Accelerator Systems for Heavy Ion Inertial Fusion

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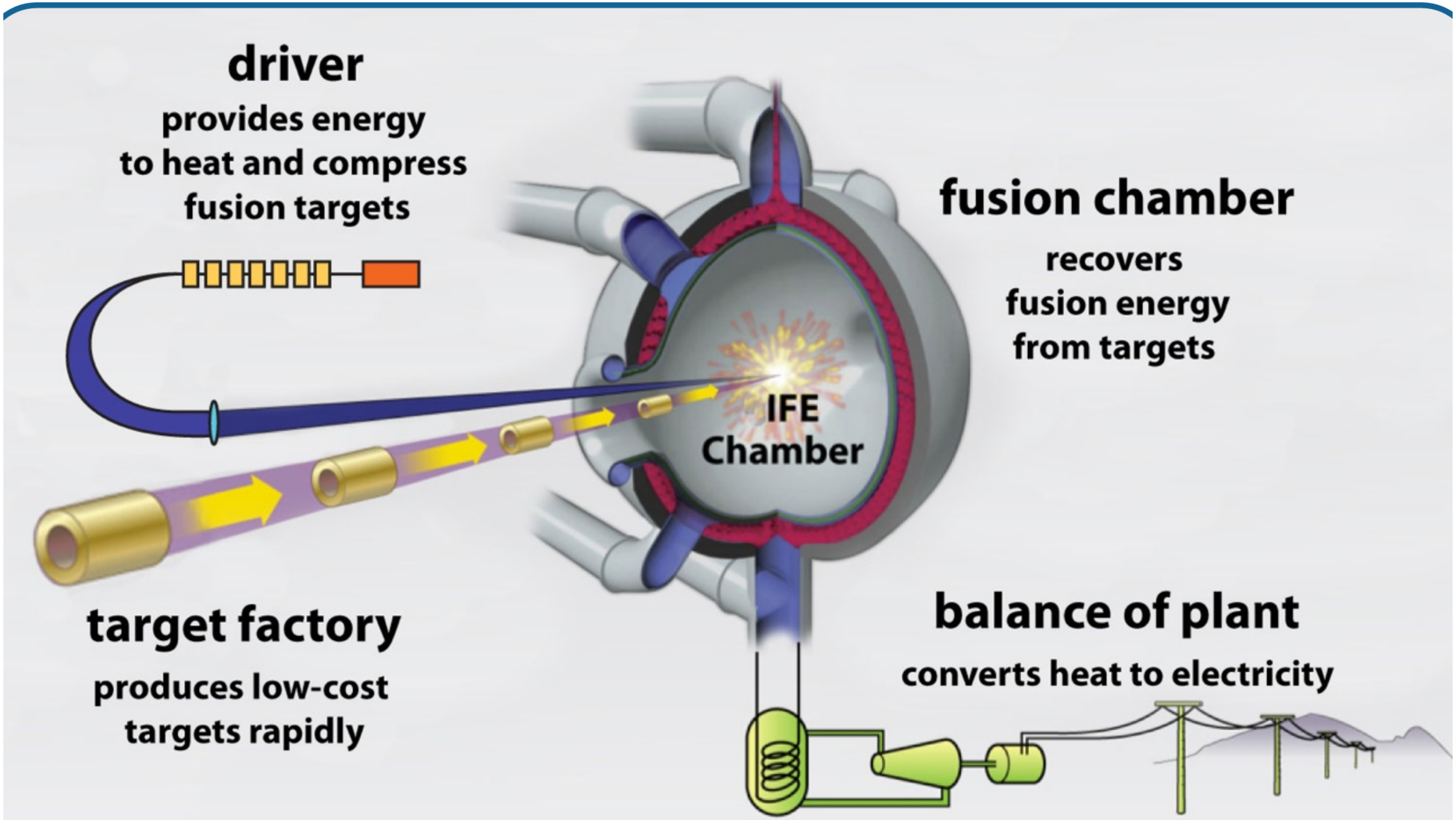
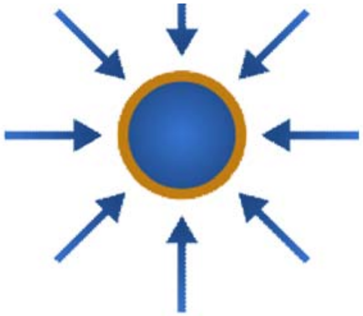
Electricity from inertial confinement fusion reactions



HIF Primer at hif.lbl.gov/public/Sharp/HIF_overview.pdf

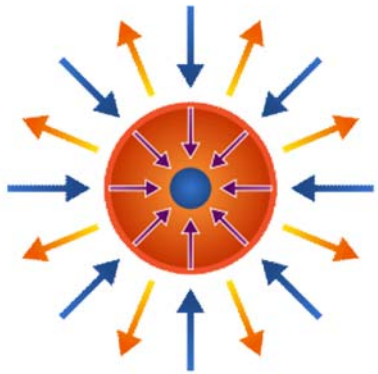
How can accelerators be used to drive fusion targets?



input energy quickly heats surface of fuel capsule

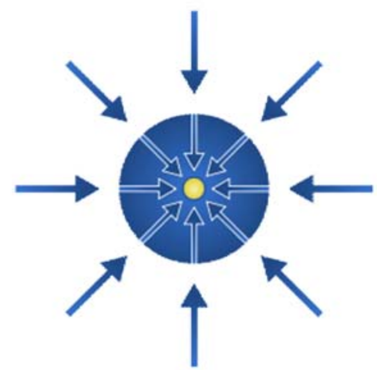
~10mg DT
ρ ~ 0.5 mg/cm³
(ρ-r 0.03-3 g/cm²)

Compression ratio up to 30:1



fuel is compressed isentropically by rocket-like blowoff of hot surface material

compressed fuel core (“hotspot”) reaches density and temperature needed for ignition



ρ ~100 g/cm³ (hotspot)
T ~ 5-12 keV
(ρ-r ~ 0.2-0.5 g/cm²)

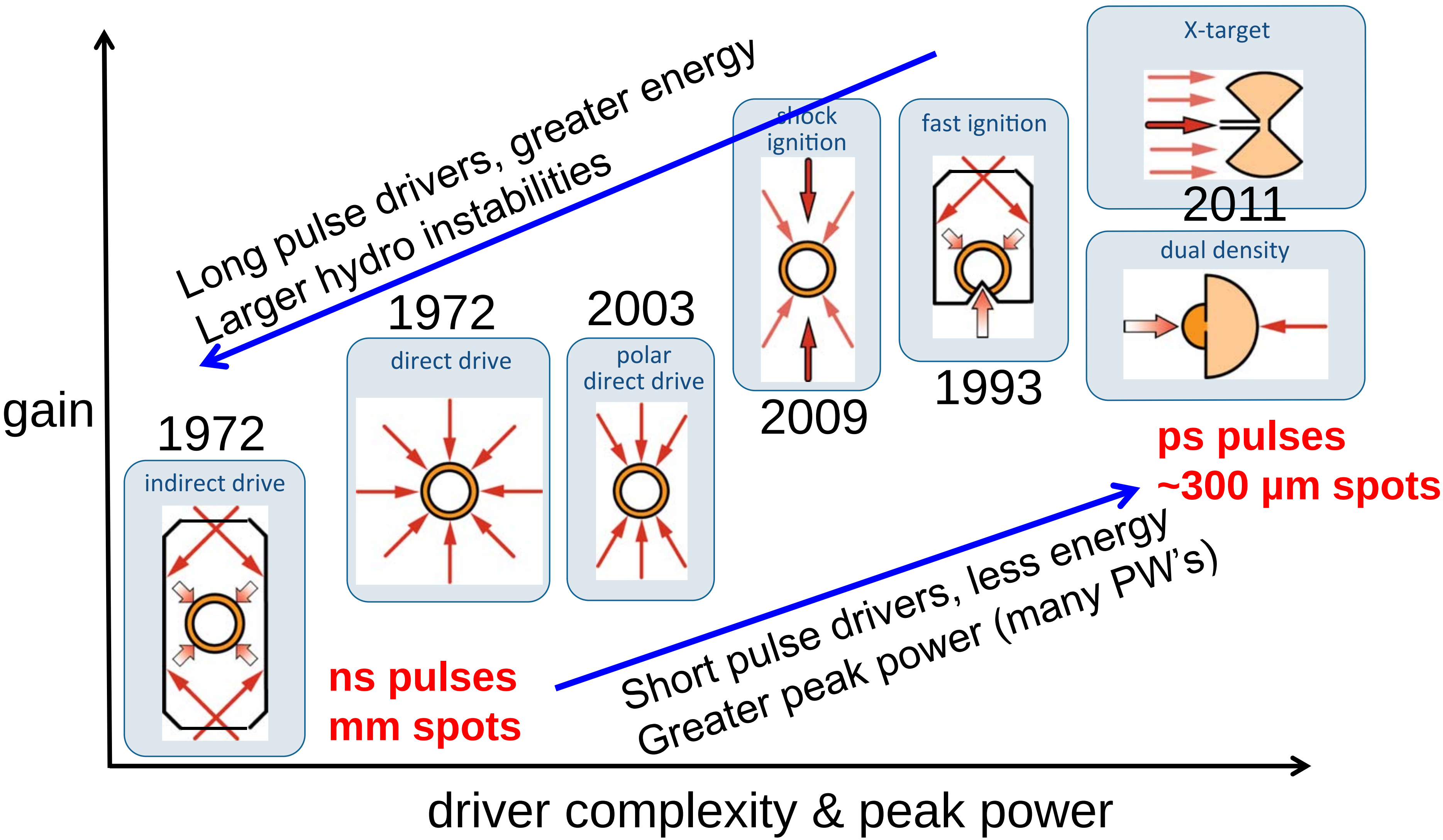
ρ ~400-800 g/cm³ (fuel)
T << 5 keV

thermonuclear burn spreads quickly through compressed fuel

0.5-2 GJ
~50ps

Courtesy W. Sharp

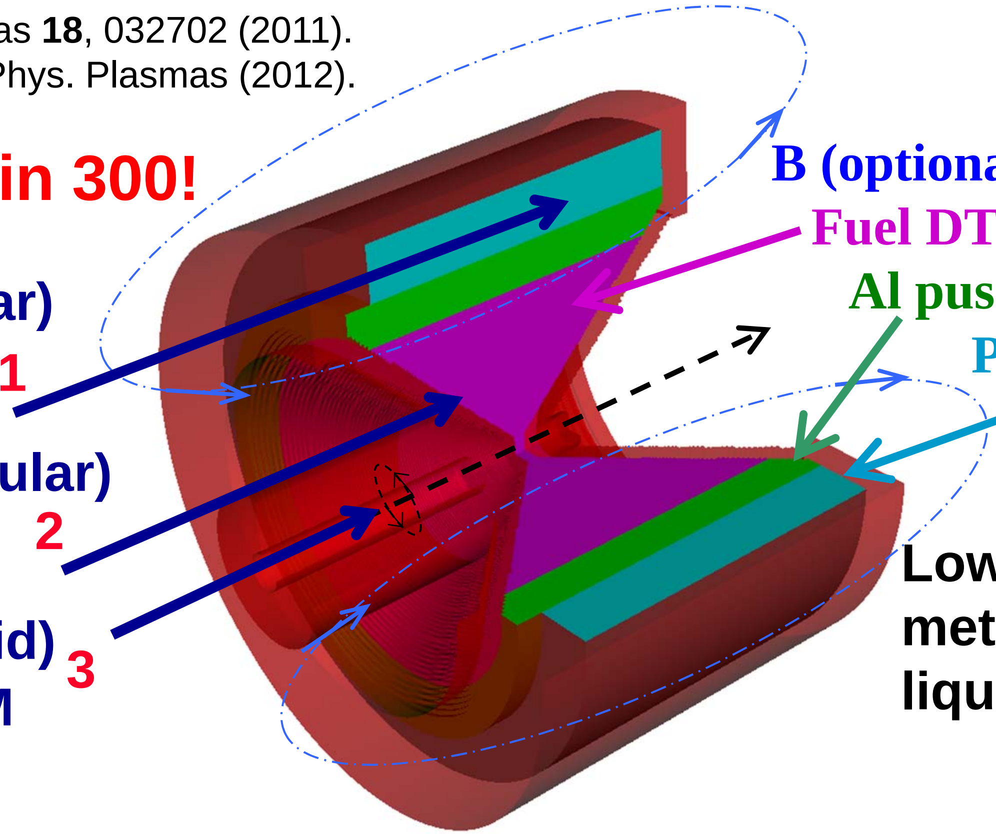
Higher gain targets require higher peak power drivers



X-target: A game changer in ion-driven fast ignition targets

Henestroza, et al., Phys. Plasmas **18**, 032702 (2011).
Henestoza, et al., submitted to Phys. Plasmas (2012).

1.5 GJ yield → Gain 300!



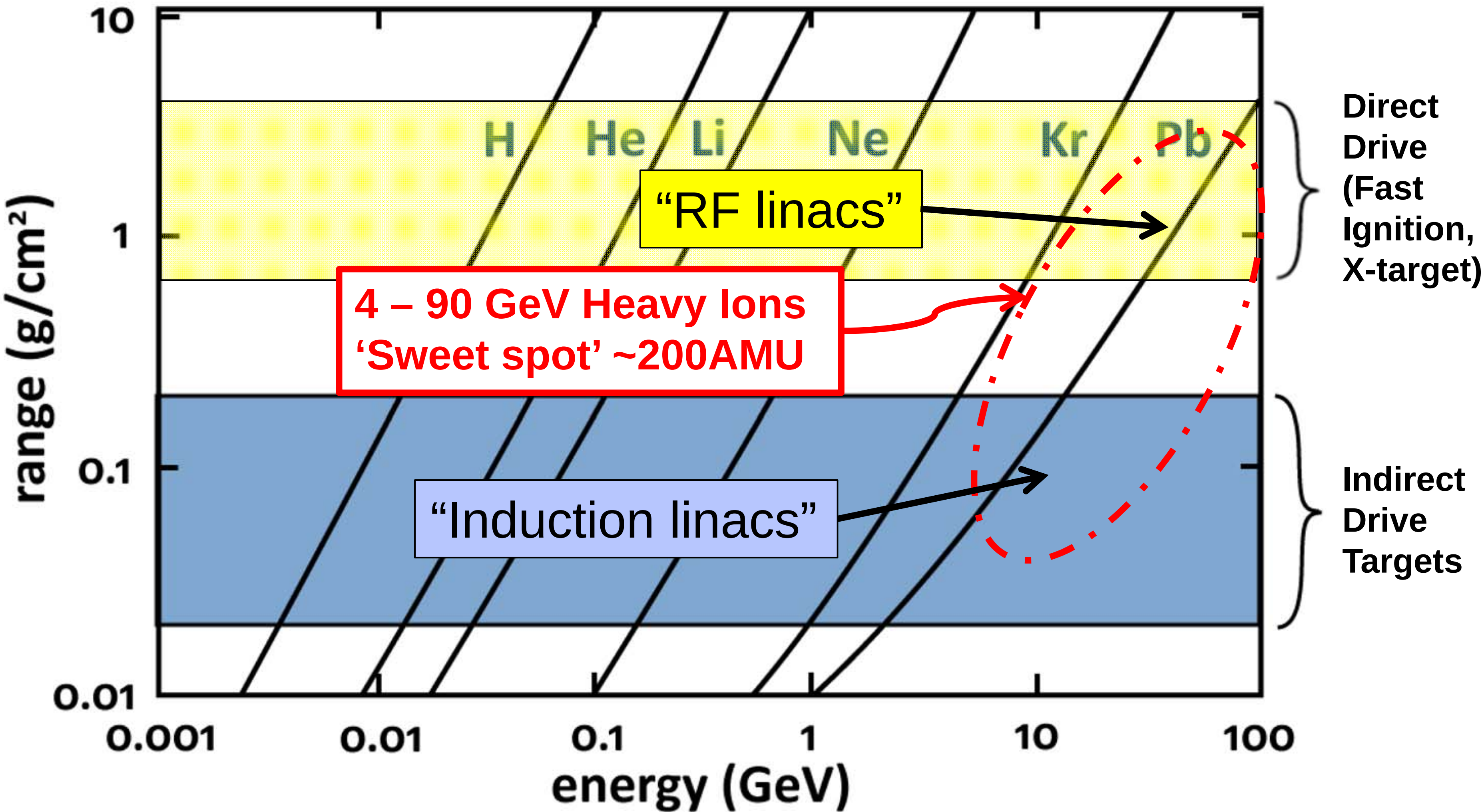
Single-sided beam illumination *along z-axis*

Compress fuel *quasi-spherically in radius for high gain!*

Lowest required fuel convergence (~5) of any 2-D high gain IFE target

→ more robust to hydro instabilities and mix ←key!

Target design determines required ion range & beam power



Need high currents!

Driver concepts must address 3 main issues

Drive beam example requirements:

Case:	Deposited energy (MJ)	Pulse duration (ns)	Beam spot (mm)	Ion energy (GeV)	Number of beams	Beam current (kA)
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- How do we achieve the necessary high beam currents?
- How do we focus the beam to ~100-500 µm spots?
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- How do we focus the beam to ~100-500 µm spots?

Facilities exist (and planned) to study driver and target concepts

NDCX-II can explore intense beam compression to sub-ns pulses relevant to shocks and HIF target physics

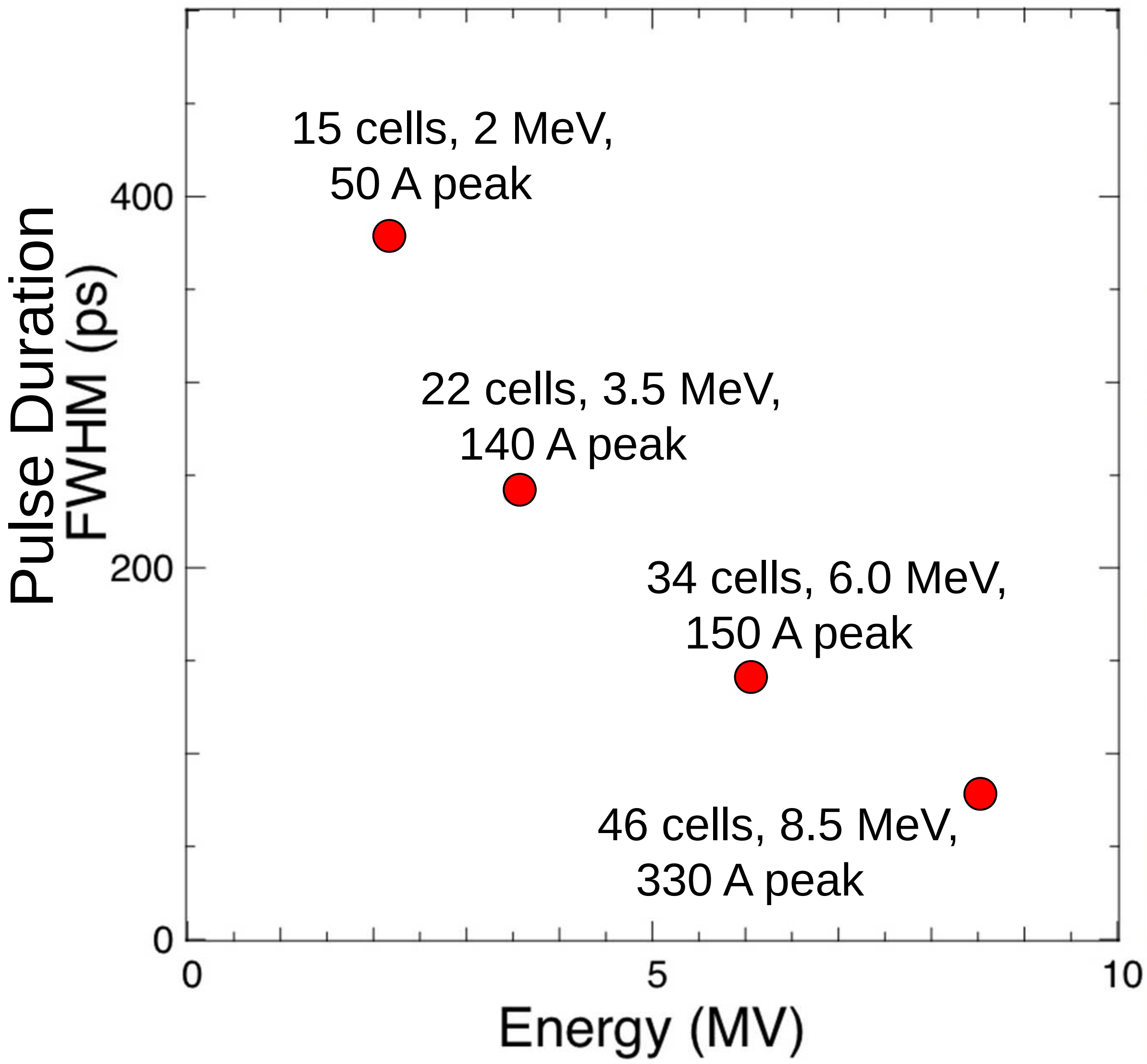
NDCX-II baseline (12 active cells)	
Ion species	Li^+ (A=7)
Ion energy	1.2 MeV
Focal radius	0.5 mm
Pulse duration	~1 ns
Peak current	~ 10

Most dimensionless parameters:

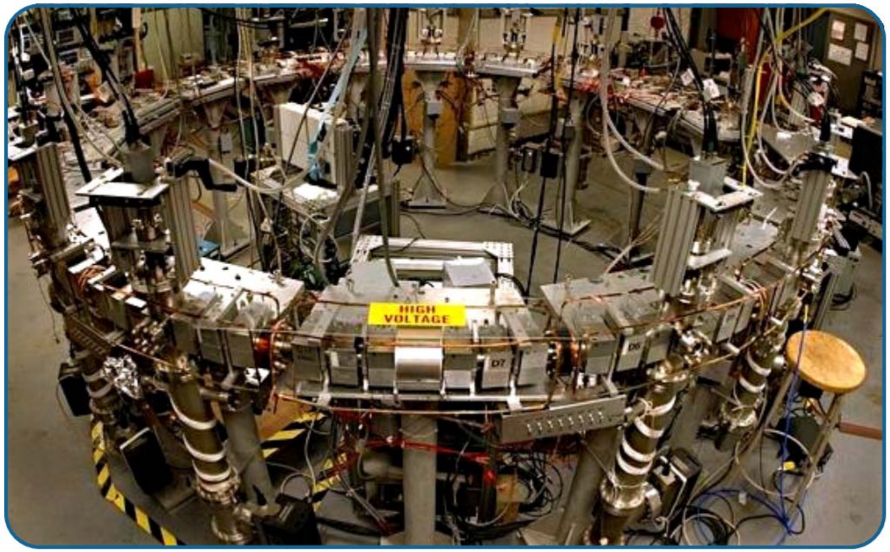
- **Perveance (< ~2 10^{-2})**
- **Tune depression (σ/σ_0)**
- **Compression ratio (500:1)**

similar to, or more aggressive than driver-scale values.

NDCX-II can explore intense beam compression to sub-ns pulses relevant to shocks and HIF target physics



Small-scale experiments can establish transport limits of space charge dominated beams



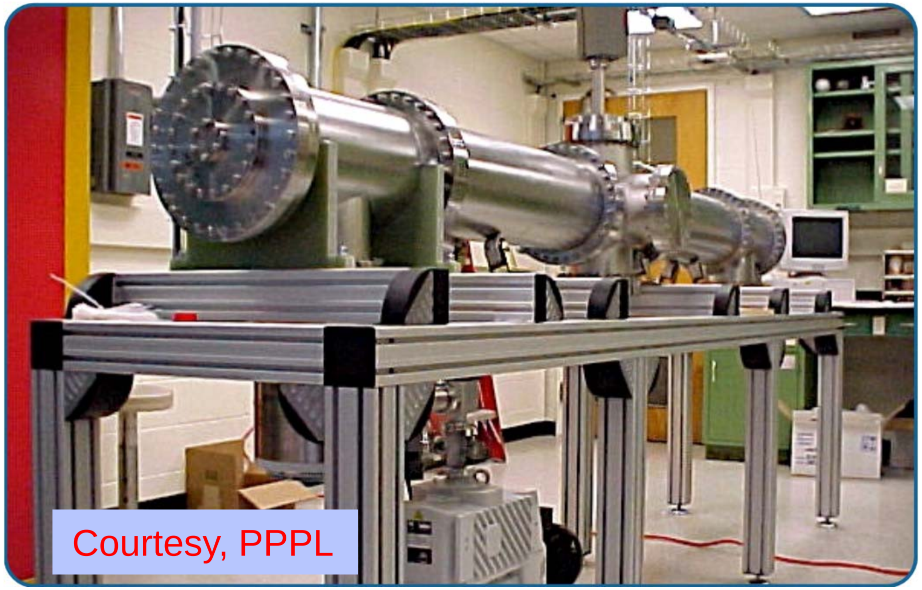
Courtesy, U. Maryland

University of Maryland Electron Ring (UMER)

- ring under construction since 1997
- completed in 2008
- low-energy electrons model intense ion beams
- dimensionless space-charge intensity similar to HIF driver
- beam has successfully completed 100s of laps

Paul Trap Simulator Experiment (PTSX)

- operating at PPPL since 2002
- oscillating electric quadrupoles confine ions
- equivalent to 1000s of lattice periods



Courtesy, PPPL

European and Asian laboratory R&D efforts for HIF drivers

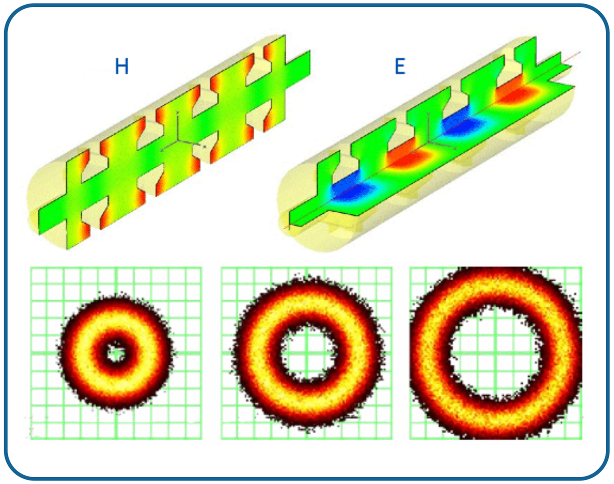
Germany - GSI

- FAIR (Facility for Antiproton and Ion Research) is being built
  - major upgrade of current and energy for existing accelerator complex
  - 5 x 10^{11} ions at 150 MeV/u in a 50-100 ns pulse
- HEDgHOB program will use FAIR to study high-energy-density physics
- LAPLAS (LAboratory PLanetary Science) will FAIR to study physics of Jupiter-like planets

Russia - ITEP

We hope for a speedy recovery!

- TWAC (TeraWatt ACcumlator) is complete
- multiple rings accelerate ions to 200 GeV/ion
- laser ion source for high-charge-state Al, Fe, and Ag ions
- rf "wobbler" developed to produce circular focal spots
  - improves the deposition symmetry
  - could allow use of fewer beams



Japan and China

(IMP, Lanzhou Heavy Ion facility)

- numerical work on beam transport, focusing, and target physics
- Paul Trap research at Hiroshima University

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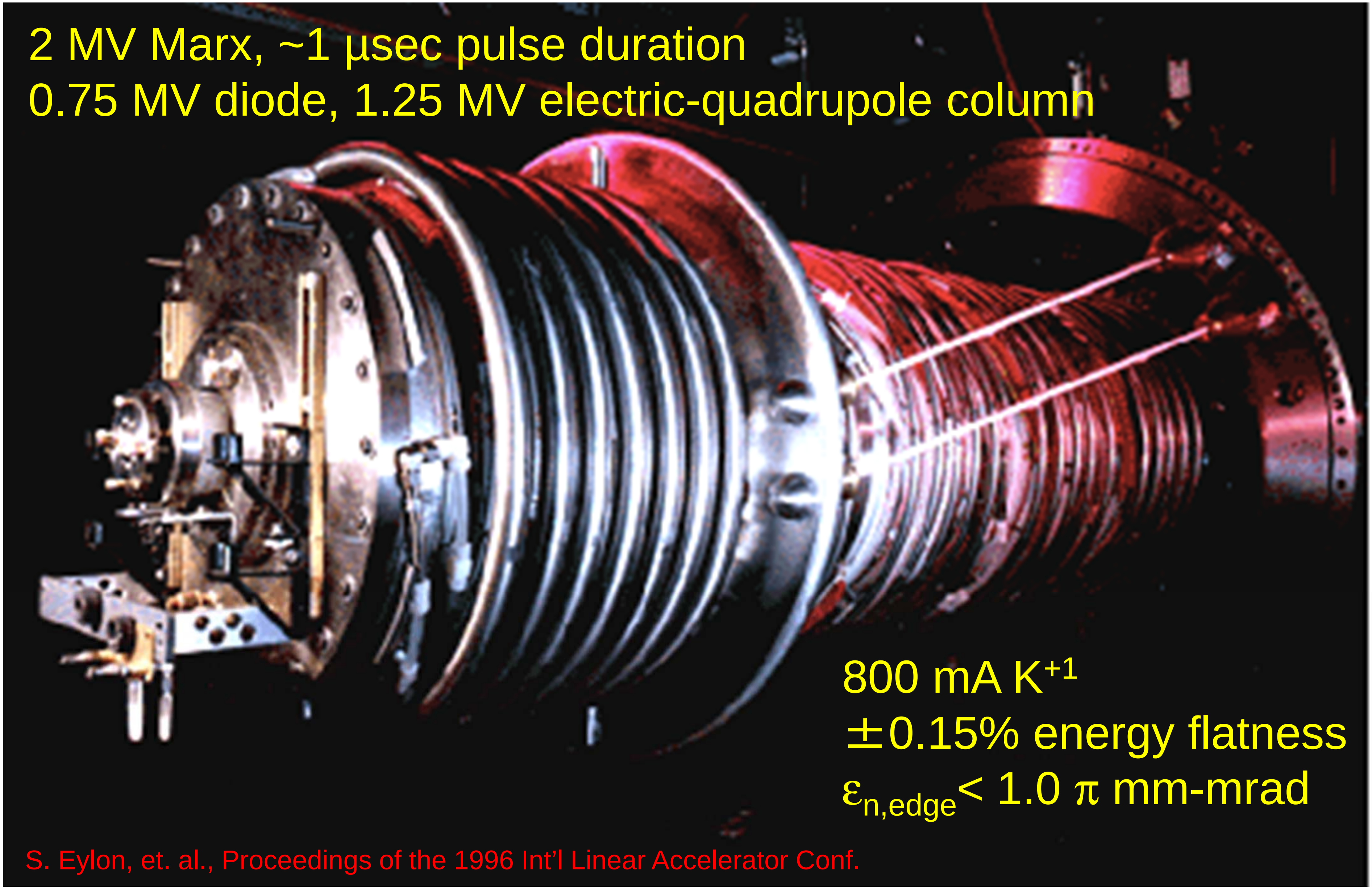
- **New sources and injectors**
- **Stack charge**
- **Merge at various stages**
- **Control beam loss, emittance, momentum spread**

LBNL 2-MV High Current Injector for induction linac driver



2 MV Marx, ~1 μsec pulse duration

0.75 MV diode, 1.25 MV electric-quadrupole column

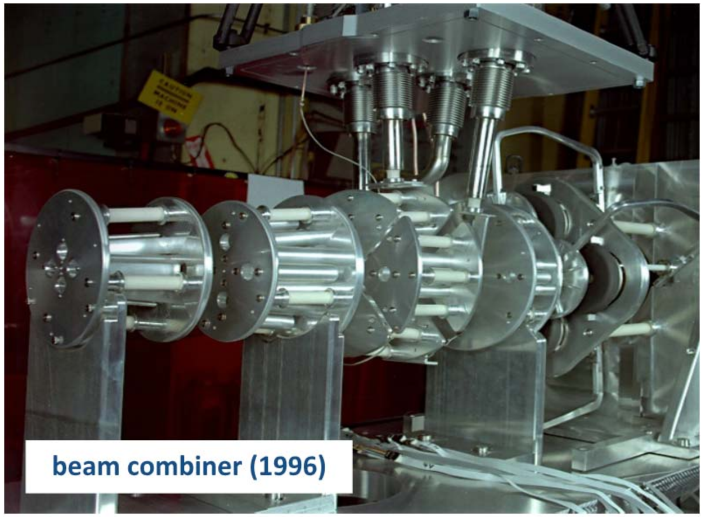
800 mA K^{+1}

$\pm$0.15% energy flatness

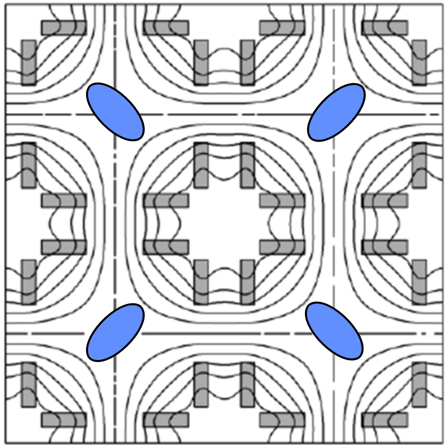
$\varepsilon_{n,edge} < 1.0\ \pi$ mm-mrad

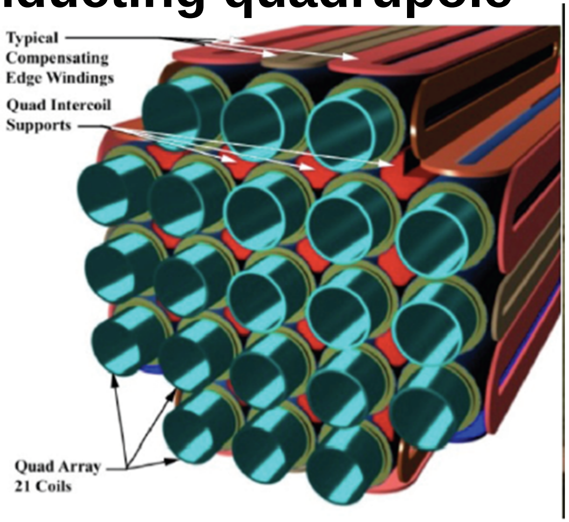
S. Eylon, et. al., Proceedings of the 1996 Int'l Linear Accelerator Conf.

Induction linacs efficiently transport *transversely stacked* beams



21-beam superconducting quadrupole

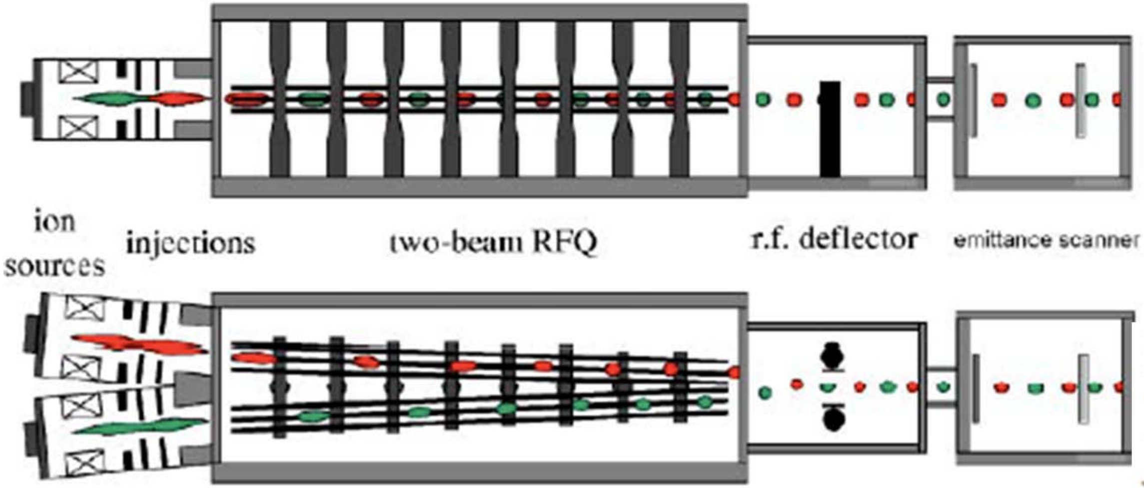




4-beam electrostatic quadrupole

Prototype quadrupole array

A novel two-beam RFQ injector *stacks longitudinally*



Funneling Expt. (Frankfurt):
Two beam RFQ + RF deflector

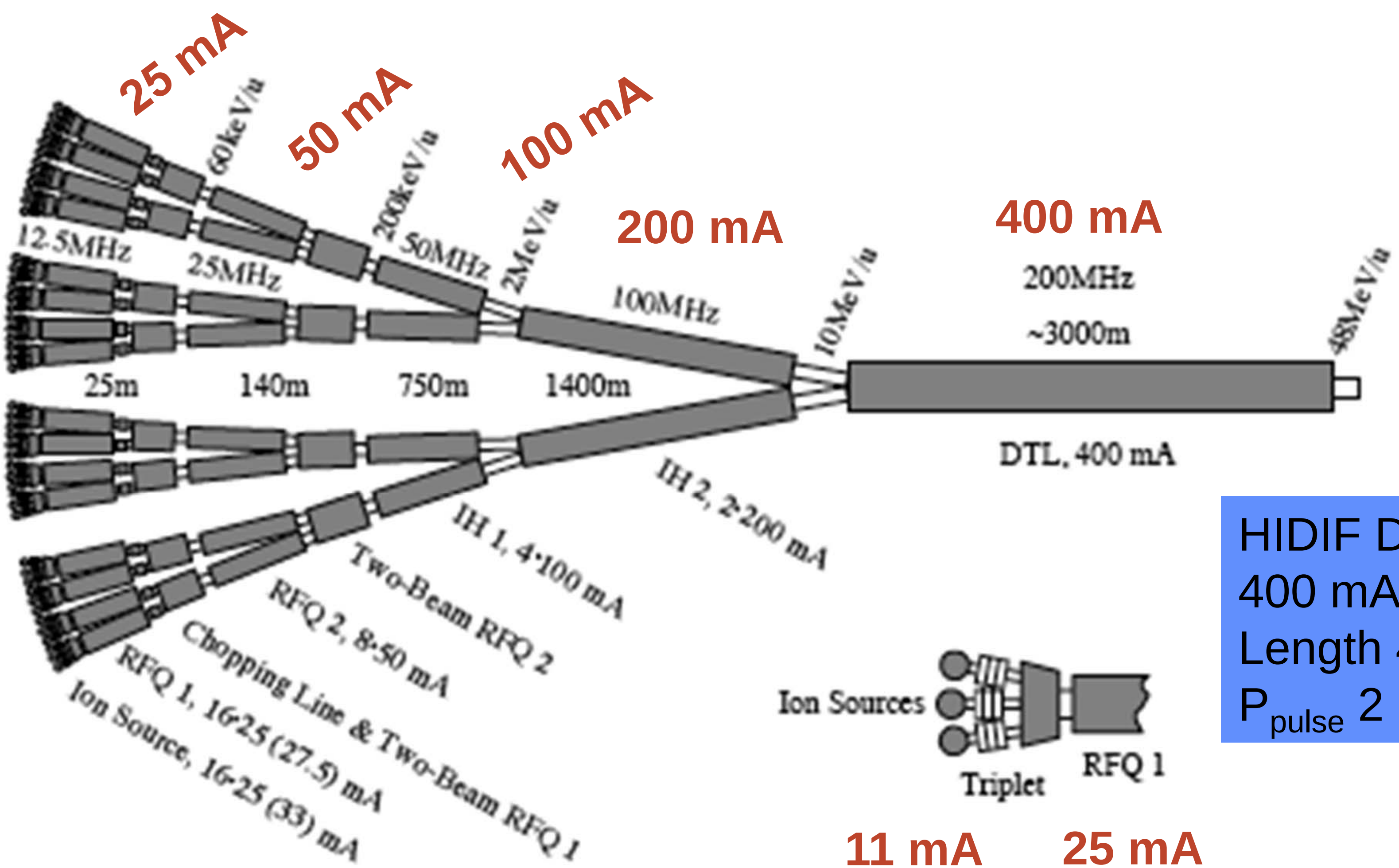
Parameters of the Two-Beam RFQ Funnel Experiment

Two-beam FRQ	He^{+}
f_0 (MHz)	54
Voltage (kV)	10.5
Tin (keV)	4
Tout (MeV)	0.16
Length (m)	2
Angle between beam axes (mrad)	75
Multigap funneling deflector	
f_0 (MHz)	54
Voltage (kV)	6
Length (cm)	54
Single gap funneling deflector	
f_0 (MHz)	54
Voltage (kV)	23
Length (cm)	2.54

Key issues:
beam matching
beam loss
emittance growth

A. Schempp, NIM A **464** (2001), 395.
H. Zimmermann, EPAC 2004.
M. Baschke, IPAC 2011

Average current increases in RF linacs through funneling



HIDIF Design:
400 mA Bi^{+1}
Length 4.5 km
P_{pulse} 2 GW (avg)

“The HIDIF Study”, I. Hofmann & G. Plass, eds.,GSI Report 98-06.

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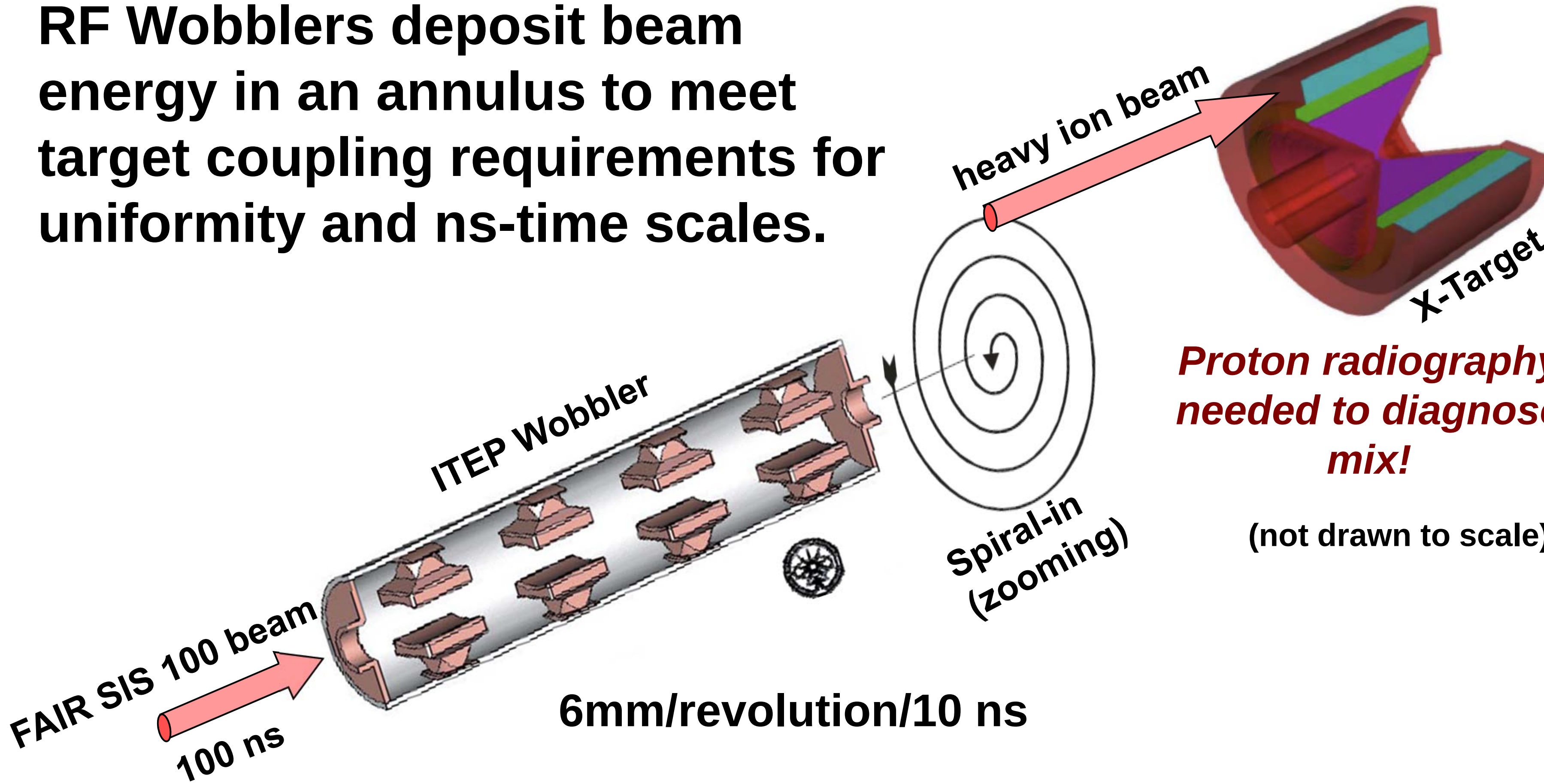
- **Final focus optics RF Wobbler**
- **Neutralizing plasmas NDCX-I, NDCX-II, GSI**
- **Two-stage focusing at target**

An 'RF Wobbler' focuses and homogenizes deposited beam power

RF Wobblers deposit beam energy in an annulus to meet target coupling requirements for uniformity and ns-time scales.

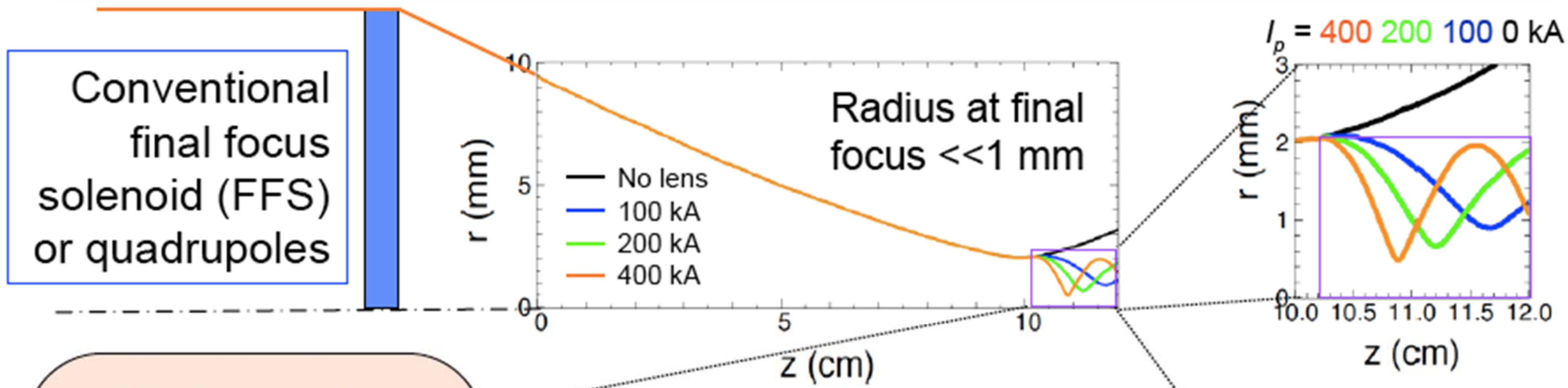


Proton radiography needed to diagnose mix!

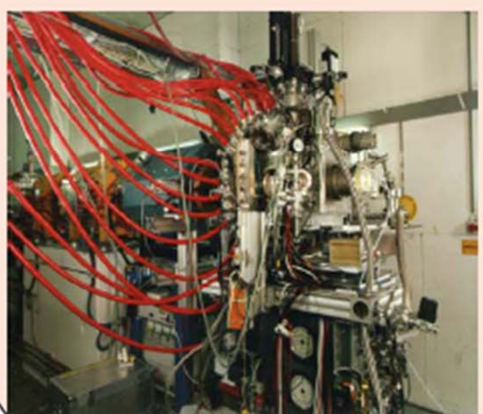
(not drawn to scale)

Spiral-in zoom drive needs 3-D target drive simulation

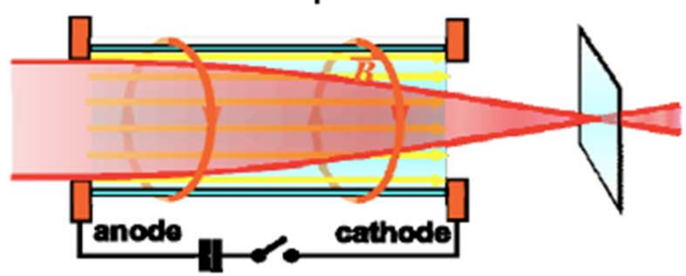
Plasma lens can remove space charge limits at final focus



GSI plasma lens (I_p=240 kA)

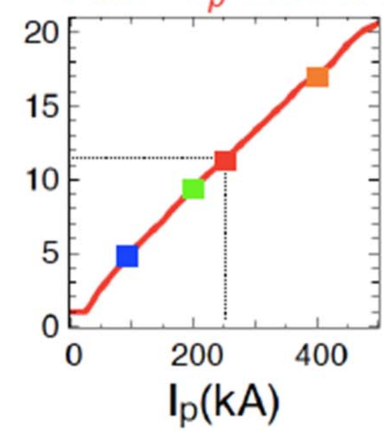


Windowless plasma lens



2 mm radius
0.5-1.5 cm length
I_p = 100-500 kA

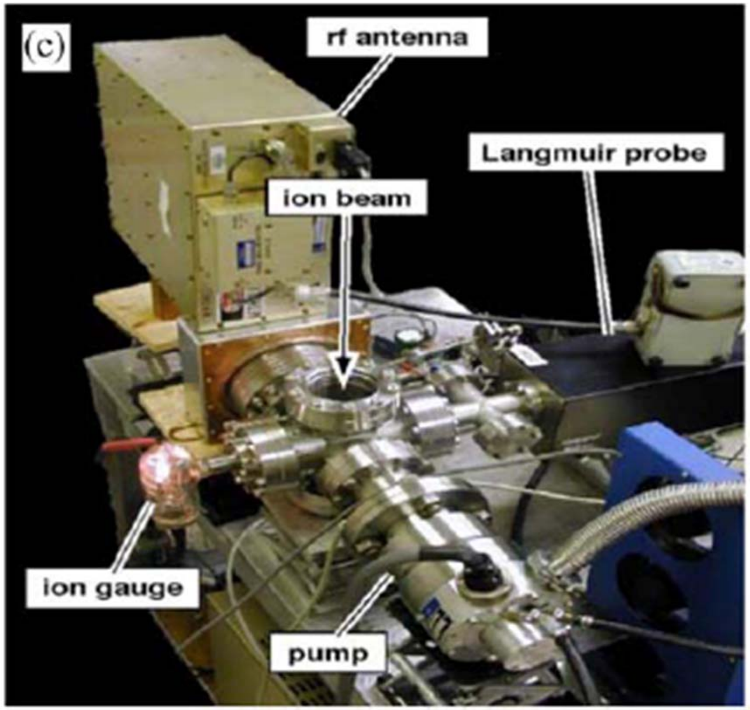
Fluence increase
>10x at I_p=250 kA



(incident beam from Warp NDCX-II simulation, post-FFS; used ideal B_θ & neutralization)

Plasma technology developed for volumetric neutralization

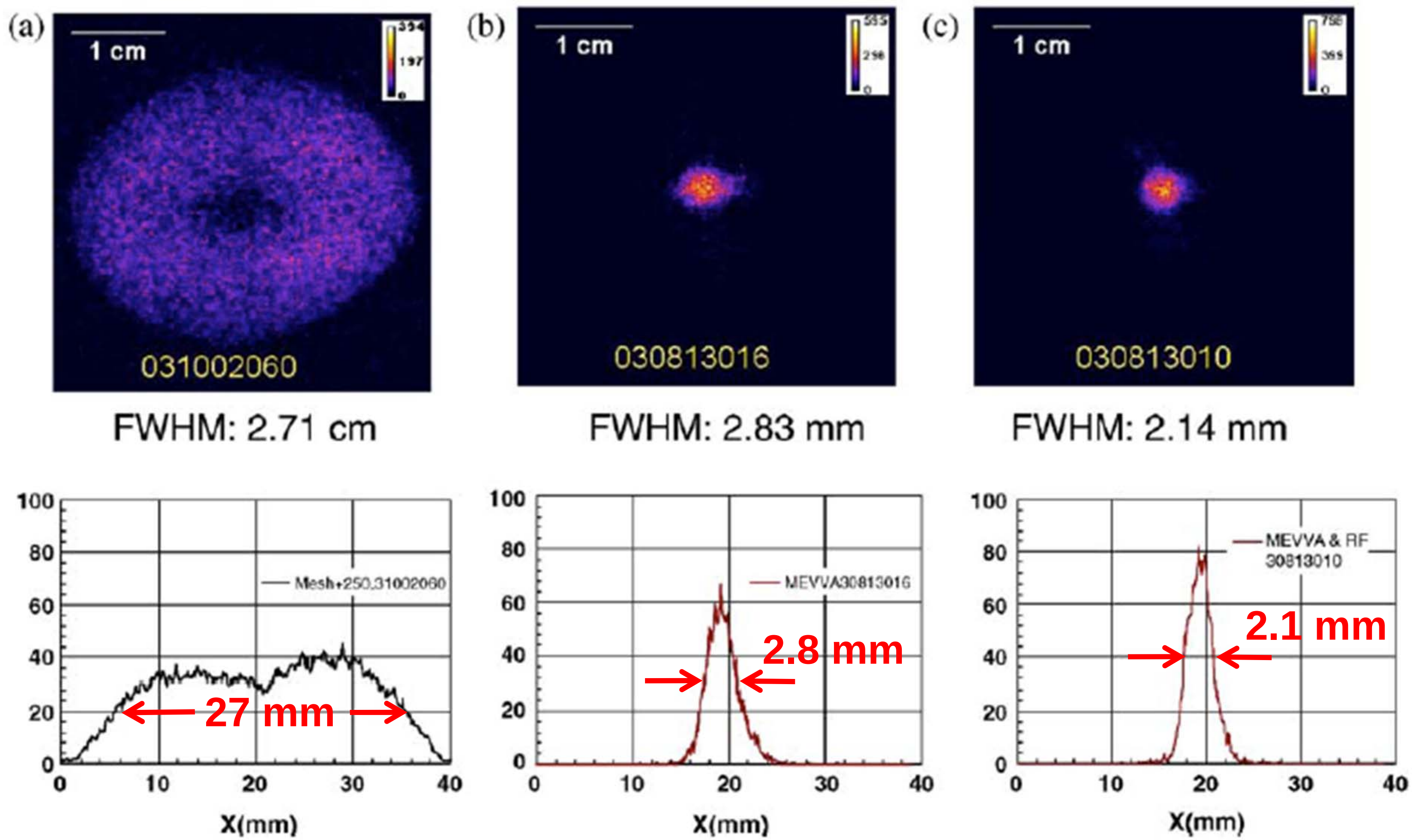
- Ferroelectric plasma source (FEPS)
  - ($N_e \sim 10^{10}$ /cm^3)
- RF sources
  - ($N_e \sim 10^{11}$ /cm^3)
- Cathodic Arc plasma source (CAPS)
  - ($N_e \sim 10^{14}$ /cm^3)



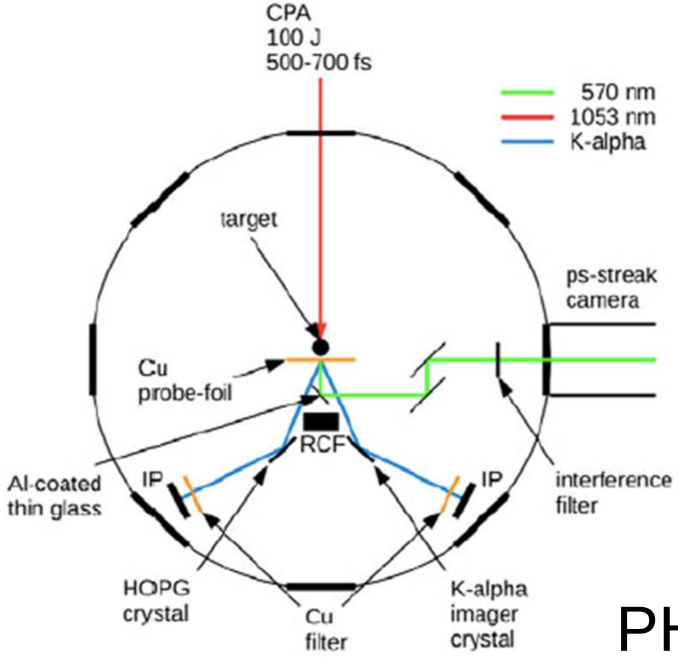
Neutralized beam transport of intense beams recovers emittance dominated focal spots

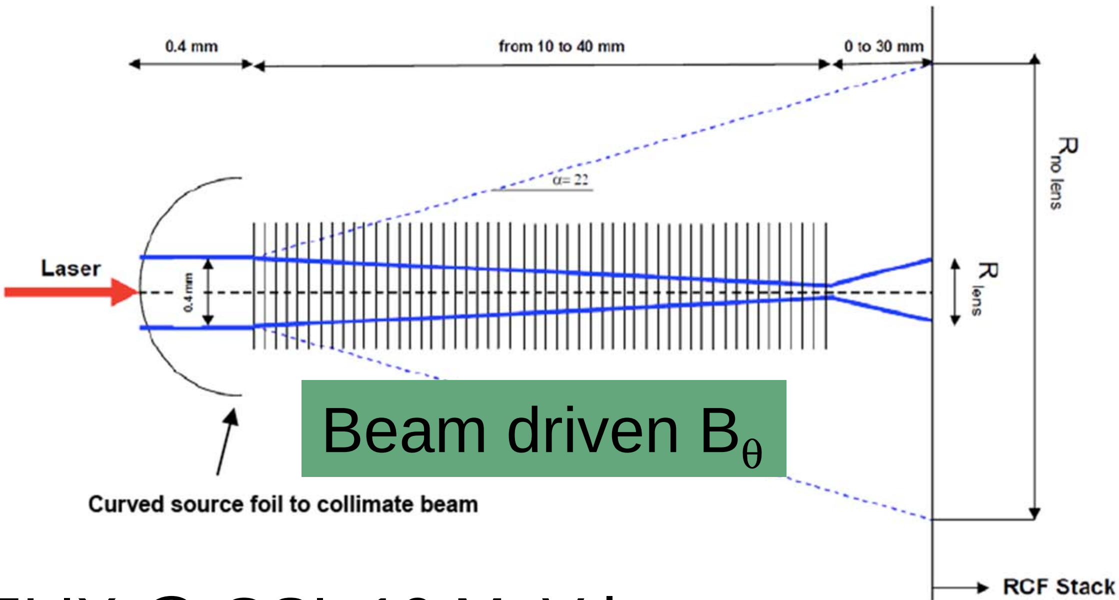
P.K. Roy, *et. al.*, NIM **A544** (2005), 225-235.

No neutralization | MEVVA only | MEVVA + RF plasma

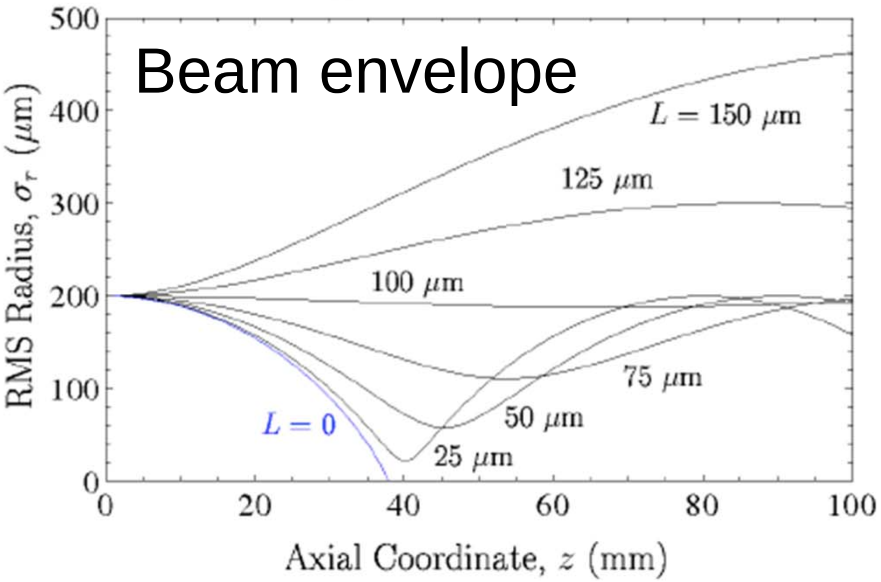


Passive foil stack focusing of intense ion beams





PHELIX @ GSI: 10 MeV laser protons



Summary:

- **100+** of **0.5 µm** thick Al foils, separated by a **20 -50 µm** gap **can pinch** the PHELIX proton beam within **40-100 mm** distance
- Preliminary design study at TUD, confirms such a **lens can be manufactured**.
- Need collimated beam: use curved foils

Driver concepts must address 3 main issues

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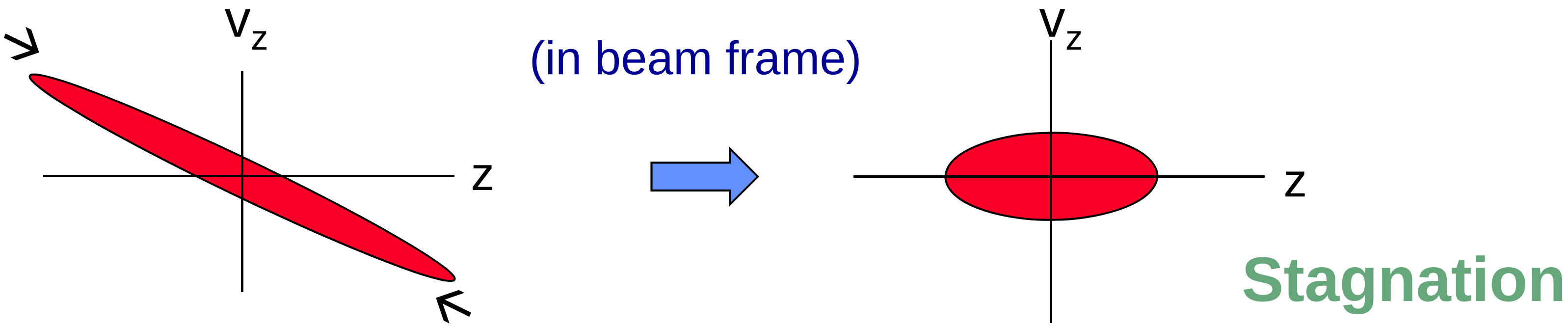
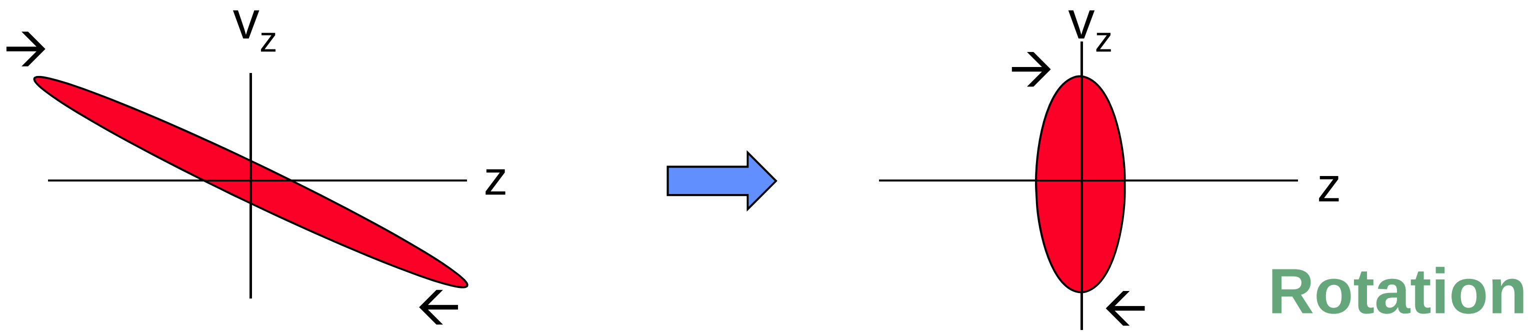
- **Vacuum compression to stagnation**
- **Space-charge neutralized beams**
- **Velocity ramp and drift (e.g. 'telescoping')**

The drift compression process is used to shorten an ion bunch

- In **non-neutral drift compression**, the space charge force opposes the inward flow, leading to a nearly mono-energetic compressed pulse:



- In **neutralized drift compression**, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread:



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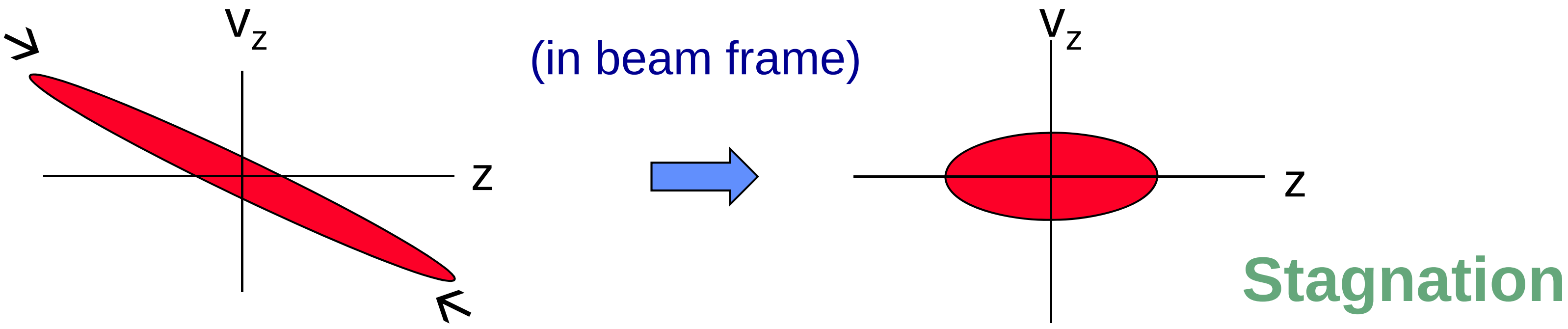

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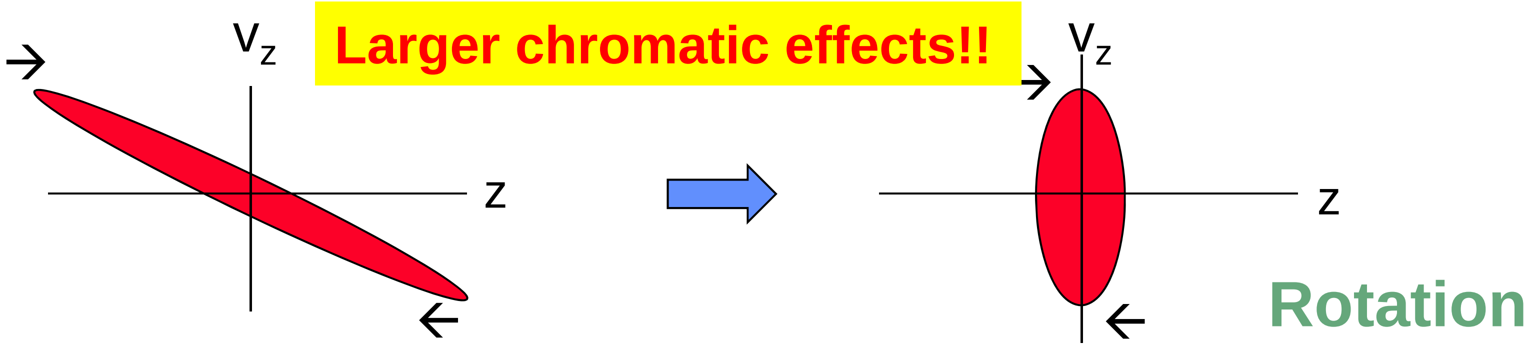
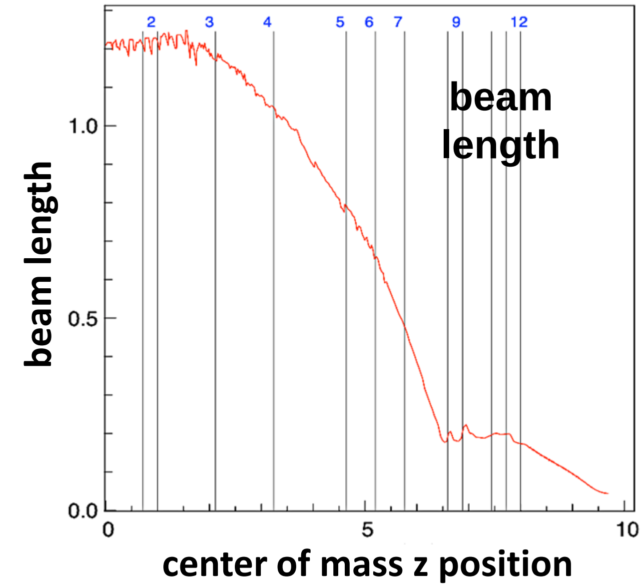
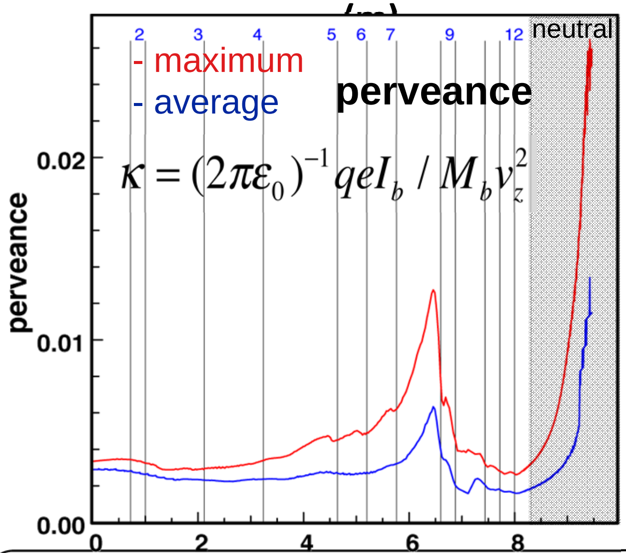
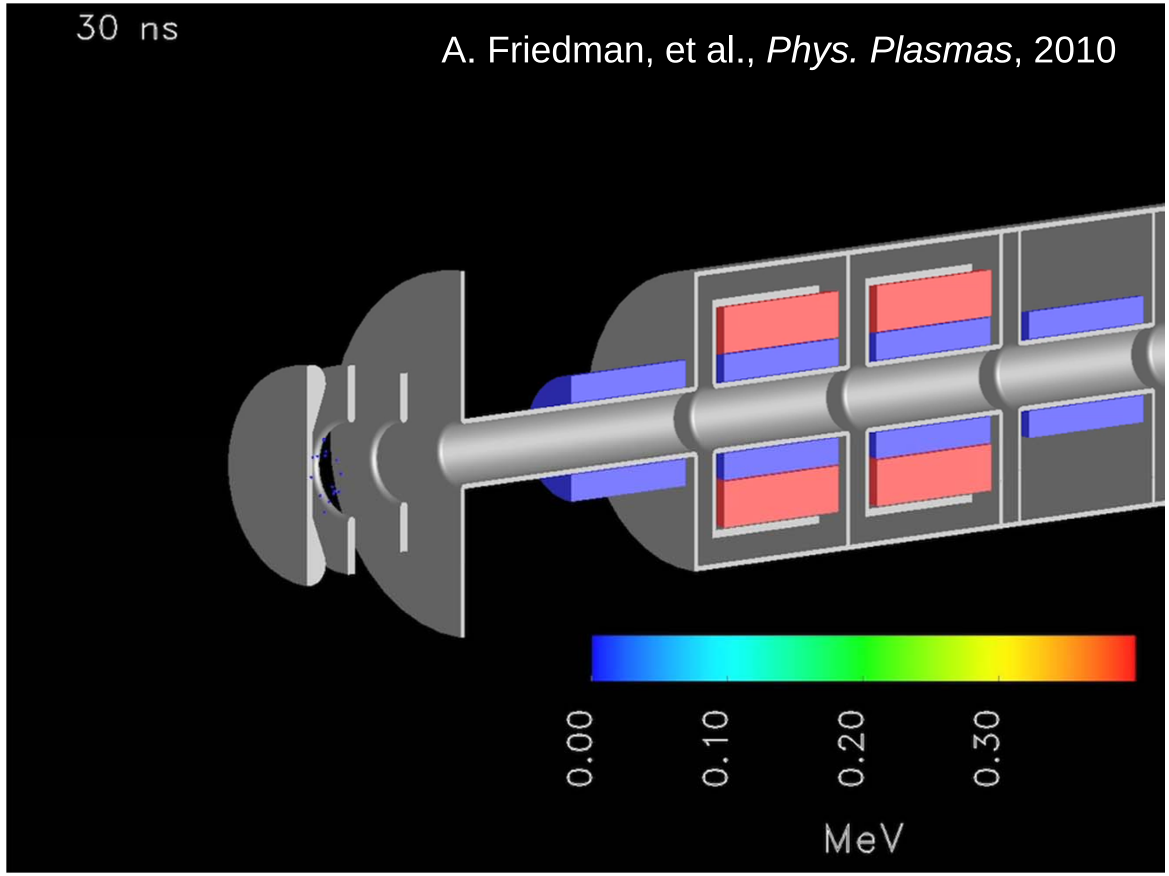


NDCX-II uses both stagnation and neutralized compression







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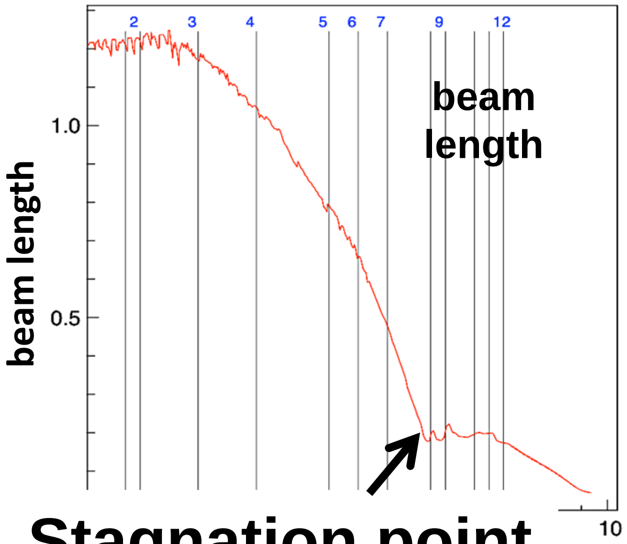
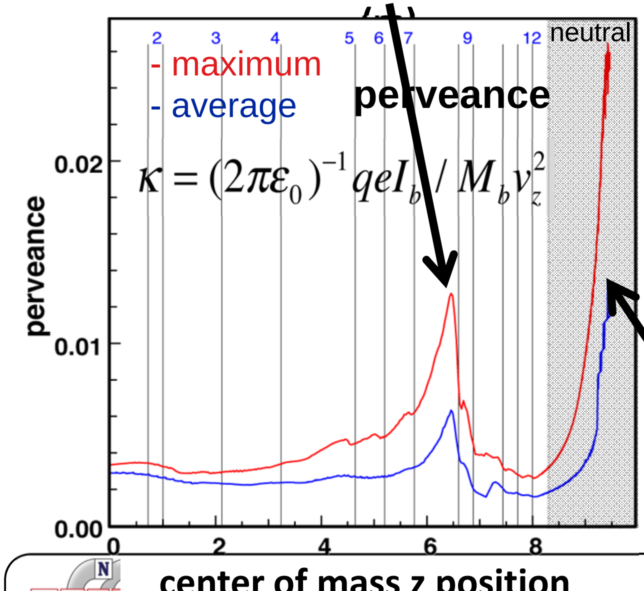
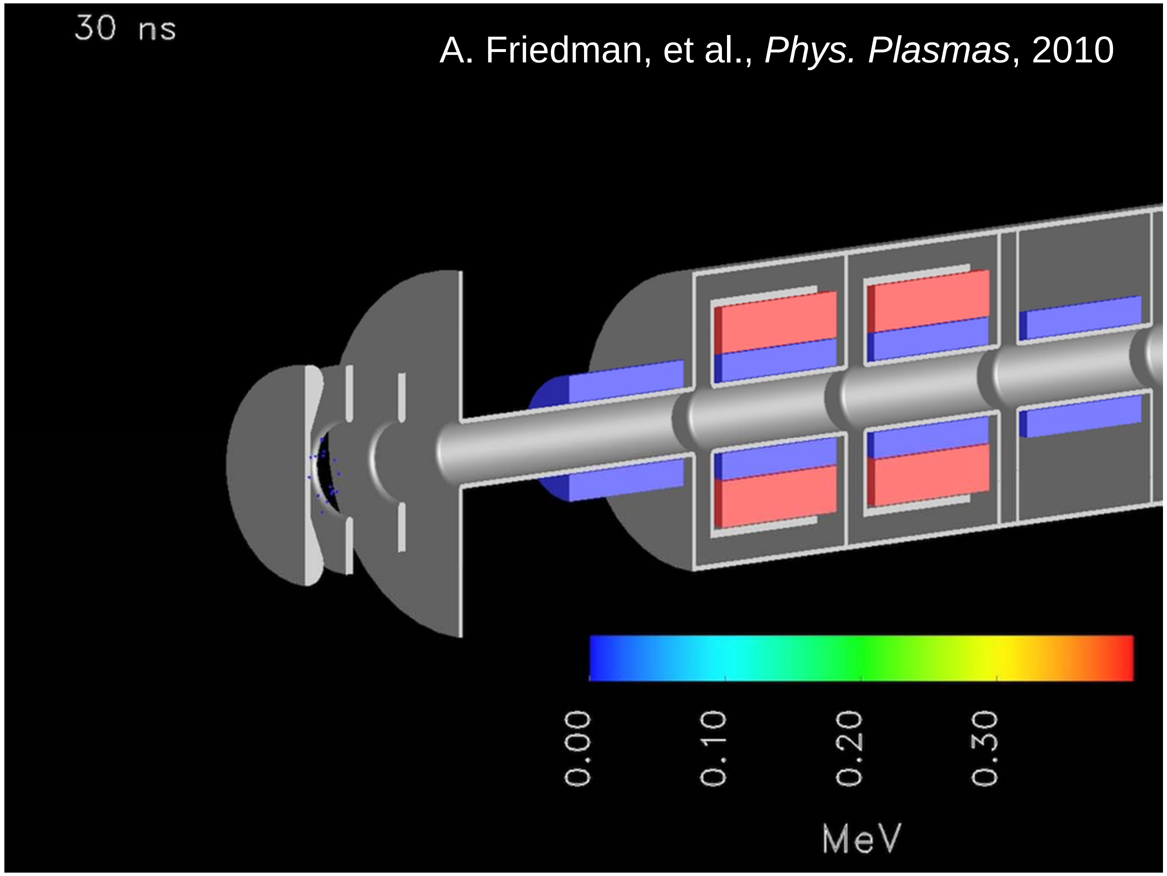


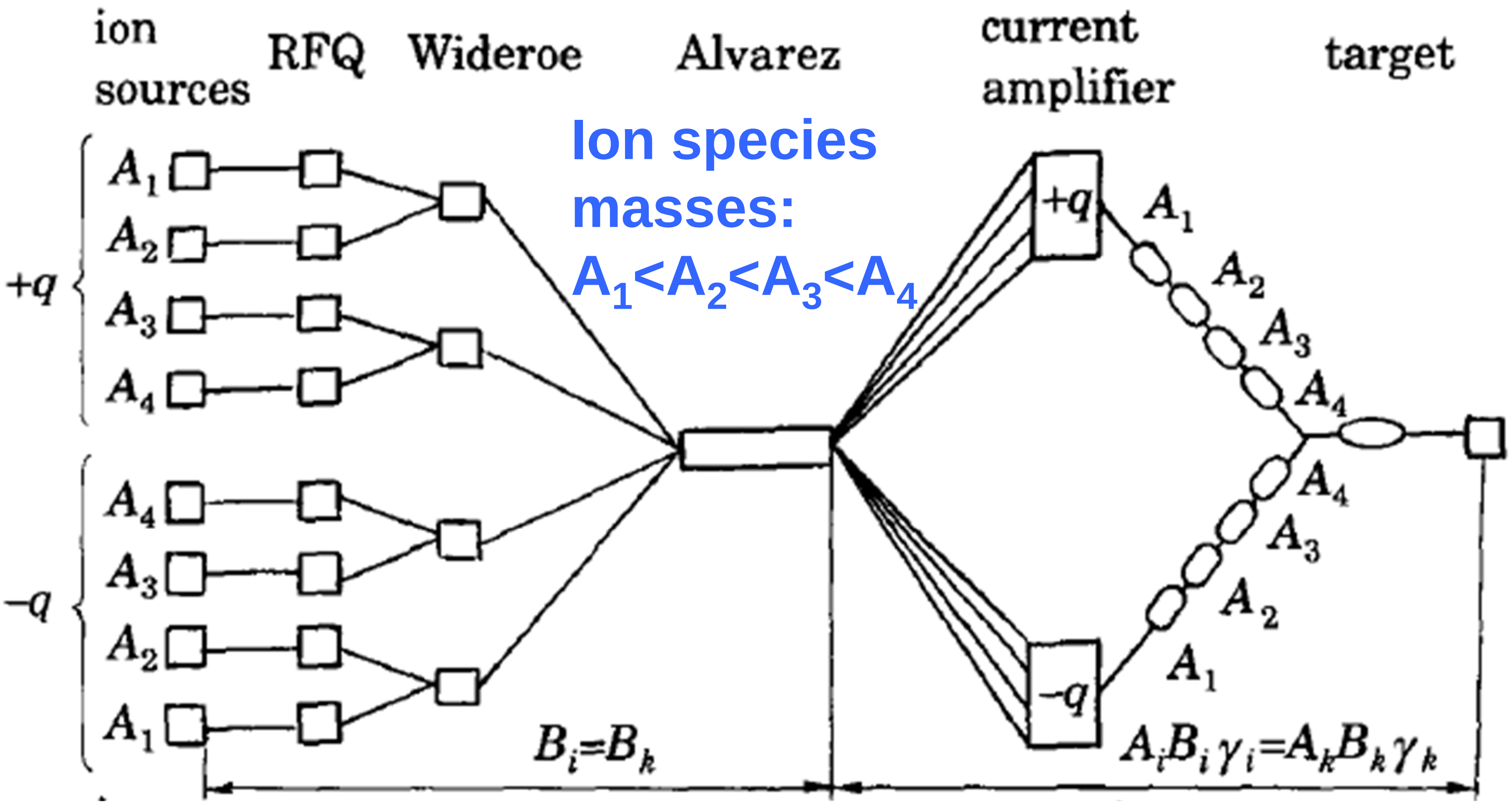
Stagnation point





Neutralized drift and compression

Multiplying current and neutralizing space charge with charge-symmetric, spread mass-state beams



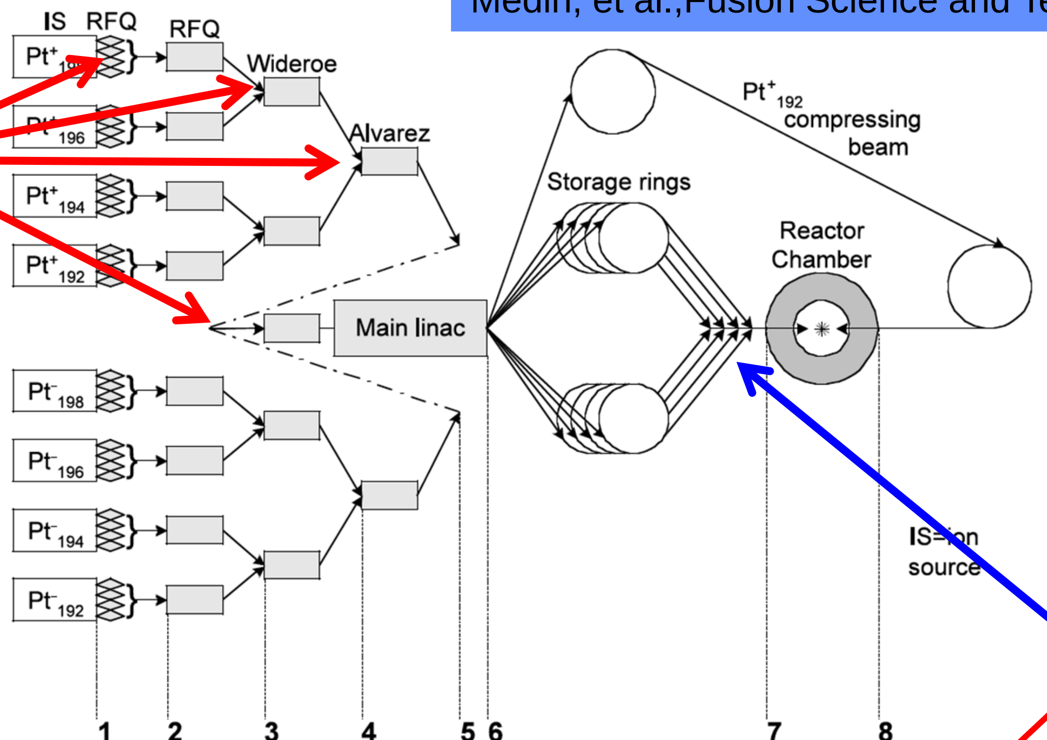
Ion species masses: $A_1 < A_2 < A_3 < A_4$

Equal velocities **Equal momenta**

D.G. Koshkarev, Il Nuovo Cimento **106** (1993), 1567.

Longitudinal stacking and merging in rf accelerators

Medin, et al.,Fusion Science and Technology **43** (2003), 437.



Beam funneling

ITEP driver 'FIHIF'

Charge-symmetrized bunches + 'Telescoping'

lighter ions overtake heavier ones.

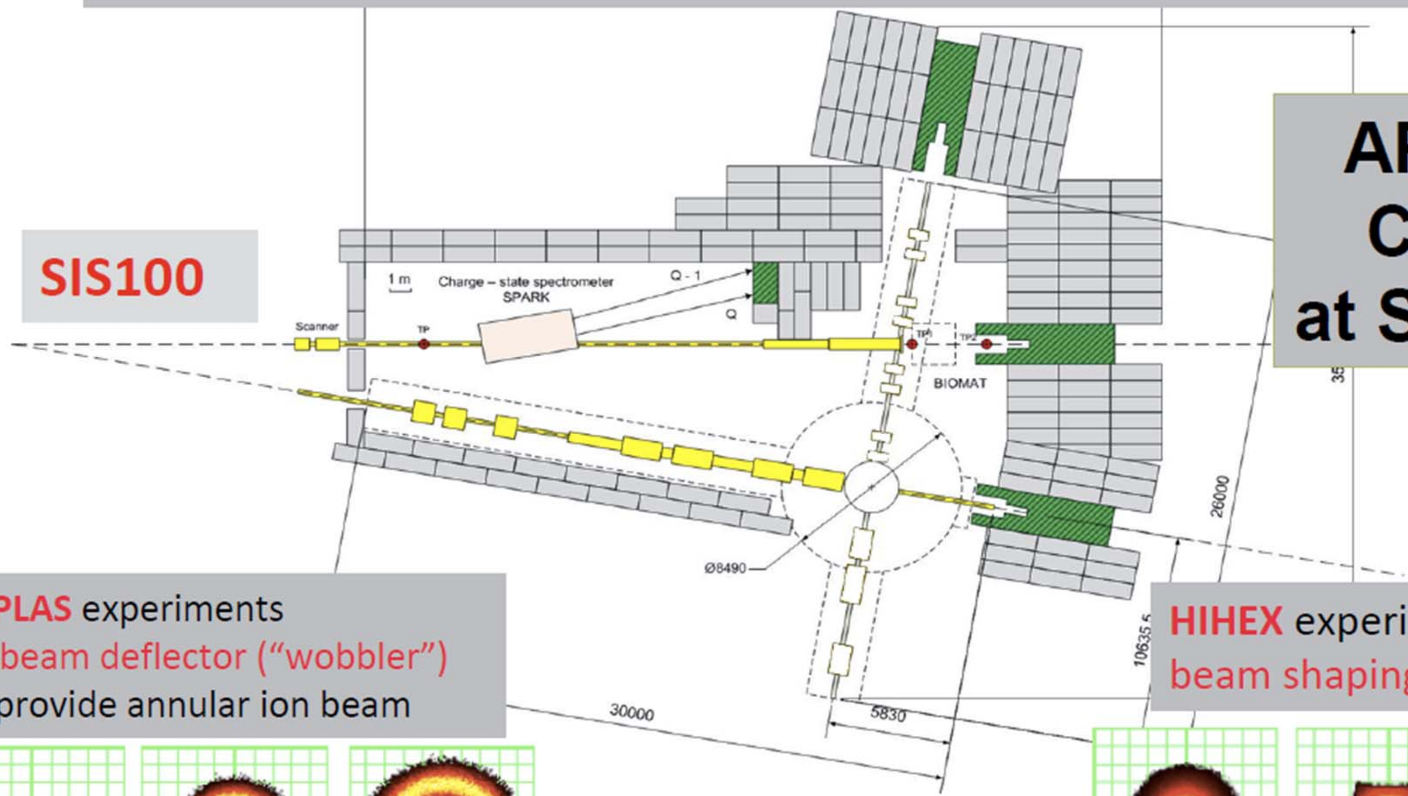
Oppositely-charged bunches neutralize each other

Station Number	Ion Energy (GeV)	Radio-Frequency (MHz)	Bunch Current (A)	Momentum Spread ($\times 10^4$)	Emittance (μm)	
1	10^{-4}		0.04	±300	0.3	
2	10^{-3}	6.25	0.16	±180	0.9	
3	10^{-2}	12.5	0.4	±36	0.9	
4	0.1	50	1	±37	0.9	
5	0.2	200	4	±75	0.95	
6	100	1000	230	±2	1	
7	100	Single bunch	20 000	±30	1	0.745
8	100	Single bunch	1600	±20	1	0.745

FAIR's SIS 100 : 70 kJ heavy ion beam is available for target physics related to HIF

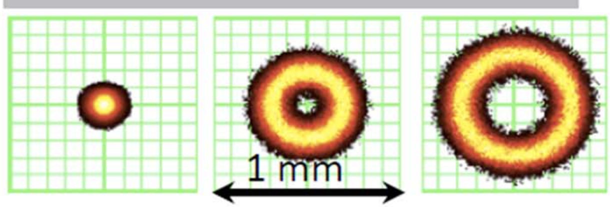
SIS-100: One beam line with replaceable elements:

SIS100



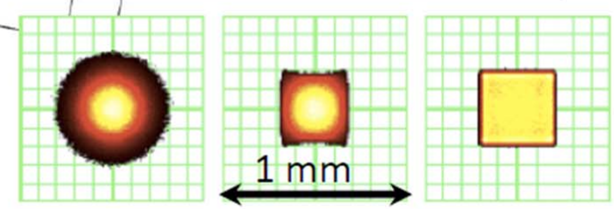
APPA Cave at SIS100

LAPLAS experiments
RF beam deflector ("wobbler")
to provide annular ion beam



Transverse distributions of beam intensity at focal plane for LAPLAS

HIHEX experiments
beam shaping system



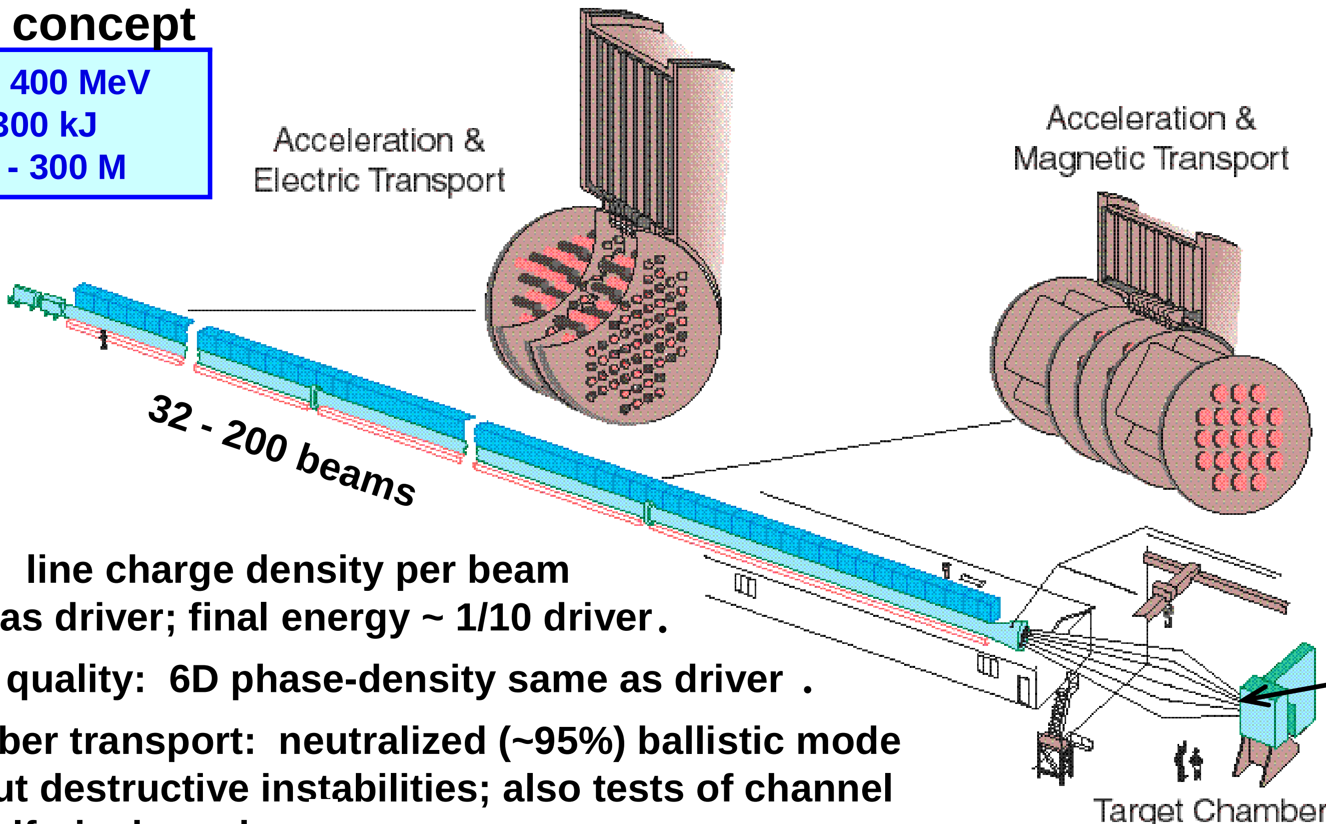
Transverse distributions of beam intensity at focal plane for HIHEX

10 kJ scale HIDIX platform can test coupling and target implosion hydrodynamics

Heavy Ion Driven Implosion eXperiment (HIDIX) (proposed)

2002 concept

~ 200 - 400 MeV
~ 30 - 300 kJ
~ $150 - 300 M



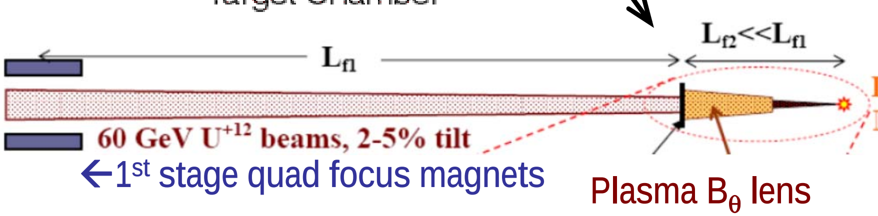
Scale: line charge density per beam same as driver; final energy ~ 1/10 driver.

Beam quality: 6D phase-density same as driver .

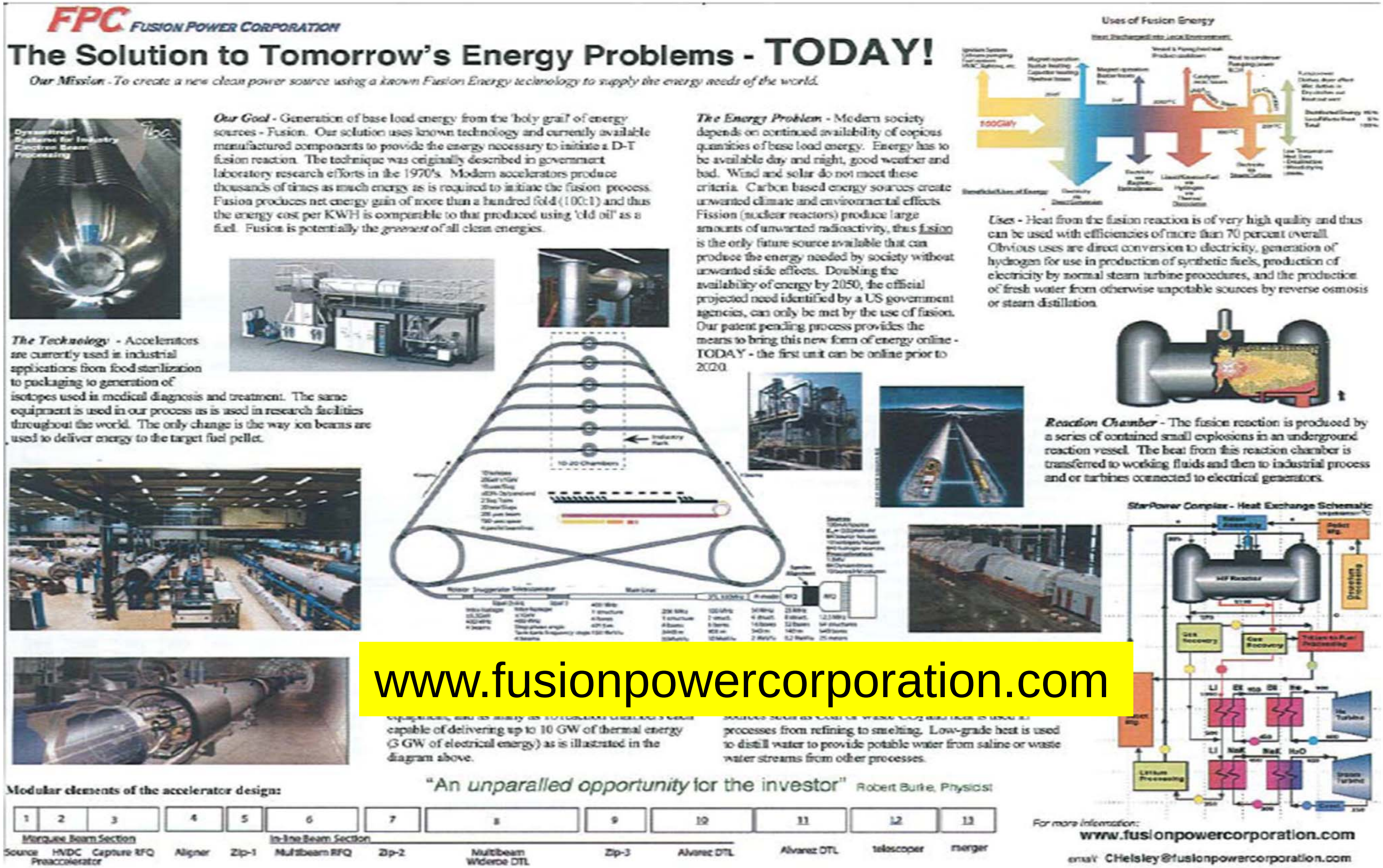
Chamber transport: neutralized (~95%) ballistic mode without destructive instabilities; also tests of channel and self-pinch modes .

Chamber technology: test driver/chamber interface .

Target temperature: 50 - 100 eV .



Fusion Power Corporation has explored the economy-of-scale for very large heavy ion drivers (20 MJ), multiple chambers -> 100 GW_{fusion}



www.fusionpowercorporation.com

Summary

- Target designs have evolved beyond the status quo for long-pulse high energy laser drivers.
  Much higher peak power needed for robust targets!

- Fast ignition schemes require short-pulse, ultra-intense beams. **→ Ion beam equivalent of CPA laser systems.**

- Advances in sources, beam handling, and final focus manipulations will soon drive target implosions in 10-100 kJ facilities. **→ Target concept verification.**

- More work and creativity is needed to realize MJ-PW-scale ion beams. **→ Can we simplify these driver concepts?**

Recent and Upcoming Symposia

HIF Primer at hif.lbl.gov/public/Sharp/HIF_overview.pdf

Workshop on Accelerators for Heavy Ion Inertial Fusion
May 23-26, 2011, Berkeley, California, USA
Reports available at http://ahif.lbl.gov

19th International Symposium on Heavy Ion Inertial Fusion (HIF2012)
August 12 - 17, 2012, Berkeley, California, USA

Website: http://hif12.lbl.gov/

Thank You!

Target and driver designs have evolved

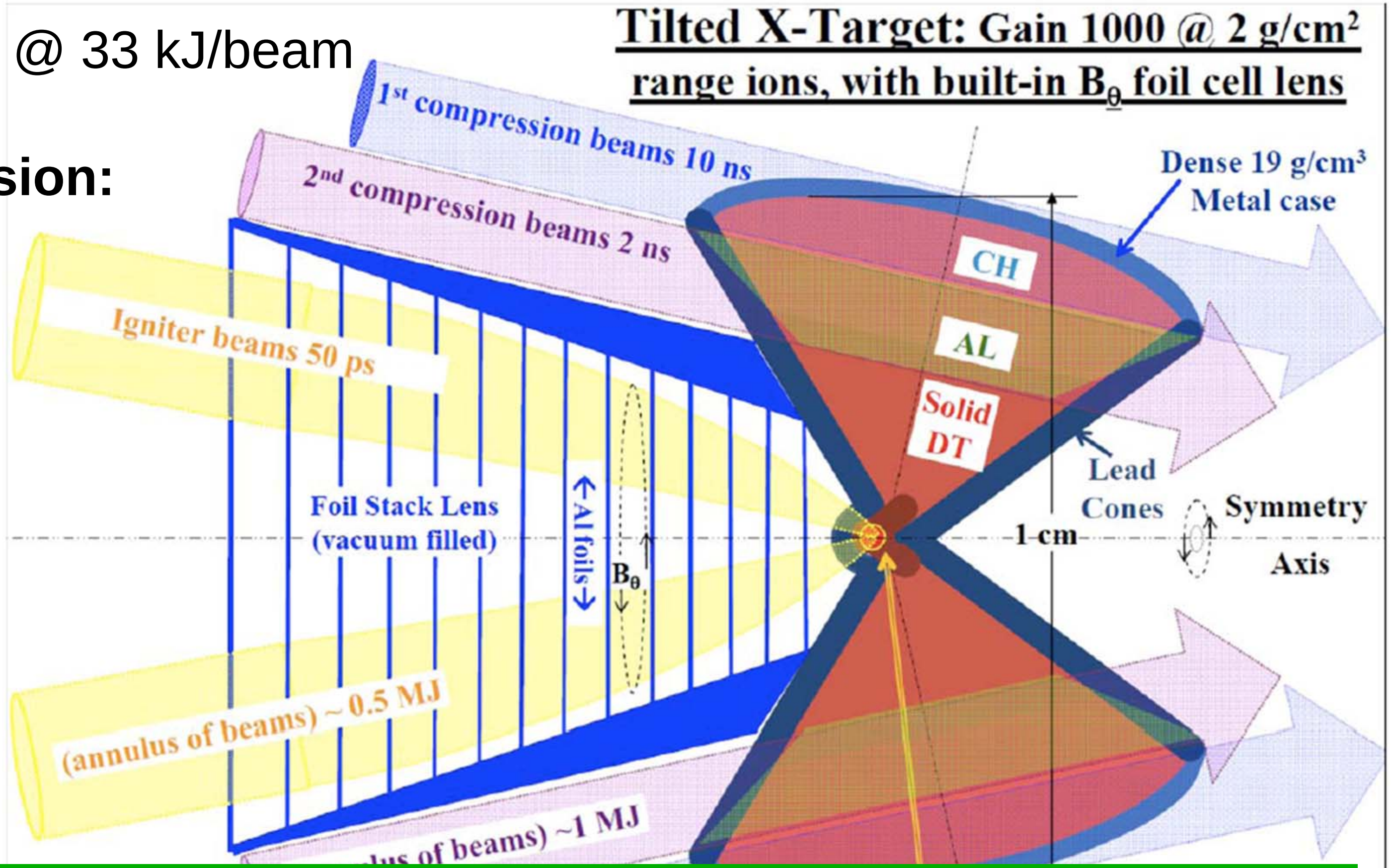
	Distributed Radiator (2001)		Hybrid (2005)		Tamped Direct Drive (2011)		ITEP Fast Ignition (2005)		X-target (2011)	
	Foot	Main	Foot	Main	Compress.	Shock	Compress.	Ignitor	Compres.	Ignitor
Energy in pulse (MJ)	**2.7**	**4.9**	**1.7**	**5**	**2**	**1**	**7.1**	**0.4**	**1,1**	**3**
Pulse duration (ns)	**6.5**	**9.3**	**7**	**11**	**20**	**0.5**	**75**	**0.2**	**5,1**	**0.2**
Beam radius (mm)	**1.8x4.1**		**3.8x5.4**		**1.9**	**2.2**	**~3**	**0.05**	**0.5**	**0.2**
Ion range, (g/cm^2)	**0.034**	**0.042**	**0.031**	**0.049**	**0.038**	**0.038**	**4**	**4**	**2**	**2**
Target acceptance angle (°)	**0-20**	**0-20**	**0-6**	**0-12**	**10, 55**	**10, 55**	**?**	**?**	**0-10**	**0-10**
Target gain (1GJ class)	**68**		**55**		**100**		**100**		**300-400**	
Target class	**Indirect-drive (hohlraum)**				**Direct-drive spherical**		**Direct-drive cylindrical**		**Direct-drive quasi-spherical**	
Ion mass (amu)	**209**		**207**		**201**		**209**		**209**	
Ion energy (GeV)	**3.3**	**4.**	**3.**	**4.5**	**3.5**		**100**		**63**	
Pulse charge (mC)	**0.82**	**1.23**	**0.57**	**1.11**	**0.57**	**0.29**	**0.07**	**0.004**	**0.02**	**0.03**
Pulse current (kA)	**125.9**	**131.7**	**81.**	**101.**	**28.6**	**571.4**	**0.9**	**20**	**0.8**	**158.7**

Conceptual X-target design with two-stage focusing

60 Beams @ 33 kJ/beam

Compression:
45 beam
1.5 MJ

Ignition:
15 beams
0.5 MJ



More exotic schemes might also utilize powered lithium lenses (~500 kA) to combine dispersion, radial focusing, and tailored dE/dx energy profiling for ultimate spot sizes.