

Design of a 1.5 GeV Full-Energy Linac for Top-Up Operation at SOLARIS

Adriana Wawrzyniak

On behalf of SOLARIS Team

SPAS'26, INP PAS, 20-22.10.26

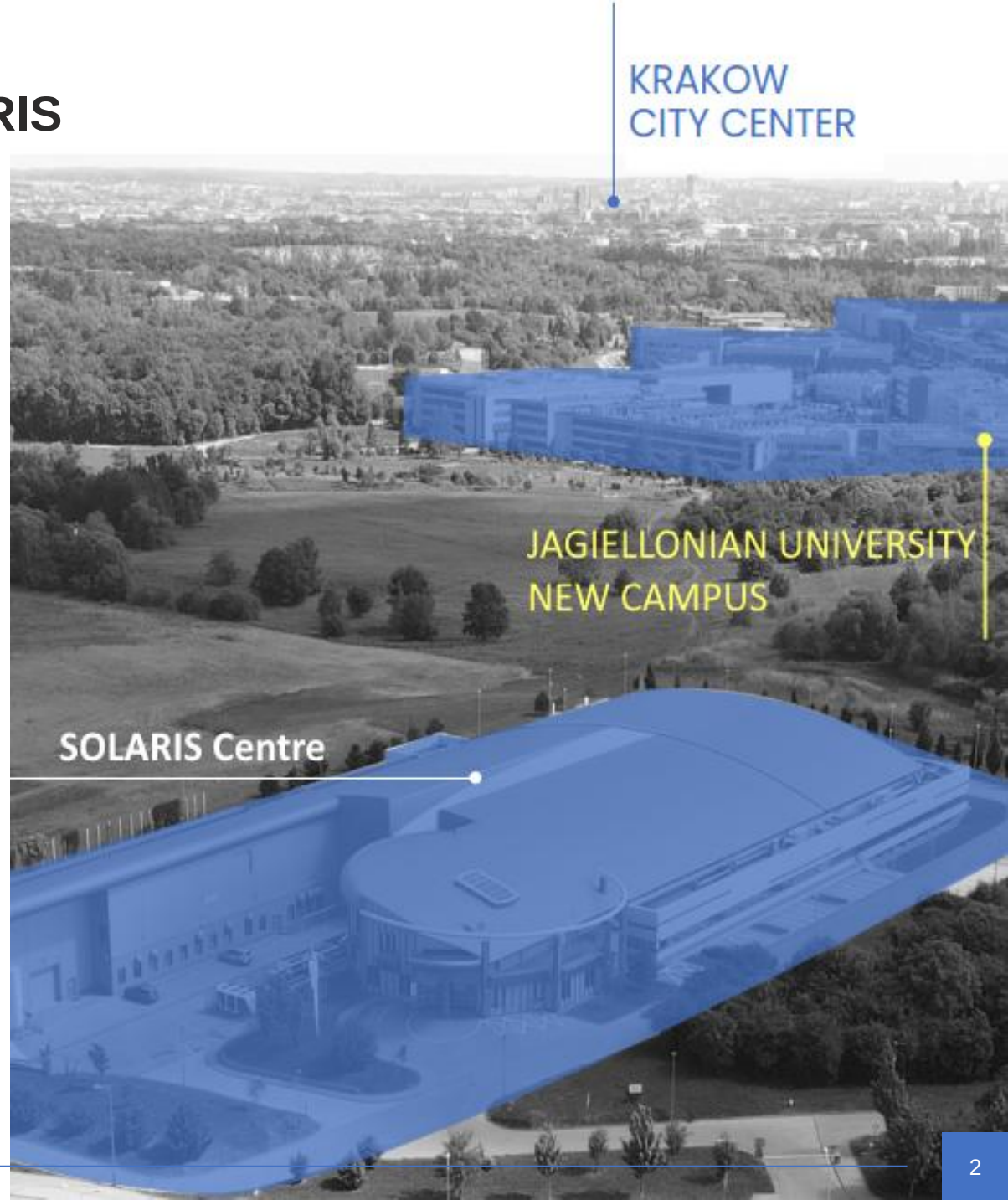
JAGIELLONIAN UNIVERSITY IN KRAKOW

SOLARIS NATIONAL SYNCHROTRON RADIATION CENTRE

SPAS 2026

National Synchrotron Radiation Centre SOLARIS

- **3rd generation light source** constructed in collaboration with MAX IV (Lund, Sweden) in 2010-2015
- Seed funding from **EU Regional Development Fund**
- Further development financed from **the national budget via research infrastructure projects** and by **partner institutions** (national and international)
- Operating **as user facility since 2018** (free of charge, open access) maintained by a dedicated program of **the Ministry of Science and Higher Education**
- The most advanced and largest **multidisciplinary scientific research too**l in Poland
- Indicated on the list of **13 Research Infrastructures** of pan-European **significance under the European Strategy on Research and Technology Infrastructure**



SOLARIS partnerships



CERIC

SOLARIS contributes 10% of research time to the Central European Research Infrastructure Consortium, which gathers unique research facilities in 8 partner facilities across the CEE region as well as in 6 associated facilities in Italy, France and the Netherlands

Open access to NMR, Mass Spec, Neutrons, Photons, Ions, Microscopy, Nanolabs, Laser science, Testing, etc.

LEAPS

Member of the League of European Accelerator bases Photon Sources, which is formed by 16 organizations representing 19 light source facilities in Europe

Access to SOLARIS



Free of charge access to state-of-the-art research infrastructures for open science projects

Calls for **regular** and **long-term** proposals announced **twice a year**, next deadline: **October 1st**

Rolling call for short experiments via **rapid access**
- feasibility tests
- supplementary measurements
- scientific merit (reviewed by PRC)

Multi-technique and interfacility proposals possible through CERIC and RIANA

Proposal success rate (call 17, spring 2026): ~50%

Travel cost supported by:

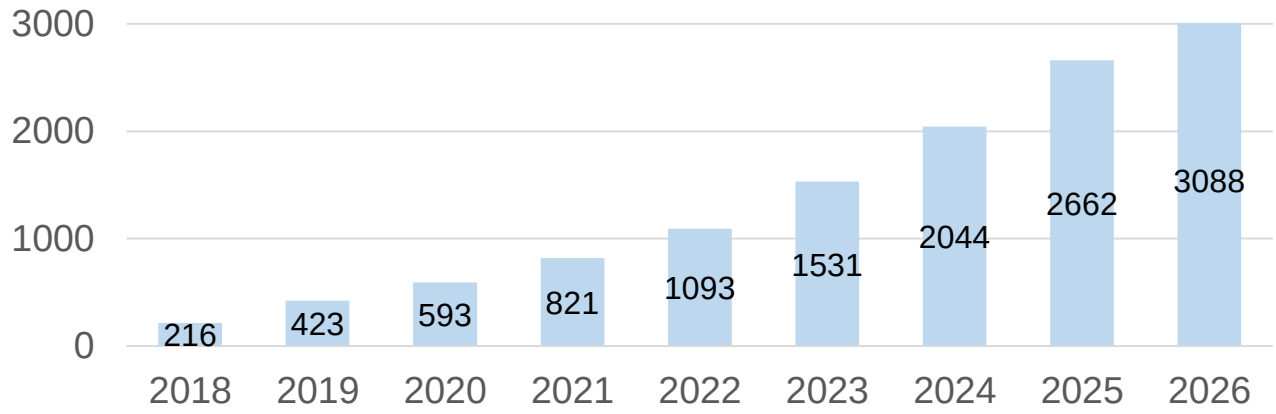
CERIC RIANA nephews

Dedicated support program for young scientists, first time users with Polish affiliation – pilot phase

Community of SOLARIS users

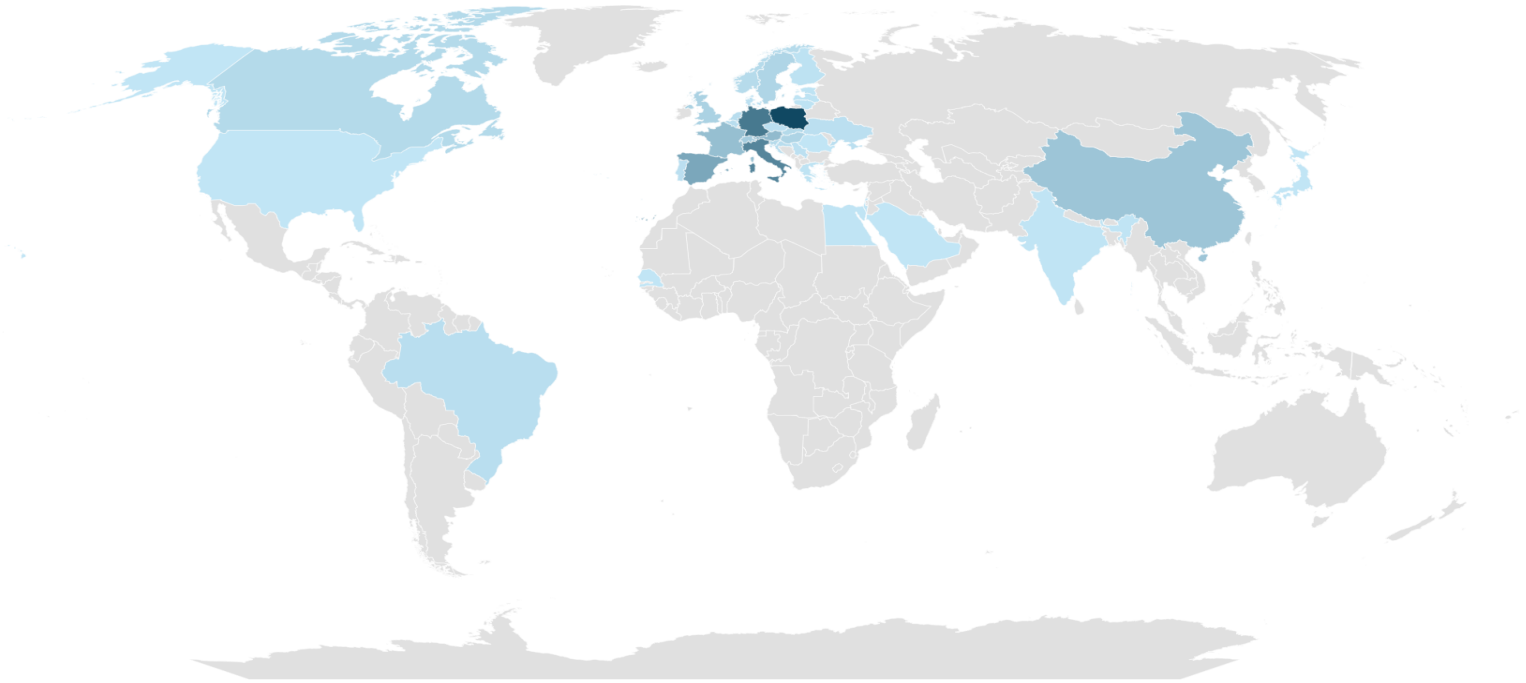
User satisfaction surveys 2024-2025:
> 4.7 average score (max. 5.0)
> 98% users plan to apply again

User organization to be established



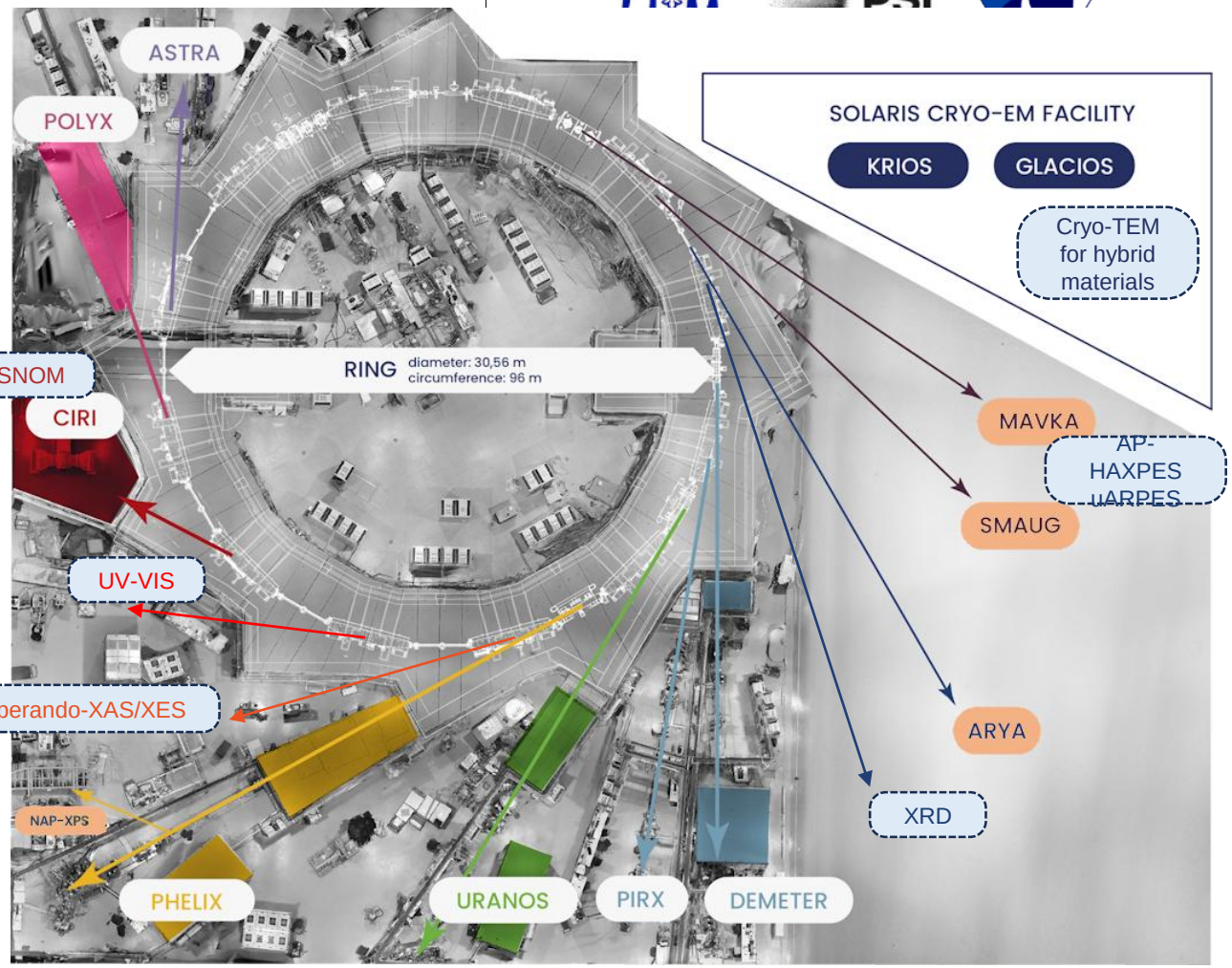
Top countries	*proposals*
Poland	1590 (>70%)
Germany	97
Italy	86
Spain	56
Czechia	50
Austria	39
France	35
China	29
Switzerland	22
USA	19
UK	19
Hungary	16

Total: >2200 *proposals*
40 *countries*



Obsługiwane przez usługę Bin
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Storage Ring & Beamlines



1.5GeV Storage ring (max. 500mA)

- 100 MHz RF system
- 300 MHz Landau Cavities
- Injection dipole kicker
- Injection duration: 300 s, +/- 20 s
- Ramping duration: 192 s
- Maximum numer of bunches: 32, operating: 29
- Tune v_x, v_y: 11.22, 3.15

AVILABLE FOR USERS UNDER CONSTRUCTION PROJECTS

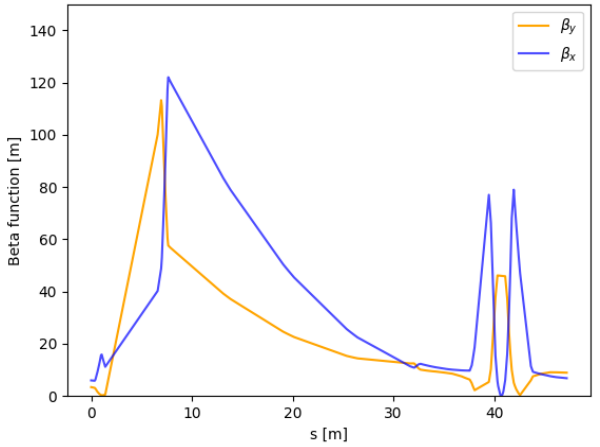
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Present LINAC layout

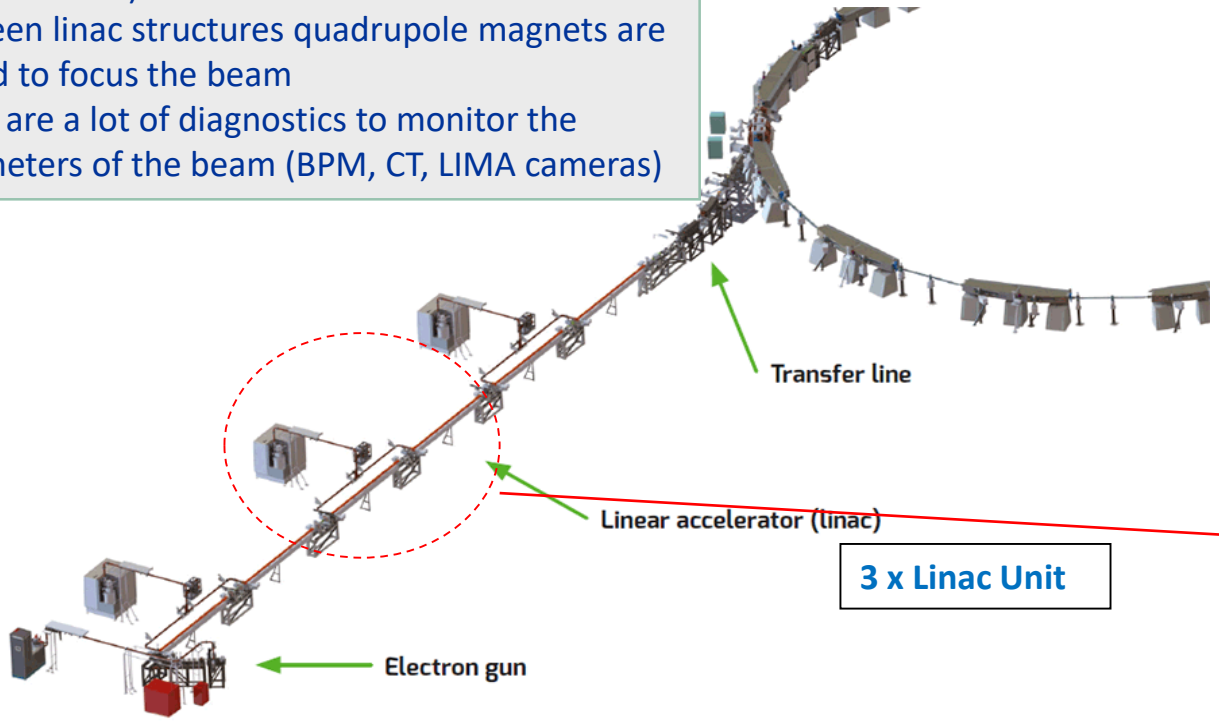
Linac components

RF Thermionic Gun with BaO cathode (Energy: 2.8 MeV, charge 100-200 pC)
Energy filter
6 S-band 2998.5 MHz accelerating structures (length: 5m)
Accelerating gradient: 20 MeV/m
3 RF Units & SLED cavities (The peak powers of the klystron and from the SLED cavity are 35MW and up to 200 MW)
Between linac structures quadrupole magnets are placed to focus the beam
There are a lot of diagnostics to monitor the parameters of the beam (BPM, CT, LIMA cameras)

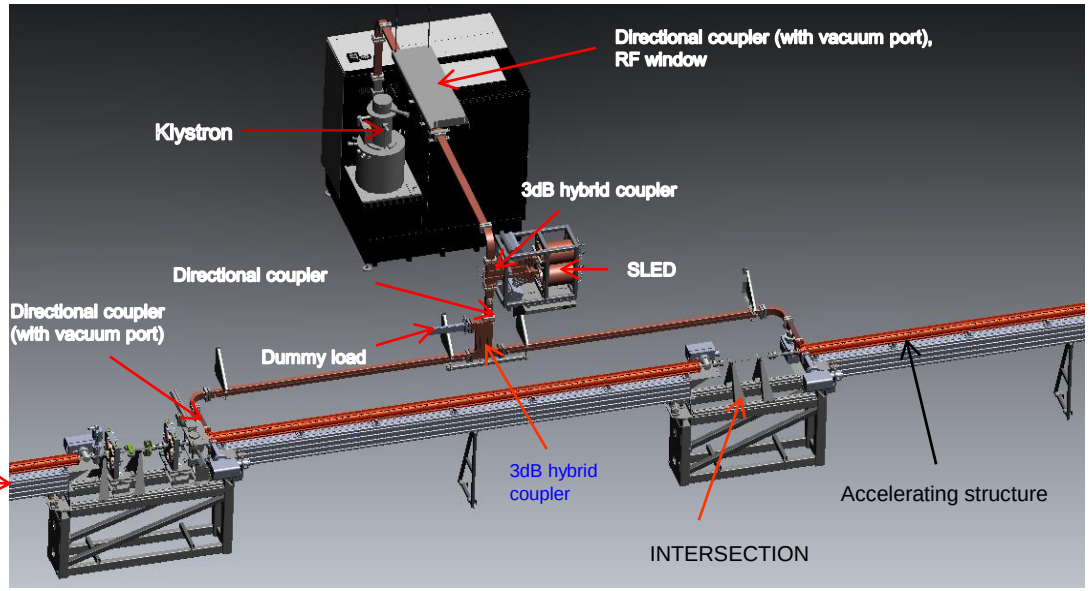
Parameters of current Linac	
Energy [GeV]	0.54
Accelerating Gradient [MV/m]	20
RF Frequence [MHz]	2998.5
Bunch charge [nC]	0.13
Hor. Emittance [mm mrad]	3.111
Ver. Emittance [mm mrad]	2.175
Rep. rate [Hz]	2
Bunch lenght on exit [ps]	14
Length [m]	40
Energy spread [keV]	400



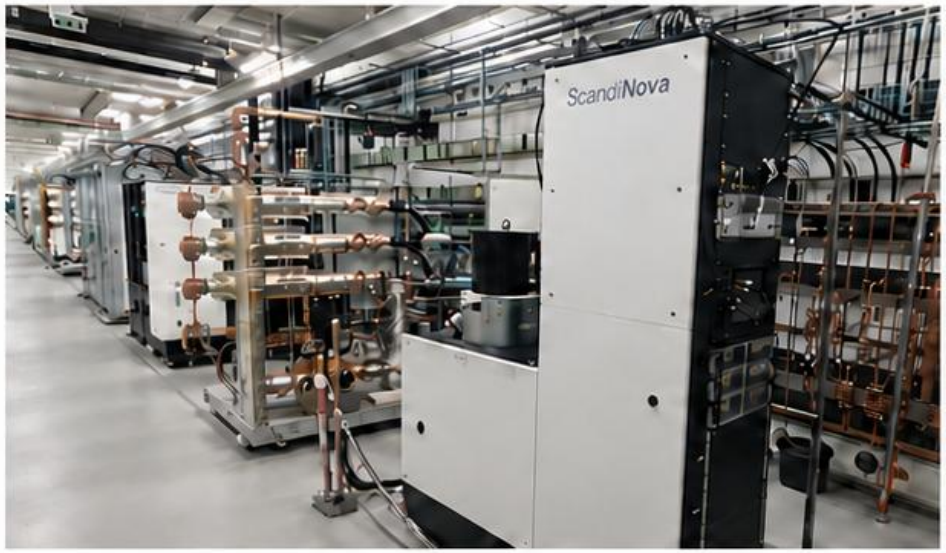
Betatron functions along current LINAC



3 x Linac Unit



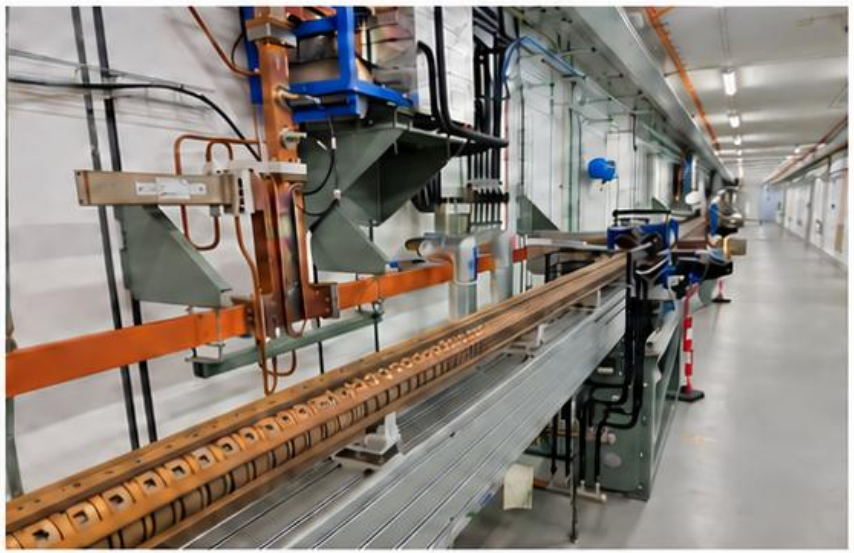
Linac Infrastructure



Klystron gallery



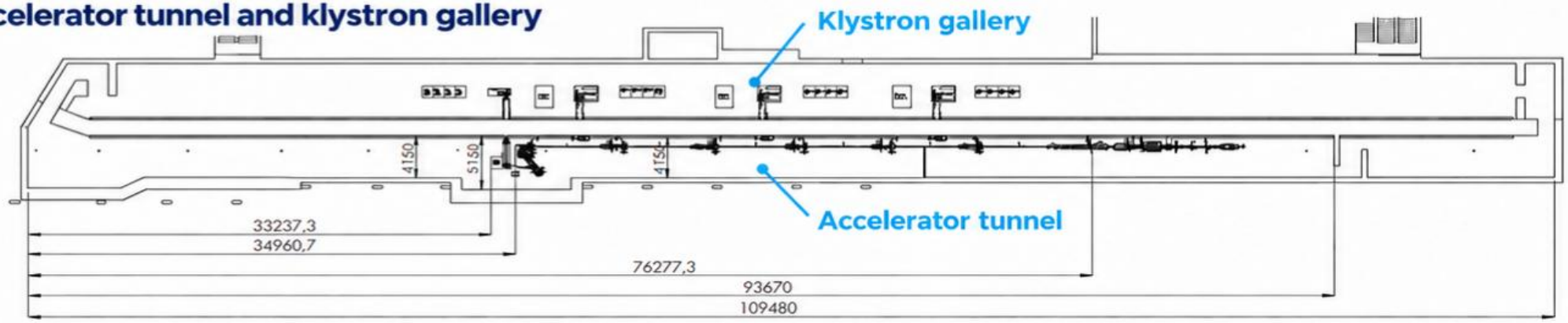
Accelerator tunnel



Accelerator tunnel

RF modulators and klystrons / Cooling systems / Magnet power supplies
Ion-pump controllers / Timing and synchronisation / Control network

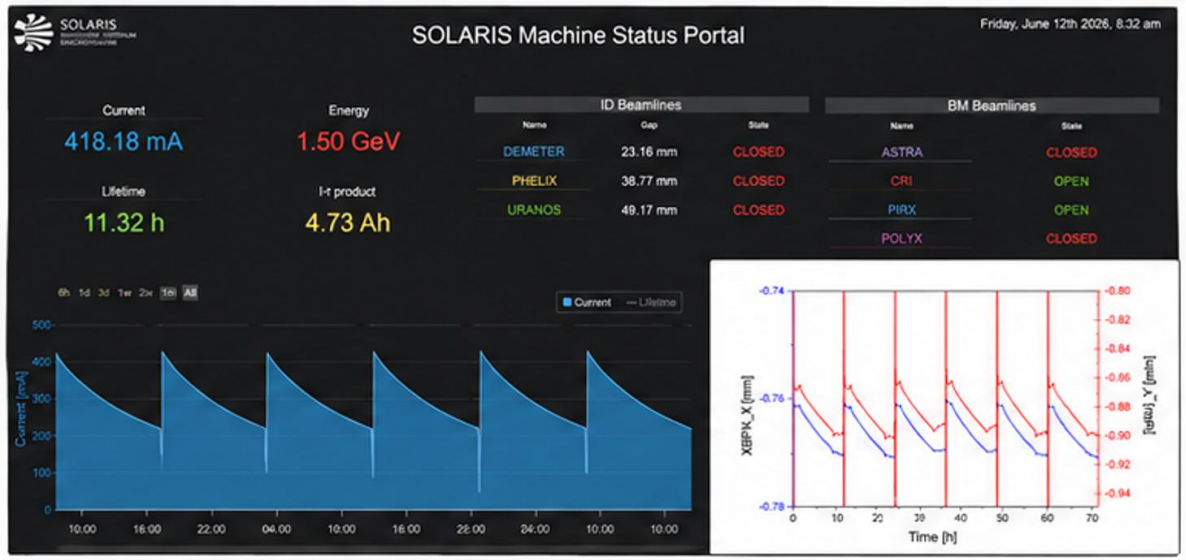
Existing accelerator tunnel and klystron gallery



Why 1.5GeV Linac?

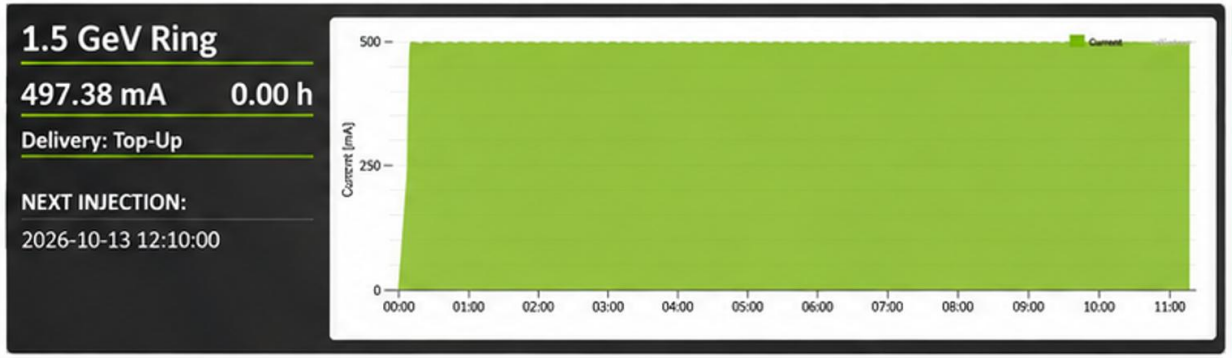
Full energy injection enables top-up operation

Present operation



- 0.54 GeV injection
- Accumulation followed by energy ramping
- Current and photon flux decay between refills
- Refill interruptions and changing thermal load

Proposed top-up operation *(illustrative)*



- **1.5 GeV injection**
- Frequent replenishment at operating energy
- Nearly constant current and photon flux
- Fewer interruptions and reduced thermal drift

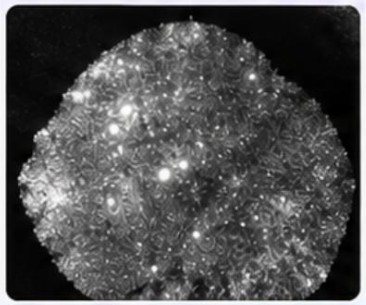
More stable experimental conditions for long, uninterrupted measurements

Top-up for advanced experiments

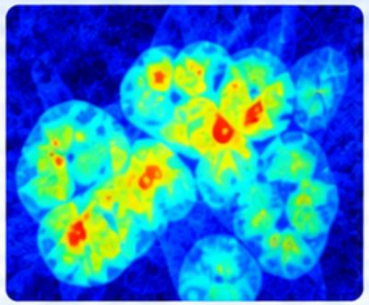
Stable photon delivery is esential for improving beamlines experiments and developing new techniques

High-resolution imaging

PEEM
Surface imaging and spectroscopy

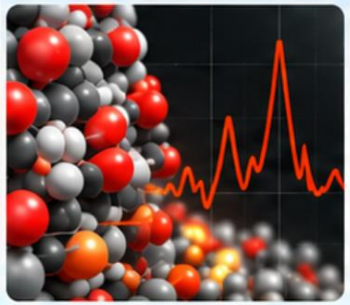


STXM
Nanoscale chemical mapping

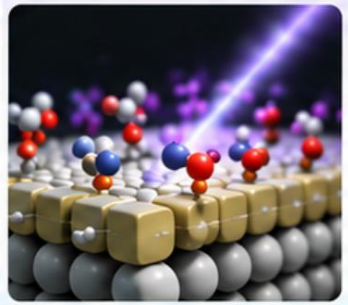


In situ and operando spectroscopy

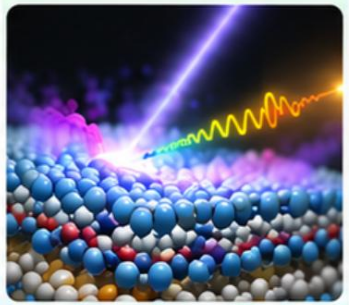
Operando-XAS
Local structure under working conditions



NAP-XPS
Surface chemistry in reactive gases

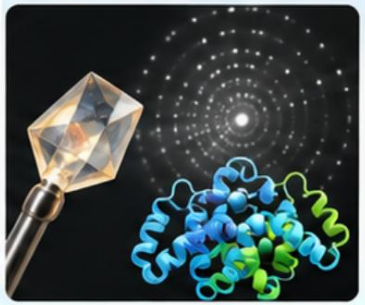


AP-HAXPES
Electronic structure at ambient pressure



Crystallography

PX
Protein structures from crystal diffraction



Shared benefits of top-up

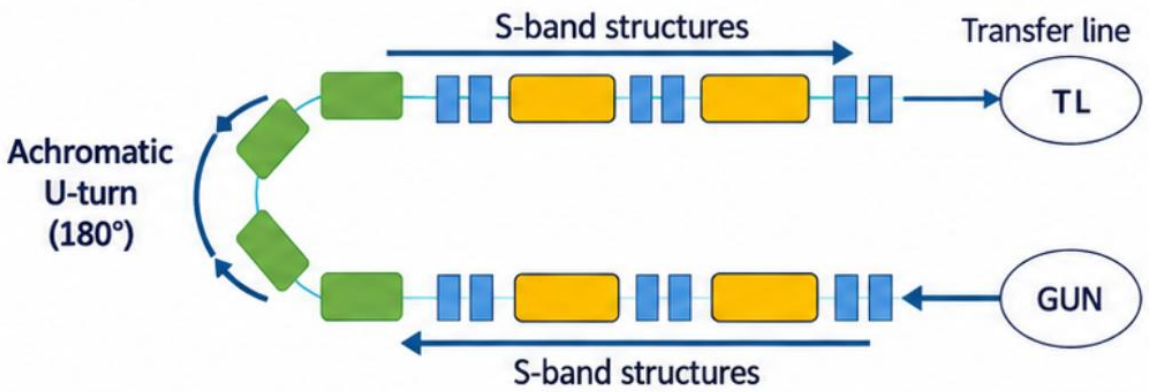
- Stable photon flux
- Reduced thermal drift
- Long, continuous acquisitions
- More reproducible datasets

Consistent acquisition conditions improve comparisons across images, spectra and diffraction datasets

More stable experimental conditions with fewer refill interruptions

Linac concepts considered but not selected

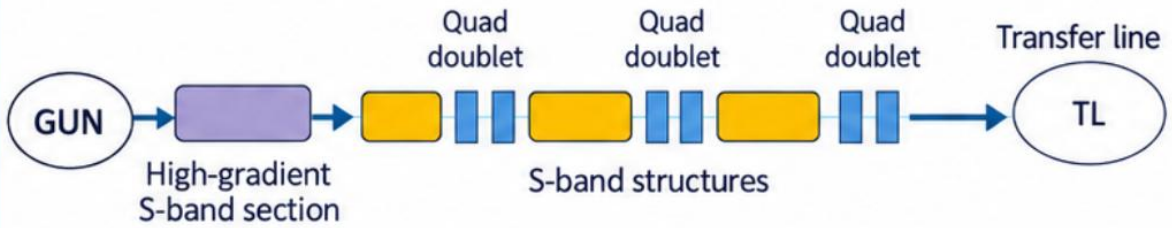
S-band with achromatic U-turn



- 17 S-band structures for 1.5 GeV
- Equivalent straight beam path: about 120 m
- U-turn at 625 MeV: 1.5 T dipoles, about 8 m beam path
  - Transverse footprint of the bend: about 4 m

Main limitation: folded layout and more complex beam transport

High-gradient S-band



- Compact straight-layout alternative
- Short-prototype result: 40 MV/m at 125 MW input RF power
- Full-linac performance and RF requirements need validation

Main challenge: high RF power and scale-up from prototype

Shafqat et al., NIM A 979 (2020), 164473

Selected baseline: hybrid S-band/C-band linac for 1.5 GeV in the existing tunnel

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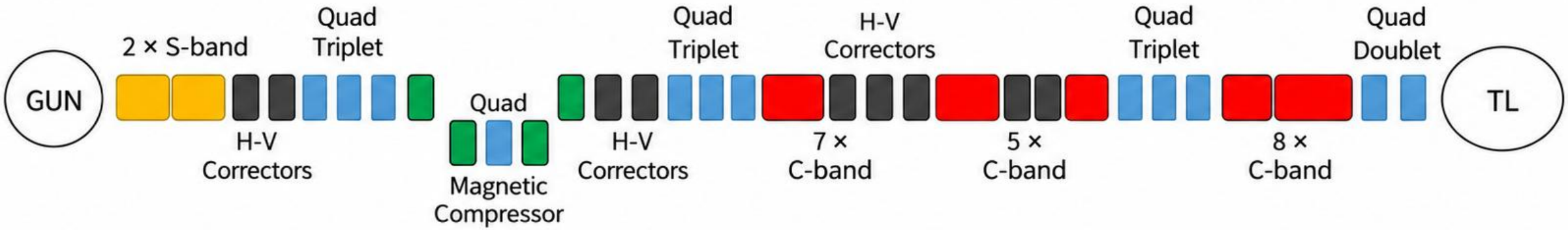
New Hybrid S-band/C-band LINAC

Electron sources:
BaO thermionic gun and an additional laser-driven photocathode gun

RF structures:
2 S-band + 20 C-band

Planned top-up injections:
every 20–30 minutes

Beam-dynamics studies:
elegant, pyAT and ASTRA



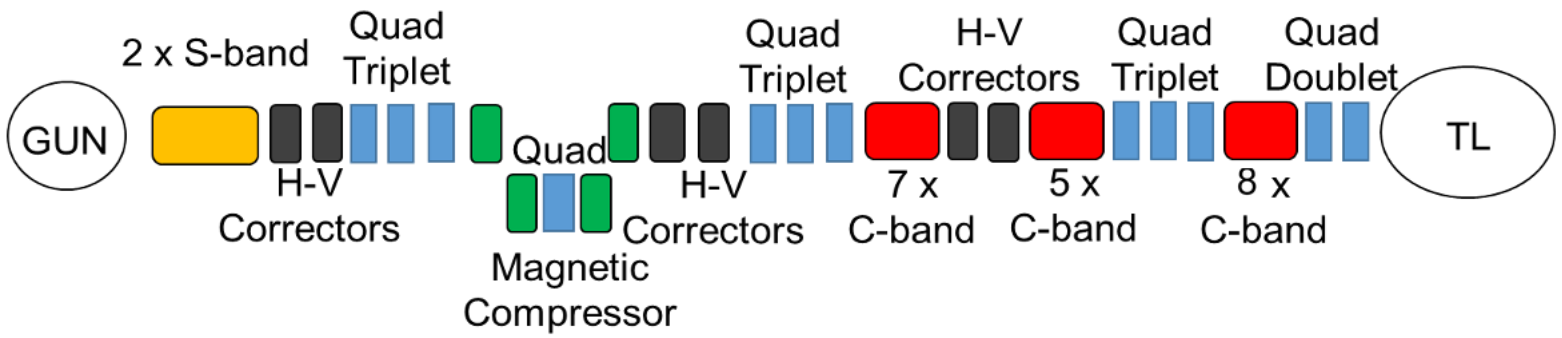
Optics and trajectory control

1. Upstream matching prepares the beam for compression and C-band acceleration.
2. Downstream matching adapts the beam optics to the transfer line.
3. Horizontal and vertical correctors control the trajectory along the linac.

Full-energy injection for top-up operation

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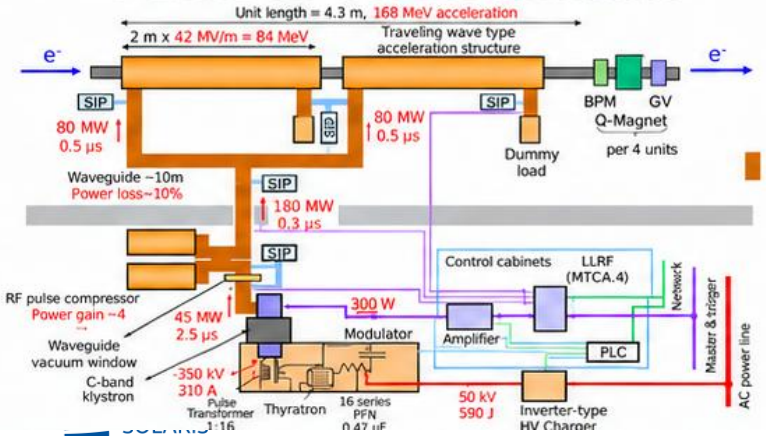
C-band RF configurations under study



Configuration I: two structures per RF unit

- 2 × 2 m structures
- 42 MV/m gradient
- 168 MeV per unit over 4.3 m

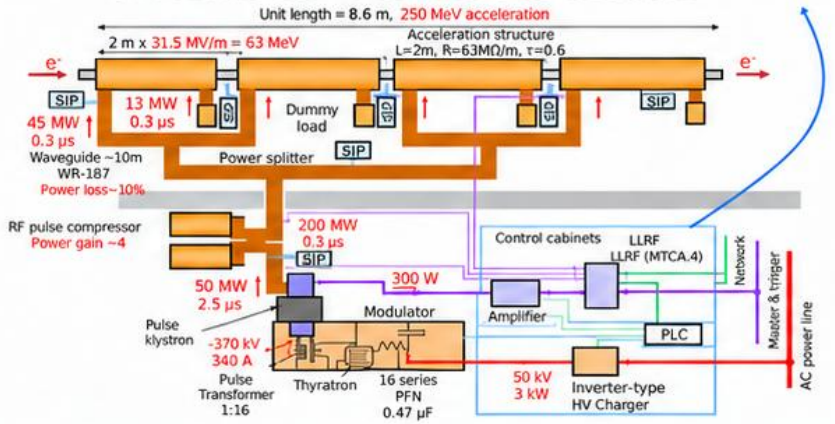
C-BAND RF CONFIGURATION I



Configuration II: four structures per RF unit

- 4 × 2 m structures
- 31.5 MV/m gradient
- About 250 MeV per unit over 8.6 m

C-BAND RF CONFIGURATION II

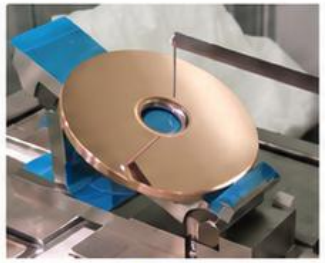


C-band accelerating structure

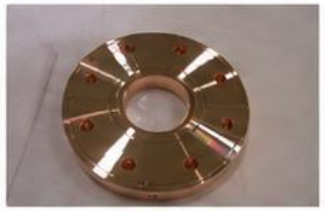
Main Parameters	
Frequency	5712 ± 0.2 MHz
Structure / coupler	Disk-loaded / J-type, double-fed
Acceleration mode	Travelling wave, quasi-constant gradient
Achieved gradient	50.1 MV/m
Phase advance per cell	2π/3
Attenuation constant, τ	0.56
Quality factor, Q	≥ 8000
VSWR	≤ 1.1
Shunt impedance	≥ 55 MΩ/m
Filling time	0.27 μs
Cells	100 accelerating + 2 coupler cells
Length	1.8 m
Waveguide	WRI48
Waveguide flange	A-DESY

5.712 GHz
Operating frequency

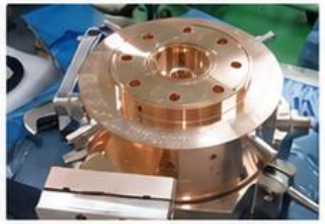
50.1 MV/m achieved
Reported structure performance



Disk



Cylinder

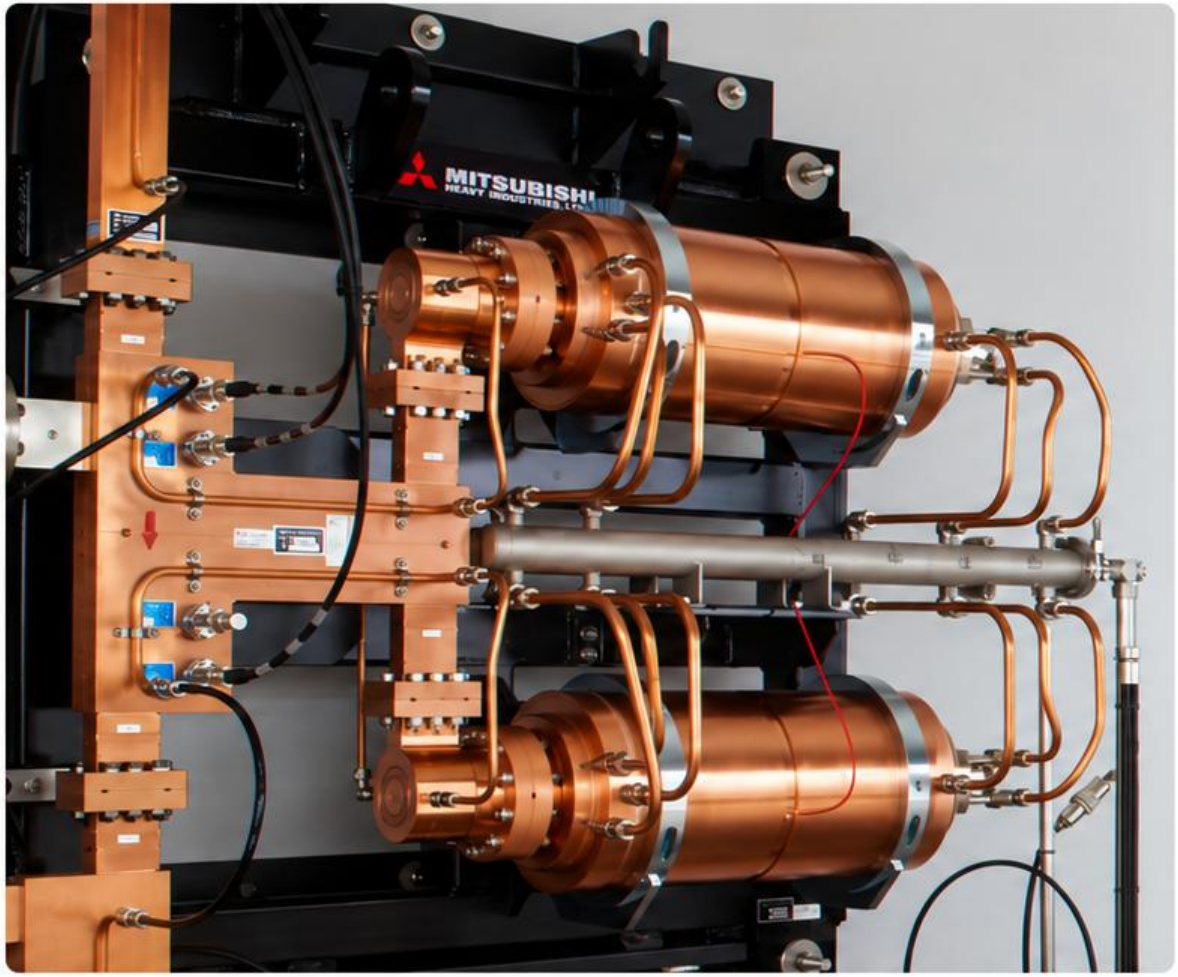


Coupler



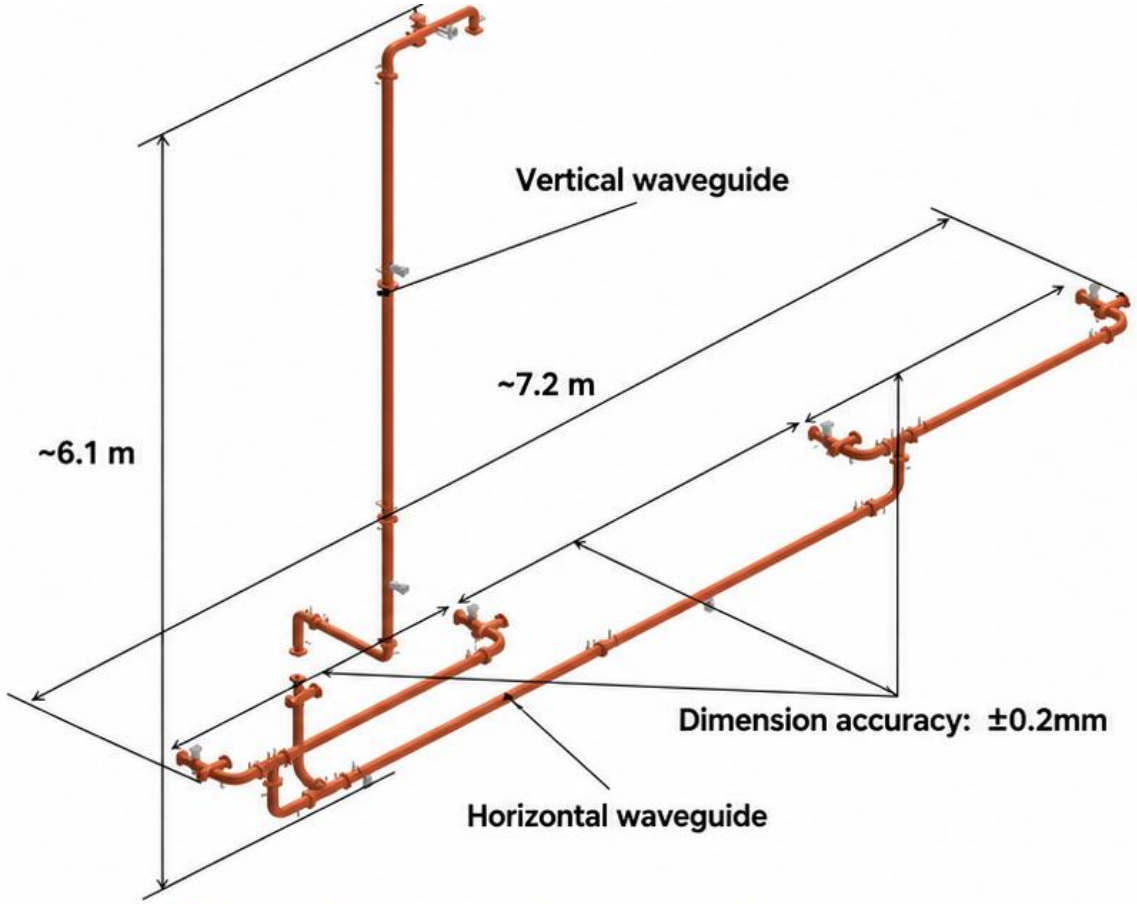
C-band Pulse compresor

Parameter	Value
Resonant frequency	5712 MHz (30°C in vacuum)
Configuration	Two resonant cavities and a 3 dB coupler
RF mode	$TE_{0,1,15}$
Quality factor	≥ 180,000
Coupling factor β	9 – 9.5
Input RF power	50 MW
Input pulse width	2.5 μs
Repetition rate	60 Hz
VSWR	≤ 1.10



Twin-cavity RF pulse compressor

C-band waveguides distribution



C-band waveguide network prototype

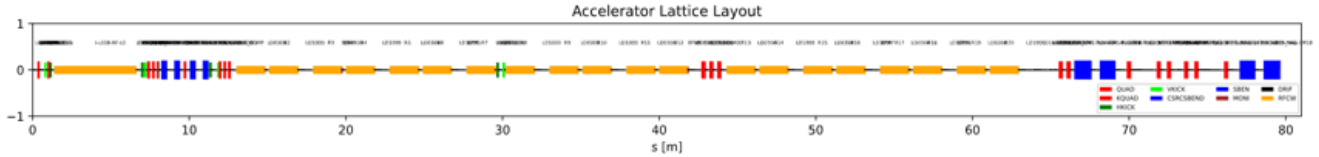
Parameter	Value
Frequency range	5712 ±20 MHz
Peak power, compressor to first splitter	320 MW
Average power	15 kW
Repetition rate	1–100 Hz
Waveguide	WR187
VSWR	< 1.04
Operating pressure	$<10^{-6}$ Pa
Splitter amplitude / phase imbalance	<0.1 dB / <3°

Simulation configurations and bunch compression

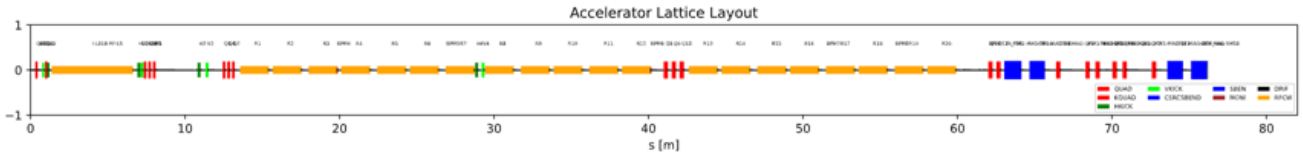
Photocathode and thermionic sources: a comparison of two modelled lattices

Model assumption	Photocathode gun	Thermionic gun
Final beam energy	1.50 GeV	1.50 GeV
Bunch charge	200 pC	200 pC
C-band RF frequency	5712 MHz	5712 MHz
Accelerating gradient	41 MV/m; last four: 20	41 MV/m; last four: 20
Energy spread	0.06%	0.7%
Bunch compressor	Included	Not included

Photocathode lattice with compressor



Thermionic lattice without compressor



Photocathode compression

1.62 ps → 0.89 ps

Compression factor: 1.82
R_{56} = −31.3 mm
Compressor length: 2.54 m

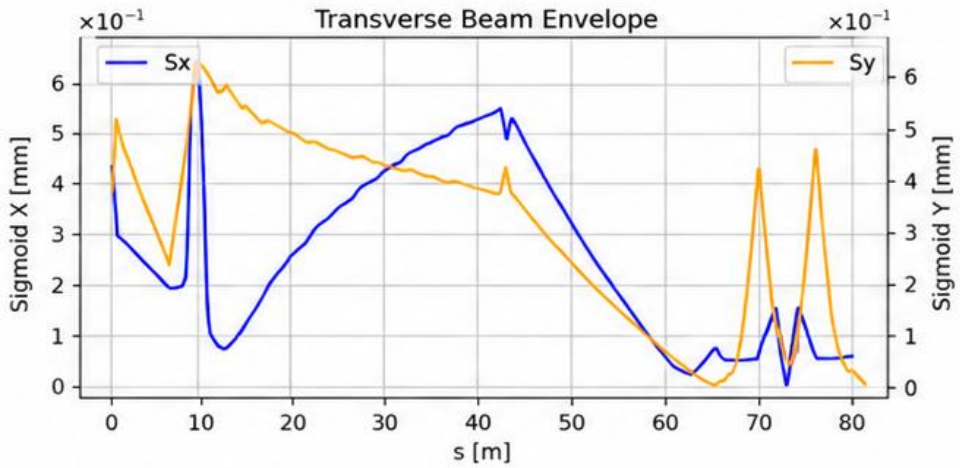
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Transverse and longitudinal beam evolution

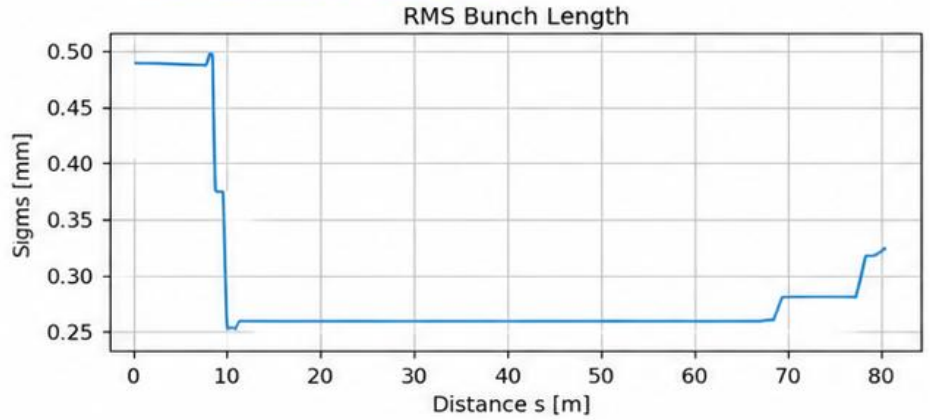
Simulation plots through the linac and transfer line

Photocathode gun

RMS transverse beam size

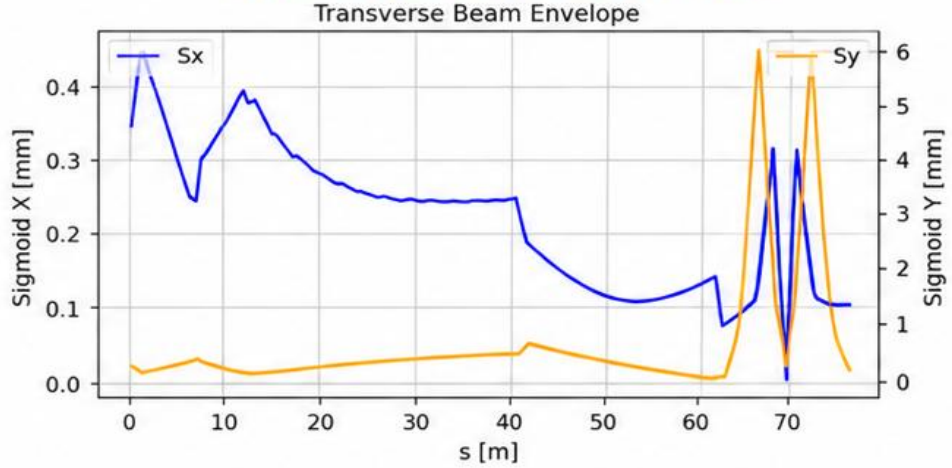


RMS bunch length

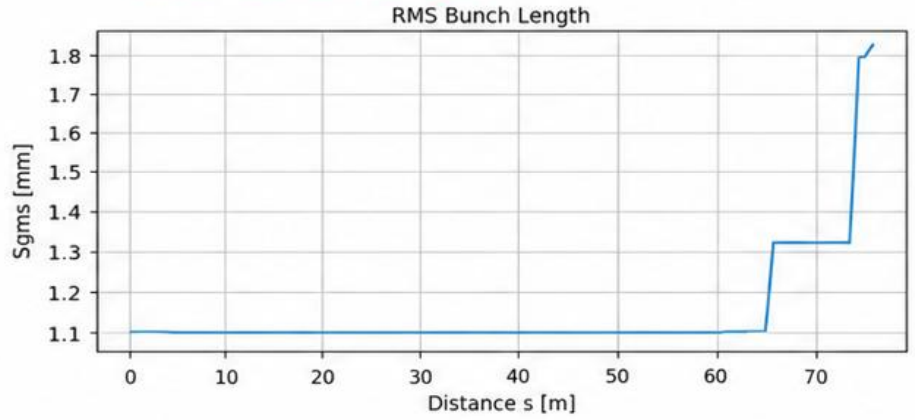


Thermionic gun

RMS transverse beam size



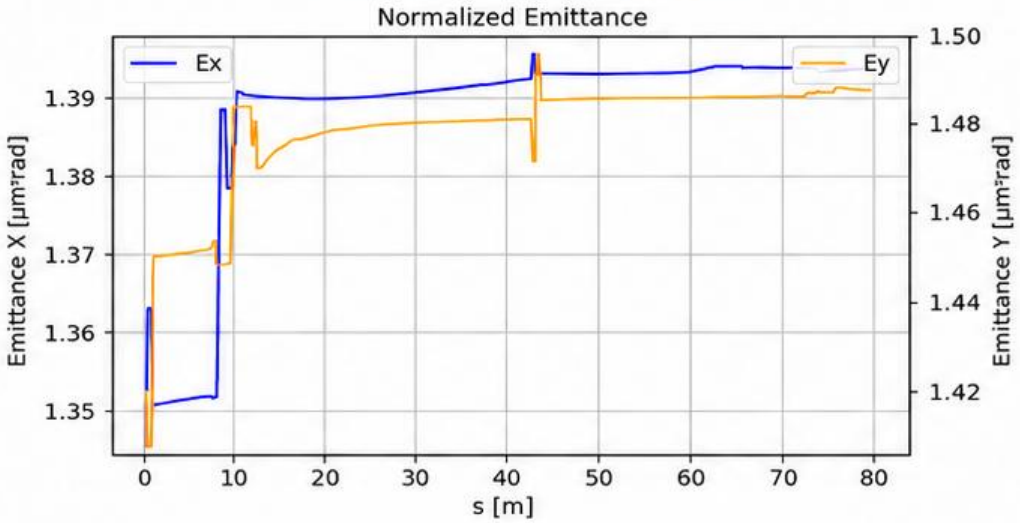
RMS bunch length



Beam quality at 1.5 GeV

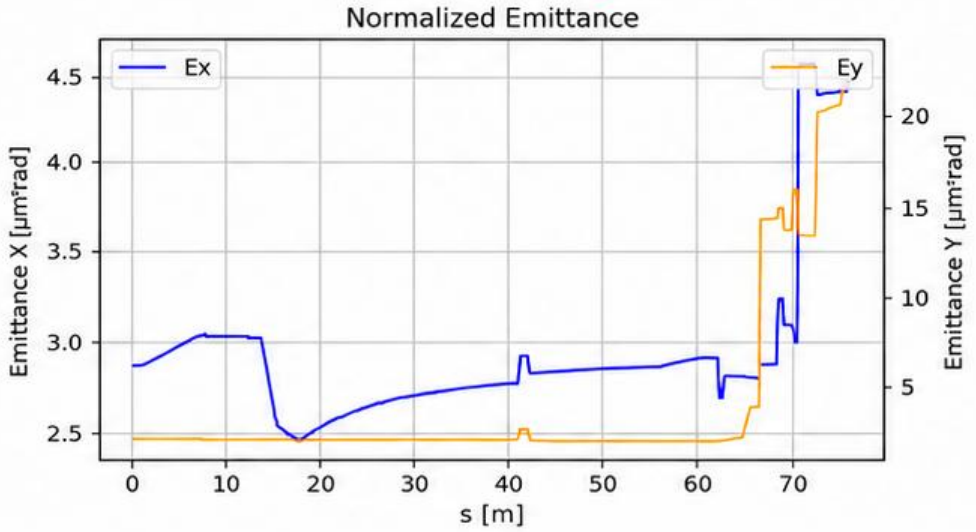
Normalized emittance along the linac and transfer line

Photocathode gun



Normalized emittance largely preserved.

Thermionic gun



Strong vertical emittance growth in the final transport section.

Output parameter	Photocathode	Thermionic
RMS energy spread [%]	0.060	0.731
RMS bunch length [ps]	1.091	6.116
Geometric emittance εx / εy [nm·rad]	0.47 / 0.50	1.50 / 7.87
RMS beam size σx / σy [μm]	60.23 / 58.91	97.11 / 174.25

Next step: optimise thermionic transport; check matching, residual dispersion and chromatic effects.

Injection requirements at 1.5 GeV

Full-energy injection must capture the incoming bunch while limiting stored-beam motion

Efficient capture

Reduce the injected-beam invariant below the horizontal acceptance

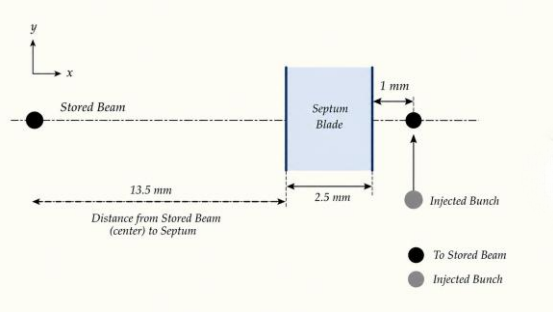
Small stored-beam perturbation

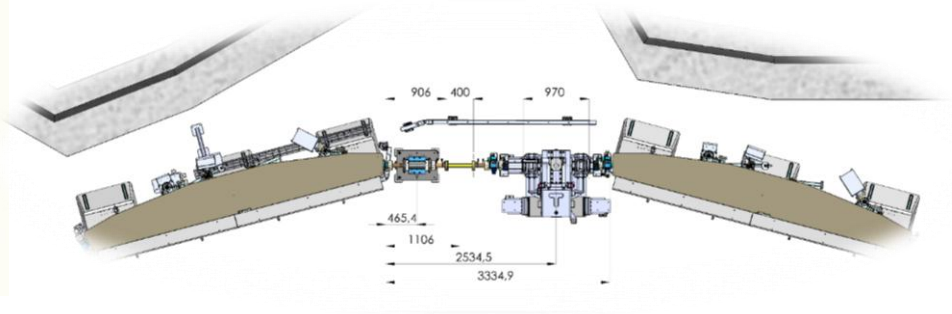
Minimise injection transients and residual betatron oscillations

Reproducible top-up

Control trajectory, kick strength and pulse timing

Injection geometry and optics





Parameter	Septum exit (IP)	Kicker (MIK)
x [mm]	−17.000	−6.651
x′ [mrad]	0	−2.187
βx [m]	5.96	5.75
αx	−0.22	0.099

Capture condition

$A^2(inj) = 50.84$ mm·mrad

Horizontal acceptance ≈ 30 mm·mrad

$A^2(red) < Acc_x$

$$x'(red) = x'(KI) + \theta(KI)$$

$$A^2(red) = \gamma x^2 + 2\alpha x x'(red) + \beta[x'(red)]^2$$

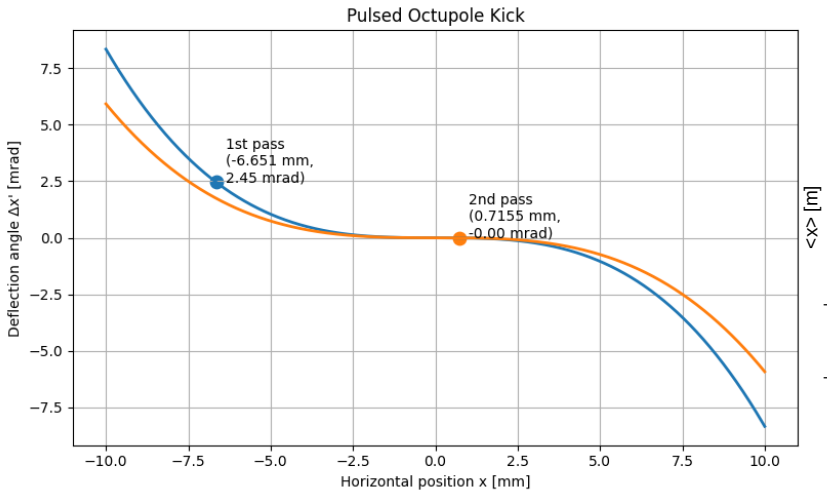
The kicker changes the trajectory angle to bring the bunch inside the acceptance.

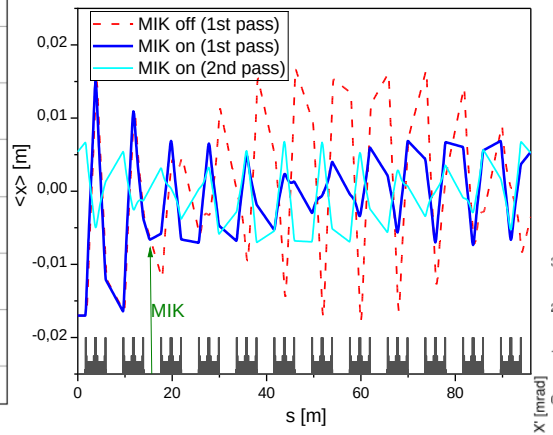
Two-turn injection with an octupole kicker

SOLARIS tracking study with an octupole-like multipole kicker as the hardware reference

Position-selective deflection

$By(x) \propto x^3$ $\Delta x' = (K_3L / 6)x^3$

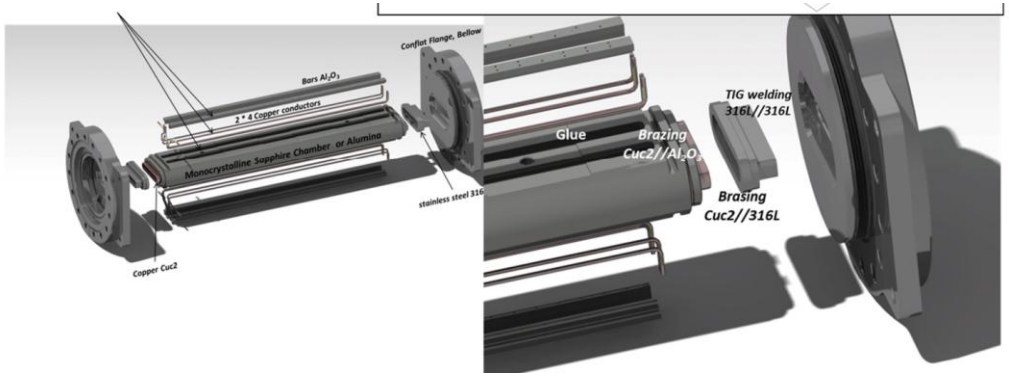




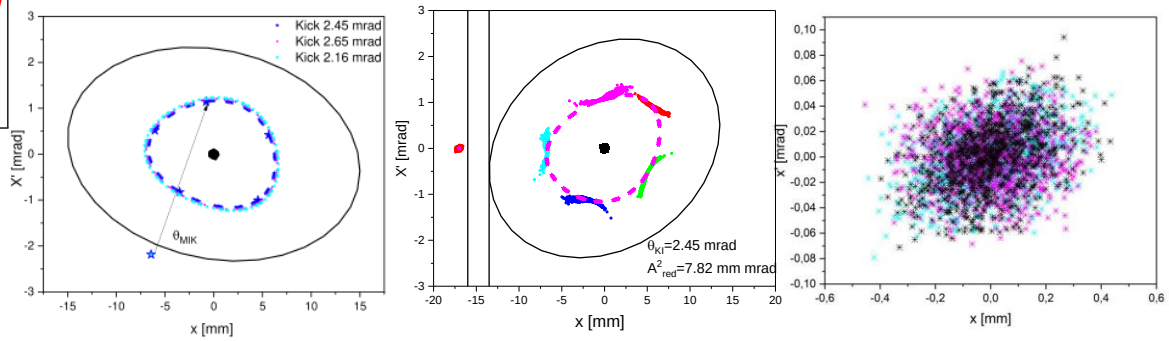
1st passage: x = −6.651 mm, kick ≈ +2.45 mrad

2nd passage: x ≈ +0.716 mm, kick close to zero

MAX IV / SOLEIL kicker



Published hardware example: octupole-like field



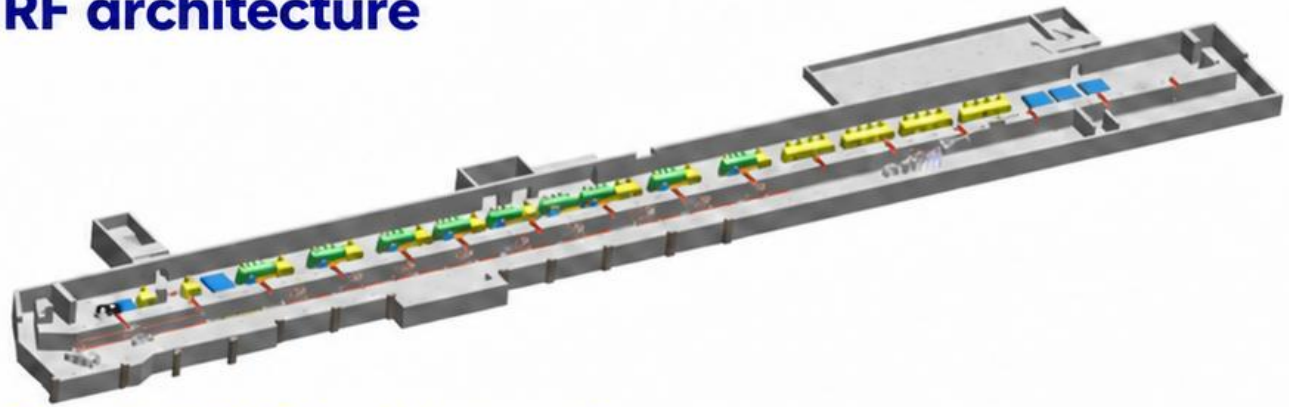
SOLARIS model: A²(red) ≈ 8 mm·mrad

Small kick near the stored-beam orbit

Hardware graphic: Da Silva Castro et al., MEDSI2018, TUPH12, Fig. 2 (CC BY 3.0).

Linac Integration: RF Systems & Laser

RF architecture



Reuse the initial S-band injector section
20 C-band structures at 5.712 GHz
Structure length: 1.8 – 2.0 m
Average design gradient: ~37 MV/m

RF integration



ScandiNova modulator



C-band pulse compressor



Waveguide distribution

High-power sources, modulators and pulse compression

Waveguide distribution and RF breakdown monitoring

LLRF amplitude and phase control

Photocathode injector option



Proposed laser: PHAROS 2H-4H, Light Conversion

Diode-pumped Yb laser: 1030 nm fundamental
Fourth harmonic: 257 nm UV
UV pulse energy: 100 – 200 µJ, model-dependent



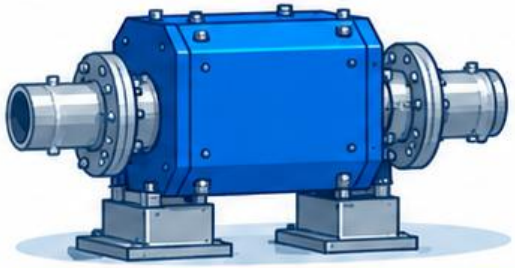
S-band RF gun with copper photocathode

- Laser-to-RF synchronisation
- UV transport, pulse shaping and spot control



Retain the thermionic injector and prepare a complementary photocathode gun

Linac integration: magnets, vacuum & controls



20 quadrupoles

Photocathode + BC configuration

Location	Magnets	Count
Injector transfer	QE1 – QE2	2
Before / after BC	Q1 – Q3, Q5 – Q7	6
Inside BC	Q4	1
Central matching	Q8 – Q10	3
Linac exit	Q11 – Q12	2
Transfer line	QF1 – QF6	6

Magnetic lengths: 0.07 – 0.20 m

Dipoles and steering correctors complement the focusing lattice



Vacuum

OFC copper structures and 316L interconnections

Ion pumps, gauges, valves and bellows

Vacuum interlocks



Mechanical integration

3D CAD integration and precision alignment

Supports, cable routes and maintenance access



Controls, timing and synchronisation

TANGO integration, acquisition and archiving

Synchronised RF, laser and injection events

LLRF amplitude and phase control

Interlocks across RF, vacuum and protection





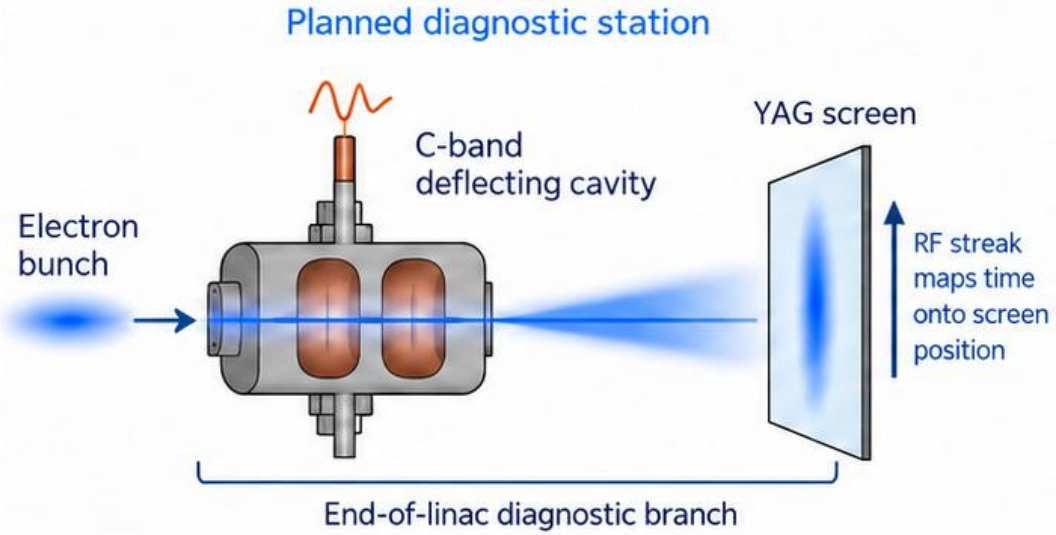
Commissioning and operational handover

FAT / SAT, RF conditioning, diagnostic calibration, beam matching and operator training

Beam Instrumentation

Instrument	Measurement and use
Stripline BPMs **Libera Single Pass**	Beam position and trajectory correction Paired BPMs: injection position and angle
YAG screens	Transverse profiles and beam size Quadrupole scans: emittance Dispersive sections: energy spread
Current transformers	Bunch charge and transmission Compare charge before and after sections
BLMs	Localise beam losses Optimise transport and injection

Longitudinal profile at linac end



Direct bunch profile and RMS duration

Compression tuning

Reference for CDR bunch-length monitors

TANGO integration: synchronised acquisition, archiving and beam tuning

C-band transverse deflecting structure







Parameter	Value
Operating frequency	5712 MHz at 28°C in vacuum
Mode	HEM11
Phase advance per cell	5π/6
Structure	Constant impedance, backward wave
Cells	77 + 2 coupling cells
Unloaded Q_0	≥ 7500
Effective shunt impedance	≥ 20 MΩ/m
Group velocity	0.021c
Filling time	0.27 μs

Longitudinal diagnostics:
RF streaking maps bunch time onto transverse position at a downstream screen.

Linac upgrade: implementation schedule



Project investment

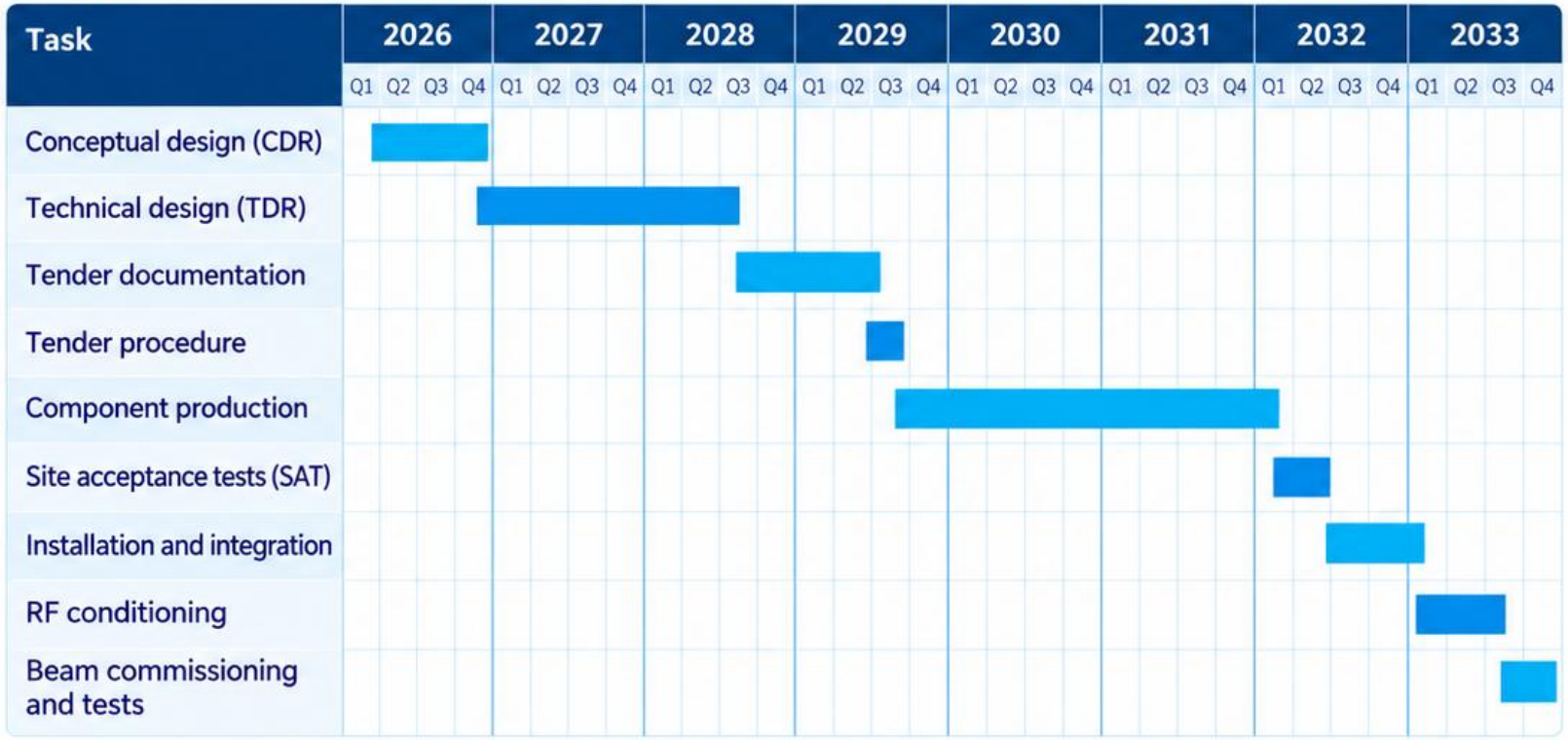
≈ €41.5 million

Requested investment, gross

Cost category	Share
Components and infrastructure	77.4%
Project personnel	13.5%
Installation and commissioning	9.1%

Peak delivery staffing: 15–25 FTE

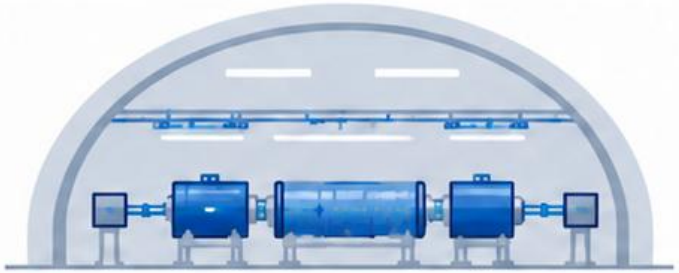
Project schedule



Key milestones

- **CDR: Dec 2026**
- **TDR: Sep 2028**
- **Return to operation: Dec 2033**

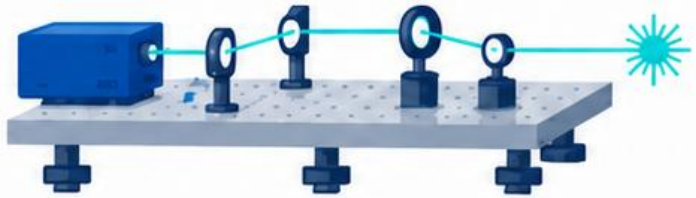
Key implementation challenges



Space and integration

Fit RF, magnets and diagnostics within the existing tunnel

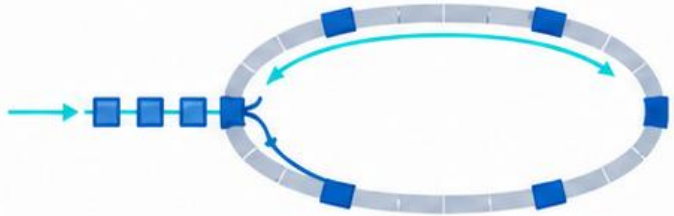
Maintain access for installation and maintenance



Photocathode laser laboratory

Establish the laser laboratory

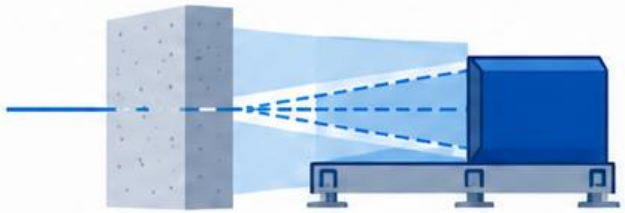
Integrate laser transport and synchronisation



Injection optimisation

Optimise the multipole kicker scheme

Control capture efficiency and stored-beam disturbance



Shielding and beam dump

Calculate and verify shielding

Validate the beam-dump design



Cooling and electrical systems

Existing utilities meet baseline demand

Assess dedicated cooling loops and LN_2 options



LLRF development

Develop linac RF control

Stabilise amplitude and phase



Future linac applications: accelerator R&D, radiation studies, FEL / short-pulse sources and a potential neutron source. Reserve space and interfaces for future experimental areas.



Thank you ☺

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