Non-invasive Beam Diagnostics with Schottky Signals and Cherenkov Diffraction Radiation

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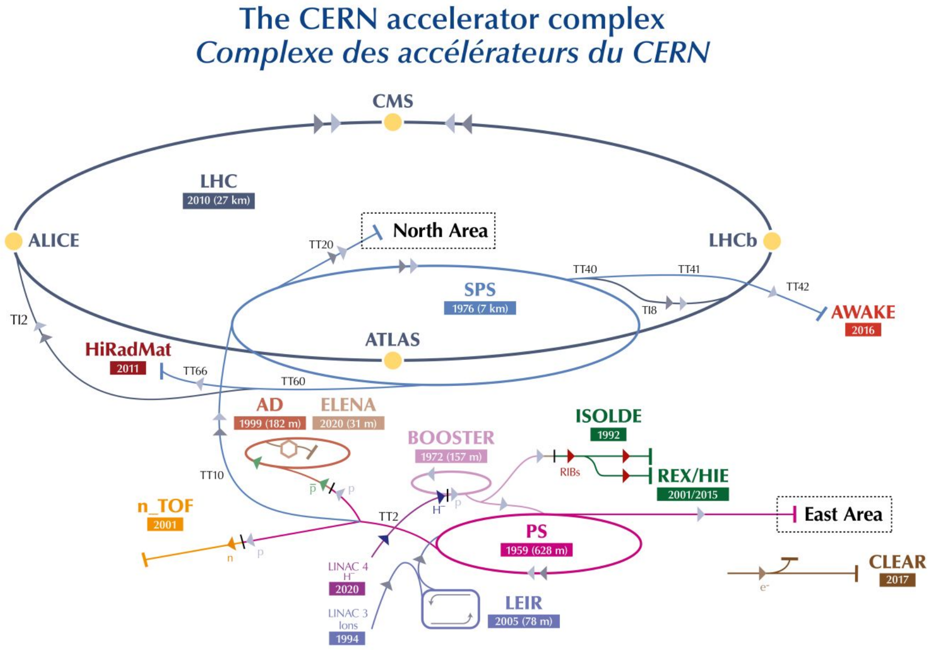
WFAIS UJ / CERN BI Group

FJA seminar, 20 Oct 2022, Warszawa

Introduction

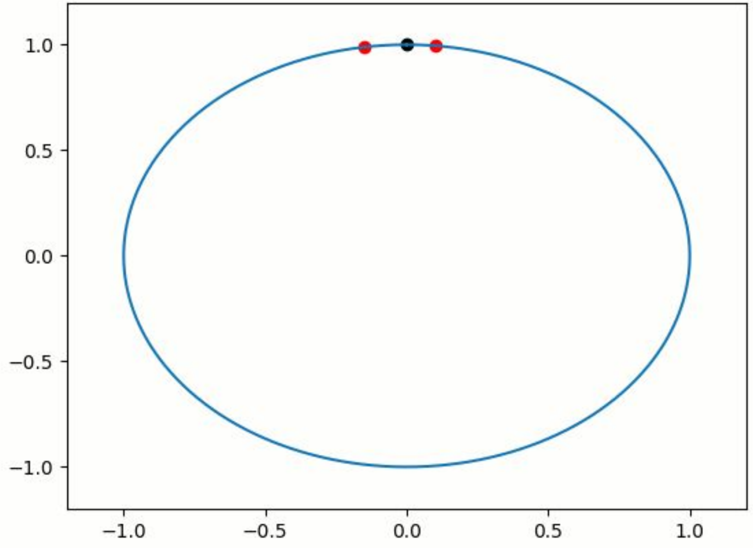
CERN Beam Instrumentation Group



The Beam Instrumentation Group is responsible for:

- **designing, building and maintaining** the instruments that allow observation of the particle beams
- measurement of related parameters **for all** CERN accelerators and transfer lines.

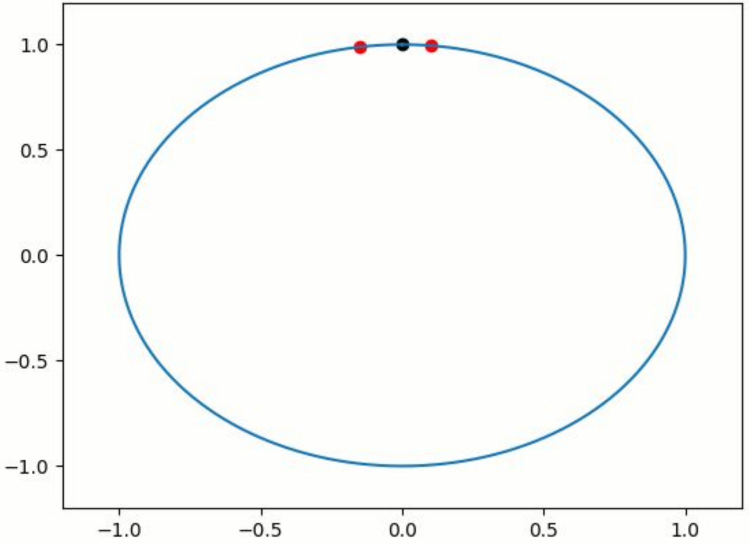
Simple Longitudinal Motion



Parameters of interest:

- f_{rev}: revolution frequency

Synchrotron oscillations

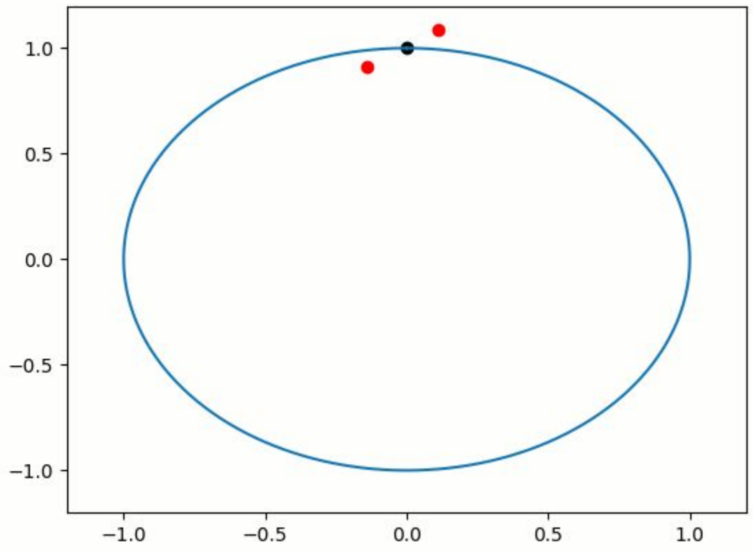


Parameters of interest:

- f_{rev} : revolution frequency
- ω_{s_i} : synchrotron frequency
  $\widehat{\tau}_i$: synchrotron amplitude
  ϕ_{s_i} : synchrotron phase

$$\tau = \tau(\widehat{\tau}, \phi_s) = \widehat{\tau} \cos\left(\omega_s t + \phi_s\right)$$

Betatron oscillations



Parameters of interest:

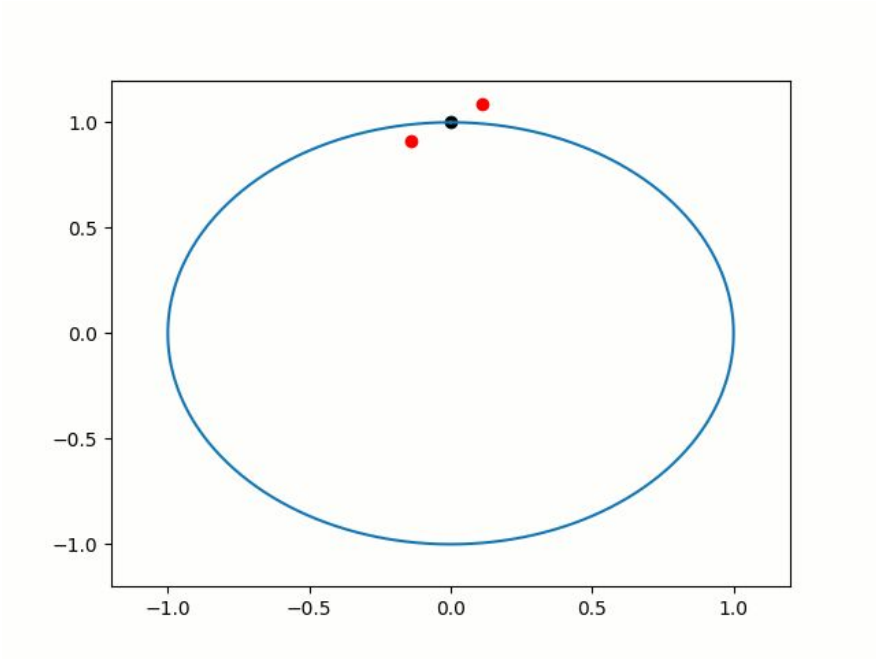
- f_{rev} revolution frequency

- ω_{s_i} : synchrotron frequency
  $\widehat{\tau}_i$: synchrotron amplitude
  ϕ_{s_i} : synchrotron phase

- Q : betatron tune (number of oscillations per one revolution)
  ϕ_{β_i} : betatron phase

x(t) = A $\cos(q\omega_0 t + \phi)$

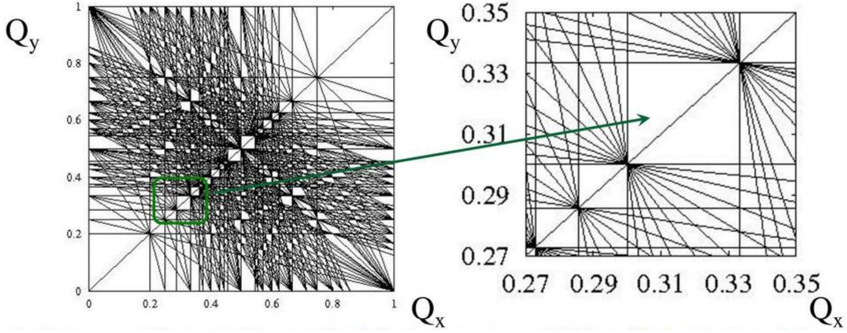
Chromaticity



Betatron tune is related to the particle momentum via chromaticity: Qξ

$$\Delta q_i = Q\xi \frac{\Delta p_i}{p_0}$$

Knowledge of betatron tune and chromaticies is vital for beam stability, resonant values should be avoided:

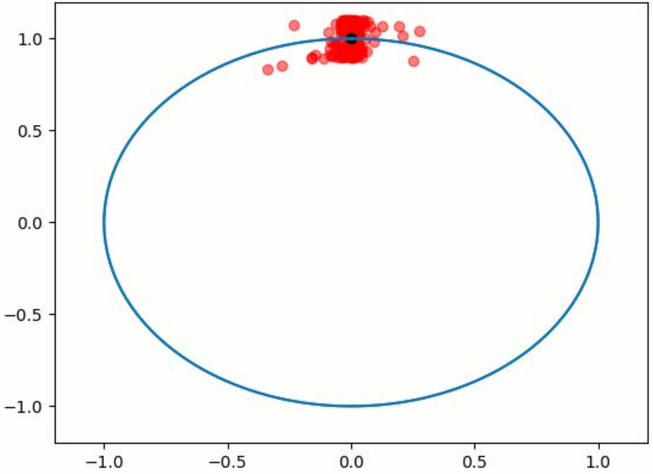


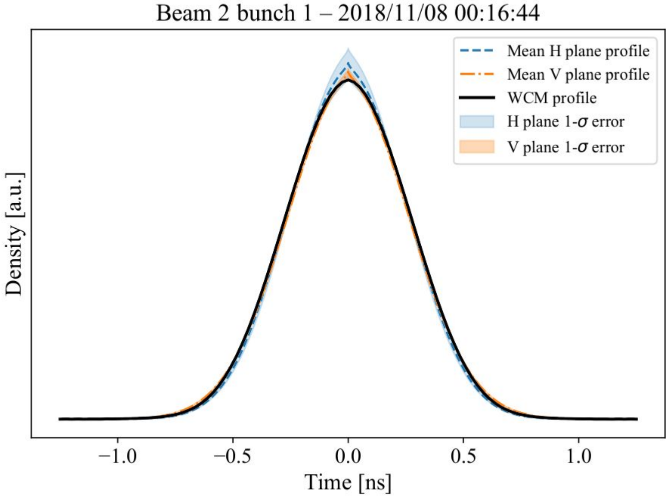
Bunch profiles & related

- Longitudinal and transverse profile
- Beam Emittance
- Bunch Intensity

In addition, monitored are:

- Beam Position
- Beam Losses





Beam diagnostic techniques

1. Coupling to the electromagnetic field carried by the moving particles:
- Beam position pick-ups,
- Beam current transformers,
- Wall current monitors

2. Observing radiation emitted by particles
- Synchrotron Radiation, Diffraction Radiation
- Transition Radiation, Cherenkov Radiation

3. Invasive methods
- Wire scanners
- OTR screens
- …

Analysis of Schottky Spectra

Motivation: Non-invasive chromaticity scans in LHC

LHC: chromaticity measured by RF Momentum modulation:

$$Q\xi = \frac{\Delta Q}{\Delta p / p}$$

the measured tune change

the RF induced momentum change (known)

This cannot be done for intensive high energy beam!

Non-invasive alternative is therefore needed.

Motivation: Non-invasive chromaticity scans in LHC

LHC alternative: chromaticity measured using Schottky signals:

- Obtained results not fully satisfactory
- Signal quality acceptable only during ion runs
- Theory supporting the measurement for bunched beam not developed

Principle of Schottky Analysis

Schottky Signal - random fluctuations of intensity/dipole moment due to the discrete structure of beam.

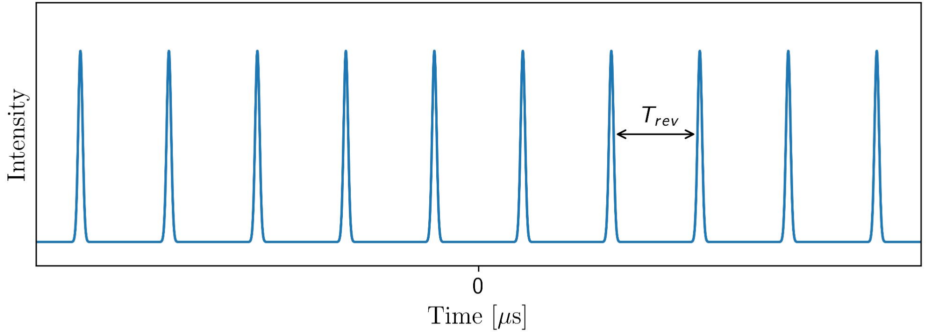
Contain information on momentum, betatron tune, chromaticity and synchrotron frequency.

Heavy ion coasting beam: fundamental diagnostic technique.

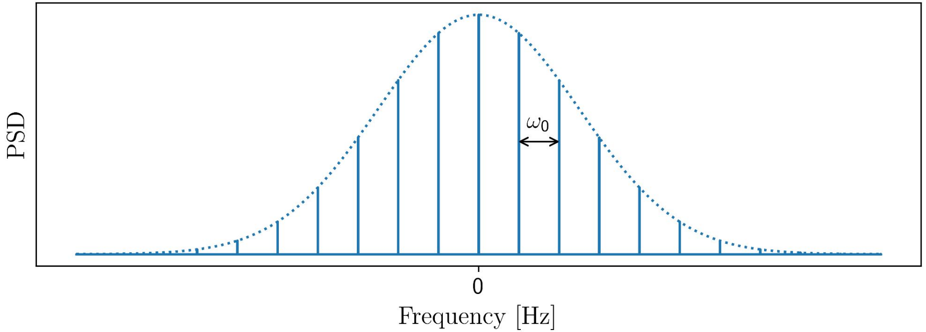
Bunched beam and proton beam: additional challenges need to be addressed.

Principle of Schottky Analysis (one bunch)

Ideal Gaussian bunch profiles:

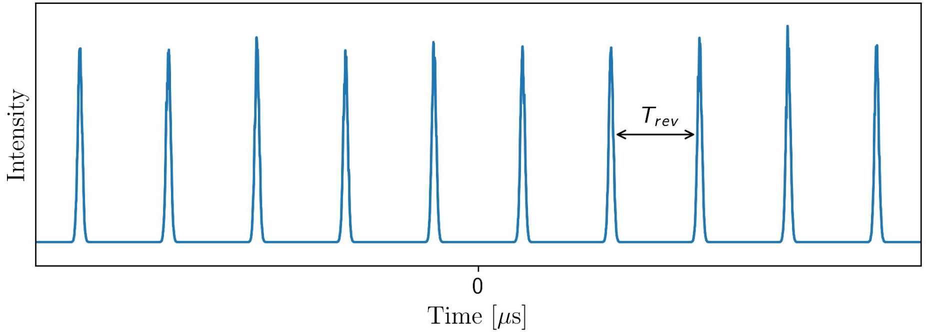


Series of pulses, power determined by bunch length

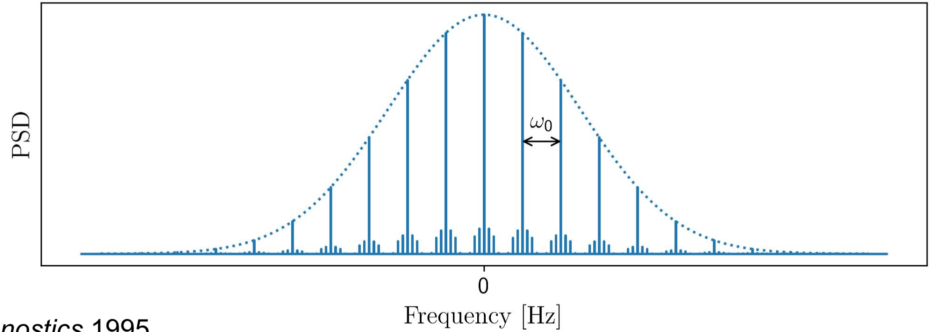


Principle of Schottky Analysis (one bunch)

Profiles with fluctuations:

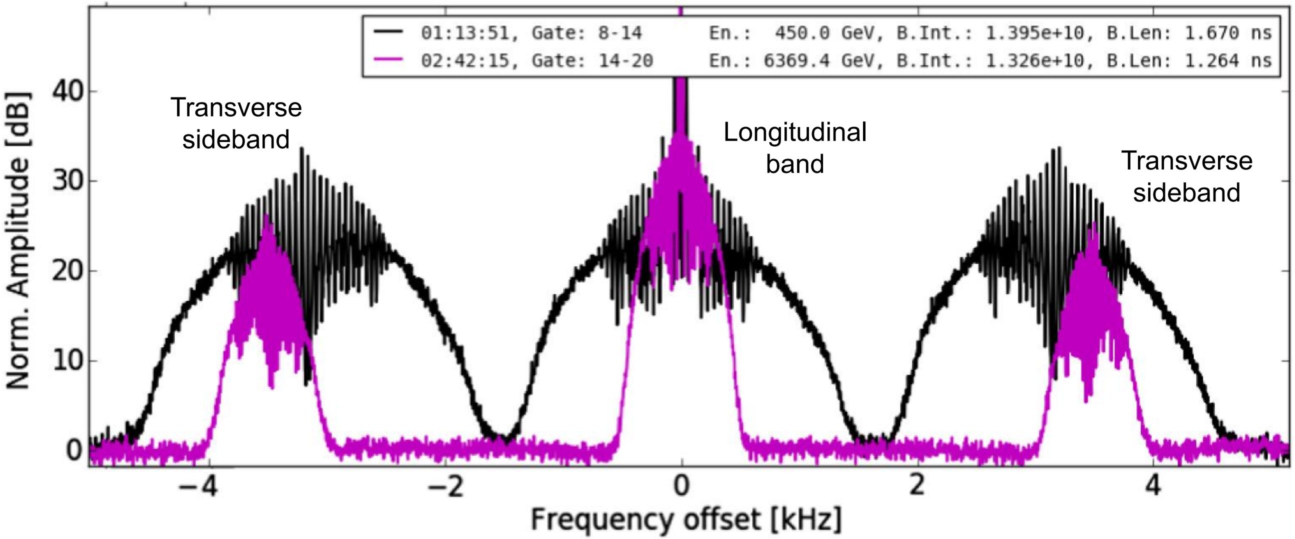


Additional subpeaks: *Schottky noise*



Recommended literature:
Simon van der Meer, *Diagnostics with Schottky noise*, 1988.
Daniel Boussard, *Schottky noise and beam transfer function diagnostics*,1995.
Swapan Chattopadhyay, *Some fundamental aspects of fluctuations and coherence in charged-particle beams instorage rings*, 1984.

Example: LHC Schottky spectrum

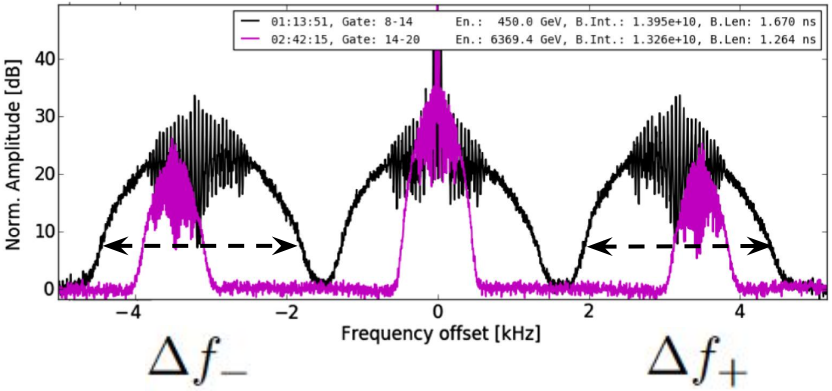


Original methods derive beam properties from width/location of the sidebands

Explicit chromaticity formula

$$Q\xi = |\eta| \left(n \frac{\Delta f_- - \Delta f_+}{\Delta f_- + \Delta f_+} - Q_I \right)$$

η - slip factor
Q_I - integer part of the tune
n - Schottky harmonic



Formula for coasted beam: proved in early 1980’.

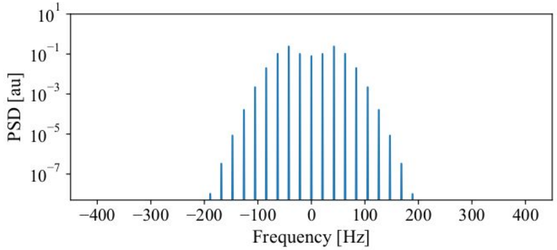
Formula for bunched beam: used without proof, definition of width changing from paper to paper.
Derived formally in 2019 by KŁ and D. Alves.
Width determined to be a frequency standard deviation around the central value.

Prevailing issue: very prone to noise

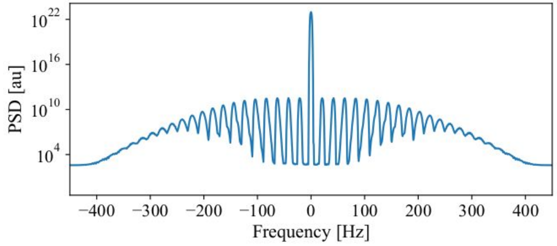
Schottky Spectrum (Longitudinal)

Described with a function of:

- Synchrotron motion amplitude (distribution)
- Nominal synchrotron motion frequency
- Random phase



(a) Single-particle PSD



(b) Multi-particle PSD

Schottky Spectrum (Transverse)

Described with a function of:

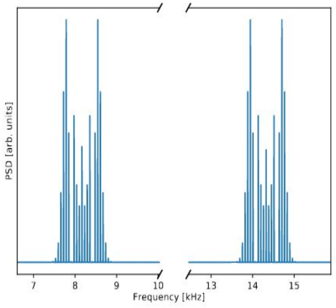
- Synchrotron motion amplitude (distribution)
- Nominal synchrotron motion frequency
- Random phase

and:

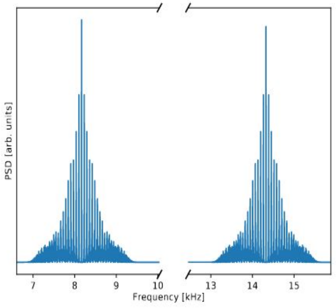
- Betatron tune
- Chromaticity
- One extra random phase

Single particle

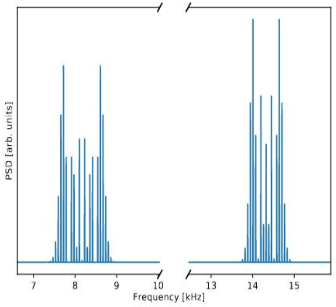
Multi-particle



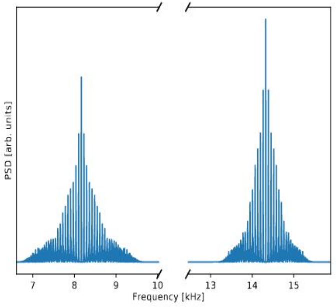
(a) $Q\xi = 0$



(a) $Q\xi = 0$



(b) $Q\xi = 20$



(b) $Q\xi = 20$

Fitting of Schottky spectra

Described with a function of:

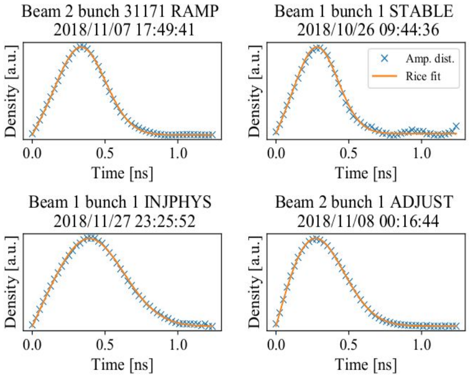
- Synchrotron motion amplitude (distribution)
- Nominal synchrotron motion frequency **1 parameter**
- Random phase **0 parameters - averaging**

and:

- Betatron tune **1 parameter**
- Chromaticity **1 parameter**
- One extra random phase **0 parameters - averaging**

Experimentally observed to follow Rice distribution

2 parameters



Fitting of Schottky spectra

Described with a function of:

- Synchrotron motion amplitude (distribution)
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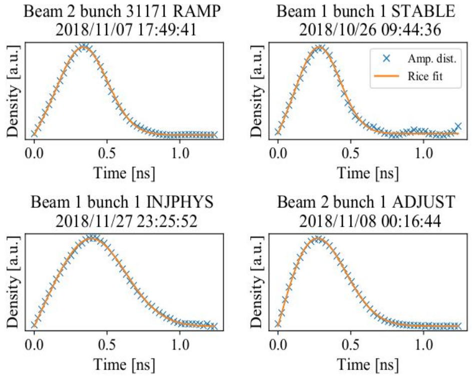
Experimentally observed to follow Rice distribution
2 parameters



and:

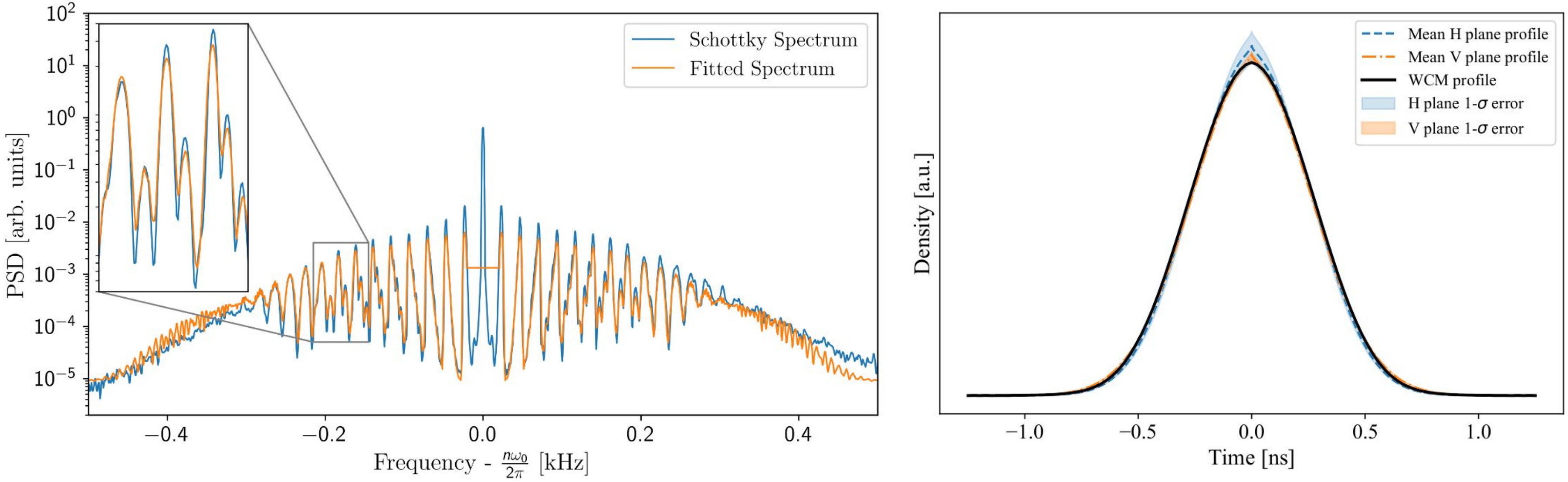
- Betatron tune **1 parameter**
- Chromaticity **1 parameter**
- One extra random phase **0 parameters - averaging**

In total we need determine 5 parameters to describe Schottky spectrum.

For an experimental spectrum, we look for parameters giving best-matching simulation using Differential Evolution Algorithm or other optimization routines.

Fitting of Schottky spectra (longitudinal)

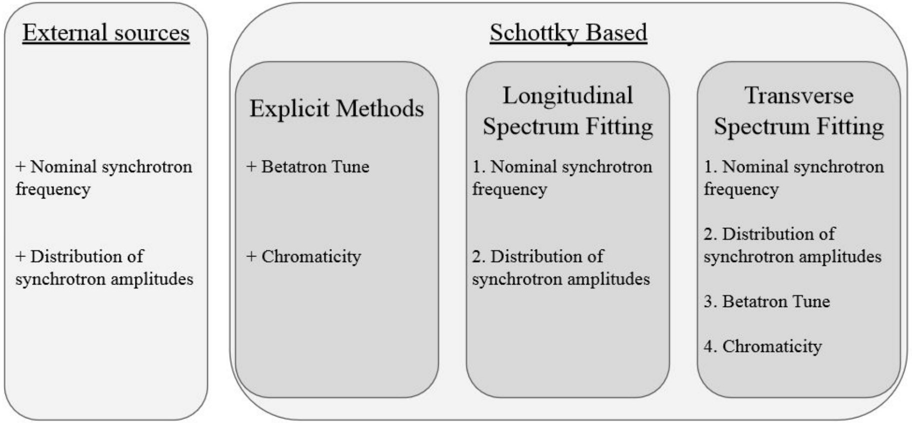
Beam 2 bunch 1 – 2018/11/08 00:16:44



Fitting of Schottky spectra

Spectra fitting doesn't need to be performed “all at once”. Among possibilities are :

- Independent fit of longitudinal and transverse sidebands,
- Taking fit parameters from external devices,
- Mixing fitting procedures with explicit formulae.



External sources

+ Nominal synchrotron frequency

+ Distribution of synchrotron amplitudes

Schottky Based

Explicit Methods

+ Betatron Tune

+ Chromaticity

Longitudinal Spectrum Fitting

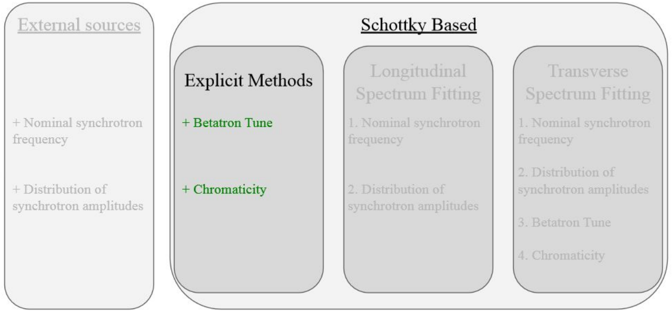
1. Nominal synchrotron frequency
2. Distribution of synchrotron amplitudes

Transverse Spectrum Fitting

1. Nominal synchrotron frequency
2. Distribution of synchrotron amplitudes
3. Betatron Tune
4. Chromaticity

Fitting of Schottky spectra: benchmarking

Scenario 1



External sources
+ Nominal synchrotron frequency
+ Distribution of synchrotron amplitudes

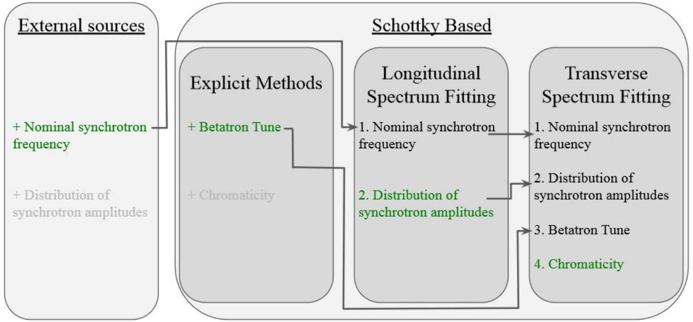
Schottky Based

Explicit Methods
+ Betatron Tune
+ Chromaticity

Longitudinal Spectrum Fitting
1. Nominal synchrotron frequency
2. Distribution of synchrotron amplitudes

Transverse Spectrum Fitting
1. Nominal synchrotron frequency
2. Distribution of synchrotron amplitudes
3. Betatron Tune
4. Chromaticity

Scenario 2



External sources
+ Nominal synchrotron frequency
+ Distribution of synchrotron amplitudes

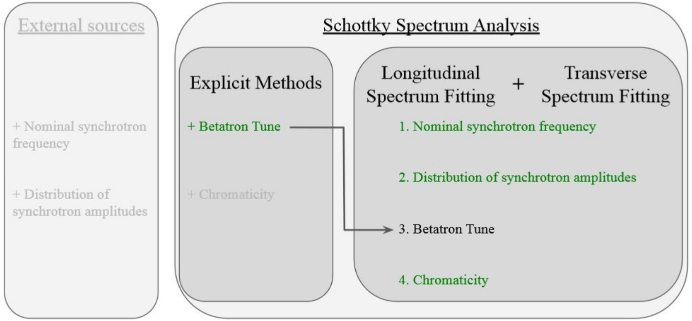
Schottky Based

Explicit Methods
+ Betatron Tune
+ Chromaticity

Longitudinal Spectrum Fitting
1. Nominal synchrotron frequency
2. Distribution of synchrotron amplitudes

Transverse Spectrum Fitting
1. Nominal synchrotron frequency
2. Distribution of synchrotron amplitudes
3. Betatron Tune
4. Chromaticity

Scenario 3



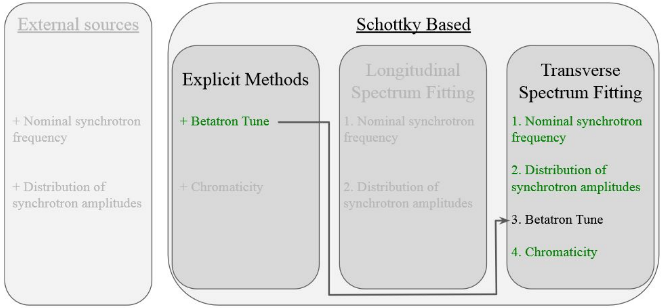
External sources
+ Nominal synchrotron frequency
+ Distribution of synchrotron amplitudes

Schottky Spectrum Analysis

Explicit Methods
+ Betatron Tune
+ Chromaticity

Longitudinal Spectrum Fitting + Transverse Spectrum Fitting
1. Nominal synchrotron frequency
2. Distribution of synchrotron amplitudes
3. Betatron Tune
4. Chromaticity

Scenario 4



External sources
+ Nominal synchrotron frequency
+ Distribution of synchrotron amplitudes

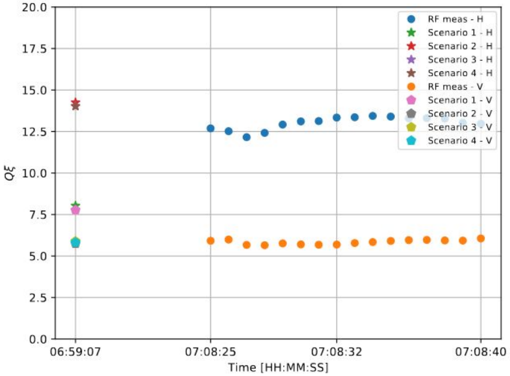
Schottky Based

Explicit Methods
+ Betatron Tune
+ Chromaticity

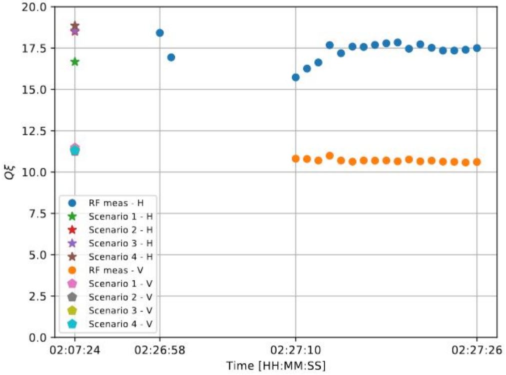
Longitudinal Spectrum Fitting
1. Nominal synchrotron frequency
2. Distribution of synchrotron amplitudes

Transverse Spectrum Fitting
1. Nominal synchrotron frequency
2. Distribution of synchrotron amplitudes
3. Betatron Tune
4. Chromaticity

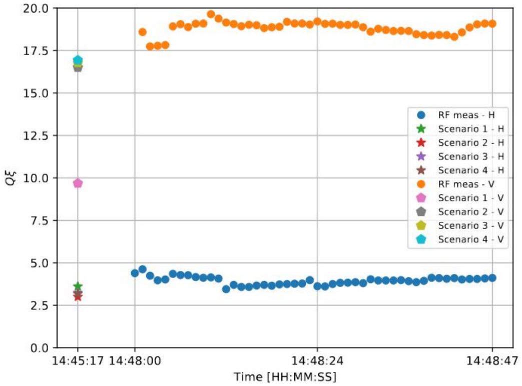
Fitting of Schottky spectra: benchmarking



Chromaticity measurements during LHC fill 7486.



Chromaticity measurements during LHC fill 7443.



Chromaticity measurements during LHC fill 7435.

Good agreement with RF modulation technique. Scenario 1 (baseline method) happens to fail.

Accelerating Schottky Analysis

A.S Hassan, L. Kennedy CERN-STUDENTS-Note-2021-022
L. Kennedy, CERN-STUDENTS-Note-2021-124

CERN Summer Student Project of two undergraduate students (Jun - Sep 2021).

Original implementation (“proof of concept”): **371 seconds** per spectrum.

Parallelized (5 cores) optimized solution: **81 seconds** per spectrum

After using previous results as initial guess: **7.9 seconds** per spectrum

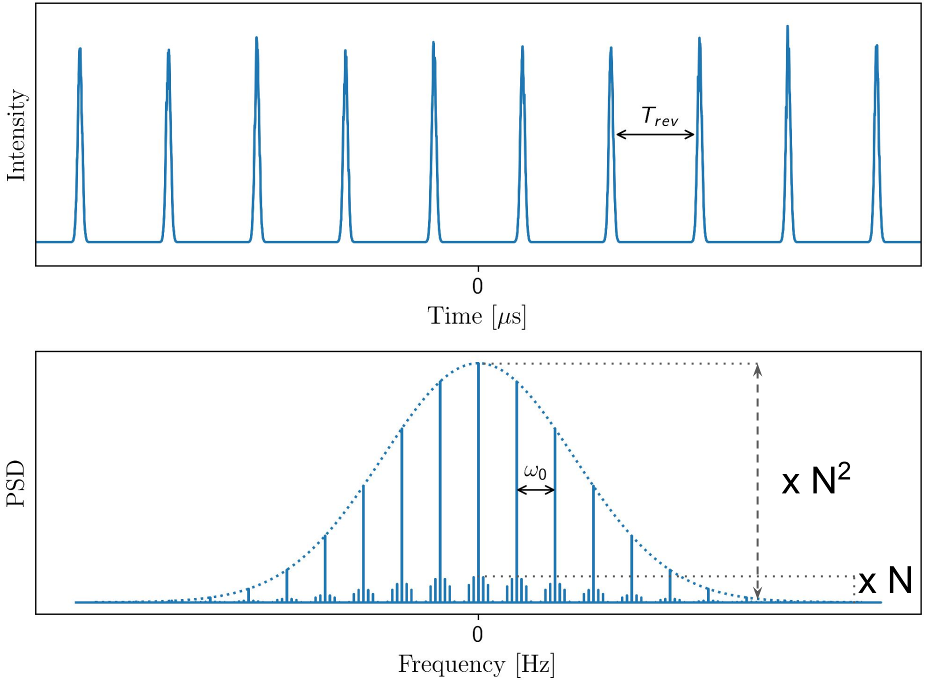
Obtained time performance is satisfactory, as LHC Schottky System provides one spectrum every **10 seconds**.

How to deal with protons?

Number of Pb^{82+} ions in LHC bunch ~ 10^7

Number of protons in LHC bunch ~ 10^{11}

Huge dynamic range required to measure the Schottky signal.

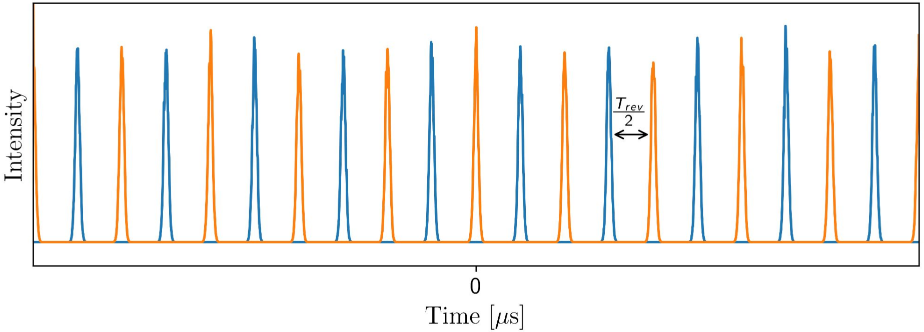


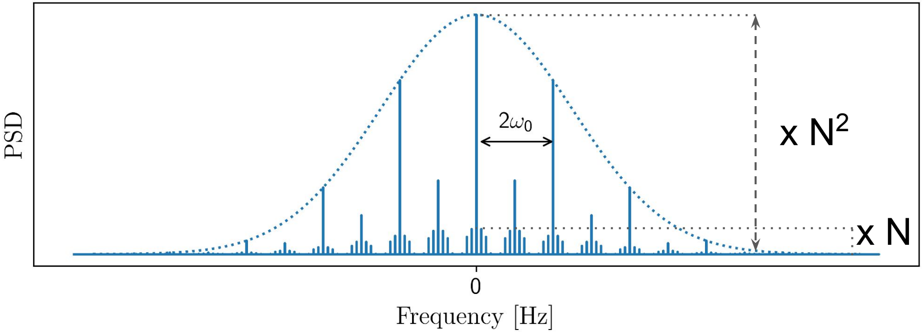
How to deal with protons?

Proposed solution: gating on two opposite bunches ⇒ Coherent peaks only on even harmonics.

In fact, we can gate even on two closer bunches to obtain cancellation on certain harmonics.

Procedure awaiting experimental verification on LHC beam.





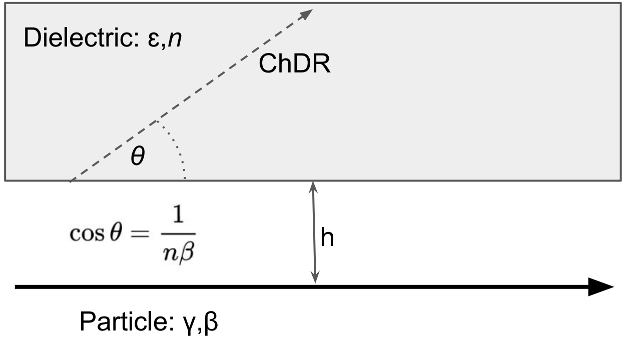
Summary of Schottky activities

- A new approach to Schottky-based diagnostic proposed and benchmarked. In comparison to previous methods:
  - More robust to signal imperfections,
  - Slower, but still can run online,
  - Can be used not only for chromaticity and tune measurements, but also for longitudinal characteristics estimation.
- Schottky spectrum theory has been revisited. Explicit chromaticity formula has been proved.
- Idea how to improve proton spectra await experimental verification.

Studies on the Cherenkov Diffraction Radiation

Cherenkov Diffraction Radiation (ChDR)

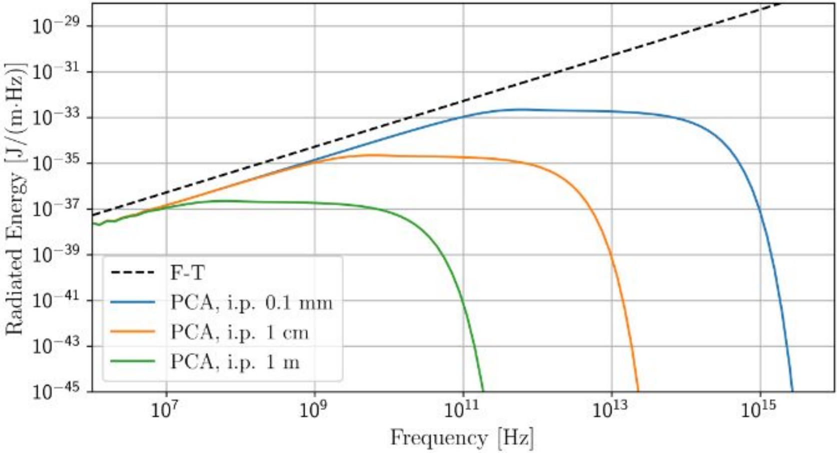
Emitted when a charged particle passes **in the vicinity of** the dielectric medium at speed greater than phase velocity of the light in this medium.

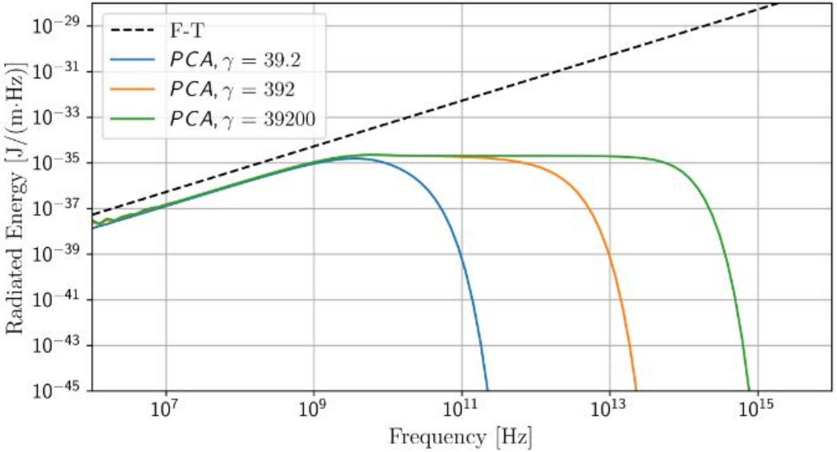


Dependence of ChDR on key beam parameters

Cherenkov Diffraction Radiation features strong dependence on both particle energy and distance between the radiator and particle.

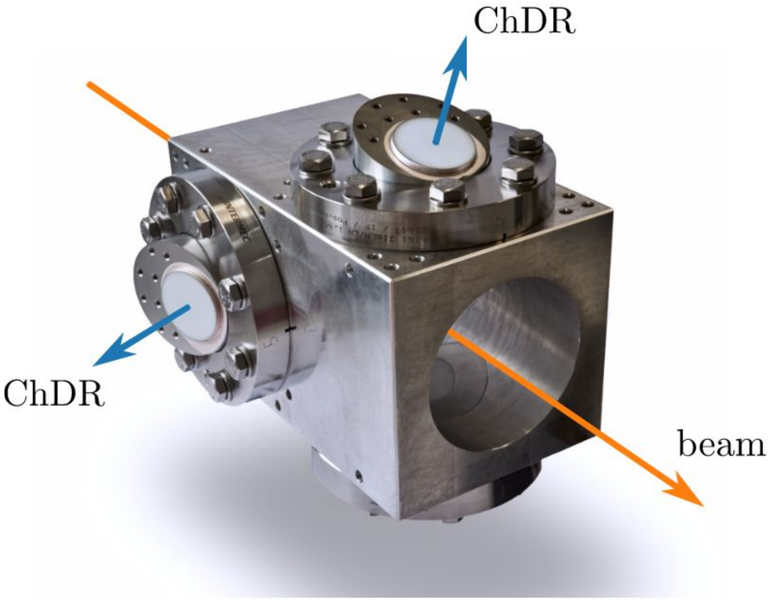
Calculations based on one of ChDR models, Polarization Current Approach:





ChDR for Beam Diagnostics

- **<u>Non-invasive</u>**
- **<u>Very simple design</u>**
- **<u>Photon emission at large angle</u>**



ChDR for Beam Diagnostics

Demonstrations of beam diagnostics with ChDR:

- ➢ Transverse bunch profile at ATF-2 in KEK (Proceedings of IPAC2019, WEPGW077)
- ➢ Bunch length at CLEAR at CERN (Phys. Rev. Accel. Beams 23, 022802, 2020)
- ➢ Beam position at CLEAR at CERN (Proceedings of IBIC2021, MOPP17)

Other facilities that confirmed feasibility of observation of ChDR:

- CESR at Cornell University, USA (Phys. Rev. Lett. 121, 054802, 2018; Phys. Rev. Accel. Beams 23, 042803, 2020)
- Diamond Light Source, UK (Proceedings of IBIC2019, WEPP037)
- CLARA at Daresbury Laboratory, UK (Proceedings of IBIC2019, TUCO02)
- t-ACTS at Tahoku University, Japan (Proceedings of IPAC2019, WEPGW031)
- Microtron at Tomsk Polytechnic University, Russian Federation (Scientific Reports 10, 20961, 2020)

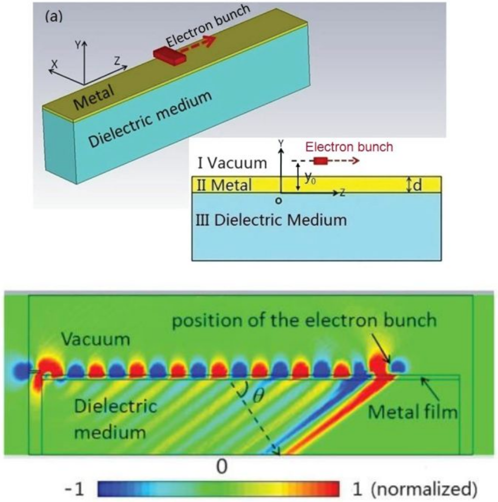
Under investigation application of ChDR as a tool for beam diagnostics in:

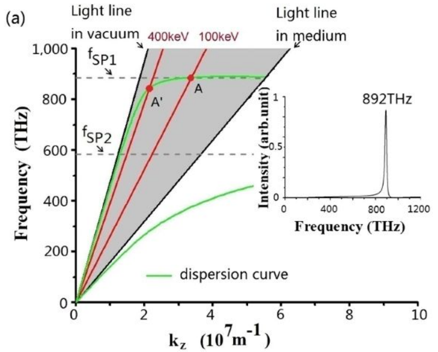
- ★ Advanced WAKEfield Experiment (Proceedings of IPAC2022, MOPOPT053, Proceedings of IBIC2021, MOPP17)
- ★ Future Circular electron-positron Collider (FCC-ee) (A. Schloegelhofer, FCC Week 2022)

ChDR from multilayered radiators

Motivation:

- Obtain strong monochromatic radiation via Surface Plasmon Polariton
- Prevent creation of electron clouds in synchrotrons by coating the radiators





S. Liu et al, *Surface Polariton Cherenkov Light Radiation Source*, Phys. Rev. Lett. 109, 153902 (2012).

ChDR from multilayered radiators

Motivation:

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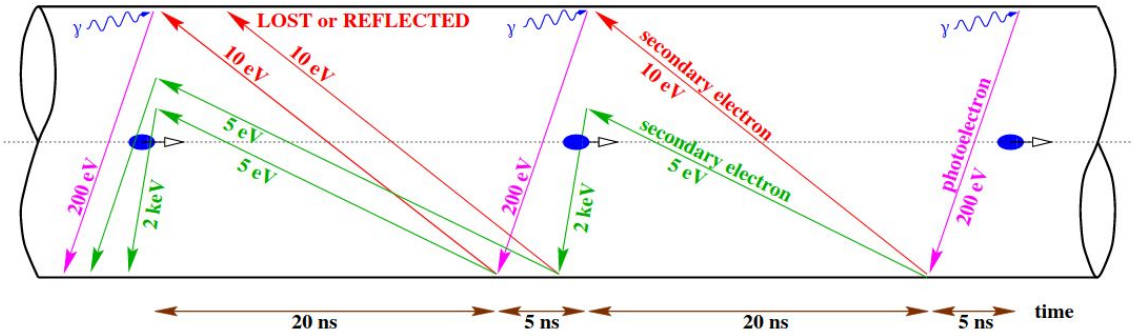


F. Zimmermann, Electron-Cloud Effects in the LHC

Methods of simulating ChDR

- Analytical solutions
  - Simple radiators
  - Usually only far-field
  - Fast
- Commercial software (CST):
  - Radiators of various shape
  - Near field
  - Computation time is case-dependent

Nothing designed for time-efficient calculations with coated radiators

Simulation Framework for multilayered ChDR

IW2D - N. Mounet (2012) for calculations of LHC wakefield and beam impedance.
N. Mounet PhD Thesis, Lausanne, EPFL (2012)

IW2D Fields - Code extension for multilayered ChDR calculations.
KL et al., Proceedings of IBIC2020, TUPP28

IW2D and it’s extension IW2D Fields:

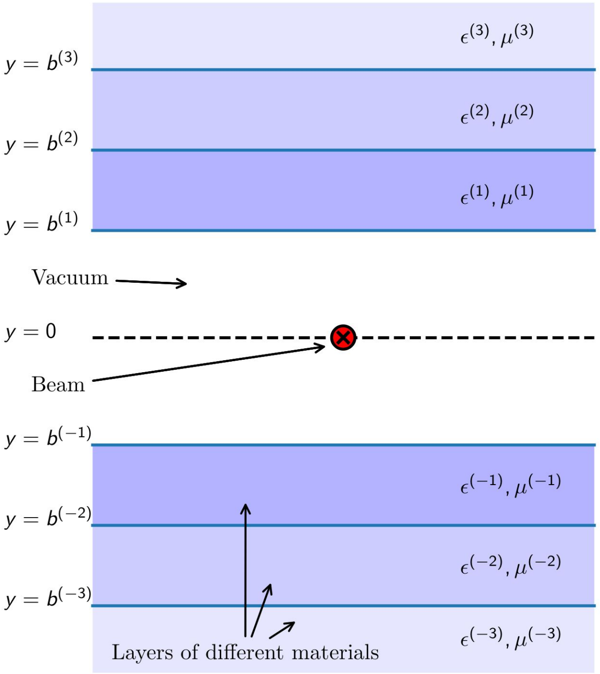
- Numerically solve EM boundary problems in the frequency domain, calculate EM field for discrete set of geometrical points
- Two geometries: cylindrical and flat layers
- Very fast thanks to C++ implementation of developed matrix formalism, supports parallelism
- Codes with a Python wrappers are available at CERN’s Gitlab

IW2D Fields

KL et al., Proceedings of IBIC2020, TUPP28

Geometries:

- Longitudinally infinite
- Layers of arbitrary, frequency-dependent permittivity and permeability
- No restrictions on number of layers or their size



IW2D Fields

KL et al., Proceedings of IBIC2020, TUPP28

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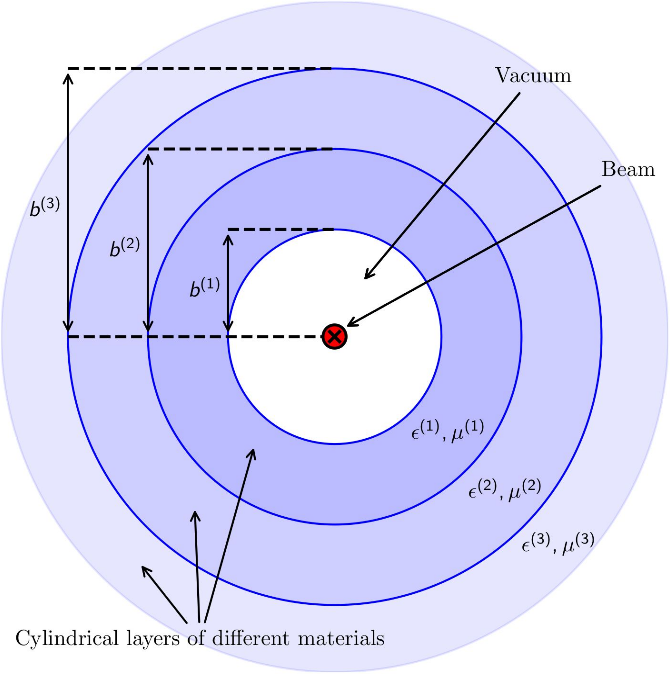
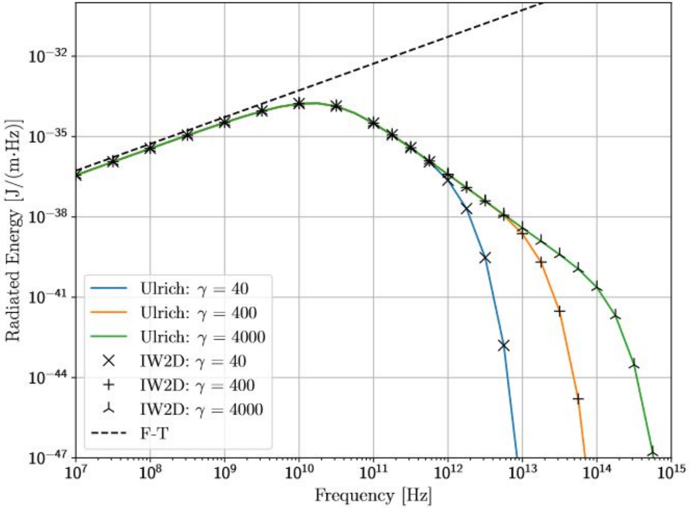
- Longitudinally infinite
- Layers of arbitrary, frequency-dependent permittivity and permeability
- No restrictions on number of layers or their size



Comparison with different theoretical predictions

Flat 1-layer theoretical results reported by R. Ulrich in *Zeitschrift für Physik* 194, 180-192 (1966): Charged particle travelling through the vacuum, parallel to the surface of a dielectric half-space.

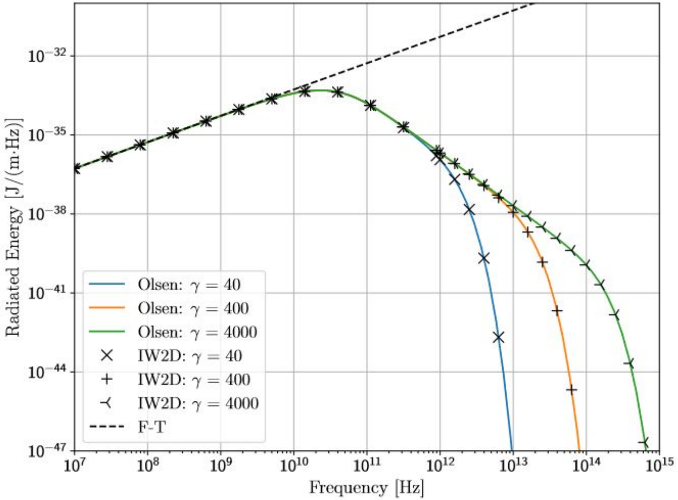
Comparison for different relativistic gamma factors:



Comparison with different theoretical predictions

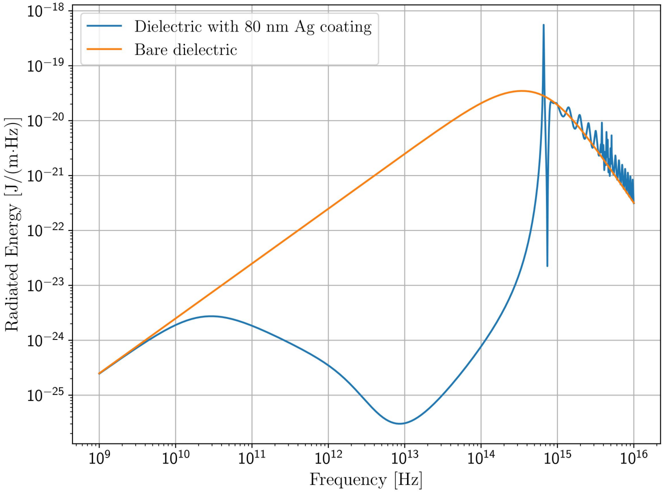
Cylindrical 1-layer theoretical results presented by H. A. Olsen in *Physical Review A*, 21, 6 (1980):
Charged particle travelling through the vacuum cylinder, surrounded by infinite dielectric.

Comparison for different relativistic gamma factors:



IW2D application: Surface Polariton Cherenkov Light Source

IW2D can be used in search of special radiator-coating configurations, leading to a very strong monochromatic radiation.



Geometry and beam parameters compatible with Dielectric Laser Accelerator described in:

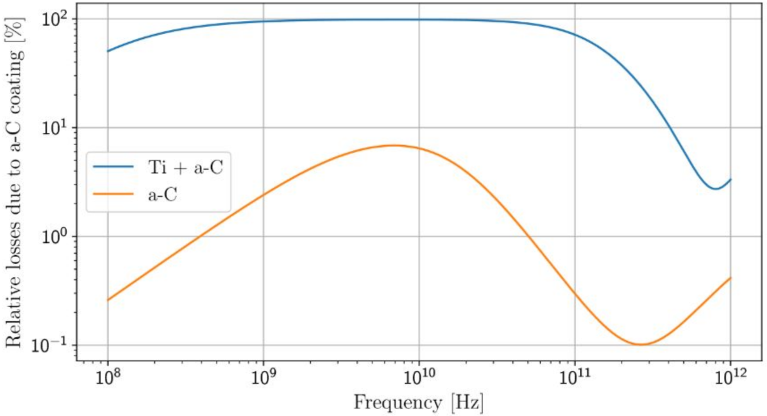
E. Peralta et al., “Demonstration of electron acceleration in a laser-driven dielectric microstructure,” Nature, vol. 503,p. 91, 09 2013.

IW2D application: ChDR and e-cloud mitigation

With IW2D we can estimate to what extent additional layer of coating suppresses radiation yield.

e-Cloud mitigation in the LHC:

1. 400 nm amorphous Carbon layer
2. Possible additional 80 nm Titanium for adhesion



- Pure a-C: **acceptable effect**
- Ti + a-C: 99% **supression**

Edge effects in ChDR emission

Stationary ChDR:

Bolotovski, Ulrich, Olsen

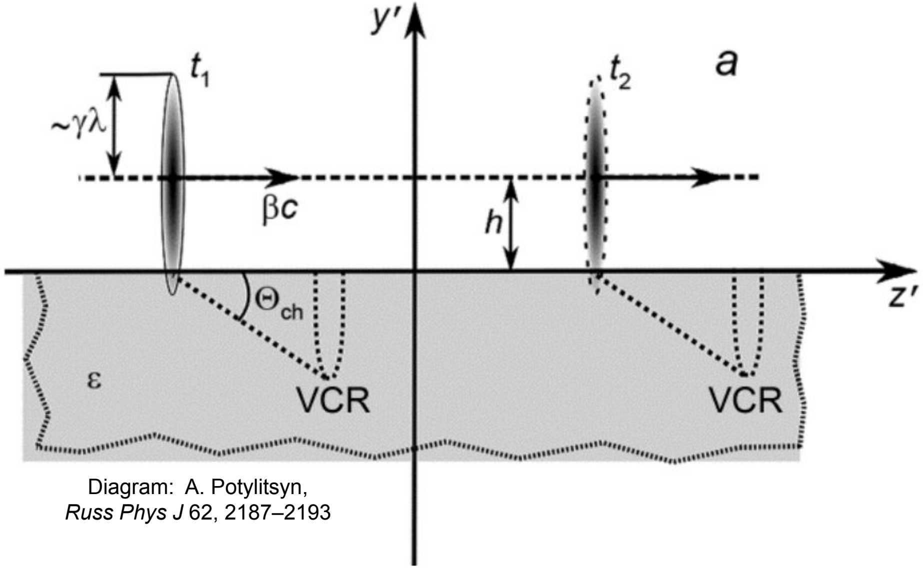
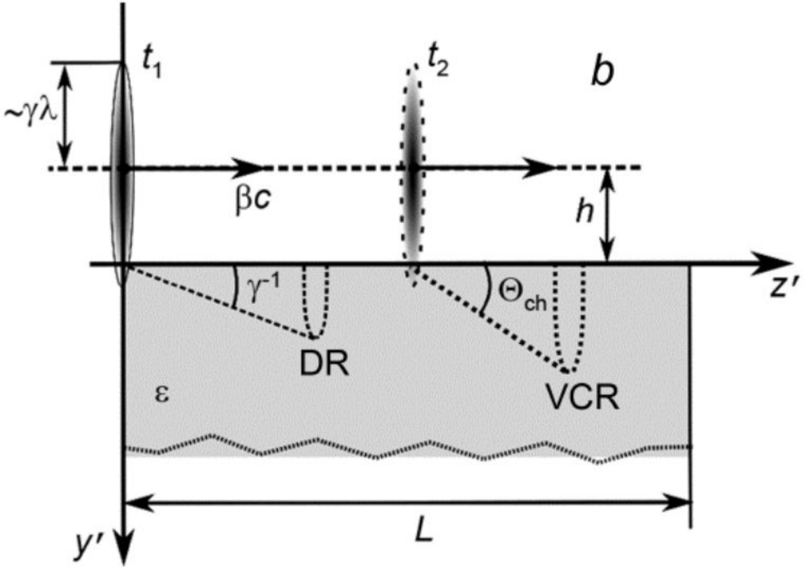


Diagram: A. Potylitsyn,
Russ Phys J 62, 2187–2193

B.M. Bolotovskii, Sov. Phys. Usp. 4 781 (1962).
Ulrich, Z. Physik 194, 180–192 (1966).
H. A. Olsen and H. Kolbenstvedt, Phys. Rev. A, vol. 21, Jun 1980.

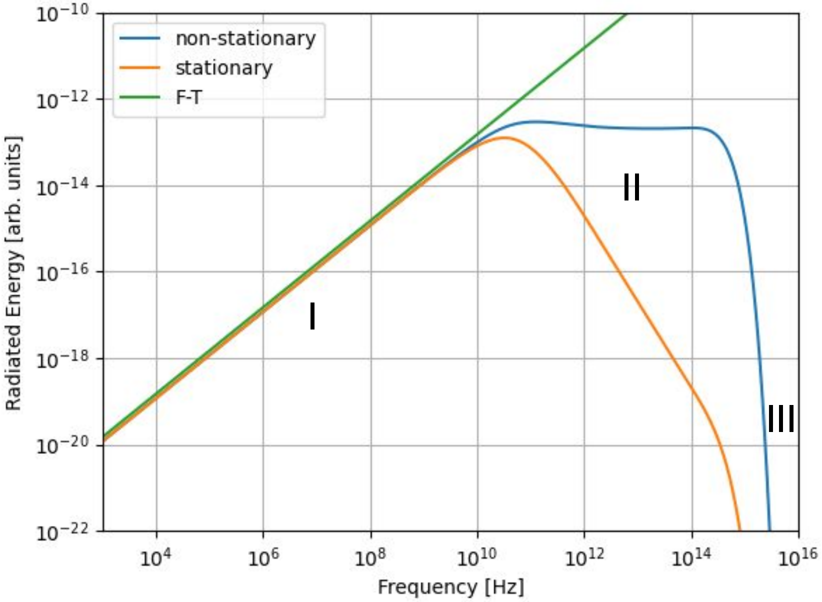
Non-stationary ChDR:

Polarization Current Approach (PCA)



Karlovets, D.V., Potylitsyn, Jetp Lett. 90, 326 (2009).

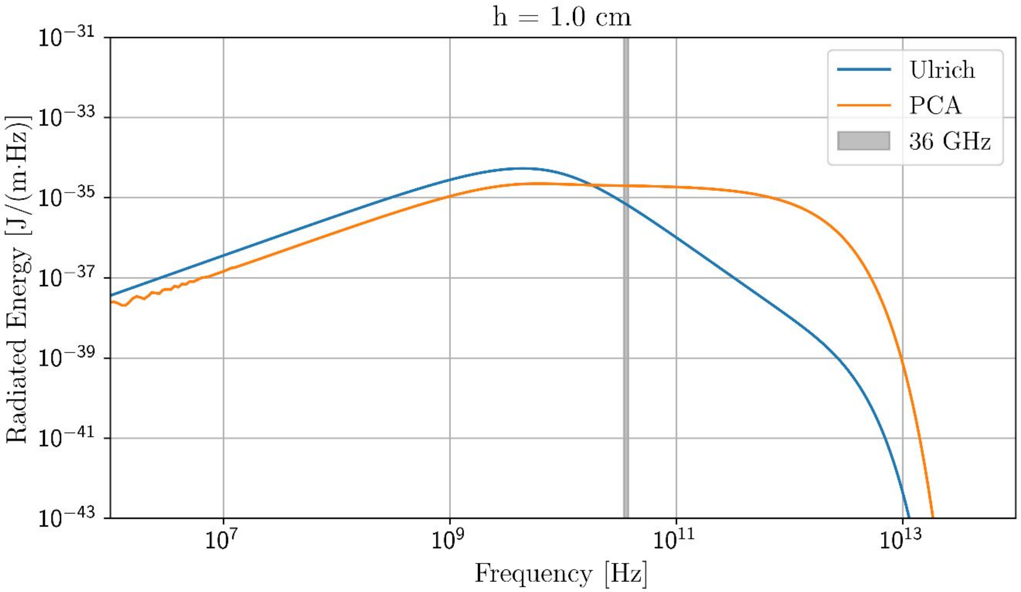
Most prominent differences between models



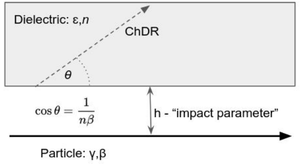
In both models three frequency regions can be distinguished:

I. $\lambda > h$: energy proportional to the frequency, like in F-T model
II. $\lambda < h < \gamma\lambda$: energy falling quadratically with frequency for stationary models and constant for non-stationary
III. $\gamma\lambda < h$: energy falling exponentially

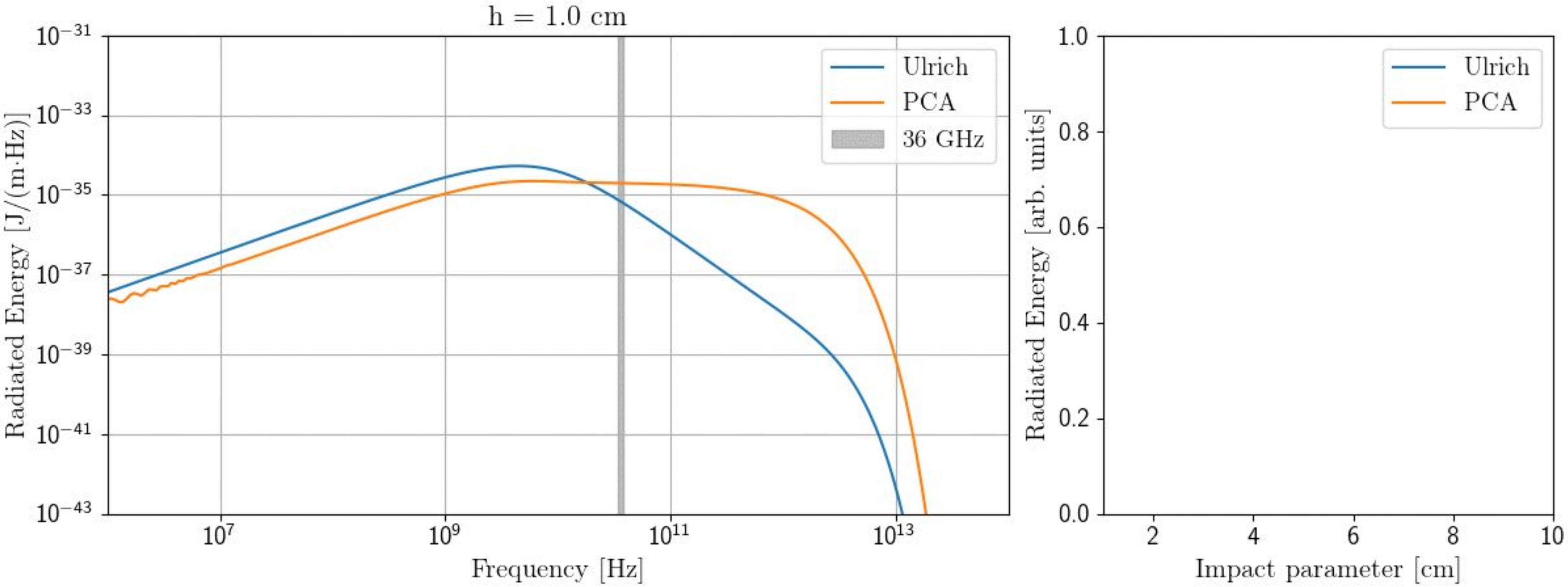
Proposed experimental verification at clear



h = 1 cm
$\gamma \approx 392$
eps = 2.1
freq = 36 GHz

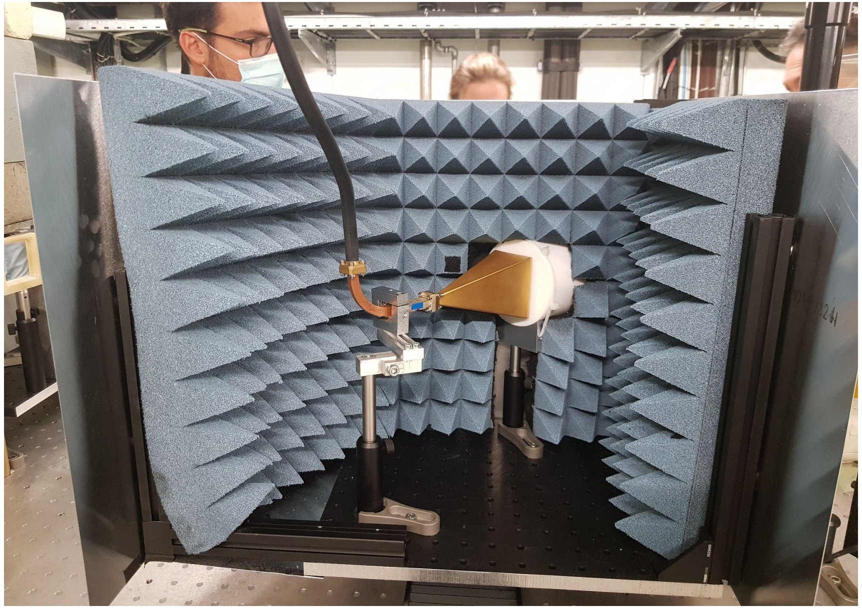


Proposed experimental verification at clear



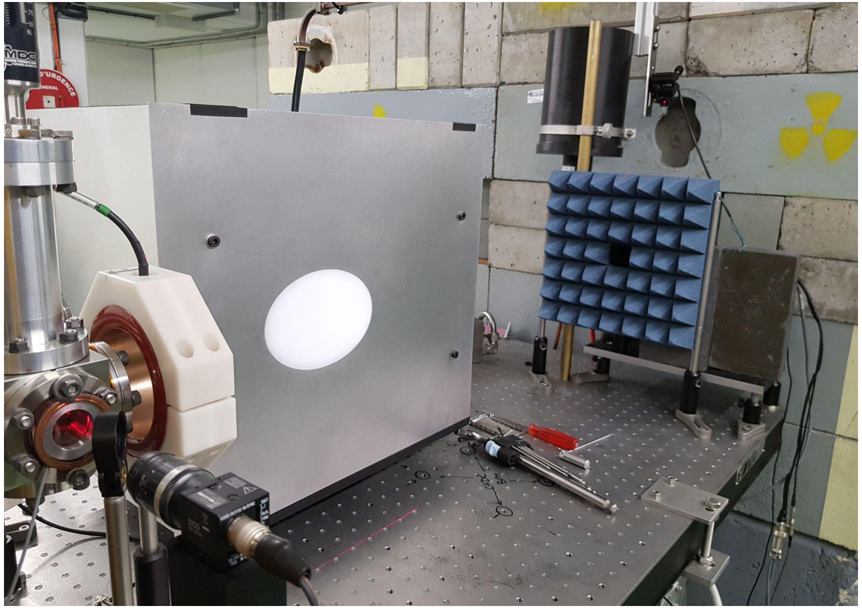
ChDR models: experimental verification

Schottky Diode with 36 (30) GHz filter



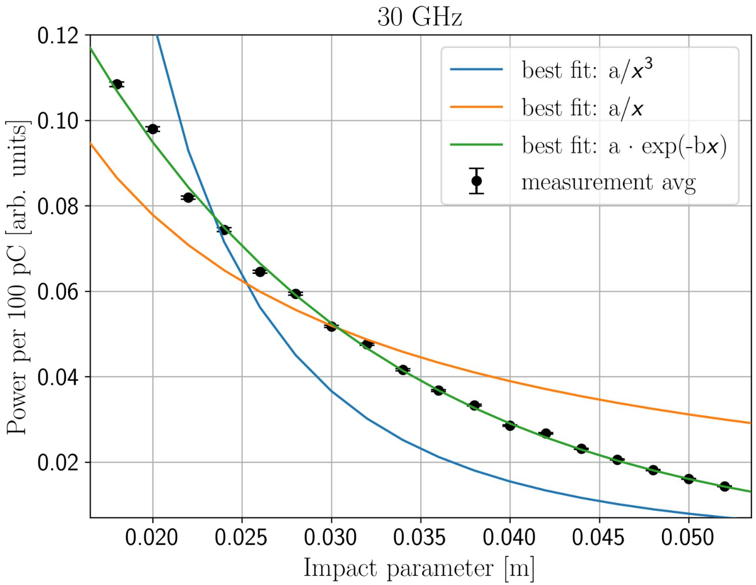
Setup at in-air test stand.

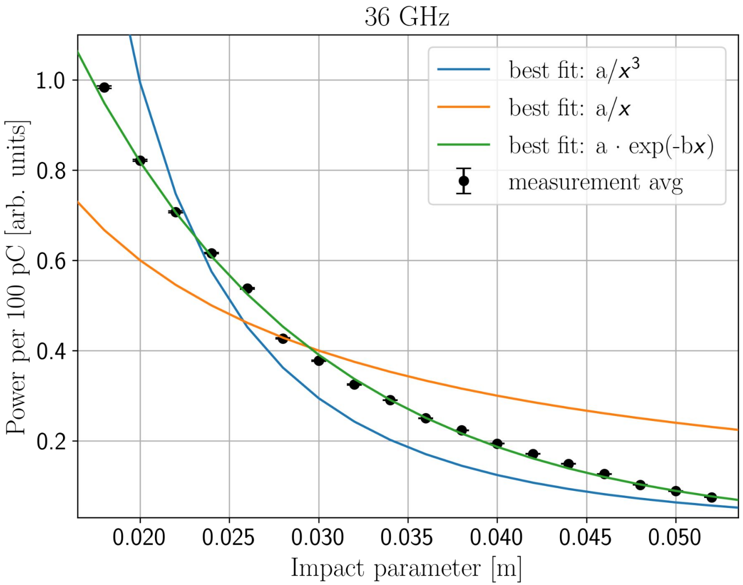
Motor range 0.7-11.7 cm from the beam.



In-air Cherenkov hits the radiator only for i.p. below 1 cm

Impact scan results





exponential b ≈ 73.25

exponential b ≈ 58.76

Analogous results obtained for three other beam energies: 100, 150 and 200 MeV

Summary of ChDR activities

- A simulation framework for ChDR estimation in case of multilayered radiators has been developed and benchmarked against well-established theoretical result. It enabled creating analyses on:
    - Possibilities of plasmonic enhancement of ChDR,
    - Effect of e-Cloud mitigating coatings on ChDR,
- A discrepancy between different ChDR models had been observed. Experimental verification has not supported any of them, but provided a very consistent result.

Thank you for your attention!