U. Dorda

30.06.2015

DESY – Zeuthen

Technisches Seminar

SINBAD

Short **IN**novative **B**unches and **A**ccelerators at **D**esy

The Idea I

- Particle accelerators are
  - very useful tools for users
  - but also very expensive (and big)
- Current accelerators are very, very sophisticated improvements to old concepts.
  - Let's try to push them even further
  - Let's try to bring novel concepts closer to usability
- DESY is one of the world-leading accelerator facilities due to constant R&D
  - E.g. superconducting RF
- Helmholtz ARD program

The Idea II

- Turn the DORIS storage ring plus central halls into a **dedicated** multi-purpose accelerator R&D facility with several experiments from **ultra-fast** science and **high gradient** accelerator modules.
- Based e.g. on the ongoing LAOLA activities, it is intended to provide a space for **long-term** dedicated accelerator R&D with multiple experiments using a common infrastructure.
  - e.g. one central high power laser used for several experiments.
- Project goals:
  - Production of ultra-short electron bunches for ultra-fast science.
  - Construction of a plasma accelerator module with usable beam quality for applications.
  - Setup of an attosecond radiation source with advanced technology

The MPY - ARD team

R. Aßmann (DESY leading scientist)

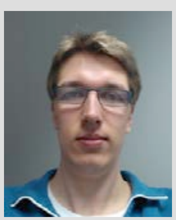
SINBAD

B. Marchetti
PI. ARES linac

J. Zhu
PhD student
ARES magnetic compression

U. Dorda
SINBAD PL.

R. Mundt
support for networking activities, applications for third-party funding, …



M. Hachmann
PhD-student
REGAE

F. Mayet
FLASH optimization

J. Bödewadt
FLASH seeding

M. Weikum
PhD-student
Attosecond-beam generation
Collaboration U. Strathclyde

More to be hired....

Relying on the support of the other DESY groups!

Introduction to

advanced accelerator concepts

Lasers, Plasmas, Dielectrics

one formula to define it all

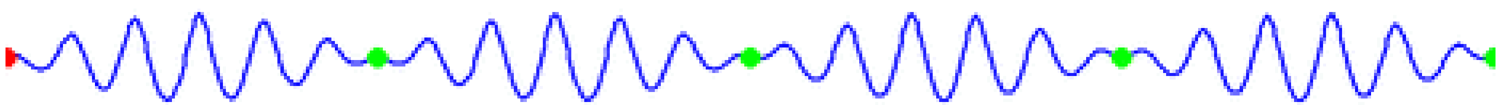
- The force $\vec{F}$ experienced by a particle of charge q

$$\vec{F} = q\,(\vec{E} + \vec{v}\;x\;\overrightarrow{B})$$

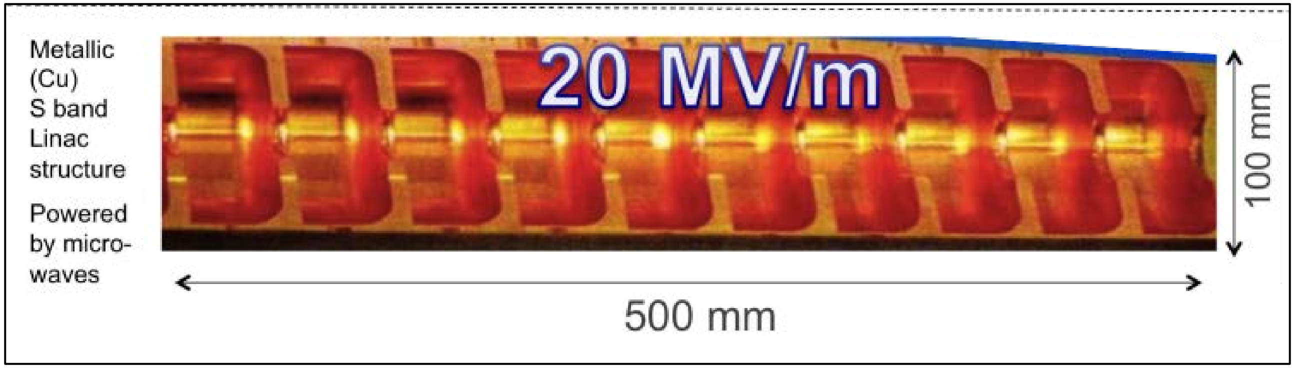
  - $\vec{E}$ is the electric field vector
  - $\vec{B}$ is the magnetic field vector
  - $\vec{v}$ is the particles velocity
- Magnetic fields to bend, electric field to accelerate
- “Normally”
  - RF-cavities e.g. 20MV/m
  - Dipoles 1.5T

Electric field in normal linacs

- Traveling wave linac structures are circular waveguides.
- In TWS-linacs the TM01-mode is used.
  - Magnetic fields are purely transversal
  - There is a longitudinal electric field component which accelerates the electrons.
- Typical Parameters: 3GHz, 20 MV/m
- For efficient acceleration, the electrons must ride on the crest of the electric field wave.
- The phase velocity velocity in a “pure” waveguide is greater than c_0
  - Red dot moves with the phase velocity
  - Green dot propagates with the group velocity

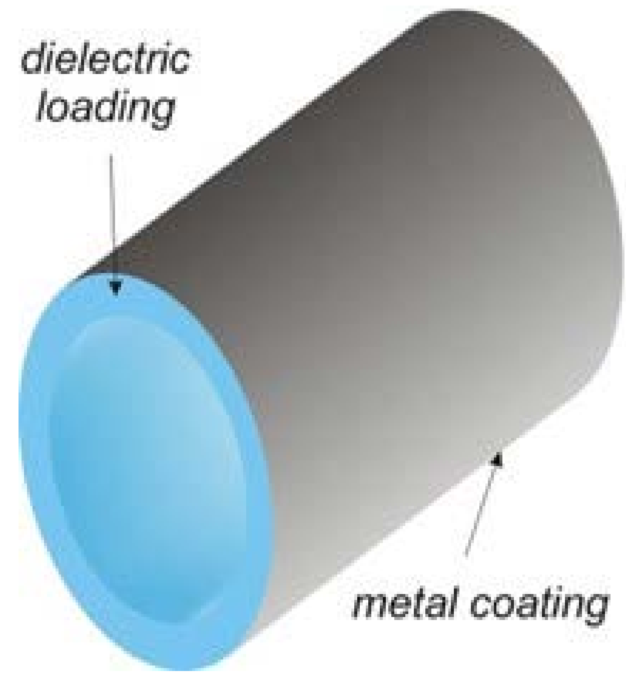


- Irises are added to slow down the phase velocity!



Electric fields in dielectric structures

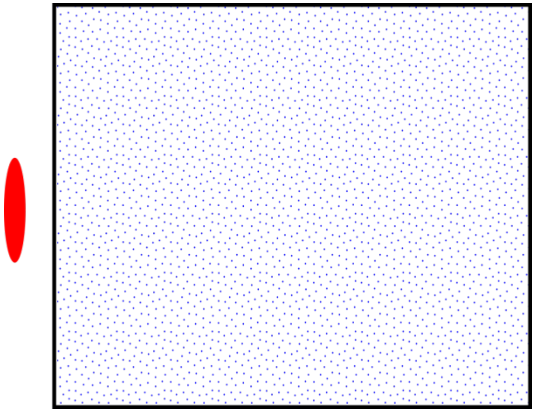
- Using the TM01 mode in circular waveguides
- Phase-velocity is reduced by dielectric loading
  - e.g. Quarz $\varepsilon_r = 4.4$
- The RF is replaced by lasers
  - High electric fields: hundreds of MV/m
  - f = 500GHz
    - Break down limit much higher.



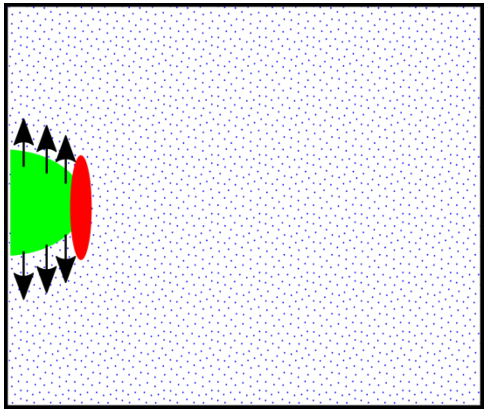
Electric field in Plasmas

- In free space, EM-waves propagate as TEM waves
  - Only transversal field components
- The plasma is needed to “transfer” the transverse electric field into a longitudinal field
  - Instead of a laser, also a high current beam can be used (“laser driven” vs. “beam driven”).
  - The pondermotive force of the laser/ Space charge force of the drive beam creates plasma wakes creating ultra-high accelerating gradients and transverse (de-) focusing fields

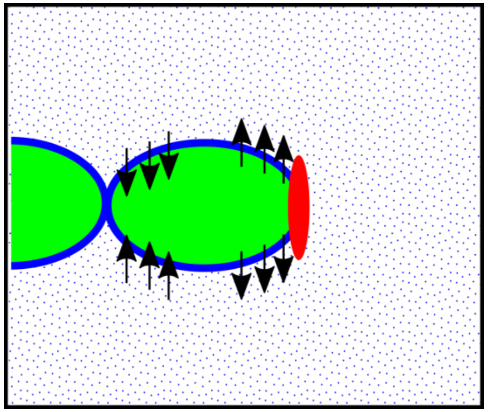
Plasma acceleration 101



A laser is focused into a neutral plasma



- The electrons are repelled
- Due to the higher mass, the positive ions remain in place (green area is positively charged)



- The electrons are pulled back by the positive ions
- An oscillation starts, creating a bubble
- The charge separation leads to strong longitudinal and transverse electric fields

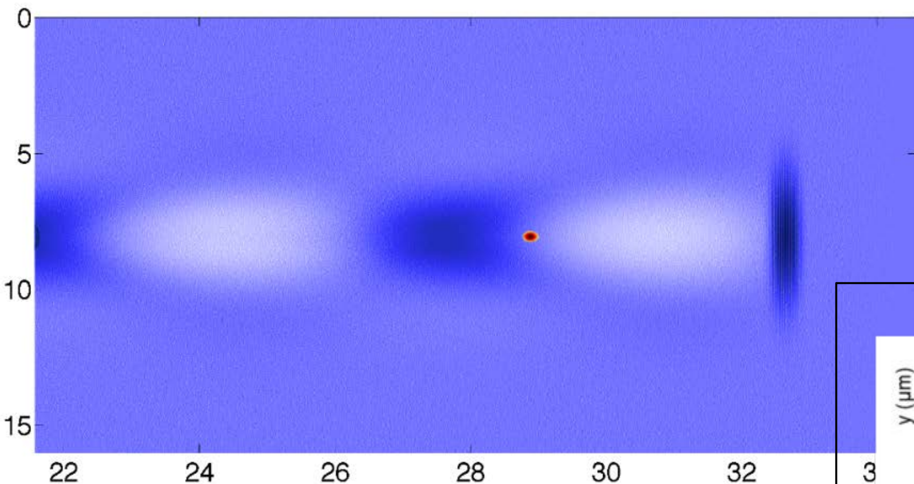
Plasma acceleration 101 continued

- The bubble extensions depend on the plasma density
  - The higher the density, the shorter the bubble
  - The higher the density, the higher the achievable gradient
- Beam- vs. Laser driven
  - Beam diven: Space charge repels the electrons
  - Laser driven:
    - Ponderomotive force is a nonlinear force that a charged particle experiences in an <u>inhomogeneous</u> oscillating electromagnetic field.
- Acceleration length is limited by
  - Depletion of laser power
  - Dephasing of laser and electrons
  - Defocusing of the laser

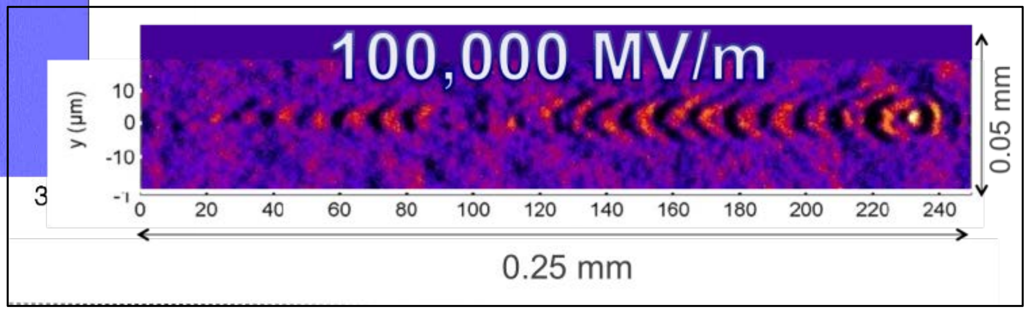
External vs. internal injection

External injection	Internal injection
+ Known and controllable (within limits) initial beam phase space + Staging possible/ prove of staging - Synchronization - Transverse matching	+ More compact/cheaper/simpler + Higher plasma densities (= higher gradients) can be used - Control over the injection phase - Control over bunch charge and length (e.g. defines final energy spread)

Most experiments use internal injection as it's simpler and cheaper



Simulation



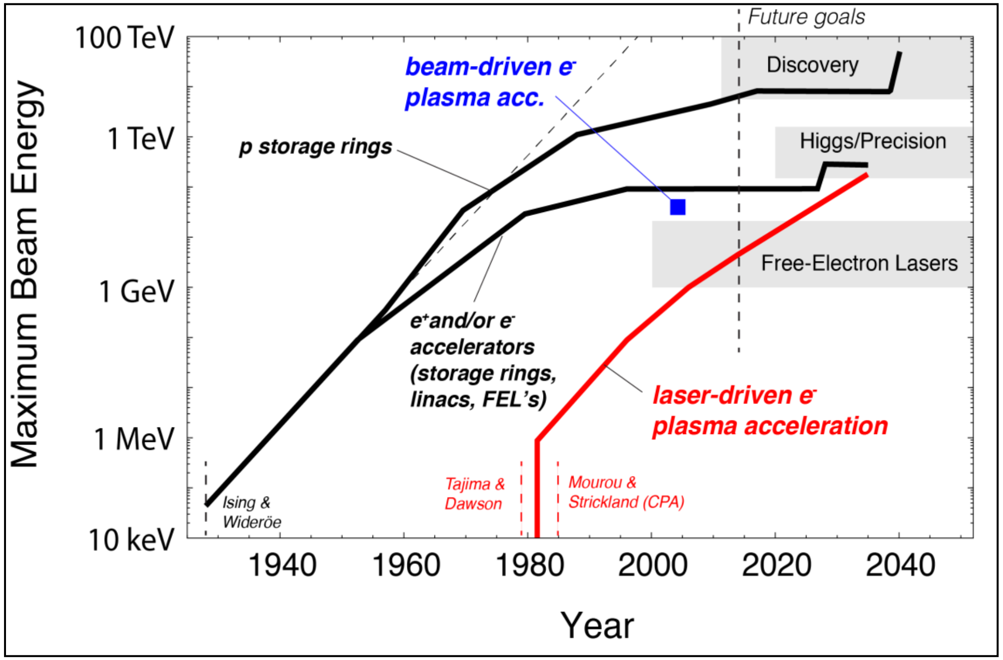
Experiment

Some of the issues

- Exact control of the plasma needed
  - Stability, reproducibility, …
- Stability of the high power lasers (100s of TW)
  - At a later stage: repetition rate
- For external injection: Extreme timing requirements: fs-synchronisation of laser to electrons
- Extremely high transverse fields
  - Matching into the plasma requires very small beta-functions
- High gradient creates high energy spread
  - Matching out of the plasma is difficult and causes blow-up
  - Possible remedy: beam loading, inject ultra-short bunches

plasma acceleration applications

- The required high power lasers become more and more compact. Rapid laser development and progress!
- Experiments worldwide have shown GeV energy gain.
- Potential for ultra-compact accelerators
  of e^-, p and ions. Reduced size & cost(?).
- Challenge:
  Usability – Stability – Quality
- Beam quality challenges in terms of
  - Reproducibility
  - Energy spread
  - Emittance growth
- DESY has decades of experience on these challenges! We know how to achieve small beam size, reach tight tolerances, measure perturbations and correct them!



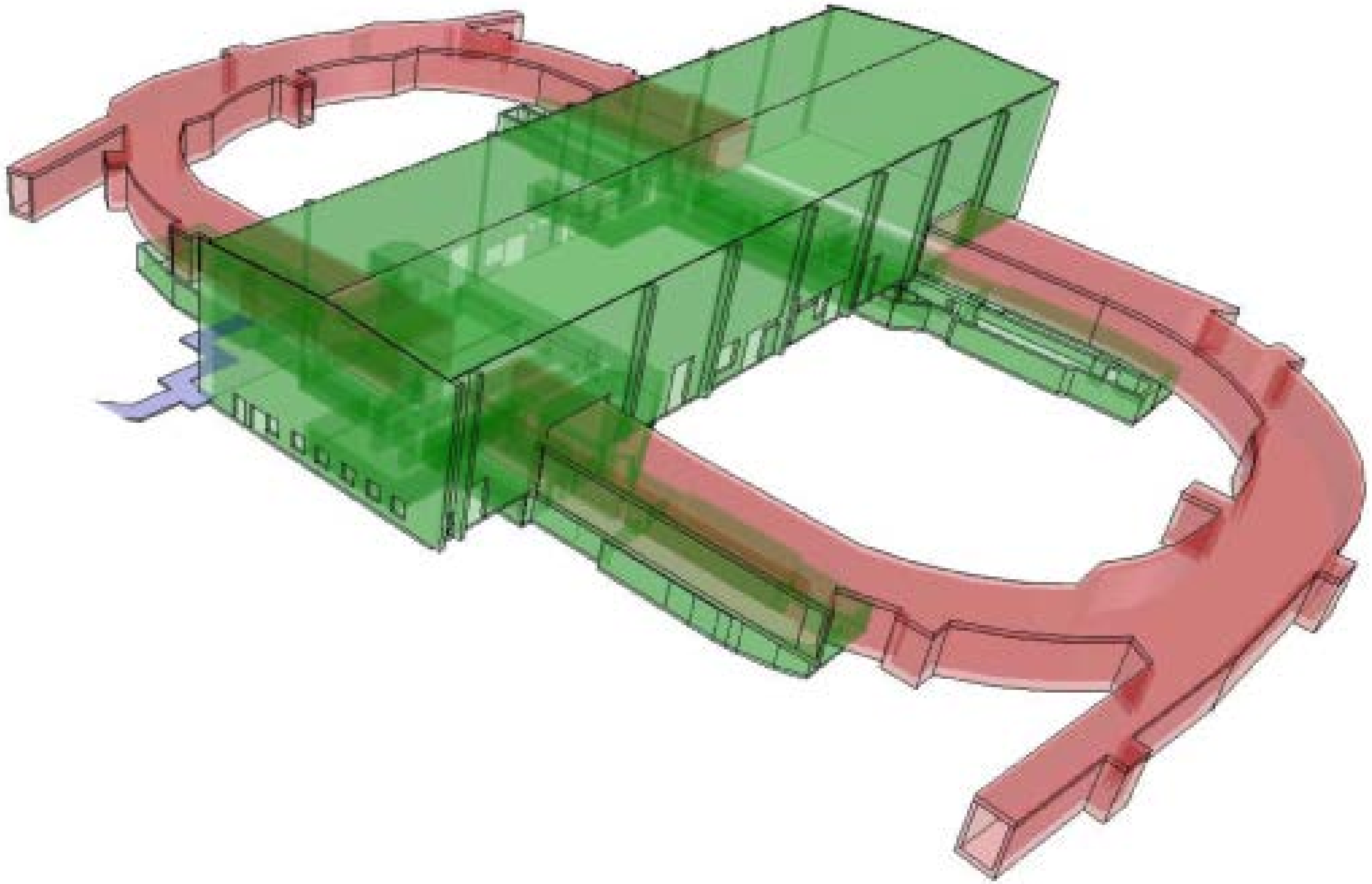
SINBAD

Where? Why? Who?

Location in DESY-Hamburg site

- In the old DORIS facilities
- Next to the Control room
- Beam lines to DESY

The location



- 290 m RP-shielded tunnel in racetrack shape
    - 2 long straight sections of more than 70m
- Central hall (650m^2) + additional side rooms & cellars

Facility: now – Clean up

- More than half of the beam line elements are removed
- De-cabling inside tunnel progressing well

Big Thanks to all the involved DESY groups – especially S. Baark (MEA)!

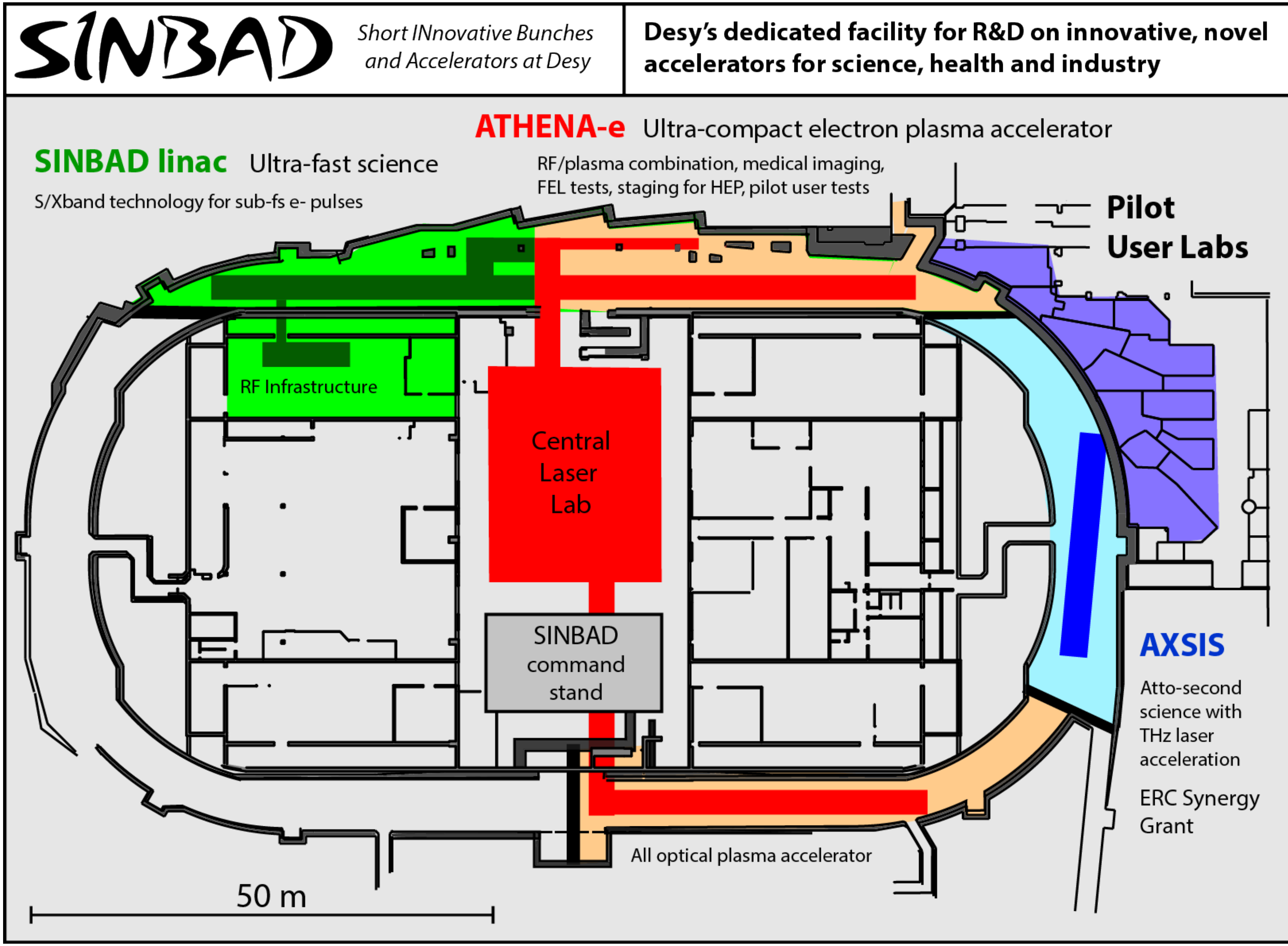
Facility: next - Plan Infrastructure

- Fix building (remove pillars, renovate floor, fill holes, …)
- Water, power, air-conditioning, IT, …
  - Collection of requirements ongoing
  - Alignment with several neighbouring activities needed to establish an overall concept.
  - Tricky to find compromise between affordability, flexibility and extendability.
- Start CAD efforts (getting the building…)
- Hopefully we can complete the refurbishment inside the tunnel by mid 2016.

"Disclaimer"

- Budget is allocated for a baseline setup and continuous operation
  - The AXSIS experiment is a collaboration funded by an ERC synergy grant
- There are further proposals being submitted to attract additional funding: ATHENA
- It strongly relies on the support of the DESY groups and collaborators (especially UHH).

Layout for athena proposal submission

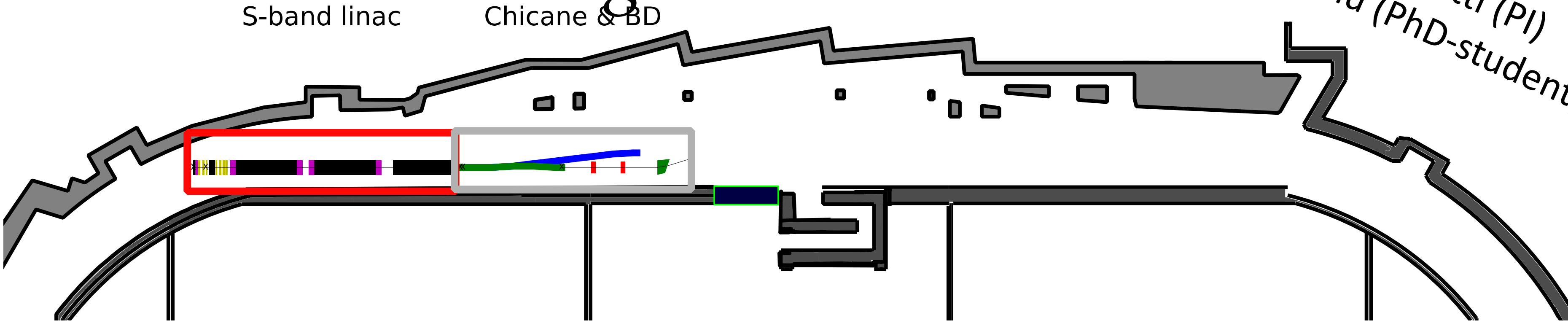


SINBAD-LSS1

Linac for ultra-short bunches feeding plasma and more

LSS1: Sinbad linac: Stage 1

B. Marchetti (PI)
J. Zhu (PhD-student)

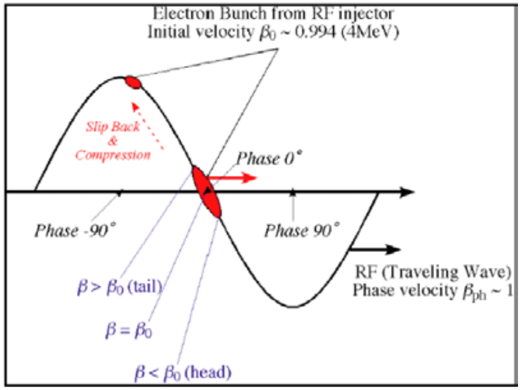


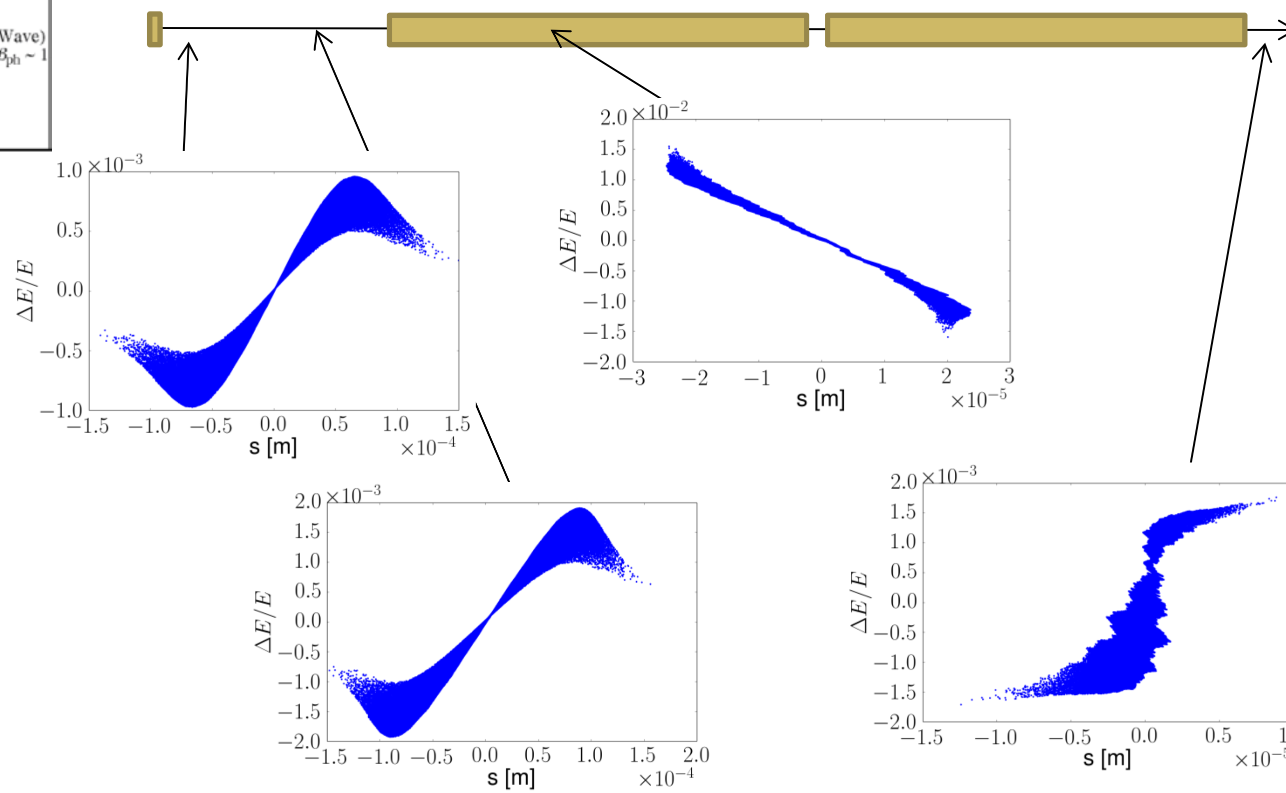
Conventional technology pushed to it's limits

- Stage 1 layout comprises:
  - REGAE-type RF-gun (S-band)
  - 2 linac-II type S-band RF-structures
  - Magnetic compressor with slit
- Design studies focus on short bunch length & low timing jitter
  - while keeping flexibility for "user" requirements (higher charge, longer bunches)
  - RF-compression, magnetic compression with slit, hybrid compression
- Beam properties:
  - $E \geq 100$ MeV
  - Q: 0.5-20 pC (up to 1nC)
  - T: single fs FWHM (for low charges)
  - Ex < 0.5 mm mrad
- First beam from gun targeted within 2017, linac 2018

RF compression concept

- The first TWS is not used for acceleration but for bunch compression





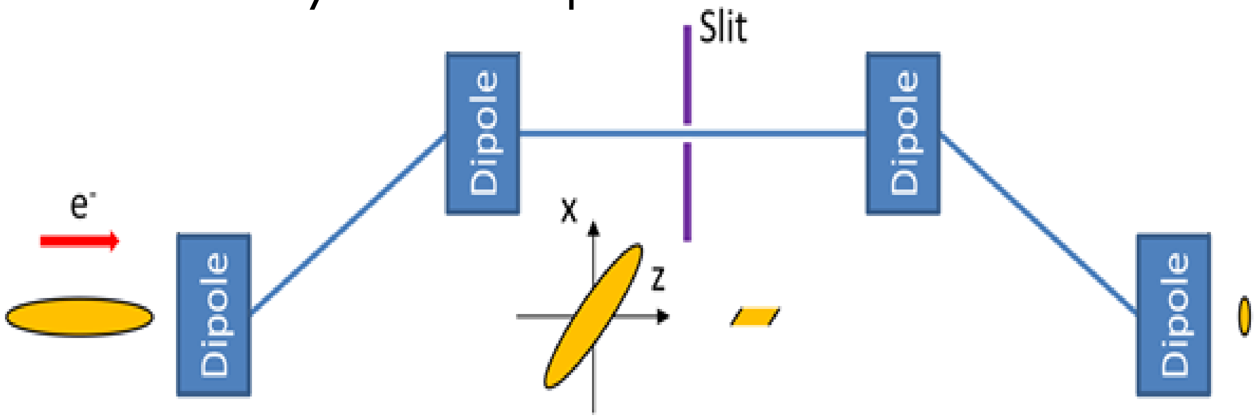
Magnetic/ Slit method

> Add an energy-chirp during acceleration

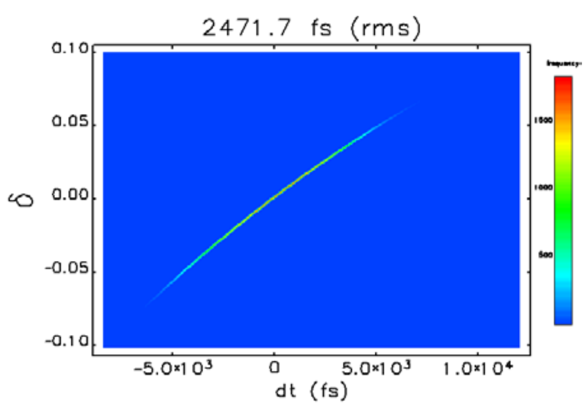
> Add a 4-dipole chicane with $\Delta s = R56\frac{\Delta p}{p}$

> In the center, the electrons are aligned according to their energy ∝ time: $\Delta x = D_x\frac{\Delta p}{p}$

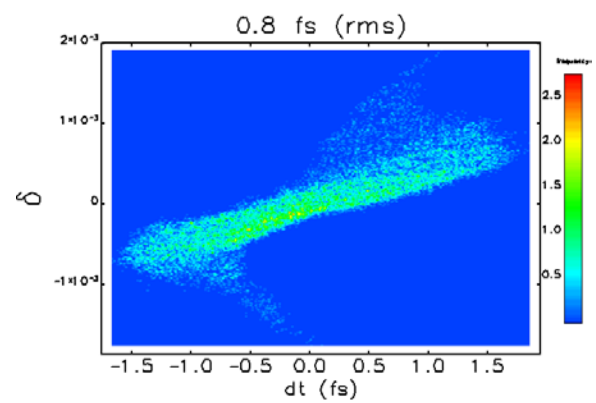
> Add a slit to cut out only the central part



Before: 20pC, 2500fs (RMS)



After: 0.37pC, 0.8fs (RMS)



Chicane parameters:

- Chirp: -35/m
- Slit width: 0.3mm
- R56: 28.7 m
- D_x: 20 mm

The "Details"

The design has to be done while considering:

> Space charge effect

> CSR in dipole-chicane

> Wake fields (e.g. in X-band structures with small apertures)

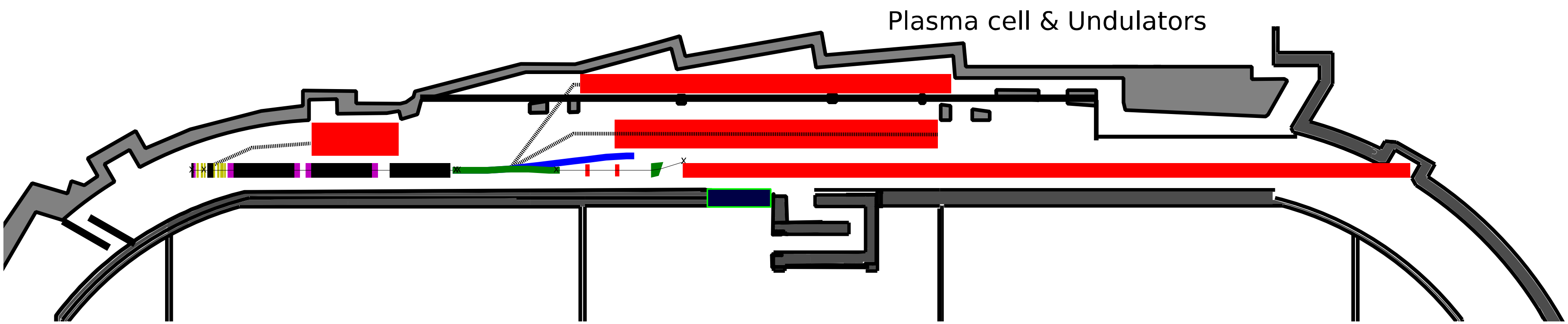
> Design for maximal jitter-tolerances

> Misalignments

> Magnet imperfections, …

→ The basic design is chosen, optimization ongoing

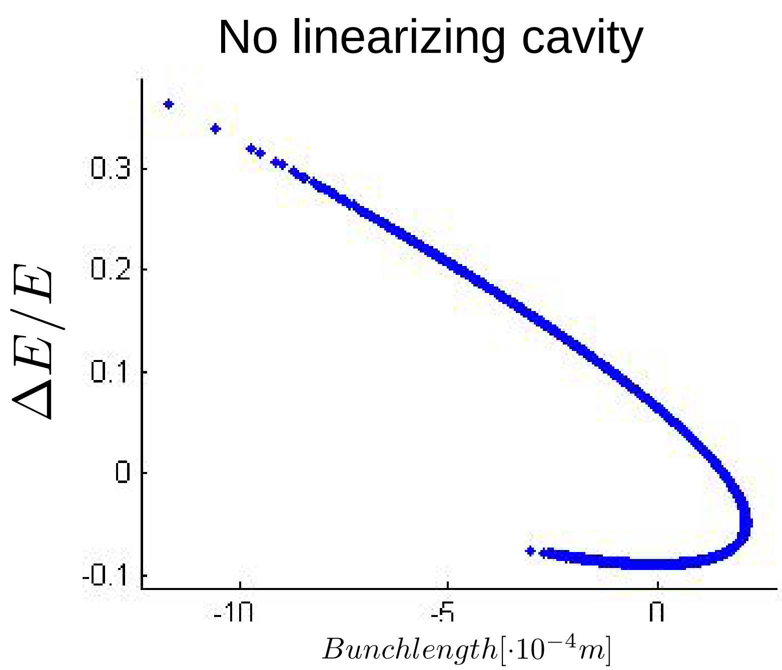
LSS1: Sinbad linac: Stage II

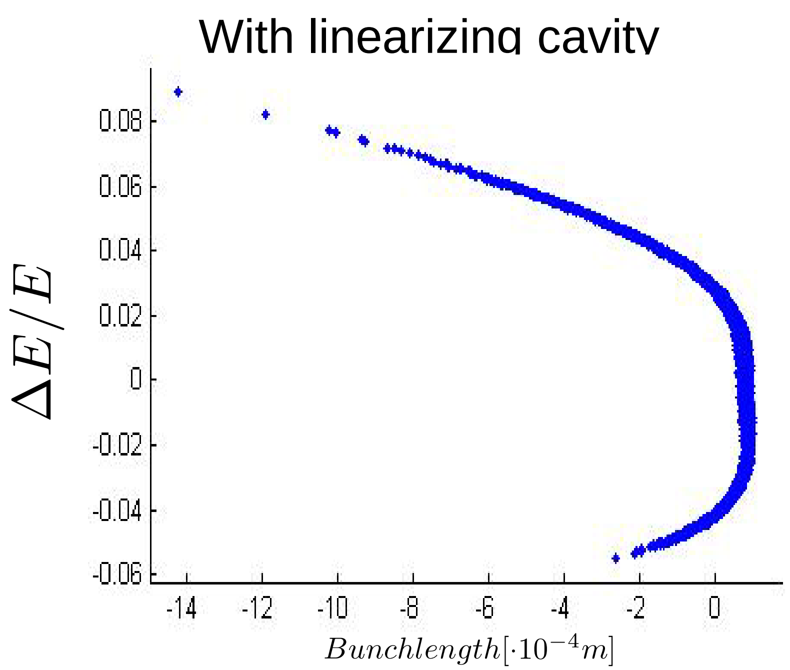


- To big extend relying on ATHENA funding (t ≥ 2018)
- The linac is further optimized
  - Especially arrival time jitter < 10fs…
  - X-band RF for linearizer and TDS
- “Applications”
  - External injection into plasma → HP laser
    - Stage II+: add undulators → **FEL**
  - “Laser Accelerators on a Chip” – SINBAD as part of a proposal to the Moore foundation for a collaboration lead by SLAC towards the realization of a **dielectric laser accelerator** (decision this summer), (sub fC, MHz rep rate, 400MV/m). Contribution: Testing of structures with 100MeV beam.
  - E.g. **Medical imaging station** in Athena-proposal

Phase space linearization concept

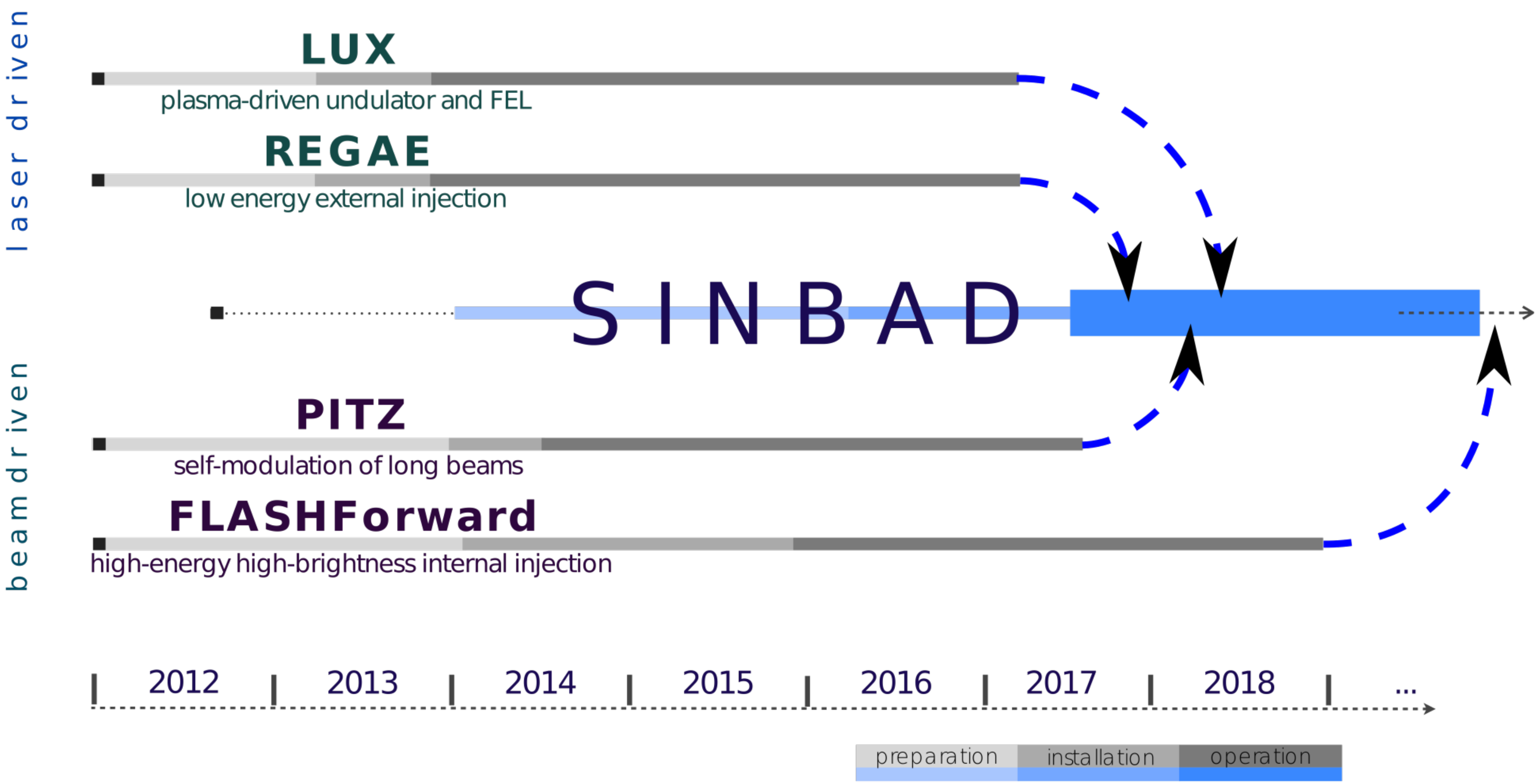
- Adding a higher harmonic RF-system to locally compensate for the RF-curvature
- Allows to achieve even shorter bunch lengths
- Requires higher order RF system (X-band: 11.9942 GHz, Total av. Gradient~5MV)





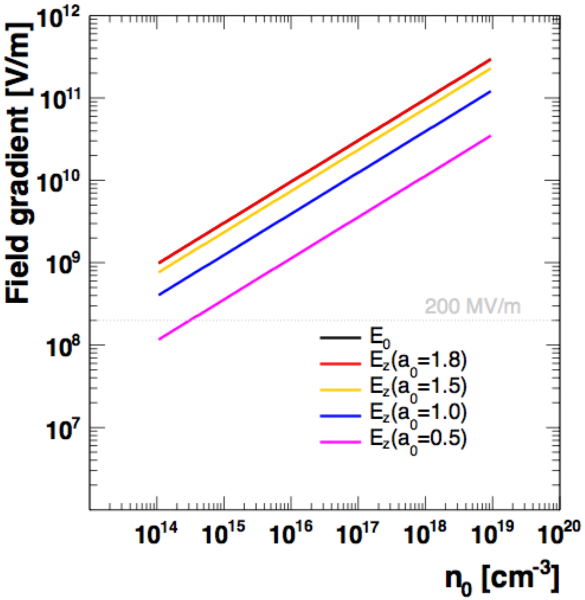
SINBAD in the LAOLA context

- Based on the experience of the ongoing LAOLA experiments
- LAOLA = Collaboration UHH and DESY on plasma wakefield acceleration



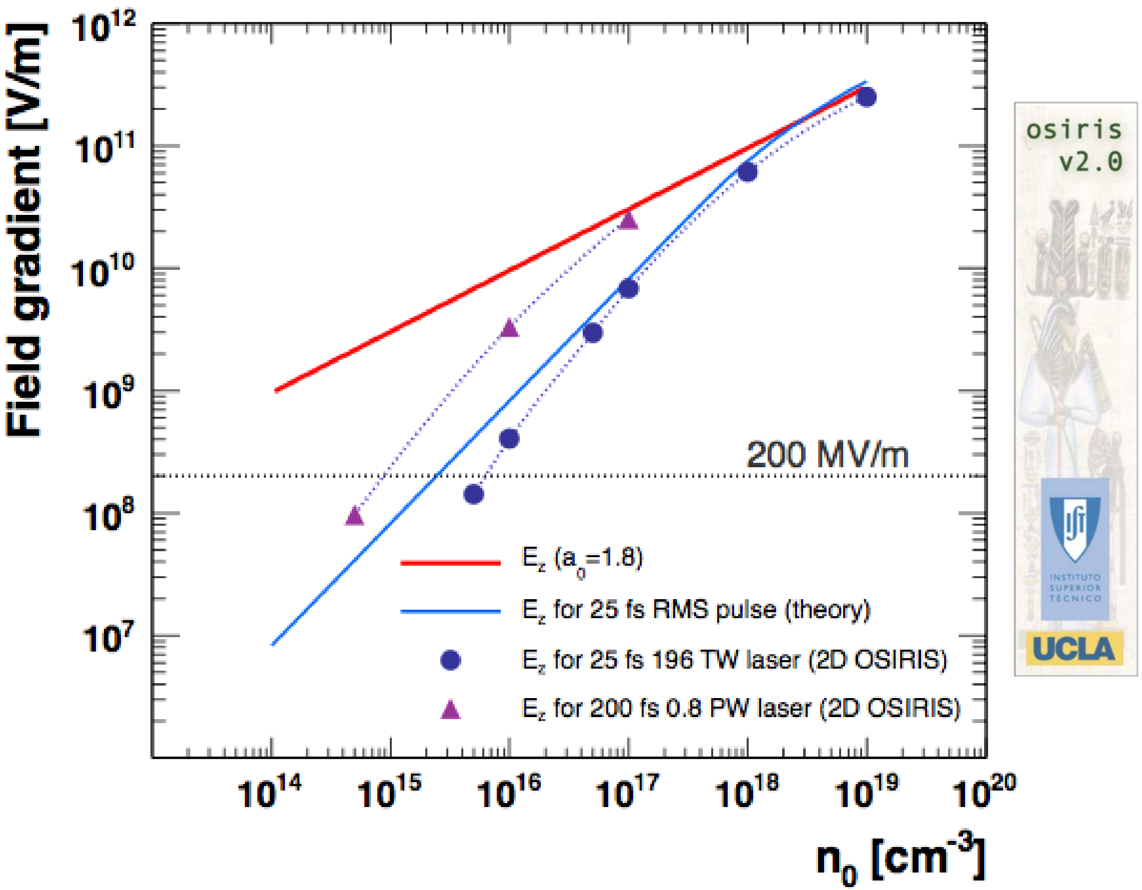
External injection at sinbad

- ARES = 100MeV → e^- ultra-relativistic → "no" de-phasing issue
- Scaling laws:
  - Accelerating gradient $E_0[V/m] \approx 96\sqrt{n_0[cm^{-3}]}$
  - Plasma bubble length: $\lambda_p \propto 1/\sqrt{n_0}$
  - Acceleration length (depends on diffraction and dephasing): $l \propto 1/\sqrt{n_0^3}$
- Lower plasma densities "relax" synchronization, transverse matching, ...



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

Achievable Acceleration



Minimal desirable gradient at SINBAD for stage 1: 200 MV/m
(about 10 times more than usual gradient in conventional machines)

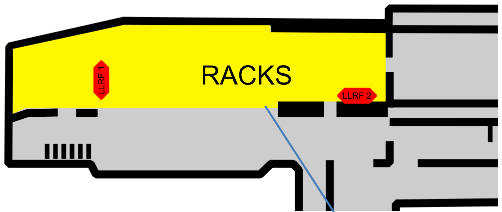
With existing laser: Achievable at n = 5 x 10^{15} cm^{-3}

Sinbad stages

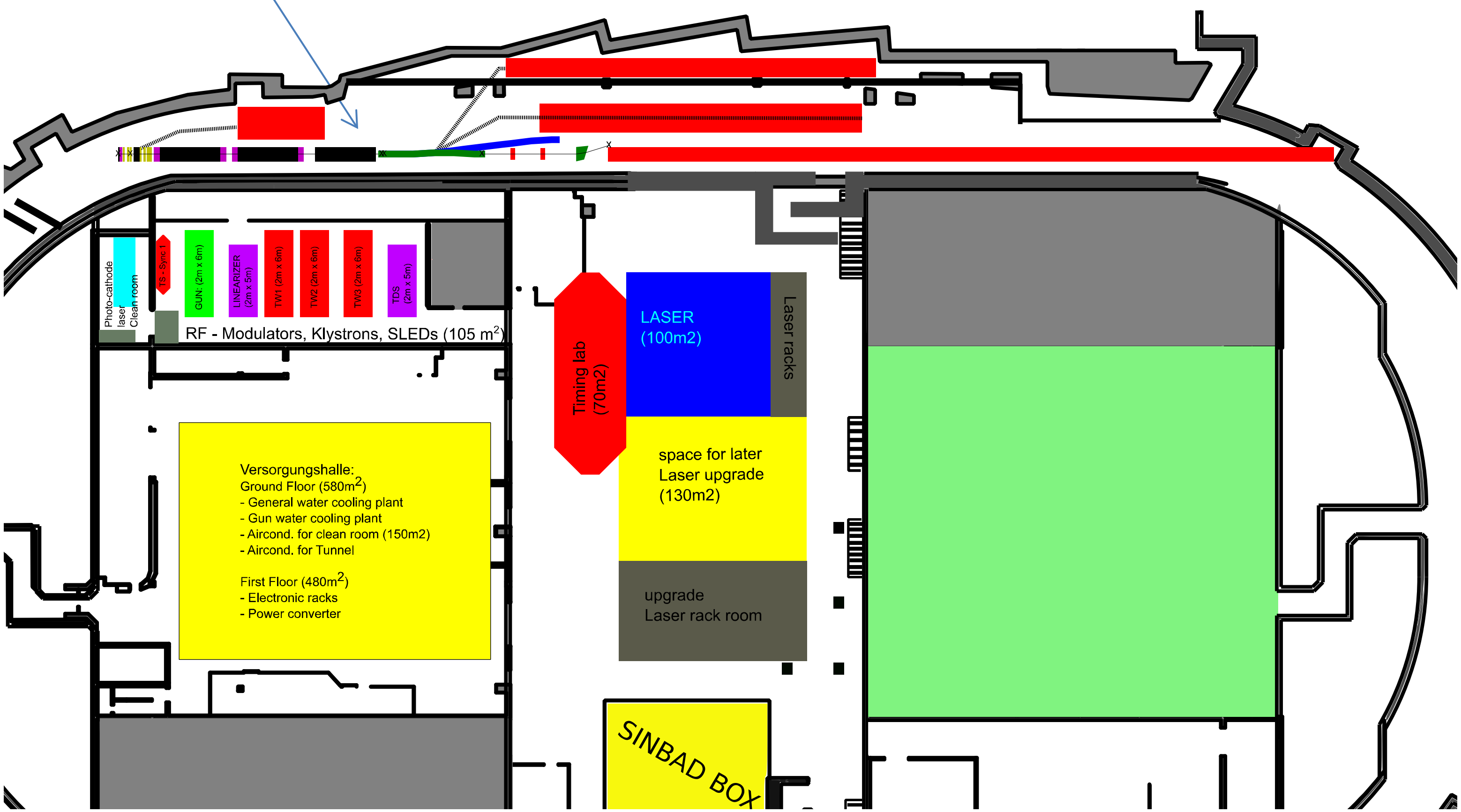
Example: Simulations at n =10^{17}

- 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

LSS1: Sinbad linac: infrastructure



Cellar: Used for racks

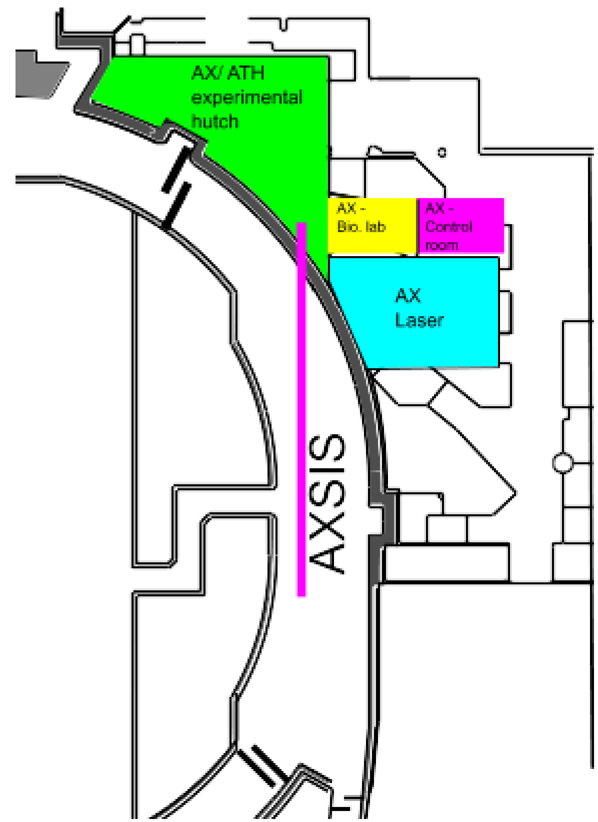


AXSIS

Attosecond X-ray Science: Imaging and Spectroscopy

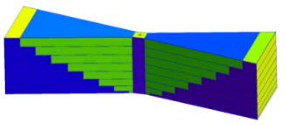
AXSIS 1

- THz-laser acceleration in dielectric-loaded waveguide & ICS
- Collaboration between F. Kaertner, H. Chapman, R. Assmann & P. Fromme
- Funded by an ERC synergy grant
- Location:
  - Accelerator & ICS in ARC-1
  - “Users” & Laser labs in former Hasylab user areas
- Targeted beam parameters
  - E: 15 and 25 MeV (4 &12keV photons)
  - Q: up to 1pC
  - kHz rep rate
  - T: single/sub-fs …
- Tight time-line (funding ends 2020):
  - 2016: Gun tests
  - 2018: THz-acceleration
  - 2020: ICS & user X-ray spectra

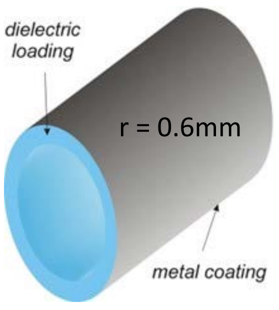


AXSIS II

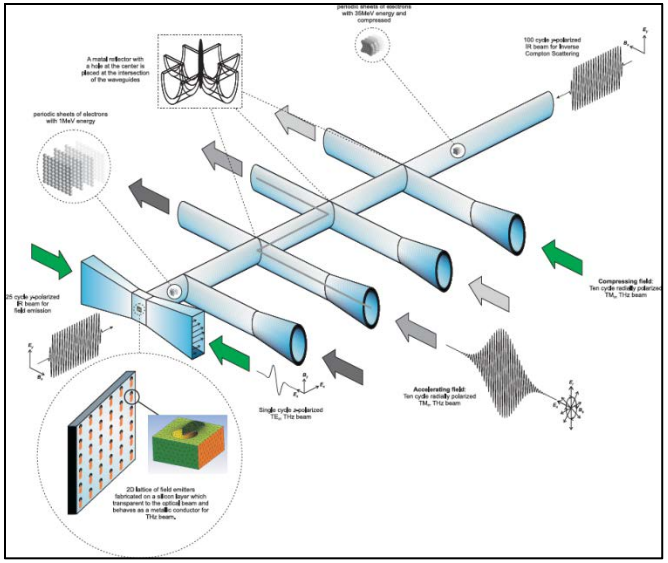
- Gun: A. Fallahi proposed advanced THZ gun designs (with our REGAE-type one as back-up?)



- Linac:
  - 25mJ, TM01, 300GHz pulse propagating in circular waveguide, loaded with dielectric (e.g. Quarz $\varepsilon_r = 4.4$) to slow down v_{phase}
  - Gradients of several hundred MV/m over few cm length.



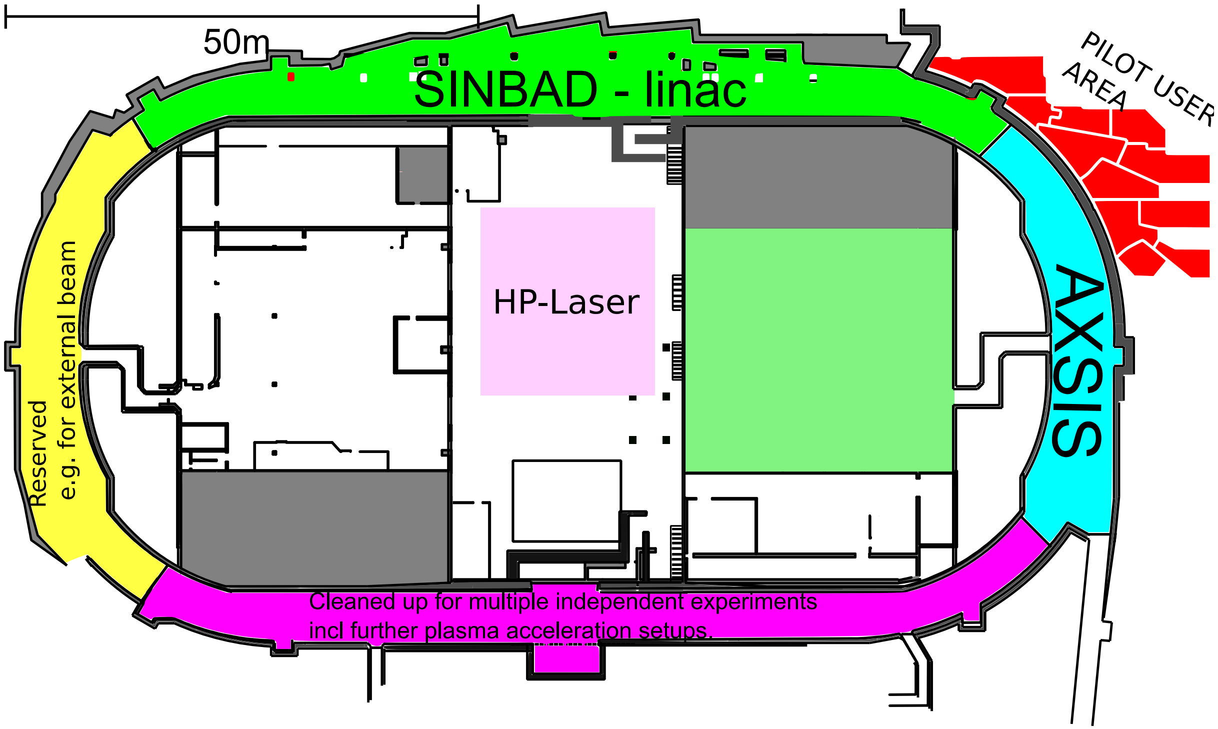
- ICS with 1J THz-laser
- Some of the challenges:
  - THz laser-power (and rep-rate)
  - Beam transport & focusing
  - Beam diagnostics



OTHER

ATHENA & future possibilities

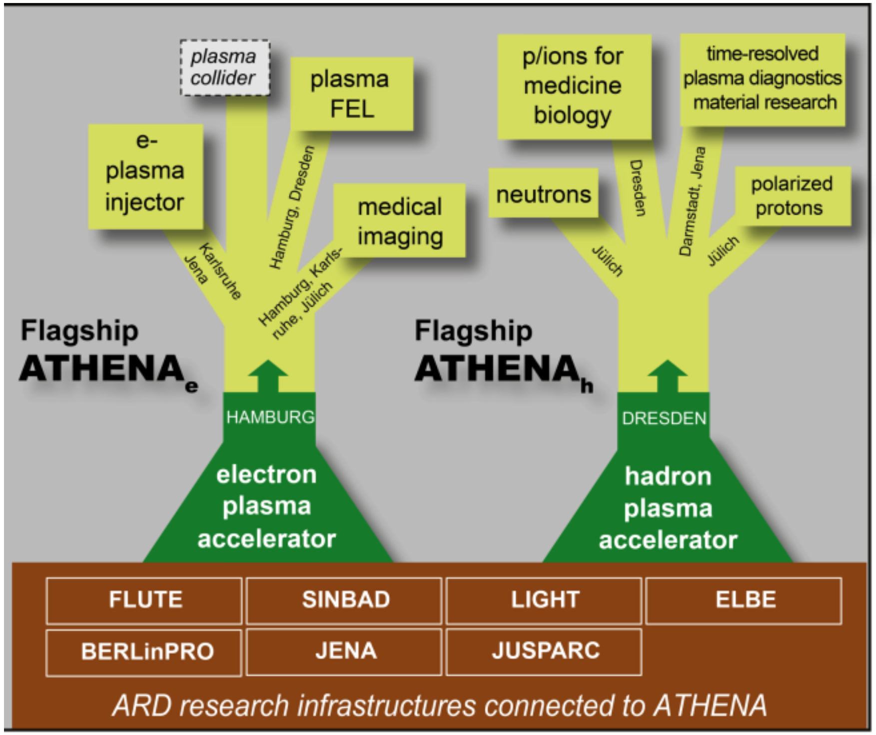
Long time options



- Multiple beam lines fed by linac
- 4 experimental regions: e.g. Lux successor in LSS2
- External beam option: Transport Beam from Linac 2 to SINBAD in order to
    - Allow beam driven plasma experiments (800MeV electrons)
    - Allow positron plasma acceleration (up to 450MeV positrons)
    - Beam parameters must be improved! Additional RF-gun for linac 2?
    - FEL seeding tests?

Athena - proposal

- Request for Helmholtz strategic investment funds
- *"ATHENA provides the infrastructure required for* ***bringing compact and cost-effective plasma accelerators to user readiness****. Flagship projects will be set up in Hamburg (electrons) and Dresden (hadrons). Applications for science, medicine and industry will be developed in all centers."*
- Joint effort of 7 Helmholtz centers lead by DESY.
- ATHENAe hosted at SINBAD.
- Submission deadline: June 2015
- Decision: Spring 2016



Acknowledgements

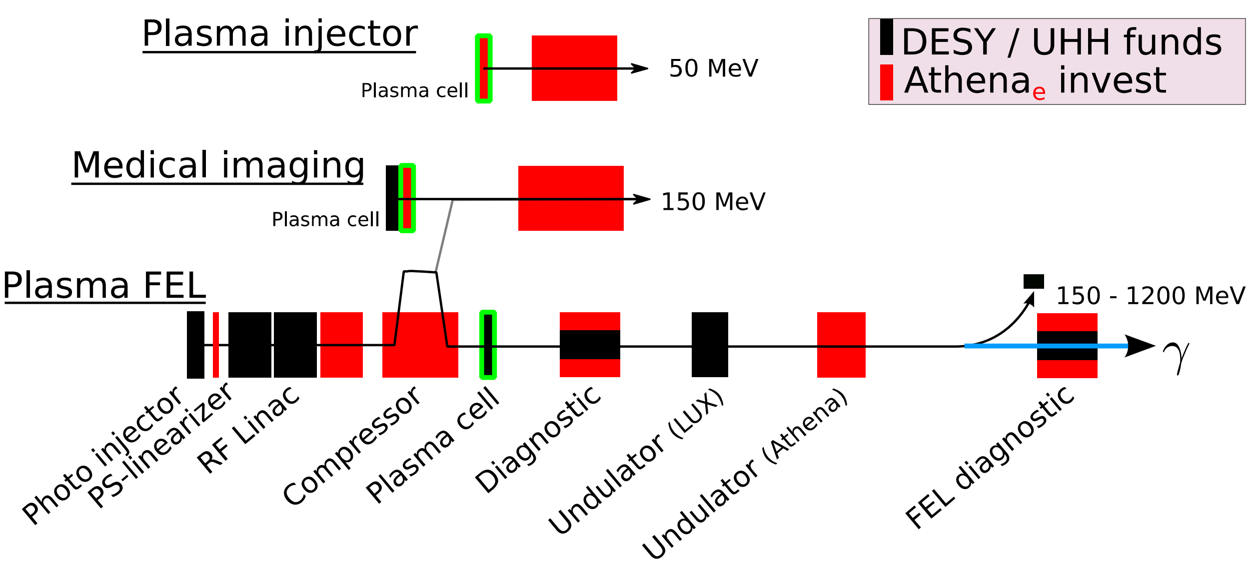
- All DESY groups involved in the facility clean up and planning of future experiments!
- LAOLA collaboration partners
- R. Assmann, B. Marchetti, J. Zhu,

Backup Slides

Athena @ SINBAD

Deliverables:

- Setup of a central laser lab.
- Setup of two independent experimentation areas for LWFA
- Set up of a medical imaging beam line
- Diagnostics for ultra-short electron pulses with resolution less than 1 fs.
    - X-band RF, laser wire scanner
- Inject pre-existing conventional RF linac into the plasma for LWFA areas
- Energy upgrade of the RF linac
- Installation of undulators for tests on LWFA for FEL's
- 50MeV injector for KIT



Further main contributions funded for SINBAD:

- Improved timing system
- Laser wire scanner
- Plasma diagnostic

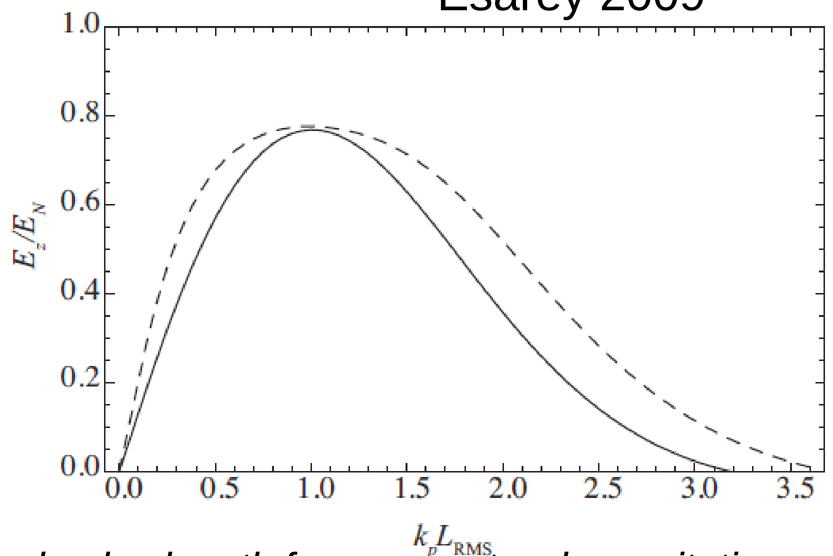
Laser and Beam parameter

Ti:Sa ANGUS laser

- In use for LUX/REGAE
- Operated by A. Maier's group
- Tailored for 10^{18} cm $^{-3}$

- a0: 1.8
- Spot size (FWHM): 50 um
- Pulse length (FWHM): 25 fs
- Peak power: 200 TW
- Energy in the pulse: 5 J
- Wavelength: 800 nm

Esarey 2009



Optimal pulse length for resonant wake excitation
→ *At low densities longer pulses required* $(\mathrm{k}_p \propto \sqrt{n})$

Target input beam parameters:

- Bunch energy 100 MeV
- Energy-spread: 0.1 - 0.4%
- Bunch length (RMS): 1 fs
- Arrival time jitter: 10 fs
- Transverse position jitter: few µm
- Charge: 0.5 - 20 pC
- Transverse emittance: < 0.5 mm mrad