Investigation of Beam - Plasma Interaction as Specific Problem of the Heavy Ion Driver-Target Interface

IAEA Research Contract No: 11637/RBF

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ITEP-MOSCOW

CRP

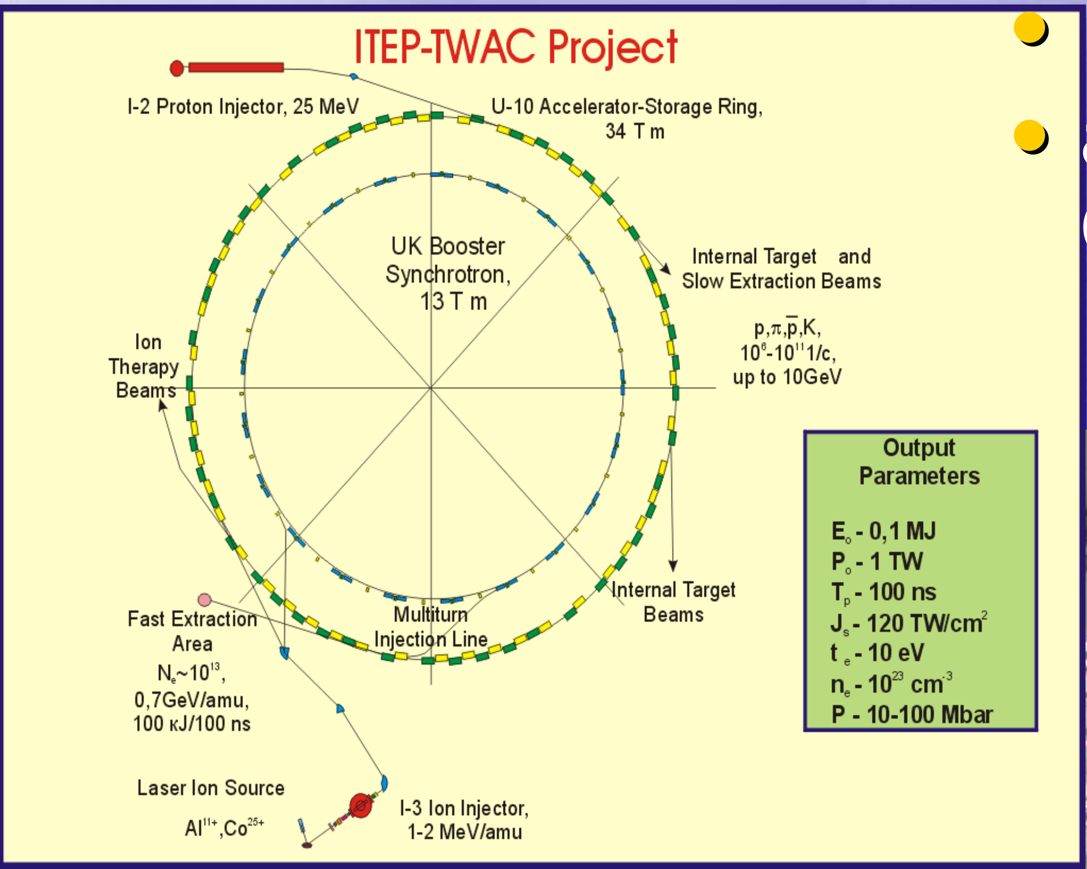
"Elements of Power Plant Design for IFE"

Vienna
November 2003

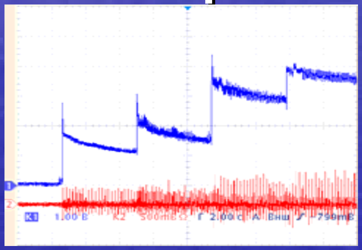
OUTLINE

- HIF-E activities in Russia
- ITEP-TWAC - test facility for IFE
- Explosive driven plasma target experiment
- 110 keV/u Cu 2+ stopping power experiment

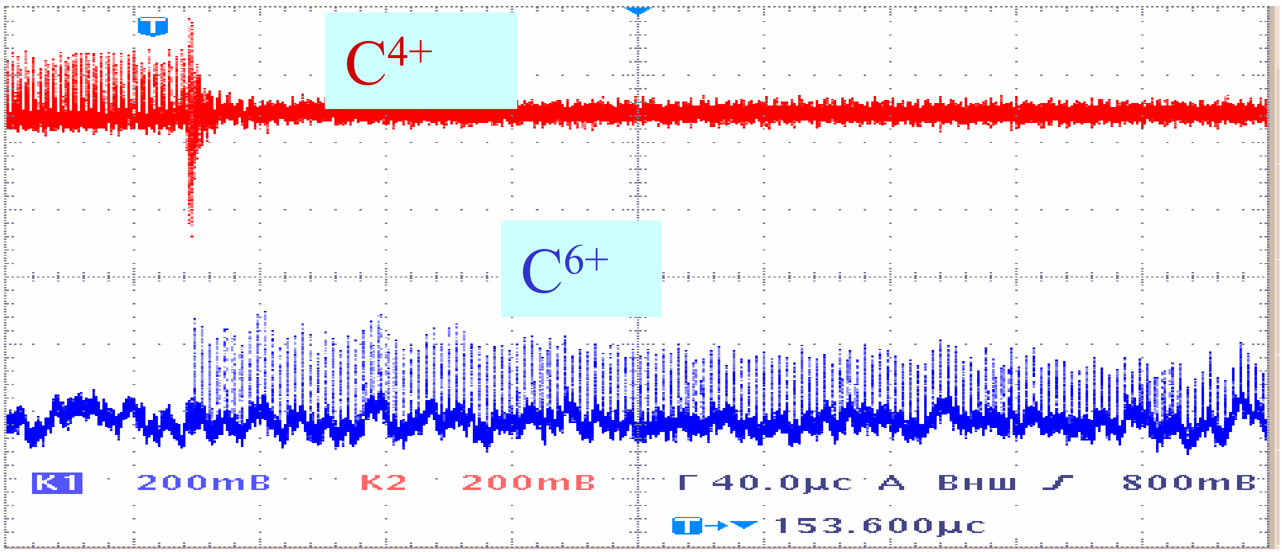
ITEP-TWAC project in progress

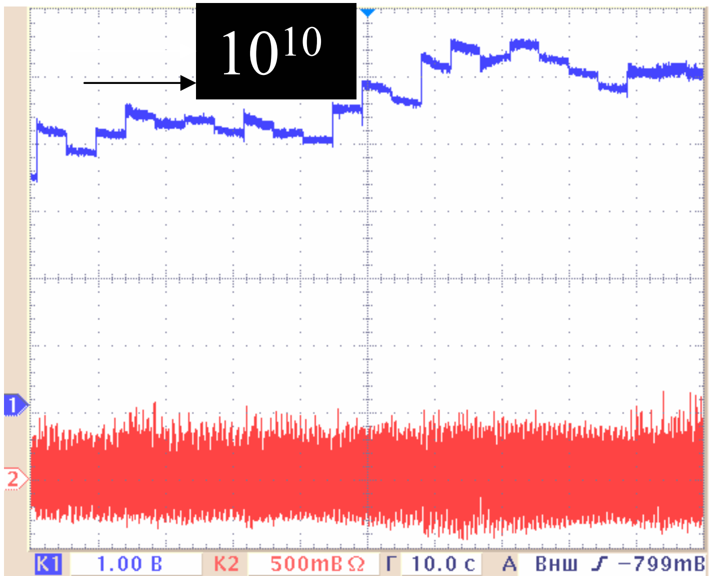


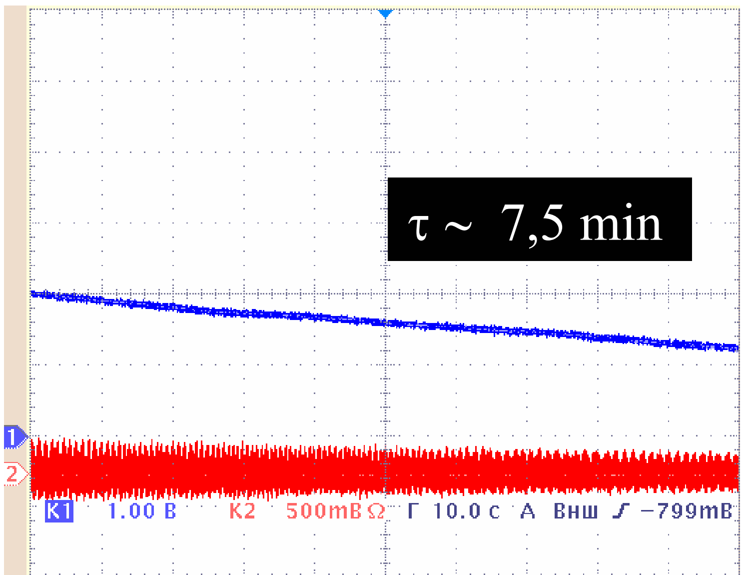
- $>10^{10}$ C6+ accumulated
- accelerated up to 4 GeV/u



TWAC ions accumulation mode



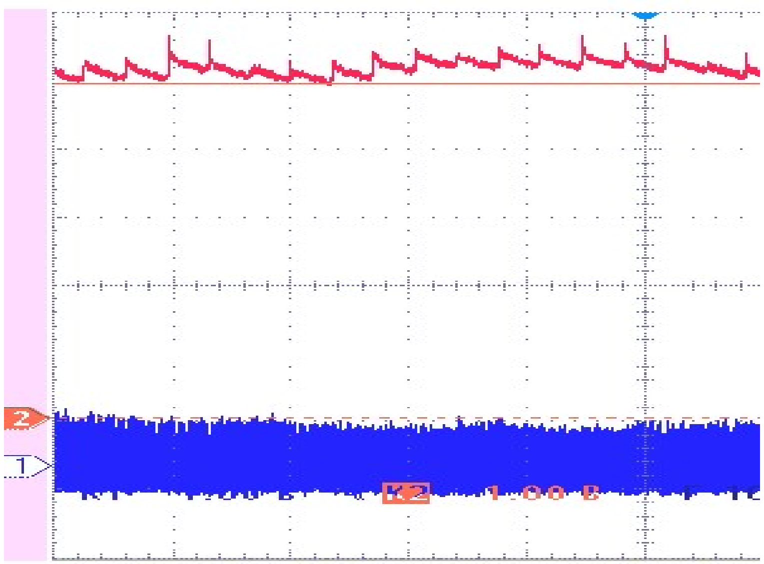




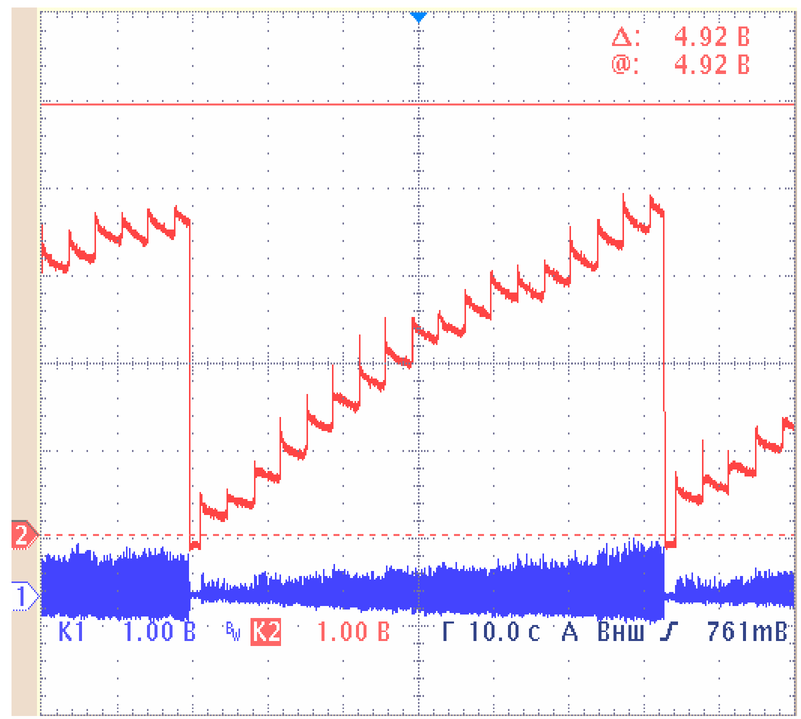
Recent Progress in Beam Intensity

Accumulation of 200 MeV/n C6+ ion in U-10 ring

10^10



Fast extraction of accumulated beam



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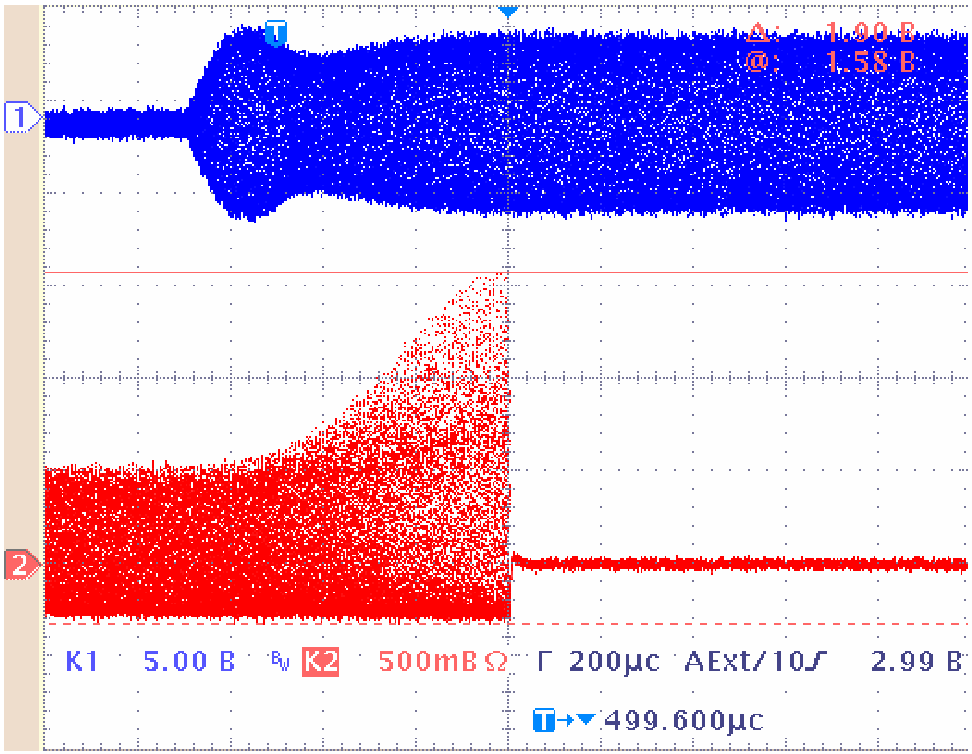
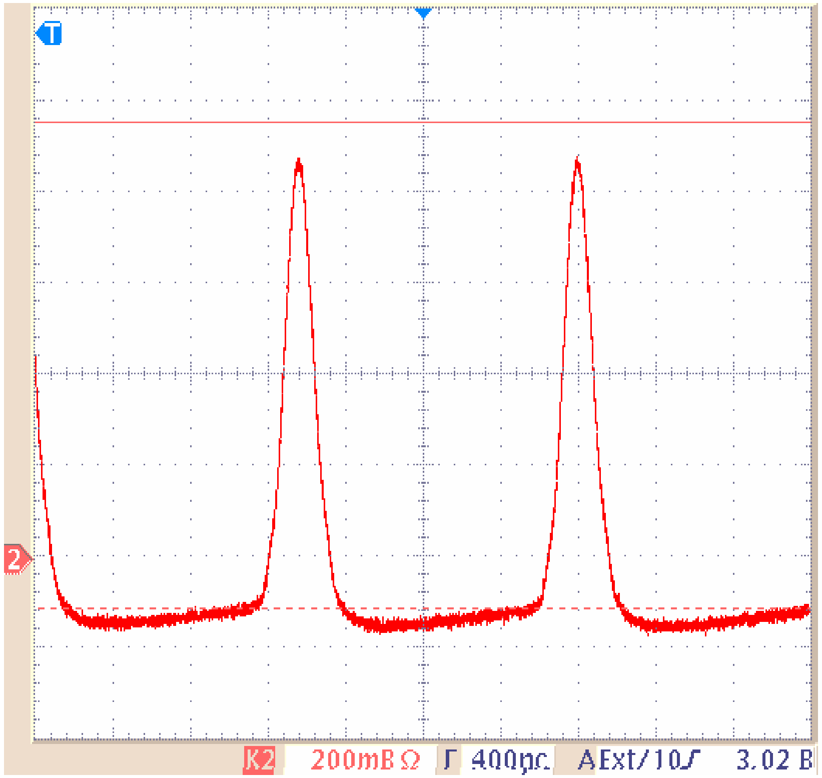
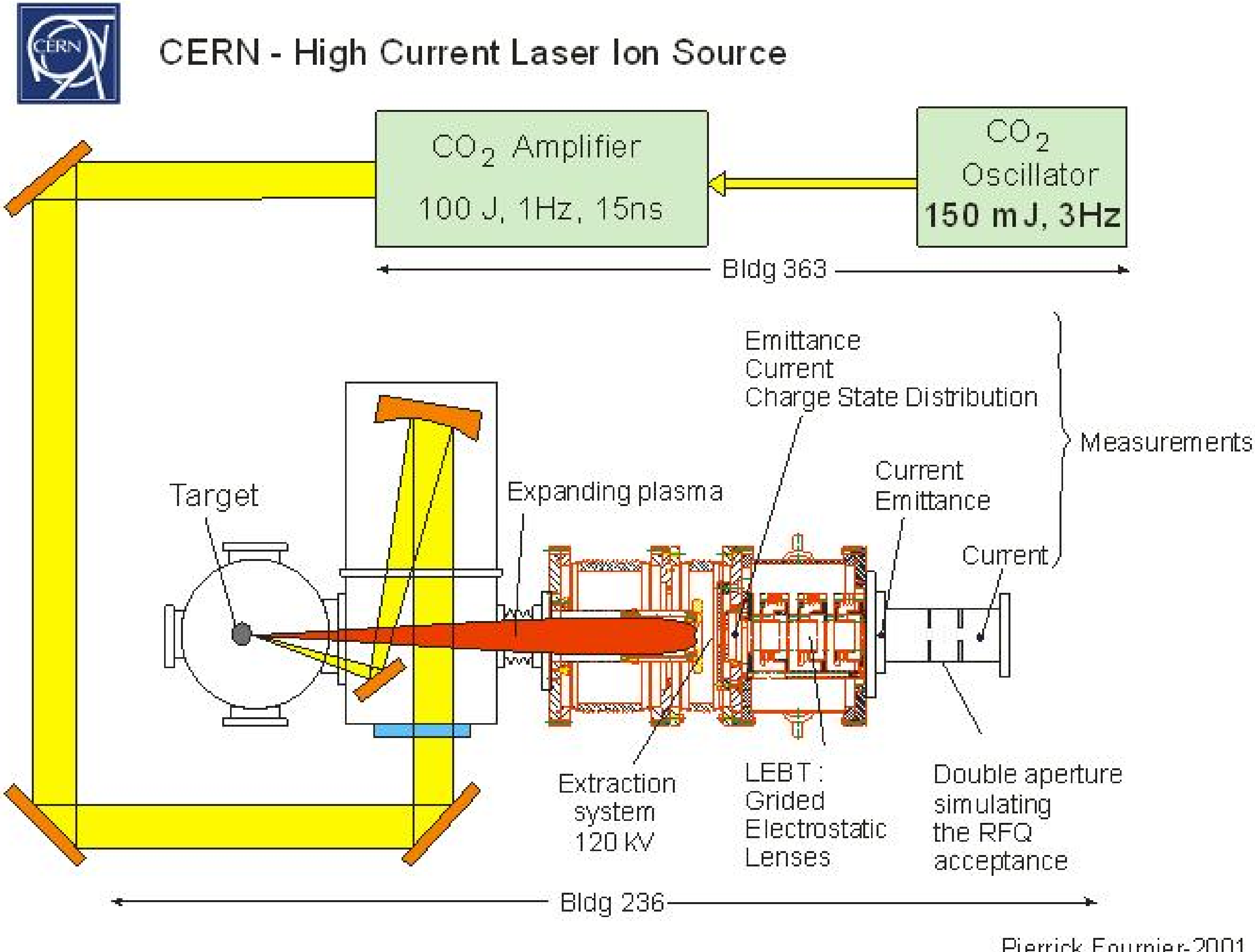
Bunch compression for 213 MeV/u C6+ (RF : f_0 = 695 кHz, 10 кV)



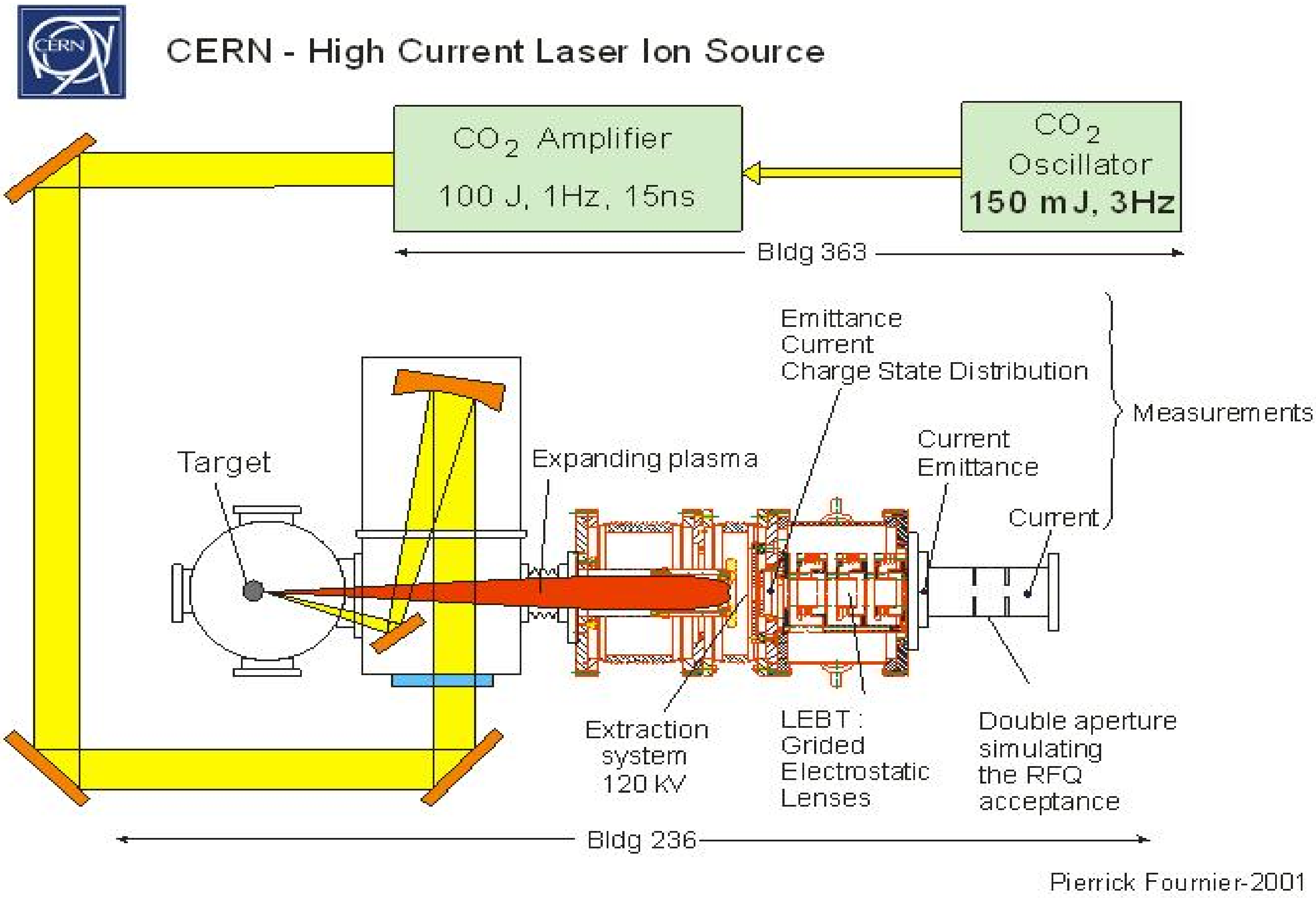


Laser Ion Source

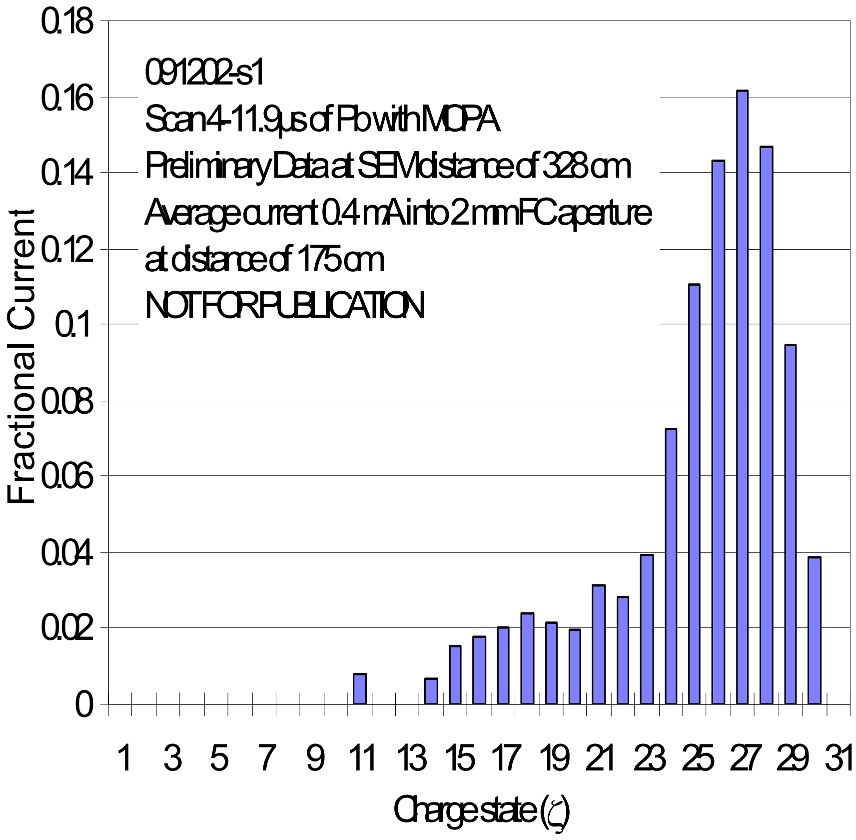


Laser Plasma Ion Source

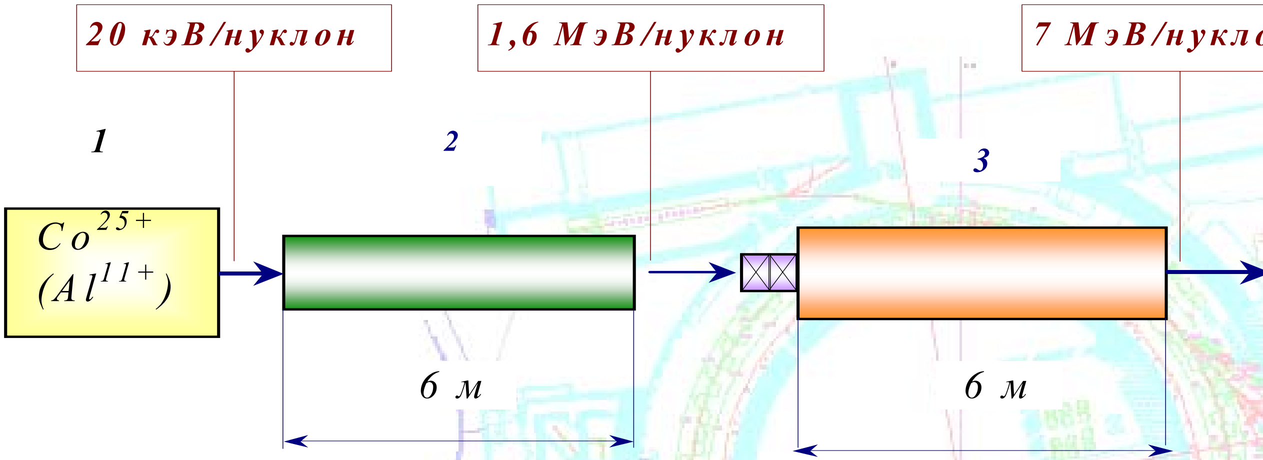
Capable of delivering Pb, In, Nb… ions with rep-rate 1 Hz
For Pb 25+ : 7,7 mA / 3.5 mks , 0.6 10 E10 ions measured,
emittance – 0.2 mm mrad (normalized)



LASER ION SOURCE: 100J / 20 ns, 1 Hz rep-rate CO_2 LASER ITEP-TRINITI-CERN collaboration



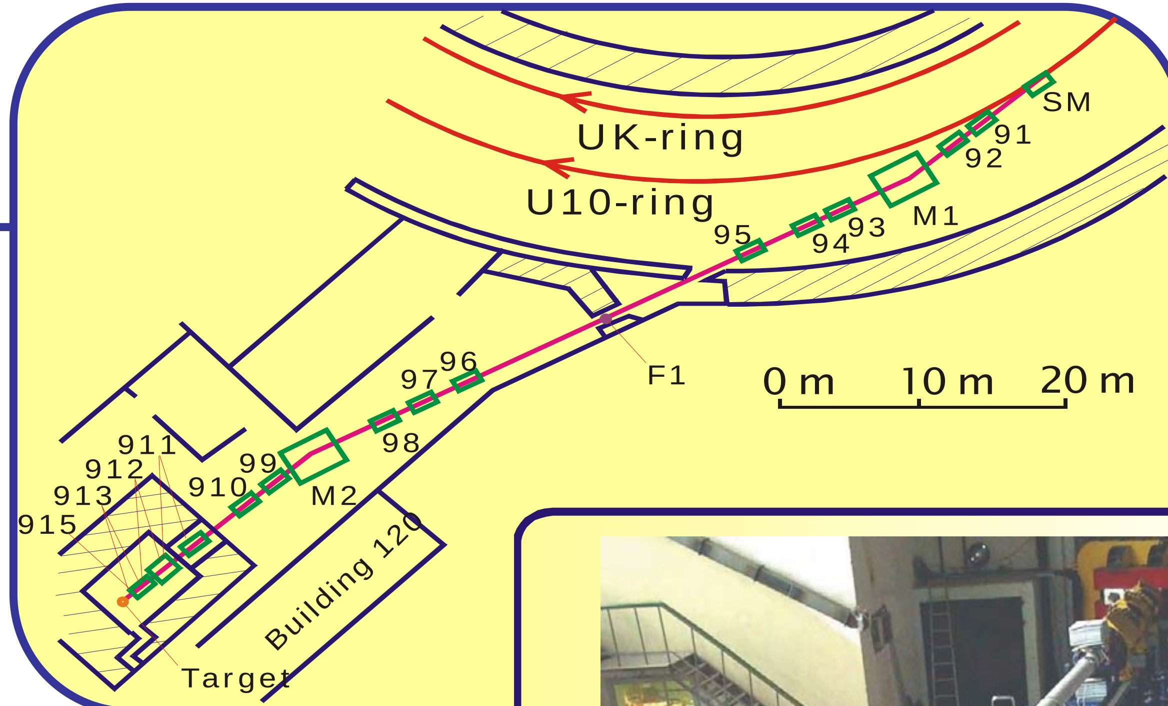
Структурная схема и параметры инжектора И-4 ускорительно-накопительного комплекса ИТЭФ-ТВН

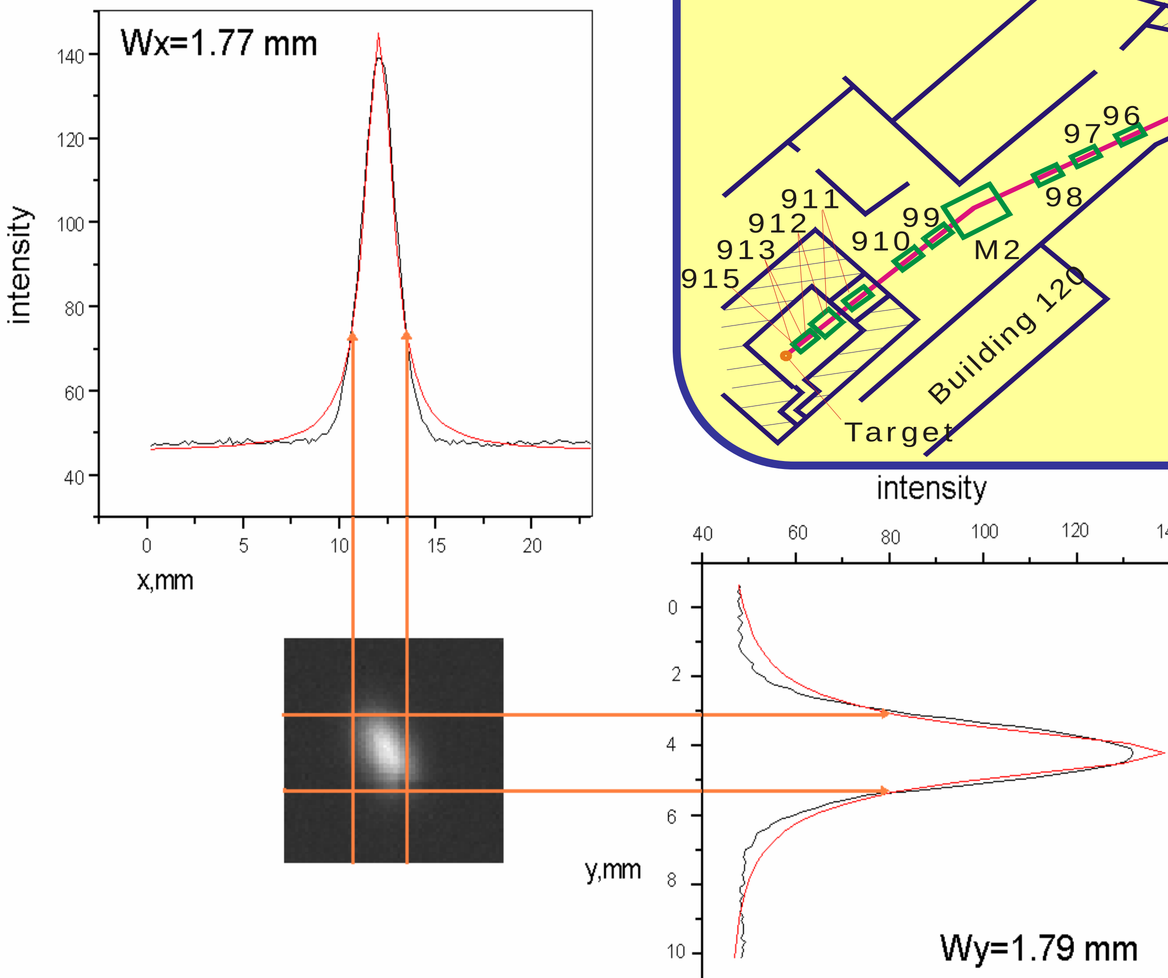


Удельный заряд ионов Z/M	1/3
Входная энергия ионов	20 кэВ/н
Ток пучка на входе в ускоритель (для смеси ионов разной зарядности)	100 мА
Эмиттанс пучка (норм.) на входе в ускоритель	0.25÷0.3 см.мрад
Выходная энергия ионов	7 – 8 МэВ/н
Частота повторения импульсов тока не более	25 Гц
Ток пучка на выходе ускорителя (Z/M=1/3)	16 мА
Длительность импульса тока пучка не более	15 мкс

High energy density experimental area

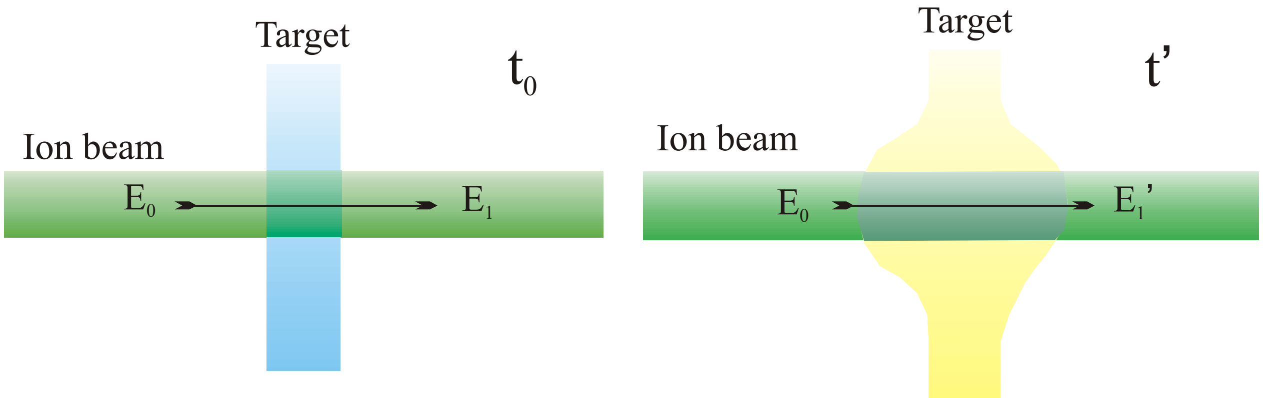
ITEP-TWAC





Ion beam induced Gamma diagnostic

(I.Roudskoy, ITEP-Moscow)



- MeV Gamma rays escape from the entire depth of the target
- The cross-section for Gamma rays generation *<u>is independent</u>* on thermodynamic state of target matter

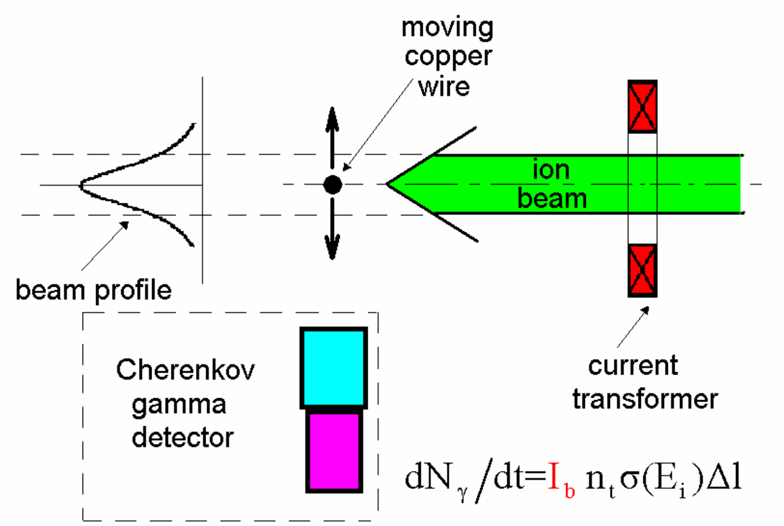
$$dN_\gamma / dt = I_b \, n_t \sigma(E_i) \Delta l$$

Ib =dN$_t$/dt – beam current
n_t – target density
σ(E)– the total cross-section of nuclear excitation.

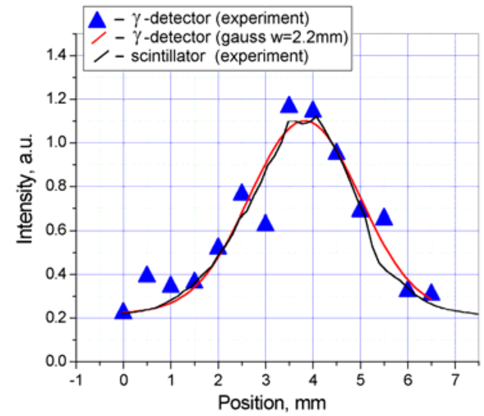
$$dN_\gamma(t) / dt \sim \Phi(t) = n_t(t) u_b F$$

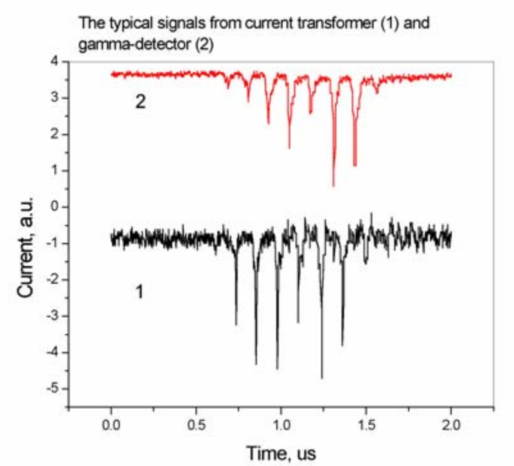
Φ(t) – the particles flux through lateral surface of the region irradiated by the ion beam;
u_b – mass velocity of the target matter;
F – lateral area of the region.

Beam profile measurements by induced Gammas



$$dN_\gamma / dt = I_b \, n_t \sigma(E_i) \Delta l$$





Intensity target values for ITEP-TWAC :

- Ion **accumulation mode** –
300-700 MeV/u and 10^{12} – 10^{13} particles,
~100 ns pulse;

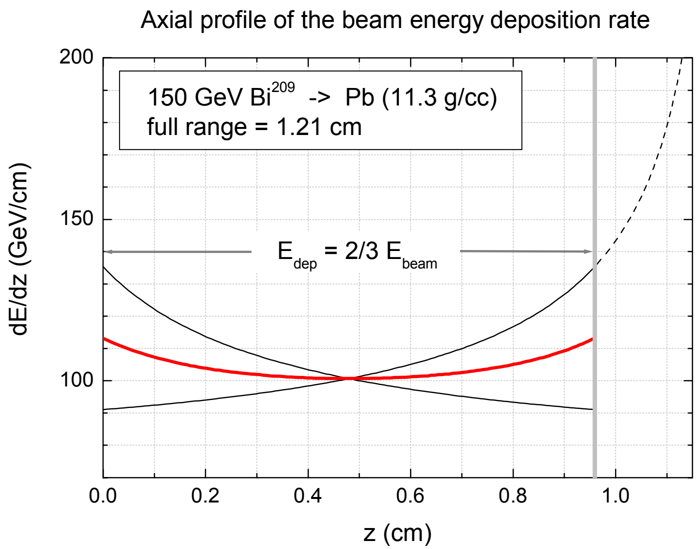
- Ion **acceleration mode** - up to 4.3
GeV/u and up to 10^{10} particles/s;

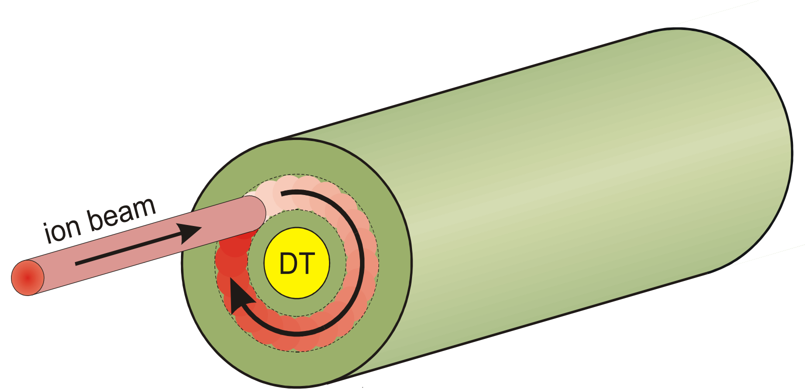
- **Medical application** mode –
~ 250 MeV/u,
10^{9} - 10^{10} particles/s.

Principal motivation for cylindrical targets

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



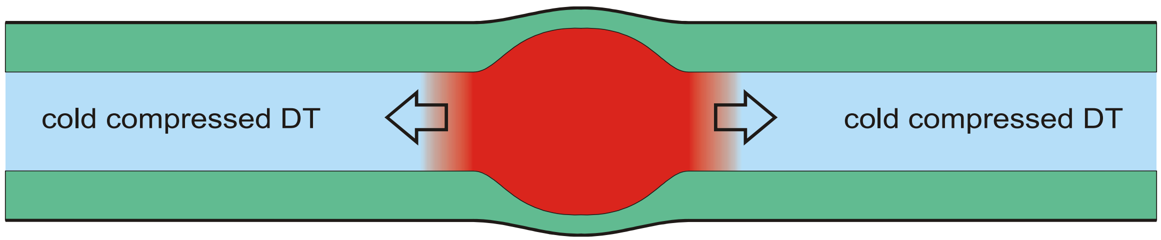


Direct drive may become a competitive target option when

- **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.**

The problem of ignition in cylindrical geometry

We assume that thermonuclear burn is initiated in a short section with $\rho\Delta z \sim 1$ g/cm^2 and propagates as a burn wave along the compressed DT fiber.



The conventional (NIF-like) ignition mode by means of fast hydrodynamic compression does not seem to be realistic for heavy ion driven cylindrical targets because of

- high needed implosion velocities, $v_{im} \sim 3\times10^7$ cm/s, and
- less effective compression and adiabatic heating in cylindrical implosions as compared to spherical ones when roughly the same radial convergence ratios C_r are assumed:

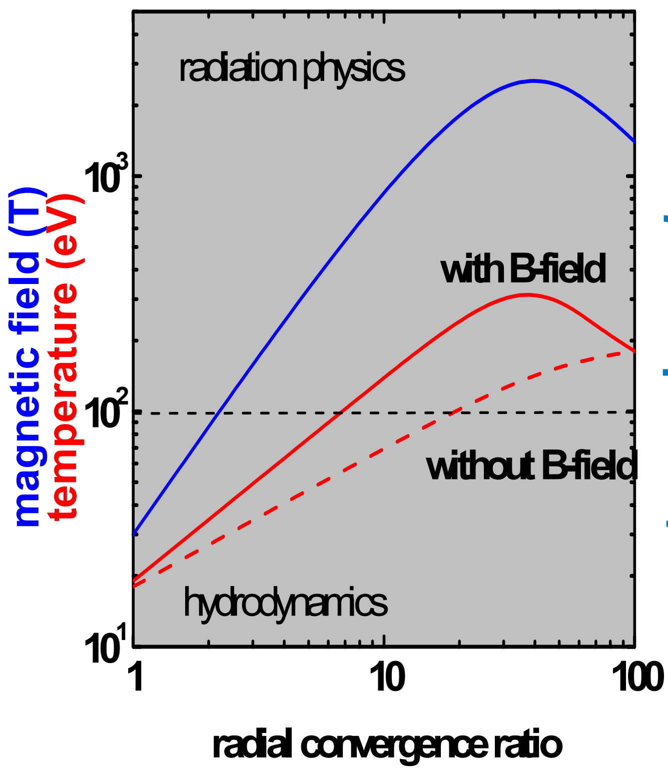
$$\rho \propto \begin{cases} C_r^3, & \text{sph}, \\ C_r^2, & \text{cyl}, \end{cases} \qquad T \propto \begin{cases} C_r^2, & \text{sph}, \\ C_r^{4/3}, & \text{cyl}. \end{cases}$$

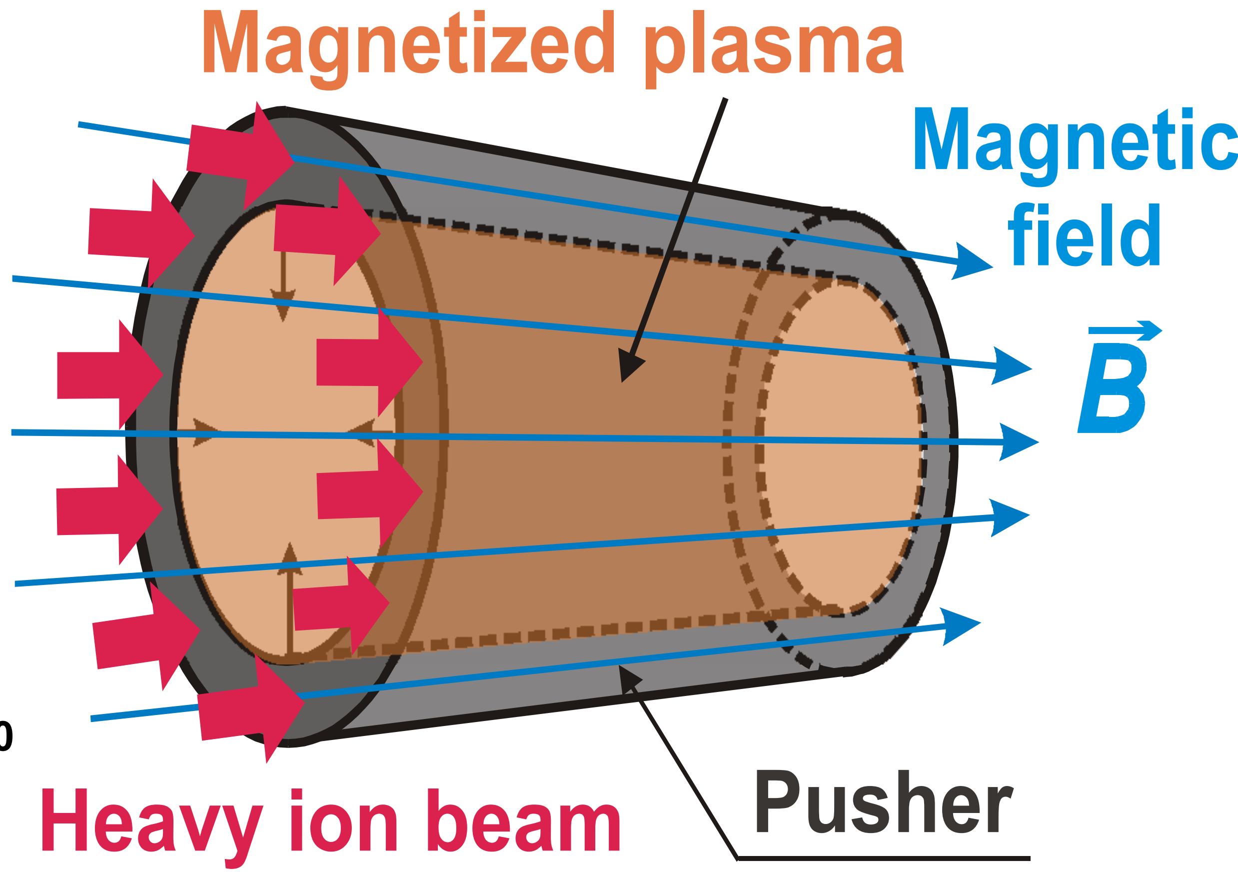
Instead, we see two possible alternatives:

1) **slow ignition of magnetized and initially preheated DT section (A. Kemp), or**

2) **fast ignition by a heavy-ion pulse of ultra-high power (D.G. Koshkarev).**

M.M.Basko,M.D.Churazov, A.Kemp, J.Meyer-ter-Vehn –
Magnetized target fusion in cylindrical geometry,–
NIM A 464 (3001) 196-300.



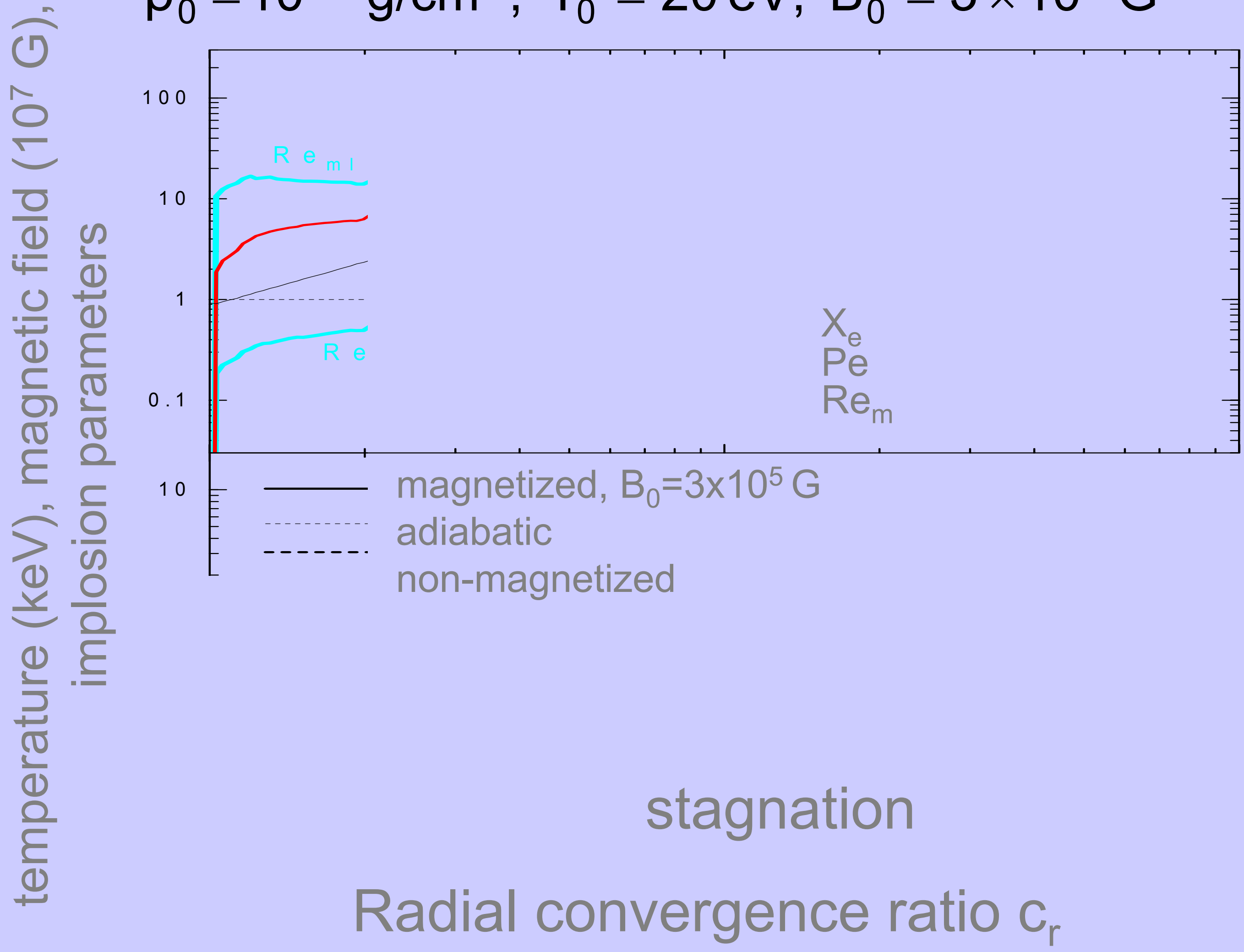


Implosion dynamics for the TWAC beam

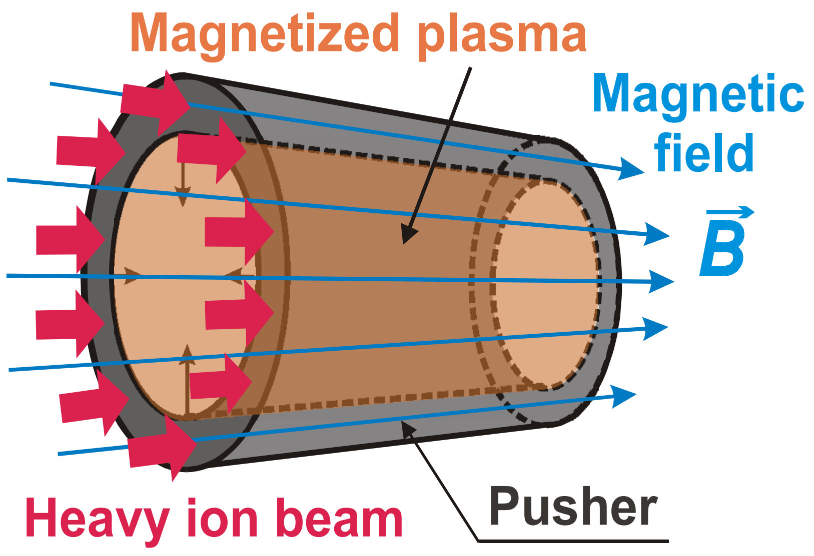
(beam energy 85 kJ)

$\varepsilon = 100$ kJ/g, $t_p = 100$ ns, $r_{foc} = 0.8$ mm,

$\rho_0 = 10^{-4}$ g/cm^3, $T_0 = 20$ eV, $B_0 = 3 \times 10^5$ G

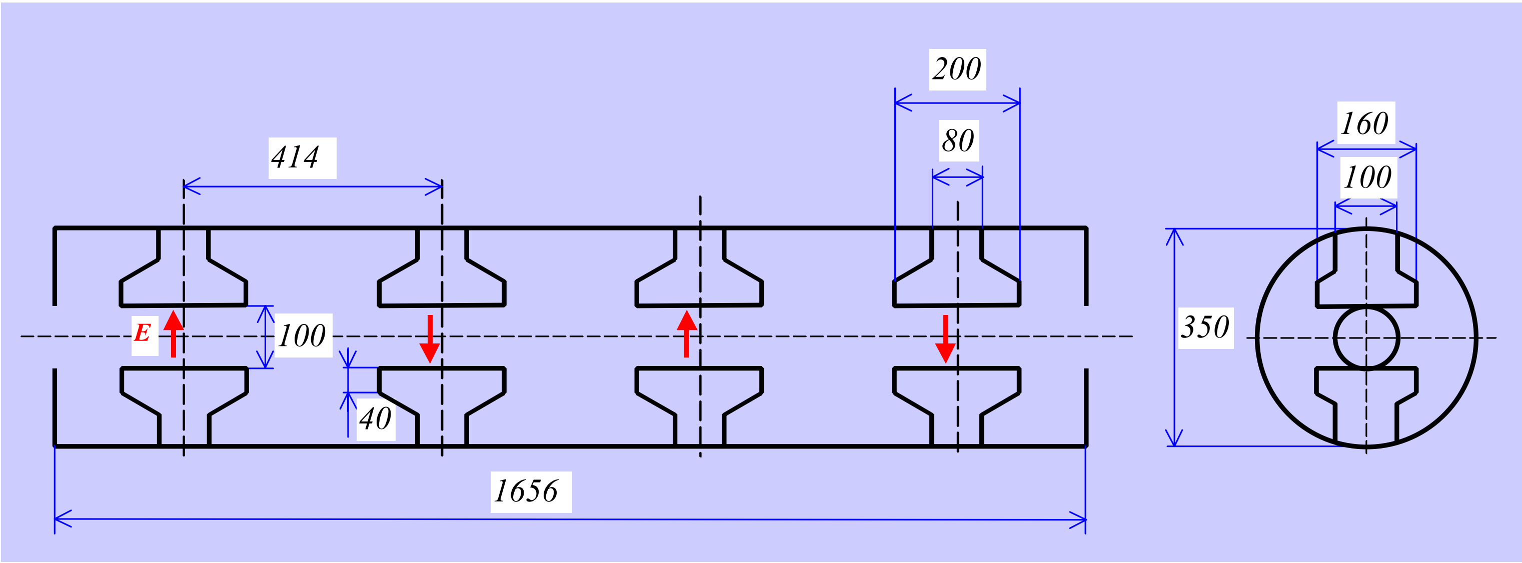


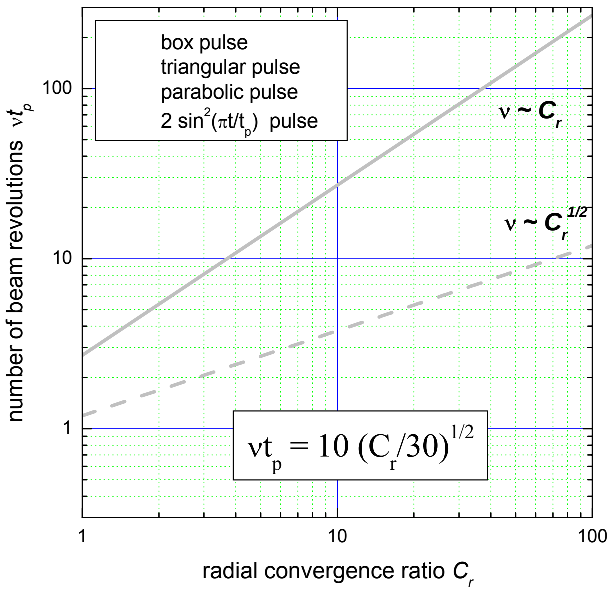
Required experimental technique



- RF WOBBLER system 300 MHz
- Plasma pre-heating $T_o \sim 20$ eV (by the laser ?)
- Pulsed magnetic field $B_o \sim 3\ 10^5$ G

RF parameters of the 300 MHz cavity





Aperture 100 mm

RF voltage 1 MV

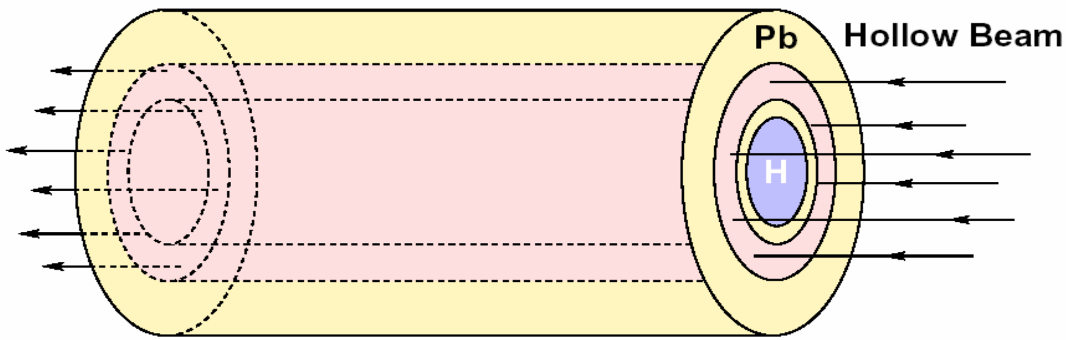
Maximum electric field on the axis -10 MV/m

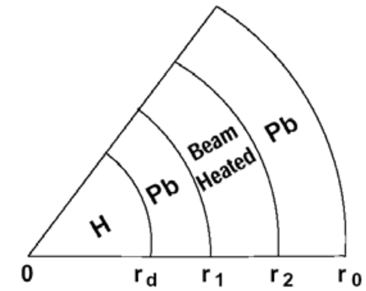
Quality factor 14000

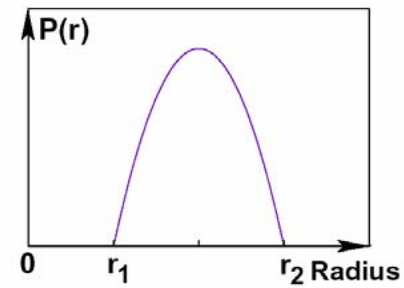
Power dissipation 1.8 MW

Maximum beam deflection 3,5 mrad

Low entropy compression





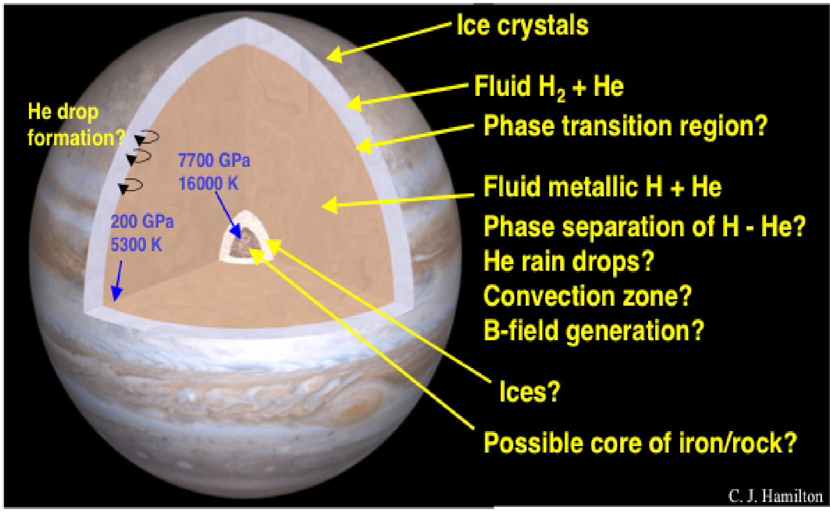


Target Parameters	Beam Parameters
$r_d = 0.4$ mm	2.7 GeV/u Uranium
$r_1 = 0.6$ mm	$N = 0.2 - 1.5 \times 10^{12}$
$r_2 = 2.1$ mm	$\tau = 20$ ns
$r_0 = 3.5$ mm	$E_b = 21 - 155$ kJ
$L = 1.0$ cm	$R_{ion} = 5.9$ cm

N.Tahir et al.

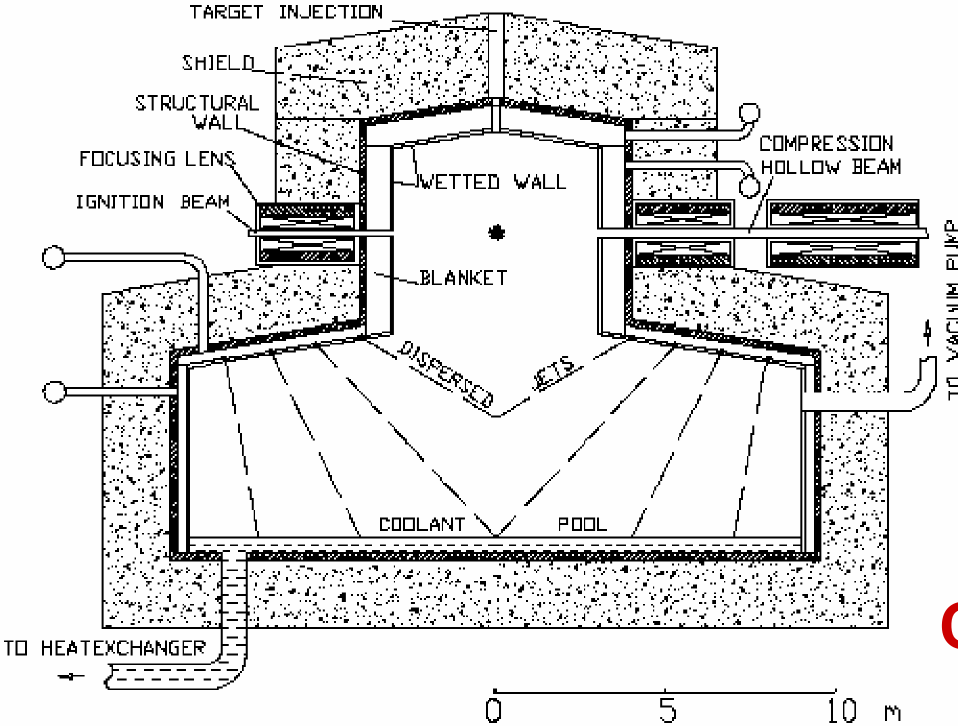
$\rho = 1 - 2\ g/cm^3$ $\qquad$ $P = 2 - 10$ Mbar

$T = 0.2 - 0.6$ eV



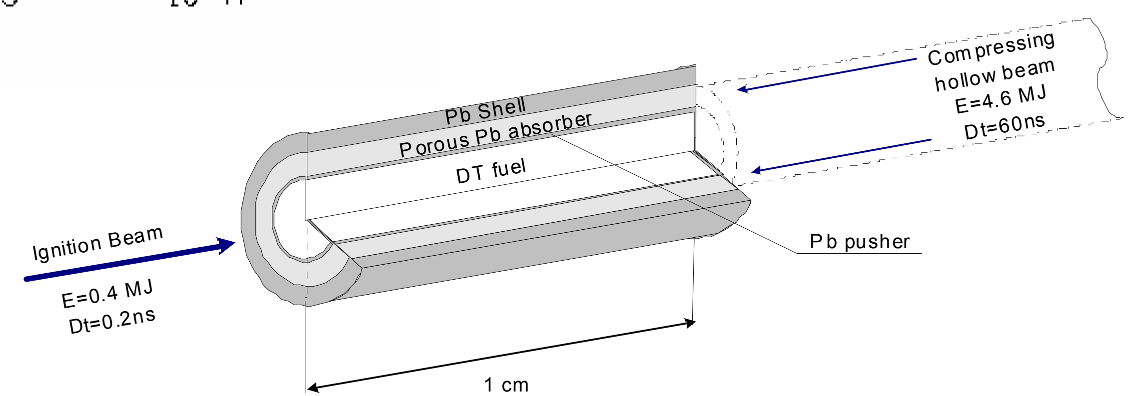
Reactor Chamber and Balance-of-Plant Characteristics for Fast-Ignition Heavy ion Fusion Power Plant.

S.Medin, M.Churazov, D.Koshkarev, B.Sharkov, Yu.Orlov, V.Suslin, E.Zemskov



Fusion Science and Technology v 43, N 3, FUSTE8(3), 437-446 (2003)

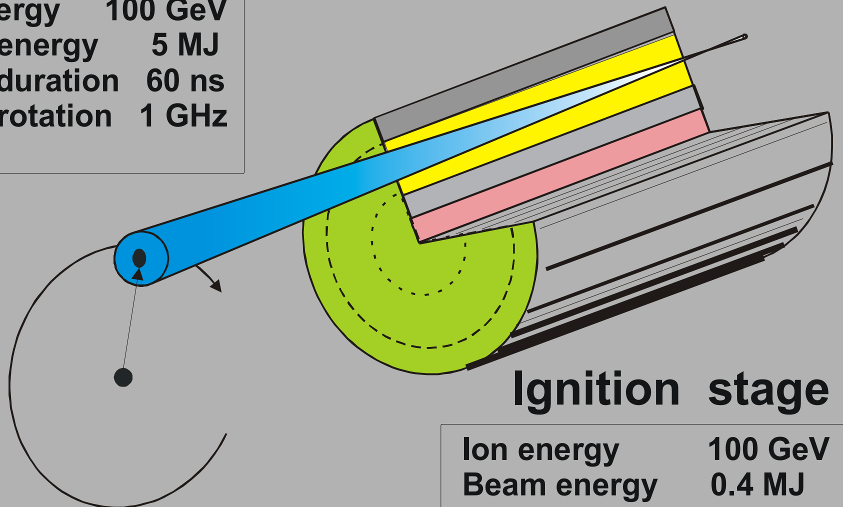
Cylindrical target for FIHIF



Fast ignition in HIF

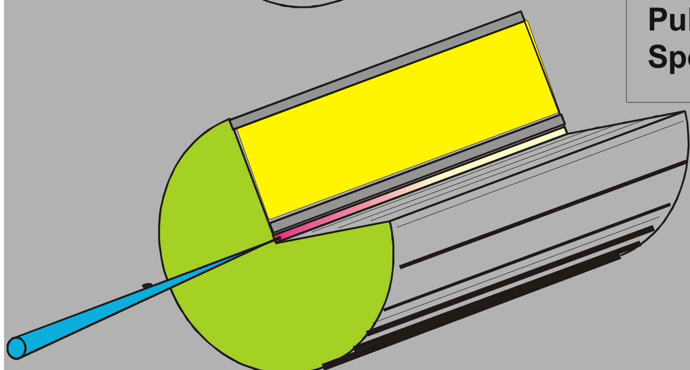
Compression stage

Ion energy	100 GeV
Beam energy	5 MJ
Pulse duration	60 ns
Beam rotation	1 GHz

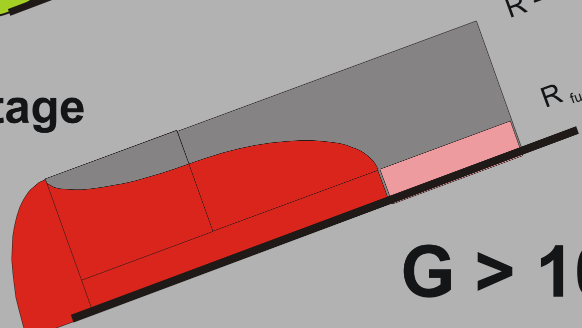


Ignition stage

Ion energy	100 GeV
Beam energy	0.4 MJ
Pulse duration	0.2 ns
Specific power	4.10^{18} W/g



Burning stage



G > 100

COMBINED INERTIAL FUSION-FISSION SCHEME

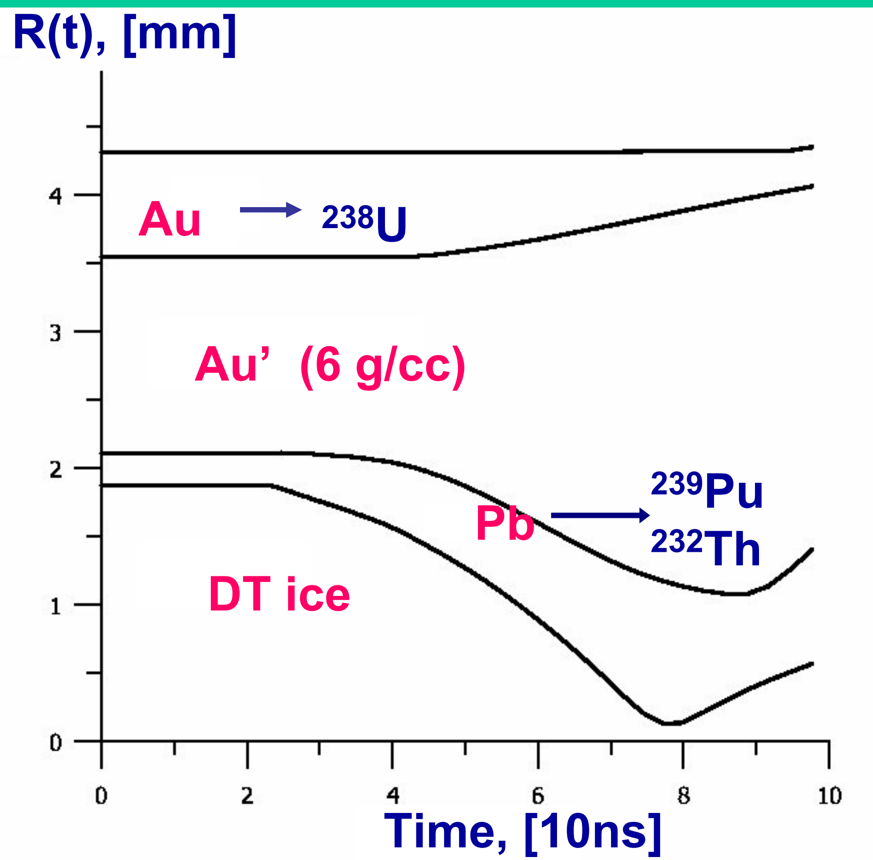
D.Koshkarev & B.Sharkov
JETF Letters (2002) v 75, 7-8, pp 371-373

Target compression

- cylindrical symmetry of compression is provided by fast rotation (1 GHz) of the ion beam
- Ion pulse (80 ns) is tailored in time and space
- parameters at stagnation:

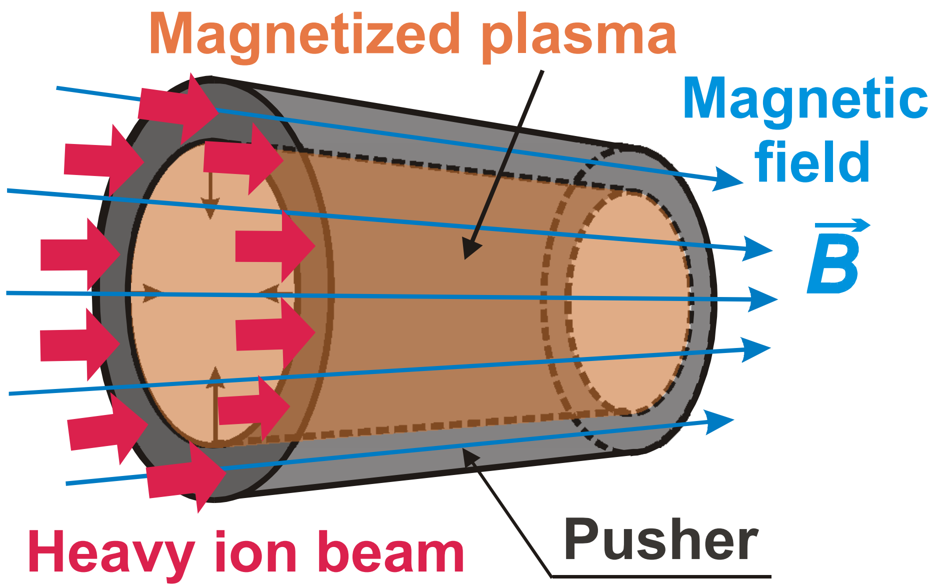
  DT density = 100 g/cc

  fuel radius = 0.005 cm



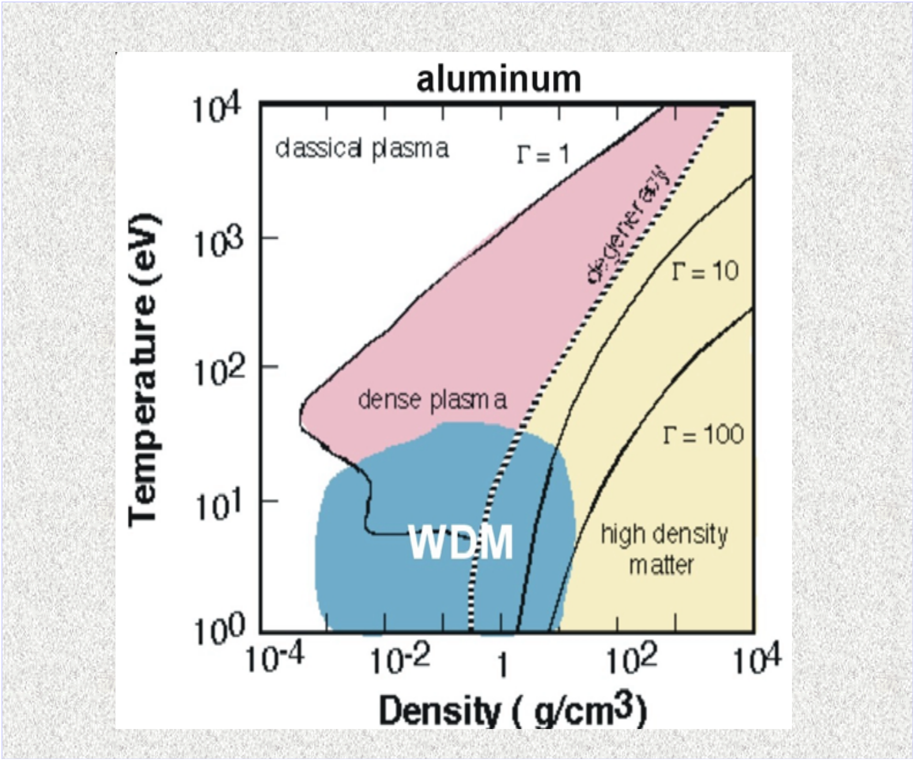
IFE related Physics for TWAC

- High T plasmas :
  cylindrical implosions
  (r/r_o ~10, ρ/ρ_o >5)
- High B fields ~100 MG
- Low entropy cylindrical compression
- Accelerator physics for Heavy Ion IFE



Outlook

- Warm dense matter physics – a hot topic for forth-coming experimental campaign;
- New laser, HC-HZ front end, e-cooling;
- 20 Hz cycling mode;
- TWAC project is well in progress



Participants

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Energy Loss of 5.9 MeV/u and 11.4 MeV/u C-ions in Shockwave-driven, Non-ideal Plasmas

Collaboration:
GSI Darmstadt, TU Darmstadt, ITEP Moscow, ICP Chernogolovka

GSI, Darmstadt/TU Darmstadt:

K. Weyrich, H. Wahl, M. Geißel, D.H.H. Hoffmann

ITEP, Moscow:

A. Golubev, A. Fertman, A. Kantzyrev, B. Sharkov

ICP Chernogolovka:

M. Kulish, A. Dudin, V. Mintsev, V. Fortov, V. Gryaznov

Strongly-coupled, non-ideal Plasmas

Γ-Parameter characterizes a plasma

$\Gamma = e^2/kTr_D$ (potential energy/ kinetic energy)

$\Gamma \ll 1$ weakly coupled plasma (ideal plasma)

$dE/dx \sim Z_{eff}^{\ 2}$

$\Gamma \geqslant 1$ strongly coupled plasma (non-ideal plasma)

$\Longrightarrow$

Correlation effects
Multiple scattering,
dynamic screening,
lowering of ionization energy

$\Downarrow$

$dE/dx \sim Z_{eff}^{\ a}$ $\quad a < 2 \quad$ for $\Gamma \approx 1$

$\Longleftarrow$

$dE/dx \sim Z_{eff}^{1.43}$ (Zwicknagel)
high density, low temperature, low ion velocity
a between 1.5 - 1.7 observed in experiments
with electron cooling devices for ion beams

Determination of Plasma Parameters n_e and T_e

Input Parameters:

Initial Gas Pressure

Shockwave velocity

⟹

Data Base:

Spectroscopic Measurements at and Plasma Diagnostics at IPCP

Variation of:

Initial Gas Pressure
and Gas Type
RDX-Charge
Flyer-plate Type

⟹ Code-Development

⟹

Resulting Parameters:

n_e of plasma

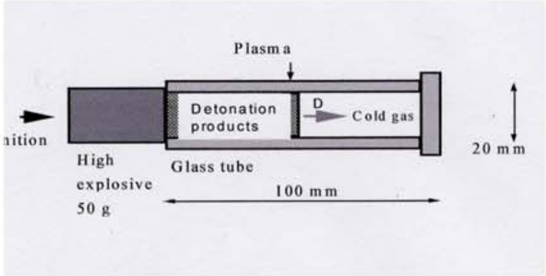
T_e of Plasma

Γ-Parameter

Compression Factor

Experiments with Shockwave-driven Plasmas

Date	Ion	Target	Results
1996-1998	p^+, 3 MeV Xe	2 tube generator	Energy loss of p
August 2001	------------------ --	------------------ --	Commissioning of beam-line, ignition machine, detonator-tests
November 2001	C, 5.9 MeV/u $\Rightarrow$ Xe	Small, detonator-driven targets	First results for dE/dx in Xe-plasma (10^{19} cm^{-3})
April 2002	C, 5.9 MeV/u $\Rightarrow$ Xe	Small targets and 2 tube-targets (short 1. tube)	Preliminary results for dE/dx in Xe-plasma (10^{20} cm^{-3})
August 2002	Ar, 5.9 MeV/u $\Rightarrow$ Xe	1 tube-target with plasma gap	First data for dE/dx in Xe-plasma (10^{20} cm^{-3})
December 2002	C, 5.9 MeV/u and 11.4 MeV/U $\Rightarrow$ Ar	1 tube-target with 4 mm plasma gap	Data for dE/dx in Ar-Plasma (10^{19}-10^{20} cm^{-3})

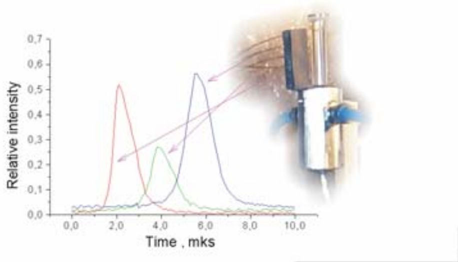


1-tube-linear type

2-tubes type

Plasma Creation and Diagnostic Measurements

Plasma Creation: Detonation of 55 g RDX
Flyerplate accelaration
Plasma layer in front of shockfront

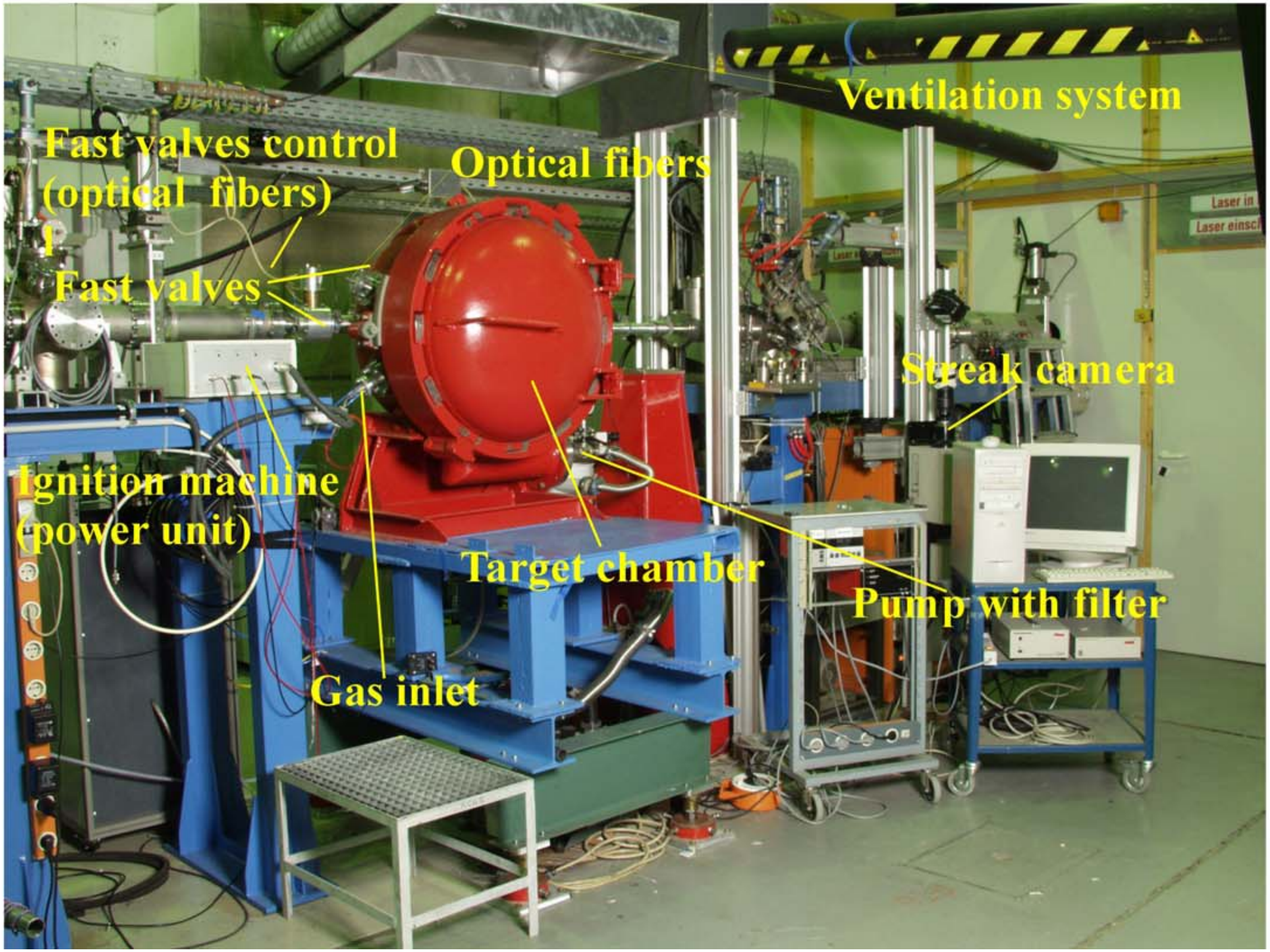


Plasma Diagnostics: Optical fibers connected to photodiodes
(Streak camera)

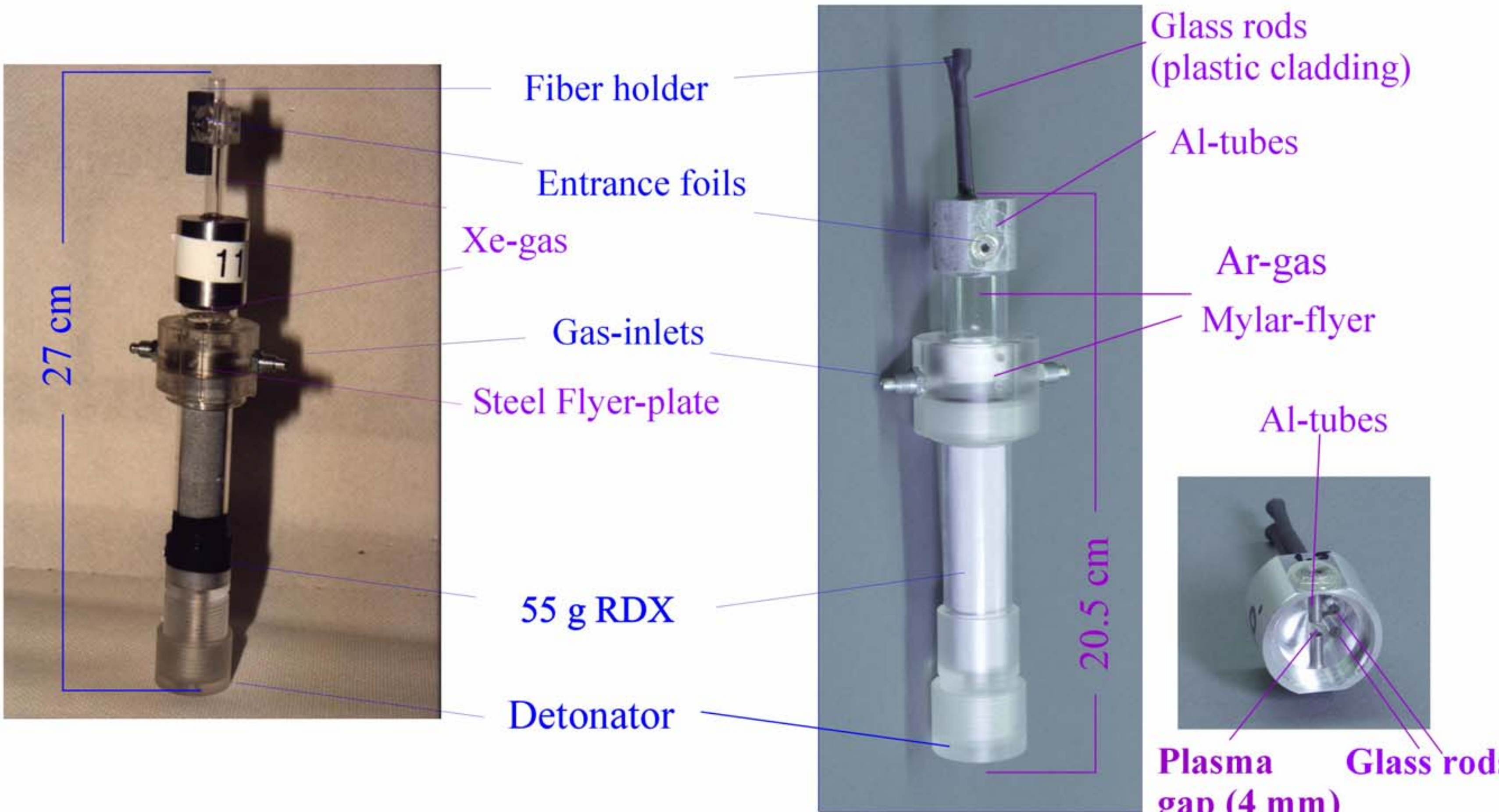
Energy Loss Diagnosis: TOF measurement with Stopdector (MSP)

(Charge State Diagnostic: 10° Magnetic spectrometer)

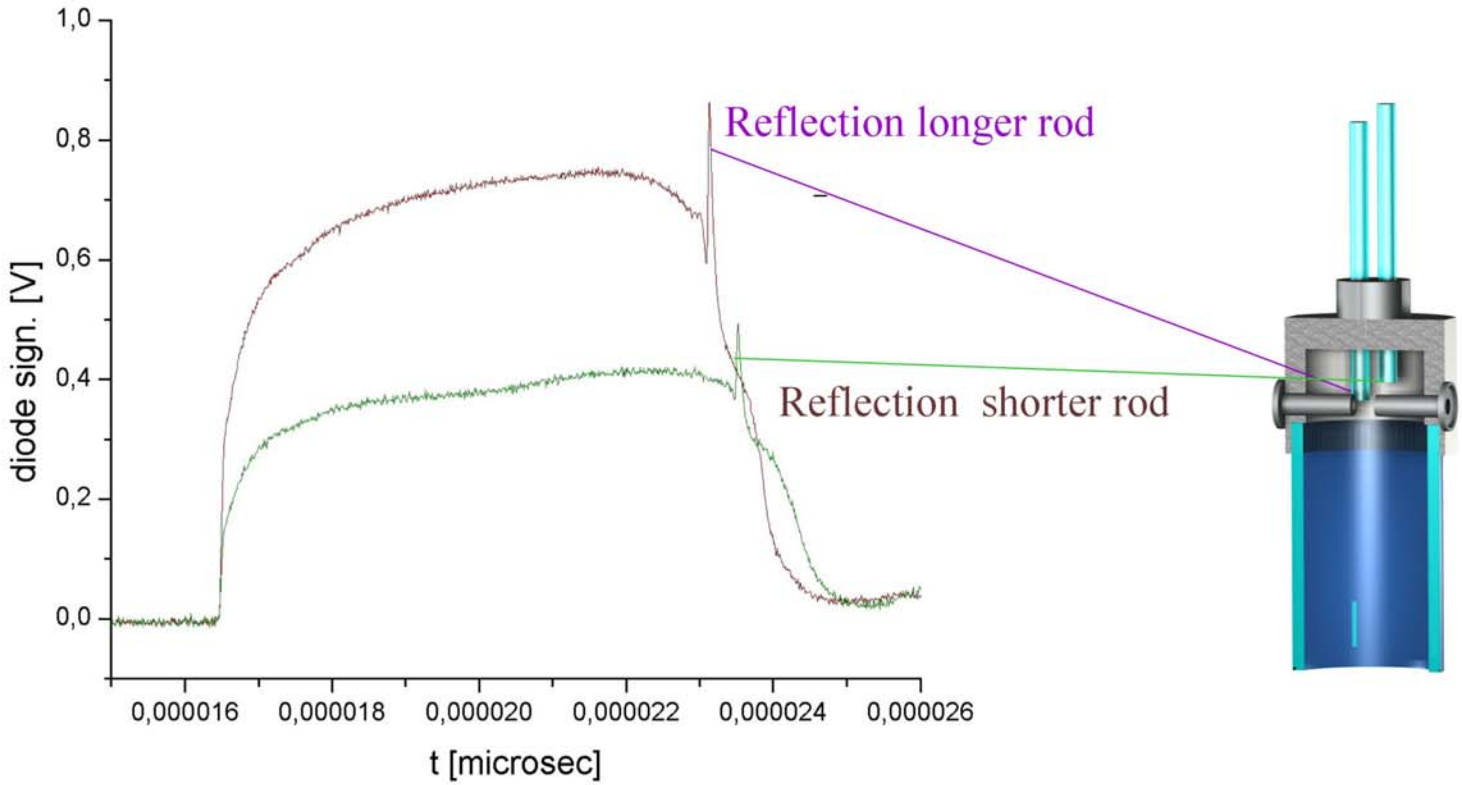
Experimental Set-up with the Explosive Target at Z6



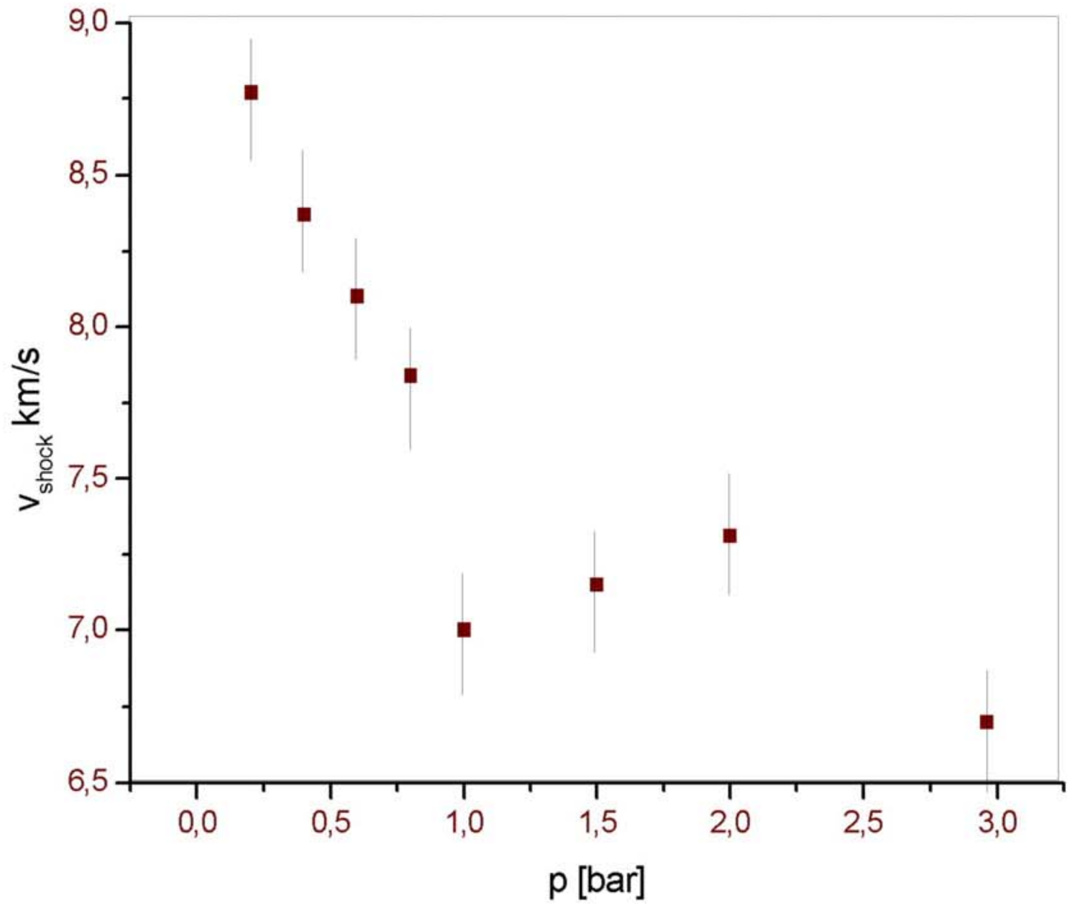
Evolution of Target Configuration from April to December 2002



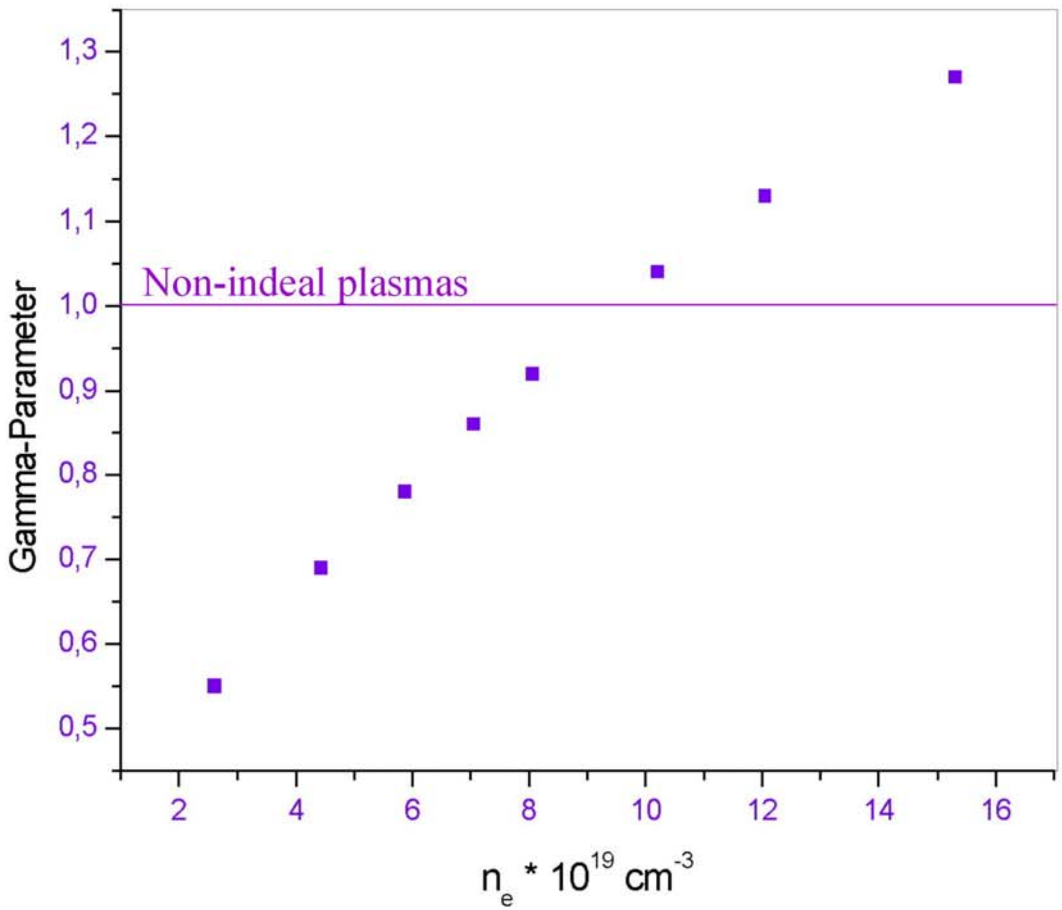
Measurement of Shockwave Velocity



Shockwave Velocity in Ar-gas between 0.2 - 3.0 bar

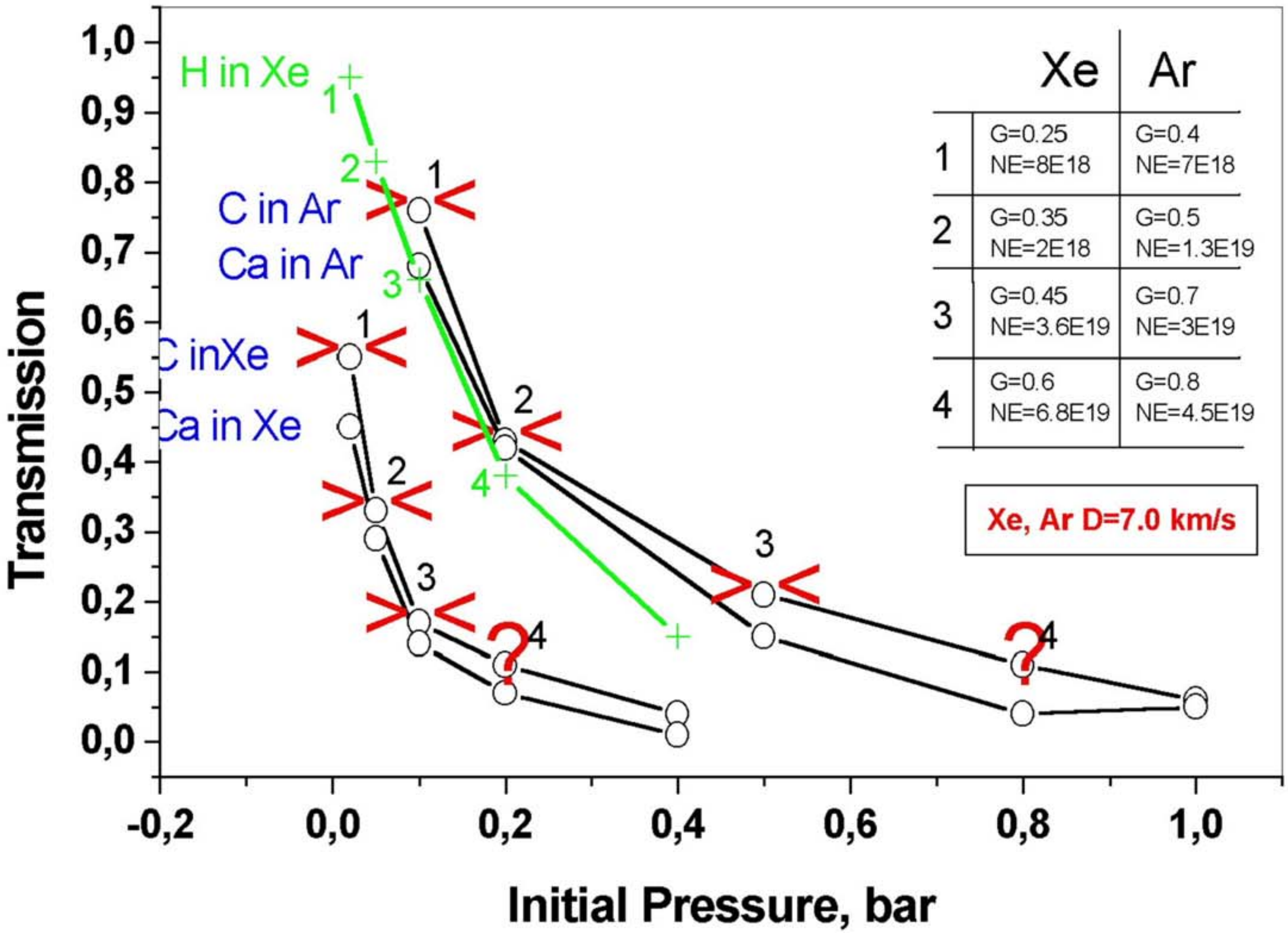


Free Electron Density and Γ-Parameter



Beam-Transmission and Straggling

H (3 MeV), C and Ca (6 MeV/u) in 4 mm Ar- and Xe-plasma



	Xe	Ar
1	G=0.25 NE=8E18	G=0.4 NE=7E18
2	G=0.35 NE=2E18	G=0.5 NE=1.3E19
3	G=0.45 NE=3.6E19	G=0.7 NE=3E19
4	G=0.6 NE=6.8E19	G=0.8 NE=4.5E19

Experimental Conditions

Shockwave-driven plasmas →

- Targets with high explosives
- Fast detonators
- Ignition machine
- Explosion chamber
- Fast valves

Synchronisation of ion beam and explosion

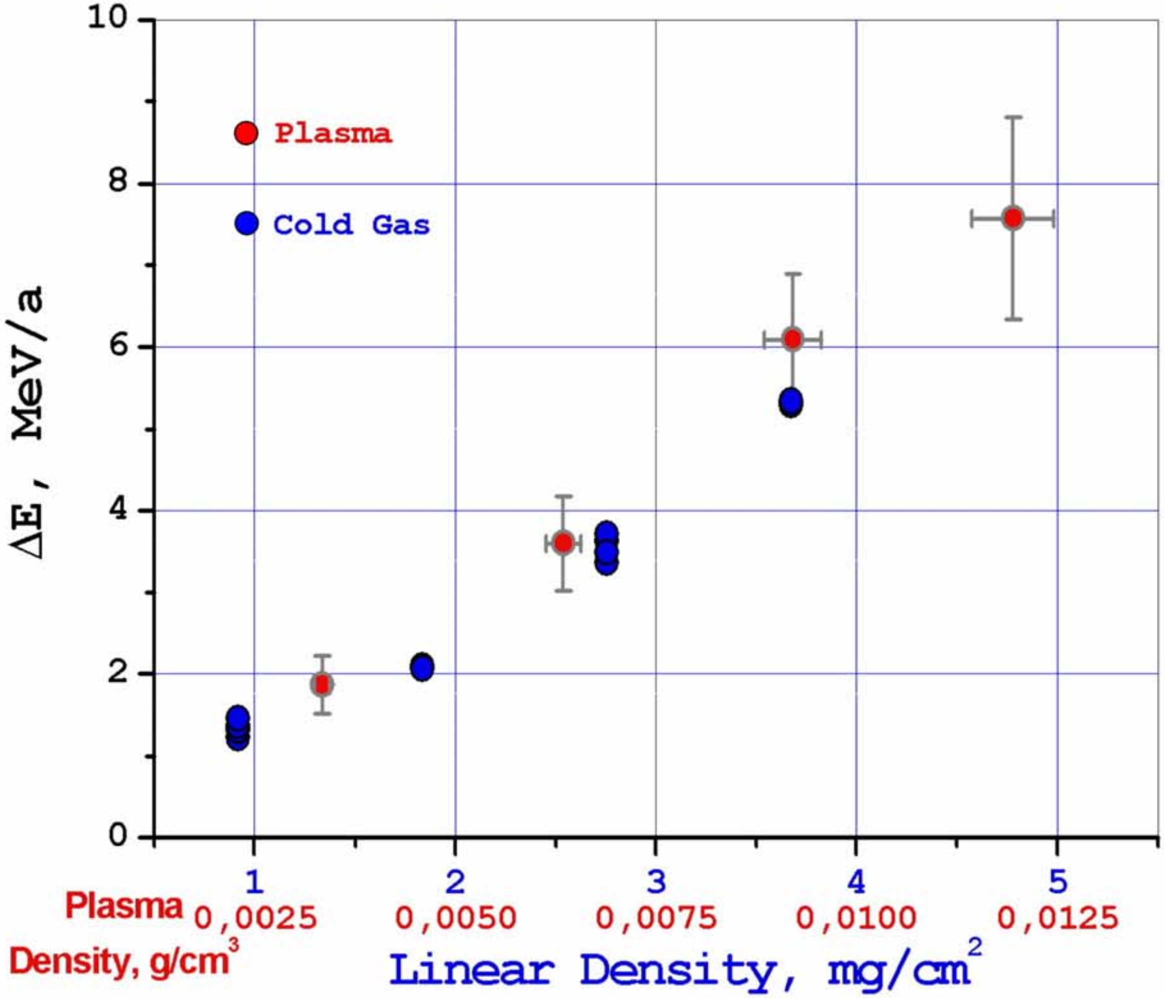
Diagnostics

Shockwave velocity →
- **Fiber optical system**
- **Streak camera images**

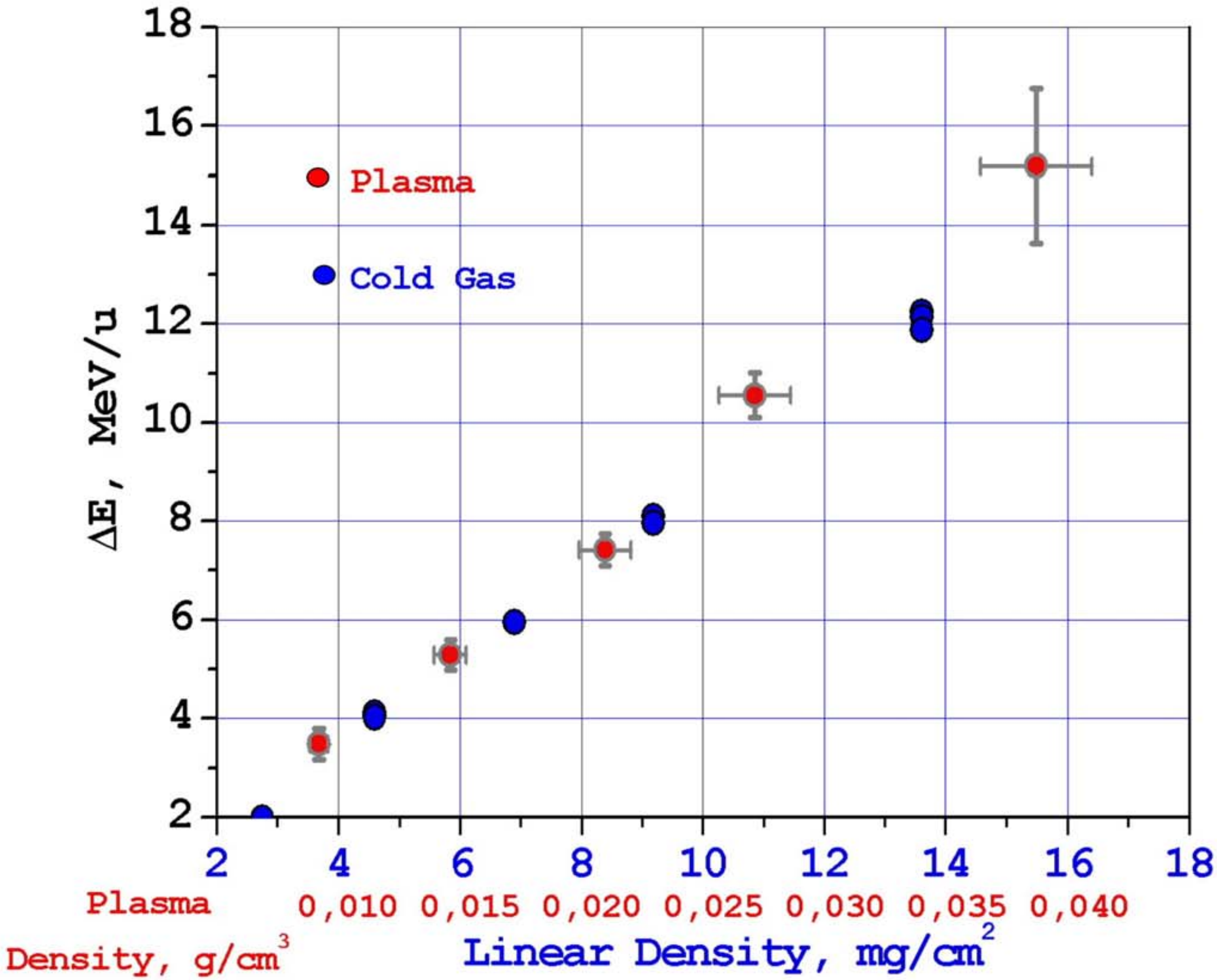
Energy loss dE/dx → **Stop detector with MSP**

Charge state distribution → **Magnetic spectrometer 10 ° magnet and scintilator**

Energy Loss of 5.9 MeV/u C-ions in Ar-gas and -plasma



Energy Loss of 11.4 MeV/u C-ions in Ar-gas and -plasma



Conclusions from the Experiments

- A successful target design has been developped with the 'Gap-target'
- Systematic variation of gas pressure up to high pressures (3 bar) and therefore high free electron densities (> 10^{20} cm^{-3}) and Γ–Partameters > 1 have been achieved with the Ar-plasma
- For systematic investigations the measurements have to be extended to heavier ions than ^{12}C interacting with the Ar-plasma (April 2003, Ar-ions)
- Charge state measurements have to be implemented for investigating the Z_{eff} dependence of dE/dx
- The straggling and transmission problem has to be solved for Xe-plasma also, development of a more sensitive detector
- Hydrogen and Hydrogel plasmas instead of Argon and Xenon in later stages

Investigation of 110 keV/u heavy ion beams interaction with hydrogen plasma

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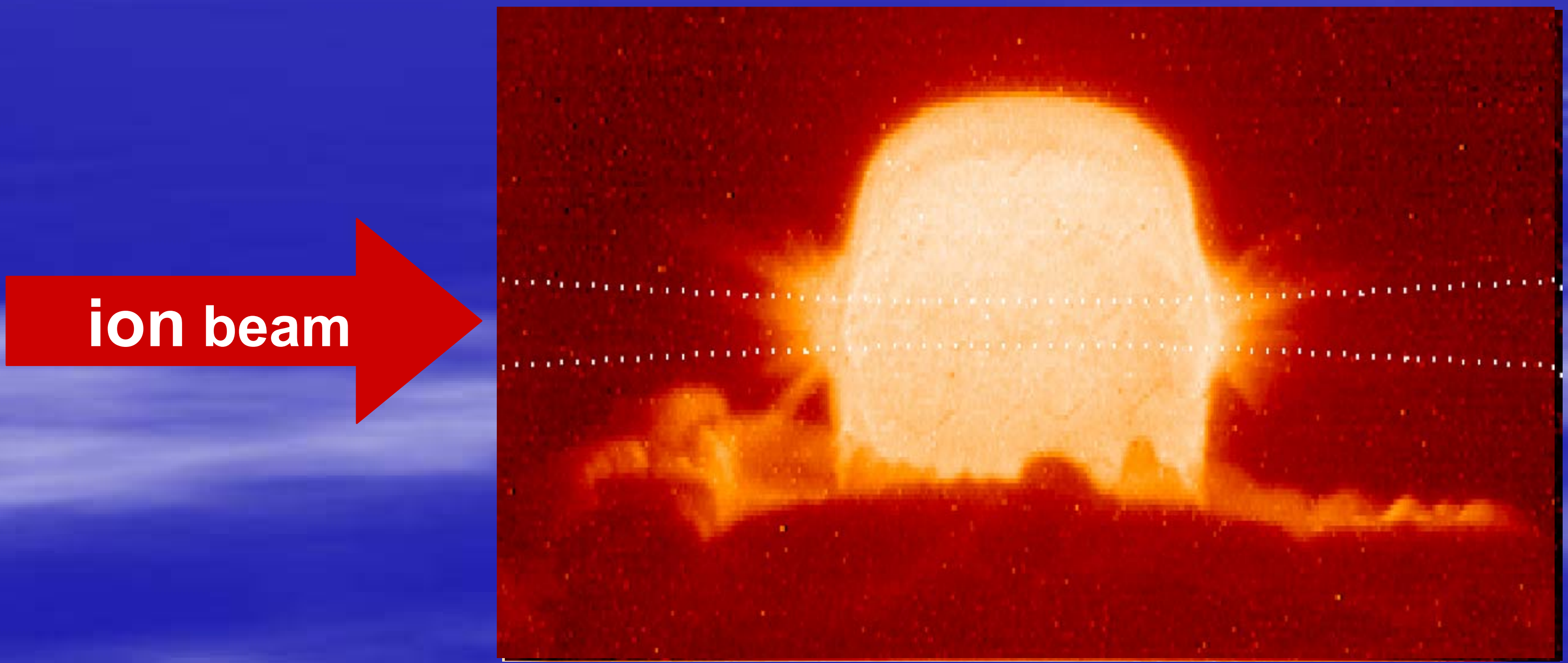
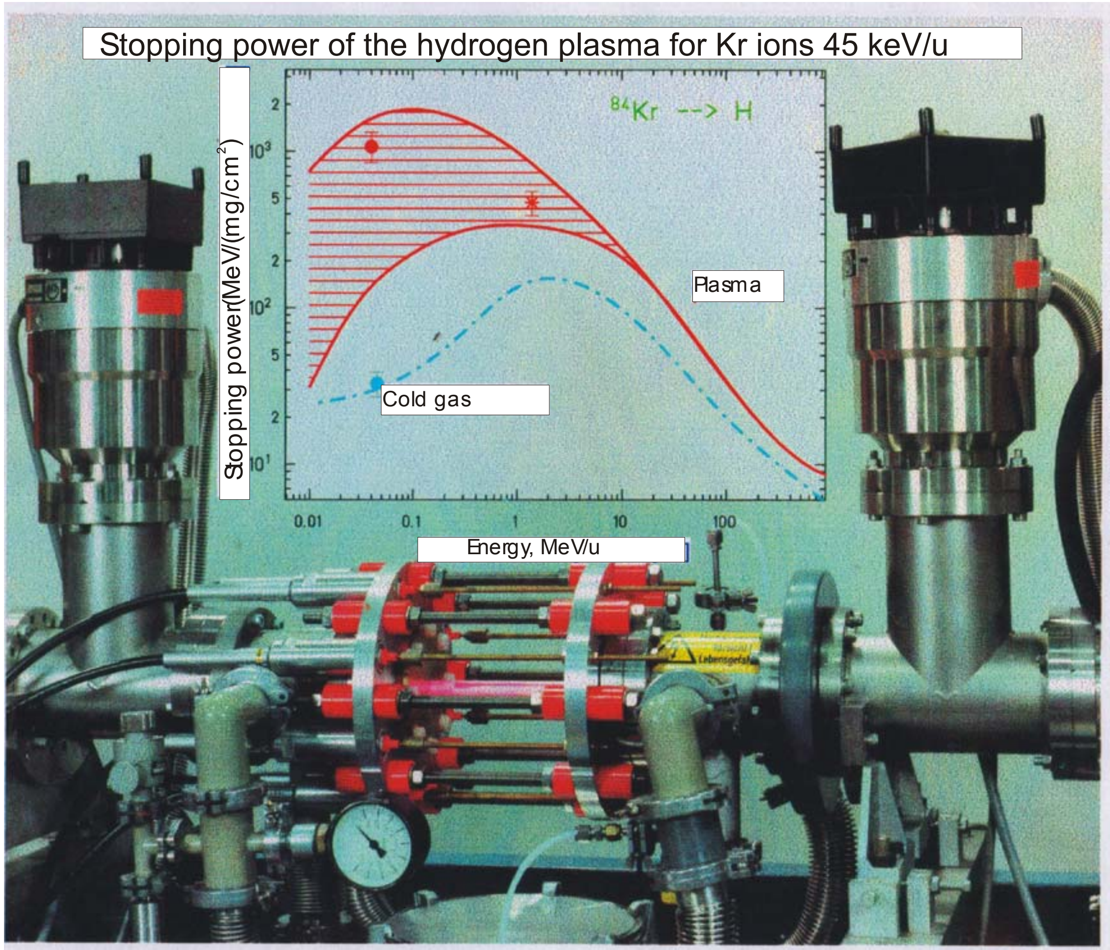
1- ITEP, Moscow, Russia, 2 -MEPhI, Moscow, Russia,
3 - MPTI, Moscow, Russia
4 - GSI, Darmstadt, Germany

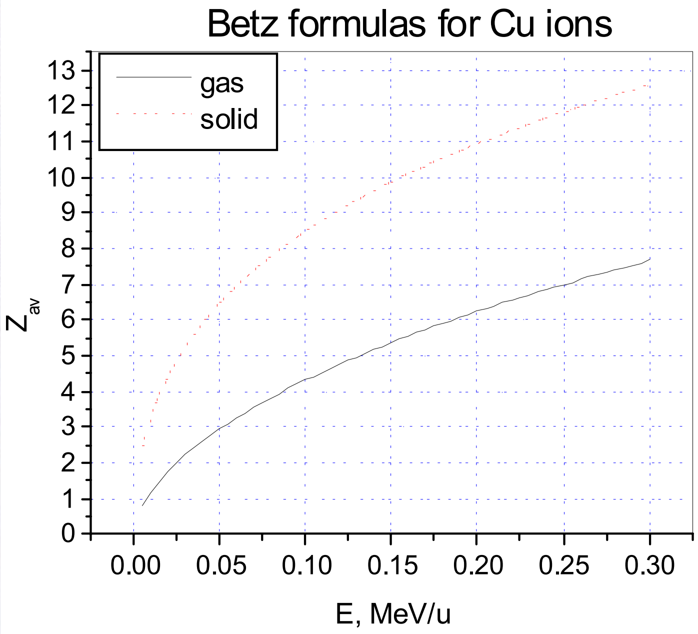
Motivation : Heating Matter with Heavy Ion Beams

Ne^{10+} beam at E_0 = 300MeV/u passing through a Kr crystal

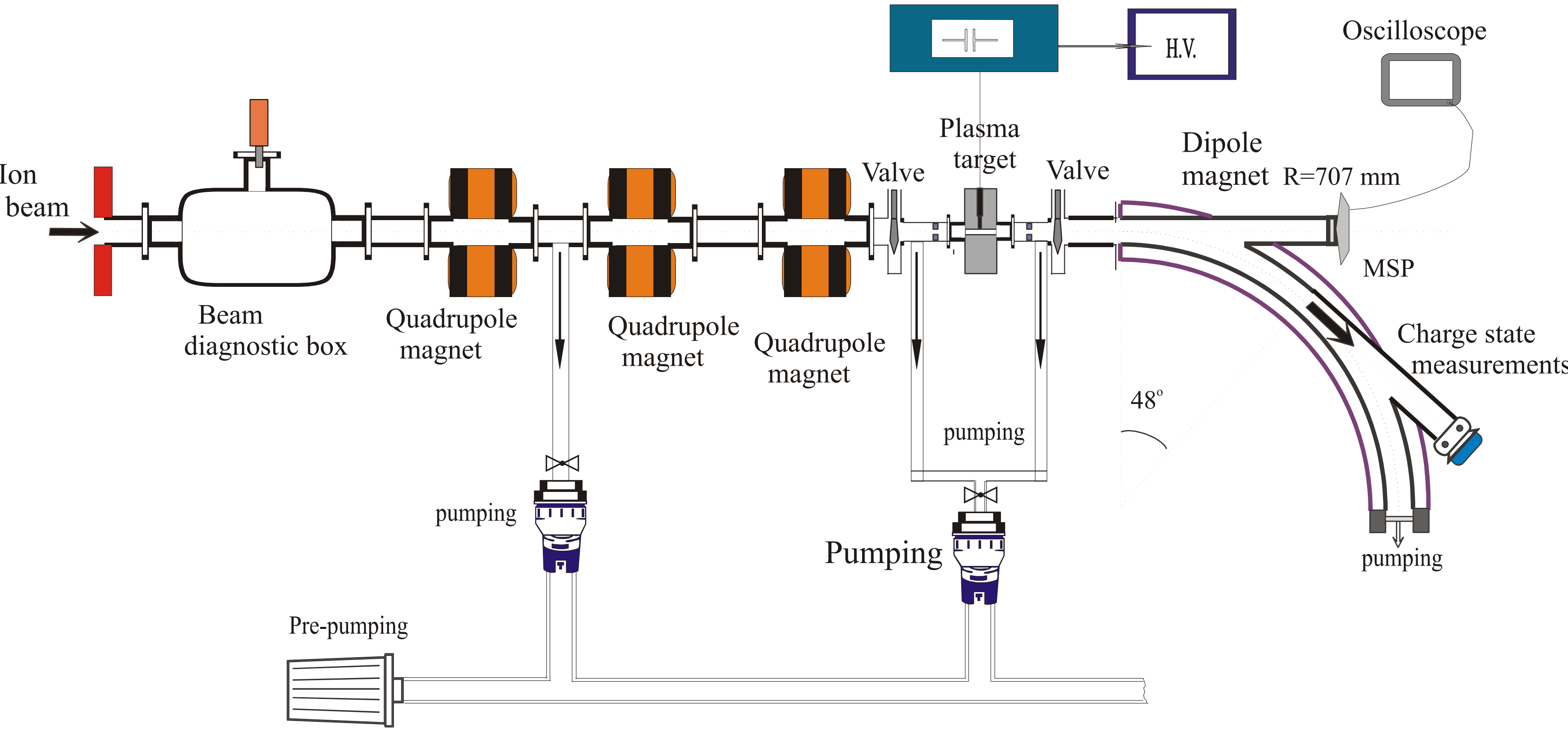


GSI pioneering experiments

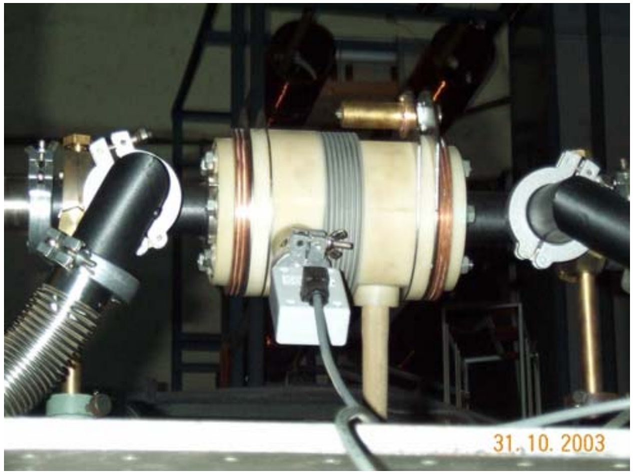


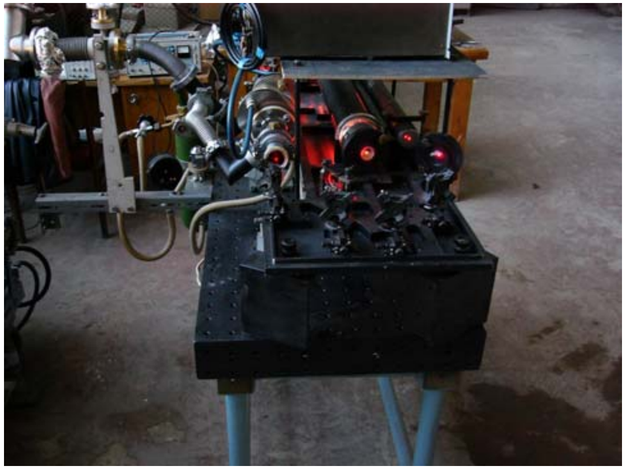


110 keV/u Cu2+ energy loss experiment

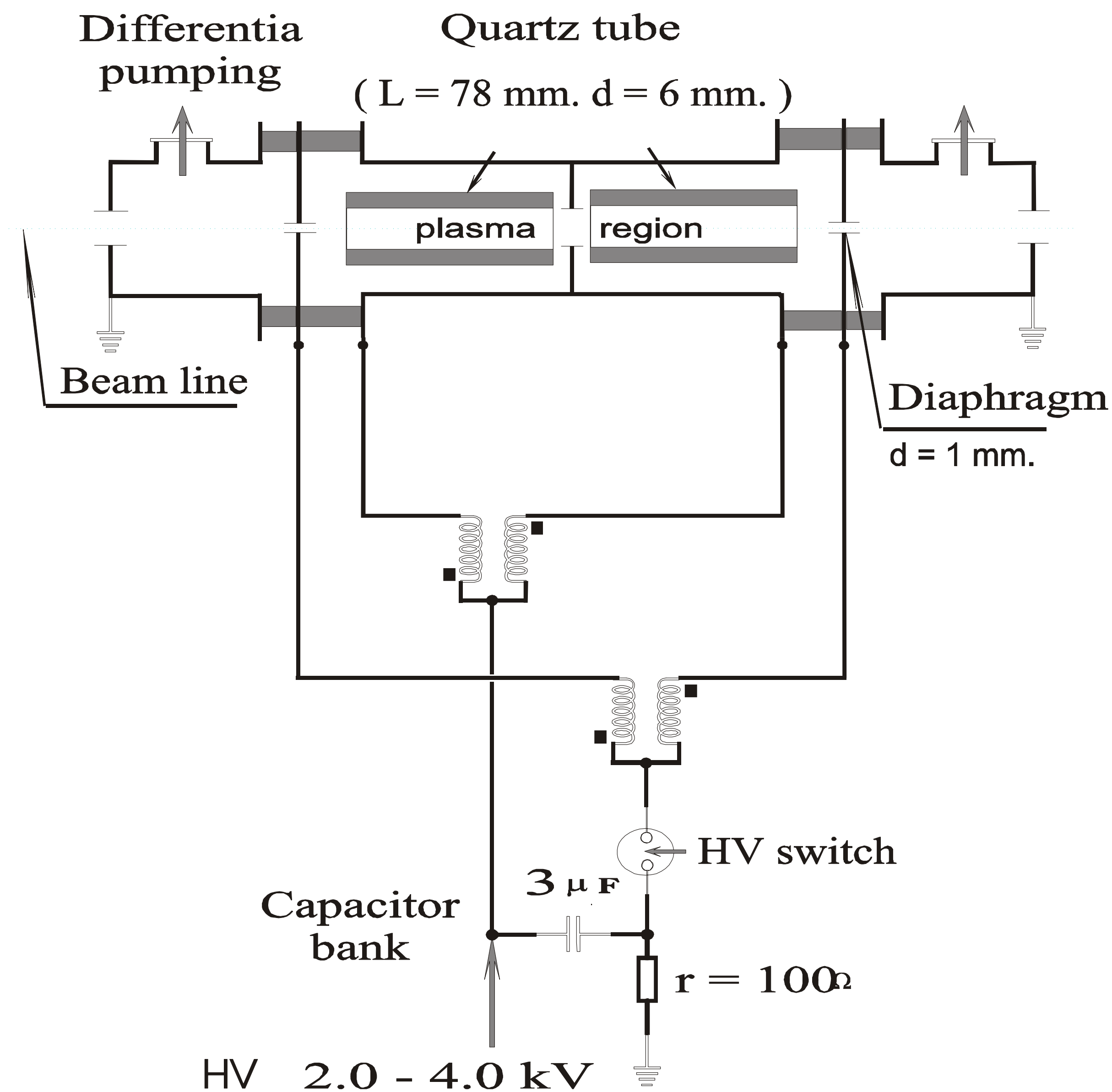


Experimental setup for beam plasma interaction measurements



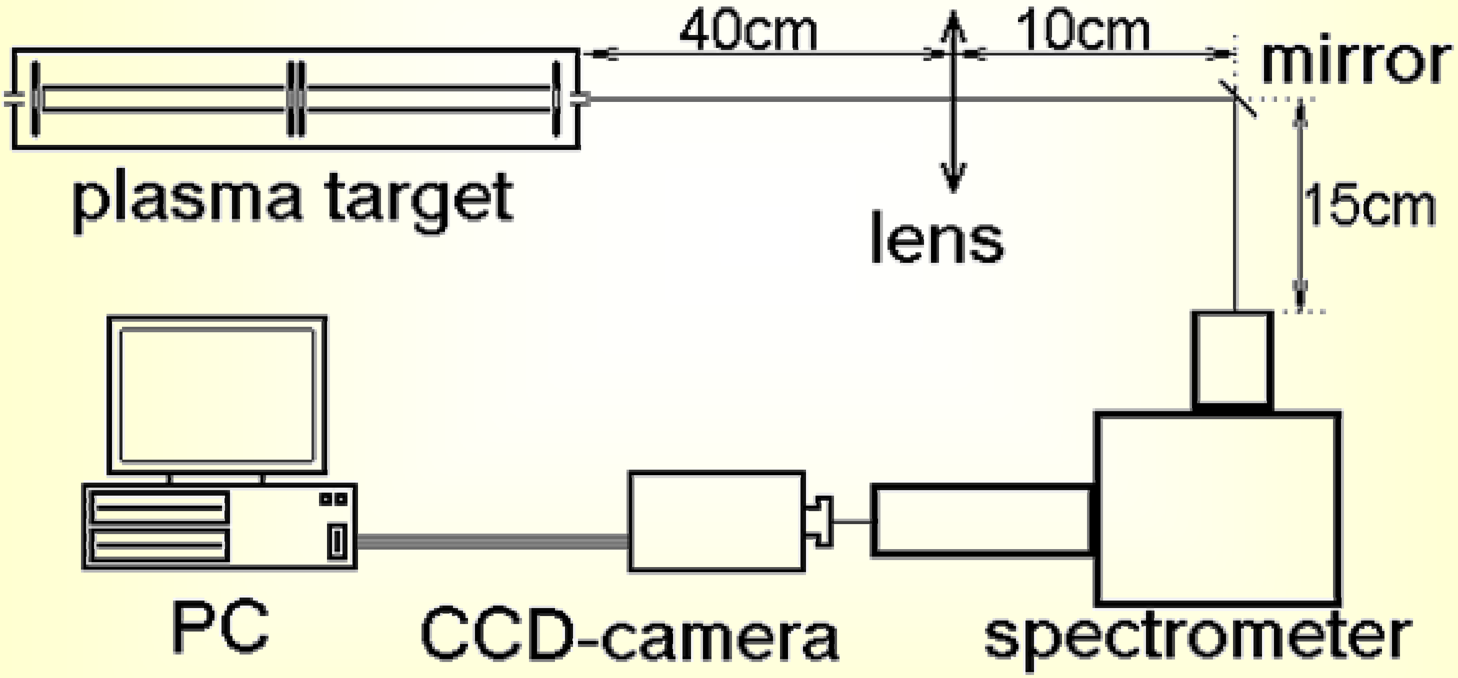


Plasma Target Design



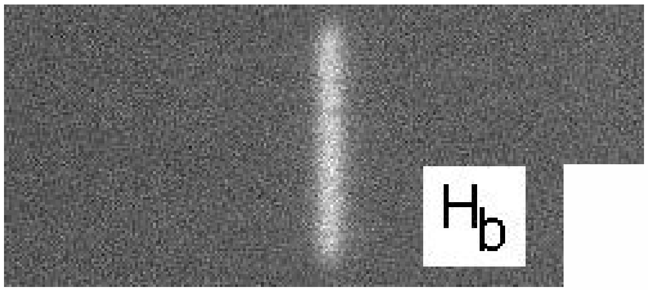
Plasma target spectroscopy

Experimental setup



Results of the spectroscopic measurements

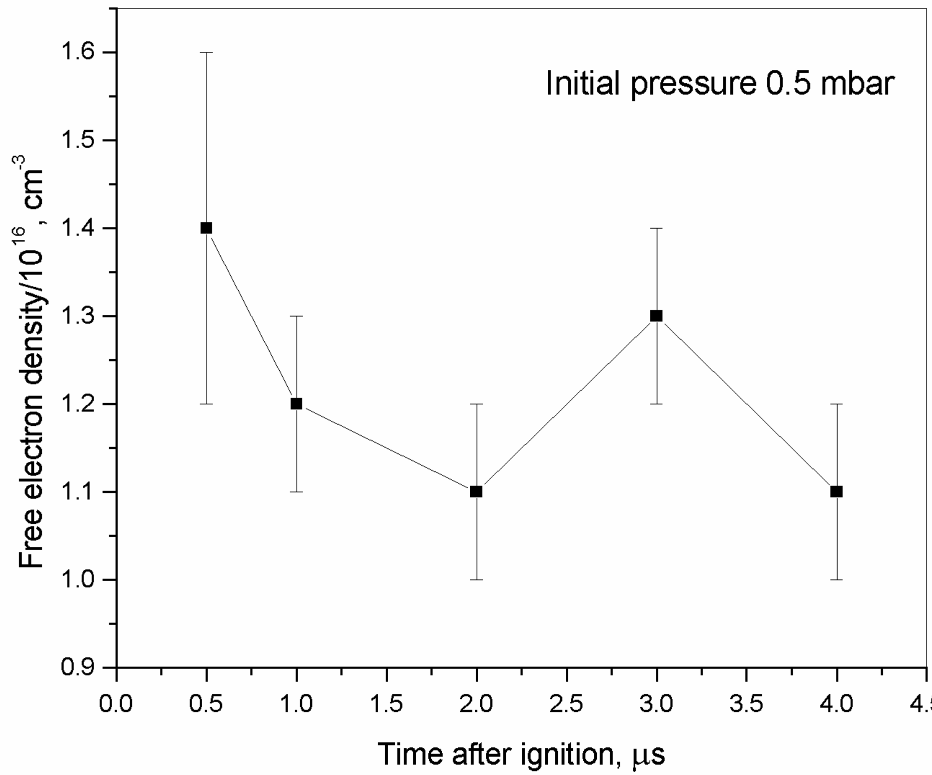
Typical image of Hb line:



Width of Hb line is proportional to free electron density in plasma

$$\Delta \approx n_e^{2/3}$$

Taking images with 1μs exposition and different delay allows to determine a time-resolved behavior of electron density.



SUMMARY

- ITEP-TWAC project is well in progress aiming at HIF-E related experiments

- Stopping of C ions in explosively driven plasma has been investigated

- Experimental set up for 110 keV/u Cu2+ ion stopping experiment is in commissioning phase