Plans for laboratory pair plasma diagnostics

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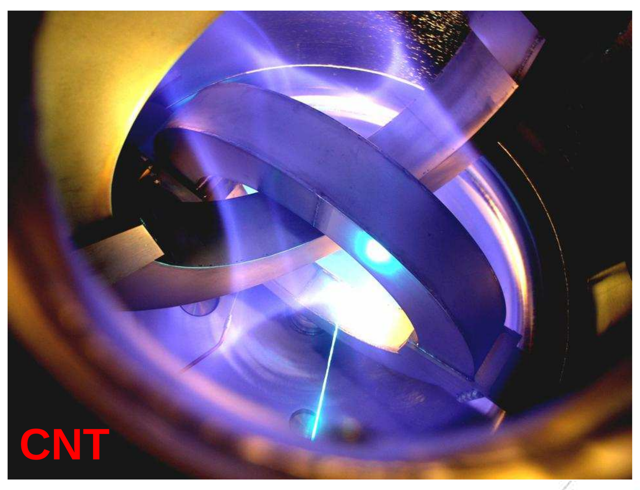
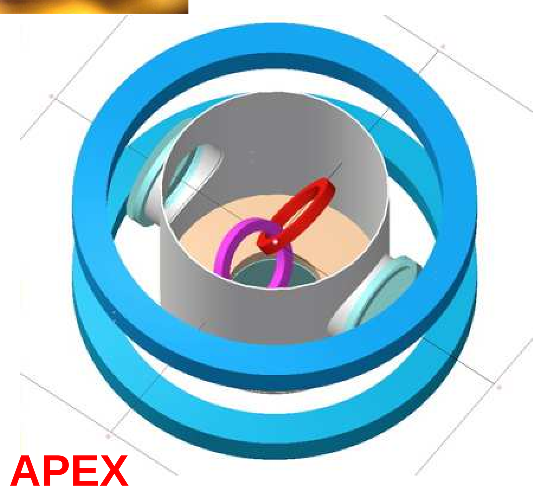
APEX experiment

- **APEX** will be a small superconducting **stellarator** dedicated to the study of **e^+ - e^- plasmas.**
- Design based on the **Columbia Non-neutral Torus (CNT)** [1]:
  - 2 interlocking coils inside the chamber.
  - 1 Helmholtz pair outside the chamber.
- However, CNT relied primarily on internal probes for diagnostics, while **APEX** must be **diagnosed without invasive probes.**
- The **low densities** at APEX make the use of **non-perturbative** diagnostics (e.g., reflectometry, Thomson scat.) **very challenging**.

	CNT	APEX
B field (T)	0.2	2
p_n (Torr)	10^{-9}	10^{-10}
Major radius (cm)	30	15
Minor radius (cm)	16	7
T (eV)	2 - 20	0.2 - 2
n_e (m^{-3})	3×10^{12}	10^{13}
n_p (m^{-3})	0	10^{13}
λ_D (cm)	1.0	0.1 - 0.3
Confinement time (s)	0.09	1

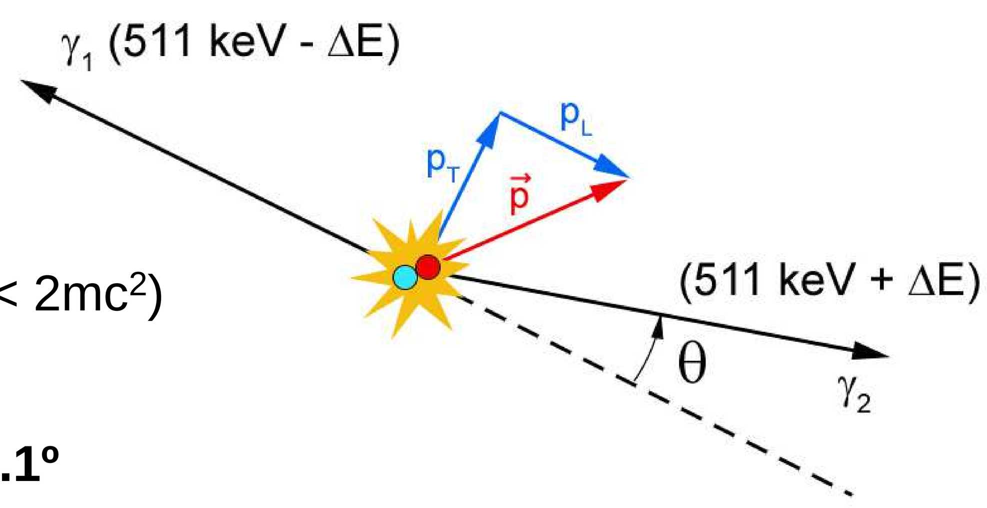




γ-coincidence detection

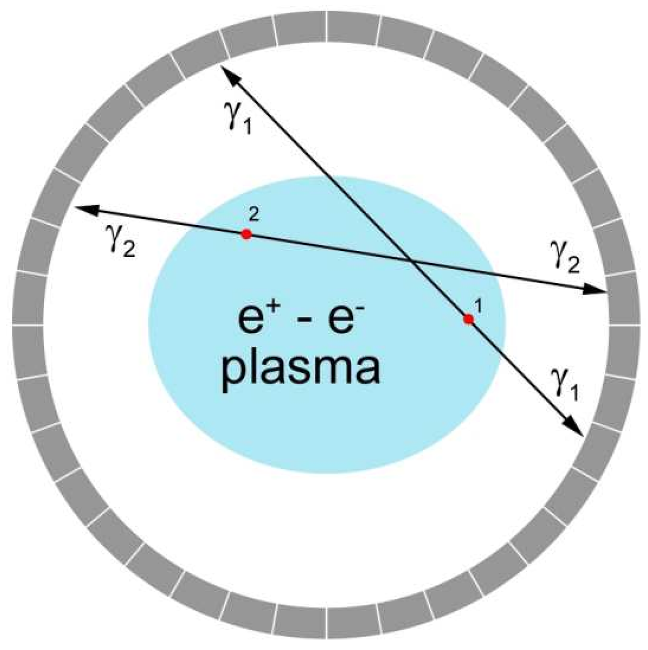
- Array of γ-detectors to detect the 511 keV annihilations.
- For a n = 10^{13} m^{-3}, T = 1 eV e^+ - e^- plasma**:**
  - ν_{ep} **≈ 10^{-5} s^{-1}** (not limiting the plasma lifetime)
  - Still, for N = 10^{11} e^+ , **1 annihilation occurs every μs**
- Two-photon γ-annihilations will be detected within a coincidence time window (10 to 100 ns). Similar to what is used in γ–spectroscopy, and PET (Positron Emission Tomography).

- Info from γ-coincidence detection:
  - Line along which each annihilation occurs.
  - Where? **±10 cm error** with fastest γ-detectors.
  - **Energy Doppler shift:** $\Delta E \approx {}^1/_2\, p_L c$ (for pc << $2mc^2$)
  - **Angular deviation:** $\Delta\theta \approx p_T / (m_0 c)$
  - For a **$T_e = T_p \approx$ 1 eV** plasma: **$\Delta E \approx$ 0.6 keV, $\Delta\theta \approx 0.1^o$**



Technical requirements for γ-detectors in APEX

- **High stopping power** for 511 keV photons.
- **High timing resolution** (10 – 100 ns) to detect single annihilation events.
- **Good energy resolution** (≤ 1 keV at 511 keV).
- **Good spatial resolution** (many small detectors).
- Compatible with **strong B fields** (2 T). Cannot use vacuum tubes (e.g., μ-channel plates, photomultipler tubes).
- **UHV compatible** (~ 10^{-10} Torr).



Scintillator + Photodetector

Scintillators

	Density (g/cm^3)	Light yield (photon/keV)	τ_{decay} (ns)	E resolution (FWHM, %)
NaI (Tl)	3.67	38	250	7
BaF_2	4.88	1.8	0.7	-
BGO	7.13	9	300	12
LYSO	7.10	32	41	8
$LaBr_3$	**5.08**	**63**	**16**	**2.9**

Properties specified by *Saint-Gobain Ceramics & Plastics, Inc.*

Photodetectors

	Gain	B field compatible	Active area	Num. of elements	Bias voltage
PMTs	10^6	**No**	~1 cm^2	~1	~1000 V
APDs[a]	**100**	**Yes**	**2.6 mm^2**	**32**	**325 V**
SiPMs[b]	4×10^5	Yes	9 mm^2	8100	53.8 V

[a] *Hamammatsu S8550* APD array
[b] *Photonique SSPM-0604BE-TO5* (production date: 2007)

HPGe detectors

- Cryogenically cooled High Purity Ge diodes.
- **Energy resolution:** ~1.2 keV at 511 keV
- **Compatible** with high **B field strengths**.
- Lower densities than scintillators
- Timing resolution: **4.5 ns**
- **Require continuous LN_2 cooling.**

Pellet injection

- 0.2 mm diameter pellets injected at ~200 m/s.
- At T_e=T_p **no sheath** is formed in quasineutral pair plasmas.
- Pellet material prevents e^+ conversion into Ps.
- **∂N_{anh} / ∂t** will be equal to the **e^+ arrival rate**:

$$\frac{\partial N_{anh}}{\partial t} = 2\pi r_{pellet}^2\, n_p \sqrt{\frac{T_p}{2\pi m_p}}$$

- **(∂N_{anh} / ∂t)$_{pellet}$** = 4×10^{11} **>> (∂N_{anh} / ∂t)$_{plasma}$**
- But only **0.2 % of plasma inventory** is **removed**.

Planned diagnostic scheme

- Fast **scintillator + APD** γ-detection system:
  - Verify e^+ are successfully injected and confined.
  - Measure **number of annihilations** (ΣN_{anh}) and estimate **average density** (n).
  - Measure annihilation rate, **∂N_{anh} / ∂t = f(T, n)**
  - ΔE/E ≈ 8% (40 keV). **Cannot measure T < 4 keV**
- Set of coincident **HPGe detectors**:
  - ΔE/E ≈ 1 keV at 511 keV. **Can measure T > 2 eV**
- **Pellet injection system** will increase **∂N_{anh} / ∂t during 500 μs pulses.**
- **Ion beam probe** to measure the internal E field.

References

[1] T. Sunn Pedersen et al., Fusion Sci. and Technol. **50**, p. 372 (2006)