EPFL

Overview of the FCC Software framework developments

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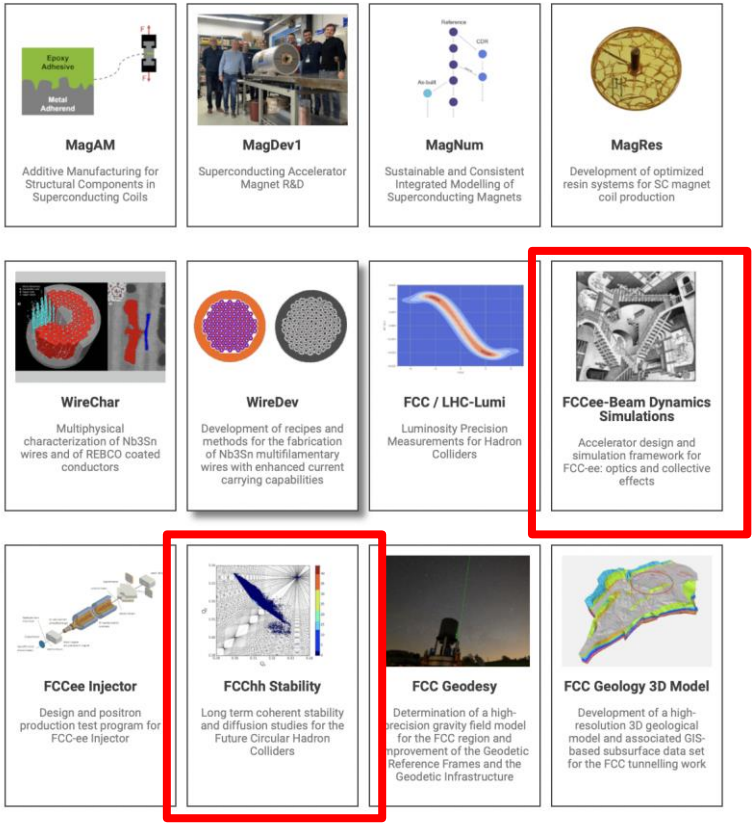
FCC Software Framework (SF) Project

Executive Abstract:
Develop a modular and expandable software framework for FCC-ee design and simulation work.
Includes a multi-turn, multiple interaction points model of a Future Circular Lepton Collider (FCC-ee) including a full lattice description with errors, beam-beam modules, beamstrahlung, radiative Bhabha scattering and strong damping for beam lifetime and particle losses studies in a self-consistent approach. Allow studies of collective effects interplay.



- FCC stability project : electron cloud studies
- ML4FCC project with Suisse Data Science Center (SDSC)
- Recently approved polarization project

www.chart.ch

FCC Software Framework

- **Review** of available tools: pyAT, Sixtrack/Xtrack, BMAD, GUINEAPIG, …
- **Identify key** parts/components of the **development** fundamental for FCC-ee studies
  - physics models (Beam-Beam, BS, lattice description, impedance, e-cloud…)
  - technical needs and benefits (different codes, speed, computing resources)
- Great **synergies with CERN ABP Computing WG** developments and modernization

  → develop a common, modern and robust tool for hadron and lepton community

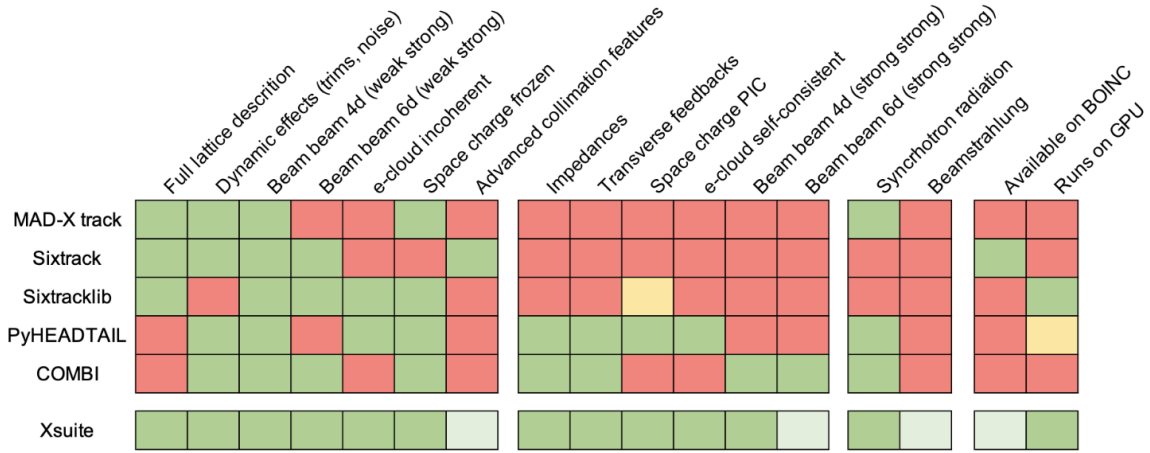
  → maintenance, reproducibility of results, extensive testing and debugging
- Define a general strategy for the developments to open **tools to a larger community/collaboration** i.e. FCC-ee, FCC-hh, muon, light sources…

GOAL: prepare for a simulation campaign where several effects interplay

XSUITE for LHC, HL-LHC and Injectors

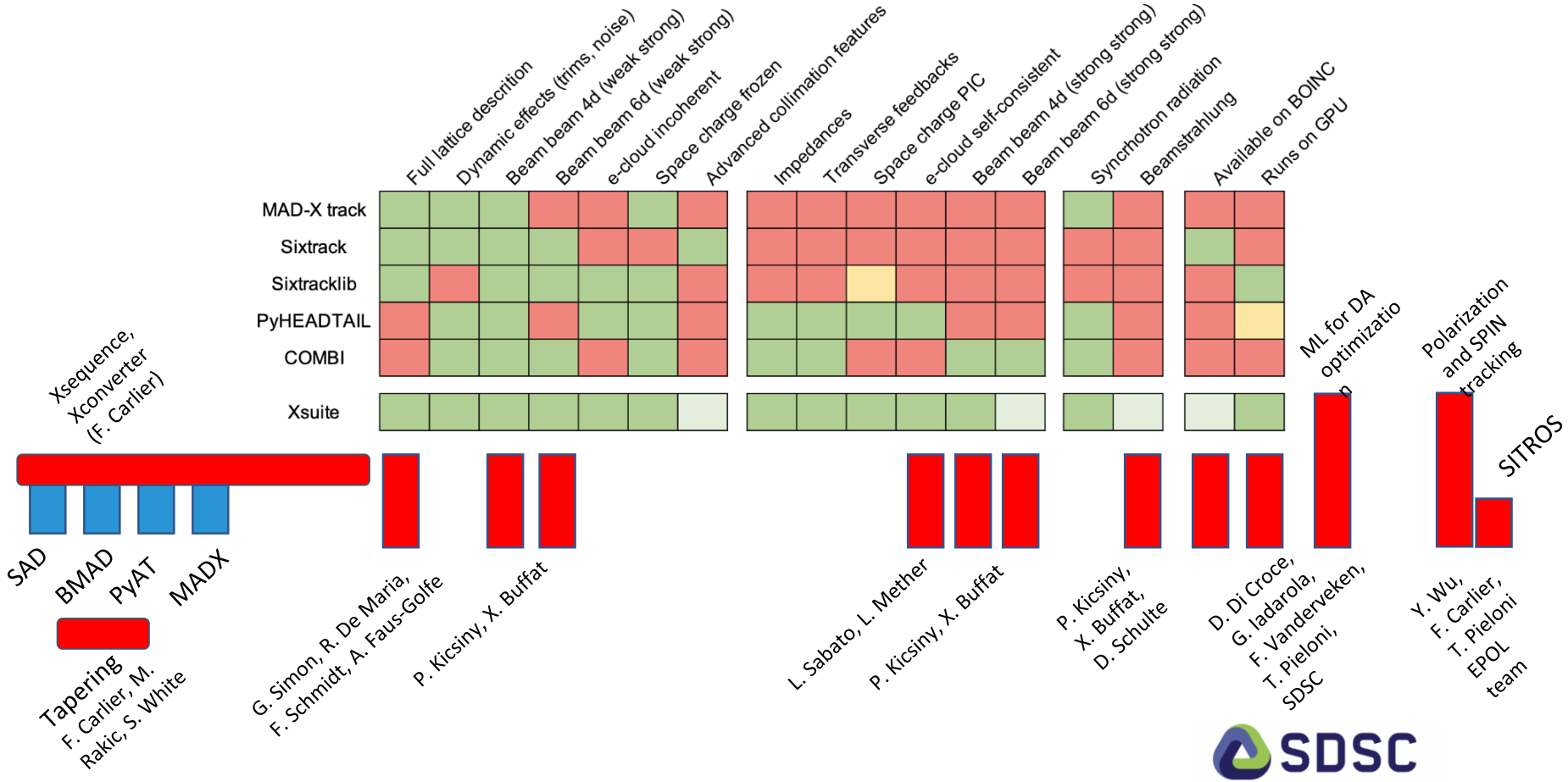
Project launched to **rationalize and modernize software for multiparticle simulations**

- Moved **from a heterogenous range of programs** each with limited capabilities to an **integrated modular toolkit** (Xsuite)
  - Covering with a single toolkit **injectors, LHC, HL-LHC and design studies** (**FCC Framework**)
  - Exploitation of **modern computing platforms** (e.g. GPUs) for a wide range of applications
  - Strong **simplification** of development and maintenance process (removes several duplications)

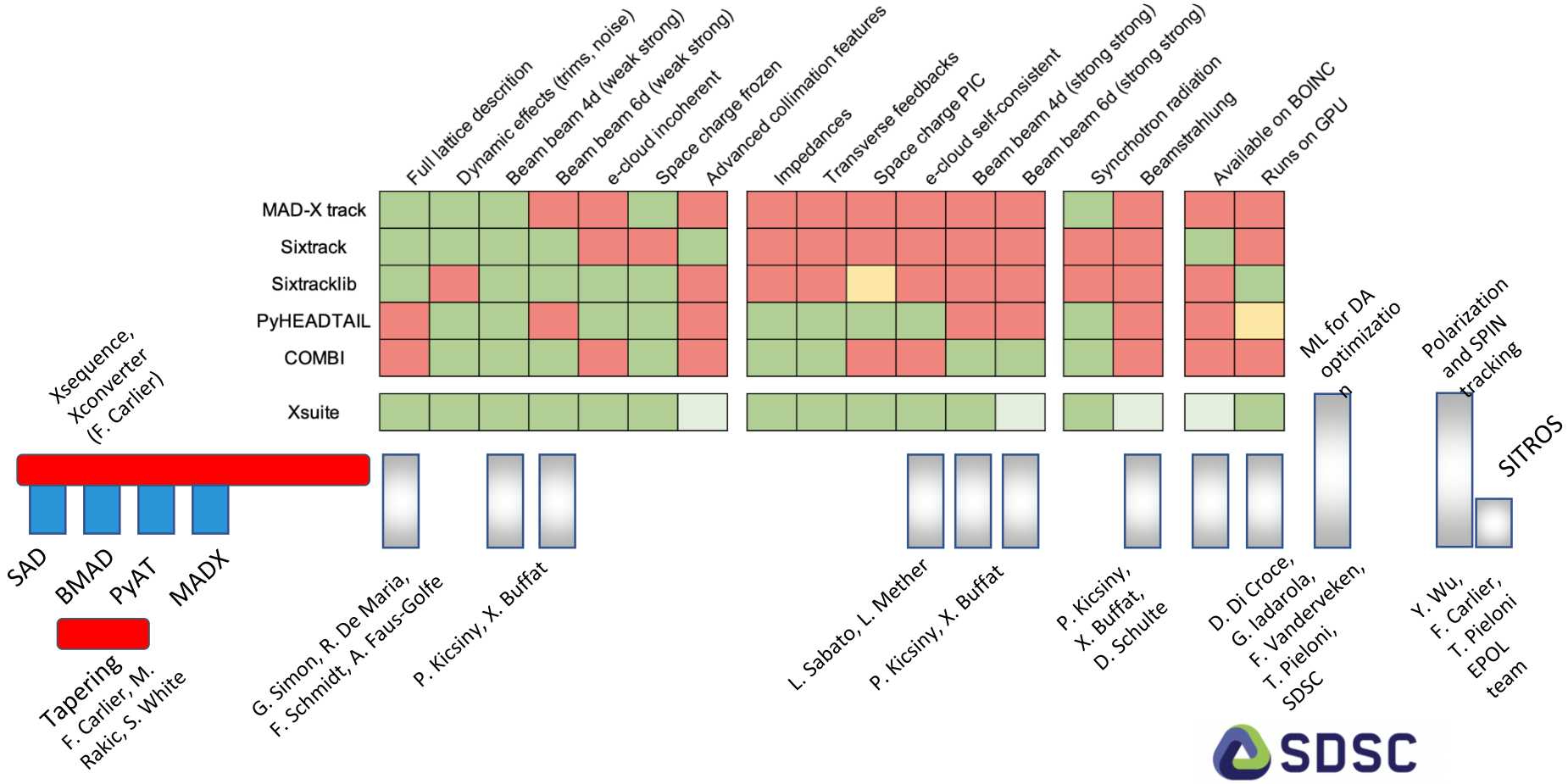


G. Iadarola
R. De Maria
and BE/ABP

Synergies and new developments



Lattice management and tapering

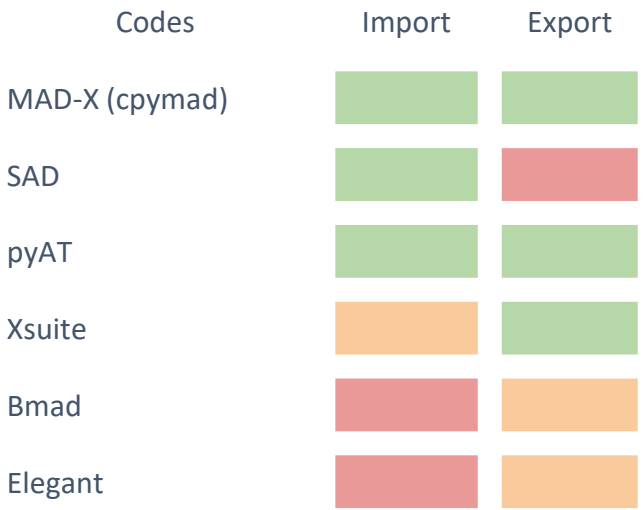


SDSC

Xsequence/Xconverter

Xsequence package being developed in the framework of FCC-ee in order to:

- Simplify **lattice conversions** to the different codes of interest
- Offer an **expandable platform** for users to contribute tools for specific conversions
- **Simplify the creation of models** for the large simulation campaigns by **controlling errors and tuning knobs**
- **Description of circuits** using **xdeps** package **(R. de Maria)**
- **Ensure model consistency** between platforms for comparative simulations



For more details:
https://indico.cern.ch/event/1085318/

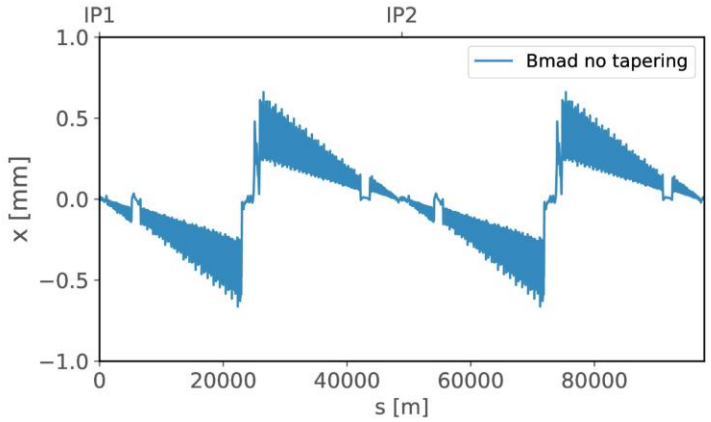
Tapering was developed for Bmad and pyAT

Loss of energy due to synchrotron radiation changes strength of:

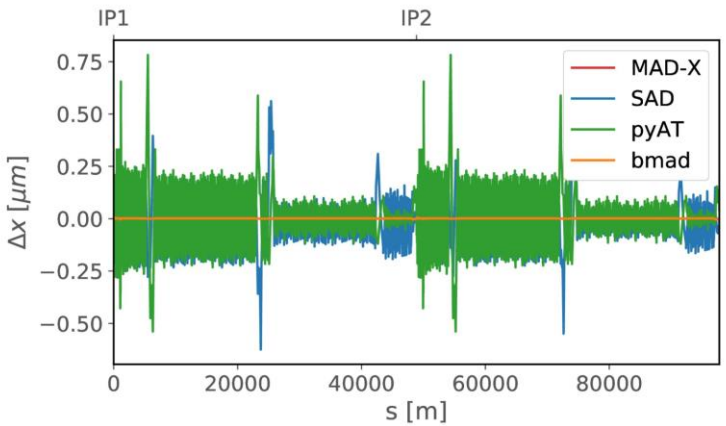
- Dipoles → Sawtooth orbit offsets throughout accelerator
- Other magnets → Perturbation of optics

Tapering scheme: Adjusting magnetic strengths to compensate for energy loss and retrieve reference orbit and optical functions

SAD comparison (L. van Riesen-Haupt)
https://indico.cern.ch/event/923801/
Bmad (F. Carlier)
https://indico.cern.ch/event/1018475/
pyAT (S. White, M. Rakic, F. Carlier)
https://indico.cern.ch/event/1018475/
F. Carlier
https://indico.cern.ch/event/995850/

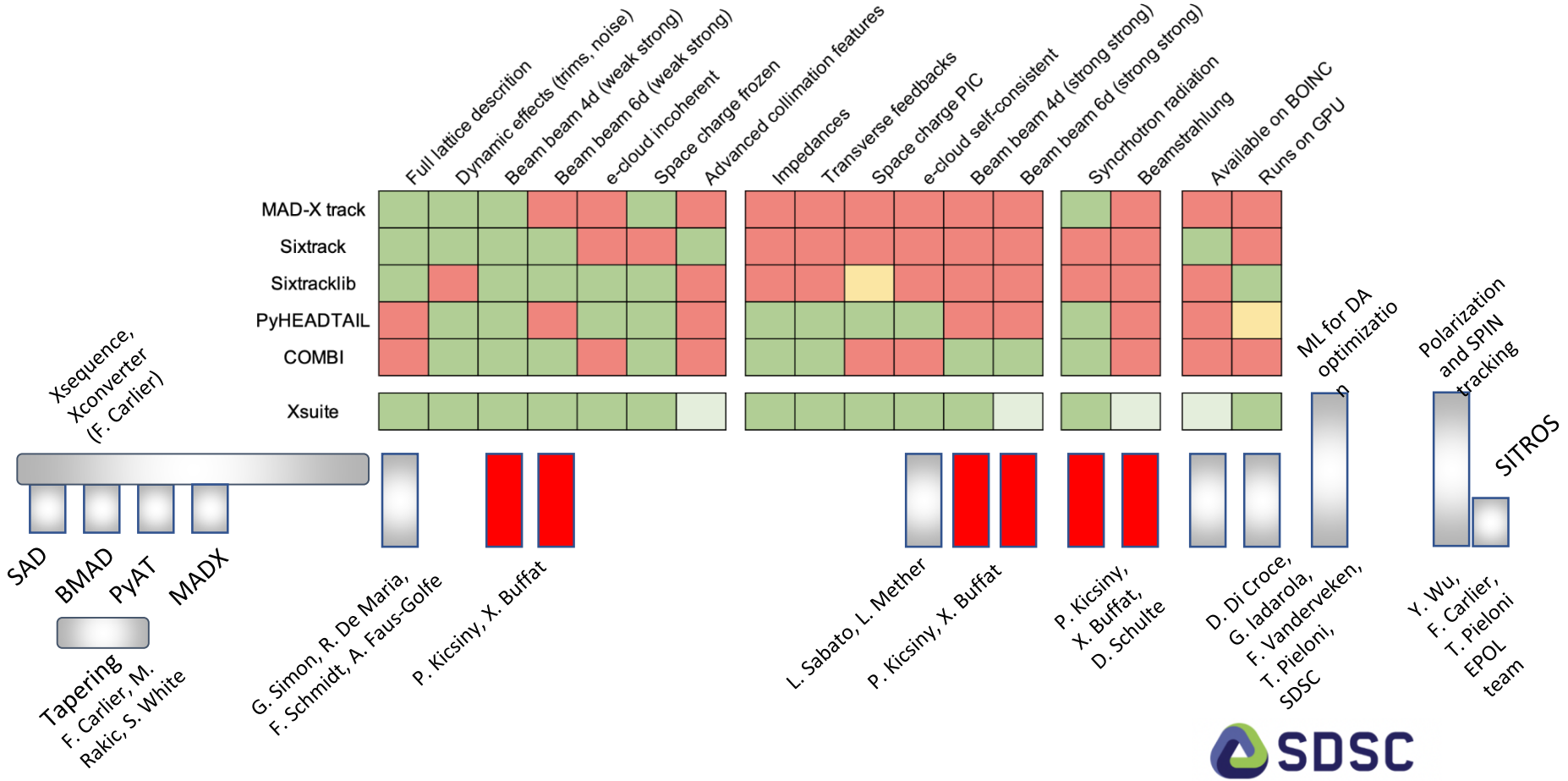


Tapering



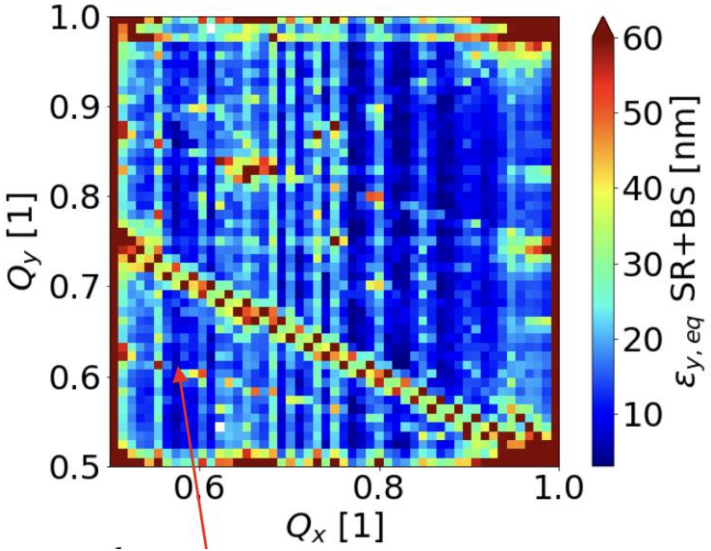
A. Abramov "FCC-ee Collimation Studies" at 16:45.

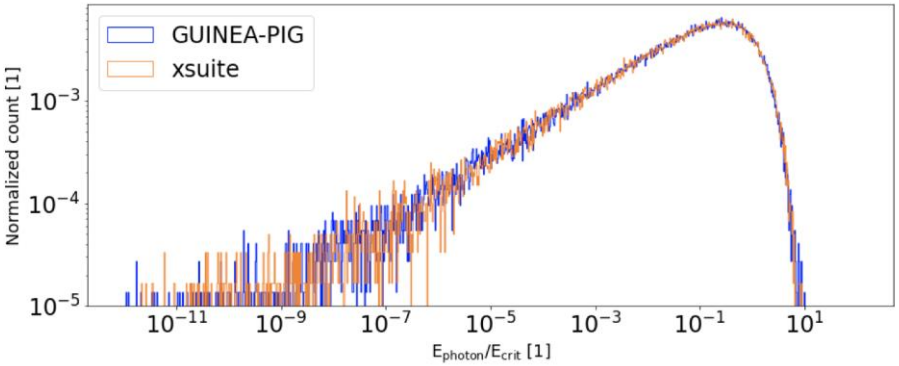
Beam-beam, Beamstrahlung, Synchrotron Radiation



Beam-Beam, Beamstrahlung, Synchrotron Radiation

- **Beam-beam simulations: SS, WS, Quasi SS**
- **Beamstrahlung** effect implemented and benchmarked
- **First pilot studies for FCC-ee** are ongoing including:
  - Synchrotron radiation
  - Strong-strong and Weak-strong 6D beam beam
  - Beamstrahlung



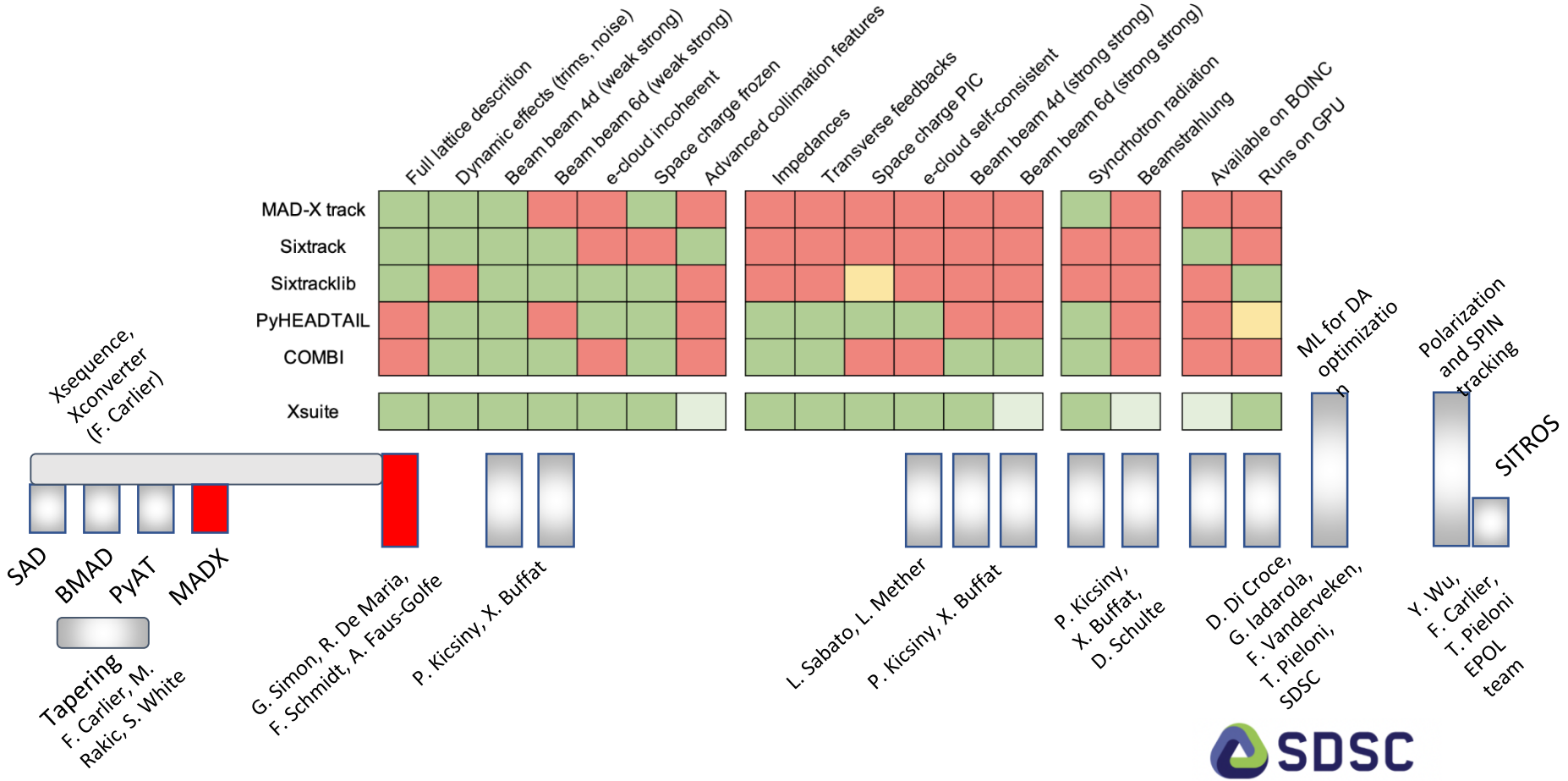


Next steps:

- Bhabha Scattering
- Crab Waist scheme

P. Kicsiny "Simulations of FCC-ee beam-beam effects with xsuite" this session

Lattice, imperfections and radiation



Lattice, imperfections and radiation

- **Invest on MAD-X code to create a solid platform for FCC-ee**
  - MAD-X already used for FCC-ee studies, has synergies with many other projects.
- **Radiation effects in MAD-X** used in many FCC-ee studies:
  - Few calculations have shown inconsistent results related to thin multipole elements and solenoid
  - Some usability issues have been identified related to tapering in the last version
- **Stabilize radiation calculations in MAD-X**
  - Review and document radiation related physics applied to MAD-X
  - Compare calculations on FCC-ee or other test lattices using different methods such as direct tracking, map formalism, radiation integral formalism
  - Coordinate with optics studies for defining priorities such as interaction region modelling and vertical emittance studies

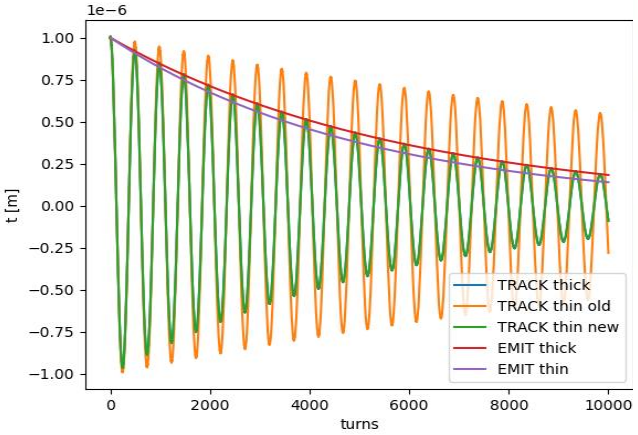
R. De Maria talk on MADX in this session

Lattice, imperfections and radiation

Investigating different tracking methods in MADX

- Identified and corrected bug in TRACK for thin multipole resulting in incorrect damping times
- Collected other issues that are under investigations:
  1) tapering introduces optics beating
  2) equilibrium emittance not correct for tilted solenoid
  3) twiss energy loss does not take the gamma of the closed orbit correctly into account
  4) issue with radiation of multipoles in track and emit
  5) adding ktap on additional elements
  6) synchrotron radiation integrals zero with zero length elements

Deterministic damping

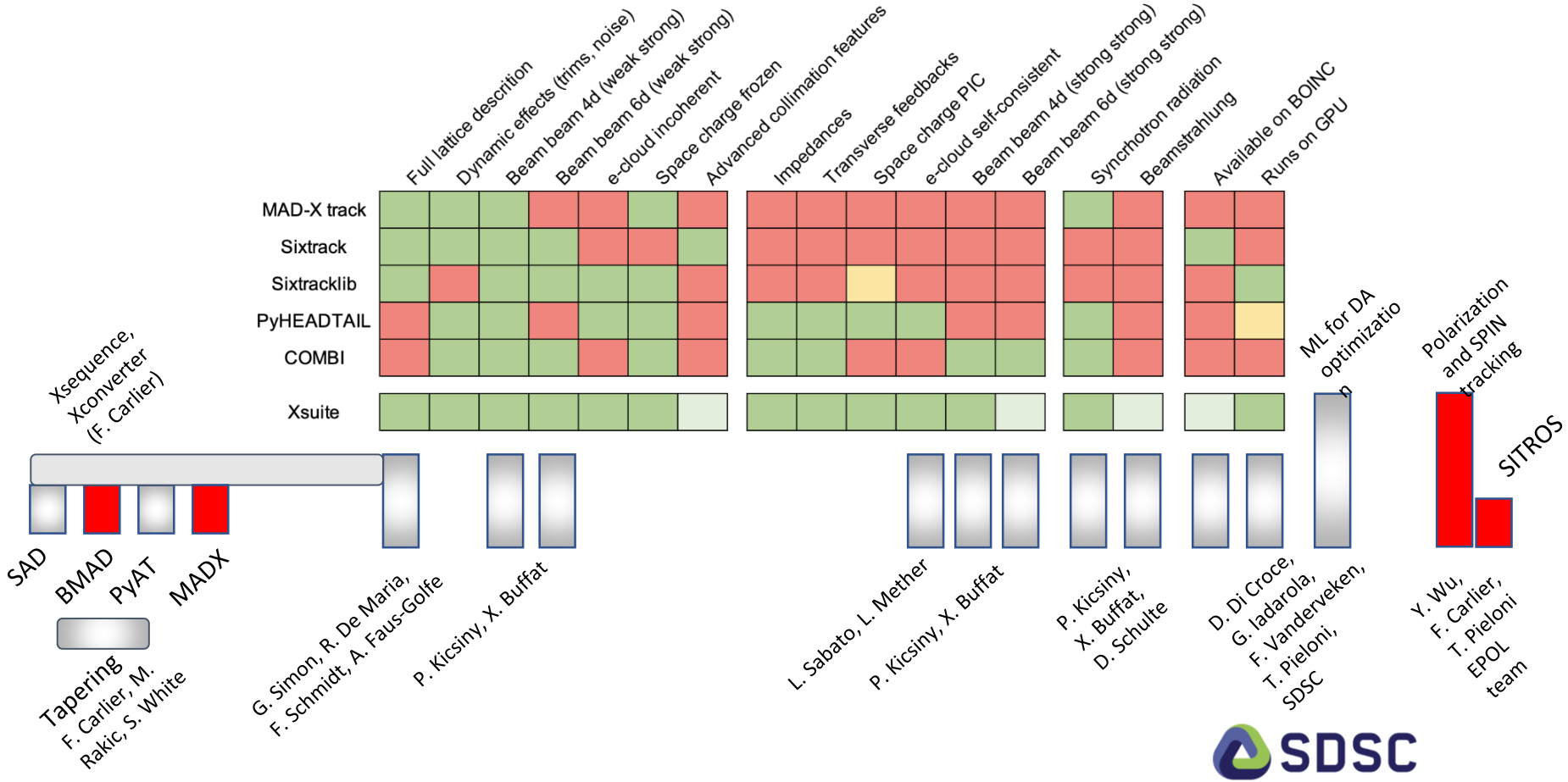


$$t[turns] = t_0 e^{-\alpha_t T_0 \, turns}$$

Method	Damping constant $\alpha_t[1/s]$
EMIT Thick	196.3
EMIT Thin	227.4
TRACK Thick	196.3
TRACK Thin (before fix)	70.12
TRACK Thin (after fix)	198.4
Twiss thin using $D = \frac{\oint k_0 D_x (k_1 + k_0^2)\, ds}{\oint k_0^2 \, ds}$ $\alpha_t = \frac{W_0}{2E_0 T_0}(2 + D)$	198.2

G. Simon poster session Thursday 17:30: "Synchrotron radiation improvements in MAD-X for FCCee studies**"**

Polarization and spin tracking



Polarization and Spin dynamics

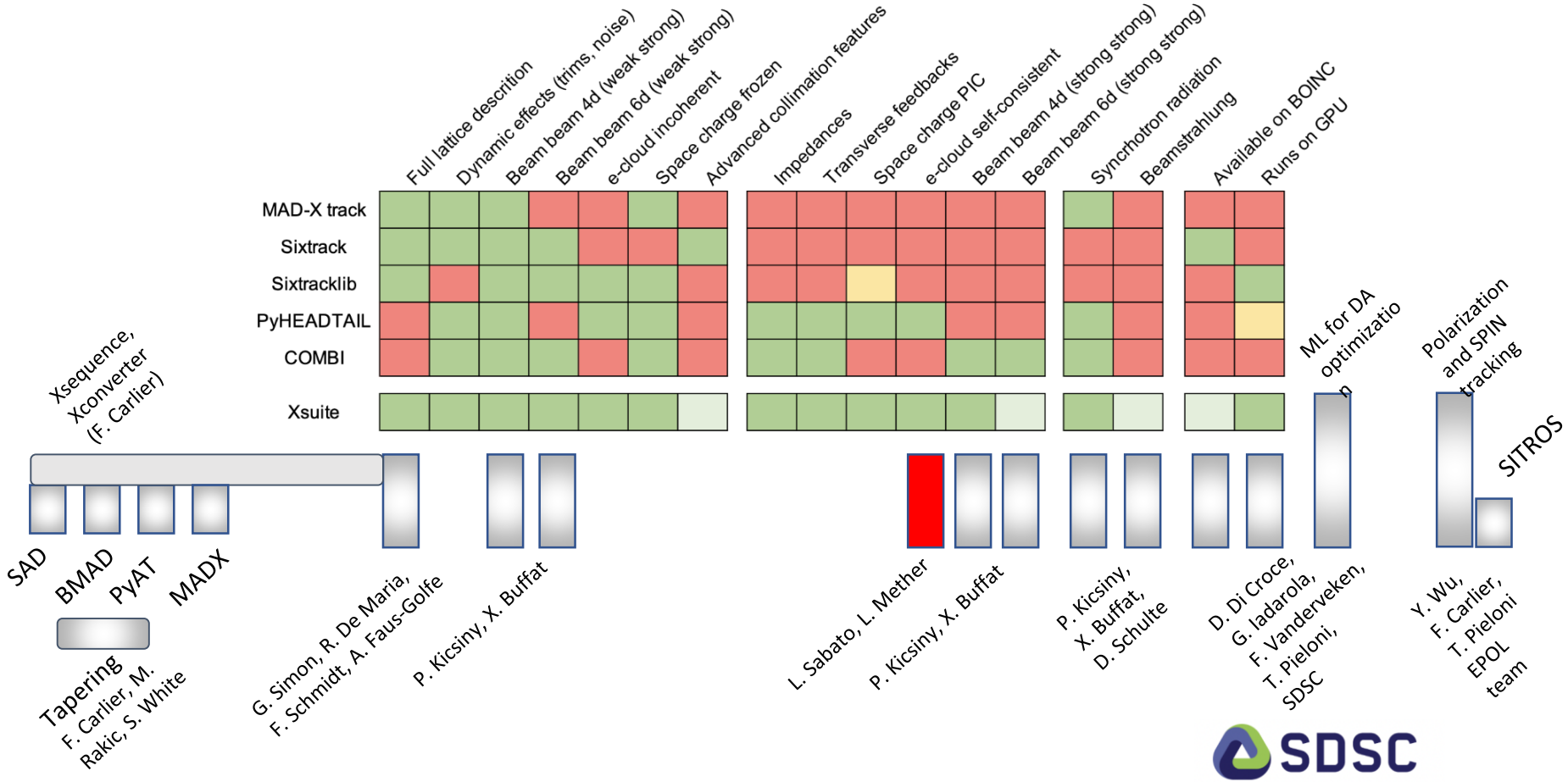
1. First simulations of **spin dynamics in Bmad for FCC-ee**
   - Allows full lattice description, errors, misalignments and corrections.
   - Comparison of Bmad vs. SITROS in linear and nonlinear spin simulations
   - Study the effects of machine errors on achievable polarization and the possible need of spin orbit matching.

Y. Wu EPOL2 session Thurs 9am: "Simulations of the Spin Polarization for the Future Circular Collider e+e− using Bmad"

1. **Spin part of Madx-PTC** has been compared to **Bmad-PTC** to good agreement.
   - Calculation of linear polarization limits still need to be developed using Madx-PTC output. More details at link.

The goal is to use the developed codes to study resonant depolarization for energy calibration using full lattice descriptions. Project approved by CHART starting on 15th July.

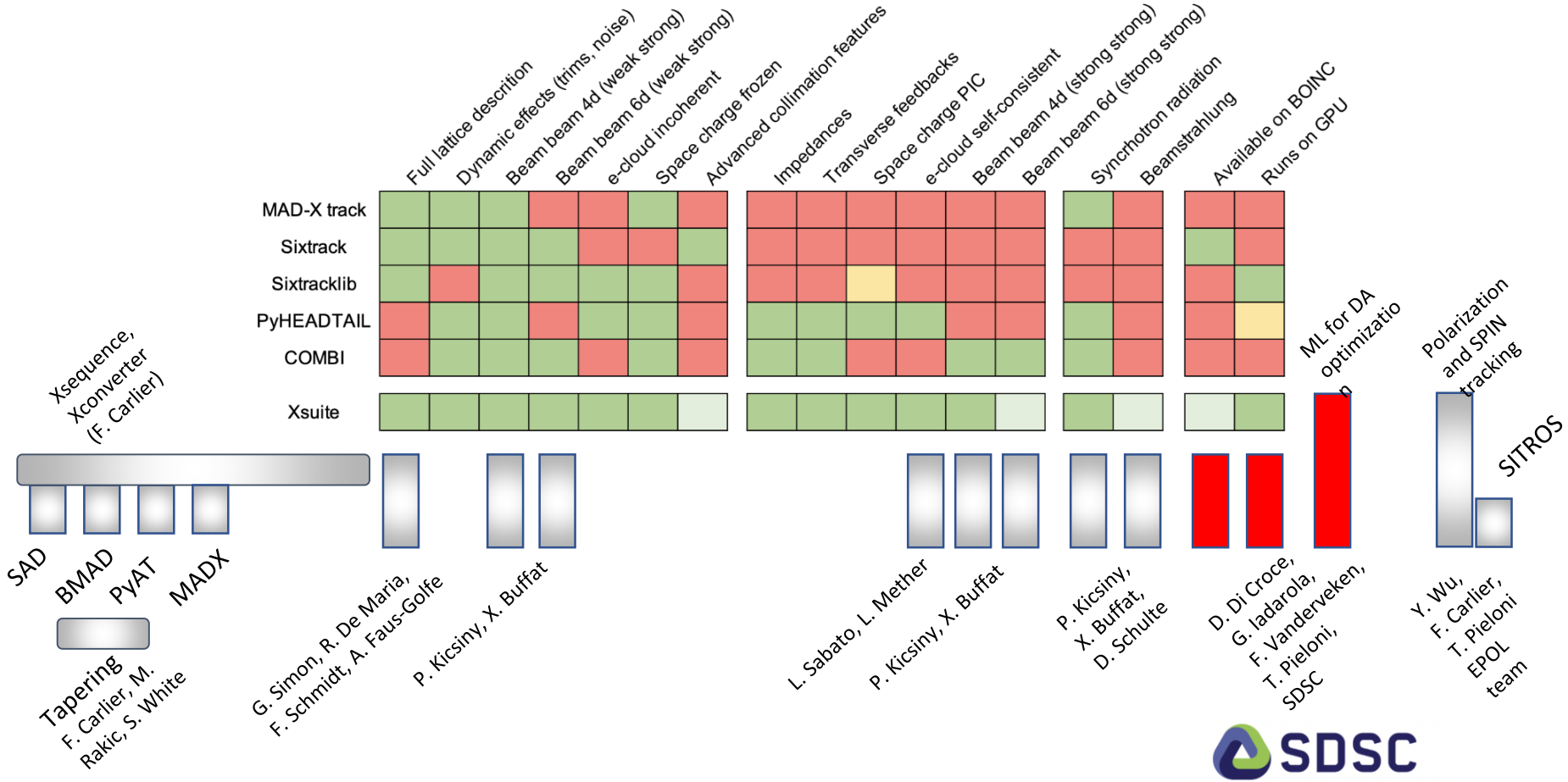
Electron Cloud



Electron Cloud studies and developments

- Improve the model of the electron cloud formation based on the current state of knowledge (from both lab and the LHC experience): i.e. improvement of the energy spectrum model of the emitted electrons using lab measurements
- Validate the existing numerical tools for electron cloud build-up based on the LHC RUN3 data set
- Development code and benchmark of PyECLOUD for Xsuite in the software framework for FCC
- By using the results of the model, propose modifications for the design of the vacuum chambers of the FCC in terms of shape, material, coating or surface treatment
- Contribute to the development of a framework for comprehensive beam dynamics simulations on the combined effect of persisting electron cloud, beam-beam and impedance aiming at the prediction of stability limits and beam lifetime evolution during collisions
- Details at link.

ML4FCC


Full lattice description
Dynamic effects (trims, noise)
Beam beam 4d (weak strong)
Beam beam 6d (weak strong)
e-cloud incoherent
Space charge frozen
Advanced collimation features
Impedances
Transverse feedbacks
Space charge PIC
e-cloud self-consistent
Beam beam 4d (strong strong)
Beam beam 6d (strong strong)
Synchrotron radiation
Beamstrahlung
Available on BOINC
Runs on GPU
MAD-X track
Sixtrack
Sixtracklib
PyHEADTAIL
COMBI
Xsuite
Xsequence, Xconverter (F. Carlier)
ML for DA optimizatio n
Polarization and SPIN tracking
SITROS
SAD
BMAD
PyAT
MADX
Tapering
F. Carlier, M. Rakic, S. White
G. Simon, R. De Maria, F. Schmidt, A. Faus-Golfe
P. Kicsiny, X. Buffat
L. Sabato, L. Mether
P. Kicsiny, X. Buffat
P. Kicsiny, X. Buffat, D. Schulte
D. Di Croce, G. Iadarola, F. Vanderveken, T. Pieloni, SDSC
Y. Wu, F. Carlier, T. Pieloni EPOL team

ML4FCC PROJECT

SDSC

- Higher computational complexity for FCC → Multiple effects; Synchrotron radiation, 6D beam-beam interactions, beamstrahlung, impedance, lattice, polarization… → need for computational resources, automatized simulation submissions, analysis and optimization of parameters → possible use of ML details at link
- BOINC system ideal to submit jobs for FCC tracking simulations!
  - An improved tracking simulation tool has been developed Xtrack (part of Xsuite)
  - BOINC app for FCC simulation is being developed to involve worldwide volunteers to the global effort of designing a Future Circular Collider vis the LHC BOINC system "FCC@home"
  - Possible to develop GPU support for BOINC app
- Develop an active learning framework to continuous update the DA model with new simulated data in order to explore new parameter space
  - Provide FCC (DA) model and tuning knobs for machine design and optimization.

Summary

- Simulating the beam dynamics for the FCC-ee is a **challenging goal!**
- **Multiple effects** will need to be studied together for a final and robust understanding and design
- Design and Optimization of the machine parameters can profit of novel technologies for **speed, reproducibility and automatization of tuning**
- Developments should be done profiting from **different communities**: lepton colliders, light sources, hadron colliders
- Simulations tools are fundamental to permit **reproducibility, good practise, involve younger generations**
- **Synergies** with the CERN Computing WG are fundamental to guarantee maintainability of tools in a long term prospective, profit of expertise in modelling and constant testing

Many developments are on-going and first results presented:

- P. Kicsiny “Simulations of FCC-ee beam-beam effects with xsuite”
- R. De Maria talk on MADX developments in this session
- A. Abramov ”FCC-ee Collimation Studies”
- Y. Wu EPOL2 session Thurs 9am: “Simulations of the Spin Polarization for the Future Circular Collider e+e− using Bmad”
- G. Simon poster session Thursday 17:30: “Synchrotron radiation improvements in MAD-X for FCCee studies”

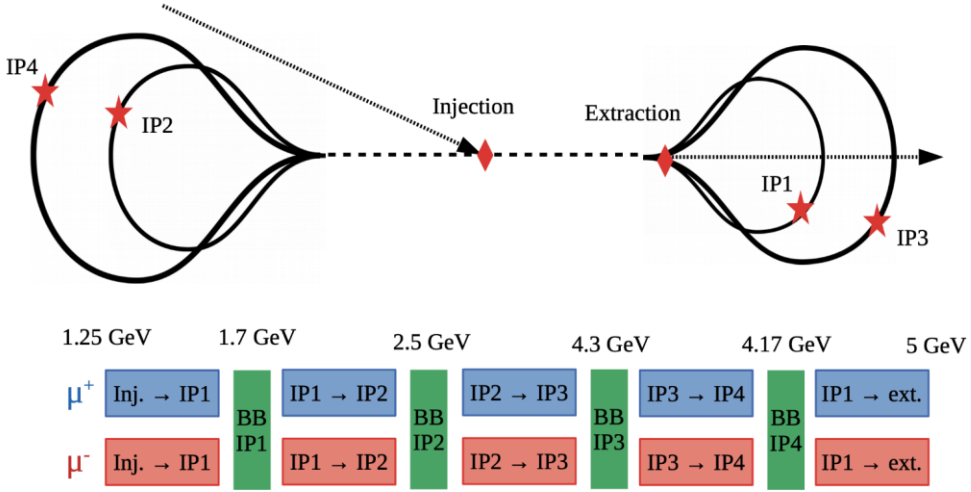
Comments, ideas, contributions are very welcome!

EPFL-LPAP FCC-ee Software Framework Meetings: https://indico.cern.ch/category/9606/

Beam-beam interactions for muon collider

X. Buffat

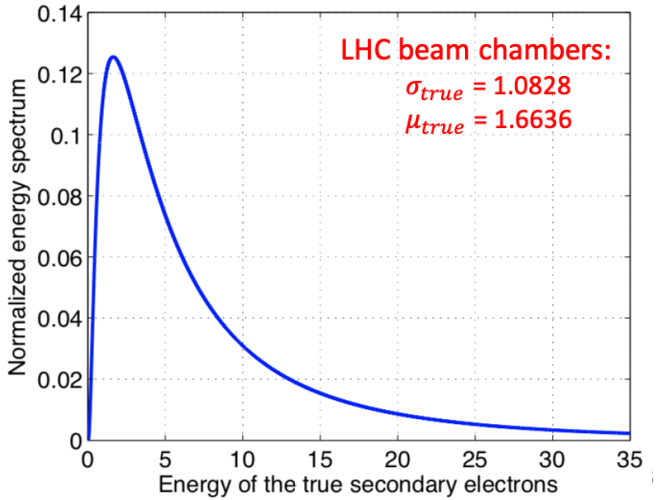
Xsuite used for first studies on **beam-beam effects** in recirculating linac for **muon collider**



Electron Cloud studies and developments

- Improve the model of the electron cloud formation based on the current state of knowledge (from both lab and the LHC experience)
  - Improvement of the energy spectrum model of the emitted electrons, using lab measurements

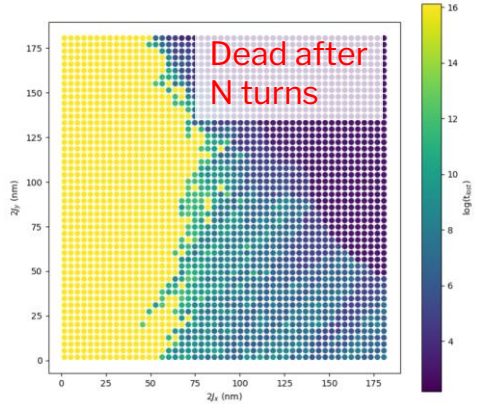
$$\frac{dn_{true}}{dE} = \frac{1}{E\sigma_{true}\sqrt{2\pi}} e^{-\frac{(ln(E)-\mu_{true})^2}{2\sigma_{true}{}^2}}$$

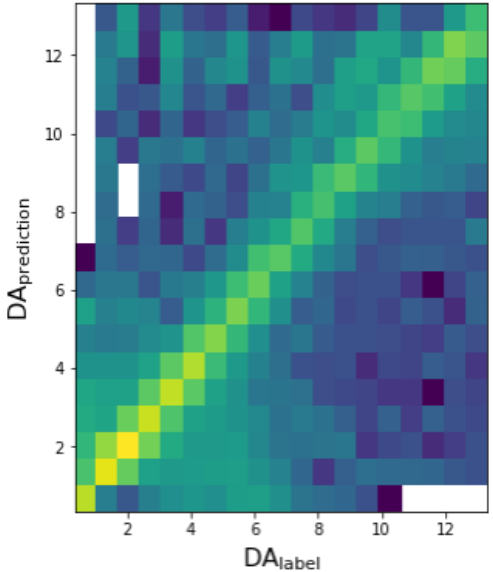


[] B. Henrist et al., "Secondary Electron Emission Data for the Simulation of Electron Cloud", cds 2002.

ML4FCC PROJECT

- GNN for 3D/4D DA border detection
  - producing synthetic data
- Xtrack BOINC app development
  - standalone binary available for Windows and Linux + test server and test application ready to test BOINC API
- DA regressor and particle loss GAN for various configurations of accelerator
  - DA regressor developed using existing Sixtrack data while preparing to produce FCC-ee Xtrack simulation





Test MAE = 6%