Examples to Electron Sources

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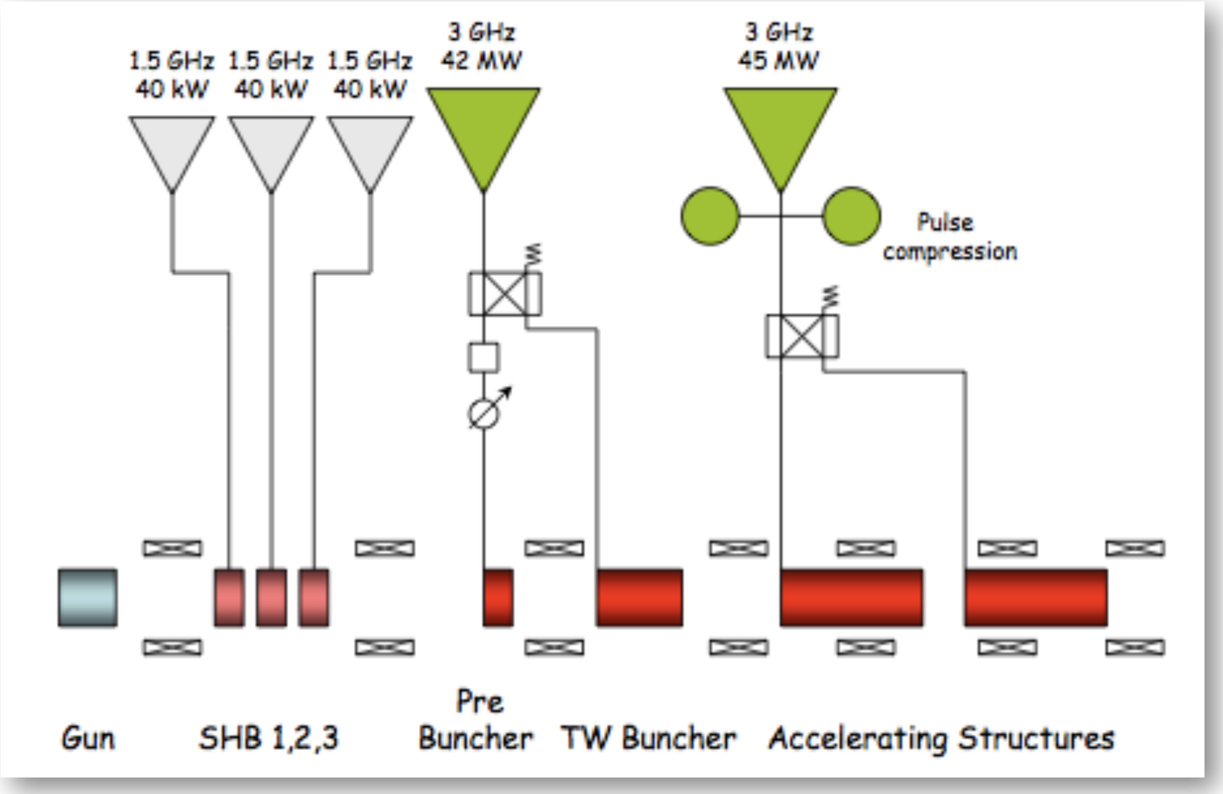
Contents

- **Alternative technologies:** “pro et contra”
  - Historical, thermionic source;
  - Modern, laser-driven RF systems (aka photoinjector);
  - Conservative, thermionic RF systems.
- **Instrumentation (for a Photoinjector)**
- **Some examples from real life observables**
- **Conclusions and outlook**

Contents

Alternative Technologies 1: Thermionic Sources

The existing thermionic gun for the CLIC Test Facility 3



- The continuous 1.6 μs long drive beam pulse is generated by a thermionic gun,
- then, time structure is produced by
  - three 1.5 GHz sub-harmonic bunchers
  - a S-band pre-buncher
  - a traveling wave buncher
- beam proceeds to two accelerating sections.

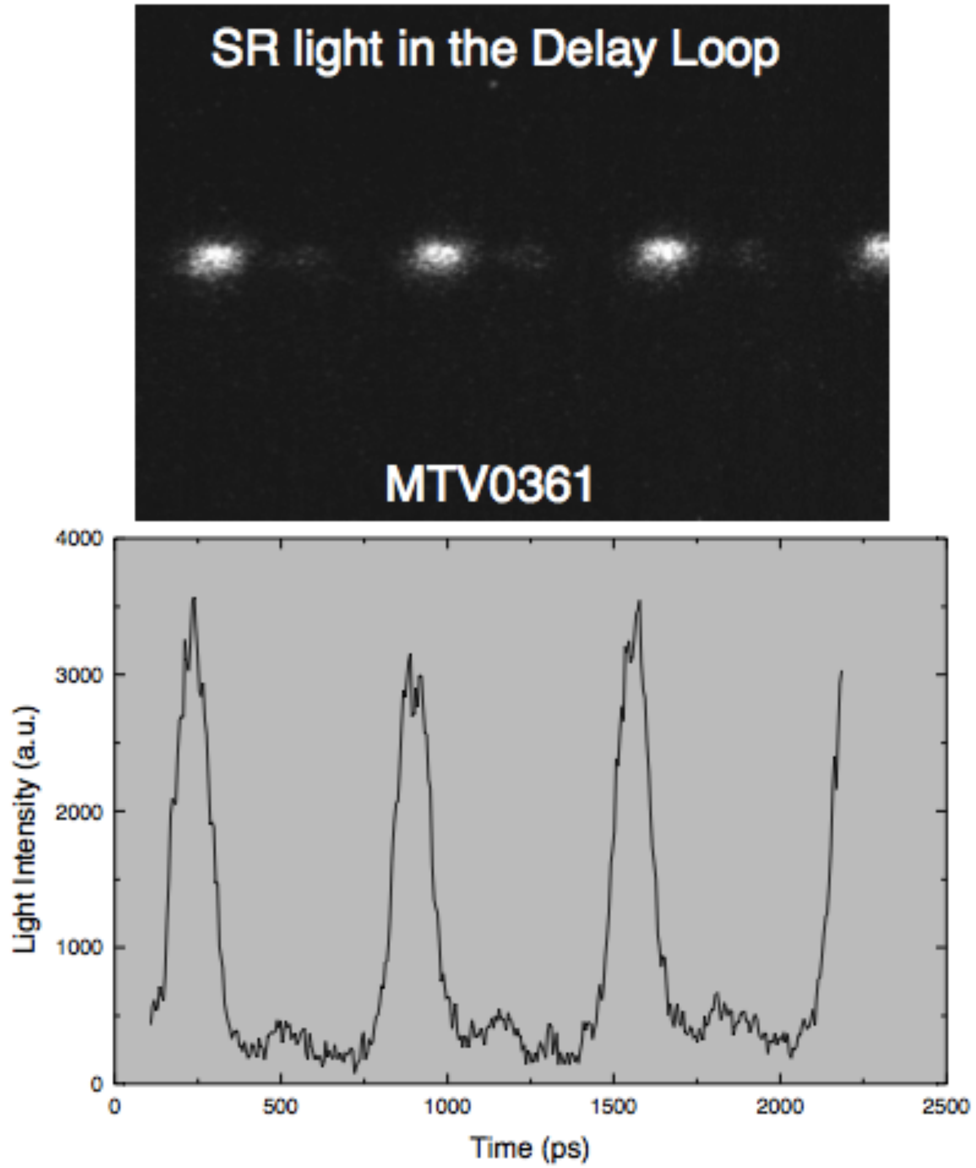
Alternative Technologies 1: Thermionic Sources

The existing thermionic gun for the CLIC Test Facility 3

Parameter	Specification
Energy [MeV]	20
Current [A]	3.5
Pulse Train Duration [µs]	1.6
Number of Bunches / Train	2310
Bunch Separation [ns]	0.67
Bunch Length (FWHM) [ps]	8
Charge / Bunch [nC]	2.33
Energy Spread (%)	<1
Normalized Emittance [mm mrad]	<25

Alternative Technologies 1: Thermionic Sources

The existing thermionic gun for the CLIC Test Facility 3



Problem, Parasitic Charge (Satellite Bunches)

Streak camera measurements can reveal the parasitic charge.

- 7-8% parasitic charge (satellite bunches) due to the sub-harmonic bunchers.
- The charge inside the satellite bunches is unusable for the rest of the operation,
- Disturbs the acceleration of the main beam.
- Compactness, flexibility, stability?

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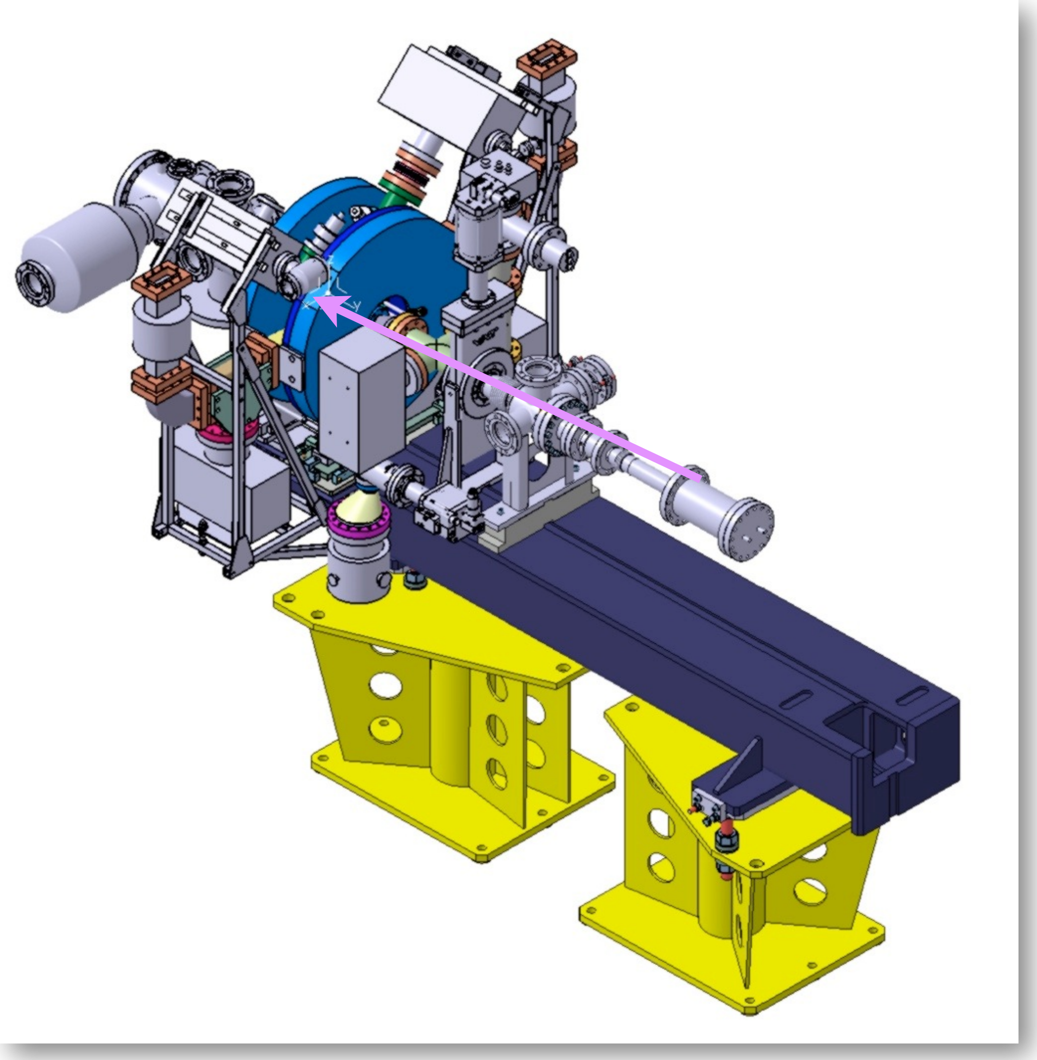
Alternative Technologies 2: Laser Driven RF Systems

- A photoinjector with the specifications of CTF3 thermionic gun.
- The project is in the framework of the “Coordinated Accelerator Research in Europe (CARE)” program.



- A photoinjector is an electron source that uses **laser** pulses in order to extract electrons from the surface of a metallic or semiconductor **cathode** by using the **photoemission** process.
- The electron beam resembles the temporal structure of the laser beam therefore it is **a compact system** without any need for an additional bunching system.
- An **RF cavity** is used for rapid acceleration of the electrons after the emission.
- Solenoid magnets are placed in order to focus the space charge dominated beam and achieve the **emittance compensation**.

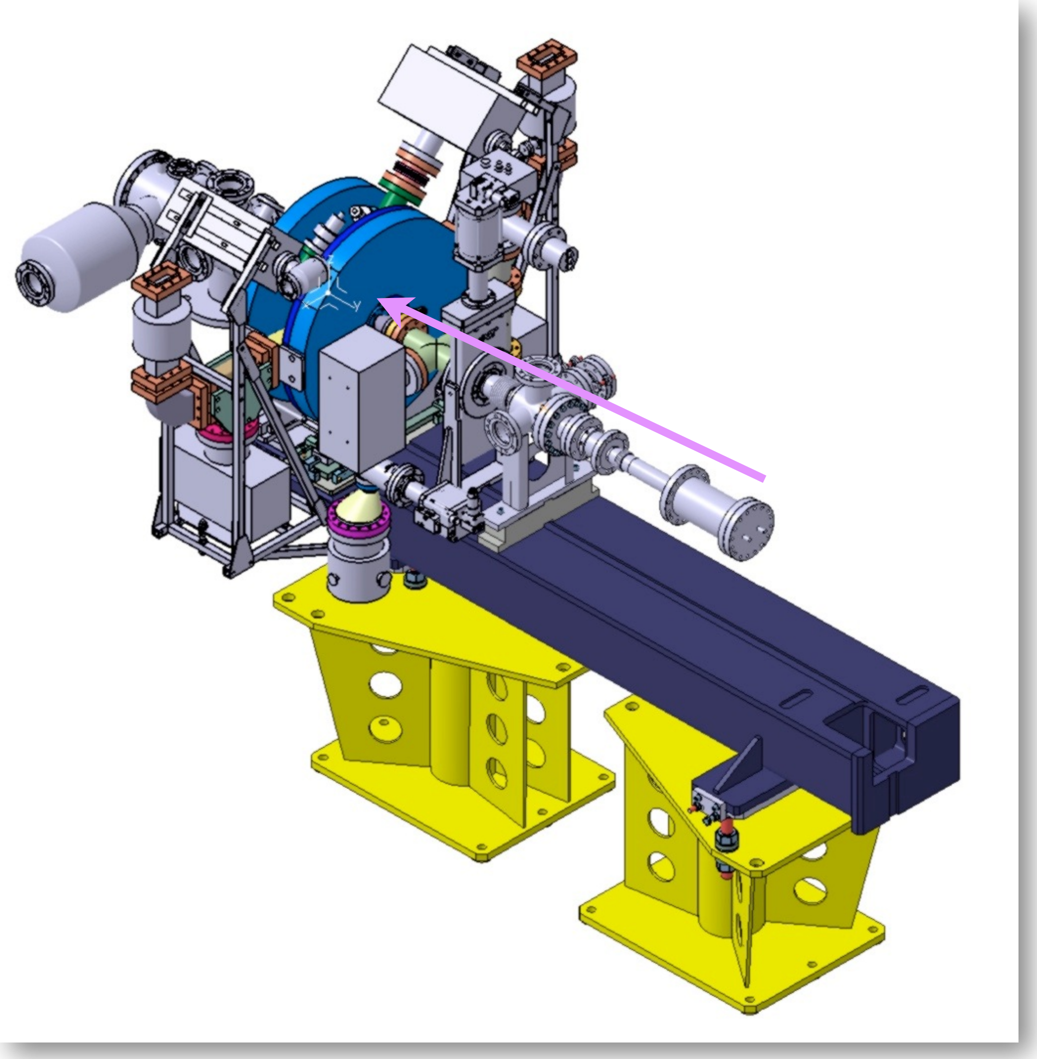
- A collaboration, “Laboratoire de l'Accélérateur Linéaire (LAL)” RF gun; “Rutherford Appleton Laboratory (RAL)” Laser; “European Organization for Nuclear Research (CERN)” Photocathode production, Overall coordination, Commissioning.

Alternative Technologies 2: Laser Driven RF Systems

Research objectives

- Comprehensive **simulations** for the PHIN photoinjector beam dynamics,
- Optimization of the **working point** providing the specifications,
- Full **experimental characterization** of the PHIN beam for short and long pulse trains,
- Development of a **single shot emittance measurement system** for space charge dominated beams,
- To measure the beam properties and their **stability along the bunch train** (time-resolved measurements),
- To compare the measurement results with the simulations,
- Eventually, to study the consequences of the findings to constitute a **preliminary RF gun design for CLIC-DB injector**.

Alternative Technologies 2: Laser Driven RF Systems

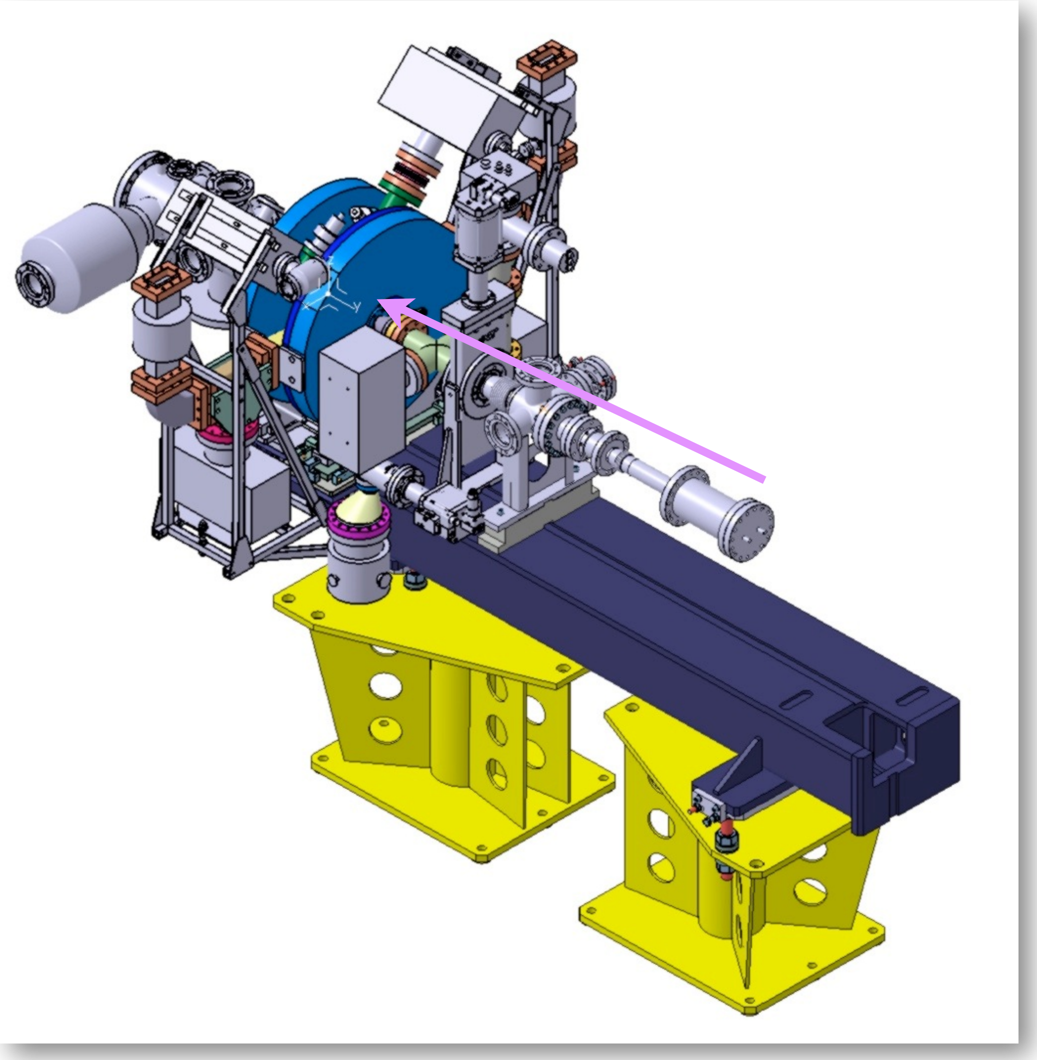


- The basic concepts and the implementation of the photoinjector date back to 1980s. But, ***the PHIN photoinjector is novel due to the following reasons:***

- high charge specification of 2.33 nC
- 1.2 μs long pulse train generation with 1908 bunches,
- challenging stability requirements: amplitude (charge) stability requirement of 0.25%,

Alternative Technologies 2: Laser Driven RF Systems

A practical model for the optimization studies, C. Travier's Model



- **Production of the specified charge value, transmission,**
  - The nominal laser spot size,
  - Maximum achievable gradient,
  - The emission phase of the particles with respect to the RF field,
- **Compromise between minimum emittance and minimum energy spread,**
  - The proper beam focusing for the emittance compensation,
- **Eventually, determination of a working point for a particular set of specifications.**

Alternative Technologies 2: Laser Driven RF Systems

What can you get from a PHIN type photoinjector?

Parameter	Specification	Achieved
RF		
RF Gradient (MV/m)	85	85
RF Frequency (GHz)	2.99855	2.99855
Electron Beam		
Charge per Bunch (nC)	2.33	4.4
Charge per Train (nC)	4446	5800
Train Length (ns)	1273	1300
Number of Bunches/Train	1908	1950
Current (A)	3.5	6.6
Normalized Emittance (mm mrad)	<25	14
Energy (MeV)	5.5	5.5
Energy Spread (%)	≤1	0.7
Laser and Cathode		
Charge Stability (%)	<0.25	0.8-2.4
Cathode	Cs_2Te	Cs_2Te
Quantum Efficiency (%)	3	18 (peak)
UV Laser Energy / Pulse (nJ)	370	400
Micropulse Repetition Rate (GHz)	1.5	1.5
Macropulse Repetition Rate (Hz)	1-5	1-5

- All the specifications have been **fulfilled** during the commissioning (except the charge stability)
- A **feedback stabilization** system is planned to be built for the laser intensity stability in order to improve the charge stability.
- **Correlation** between the electron beam, the laser and the RF pulse shape has been understood via the measurements along the pulse train.
- All measurement results can be **reproduced successfully by the single bunch simulations**.

Contents

Alternative Technologies 3: Thermionic RF Systems

Femtosecond electron bunches from an RF-gun

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Received 8 December 2003; received in revised form 3 May 2004; accepted 27 May 2004
Available online 29 July 2004

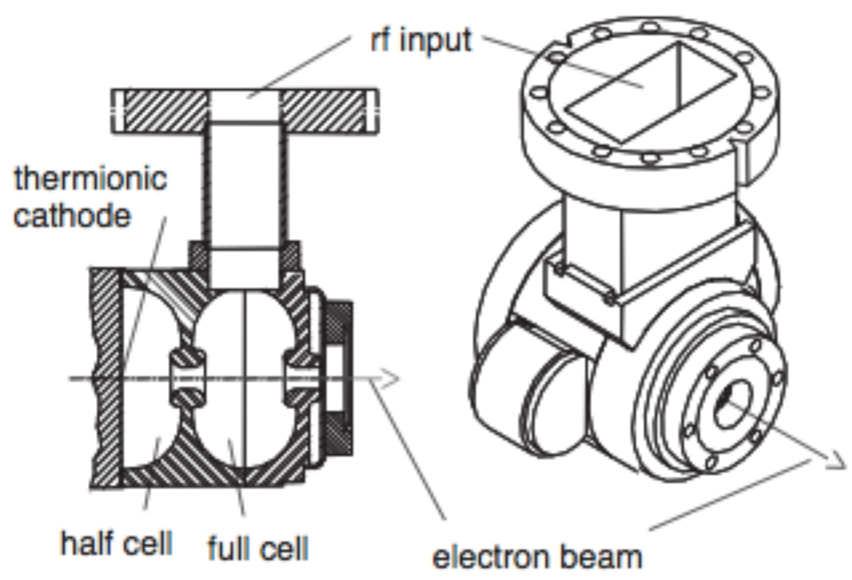


Fig. 1. RF-gun cross-section and 3D-view.

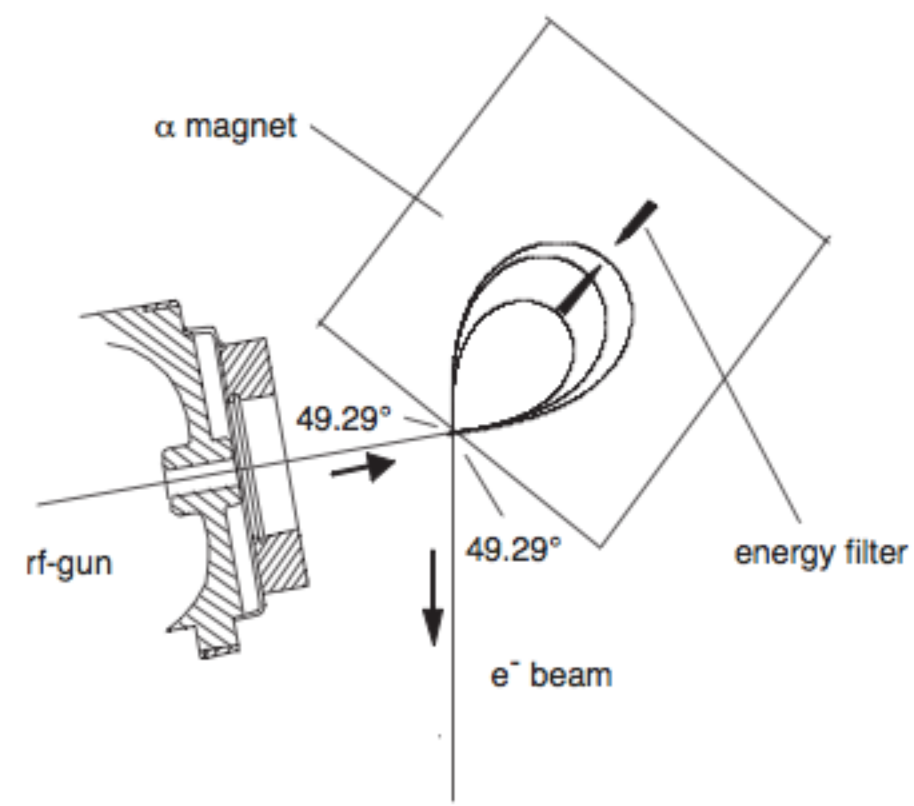
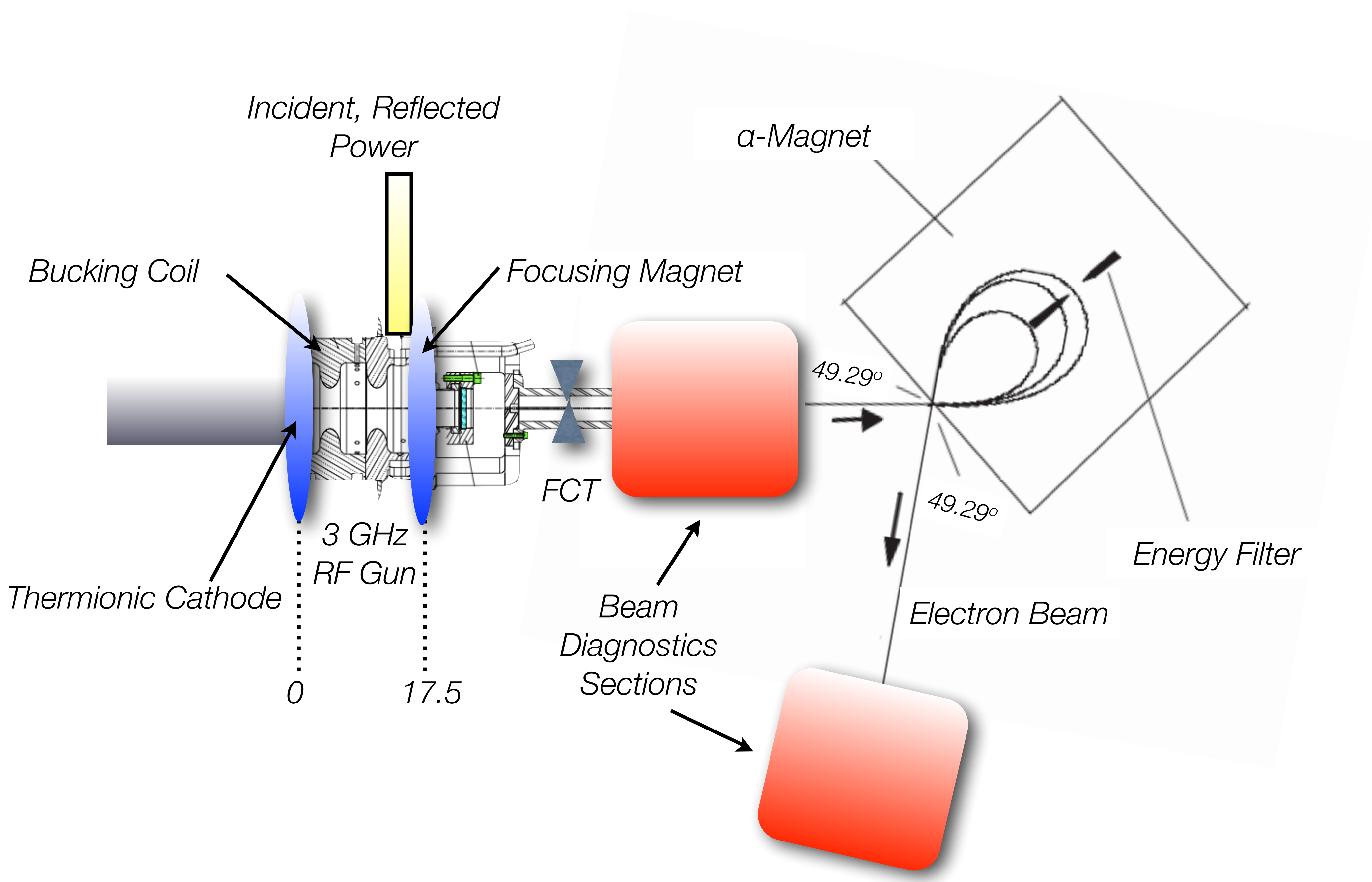


Fig. 3. Rf-gun and α-magnet layout (schematic).

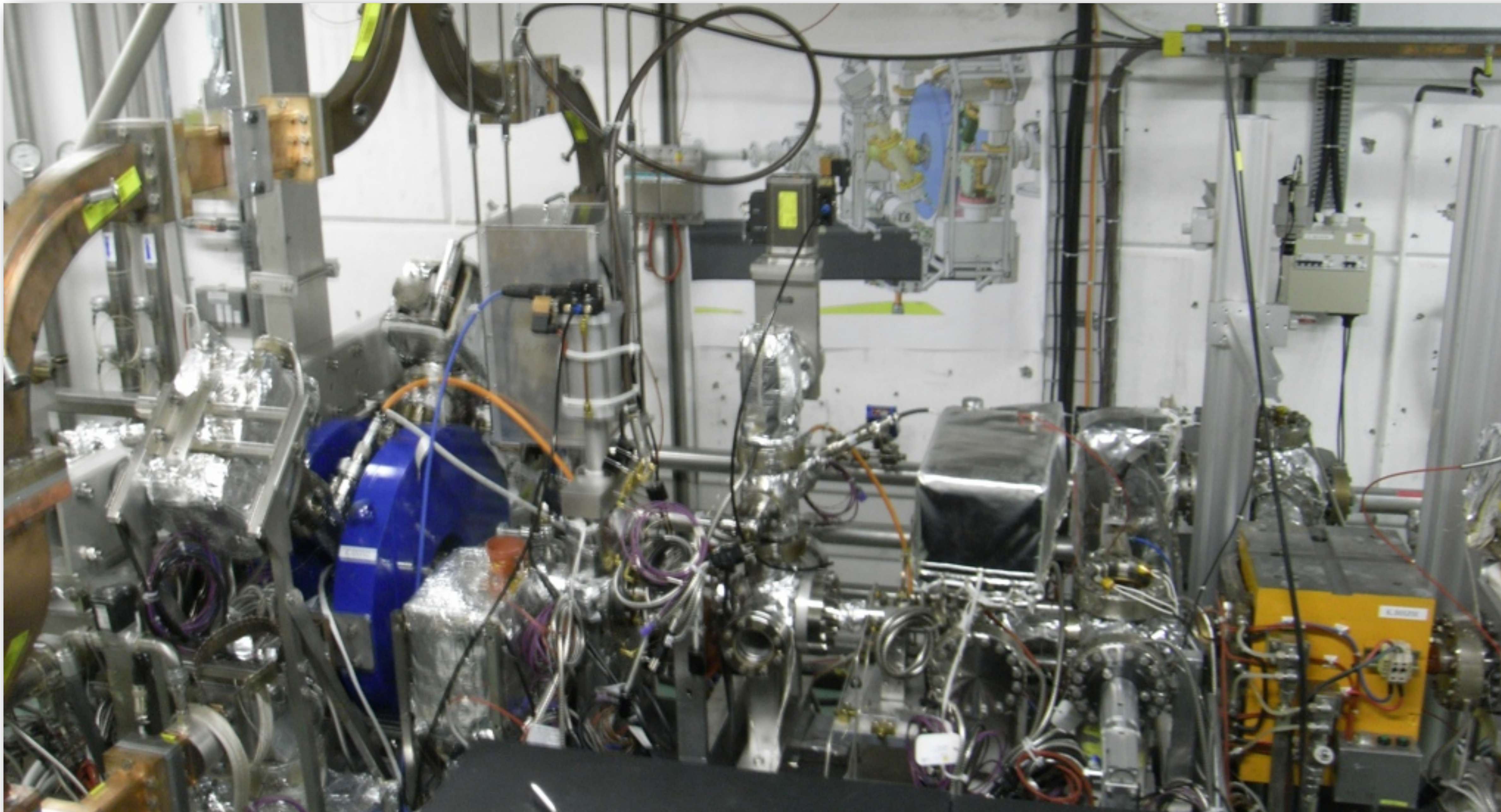
Nuclear Instruments and Methods in Physics Research A
533 (2004) 258–269

Alternative Technologies 3: Thermionic RF Systems

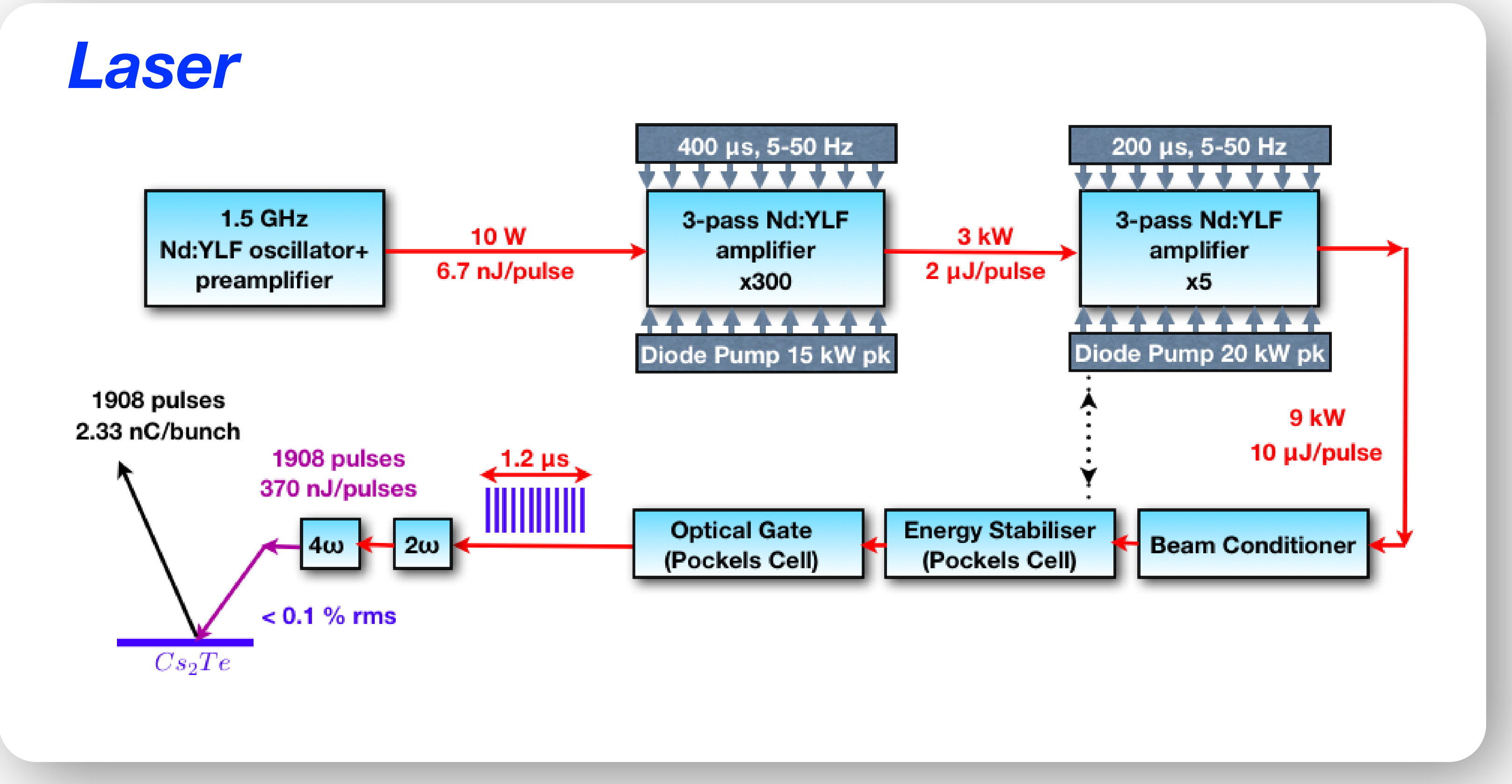


Contents

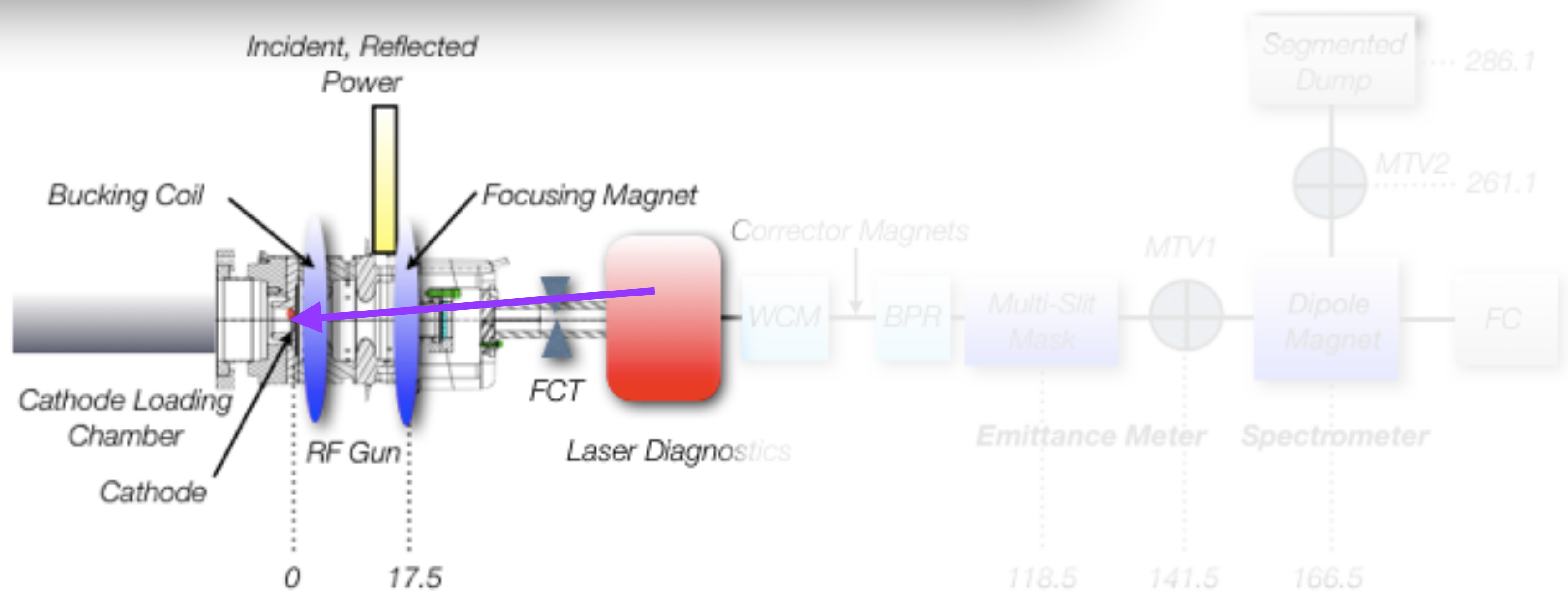
Instrumentation (for a Photoinjector)



Instrumentation (for a Photoinjector)

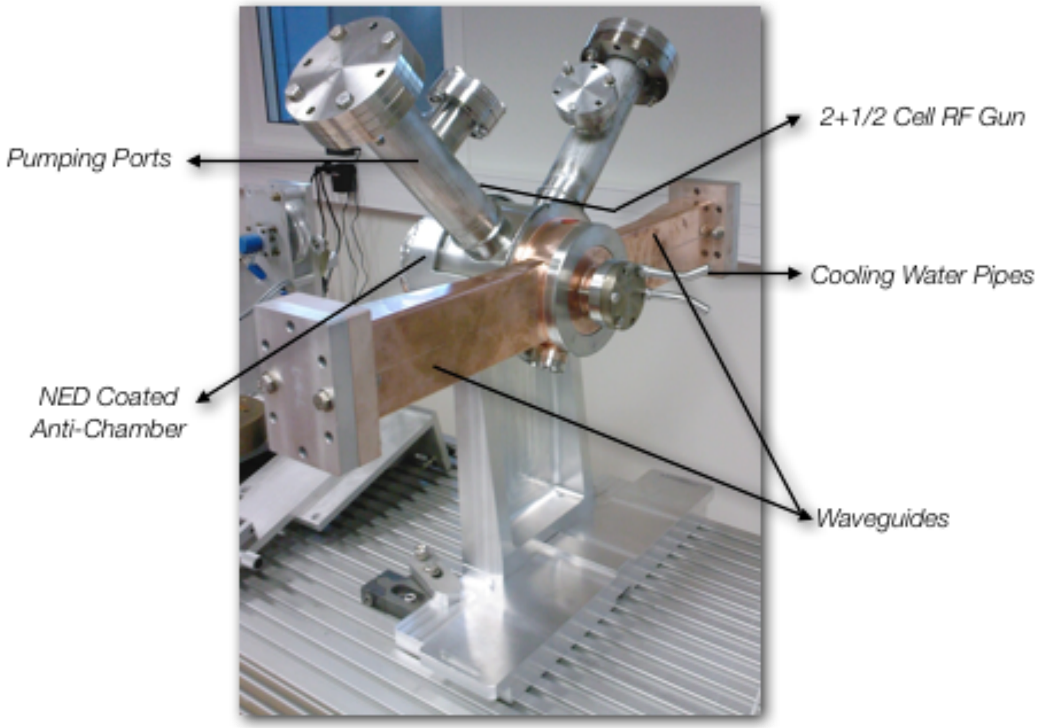


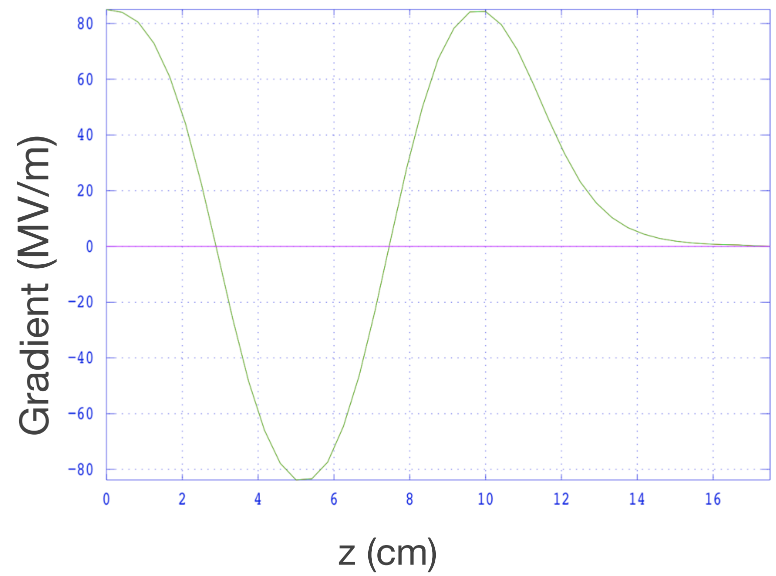
- Continuous pulses from Nd:YLF oscillator @ 1.5 GHz,
- Several amplification stages from 6.7 nJ to 370 nJ (after UV conversion) per pulse,
- Pulse train length adjustment to 1.2 µs by using Pockels cells
- UV conversion
- Illuminates a Cs_2Te cathode

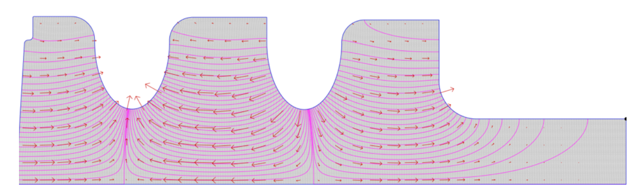


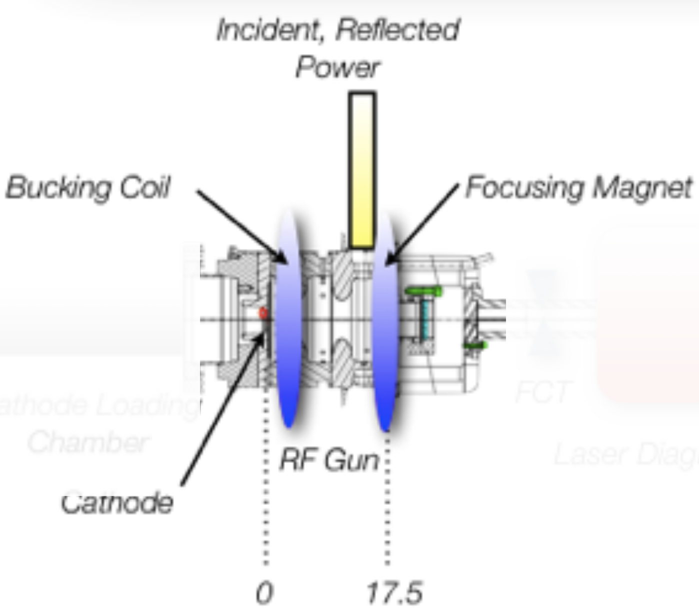
Instrumentation (for a Photoinjector)

RF Gun



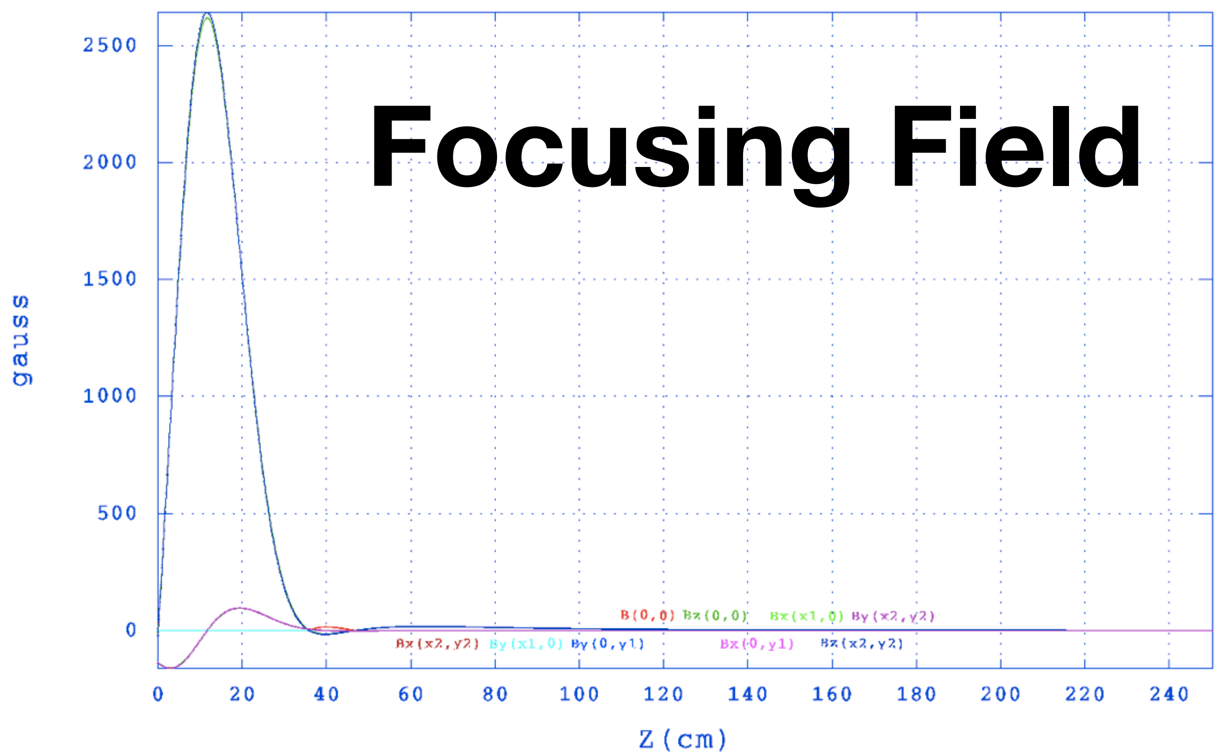


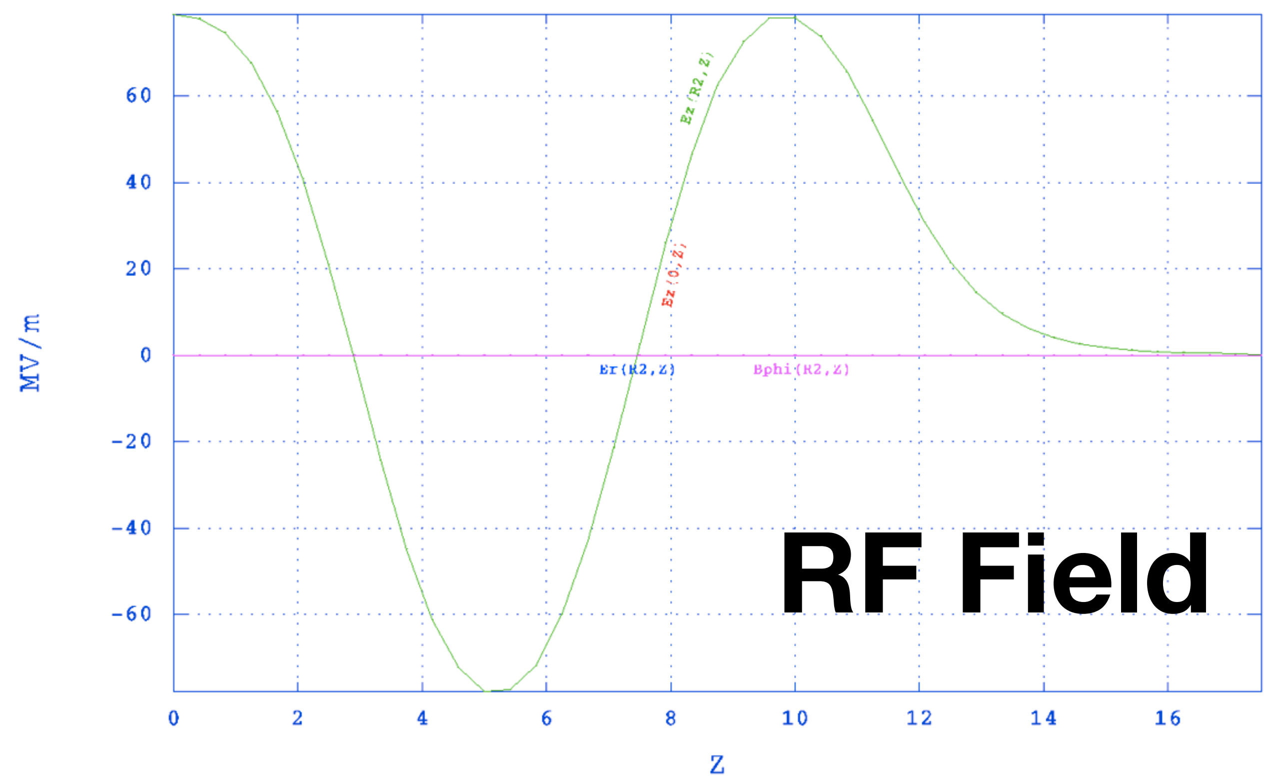


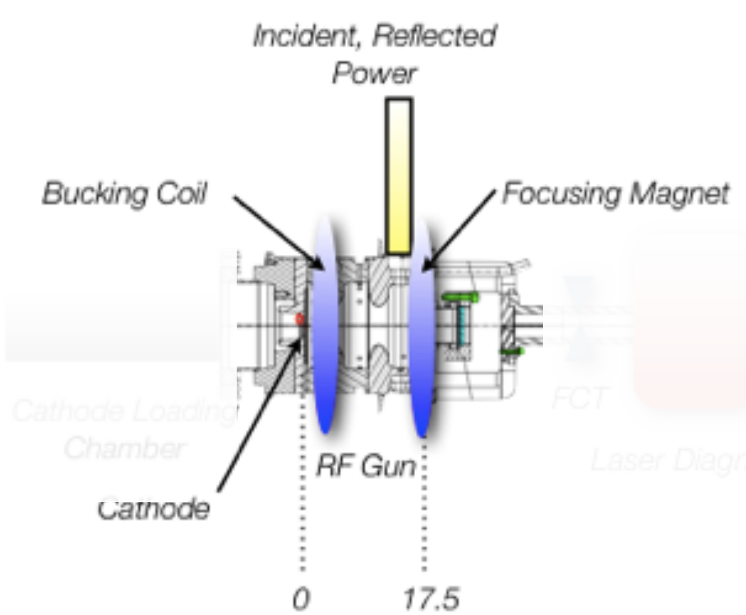


- Normal conducting 2+1/2 cell RF cavity
- Tuned to S-band (3GHz) in π-mode
- Acceleration under the gradient of 85 MV/m
- Simulations by using SUPERFISH
- The field map has been used for the beam dynamics simulations with PARMELA
- Optimized for high charge, low electrical breakdown and dark current (half cell wall angle, elliptical irises)
- Optimized for good dynamic vacuum as a necessity for high charge production (Non-Evaporable Getter, NEG, coating of anti-chamber)
- Two coils for the proper focusing of the beam.

Instrumentation (for a Photoinjector)



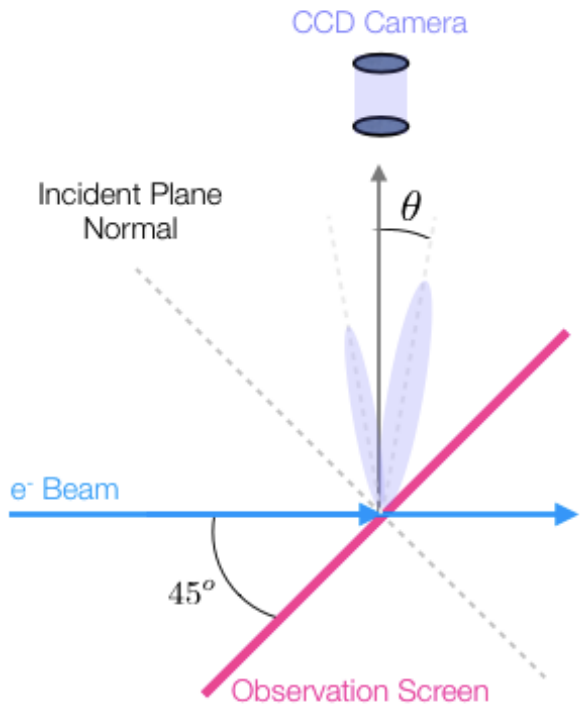




Field settings for the optimised horizontal emittance, injection and RF phases.

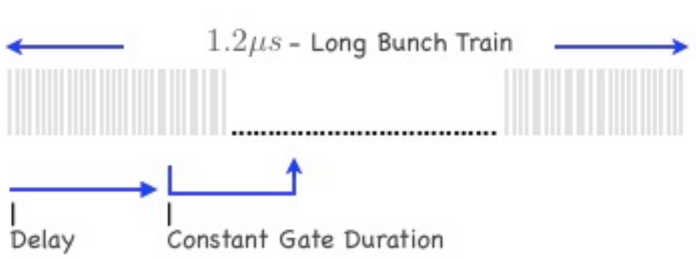
Instrumentation (for a Photoinjector)

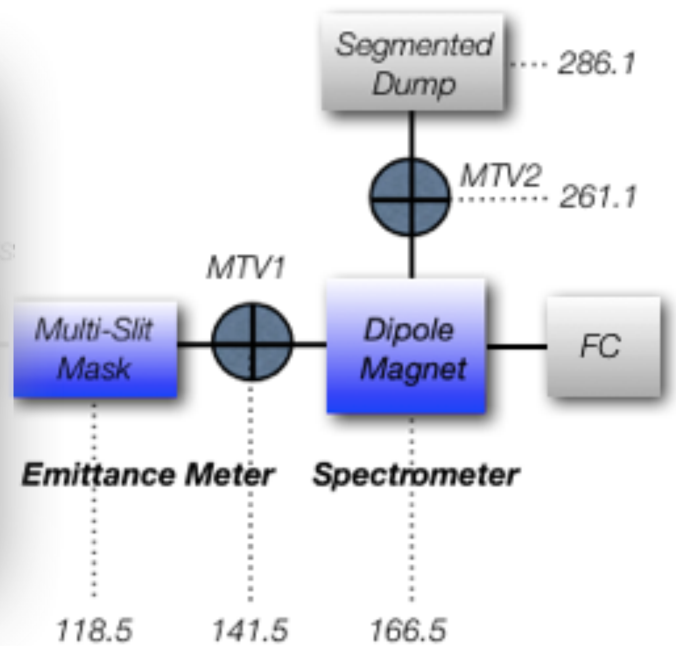
OTR Profiling



- Charged particles emit Optical Transition Radiation (OTR) while crossing a boundary with different dielectric properties.
- OTR is used to measure the beam profile as a diagnostics tool.
- In PHIN, two OTR monitors for emittance-meter (MTV1) and spectrometer (MTV2).
- OTR can be detected by a ICCD (Intensified Charge Coupled Device) camera,
- Gateability of ICCD is used for the time-resolved measurements.

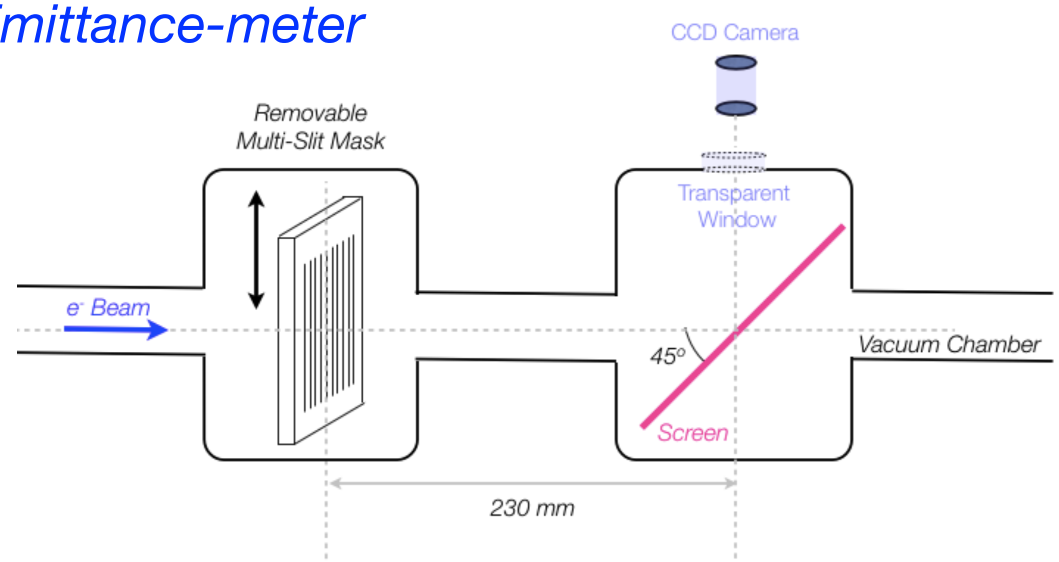
Time-Resolved OTR Profiling



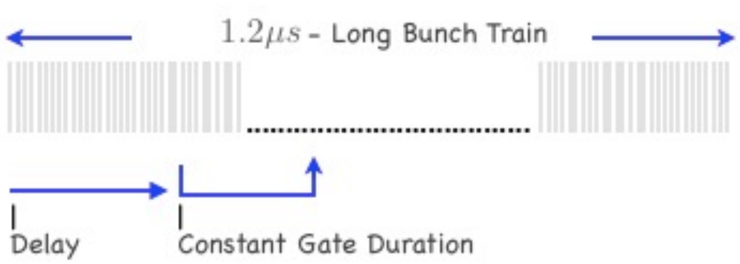


Instrumentation (for a Photoinjector)

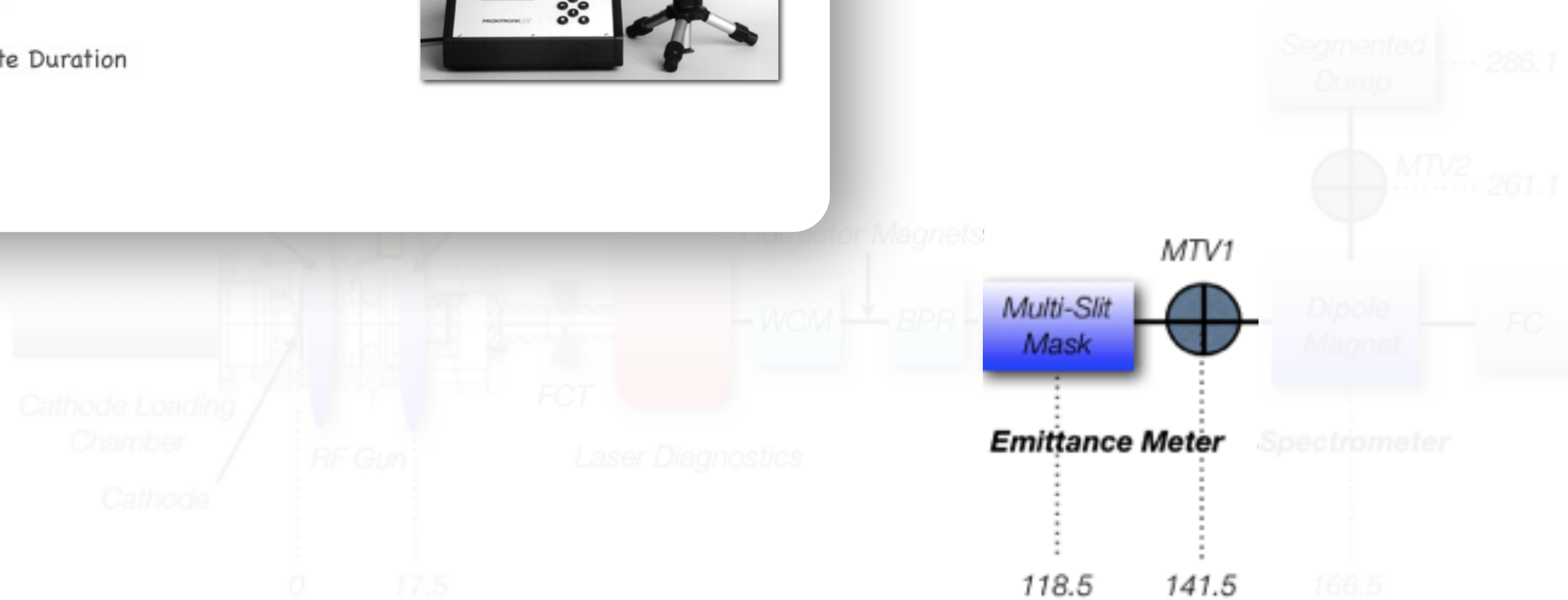
Emittance-meter



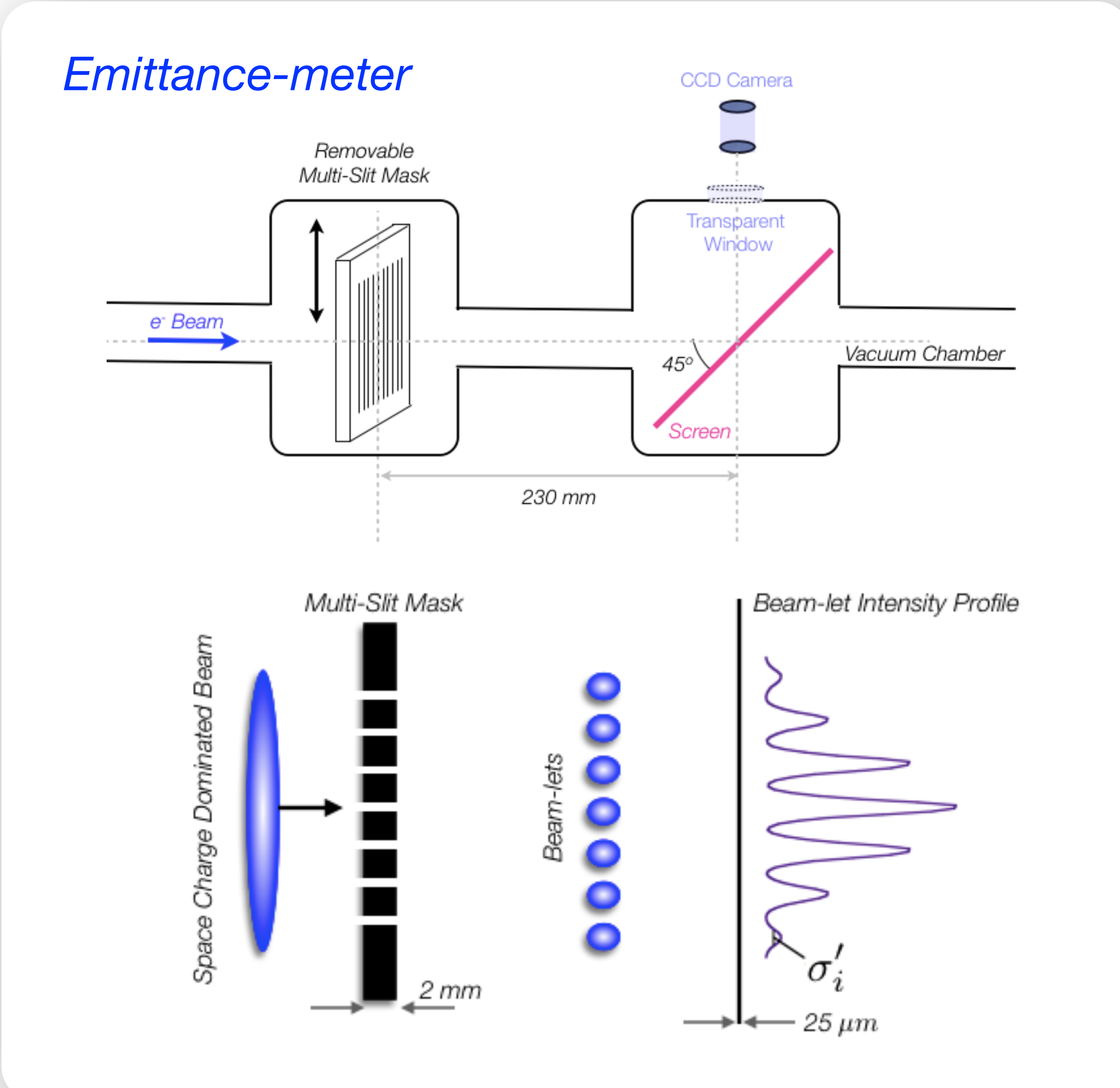
Time-Resolved OTR Profiling



- Transverse emittance has been measured by using **multi-slit (MS) method**.
- The MS method is suitable for **the space charge dominated low-energy beams**.
- Gateability of ICCD is used for the time-resolved measurements.



Instrumentation (for a Photoinjector)



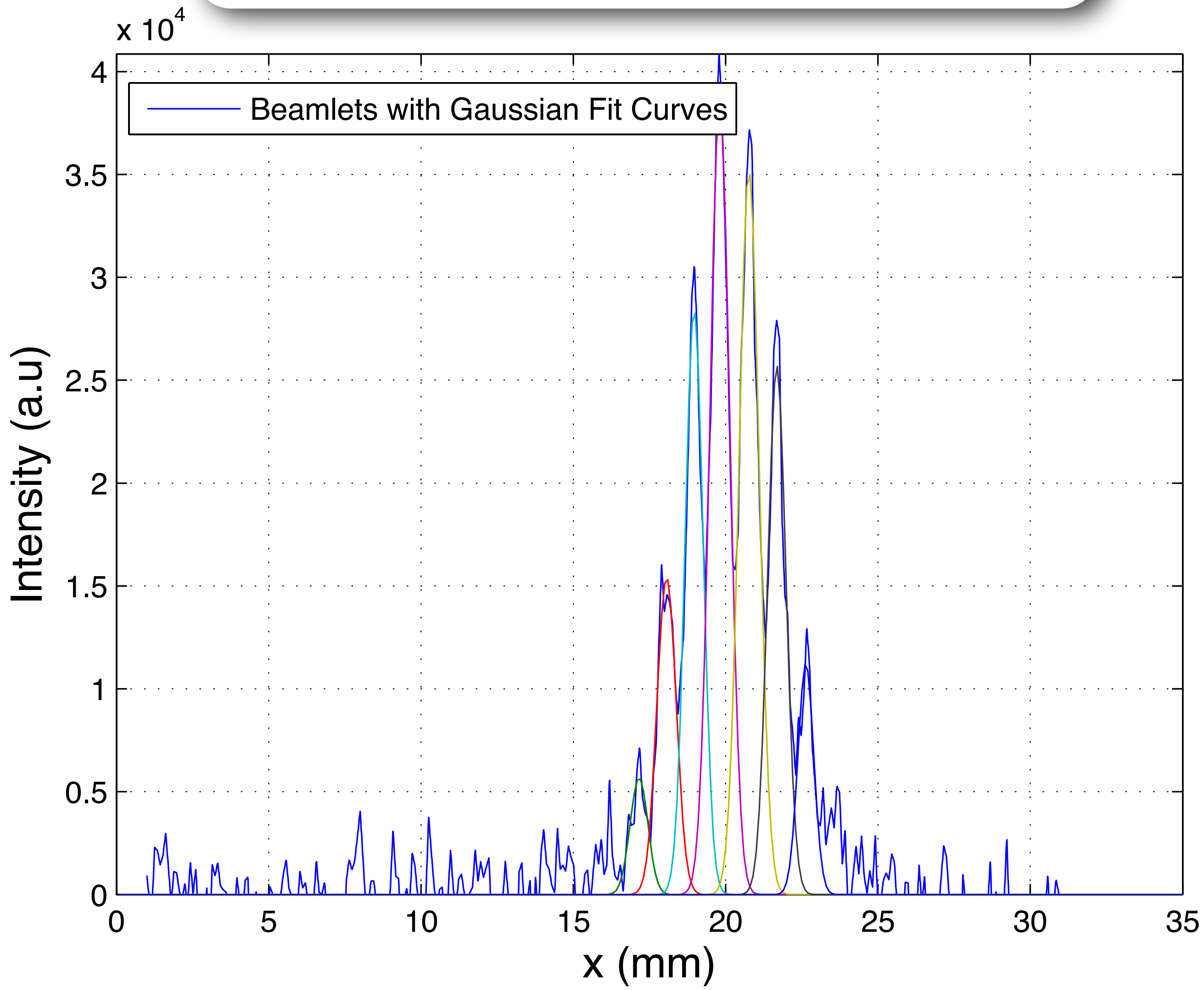
According to the MS method

- The MS mask is introduced in front of the beam,
- The beam is sliced into individual beamlets,
- The moments of the beamlets are determined from the beam profile,
- And the emittance of the former beam is calculated.
- Multi-slit method has been implemented for the first time at CERN during the PHIN commissioning studies.
- Research Outcome: Development of an analysis method and producing several algorithms by considering <u>different background (noise) patterns</u>.
- **PHINEMA**: **PHIN** photo-injector **E**mittance **M**easurement and **A**nalysis software

Instrumentation (for a Photoinjector)

ρ_i *, intensity of individual beamlets.*

$x_{i,c}$ *, mean positions of the beamlets.*



$x'_{i,c} = < x_i - iw > /L$ *, divergences of the beamlets*

σ'_i *, spread on the divergences.*

Emittance Calculation

The definition of the transverse geometric emittance.

$$\epsilon_x \equiv \sqrt{< x^2 >< x'^2 > - < xx' >^2}$$

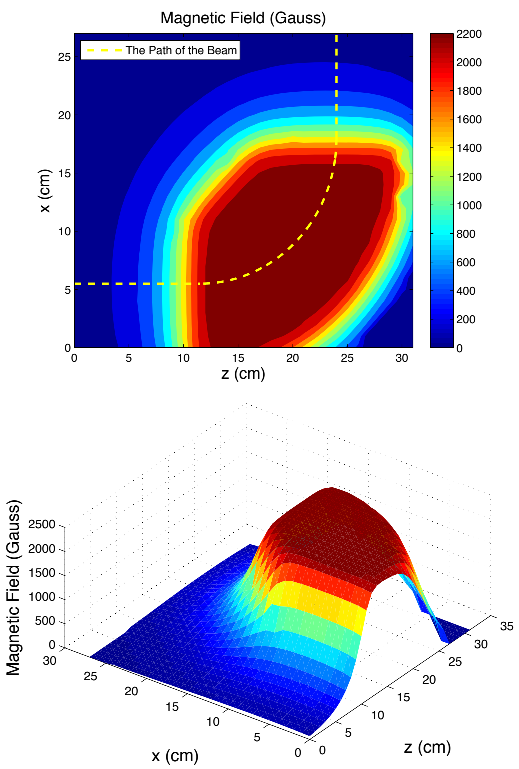
$$< x^2 >= \frac{\sum_{i=1}^{N} \rho_i x_{i,c}^2}{\sum_{i=1}^{N} \rho_i}$$

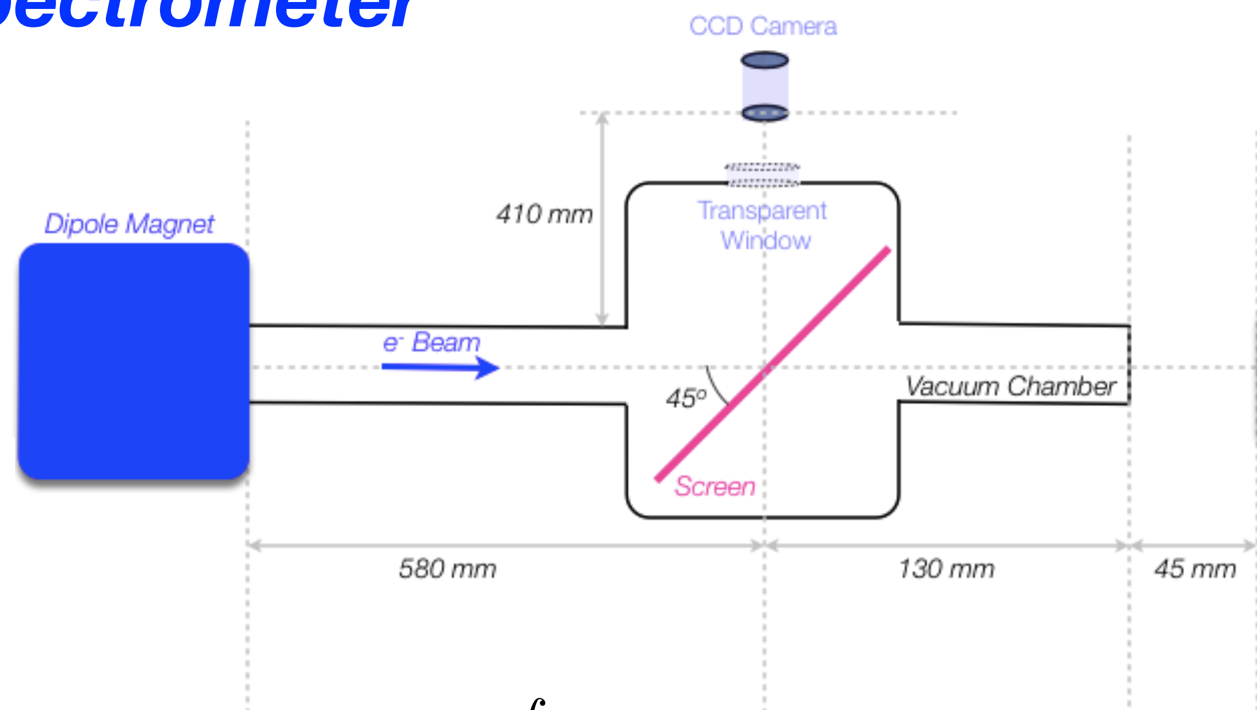
$$< x'^2 >= \frac{\sum_{i=1}^{N} \rho_i (x_{i,c}'^2 - \sigma_i'^2)}{\sum_{i=1}^{N} \rho_i}$$

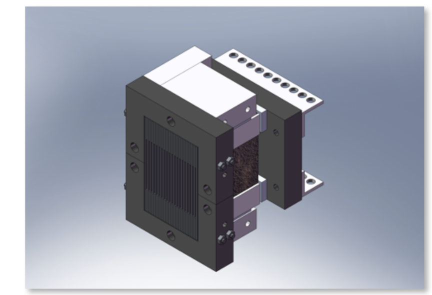
$$< xx' >= \frac{\sum_{i=1}^{N} \rho_i x_{i,c} x'_{i,c}}{\sum_{i=1}^{N} \rho_i}$$

Instrumentation (for a Photoinjector)

Magnetic Spectrometer

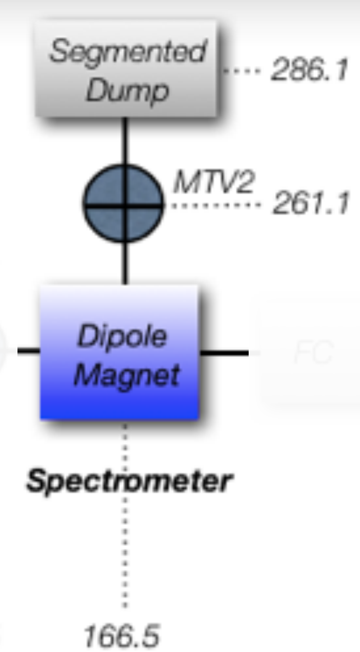






$$E = \frac{ec}{\alpha_{tot}} \int_{path} B_z ds$$

- A magnetic spectrometer has been used for the energy measurements.
- Principle: measurement of the beam momentum distribution after a dipole with a known magnetic field.
- Beam momentum distribution can be observed by using an OTR profile monitor or a segmented dump.



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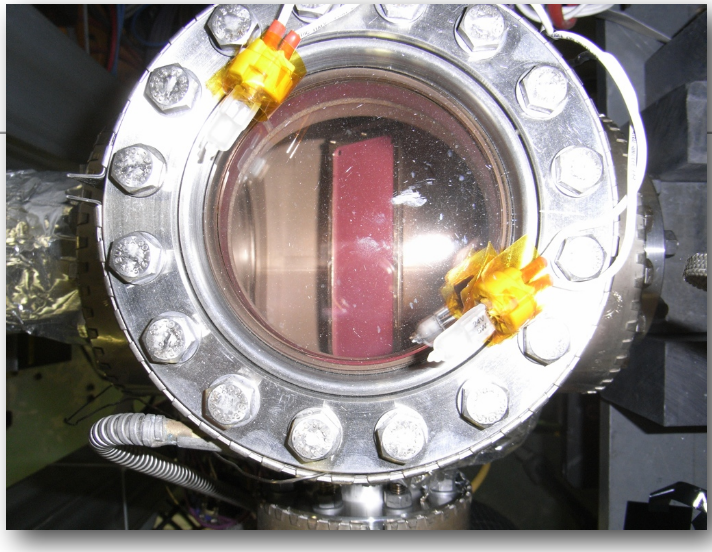
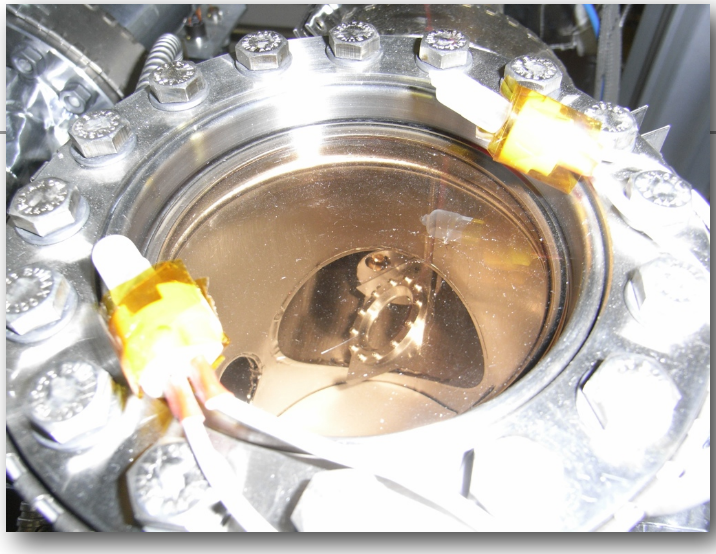




Possible Background Sources for OTR Measurements

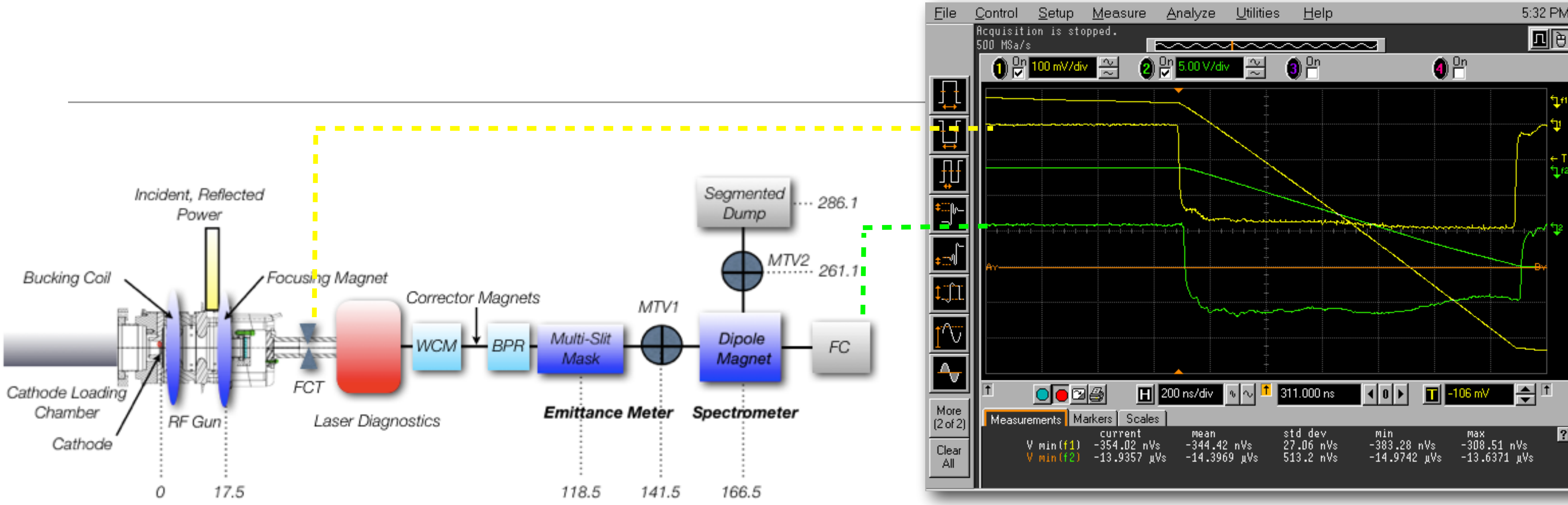
- the electrons that are not stopped by the slit-mask,
- the overlapping between the individual beamlets,
- x-rays
- external light pollution
- radiation due to the heating of the OTR screen

Possible Cure

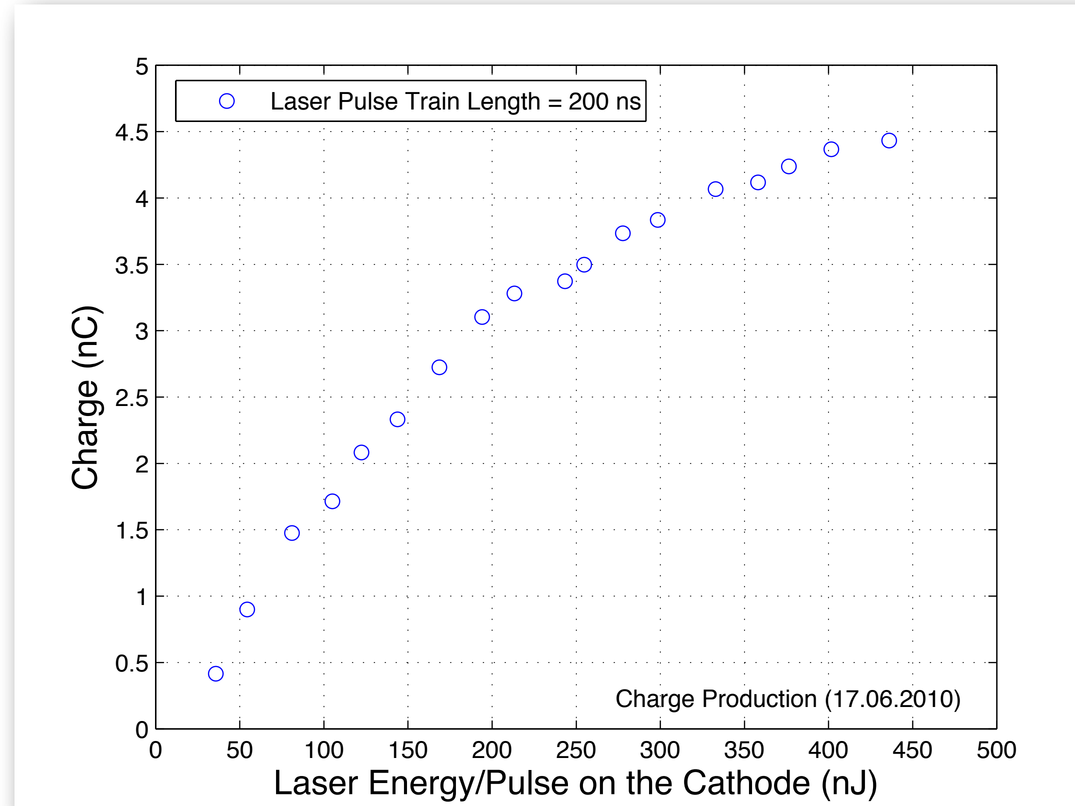
***First of all*, consider the intensity of the beam, gain and spectral sensitivity of the camera, type of the observation screen, always respect the signal/noise ratio.**

- thickness of the multi-slit mask,
- optimization of distance between the screen and the mask,
- shielding the camera properly,
- shielding or using a light-tight enclosure,
- offline treatment (usually the background has a Gaussian distribution in this case),

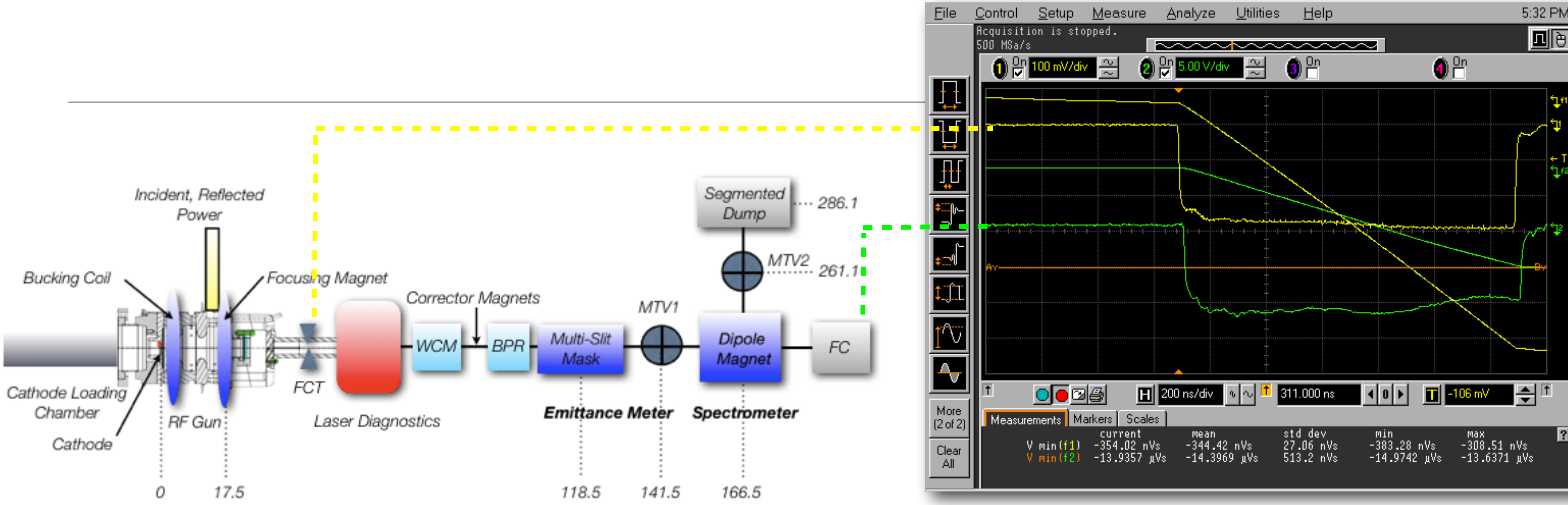
Instrumentation (for a Photoinjector)



- In the most of the charge measurements, the FCT has been preferred due to its location after the RF gun.
- Nevertheless, the FC is the most useful in order to study the charge transmission along the downstream of the beamline.
- In principle, the charge production saturates with the increasing laser energy per pulse.
- **The maximum achievable charge has been measured as 4.4 nC during the commissioning which even exceeds the specification.**



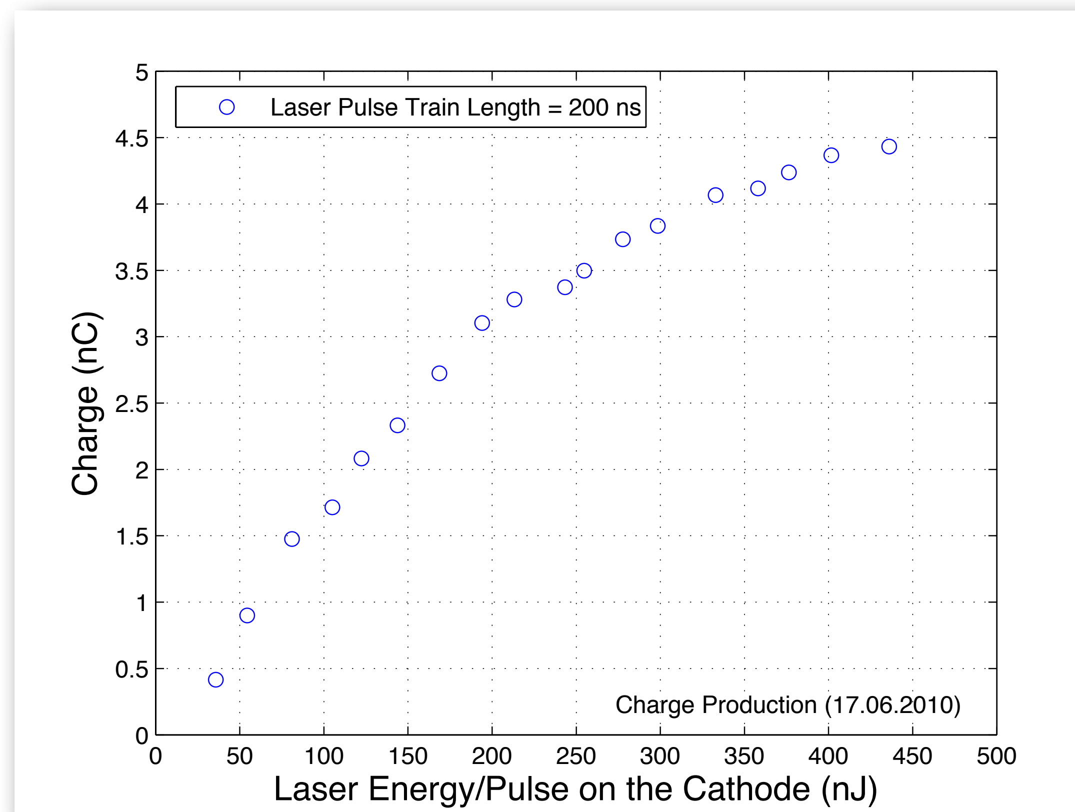
Instrumentation (for a Photoinjector)



Consistency with theoretical prediction.

$$Q_{max}[nC] = \frac{E_{acc}[MV/m]\sigma_x^2}{18} = \frac{85[MV/m](1[mm])^2}{18} = 4.7nC$$

- **The maximum achievable charge has been measured as 4.4 nC during the commissioning which even exceeds the specification.**



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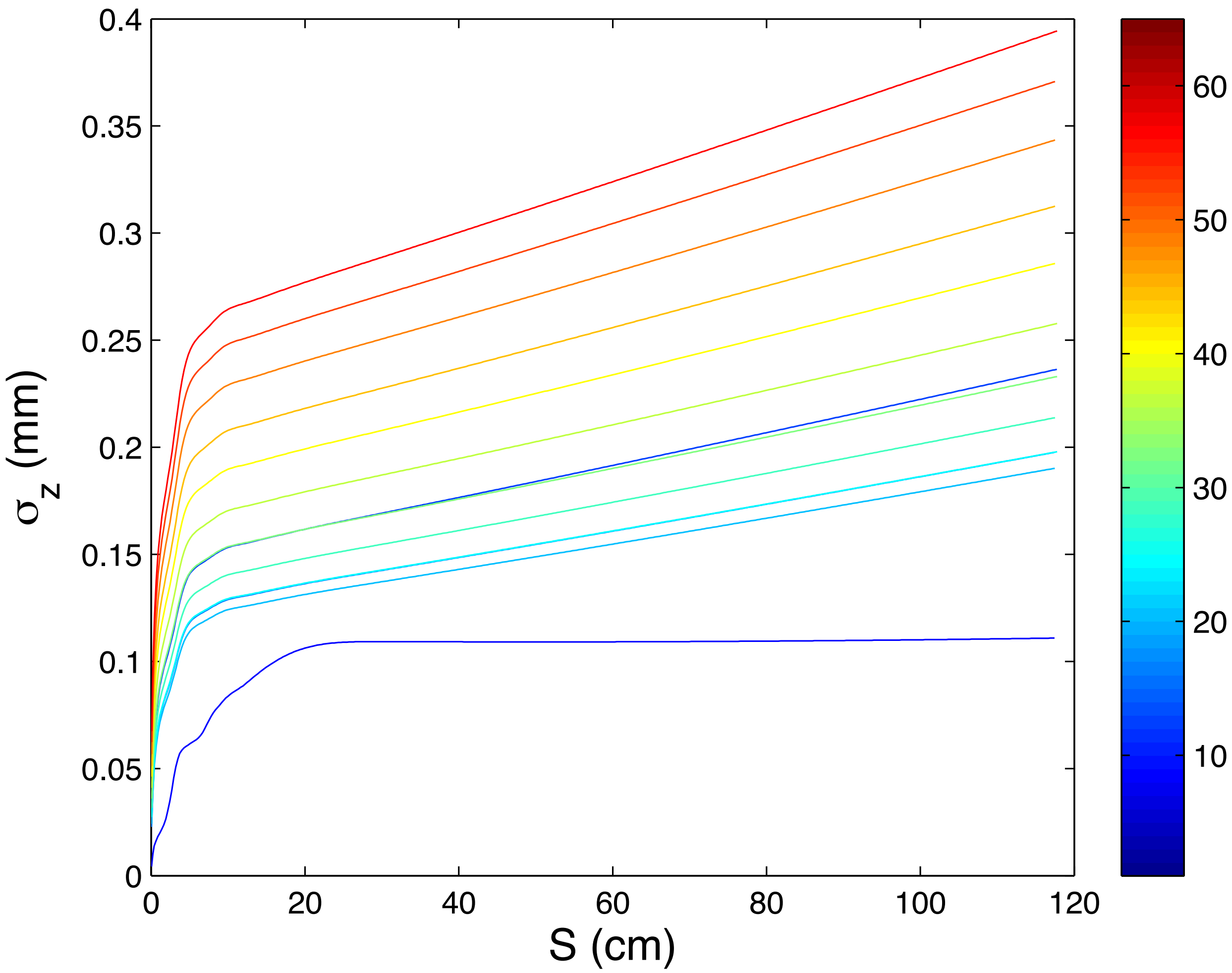
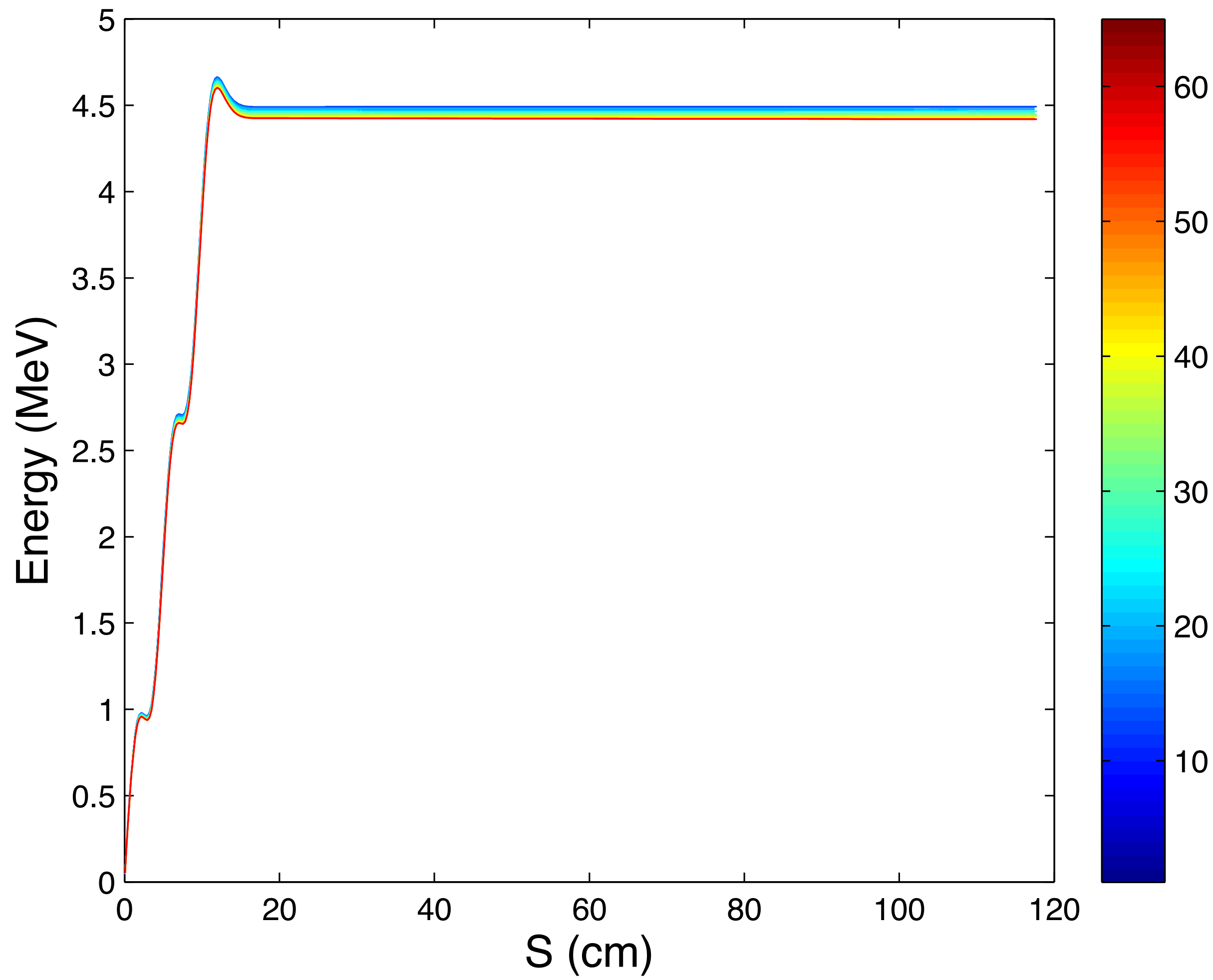
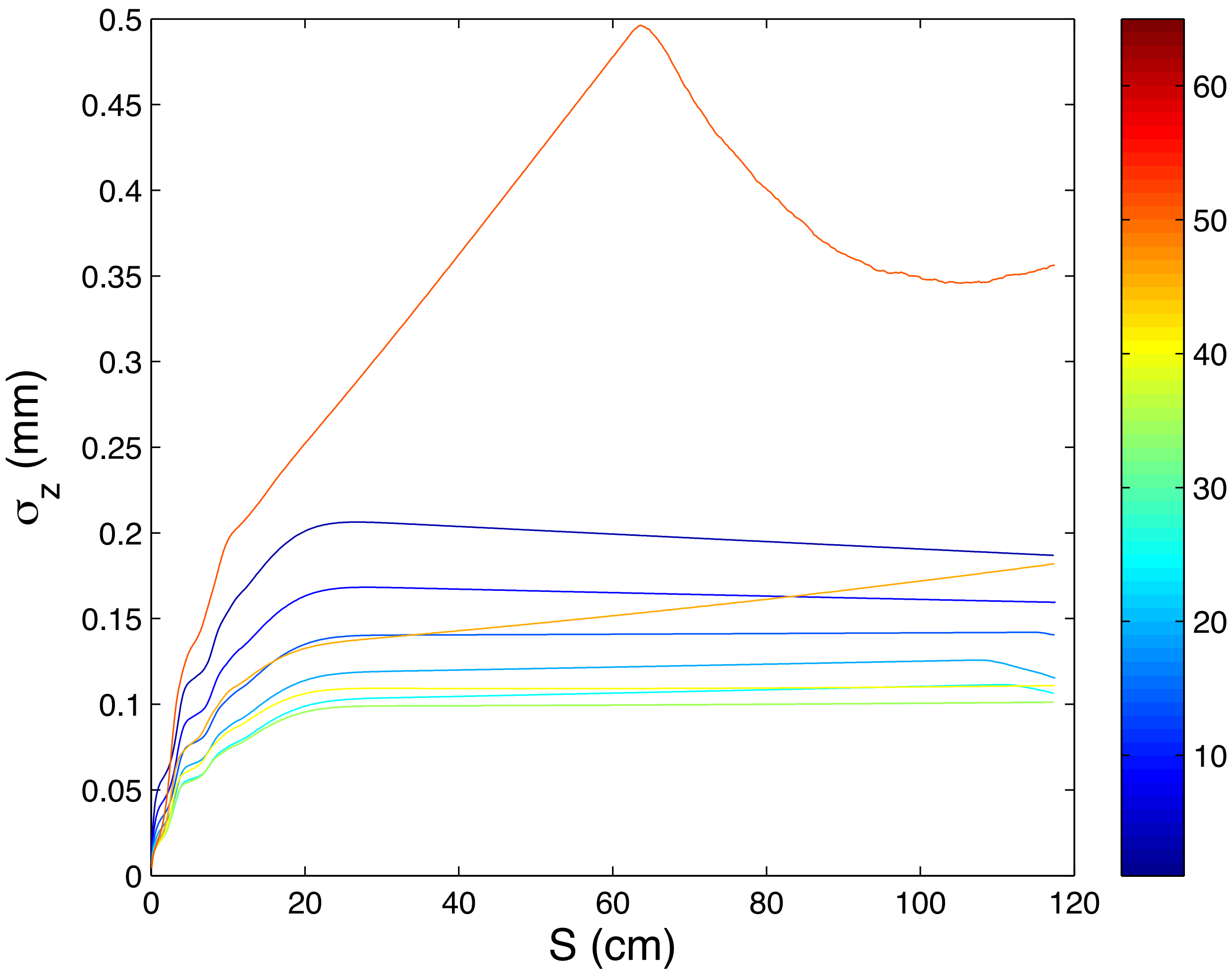
Some Examples to Real Life Observables

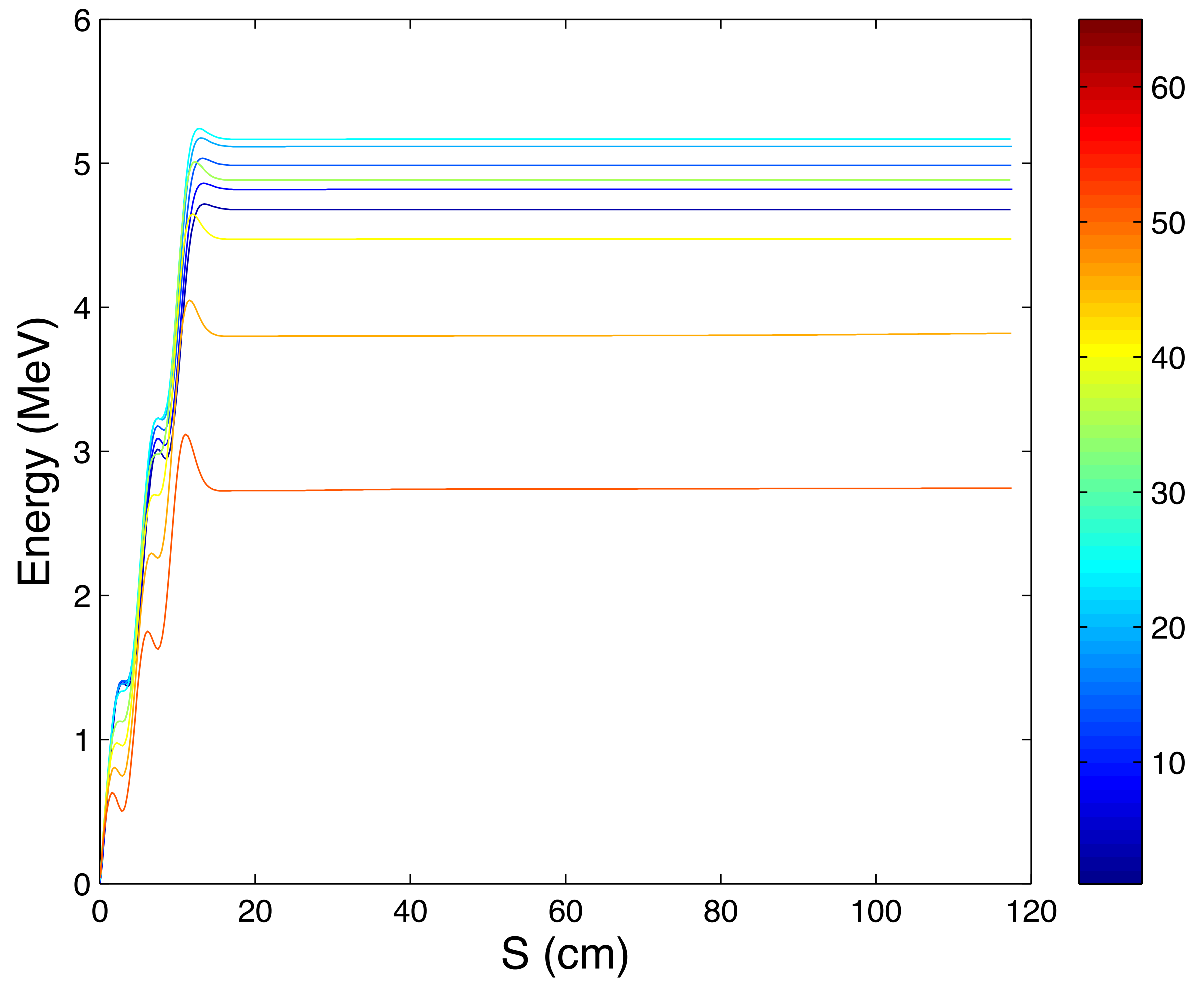




Scan: Particle phase 0-120^{o}

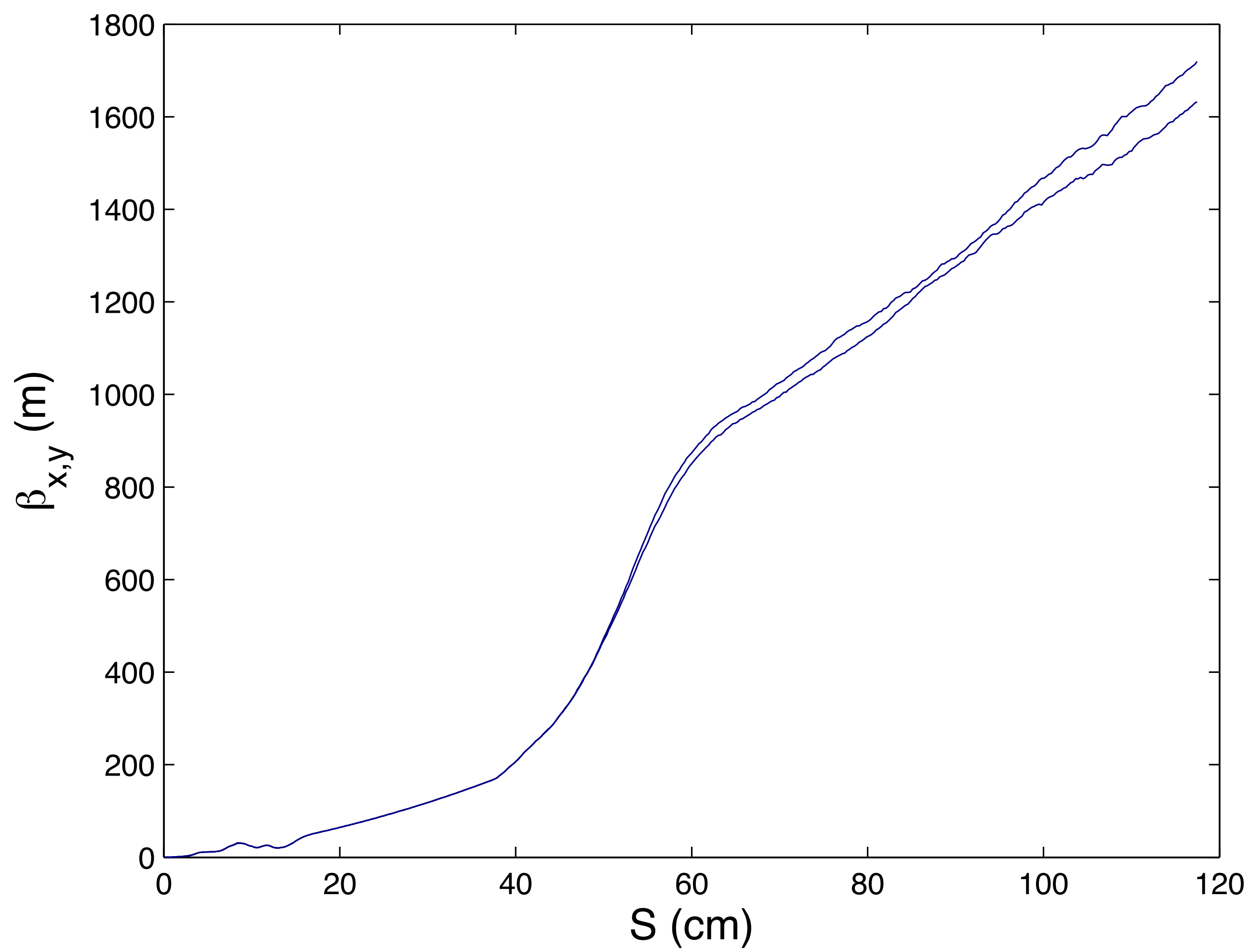
Some Examples to Real Life Observables

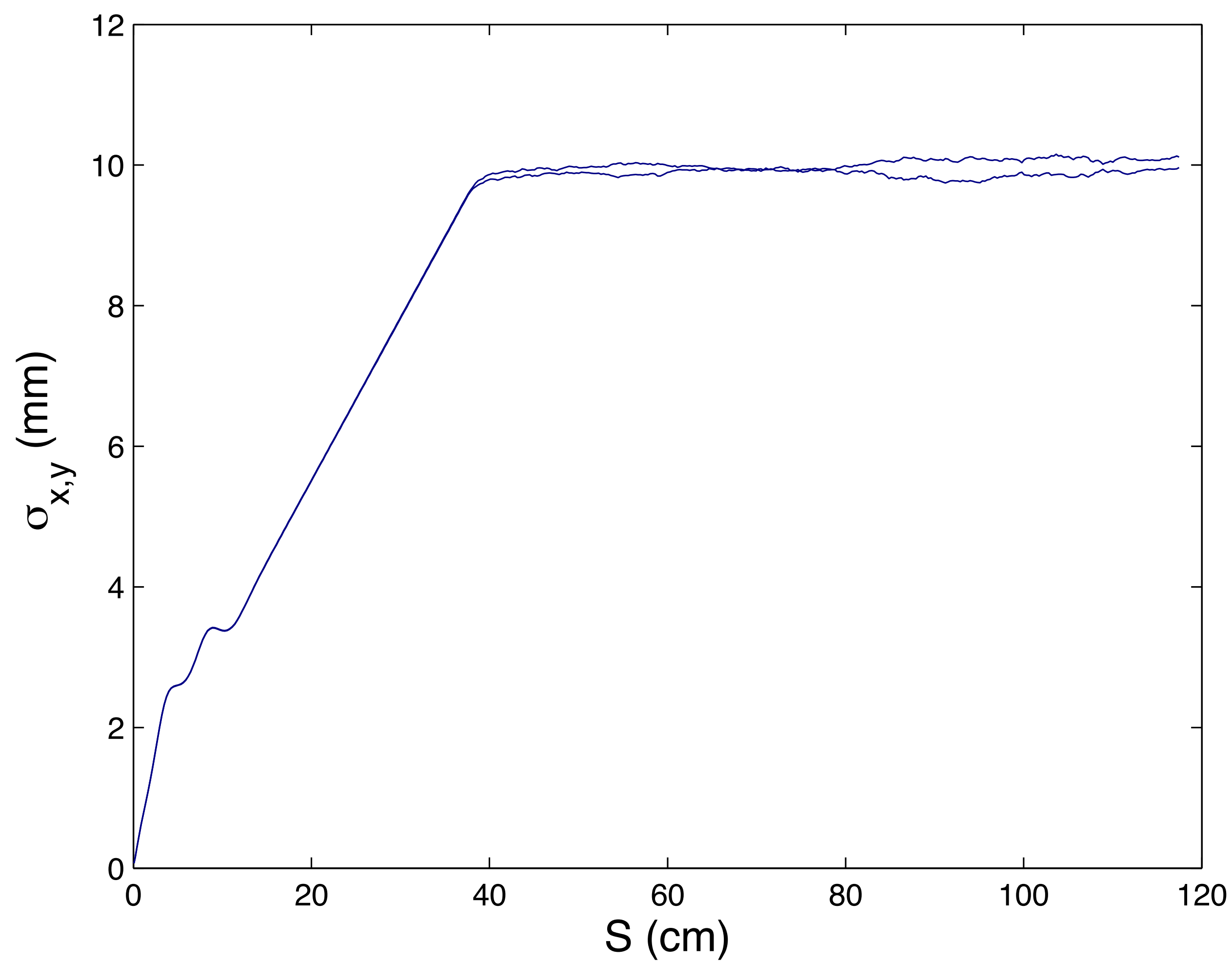




Scan: RF phase 10-100°

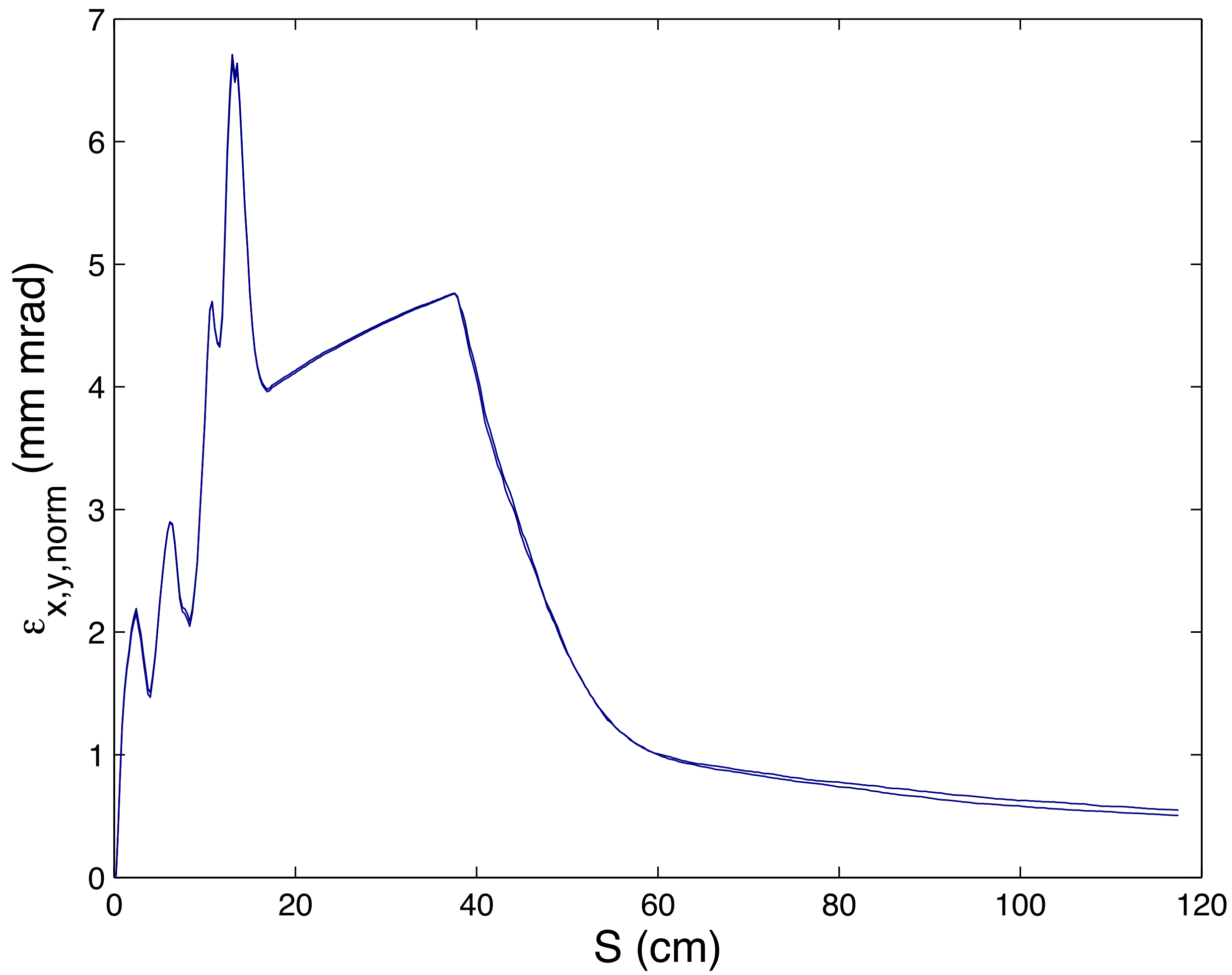
Some Examples to Real Life Observables

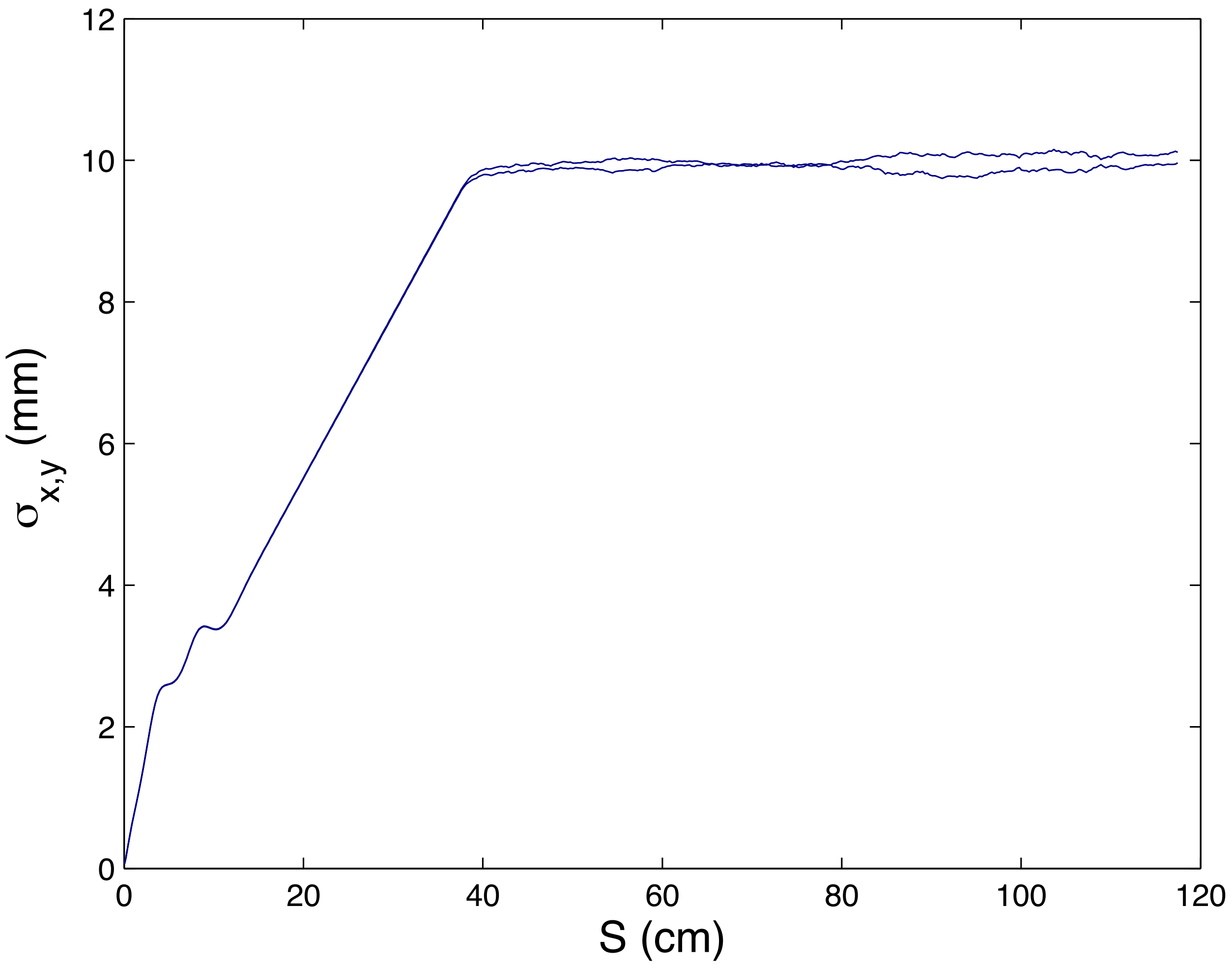




No focusing: Excessive particle loss ~30 cm.

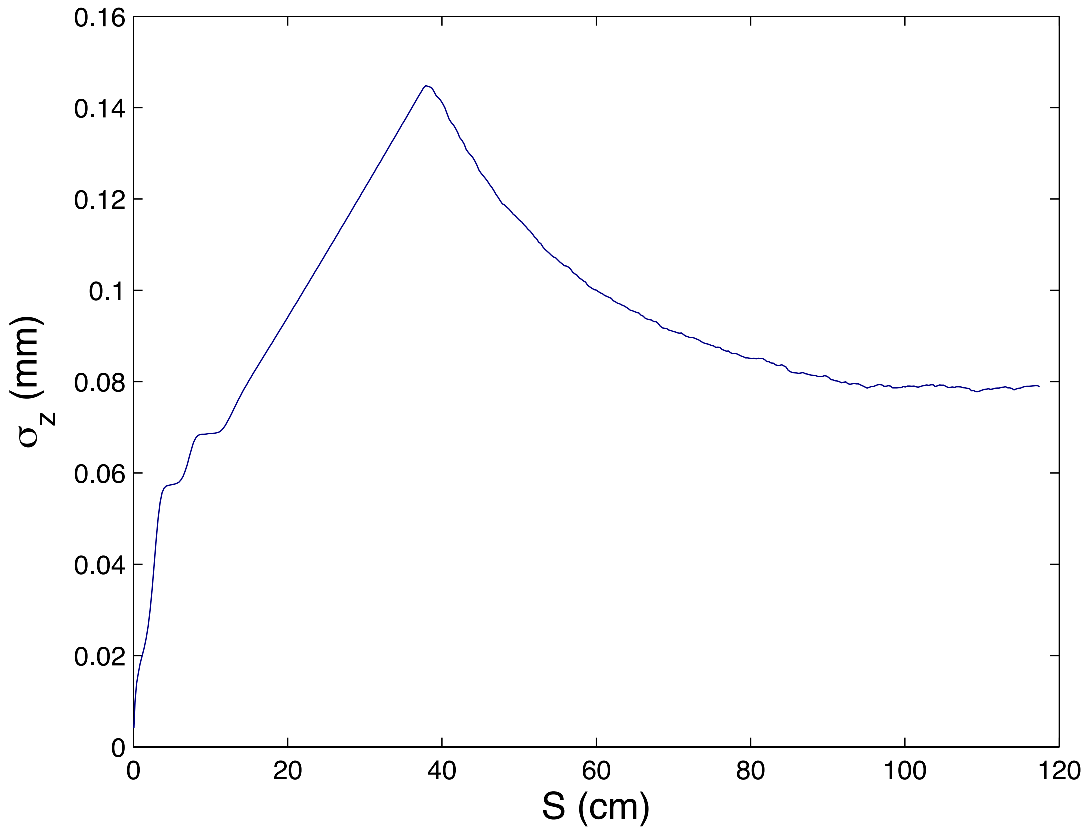
Some Examples to Real Life Observables

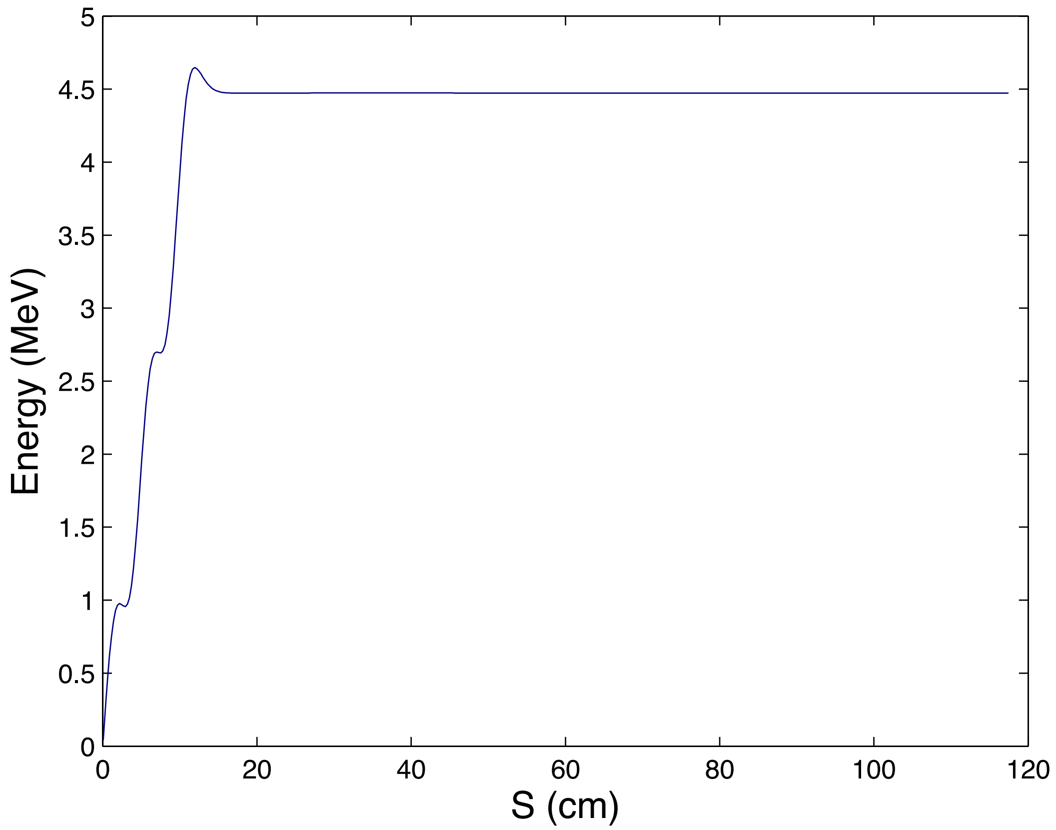




No focusing: Emittance is space-charge dominated, significant particle loss leads to “artificial” emittance drop.

Some Examples to Real Life Observables

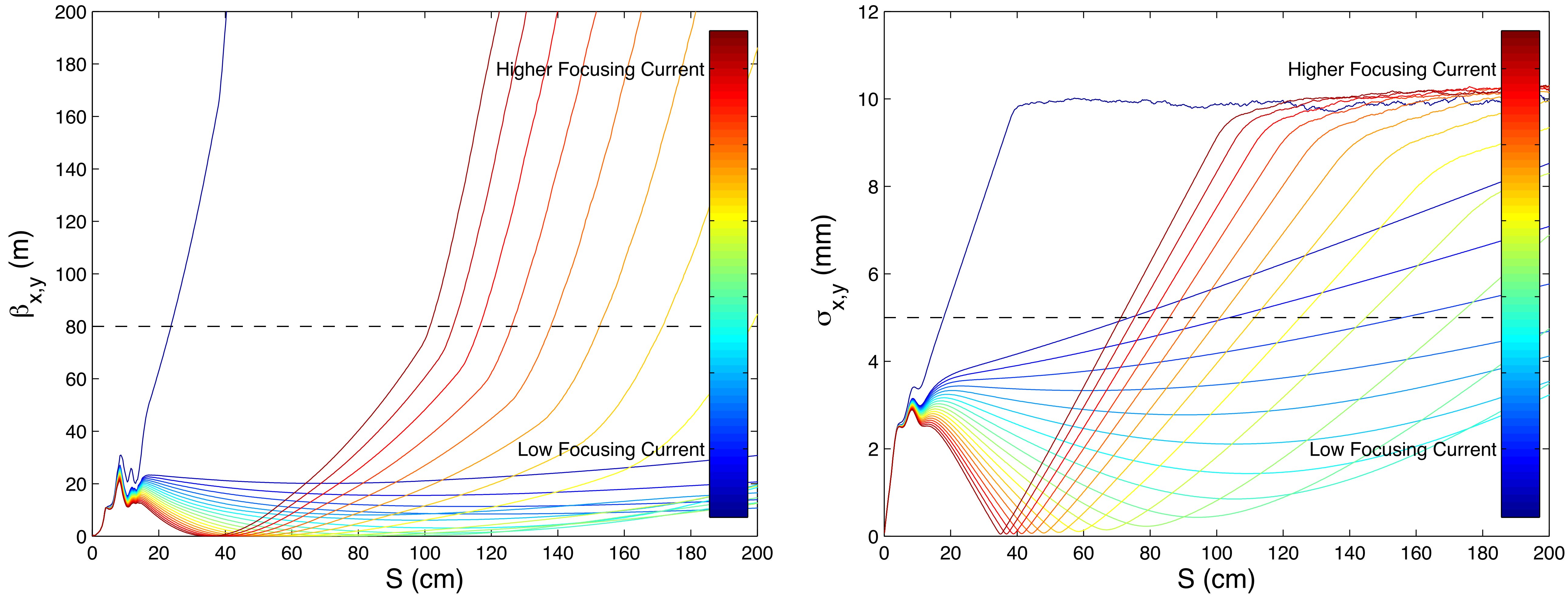




No focusing

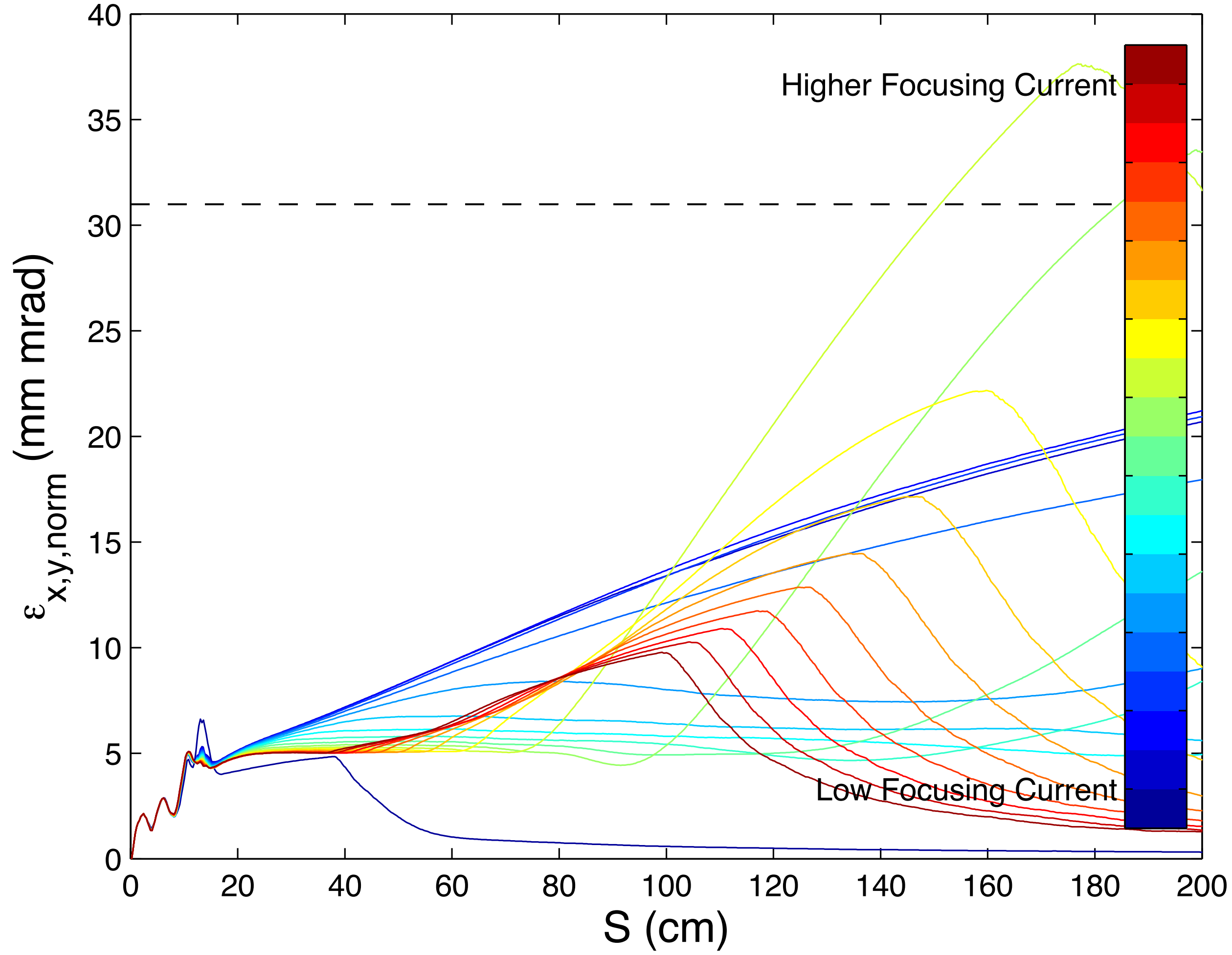
Some Examples to Real Life Observables

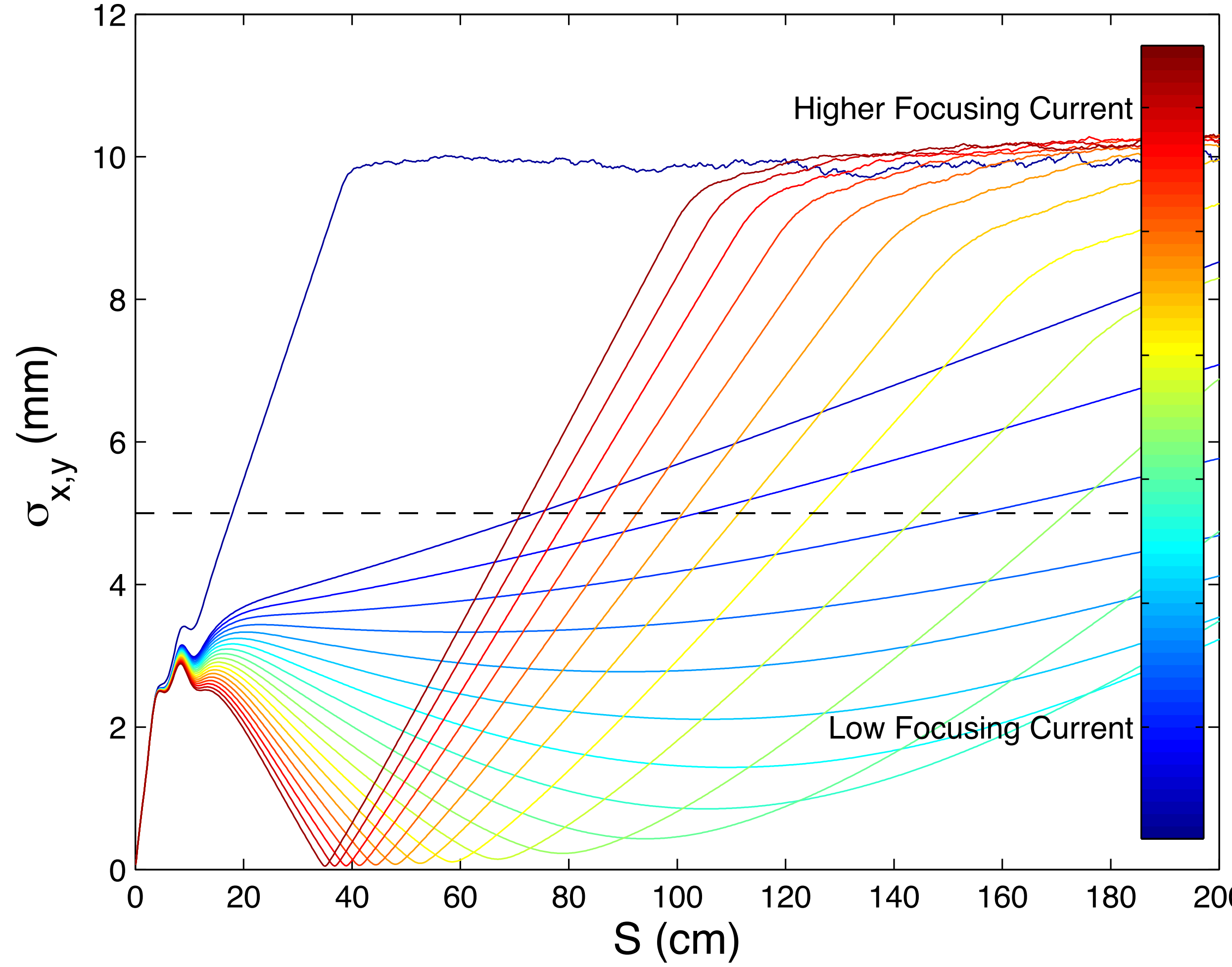
Solenoid scan



Some Examples to Real Life Observables

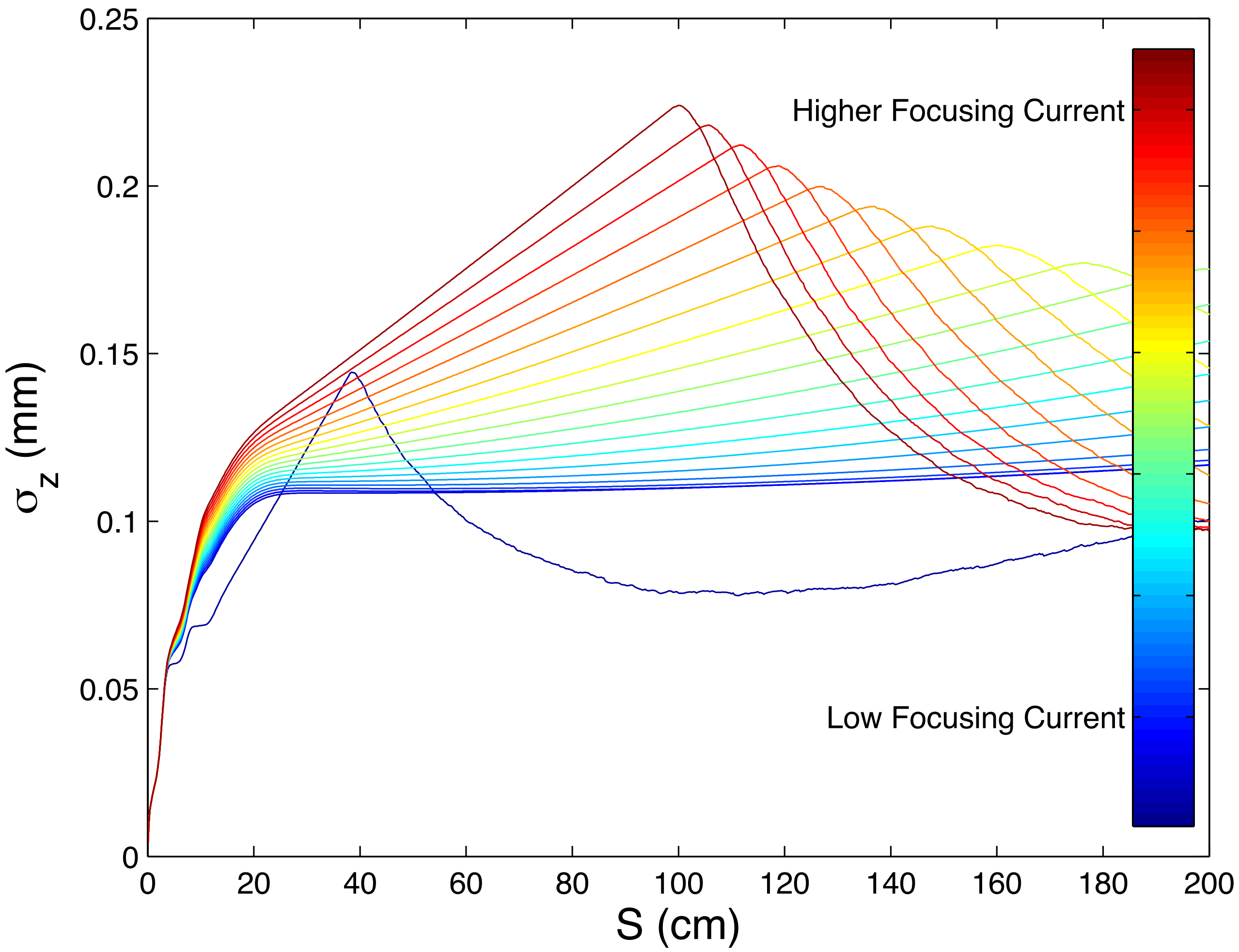
Solenoid scan





Some Examples to Real Life Observables

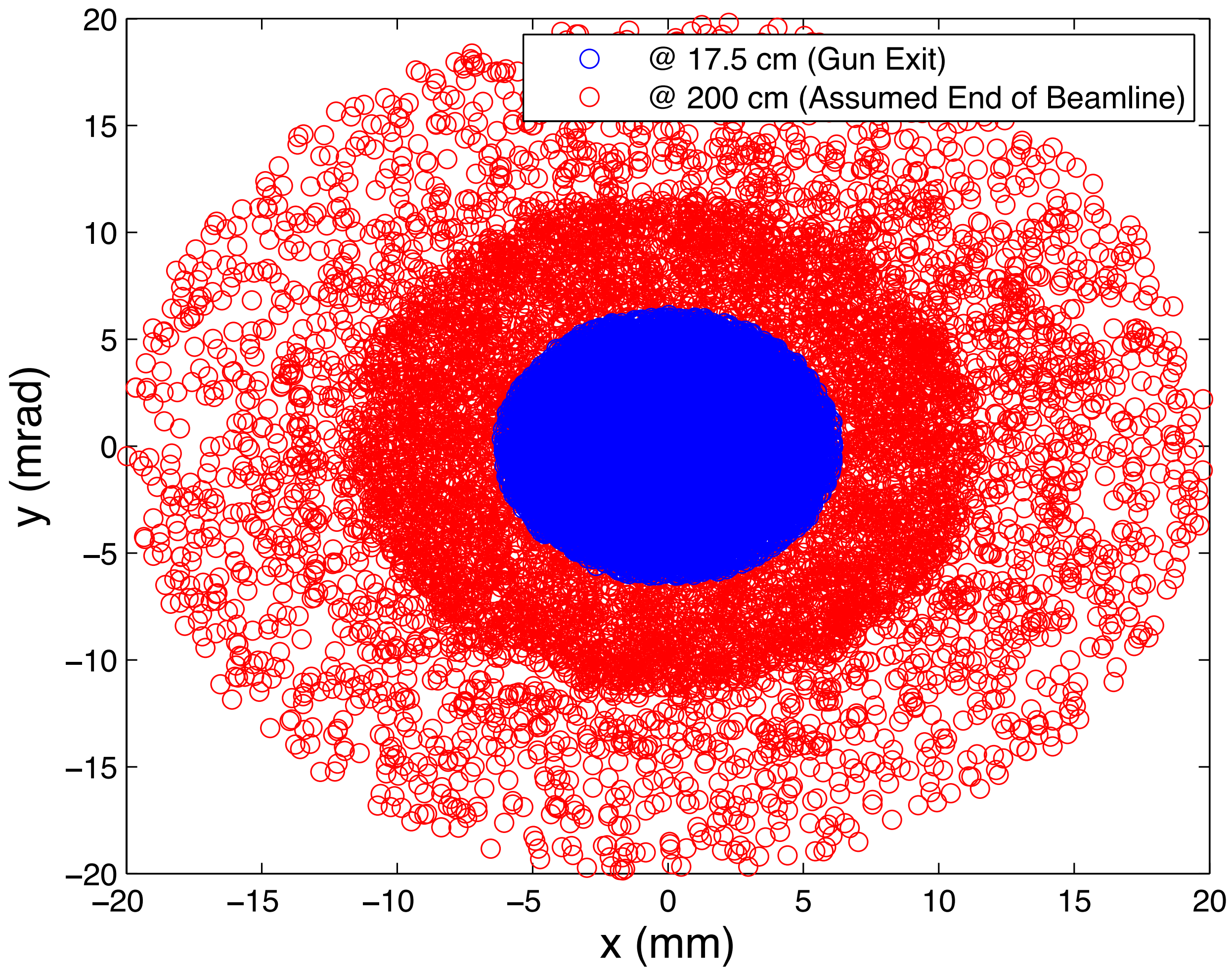
Solenoid scan



Bunch lengthening with increasing focusing. Coupling between transverse and longitudinal planes?

Some Examples to Real Life Observables

Particle Distribution, Real Space



For initial distribution, Gaussian distribution was taken into account.

Contents

Conclusions and Outlook

- Different technologies available, thermionic, laser-driven RF, thermionic RF,
- Cold atom trap based electron source?
- All options should be studied in terms of cost, robustness, novelty, integration, system requirements,
- α-magnet for bunch compression should be studied in more detail; longitudinal phase space, bunch compression,
- **Let's continue with real life examples and simulate a photoinjector by using PARMELA code...**