EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA Preparatory Phase

EuPRXIA@SPARC_LAB energy boosting to 5 GeV by LWFA and external injection

Andrea R. Rossi

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From EuPRAXIA CDR

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THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

EuPRAXIA Conceptual Design Report

Plasma accelerators: Two types of plasma accelerators are foreseen at the PWFA site of EuPRAXIA: one focussed on high beam quality for radiation generation and the other aiming to produce high-charge, high-average-power electron beams suitable for positron generation and as test beams. The *baseline* in both cases considers the external injection of the electron drive and witness beams from the RF accelerator into a weakly non-linear plasma stage to achieve beam-driven wakefield acceleration up to 1 GeV. The generated electron bunches based on current results comply with the requirements for both types of accelerator stages but could be optimised further towards high charge or high quality in the future. A detailed design is described in Section 17. Additionally, potential *future development paths* are foreseen through (1) increasing the energy reach to 5 GeV (see Sect. 17.2) as well as (2) improving the beam quality further, for example through using the RF-accelerated electron beam as a driver in a beam-driven plasma wakefield injector based on the Trojan horse injection mechanism (more details in Sect. 26).

Boundary conditions

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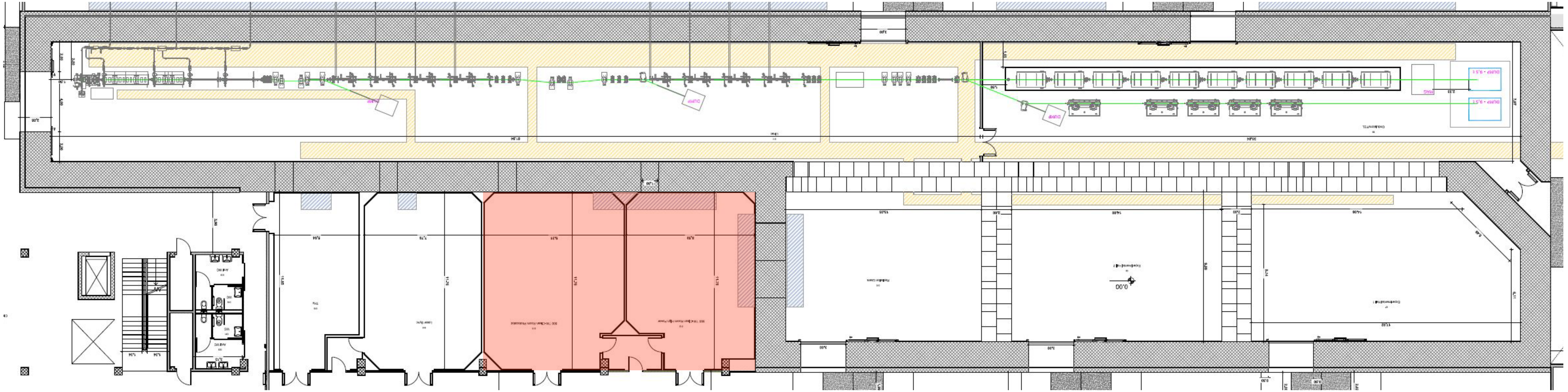
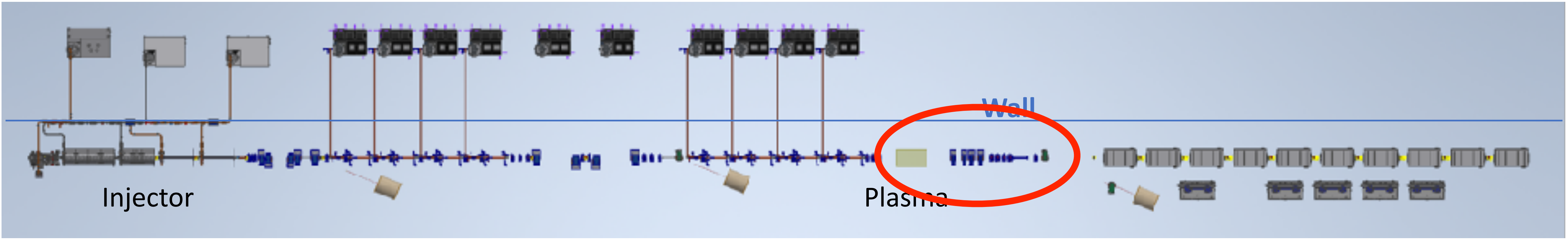
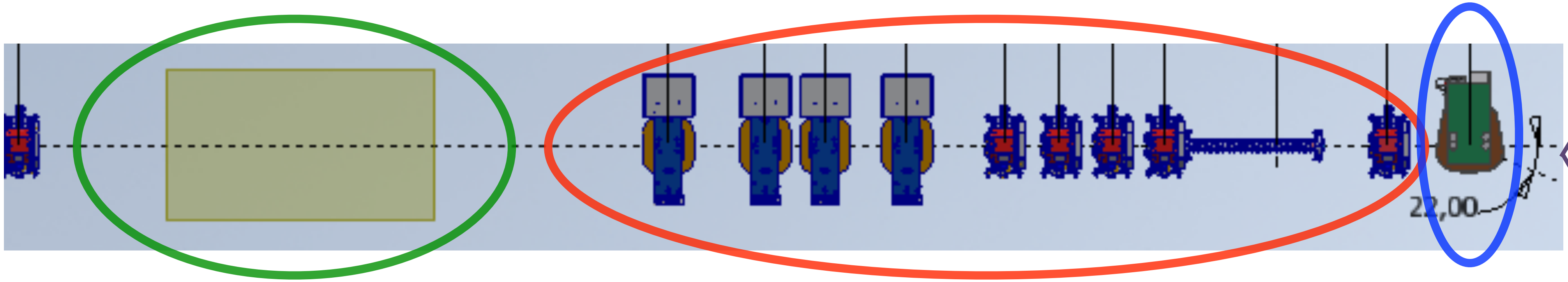




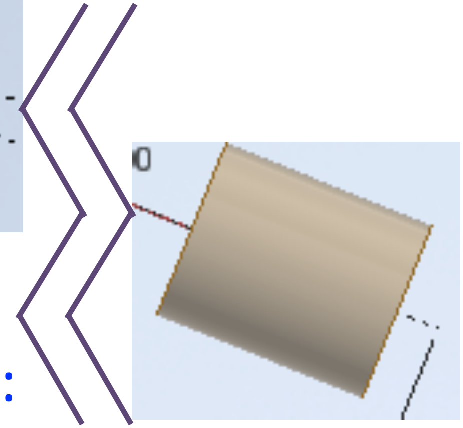
<u>But also an operating user facility</u>!

The interaction chamber, transfer line and diagnostic dipole



DUMP:

Only a placeholder!



INTERACTION CHAMBER:

Contains plasma target and optics for matching and capture of the electron bunch(es)

TRANSFER LINE:

A chicane for separating driver(s) from witness.

Quadrupoles for transport and matching to the dipole.

Diagnostics.

DIPOLE:

A bending magnet that opens dispersion and allows energy measurement.

We assume 22 deg bending angle.

The spectrometer dipole @ 5 GeV

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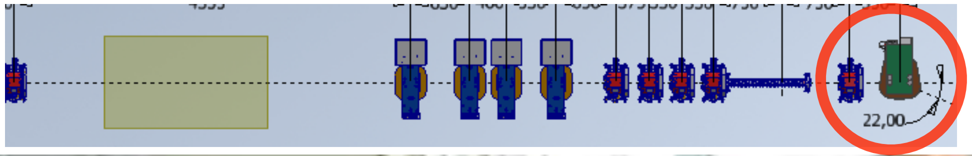

SESAME bending dipole @ 2.5 GeV

Bending radius [mm]	5729.58
Bending angle [deg]	22.5
Central field [T]	1.455
Field gradient [T/m]	-2.79
Central vertical gap (total) [mm]	40
Magnetic length [mm]	2250

https://www.sesame.org.jo/accelerators/technology/magnets-and-ids

SC option?

Possible, but expensive.

Assuming a bending angle as the 1 GeV spectrometers (same resolution)

EuPRAXIA@SPARC_LAB bending di

Bending radius [mm]	≈ 10000
Bending angle [deg]	22.5
Central field [T]	≈ 1.7
Field gradient [T/m]	-2.79
Central vertical gap (total) [mm]	40
Magnetic length [mm]	≈ 4000

Transfer line

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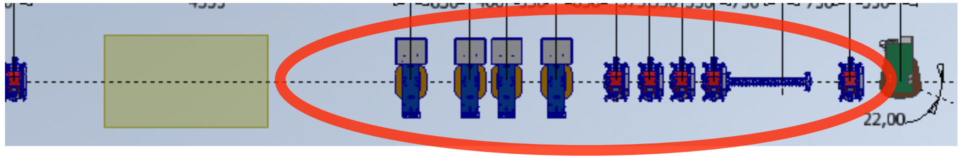

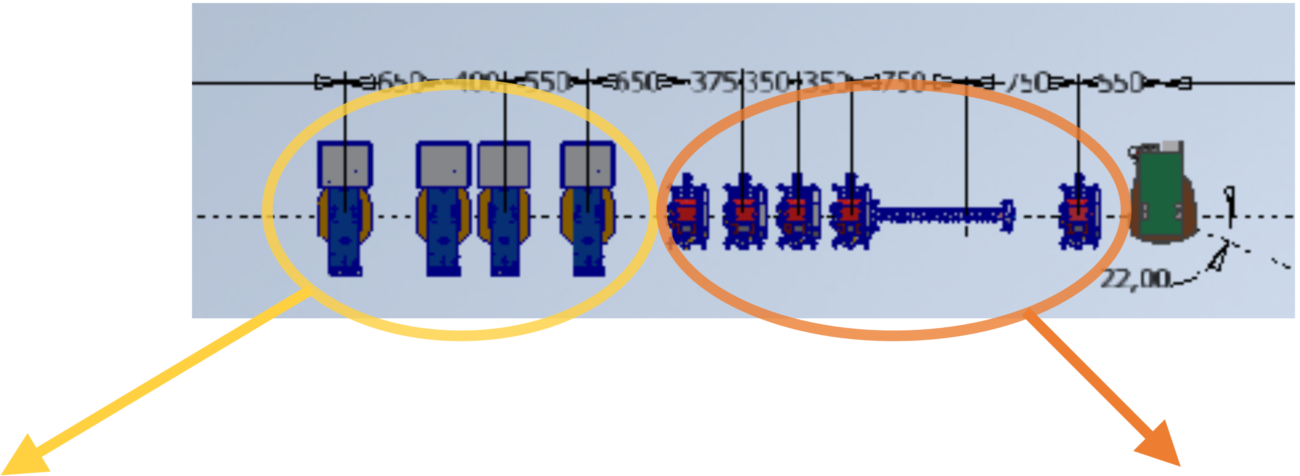

Driver - Witness separation chicane: most probably not needed.

Transfer - matching line (3125 mm).
Very rough approximation: $\times 3 \approx 10$ m

Again, SC magnets could be a viable but expensive alternative.

The PWFA option: high transformer ratio

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THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

EuPRAXIA Conceptual Design Report

17.2 Numerical Design for the 5 GeV Case

17.2.2 Driver Train Structure and Transformer Ratio

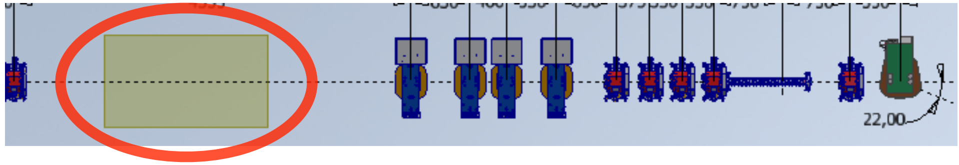
We assume a train of driver bunches generated by an X-band RF linac up to the energy of 1.2 GeV. Increasing energy transfer in a PWFA stage requires a driving structure with a higher transformer ratio R_T than the 1 GeV case. This condition can be obtained by utilising a train of drive electron bunches [192]. An energy increase from 1.2 GeV to 5 GeV requires an effective transformer ratio of $R_T \approx 3.2$, whereby

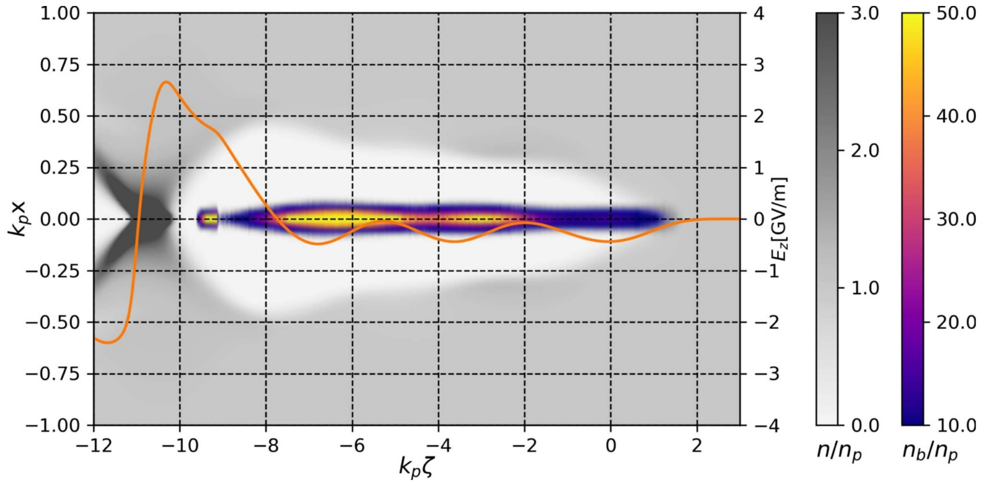
...

we designed an ideal train of 3 drivers with ramped increasing charge densities.

...

emittance of the two bunches is chosen arbitrarily as $\varepsilon_{n,xy}$ =1 mm mrad. The charges are Q_1=40 pC, Q_2=140 pC, and Q_3=270 pC. They are properly calibrated to obtain





Train of 4 bunches (3D+1W) with tuned, increasing charge and tailored current profile

Plasma chamber: the PWFA option

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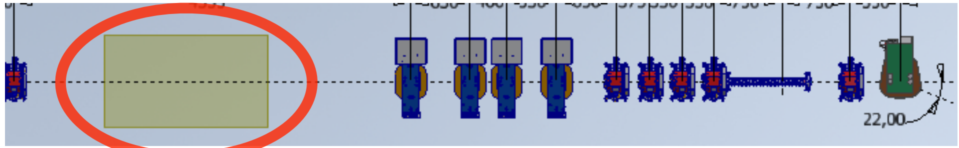
EuPRAXIA Conceptual Design Report

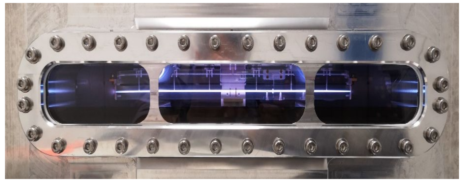
17.2 Numerical Design for the 5 GeV Case

17.2.3 Bunch Acceleration

The witness is designed with the energy of $E = 1.2$ GeV and an initial uncorrelated energy spread of $\sigma_E = 0.7$ %. As in the 1 GeV case, a triangular current shape is chosen to reduce the energy spread growth with an RMS bunch length of $\sigma_z = 3.6$ µm. The transverse emittance is arbitrarly chosen as $\varepsilon_{n,xy} = 0.7$ mm mrad, and the Twiss functions are $\alpha_{x,y} \approx 1$ and $\beta_{x,y} \approx 22$ mm, to reach the matching condition from equation (17.1) at the beginning of the plateau. The peak field is located at the bubble closure with a value of $E_z \approx 2.7$ GV/m (see Fig. 17.3). The bunch separation between the centroids of the last driver and the witness is set as 0.46 λ_p, corresponding to ≈97 µm in order to minimise the energy spread growth. With this fixed, the mean accelerating gradient acting on the witness is $E_z \approx 1.6$ GV/m.



1 GeV plasma target: $\approx 40 - 60$ cm,
int chamber ≈ 3 m (contains PMQs)

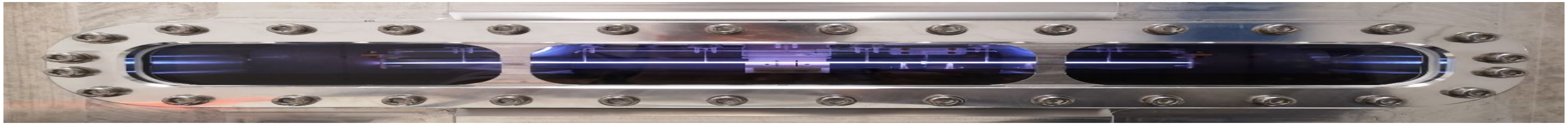


ASSUME:

- $E_{in} = 1.2$ GeV
- $\langle E_z \rangle \approx 2.0$ GeV

The only way to reduce size is improving WP average field.

5 GeV plasma target: ≈ 250 cm, int chamber 5 m - 7 m (?)



LWFA: external injection

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INFN
Istituto Nazionale di Fisica Nucleare

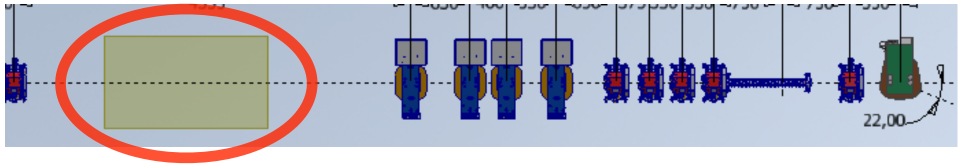
LNF–18/03
May 7, 2018

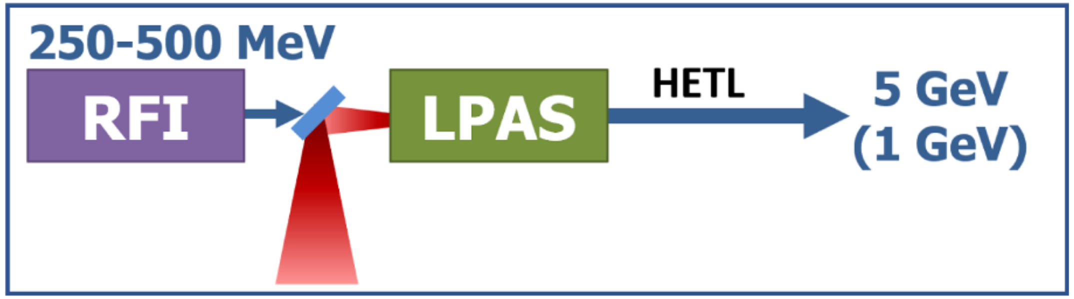
EuPRAXIA@SPARC_LAB

Conceptual Design Report

	Units	value
Central wavelength	nm	800
Bandwidth	nm	60 - 80
Repetition rate	Hz	1 - 5
Max energy before compression	J	20
Max energy on target	J	13
Min pulse length	fs	25
Max power	TW	500
Contrast ratio		10^{10}
Laser spot size at focus (optics dependent)	µm	2 - 50
Peak power density at focus (optics dependent)	W/cm^2	10^{22} - 10^{19}

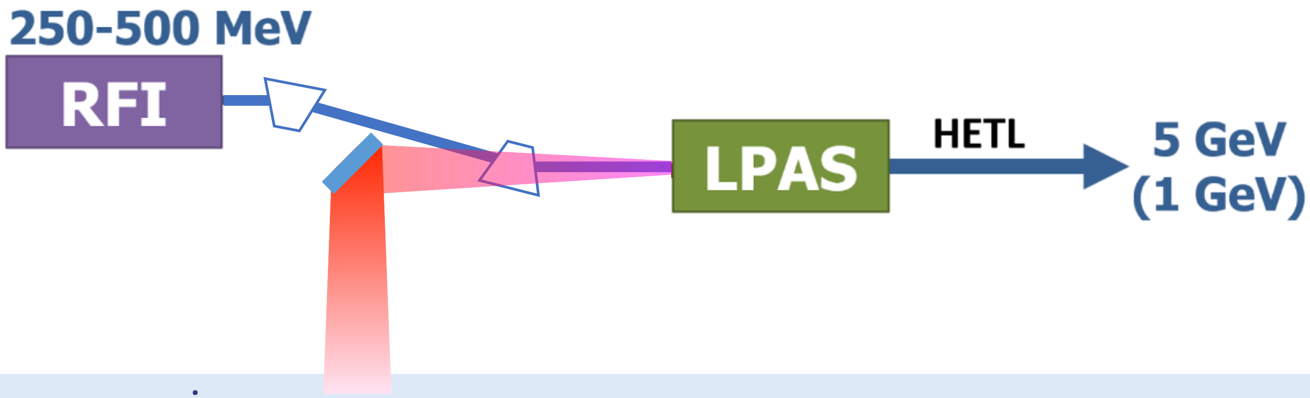
Table 11.2: Laser beam parameter for the upgraded FLAME laser.





I assume **discharge capillaries**. The high power laser pulse needs to be guided for the whole capillary length.

I am **NOT** considering the laser transport system!



Plasma chamber: the LWFA option

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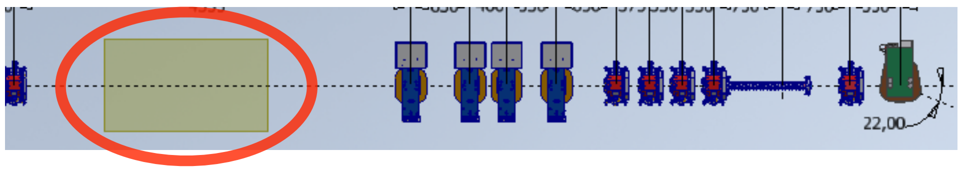

ASSUME:

- $E_{in} \sim 0.5 - 1.0$ GeV
- $\langle E_z \rangle \gtrsim 7.0$ GeV

5 GeV plasma target: ~ 50 cm, int chamber 3 m - 5 m

Straight PWFA

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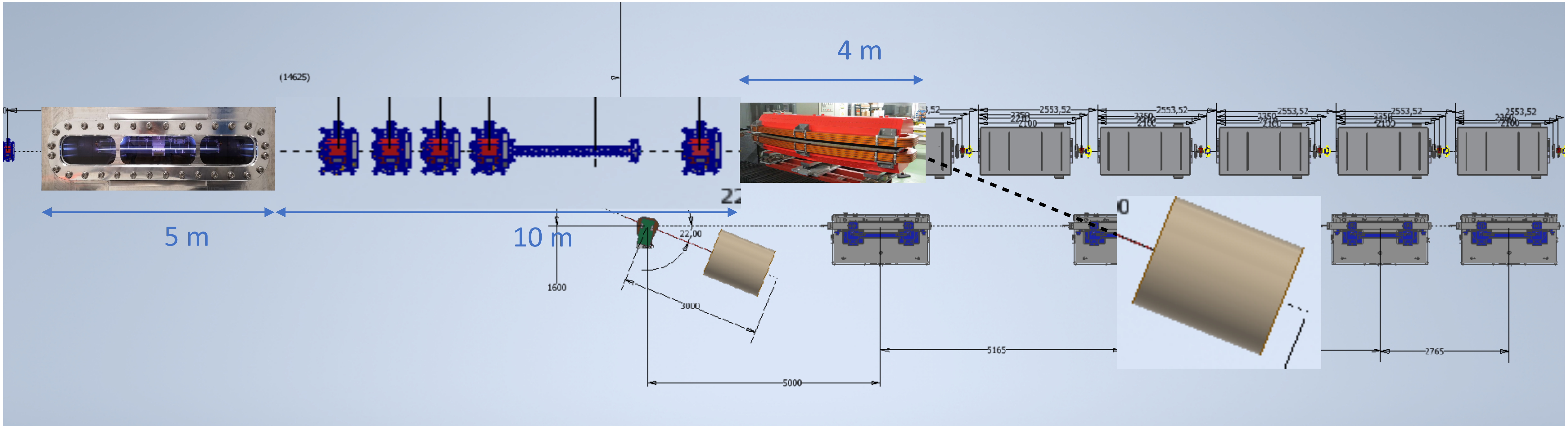
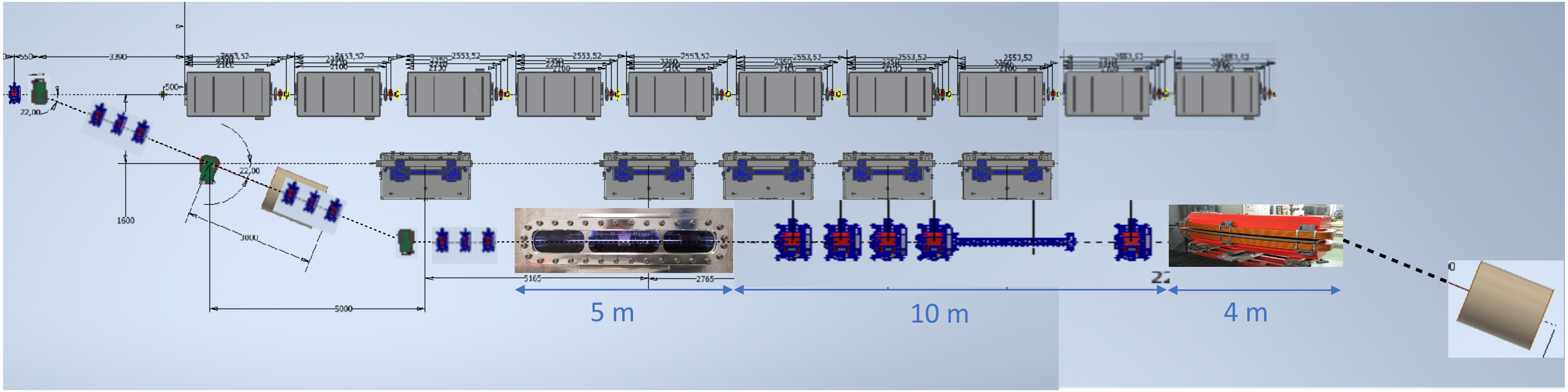


The most trivial solution is "invasive"!

It's implementation prevents facility operation for a long time and requires significant intervention and careful planning

Dogleg PWFA



PROS:

- Compatible with facility current layout
- All PWFA

CONS:

- Large bending angle (22 deg)
- Highly risky: dogleg + COMB structure

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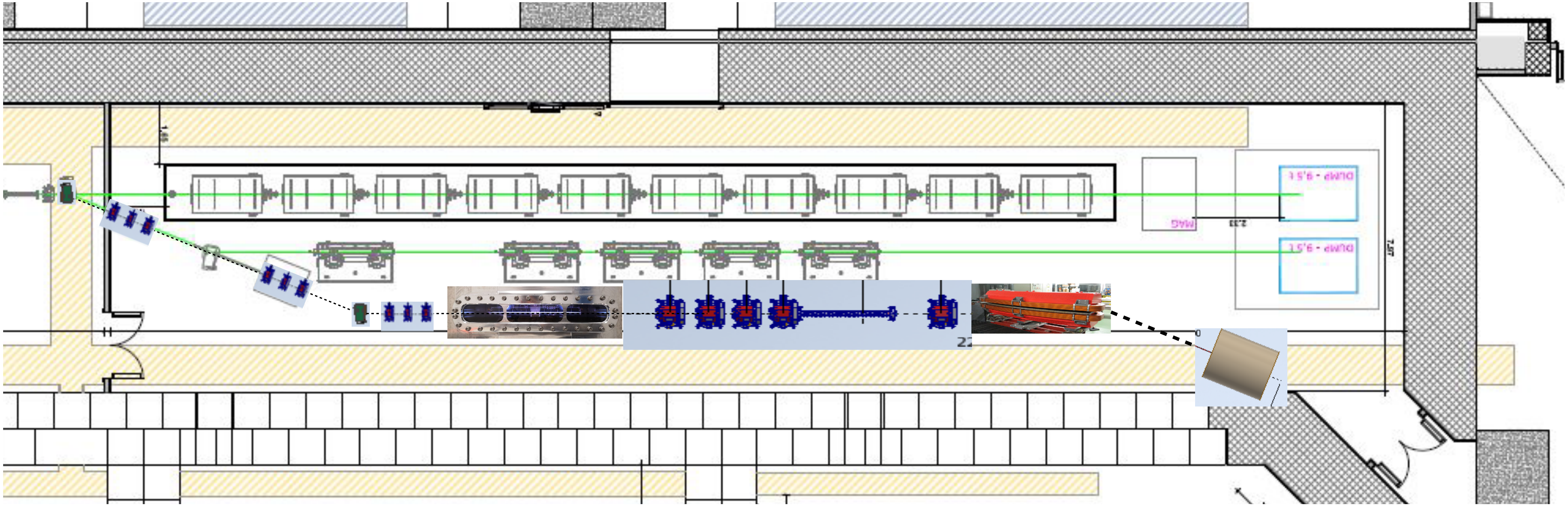
Dogleg PWFA: building constraints



Dogleg LWFA: injection @ 500 - 600 MeV

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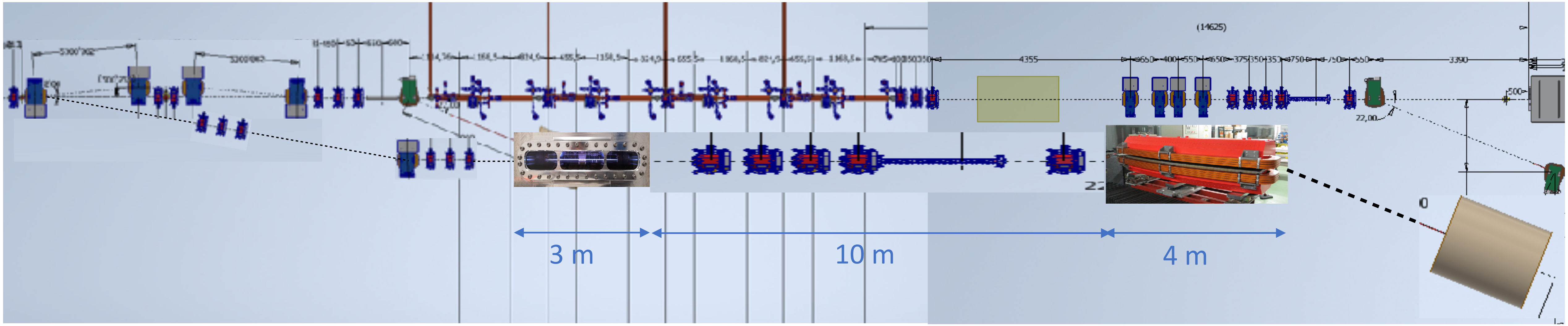


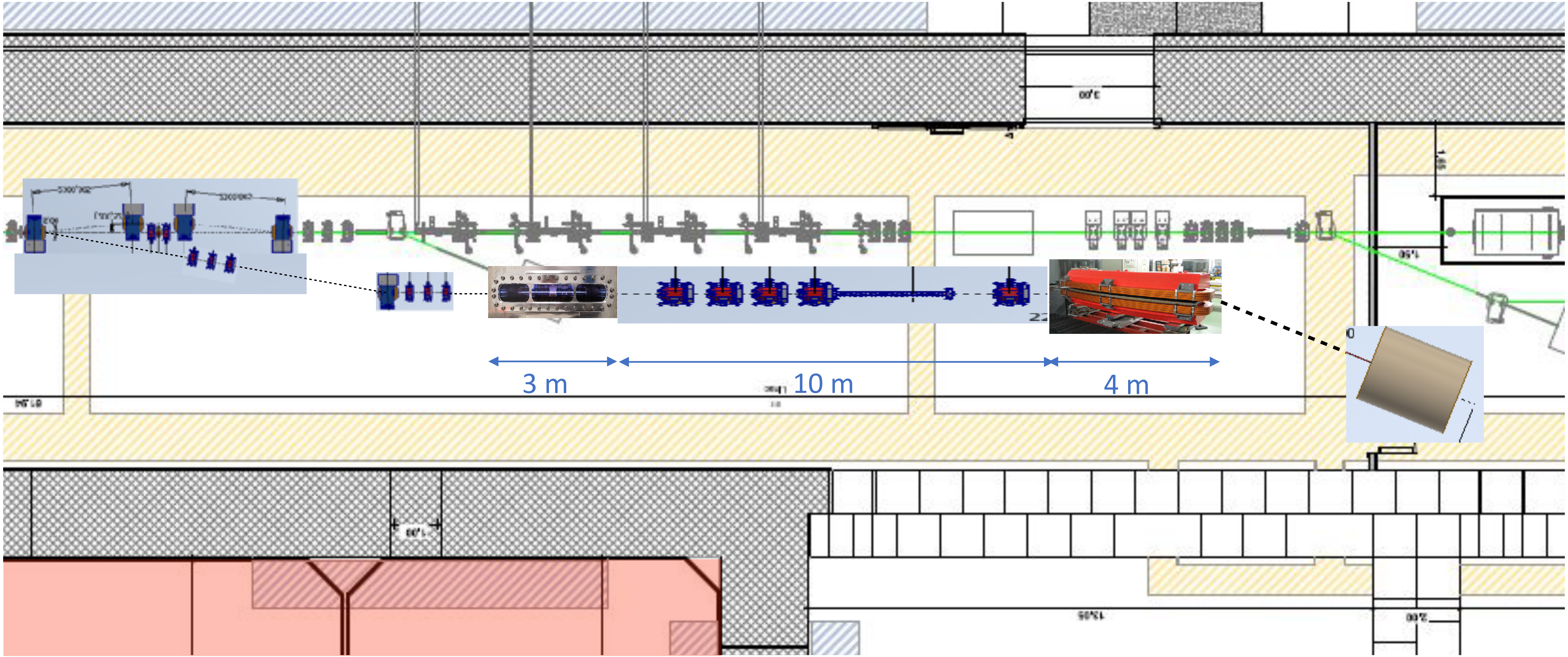
PROS:

- Compatible with facility current layout
- Dogleg with smaller angle (10 deg)
- Works with 12J laser on target
- Undulator room downstream

CONS:

- No PWFA at all
- Risky: long laser guiding
- Low rep rate
- Laser should be removed

Dogleg LWFA @ 500 MeV: building constraints



Dogleg LWFA: injection @ 100 MeV

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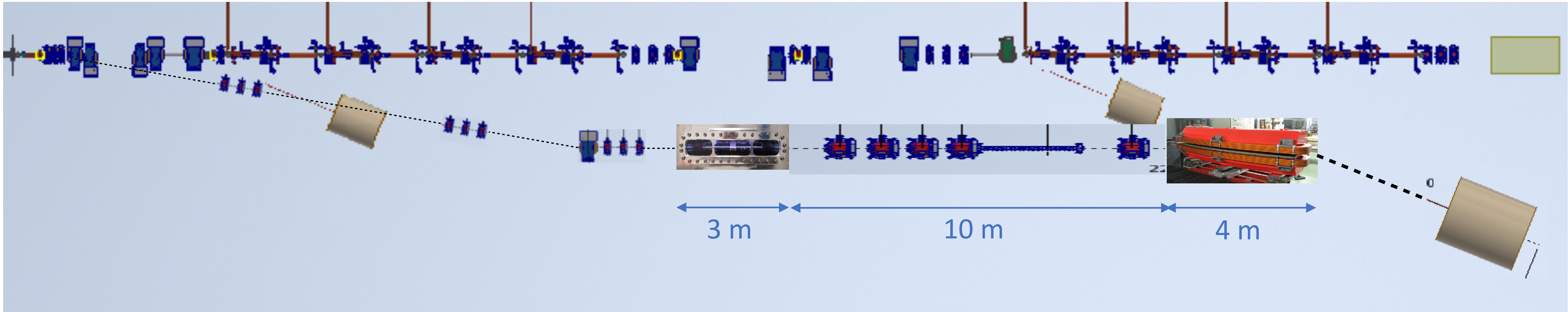

PROS:

- Compatible with facility current layout
- Dogleg with smaller angle (10 deg)
- Lot of space downstream

CONS:

- No PWFA at all
- Lower injection energy, requires 1 PW laser
- Risky: long laser guiding
- Low rep rate

Dogleg LWFA @ 100 MeV: building constraints

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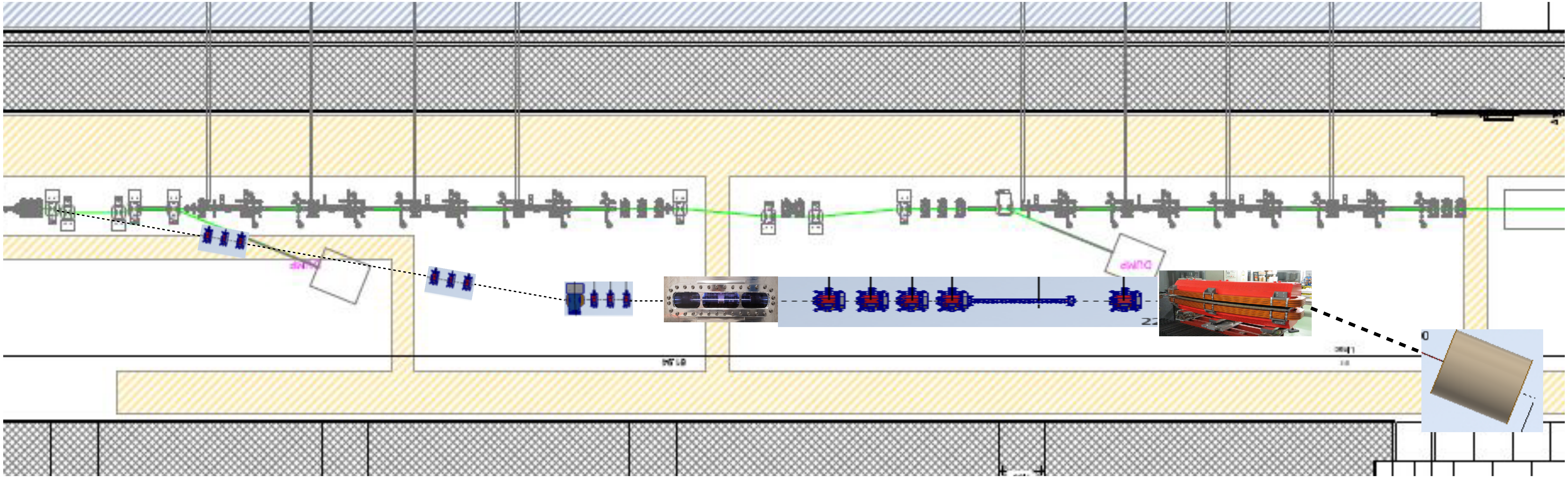
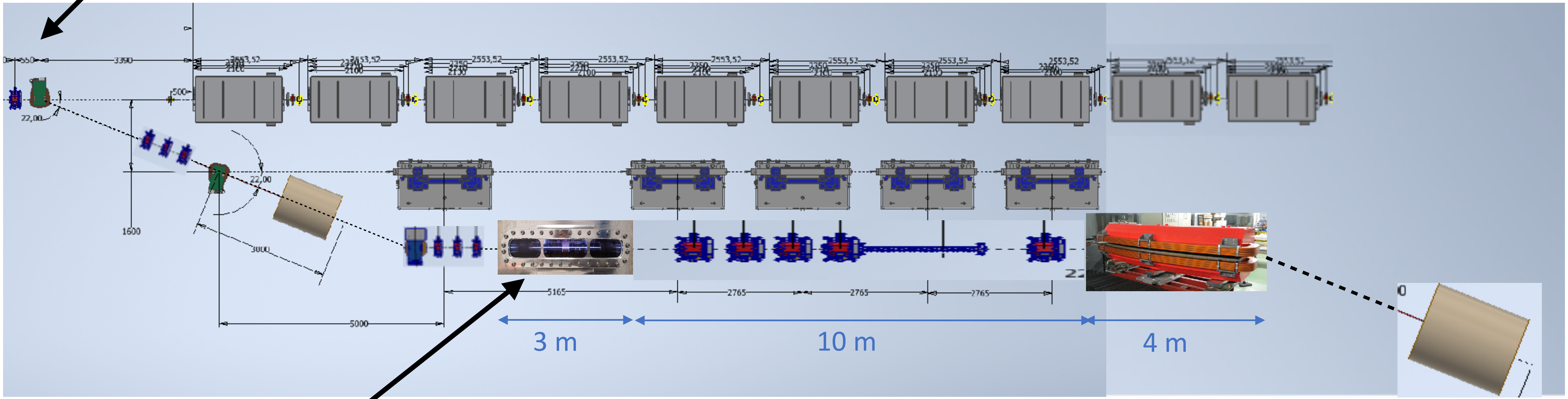


Hybrid PWFA + dogleg LWFA, option 1

From PWFA: E_{out} = 1.0 - 1.7 GeV



LWFA: E_{in} = 1.0 - 1.7 GeV E_{out} = 5.0 GeV

PROS:

- Compatible with facility current layout
- PWFA + LWFA!

CONS:

- Large angle dogleg
- Risky: long laser guiding
- Staging

Hybrid PWFA + LWFA 1: building constraints

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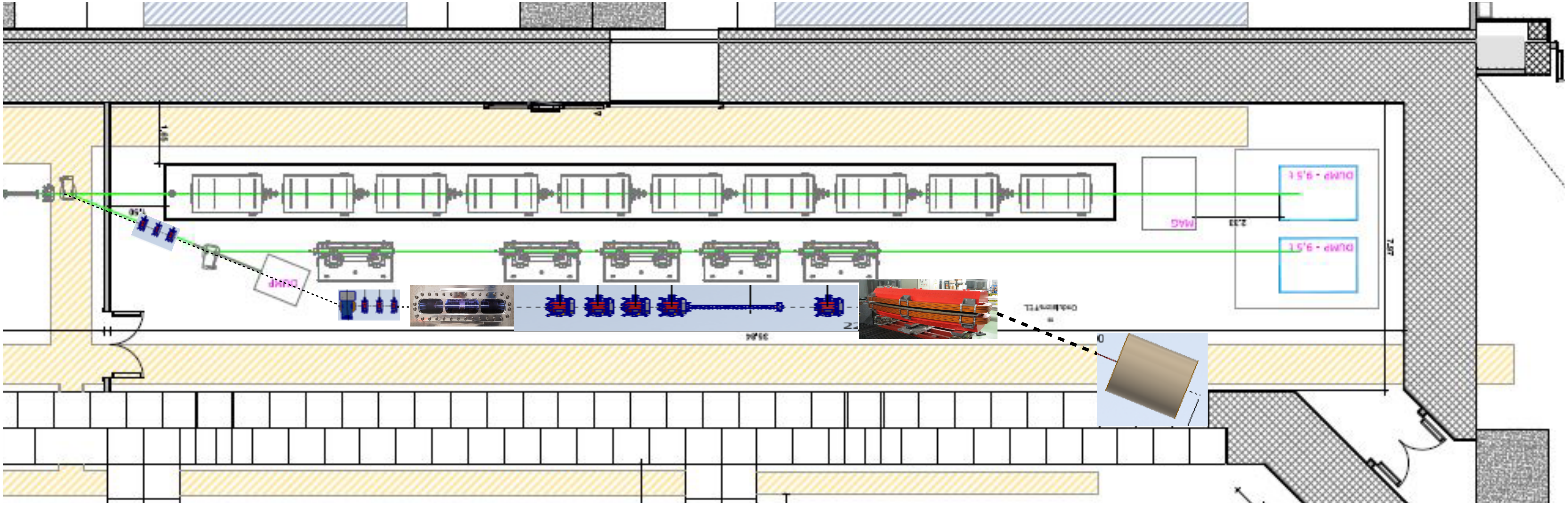
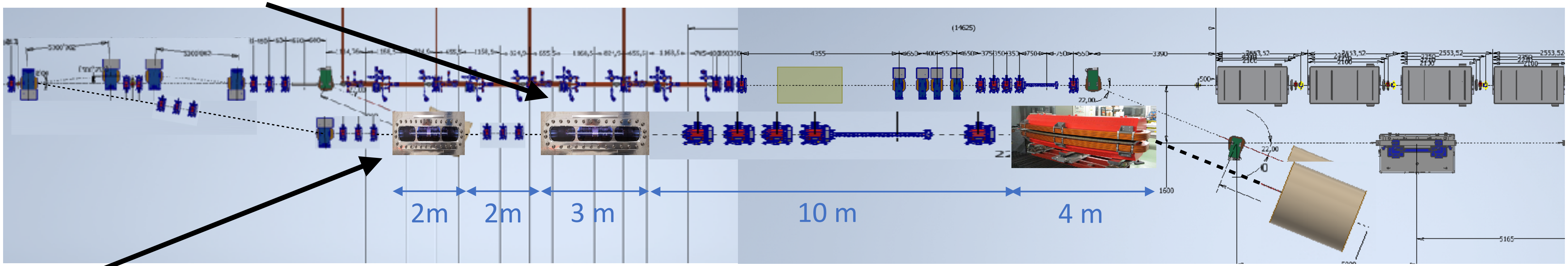


Hybrid PWFA + dogleg LWFA, option 2

LWFA: E_{in} = 1.0 GeV E_{out} = 5.0 GeV



PWFA: E_{in} = 500 MeV E_{out} = 1.0 GeV

PROS:

- Compatible with facility current layout
- Small dogleg angle (10 deg)
- Only 1D + 1W in dogleg
- PWFA + LWFA!

CONS:

- Comb structure in dogleg
- Risky: long laser guiding
- Staging

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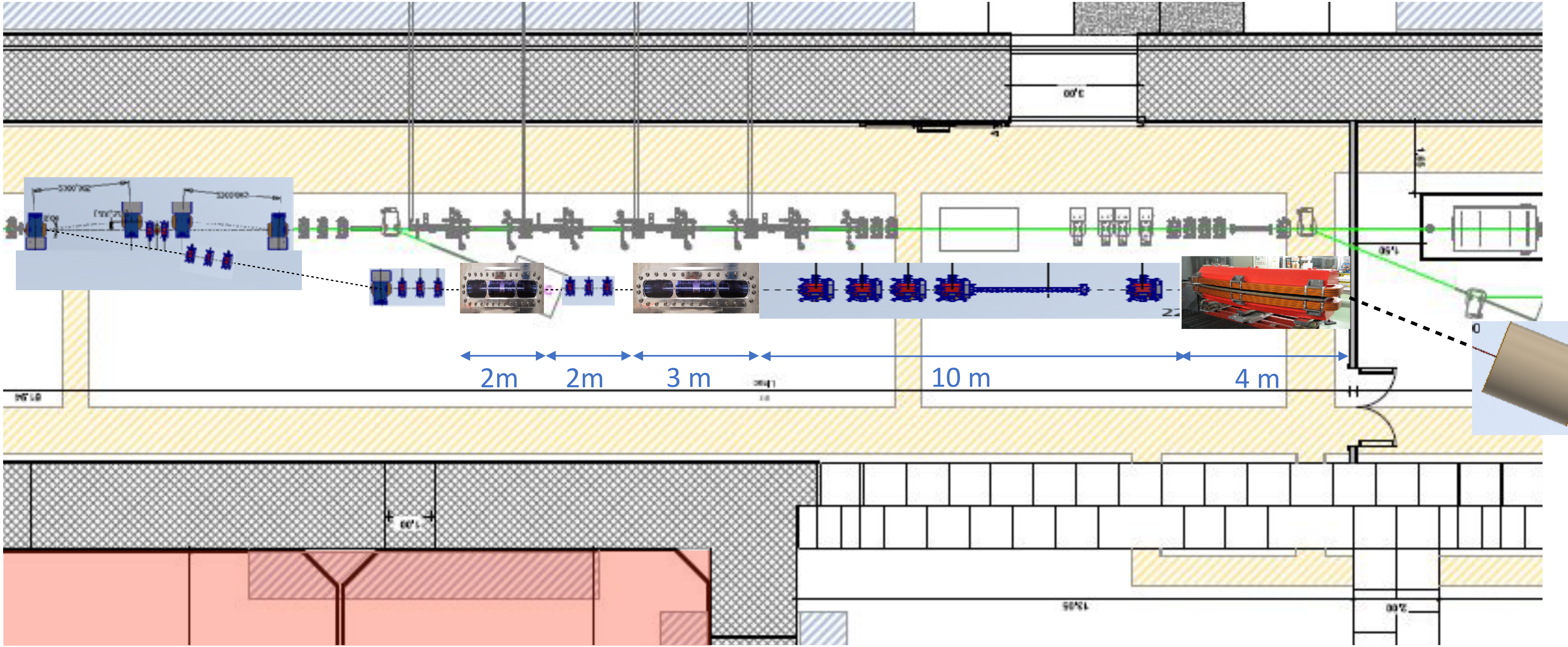
Hybrid PWFA + LWFA 2: building constraints



Risk mitigation

- Hose instability/dispersion related problems: Dumper bunch, arXiv:2409.12041v1

Oscillation damper for misaligned witness in plasma wakefield accelerator

K.V. Lotov, I.Yu. Kargapolov, P.V. Tuev
[1] *Novosibirsk State University, Novosibirsk 630090, Russia*
[2] *Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*

(Dated: 19 September 2024)

- Long guiding channel: filament, HOFI

- Laser removal: plasma mirror

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EuPRAXIA Preparatory Phase

Thanks for your attention

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EuPRAXIA
Preparatory Phase

Backup slides

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Dogleg LWFA: injection @ 500 - 600 MeV

Laser parameters:
σ_{tr} = 40 μm
E_l = 12 J
σ_τ = 30 fs

Bunch parameters:
q = 30 pC
E_{in} = 500 MeV
σ_τ = 13 fs

$n_0 = 5 \times 10^{16}\ cm^{-3}$