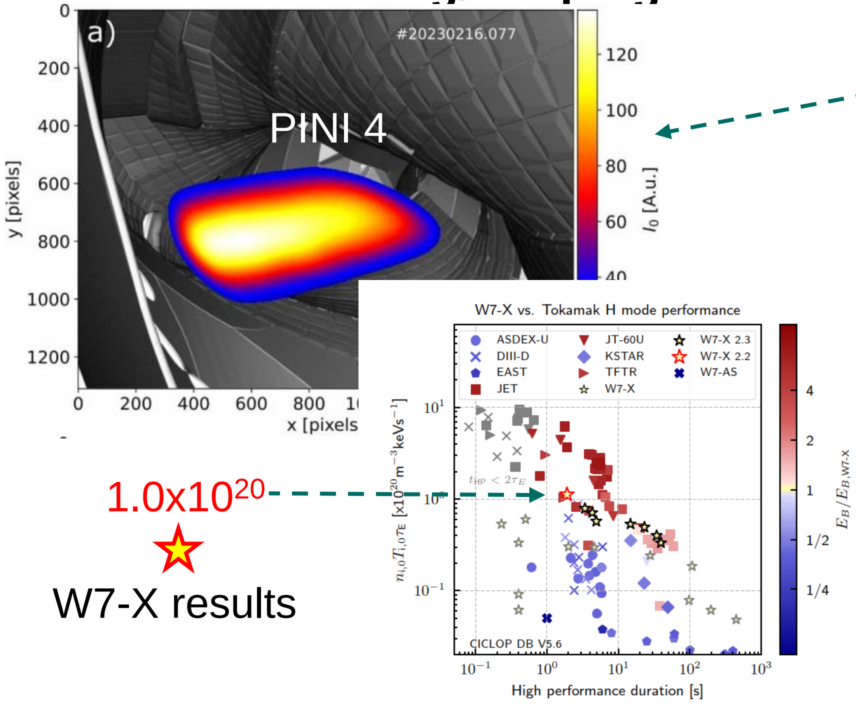
New People!

We are looking for new members for our Group

Uses of the NBI on W7-X

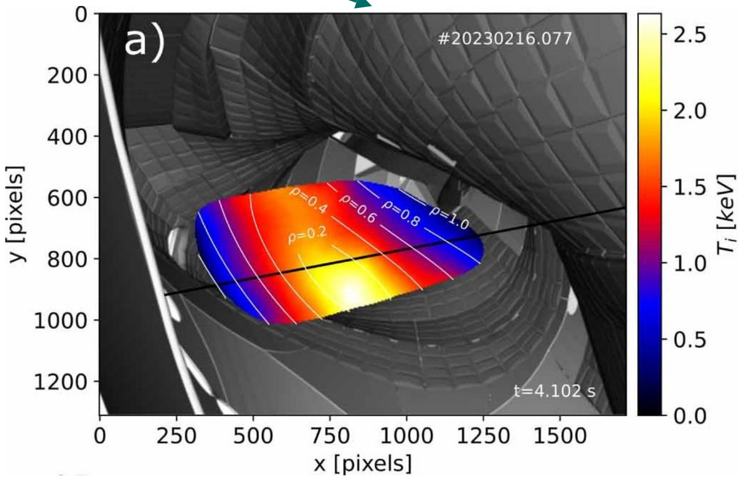
Heating / High Performance[3]

- ~7 MW of Heating (H)
- Current Drive
- Fueling/Shaping



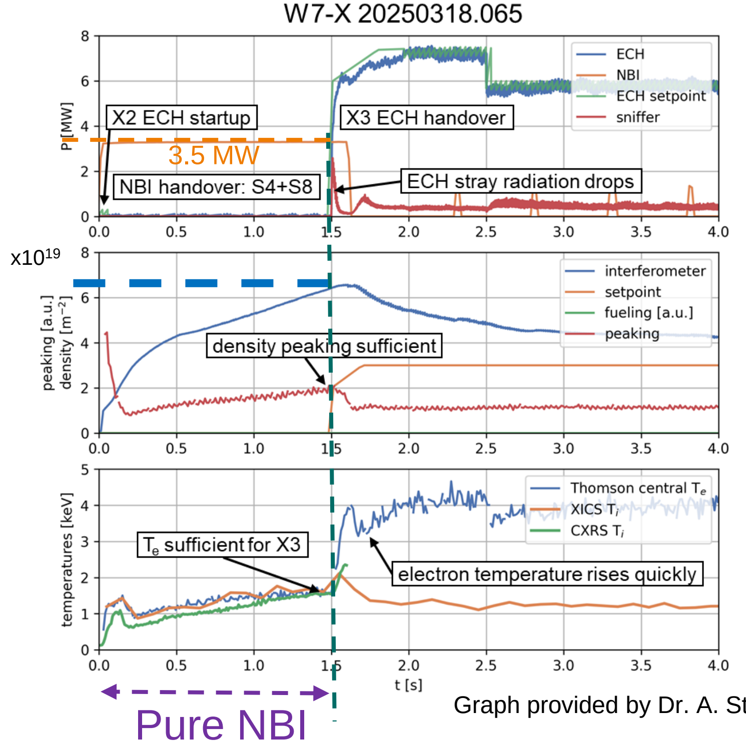
Diagnostics

- CXRS (T_i and many more)
- Impurity density profiles
- Transport coefficients
- CICERS[2]



Low Field Startup (1.8 T)

ECRH: 101 GHz (300 kW)



Graph provided by Dr. A. Stechow

[2]R Lopez-Cansino *et al* 2024 *Plasma Phys. Control. Fusion* **66** 045012

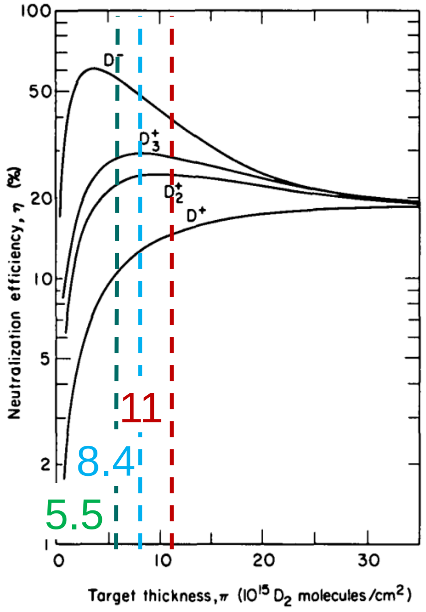
[3]S Bannmann *et al*, submitted to *Phys. Rev. Lett.*

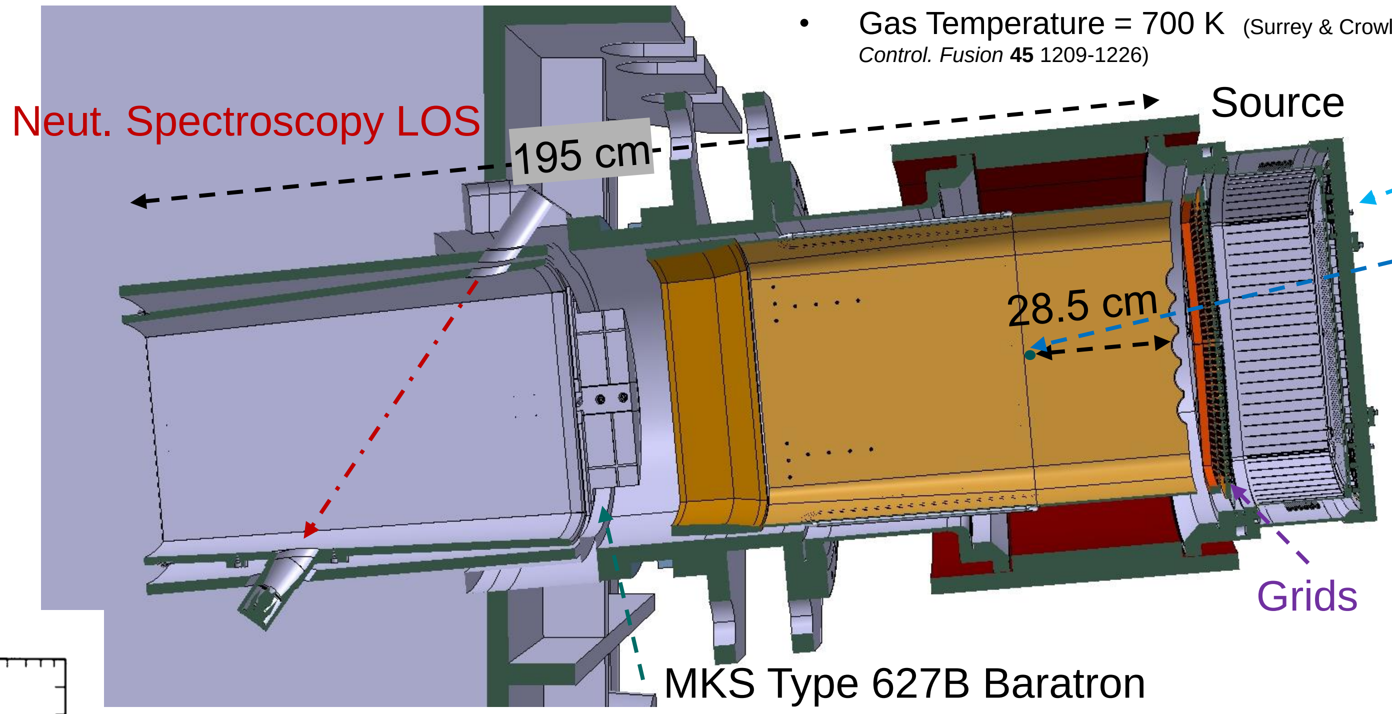
The (Un)expected IV (Neutralizer)

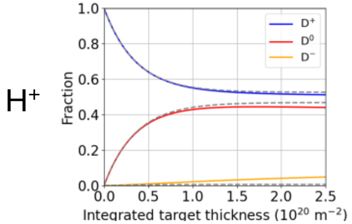
Theory

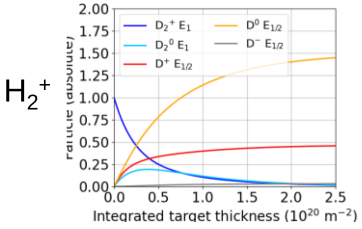
Target Thickness Assumptions:

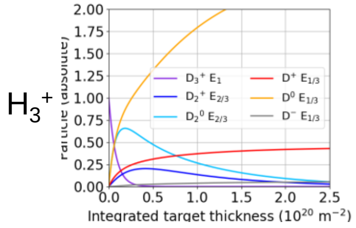
- Calculated pressure slope = constant (line)
- Measured pressure = neutralizer pressure
- Gas Temperature = 700 K (Surrey & Crowley 2003 *Plasma Phys. Control. Fusion* **45** 1209-1226)

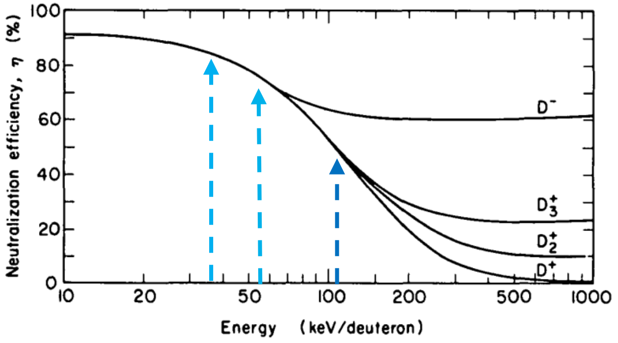












K.H. Berkner, *et al.* 1975 *Nucl. Fusion* **15** 249

55 keV, H		Target Thickness (m^{-2})			
		5.5×10^{19}	8.4×10^{19}	11.1×10^{19}	No Adj.
Species	Current (%)	η (%)	η (%)	η (%)	η (%)
H^+	60	25	33	35	48
H_2^+	33	68	78	78	78
H_3^+	7	77	82	79	82
Total η (%)		**43**	**51**	**53**	60

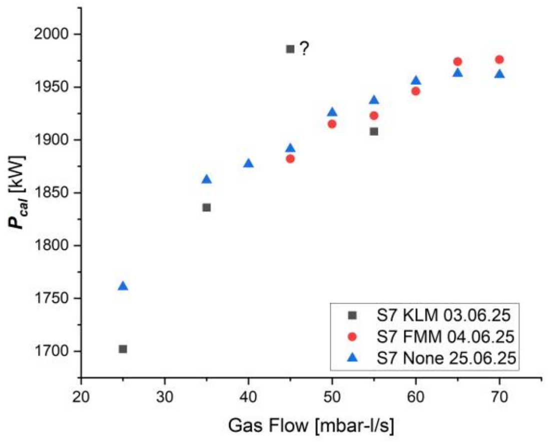
N. den Harder *et al.* 2019 *Fus. Eng. Des.* **146** 518-521

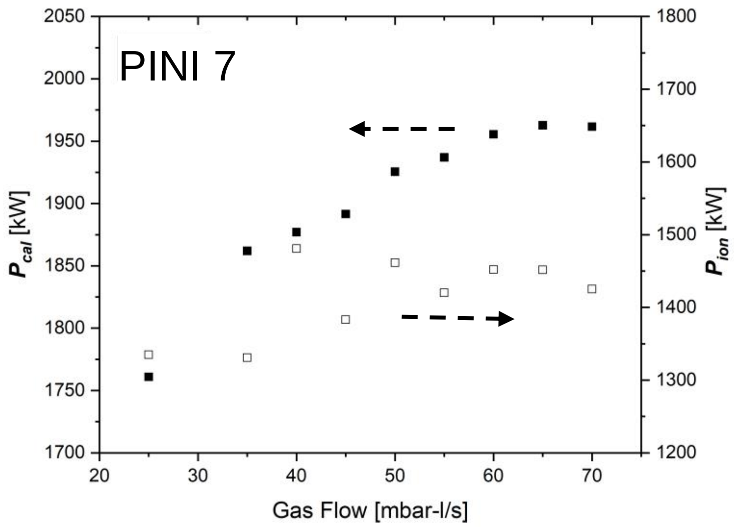
55 keV, H	**Target Thickness (m^{-2})**		
	5.5×10^{19}	8.4×10^{19}	11.1×10^{19}
P_{neut} (MW)	2.3	2.6	2.7
P_{ion} (MW)	2.6	2.3	2.2
η (%)	**46**	**52**	**54**

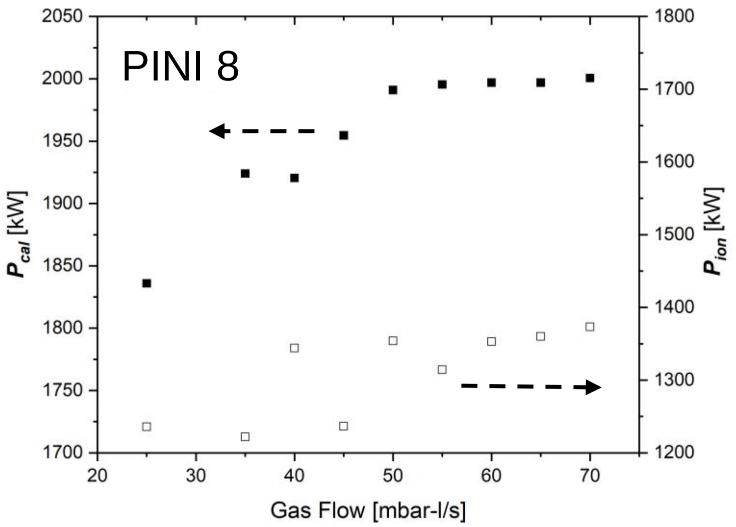
The Unexpected IV (Neutralizer)

Practice

Data from 25.06.25







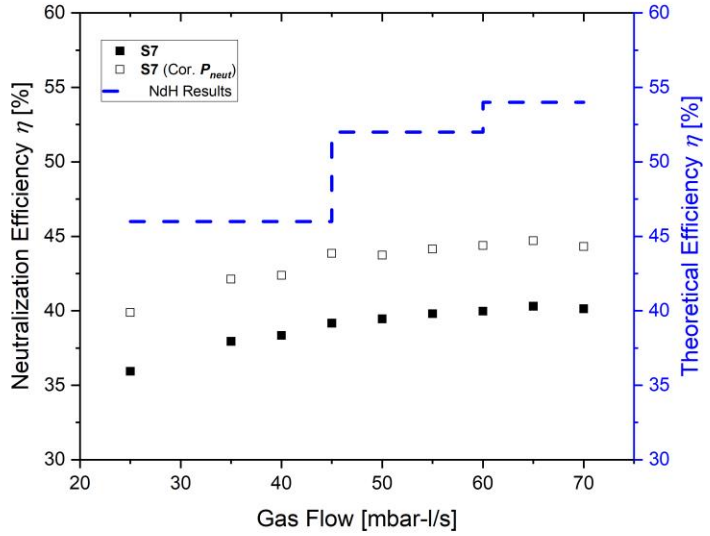
NOTE: 1MW electrical power <u>NOT</u> accounted for!!!

Results:

- η lower than predicted!
- P_{cal} lower than predicted
- $P_{ion} < P_{cal}$ ✓
- P_{ion} increases!

55 keV, H	Target Thickness (m^{-2})		
	5.5×10^{19}	8.4×10^{19}	11.1×10^{19}
P_{neut} (MW)	2.3	2.6	2.7
P_{ion} (MW)	2.6	2.3	2.2
η (%)	**46**	**52**	**54**

NdH Code Predictions



The Unexpected V (Residual Ion Deflection Magnet)

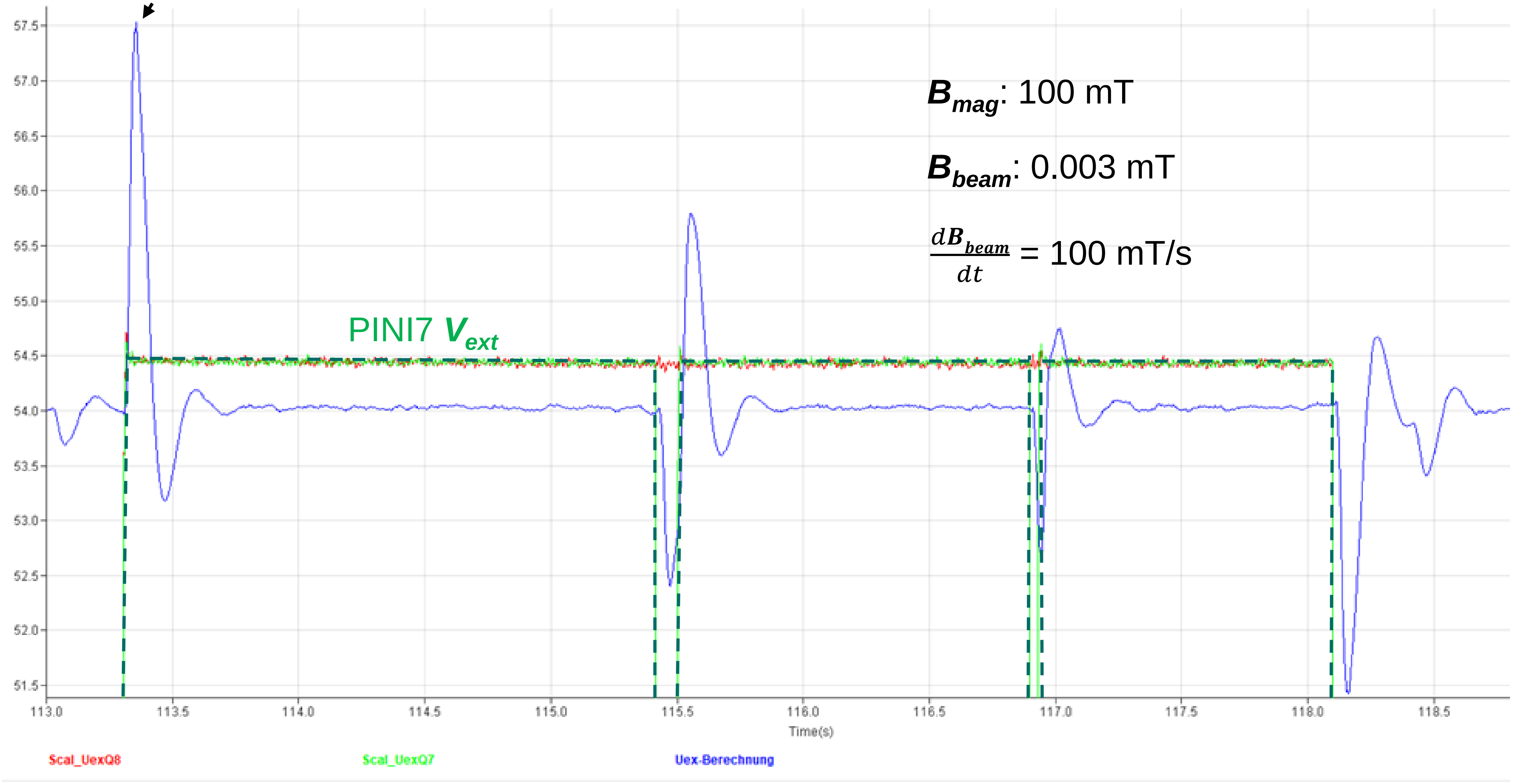
Beam voltage the magnet is set to deflect calculated from I_{mag}(measured at 1 kHz)

B_{mag}: 100 mT

B_{beam}: 0.003 mT

$\frac{dB_{beam}}{dt}$ = 100 mT/s

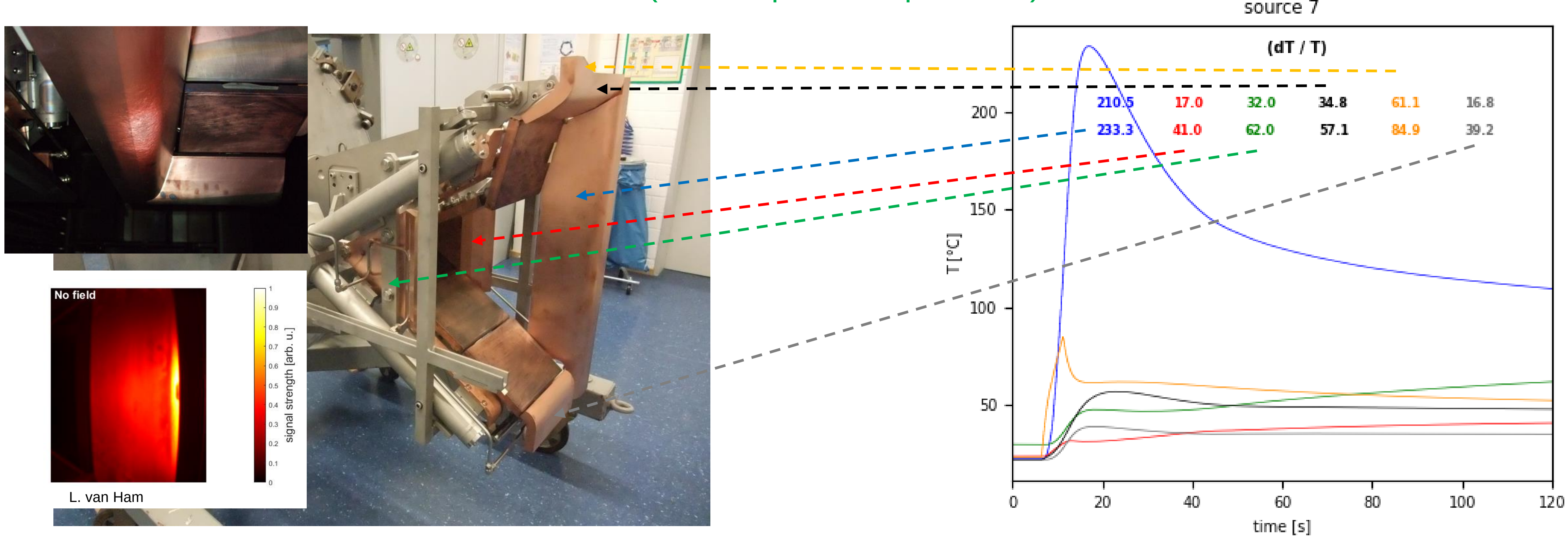
PINI7 V_{ext}



Wendelstein 7-X

Unexpected VI: Limitations on NBI Operational Time

- **Limits operation to 5 s in H due to overheating of inertial cooled „Wing“**
  - Solution – new „Wing“ with active cooling (now in use on AUG NBI)
  - Status: will be installed next MP (>60 s operation possible)



5 s 55keV/90A