Laser operation experience at CERN

Valentin Fedosseev
SY-STI-LP

2nd PBC technology mini workshop: lasers & optics
10 December 2021

Outline of the presentation

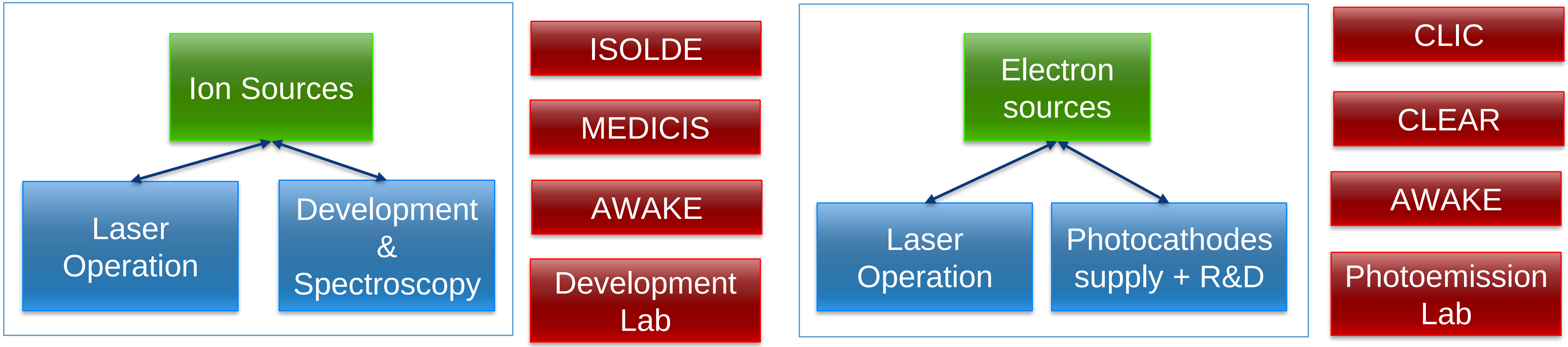
1. Mandate of SY-STI-LP section
2. Laser ion source RILIS at ISOLDE
3. Photoinjector laser systems
4. AWAKE laser system
5. Summary

Disclaimer

Only laser systems under responsibility of SY-STI-LP are covered in this presentation

Mandate

The <u>Lasers and Photocathodes</u> section is responsible for ***laser installations and optical beamlines used to produce charged particle beams*** in the CERN accelerators complex and research facilities


Ion Sources

Laser Operation

Development & Spectroscopy

ISOLDE

MEDICIS

AWAKE

Development Lab

Electron sources

Laser Operation

Photocathodes supply + R&D

CLIC

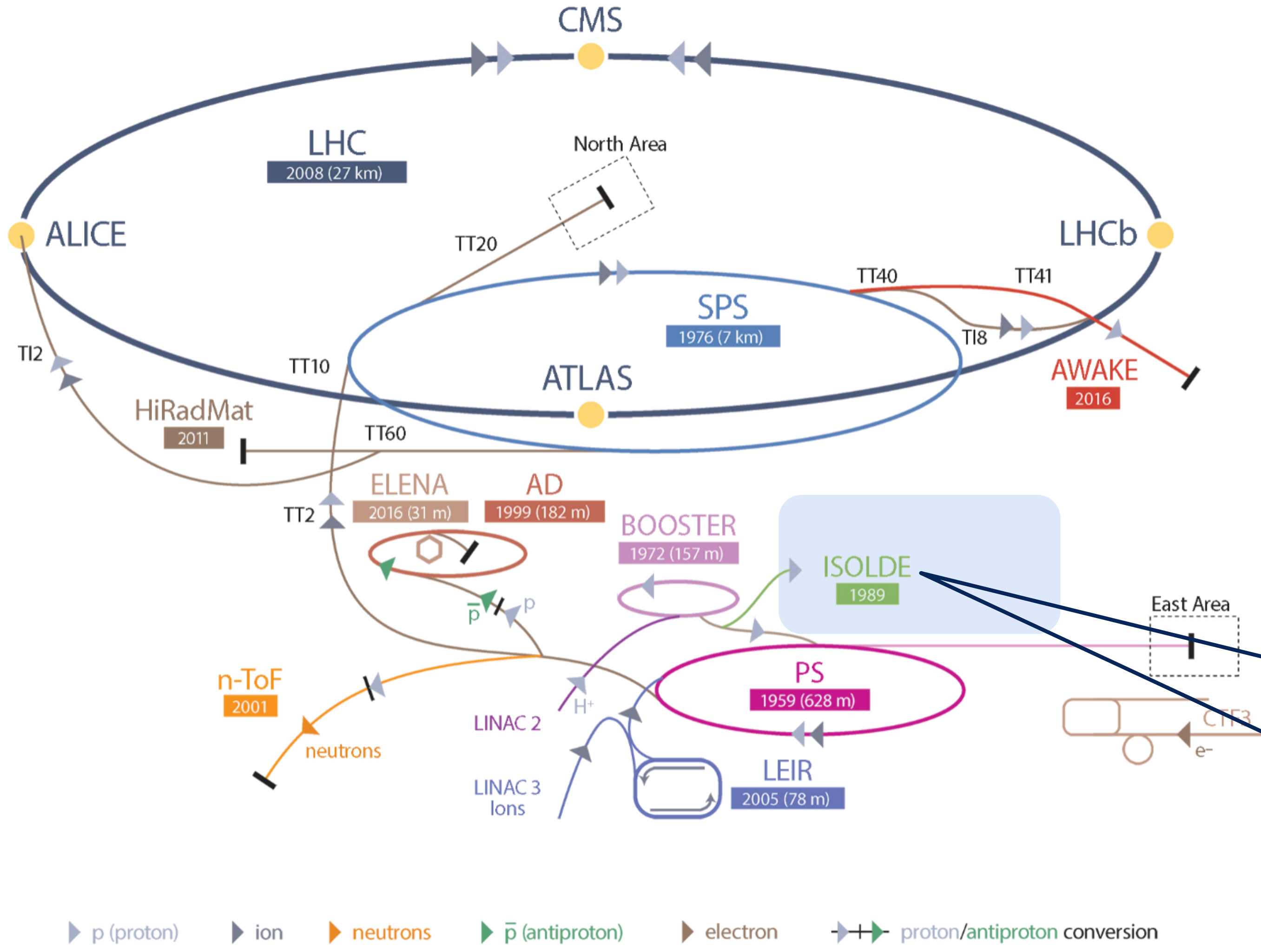
CLEAR

AWAKE

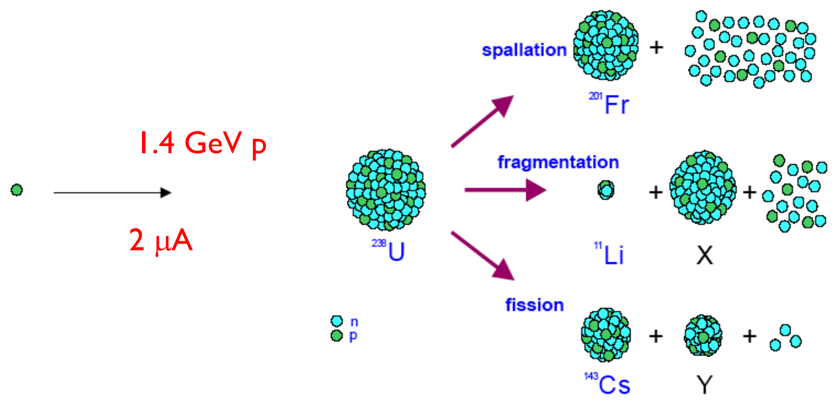
Photoemission Lab

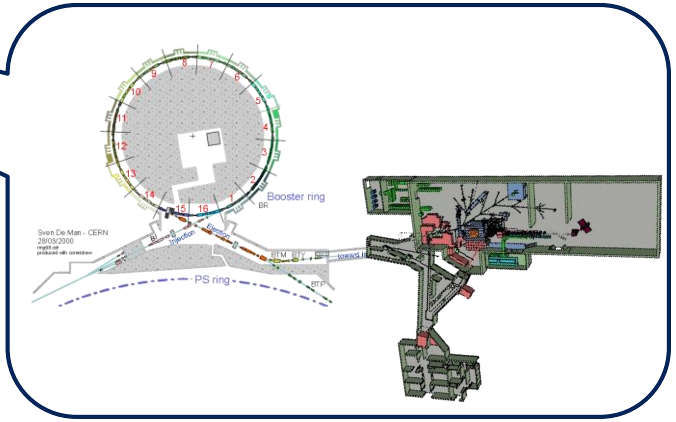
+ Support for laser applications in the AT sector, including safety aspects.
+ Training network (LISA)
+ Knowledge Transfer (@RILIS, @CLEAR)

ISOLDE in the CERN accelerator complex



Delivers yearly >3000 h of radioactive ion beams by means of two target stations





The ISOLDE Laboratory

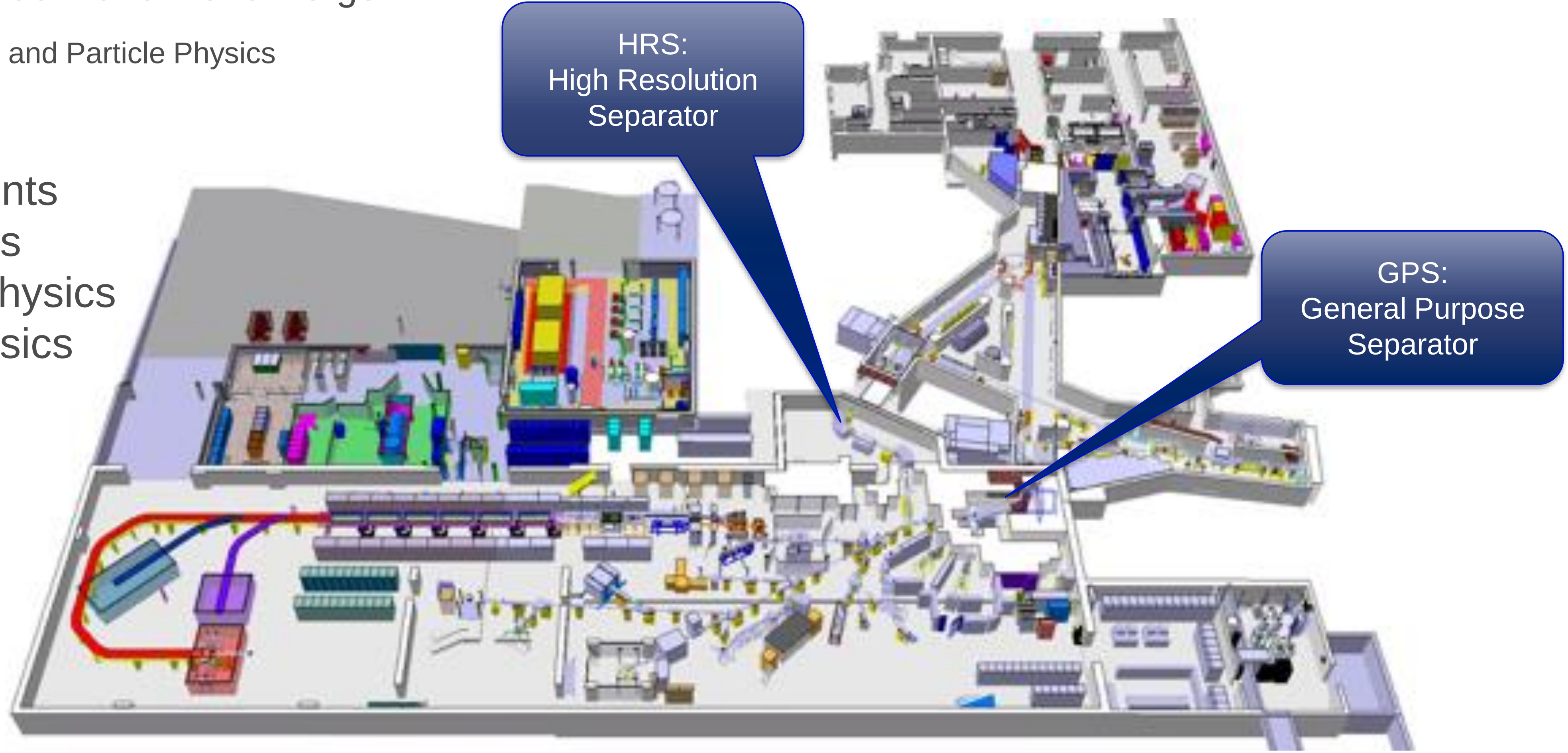
Focus on Exotic Beams at ISOLDE: A Laboratory Portrait

Guest Editors: Klaus Blaum and Maria Borge

Journal of Physics G: Nuclear and Particle Physics
Focus issues 2017-2018

> 80 active experiments

- Nuclear physics
- Nuclear astrophysics
- Solid state physics
- Life science

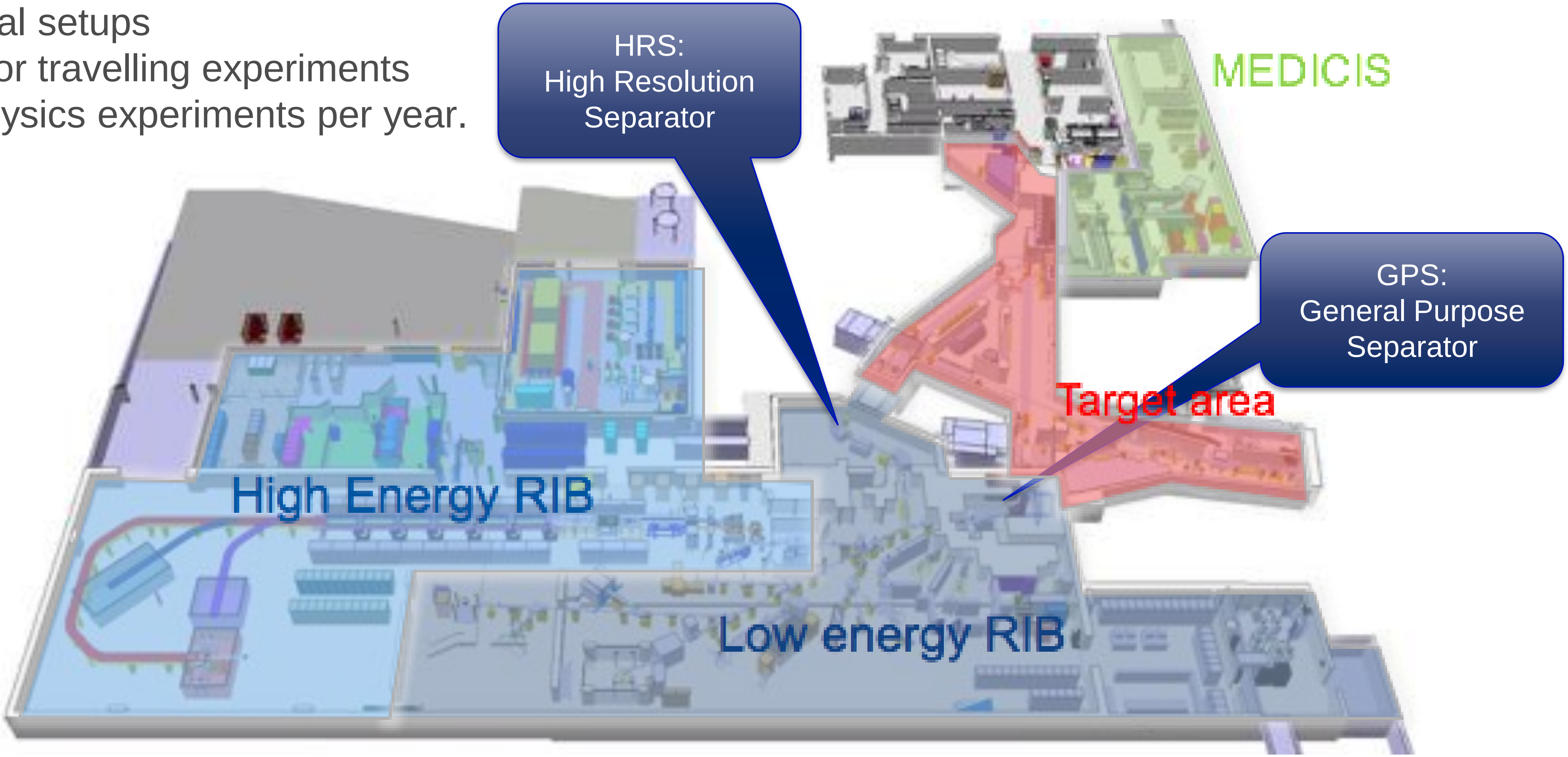


HRS:
High Resolution Separator

GPS:
General Purpose Separator

The ISOLDE Laboratory: target and experiment areas

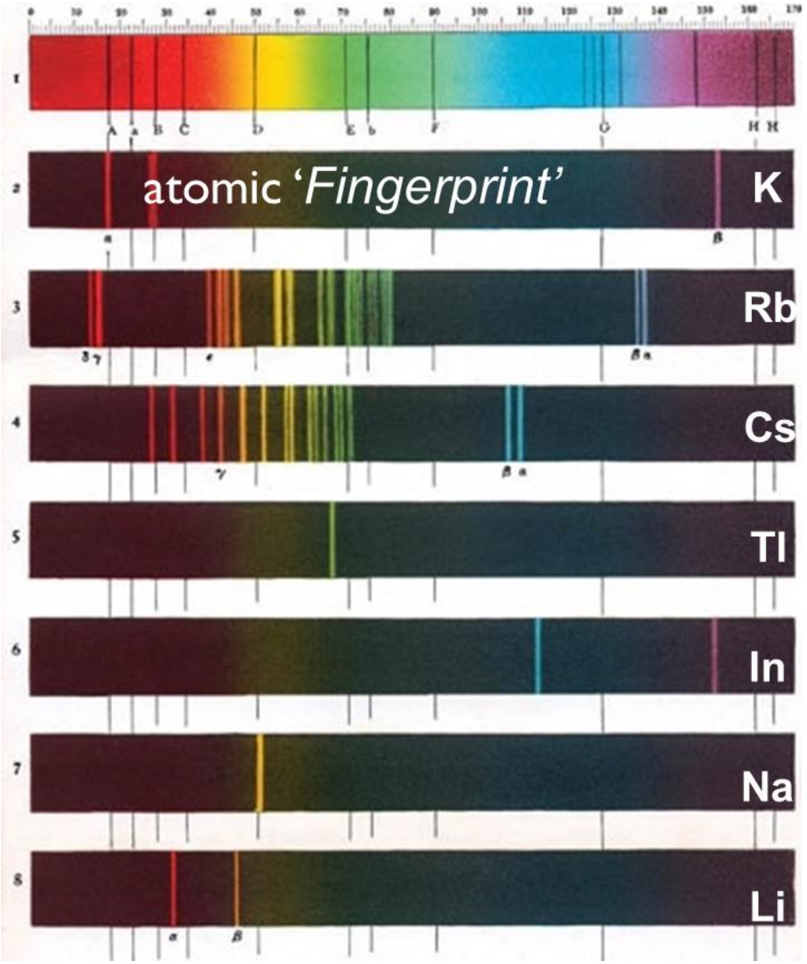
- 12 beam lines
- 10 fixed experimental setups
- Temporary setups for travelling experiments
- Over 50 different physics experiments per year.

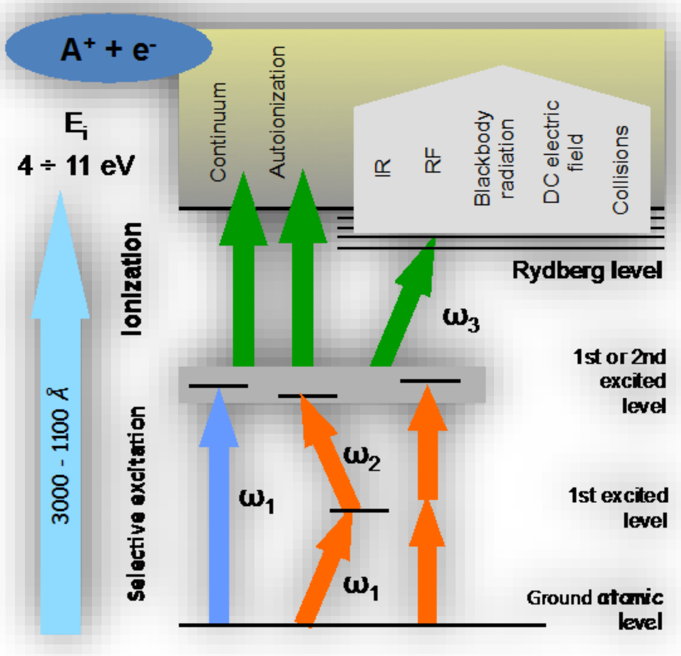


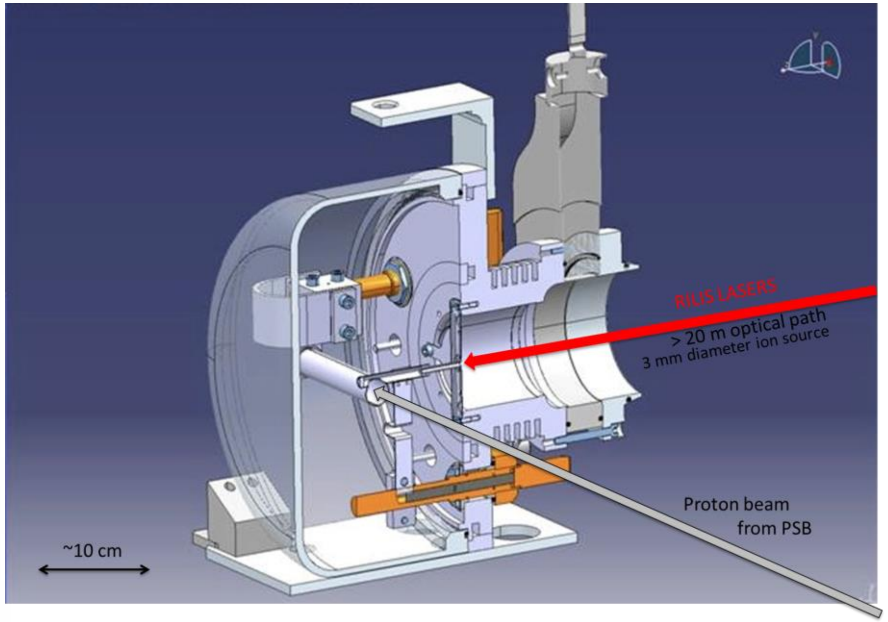
HRS:
High Resolution
Separator

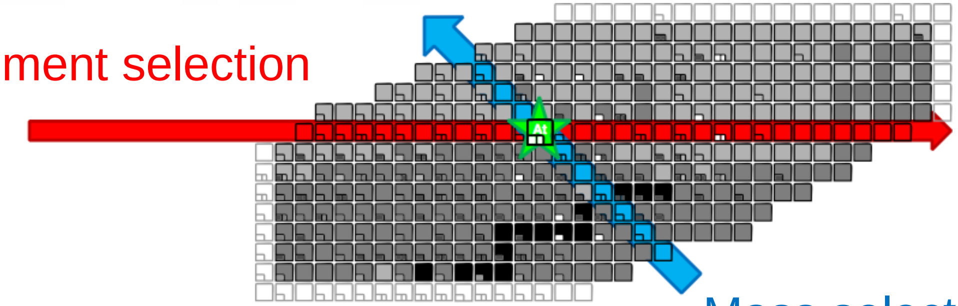
GPS:
General Purpose
Separator

Resonance Ionization Laser Ion Source: RILIS





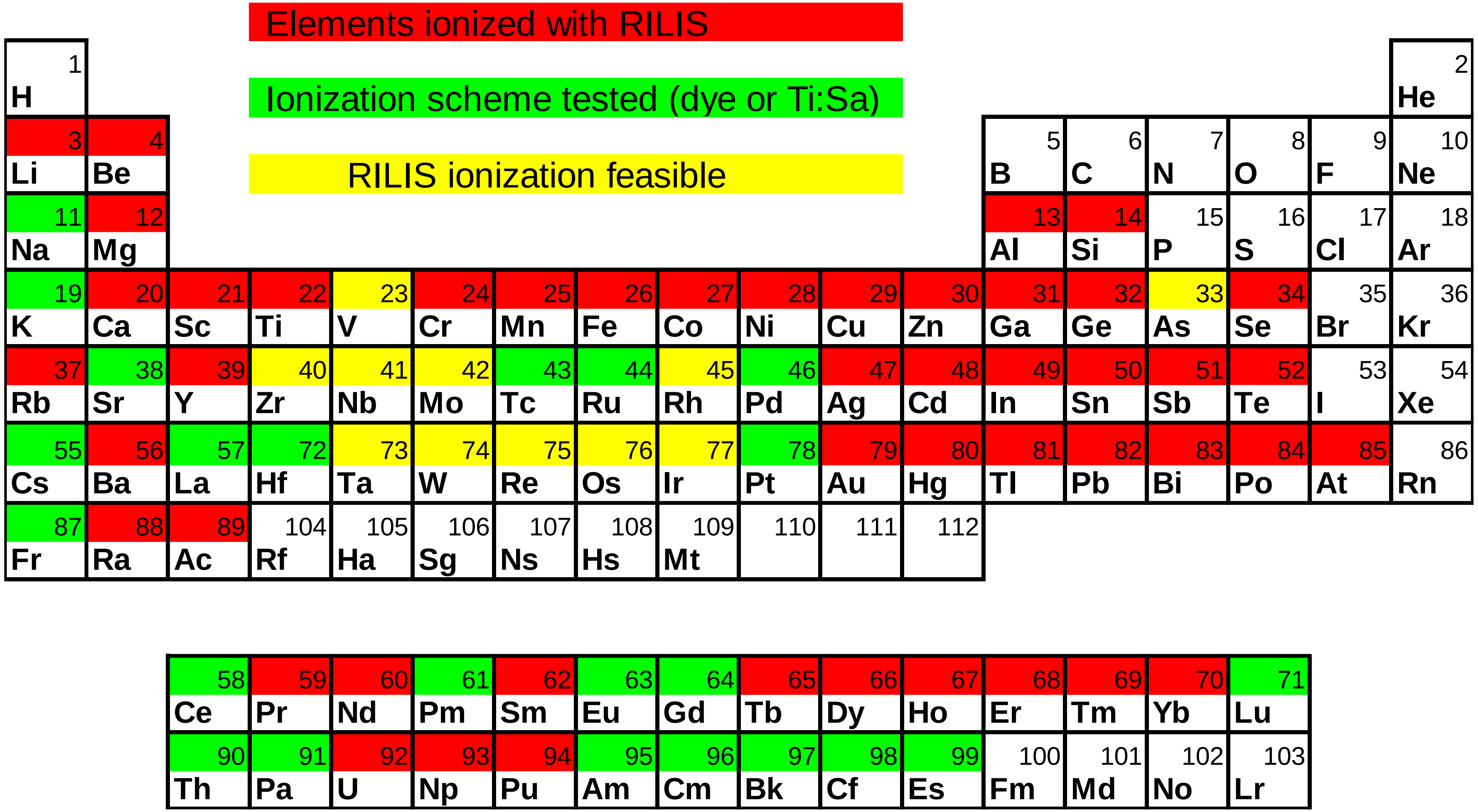




Hot-cavity RILIS:
T ≈ 2100 °C

Ionization efficiency
10-30%

RILIS ion beams



🟥 Elements ionized with RILIS

🟩 Ionization scheme tested (dye or Ti:Sa)

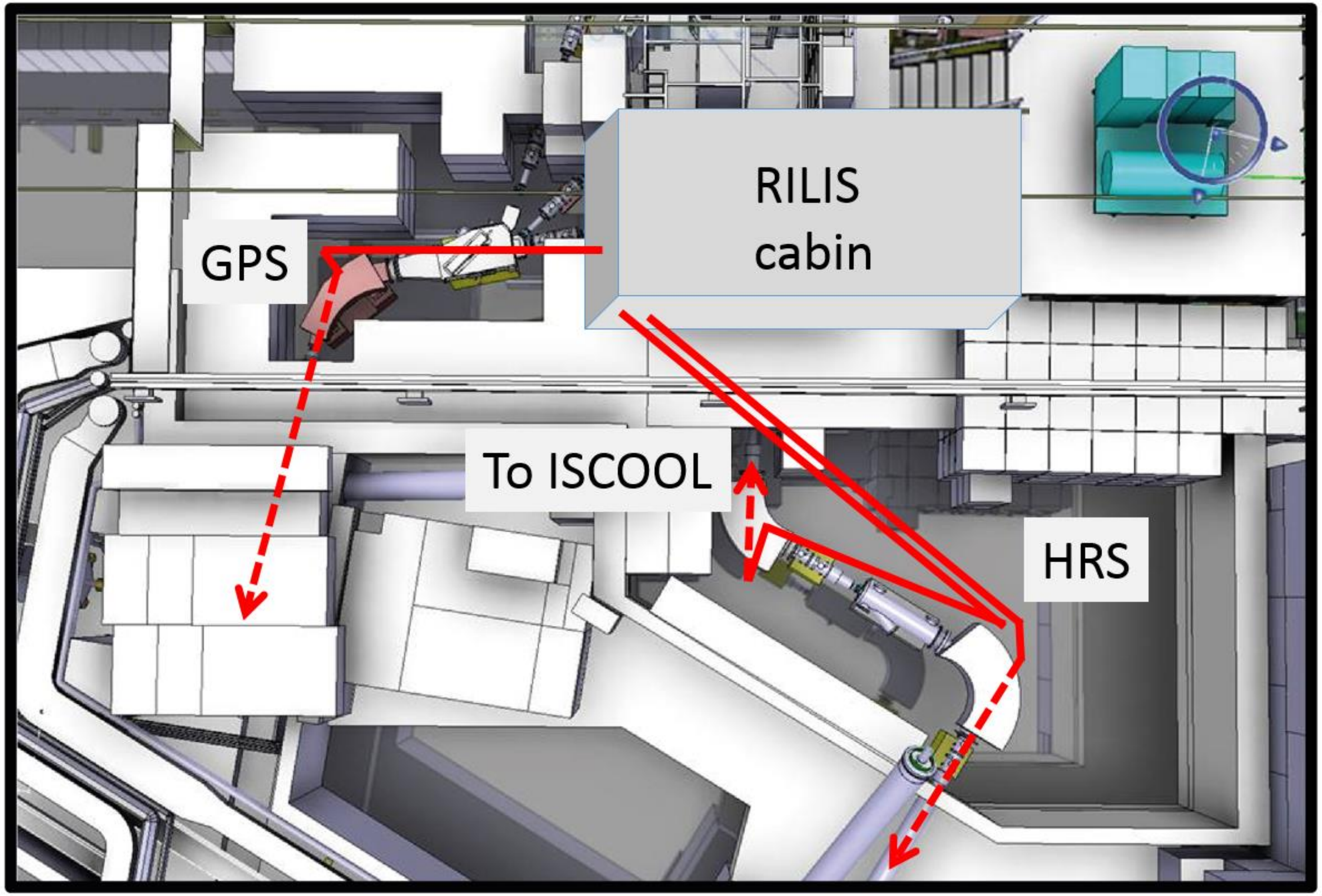
🟨 RILIS ionization feasible

1 H																	2 He
🟥 3 Li	🟥 4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
🟩 11 Na	🟥 12 Mg											🟥 13 Al	🟥 14 Si	15 P	16 S	17 Cl	18 Ar
🟩 19 K	🟥 20 Ca	🟥 21 Sc	🟥 22 Ti	🟨 23 V	🟥 24 Cr	🟥 25 Mn	🟥 26 Fe	🟥 27 Co	🟥 28 Ni	🟥 29 Cu	🟥 30 Zn	🟥 31 Ga	🟥 32 Ge	🟨 33 As	🟥 34 Se	35 Br	36 Kr
🟥 37 Rb	🟩 38 Sr	🟥 39 Y	🟨 40 Zr	🟨 41 Nb	🟨 42 Mo	🟩 43 Tc	🟩 44 Ru	🟨 45 Rh	🟩 46 Pd	🟥 47 Ag	🟥 48 Cd	🟥 49 In	🟥 50 Sn	🟥 51 Sb	🟥 52 Te	53 I	54 Xe
🟩 55 Cs	🟥 56 Ba	🟩 57 La	🟩 72 Hf	🟨 73 Ta	🟨 74 W	🟨 75 Re	🟨 76 Os	🟨 77 Ir	🟩 78 Pt	🟥 79 Au	🟥 80 Hg	🟥 81 Tl	🟥 82 Pb	🟥 83 Bi	🟥 84 Po	🟥 85 At	86 Rn
🟩 87 Fr	🟥 88 Ra	🟥 89 Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110	111	112						

🟩 58 Ce	🟥 59 Pr	🟥 60 Nd	🟩 61 Pm	🟥 62 Sm	🟩 63 Eu	🟩 64 Gd	🟥 65 Tb	🟥 66 Dy	🟥 67 Ho	🟥 68 Er	🟥 69 Tm	🟥 70 Yb	🟩 71 Lu
🟩 90 Th	🟩 91 Pa	🟥 92 U	🟥 93 Np	🟥 94 Pu	🟩 95 Am	🟩 96 Cm	🟩 97 Bk	🟩 98 Cf	🟩 99 Es	100 Fm	101 Md	102 No	103 Lr

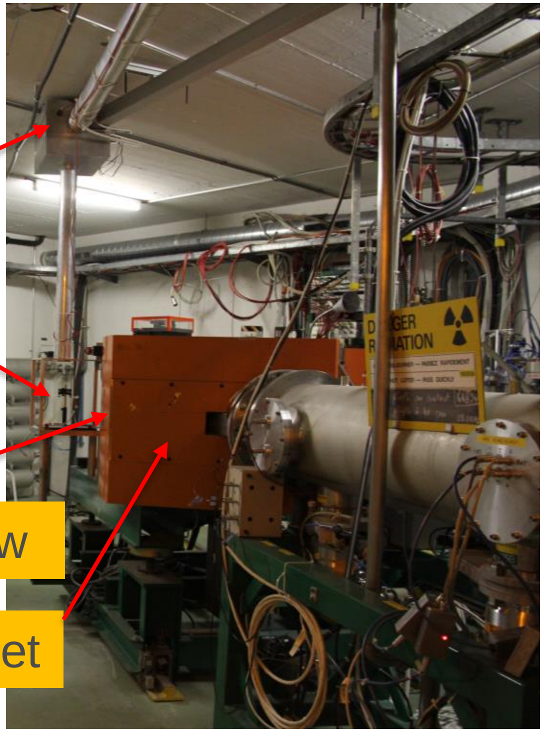
Ion beams of 48 elements have been produced at ISOLDE with RILIS

RILIS at ISOLDE facility



Laser beams transported to:

- GPS Frontend, ~18 m
- HRS Frontend, ~23 m
- Gas-filled Paul trap ISCOOL ~20 m

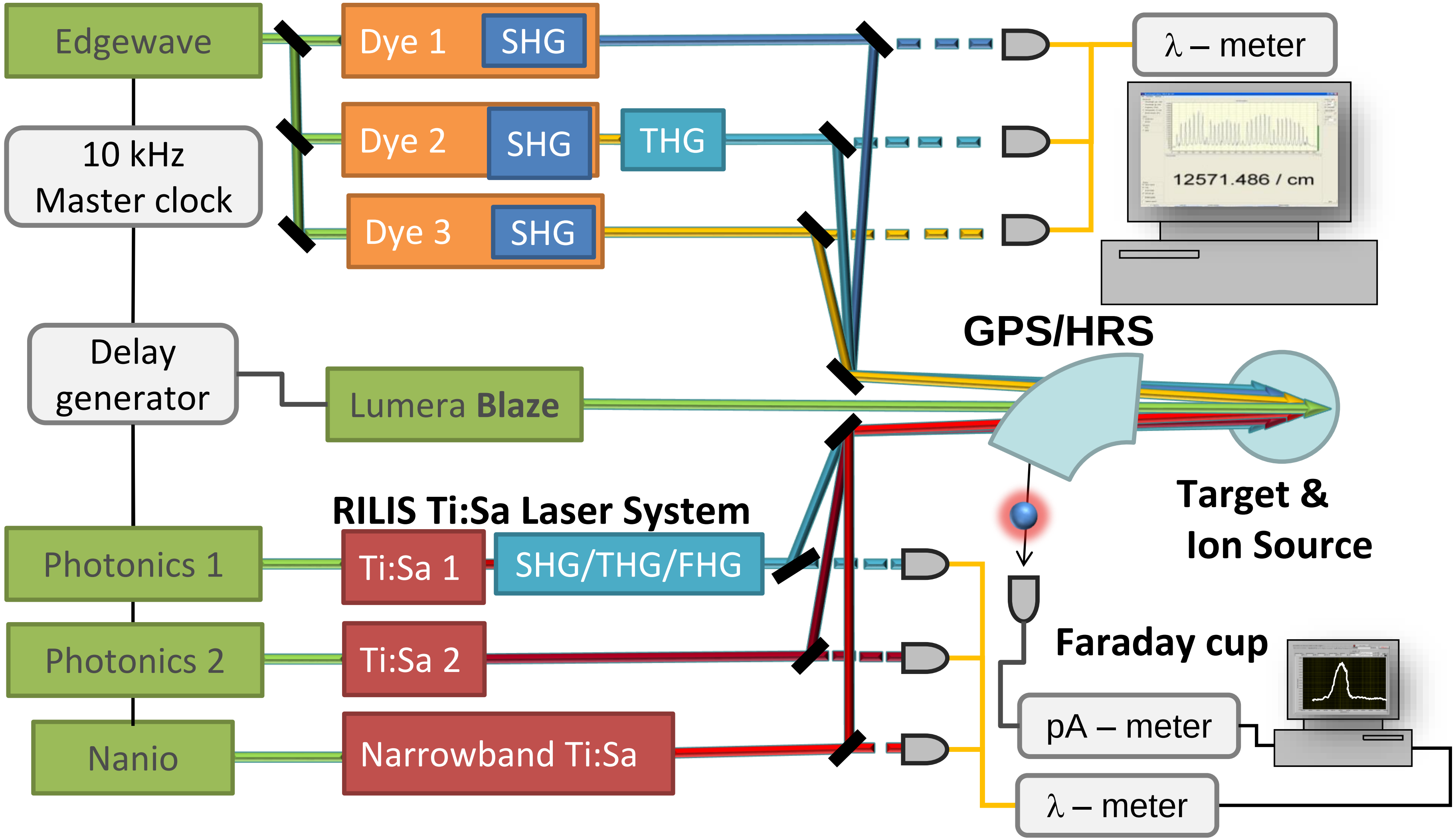


90º prisms

Vacuum window

HRS 90º magnet

RILIS Laser Setup (simplified scheme)



RILIS laser setup

Industrial grade
10 kHz Nd:YAG/YVO lasers

Photonics

60 W

InnoLas

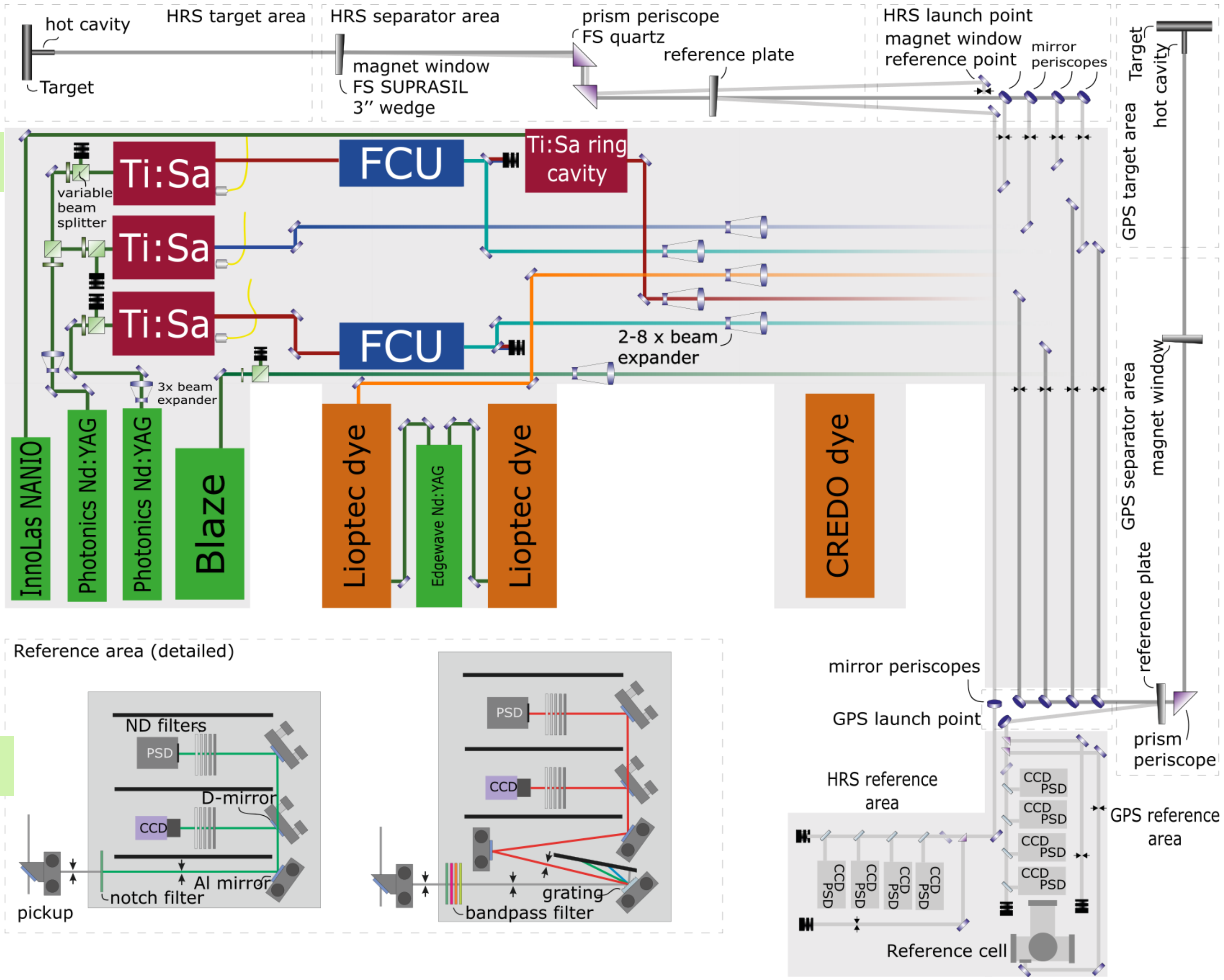
18 W

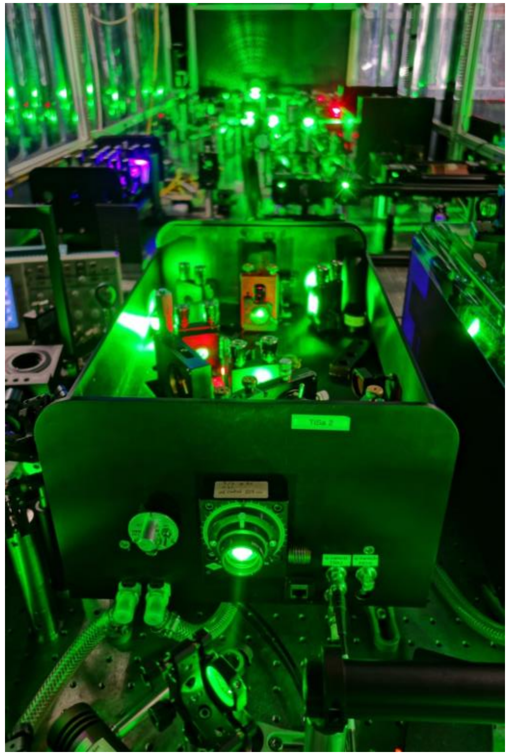
Lumera

40 W

EdgeWave

100 W

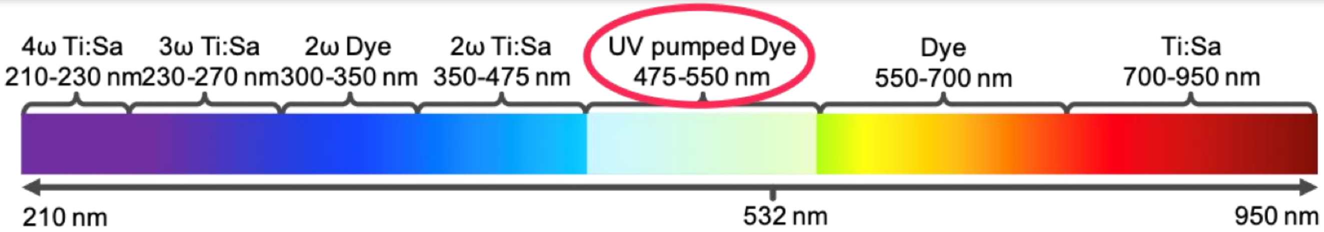


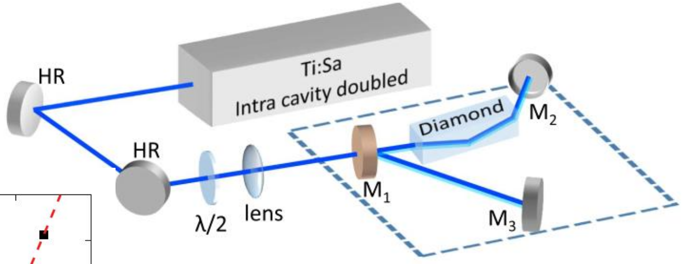


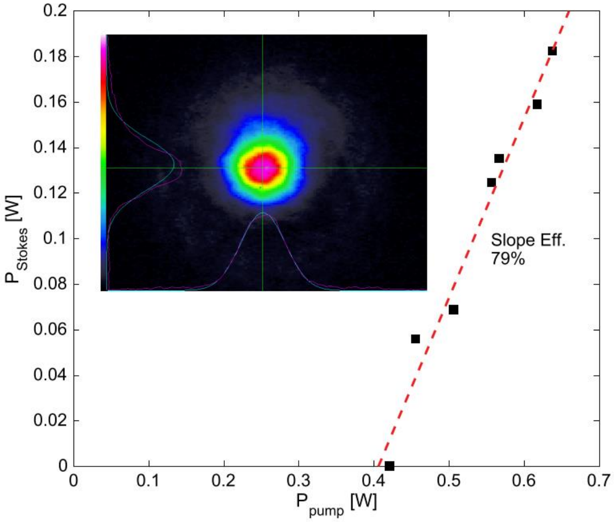
**Tuning range
210 – 950 nm**

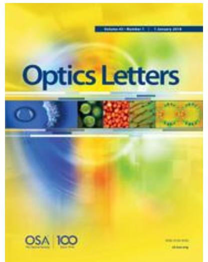
Diamond Raman lasers for RILIS

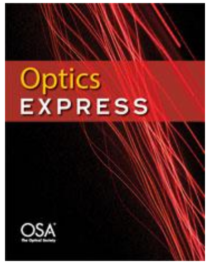
Broadband:
To extend the Ti:Sa tuning range towards the UV pumped dye range

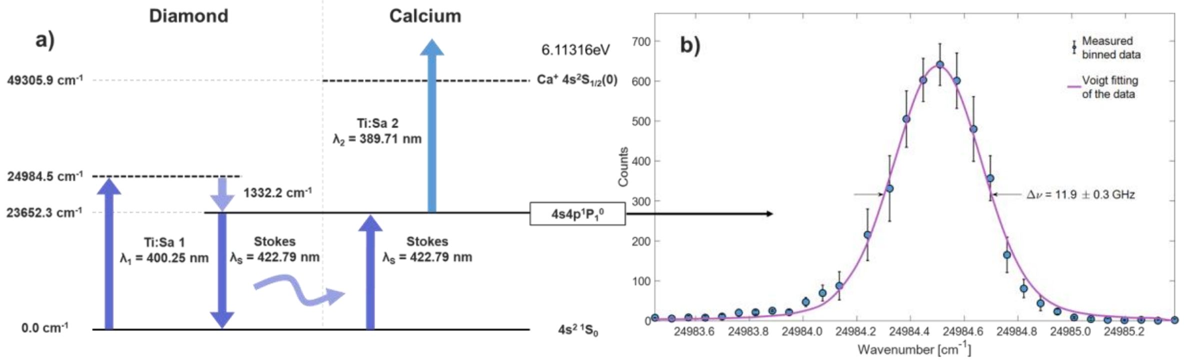


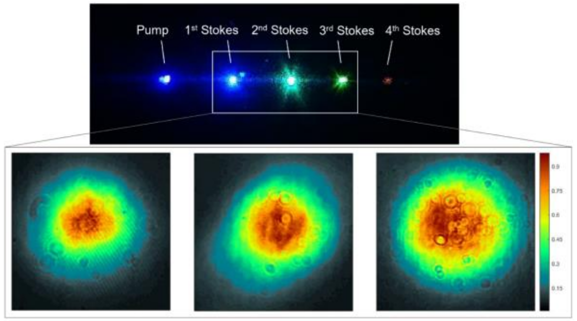












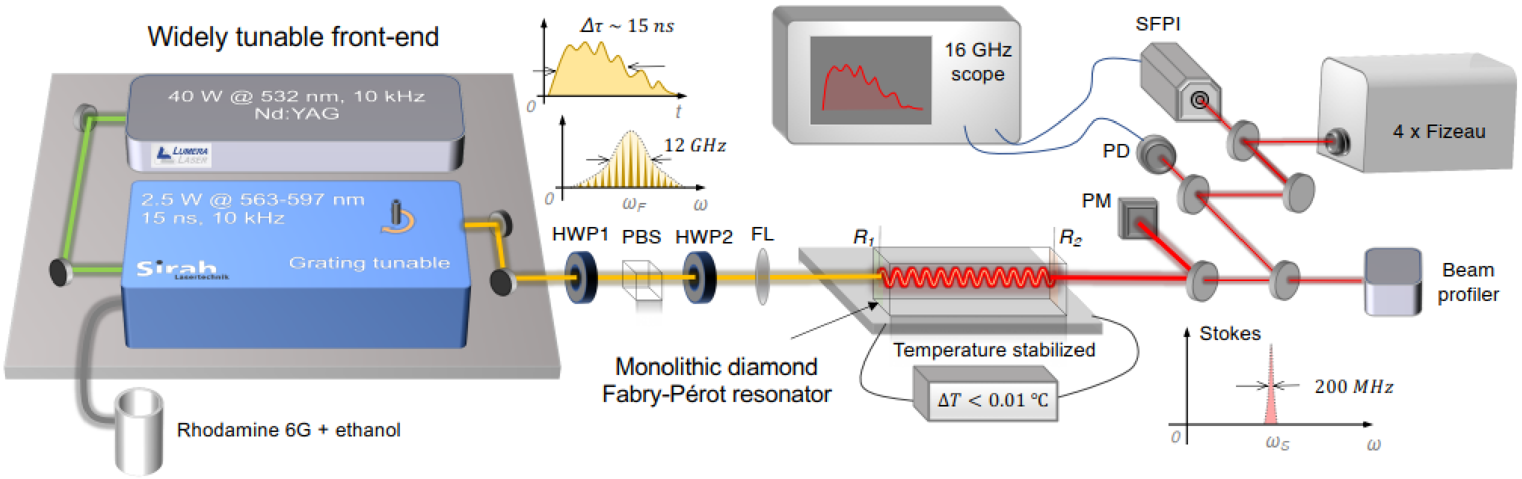
K. Chrysalidis et al, Opt. Lett. 44(16), 3924–3927 (2019)

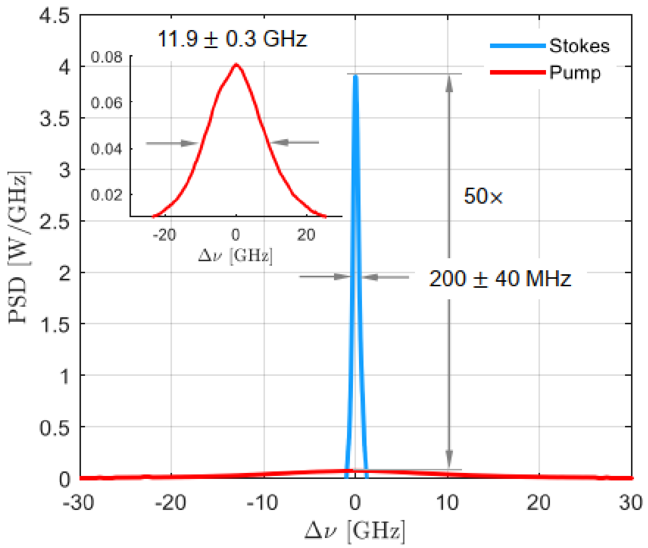
D. Talan Echarri et al., Optics Express 28(6), 8589 (2020)

Diamond Raman lasers for RILIS

Narrowband:
To enable laser spectroscopy with a laser line width ~ 10x narrower than is currently possible with RILIS lasers

KT project “Singular light”





Stokes spectral squeezing via phonon resonant interaction in diamond

E. Granados et al., Request for grant of European patent submitted 18.12.2020
E. Granados et al., a paper submitted to Optica

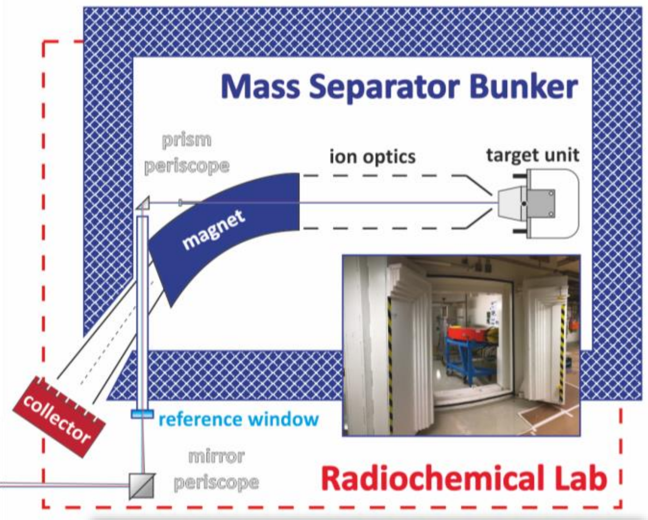
MEDICIS Laser Ion Source Setup At CERN (MELISSA)

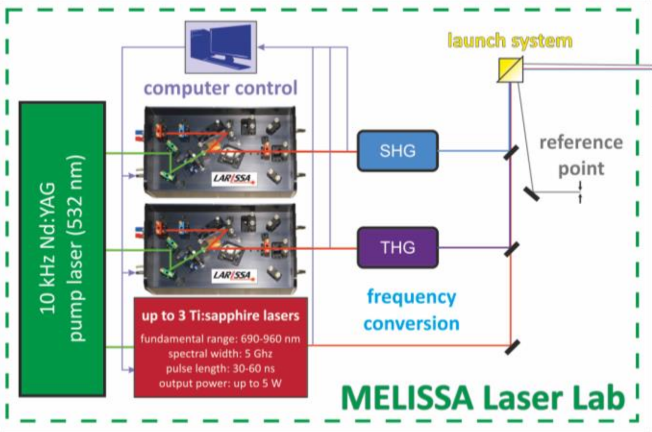
MEDical Isotopes Collected from ISOLDE – facility for production of medical isotopes for research in radiopharmaceutical science

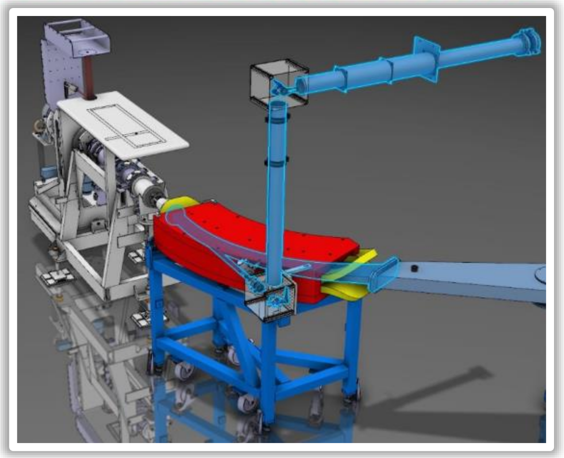
Long-lived radio-isotopes

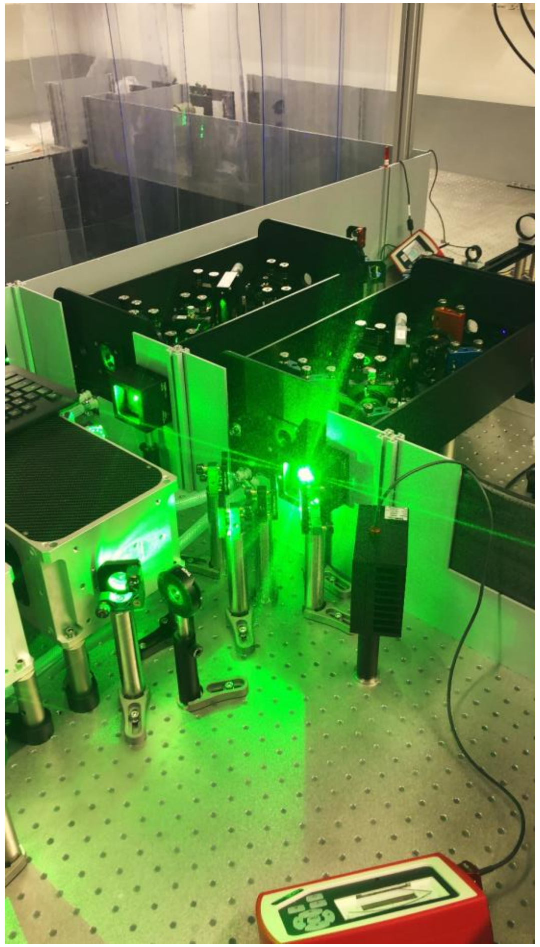
- Produced in a cold target (at ISOLDE or elsewhere)
- Transported to the MEDICIS front-end
- Extracted by heating the target material
- Ionized and mass-separated
- Collected on a substrate
- Shipped to medical research laboratories

Sm-153
Tb-155, Tb-149
Er-169
Tm-167
Yb-175
Ac-225





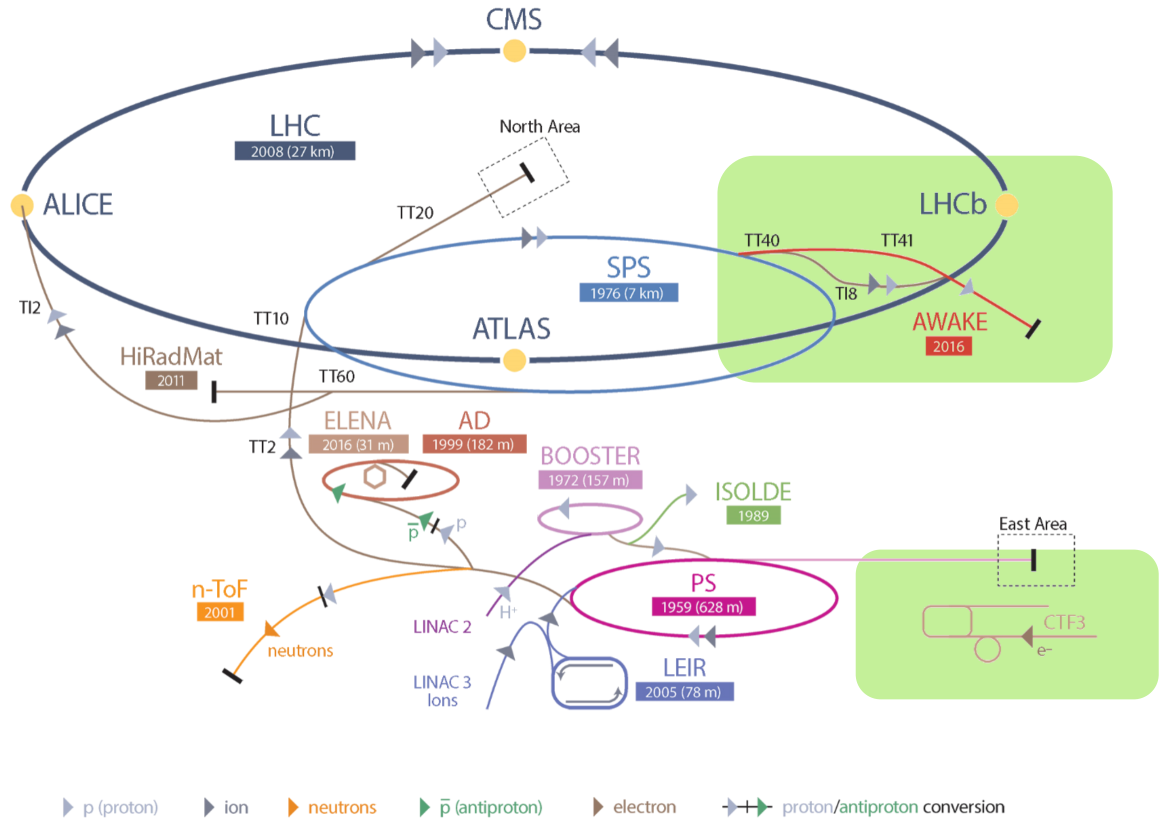




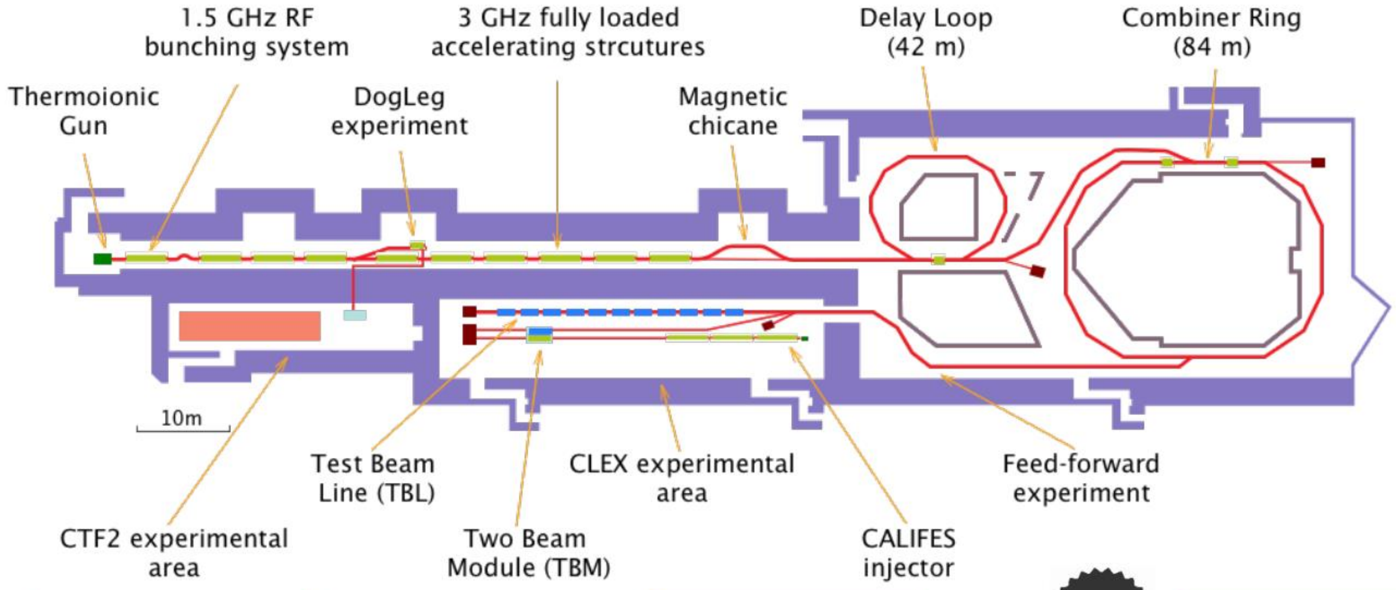
Setup similar to RILIS, based on Ti:Sapphire lasers

Lepton beams at CERN

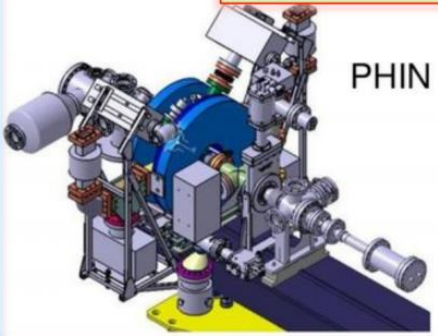
- Next generation of colliders (“Higgs factories”) will likely use leptons instead of hadrons exclusively:
  - CLIC (multi-TeV electron-positron collisions)
  - FCC-ee/eh
- Accelerator R&D :
  - AWAKE: Proton-driven plasma wakefield acceleration experiment
  - CLEAR: CERN Linear Electron Accelerator for Research



CLIC Test Facility (CTF3)



DRIVE beam



PHIN

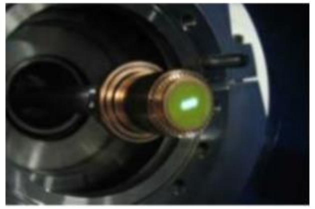
Cs_2Te / Cs_3Sb
Co-deposition

Now at:

AWAKE

MAIN beam

Cs_2Te @ CALIFES
In-situ, dual layer

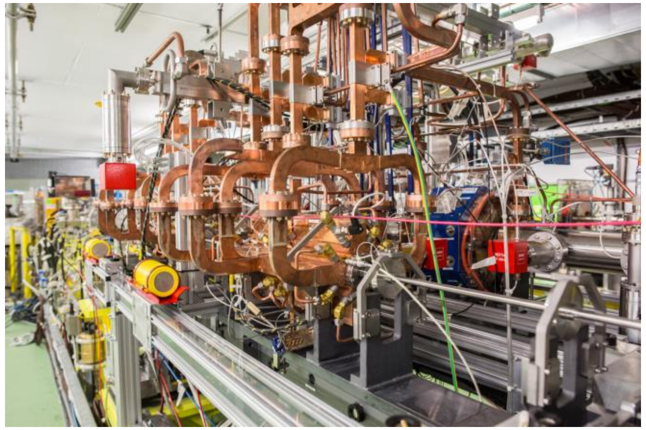


NEW

clear

Test facility for:

- X-band technology
- Bunch compression
- Advanced beam dynamics
- Plasma lens, AWAKE…
- Wakefield physics
- Radiation studies



PHIN laser

- CLIC needs 140 us long train
  - Previous tests showed decay over the train.
  - Beam profile degrades in step with UV power level.
  - Stability requirement (0.25% rms) was not met.
  - Damage occurs in crystals when using full length train
- Aim of this study:
  - Identify damage levels, feasibility for CLIC
  - Test response to long trains with 1/3 of the repetition rate (500 MHz instead of 1.5 GHz)
  - Testbench for different crystals.
  - Operation in parallel to CALIFES laser.

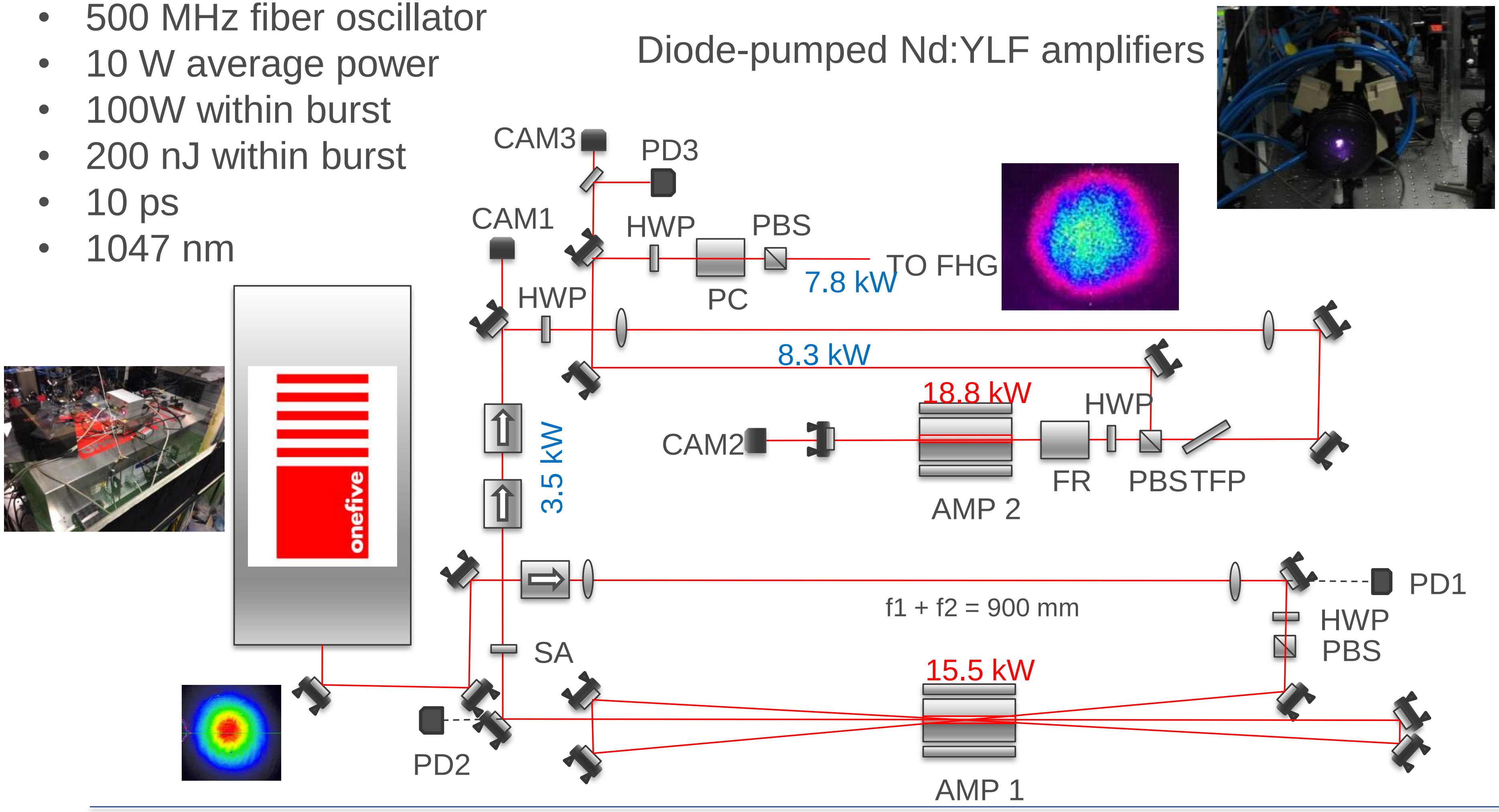
		DRIVE beam		MAIN beam
		PHIN	CLIC	CALIFES
Electrons	charge/bunch (nC)	2.3	8.4	0.6
	gate (ns)	1200	140371	19.2
	bunch spacing(ns)	0.666	1.992	0.666
	bunch length (ps)	10	10	10
	Rf reprate (GHz)	1.5	0.5	1.5
	number of bunches	1802	70467	32
	machine reprate (Hz)	5	100	5
	margine for the laser	1.5	2.9	1.5
	charge stability	<0.25%	<0.1%	<3%
	QE(%)	3	2	0.3
Laser in UV	laser wavelegth (nm)	262	262	262
	energy/micropulse on cathode (nJ)	363	1988	947
	energy/micropulse laserroom (nJ)	544	5765	1420
	energy/macrop. laserroom (uJ)	9.8E+02	4.1E+05	4.1E+01
	mean power (kW)	0.8	2.9	2.1
	average power at cathode wavelength(W)	0.005	41	2.E-04
	micro/macropulse stability	1.30%	<0.1%	<3%
Laser in IR	conversion efficiency	0.1	0.1	0.15
	energy/macropulse in IR (mJ)	9.8	4062.2	0.3
	energy/micropulse in IR (uJ)	5.4	57.6	9.5
	mean power in IR (kW)	8.2	28.9	14.2
	average power on second harmonic (W)	0.49	406	1.E-03
	average power in final amplifier (W)	9	608	15

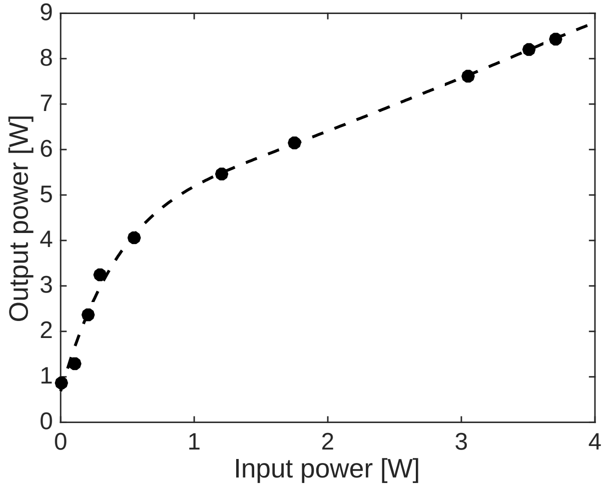
PHIN laser in 2021

Genki -10 XP burst

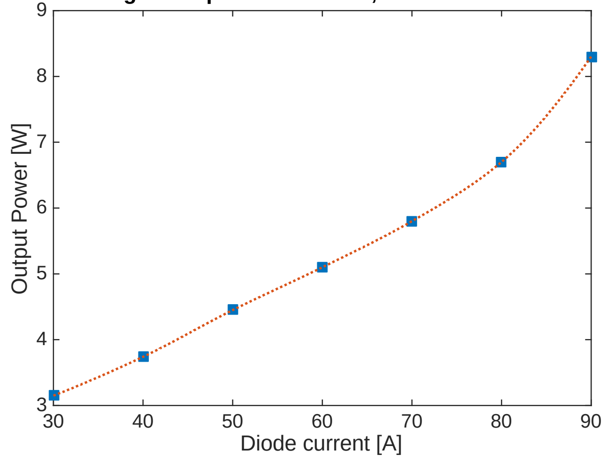
- 500 MHz fiber oscillator
- 10 W average power
- 100W within burst
- 200 nJ within burst
- 10 ps
- 1047 nm

Diode-pumped Nd:YLF amplifiers





Seeding at full power in PHIN 1, PHIN 2 current scan



CERN Linear Accelerator for Research: clear

- Multipurpose e- accelerator operating since 2017 and until 2025.
- *“The primary focus for CLEAR is general accelerator R&D and component studies for existing and possible future accelerator applications.”*
  - High gradient accelerators
  - Plasma technology
  - Accelerator components for HL-LHC and AWAKE
  - Characterization of electronic components
  - Medical applications
  - THz beam generation
  - Others…

CHUV Centre hospitalier universitaire vaudois

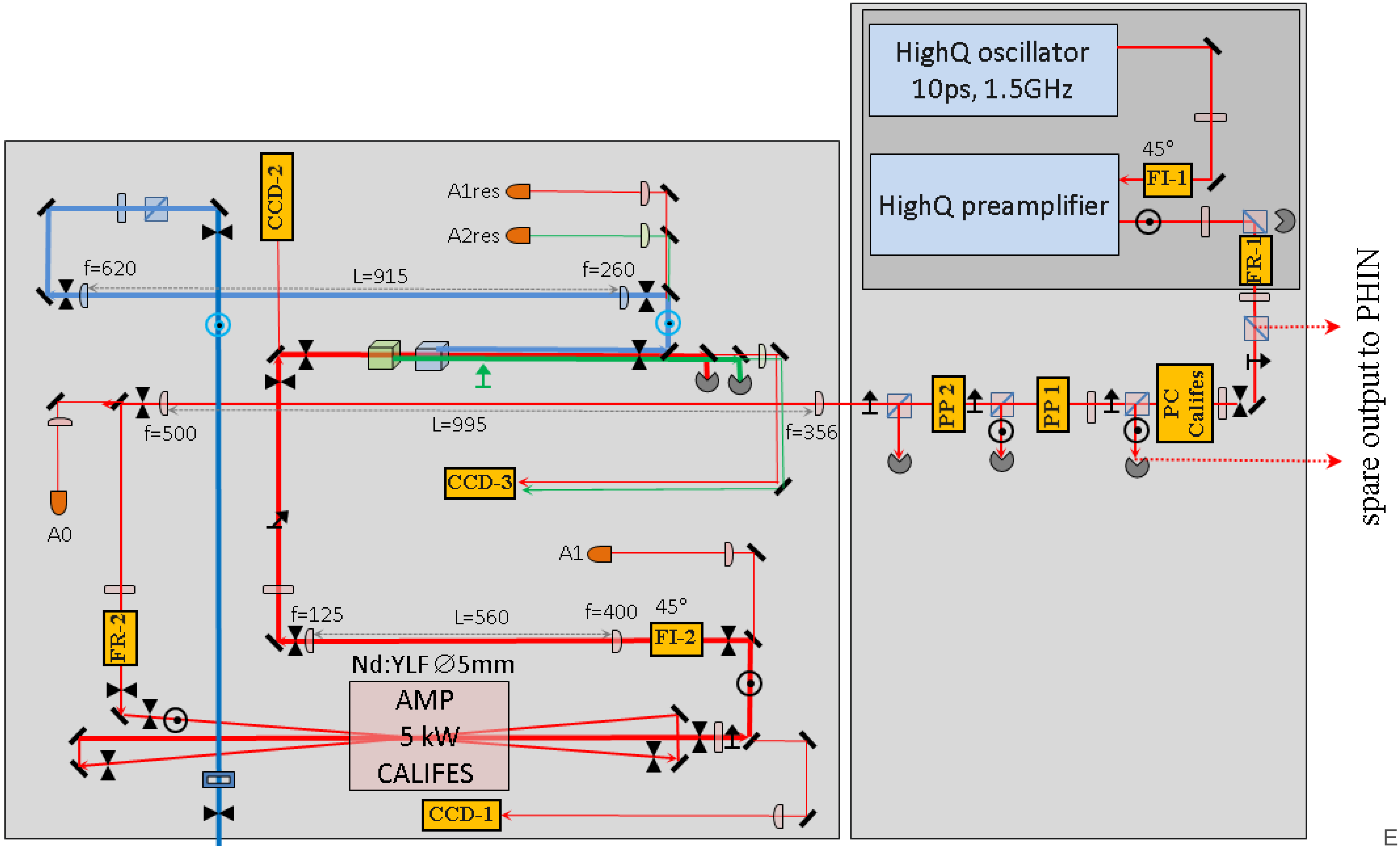
vesper clear

esa European Space Agency

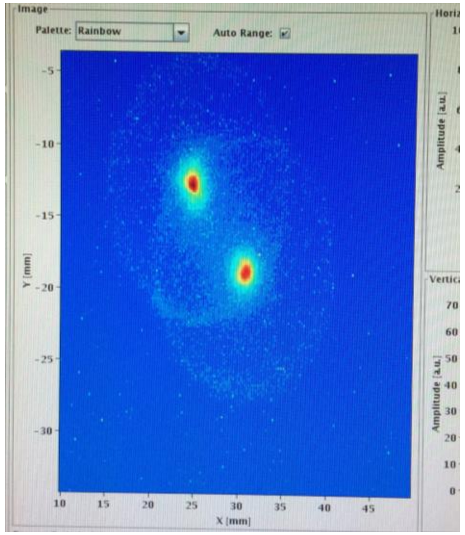
LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

CERN IRRAD Proton Facility

CLEAR laser (original version)

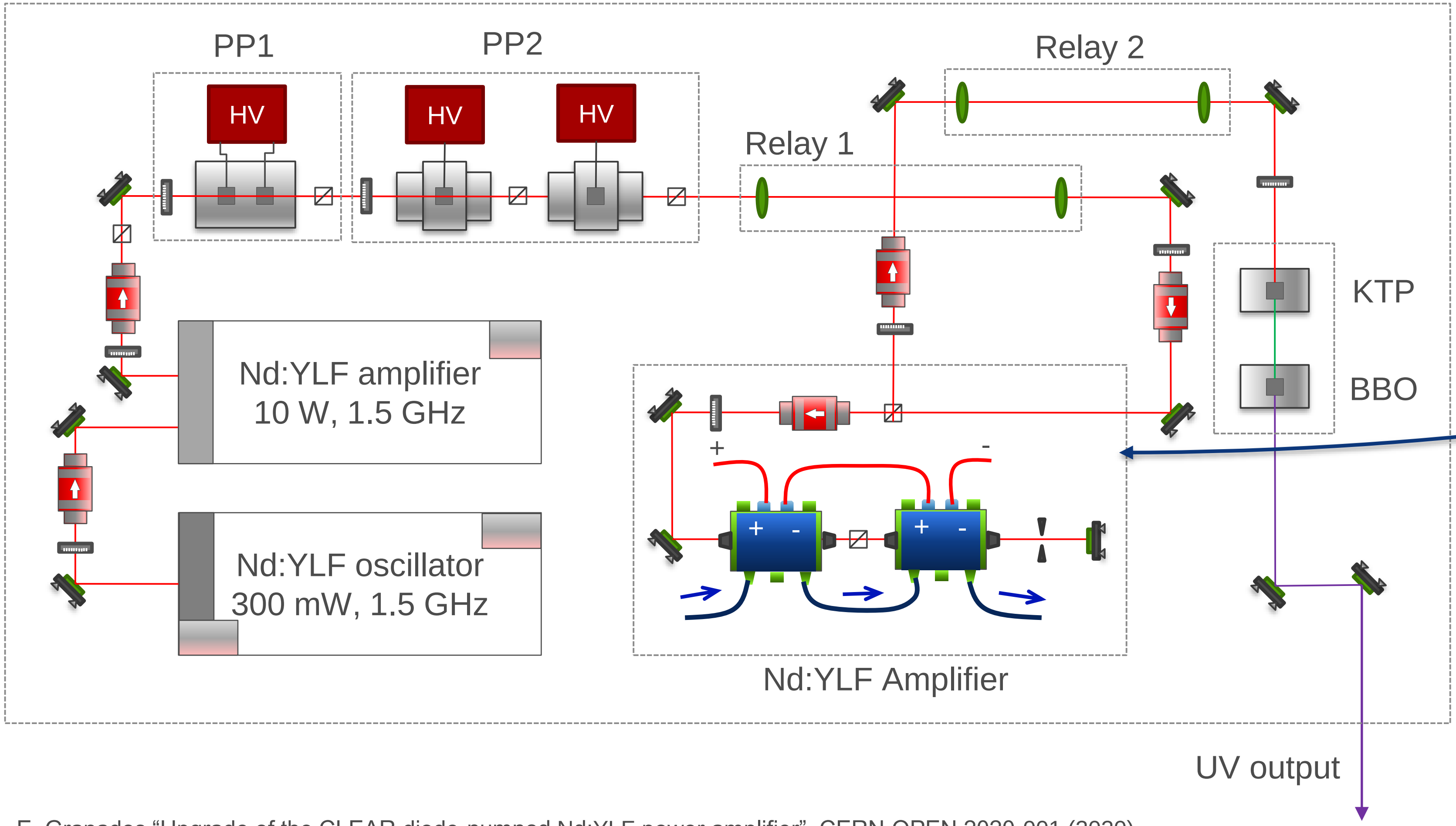


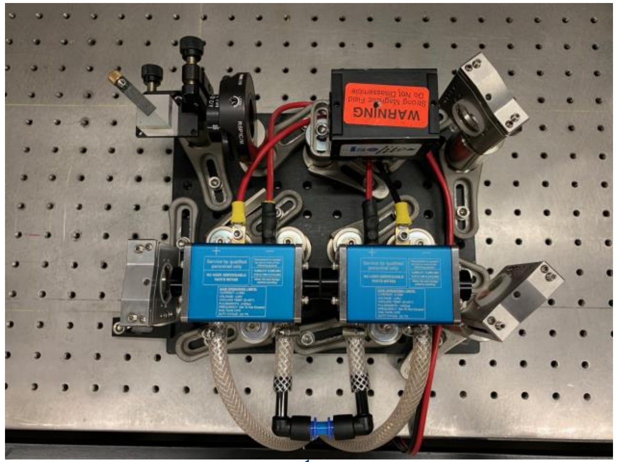
max UV output to CALIFES:
12 uJ/pulse



E. Granados, E. Chevallay, V. Fedosseev, H. Panuganti “Capabilities and performance of the CLEAR facility photo-injector laser”, CERN OPEN 2020-002 (2019)

CLEAR laser upgrade 2020-2021

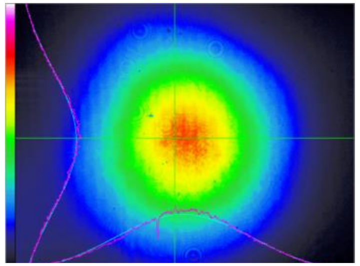




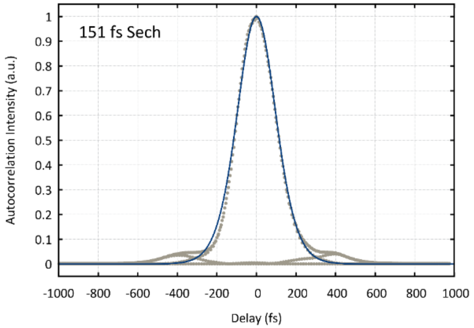
E. Granados "Upgrade of the CLEAR diode-pumped Nd:YLF power amplifier", CERN OPEN 2020-001 (2020)

New photo-injector at CLEAR/CTF2

Ultrafast PHAROS laser from Light Conversion (Yb-doped fiber technology)
Installed in CLEAR laser lab and tested

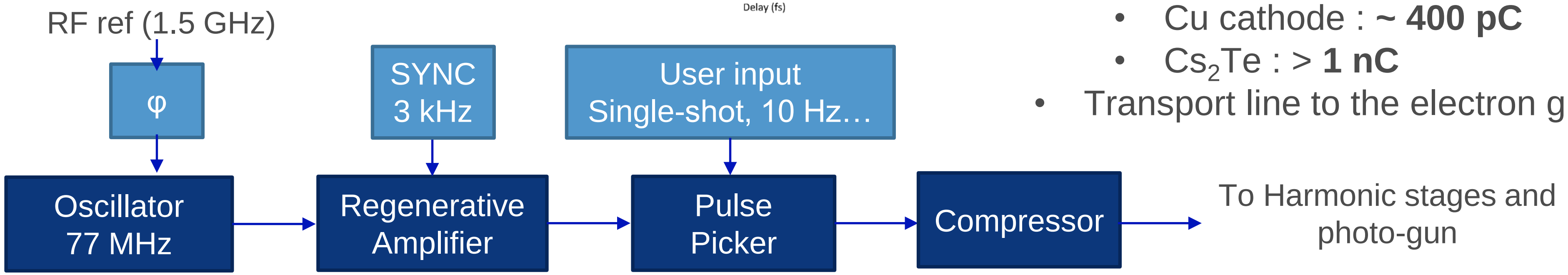


163300, pulse width 151 fs (Sech)



Wavelength	Pulse energy	RMS	Pk-Pk
1030 nm	2.21 mJ	0.043%	0.099%
515 nm	1.23 mJ	0.053%	0.38%
257 nm	**415 uJ**	**0.11%**	**0.77%**

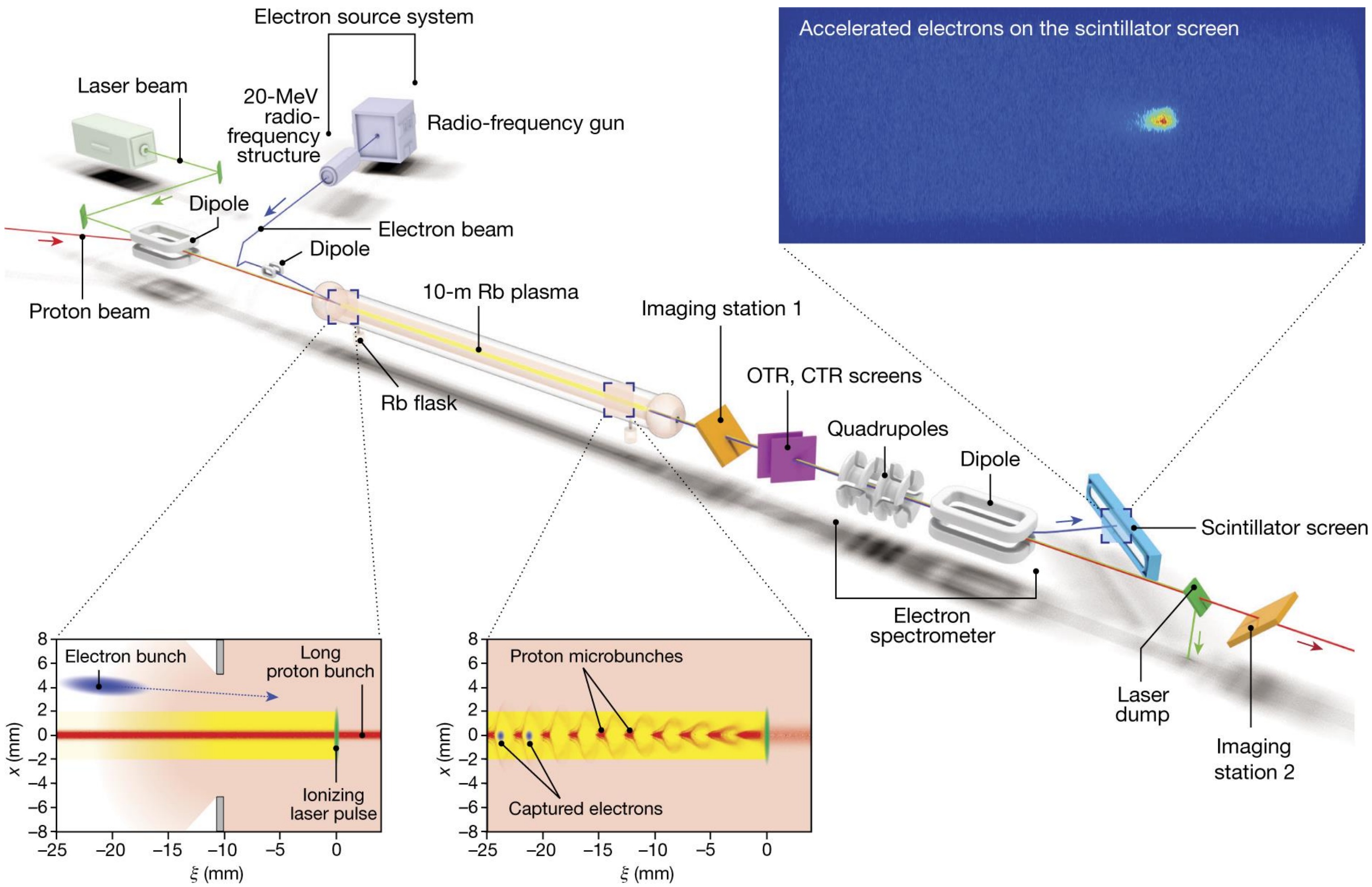
- Designed to operate with both Cu or Cs2Te cathodes
- Variable pulse duration from < 300 fs up to > 5 ps
  - Requires multiple harmonic stages or UV stretcher.
- Synchronizable to RF (1.5 GHz) reference
- Expected maximum charge production:
  - Cu cathode : ~ **400 pC**
  - Cs_2Te : > **1 nC**
- Transport line to the electron gun under construction



RF ref (1.5 GHz)
φ
SYNC
3 kHz
User input
Single-shot, 10 Hz…
Oscillator
77 MHz
Regenerative
Amplifier
Pulse
Picker
Compressor
To Harmonic stages and
photo-gun

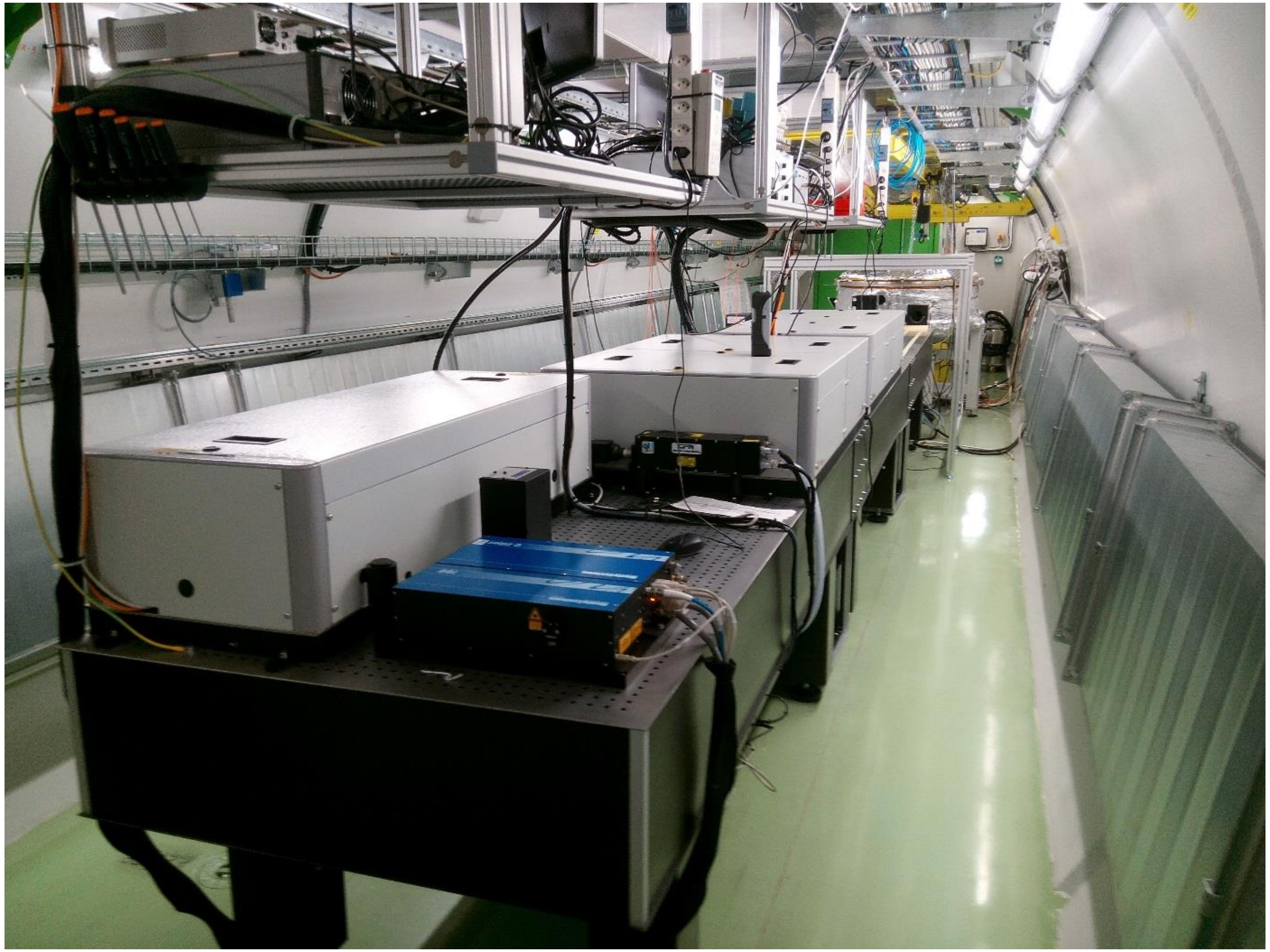
AWAKE experiment

- Proof-of-principle experiment: wakefield plasma acceleration using a proton bunch as a driver, a world-wide first.
- It demonstrated acceleration of a low-energy witness bunch of electrons from 15-20 MeV to several GeV over a short distance (~10 m) by creating a high acceleration gradient of several GV/m
- Our contribution:
  - IR beam delivery, diagnostics.
  - UV beam generation, delivery, and photocathode, diagnostics.
  - Experimental and laser support



Nature volume 561, pages 363–367(2018)

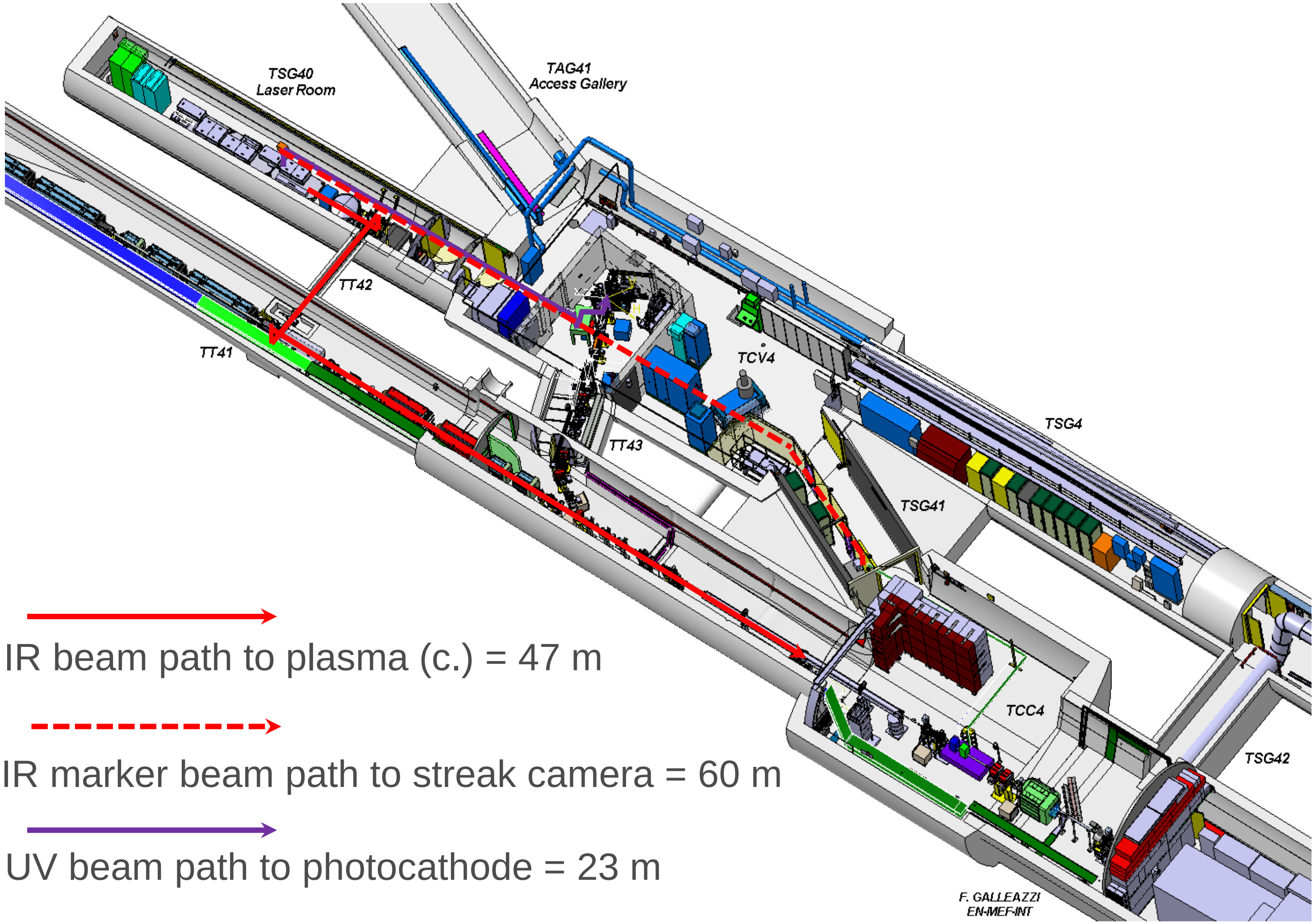
AWAKE laser



Amplitude Technology CENTAURUS 100 fs

Performance	Measured Value
Repetition Rate	10 Hz
Central Wavelength	780-785 nm
Spectral Bandwidth	24 nm
Pulse duration	120 fs
Output Energy (uncompressed)	663 mJ
Output Energy (after compression)	500 mJ
Secondary output (uncompressed)	3 mJ
Energy stability	1.02%
Beam pointing stability	4.2 µrad
Temporal intensity contrast	$2 \cdot 10^{-7}$
Polarization (linear)	250:1

AWAKE laser beams



IR beam path to plasma (c.) = 47 m

IR marker beam path to streak camera = 60 m

UV beam path to photocathode = 23 m

Laser beam to plasma cell

- λ = 780 nm
- t pulse = 120 fs
- E = 450 mJ

Laser beam to streak camera (“time marker”)

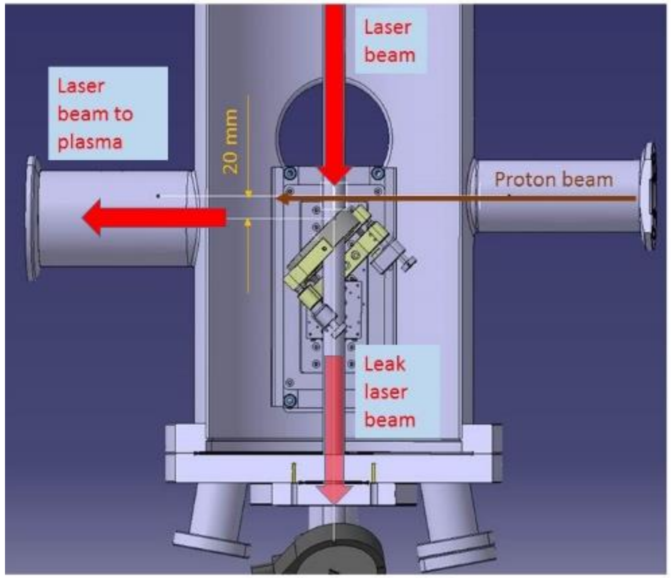
- λ = 780 nm
- t pulse = 120 fs,
- E ≈ 0.01 mJ

Laser beam to electron gun

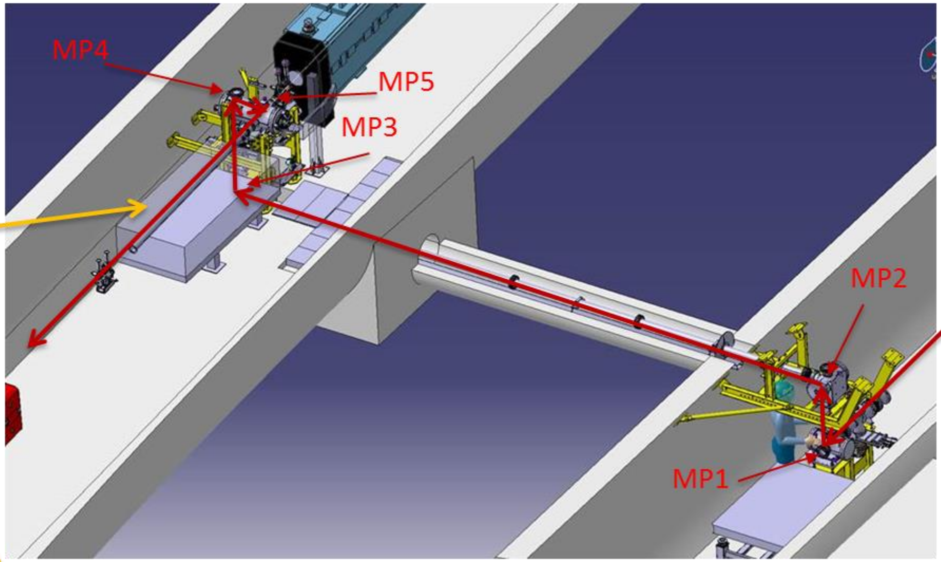
- λ = 260 nm
- t pulse = 0.3-10 ps
- E = 100-300 nJ

IR laser beam to plasma

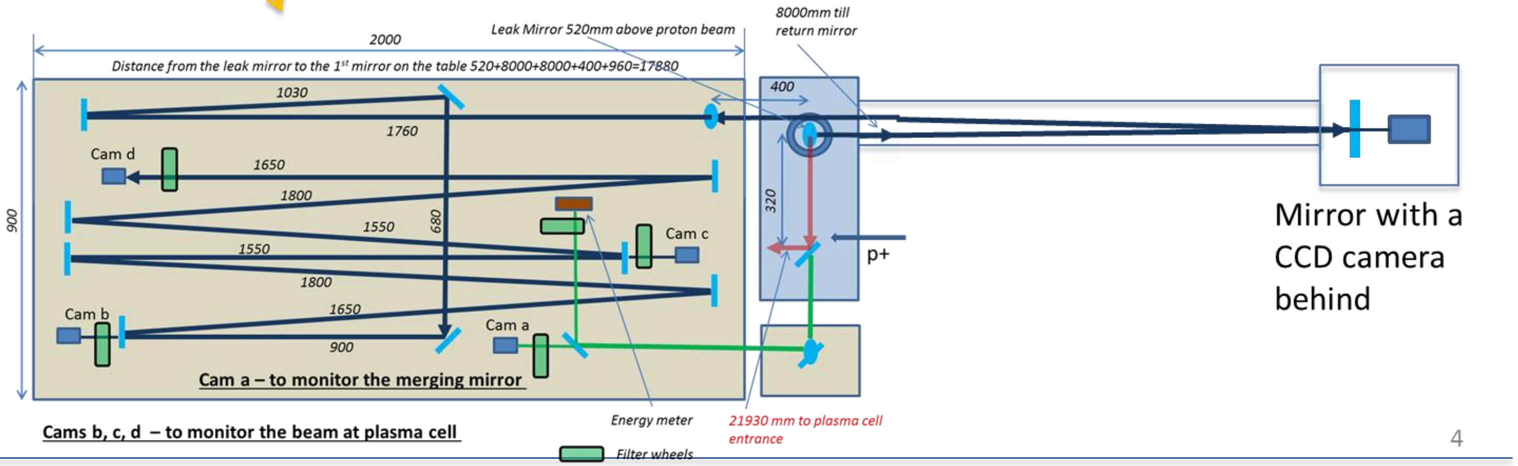
Proton-laser beam merging
22 m upstream of the plasma cell



Beam diagnostics setup



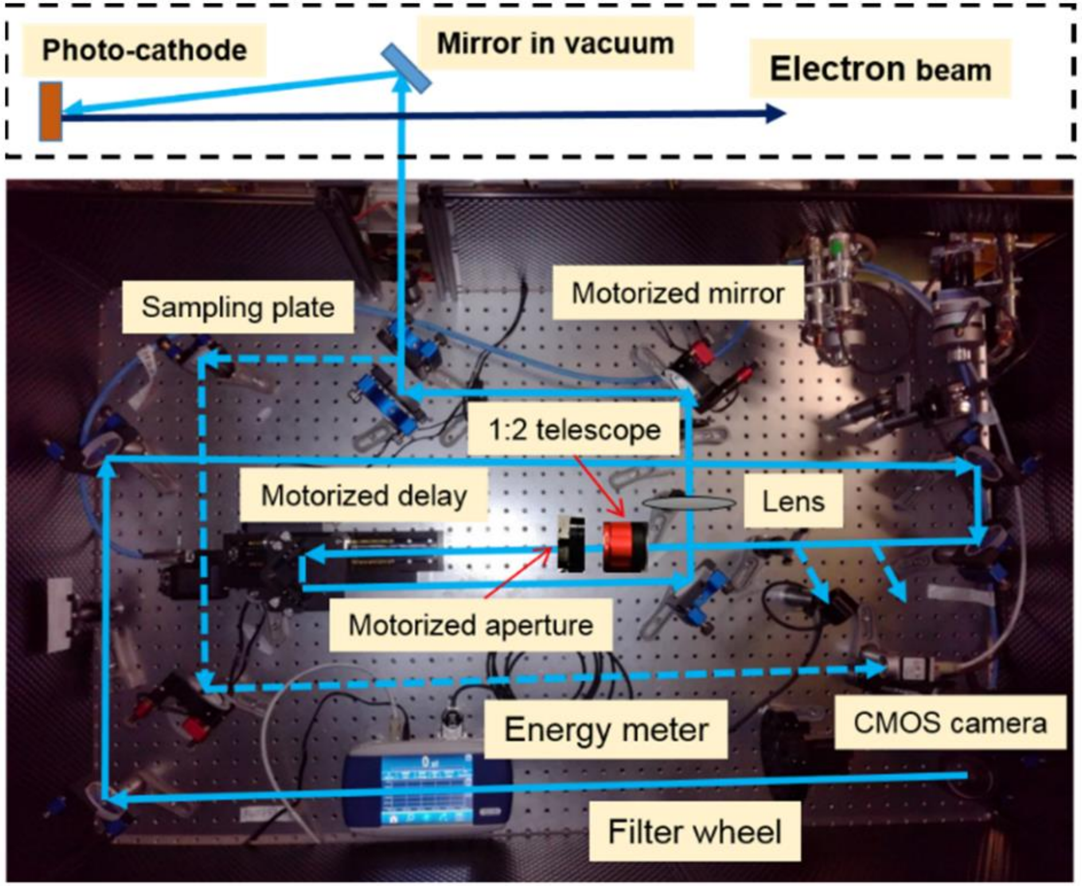
Pulse compressor under vacuum

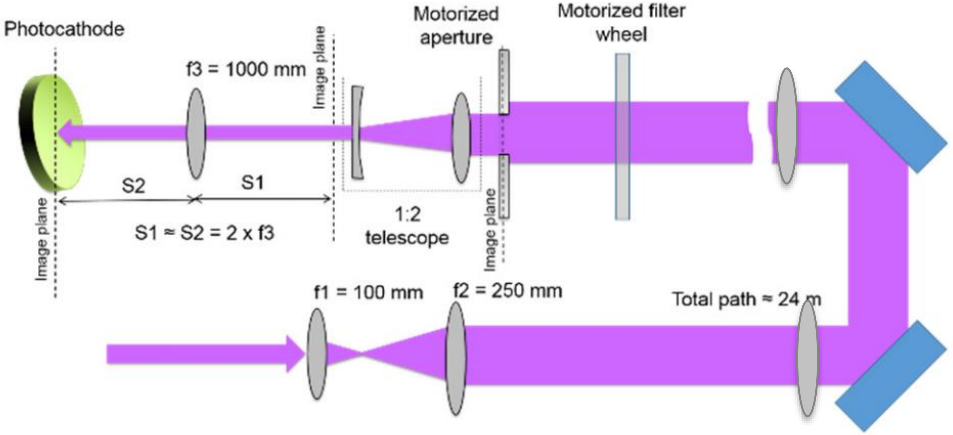


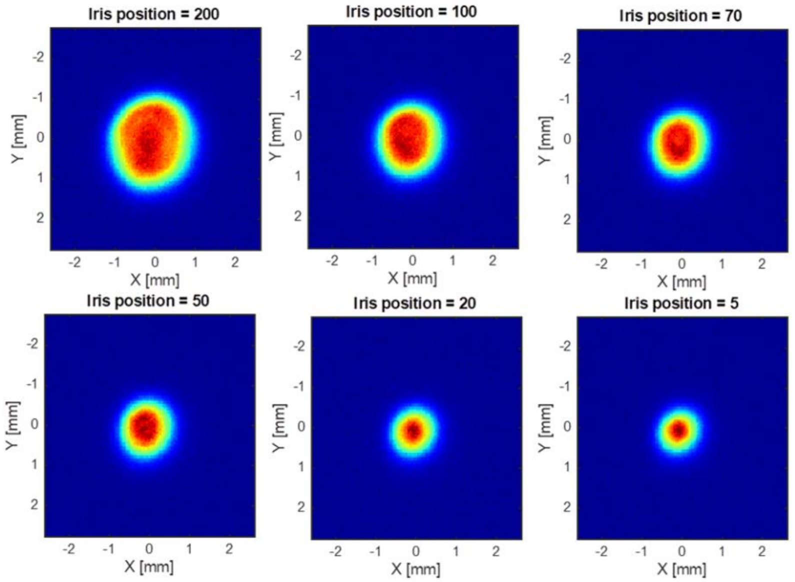
Mirror with a CCD camera behind

AWAKE photo-injector

PHIN e-gun

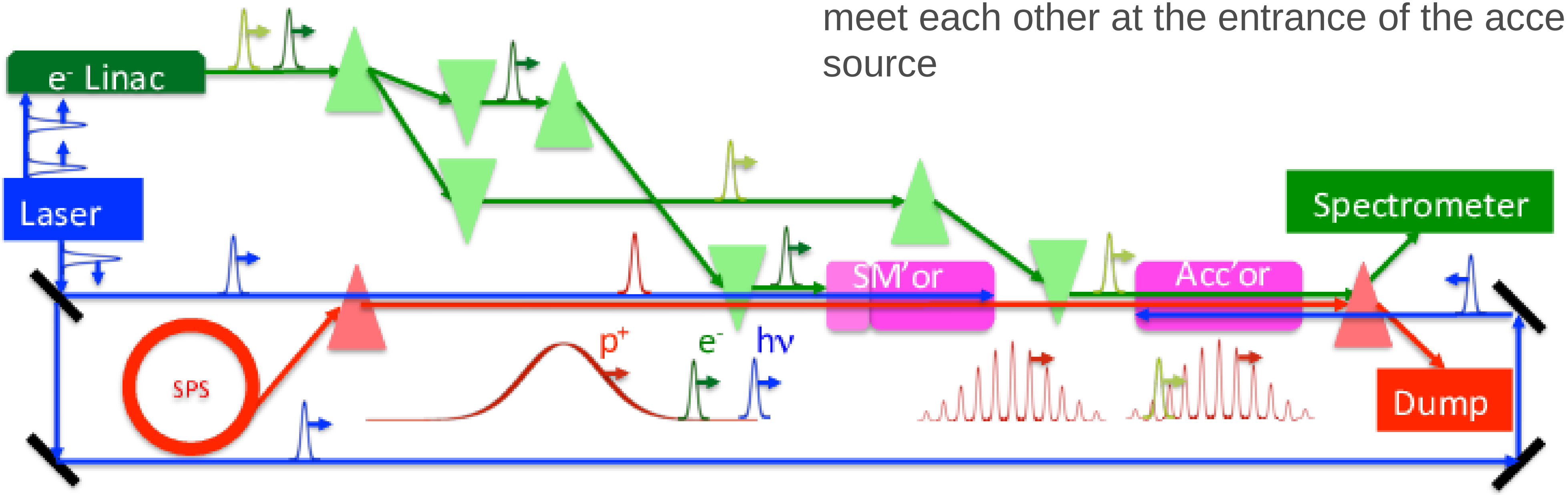






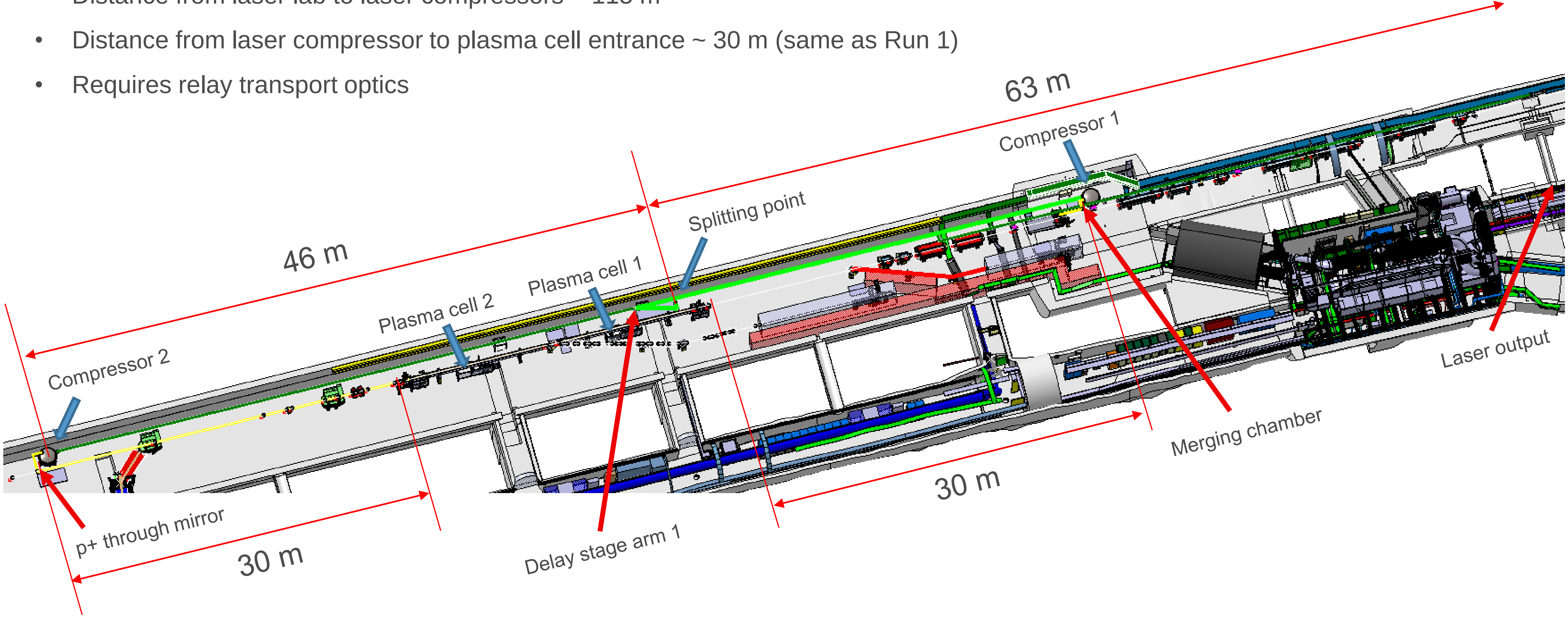
AWAKE Run 2 project

- The experiment will use two plasmas, electron bunch seeding for the SM process, on-axis external injection of an electron bunch and electron bunch parameters to reach plasma blow-out, beam loading and beam matching.
  - ➢ Two high power laser pulses propagating in opposite directions ionize Rb vapour in each plasma source
  - ➢ Witness electron bunch and the ionizing laser pulse meet each other at the entrance of the accelerator source

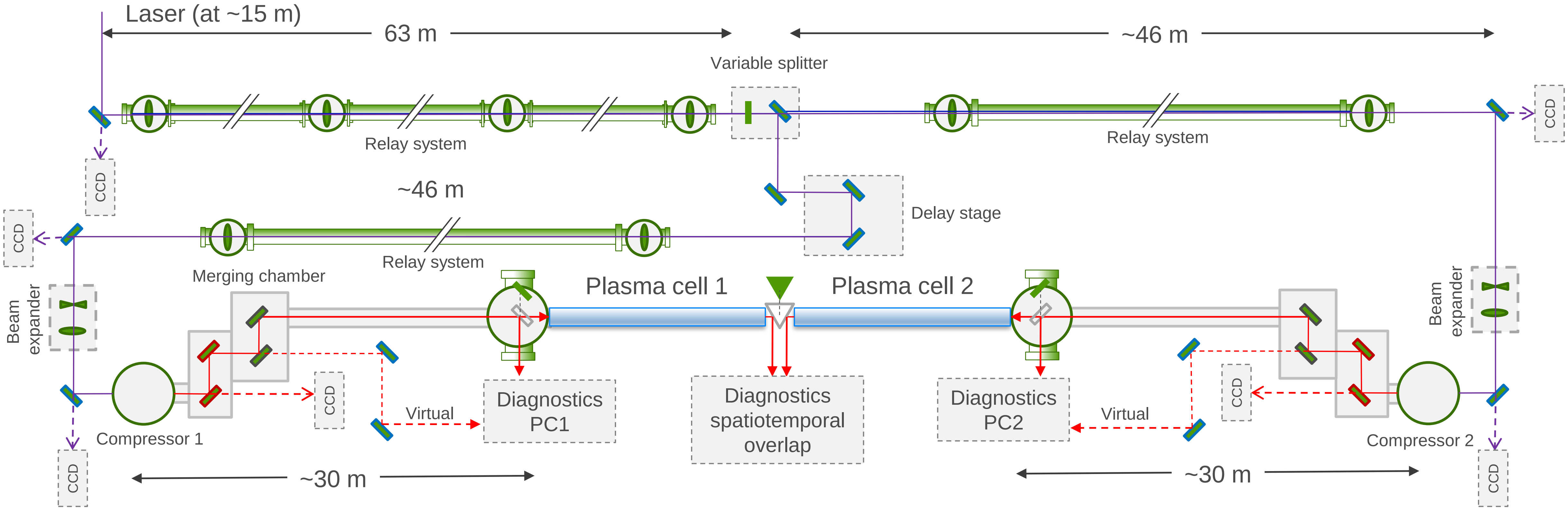


AWAKE Run 2 project

- Distance from laser lab to laser compressors ~ 115 m
- Distance from laser compressor to plasma cell entrance ~ 30 m (same as Run 1)
- Requires relay transport optics

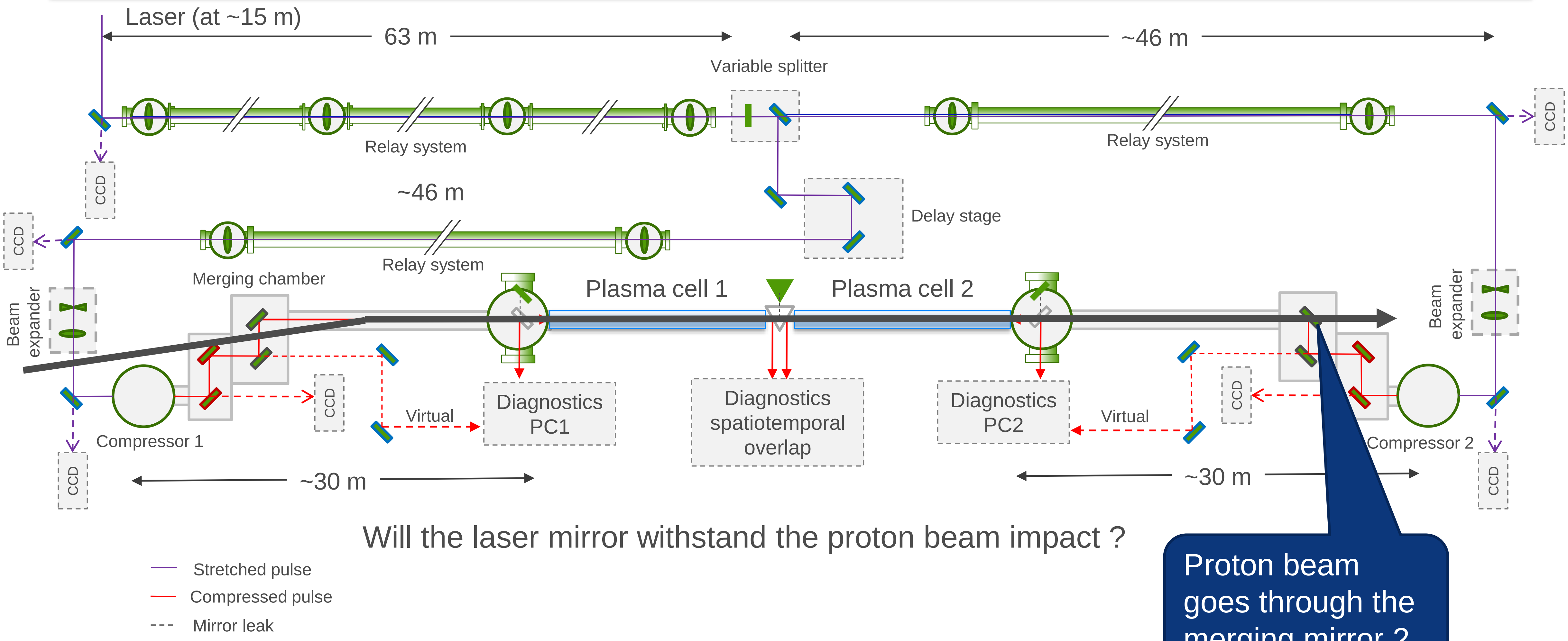


AWAKE Run 2 project



- Relay imaging systems require only low-level primary vacuum, blue mirrors are “in air”
- Focusing on plasma cell attained by mismatching beam expanders
- Content of diagnostics sets still to be determined, location of safety devices, etc…

AWAKE Run 2 project



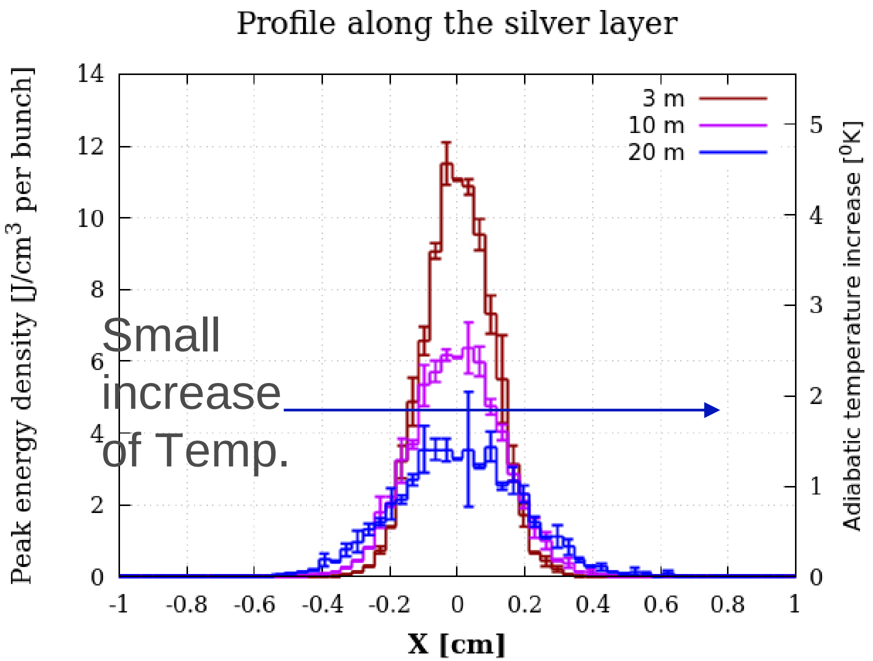
Will the laser mirror withstand the proton beam impact ?

Proton beam goes through the merging mirror 2

Run 2 study: proton beam impact on laser mirror

Energy deposition model

- Single SPS bunch of 3E11 protons at 400 GeV
- Mirror placed at two locations from the laser cell:
  - 3 m (σ~0.9 mm) and 20 m (σ ~1.6 mm)
- The mirror is modeled as a **100 nm silver layer** on a **5 (12) mm silica substrate**



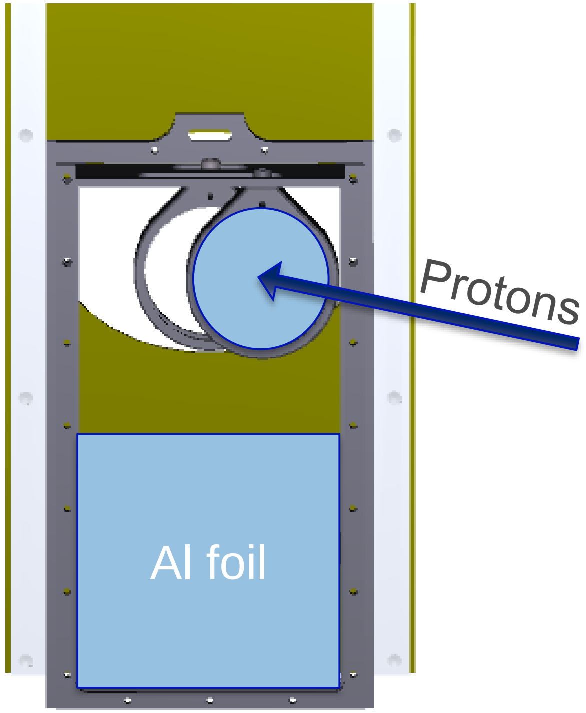
Small increase of Temp.

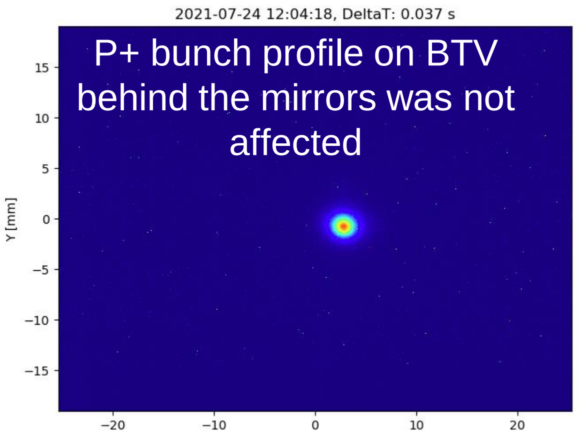
Calculated by to Luigi Salvatore Esposito (SY-STI)

Experiment at AWAKE during Run 2a (2021)

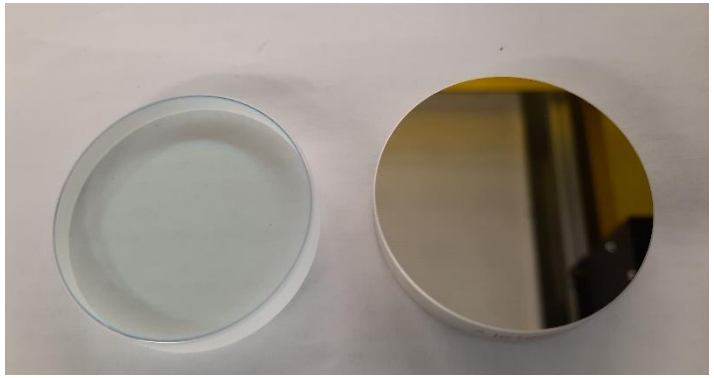
Assembly of 2 mirrors placed in the proton beam at 10m downstream the plasma cell

Mirror 1 – dielectric R>99.5%
Mirror 2 – silver R>96%





P+ bunch profile on BTV behind the mirrors was not affected



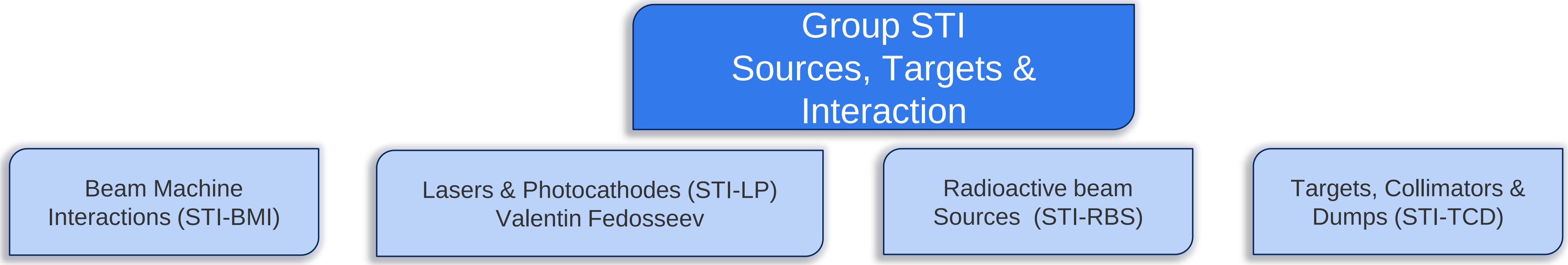
Number of bunches on mirrors:	**8015**
Total number of protons:	**1.2×10^{15}**
Average bunch population:	**1.5×10^{11}**

No visible damage of the reflecting coatings !

Summary

- Multiple users facility at CERN profit from charged particle beams produced using laser technology
  - RILIS systems at ISOLDE and MEDICIS are essential for isobaric purity of delivered radioactive ion beams
  - Electron sources of existing and future lepton accelerator requite robust photocathodes and high-quality laser beams
  - Plasma created by high-intensity laser beams enables conditions for self-modulation of high energy proton bunches and wake-field acceleration
- Laser development directions are defined by expanding requirements for new and higher quality particle beams

Acknowledgements



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Thank you for your attention!