Beam monitoring using Optical Transition Radiation (OTR)

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Abstract

- Optical Transition Radiation (OTR) has been used for diagnostic purposes in particle beams for several reasons. For instance, linearity with beam current, polarization, spectrum and time of formation are all characteristics that make OTR an excellent tool to monitor beams in a wide range of energies. It will be presented how OTR plays this important role for a complete beam characterization, as well as some experimental data from an OTR based tool used for the diagnostic of low energy and low current electron beams of the IFUSP Microtron.

Summary

- Introduction
  Theoretical background
  Transition Radiation characteristics

- OTR used in beam diagnostics
  Examples of uses of OTR in beam diagnostics
  When is an OTR based diagnostic device necessary?

- The OTR based tool for the IFUSP Microtron
  IFUSP Microtron facilities
  Design & Experimental data

- Conclusions

Introduction

- *Theoretical background*
- *Main characteristics*

Introduction

Theoretical background

Definition:

- When a particle travels with constant velocity and crosses the boundary between two media with different electromagnetic properties, it emits radiation with particular angular distribution, polarization and spectra.

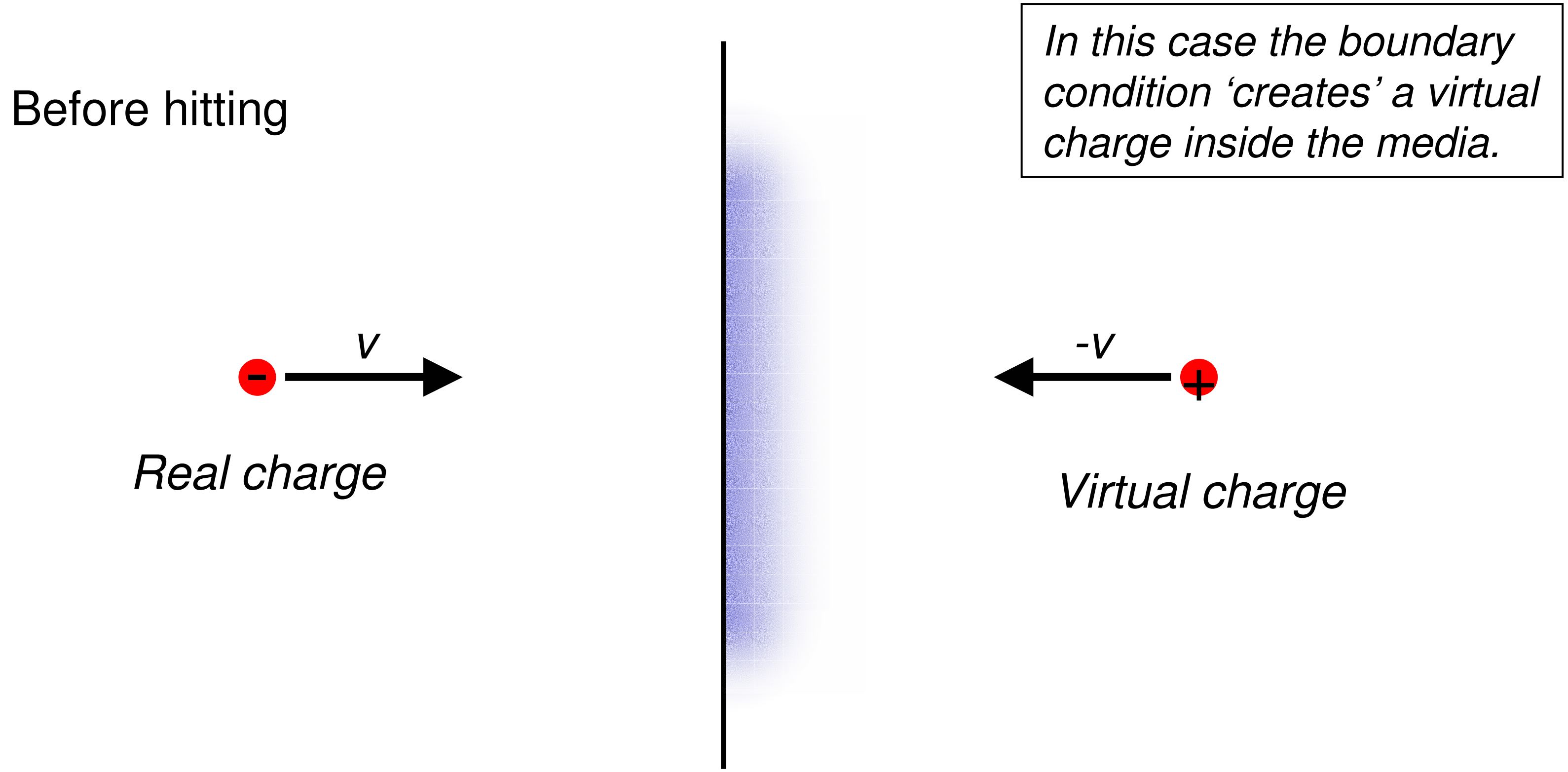
Predicted by Ginzburg and Tamm in 1946.

Firstly observed by Goldsmith and Jelley in 1959.

Introduction

Theoretical background

In the limit case of a particle incident on a perfect conductor infinite plane:

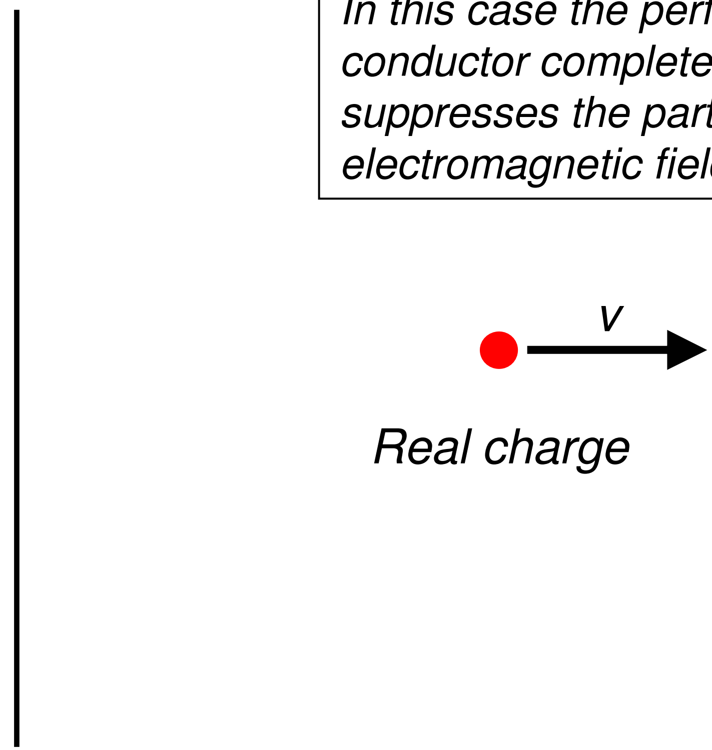


Introduction

Theoretical background

In the limit case of a particle incident on a perfect conductor infinite plane:

After hitting



In this case the perfect conductor completely suppresses the particle electromagnetic field.

Introduction

Theoretical background

This sudden variation in the electromagnetic field induces to emission of radiation.

- Differently to *Cherenkov* radiation, transition radiation occurs to any particle velocity.

- Differently to *Bremstralung* radiation, transition radiation does not vanishes to infinite particle mass.

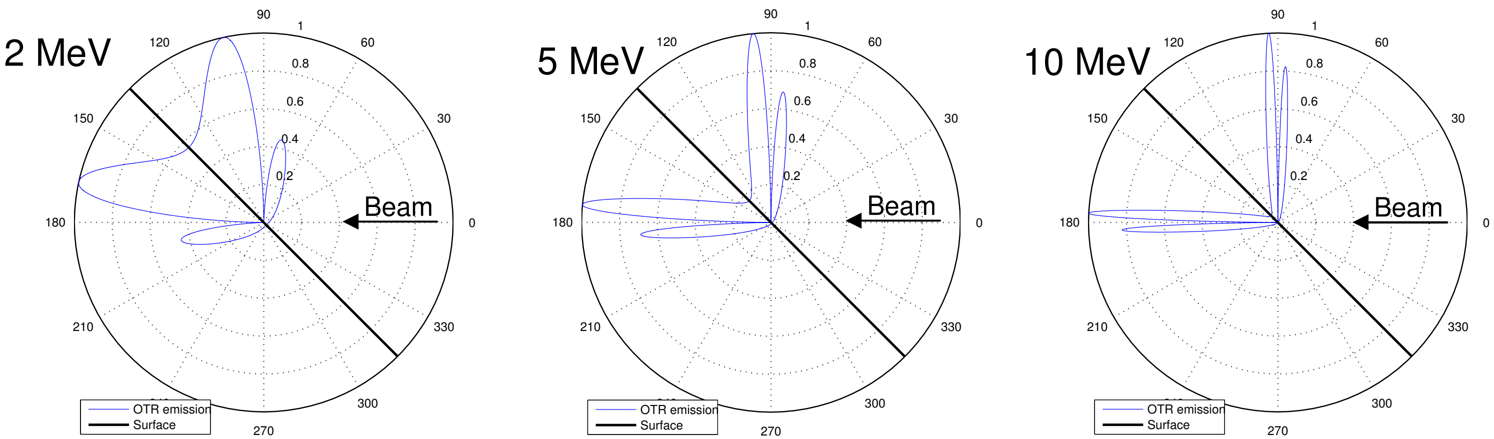
Introduction

Theoretical background

The angular distribution in the plane containing the vector of the particle velocity and the normal to the surface is given by:

$$\frac{d^2W}{d\omega d\Omega} = \left(\frac{e^2v^2}{2\pi^2c^3}\right)\cdot\left[\frac{\sin(\theta-2\varphi)}{\left[1+\frac{v}{c}\cos(\theta-2\varphi)\right]}+\frac{\sin\theta}{\left[1-\frac{v}{c}\cos\theta\right]}\right]^2$$

Important in the OTR device design!

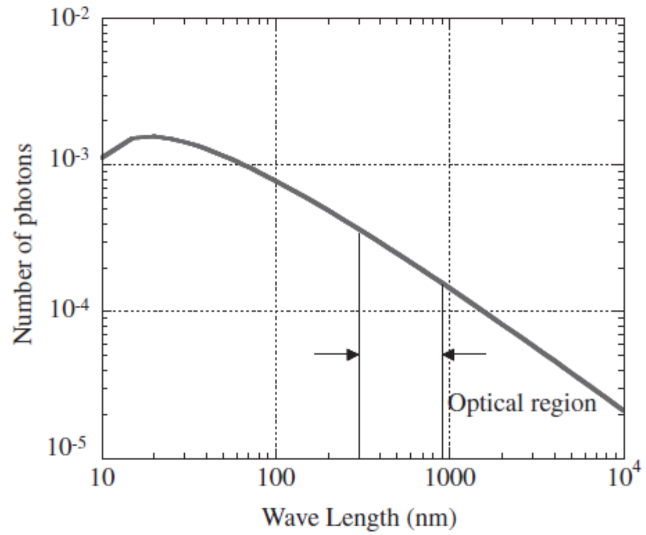


Introduction

Main characteristics

The radiation spectra is continuum

$$\frac{dN_{photon}}{d\lambda} = \frac{2\alpha}{\pi\lambda}\left\{\ln\left(\frac{\gamma\lambda}{\lambda_{pe}}\right) - 1\right\}$$



F. Sakamoto, et. al - **Emittance and energy measurements of low-energy electrons beam using optical transition radiation techniques**, JJAP vol.44, 3, 2005, 1485-1491.

Limit of perfect conductor model:

- Intensity is strongly attenuated near the plasma oscillation wavelength

Obs.: for metals the plasma oscillation wavelength is of order of 10 nm in the visible range (300-1000 nm) the perfect conductor is a good approximation.

Introduction

Main features

- Characteristic polarization (will be seen later)
- It is linear with the incident charge (no saturation)
- The time of formation is too short (no mean time)
- Initial phase (coherency capabilities)

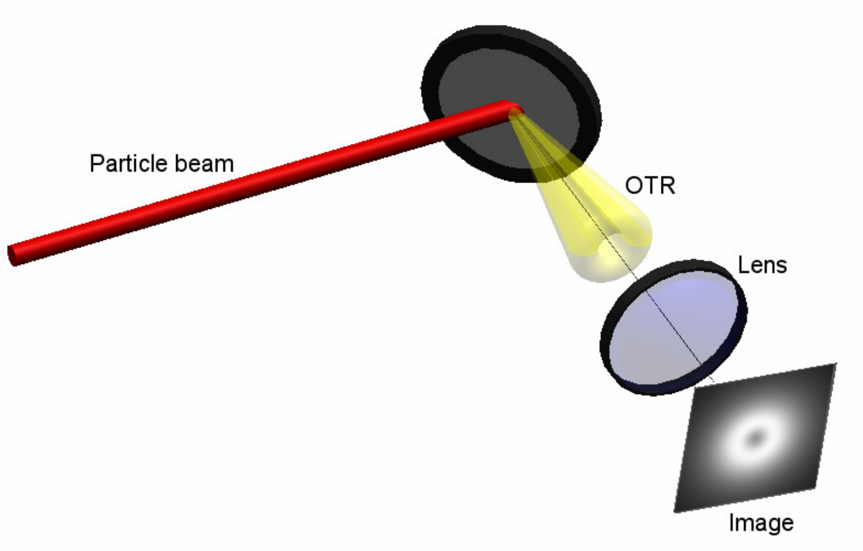
OTR used in beam diagnostics

- *Examples of uses of OTR in beam diagnostics*
- *When is an OTR based diagnostic device necessary?*

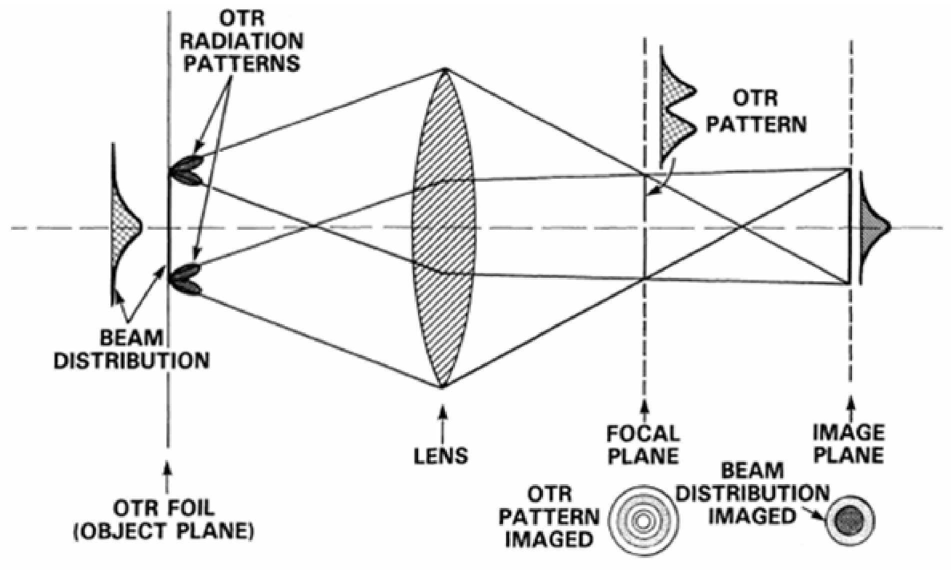
OTR used in beam diagnostics

Single foil OTR measurement

This method consists of observe the radiation emitted by charges in the transition of a single surface.



Modes of operations

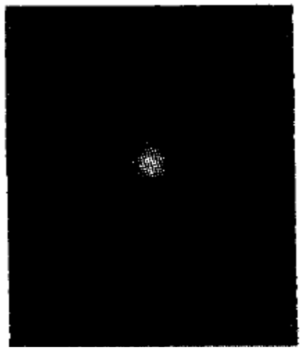


C. B. Reid - **Measurement of electron beam emittance using optical transition radiation and development of a diffuse screen electron beam monitor**, Doctorate thesis, Naval Postgraduate School, Monterey, California.

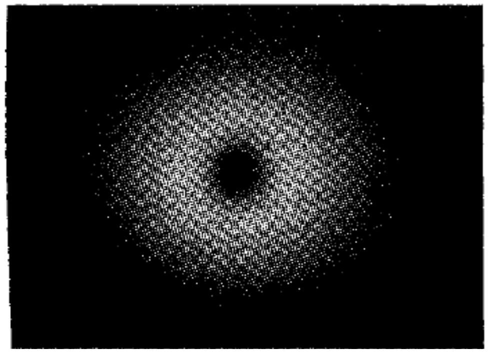
OTR used in beam diagnostics

<u>Single foil OTR measurement</u>

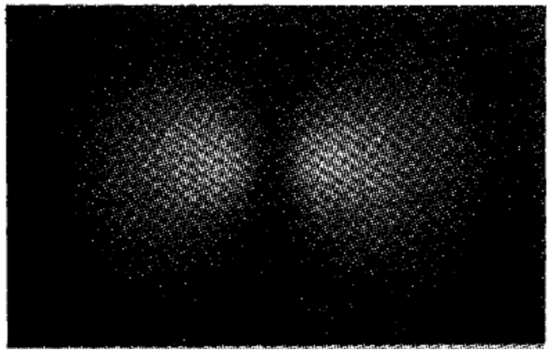
Modes of operation



Near field observation



Far field observation



Far field observation of the horizontal polarization

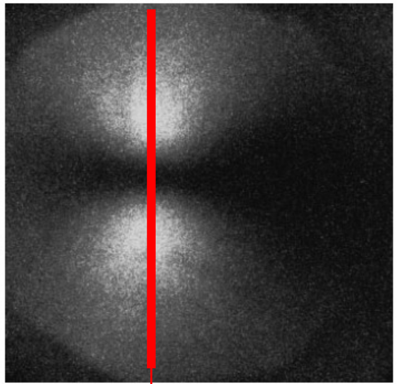
R. B. Fiorito and D. W. Rule - **Optical transition radiation beam emittance diagnostics**, AIP/BIW, vol 319, 21-37.

OTR used in beam diagnostics

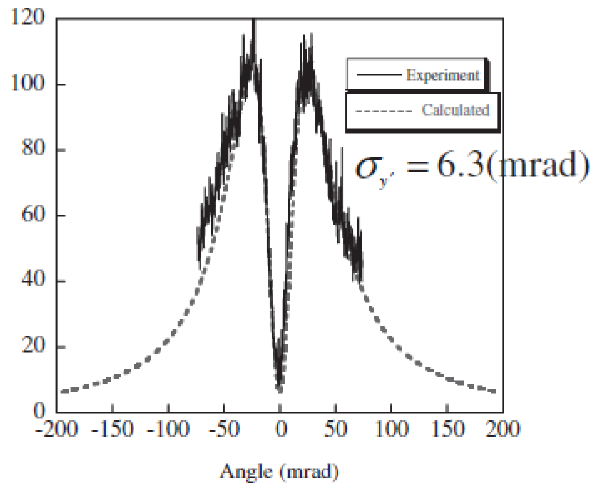
Single foil OTR measurement

- The angular distribution brings the information of the beam energy and divergence.

- The peak position is inversely proportional to the beam energy.
- The observed image is a convolution of the emission of a single electron and the beam divergence distribution.



Vertical polarization of OTR image of 22 MeV electrons



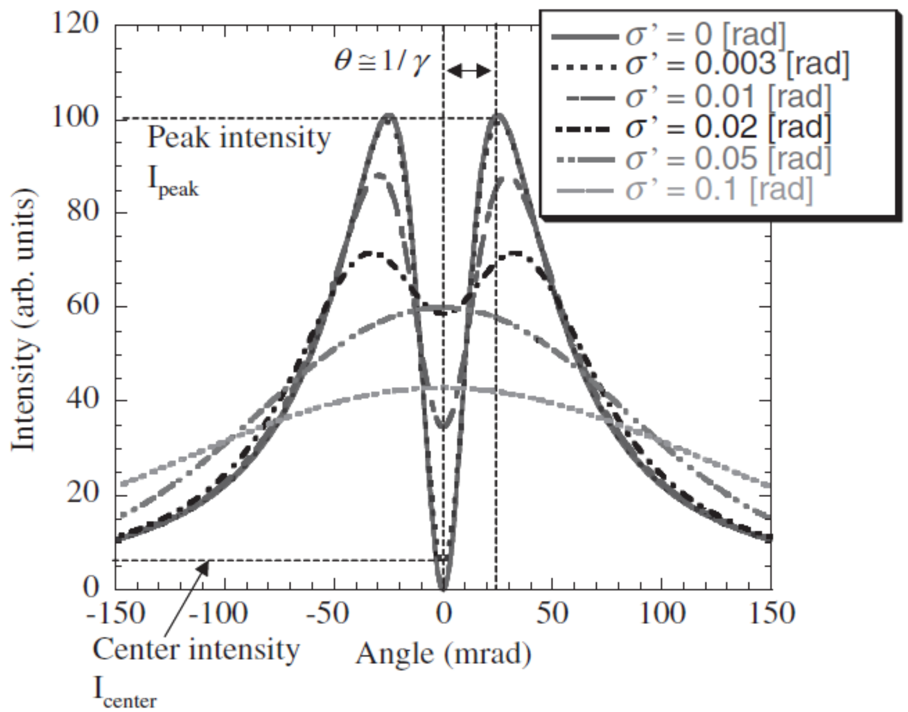
F. Sakamoto, et. al - **Emittance and energy measurements of low-energy electrons beam using optical transition radiation techniques**, JJAP vol.44, 3, 2005, 1485-1491.

OTR used in beam diagnostics

Single foil OTR measurement

- Resolution and systematic errors limits this method:

- The value of beam divergence interferes in the energy measurement
- The value of beam divergence is limited in the interval of $1/\gamma$ and γ



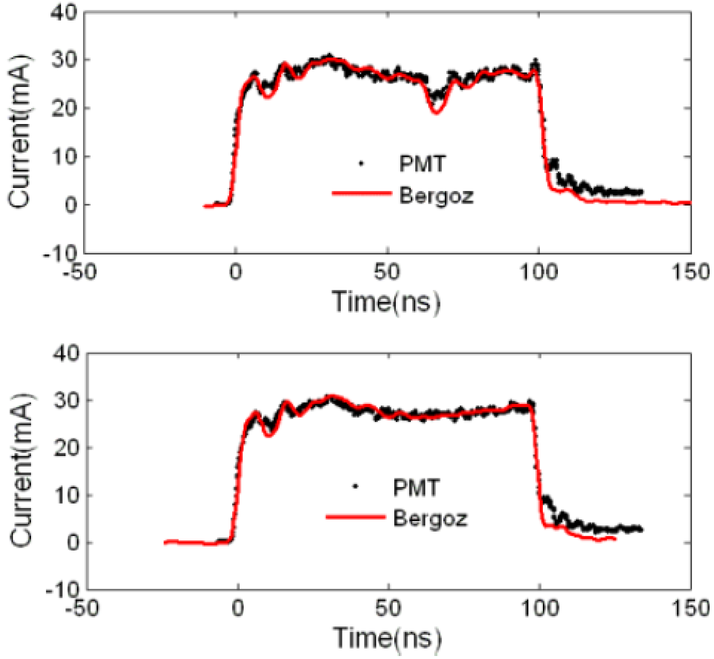
F. Sakamoto, et. al - **Emittance and energy measurements of low-energy electrons beam using optical transition radiation techniques**, JJAP vol.44, 3, 2005, 1485-1491.

OTR used in beam diagnostics

Single foil OTR measurement

As OTR is practically instantaneously formed, it can be used to measure beam variations as function of time.

More important than that, OTR has time-resolved capabilities.



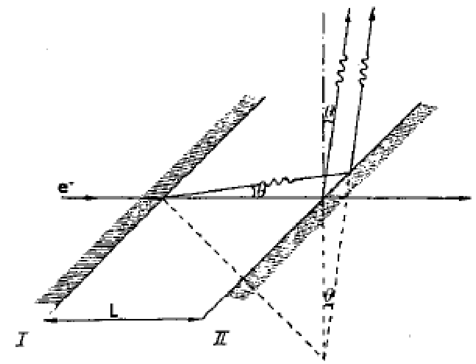
K. Tian, et. al – **Fast imaging of time-dependent distribution of intense beams**, In: proceedings of PAC07, New Mexico, USA.

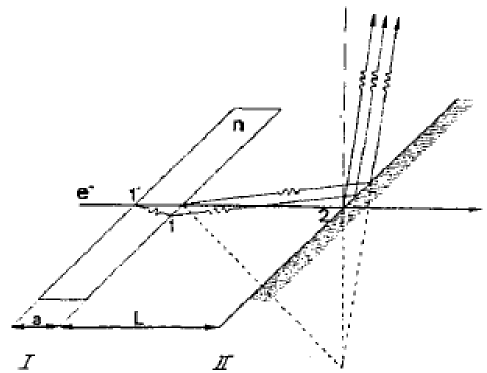
OTR used in beam diagnostics

Double foil OTR measurement (OTR interferometer)

This method consists of analyzing the interference pattern of OTR emitted by two or more interfaces.

Interferometer method has a higher resolution and no limitations on divergence measurements compared to the single foil method.



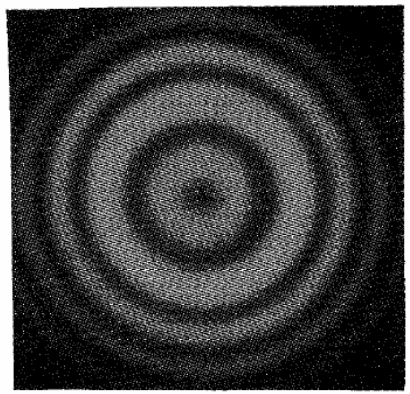


R. B. Fiorito and D. W. Rule - **Optical transition radiation beam emittance diagnostics**, AIP/BIW, vol 319, 21-37.

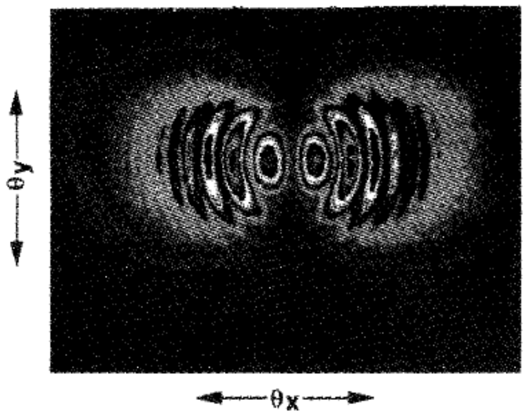
OTR used in beam diagnostics

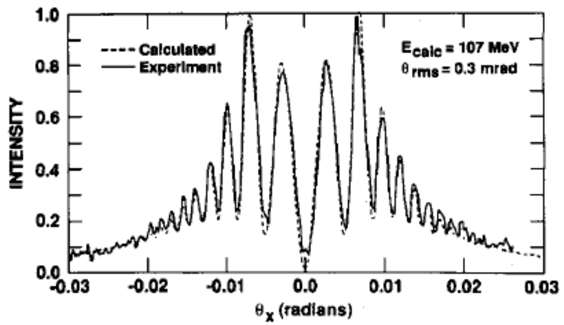
Double foil OTR measurement (OTR interferometer)

OTRI



R. B. Fiorito and D. W. Rule - **Optical transition radiation beam emittance diagnostics**, AIP/BIW, vol 319, 21-37.

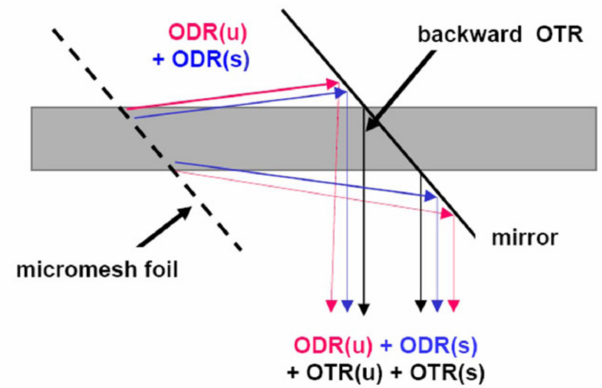




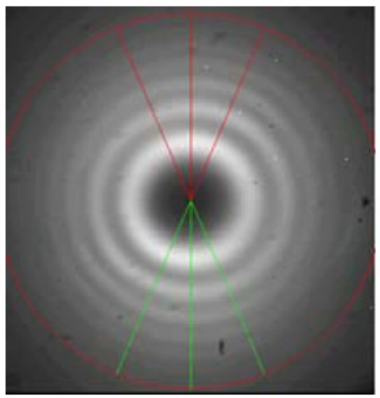
OTR used in beam diagnostics

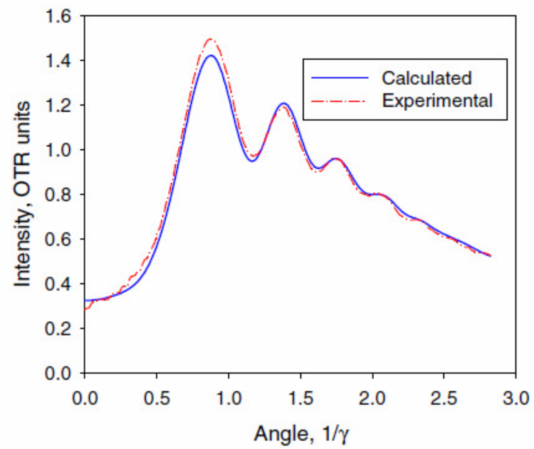
OTR + ODR interferometer

OTDRI



This method consists of analyzing the pattern of interference between the transition radiation and diffraction radiation.



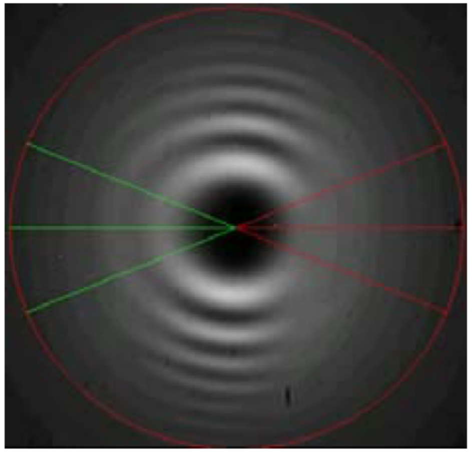


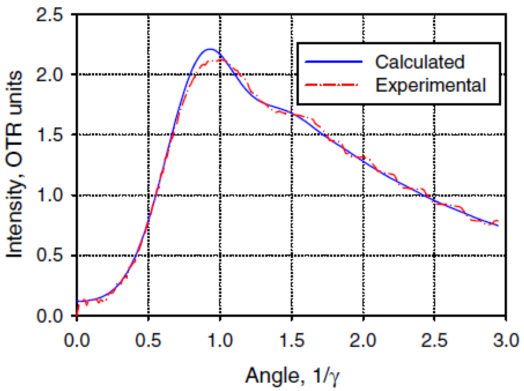
R. B. Fiorito, et.al - **Interference of diffraction and transition radiation and its application as a beam divergence diagnostic**, PRST-AB, 9, 052802 (2006).

OTR used in beam diagnostics

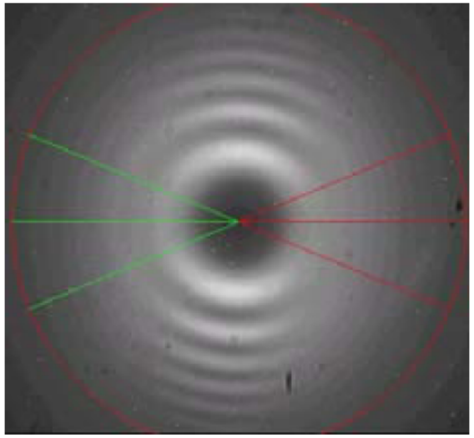
OTRI and ODTRI differences:

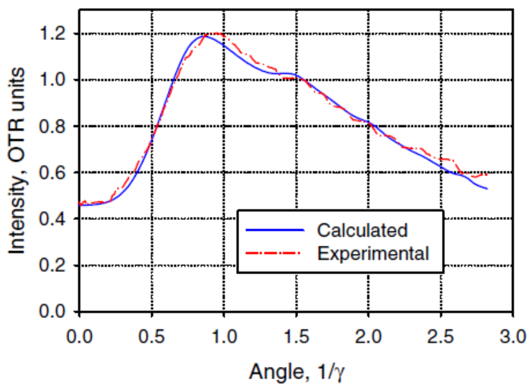
OTRI





ODTRI



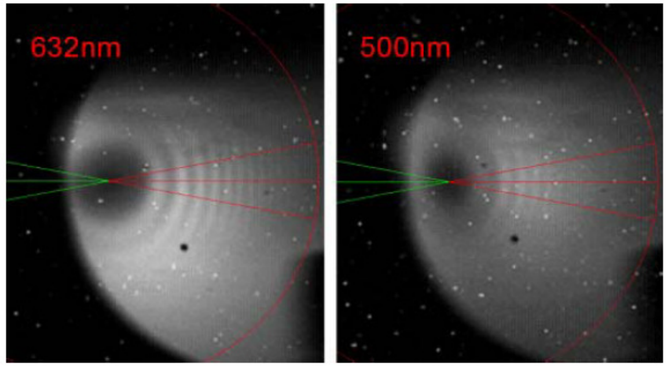


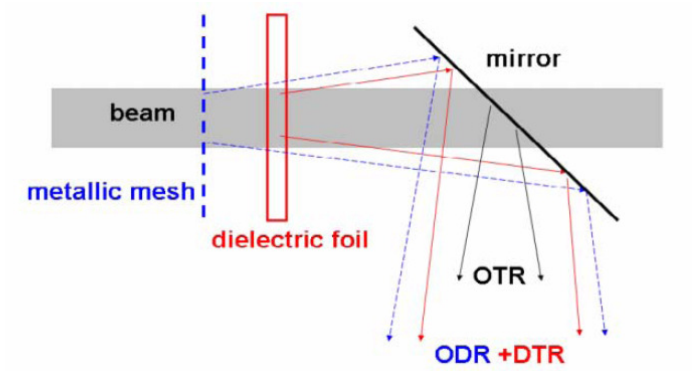
R. B. Fiorito, et.al - **Interference of diffraction and transition radiation and its application as a beam divergence diagnostic**, PRST-AB, 9, 052802 (2006).

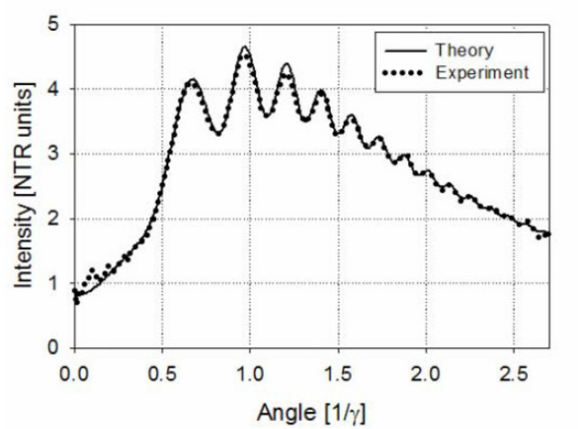
OTR used in beam diagnostics

ODR + DTR + OTR interferometer

This method consists of analyzing the pattern of interference between the diffraction radiation and transition radiation of a thin transparent dialectical foil and a conductor foil.



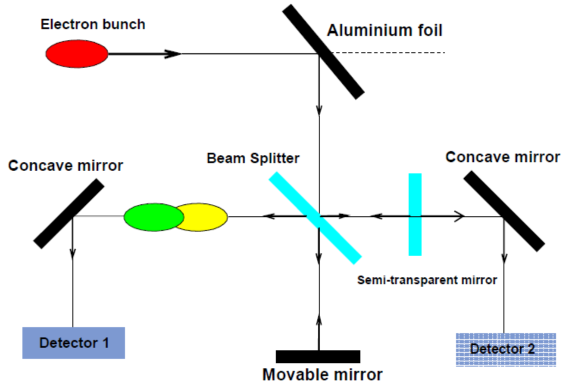




R. B. Fiorito, et. al – **Optical diffraction-dielectrical foil radiation interferometry diagnostic for low energy beams**, In: proc. of PAC07, New Mexico, USA.

OTR used in beam diagnostics

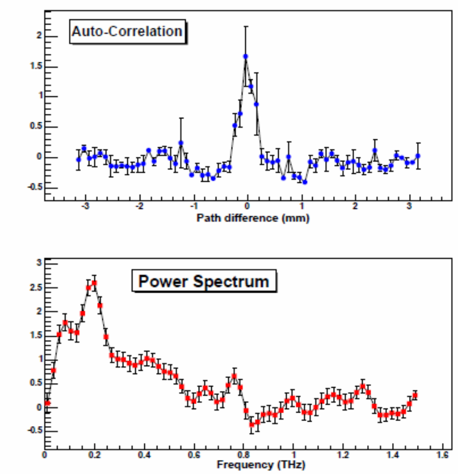
Uses of coherent emission of OTR

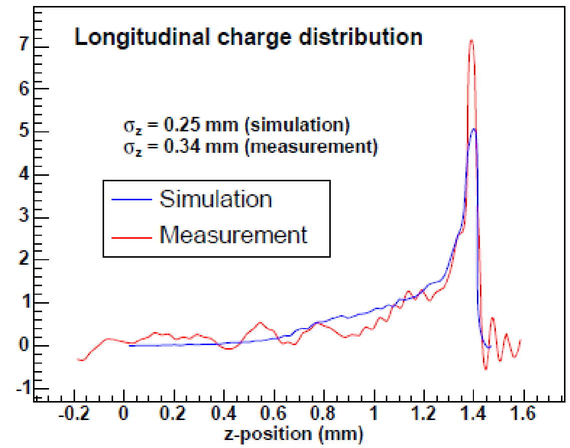


This method consists of analyze the OTR spectra and by means of a signal deconvolution it is possible to measure the longitudinal charge distribution.

$$I(\omega)=N(N-1)\cdot I_e\cdot|f(\omega)|^2$$

$$f(\omega)=\int\rho(z)\cdot\exp(i\omega z/c)\cdot dz$$





D. Mihalcea, et. al - **Longitudinal electron bunch diagnostic using coherent transition radiation**, In: proceeding of PAC05, Tennessee, USA.

OTR used in beam diagnostics

When is an OTR diagnostic device necessary?

When there is a need for:

- Time-resolved measurement;
- High spatial resolution;
- Measurement of many parameters in a single point;

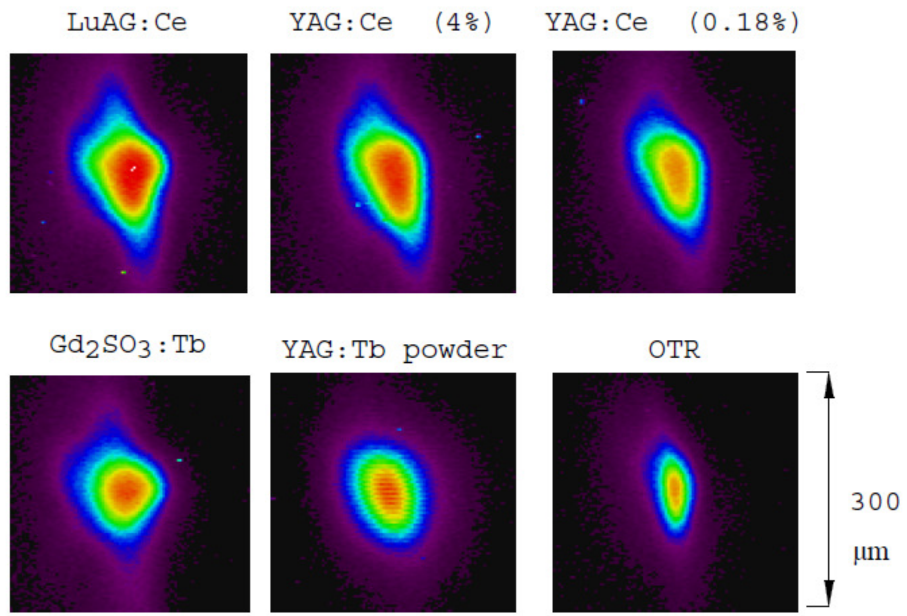
Or:

- When an optical instrumentation is preferred;
- When the charge distribution need to be measured (in substitution of phosphor screens);

OTR used in beam diagnostics

As OTR is has a linear dependency with the incident charge, this process of radiation production has a great advantage over fluorescence.

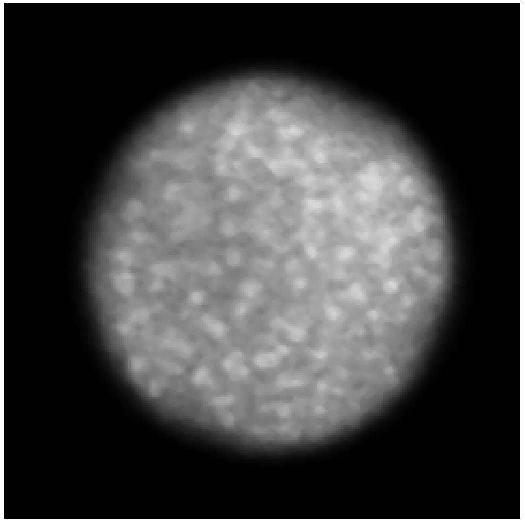
The actual charge distribution can be measured.

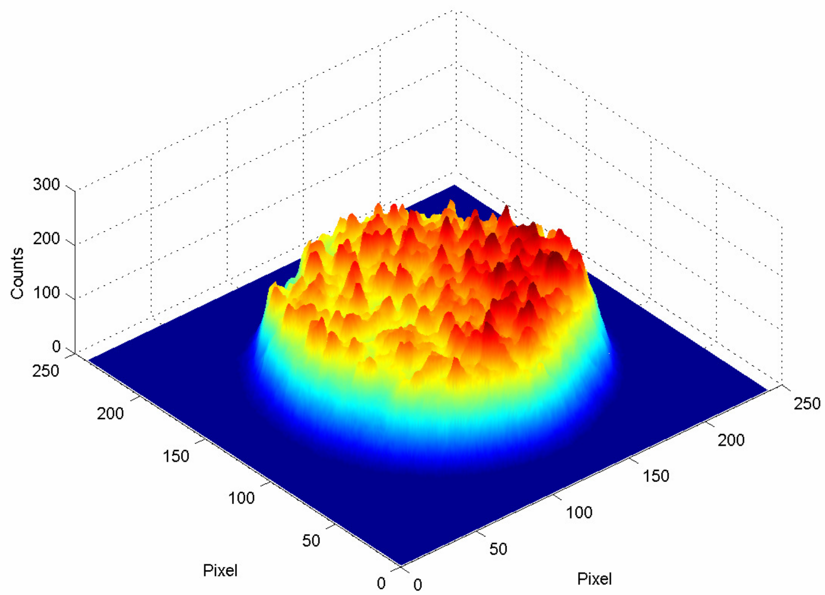


A. Murokh, et. al - **Limitations on measuring a transverse profile of ultra-dense electron beams with scintillators**, In: proc. of PAC01, Chicago, USA.

OTR used in beam diagnostics

- Granularities in the phosphor reduces the resolution of spatial measurements;
- OTR does not present any granularity;





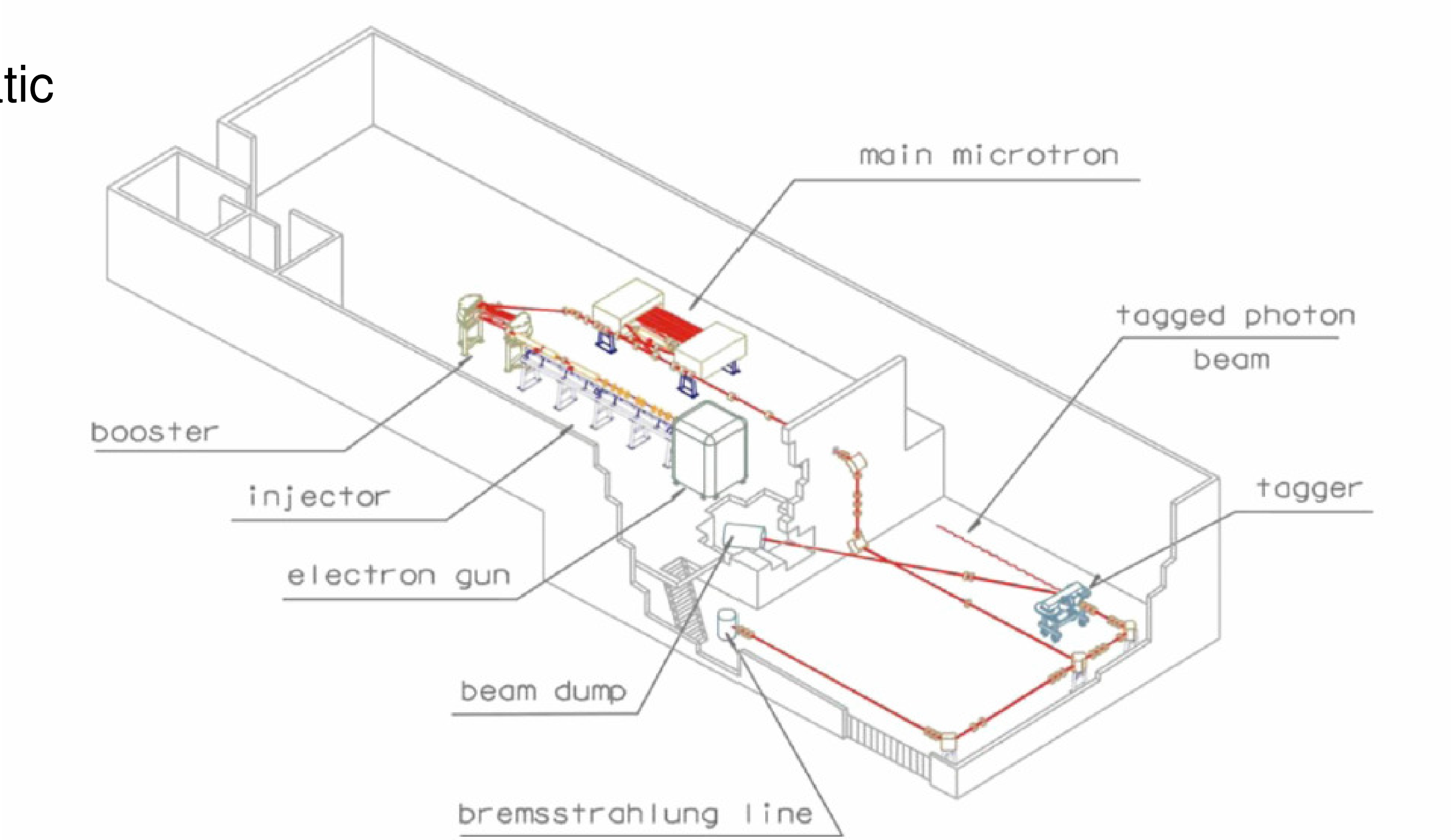
The OTR based tool for the IFUSP Microtron

- *IFUSP Microtron facilities*
- *Design & Experimental data*

The OTR based tool for the IFUSP Microtron

IFUSP Microtron facilities

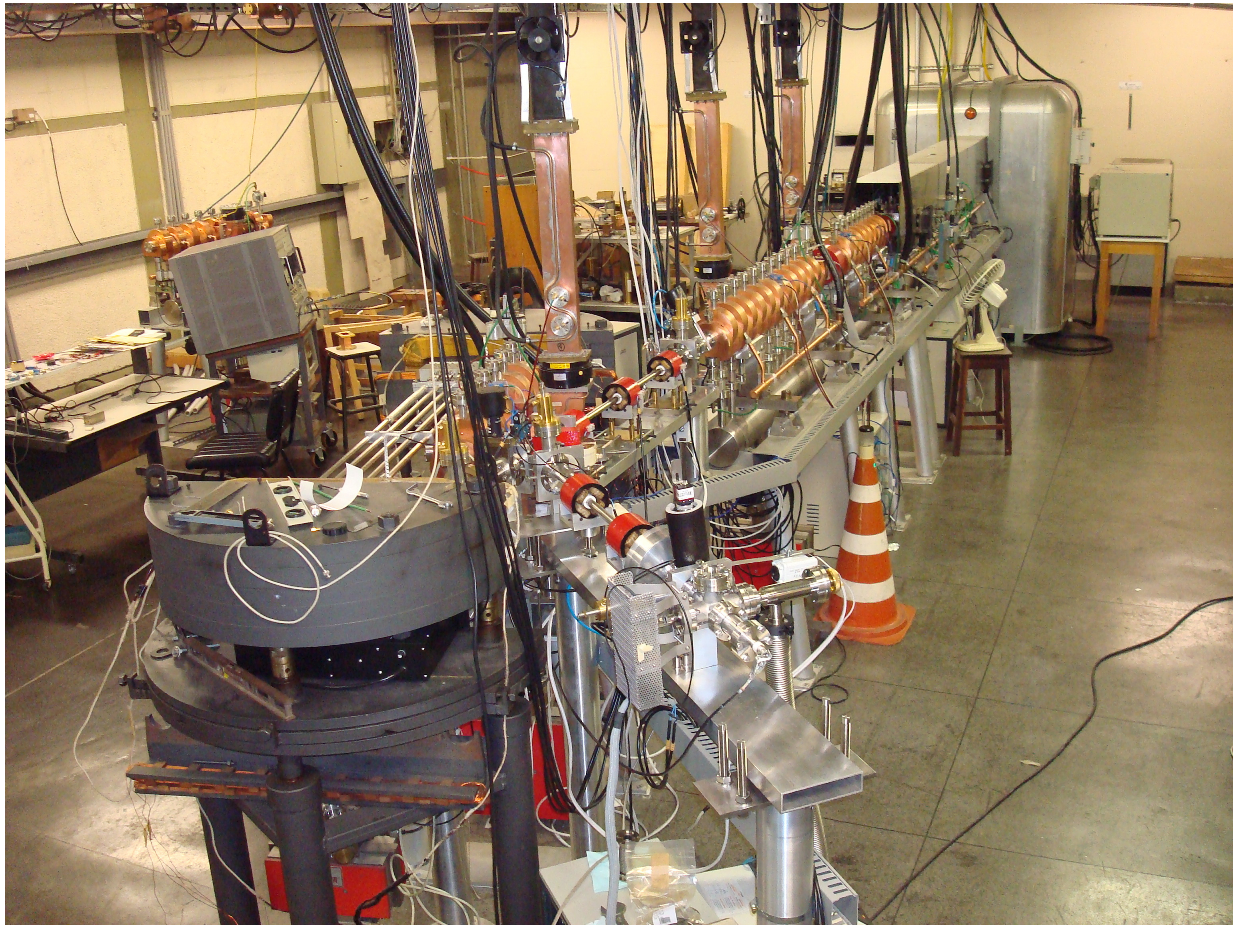
Schematic view



The OTR based tool for the IFUSP Microtron

IFUSP Microtron facilities

Current status



The OTR based tool for the IFUSP Microtron

IFUSP Microtron facilities

- Atomic Research
- Interaction of High Energy Electrons with Matter
- Radiotherapy Research
- Radiation Physics
- Nuclear Resonance Fluorescence
- Photonuclear Reactions

The OTR based tool for the IFUSP Microtron

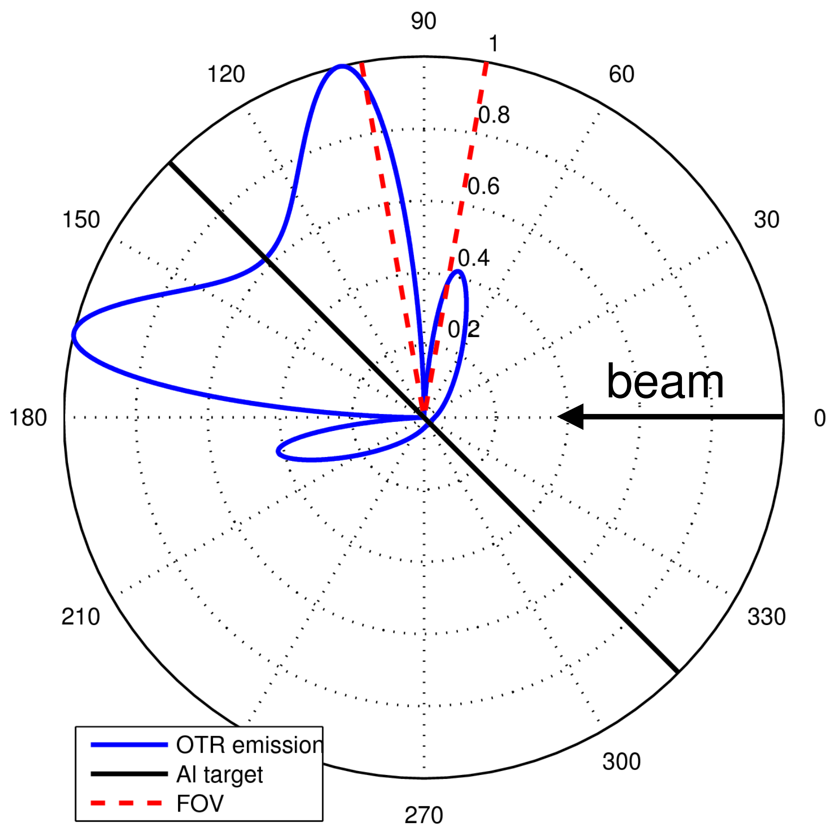
IFUSP Microtron facilities

Needs for a diagnostic device:

- Measurement of the actual charge distribution before the sample chamber.
- Phase space diagnostic before the microtron booster.

The OTR based tool for the IFUSP Microtron

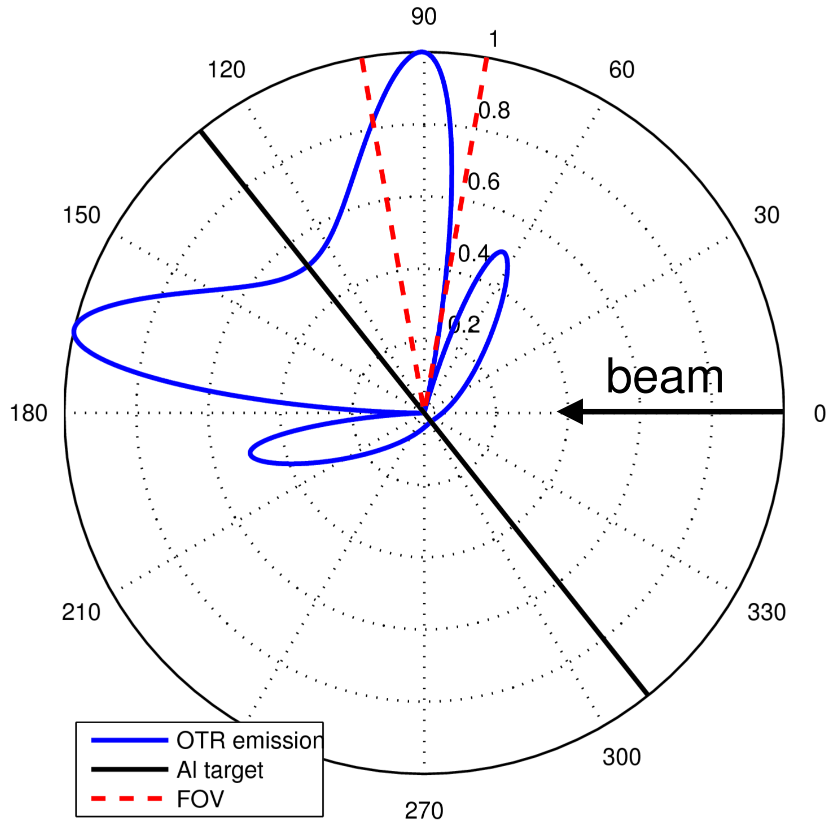
- OTR intensity is usually low intense;
- The main issue in the design of an OTR device for 1.8 MeV is the low intensity and the spread angular distribution;
- Our design has an additional challenge: low current (μA~nA);



45º incidence

The OTR based tool for the IFUSP Microtron

- In our design, the solution adopted was to change the incidence angle in order to increase the radiation emitted in the camera direction;
- A numerical integration in the field of view indicates a intensity 150% higher then the 45º incidence case;

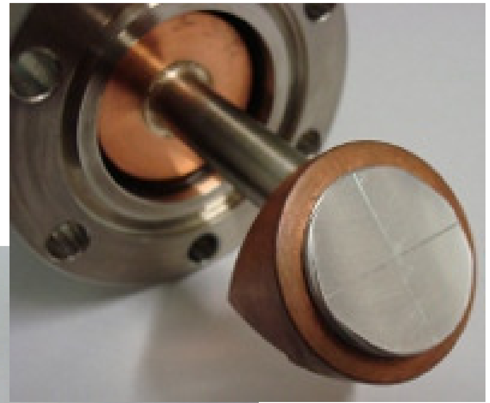


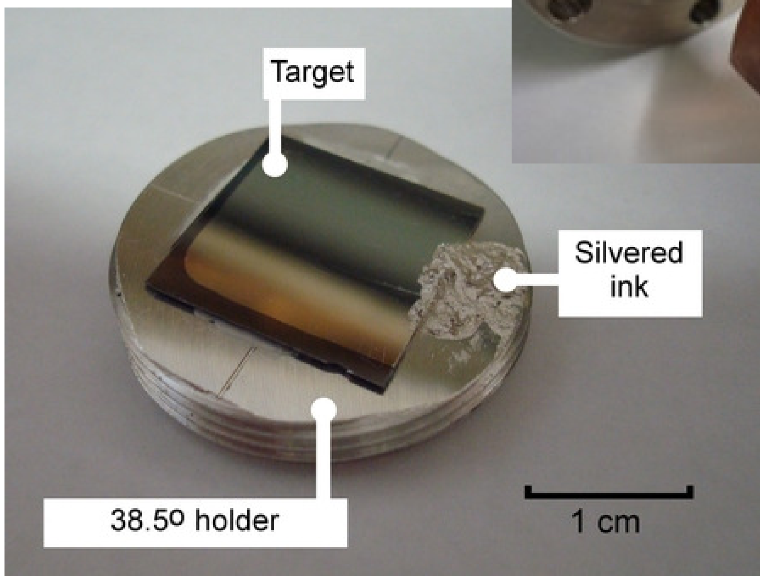
38.5º incidence

The OTR based tool for the IFUSP Microtron

- The target holder corrects the angle of incidence.
- The target consists of a silicon substrate coated with a Aluminum film of 200 nm thick.

- Silvered ink provide electrical contact between the target and the holder, in order to avoid charge concentration.



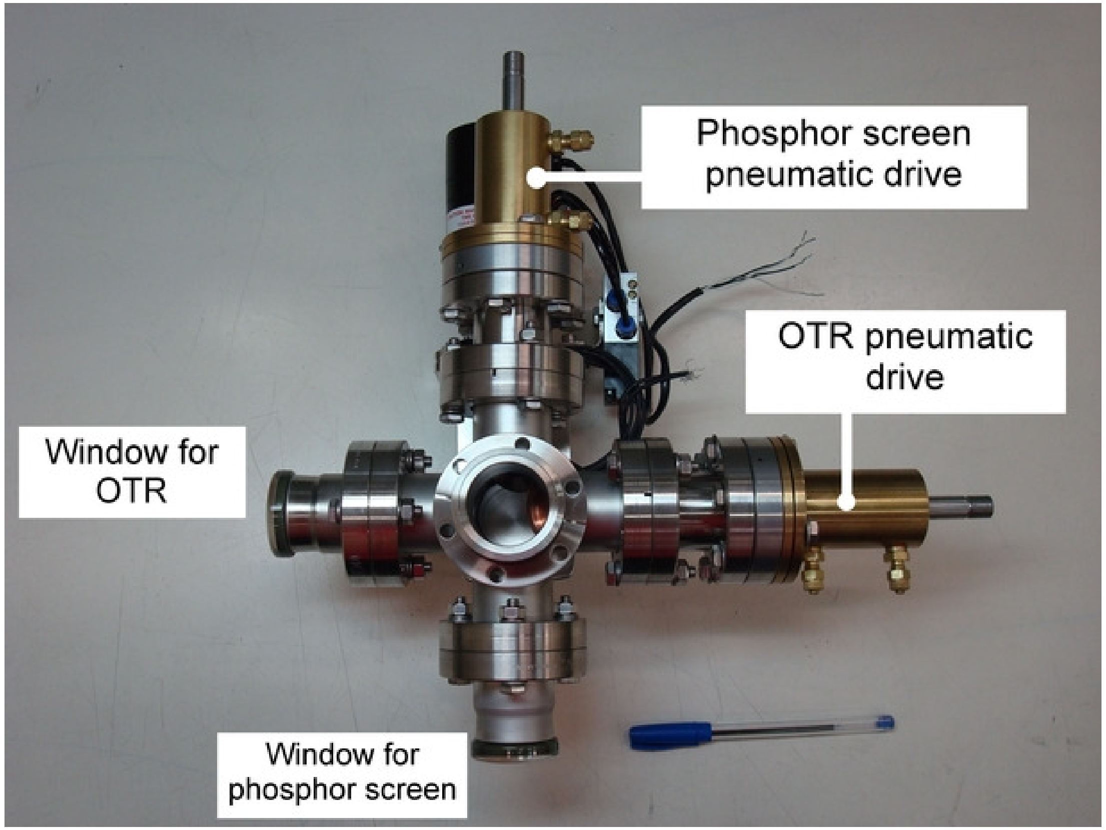


The OTR based tool for the IFUSP Microtron

- Our OTR device has a regular phosphor screen mounted in right angle to perform beam positioning during the machine normal operation;
- Two different cameras are coupled to the windows;

Regular CCD camera to phosphor screen;

Special CCD camera to OTR;



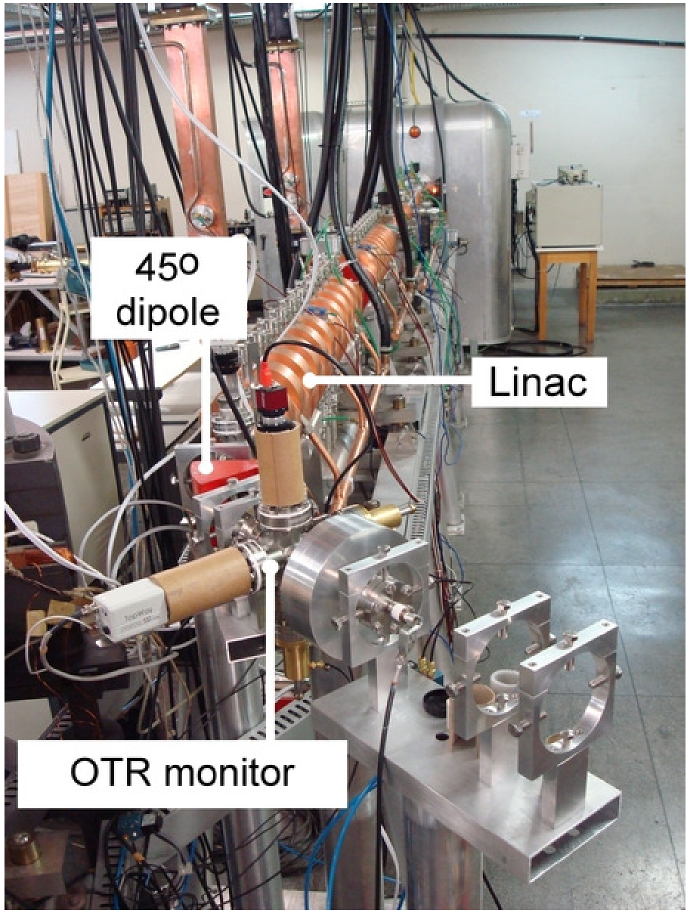
The OTR based tool for the IFUSP Microtron

What is special about the OTR camera?

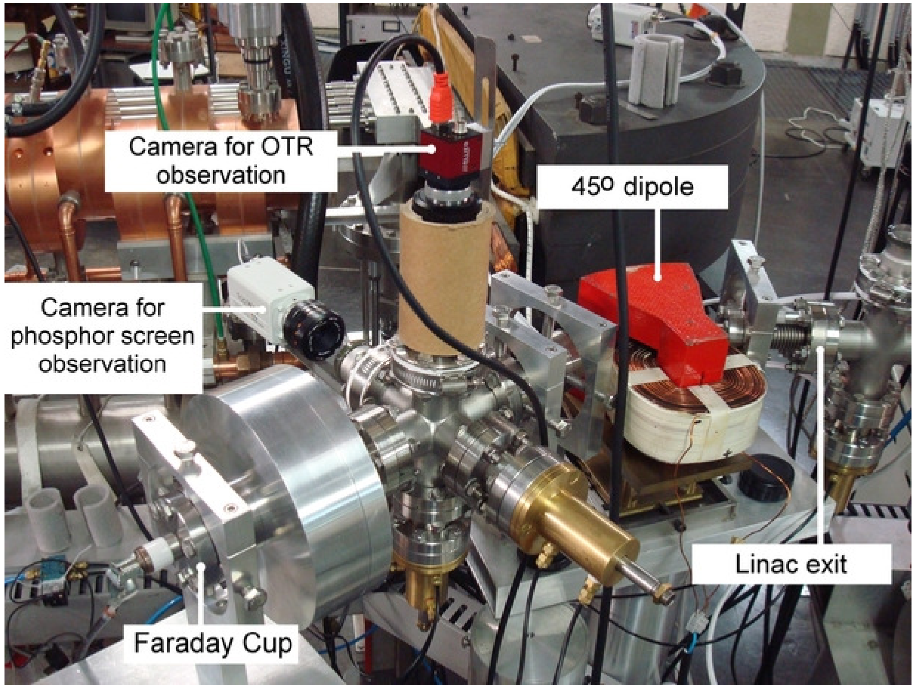
- Adjustable shutter speed;
- Adjustable gain;
- Adjustable gamma correction;
- Firewire connection;
- Automatic sequence of shots;

AVT Guppy F-038B – Allied Vision

The OTR based tool for the IFUSP Microtron

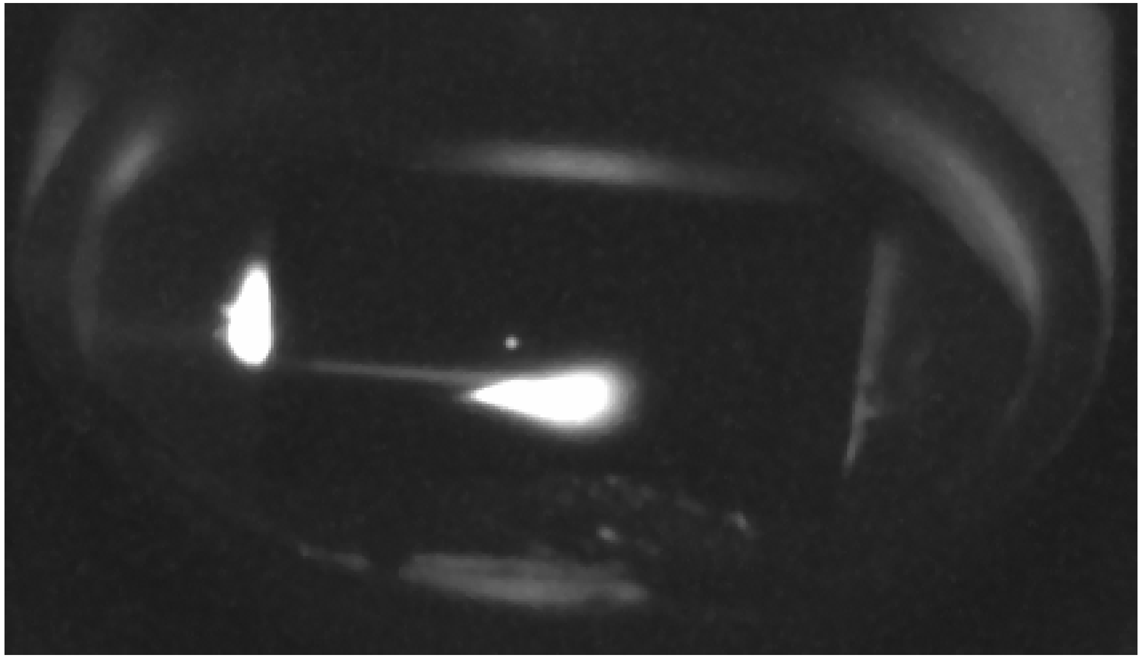


- Provisional installation right after the 1.8 MeV linac injector.
- A 45° dipole creates high dispersion function at the monitor position to energy spread measurement.



The OTR based tool for the IFUSP Microtron

- First image with the device;
- Many artifacts were found, however, there is a suspicious OTR image;
- Some tests makes necessary;



The OTR based tool for the IFUSP Microtron

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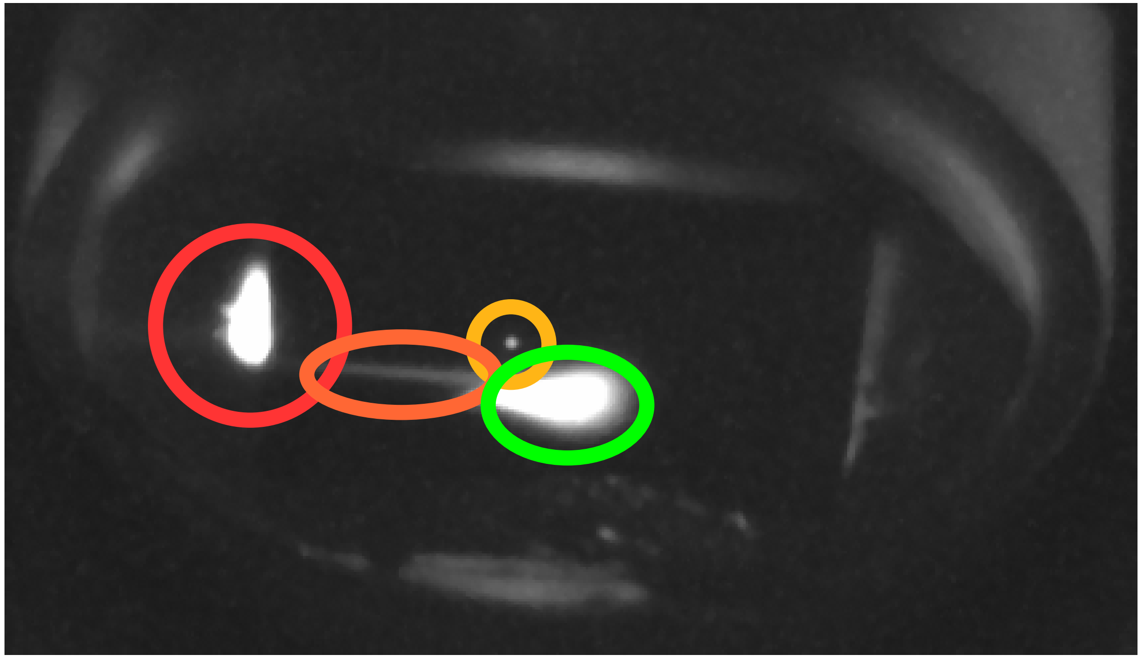


- Fluorescence of the vacum glue (unexpected);
- Dust in the vacum window;
- OTR?

If yes:

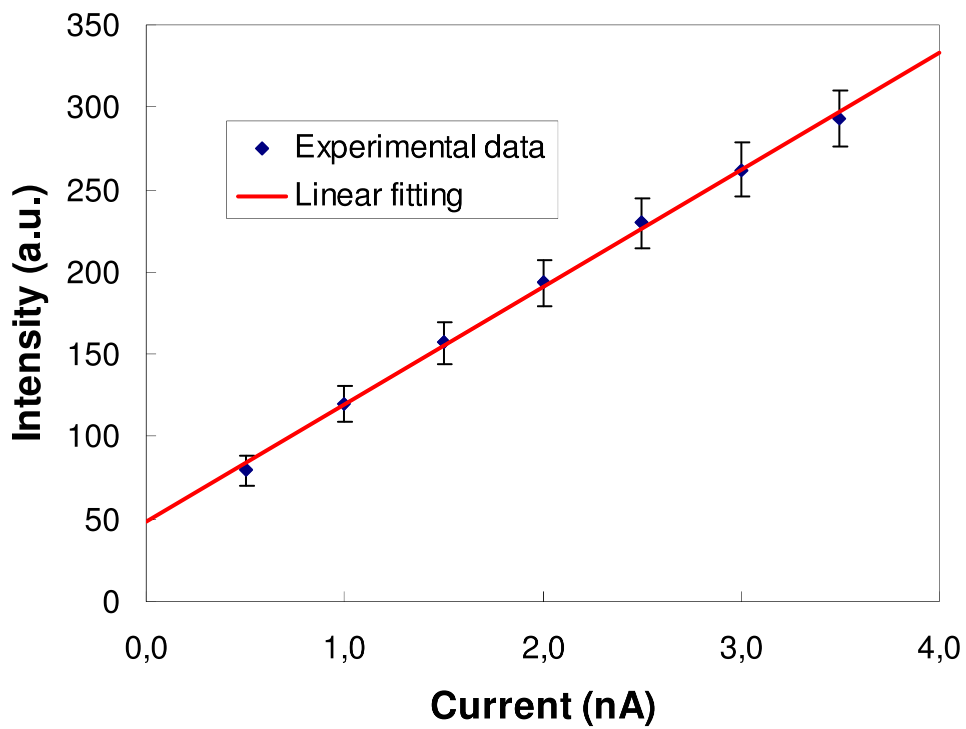
- Low energy electrons;
- The beam;

The OTR based tool for the IFUSP Microtron

Test 1 – Linearity

Test performed with the variation of the beam repetition rate.

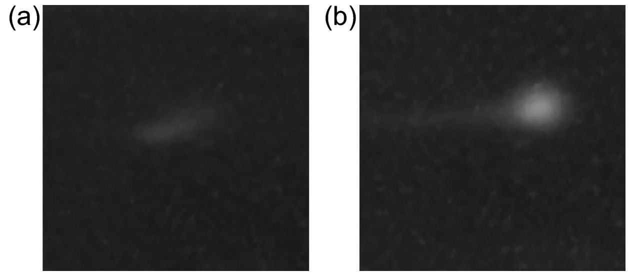
Each point represents a time integration over 1 sec.



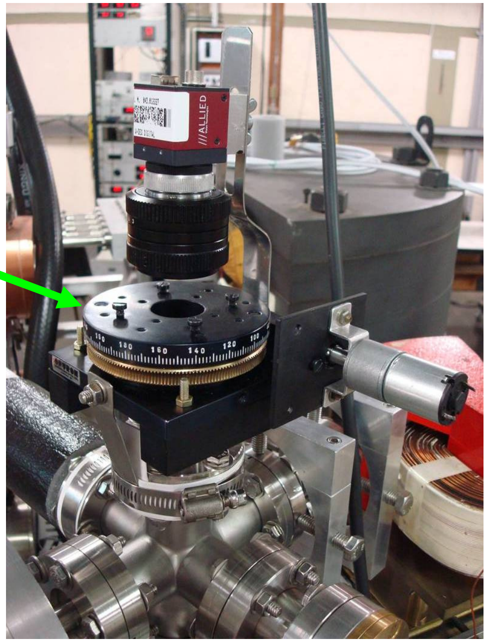
The OTR based tool for the IFUSP Microtron

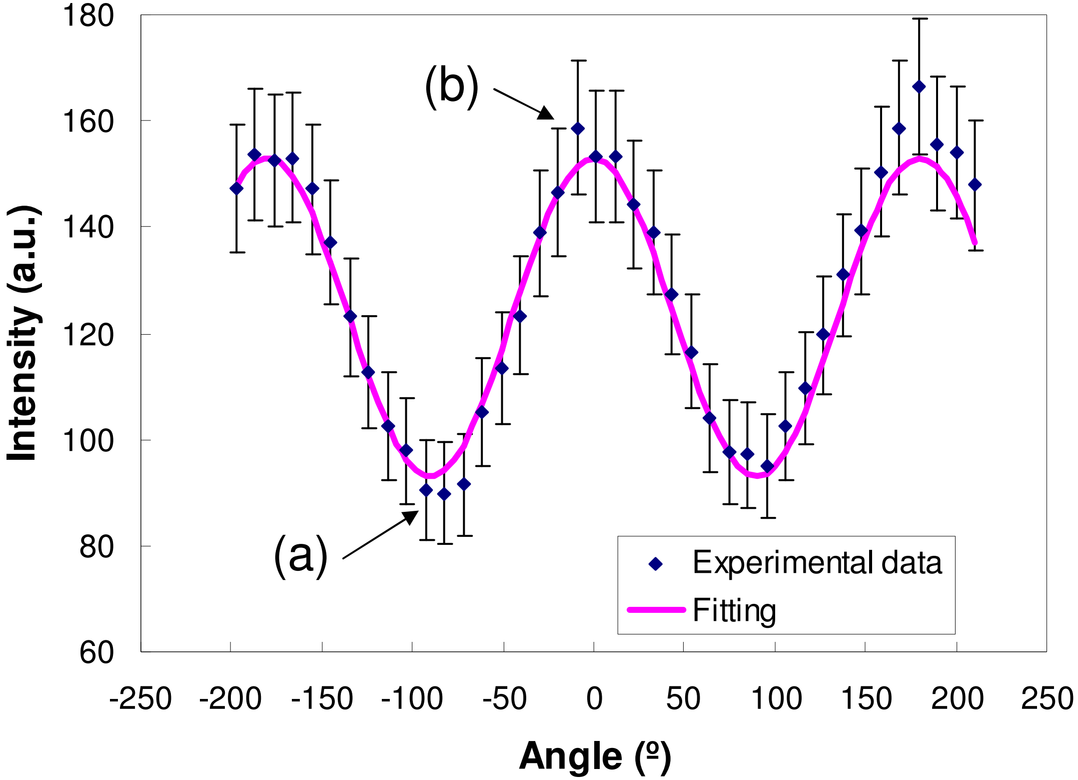
Test 2 – Polarization

Test performed with the variation of the angle of a polarizer in a goniometer;



Goniometer

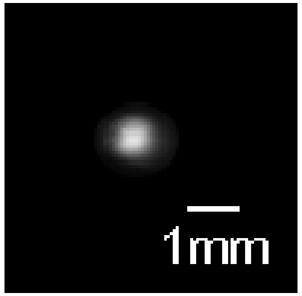


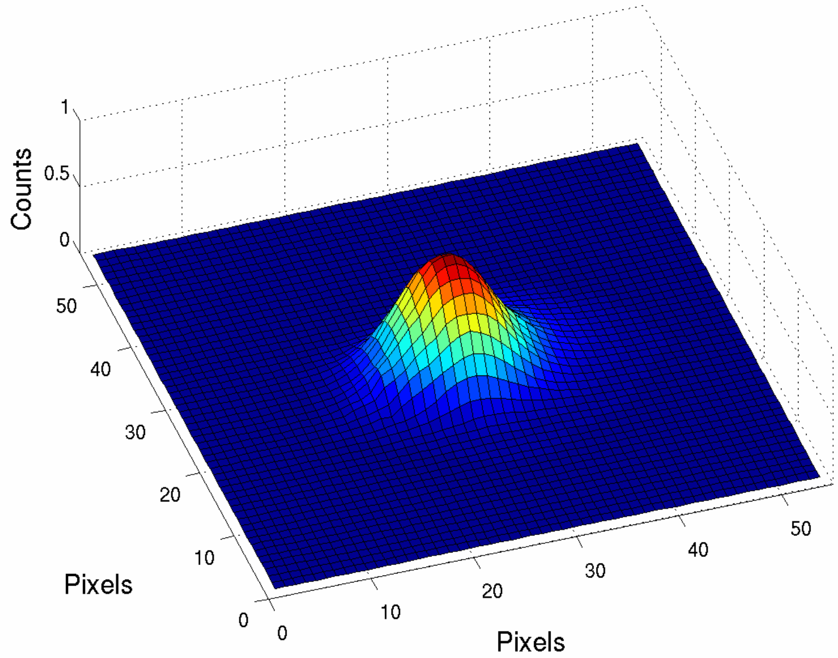


The OTR based tool for the IFUSP Microtron

- Charge distribution measurement

- As the OTR is linear dependent to the incident charge, the observed image corresponds to the charge distribution





The OTR based tool for the IFUSP Microtron

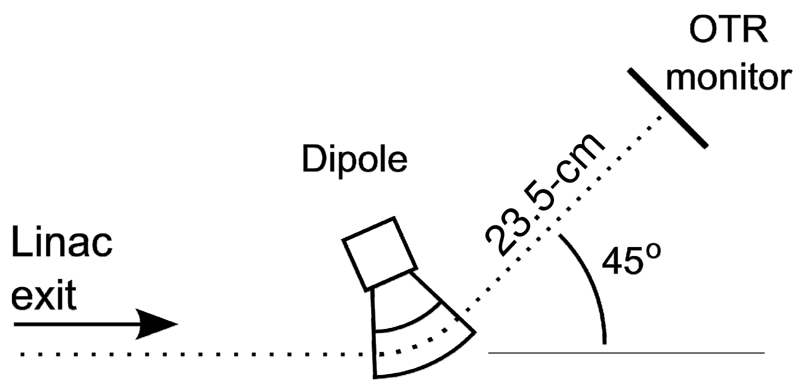
- Energy spread measurement

- Energy spread may be measured in a point of the accelerator where the dispersion function has a value much higher than the beam radius.

$$\frac{\Delta p}{p_0} = D(L) \cdot x$$

$$D(L) = \rho_0 (1 - \cos\theta) + L \sin\theta - L \tan\delta (1 - \cos\theta)$$

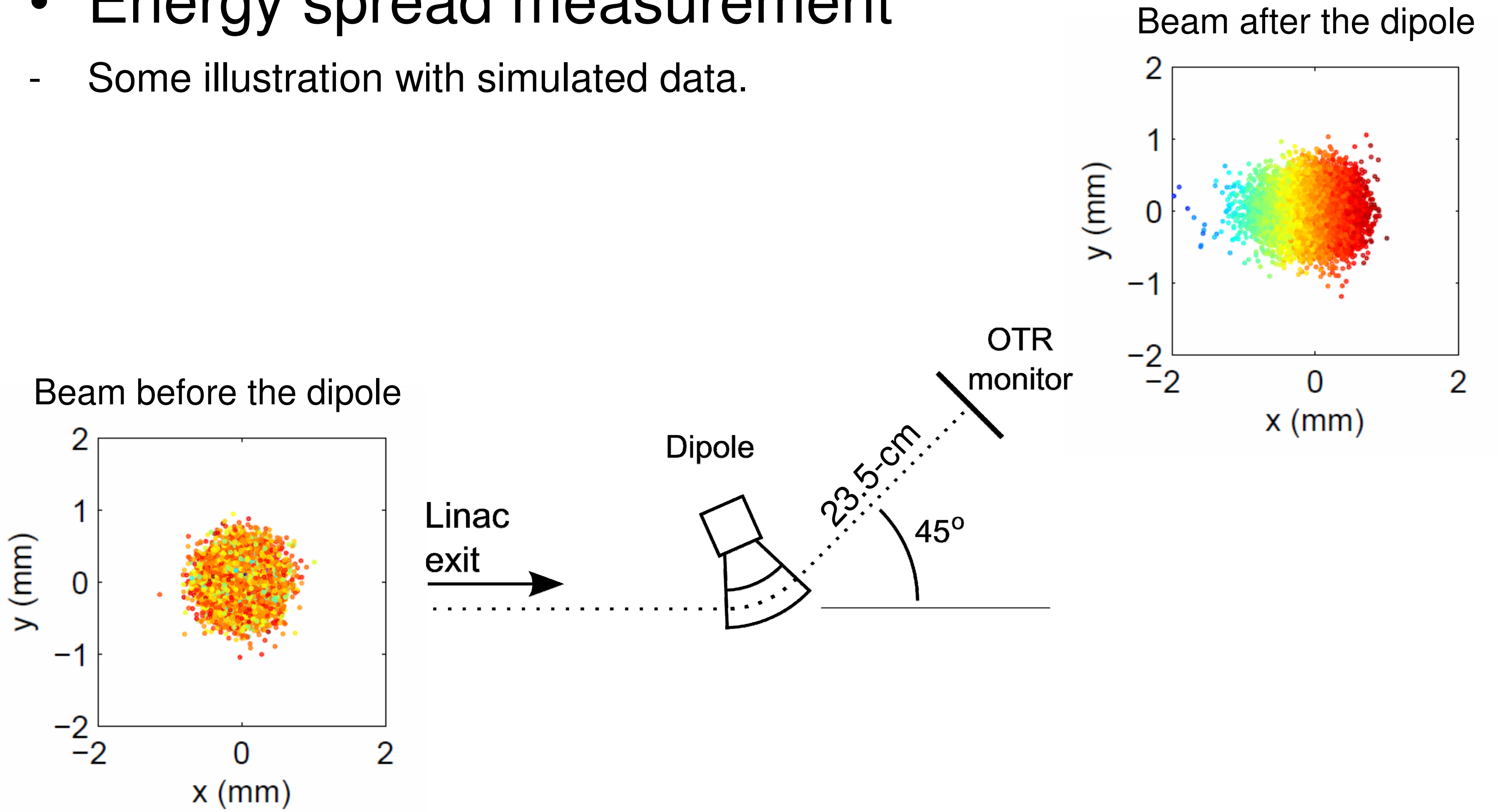
$$\text{where} \quad \rho_0 = \frac{\theta}{l_{ef}} \quad \text{and} \quad l_{ef} = \frac{1}{B_0} \int B(s) \cdot dl$$



The OTR based tool for the IFUSP Microtron

- Energy spread measurement

- Some illustration with simulated data.

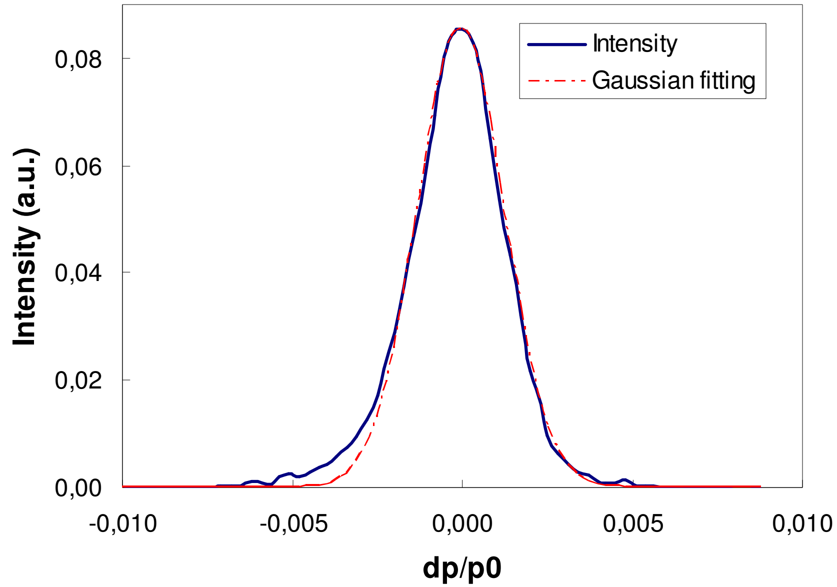


The OTR based tool for the IFUSP Microtron

- Energy spread measurement

- The beam energy distribution was measured;
- The energy distribution has a gaussian shape with a little longer tail in the lower energies region;
- Data used to optimize the chopper/buncher system;

$$\frac{\Delta p}{p_0}_{HWHM} = 1{,}8.10^{-3}$$



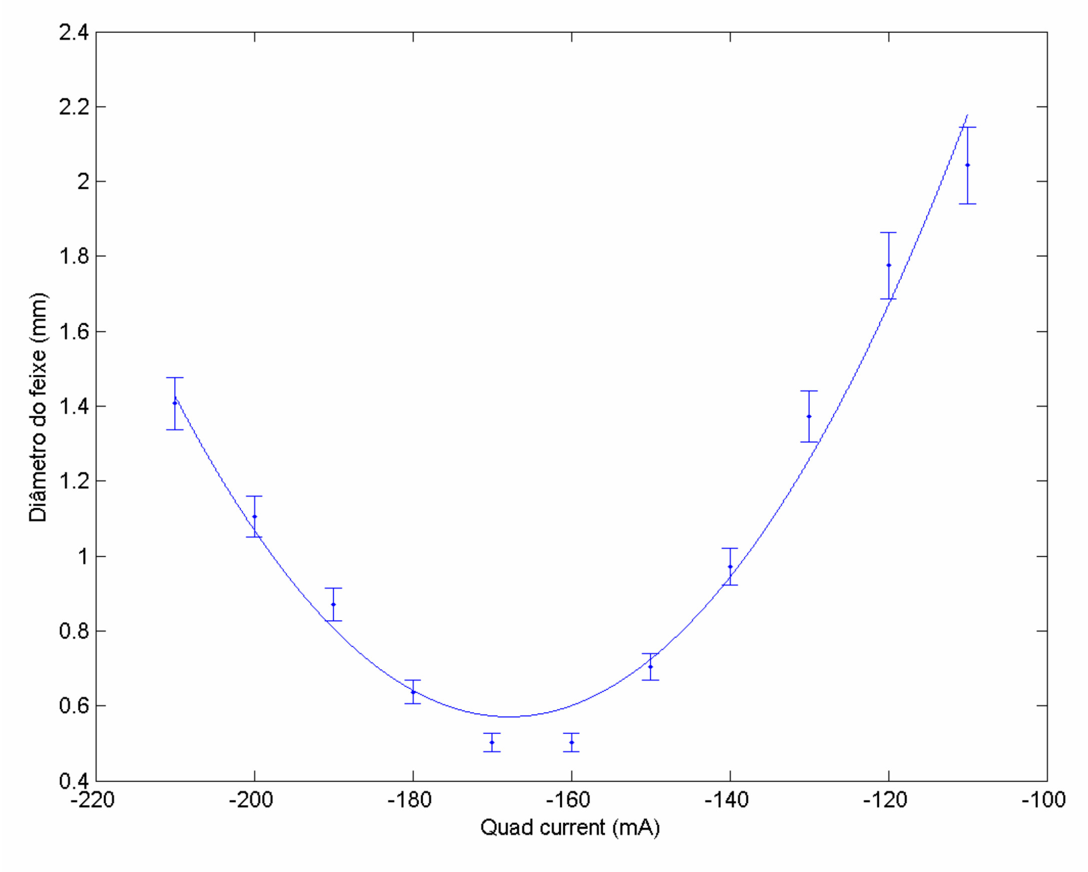
The OTR based tool for the IFUSP Microtron

- Emittance measurement

- Some illustrative data

Quad scan method

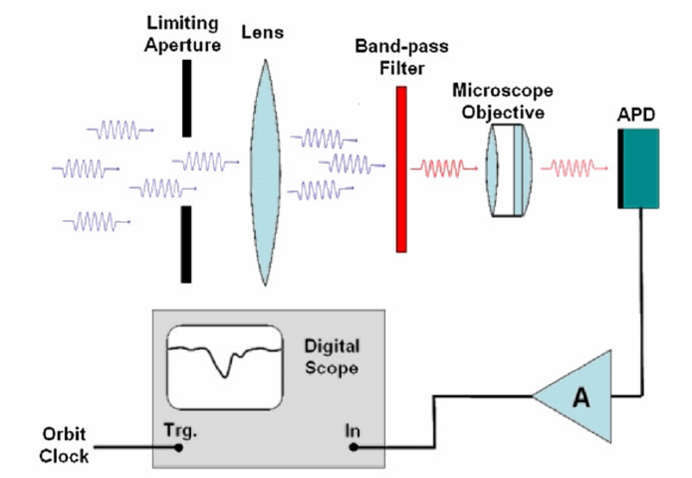
ε = 1.6 π.mm.mrad

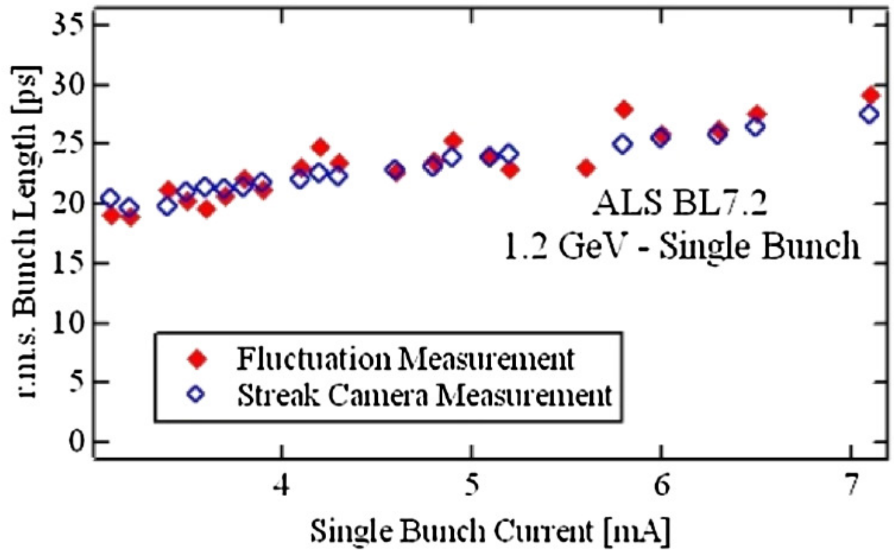


The OTR based tool for the IFUSP Microtron

Some innovative measurement:

- Use of incoherent radiation to measure bunch length;
- Dr. Sannibale et. al, showed the viability of the use of incoherent synchrotron radiation;
- We intend to use incoherent OTR to the same purpose;

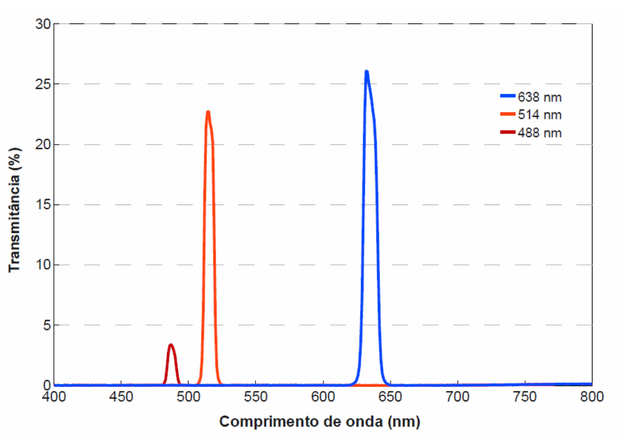


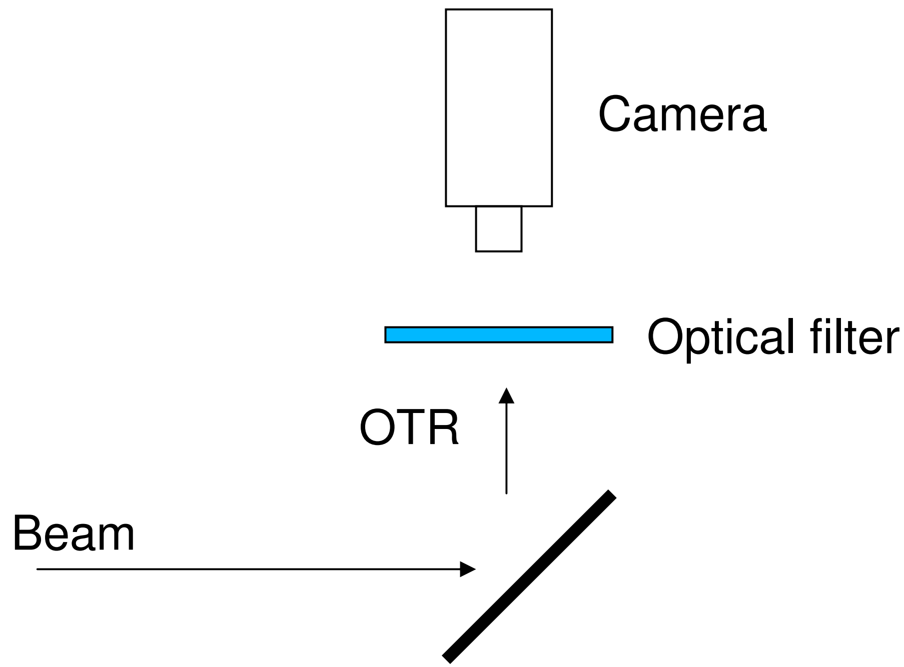


F. Sannibale, et. al – **Absolute bunch length measurements by incoherent radiation fluctuation analysis**, PRST-AB 12, 032801, 2009.

The OTR based tool for the IFUSP Microtron

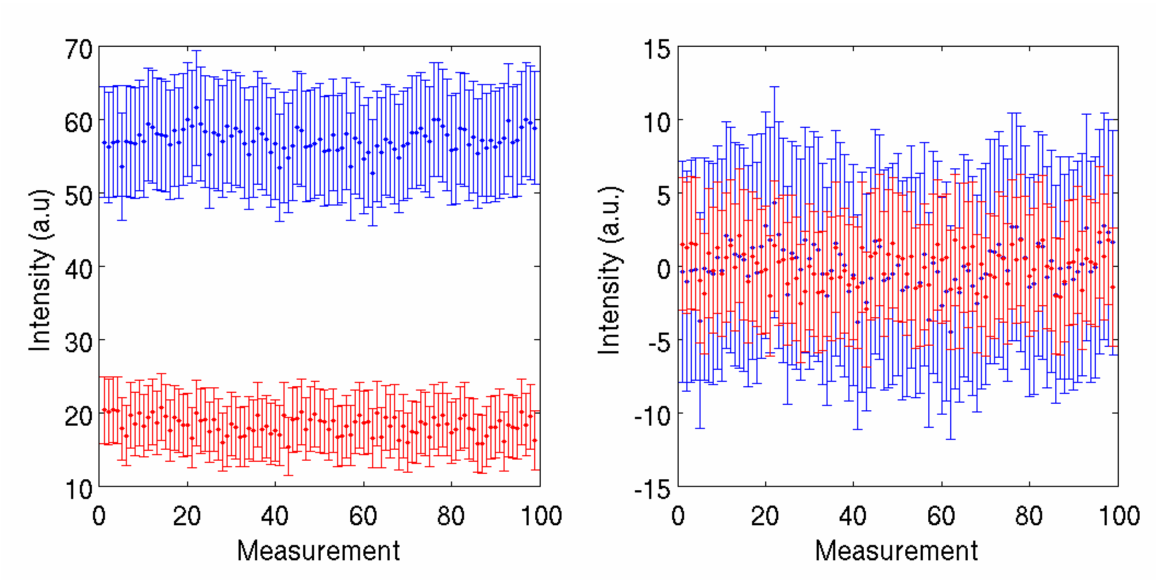
- OTR intensity is measured integrating the intensity in the image (extracting background)
- Many measurements are required (uncertainty goes with the inverse square root of the number of samples)





The OTR based tool for the IFUSP Microtron

- Preliminary measurements indicates a fluctuation of the OTR intensity;
- Calculating the bunch length it is found 3,1 ps (2.6º).
- Simulations of the linac injector with the PARMELA code indicates a bunch length in the linac exit of 2º.



Conclusions

Conclusions

- OTR based diagnostic devices are very versatile
- Allow the measurement of many beam characteristics in a single point
- Very high resolution measurements can be achieved
- Time-resolved measurements can be performed
- Construction is relatively simple
- Can be used in low energies with restrictions of applicability
- The actual transverse charge distribution can be obtained

Acknowledgements

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Dr. Marcos Martins (advisor)
Dr. Vito Vanin (LAL director)
Dr. Paulo Pascholati
Ms. Cristiane Jahnke

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Dr. Marcel Dupret (LAMFI-IFUSP)

Optical filter

Dr. Marcelo Martineli (LMCAL-IFUSP)

Financial support: FAPESP CNPq