



Advances of Synchrotron Radiation in FLUKA

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at Synchrotron Radiation Sources — RadSynch25

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With the advancements of **synchrotron radiation models**, and the addition of **photon reflectivity capabilities**, FLUKA can potentially be used for *end to end radiation/machine protection simulations of photon beams*.

Furthermore, since the 2021 addition of transport of charged particles in electric fields (including GHz E/B RF fields), as demonstrated in LCLS-II studies, simulations can start further upstream, *including acceleration of beams through cavities and transport along accelerator lines*.

This presentation focuses on synchrotron radiation modelling capabilities **(and how to use them!)** and the interrelation with the transport capabilities of charged particles in E/B fields.



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Available online at:
<https://www.epj-n.org>

Status and advances of Monte Carlo codes for particle transport simulation,
 edited by Andrea Zoia, Cheikh Diop and Cyrille de Saint Jean

REGULAR ARTICLE

OPEN ACCESS

The FLUKA code: Overview and new developments

The FLUKA Collaboration: Francesca Ballarini^{1,2}, Konstantin Batkov³, Giuseppe Battistoni⁴, Maria Giuseppina Bisogni^{5,6}, Till T. Böhlen⁷, Mauro Campanella⁴, Mario P. Carante^{1,2}, Daiyuan Chen⁸, Angelica De Gregorio⁹, Pavel V. Degtiarenko¹⁰, Pedro De la Torre Luque¹¹, Ricardo dos Santos Augusto¹², Ralph Engel¹³, Alberto Fassò¹⁵, Anatoli Fedynitch¹⁶, Alfredo Ferrari^{13,14,*}, Anna Ferrari¹⁷, Gaia Franciosini¹⁸, Aafke Christine Kraan⁶, Julie Lascaud¹⁹, Wenxin Li²⁰, Juntao Liu²⁰, Zhiyi Liu²⁰, Giuseppe Magro²¹, Andrea Mairani^{22,21}, Ilaria Mattei⁴, Mario N. Mazziotta²³, Maria C. Morone^{24,25}, Stefan E. Müller¹⁷, Silvia Muraro⁴, Pablo G. Ortega²⁶, Katia Parodi¹⁹, Vincenzo Patera^{18,27}, Lawrence S. Pinsky²⁸, Ricardo L. Ramos², Johannes Ranft^{29,†}, Valeria Rosso^{5,6}, Paola R. Sala^{30,**}, Mario Santana Leitner³¹, Giancarlo Sportelli^{5,6}, Thomas Tessonier²², Kristian S. Ytre-Hauge³², and Lorenzo Zana¹⁰

Most recent FLUKA developments are captured in the EPJ 2024 paper, but the latest synchrotron model is a newer feature



Synchrotron radiation from *any* charged particle can be simulated in FLUKA down to 1eV photons

Polarization of the synchrotron photons is accounted for as a function of their wavelength

A threshold can be set under which photons are considered “optical” within FLUKA

There are two ways to simulate synchrotron radiation:

- Previously existing implicit method as a special **source card**
- **New** explicit **coupled charged particle x photon** emission transport



In this method simulations start by **sampling the energy/direction** (and birth position) of synchrotron photons as “primaries” *from a virtual arc path of charged particles*.

A **built-in special source** function is invoked directly via the input file (**SPEC-SOURCE** / SYNC-RAD card).

The SPEC-SOUR card requires information on the magnetic field (strength, direction and extent/path) through which a specified charged particle (type & energy / momentum) *would* emit synchrotron radiation.

Up to two arcs (or helix in FLUKA2025.1+) can be described → this can be used to **simulate synchrotron radiation from most bends**.

Results are normalized per emitted photon, i.e., for most purposes they will need to be **rescaled to the number of charged particles**.

SYNCHROTRON EMISSION AS A SOURCE: example



For example, synchrotron radiation down to 1 eV is generated from a **1 GeV/c electron** beam through a **90° bend of 1 T field** perpendicular to the initial **z** beam direction:

```
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....
DEFAULTS                                                                                   PRECISION
#define Pbeam 1.0
#define Tfield 1.0
#define rhoc 100.0*Pbeam/(0.2998*Tfield)
#define arc 3.1415926*0.5*rhoc
* --+---1---+---2---+---3---+---4---+---5---+---6---+---7---+---
*           e-      p=1GeV      1 T      1 eV
SPEC SOUR    ELECTRON    $Pbeam    -$Tfield    1E-9      1.      0.0 SYNC-RAD
SPEC SOUR    $arc
BEAM POS     0.00      0.0      0.0      0.0000      0.0000      0.0
* --+---1---+---2---+---3---+---4---+---5---+---6---+---7---+---
```

SYNCHROTRON EMISSION AS A SOURCE: example

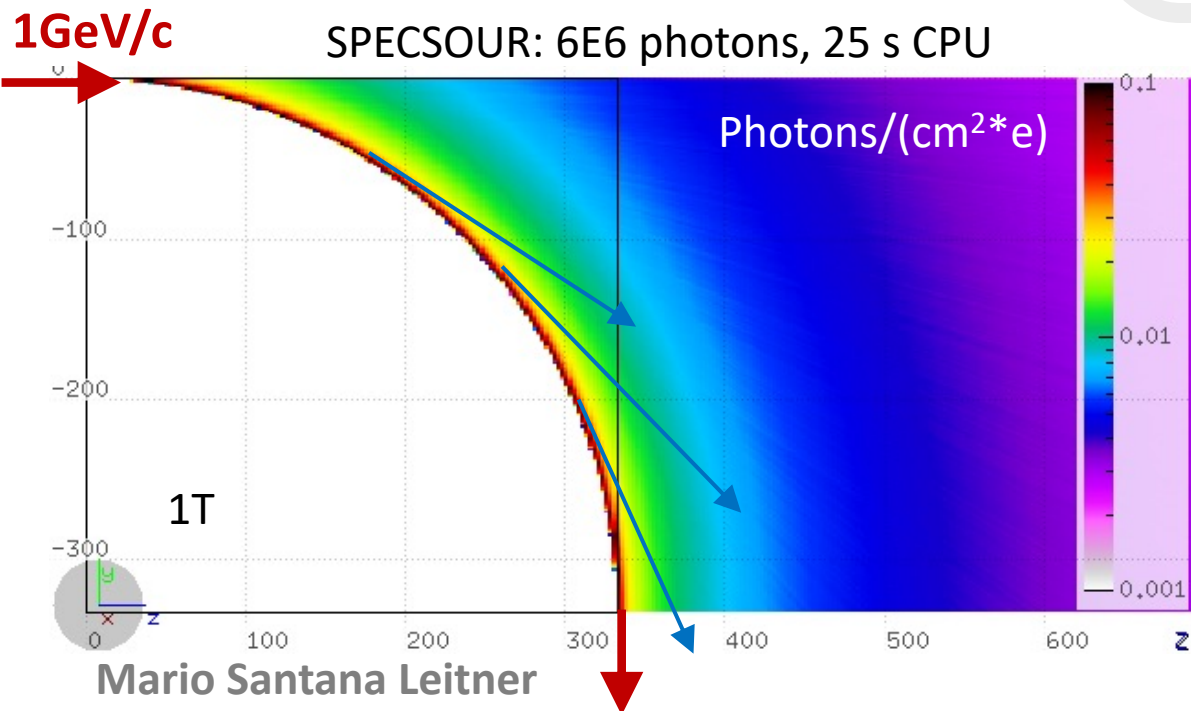


The output file(s), echo the arc [cm] and the photon emission per unit length [cm] (i.e., per electron) → the product of the two = photon yield, e.g., *27.825 photon/e⁻*

```
Nominal arc:      523.94807      cm
Arc angle:       1.5707568      rad
Actual curvature radius: 333.56410      cm
Actual arc:      523.94807      cm
Transverse p_T:  1.00000 GeV/c  and gamma: 1956.95145

Critical energy:  0.0000006650 GeV

Photon emission threshold      : 1.000000000E-09 GeV
Photons >1 eV/nominal unit length: 5.31071003E-02 cm^-1
```





Additional feature introduced in FLUKA2025.1

Activated via SYNCRAD card for selected vacuum regions (“SYNCRON” SDUM in the ASSIGNMAT card) with a magnetic field.

Like for the source implementation, it can be applied to *any charged particle* that FLUKA can track, and it can lead to photons of energy as low as 1 eV, with an option to set a threshold to differentiate optical photon treatment.

This implementation also allows for selectively enabling synchrotron radiation from *primary (beam) particles, or secondaries*, or all.

Charged particles do *not* need to be ultra relativistic; the lower limit is set at a Lorenz factor $\gamma_L=3$, i.e., 1.02 MeV kinetic energy electrons ($\beta_e=0.943$)

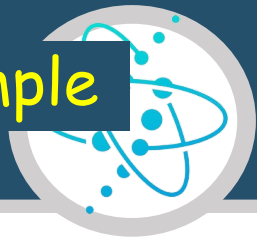


Loss of momentum of the charged particle in the generation of synchrotron radiation is accounted for (as illustrated later in this presentation).

It can be used to compute synchrotron radiation from bends (arcs), but also from **any trajectory** induced from **arbitrarily complex** magnetic fields.

Advancements (non 90° pitch restriction, inclusion of moderately relativistic regime) have also been ported back to the SPEC-SOURCE approach.

SYNCHROTRON EMISSION ALONG CHARGED PARTICLE PATH: *example*



The previous example was reproduced by having 1 GeV/c electrons ‘actually’ go through a dipole field of 1 T describing a 90° turn, with synchrotron radiation activated:

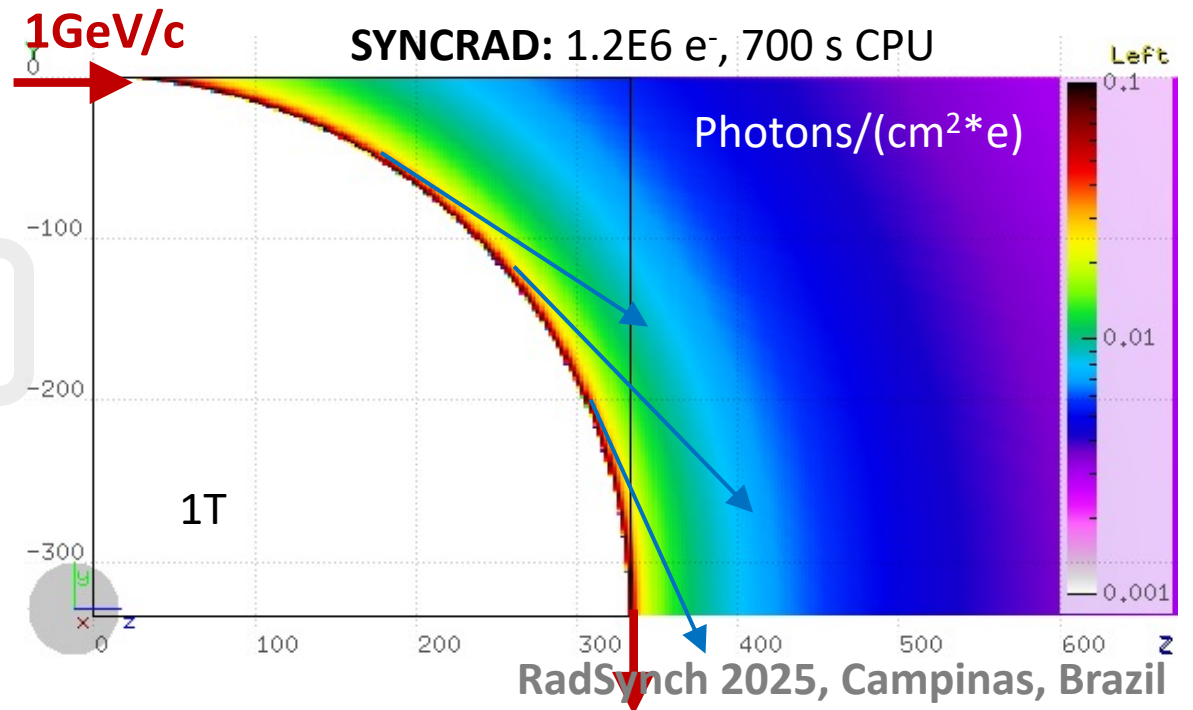
```
ASSIGNMA      VACUUM      MAGNV1      MAGNV1      1.0      SYNCRON
MGNFIELD      0.01      0.01      0.01      1.0      0.0      0.0RUNGKUTT
SYNCRAD      1.0      MAGNV1      MAGNV1      1.0      1.0
SYNCRAD      1E-9      1E-9      3.0      1.0      20.0      SYNCRALL
```

The output file(s), also list information that can be used to derive the photon yield and average energy.

```
Total number of sync. rad. photons generated:      5493294
Total weight of the sync. rad. photons generated:  5.493294E+06
Total energy of the sync. rad. photons generated:  1.308815E+00 GeV
```

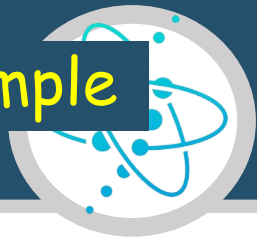
In the example, for each run of 2E5 electrons $\sim 5.49E6$ photons are generated, i.e., *27.482 photons/e⁻*

Mario Santana Leitner



RadSynch 2025, Campinas, Brazil

SYNCHROTRON EMISSION ALONG CHARGED PARTICLE PATH : *example*

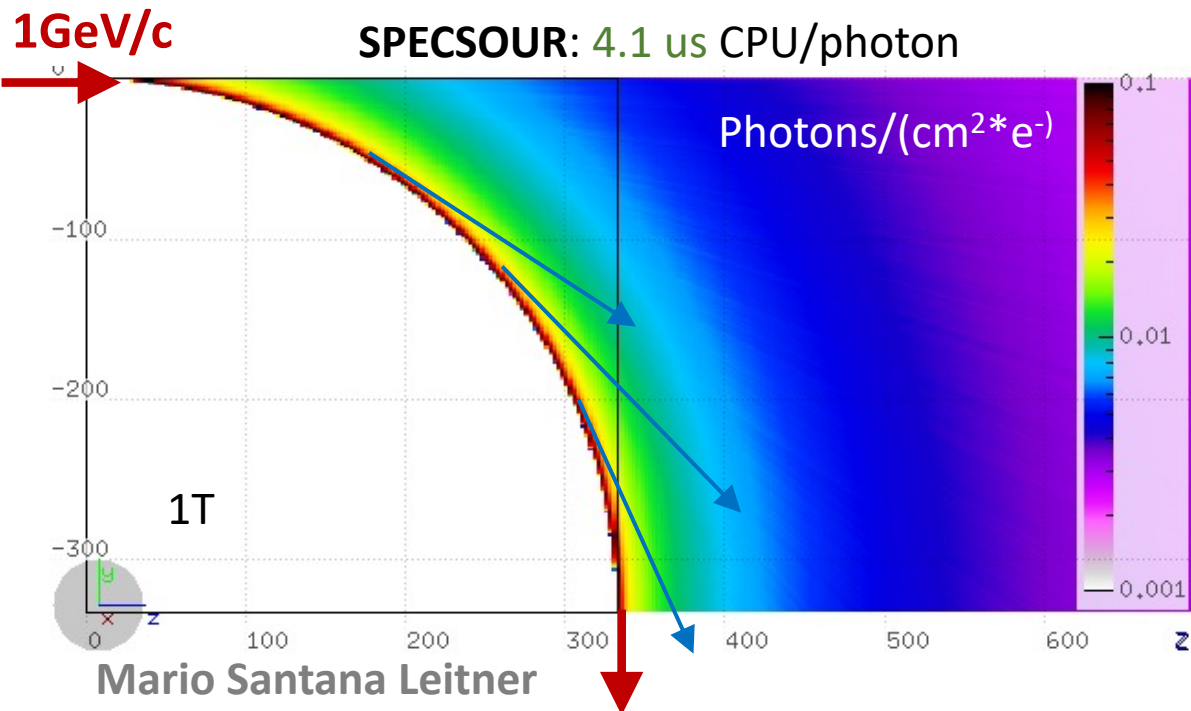


(fluences largely averaged over ± 5 cm in the perpendicular plane)

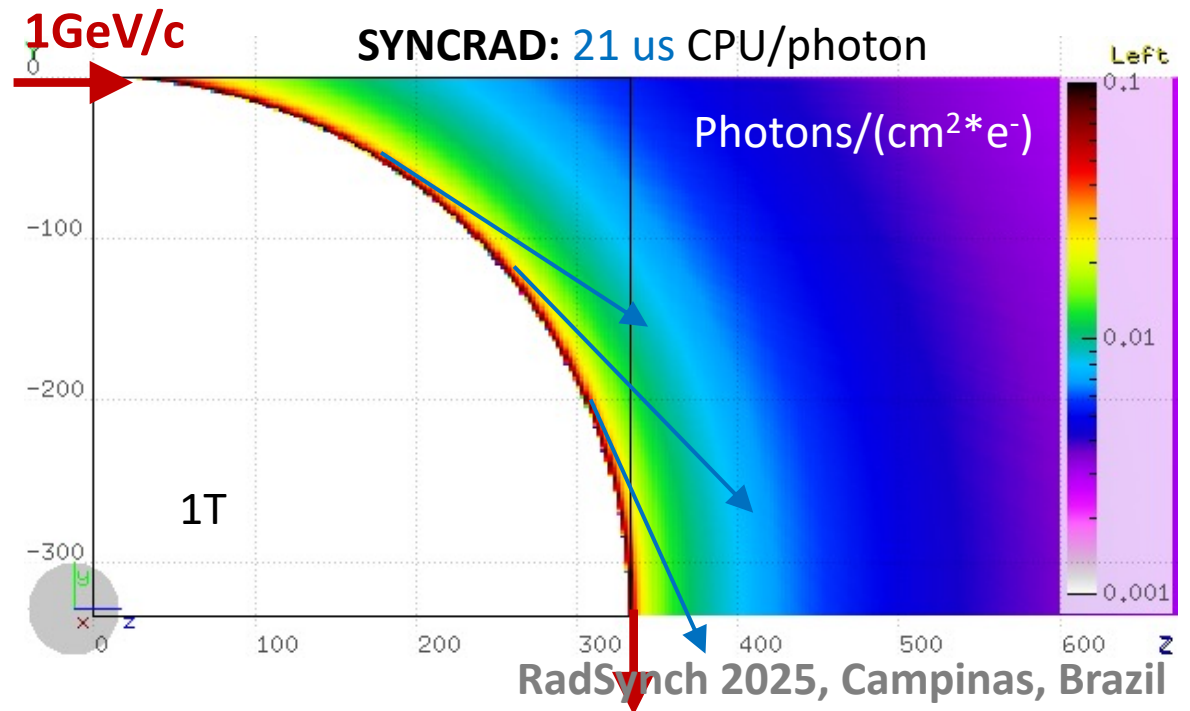
Virtually same results found with the two methods... ready to simulate more complex trajectories...

How about a wiggler?

27.825 [photon/e⁻]



27.482($\pm 0.04\%$) [photon/e⁻]



SYNCHROTRON EMISSION FROM A PLANNAR WIGGLER : *example*



A simple planar wiggler described with a single sinusoidal field $B(z) = B_0 \cos(Z*k_u)$ was simulated via the `magfld.f` FLUKA magnetic routine.

```
B = B0 * COS(ZCURR*ku)
IF ( B .LT. 0D0 ) THEN
  BTY = -BTY
  B = -B
END IF
```

From magfld.f

The following parameters were used:

$$B_0 = 1 \text{ T} \quad | \quad k_u = 2 \pi / \lambda_u \text{ with } \lambda_u = 4 \text{ cm} \text{ and } N_u = 10 \text{ periods}$$

The corresponding K value is: $\frac{eB_0}{k_u m_e c} = 3.74 > 1$

→ wiggler mode (vs. undulator), i.e., broadband spectrum resulting from the incoherent sum of emission in the $2*N$ bends

→ Monte Carlo approach is directly fully applicable

Note: for $K \ll 1$ (and $N \gg 1$) Monte Carlo approach can still be informative, but use with caution, especially at selected narrow angles or for wave-length dependent calculations

SYNCHROTRON EMISSION FROM A PLANNAR WIGGLER: *example*



A simple planar wiggler described with a single sinusoidal field $B(z) = B_0 \cos(Z*k_u)$ was simulated via the `magfld.f` FLUKA magnetic routine.

```
B = B0 * COS(ZCURR*ku)
IF ( B .LT. 0D0 ) THEN
  BTY = -BTY
  B = -B
END IF
```

From magfld.f

The following parameters were used:

NOTE: Maxwell laws not fulfilled by this simple field.

Realistic fields are more complex and include ramp-up/down modulation at each end of the undulator with tapering, etc.: implementations might need to sum the fields from the individual N magnets

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→ Monte Carlo approach is directly fully applicable

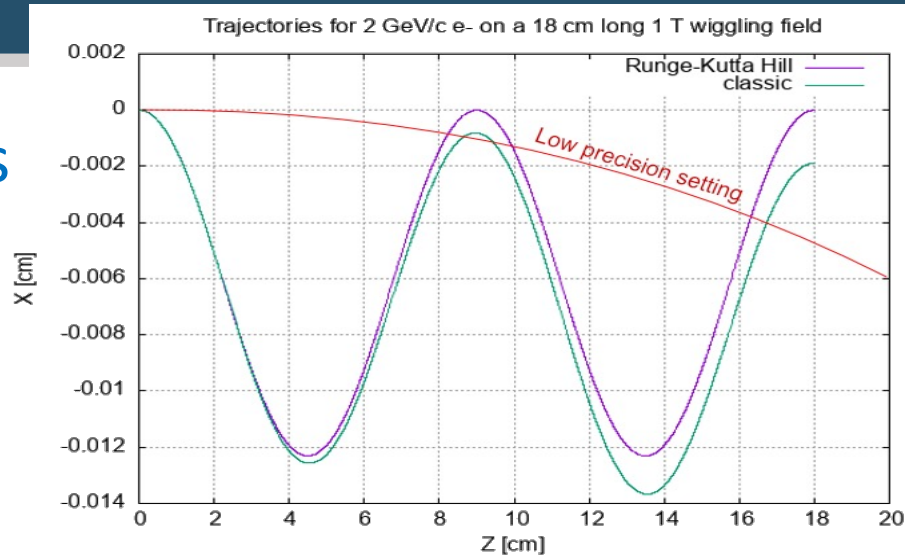
Note: for $K \ll 1$ (and $N \gg 1$) Monte Carlo approach can still be informative, but use with caution, especially at selected narrow angles or for wave-length dependent calculations

SYNCHROTRON EMISSION FROM A PLANNAR WIGGLER: *example*



It is imperative to **verify that electrons are precisely transported** through the wiggler before proceeding further

(The direction of incoming and outgoing electrons should also be unchanged...)



Examples of wrongly set fields leading to drifting or totally off trajectories (here STEPSIZE was not constrained)

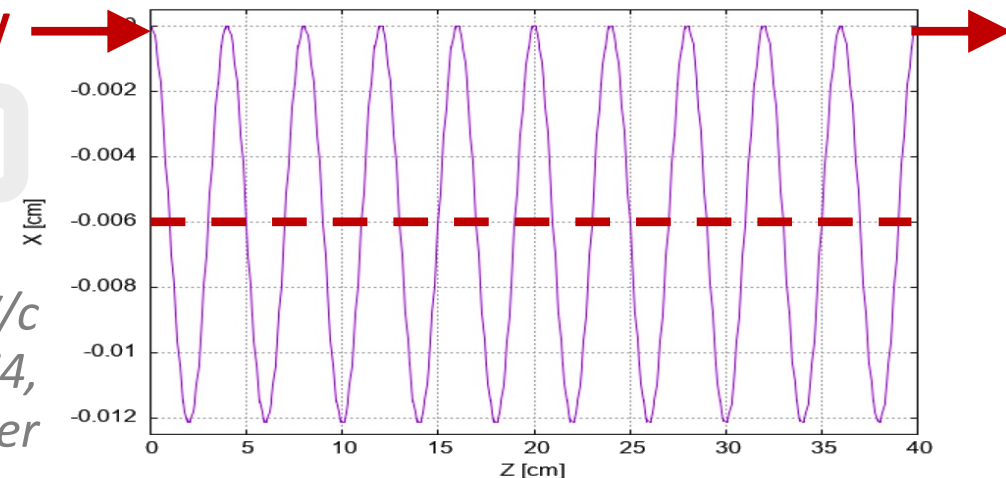
MGNFIELD and **STEPSIZE** cards are typically both needed to tighten the trajectory. ‘Recently’ introduced (2021) **Runge-Kutta-Hill** algorithm is often more efficient in non-uniform fields for equal precision settings

MGNFIELD	0.01	0.01	0.01	0.0	0.0	0.0	RUNGKUTT
STEPSIZE	0.0001	0.2	MAGNV1	MAGNV1	1.0		

NOTE: in this simple description the central trajectory of electrons in the undulator is offset with respect to the rest of the beamline

Trajectory of 20 MeV/c electrons through the $K=3.74$, $\lambda_u = 4$ cm, $N=10$ wiggler

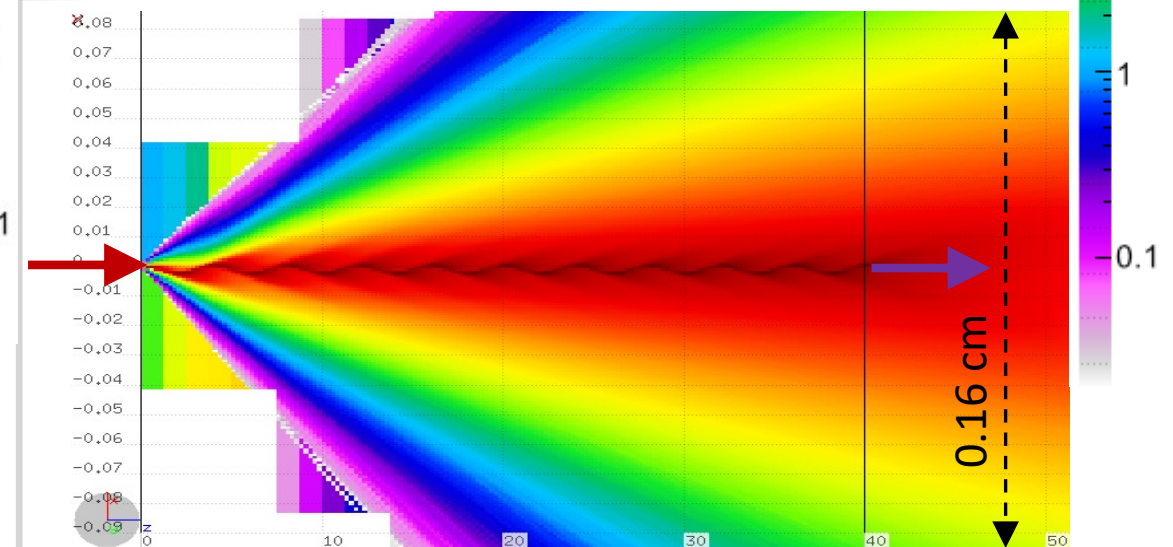
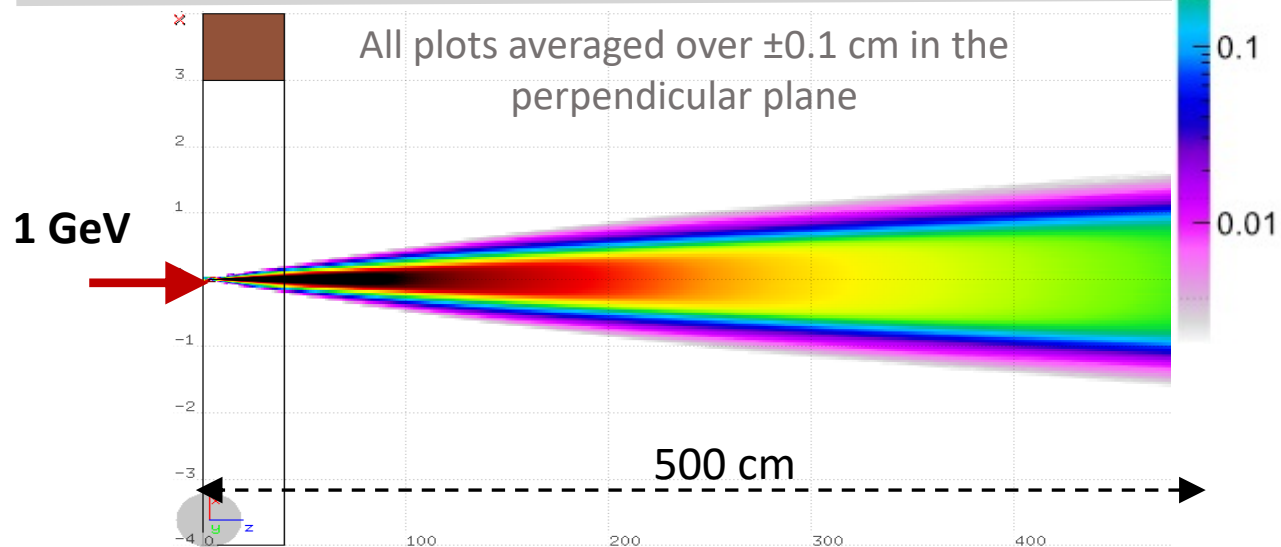
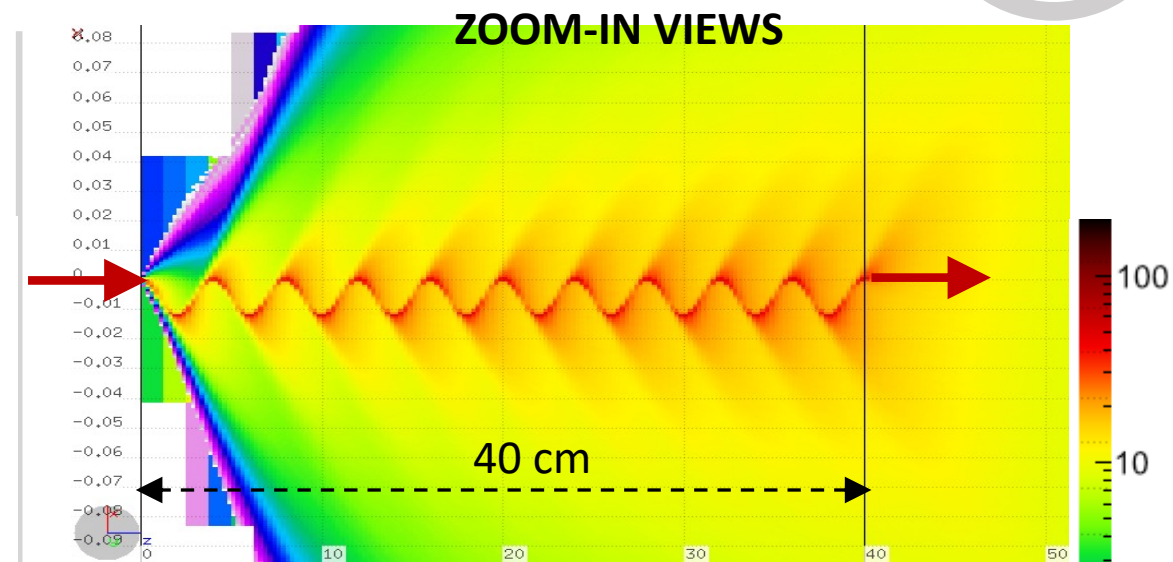
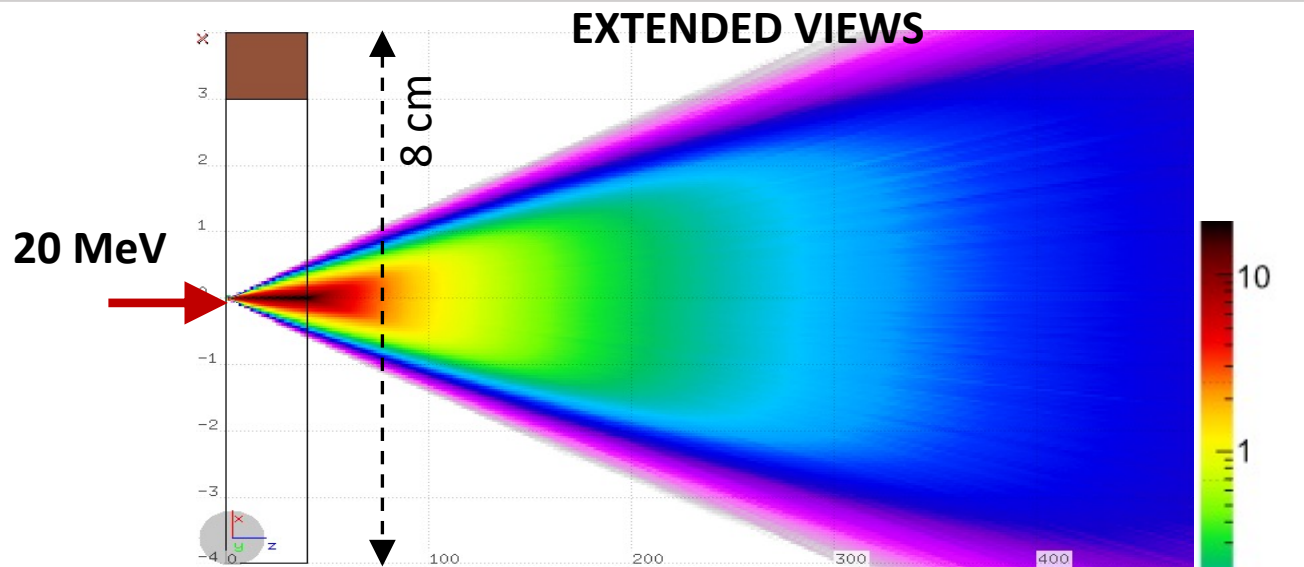
20 MeV →



SYNCHROTRON EMISSION FROM A PLANNAR WIGGLER: *example*



photons/(cm²·e⁻)

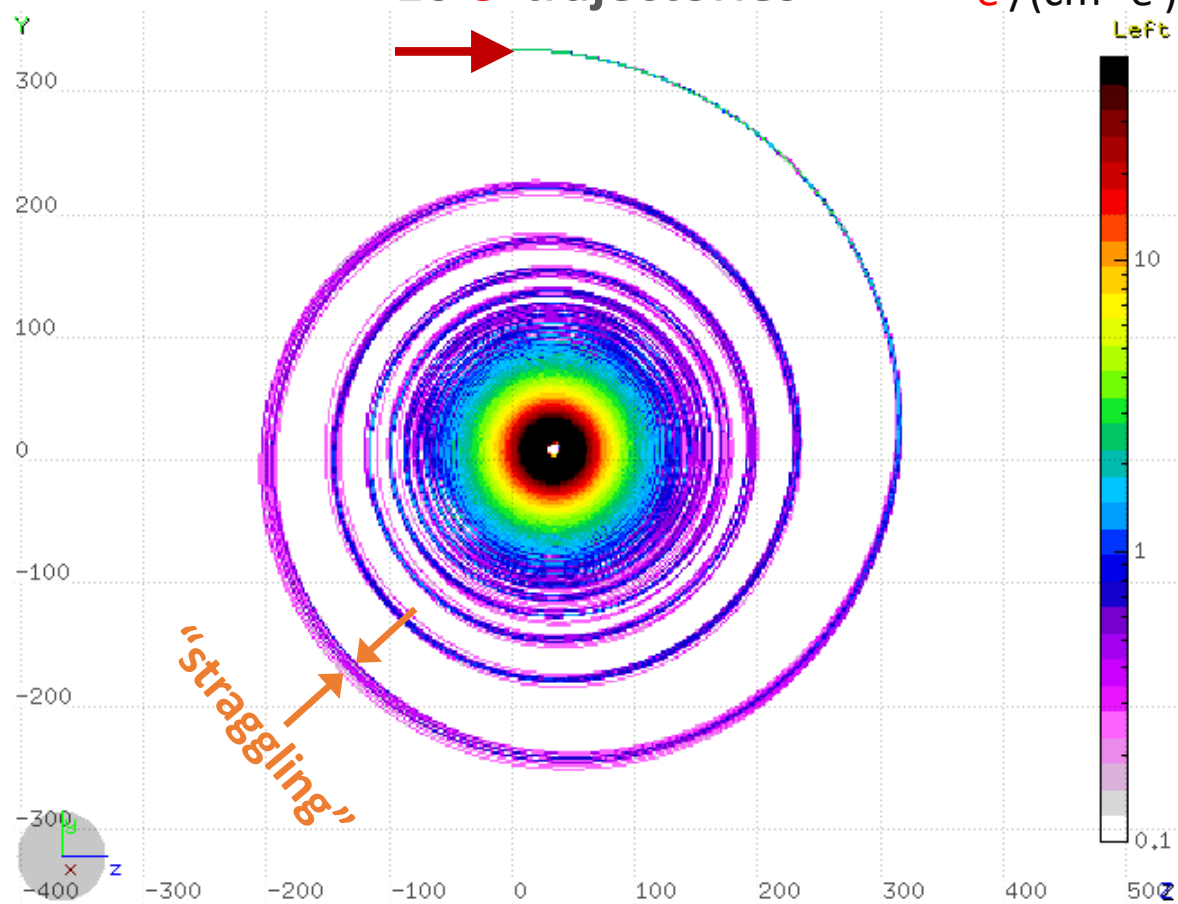


BEAM ENERGY LOSS VIA SYNCHROTRON EMISSION



30 GeV e^- beam on a 30 T field

10 e^- trajectories



As well known in this community, synchrotron emission is one important mechanism of energy loss of the stored beam.

FLUKA 2025.1+ fully couples the charged particle transport with the emitted photons.

Synchrotron emission is a stochastic process, intrinsically reproduced by FLUKA

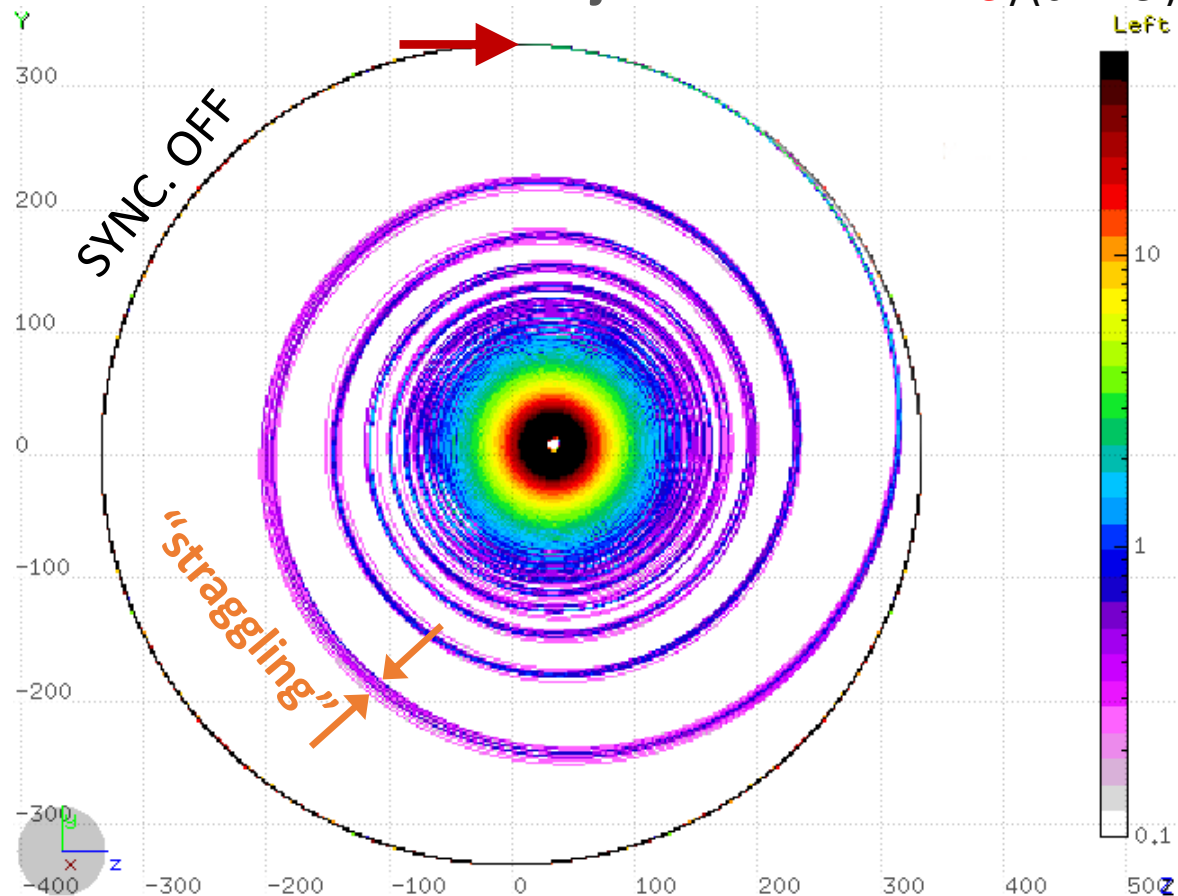
NOTE: TIME-CUT card with 9000 ns was set to avoid infinite spinning

BEAM ENERGY LOSS VIA SYNCHROTRON EMISSION



30 GeV e^- beam on a 30 T field

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Switching off Synchrotron emission, shows a correct circular trajectory (no precision-driven drift in multiple turns)

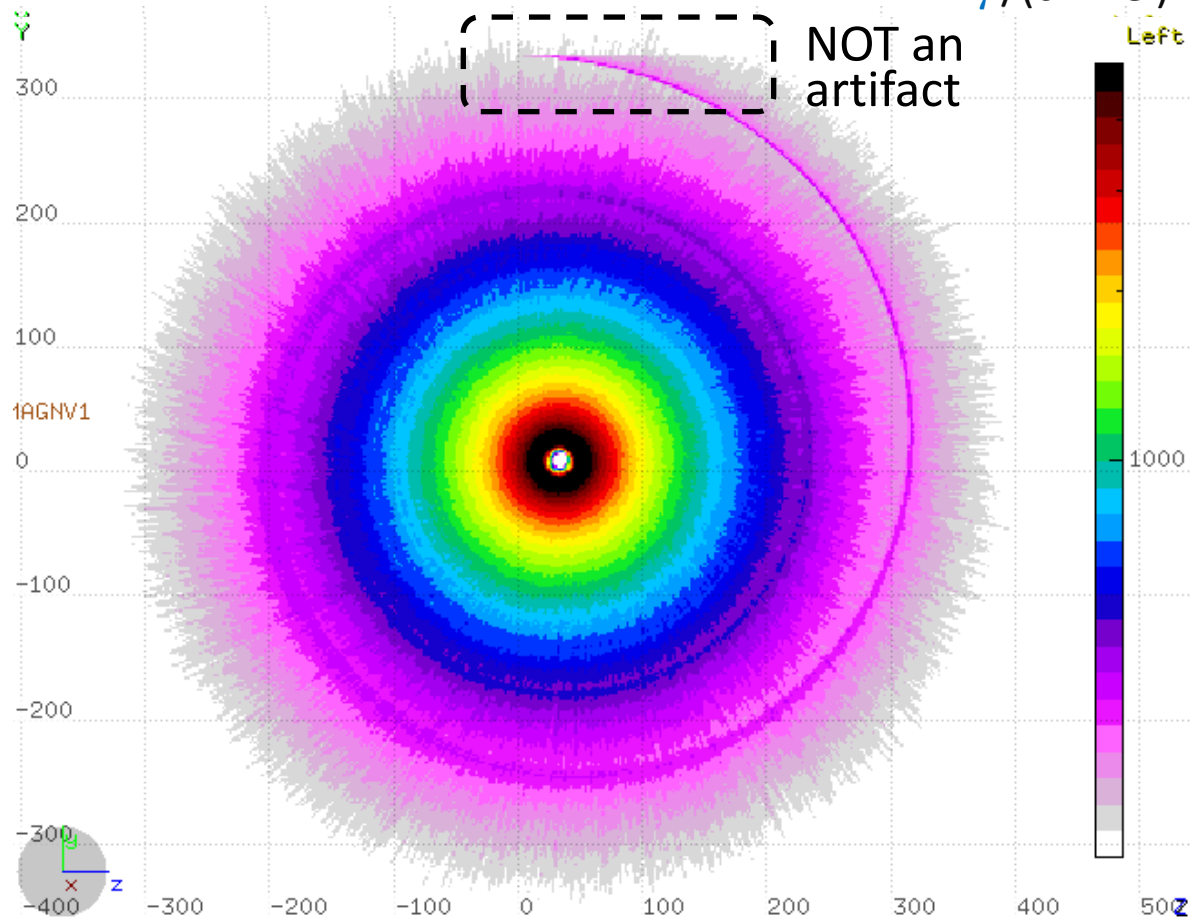
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BEAM ENERGY LOSS VIA SYNCHROTRON EMISSION



30 GeV e^- beam on a 30 T field

Photon emission > 1 eV $\gamma/(\text{cm}^2 \cdot e^-)$



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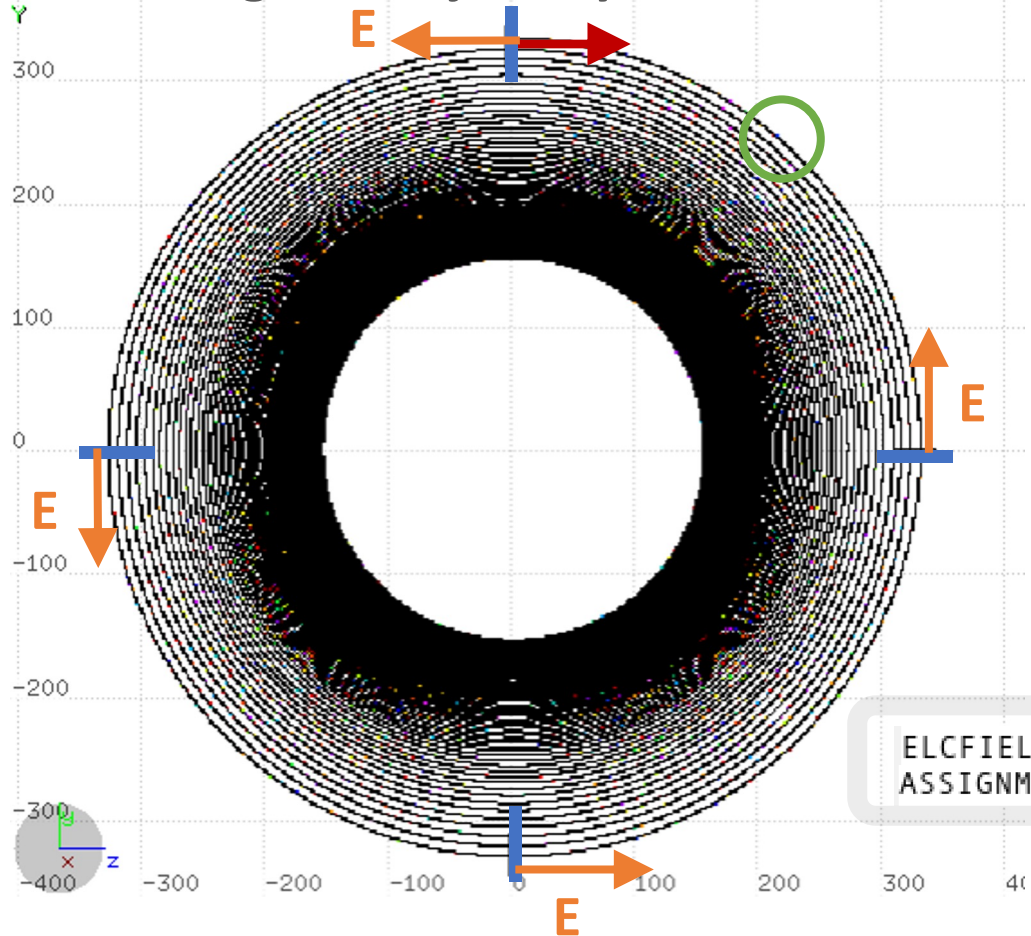
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BEAM ENERGY RESTORATION VIA **EFIELDS** (CAVITIES,...)



10 GeV e⁻ beam on a 10 T field
single e⁻ trajectory for 3000 ns



The RUNGE-KUTTA-HILL tracking that was mentioned earlier was added in 2021 to allow tracking of charged particles under arbitrarily complex **E-fields** (such as highly inhomogeneous GHz cycling RF E/B fields).

4 short 'cavities' splitting that energy were inserted to compensate radiative losses...

Measuring a step of ~ 8 cm in the 10 GeV / 10 T helical trajectory, a loss of ~ 230 MeV/turn (initial turns) is inferred.

ELCFIELD	0.01	0.01	0.01	0.0	0.0	0.0RUNGKUTT
ASSIGNMA	VACUUM	ELECA1	ELECA4		3.0	

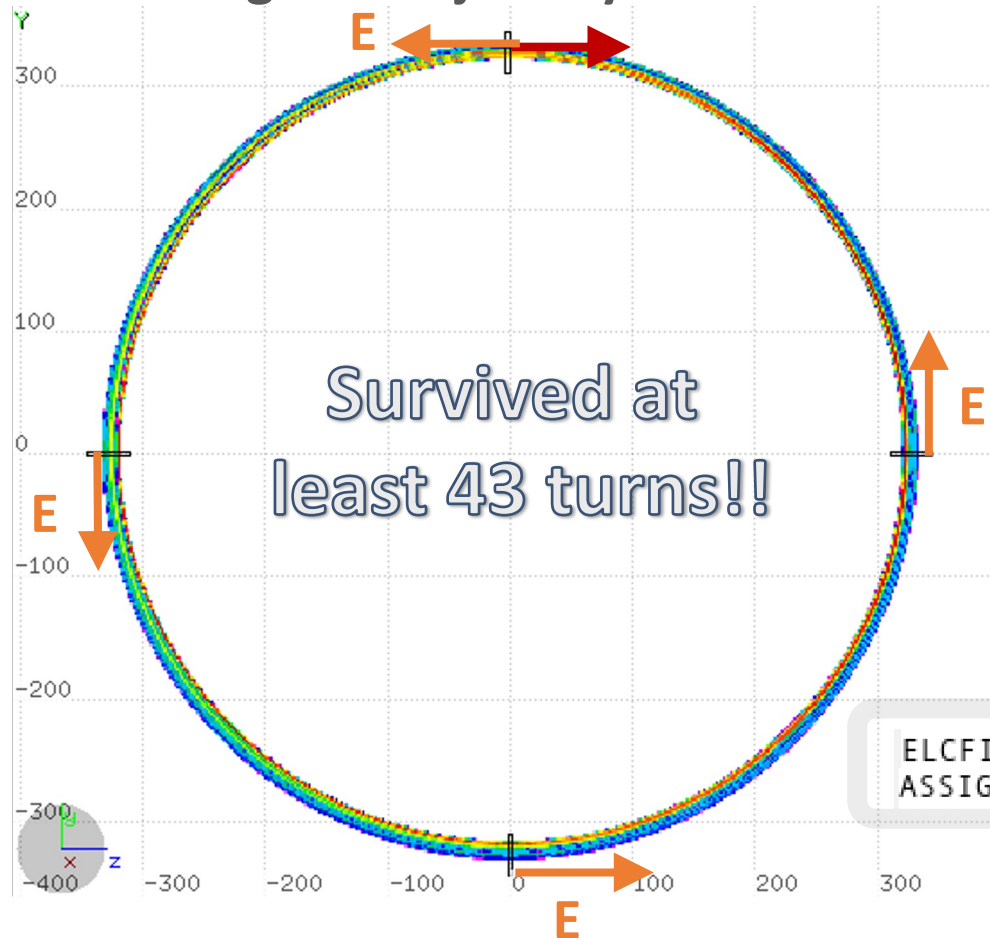
Both `elefld.f` and `magfld.f` routines were used

NOTE: **TIME-CUT** card with 9000 ns was set to avoid infinite spinning

BEAM ENERGY RESTORATION VIA **EFIELDS** (CAVITIES,...)



10 TeV e⁻ beam on a 10 T field
single e⁻ trajectory for 3000 ns



The RUNGE-KUTTA-HILL tracking that was introduced earlier was added in 2021 to allow tracking of charged particles under arbitrarily complex E-fields (such as highly inhomogeneous GHz cycling RF E/B fields).

4 short 'cavities' splitting that energy were inserted to compensate radiative losses...

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ASSIGNMA	VACUUM	ELECA1	ELECA4		3.0	

Both `elefld.f` and `magfld.f` routines were used

NOTE: **TIME-CUT** card with 9000 ns was set to avoid infinite spinning

EFIELDS - FIELD EMISSION (DARK CURRENT)



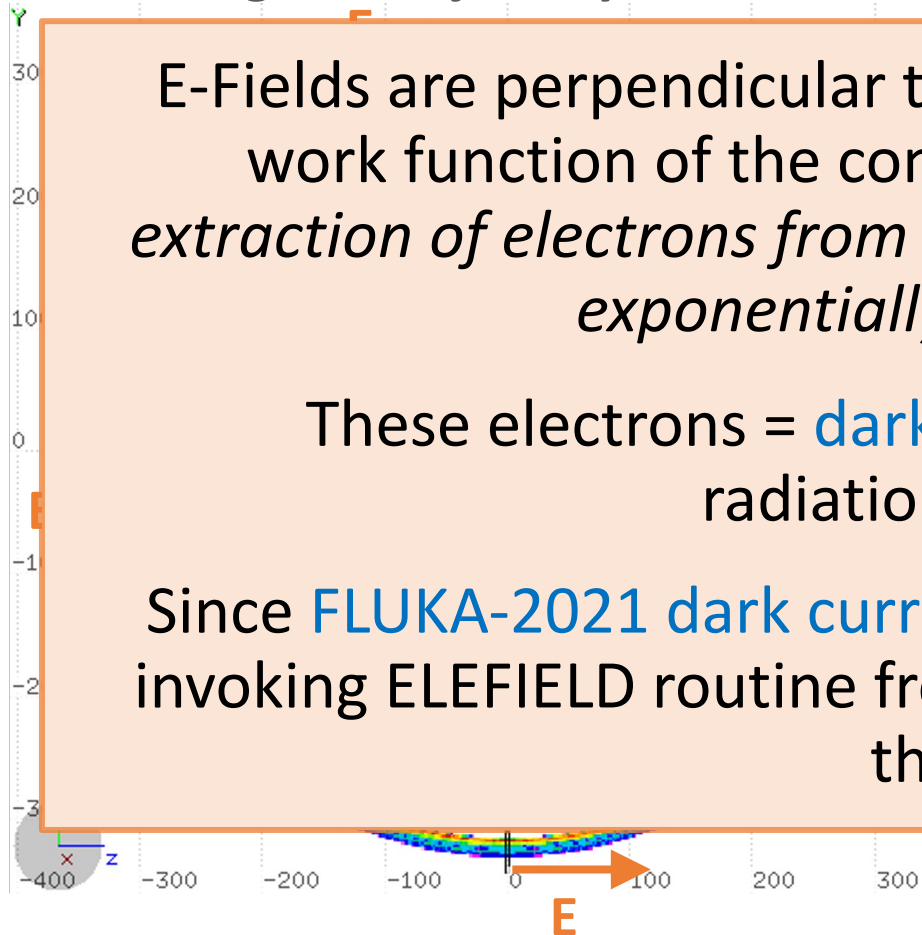
10 TeV e^- beam on a 10 T field
single e^- trajectory for 3000 ns

The RUNGE-KUTTA-HILL tracking that was introduced earlier was added in 2021 to allow

E-Fields are perpendicular to cavity walls, reducing (when in peak phase) the work function of the conductor (*Schottky effect*) and thereby enabling extraction of electrons from the metal lattice (*tunnel effect*), with a probability exponentially rising with the E-field amplitude.

These electrons = **dark current**, can get accelerated and become a radiation/machine protection hazard.

Since **FLUKA-2021 dark current generation and transport can be simulated** by invoking ELEFIELD routine from the source.f routine (generation) and enabling the subsequent transport



Both elefld.f and magfld.f routines were used

NOTE: **TIME-CUT** card with 9000 ns was set to avoid infinite spinning



New FLUKA models add capabilities to address the machine/radiation protection studies in light sources (among many other applications).

This is not meant to replace well established codes and efficient analytical codes, but rather to expand the available toolbox of this community.

Feedback and acknowledgements are both appreciated.



QUESTIONS ...?