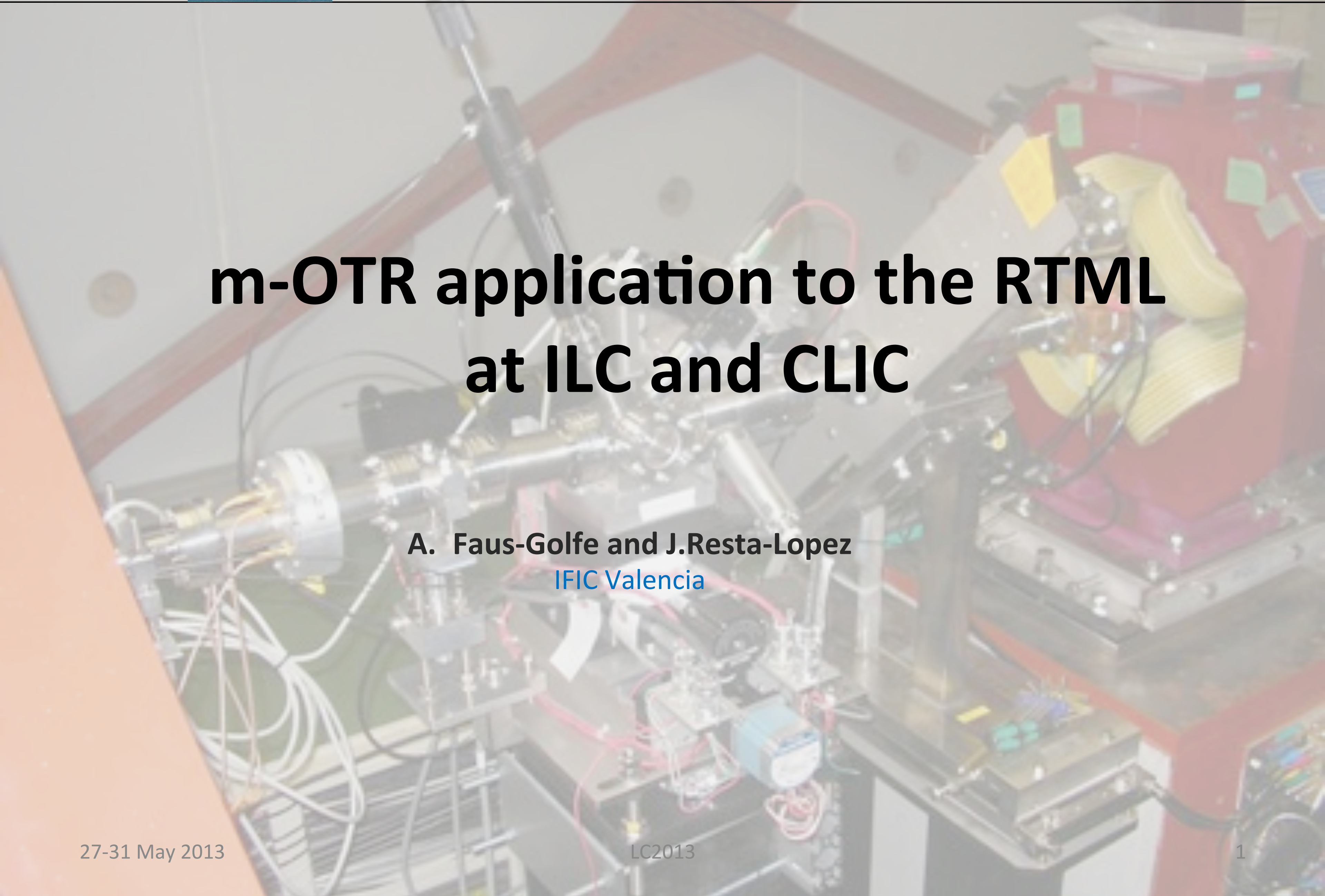

m-OTR application to the RTML at ILC and CLIC

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IFIC Valencia

Outline

- Introduction
  - The m-OTR system of ATF2
  - The emittance reconstruction analysis

- Lessons learned and implications to ILC and CLIC

- Figure of merit

- m-OTR system for ILC RTML
- m-OTR system for CLIC RTML

- Conclusions and Future studies

Introduction The m-OTR system of ATF2

- The multi-OTR system is made of **4 OTRs** installed in the zero-dispersion part of ATF2 EXT line

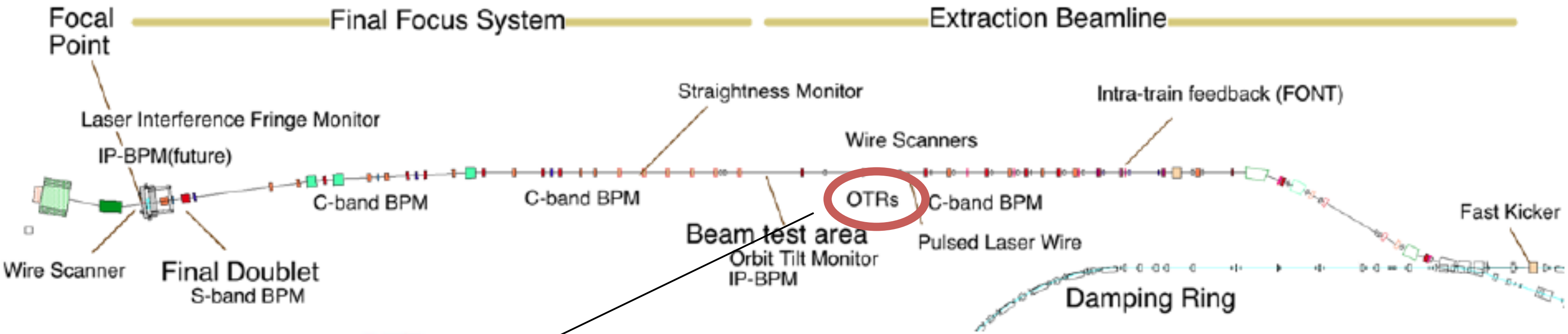
- The objective of this project is the **fast measurement of the emittance** (single shot for beam size, 1min for emittance) with:
  - high statistics
  - **2um** resolution
  - **$2\text{x}10^{10}$ single bunch** and **$2\text{x}10^{11}$** for **20 multi-bunched** beam (2.8 ns spacing)

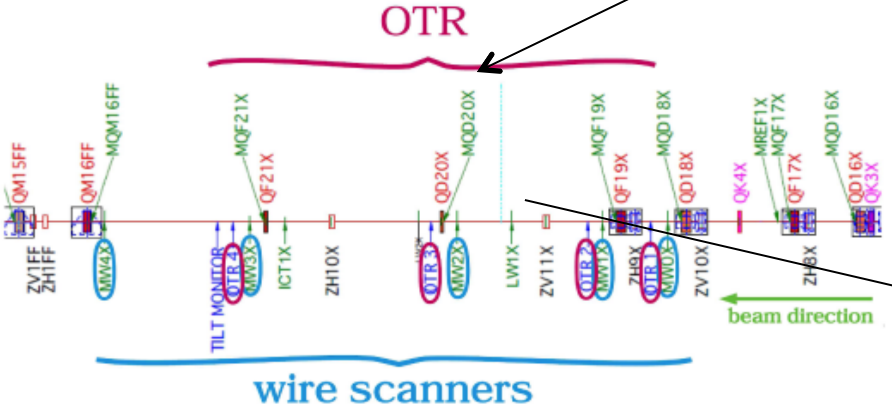
- The design is based on OTR1X at ATF EXT line (**5um resolution with $2\text{x}10^{10}$)** including improved features (compactness, calibration setup, demagnifier system..)

- The system **is installed near WS** for comparison and confirmation of OTR as a beam emittance diagnostic device

Introduction

Location and Optics

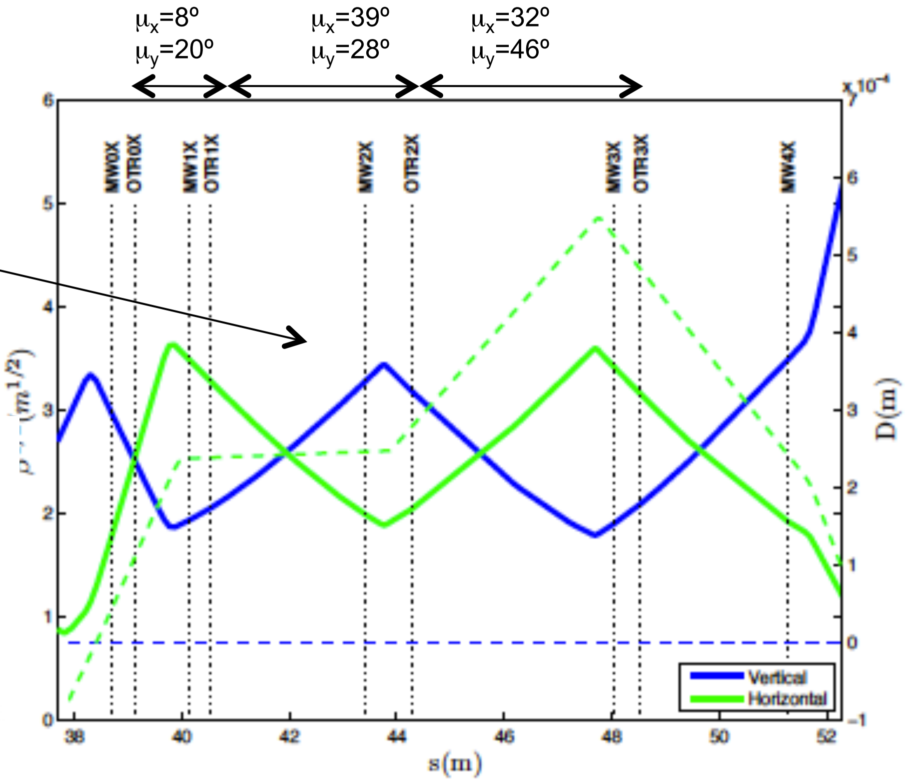




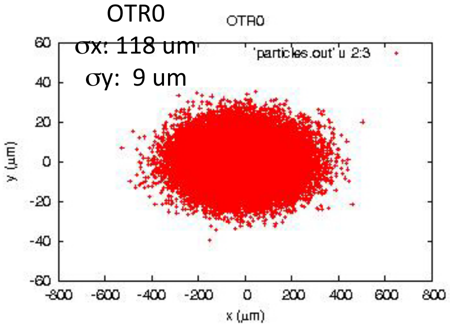
μ_x=8°
μ_y=20°

μ_x=39°
μ_y=28°

μ_x=32°
μ_y=46°



Location is not optimized, free space criterium has been taken into account

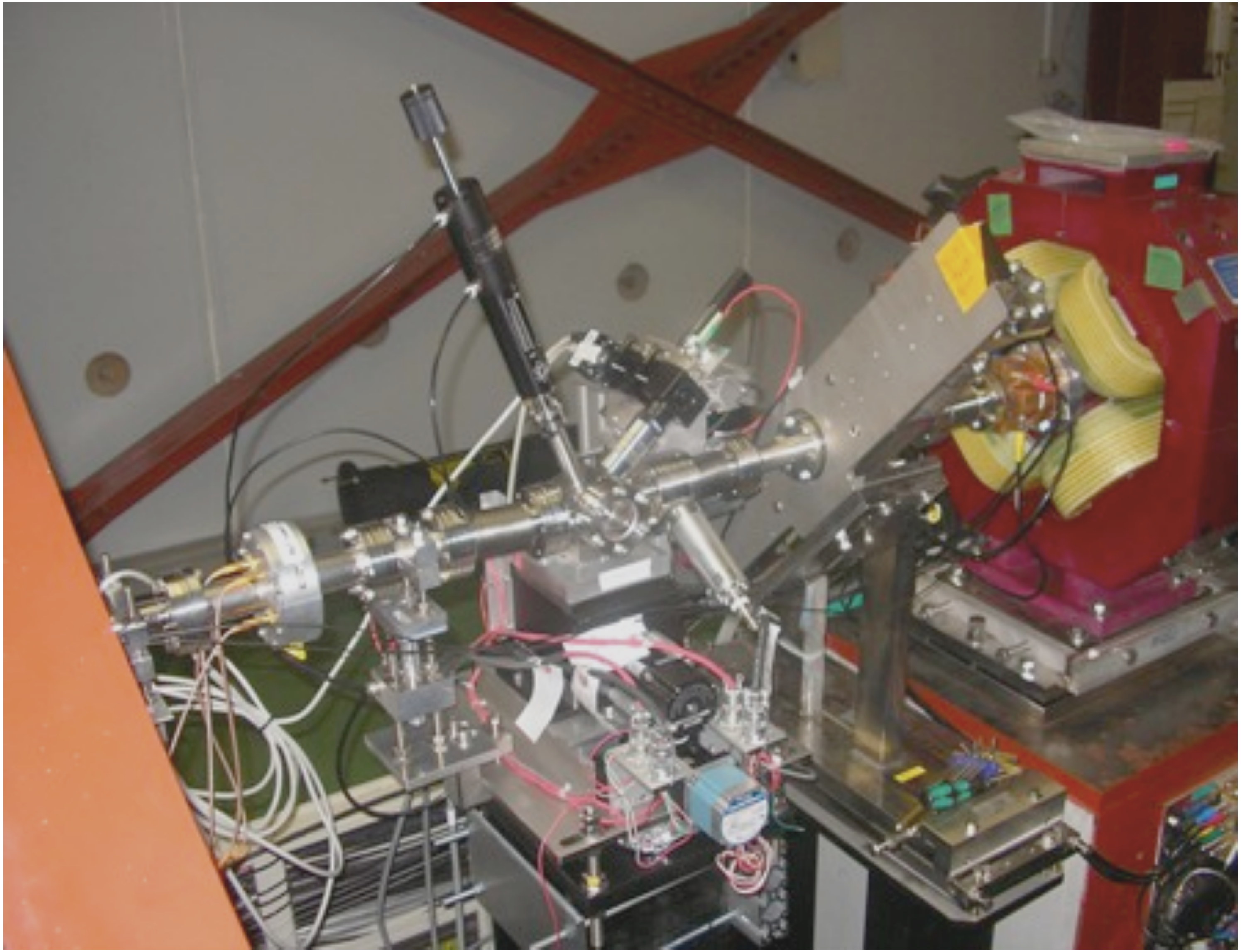


OTR0
σx: 118 um
σy: 9 um

Introduction Timeline

- **Proposal to ATF2 collaboration** June 2009
- **Design and Construction** Fall 2009
- **Calibration at IFIC and SLAC labs** February 2010
- **Installation in the ATF2 EXT line** April-May 2010
- **First Test with beam** June 2010
- **Test, Software Developments for beam size and emittance reconstruction and implementation in ATF2 control system** Fall 2010
- **New targets, Calibration system and Camera protection system** November 2010
- **Software Developments, Calibration and First Beam Measurements** Nov-Dec 2010
- **New LAN Control system** February 2011
- **Systematic Measurements I (before Tohoku earthquake)** January-March 2011
- **Design and Construction of a Demagnifier system** January-April 2011
- **Installation of the Demagnifier system** August 2011
- **Development of Coupling correction software algorithms** from September 2011
- **Systematic Measurements II (after Tohoku earthquake)** Nov 2011- Dec 2012
- **Proposal of new Target holders and Optical system** September 2012
- **Design and Construction of new Target holders** February-December 2012
- **New Target holder Installation** February 2013
- **Systematic measurements III** from March 2013

The m-OTR system of ATF2



Single OTR panel

number of measurements

Working mode & Reference system

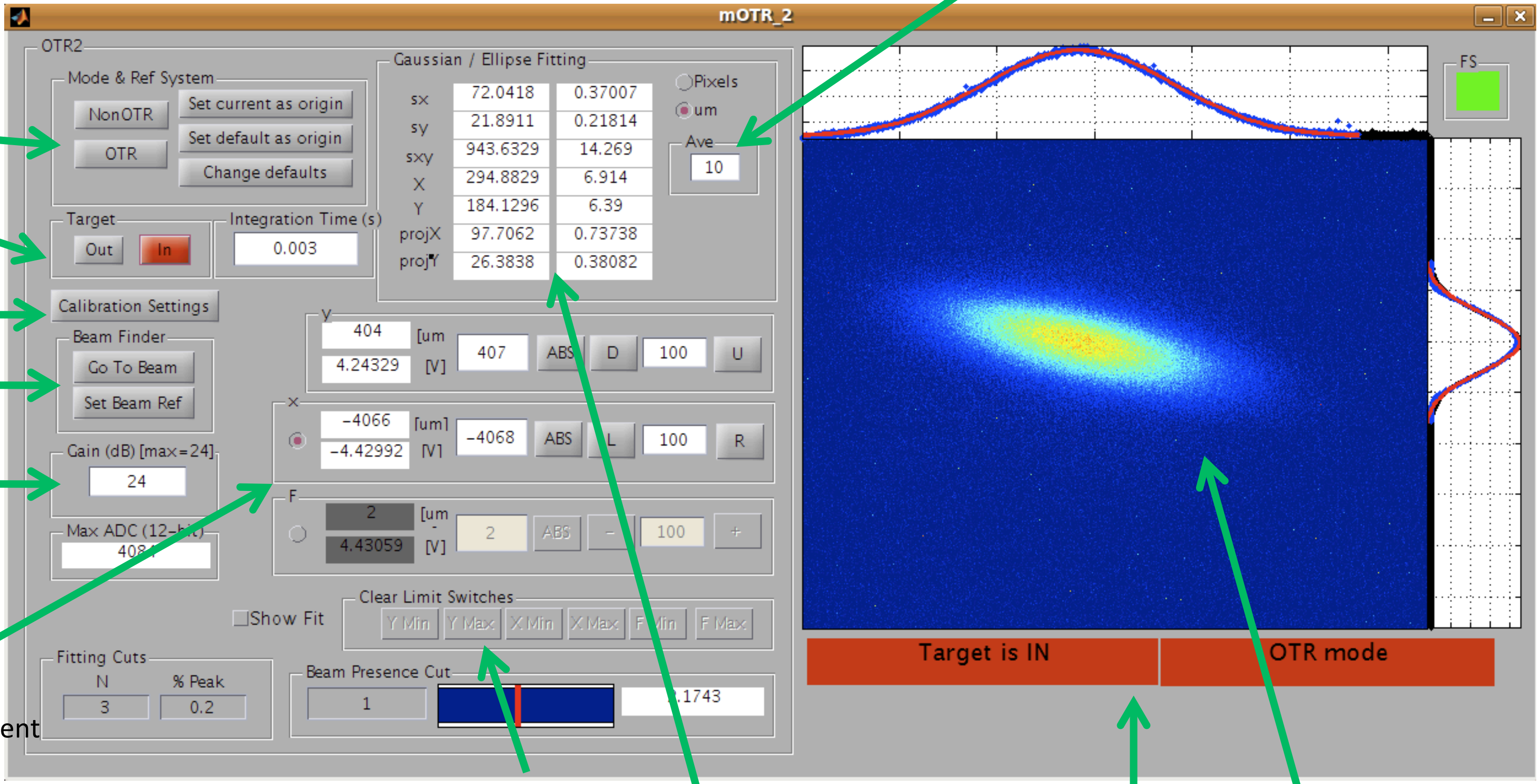
Target control

Calibrations

Beam finder

CCD Gain

Position & movement of the movers



Integration Time (s): 0.003

Gaussian / Ellipse Fitting

sx	72.0418	0.37007
sy	21.8911	0.21814
sxy	943.6329	14.269
X	294.8829	6.914
Y	184.1296	6.39
projX	97.7062	0.73738
projY	26.3838	0.38082

○ Pixels
● um

Ave: 10

Gain (dB) [max=24]: 24

Max ADC (12-bit): 408

Y: 404 [um], 4.24329 [V]; 407; 100

● X: -4066 [um], -4.42992 [V]; -4068; 100

○ F: 2 [um], 4.43059 [V]; 2; 100

☐ Show Fit

Fitting Cuts: N 3; % Peak 0.2

Beam Presence Cut: 1; .1743

Limit switches status

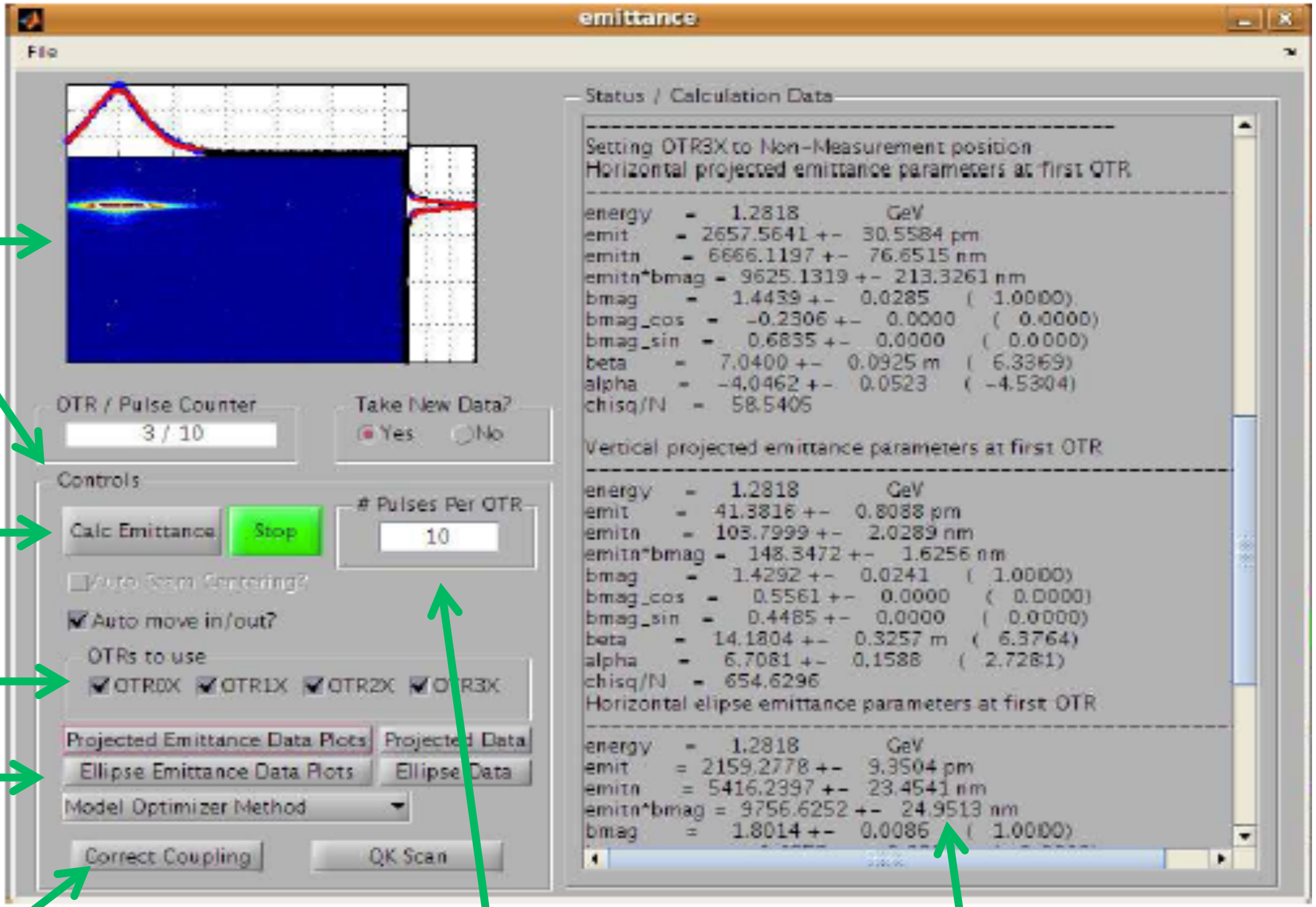
Machine status

Ellipse fitting and analysis

CCD image and beam fitting

Beam size and Emittance Measurements

Emittance panel



OTR / Pulse Counter: 3 / 10

Take New Data? ● Yes ○ No

Controls

Pulses Per OTR: 10

☐ Auto Beam Centering?

☑ Auto move in/out?

OTRs to use: ☑ OTR0X ☑ OTR1X ☑ OTR2X ☑ OTR3X

Status / Calculation Data

```
-----------------------------------------------
Setting OTR3X to Non-Measurement position
Horizontal projected emittance parameters at first OTR
----------------------------------------------------------------
energy    =    1.2818          GeV
emit      =  2657.5641 +-   30.5584 pm
emitn     =  6666.1197 +-   76.6515 nm
emitn*bmag =  9625.1319 +-  213.3261 nm
bmag      =    1.4439 +-    0.0285    (  1.0000)
bmag_cos  =   -0.2306 +-    0.0000    (  0.0000)
bmag_sin  =    0.6835 +-    0.0000    (  0.0000)
beta      =    7.0400 +-    0.0925 m  (  6.3369)
alpha     =   -4.0462 +-    0.0523    ( -4.5304)
chisq/N   =   58.5405

Vertical projected emittance parameters at first OTR
----------------------------------------------------------------
energy    =    1.2818          GeV
emit      =   41.3816 +-    0.8088 pm
emitn     =  103.7999 +-    2.0289 nm
emitn*bmag =  148.3472 +-    1.6256 nm
bmag      =    1.4292 +-    0.0241    (  1.0000)
bmag_cos  =    0.5561 +-    0.0000    (  0.0000)
bmag_sin  =    0.4485 +-    0.0000    (  0.0000)
beta      =   14.1804 +-    0.3257 m  (  6.3764)
alpha     =    6.7081 +-    0.1588    (  2.7281)
chisq/N   =  654.6296
Horizontal elipse emittance parameters at first OTR
----------------------------------------------------------------
energy    =    1.2818          GeV
emit      =  2159.2778 +-    9.3504 pm
emitn     =  5416.2397 +-   23.4541 nm
emitn*bmag =  9756.6252 +-   24.9513 nm
bmag      =    1.8014 +-    0.0086    (  1.0000)
```

Current OTR info

Start/stop emittance procedure

Number of OTR to be used

Data analysis and plots

Automatic Coupling correction

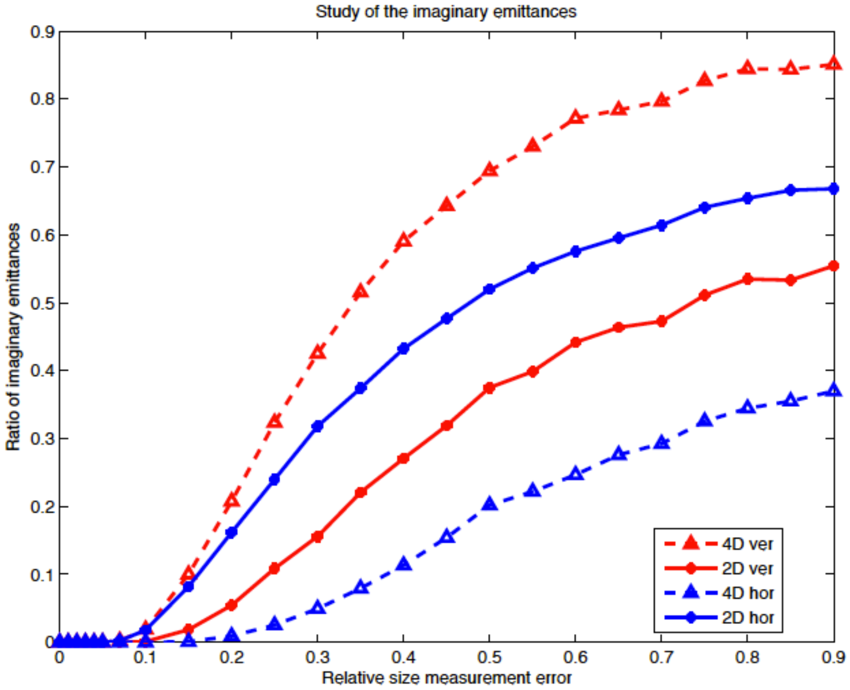
number of measurements per OTR

Calculation data

Introduction

Emittance Reconstruction

The **emittances** could be reconstructed from the **beam size measurements** at different locations along the beamline. The **2D** (transverse) and **4D** (intrinsic) emittances could be obtained by **solving numerically three separated systems** of coupled equations. When the number of measurement stations is greater than four, these **systems are overdetermined**, and the numerical solutions can lead to unphysical results. The incidence of such meaningless results usually increases if the measurements are noisy. Numerical rules can be used to study the conditioning of these systems.



The **main objective** of this work is to **study analytically** the conditions of **solvability of these systems of equations** and its implication in the emittance reconstruction algorithms used in the accelerators. The aim is to give some hints about the **optical constrains** and the **location** of the **measurement stations**.

Emittance Reconstruction

In the general case of ***N*** measurement stations. The system has **unique solution (σ_1 σ_2 σ_5)** if and only if the rank of both M_X and M_X^* is equal to three. This give us two conditions:

Condition1: $\boxed{\phi_x^{(ji)} \neq n\pi, \forall(i,j)}$

The **measurement** stations should be **located** at places where the **phase advances** correspond to **different snapshots** of the beam. This is the only required condition in the case of **3** measurement stations.

For **4 or more stations** a second condition is required to get a unique solution.

Condition 2: $\boxed{-\hat{\sigma}_1^{(i)}\Delta_{3x}(jkl)+\hat{\sigma}_1^{(j)}\Delta_{3x}(ikl)-\hat{\sigma}_1^{(k)}\Delta_{3x}(ijl)+\hat{\sigma}_1^{(l)}\Delta_{3x}(ijk)=0, \forall(ijkl)}$

$$\Delta_{3x}(ijk)=2\beta_x^{(i)}\beta_x^{(j)}\beta_x^{(k)} sin\phi_x^{(ji)} sin\phi_x^{(ki)} sin\phi_x^{(kj)}$$

$$A_{4x}(ijkl)=-\hat{\sigma}_1^{(i)}\Delta_{3x}(jkl)+\hat{\sigma}_1^{(j)}\Delta_{3x}(ikl)-\hat{\sigma}_1^{(k)}\Delta_{3x}(ijl)+\hat{\sigma}_1^{(l)}\Delta_{3x}(ijk)$$

Condition 2 involve the β and the **measurements**, one can see that **in general** the **equality cannot be exactly satisfied**. One could replace the **zero** by some previously **fixed error value**, related with the error of the **measurements**.

Idem for vertical plane.

Introduction

Emittance Reconstruction

In the general case of ***N*** measurement stations we have M_{XY} and M_{XY}^*, the system has **unique solution (σ_3 σ_4 σ_6 σ_7)** if and only if the rank of both M_{XY} and M_{XY}^* is equal to four. This give us two more conditions:

Condition 3:

$$\begin{aligned}&\cos(\varphi_x^{(ji)}+\varphi_x^{(lk)})\left[\cos(\varphi_y^{(ki)}+\varphi_y^{(lj)})-\cos(\varphi_y^{(ki)}-\varphi_y^{(lj)})\right]\\&+\cos(\varphi_x^{(ki)}+\varphi_x^{(lj)})\left[\cos(\varphi_y^{(ji)}-\varphi_y^{(lk)})-\cos(\varphi_y^{(ji)}+\varphi_y^{(lk)})\right]\\&+\cos(\varphi_x^{(ji)}-\varphi_x^{(lk)})\left[\cos(\varphi_y^{(ji)}+\varphi_y^{(lk)})-\cos(\varphi_y^{(ki)}+\varphi_y^{(lj)})\right]\neq 0,\forall(ijkl)\end{aligned}$$

This is the only required condition in the case of **4** measurement stations. In the particular case where $\boldsymbol{\phi_x^{(ji)}=\phi_y^{(ji)}}$ the system has **no solution.**

For **5 or more stations** an additional condition is required to get a **unique solution**.

Condition 4:

$$\hat{\sigma}_3^{(i)}\Delta_4(jklm)-\hat{\sigma}_3^{(j)}\Delta_4(iklm)+\hat{\sigma}_3^{(k)}\Delta_4(ijlm)-\hat{\sigma}_3^{(l)}\Delta_4(ijkm)+\hat{\sigma}_3^{(m)}\Delta_4(ijkl)=0,\forall(ijklm)$$

$$\begin{aligned}&-8(\beta_x^{(i)}\beta_y^{(i)}\beta_x^{(j)}\beta_y^{(j)}\beta_x^{(k)}\beta_y^{(k)}\beta_x^{(l)}\beta_y^{(l)})^{-1/2}\Delta_4(ijkl)=\cos(\varphi_x^{(ji)}+\varphi_x^{(lk)})\left[\cos(\varphi_y^{(ki)}+\varphi_y^{(lj)})-\cos(\varphi_y^{(ki)}-\varphi_y^{(lj)})\right]\\&+\cos(\varphi_x^{(ki)}+\varphi_x^{(lj)})\left[\cos(\varphi_y^{(ji)}-\varphi_y^{(lk)})-\cos(\varphi_y^{(ji)}+\varphi_y^{(lk)})\right]+\cos(\varphi_x^{(ji)}-\varphi_x^{(lk)})\left[\cos(\varphi_y^{(ji)}+\varphi_y^{(lk)})-\cos(\varphi_y^{(ki)}+\varphi_y^{(lj)})\right]\end{aligned}$$

$$A_5(ijklm)=+\hat{\sigma}_3^{(i)}\Delta_4(jklm)-\hat{\sigma}_3^{(j)}\Delta_4(iklm)+\hat{\sigma}_3^{(k)}\Delta_4(ijlm)-\hat{\sigma}_3^{(l)}\Delta_4(ijkm)+\hat{\sigma}_3^{(m)}\Delta_4(ijkl)$$

One could replace the **zero** by some previously **fixed error value**, related with the error of the **measurements**.

Lessons learned and Implications for ILC and CLIC

- The **m-OTR system** of the ATF2 EXT has demonstrated its performances as a **fast** (1min) and **reliable** system for measuring the beam size and the emittance. The system is **totally integrated** in the **online model** and it is **crucial** for **tuning procedures** of the beamline as: coupling correction, beta matching, energy spread measurements…Studies to ameliorate these procedures are ongoing

- We have **studied analytically** the **conditions of solvability** of the systems of equations involved in the process of emittance reconstruction and we have obtained some rules about the **locations** of the **measurement stations** to avoid unphysical results. **Simulations** are being made to test the robustness with high coupling scenarios and measurement errors. The results of these studies will be very **useful** to better determine the location of the emittance measurement stations in the **diagnostic sections** of **FLC**s.

- OTR monitors are **mature** and **reliable** diagnostic tools that could be **very suitable** for the setup and tuning of the machine in single-bunch mode. It can be very useful during **start up** and **commissioning** phases of the **RTM**L. The **feasibility** of using a m-OTR system in **transfer lines** of the **ILC RTML** as well as a study of the different **materials** for the OTR **target** and possible limitations of operation is presented in the following.

Figure of merit

In order to adapt a m-OTR system to a linear collider RTML context, the key point is the selection of a suitable material to make the OTR radiator (target) in order to avoid its damage when the beam goes through it.

Temperature rise in the target per pulse

(assuming target foil thickness < 1 radiation length)

$$\Delta T_{inst} = \frac{1}{\rho C_p}\left(\frac{dE}{dz}\right)\frac{N_b N_e}{2\pi\sigma_x\sigma_y}$$

ρ: material density
C_p: specific heat
N_b: number of bunches per pulse
(N_b=1, single-bunch operation)
N_e: number of particles per bunch
(dE/dz): collision stopping power
(Bethe-Bloch formula)

compare ⟷

Limit for thermal induced mechanical fracture:

$$\Delta T_{fr} \cong \frac{2\sigma_{\mathrm{UTS}}}{\alpha_{\mathrm{T}} Y}$$

σ_{UTS}: ultimate tensile stress
α_T: thermal expansion coefficient
Y: Young modulus

Condition:

$$\Delta T_{inst} < \Delta T_{fr}$$

$$\Delta T_{inst} < (T_{melt} - 293\ \mathrm{K})$$

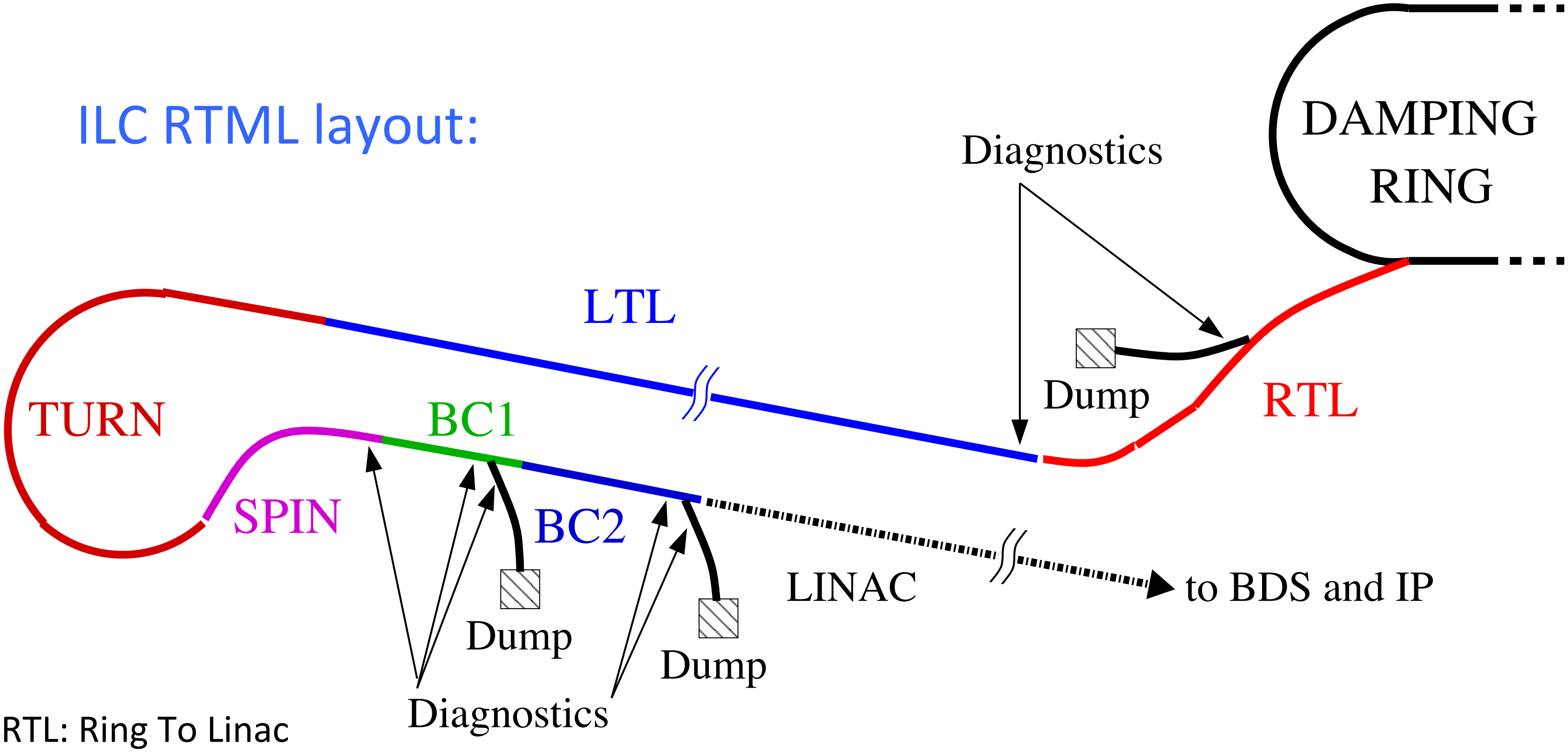
Mechanical and thermal properties of various materials

Property	Kapton*	Al	Be	Ti	W
σ_{UTS} [MPa]	231	50	370	220	980
Y $[\times 10^5 \mathrm{MPa}]$	0.025	0.68	2.87	1.16	4.11
α_{T} $[\times 10^{-6} \mathrm{K}^{-1}]$	20	23.1	11.6	8.6	4.5
k [W/(mK)]	0.12	210	200	17	163
C_p [J/(gK)]	1.09	0.91	1.925	0.528	0.134
T_{melt} [K]	–	933.37	1546	1923	3643

*Kapton does not melt, but decomposes at 793 K

Multi-OTR System for ILC RTML

ILC RTML layout:



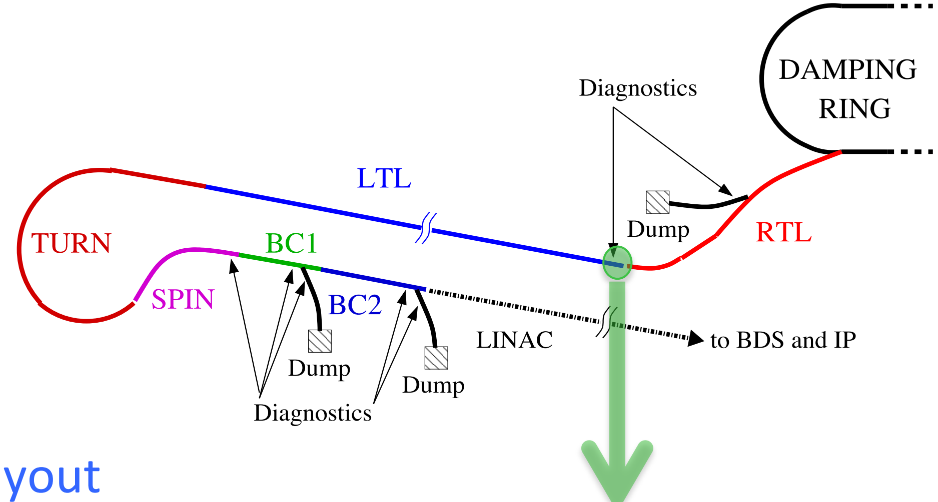
RTL: Ring To Linac
LTL: Long Transfer Line
TURN: Turnaround
SPIN: Spin Rotator
BC1: First Bunch Compressor
BC2 : Second Bunch Compressor

Here we study the following cases:

- Assuming m-OTR system at the beginning of the LTL
- At the end of the RTML (end of BC2)

Multi-OTR System for ILC RTML

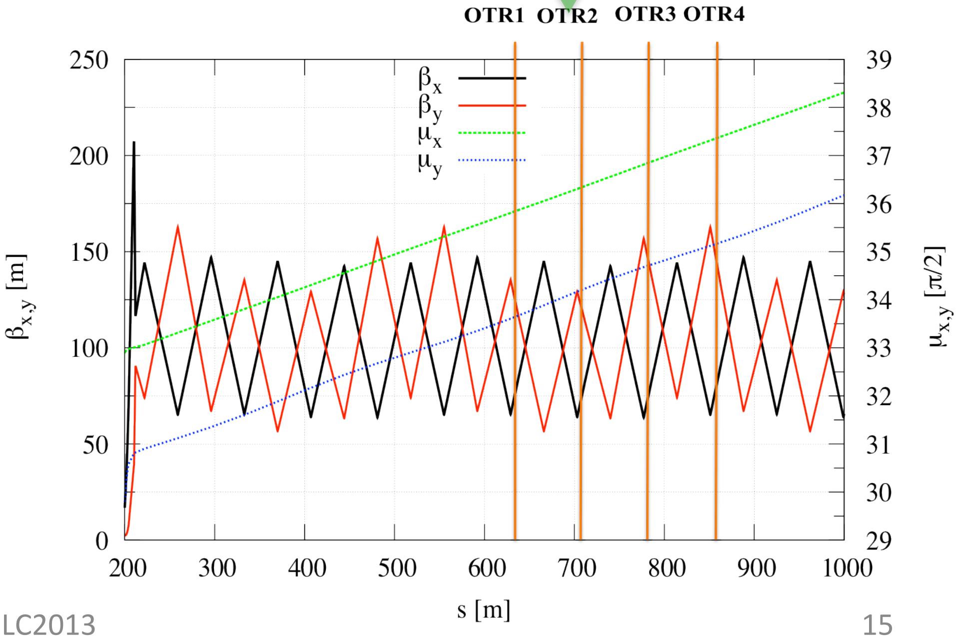
At the beginning of LTL:



Beam parameters

Parameter	Start RTML
E	5 GeV
N_e	$2x10^{10}$
σ_z	6 mm
$\sigma_{\Delta E/E}$	0.13%
$\gamma\varepsilon_x$	8 µm
$\gamma\varepsilon_y$	20 nm

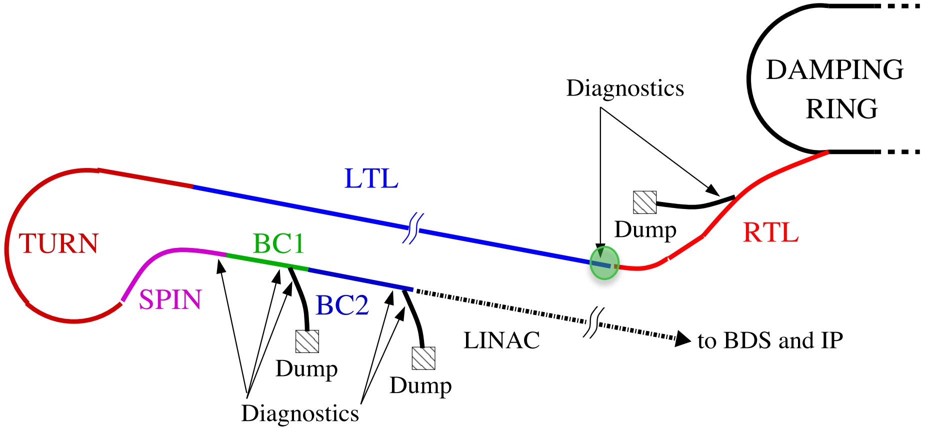
Optics layout



- The LTL lattice mainly consists of FODO cells with $\mu_{x,y}=\pi/4$ phase advance
- For coupling correction, skew quadrupoles can be placed in the FODO cells upstream of this system

Multi-OTR System for ILC RTML   OTR target damage study

At the beginning of LTL:



$\sigma_x \approx 239\ \mu\text{m}\ (\beta_x \approx 70\ \text{m})$
$\sigma_y \approx 17.5\ \mu\text{m}\ (\beta_y \approx 150\ \text{m})$

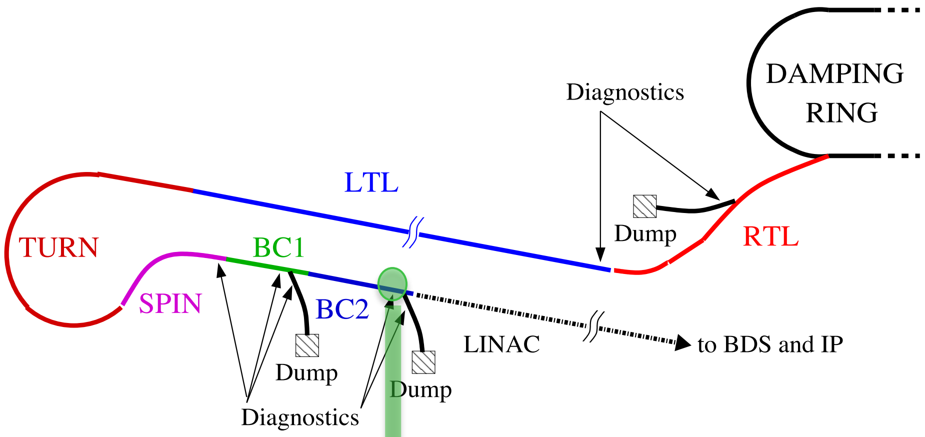
Assuming single bunch operation

Material	$\frac{dE}{dz}\ \left[\frac{\text{MeV}}{\text{cm}}\right]$	ΔT_{inst} [K]	ΔT_{fr} [K]
Kapton	3.297	25.973	9240
Al	5.778	28.675	63.662
Be	3.704	12.682	222.28
Ti	9.112	46.35	441.06
W	32.366	152.6	1059.7

ΔT_{inst} below the fracture limit and far below below the temperature excursion for melting ($T_{melt} - 293$ K). No damage is expected in this case operating in single bunch mode

Multi-OTR System for ILC RTML

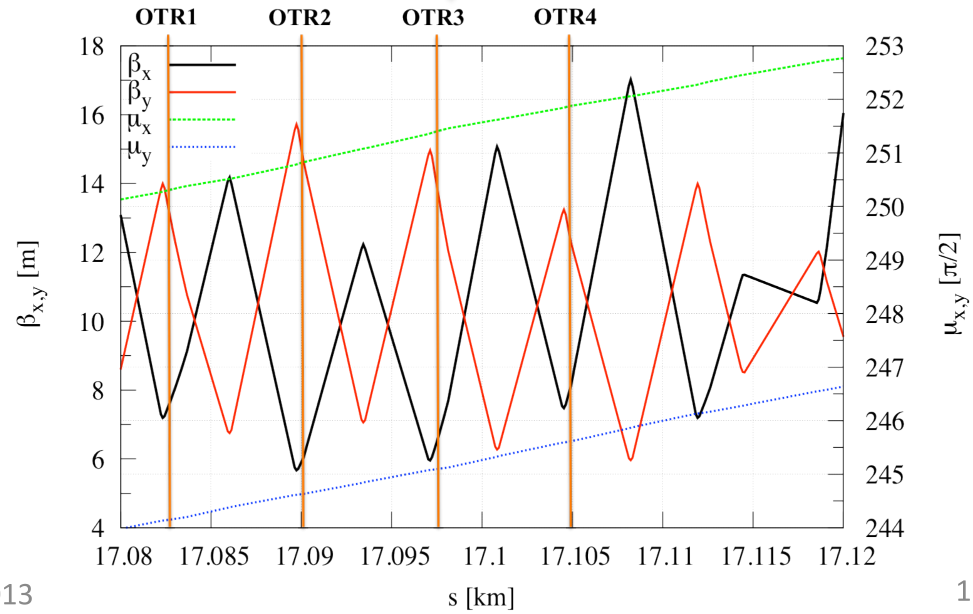
At the end of BC2:



Beam parameters

Parameter	End RTML
E	15 GeV
N_e	$2\text{x}10^{10}$
σ_z	0.3/0.15 mm
$\sigma_{\Delta E/E}$	1.07%
$\gamma\varepsilon_x$	8 µm
$\gamma\varepsilon_y$	20 nm

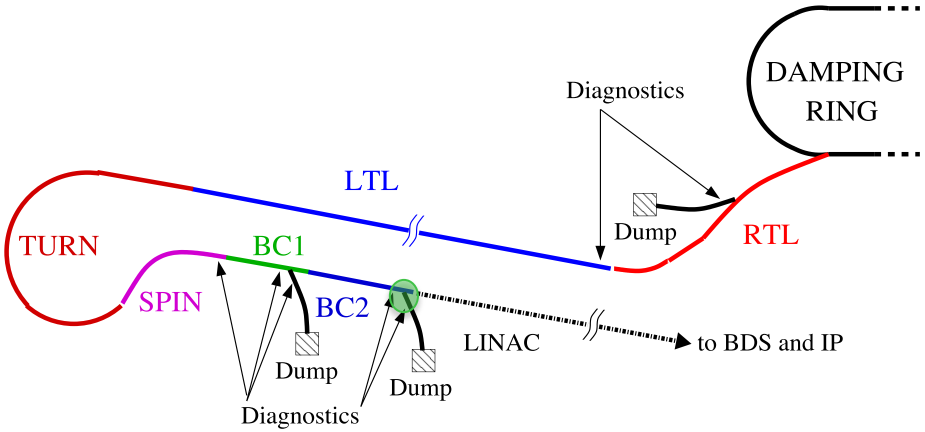
Optics layout



Multi-OTR System for ILC RTML   OTR target damage study

At the end of BC2:

$\sigma_x \approx 75.6\ \mu\text{m}\ (\beta_x \approx 7\ \text{m})$
$\sigma_y \approx 5.3\ \mu\text{m}\ (\beta_y \approx 14\ \text{m})$



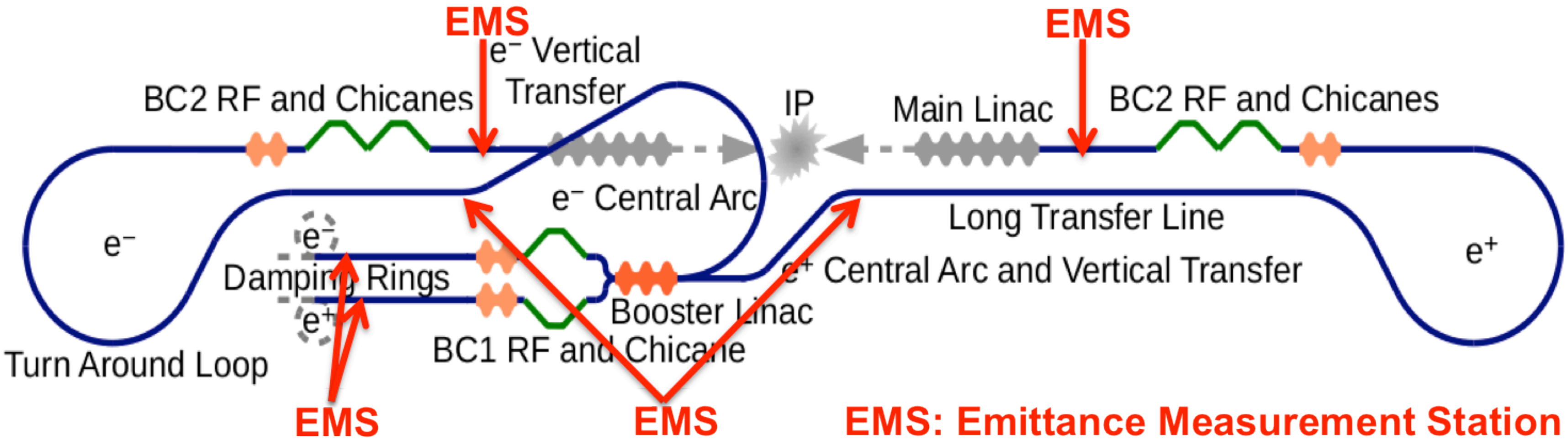
Assuming single bunch operation

Material	$\frac{dE}{dz}\left[\frac{\text{MeV}}{\text{cm}}\right]$	ΔT_{inst} [K]	ΔT_{fr} [K]
Kapton	3.665	298.81	9240
Al	5.996	307.96	63.662
Be	3.822	135.43	222.28
Ti	9.386	494.12	441.06
W	33.678	1643.3	1059.7

- In this case stress fractures may be generated for targets made of Al, Ti and W. These calculations indicate that Kapton and Be could avoid damage.
- The use of Be could be discouraged due to its toxicity. Kapton could be a good candidate

Multi-OTR System for CLIC RTML

CLIC RTML layout:



We study the following cases:

- Assuming m-OTR system at the beginning of the RTML
- At the end of the RTML (end of BC2)

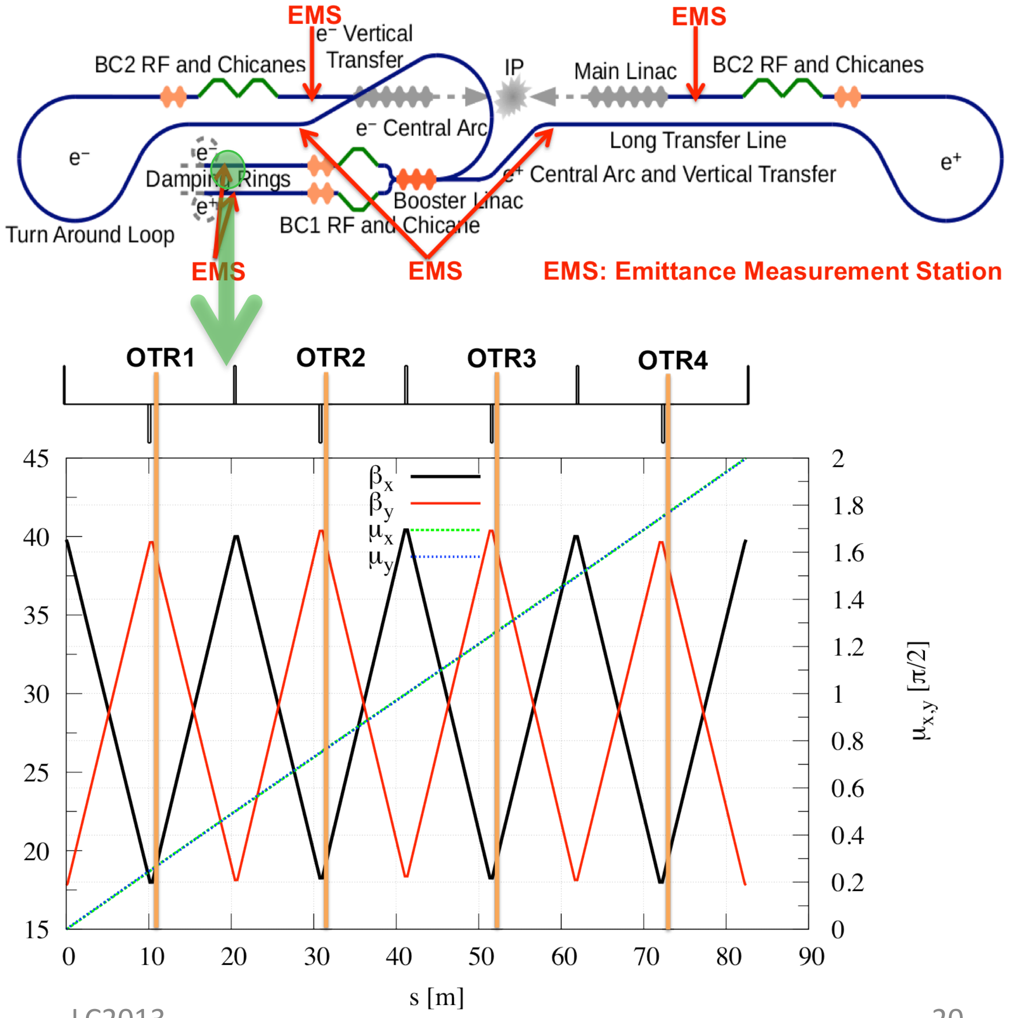
Multi-OTR System for CLIC RTML

At the beginning of RTML:

Beam parameters

Parameter	Start RTML
E	2.86 GeV
N_e	4×10^9
σ_z	1.8 mm
$\sigma_{\Delta E/E}$	0.12%
$\gamma\varepsilon_x$	500 nm
$\gamma\varepsilon_y$	5 nm

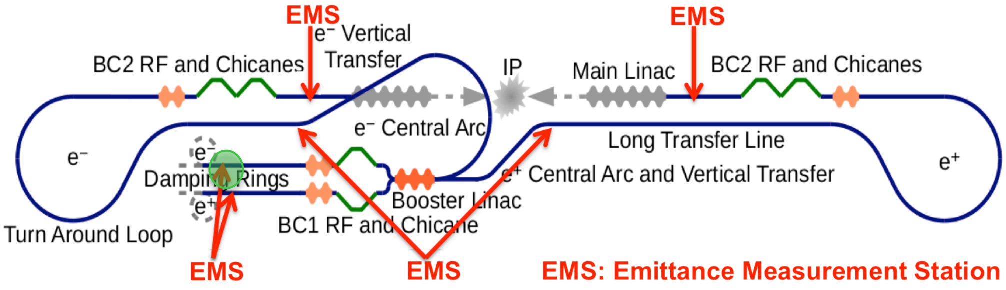
Optics layout
(2D EMS)



Multi-OTR System for CLIC RTML OTR target damage study

At the beginning of RTML:

$\sigma_x \approx 40\ \mu m\ (\beta_x \approx 17.8\ m)$
$\sigma_y \approx 6\ \mu m\ (\beta_y \approx 39.8\ m)$



Material	$\frac{dE}{dz}\ \left[\frac{\mathrm{MeV}}{\mathrm{cm}}\right]$	ΔT_{inst} [K]	ΔT_{fr} [K]
Kapton	3.235	90.931	9240
Al	5.665	100.31	63.662
Be	3.633	44.383	222.28
Ti	8.935	162.17	441.06
W	31.691	533.12	1059.7

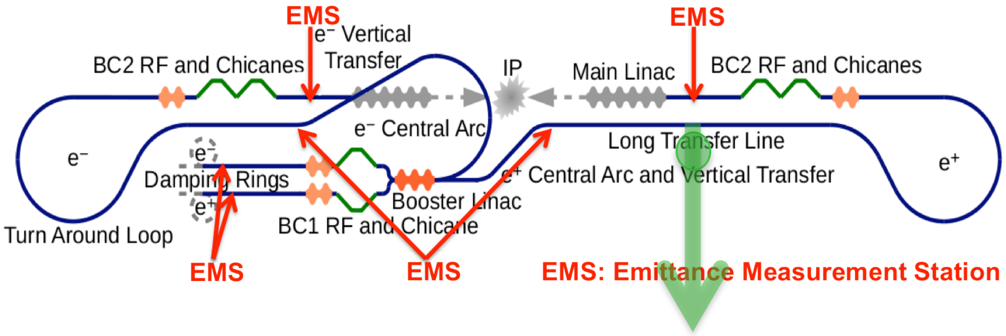
Kapton, Be, Ti and W are below the fracture limit and Al surpasses such limit

Multi-OTR System for CLIC RTML

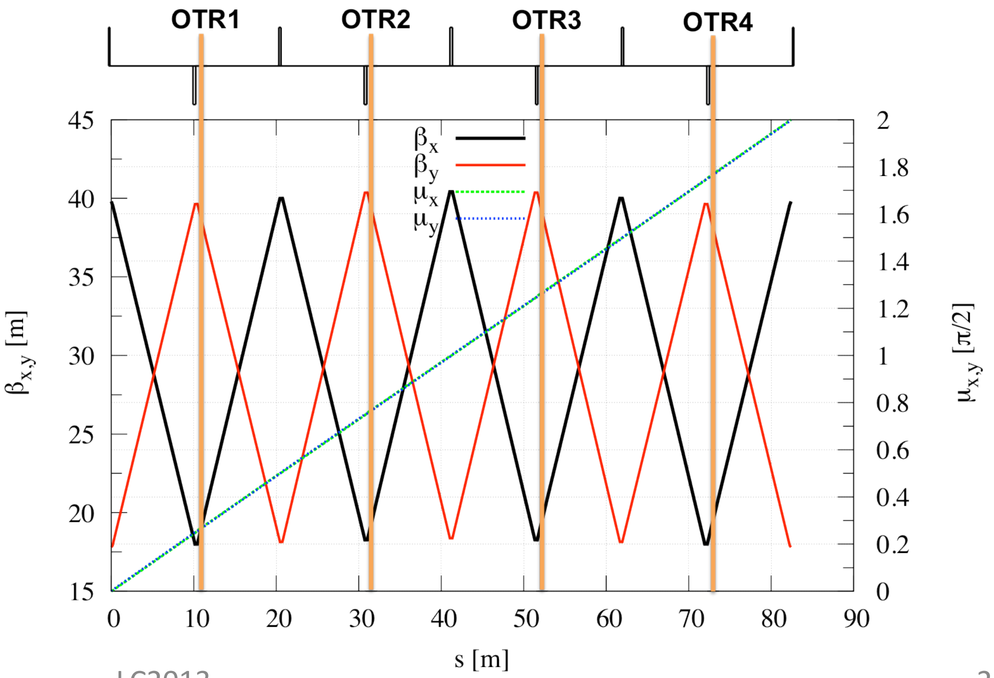
At the end of RTML:

Beam parameters

Parameter	End RTML
E	9 GeV
N_e	3.72×10^9
σ_z	44 µm
$\sigma_{\Delta E/E}$	< 1.7%
$\gamma\varepsilon_x$	< 600 nm
$\gamma\varepsilon_y$	< 10 nm



Optics layout (2D EMS)



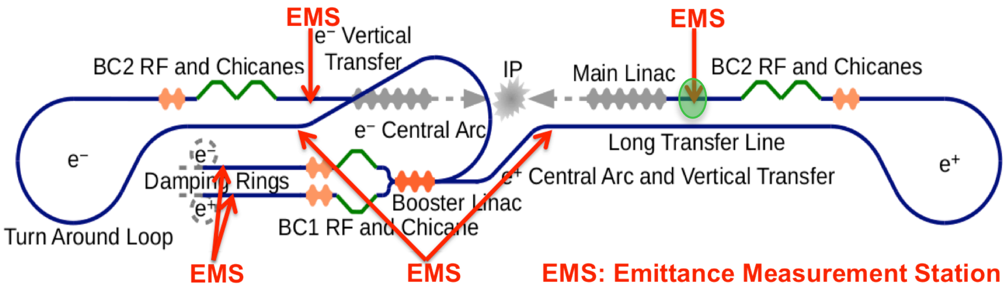
Multi-OTR System for CLIC RTML

OTR target damage study

At the end of RTML:

$\sigma_x \approx 24.6\ \mu m\ (\beta_x \approx 17.8\ m)$

$\sigma_y \approx 4.7\ \mu m\ (\beta_y \approx 39.8\ m)$



Material	$\frac{dE}{dz}\ \left[\frac{\text{MeV}}{\text{cm}}\right]$	ΔT_{inst} [K]	ΔT_{fr} [K]
Kapton	3.365	176.11	9240
Al	5.894	194.38	63.662
Be	3.779	85.984	222.28
Ti	9.302	314.44	441.06
W	33.061	1035.9	1059.7

Kapton, Be, Ti and W are below the fracture limit and Al surpasses such limit

Conclusions and Future Studies

- Multi-OTR systems can be used to make fast emittance measurements and contribute to the tuning of the RTML of Linear Colliders.
- They are intended to be used in single bunch or low charge mode operation of the machine.
- This system could be very useful during setup and commissioning phases.
- The key point is the selection of suitable materials to make OTR targets, which survive the impact of the pulses.
- According to the thermal calculations presented in this paper, Kapton and Be could be good candidates to be used as OTR radiators in the context of both the ILC and CLIC RTML.

Conclusions and Future Studies

From the point of view of the system itself:

- Making a turn-key and reliable system giving accurate and consistent measurements:
    - Technical improvements: camera gain and iris control, tilit and optical alignment
    - Issues: Systematic errors from intensity dependence and Wakefiels from simultaneous measurements

From the point of view of ILC and CLIC studies:

- The next step will be the study of a optimized system from the point of view of emittance reconstruction.

Thanks for your attention