LOW EMITTANCE MUON BEAMS FROM POSITRONS

Francesco Collamati (INFN-Roma)
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Outline

• Introduction: Why a muon collider
• Proposal for a novel technique for direct muon production
  • Target choice & accelerator scheme
  • Multi-turn simulations
  • Muons’ emittance
• Experimental tests
• Conclusion and perspectives
Why a Muon Collider?
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• PROs:
Why a Muon Collider?

• **PROs:**
  • Muons are ~200 times heavier than electrons:
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  • **Accelerator:**
    • No *synchrotron radiation* (limit of circular e⁺e⁻ colliders)
      ➔ much **higher energies** are reachable
      (~3TeV in 4km circumference)
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        ➜ much higher energy **resolution**
  • Precise measurements and access to new resonances
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        - much higher energy **resolution**
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  - **Physics:**
    - Higgs coupling \(\propto m^2\)
      - Much bigger production of Higgs boson (also s-channel)
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- **CONs:**
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  - **Muons decay** in $2.2 \mu s$!
  - The whole chain (generation, acceleration, interaction) must be very **quick**!
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• **CONs:**
  
  • **Muons decay** in $2.2\mu s$!
    
    • The whole **chain** (generation, acceleration, interaction) must be very **quick**!
  
  • Traditional muon production scheme leads to **large emittance** beams:
    
    $p + \text{target} \rightarrow \pi/K \rightarrow \mu$
  
  • Muons are produced with a variety of angles and energies ($P_\mu \sim 100\text{MeV}/c$)
  
  • **Cooling** needed!
    
    $\rightarrow$ tradeoff monochromaticity/luminosity
Direct muon production

Novel Approach
Direct muon production

• Exploiting the interaction of accelerated positrons on fixed target: $e^+ e^- \rightarrow \mu^+ \mu^-$
Direct muon production

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- **Advantages:**
Direct muon production

• Exploiting the interaction of accelerated positrons on fixed target: \( e^+ e^- \rightarrow \mu^+ \mu^- \)

• **Advantages:**
  
  • **Low emittance** possible:
    
    \( \theta_\mu \) is tunable with \( \sqrt{s} \), and is very small close to the threshold
Direct muon production

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• **Advantages:**
  
  • **Low emittance** possible: $\theta_\mu$ is tunable with $\sqrt{s}$, and is very small close to the threshold

  • **Small energy spread**: depends on $\sqrt{s}$, small at threshold ($210\text{MeV}$)
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    - **Low background:** low emittance allows for good luminosity with reduced muon flux
    - **Reduced losses** from decay: asymmetric collision allows high boost (and both muons’ collection)
Exploiting the interaction of accelerated positrons on fixed target: $e^+e^- \rightarrow \mu^+\mu^-$

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- **Low background**: low emittance allows for good luminosity with reduced muon flux
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**Disadvantages:**

- **Rate**: much smaller cross section wrt protons ($\mu$b vs mb)
Direct muon production

\[ \theta_{\mu}^{\text{max}} = \frac{4m_e}{s} \sqrt{\frac{s}{4} - m_\mu^2} \]

\[ \Delta E = \frac{\sqrt{s}}{2m_e} \sqrt{\frac{s}{4} - m_\mu^2} \]

\[ \sigma(e^+ e^- \rightarrow \mu^+ \mu^-) \]
Target choice
Target choice

- Due to low cross section, the target choice is crucial: 
  \[ N_{\mu\mu} = N_{e+\rho e-} L \sigma_{(e+e-\rightarrow \mu+\mu-)} \]
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- Criteria:
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- Criteria:
  - ↓ **emittance** → thin target
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- Due to low cross section, the target choice is crucial: $N_{\mu\mu} = N_{e^+\rho_e^-} L \sigma_{e^+e^- \rightarrow \mu^+\mu^-}$

- Criteria:
  - $\downarrow$ **emittance** $\rightarrow$ thin target
  - $\uparrow$ **rate** $\rightarrow$ high $Z$&$\rho$

\[
\mu \begin{align*}
\tag{7}
N_{\mu\mu} &= N_{e^+\rho_e^-} L \sigma_{e^+e^- \rightarrow \mu^+\mu^-} \\
\text{if } L \text{ was a drift} & \\
\text{Muons produced uniformly along target}
\end{align*}
\]
Target choice

• Due to low cross section, the target choice is crucial: $N_{\mu\mu} = N_{e^+e^-} L \sigma (e^+e^- \rightarrow \mu^+\mu^-)$

• Criteria:
  • ↓ emittance ➞ thin target
  • ↑ rate ➞ high Z&$\rho$
  • ↓ positron loss (brem.+bhabha) (recirculation) ➞ low Z
Target choice

- Due to low cross section, the target choice is crucial: \( N_{\mu\mu} = N_{e^+e^-}L\sigma(e^+e^-\rightarrow\mu^+\mu^-) \)

- Criteria:
  - ↓ **emittance** → thin target
  - ↑ **rate** → high Z&\( \rho \)
  - ↓ **positron loss** (brem.+bhabha)
    - (recirculation) → low Z
  - Very **intense e\(^+\) source** \( (10^{18} \text{ e}^+/\text{s } @T) \)
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  • ↓** emittance** \( \rightarrow \) thin target
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• Possible choices:
Target choice

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  - ↓ emittance $\rightarrow$ thin target
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- Possible choices:
  - Heavy materials (Cu...) $\iff$ thin target ($\varepsilon_{\mu} \propto L$)
    - Small $\varepsilon_{\mu}$, but high $\rho$ brings to MS and $e^+$ loss
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  - ↓ emittance $\Rightarrow$ thin target
  - ↑ rate $\Rightarrow$ high $Z$ & $\rho$
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  - Heavy materials (Cu...) $\Leftrightarrow$ thin target ($\varepsilon_{\mu} \propto L$)
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  - Very light materials $\Leftrightarrow$ thick target $O(1 \text{ m})$
    - Emittance growth due to extended production of muons
Target choice

- Due to low cross section, the target choice is crucial: \( N_{\mu\mu} = N_{e+\rho e-} L \sigma (e+e- \rightarrow \mu+\mu- ) \)

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  - \( \uparrow \) **rate** \( \rightarrow \) high Z&\( \rho \)
  - \( \downarrow \) **positron loss** (brem.+bhabha) (recirculation) \( \rightarrow \) low Z
  - Very **intense e\(^+\) source** (\( 10^{18} e^+ / s@T \))

- Possible choices:
  - Heavy materials (Cu...) \( \Leftrightarrow \) thin target \( (\varepsilon_\mu \propto L) \)
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  - Very light materials \( \Leftrightarrow \) thick target \( O(1m) \)
    - Emittance growth due to extended production of muons
  - Possible **tradeoff**: not too heavy materials (Be, C, Li) and not too thin target
Accelerator Scheme

(not to scale)
Accelerator Scheme

- **From $e^+$ source to ring:**
  - $e^-$ on conventional Heavy Thick Target (TT) for $e^+e^-$ pairs production
    - possibly with $\gamma$ produced by $e^+$ stored beam on T
  - Adiabatic Matching Device (AMD) for $e^+$ collection
  - Acceleration (linac / booster), injection

(not to scale)
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**e^+ ring:**
- A 6.3 km 45 GeV storage ring with target T for muon production
Accelerator Scheme

• **From e\(^+\) source to ring:**
  - e\(^-\) on conventional Heavy Thick Target (TT) for e\(^+\)e\(^-\) pairs production
    - possibly with γ produced by e\(^+\) stored beam on T
  - Adiabatic Matching Device (AMD) for e\(^+\) collection
  - Acceleration (linac / booster), injection

• **e\(^+\) ring:**
  - A 6.3 km **45 GeV** storage ring with target T for muon production

• **From μ\(^+\)μ\(^-\) production to collider:**
  - Produced by the e\(^+\) beam on target T with E(μ)\(\approx\)22GeV, γ(μ)\(\approx\)200 \(\rightarrow\) \(τ_{\text{LAB}}(μ)\)\(\approx\)500μs
  - Accumulation Ring: 60m isochronous and high mom. accept. for μ recomb. (\(τ_{\text{LAB}}(μ)\)\(\approx\)2500 turns)
  - Fast acceleration
  - Muon collider

(not to scale)
Accelerator Scheme

<table>
<thead>
<tr>
<th>e+ ring parameter</th>
<th>unit</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>km</td>
<td>6.3</td>
</tr>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>45</td>
</tr>
<tr>
<td>bunches</td>
<td>#</td>
<td>100</td>
</tr>
<tr>
<td>e+ bunch spacing = Trev (AR)</td>
<td>ns</td>
<td>200</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
<td>240</td>
</tr>
<tr>
<td>N(e+)/bunch</td>
<td>#</td>
<td>3 \cdot 10^{11}</td>
</tr>
<tr>
<td>U₀</td>
<td>GeV</td>
<td>0.51</td>
</tr>
<tr>
<td>SR power</td>
<td>MW</td>
<td>120</td>
</tr>
</tbody>
</table>

(also 28 km foreseen to be studied as an option)
Accelerator Scheme

<table>
<thead>
<tr>
<th>e⁺ ring parameter</th>
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<tr>
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Key topics for this scheme:
- Low emittance and high mom. acc.
- 45GeV e⁺ ring
- O(100kW) class target in the e⁺ ring
- High rate positron source
- High mom. acc. μ accumulator rings

(Also 28 km foreseen to be studied as an option)
6TeV μ collider draft
Parameters (no lattice yet)

\[ \mu^+\mu^- \text{ rate} = 9 \times 10^{10} \text{ Hz, } \varepsilon_N = 40 \text{ nm} \]
if: LHeC like e+ source with 25% mom. accept. e+ ring and \( \varepsilon \) dominated by μ production

thanks to very small emittance
(and lower beta*)
comparable luminosity
with lower \( N_\mu/\text{bunch} \)
(\( \rightarrow \) lower background)

Of course, a design study is needed to have a reliable estimate of performances
Radiological hazard due to neutrinos

Colin Johnosn, Gigi Rolandi and Marco Silari


muon rate:
\[ p \text{ on target option } 3 \times 10^{13} \mu/s \]
\[ e^+ \text{ on target option } 9 \times 10^{10} \mu/s \]
Low emittance 45GeV e\(^+\) ring

- Circumference 6.3 km: 197 m \times 32 cells (no injection section yet)
- Physical aperture=5 cm constant no errors
- Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies

<table>
<thead>
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<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV 45</td>
</tr>
<tr>
<td>Circumference</td>
<td>m 6300</td>
</tr>
<tr>
<td>Coupling(full current)</td>
<td>% 1</td>
</tr>
<tr>
<td>Emittance x</td>
<td>m (5.73 \times 10^{-9})</td>
</tr>
<tr>
<td>Emittance y</td>
<td>m (5.73 \times 10^{-11})</td>
</tr>
<tr>
<td>Bunch length</td>
<td>mm 3</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA 240</td>
</tr>
<tr>
<td>RF frequency</td>
<td>MHz 500</td>
</tr>
<tr>
<td>RF voltage</td>
<td>GV 1.15</td>
</tr>
<tr>
<td>Harmonic number</td>
<td># 10508</td>
</tr>
<tr>
<td>Number of bunches</td>
<td># 100</td>
</tr>
<tr>
<td>N. particles/bunch</td>
<td># 3.15 \times 10^{11}</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.068</td>
</tr>
<tr>
<td>Transverse damping time</td>
<td>turns 175</td>
</tr>
<tr>
<td>Longitudinal damping time</td>
<td>turns 87.5</td>
</tr>
<tr>
<td>Energy loss/turn</td>
<td>GeV 0.511</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>(1.1 \times 10^{-4})</td>
</tr>
<tr>
<td>RF acceptance</td>
<td>% \pm 7.2</td>
</tr>
<tr>
<td>Energy spread</td>
<td>dE/E (1 \times 10^{-3})</td>
</tr>
<tr>
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</tr>
</tbody>
</table>
Preliminary low-β IR for muon target insertion

• Further optimisations are underway:
  • Match the transverse minimum beam size with constraints of target thermo-mechanical stress
  • Match with other contributions to muon emittance (production, accumulation)
  • Dynamic and momentum aperture can be optimised

@target: $\beta_x = 1.6\text{ m}; \beta_y = 1.7\text{ m}; D_x = 5.4\text{ mm}$

@target location:
- $D_x \approx 0$
- low-β

Dynamic aperture

Momentum aperture
Multi-turn simulations
Multi-turn simulations

1. **Initial 6D** distribution from the equilibrium emittances
2. 6D $e^+$ distribution **tracking up to the target** (AT and MAD-X PTC)
3. Tracking **through the target** (FLUKA/GEANT4)
4. Back to tracking code
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- Gets an **angular kick** due to MS \(\rightarrow\) changes beam divergence and size \(\rightarrow\) **emittance increase**
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**At each pass** through the Target the $e^+$ beam:
- Gets an **angular kick** due to MS $\rightarrow$ changes beam divergence and size $\rightarrow$ **emittance increase**
- Undergoes **bremsstrahlung** energy loss $\rightarrow$ crucial role of **momentum acceptance** of $e^+$ ring
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⊕ **natural radiation damping**
Positron lifetime with Be target
Positron lifetime with Be target

beam lifetime $\sim 35$ turns

$37\%$

3mm Be Target (0.8% $X_0$)
Positron lifetime with Be target

beam lifetime ~35 turns

radiative loss is dominant
Positron lifetime with Be target

Beam lifetime \(~35\) turns

Radiative loss is dominant

Lifetime \(\propto 1/\text{thickness as expected}

\begin{align*}
\text{No. of particles} & \quad 10^3 \\
\text{turn} & \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \\
37\% & \quad \text{3mm Be Target (0.8\% Xo)}
\end{align*}
Multi-turn simulations

MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with 3 mm Be target along
Multi-turn simulations

MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with 3 mm Be target along after target, before turn
Multi-turn simulations

MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with 3 mm Be target along

after target, before turn

turn n 35

MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with 3 mm Be target along
Multi-turn simulations

MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with **3 mm Be** target along after target, before turn

**TARGET**

Geant4/FLUKA

**BEAM-LINE**

AT/MAD-X PTC

turn n 35

35 turns superimposed

MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with **3 mm Be** target along
Evolution of $e^+$ beam size and divergence

bremsstrahlung and multiple scattering artificially separated by considering alternatively effects in longitudinal (dominated by bremsstrahlung) and transverse (dominated by multiple scattering) phase space due to target; in blue the combination of both effects (realistic target)

- Some bremsstrahlung contribution due to residual dispersion at target
- Multiple scattering contribution in line with expectation \((n_D=\text{number of damping turns})\): \(\sigma_{\text{MS}} = \frac{1}{2} \sqrt{n_D \sigma_{\text{MS}}^2} \beta\)
- One pass contribution due to the target: \(\sigma_{\text{MS}} = 25 \mu\text{rad}\)
Muons’ emittance

$$\varepsilon(\mu) = \varepsilon(e^+) \oplus \varepsilon(\text{MS}) \oplus \varepsilon(\text{rad}) \oplus \varepsilon(\text{prod}) \oplus \varepsilon(\text{AR})$$

- $\varepsilon(e^+)$ = $e^+$ emittance
- $\varepsilon(\text{MS})$ = multiple scattering contribution
- $\varepsilon(\text{rad})$ = energy loss (brem.) contribution
- $\varepsilon(\text{prod})$ = muon production contribution
- $\varepsilon(\text{AR})$ = accumulator ring contribution

would like all contributions of same size. knobs:

- $\beta_x, \beta_y$ @ target & target material
- $\beta_x, \beta_y, D_x$ @ target & target material
- $E(e^+)$ & target thickness

AR optics & target

Now: $\varepsilon(\mu)$ dominated by $\varepsilon(\text{MS}) \oplus \varepsilon(\text{rad}) \rightarrow$ lower D & $\beta$s @ target with beam spot at the limit of target survival

Also test different materials:

- **Crystals** in channeling: better $\varepsilon(\text{MS}), \varepsilon(\text{rad}), \varepsilon(\text{prod})$
- **Light liquid jet** target: better $\varepsilon(\text{MS}), \varepsilon(\text{rad})$ and gain in lifetime & target thermo-mechanical characteristics
Test Beam

- Performed on the last week of July 2017, @CERN North Area (H4) founded by CSN1-INFN

- Use tertiary 45GeV e$^+$ beam, up to $5 \times 10^6$ /spill with amorphous targets, to:
  - measure muon production rate, cross section..
  - measure muons kinematic properties: emittance…

Expected $\sigma_{ee\mu \mu} < 1 \mu$b, 5 order of magnitudes smaller than Bhabha!
- a few muon pairs per spill

Proposal of a beam test to study the feasibility of a low emittance muon beam using positrons on target

M. Antonelli$^1$, F. Anulli$^2$, F. Bagli$^3$, F. Bedeschi$^4$, A. Bertolin$^5$, M. Biagini$^1$, M. Boscolo$^1$, R. Camattari$^3$, G. Cibinetto$^5$, F. Collamati$^1$, S. Dabagov$^1$, R. Di Nardo$^1$, M. Dreucci$^1$, V. Guidi$^3$, S. Guiducci$^1$, D. Lucchesi$^5$, A. Lupato$^5$, A. Mazzolari$^3$, L. Morandin$^5$, L. Palumbo$^2$, M. Prest$^6$, R. Rossin$^5$, M. Rotondo$^1$, L. Sestini$^5$, T. Spadarò$^1$, R. Tenchini$^4$, G. Tonelli$^4$, E. Vallazza$^6$ and M. Zanetti$^5$

1Frascati National Laboratory, INFN
2University La Sapienza, Rome and INFN
3University of Ferrara and INFN
4University of Pisa and INFN
5University of Padua and INFN
6University of Insubria and INFN
Summary

• A novel approach to muon production can allow the design of a muon collider:
  • Low emittance (⇒ no needing for cooling)
  • Low rate (⇒ target load)
• First design of low emittance e⁺ ring with preliminary studies of beam dynamics
• Optimisation requires other issues to be preliminary addressed
  • Target material & characteristics
  • e⁺ accelerator complex
  • Muons accumulator rings design
• Preliminary studies are promising, we will continue to optimise all the parameters, lattices, targets, etc. in order to assess the ultimate performances and the feasibility of such a machine
Backup
Muon Accumulator Rings considerations

- Isochronous optics with high momentum acceptance ($\delta \geq 10\%$)
- Multiple pass through the target leads to emittance increase due to Multiple Scattering:
  - Beam divergence:
    - A factor 3 (2) increase in beam divergence is expected at 45 (50) GeV
  - Beam size:
    - Depends on optics, need low-\(\beta\) to suppress size increase
  - This contributions can be strongly reduced with crystals in channeling

![Graph showing beam divergence vs. Accumulator turns with two curves for different electron energies]
Target considerations

- The goal is to have a beam size as small as possible, but:
- Constraints for **power removal** (200kW) and **temperature rise**
  ➔ move target (for free with liquid jet)
  ➔ e+ bump every 1 munch muon accumulation
- Possibilities:
  - **Solid target**: simpler and better wrt temperature rise:
    - Be, C
      - Be target: @HIRadMat safe operation with extracted beam from SPS,
        beam size 300 µm, N=1.7x10^{11} p/bunch, up to 288 bunches in one shot
  - **Liquid target**: better wrt power removal
    - Li, difficult to handle! lighter materials (H, He)
      - Lli jets examples from neutron production (Tokamak divertor). 200kW
        beam power removal seems feasible, minimum beam size to be understood
Multi-turn simulations

MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with 3 mm Be target along the ring (not at IR center in this example)
Preliminary considerations on $e^+$ source

The generator is made of $\text{NX}_0$ of Tungsten
Positrons in the target create photons at very small angles wrt to the beam (via Brem and (little) radiative bhabha: $e^+ e^- \rightarrow e^+ e^- \gamma$)

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Preliminary considerations on $e^+$ source

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Photons in the Generator create positrons
(via pair production)

These positrons could be accelerated and re-injected into the beam

The generator is made of NX$_0$ of Tungsten

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Preliminary considerations on $e^+$ source

Geant4 simulation

Total flux

Generator of $5X_0$ of W (1.8cm)
Preliminary considerations on $e^+$ source

**Geant4 simulation**

**Total flux**
**Geant4** simulation

Electron flux

Generator of $5X_0$ of W (1.8cm)

Be Target