ATHENA$_e$ infrastructure

Accelerator Research and Development
ARD
A program by the Helmholtz association

JÜLICH FORSCHUNGSZENTRUM

GSI

KIT Karlsruhe Institute of Technology

DESY

HZB Helmholtz Zentrum Berlin

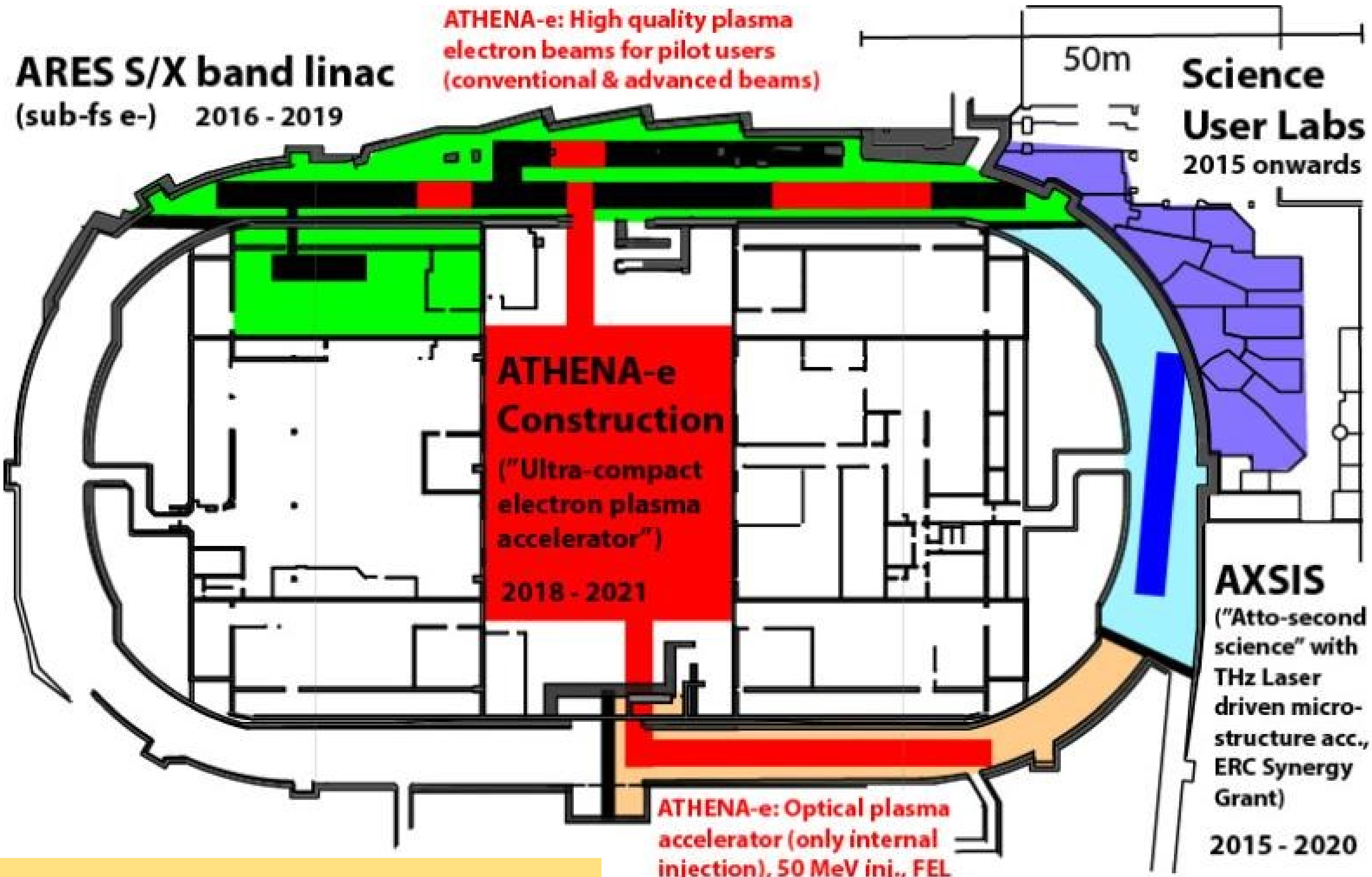
HZDR

HI Jena Helmholtz Institute Jena

B. Marchetti
DESY
for the ATHENA team

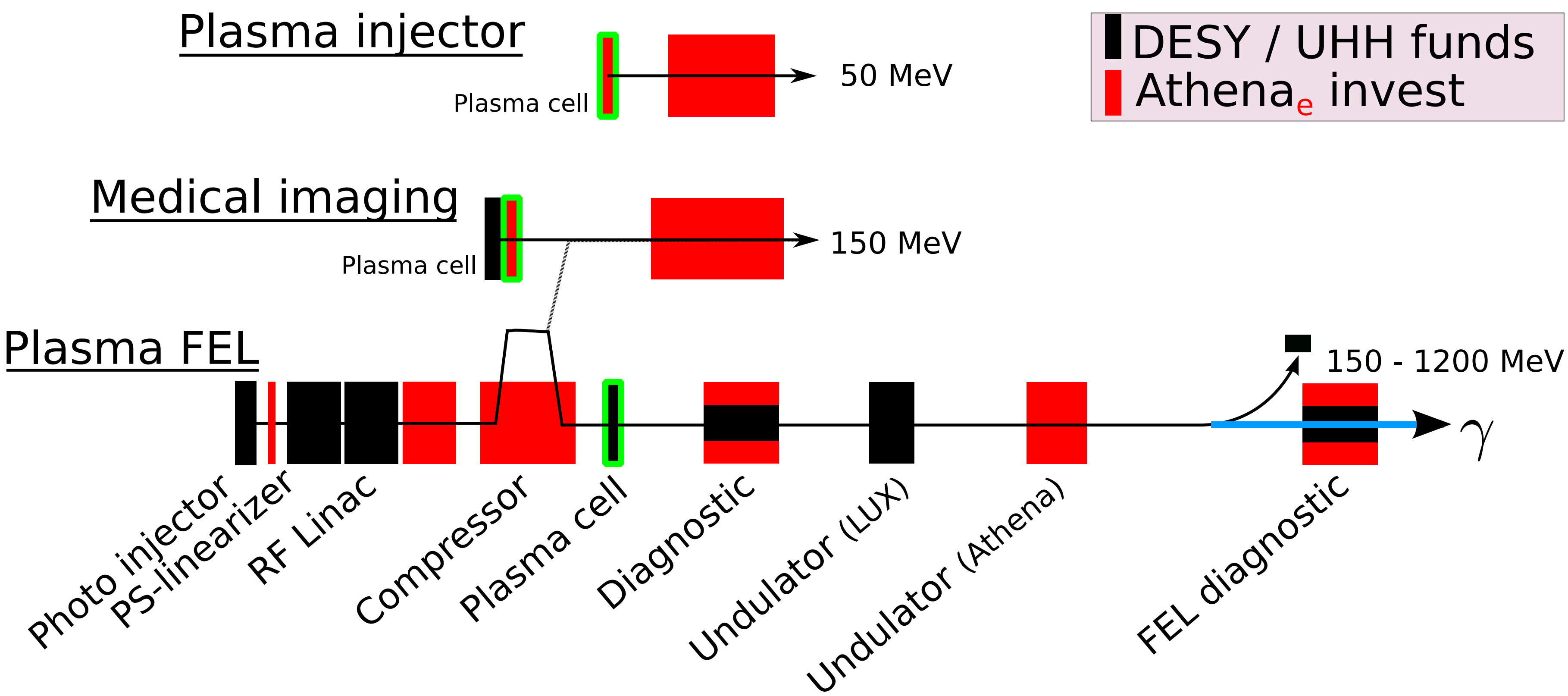
HELMHOLTZ GEMEINSCHAFT

SINBAD as host to ATHENA$_e$



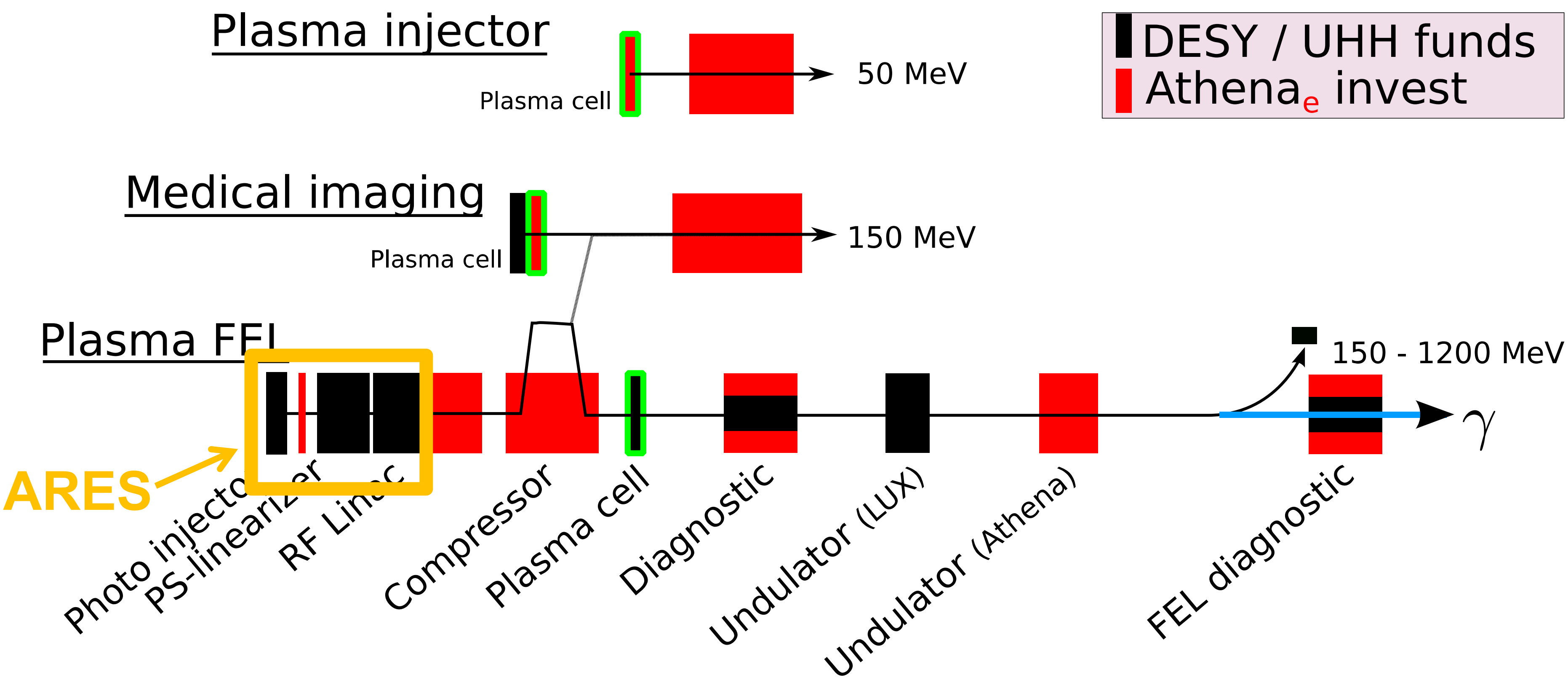
SINBAD
Short **IN**ovative **B**unches and **A**ccelerators at **D**esy
PL: Ulrich Dorda

ATHENA$_e$ hosted at DESY



Direct **comparison** of performances of **conventional acceleration vs PWFA** (internal + external injection), both driven by lasers (baseline) and e-beams

ATHENA$_e$ hosted at DESY



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(internal + external injection),
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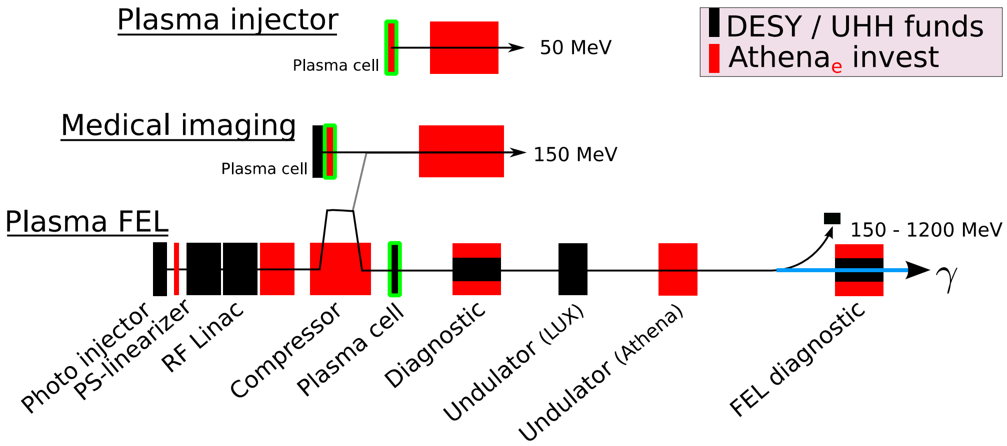
Main extension to ARES through ATHENA

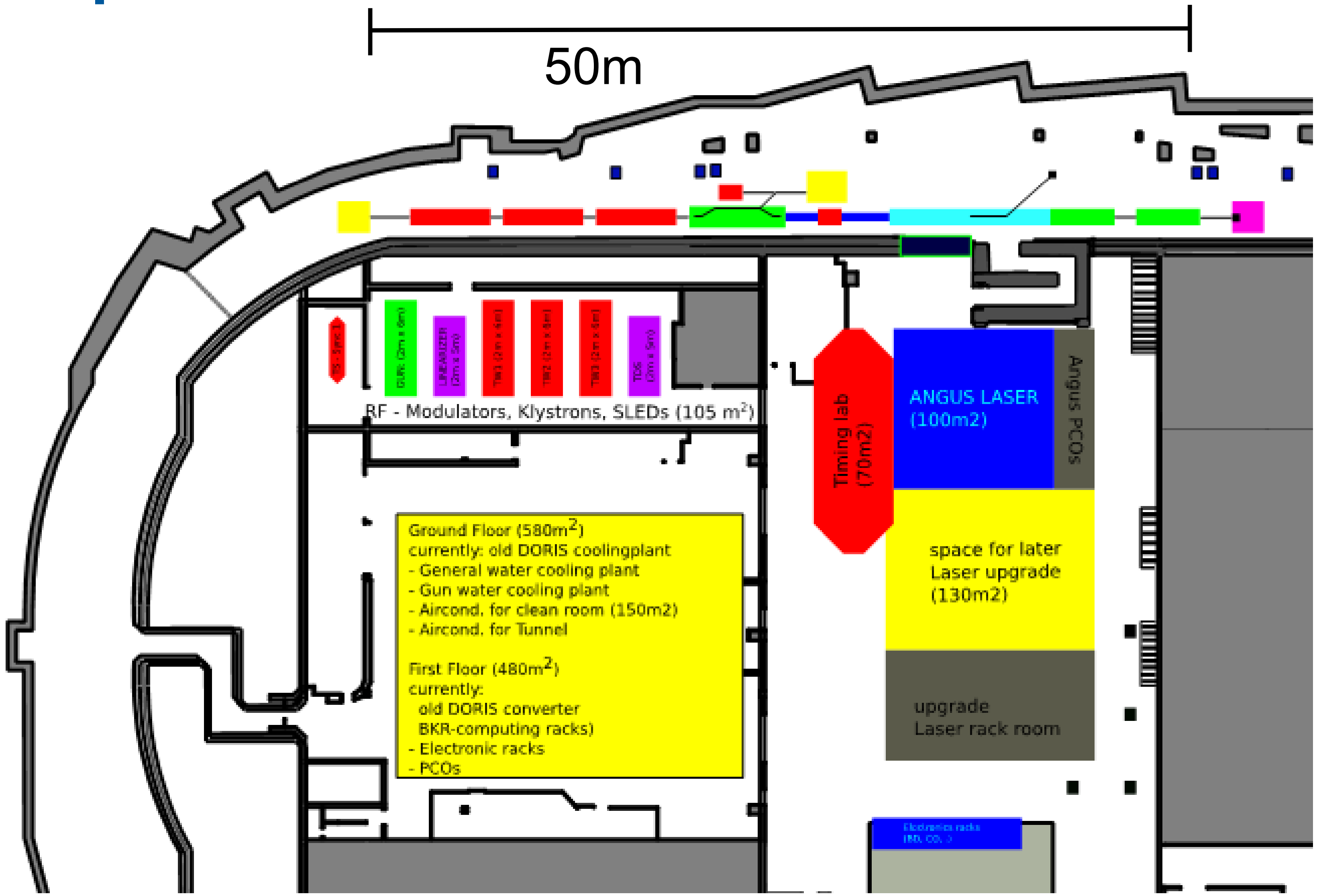
- Bunch compressor/ dogleg
- Energy upgrade of linac
- X-band for Transverse Deflecting Structure (TDS) and Phase Space (PS) linearization
- Timing synchronization upgrade
- Additional undulators
- Imaging beam line



ARES

ACCELERATOR **R**ESEARCH **E**XPERIMENT AT **S**INBAD

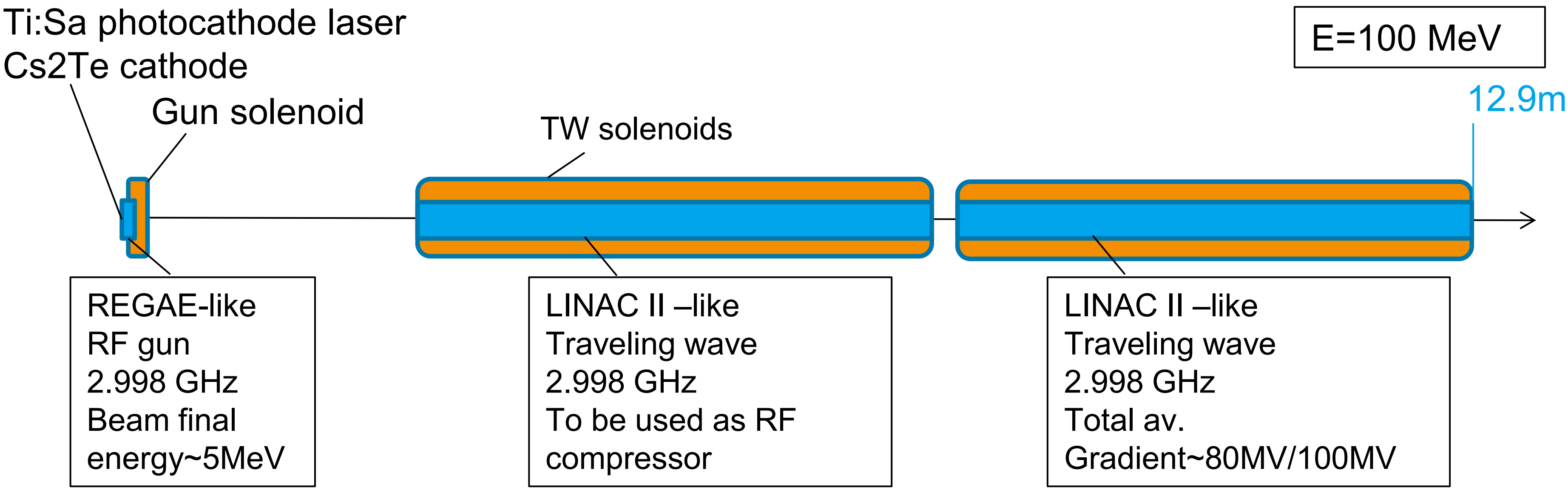
Required Infrastructure



ARES linac

- Initial stand-alone goal: acceleration of ultra-short bunches in a conventional compact linac.
  - Reaching the sub-fs domain **(FWHM bunch length ≤ 1 fs)**
  - E-bunch energy **100 MeV** (later upgrade to 200 MeV)
  - Nominal Charge for ultra-short bunches with RF compression: **0.2-20 pC**
  - Maximal Charge that can be extracted from the cathode: 1nC
  - Energy spread: **0.1 - 0.4 %**
  - Transverse emittance **< 0.5 mm mrad**
- Second stage: ARES in the context of ATHENA
  - External injection into plasma cell + FEL
    - Arrival time jitter (RMS) **≤ 10 fs**
    - Transverse position jitter **≤ few µm**
  - Imaging set-up (Thomson scattering)

ARES linac baseline layout



Q=0.5 pC, Ne=3.12*10^6

Beam at the exit of the linac for 3 different working points

$FWHM_z$ [fs]	Q % in 1 FWHM	E [MeV]	ΔE/E	$\sigma_{x,y}$ [mm]	$n\varepsilon_{x,y}$ [mm*mrad]	$(\alpha_{x,y},\beta_{x,y}$ [m])	(I_p local, I_p 1FWHM)[A]
2.1	50.6	110	0.1%	0.6	0.07	-71, 1284	150, 133
2.7	62.2	111	0.1%	0.15	0.05	0.9,79	150, 115
4	70	111	0.3%	0.009	0.05	0.03, 0.3	100, 87

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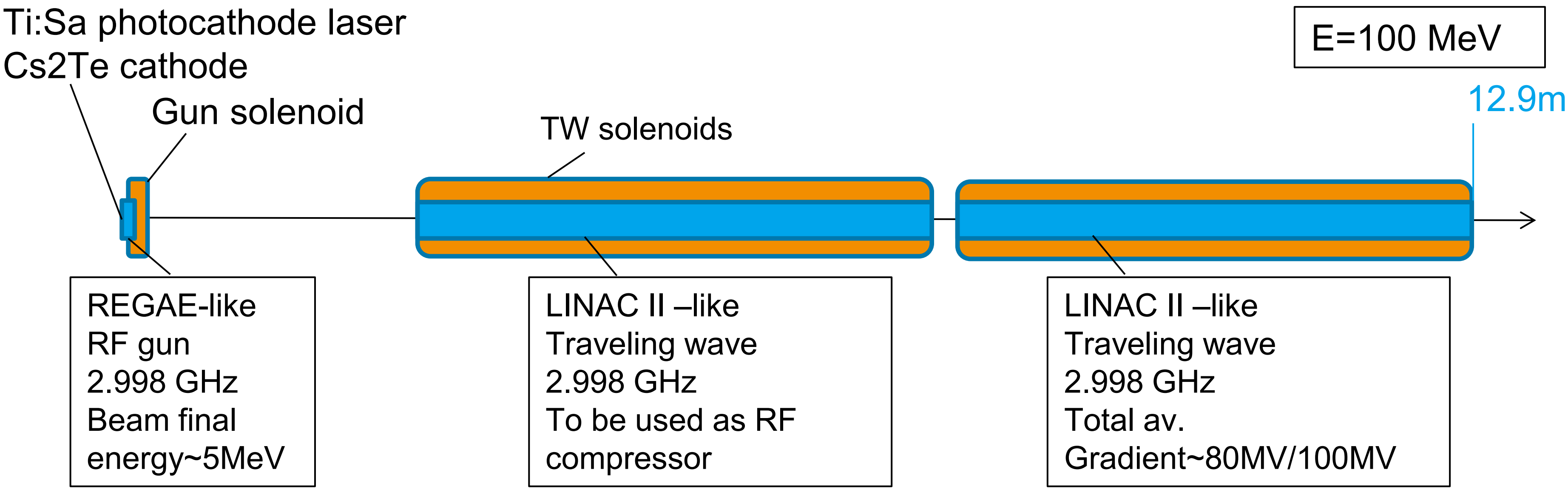

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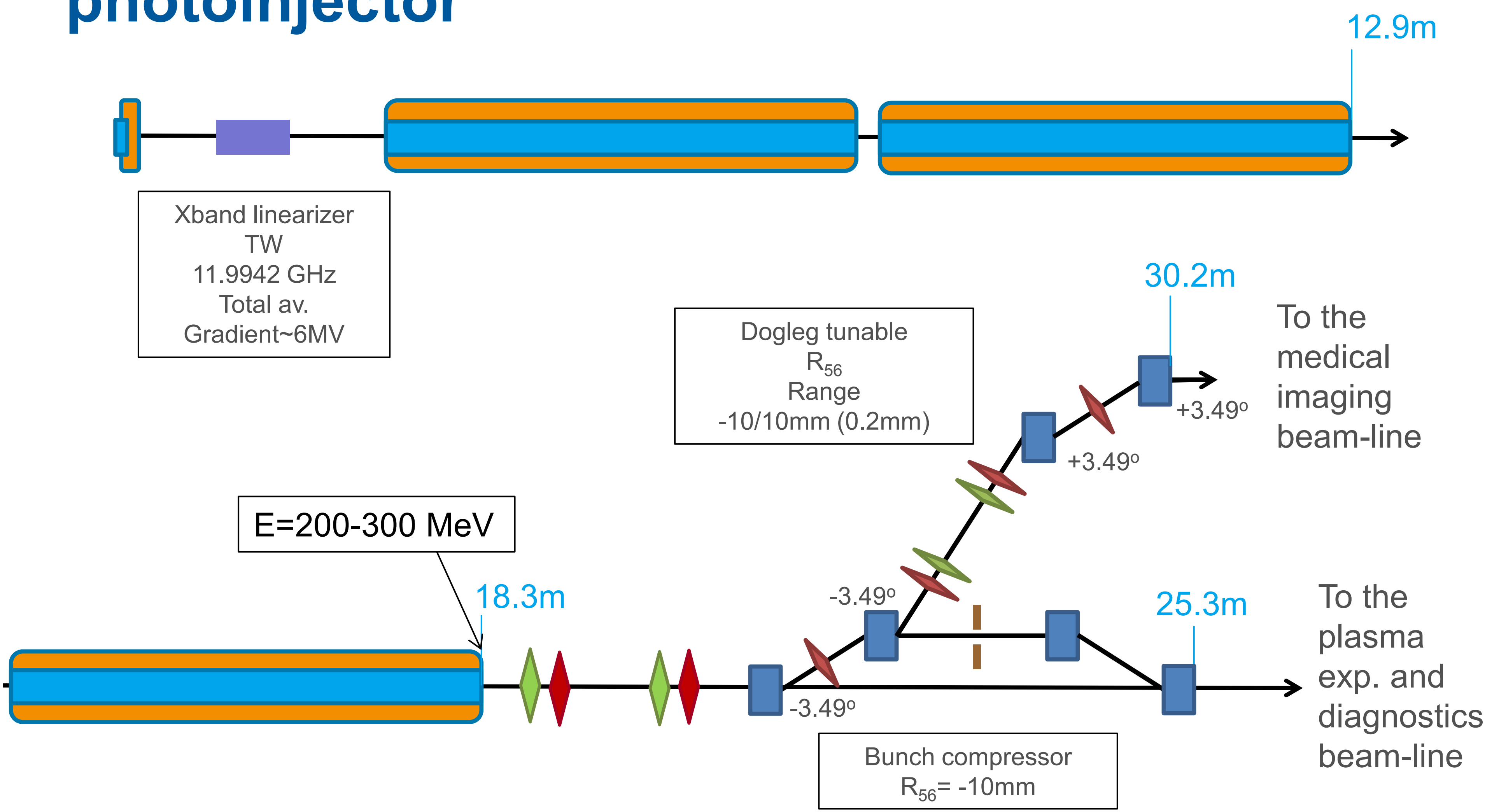
Small spot-size for matching into plasma

ARES – upgraded layout of the photoinjector



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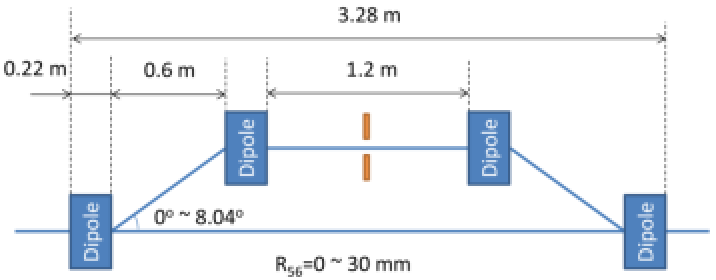
Bunch Compressor



Working point A

Initial charge (pC)	10
Gun gradient (MV/m)	110.0
Gun phase (deg)	0.0
Laser pulse duration (ps)	3.0
TW1 gradient (MV/m)	23.9
TW1 phase (deg)	-59.2
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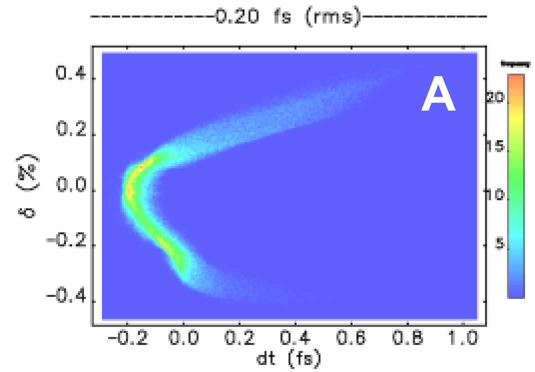
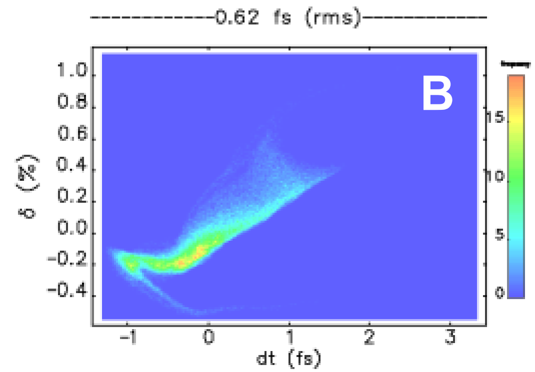
TW1 phase (deg)	-59.2
R56 (mm)	10.0
Slit width (mm)	0.4
Final charge (pC)	**0.38**
ε_x (µm)	**0.05**
ε_y (µm)	**0.05**
Energy spread	**0.0019**
Current (A)	**650**

Working point B

Initial charge (pC)	100
Gun gradient (MV/m)	110.0
Gun phase (deg)	0.0
Laser pulse duration (ps)	3.0
TW1 gradient (MV/m)	23.9
TW1 phase (deg)	-60.0
TW1 gradient (MV/m)	23.9
TW1 phase (deg)	-60.0
R56 (mm)	10.0
Slit width (mm)	0.4
Final charge (pC)	**2.77**
ε_x (µm)	**0.24**
ε_y (µm)	**0.18**
Energy spread	**0.0022**
Current (A)	**1528**



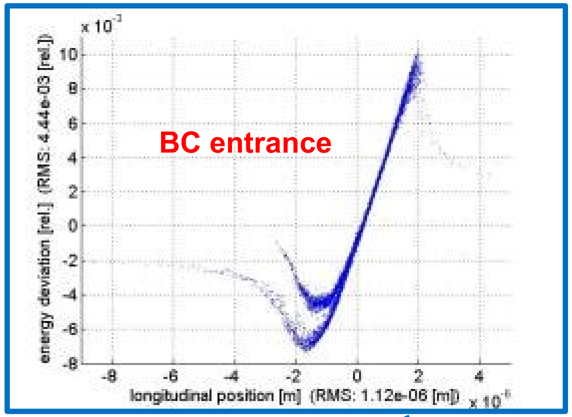


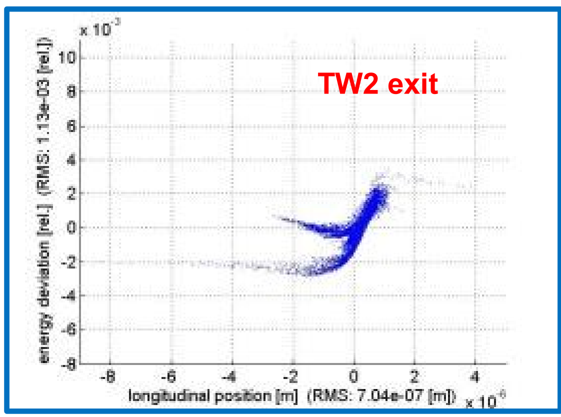
Study and simulations: J. Zhu

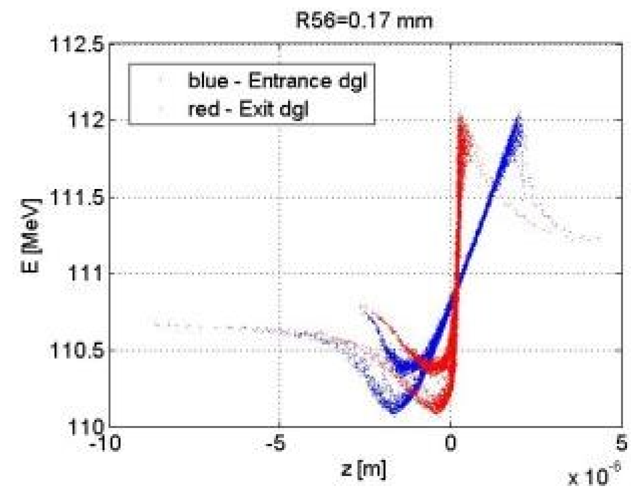
References:
P. Emma, Phys. Rev. Lett. 92, 074801(2004)
S. Di Mitri, PRSTAB 16, 042801 (2013)

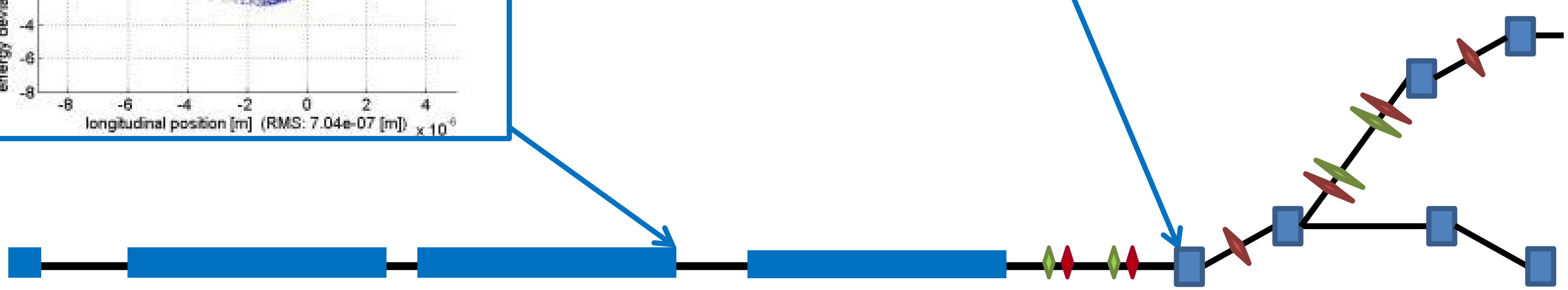
Dogleg – hybrid compression scheme

Tunable chirp regulated by the focusing of the solenoids around TW2









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One more LINAC II–like
Traveling wave structure (2.998 GHz),
Total av. Gradient~80MV/100MV

Total energy upgrade:
200 MeV (on-crest) → 300 MeV(on-crest)

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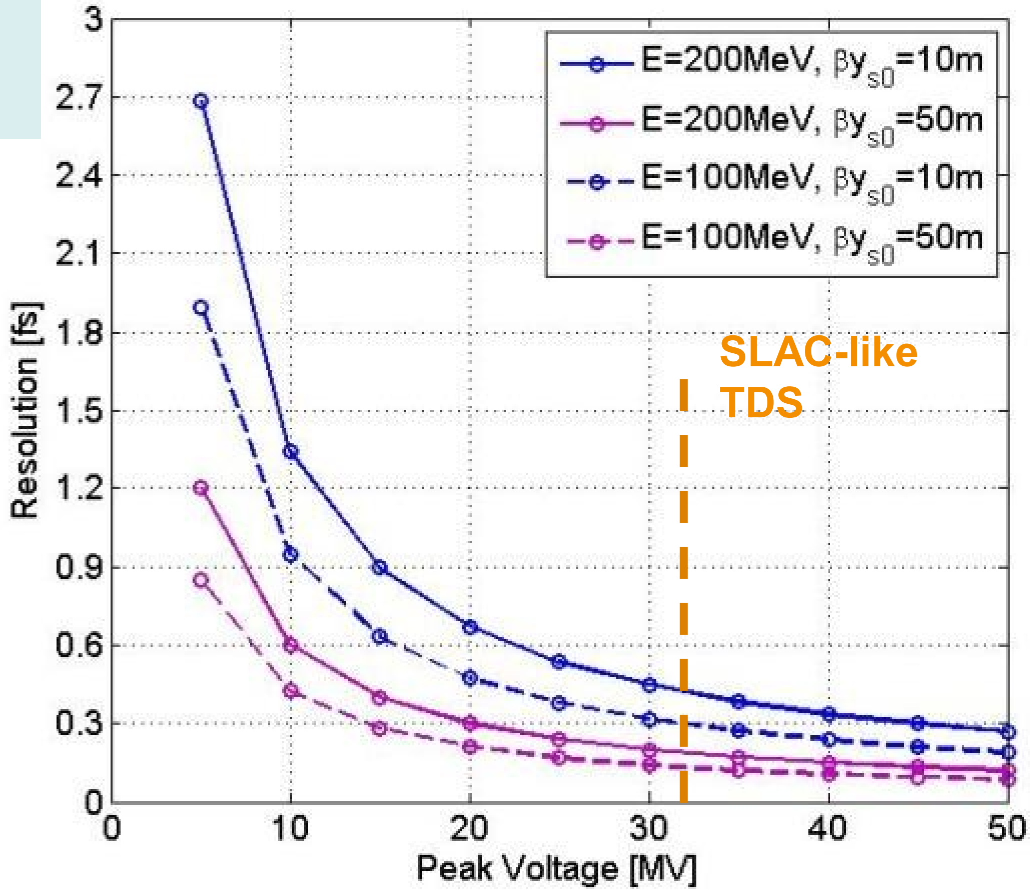
Xband Transverse Deflecting Structure for beam diagnostics

Presently Xband RF deflectors are the highest resolution (~1fs) bunch length diagnostics device.
Cfr: C. Behrens et al., Nat. Commun. 5, 3762 (2014)

Beam parameters:
$\varepsilon n_{x,y}$=0.1 mm mrad
$\Delta\varphi=\pi/2$ (phase advance between the cavity and the screen)

RF cavity parameters:
f=11.9920 GHz

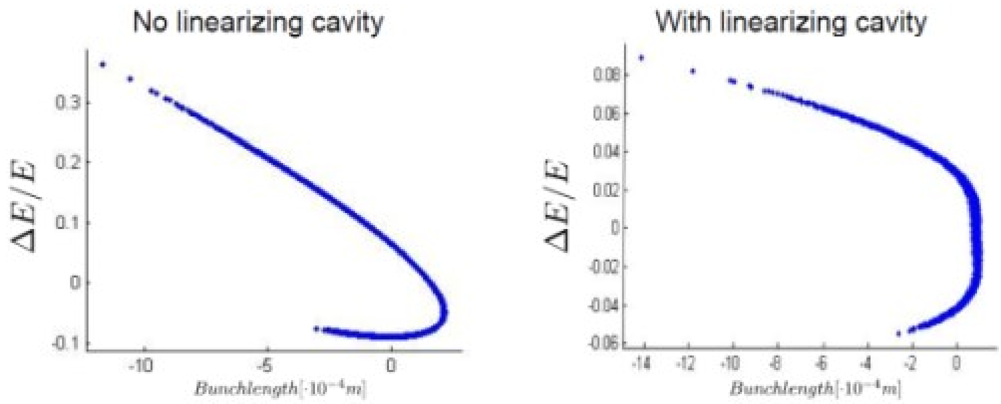
$$\mathcal{R}_{t,e} = \frac{\sigma_{y0}}{S_y} = \frac{\sqrt{\beta_y(s)\varepsilon_y}E}{\sqrt{\beta_y(s)\beta_y(s_0)}\sin(\Delta\phi_y)e\omega V_y}$$



Cfr: P. Emma et al., LCLS-TN-00-12
M. Röhrs et. al., PRSTAB 12 050704 (2009)

Xband linearizing cavity

> Principle of operation:



- If the length of the photo-cathode laser pulse at the cathode is ~ > 2-3ps, the non-linearity in the phase space of the beam caused by the sinusoidal shape of the RF is not negligible.

    - Optimization of the single bunch compression

    → *Cfr: K. Flöttmann, NIM A 740, p. 34-38 (2014).*

    - Compression of train of bunches (total length of the train 3-10 ps)

    → *Cfr: M. Ferrario et al., Nucl. Instrum. Methods Phys. Res. A 637, S43-S46 (2011).*
    → *E. Chiadroni et al., Rev: Sci. Instrum. 84, 022703 (2013).*
    →*B. Marchetti et al., Proc. of IPAC11, THPS101 (2011).*

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- Timing synchronization upgrade → Holger Schlarb
  - LLRF development (Xband)
  - Pulsed Optical Synchronization
  - Klystron ultra-fast stabilization
- Additional undulators
- Imaging beam line

- **Basic system for operation:**

<10 fs local RMS jitter
~ 50fs pkpk drift

- **Upgrade:**

< 5 fs local RMS jitter
<10fs pkpk drift

Talk:
„ST3: ps and fs electron and photon beams“
Wed 25/02, 8:30

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Talk:
„FEL applications“
Wed 25/02, 15:20

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Brilliant hard X-rays from laser-driven Thomson-source:
image in-vivo medical diagnostic agents such as anti-bodies coupled to Gold nano-clusters whose X-ray fluorescence light is the signal.
The potential is to reach sensitivities beyond Magnetic Resonance Tomography.

Plasma Acceleration

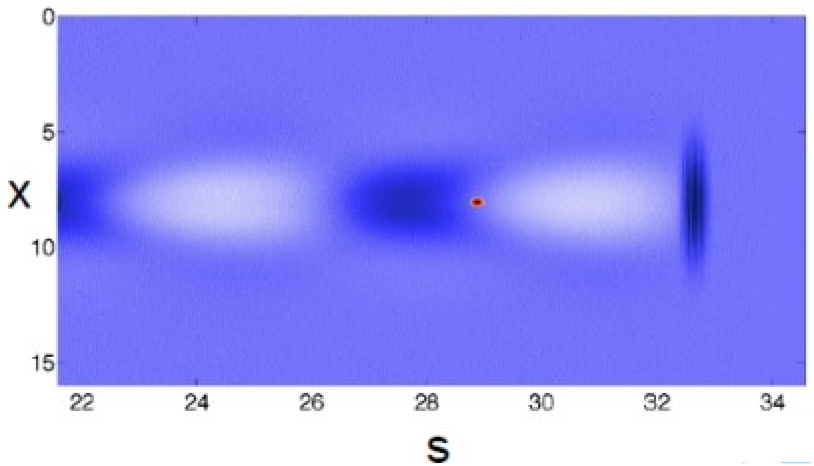
STABILITY FOR APPLICATIONS

External vs Internal Injection

- Electrons can be externally injected or internally created

External injection	Internal injection
+ Known and controllable (within limits) initial beam phase space + Staging is possible / prove of staging - Synchronization - Transverse matching	+ More compact/cheaper/simpler + Higher plasma densities (= higher gradients) can be used - Control over the injected phase-space volume

- It is clear that staging will be needed to reach high energy physics energies. External injection is the crucial step towards this goal.
- Most experiments use internal injection as it's simpler and cheaper



External Injection at SINBAD

- ARES = 100MeV → e- ultra-relativistic → "no" (less) de-phasing issue
- Scaling laws:
  - Accelerating gradient: $\mathrm{E}_0[V/m] \approx 96\sqrt{n_0[cm^{-3}]}$
  - Plasma bubble length: $\lambda_p \propto 1/\sqrt{n_0}$
  - Acceleration length (depends on diffraction and dephasing): $\mathrm{l} \propto 1/\sqrt{n_0^3}$

Plasma density [cm^{-3}]	Wavelength	Period	Skindepth
10^{19}	10.6 μm	35.3 fs	1.68 μm
10^{18}	33.4 μm	101.3 fs	5.31 μm
10^{17}	106 μm	353.3 fs	16.8 μm
10^{16}	334 μm	1.0 ps	53.1 μm
10^{15}	1.06 mm	3.53 ps	0.168 mm
10^{14}	3.34 mm	10.0 ps	0.531 mm

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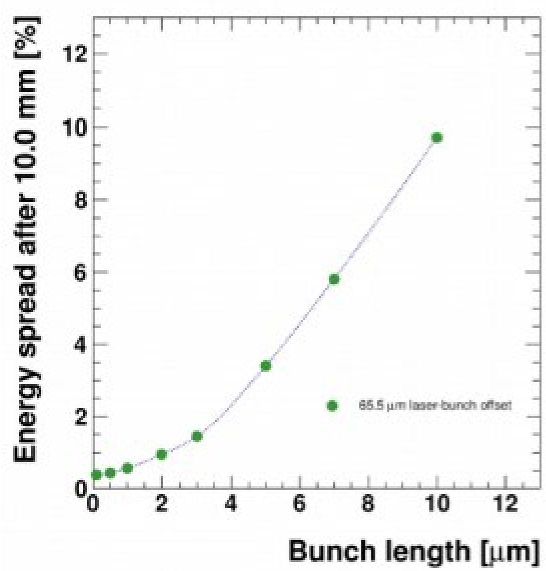
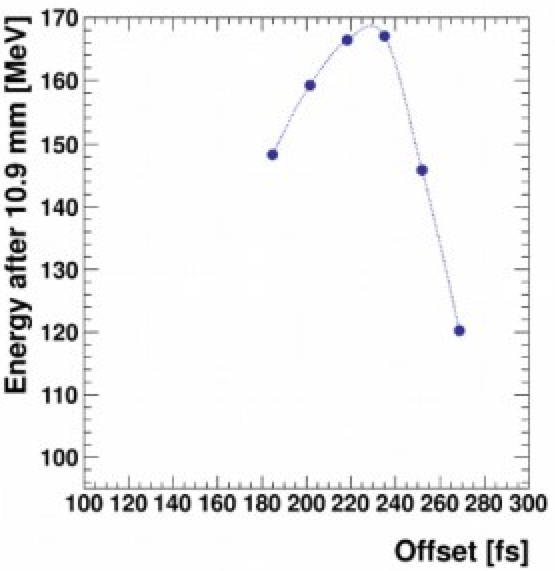
SINBAD/LAOLA Stages – 200 MeV beam

Study and simulations: J. Grebenyuk

Example: Simulations at $n = 10^{17}$





- Laser guiding to achieve high energies at low densities is needed
- Driver-bunch RMS synchronization jitter requirements: 5 - 30 fs
- With good synchronization & ultra-short injected bunches, a single-shot energy spread below 1% is achievable
- Bunch length with RMS < 5 fs bunches desirable
- When matched, no emittance degradation → matching to small beta required (optics + adiabatic density transitions)
- Initial stage at $n = 10^{16}$ has "relaxed" requirements

SINBAD/LAOLA Stages – 1 GeV beam

Study and simulations: J. Grebenyuk

Plasma density [cm^{-3}]	10^{18}	10^{17}	10^{16}	0.5×10^{16}
Skindepth, k_p^{-1} [μm]	5.31	16.8	53.1	75.2
Plasma wavelength, λ_p [μm]	33.4	106	334	472
Injection beam energy [MeV]	100	100	100	100
Laser pulse duration [fs]	25	25	25	25
Field gradient (OSIRIS) [GV/m]	62	7.58	0.46	0.21
Accelerating region, $\lambda_p/4$ [μm]	8.35	26.5	83.5	118
200 MeV stage length [m]	1.6×10^{-3}	13.2×10^{-3}	0.22	0.48
1 GeV stage length [m]	16×10^{-3}	0.13	2.2	4.8
Matched β [mm]	0.1	0.3	1	1.5

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That's about it...

Aknowledgments

- ATHENA preparation team !
- LAOLA team !
- All involved DESY groups !

…Thank you for the attention!