The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR 1698/7

WORKSHOP ON PLASMA PHYSICS

7 - 11 March 2005

Neutron Emission Characteristics of Pinched Dense Plasmas

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"Neutron emission characteristics of pinched dense plasmas"

Hellmut Schmidt

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Acknowledgements to
Rainer Schmidt
Ulrich Jäger

- **Introduction**

- **Distinct Plasma Focus Phases**
- **Fusion Reaction Kinetics**
  in Plasma Neutron Sources
  Beam target neutron production

- **Neutron Measurements**

- **Reaction Proton Diagnostics**
- **Gyrating Particle Model**
- **Conclusions**

- The plasma focus is a pulsed source of
  - Ions
  - Electrons
  - Electromagnetic radiation
    - Microwave emission
    - IR emission
    - VIS emission
    - UV emission
    - EUV emission
    - X-ray emission

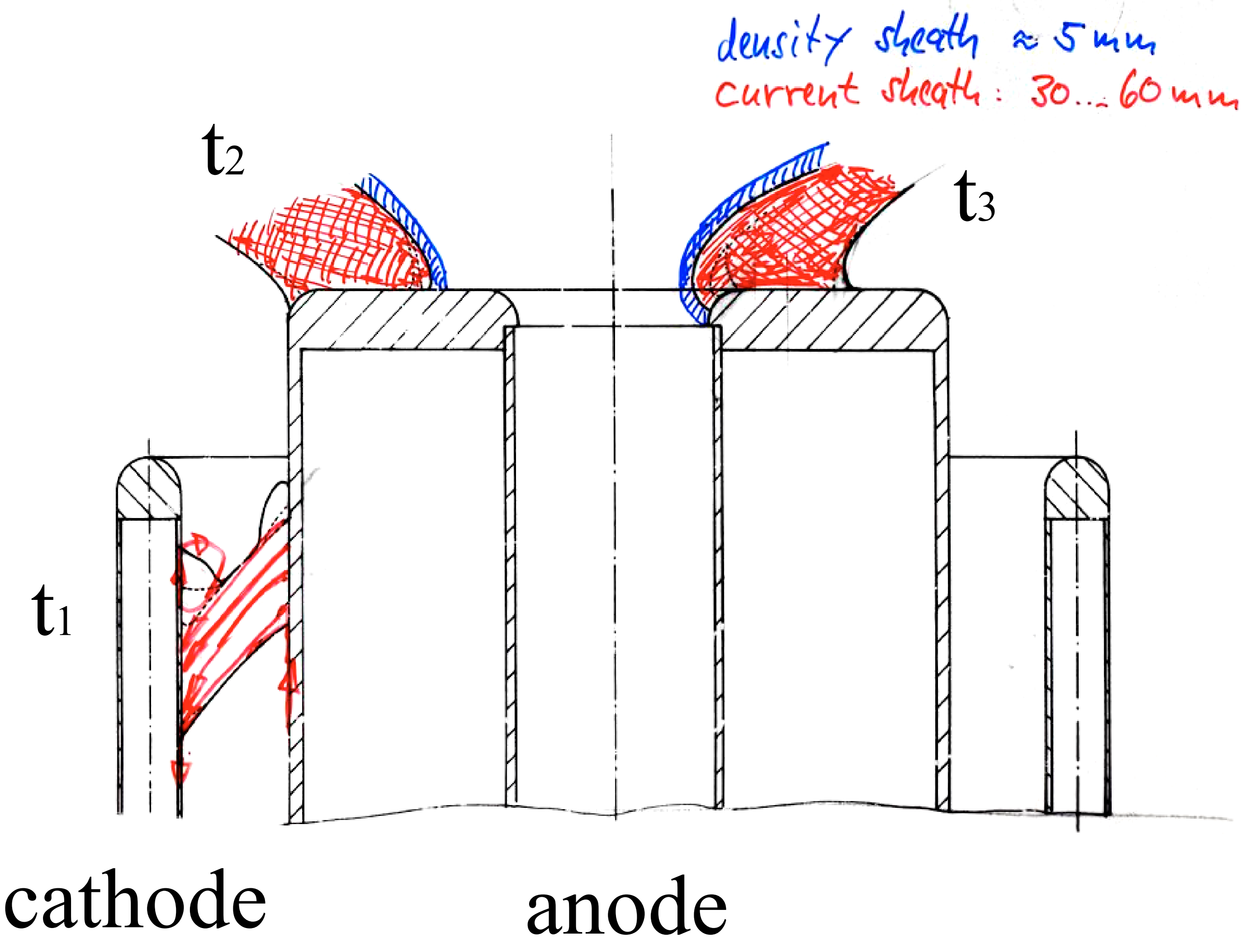
Energy input W from 0.1 kJ to > 1 MJ

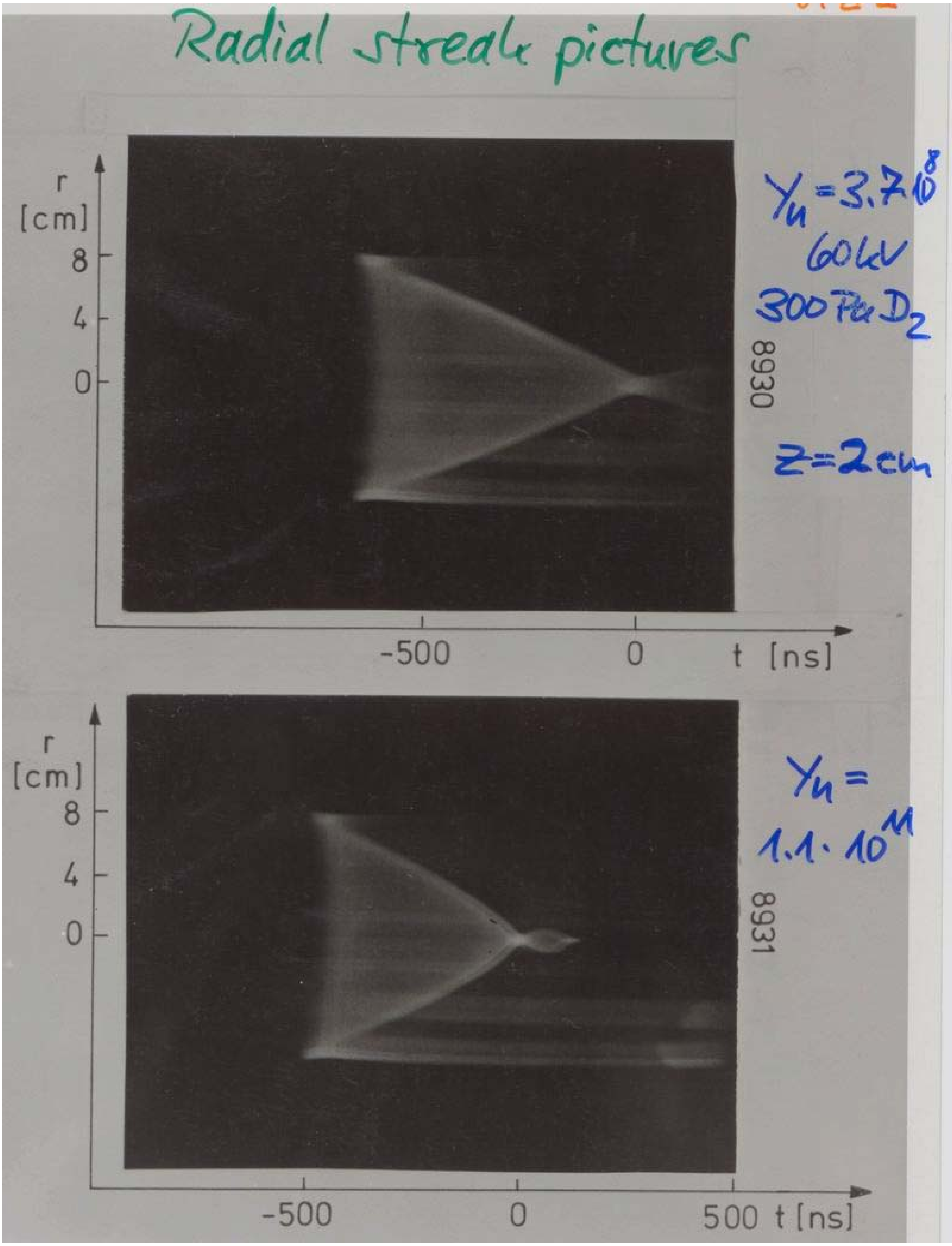
Neutron yield scales with square of W

Neutron yield efficiency scales with W !

Saturation in neutron yield occurs for W ≈ 1 MJ

Current and Density Sheaths in a Mather type Plasma Focus





Radial streak pictures
r [cm]
8
4
0
-500
0
t [ns]
8930
Yn = 3.7 10^8
60kV
300Pa D2
z = 2cm
r [cm]
8
4
0
8931
Yn = 1.1 · 10^11
-500
0
500 t [ns]

Plasma Focus Phases

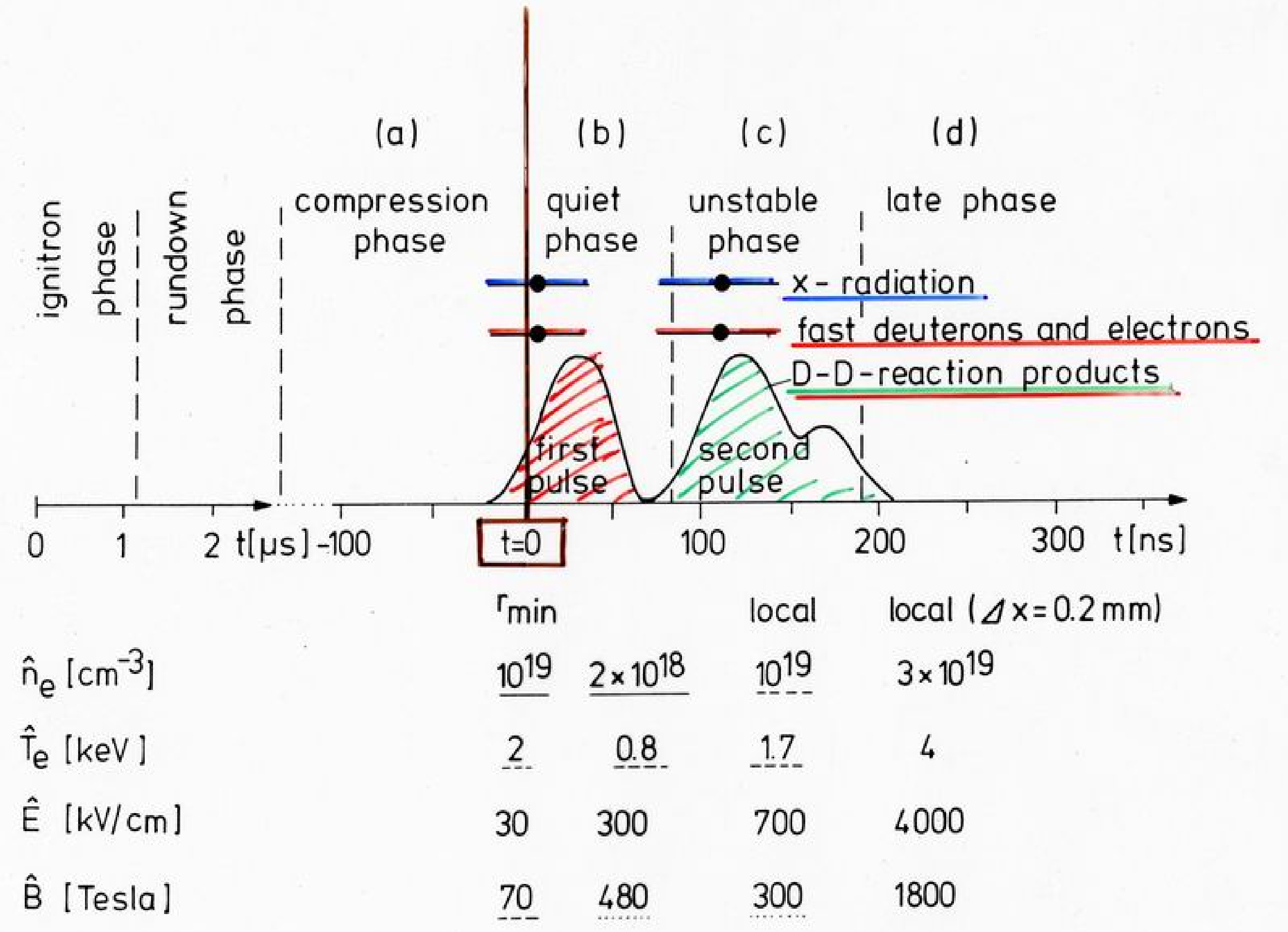
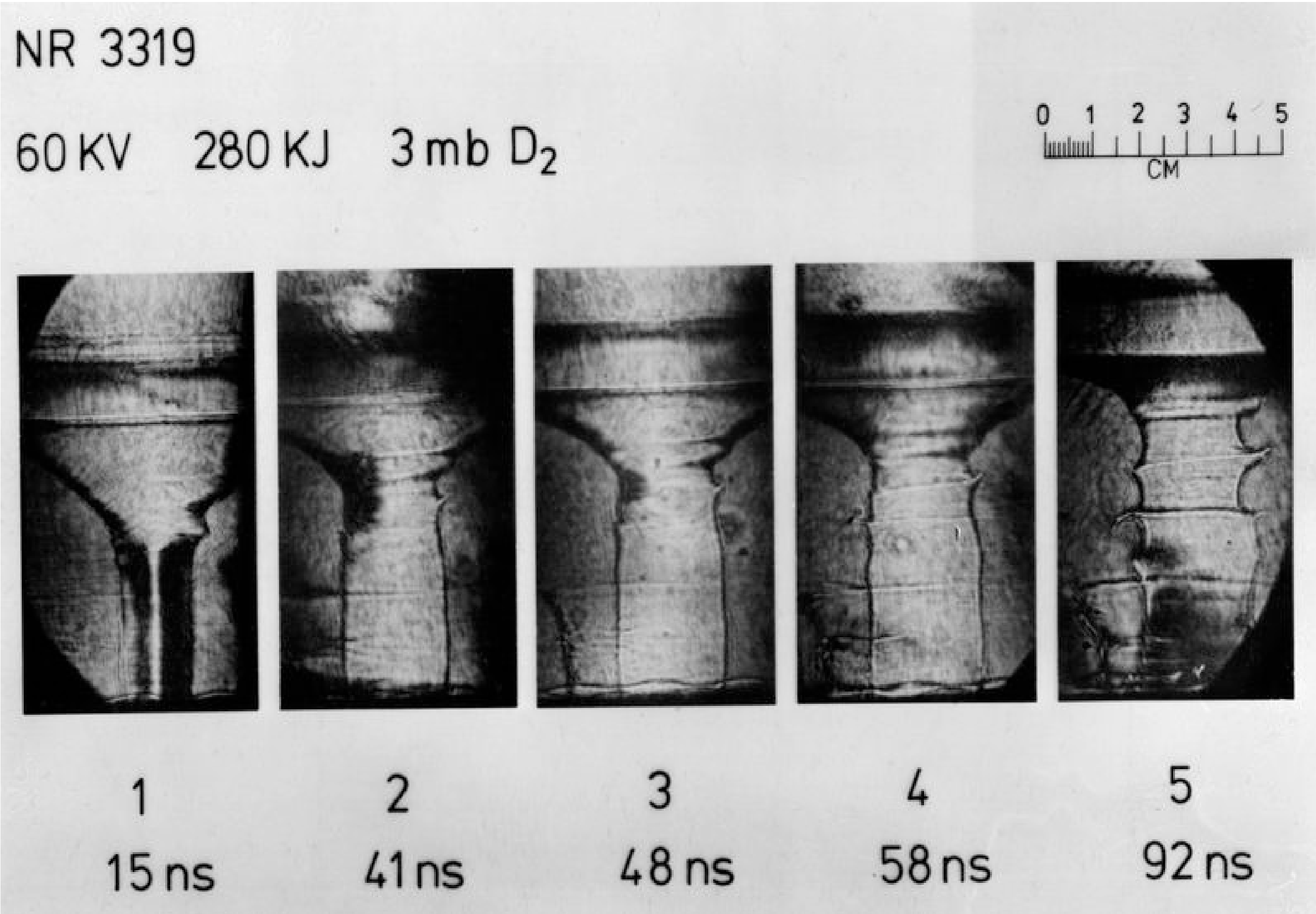


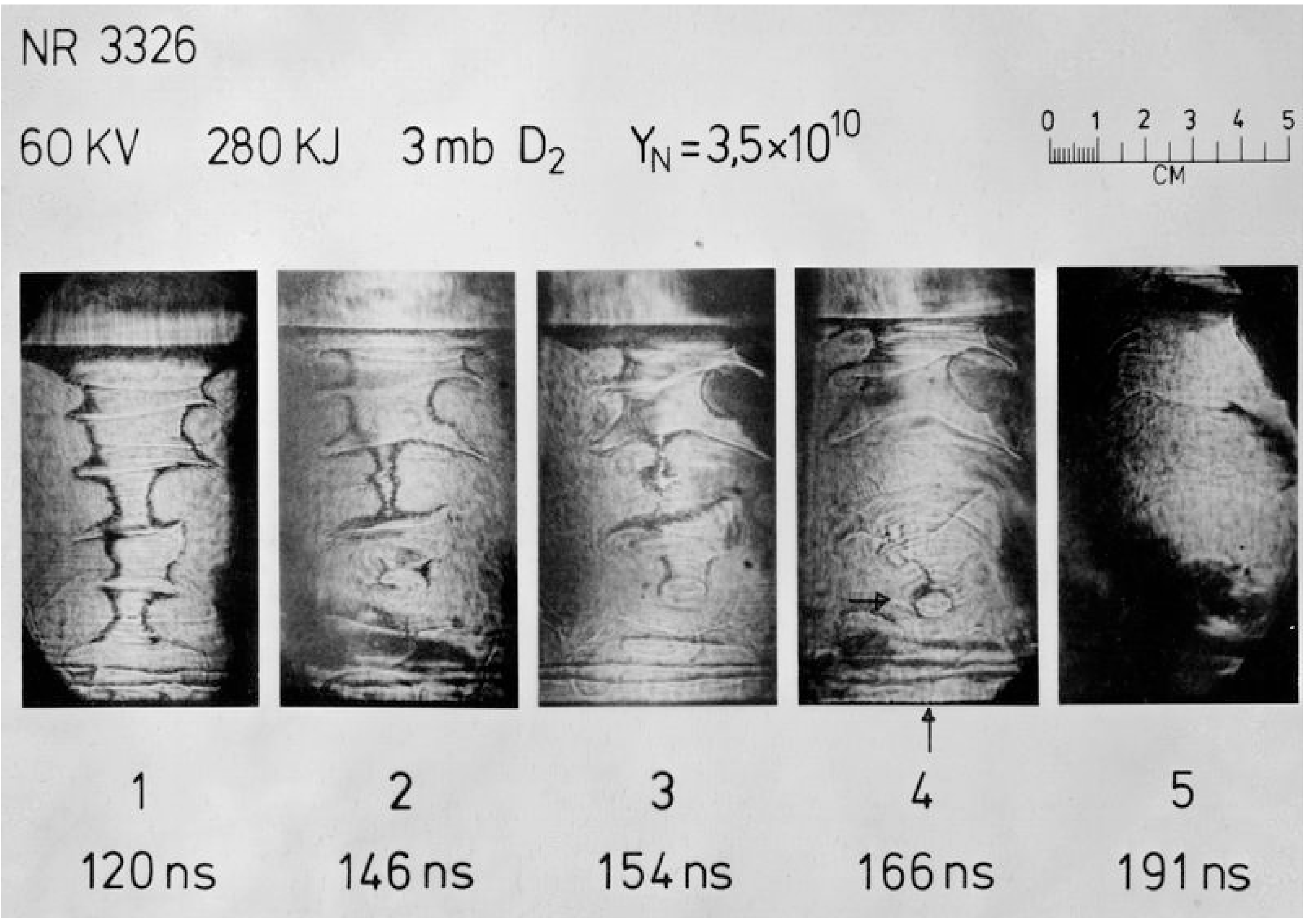
Fig. 3: Plasma focus phases with emission periods of D-D-reaction products (neutrons, protons), X-radiation, electrons and deuterons. Data for electron density and temperature, electric and magnetic fields, as obtained experimentally (underlined) or theoretically, are also given for the two fusion phases.

5 Schlieren pictures

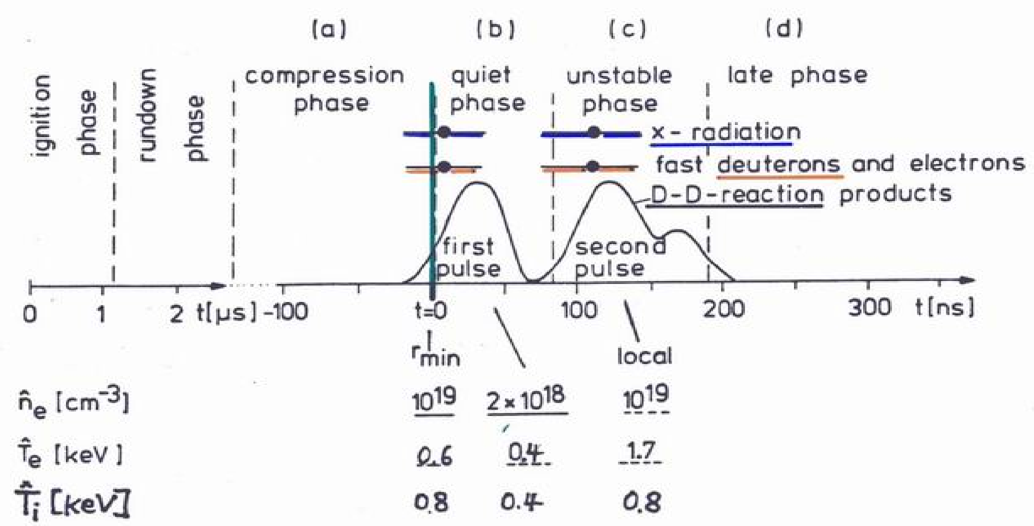


First neutron pulse

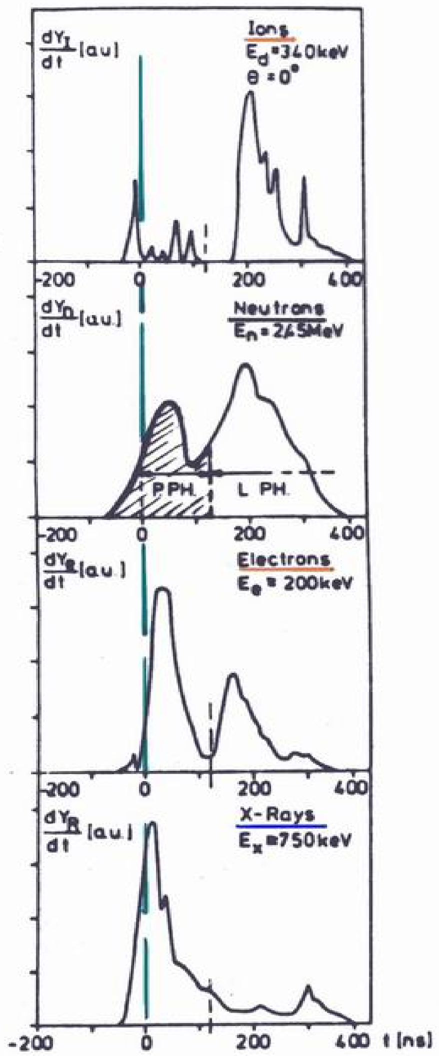
5 Schlieren pictures



Second neutron pulse



Examples of emissions



deuterons (340 keV) ↑ +z

neutrons

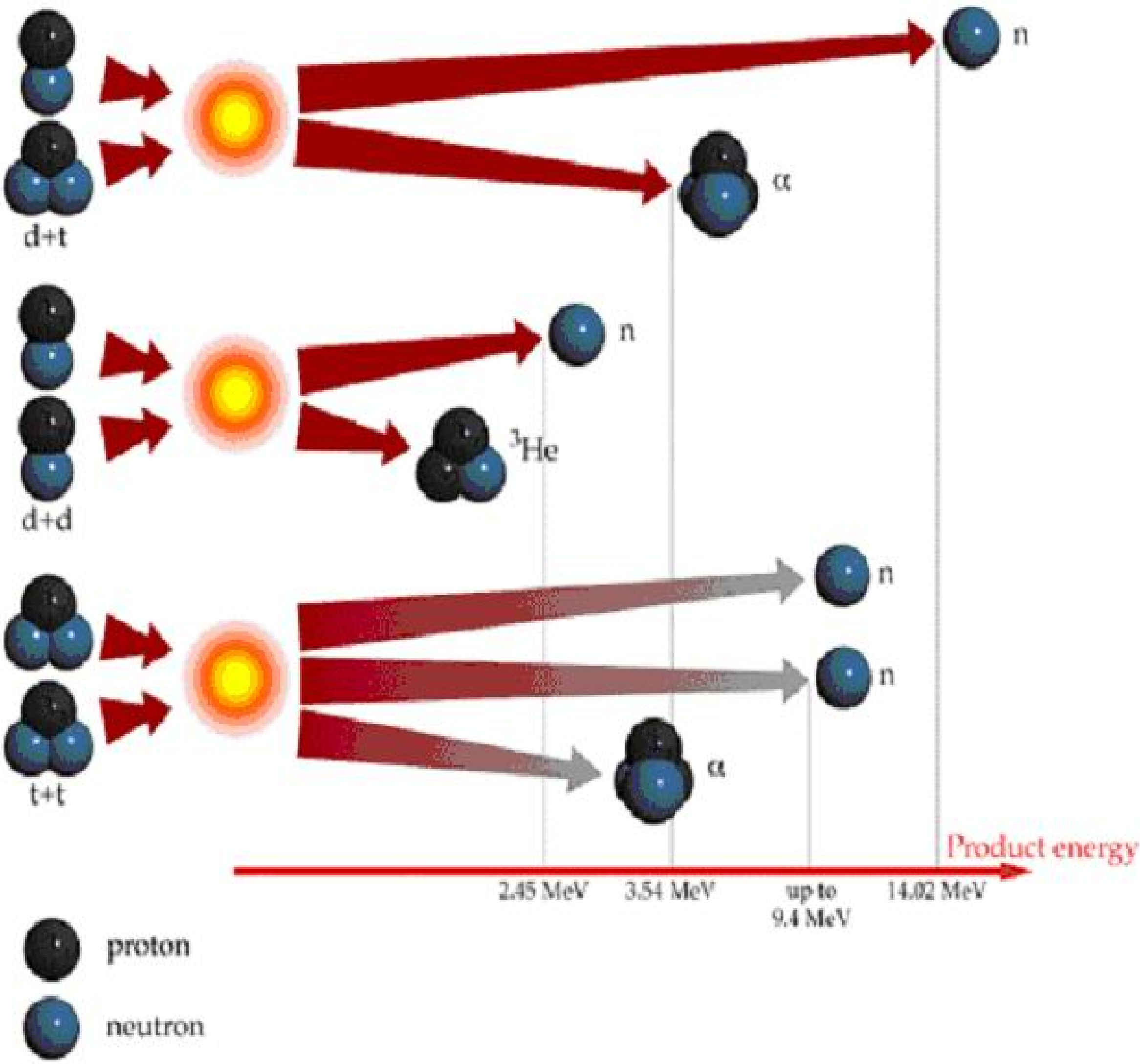
electrons (200 keV) ↓ −z

hard X-rays (750 keV)

fusion reactions

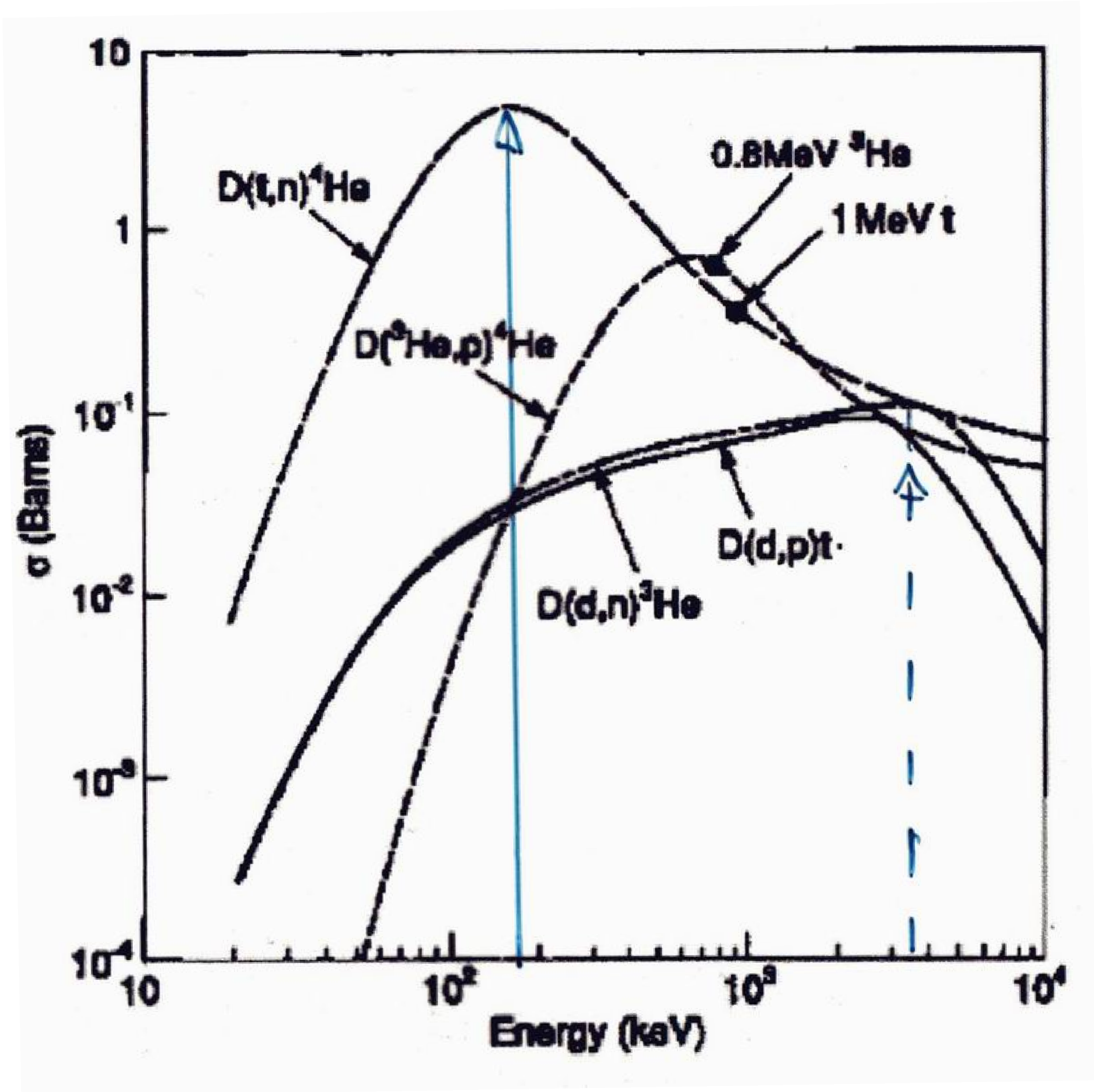
$^{2}D + ^{2}D$ -->	$^{3}He + \underline{^{1}n} + 3.27\ MeV$	neutrons
	$^{3}T + \underline{^{1}p} + 4.03\ MeV$	protons
$^{2}D + ^{3}T$ -->	$^{4}He + \underline{^{1}n} + 17.61\ MeV$	
$^{2}D + ^{3}He$ -->	$^{4}He + \underline{^{1}p} + 18.35\ MeV$	

Energy of fusion products



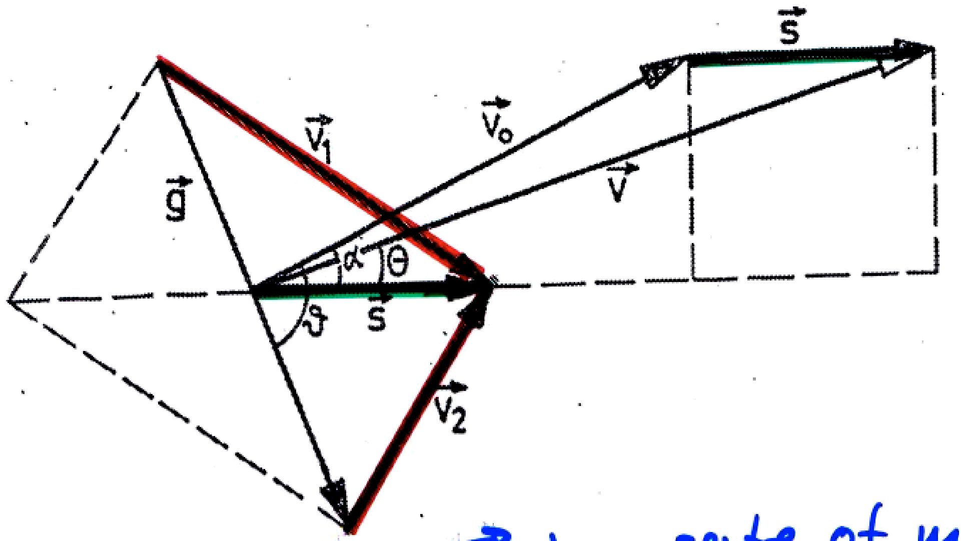
D-D neutrons 2.45 MeV

Fusion Reaction Cross Sections



Fusion reaction kinetics

collision of two deuterons



$\vec{s} = \frac{1}{2}(\vec{v}_1 + \vec{v}_2)$ centre of mass velocity

$\vec{g} = \vec{v}_1 - \vec{v}_2$ relative velocity

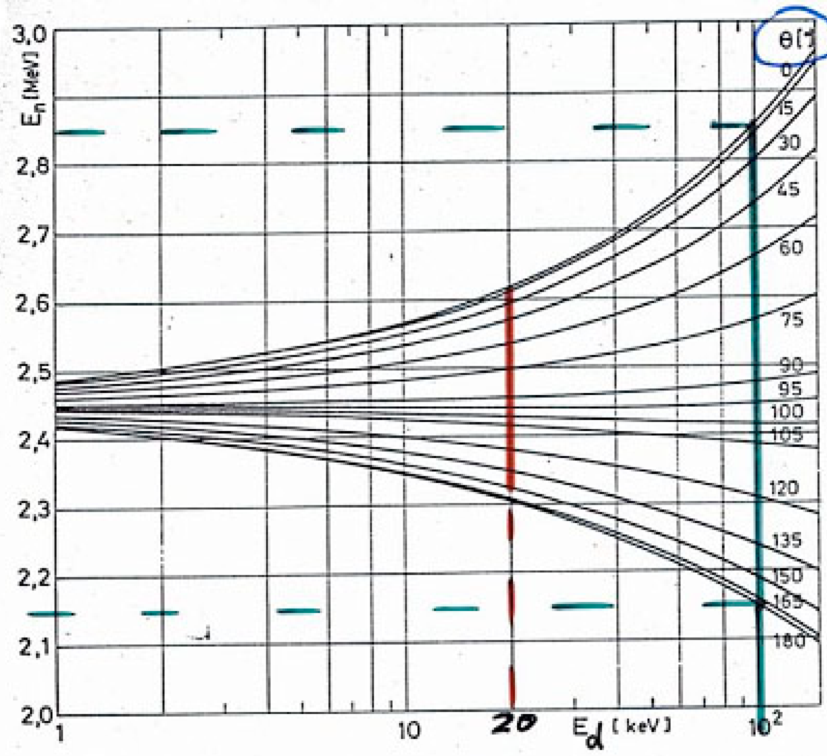
$E_D = \frac{1}{2} m_D g^2$ deuteron energy

$\alpha, \vec{v}_0$: centre of mass frame

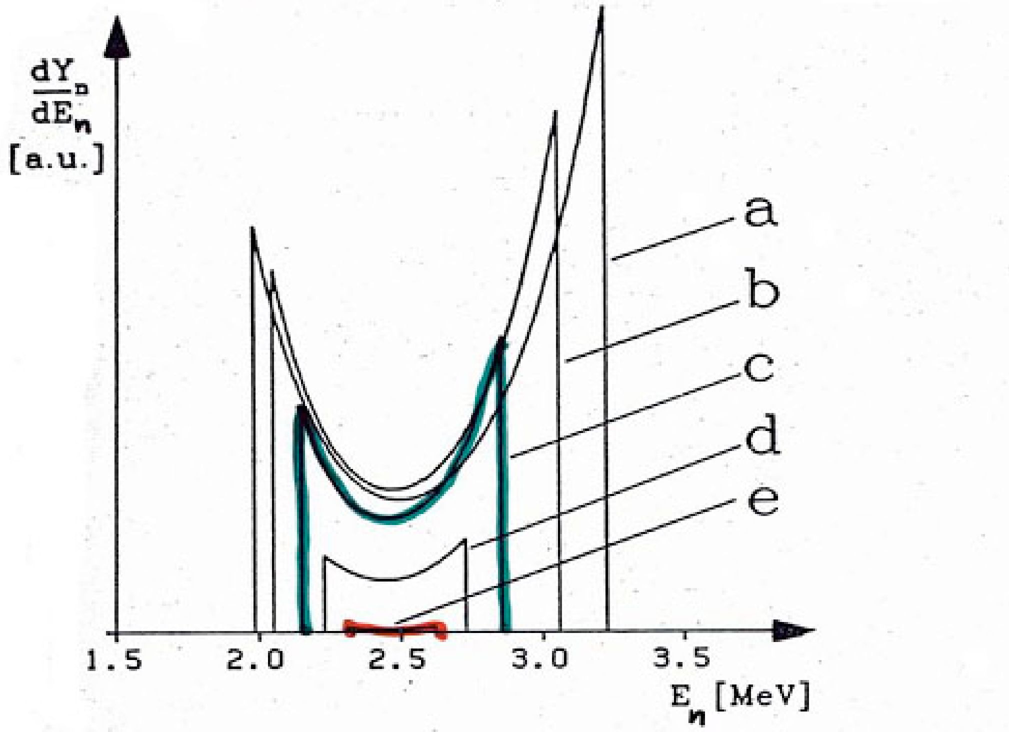
$\Theta, \vec{v}$: laboratory frame

$$E_n(E,\theta) = E\frac{m_D\, m}{(m + m_{He})^2}\left[2\cos^2\theta + \frac{m_{He}(m_{He}+m)}{m_D\, m}\left(\frac{Q}{E} + \left(1 - \frac{m_D}{m_{He}}\right)\right) + 2\cos\theta\sqrt{\cos^2\theta + \frac{m_{He}(m_{He}+m)}{m_D\, m_n}\left(\frac{Q}{E} + \left(1 - \frac{m_D}{m_{He}}\right)\right)}\right]$$

$$E_n(E,\theta) = E\frac{m_D\, m}{(m + m_{He})^2}\left[\, 2\cos^2\theta + \frac{m_{He}(m_{He} + m)}{m_D\, m}\left(\frac{Q}{E} + \left(1 - \frac{m_D}{m_{He}}\right)\right) + 2\cos\theta\sqrt{\cos^2\theta + \frac{m_{He}(m_{He} + m)}{m_D\, m_n}\left(\frac{Q}{E} + \left(1 - \frac{m_D}{m_{He}}\right)\right)}\,\right]$$

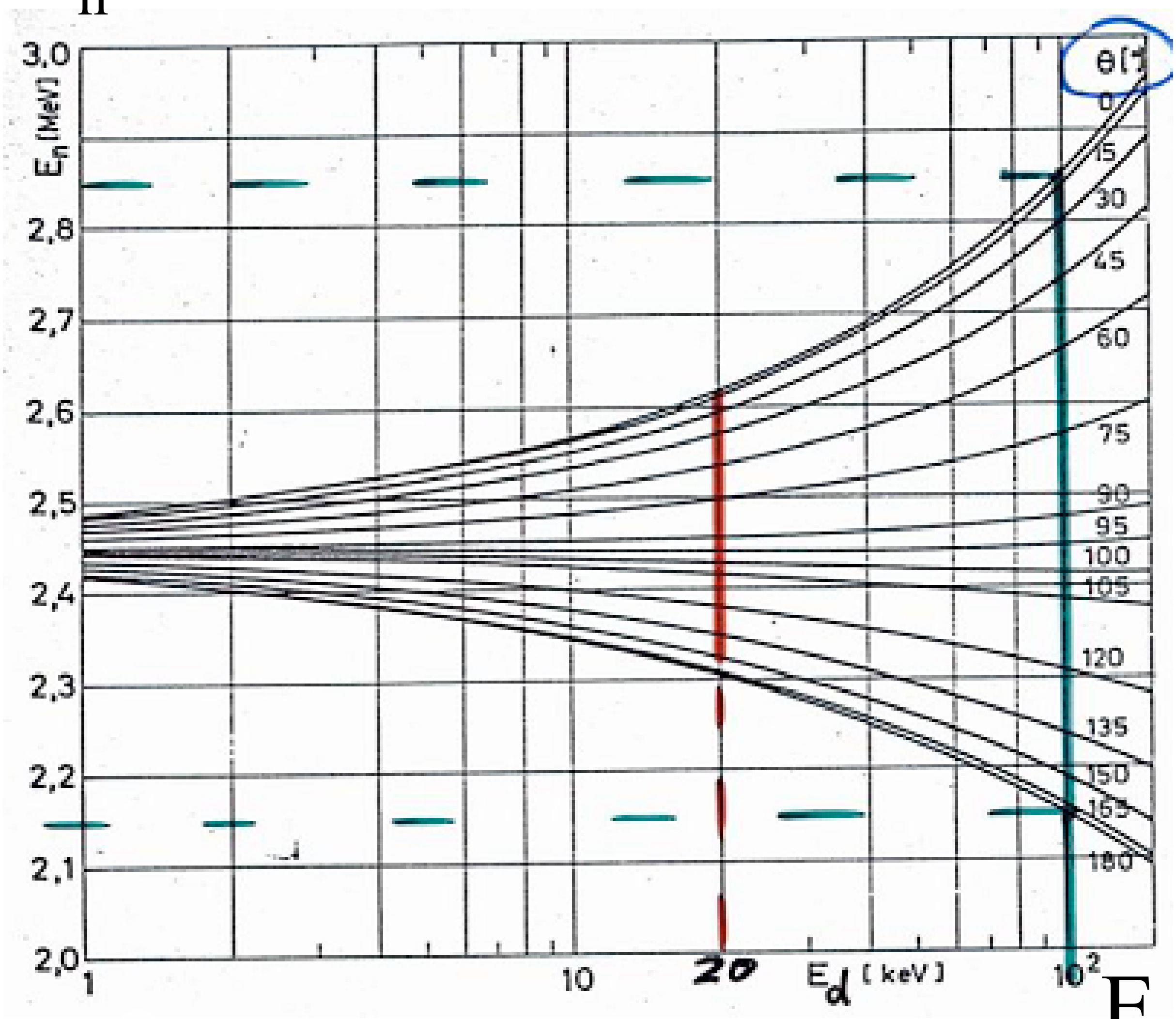


Neutronenenergie E_n bei einem Beschleuniger als Funktion von Deuteronenenergie E_d und Emissionswinkel θ .



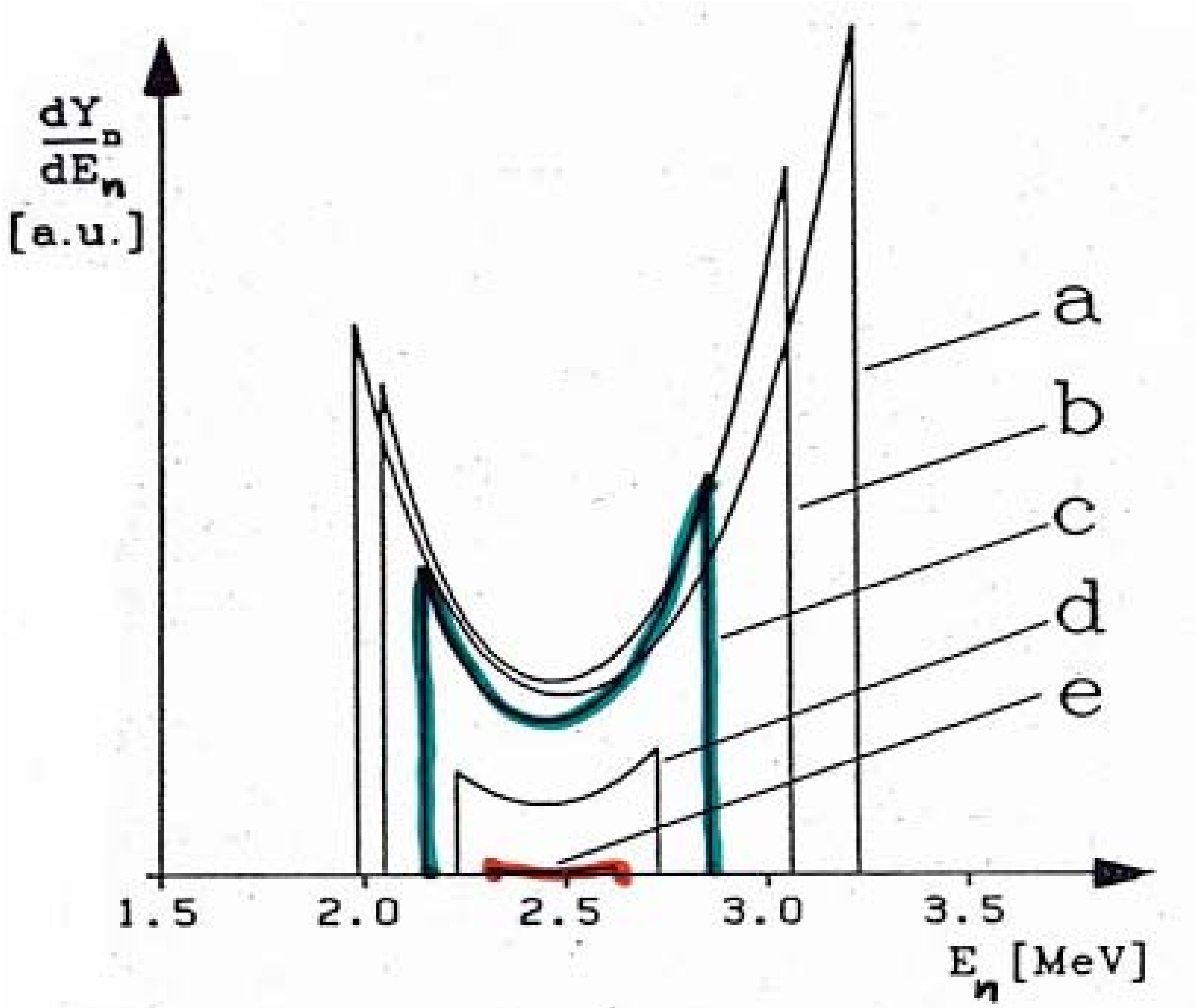
Untereinander normierte Neutronenspektren verschiedener mono-energetischer, isotroper Deuteronenstrahlen auf ein ruhendes Target. Deuteronenenergien E_D: 300 keV (a), 200 keV (b), 100 keV (c), 50 keV (d) und 20 keV (e).

E_n Theta

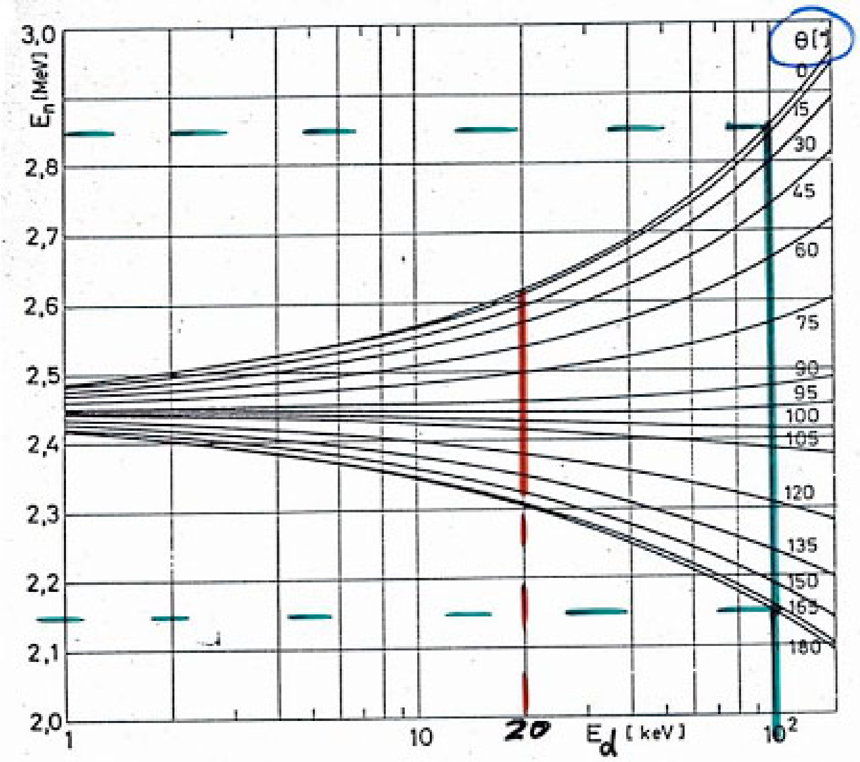


E_d

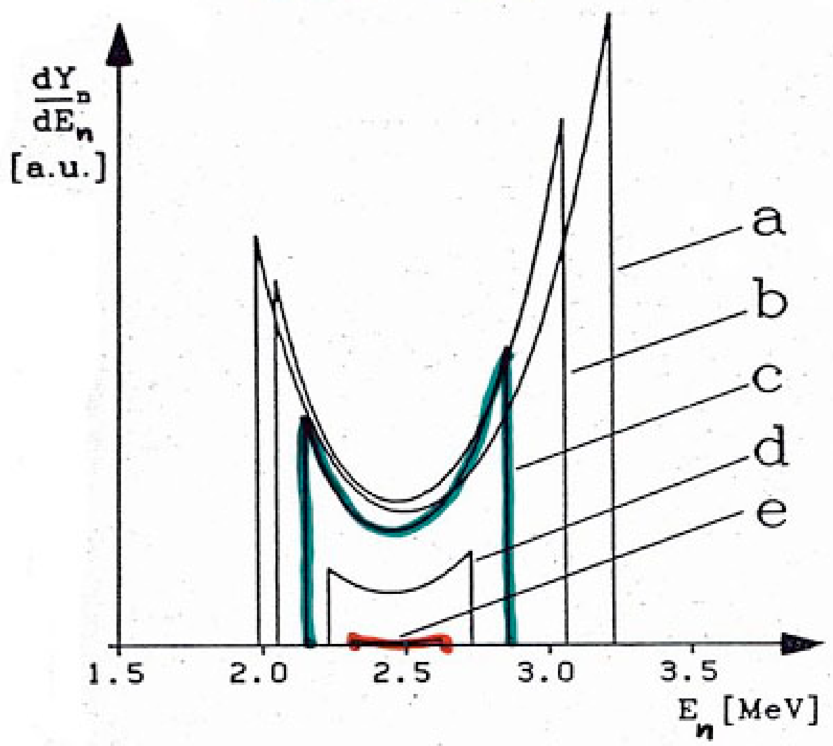
Neutron energy E_n as a function of deuteron energy E_d and emission angle Θ for D-D collisions.



Standardized neutron spectra
from mono-energetic isotropic deuteron beams
interacting with a solid target at rest.
Beam energy E_d : 300 keV (a), 200 keV (b),
100 keV (c), 50 keV (d) and 20 keV (e)



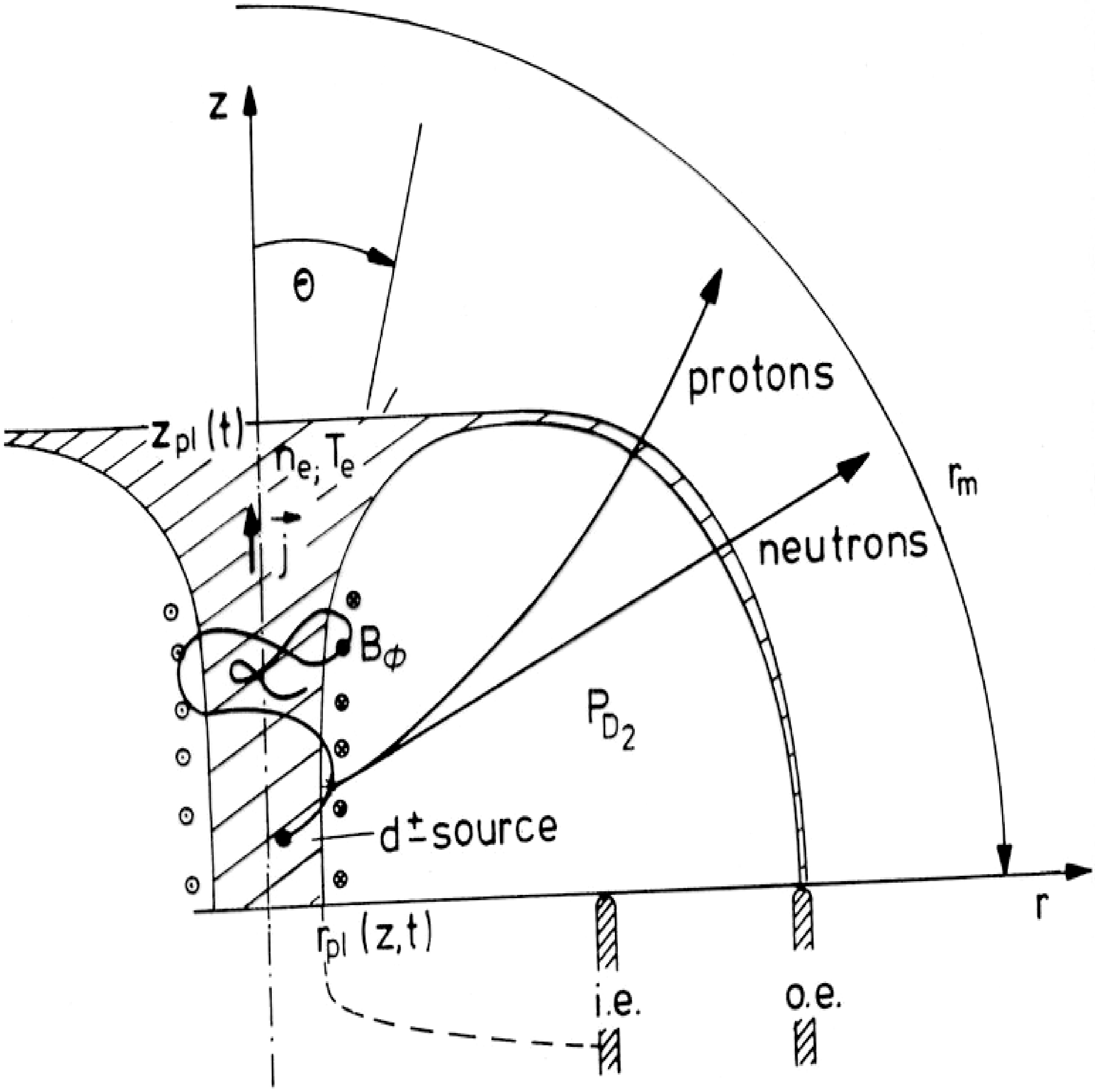
Neutronenenergie E_n bei einem Beschleuniger als Funktion von Deuteronenenergie E_d und Emissionswinkel θ.



Untereinander normierte Neutronenspektren verschiedener monoenergetischer, isotroper Deuteronenstrahlen auf ein ruhendes Target. Deuteronenenergien E_D: 300 keV (a), 200 keV (b), 100 keV (c), 50 keV (d) und 20 keV (e).

Beam Target Processes and their verification

Ion Trajectories in the Azimuthal Magnetic Field of the Pinch Current



Beam-Target neutron production ! ?

statement to be verified:

deuterons of mean energy 15 – 150 keV
contribute mainly and essentially
to fusion yield

The following processes take place:

- acceleration of deuterons
  by high transient electromagnetic fields
- „absorption“ of those deuterons
  in the pinch plasma
- collisions (scattering, charge exchange)
  in the surrounding gas / plasma

-> no direct observation of the deuteron distribution (which is responsible for fusion reactions)

-> Indirect methods

-Neutron spectroscopy
(time-of flight, nuclear emulsions)

-Neutron flux anisotropy

-Neutron source location and intensity distribution
(integral and/or time resolved measurements)

NEUTRONS

angular resolution

---> anisotropy
beam target processes

temporal resolution

---> two (three) pulses
various pinch phases

spatial resolution

---> dimensions of source
(better using proton measurements)

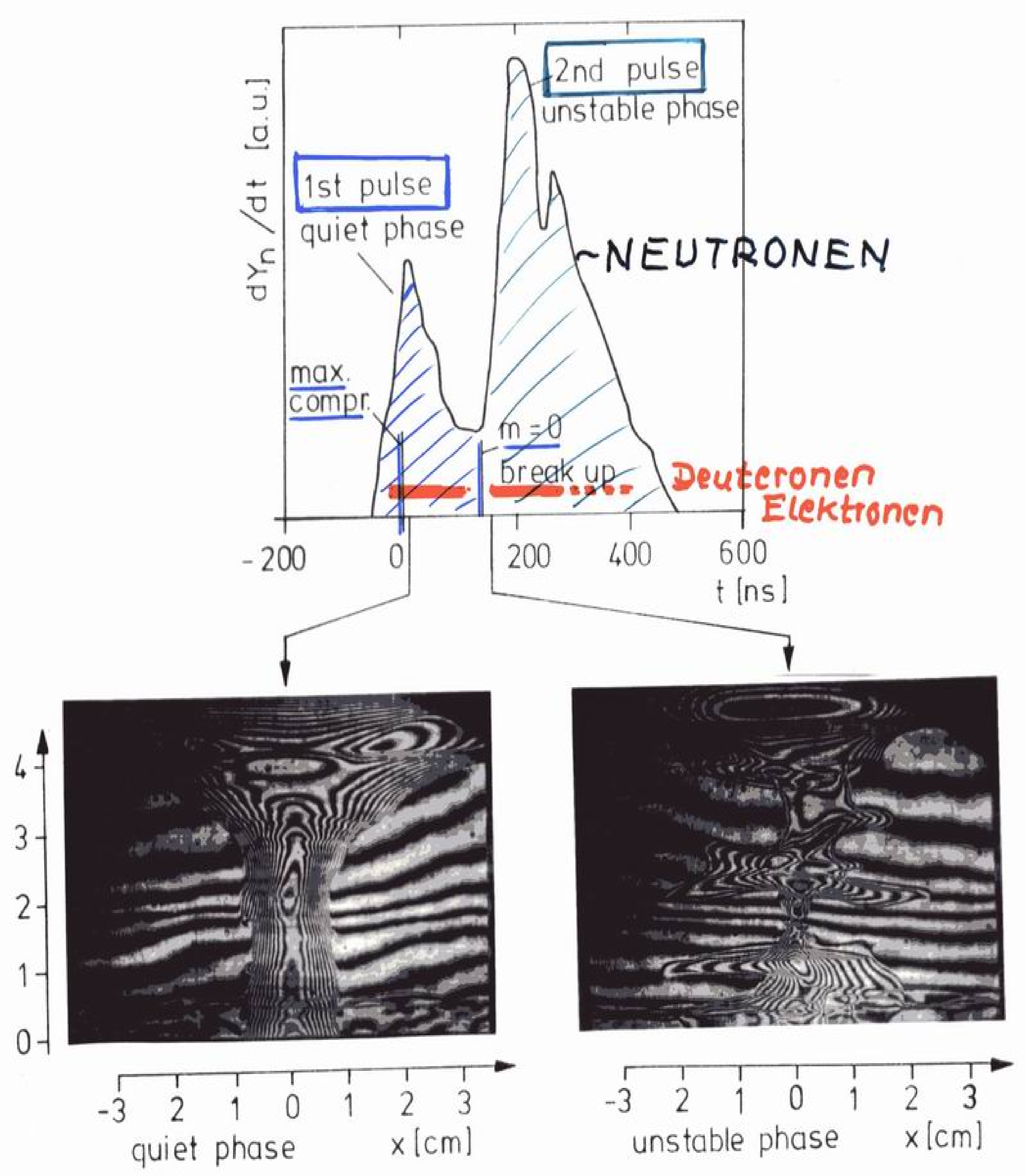
axial propagation of source

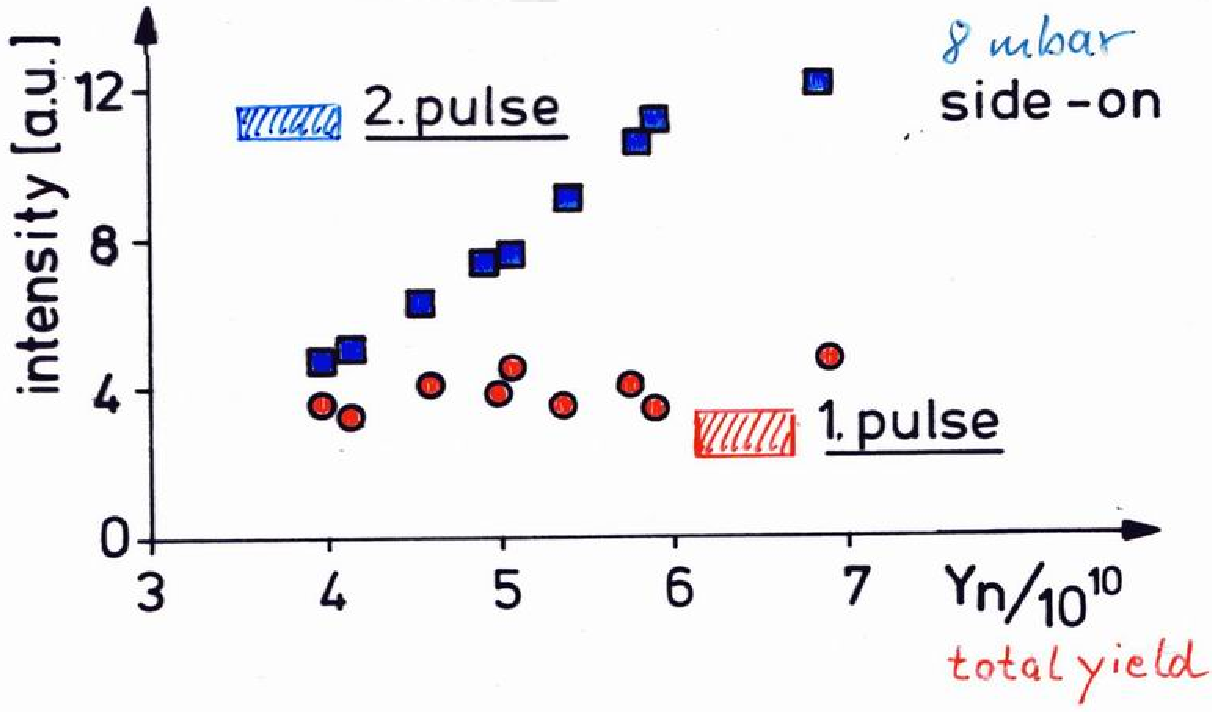
spectral resolution

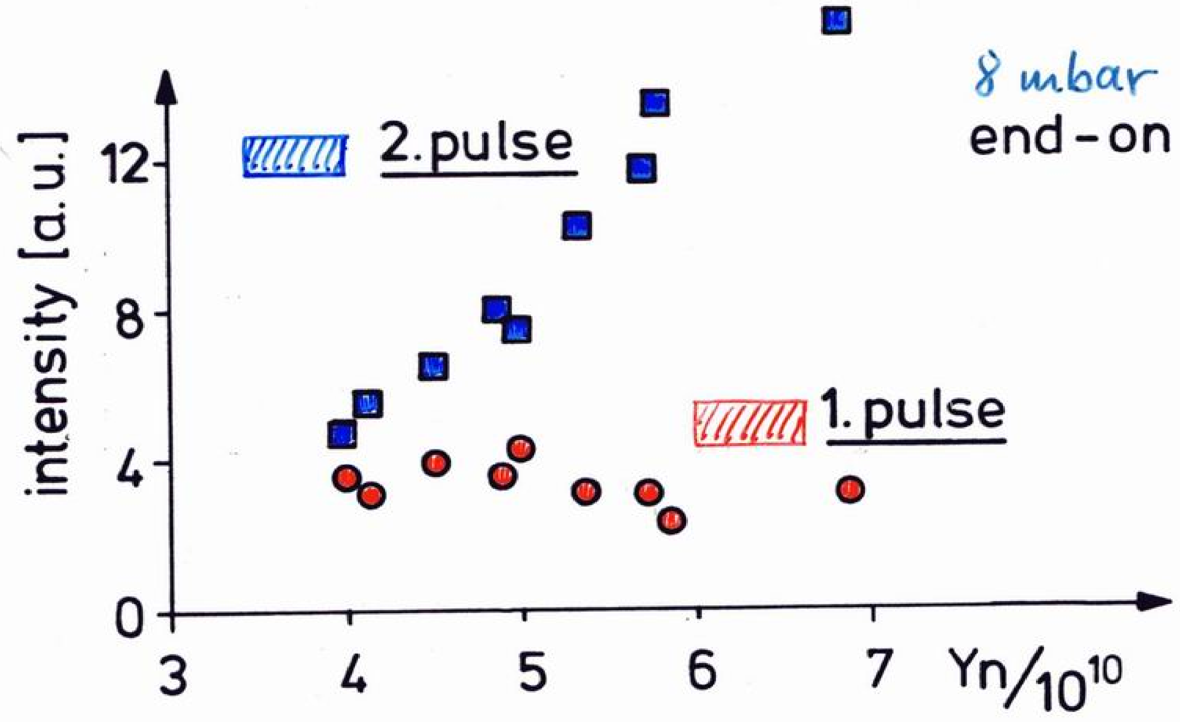
---> energy of deuterons

relaxation of deuterons

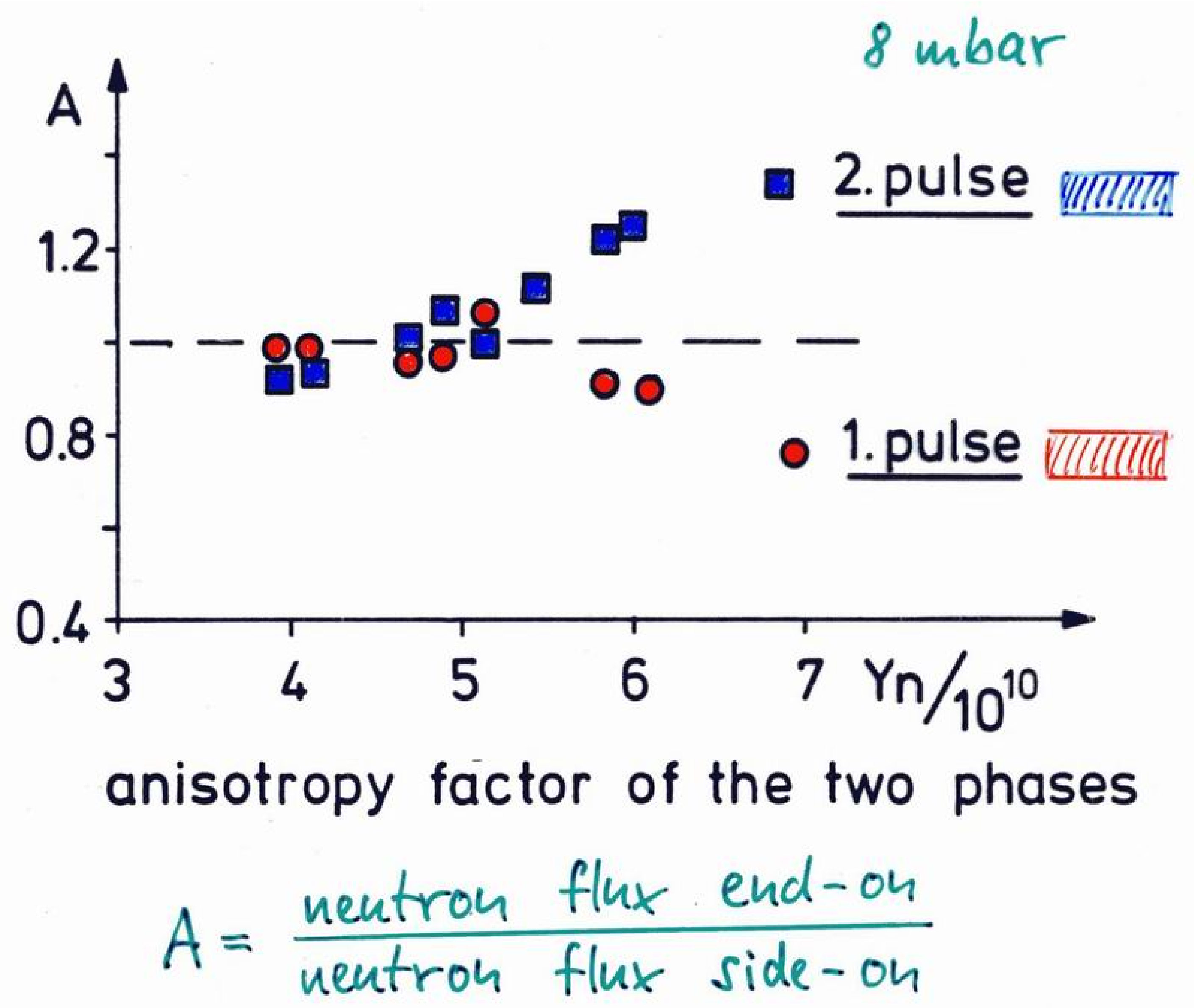
Two Neutron emitting Phases Correlated to Plasma Dynamics



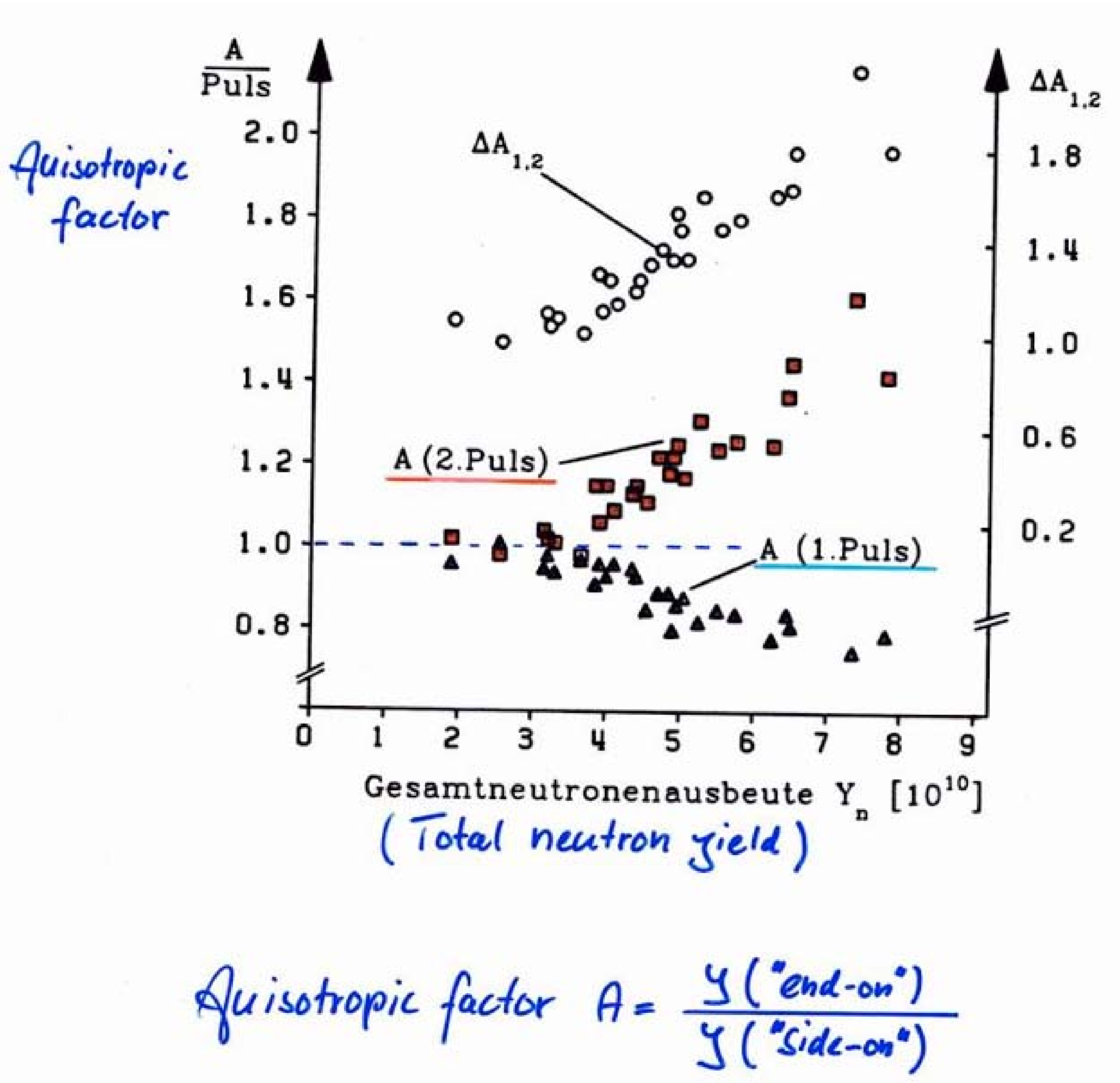




neutron yield of the two phases

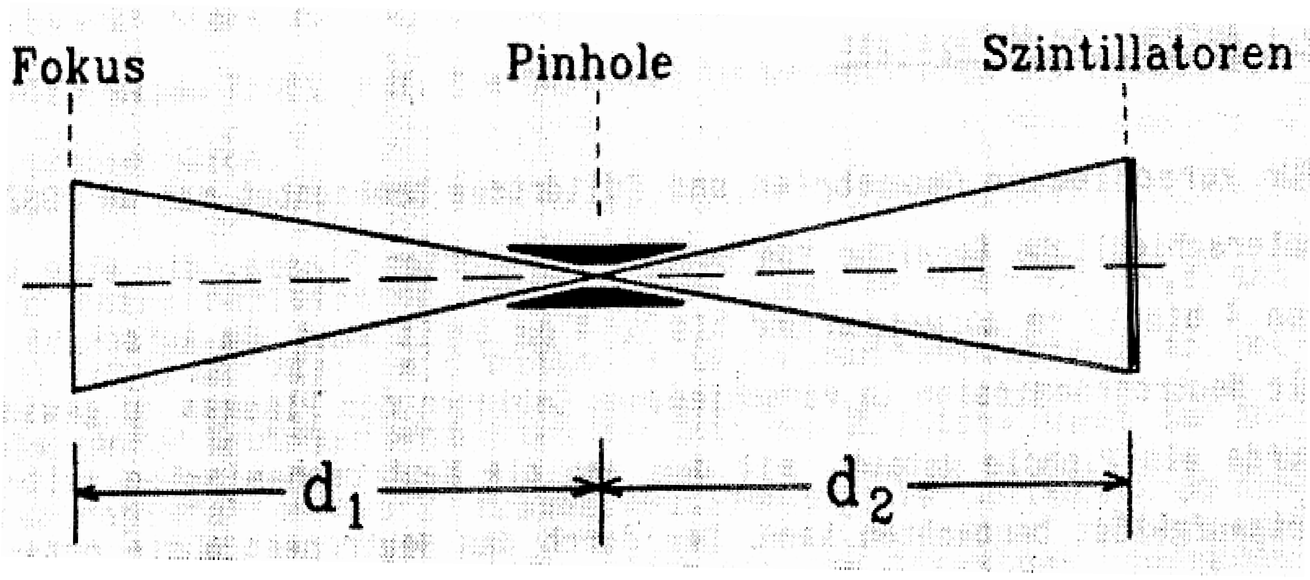

8 mbar
A
1.2
0.8
0.4
3
4
5
6
7
Yn/10^10
2. pulse
1. pulse
anisotropy factor of the two phases
A = neutron flux end-on / neutron flux side-on

Anisotropy of neutron emission

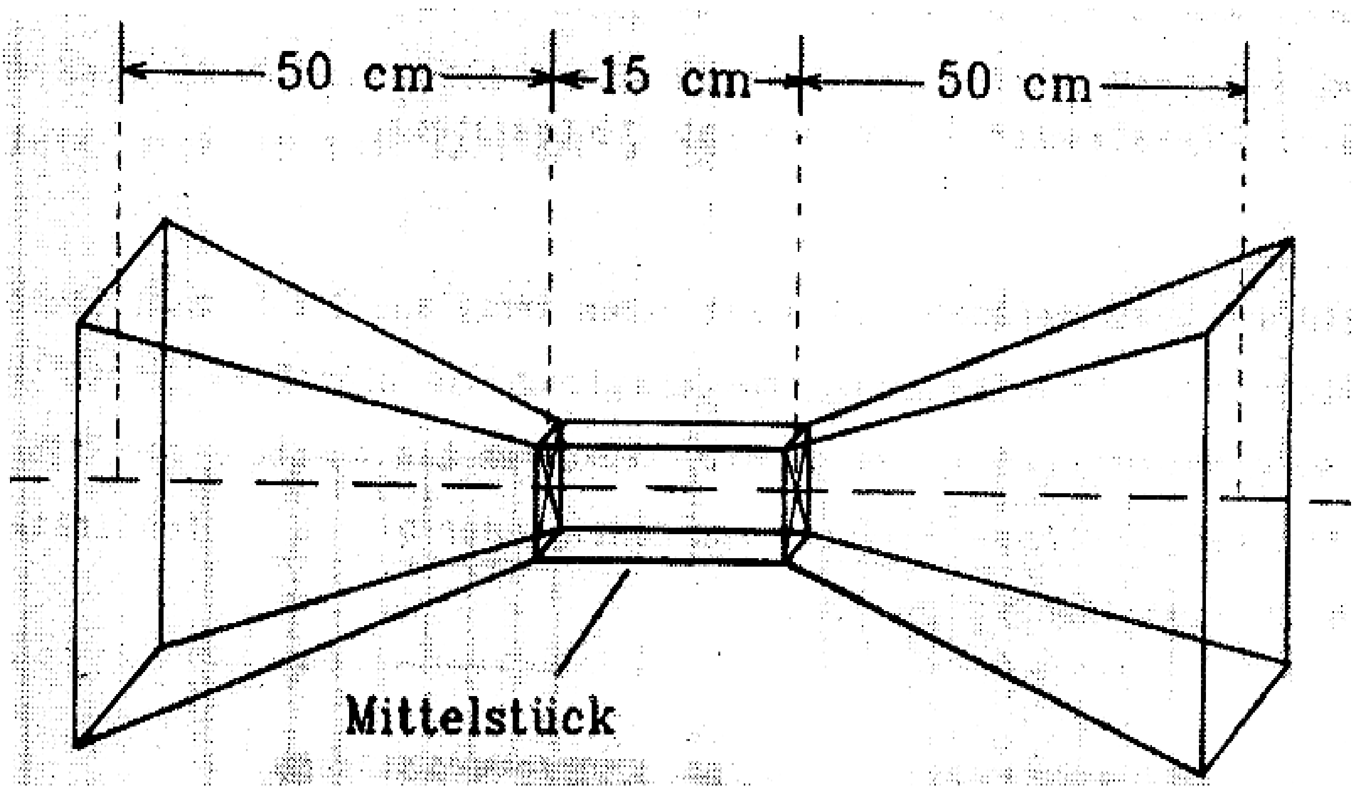


Results of neutron pinhole measurements

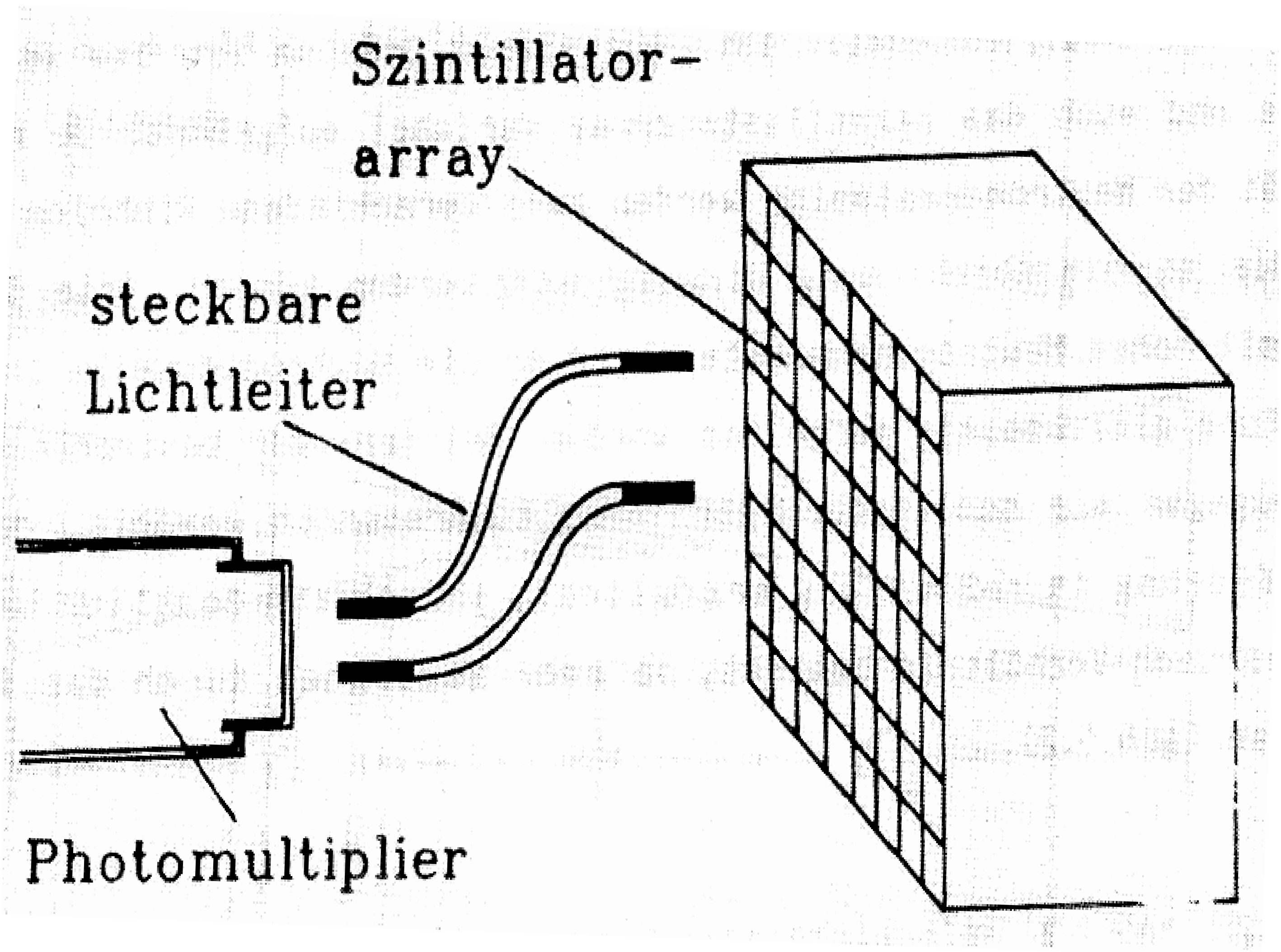
Pinhole for Neutrons



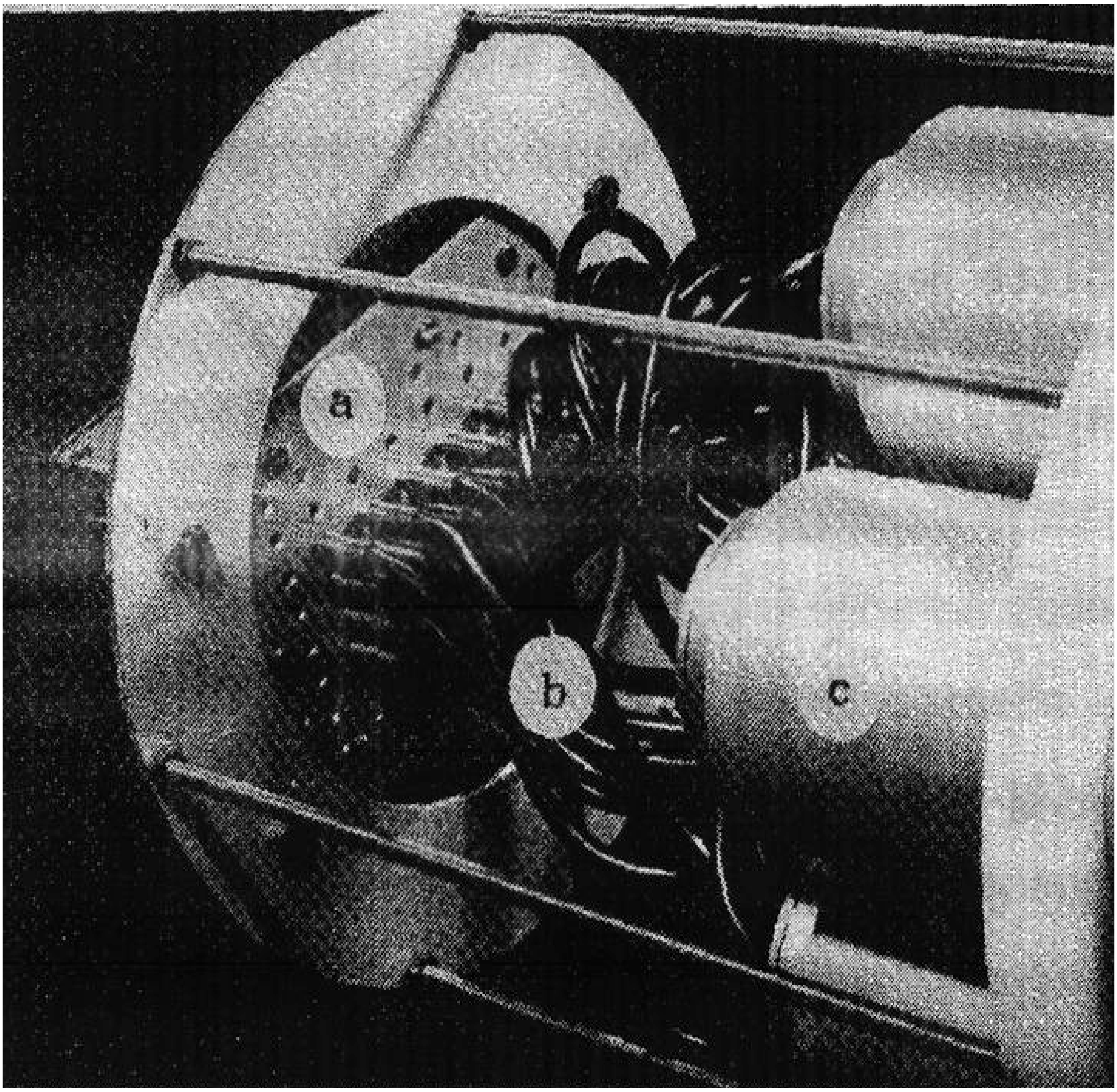
Pinhole for Neutrons



Array of Scintillators Connected via Light Fibres to Photomultipliers



a - Scintillator-array b - light pipes



7 PM-tubes

Neutron pinhole measurements

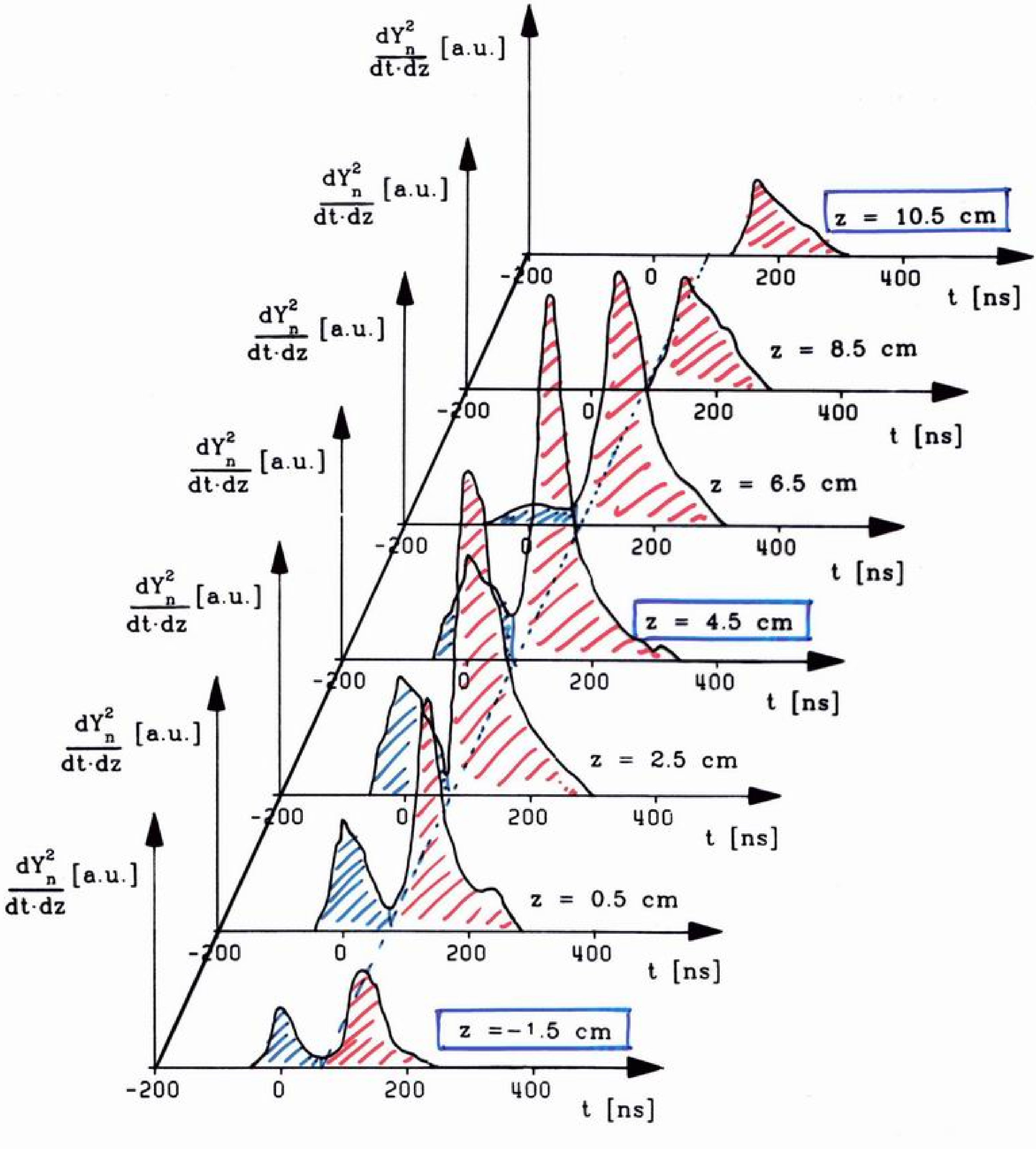
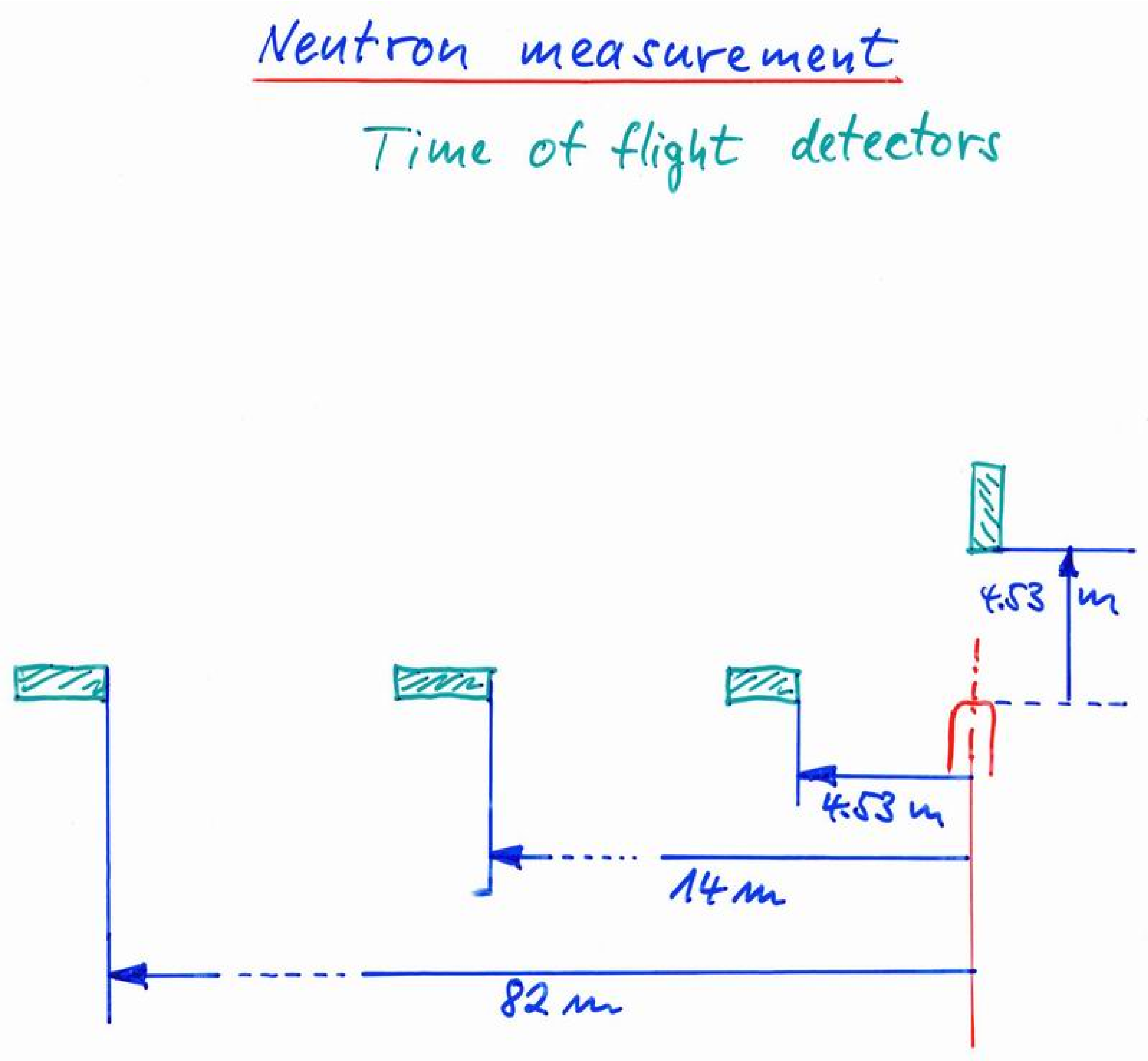


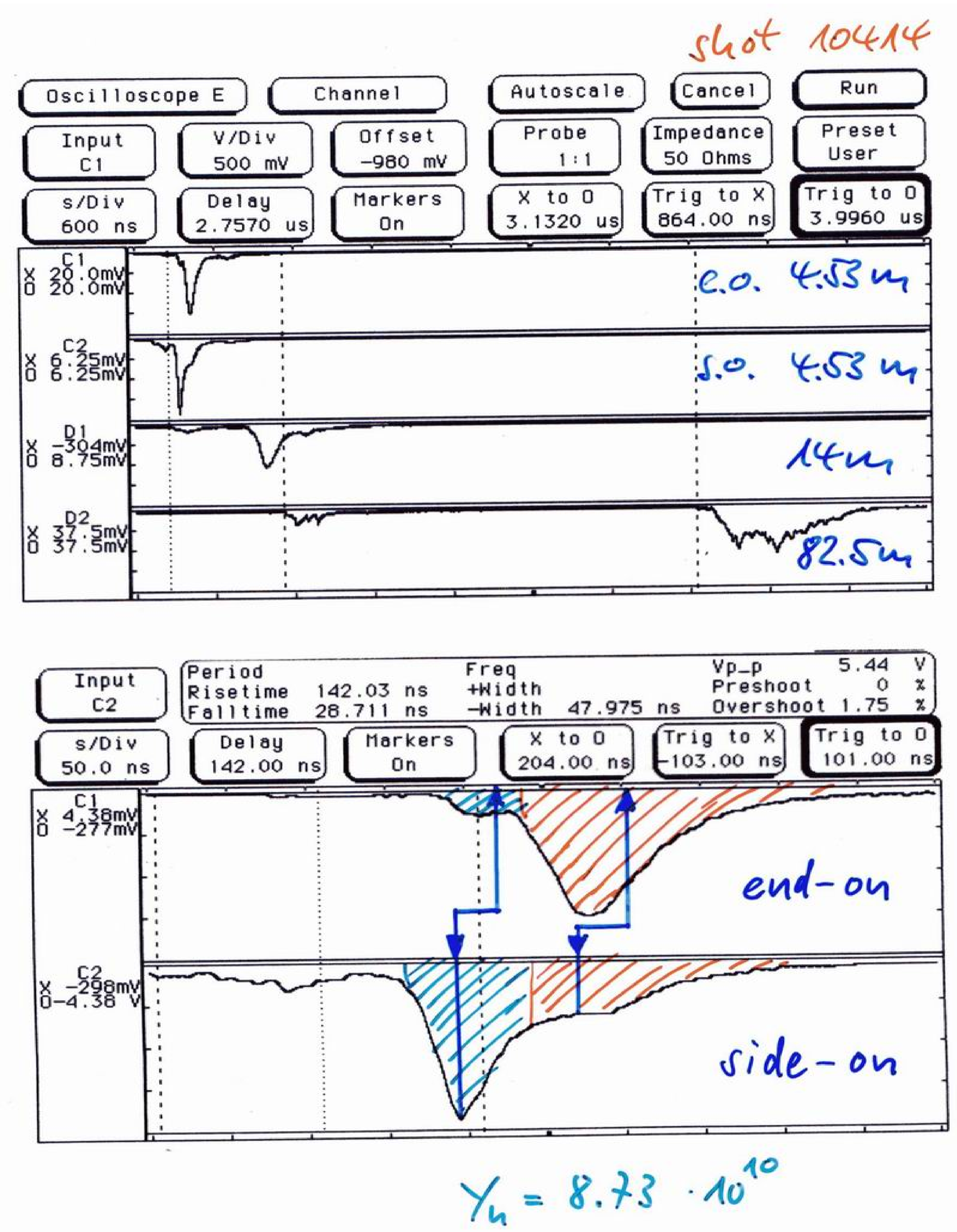
Fig. 9: Result of neutron pinhole measurements. Neutron emission spatially resolved in axial direction (resolution $\Delta z \leq 2$ cm, $\Delta t \leq 20$ ns) on POSEIDON (280 kJ, 60 kV, 500 Pa D_2, $Y_n = 6.6 \cdot 10^{10}$, hollow inner electrode, 131 mm diameter).

Neutron

Time of Flight

Measurements


Neutron measurement
Time of flight detectors
4.53 m
4.53 m
14 m
82 m


shot 10414
Oscilloscope E
Channel
Autoscale
Cancel
Run
Input C1
V/Div 500 mV
Offset -980 mV
Probe 1:1
Impedance 50 Ohms
Preset User
s/Div 600 ns
Delay 2.7570 us
Markers On
X to O 3.1320 us
Trig to X 864.00 ns
Trig to O 3.9960 us
e.o. 4.53 m
s.o. 4.53 m
14 m
82.5 m
Input C2
Period
Risetime 142.03 ns
Falltime 28.711 ns
Freq
+Width
-Width 47.975 ns
Vp_p 5.44 V
Preshoot 0 %
Overshoot 1.75 %
s/Div 50.0 ns
Delay 142.00 ns
Markers On
X to O 204.00 ns
Trig to X -103.00 ns
Trig to O 101.00 ns
end-on
side-on
Yn = 8.73 · 10^10

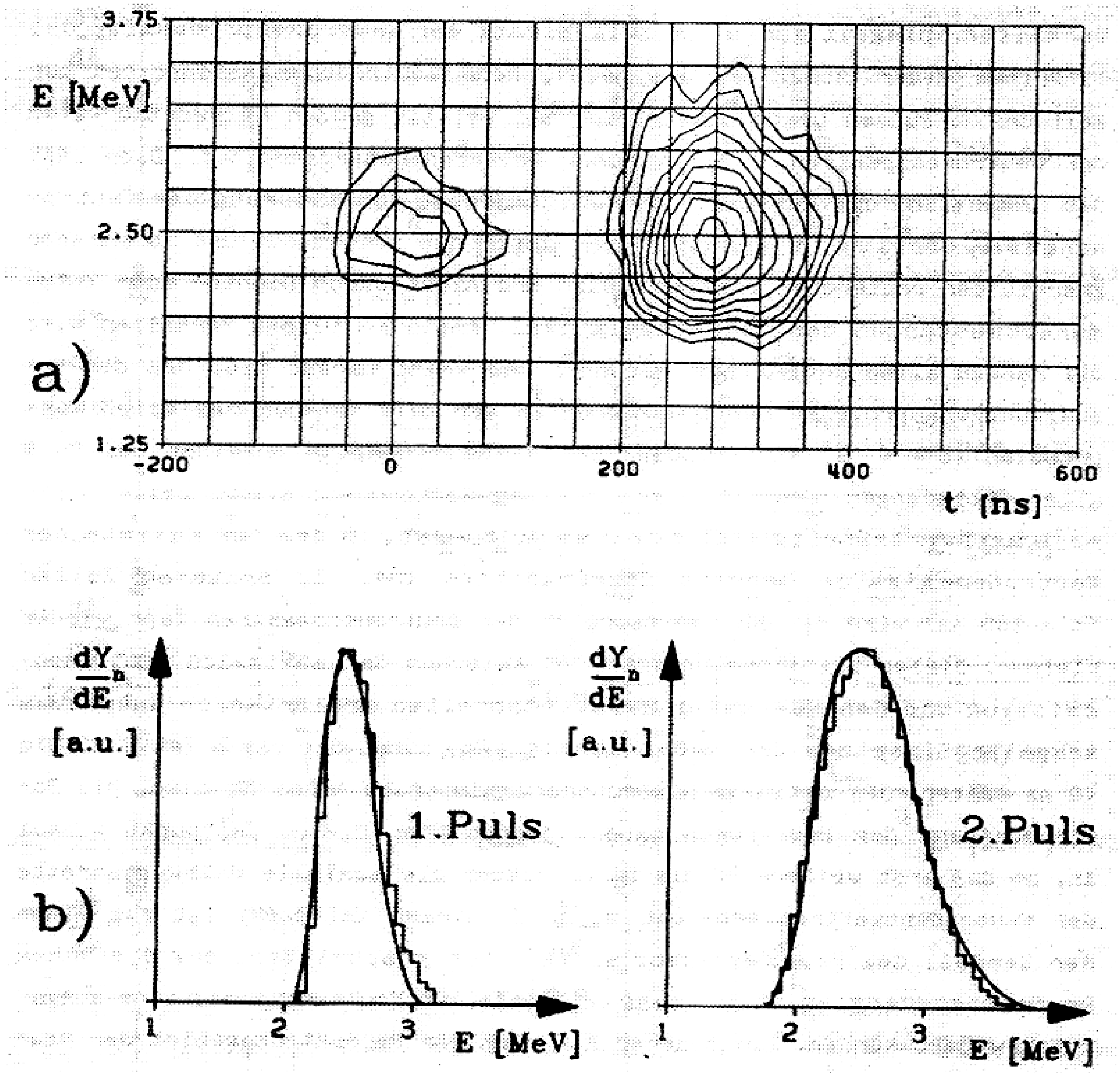


Abb. 6.14: Rekonstruktion einer typischen POSEIDON-Entladung, Schuß Nr. 7522, breiter Elektrodenabstand, Ladespannung 70 kV, Fülldruck 8 mbar.
a) Höhenlinienbild.
b) Neutronenspektren der Einzelpulse (zeitintegriert): ermittelt aus der rekonstruierten Quellfunktion (Stufenfunktion) und berechnet nach dem verallgemeinerten "Beam-Target"-Modell (glatte Kurve).

Neutronenspektren

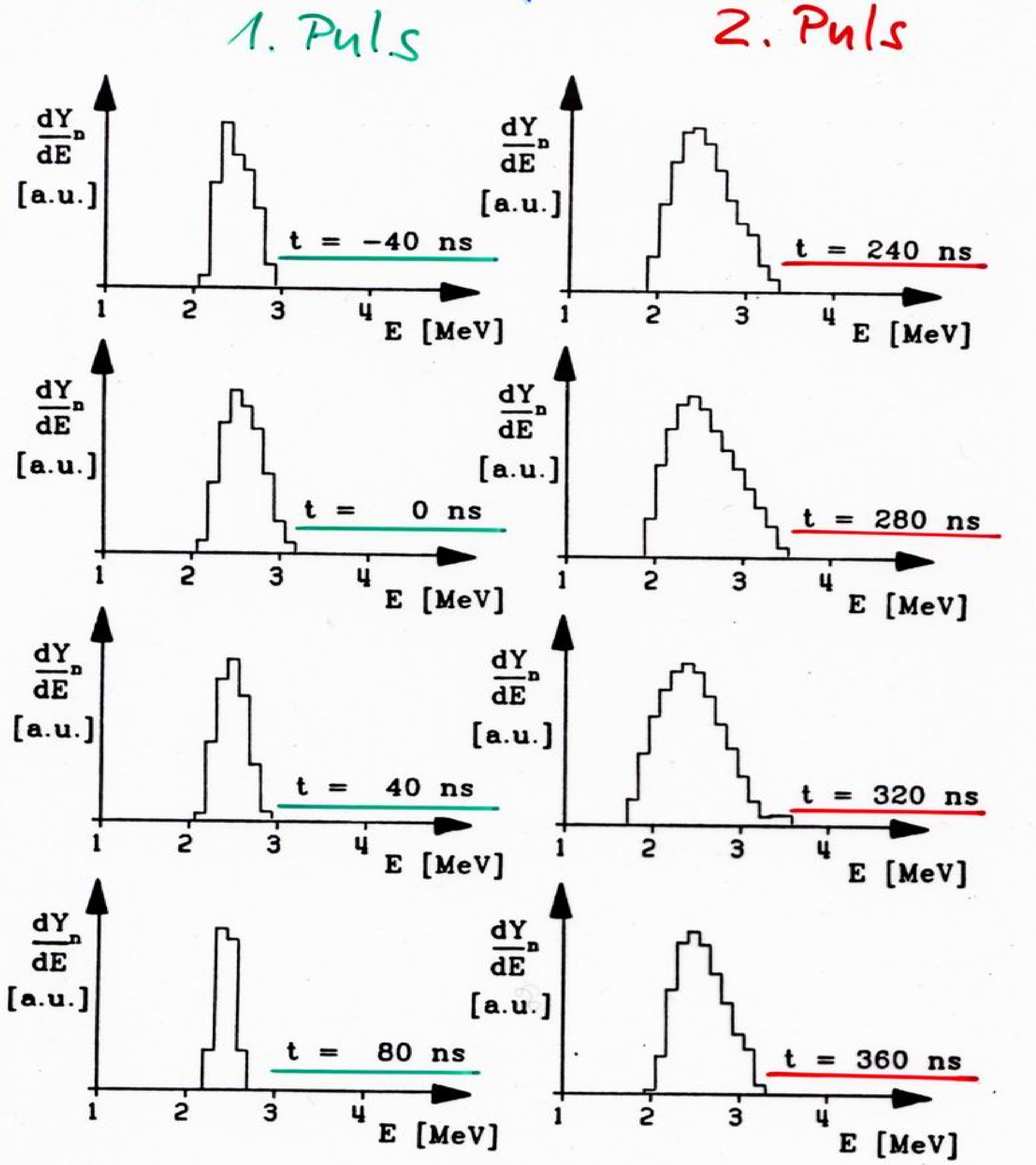


Abb. 6.15: Neutronenspektren einer typischen POSEIDON-Entladung zu verschiedenen Zeiten, Schuß Nr. 7522 (vgl. Abb.6.14a).

Neutronenspektren

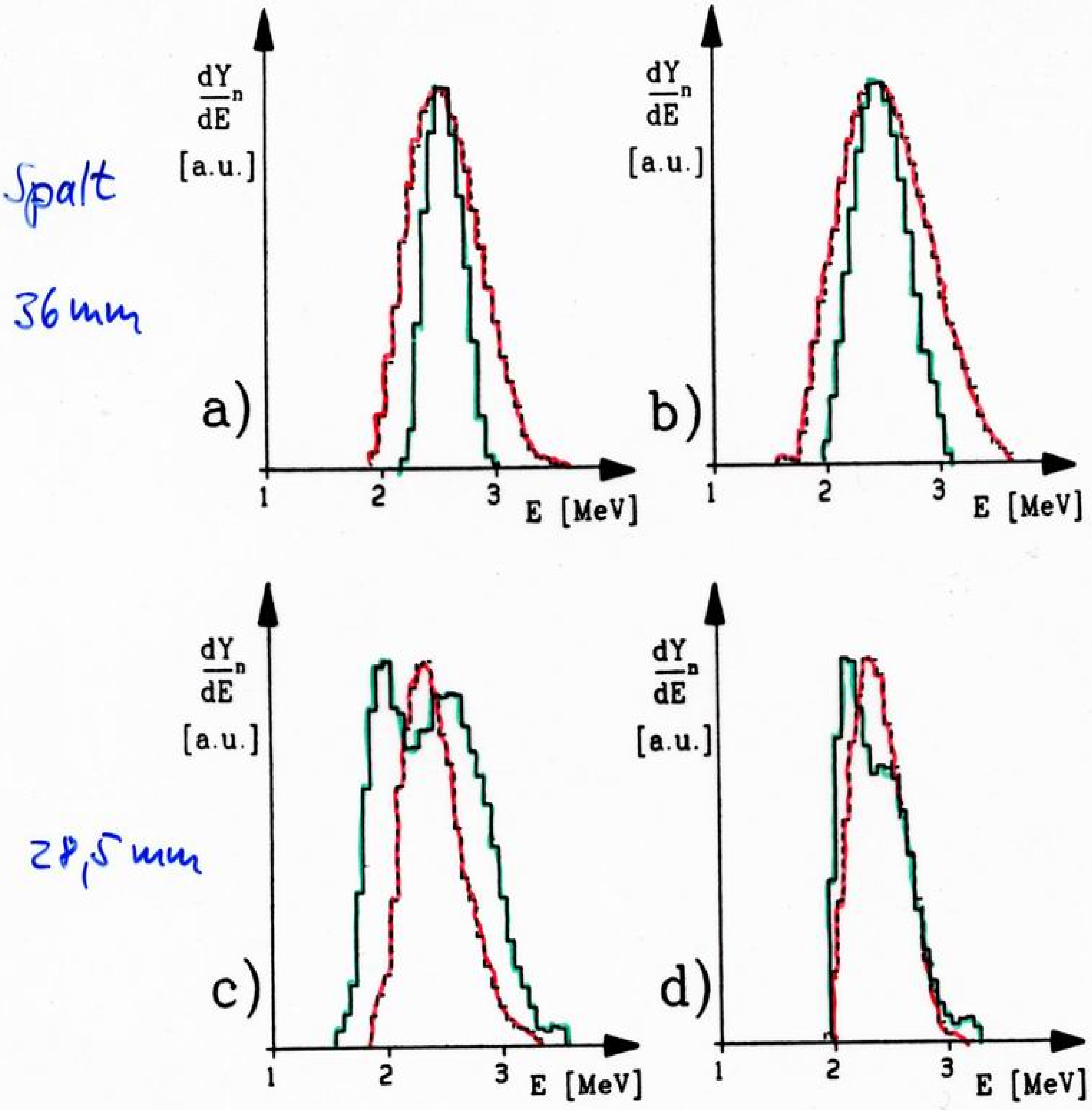


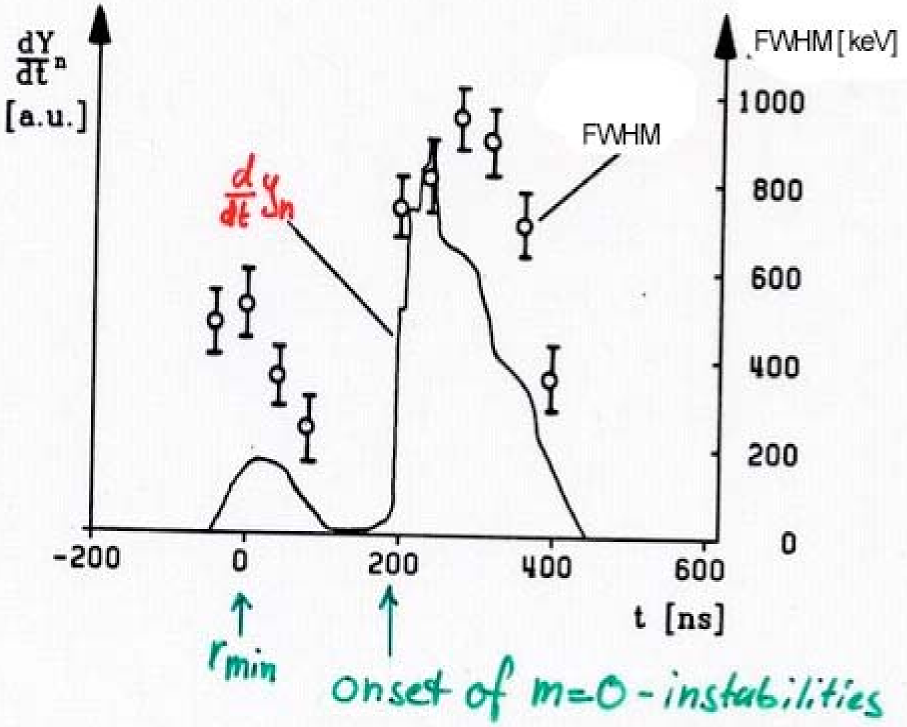
Abb. 6.19: Typische Neutronenspektren des 1. Pulses (——) und des 2. Pulses (– – –) mit breitem (a,b) und engem (c,d) Elektrodenabstand.

$Y_n/10^{10}$			Y_2/Y_1
1.6	a) Y_n(1.Puls) = $0{,}3\cdot10^{10}$,	Y_n(2.Puls) = $1{,}3\cdot10^{10}$.	4.3
6.2	b) Y_n(1.Puls) = $0{,}6\cdot10^{10}$,	Y_n(2.Puls) = $5{,}6\cdot10^{10}$.	9.3
2.7	c) Y_n(1.Puls) = $1{,}9\cdot10^{10}$,	Y_n(2.Puls) = $0{,}8\cdot10^{10}$.	0.4
1.3	d) Y_n(1.Puls) = $0{,}5\cdot10^{10}$,	Y_n(2.Puls) = $0{,}8\cdot10^{10}$.	1.6

Neutron Yield and

FWHM of Neutron Spectra
as a function of time

-> relaxation of deuterons



Typical POSEIDON shot, voltage 70 kV, filling pressure 8 mbar.

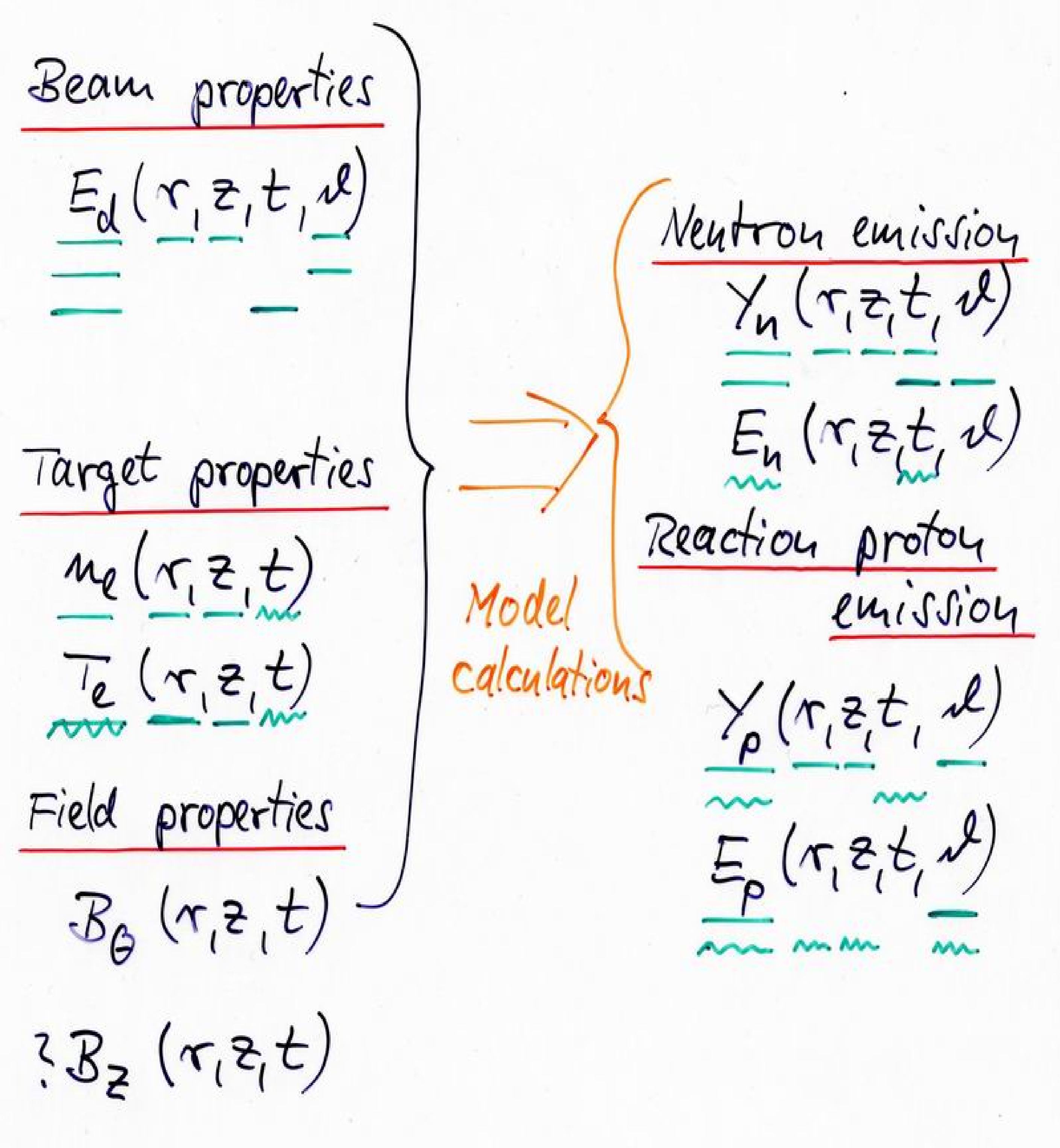
Y_n (1. pulse) = $0.6 \cdot 10^{10}$

Y_n (2. pulse) = $4.1 \cdot 10^{10}$

Why

Reaction Proton

Diagnostics?

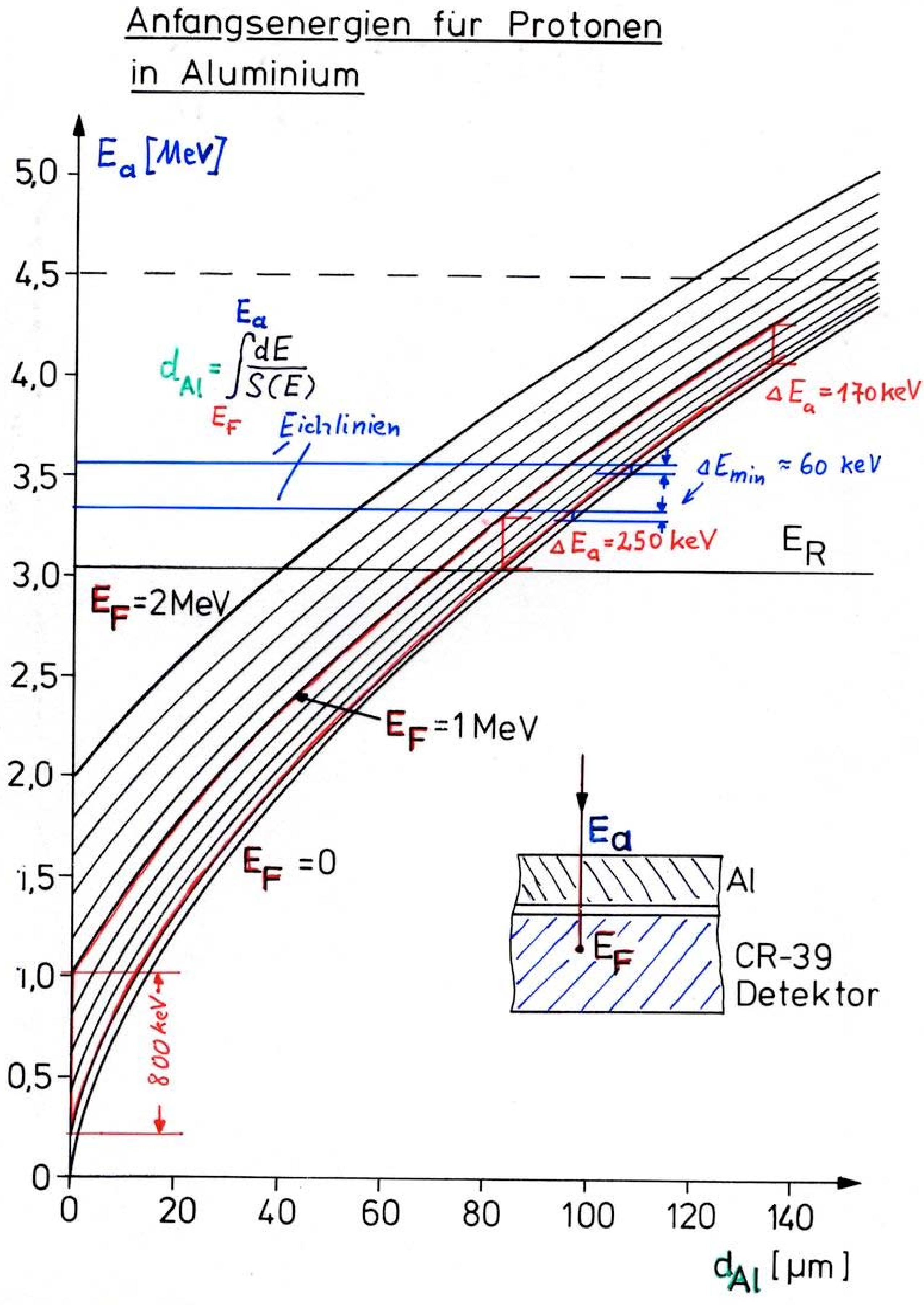

Beam properties
$E_d(r,z,t,\vartheta)$
Target properties
$n_e(r,z,t)$
$T_e(r,z,t)$
Field properties
$B_\Theta(r,z,t)$
? $B_z(r,z,t)$
Model calculations
Neutron emission
$Y_n(r,z,t,\vartheta)$
$E_n(r,z,t,\vartheta)$
Reaction proton emission
$Y_p(r,z,t,\vartheta)$
$E_p(r,z,t,\vartheta)$

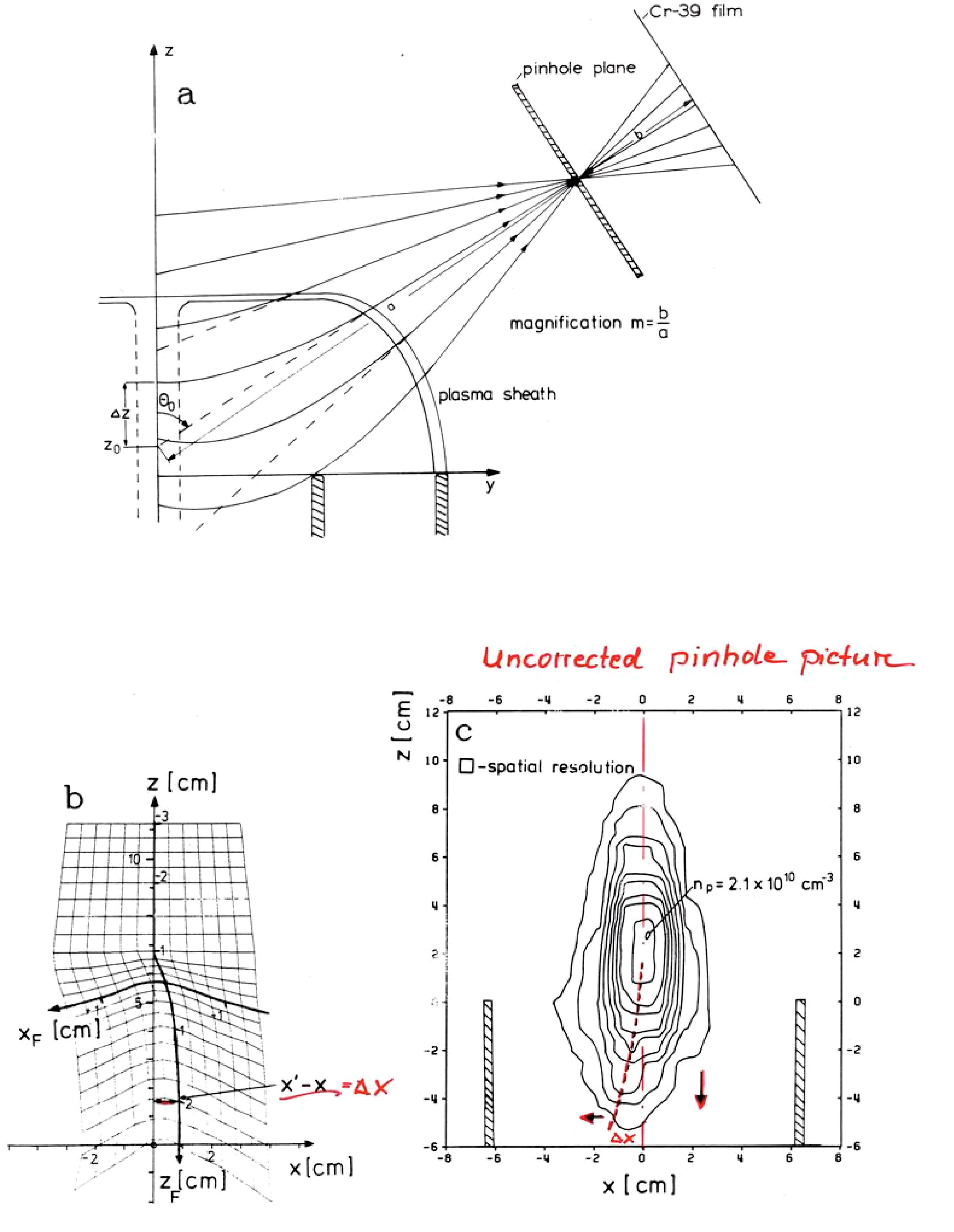
Solid state nuclear track detectors are used for the registration of protons

Individual particles can be registered using an etching process.

Small craters are visible under the Microscope

Spectral information can be obtained using absorbing metal foils


Anfangsenergien für Protonen
in Aluminium
E_a [MeV]
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0
$d_{Al} = \int_{E_F}^{E_a} \frac{dE}{S(E)}$
Eichlinien
$\Delta E_a = 170$ keV
$\Delta E_{min} \approx 60$ keV
$\Delta E_a = 250$ keV
E_R
E_F=2MeV
E_F=1MeV
E_F =0
800 keV
E_a
Al
E_F
CR-39
Detektor
0
20
40
60
80
100
120
140
d_{Al} [μm]



from ΔX → B_z → I_φ ≈ 200 to 600 kA

Fig. 10

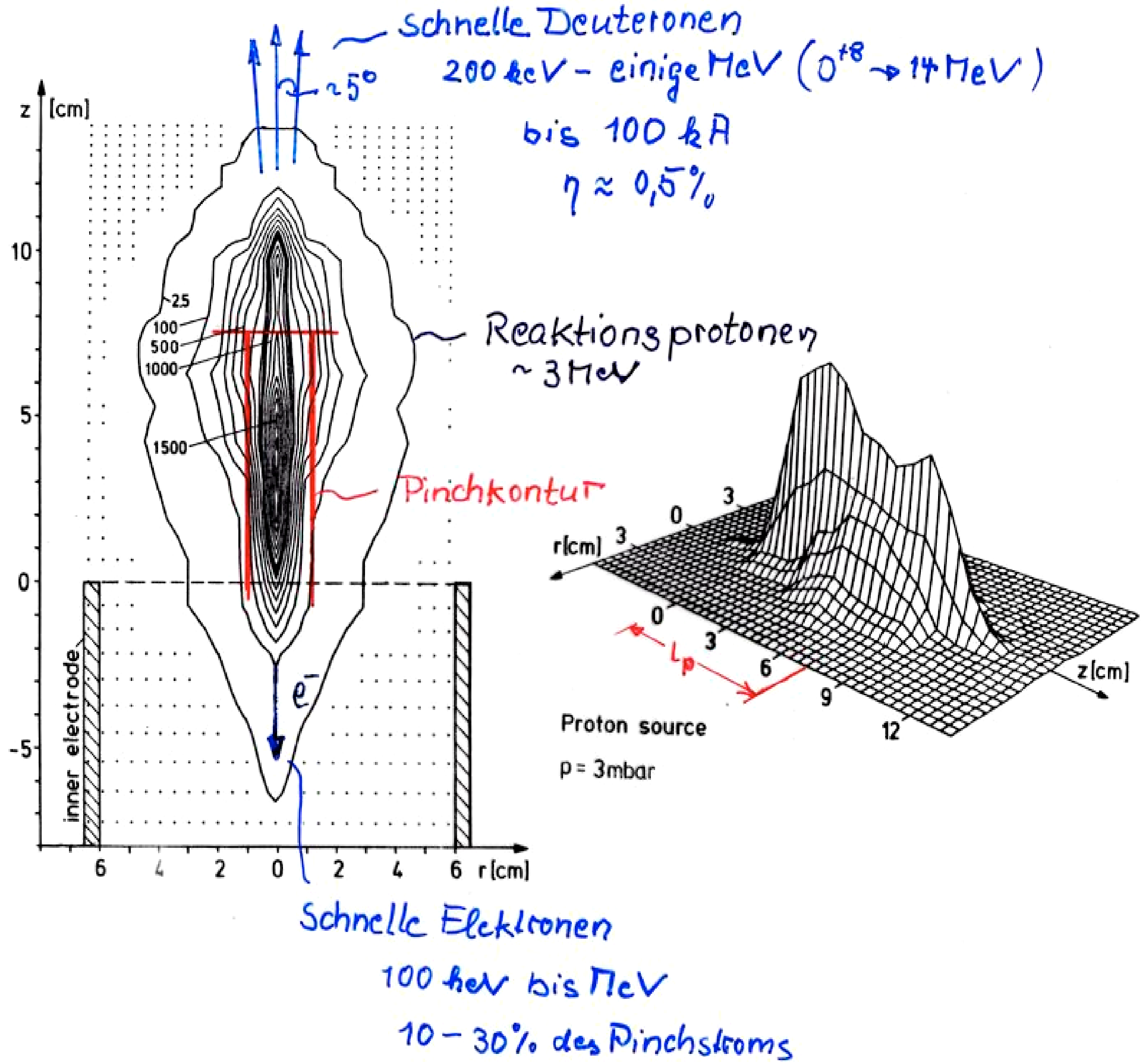


Bild der Reaktionsprotonen (Neutronen) Quelle
(Äqui-Dichte Linien, entabelt)

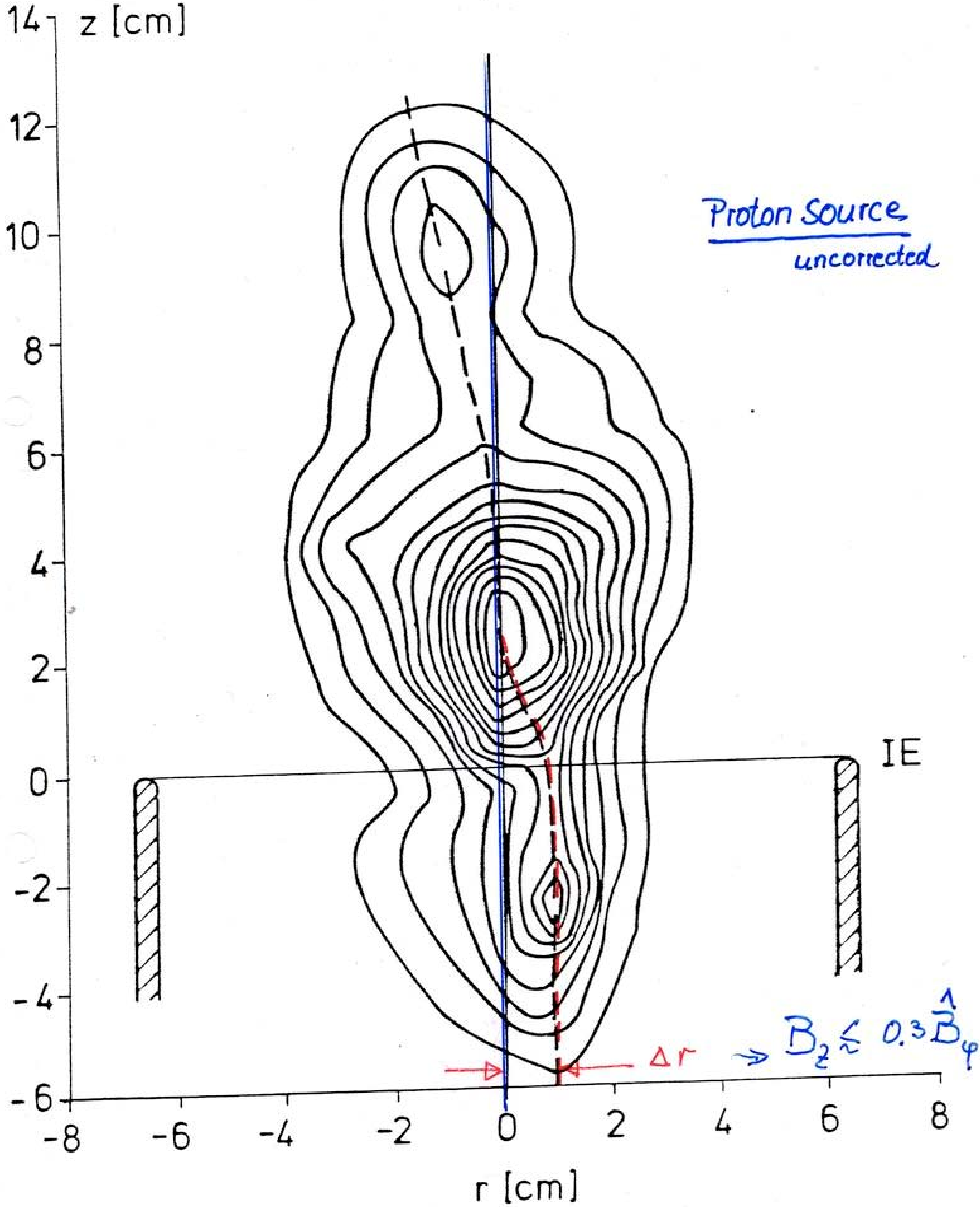


Fig. 7: Pinhole picture of the reaction proton source, uncorrected for beam deviation by focus magnetic fields. The contours are lines of constant proton density on the film. IE = inner electrode. W_0 = 280 kJ; p_0 = 5 mbar D_2.

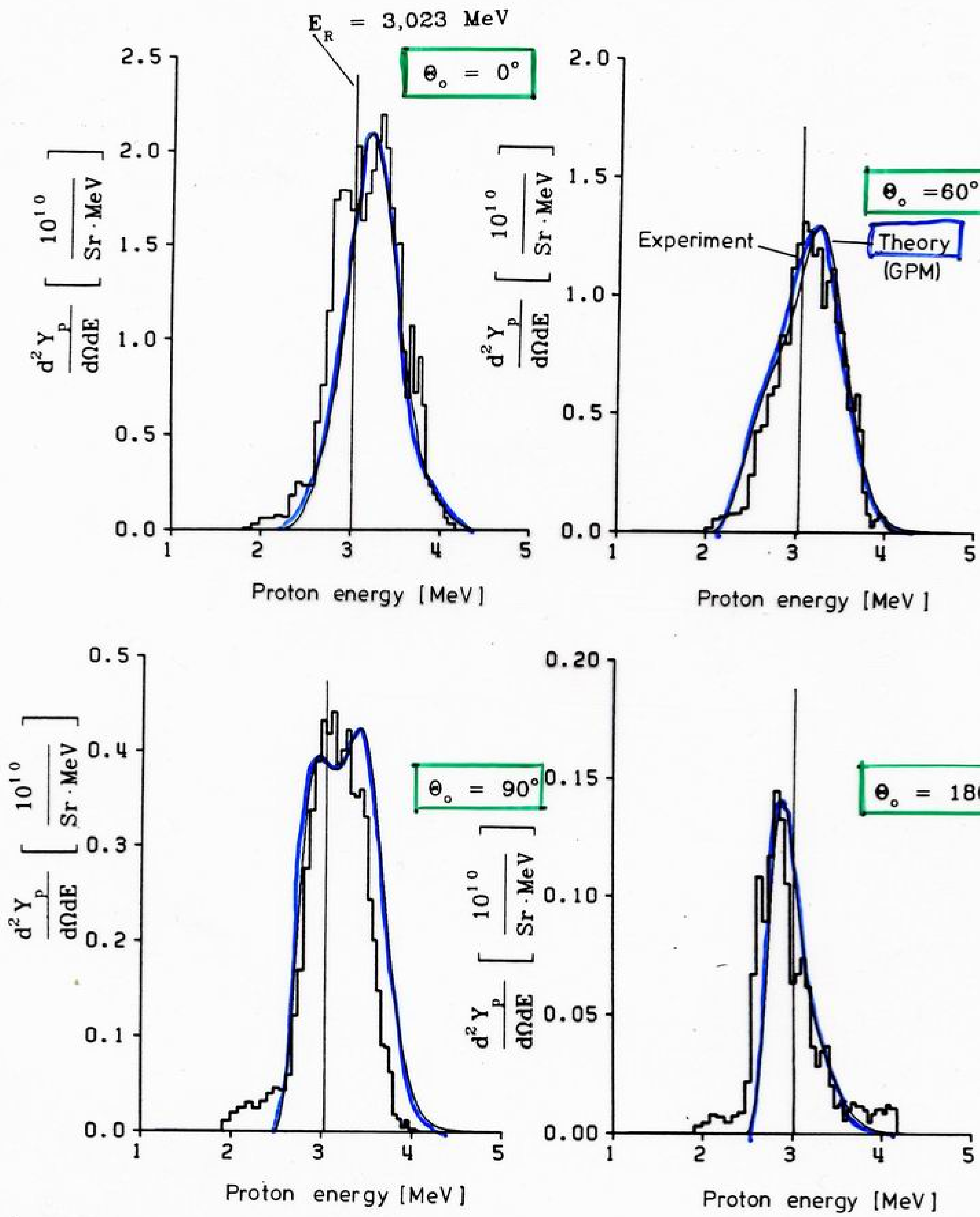
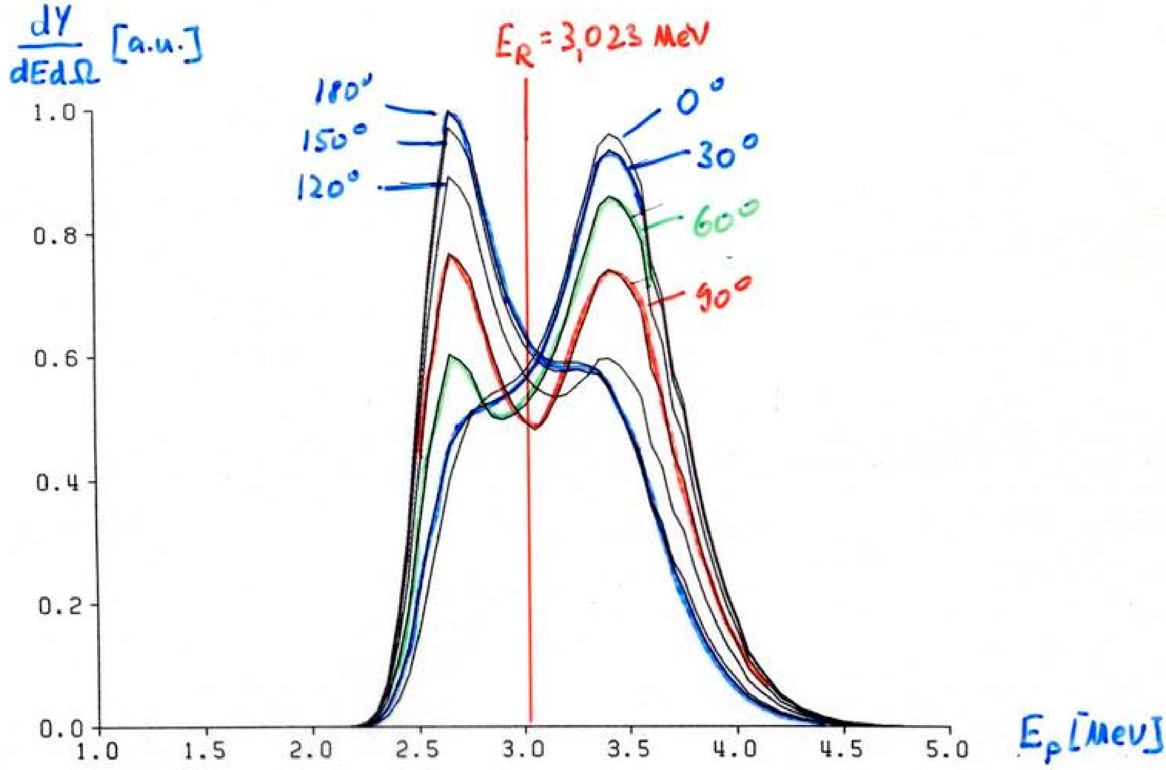
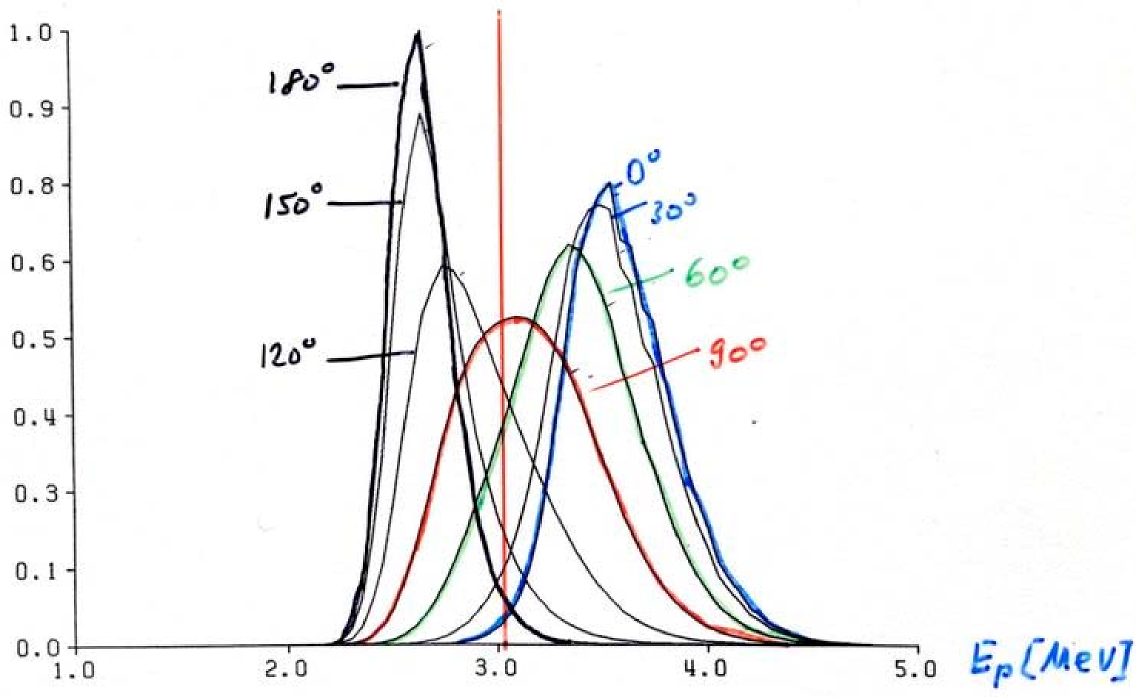


Fig. 14: Reaction proton spectra on POSEIDON (280 kJ, 60 kV, 500 Pa D_2), proton yield $Y_p = 5.7\cdot10^{10}$, contribution of the first pulse 34%. For the GPM-calculations [30] of the curves the following parameters were taken: $T_{i1}{}^* = 75$ keV, $N_{b1} = 5\cdot10^{16}$, $T_{i2}{}^* = 200$ keV, $N_{b2} = 3\cdot10^{14}$, $A_d = 3$, $I_{pl} = 790$ kA.



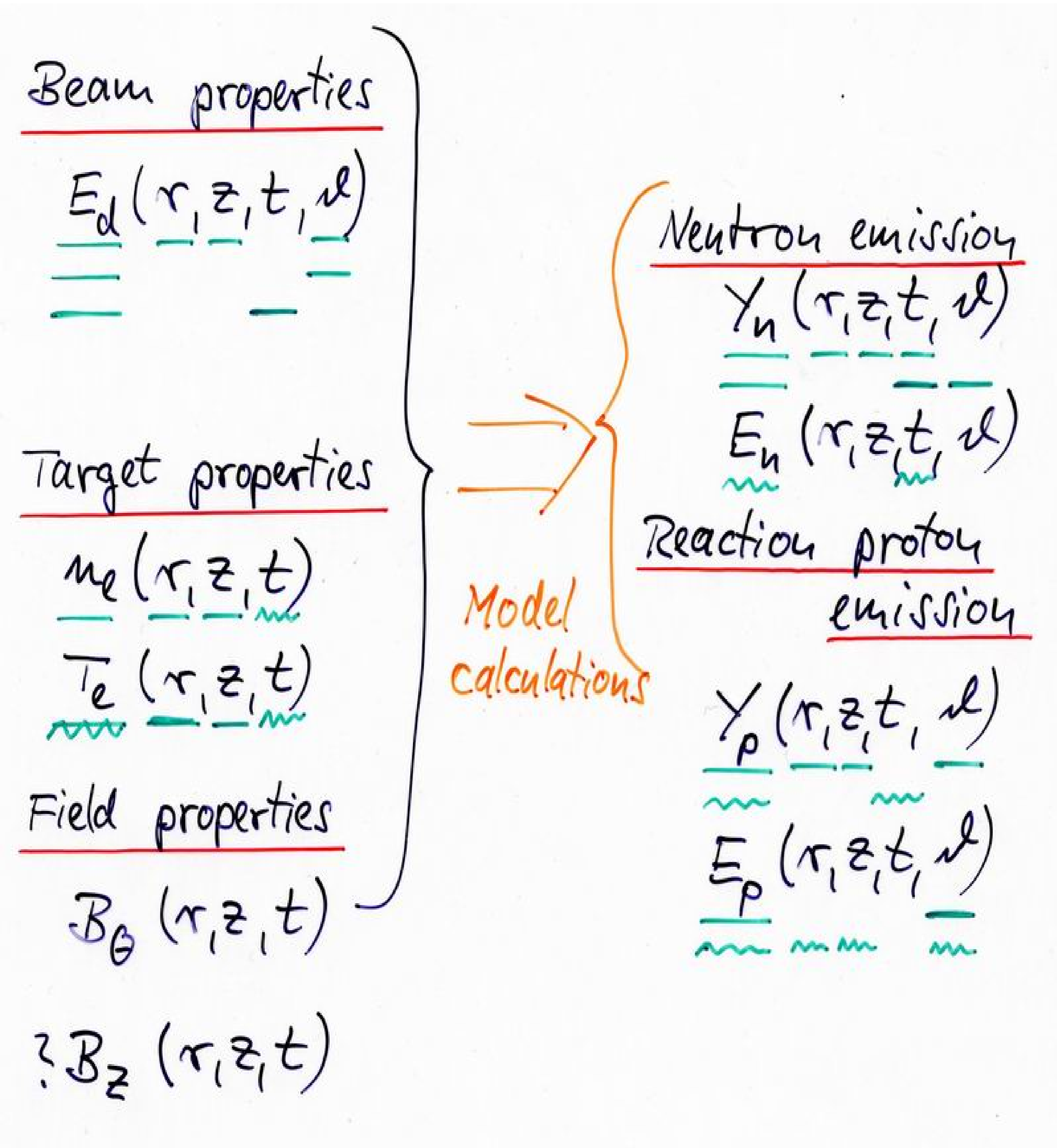
Calculated reaction proton spectra (T_i^* = 100 keV)

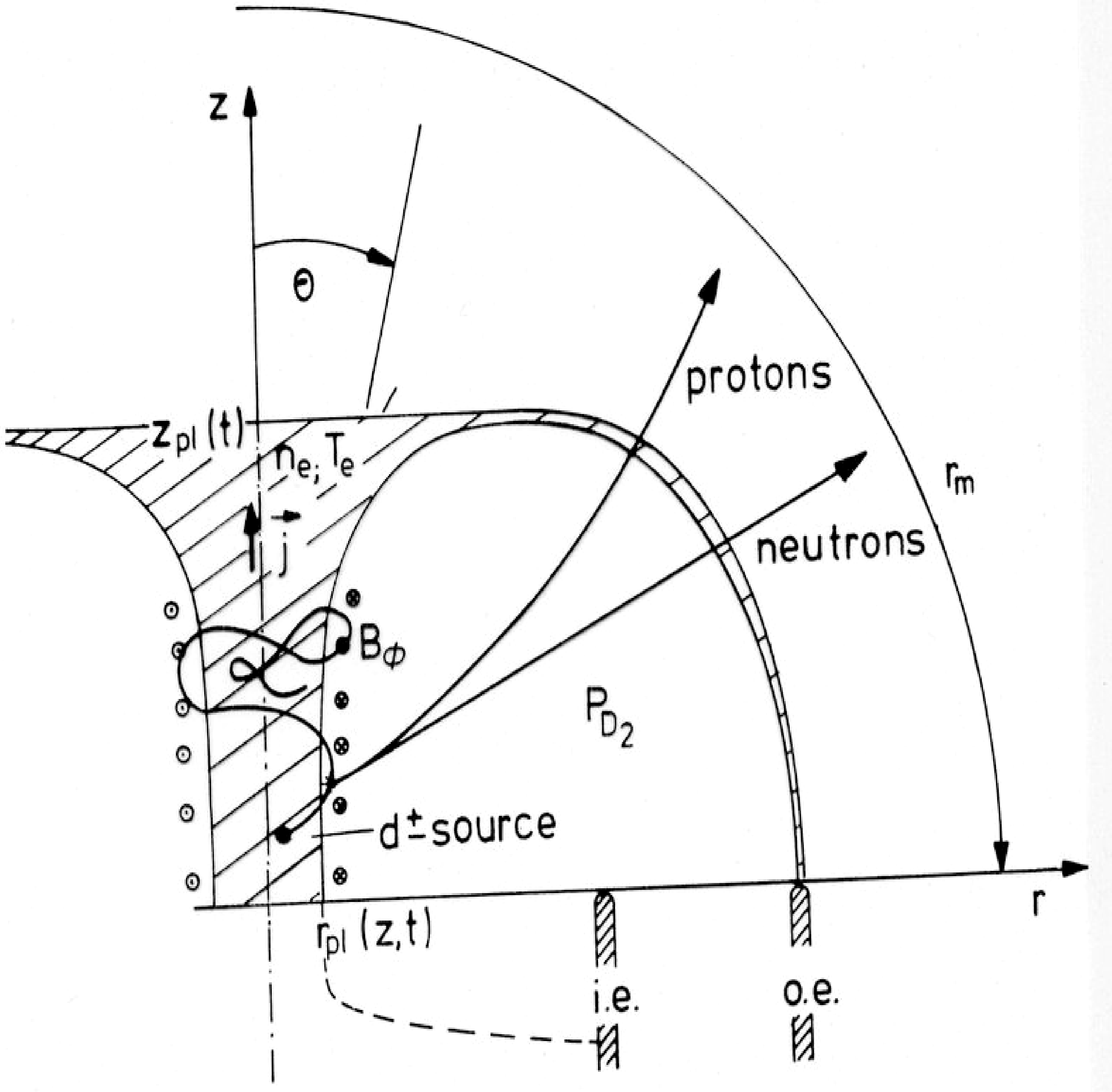
Anisotropy factor: A_d = 5



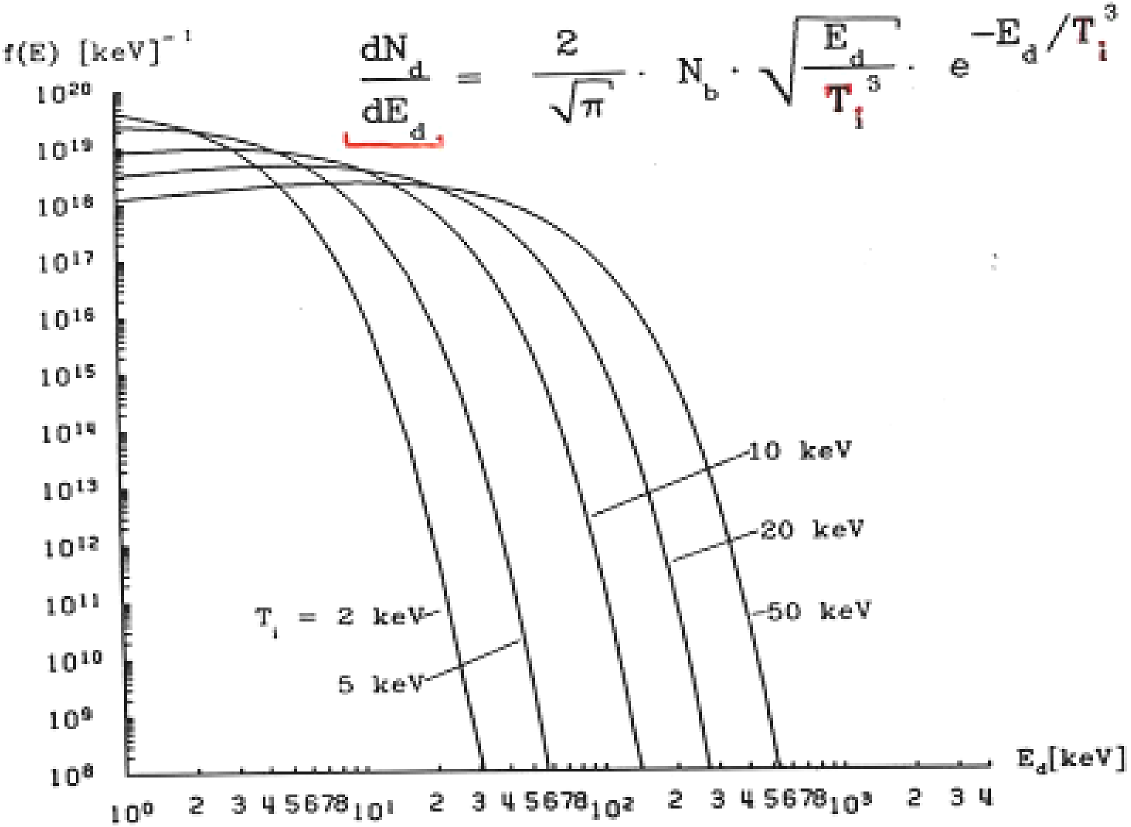
(A_d = 10 ; T_i^* = 100 keV)

Gyrating Particle Model

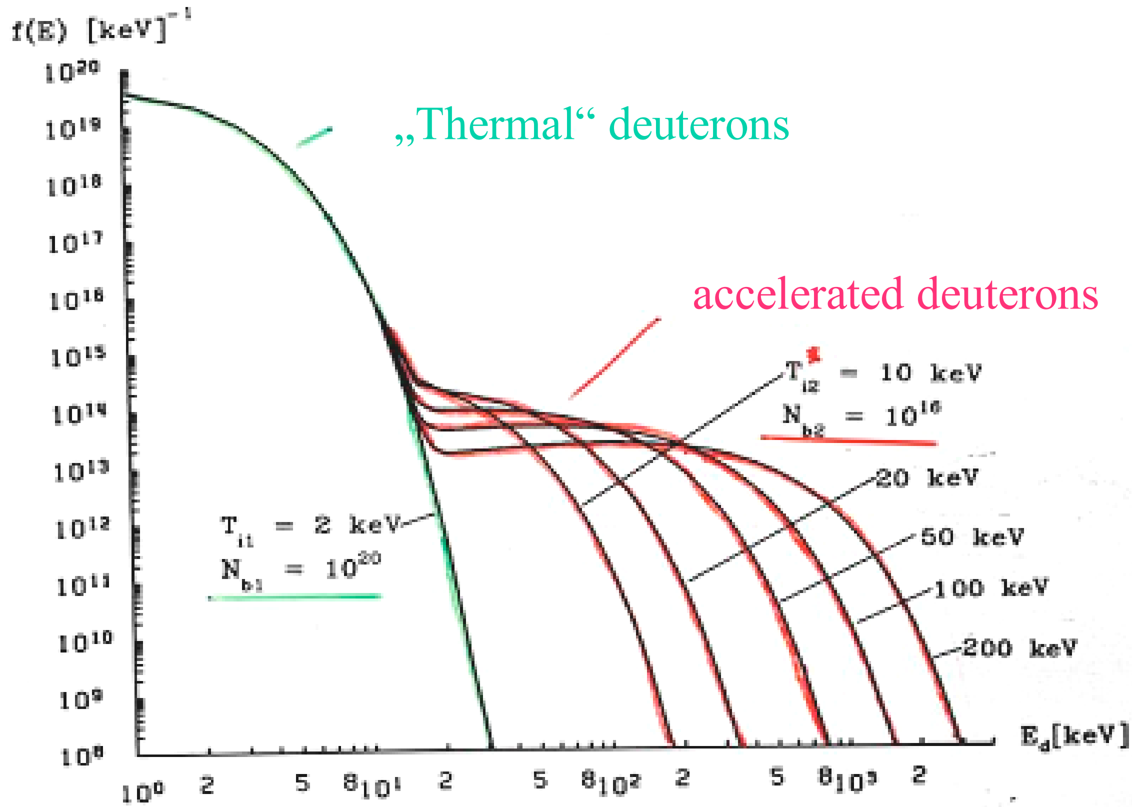

Beam properties
$E_d(r, z, t, \vartheta)$
Target properties
$n_e(r, z, t)$
$T_e(r, z, t)$
Field properties
$B_\Theta(r, z, t)$
? $B_z(r, z, t)$
Model calculations
Neutron emission
$Y_n(r, z, t, \vartheta)$
$E_n(r, z, t, \vartheta)$
Reaction proton emission
$Y_p(r, z, t, \vartheta)$
$E_p(r, z, t, \vartheta)$


z
Θ
protons
$z_{pl}(t)$
$n_e; T_e$
r_m
$\vec{j}$
neutrons
B_ϕ
P_{D_2}
$d^\pm$source
r
$r_{pl}(z,t)$
i.e.
o.e.

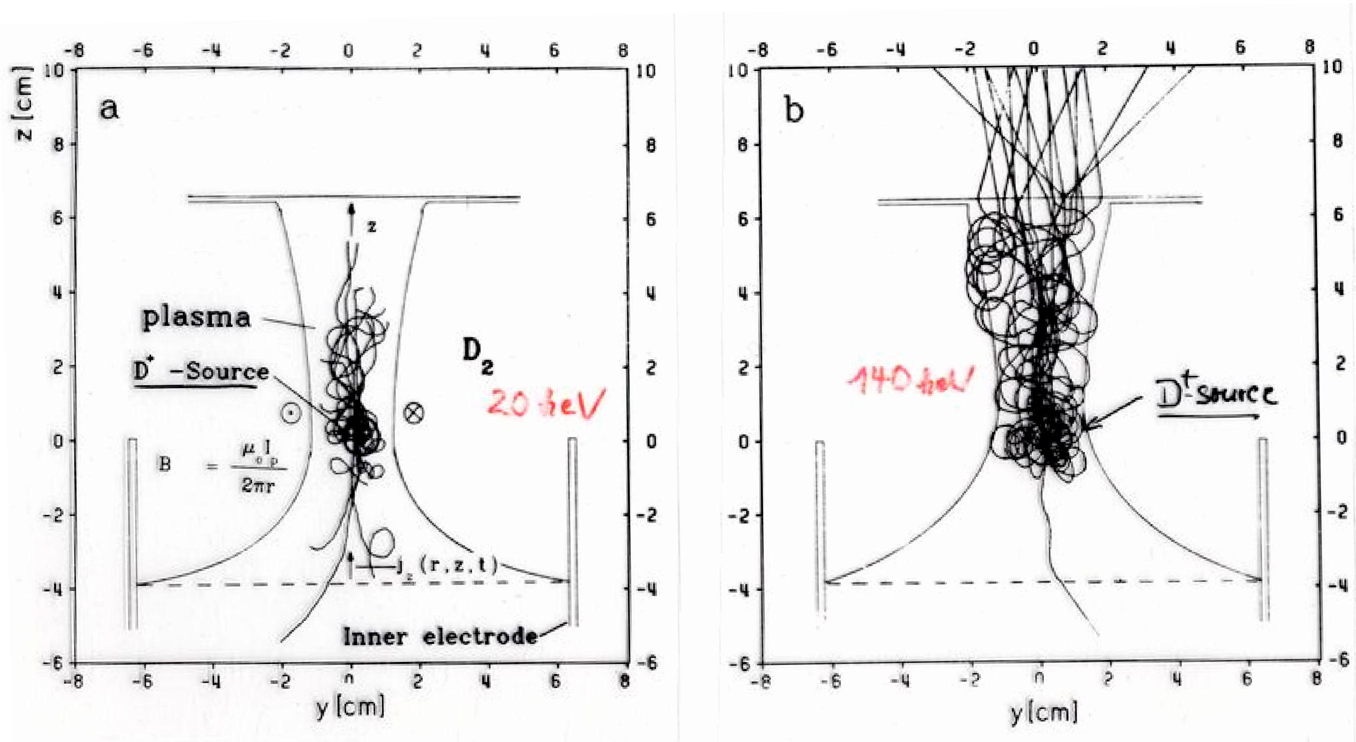
$$\frac{dN_d}{dE_d} = \frac{2}{\sqrt{\pi}} \cdot N_b \cdot \sqrt{\frac{E_d}{T_i^3}} \cdot e^{-E_d/T_i^3} \left[\frac{1}{\text{keV}} \right]$$

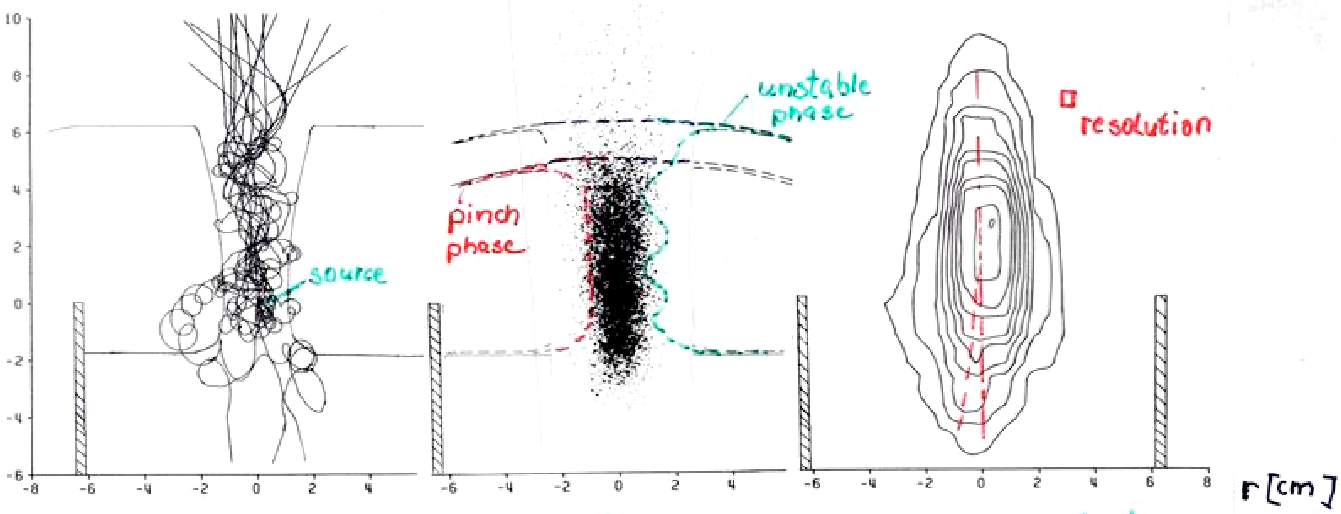


Verteilungsfunktion für eine Temperatur (N = 10^{20})



Verteilungsfunktionen für 2 Temperaturen

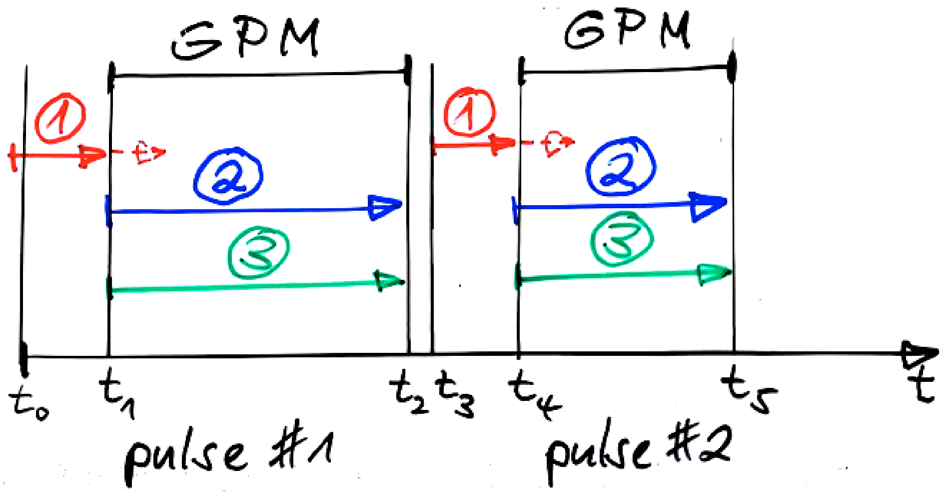

a
z [cm]
z
plasma
D+ -Source
D2
20 keV
B = μo Ip / 2πr
jz (r,z,t)
Inner electrode
y [cm]
b
140 keV
D+ source
y [cm]



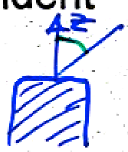
calculated d^+ trajectories
140 keV, isotopic emission, point source

calculated fusion proton source
(1 point 10^7 readions)

experimental proton pinhole picture (Lines of equal proton density)



(1) ion acceleration in time- and space-dependent electromagnetic fields
---> deuteron distribution f_{D1} $(E,\mathbf{r},t,\Theta)$



GPM

(2) ion relaxation
predominantly by Coulomb collisions with electrons T_e, $n_e(\mathbf{r},t)$, $\mathbf{B}$ $(\mathbf{r},t)$
---> deuteron distribution f_{D2} $(E,\mathbf{r},t)$

(3) fusion reactions of the fast deuterons with the target $n_{i,o}(\mathbf{r},t)$

measured quantities

(4) fusion products $n(E,t)$ and $p(E,t)$ pass through the plasma/gas up to the detectors.
protons experience deviations in $B(\mathbf{r},t)$

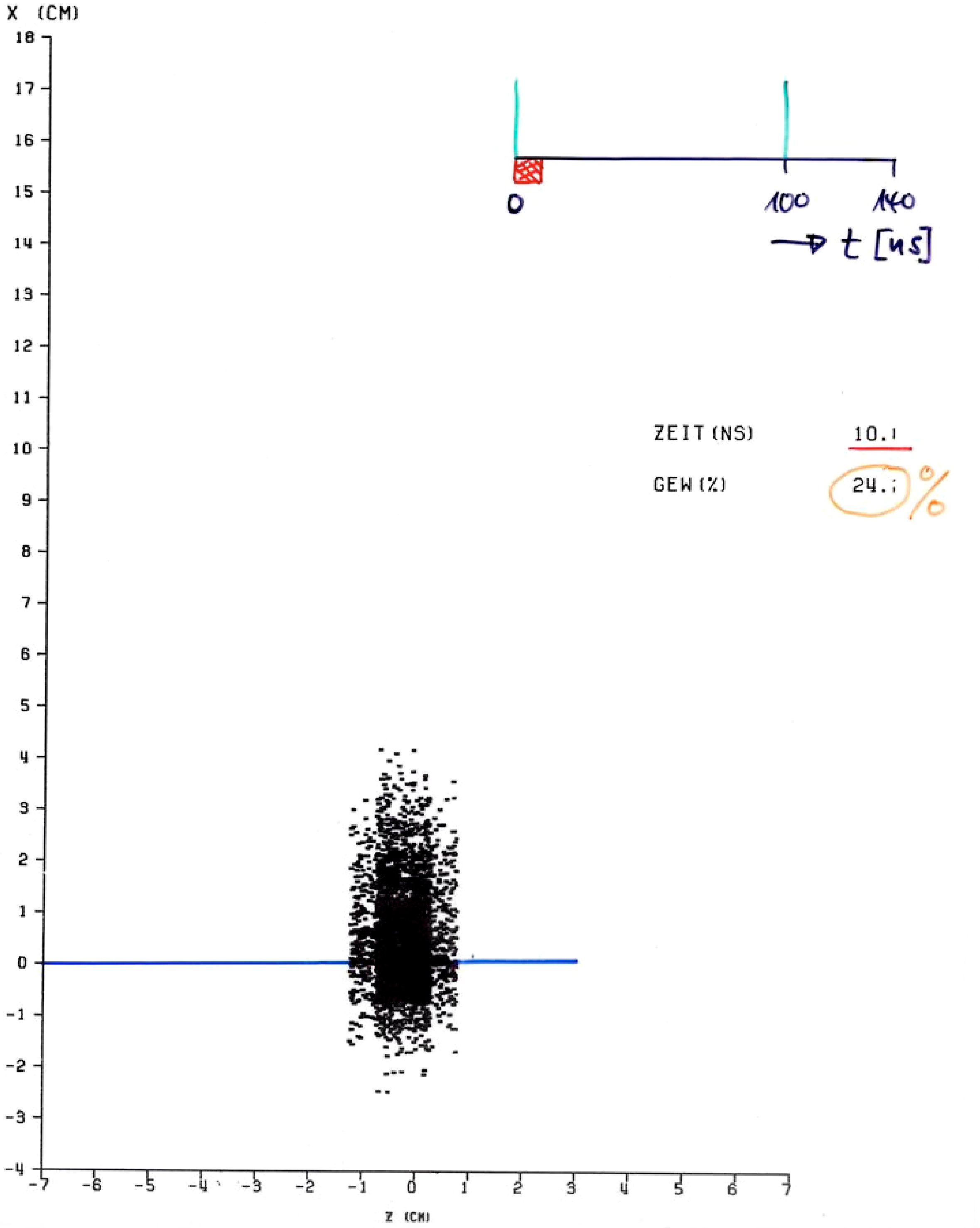
POSEIDON diagnostics:

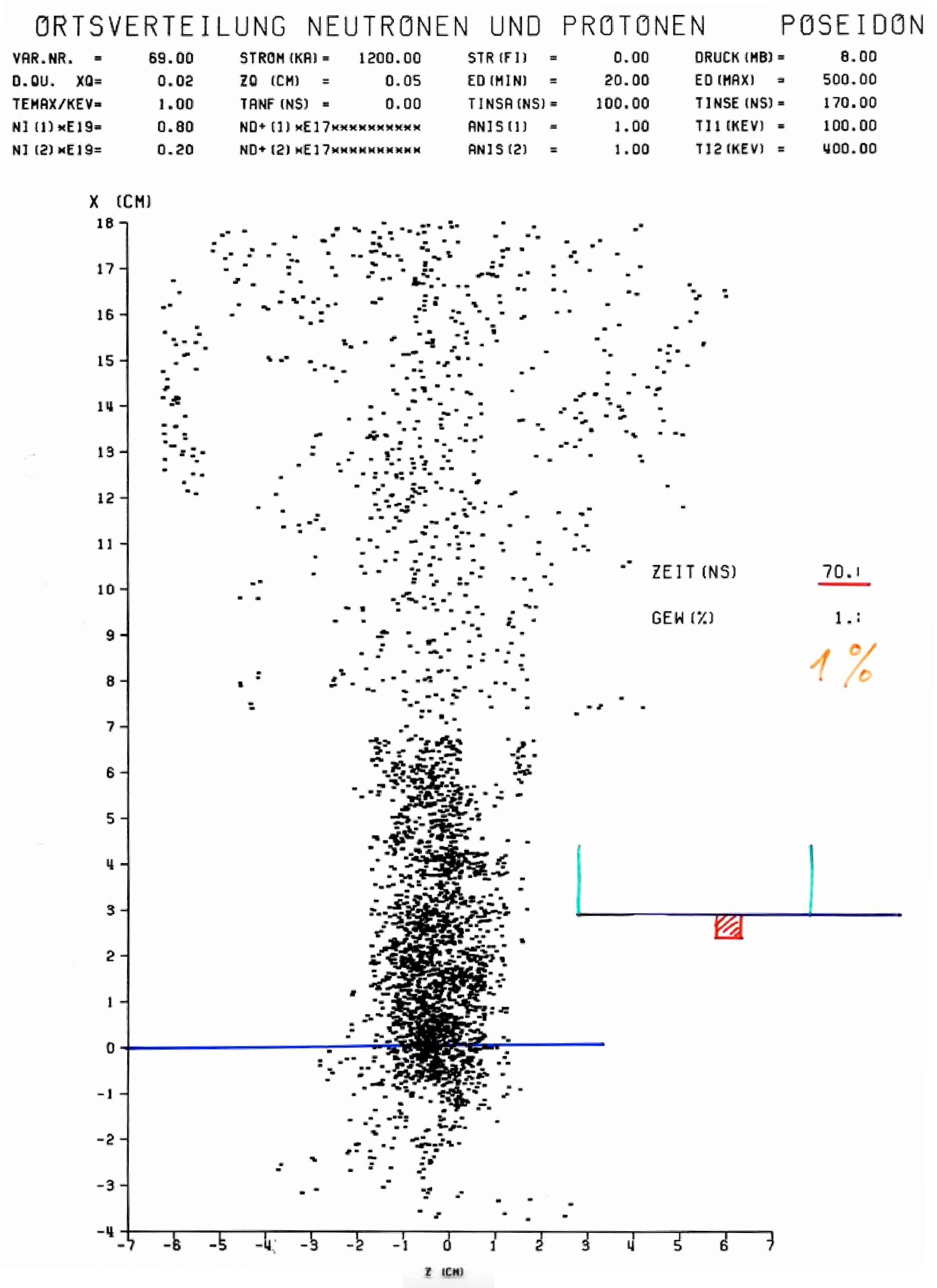
neutrons $n(E,t)$ in one direction (side on)

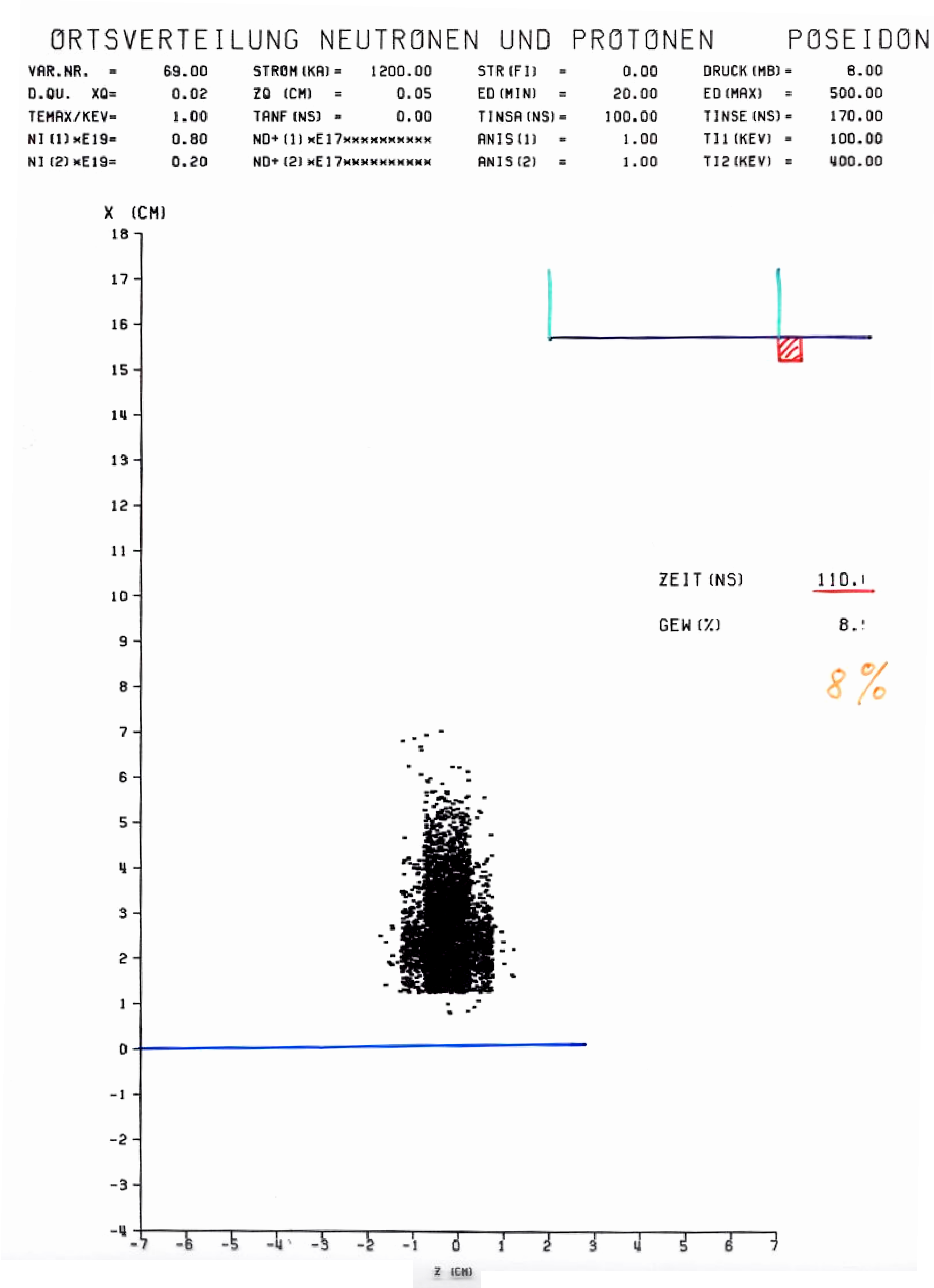
protons $p(E)$ in 8 directions

ØRTSVERTEILUNG NEUTRØNEN UND PRØTØNEN POSEIDØN

VAR.NR. =	69.00	STRØM (KA) =	1200.00	STR (FI) =	0.00	DRUCK (MB) =	8.00
D.QU. XQ=	0.02	ZQ (CM) =	0.05	ED (MIN) =	20.00	ED (MAX) =	500.00
TEMAX/KEV=	1.00	TANF (NS) =	0.00	TINSA (NS) =	100.00	TINSE (NS) =	170.00
NI (1) *E19=	0.80	ND+ (1) *E17**********		ANIS (1) =	1.00	TI1 (KEV) =	100.00
NI (2) *E19=	0.20	ND+ (2) *E17**********		ANIS (2) =	1.00	TI2 (KEV) =	400.00




ØRTSVERTEILUNG NEUTRØNEN UND PRØTØNEN
PØSEIDØN
VAR.NR. = 69.00
STROM (KA) = 1200.00
STR (FI) = 0.00
DRUCK (MB) = 8.00
D.QU. XQ= 0.02
ZQ (CM) = 0.05
ED (MIN) = 20.00
ED (MAX) = 500.00
TEMAX/KEV= 1.00
TANF (NS) = 0.00
TINSA (NS) = 100.00
TINSE (NS) = 170.00
NI (1) *E19= 0.80
ND+ (1) *E17**********
ANIS (1) = 1.00
TI1 (KEV) = 100.00
NI (2) *E19= 0.20
ND+ (2) *E17**********
ANIS (2) = 1.00
TI2 (KEV) = 400.00
X (CM)
ZEIT (NS)
70.1
GEW (%)
1 %
Z (CM)


ØRTSVERTEILUNG NEUTRØNEN UND PRØTØNEN POSEIDØN
VAR.NR. = 69.00
STRØM (KA) = 1200.00
STR (FI) = 0.00
DRUCK (MB) = 8.00
D.QU. XQ= 0.02
ZQ (CM) = 0.05
ED (MIN) = 20.00
ED (MAX) = 500.00
TEMAX/KEV= 1.00
TANF (NS) = 0.00
TINSA (NS) = 100.00
TINSE (NS) = 170.00
NI (1) *E19= 0.80
ND+ (1) *E17**********
ANIS (1) = 1.00
TI1 (KEV) = 100.00
NI (2) *E19= 0.20
ND+ (2) *E17**********
ANIS (2) = 1.00
TI2 (KEV) = 400.00
X (CM)
ZEIT (NS) 110.1
GEW (%) 8.
8 %
Z (CM)

ØRTSVERTEILUNG NEUTRØNEN UND PRØTØNEN ZEITINT.

VAR.NR. =	69.00	STRØM (KA) =	1200.00	STR (FI) =	0.00	DRUCK (MB) =	8.00
D.QU. XQ=	0.02	ZQ (CM) =	0.05	ED (MIN) =	20.00	ED (MAX) =	500.00
TEMAX/KEV=	1.00	TANF (NS) =	0.00	TINSA (NS) =	100.00	TINSE (NS) =	170.00
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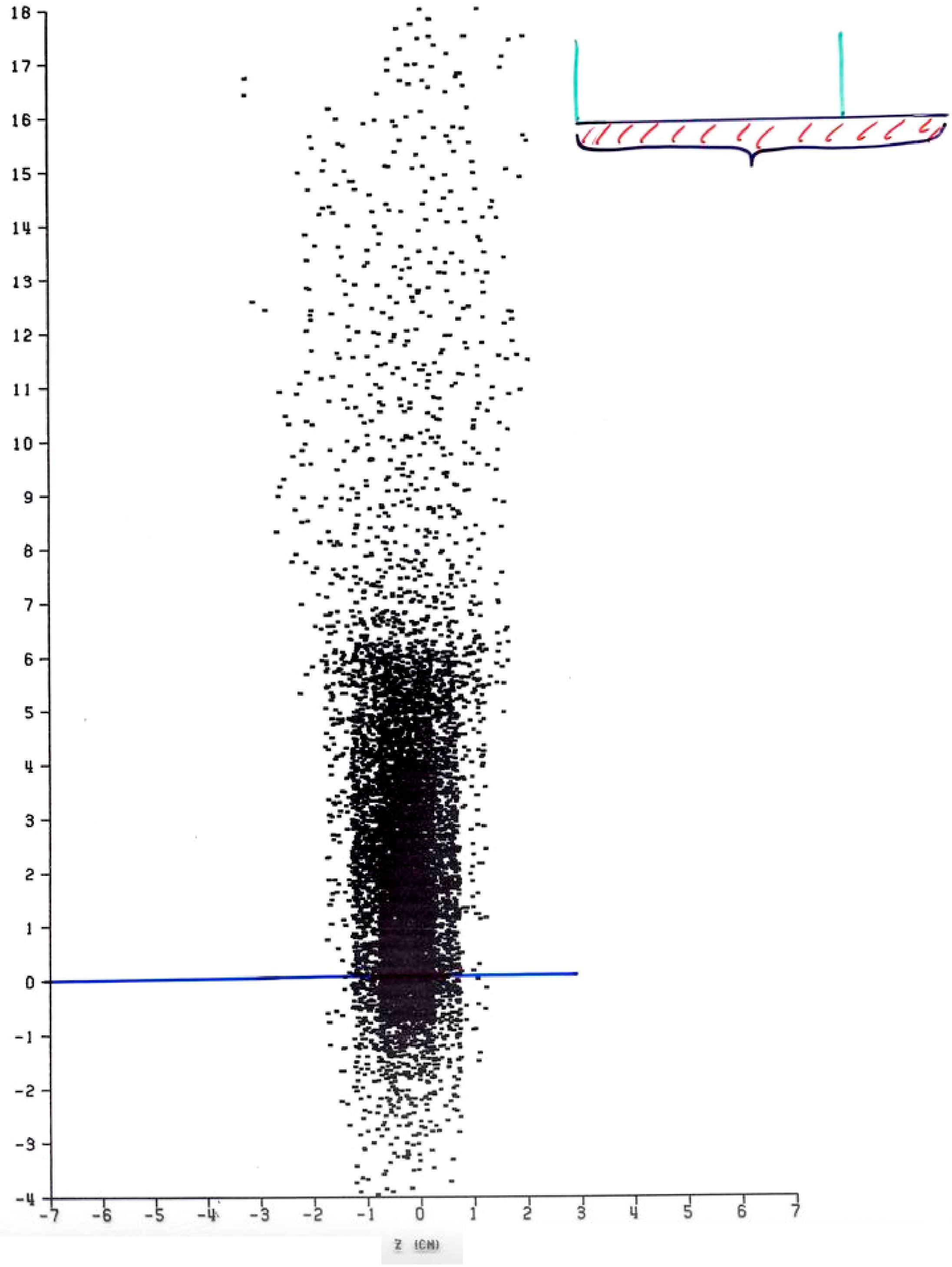

Conclusions

Neutron diagnostics deliver valuable information on various processes which occur in the plasma, such as:

Pinch dynamics

fast ion beams interacting
with a target

fast ion energy distributions

Fusion neutron measurements
should be complemented by
Fusion proton measurements.

NEUTRONS

angular resolution

---> anisotropy
beam target processes

temporal resolution

---> two (three) pulses
various pinch phases

spatial resolution

---> dimensions of source
(better using proton measurements)

axial propagation of source

spectral resolution

---> energy of deuterons

relaxation of deuterons

Neutrons originate predominantly from a Nonthermal Plasma

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Thank you

for your

attention