Performance of laser accelerated ion beams for therapy applications

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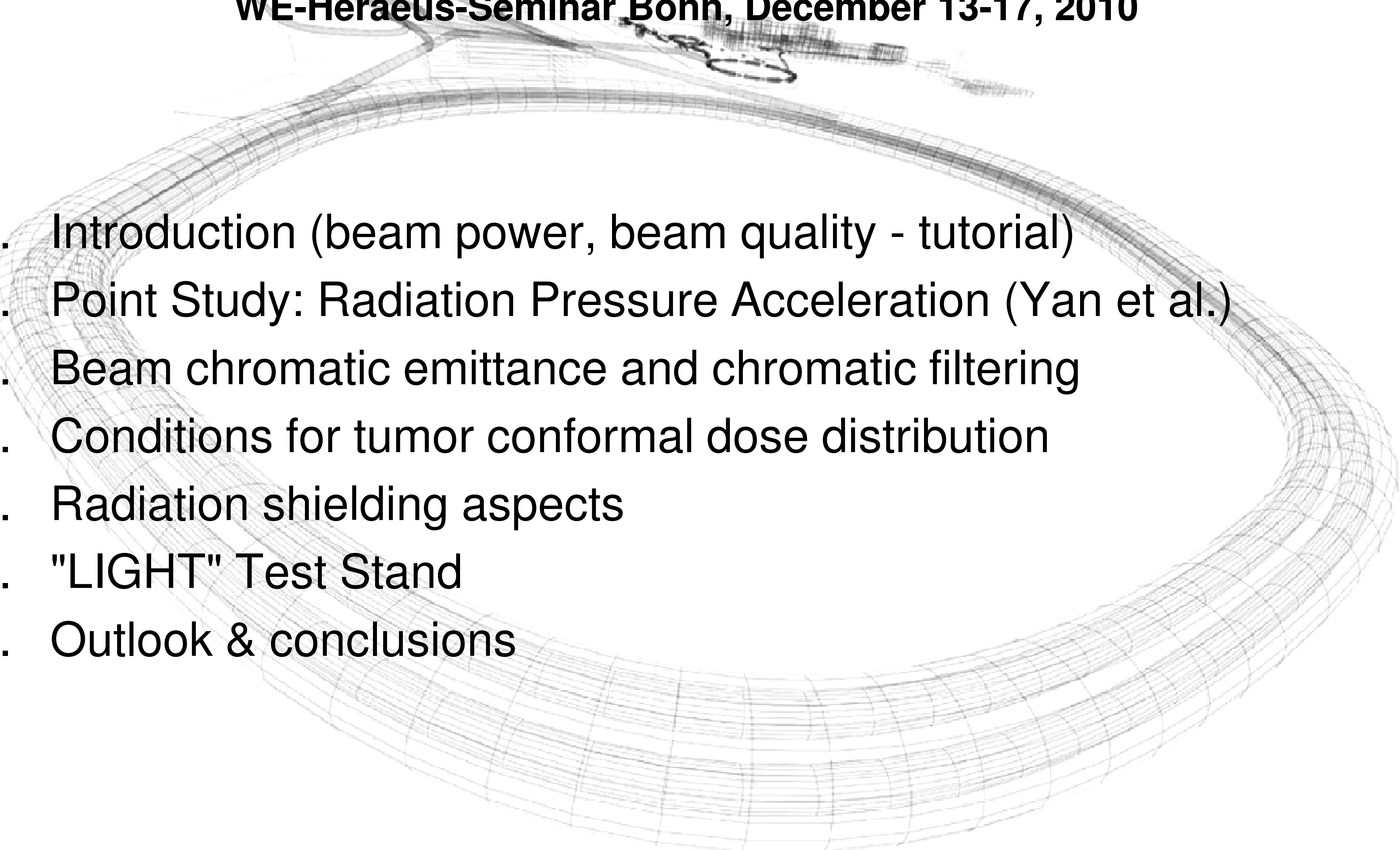

1. Introduction (beam power, beam quality - tutorial)
2. Point Study: Radiation Pressure Acceleration (Yan et al.)
3. Beam chromatic emittance and chromatic filtering
4. Conditions for tumor conformal dose distribution
5. Radiation shielding aspects
6. "LIGHT" Test Stand
7. Outlook & conclusions

Acknowledgment:

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LIGHT-collaboration

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

Progress in laser ion acceleration

Laser ion acceleration has triggered enthusiasm
towards potential therapy applications due to:

- required energies are approached (60 MeV p)
- high "quality" of beams (small 6D phase space)
- abundance of protons per shot (> 10^{11})
- high rep rate laser available (10 Hz)
- laser accelerator compact

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 (p)	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!
- Laser ions require different path than accelerator ions!
- Quantify here along one model of laser acceleration (point study)

Beam power - can lasers compete with?

High beam power is crucial for many accelerator applications, where high rates of "secondary particles" are needed

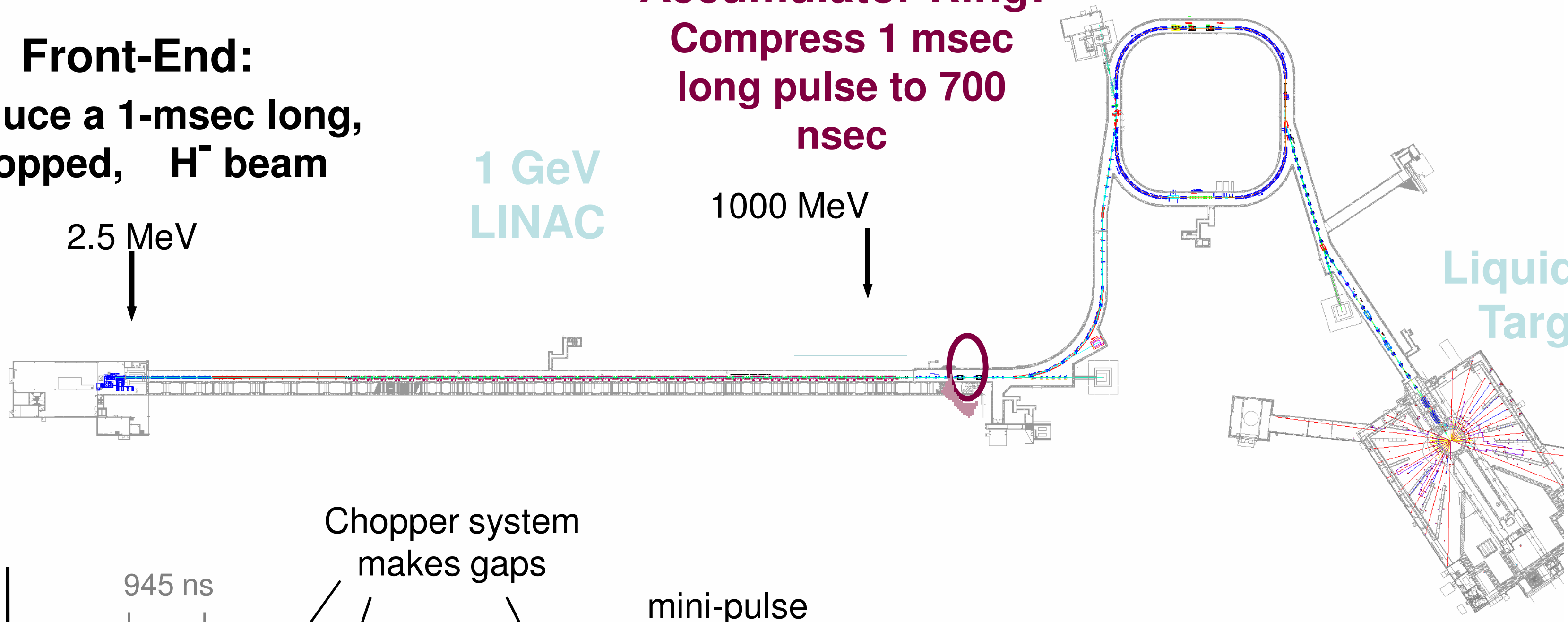
- spallation neutron sources (material research etc., SNS, JPARC, ESS, ...) 1-10 MW
- radioactive beams (nuclei off stability, FAIR-GSI, FRIB, ...)
- nuclear waste transmutation (accelerator driven reactors to burn waste, MYRRHA-project in EU) 10-50 MW
- neutrino factories ~ few MW proton driver

SNS Accelerator Complex

Spallation Neutron Source, Oakridge

Front-End:

Produce a 1-msec long, chopped, H^- beam



2.5 MeV

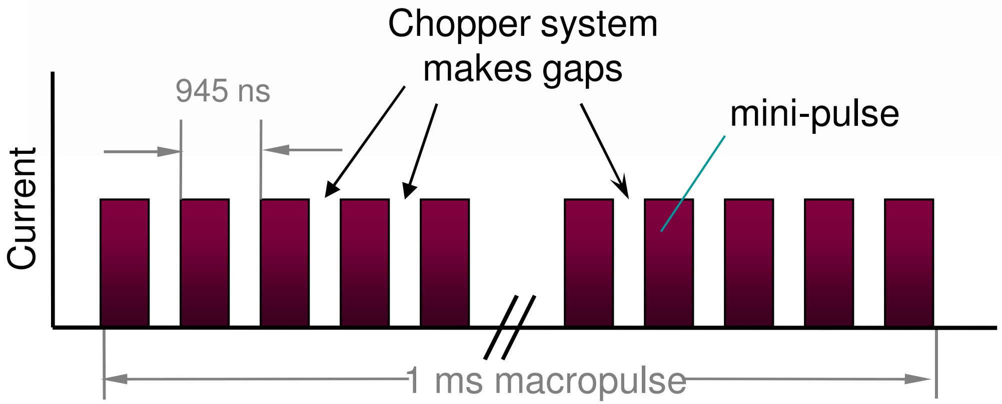
1 GeV LINAC

1000 MeV

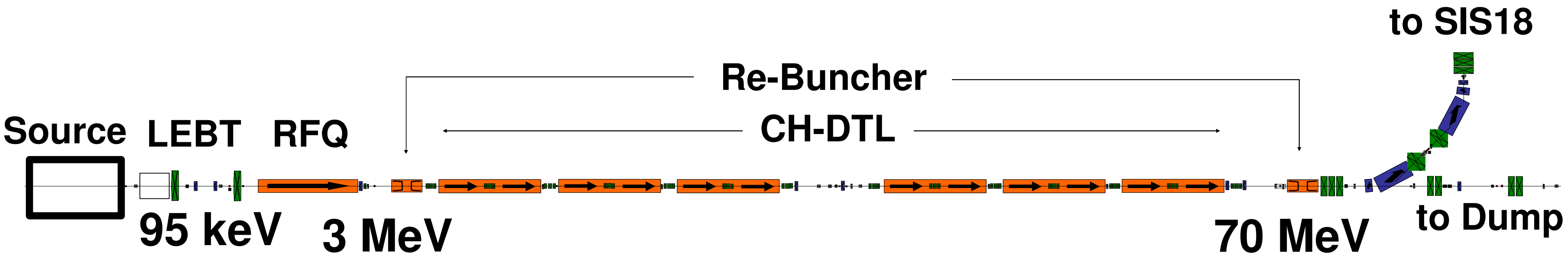
Accumulator Ring:

Compress 1 msec long pulse to 700 nsec

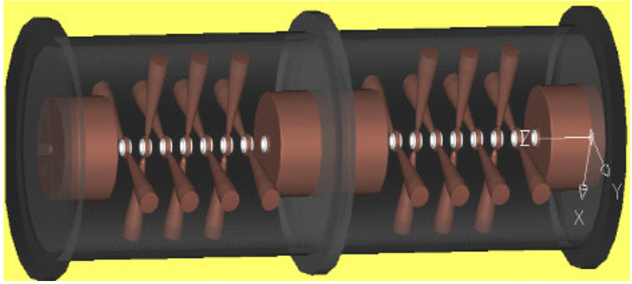
Liquid Hg Target



New Proton Linac Injector for FAIR at GSI



Crossed-bar H-Structure



(Univ. Frankfurt U. Ratzinger)

Beam Energy	70 MeV
Beam Current	70 mA
Protons / Pulse	$7 \cdot 10^{12}$
Pulse Length	36 µs
Repetition Rate	4 Hz
RF Frequency	352 MHz

Conventional p Accelerators   Laser Accelerators

Beam power

	MeV	p/sec	beam power
SNS Oakridge (Spallation Neutron Source):	1000	**10^{16}**	1 MW (average) (50 MW in 600ns)
FAIR-GSI p driver linac (antiproton facility) :	70	**~$3x10^{13}$**	100 (MW in 30µs)
Proton therapy (typical, 10^{9} per shot):	~ 250	**<10^{10}**	~ 0.2 W

10 Hz/10 J Petawatt class laser (today) ~ 100 W average power

efficiency of photons into protons/ions:

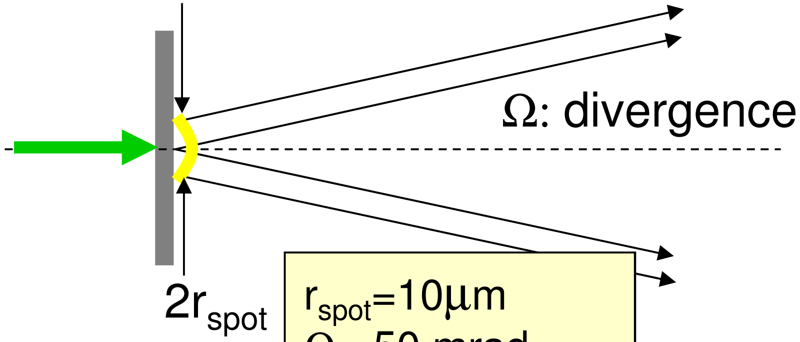
- ~ 10^{-2} is realistic efficiency
- ~ 1 W proton beam possible - "overproduction" for therapy needs
- therapy application within reach in terms of average power

Beam quality

transverse emittance: $\varepsilon = r_{spot} \times \Omega$ [mm mrad}

RF accelerator

Laser accelerator



Spallation Neutron Source (SNS):
$\varepsilon = \varepsilon_n/(\beta\gamma) \sim 0.3$ mm mrad ($\beta = v/c$)
$\varepsilon \sim 3$ mm mrad at 10 MeV
$\varepsilon \sim 0.3$ mm mrad at 1 GeV

$r_{spot} = 10\mu m$
$\Omega = 50$ mrad
$\varepsilon = 0.5$ mm mrad

longitudinal phase space area eV x sec

typically 10^{-3} eVsec in a linac bunch
(independent of β)
0.5 eVsec in a synchrotron

typically 10^{-6} eVsec due to short laser pulse

but: the large eV spread "spoils" emittance after focusing

High beam quality – small emittance

Sufficiently small beam emittance can be important:

- avoid beam loss in high power accelerators
  - in linear accelerators 1 W/m beam loss criterion for hands-on maintenance
- secondary particle collection: efficient collection requires **small angles and energy spread** (antiproton collector from proton target etc.) - stronger criterion!
- in laser produced beams (unfortunately) angles and energy spread not so small
- high resolution target experiments

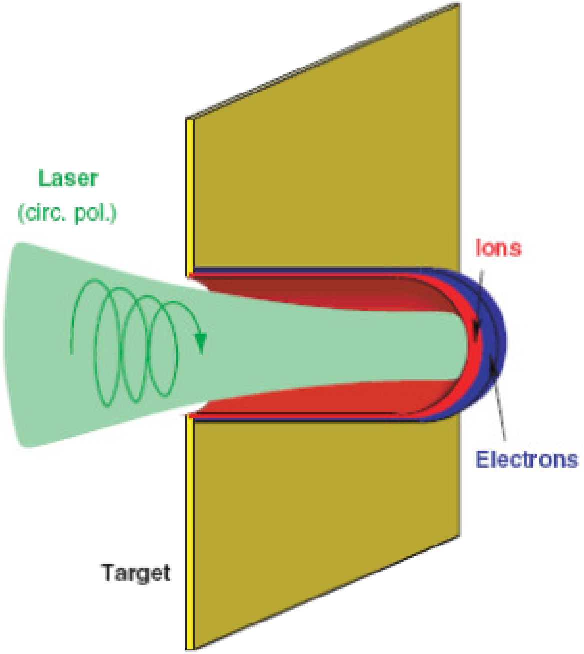
"Point Study": Coherent Acceleration of Ions (CAI, RPA, 2009)

using simulation model by X. Yan et al. - "one of several models"

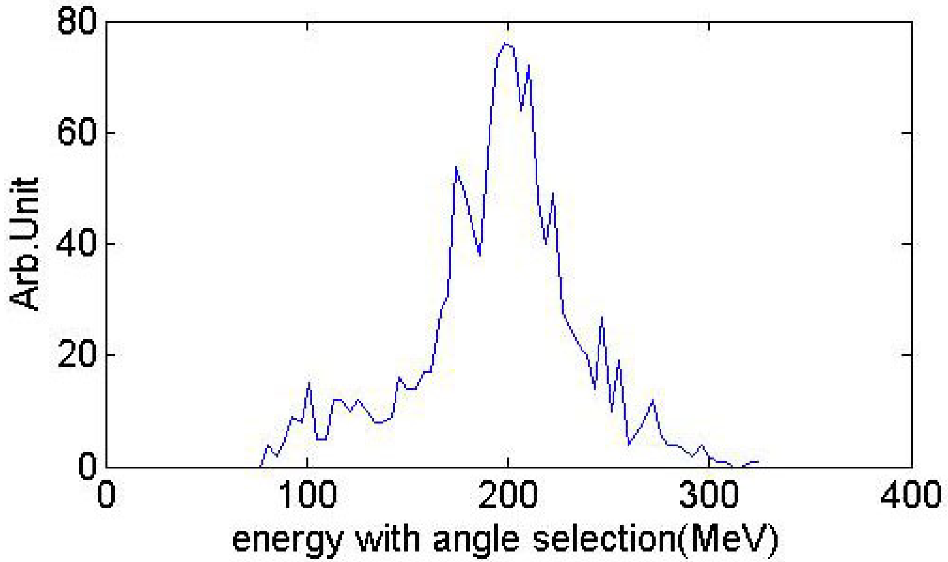
- claim ~ 10^{12} p for energies up to GeV with 10^{22} W/cm^2
- "narrow" peaked energy spectrum ("clump")
- a "theoretical model" – not the only one!

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
- critical issues!
- note: p yield factor 5-10 lower for 5 μm spot radius we discuss high yield case (higher laser energy)

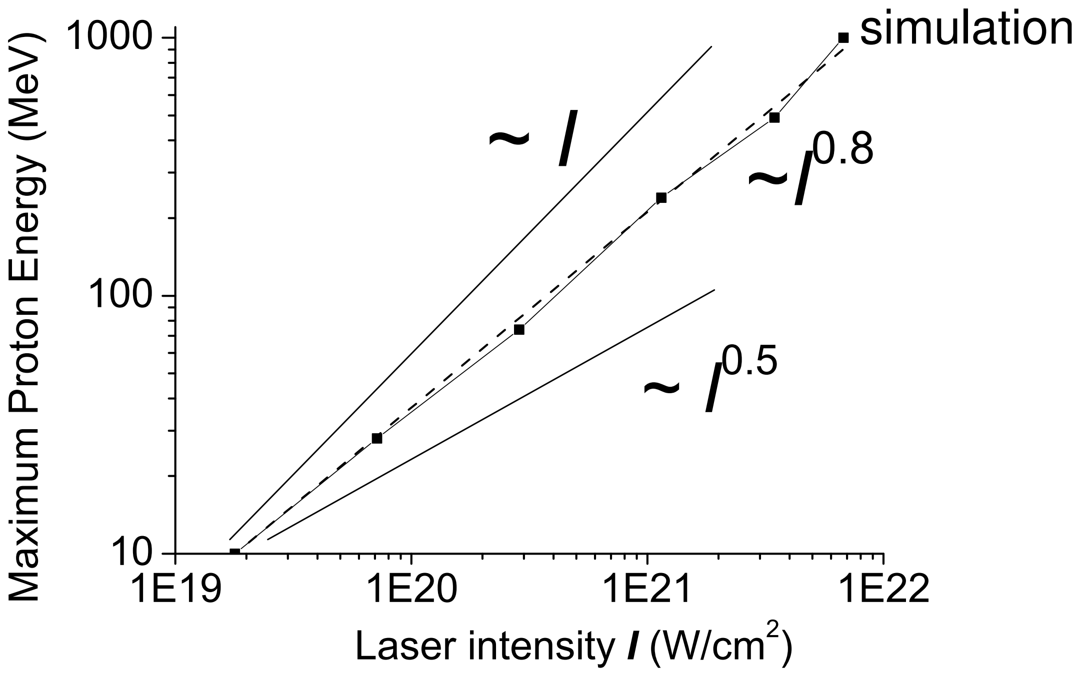


source: Tajima et al., RAST 2, 2009



Proton energy scaling

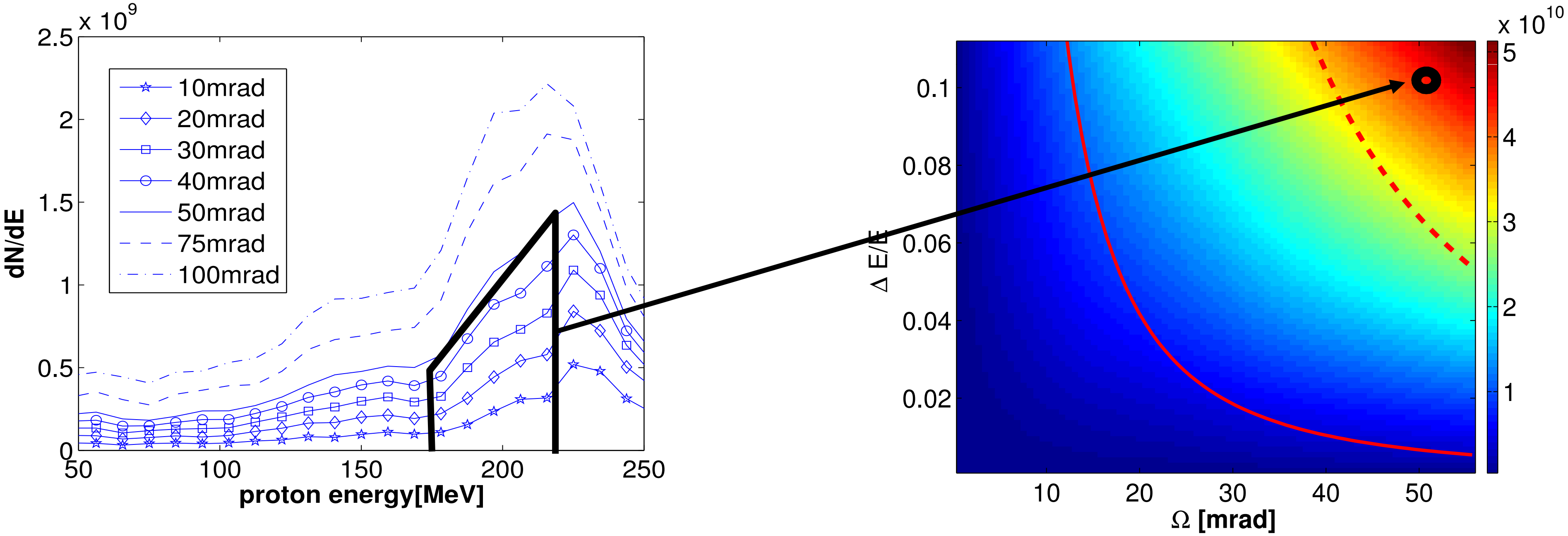
E_{max} ~ I (analytical) or $I^{0.8}$ (simulation)
due to **self-organizing** regime with relativistic
transparency in outer region of spot
(Yan et al. PRL 103, 2009)



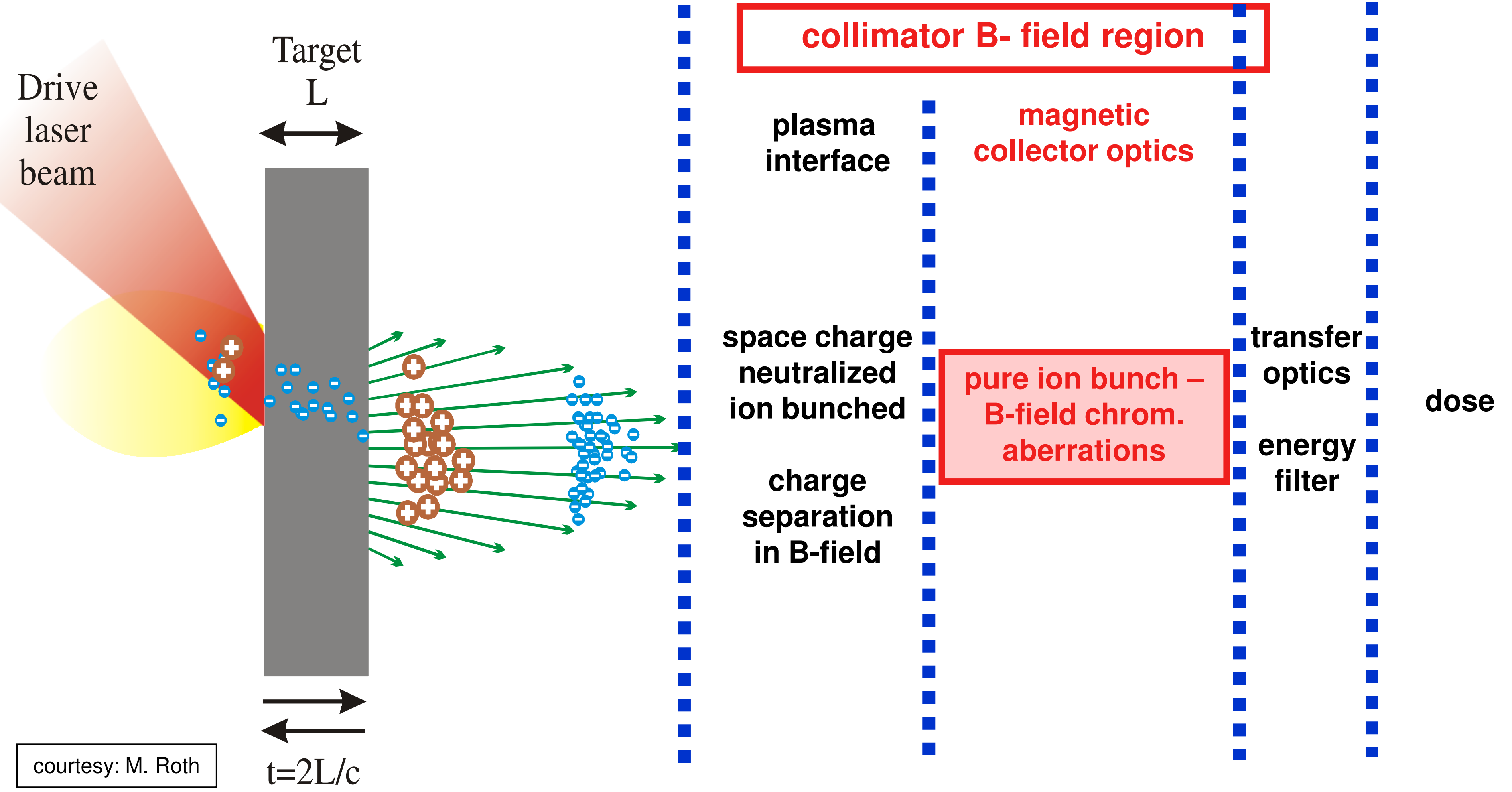
Spectral yield

spectral density E, Ω (rad)

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



Beam quality after production depends on interfaces!



courtesy: M. Roth

collimator B- field region

plasma interface	magnetic collector optics		
space charge neutralized ion bunched charge separation in B-field	pure ion bunch – B-field chrom. aberrations	transfer optics energy filter	dose

6 D phase space volume: very small | filamentation? | **effective increase** | ~ const.|

Ion collector options

Collection of "secondary particles" is an issue, if born under large angular and energy spread – common problem

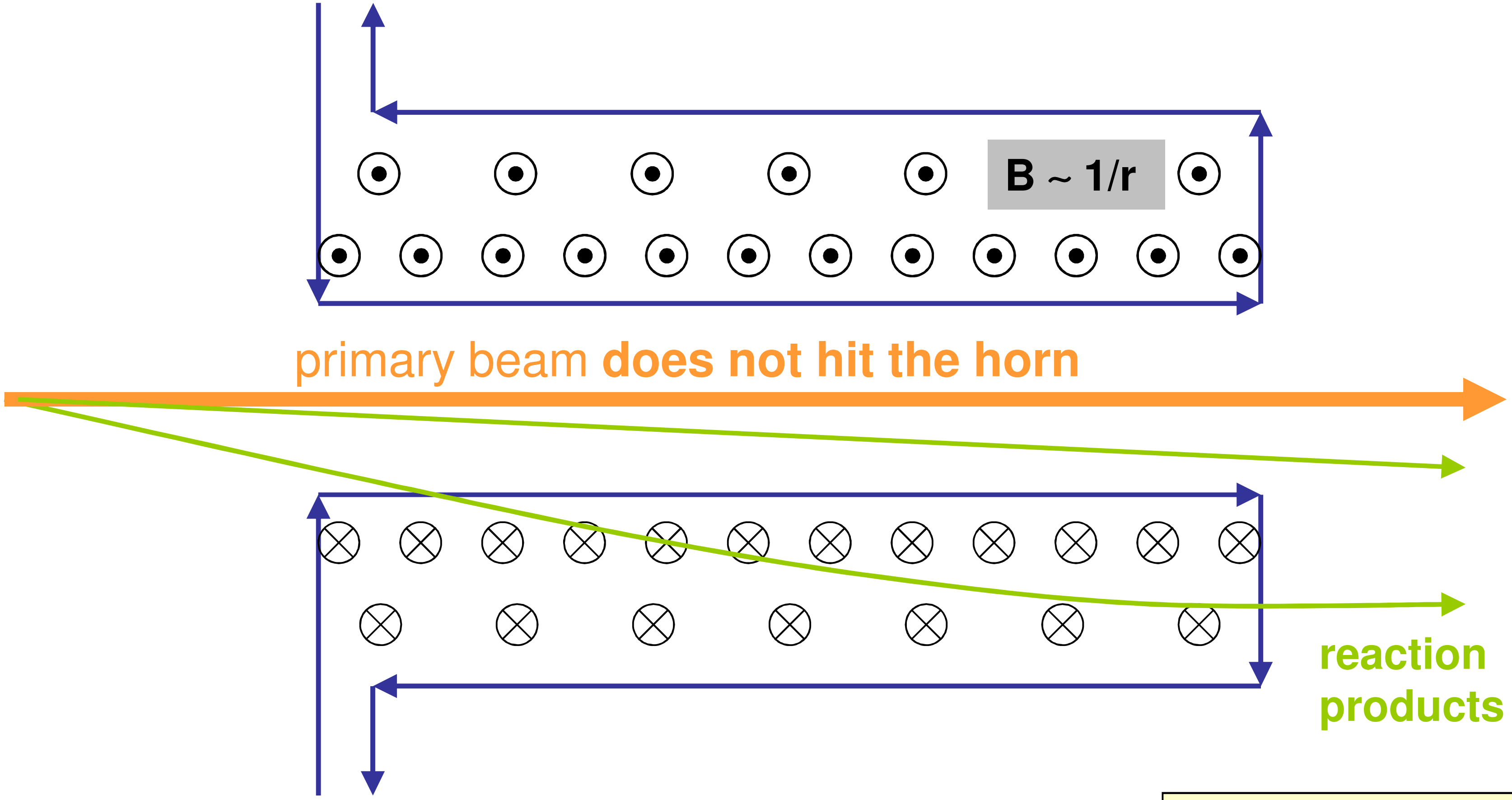
no collector – angle selection by small aperture

solenoid lens

quadrupole triplet or quadruplet

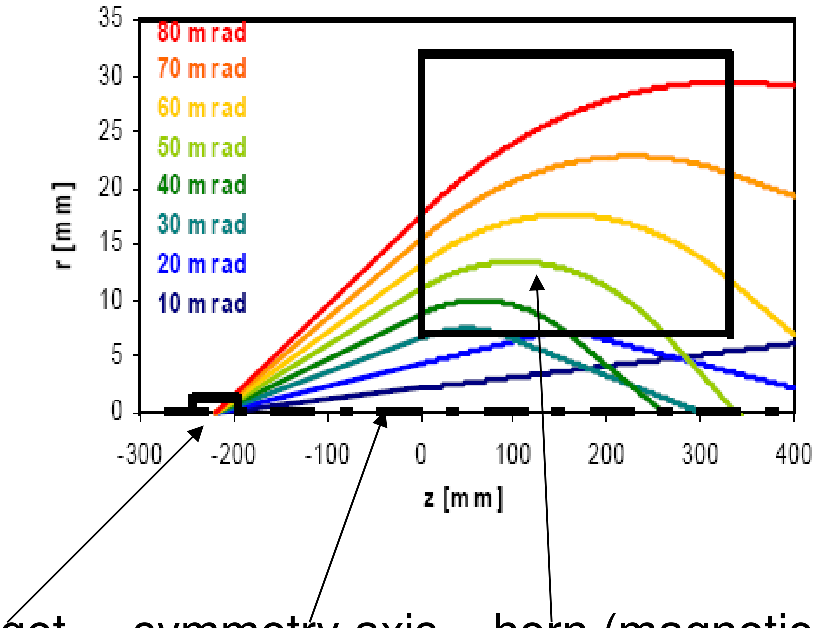
magnetic horn (used for antiprotons) not well-suited here

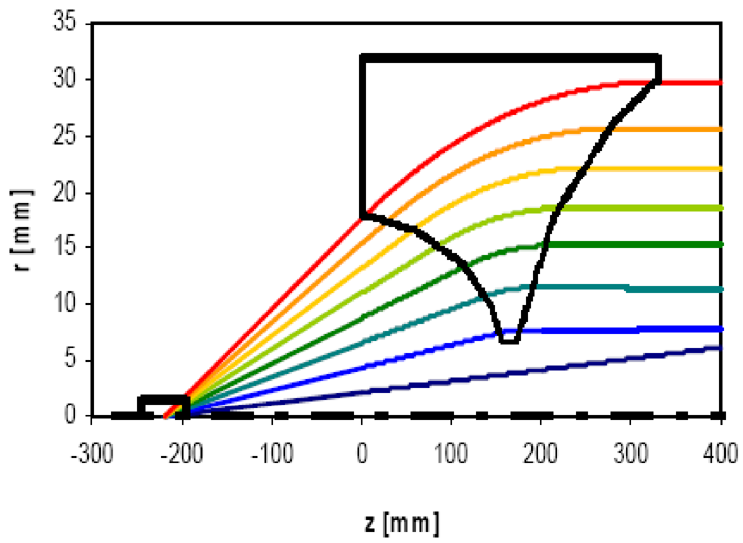
Collecting pbars: Magnetic Horn



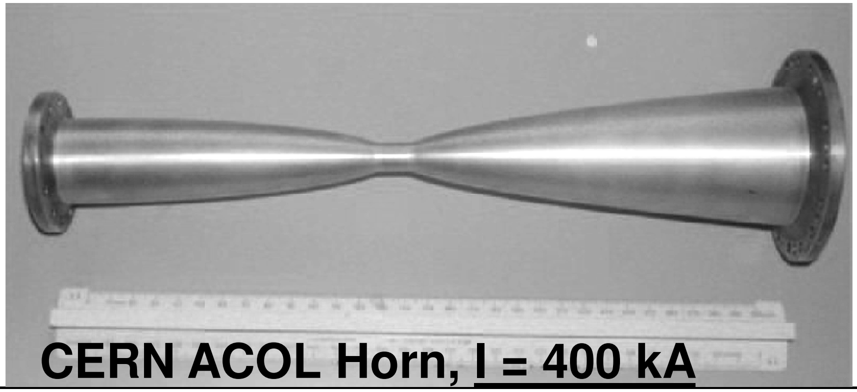
courtesy K. Knie, GSI

Magnetic Horn





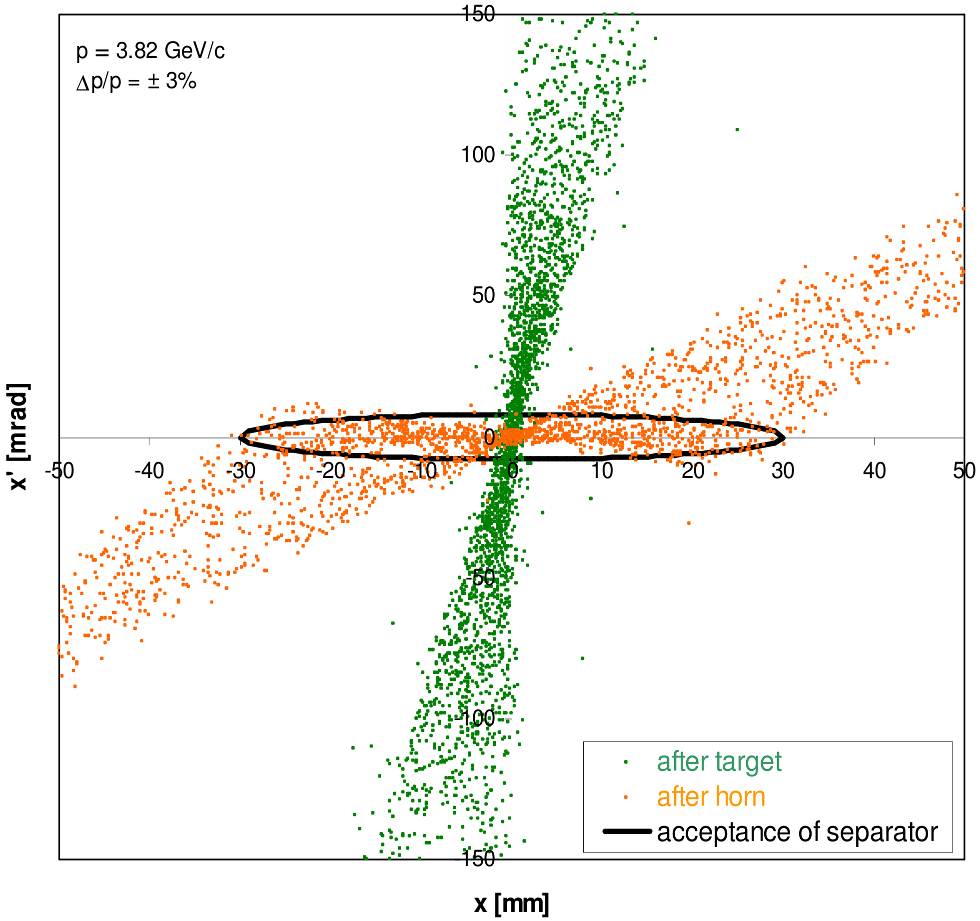
target symmetry axis horn (magnetic field area)



CERN ACOL Horn, I = 400 kA

courtesy K. Knie, GSI

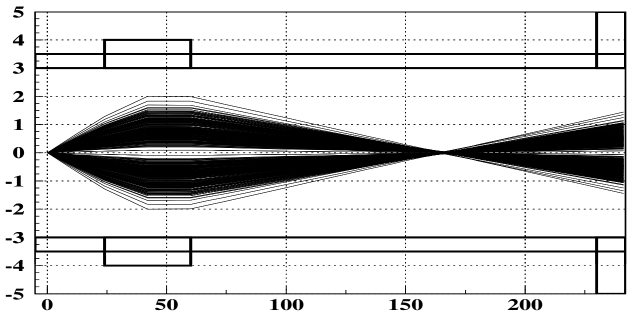
MARS Simulation of the pbar Yields



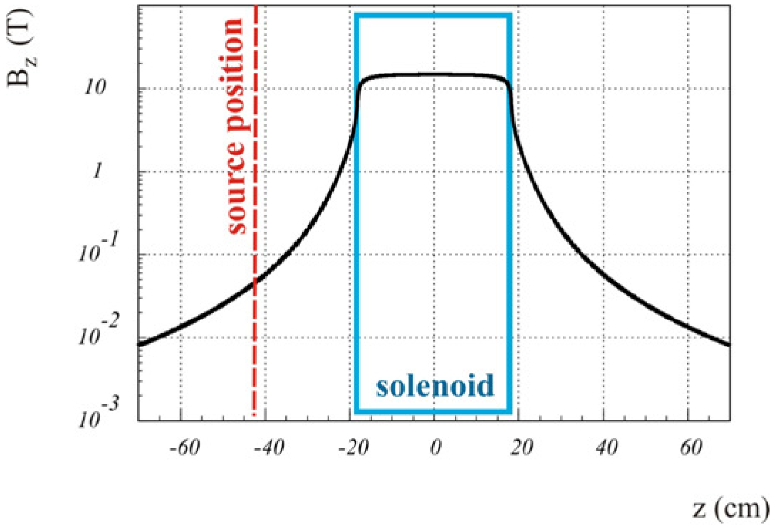
$$\text{yield} = \frac{\text{pbars in the ellipse}}{\text{primary protons}}$$

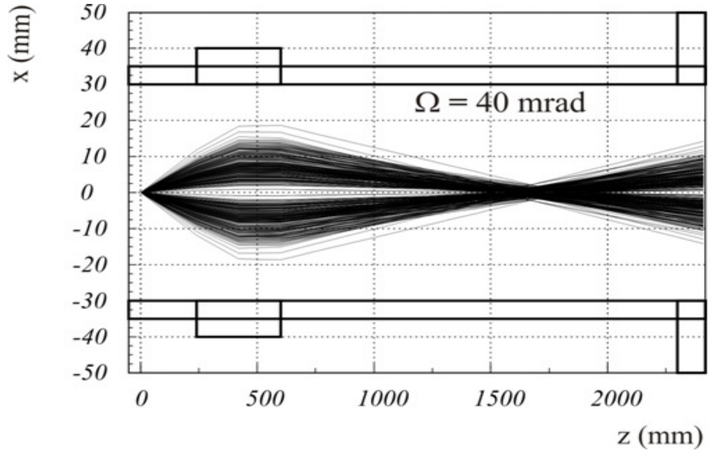
DYNAMION tracking code*: includes 2nd (chromatic) and higher order aberrations

- different energies experience different focal lengths δf/f~δE/E
- minor effect are 3rd order aberrations
- space charge matters near laser target (preferrably not in B-field)



ΔE/E=0
Ω=40 mr

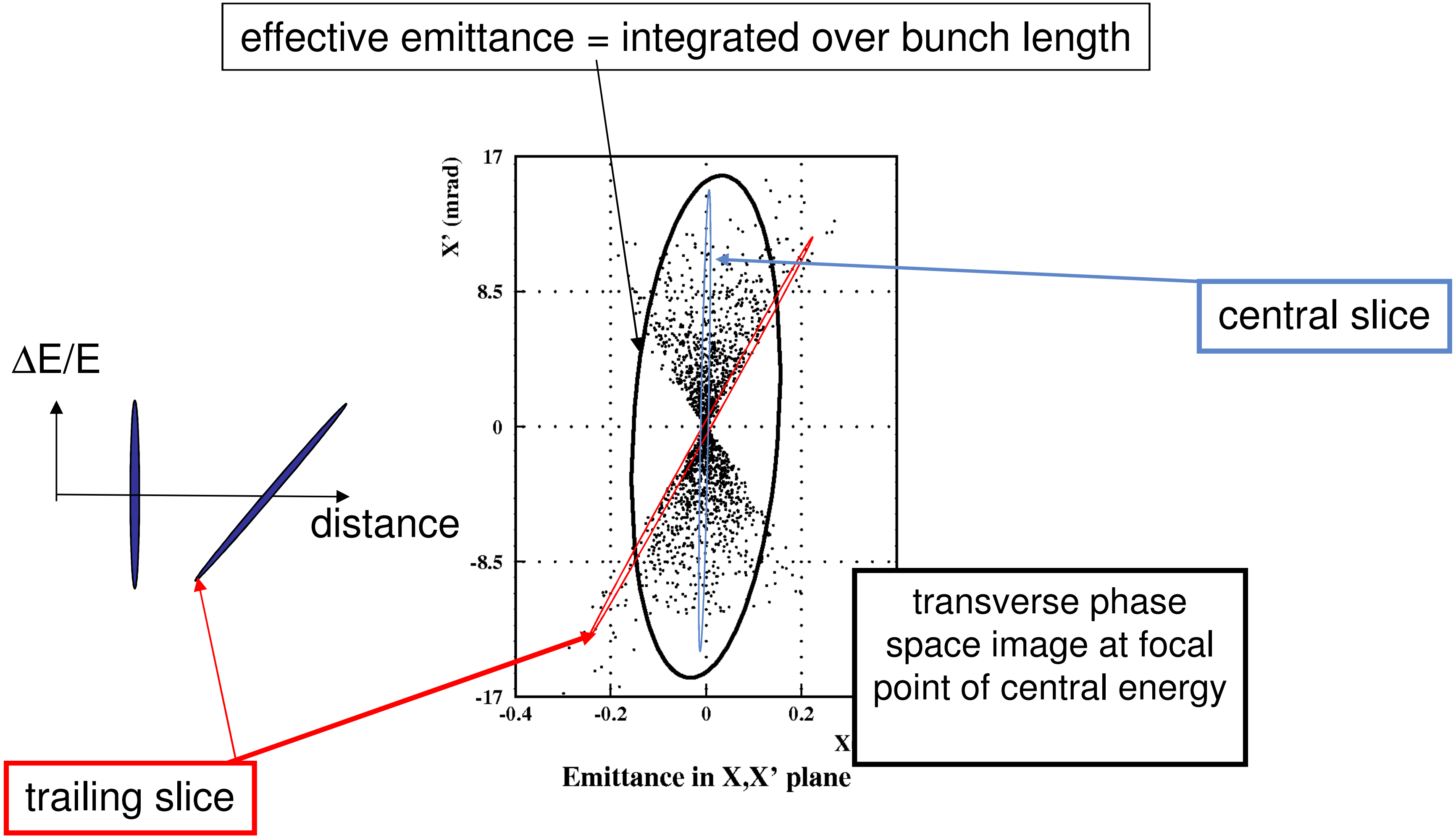




ΔE/E=0.05
Ω=40 mr

* S. Yaramishev et al.

Target measures time integrated emittances



effective emittance = integrated over bunch length

central slice

transverse phase space image at focal point of central energy

trailing slice

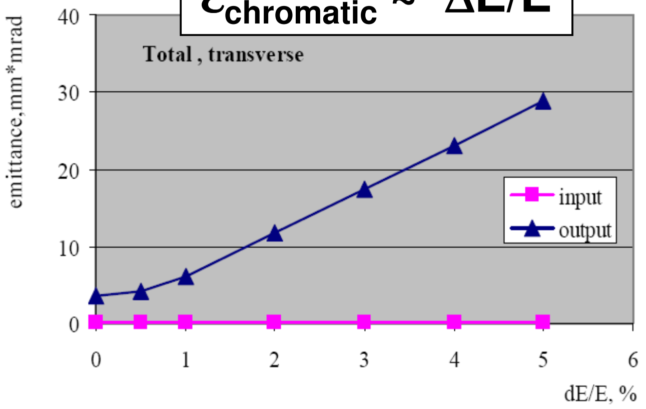
Emittance in X,X' plane

Chromatic emittance scaling

$\varepsilon_{\mathbf{chromatic}} = \alpha_c \; \Delta E/E \; \Omega^2_s$ [m rad]
"design basis"

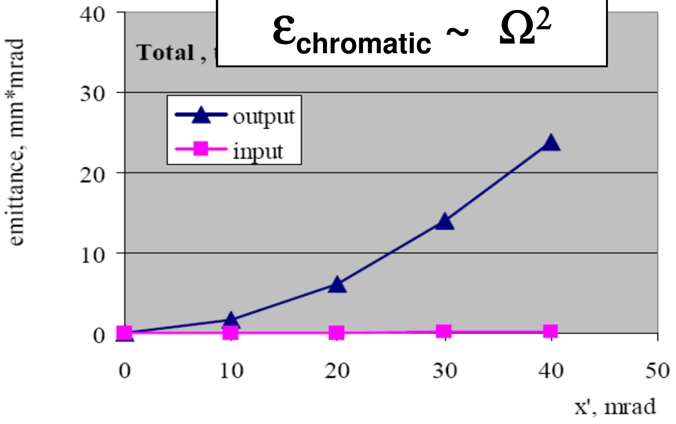
- find α_c = 0.3 m/rad for assumed solenoid (240 mm long)
- for longer solenoid benefit from B ~ L^{-1}, but α_c also increasing
- example: $\Delta E/E=0.05$, $\Omega_s=25$ mrad
  $\varepsilon_{chromatic}=10$ mm mrad
- for quad channel α_c ~ 3...5 times larger

chromatic emittance determines minimum spot size behind collector lens
  cannot reach small spot again
  except for fully or largely achromatic focusing (bends, sextupoles) (α_c~0)



linear law

$\varepsilon_{\mathbf{chromatic}} \sim \Delta E/E$



quadratic law

$\varepsilon_{\mathbf{chromatic}} \sim \Omega^2$

Options to reach conformal dose distributions

aperture collimation – focusing collection

Aperture collimation on target – no focusing

+ combining energy modulation (bends + apertures) with intensity modulation

- C.-M. Ma et al. (Fox Chase Cancer Center, Philadelphia, 2006)
- **Aperture collimated beam** : distance source – tumor target sets limit to beamlet size for scanning (0.5 cm radius over 1m: source divergence < 5 mrad)

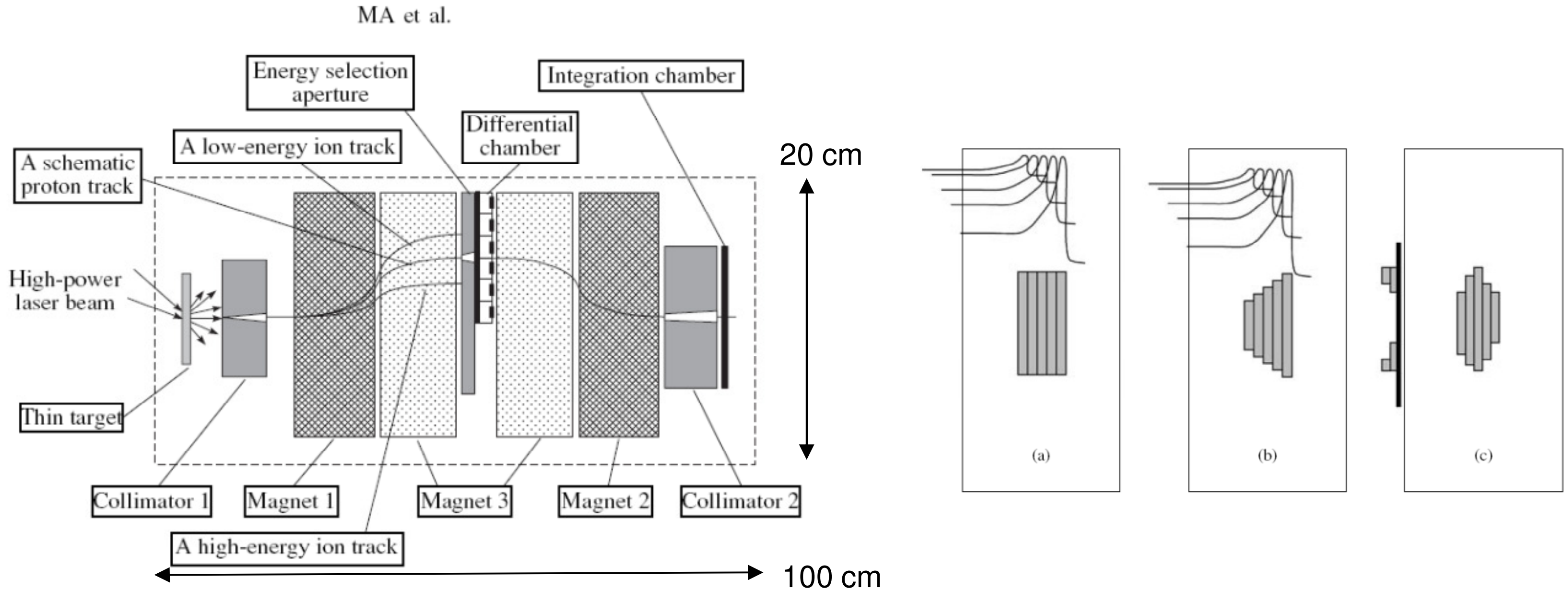


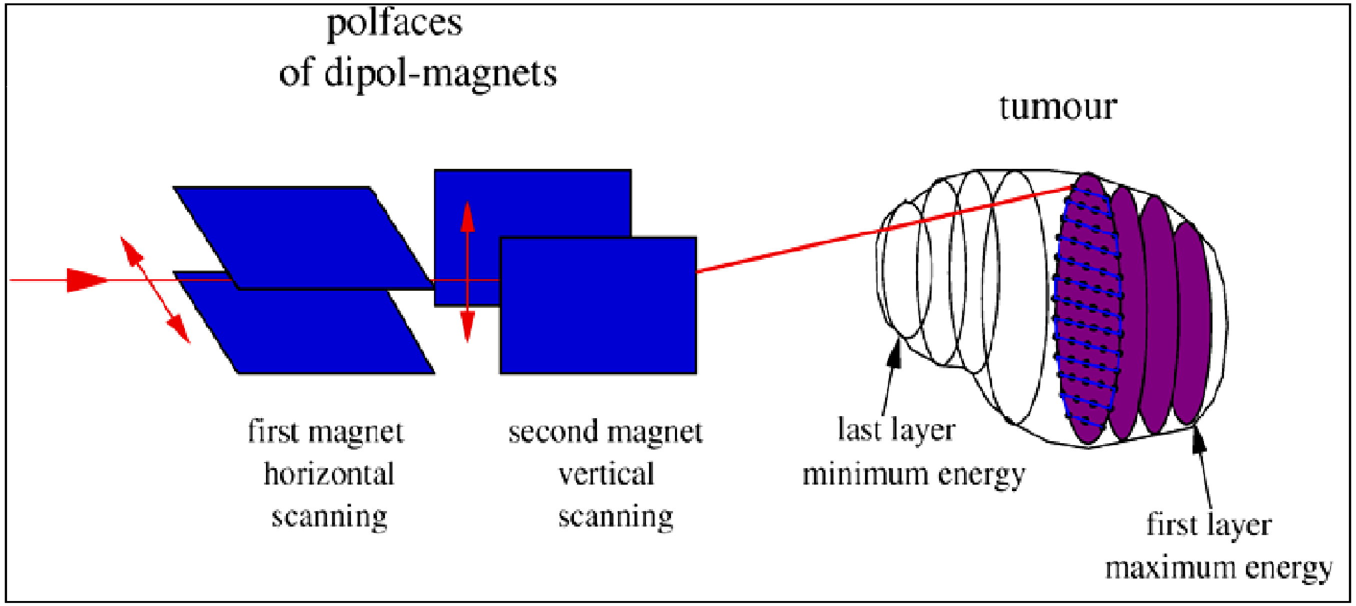
Fig. 3. A schematic diagram showing the particle selection, beam collimation and output monitoring system.

Raster scanning (HIT): highest quality of tumor conformal irradiation:

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

- (1 spill= 1 energy layer)

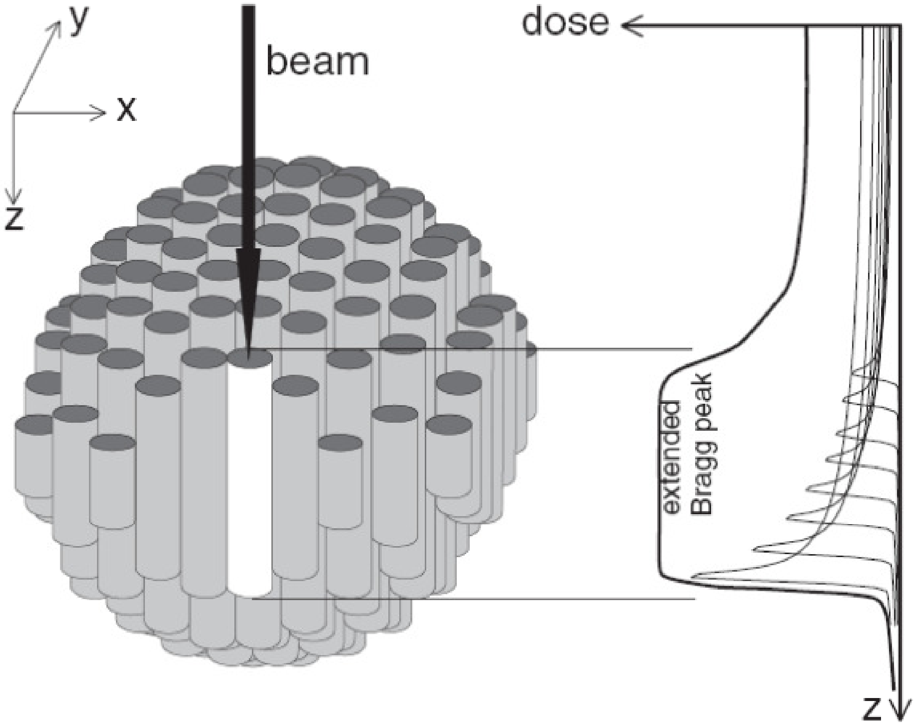
probably not suitable for laser



Depth scanning with Spread-Out Bragg Peak

matches well with laser ions

- Weber et al. (2000), GSI, proposed wedge absorber to broaden ΔE from synchrotron
- **laser ions: naturally broad energy profile depth scanning applicable**
- **quantify shots and intensities using chromatic emittance scaling**



Dose requirements

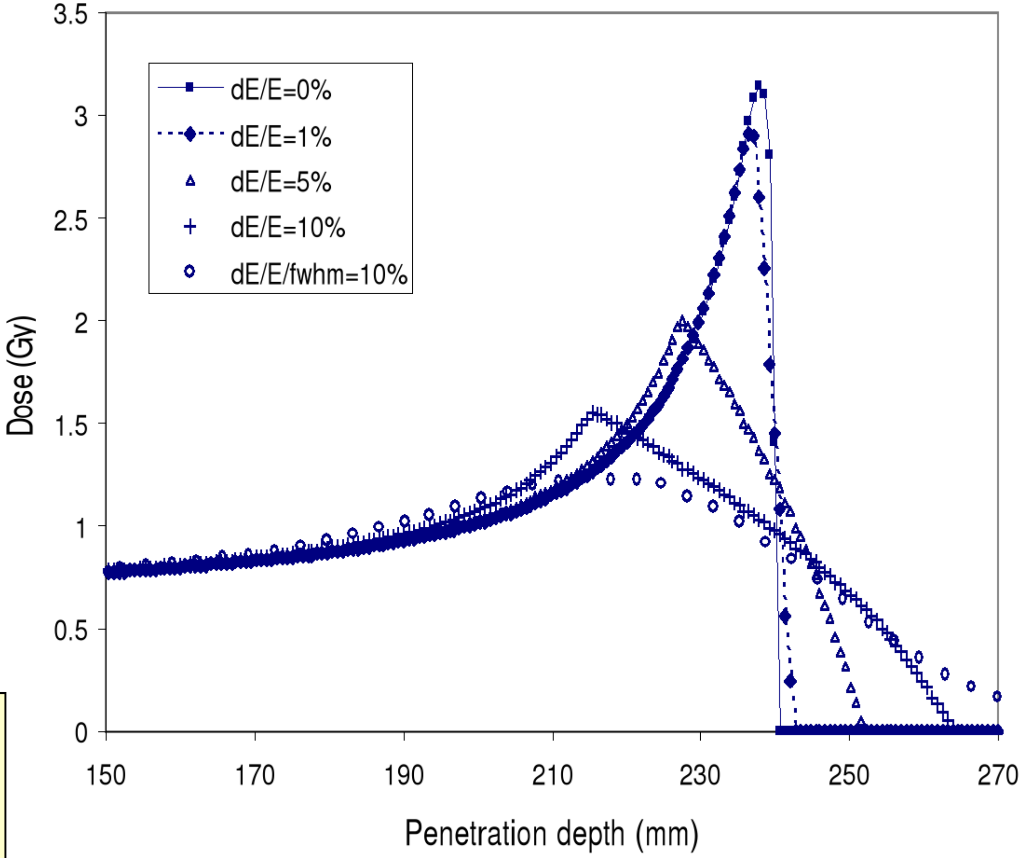
$$F = \frac{6\times 10^8 D\rho}{dE/dx}\left[\frac{particles}{cm^2}\right]$$

F: fluence
D: dose [Gy]
dE/dx: keV/µm
(linear energy transfer)

a "standard dose" of 2 Gy requires $6\mathrm{x}10^8$ p/cm^2 for ΔE/E<1%

(peak intensity requirement)

- large ΔE/E ~ 5 -10% per shot desirable for efficient use of production spectrum
- sharp fall-off at distal layer requires small ΔE/E<1%



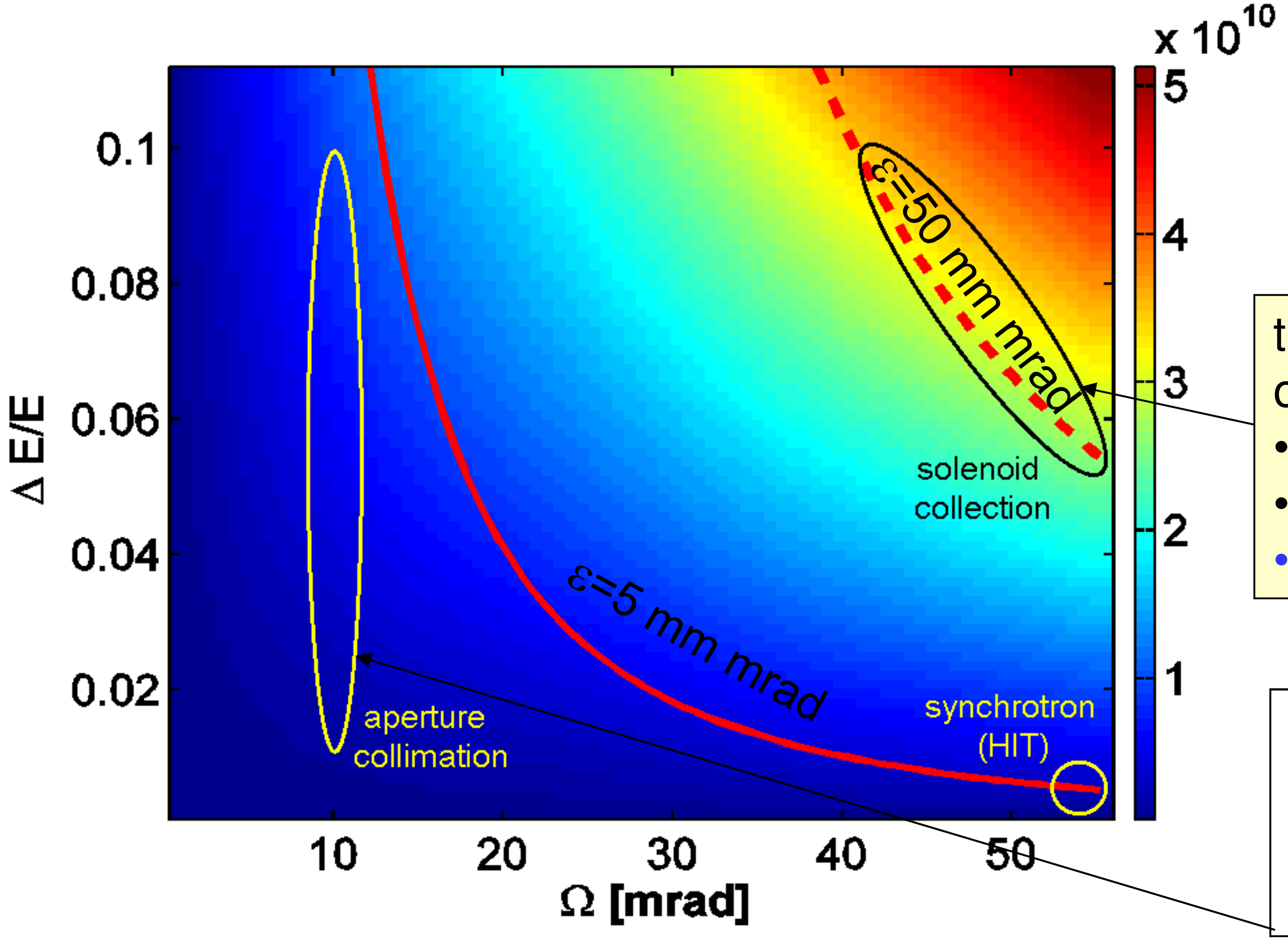
Depth dosis profiles of 200 MeV protons in water with initial fluences 10^9/cm^2.
(fitted to monoenergetic beam data P. Kundrat et al., 2007)

Chromatic emittance – spectral yield of Yan-model

$\varepsilon_{chromatic} = \alpha_c \, \Delta E/E \, \Omega^2{}_s$ [m rad]

- defines curves of constant emittance
- "usable" fraction of yield for given final emittance

total p yield ~10^{12}



therapy beam on ~1 cm^2 spot

- yield: 2-3x10^{10}
- need: 6x10^8
- large margin!

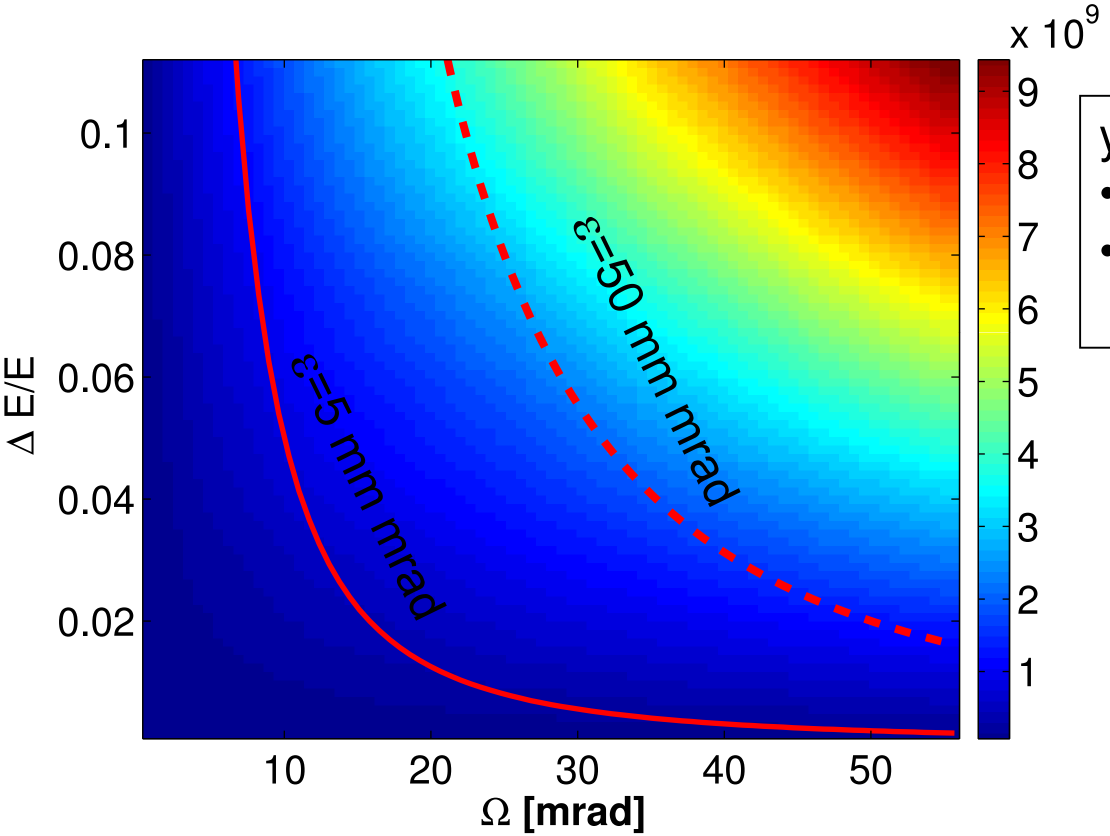
aperture collimation:
~ yield: 10^9
no margin!

Collector focused beam advantageous

solenoid or quad triplet lens

- **only aperture** – ballistic collimation:
  - no margin in intensity
  - very poor use of proton yield
- **solenoid (or quad) focusing:** proton yield 2-3x10^{10} per shot within ε=50 mm mrad chromatic emittance
  - still factor of 30 intensity margin
  - can be used to optimize target and laser pulse towards factor 5-10 lower yield and lower (average) laser power
  - enough margin for uncertainties on acceleration physics

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



yield:
- ~ 1/20-th of protons
- need only 1/40-th of p yield (higher LET!)

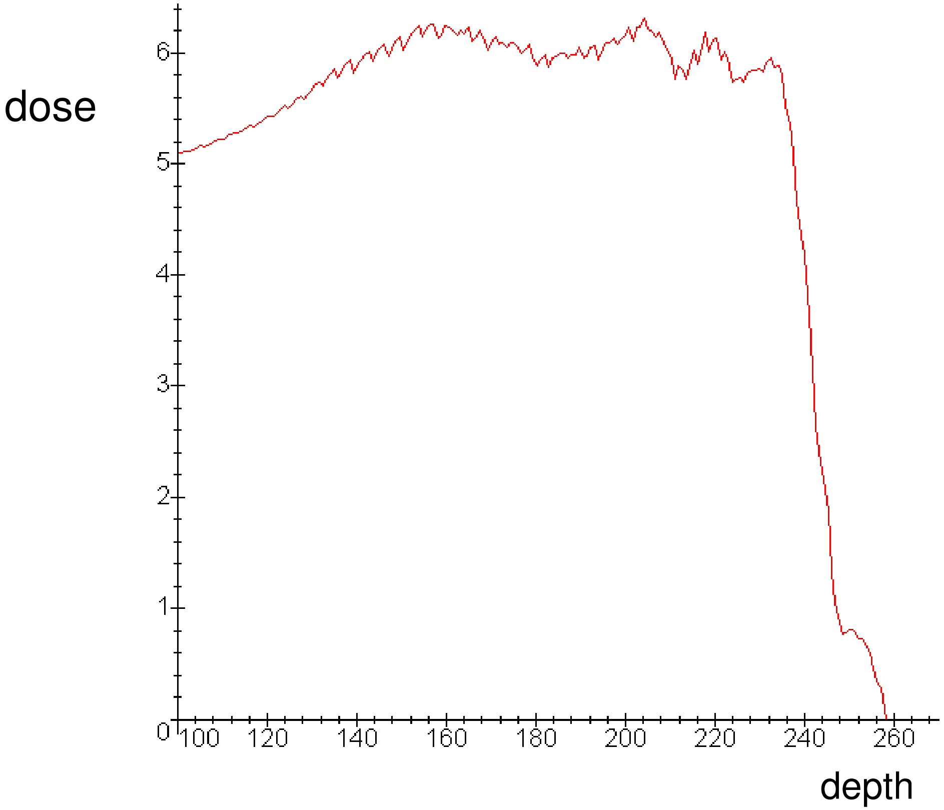
assumed α_c ~ 1
(solenoid collimator)

Some parameters resulting from present point study

- ideally ~ 5 SOBP's to cover full depth ~ (50-250 BP's in HIT)
- laser ions: 10x10 transverse voxels
- ~ 500 per side 10^3 per fraction if ideal jitter <5%
- ~ 5 shots to corrrect intensity jitter of 50% (no in-flight control as too short)
- 5 10^3 shots or 8 min per fraction for 10 Hz laser system

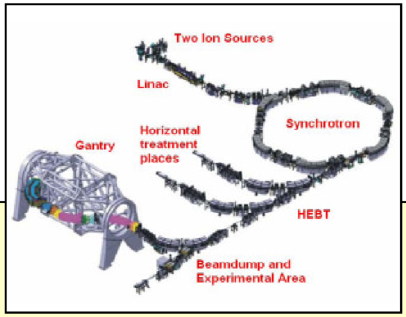
Example using chromatic filtering (not optimized)

used only 4 SBOP's at 200 (+/-1%), 190 (5%), 185 (5%), 165 (5%) MeV
need some more to reduce dose fluctuation



Summary requirements HIT laser ions

(our point study)



	HIT	10 Hz laser system
	p / C^{6+}	p / C^{6+}
energy range:	50-250 MeV / 88-430 MeV/u	
max. particles needed:	spill: 4 10^{10} / 1×10^{9}	shot: 6×10^{8} / 2×10^{7} (on $1\times1\,cm^{2}$)
intensity variation:	10^{-3} ... 1	
ion beam emittance :	3-5 mm mrad	~ 50 mm mrad
beam size (fwhm):	4-10 mm	>10-20 mm
energy steps:	~ 50	5-10
energy width (ΔE/E):	< 0.005	~0.05-0.1
voxels:	~ 20 k	~ 5 k
duration of fraction	~ 15 min	~ 8 min (5 intensity correction shots included)

Linac: 7 MeV/u
Synchrotron: 50-430 MeV p, He, C, O

Laser requirements (~ HIT parameters)

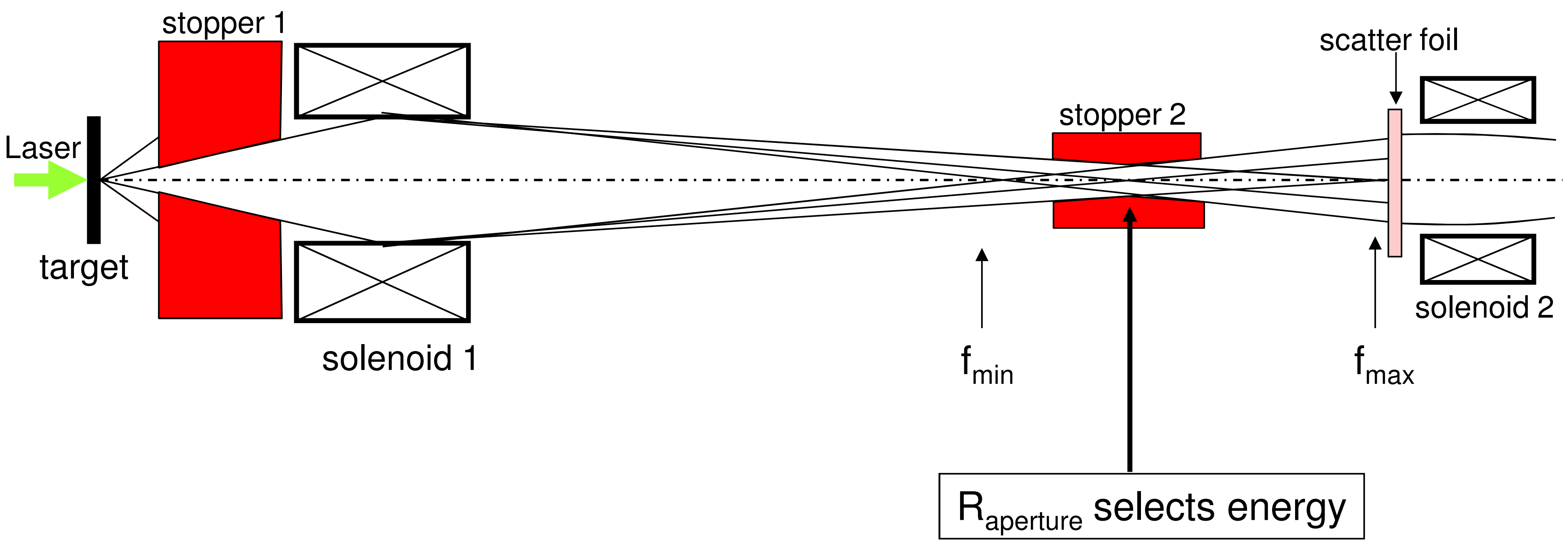
ICFA/ICUIL workshop (GSI, April 2010) recommendations

	laser p	laser carbon
rep rate	10 Hz	10 Hz
W/cm^2	1-3 10^{21}	1-3 10^{22}
pulse duration fs	50-150	50-150
rise time fs	<20	<20
contrast 5ps/500ps	$10^{-8}/10^{-12}$	$10^{-9}/10^{-13}$
spot radius μm	5 10*)	5
laser power PW	1-3 10*)	10-30
laser pulse energy J	150 400*)	1500
laser average power kW	1.5 4*)	15
laser cost target M€	2.5-5	5-10

*) increased spot in simulations by Yan, 2009

Chromatic effect can be used as energy filter

- replacing bending magnet (= dispersive energy filter)
- combined function: focusing (higher yield) + energy selection

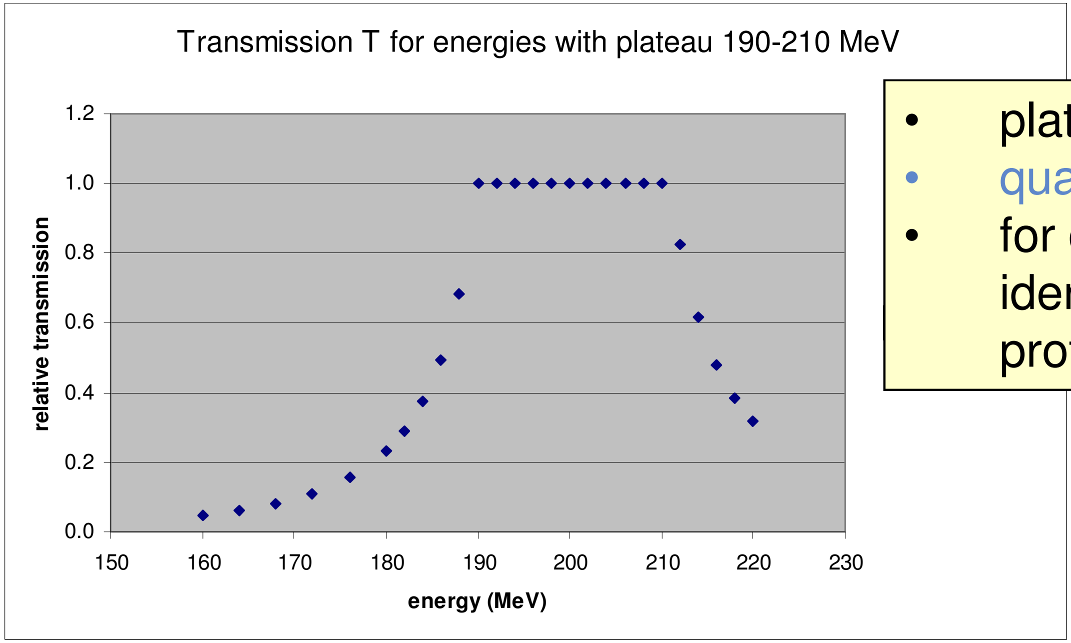


Radius of aperture well-defined

$$\varepsilon_{chromatic} = R_A \Omega_2 = R_A \Omega \cdot L_1 / L_2$$

Ω divergence at source
Ω_2 divergence behind solenoid
L_1 distance target-solenoid
L_2 distance solenoid-aperture

$$\Rightarrow R_A = \alpha_c \frac{\Delta E}{E} \Omega \cdot L_2 / L_1 ,$$



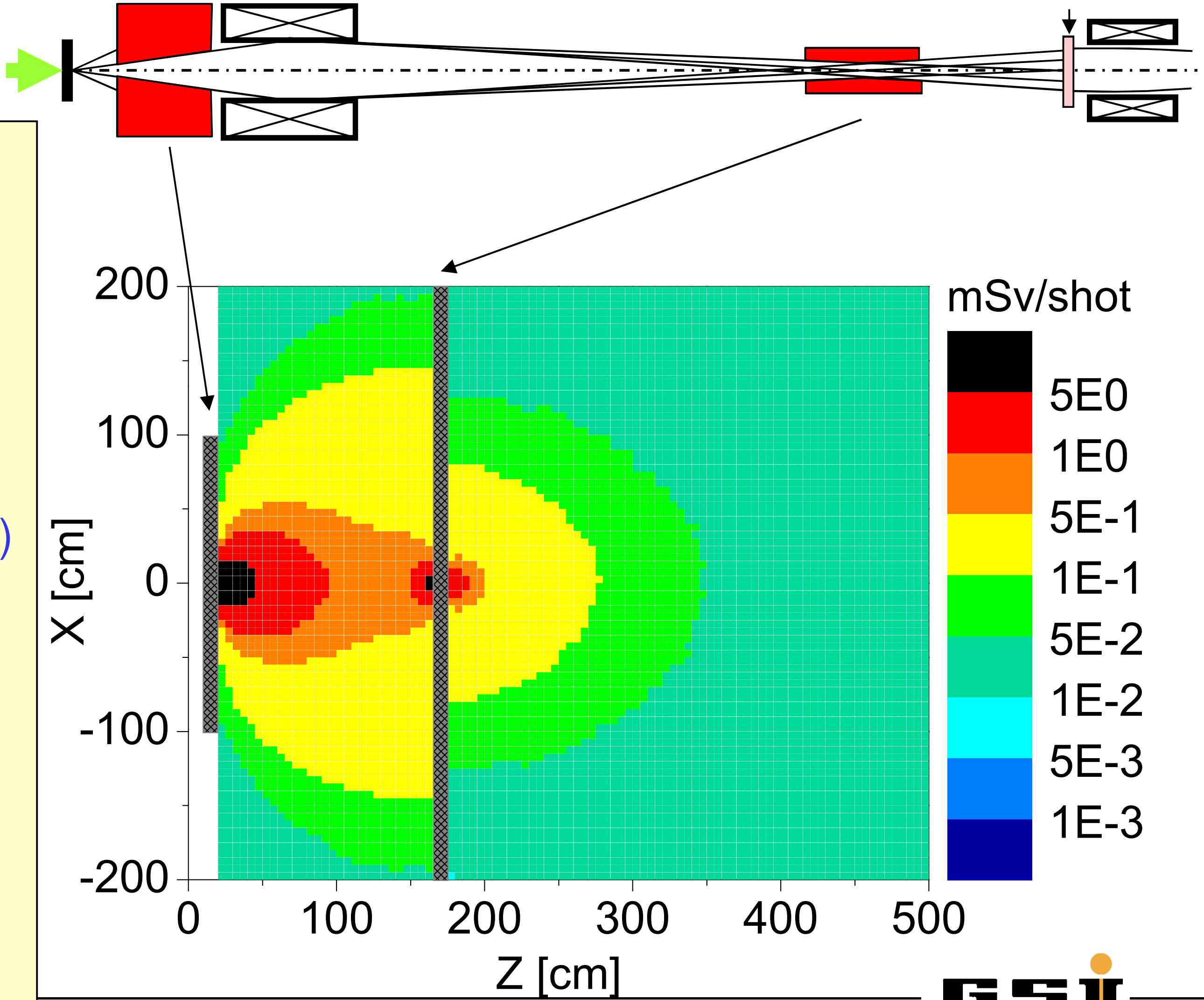
- plateau inside $\Delta E/E$
- quadratic fall-off outside
- for different energies identical transmission profile if $B_{solenoid} \sim \beta\gamma$

Some estimates of radiation load

FLUKA-calculations (I. Strasik,GSI)

assumed:

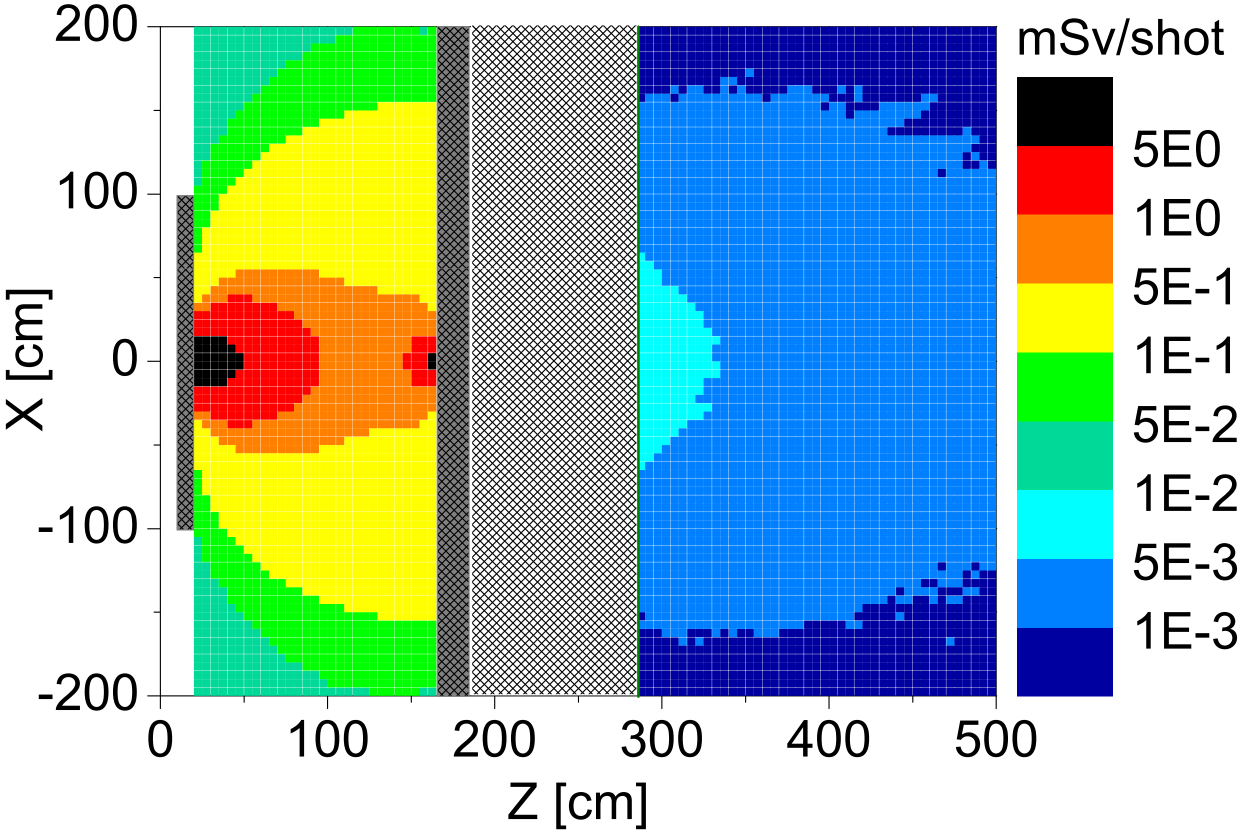
1. 1.5×10^{11} p at source
2. 3×10^{10} p (20 mr) into solenoid
3. 2×10^{10} p through energy filter aperture
4. find 0.05 mSv per shot (CT ~ 1-10 mSv)
5. cannot tolerate large number of shots at assumed full power
6. another reason to optimize towards ~10x lower yield
7. neutron absorber needed



Additional neutron absorber

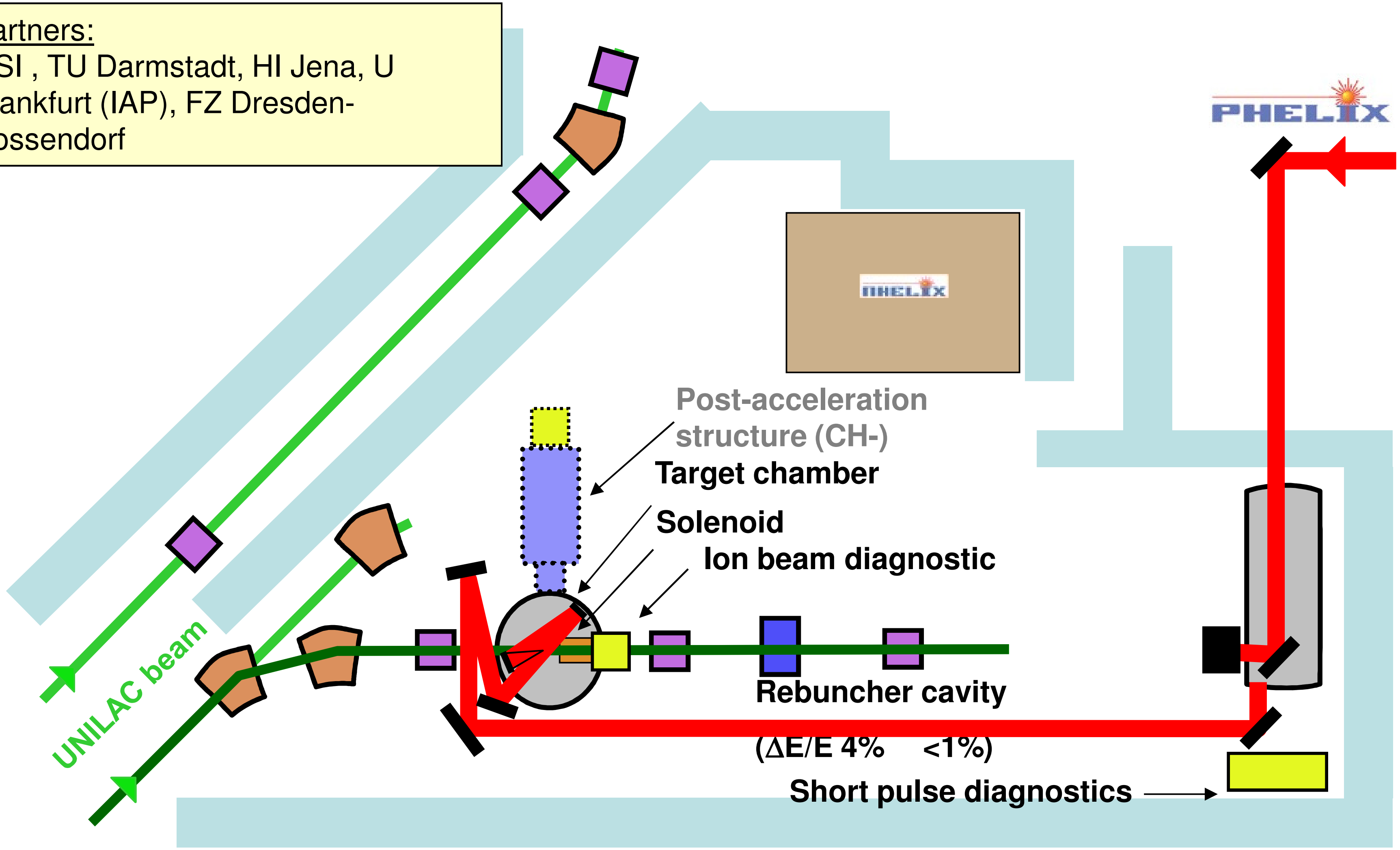
additional neutron absorber reduces to acceptable level

factor 10x reduction!



LIGHT: Test stand at GSI Z6 experimental area

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



Post-acceleration structure (CH-)

Target chamber

Solenoid

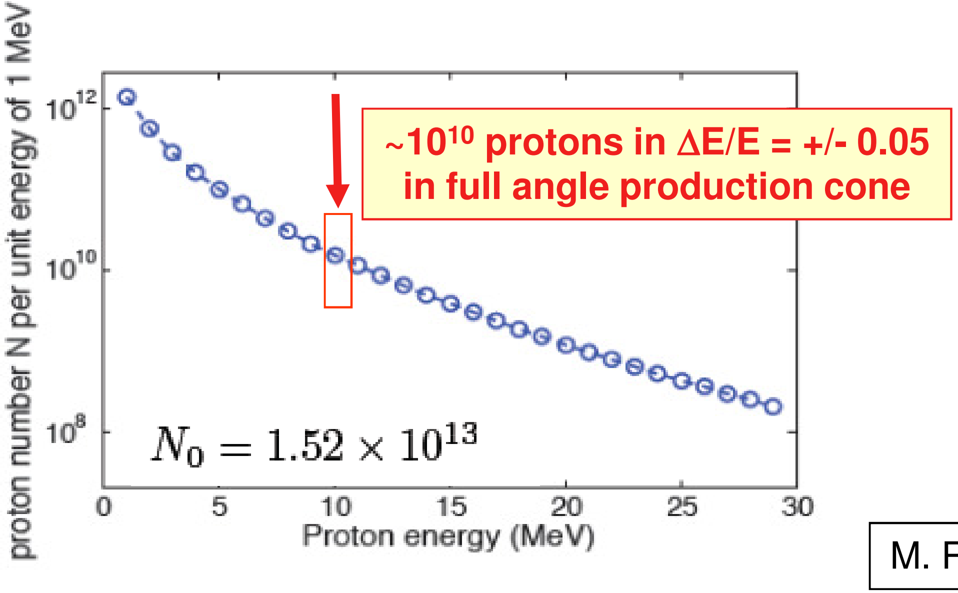
Ion beam diagnostic

Rebuncher cavity

(ΔE/E 4% <1%)

Short pulse diagnostics

Chromatic emittance scaling can be tested



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

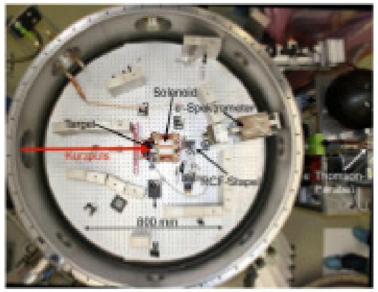
M. Roth et al., 2009

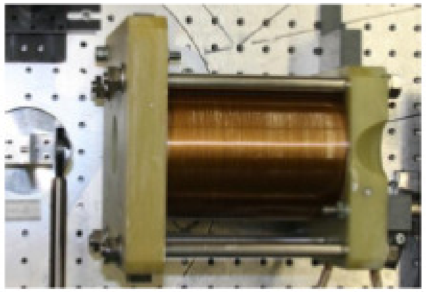
our scaling predicts:

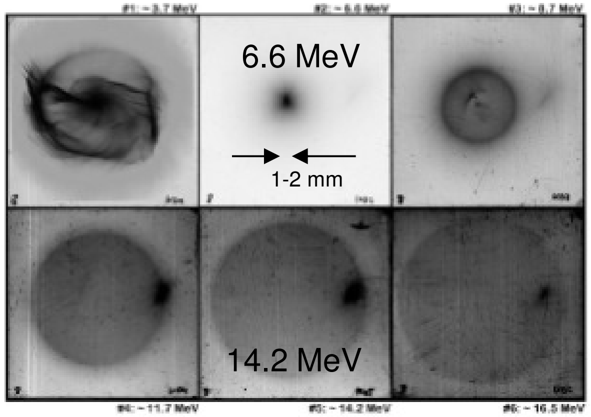
$\Delta E/E$= +/- 0.05 and Ω_{source}= 172 mrad (10°) $\varepsilon_{chromatic}$ ~ 100 mm mrad

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

Capture of laser-accelerated proton beams with a solenoidal magnetic field

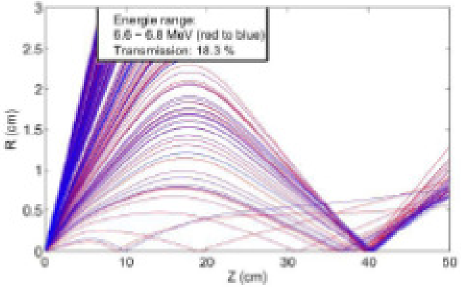


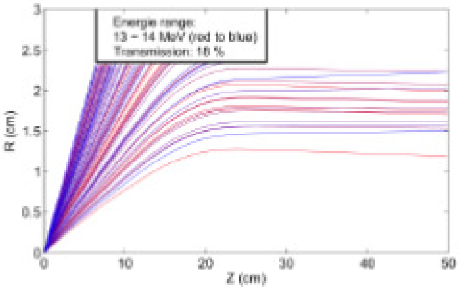


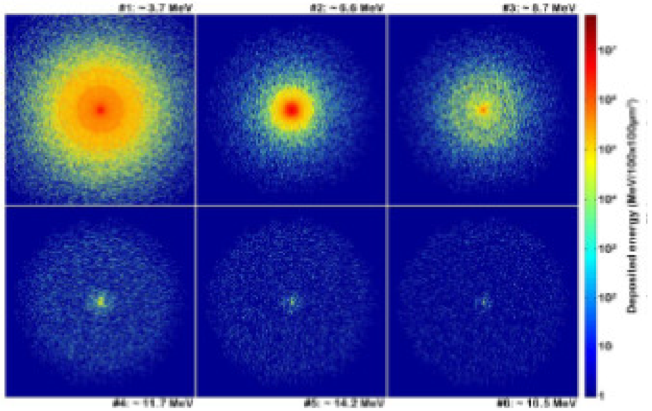


Experiment at Phelix/GSI (top):
- *(left)* setup target chamber
- *(middle)* solenoid version 2
- *(right)* proton signal in RCF detector stack (contrast optimized for the last 3 layers)

Warp PIC simulations (bottom):
- *(right)* simulated proton signal in virtual RCF detector stack,
- *(middle)* proton trajectories for collimation
- *(left)* proton trajectories for focussing







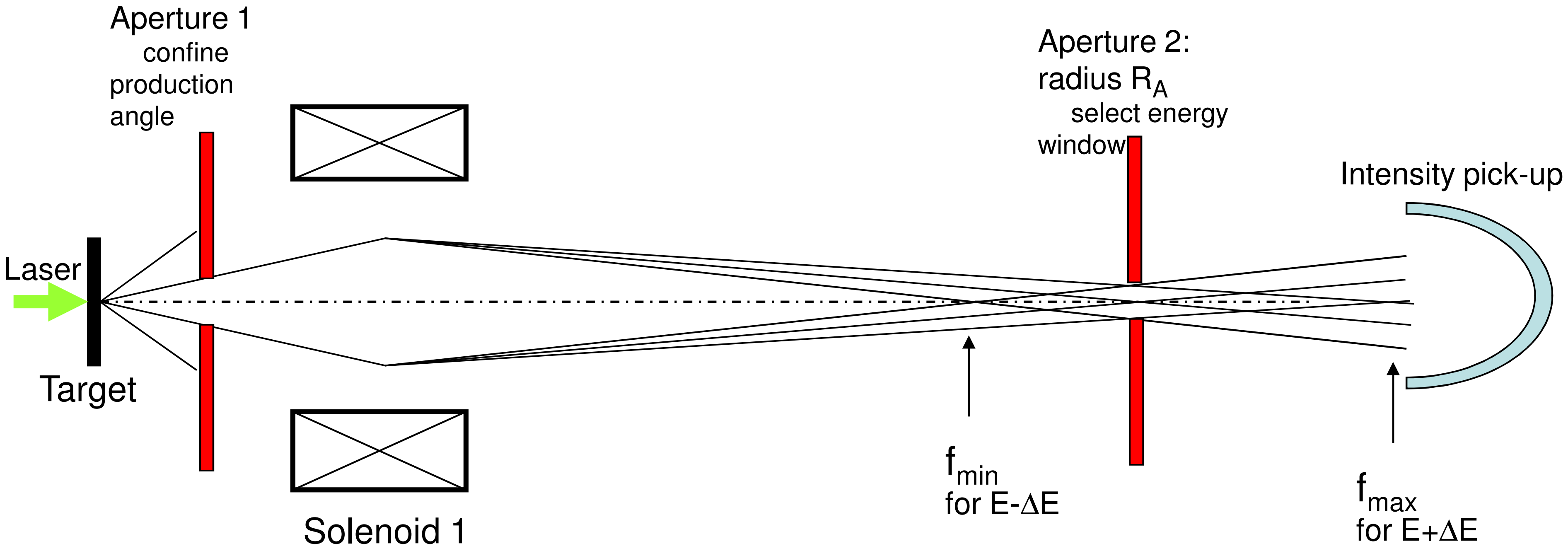
Knut Harres, Frank Nürnberg, Prof. Markus Roth, June 2010

Chromatic emittance filter can be used for diagnosing protons generated by PHELIX

$R_A = \alpha_C \, \Delta E/E \times \Omega_{source} \times L2/L1$

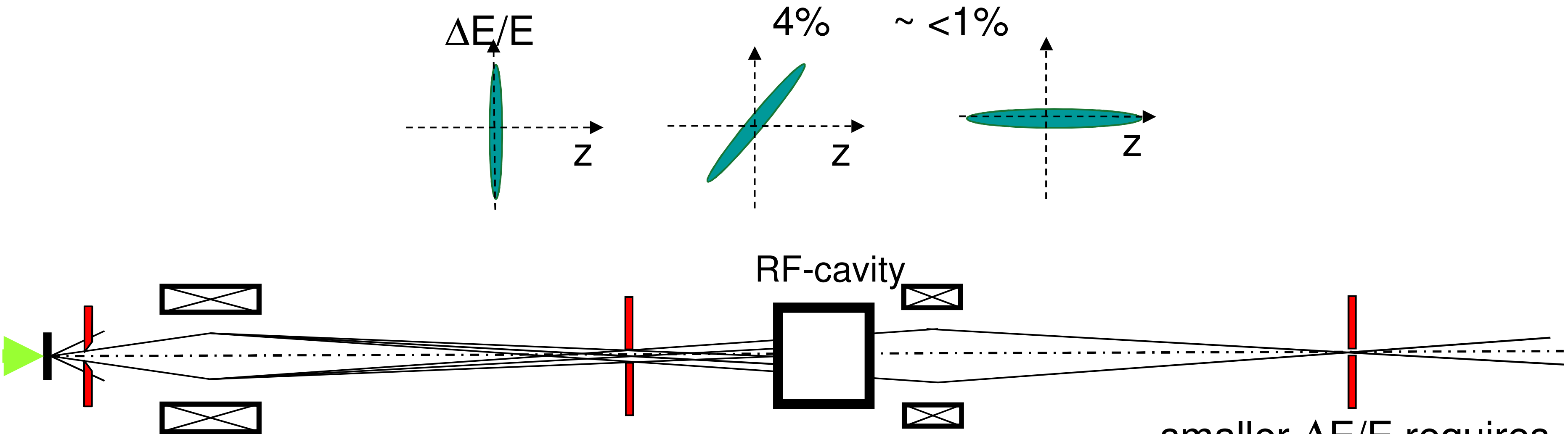
telescope ratio: L1: distance source-solenoid
L2: distance solenoid-aperture

- example: $\alpha_C = 0.1$ $\Delta E/E = 0.05$ $\Omega = 0.1$ rad $L2/L1 = 10$ $R_A = 0.005$ m



Reduction of yield to ΔE/E~0.04 window for bunch rotation experiment is mandatory

- otherwise swamp RF + diagnostics with off-energy protons
- with a second (weaker) solenoid and a third sub-mm aperture matched to ΔE/E<0.001 measure "success" of rotation by mere intensity measurement



smaller ΔE/E requires smaller R_A (~ 1-2mm)

with RF off: measure reduced intensity (smaller ΔE/E transmission!)
RF on: "same" intensity as behind first aperture, if all particles rotated
(difference ~ compression factor)

Conclusions / Outlook

Beam quality determined by "collector" – scaling

"Point Study" based on Yan et al. shows sufficient intensity margin (factor ~30) for solenoid collector

No collector (only aperture) – little attractive

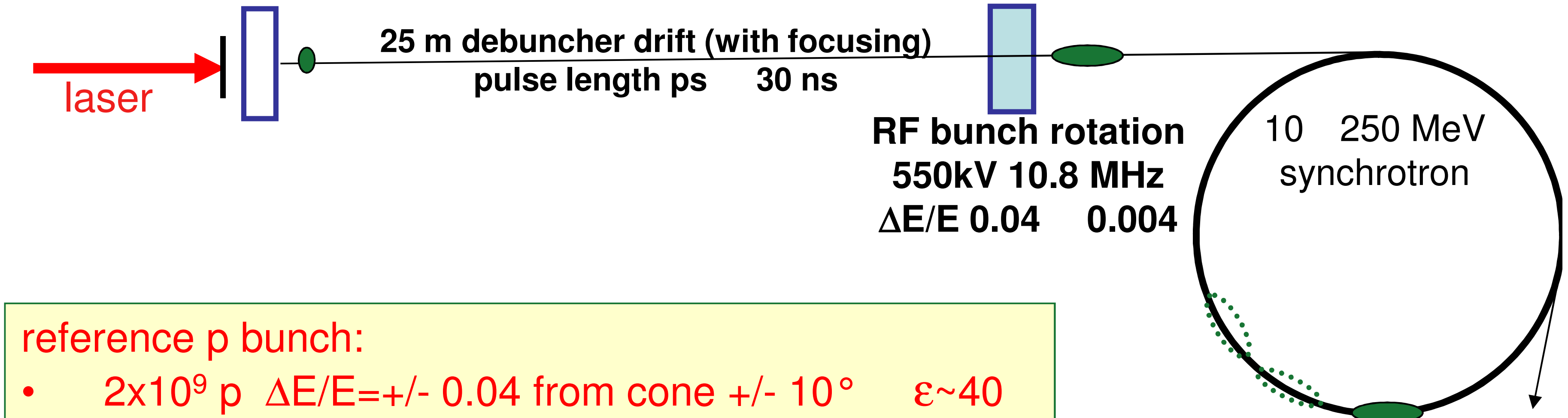
Chromatic energy filter – combined function collection + energy selection (replace dipole filter)

10 Hz laser system: 1 fraction < 10 min possible

Yan et al. requires 4 kW average power (10 PW peak) – cost? Optimize towards lower power and yield!

Question: is a synchrotron injection with laser ions at 10 MeV competitive with linac?

(10 MeV laser ions "state of the art")



laser

25 m debuncher drift (with focusing)

pulse length ps   30 ns

RF bunch rotation
550kV 10.8 MHz
ΔE/E 0.04   0.004

10   250 MeV
synchrotron

repeat 25 times bunch into bucket of 10.8 MHz (~100 kV)

reference p bunch:

- 2×10^9 p ΔE/E=+/- 0.04 from cone +/- 10°   ε~40 mm mrad   δp/p~0.004
- matches well with space charge limit in ring of ΔQ~ -0.1 required for ~1 s storage!!
- would need 10 Hz laser system (25 bunches to fill synchrotron in few seconds)
- need long debuncher line and bunch rotator
- a linac works for sure (6-7 M€)