TNSA – A New Particle Source for Conventional Accelerators

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HELMHOLTZ GEMEINSCHAFT | GSI | TECHNISCHE UNIVERSITÄT DARMSTADT | HIC for FAIR Helmholtz International Center | PHELIX | Forschungszentrum Dresden Rossendorf | HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

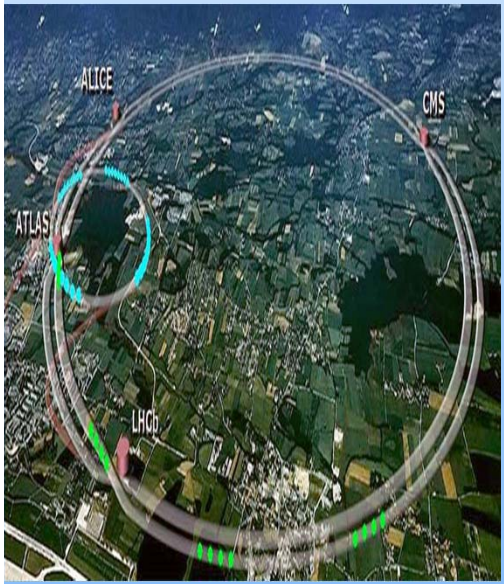
Outline

- Introduction.
- Acceleration Mechanisms – TNSA.
- PHELIX Laser and LIGHT Project.
- Injector for Accelerators.
- Experimental Setup – Proton Spectrum.
- Pulsed Solenoid – LASIN Simulations.
- CH- Structure.
- Gain Voltage Effect.
- RF Power for a Single Bunch.
- Conclusions and Outlooks.

Particle Acceleration

➢ Limitations of conventional accelerator technology mean that kilometer-sized accelerators are required for high energy particles.

➢ The accelerating field gradient of laser protons has at least four order of magnitude larger than of conventional accelerator (TV/m in compare with MV/m).




LARGE AND SMALL: (Left) Conventional accelerator at CERN. (Center) Part of the linear accelerator beamline. (Right) Benchtop laser particle accelerator for multi- MeV experiments.

Laser-Plasma Interaction

Ponderomotive Force

$$\boldsymbol{F_p} = -\frac{e^2}{4m\omega^2}\nabla|\boldsymbol{E_s}|^2 \quad \Rightarrow \quad \frac{F_{pi}}{F_{pe}} = \frac{m_e}{m_i}$$

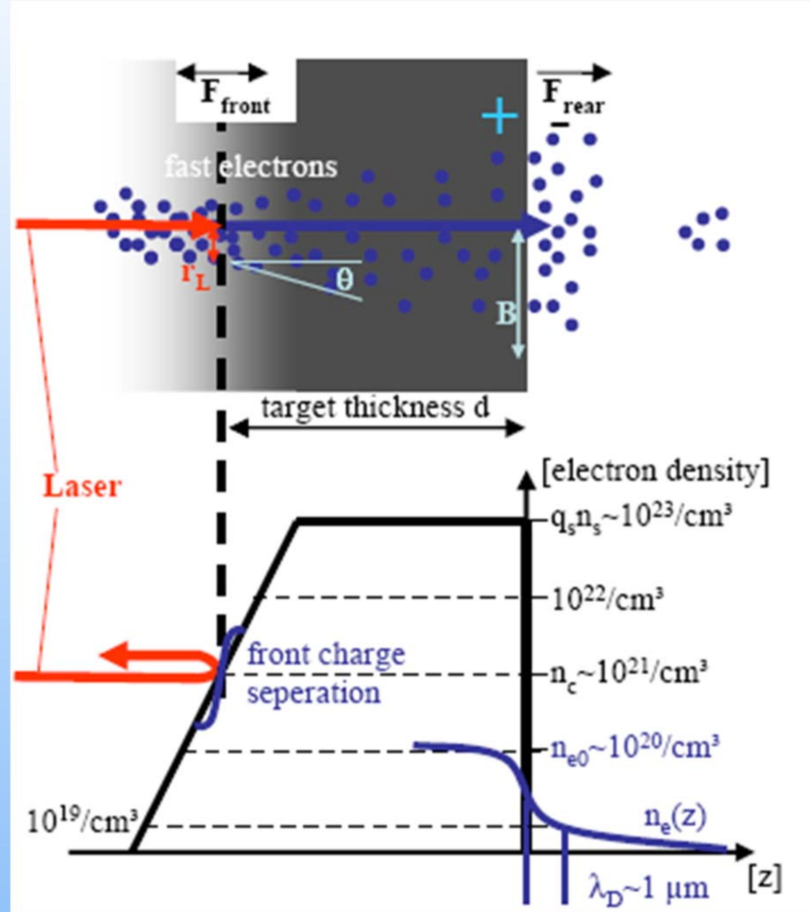
- Electrons are pushed by laser pulse.
- Immobile ion background repelling electrons.

Electron oscillate with plasma frequncy.

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

Critical density

$$n_c = \frac{\varepsilon_0 m \gamma {\omega_L}^2}{e^2}$$



"Ion acceleration driven by high-intensity laser pulses", J. Schreiber, München, 2006.

Ion Acceleration Mechanisms

➢ Acceleration mechanisms depend on different conditions:

- Laser pulse: intensity, energy, per-pulse, polarization, pulse duration….
- Target properties: density, thickness, mass….

❑ If the electrons are dominated by a Thermal Spectrum, they will expand in vacuum resulting in a huge accelerating field

Target Normal Sheath Acceleration mechanism (TNSA)

❑ If the thermal electrons are suppressed, an accelerating field is induced by the balance between light pressure and electrostatic force

Radiation Pressure Acceleration mechanism (RPA)

TNSA and Transporting to CH-DTL

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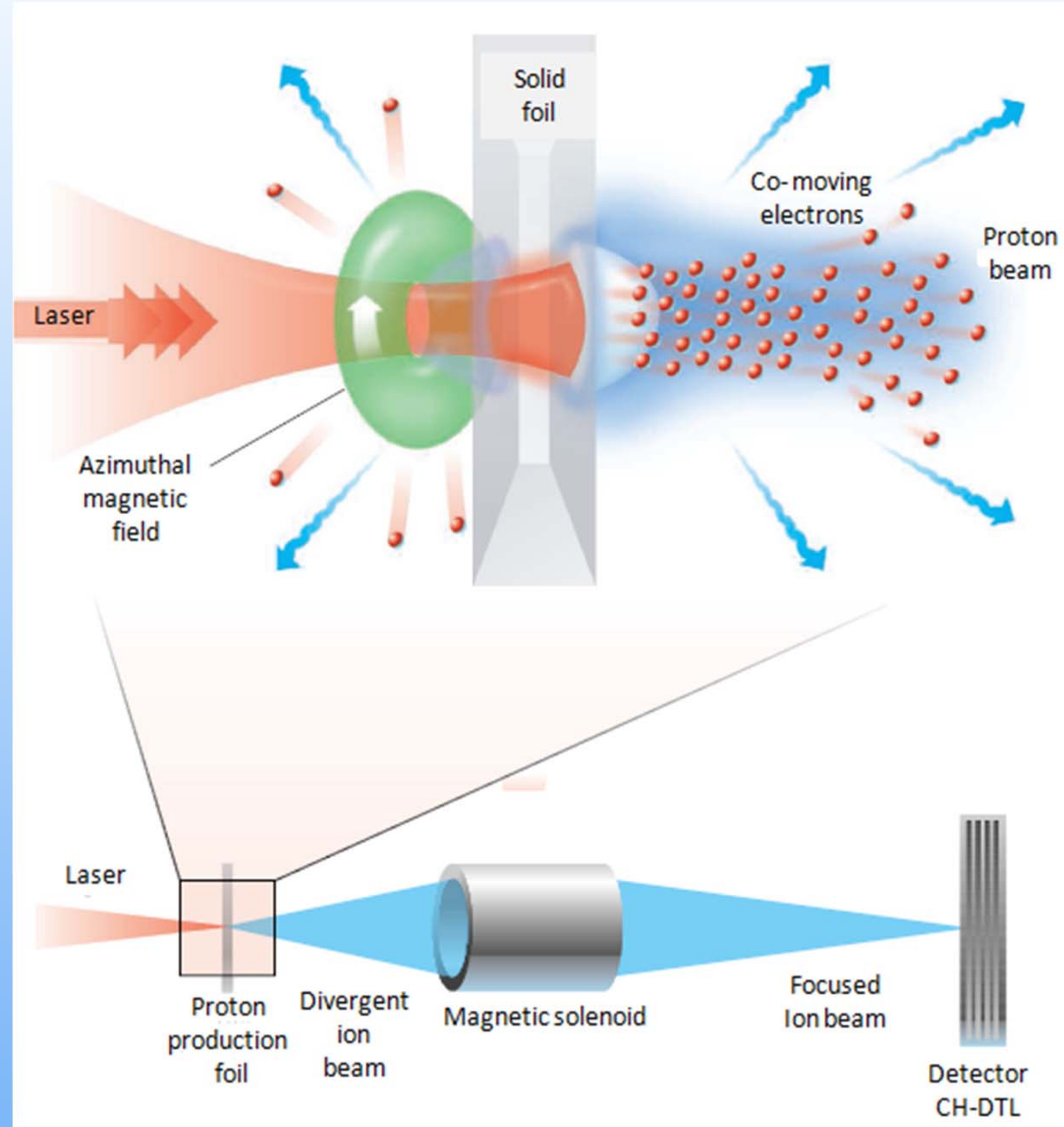
The TNSA mechanism:

I. Laser electron acceleration
II. Charge separation
III. Quasi static electric field
IV. Ion acceleration

TNSA characteristics:

1. Linear polarized laser like in PHELIX.
2. Electric field E~TV/m.
3. Large angular divergence.
4. Energy spread > 100%.
5. Target ~ tens of µm.
6. Protons are accelerated to MeV range.



Characteristics of TNSA protons

Laser-accelerated ion beams have unique characteristics compared to conventional accelerators

Benefits:

- Large accelerating fields
  TV/m vs. MV/m
- Short acceleration distance
  ~ 10μm vs. ~ 100m
- Short initial pulse duration
  < ps vs. > ns
- Small initial longitudinal emittance
  1μeVs vs. 1eVs (CERN SPS)
- Small initial transverse emittance
  < 0.1 mm-mrad vs. 1 πmm-mrad (CERN SPS)

Challenges:

- High divergence.
- Broad energy spectrum.
- Low repetition rate.
- Poor controlled particle energy.

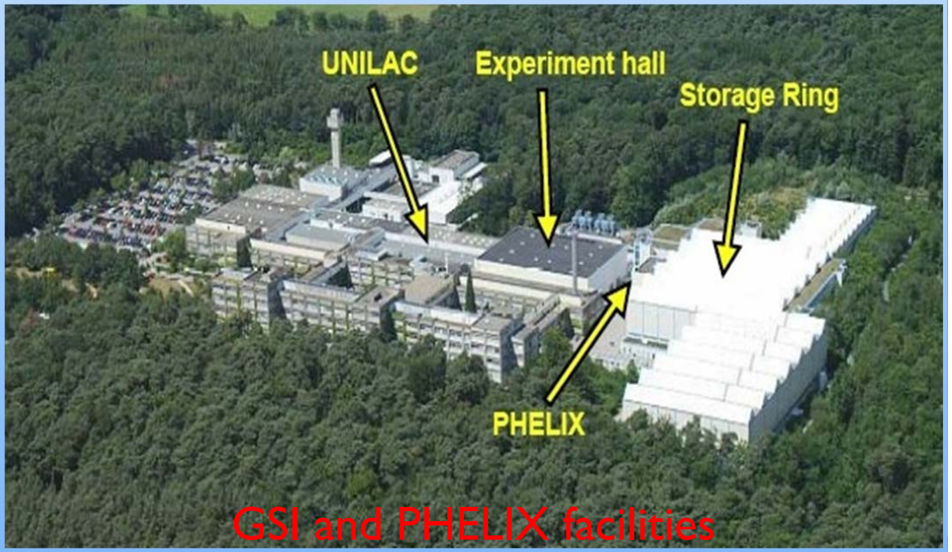
✓ For special application Laser accelerated ions could be an alternative for conventional

Ion source – RFQ – DTL front end

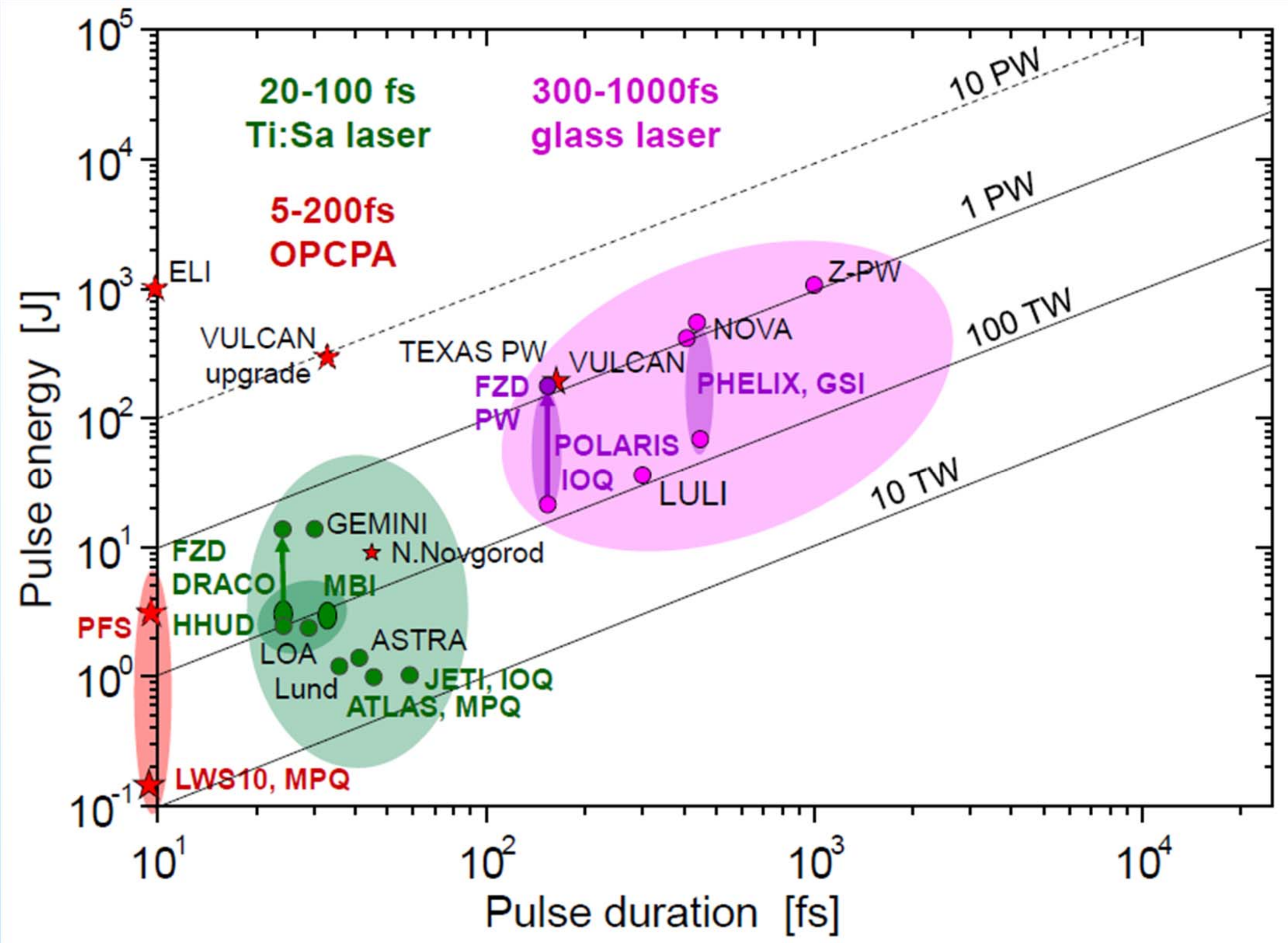
PHELIX: Petawatt High - Energy Laser for Heavy - Ion eXperiments.

- ❑ PHELIX has been completed in 2008.
- ❑ Two Options:
- ➢ Long pulse mode: pulse of length from 0.7 – 20 ns with kJ energy.
- ➢ Short pulse mode: pulse of length 0.7 – 20 ps with energy up to 120J.

PHELIX Laser Parameters		
	Long pulse	Short pulse
Pulse duration	0.7 -20 ns	0.7-20 ps
Energy	0.3 – 1 kJ	120 J
Max intensity	$10^{16} W / cm^2$	$10^{20} W / cm^2$
Rep. rate at max power	1 shot every 60 min	

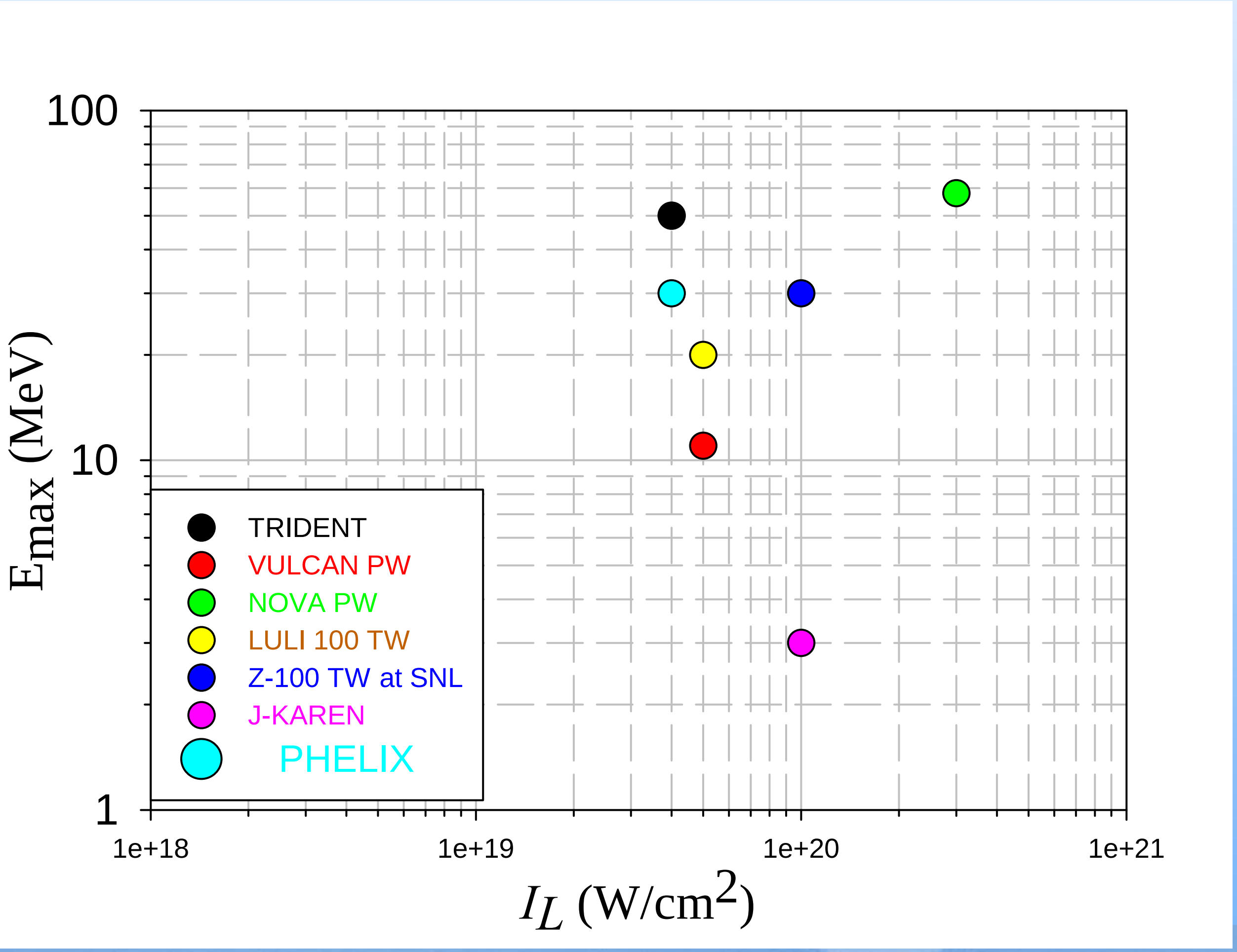


High Power Lasers Worldwide (M. Bussmann)

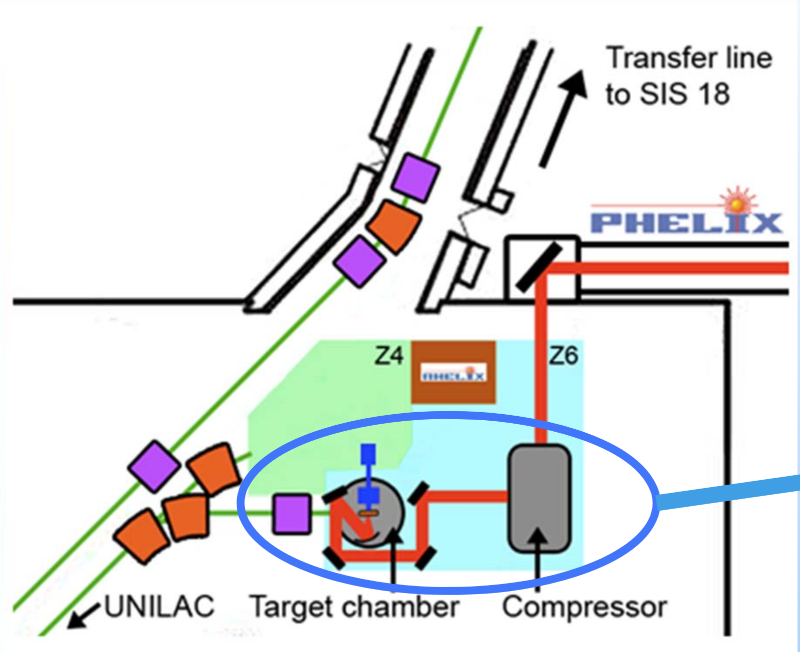


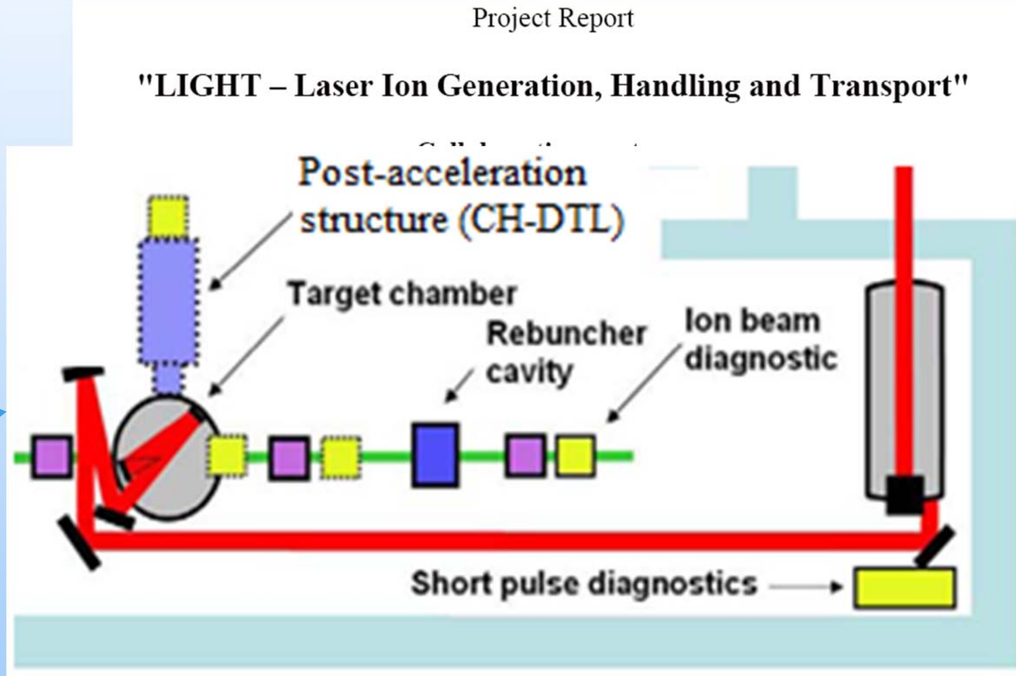
Characteristics of Laser-accelerated protons

Large number of expriments have been performed to study the dependance of the accelerated ion properties on the laser parameters (rare side acceleration).



LIGHT Project





Collaboration Partners:

- TU- Darmstadt
- GSI
- IAP- Frankfurt
- Helmholtz-Institute Jena
- FZ- Dresden
- EMMI

➢ Expected laser parameters:

- Beam diameter: 12 cm
- wavelength: 1053 nm
- pulse duration: 500 fs
- Pulse energy: 50 J
- Repetition rate: 1 shot/60 min

Objectives

- Investigate the physics of proton (ion) generation by ultra-intense laser.
- Collimate the proton beam by a solenoid and transport into bunch rotation cavity.
- Post-acceleration by a CH - DTL.
- Analyze 6D phase space distribution and beam transmission.
- Correlation between energy distribution and transverse divergence.
- Optimize laser and target configurations, target solenoid stand-off distance.
- Check of the reproducibility of the beam parameters
- Interaction with intense B- field, context of early de-neutralization and space charge effects.

Time Plan

	Task	Finished
Phase 1	Setup of laser infrastructure, 1st experimental commissioning	02/2011
Phase 2	Experimental commissioning; solenoid, bunch rotation cavity	02/2012
Phase 3	Ion transport	12/2012

➢ Future proposal:

- Post acceleration cavity of generated protons with a conventional accelerator, CH- DTL.
- Adaptive optics system, optimize focal spot intensity for higher proton yield.

Injector for Conventional Accelerators

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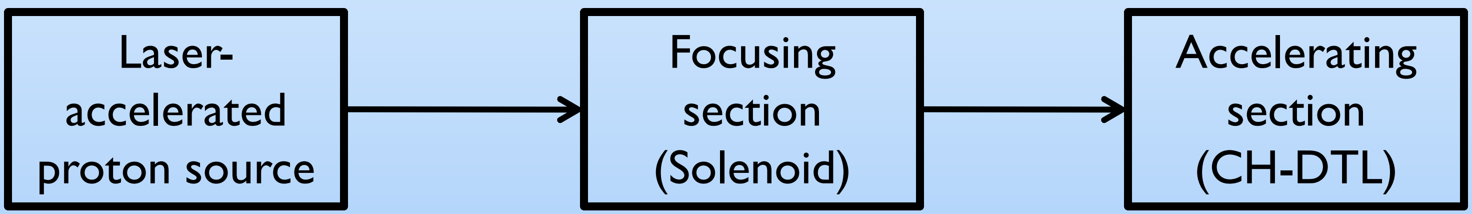
- The coupling between laser accelerated protons with conventional DTL for further acceleration seems possible.
- This hybrid will benefit from the unique characteristics of the laser accelerated proton source and from the flexibility of RF based accelerator structure.



Scheme of the hybrid accelerator

Motivation:

- Single Bunch generation; Small emittances and extremely high particle number.

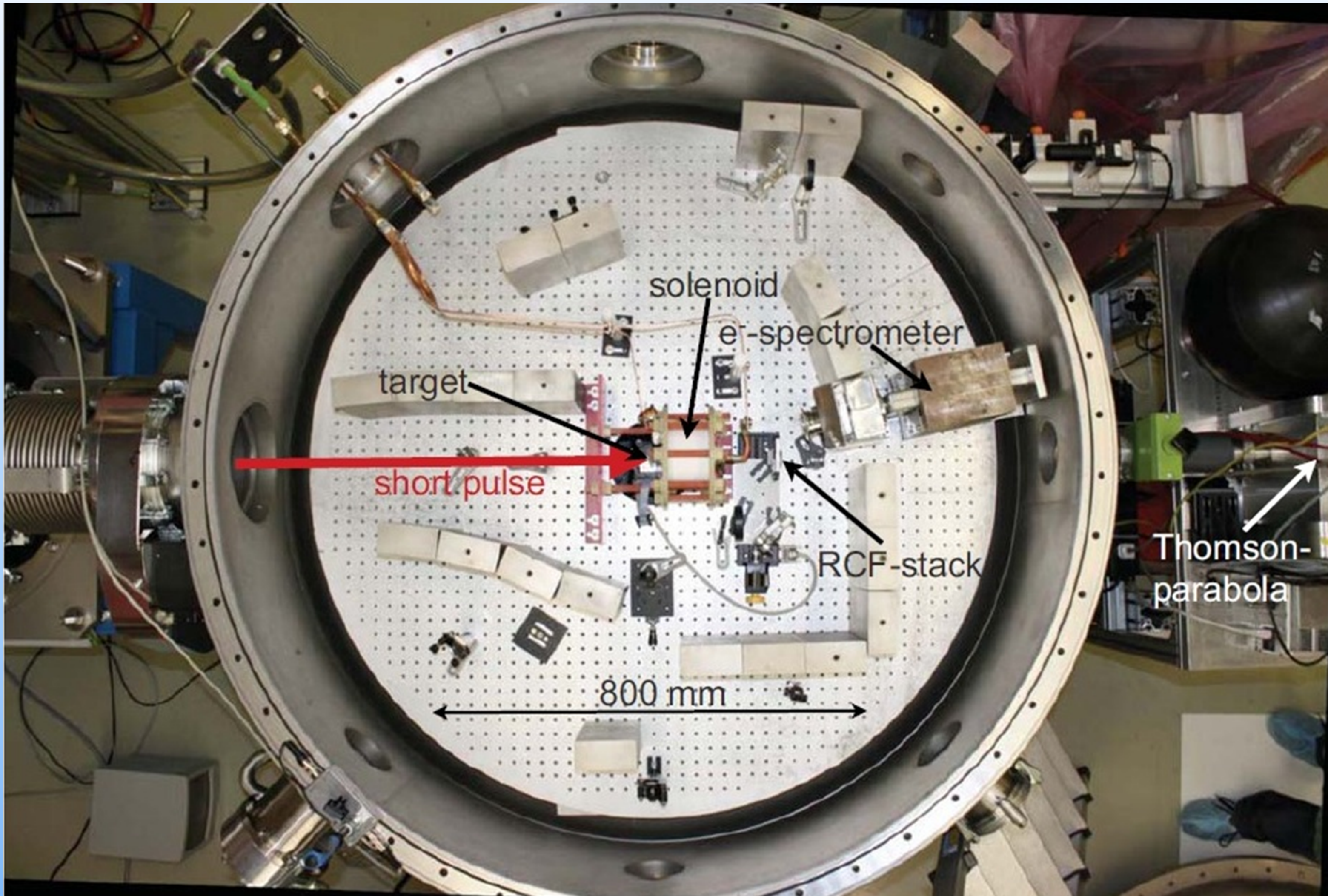
Advantage:

- Beam parameters and quality are comparable or better
- Smaller size and easier to operate.

Open Question:

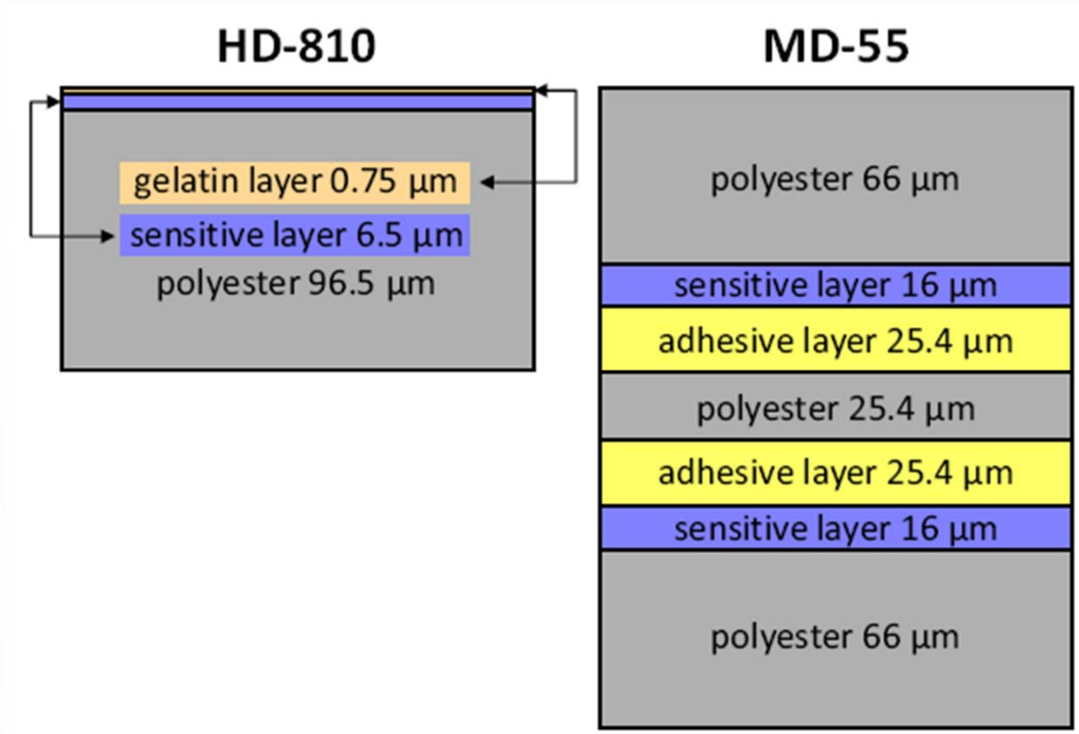
- Phase Space Matching [Longitudinally and Transversely].
- Repetition Rate; determine by laser (PHELIX: 1 shot per 60 min).

Typical Experimental Setup

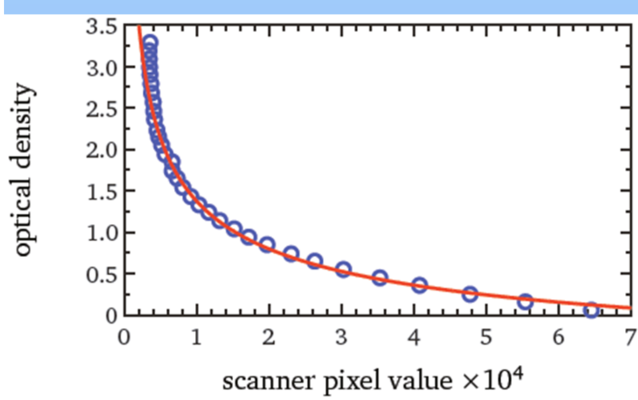


K. Harres et al., Physcis of Plasmas **17**, 023107 (2010).

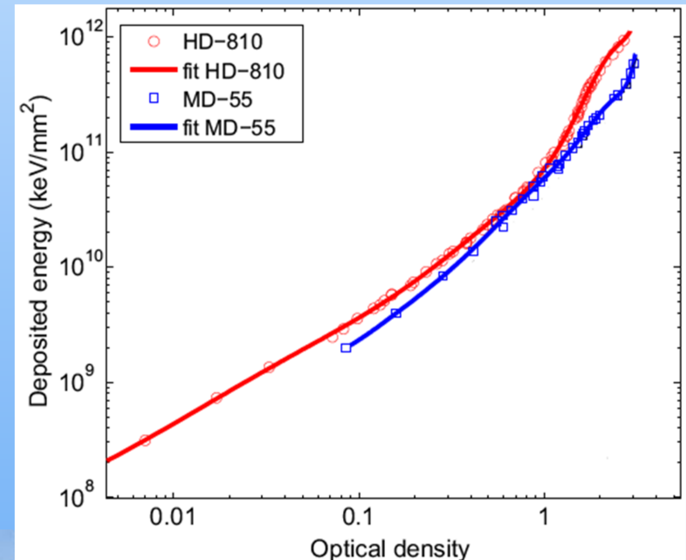
Proton Diagnostic with Radiochromic Films



Density (g/cm³)	Composition			
	C (%)	H (%)	O (%)	N (%)
1.35	45.44	36.36	18.20	0.00
1.08	29.14	56.80	7.12	6.94
1.20	33.33	57.14	9.53	0.00
1.20	22.31	53.52	11.12	12.75



$$E_{dep} = \exp\left(\sum_i a_i OD^{b_i}\right) \frac{keV}{mm^2}$$



Proton beam detection

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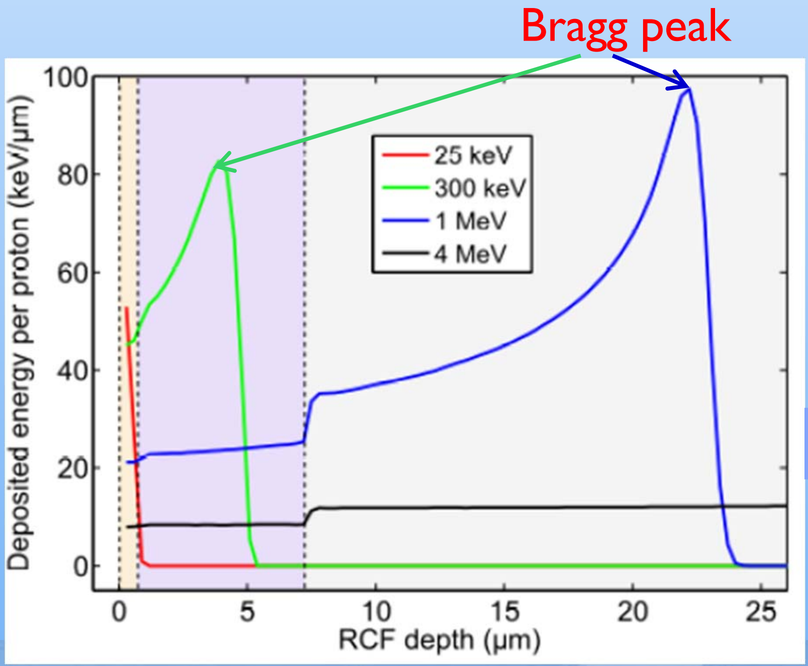
- Radiochromic film (RCF) is a dosimetry medium which is sensitive to ionising radiation.
- Stacks of RCFs may be employed to detect and measure the characteristics of laser-driven proton beams.
- More energetic protons will penetrate to greater depths in the film pack, hence spectral information can be gleaned from RCF data.
- Since the bulk of proton energy deposition occurs in the region around the Bragg peak, different layers in the RCF stack can be assigned different energies.



SRIM code - 2010

HD-810 film

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Proton Beam Parameters for PHELIX (F. Nürnberg thesis)

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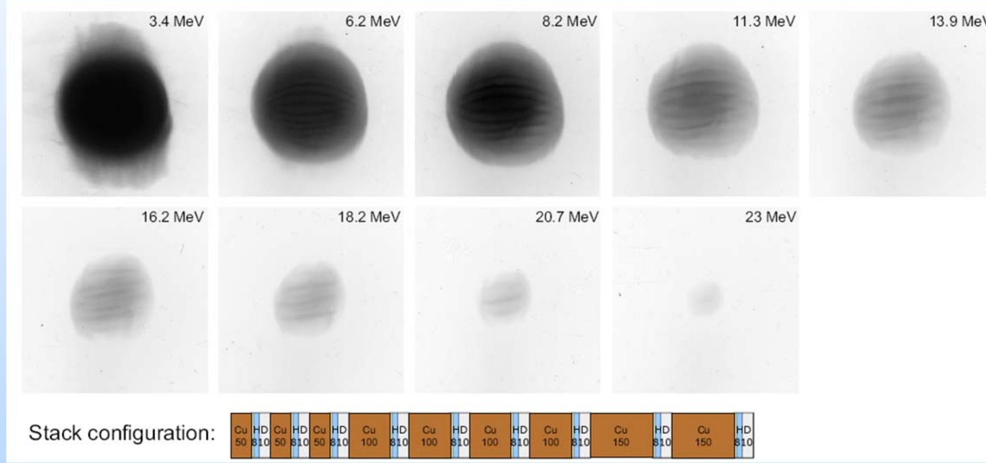
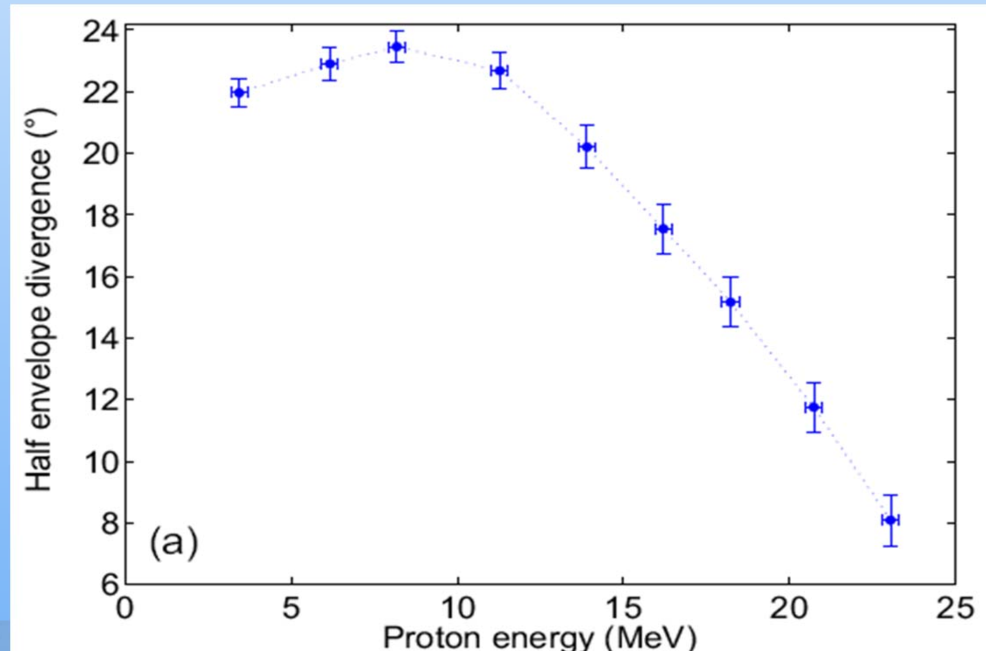
- ✓ Stacks of RCFs may be employed to detect and measure the characteristics of laser-driven proton beams.
- ✓ By knowing the size of proton beam in RCF and the distance between target and detector, the envelope divergence can be determined.

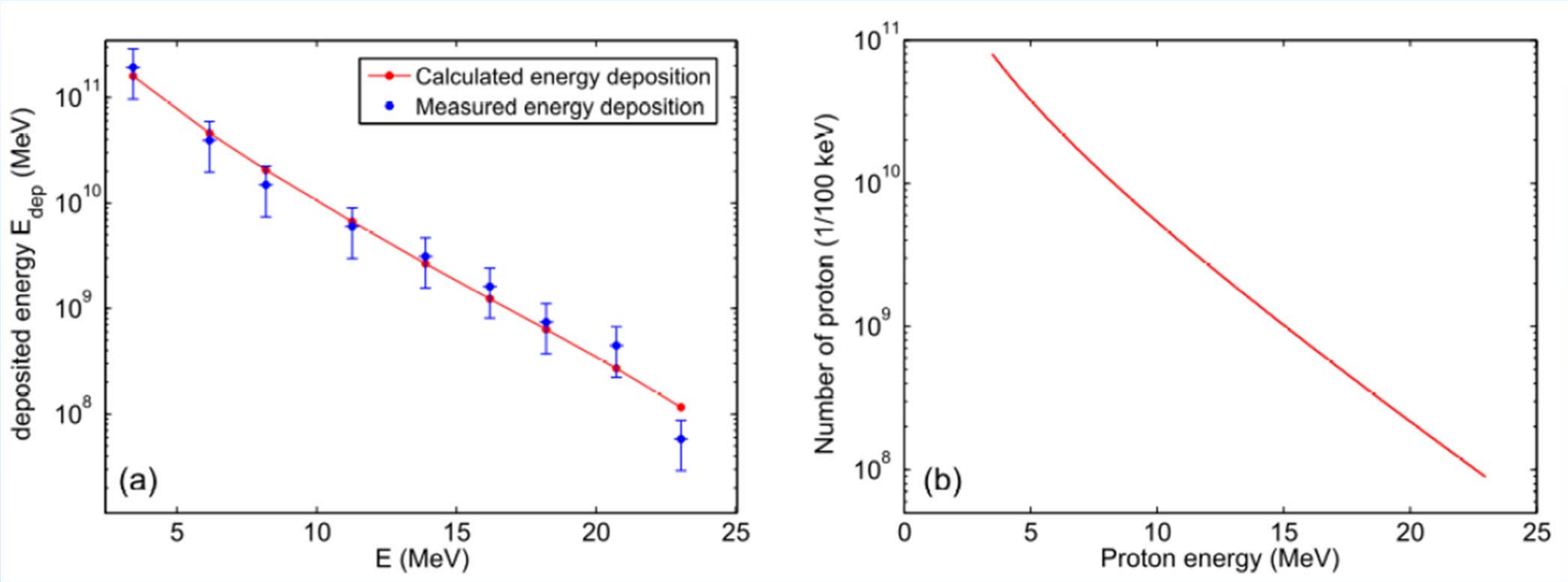


- o For small proton energies the angle of beam spread in nearly constant.
- o BUT for increasing energy the angle decreases approximately linear.



Proton Spectrum

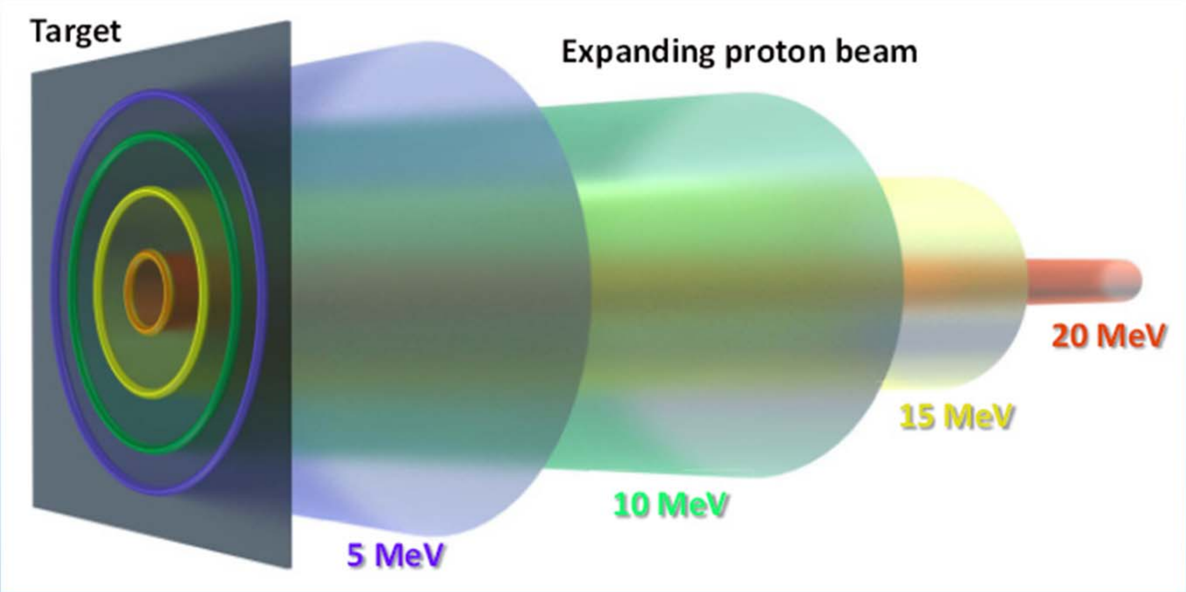
The proton energy in RCF is known from the Bragg peak, which is determine from the losing kinetic (deposited) energy curve.



$$E_{total} = \int \frac{dN(E')}{dE} \times E_{loss}(E')\, dE'$$

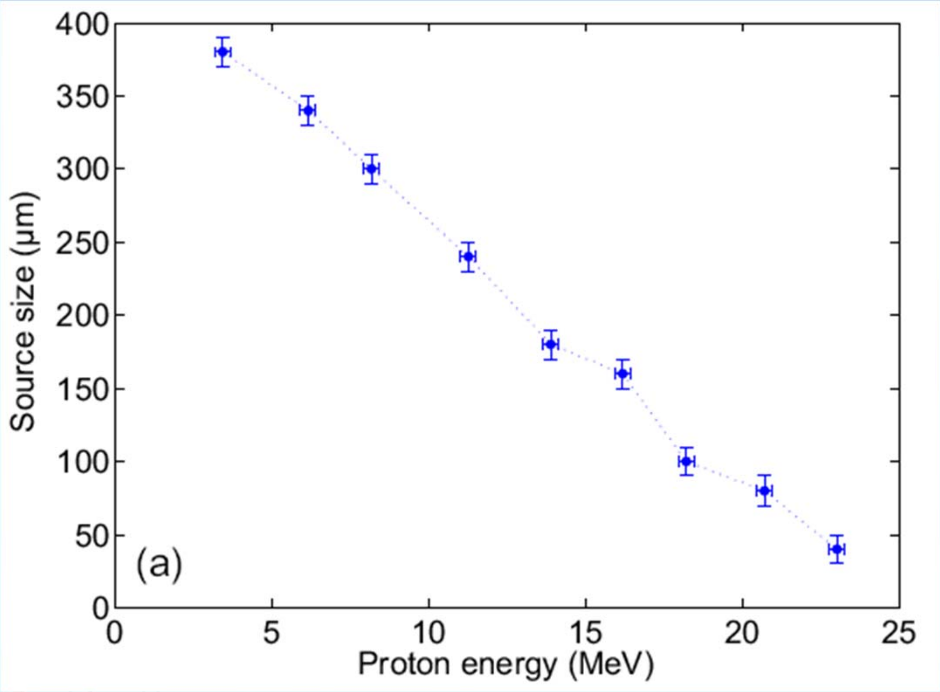
$$N_0 = 6.69\times10^{12} \text{ and } k_B T = 3.97\,MeV$$

$$\frac{dN}{dE} = \frac{N_0}{\sqrt{2Ek_B T}} \times \exp\left(-\sqrt{\frac{2E}{k_B T}}\right), \text{Isothermal, quasi-neutral plasma expansion}$$



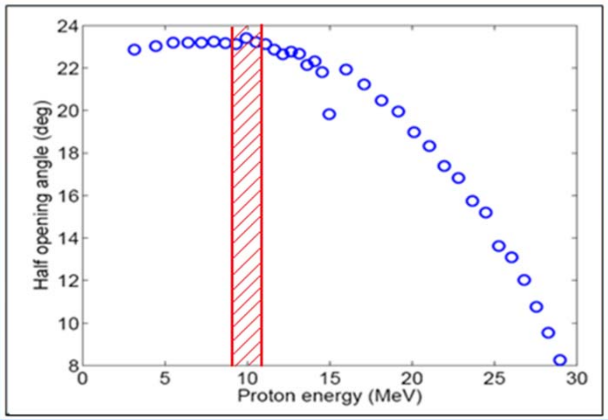
- The highest energy protons are accelerated in the center.

- The diameter of the proton source on the rear surface of the target decreases linear with increasing proton energy.



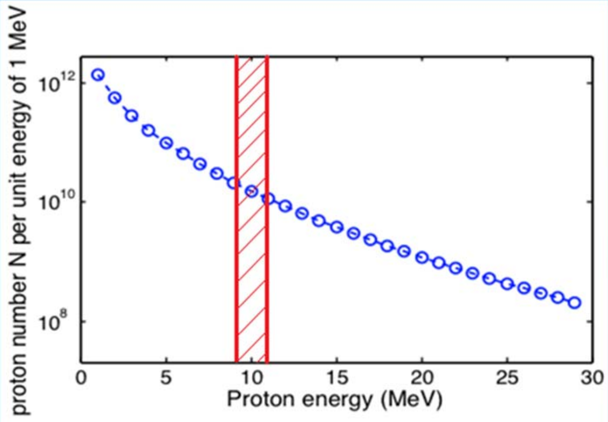
Phase Space Matching

- Transverse:
  - Strongly angular divergent with energy dependent (up ±25°); requires strong focusing pulsed solenoid (B > 18 T).
  - Geometric aberration.



Courtesy M. Roth

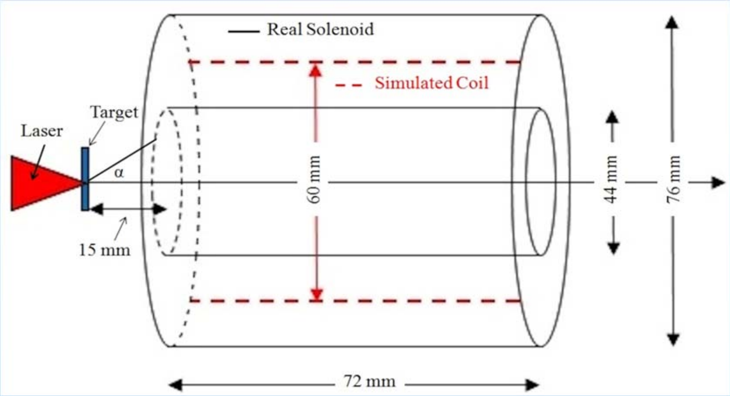
- Longitudinal:
  - An exponential particle spectrum with an energy spread of 100%.
  - Chromatic aberration.
  - Small part of energy spectrum can use classical accelerators.
  - Short bunch length (<1ps); Small phase spread < 0.1 degree.

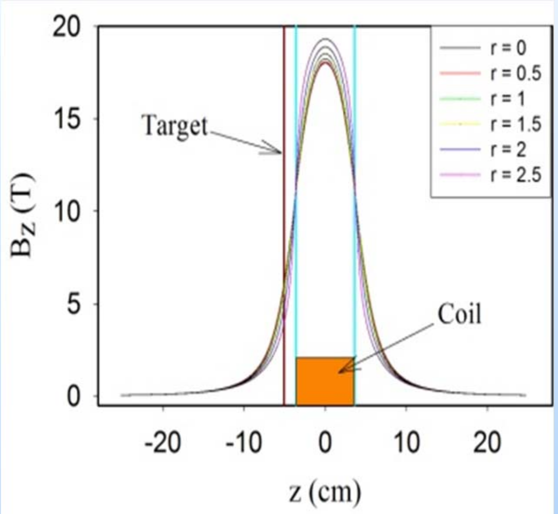


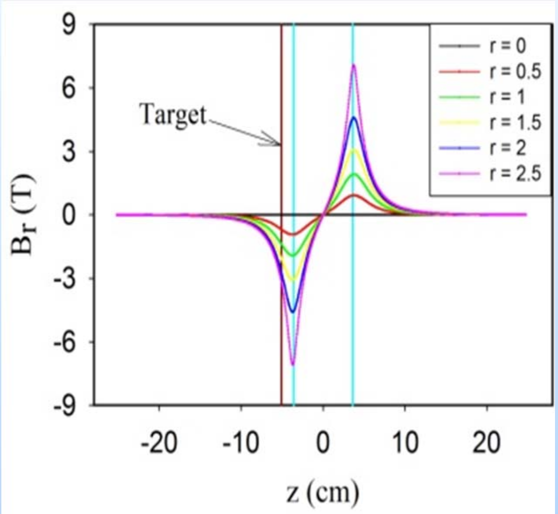
Courtesy M. Roth

Magnetic Solenoid – LASIN:

- ✓ 33 turns on coil.
- ✓ Current 42 kA.
- ✓ $B_{\max,\,axis} \approx 18T$



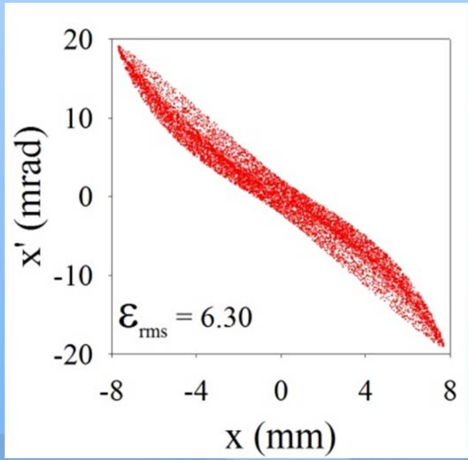




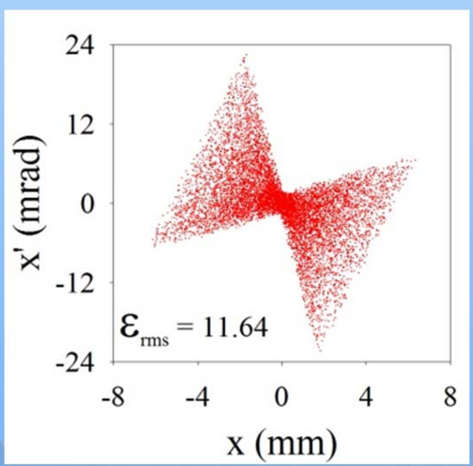
Chromatic and Geometric Aberrations:

- ➢ The ratio > 1 at zero spread – geometric.
- ➢ The ratio is energy dependent – chromatic.

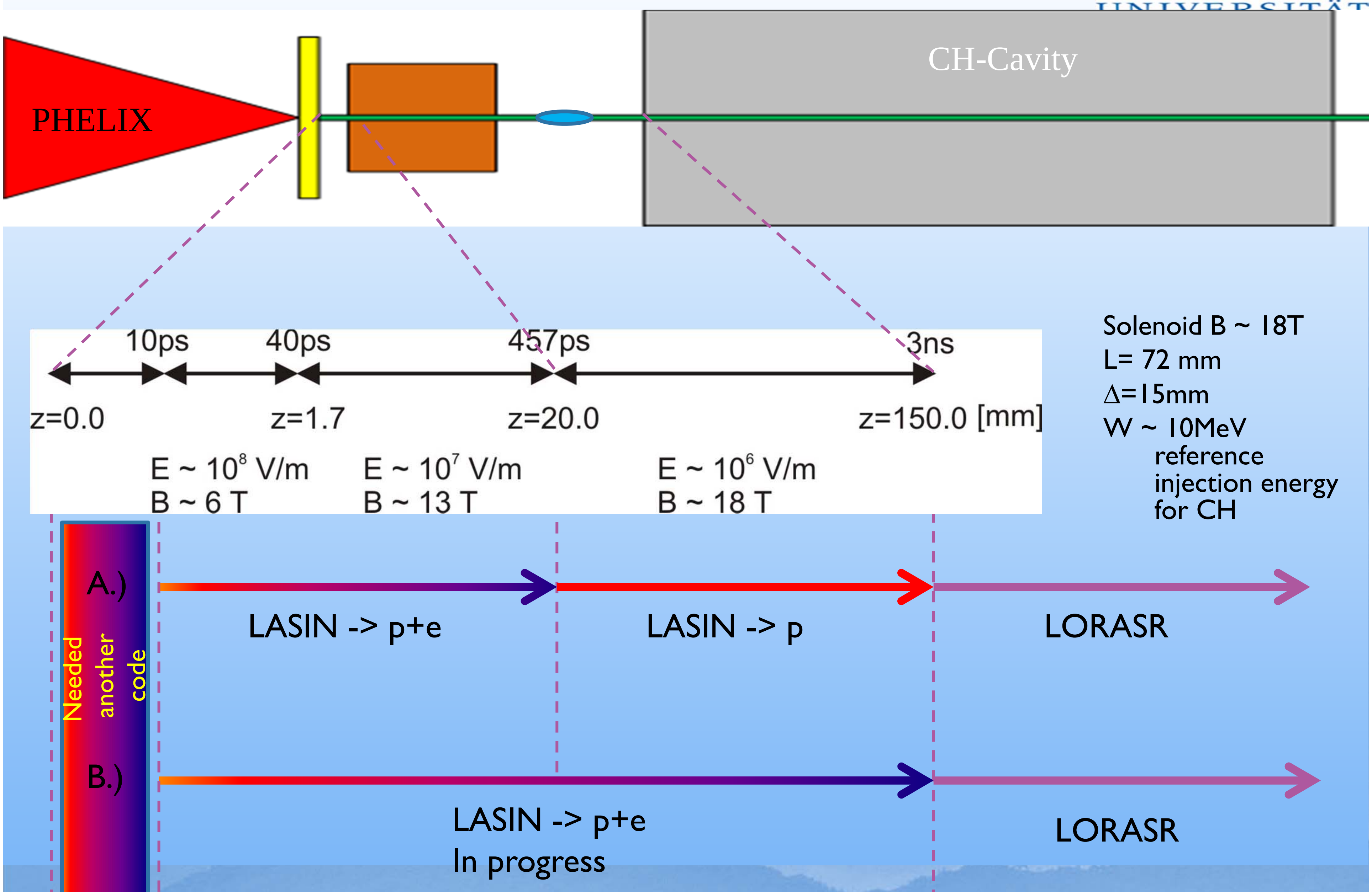
Geometric θ = ± 10°



Chromatic Δp/p= ± 10%

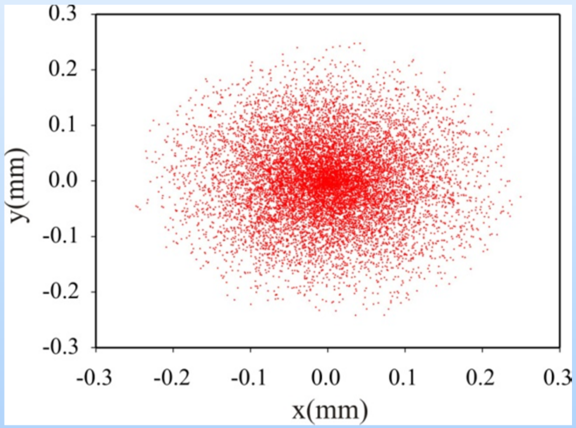


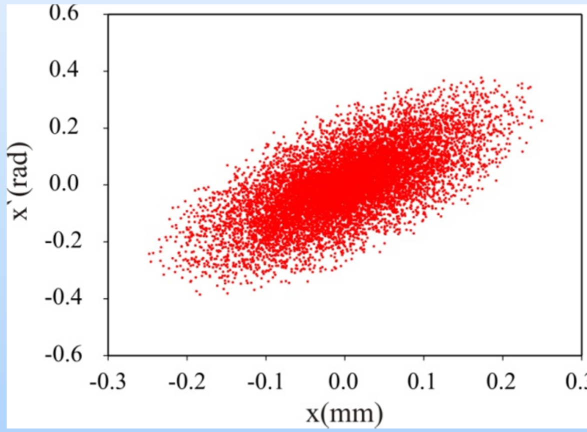
Simulation Strategy

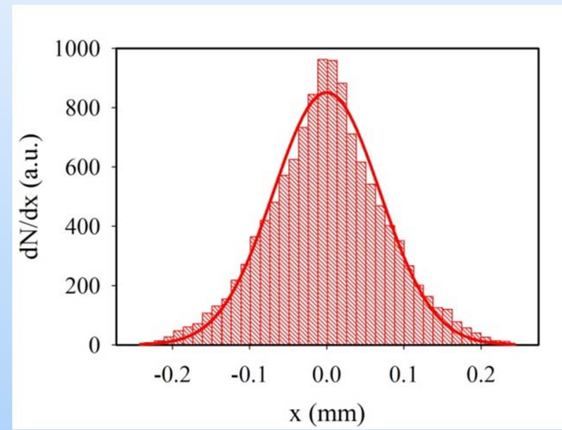


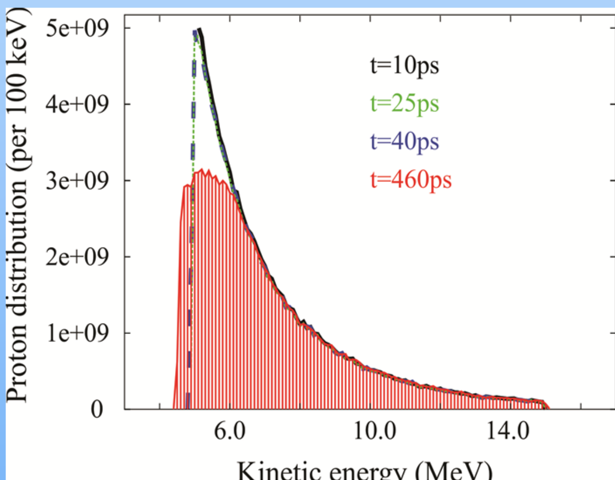
Generation of Particle Distribution

- In TNSA process, the protons are expected to be space charge neutralized to a high degree with the co-moving electrons.



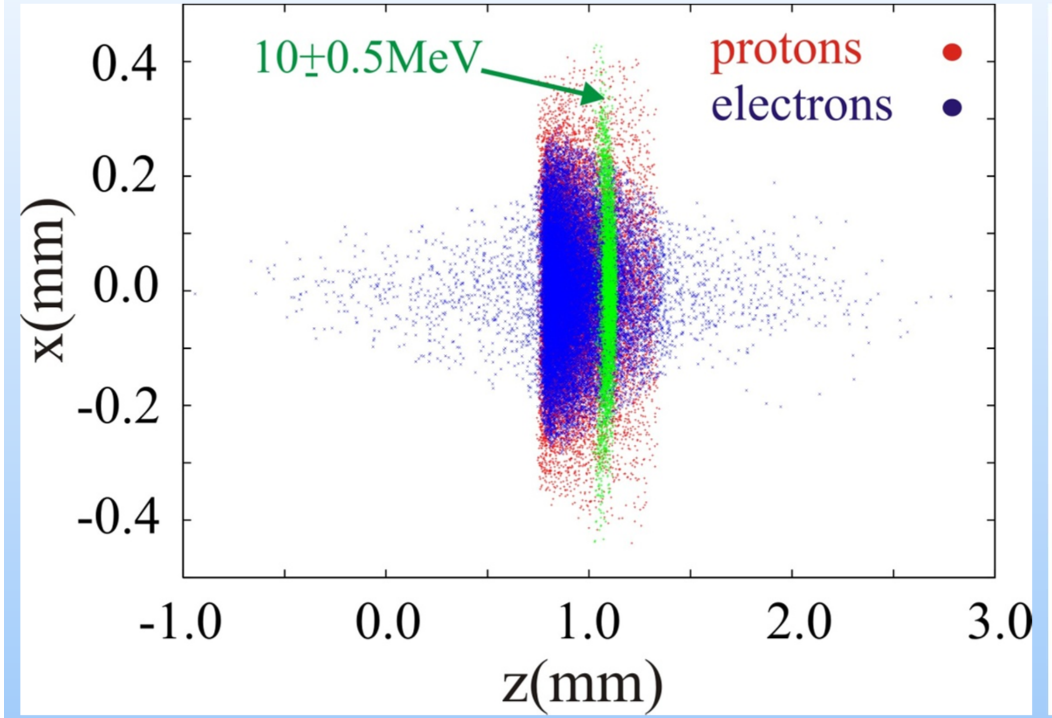


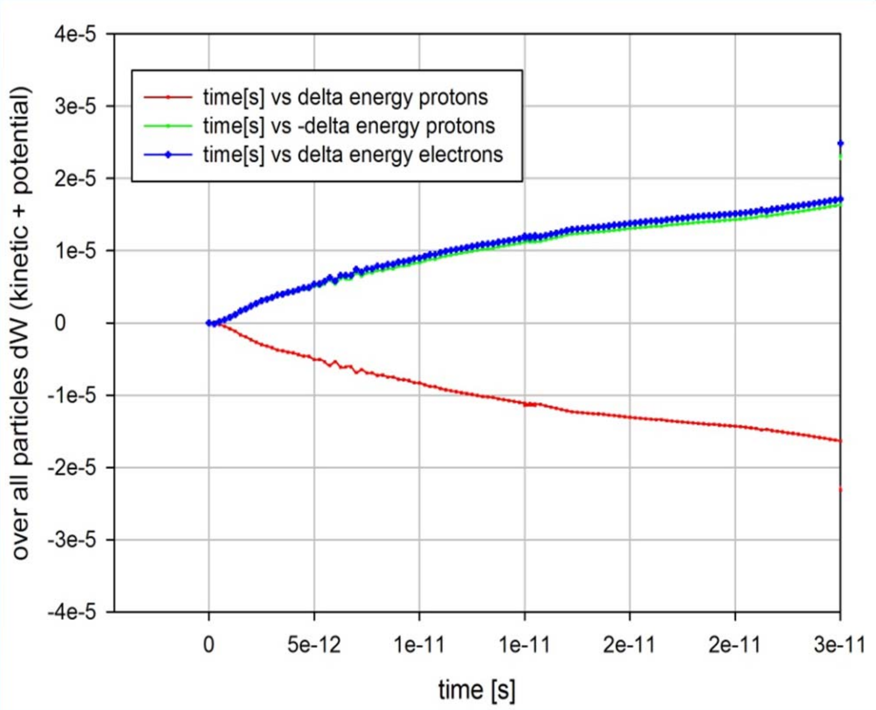




- Gaussian distribution in x,x´ and x,y.
- 2σ radius dependent on energy.
- Isothermal in energy.
- Data from F.Nürnberg thesis.
- 10^7 Macroparticles (electrons and protons).
- 250000 Macroparticles for protons in 10 ± 0.5MeV.
- Over all energy range 5-15MeV.

At t ~ 30 ps

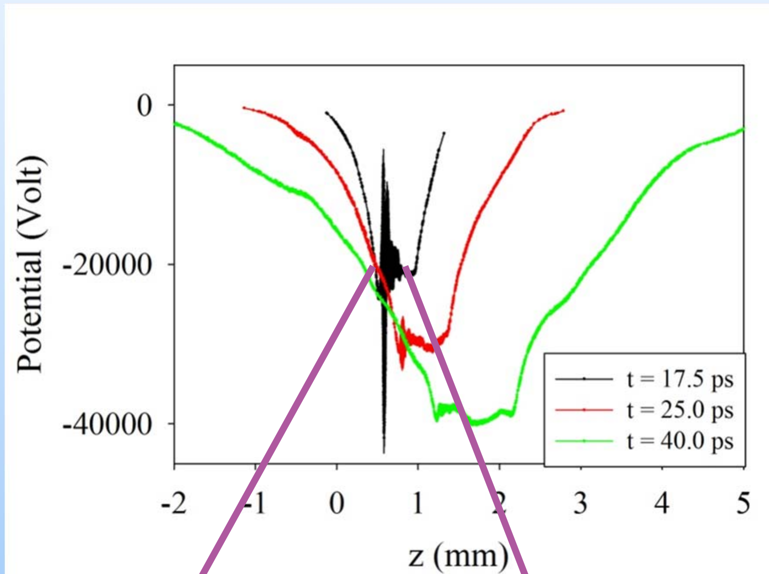


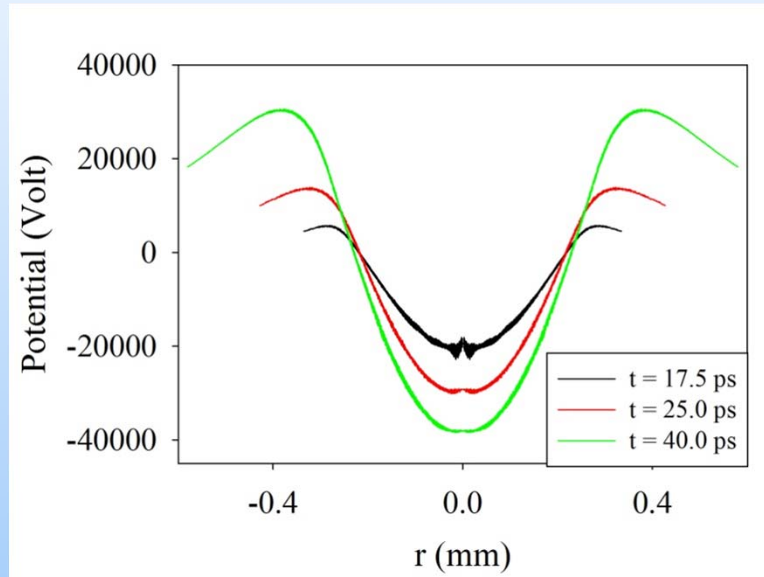


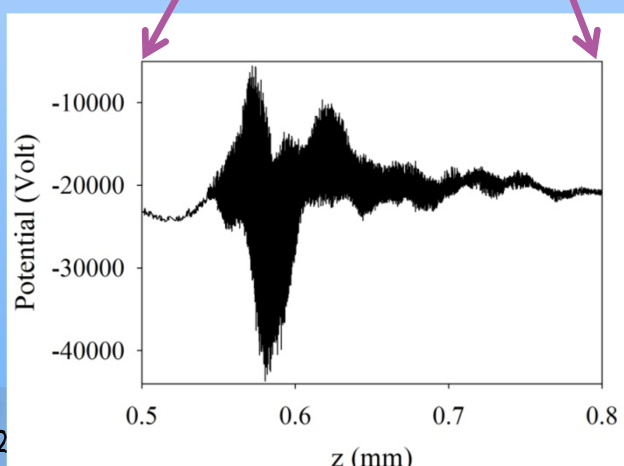
- Growing electrostatic energy by charge separation is delivered from transversal energy of protons.
- specie to specie transfer.

Potential Distribution - electrons

- Due to magnetic field, the charge separation leads to a negative on axis potential.







- Minimum electric potential on axis of about - 40kV.
- The potential is reaching almost constant along z – axis within the bunch at t = 40ps.
- An initial plasma oscillation is almost damped at t = 40 ps.

Tracking through the Solenoid

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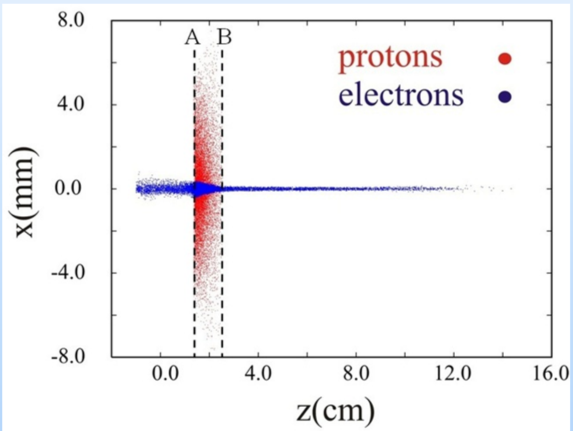
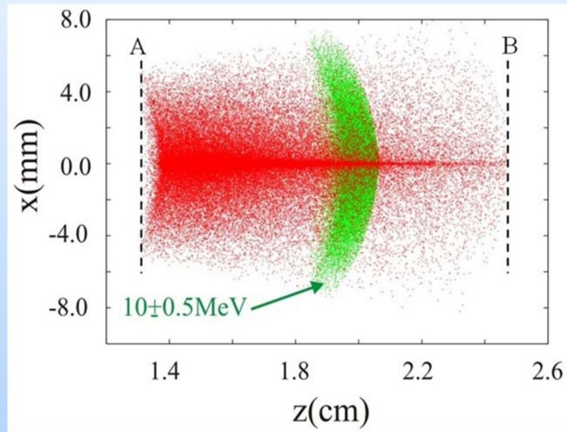
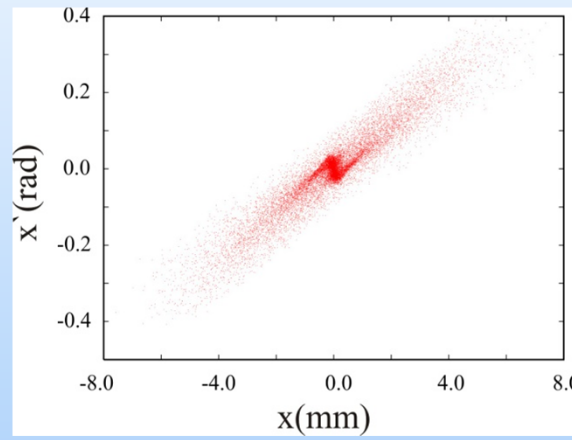
- The electrons start to escape and accelerated to high energies in both z-directions.
- The central part of proton distribution (r<|500μm|) is strongly focused.

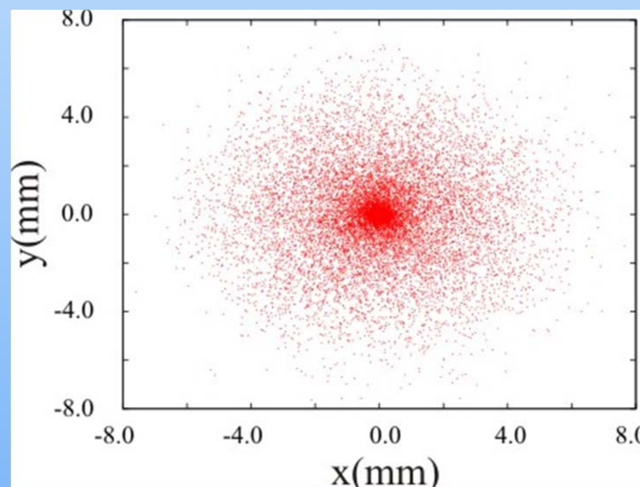
460 ps = 2cm

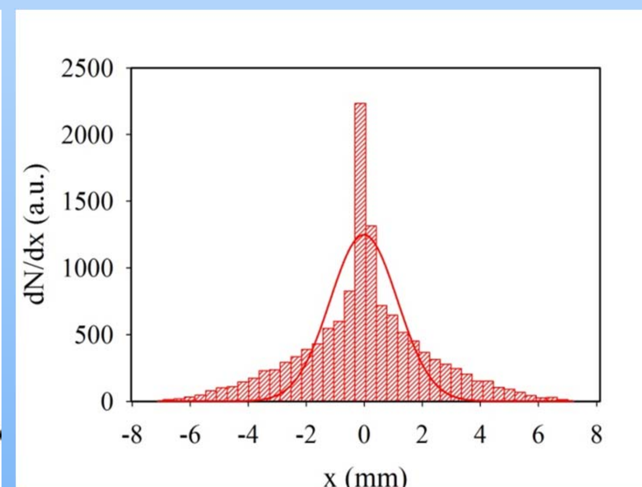






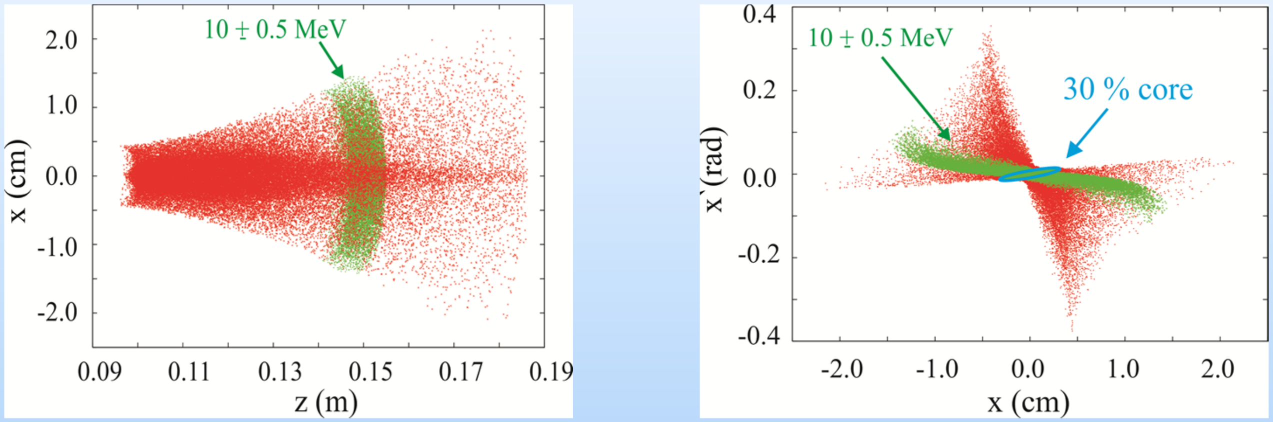
- Peaked proton dist. due to on axis electrons.





Up to t ≈ 3.4 ns corresponds to z = 15 cm center of bunch

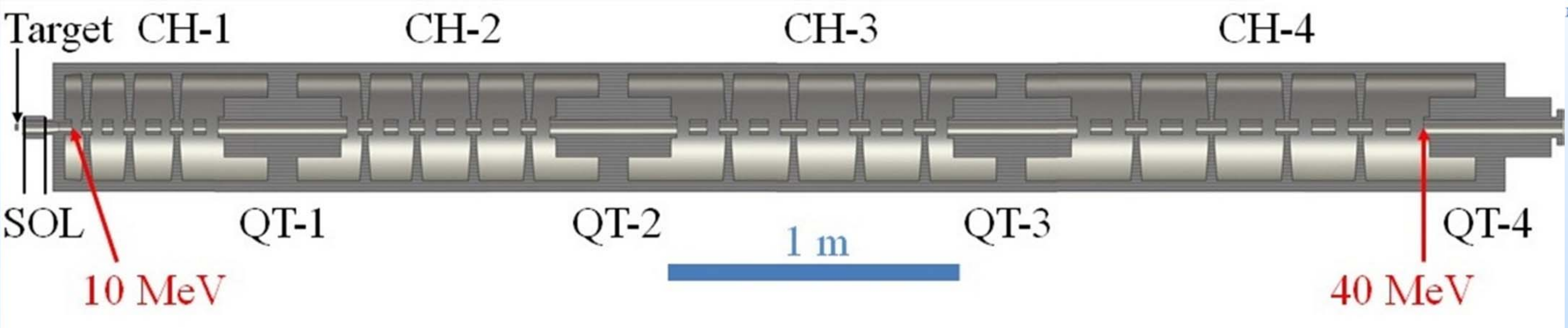
- Due to space charge relaxing, the influence of co-moving electrons can be neglected.



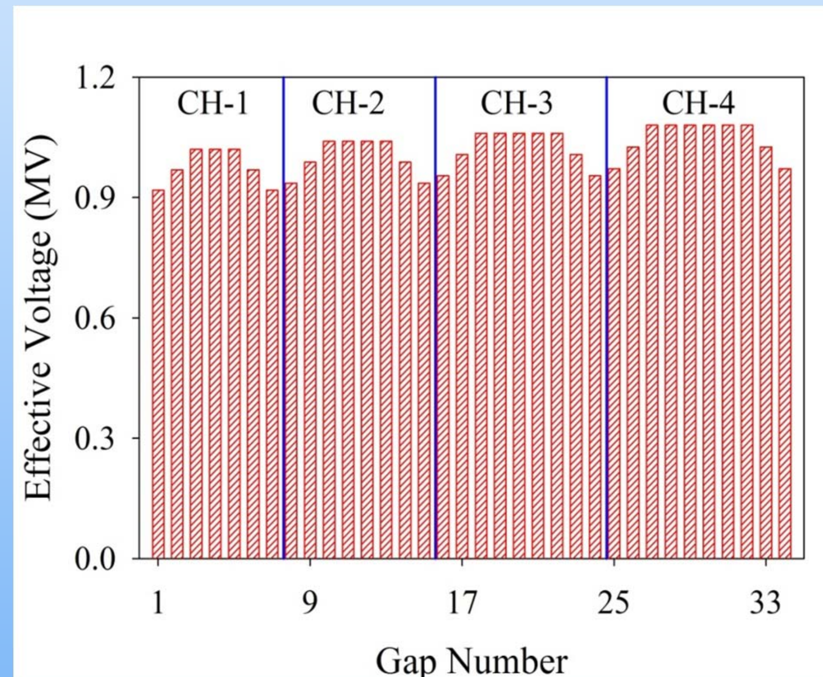
- The selected energy band 10±0.5 MeV will be injected into the CH-DTL.
- A maximum potential on axis of +14 kV was reached at position z = 11 cm, while its level for the energy of interest 10 MeV, z ≈ 15 cm was reached +4 kV.

- The simulation with LASIN ends at this point, and the proton distribution was adapted as input dist. for CH – DTL.

Design for a Dedicated CH – DTL

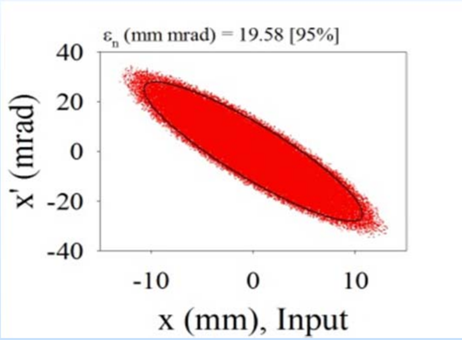


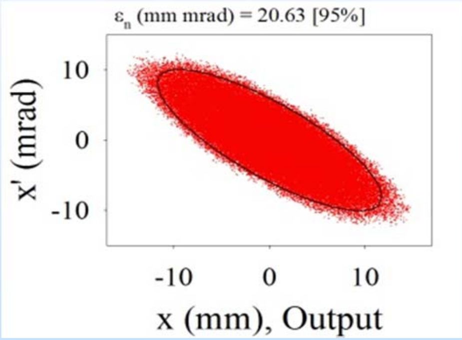
- Four cavities with 34 gaps.
- Operating frequency: 325 MHz.
- Accelerating gradient: vary from 7 – 12.6 MV/m.
- A proton bunch will be accelerated from 10 – 40 MeV.
- To avoid beam losses, the first cavity is limited by 7 gaps.
- Total length: 5 m.
- High gap voltage of order 1 MV is needed.



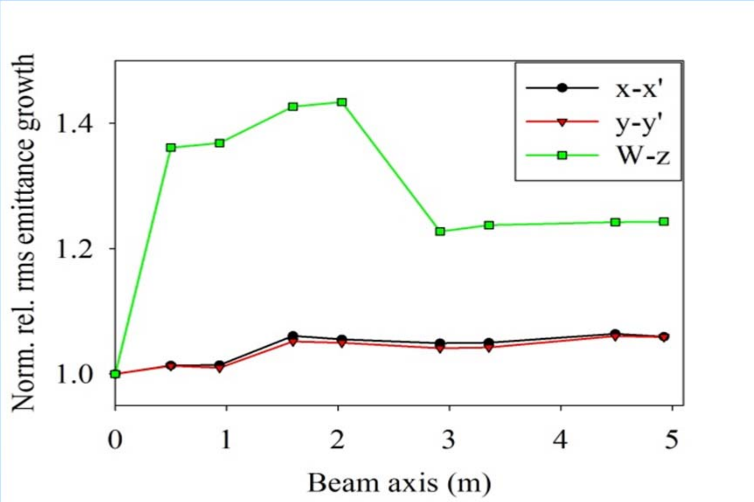
Matched Beam Case

Table 1: Normalized rms- emittance values for the input and output distribution with 500 mA beam current.		
Emittance	Input	Output
Transverse/ $mm \cdot mrad$	x: 3.85	4.08
	y: 3.85	4.06
Longitudinal/ $keV \cdot ns$	5.37	6.68

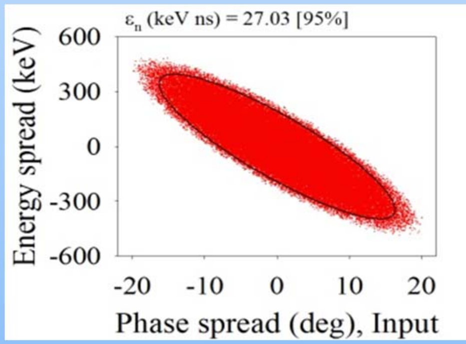


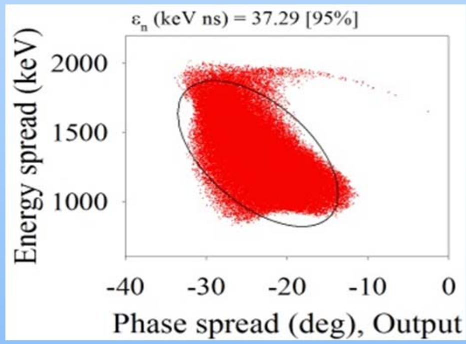


Transversal particle distribution



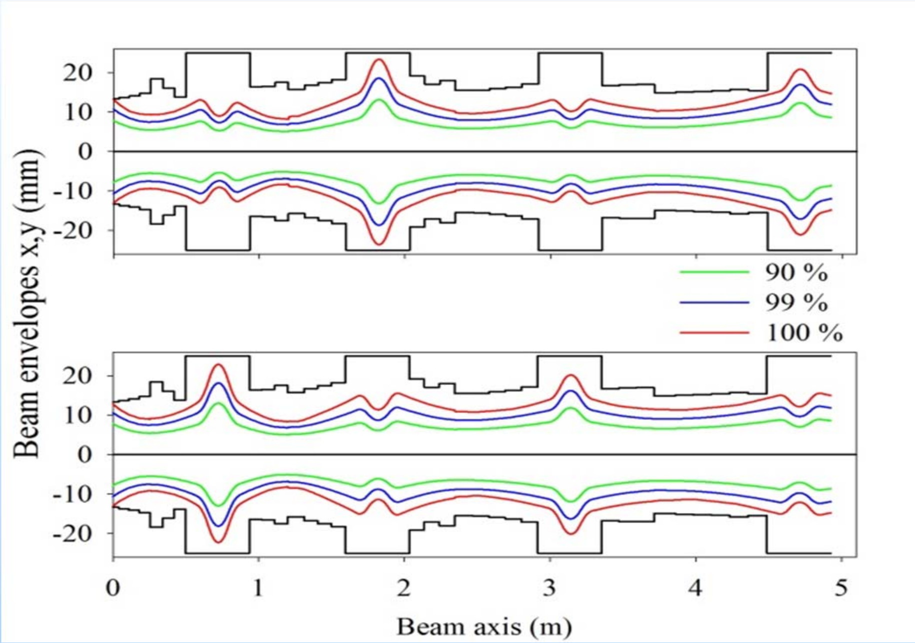
RMS- emittance growth

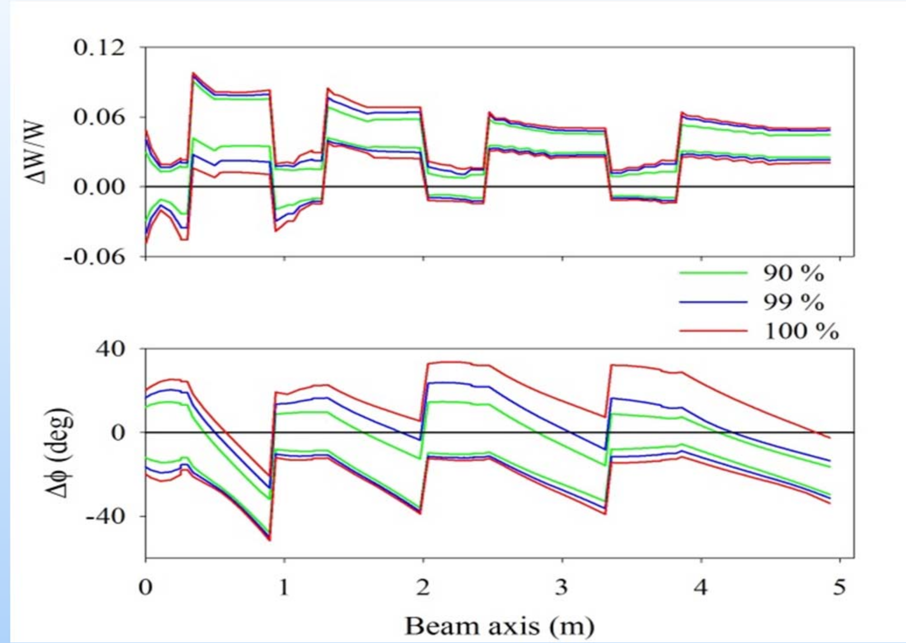




Longitudinal particle distribution

Beam Dynamics



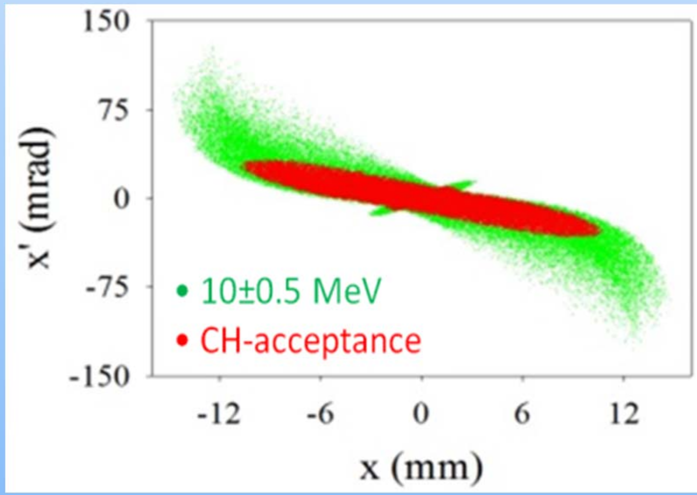


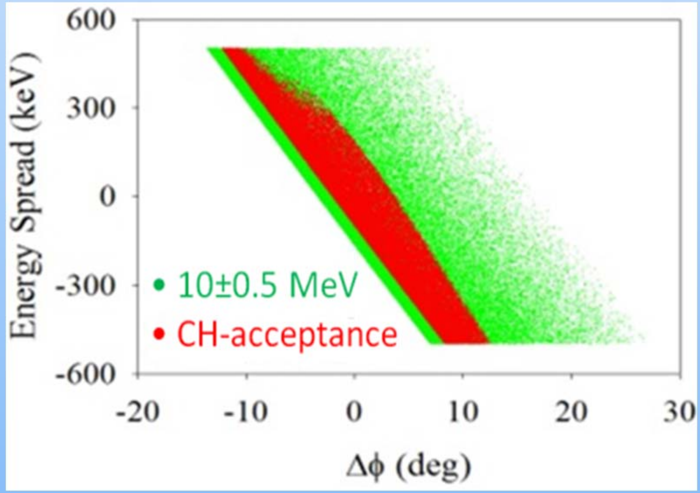
- The capability of CH- DTL to accelerate 500 mA proton bunch is approved.
- The magnetic field gradients of the quadrupoles are ranging up to 50.5 T/m.
- These simulations allow estimating the capability of the CH- structure for high current beams.

Laser accelerated proton case

Table 2: Normalized rms- emittance values for the input and output distribution for the laser accelerated case.

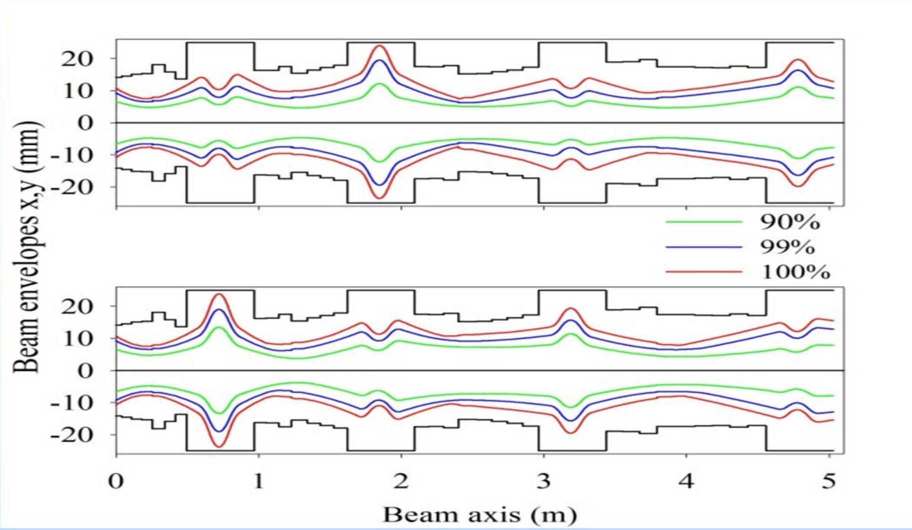
Emittance	Input	Output
Transverse/ $mm \cdot mrad$	x: 2.89	3.06
	y: 2.89	3.33
Longitudinal/ $keV \cdot ns$	5.34	6.86

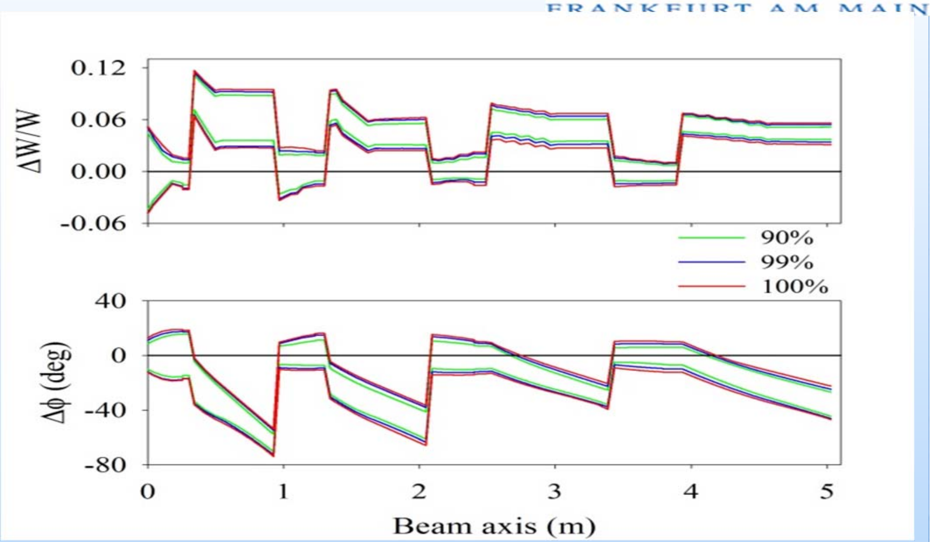




- 72% of the total number (as shown in red) is accepted by CH-DTL. The other particles are truncated with respect to the beam simulations.

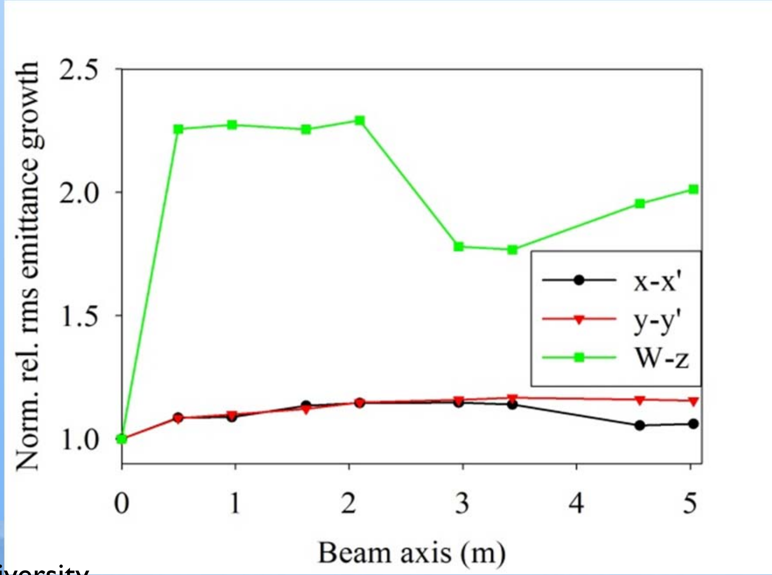
Beam Dynamics





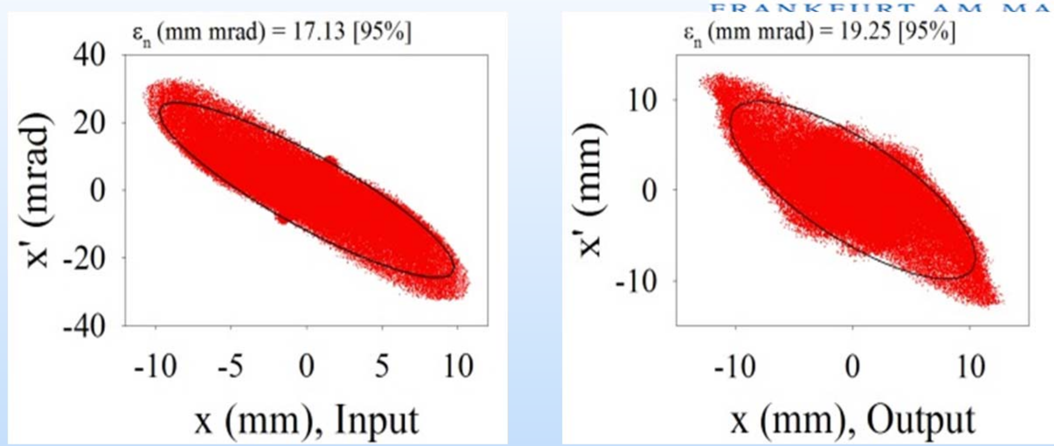
Transversal (left) and longitudinal (righ) beam envelopes

- The normalized relative rms- emittance growths was reached up to 2 factor in longitudinal plane and less than 16% in each transverse plane.
- In comparing with matched case, the deformed longitudinal emittance is the main reason for the longitudinal emittance growth.

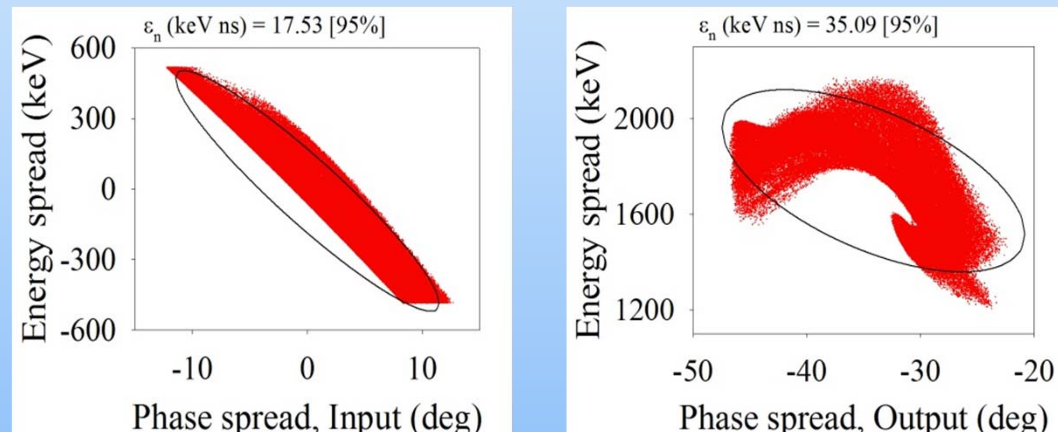


Particle Distribution

Transversal particle distributions at the entrance and exist of CH-DTL



Longitudinal particle distribution at the entrance and exist of CH-DTL.



- The optimized magnetic field of the quadrupoles are ranging up to 50.8 T/m.

Beam Parameters Dependent on Gain Voltage

- The high acceleration gradient is not only needed to accelerate to high energy but also to prevent the beam losses.
- Two cases are compared ($\Delta E = \pm$ 0.5 MeV):
  - Acceleration from 10 – 40 MeV within 4.92 m length.
  - Acceleration from 10 – 25 MeV within 4.54 m length (50% reduction).

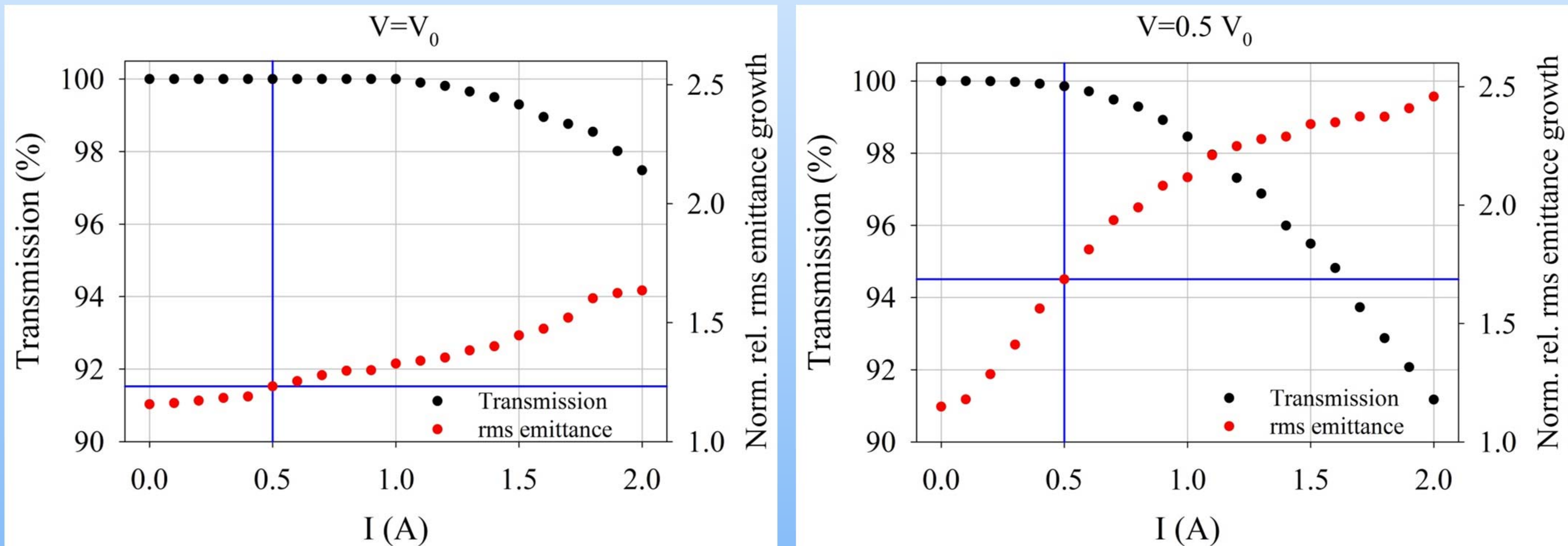


Table 3: A comparison between different accelerating gradient cases in terms of the transmission and normalized rel. rms emittance growth at different beam current.

Current (A)	Acc. gradient	Transmission (%)	Norm. rel. rms emittance growth
0.0	V_0	100.0	1.16
	$0.5V_0$	100.0	1.15
0.5	V_0	100.0	1.23
	$0.5V_0$	99.8	1.69
1.0	V_0	100.0	1.32
	$0.5V_0$	98.5	2.12

- For the 1st case where the accelerating gradient was V_0 resulting 100% transmissions up to 1 *A*. While in 2nd case, 100 % transmission is valid up to 400 *mA* only. Beyond this point, the transmission starts to decrease with increasing beam current.

- The emittance growth shows quite different between V_0 and 0.5 V_0 case.

Beam Power for a Single Bunch (U. Ratzinger)

- One great advantage of high current, single bunch passage along the cavity is that the amplifier only has to provide the loss power in the cavity walls.

$$W = \frac{P_{loss} \cdot Q_0}{\omega} \qquad P_{loss} = \frac{\left(N_G T_f U_0\right)^2}{Z_{eff} \cdot L}$$

$$Q_{Bunch} = \frac{2 \cdot A \cdot W}{T_f \cdot U_0 \cdot N_G}$$

For the first cavity of the proposed linac, the cavity parameter can be estimated to

$L = 0.5\ m;\ Z_{eff} = 60\ M\Omega/m;\ N_G = 7\ gaps;\ T_f = 0.8;\ U_0 = 1.0\ MV;\ Q_0 = 12500$

➢ The wall losses results in P_{loss} = 1.05 MW, and the stored field energy W = 6.43 J.

➢ The tolerance A = 0.01, $Q_{Bunch} = 2.3\ \times 10^{-8} C$ and this corresponding to a proton number $N_p = 1.44\ \times 10^{11}$per bunch.

❑ This shows that the single bunch beam load will not affect the cavity oscillations.

Conclusion and Outlook

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✓ Special features of TNSA require special code development (3D – PIC LASIN code).

✓ CH- DTL simulations approved with 500 mA equivalent linac current and even more??

✓ The first CH- cavity for Laser accelerated protons is demonstrated.

✓ Realistic distribution – with co-moving electrons is generated (input from measurements and simulations) and used in LORASR simulations.

✓ Effective acceptance and acceleration of 72% of the whole protons is proved.

✓ Emittance growth in longitudinal plane due to the deformed input emittance.

✓ Comparison of A.) with B.) simulations.

✓ Further improvement could be needed.

✓ Continue the CH- DTL design by MWS – Simulations and technical developments, beam loading …..

✓ Built the first dedicated cavity….

"Anyone who has never made a mistake has never tried anything new" Albert Einstein 

Thank you for Listening!!