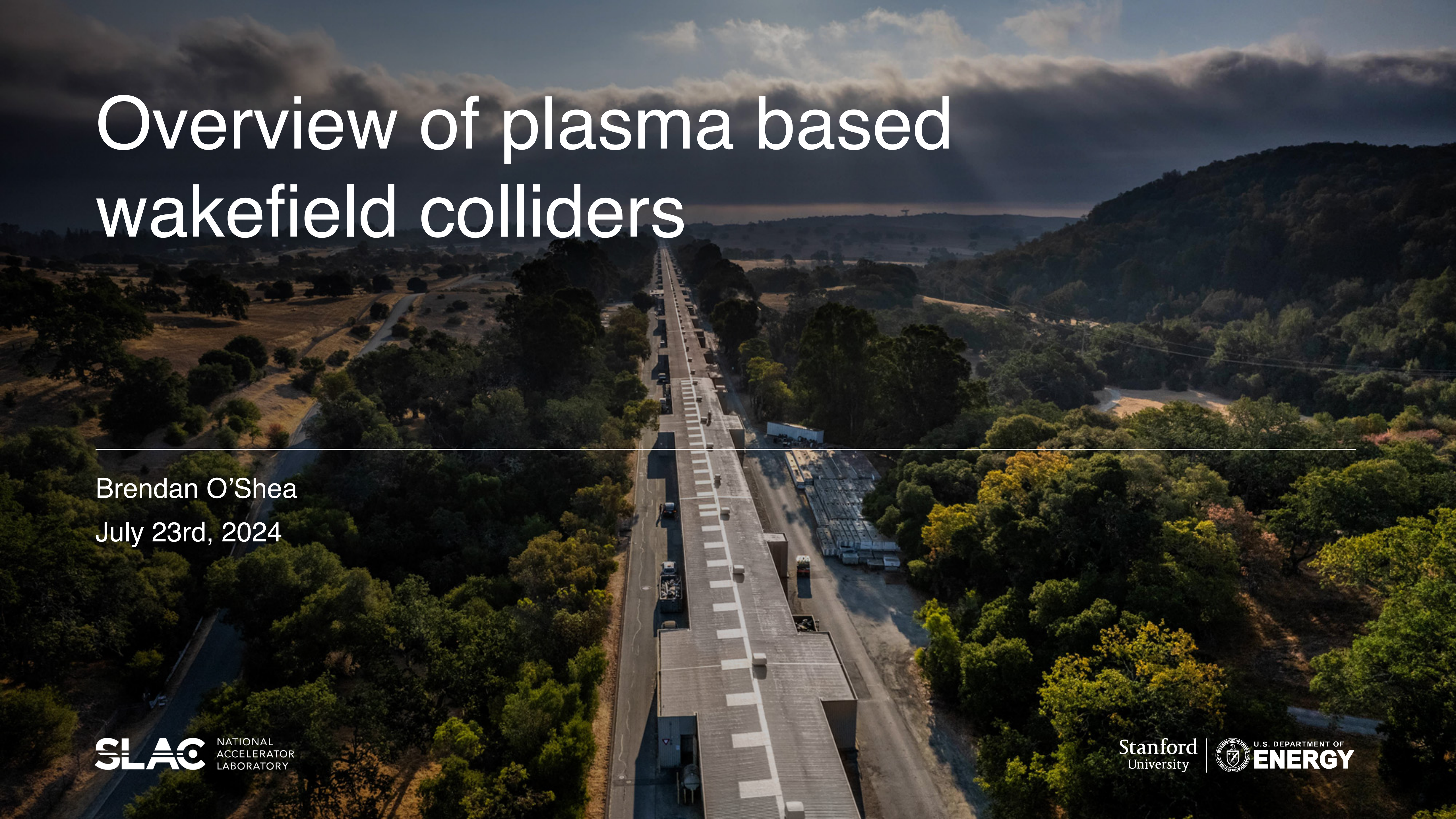


Overview of plasma based wakefield colliders

Brendan O’Shea

July 23rd, 2024

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Plasma Wakefield Based Colliders

Cost reduction is key - improvements in collider length, gradient and/or efficiency would all be wins

- Four concepts for plasma wakefield based colliders
- Main motivation is cost:
  - High gradient (shorter is cheaper)
  - Efficiency (heavy beam-loading)
- Higher gradient generally means shorter wavelength, transverse Wakefields scale faster
- Efficiency through heavy beam-loading means high beam currents, stronger coupling to undesirable modes
- Self consistency means we quantitatively understand every component of a wakefield collider

A Linear Collider Based on Nonlinear Plasma Wake-field Acceleration*

J. Rosenzweig, N. Barov, E. Colby¥
Dept. of Physics and Astronomy, UCLA
405 Hilgard Ave., Los Angeles, CA 90095-1547

P. Colestock
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510

Snowmass 1996

A CONCEPT OF PLASMA WAKE FIELD ACCELERATION LINEAR COLLIDER (PWFA-LC)*

Andrei Seryi, Mark Hogan, Shilun Pei, Tor Raubenheimer, Peter Tenenbaum (SLAC), Tom Katsouleas (Duke University), Chengkun Huang, Chan Joshi, Warren Mori (UCLA, California), Patric Muggli (USC, California).

PAC09

A BEAM DRIVEN PLASMA-WAKEFIELD LINEAR COLLIDER FROM HIGGS FACTORY TO MULTI-TEV*

J.P. Delahaye, E. Adli, S.J. Gessner, M.J. Hogan, T.O. Raubenheimer, SLAC,
W. An, C. Joshi, W. Mori, UCLA

Snowmass 2013

A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration

B Foster[1,2,*], R D'Arcy[1,2] and C A Lindstrøm[3]

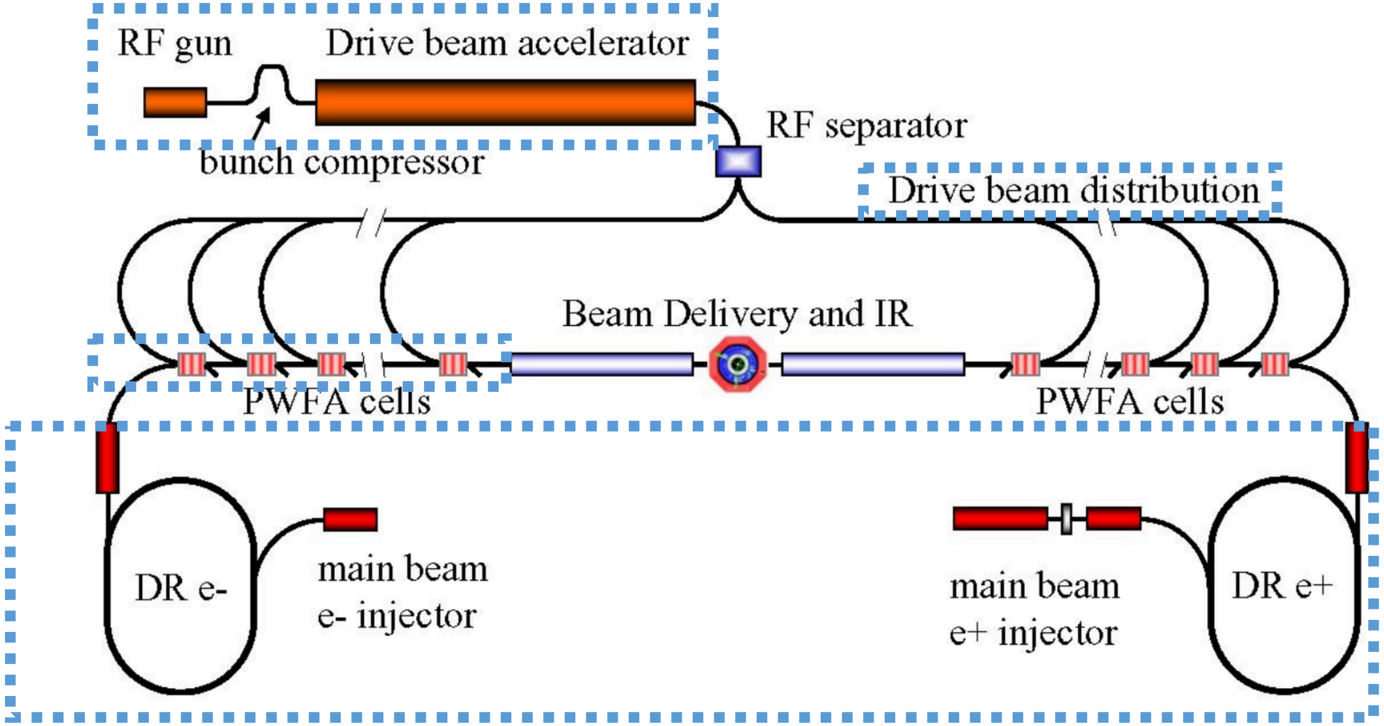
[1] John Adams Institute for Accelerator Science at University of Oxford, Oxford, United Kingdom
[2] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[3] Department of Physics, University of Oslo, Oslo, Norway

2023

An accelerator in a collider

Trade-offs are key: we need 'subsystem' models that can be used for global optimization

- Key components
    1. Drive beam generation
    2. Main (witness) beam generation
    3. Drive beam distribution and combination with main beam
    4. Wakefield accelerators
    - Beam Delivery System
    - Machine Detector Interface
    - Detector
- Drive and main generation look fairly straightforward, synergy with structure based wakefields



- Need ownership of models for instabilities

Beam Break-Up and Transformer Ratio

Luminosity and efficiency are tied together, must connect wakefield and magnet position models

- Beam Break-Up is an intra-beam effect in the main beam only
  - Heavy beam loading is good for efficiency, but makes it easier to excite undesired modes

$$\frac{F_t}{F_r} \approx \frac{(P_w/P_d)^2}{4(1-(P_w/P_d))}$$

- More energy spread, more energy gain tend to be better for mitigating BBU
- For a given charge there is an optimum transformer ratio, R~2

$$|E_+| \leq 2k_{\parallel}|Q|\frac{2R}{1+R^2}$$

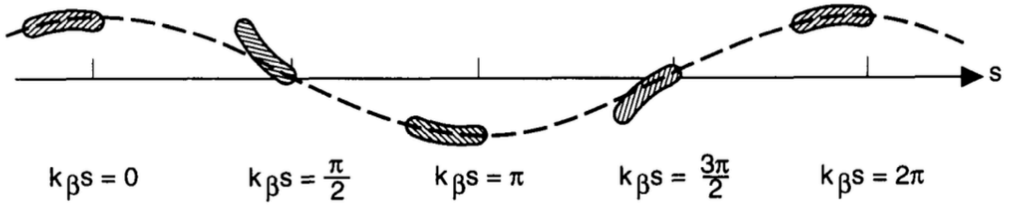
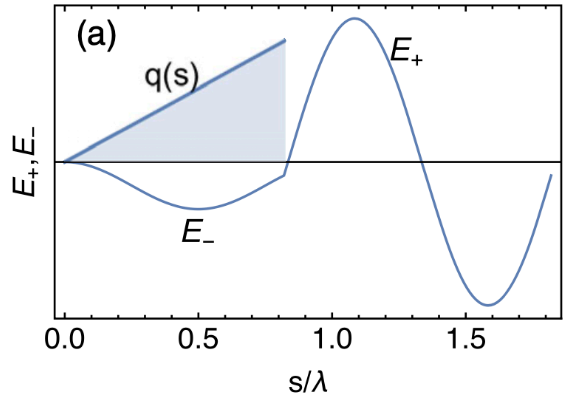


Figure 3.3. Sequence of snapshots of a beam undergoing dipole beam breakup instability in a linac. Values of $k_\beta s$ indicated are modulo 2π. The dashed curves indicate the trajectory of the bunch head.

$$y_2(s) = \hat{y}\cos(k_\beta + \Delta k_\beta)s + \frac{N r_0 W_1(z)}{4k_\beta\,\Delta k_\beta\,\gamma L}\hat{y}\left[\cos(k_\beta s + \Delta k_\beta\, s) - \cos k_\beta s\right]. \tag{3.40}$$

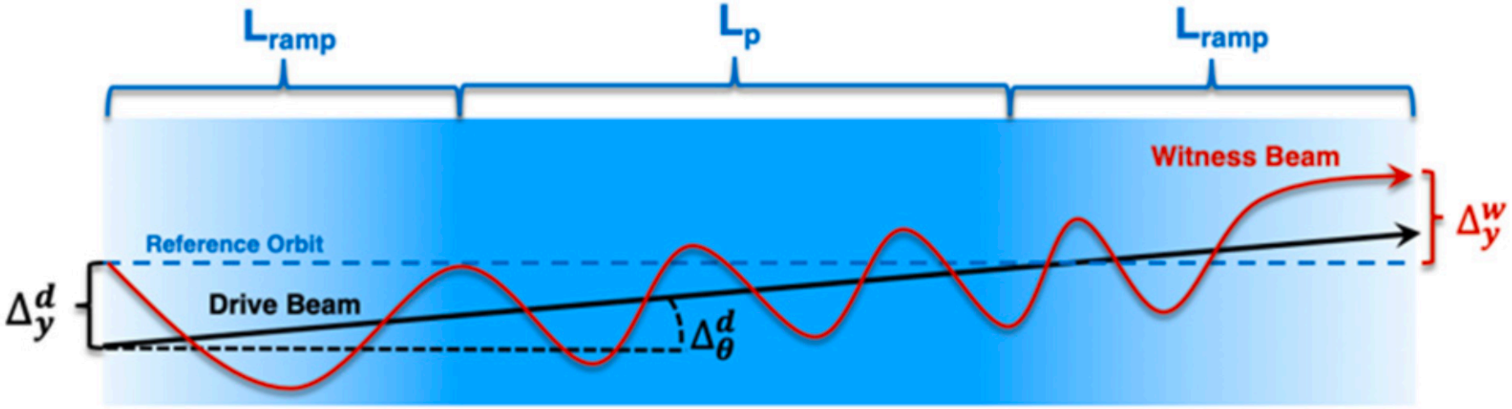


Physics of Collective Beam Instabilities in High Energy Accelerators, Chao, (1993)
Efficiency versus instability in plasma accelerators, Lebedev et al, PRAB (2017)
Upper limit for the accelerating gradient in the collinear wakefield accelerator as a function of the transformer ratio, Baturin, PRAB (2017)

Alignment : Magnets + Girders

All accelerator physics is very important to a wakefield collider

- The analogue to accelerator alignment is drive-main alignment
    - Analysis (without acceleration) shows sub-micrometer tolerances required
- Errors in girder and magnet locations are absolute
    - FCC-ee work shows that sub 10 um rms misalignment of quads is possible in simulation
- Ground motion is on the scale of 1-10 nm



RMS accelerator alignment errors

$$< y_{acc}^2 > \leq A \frac{G L_{cell}^3}{\delta_{BNS}^2 \gamma_i^2}$$

G: Gradient
L_{cell}: Length of focusing cell (plasma)
δ_{BNS}: Energy spread of beam
γ_i: Initial beam energy in accelerator

SLAC

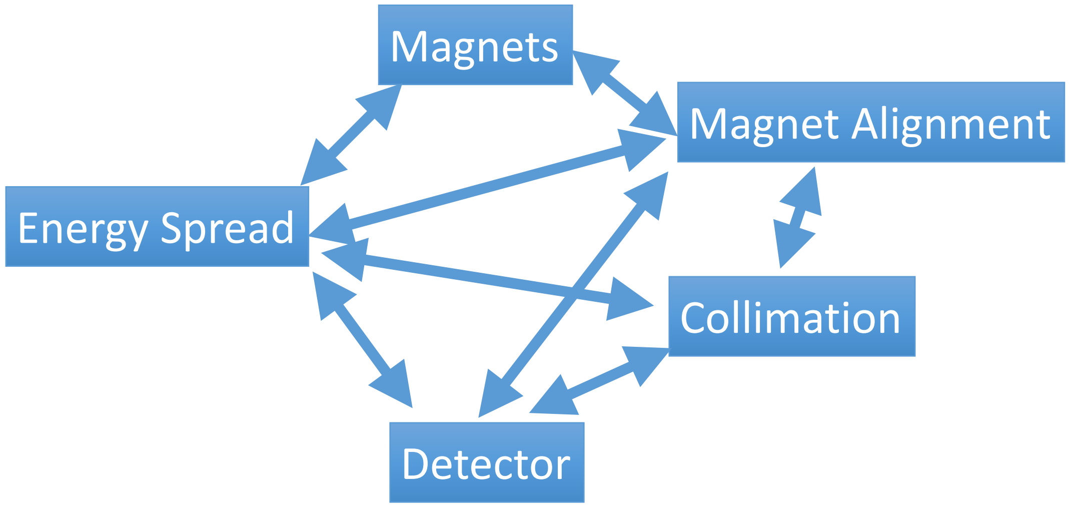
TRANSVERSE JITTER TOLERANCE ISSUES FOR BEAM-DRIVEN PLASMA ACCELERATORS, White, doi:10.18429/JACoW-IPAC2019-THPGW087

"Advanced Accelerator System Requirements for Future Linear Colliders", Dugan, Presentation AAC 2004

Conclusions

There are many ways to assemble a wakefield based collider, a lot of options to explore!

- Self consistency means we quantitatively understand every component of a wakefield collider
- As physicists we typically ignore numerical constants and just examine scaling, for a collider design we do not have that luxury
- For instruments like colliders a factor of 2 is an enormous difference in cost, we need to find those factors of 2
- Positron acceleration will require very careful attention
- Next steps: Build models for drive beam distribution, drive+main combination, accelerator module itself



(Notice that nothing here is a plasma)