# Laser accelerated ions and their potential for therapy accelerators

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3. Beam quality source-collimation-accelerator
   - PHELIX-GSI experiment
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4. Impact on accelerator scenarios
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M. Roth (TU Darmstadt), M. Droba (U Frankfurt)

# 1. Introduction to p driver parameters

## What are lasers competing with?

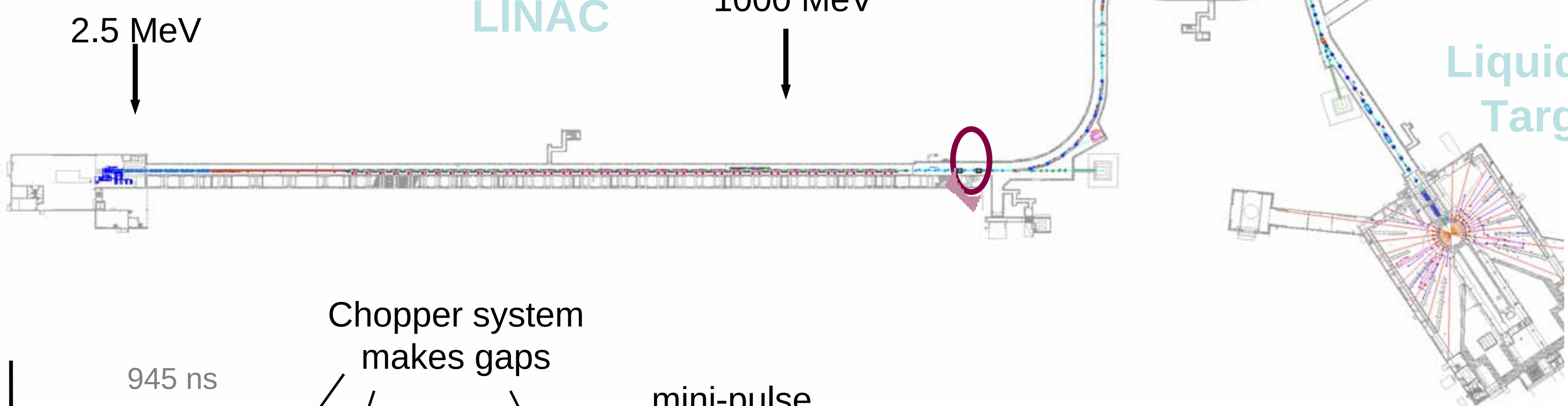
### SNS Accelerator Complex

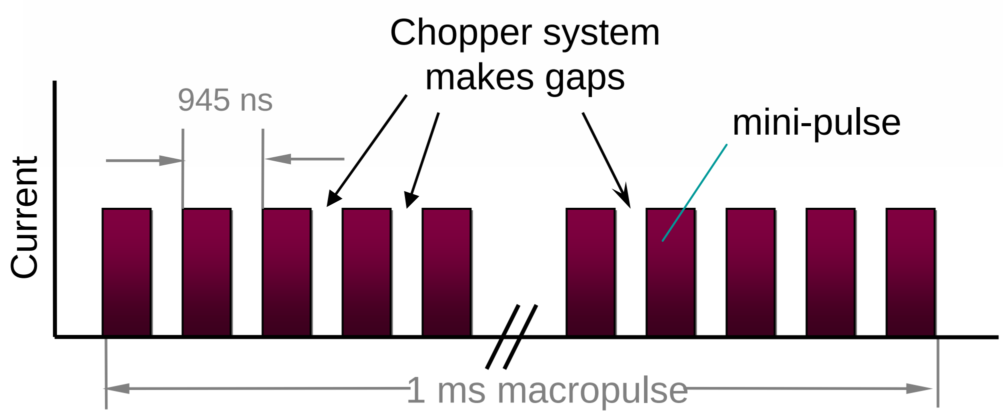
**Front-End:**

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

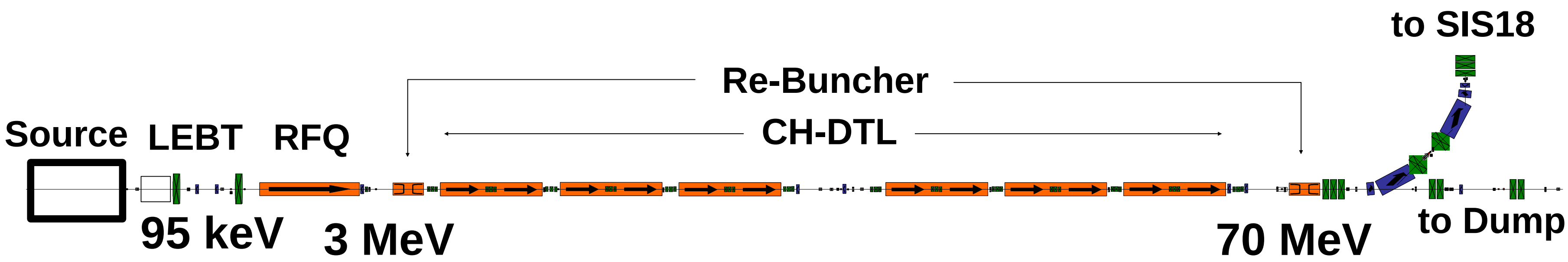
**Accumulator Ring:**

**Compress 1 msec long pulse to 700 nsec**

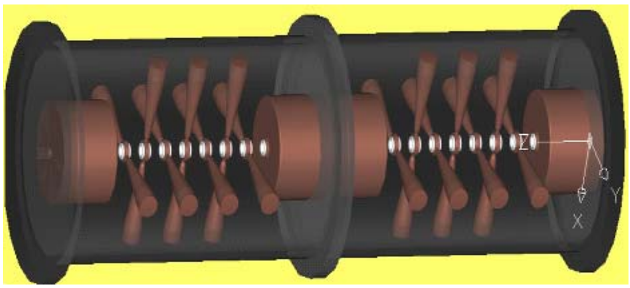


# Injector Chain: New Proton Linac for FAIR at GSI




**<u>C</u>rossed-bar <u>H</u>-Structure**

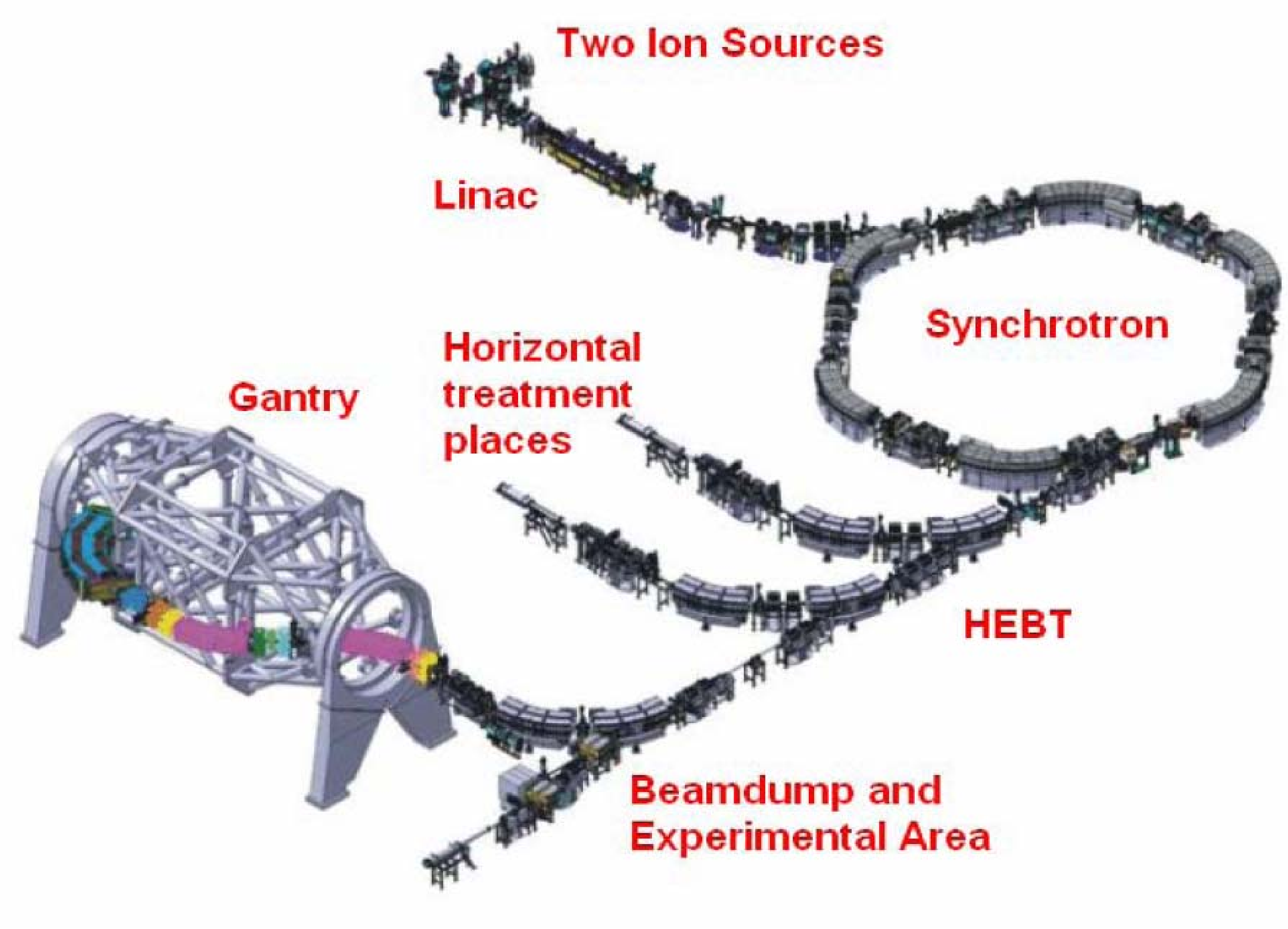


(Univ. Frankfurt U. Ratzinger )

| | |
|---|---|
| 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 |

# 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<br>~ $5x10^{7}$ / 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) |

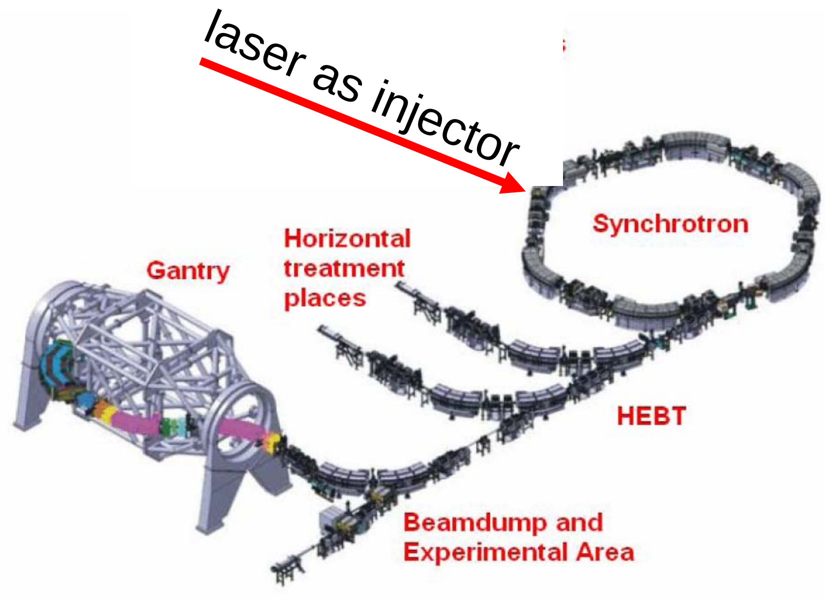
→ efficiency of "photons into usable protons/ions" crucial !!
(example: in GSI-PHELIX experiment ~ $3x10^{-5}$)

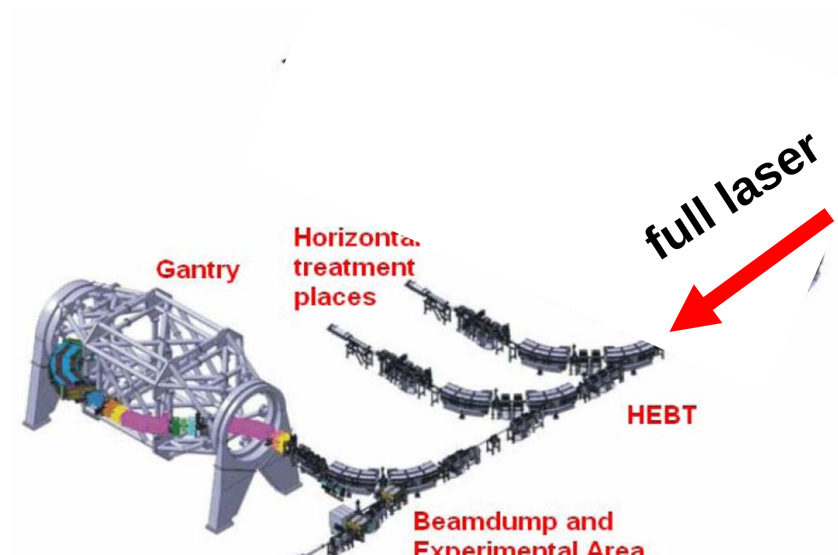
# 2. Proton/Ion Therapy Accelerators

**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)

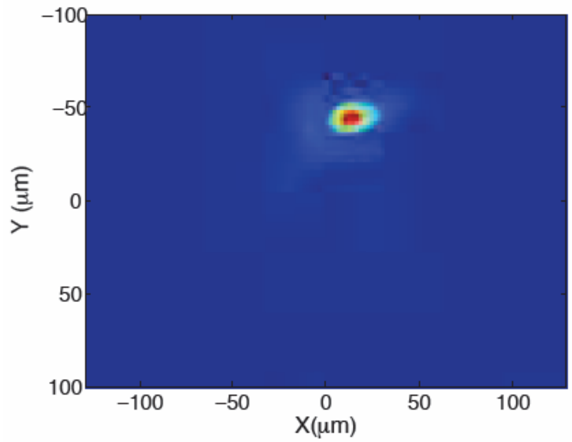
proton beam space charge further downstream - appears controllable

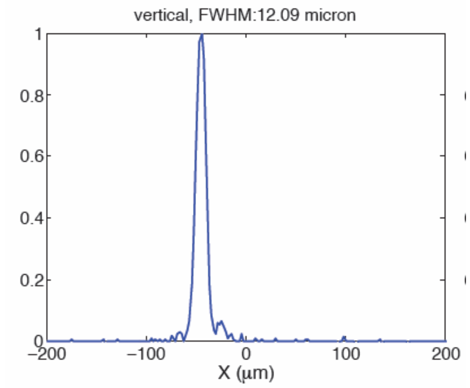
("geometric" aberration by nonuniform space charge)

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

## used as reference case here

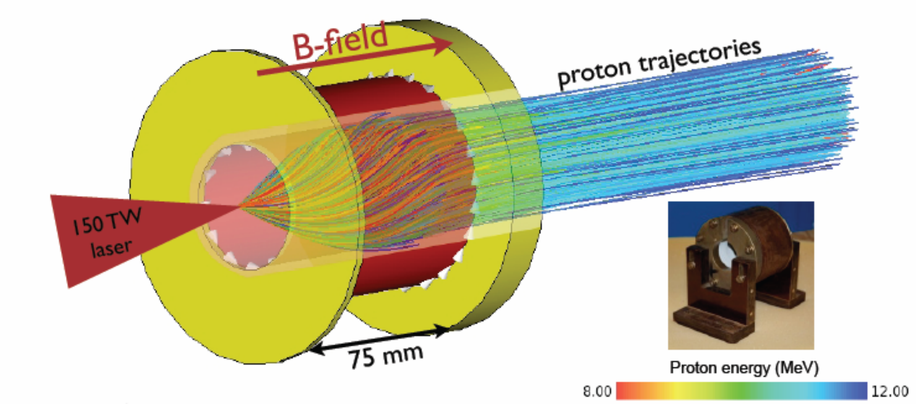
In 2008 demonstrated first time:
- 170 TW power
- 700 fs pulse length (120 J)
- novel copper focusing parabola
- spot size 12 X 17 μm (FWH
- Intensity: ~ 4 x $10^{19}$ W/cm$^2$



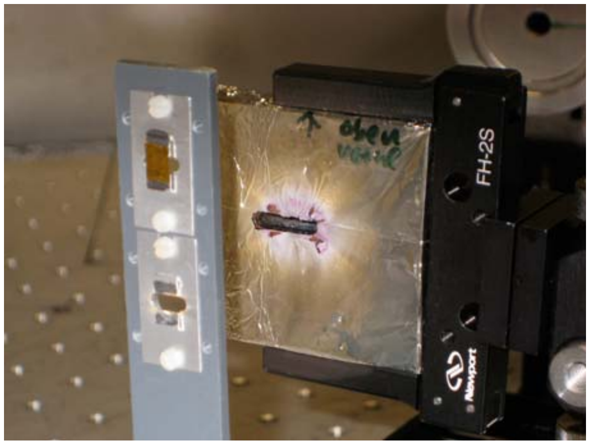

EXPERIMENT: Laser Ion Acceleration (TUD - GSI)

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

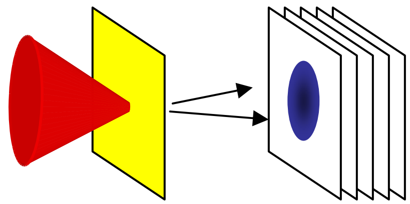


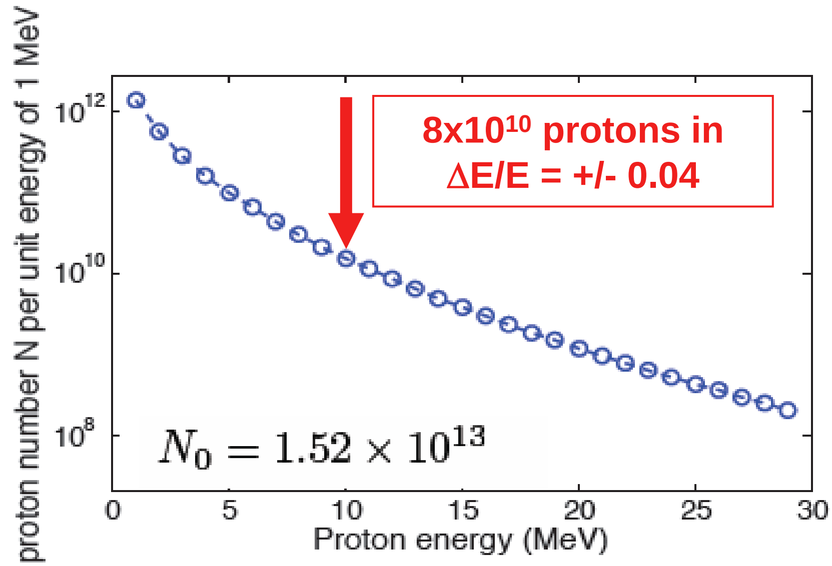

(Simulation CST-Studio, I. Albers,TUD)

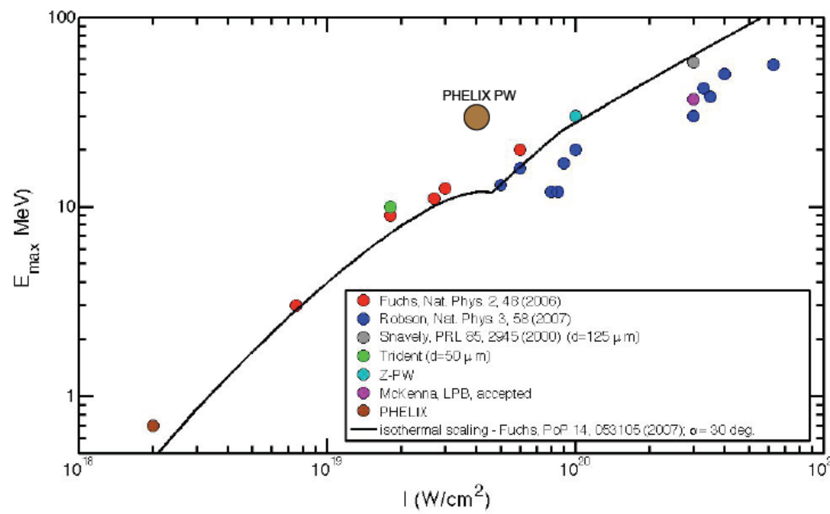
# Results of the first PHELIX experiment on laser proton acceleration




Setup to test proton production






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

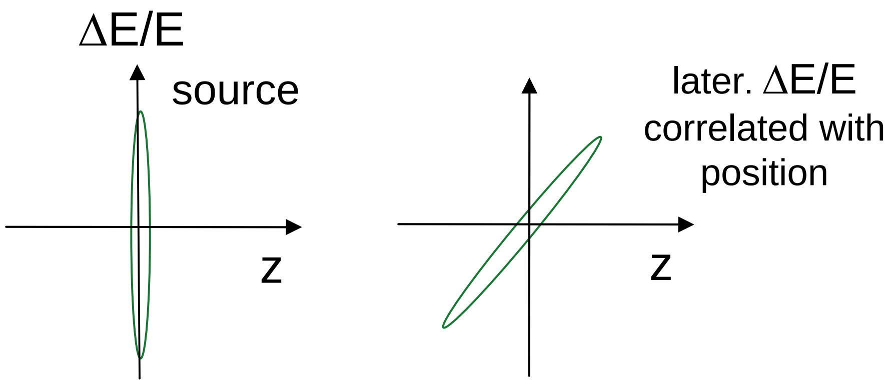
# Chromatic effect blows up integrated emittance

## from bunch head to tail – common collimation problem

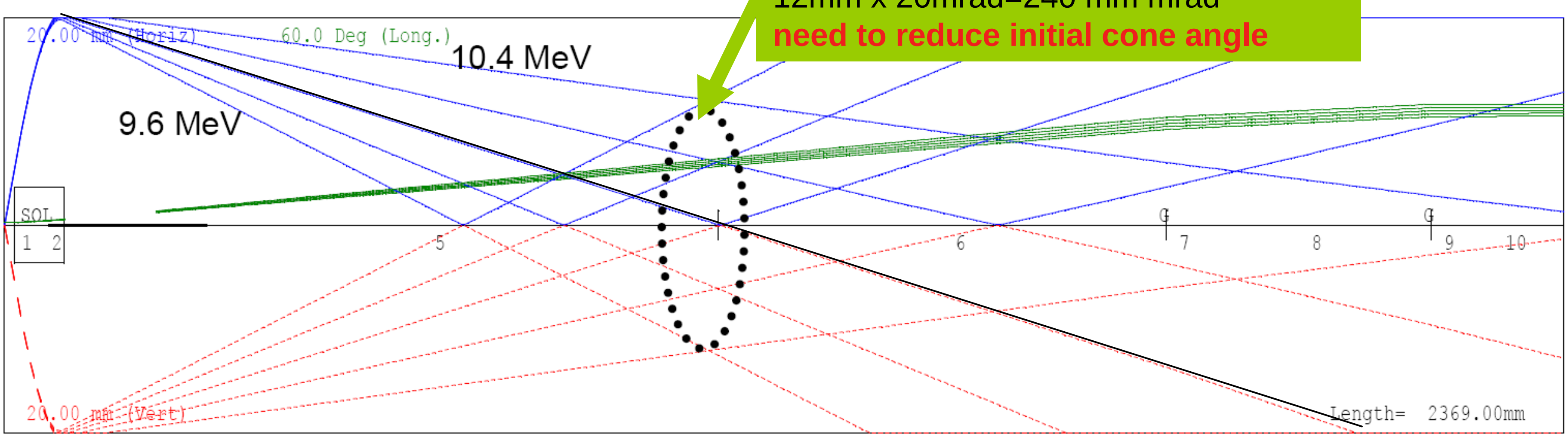
## solenoid focusing: $\Delta f/f \sim 2\, \Delta p/p$

**10 MeV protons produced at 20° opening cone**

- modeled $\Delta E/E = +/-0.04$ 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

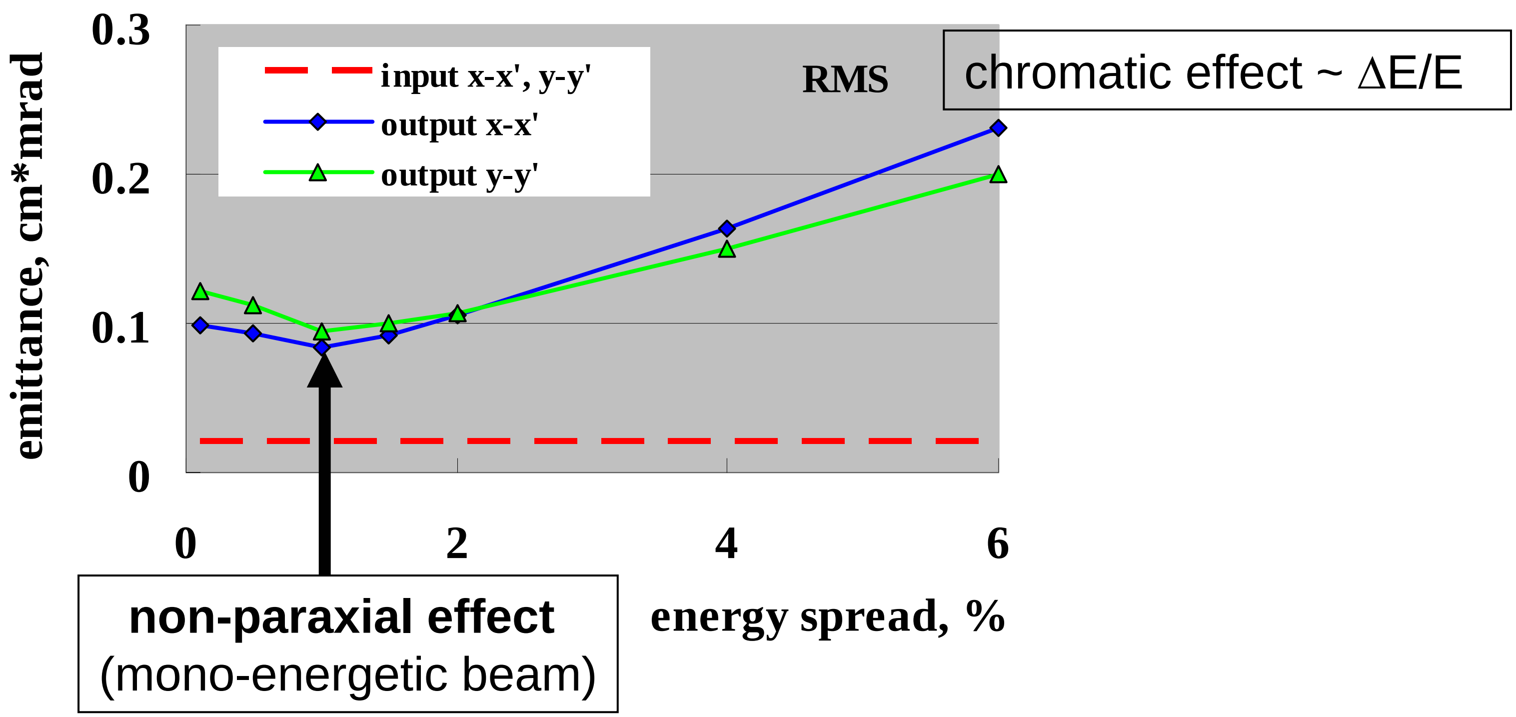



effective spot with enlargement to:
12mm x 20mrad=240 mm mrad
**need to reduce initial cone angle**



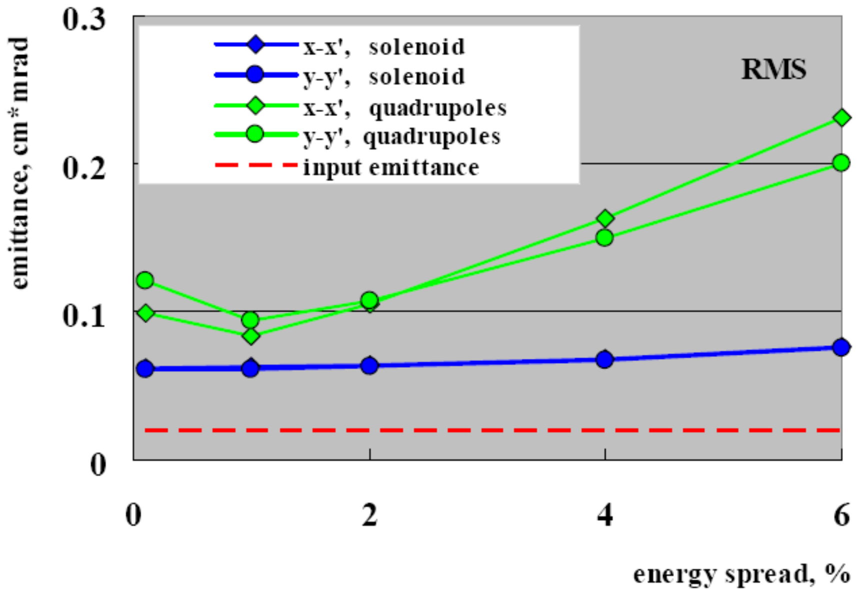
# Detailed tracking simulation with DYNAMION* code (quadrupole channel)

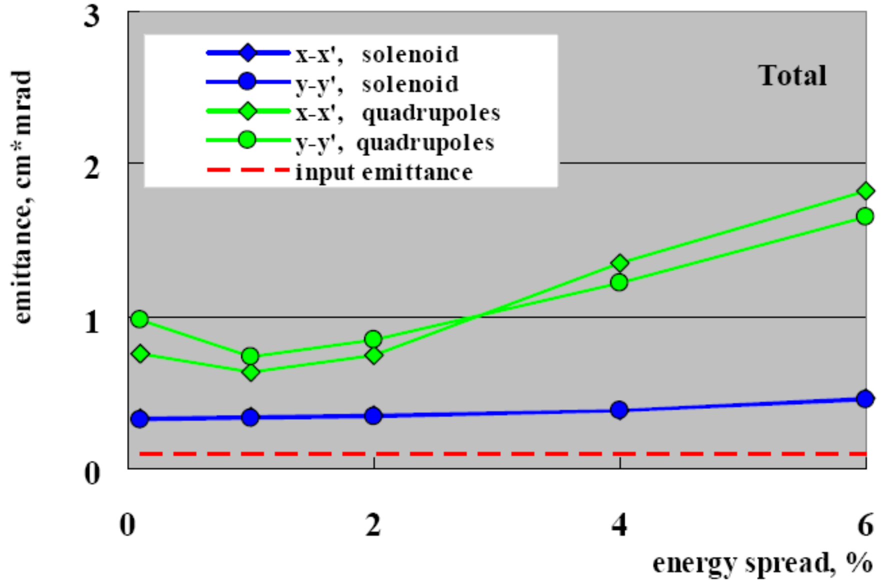
- reduced cone angle from $22^0$ to $2.5^0$
- confirms chromatic effect
- shows also nonparaxial effect



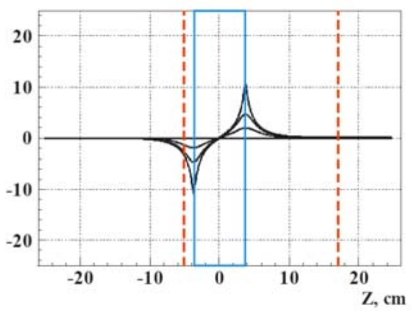

* *S. Yaramishev et. al.*

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




"real" solenoid field

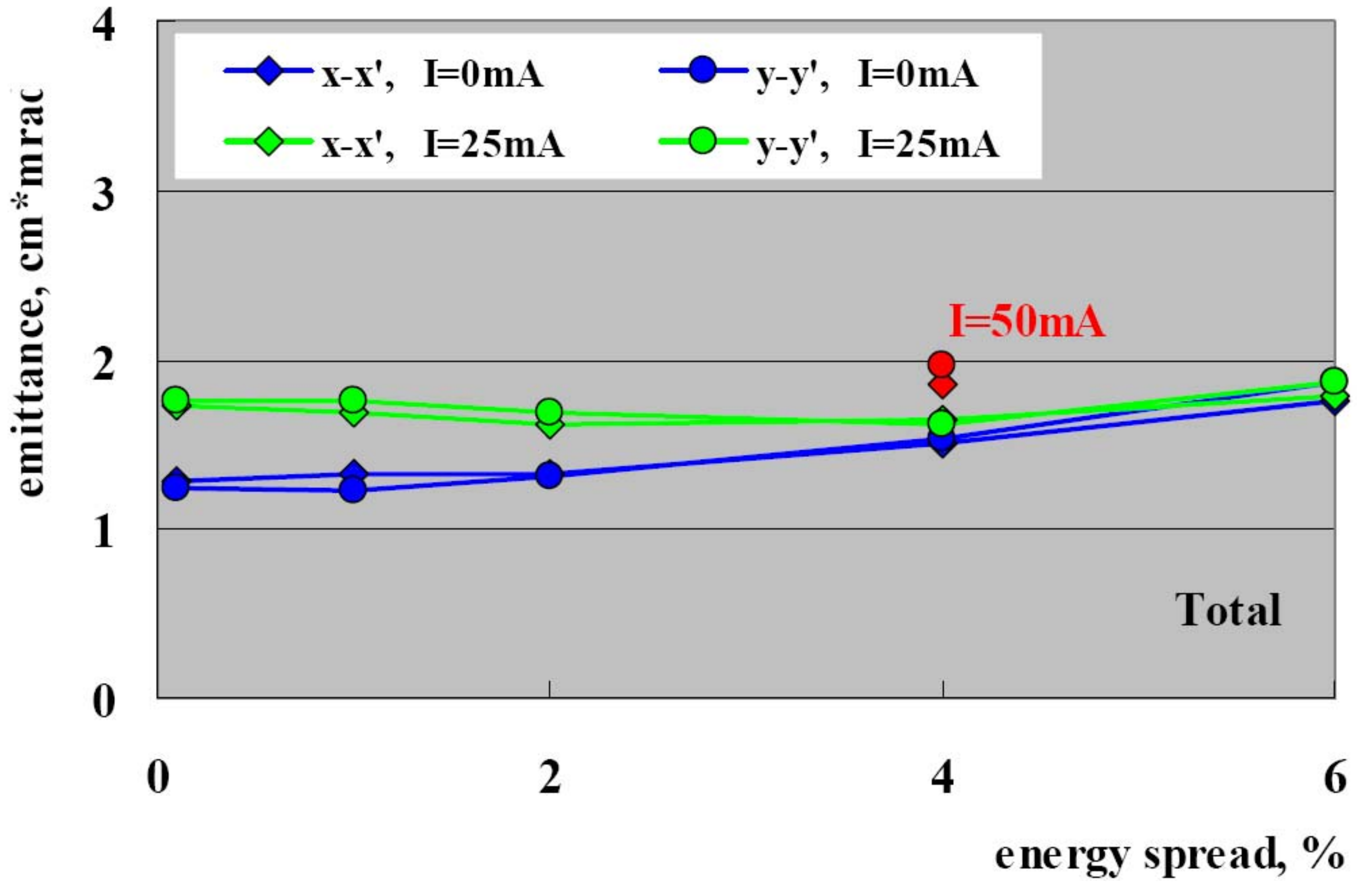



solenoid

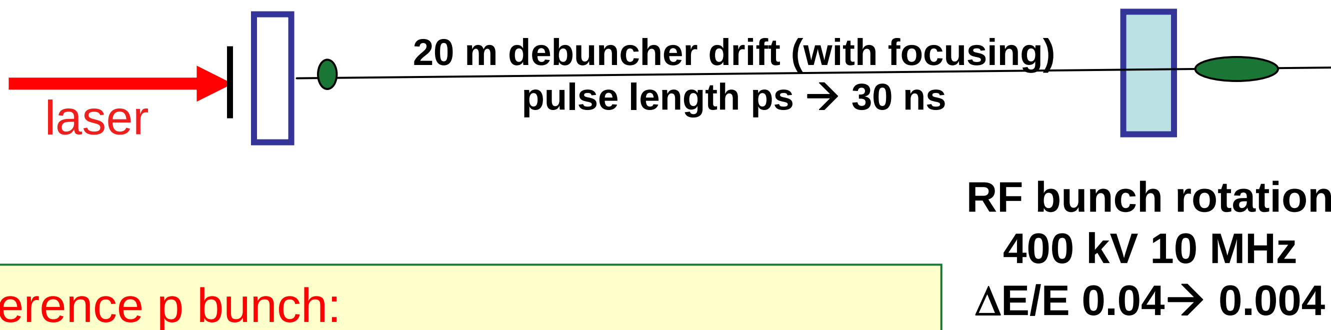
- requires large field of 16 T
- symmetric focusing avoids large excursions as in quadrupoles
- larger distance source-solenoid reduces field, but increases chromatic effect → approaching quadrupole

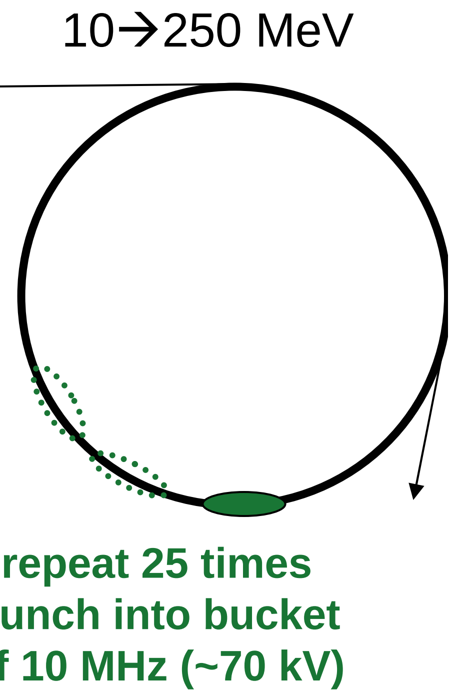
# Combined chromatic and space charge effects

production cone angle 5⁰ (86 mrad) ΔE/E = +/-0.04
extrapolate to 10⁰ at 30 mA → ε~40 π mm mrad with $2x10^9$ p (reference bunch)



# Applied to synchrotron injection at 10 MeV




reference p bunch:
$2\times10^9$ p  $\Delta E/E = +/- 0.04$ from cone +/- 10° →
$\varepsilon \sim 40\,\pi$ mm mrad   $\delta p/p \sim 0.004$
→ match well with space charge limit in ring !!

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 | $N_{bunch}$ | $N_{ring}$ | $\Delta Q_{inc}$ (space charge) | h | $\varepsilon_{final}$ 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" $3 \times 10^{-3}$ of proton and $3 \times 10^{-5}$ 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!!