Accelerator Technology and Power Plant Design for Fast Ignition Heavy Ion Fusion Energy

Boris Sharkov (ITEP-Moscow)

M.Basko,M.Churazov,, D.Koshkarev,
S.Medin, Yu.Orlov, Parshikov A. N., Suslin V.M.

ITEP-Moscow
IHED RAS
Keldysh IAM RAS

20th IAEA FEC
Villamoura 2004

Outline

- Basic principles
- Target for FI IFE
- Energy release partition
- HI Accelerator – Driver
- Reactor Chamber
- Chamber Wall Response
- Power Plant
- ITEP-TWAC facility
- Conclusions

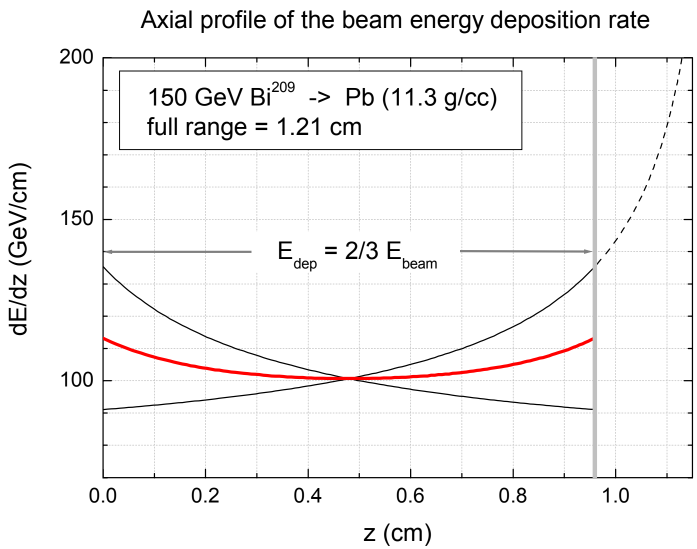
Driver efficiency ≥ 25%
High repetition rate ~ 1-10 Hz
High reliability based on developed accelerator technologies

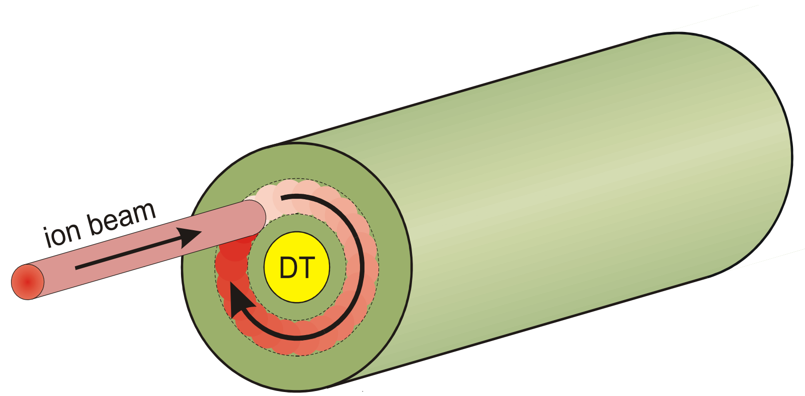
Principal motivation for cylindrical targets

M.Basko et al., HIF 2002

Near-relativistic heavy ions with energies ≥ 0.5 become an interesting alternative driver option for heavy ion inertial fusion (D.G. Koshkarev).

Bi ions with energies 100-200 GeV have relatively long ranges of ~7-18 g/cm^2 in cold heavy metals. Such ranges can be naturally accommodated in cylindrical targets with axial beam propagation.





Direct drive may become a competitive target option when

- **azimuthal symmetry is ensured by fast beam rotation around the target axis,**
- **axial uniformity is controlled by discarding the Bragg peak, and (possibly) by two-sided beam irradiation,**
- **a heavy-metal shell (liner) is used to compress the DT fuel.**

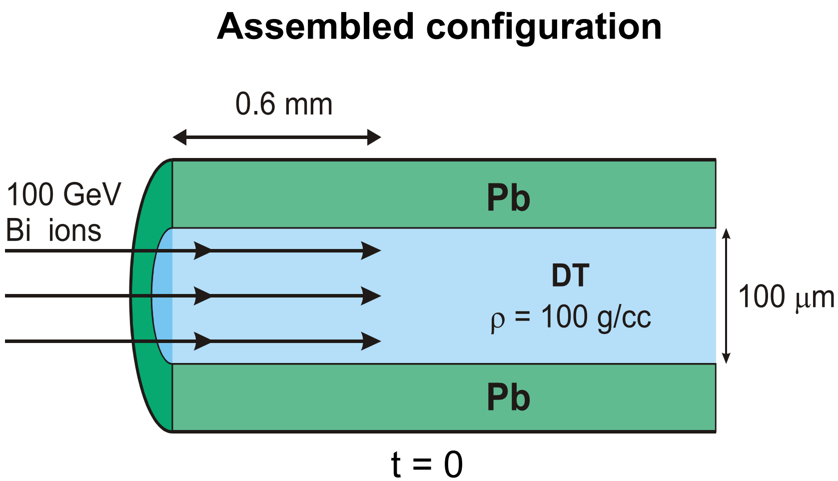
M.Basko *et al*., HIF 2002

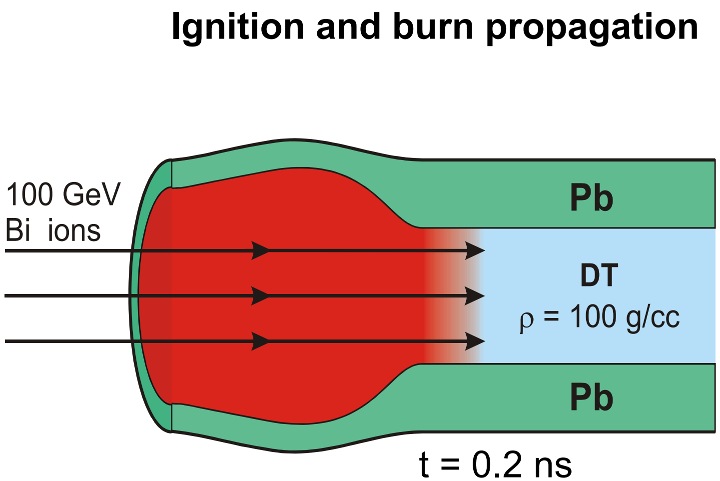
Fast ignition with heavy ions: assembled configuration

M.Basko et al., HIF 2002

With a heavy ion energy $\geq$ 0.5 GeV/u, we are compelled to use cylindrical targets because of relatively long ($\geq$ 6 g/cm^2) ranges of such ions in matter.

The ion pulse duration of 200 ps is still about a factor 4 longer than the envisioned laser ignitor pulse. For compensation, it is proposed to use a massive tamper of heavy metal around the compressed fuel:

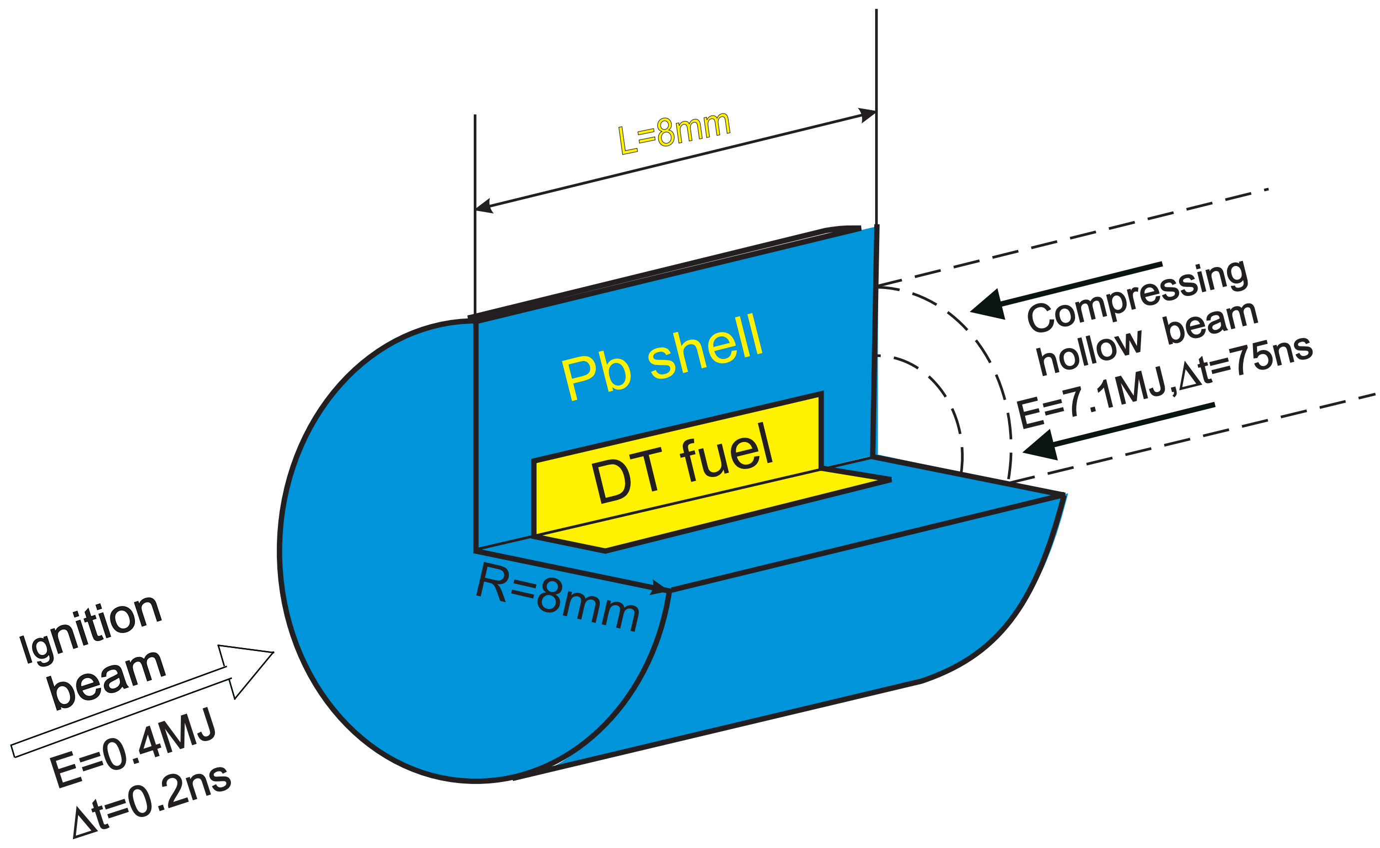




Fuel parameters in the assembled state: ρ_{DT} = 100 g/cc, R_{DT} = 50 μm, $(\rho R)_{DT}$ = 0.5 g/cm^2.

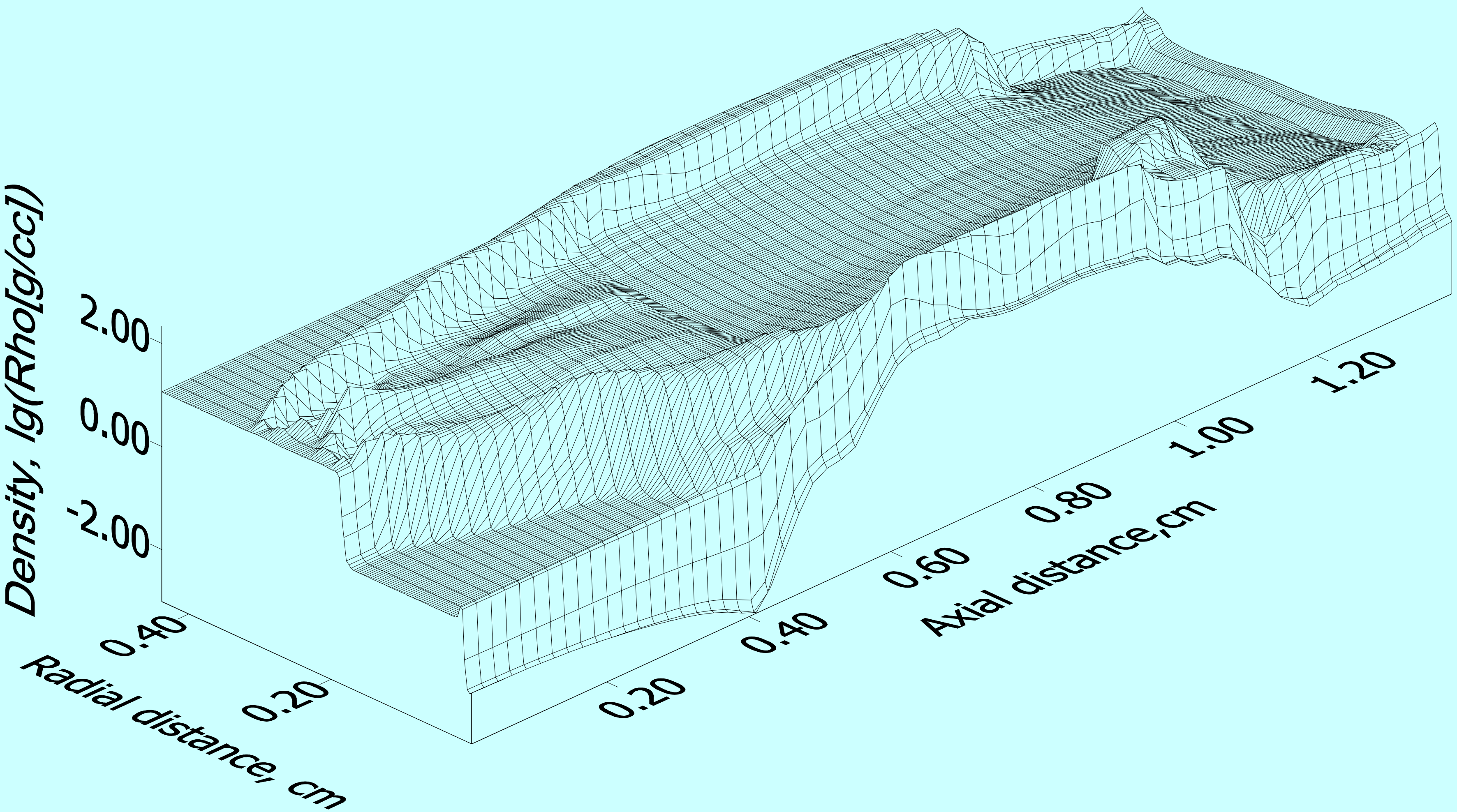
2-D hydro simulations (ITEP + VNIIEF) **have demonstrated that the above fuel configuration is ignited by the proposed ion pulse, and the burn wave does propagate along the DT cylinder!**

Cylindrical FIHIF Target

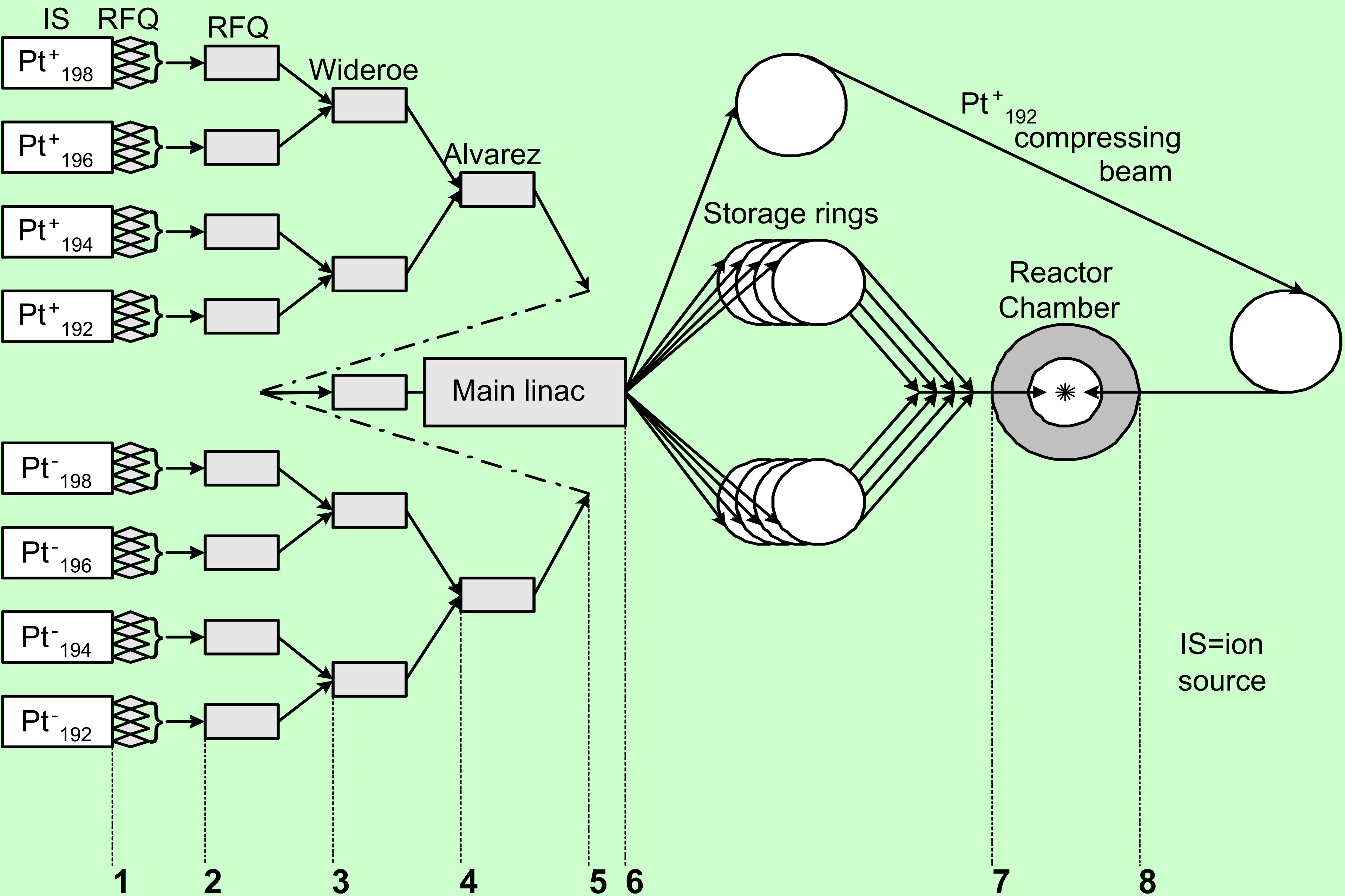


Density distribution in compressed cylindrical target for FIHIF (t=30ns)

M.Churazov 2004, 2D hydro



FIHIF Driver Scheme



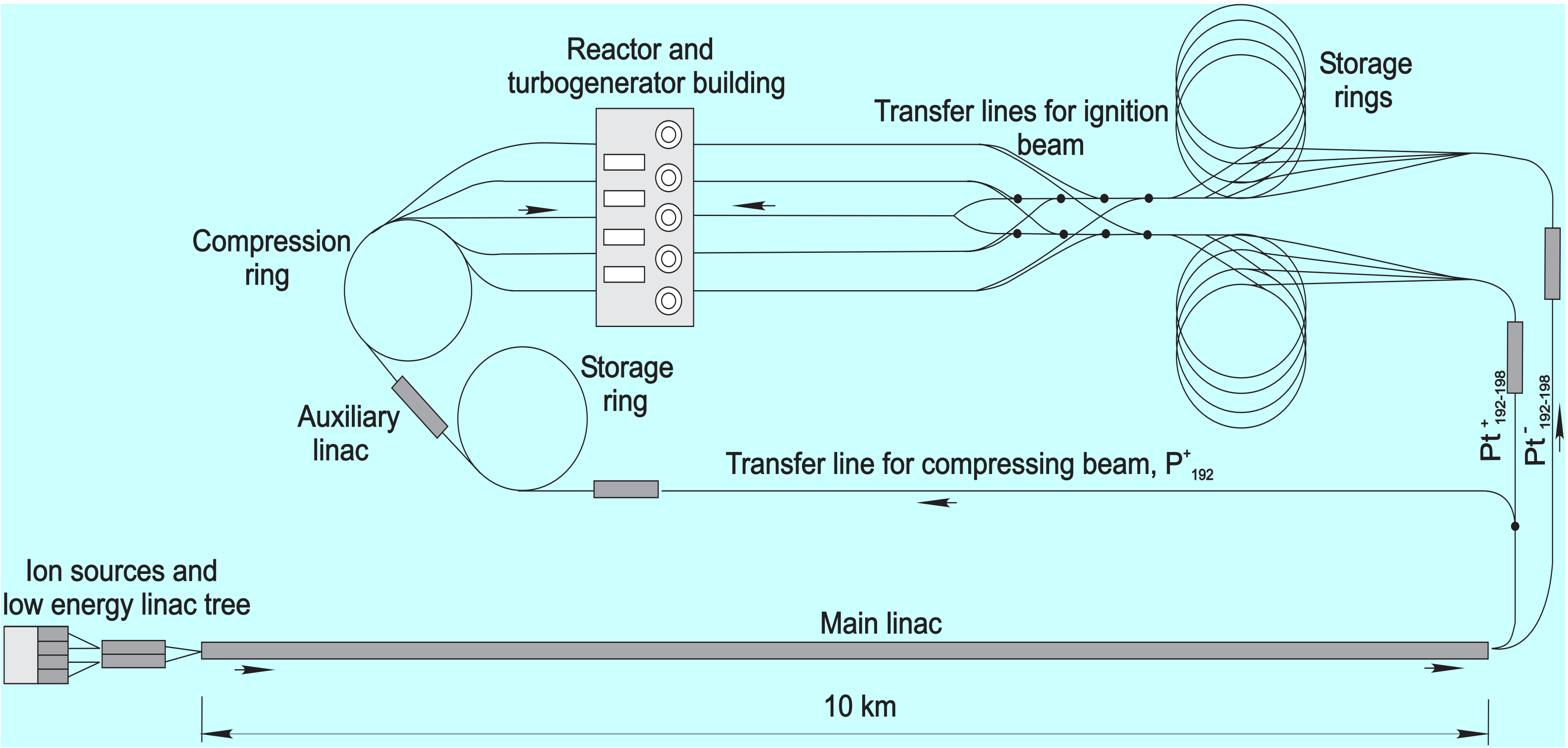
Beam parameters of HIF driver for fast ignition fusion						
Station number	Ion energy (GeV)	RF frequency (MHz)	Bunch current (A)	Momentum spread ($x10^4$)	Emittance (μm)	β=v/c
1	**10^{-4}**		**0.04**	**±300**	**0.3**	**0.001**
2	**10^{-3}**	**6.25**	**0.16**	**±180**	**0.9**	**0.003**
3	**10^{-2}**	**12.5**	**0.4**	**±36**	**0.9**	**0.010**
4	**0.1**	**50**	**1**	**±37**	**0.9**	**0.033**
5	**0.2**	**200**	**4**	**±75**	**0.95**	**0.047**
6	**100**	**1000**	**230**	**±2**	**1**	**0.745**
7	**100**	**Single bunch**	**20000**	**±30**	**1**	**0.745**
8	**100**	**Single bunch**	**1600**	**±20**	**1**	**0.745**

HIGH POWER HEAVY ION DRIVER

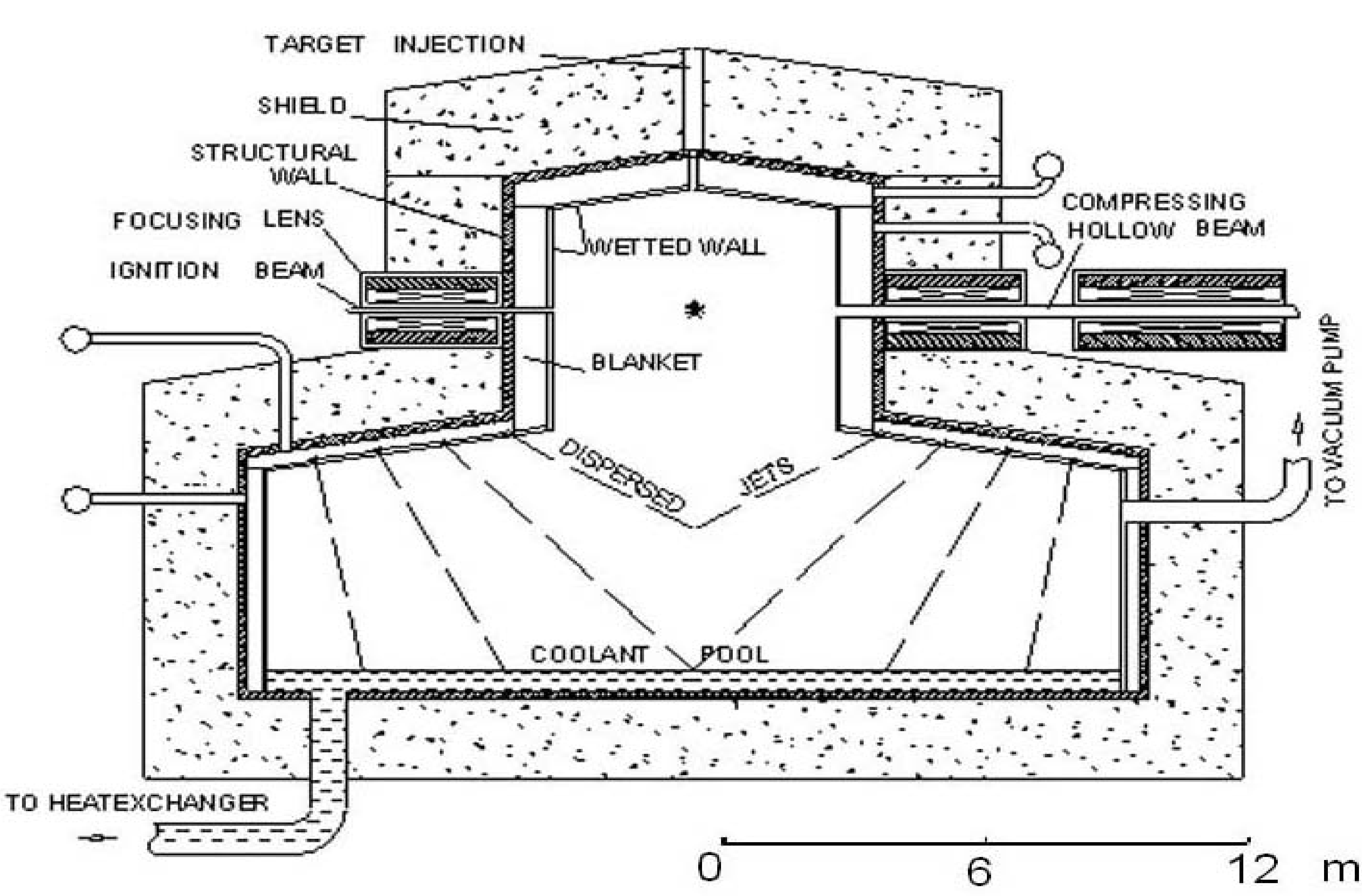
Ions		$Pt^{+,-}_{192,194,196,198}$
Ion energy	(GeV)	100
Compression beam		
Energy	(MJ)	7.1 (profiled)
Duration	(ns)	75
Maximum current	(kA)	1.6
Rotation frequency	(GHz)	1
Rotation radius	(mm)	2
Ignition beam		
Energy	(MJ)	0.4
Duration	(ns)	0.2
Maximum current	(kA)	20
Focal spot radius	(μm)	50

Main linac length	(km)	10
Repetition rate	(Hz)	2x4 (reactor)
Driver efficiency		0.25

Ground plan outline for FIHIF power plant



REACTOR CHAMBER FOR FIHIF POWER PLANT



REACTOR CHAMBER CHARACTERISTICS

Fusion energy per shot	(MJ)	750
Repetition rate	(Hz)	2
Li/Pb atom density	(cm^{-3})	10^{12}
Coolant temperature	(^oC)	550
Explosion cavity diameter	(m)	8
Number of beam penetrations		2
First wall material		SiC (porous)
Coolant tubes material		V-4Cr-4Ti
Blanket energy multiplication		1.1

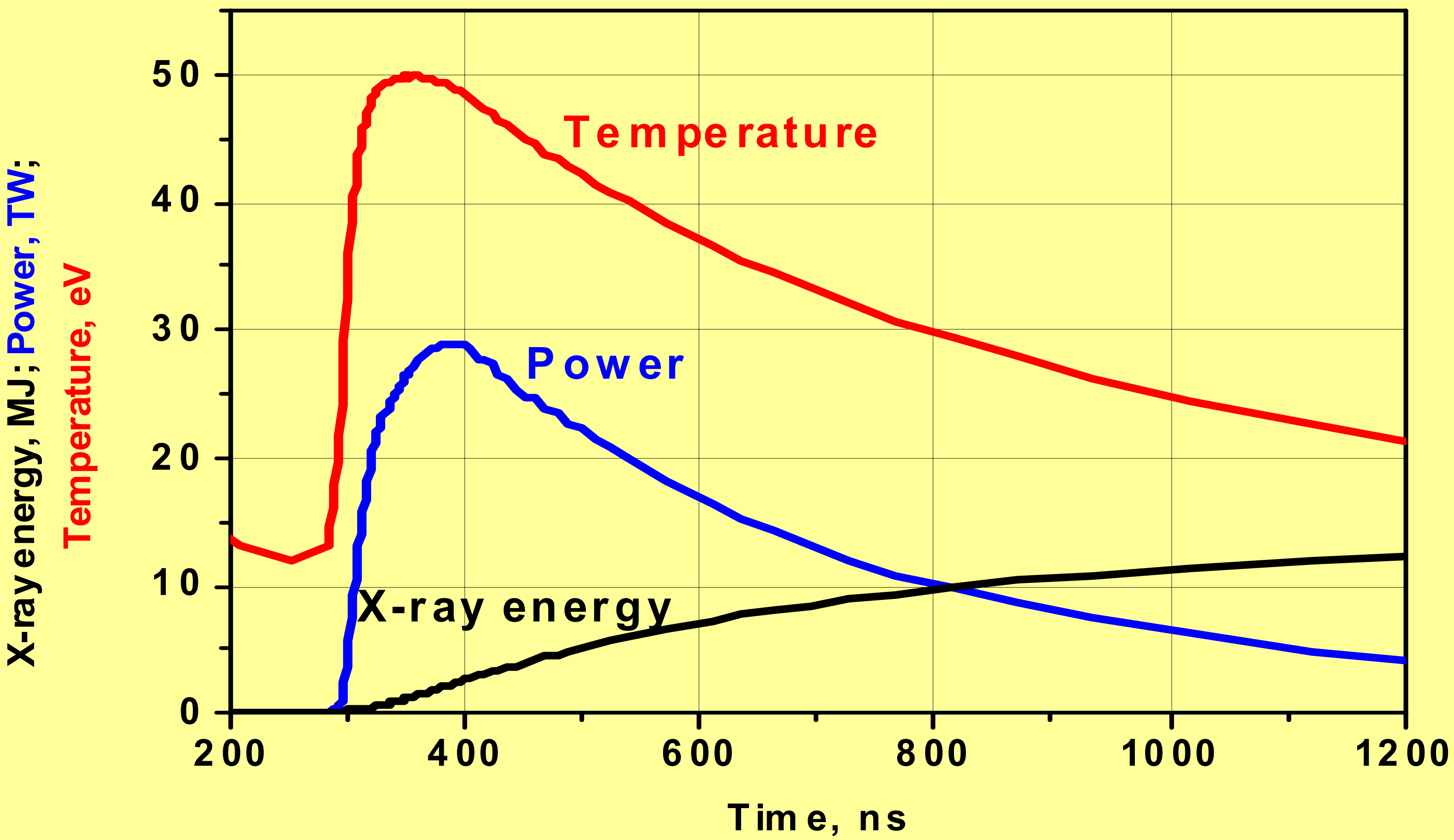
CYLINDRICAL TARGET

DT fuel mass	(g)	0.006
Total mass	(g)	4.44
Length	(mm)	~8.0
ρR parameter	(g/cm^2)	0.5
Burn fraction		0.39
Gain		100
Fusion yield	(MJ)	750

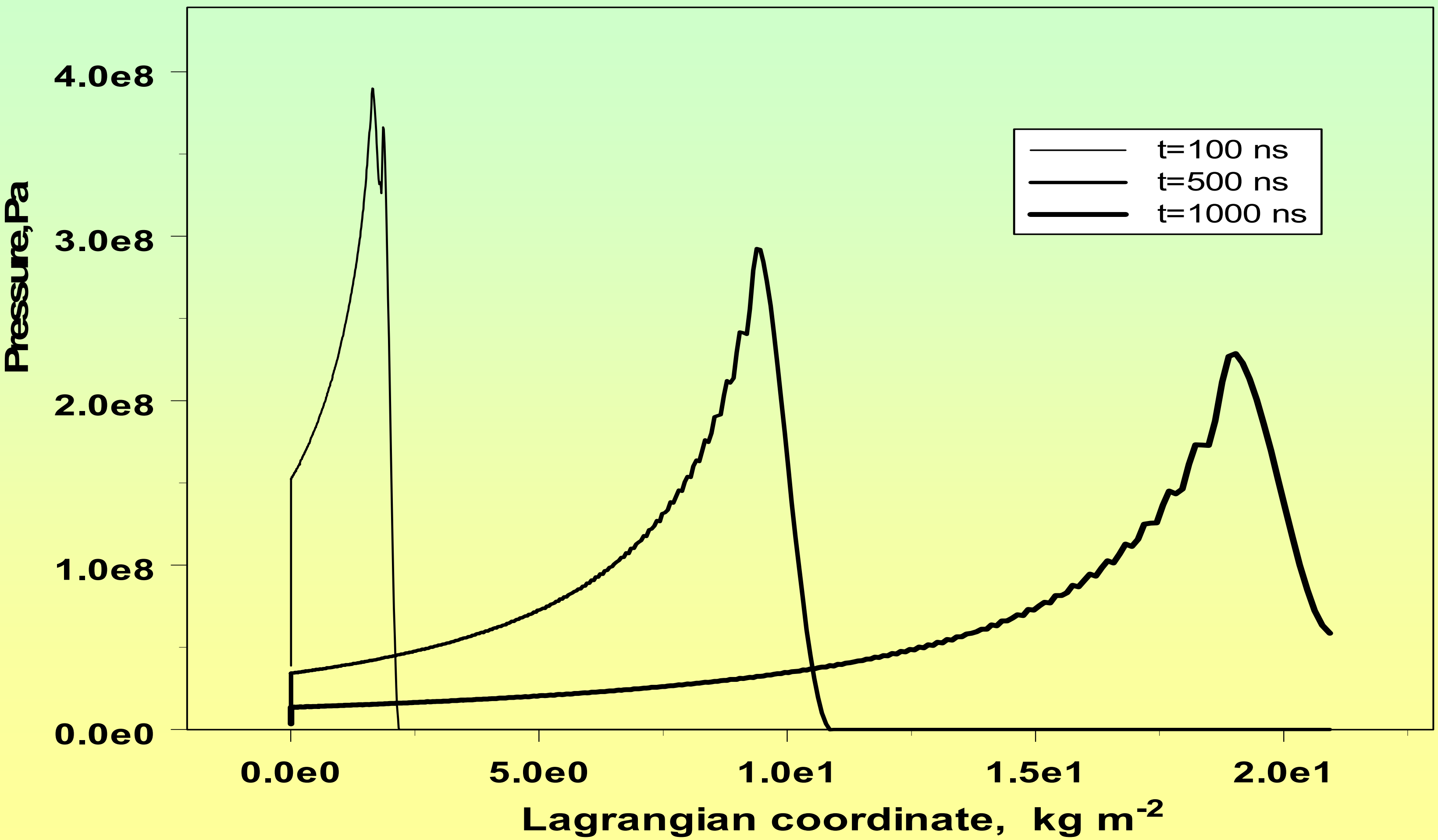
Energy release partition

X-ray	(MJ)	17
Ion debris	(MJ)	153
Neutrons	(MJ)	580

Temporal profiles of X-radiation characteristics for FIHIF cylindrical target

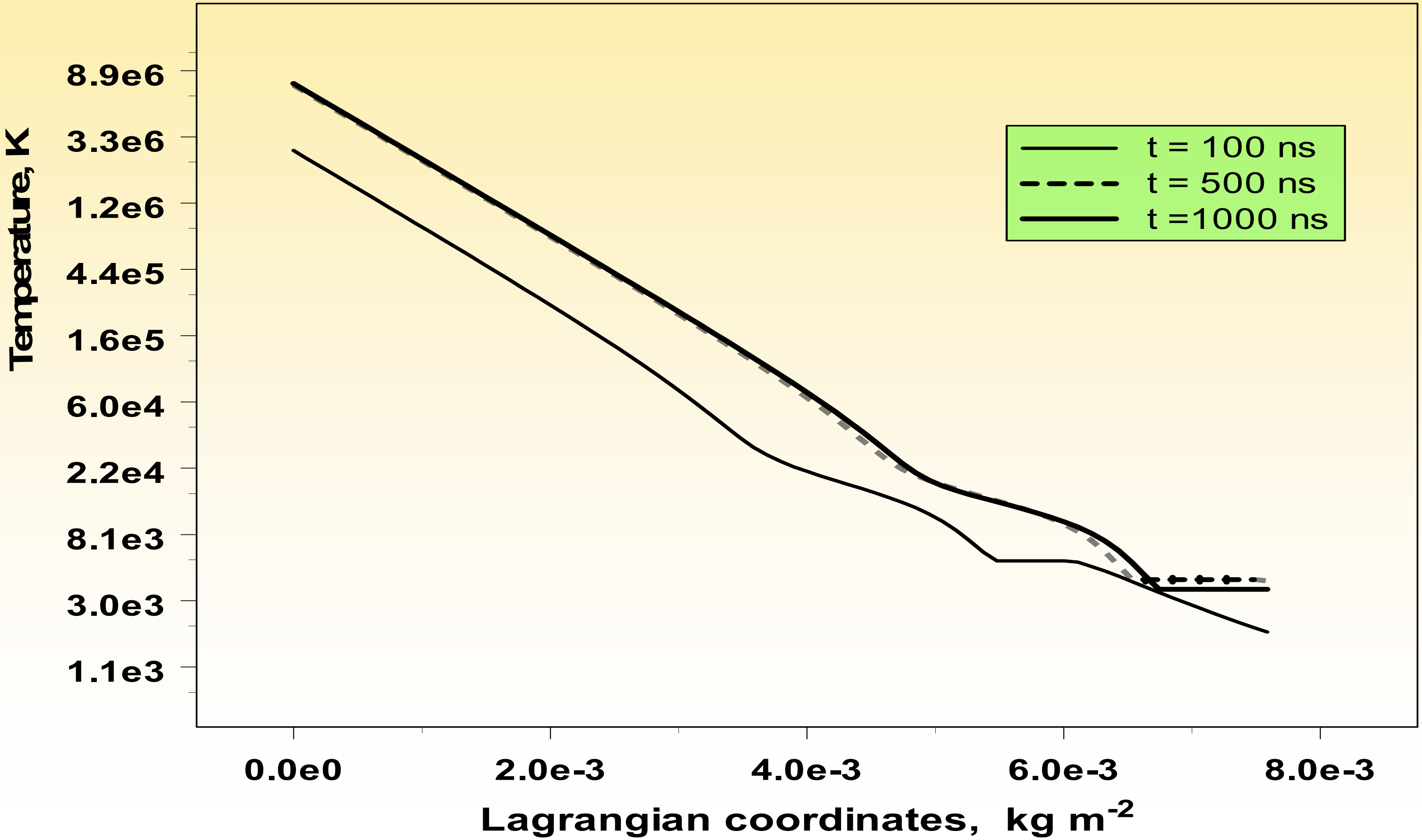


Shock wave profiles generated by X-ray radiation in liquid film at the first wall

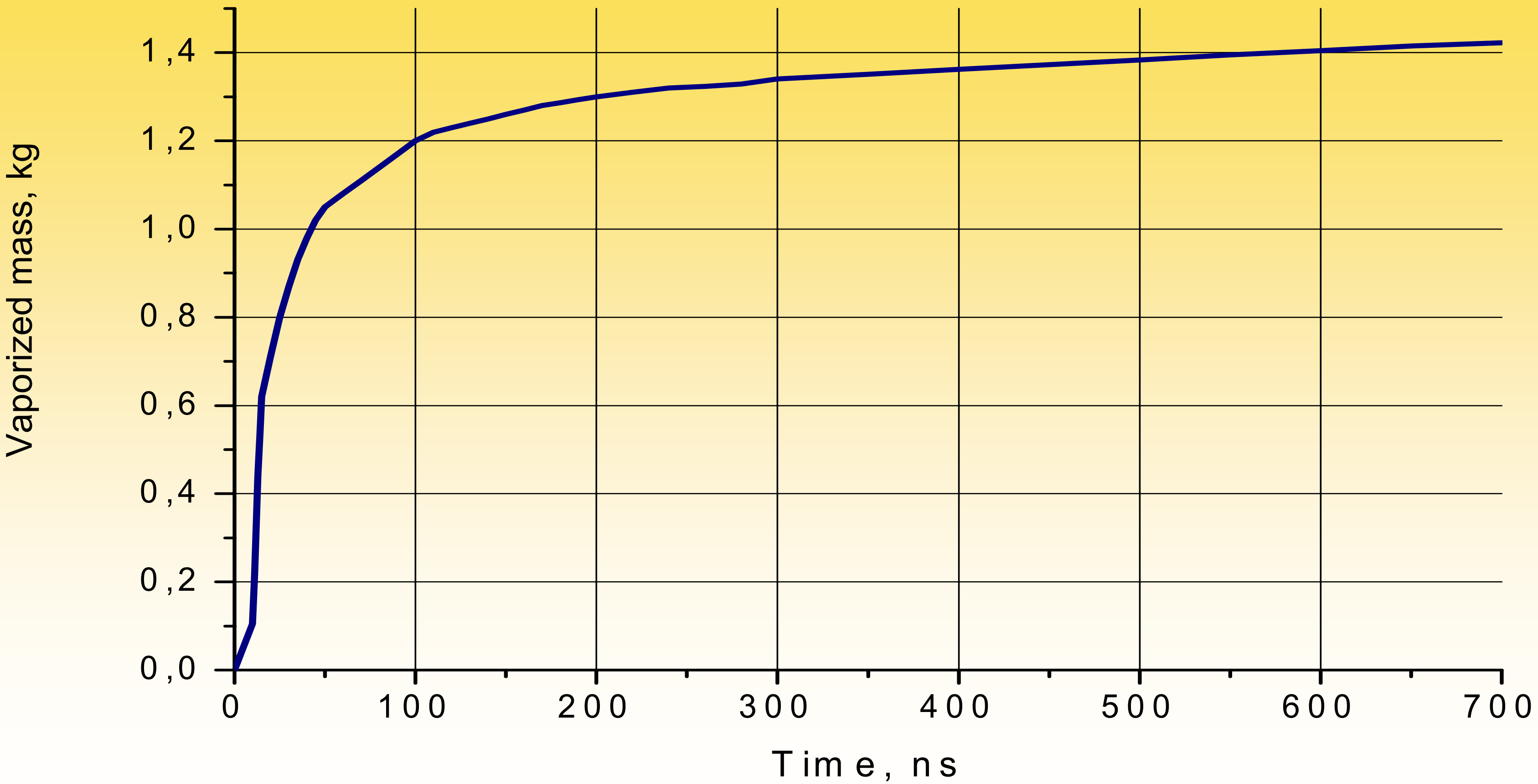


Pressure distribution in liquid film at different times

Temperature profile in liquid protecting layer of the first wall

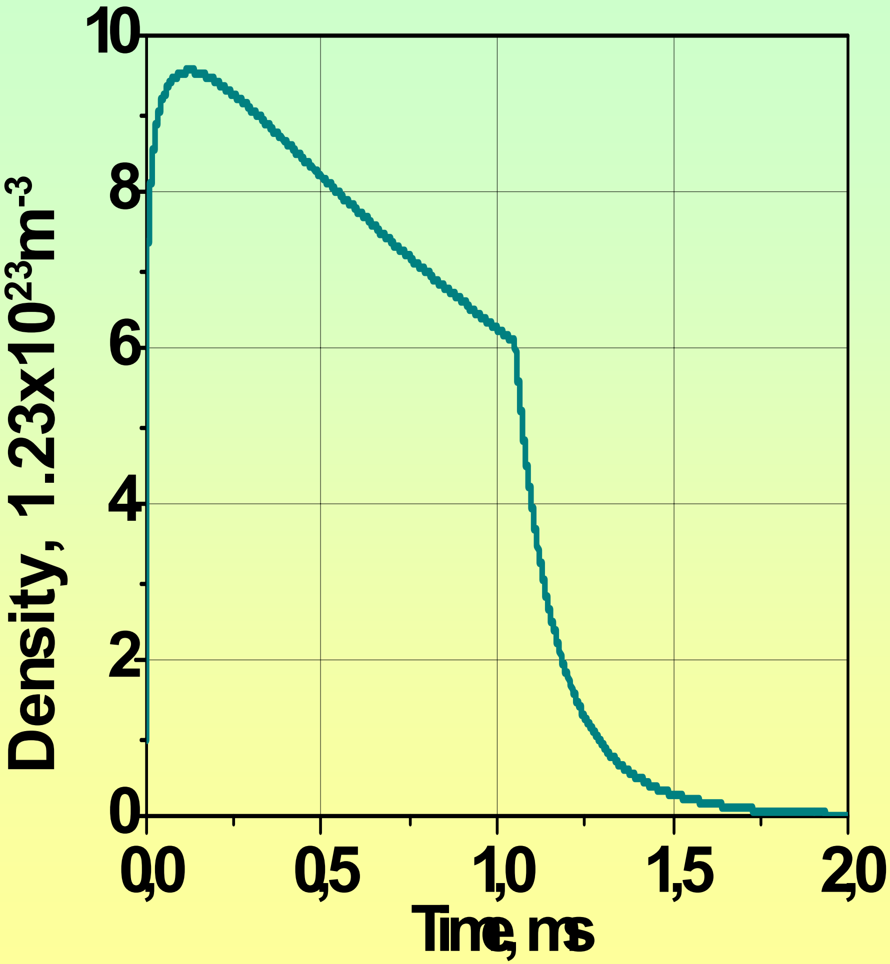


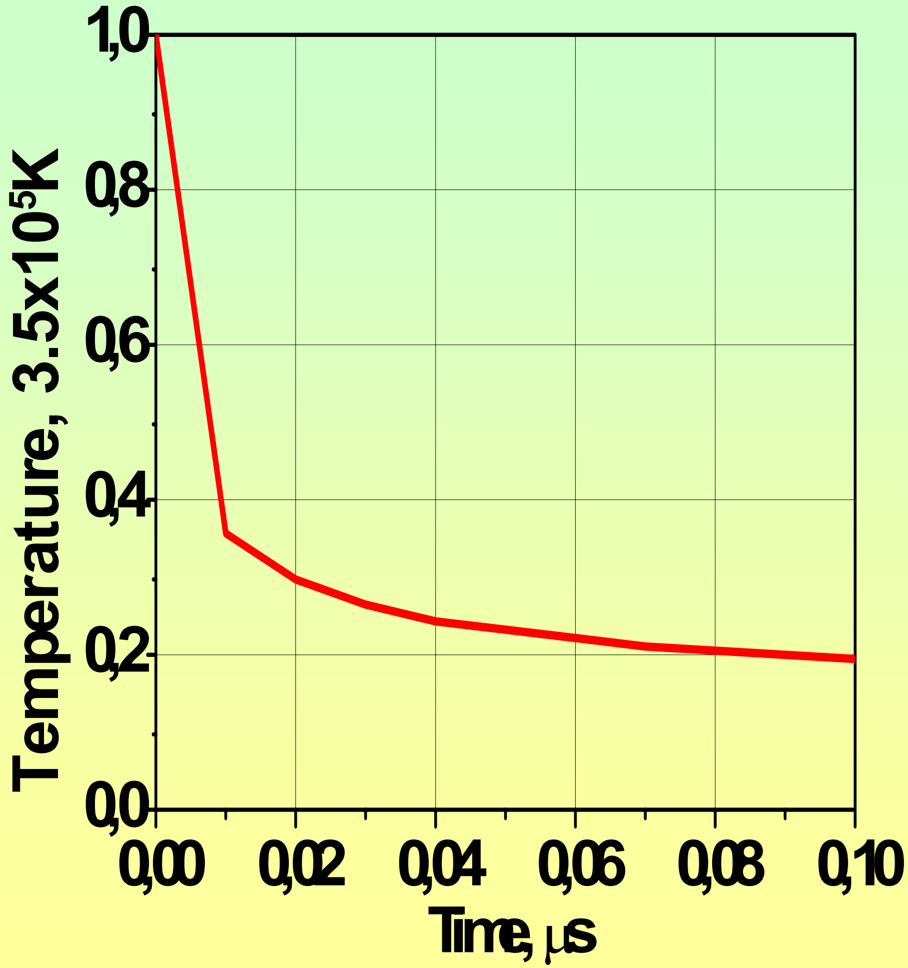
Vaporization rate of liquid film on the first wall



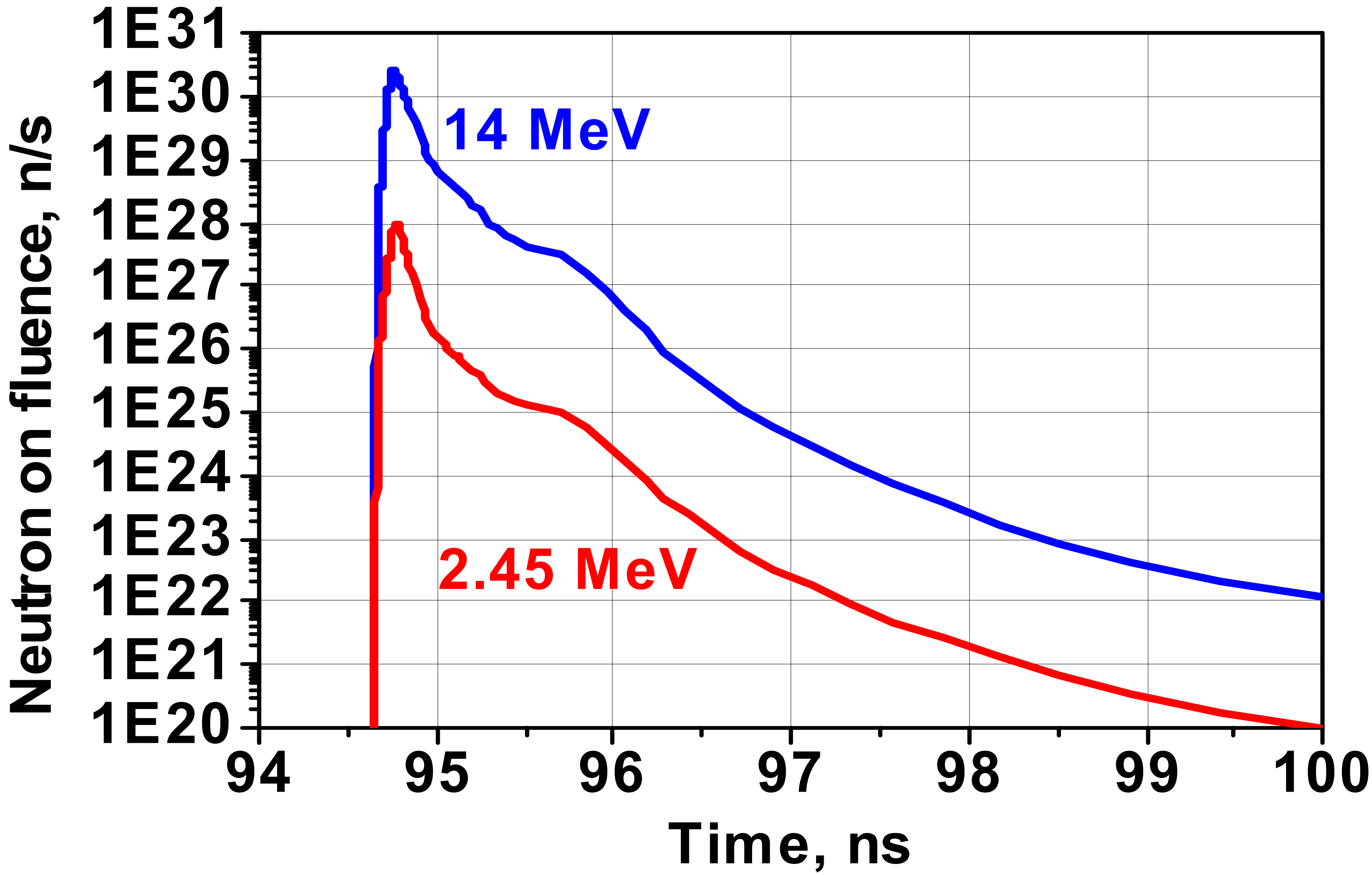
Temporal evolution of the evaporated mass

Evaporation-condensation dynamics

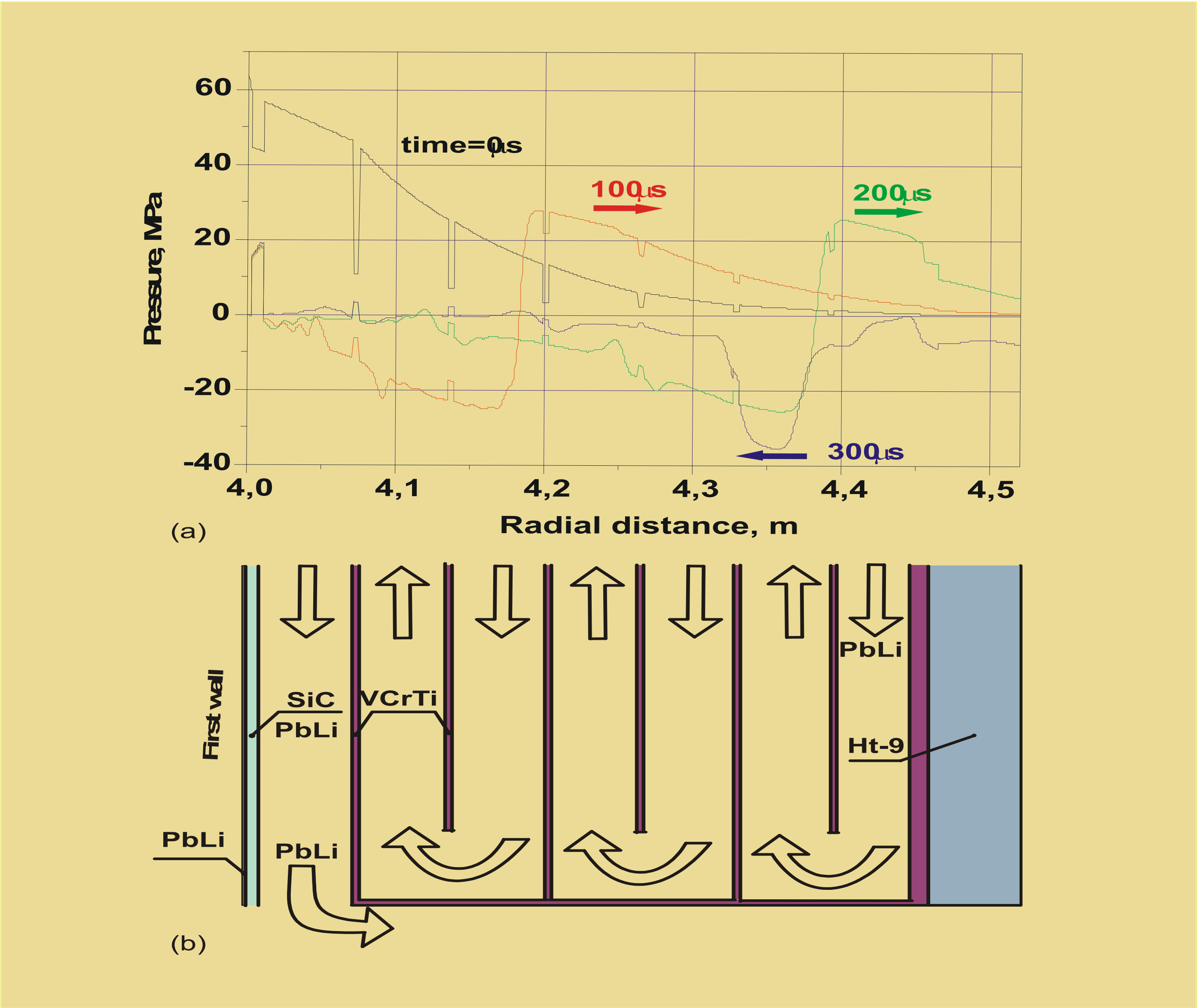




FIHIF target neutron pulse



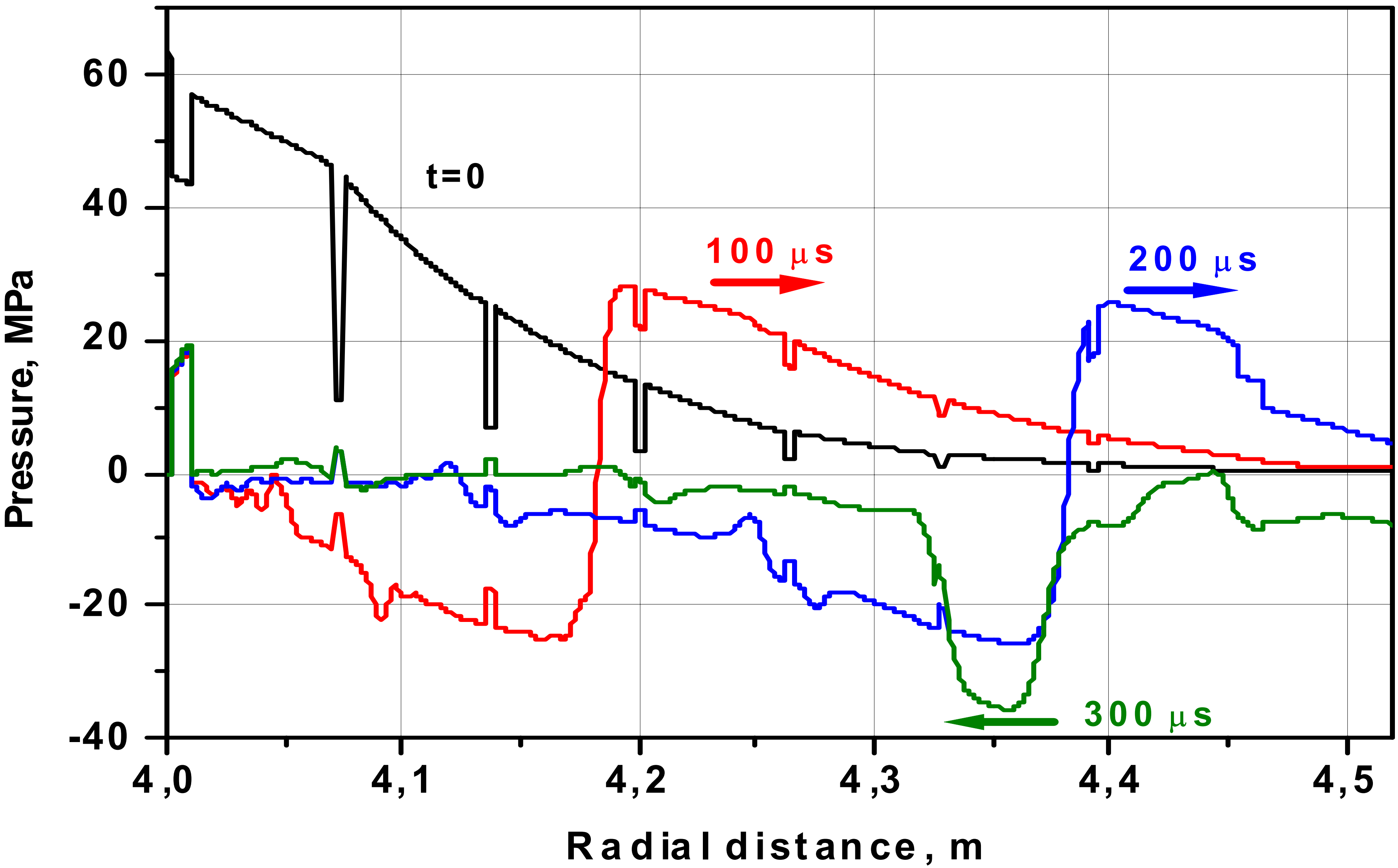
Pressure distribution in FIHIF blanket at different times



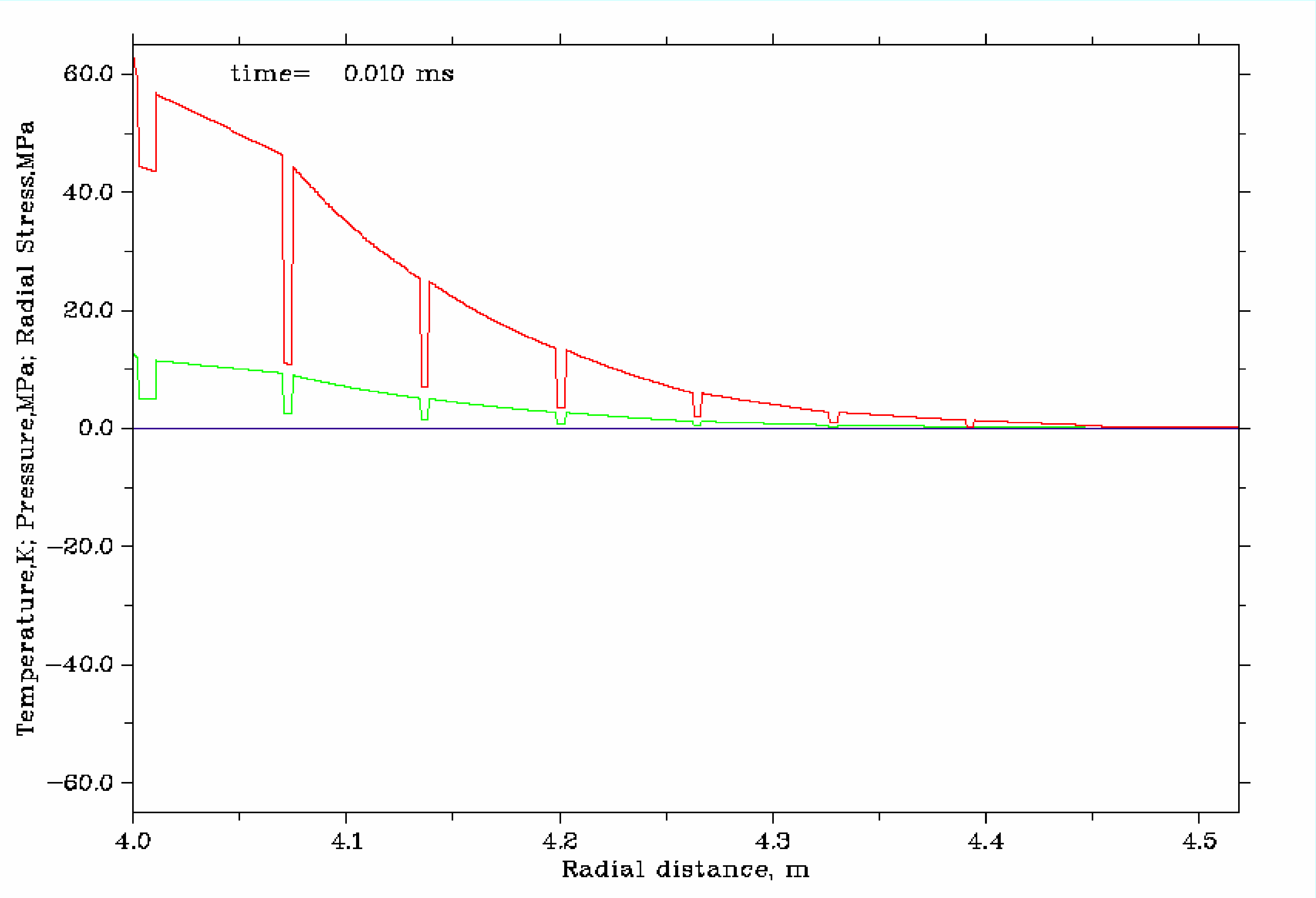
FIHIF Blanket Structure and Neutron Energy Deposition

Material of blanket zones	R, cm	ΔR, cm	ρ, g/cm^3	M, 10^3 kg	Q/V, MJ/m^3	Q, MJ	ΔT, K
1. PbLi	400,0	400	$3{,}4\cdot10^{-10}$	10^{-7}	$5\cdot10^{-9}$	$1{,}3\cdot10^{-6}$	66,6
2. PbLi	400,0	0,2	9,0	3,3	23,8	8,8	13,0
3. SiC/PbLi	400,2	0,8	5,7	9,3	20,7	33,7	5,1
4. PbLi	401,0	6,0	9,0	110,8	18,5	237,7	11,1
5. V/4Cr/4Ti	407,0	0,4	5,9	4,9	8,9	7,4	2,8
6. PbLi	407,4	6,0	9,0	113,6	12,2	164,0	7,3
7. V/4Cr/4Ti	413,4	0,4	5,9	5,0	6,1	5,2	1,7
8. PbLi	413,8	6,0	9,0	116,1	6,5	88,8	4,0
9. V/4Cr/4Ti	419,8	0,4	5,9	5,1	2,8	2,4	0,9
10. PbLi	420,2	6,0	9,0	119,7	4,1	55,5	2,0
11. V/4Cr/4Ti	426,2	0,4	5,9	5,2	1,1	0,9	0,5
12. PbLi	426,6	6,0	9,0	123,7	1,5	23,6	0,9
13. V/4Cr/4Ti	432,6	0,4	5,9	5,4	0,8	0,7	0,2
14. PbLi	433,0	6,0	9,0	128,8	0,9	13,3	0,4
15. V/4Cr/4Ti	439,0	0,4	5,9	5,6	0,2	0,2	0,1
16. PbLi	439,4	6,0	9,0	133,0	0,3	4,4	0,2
17. V/4Cr/4Ti	445,4	1,0	5,9	14,5	0,1	0,2	0,05
18. HT-9	446,4	6,0	7,9	112,2	0,07	1,0	0,01
19. Concrete	452,0	400	2,0	-	-	Total: 647,8	

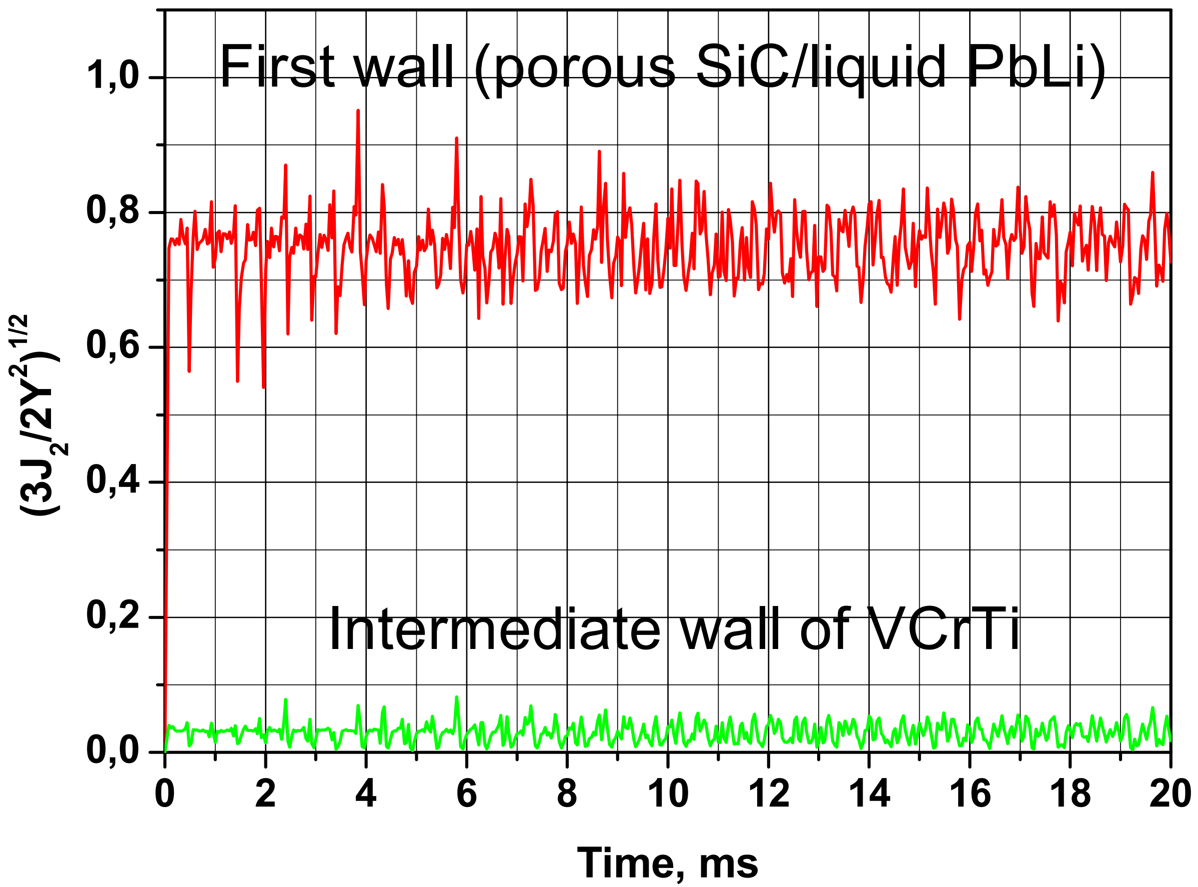
Pressure distribution in FIHIF blanket at different times



Pressure, Temperature and Radial stress temporal evolution in FIHIF blanket

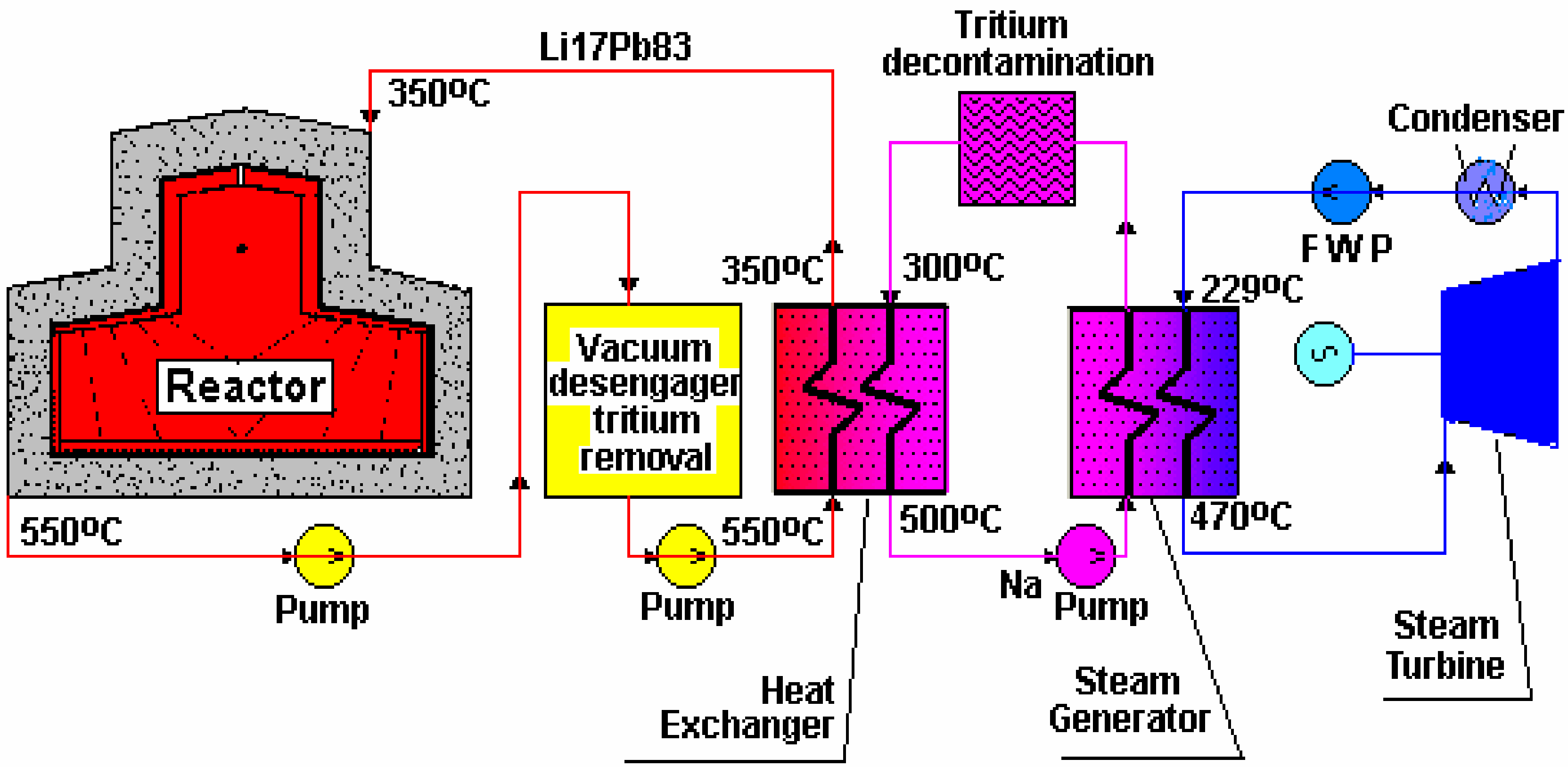


Determination of material state in blanket design under neutron pulse impact



Temporal variation of equivalent stress $\sigma_{eq} = (3\mathbf{J}_2/2)^{1/2}$ **normalized by yield stress Y (Y= 35 MPa for SiC/PbLi and 280 MPa for V-Cr-Ti).**

The von Mises criterion $\sigma_{eq}/\mathbf{Y} \leq 1$ **determines elastic/plastic material behaviour.**



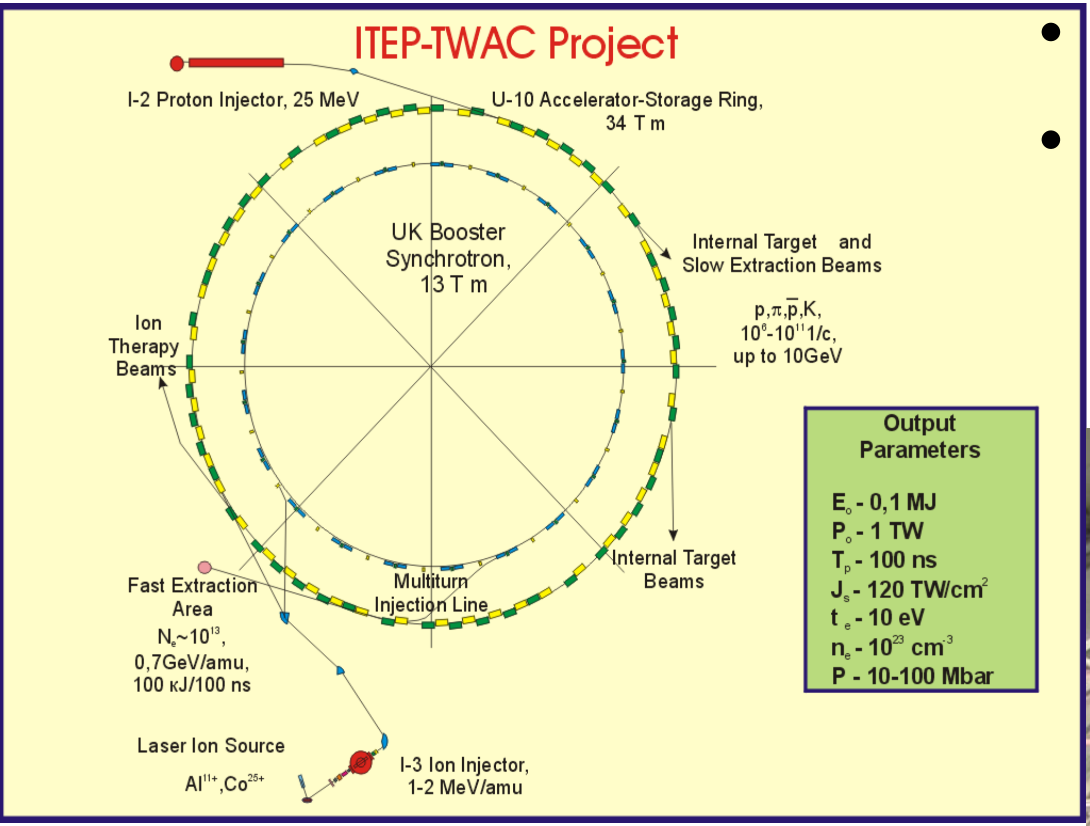
Thermal schematic of FIHIF power plant

- The reactor chamber with a wetted first wall has a minimum number of ports for beam injection.
- A massive target significantly softens the X-ray pulse resulting from the microexplosion.
- A two-chamber reactor vessel mitigates the condensation problem and partly reduces the vapor pressure loading.
- Three loops in the energy conversion system make it easier to optimize the plant efficiency and to develop the thermal equipment.

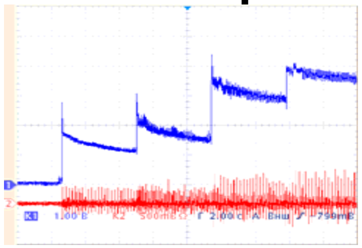
ENERGY CONVERSION SYSTEM

Primary coolant loop $Li_{17}Pb_{83}$	
Max./min. temperature (°C)	550/350
Mass flow rate (ton/s)	13.1
Pump power (MW)	11.6
Intermediate coolant loop Na	
Max./min. temperature (°C)	500/300
Mass flow rate (ton/s)	6.40
Pump power (MW)	3.77
Steam cycle	
Steam parameters (MPa/°C/°C)	18/470/470
Net efficiency	0.417
Power plant parameters	
Net power (per 1 chamber) (MW)	670
Net efficiency	0.373

ITEP-TWAC project in progress



- $>10^{10}$ C6+ accumulated
- accelerated up to 4 GeV/u

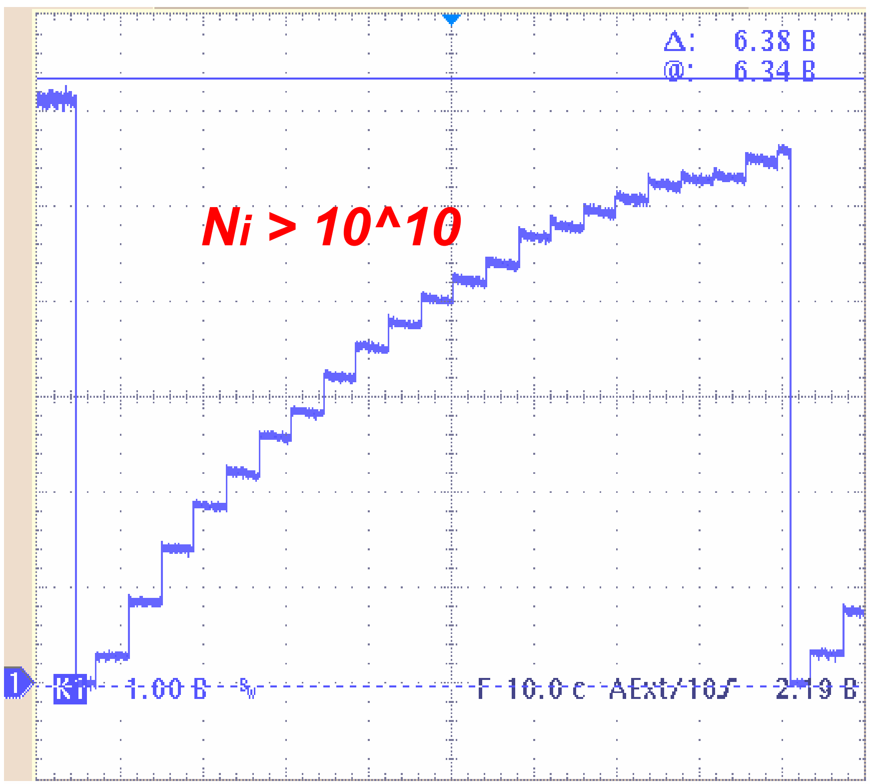


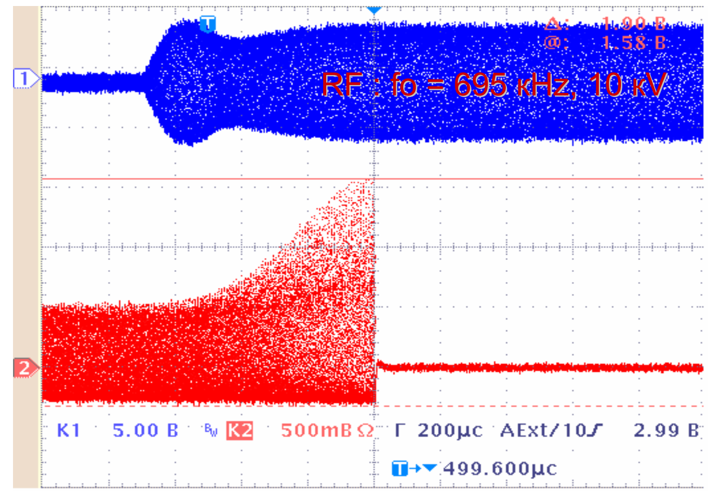
B.Sharkov ITEP

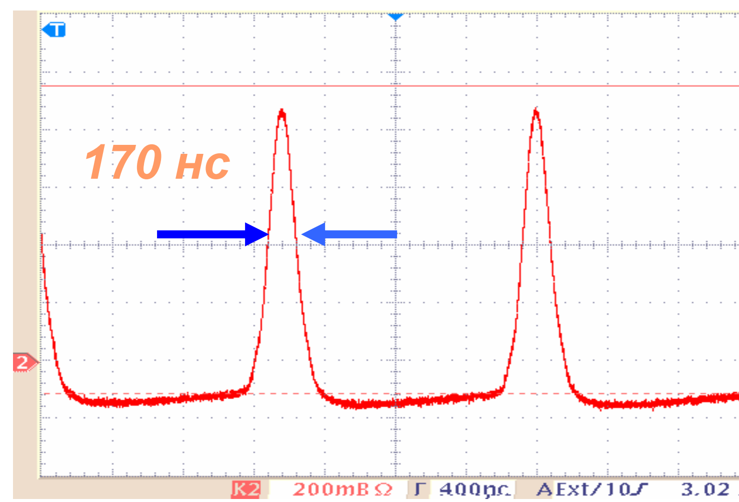
Non-Liouvillian stacking process

ВЧ группировка пучка

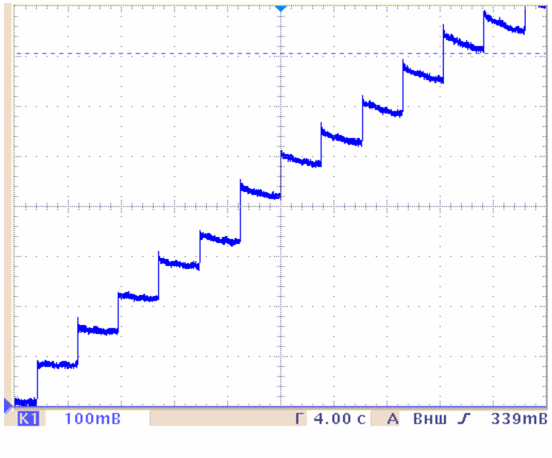
Процесс накопления ядер С 6+

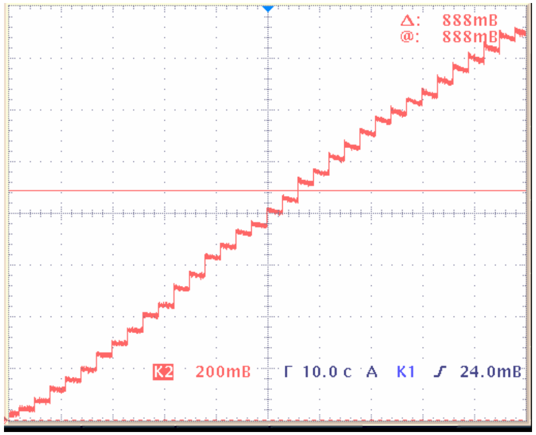




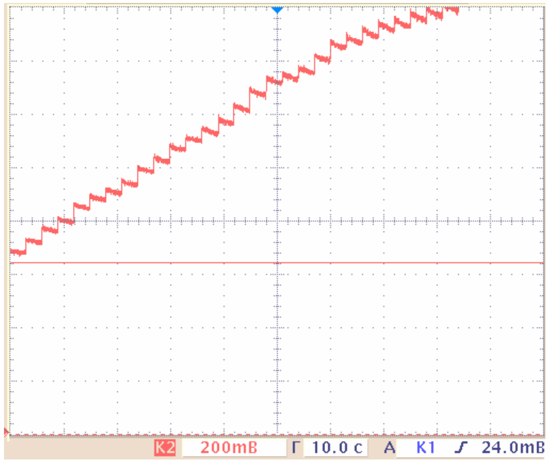


Ion accumulation C^{6+} in U-10 (213 MeV/u)

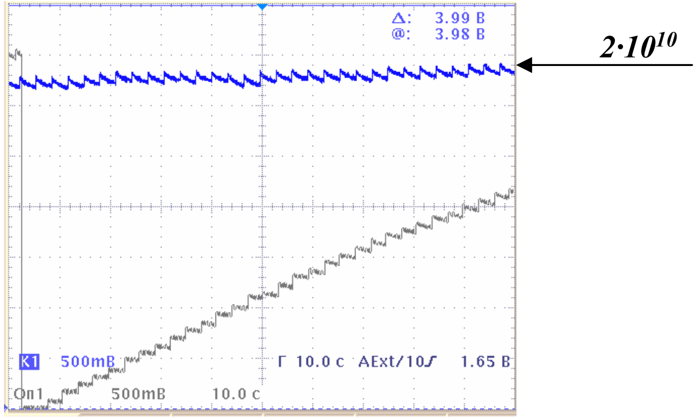




Линейный рост интенсивности ~ 100 с (> 30 циклов)



Снижение темпа накопление



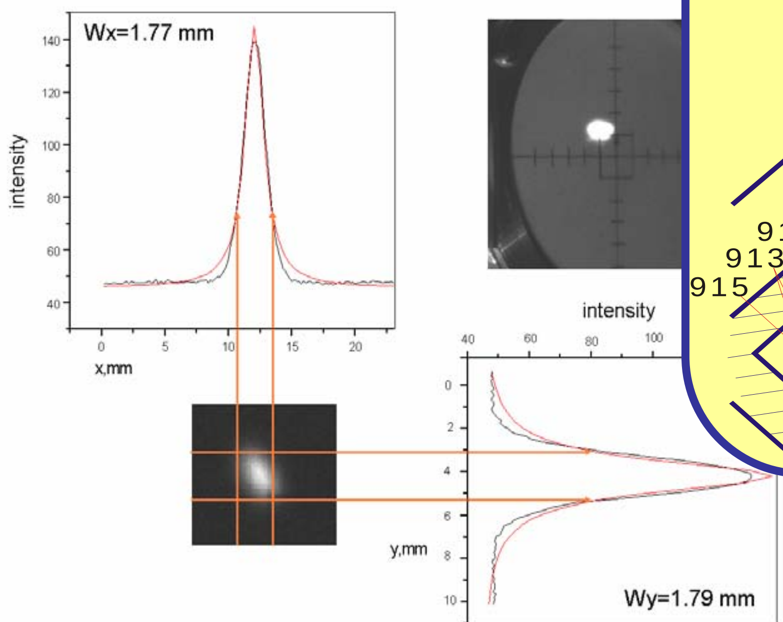
Максимальная интенсивность

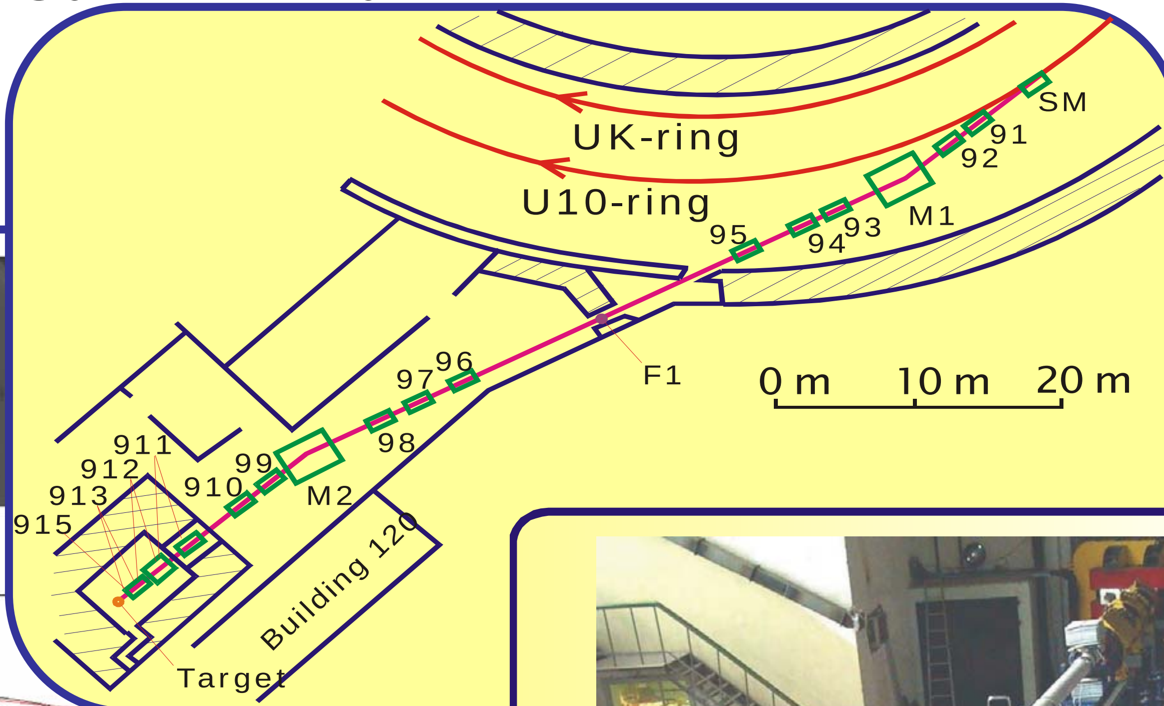
Accelerator Technology Issues

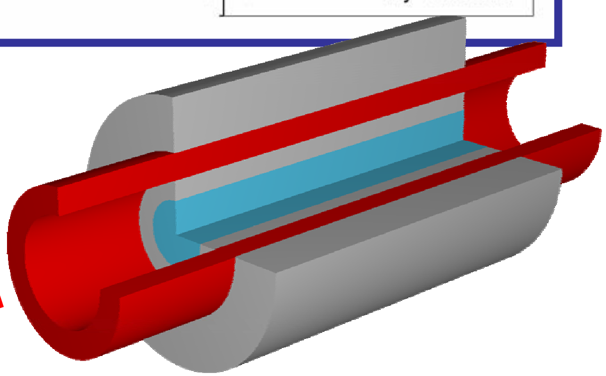
- High current injection,
- Accumulation / stacking
- Bunch compression,
- IBS and vacuum instability
- Fast extraction
- Beam transport and focusing
- Generation of hollow beams –“wobbler”

High energy density experimental area

ITEP-TWAC



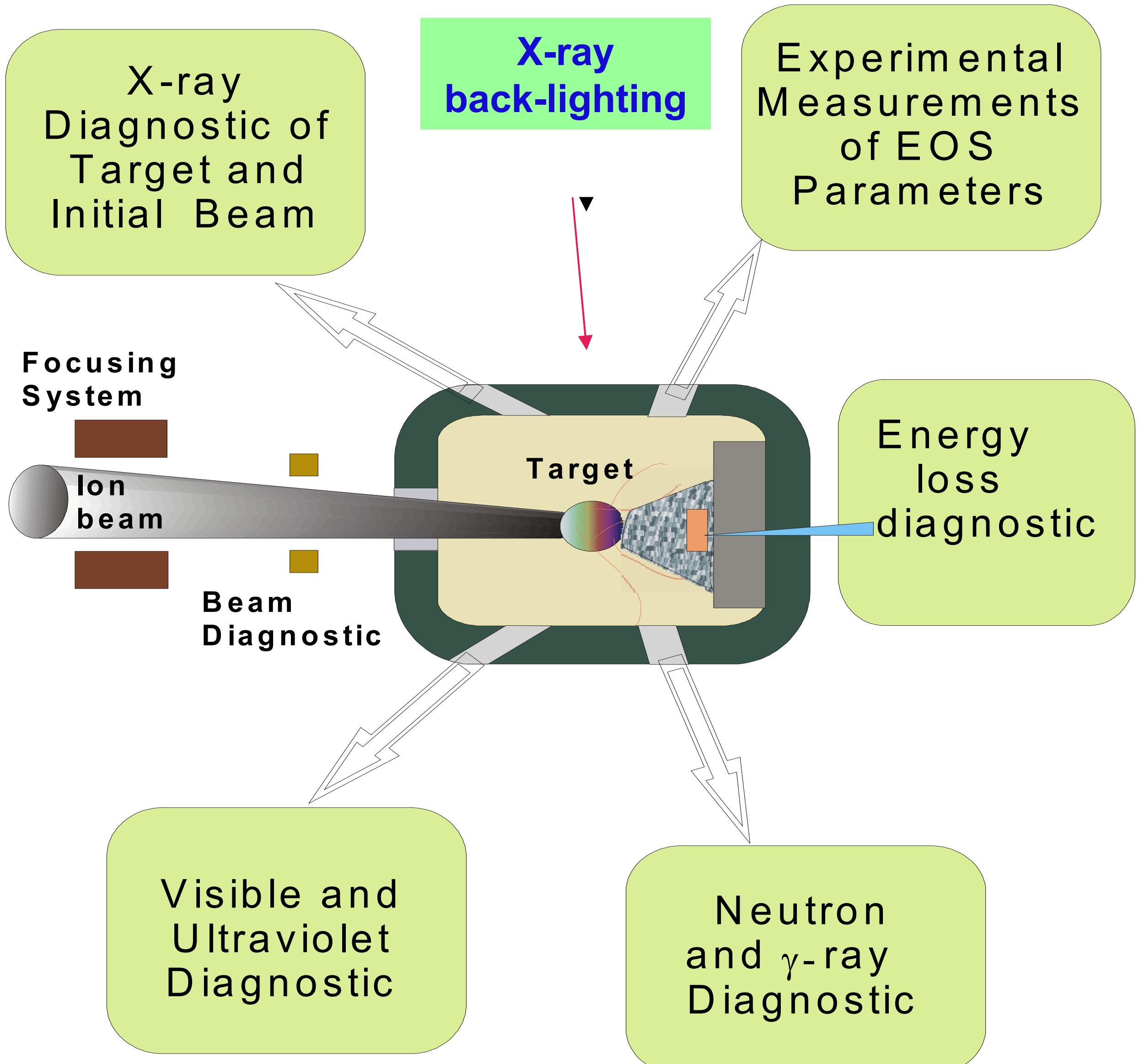




ion beam

Cylindrical implosion experiment 300 MHz wobbler

Development of Diagnostic Methods



CONCLUSIONS :

- a power plant concept for fast ignition HIF is formulated, which is consistent with the newly proposed driver–target–chamber design.

- ITEP-TWAC facility is suitable for accelerator technology developments:

- **Positive features :**

  - **A massive target significantly softens the X-ray pulse resulting from the microexplosion.**
  - **The reactor chamber with a wetted first wall has a minimum number of ports for beam injection.**
  - **A two-chamber reactor vessel mitigates the condensation problem and partly reduces the vapor pressure loading.**
  - **Three loops in the energy conversion system make it easier to optimize the plant efficiency and to develop the thermal equipment.**

- **Problems of concern**:

driver length,

target positioning in flight,

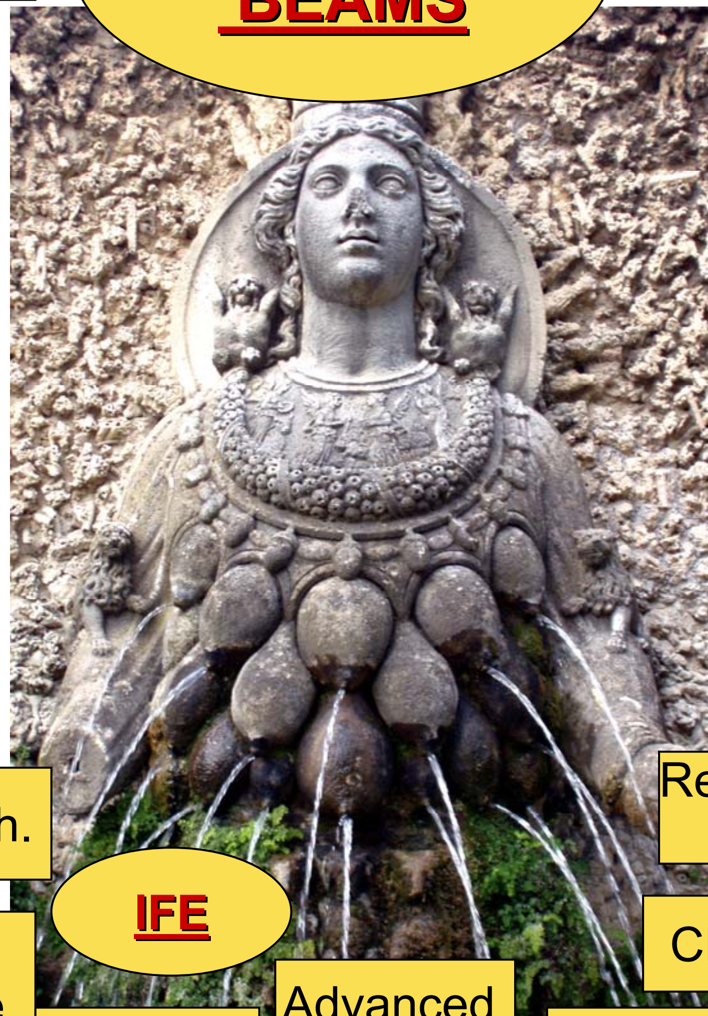
the of vapor fog problem in the chamber,

pressure-stress pulsations in the blanket.

Experiments in frame of IAEA CRP

Post Scriptum

HEAVY ION BEAMS



HED Ph.

Rel. nuclear Ph.

IFE

Material science

CBM

Medicine

Advanced diagnostics

Accelerator Physics

antique
Goddess of Fertility

Roma-Tivoli 2004