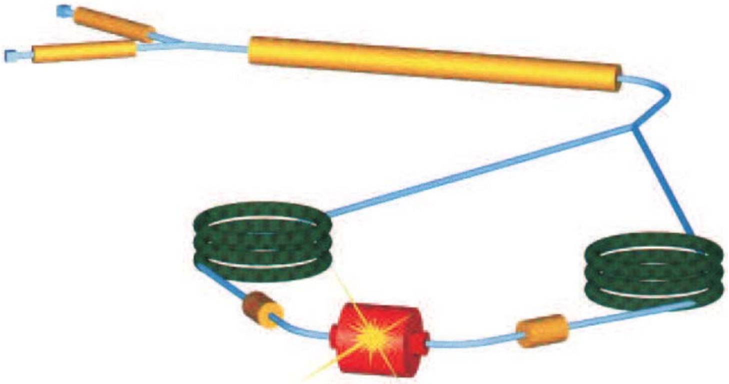
Boris Sharkov, (ITEP-Moscow), :

HIF E – activities in Europe and in Russia

Outline

1. HI IFE (introduction)
2. RU IFE concept and respective activities
3. International FAIR
4. HED Physics with Intense HIB at FAIR
   - basic experiments
   - results of numerical simulations
   - relevance to HI IFE
   - requirements for performance of experimental campaign
   - specific diagnostic methods
   - current experimental activities towards FAIR
5. Outlook

Basic motivations for HI IFE

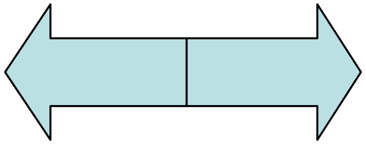


- Intrinsic efficiency $\eta G>10$
- High repetition rate ~1 - 10 Hz
- Reliability / durability to last billions of shots
- Final focusing magnets tolerant to neutrons and target debris
- Compatibility of beams to propagate through the poor vacuum of fusion chamber
- Effective beam-target coupling
- Mature driver technology

A.W.Mashke 1979

Consideration of HIFE leads to special driver - and - target combinations

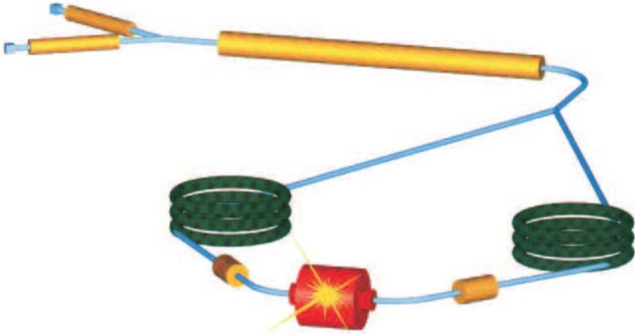
Drivers
determined by target requirements



Targets
tailored specifically for accelerators

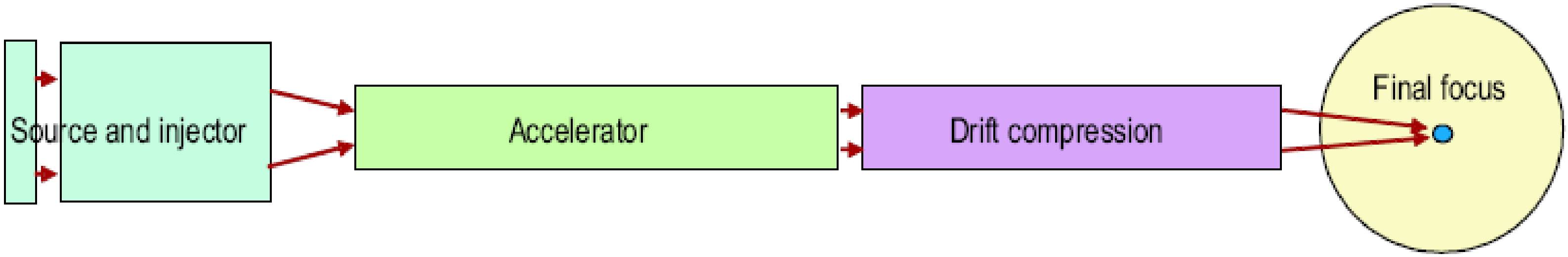
Challenging aspect : short pulse length < 10ns – i.e. 10E4 compression
small focal spot ~ 1-2 mm
@ large distance ~ 5 m

Two complimentary accelerator scenarios as potential IFE drivers :



1. **The RF linac & storage ring approach**
   – *HIBALL, HIBALL-II (R.Bock 1984, GSI Darmstadt)*
   - *ITEP-Moscow (Koshkarev, V.Imshennik, P.Zenkevich -1987)*

2. **The induction linear accelerator concept** – *US (LBNL, LLNL, Princeton)*

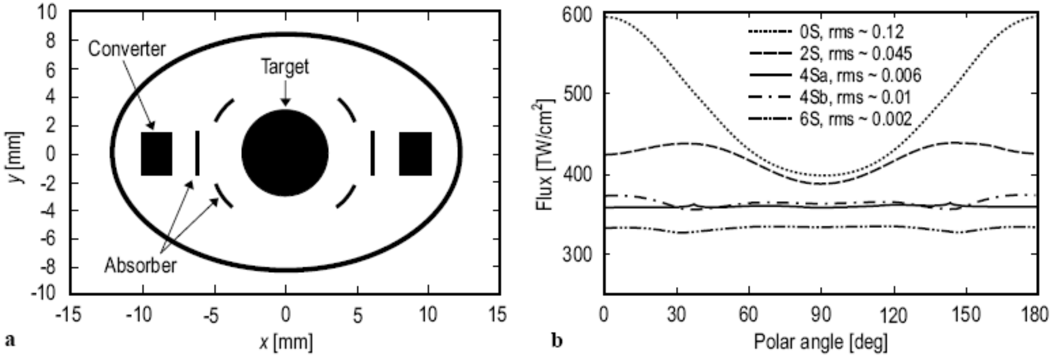


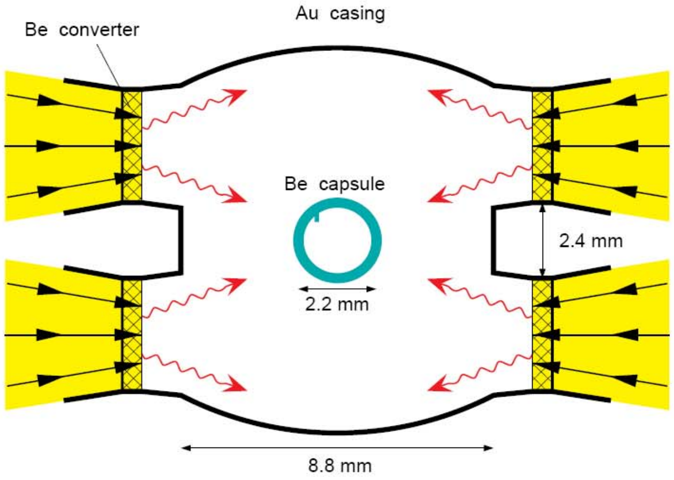
Heavy ion targets with hydrodynamic ignition

Indirect drive option is considered to be feasible for heavy ion targets in the hydrodynamic ignition mode.

The fusion capsule can be similar to those of laser-driven hohlraums

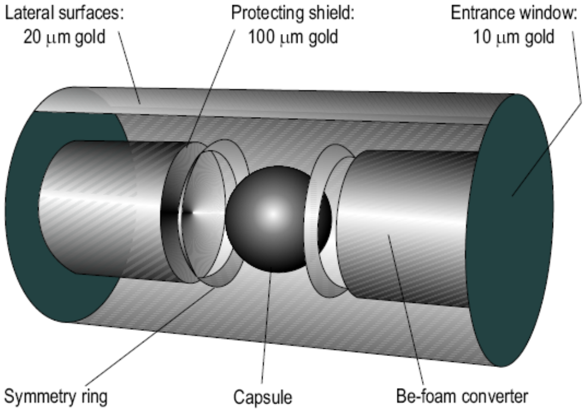
J.Maruhn 1997

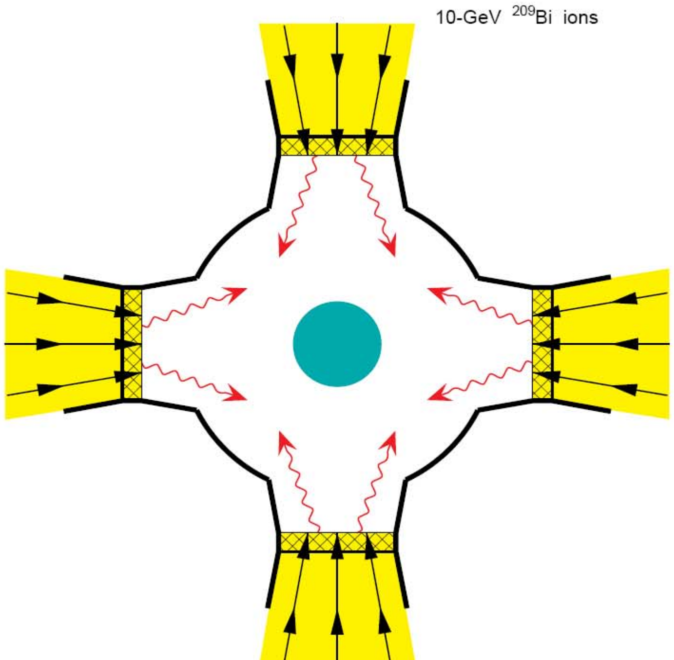




R.Ramis 1998

2 converters
3 MJ/6 ns





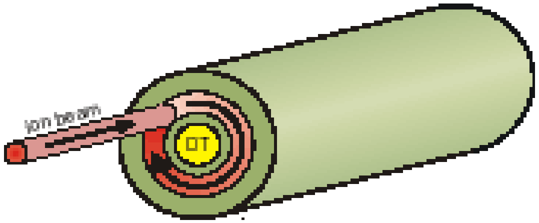
"Russian" target
M.Basko, V.Vatulin 1997
8 (10) converters 1.7 mm each,
Energy deposiion 4.5 MJ/6ns

(IAEA-2004) Russian studies of fast ignition using 100 GeV heavy-ion synchrotrons:

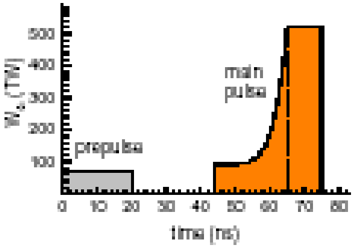
Bi ions with energies 100-200 GeV have relatively long ranges of ~7-18 g/cm2 in cold heavy metals. Such ranges can be naturally accommodated in cylindrical targets with axial beam propagation.

Fast ignition with heavy ions: target performance

Direct drive cylindrical target: compression stage

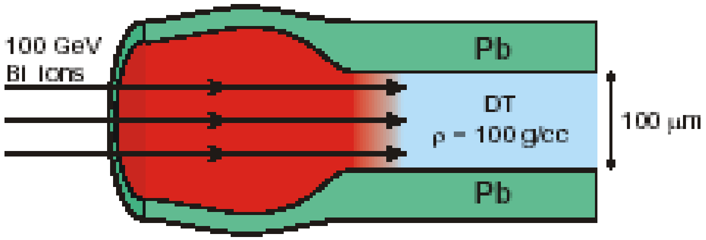


Compression pulse:



- Target compression is accomplished by a separate beam of ions with the same energy of E_i = 0.5 GeV/u.
- Azimuthal symmetry is ensured by fast beam rotation around the target axis (~10 revolutions per main pulse).
- Relative inefficiency of cylindrical implosion is partly compensated for by direct drive.

Ignition and burn propagation



Ignition pulse:

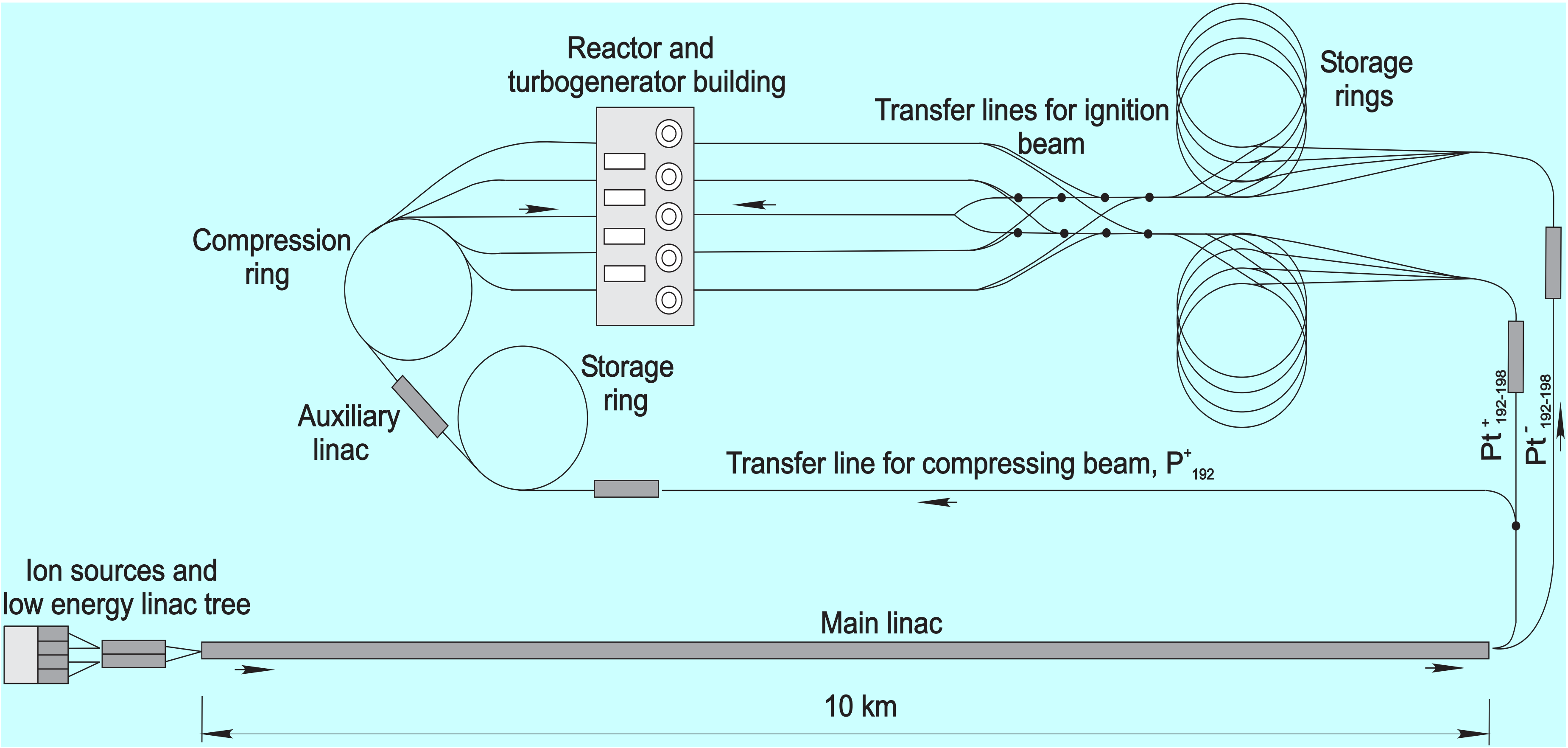
beam energy: E_{igb} = 400 kJ
pulse duration: t_{igp} = 200 ps
beam power: W_{igb} = 2 PW
focal radius: r_{foc} = 50 μm
irradiation intensity: $I_{igb} = 2.5\times10^{19}$ W/cm²

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.

An energy gain of G ≈ 100 can be expected.

HI IFE Concept
Ground plan for HIF power plant

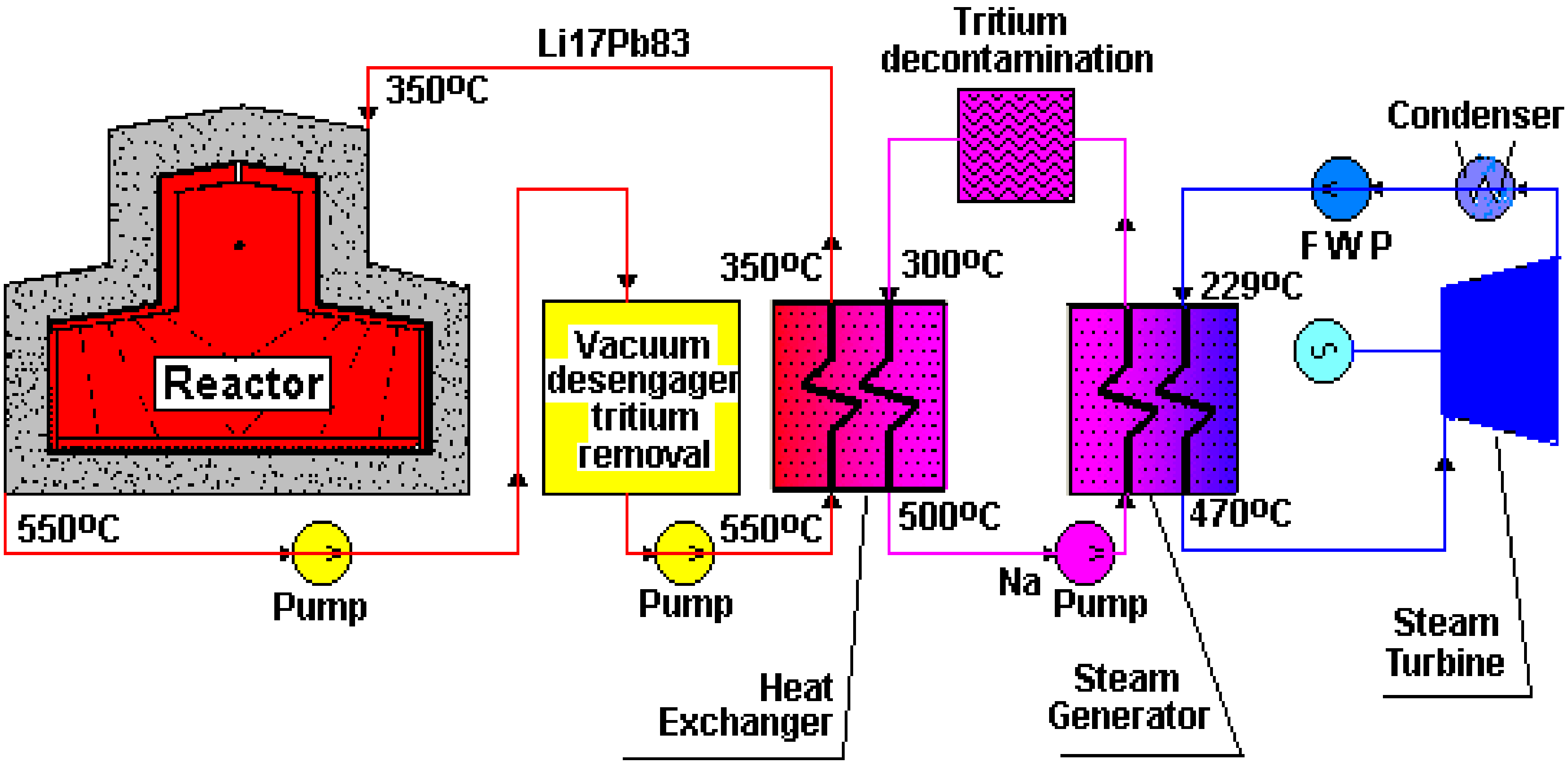
B.Y. Sharkov BY, N.N. Alexeev, M.M. Basko et al., Nuclear Fusion 45(2005) S291-S297.



HIGH POWER HEAVY ION DRIVER

Ions		$\mathrm{Pt}^{+,-}_{192,194,196,198}$
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**

HIF Power Plant 1 GW + accelerator 100 GeV Pt+



Thermal schematic of FIHIF power plant

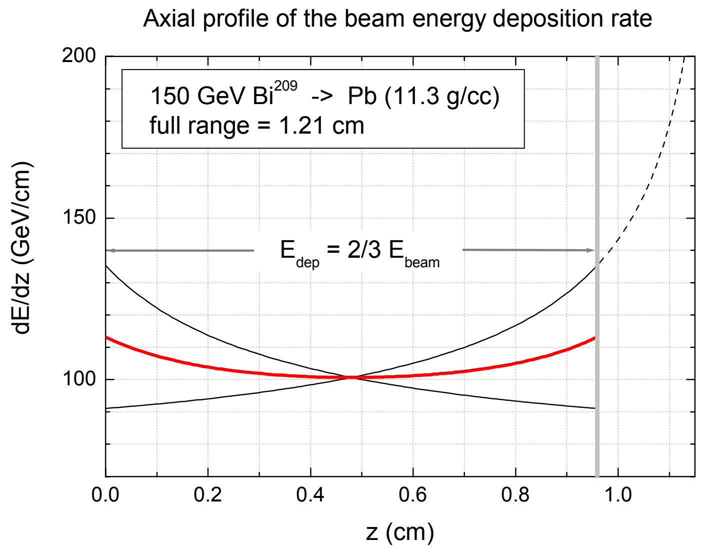
- The reactor chamber with a wetted first wall has a minimum number of ports for beam injection.
- A massive target significantly softens the X-ray pulse resulting from the microexplosion.
- A two-chamber reactor vessel mitigates the condensation problem and partly reduces the vapor pressure loading.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

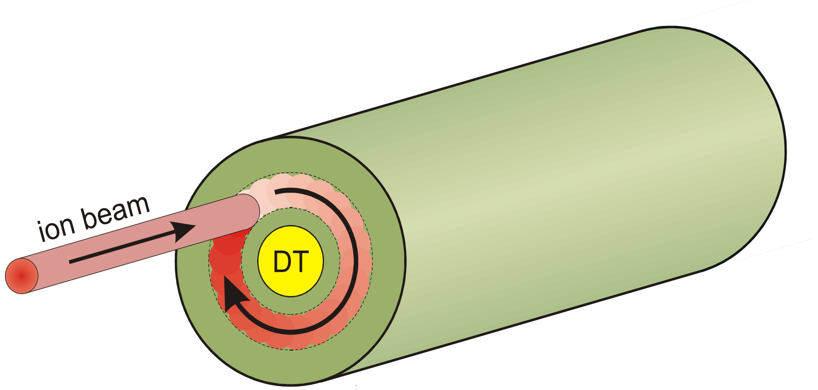
Principal motivation for cylindrical targets

M.Basko et al., HIF 2002

Near-relativistic heavy ions with energies ≥ 0.5 GeV/U 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.


Axial profile of the beam energy deposition rate



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

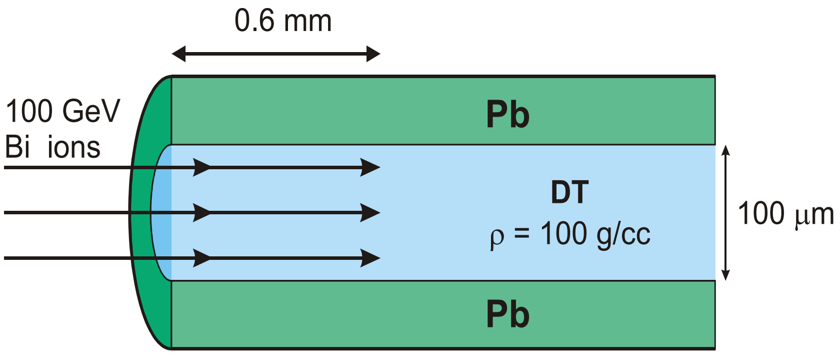
Fast ignition with heavy ions: assembled configuration

M.Basko et al., HIF 2002

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

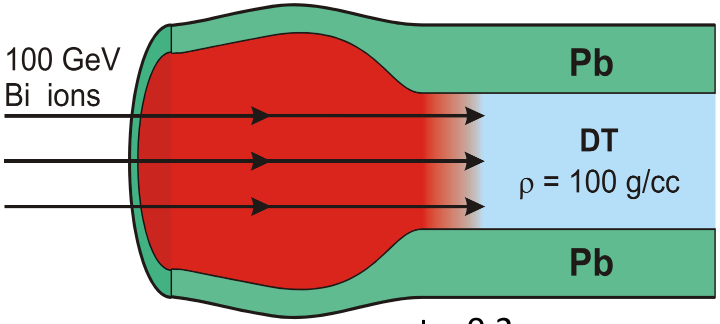
The ion pulse duration of 200 ps is still about a factor 4 longer than the envisioned laser ignitor pulse. For compensation, it is proposed to use a massive tamper of heavy metal around the compressed fuel:

Assembled configuration



t = 0

Ignition and burn propagation



t = 0.2 ns

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!

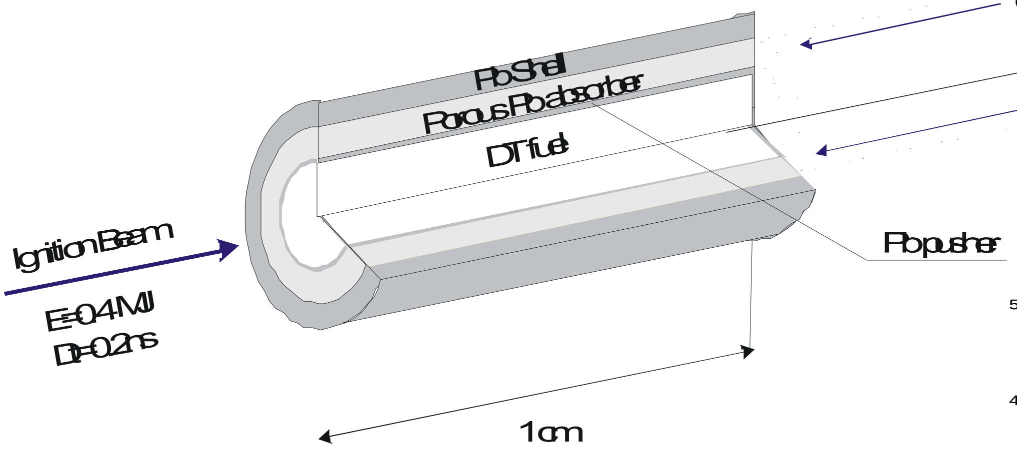
CYLINDRICAL TARGET

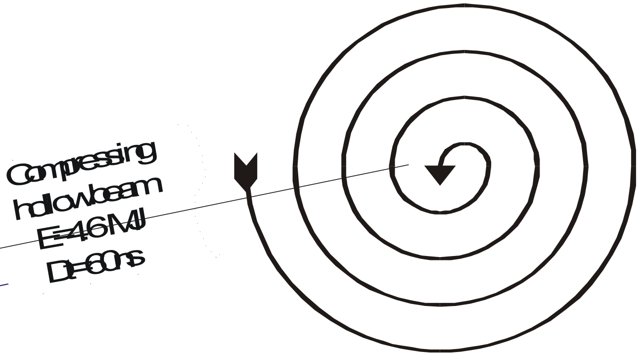
DT fuel mass	(g)	0.006
Total mass	(g)	4.44
Length	(mm)	8.0
ρR parameter	(g/cm^2)	0.5
Burn fraction		0.39
Gain		~120
Fusion energy	(MJ)	750

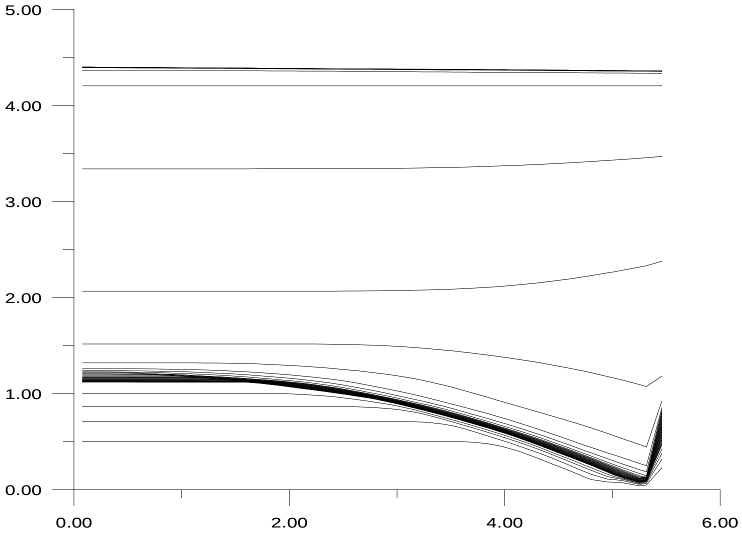
Energy release partition

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

Target irradiation by rotating ion beam







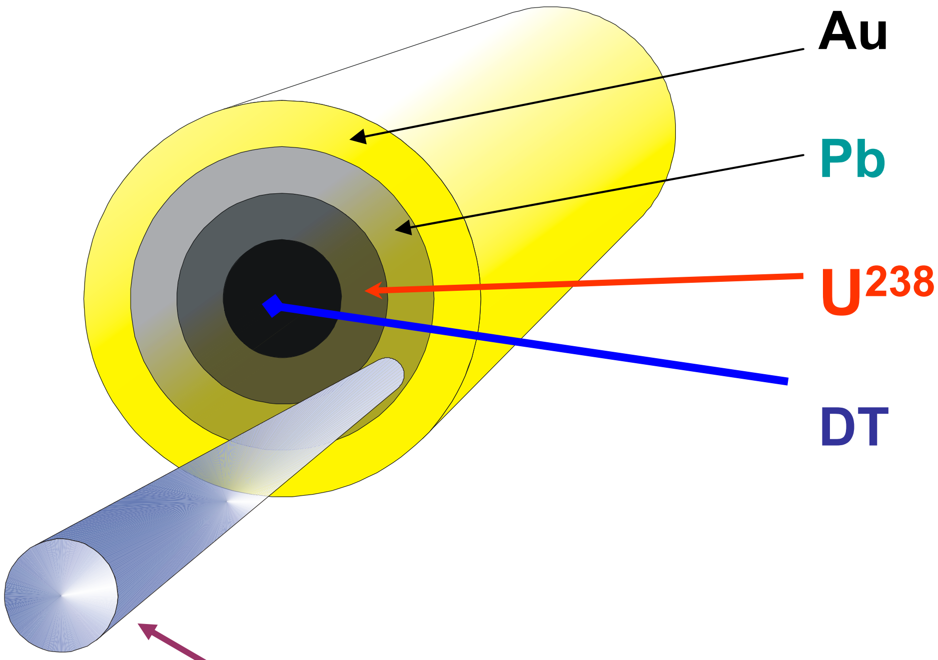
$\rho \geq 100$ g/cm3 ,

$\rho R \geq 0.5$ g/cm2

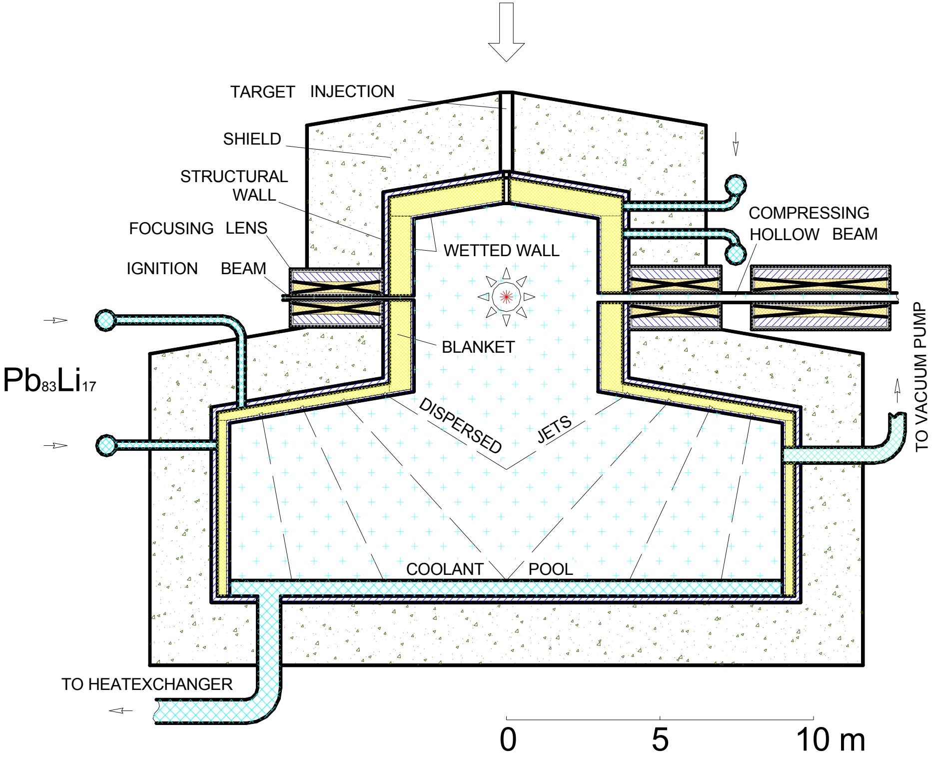
E = 6.3 MJ (*instead 7.1 MJ*)

Fusion – Fission - Fusion

- **10 MJ Heavy Ion Driver -> directly driven cylindrical target**
- **Cylindrical implosion of DT fuel -> DT-neutrons generation**
- **DT-neutrons -> fission of U_{238} pusher material**
- **Better confinement, additional compression of DT**
- **Burn fraction & energy gain enhancement**



10 MJ ion beam
Rotation ~1 GHz



REACTOR CHAMBER FOR FAST IGNITION HEAVY ION FUSION

REACTOR CHAMBER FOR HIF POWER PLANT: wetted first wall design

Orlov Yu.N., Basko M.M., Churazov M.D. et al., Nuclear Fusion ***45 (6) ,*** *531 – 536, (2005).*

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

S.A.Medin[1], M.M.Basko[2], Yu.N.Orlov[3]

[1]Joint Institute for High Temperatures
[2]Institute for Theoretical and Experimental Physics
[3]Keldysh Institute for Applied Mathematics

Response of the first wetted wall of an IFE reactor to the energy release from a direct-drive DT capsule

GOAL OF RESEARCH

Hydrodynamics of IFE reactor chamber induced by the capsule explosion:

(a) DT capsule implosion and burn,

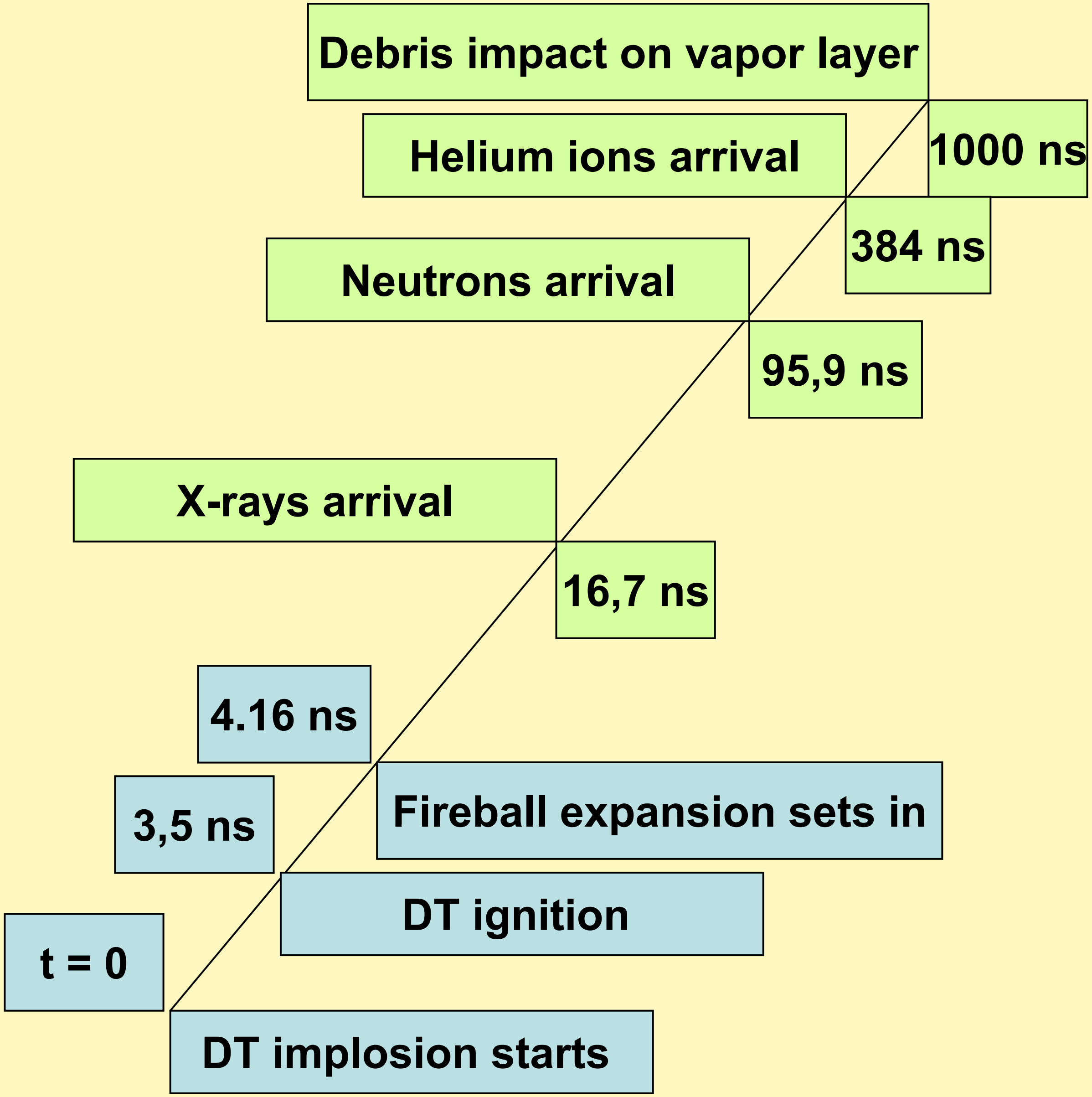
(b) X-ray and charged particles stopping,

(c) Radiation transport in the chamber,

(d) Liquid film ablation,

(e) Neutron deposition in blanket.

COMPUTED EVENTS IN REACTOR CHAMBER



Debris impact on vapor layer

1000 ns

Helium ions arrival

384 ns

Neutrons arrival

95,9 ns

X-rays arrival

16,7 ns

4.16 ns

Fireball expansion sets in

3,5 ns

DT ignition

t = 0

DT implosion starts

Computation of the liquid film response to X-ray, neutron and helium ions heating

Physics of the RAMPHY radiation-hydrodynamics code

* 1D-2T Lagrangian (spherical, cylindrical, planar)

* Plasma thermal conduction and viscosity

* Radiation diffusion and relaxation between plasma and radiation temperatures

* Mean Rosseland and Planckian opacities

* Neutron diffusion and heating (MCNP)

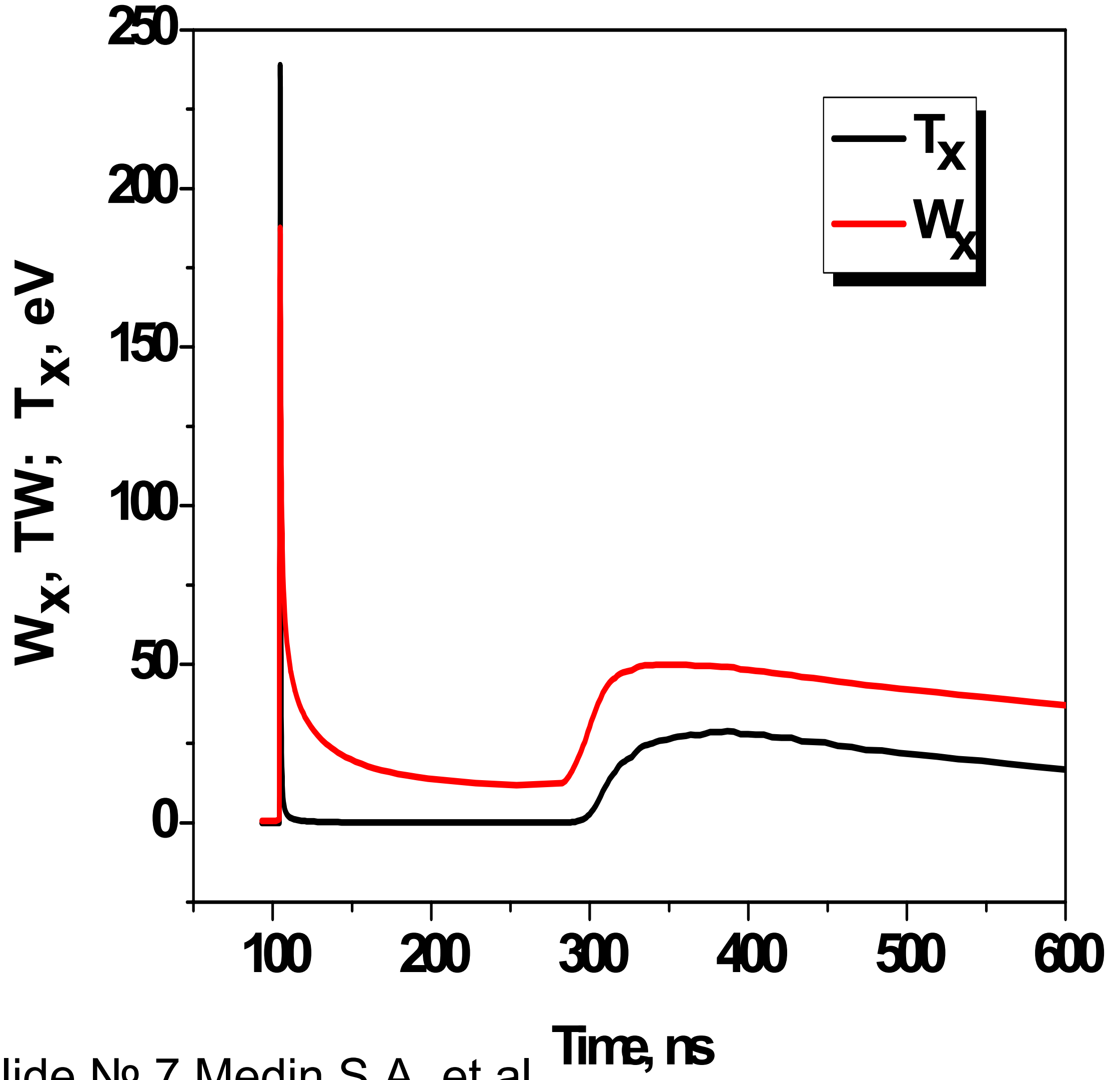
* Condensed matter strength and spallation

* Wide-range equation of state, phase transitions and ionization

* Applied energy sources: X-ray and fast ions volumetric energy deposition

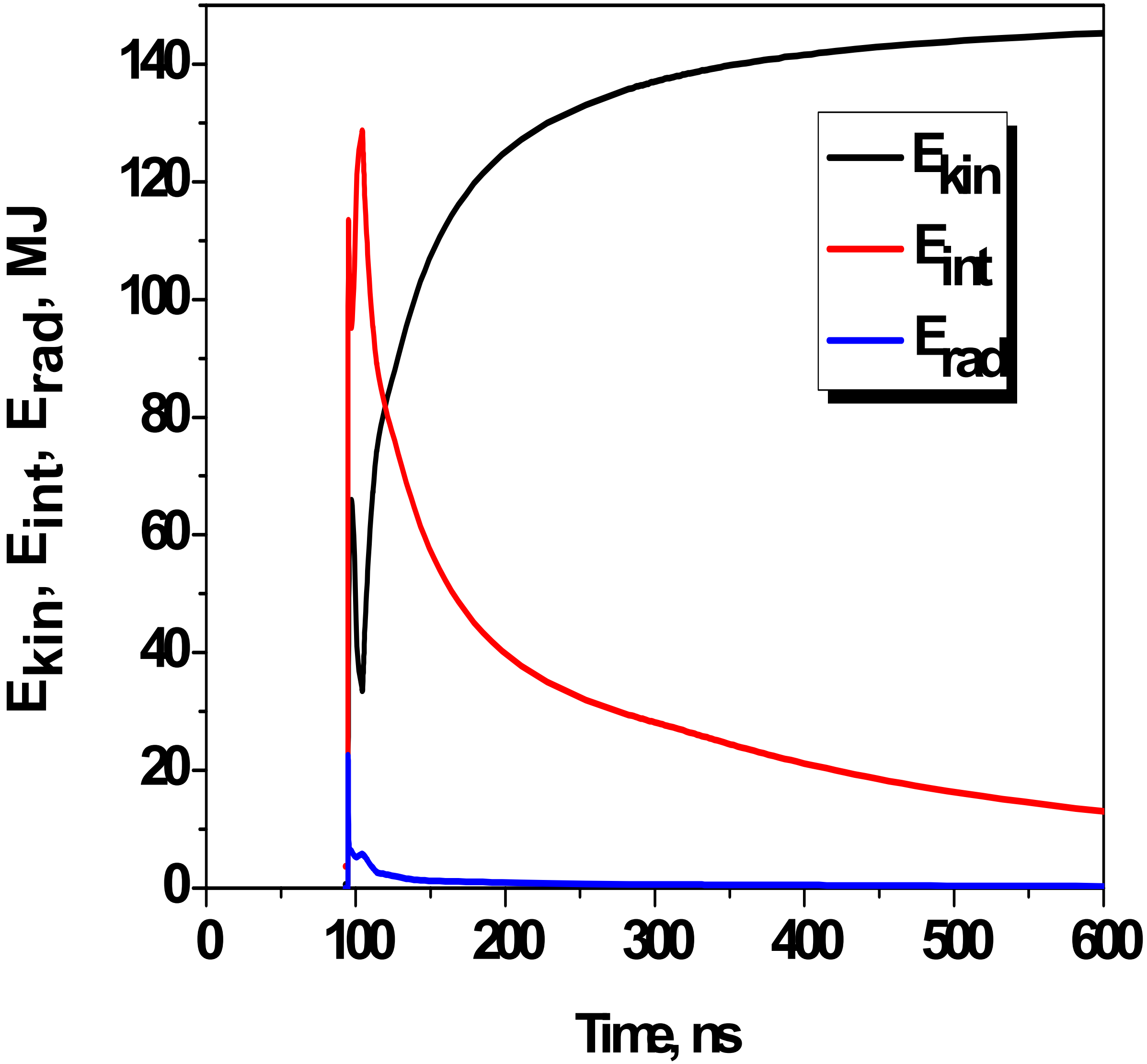
X-ray, N and Ion Debris Impact on the First Wetted Wall of IFE Reactor

X-ray emission from the HIF cylindrical target.



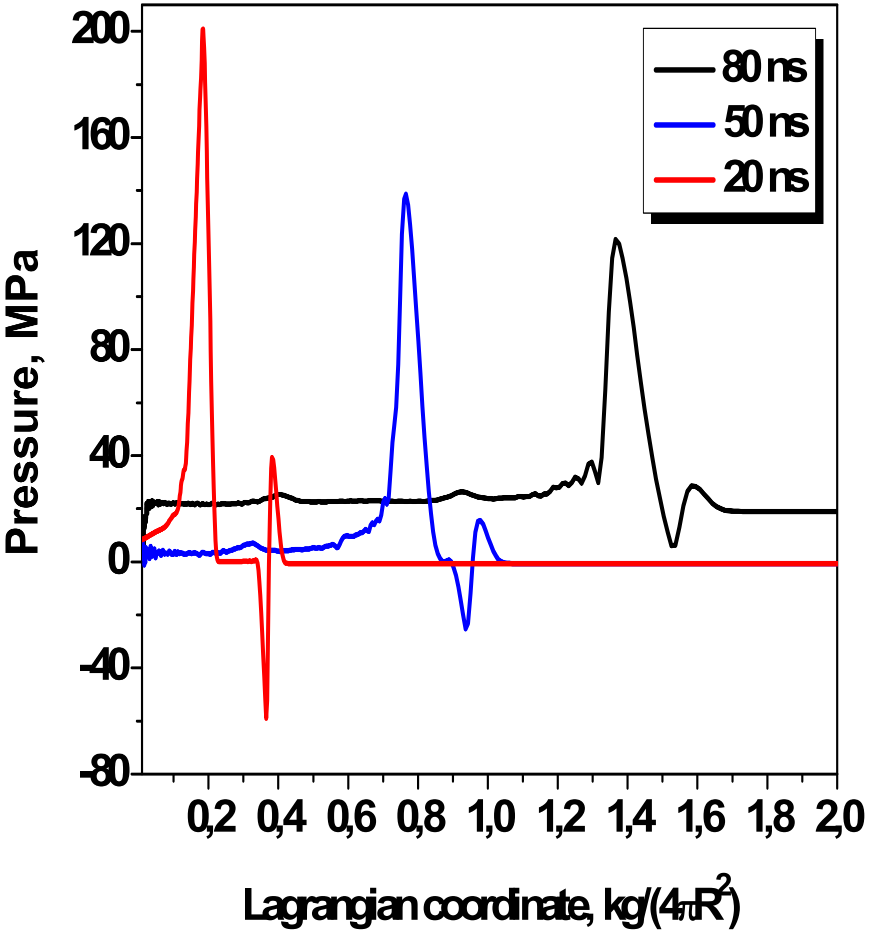
- X-ray prepulse is generated by shock arriving at the target surface at t=104ns.
- Prepulse FWHM equals 0.5ns.
- X-ray main pulse starts at t=300ns. Its FWHM equals 360ns.

Target history after fuel microexplosion

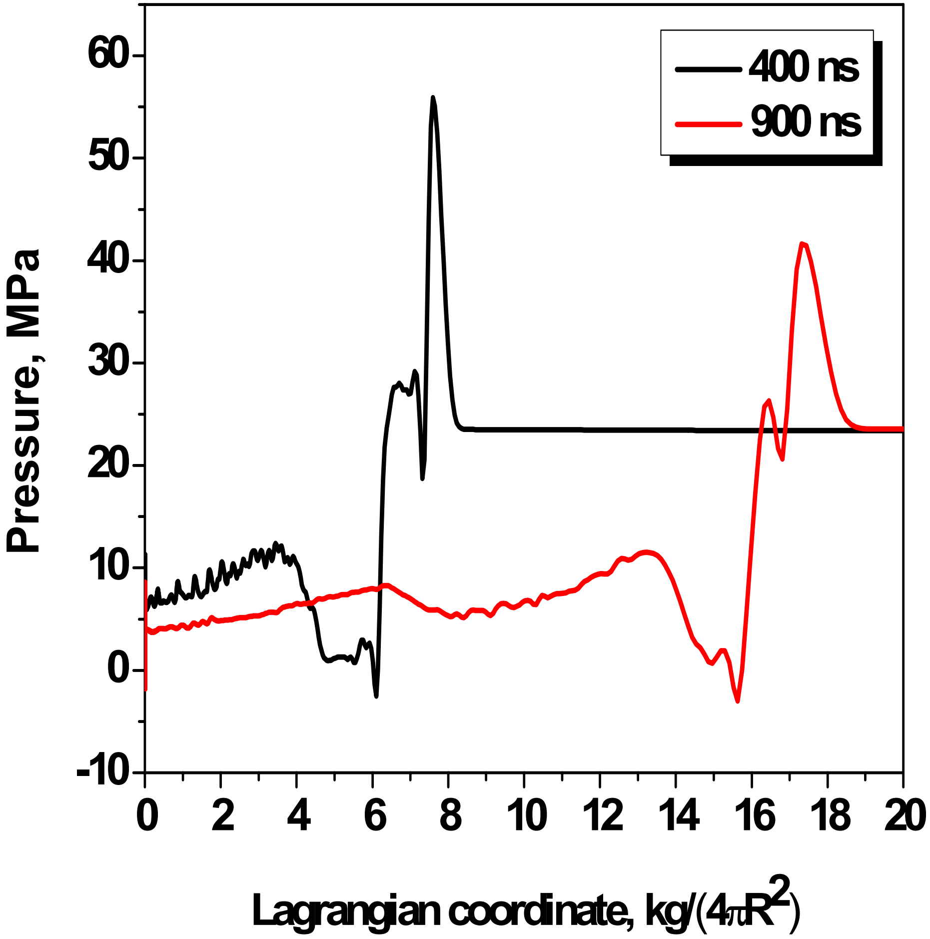


- The first maximum of E_{int} corresponds to the fusion flare at t=95 ns
- The second maximum of E_{int} corresponds to the shock arrival at the target surface at t=104 ns
- The E_{int} pulsation is caused by the shock refraction in non-uniform shell.

X-ray impact on the liquid film at the first wall

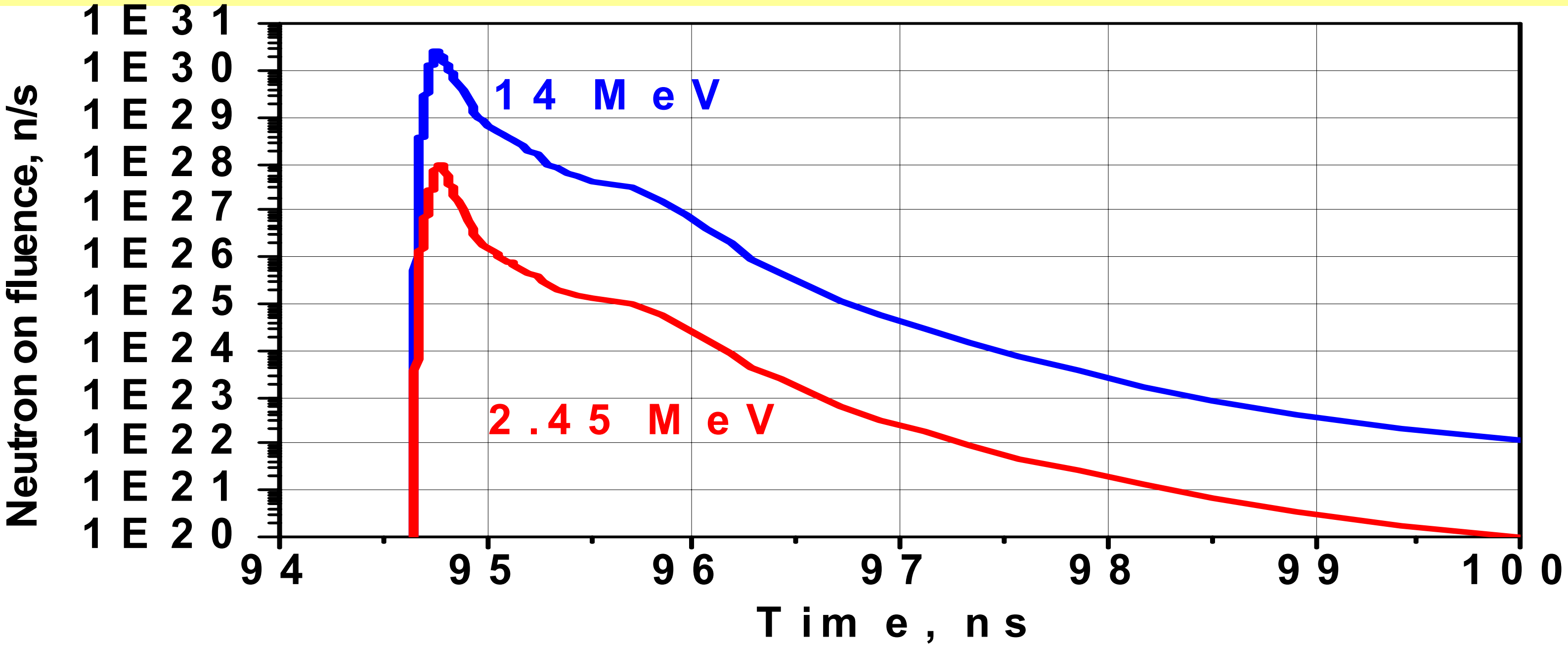


Pressure profiles in the liquid film at various times for the X-rays prepulse impact. R=5m.



Pressure profiles in the liquid film at various times for the X-rays main pulse impact. R=5m.

FIHIF target neutron pulse



MCNP code, spherical approximation, 2D neutron transport

Medin S.A., Orlov Yu.N., Suslin V.M. Preprint of KIAM of RAS 62 (2004)

Average neutron energy ~12.2 MeV

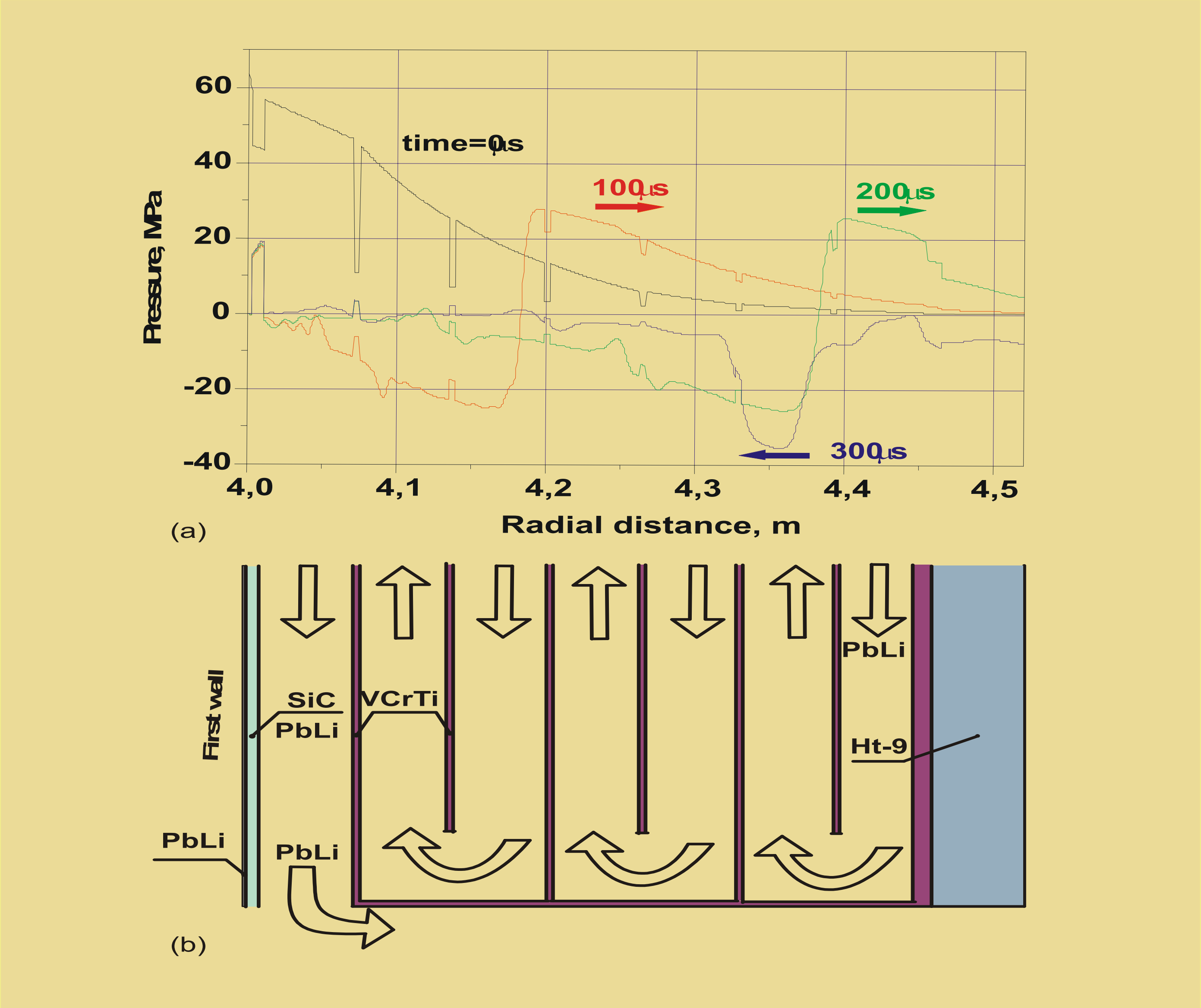
Tritium breeding ratio (TBR) of the blanket ~ 1.112

blanket multiplication factor ~ 1.117

total energy release per shot ~ 818 MJ

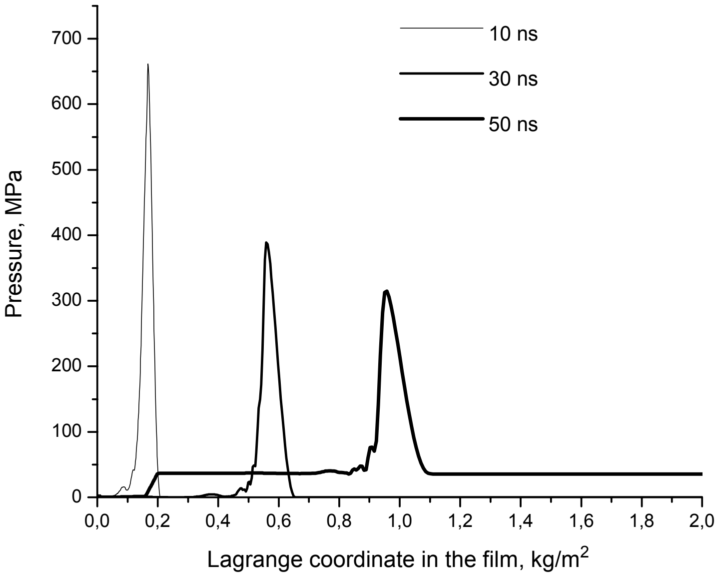
Pressure distribution in FIHIF blanket at various times

1D hydrodynamic equations in cylindrical geometry

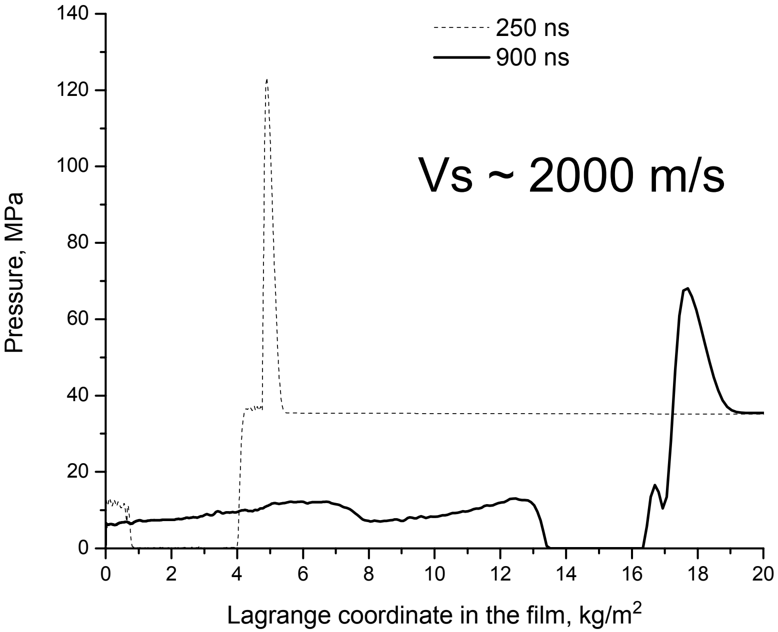


Liquid wall response

liquid film of eutectic Li17Pb83
real equation of state for Pb,
ionization processes (Saha) ,
heat conductivity (Rosseland mfp)



Pre-pulse shock wave propagation



Vs ~ 2000 m/s

Shock wave propagation in the liquid film from the main X-ray pulse

Input data for computation of the first wall response to X-ray, neutron and helium ions heating

Initial conditions for the liquid Pb film

T_0 = 823 K, P_0 = 0, ρ_0 = 10.55 g cm-3

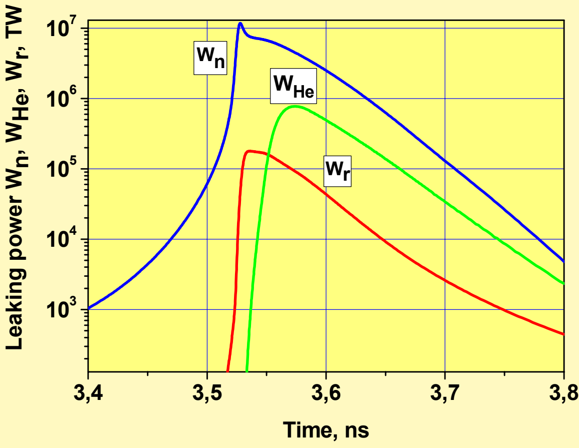
Boundary conditions for the liquid Pb film

Free surface: P = 0, dT/dr = 0, $k_r \mathrm{grad} T_r = -\sigma T_r$^4

Liquid-wall interface: dU/dr = 0, dP/dr = 0, dT/dr = 0

Deposited energy sources

Temporal energy profiles deposited by X-rays, neutrons and fast He4 ions



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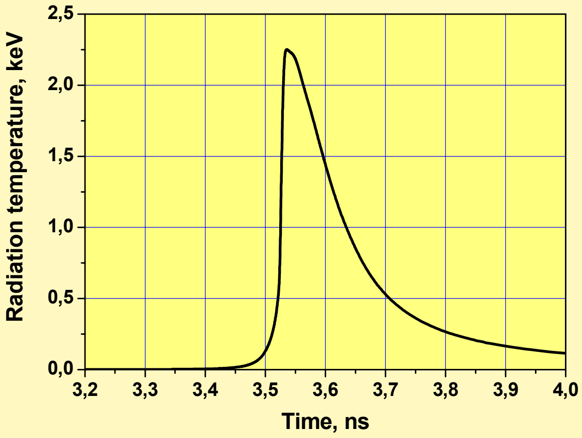
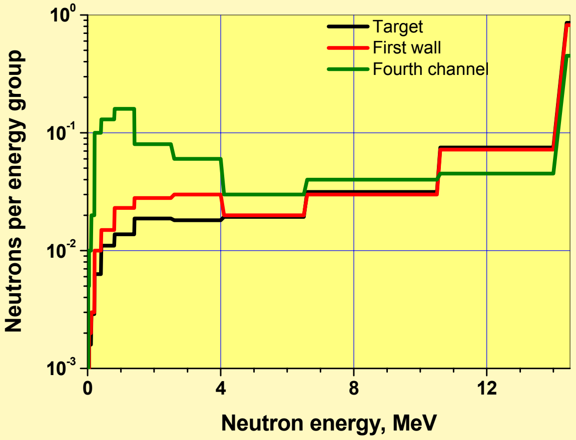
X-ray temperature at the DT fireball surface



Neutron spectra



SUMMARY-1

- Heavy ion beams are well adjusted to a massive cylindrical target.

- X-ray emission profile with short intense prepulse and low-amplitude extended main pulse.

- The vapor layer generated by the prepulse shields the liquid film from the main X-ray pulse.

- The target ion debris is absorbed by the vapor layer as well, and vapor reradiation leads to revaporization of the liquid film.

Summary-2

- **mechanical loading of the first wall material turns out to be tolerable to X-ray impact of the first wall**
- **relaxation of the fog atmosphere of the reactor chamber to the initial conditions is fast enough (from 1 to 10 ms): not a limiting factor for the repetition rate,**
- **fast condensation of vapor is well accomplished, when an array of dispersed jets is employed,**
- **2D neutron transport in the reactor chamber determines tritium breading ratio (1.112) and blanket energy multiplication factor (1.117) and provides data on thermal energy density distribution for the blanket design,**
- **The problem of vapor fog/droplets inside the chamber - major concern for the reactor design.**
- **Experiments required (new IAEA CRP)**

Tivoli XVII century

Росатом (Rosatom)

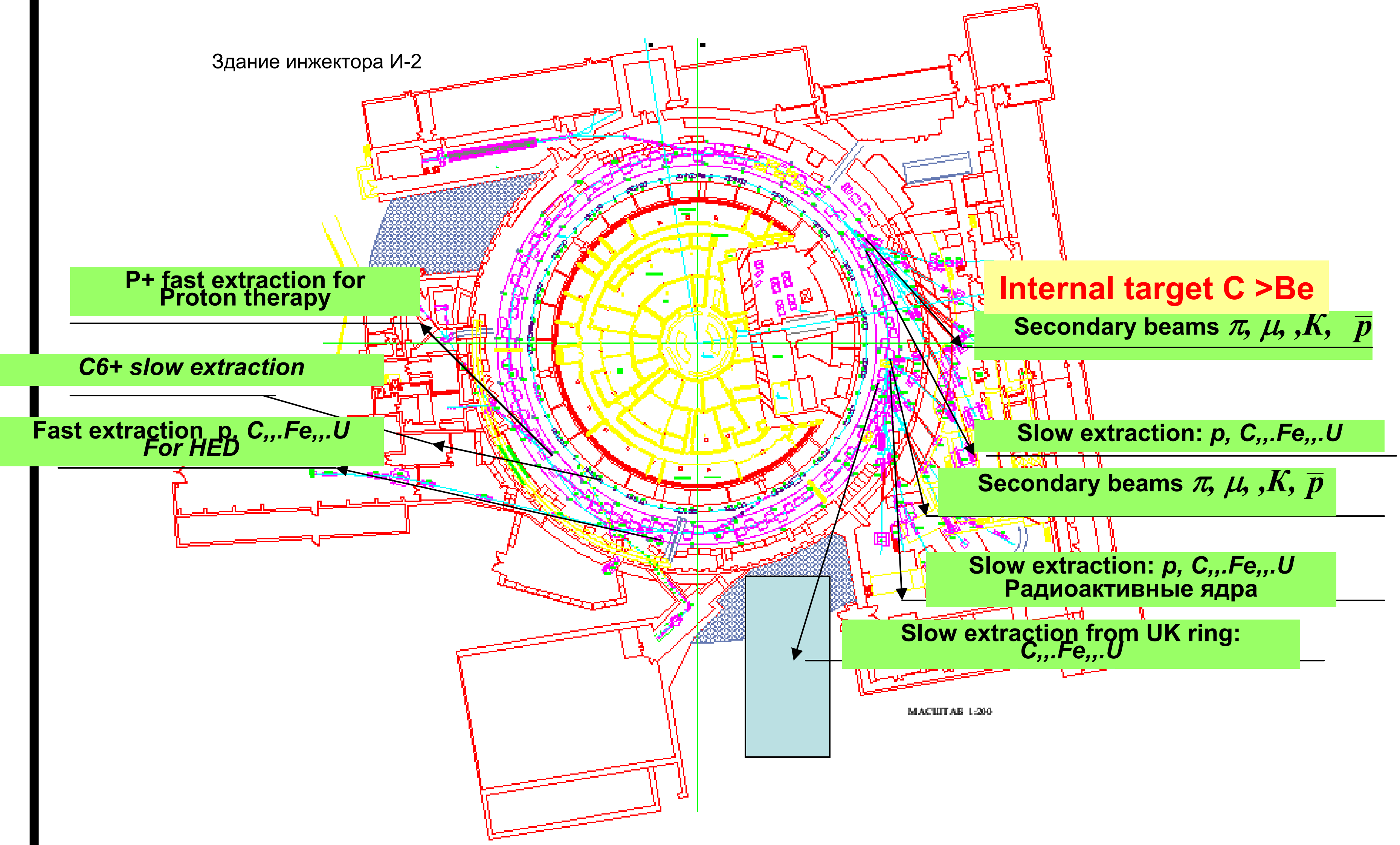
РАН (RAS)

Научно-координационный Совет

- **Н/Т секретариат**
- ВНИИЭВ
- ВНИИТФ
- ФЭИ
- ИТЭФ
- ИХПФ РАН
- ИТЭС РАН
- ТРИНИТИ

Центр Исследований Экстремальных Энергетических Процессов Росатом –РАН

ITEP-TWAC Facility in Progress



P+ fast extraction for Proton therapy

C6+ slow extraction

Fast extraction *p, C,,.Fe,,.U For HED*

Internal target C >Be

Secondary beams $\pi, \mu, ,K, \bar{p}$

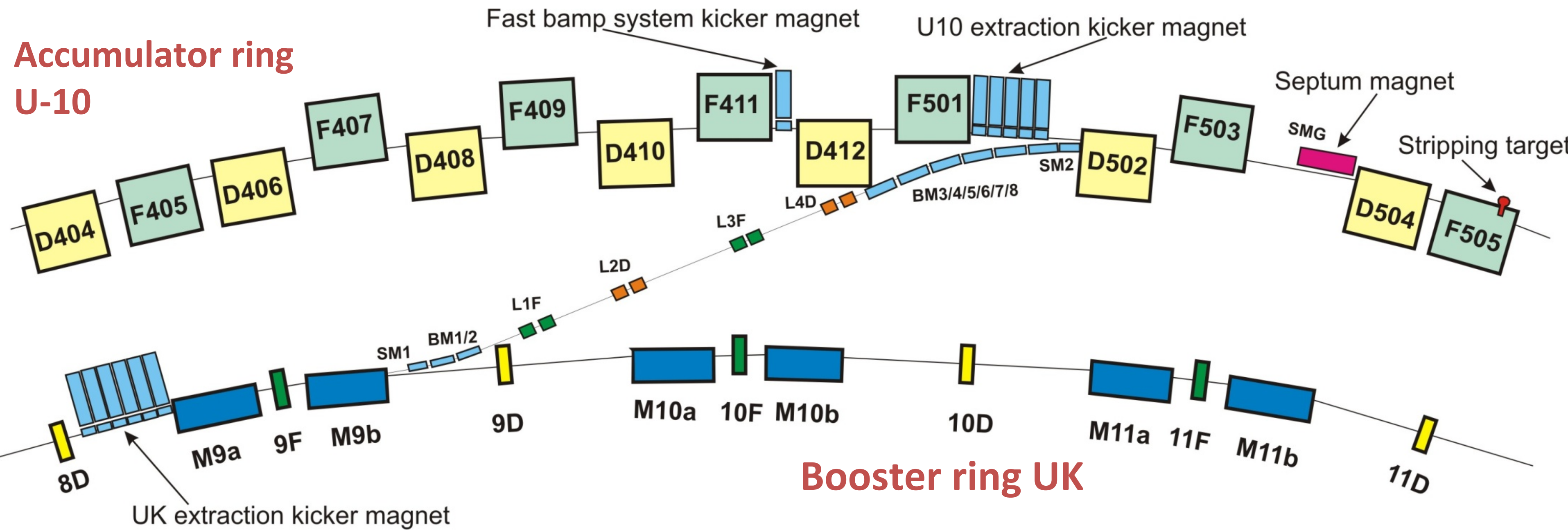
Slow extraction: *p, C,,.Fe,,.U*

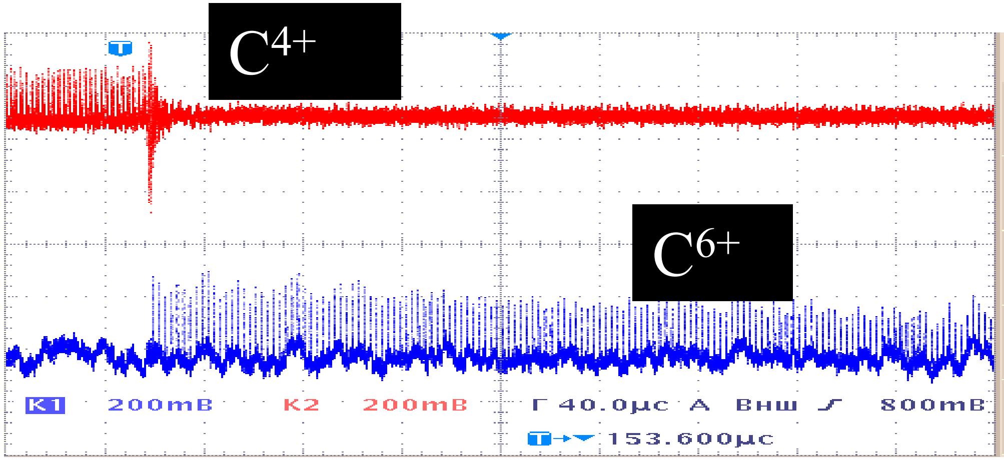
Secondary beams $\pi, \mu, ,K, \bar{p}$

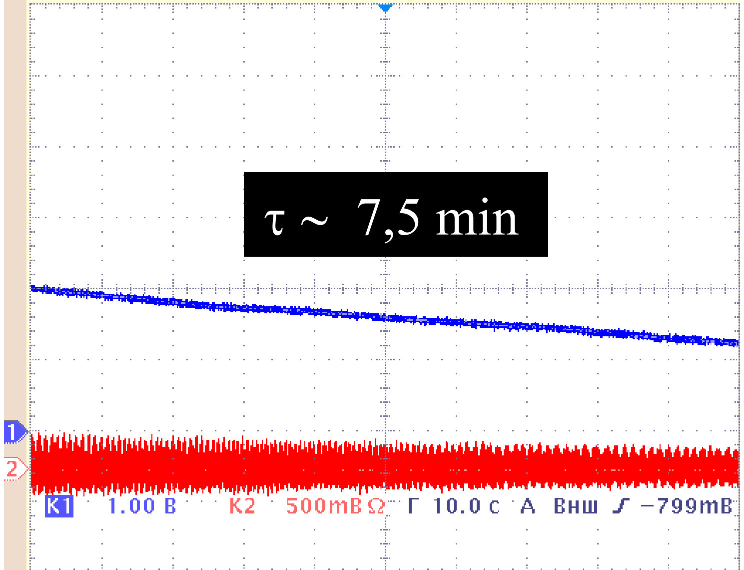
Slow extraction: *p, C,,.Fe,,.U*
Радиоактивные ядра

Slow extraction from UK ring: *C,,.Fe,,.U*

Non-Liouvillian Injection into the storage ring

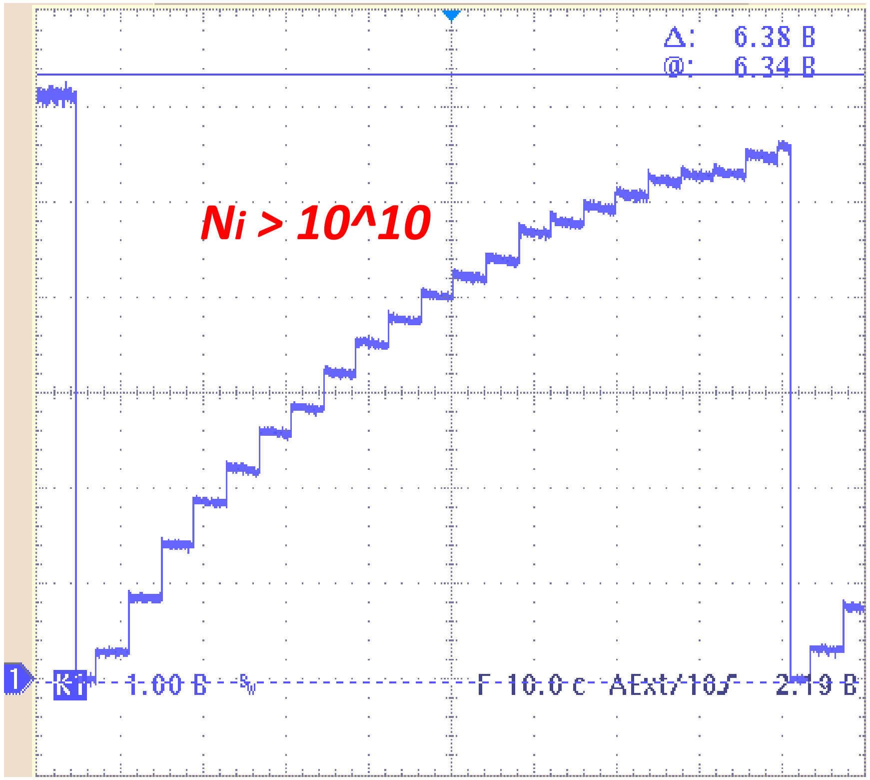




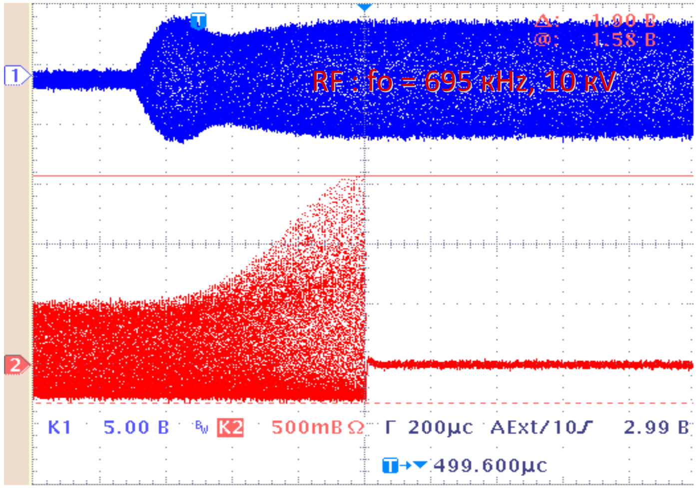


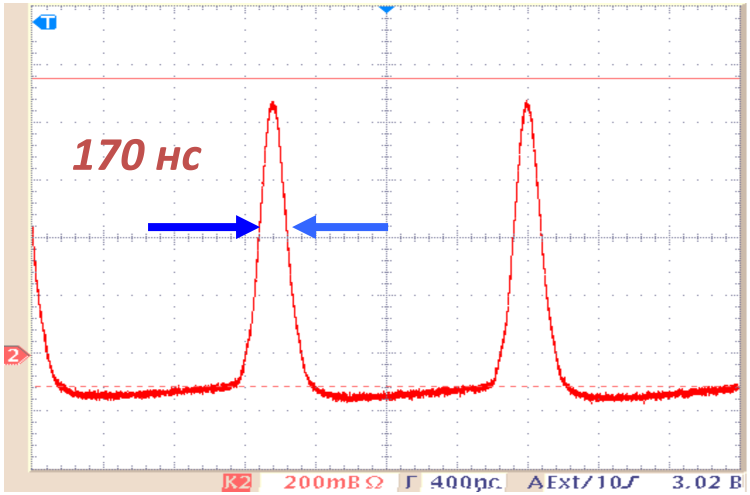
Non-Liouvillian stacking process

Stacking process for 213 MeV/u C6+



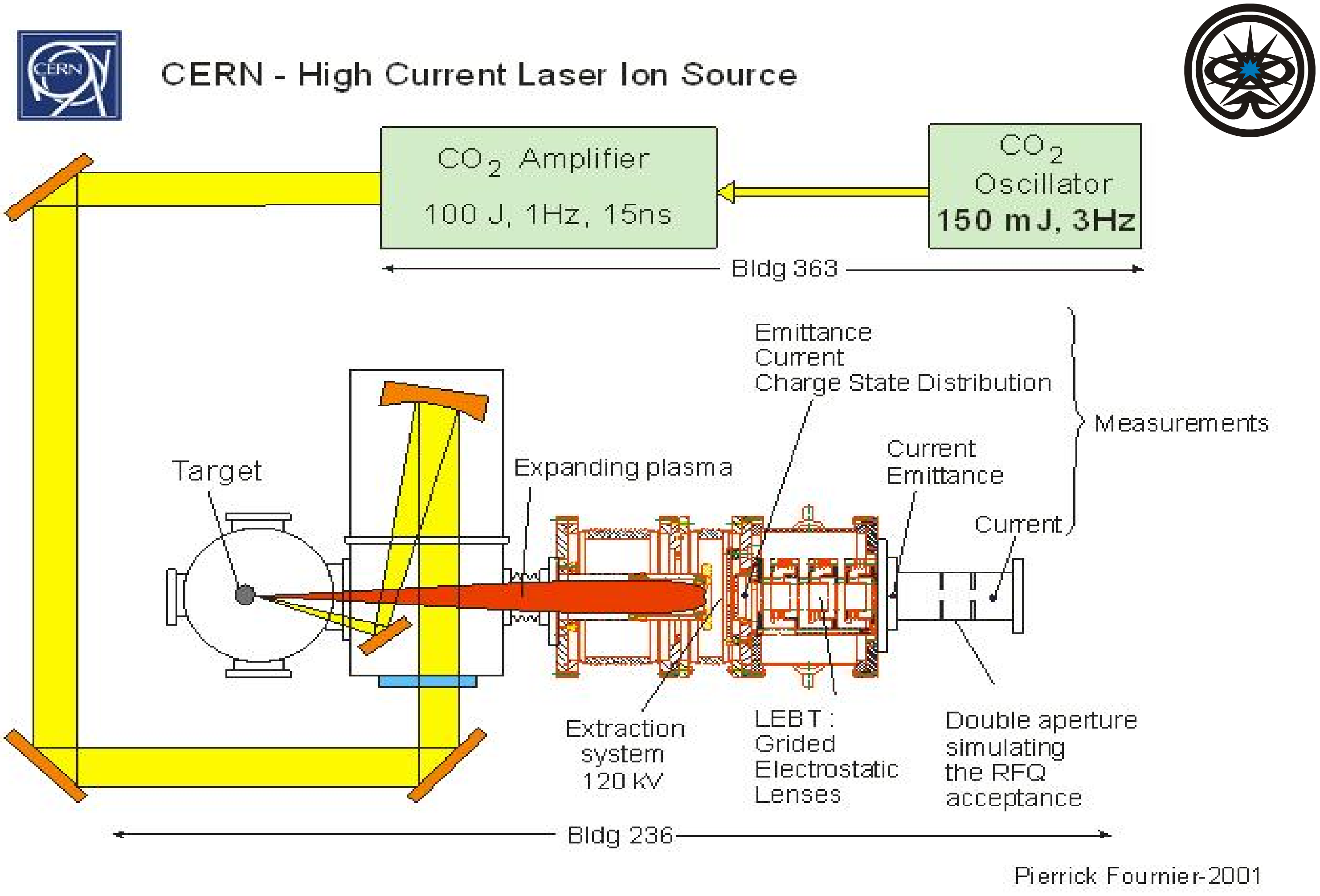
RF bunch compression





Laser Plasma Ion Source –at ITEP

Capable of delivering Pb, In, Nb… ions with rep-rate 1 Hz
For Pb 25+ : 7,7 mA / 3.5 mks , 0.6 10 E10 ions measured
emittance – 0.2 mm mrad (normalized)



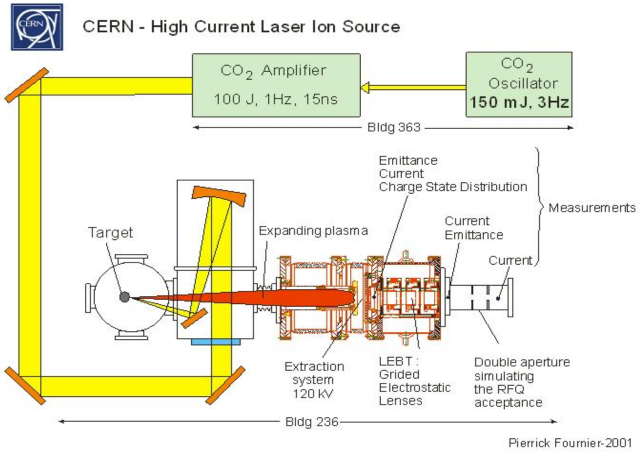
ITEP Solutions

1:Laser ion source

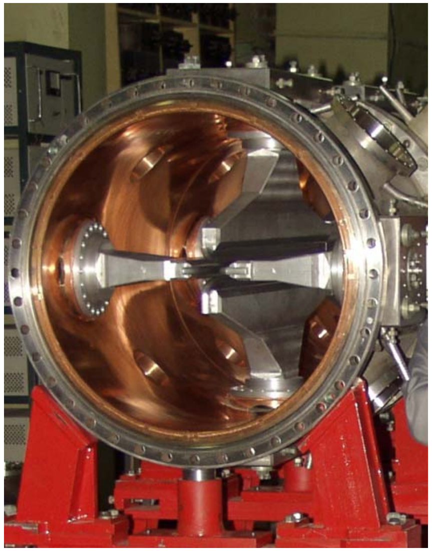
2: RFQ accelerator

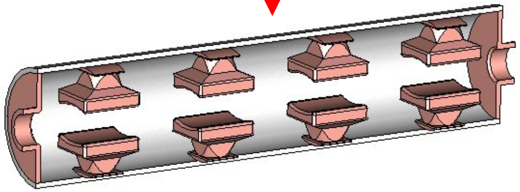
3: Non-Liouvillian stacking

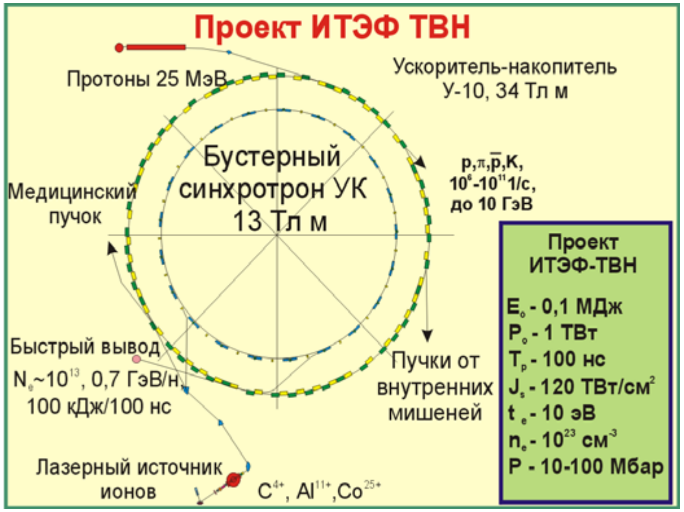
4. RF wobbler technique



Pierrick Fournier-2001



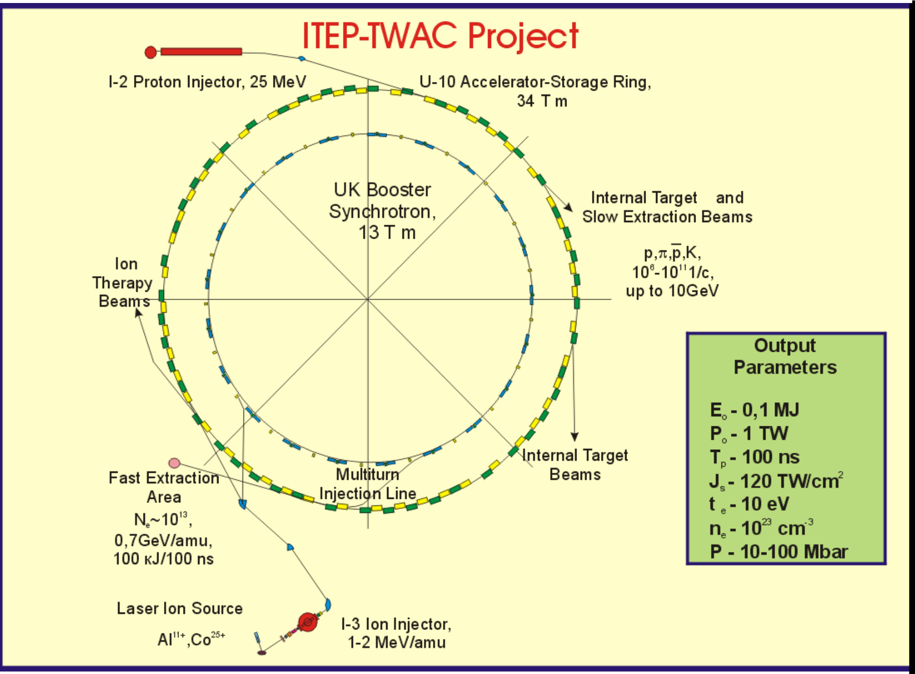




Проект ИТЭФ-ТВН

E_0 - 0,1 МДж
P_0 - 1 ТВт
T_p - 100 нс
J_s - 120 ТВт/см^2
t_e - 10 эВ
n_e - 10^{23} см$^{-3}$
P - 10-100 Мбар

ITEP-TWAC project in progress

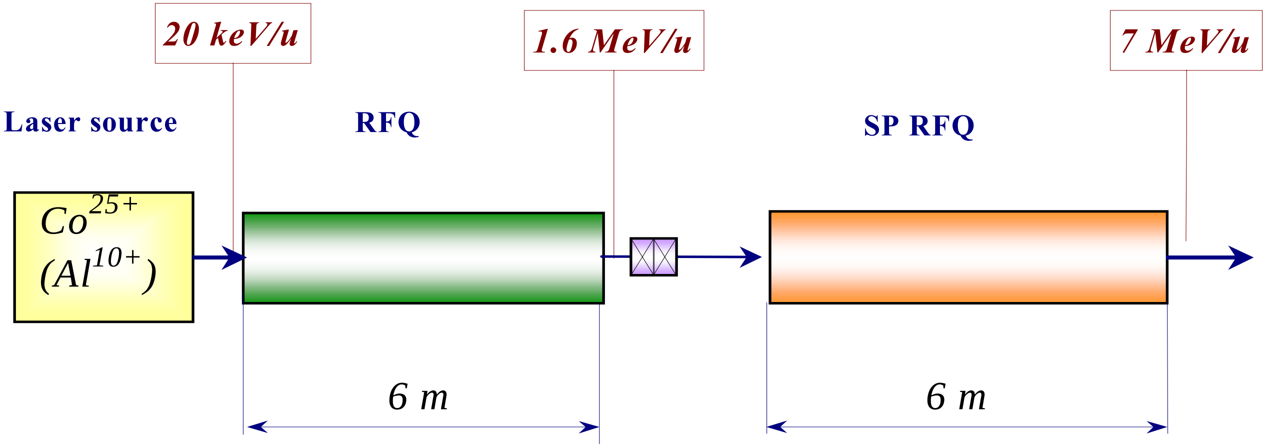


Mode of operation	Accelerators	Beam energy, MeV/u	Mode of beam extraction
Proton acceleration	*I-2* *I-2/* *U-10*	25 up to 230 up to 3000 up to 9300 up to 3000 (9300)	pulse, 10 μ/s medical extraction, 200 ns, fast extraction, 800 ns, internal target, 1s slow extraction, 1s
Ion acceleration, *C, Al, Fe,(Pb,U)*	*I-3/UK* *I3/UK/* *U-10*	1,5 - 400 50 - 4000	fast extraction, 800 ns, internal target, 1s, slow extraction, 1s
Nuclei accumulation , *C, Al,Fe, (Co,Zn)*	*I3/UK /U-10*	200-300 700-1000	fast extraction with compression to 150 ns, continues extraction of stacking beam

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”**
- **Induced radioactivity issues**

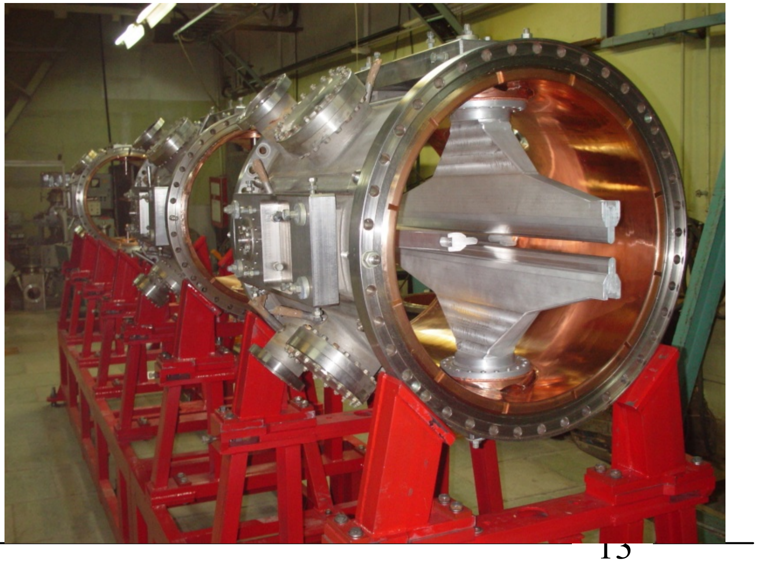
Layout of the new injector linac



Output energy	7 – 8 MeV/u
Beam pulse duration	15 μs
Beam current of the main component	16 mA
Beam emittance	4π mrad*mm
Operation frequency	81.4 MHz

Parameters of the RFQ cavity

Operation frequency, MHz	81.4
Inner cavity diameter, m	0.56
Cavity length, m	6
Nearest dipole mode, MHz	98
Quality factor	11000
Storage energy, J	8.3
RF power losses, kW	600



Assembling of the RFQ cavity with aluminum model electrodes

ITEP-TWAC, Experimental Area for PP

Пучки B511 и B512. Вид сверху.