Combined Laser-Ion Experiments at Z6/GSI

Workshop on High Energy Density Physics Opportunities at FAIR

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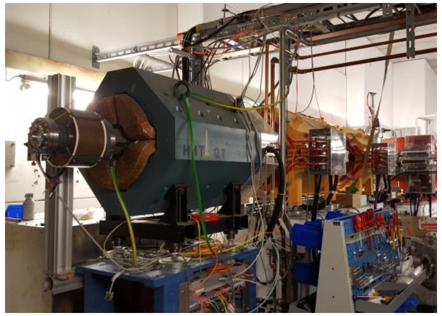
Experimental sites at GSI for Plasma Physics until 2028

Target station Z6 at UNILAC

Ions
- energy: 3 - 12 MeV/u
- intensity: ~1 pmA

Laser
- 200 J @ 1 – 10 ns, 2ω
- 30 J @ 0.3 – 2 ps (100 TW)

Target station HHT at SIS18

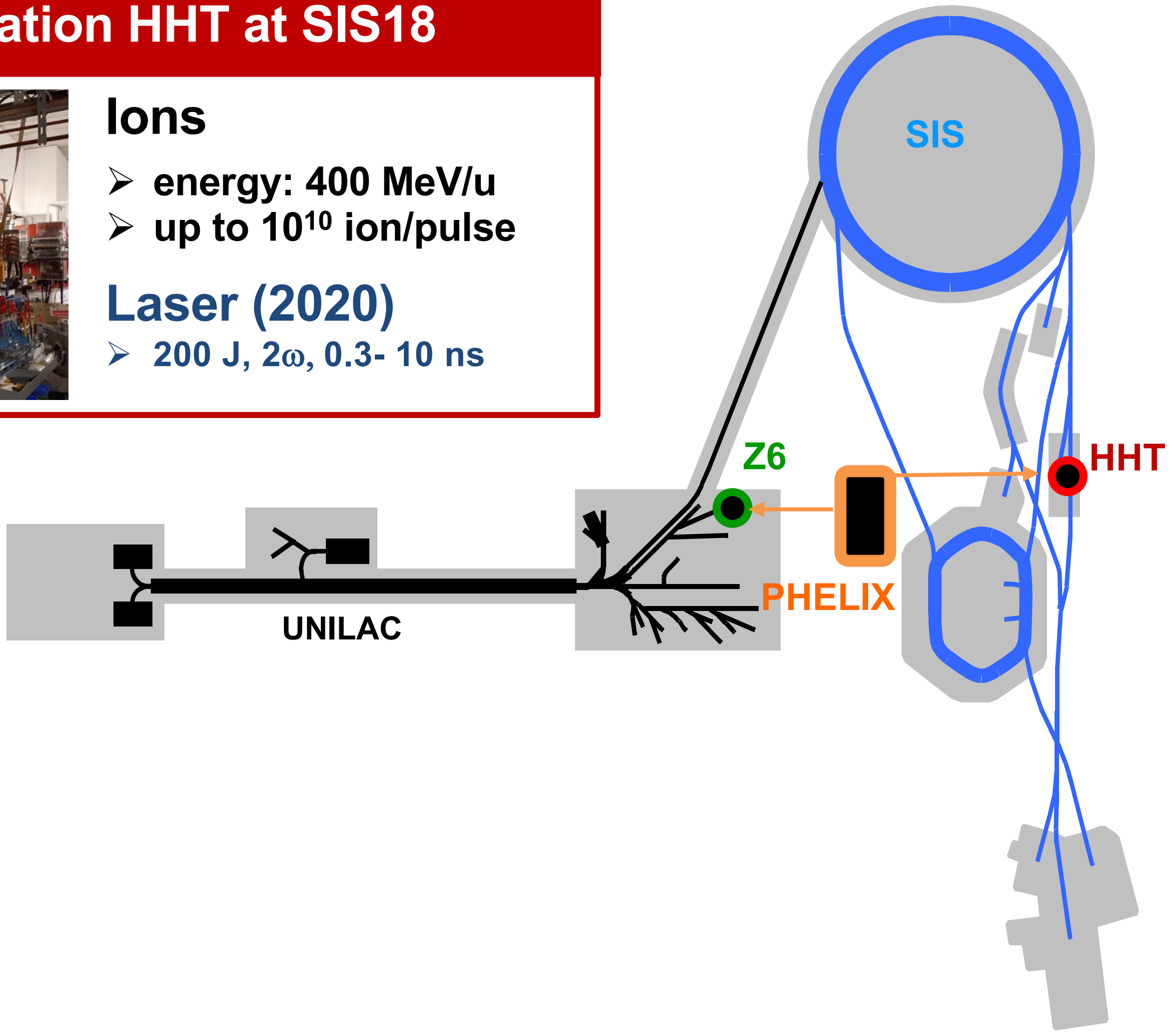


Ions
- energy: 400 MeV/u
- up to 10^{10} ion/pulse

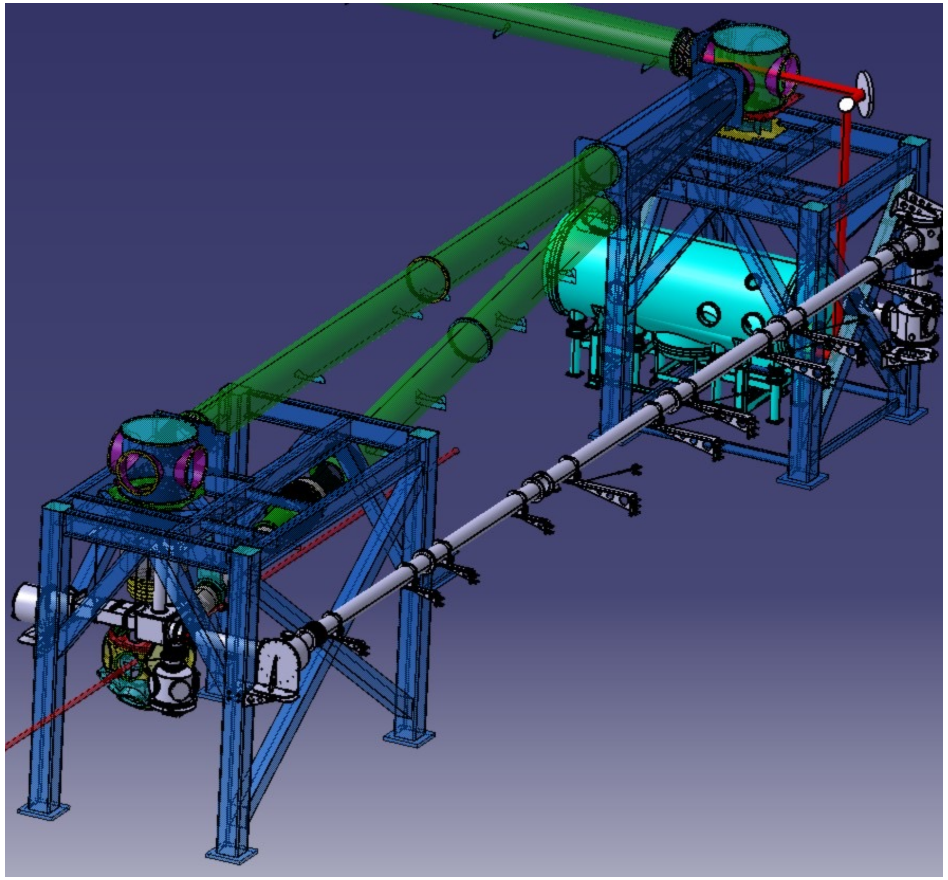
Laser (2020)
- 200 J, 2ω, 0.3- 10 ns

PHELIX
High Energy / High Intensity Laser

- stand alone experiments
- 0.5 PW, 200 J @ 400 fs
- high temporal contrast
- double-beam option



Laser and Ion beam parameters at Z6



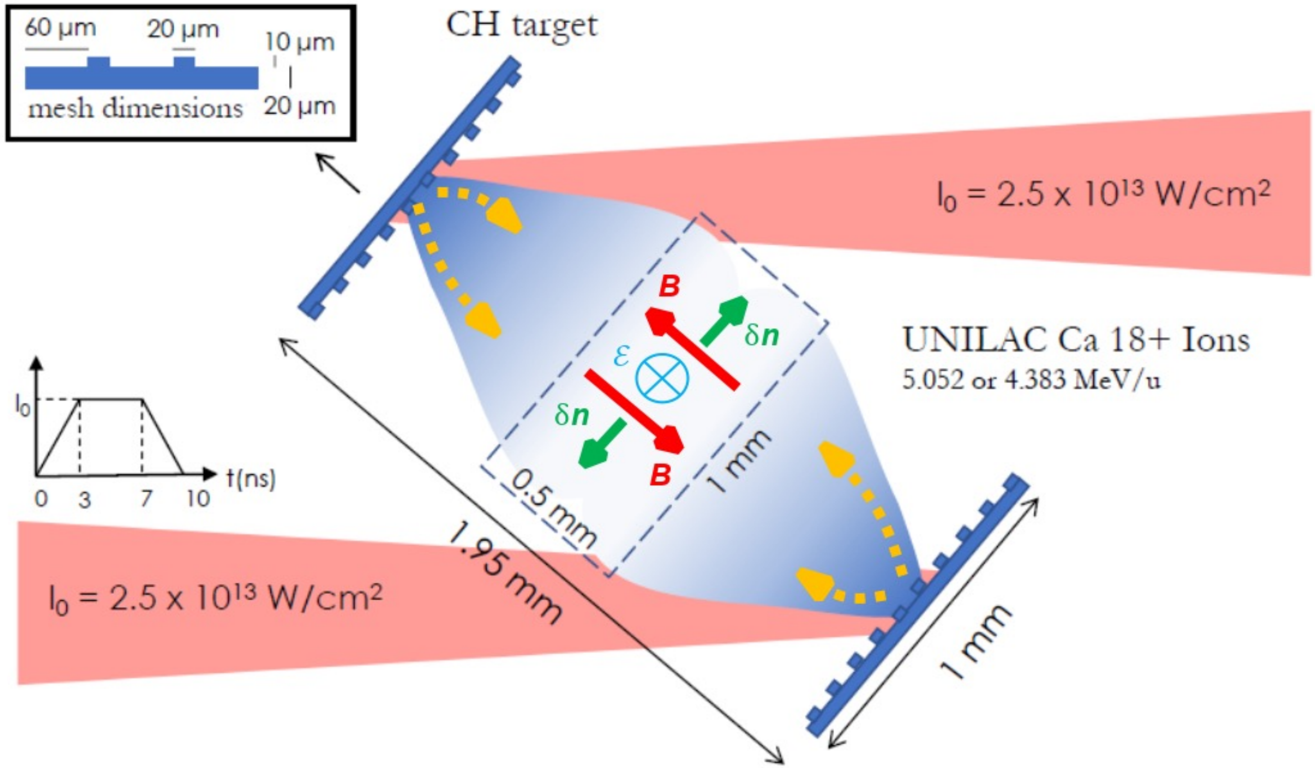
- ✓ Unilac ion beam: probing
  - $3<Z<92$
  - E = 3 -13 MeV/u
  - f=108/36 MHz, Δt_{ion} = 3 ns (FWHM)

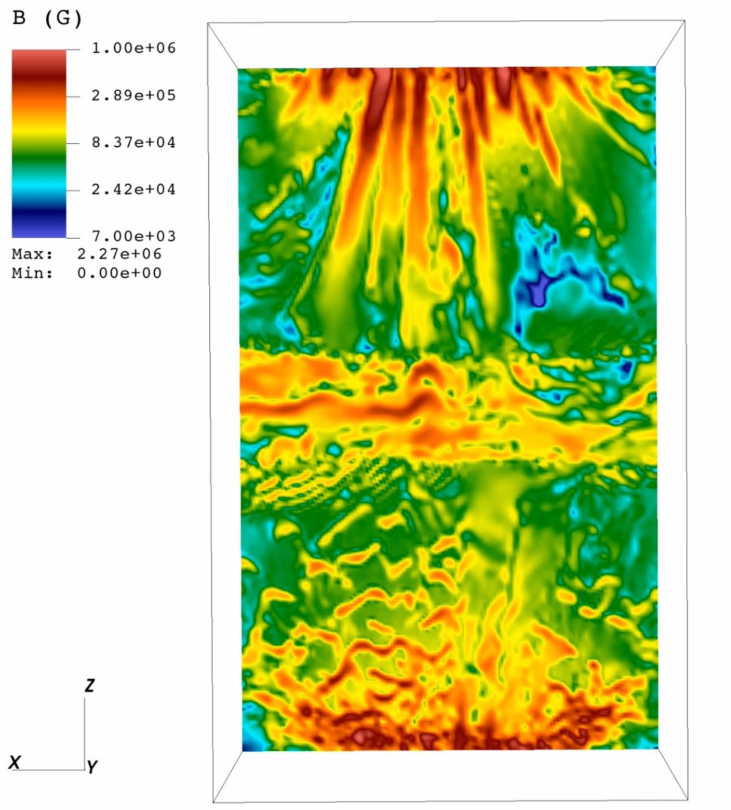
- ✓ Phelix laser beam: different laser parameters for different experiments
  - 170 J @ 0.7 - 20 ns, 2ω
    → 10° (90° beam line not realized)
  - 30 J @ 0.5 ps → 100 TW beam line

- ✓ nhelix laser beam: 2 laser beams simultaneously on the target:
  - 120 J, 9 ns @1w (60 J, 7 ns @ 2ω)
  - 1 mJ @ 0.7 ns (3ω, interferometry)

Ion beam, one Phelix laser beam and two nhelix laser beams synchronized with Δt < 1 ns in the target chamber

Z6: Particle acceleration in a laser-driven magnetized plasma



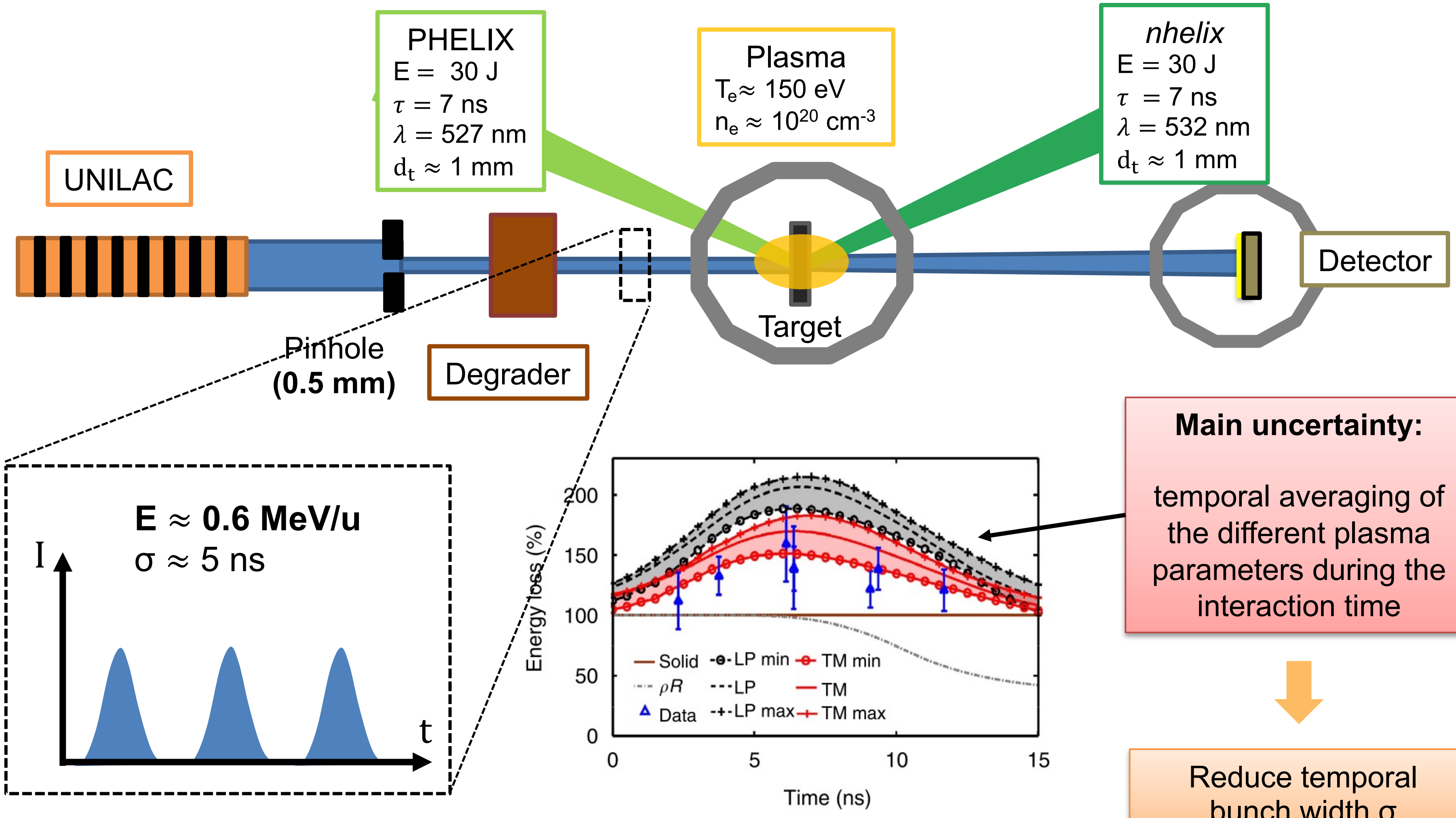


Drive Beams	Measured ΔE (MeV)	Theory ΔE (MeV)
2	$+0.34 \pm 0.17$	$>+0.17$
1	$+0.14 \pm 0.28$	-

Experiment proposed by G. Gregory et al. University of Oxford

Courtesy of T. Campbell, Univ. of Oxford

Z6: Coupling effects in energy loss of ions in plasma



W. Cayzac et al., Nature Communications (2017)

Main uncertainty:

temporal averaging of the different plasma parameters during the interaction time

Reduce temporal bunch width σ

Courtesy of W. Cayzac

LIGHT Collaboration: Laser Ion Acceleration at Z6

Funding Institutes (2010):

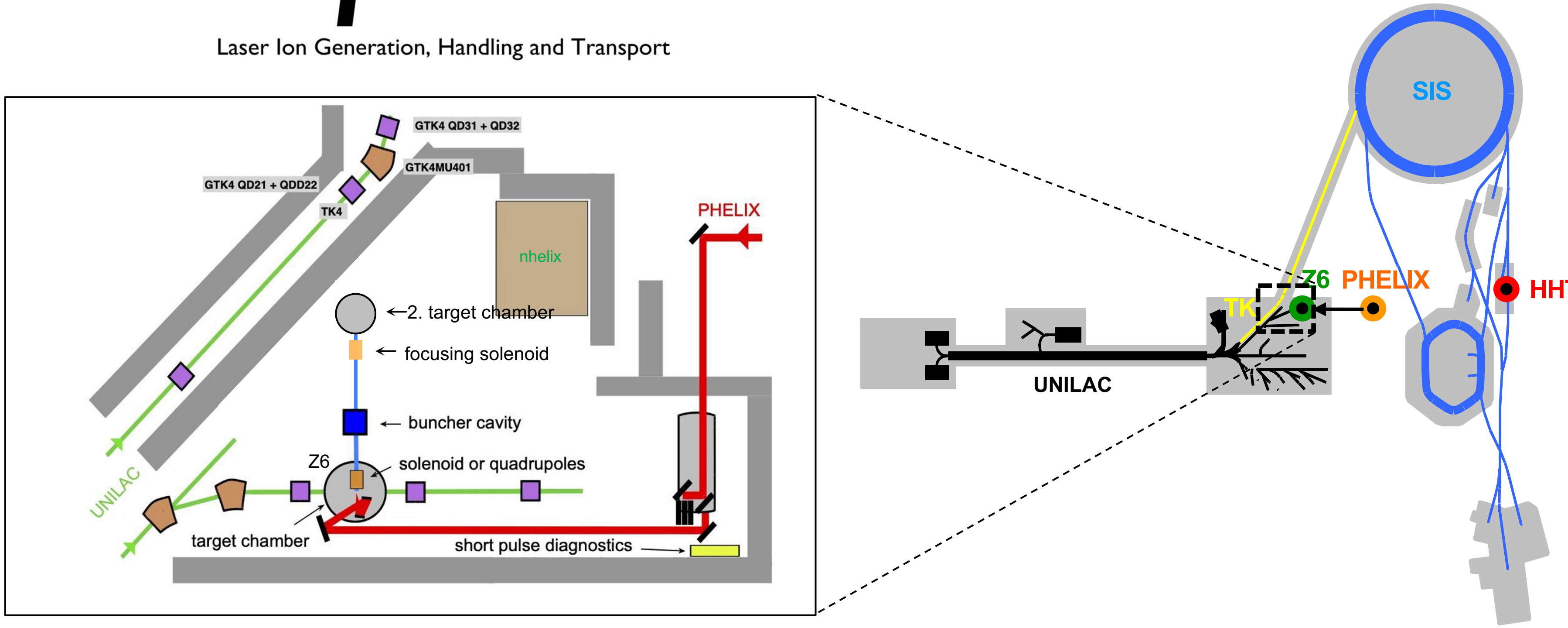
- TU-Darmstadt
- HI Jena
- HZ Dresden
- GU Frankfurt
- GSI Plasma physics
- GSI Accelerator dep.

Mission:

Use of **protons** (ions) accelerated by means of the **PHELIX** laser and provide **transport, focusing and bunch rotation** of the laser generated particle bunches by **conventional ion optics and RF technology** in a "test stand" located at the Z6 experimental area of GSI

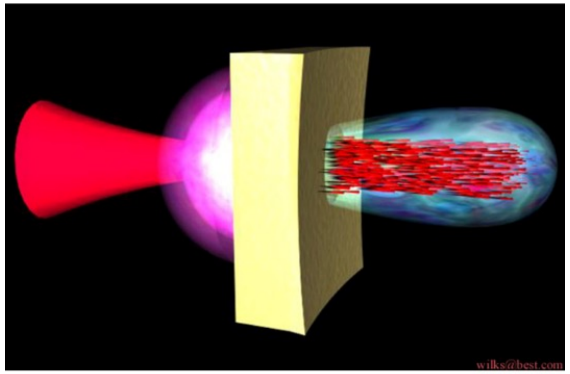
LIGHT

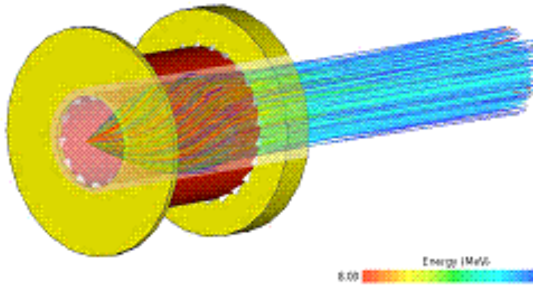
Laser Ion Generation, Handling and Transport

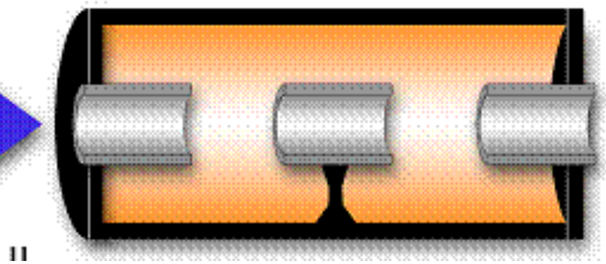


30 J (Ø=12 cm) @ 0.5 ps
=> 100 TW => 10^{19} W/cm²

LIGHT – Laser Ion Generation, Handling and Transport







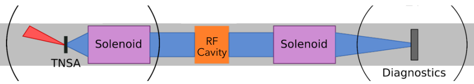
Step 1:
- Generation and Characterization of the proton beam via TNSA
- Target optimization for high conversion efficiency (laser to ion) and low ion beam divergence angle
- Ion energy spectrum shaping

Step 2:
- Collimation of the proton beam
- Separation of the electrons
- Selection of the proton energy interval
- Proton beam divergence control
- Space charge

Step 3:
- Setting up of a buncher unit based on existing 108 MHz technology at GSI
- Compression of chosen energy interval
- Diagnostic of the compressed proton bunch

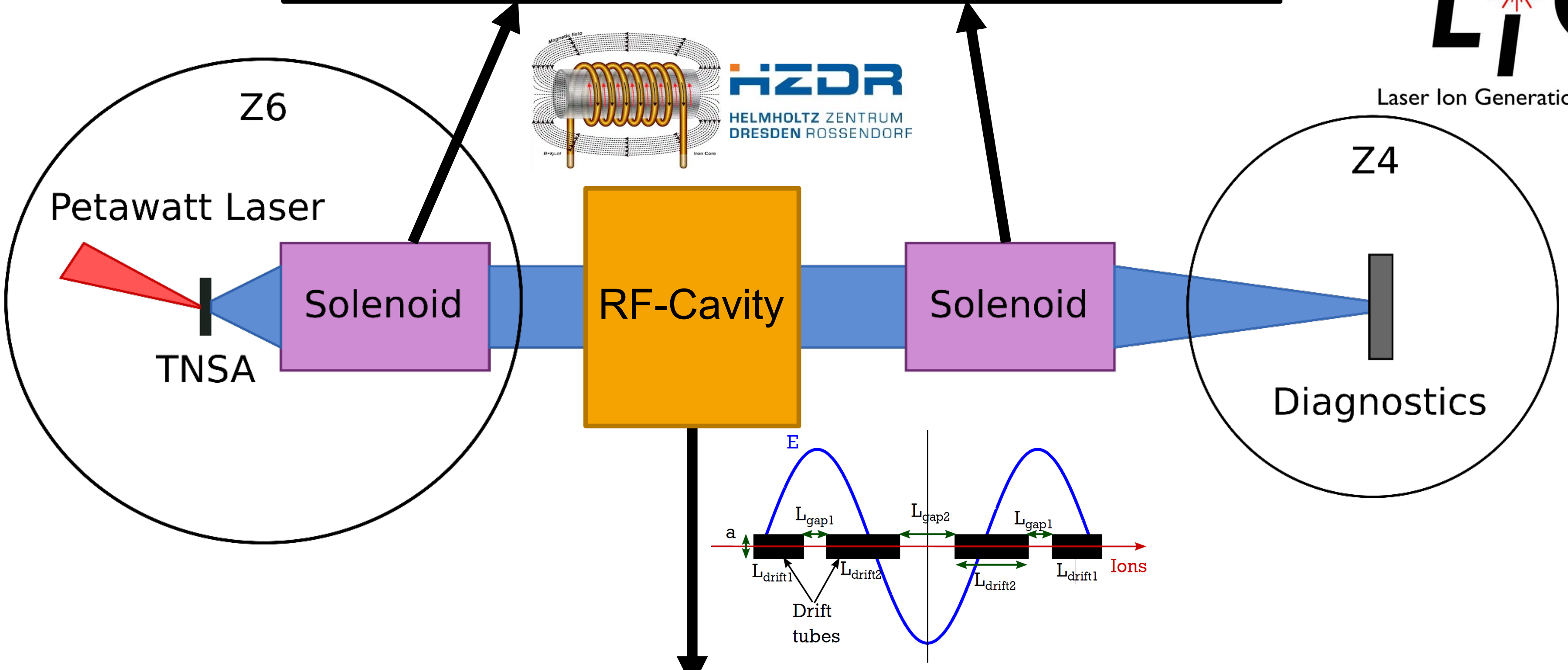
Goal: proton bunch with 10^{10} protons in few ns with an energy of E = 10 MeV and DE = 4%

LIGHT – Laser Ion Generation, Handling and Transport



PHELIX
$E = 30 - 40$ J
$\tau = 650$ fs
$\lambda = 1053$ nm
$d_t \approx 3.5$ μm
$I > 10^{19}$ W/cm²

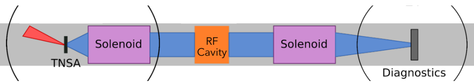
Energy selection, transport and transverse focusing

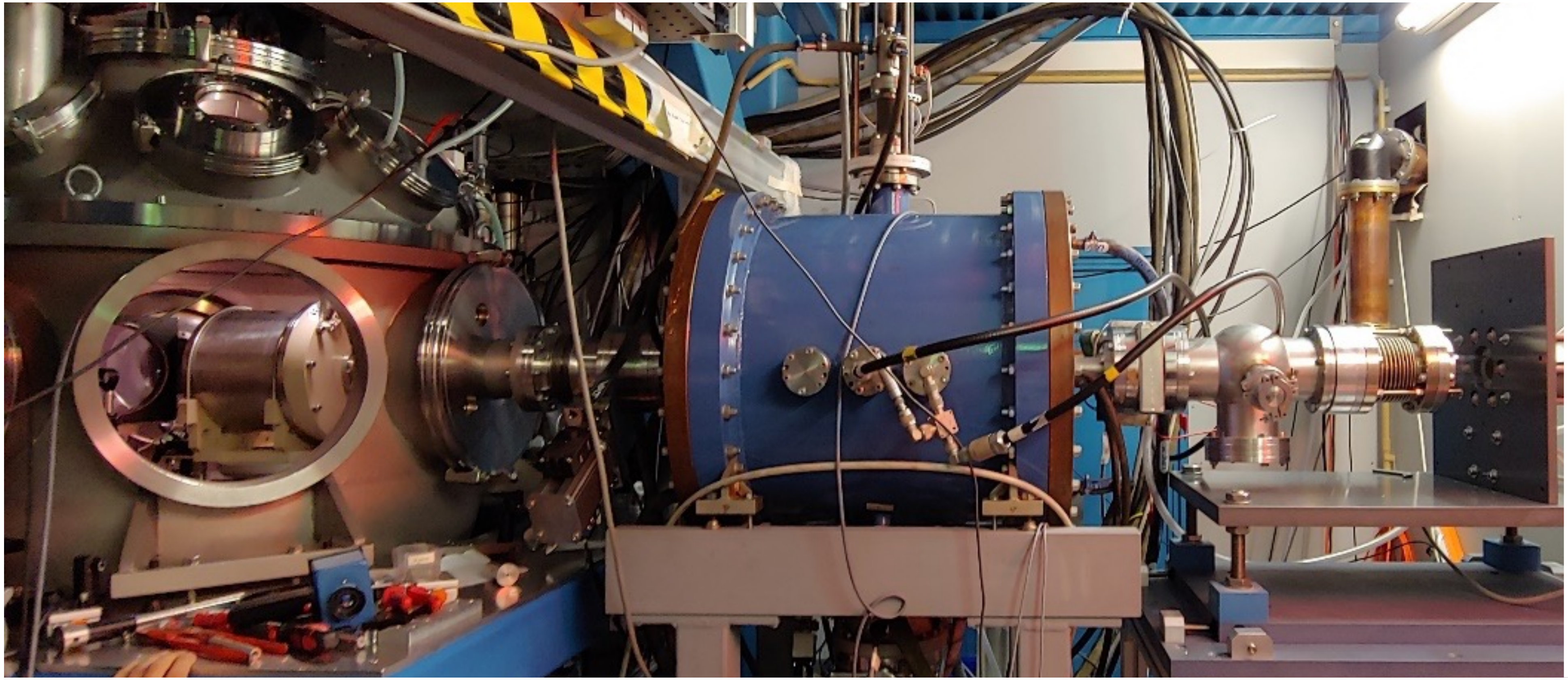


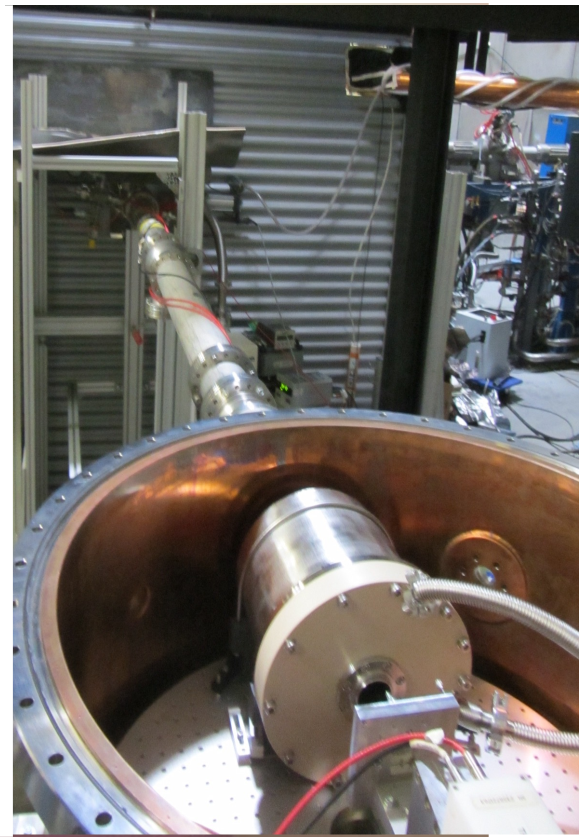
Laser Ion Generation, Handling and Transport

Longitudinal manipulation (reduction of energy spread → 3% / temporal compression → sub-ns)

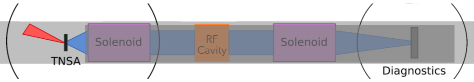
LIGHT – Laser Ion Generation, Handling and Transport

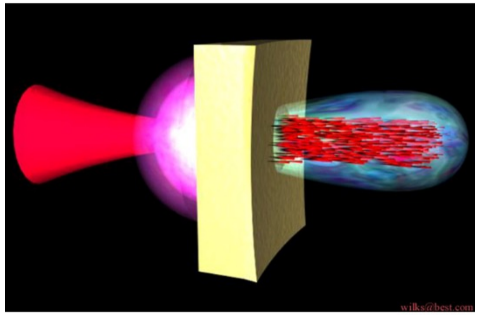






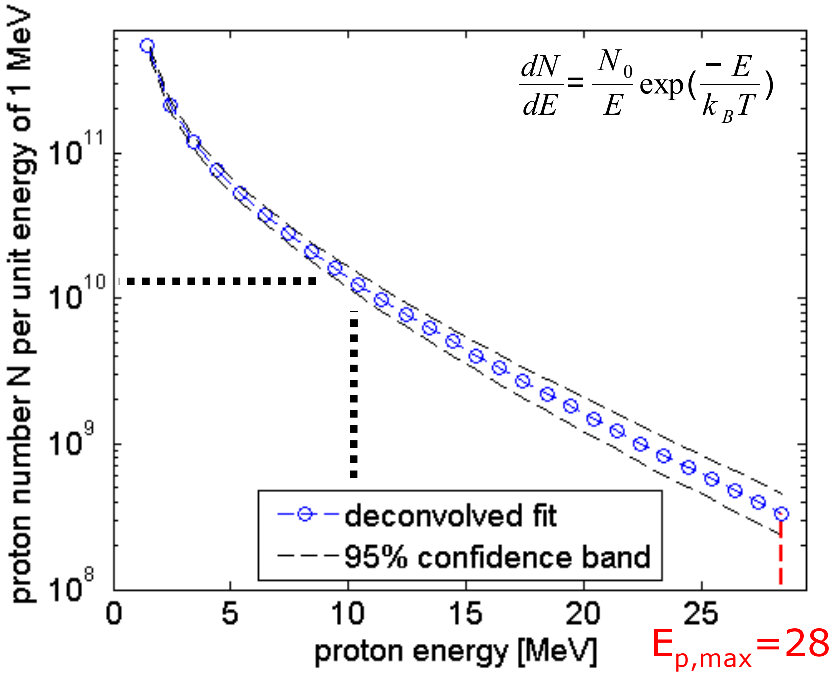
Characterization of the TNSA ion source



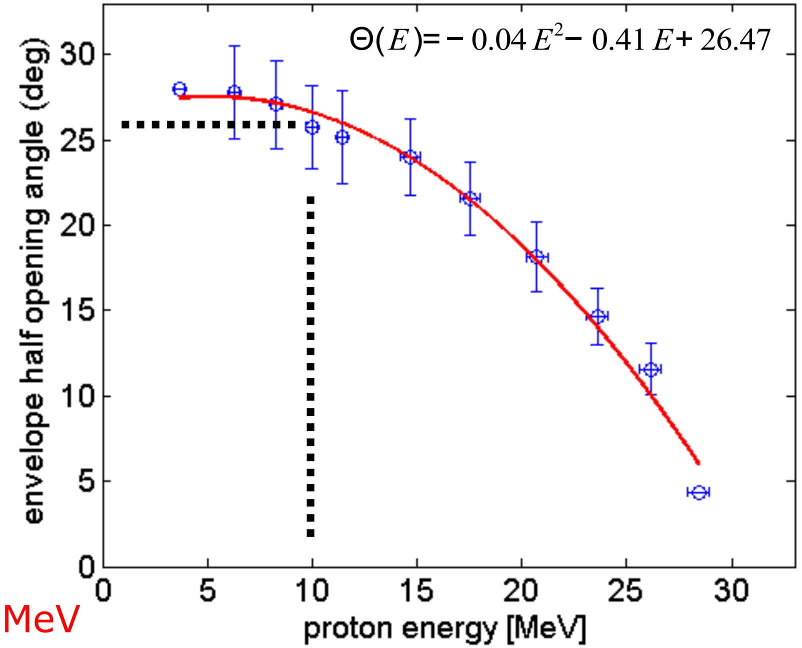


PHELIX
E = 30 - 40 J
τ = 650 fs
λ = 1053 nm
$d_t \approx 3.5$ μm
I > 10^{19} W/cm²

Energy spectrum



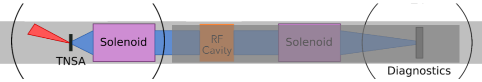
angular divergence (FWHM)

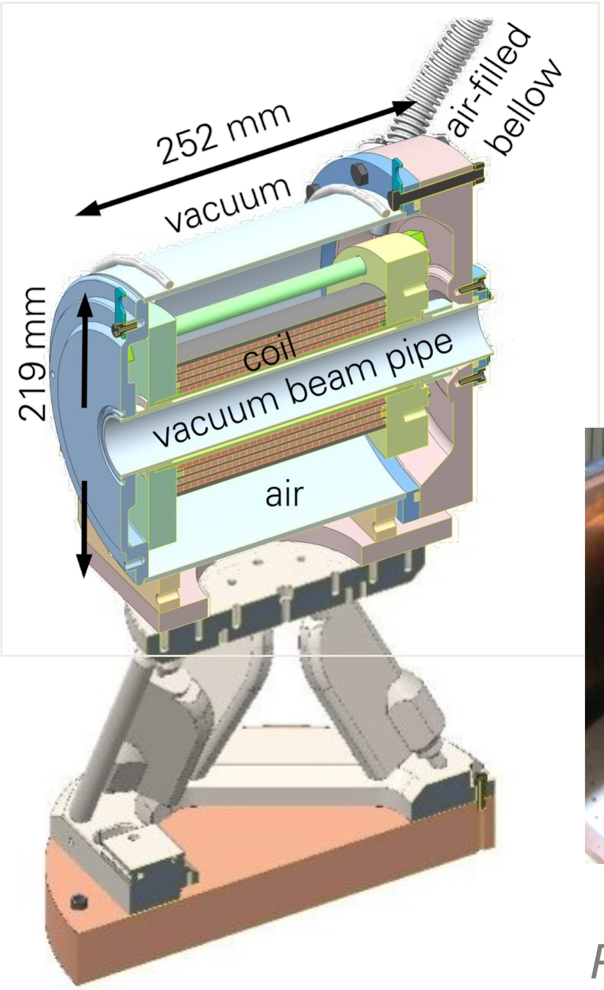


- detection of full proton beam via RIS* @4cm behind source
- source size @10MeV: approx. 50μm

*F. Nürnberg *et al.*, RSI **80**, 033301

Solenoid – collimation and energy selection

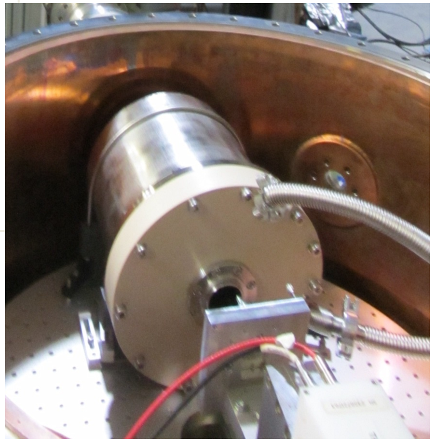




Ion species and charge state

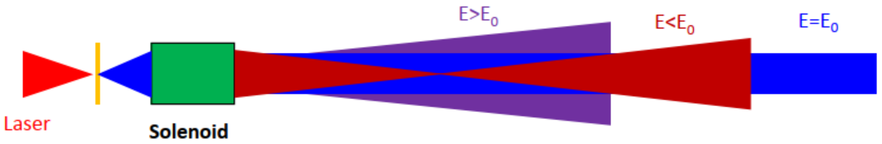
Energy of Ions

$$\frac{1}{f} = \frac{q^2}{m^2} \frac{1}{4\gamma^2 v_z^2} \int B^2 dz$$



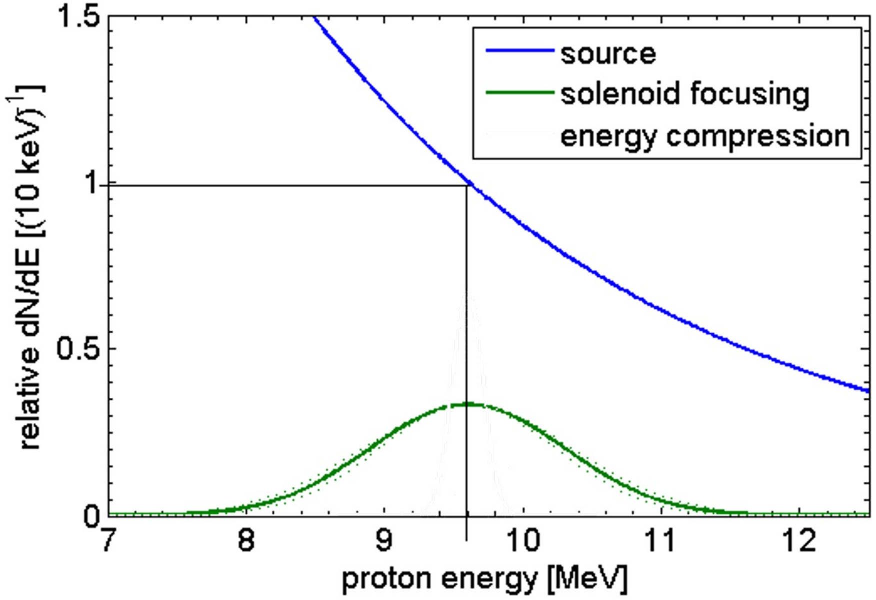
Provided by HZDR

Energy Selection by means of chromatic focusing

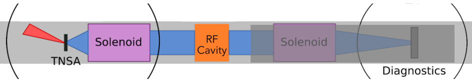


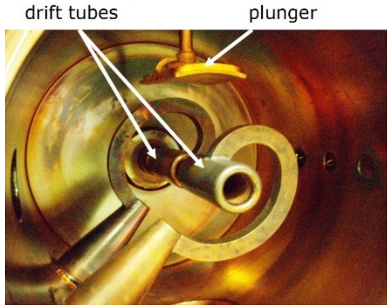
Efficient Transport of Protons already demonstrated:

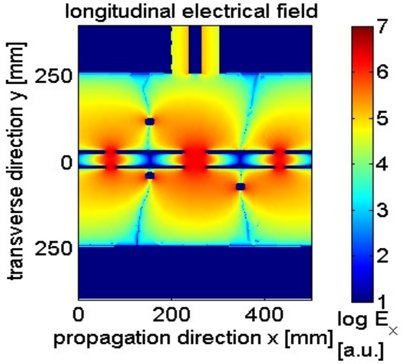
- 34 % of Protons in 8 MeV ± 0.5 MeV Energy range
- Equals $N_P > 10^9$ Protons

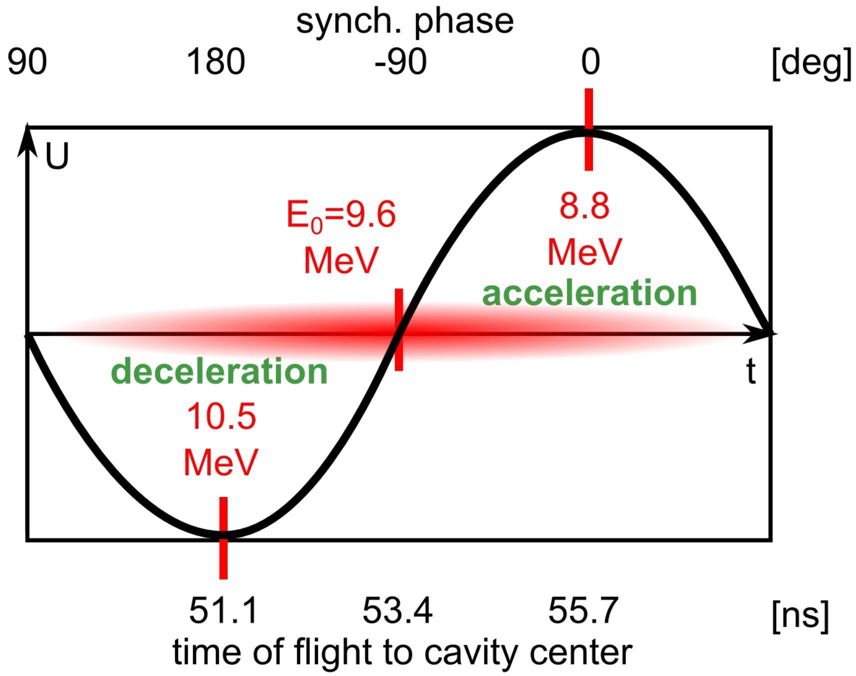


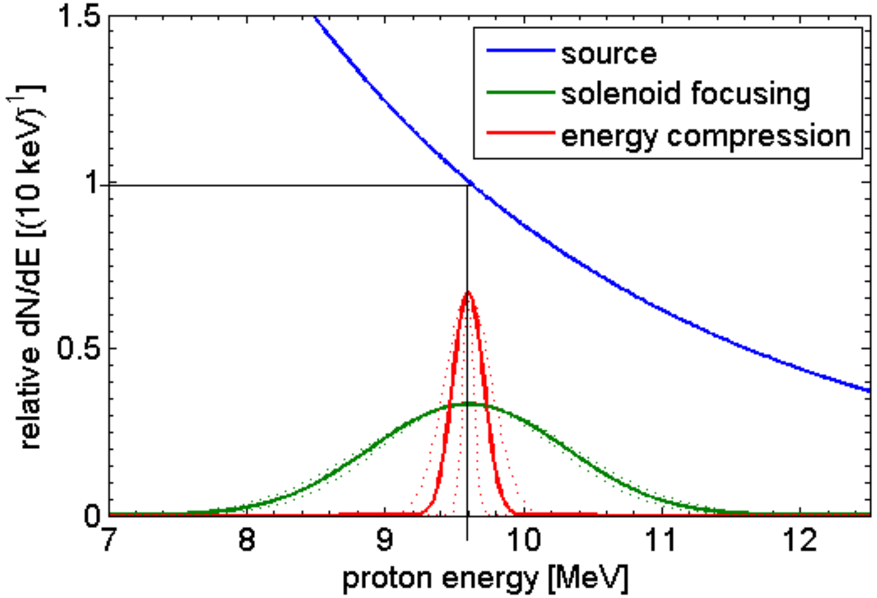
Cavity: Phase Space Modulation











Cavity

- 3-gap spiral resonator
- driven by the UNILAC RF generator
- in future own RF generator
- 108.4 MHz (UNILAC)
- RF power >100 kW
- applied potential >±1MV

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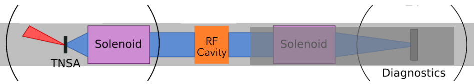

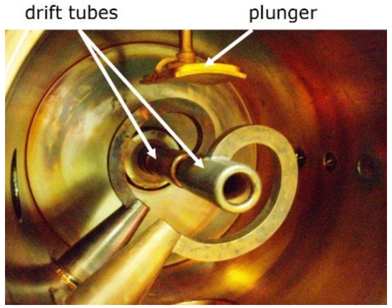

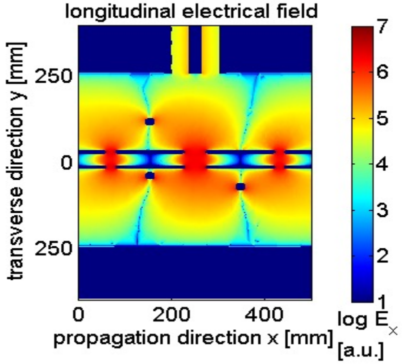

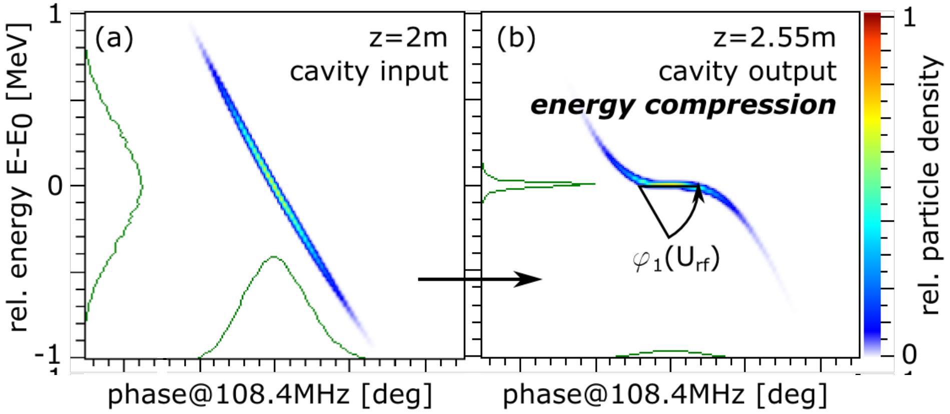

- TNSA source with PHELIX at Z6
  → >10^{10} protons @(10±0.5)MeV
- collimation and transport via solenoid
  → **34% efficiency** @(10±0.5)MeV
  → **$\Delta E/E_0$=(18±3)%**
- energy compression via cavity
  → **$\Delta E/E_0$=(2.7±1.7)%**
  → 1.7x10^9 **(±15%)** protons detected in FWHM

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- 3-gap spiral resonator
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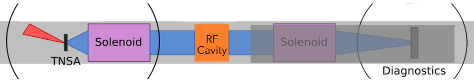
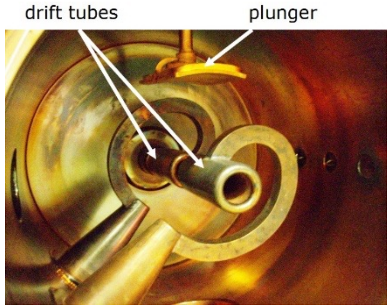
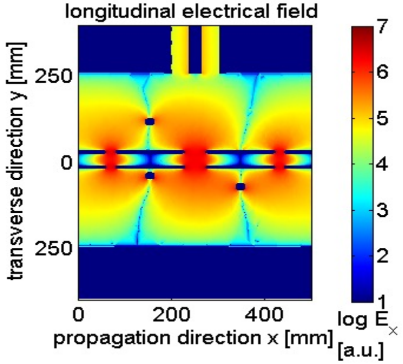
Cavity: Phase Space Modulation







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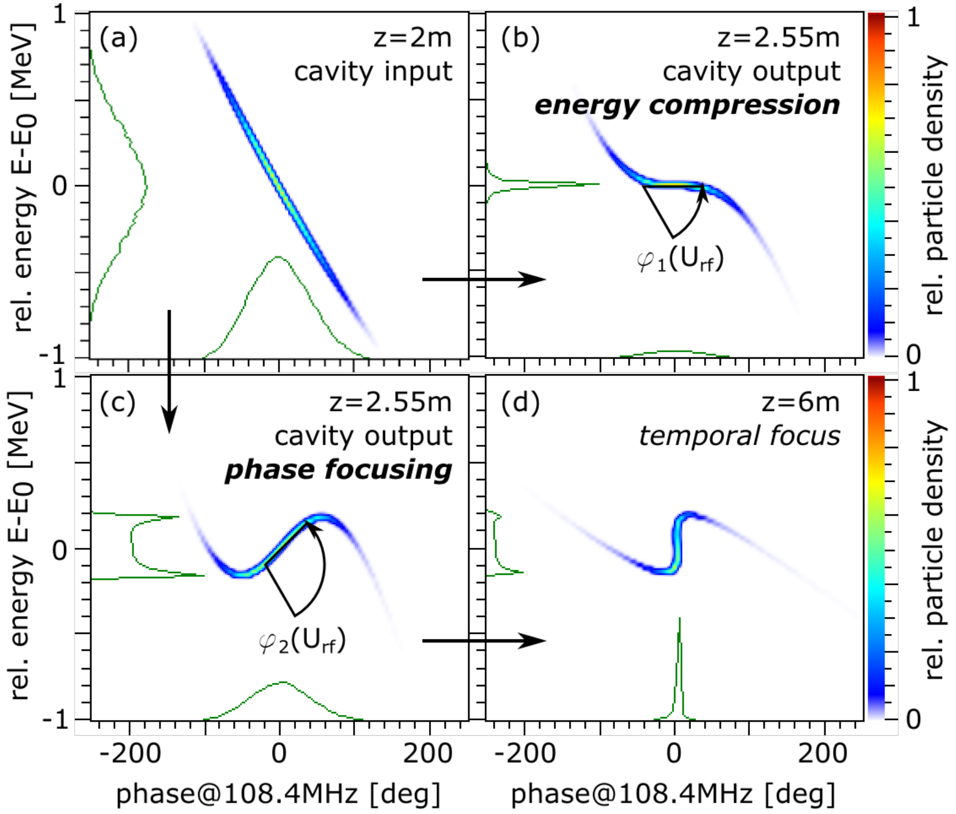

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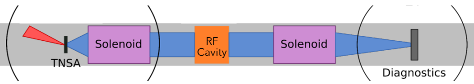
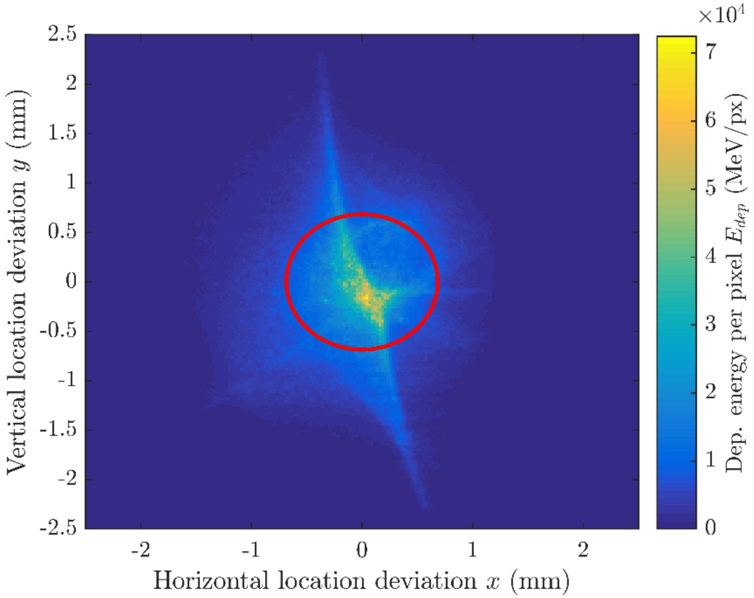
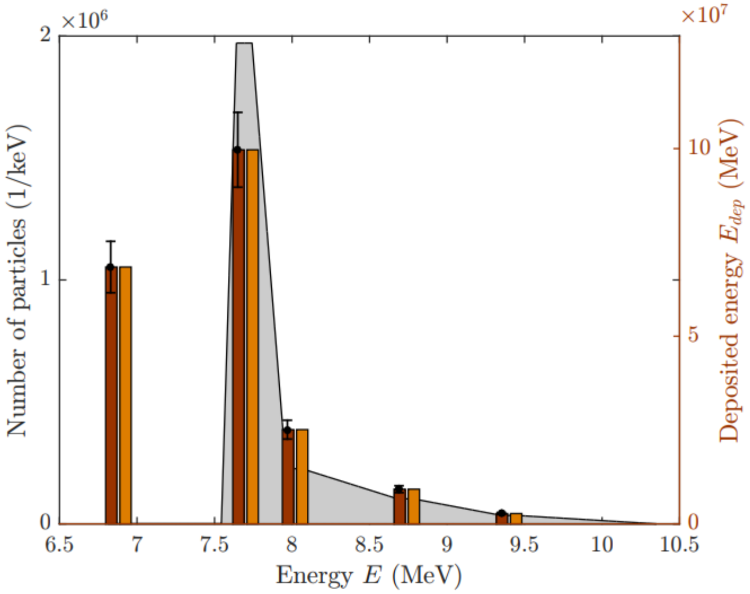
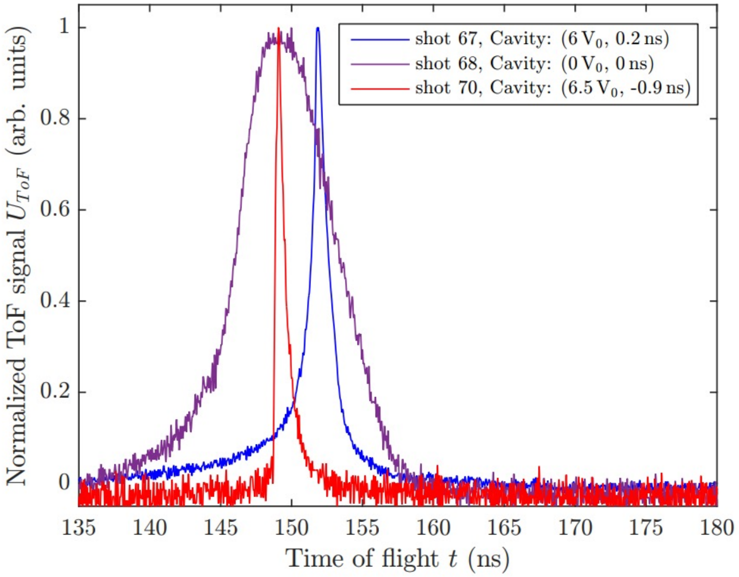
- energy compression via cavity
  → $\Delta E/E_0$=(2.7±1.7)%
  → 1.7×10^9 (±15%) protons detected in FWHM
- phase focusing experiments
  → 6m laser-driven ion beamline
  → **(742±40) ps** bunch length detected
  → 1st application for material science experiments

Beamtime 2020 7.7 MeV Protons - Results



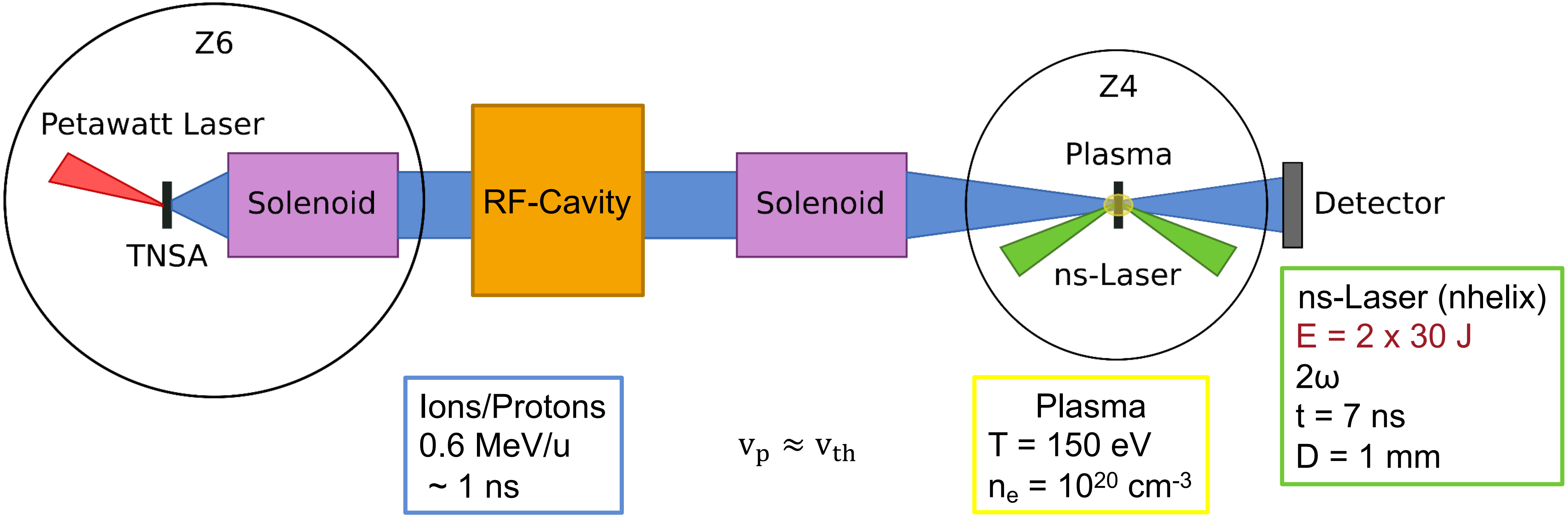






Parameter	Value
Number of protons	(7.29 ± 0.64) x 10^8 protons
Peak-Energy (ToF)	(7.72 ± 0.14) MeV
Temporal bunch width (FWHM)	(742 ± 40) ps
Focal spot (encircles 50 % of the ions)	(1.38 ± 0.02) mm

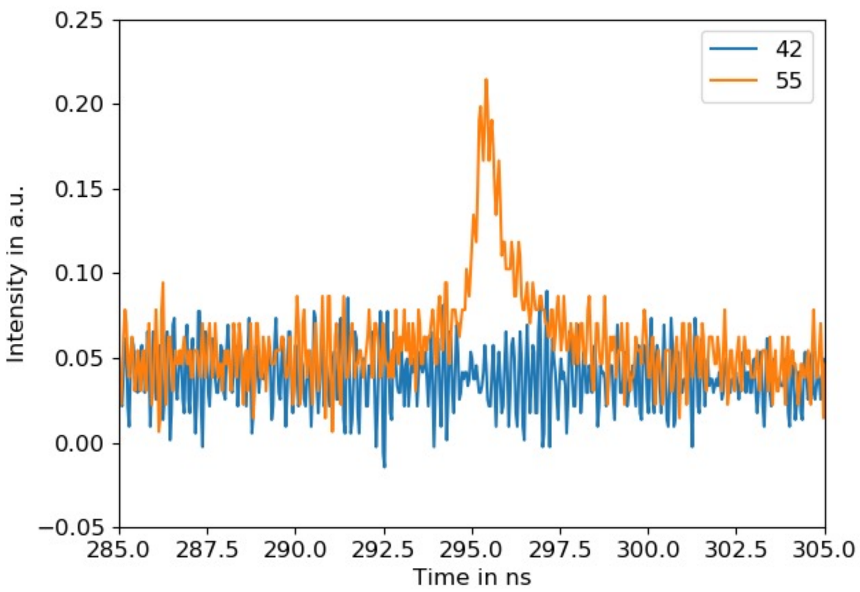
Stopping Power Experiments with LIGHT

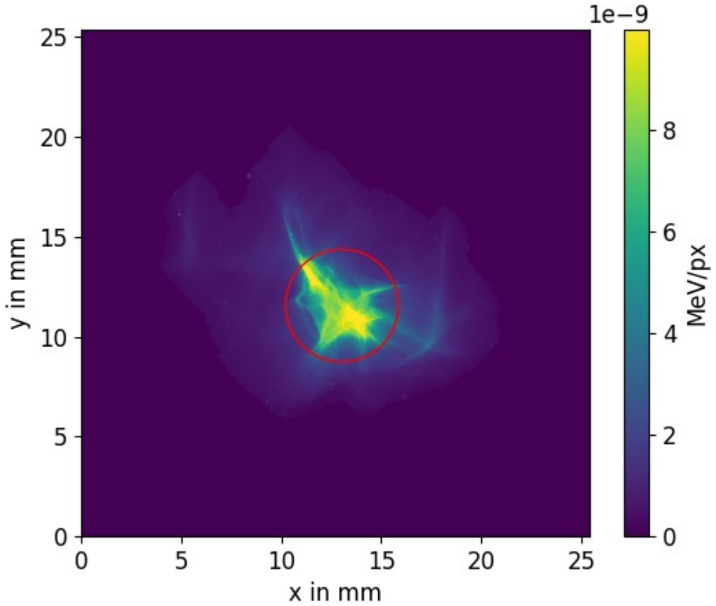


Carbon Ions and Protons as projectiles for better benchmarking of theories

Preparational beamtimes needed to demonstrate transport of ions/protons

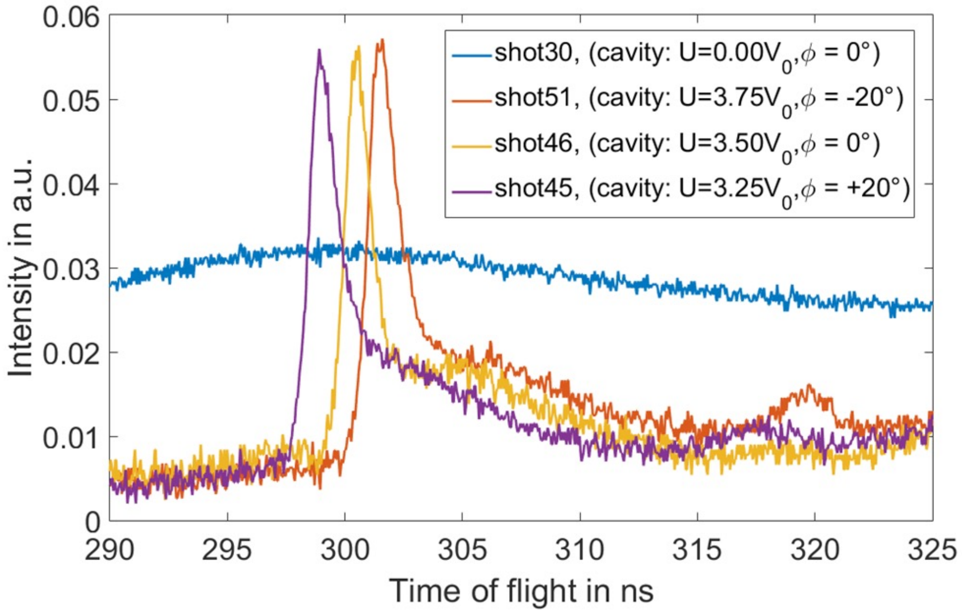
Proton Bunch Parameters June 2022

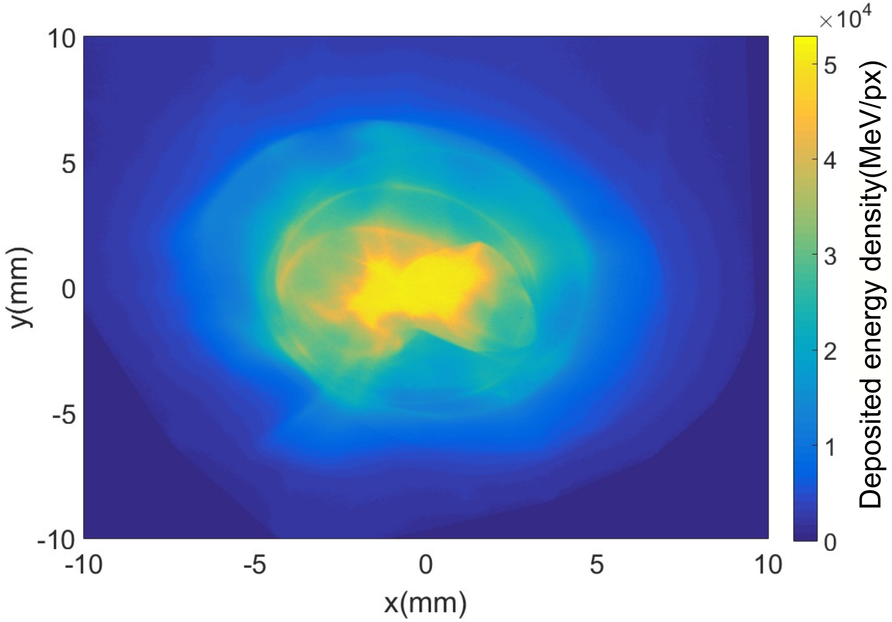




Parameter	Value
Peak-Energy (ToF)	0.6 MeV
Temporal bunch width (FWHM)	760 ps
Focal spot (encircles 50 % of the ions)	5.64 mm

Carbon Ion Bunch Parameters January 2021

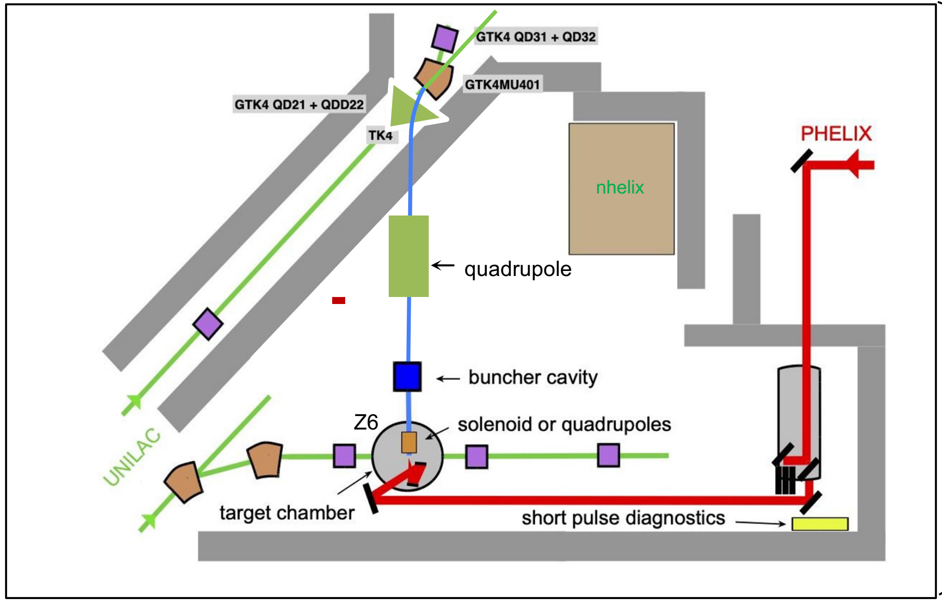


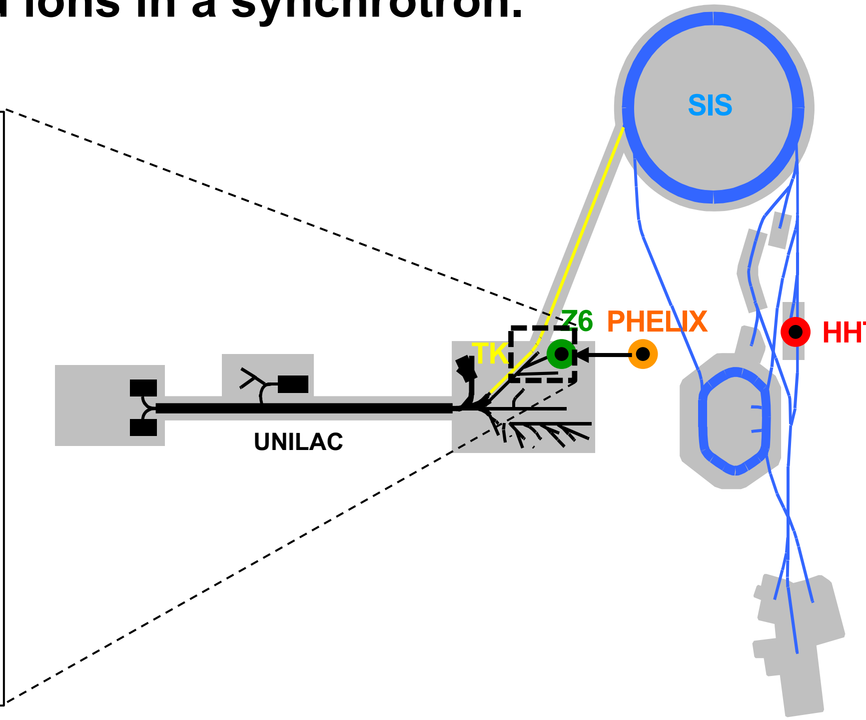


Parameter	Value
Peak-Energy (ToF)	0.6 MeV/u
Temporal bunch width (FWHM)	1.23 ns
Focal spot (encircles 50 % of the ions)	8.4 mm

Future Project: Injection of Laser accelerated ions into SIS18

First laser accelerated ions in a synchrotron.





Beam parameters for injection:

+ E = 11.3 MeV/u
-- N ≈ 10^{10} protons in 1 shot
+ Normalized horizontal emittance: $\varepsilon^{1\sigma}$ = 0.78 mm mrad.
+ Normalized vertical emittance: $\varepsilon^{1\sigma}$ = 2.49 mm mrad.
-- Energy spread $\Delta E/E = \pm 0.2$ %.

Thank you!