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The Integrated Laser-driven Ion Accelerator System and (Laser-driven) Ion Beam Radiotherapy

(or ‘ILDIAS and LIBRT’)

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“Workshop on Innovative Delivery Systems in Particle Therapy” 23-25 February 2017;
Molecular Biotechnology Centre, University of Torino and CNAO National Centre of Oncological Hadrontherapy, Pavia

Coarse Outline

- Sophistication of Ion Beam Radiotherapy (IBRT)
- Why We Consider Laser-drivers (How did this get started ?)
- The Integrated Laser-driven Ion Accelerator System (ILDIAS)
- New Commercial Sources
- Other Key Programmes for ILDIAS development for LIBRT
- Strategic Guidance

(i.e. neither a laser nor a laser-plasma talk)

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Conventional Ion Beam Radiotherapy (IBRT) - Highly Evolved, Sophisticated, Controlled

(multiple generations…)

medical accelerator development (cyclotron (proton) or synchrotron (carbon ion) machines)
includes beam transport, instrumentation/diagnostics as enablers
and beam delivery for treatment (includes gantry)

What began as an accelerator research laboratory decades ago that could provide IBRT with occasional beam time has evolved to a specialized hospital that includes a dedicated full scale medical accelerator with appropriate beam delivery and treatment planning.

Some Basic Beam Requirements …

$$\varepsilon\ (for\ 30\ cm\ penetration) = \sim 250\ MeV\ for\ protons\ \left(\sim 430\frac{MeV}{u}\ for\ C^{+6}\right)$$

typical $\frac{\Delta\varepsilon}{\varepsilon} \sim 10^{-3}$ with range steps of 0.5 g/cm^2

beam pointing precision at mm level

localization - dose distribution conforms closely to tumor volume
(spares surrounding healthy tissue as much as possible)

dose measurement accuracy ~ +/- 3-5 % (absolute dosimetry standards)
=> high control level for fluence, steering and energy control

treatment fraction duration – few minutes

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Other Typical Performance Requirements …

large precise gantry (getting smaller with superconducting technology)

beam handling/shaping in delivery – intensity modulation/multiple irradiation fields,
passive (broad beam) and active (steered narrow beam) modes, gating to address tumor motion
("Improving scanning is still substantial work" - S. Psoroulas of PSI)

engaged commercial development of full systems (Varian, IBA, Hitachi, Mitsubishi, Sumitomo, MEVION…) - turn key, certified full treatment facilities

reliabilibity => cyclotron can last ~ 30 years, turn-key, high reliability (10-12h/d; 5-6d/wk; 48-50 wk/yr
machine costs ~ 10 Meuros (~ 20% cost of full facility), serve several treatment rooms
full facility costs down to ~ $30 M (includes servicing over long term) with size ~ 200-260 m^2

growing demand => ~ 62 facilities worldwide (55 deliver only protons) & ~ 30 new ones coming/propose
~ 55000 total patients treated by 2008
~ 18000 patients treated in 2015 alone

Future Trends: smaller machines (single room facilities), tumour tracking, image-guided therapy, adaptive therapy, improved precision for range measurement and smaller (early stage) tumor detection (mm precision)

1 Gy Dose to 1 Litre Tumour in 100 Seconds

(0.6 Gy/L/min)

total number of protons for full tumor volume — *5×10^{11}*

<u>average</u> proton delivery rate — *5×10^{9} /second*

(~ 1 nanoampere cw – ready provided by existing accelerators)

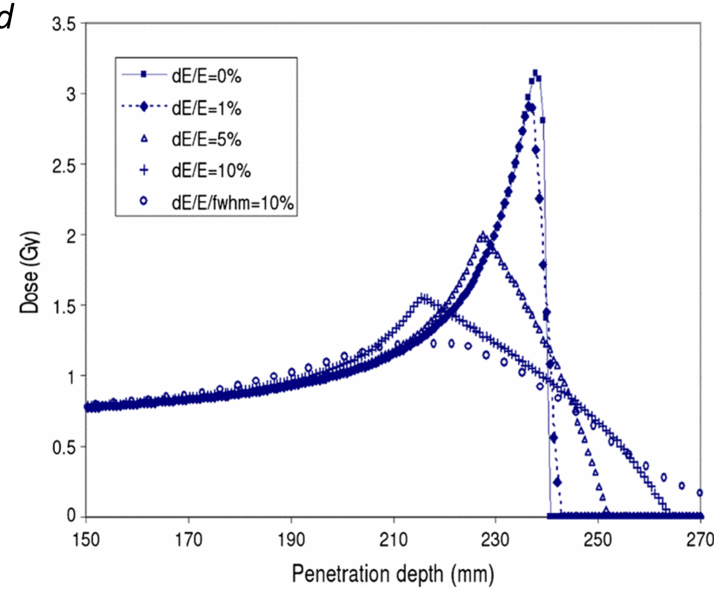
number or protons per voxel (relevant to active scanning mode) (1000 voxels; 1 voxel = 1 cm^3) — *5×10^{8} /voxel*

number of treated voxels/second — *10*

number of protons /bunch (1 ion bunch per laser pulse) — *5×10^{8} /bunch (at tumor)*

number of bunches per voxel — *1*

(for 1 Gy this means no repainting @ 10 Hz and single bunch dose must be very well controlled



* I. Hofmann et al PRSTAB **14**, 031304 (2011)

if laser-driven bunches:

<u>single bunch</u> delivery rate — *10^{19} protons/second* — *(for 50 picosecond bunch duration*

(single bunch dose rate) — *(2 x 10^{10} Gy/second)* — *example in laser-driven case)*

IBRT is a successful application that is not waiting for laser intervention.

How/why does the high power laser come into this ?

Will lasers ever be able to deliver ion beams of similar quality to match IBRT state-of-the-art ?

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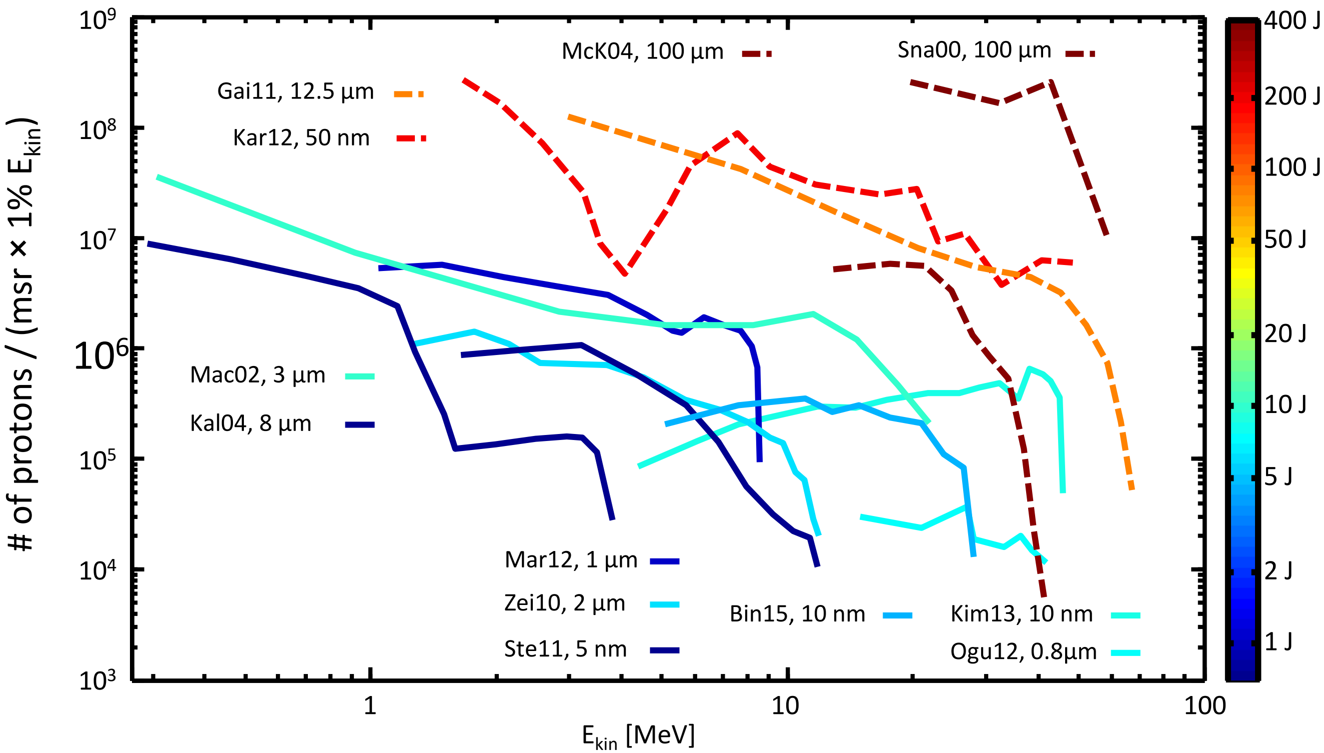
The basis for considering laser-driven ion beam radiotherapy (LIBRT) is low emittance, energetic particle yields from intense laser-plasma interactions with targets *

(began in earnest ~ 2000 ; proton energy increased from 58 to 85 MeV in 17 years)

Differential Proton Yield



current published record ** :

3×10^5 p/(msr MeV) at **85 MeV** (solid angle < 3 str)

driver ~ 10^{20} W/cm^2 (0.5 – 0.8 psec)

~ 0.9 micron plastic target
~ 7 % efficiency

(note: 30 degree full divergence => ~ 200 msr solid angle)

** *F. Wagner et al., PRL 116, 205002 (2016)*

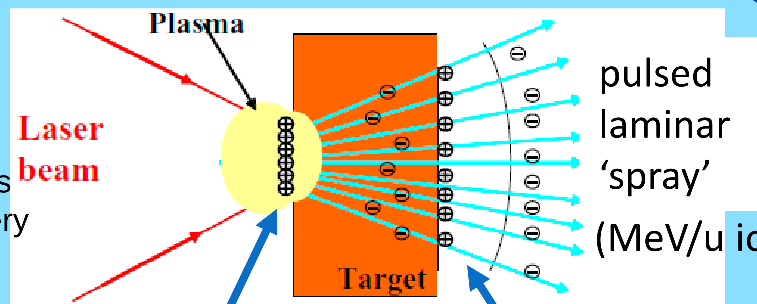
* *J. Schreiber et al RSI **87**, 071101 (2016)*

Laser-Plasma Photoinjector (for ILDIAS):
High Brightness Ion Emission

Pulse Energy:	up to ~ 10's J
Pulse Power :	**~ 100 TW (10^{14} W) to ~ PW (10^{15} W)**
Pulse Intensity:	10^{18} to > 10^{21} W/cm^2
at repetition-rate:	ss (single shot) up to ~ Hz (want 10 Hz or more)

(back-illuminated photoanode
In contrast to typical form of
RF Photoinjectors;
wherelaser-driven plasma
provides 'extraction' field)

functional
viewpoint
wrt accelerator
source
development



(focus
to very
high
Intensity)

rapid electron
acceleration
to relativistic
energies

extraction field
~ 10^{12}V/m
(charge separation)

Unique Setting: Extreme Interaction (high field, high density, high energy, ultrafast)

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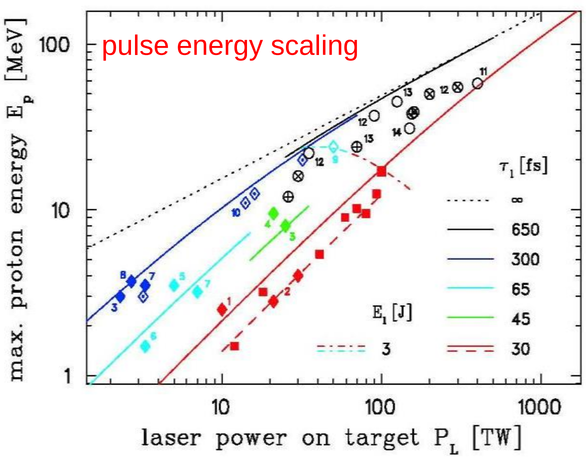
Table I. Typical 'At-Source' Proton Bunch Features: Pulsed Laminar Spray of Ions with a Very Large Energy Spread*, **

For ~ 100 MeV protons:
PW laser requirement 'on target' with focusing to $10^{22\text{-}23}$ W/cm² level (laser system capability must be higher)
***



*** *K. Zeil et al.,NJP 12, 045015 (2010) - red squares are data using the DRACO laser*

Charge/Duration (peak current)	*10's to 100's nCoulombs/~ psec (10's to 100's kiloamp)*
Divergence	***10's of degrees (full angle)***
Extraction (accelerating) Field	*~ TV/m*
Maximum kinetic energy, $\varepsilon_{max}{}^{p}$ (protons)	*~ 85 MeV (current record)*
Energy Spread, $\frac{\Delta\varepsilon}{\varepsilon_o}$	***> 100 % (using ε_o = spectral median)***
Low transverse emittance, ϵ_x (high brightness)	*~ 10^{-3} mm mrad (geometrical – full bunch)*
Repetition-rate (equals laser repetition rate)	***up to 1 Hz demonstrated***
Efficiency (full ion spectrum), η	***0.1 to few % levels*** $\left(\frac{\text{particle kinetic energy}}{\text{incident laser pulse energy}}\right)$

* *well-studied Target Normal Surface Acceleration (TNSA) regime*

** *P.R. Bolton NIM **A809**, 149 (2016)*

PW Era is Here: Can Purchase a PW laser but the 'PW Hammer' Alone is not Enough for LIBRT (or many other applications)…

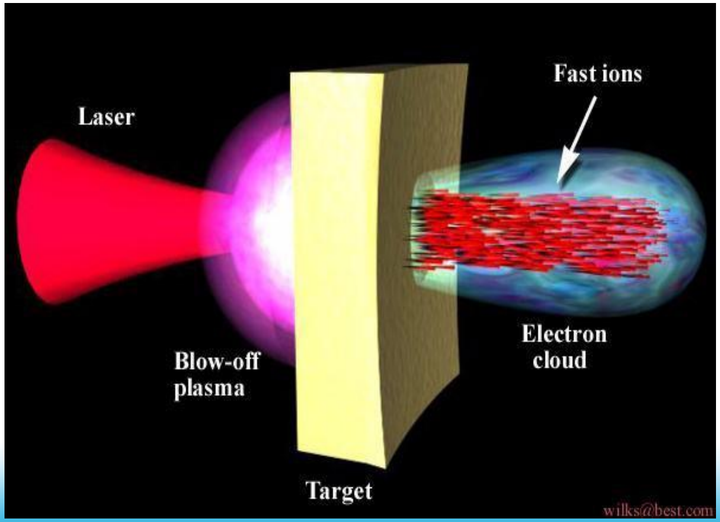
to operate at ~ 250 MeV need higher
E^{p}_{max} (possibly up to ~ 400 MeV; depending on spectral profile)

focused intensity ~ 10^{22} W/cm^2 or more (=> diffraction-limited focusing)
(few PW lasers with 10's joule pulse energies and 10's fsec duration;
note that 1 ***PW on target*** means a few PW system is needed)

rep-rate ~ 10 Hz or more **(*cryo-cooled 10 Hz/>100 J pump (DiPOLE) recently demonstrated at STFC/RAL => enable first diode pumped (ir) PW system; such 10 Hz systems expected to be large (~ 400 m^2 footprint) and costly (10's of Meuros) – just the laser !)**

** Klaus Ertel, private communication and see Banerjee et al OL **37**, 2175 (2012)*

'PW hammer' alone is not enough =>must develop new PW era technologies for control/finesse of



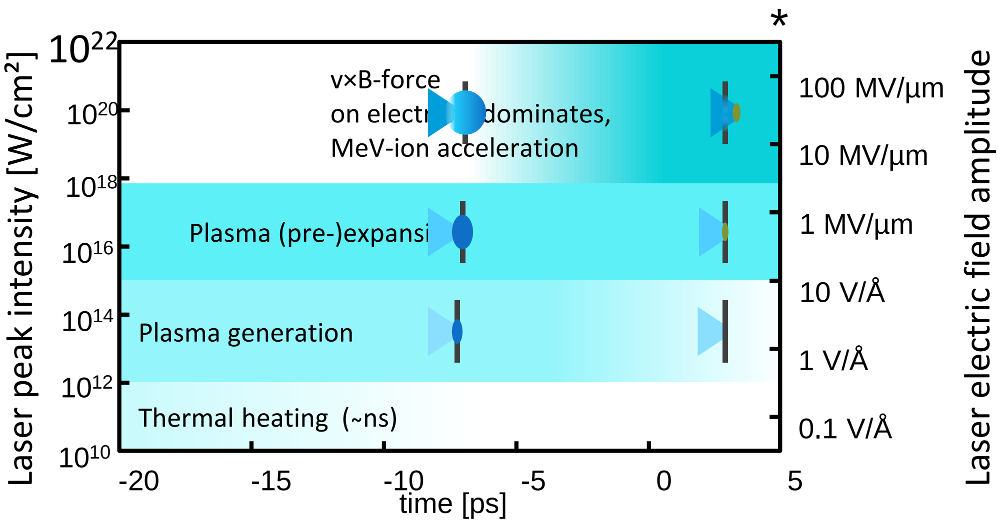
'Clean' pulses:
control/stabilize pulse parameters
(energy ~ few %, duration, spotsize, pointing)

pulse 'tailoring'/shaping (tailoring laser pulse & target plasma)
(eg. for transverse profile – adaptive optics
for longitudinal profile – single pulse contrast measurement and control at 10^{-12} level or better)

turn key rep-rated laser with high reliability
(same as for cyclotrons or synchrotrons)

PW pulses must be extremely ‘Clean’ => Develop Pulse ‘Cleaning’ Techniques

*** Olympiaturm modification of R. Marjoribank’s example using Toronto’s CN Tower*



* *J. Schreiber et al RSI **87**, 071101 (2016)*

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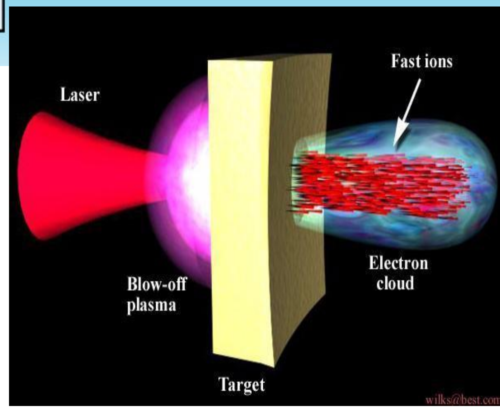
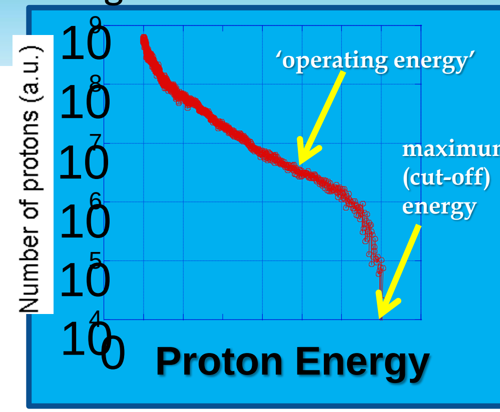
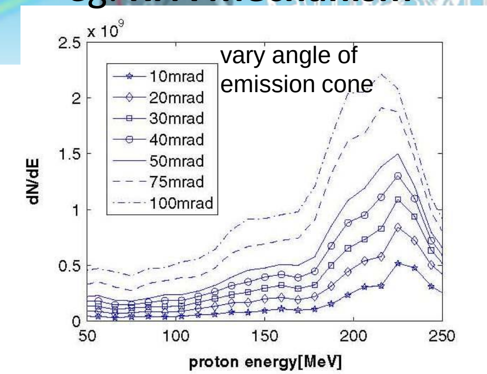
Single Pulse Laser-plasma interaction at Target Site is an Ultrafast Extreme Field Interaction



eg. **TNSA Mechanism**



eg. **RPA Mechanism** **



400 nm H target; I_{laser}= 3x 10^{21} W/cm; 10 PW / 66 fsec

Current Effort:

typically very low repetition-rate (single shot in most very high power cases)

focus on physics (and scaling) of laser-plasma interactions and energetic particle/photon yields

address single shot capabilities – what is possible with given target/intensity

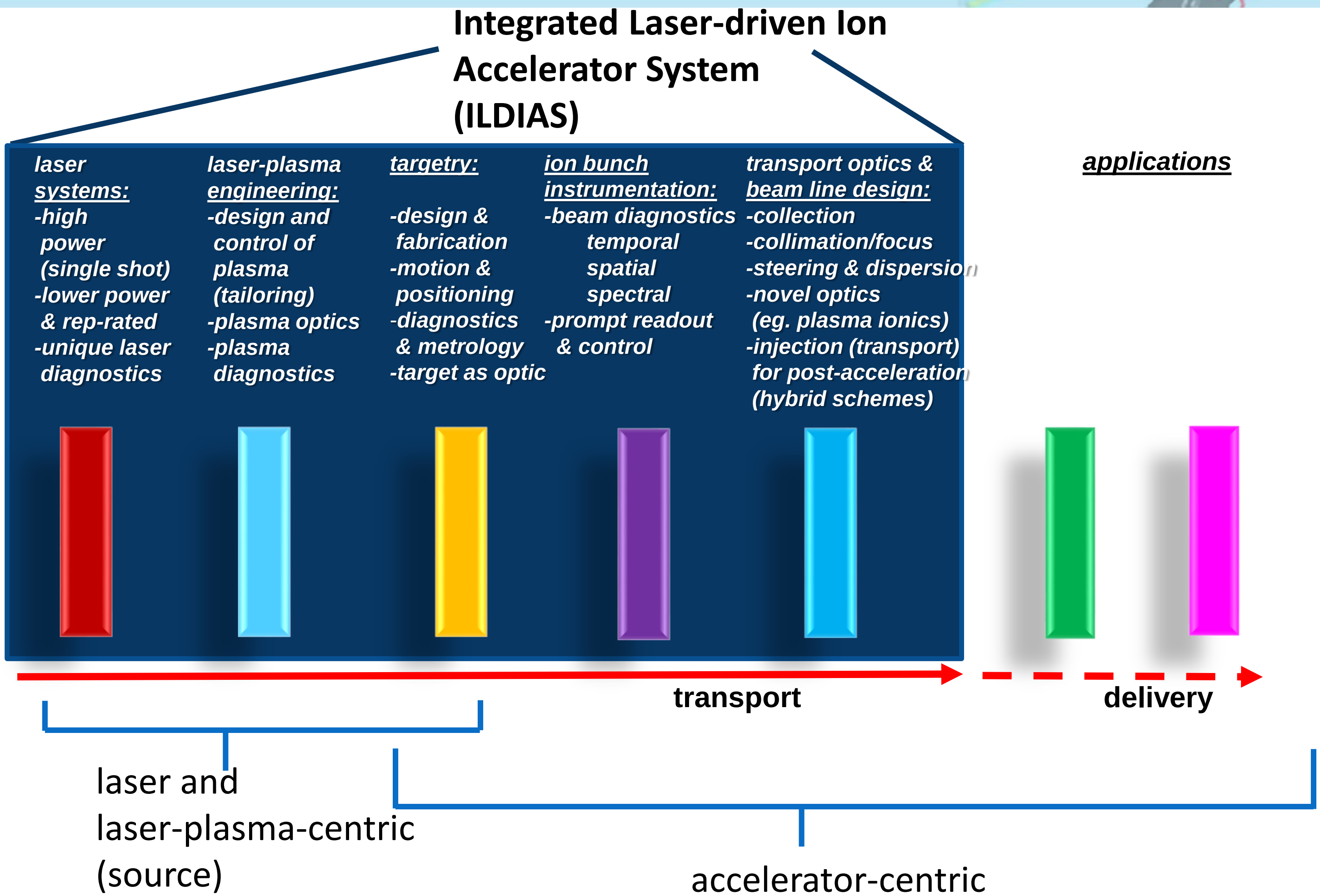
these are effectively studies of candidate <u>sources</u> for laser-driven accelerators (where we define <u>source</u> to be 'laser + target + laser-plasma')

LIBRT demands machines of medical accelerator quality and we must therefore develop the 'integrated laser-driven ion accelerator system (ILDIAS)' operating at a judicious 'operation energy'

=> accelerator innovation with lasers continues …

*** I. Hofmann et al., Phys Rev. STAB <u>14</u>, 031304 (2011*

LIBRT Requires Sophisticated 'MACHINE' Development *:
ILDIAS is an Accelerator Advancement (not a Replacement)



* P.R. Bolton NIM ***A809***, 149 (2016)

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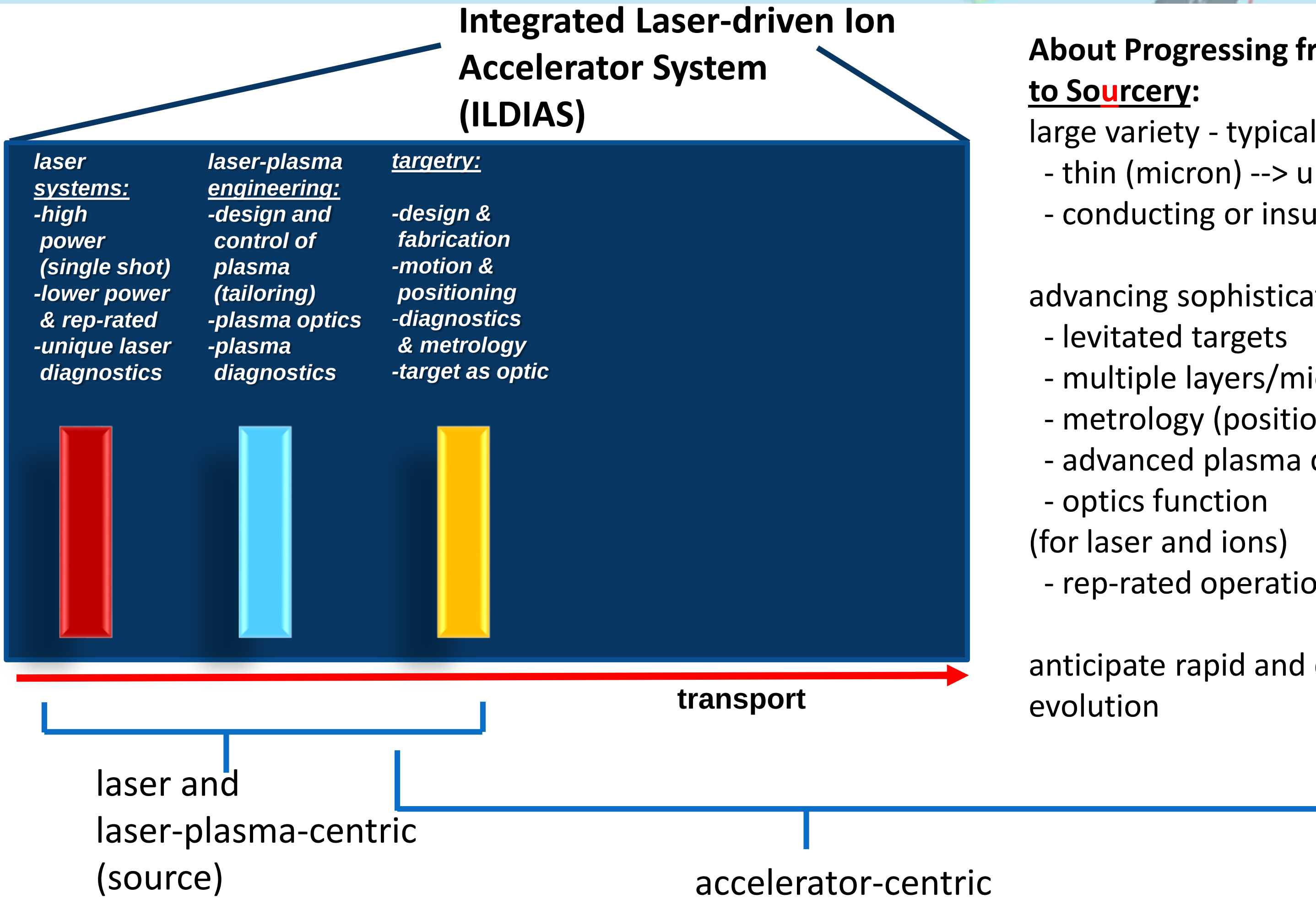
Components of the ILDIAS Source:



About Progressing from Targetry to Sourcery:

large variety - typically thin foil
- thin (micron) --> ultrathin (nm)
- conducting or insulating

advancing sophistication
- levitated targets
- multiple layers/microstructures
- metrology (positioning, state)
- advanced plasma diagnostics
- optics function

(for laser and ions)
- rep-rated operation is essential

anticipate rapid and diverse evolution

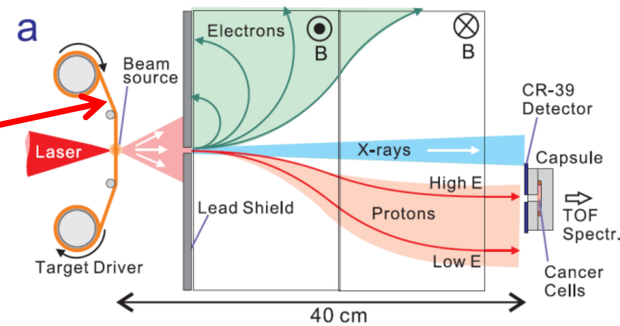
"Workshop on Innovative Delivery Systems in Particle Therapy" 23-25 February 2017; Molecular Biotechnology Centre, University of Torino and CNAO National Centre of Oncological Hadrontherapy, Pavia

Evolving Diversity for Targets:

(i) Rep-rated Operation with Tape on a Reel *

Moving Tape Targets *

a thin tape target on a reel (6-13 micron thickness) has capability for 1 Hz operation *



Laser energy: 0.6 J @ 1 Hz
Duration: 35 fs (FWHM)
Intensity: 5×10^{19} W/cm^2

10^{10} bunch charge (>1MeV)

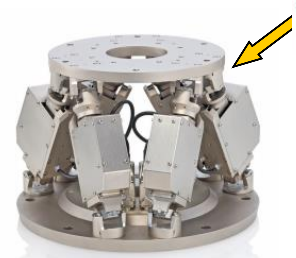
irradiation level ~ 10^3 /ns mm^2
~ 15 ns bunch duration (0.8 – 2.4 MeV)
integrated dose ~ 20 Gy (200 laser shots)

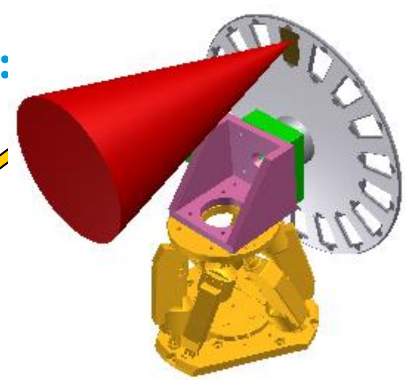
A. Yogo et al., Appl. Phys. Lett. 94, 181502

(ii) Automated Target Wheel for Rep-rated Operation at LMU **

System Components:

- 1000 targets
- automated
- positioning

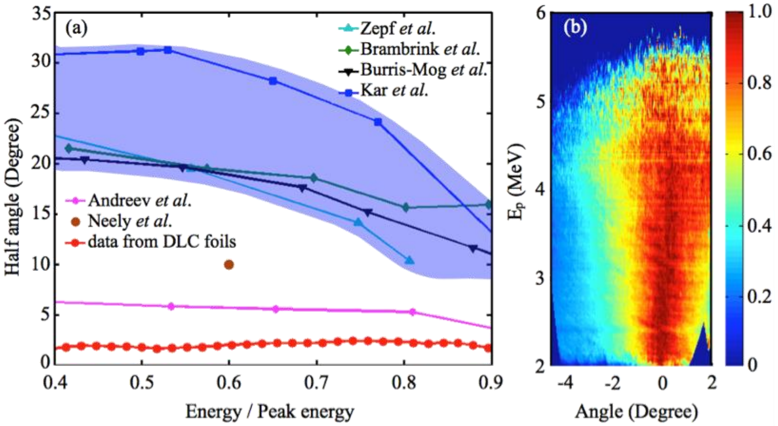




*** courtesy of J. Schreiber and Y. Gao*

Sophisticated Targetry Studies at LMU (Schreiber Group): Ultrathin and Multi-layered Target Yields

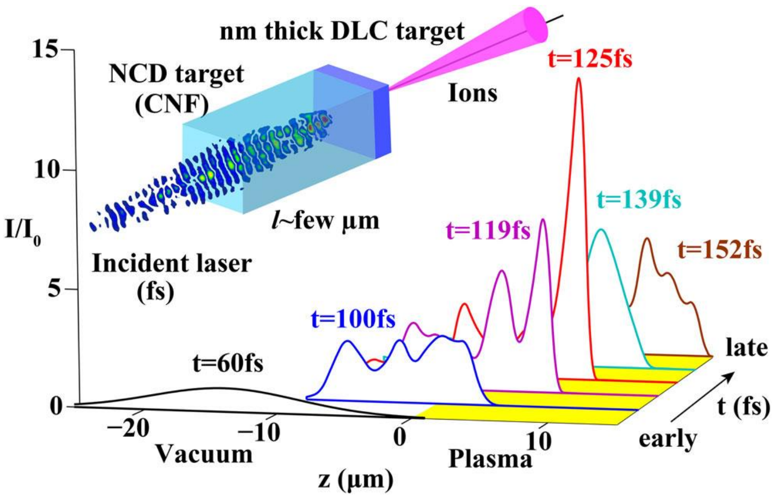
ultrathin diamond-like carbon (DLC) *



(ultrathin (nm scale) targets noticeably reduce angular divergence of ion emission)

* J. Bin et al. Physics of Plasmas **20**, 073113 (2013)

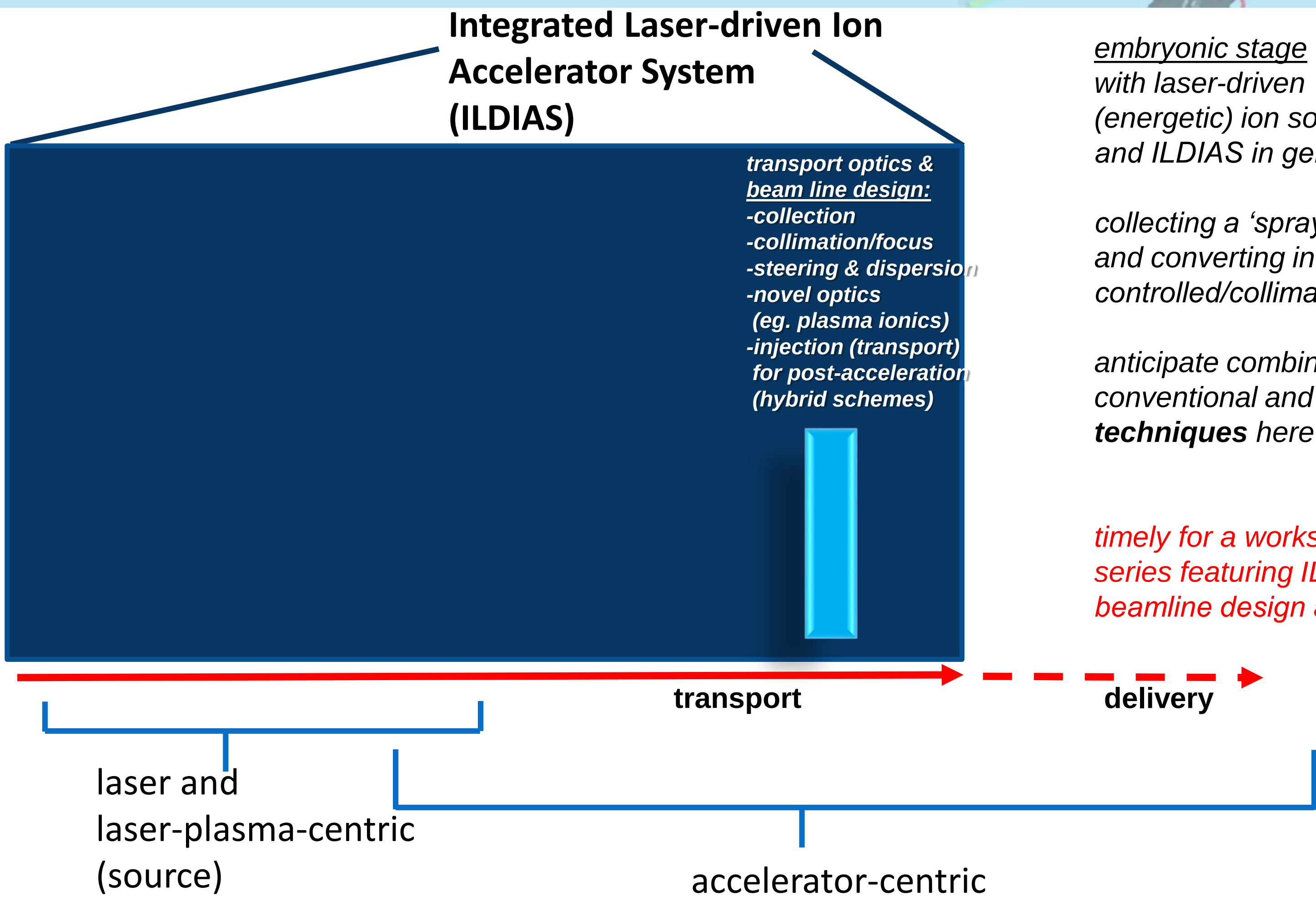
Carbon Nanofoam + DLC **



(application of plasma photonics – i.e. laser optic where result is maximum ion energy increase with foam thickness)

*** J. Bin et al. Phys. Rev.Lett. **115**, 064801 (2015)*

Beam Line Optics: Embryonic Stage



<u>embryonic stage</u> with laser-driven (energetic) ion sources and ILDIAS in general …

collecting a 'spray' and converting into a controlled/collimated 'beam'

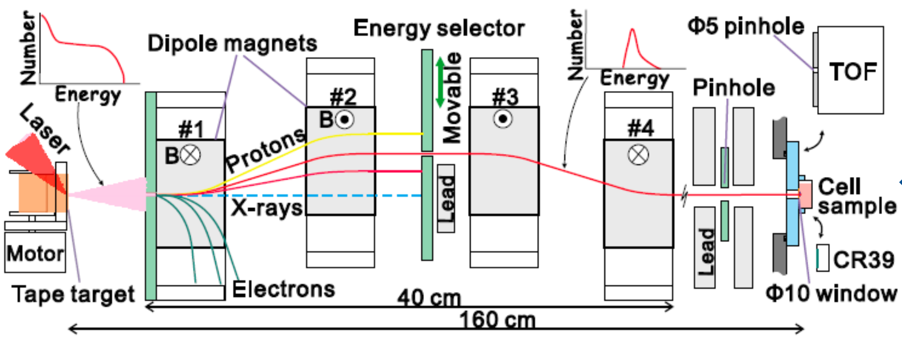
*anticipate combination of conventional and **novel techniques** here*

timely for a workshop series featuring ILDIAS beamline design and optics …

"Workshop on Innovative Delivery Systems in Particle Therapy" 23-25 February 2017; Molecular Biotechnology Centre, University of Torino and CNAO National Centre of Oncological Hadrontherapy, Pavia

Conventional Optics (Quad and Chicanes are Easier but Less Efficient)

*The Chicane with a (mid-plane) 'Tuning' Aperture**



4 MeV protons @ 1 Hz (30 % energy spread)

- 0.8 T magnets
- 5 mm tuning aperture
- deliver $5\text{x}10^5$ protons per laser shot to DNA DSB experiment (0.2 Gy)
- poor transmission (inefficient)

* *Yogo et al APL **98**, 053701 (2011) & system proposed by C.-Ma Laser Phys.16,639(2006)*

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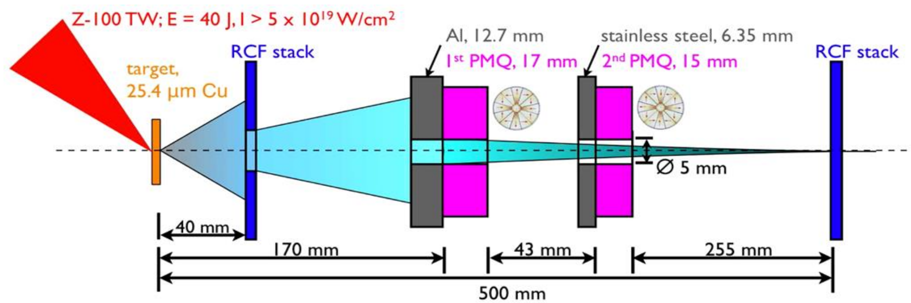
14 MeV protons @ single shot

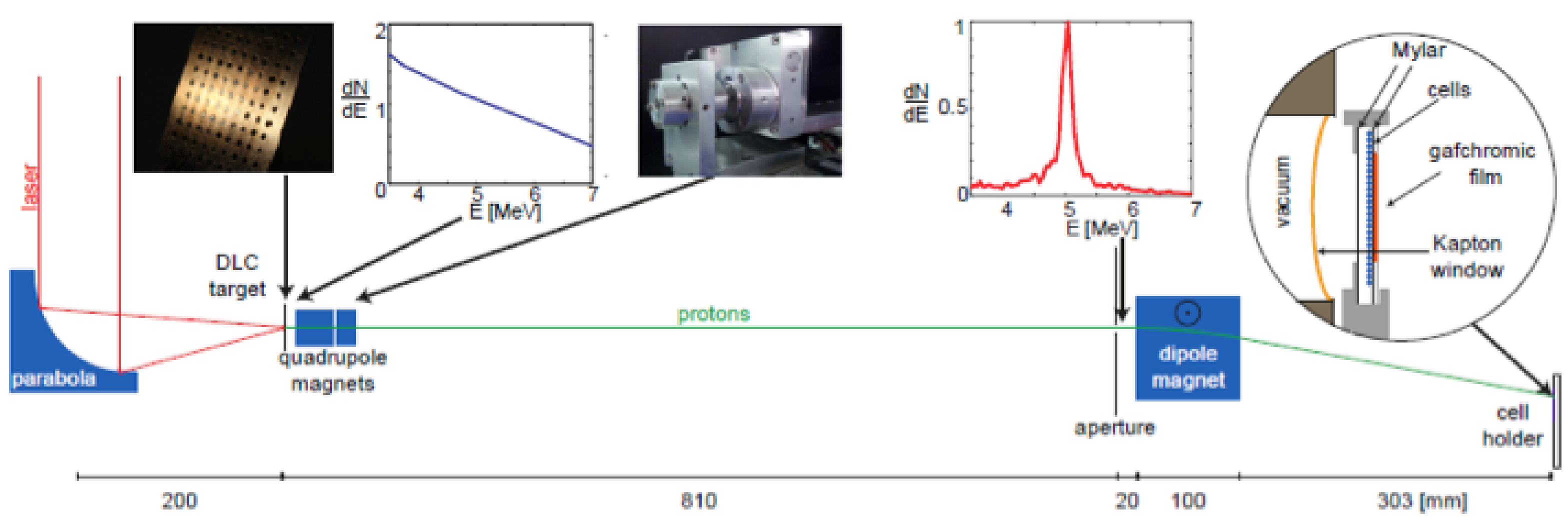
- 500 T/m quad gradient
- focus to ~ 170 micron diameter
- spatial filtering potential
- deliver ~ 10^6 protons per laser shot
- poor transmission (0.1 % for magnets and only 0.01 % from source)

*Miniature PMQ Pair ***



*** M. Schollmeier er al., PRL 101, 055004 (2008) – single-shot results at 14 MeV*

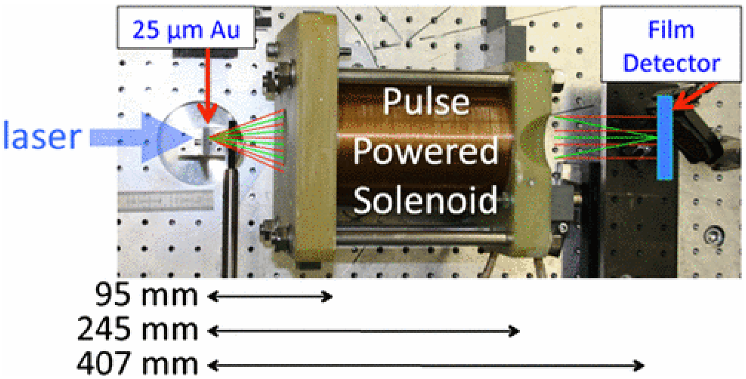
*Miniature Quadrupole Magnets (PMQs) Used to Demonstrate a laser-driven nanosecond proton source for radiobiological studies at LMU **



* courtesy of J. Schreiber and J. Bin et al Appl. Phys. Lett. ***101***, 243701 (2012)

Novel Optics: Pulsed Large Aperture High Field Solenoid and Laser-driven Microplasma Lens

*Pulsed High Field Solenoid **

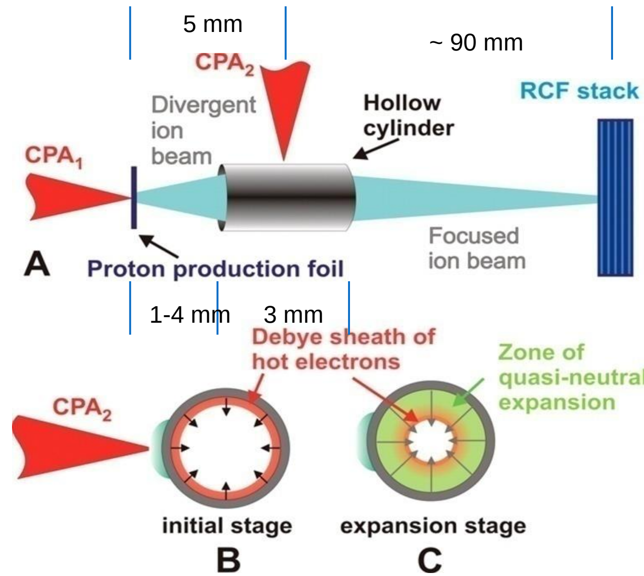


** T. Burris-Mog et al.Phy Rev STAB **14**,121301 (2011)*

*and K. Harres et al., Phys of Plasmas **17**, 023107 (2010)*

- pulsed excitation current to high field (~ 7 - 9 T)
- low loss (transmission through unit is high, 10's %)
- ~ 5 cm bore means can accept large divergence
- handle high peak current
- rep-rate can be a challenge

*Laser-driven Microplasma Lens ***



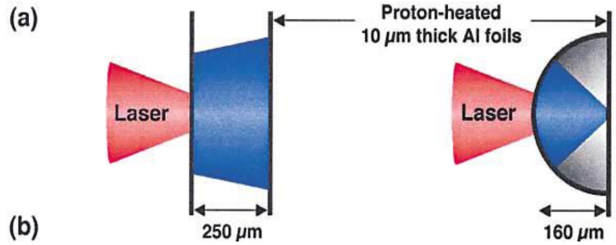
*** Toncian et al., Science <u>**312**</u> [5772], 410 (2006).*

Focus and Filter Functions (plasma ionics):

- **time-dependent focusing**
  ~ 10 psec dynamics
  & can be synchronized
- **small acceptance**
- **suitable for high proton energy and high peak current**

Novel Optics: Target Shaping – Target as Ion Optic

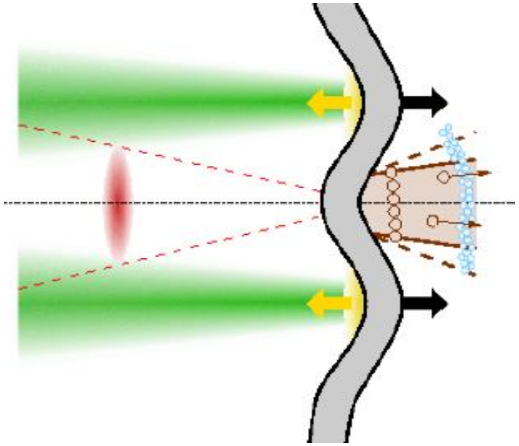
*Ballistic Focusing with Curved Targets (Sources): Source as Optic *, ****



- demonstrated at JANUSP (LLNL)*: ~ $5x10^{18}$ W/cm^2 in 100 fsec (~ 100 nC bunches)
- 1-2 % efficiency

**K. Patel et al PRL 91, 125004 (2003)*

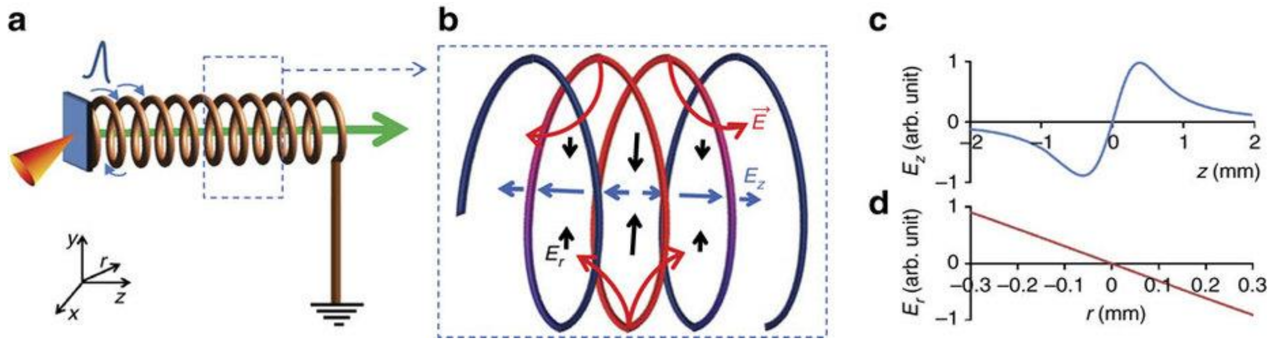
Laser-driven shockwave shaping of the target rear surface (i.e. double pulsing) ***



**** O. Lundh et al APL 92, 011504 (2008).*
D. Carrol, Coulomb'09 - June 2009, Senigallia, Italy.
K. Zeil et al., NJP 12, 045015 (2010).

Helical Coil Target: Ion Optic, Energy Filter and All-optical Post-acceleration

*target: 10 micron Au foil + 100 micron Al wire **



EM pulse propagates in wire at ~ 0.96 c

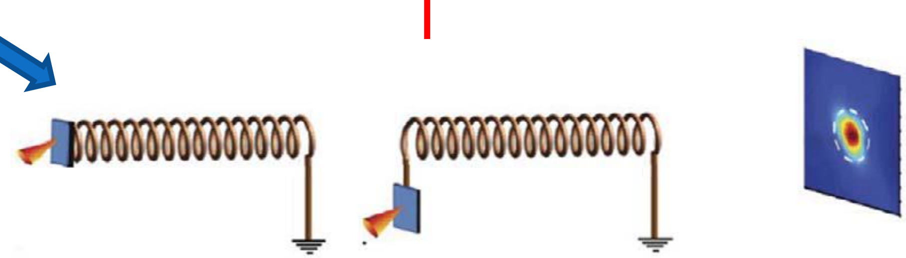
proton acceleration gradient ~ 0.5 GeV/m
(can increase with higher laser intensity)

all-optical post-acceleration, energy selection and focusing

overall collection efficiency ~ 7 %

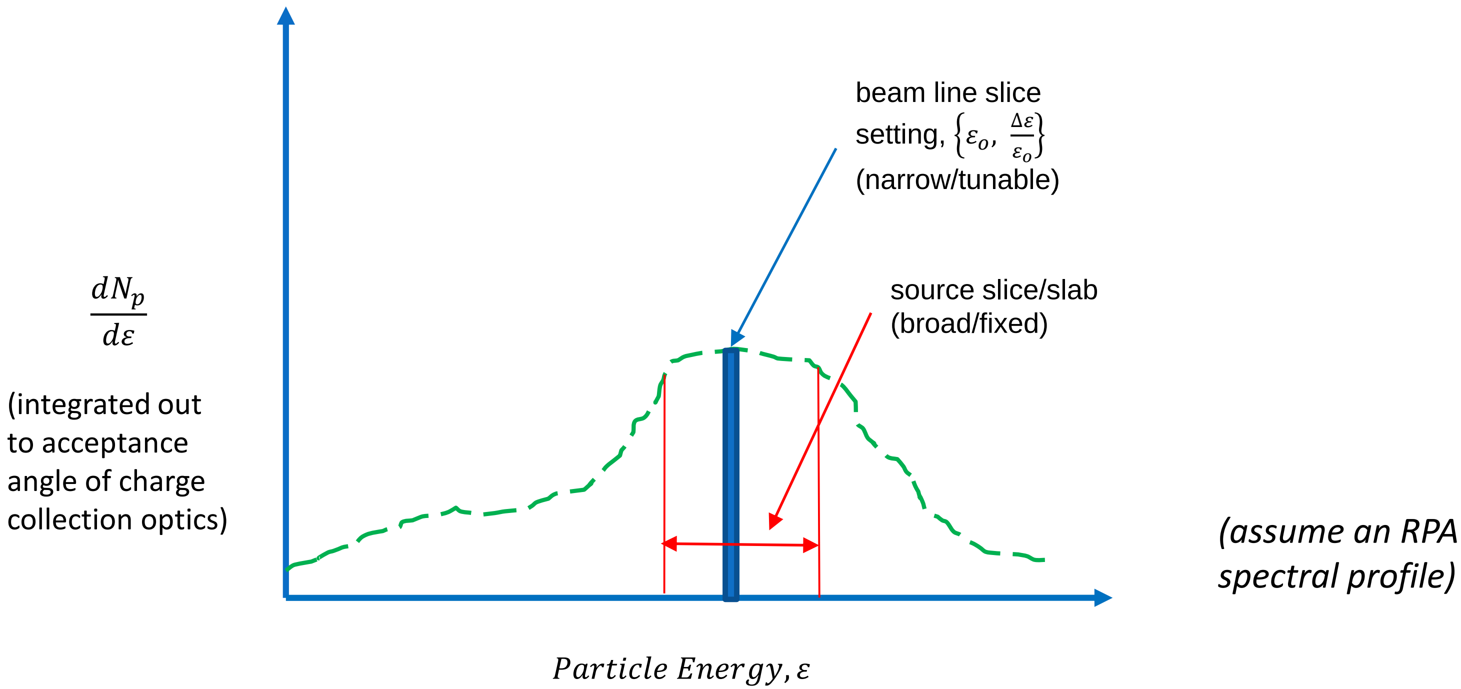
potential for 'staging'

In general: ILDIAS exhibits notable potential for innovative targetry, Instrumentation and beam optics/beam line design



* *S.Kar et al Nat. Comm.* ***7****, 10792 (2016).*

First Implementation of Ion Energy Control: Emitted Spectrum from Target is Repeated with Each Pulse



(use beam line optics to adjust/tune the nominal energy and energy spread and not the laser intensity)

** P.R. Bolton NIM **A809**, 149 (2016)*

Impressive Recent Commercial Development: Sources Rapidly Becoming More Compact and Cheaper (not yet with lasers)

newest cyclotrons compatible with single room treatment and gantry embedment (MEVION)

IBA S2C2 (SC synchro-cyclotron)	250 MeV p	<50 ton	2.5 m pole dia.	1 KHz modulation (rep) (RF varied 63-93 MHz) (10 microsecond pulses) **6-7 Tesla B field**

"Part IV: The Superconducting Cyclotron Project S2C2"

(https://indico.cern.ch/event/286275/contributions/214/attachments/531390/73)

MEVION S250 (SC synchro-cyclotron); (single room; gantry mounted source; cost ~ $30 M)	250 MeV p	17 ton	1.8 m pole dia.	500 Hz modulation rate **8.5 Tesla B field**

More to Come - rapid commercial development => relative assessments for laser-case must be ongoing/updated frequently

PW lasers are huge and costly; so, ILDIAS developments are not competitive with recent commercial developments (wrt size/cost/reliability/operability)

However, ILDIAS can bring unique innovations/enhancements/novel concepts to accelerator development in the near-to-intermediate future (for a variety of milestone applications) …

Distinguishing ‘machine’ and ‘application’

LIBRT application clearly remains a very long term endeavor (distant aspiration) for which strategies must emphasize **unique laser capability** and not replication …(distant => decades)

Nonetheless, a few labs are seriously exploring LIBRT

examples of other key EU/UK programmes: onCOOPtics
ELIMED
A-SAIL

A-SAIL - “Advanced Strategies for Accelerating Ions with Lasers”

at *Queen’s University, Belfast (PI- Marco Borghesi),*
Rutherford Appleton Laboratory (RAL),
Imperial College, London,
University of Strathclyde

(for A-SAIL --> https://www.qub.ac.uk/research-centres/A-SAILProject/)

Start Year (duration) – 2013 (6 years)

Funding level - 4.5 Mpounds (from Engineering and Physical Sciences Research Council, EPSRC)

General Goal(s) – focus on researching science and technologies needed for LIBRT (all-optical);

Notable feature(s) – basically ILDIAS development (same components); no dedicated laser facility; this also includes a strong radiation biology component that steers the agenda

Seriousness - science & technology aimed explicitly at guiding LIBRT development as part of innovative healthcare technology for the future

ELI-MED and ELIMAIA: *ELI-Beamlines, Prague*

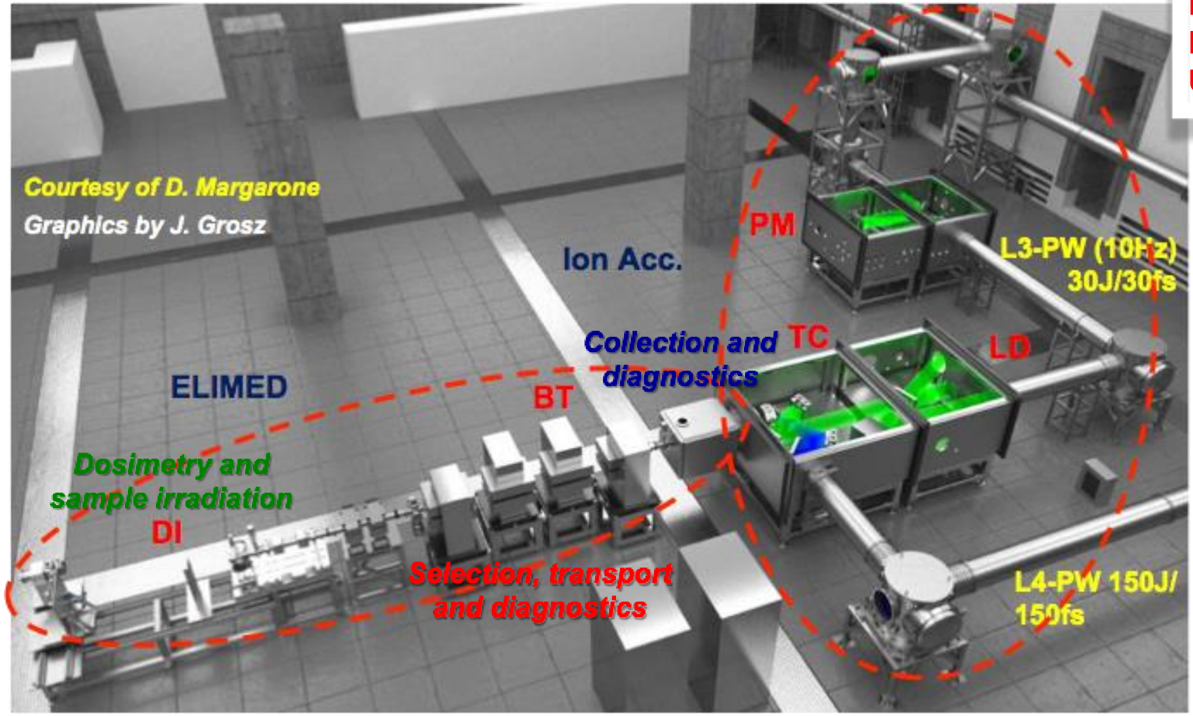
ELIMAIA hall and the ELIMED beamline

ELI Multidisciplinary **A**pplications of laser-**I**on **A**cceleration = user programme

ELI MEDical and multidisciplinary applications = applications beamline (i.e. part of ELIMAIA)

Flexible
Protons and ions transpo
Installations: within 2017
Users' addressed

Experimental Hall 4



Project Leader
Dr GAP Cirrone,
pablo.cirrone@lns.infn.it

3. Research project onCOOPtics

oncooptics

TECHNISCHE UNIVERSITÄT DRESDEN

University Hospital Carl Gustav Carus Dresden

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

OncoRay + ultra optics

IOQ Jena

Friedrich Schiller University of Jena

Fraunhofer Institute for Applied Optics and Precision Engineering

IOF

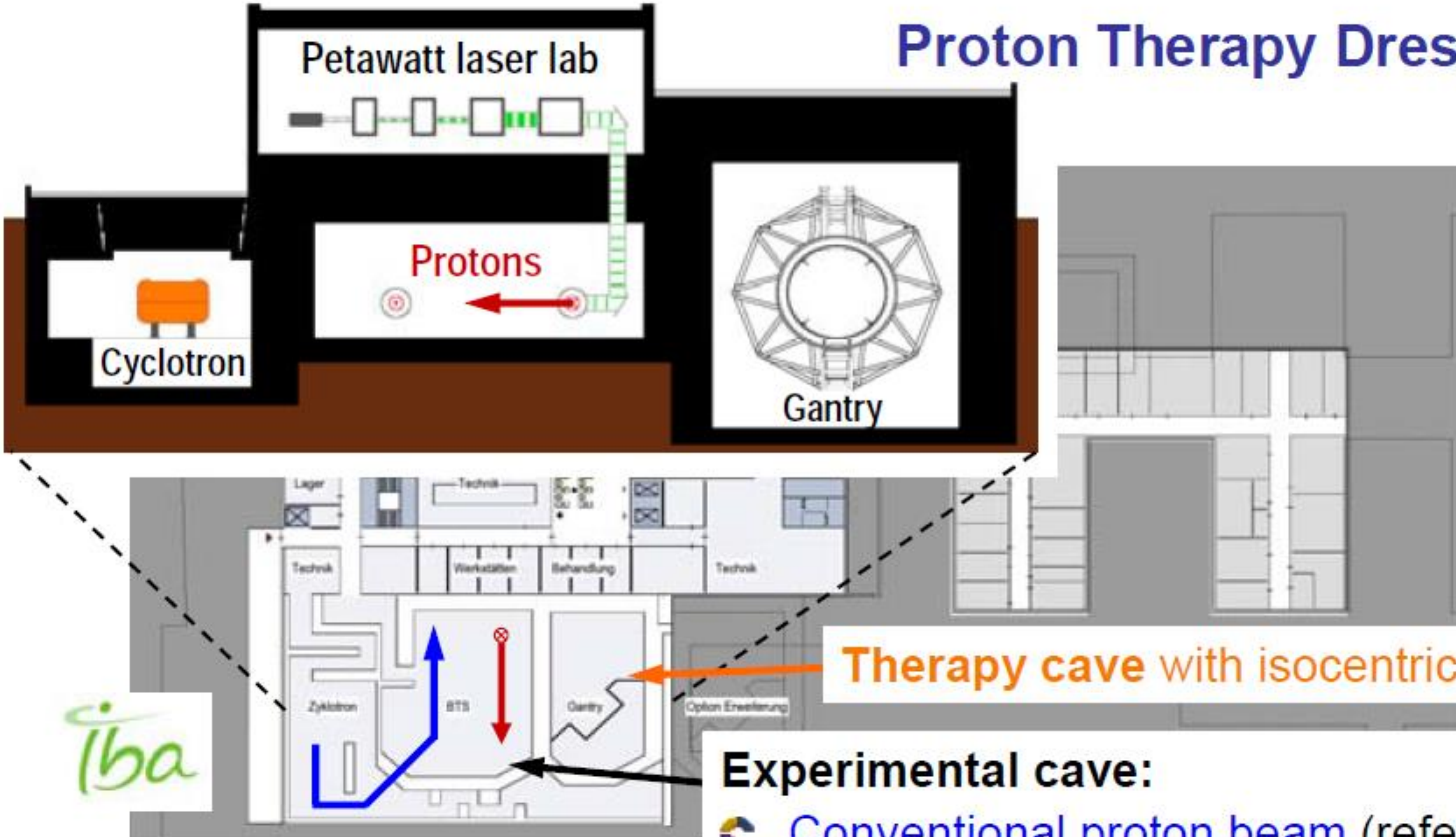
Supported by Bundesministerium für Bildung und Forschung

2007-2012, 11.5 Mill. €
(grant no. 03ZIK445)

2012-2017, 6.7 Mill. €
(grant no. 03Z1N511)

5. Towards preclinical prototype

Proton Therapy Dresden



Therapy cave with isocentric gantry

Experimental cave:

- Conventional proton beam (reference)
- Laser-driven protons (prototype system)

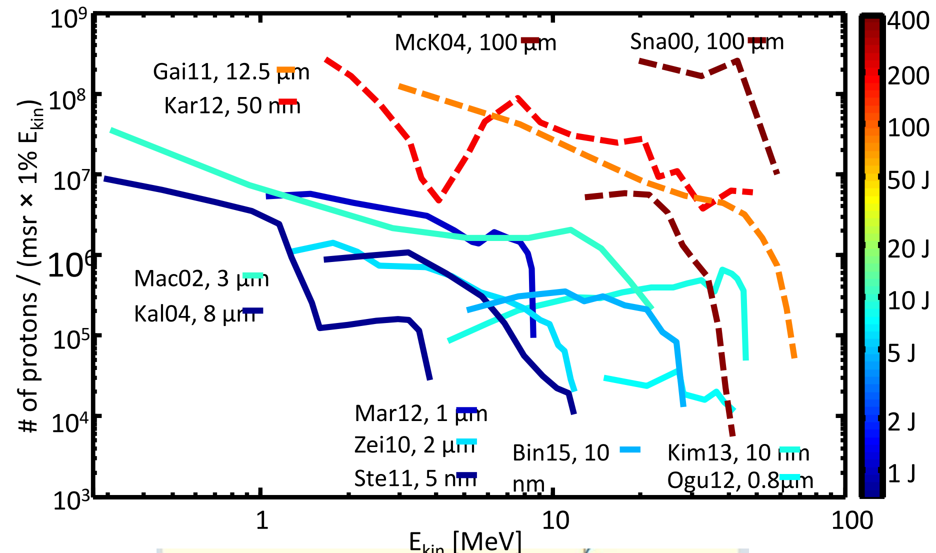
⇨ ***Integrating prototype laser accelerator into clinical setting***

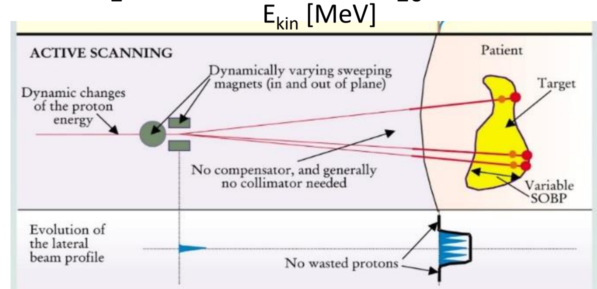
The basis for considering laser-driven ion beam radiotherapy (LIBRT) is low emittance, energetic particle yields from intense laser-plasma interactions *

1 Gy Dose to 1 Litre Tumour in 100 Seconds

total number of protons for full tumor volume	*$5x10^{11}$*
<u>average</u> proton delivery rate	*$5x10^{9}$/second*
(~ 1 nanoampere cw – already provided by existing accelerators)	
number or protons per voxel (relevant to active scanning mode) (1000 voxels; 1 voxel = 1 cm^3)	*$5x10^{8}$/voxel*
number of treated voxels/second	*10*
number of protons /bunch (1 ion bunch per laser pulse)	*$5x10^{8}$/bunch (at tumor)*
number of bunches per voxel (for 1 Gy this means no repainting @ 10 Hz and single bunch dose must be very well controlled)	*1*

Protons at target:



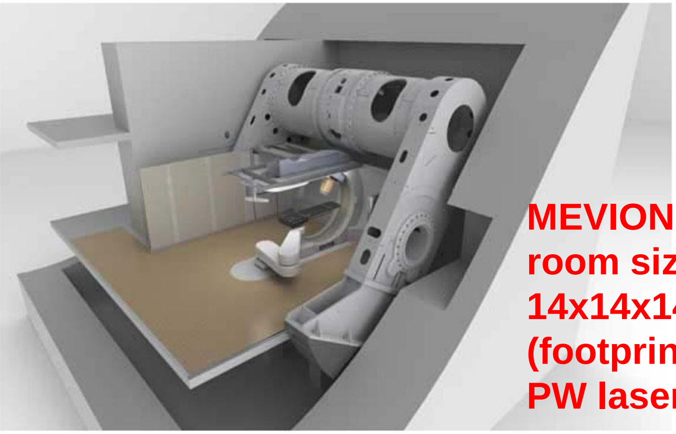


* *J. Schreiber et al RSI **87**, 071101 (2016)*

(example: for 30 degree full divergence => ~ 200 msr solid angle => need large acceptance 'collection' optics and highly efficient beam handling between source and tumor)

What needs to happen with laser-driven sources for LIBRT to become feasible (in a Replication Strategy) ?

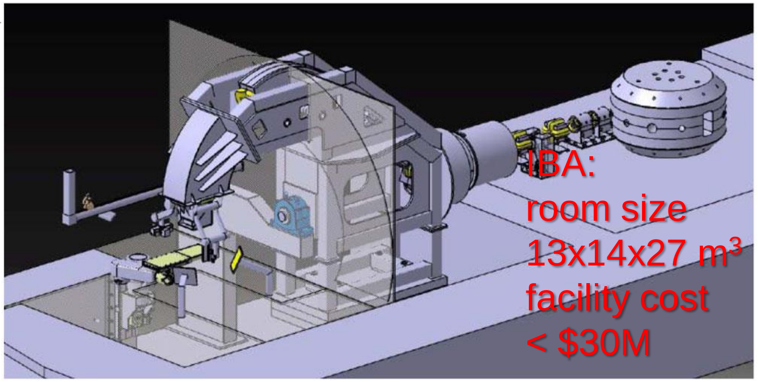
increase maximum ion energies to ~ 350 - 400 MeV/nucleon *
(assume TNSA-like spectral profile)



reduce & stabilize energy spread and nominal energy control

bunch charge (or # protons/bunch) yield:
stabilize and increase by orders of magnitude
(IBRT requires 3-5 % dose accuracy)

cost/size must be greatly reduced (competitive with cyclotron ?)



source stability/control - greatly enhanced =>
new instrumentation/diagnostics

ease of operation (turn–key)/uptime/reliability:
comparable to conventional sources

With a Replication Strategy - future LIBRT would need to compete with even further advanced (conventional) IBRT for which compact superconducting cyclotrons will likely be embedded into a compact superconducting gantry

(for latest assessment of laser-driven feasibility see Linz and Alonso Phys. Rev. Accel. & Beams **19**, 124802 (2016))*

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Dose of Reality and Strategic Guidance
- *some key points (also lessons learned)*

Distinguish laser-driven machine (ILDIAS) development as an Accelerator Frontier
distinct from applications (such as LIBRT):

Focus on unique capabilities of laser-driven case for ILDIAS
and separably for diverse applications (nonmedical and medical)

ILDIAS R&D for increasing ion energy needs at least two parallel paths:
directly confront accelerator challenge

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distinct from applications (such as LIBRT):
- LIBRT is a distant aspiration but we can expect near-medium term ILDIAS beam development for other uses
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- about developing laser-driven accelerator quality machines (more than just ion sprays)

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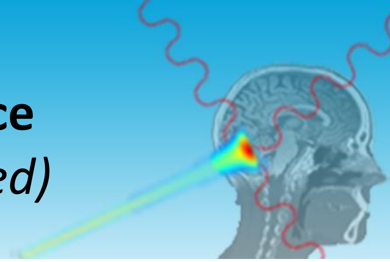

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  and comparisons must be frequent and ongoing given the rapid progress of conventional sources)
- in typical fashion, let the laser naturally afford developments that exploit unique features of laser-accelerati
  and can explore **possible application niches**
  (uniqueness => low emittance, short bunch duration, **multiple synchronous beams**)
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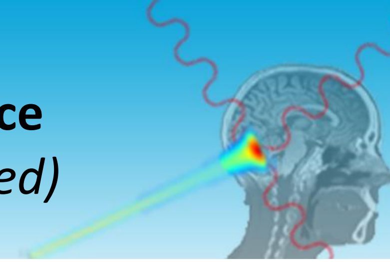

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ILDIAS R&D for increasing ion energy needs at least two parallel paths:
directly confront accelerator challenge
- (i) single shot (or low rep) capability - laser-plasma yields at highest laser intensities with 'tailored' pulses ar
  targets that explore relevant laser-plasma physics issues and their scaling
  (single shot laser-plasma yields to date are really studies of **candidate energetic sources** for ILDIAS)
- (ii) higher rep-rated ILDIAS development at reduced ion energies to demonstrate controlled beam line devel
  test bed for innovative components and some applications; ultimately about accelerator quality
  (i.e. beam line development optimized for 'operating' energies)

Dose of Reality and Strategic Guidance

- *more key points (also lessons learned)*

'En Route' Applications: pursue other applications - more doable and nearer term

LIBRT application: a distant aspiration that can motivate energetic ILDIAS development: avoid becoming 'fusionesque'

Dose of Reality and Strategic Guidance

- *more key points (also lessons learned)*

‘En Route’ Applications: pursue other applications - more doable and nearer term

- ILDIAS not limited to LIBRT and its progress will likely be marked by other milestone applications
- demonstration of more doable nearer term applications provides needed progress milestones to promote continued support
- some applications will require only the emergent ‘spray’ from laser targets
- encourage establishment of a user community to develop meaningful and doable applications in near term

LIBRT application: a distant aspiration that can motivate energetic ILDIAS development: avoid becoming ‘fusionesque’

Dose of Reality and Strategic Guidance

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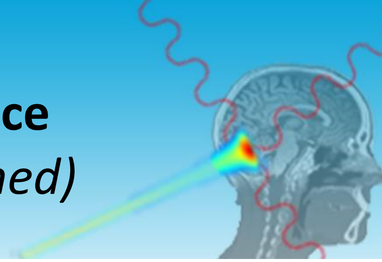

'En Route' Applications: pursue other applications - more doable and nearer term

LIBRT application: a distant aspiration that can motivate energetic ILDIAS development: avoid becoming 'fusionesque'

- **will need more intimate and leading engagement from physicians**
  (the "Field of Dreams" approach does not work – i.e. 'If you build it, they will come')
- LIBRT demands sustaining long term comprehensive multidisciplinary collaborations where end point practitioners (physicians) are intimately involved
- **parallel focus on laser-driven irradiation in radiobiological and ion impact studies**
- **identify exploitable unique features (what are they ?) of laser-driven case (no other justification)**

- most applications will be implemented at some operating energy and not the cutoff or maximum ion energy (for LIBRT, if the operating energy is 250 MeV then the maximum energy can be much higher)
- **establish a vision/consensus of initial implementation to clarify early meaningful goals**: not yet done
  - identify niche(s) and key minimal requirements
  - do we develop ion imaging/radiography in parallel ?
  - begin with small animal cases ? – then, focus on lower energy ILDIAS and lower power lasers (helps greatly because LIBRT will not operate at cutoff energies)
- **in a 'Replicative Strategy' duplicating conventional source features is not adequate** and
  we will likely need companion novel laser-driven instrumentation/diagnostics (i.e. multiple beams)
- remember, it took decades to get from x-ray imaging to x-ray therapy and decades for IBRT to get where
  it is now !

Forum for Exchange and Highlighting/Tracking ILDIAS Development: Started with Targetry Workshop Series: a Focus on ILDIA Sources

(Garching, October 2013
see http://www.med.physik.uni-muenchen.de/laser acceleration/targetry-workshop/index.html)

(Paris, April 2015
see http://www.targ2plasma.com/

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ILDIAS Requires Global Scale Multidisciplinary Collaborations/Consortia/Users: Demands Regular International Forum for Exchange and Highlighting New Developments/ Ideas

ILDIAS meetings/documentation: adopt accelerator mindset, move beyond the setting of laser-plasma experiment, establish interested community of users

- **instrumentation workshops** (Abingdon 2010, Paris 2012 and Garching 2015)
- **targetry workshops** (Targ1 in Garching 2013 and Targ2 in Paris 2015)

- the **third Targetry workshop, Targ3** will happen Salamanca during June 21-23, 2017

- **now need regular meetings for highlighting beam line design and beam line optics**

- I suggest cyclically combining the above 3 workshop types **(targetry, instrumentation, ion optics)** to more fully highlight/document ILDIAS development (ideally with a common website for open access to all workshop material)

- new Quantum Beam Science journal (QuBS from MDPI)) will feature a special issue dedicated to ILDIAS

Thank you …