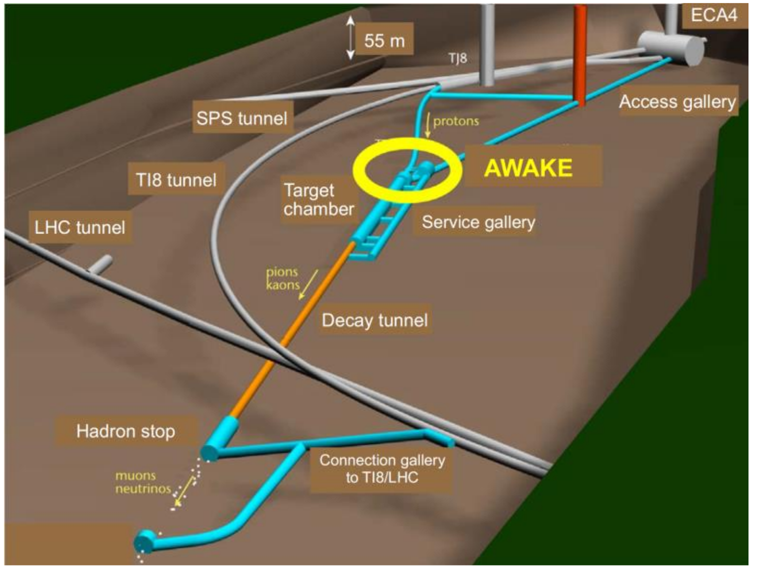
Diagnostic of coherent transition radiation for measuring micro-bunch formation in AWAKE

Falk Braunmueller & Mikhail Martyanov,

Patric Muggli, Christopher Allen Caldwell, and the AWAKE-team



25 October 2016

Paris
LA^{3}Net – Novel Accelerators

Outline

- The Self-Modulation Instability (SMI)
- TR and CTR basics
- CTR from Self-Modulation Instability (SMI) in AWAKE
- Overview of CTR-diagnostics
- Frequency-analysis with heterodyne measurement
- Outlook

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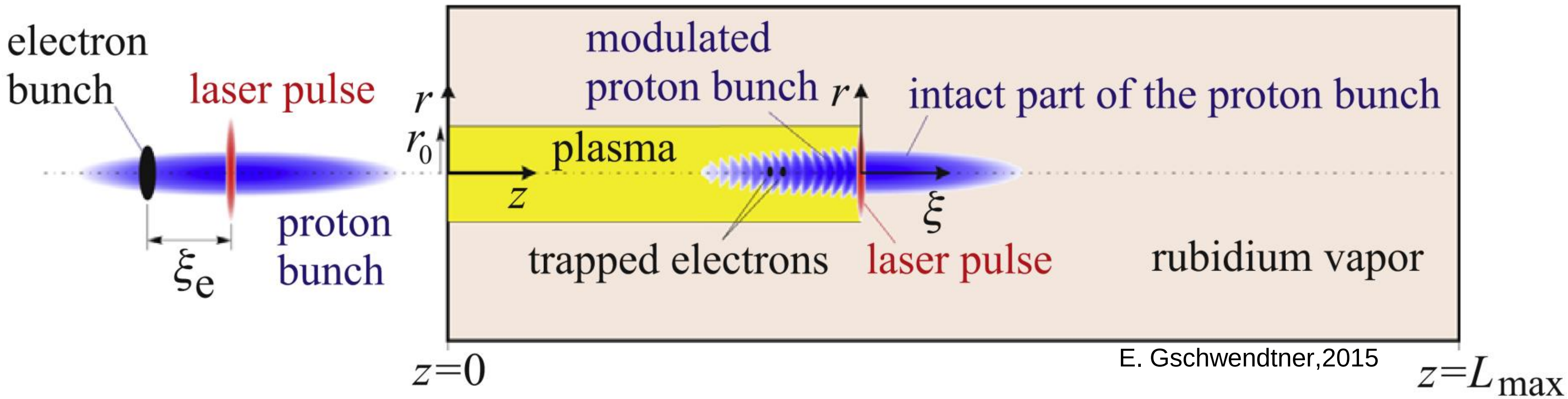
Self-modulation instability (SMI)

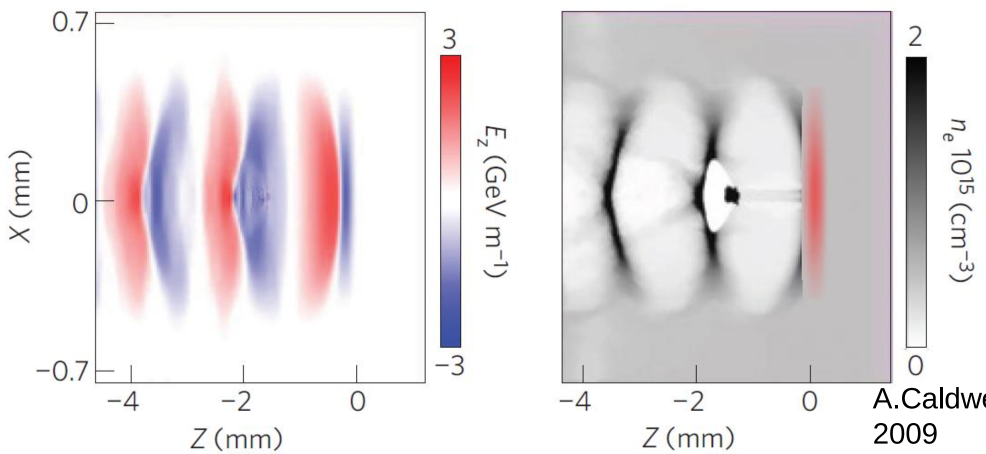


E. Gschwendtner,2015

Reducing 12 cm bunch to micro-bunches:

Self-modulation Instability

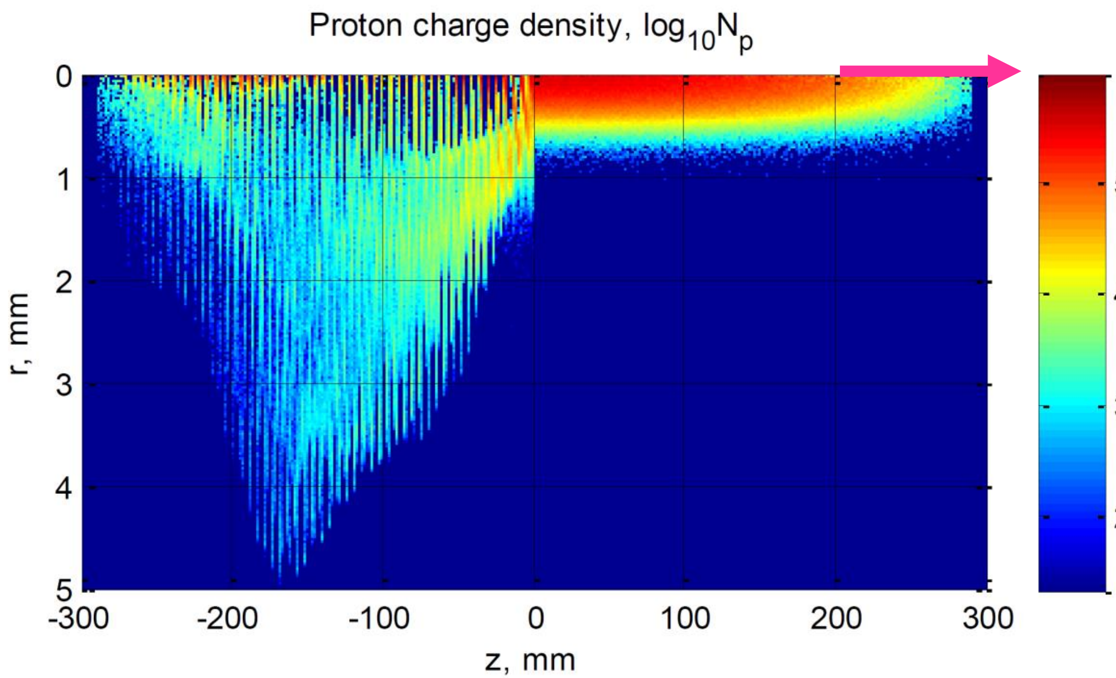
→ radially modulated bunch density, with plasma-wavelength



A.Caldwell, 2009

Indirect Measurement of SMI

Analyze p+-bunch with microbunch-train after plasma cell



3 Methods:

- **Measurement of bunch-size on scintillating screen**
- **Optical transition radiation: direct signal from each proton**
- **Coherent transition radiation: Measure electric field component from charge density modulation**

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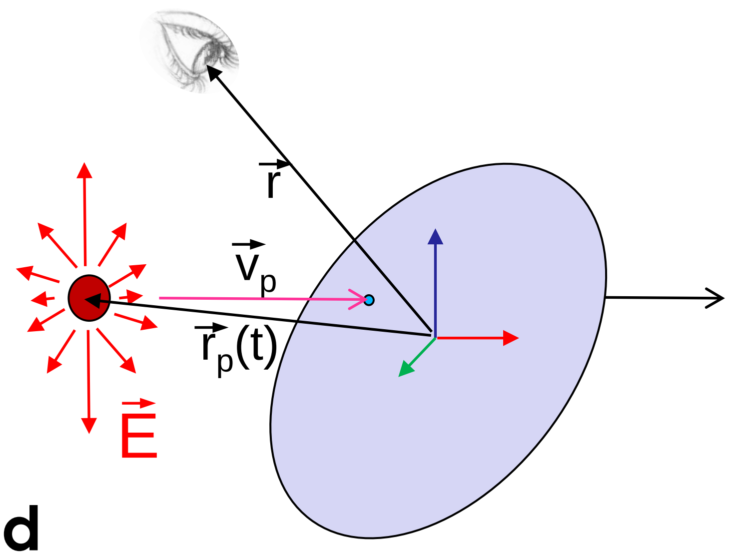
Transition radiation

Relativistic particles incident on metallic / dielectric surface

➔ Radiation from induced surface-currents

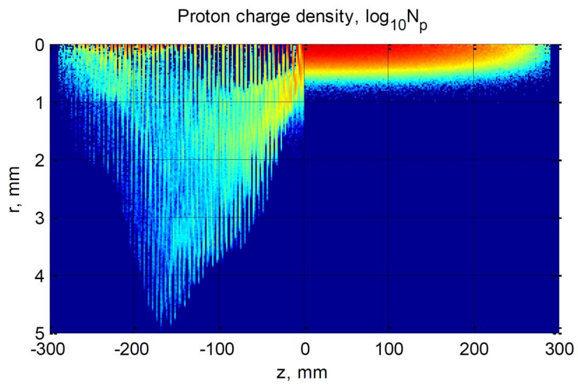


Approaches (e.g.):

- Virtual photon method
- Surface-current method

Investigate effects of near-field and finite screen

AWAKE CTR-simulations



COHERENT transition radiation:

- $\sim N_{p+}^2$

  → much stronger

Using p+-distribution from beam-plasma PIC-simulation

Summing up fields of each p^+

Proton-bunch modulated at plasma wavelength

→ **CTR-signal at plasma frequency**

Vary Plasma density between $n=10^{14}$ cm^{-3} and $n=10^{15}$ cm^{-3}

→ **Plasma frequency between**

f_{plasma} =90GHz and

f_{plasma} = 300GHz.

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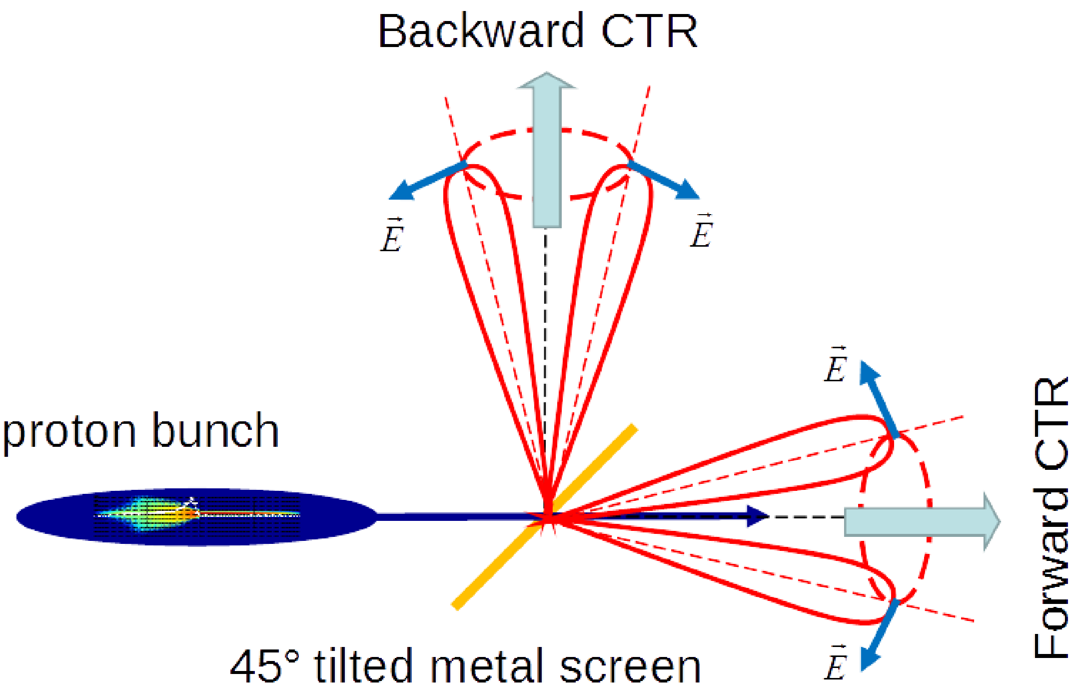
Coherent Transition radiation



Self-modulation Instability

→ radially modulated bunch density

→ Radially polarized CTR-electric field

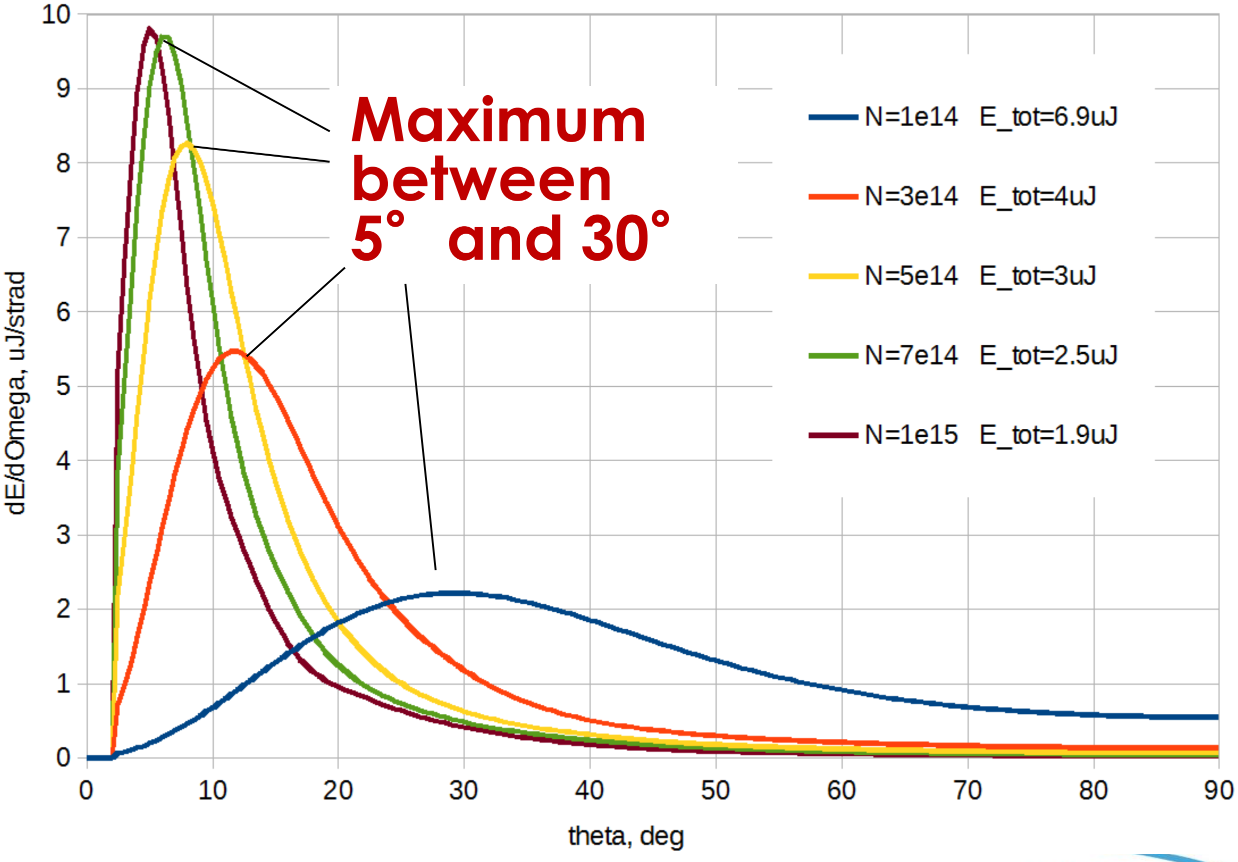
CTR-signal from SMI

Simulation of CTR-radiation in AWAKE:

- **Ginzburg-Frank**
- **Surface current method.**

At angle much larger than 1/γ !

Angular CTR-energy distribution



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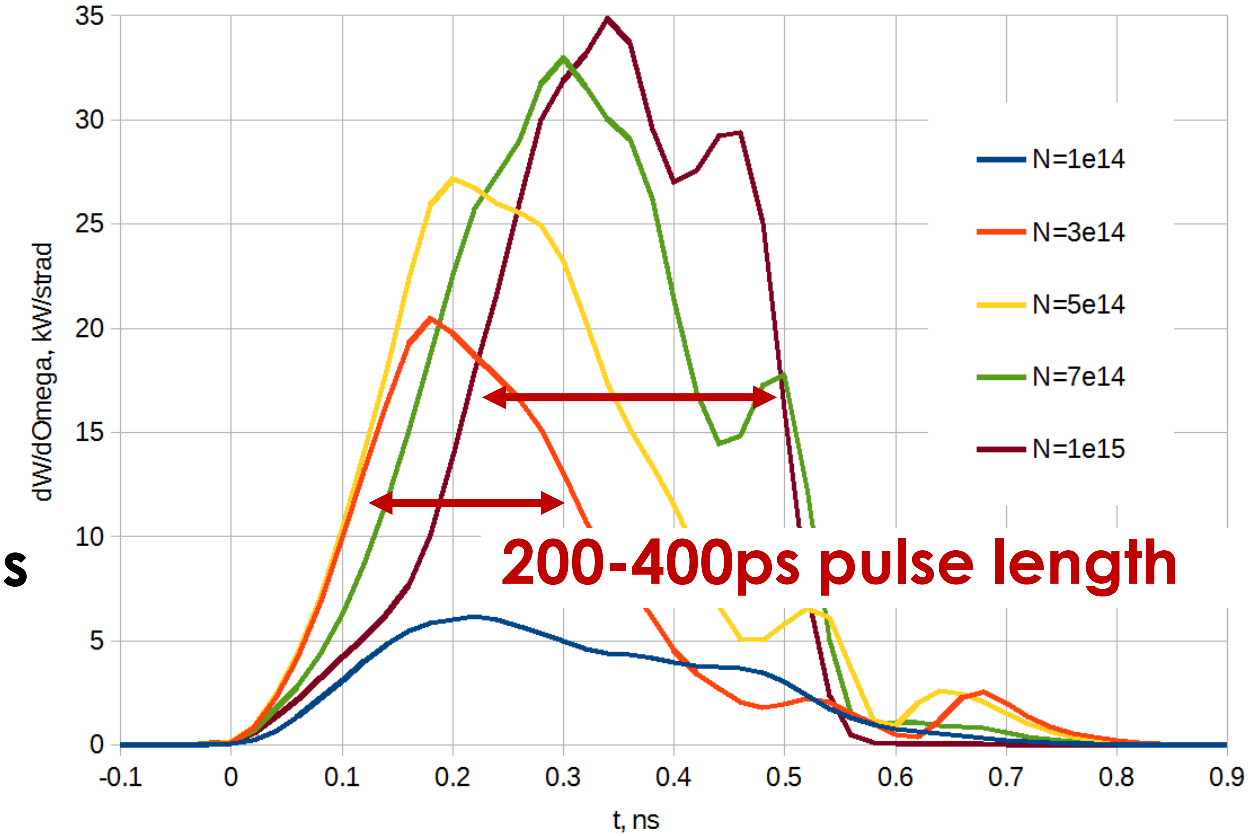
CTR from SMI in AWAKE

Strong signal:

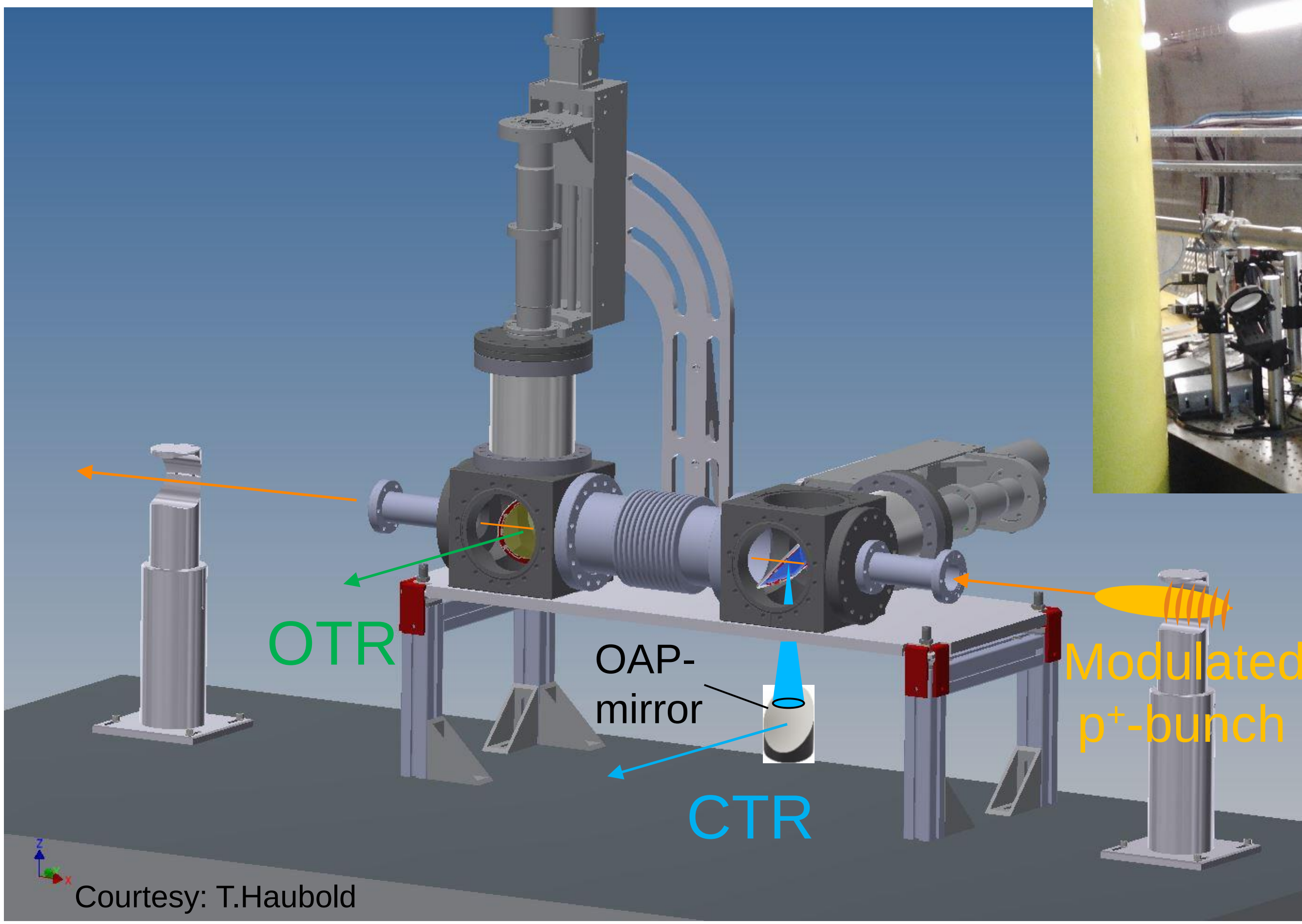
~5-30kW/strad at angle $\theta(E_{max})$

Short pulse with ~50-100 oscillations at 90-300GHz

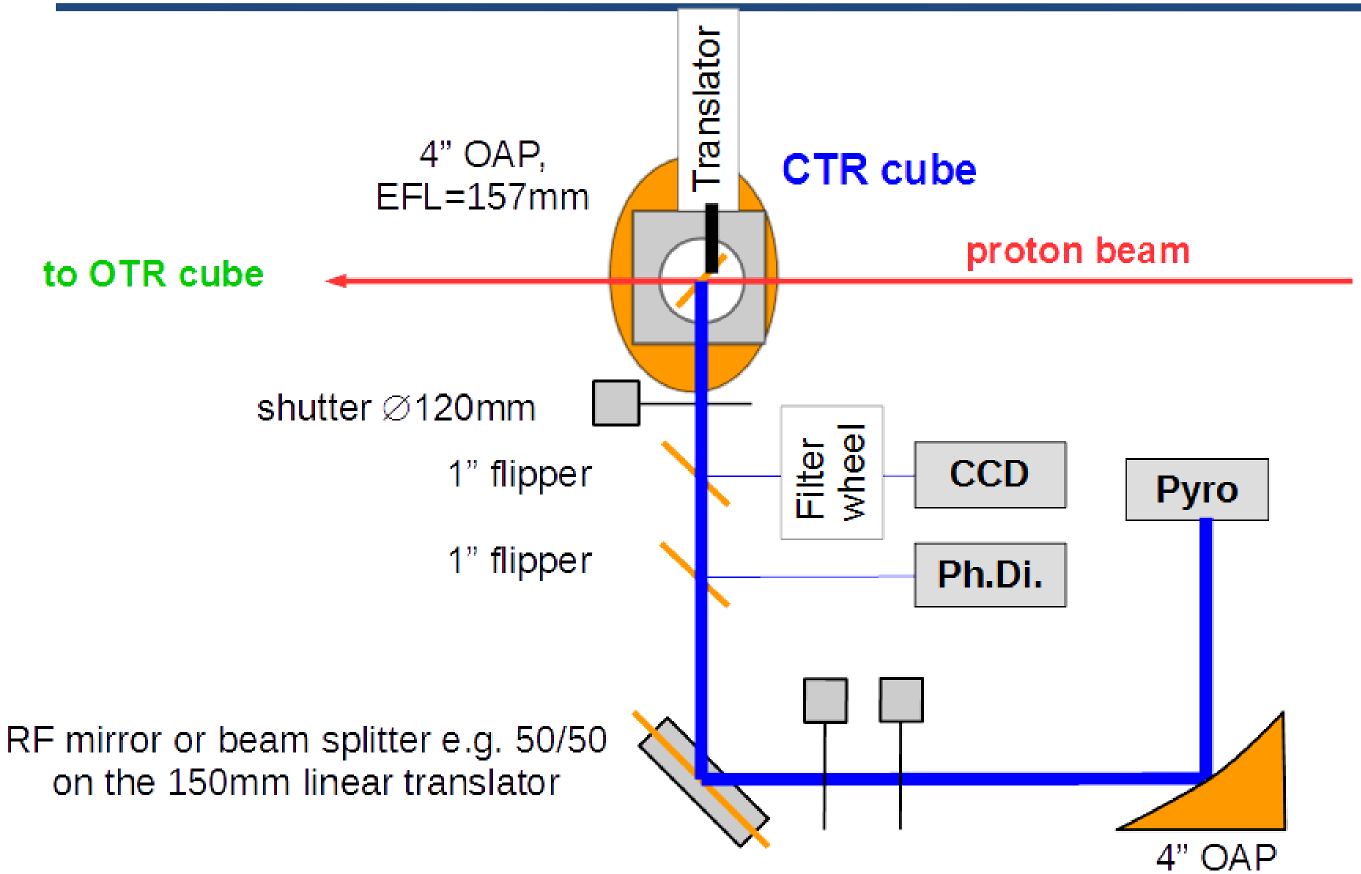
Temporary evolution of CTR-pulse



Diagnostics for SMI-CTR

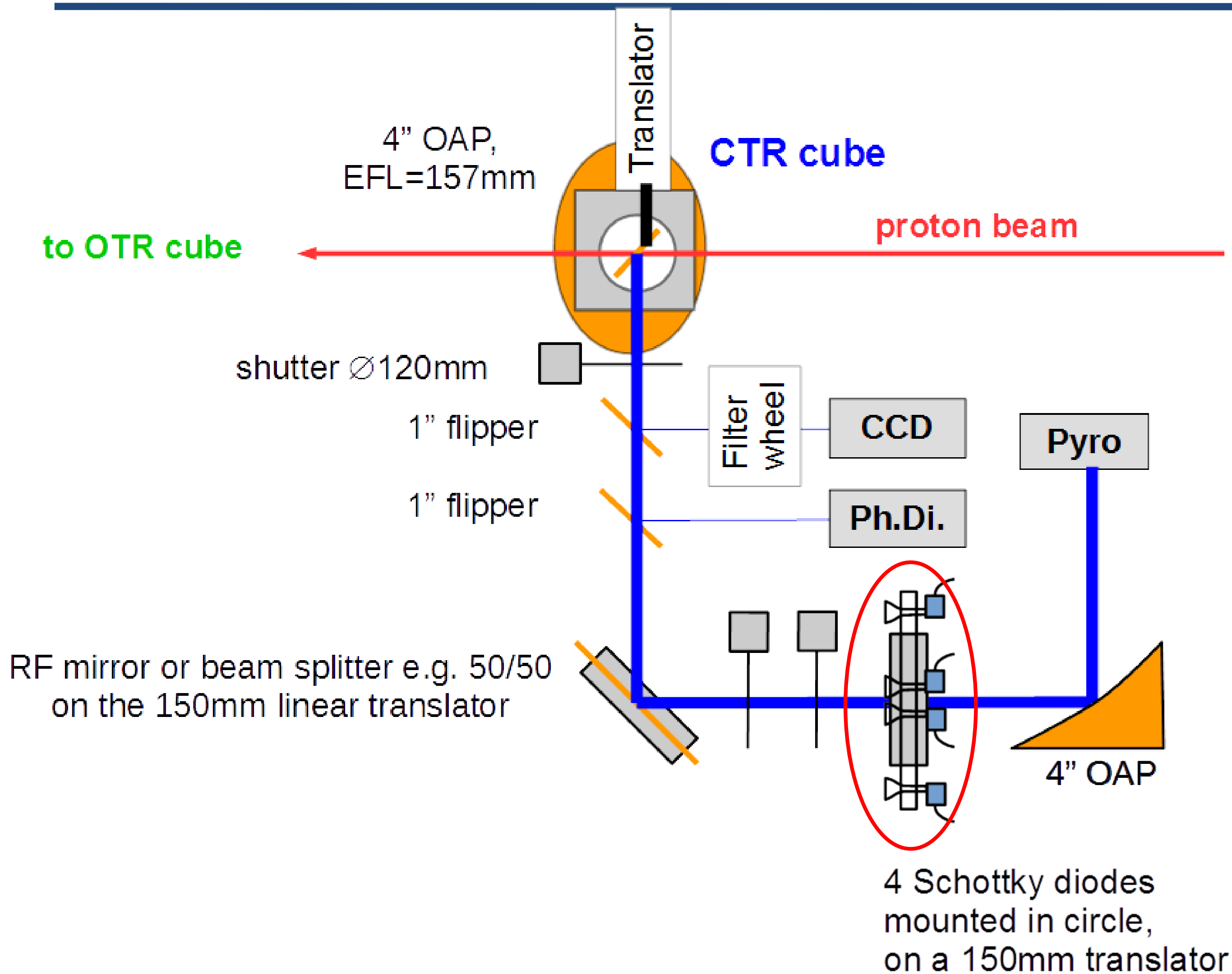


CTR-diagnostics: Overview



1) **Integrated TR-measurement**

CTR-diagnostics: Overview



1) **Integrated TR-measurement**
2) **Time-resolved CTR-power measurement: different bandwidth-systems**

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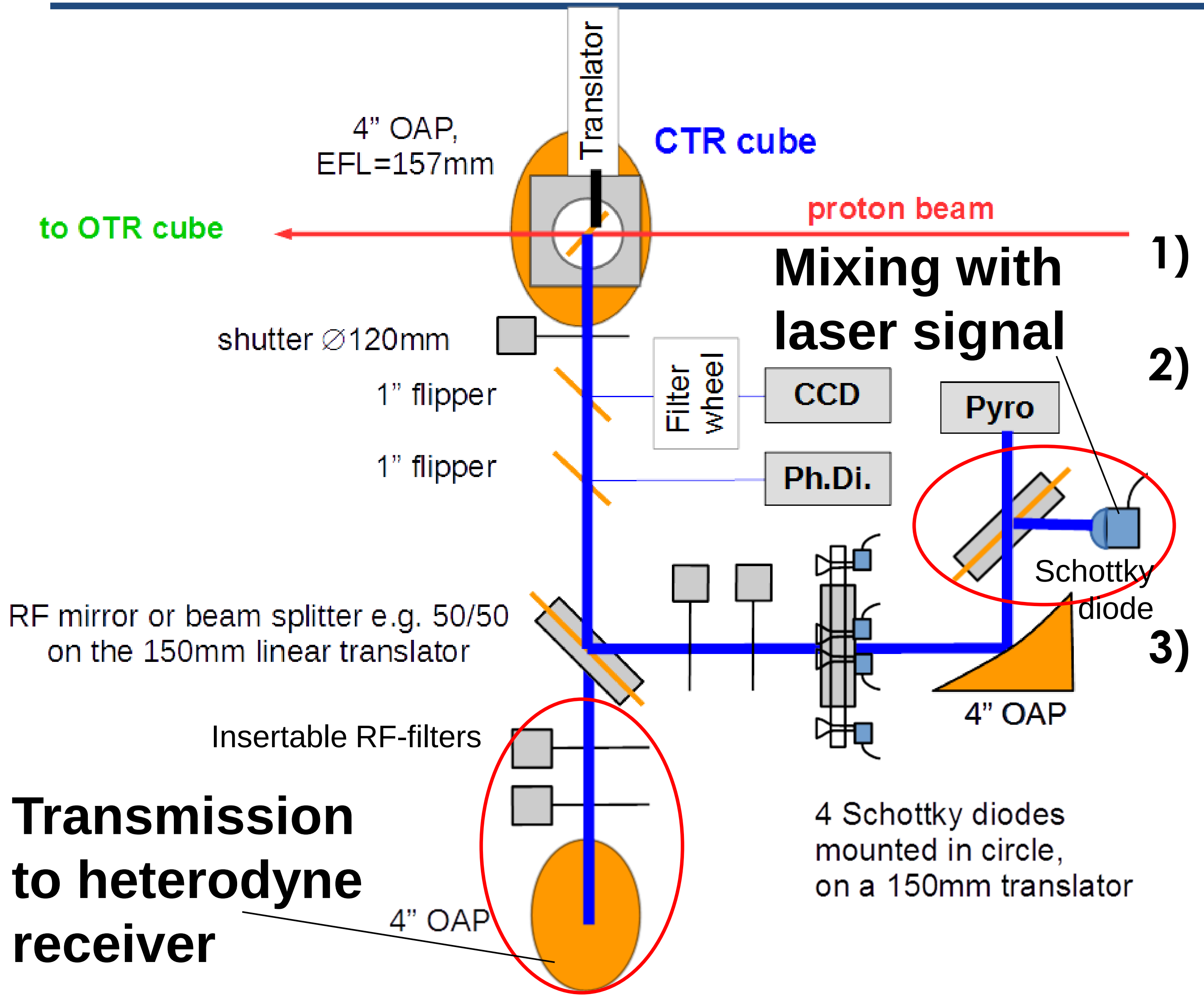
CTR-diagnostics: Overview



1) **Integrated TR-measurement**
2) **Time-resolved CTR-power measurement: different bandwidth-systems**
3) **Frequency-measurement of CTR-signal: 2x Heterodyne measurements of f_{plasma}**

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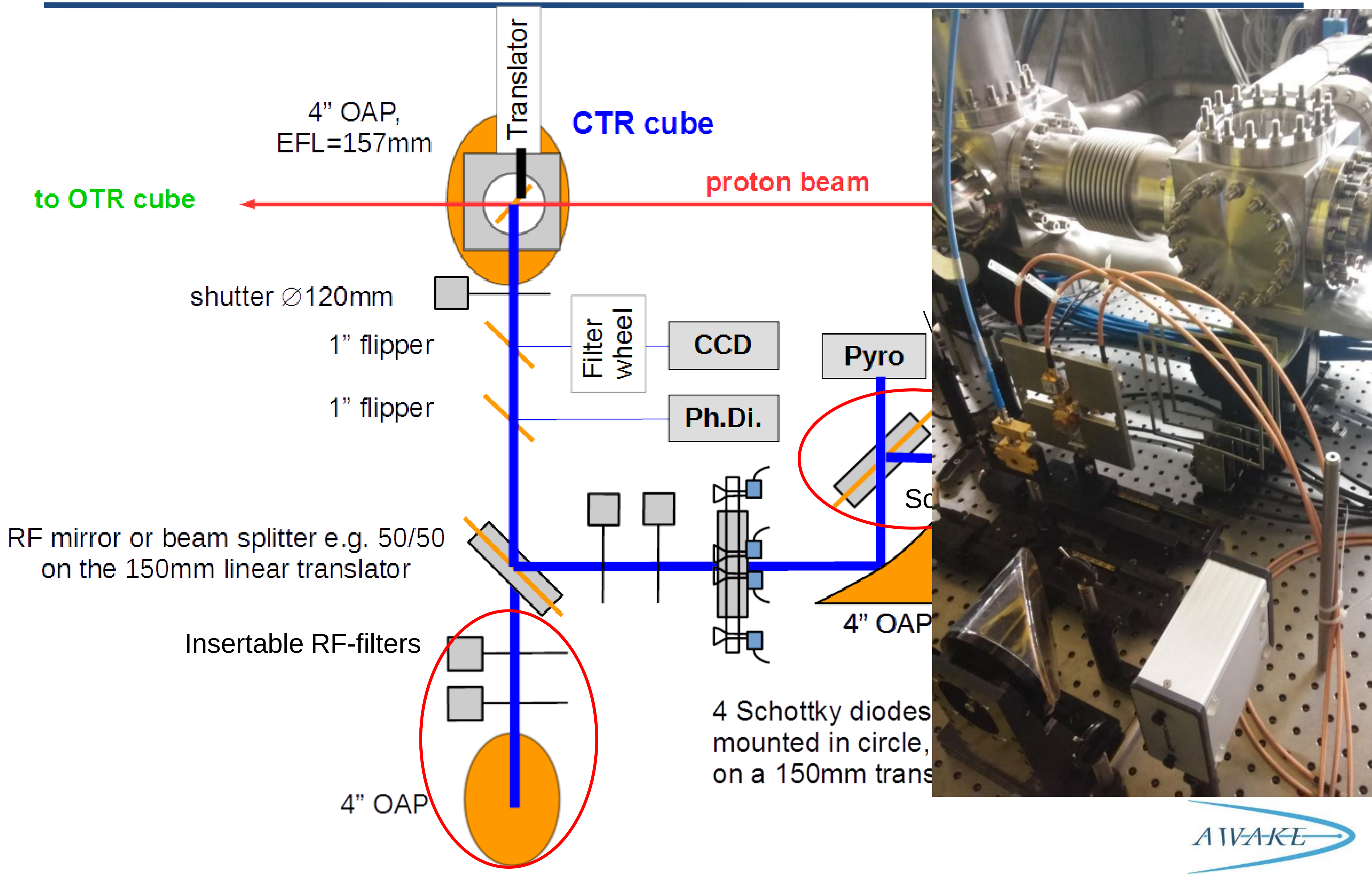
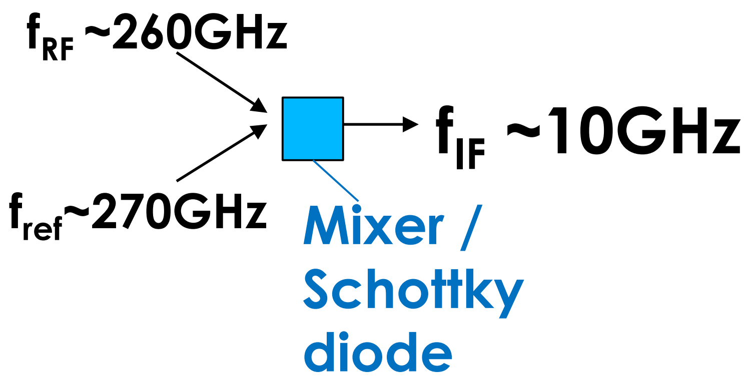
CTR-diagnostics: Overview

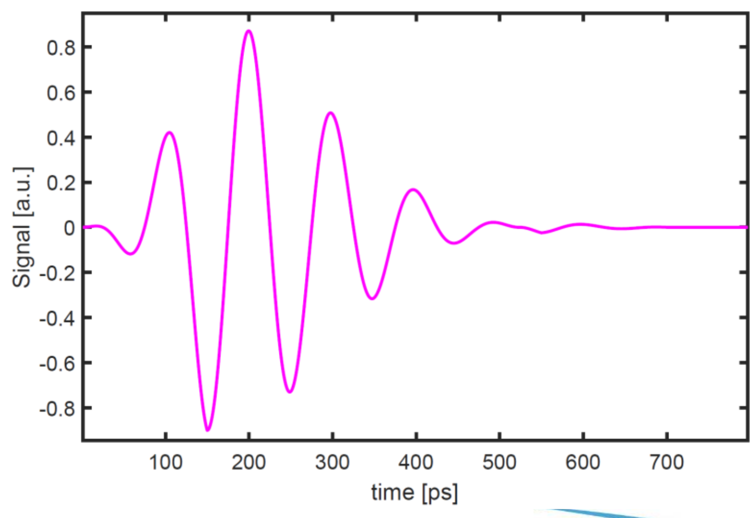


2x Heterodyne Measurement

- **Down-mixing CTR-signal by known reference:**
  $f_{IF} = f_{RF} - f_{ref}$
- **Measurement of signal f_{IF} ~ 10-20 GHz on fast oscilloscope (20-40GHz bandwidth)**
- **Beamline at 15m distance from oscilloscope (shielding)**

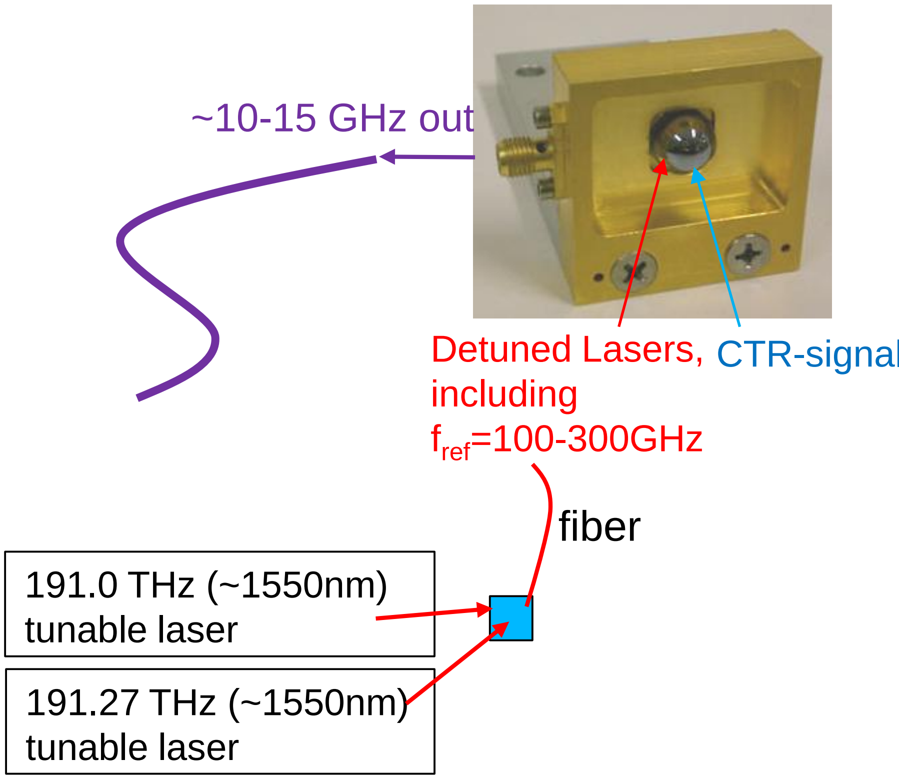


Expected signal (f_{IF}=10GHz)



Heterodyne Measurement 1

- Mixing of reference with CTR close to beamline
- Reference signal by mixing slightly detuned lasers
- Transmission of f_{IF}~10-20GHz in low-loss coaxial cables
- Tunable over entire CTR frequency-range



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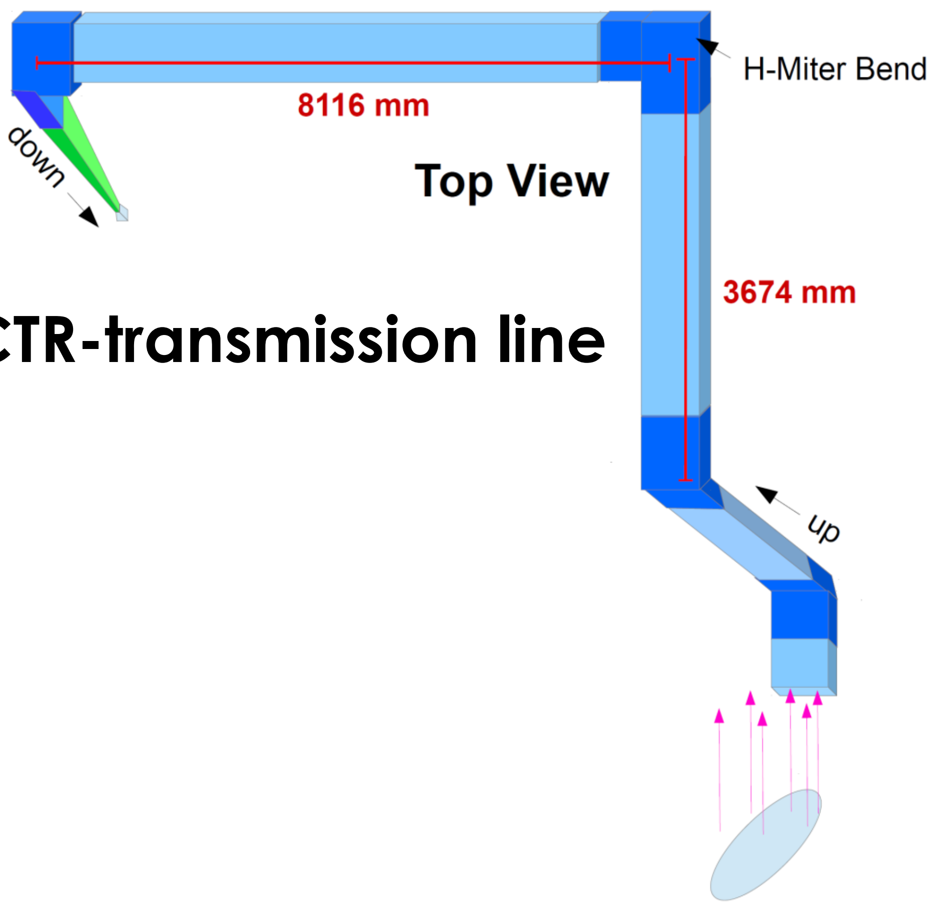
Heterodyne Measurement 2



CTR-transmission line

Mixing of reference with CTR close to oscilloscope

WR90 rectangular waveguide (23x10mm) with 'tall' TE_{10}-mode:

Best compromise between
- Ohmic losses
- Miter bend losses
- Taper losses
- Alignment sensitivity

E-field polarization

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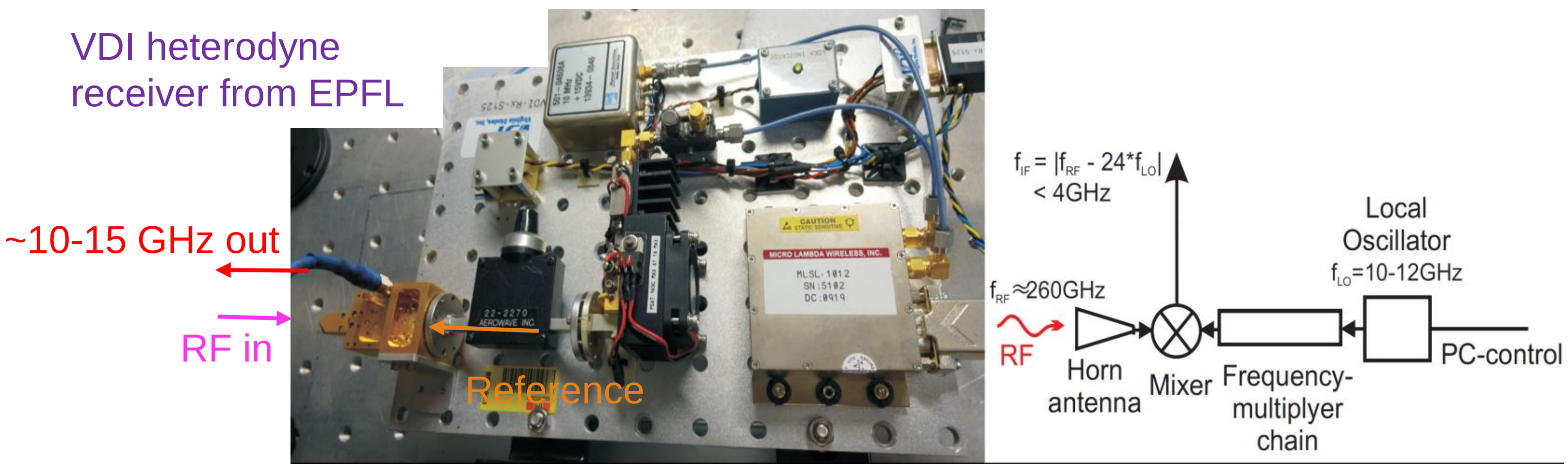
Heterodyne Measurement 2

- **Reference signal by frequency-multiplied tunable local oscillaterTransmission of RF over 15m**
- **Only over less than one waveguide-bandwidth**
- **Better signal efficiency**



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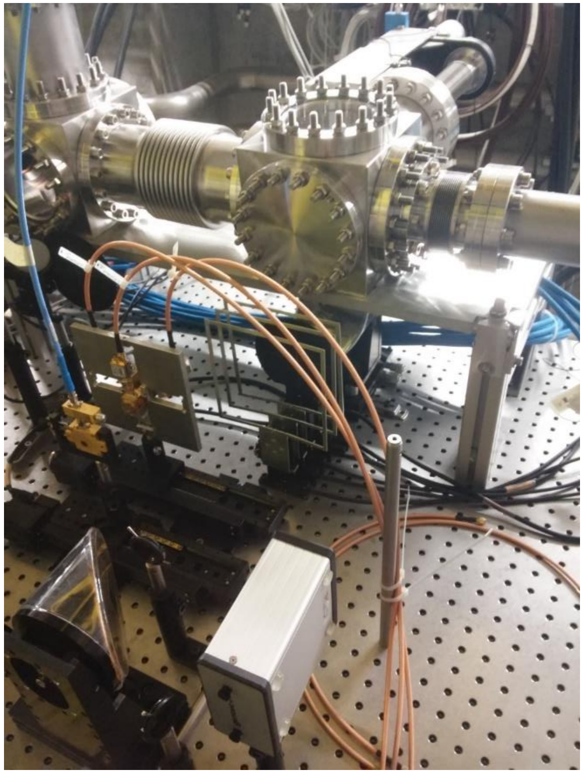
Status & Outlook

- All diagnostics close to beamline installed and commissioned
- RF-transmission line installation in next weeks
- First SMI-experiments for 1 week in December 2016



Summary & Planning

- **Essential measurement of microbunch-train due to SMI**
- **CTR-simulations predict strong signal plasma-frequency, at larger angles**
- **Variety of diagnostics for integrated, time-resolved and frequency-resolved measurement**
- **Two kinds of heterodyne measurement**
- **First measurements expected end of this year**

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Thank you for your attention!

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Details of CTR-calculation

Single particle Ginzburg-Frank (GF) formula - valid for infinite screen and far-field

Spectral components of electric and magnet fields are:

$$\vec{E}_{0\omega}(\vec{r}) = \frac{eZ_0}{(2\pi)^{3/2}} \frac{e^{i\omega(t_s - R(t_s)/c)}}{R} \frac{\vec{s}\times\vec{s}\times\vec{\beta}}{1-(\vec{s}\vec{\beta})^2}, \qquad \vec{B}_{0\omega}(\vec{r}) = \frac{\vec{n}\times\vec{E}_\omega(\vec{r})}{c}$$

Spectral energy density angular distribution:

$$\frac{d^2 W_0}{d\omega\, d\Omega} = \frac{e^2 Z_0}{4\pi^3}\left|\frac{\vec{s}\times\vec{s}\times\vec{\beta}}{1-(\vec{s}\vec{\beta})^2}\right|^2 = \frac{e^2 Z_0}{4\pi^3}\left(\frac{\beta\sin\theta}{1-\beta^2\cos^2\theta}\right)^2$$

Far-field CTR for a bunch:

$$\vec{E}_\omega(\vec{r}) = \sum \vec{E}_{0\omega}(\vec{r}, t_s) = \frac{e^{ikr}}{r}\frac{eZ_0}{(2\pi)^{3/2}}\frac{\vec{s}\times\vec{s}\times\vec{\beta}}{1-(\vec{s}\vec{\beta})^2}\sum e^{i\varphi_s}$$

$$\frac{d^2 W}{d\omega\, d\Omega} = \frac{d^2 W_0}{d\omega\, d\Omega}\left|\sum e^{i\varphi_s}\right|^2 \approx \frac{d^2 W_0}{d\omega\, d\Omega}\left(N + N(N-1)\left|F\left(\frac{\omega}{V}\sin\theta, \frac{\omega}{V}\right)\right|^2\right)$$ - GF

Surface current (SC) method - valid for flat screen of any shape and any distance towards observer

Vector-potential of the surface field $\vec{E}_s(\omega)$ as a source:

$$\vec{A}_\omega = -\frac{1}{2\pi}\int \frac{e^{ikR}}{R}[\vec{n}\times\vec{E}_s]\, d^2\vec{r}_s \qquad \vec{R} = \vec{r} - \vec{r}_s$$

Spectral components of electric and magnetic fields:

$$\vec{E}_\omega = -\operatorname{rot}\vec{A}_\omega \qquad \vec{B}_\omega = \frac{i}{ck}(\nabla \operatorname{div} + k^2)\vec{A}_\omega$$

$$\vec{E}_\omega = \frac{k^2}{2\pi}\int \frac{e^{ikR}}{(kR)^2}(ikR-1)[\vec{s}\times\vec{n}\times\vec{E}_s(\vec{r}_s)]\, d^2\vec{r}_s$$

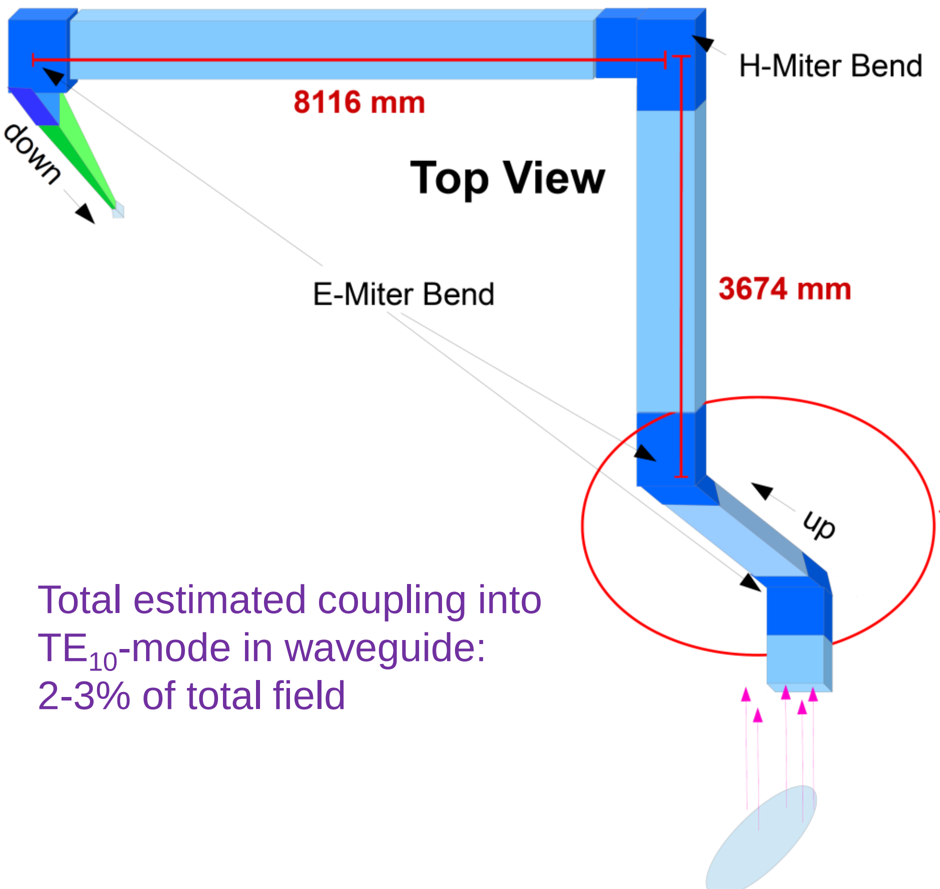
$$\vec{B}_\omega = -\frac{ik^2}{2\pi c}\int \frac{e^{ikR}}{(kR)^3}\{[\vec{n}\times\vec{E}_s](k^2R^2 + ikR - 1) - \vec{s}(\vec{s}\cdot[\vec{n}\times\vec{E}_s])(k^2R^2 + 3ikR - 3)\}\, d^2\vec{r}_s$$ - SC

Virtual photons approach as a particular case of SC method:

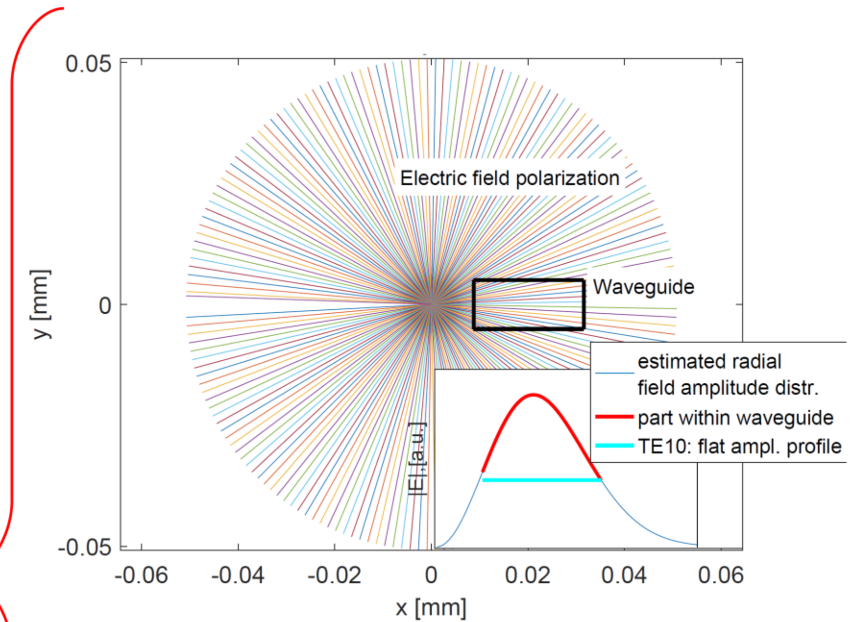
$$kR \gg 1, \quad \theta \ll 1 \quad (\vec{s}\cdot\vec{E} \approx 0, \quad \vec{s}\cdot\vec{n} \approx 0, \quad \vec{s}\cdot[\vec{n}\times\vec{E}] \approx 0)$$

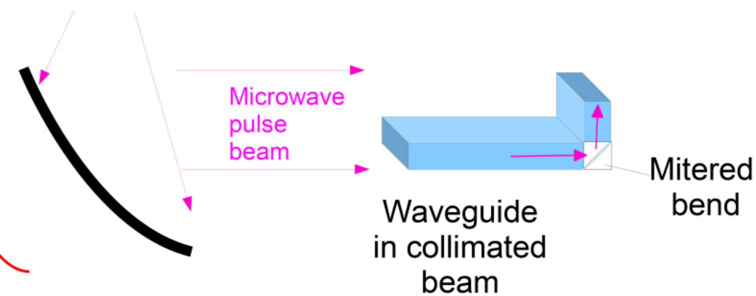
$$\vec{E}_\omega = -\frac{ik}{2\pi}\int \frac{e^{ikR}}{R}\vec{E}_s\, d^2\vec{r}_s \qquad \vec{B}_\omega = \frac{\vec{n}\times\vec{E}_\omega}{c}$$

CTR-Transmission line



Total estimated coupling into TE_{10}-mode in waveguide: 2-3% of total field





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