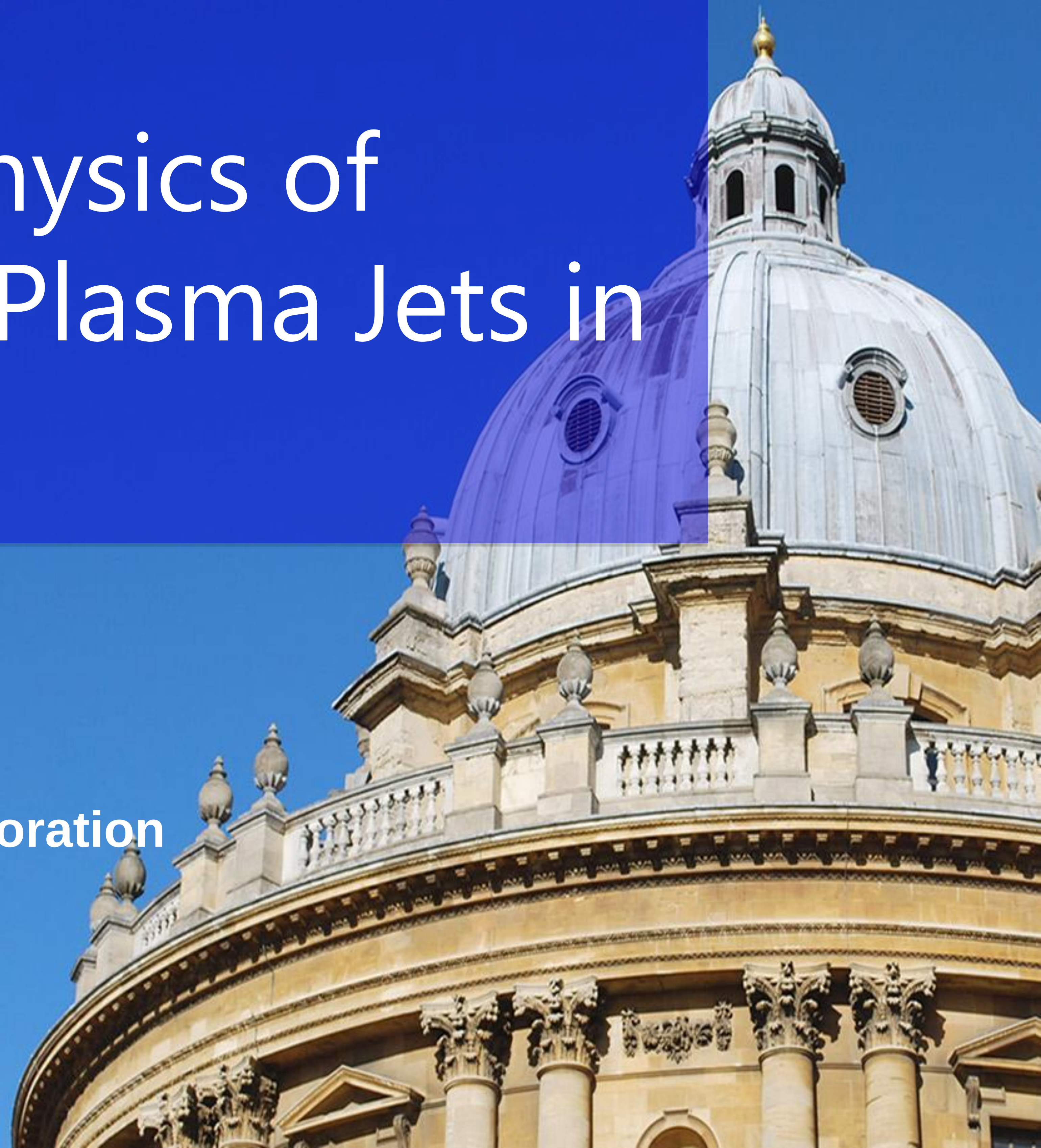
Fireball@LNF

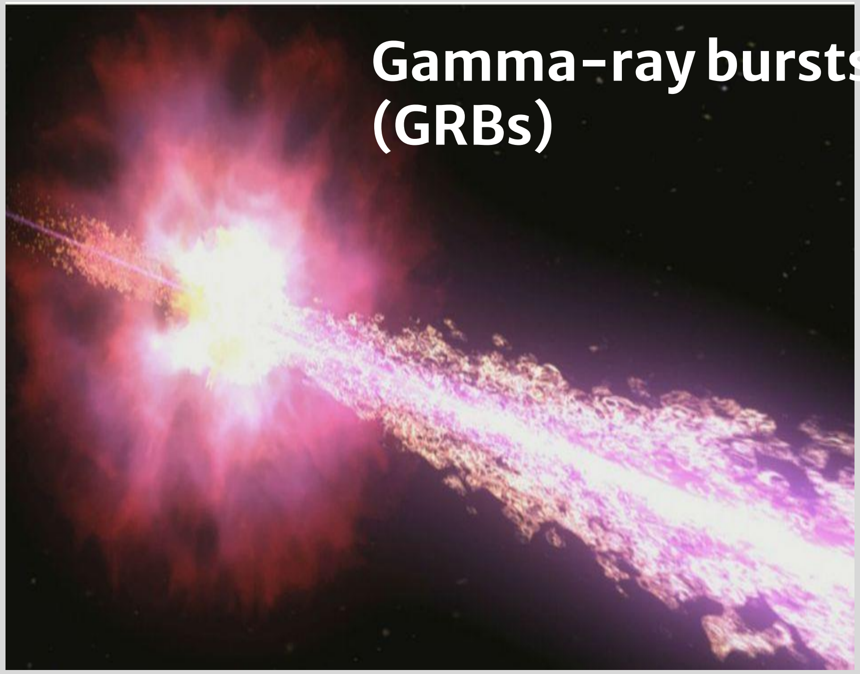
Unveiling the Physics of Relativistic Pair Plasma Jets in the Laboratory

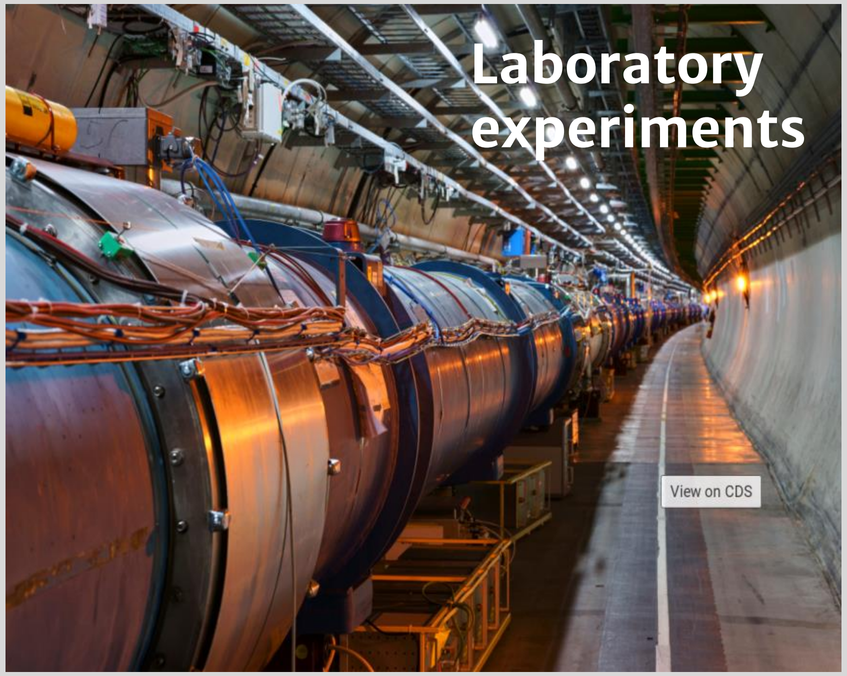


R. Bingham (STFC, Strathclyde)
G. Gregori (Oxford)
On behalf of the Fireball Collaboration

European Research Council
Established by the European Commission

Unveiling the Physics of Relativistic Pair Plasma Jets in the Laboratory



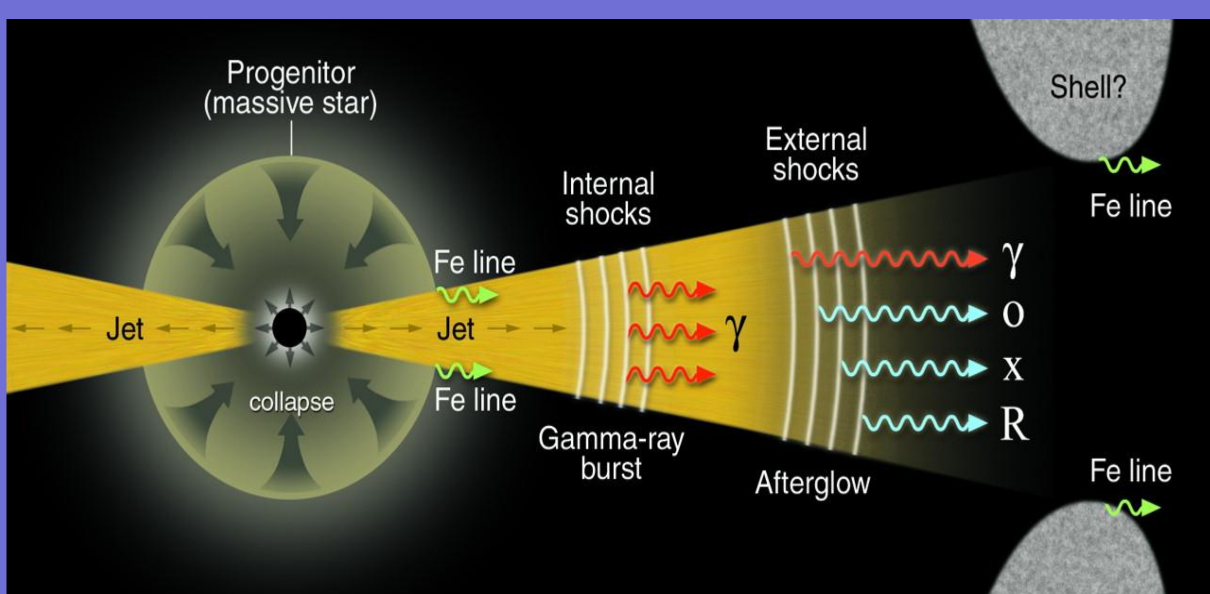


- **GRBs and Blazar jets are examples of energetic astrophysical beams.**
- **Particle transport in turbulent and magnetized plasmas remains a challenge:**
  - What makes the beam unstable?
  - How are magnetic fields produced and amplified?
  - How can cosmic-rays be accelerated to the highest energies?
- **Observations have not provided direct evidence of these processes.**

Pair jets are among the most extreme processes in the Universe

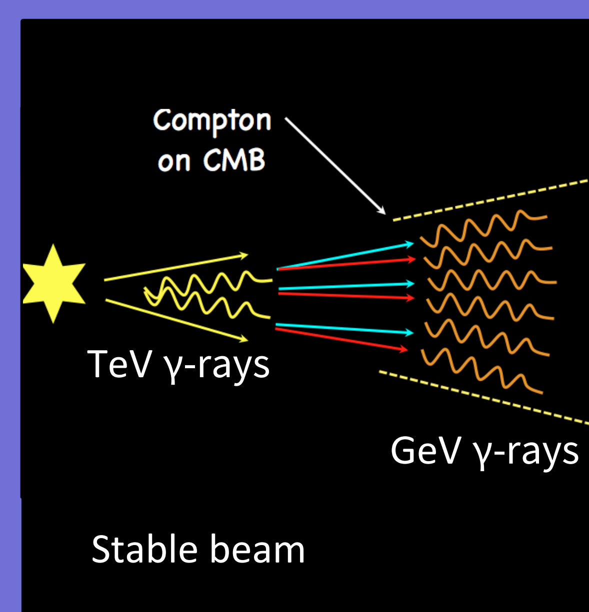
GRBs

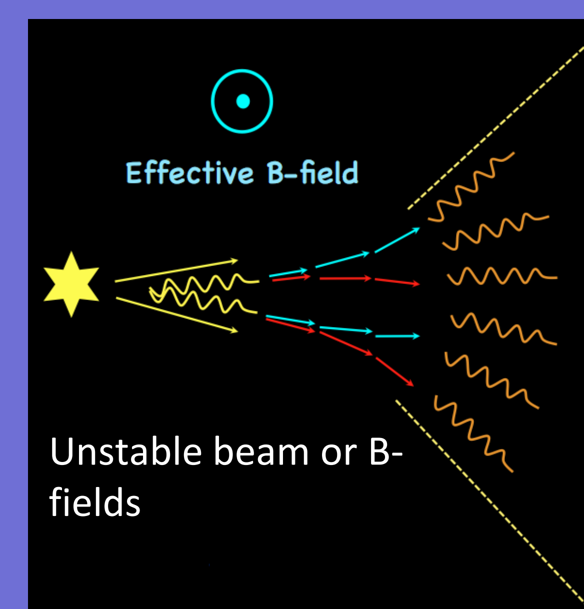
- In the **Fireball** model, jets are produced by core-collapse supernovae or neutron star mergers.
- Plasma processes are believed to be responsible for the instabilities.
- There are alternative model where plasma blobs are ejected by older stars.



Jets from Blazars

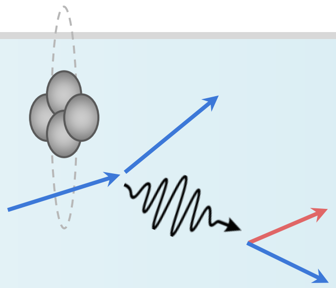
- Relativistic beams are produced by blazars
- The pairs inverse Compton scatter on the CMB to produce GeV γ-rays.
- Lack of GeV γ-rays in the measured spectra is either due to B-fields or beam instabilities.

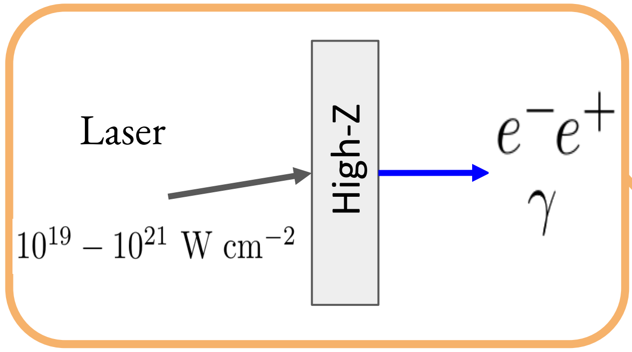


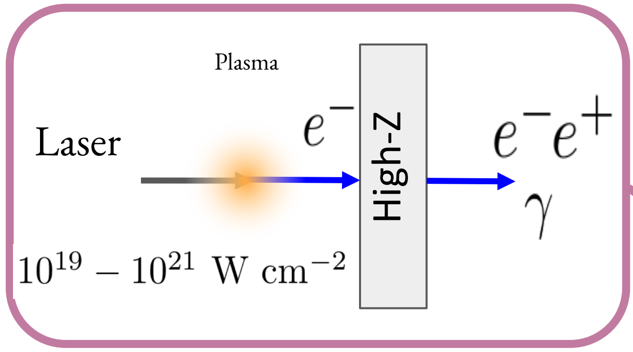


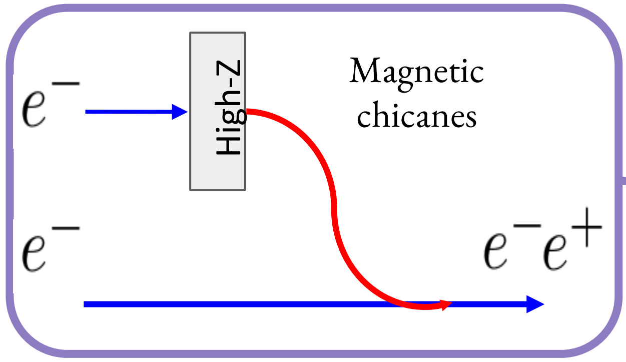
Generation of pair beams in the laboratory

Bethe-Heitler process









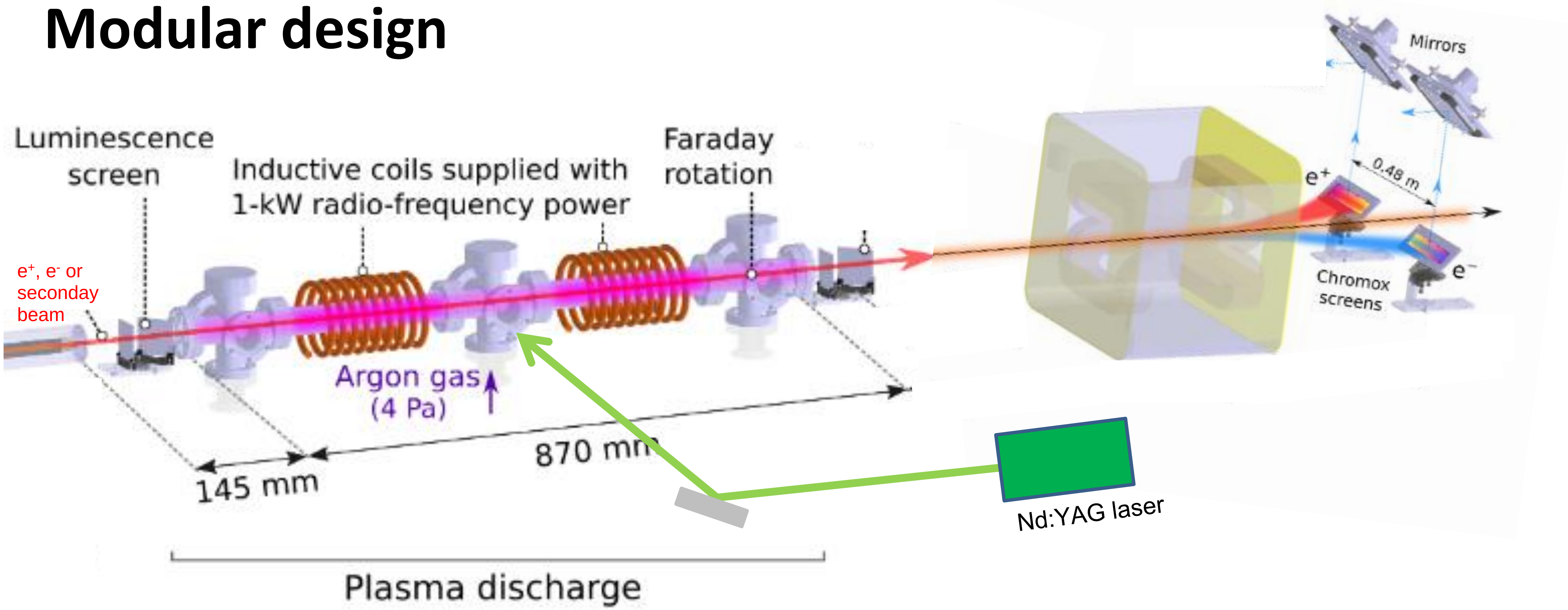
Facility	Positron Yield	Pulse duration	Ref.
Omega (LLE), JLF (LLNL), Orion (AWE),	**10^{10} - 10^{12}** not quasineutral not collimated	1-10 ps	Chen et al. (2015)
Texas PW (UT Austin)	**10^{8} - 10^{10}** not collimated	100-250 fs	Liang et al. (2015)
JLF (LLNL), Gemini (RAL), IOFM (Shanghai)	**10^{7} - 10^{9}**	50-100 fs	Williams et al. (2015) Sarri et al. (2015) Xu et al. (2016)
FACET II (SLAC) Under commissioning	**10^{9} - 10^{10}**	~150 ps	V. Yakimenko et al. (2019)

→ So far the main effort of electron-positron beam generation has been focused on using high-power lasers.

→ Laboratory experiments can probe the microphysics that is not accessible by observations (or even numerical simulations).

Proposed setup for BTF

Modular design



- → Using e^+, e^- or secondary beam (neutral) from high-Z primary.
- → Flux concentrator to collimate pair beam.
- → Plasma cell simulates background interstellar plasma.
- → Interaction laser to probe inverse Compton and high-field physics.

Compared to previous approaches: higher densities, better control of charge neutrality, higher rep rate, etc.

Fireball team

The FIREBALL collaboration includes several institutions in the UK/EU/US

G Gregori, S Sarkar, E Los, H Ramm, S Zhang, T Huffman

R Bingham, J Halliday

C Arrowsmith, D Froula

B Reville

L Silva, P Bilbao

Current funding (until 2029)

ERC Advanced Grant (converted to UKRI Frontier Grant): €1.2m

Future project

Working on a joint ERC Synergy Grant proposal on extreme astrophysics (Theory/Experiments/observations)

Fireball@CERN

N Charitonidis, A Goillot, V Stergiou

Fireball@LNF

L Foggetta, C Curceanu, A Scordo, C Di Giulio, A Vannozzi,

Questions on the micro-physics of pair jets we want to address

What makes the beam stable or unstable?

–We will vary beam divergence, baryon loading and beam/ambient density ratio.

How are magnetic fields produced and amplified?

–Instabilities exhibit different growth rates. Merging of filaments at later times depends on dominant process.

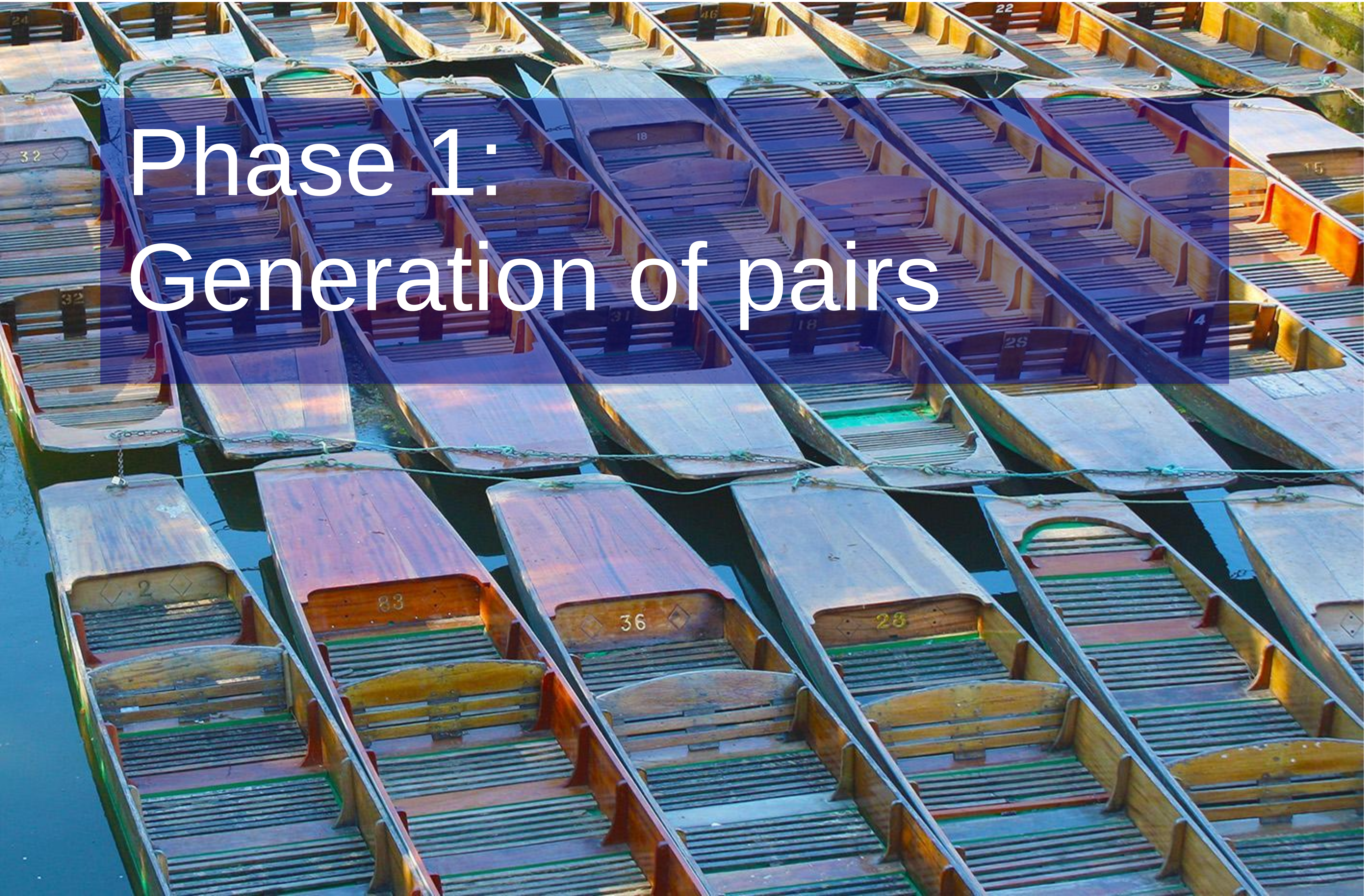
What process is responsible for the emission from GRBs?

–We will compare synchrotron *vs* inverse Compton scattering to test predictions from Fireball vs Cannonball.

How can cosmic-rays be accelerated in astrophysical jets?

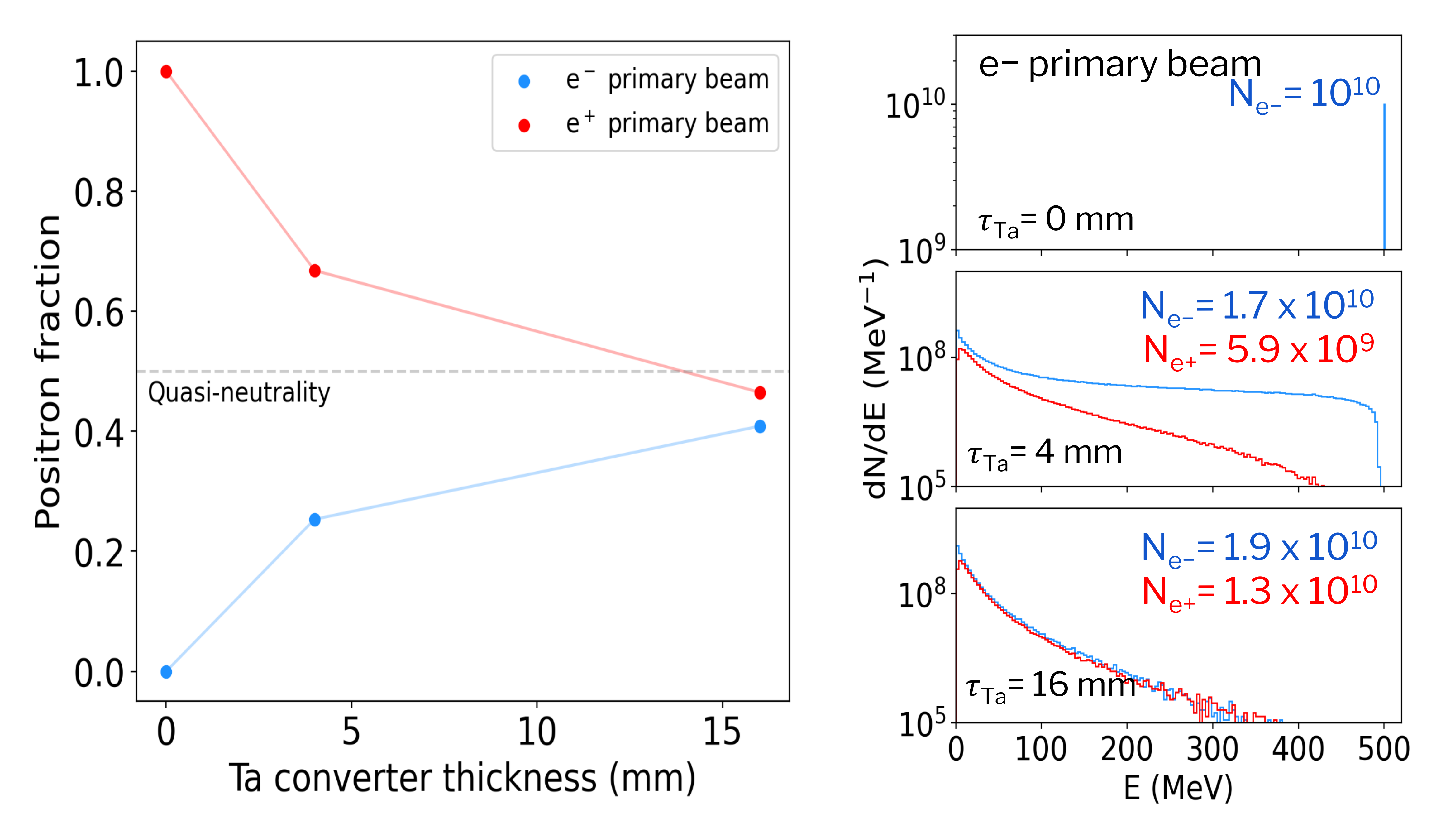
–Coherent magnetic fields are needed. Experiments will determine if pairs can be accelerated to tens of MeVs.

Phase 1: Generation of pairs



We have already investigated pair beam generation on BTF using a Ta converter

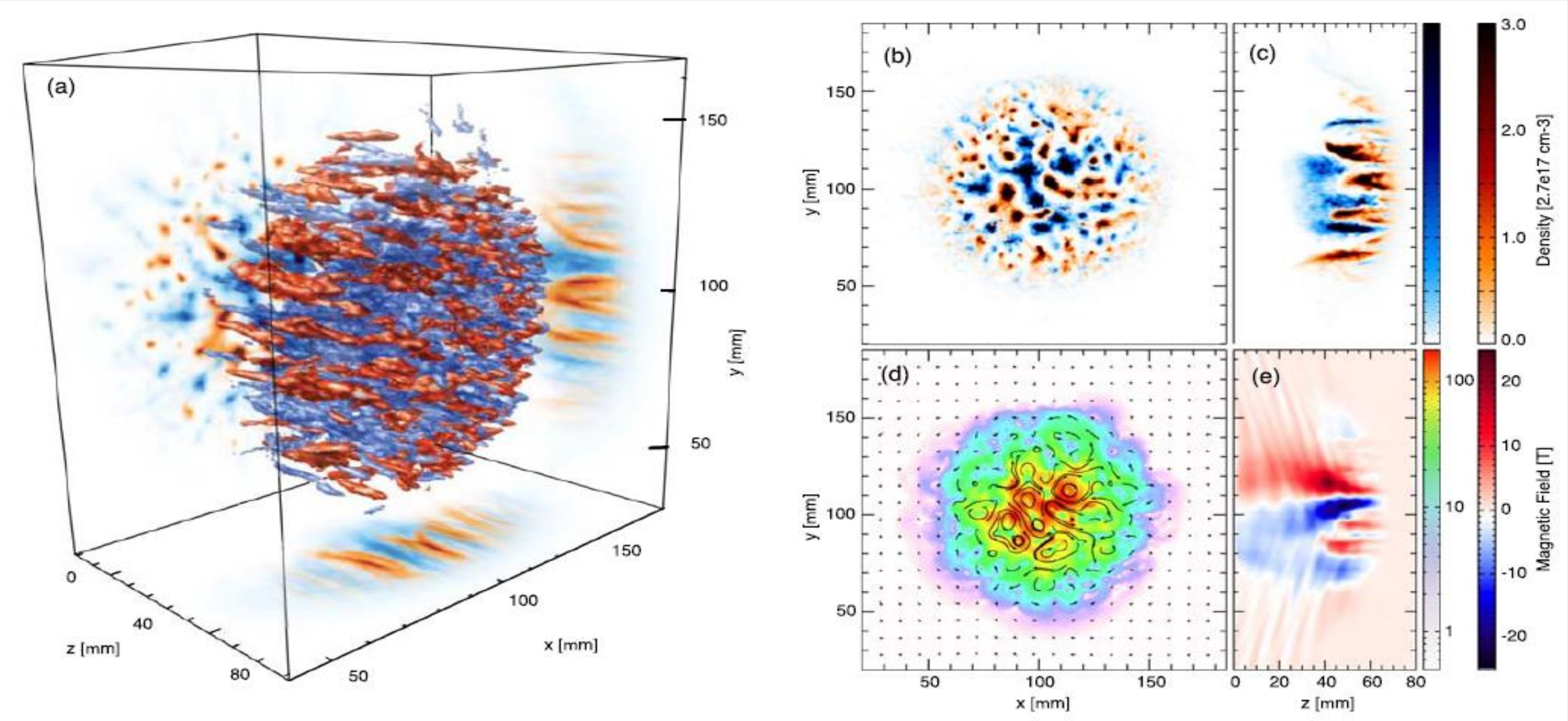
FLUKA simulations



Approximate beam densities = 10^8–10^9 cm^{-3} (assuming 1 cm^2 beam size and 1.5 ns pulse.

As the pair beams propagate through the ambient plasma, instabilities develop

Shukla et al. (2020)



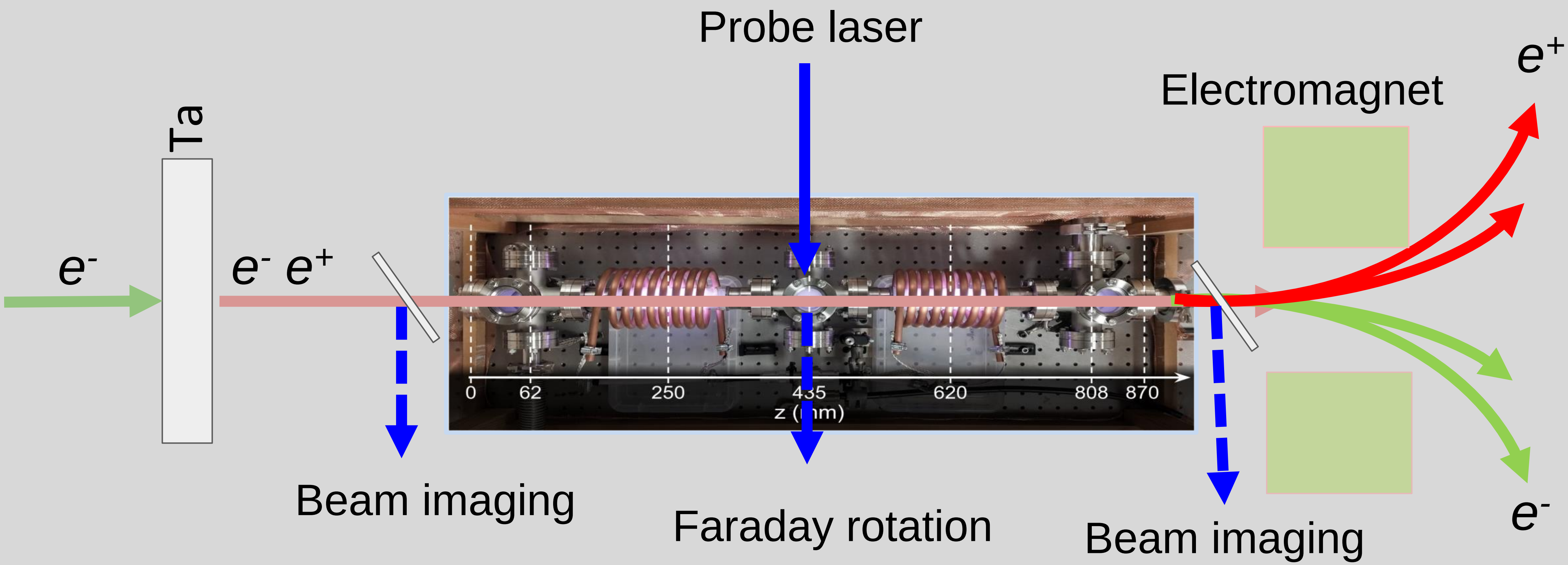
→ These kinetic instabilities are the main culprit for the generation of internal shocks, magnetic fields and particle acceleration.

→ In our work at **Fireball@CERN** we have successfully investigated the formation of these instabilities (***Arrowsmith et al. Nat. Comm. 2024***).

→ However, no access at CERN will be possible after 2025 (LS3); no high-power laser is available; no dedicated e^+, e^- beams.

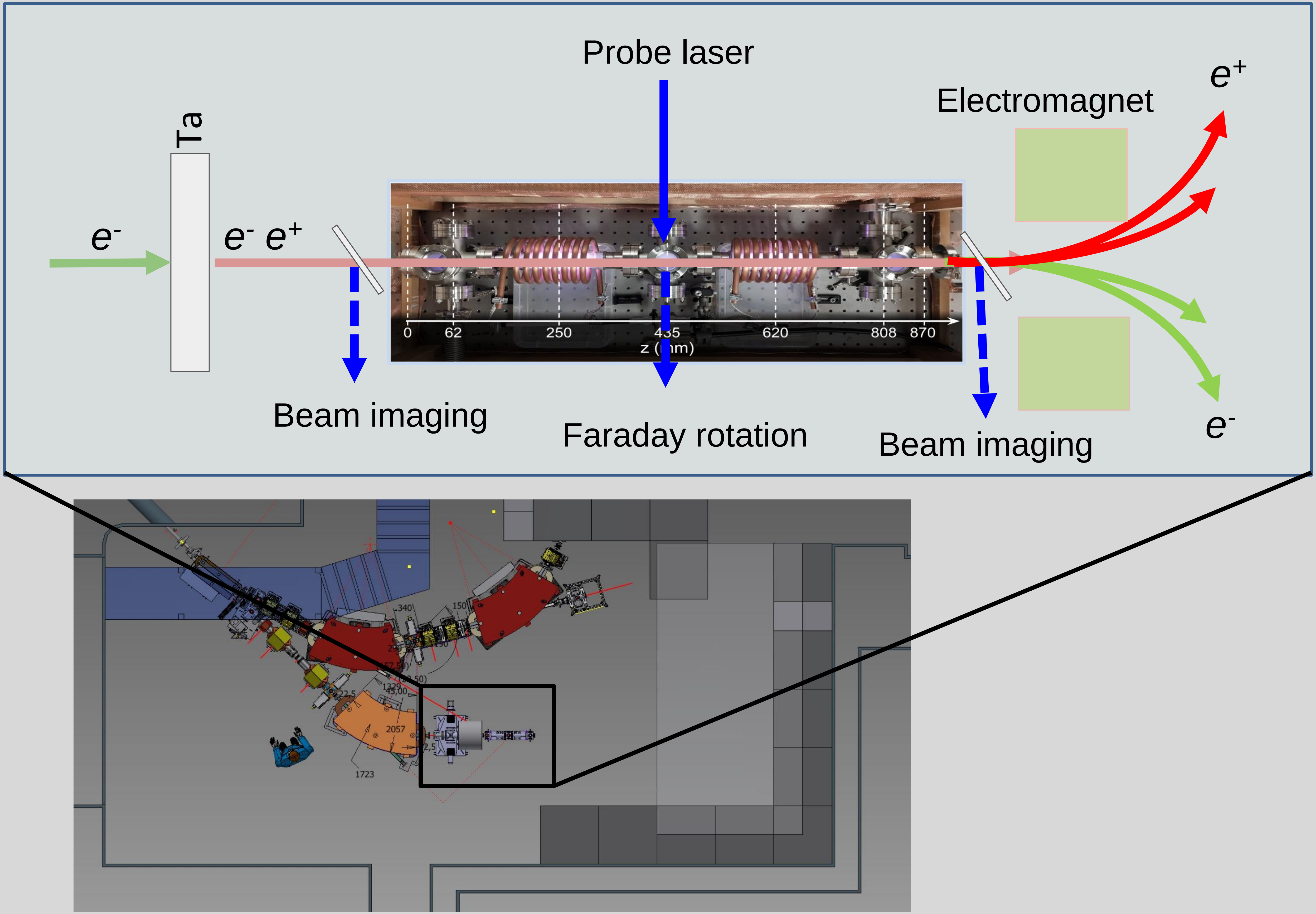
→ **Fireball@LNF** is an important continuation of what we started at CERN.

As the pair beams propagate through the ambient plasma, instabilities develop

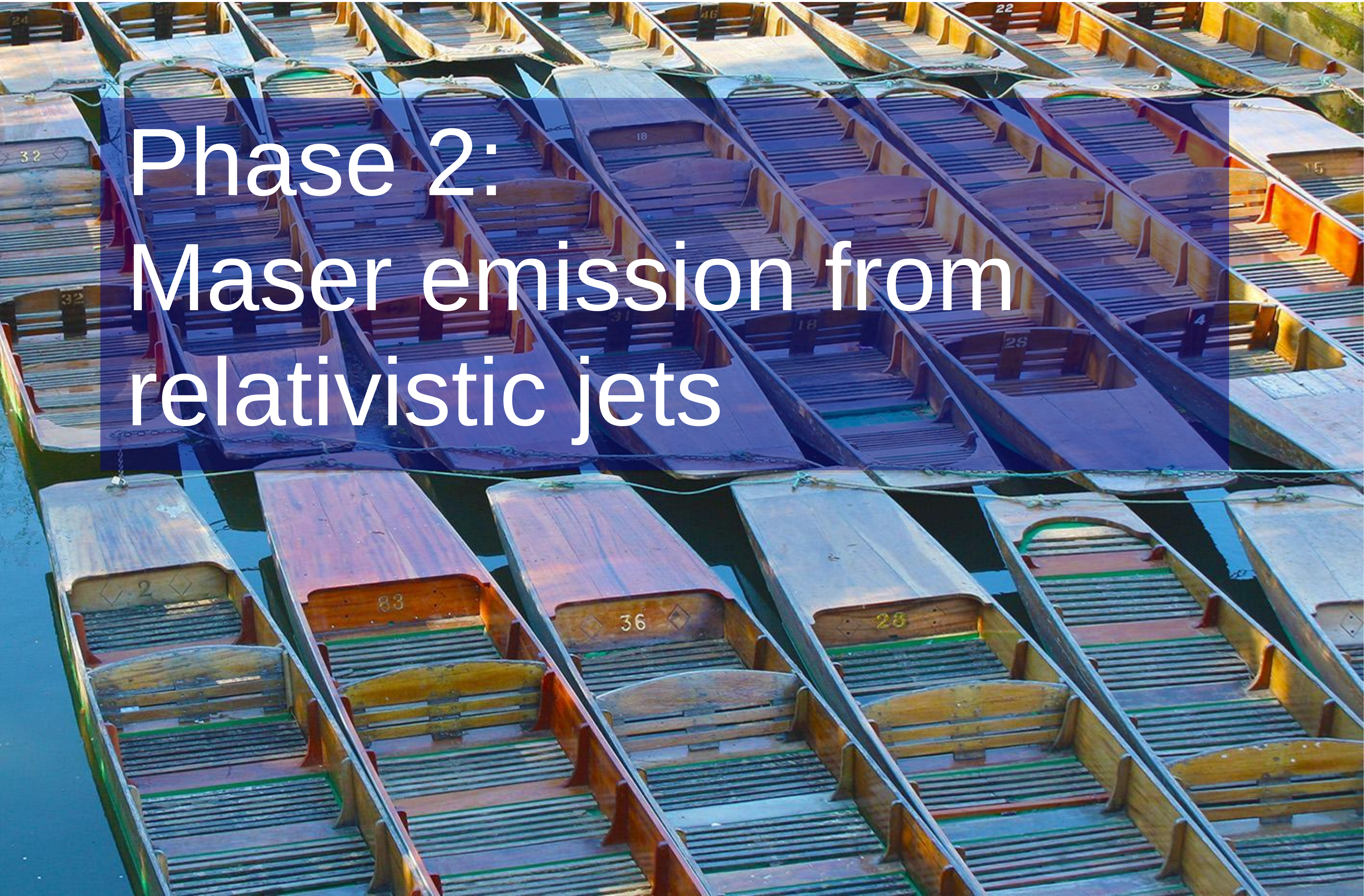


- → **Fireball@LNF** builds upon our CERN experience.
- → At BTF we will develop a higher density plasma cell (by replacing the current 1 kW with a pulsed-5 kW RF power supply; and operating at higher pressures, above 10 mTorr) – $n_e > 10^{14}$ cm^{-3}
- → Expect to achieve conditions where shocks start forming.

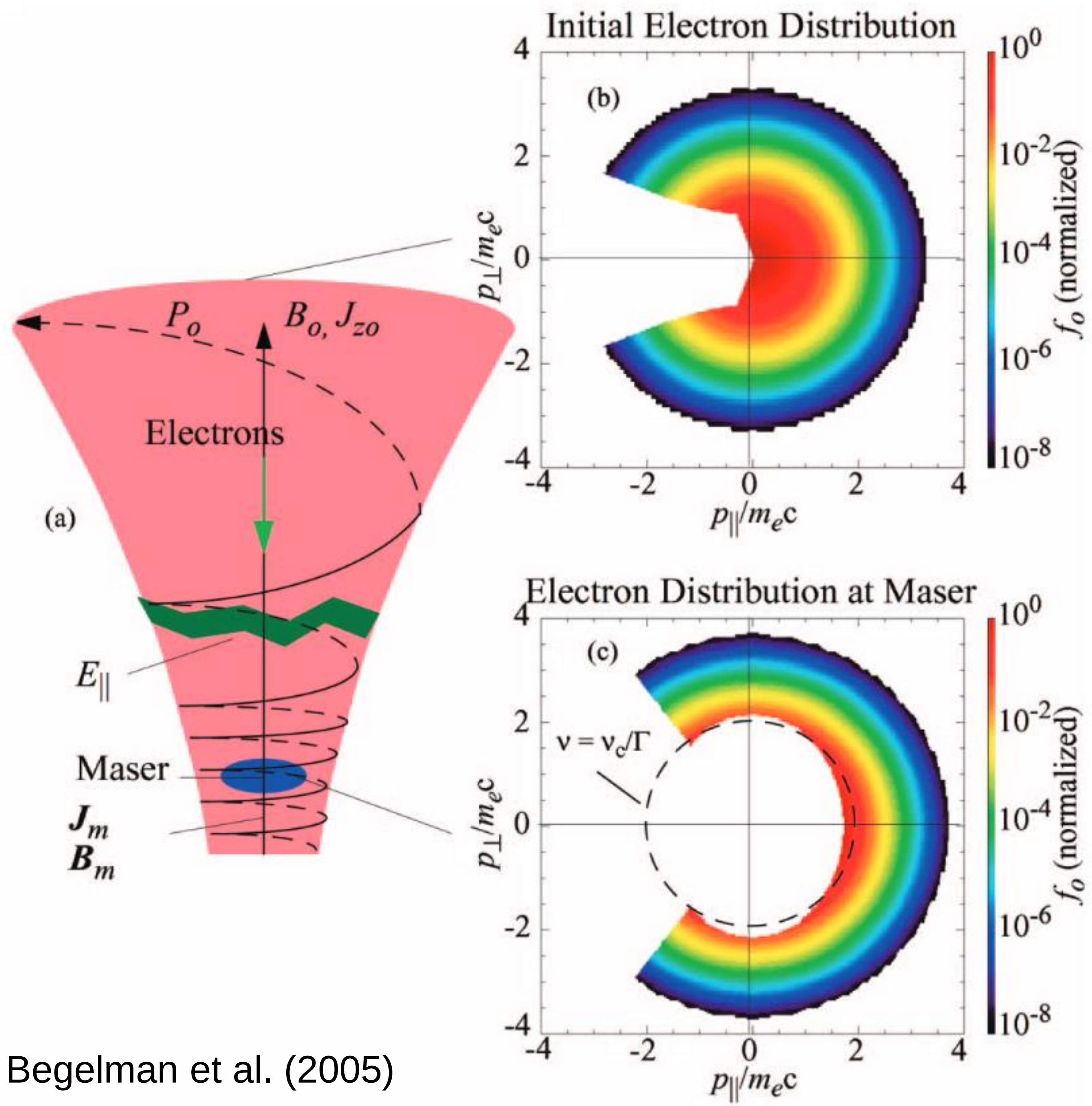
Design and preparation needed for installation into BTF



Phase 2: Maser emission from relativistic jets



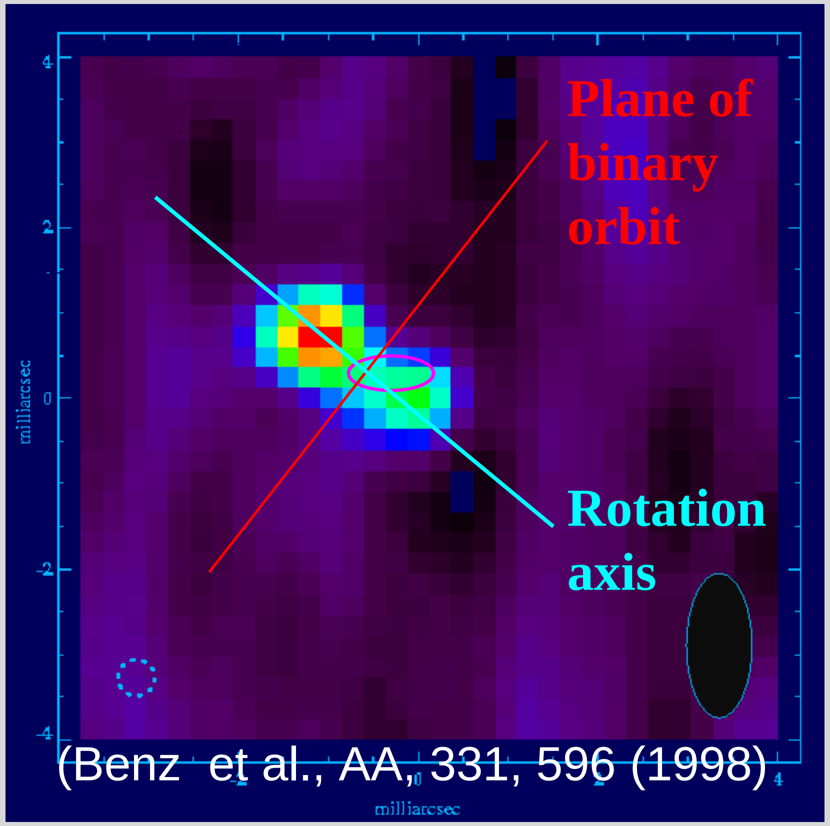
Maser instability explains non-thermal cyclotron radio emission from jets



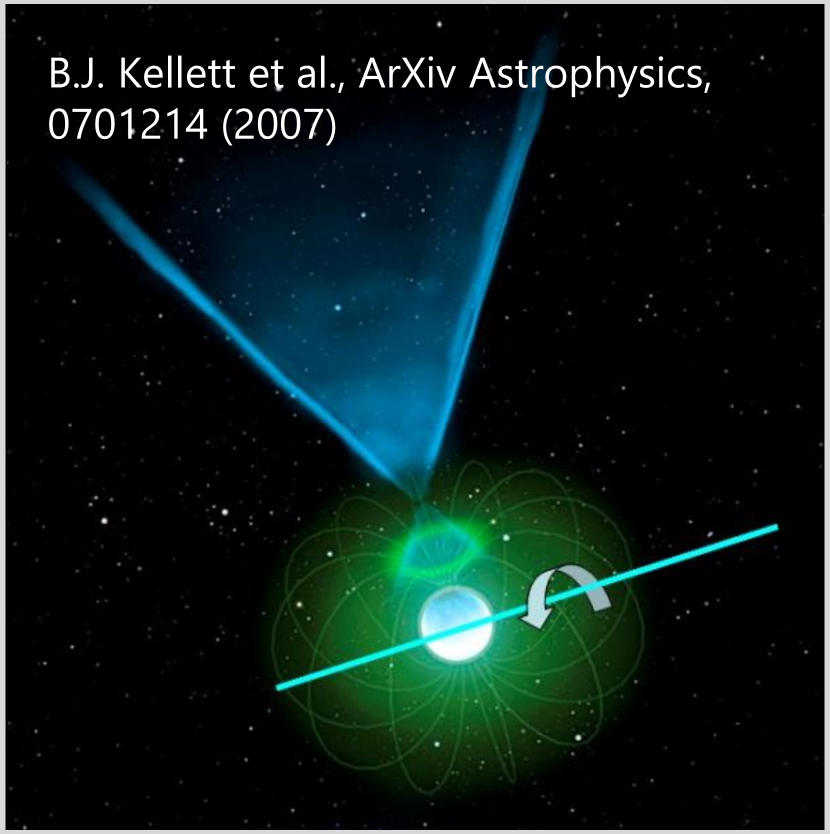
Begelman et al. (2005)

- e$^+$, e$^-$ or pair beams enter a region of converging B-field.
- Cyclotron resonance condition: for small parallel wavenumber, resonant frequency is shifted below cyclotron frequency by an amount dependent on the particle energy.
- The effect of cyclotron resonance is to produce diffusion of the particle in velocity space, mainly in the perpendicular direction (momentum conservation).

Maser instability explains non-thermal cyclotron radio emission from jets



(Benz et al., AA, 331, 596 (1998))


B.J. Kellett et al., ArXiv Astrophysics, 0701214 (2007)

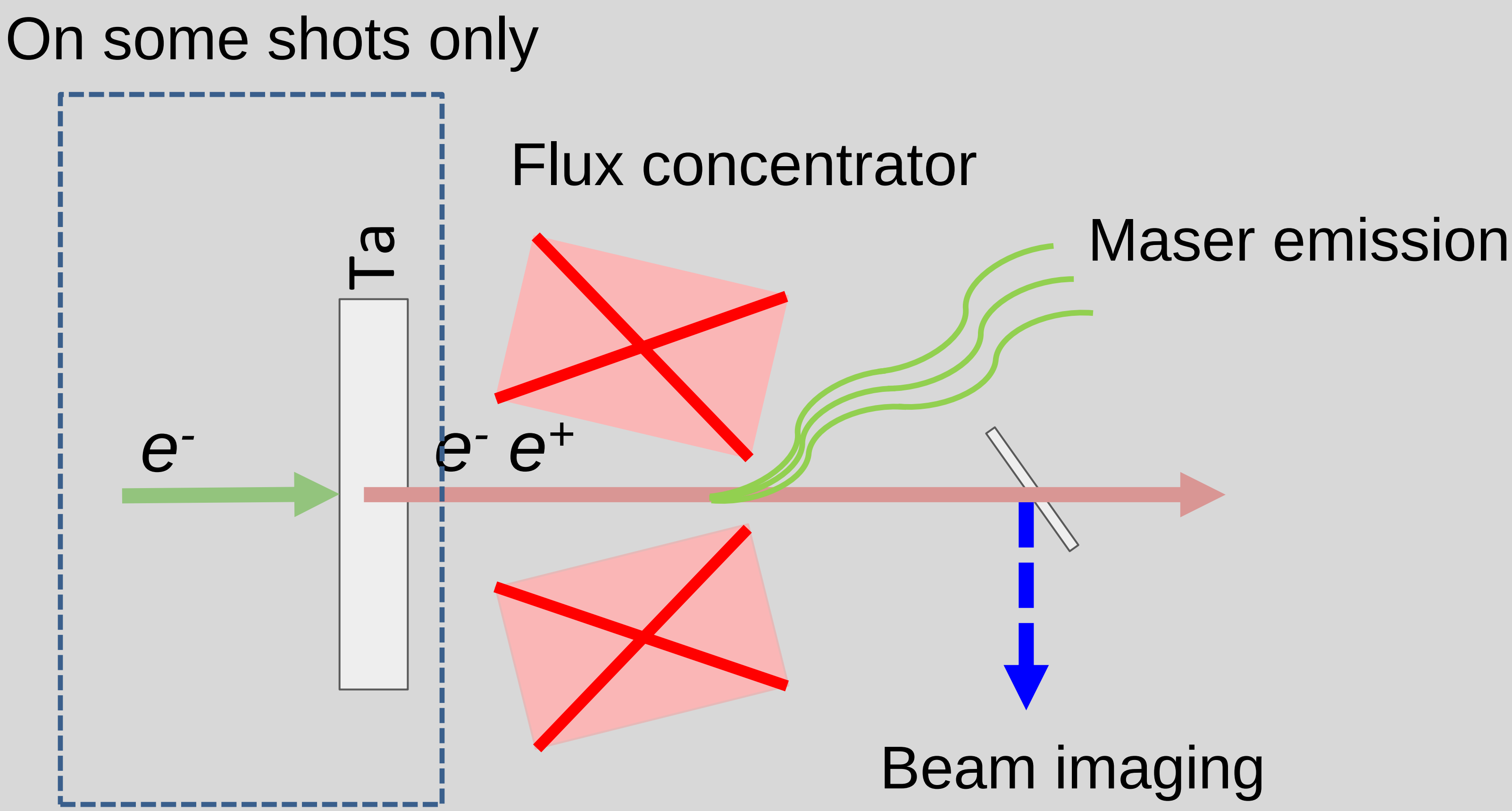
→ Maser emission is believed to explain some (enigmatic) FRB observations, but lack of direct measurements and simulations cannot rule out other processes.

→ Maser process also occurs in star flares, magnetars and other compact objects.

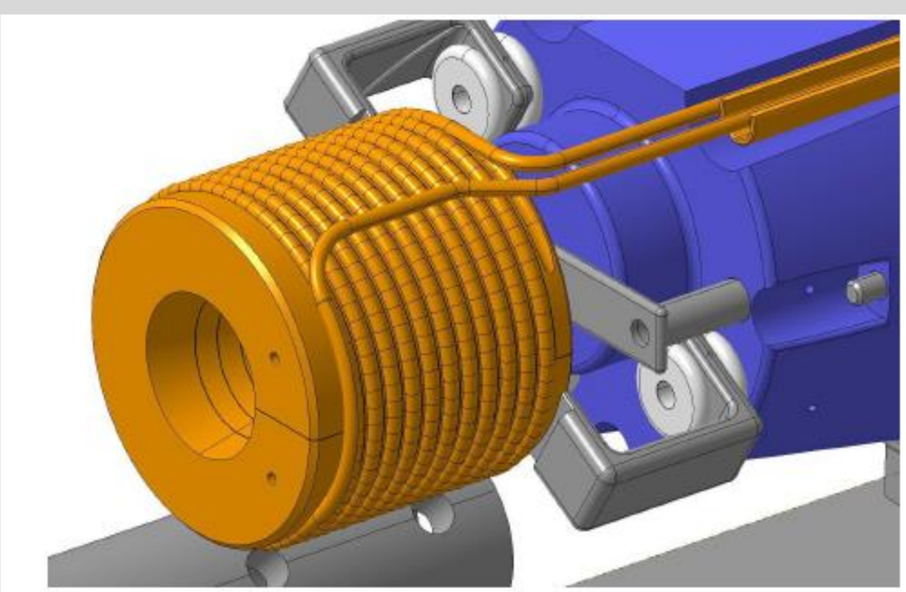
→ The maser effect has been seen in the laboratory (Speirs et al. 2010) only for low-energy electrons and not for relativistic pairs.

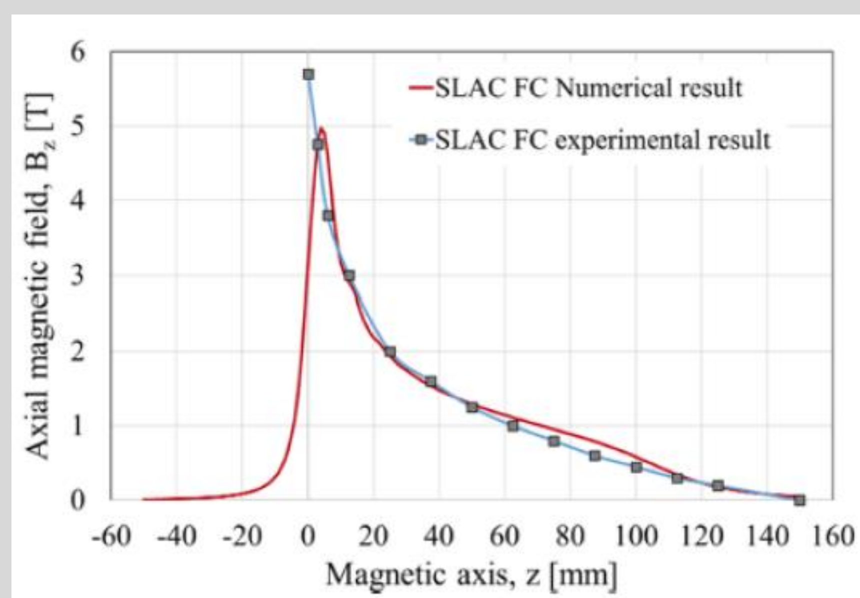
→ At BTF we will study the maser emission, its polarization and total radiated power by considering beams of electrons, positrons and pairs (expect change in the polarization).

Implementation of the maser instability experiment at the BTF

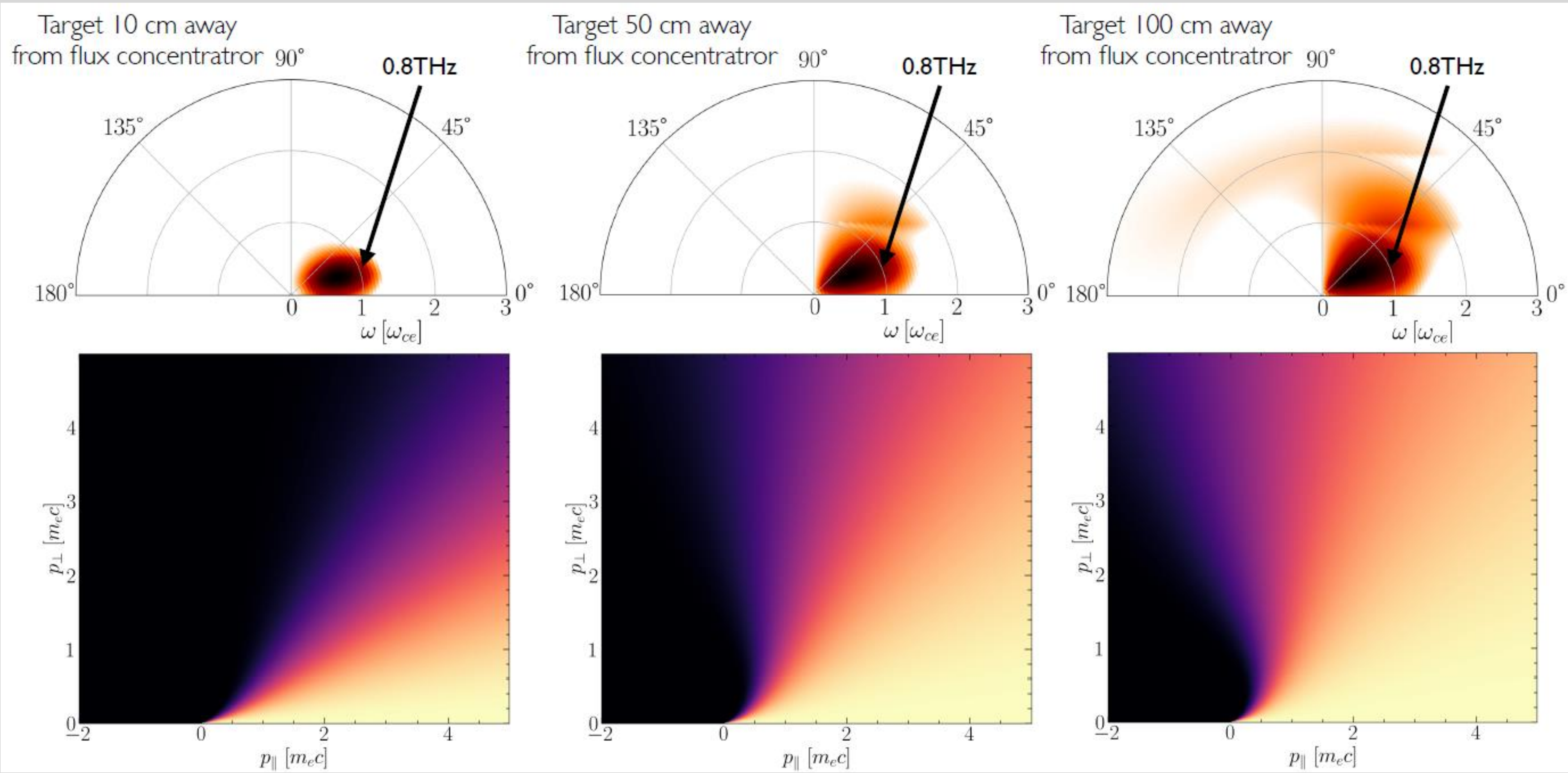


- Flux design taken from SLAC.
- LNF (**A Vannozzi**) is developing a similar coil that can be used on these experiments.
- Further simulations and full integration with BTF is needed.



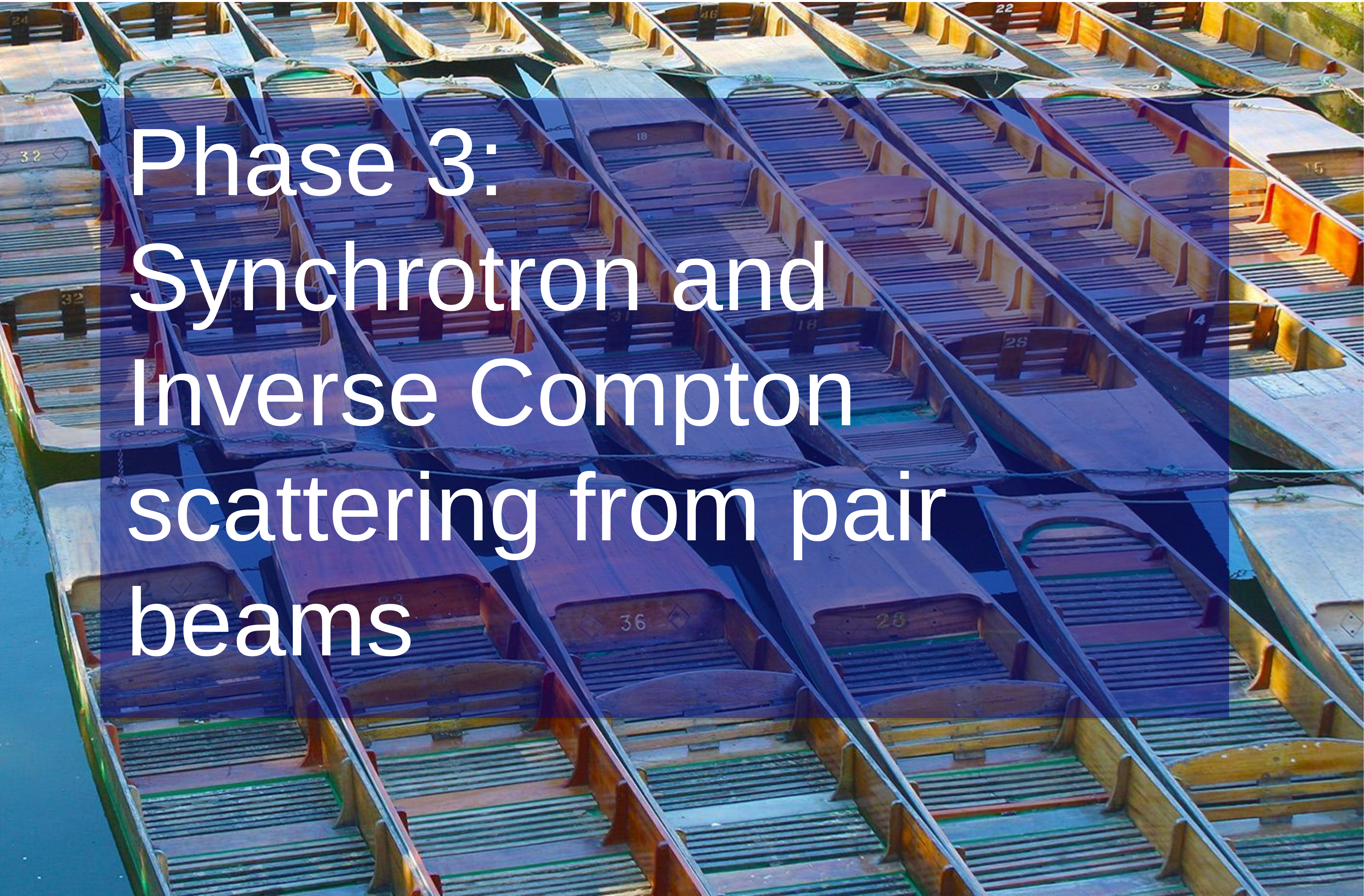


Numerical simulation with realistic beam parameters shows Maser



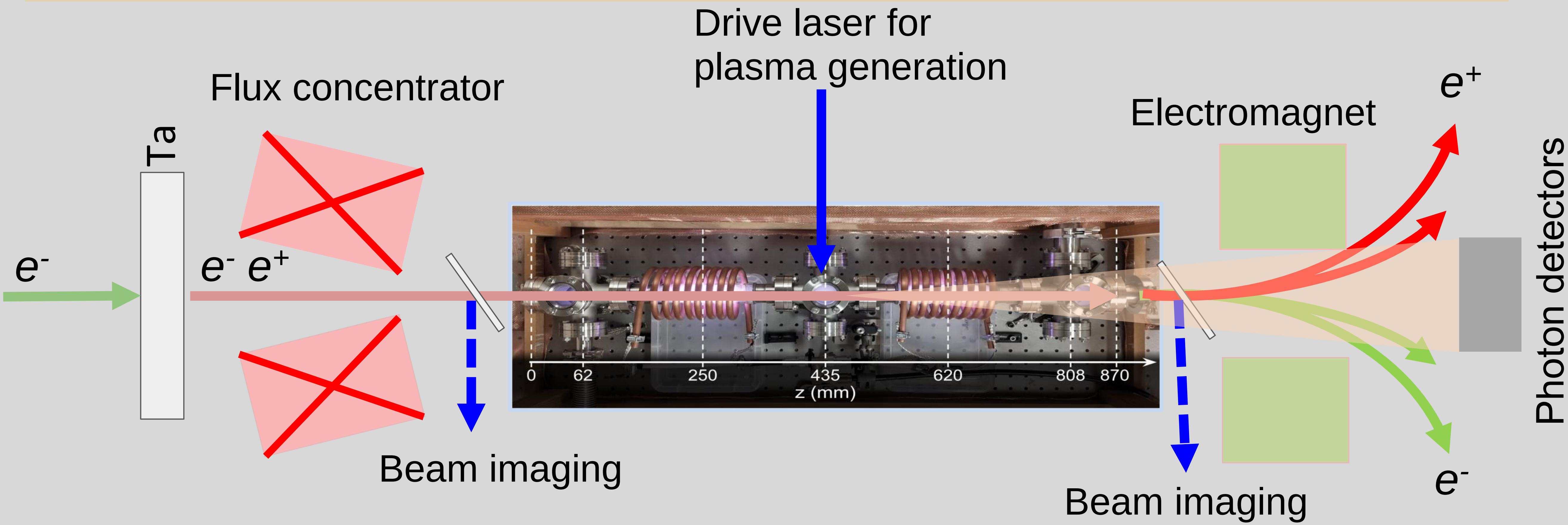
- → Expect maser emission concentrated at 0.8 THz (and harmonics), with polarization dependence (depending on the changes).
- → Maser emission depends on distance between Ta target and flux concentrator.
- → LNF (**C Di Giulio**), Oxford and STFC have expertise in the detection at these frequencies, but further work is needed to finalize the design.

Phase 3: Synchrotron and Inverse Compton scattering from pair beams



GRB emission models: synchrotron *vs* inverse Compton scattering

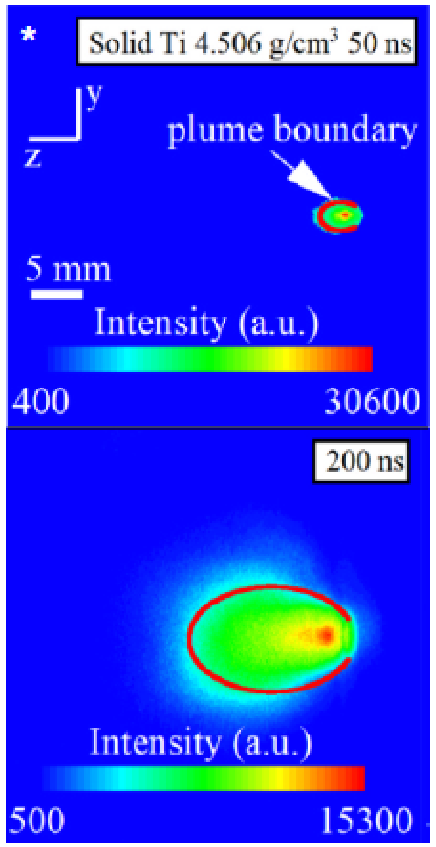
- Fireball model: instabilities → shocks → B-field → radiation → cosmic rays.
- Alternative model (Cannonball) where plasma blobs are ejected.
- Which is the correct model?
- Experiments can be used to compare the two processes.



- Synchrotron: Instabilities produce a B-field which scatter pairs and emit radiation.
- Inverse Compton scattering: using laser to produce plasma blobs, which emit x-rays which scatter off the pair beam.
- Large frequency separation between these two processes.

Inverse Compton scattering from laser-produced plasmas

Laser-produced Photon plasma



What is the density of photons?

Some estimates:

10 J laser

1% efficiency conversion

1 keV photons (soft x-rays)

We expect then

6.2×10^{14} photons in a radius r

How to calculate the scattering rate?

The number of scattered photons per electron is:

$$N_s = 2\rho_\gamma \sigma c t_{int}$$

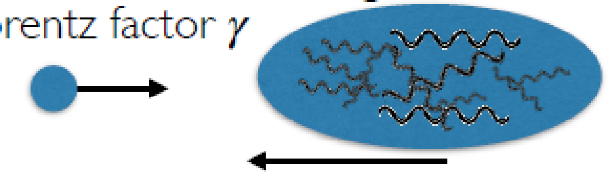
ρ_γ: photon density,

σ:cross-section, t_{int}: interaction time

Laboratory Frame

Photon gas: $h\nu \sim 1$ keV

With Lorentz factor γ



$\sim r$

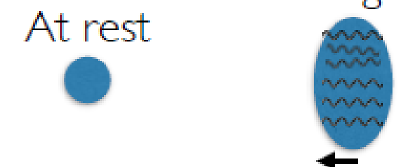
Electron frame

Klein-Nishina cross section peaks at $\theta = 0$, so $\sigma = r_e^2/\epsilon_{\gamma}$.

$$N_s = \frac{3\#p}{\pi r^2}\frac{r_e^2}{\gamma \hbar \nu}$$

At rest

Photon gas: $\gamma h\nu \sim \gamma$ keV



$\sim r/\gamma$

Back in the lab frame: number of scattered photons

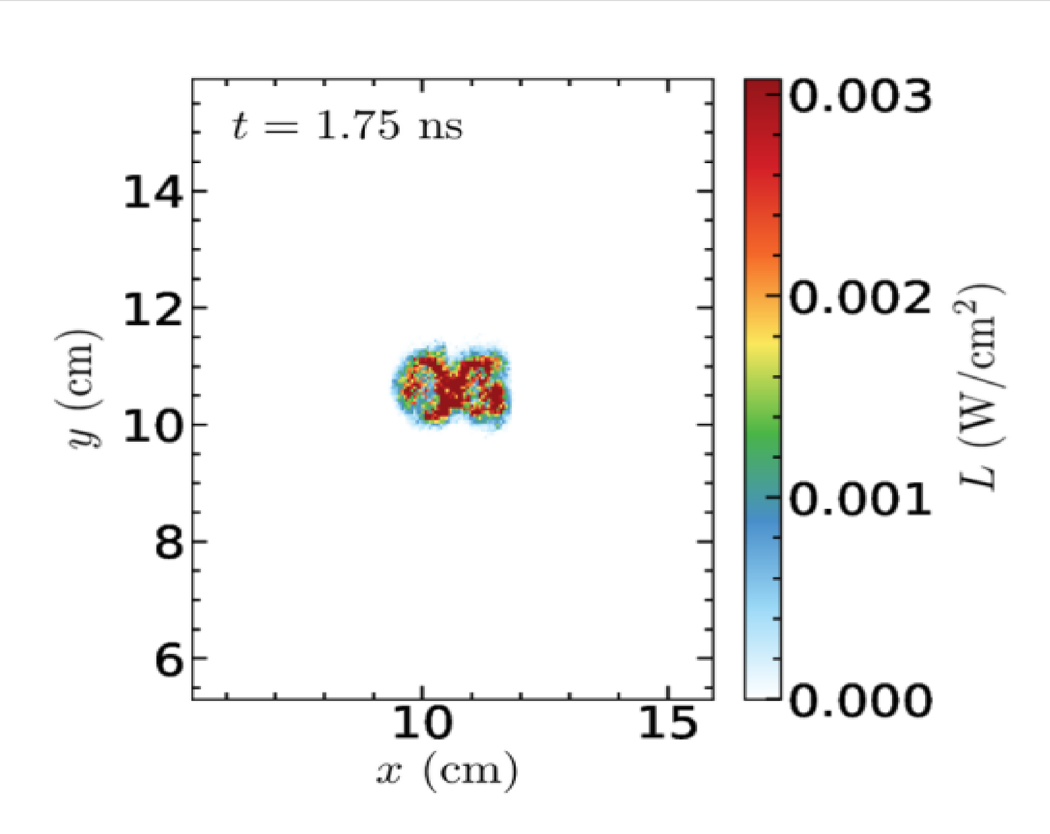
$$N_s\,[100] \simeq \frac{E\,[10\,J]\;\eta\,[1\%]\;n_e\,[10^{11}]}{\nu^2\,[1keV]\;r^2\,[5\,mm]\;\gamma\,[100]}$$

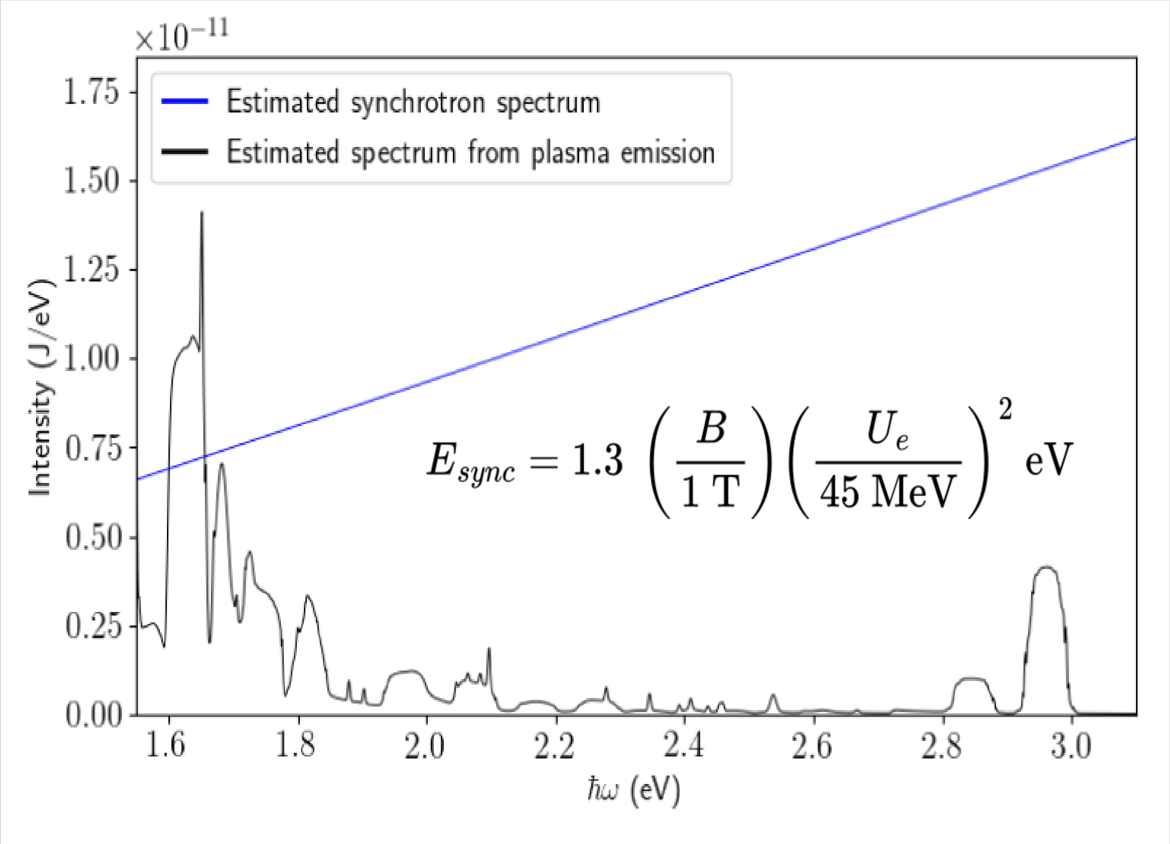
- → Preliminary analysis shows that we can generate 100s of ICS photons at 20-40 MeV.
- → Spectrometer design needs to be performed but LNF (**C Curceanu, A Scordo**) and Oxford have expertise within team to develop this.

Synchrotron emission from plasma instabilities occurs at optical wavelenghts

- Peak of synchrotron emission expected at optical wavelengths (and distributed over a large wavelength range).
- Kinetic (and atomic) simulations used to estimate synchrotron power vs optical line radiation from background plasma.

- Comparison between synchrotron and ICS will provide important information towards our understanding of how GRB's spectra are formed.





Tentative schedule

Proposed time-line for the Fireball experiments

	T0				T0+1				T0+2				T0+3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Design	■	■	■				■	■			■	■				
Installation				■	■				■				■			
Phase 1						■										
Phase 2										■						
Phase 3														■		

Thank you for your attention!