High Power Lasers:
Powerful Tools to Extreme Matter Studies


Picture: G. Otto, GSI

Vincent Bagnoud

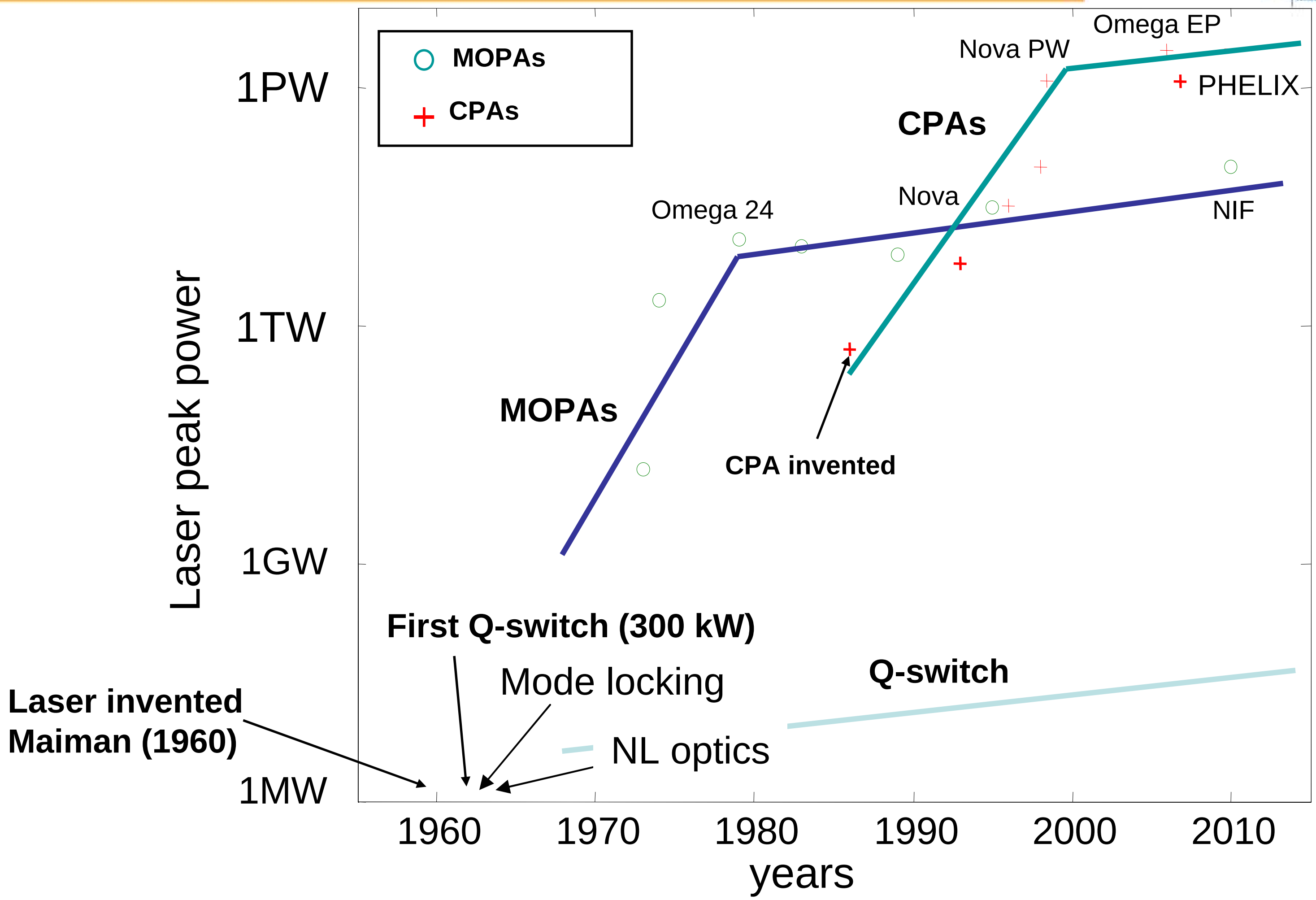
Plasma Physics department, GSI-Darmstadt

v.bagnoud@gsi.de

Summary

- **Introduction to Higher Power lasers**
  - **Enabling discoveries allowed high power lasers to reach the petawatt level in less than 40 years**
  - **An interesting technological race between CPA and OPCPA**
  - **The temporal contrast of lasers is a hot topic nowadays**
- **Experiment Program at PHELIX**
  - **Progress on ion stopping experiments**
  - **Recent results in x-ray generation**
  - **Ion acceleration and the LIGHT project**
- **Extreme Matter studies with Lasers**
  - **Test of vacuum birefringence at HIJ**
  - **plans for FAIR**

The peak power of lasers has boomed since the 60's



1 TW compares to the electrical power production in the world

The boom of lasers has relied on many enabling technologies

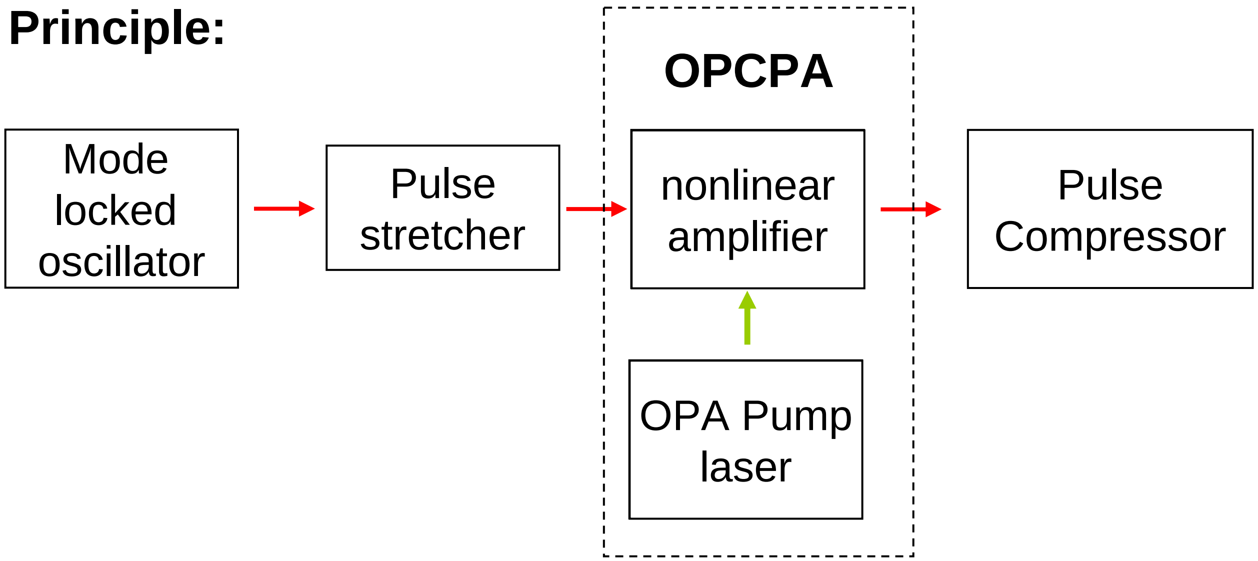
$$P_{peak} = \frac{E_{pulse}}{\delta t}, \quad P_{avg} = \frac{\sum E_{pulse}}{\Delta t}, \quad E_{pulse} \approx F_{saturation} . S^{*}$$

* The transverse dimension of laser materials cannot exceeds its length

Technology	Compatible for short pulse	High energy	Average power
Nd:Glass (1970's)	Medium (1 ps)	Medium	Low
Ti:sapphire (1990's)	Yes (10 fs)	Low	Yes
Yb^{+} materials (2000's)	Yes (100 fs)	Yes (limited by damage threshold)	Yes
CPA (1984)	Yes at 800 nm	medium	N/A
OP-CPA (1992)	Yes at 900 nm	medium	Yes
Diode-pumping (1990's)	N/A	yes	Yes

Chirped Pulse Amplification (CPA) versus Optical Parametric CPA

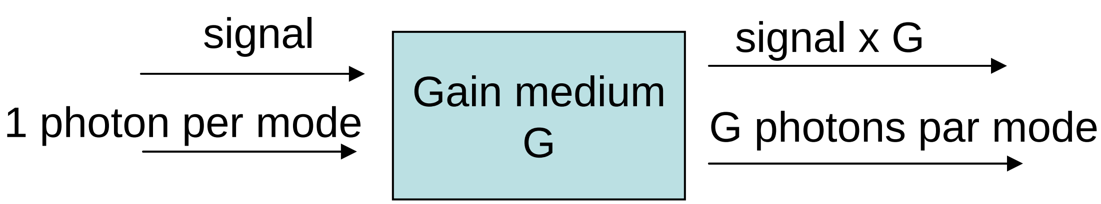
- **Principle:**



- **Advantages**
  - **CPA allows to release the requirements on the pump laser**
  - **OPCPA requires a complicated pump laser but simplifies the amplifier**
- **Current Projects:**
  - **Apollon-10 P (ILE - France) – Ti:sapphire CPA system**
  - **VULCAN 10 PW (RAL – UK) – OPCPA pumped by Vulcan**

Temporal contrast is foremost for modern high power lasers

- **Amplified spontaneous emission (ASE) is the main limit in a standard CPA scheme**
- **ASE can be analyzed in a general noise theory in quantum amplifiers**



- **In first approximation a CPA system operates with 10^8 injected photons, which is the standard contrast level in a CPA or OPCPA system**

A 10^{22} W/cm^2 standard CPA laser system exhibits a nanosecond pedestal at 10^{14} W/cm^2

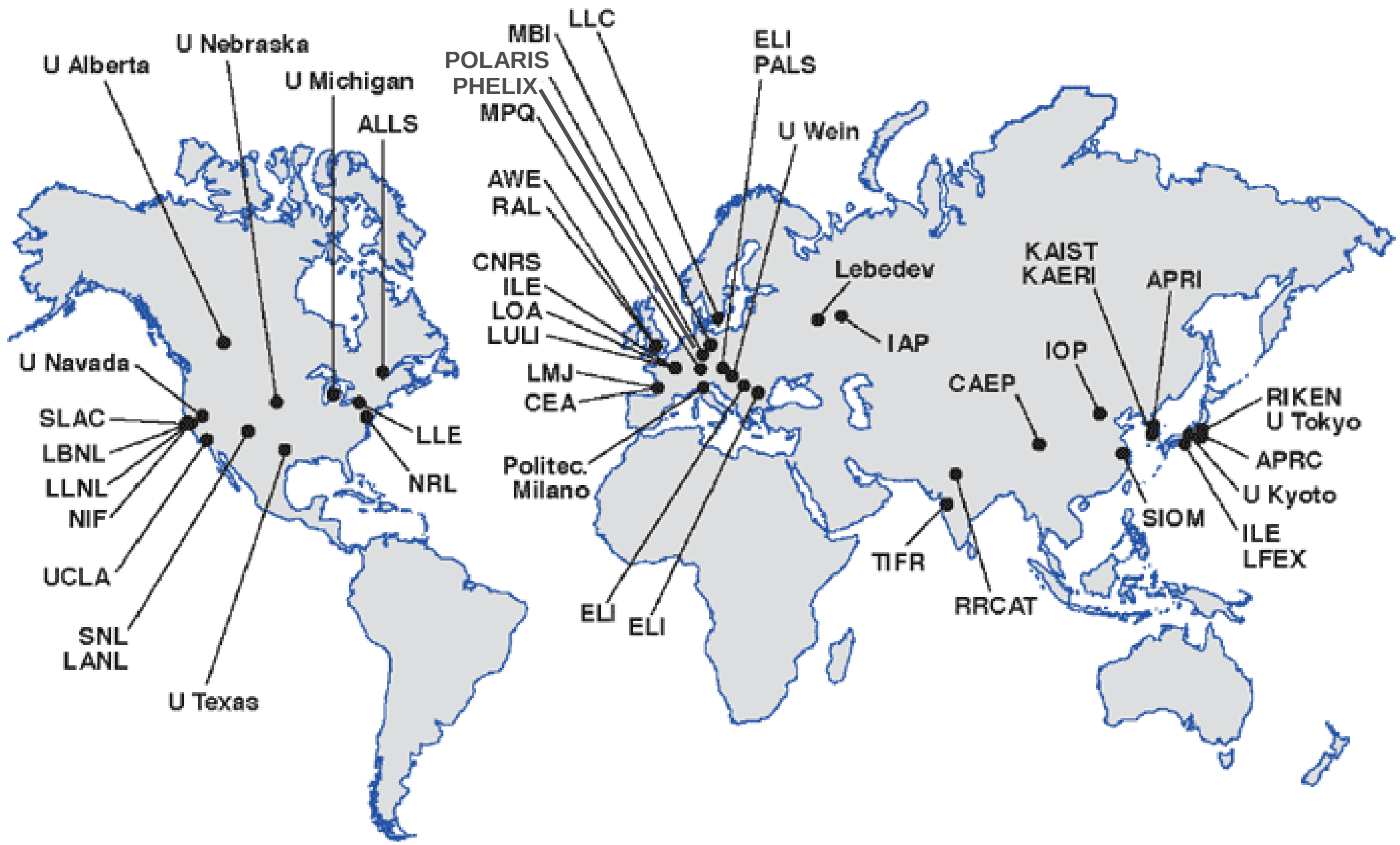
Recent works have tried to increase the number of photons injected into the amplifier

- The acceptable temporal contrast for high power lasers must be 10^{10} and up to 10^{12} for intensities beyond 10^{21} W/cm^2
  - It guaranties that the pedestal intensity stays below 10^9 W/cm^2 on the nanosecond scale
  - That requires an increase of the injected pulse energy by 10^4 to 10^6

Clean pulses with an energy of 10 μJ to 1 mJ are necessary

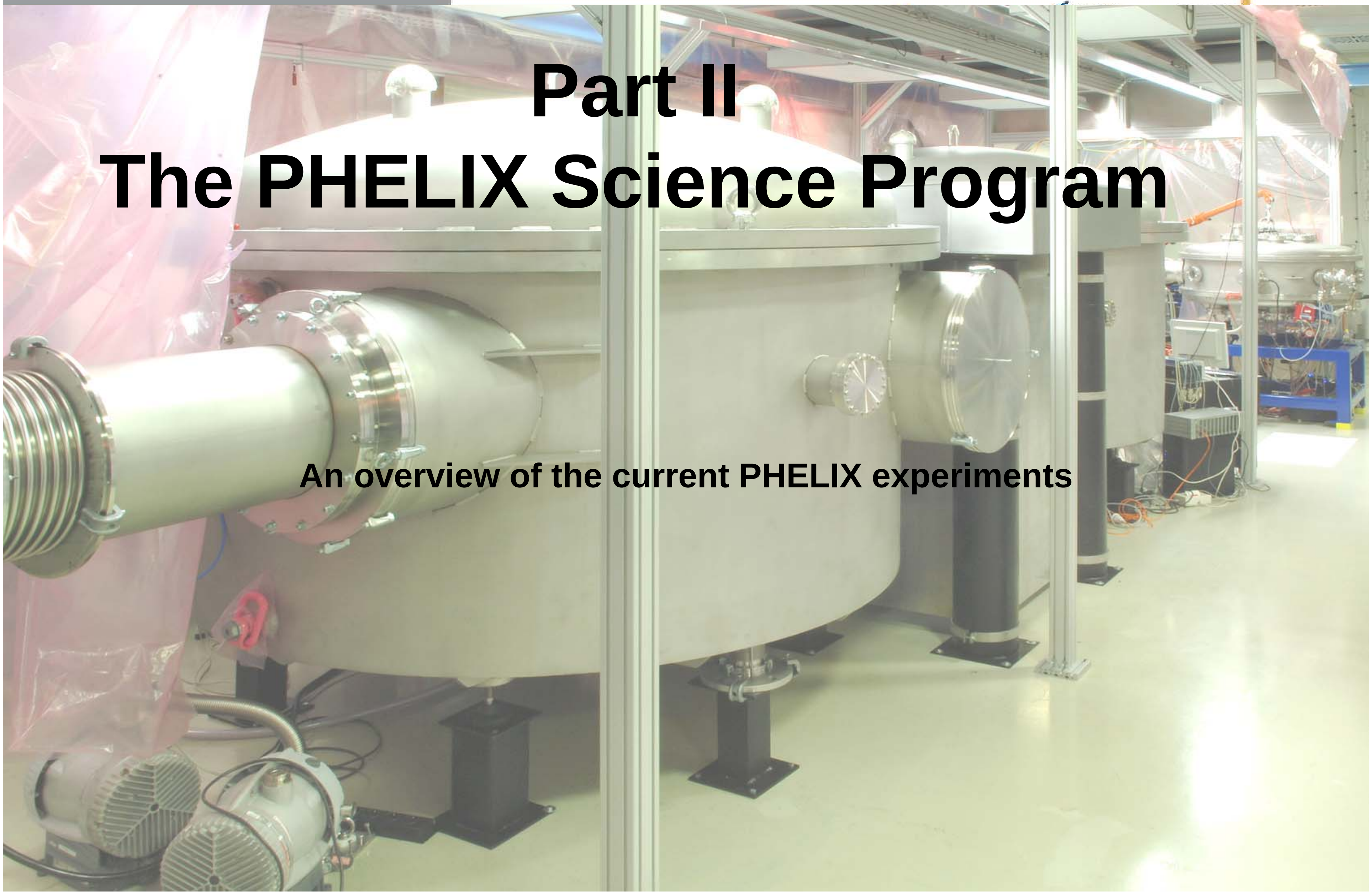
- Techniques that work
  - « pulse cleaning » in a double CPA scheme with a cleaning scheme showing an extinction ratio close to 10^4 - 10^6
  - ultra-fast OPA (uOPA)
- Techniques that do not work
  - Pre-amplification with fast electro-optical gating
  - Nanosecond OPCPA

High power lasers in the world*, present and future facilities



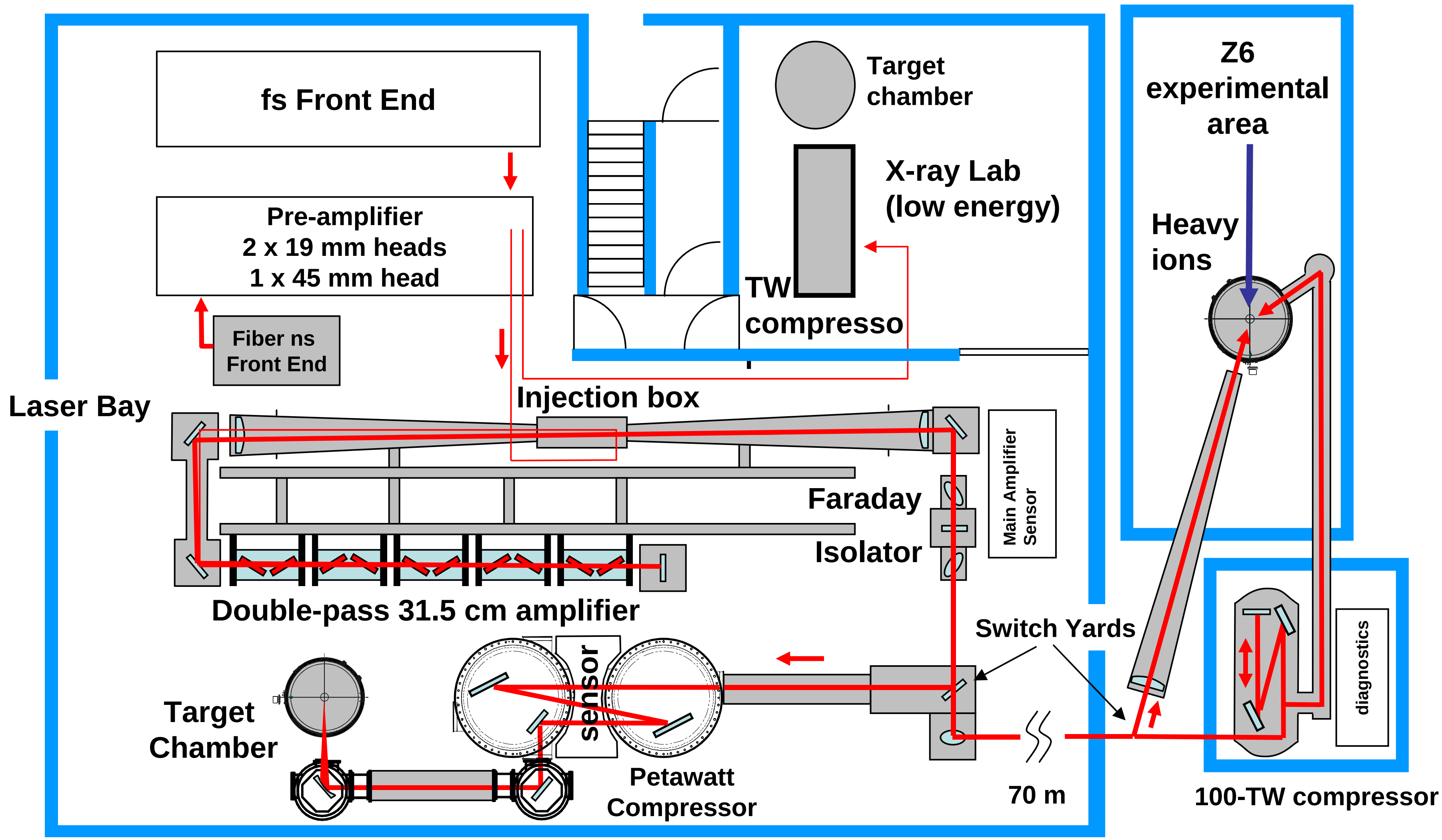
* Source ICUIL web page for lasers with >100 TW peak power

Part II
The PHELIX Science Program



An overview of the current PHELIX experiments

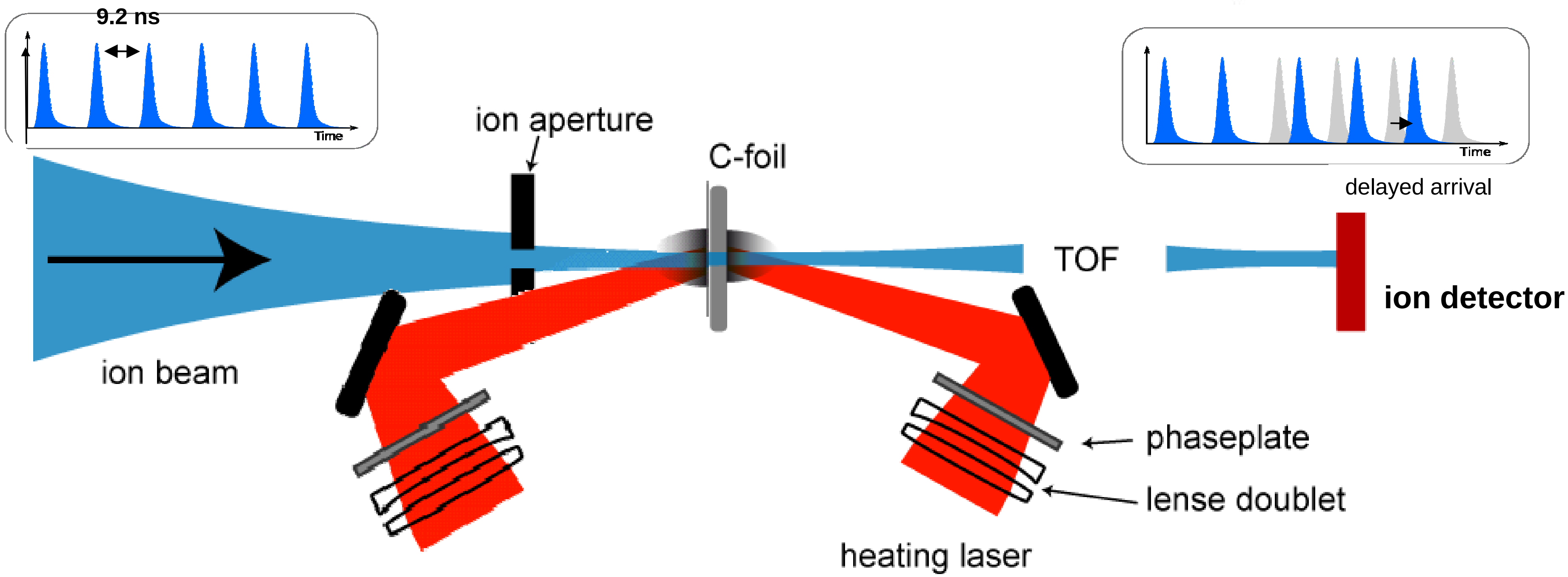
Schematics of PHELIX



Performance of PHELIX in 2010

	Long pulse	Short pulse
Pulse duration	0.7 – 20 ns	0.5 – 20 ps
On-target energy	0.3 – 1 kJ	120 J
Maximum intensity	10^{16} Wcm^{-2}	10^{20} Wcm^{-2}
Repetition rate at joule level	1 shot every 3 min	
Repetition rate at maximum power	1 shot every 1h	
Temporal contrast	50 dB	60 to 80 dB depending on settings

Interaction of energetic ions with a hot Plasma target

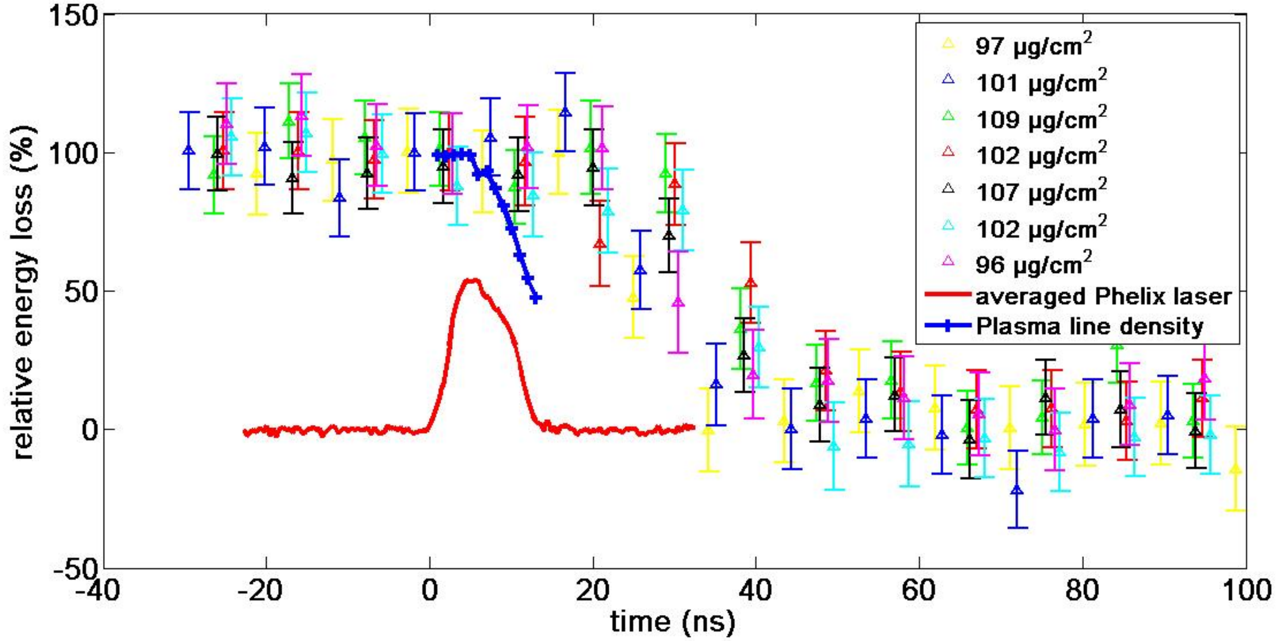


- projectile**:**
  - **Ar^{16+}**
  - **E = 4 MeV/u**
- target:
  - **C foils**
  - **100 – 300 µg/cm²**

- laser parameters:
  - **λ = 1.054 (527) µm**
  - **E = 2 x 50 J**
  - **T_{pulse}= 7 ns (FWHM)**
  - **d_{focus}= 1 mm (random phase plate)**

- stop detector:
  - **polycrystalline CVD diamond**
  - **thickness: 19 µm**

Progress in ion stopping (Courtesy of A. Frank)



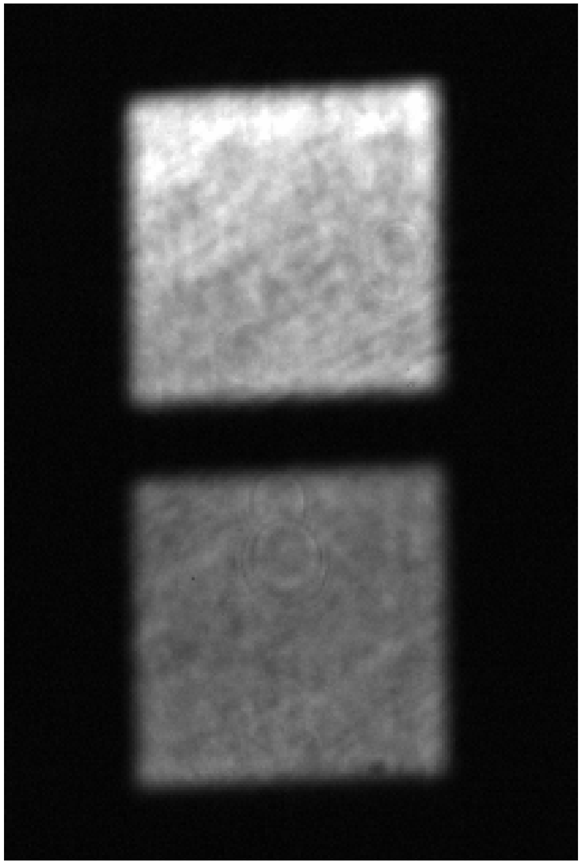
- **The combined use of PHELIX and nhelix yields a significant improvement in quality of the experimental data**
- **Plasma uniformity upon double-sided heating of planar target is the key issue**
- **Recently the conversion of the laser light to 527 nm (both PHELIX and nhelix) has improved the data even more (data still under analysis)**

Theory plasma: Basko, Maruhn, Tauschwitz

Progress in X-ray generation*

- Recently a pump-probe scheme has been implemented at PHELIX
- Two sub-aperture beams are simultaneously amplified and separately focused allowing for the generation and diagnosis of hot dense plasma with x-rays
- Each laser beam carries > 100 TW laser pulses
- The delay between the pulses is adjustable from 0 to 2 ns
- The experiment is still in progress and data under analysis

PHELIX is the only facility in Germany to offer this capability



Near field image recorded at the end of chain sensor

*** Developed with the EMMI group of Dr. Paul Neumayer**

Parametric amplification in the XUV/soft x-ray spectral range has been demonstrated

nature physics

ARTICLES

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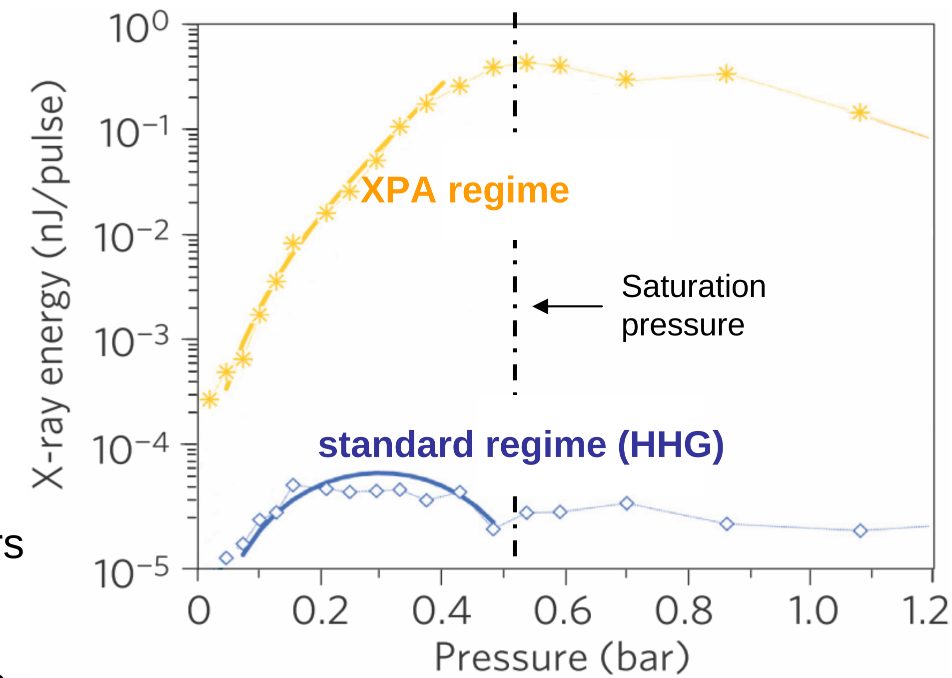
Laser-driven amplification of soft X-rays by parametric stimulated emission in neutral gases

J. Seres[1,2], E. Seres[1], D. Hochhaus[3,4,5], B. Ecker[3,4], D. Zimmer[3,4,6], V. Bagnoud[3], T. Kuehl[3,4] and C. Spielmann[1,2]*

[1]Institute of Optics and Quantum Electronics, Friedrich-Schiller-University Jena, Max-Wien-Platz 1, 07743 Jena, Germany, [2]Department of Physics I. University of Würzburg, Am Hubland, 97074 Würzburg, Germany, [3]GSI Helmholtz Centre for Heavy Ion Research GmbH, Planckstrasse 1, 64291 Darmstadt, Germany, [4]Department of Physics, Johannes-Gutenberg-University Mainz, Staudingerweg 7, 55128 Mainz, Germany, [5]EMMI Extreme Matter Institute, Planckstrasse 1, 64291 Darmstadt, Germany, [6]LASERIX-CLUPS, LPGP UMR 8578, Université Paris-Sud 11, Bat 210, 91405 Orsay, France.
*e-mail: christian.spielmann@uni-jena.de.

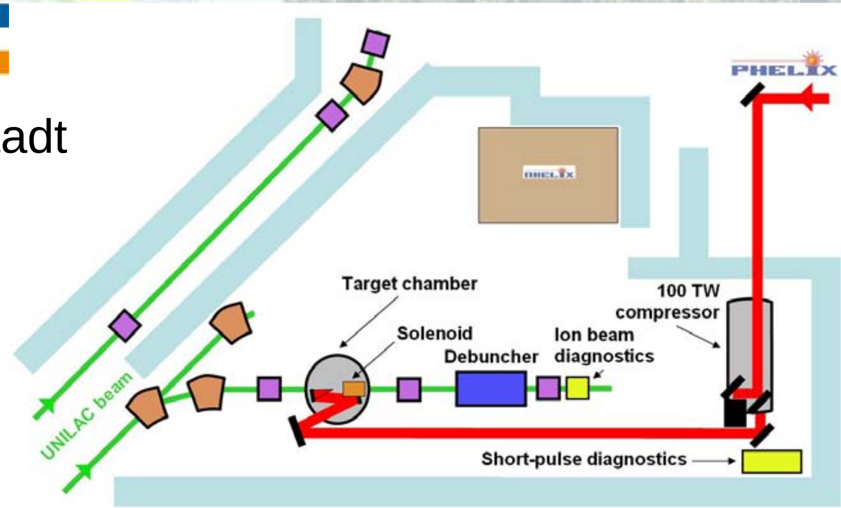
- We discovered an amplification mechanism based on parametric amplification :
  X-ray Parametric Amplification (XPA)
- We experimentally observed amplification factors **up to 8 x 10^3** at 260 eV photon energy
- Our theoretical model describes for the first time the conditions for parametric amplification in the XUV and gives excellent agreement to experimental observations



Experimental signature of a parametric process (exponential gain) in the XUV

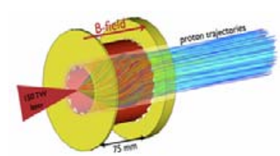
LIGHT – Laser Ion Generation, Handling and Transport

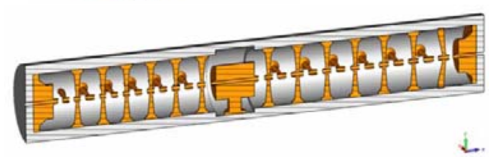
- Joint research project located at GSI Darmstadt

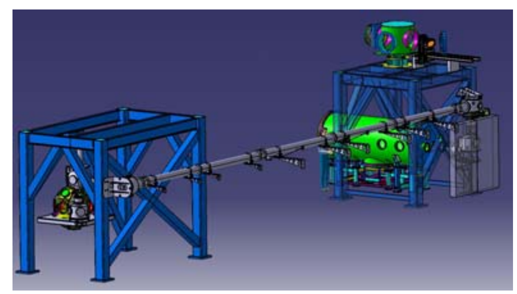


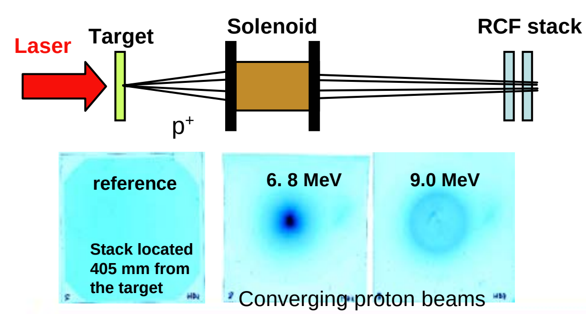
Project partners:

- **TU Darmstadt** (Project leader M. Roth; acceleration experiments, collimation simulations, target development)
- **Helmholtz Institute Jena** (Project coordination, 100TW compressor, short laser pulse and ion beam diagnostics)
- **GSI** Plasma Physics, Accelerator, Beam Diagnostics, Atomic Physics Depts. (PHELIX Laser, timing, control system, beamlines, accelerator structures, beam diagnostics)
- **FZ Dresden-Rossendorf** (Solenoid for collimation + PSU)
- **JWG University Frankfurt** (Accelerator structure development)







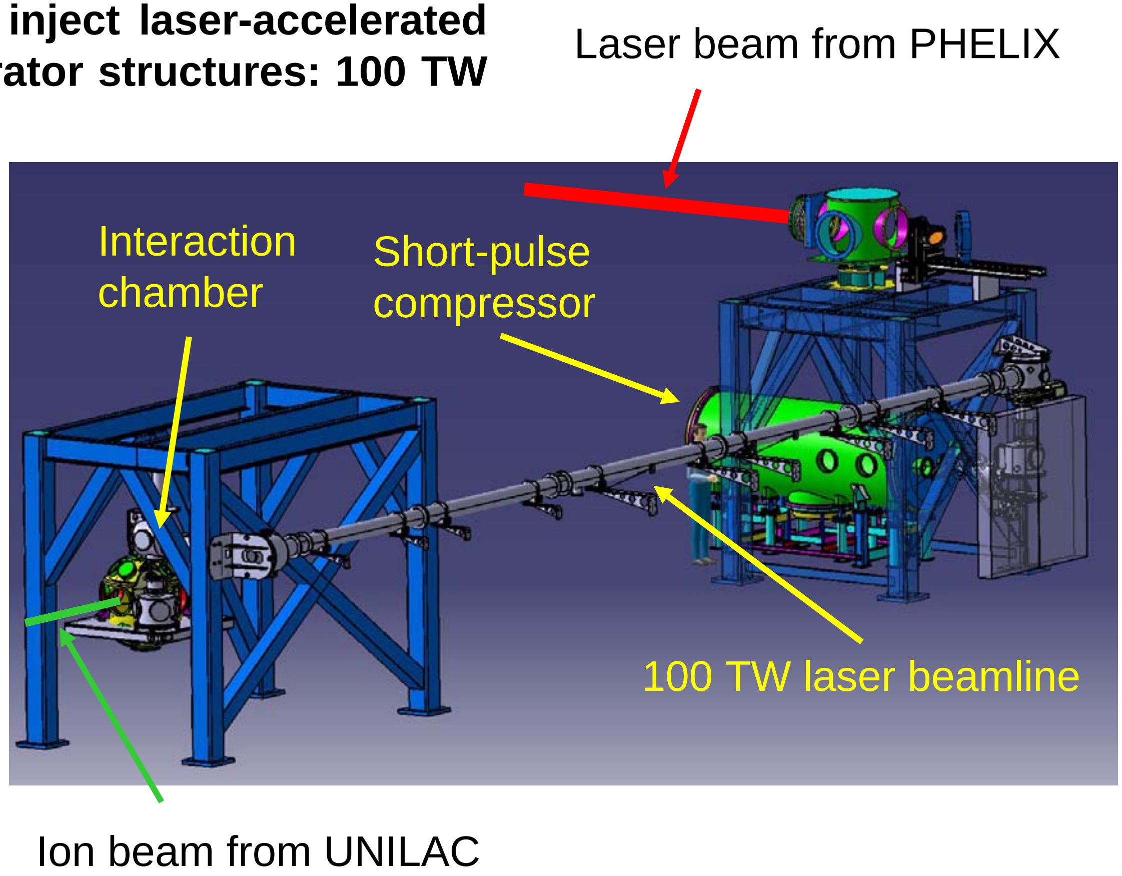


Contributors:
A. Almomani, V. Bagnoud, W. Barth, A. Blazevic, C. Brabetz, T. Burris, T. Cowan, M. Droba, H. Eickhoff, P. Forck, K. Harres, I. Hofmann, O. Jäckel, M. Kaluza, F. Nürnberg, A. Orzhekhovskaya, G. Paulus, U. Ratzinger, C. Rödel, <u>M. Roth (PI)</u>, T. Stöhlker, A. Tauschwitz, W. Vinzenz, S. Yaramishev, <u>B. Zielbauer (PC)</u>

Progress on the 100 TW project

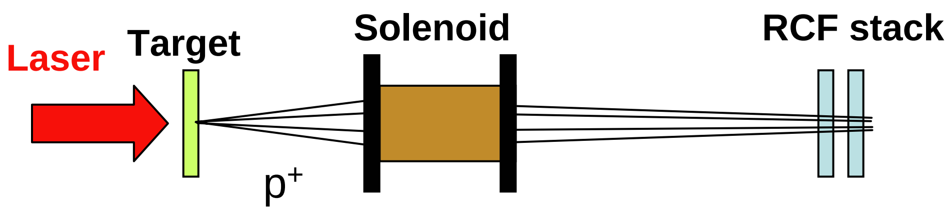
- **GSI together with HI Jena, are building a short-pulse beamline to the Z6 target area to inject laser-accelerated particles into conventional accelerator structures: 100 TW project**

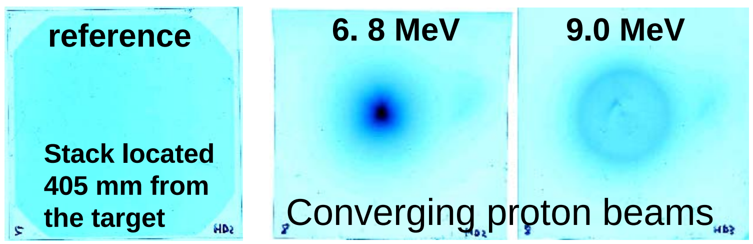
- **Project status**
  - **Conceptual Design Report (CDR) written**
  - **Funding of 250 kEuros/year (GSI, HI Jena) for 3 years secured**
  - **Vacuum beamline ready in December 2010**
  - **Short pulse compressor commissioned**
  - **First acceleration experiment in January 2011**



Results in particle acceleration

- **Up to 14 MeV protons were collimated using a coil developed at FZD (data courtesy of TU Darmstadt)**





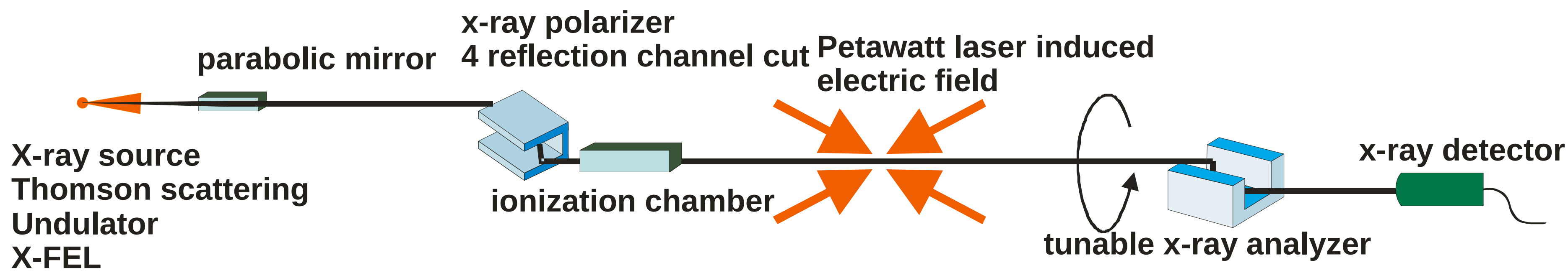
Radio-Chromic Film (RCF) stacks

- **A pulsed solenoid was used to collimate laser accelerated protons**
- **Protons with energies lower than 14 MeV were refocused (see RCF stack images), protons with ~14 MeV were collimated**
- **The experiment is relevant to the 100 TW project supported by Euratom, GSI, TU Darmstadt, HI Jena, FZD**
- **Applications to heating of Warm Dense Matter and energy transport in plasma are expected**

Part III: High Power lasers for Extreme Matter Studies

A selection of future experiments planned at GSI and HIJ

Test of vacuum birefringence with high power lasers*



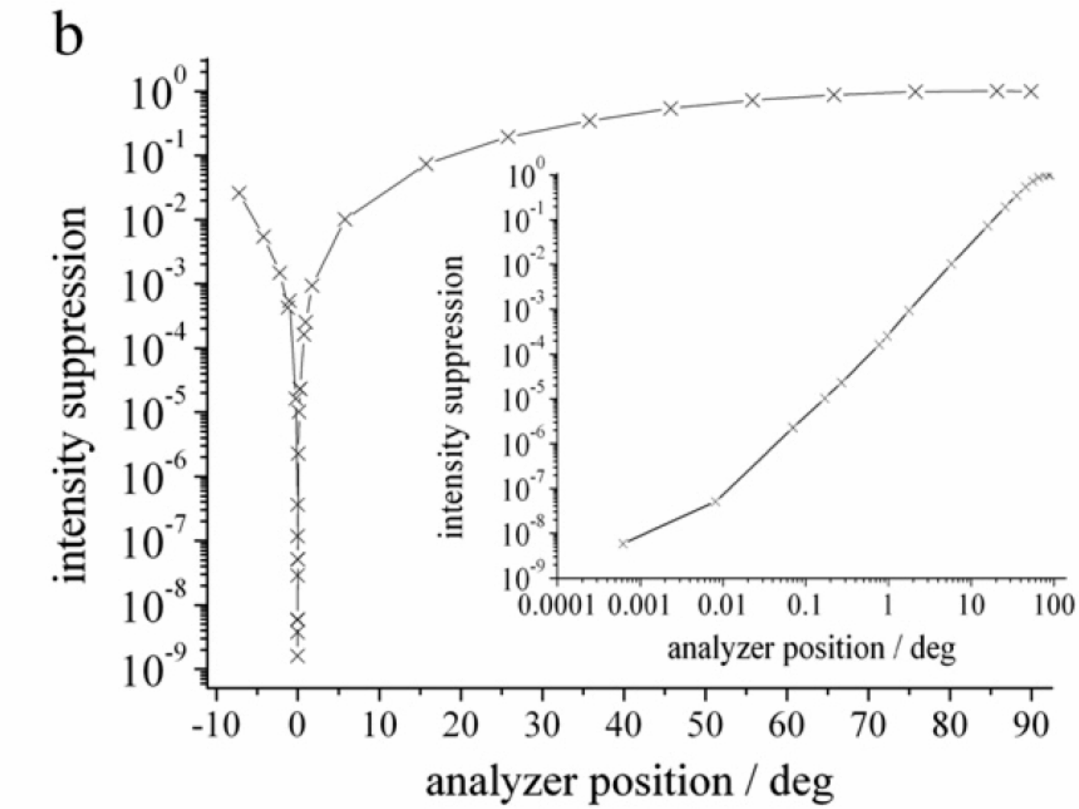
- The theory of strong electric field induced phase shift of a electromagnetic wave in birefringent vacuum predicts an ellipticity ~ $(D\Phi/2)2 \sim 10^{-11}$ for $I_0 = 10^{22}$ W/cm^2
- Requirements

source	Polarizer
• high photon number, • small source size: small interaction volume and small beam divergence • narrow bandwidth	• Adapted to the few keV range • 10^{-11} efficiency via multiple reflection scheme

* Experiment planned by the HIJ

Recent results* on x-ray polarimetry are encouraging

- **A polarizer/analyzer setup based on 4 reflections on Si crystals shows very good extinction ratios for photon energies at 6 keV**

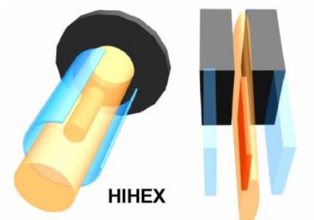


*** B. Marx et al. / Optics Communications 284 (2011) 915–918**

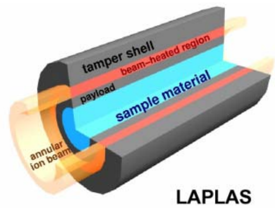
Diagnostics of Warm Dense Matter

- **WDM is important for basic science (astrophysical objects, theoretical complexity), and technical applications**
- **WDM offers challenges: expansion schemes fail, high-performance computing**

WDM research at GSI/FAIR



Heavy Ion Heating and Expansion



Laboratory Planetary Science

Laser generated ultra bright sources enables crucial diagnostic techniques (x-ray radiography, x-ray Thomson scattering, x-ray diffraction, optical properties (opacity, plasmon resonances, conductivity, …)

High pulse energy and increased repetition rates necessary

Summary/Conclusion

- **Introduction to Higher Power lasers**
  - Enabling discoveries allowed high power lasers to reach the petawatt level in less than 40 years
  - An interesting technological race between CPA and OPCPA
  - The temporal contrast of lasers is currently a hot topic
- **Experiment Program at PHELIX**
  - Progress on ion stopping experiments
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  - Recent result in x-ray generation
- **Extreme Matter studies with Lasers**
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Thank You