ARES - An electron linac for reaching the atto-second regime at SINBAD

B. Marchetti (DESY)
PI SINBAD-ARES linac

ARD lunch seminar
18.03.2016 – DESY Hamburg
Outline

- Introduction: Why Short Bunches and the SINBAD Facility?
- The ARES linac: A Design for Sub-Femto Second Bunches
- Plasma Acceleration with the ARES linac
- Final Considerations and Summary
Outline

- Introduction: Why Short Bunches and the SINBAD Facility?
- The ARES linac: A Design for Sub-Femto Second Bunches
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- Final Considerations and Summary
Applications of accelerators

Accelerators are of fundamental importance for:

> Research in high energy physics
> Radiation generation (SR and CSR, FELs, CTR etc.)
> Medical applications (radiation therapy, hadron therapy etc.)
> …

Many applications demand for
- Compactness
- Cost efficiency
Scaling of the accelerating gradient and dimensions with the RF frequency

- Correlation
  - RF frequency
  - gradient
  - cell length
- Moving to higher frequencies the accelerators are more compact
- W-band is attractive but not trivial to achieve because…

Advanced acceleration

- **W band 75-110 GHz**
  - Gradient > 1.0 V/m
  - Cell length < 0.2 cm
- **C band 4-8 GHz**
- **L band (SC) 1-2 GHz**
- **S band 2-4 GHz**
- **Ka band 27-40 GHz**

Gradient [MV/m] vs. Cell length [cm]
**High Gradient Accelerators**

- No **klystrons** for high frequencies! → Use particle bunches or laser pulses as drivers.
- Material limitations → dielectric materials, plasma cavities, …

**Two main directions:**

1. **Microstructure Accelerator**
   - Laser- or beam driven
   - Vacuum accelerators
   - Conventional field design

2. **Plasma Accelerator**
   - Laser- or beam driven
   - Dynamic Plasma Structure
   - Plasma field calculations
Examples of novel high gradient acceleration techniques (1/3)

Plasma Wakefield Acceleration (PWA)

- accelerating gradients up to hundreds GV/m (LPA)
- single stage acceleration of beams up to more than 4 GeV energy (LPA)
- transfer GeV energy from a driver to a witness bunch maintaining its high beam quality (beam driven PWA).

Examples of novel high gradient acceleration techniques (2/3)

**Dielectric Wakefield Acceleration (DWA)**
- Driver electron beam to load wake-fields on the dielectric structure
- **Gradients** up to few GV/m have been demonstrated

**Dielectric Laser Acceleration (DLA)**
- μJ laser pulse having μm wavelength.
- micro-structure made by a dielectric material, e.g. SiO₂ or Si.
- The achievable **gradients** are of the order of few hundreds MV/m.


Examples of novel high gradient acceleration techniques (3/3)

**THz based acceleration**

- mJ THz laser
- metallic structure loaded with dielectrics
- In principle should allow reaching high gradients (GV/m) together with a high repetition rate

Hosted at SINBAD belongs to this category.

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Interim Summary

- Novel accelerators operate with **short wavelengths**
- Require **short bunch lengths** for injection to **minimize RF curvature effect**
- In some cases relativistic beam energies help with the phase velocity matching

- ... Very short, relativistic bunches not easily available, therefore

→ **SINBAD facility and ARES linac.**
SINBAD
(Short and INnovative Bunches and Accelerators at Desy)

SINBAD linac
Ultra-fast science

ACHIP
use of ARES short bunches for an accelerator on a chip

Dedicated multi-purpose accelerator R&D facility with several experiments for ultra-fast science and high gradient accelerator modules.

Project Leader:
Ulrich Dorda
SINBAD
(Short and INnovative Bunches and Accelerators at Desy)

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SINBAD linac
Ultra-fast science

AXSIS
Atto-second science with THz laser acceleration

PI ARES linac at SINBAD: B. Marchetti
SINBAD
(Short and INnovative Bunches and Accelerators at Desy)

2014
- Start preliminary study phase
- Approval by the DESY Stiftungsrat
- DORIS removal & building refurbishment
- Nonstrategic investment funds approved by ministry

2015
- Linac layout preliminary layout freeze

2016
- Technical infrastructure installation
- RF-gun installation

2017
- Linac installation
- First beam from RF-gun

2018
- First beam from Linac
- Research line operation start

2019

Today
Outline

> Introduction: Why Short Bunches and the SINBAD Facility?

> The ARES linac: A Design for Sub-Femto Second Bunches

  - SINBAD-ARES as an accelerator R&D experiment
  - Design Philosophy from Application Boundary Conditions
  - Layout and some technical highlights
  - Beam parameters and compression techniques

> Plasma Acceleration with the ARES linac

> Final Considerations and Summary
ARES (Accelerator Research Experiment at Sinbad)

- Conventional linac (S-band norm. cond.) for the production of ultra-short bunches:
  - Charge: 0.5-20 pC (up to 1nC)
  - Energy ~ 100 MeV
  - Bunch length: few fs / sub-fs
  - Transverse norm. emittance < 0.5 mm*mrad
  - Arrival Time jitter stability < 10 fs RMS
SINBAD-ARES linac as an Accelerator R&D Experiment

- **Goal**: production & characterization of ultra-short bunches (tFWHM≤1fs)

  → Charge as high as possible
  → Relaxed transverse spot-size (>100 μm)

  → Mainly technical challenges

**Challenges in beam diagnostics:**

- **Low charge:**
  - Low signal/noise ratio
  - Some diagnostics not yet available/under development

- **Sub-fs longitudinal resolution** is needed: state of the art are Xband TDS with 1 fs resolution.

**Challenges in synchronization:**

- **fs level** synchronization is needed (both RF-RF and laser-RF).

The requirements demand a very careful design of all systems (e.g. water cooling).
SINBAD-ARES linac as an Accelerator R&D Experiment

- **Goal:** production & characterization of ultra-short bunches (tFWHM ≤ 1 fs)

  - Charge as high as possible
  - Relaxed transverse spot-size (>100 μm)
  - ...

Ch. diag

- L

We rely on the strong experience of the technical groups at DESY thanks to REGAE, European XFEL, etc...

state of the art are Xband TDS with 1 fs resolution.

The requirements demand a very careful design of all systems (e.g. water cooling).
SINBAD-ARES linac - general philosophy for future experiments

• Who will be the „users“ of the SINBAD linac?

→ Experiments involving Novel High Gradient Acceleration Techniques: e.g. LPWA, Dielectric Wake-Field Acceleration, THz laser acceleration in dielectric-loaded structures…

• What types of e-beam will such experiments need?

Initially
→ characterization of the acceleration method and optimization of the beam quality of the accelerated beam

At a later stage
→ pilot user experiments involving e.g. radiation production (via FEL, ICS …)

• Ultra-short probes → time resolution
• Ultra-high stability → synchronization
• Small transverse focus (tens of μm – few μm)

• Sufficiently high brightness → radiation generation
• The e-bunch duration has to be tuned, according to the requirements for the production of radiation.
Special attention is being given to the **flexibility** and the **stability** of the elements:

- Load-lock system for **cathode exchange**
- **2 gun solenoids** respectively for low charge/high charge WPs
- Each **RF cavity** fed by one klystron. **No SLEDs**.
- Flexible **photo-cathode laser** system

**SINBAD-ARES linac – some technical details**

- RF gun, 2.998 GHz *(REGAE-type)*
  - Beam final energy ~ 5 MeV

- TW RF cavity, 2.998 GHz
  - Max. accelerating gradient ~ 20 MV/m

- **Dogleg tunable** $R_{56}$
  - Range -10/10 mm

- Slit

- **Bunch compressor** $R_{56} = -10$ mm

- **Gun solenoid**

- **TW RF cavity, 2.998 GHz**
  - To be used as RF compressor

- Space for future beam energy upgrade
Production of short pulses starts at the photo-cathode:

- Specifications coming from beam dynamics (flexibility WP bunch compression)

- **Cs$_2$Te:**
  - QE = 4%-11%
  - Response time~ps

- **Cu:**
  - QE = 0.014%
  - Response time<ps
Production of short pulses starts at the photo-cathode:

- Specifications coming from beam dynamics (flexibility WP bunch compression)
- Experience with available laser systems on the market (laser group, LAOLA colleagues…)}
ARES Photo-Cathode laser
(specified and already installed at temporary location)

- Production of short pulses starts at the photo-cathode:
  - Specifications coming from beam dynamics (flexibility WP bunch compression)
  - Experience with available laser systems on the market (laser group, LAOLA colleagues…)

- Optimal solution identified:
  - Yb doped laser
  - Pulse energy ≥1mJ
  - Central wavelength: 1030 nm (4th harmonic 257 nm)
  - Pulse length range tunable: 180fs-10ps

- Note: This is different from other photo cathode lasers at DESY.
ARES Photo-Cathode laser at DESY

- Laser setup in I. Hartl’s laboratory.
- It is operated by Lutz Winkelmann for experiments on laser shaping.
ARES – planned diagnostics in the RF gun region

- Gun + coupler + laser vacuum mirror
- Dual plane steerer
- Reference for BPM
- BAM
- Dipole
- Dual plane steerer
- BPM
- Vacuum valve
- Low charge solenoid
- Vacuum valve
- Diagnostics cross-section (screen + pepperpot + collimator + faraday cup)
- Diagnostics cross-section (screen + collimator)
- BCM
ARES: compression techniques and beam dynamics

- Very short bunches must address many physics limitations:
  - Space charge
  - Non-linearity of phase space
  - CSR
  - Tolerances …

- Three techniques studied and possible to implement:
  - Velocity Bunching (VB)
  - Magnetic Compression with slit (MC)
  - Hybrid combination of VB and MC:
    - In the chicane (fixed $R_{56} = -10$ mm)
    - In the dogleg (variable $-10mm < R_{56} < +10mm$)

- All of them have their advantages and disadvantages

- Now: Going through in detail...
Bunch compression by velocity bunching

Electron Bunch from RF injector
Initial velocity $\beta_0 \sim 0.994$ (4MeV)

Simultaneous compression and acceleration of a non-yet-relativistic beam

VELOCITY BUNCHING

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VB1</th>
<th>VB2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM [fs]</td>
<td>2.7</td>
<td>4</td>
</tr>
<tr>
<td>ΔE/E [%]</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>σx,y [mm]</td>
<td>0.15</td>
<td>0.009</td>
</tr>
<tr>
<td>nεx,y [μm]</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Ip (1 FWHM) [A]</td>
<td>115</td>
<td>87</td>
</tr>
</tbody>
</table>

Q=0.5pC  
E=110 MeV
Injection of WP3 in a THz driven dielectric loaded structure (AXSIS type)

Simulation by Ulrich Dorda

U. Dorda et al.
doi:10.1016/j.nima.2016.01.067
Study done by Jun Zhu – PhD student designing the magnetic lattice of ARES linac

Supervisor: B. Marchetti

- S. Di Mitri et al., PRSTAB 16, 042801 (2013).

J. Zhu, R. Assmann, M. Dohlus, U. Dorda, B. Marchetti,
„Sub-fs electron bunch generation with sub-10-fs bunch arrival-time jitter via bunch slicing in a magnetic chicane“, submitted manuscript.
### Summary of the working points for the main beamline

<table>
<thead>
<tr>
<th></th>
<th>VB (Velocity Bunching)</th>
<th>MC (Magnetic Compression)</th>
<th>VB+MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q final [pC]</td>
<td>0.5</td>
<td>0.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Q initial [pC]</td>
<td>0.5</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>(t_{\text{RMS}}) [fs]</td>
<td>2.486</td>
<td>0.21 (0.27)</td>
<td>0.66 (0.87)</td>
</tr>
<tr>
<td>(t_{\text{FWHM}}) [fs]</td>
<td>4.1</td>
<td>0.14 (0.29)</td>
<td>1.53 (1.42)</td>
</tr>
<tr>
<td>E [MeV]</td>
<td>110.9</td>
<td>100.2 (100.2)</td>
<td>101.6 (101.8)</td>
</tr>
<tr>
<td>(\Delta E/E)</td>
<td>0.3%</td>
<td>0.20% (0.18%)</td>
<td>0.18% (0.16%)</td>
</tr>
<tr>
<td>(x_{\text{RMS}}) [mm]</td>
<td>0.009</td>
<td>0.058 (0.057)</td>
<td>0.084 (0.083)</td>
</tr>
<tr>
<td>(y_{\text{RMS}}) [mm]</td>
<td>0.009</td>
<td>0.059 (0.058)</td>
<td>0.092 (0.088)</td>
</tr>
<tr>
<td>(n\varepsilon_x) [(\mu\text{m})]</td>
<td>0.054</td>
<td>0.068 (0.072)</td>
<td>0.19 (0.21)</td>
</tr>
<tr>
<td>(n\varepsilon_y) [(\mu\text{m})]</td>
<td>0.054</td>
<td>0.063 (0.065)</td>
<td>0.16 (0.15)</td>
</tr>
<tr>
<td>Peak current (I) [A]*</td>
<td>57</td>
<td>953 (759)</td>
<td>1173 (879)</td>
</tr>
<tr>
<td>(B) [A/m(^2)]***</td>
<td>1.97 (\times) 10(^{16})</td>
<td>2.13 (1.63) (\times) 10(^{17})</td>
<td>3.74 (2.71) (\times) 10(^{16})</td>
</tr>
</tbody>
</table>

\*Peak current:

\[
I = \frac{Q_{\text{tot}}}{3.5t_{\text{RMS}}}
\]

**Local peak current:

\[
I_L = \frac{Q_{\text{tot}}}{t_{\text{FWHM}}}
\]

***Brightness:

\[
B = \frac{I}{n\varepsilon_x n\varepsilon_y}
\]
Sources of Arrival Time Jitter

Timing Laser-to-RF

Laser intensity (charge)

TW1 Phase/amplitude

TW2 Phase/amplitude

RF-Gun Phase/amplitude

Beam arrival time jitter $\sigma_{tb}$
<table>
<thead>
<tr>
<th>Jitter source</th>
<th>Unit</th>
<th>Sensitivity for 10-fs timing jitter</th>
<th>RMS tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.7 pC</td>
<td>2.7 pC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MC</td>
<td>VB+MC</td>
</tr>
<tr>
<td>Laser-to-RF</td>
<td>fs</td>
<td>42437.1</td>
<td>159.8</td>
</tr>
<tr>
<td>Gun charge</td>
<td>%</td>
<td>5.8</td>
<td>301.6</td>
</tr>
<tr>
<td>Gun phase</td>
<td>deg</td>
<td>1.75</td>
<td>0.61</td>
</tr>
<tr>
<td>Gun voltage</td>
<td>%</td>
<td>0.61</td>
<td>0.72</td>
</tr>
<tr>
<td>TWS1 phase</td>
<td>deg</td>
<td>0.021</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>deg</td>
<td>0.022</td>
<td>0.13</td>
</tr>
<tr>
<td>TWS1 voltage</td>
<td>%</td>
<td>0.055</td>
<td>0.073</td>
</tr>
<tr>
<td>TWS2 voltage</td>
<td>%</td>
<td>0.064</td>
<td>0.040</td>
</tr>
<tr>
<td>BC B-field</td>
<td>%</td>
<td>0.030</td>
<td>0.030</td>
</tr>
<tr>
<td>$\sigma_{t_b}$</td>
<td>fs</td>
<td>\</td>
<td>\</td>
</tr>
</tbody>
</table>
Compression of the beam along the dogleg with RF phase jitter compensation

- Basic idea: compressing the e-bunch via VB+MC while compensating the arrival time jitter at the dogleg exit.

- Analytical approach firstly proposed in: R. Brinkmann, Ideenmarkt Beschleuniger Seminar, DESY 2012.

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We restrict ourselves to the study of the compensation of the phase jitter in TW1 (dominant jitter for VB+MC)

B. Marchetti et al.  
doi:10.1016/j.nima.2016.03.041
Constraint on beam compression

Maximum compression:

\[
\frac{\Delta p}{p} = h_1 z + h_2 z^2 + h_3 z^3
\]

\[R_{56mc} = -\frac{1}{h_1}\]
Constraint on jitter compensation

Jitter compensation:

\[ dt_1 = -dt_2 \]

\[ dt_2 = \frac{R_{56}}{c} \frac{d\gamma}{\gamma} \]

\[ R_{56jc} = -c \frac{dt_1}{\frac{d\gamma}{\gamma}} \]
Semi-analytical approach

➢ Start with a certain machine setup (laser param., solenoids, RF gradients etc.)

➢ Scan of phase of RF compressor with ASTRA simulations

➢ ASTRA’s outputs read by Matlab routines analyzing the phase-space and jitter of the beam

➢ Calculation of $R_{56mc}$ and $R_{56jc}$

➢ Extrapolation of information for finding a new working point (hopefully better)
Can we have $R_{56jc} = R_{56mc}$?

Starting point:

- Beam compressed in TW1 and accelerated in TW2
- Maximum compression at the linac exit
Can we have \( R_{56jc} = R_{56mc} \)?

- **Full compensation of the jitter** happens for:
  - high positive \( R_{56} \) values
  - over-compression of the beam at the linac exit

- Equivalent to running TW1 on crest and using the space charge chirp to compress the beam (*)

- We can have also a **partial compensation** of the jitter.

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*Scan of the phase of the RF compressor*
Can we have $R_{56jc} = R_{56mc}$?

**WPC:**
- The second TW is operated off-crest (the VB is distributed between 2 cavities)
- $E \sim 50$ MeV

The correlation of the chirp of the arrival time jitter switches sign!

- No full jitter compensation possible
- **Partial jitter compensation** occurs for:
  - under-compressed beams at linac exit
  - using a **small negative $R_{56}$**.

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![Graph showing $R_{56}$ vs. $\phi_{TW1}$ for WPA and WPC cases.](image-url)
Examples of new working points at the dogleg exit

- Beam3 has an excellent stability
- The beams have completely different evolution and characteristics
- Exciting experimental work can be done to compare those different setups at ARES!

\[ \Delta \varphi_{TW1} = 0.02 \, \text{deg} \]

|       | Initial $\sigma_z$ [fs] | $-dt_2/dt_1$ [%] | $R_{56}$ [mm] | $T_{56}$ [mm] | Final $\sigma_z$ [fs] | $|dt_1 - dt_2|$ [fs] |
|-------|--------------------------|------------------|---------------|--------------|-----------------------|---------------------|
| BEAM1 | 3.4                      | 0.14             | 0.5           | 14.2         | 2.2                   | 17                  |
| BEAM2 | 21.8                     | 5.8              | 9.6           | 124          | 3.2                   | 21                  |
| BEAM3 | 33.1                     | 16               | -1.1          | 23.5         | 2.2                   | 13                  |
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➢ Introduction: Why Short Bunches and the SINBAD Facility?

➢ The ARES linac: A Design for Sub-Femto Second Bunches

➢ Plasma Acceleration with the ARES linac
  - Goals of LPWA @ SINBAD: high quality acceleration
  - ATHENAe

➢ Final Considerations and Summary
SINBAD as host to $\text{ATHENA}_e$

- Plasma experiment at SINBAD funded through the ATHENA proposal
- Skip the proposal details $\rightarrow$ want to focus on the ARES beam quality for plasma applications
Main extension to ARES through ATHENA

- Energy upgrade of linac
- X-band for Transverse Deflecting Structure (TDS) and Phase Space (PS) linearization
- Timing synchronization upgrade
- Additional undulators
- Imaging beam line
Plasma acceleration with external injection at SINBAD

- Work at low plasma density ($10^{16}-10^{17}$ cm$^{-3}$)
  - Accelerating gradient: $E_0 (V/m) \approx 96 \sqrt{n_0} (cm^{-3})$
  - Plasma wavelength: $\lambda_p \sim \frac{1}{\sqrt{n_0}}$
  - Acceleration length (depends on diffraction and dephasing): $L \sim \frac{1}{\sqrt{n_0^3}}$

<table>
<thead>
<tr>
<th>Plasma density [cm$^{-3}$]</th>
<th>Wavelength</th>
<th>Period</th>
<th>Skindepth</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{19}$</td>
<td>10.6 μm</td>
<td>35.3 fs</td>
<td>1.68 μm</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>33.4 μm</td>
<td>101.3 fs</td>
<td>5.31 μm</td>
</tr>
<tr>
<td>$10^{17}$</td>
<td>106 μm</td>
<td>353.3 fs</td>
<td>16.8 μm</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td>334 μm</td>
<td>1.0 ps</td>
<td>53.1 μm</td>
</tr>
<tr>
<td>$10^{15}$</td>
<td>1.06 mm</td>
<td>3.53 ps</td>
<td>0.166 mm</td>
</tr>
<tr>
<td>$10^{14}$</td>
<td>3.34 mm</td>
<td>10.0 ps</td>
<td>0.531 mm</td>
</tr>
</tbody>
</table>
Plasma acceleration with external injection at SINBAD

- ARES = 100MeV → less de-phasing issue at the injection

Laser pulse, plasma wave travel with $v_{\text{wave}} = v_g < c$
Electrons travel with $v_e \approx c > v_{\text{wave}}$

Matching of the beam

The ion channel left in axis, where the beam passes, induces an extremely strong focusing field:

\[ g = 960\pi \left( \frac{n_0}{10^{14} \text{cm}^{-3}} \right) \frac{T}{m} \]

In order to avoid un-controlled growth of the transverse emittance of the beam, the injected e-bunch has to be matched with the focusing channel described by:

\[ k_\beta = 0.2998 \frac{g}{E} \]

\[ \beta = \frac{1}{k_\beta}, \alpha = 0 \]

300 kT/m for \(10^{16} \text{ cm}^{-3}\)

\(\beta = 1.1 \text{ mm for 100 MeV}\)

Lower plasma density increases beta function

Courtesy of R. Assmann
Matching of the beam

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Lower plasma density increases beta function

Courtesy of R. Assmann

This requirement can be additionally relaxed by using a tailored plasma profile!

_Cfr: I. Dornmair et al. PRSTAB 18, 041302 (2015)._
Matching of the beam from the BC exit at SINBAD

- Elongation of the bunch length along a drift for a SC dominated beam:
  \[ \sigma_z \approx e^{Lh/y^2} \sigma_{z,0} \]

- Emittance growth due to chromatic aberrations:
  \[ \frac{\Delta \varepsilon_{x,y}}{\varepsilon_{x,y}} = \frac{1}{2} \sigma_\delta^2 \beta_{x,y}^2 / L^2 \]

- Increase in the spot-size due to chromatic aberrations:
  \[ \frac{\Delta \sigma_{x,y}}{\sigma_{x,y}} = \frac{1}{2} \sigma_\delta \frac{L}{\beta_{x,y}} \]

\[ \sigma_t @ BC \text{ exit} = 0.35 \text{fs} \rightarrow \sigma_t @ \text{plasma chamber entrance} = 1.5 \text{ fs} \]

Cfr: J. Zhu et al.  
doi:10.1016/j.nima.2016.01.066

CS parameters at the plasma target:  
\( \beta_x = 2.1 \text{ cm} \)  
\( \alpha_x = 0.34 \)  
\( n\varepsilon_x = 0.16 \mu \text{m} \)  
\( \beta_y = 2.7 \text{ cm} \)  
\( \alpha_y = 0.18 \)  
\( n\varepsilon_y = 0.14 \mu \text{m} \)
Almost hard-edge plasma model + laser guiding

\[ n = 4.25 \times 10^{16} \text{ cm}^{-3} \]
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Summary

> The ARES linac is the central part of the SINBAD facility, designed to address needs for **ultra-fast science** and **R&D on novel acceleration techniques**.

> A detailed **conceptual design** with a large flexibility in working points has been worked out, with bunch lengths **down to 0.2 fs (rms)**.

> Sensitivity and **tolerances** have been specified.

> The **technical implementation** of the linac design is ongoing:

  - **First crucial components have been procured**, e.g. an optimized photo-injector laser.
  - Iterations of the machine **technical design** and procurement of other components ongoing. Major work spent on **detailed technical specifications** (not shown here).

> First **start to end simulations for applications on plasma accelerators** have been performed and presented.

> Further work ongoing for R&D with ARES for dielectric accelerators (ACHIP and AXSIS), ultra-fast science, medical imaging, …

> **Thanks to the support from my DESY colleagues!**
A special thank you goes to the **colleagues in the ARD and MPY collaborating with the SINBAD project**. In particular I would like to thank the following colleagues for profitable discussions, advices and help:

- R. Assmann, U. Dorda, J. Zhu
- K. Floettmann, R. Brinkmann, J. Grebenyuk, M. Weikum
- R. Mundt

...Old picture! We are many more now 😊
Acknowledgments (2/2)

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