Heavy Ion Fusion

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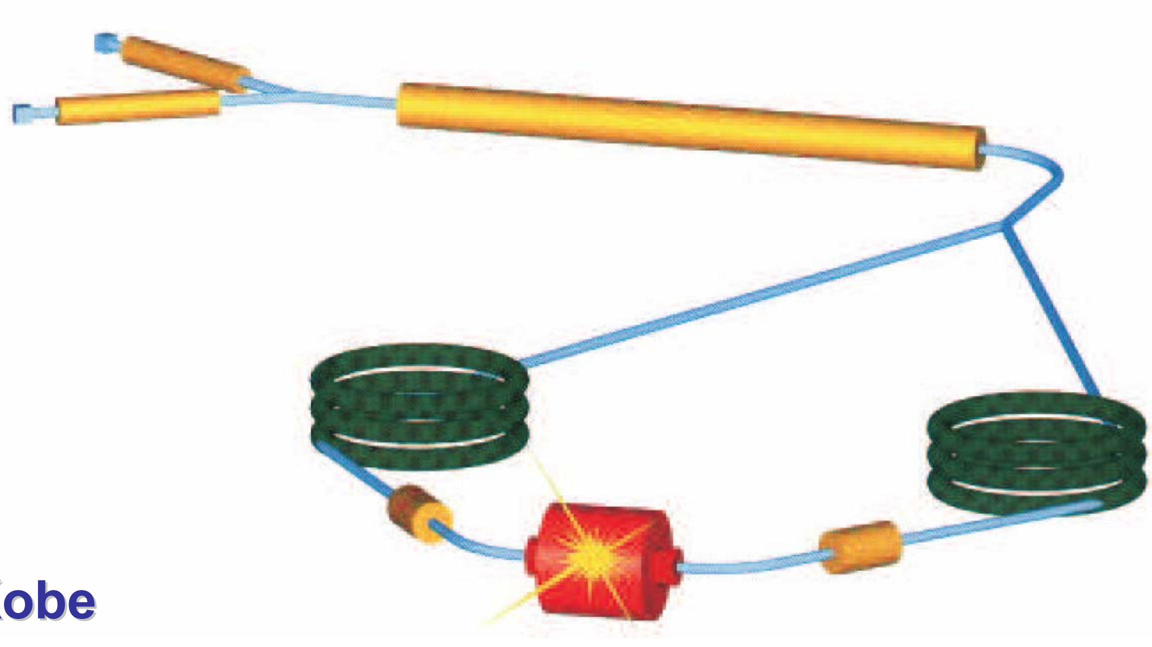
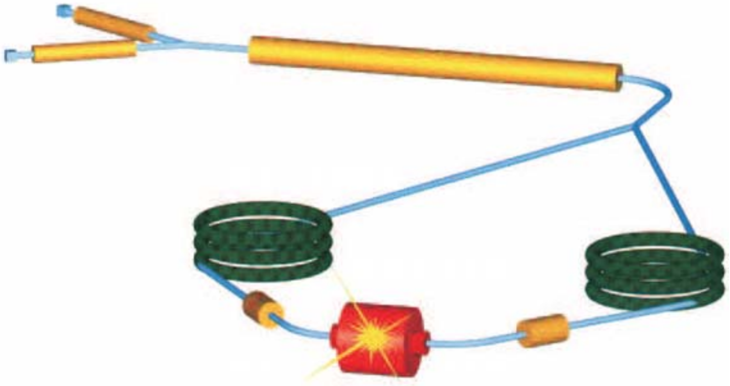


IFSA 2007, Kobe

Outline

- Introduction
- Driver – Target – Reactor Chamber consistence issues
- Search for brake-through ideas/solutions
- Present status and current experimental activities
- Outlook
- Conclusions

Basic motivations for HI IFE



- Intrinsic efficiency $\eta G > 10$
- High repetition rate ~1 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

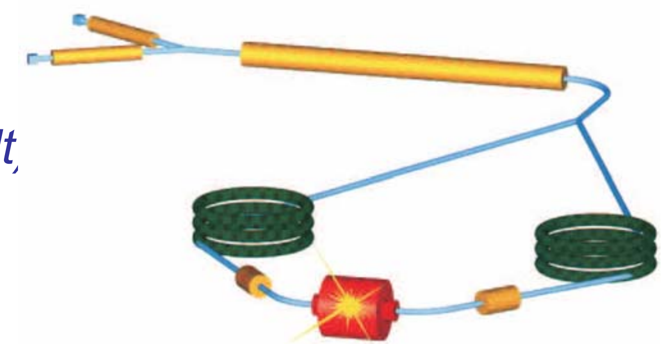
Drivers
determined by target requirements

Targets
tailored specifically for accelerators

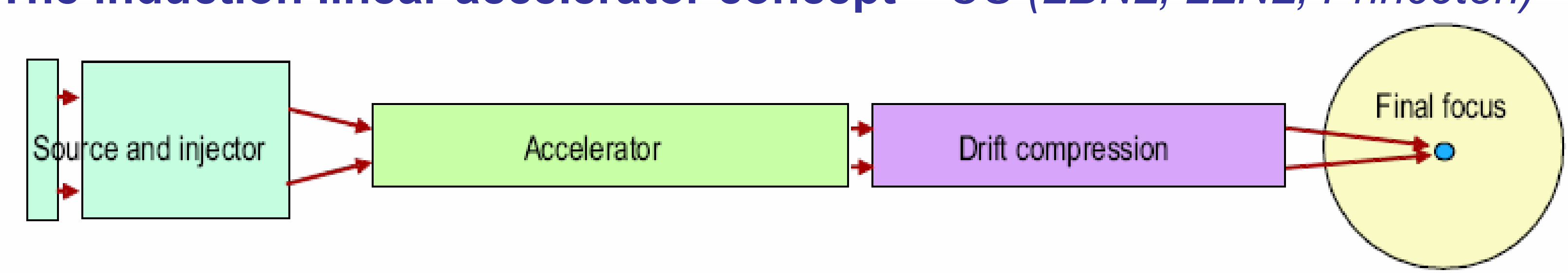
Challenging aspect : short pulse length < 10ns – i.e. 10E4 compression
small focal spot ~ 1-2 mm
@ large distance ~ 5 m

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)*

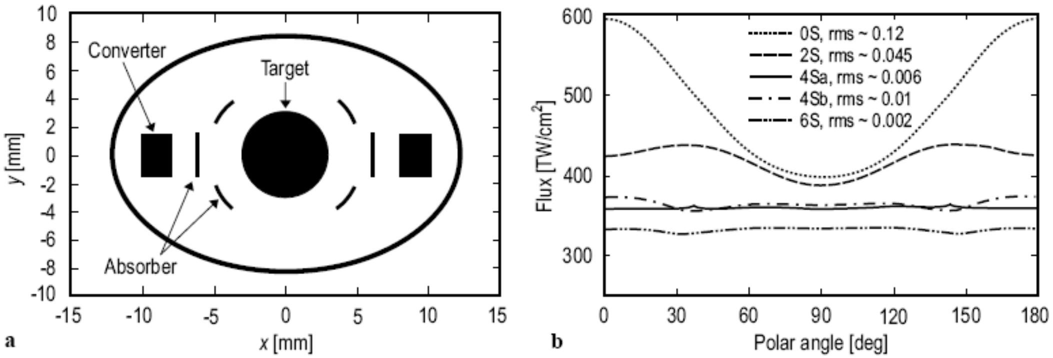


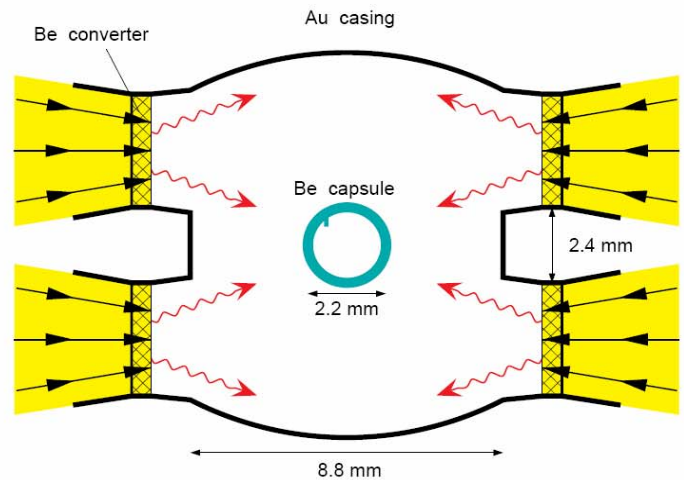
Heavy ion targets with hydrodynamic ignition

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

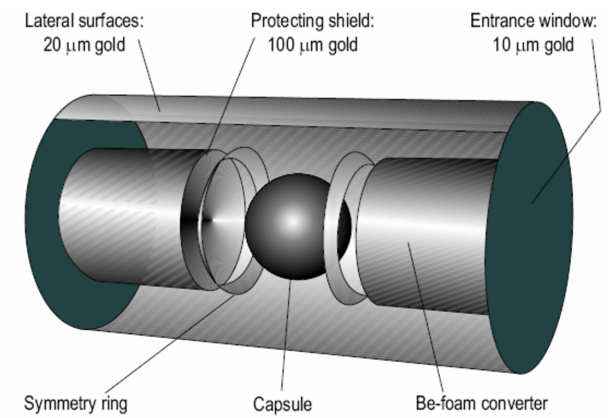
J.Maruhn 1997

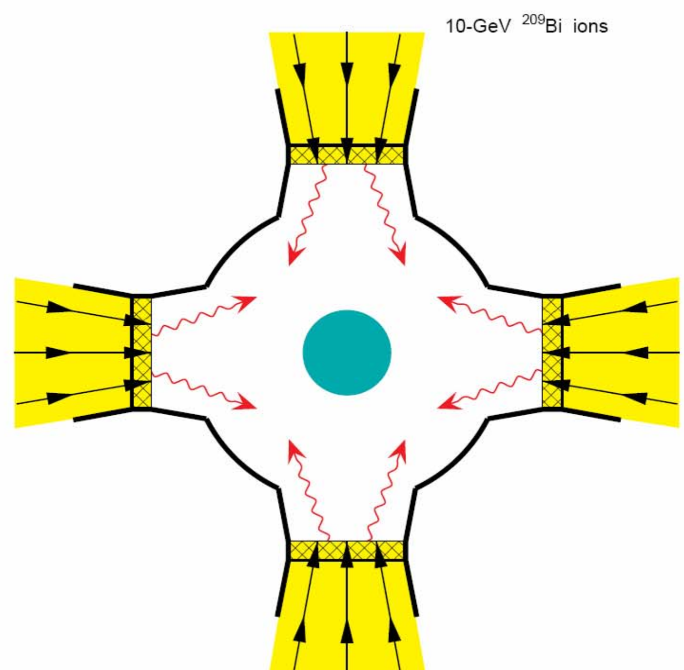




R.Ramis 1998

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

Distributed-radiator target
(D.Callahan *et al*., LLNL)

Hybrid target

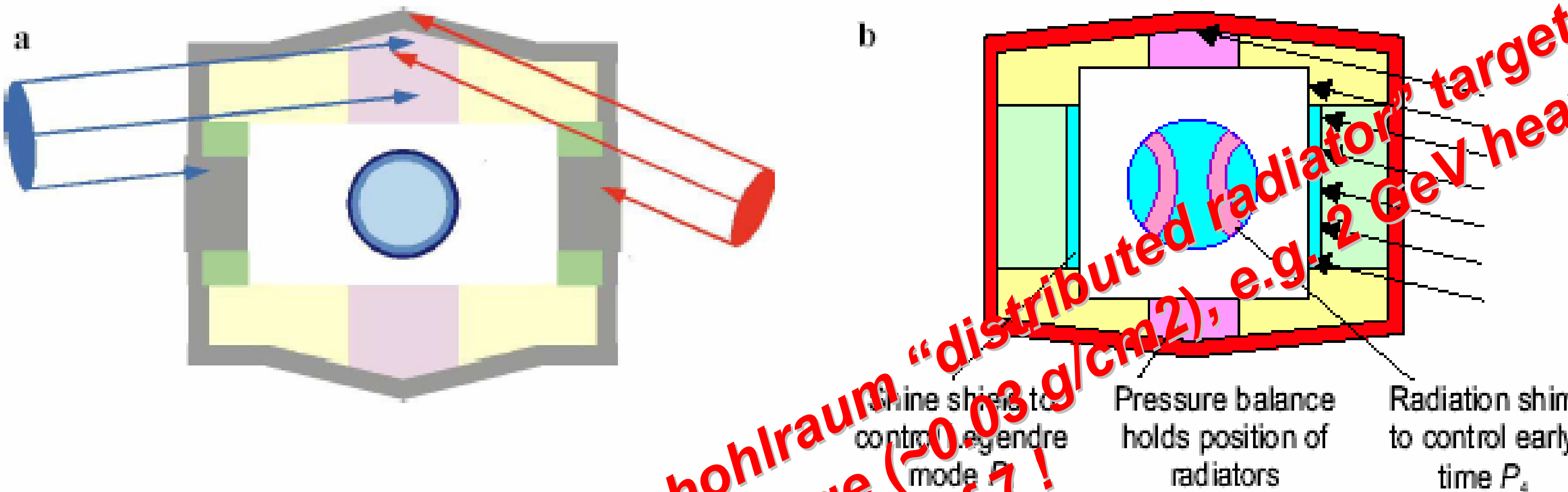


Fig. 10.12. (a) The Distributed-Radiator Target (DRT) for 120 beams up to 24° incident angle. (b) The Hybrid Target (HT) allows larger focal spot radii with fewer beam directions at smaller incident angles.

Conventional heavy ion hohlraum "distributed radiator" targets require ~7 MJ of medium range (~0.03 g/cm2), e.g. 2 GeV heavy ions, capsule absorbs 1 MJ out of 7 !

Cylindrical hohlraum, two-sided irradiation with several beam cones

Ion energy (Pb): 3 GeV → 4 GeV
Beam energy: 6.2 MJ
Energy gain: 55

P4 target with a spherical hohlraum
(M.Basko, ITEP)

Two-cone P4 irradiation scheme

Ion energy (Bi): 5 GeV
Beam energy: 6.1 MJ
Energy gain: 78

To ignite a target requires:

T_r ~ 240 – 300 eV, P[W/g] = (E_i · I(kA)) / (R· πr_f E2) ~ ~ 10E4 [TW/g]

Maschke current limit for beam transport:

$$I_0 = 1.8 \times 10^6 \, (A/Z)^{1/3} \, B_0^{2/3} \, (\beta\gamma)^{5/3} \, \varepsilon_N^{2/3} \, .$$

Preference for high A and E_i but is in conflict with small Range "focusability" - small emittance !

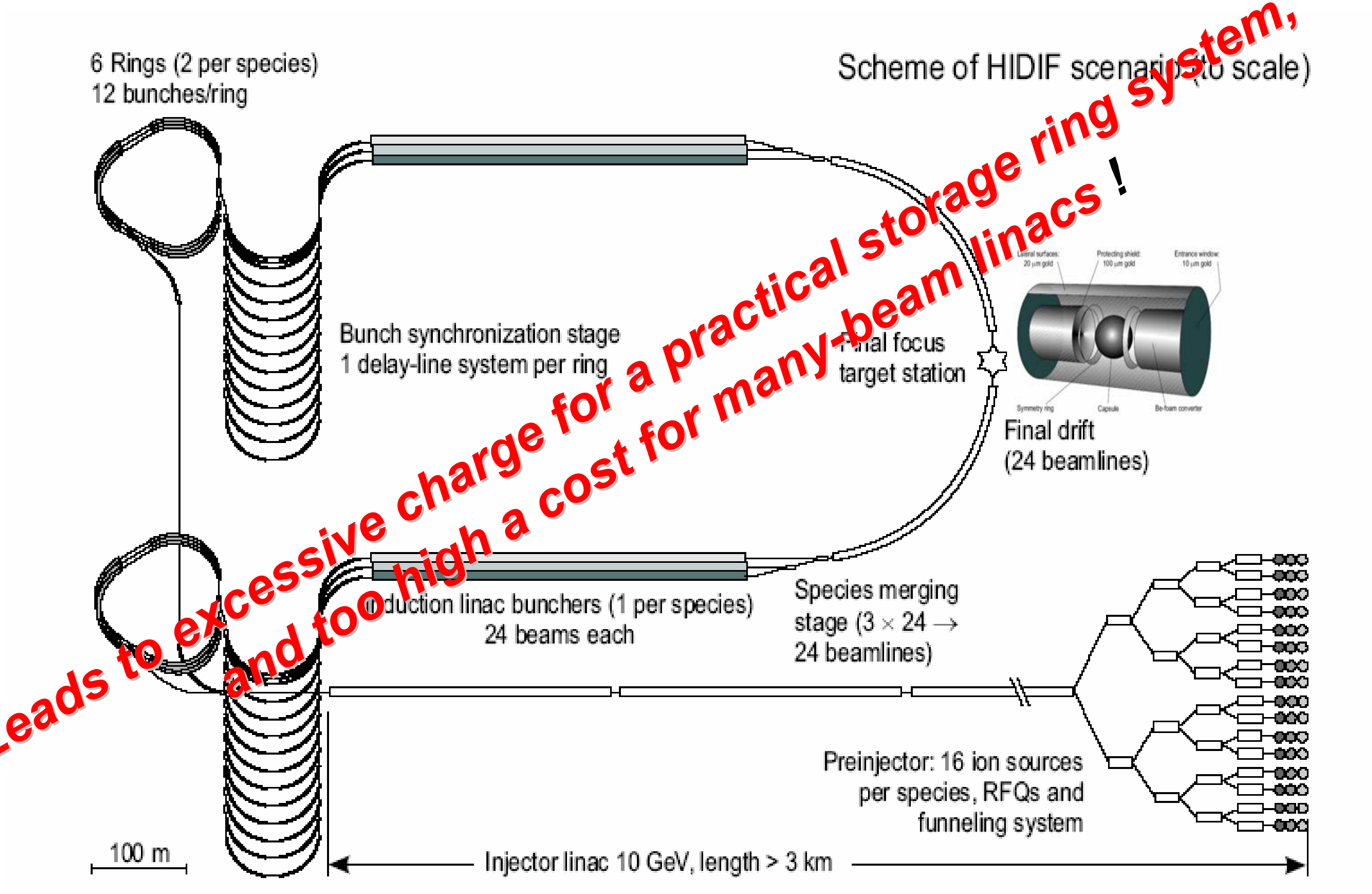
$$I_0 \sim E^{5/6} \qquad T \sim E^{11/6},$$

Compromise beam parameter set :

Ion species	$^{209}Bi^{1+}$
Kinetic energy	10 GeV
Total energy	5 MJ
Final pulse duration	10 ns
Final momentum spread	3×10^{-3}
Emittance at target	20 mm mrad
Spot radius	3 mm
Ion range	0.3 g/cm^2
Specific power	10^{16} W/g

HIDIF study R.Bock & I.Hofmann GSI 1997

10 GeV, 2 10E15 Bi+ (3 sp), 51 kA, 3-4 MJ, 507 TW, 50 Hz



Leads to excessive charge for a practical storage ring system, and too high a cost for many-beam linacs !

An ion bunch must be compressed to a small volume against its thermal pressure and space charge forces

<u>Goal of HIF science :</u>

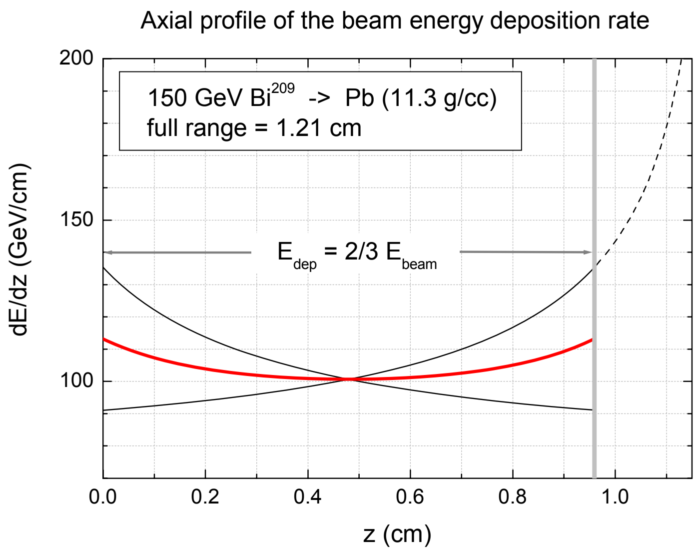
explore limits to beam brightness that lead to lowest energy to drive targets !

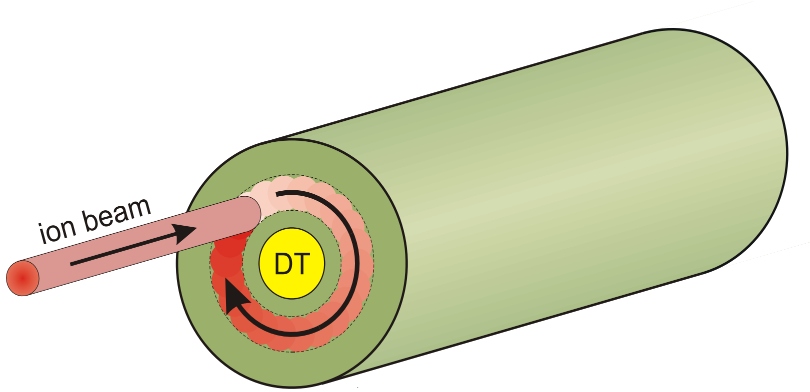
Principal motivation for cylindrical targets

M.Churazov,
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 GeV have relatively long ranges of ~6-7 g/cm² in cold heavy metals. Such ranges can be naturally accommodated in cylindrical targets with axial beam propagation.



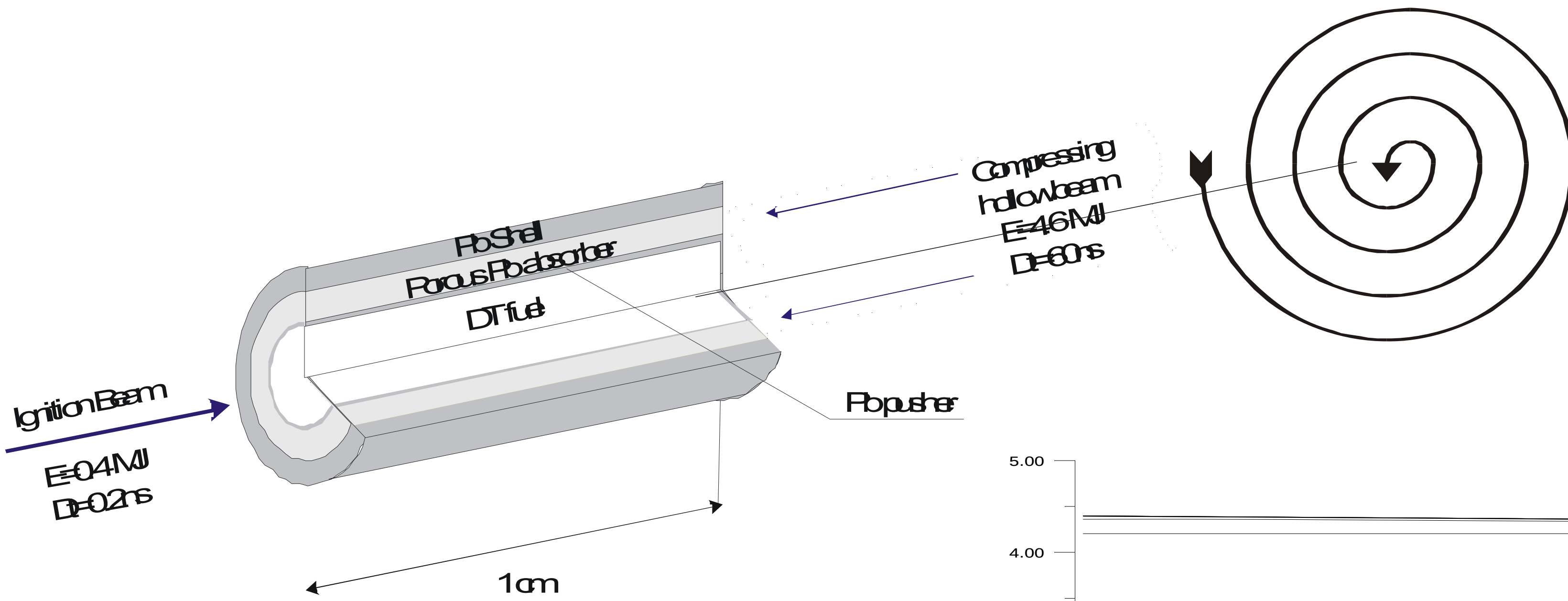


Direct drive may become a competitive target option when

- **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.**

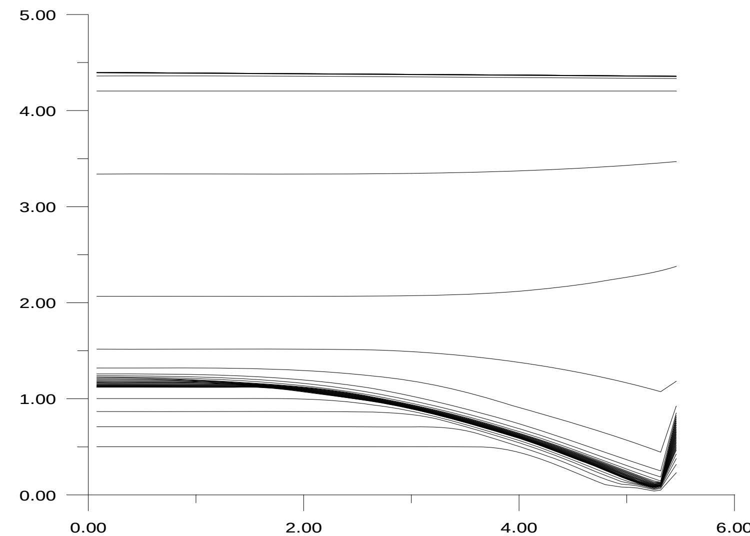
M.Basko *et al.*, HIF 2002

Target irradiation by rotating ion beam

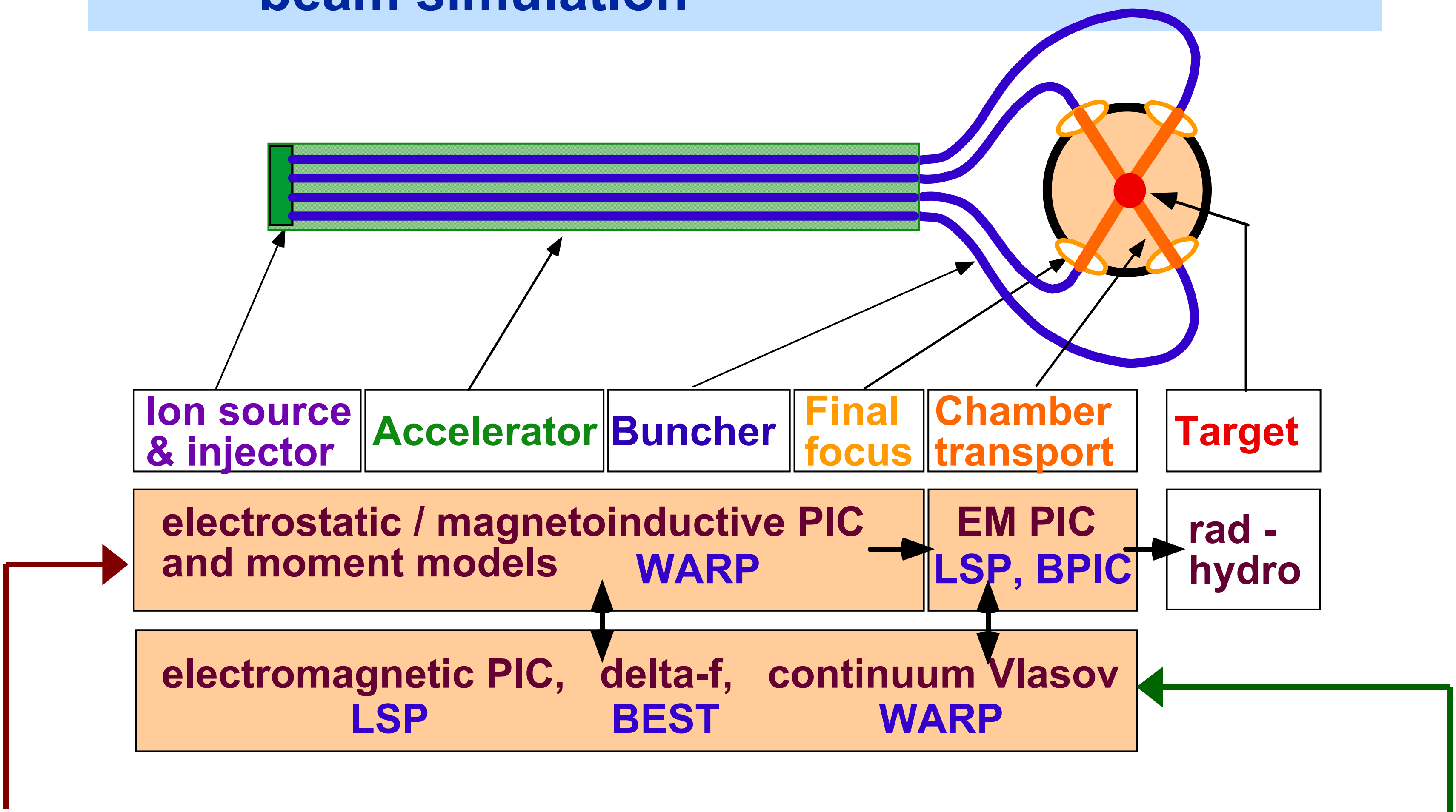


$\rho \geq 100$ g/cm3 , $\rho R \geq 0.5$ g/cm2

E=6.3 MJ versus 7.1 MJ



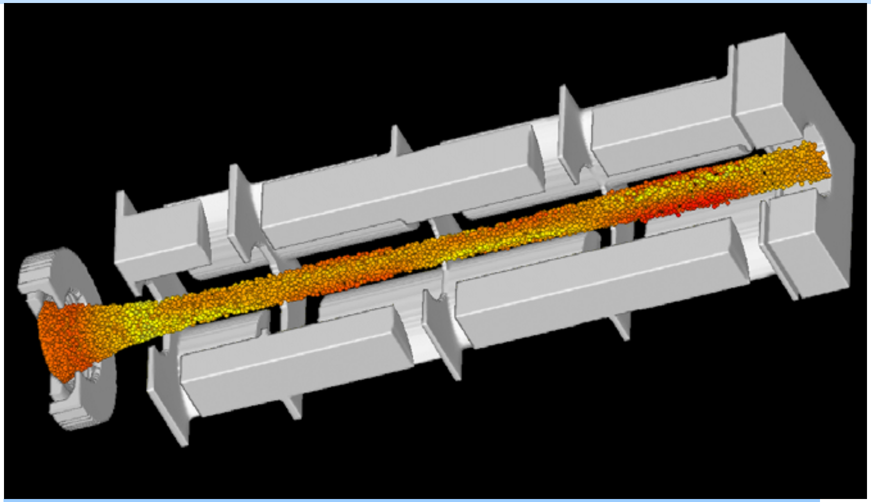
Goal: integrated and detailed source-to-target beam simulation



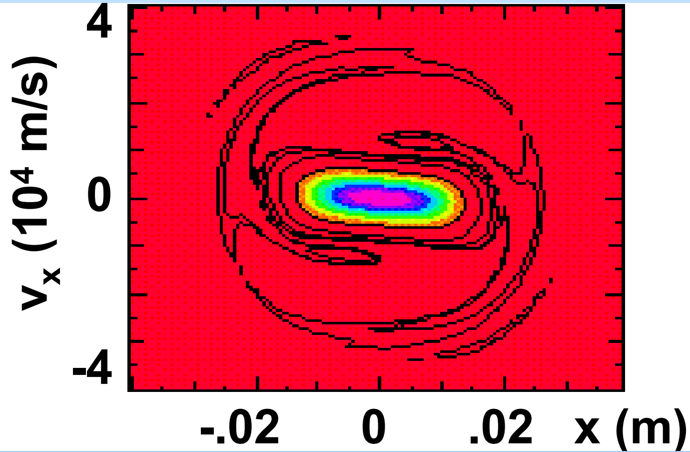
"**main sequence**" tracks beam ions consistently along entire system

instabilities, halo, electrons, ... are studied via coupled **detailed models**

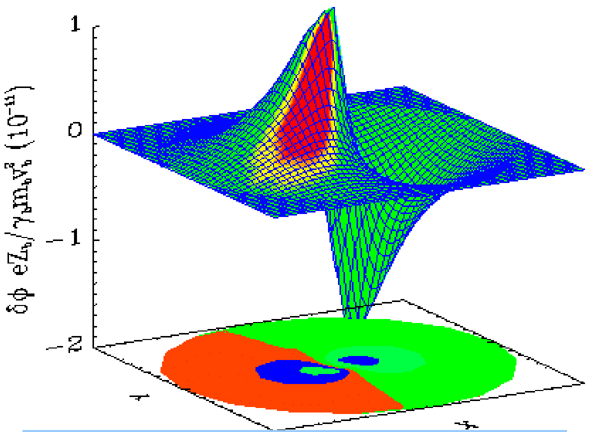
Simulation tools are used to resolve a wide range of issues



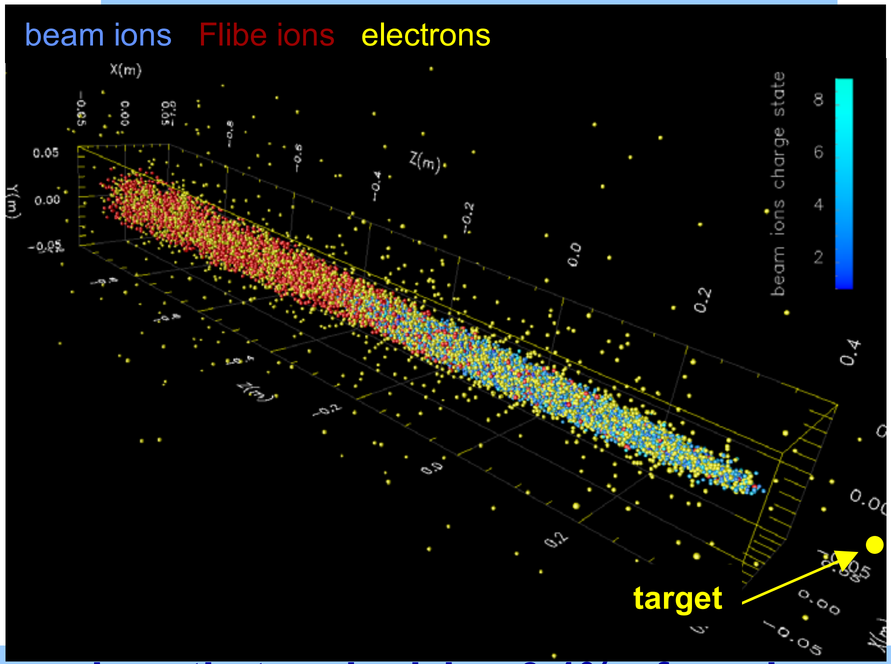
WARP3d PIC simulations quantify effect of large focusing potentials and aberrations in ES quadrupole injector



Vlasov model WARP-SLV reveals low-density beam halo structure



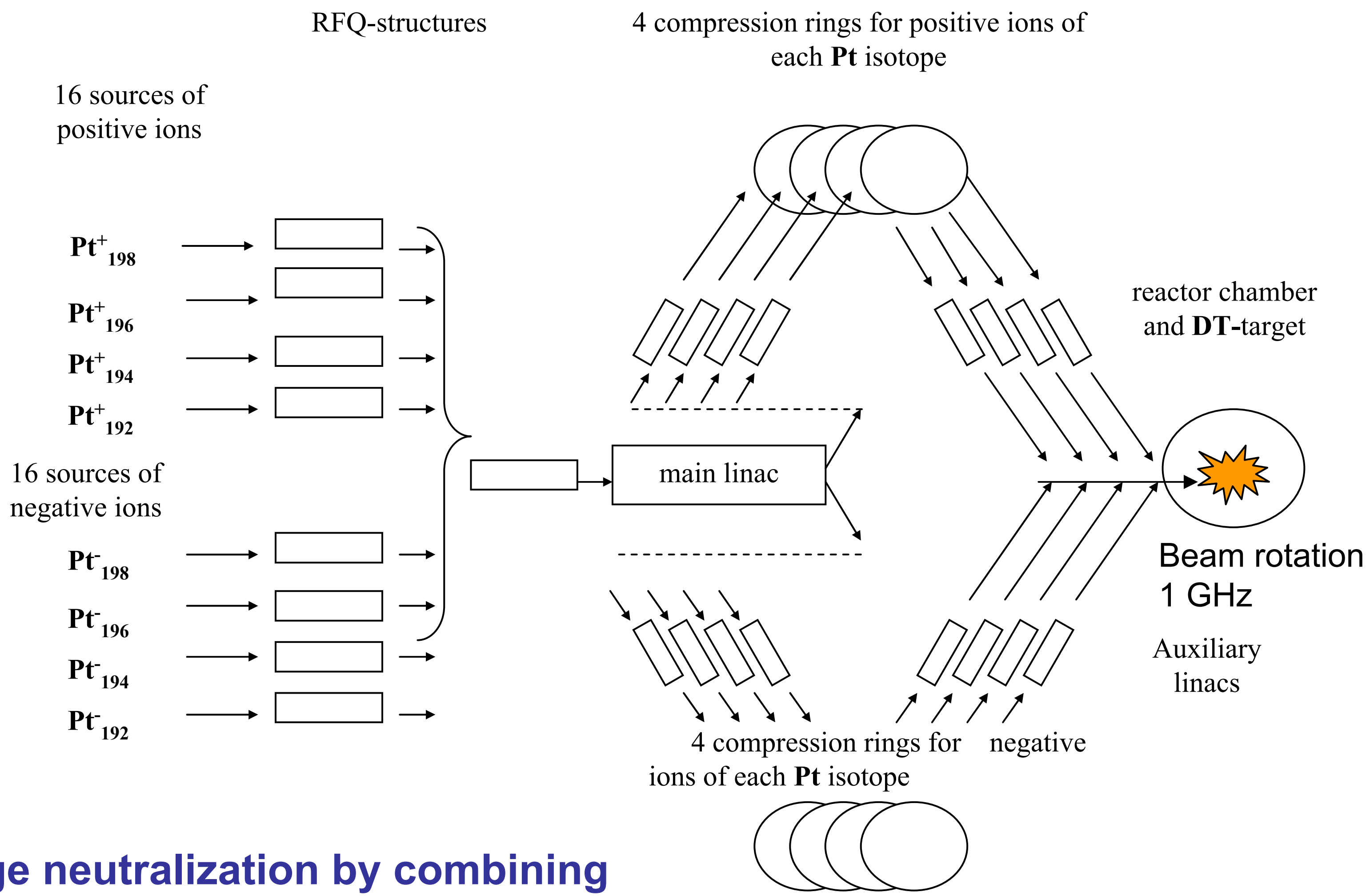
3-D δf code BEST runs show structure of two-stream mode



BPIC runs show that preionizing 0.1% of gas increases fraction of beam hitting 2.85 mm spot from 76% to 95%

Charge symmetric driver (Koshkarev 1998)

12 MJ, 320 TW, 100 GeV, eff. 25%, 11 km long, D~0.9 mm



beam charge neutralization by combining pairs of beams with opposite charges at the last stage of the drift compression and focusing

Fast ignition with heavy ions

Heavy ions would be a far better than laser candidate for a fast ignitor beam provided that the required intensity of irradiation could be ensured.

A proposal by D.G. Koshkarev from ITEP:

- **increase the ion energy from the conventional E_i = 3–5 GeV to E_i = 100 GeV per ion;**
- **employ the method of non-Liouvillian compression of beams of simultaneously accelerated ions with 4 different masses and opposite electric charges;**
- **use beam charge neutralization by combining pairs of beams with opposite charges at the last stage of the beam compression.**

As a result, one can obtain a heavy ion beam with the following parameters:

beam energy: E_{igb} = 400 kJ
pulse duration: t_{igp} = 200 ps
beam power: W_{igb} = 2 PW

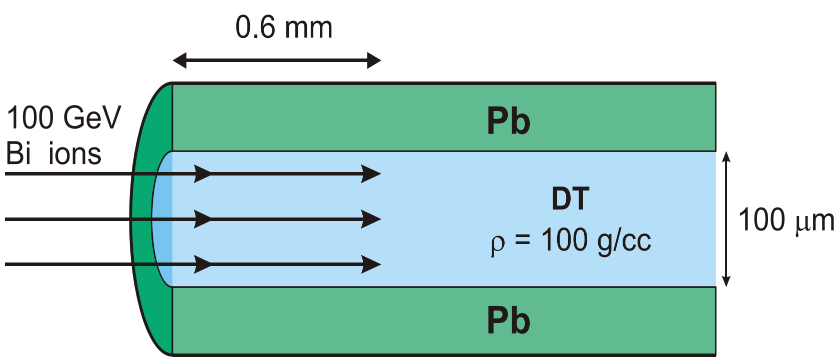
focal radius: r_{foc} = 50 μm
irradiation intensity: $I_{igb} = 2.5\times10^{19}$ W/cm^2

Fast ignition with heavy ions: assembled configuration

With a heavy ion energy ≥ 0.5 GeV/u, we are compelled to use cylindrical targets because of relatively long (≥ 6 g/cm²) ranges of such ions in matter.

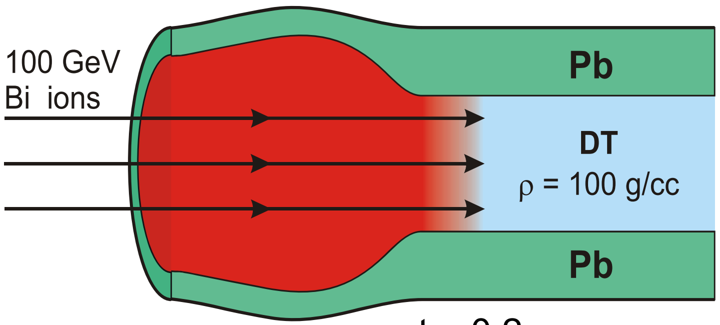
The ion pulse duration of 200 ps is still about a factor 4 longer than the envisioned laser ignitor pulse. For compensation, it is proposed to use a massive tamper of heavy metal around the compressed fuel:

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/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!**

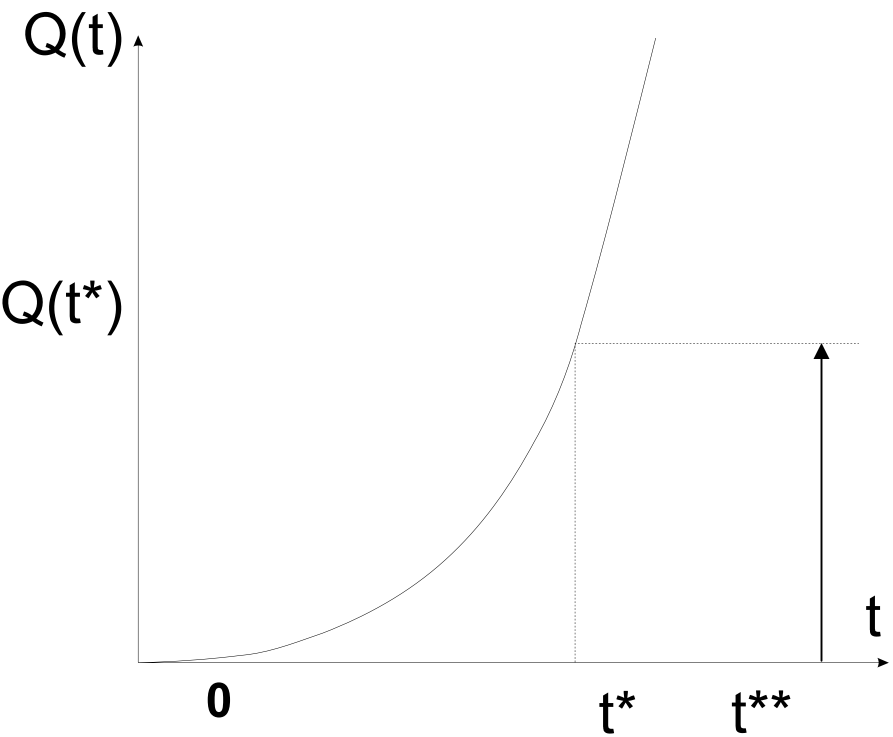
CYLINDRICAL TARGET

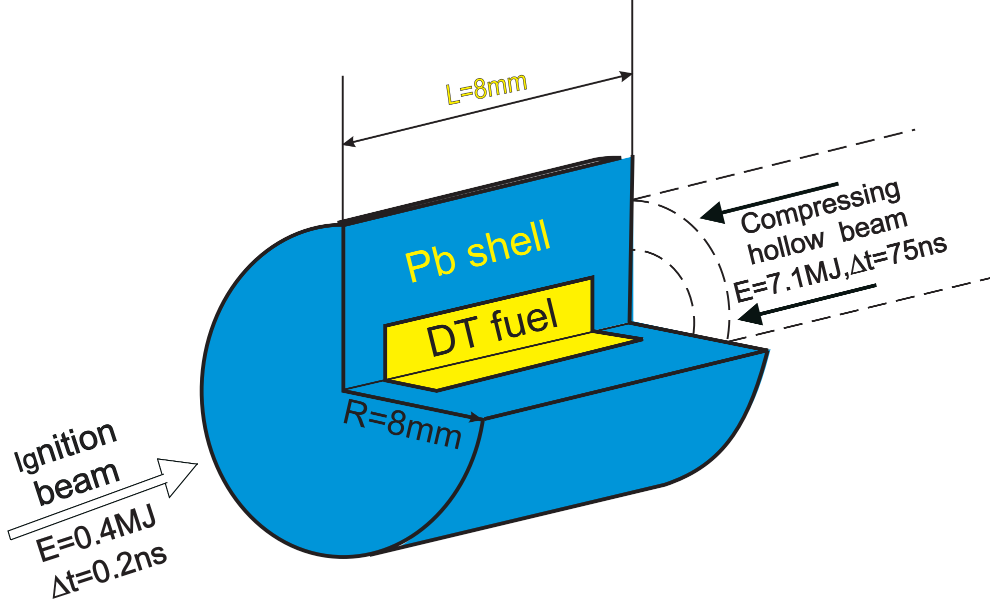
DT fuel mass	(g)	0.006
Total mass	(g)	4.44
Length	(mm)	~8.0
ρR parameter	(g/cm^2)	0.5
Burn fraction		0.39
Gain		100
Fusion yield	(MJ)	750

Energy release partition

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

Quasi-isentropic cylindrical compression





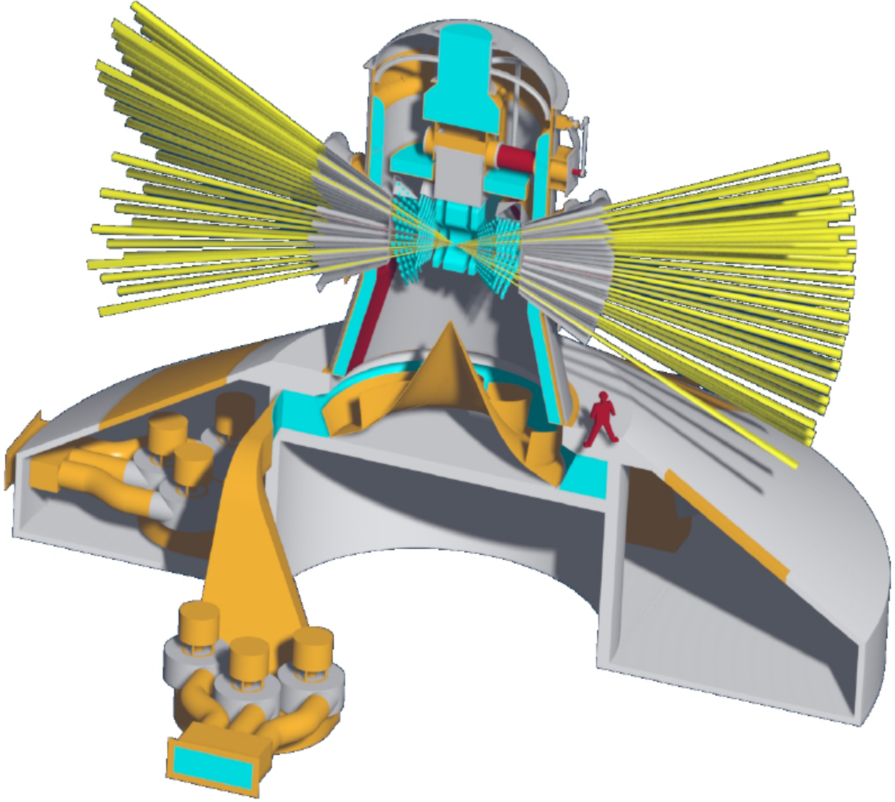
0 - t* - isentropic regime;
Q(t*) – peak power deposition;
t - end of the energy deposition;**
F(t) – total deposited energy;**
t* < t < t - limited specific deposition power;**

EOS: ideal gas $\gamma = 5/3$

$$P(t=0) = \frac{\rho_0}{\gamma} c_0^2$$

The temporal dependence Q(t) is obtained on the basis of a self-similar solution for isentropic compression of an initially uniform cylindrical gas volume ($\rho=\rho_0$, $c=c_0$) [1].

1. Г.В. Долголева, А.В. Забродин. (G.Dolgoleva, A.Zabrodin).
Построение решения в задаче движения слоистых оболочек
//Вопросы атомной науки и техники. Сер.: Математическое моделирование физических процессов, 1996, вып.3, с.27-34.

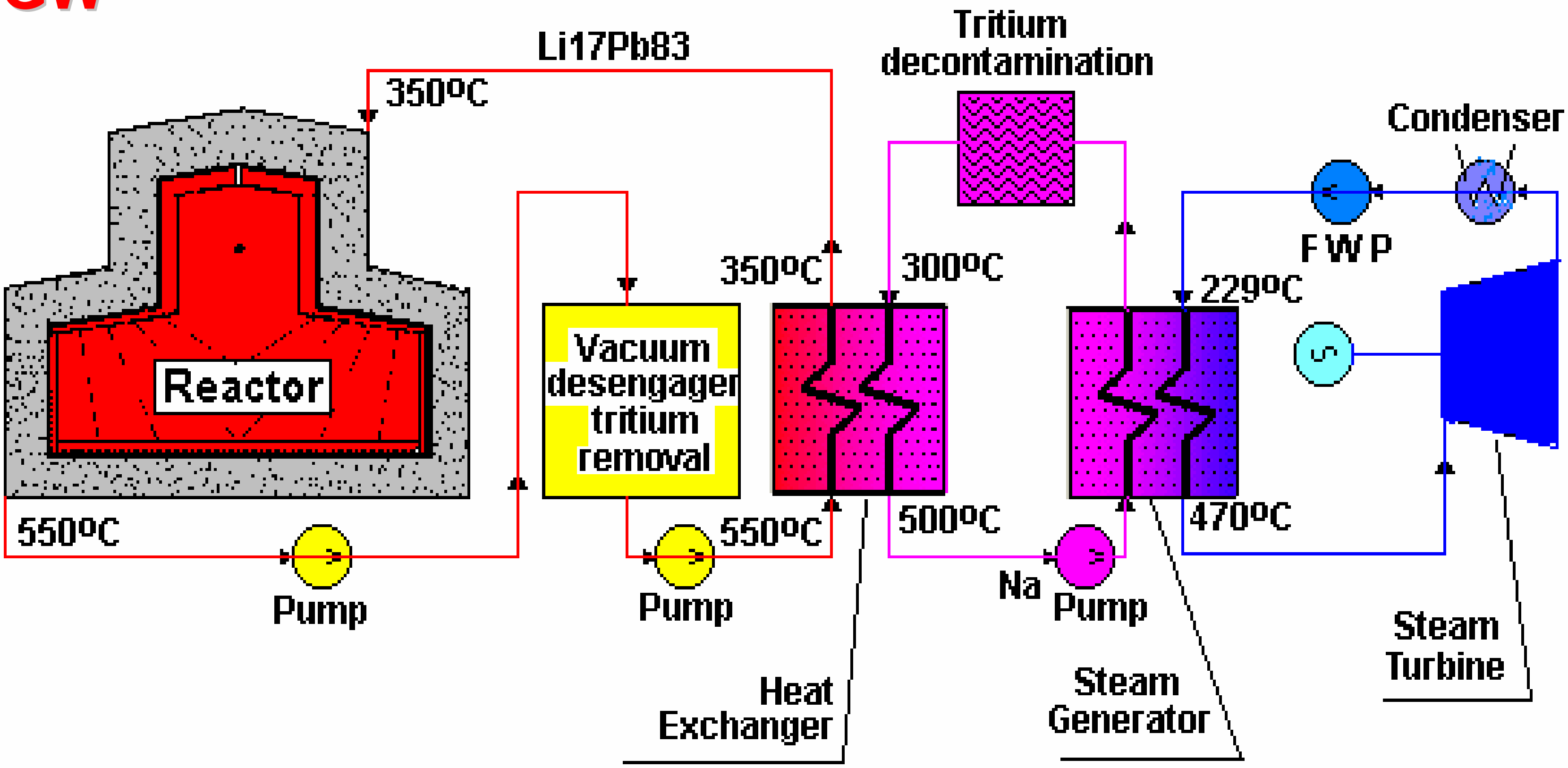


R.W.Moir 1996 thick-liquid wall design for cooling, breeding and first wall protection

REACTOR CHAMBER FOR HIF POWER PLANT: wetted first wall design

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

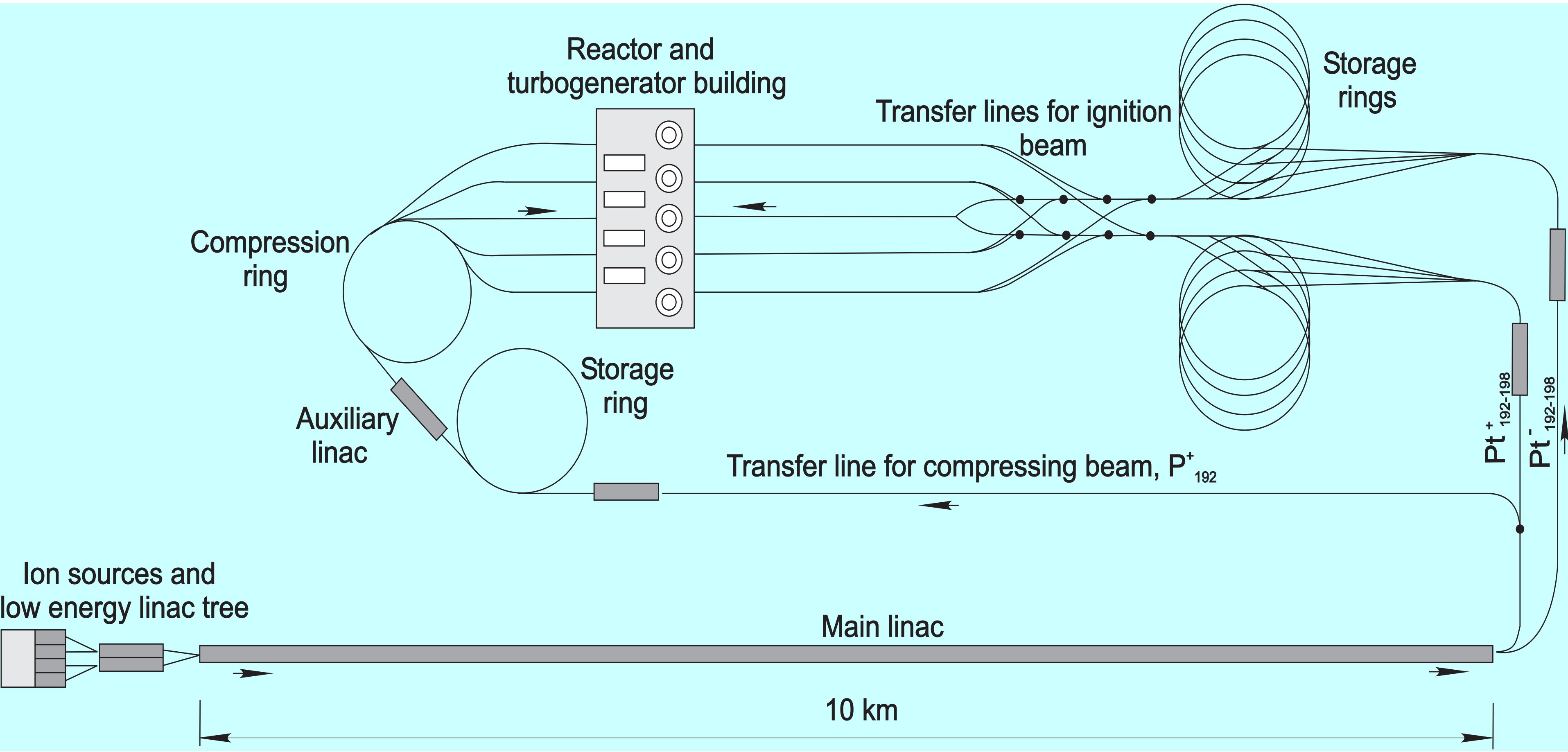
1 GW



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.

Ground plan
for HI IFE power plant



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

Goal of HIF-VNL science: explore limits to beam brightness that lead to lowest energy to drive targets

Through advanced diagnostics, beam control algorithms, optimized focusing systems, innovative target designs and good plasma neutralization

move from "Conservative" to "Potential" :

Focal spotsize: Rf ~ 2.5 mm ⇒ 1 mm or less
Ion kinetic energy: Ei ~ 10 GeV ⇒ 1 GeV or less
Total beam energy ~10 MJ ⇒ 1 MJ or less

Exploring application of new beam compression and focusing advances for HEDP *towards heavy ion fusion.*

(1) Neutralized beam compression and focusing enables ablative ***direct drive with low range ions*** at **high beam-to-fuel-energy coupling efficiency** > 15 to 25 %.

↓

(2) High beam-to-fuel coupling efficiency enables high ρr > **6 to10 g/cm^2 T-lean fuel assemblies** that self-absorb most neutron energy at moderate driver energies of 3 to 4 MJ.

↓

(3) Self-breeding T-lean targets enable > 90% of the fusion yield captured into target shells for **low-cost direct plasma MHD conversion** ➔ ultimately low CoE < coal or fission.

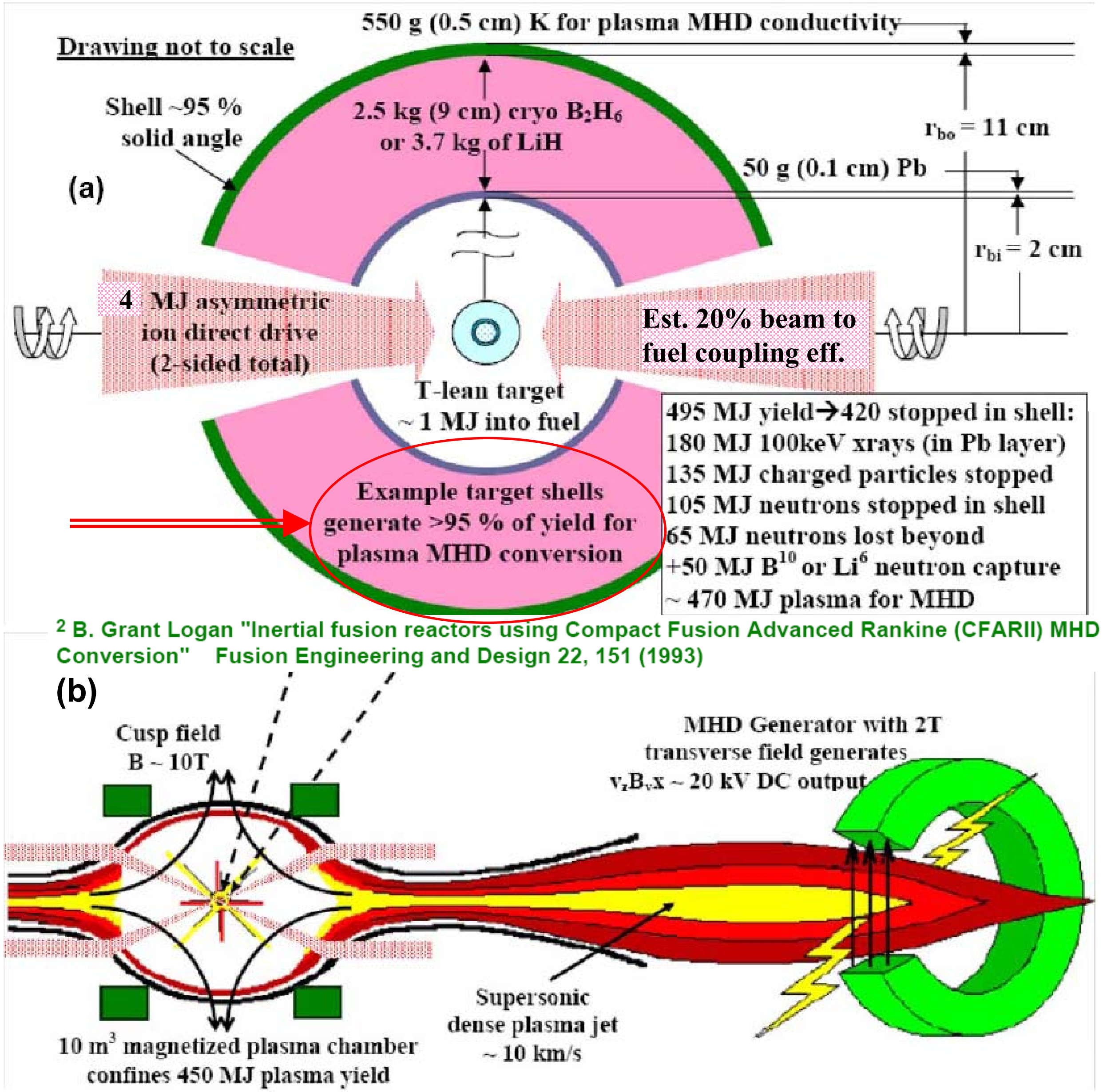


Figure 4: (a) Example target shell for efficient conversion of T-lean target output into 1 to 2 eV dense plasma for direct MHD conversion. All shell materials condense and recycle (Rankine cycle).
(b) Schematic of the CFAR MHD scheme (adapting the old 1992 CFAR Logo!)--no detailed design yet.

High efficiency ion direct drive enables CFAR plasma direct conversion at moderate yields

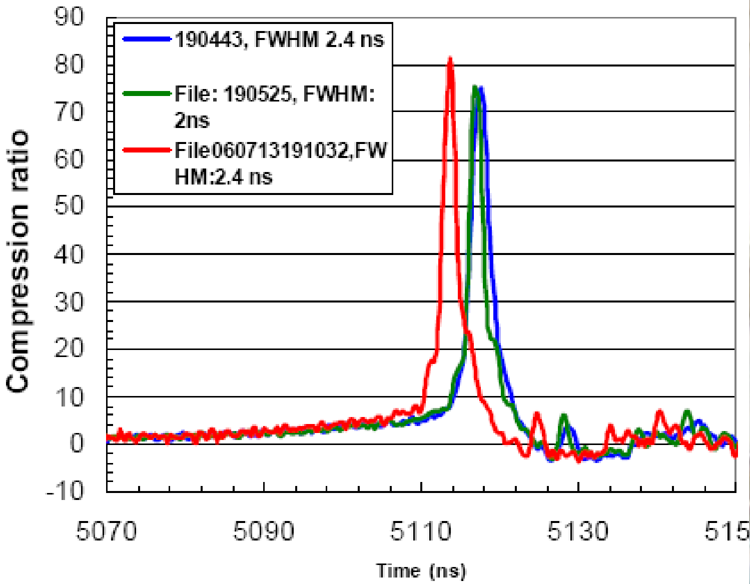
Note key facts about the marriage of T-lean targets (Max Tabak 1996) to CFAR MHD conversion:
(1) Most T-lean target yield can be captured for direct plasma MHD conversion, even down to 1MJ–scale DEMO drivers.
(2) Plasma conductivity is 10^4 times greater at 25,000 K than at 2500 K→ the extractable MHD conversion power density ~σu^2, where u~10km/s is the plasma jet velocity, is >30 times the power density of steam turbine generators[2].
→As a consequence, the CFAR Balance of Plant *cost* can be much lower, < $ 80 M/ GWe!

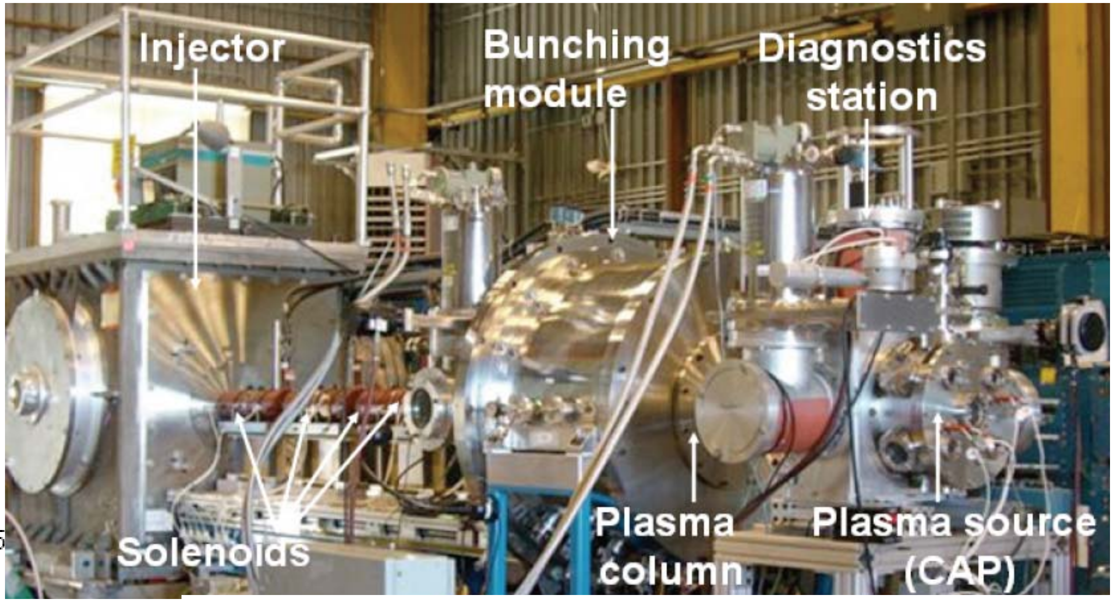
See Grant Logan F03.2

Present Status

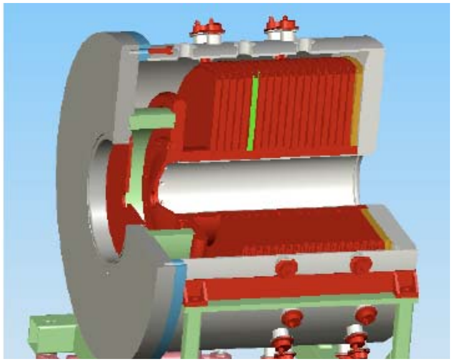
The neutralized drift compression experiment (NDCX-I) continues to improve longitudinal compression of intense neutralized ion beams

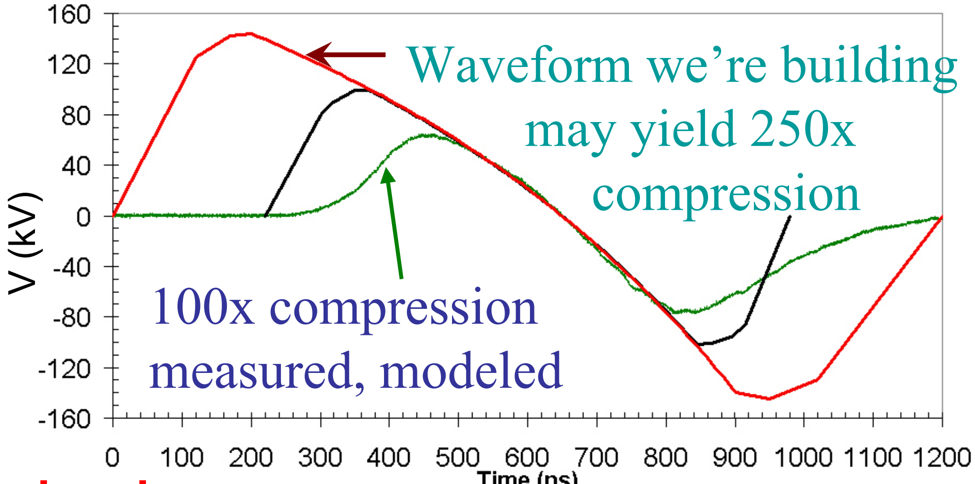
Shorter pulses (2.4 ns) obtained with new Ferro-electric plasma source





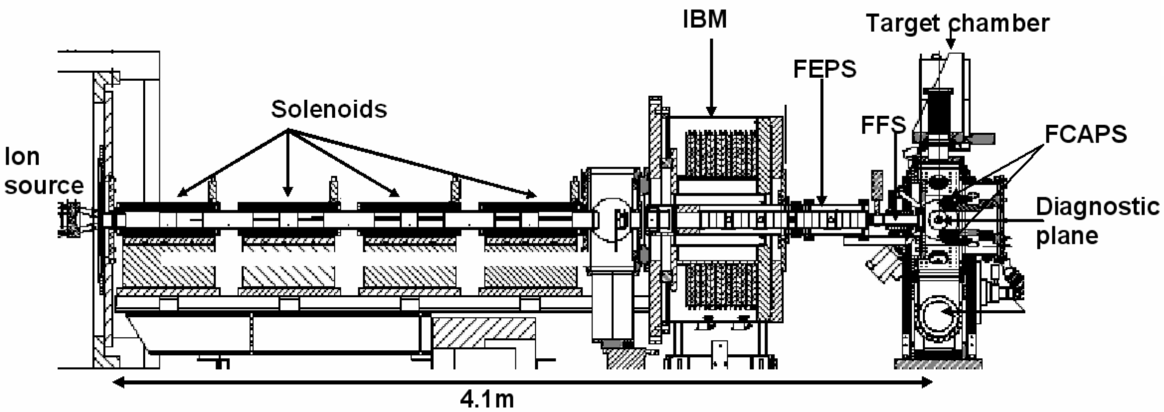
Simulations predict higher compression with new induction bunching module to be installed this summer



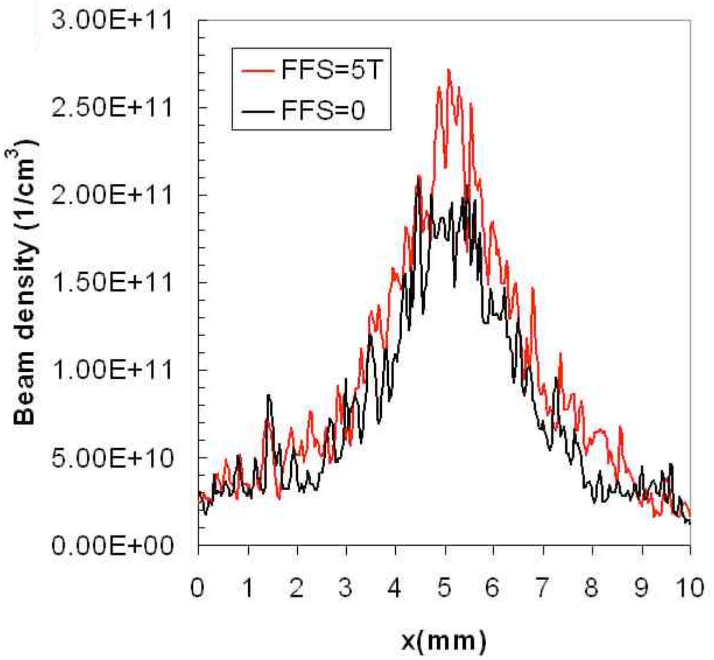


Adds a velocity ramp from the tail to the head

In June 2007, first tests using a 5 T final focus magnet increased final focus beam intensity on axis -further optimization in progress



NDCX Left to right: 315 keV, 25 mA K+ ion source, solenoid transport section, induction bunching module (IBM) which imparts the velocity ramp on a 150 ns slice of the injected beam, ferroelectric plasma source (FEPS), 5T final focus solenoid (FFS), and new target chamber containing diagnostics at the target plane and two filtered cathodic arc plasma sources (FCAPS).



Beam density profiles at the target focal plane with the final focus solenoid on (FFS=5T) and off (FFS=0).

US Heavy ion driven HEDP and Fusion:

- **Heavy Ion Fusion Science experiments and simulations on NDCX I are making outstanding progress in neutralized beam compression and focusing in background plasma.**

- **Warm Dense Matter experiments are beginning**
  -- Transient darkening experiments on HCX
  -- Metallic foam studies at GSI
  -- Target heating experiments (~.2 - .5 eV) to begin this year on NDCX I
  -- 1 eV experiments on NDCX II by 2010

- **Hydrodynamics experiments for stability and ion ablative direct drive physics are being studied for NDCX II.**

- **Analytic and hydro code calculations are being pursued for heavy ion fusion in two-sided polar direct drive geometry.**

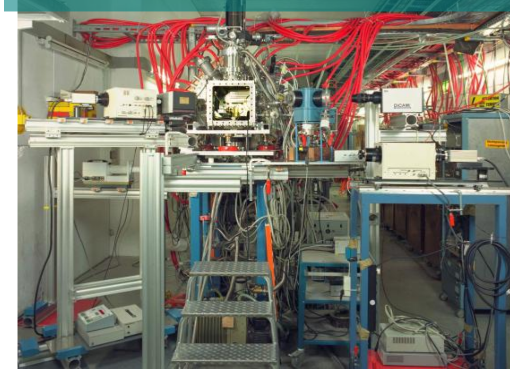
Present Plasma Physics experimental areas at GSI- Darmstad, Germany

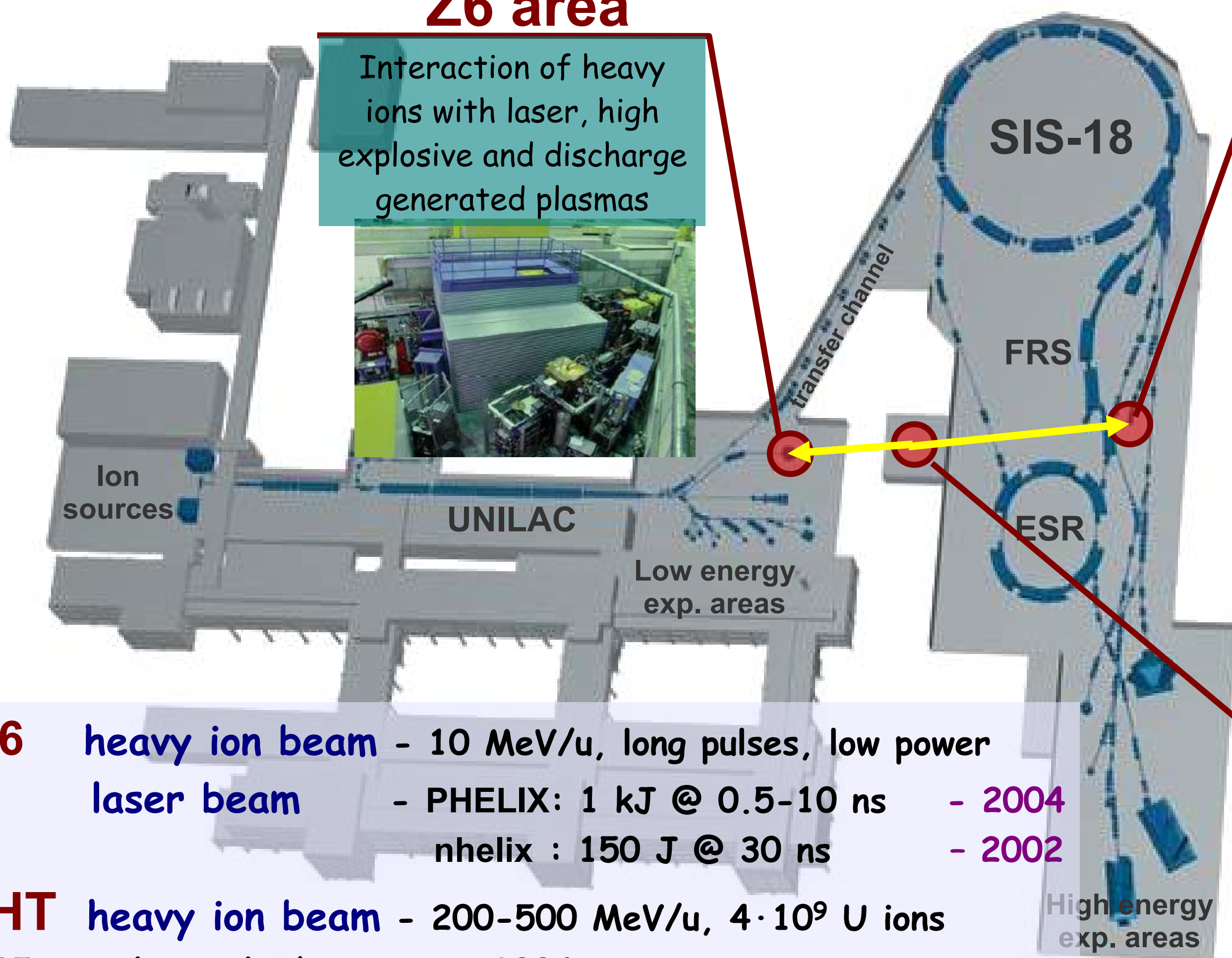
Z6 area

Interaction of heavy ions with laser, high explosive and discharge generated plasmas

HHT area

HED matter generated by intense heavy-ion beams





PHELIX

Petawatt High-Energy Laser for Ion-Beam Experiments

Z6 heavy ion beam - 10 MeV/u, long pulses, low power

laser beam - PHELIX: 1 kJ @ 0.5-10 ns - 2004

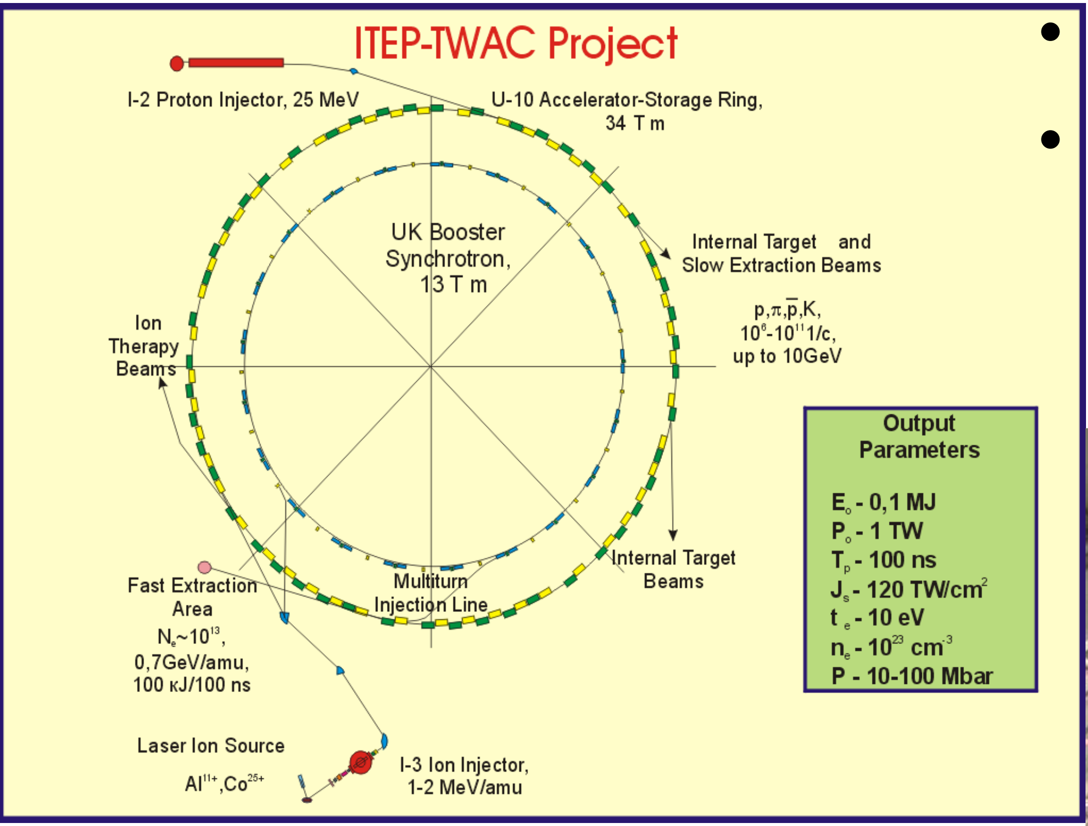
nhelix : 150 J @ 30 ns - 2002

HHT heavy ion beam - 200-500 MeV/u, $4 \cdot 10^9$ U ions in 125 ns pulse, ~ kJ/g -2004

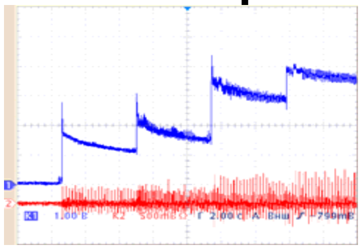
laser beam - PHELIX: 0.5 kJ @ 0.5 ps (PW) -2006

1-5 kJ @ 10 ns

ITEP-TWAC project in progress



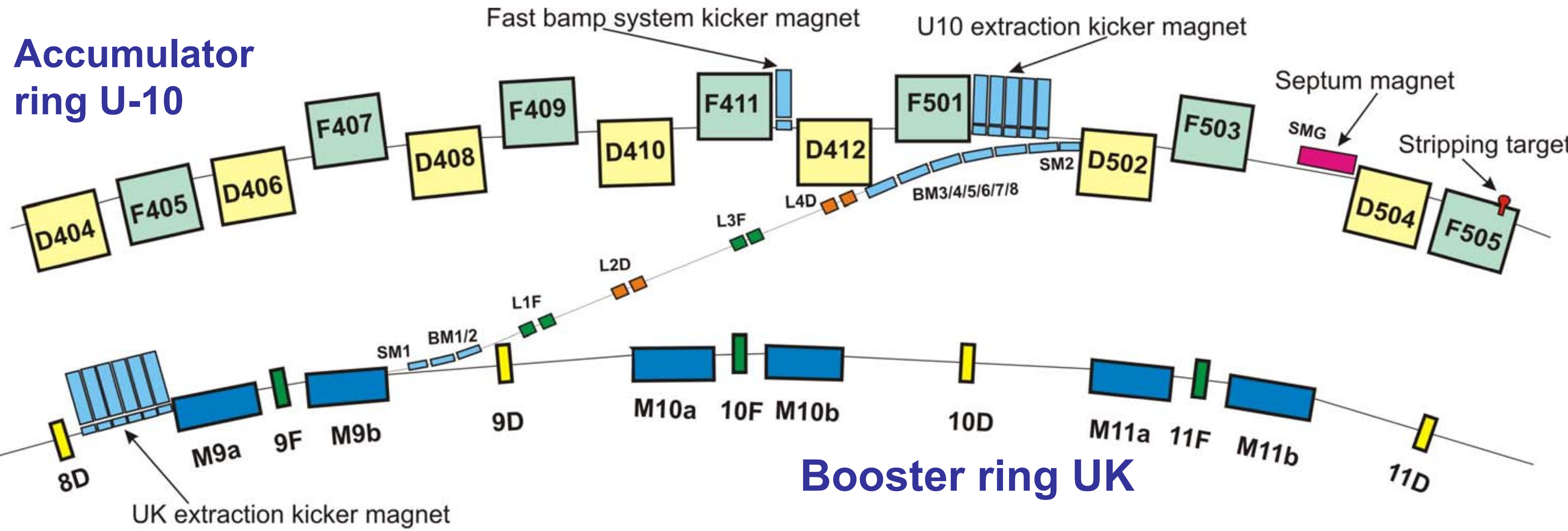
- $>10^{10}$ C6+ accumulated
- accelerated up to 4 GeV/u

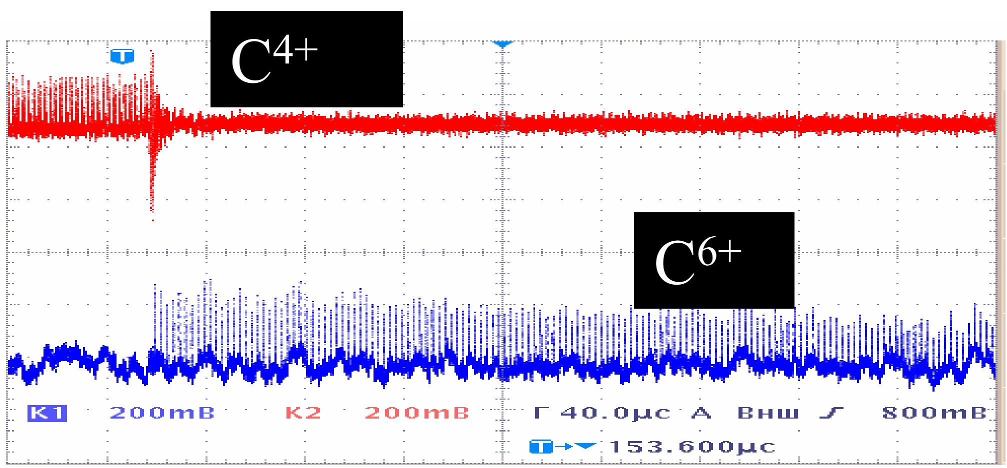


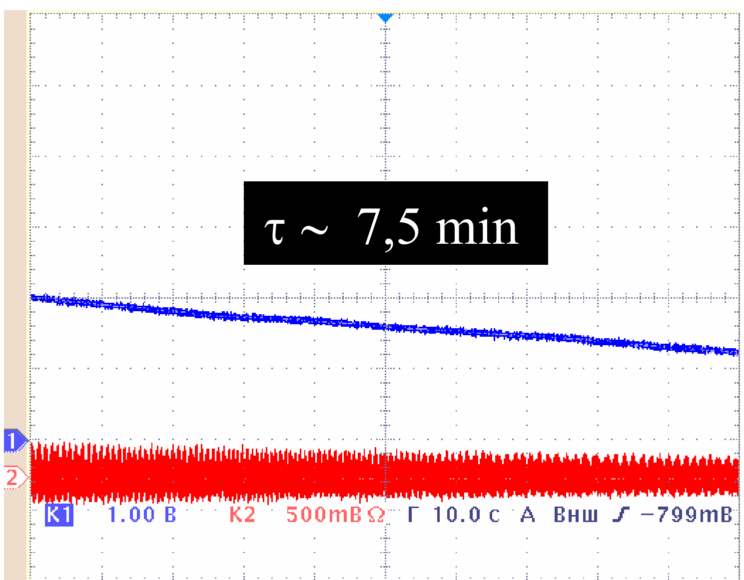
HIF Accelerator Technology Issues

- 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**

Non-Liouvillian Injection into the storage ring



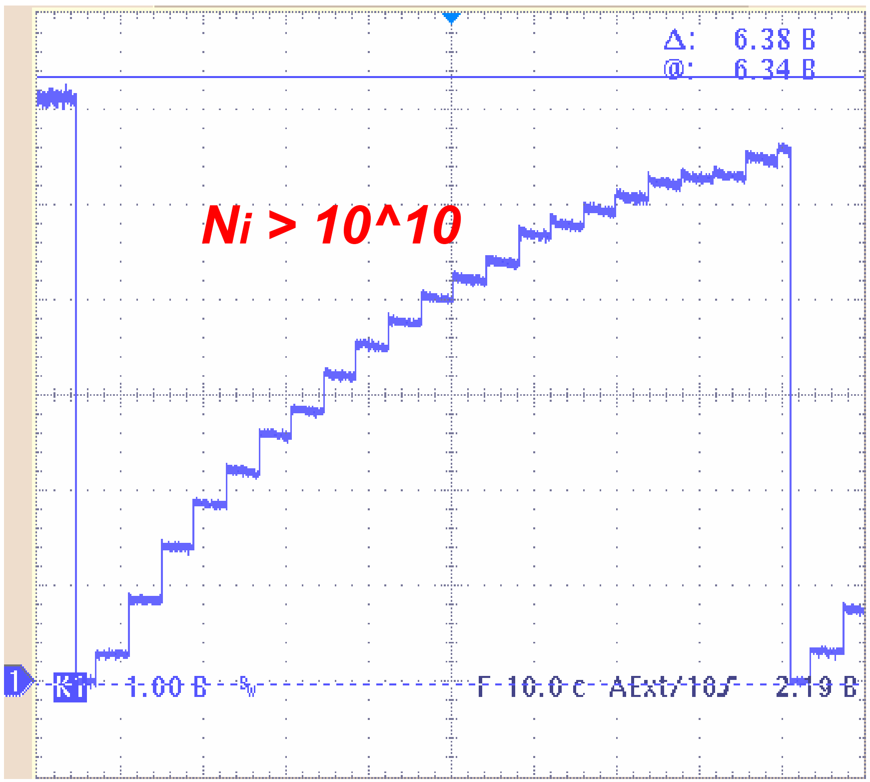


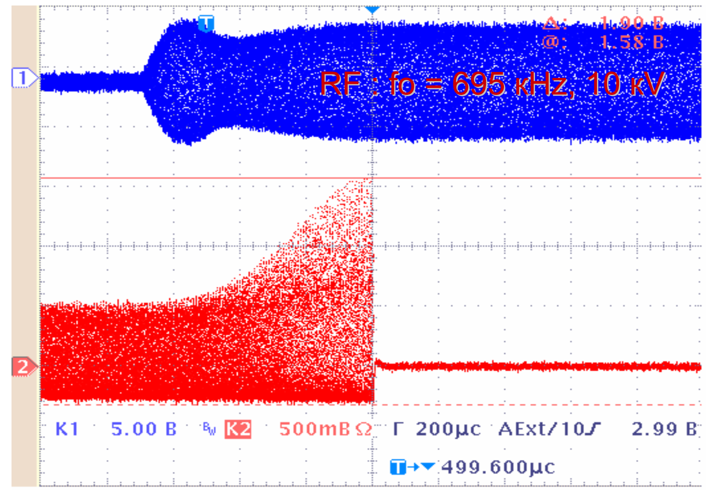


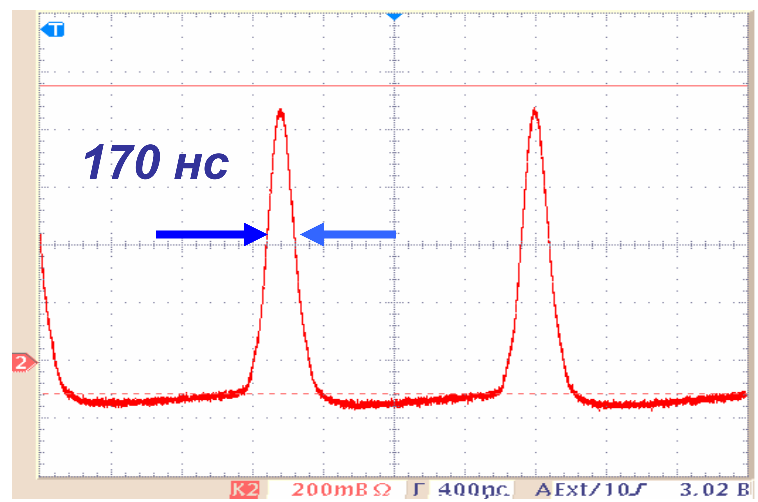
Non-Liouvillian stacking process

RF bunch compression

Stacking process for 213 MeV/u C6+

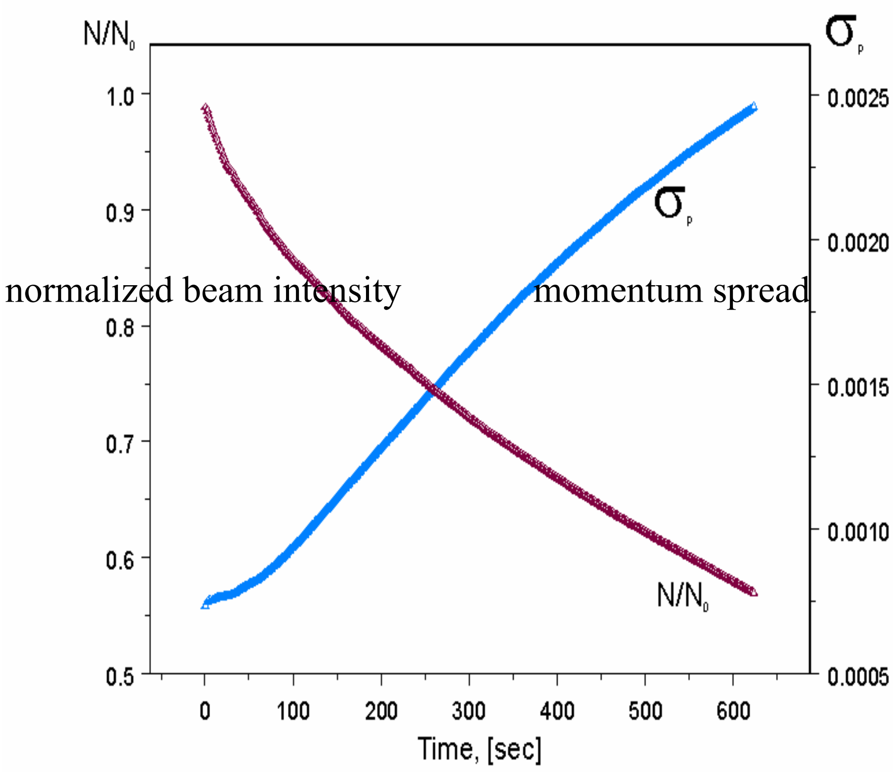






"**Beam Physics Group**" (P. R. Zenkevich et al) :
Intra-beam scattering (IBS) & Coherent instabilities.
for ITEP-TWAC and HESR p-bar storage ring of FAIR

INTAS-GSI grant "Advanced Physics Dynamics" Ref. Nr. 03-545584

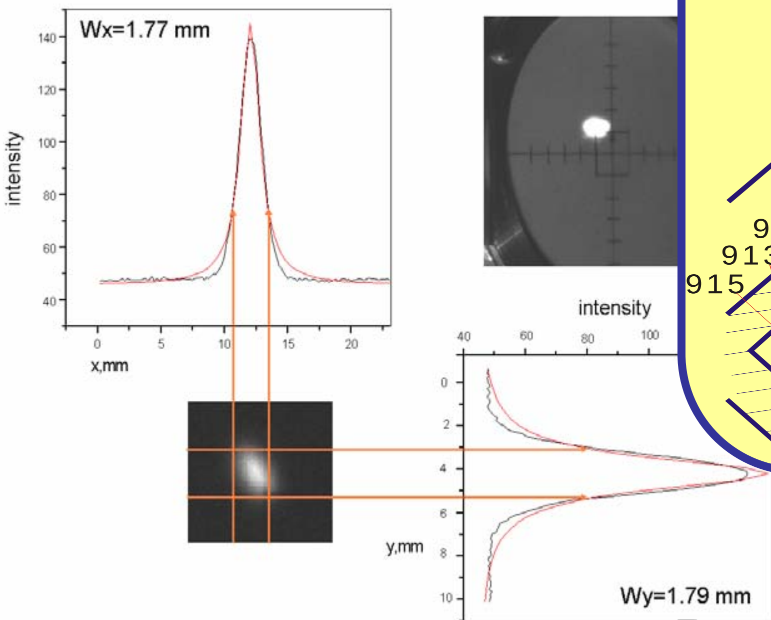


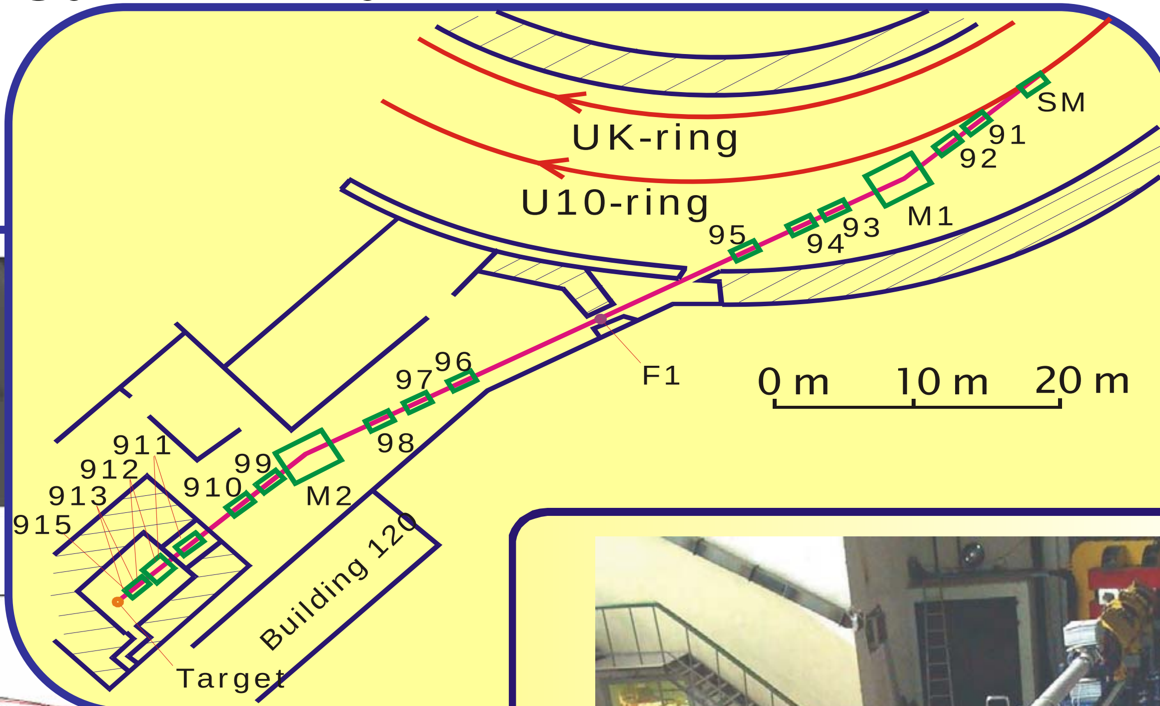
longitudinal heating of the beam due to multiple intra-beam scattering (IBS) results in a growth of the momentum spread and beam losses it limits a power of the extracted beam in TWAC.

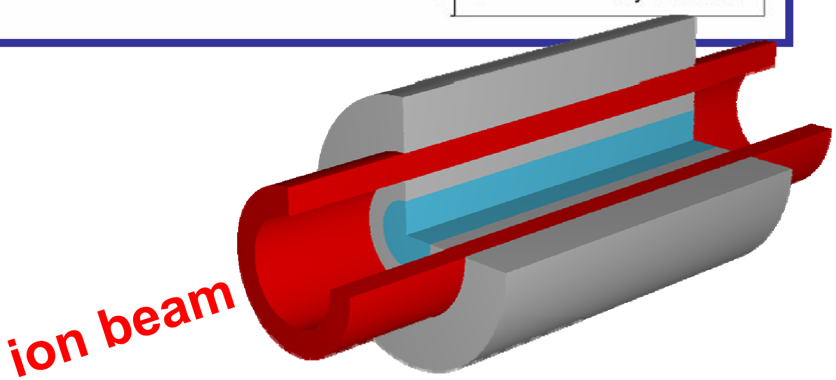
P. R. Zenkevich at this Symposium:
"Last Advances in Analysis of Intra-Beam Scattering in the Hadron Storage Rings".

High energy density experimental area

ITEP-TWAC

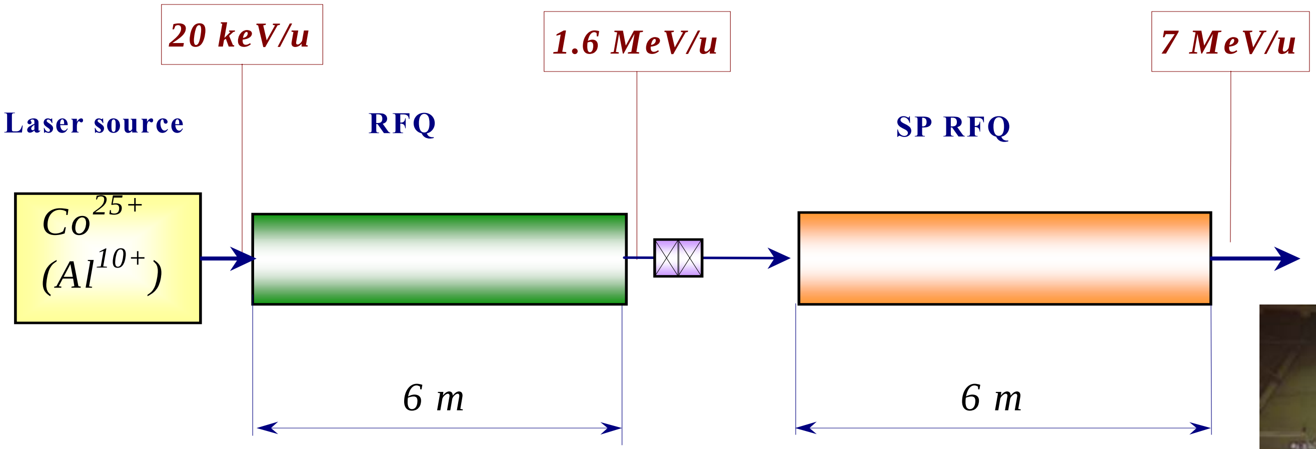






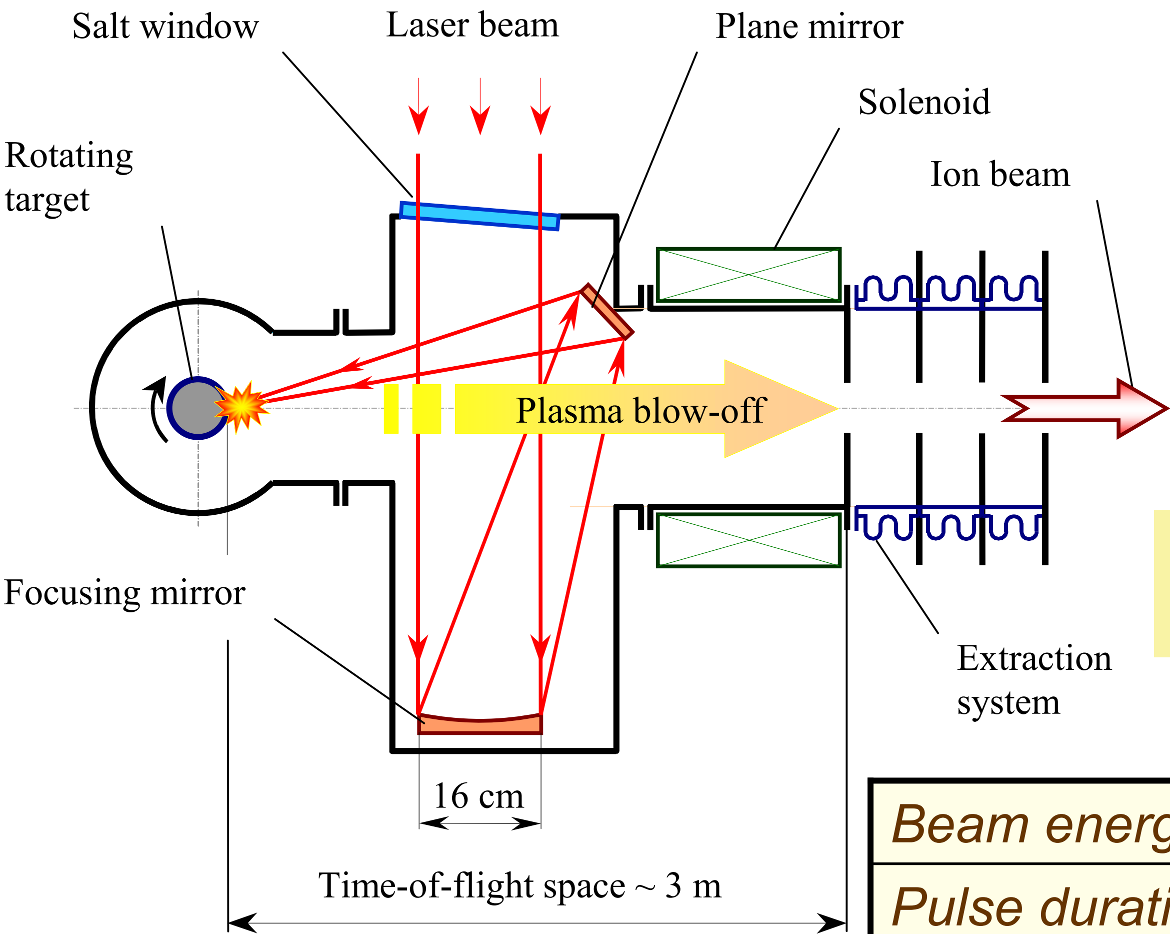
Cylindrical implosion experiment
300 MHz wobbler

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

CO_2 Laser ion source



Target with diameter of *150 mm* and height of *200 mm* for more than *$2*10^6$* shots

3 mA 80 MeV Fe 16+ Measured !

Beam energy	*100 J*
Pulse duration	*20-50ns*
Laser beam diameter	*16 cm*
Repetition rate	*1 Hz*

SUMMARY

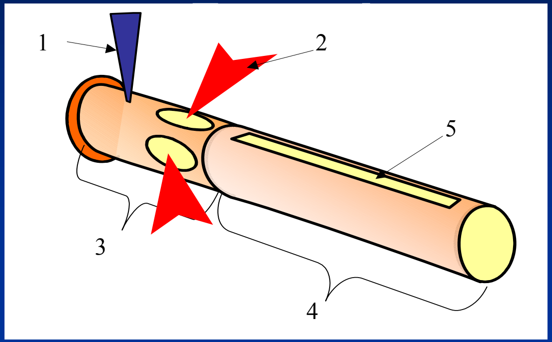
We have a large knowledge base developed in heavy ion fusion research over the last thirty years to build upon:

1. Theory and simulations of intense, space-charge dominated beams: transport, beam brightness evolution, collective effects, instabilities, e-clouds, neutralization, compression and focusing.
2. High brightness beam transport: development of experimental control and understanding of intense beam centroid motion, 4-D distribution evolution, emittance growth, transport limits, and multi-species gas and e-cloud effects.
3. Longitudinal beam compression: experimental control of longitudinal velocity distributions allows up to 60 X longitudinal compression factors, enabling few-ns pulses needed for near-term target experiments.
4. Focusing onto targets: Near emittance-limited beam spots (over 20 X in radial compression to 1 mm spots) using plasma neutralization of otherwise highly space-charge dominated beams.
5. Beam-target interactions: ITEP- GSI- VNIIEF s have measured and calculated heavy ion beam dE/dx within a few percent, focused to < 300 micron spots, compressed to < 130 ns pulses, and heated metal targets to 1 eV.

OUTLOOK

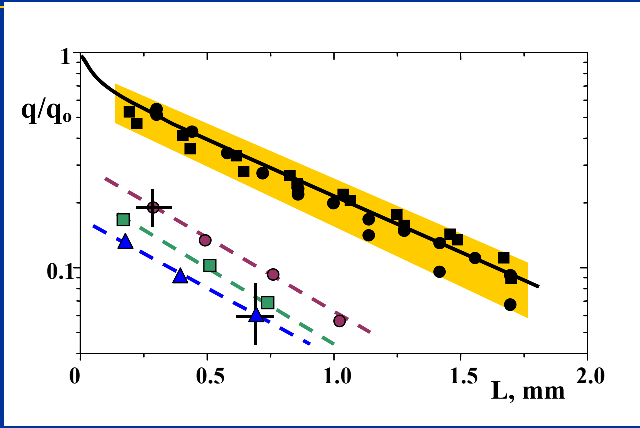
"ISKRA-5" laser facility 3 kJ / 0.4 ns

X-ray transport experiments



1-holder, 2- laser beams, 3- "Illuminator", 4- cylindrical channel, 5- diagnostic slit

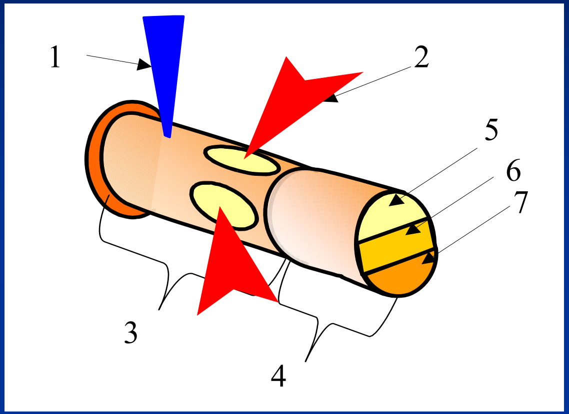
The normalized x-ray flux along cylindrical channels in the range 0.2<hv<1 keV



The shaded area corresponds to the experimental data spread for gold channel, ● - indium, ■ - copper and △ -magnesium.

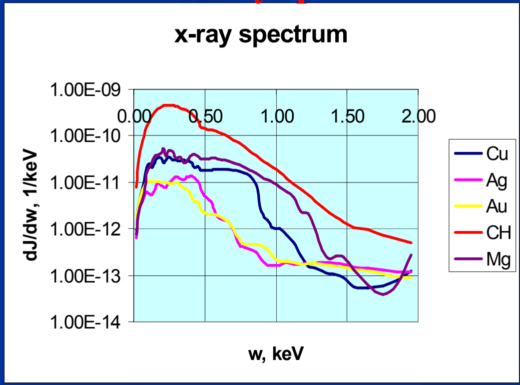
X-ray materials heating experiments

Target scheme

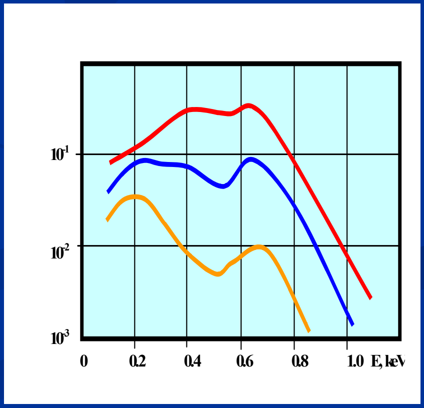


1-holder, 2- laser beams, 3- "Illuminator", 4- cylindrical box, 5- free zone, 6,7- zones for location of testing materials.

Theoretical x-ray spectrum

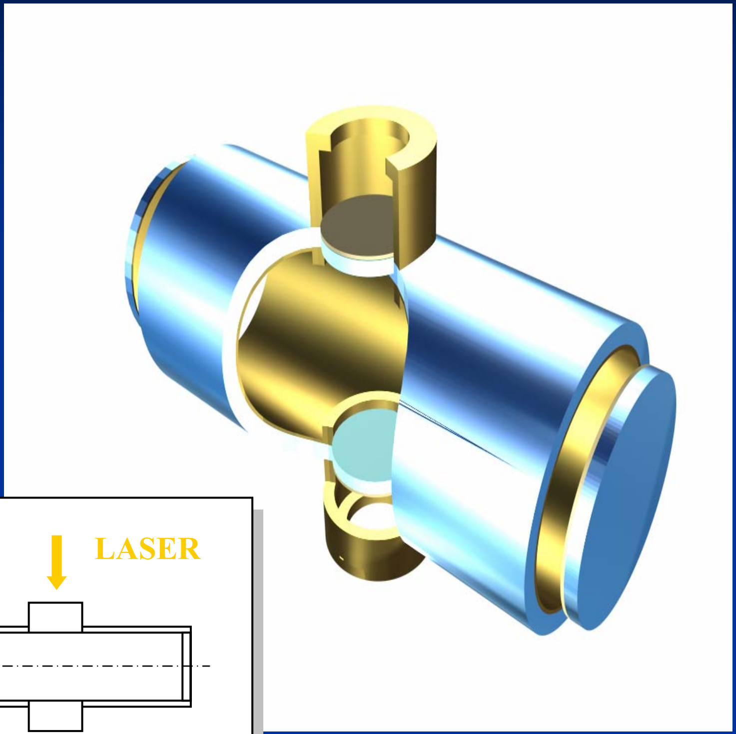


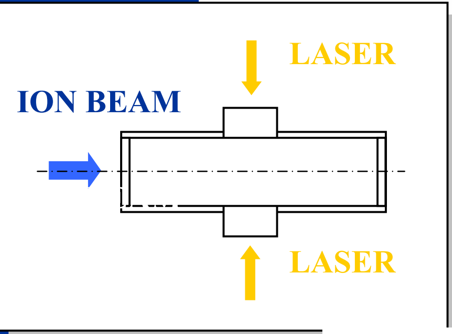
Experiments.

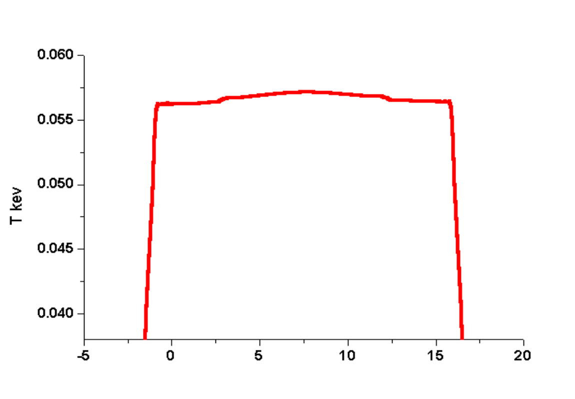


Free zone, Au – 0.2 μm, Au – 0.4 μm,

Indirect targets for ion stopping experiment for *Phelix* + *Unilac*







I. Vacuum target

High-Z plasma can be produced by evaporation
of the material from inner target walls.
Plasma parameters:
T ~ 50-100eV, N~10^20 1/cm3,
practically any material

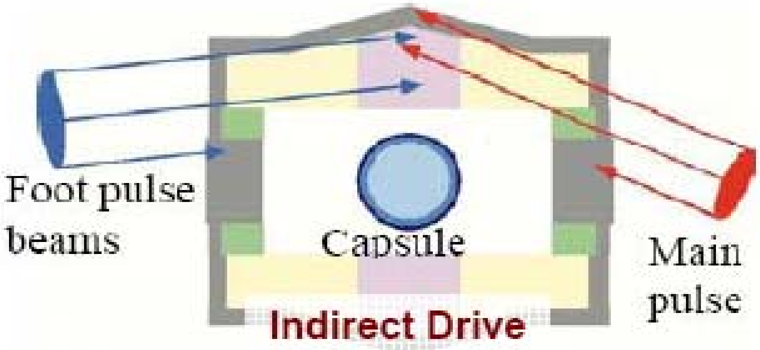
II. Target filled with low-Z low-density material

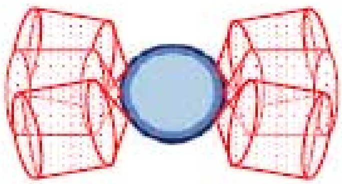
X-ray target with inner filling can be used to investigate ion stopping in hot low-Z plasma.
For example, a CH plasma with T~0.1keV and N~10^21 1/cm3 can be produced.

Plasma temperature inside the target (spatial distribution)

Analytic and hydro code calculations are being pursued for heavy ion fusion in two-sided polar direct drive geometry

Indirect drive versus polar direct drive for heavy ion fusion



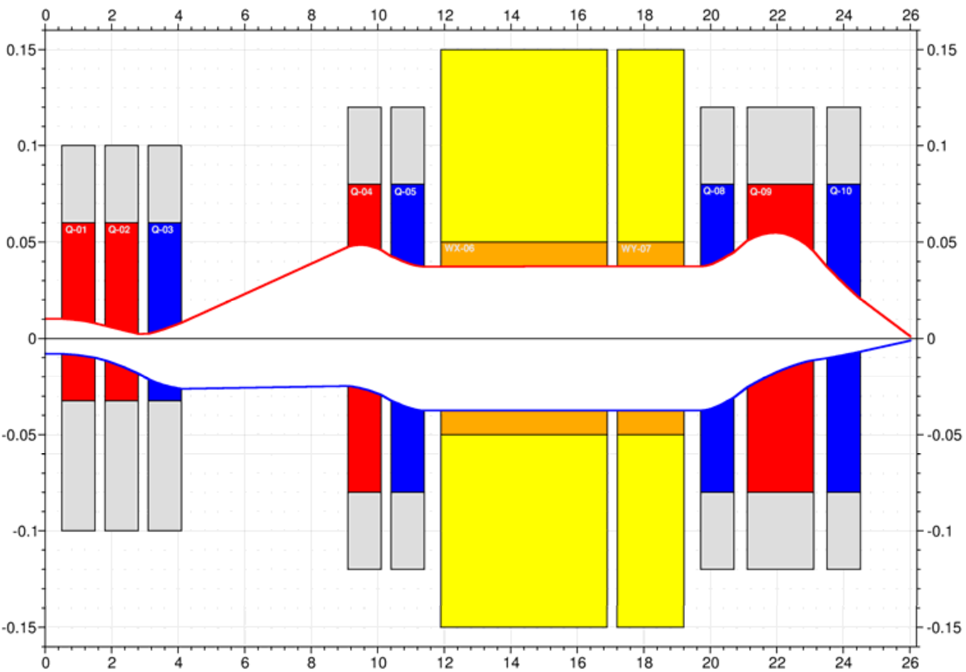


Beam smoothness: (insensitive)	< 1 % (*only* low l-mode issues)
Minimum # pulses: ~12 azimuth x 5 picket fence pulse shaping x 2 ends ~120	~ 20 azimuth x 10 picket fence pulse shaping x 2 ends ~ 400
Ion beam spot radius ~2 mm	~2 mm (1 mm for shock ign.)
Capsule absorbed energy ~ 1 MJ	~ 1 MJ
In flight aspect ratio ~ 36	~ 30 (or 10 for shock ignition)
Ion beam drive energy ~ 7 MJ	~ 1 MJ
Peak beam power ~ 500 TW	~ 200 - 500 TW (final shock)
Yield (Gain) ~ 400 MJ (57)	Yield (Gain) ~ 100 MJ (100)

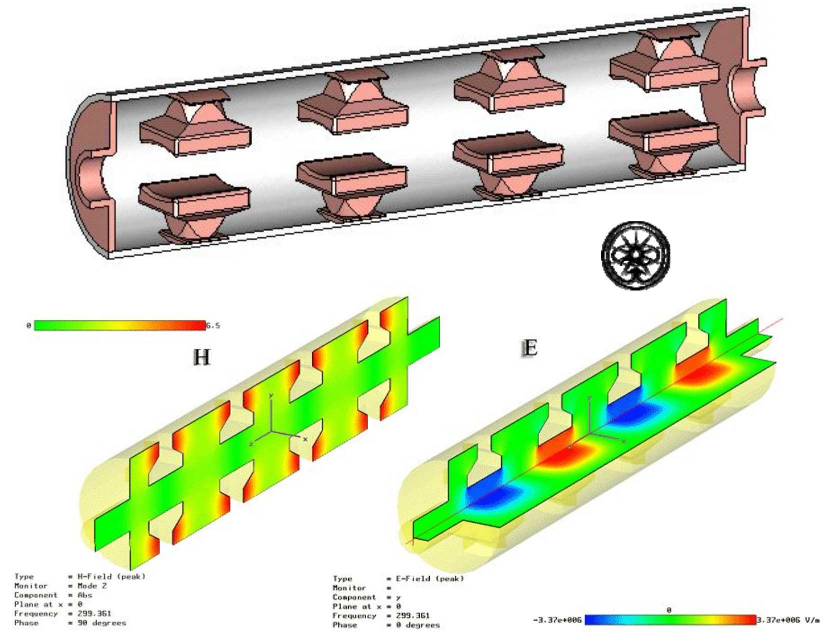
Polar direct drive tests in NIF are of paramount importance !

ITEP/GSI collaborators are developing the tools to test dynamic stabilisation of ion direct drive RT instability - LAPLAS technology

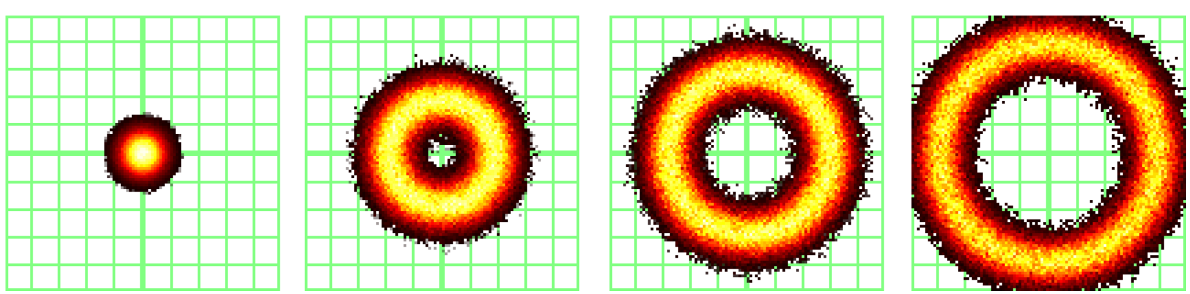
Layout of the **LAPLAS** beam line



ITEP design of rf beam deflector (wobbler)



Transverse beam intensity distribution in the focal spot

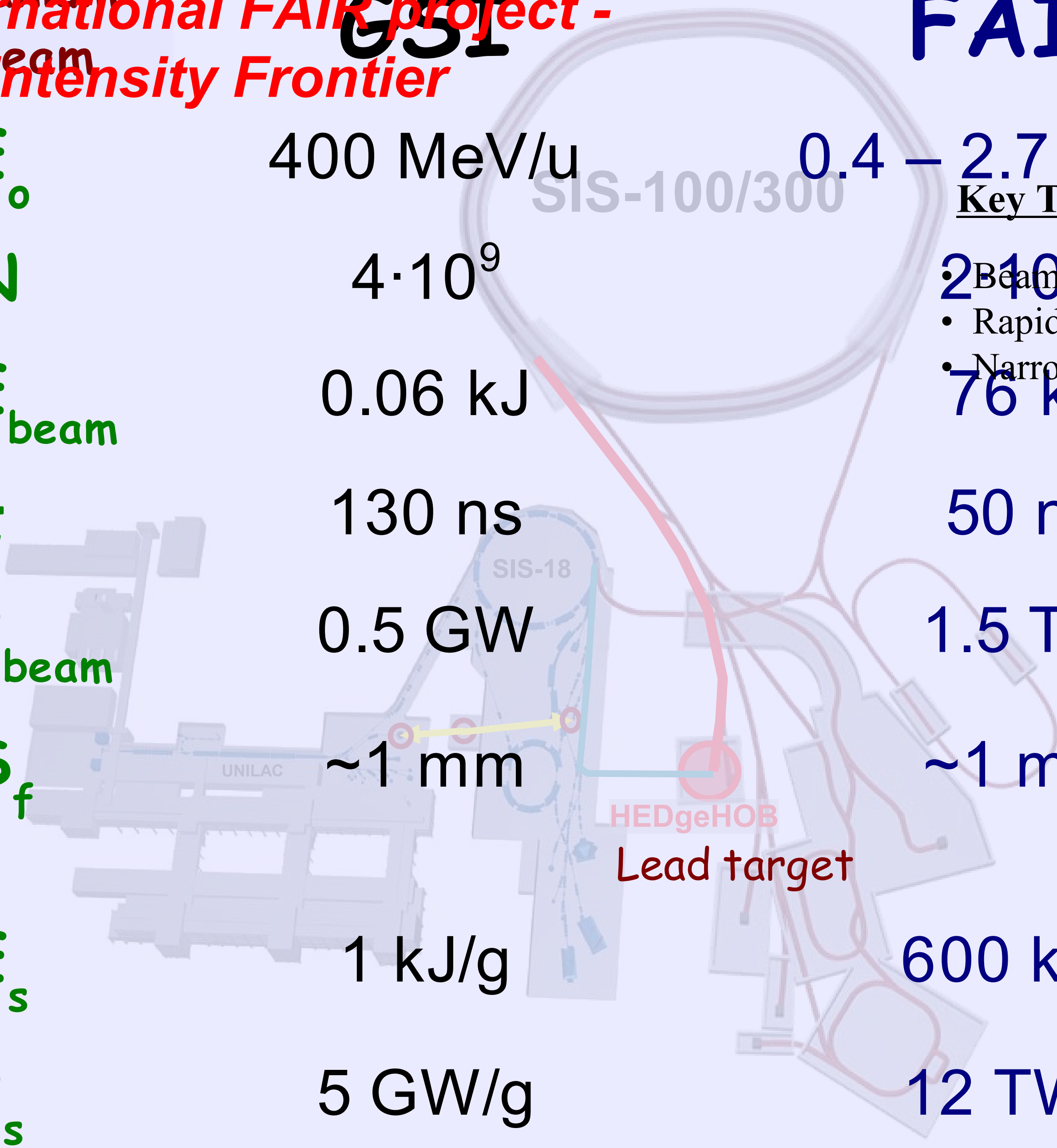


International FAIR project - the Intensity Frontier

Uranium beam	GSI	FAIR	
E_o	400 MeV/u	0.4 – 2.7 GeV/u	
N	$4 \cdot 10^9$	$2 \cdot 10^{12}$	$\times 500$
E_{beam}	0.06 kJ	76 kJ	
τ	130 ns	50 ns	
P_{beam}	0.5 GW	1.5 TW	$\times 3000$
S_f	~1 mm	~1 mm	
E_s	1 kJ/g	600 kJ/g	$\times 600$
P_s	5 GW/g	12 TW/g	$\times 2400$

Key Technologies

- Beam cooling
- Rapidly cycling superconducting magn
- Narrow bunching of beams

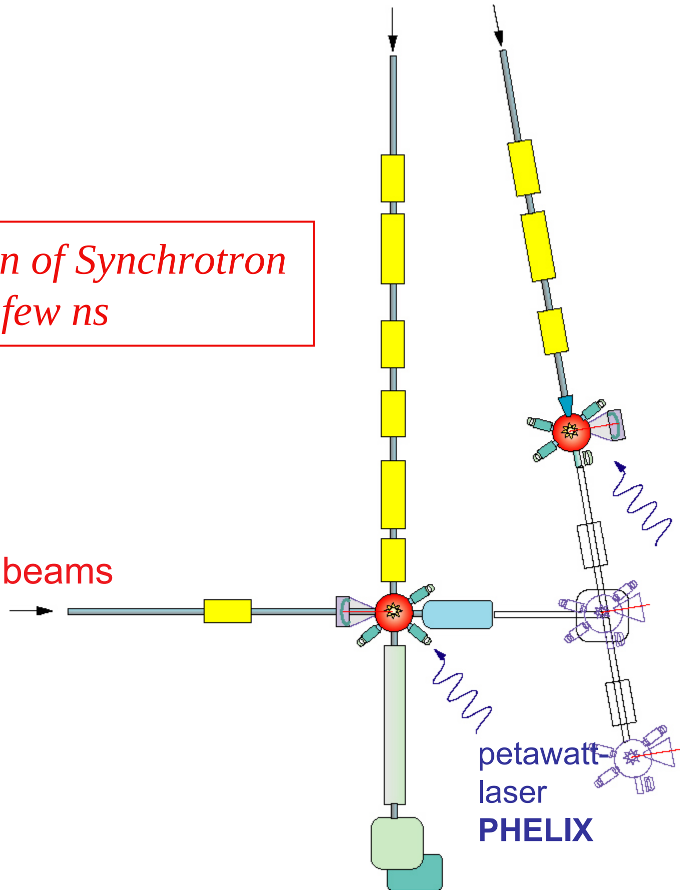


Plasma Physics with highly Bunched Beams

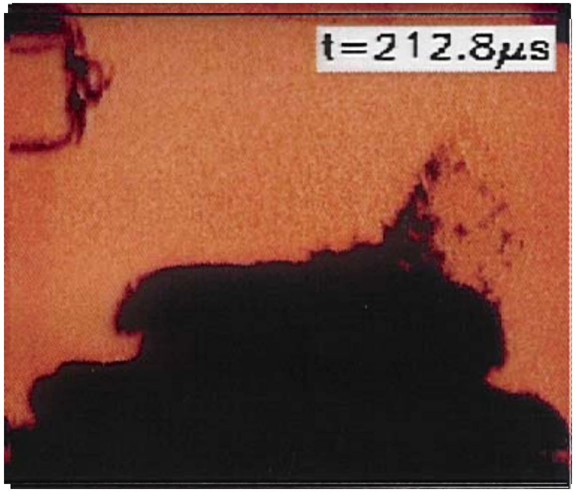
Bulk matter at very high pressures, densities, and temperatures

ΔE Energy loss of heavy ions in hot plasma is larger than in cold matter

Synchronization of Synchrotron and Laser to a few ns



Today:
30mm Xenon Crystal
10^{10} Ne^{10+} -Ions **=>>**



Expected Beam Parameters

SIS 100 (GSI)

N = 2 x 10^{12} Uranium

E_0 = 1 GeV/u

E_{tot} = 80 kJ

τ = 50 ns

Range in solid Pb ≈1.55 cm

beam radius ≈ 0.05 cm

E_s = 600 kJ/g

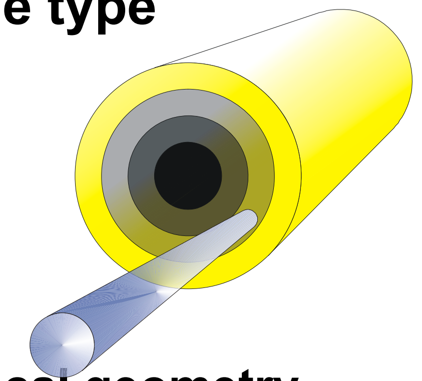
P_s = 12 TW/g

CERN LHC: 300MJ of P+ beam

N.Tahir, D.H.H.Hoffmann, V.Fortov, B.Sharkov, 2003

CONCLUSION

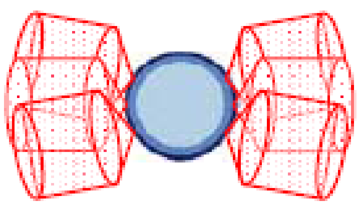
Two relatively-new pathways to HI IFE depending on the type of heavy ion driven target



European (ITEP - GSI) :

• ***Direct-drive*** **heavy-ion-driven fast ignition targets in cylindrical geometry using ~5 MJ of** ***long range (~ 6 g/cm2) 100 GeV*** **heavy ion beams (ITEP/IAM/IHED concept),**

(can build upon the GSI/ITEP WDM program).



US (VNL) WDM:

• ***Direct-drive*** **heavy-ion-driven spherical implosions using conventional central ignition, late-shock ignition (R. Betti -Rochester),**

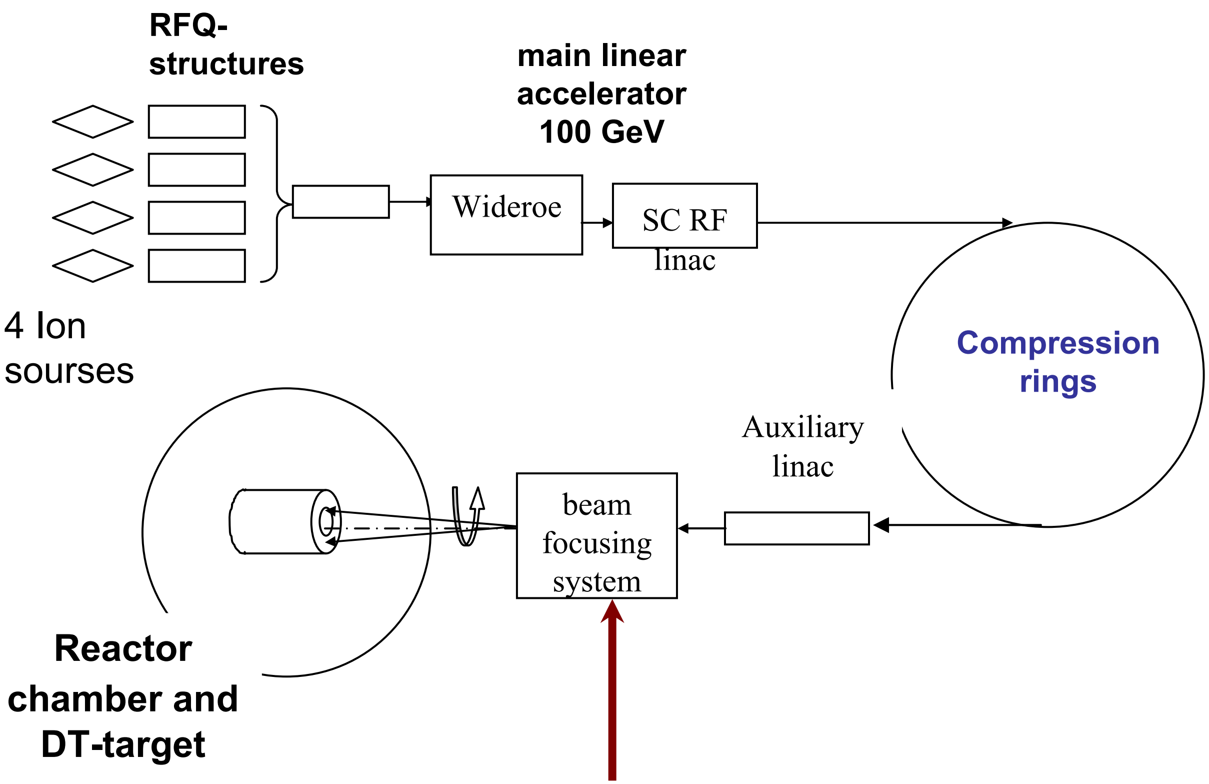
• **~1 MJ of** ***short range (~ 0.003 g/cm2) 200 MeV*** **heavy ion beams with neutralized compression and focusing**

(can build upon US WDM program).

Back up slides

Accelerator –Driver

D.G.Koshkarev



Beam rotation (wobbler) ≈1 GHz

Total energy - 12 MJ (37.5 ns)

Efficiency - 25%

Ion energy - 100 GeV

Total linac length – 11 km

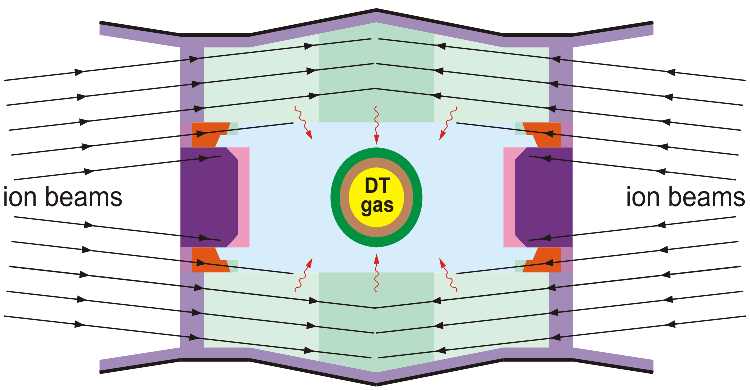
Total Beam Power - 320 TW

Focused beam D – 0.9 mm

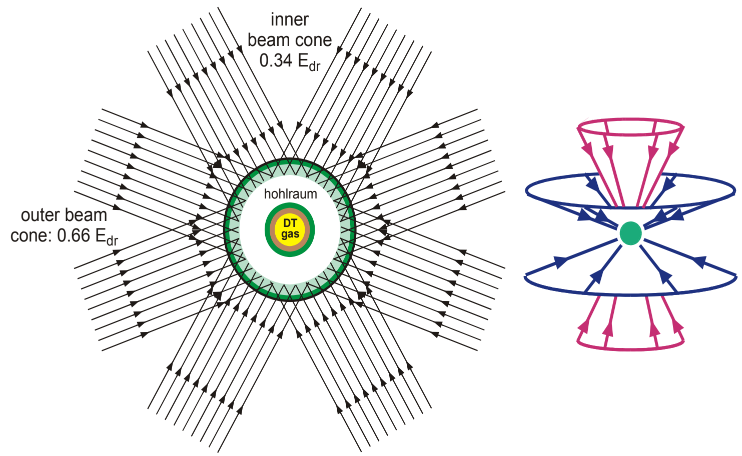
Heavy ion targets with hydrodynamic ignition

Only indirect drive option is considered to be feasible for heavy ion targets in the hydrodynamic ignition mode. The fusion capsule may be taken over from the laser targets.

Distributed-radiator target
(D.Callahan *et al*., LLNL)



P4 target with a spherical hohlraum
(M.Basko, ITEP)

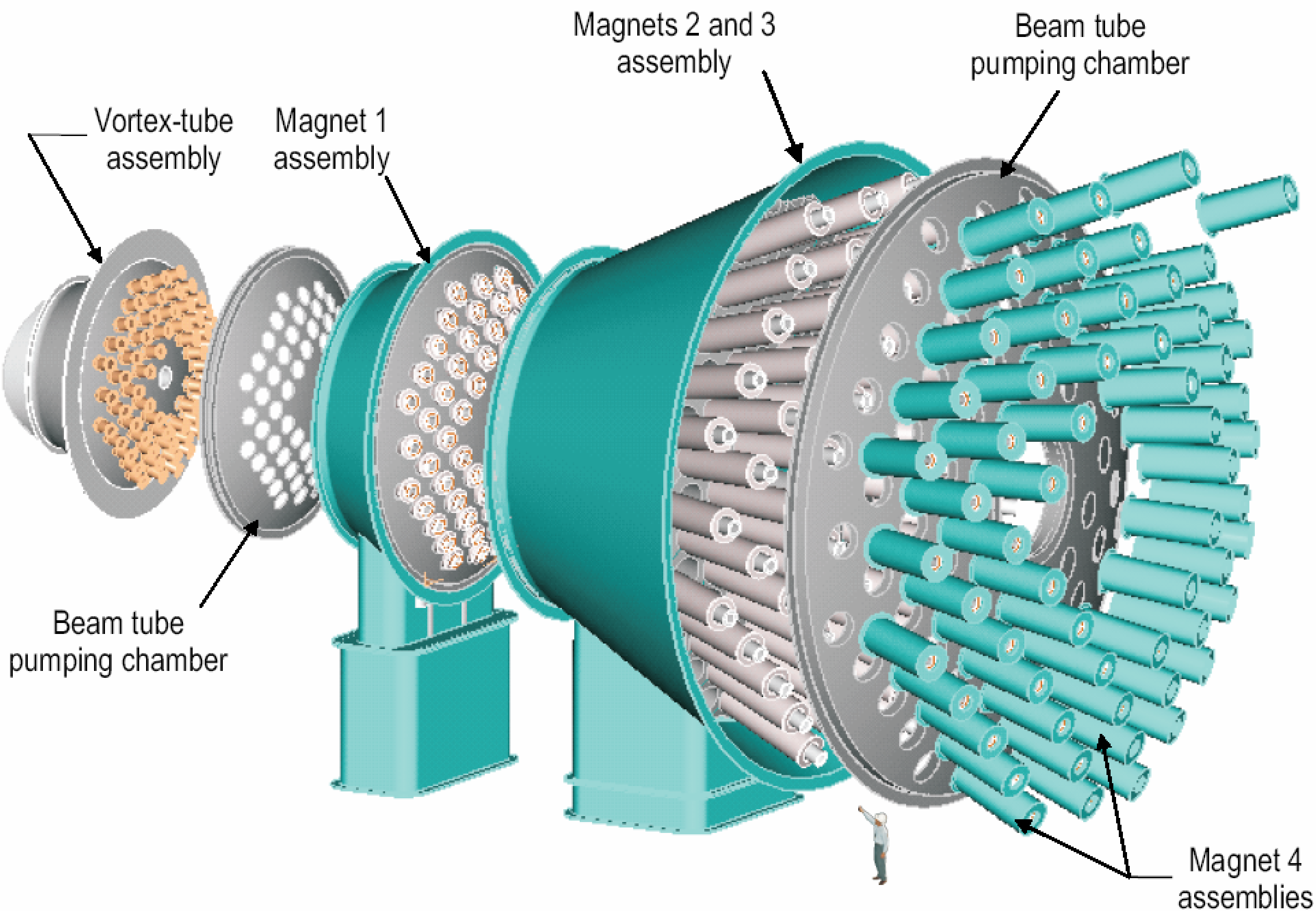


Cylindrical hohlraum, two-sided irradiation with several beam cones

Ion energy (Pb):	3 GeV $\rightarrow$ 4 GeV
Beam energy:	6.2 MJ
Energy gain:	55

Two-cone P_4 irradiation scheme

Ion energy (Bi):	5 GeV
Beam energy:	6.1 MJ
Energy gain:	78


Magnets 2 and 3
assembly
Beam tube
pumping chamber
Vortex-tube
assembly
Magnet 1
assembly
Beam tube
pumping chamber
Magnet 4
assemblies

Highlights of the US heavy ion fusion science program

- Compressed intense heavy ion beams in neutralizing background plasma in NDCX-I: 200 ns down to 2 ns FWHM.

- Begun heavy-ion driven isochoric target heating experiments to 1 eV in joint experiments with GSI, Germany, to develop HEDP diagnostics*.

- Unique diagnostic measurements of electron cloud effects on intense heavy-ion beam transport in both quadrupole and solenoid magnets.

- Computer simulation models that match the experimental results in both neutralized beam compression and e-cloud studies.

- ATA accelerator equipment sufficient for 3 to 6 MeV NDCX-II next step for both warm dense matter and ion direct drive target physics experiments.

- In-house capability to run HYDRA code for NDCX target design support, and to explore new heavy ion fusion direct drive target concept**.

ITEP-TWAC, Experimental Area for HED

Пучки В511 и В512.   Вид сверху.

Reasons to re-consider direct drive for heavy ion fusion

With modern (mostly DT) direct drive capsules *and* super-efficient heavy ion beam coupling, <1 MJ drive may suffice for ηG >20!

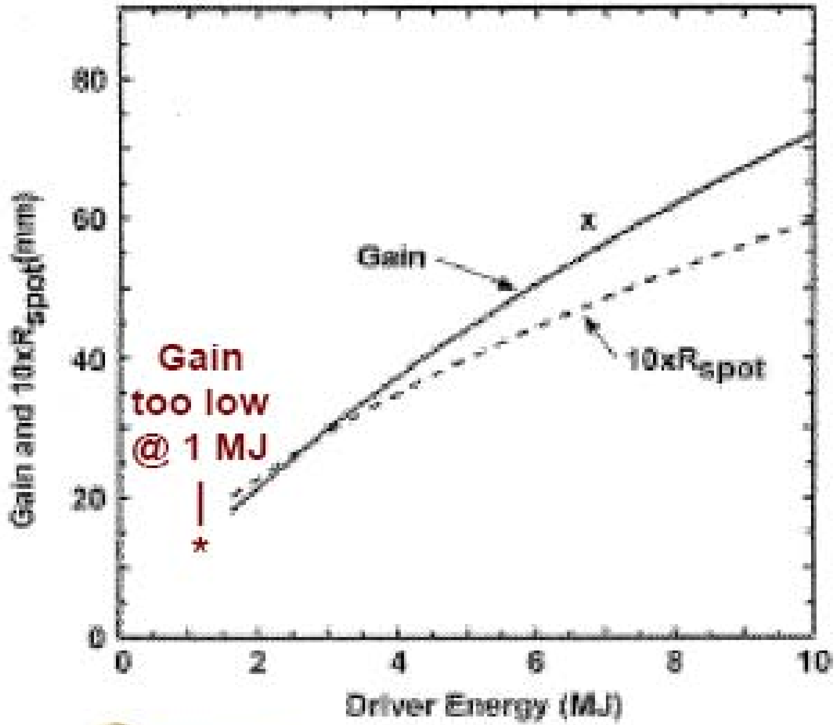
1. Laser beam smoothness now makes direct drive viable for NIF test→ enables early direct-drive ignition tests *in polar geometry, suitable for liquid protected chambers.*
2. Direct drive fuel capsule radii (~ 2mm) allow *ion beam spots comparable to indirect drive needs*. (The larger hybrid HI target exception unduly restricted beam illumination solid angle <10° → difficult for many beams).
3. Neutralized beam drift compression now allows multiple pulses of lower range ions *→ion picket fences→ more pulse shape contrast possible.*
4. Upstream ion beam RF modulation→ *new dynamic RT stabilization!*
5. Thin *metal enclosures might still be used* with ion direct drive, even if only as a thin sabot to protect the cryo-capsules.

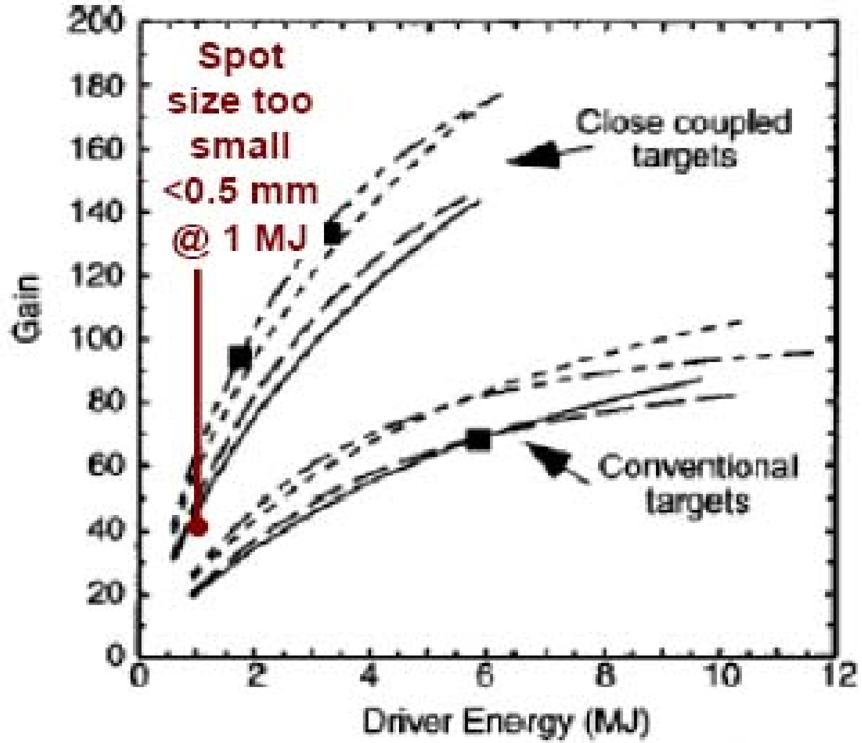
→ *Pursuit of direct drive allows HIF to take advantage of ongoing progress in modern laser facilities as much as it has for indirect drive.*

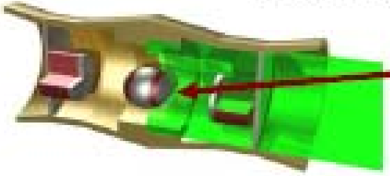
Key issue: previous heavy ion fusion target designs do not scale well to low energy (1 MJ) (Debbie Callahan)

Phys. Plasmas, Vol. 7, No. 5, May 2000

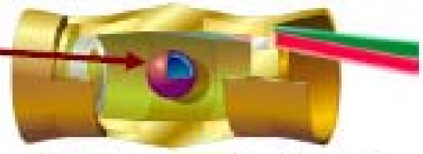
Callahan's HIF04 NIMA paper for HYBRID





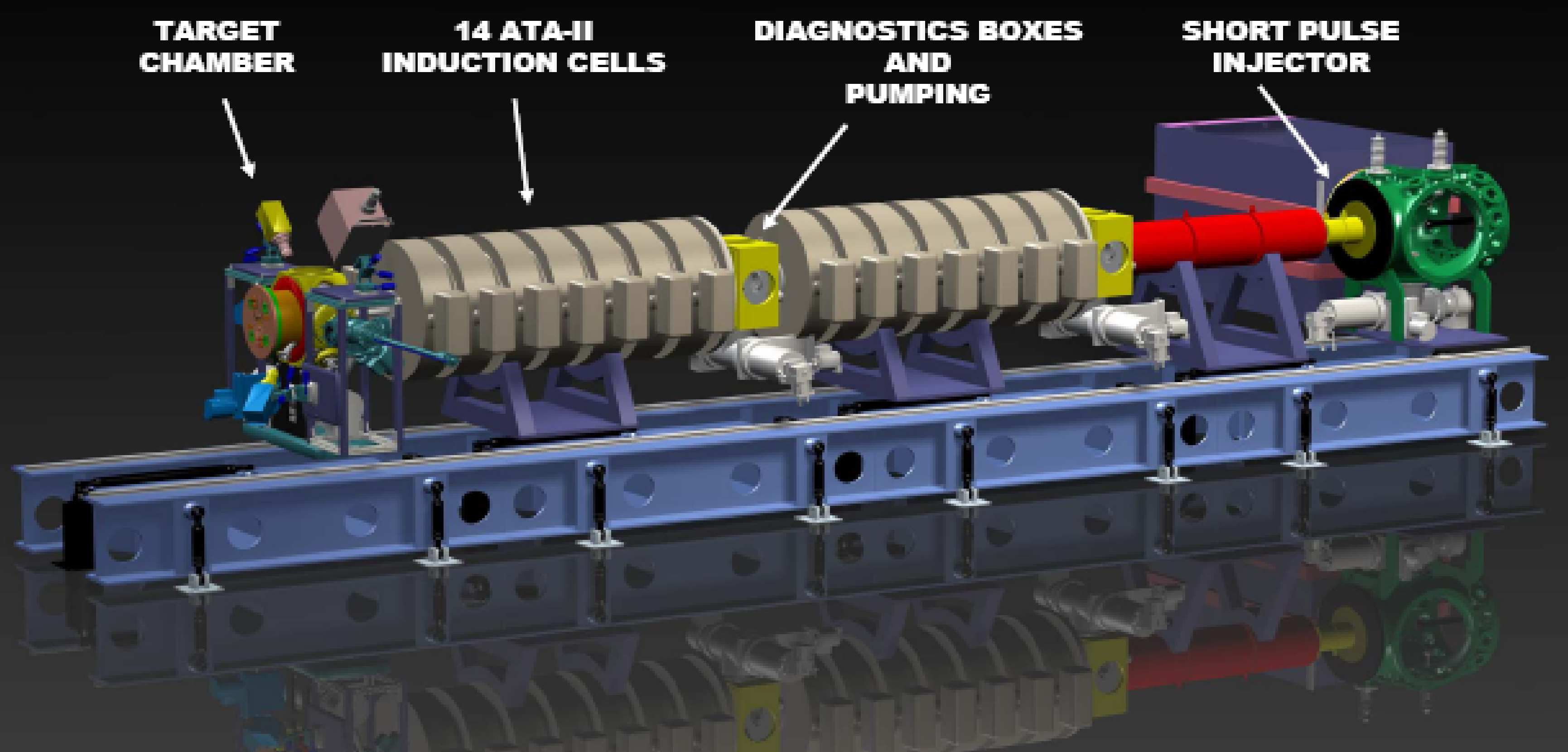


2 mm radius capsules absorb only 1 MJ out of 7!



Campaign Level I can use existing equipment for both 3 MeV Li Bragg peak WDM and new double-pulse direct-drive experiments

Thanks to LLNL Beam Research Program, we have enough parts for 6 MeV of acceleration.
Our main cost item would be to replace solenoids to 1.5 to 2 T (6 m x 100K/m ~ $600K)



→NDCX-II: Validates CD-0 pre-requisite for IBX-HEDPX

SHOWN USING AVAILABLE ATA CELLS.
Blumlein pulsed power modules not shown.

Ed Lee is working on NDC focusing schemes offering dramatically smaller driver/chamber interfaces with 20 beams/end @ 3-5 pulses = 120 to 200 bunches for target pulse shaping. *5X higher peak beam power enabled.*

RPD multi-beam vacuum quadrupole final focus arrays dwarf HYLIFE chamber. Demo version needed 5.5 MJ ETF/DEMO chamber for 280 MJ yield =88% of RPD.

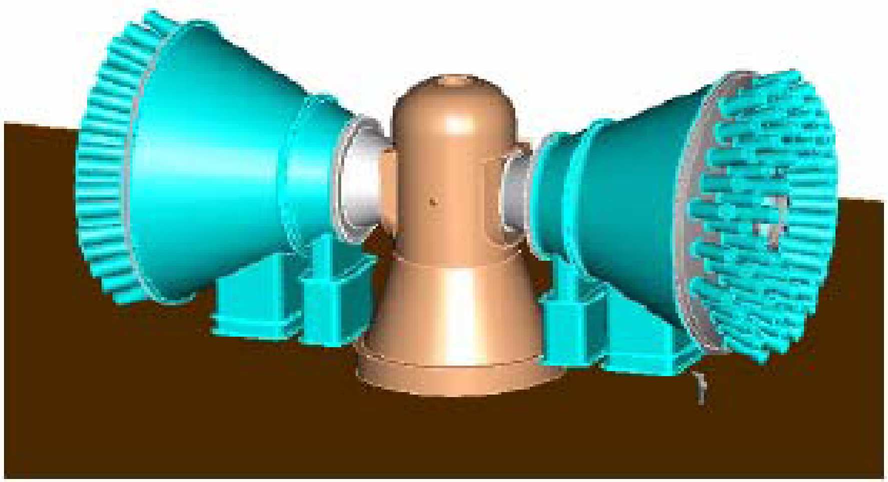
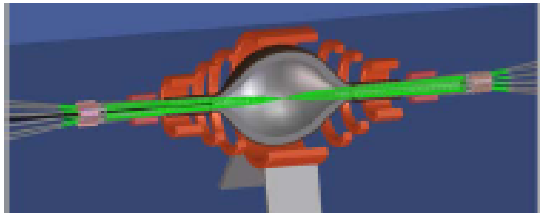
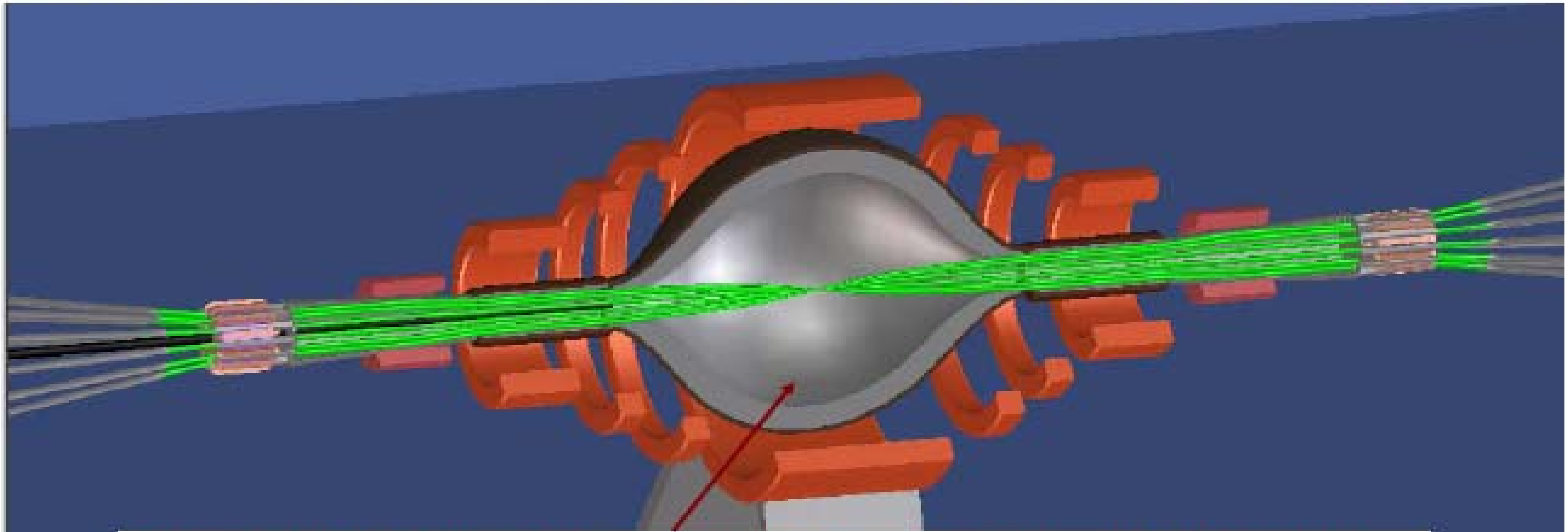


Fig. 3. An isometric view illustrating the coupling of final focus magnet array with the chamber.

Can we find target solutions for 1 to 2 MJ driver energy with 40 MJ yields for HIF DEMO exploiting new pulse shaping capability with NDC, and can we develop 10 to 20 Hz pulse rate vortex chambers with < 10 cent targets for economical DEMO net electricity?



Serendipity: with special overcoated hohlraum targets, the new magnetized vortex chamber is ideal to confine target plasma well enough to neutralize the beam on subsequent shots (even after 20x decay)



Assume ~1 m^3 cavity volume, 2 m^2 liquid cavity surface, ~ 40 MJ magnetic field energy damps turbulence from 30-40% of fusion yield captured into a special target coated with a thick Flibe layer

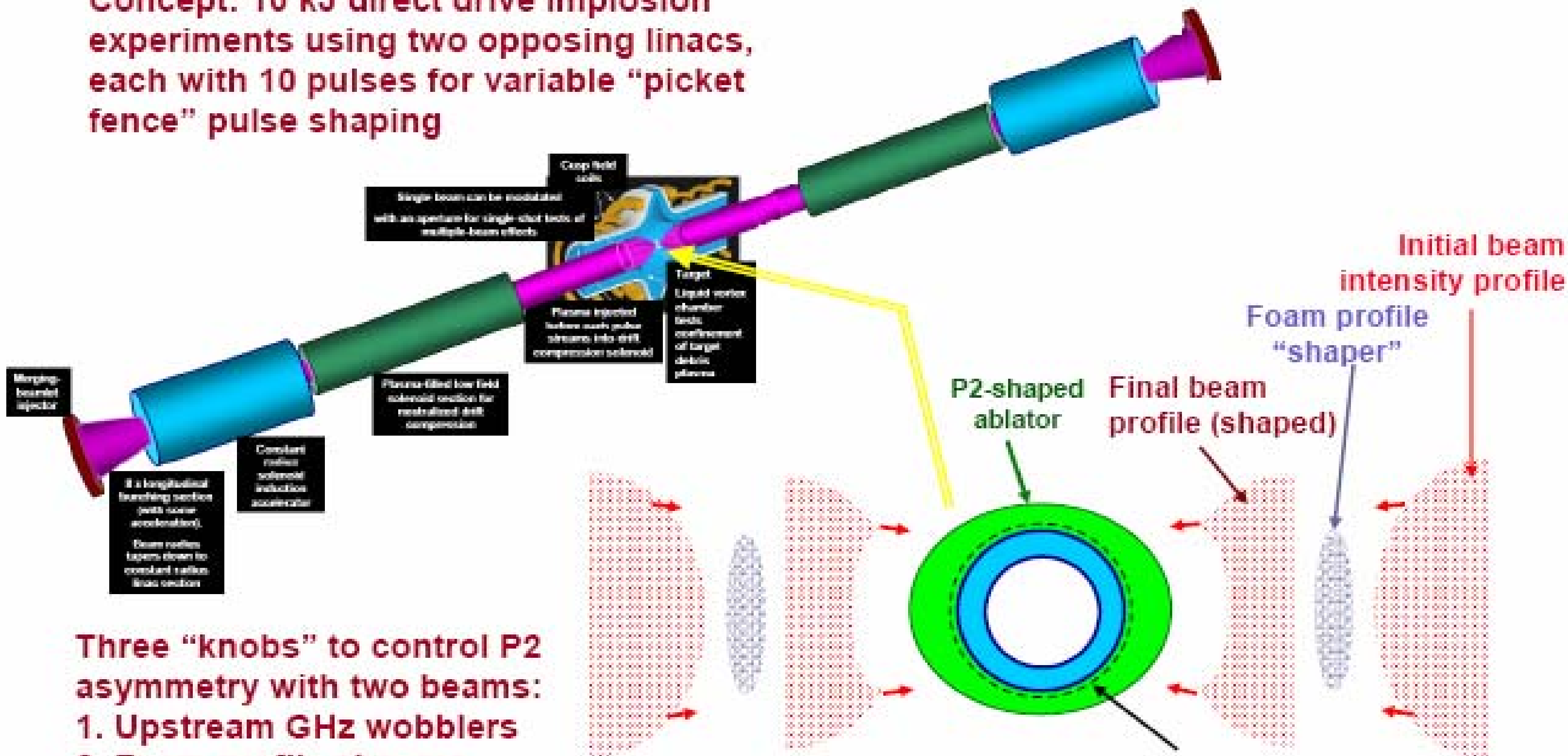
Liquid Flibe	Dense vapor	Magnetized resistive plasma

Constant pressure (r) to liquid (after a few bounces)

Density gradient ... Temperature gradient

Campaign Level II: In addition to IB-HEDPX, a new accelerator tool is needed to explore heavy-ion-specific fusion target physics in parallel with NIF operation

Concept: 10 kJ direct drive implosion experiments using two opposing linacs, each with 10 pulses for variable “picket fence” pulse shaping



Three “knobs” to control P2 asymmetry with two beams:

1. Upstream GHz wobblers
2. Foam profile shapers
3. Ablator shaping

Goal is implosion drive pressure on the Cryo D_2 payload with < 1 % non-uniformity

Boris Yu. Sharkov