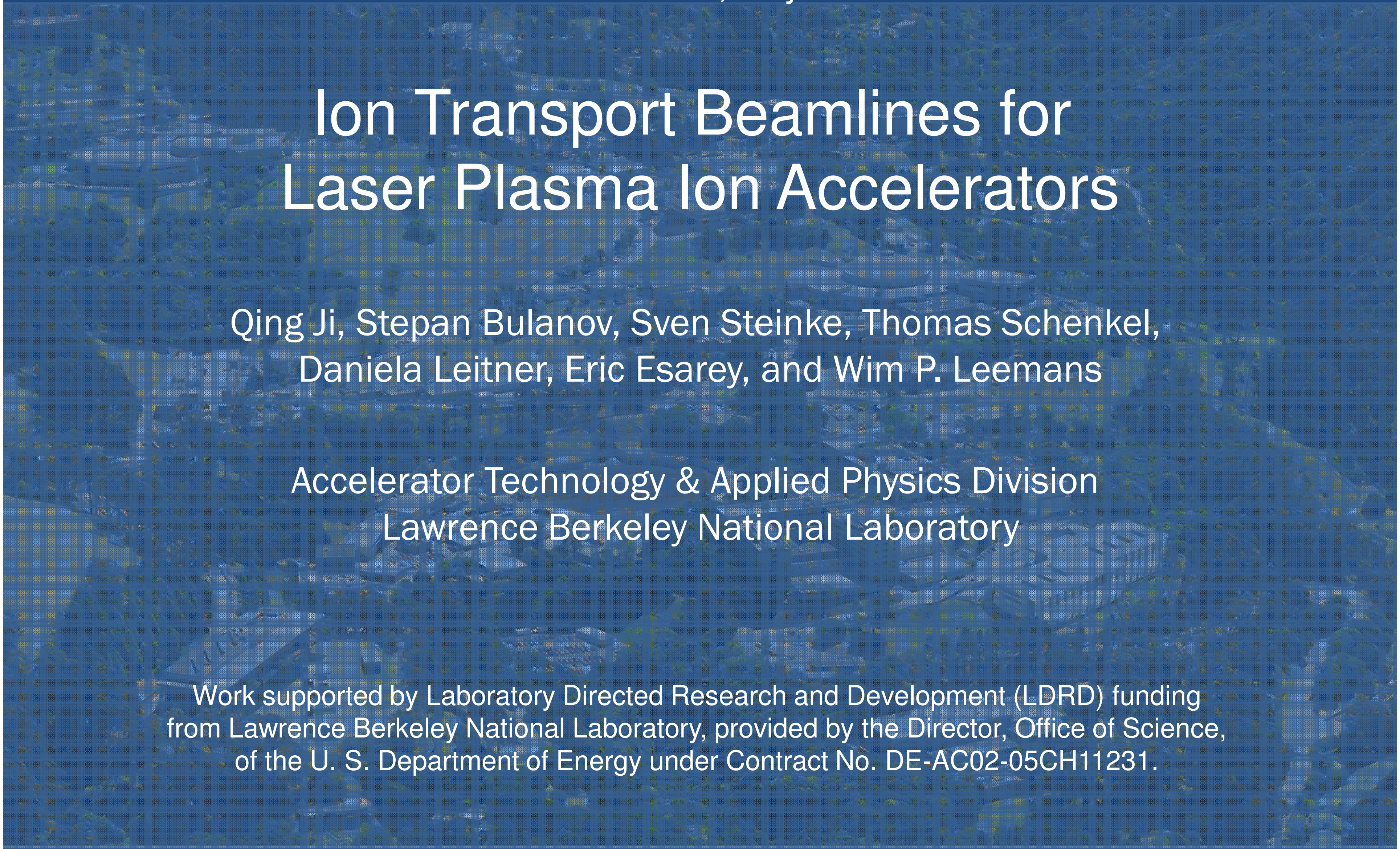
3th EliMED Workshop
September 7-9, 2016
Catania, Italy



Ion Transport Beamlines for Laser Plasma Ion Accelerators

Qing Ji, Stepan Bulanov, Sven Steinke, Thomas Schenkel,
Daniela Leitner, Eric Esarey, and Wim P. Leemans

Accelerator Technology & Applied Physics Division
Lawrence Berkeley National Laboratory

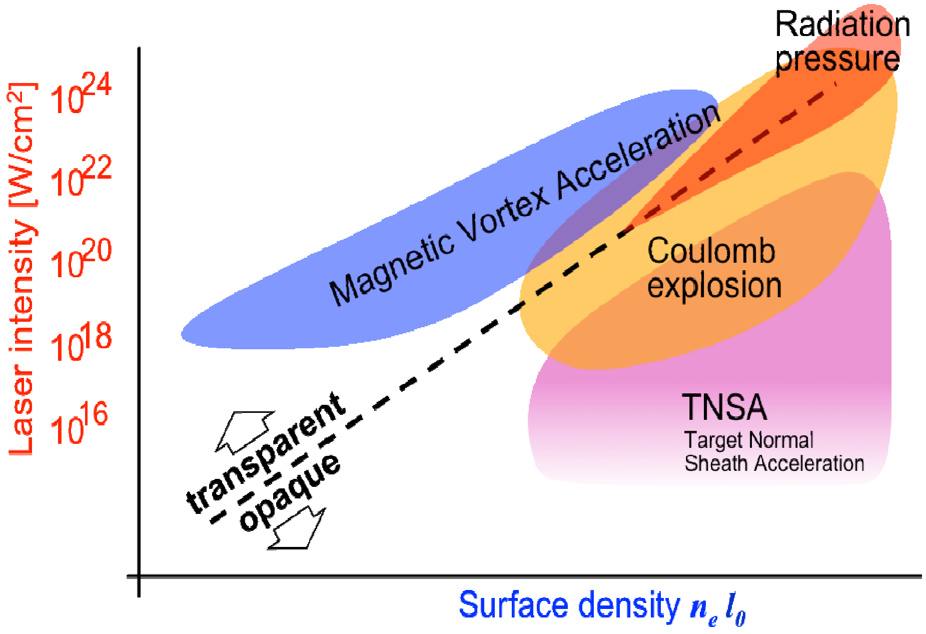
Work supported by Laboratory Directed Research and Development (LDRD) funding from Lawrence Berkeley National Laboratory, provided by the Director, Office of Science, of the U. S. Department of Energy under Contract No. DE-AC02-05CH11231.

Outline

- Introduction
- Some existing ion beamlines for laser-driven ions
- Survey of key elements for beam transport and energy selection
    - Solenoids vs. Quadrupole
    - Active plasma lens
    - Energy selection systems
    - Combined-function AG-CCT and CCT dipole magnets
- BELLA-i beamline design
- Summary

Laser plasma ion acceleration is of great interest to reduce the size and cost of future accelerators

- The particle acceleration is one of the cornerstones of the fundamental physics.
- Conventional technology of particle acceleration leads to large scale facilities, high construction and operation costs.
- Advanced acceleration concepts are of great interest to reduce the size and cost of future accelerators.
- In laser plasma acceleration, particles are accelerated by strong electromagnetic fields generated by laser pulses in plasma.
- Application:
  - Injector of conventional accelerator
  - Hadron therapy
  - Radiography
  - Nuclear physics studies
  - Warm dense matter studies
  - … …



The laser ion acceleration mechanism is determined by laser Intensity and target surface density

S. S. Bulanov, et al., Physics of Plasmas 23 , 056703 (2016);

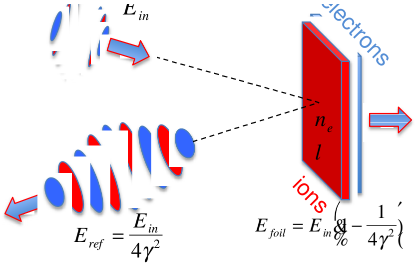
Typical "at-source" ion bunch in the TNSA regime

	Laser ion source	**Conventional Accelerator injector**
Extraction (accelerating field)	~ 1-10TV/m	~ 10MV/m
Maximum kinetic energy (protons)	~ 10's to 100 MeV	10's keV
Energy spread, $\Delta E/E_0$	>100% (using E_0=spectral median)	<1%
Ion species and charge state	Mixed	Typically pure
Divergence	100's mrad to couple rads (full angle)	10's mrad
Transverse emittance	~ 10^{-3} mm mrad	~ 0.25 mm mrad
Repetition-rate	Up to 10 Hz demonstrated	Up to cw
Charge/duration (peak current)	10's to 100's nC/ ~ psec (10's to 100's kiloamp)	10's to 100 mA

Ref: P R Bolton, "The integrated laser-driven ion accelerator system and the laser-driven ion beam radiotherapy challenge", NIMA 809 (2016) 149-155.

Advanced Acceleration Mechanisms by PW Lasers

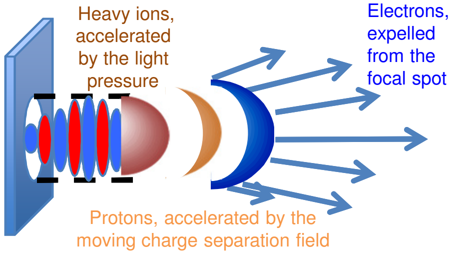
Radiation Pressure Acceleration



T. Esirkepov, *et al.,* Phys. Rev. Lett. **92,** 175003 (2004)

- Target: thin solid density foils
- Ion Energy ~ Laser Power
- 1 PW ⇨ 200 - 300 MeV

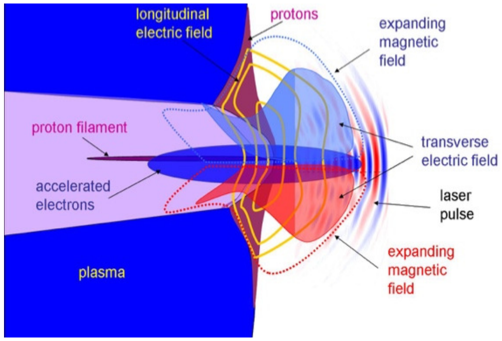
Directed Coulomb Explosion



S. S. Bulanov, et al., Med. Phys. 35, 1770 (2008)

- Target: thin solid density double layer foils
- Ion Energy ~ Laser Power
- 1 PW ⇨ 200 - 300 MeV

Magnetic Vortex Acceleration



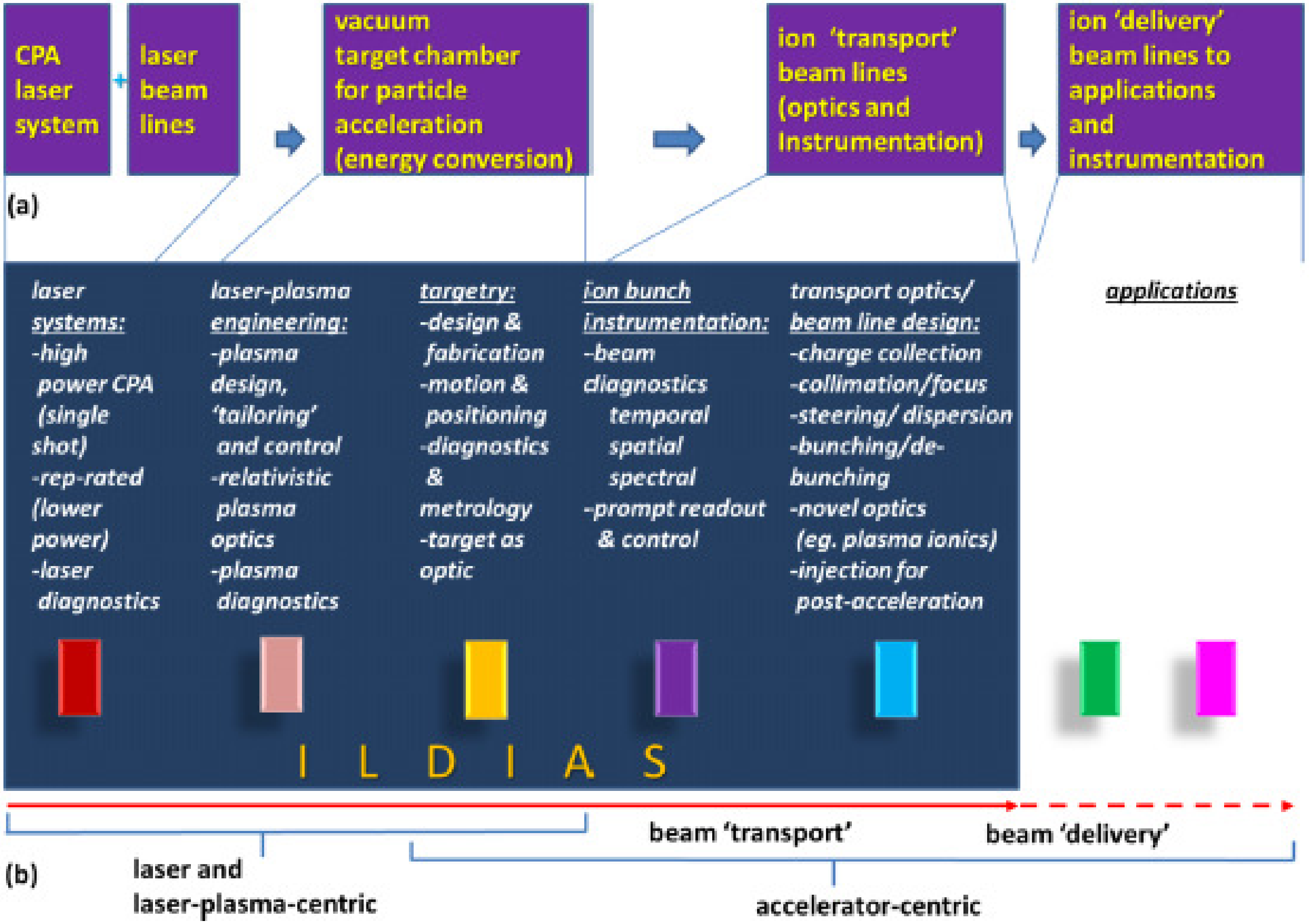
A. V. Kuznetsov, *et al.*,Plasma Phys. Rep. 27, 211 (2001).

- Target: plasma slab of near critical density
- Ion Energy ~ Laser Power$^{2/3}$
- 1 PW ⇨ GeV

Review papers on ion acceleration:

G. Mourou, *et al.*, Rev. Mod. Phys 78, 309 (2006)
H. Daido, *et al.*, Rep. Prog. Phys. 75, 056401 (2012)
A. Macchi, *et al.*, Rev. Mod. Phys. 85, 751 (2013).

Integrated Laser-driven ion Accelerator System



laser systems:
-high power CPA (single shot)
-rep-rated (lower power)
-laser diagnostics

laser-plasma engineering:
-plasma design, 'tailoring' and control
-relativistic plasma optics
-plasma diagnostics

targetry:
-design & fabrication
-motion & positioning
-diagnostics & metrology
-target as optic

ion bunch instrumentation:
-beam diagnostics
temporal
spatial
spectral
-prompt readout & control

transport optics/ beam line design:
-charge collection
-collimation/focus
-steering/ dispersion
-bunching/de-bunching
-novel optics (eg. plasma ionics)
-injection for post-acceleration

applications

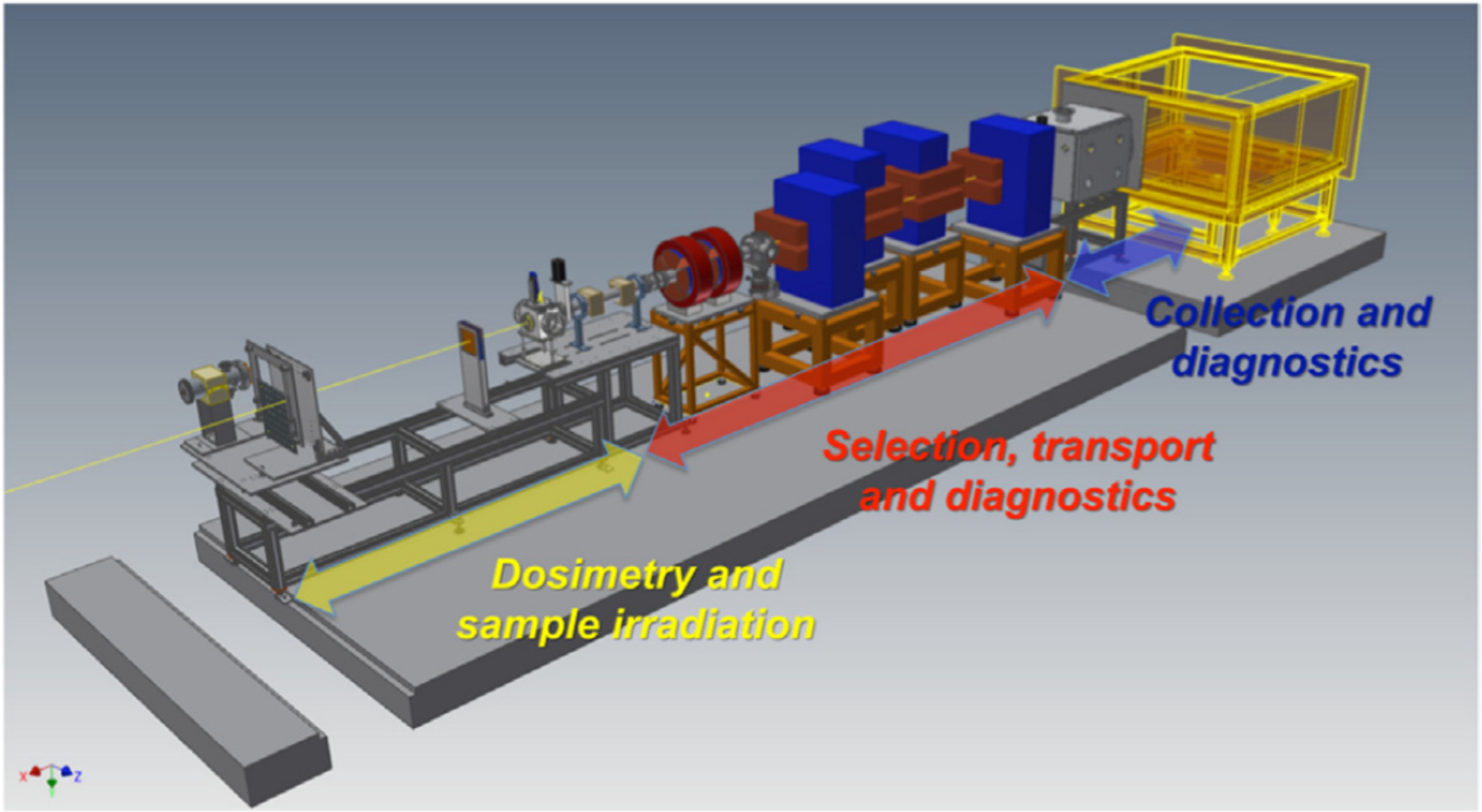
Ref: J. Schreiber, P. R. Bolton, and K. Parodi, Review of Scientific Instruments 87, 071101 (2016)

Large energy spread and wide beam divergence angle pose a challenge in beam optics design

- Energy range from 10s MeV to 100s MeV/u
- Beam divergence angle typically over 50 mrad.

	Magnetic Rigidity Bρ (T·m)
50 MeV proton	1.031
100 MeV proton	1.478
250 MeV proton	2.424
100 MeV/u He^{2+} or C^{6+}	2.956
200 MeV/u He^{2+} or C^{6+}	4.285
450 MeV/u C^{6+}	6.806

ELIMED beamline: Layout



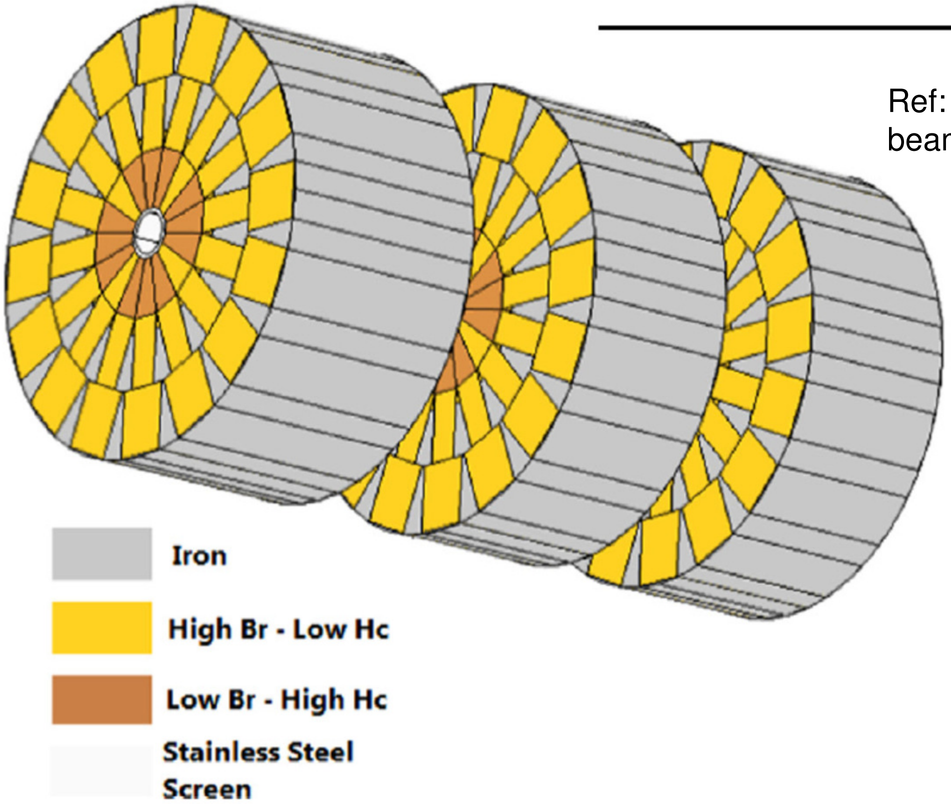
Ref: F. Romano et al, “The ELIMED transport and dosimetry beamline for laser-driven ion beams”, NIMA 829 (2016) 153-158.

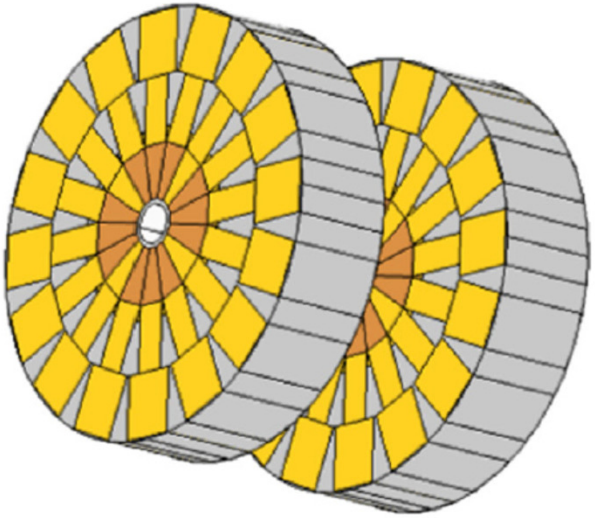
ELIMED: Permanent Magnet Quadrupoles for beam collection

To collect ions from 3 – 60 MeV/u

No. of PMQs	Geometric length (mm)	Field gradient (T/m)	Bore diameter (mm)
1	160	101	30
2	120	99	30
2	80	94	30

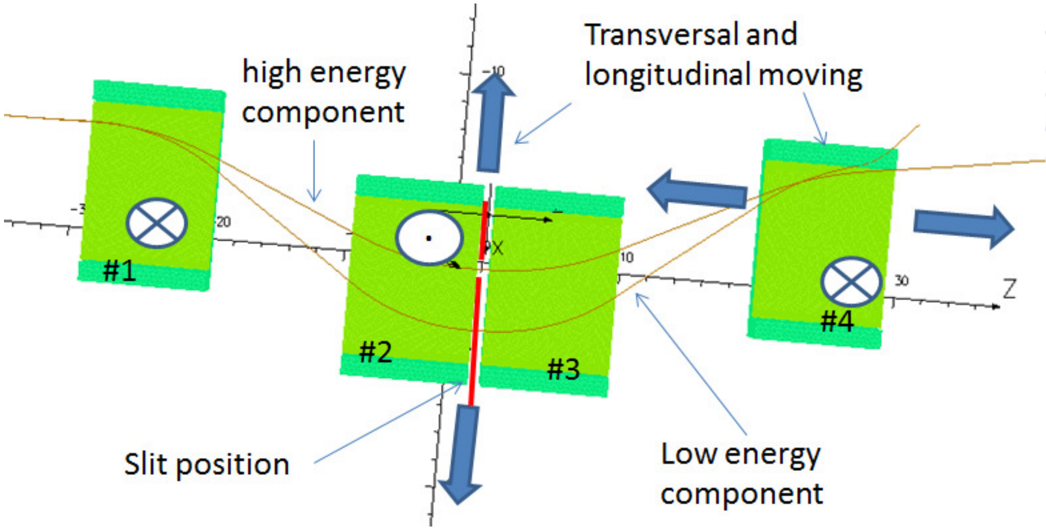
Ref: F. Romano et al, “The ELIMED transport and dosimetry beamline for laser-driven ion beams”, NIMA 829 (2016) 153-158.

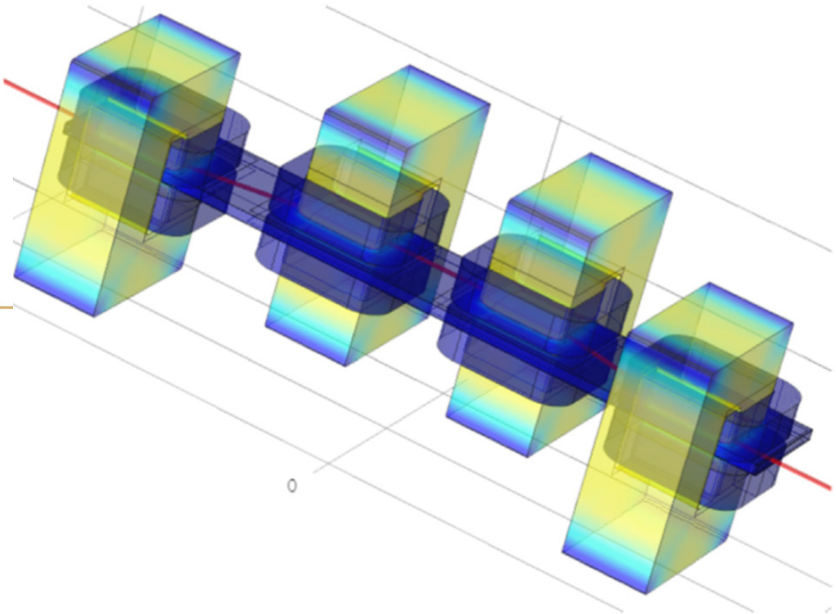




ELIMED: Energy Selection System

A fixed energy resolution of 5% if an aperture of 5 mm is used

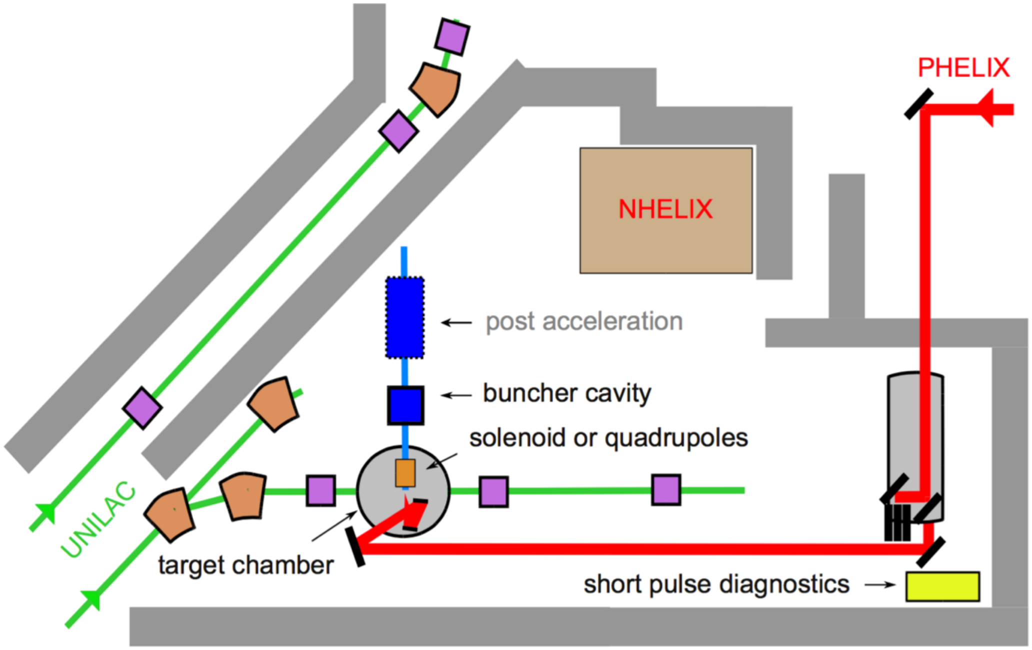




Dipoles	**B field**	**Length**	**Effective length**	**Gap**
4	0.085–1.2 T	400 mm	450 mm	59 mm
GFR	**B uniformity**	**Curvature radius**	**Drift length**	**Max J**
100 mm	$< 0.5\%$	2.593 m	500 mm	2.53 A/mm^2

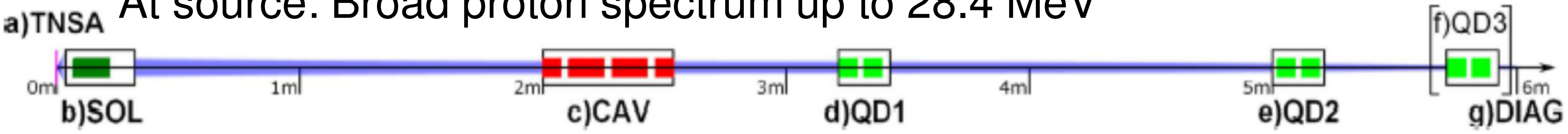
Ref: F. Romano et al, “The ELIMED transport and dosimetry beamline for laser-driven ion beams”, NIMA 829 (2016) 153-158.

LIGHT beamline at GSI: towards high peak intensities for ultra-short MeV-range ion bunches



Ref: S. Busold et al “Shaping laser accelerated ions for future applications – The LIGHT collaboration”, NIM A 740 (2014) 94-98.
S. Busold et al “Towards highest peak intensities for ultra-short MeV-range ion bunches”, Sci. Rep, 2015

At source: Broad proton spectrum up to 28.4 MeV

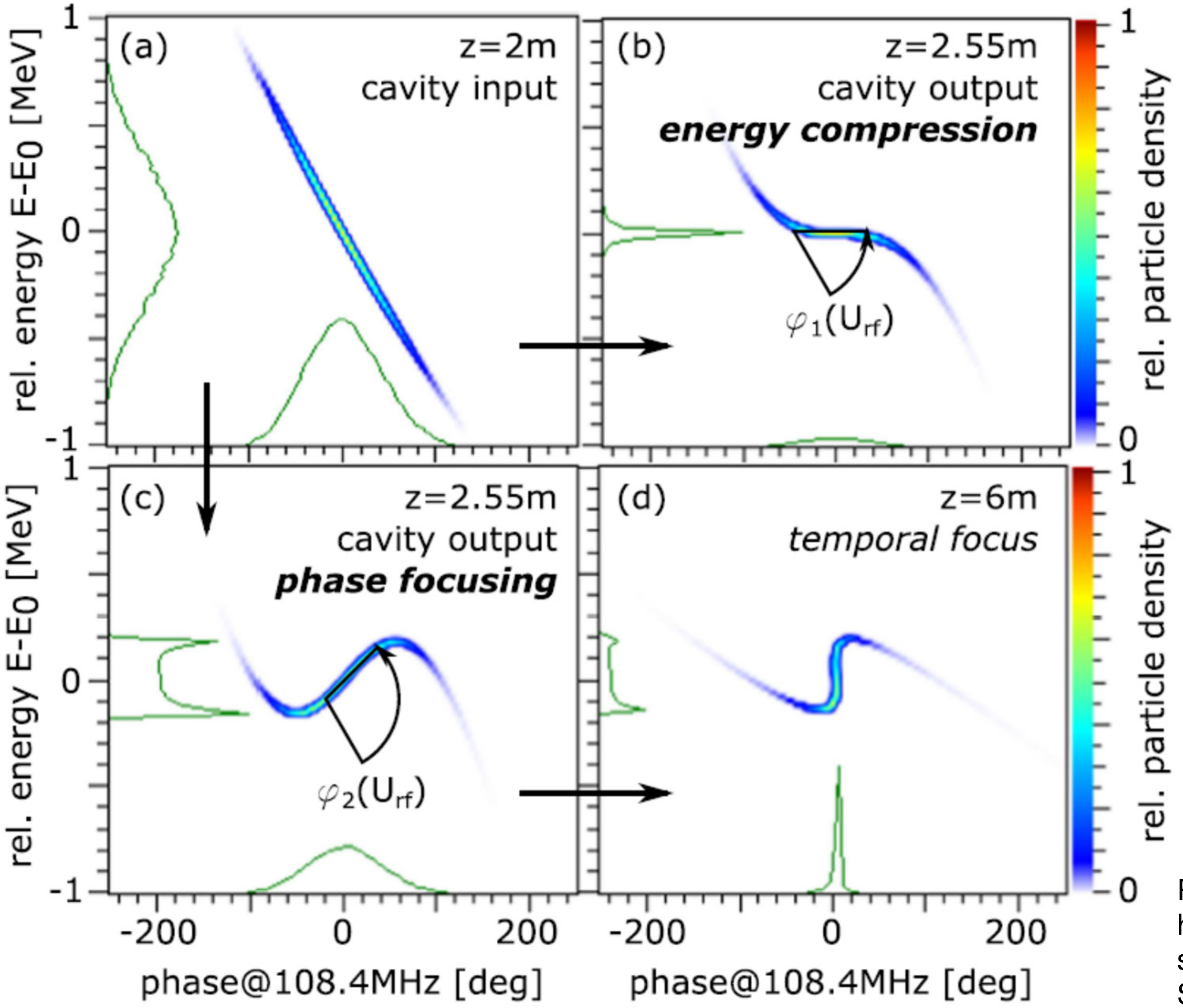


Energy selection and collimation

RF cavity for longitudinal phase rotation

Quadrupole doublets for beam transport

RF cavity for *Energy compression* or *Phase focusing*



Ref: S. Busold et al "Towards highest peak intensities for ultra-short MeV-range ion bunches", Sci. Rep, 2015

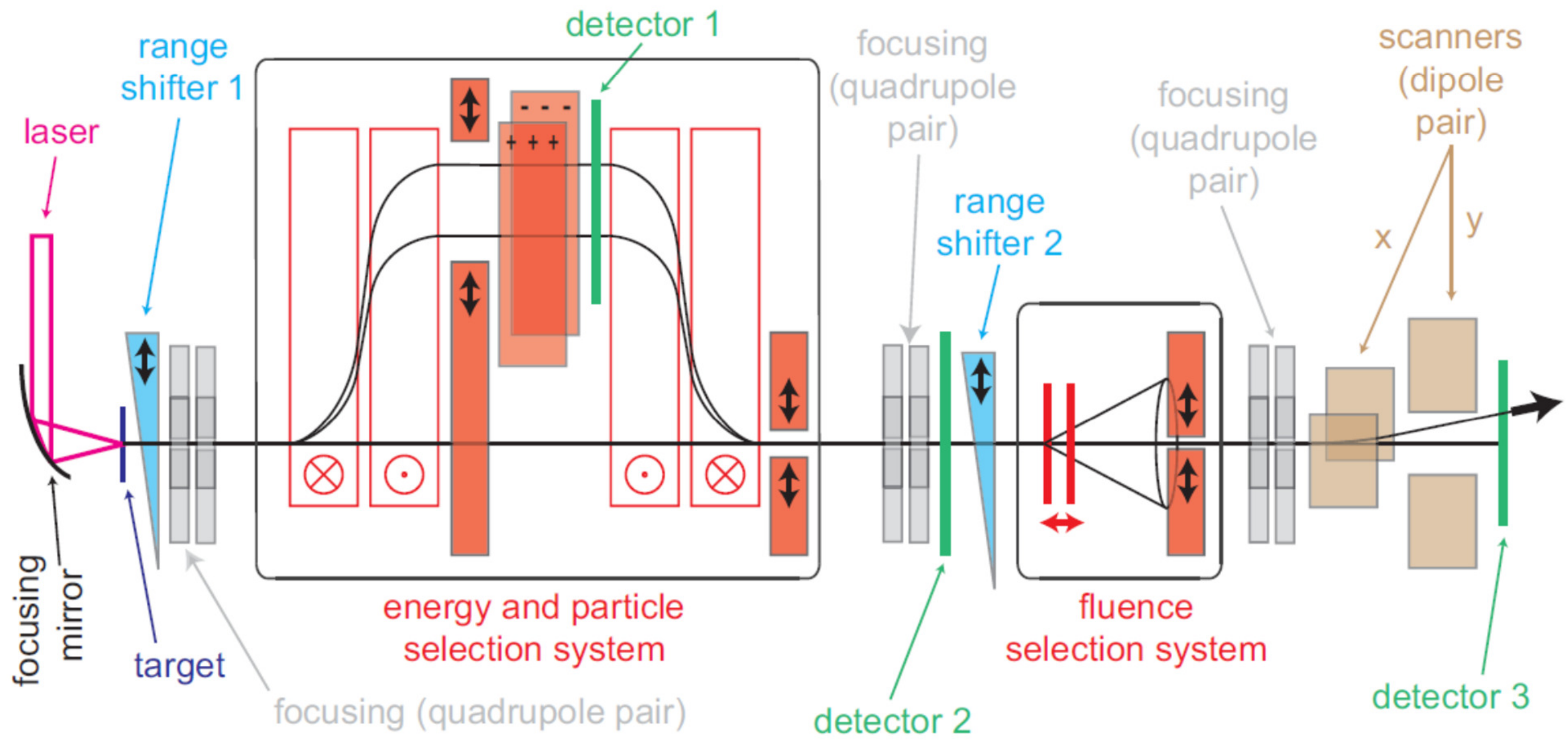
Laser-driven beamline for delivering intensity modulated radiation therapy

J. Biophotonics **5**, No. 11–12, 903–911 (2012) / **DOI** 10.1002/jbio.201200078

Journal of
BIOPHOTONICS

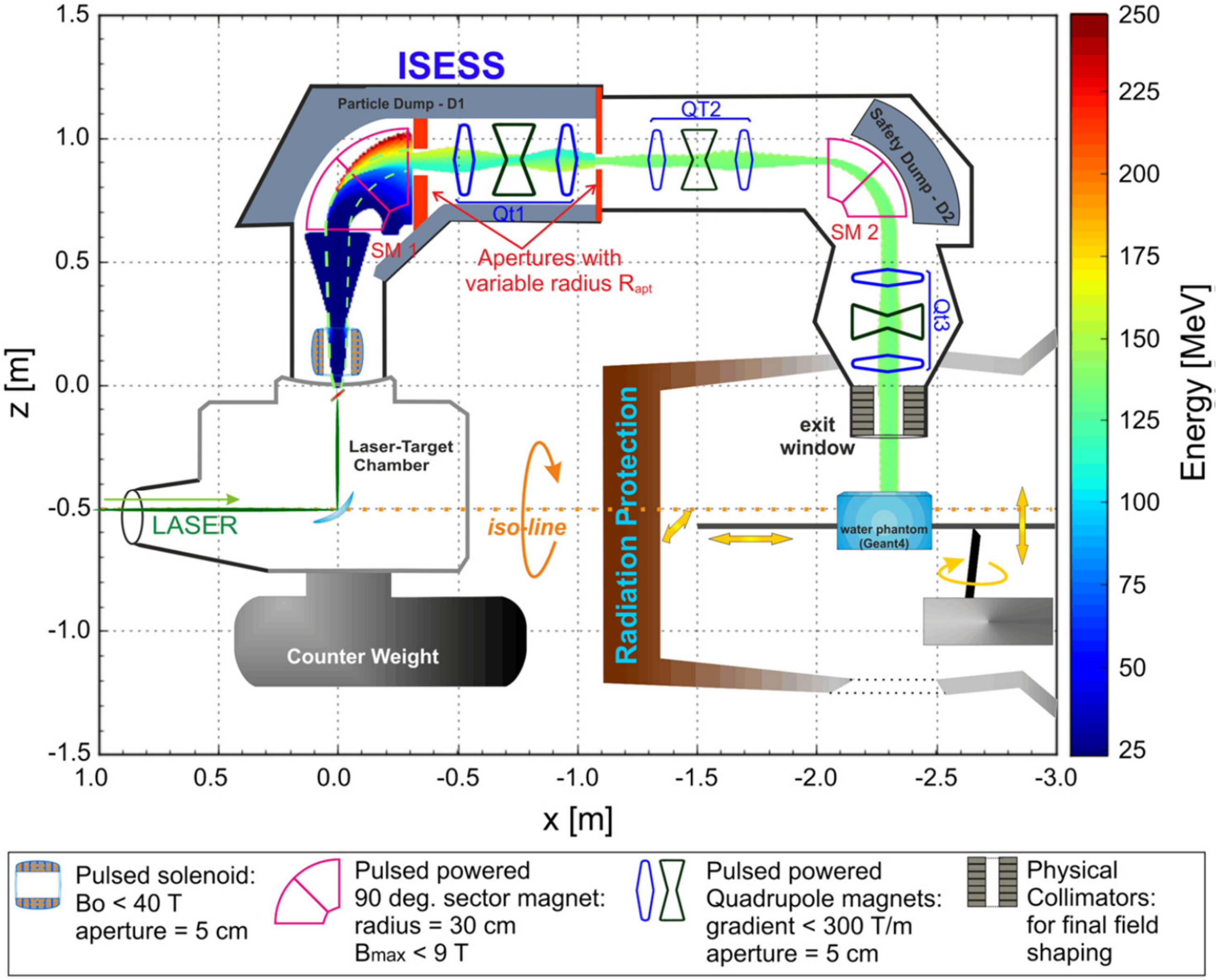
Laser-driven beam lines for delivering intensity modulated radiation therapy with particle beams

*Kerstin M. Hofmann, Stefan Schell, and Jan J. Wilkens**



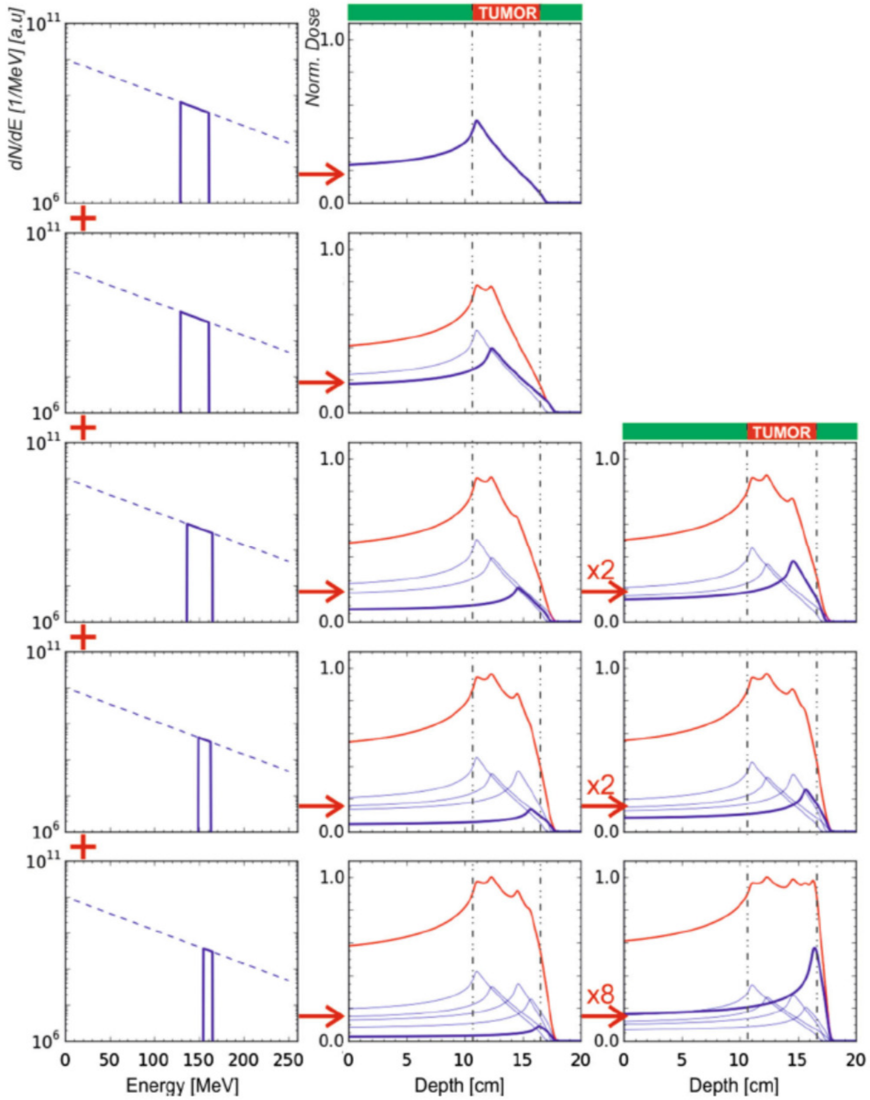
A compact solution for ion beam therapy with laser accelerated protons

Ref: U. Masood et al, “A compact solution for ion beam therapy with laser accelerated protons”, Appl. Phys. B (2014) 117:41-52.



Delivery of Single-field-uniform-dose by superimposing individually filtered laser accelerated protons

Ref: U. Masood et al, “A compact solution for ion beam therapy with laser accelerated protons”, Appl. Phys. B (2014) 117:41-52.



Solenoids vs. Quadrupoles in focusing and energy selection of laser accelerated protons

Large transmission rate

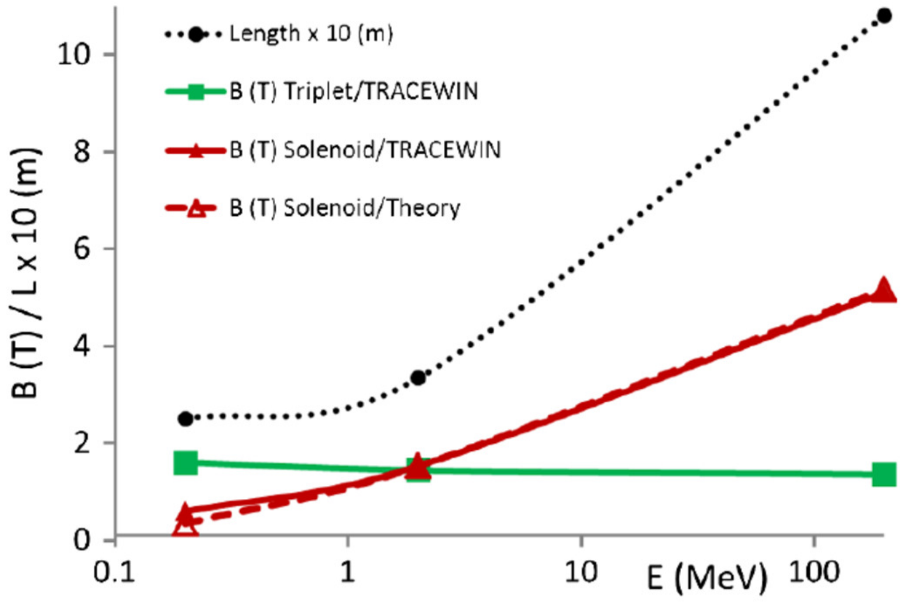
- Solenoids

Beam focusing

- At sub- and few MeV, both solenoids and quadrupoles are quite effective
- Energies > 20 MeV, B_solenoid > B_quadrupole for the same effective length
  - At high energies, quadrupole triplets are preferred.

Energy selection

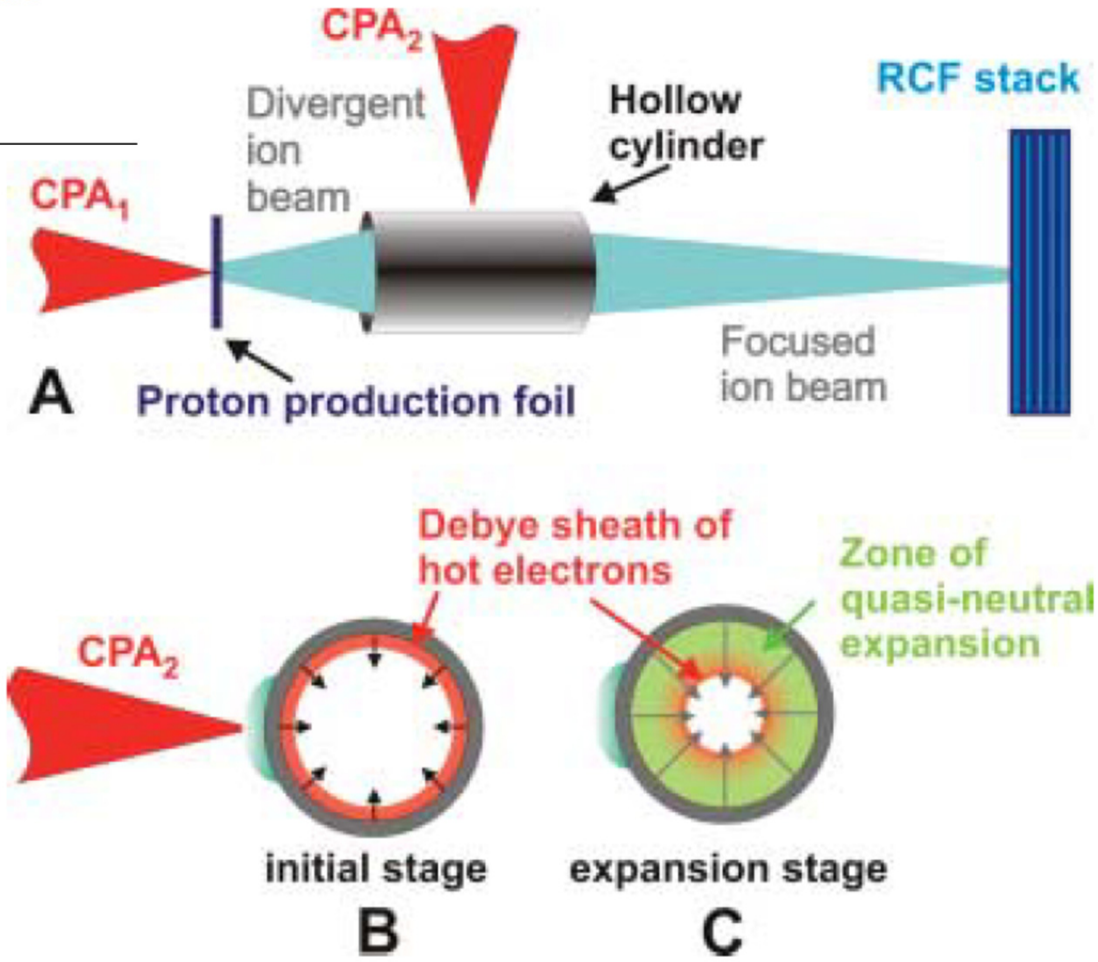
- E↑, focal length↑. So with an aperture at the focal point (or the waist of the beam envelope) can select ions at various of energies.



Ref: I. Hofmann, “Performance of solenoids versus quadrupoles in focusing and energy selection of laser accelerated protons”, PRST-AB 16, 041302 (2013).

A laser-driven microplasma lens for protons has been demonstrated.

Ultrafast Laser-Driven Microlens to Focus and Energy-Select Mega-Electron Volt Protons
Toma Toncian, *et al.*
Science **312**, 410 (2006);
DOI: 10.1126/science.1124412



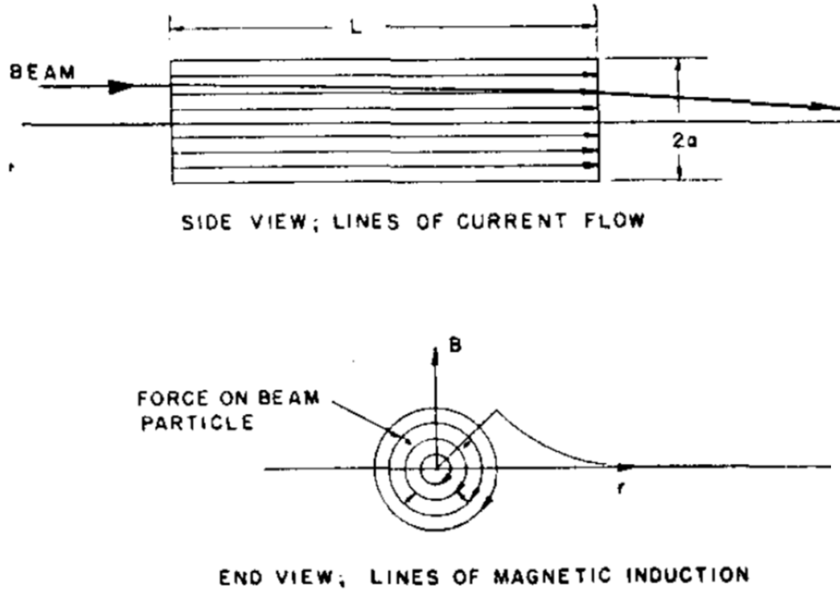
A Magnetic arc lens was utilized to focus 350 MeV proton beam.

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 21, NUMBER 5 MAY, 1950

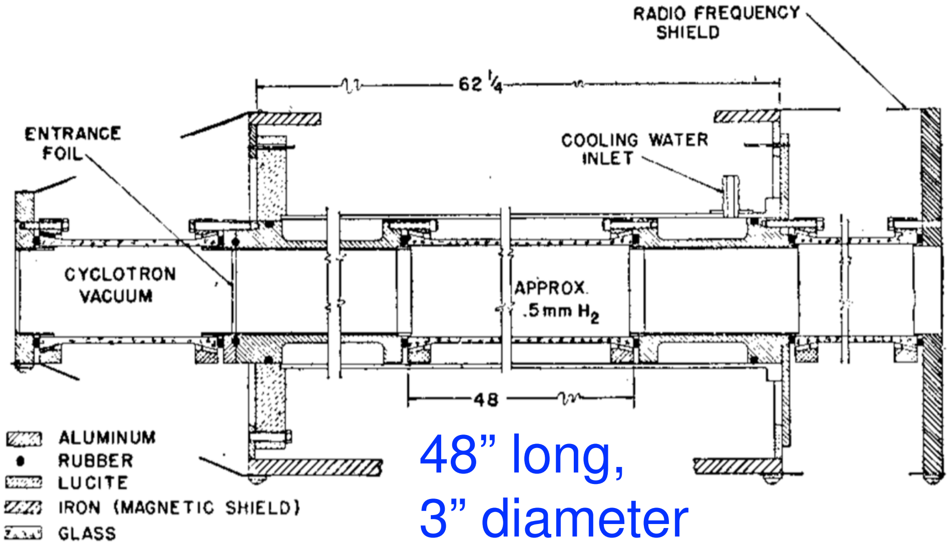
A Focusing Device for the External 350-Mev Proton Beam of the 184-Inch Cyclotron at Berkeley

W. K. H. Panofsky and W. R. Baker
Department of Physics, Radiation Laboratory, University of California, Berkeley, California

(Received January 11, 1950)

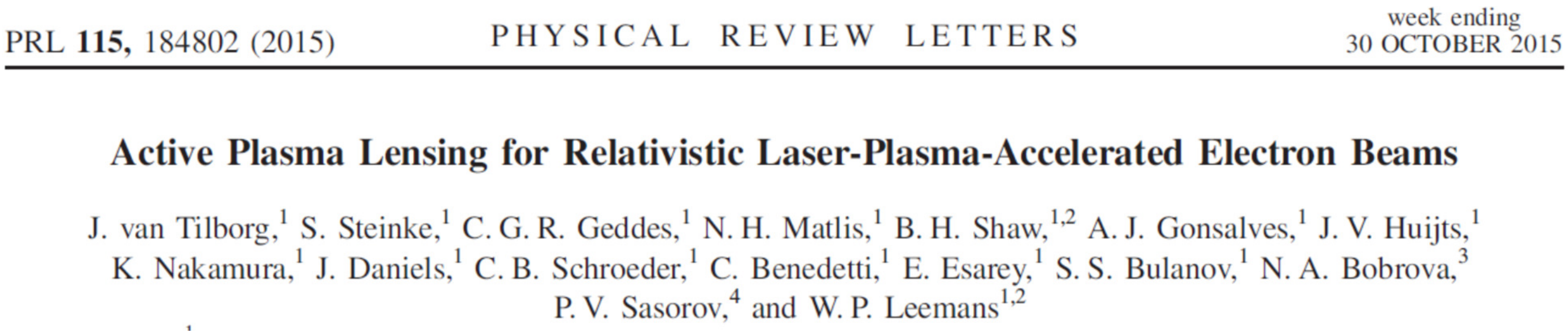


If the current density is uniform, $B \propto r$



48” long,
3” diameter

Using a discharge-capillary active plasma lens to focus 100s MeV LPA electron beam has been demonstrated.

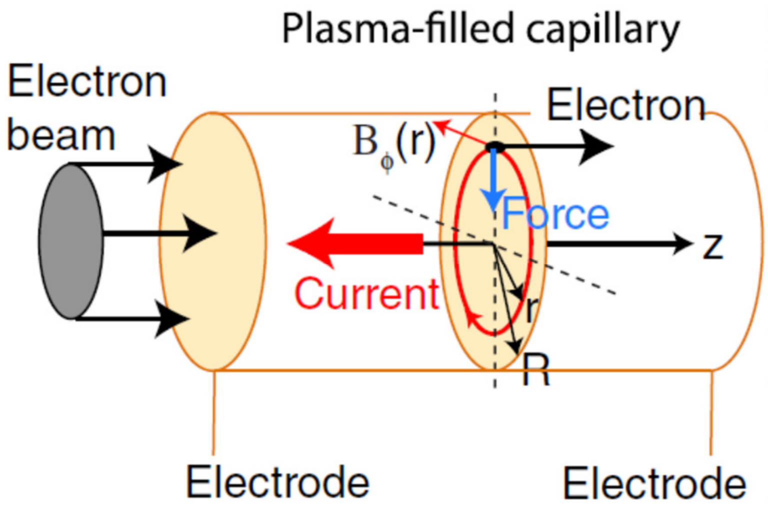


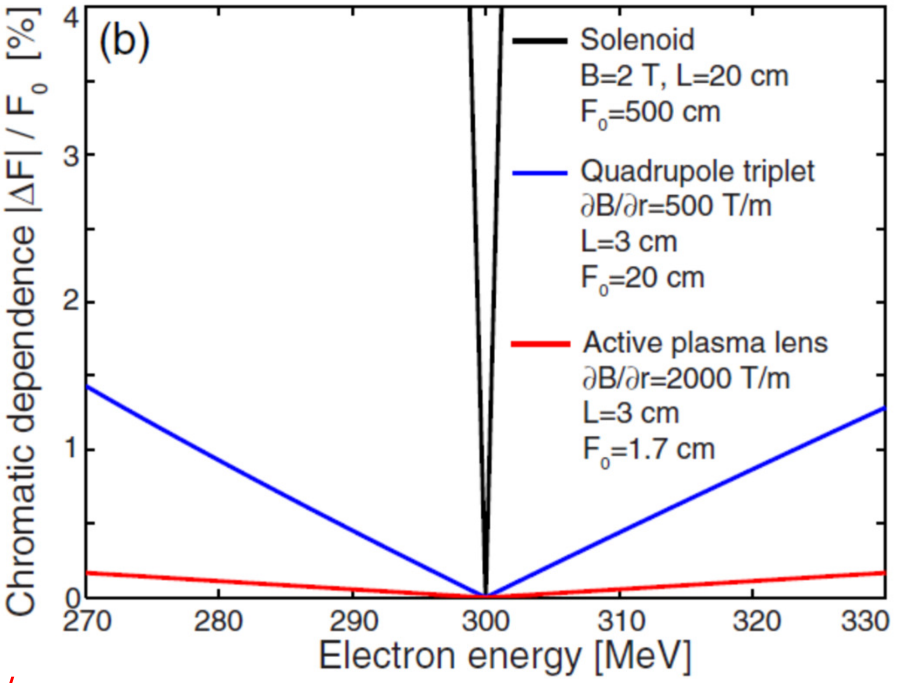
PRL **115,** 184802 (2015) PHYSICAL REVIEW LETTERS week ending 30 OCTOBER 2015

Active Plasma Lensing for Relativistic Laser-Plasma-Accelerated Electron Beams

J. van Tilborg,[1] S. Steinke,[1] C. G. R. Geddes,[1] N. H. Matlis,[1] B. H. Shaw,[1,2] A. J. Gonsalves,[1] J. V. Huijts,[1] K. Nakamura,[1] J. Daniels,[1] C. B. Schroeder,[1] C. Benedetti,[1] E. Esarey,[1] S. S. Bulanov,[1] N. A. Bobrova,[3] P. V. Sasorov,[4] and W. P. Leemans[1,2]

A few cm long, 0.25 -1mm dia.

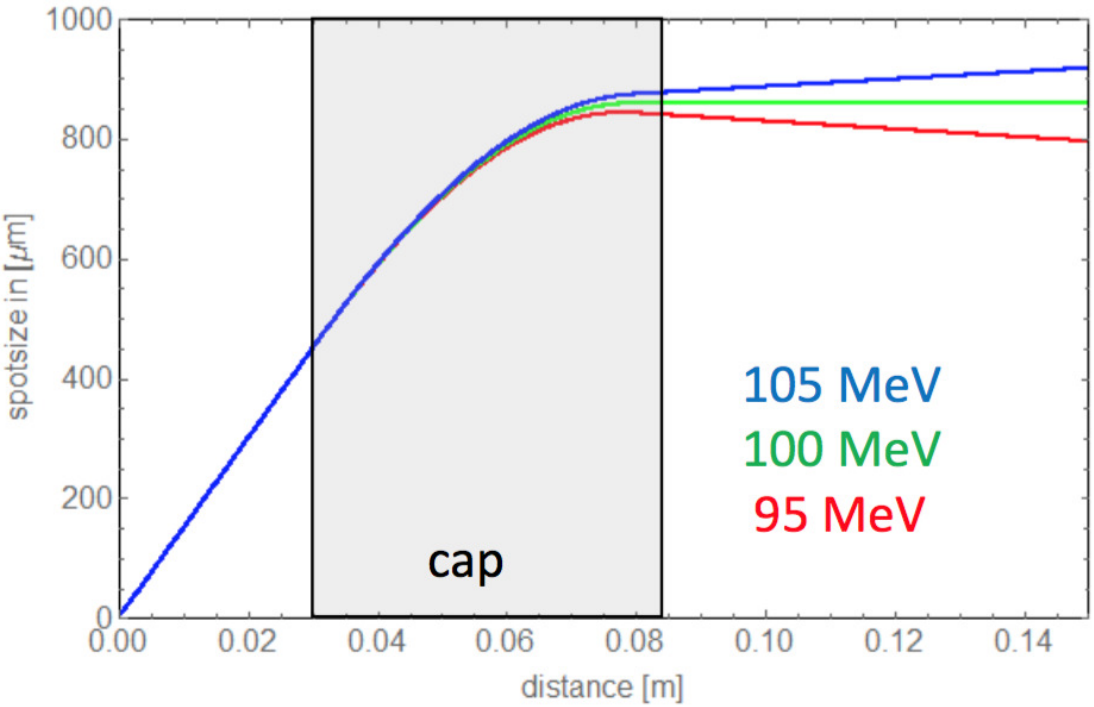




$$\partial B_\phi/\partial r = \mu_0 I_0/(2\pi R^2)$$

Up to 3000T/m

Simulations show that It is also feasible to focus laser accelerated ions using active plasma lens.

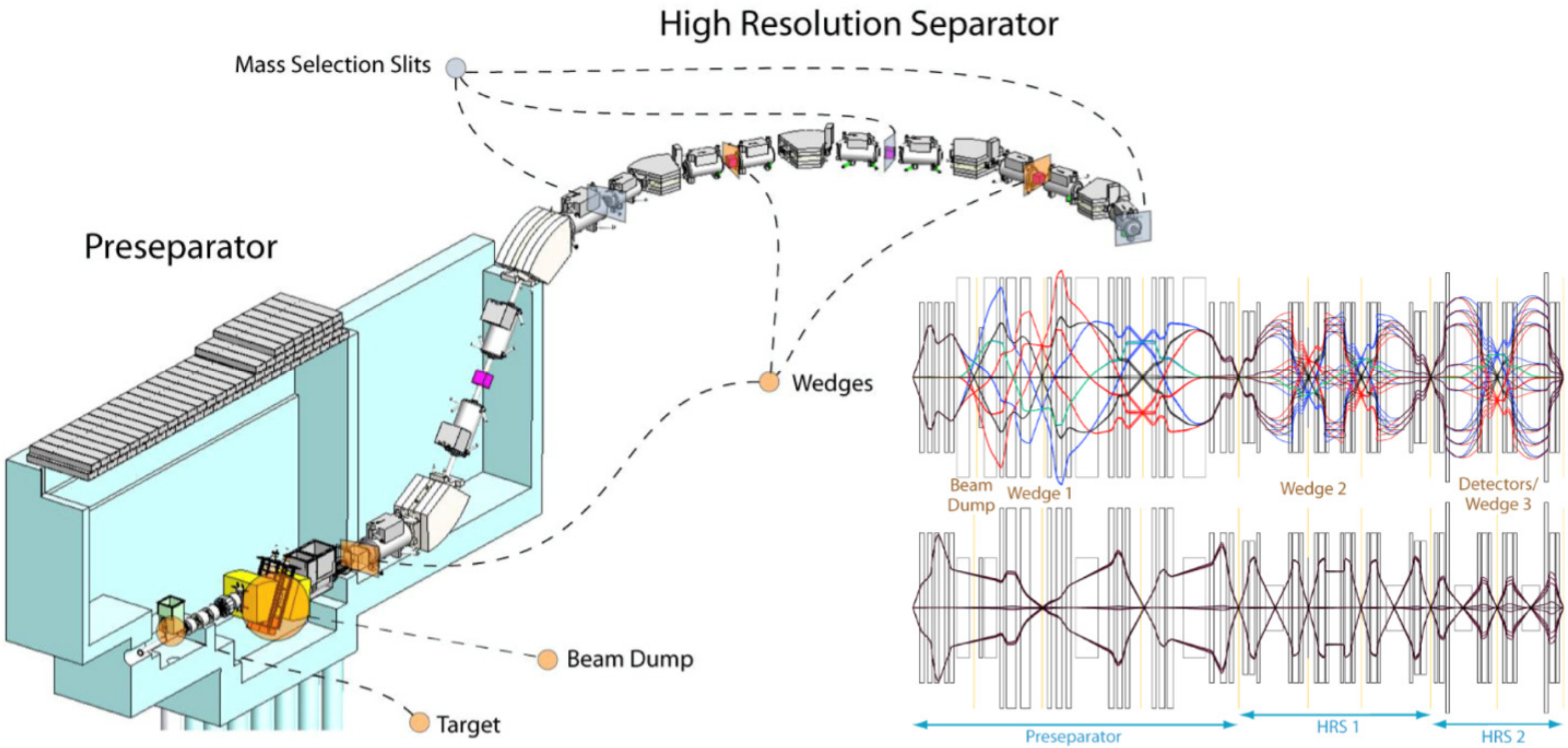


Proton beam
Source size: 5 μm
Divergence: 15 mrad

Capillary
Radius: 1 mm
Length: 5 cm
B field gradient: 140 T/m (max. 3000T/m)

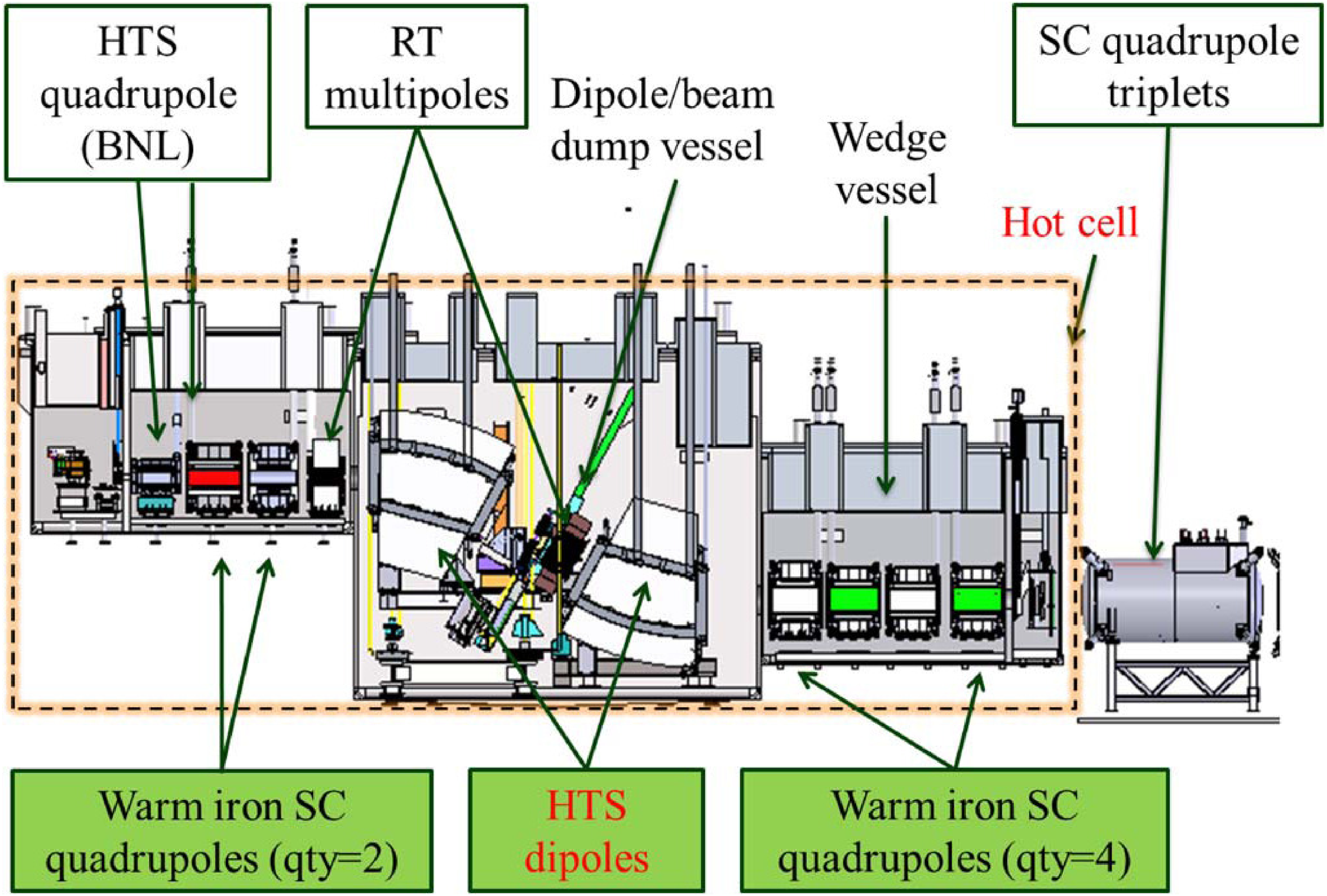
What else can we learn from other accelerator facilities?

FRIB Fragment Separator



Ref: D. J. Morrissey, “Status of the FRIB project with a new fragment separator”, J. Physics conference series 267 (2011) 012001.

FRIB Fragment Separator



HTS quadrupole (BNL)

RT multipoles

Dipole/beam dump vessel

Wedge vessel

Hot cell

SC quadrupole triplets

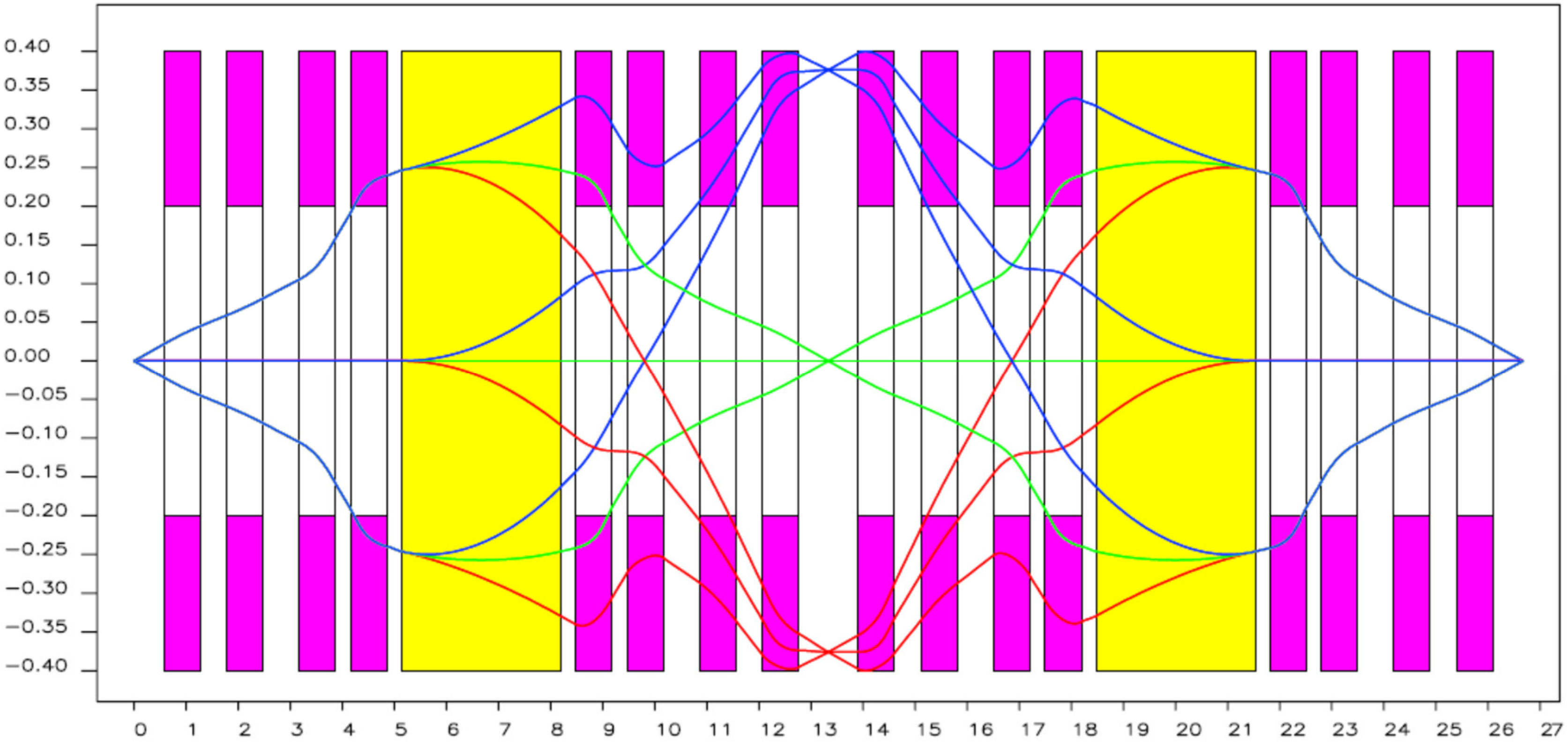
Warm iron SC quadrupoles (qty=2)

HTS dipoles

Warm iron SC quadrupoles (qty=4)

Symmetry-based design of fragment separator optics

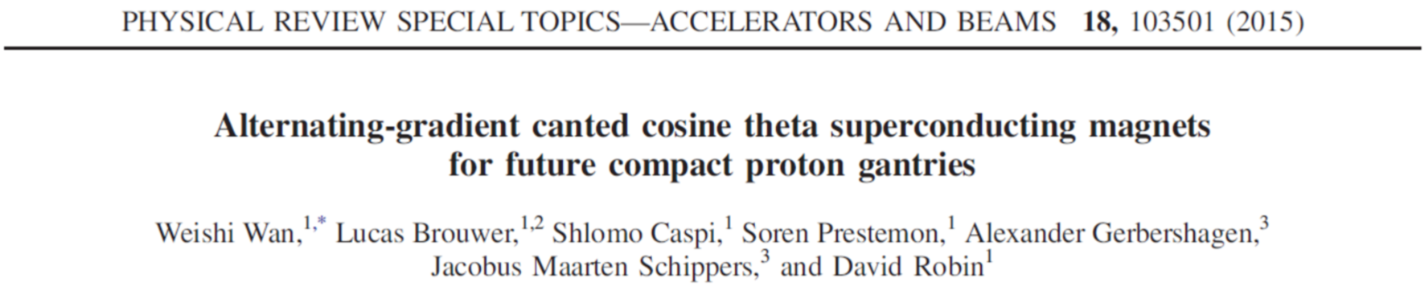
First order horizontal beam envelope
Initial beam: +/- 1mm, +/- 50 mrad, +/-16% energy dispersion



Multipoles Dipole Multipoles Dipole Multipoles

Ref: B. Erdelyi et al, "Symmetry-based design of fragment separator optics", PRST-AB, 10, 064002 (2007).

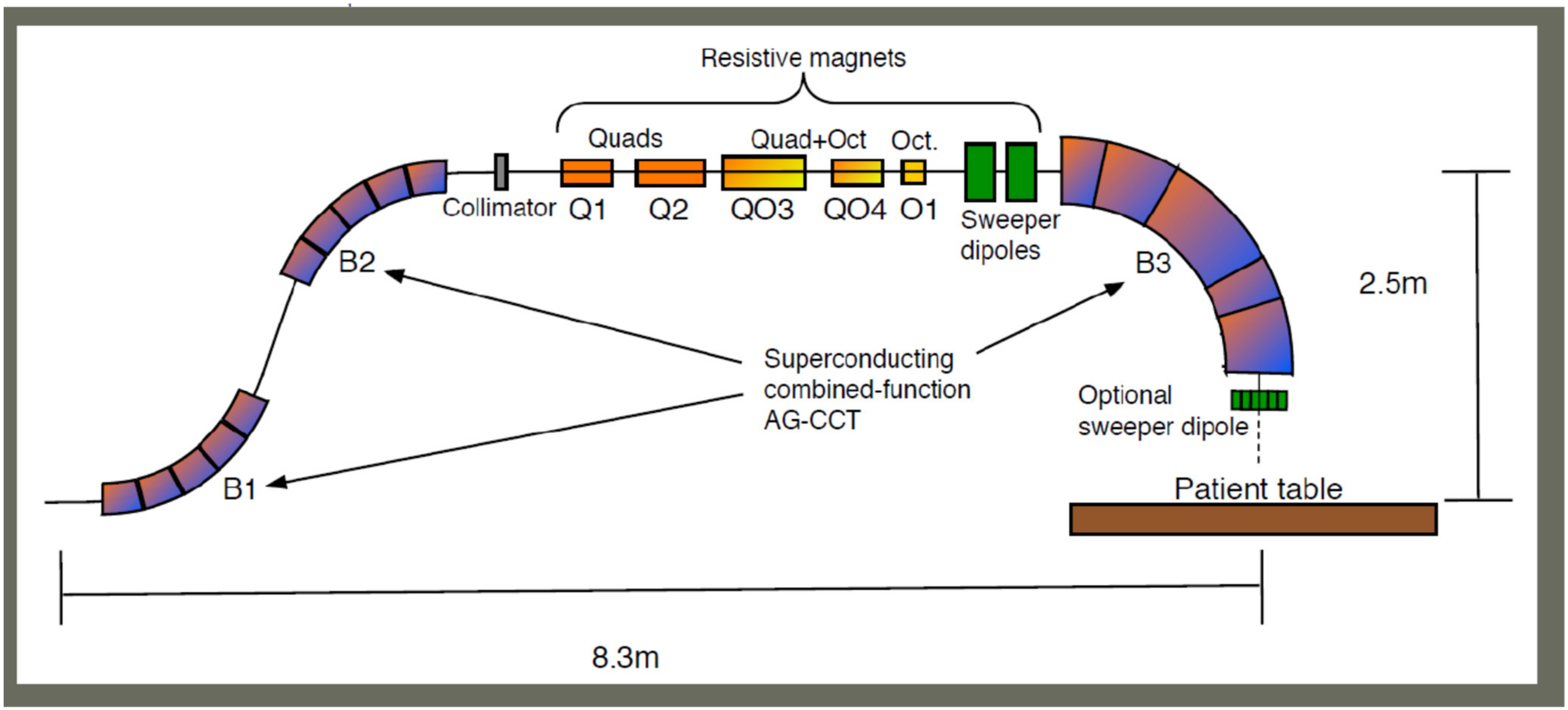
Alternating-gradient canted cosine theta (AGCCT) superconducting magnets enables future compact proton gantries.



PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 103501 (2015)

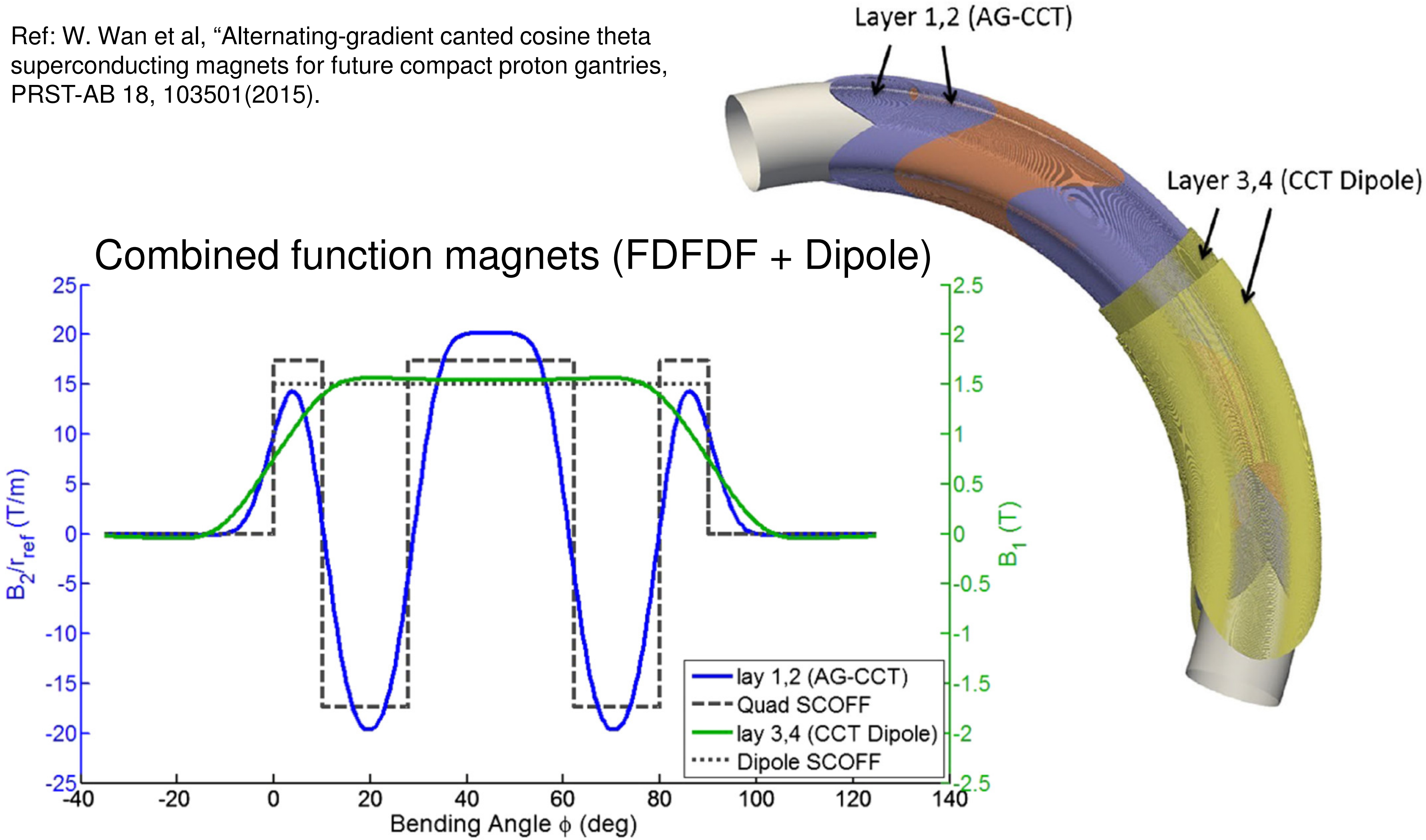
Alternating-gradient canted cosine theta superconducting magnets for future compact proton gantries

Weishi Wan,[1,*] Lucas Brouwer,[1,2] Shlomo Caspi,[1] Soren Prestemon,[1] Alexander Gerbershagen,[3]
Jacobus Maarten Schippers,[3] and David Robin[1]



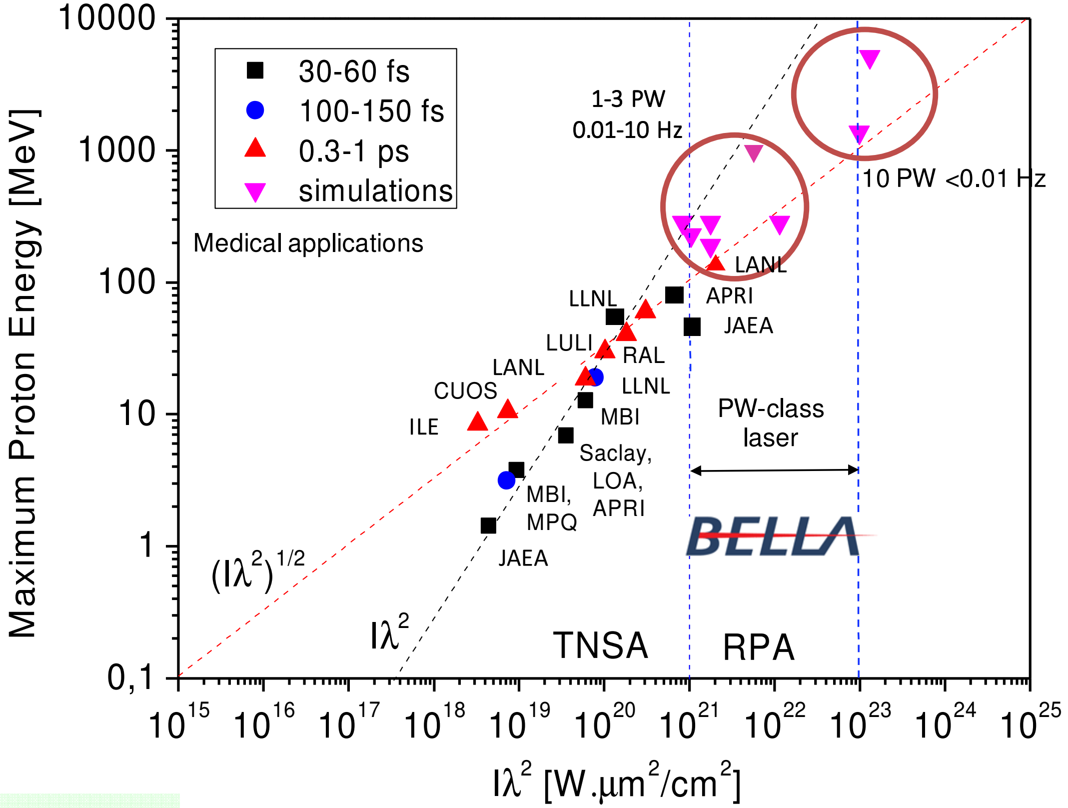
Large aperture AG-CCT superconducting magnets enables beam optics with larger acceptance and lighter weight.

Ref: W. Wan et al, “Alternating-gradient canted cosine theta superconducting magnets for future compact proton gantries, PRST-AB 18, 103501(2015).

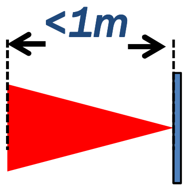


Combined function magnets (FDFDF + Dipole)

BELLA-i: A collaborative user facility for relativistic plasma physics and high energy density physics



Ion acceleration



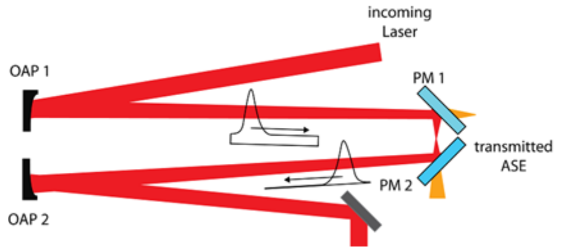
Intensity ~3-5x10^{21} W/cm^2

Acc. fields ~TV/m

4-5 micron spot

+

Plasma mirror technology for contrast clean-up

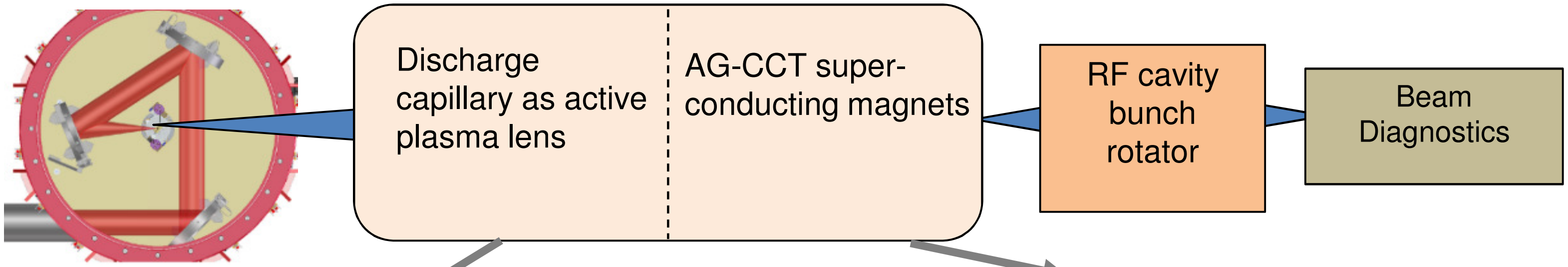


Ion Acceleration Experiments at BELLA-i

BELLA-i	phase 1	phase 2	phase 3
peak intensity (W/cm^2)	2 x 10^{19}	3 x 10^{21}	3 x 10^{21}
pulse length	30 fs	30 fs	30 fs
peak pulse energy	40 J	40 J	40 J
laser spot size	55 µm	5 µm	5 µm
peak repetition rate	1 Hz*	1 Hz*	1 Hz
contrast (ns)	10^{-10}	10^{-10}	>10^{-14}
diagnostics (details to be determined)	• optical spectrometers • ion and electron spectrometers • …	• optical pump- probe • betatron x-rays • MeV protons • …	• same as 2 • beamline for experiments with laser accelerated ions • …
1st access (estimates)	2017-2018	2018-2019	2019-2020

1. experiments with the existing, long focal length BELLA beamline in the existing cave
2. experiments in the existing BELLA cave with a new dual-beam line
    - * shielding in the BELLA cave limits the repetition rate for experiments with generation of intense pulses of >20 MeV protons
3. experiments in a new cave with improved shielding and with a beam line for laser accelerated ions
    - * improved shielding in a three-times larger experimental area for continuous operation at 1 Hz

Ion Collection and beam Transport Beamlines for BELLA-i

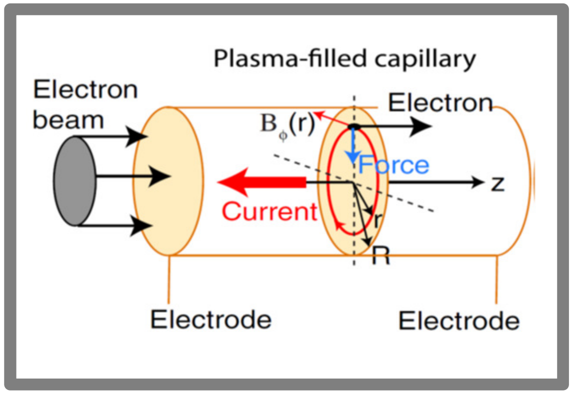


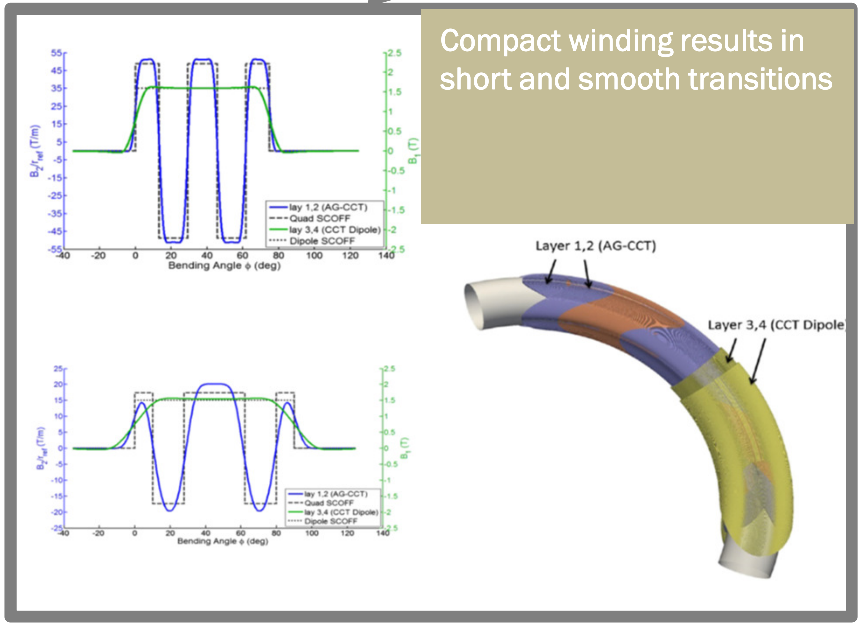
Discharge capillary as active plasma lens

AG-CCT super-conducting magnets

RF cavity bunch rotator

Beam Diagnostics



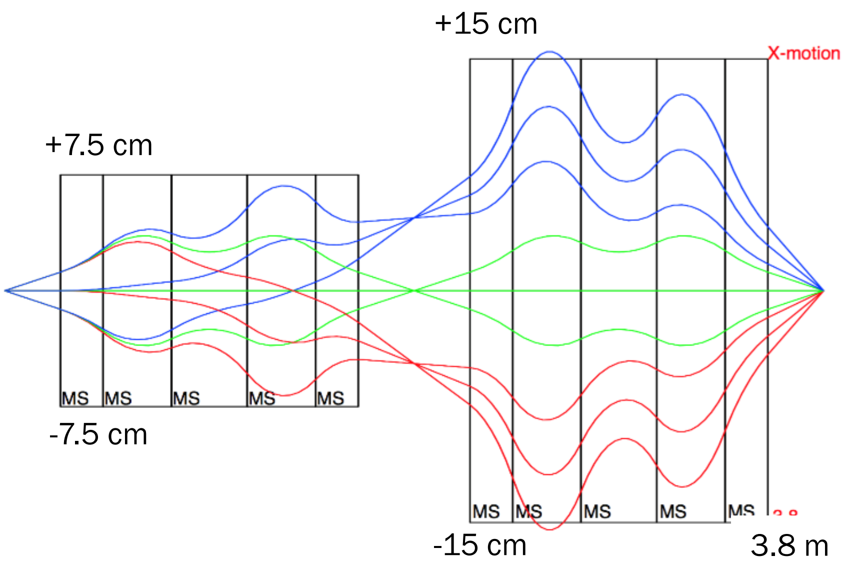


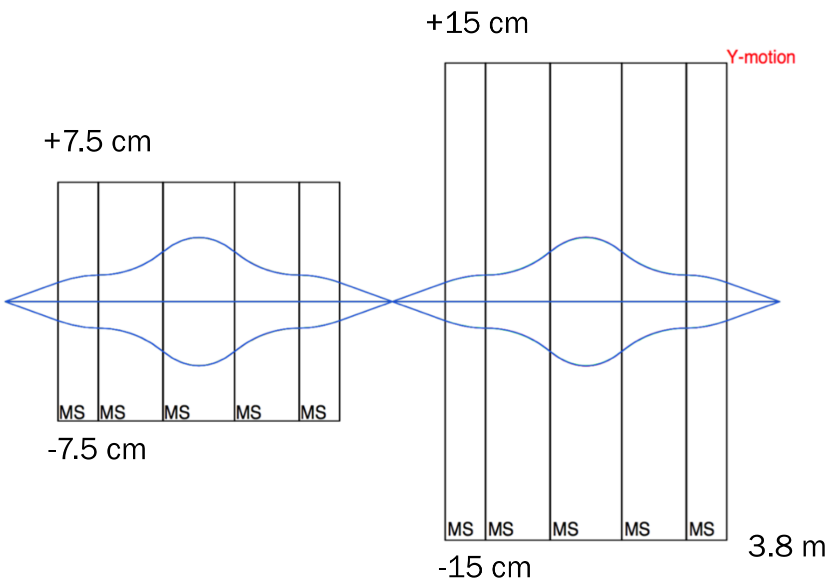
Compact winding results in short and smooth transitions

Ref: J. van Tilborg *et al*, Phys. Rev. Lett. **115**, 184802 (2015).

Ref: W. Wan *et al*, Phys. Rev. STAB **18**, 103501 (2015).

Compact Beam Transport and Energy Selection System using Combined-function AGCCT magnets





Initial beam divergence: ± 40 mrad

Energy dispersion: ± 12%

Simulation code: COSY Infinity program, http://www.bt.pa.msu.edu/index_cosy.htm

Properties of Combined-function AG-CCT Magnets

	B1	B2
Bore radius (mm)	75	150
Bending radius (m)	1.50	
F Angle (degree)	8.61	
D Angle (degree)	13.76	
F Angle (degree)	15.26	
D Angle (degree)	13.76	
F Angle (degree)	8.61	

Beam Energy (MeV/u)	Quadrupole gradient (T/m)	Dipole field (T)
200	25.4	1.4
150	21.7	1.2
100	17.5	0.96
50	12.3	0.67
25	8.6	0.47
10	5.4	0.3

Summary

- Laser plasma ion source, together with beam transport system to achieve low energy spread, high controllability and stability, can form the core of a new generation of ion accelerators.
- High energy spread and large beam divergence angle pose challenges in beam optics design.
- A lot of progress has been made laser-accelerated ion collection, beam shaping, focusing, and beam transport.