Laser acceleration ond applications

I. Hofmann, GSI - HIJena

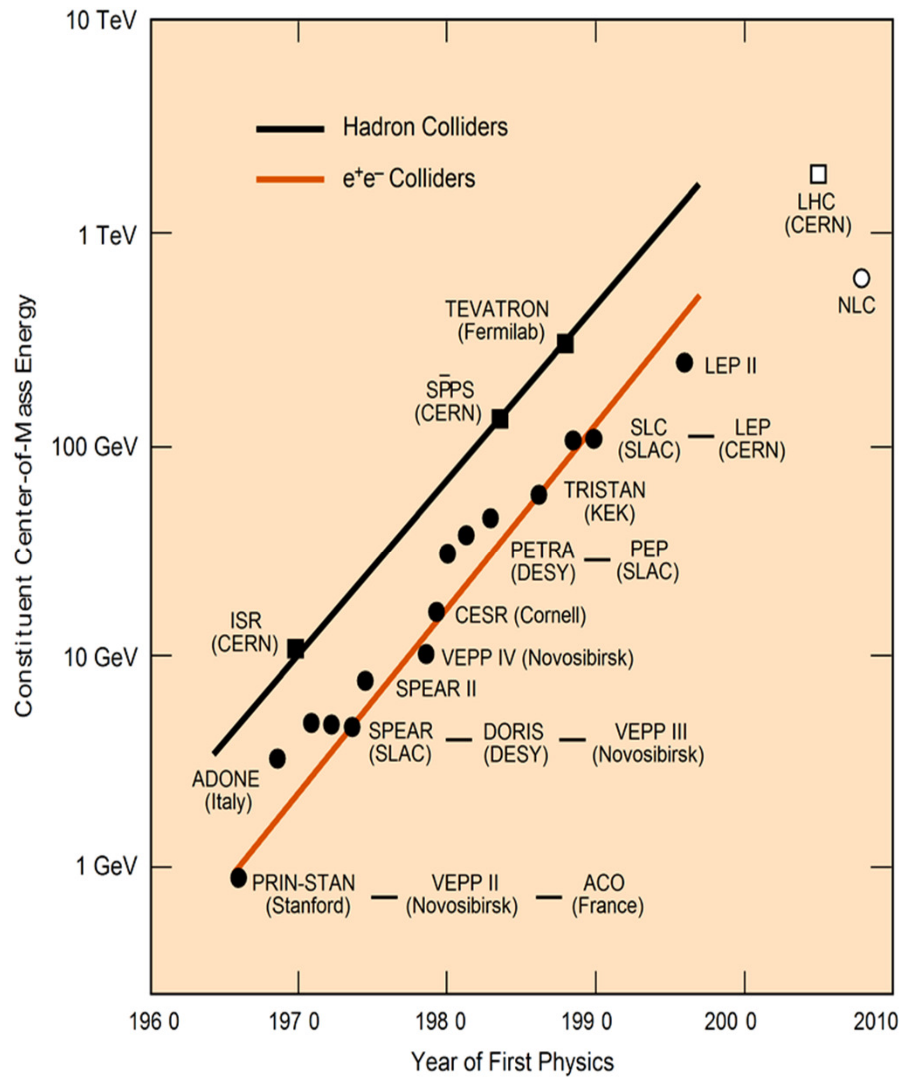
517th Heraeus-Seminar 18 October 2012

1. Laser Acceleration – overview
2. Applications for electrons
3. Laser protons acceleration
4. Therapy application
5. Actual developments
6. Conclusions

Where are accelerators today?

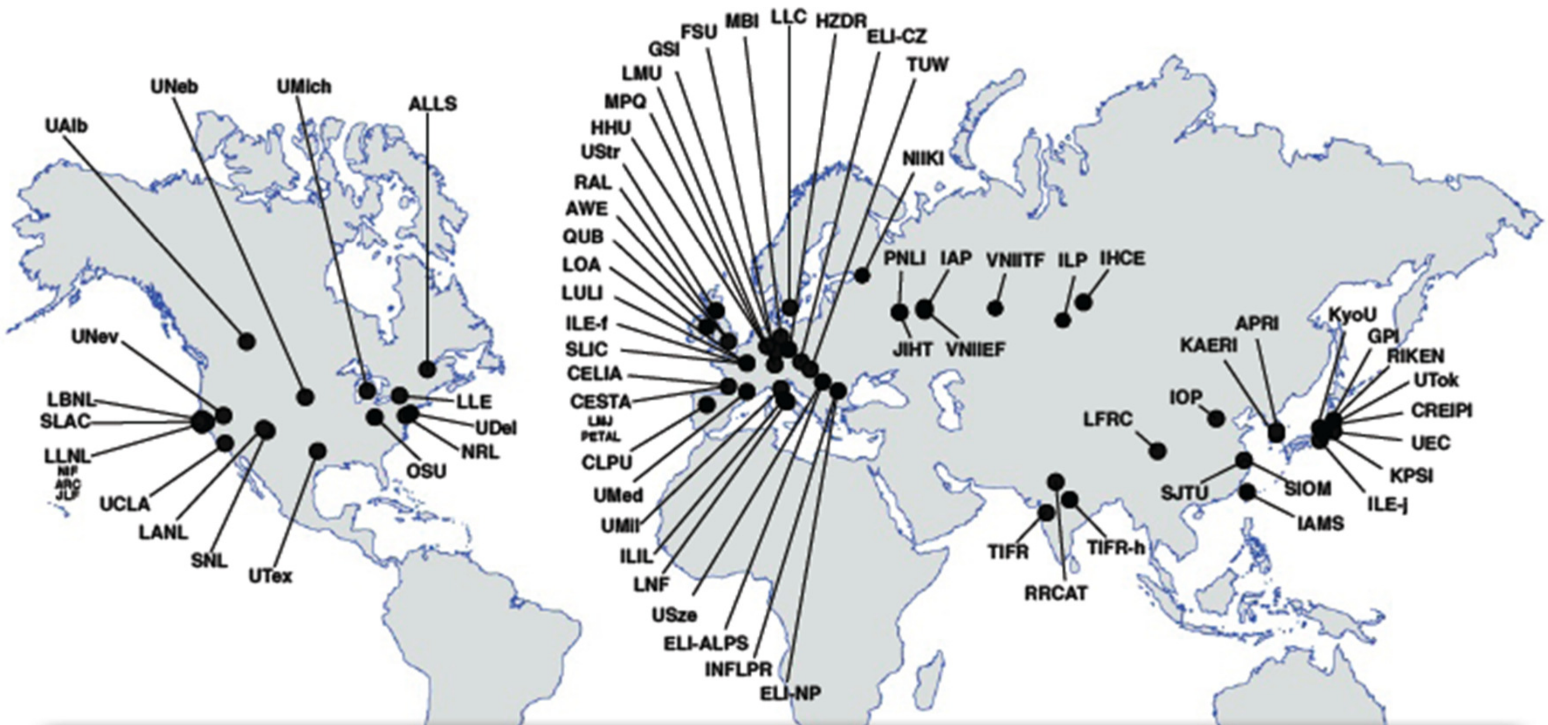
~26.000 accelerators worldwide

– ~ 44% are for radiotherapy,
– ~ 41% for ion implantation,
– ~ 9% for industrial processing and research,
– ~ 4% for biomedical and other low-energy research,
– ~ 1% with energies > 1 GeV for science and research



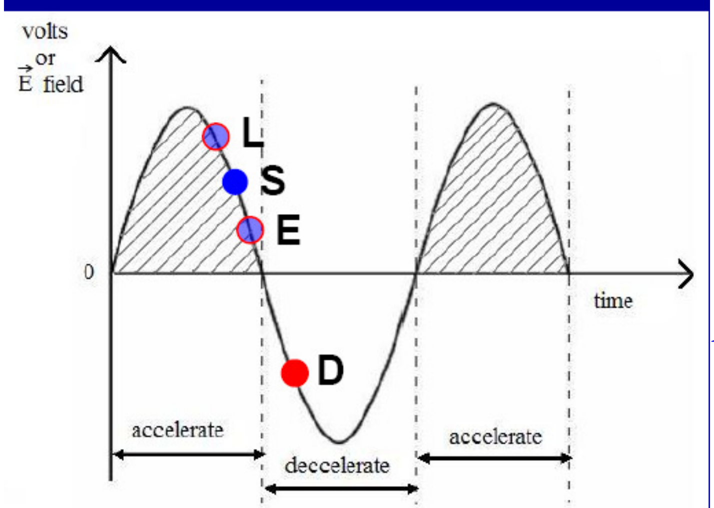
2010 ICUIL World Map of Ultrahigh Intensity Laser Capabilities

IZEST constituency resides in UHIL community



- the total peak power of all the CPA systems operating today is ~11.5 PW
- by the end of 2015 planned CPA projects will bring the total to ~127 PWs
- these CPA projects represent ~$4.3B of effort by ~1600 people (no NIF or LMJ)
- these estimates do not include Exawatt scale projects currently being planned

Laser acceleration – the idea



- In conventional RF cavities fields < 100 MeV/m for 10 GHz RF
- Much higher fields not tolerable
- But lasers in vacuum or in plasmas (no breakdown!)
- → plasma waves for acceleration
  - 1979: Tajima and Dawson predicted GeV/cm in plasmas of 10^{18} cm^{-3} using lasers of $>10^{18}$ W/cm^2

Amplitude of the transverse electric field of linearly polarized laser:

$$E_L[\mathrm{TV/m}] = \frac{m_e c^2 k}{e} a_0 \cong 3.21 \frac{a_0}{\lambda[\mu\mathrm{m}]} \cong 2.7 \times 10^{-9} I^{1/2} \left[\mathrm{W/cm^2}\right]$$

→ I =1×10^{18} W/cm^2 gives E_L =2.7 TV/m

source: K. Nakajima, KEK

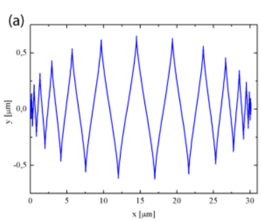
Lawson-Woodward Theorem

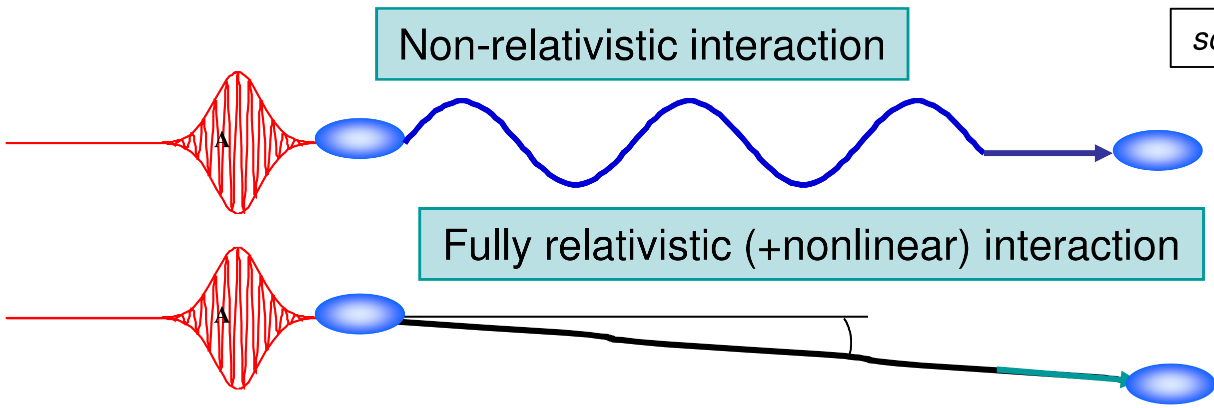
(J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979)

The net energy gain of a relativistic electron interacting with an electromagnetic field **in vacuum** is zero.

The theorem assumes that
(i) the laser field is in vacuum with no walls or boundaries present,
(ii) the electron is highly relativistic (v ≈ c) along the acceleration path,
(iii) no static electric or magnetic fields are present,
(iv) the region of interaction is infinite,
(v) **ponderomotive effects (nonlinear forces, e.g. v x B force) are neglected (electrons pushed towards lower laser density).**

source: K. Nakajima, KEK



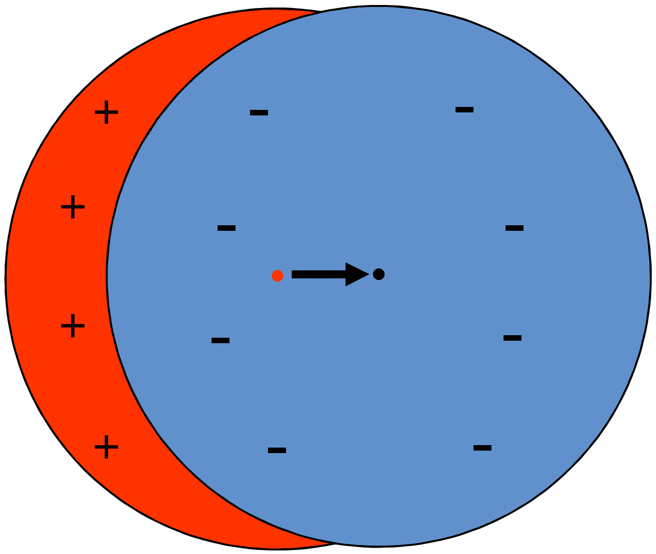


$$\Delta\gamma \approx 0$$

$$\Delta\gamma \approx a^2$$

Acceleration mechanism must violate the Lawson-Woodward theorem
- number of possibilities exist herefore (ponderomotive force, **plasma background** etc.)

Plasmas as carriers of electric fields



plasma frequency of oscillation
of e sphere against p sphere

Rule of thumb:

$n_e = 10^{10}$ cm^{-3} → ν_p = 1 GHz
→ conventional accelerator beam:
for **$n_e < 10^8$ cm^{-3} → ν_p < 100 MHz**
plasma frequency "negligible" or weak perturbation in high intensity

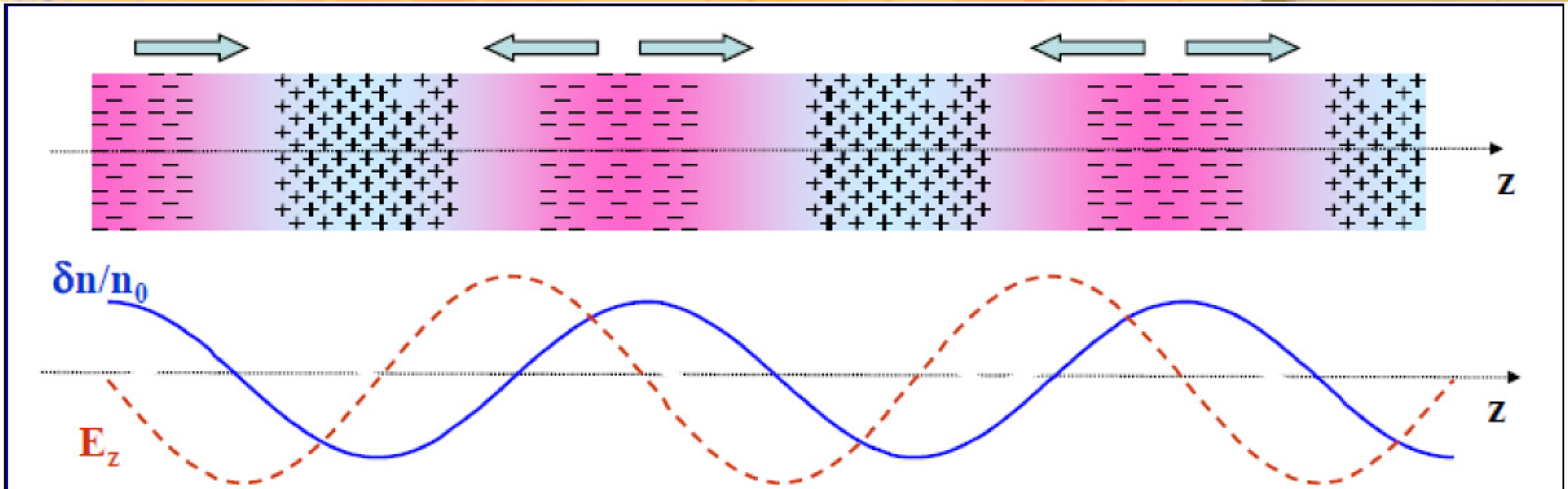
$$E_x = \frac{eN}{4\pi\varepsilon_0 R^3} x$$

$$\frac{d^2}{dt^2}\bar{x}_e = \frac{e^2 N}{4\pi\varepsilon_0 R^3 m}\bar{x}_e$$

⇒

$$\omega_p{}^2 = \frac{e^2 n_e}{3\varepsilon_0 m_e} \qquad \frac{1}{3} = 1\mathrm{D}$$

Plasma oscillations can sustain tremendous E-fields



Courtesy Jérôme Faure/LOA

$$\omega_p{}^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}$$

$n_e = 10^{10}\ cm^{-3} \rightarrow \nu_p = 1$ GHz

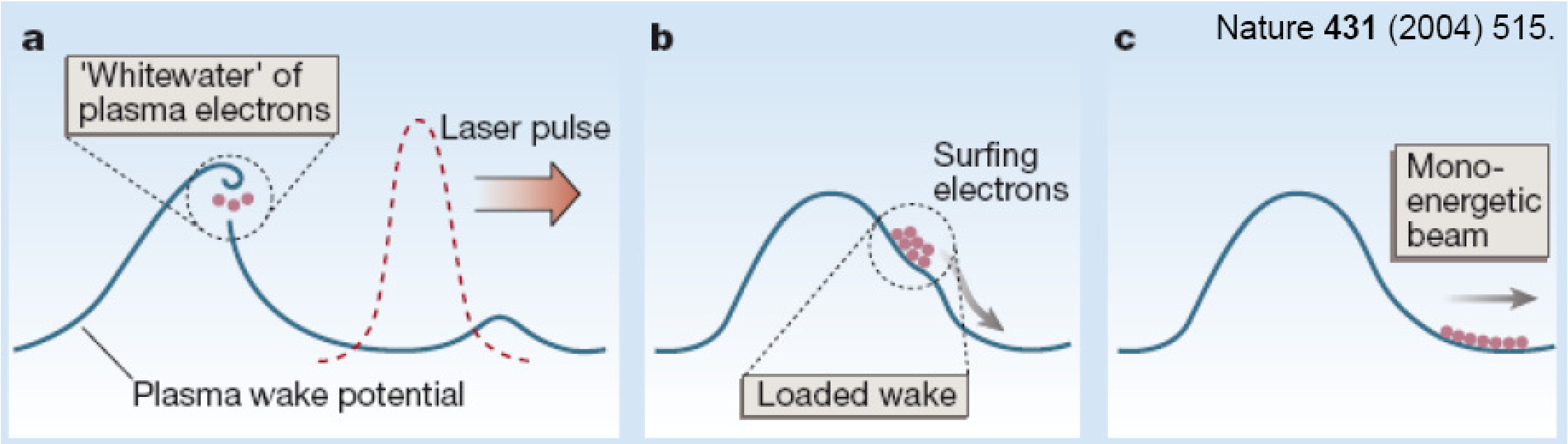
→ **for $n_e = 10^{18}\ cm^{-3} \rightarrow \nu_p = 10$ THz**

- **E_0 = 100 GV/m**
- **λ_p = 30 µm**

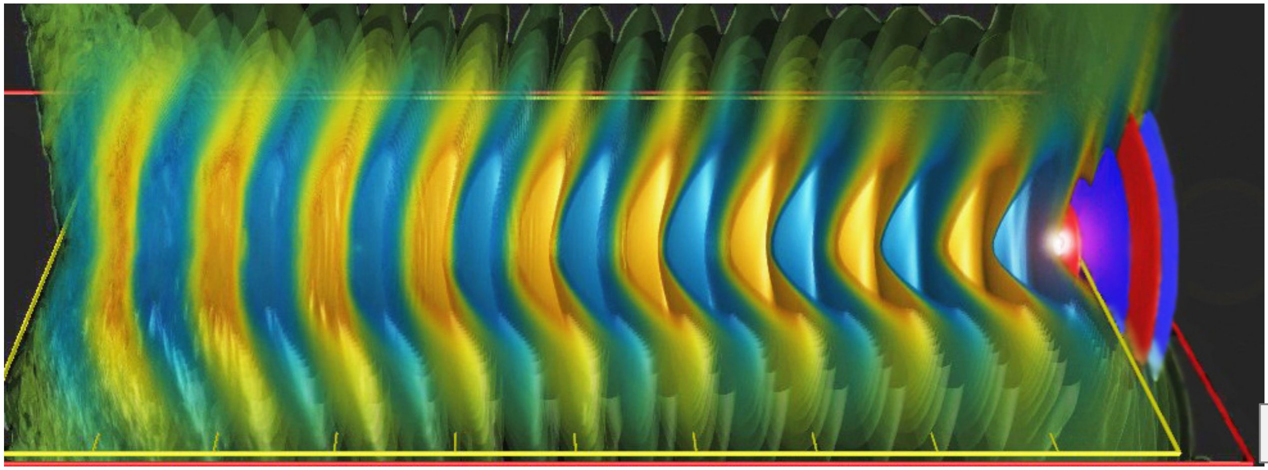
E-field of wake:

$$E_0 = c m_e \omega_p / e$$

Electrons surfing on a plasma wave



Nature **431** (2004) 515.



J.-L. Vay, LBNL

Application of Laser Electron Acceleration

- Do the much higher gradients in laser acceleration (10^3..10^4 times) lead to much reduced size and cost of laser accelerators?
- Is the efficiency wall → photons and photons → electrons competitive?
- Is the beam quality competitive with conventional RF accelerators?
- - all are open questions

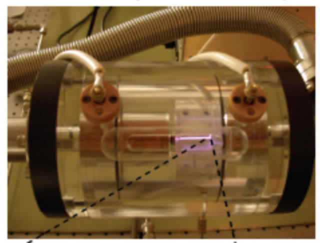
Proof-of-principle, LBNL Berkeley

Experimental demonstration: 1 GeV high-quality beam via laser-plasma accelerator

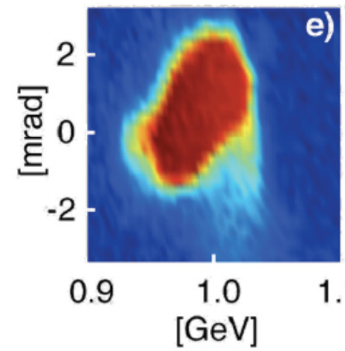
H-discharge capillary technology: plasma channel production ($1\text{-}4\times10^{18}$ cm^{-3})

40 TW,
38 fs,
1.5J,
10 Hz
25 micron spot
10^{18} W/cm^2

LBNL $Ti{:}Al_2O_3$ laser



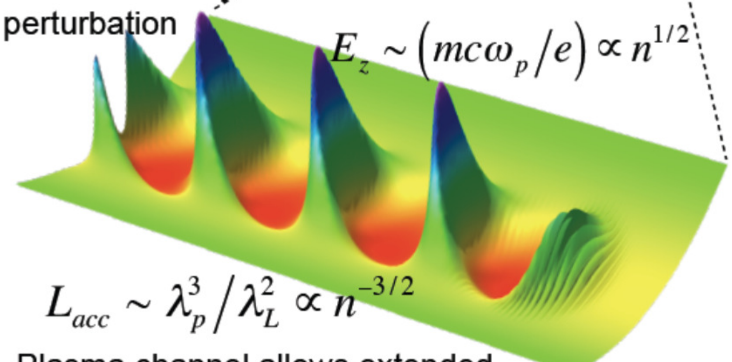
electron beam



Beam energy =1.0 GeV
Charge= Q~30 pC
1.6 mrad rms divergence
2.5% rms energy spread

Leemans *et al.*, Nature Phys. (2006).
Nakamura *et al.*, Phys. Plasmas (2007).

Electron density perturbation



$$E_z \sim (m c \omega_p / e) \propto n^{1/2}$$

$$L_{acc} \sim \lambda_p^3 / \lambda_L^2 \propto n^{-3/2}$$

Plasma channel allows extended laser-plasma interaction length

$$\Delta W[\text{GeV}] \sim eE \cdot L_{acc} \sim I[\text{W/cm}^2] / n[\text{cm}^{-3}] \propto n^{-1}$$

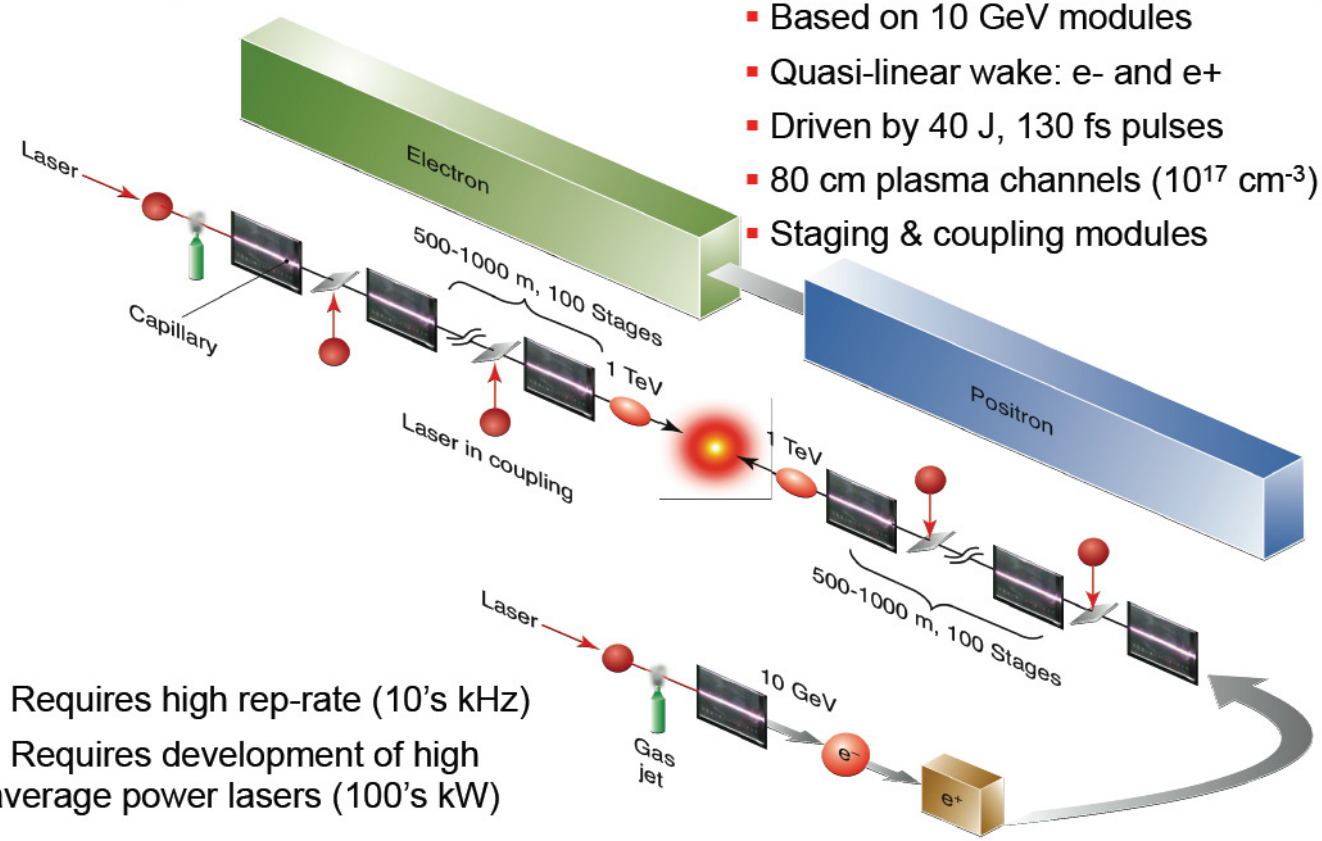
6

The "dream accelerator" of laser physicists: Linear TeV $e^+ e^-$ collider

BERKELEY LAB

Conceptual LPA Collider

- Based on 10 GeV modules
- Quasi-linear wake: e- and e+
- Driven by 40 J, 130 fs pulses
- 80 cm plasma channels (10^{17} cm^{-3})
- Staging & coupling modules



- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

Leemans & Esarey, Physics Today, March 2009

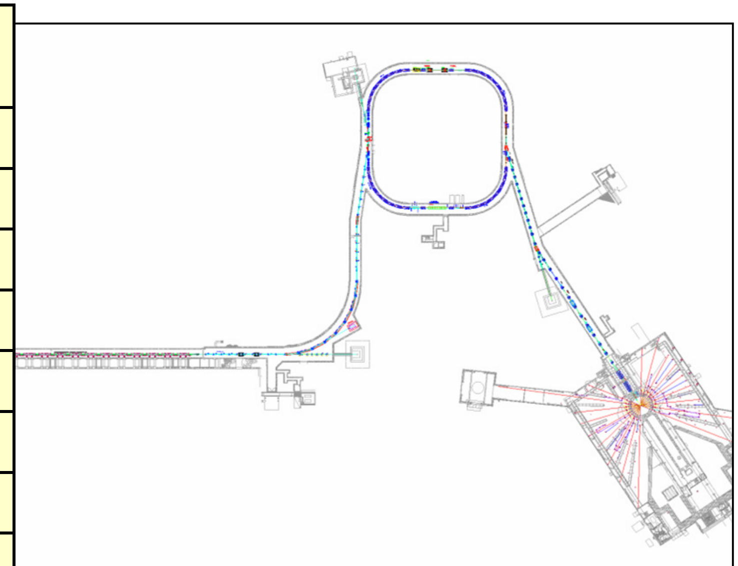
"Closer to reality": Laser Stripping of H^- Particles in Conventional High-Intensity Proton Accelerators

When the beam power is increased from the **1 MW to more than 3 MW** as envisioned in the **SNS Power Upgrade** project, the stripping foils become radioactive and produces uncontrolled beam loss

H^- ions are

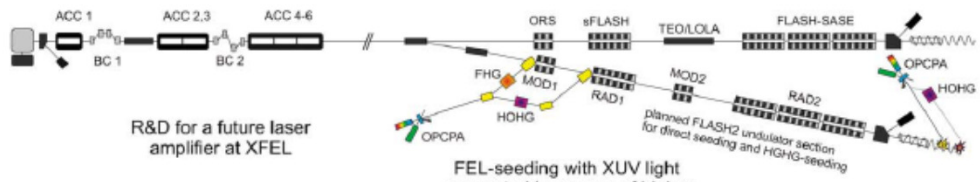
1. converted to H^0 by stripping off the first electron in a magnetic field
2. then H^0 atoms are excited from the ground state ($n = 1$) to the upper levels ($n \geq 3$) by a laser,
3. and the excited states H^{0*} are converted to H^+ by stripping the second electron in a second magnetic field.

Method	**Macropulse laser**	**Macropulse laser w/ 20x resonator**
Laser wavelength (nm)	**355**	**355**
Micropulse length (ps)	50	50
Micropulse energy (µJ)	50	2.5
Micropulse repetition rate (MHz)	402.5	402.5
Macropulse length (ms)	1	1
Macropulse energy (J)	20	1
Macropulse repetition rate (Hz)	**60**	**60**
Average power (W)	**1200**	**60**



Even more "down-to-the-earth" application:
FEL's: seeding by laser vs. spontaneous undulator radiation

Seeding – the future for pump-probe experiments



R&D for a future laser amplifier at XFEL

FEL-seeding with XUV light generated by means of higher order harmonic generation

source for pump-probe experiments

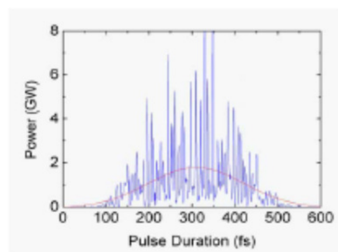
XUV-NIR
XUV-XUV

> Seeding:
- fully temporal coherent
- well defined Gaussian spectrum
- intrinsically synchronized to seeding laser

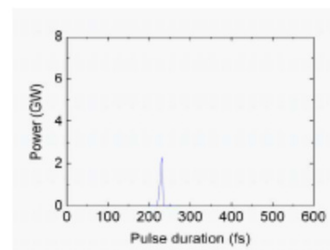
→ enables high resolution pump-probe experiments

> Requirements:
- few nJ in single VUV / XUV harmonic
- Tunable harmonics

SASE



Seeding



Protons and ions are too slow to catch the wave - only indirect acceleration via electrons

Laser Driven Acceleration of Protons

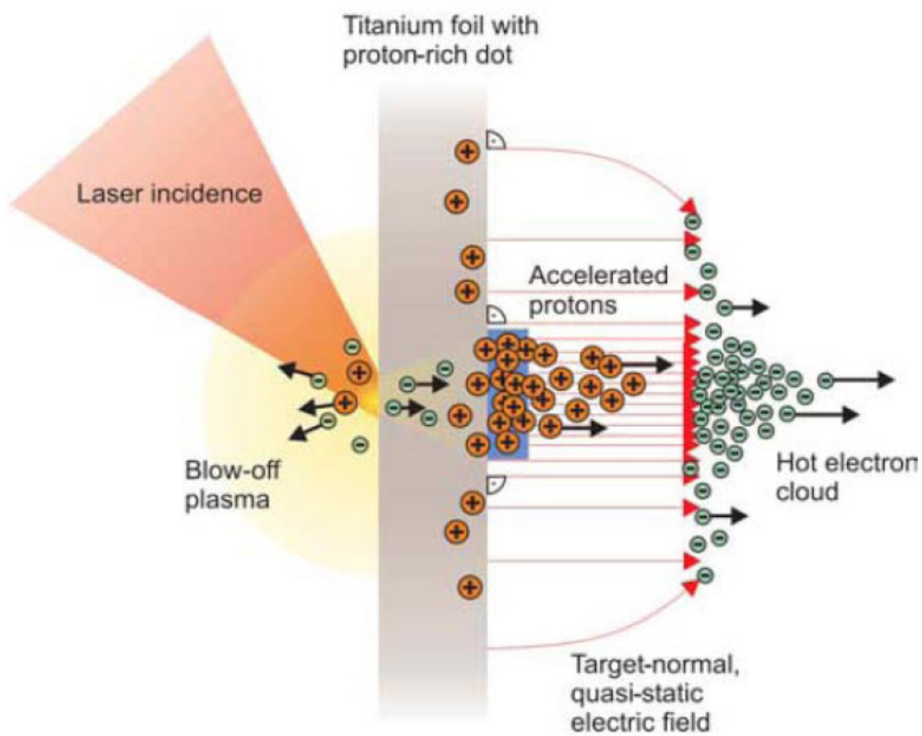
- Direct acceleration in laser field > 10^{25} W/cm^2 far beyond current lasers
- Plasma wakefield phase velocity too fast for protons & ions
- → only indirect ways

Need typically:
50 J   500 fs → 100 TW
30 μm radius → 10^{19} W/cm^2

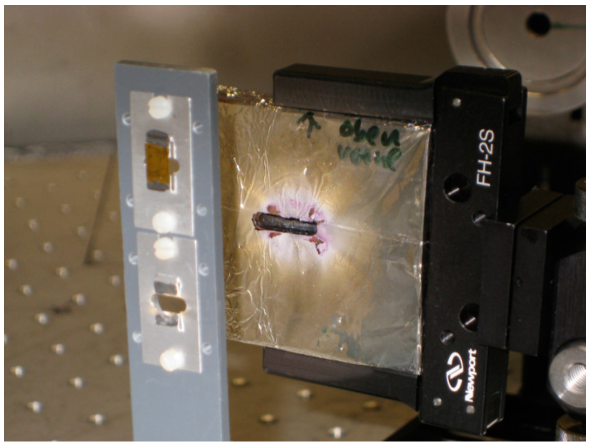
Target Normal Sheath Acceleration

"best understood" candidate:

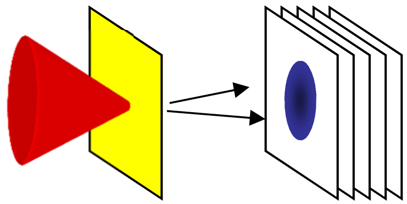
- laser creates blow-off plasma on front surface
- backside expansion accelerated electrons ionize hydrogen
- hot electrons create electric field (by space charge)
- causes acceleration of protons (electrons slowing down – end of acceleration)
- neutralized bunch of comoving p and e generated

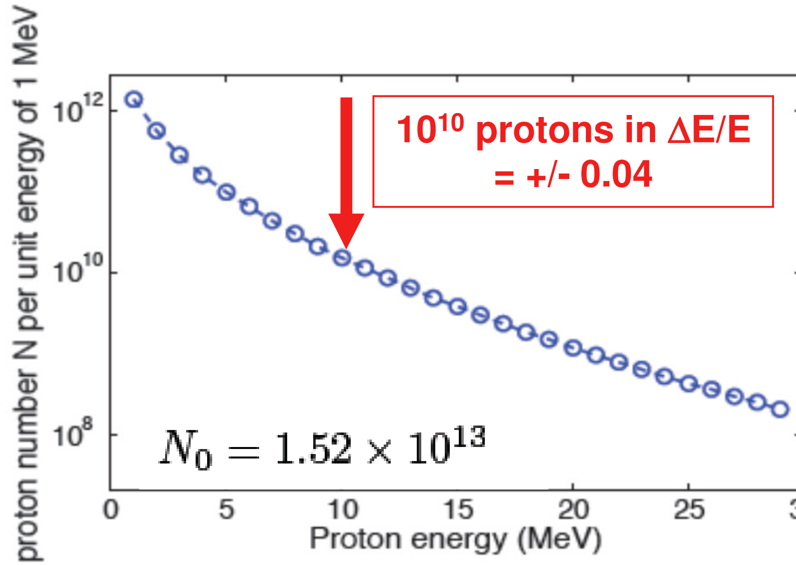


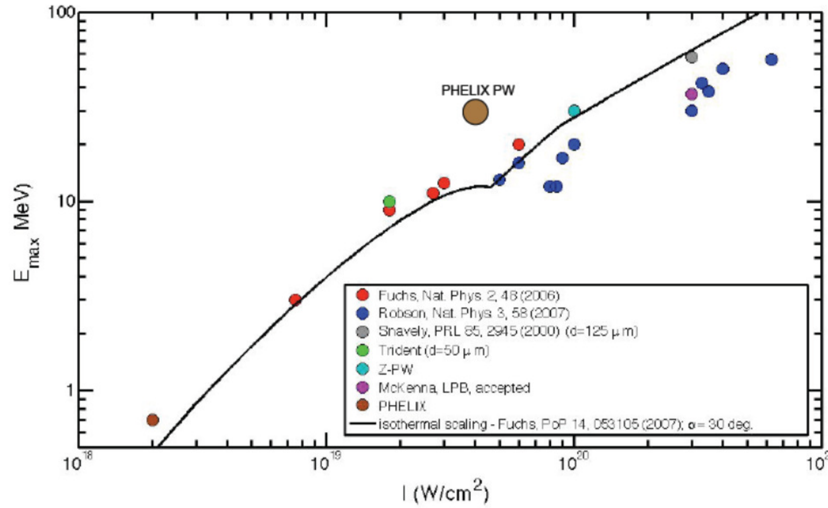
Results of the first PHELIX experiment (2009) on laser proton acceleration: TU Darmstadt – GSI collaboration



Setup to test proton production

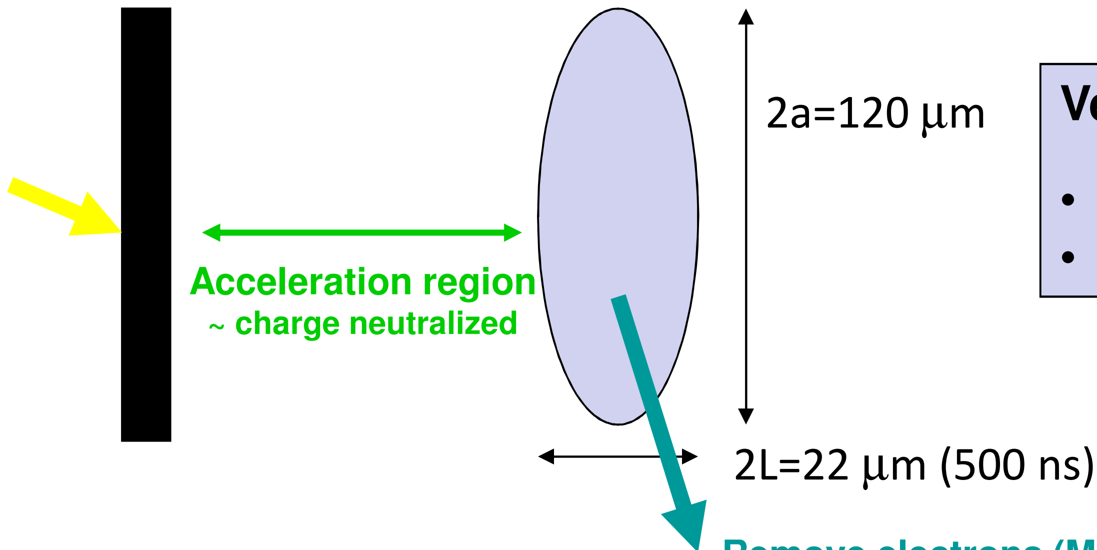






Initially record densities of accelerated protons!

Electrons are needed in the beginning: if absent, Coulomb explosion of an unneutralized p bunch



Remove electrons (Maxwellian demon – or stripping foil)

Very high p density ~ 10^{17} cm^{-3}

- Usual linacs only 10^{8} cm^{-3} !
- Explodes in free space!

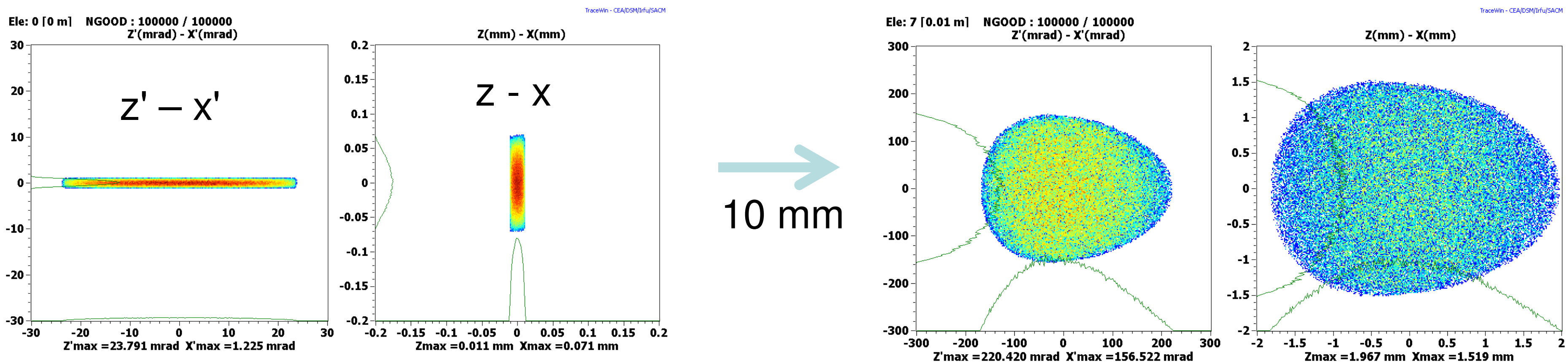
$$\text{Selffield energy}: \quad W = \frac{\varepsilon_0}{2} \iiint_V E^2 dxdydz$$

Energy conservation derived from Vlasov equation by forming moments :

$$\frac{m\gamma\beta^2 c^2}{2}\left(x'^2 + y'^2 + z'^2\right) + V_{ex} + \frac{W}{\gamma^2 N} = const$$

TRACEWIN code simulation of „Coulomb explosion“

TRACEWIN (CEA)
Linac code with fast 3D PIC solver



Strongly oblate ellipsoid →

- ~ Spherical bunch
- General behavior of Coulomb explosion?

Stopping of 10 keV electrons (20 MeV p) in 0.5 μm Cu foil has tolerable effect on protons
(FLUKA-simulations S. Sinigardi, 2012)

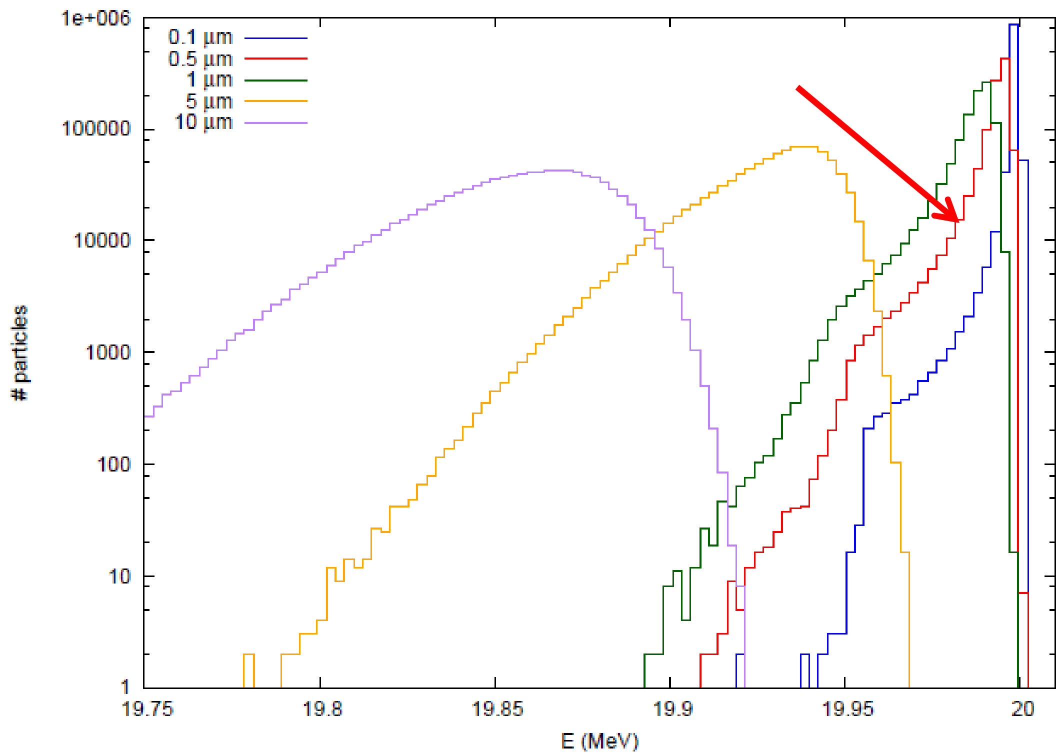


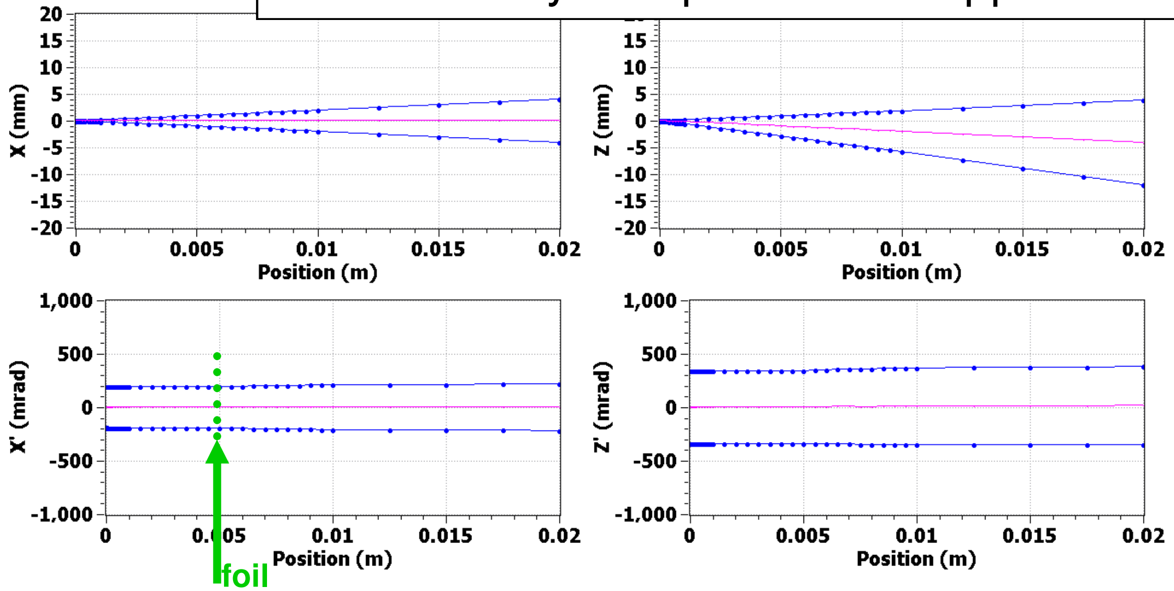
Figure 7: Protons energy spectra after different thicknesses of the copper foil - input protons: 20 MeV

Electrons can be removed by foil after 5 mm propagation

- proton bunch enlarged ballistically

- space charge effect with e^- absent is "controllable"

Total intensity 10^{12} p – realistic upper limit (~1 J protons)

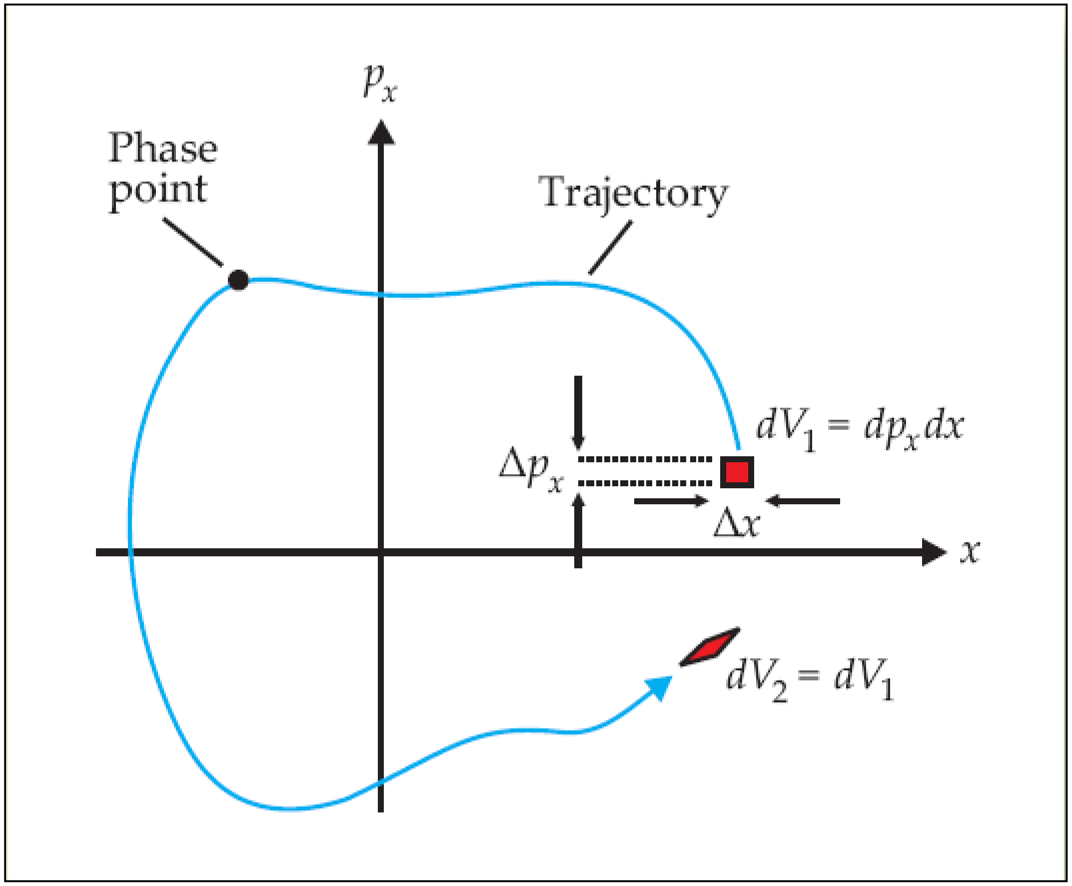


- „Small" space charge blow-up after foil at 5 mm
- Need to check space charge in rest of beam line
- Consistent approach to space charge problem

Liouville theorem – phase space

Applies to:

- ✓ 1D: xp_x if $\Phi(x,t)$
  - for red square in 2d phase plane
  - also for global ensemble area in 2d
- ✓ 3D: xp_x - yp_y - zp_z if $\Phi(x,y,z,t)$
  - for red square in 6d
  - also valid for **exact area** of global ensemble area in 6d
  - **not for projections** into xp_x or xp_y
  - **effective area always grows** in focusing or transport devices for large $\Delta E/E$ and divergences
  - **cannot maintain record phase space densities at origin! new ideas?**



Can we compare Laser Acceleration with conventional high intensity proton accelerators?

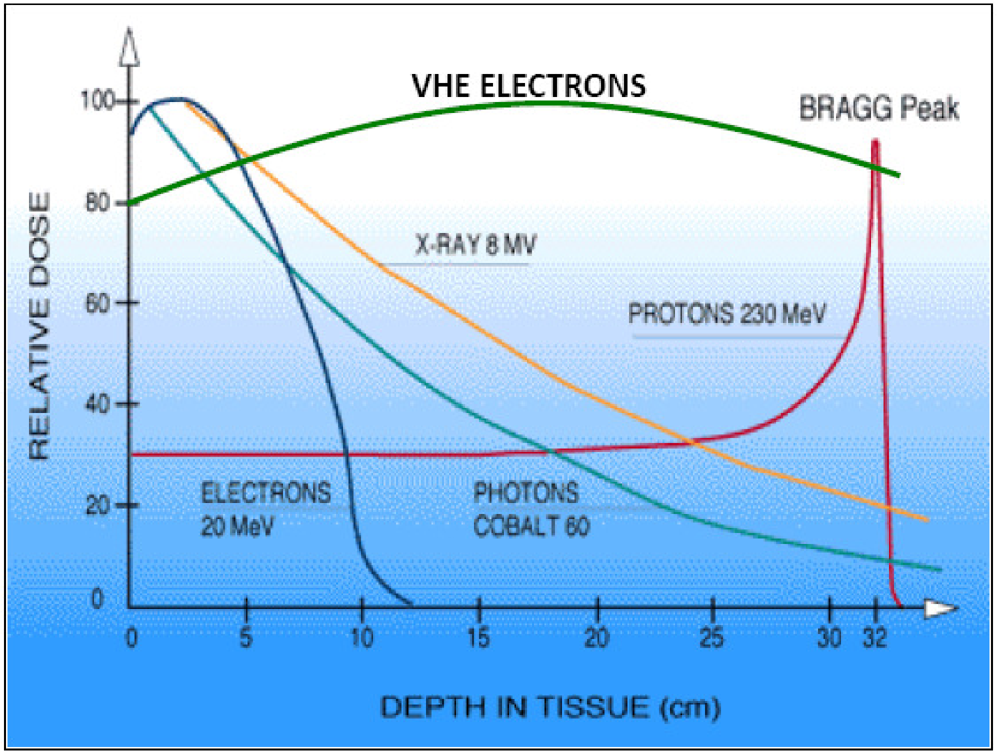
	MeV	p/sec	p/ micropulse or spill
SNS Oakridge (Spallation Neutron Source):	1000	**10^{16}**	$6x10^8$/ every 2.5 ns
FAIR p driver linac (→ antiproton facility) :	70	**~$3x10^{13}$**	$1.3x10^9$/ every 3 ns
Proton therapy (HIT Heidelberg synchrotron):	~ 250	**~10^{10}**	~ $5x10^{10}$ / 10s spill ~ $5x10^7$ / voxel (100 Hz)

	SNS	FAIR-p-linac	HIT	**5 Hz PW laser system (today)**
beam power:	1 MW	100 W	0.2 W	**150 W (in photons)**

Laser p acceleration :

- ~ 1% photon→proton efficiency → ~ 1 W p power
- in terms of intensity (average power) **may be competitive in the area of therapy**
- radiography ? (protons, neutrons?)

Medical application of laser acceleration



- electrons 150 - 250 MeV (laser wake field accelerator) for radiotherapy as alternative to 6 MeV photons currently used
- → **protons / ions for radiotherapy**

Currently discussed mechanisms
for therapy applications

source: ICFA-ICUIL Laser acceleration "white paper" 2011

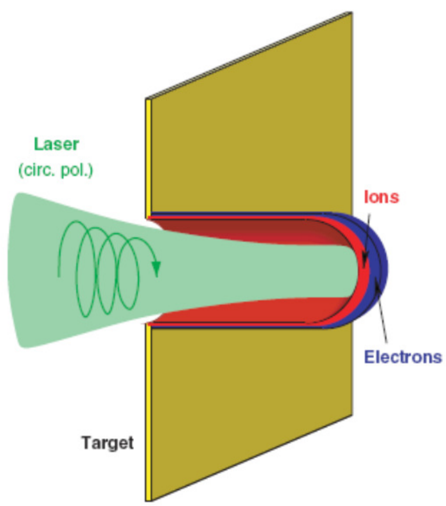
	Experiments	Status	Theory	Relevance to Therapy
Target Normal Sheath Acceleation	> 1999	$>10^{13}$ ions, robust, reproducible <70 MeV	Analytical + 2D/3D simulations	+
TNSA/BOA (Break-out-afterburner)	> 2011	120 MeV ? (LANL)	2 D / 3D simulations	++(+)
Radiation Pressure Acceleration	>2008	experimental evidence not conclusive	2 D / 3D simulations >GeV	++(+)
Coulomb explosion	-	-	2 D simulation	+
Gas Jet - RPA	> 2009	2 MeV observed	2D	++

Combine simulation spectra from Radiation Pressure Acceleration of Ions*) with ion optical simulation for collection, energy selection etc.

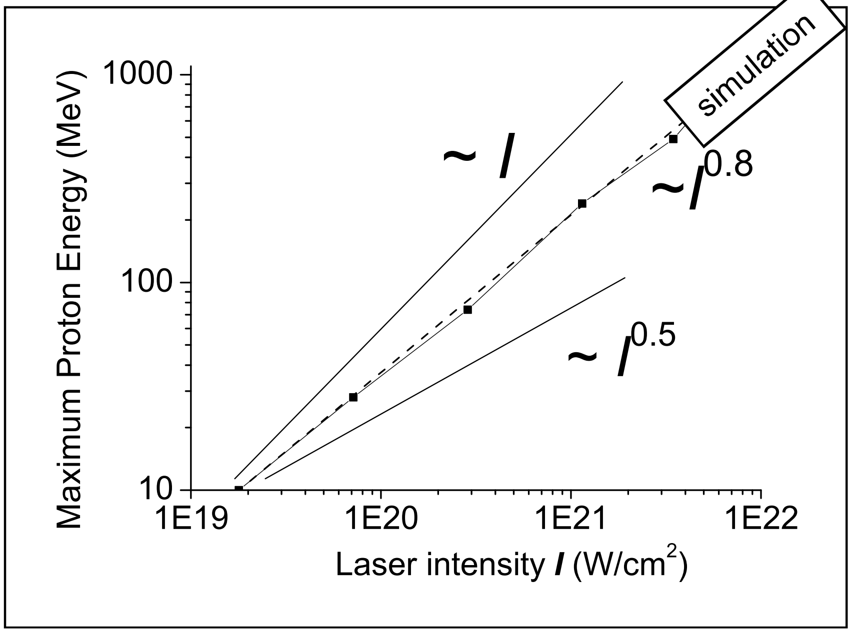
***) X. Yan et al., 2009**

Radiation Pressure Acceleration
from nm thick C foils

- > 3 10^{21} W/cm^2 / 45 fs / 10 µm spot radius
- results from 2D numerical simulation assuming circular polarized light



Scaling of MeV with laser intensity (protons)



Radiation pressure:

$$P = (1 + R - T)\frac{I}{c} = (2R + A)\frac{I}{c}$$

$$I = \langle |\mathbf{S}| \rangle = \left\langle \frac{c}{4\pi} |\mathbf{E} \times \mathbf{B}| \right\rangle$$

Spectral proton yield

from RPA simulation

selection of useful "window" for irradiation

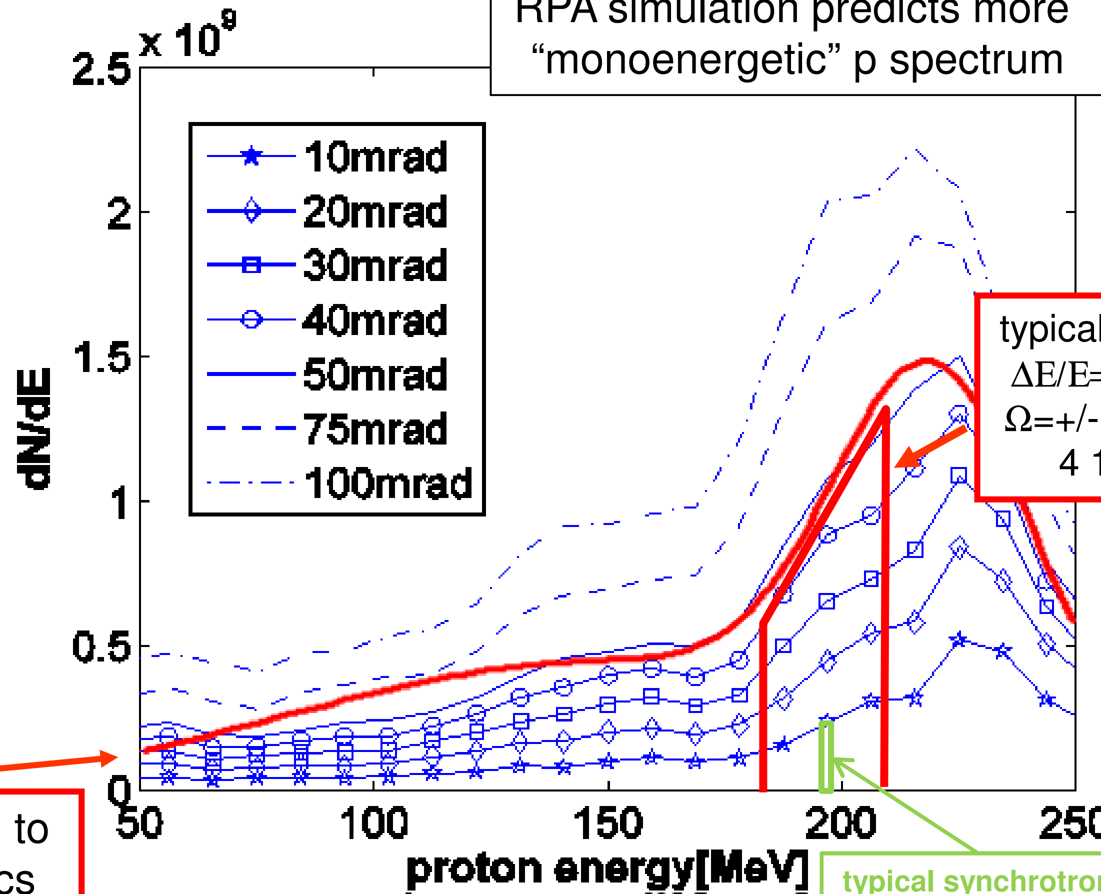
I.H., J. Meyer-ter-Vehn, X. Yan, PRST-AB (2011)

total high energy proton yield per shot: ~10^{11} ~ 3 J

spectral density E, Ω (rad)

$$\frac{dN(E,\Omega)}{dE}\left[\frac{1}{GeV}\right]$$

RPA simulation predicts more "monoenergetic" p spectrum



typical window
ΔE/E=+/– 10%
Ω=+/- 50 mrad
4 10^{10} p

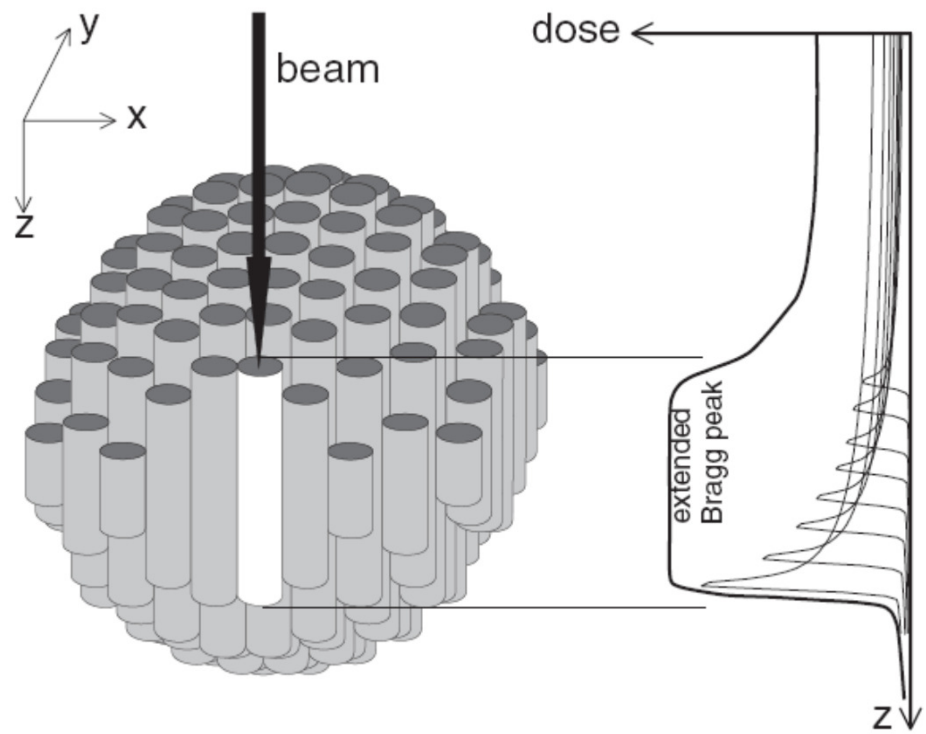
typical synchrotron window

We „fitted" energy distribution to start of simulation beam optics

How to reach depth dose uniformity?

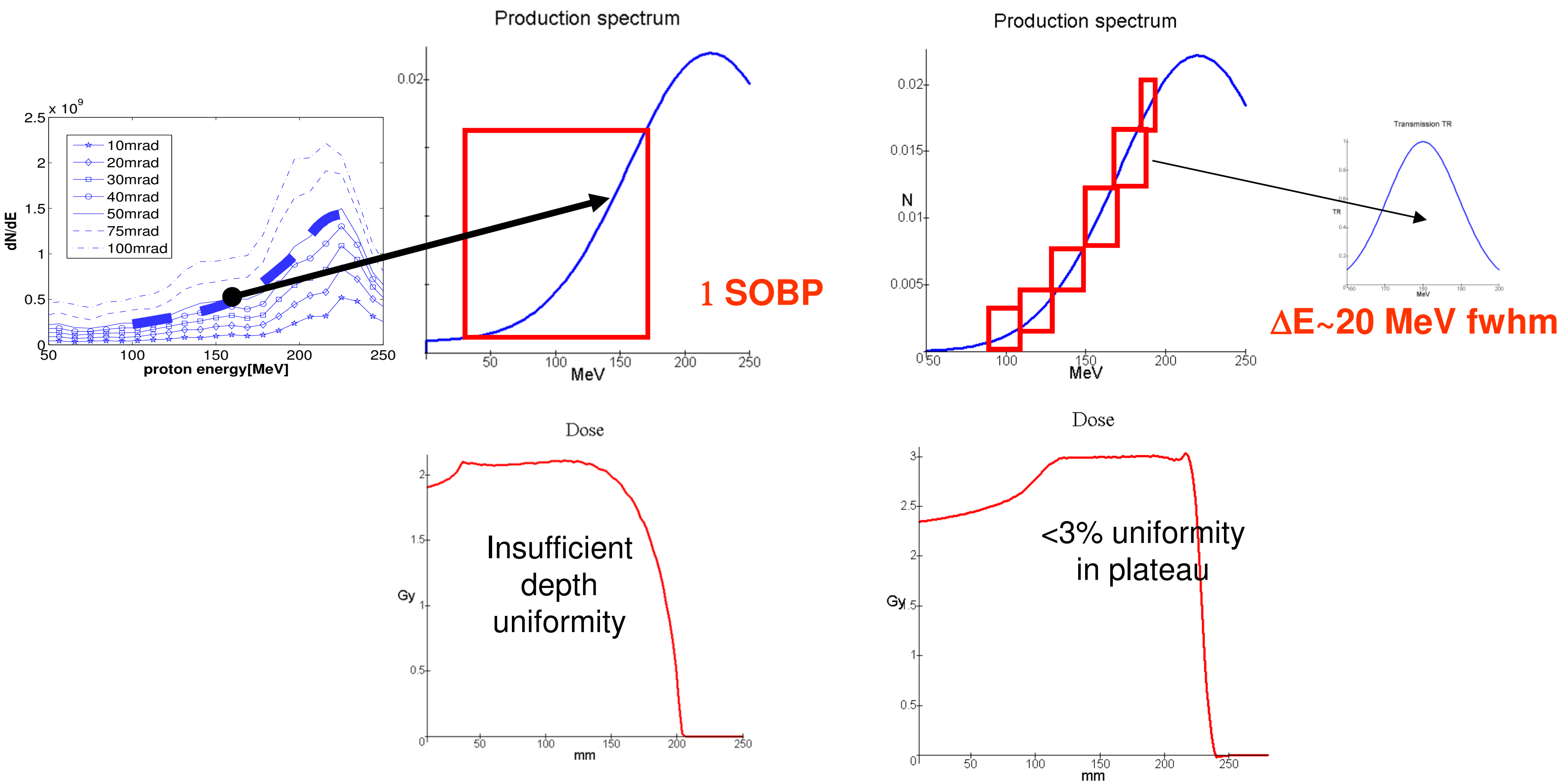
Depth scanning (U. Weber et al, 2000) with few Bragg peaks seems to match best with laser ions

- U. Weber et al. (2000) proposed ridge absorber to broaden ΔE from synchrotron (10^{-3}) for depth scanning
- laser ions: naturally broad energy profile → depth scanning applicable
- → quantify # shots and SOBP's to reach dose uniformity
- Transverse spot scanning



Alternative way : passive formation with large beam and objects

Energy spectrum – depth dose uniformity
using 5-6 SOBP’s

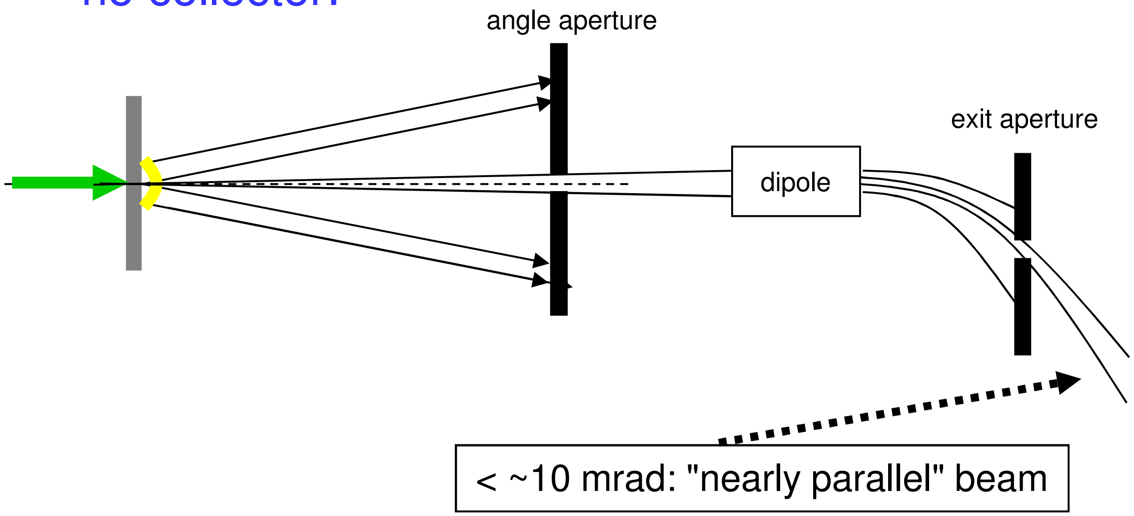


Options for ion optics from laser acceleration
can we achieve a reliable reference beam?
questioned by Linz & Alonso in 2008, PRST-AB

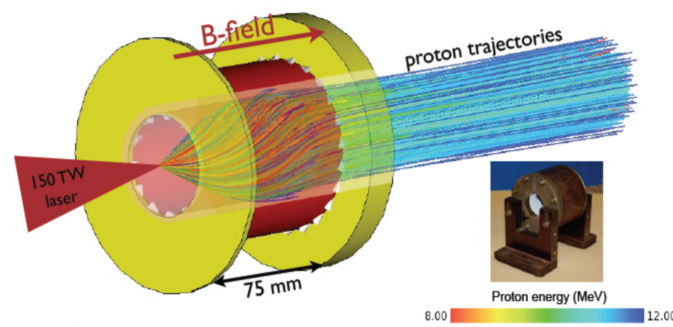
Relatively large angular and energy spread is an issue - 2 options:

- **no collector – angle selection by aperture** + dipole energy filter + exit aperture:
  - simple, preferred option in current experiments
  - reduced transmission (~10 mrad "usable")
- **collection by solenoid lens:**
  - higher transmission (~ 50 mrad „usable“ → more efficient use of p)
  - combined **collection and energy filter** due to chromatic focusing effect
- quadrupole triplet may be alternative to solenoid

no collector:



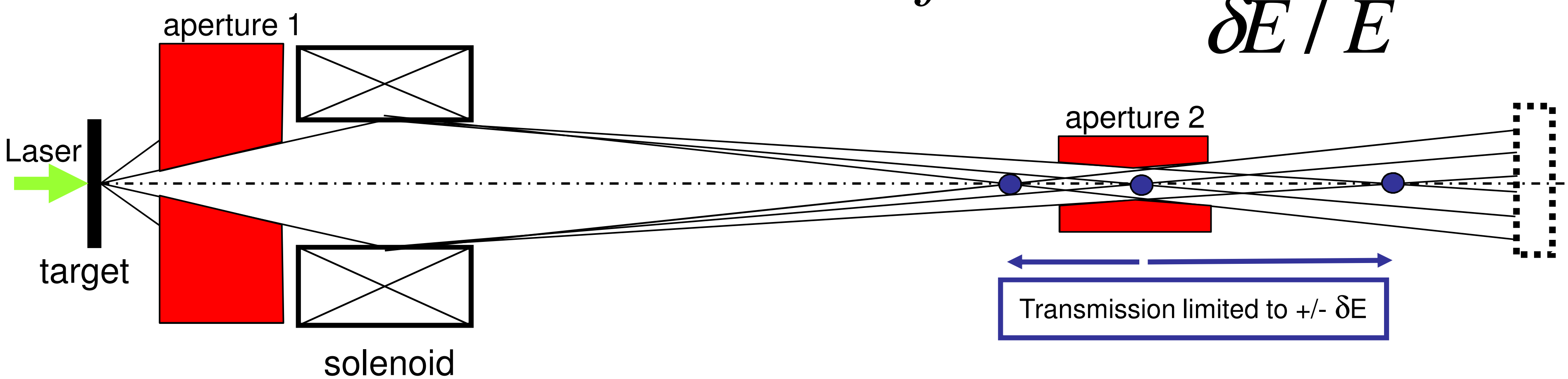
solenoid collector:



Solenoid lens collector + chromatic separator

assuming 50 … 250 MeV proton spectrum

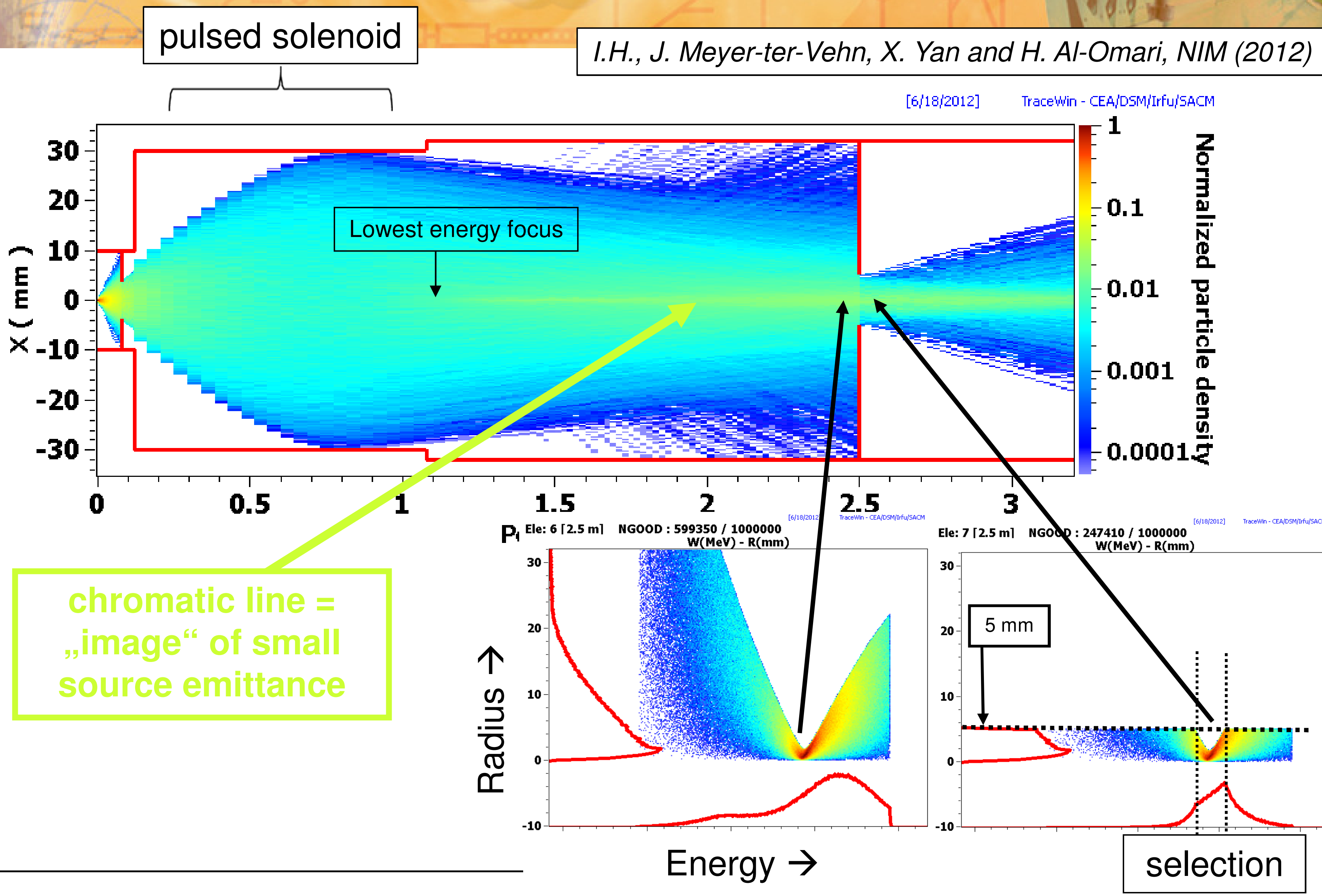
$$\delta f = \delta E \times \frac{\delta f / f}{\delta E / E}$$



- aperture 1: angular selection from target
- aperture 2: chromatic energy selection

Ion optical simulation with TRACEWIN*) code (CEA) Energy selection by chromatic focusing

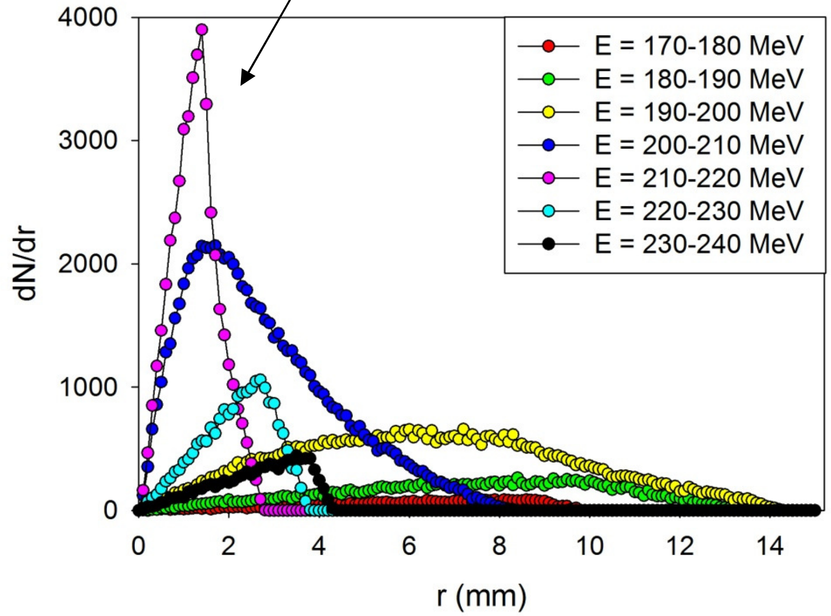
I.H., J. Meyer-ter-Vehn, X. Yan and H. Al-Omari, NIM (2012)



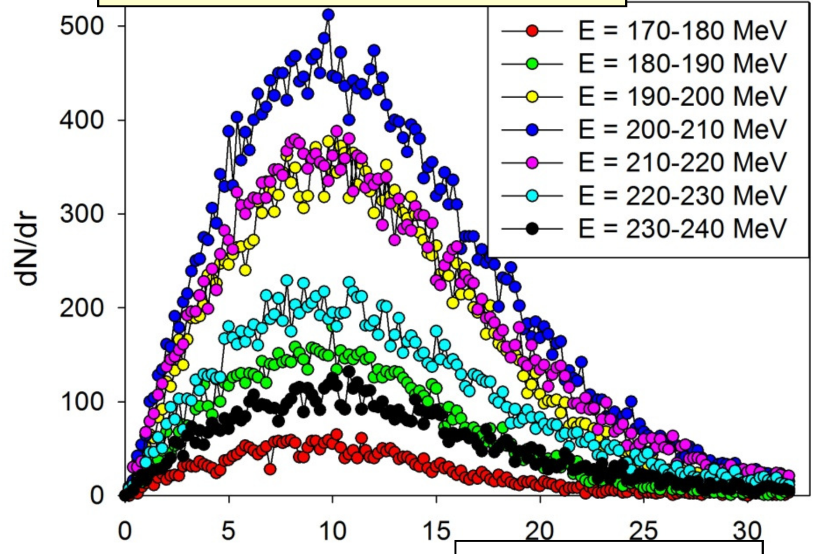
Small source emittance → correlation E-r

correlation can be removed by thin scatterer(s)

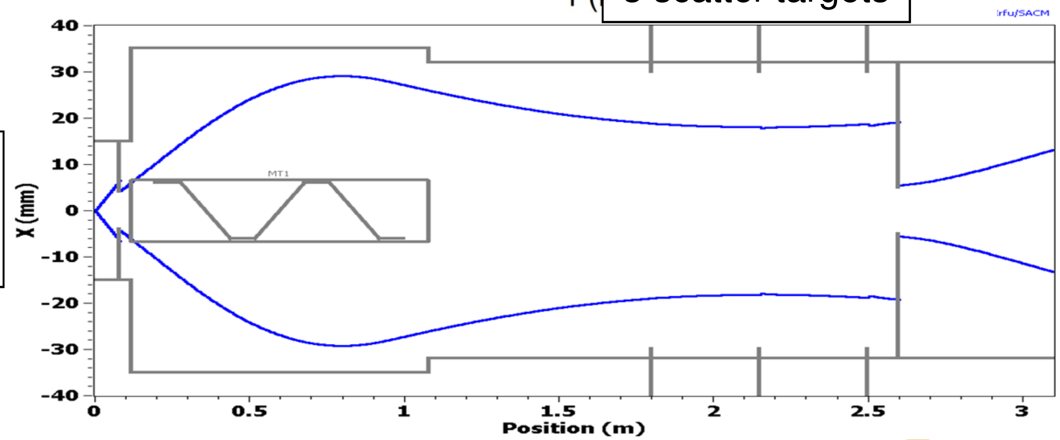
some energies have central "hot spot" in x-y



with scatterer: smoothing to ~ Gaussian for **all** energies



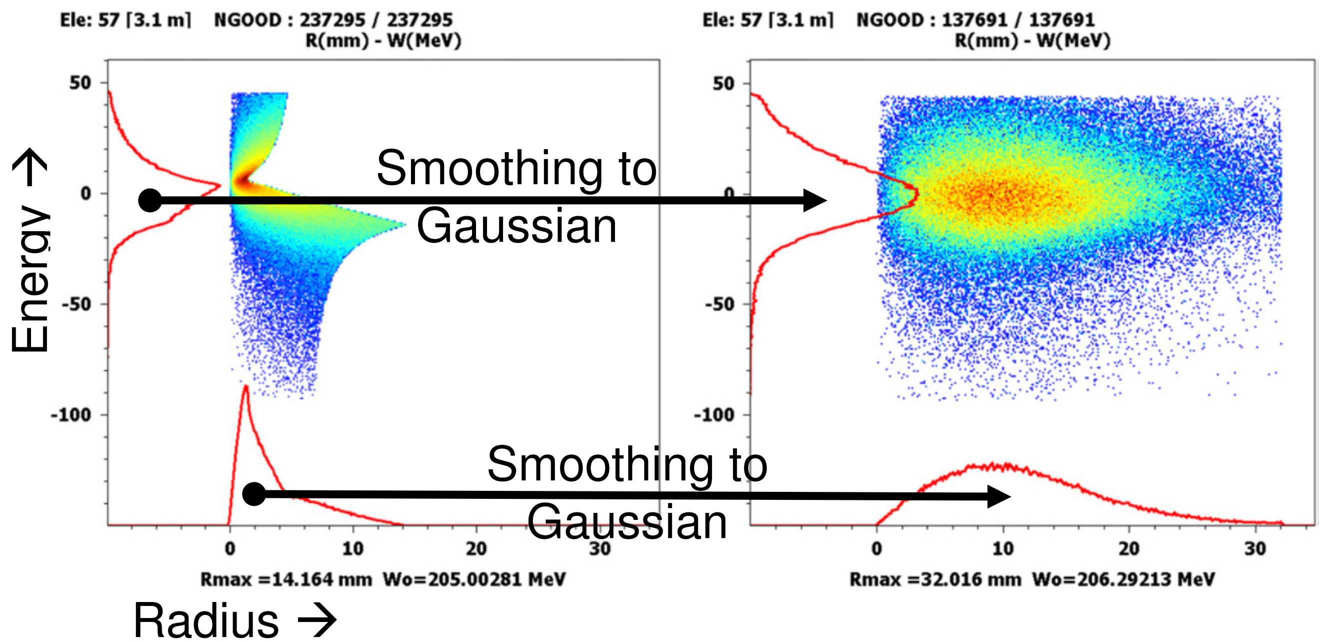
3 scatter targets



Thickness requirements of scatterers (~g/cm²):

- angular straggling ~ 5 mr
- → energy loss ~ 2% & straggling ~ 0.2%

Scatterer(s) prior to energy selection aperture: → define a robust reference beam



- Gaussian energy profile
- Gaussian radial density
- Decorrelates E-Radius
- → eliminates „memory" of laser production + lens aberrations (chromatic)
- **Well-defined „reference beam" for therapy applications (alleviates scepticism from 2008 Linz&Alonso paper)**
- Remaining uncertainty is intensity → **shot-to-shot accumulation until nominal dose is achieved (time!)**

Parameter estimates
for spot scanning or passive formation
ICFA/ICUIL workshop (Berkeley, September 2011) recommendations

Assume each laser shot gives a „reproducible“ transverse and energy profile, but not so well defined intensity → adding up small portions to achieve nominal 2 Gy dose for 1 fraction

	Spot scanning	Passive formation	Comments
Protons / laser shot	$2x10^7$	$2x10^8$	reach 2 Gy by accumulation
# transverse	10x10 Spots	10 reps for lateral uniformity	
Energy steps	10	10	ΔE/E=±5%
Reps → dose spec. (~30% intensity jitter)	40	40	10 reps 4 gantry directions
Total # shots per fraction	10000	1000	Factor ¼ applied
Duration of fraction Laser rep rate	5 min 30 Hz	1.5 min 10 Hz	

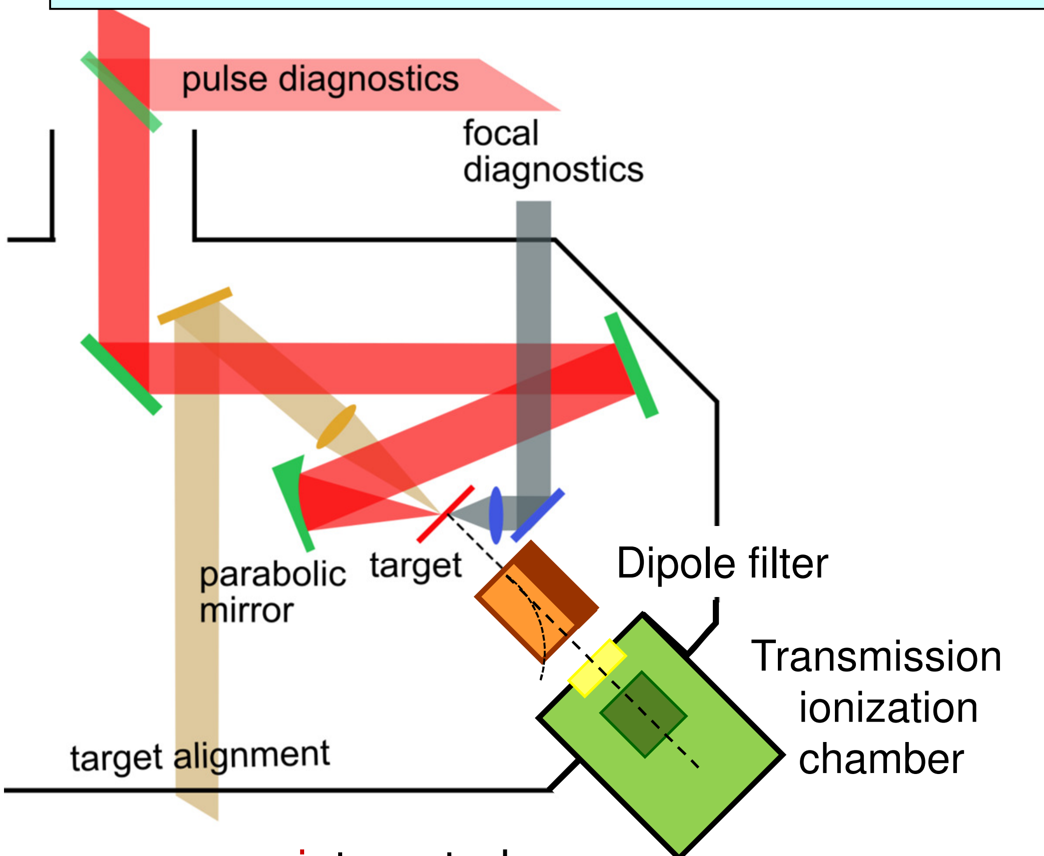
Operating laser facilities worldwide with medical context

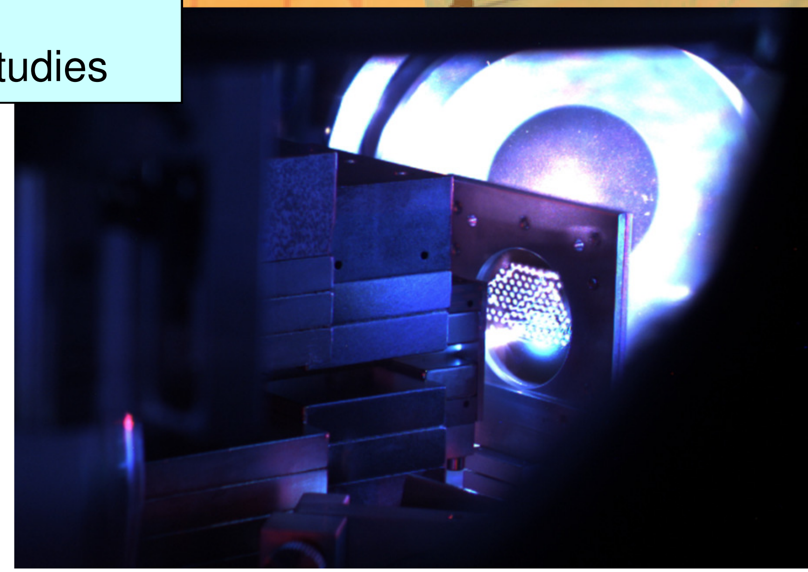
	type of laser	J / fs / Hz	p / ion MeV	e^- MeV	biophysics experiments	therapy relevant programs	Under or near construction / planning J/fs/Hz (date)
HZDR and Oncoray (Germany)	DRACO 150 TW Ti:Sapphire	**4.5 J / 30 fs / 10Hz (30J upgrade 1Hz 2012/13)**	20		Dose controlled cell irradiation and dosimetry development	Depth dose planned, translational research	PENELOPE DPSSL 150J / 150fs 1 Hz (~2015)
KPSI (Japan)	J-KAREN 250 TW Ti:Sapphire	10 J / 30 fs / 30 min/	23	200	doublestrand breaks (2 MeV) Estimation of RBE with dose controlled cell irradiation	Development of source & beamline, assessment of PET diagnostics	
Fox Chase Center (USA)	150 TW Ti:Sapphire	4.5 J / 30 fs / 3min	6		Physics studies	Prototype studies	Planning on-campus prototype facility
MPQ & LMU Munich (Germany)	ATLAS 70 TW Ti:Sa LWS 20TW OPCPA	**2 J / 25 fs / 5 Hz 0.1 J / 5fs / 10 Hz**	8	600 50	Single shot radiation biology on cell level	Development of source, & beamline	60J/20fs/1Hz (~2015) 5J/5fs/10Hz(~2015) 0.5J/5fs/1kHz (~2015)
LOA (France)	Salle Jaune 30 TW Ti:Sapphire	1 J / 30 fs / 10 Hz (2 J upgrade 0.2 Hz 2012/2013)	14	250	Dosimetric properties Cell irradiation	Depth dose planned SAPHIR	SAPHIR 6 J / 30 fs (2012)
QUB Belfast (UK)	TARANIS 60 TW, Nd:Glass	15 J (2 beams) /500 fs/ 15 min	12		Cell irradiation: dose dependent effects on single shot basis		Ion beam lines planned
GSI (Germany)	PHELIX Nd glass	150J / 700 fs /10^{-3}	< 30		Double strand breaks (at 2 MeV)	Beam line collection & energy selection	PHELIX upgrade planned
BNL (USA)	CO_2	5 J/5000 fs	5			Source R&D	

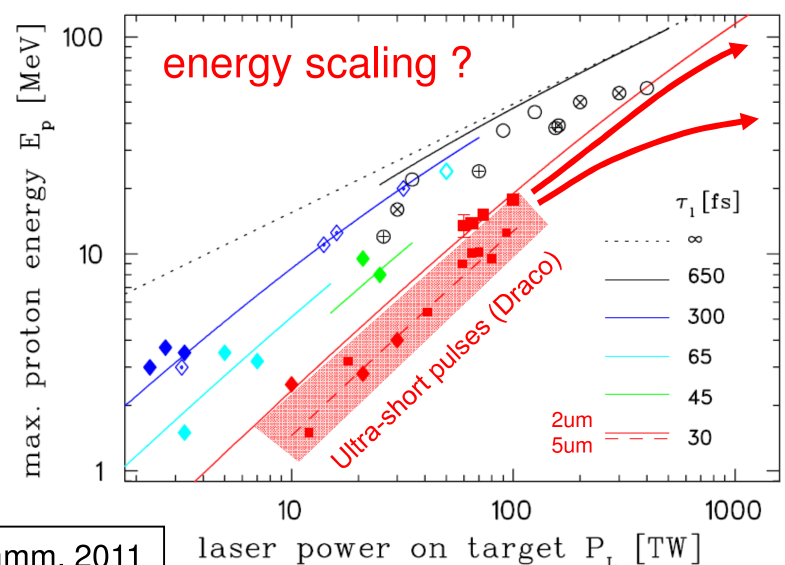
New efforts:
- Bologna-Milano-Frascati 30 MeV laser p into Linac → 60 MeV
- Asia (besides Japan)?

Progressing towards therapy: HZ-Dresden & Oncoray

Development of reliable proton sources
and online dosimetry for systematic radiobiological studies



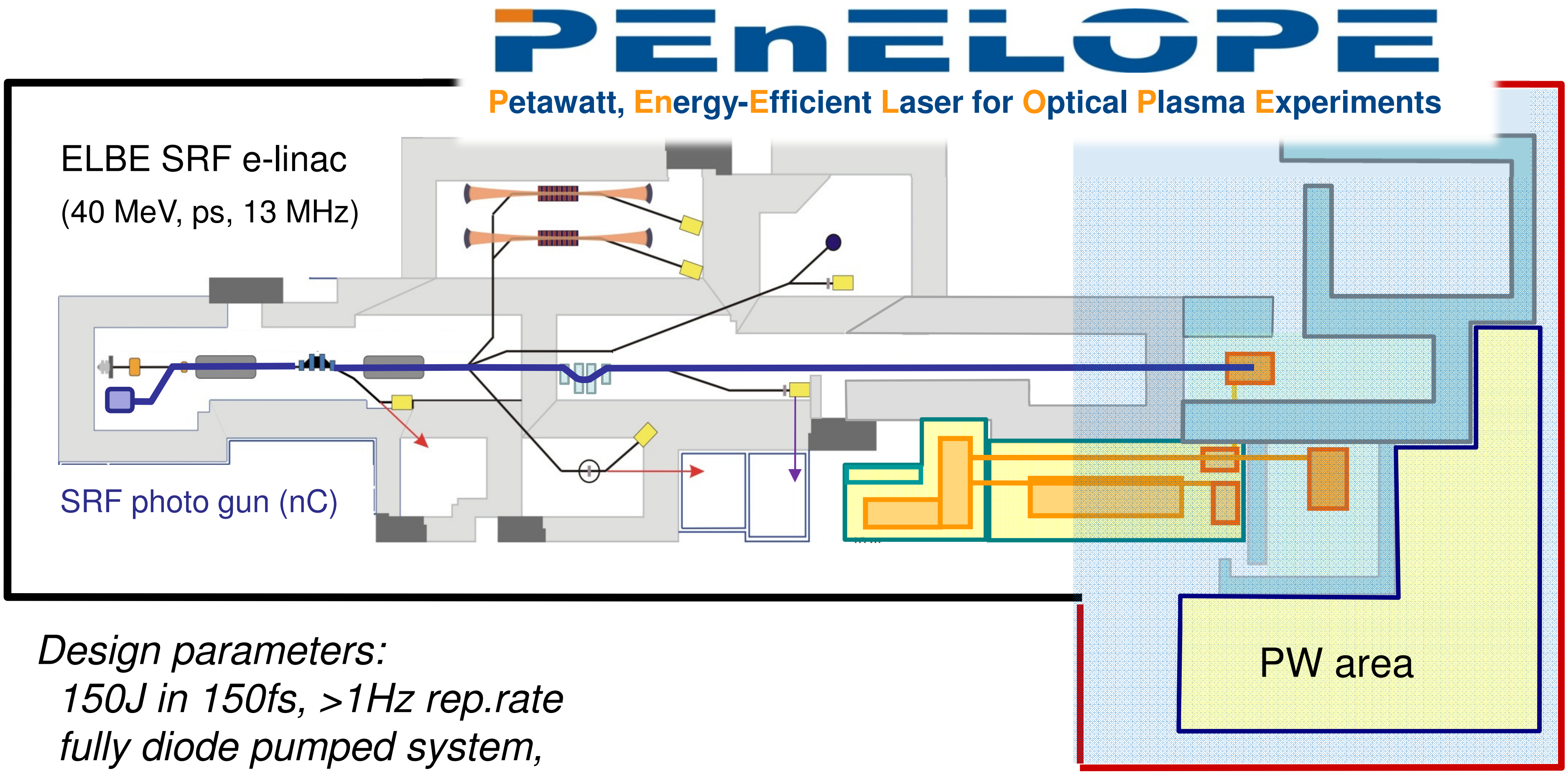




integrated
Dosimetry and
cell irradiation
system

Courtesy: U. Schramm, 2011

Next step in HZ-Dresden



Design parameters:
150J in 150fs, >1Hz rep.rate
fully diode pumped system,

Complemented by PW class Ti:Saphire laser (30J in 30fs)

Courtesy: U. Schramm, 2011

Munich Centre for Advanced Photonics (MAP), LMU, TUM, MPI

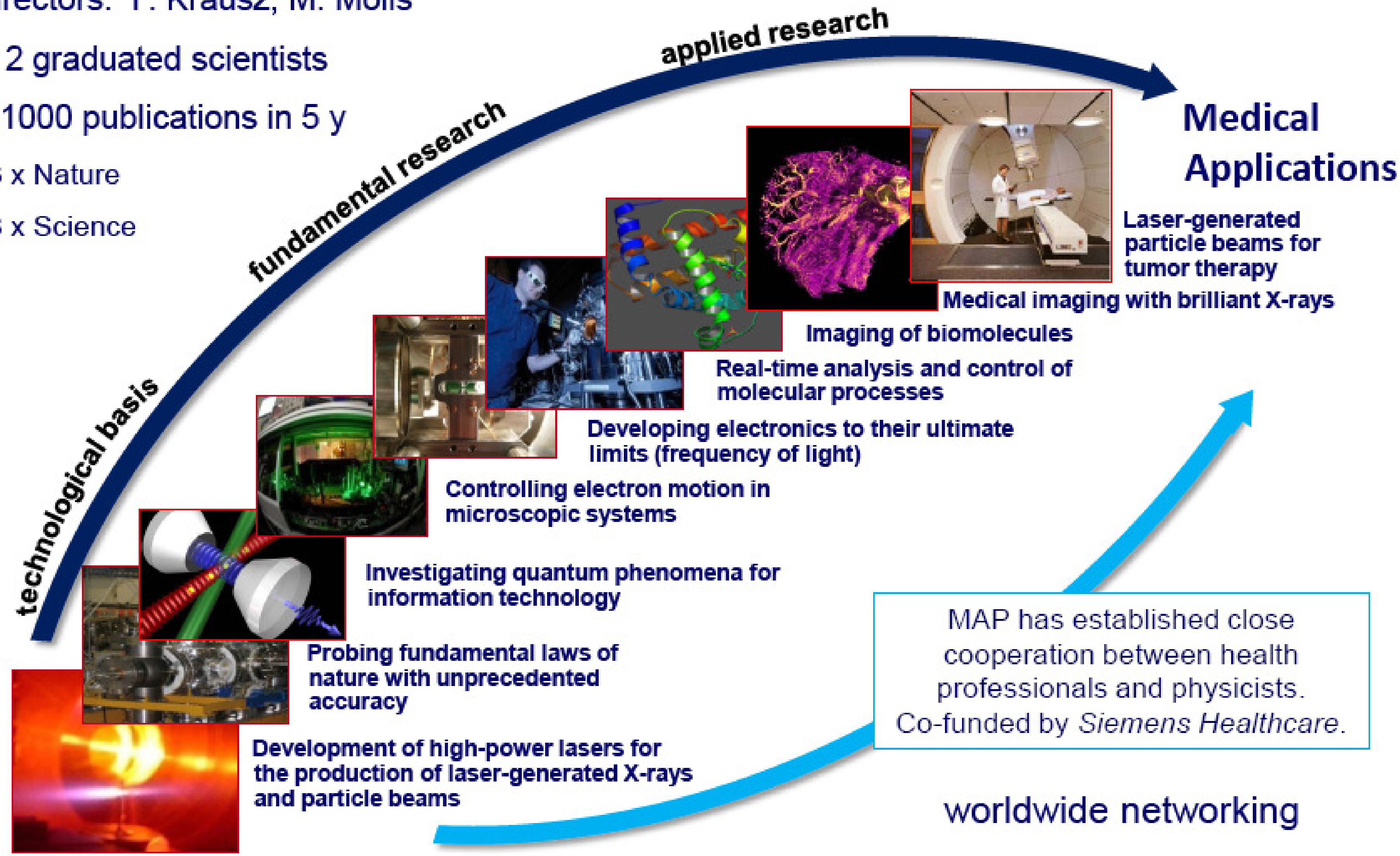
Directors: F. Krausz, M. Molls

112 graduated scientists

> 1000 publications in 5 y

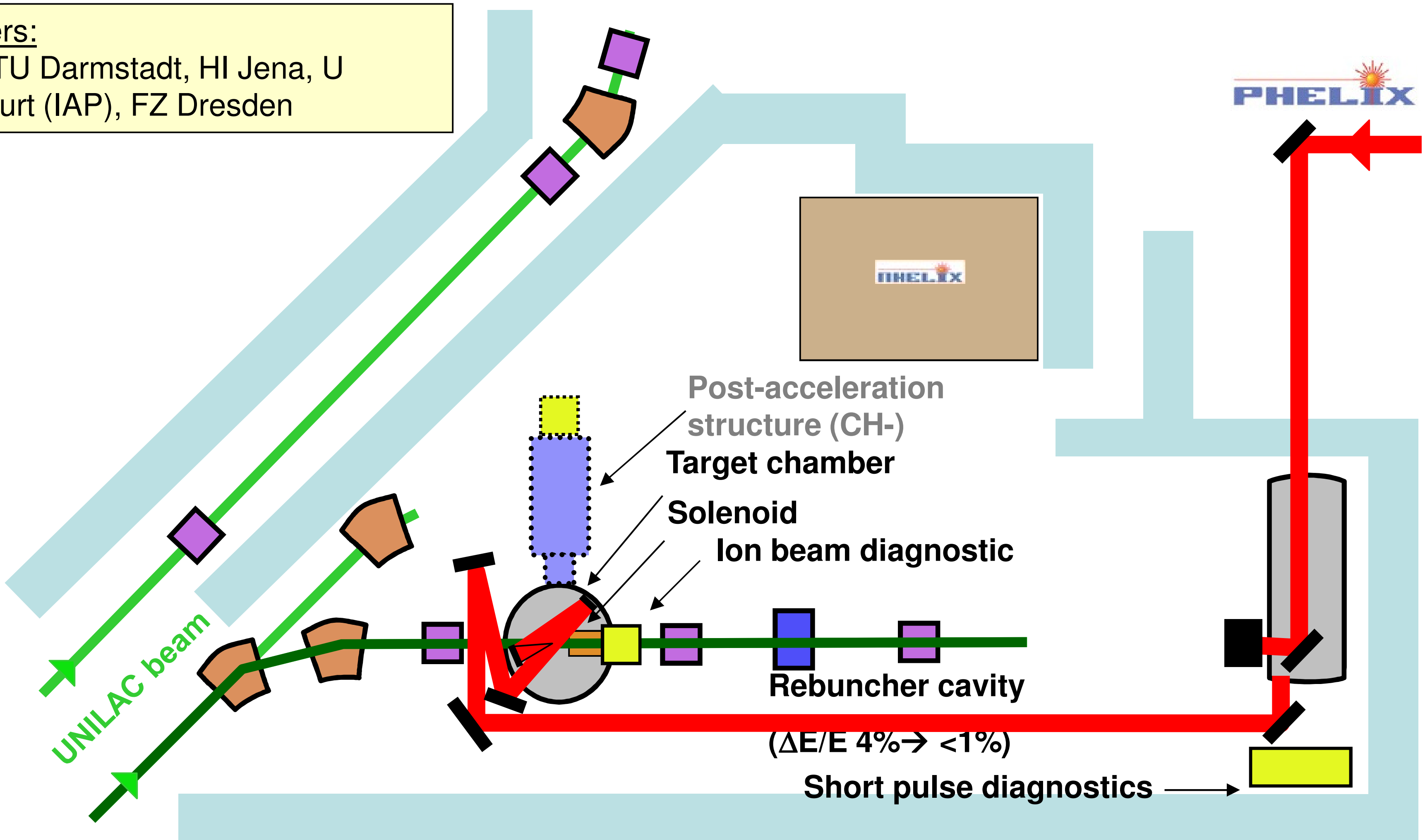
23 x Nature

18 x Science



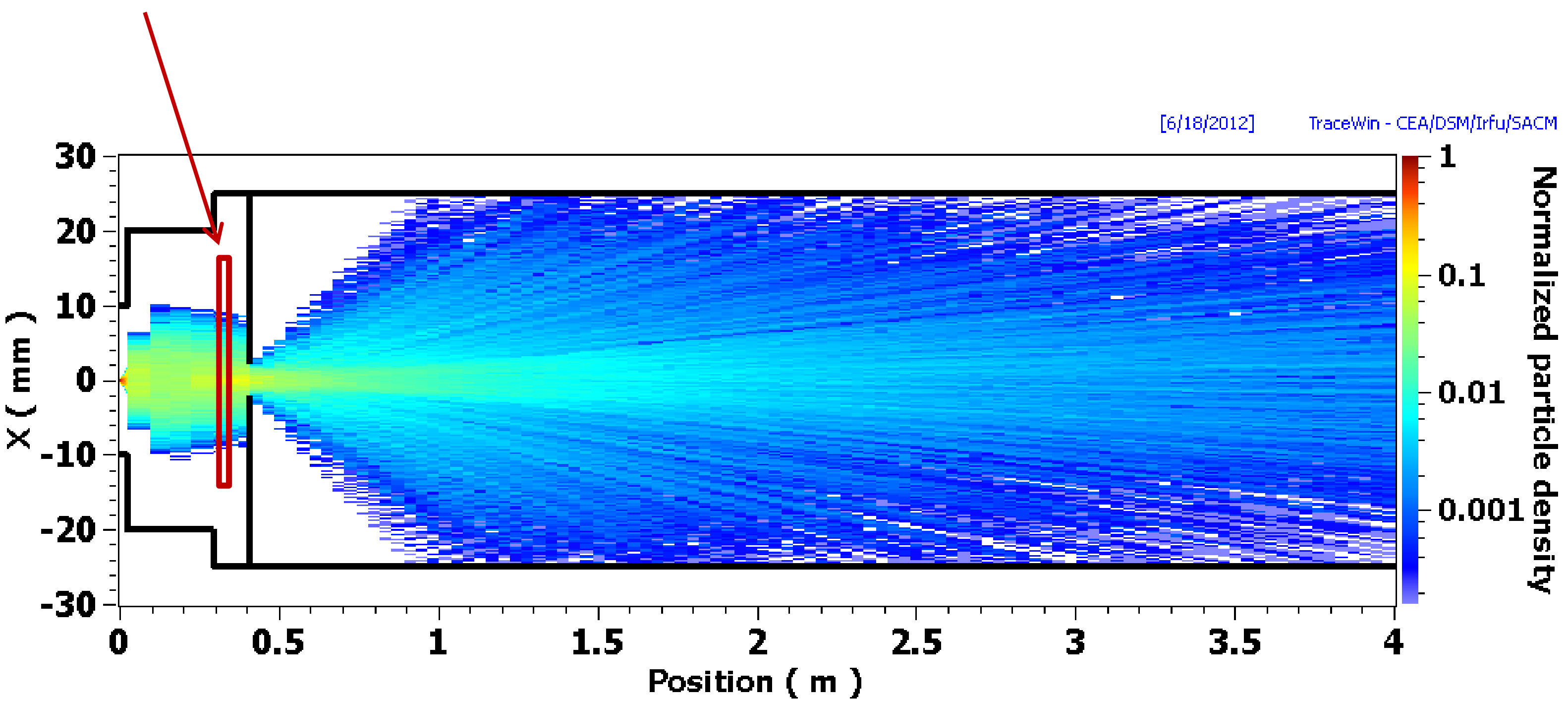
Opportunities @ LIGHT: Test stand at Z6 of GSI + Theoretical work FAIR-Theory group

Partners:
GSI , TU Darmstadt, HI Jena, U Frankfurt (IAP), FZ Dresden



Test issues of a reference beam at LIGHT

1. **Test energy selection and relationship $R_A - \alpha_{lens}$ (chromatic coefficient) by measuring energy profile (via time profile)**
2. **Electron stopping with sub-µm foil**
3. **"Smoothing" towards Gaussian reference beam with scatter targets**



Some conclusions

- ✓ Laser wakefield acceleration of electrons (1 GeV) "robust" scheme with challenging applications
- ✓ Laser proton acceleration now exceeding 100 MeV
- ✓ Good chance for medical application
  - ✓ Well-reproducible beam seems possible
  - ✓ Reliability of facility and cost?
- ✓ Several laboratories committed to advance use of laser acceleration for therapy