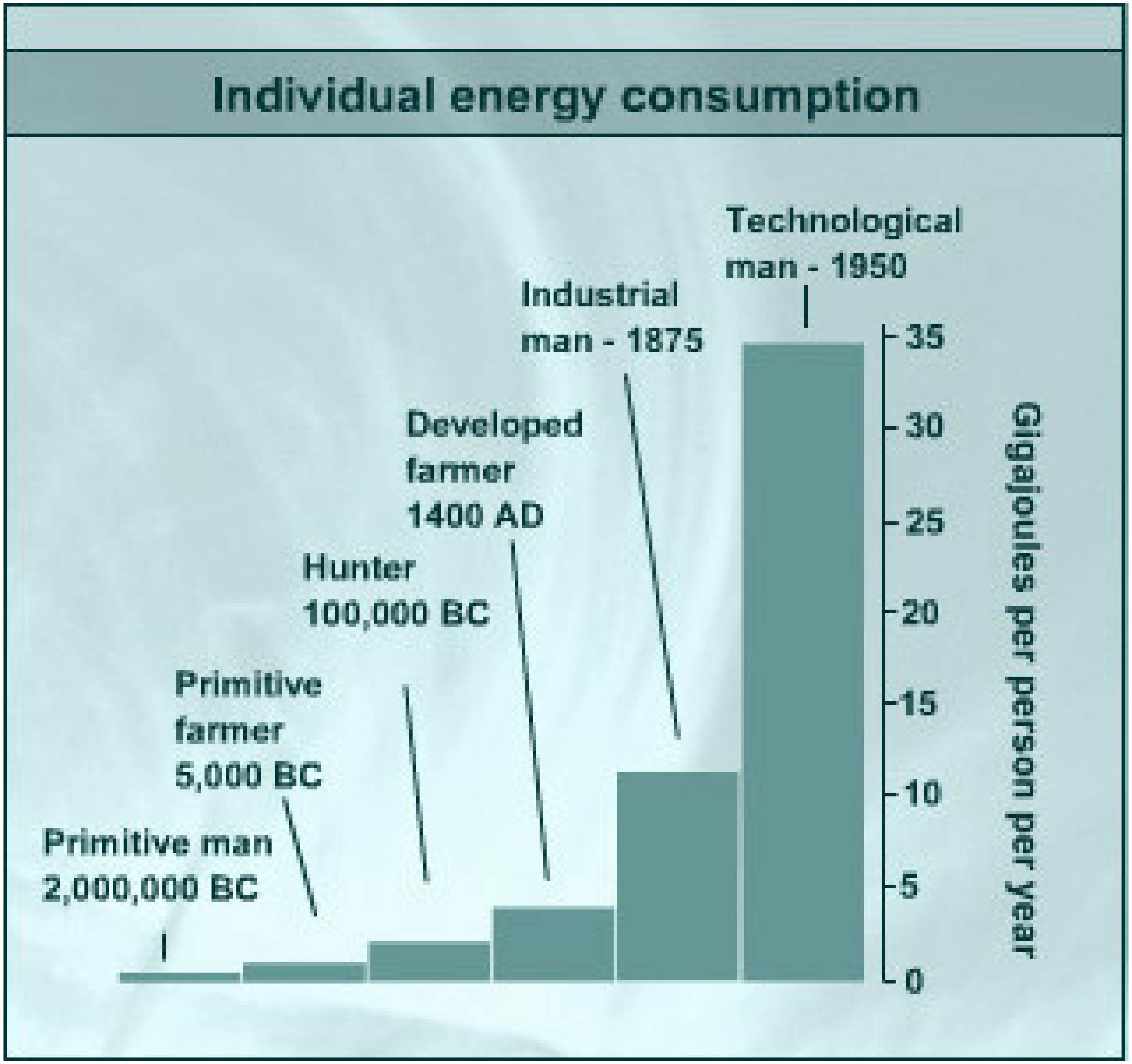
Soft X-ray spectrometer for plasma experiment Wendelstein 7-X

Dr. Ireneusz Książek,
Institute of Physics, Opole University, Opole, Poland

Outline:

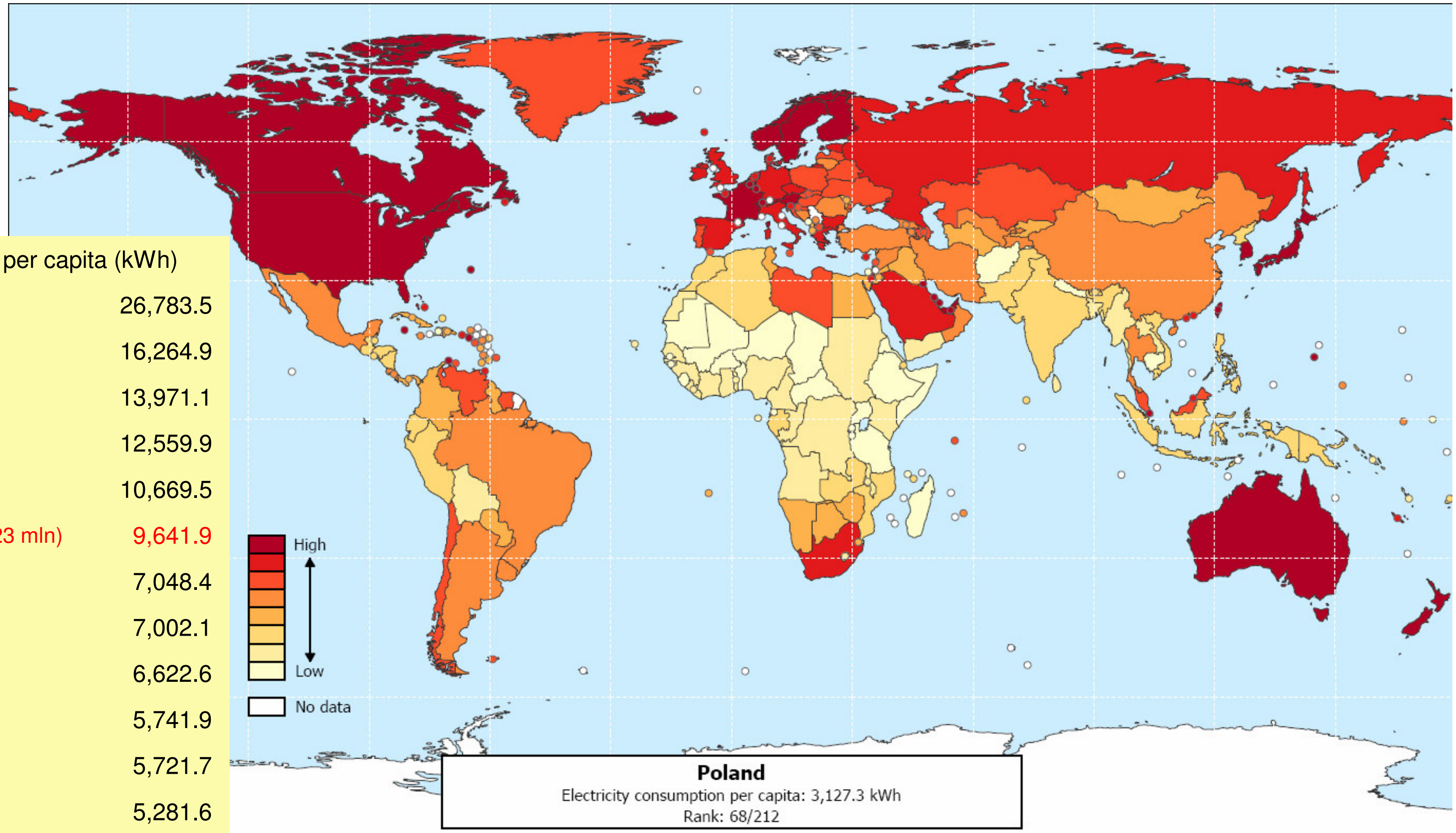
- Thermonuclear fusion
- Magnetic confinement:
  tokamak and/or/vs stellarator
- Wendelstein 7-X
- Soft X-ray radiation of high-temperature plasma
- C-/O- monitor for ASDEX-U
- C-/O- monitor for W7-X
- Detector for C-/O- monitor

Energy demand

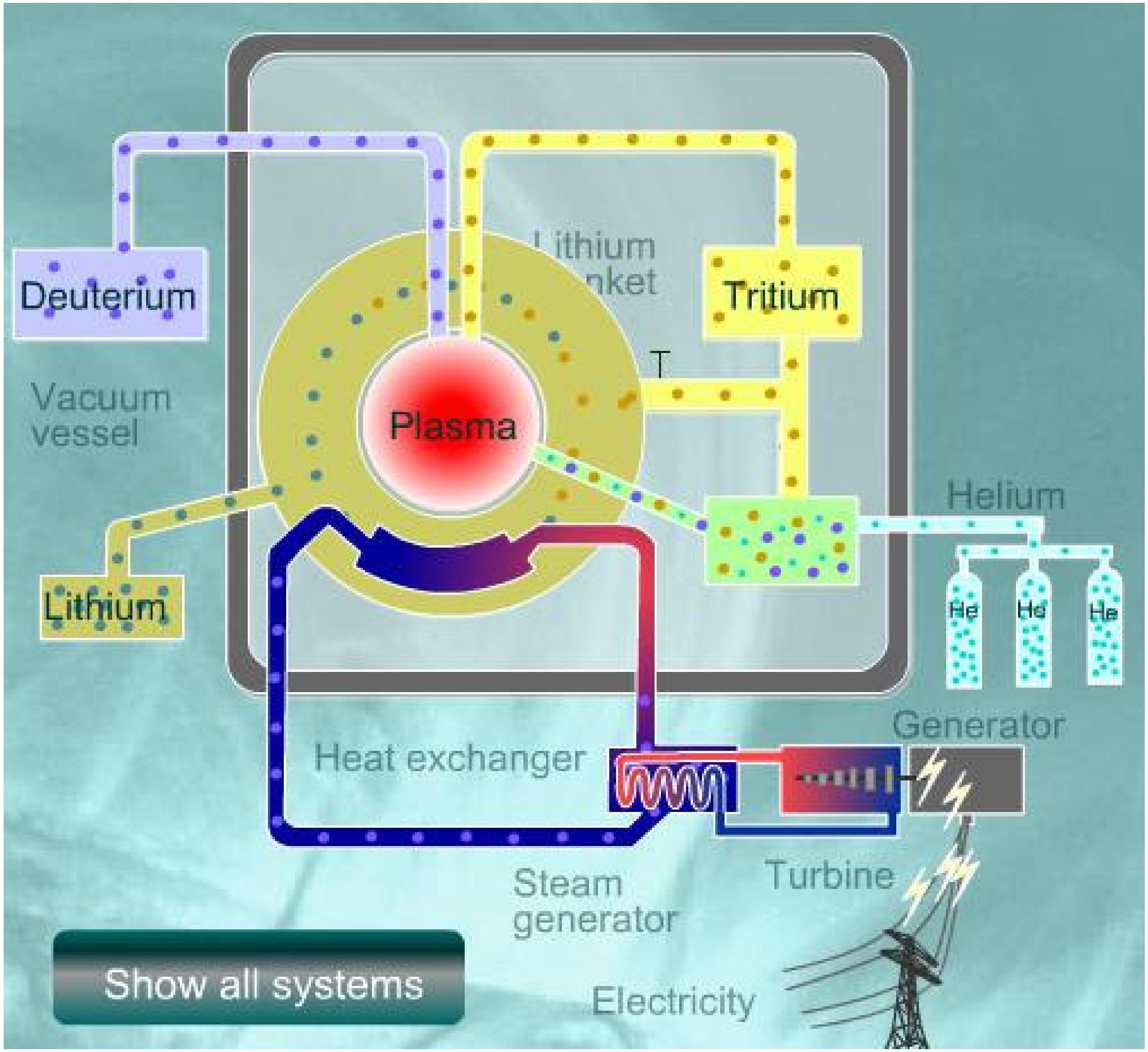

Individual energy consumption
Technological man - 1950
Industrial man - 1875
Developed farmer 1400 AD
Hunter 100,000 BC
Primitive farmer 5,000 BC
Primitive man 2,000,000 BC
35
30
25
20
15
10
5
0
Gigajoules per person per year

Electricity Consumption per capita (kWh)

1	Iceland		26,783.5
4	Canada		16,264.9
6	Kuwait		13,971.1
9	United States		12,559.9
11	Australia		10,669.5
13	Taiwan	(~23 mln)	9,641.9
26	France		7,048.4
27	Russia		7,002.1
32	Germany		6,622.6
42	Hong Kong		5,741.9
44	United Kingdom		5,721.7
47	Italy		5,281.6
68	**Poland**		**3,127.3**
86	China	(~1300 mln)	2,149.6
93	Brazil		1,920.2
156	India		425.6
198	Haiti		36.1
199	Ethiopia		33.0
206	Afghanistan		24.5
207	Central African Republic		22.9
208	Rwanda		19.5
212	Gaza Strip		0.2



Source of energy – high temperature plasma



Fusion reactions:

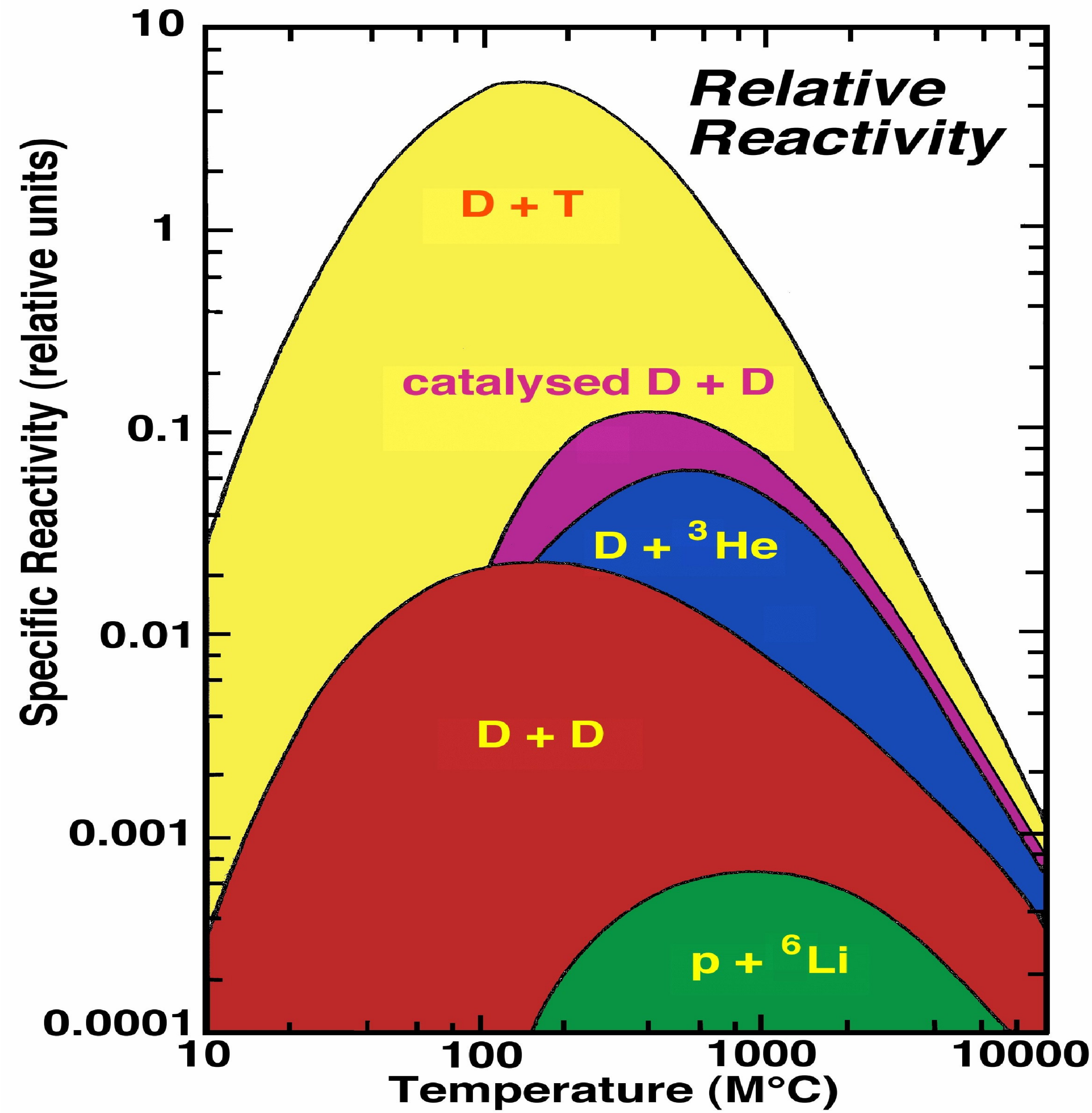
$$\mathbf{D}+\mathbf{D}\rightarrow\mathbf{T}\left(1{,}01\ MeV\right)+\mathbf{p}\left(3{,}02\ MeV\right)$$ (~50%)

$$\mathbf{D}+\mathbf{D}\rightarrow\mathbf{He^{3}}\left(0{,}82\ MeV\right)+\mathbf{n}\left(2{,}45\ MeV\right)$$ (~50%)

$$\mathbf{D}+\mathbf{D}\rightarrow\mathbf{He^{4}}\left(20\ MeV\right)$$ (~0,0001%)

$$\mathbf{D}+\mathbf{T}\rightarrow\mathbf{He^{4}}\left(3{,}5\ MeV\right)+\mathbf{n}\left(14{,}1\ MeV\right)$$

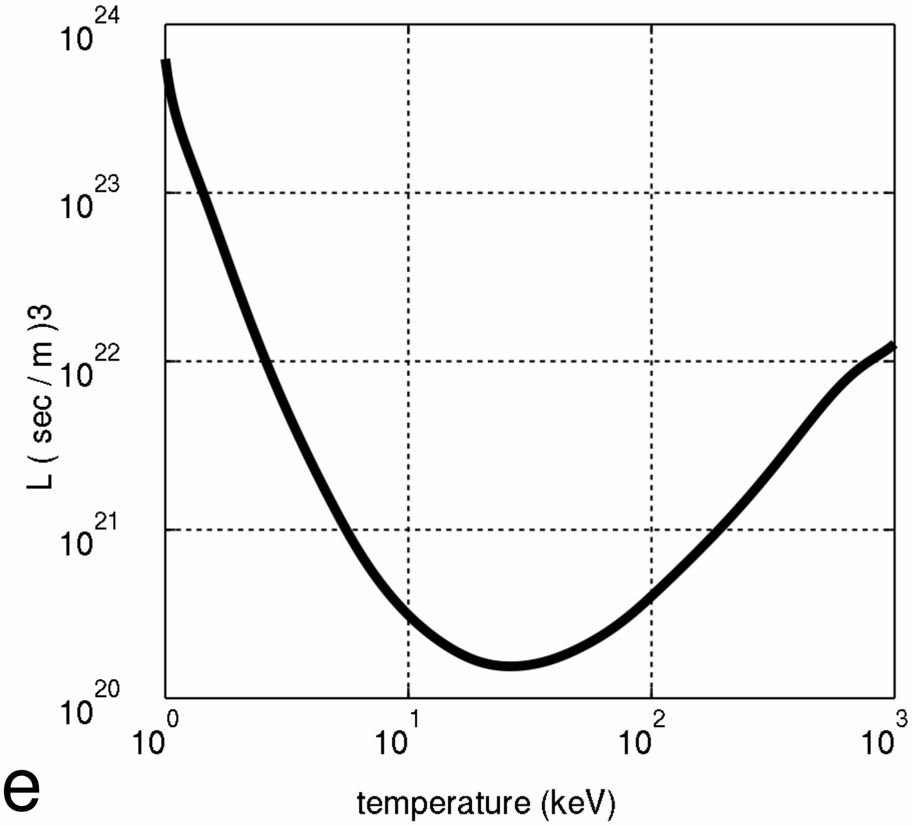
$$\mathbf{D}+\mathbf{He^{3}}\rightarrow\mathbf{He^{4}}\left(3{,}6\ MeV\right)+\mathbf{p}\left(14{,}7\ MeV\right)$$


Relative Reactivity
D + T
catalysed D + D
D + ³He
D + D
p + ⁶Li
Specific Reactivity (relative units)
10
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
Temperature (M°C)

Magnetic confinement fusion

tokamak vs. stellarator

Lawson criterion
(for D-T plasma)



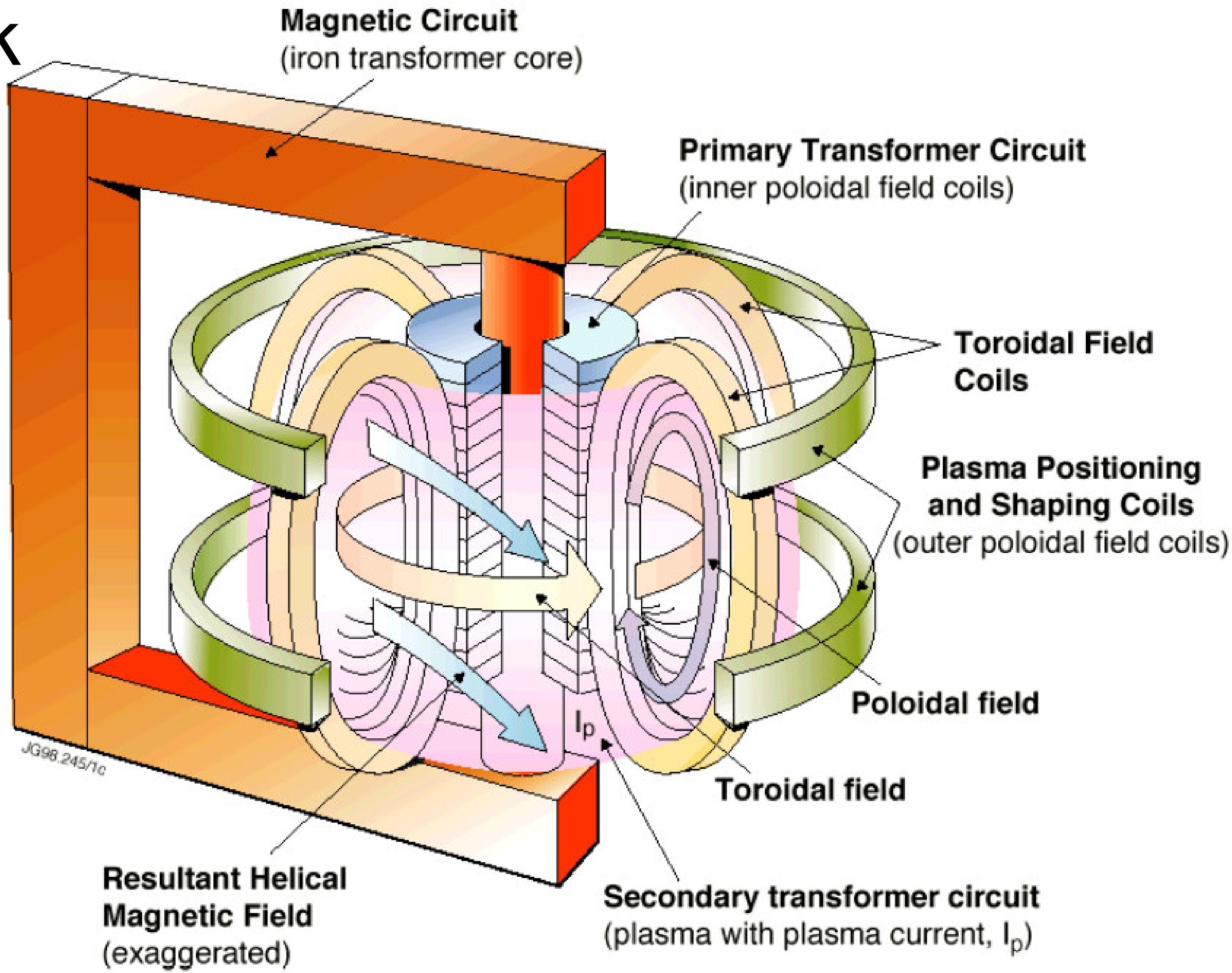
temperature

$$n \cdot T \cdot \tau > 10^{21}\ \ keV \cdot s/m^3$$

density

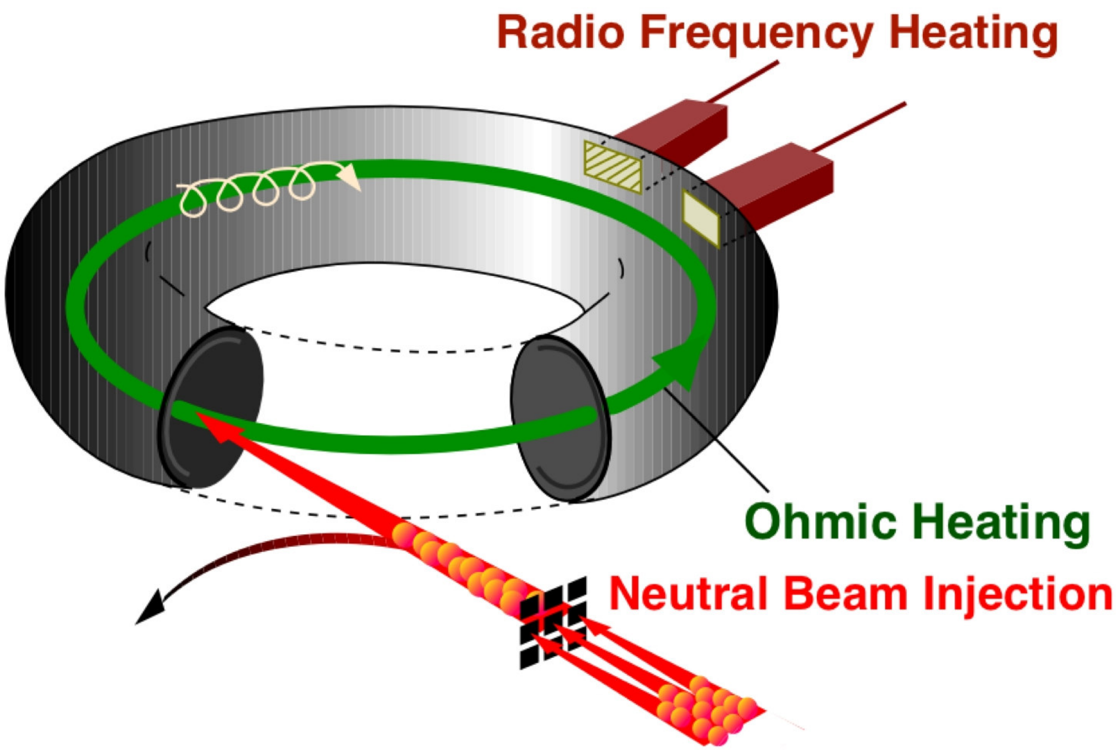
confinement time

Tokamak



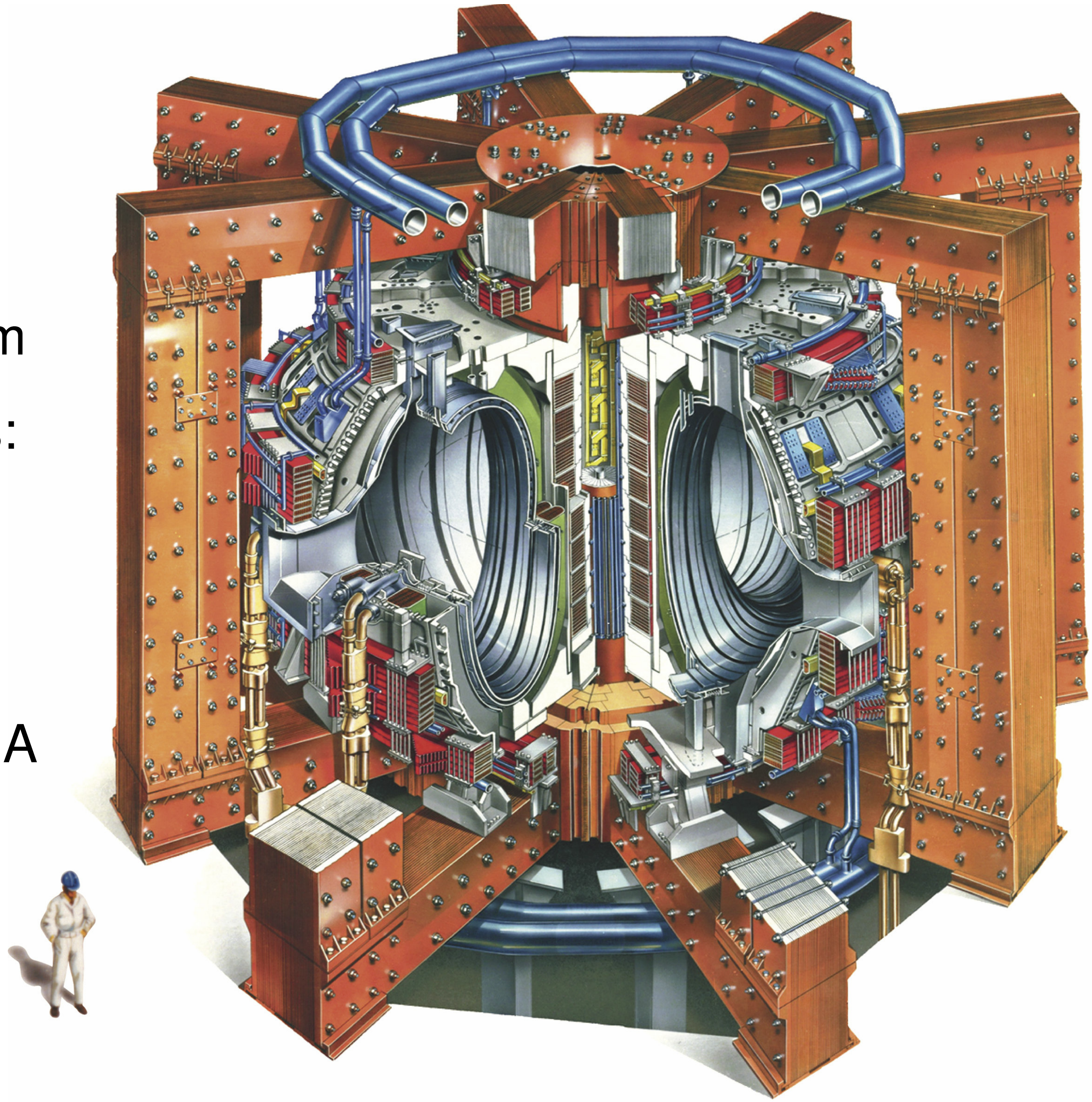
$$n \approx 10^{20} m^{-3}, \qquad \tau \approx 0.1 \div 100 s$$

Plasma heating



http://iter.rma.ac.be/en/physics/plasmaheating/index.php

JET
(Joint European Torus)



Major radius: 2,96 m

Plasma dimensions: 2,10 m × 1,25 m

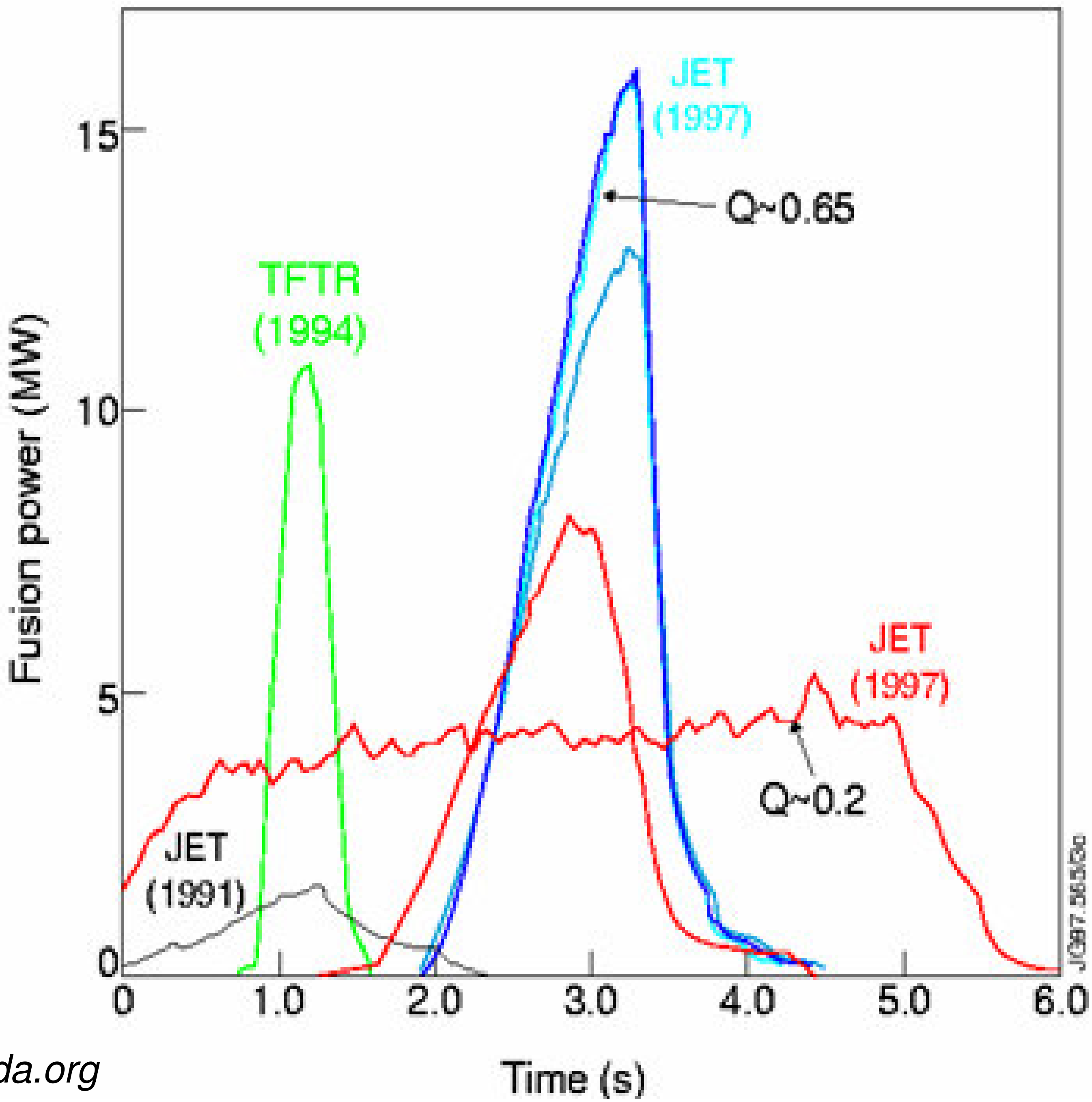
Plasma volume (approx.) 100 m^3

Plasma current 5 MA

Magnetic field: 4 T

www.efda.org

JET best result



TOKAMAK JET: www.efda.org

TOKAMAK problems

Only pulsed mode

Instabilities:

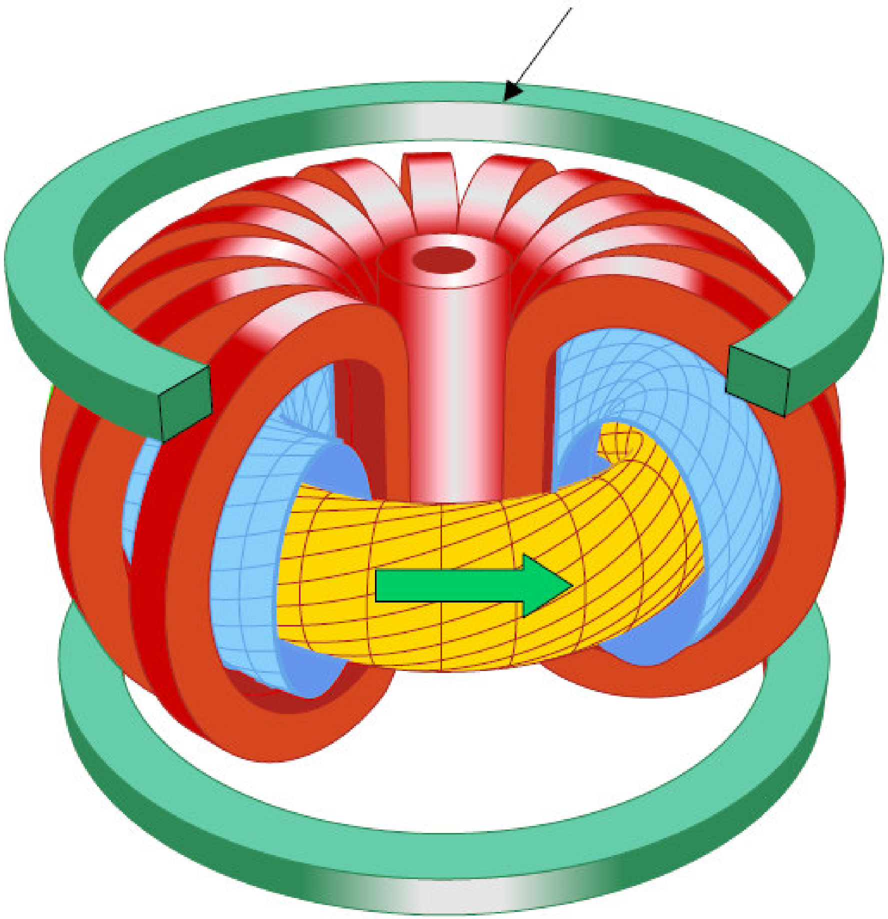
- ‘ELMs’ (Edge Localized Modes)
- ‘disruptions’

Problems to solve:

- transport theory
- material research

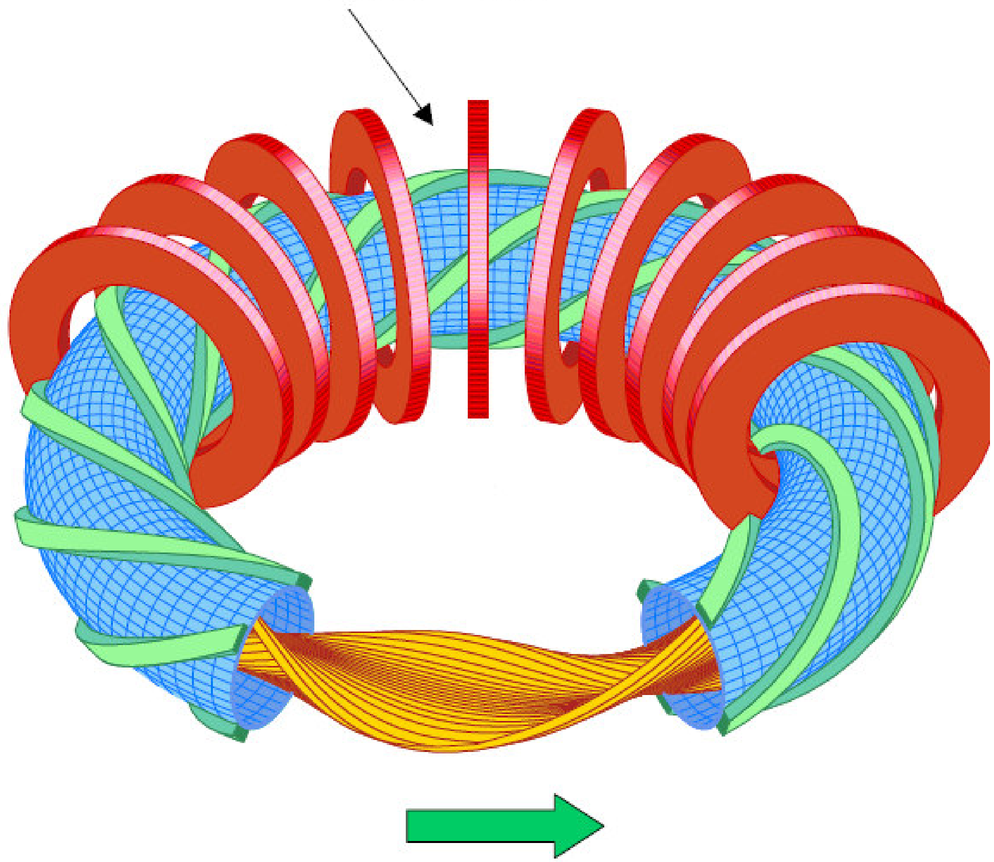
Tokamak or stellarator?

L. Artsimovich in Moskau about 1950



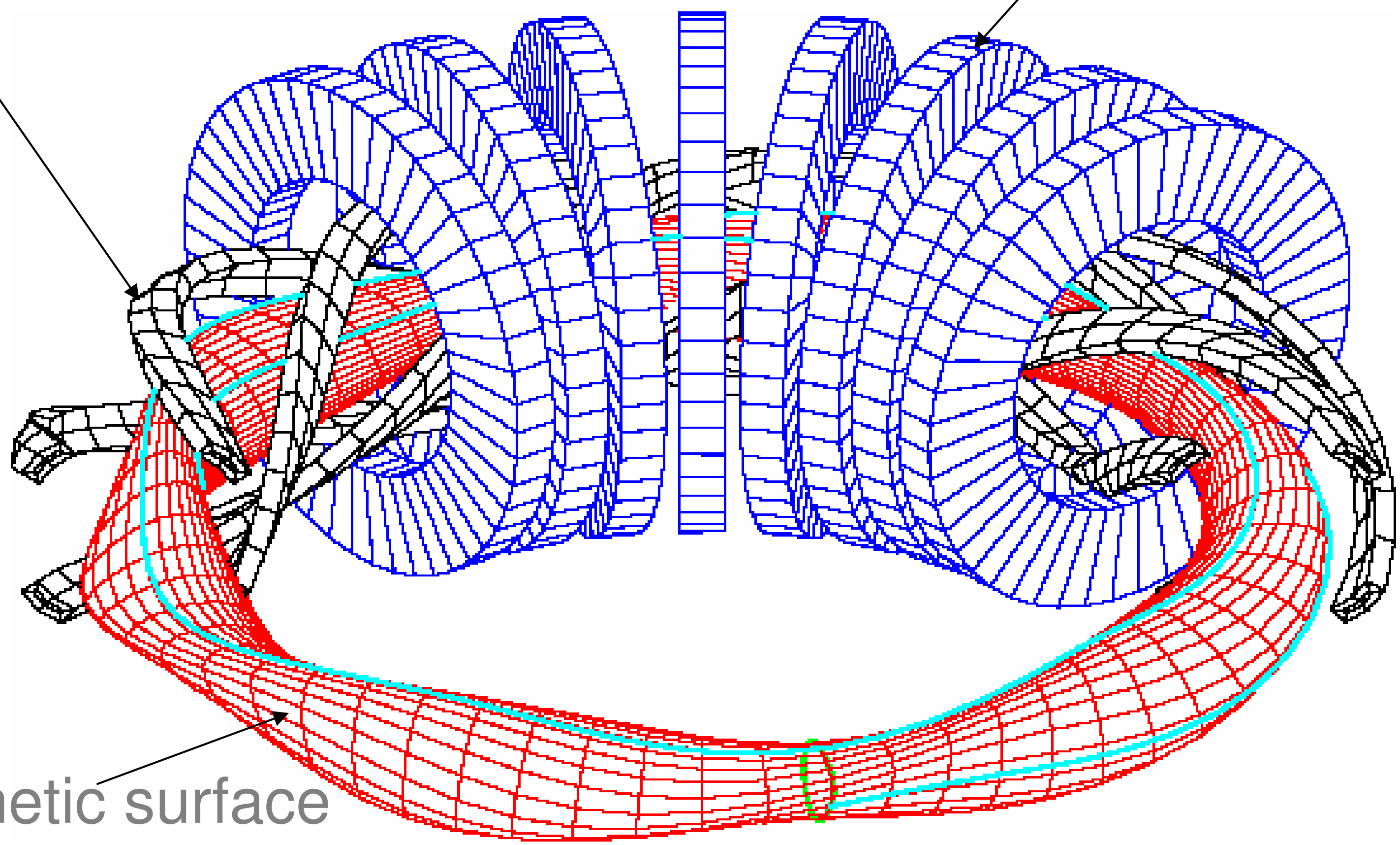
current flows in the plasma

L.Spitzer in Princeton about 1950
stella= "star"



current in external (helical) coils

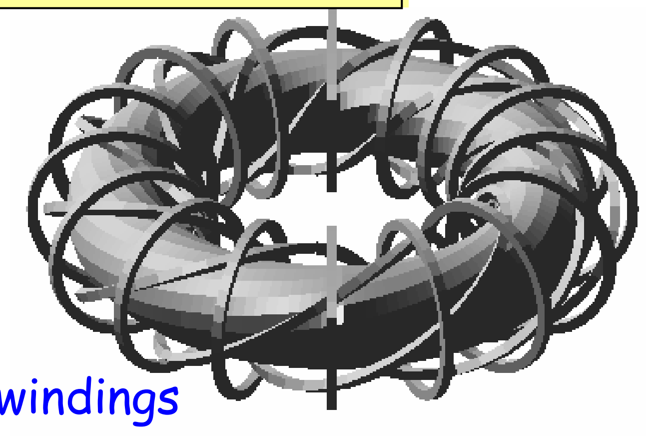
STELLARATOR, basic principle



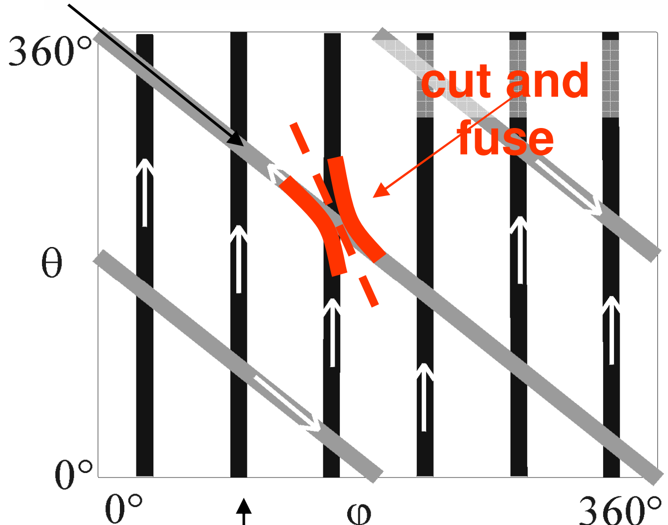
From Hans-Jürgen Hartfuß

W7-X REALIZATION, modular coils

classical Stellarator

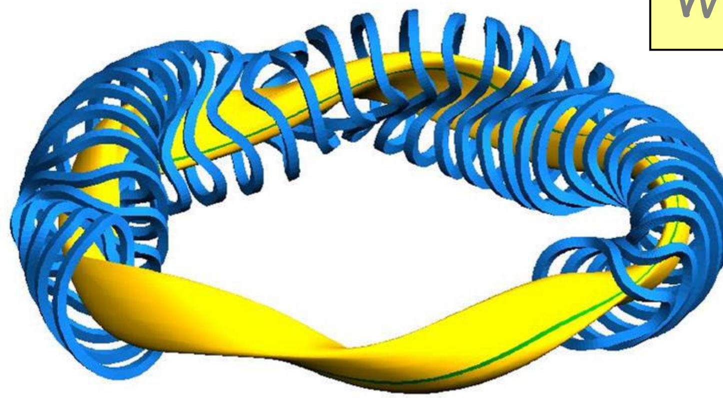


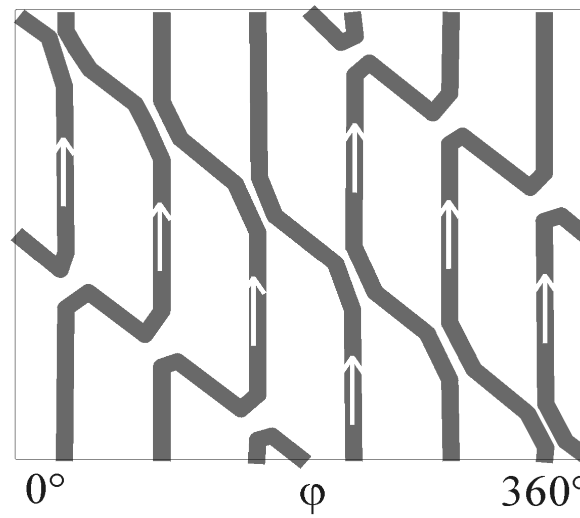
helical windings



toroidal field coil

W7-X





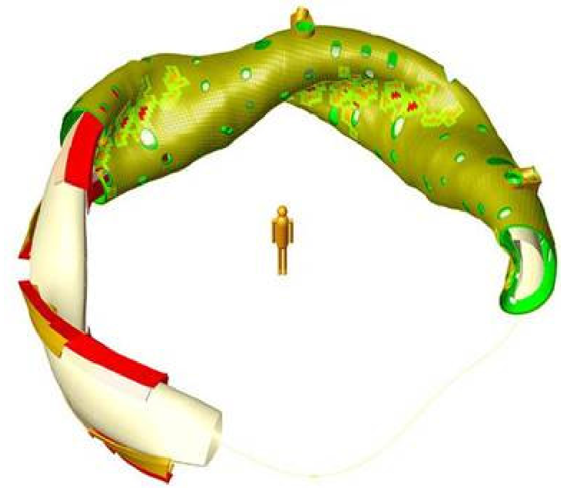
modular coils instead helical windings
avoidance of toroidal current: 3-d geometry

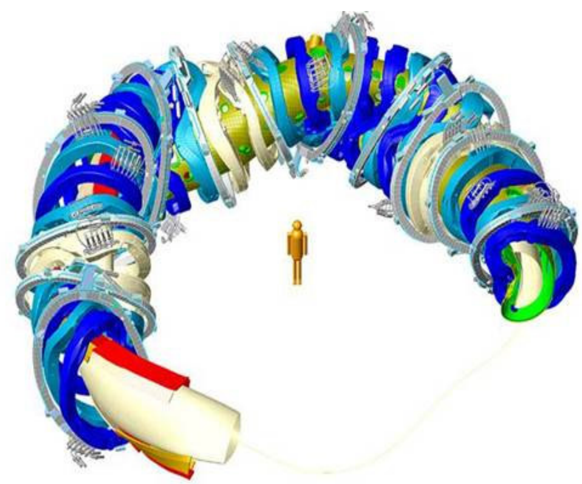
Main purposes of Wendelstein 7-X:

- producing plasmas allowing predictions on a stellarator power plant plasma
- continuous operation (up to 30 min.)
- constructing a modular superconducting coil system

W7-X, mechanical parameters

major radius	5.6 m
minor radius	0.53 m
plasma volume	30 m^3
induction on axis	3 T (2.5 T)
non-planar coils	50
planar coils	20
machine height:	4.5 m
machine diameter:	16 m
machine mass:	725 t





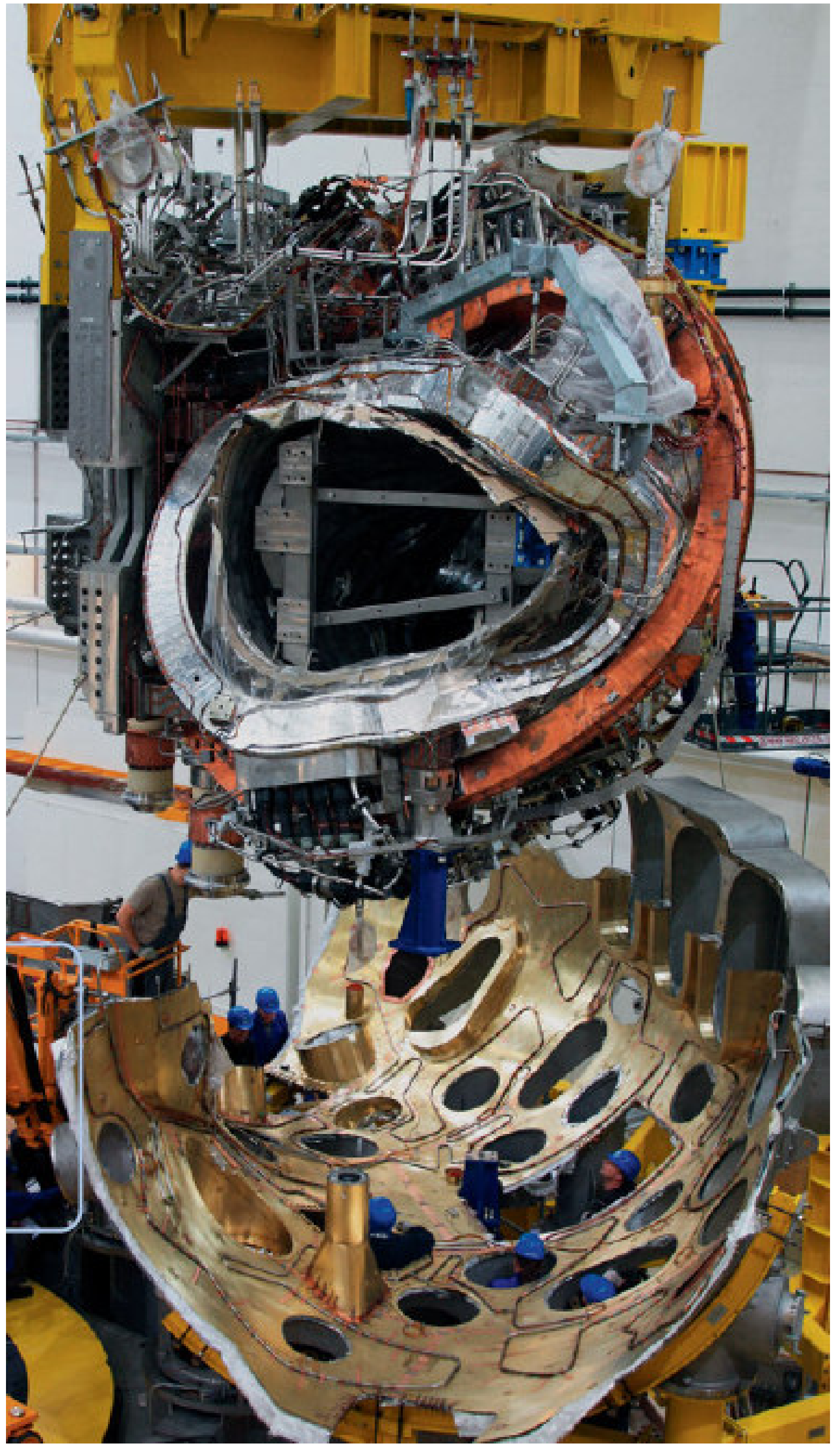
W7-X, heating, parameter range

$T_e \leq 10keV$ (electron temperature) $T_i \leq 6$ keV (ion temperature) $n_e \leq 3x10^{20}$ m^{-3} (electron density)

1 eV = 11 604 K

- ECRH: 10 MW, 140 GHz, 1800 s
  (Electron Cyclotron Resonance Heating)
- NBI: 10 MW 10 s
  (Neutral Beam Injection)
- ICRH: 2x2 MW, 30-115 MHz, 10 s
  (Ion Cyclotron Resonance Heating)

TEST ASSEMBLY, non-planar coil onto vacuum vessel



C-/O- Monitor

Measurements of most prominent lines (e.g. Lyman-α of hydrogen-like ions) of plasma impurities provide information about

- the erosion of the walls (C VI at 3.4 nm);
- the quality of the wall condition (O VIII at 1.9 nm);
- leakage in the vacuum systems (N VII at 2.5 nm);
- possible interaction of the plasma with materials containing boron (line B V at 4.9 nm);
- accumulation of impurities in plasma.

Monitor for the carbon and oxygen impurities in the ASDEX Upgrade tokamak

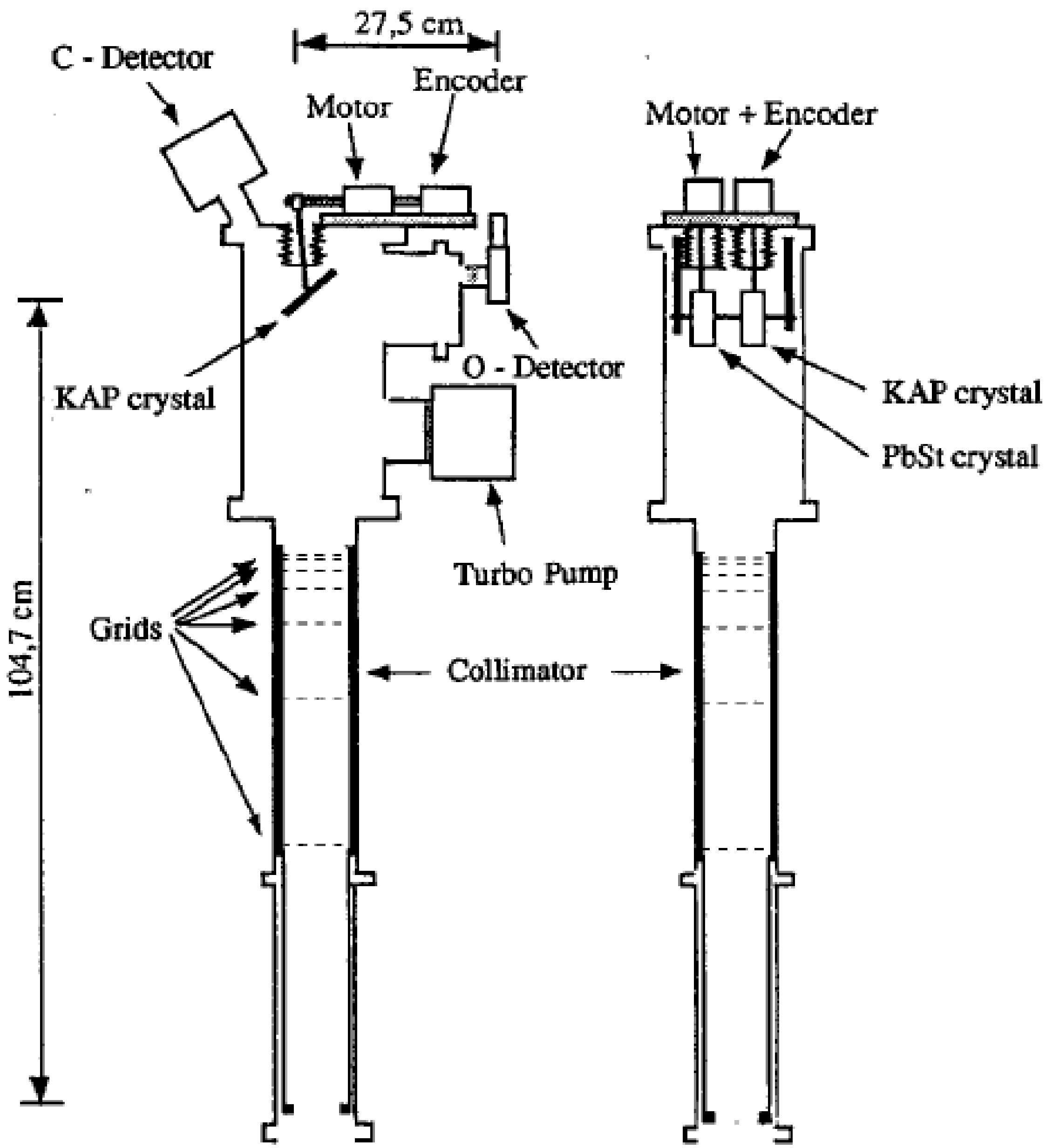
R. Neu, K. Asmussen, G. Fussmann, P. Geltenbort, G. Janeschitz, K. Schoenmann, G. Schramm, U. Schumacher, and the ASDEX Upgrade team,

Rev. Sci. Instrum. **67** (5), May 1996

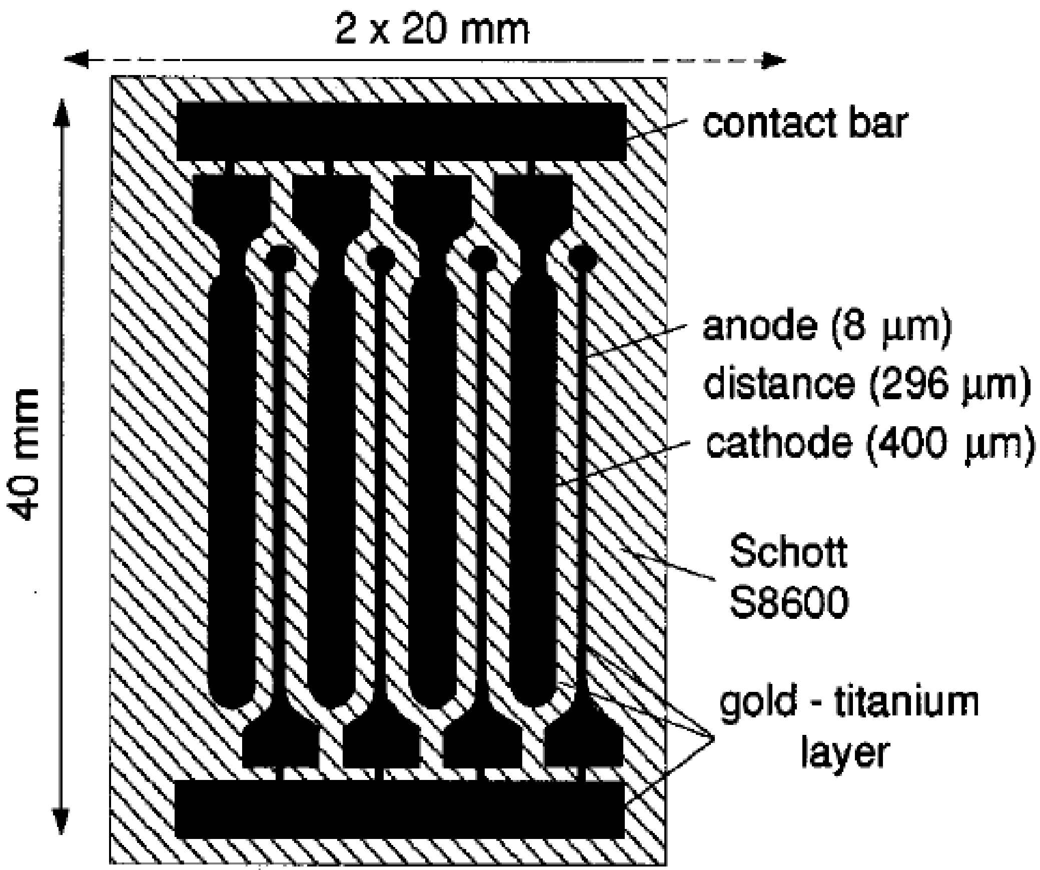
C-/O- Monitor for ASDEX-U

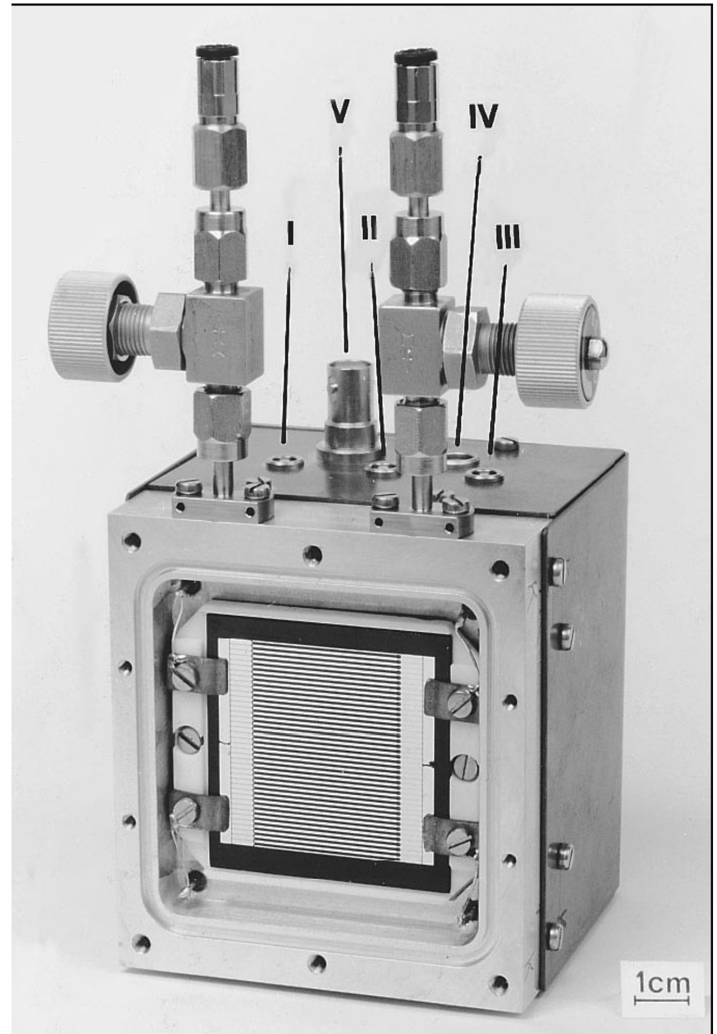
for C VI, λ=33.74 Å:
Crystal:
PbSt
2d=100.4 Å;
Filters:
1 μm polyamid,
20 Å Al.

for O VIII, λ= 18.97 Å:
Crystal:
KAP
2d=26.58 Å;
Filters:
2 μm mylar,
100 Å Al.

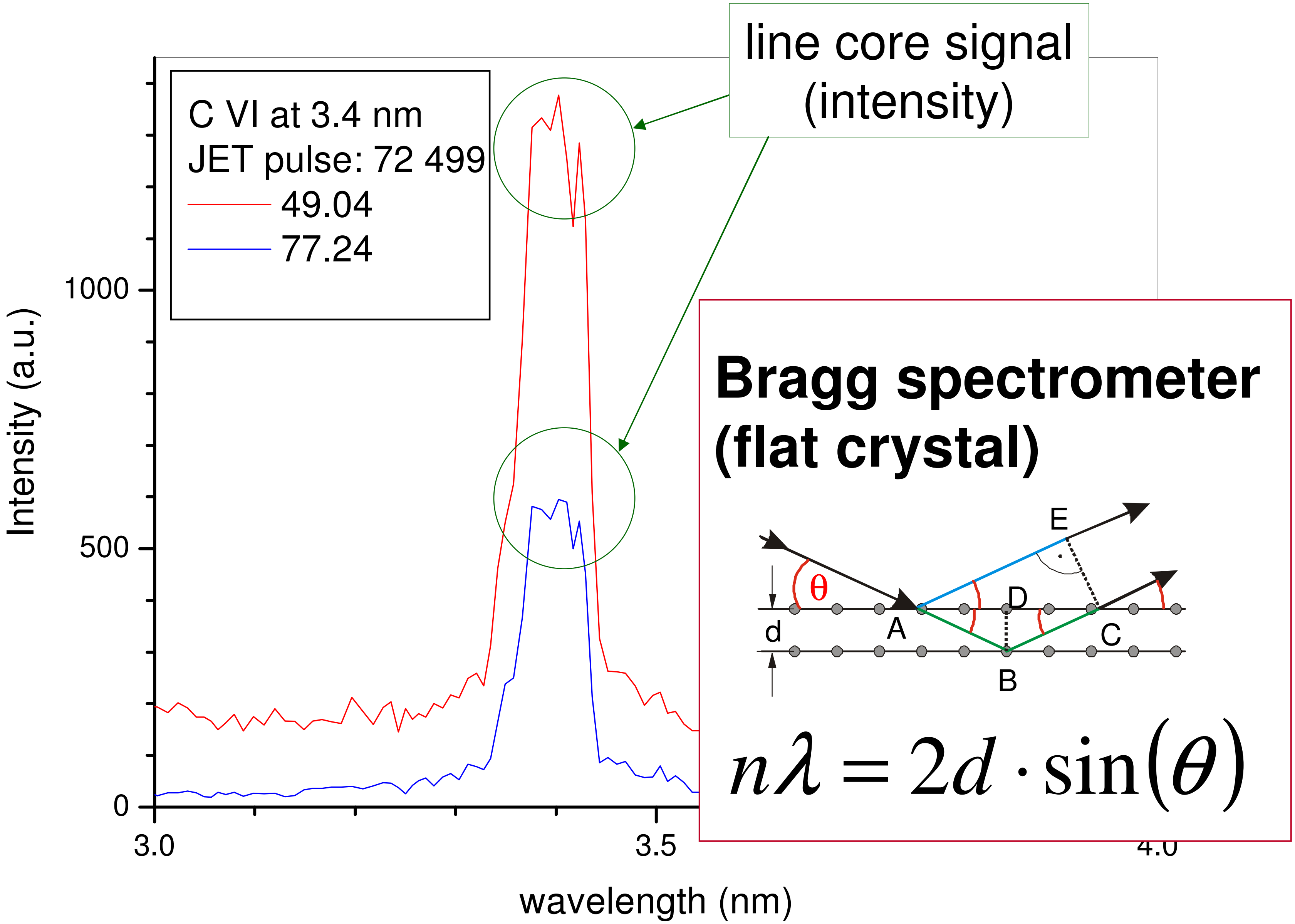


Proportional counter





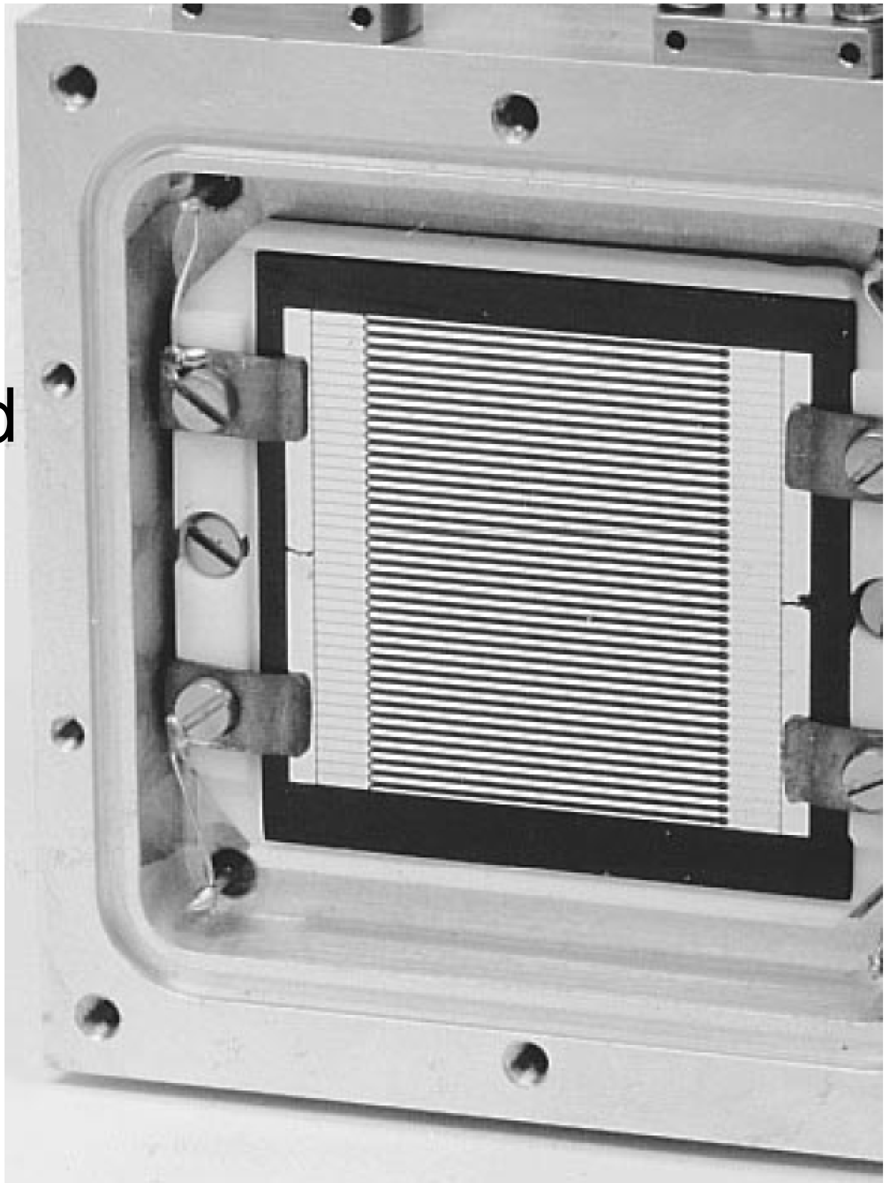
line intensity = area under profile curve



$$n\lambda = 2d \cdot \sin(\theta)$$

Main disadvantage of this construction:

As it is flat crystal Bragg-spectrometer background level is **estimated** by the count rate arising from the high energy gammas and other background radiation.



(Each proportional counter consists of two independent active areas of identical 30×20 mm^2 size. One of them is attached directly to the spectrometer using thin windows, whereas the second one has no window.)

Sample of results of by C-/O- Monitor for ASDEX-U

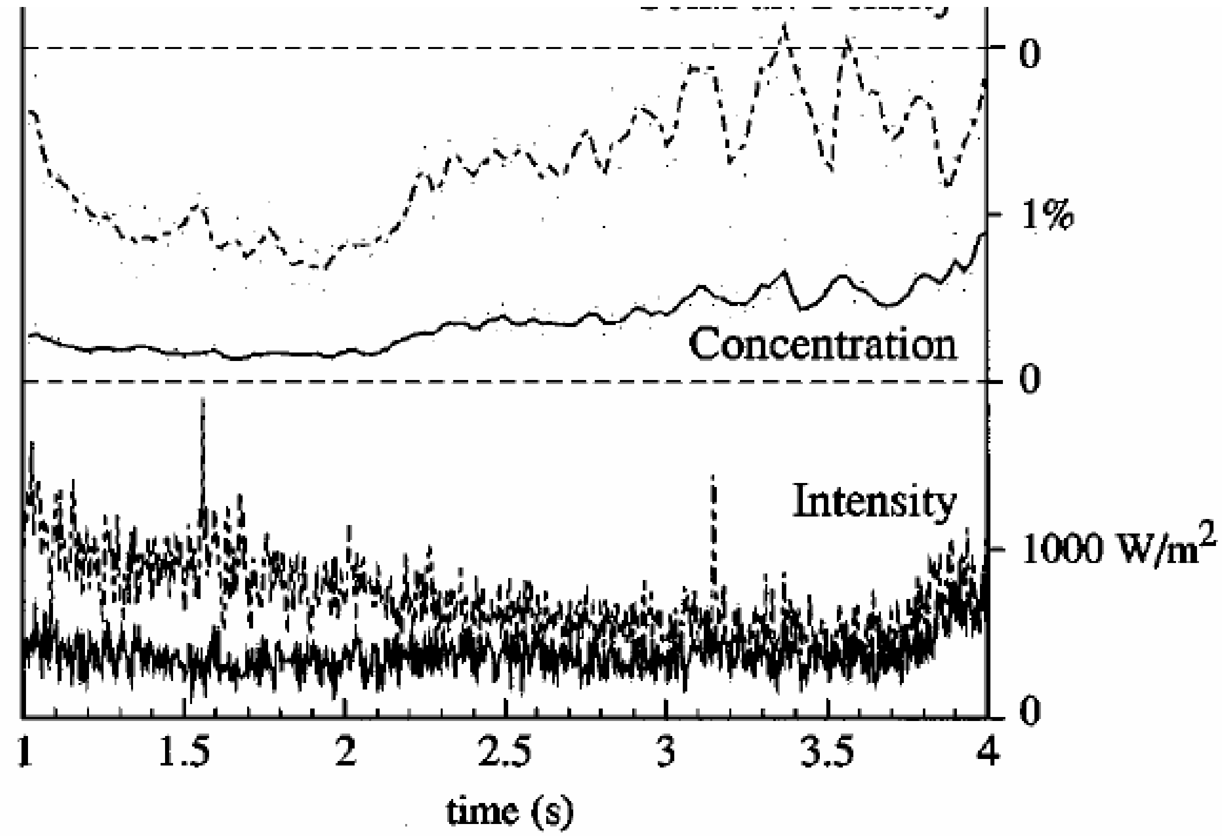


FIG. 7. Temporal behavior of the C VI and O VIII line intensities (multiplied by the factor 4π), together with the deduced concentrations and control parameters (O: solid lines; C: dashed lines) from the ASDEX Upgrade standard discharge No. 4611 ($\overline{n_e}=3\times10^{19}/\mathrm{m}^3$, $I_p=600$ kA).

Sample of results of by C-/O- Monitor for ASDEX-U

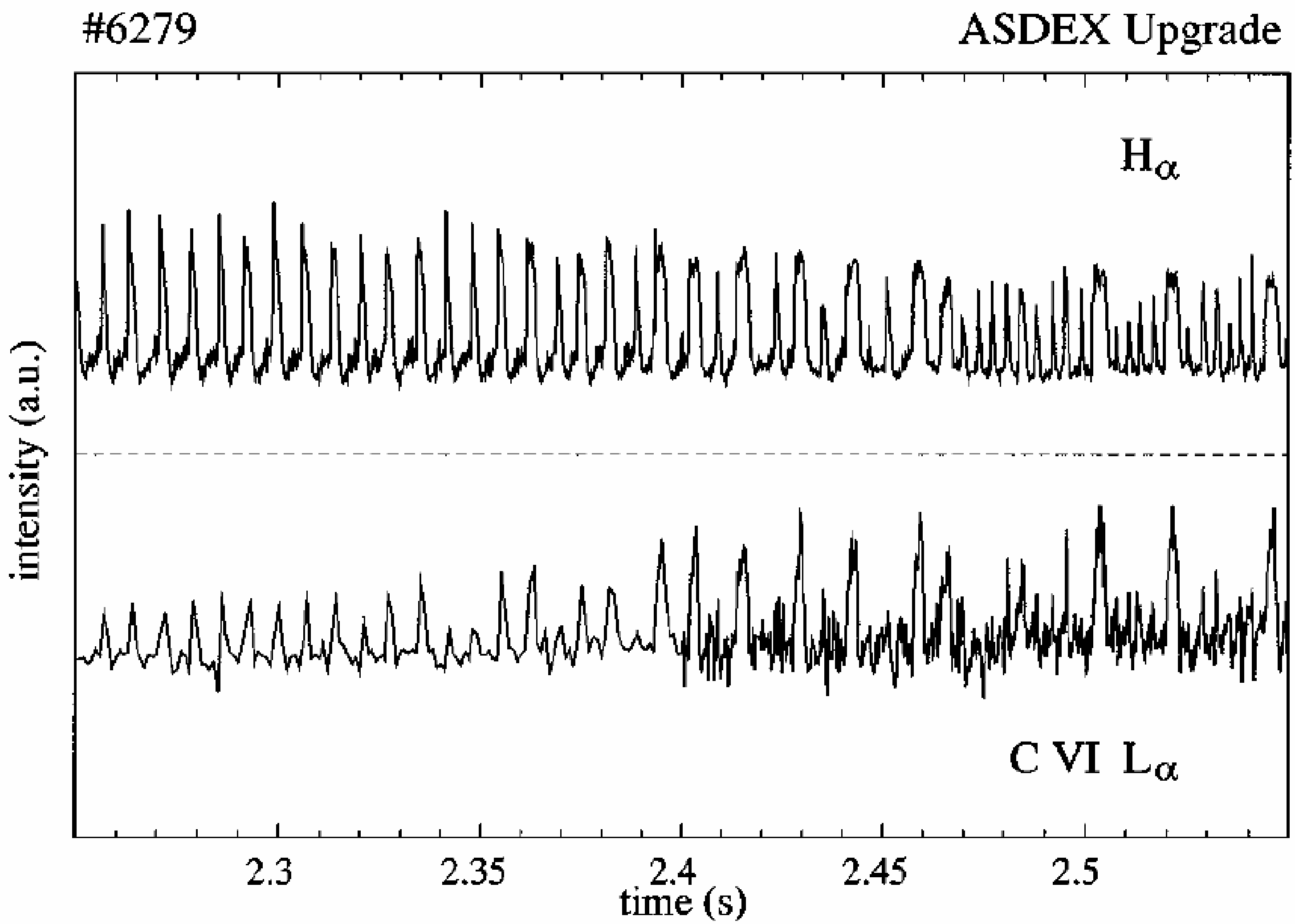


FIG. 9. C VI Lyman-α intensity as a function of time (lower curve) showing ELM activity as the Hα radiation measured in the divertor (upper curve).

C-/O- Monitor for Wendelstein 7-X

C- O- Monitor for Wendelstein 7-X

- will be a dedicated soft X-ray spectrometer;
- working with time resolution of at least 0.5 ms;
- it consists of four independent channels, fixed at wavelengths corresponding to Lyman-α lines of hydrogen-like ions of:
  - boron (at 4.9 nm; 253 eV),
  - carbon (at 3.4 nm; 365 eV),
  - nitrogen (at 2.5 nm; 496 eV),
  - oxygen (at 1.9 nm; 653 eV).

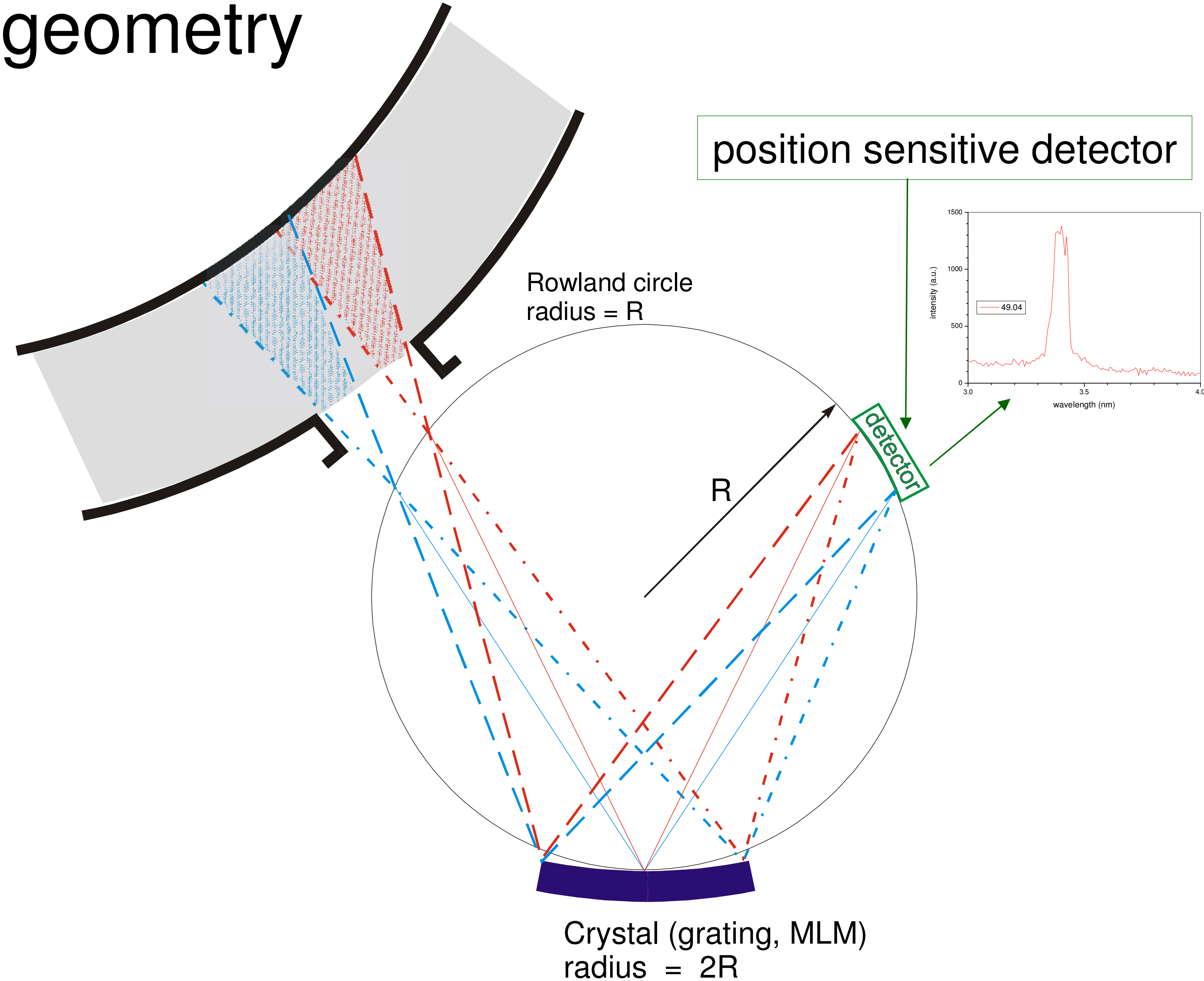
C- O- Monitor for W7-X

it consists of four independent channels, but

divided in two pairs, closed in common vacuum chambers:

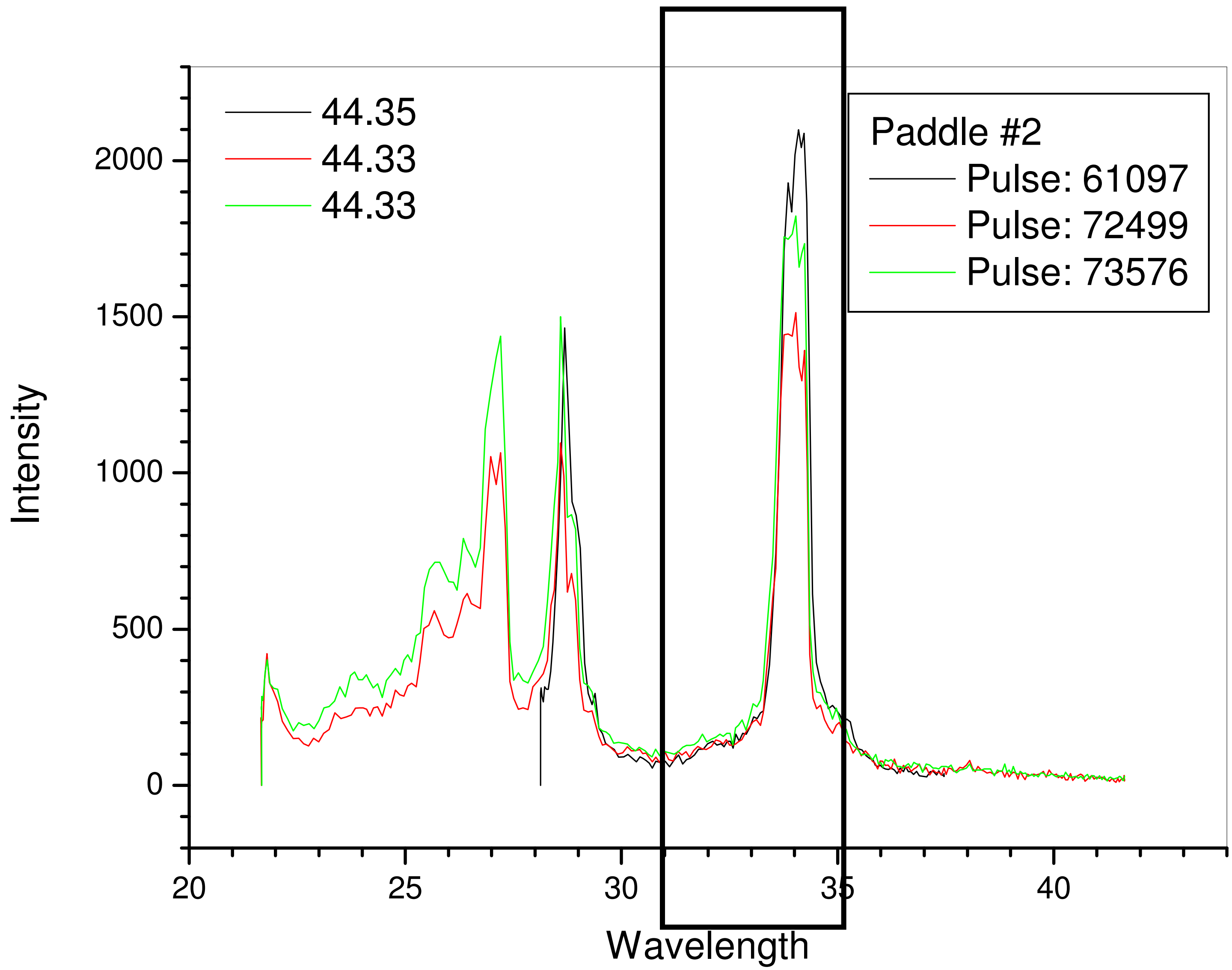
1) carbon and oxygen,
2) boron and nitrogen.

Johan geometry

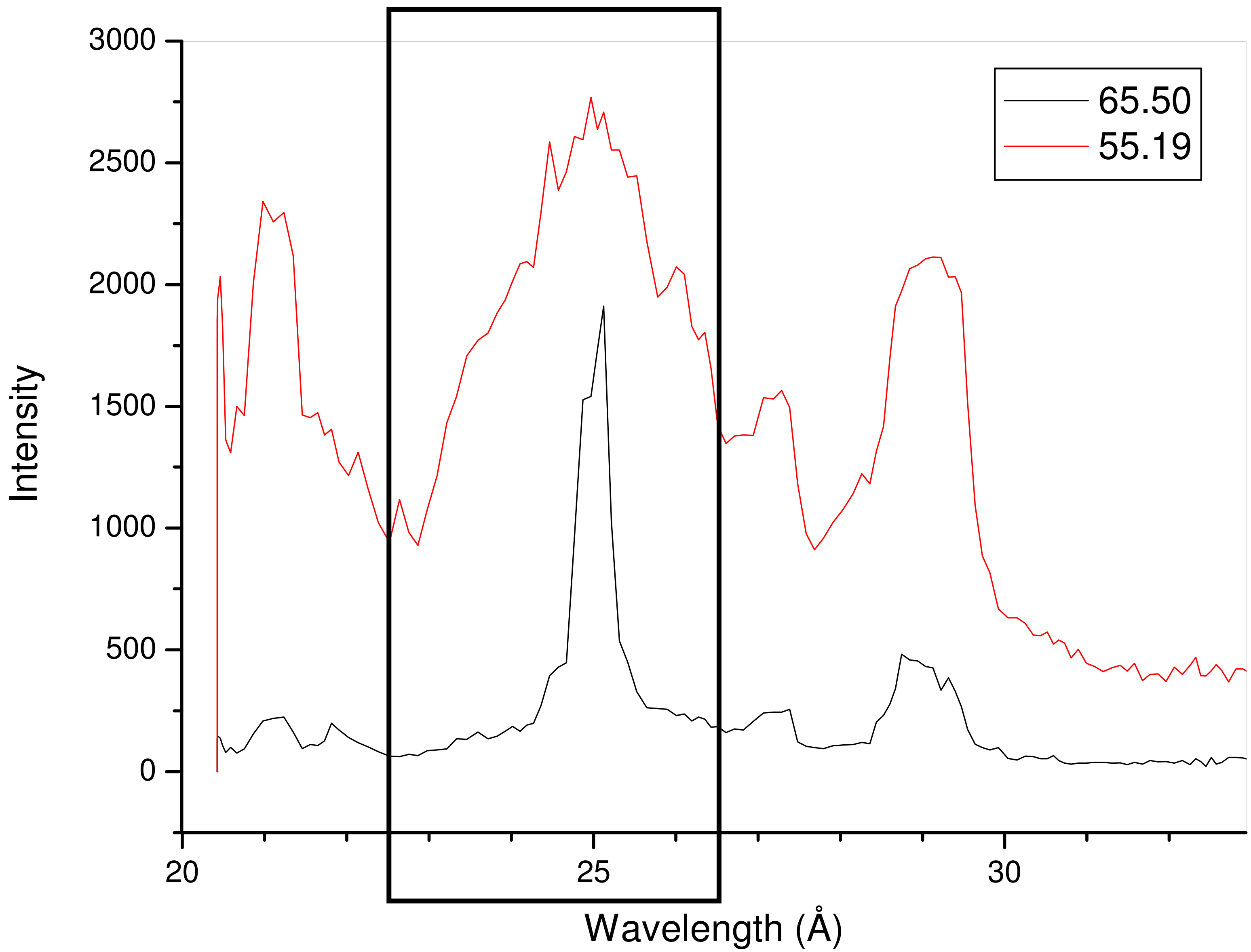


Crystal/MLM cylindrically bend

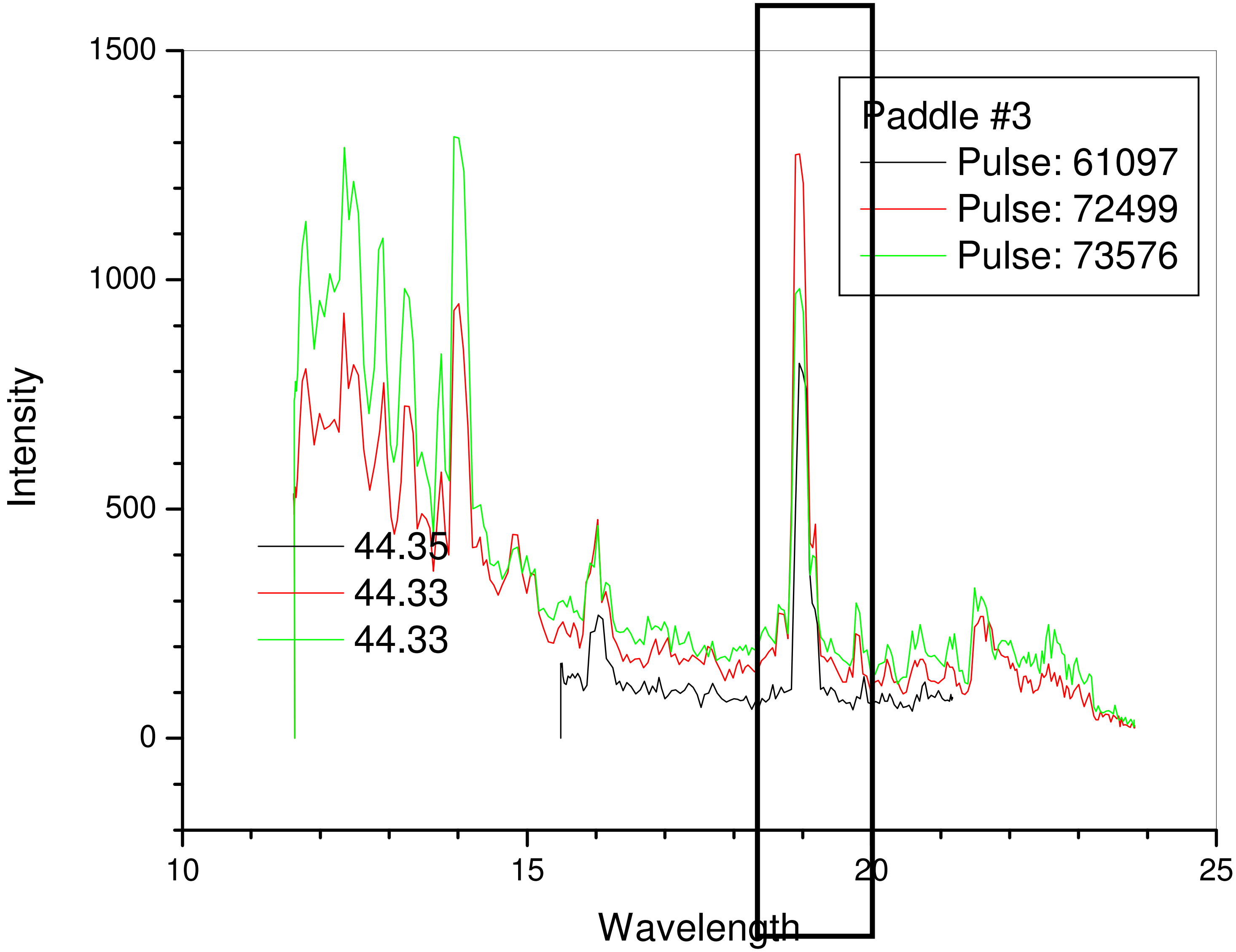
C VI spectrum

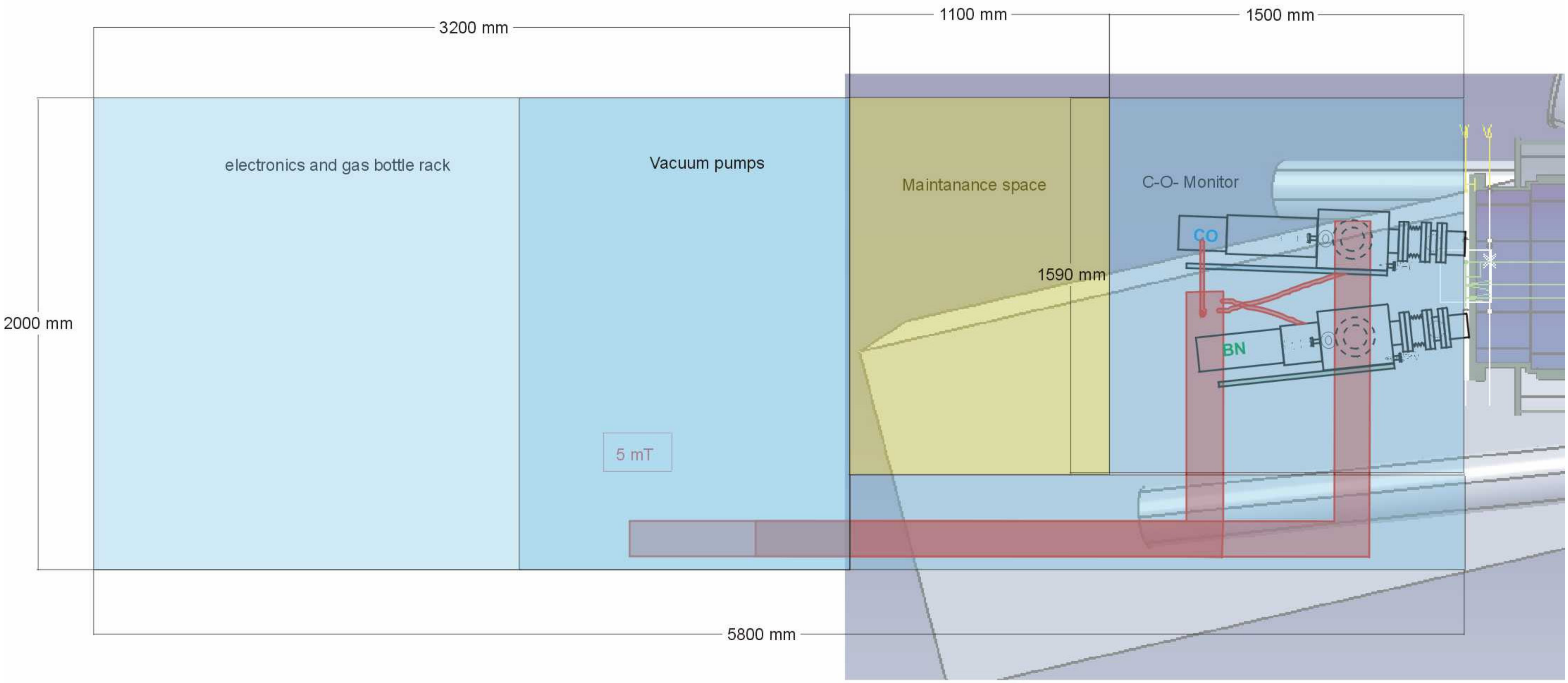


N VII spectrum

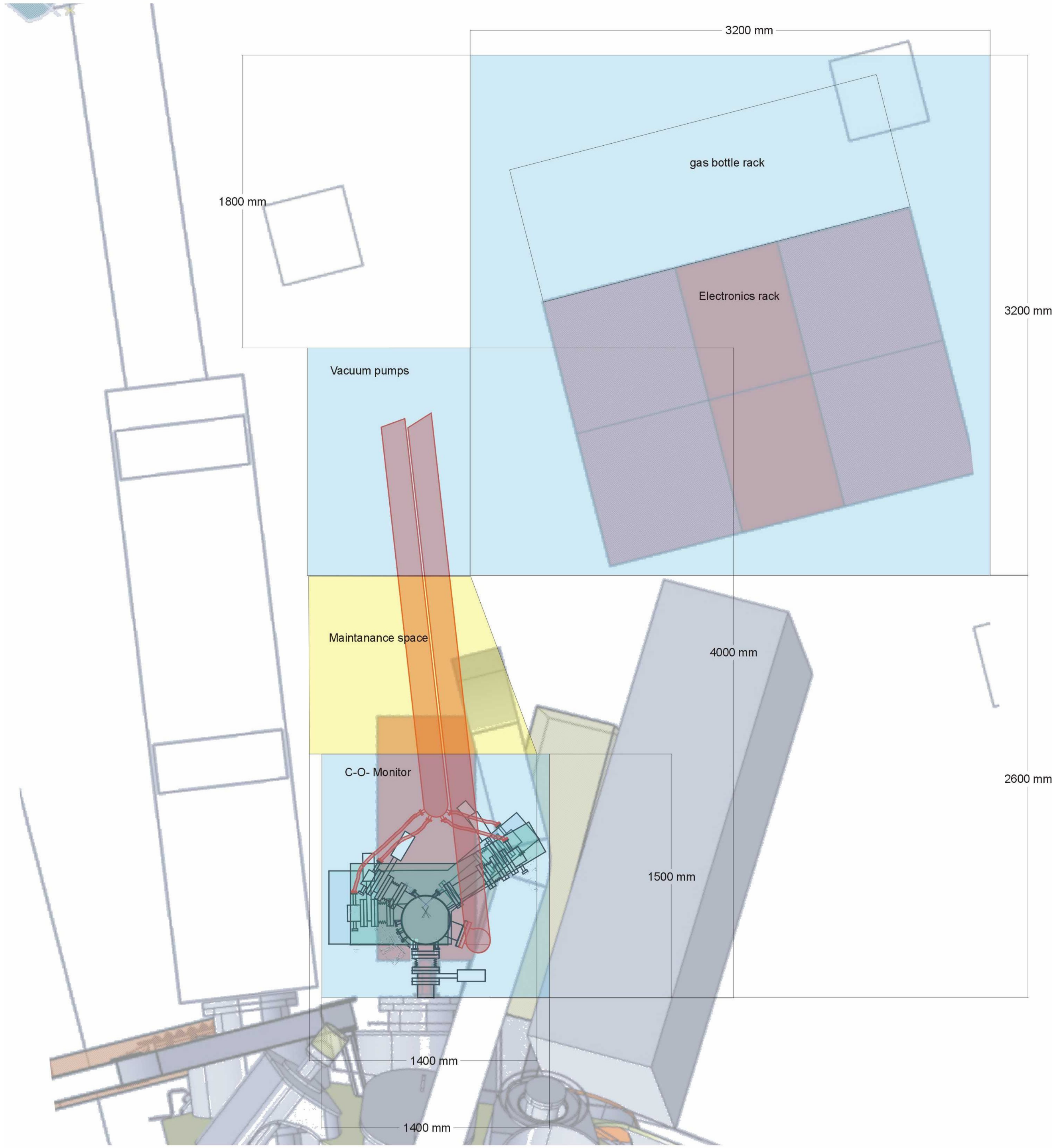


O VIII spectrum

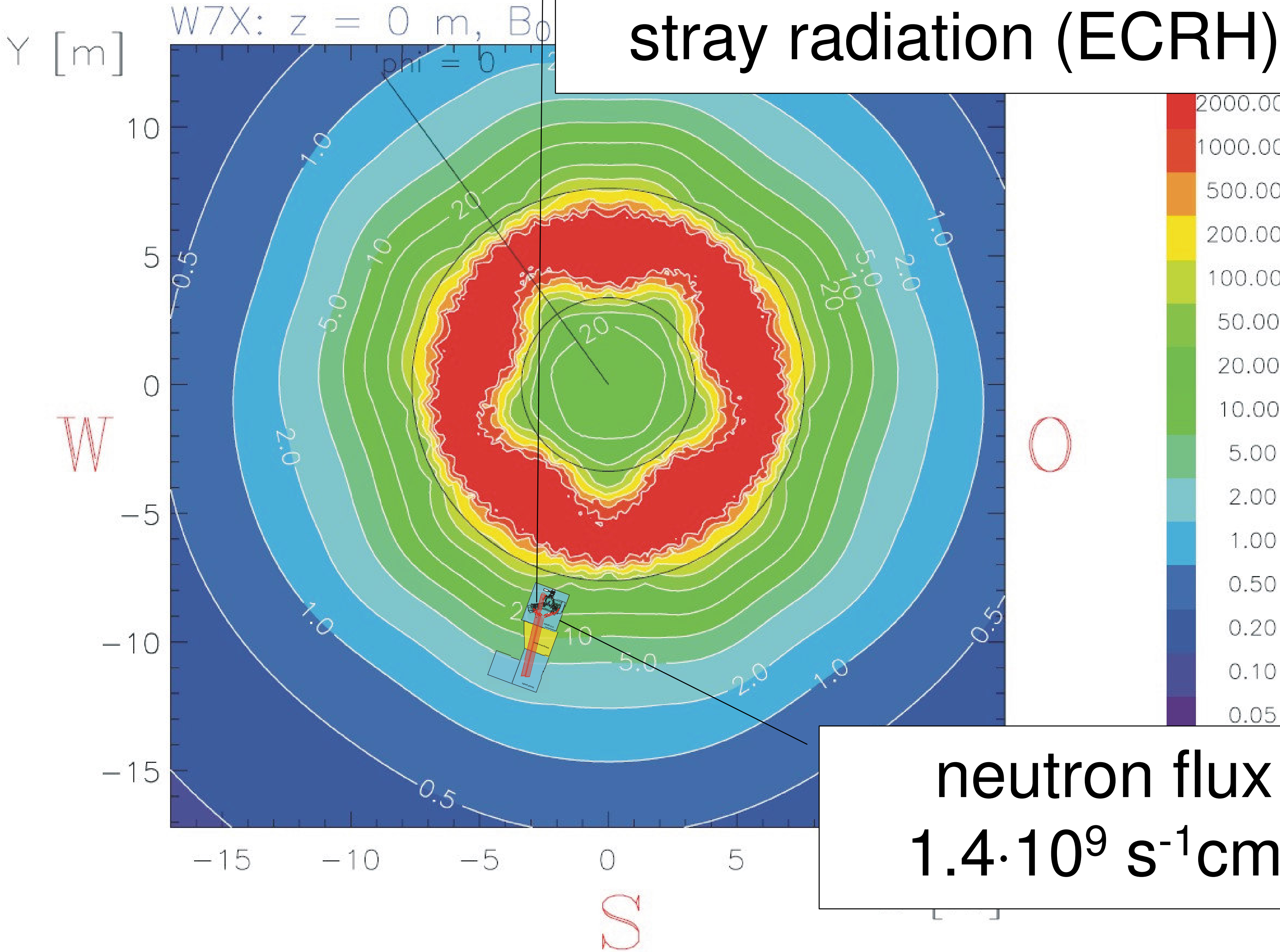




3200 mm
1100 mm
1500 mm
electronics and gas bottle rack
Vacuum pumps
Maintanance space
C-O- Monitor
CO
1590 mm
BN
2000 mm
5 mT
5800 mm


3200 mm
1800 mm
gas bottle rack
Electronics rack
3200 mm
Vacuum pumps
Maintanance space
4000 mm
C-O- Monitor
2600 mm
1500 mm
1400 mm
1400 mm

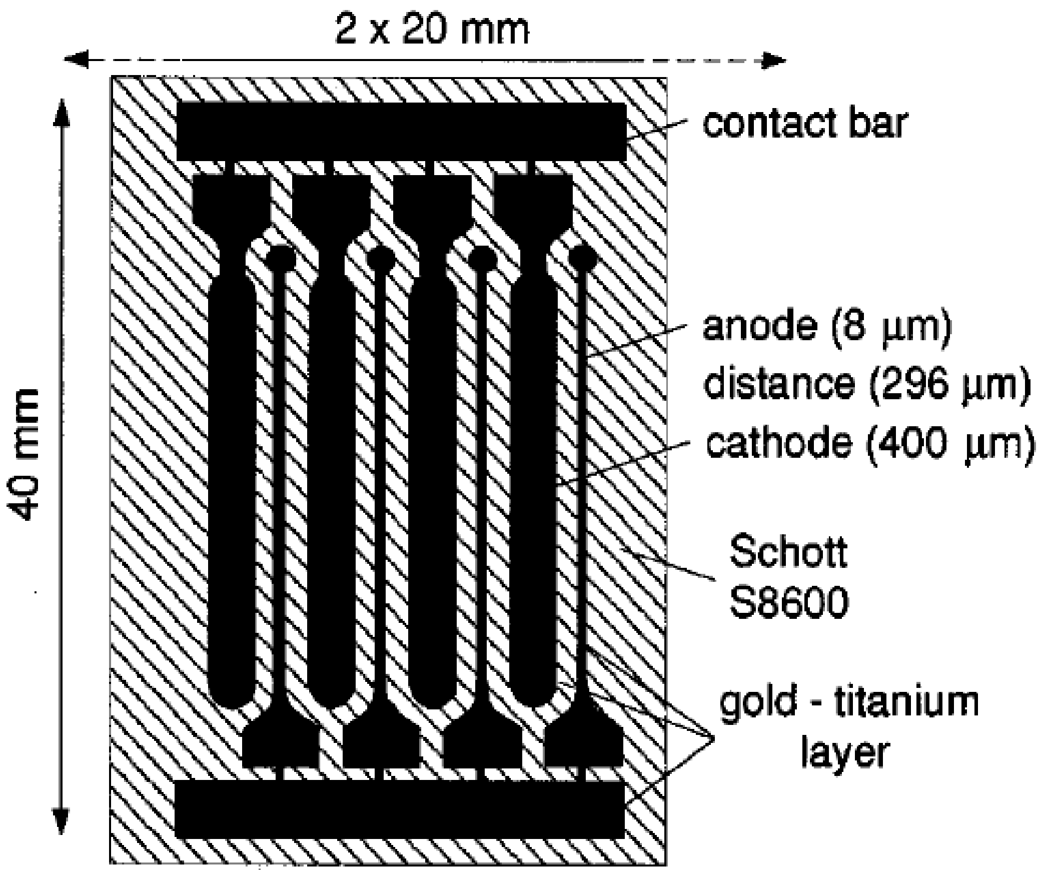
Microwave (140 GHz) stray radiation (ECRH)

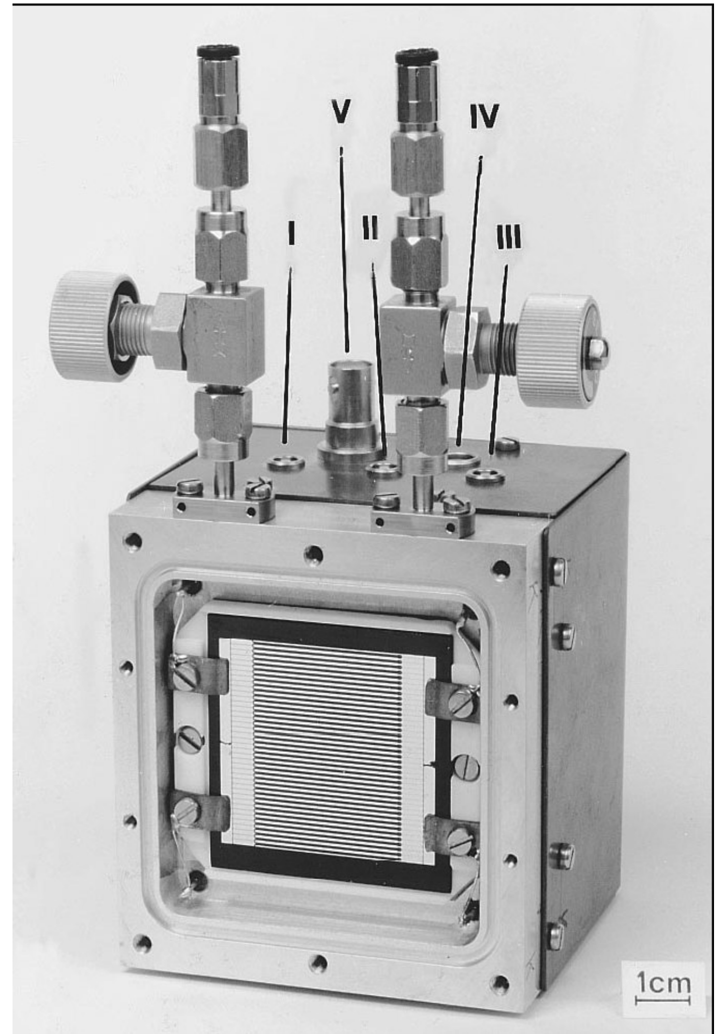


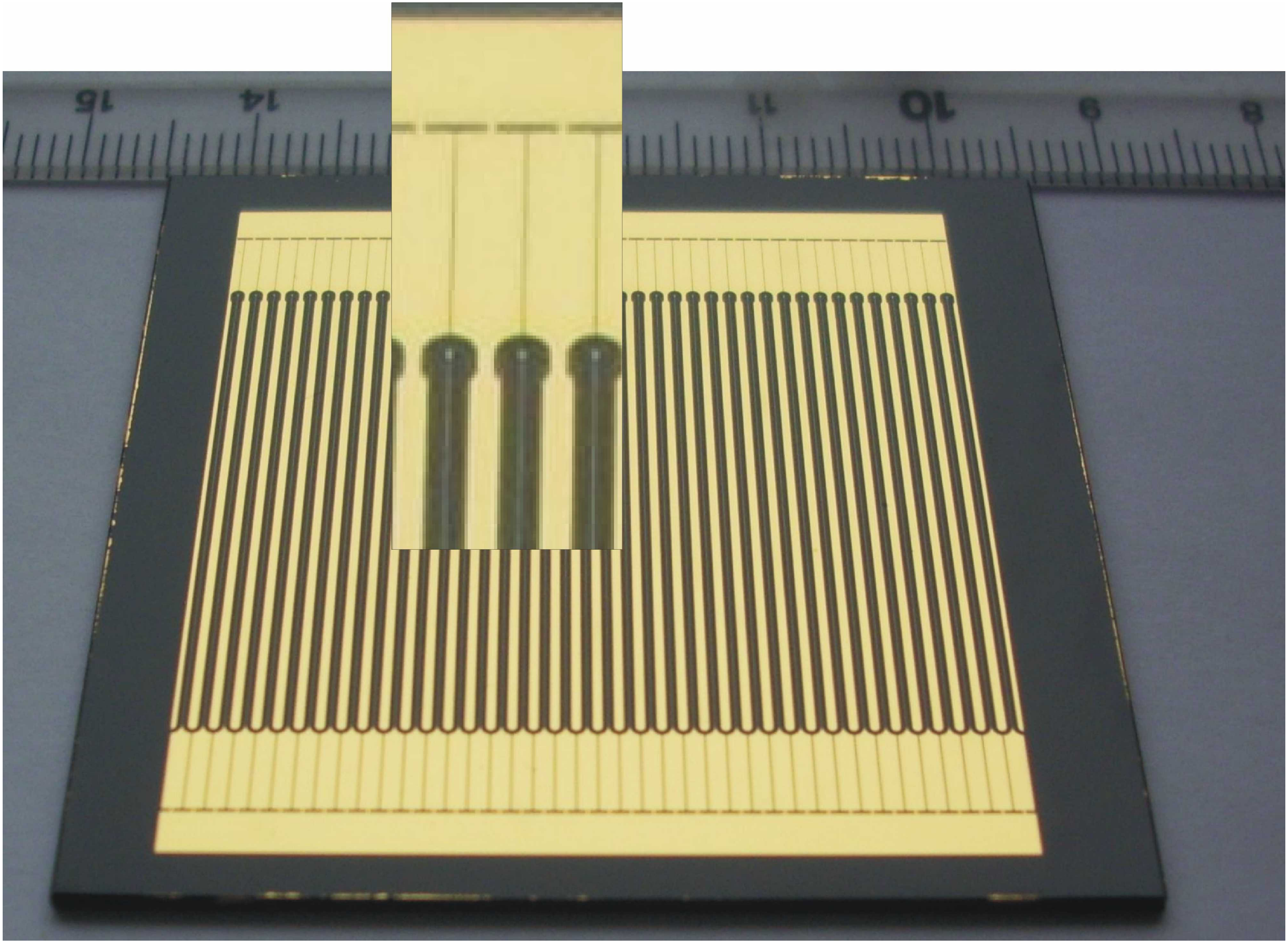
neutron flux: $1.4 \cdot 10^{9}\ s^{-1}cm^{-2}$

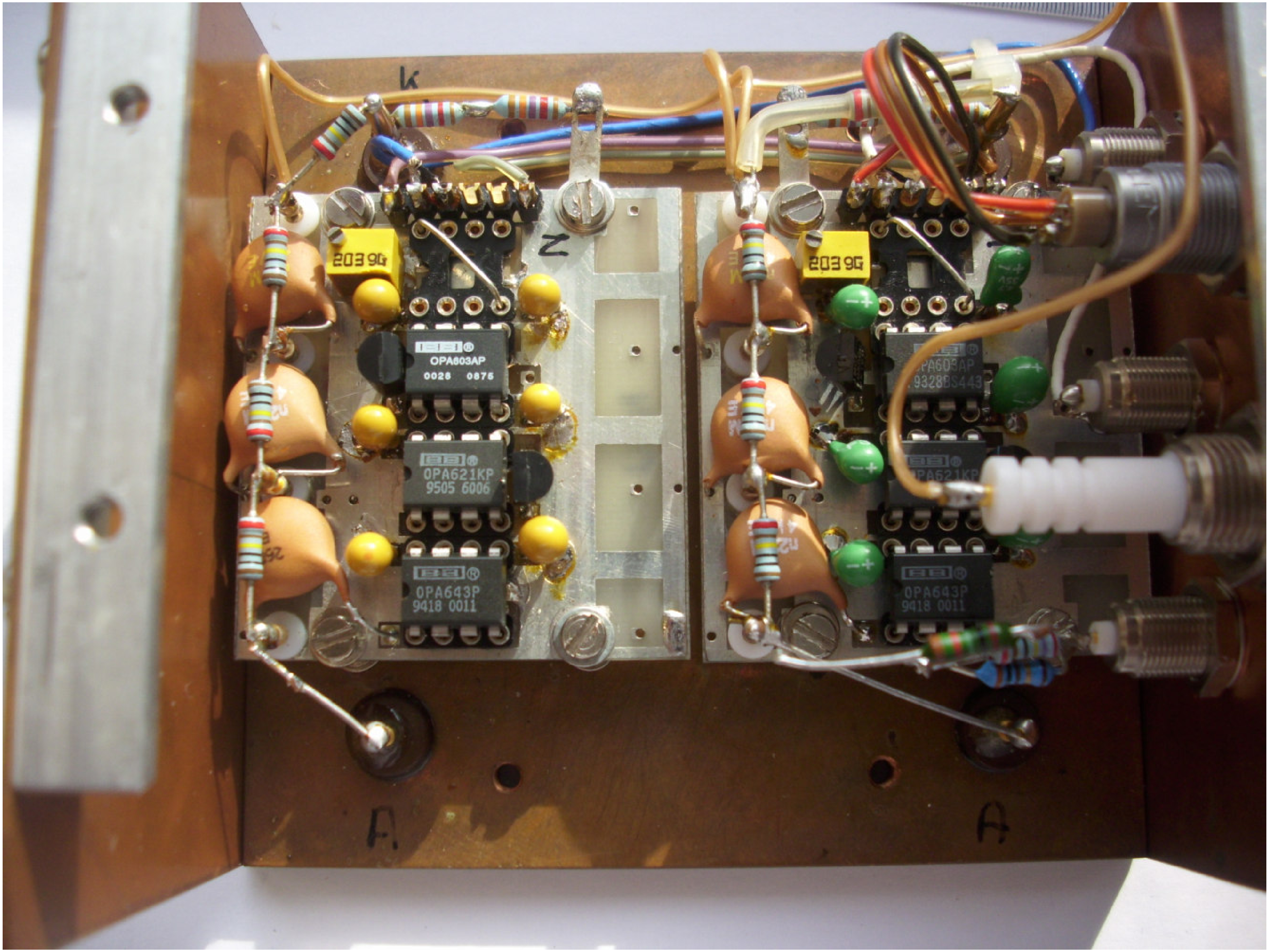
Proportional counter for C-/O- Monitor

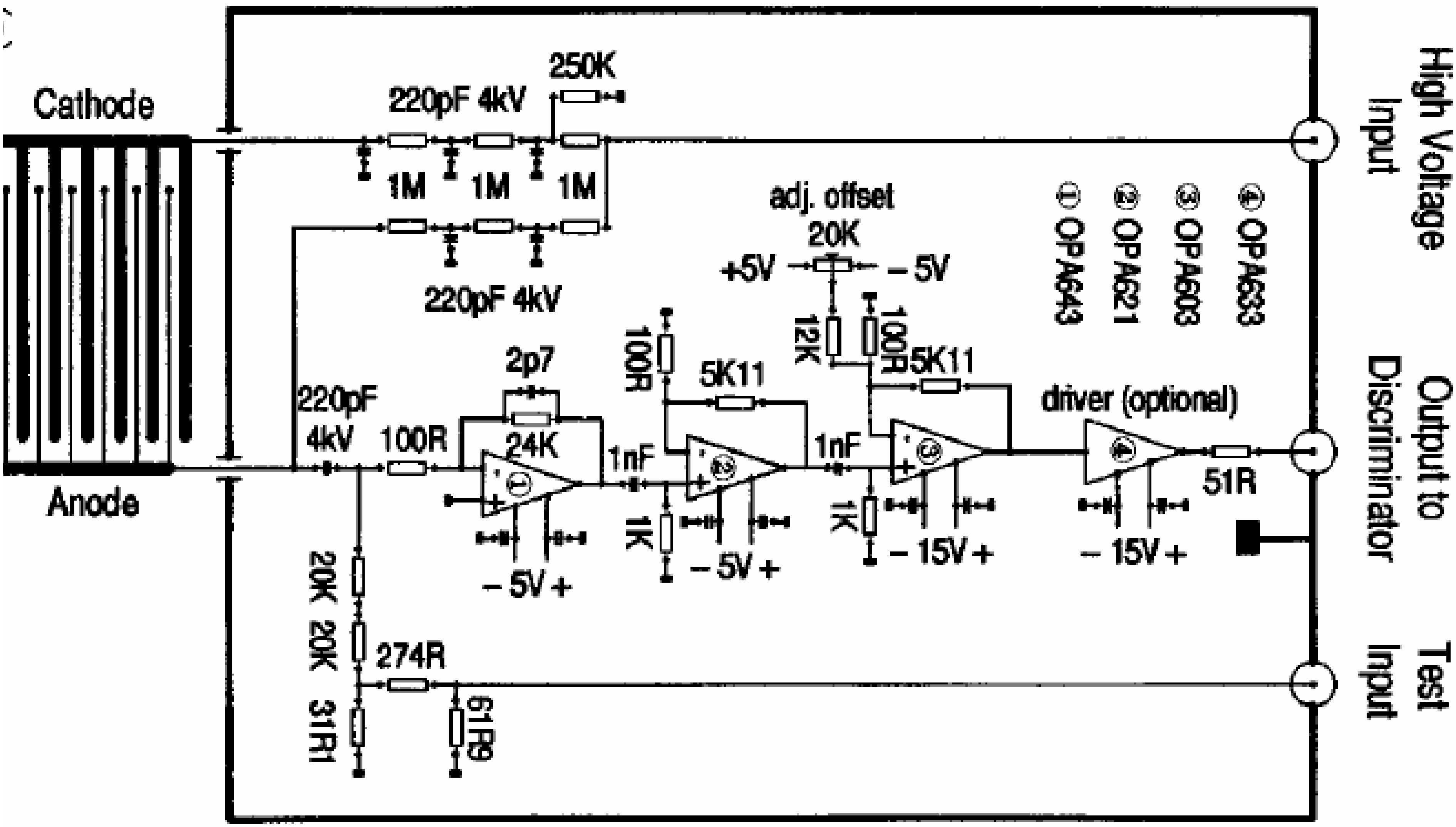
Proportional counter





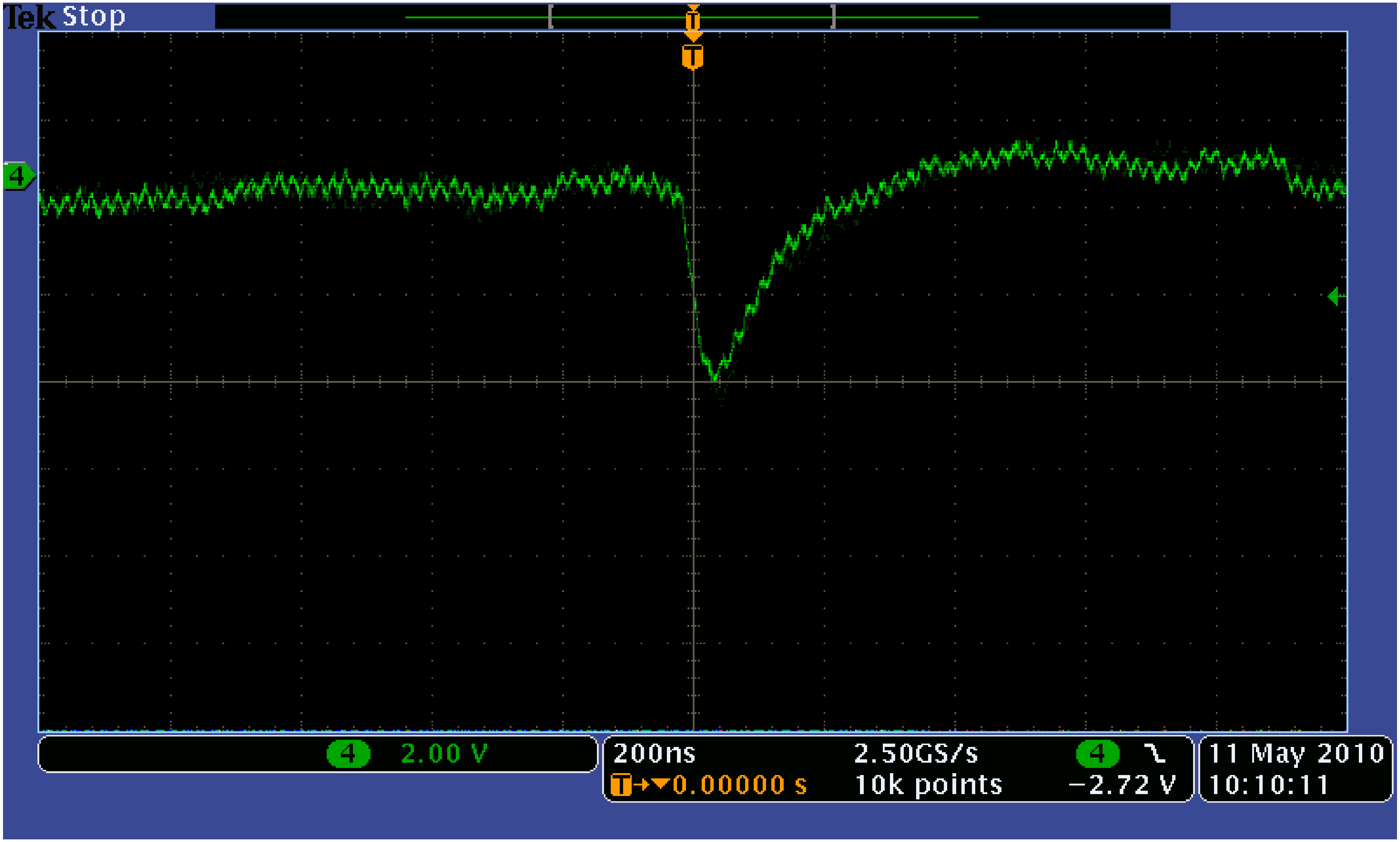



k
Z
2039G
OPA603AP
0028 0875
OPA621KP
9505 6006
OPA643P
9418 0011
2039G
OPA643P
9418 0011
A
A

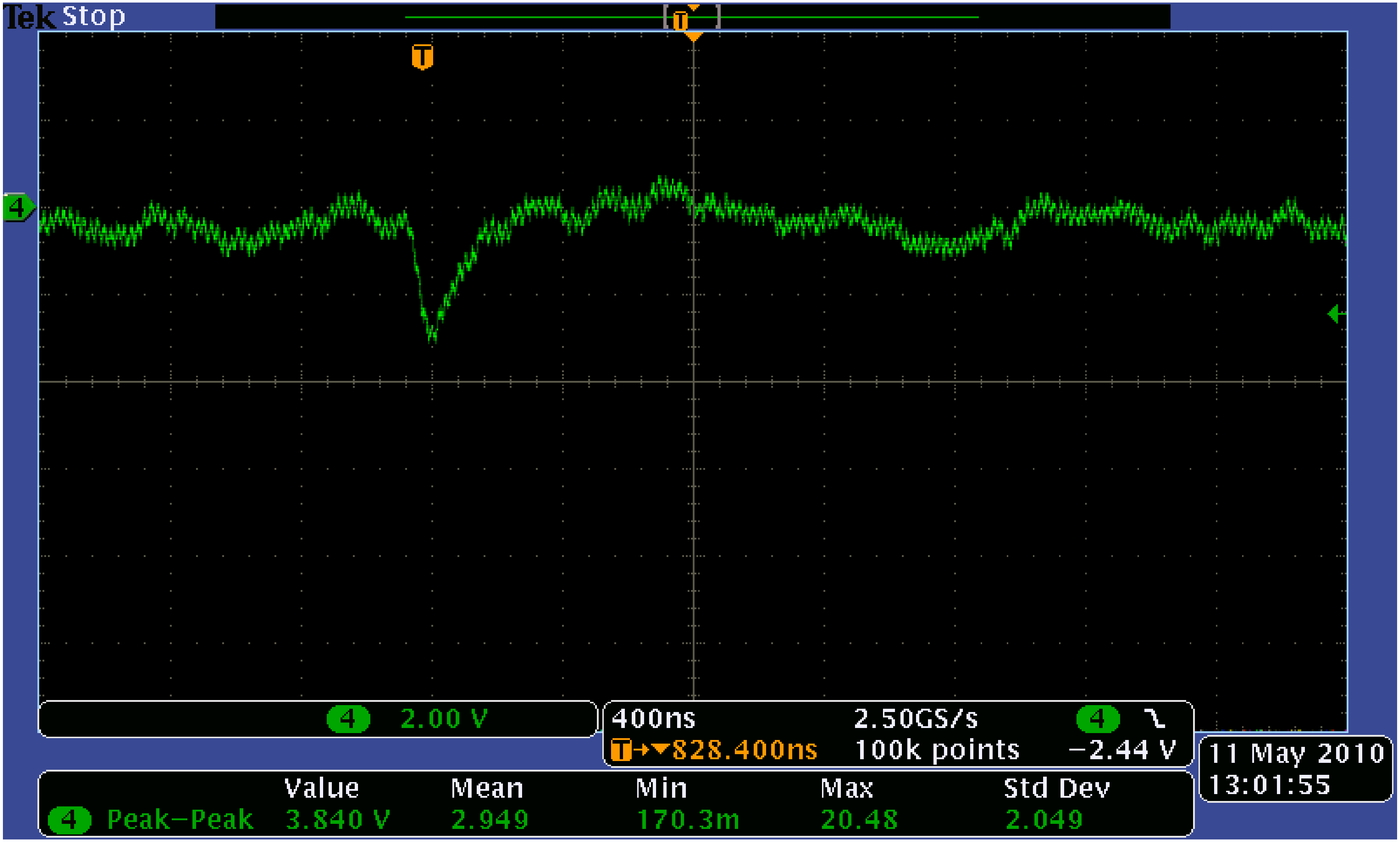


Cathode
Anode
250K
220pF 4kV
1M
1M
1M
220pF 4kV
adj. offset
20K
+5V
– 5V
12K
100R
100R
2p7
24K
220pF
4kV
100R
1nF
1K
5K11
1nF
1K
5K11
driver (optional)
51R
– 5V +
– 5V +
– 15V +
– 15V +
20K
20K
31R1
274R
61R9
① OPA643
② OPA621
③ OPA603
④ OPA633
High Voltage Input
Output to Discriminator
Test Input

Al Kα signal (1 487 eV)



Cu Lβ signal (930 eV)



Proportional counter:

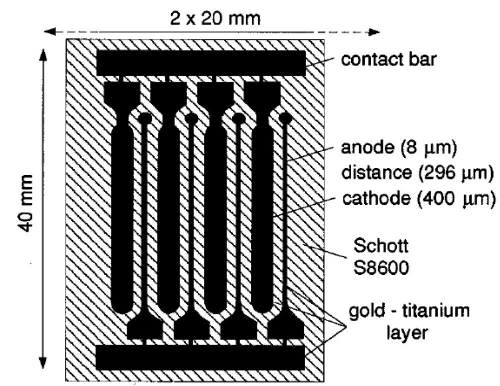
for ASDEX-U (what we have)	**for WENDELSTEIN 7-X (what we want)**
Readout of 2 channels	Readout of 40 channels
Measurement of line core and indirect estimation of continuum	Measurement of line core as well as continuum signal

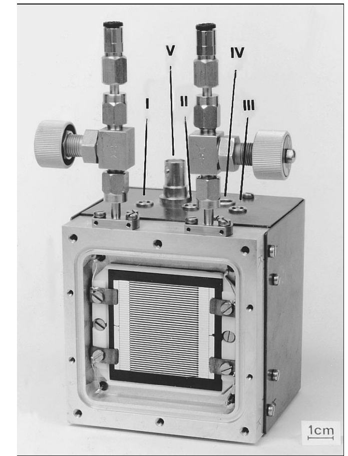
High temporal resolution

line intensity with time resolution <0.5 ms

Thank you
for your attention

Proportional counter modification

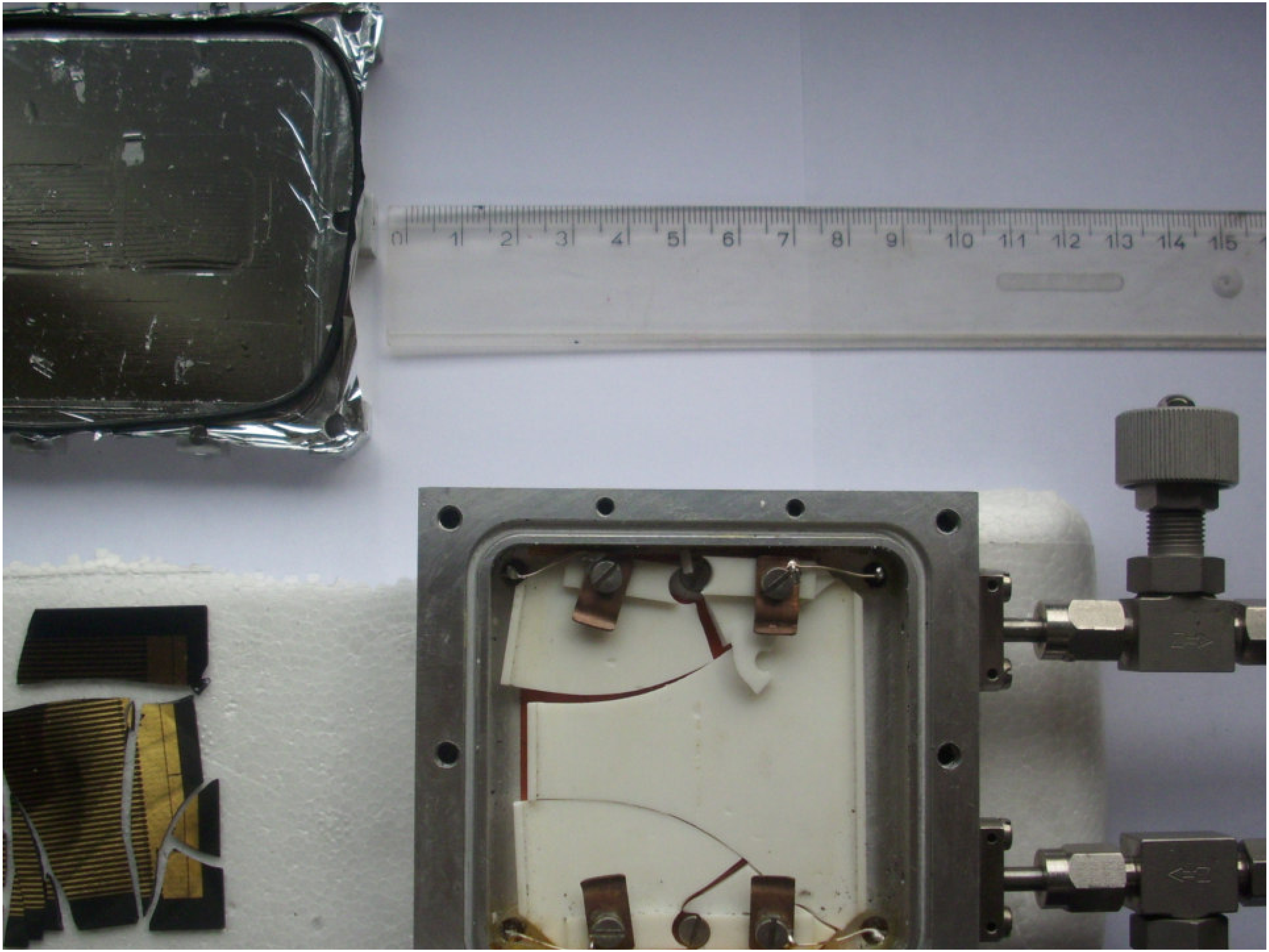


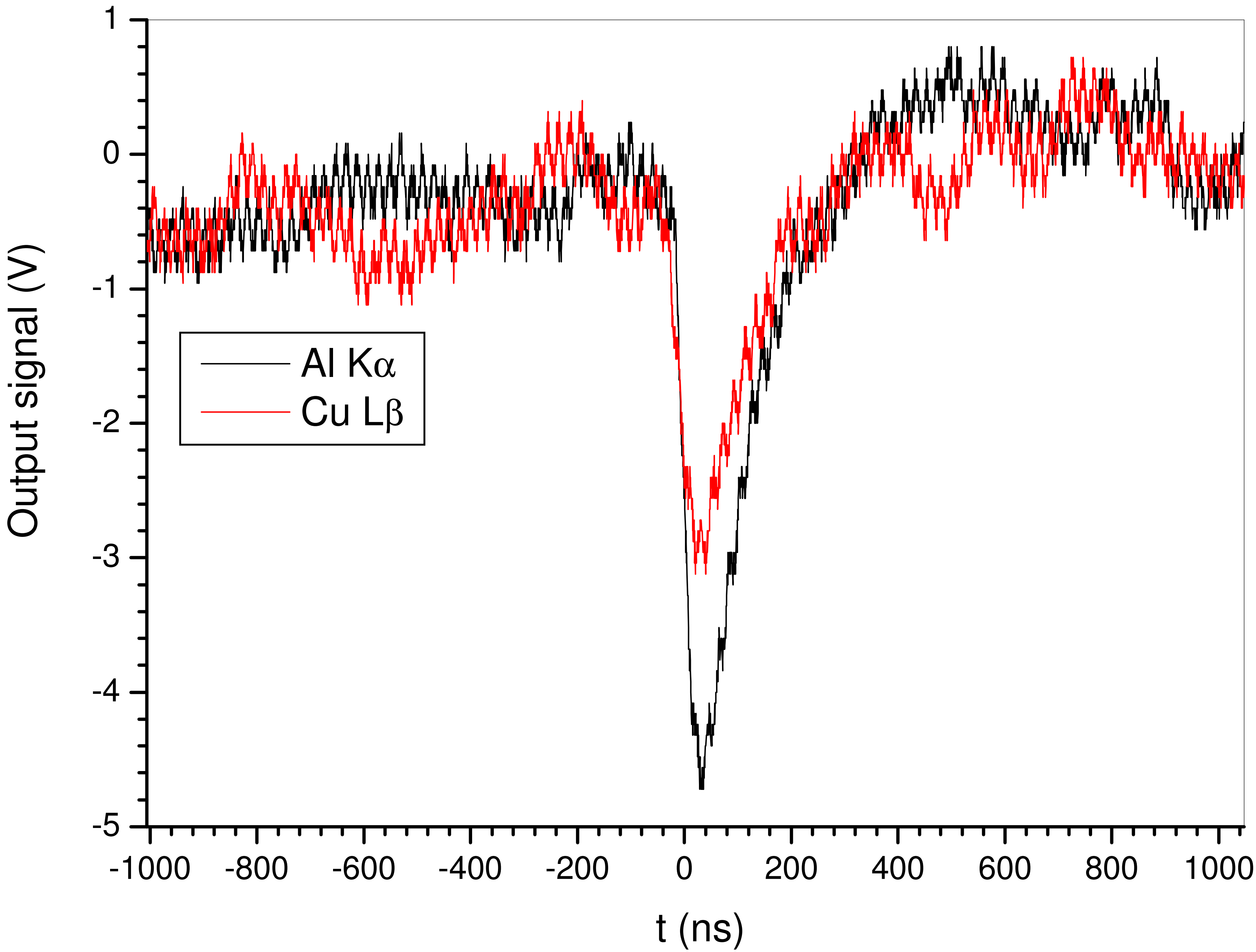


Readout of 40 separate channels

Measurement of line core as well as continuum signal

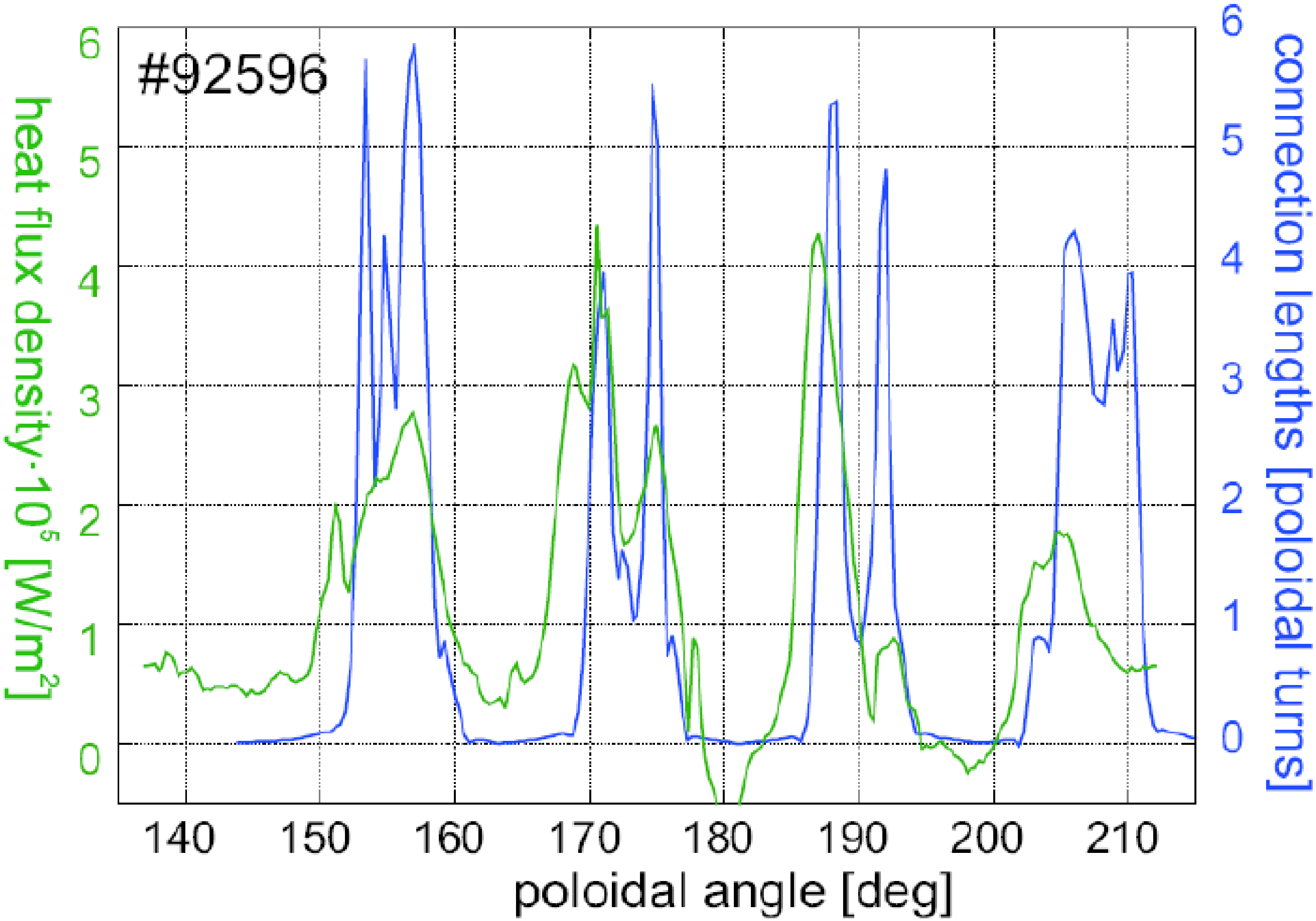
Determination of line intensity with time resolution <0.5 ms



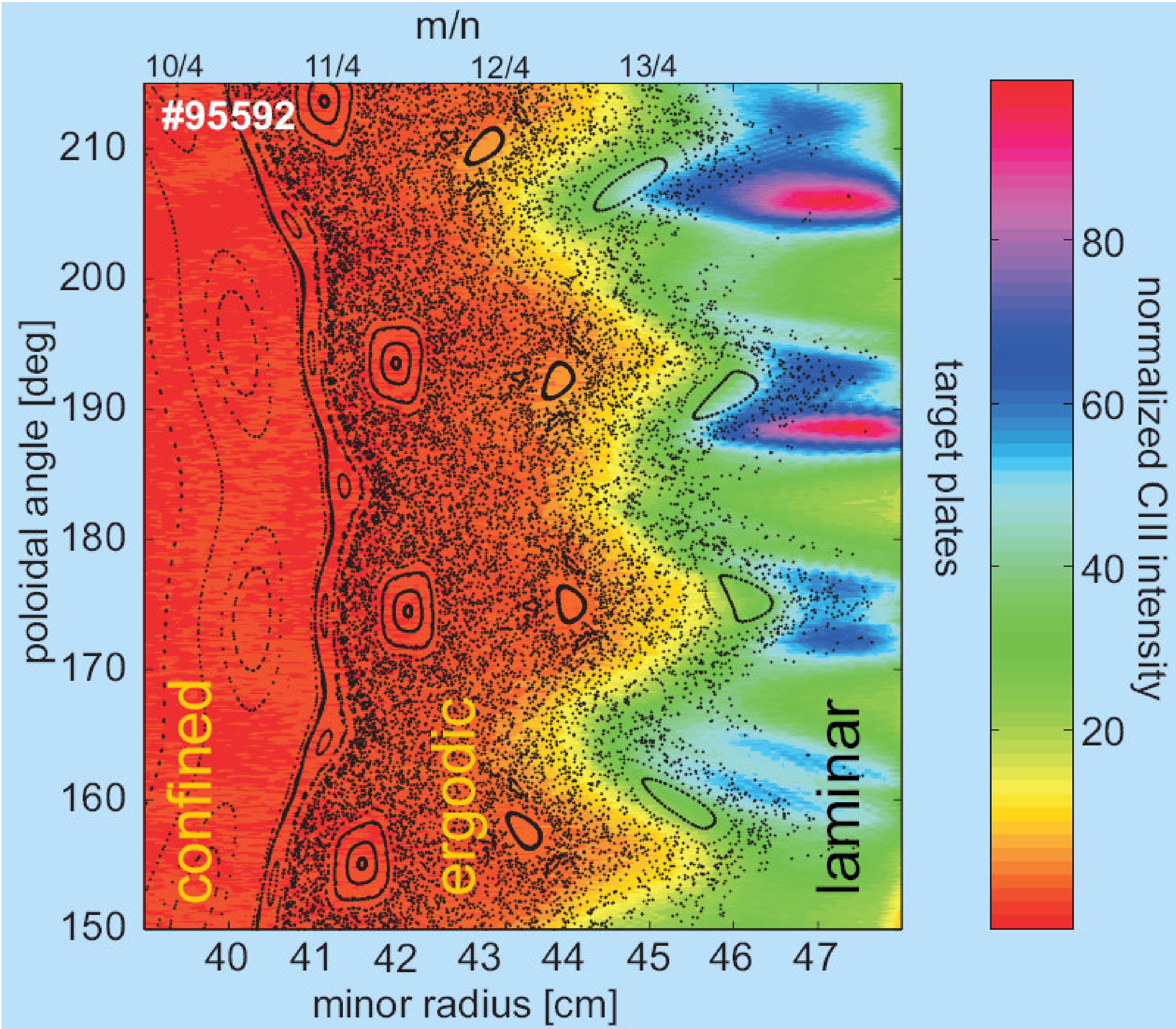


Output signal (V)
1
0
-1
-2
-3
-4
-5
Al Kα
Cu Lβ
-1000
-800
-600
-400
-200
0
200
400
600
800
1000
t (ns)

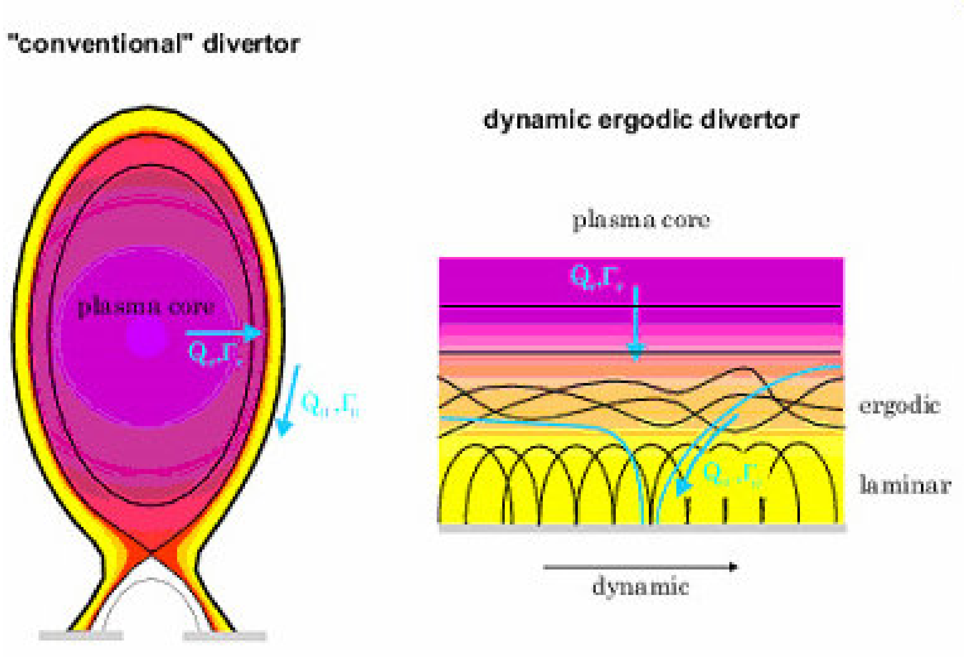
ELMs (Edge Localized Modes)

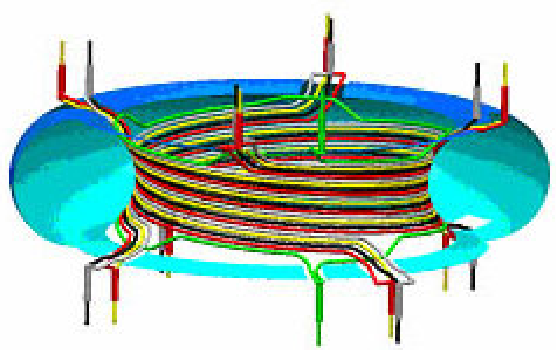


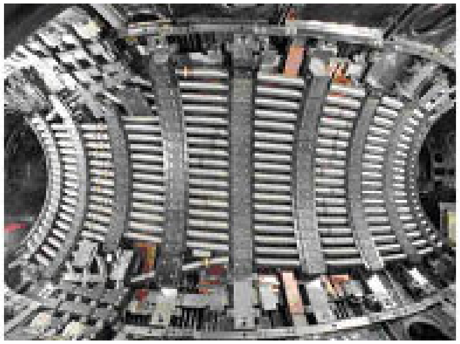
ELMs – Edge Localized Modes



DED – Dynamic Ergodic Divertor







H-mode

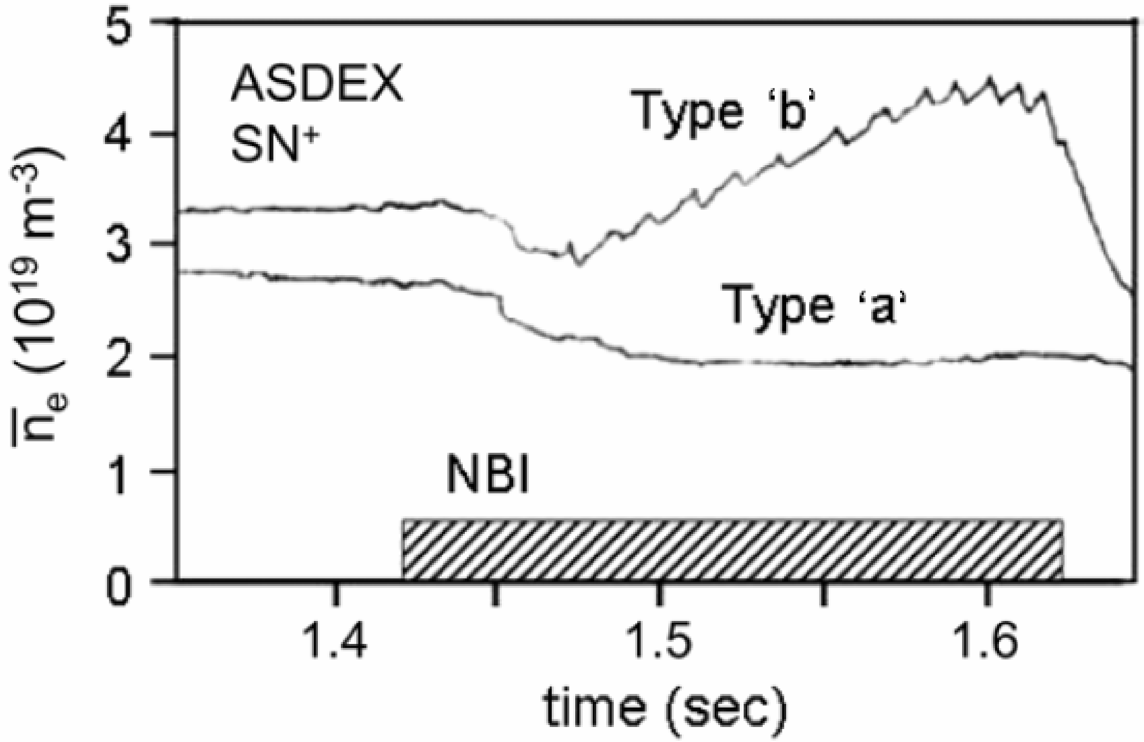
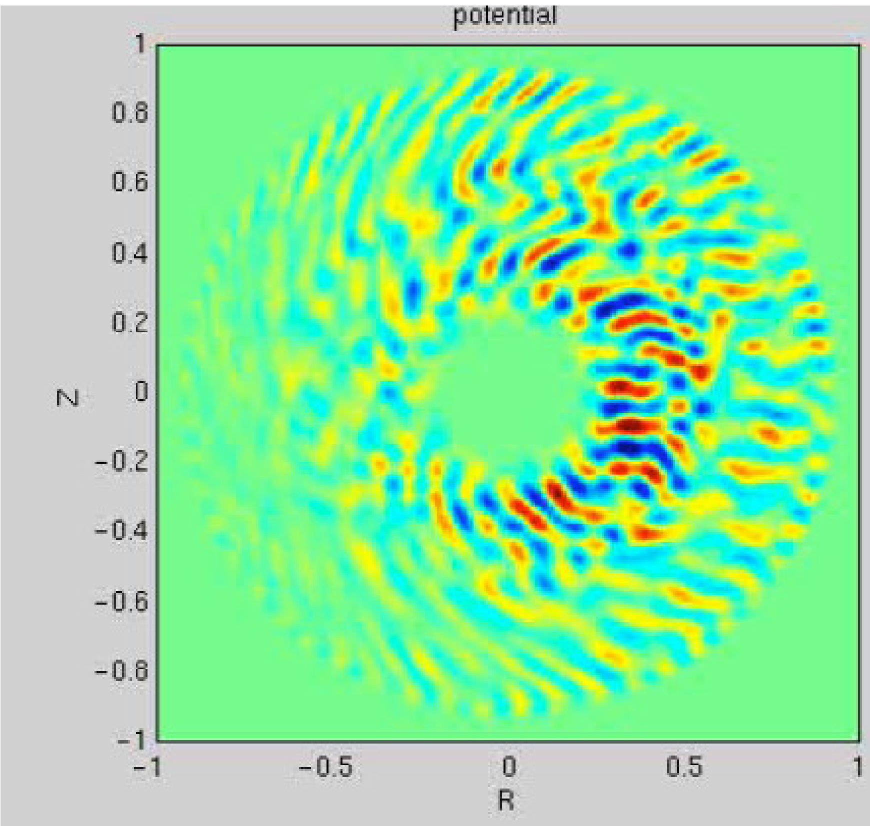


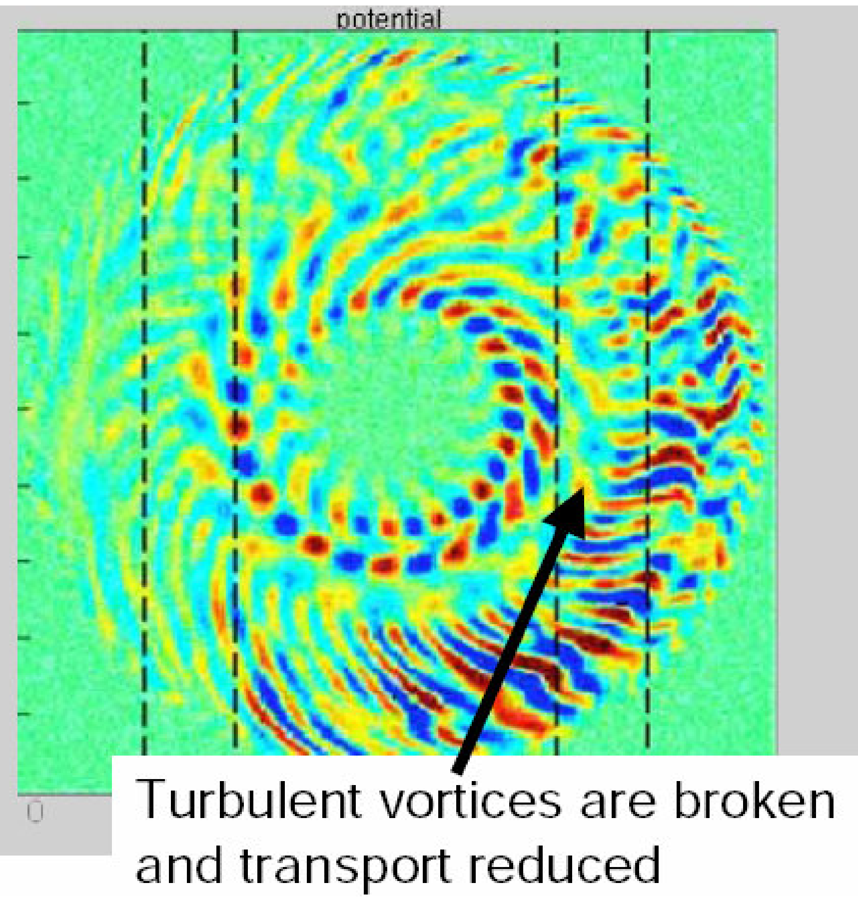
Figure 1. Line average density traces from an L-mode discharge (dubbed Type 'a' for historical reasons) and an early H-mode discharge (Type 'b'). The window of NBI heating is indicated. The configuration was SN^+ (ion-grad-B drift towards the X-point).

F Wagner, A quarter-century of H-mode studies, Plasma Phys. Control. Fusion **49** (2007) B1–B33

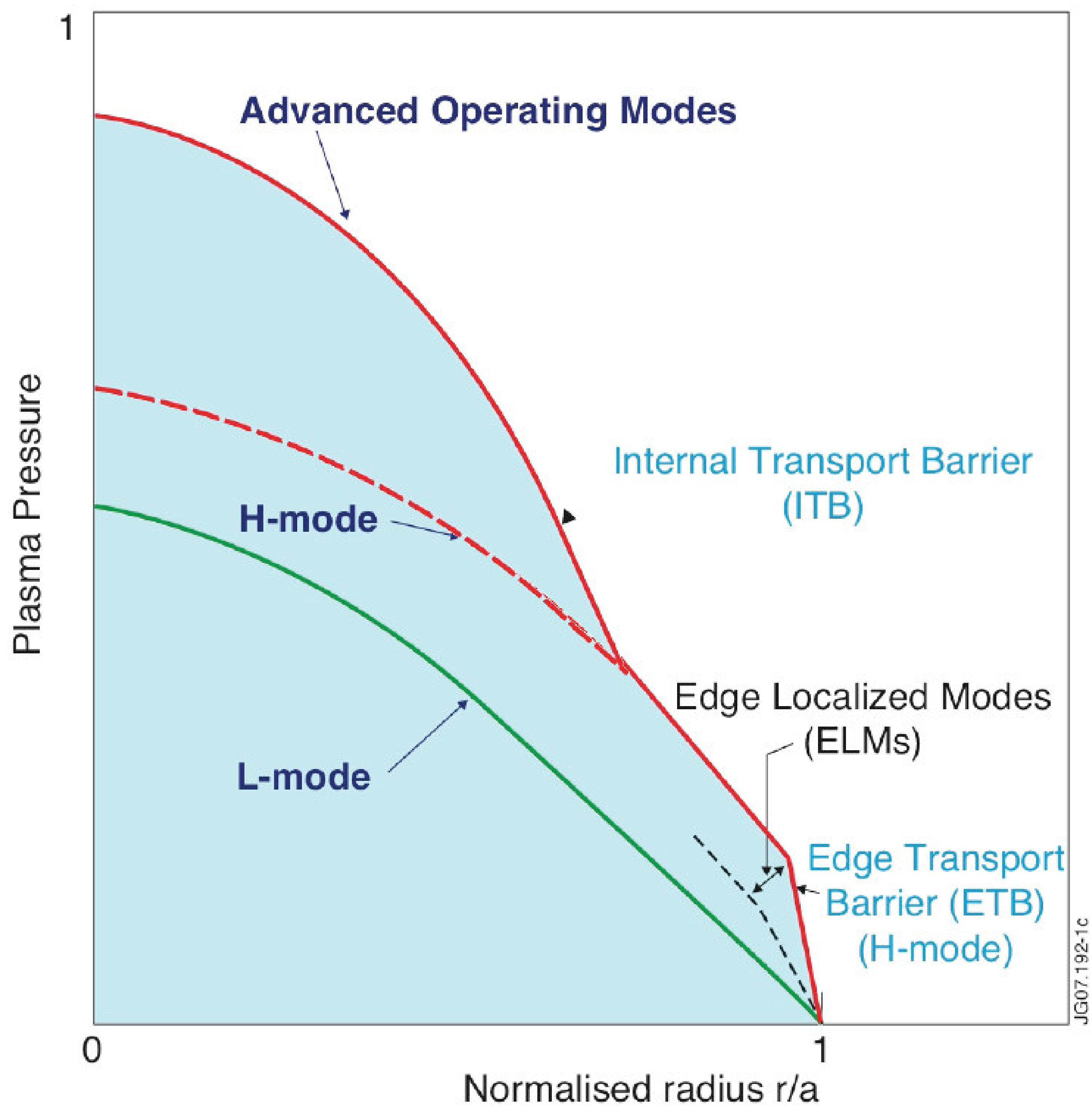
H-mode ⇒ AOM mode



H-mode



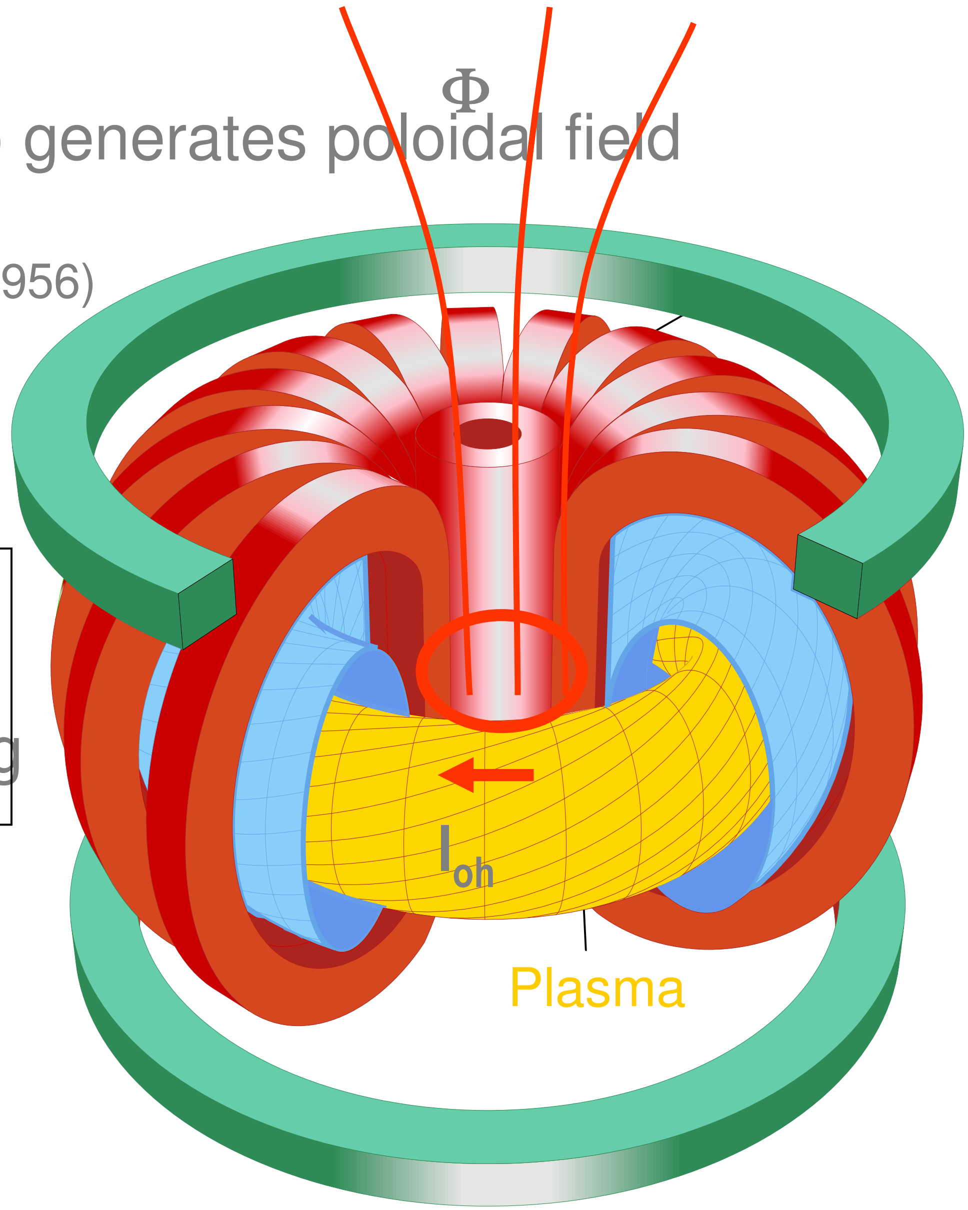
Advanced Operating Mode


1
Advanced Operating Modes
Internal Transport Barrier
(ITB)
H-mode
Plasma Pressure
Edge Localized Modes
(ELMs)
L-mode
Edge Transport
Barrier (ETB)
(H-mode)
JG07.192-1c
0
1
Normalised radius r/a

CONCEPT I, tokamak

large plasma current (MA) generates poloidal field component

Artsimovich, Sacharov (Moscow, 1956)

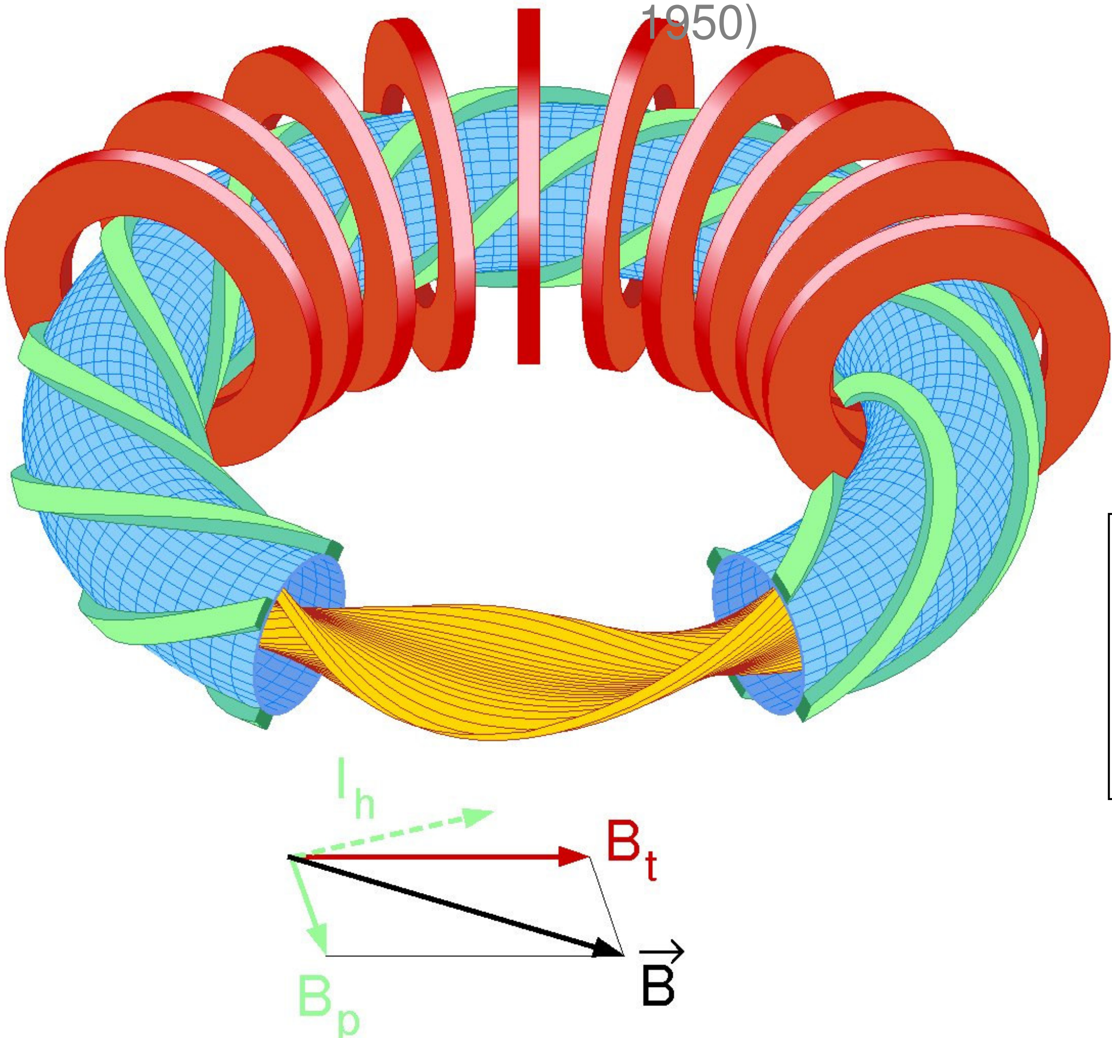


plasma current
inductively driven:
plasma transformer winding

CONCEPT II, stellarator

helical external coils create poloidal field

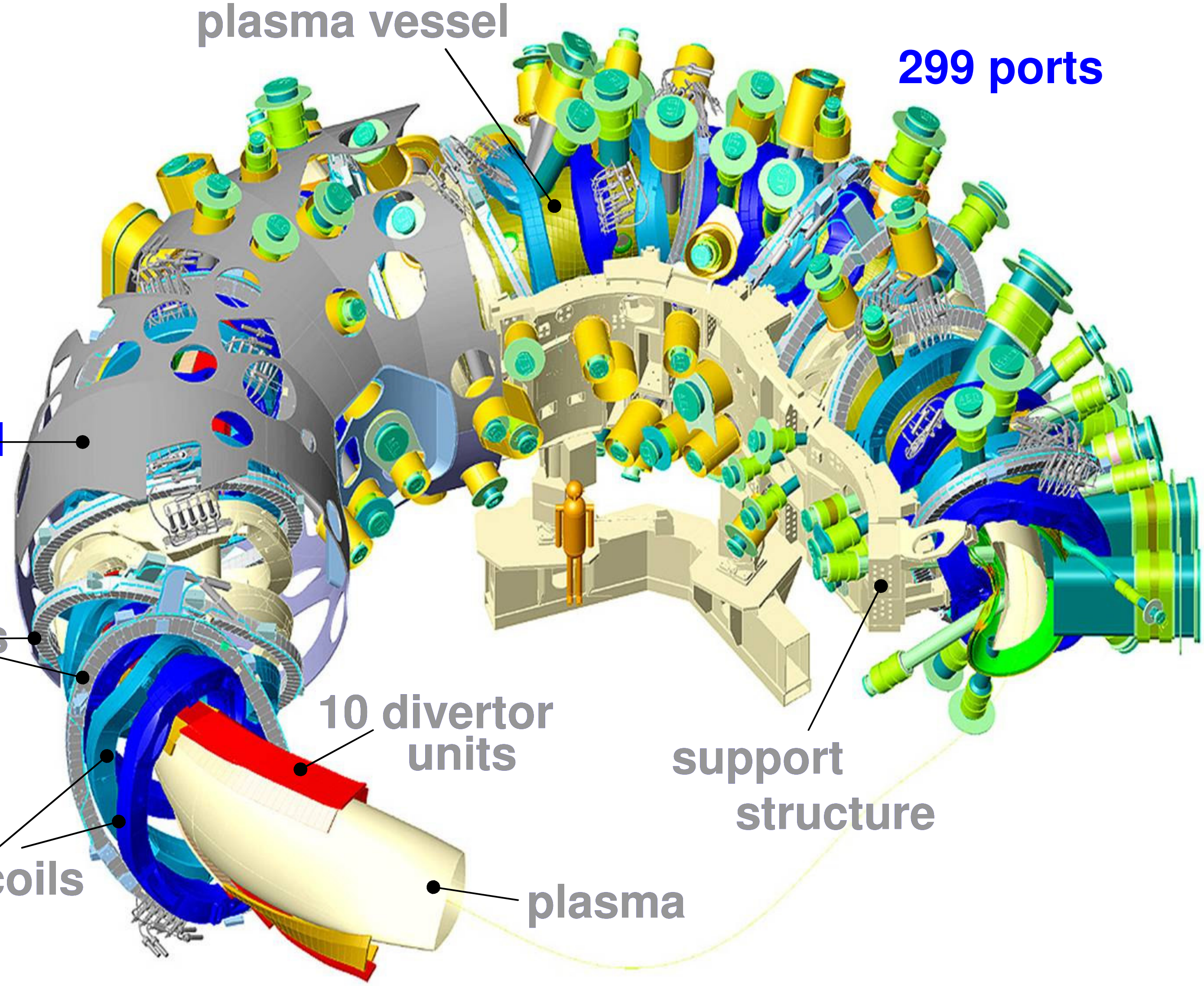
L. Spitzer jr (Princeton, 1950)



only external currents
no plasma current
intrinsically steady state

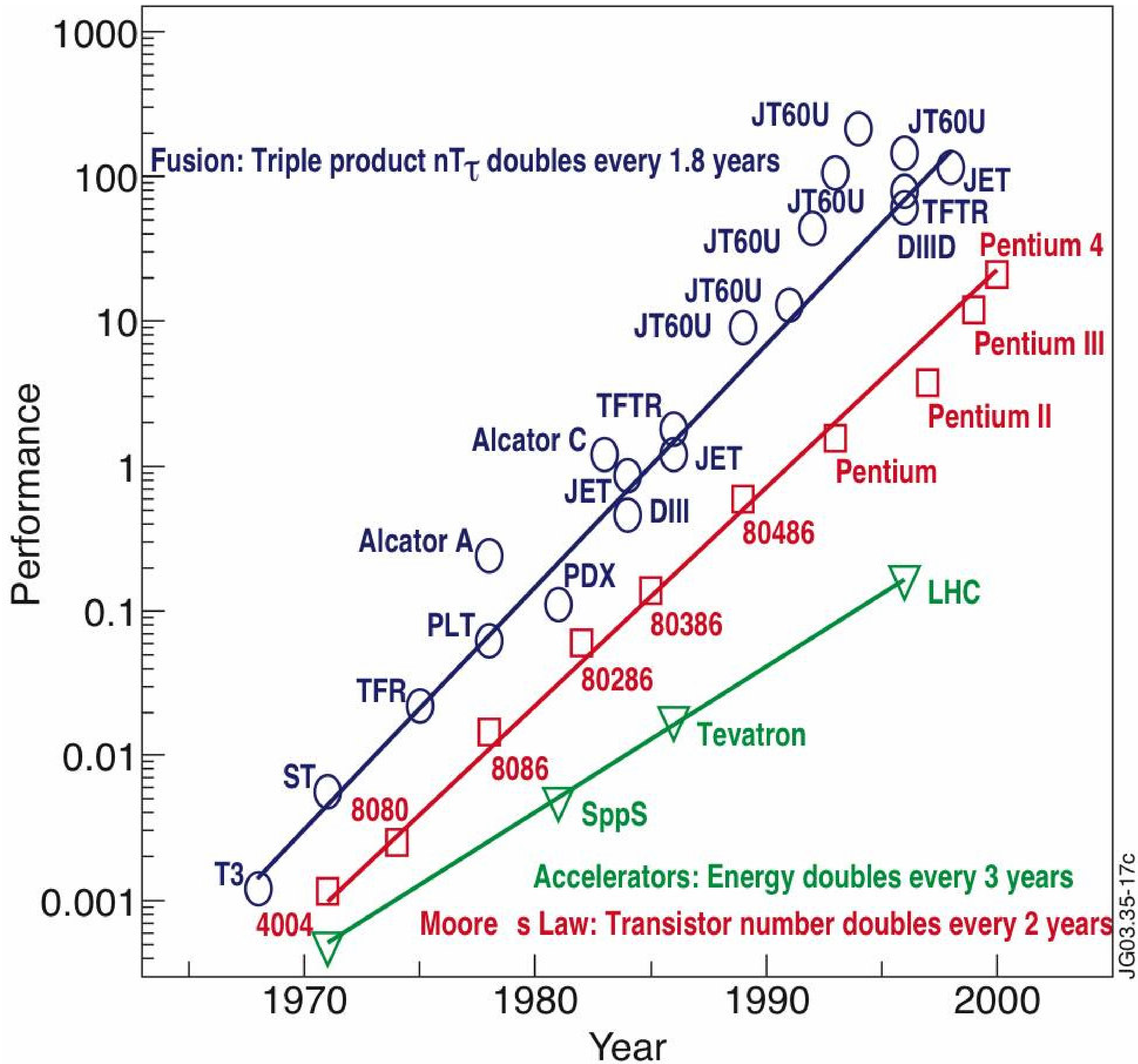
W7-X, components assembly

R = 5.6 m,
a = 0.53 m
B ≤ 3 T,
ι = 5/6 - 5/4

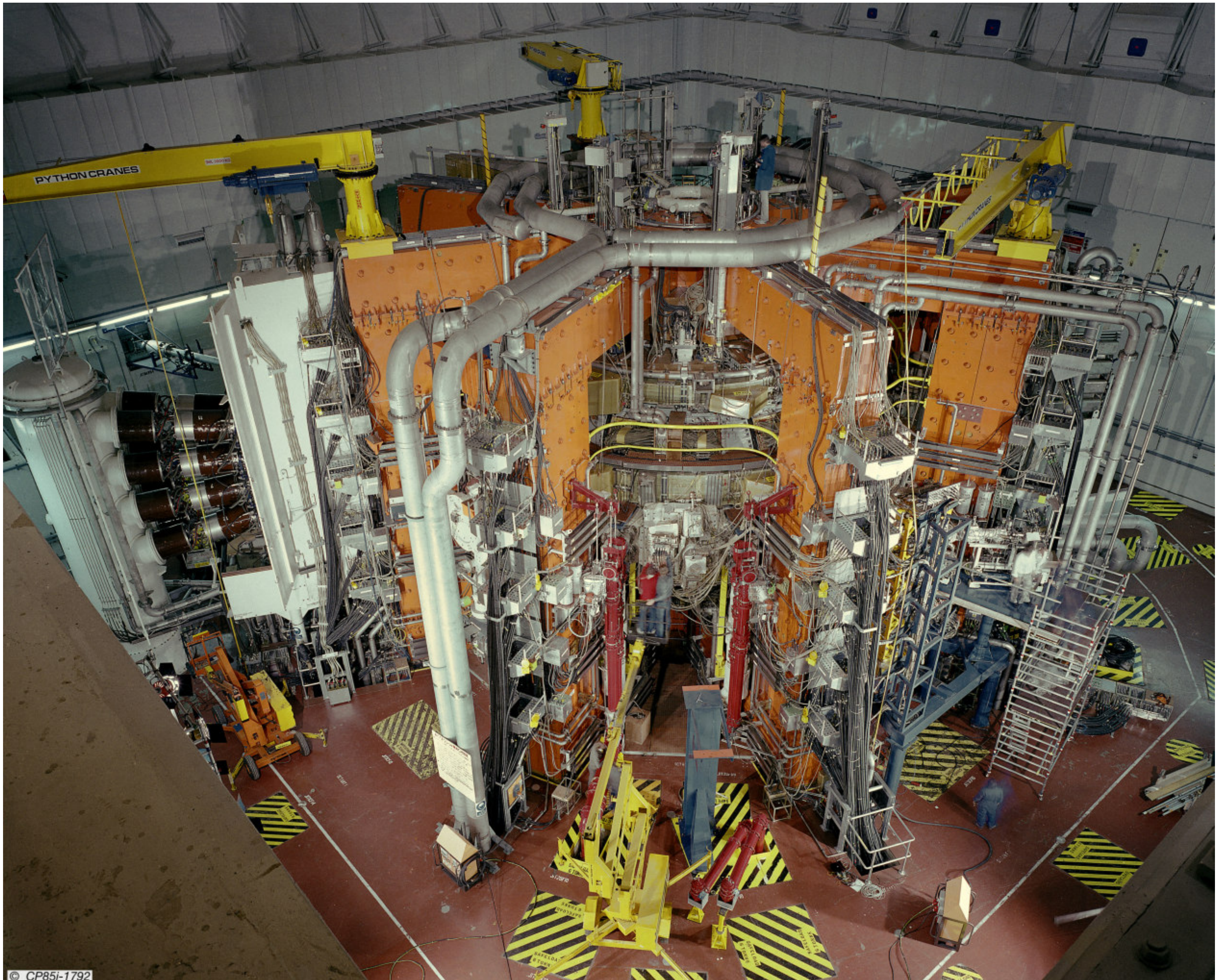


spectrometrer parameters

Line	**B V**	**C VI**	**N VII**	**O VIII**
Line wavelength (nm)	4.859	3.373	2.478	1.897
Wavelength range	4.70-5.20	3.10-3.50	2.25-2.65	1.85-2.00
Crystal	MLM	MLM	MLM	TlAP
2d (nm)	10.24	8.12	5.05	2.59
Incidence angle (deg)	28.33	24.54	29.36	47.09
Rowland circle radius (mm)	750	890	450	313
Cylindrical curvature	1 500	1 780	900	626
Arm length	712	739	441	459


Fusion: Triple product nTτ doubles every 1.8 years
Accelerators: Energy doubles every 3 years
Moore s Law: Transistor number doubles every 2 years
Performance
Year
1000
100
10
1
0.1
0.01
0.001
1970
1980
1990
2000
T3
ST
TFR
PLT
Alcator A
PDX
JET
DIII
Alcator C
TFTR
JET
JT60U
JT60U
JT60U
JT60U
JT60U
JT60U
JT60U
JET
TFTR
DIIID
4004
8080
8086
80286
80386
80486
Pentium
Pentium II
Pentium III
Pentium 4
SppS
Tevatron
LHC
JG03.35-17c

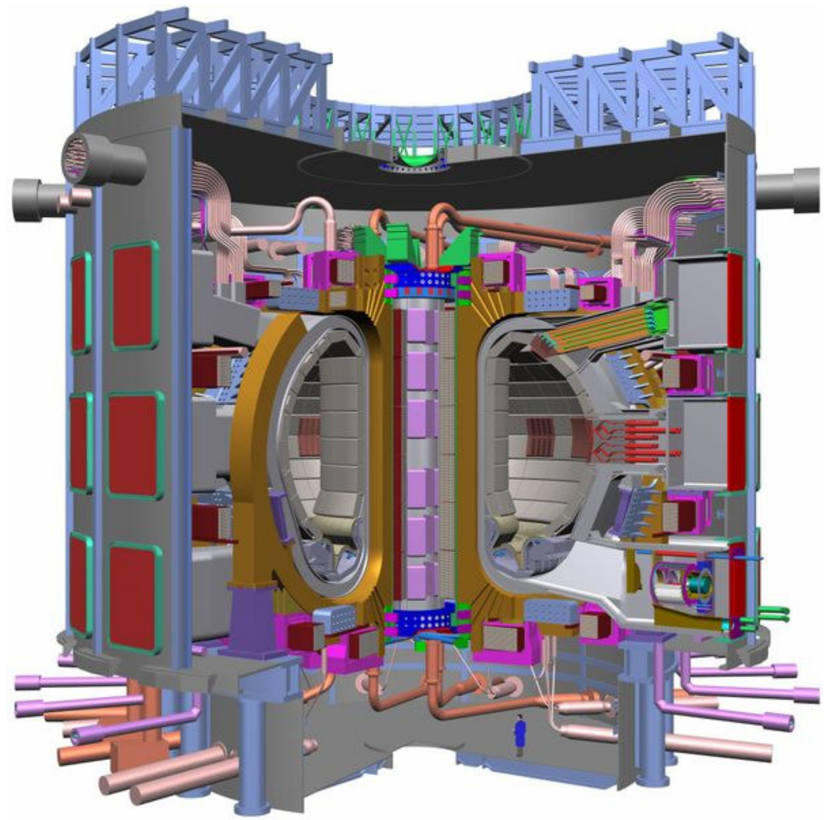
Tokamak JET



TOKAMAK JET. www.efda.org

Czym jest/będzie ITER?

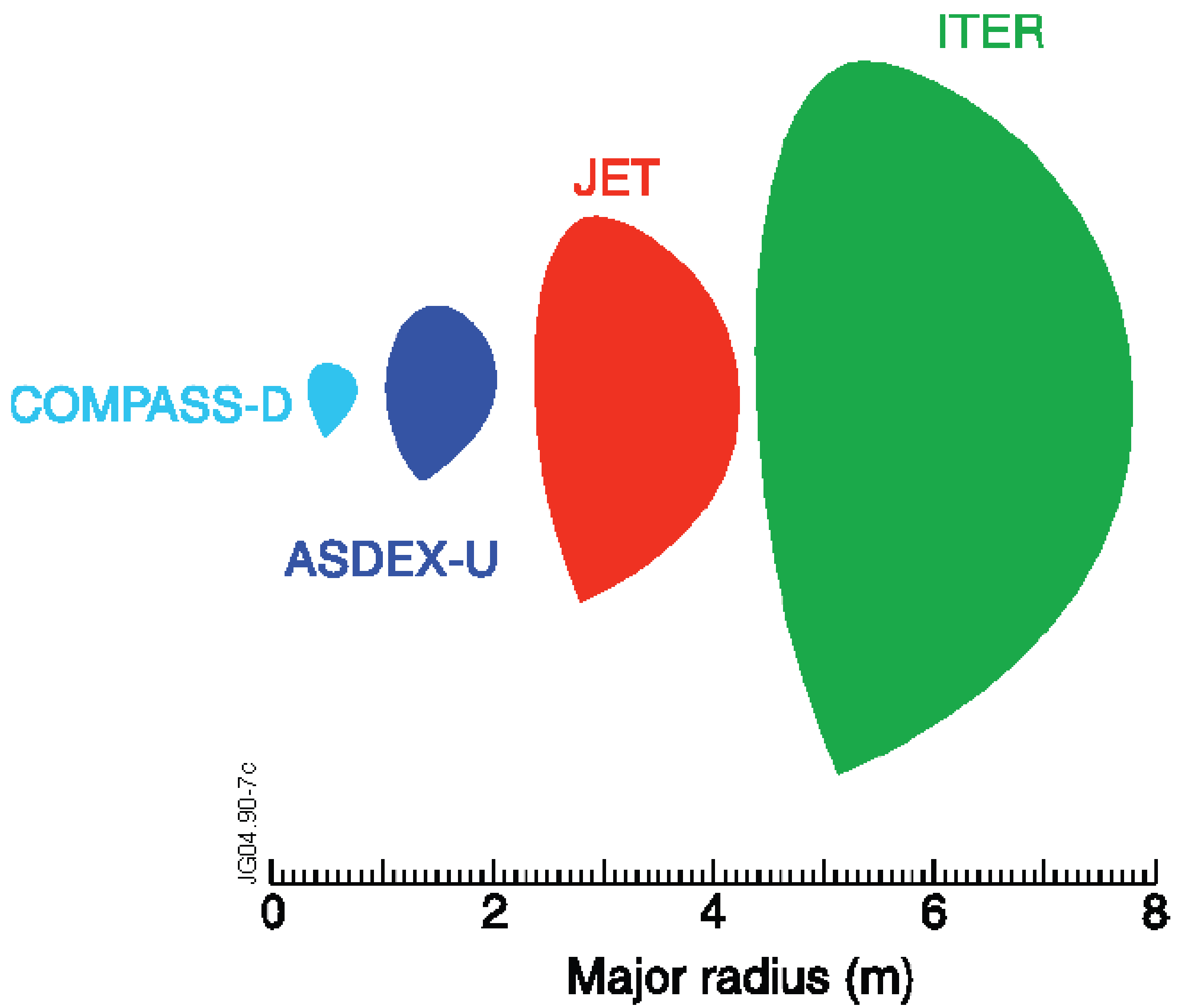
International
Thermonuclear
Experimental
Reactor

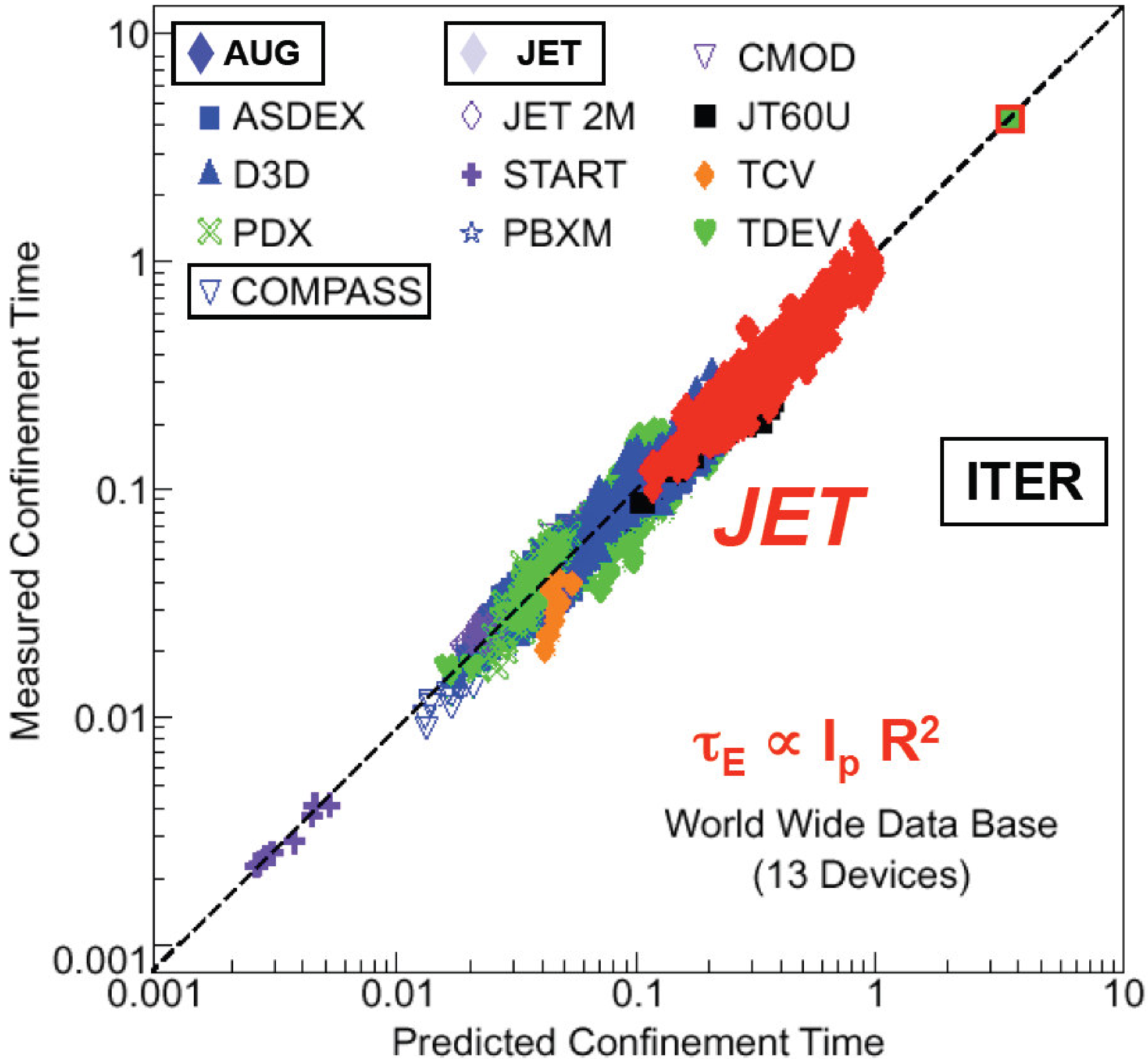


ITER
po łacinie oznacza „droga”

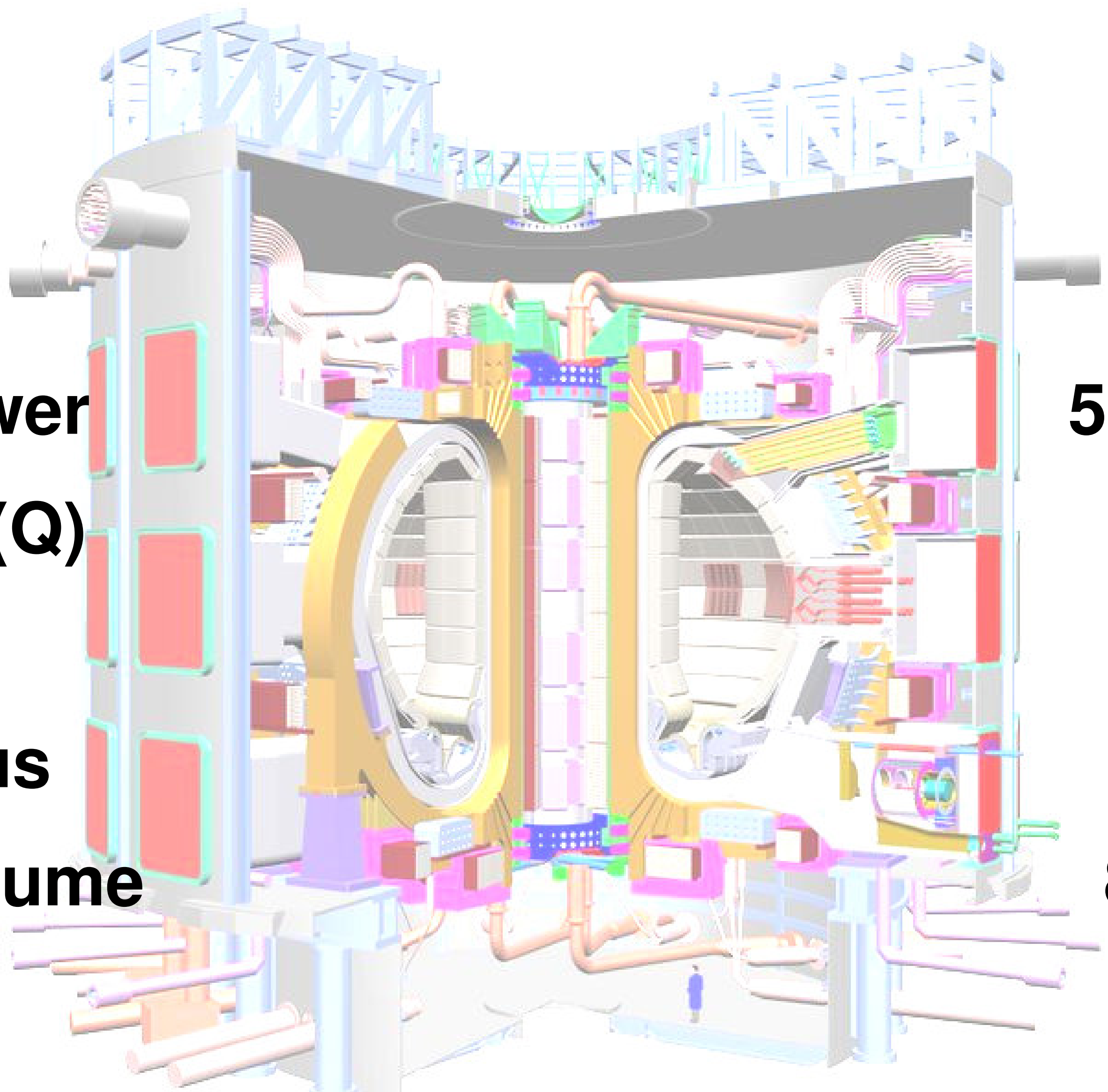
Celem eksperymentu ITER jest badanie plazmy w warunkach zbliżonych do tych jakie będą występować w reaktorze elektrowni termojądrowej.


ITER
D + T → 4 He + n + Energy
D
T
n
4He

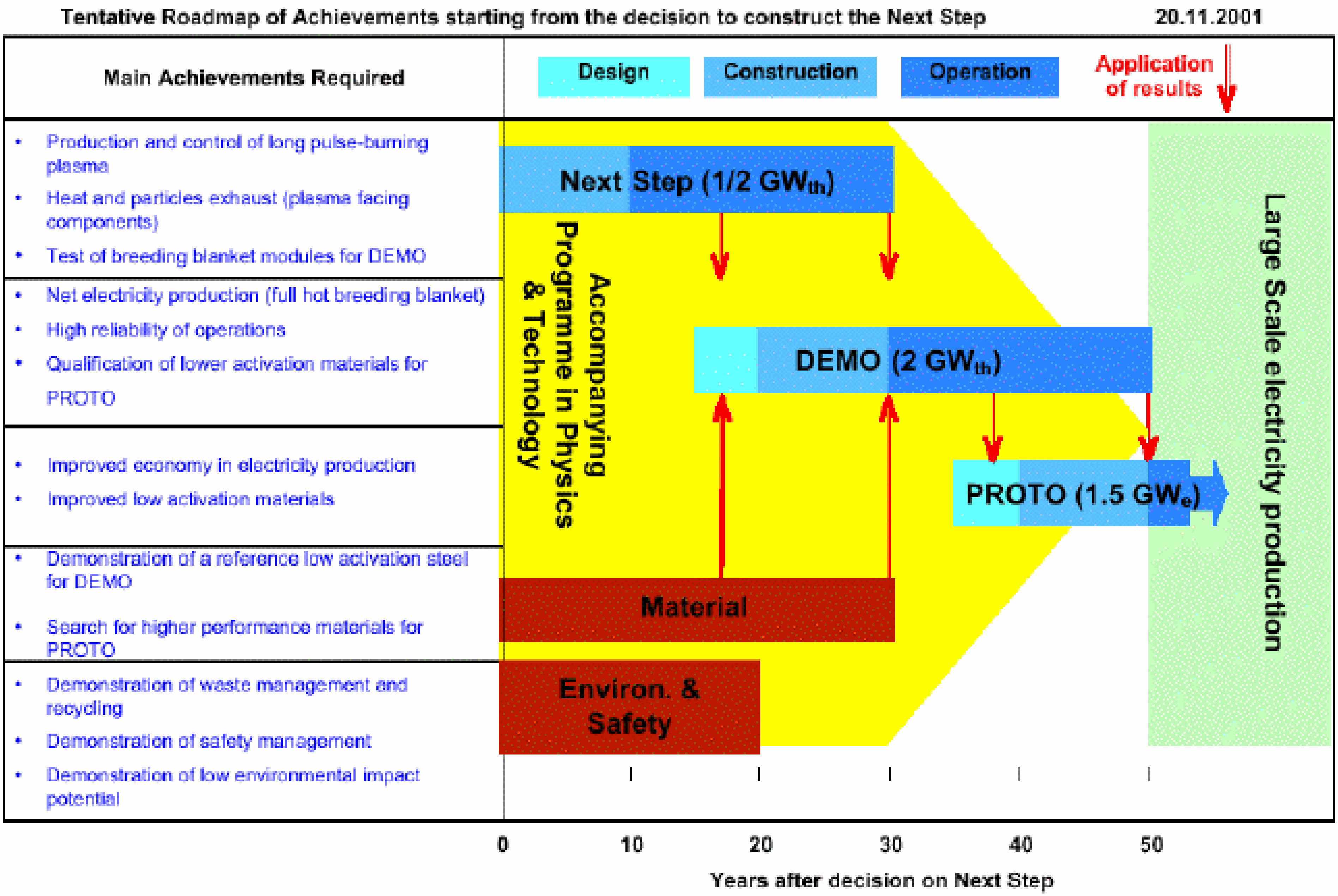

ITER
JET
COMPASS-D
ASDEX-U
JG04.90-7c
0
2
4
6
8
Major radius (m)


AUG
JET
CMOD
ASDEX
JET 2M
JT60U
D3D
START
TCV
PDX
PBXM
TDEV
COMPASS
ITER
JET
$\tau_E \propto I_p R^2$
World Wide Data Base
(13 Devices)
Measured Confinement Time
Predicted Confinement Time
10
1
0.1
0.01
0.001
0.001
0.01
0.1
1
10

ITER



Fusion power	**500 MW**
Efficiency (Q)	**≥10**
Height	**26 m**
Major radius	**29 m**
Plasma volume	**837 m^3**



Extracted from:
"Five Year Assessment Report related to the specific programme:
Nuclear energy covering the period 1995-1999" June 2000

http://www.iter.org/

Wendelstein 7-X

Under construction in Greifswald, Germany

W7-X torus hall

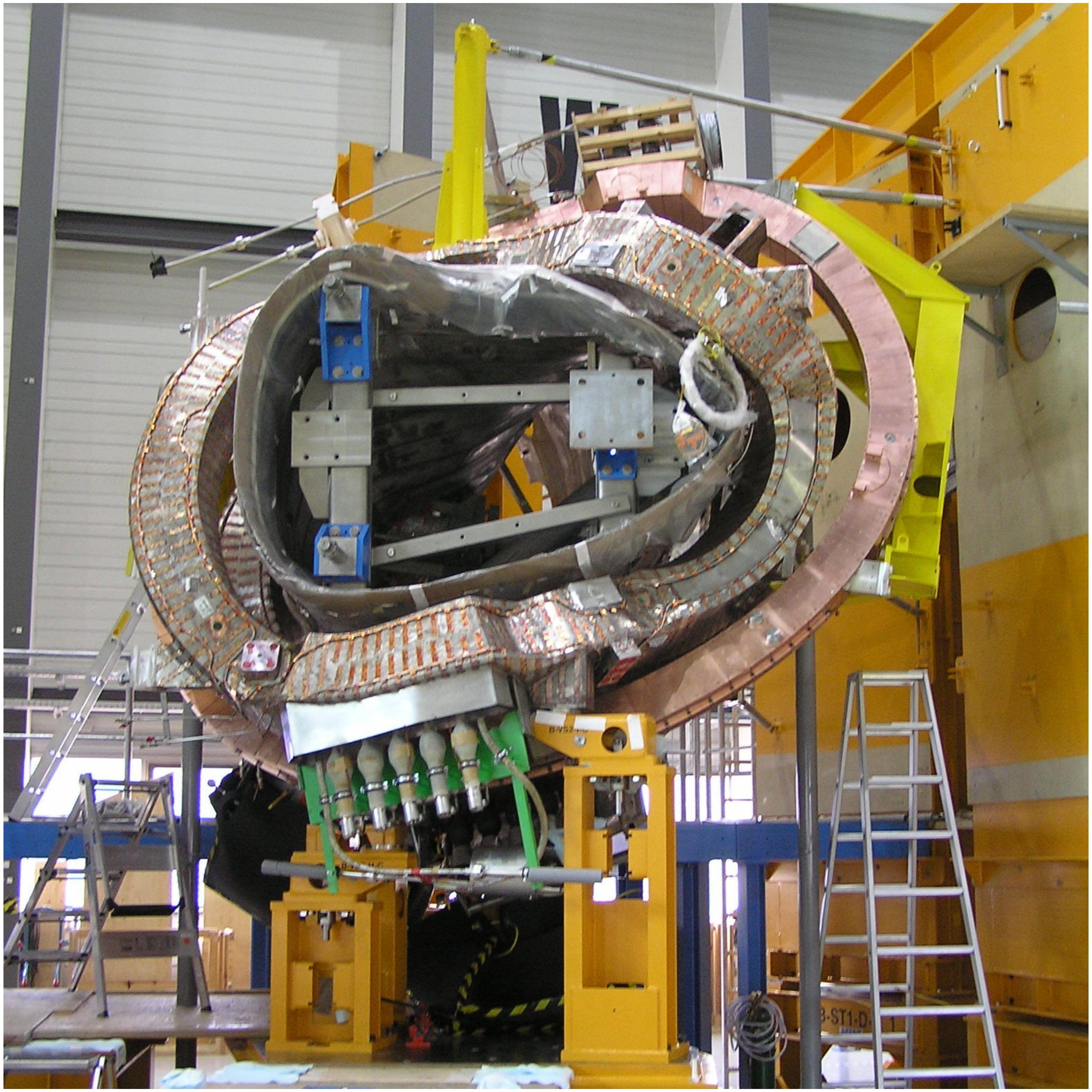
ECRH

NBI, cryogenics

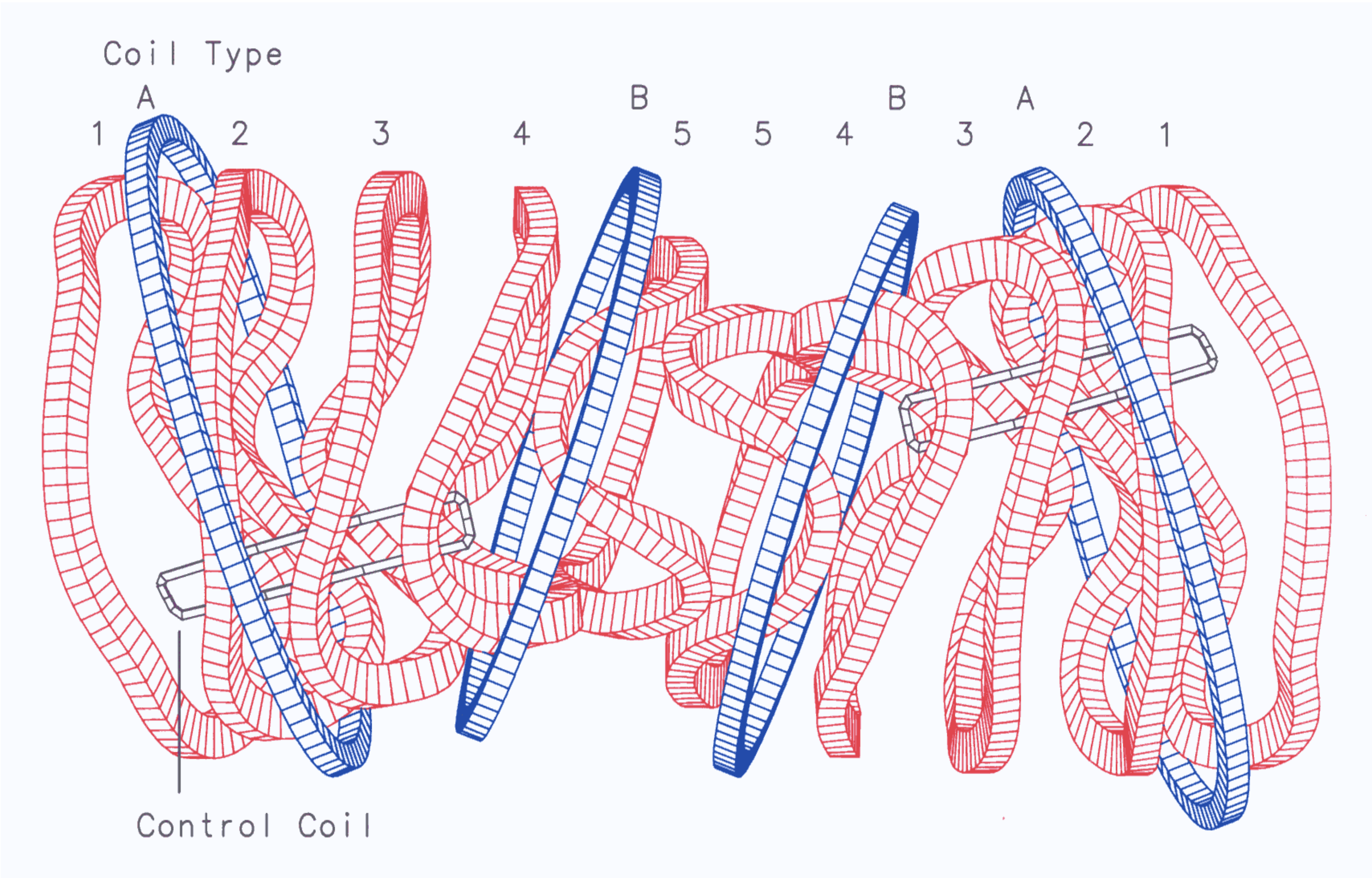
diagnostics, control room

assembly, ICRH

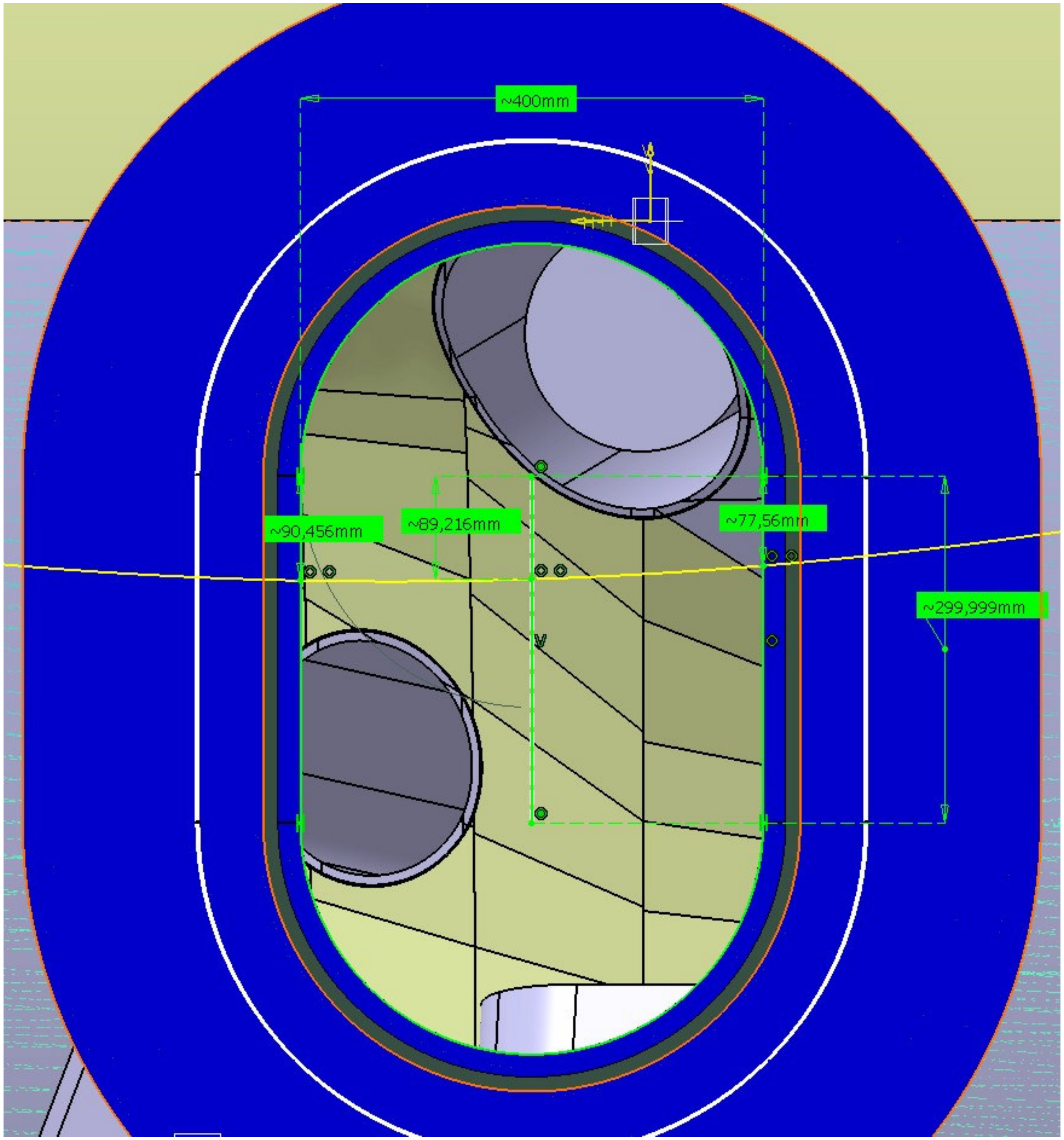
TEST ASSEMBLY, 3 coils mounted



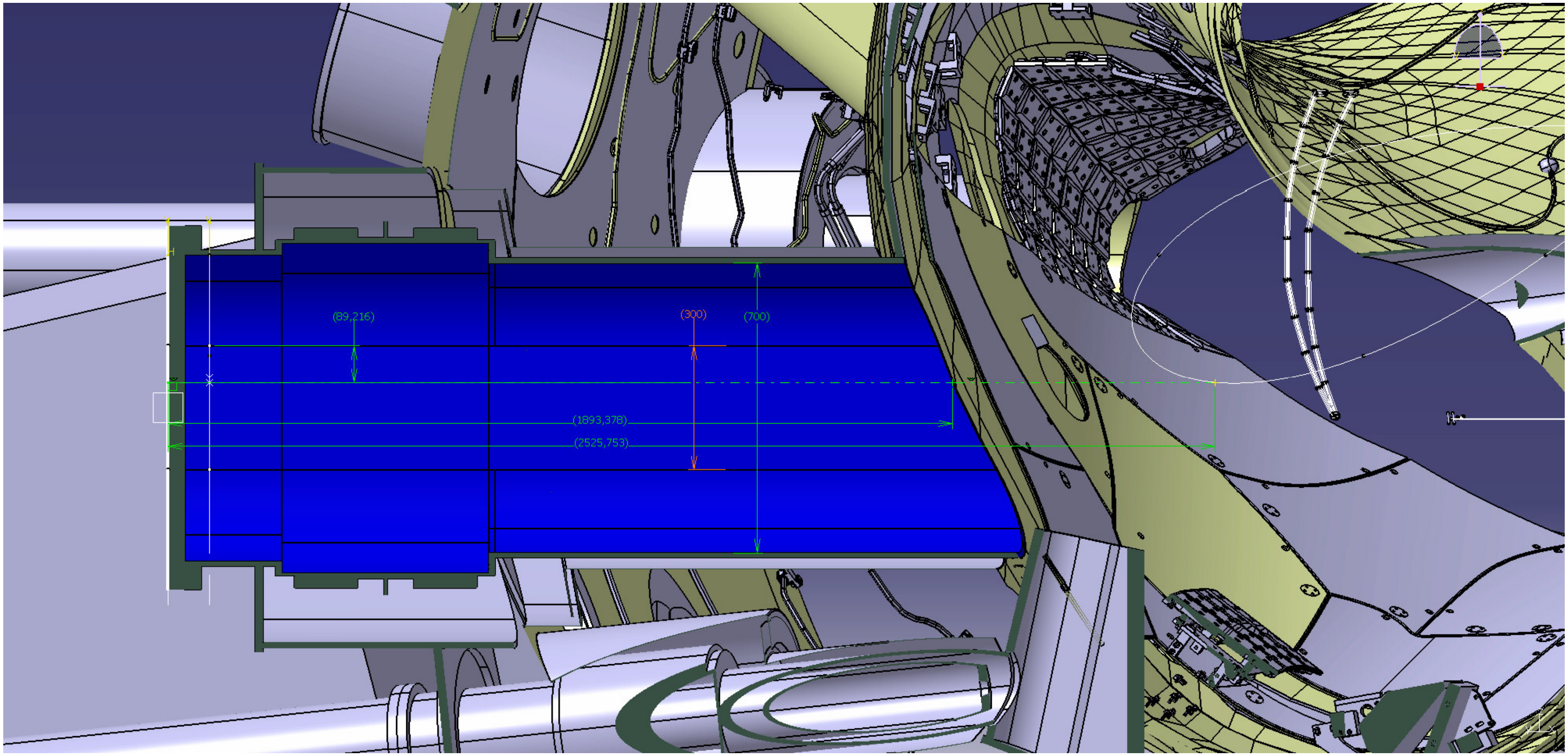
W7-X COILS, 2 x (2 planar + 5 non-planar)/module



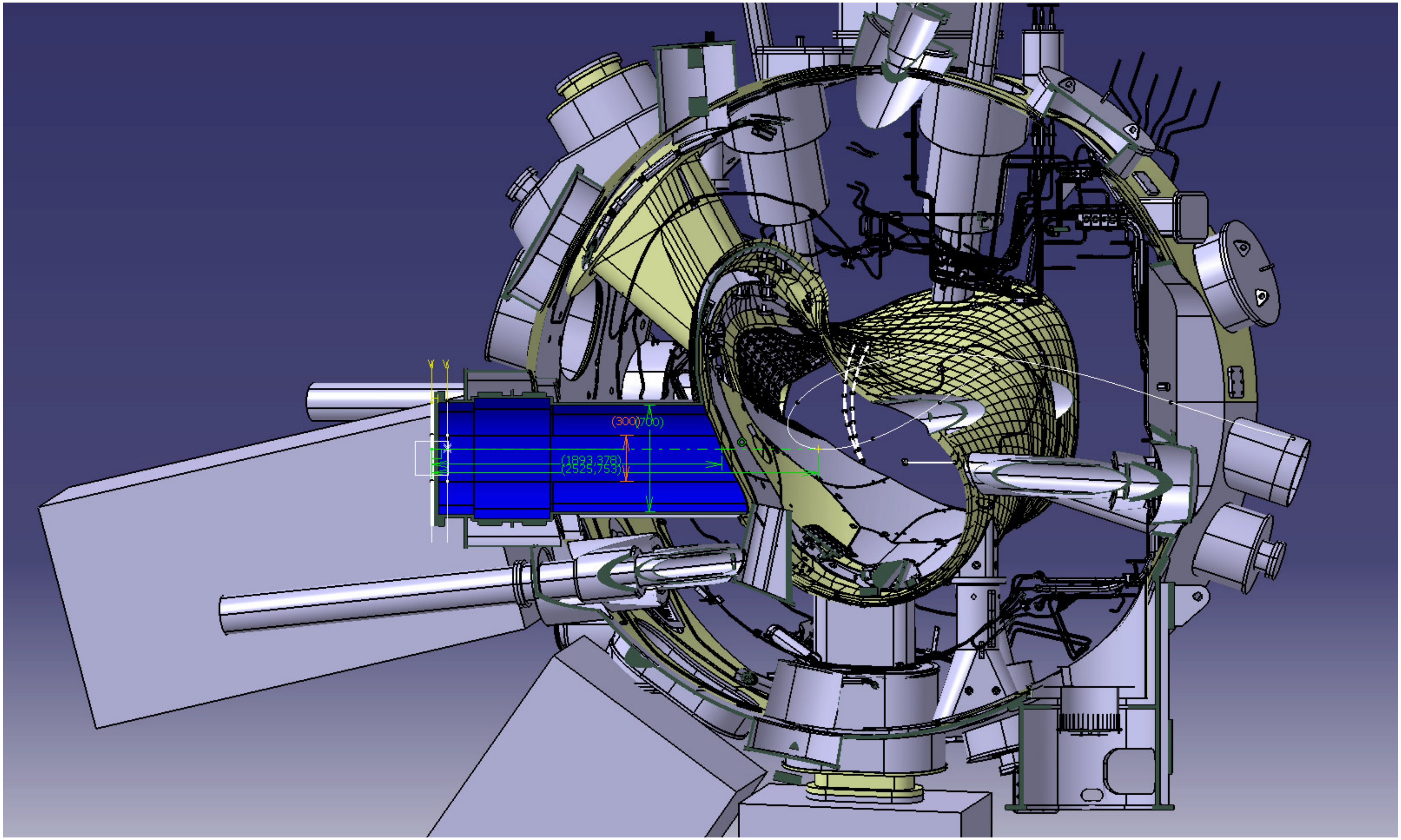
Port AEK30

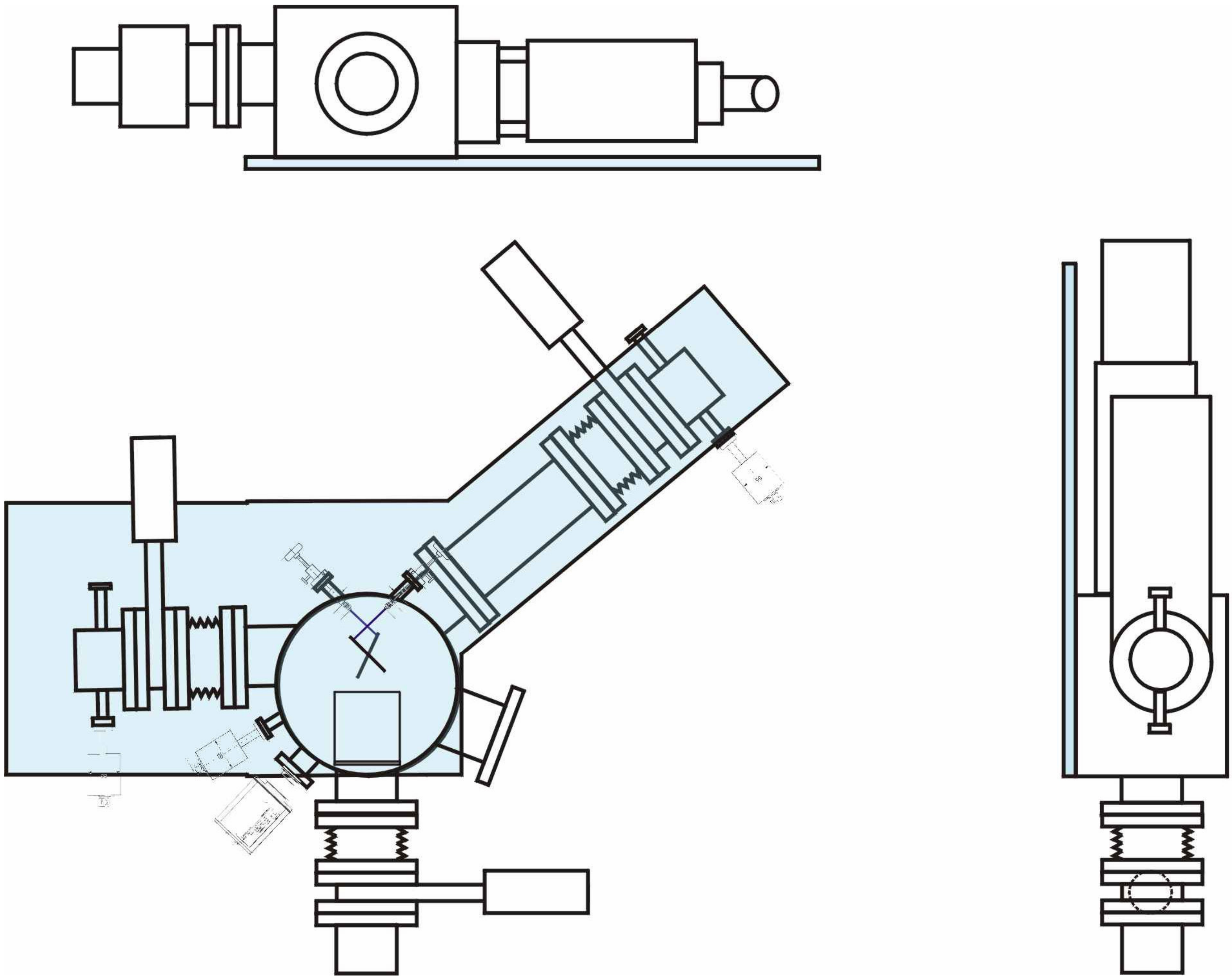


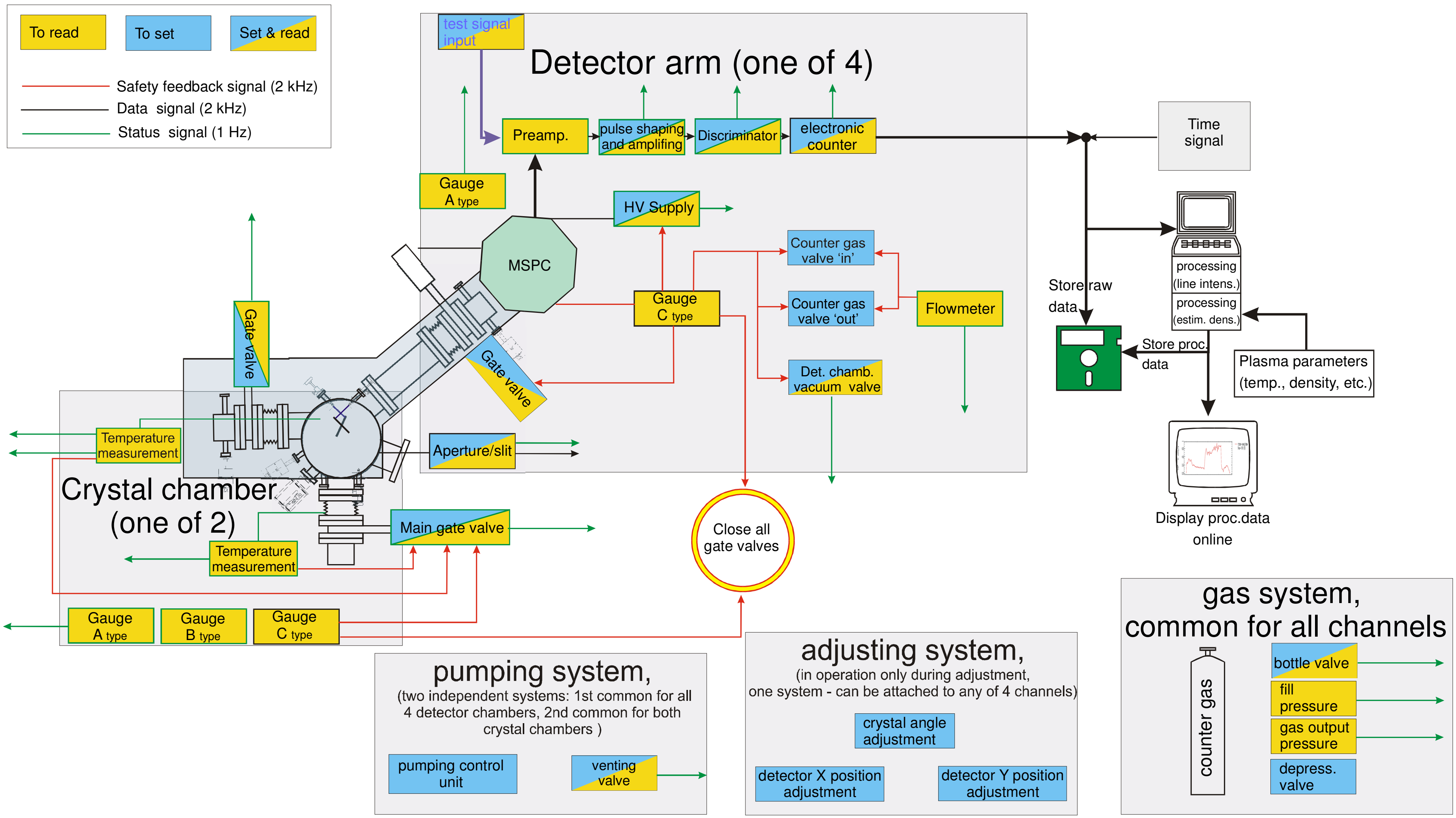
Port AEK30

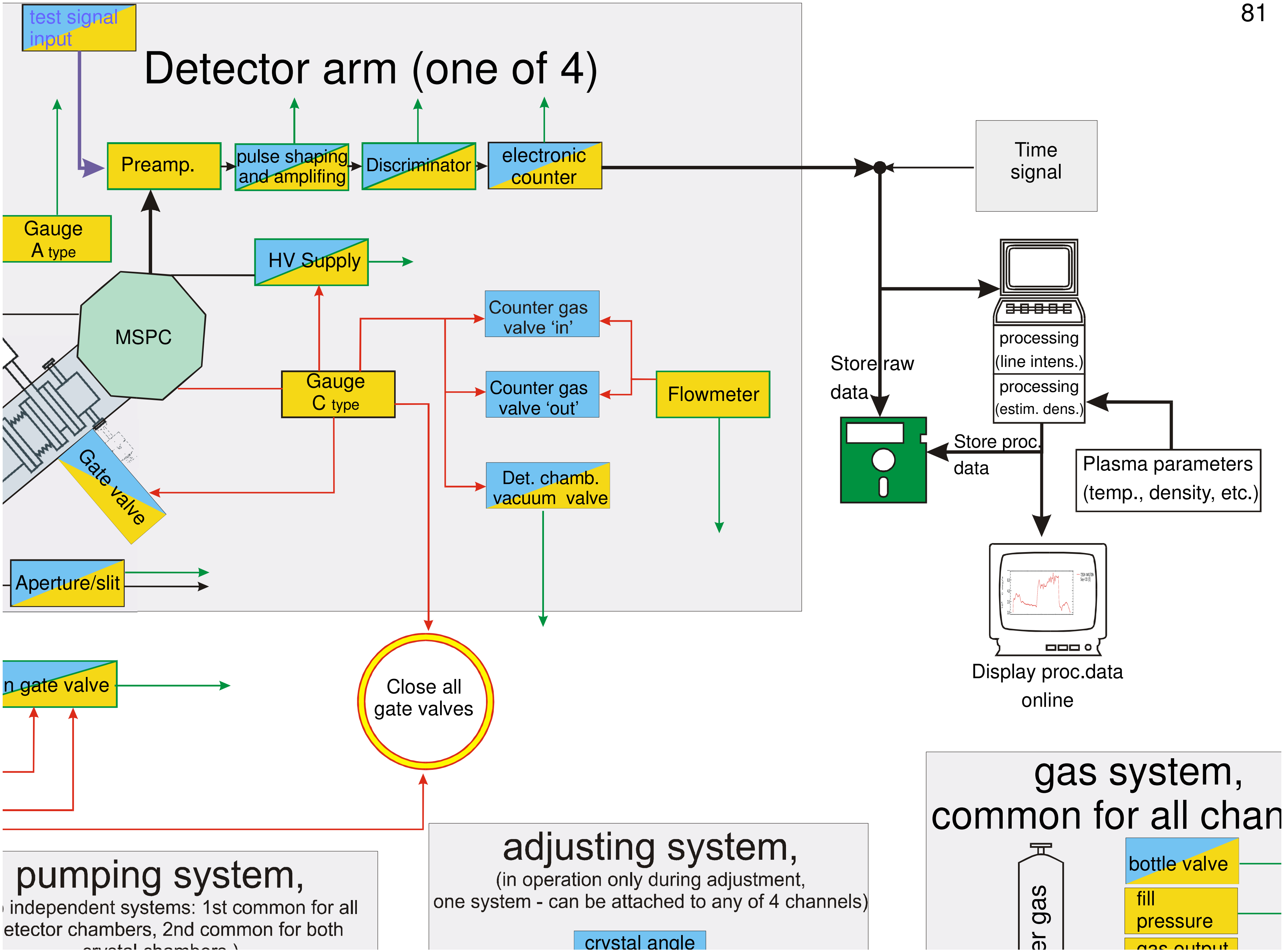


Port AEK30

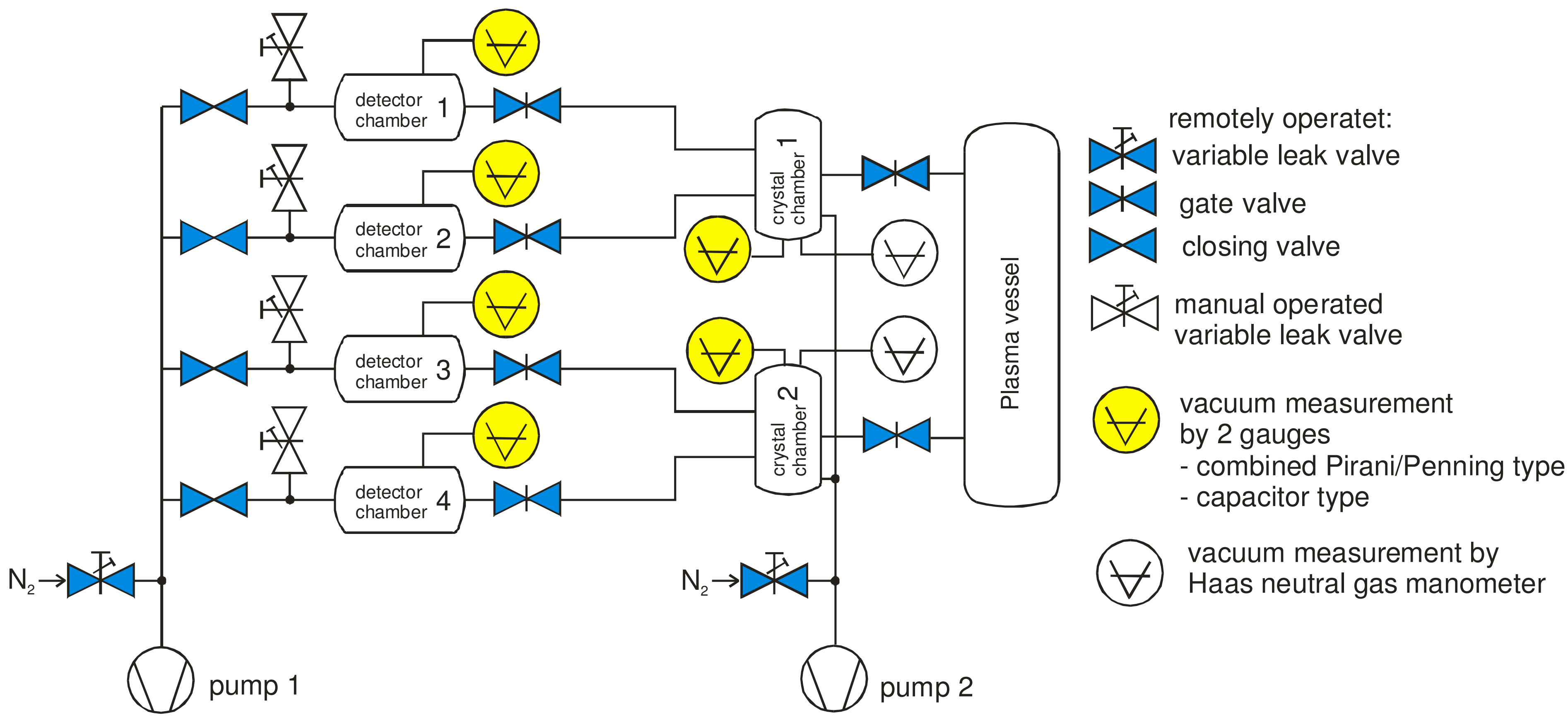





To read
To set
Set & read
Safety feedback signal (2 kHz)
Data signal (2 kHz)
Status signal (1 Hz)
test signal input
Detector arm (one of 4)
Preamp.
pulse shaping and amplifing
Discriminator
electronic counter
Time signal
Gauge A type
HV Supply
MSPC
Counter gas valve 'in'
Counter gas valve 'out'
Gauge C type
Flowmeter
Det. chamb. vacuum valve
Gate valve
Gate valve
Store raw data
processing (line intens.)
processing (estim. dens.)
Store proc. data
Plasma parameters (temp., density, etc.)
Display proc.data online
Temperature measurement
Aperture/slit
Crystal chamber (one of 2)
Main gate valve
Temperature measurement
Close all gate valves
Gauge A type
Gauge B type
Gauge C type
pumping system,
(two independent systems: 1st common for all 4 detector chambers, 2nd common for both crystal chambers)
pumping control unit
venting valve
adjusting system,
(in operation only during adjustment, one system - can be attached to any of 4 channels)
crystal angle adjustment
detector X position adjustment
detector Y position adjustment
gas system, common for all channels
counter gas
bottle valve
fill pressure
gas output pressure
depress. valve



test signal input
Detector arm (one of 4)
Preamp.
pulse shaping and amplifing
Discriminator
electronic counter
Time signal
Gauge A type
HV Supply
MSPC
Counter gas valve 'in'
Counter gas valve 'out'
Gauge C type
Flowmeter
Store raw data
processing (line intens.)
processing (estim. dens.)
Store proc. data
Plasma parameters (temp., density, etc.)
Gate valve
Det. chamb. vacuum valve
Aperture/slit
Display proc.data online
n gate valve
Close all gate valves
gas system, common for all chan
pumping system,
independent systems: 1st common for all
etector chambers, 2nd common for both
adjusting system,
(in operation only during adjustment, one system - can be attached to any of 4 channels)
crystal angle
bottle valve
fill pressure
er gas



detector chamber 1
detector chamber 2
detector chamber 3
detector chamber 4
crystal chamber 1
crystal chamber 2
Plasma vessel
N_2
N_2
pump 1
pump 2
remotely operatet:
variable leak valve
gate valve
closing valve
manual operated variable leak valve
vacuum measurement by 2 gauges
- combined Pirani/Penning type
- capacitor type
vacuum measurement by Haas neutral gas manometer