Collimation of laser accelerated ions and their application to therapy

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1. Introduction: proton drivers
2. Therapy requirements
3. Beam quality source-collimation-transport
4. Impact on specific laser acceleration model (Yan et al.)
5. Outlook & conclusions

Acknowledgment:

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TUD:
M. Roth et al.

MPQ:
J. Meyer-ter-Vehn, X. Yan

Conventional p Accelerators → Laser Accelerators?

Beam power – beam quality

	MeV	p/sec
SNS Oakridge (Spallation Neutron Source):	1000	**10^{16}**
FAIR-GSI p driver linac (→ antiproton facility) :	70	**$\sim 3\text{x}10^{13}$**
Proton therapy (typical):	~ 250	**$\sim 10^{10}$**

	SNS	FAIR-p-linac	HIT	**10 Hz PW laser system**
beam power:	1 MW	100 W	~ 0.2 W	**100 W (in photons)**

→ Laser p/ion acceleration has a potential to be competitive in therapy

→ efficiency of photons into protons/ions:
- ~ 10^{-3} seems enough, if all ions are "usable"
- ~ 10^{-2} needed if ~10% of ions "usable" for treatment → beam quality

Highly critical "review" of laser-proton therapy

by Linz & Alonso PRSTAB10, 094801 (2007):

"accelerator based therapy builds on half a century of development ..."

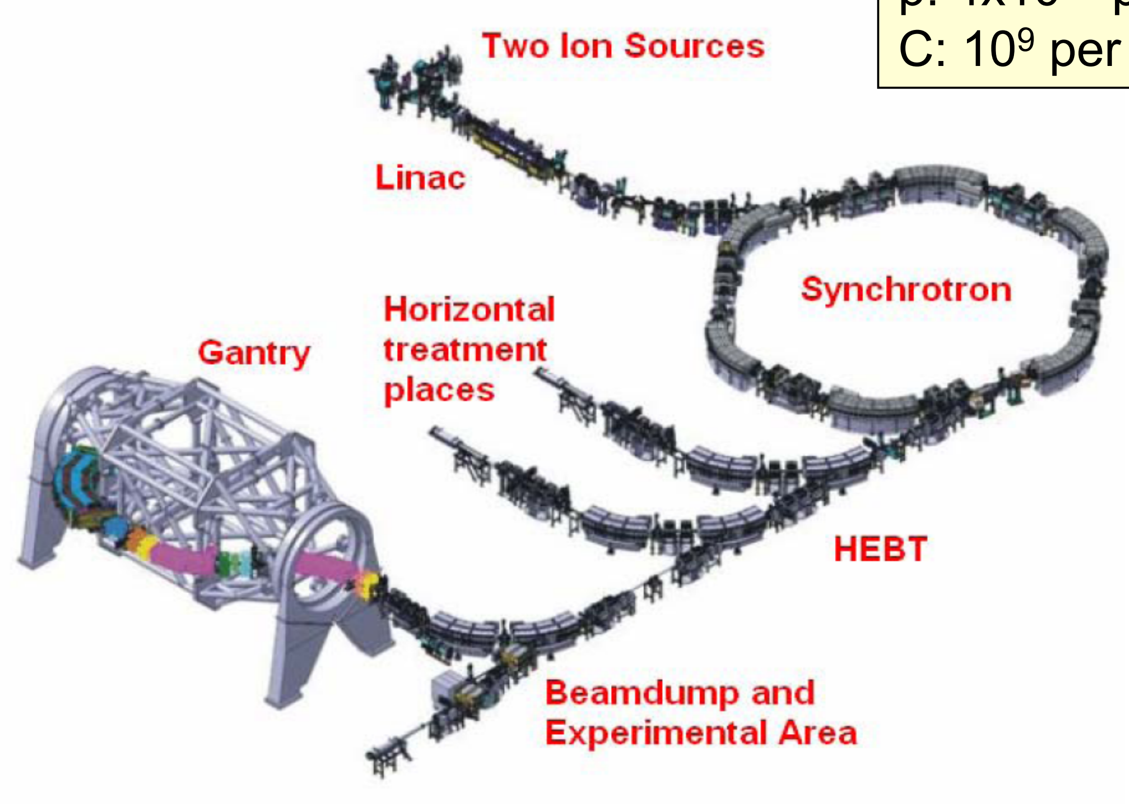
	Conventional (Cyclotron, Linac+Synchrotron)	Laser Accelerator
1. Beam Energy	200 – 250 MeV	in theory possible
2. Energy variability	"+" in synchrotron	? demanding
3. $\Delta E/E$	~ 0.1%	? demanding
4. Intensity	10^{10} /sec	$10^9/10^8$ at 10/100 Hz
5. Precision for scanning	"+" in synchrotrons	? large $\Delta p/p$

Linz & Alonso didn't quantify their highly critical arguments against laser acceleration!

Most advanced conventional approach: Heidelberg Ion Therapy Facility

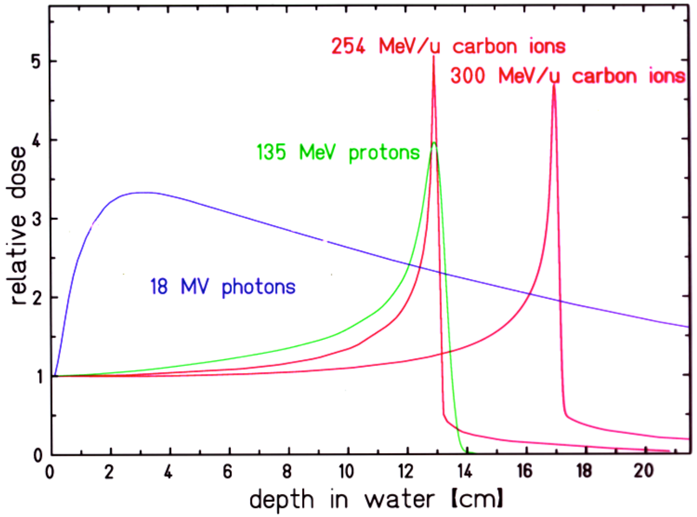
(HIT - accelerator built by GSI, fully operational since end of 2009)

Linac: 7 MeV/u
Synchrotron: 50-430 MeV p, He, C, O
p: 4x10^{10} per spill (1...10 s) → 430 MeV/u
C: 10^{9} per spill (1...10 s) → 250 MeV



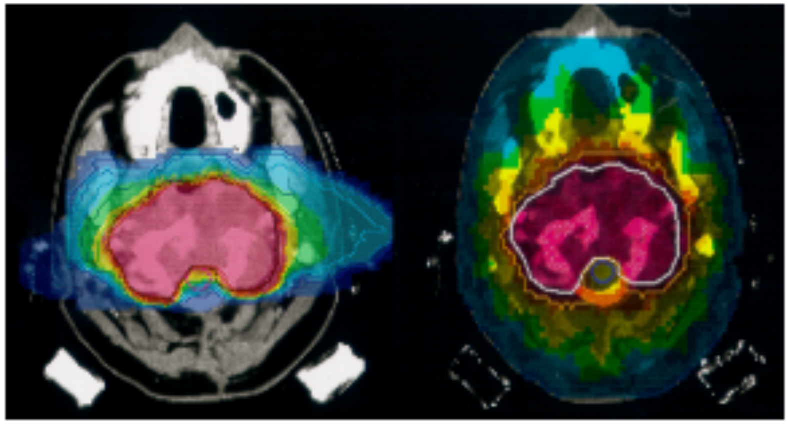
Ions versus photons (with e^- accelerators)

Ion Bragg peak:



C^{6+} ions
(2 sides)

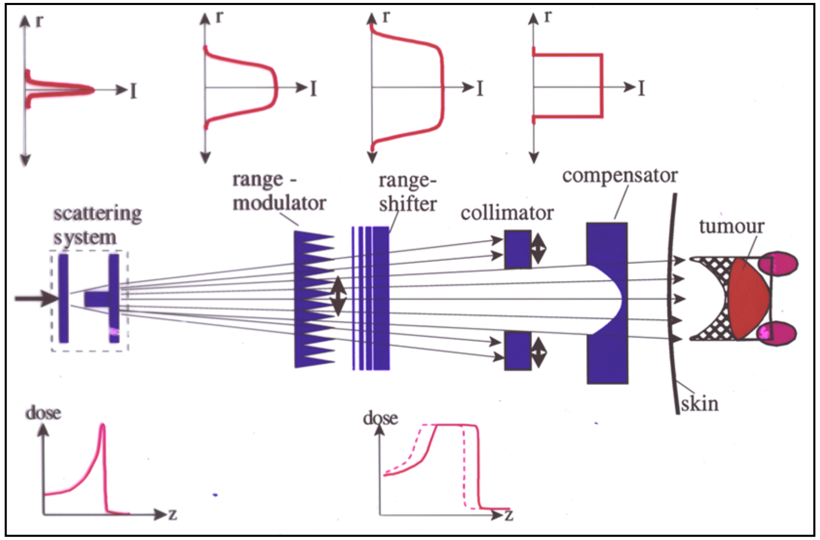
intensity modulated
photons
(9 fields)



requested dose

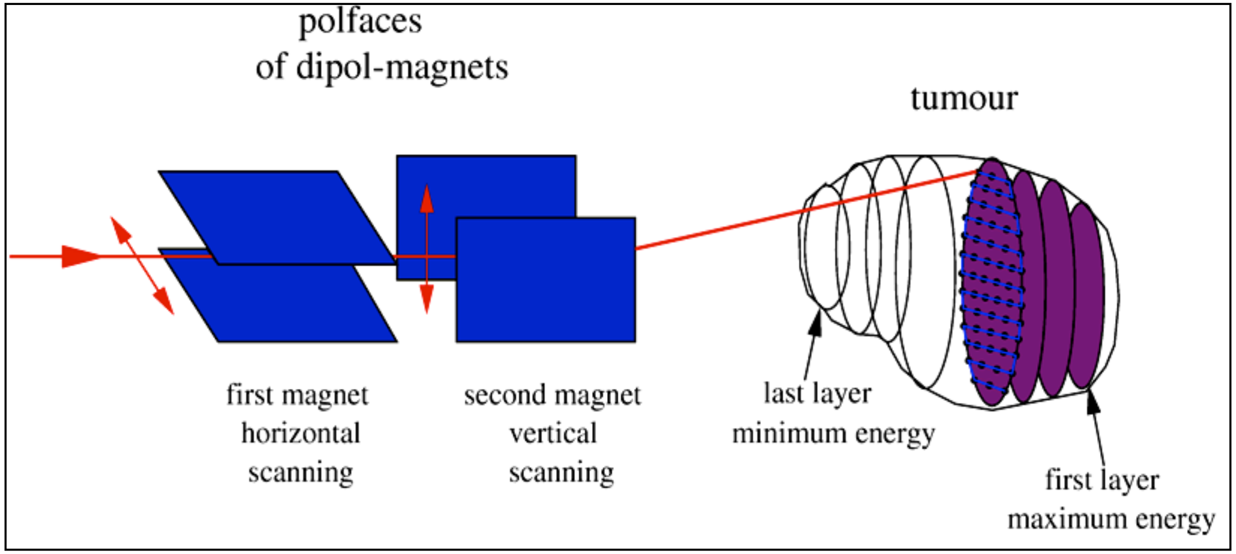
10% of requested

Passive beam modulation (cyclotrons) vs. Raster scanning (HIT)



no active manipulation
of beam (cylotrons)

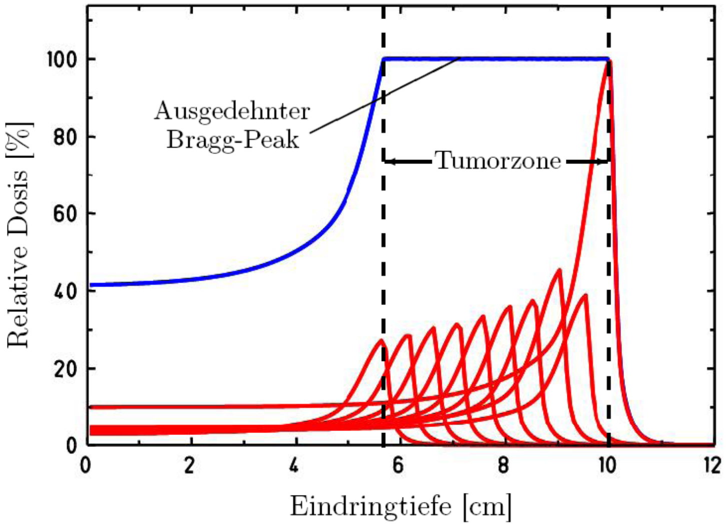
3D raster scanning:
lateral and depth scanning with
variable energy synchrotron beams

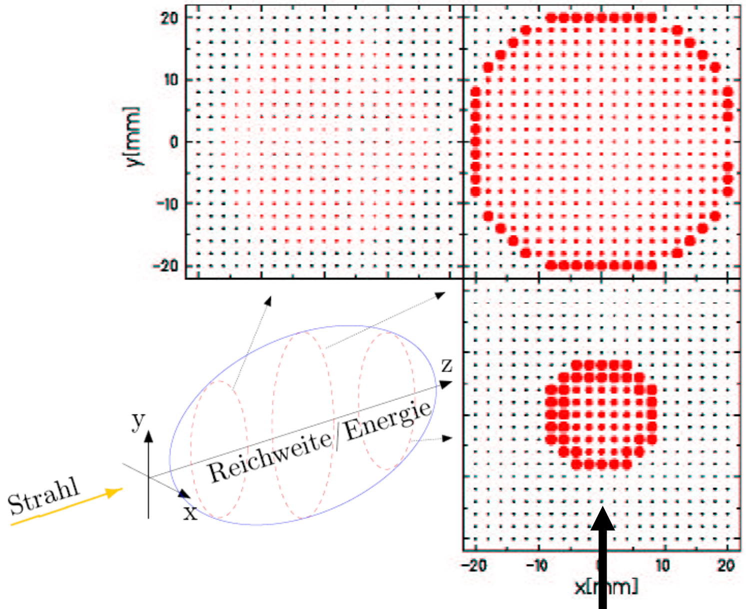


Layering in 3D

source: M. Horcicka

overlay of large number of different energy Bragg peaks to match longitudinally uniform tumor zone



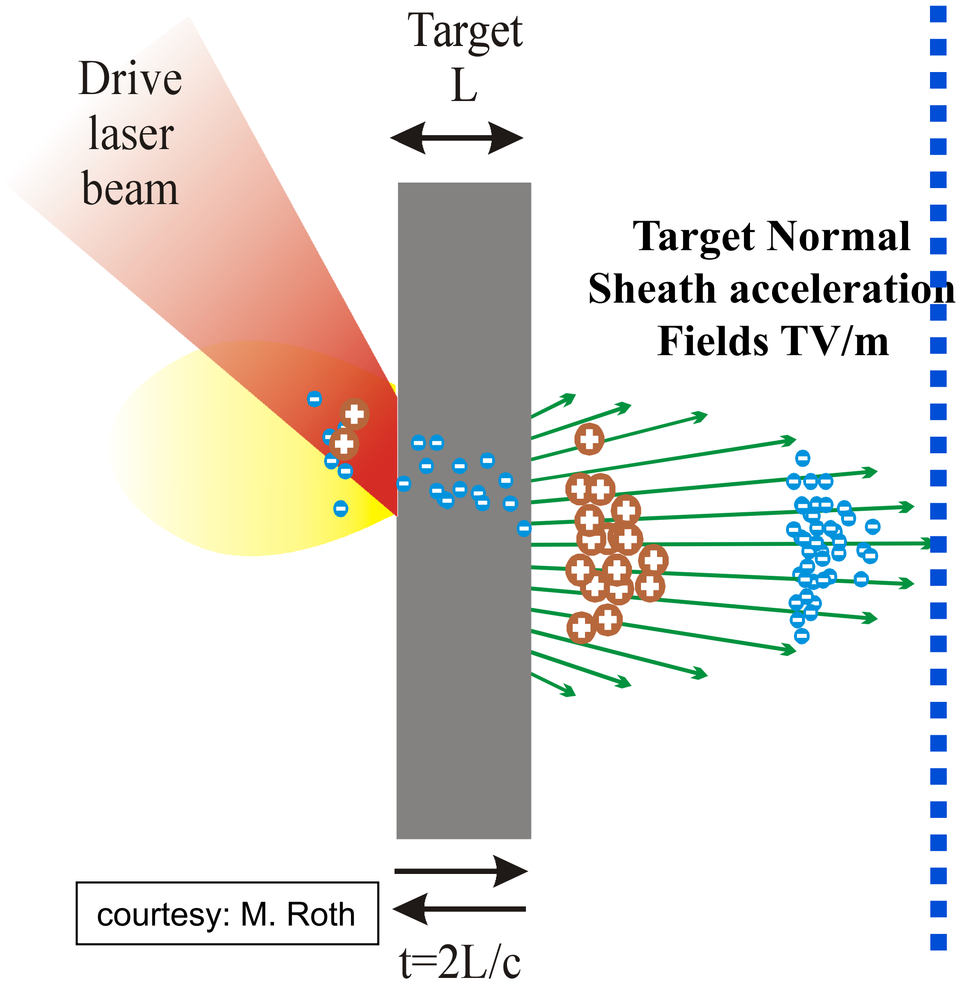


deepest layer

Competition: conventional - laser

- Cost argument: HIT ~ 70 Mio € high!
  - can lasers compete with it?
- Performance
  - beam quality + precision → this talk
  - reliability → high for synchrotrons
  - operational flexibility
    - no feedback on short laser-ion pulse (<ns)
    - < 5% tolerance on irradiation of a given pixel
  - advancement in treatment?
    - moving organs

Final quality of laser produced ion beams: depends on interfaces!



courtesy: M. Roth

collimator B- field region

plasma interface

space charge neutralized ion bunched
→
charge separation in B-field

collimator optics

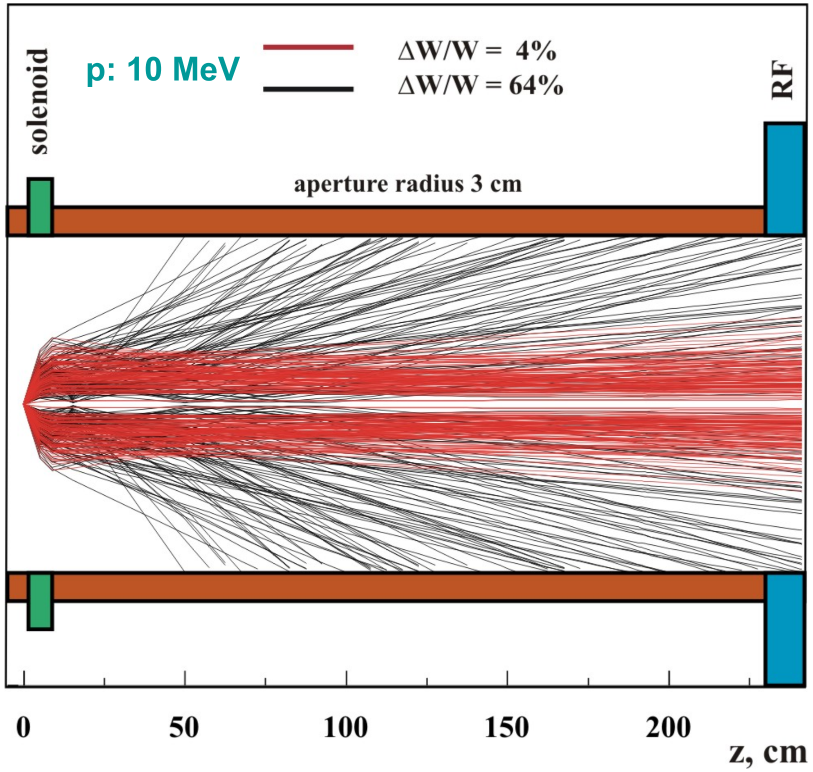
pure ion bunch – B-field aberrations

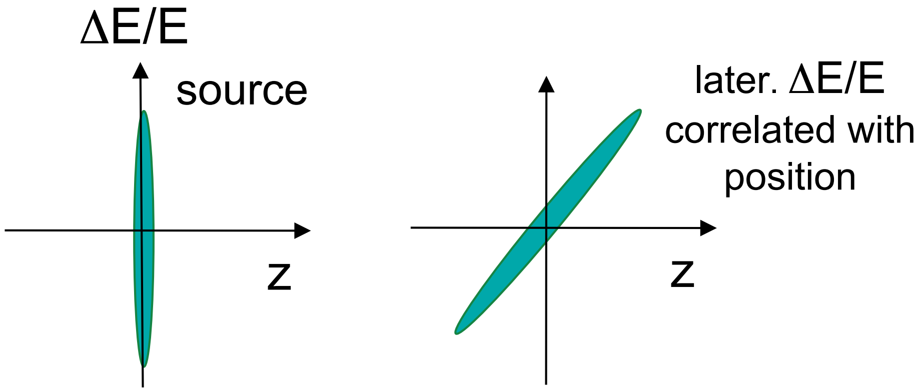
transport + focussing

conventional ion optics

6 D phase space volume: very small | filamentation? | effective increase | ~ constant

Chromatic effect in collimation lens (solenoid, quadrupoles) blows up effective emittance



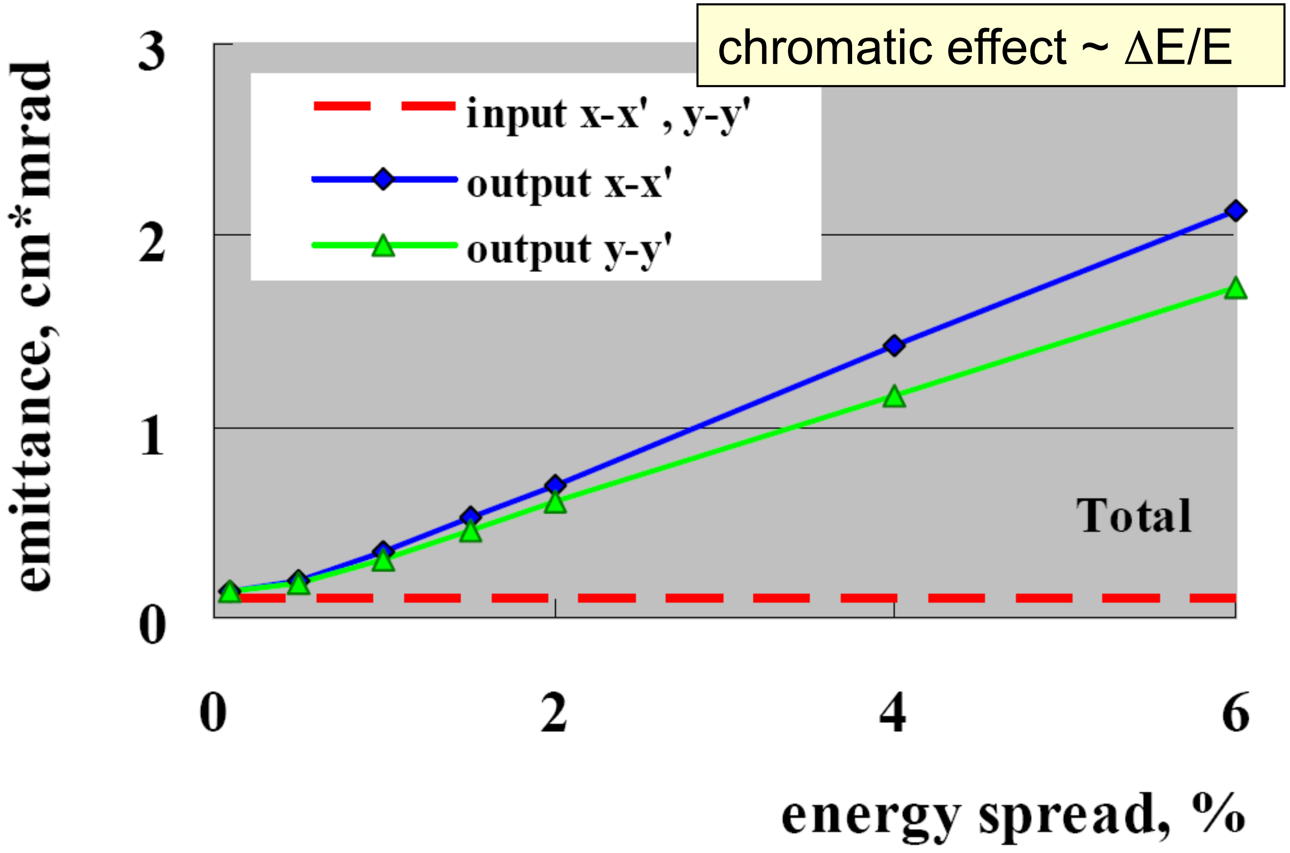


emittance = phase space volume

very high laser power →

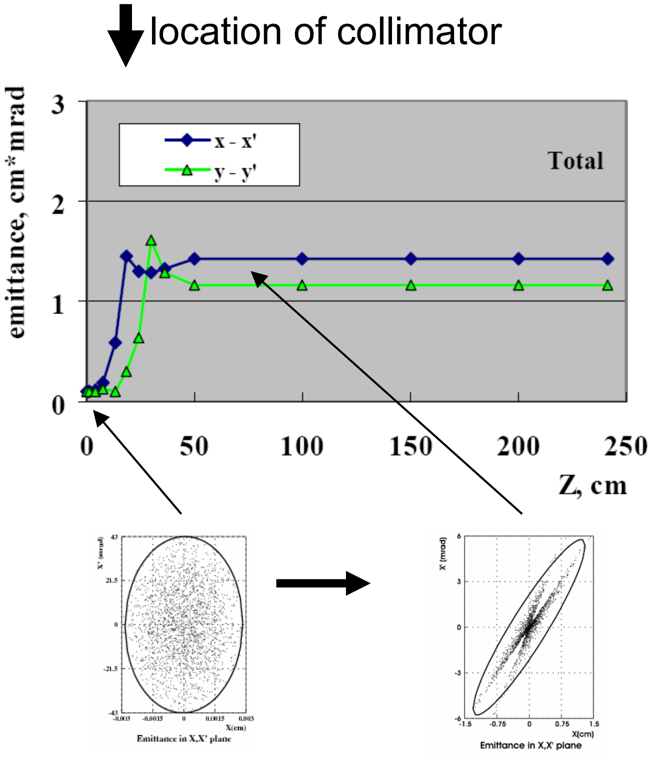
- extremely high initial phase space density
- but strong distortion in lens region along bunch → increased "effective" emittance
- how does it scale?

Detailed tracking simulation with DYNAMION* code (quadrupole channel)



chromatic effect ~ ΔE/E

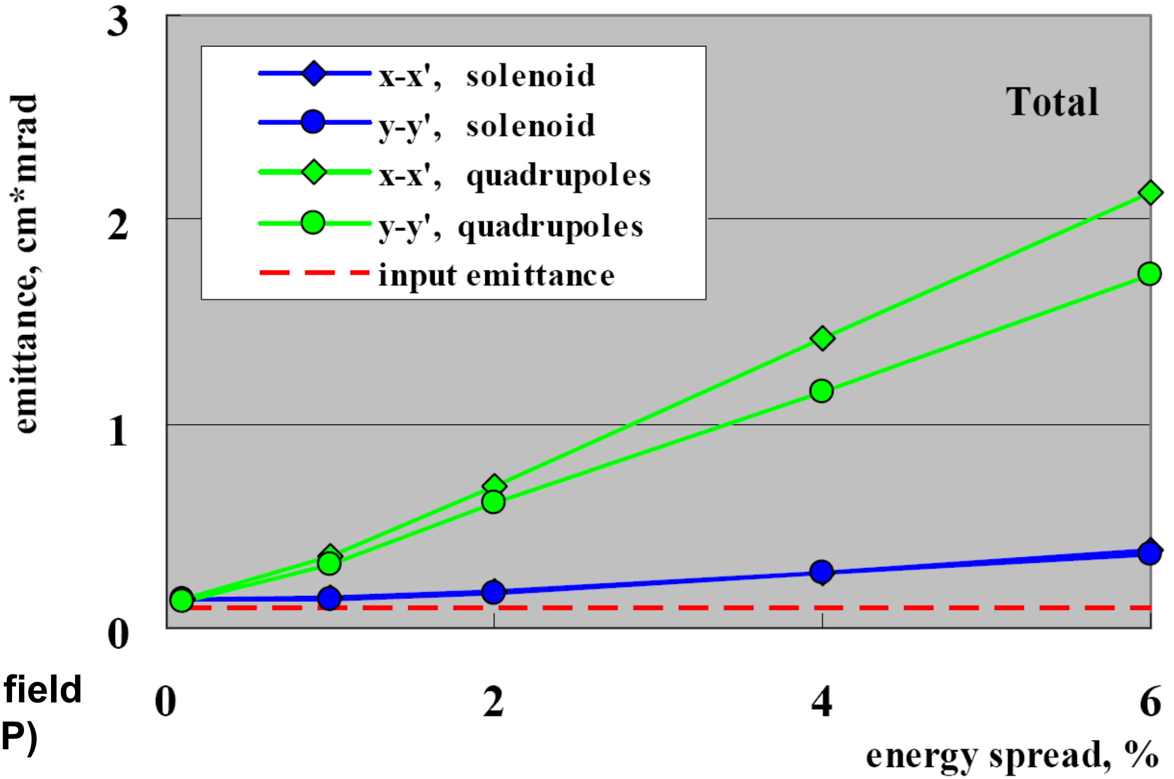
location of collimator



(zoomed out)

* S. Yaramishev et. al.

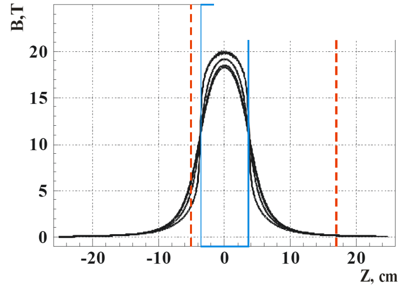
DYNAMION: comparison of quadrupole and solenoid collimators / cone angle of 2.5^0



◊ linear law

$\varepsilon_{chromatic}$ ~ ΔE/E

"real" solenoid field
(M. Droba, IAP)

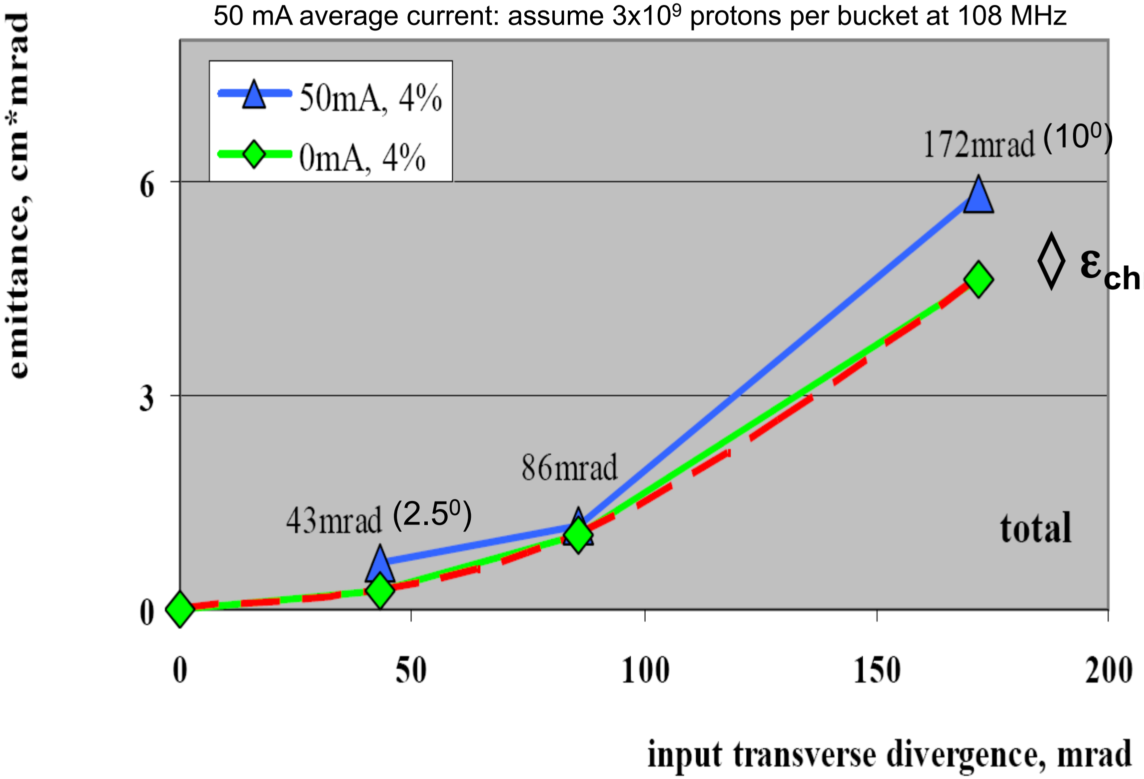


solenoid at GSI – PHELIX experiment

- 75 mm long → requires large field of 16 T for 10 MeV protons
- symmetric focusing of solenoid avoids large excursions as in quadrupoles

Combined chromatic and space charge effects → defines "usable" (=chromatic) emittance

50 mA average current: assume 3×10^9 protons per bucket at 108 MHz



◊ $\varepsilon_{\text{chromatic}} \sim (x')^2_{\text{source}}$

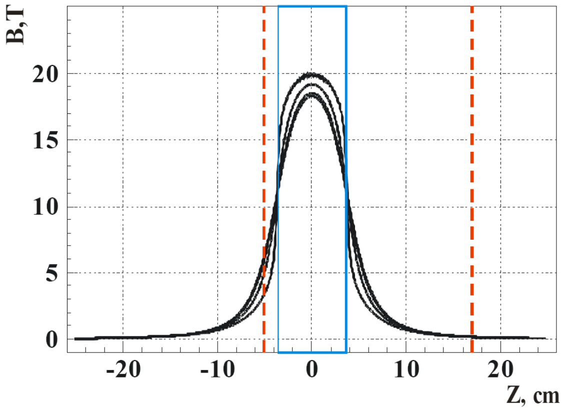
$$\boxed{\varepsilon_{\text{chromatic}} = \alpha_c\, \Delta E/E\, (x')^2_{\text{source}}}$$

"design basis"

find α_c = 0.04 m/rad
for present solenoid (75 mm)

Collimator lens technical constraints

coefficient α_c depends on
- length of solenoid
- distance source to solenoid (helps reduce B-field)
- (B x length) fixed for MeV
- pulsed solenoid at 10 Hz?



$$\varepsilon_{chromatic} = \alpha_c \, (x')^2_{source} \, \Delta E/E$$

			α_C	
10 MeV p:	**~ 6-8 T**	**15 cm**	**0.1**	**new solenoid from FZ Dresden-R.** (used in PHELIX)
250 MeV p:	**~ 6-8 T**	**75 cm**	**0.5**	**extrapolation to therapy application**
430 MeV/u C^{6+}:	**~ 9-12 T**	**150 cm**	**1**	**" "**
quadruple lenses:	**~ 2 T**		**5 ... 10**	

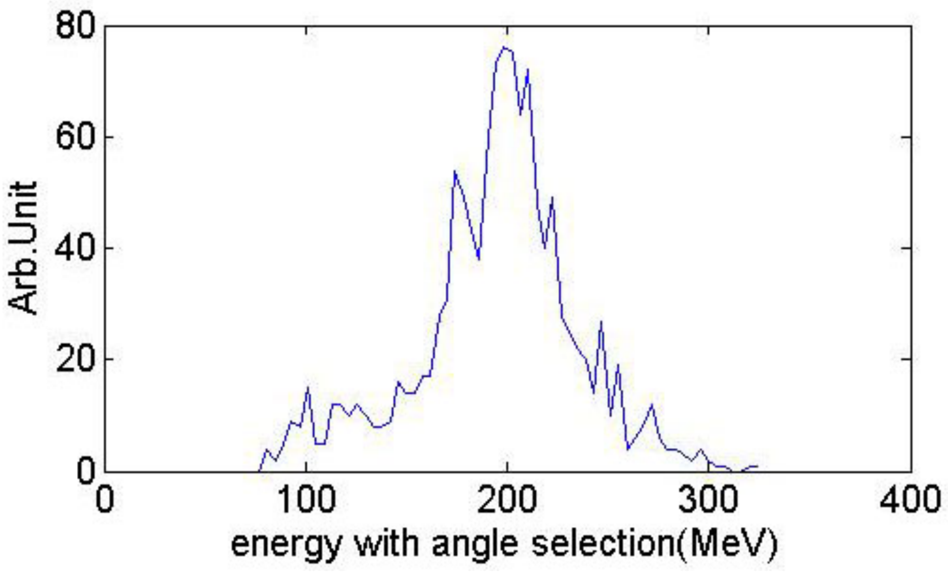
Case study using RPA by X. Yan et al.:

laser acceleration of p to 200 MeV using simulation particle spectrum (PRL, 2009) for 200 MeV p

- claim > 10^{10} p for energies up to GeV with 10^{22} W/cm^2
- narrow peaked energy spectrum ("clump")
- a "theoretical model"

Radiation Pressure Acceleration
from nm thick C foils

- > 3 10^{21} W/cm^2 / 45 fs
- results from 2D numerical situation with circular polarized light
- critical issues!

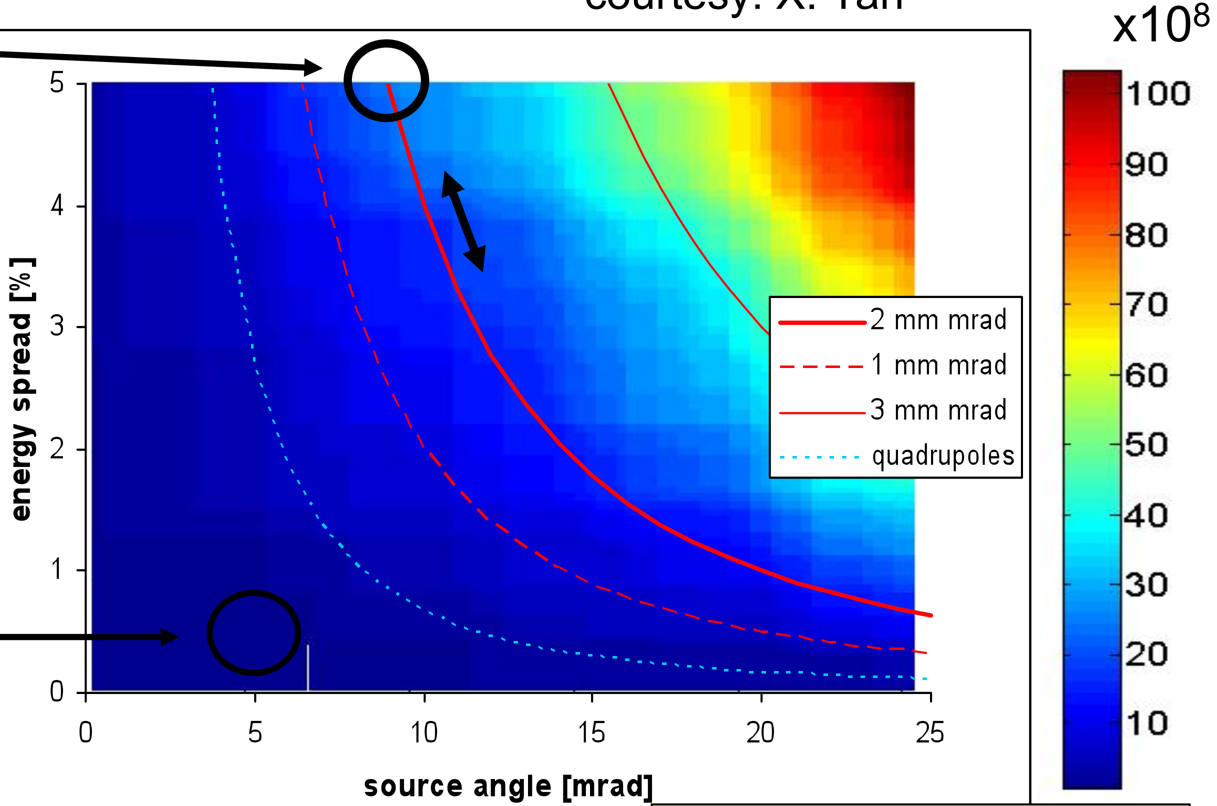


Simulation yield folded with constant "chromatic" emittance scaling law

laser acceration:
cylindrical voxel with
$\Delta E/E$~5%
and <10^9 protons
→ factor 3 margin!
~ 0.5° source angle

conventional
synchrotron 3D voxel
with $\Delta E/E$<0.5%

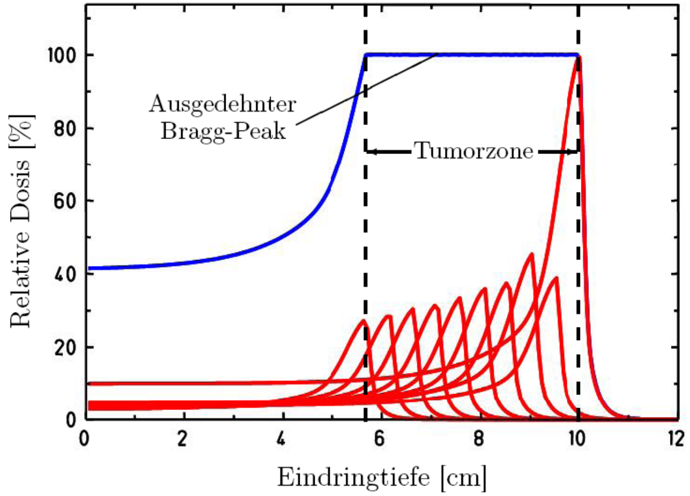
courtesy: X. Yan



assumed α_c ~ 0.5
(pulsed solenoid collimator)

Better match to laser ions: use larger ΔE – more ions per shot

~ 5-10% of total yield!



Bragg peaks overlay

- ~ 50 discrete energies for synchrotron
- use only 5-10 energies with laser (detailed study required)
- vary energy by absorber wedges

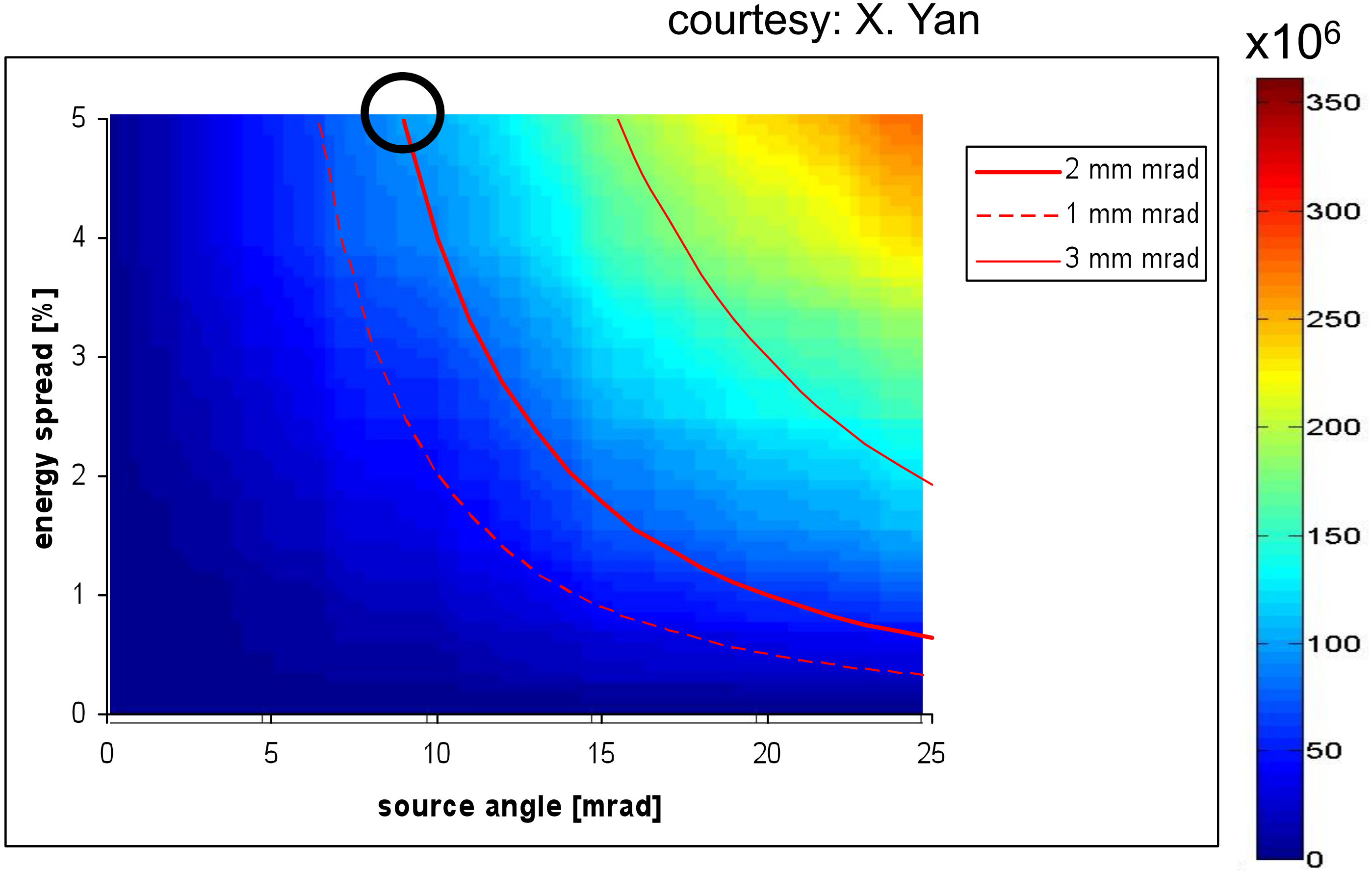
< 5% irradiation fluctuation on a volume element required by law!

- fluctuations need to be demonstrated by experiments (center energy stability?)
- crucial issue as only 1 laser shot per volume element – feedback on intensity not feasible (~ ns pulse length)
- employing only 5-10% core of production phase space reduces sensitivity to shot-to-shot energy variations

Extension of Yan et al. to C^{6+} accelerated to 400 MeV/u

laser based
cylindrical voxel with
$\Delta E/E \sim 5\%$
and $<25\times10^{6}$ C^{6+}
→ easily available

courtesy: X. Yan



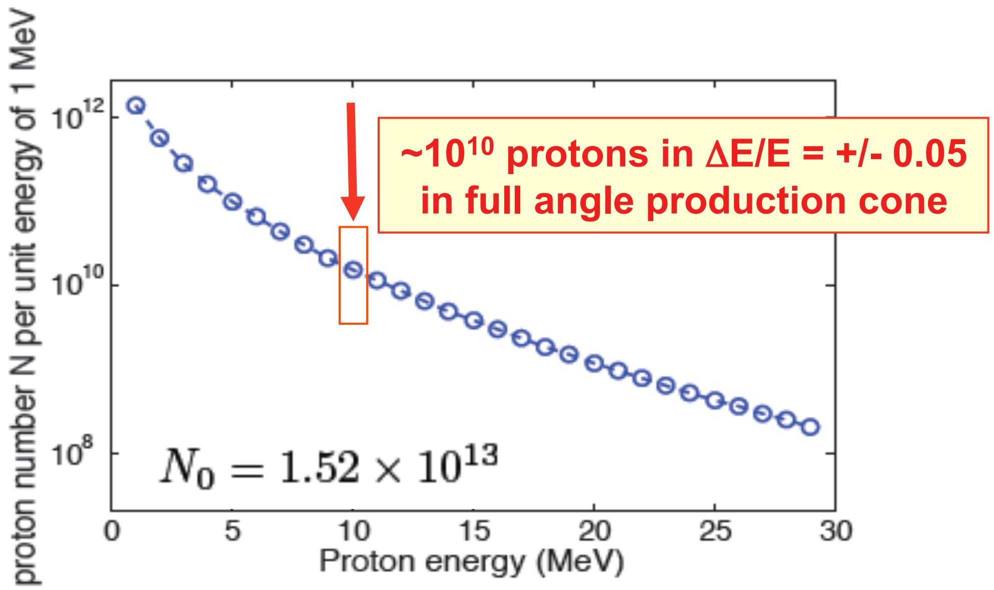
assumed $\alpha_c \sim 1$
(pulsed solenoid collimator)

Requirements compared with HIT

(Heidelberg Ion Therapy)

	p / C^{6+} (HIT)	10 Hz laser system
➢ particles / fraction (15 min):	$2\ 10^{12}$ / $5\ 10^{10}$	
shared by voxels:	20 k	2 -4 k
➢ energy range:	50-250 MeV / 88-430 MeV/u	
➢ energy steps:	~ 50	5-10
➢ intensity variation:	10^{-3} ... 1	
➢ beam size (fwhm):	4-10 mm	
➢ emittance (before window):	2-3 mm mrad	
➢ energy width:	< 0.005	~0.05

Scaling will be tested at PHELIX laser proton acceleration experiment:



~10^{10} protons in $\Delta E/E$ = +/- 0.05 in full angle production cone

our scaling predicts:

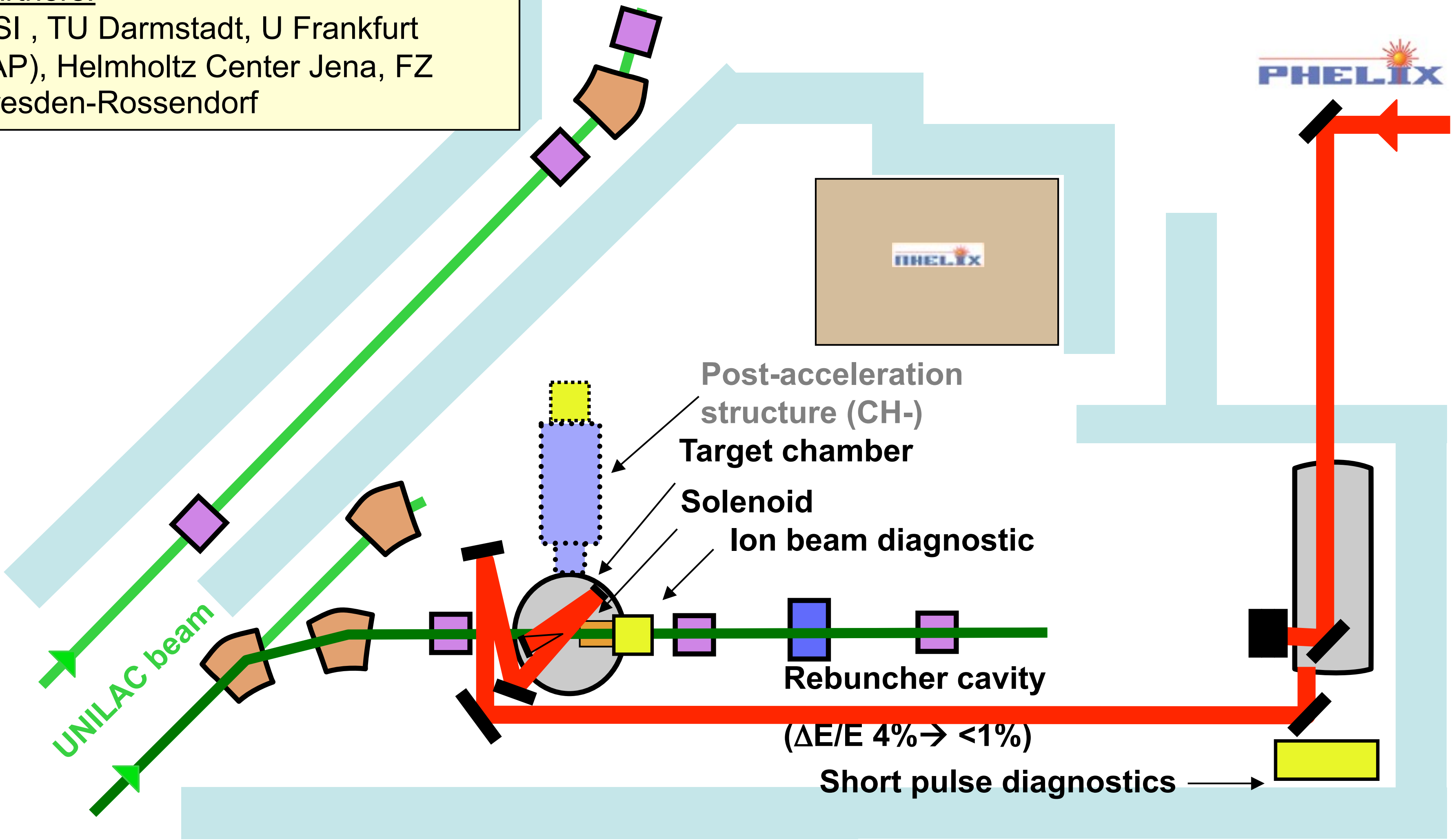
$\Delta E/E$= +/- 0.05 and x'_{source}= 172 mrad (10°) → $\varepsilon_{chromatic}$ ~ 100 mm mrad

→ 10^{10} protons (0.1% of total yield)

Test stand at GSI Z6 experimental area

accelerator equipment + new PHELIX beam line

Partners:
GSI , TU Darmstadt, U Frankfurt (IAP), Helmholtz Center Jena, FZ Dresden-Rossendorf



Conclusions

- extremely high initial phase space density degraded after first collimator
  - reduced "usable" fraction of total particle yield due to chromatic effect
  - found a scaling law for emittance
- applied "successfully" to model by X. Yan et al. on RPA
  - cut out small core of production cone (~ 0.5^0) and $\Delta E/E \sim 5\%$ to match with emittance requirement
  - "broadened" Bragg peak expected to be sufficient for radiation uniformity for only 5-10 energy groups (→detailed analysis needed)
- open:
  - does RPA acceleration work?
  - shot-shot intensity fluctuations <5% - data needed
  - have not examined >>10 Hz (kHz) laser systems