Laser accelerated ions and their potential for therapy accelerators

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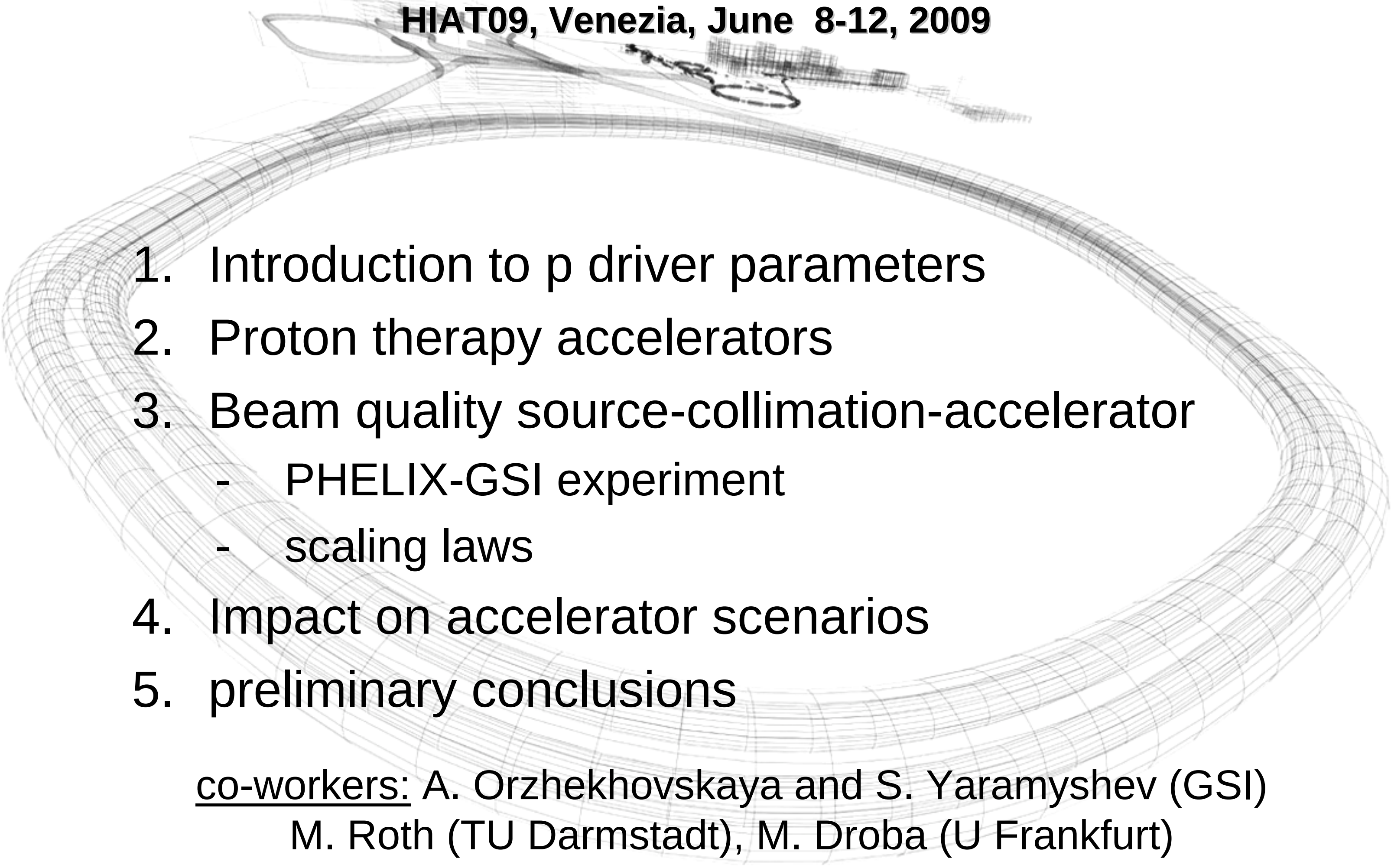

1. Introduction to p driver parameters
2. Proton therapy accelerators
3. Beam quality source-collimation-accelerator
   - PHELIX-GSI experiment
   - scaling laws
4. Impact on accelerator scenarios
5. preliminary conclusions

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M. Roth (TU Darmstadt), M. Droba (U Frankfurt)

1. Introduction to p driver parameters

What are lasers competing with?

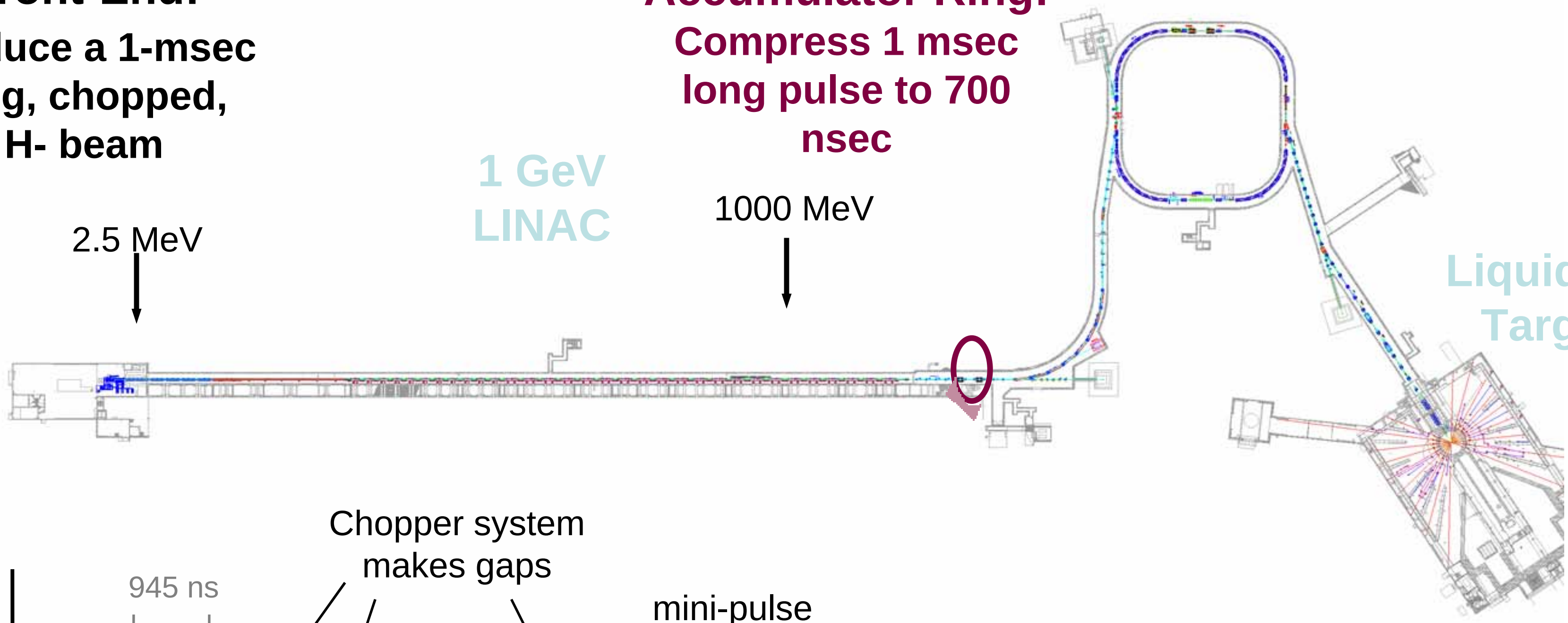
SNS Accelerator Complex

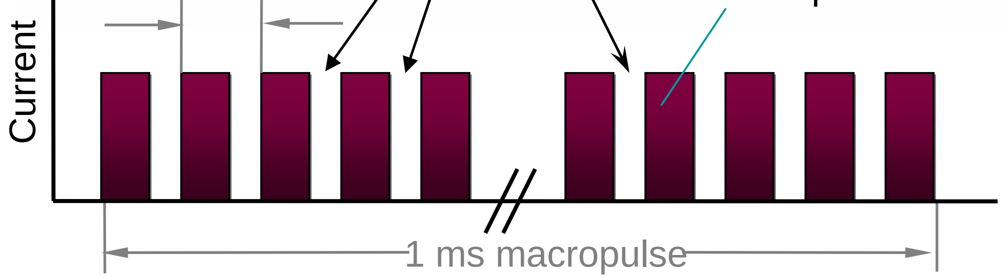
Front-End:

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

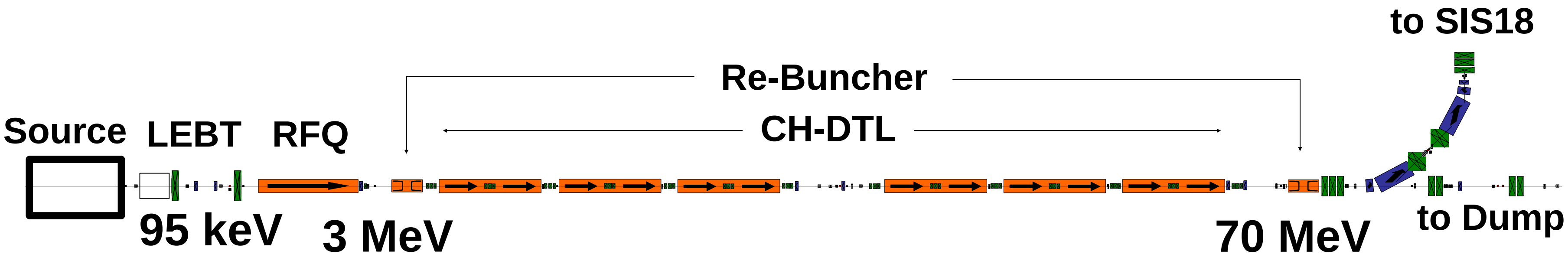
Accumulator Ring:

Compress 1 msec long pulse to 700 nsec

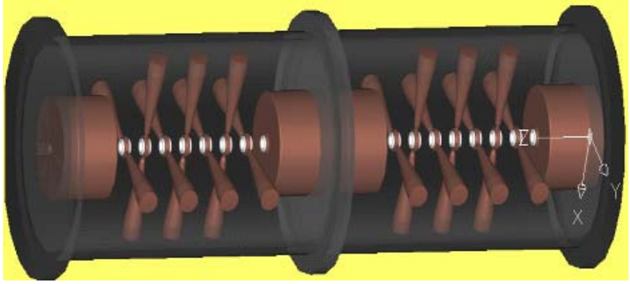




Injector Chain: New Proton Linac for FAIR at GSI



Crossed-bar **H**-Structure

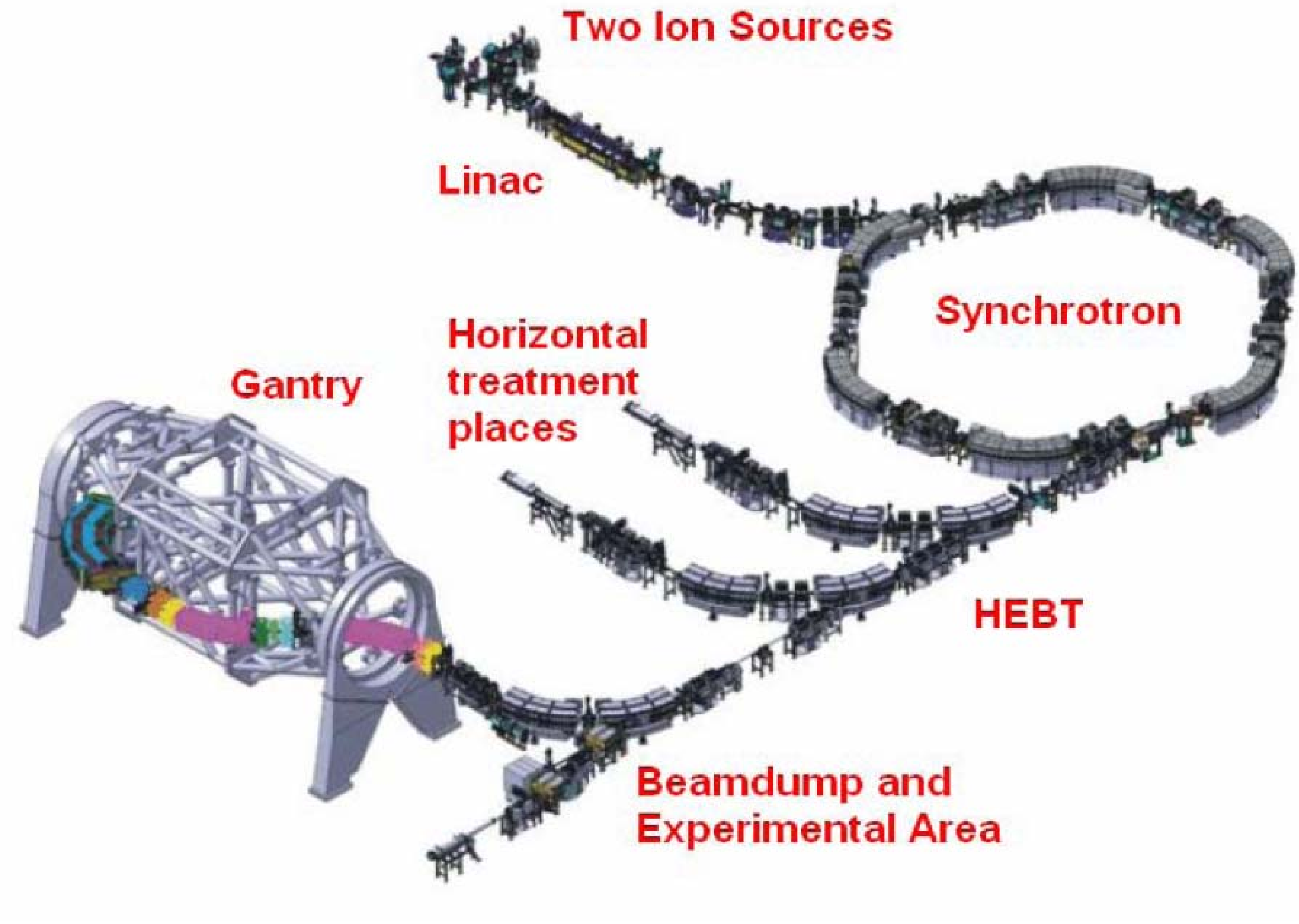


(Univ. Frankfurt U. Ratzinger)

Beam Energy	70 MeV
Beam Current	70 mA
Protons / Pulse	$7\cdot10^{12}$
Pulse Length	36 µs
Repetition Rate	4 Hz
Rf Frequency	352 MHz

Heidelberg Ion Therapy Facility

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



Summary on Proton Drivers

What can conventional proton accelerators achieve? (some examples)

	MeV	p/sec	p/ spill or micropulse
SNS Oakridge (Spallation Neutron Source):	1000	6x10^{15}	2x10^{9}/10ns
FAIR p driver linac (→ antiproton facility) :	70	~ 10^{13}	2x10^{9}/10ns
Proton therapy (typical):	~ 250	~ 10^{10}	~ 5x10^{10} / 10s spill ~ 5x10^{7} / voxel (100 Hz)

→ Laser p/ion acceleration may be competitive in the area of therapy

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

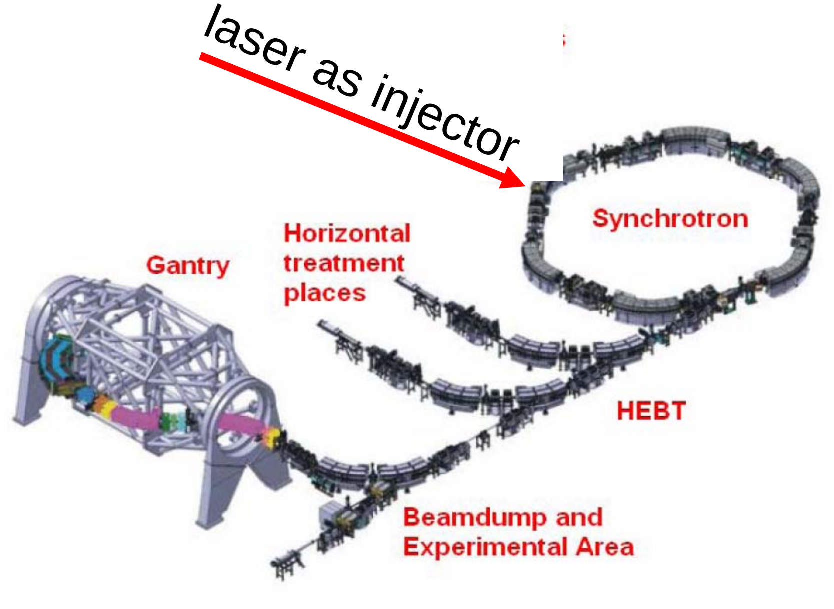
→ efficiency of "photons into usable protons/ions" crucial !!
(example: in GSI-PHELIX experiment ~ 3x10^{-5})

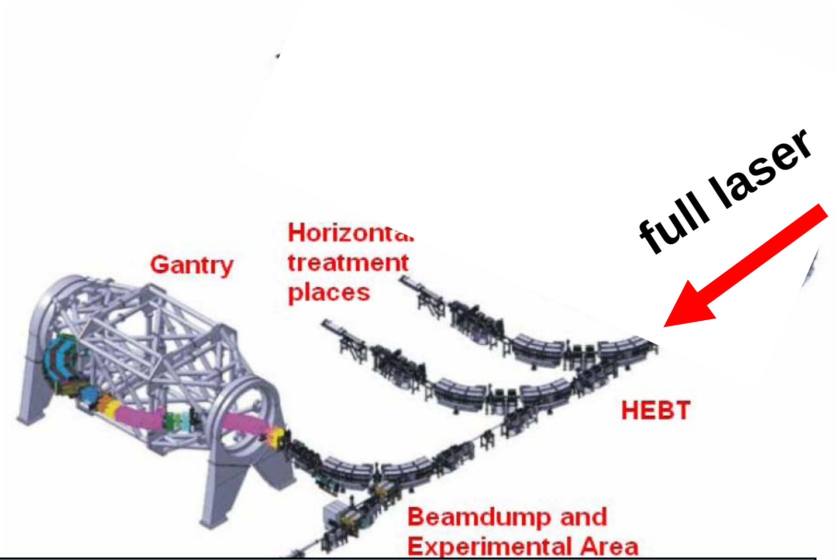
2. Proton/Ion Therapy Accelerators

two (theoretical) options:

laser + post accelerator - laser to full energy

A. Laser acceleration replacing "injector linac" + conventional post-accelerator (linac/circular)





B. Full laser acceleration → p directly to 250 MeV or C to 350 MeV → transferred to patient

Summary on issues in proton therapy

following Linz & Alonso PRSTAB10, 094801 (2007):

		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!

3. Beam quality source-collimation-accelerator

1. The production phase space is extremely small – consequence of small μm size focal spot and <ps time duration – often "sold" as attractive feature of laser acceleration
2. Can we take advantage of the extremely small production phase space?
3. No, it won't survive collection and following transport!

"Single particle" effects degrading quality:

chromatic aberration (second order effect): $\delta x \sim x' \, \delta p/p$

yet unexplored and open issues:

"Collective effects":

proton + neutralizing electron space charge at source - under study

(separation of p and e^- by solenoid B field)

proton beam space charge further downstream - appears controllable

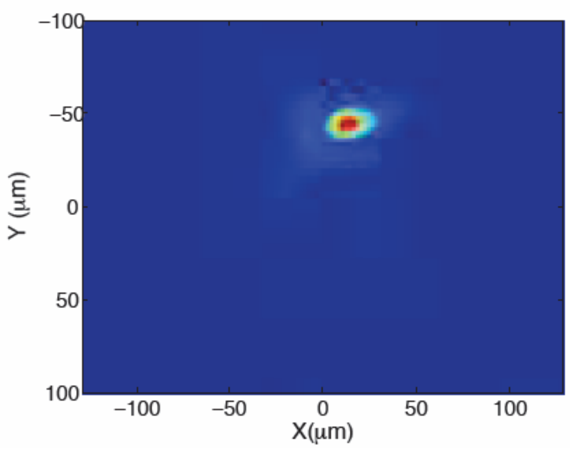
("geometric" aberration by nonuniform space charge)

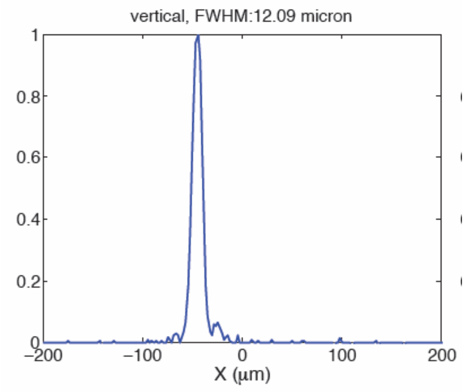
GSI-PHELIX Experiment (K. Witte et al., M. Roth et al.)

used as reference case here

In 2008 demonstrated first time:

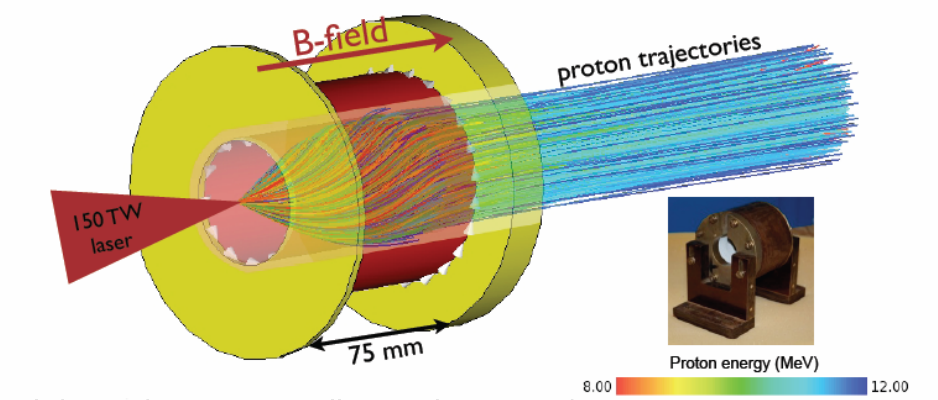
- 170 TW power
- 700 fs pulse length (120 J)
- novel copper focusing parabola
- spot size 12 X 17 µm (FWH
- Intensity: ~ 4 x 10^{19} W/cm^2





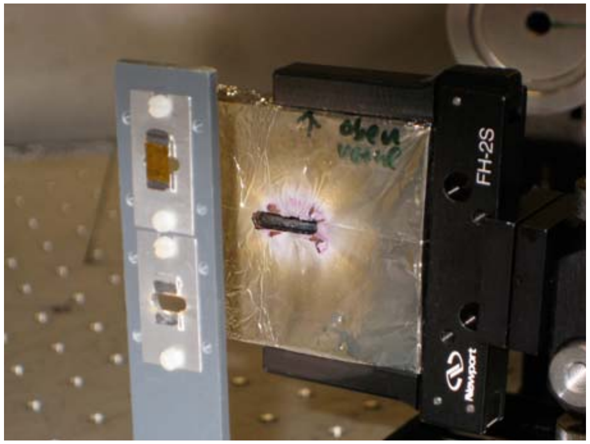
EXPERIMENT: Laser Ion Acceleration (TUD - GSI)

Goal:
Collimate an intense, laser generated proton beam using a pulsed solenoid magnet → transfer to conventional accelerator optics

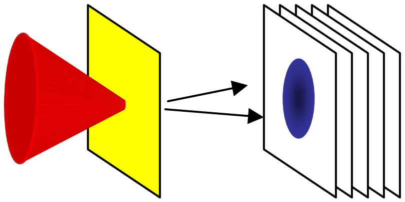


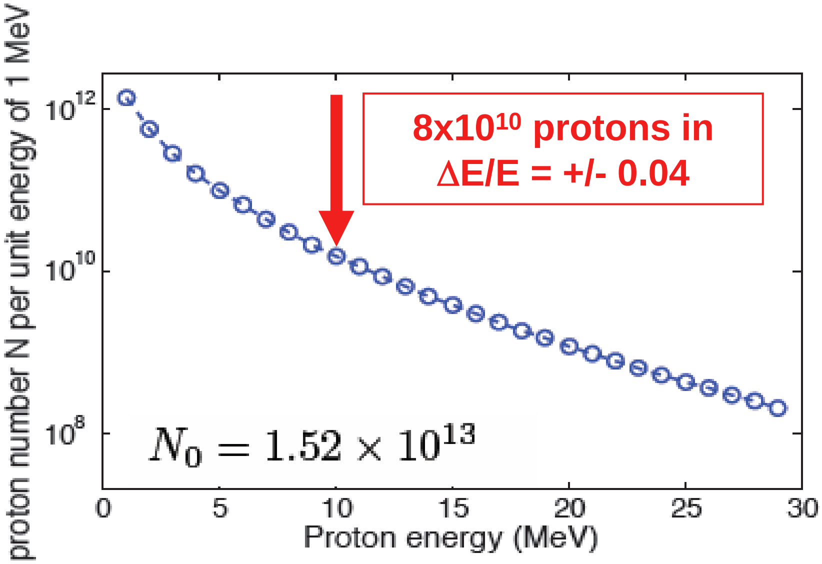
(Simulation CST-Studio, I. Albers,TUD)

Results of the first PHELIX experiment on laser proton acceleration

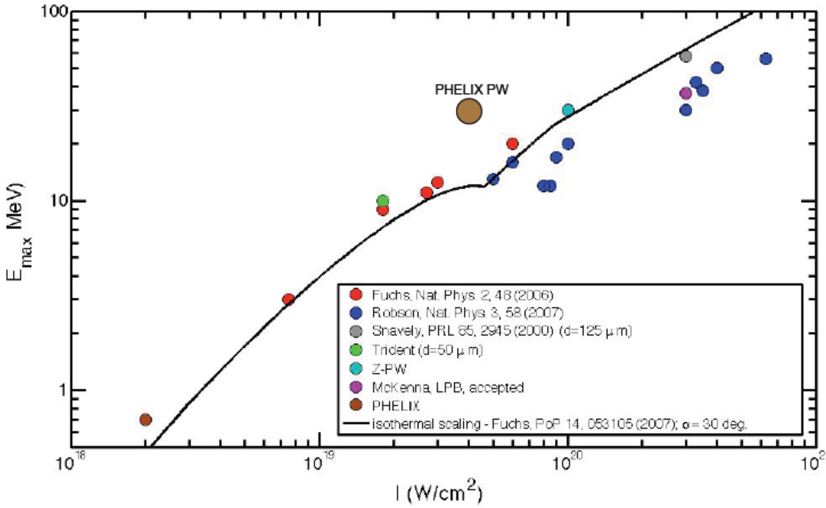


Setup to test proton production





8x10^{10} protons in ΔE/E = +/- 0.04



- **Excellent laser beam quality**
- **Ion energy comparable with other systems**
- **Ion number as calculated**
- **All on the very first shot!!**
  (further optimization pending)

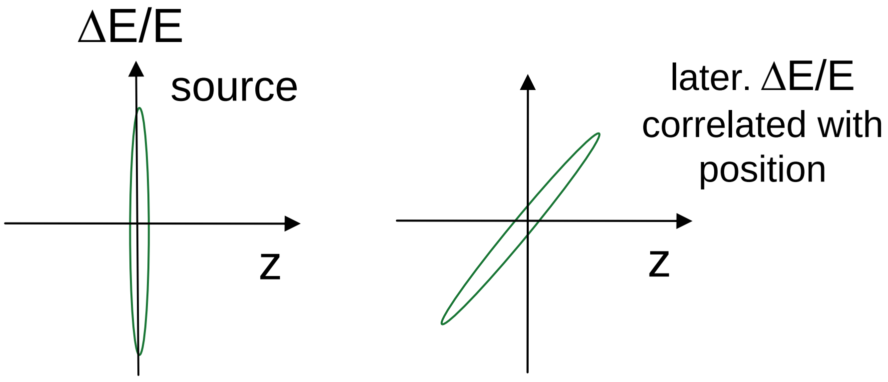
Chromatic effect blows up integrated emittance

from bunch head to tail – common collimation problem

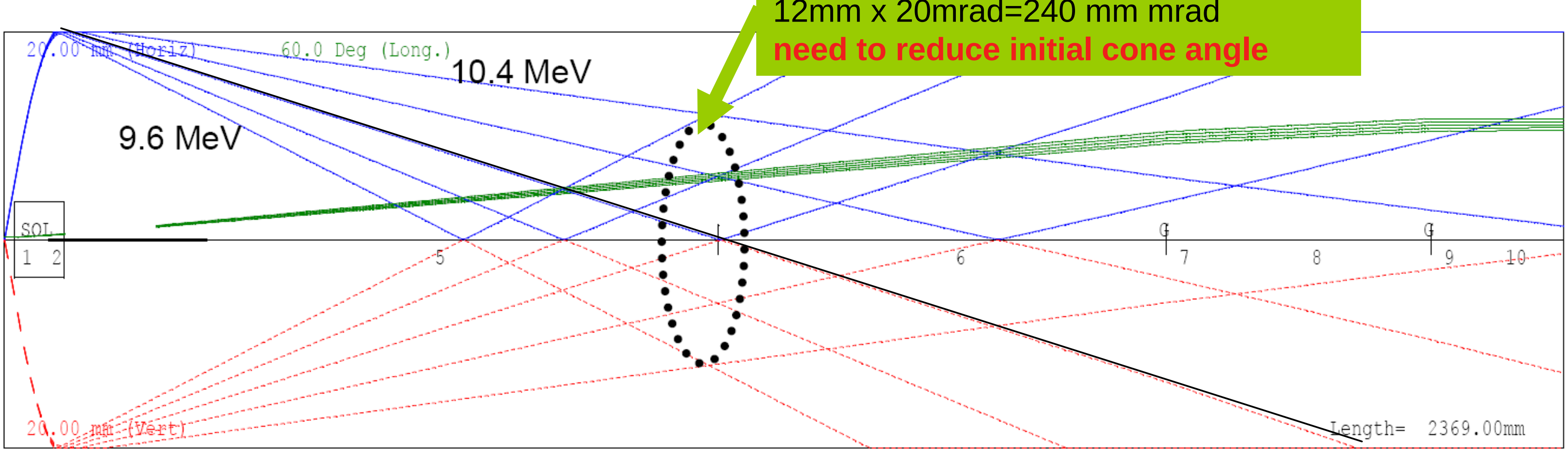
solenoid focusing: Δf/f ~ 2 Δp/p

10 MeV protons produced at 20° opening cone

- modeled ΔE/E = +/-0.04 by beams of 9.6 ... 10.4 MeV to describe chromatic **effective emittance ~ $x'_{ini}\ \Delta p/p$**
- much enlarged "effective spot"
- initial emittance < 1 mm mrad replaced by "effective emittance" 240 mm mrad

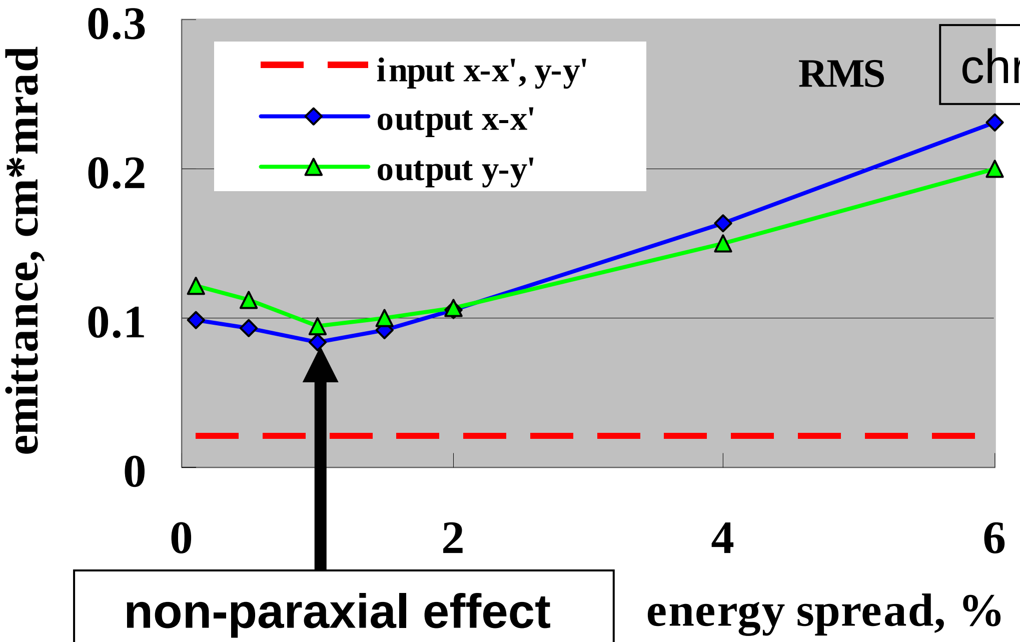


effective spot with enlargement to:
12mm x 20mrad=240 mm mrad
need to reduce initial cone angle



Detailed tracking simulation with DYNAMION* code (quadrupole channel)

- reduced cone angle from 22^0 to 2.5^0
- confirms chromatic effect
- shows also nonparaxial effect



chromatic effect ~ ΔE/E

non-paraxial effect
(mono-energetic beam)

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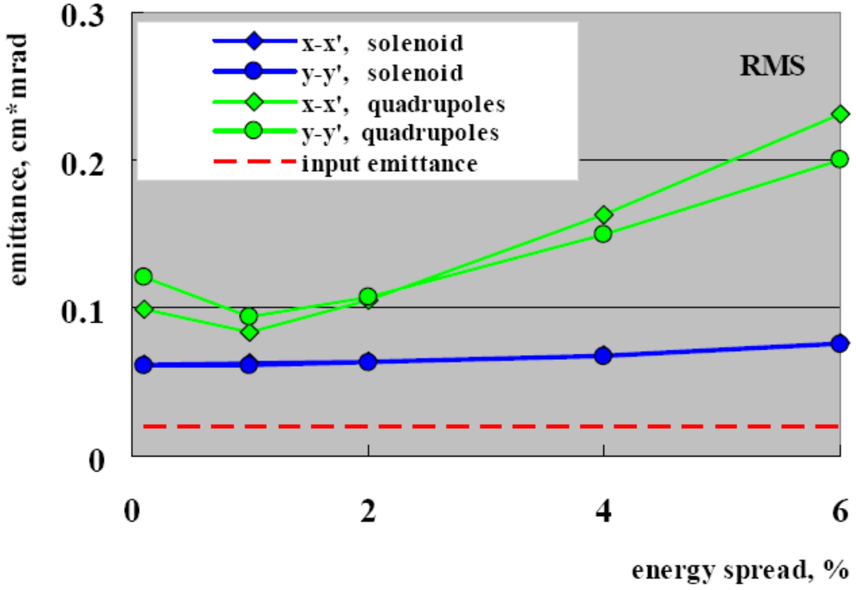
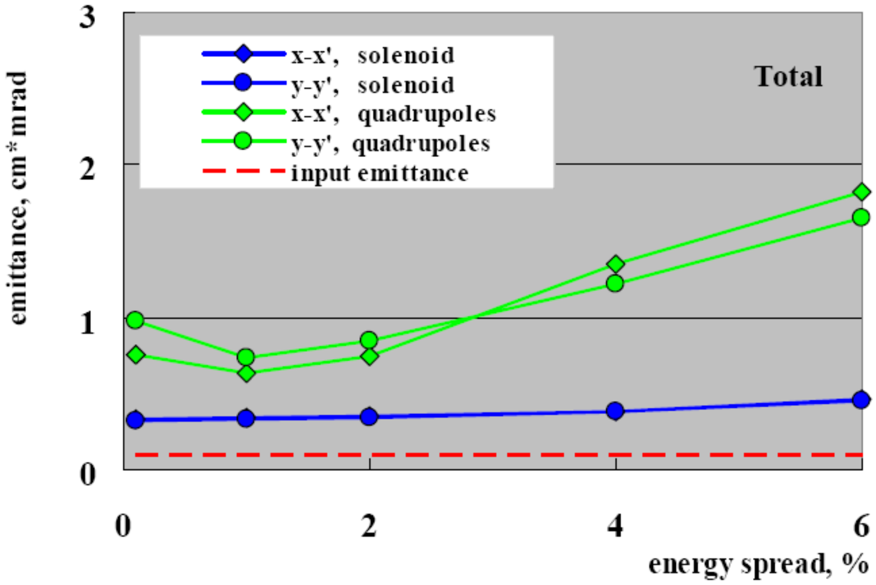
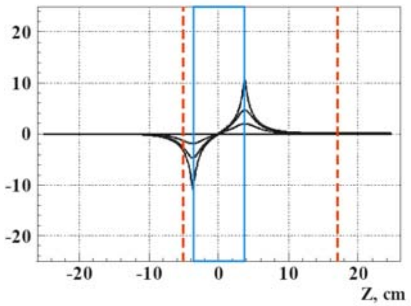
* *S. Yaramishev et. al.*

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





"real" solenoid field

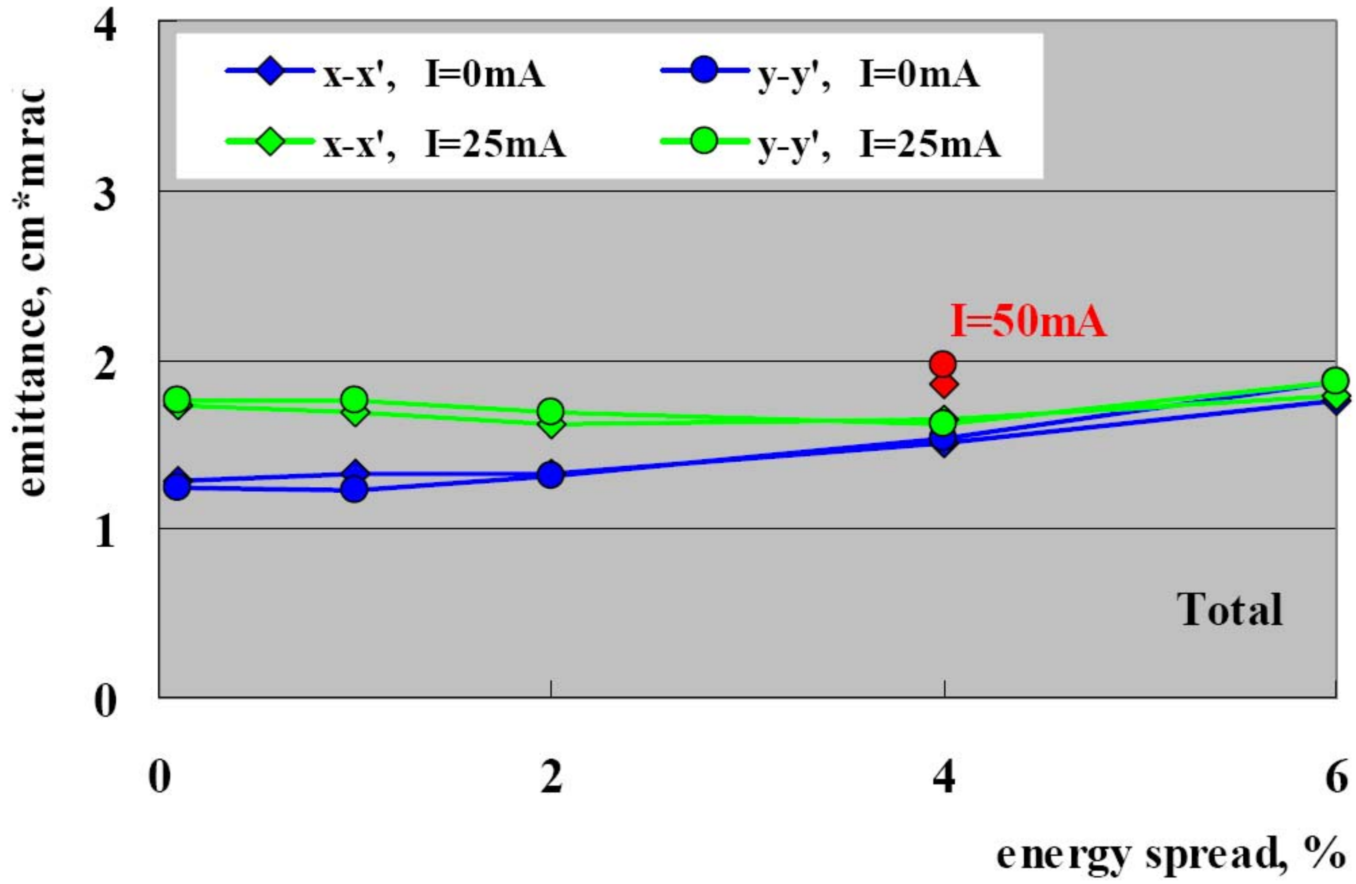


solenoid

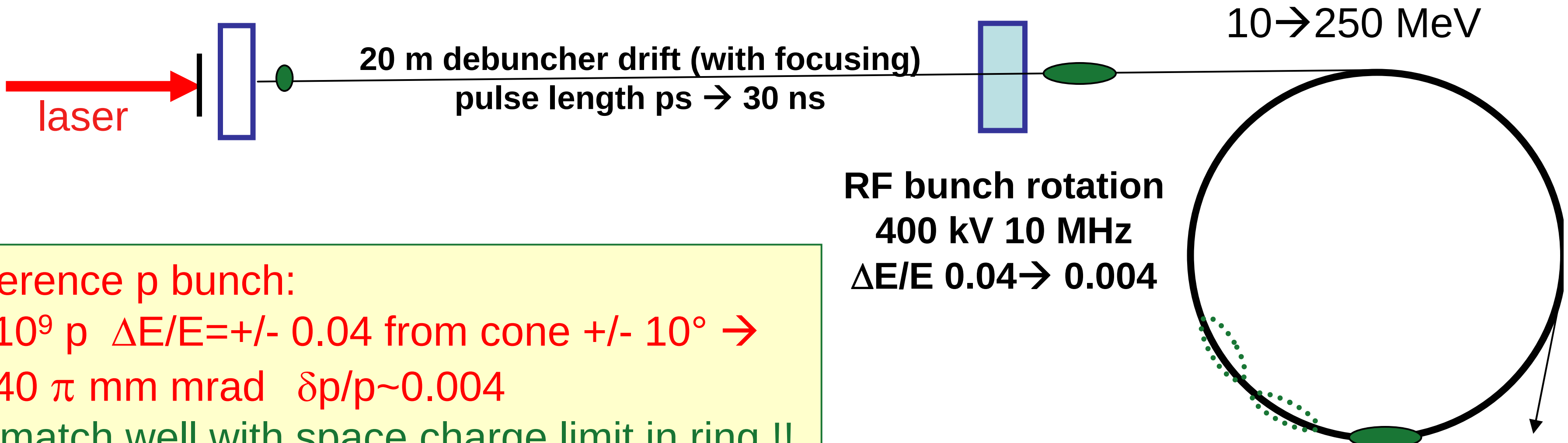
- requires large field of 16 T
- symmetric focusing avoids large excursions as in quadrupoles
- larger distance source-solenoid reduces field, but increases chromatic effect → approaching quadrupole

Combined chromatic and space charge effects

production cone angle 5⁰ (86 mrad) ΔE/E = +/-0.04
extrapolate to 10⁰ at 30 mA → ε~40 π mm mrad with 2x10⁹ p (reference bunch)



Applied to synchrotron injection at 10 MeV



10→250 MeV

20 m debuncher drift (with focusing)
pulse length ps → 30 ns

laser

RF bunch rotation
400 kV 10 MHz
ΔE/E 0.04→ 0.004

reference p bunch:
2x10^9 p ΔE/E=+/- 0.04 from cone +/- 10° →
ε~40 π mm mrad δp/p~0.004
→ match well with space charge limit in ring !!

repeat 25 times
bunch into bucket
of 10 MHz (~70 kV)

next at GSI (2009/10):
we plan experiment with single bunch and 2 m drift + 108 MHz bunch rotator
→ **diagnose 3D phase space + efficiency to verify our modeling**

Parameters: laser injector – full laser scenario

					250 MeV		Laser:	
Ion	N_{bunch}	N_{ring}	ΔQ_{inc} (space charge)	h	ε_{final} π mm mrad (estimated)	$\delta p/p_{final}$ (estimated)		
p	2x10^9	5x10^{10}	0.1 (1 s!!!)	25	~10 **assume 10° cone**	~0.001	~10 Hz ~PW	5Hz / 30J 30 fs on market
C^{6+}	6x10^8	1.5x10^{10} **every 10 s**	0.1				~10 Hz ~PW	
full laser:	N_{batch}	$N_{fraction}$						
p	5x10^7	5x10^{10} **for 3D scanning in 10 s**			<10 ? **assume 2.5° cone**	<0.001? **linac bunch rotator: ~ 2-5 m length**	100 Hz	>PW?

Conclusions

- As of today laser acceleration has a theoretical potential to compete with conventional drivers for therapy
- extremely high initial beam quality lost after collector → small "usable" fraction of total particle yield (PHELIX: "use" 3x10^{-3} of proton and 3x10^{-5} of photon yield)
- "laser injector" into synchrotron
  - should be ok (based on PHELIX data)
  - 10 Hz Petawatt laser in reach
  - hard to compete with linac technology !!
- "full energy laser" scenario lacks data
  - small cones (~2-3^{0}), smaller production $\Delta E/E$ (100%→10-20%)
  - >100 Hz laser systems, nm foils (problems?)
  - reproducibility, precision unknown
- New accelerator technologies take time!!