Diagnostics for high repetition rate ERL injectors

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**Design parameter:**

- Nominal bunch charge: 77 pC
- Bunch repetition rate: 1.3 GHz
- Beam power: up to 550 kW
- Nominal gun voltage: 500 kV
- SC linac beam energy gain: 5 to 15 MeV
- Beam current: 100 mA at 5 MeV, 33 mA at 15 MeV
- Bunch length: 0.6 mm (rms)
- Transverse emittance: < 1 mm-mrad
Diagnostics challenges for high repetition rate ERL injectors

• The dynamic range of many systems needs to be HUGE!
  Examples:
  – bunch charge: ~ fC to 100 pC
  – duty cycle: ~ $10^{-5}$ to 1

• High repetition rates of up to 1.3 GHz

• Pulsed operation AND CW operation

• Very high power levels in many systems
  – up to 550 kW beam power
  – up to 50 kW beam power from the DC gun alone
  – Laser power in the IR >100 W

• Similar beam quality similar to state-of-the-art FEL injectors
Advantages of high repetition rates: fast measurements

Emittance measurement system:

- No moving mechanical parts
  - Allows for very fast measurements (~ 2 s to 5 s)

Will be used for a parametric optimization of the injector.
Difficulties with high repetition rates

Transverse deflecting cavity

- Very good extinction ratio required in pulsed operation mode ($> 10^6$) for many integrating measurements

- Number of cavities: 1
- Max transverse kick voltage: 200 kV
- Max RF power: 3.8 kW
- Average power: 200 W
- Pulse duration: 60 µs
- Max rep. rate: 1 kHz

![Image of beam energy vs. time with unstreaked and streaked beam notes]
Difficulties with high power levels

- Main limitations:
  - Gun high voltage instabilities at various beam currents
  - Laser amplitude instabilities

Heavy beam loading even in the gun!

- 9 mA maximum current
- 5 MeV, 250 keV gun voltage
  \[\rightarrow 45 \text{ kW total beam power}\]
  \[\rightarrow 2.3 \text{ kW only from gun}\]
Laser system

Simplified layout:

- 50 MHz / 1.3 GHz Yb laser oscillator
- Pre-amplifier
- Main amplifier
- AOM
- Pockels cell
- SHG
- Beam shaping

- Work on increasing the extinction ratio for pulsed operation mode by installing acousto-optical modulator
- Implementation of additional feedback loops for laser power and timing control
We implement a beam based feedback loop based on a time-of-flight measurement. Regulation uses uTCA regulation electronics developed at DESY.
Laser Position Stabilization

- Variable attenuators increase dynamic range by 4 orders of magnitude
- At full laser power (20 – 50 W) the attenuators are operated close to the damage threshold (~30 W / cm²)
- Not yet tested over a wide range of laser operation conditions
- Dynamic range could be further increased by polarizer based attenuators
Beam current stabilization

- We implement a beam based feedback loop based on a bunch charge measurement
- Maximum regulation bandwidth: 3 MHz

Expected monitor resolution:

<table>
<thead>
<tr>
<th>Charge Measurement</th>
<th>BW= 100 kHz</th>
<th>BW= 10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 fC</td>
<td>0.012%</td>
<td>0.85%</td>
</tr>
<tr>
<td>1 pC</td>
<td>0.003%</td>
<td>0.25%</td>
</tr>
<tr>
<td>100 pC</td>
<td>0.003%</td>
<td>0.25%</td>
</tr>
</tbody>
</table>
Transverse beam profile at high beam currents

‘Flying wire’

• 20 µm carbon wire
• should withstand ~MW beam
• up to 20 m/s wire speed

Not yet commissioned
Longitudinal beam properties at high beam current

THz interferometer?
Installed but not yet commissioned

Electro-optic diagnostics?
Resolution limited by low beam energy ($1/\gamma$)
How to measure the beam positions of both beams in an ERL?

Options:
- direct sampling with several GHz ADCs
  - single bunch measurement
  - but: expensive, no high resolution ADCs available
  - sensitive to ADC timing stability
- Two-frequency down-conversion scheme
How to measure the beam positions of both beams in an ERL?

Two-frequency down-conversion scheme:

- If the second beam is not exactly at a phase of 180 deg with respect to the first beam, this causes a constant offset in the 1.3 GHz signal. → no concern
- Non-constant phases of the second beam:
  Can be corrected for with the phase information of IQ detectors?

Two beam BPMs can be tested in our ERL injector by splitting and delaying the 1.3 GHz drive laser beam.
Conclusion

Special challenges for high repetition rates
- Large dynamic range
- Large power levels

Pulsed mode / low current mode
- Many diagnostic systems can be similar to low current injectors
- All important monitors are available

High current CW mode
- Still need research on
  - Transverse beam profile measurements
  - Longitudinal beam profile measurements
  - Stability!