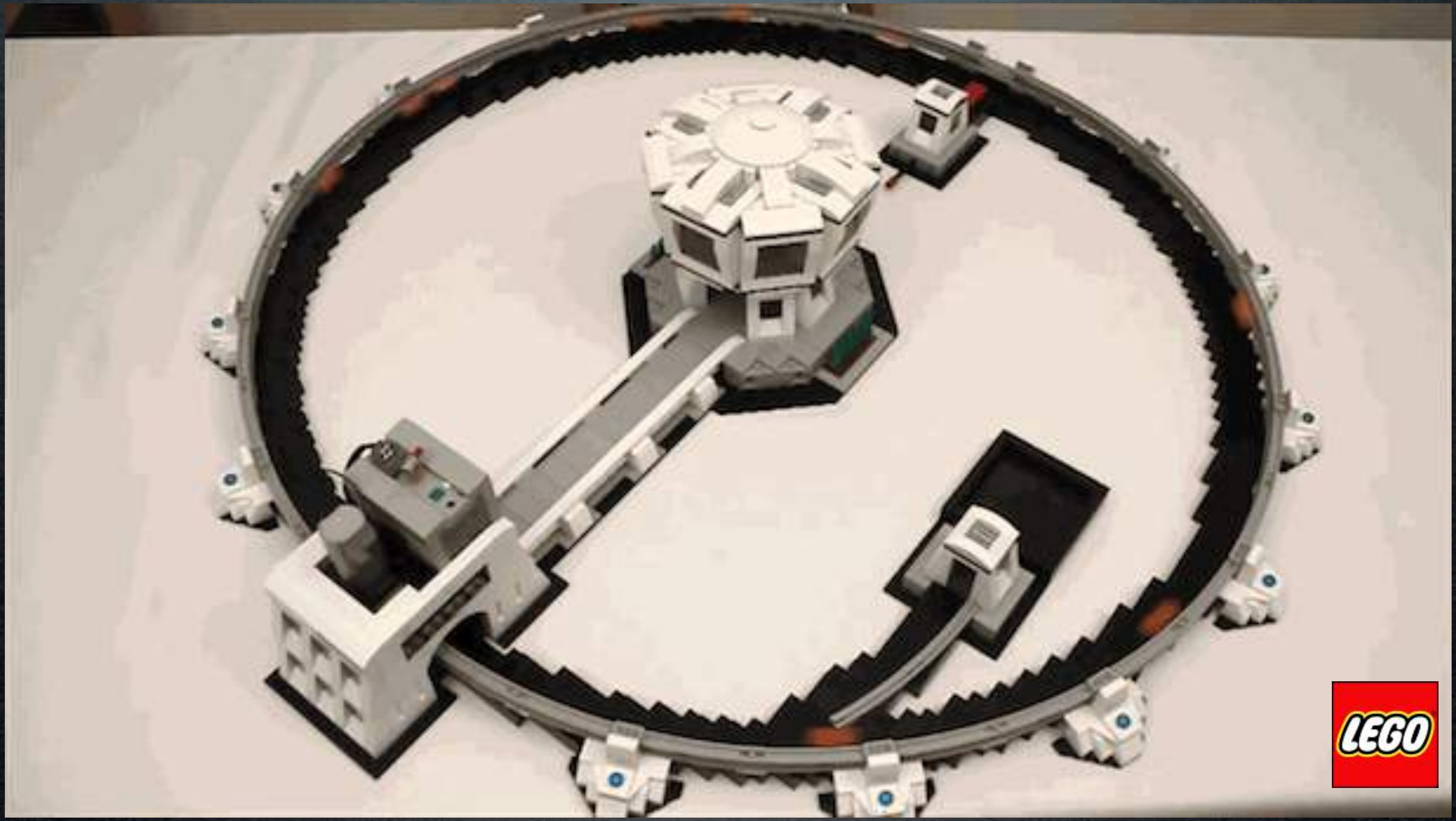
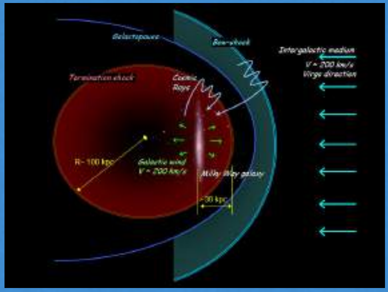
View on future Accelerator R&D

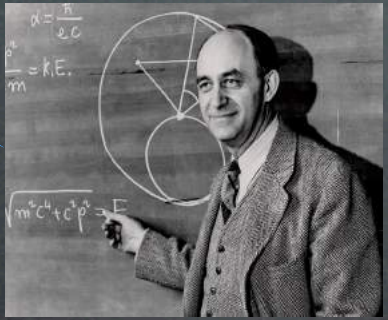
Massimo.Ferrario@LNF.INFN.IT



5-9 December 2016 - Hotel Bayside, Scharbeutz

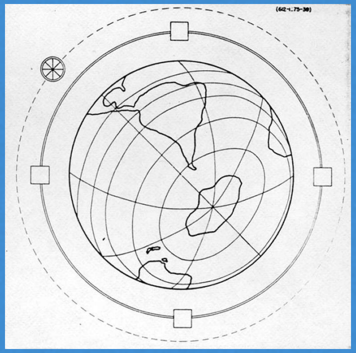
A man accustomed to dream big:





The Cosmotron

The Globatron



Was a proton synchrotron, (BNL 1953). It was the first particle accelerator to impart kinetic energy in the range of 3 GeV and to allow the extraction of the beam for experiments located physically outside the accelerator.

Fermi's Globatron: ~5000 TeV Proton beam

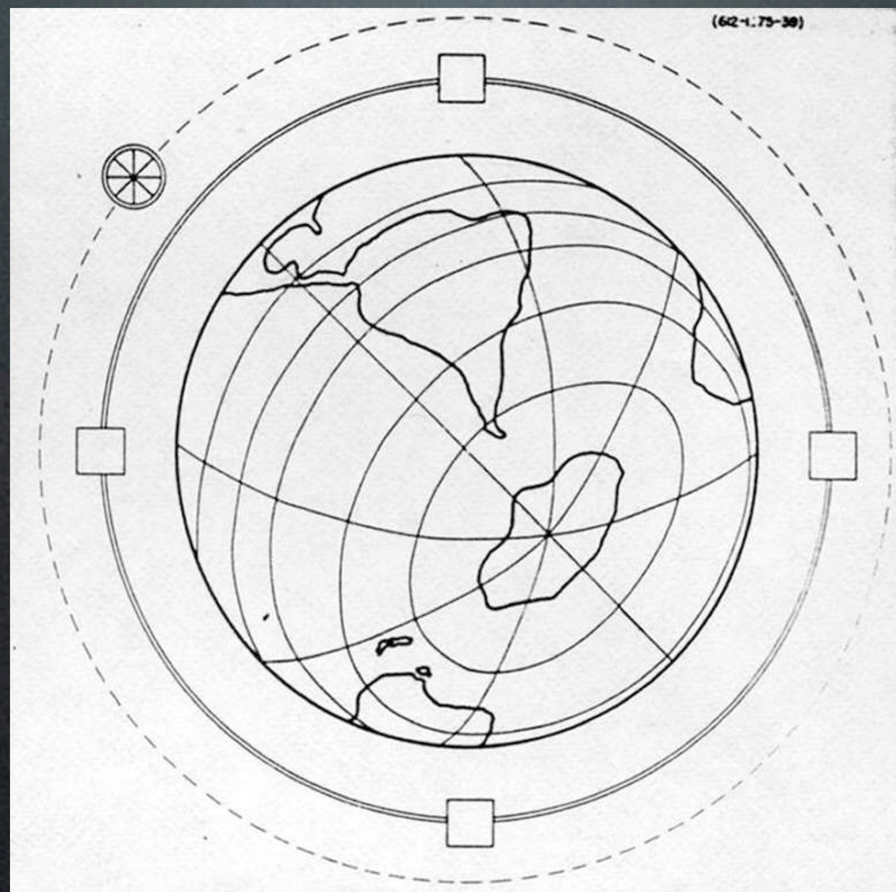
1954 the ultimate synchrotron

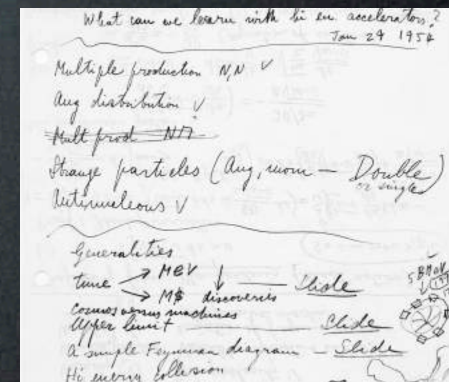
B_{max} 2 Tesla

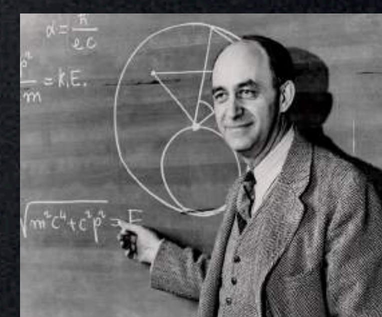
ρ 8000 km

170 G$

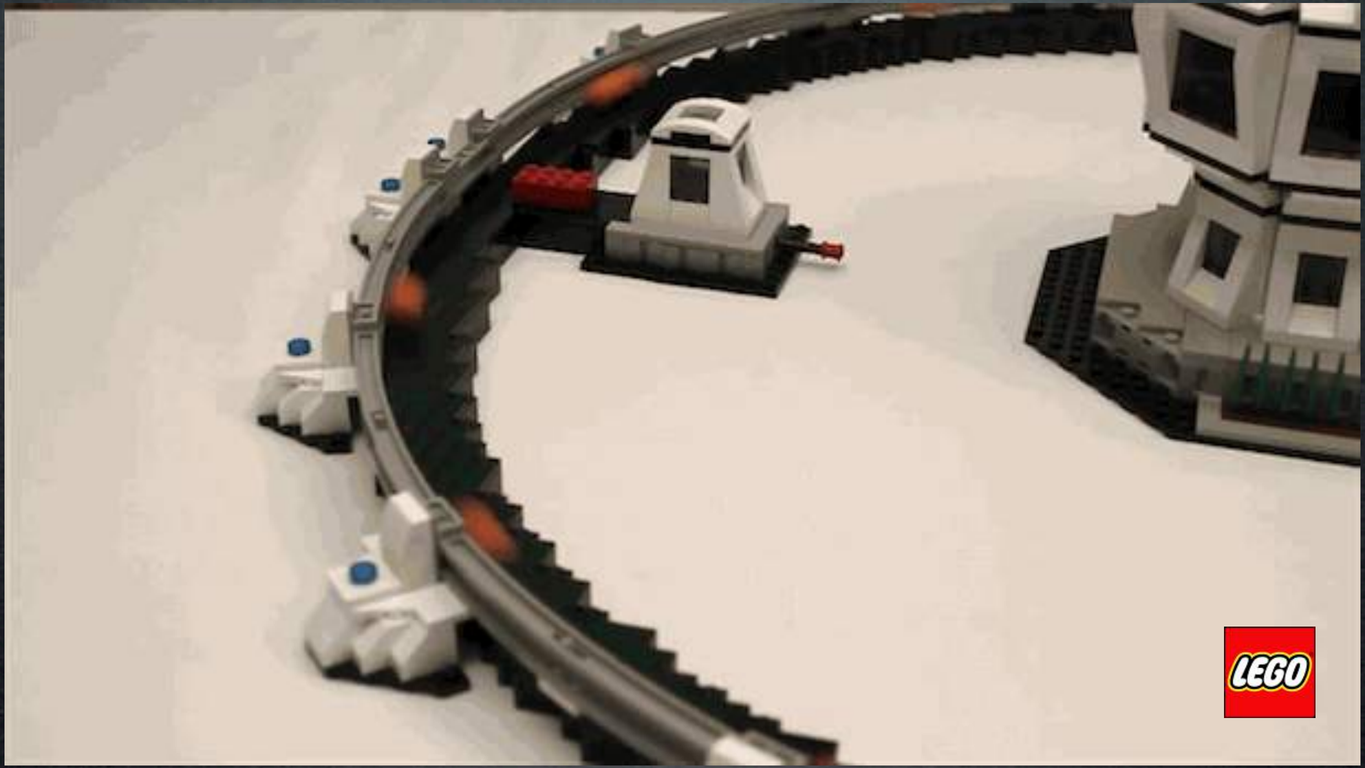
1994

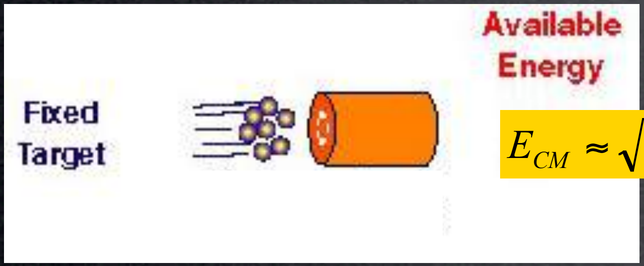






Globatron mis-dreaming: fixed target ➔ 3 TeV cm

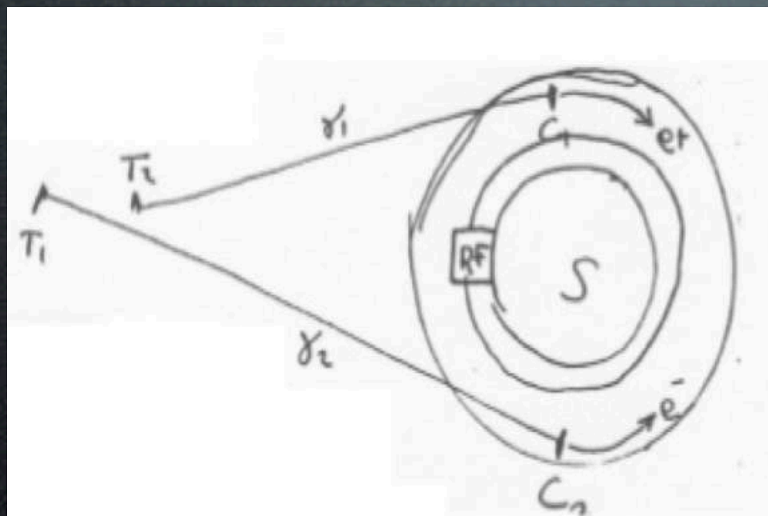




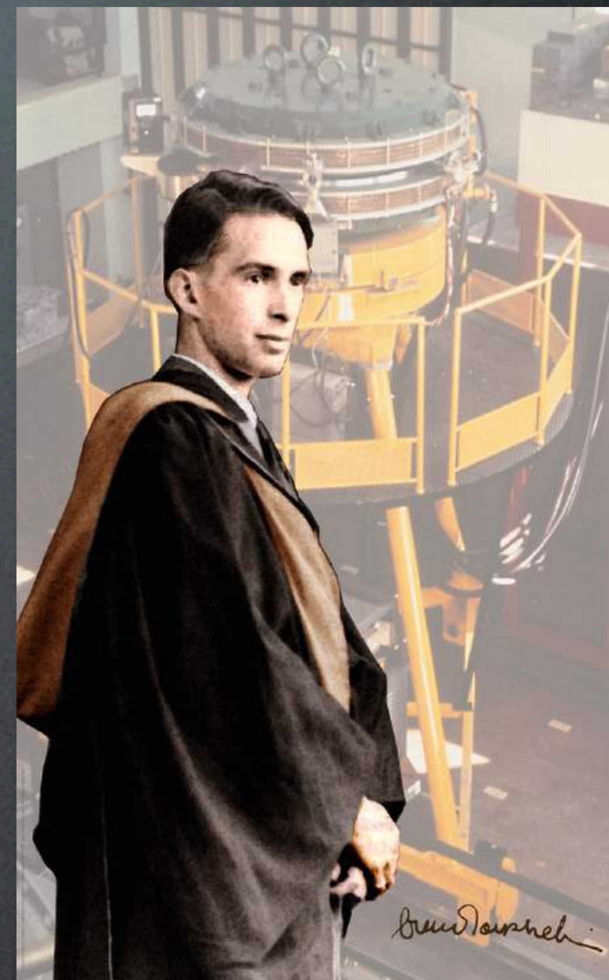
$$E_{CM} \approx \sqrt{2E_1 m_2}$$

Touschek's Anello Di Accumulazione (ADA)

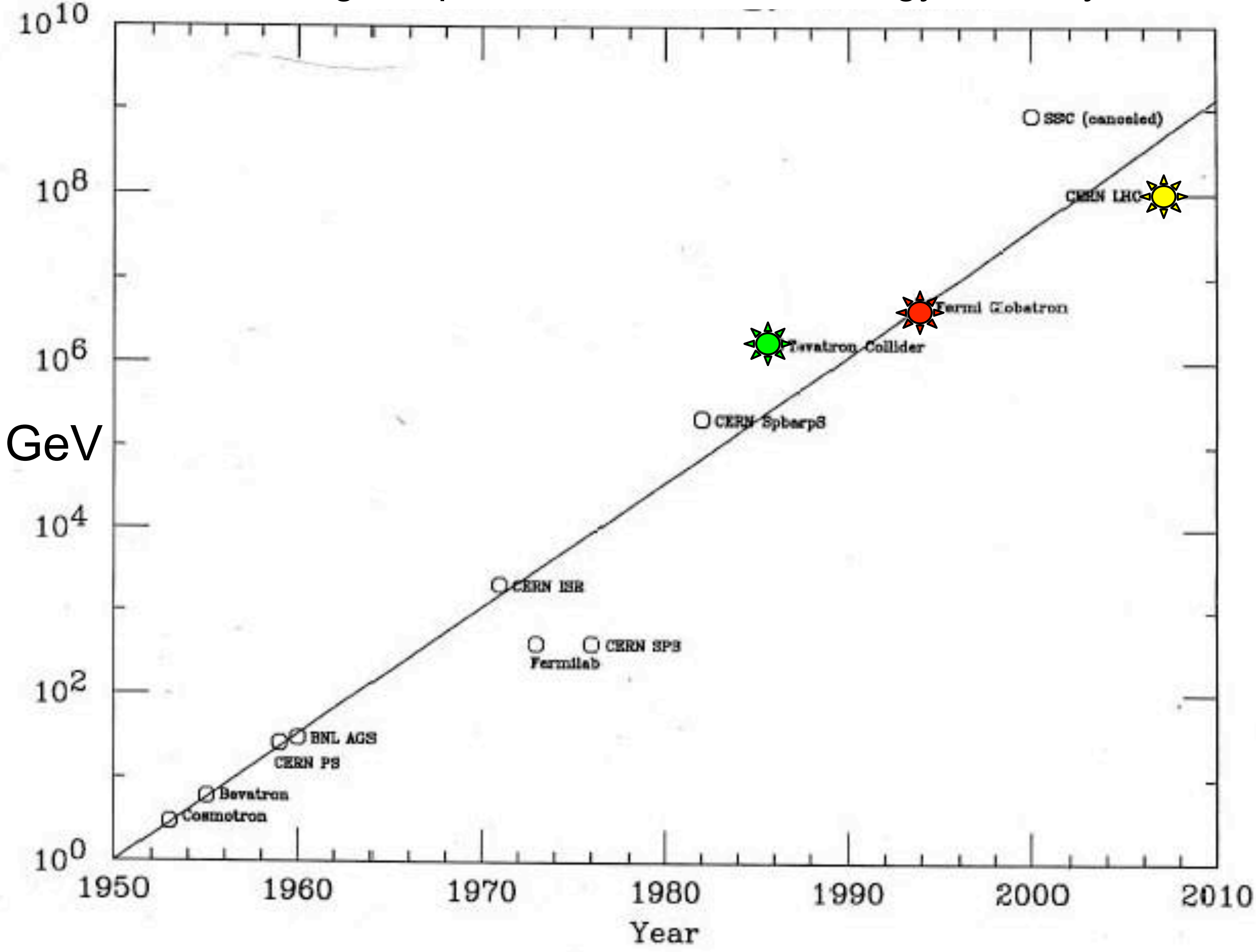
1961 the first e+e- Collider



$$E_{CM} \approx 2E$$



Fixed Target equivalent accelerator energy versus year



Hawking: the Solartron

Towards the Planck scale: 1.22×10^{19} GeV

Without further novel technology, we will eventually need an accelerator as large as Hawking expected.

“The Universe in a Nutshell”, by Stephen William Hawking, Bantam, 2001

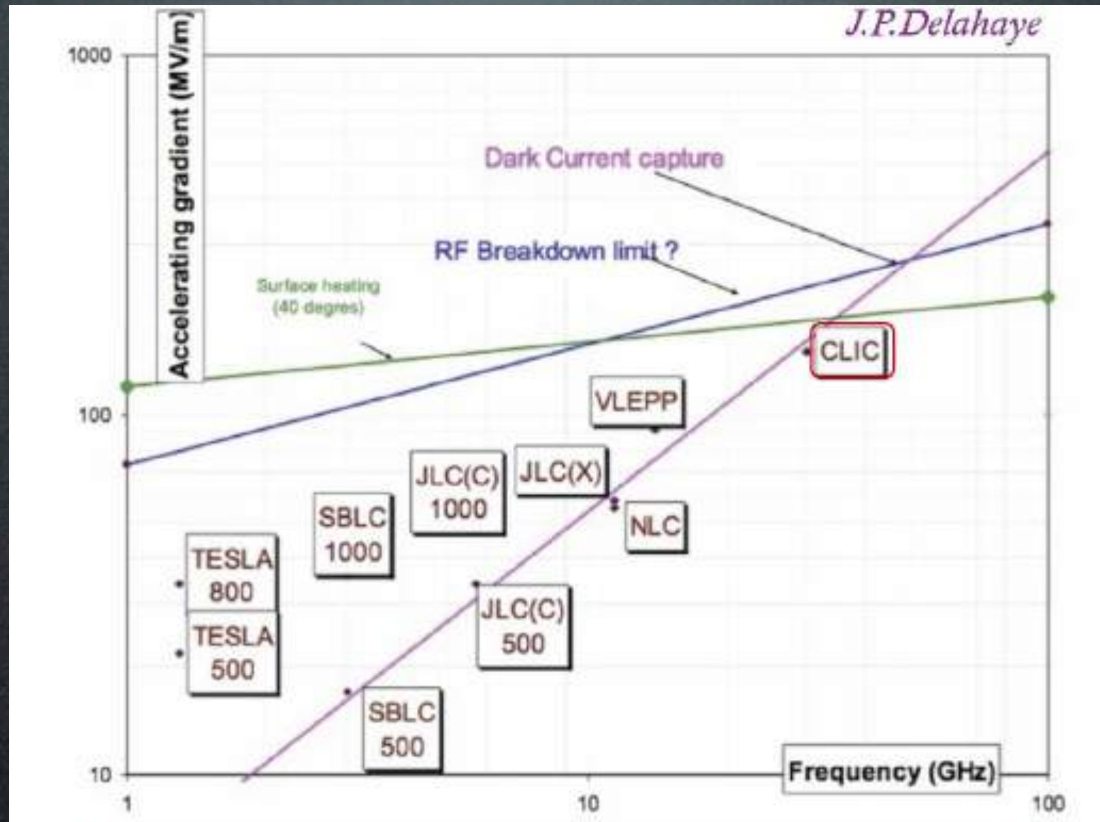
HIGH GRADIENT AAC ROAD MAP

① Miniaturization of the accelerating structures (~resonant) and beam manipulation components

② Wake Field Acceleration (~transient) (LWFA, PWFA, DWFA)

- Power sources
- Accelerating structures
- High quality beams

High field ->Short wavelength->ultra-short bunches-> low charge



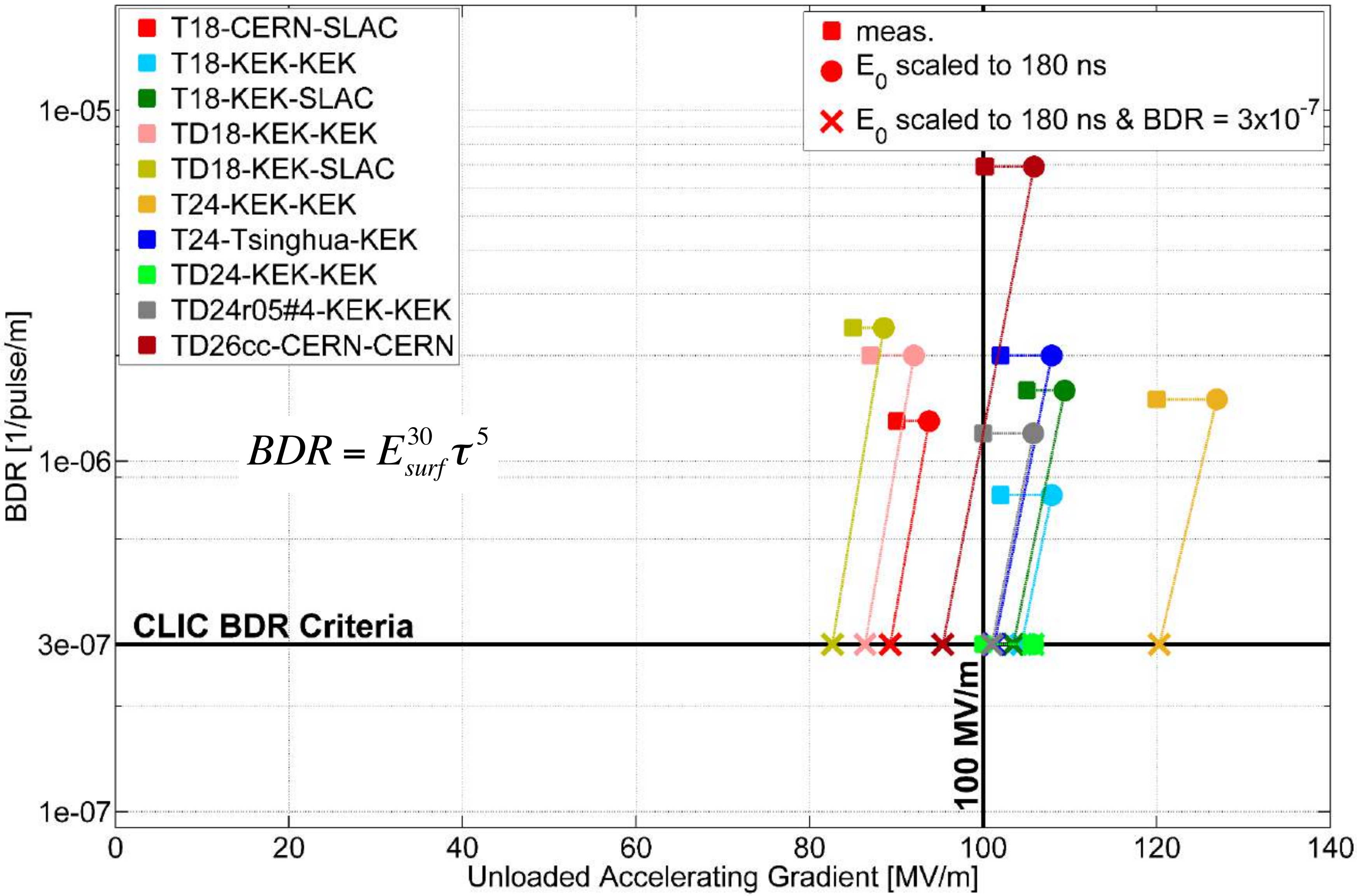
Breakdown limits metal:

$$E_s = 220(f\,[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

From x-band experience:

$$BDR = E_{surf}^{30}\tau^{5} \div \left(\omega^{-\frac{15}{2}}\right)?$$

Performance summary at CLIC specifications

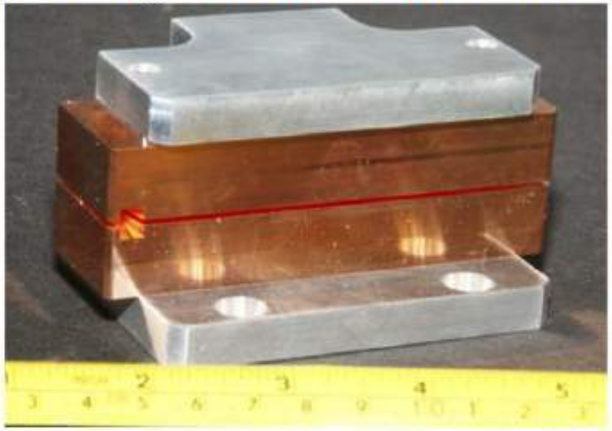


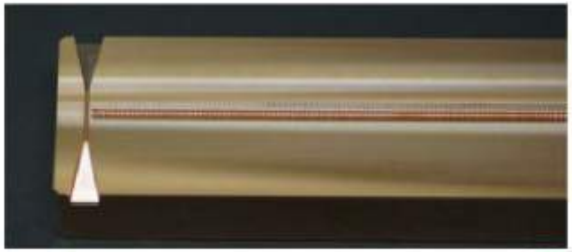
Miniaturization of the accelerating structures

Future plans for the high gradient collaboration

- The collaboration during the next 5 will address 4 fundamental research efforts:
  - Continue basic physics research, materials research frequency scaling and theory efforts.
  - Put the foundations for advanced research on efficient RF sources.
  - Explore the spectrum from 90 GHz to THz
    - Sources at MIT
    - Developments of suitable sources at 90 GHz
    - Developments of THz stand alone sources
    - Utilize the FACET at SLAC and AWA at ANL
    - Address the challenges of the Muon Accelerator Project (MAP)

mm-Wave structure to be tested at FACET



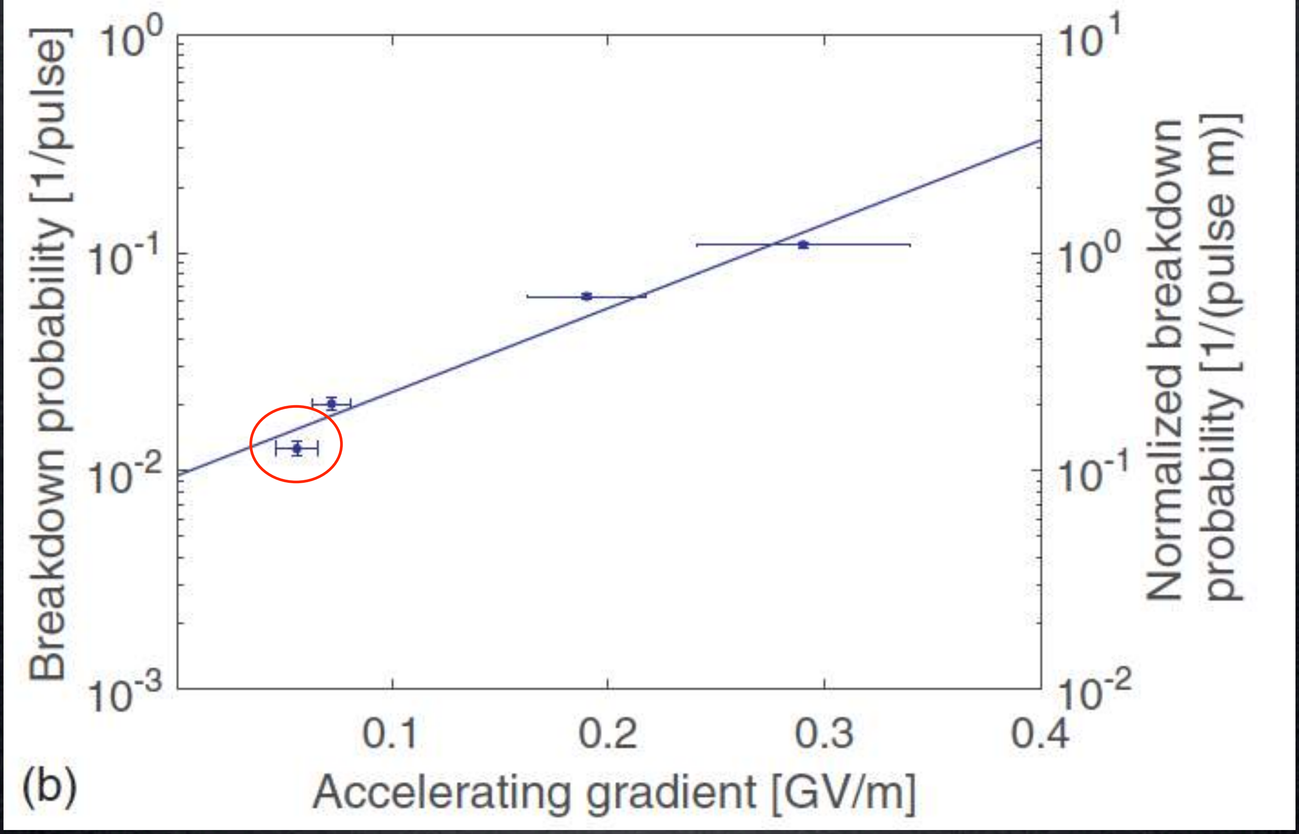


SLAC NATIONAL ACCELERATOR LABORATORY

PHYSICAL REVIEW ACCELERATORS AND BEAMS 19, 111301 (2016)

rf breakdown measurements in electron beam driven 200 GHz copper and copper-silver accelerating structures

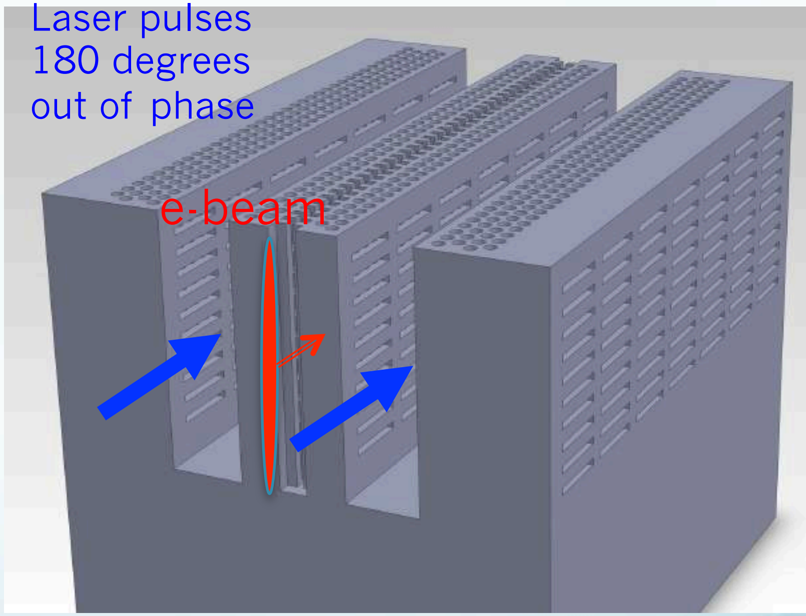
Massimo Dal Forno,[1,*] Valery Dolgashev,[1] Gordon Bowden,[1] Christine Clarke,[1] Mark Hogan,[1] Doug McCormick,[1] Alexander Novokhatski,[1] Brendan O'Shea,[1] Bruno Spataro,[2] Stephen Weathersby,[1] and Sami G. Tantawi[1]



Laser Acceleration
DLA

Dielectric Photonic Structure

- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes

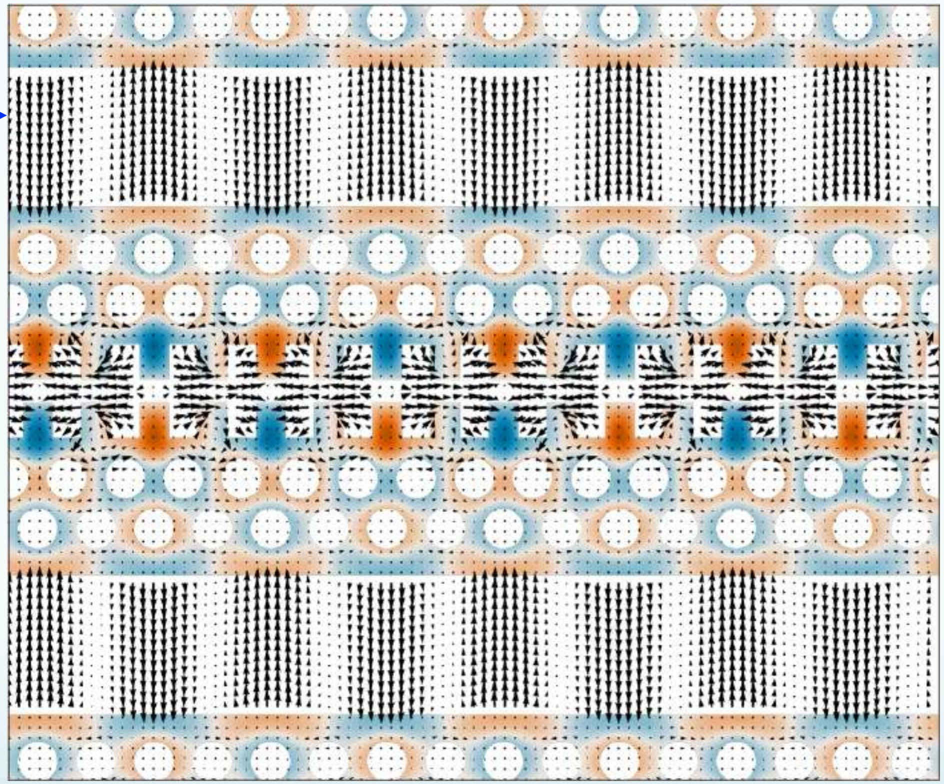


Schematic of GALAXIE
monolithic photonic DLA

Laser-Structure Coupling: TW

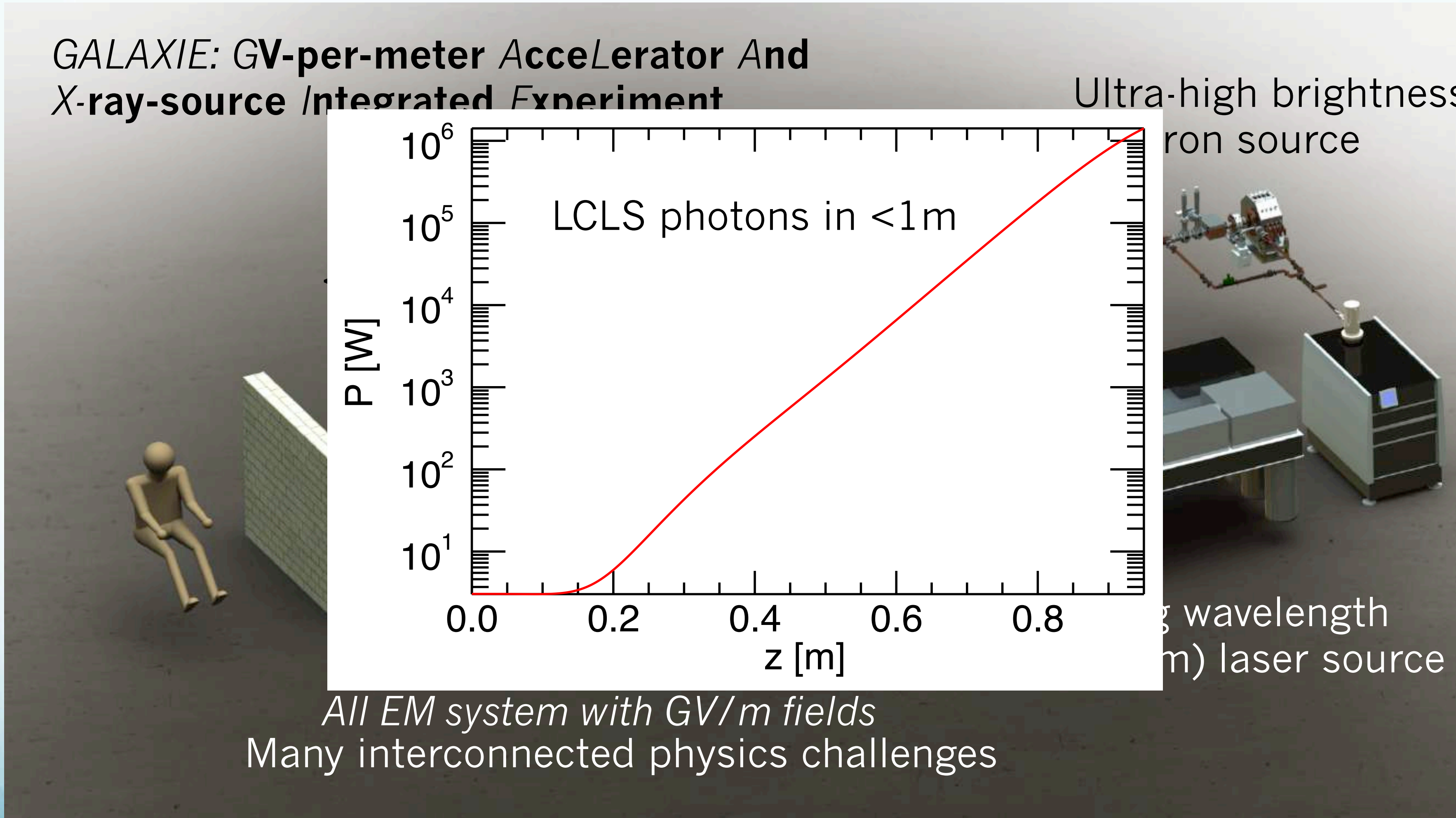
GALAXIE Dual laser drive structure, large reservoir of power recycles

Laser pulses (180 degrees out of phase)



e-beam

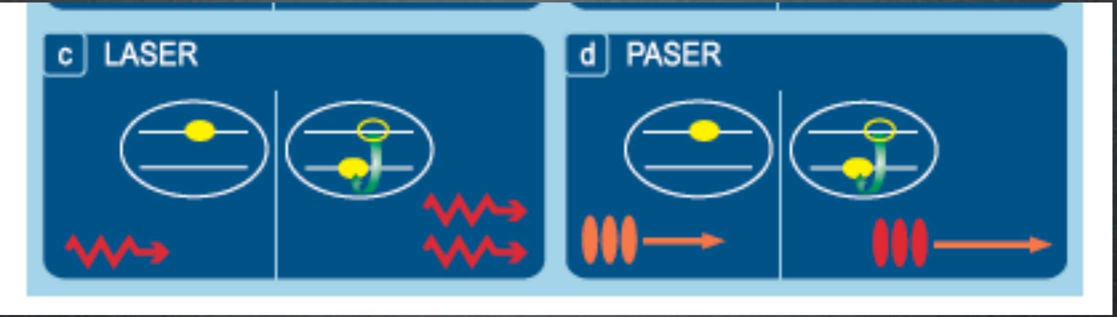
5th Gen Light Source: A Table-top X-ray FEL

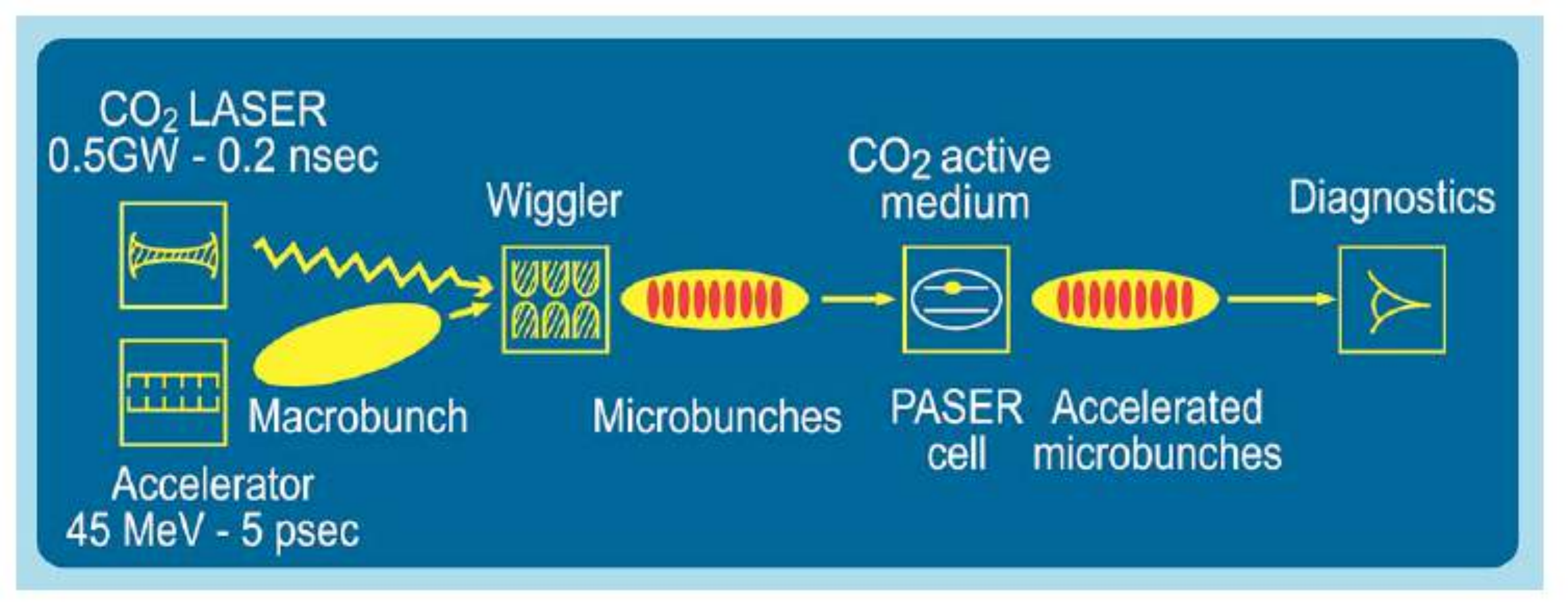


PHYSICAL REVIEW E 74, 046501 (2006)

Particle acceleration by stimulated emission of radiation: Theory and experiment

Samer Banna,* Valery Berezovsky, and Levi Schächter
Department of Electrical Engineering, Technion, Israel Institute of Technology, Haifa 32000, Israel
(Received 28 June 2006; published 23 October 2006)





PRL 97, 134801 (2006) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2006

Experimental Observation of Direct Particle Acceleration by Stimulated Emission of Radiation

Samer Banna,* Valery Berezovsky, and Levi Schächter
Department of Electrical Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel
(Received 4 June 2006; published 28 September 2006)

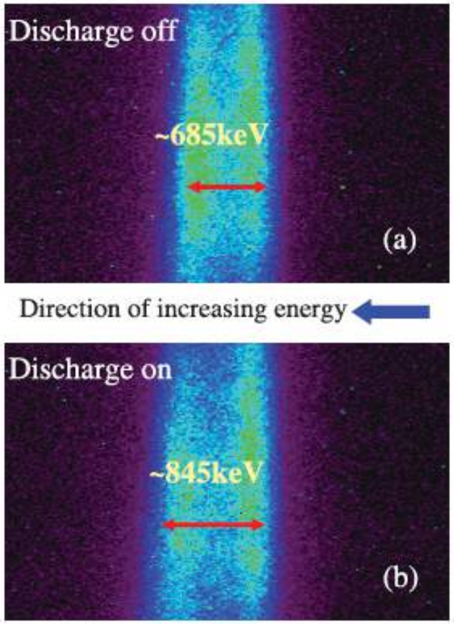


FIG. 3 (color). Raw video images from the electron energy spectrometer. Energy dispersion is in the horizontal direction. (a) Discharge is off in the PASER cell. (b) Discharge is on in the PASER cell. In both cases, ~1.5% peak-to-peak energy modulation was imparted.

Plasma Acceleration

More than the Plasma Accelerator

- In a circular accelerator facility:

  Accelerating systems < 10% of total investment

- In a linear accelerator facility:

  Accelerating systems < 30% of total investment

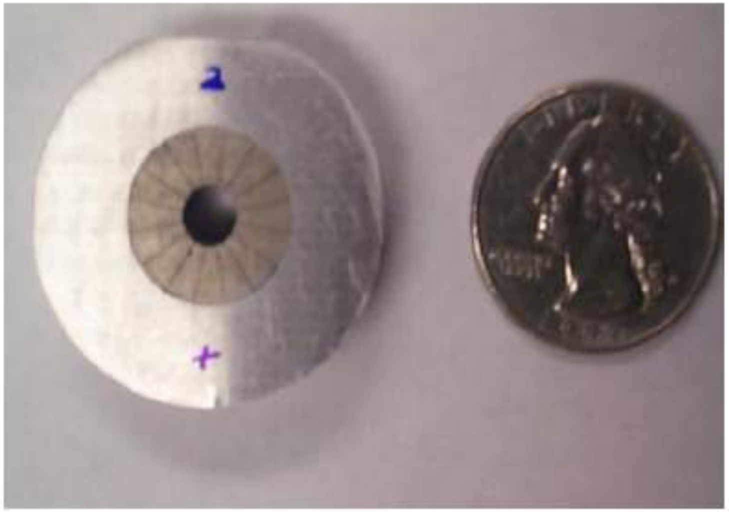
- **Highly developed (and expensive) systems** for generation/bending/focusing/diagnostics/correction/collimation/control of particle beams:
  - Accelerator facilities would not provide interesting performance without these systems.
  - **For plasma accelerators not at addressed yet**, due to focus on acceleration highlights and lack of budget

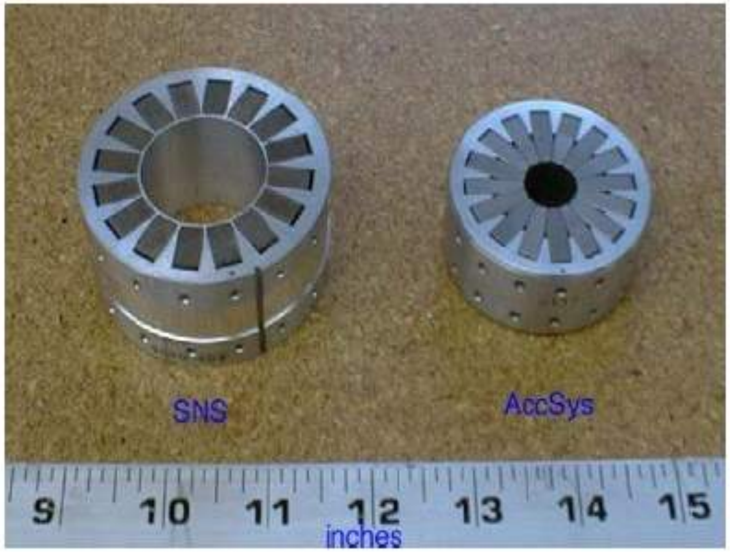
→ **EuPRAXIA to address this: build an accelerator research infrastructure for pilot users**

Beam Manipulation

Matching into/out of plasma/1

More conventional solutions: high performance beam optics like permanent magnet quadrupoles...





...reaching many hundreds of T/m gradients, adequate for energies up to few hundreds MeV.

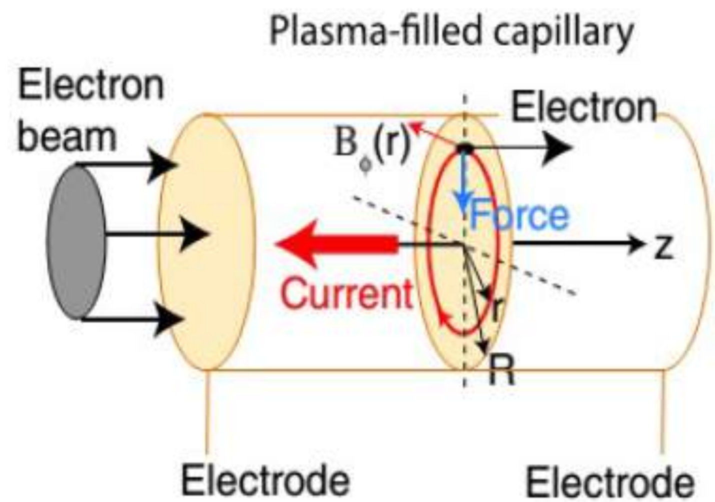
Active plasma lens

- Focusing field produced by electric discharge in a plasma-filled capillary
  - *Focusing field produced, according to Ampere's law, by the discharge current*

$$B_{\phi}(r)=\frac{1}{2}\int_{0}^{r}\mu_0 J(r')\,dr'$$

- ✔ Radial focusing
  - *X/Y planes are not dependent as in quads*
- ✔ Weak chromaticity
  - *Focusing force scales linearly with energy*
- ✔ Compactness
  - *Higher integrated field than quad triplets*
- ✔ Independent from beam distribution
  - *Not sensitive to longitudinal/transverse charge profile as in passive plasma lenses*

$$F_r = ec\left(\frac{\mu_o I_c}{2\pi R_c^2}\right)r = ecB'_{\vartheta}r$$

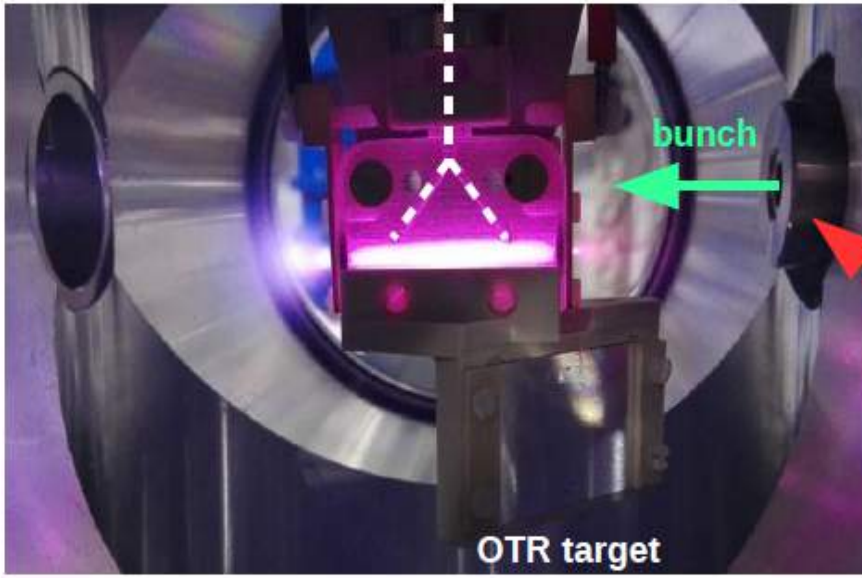


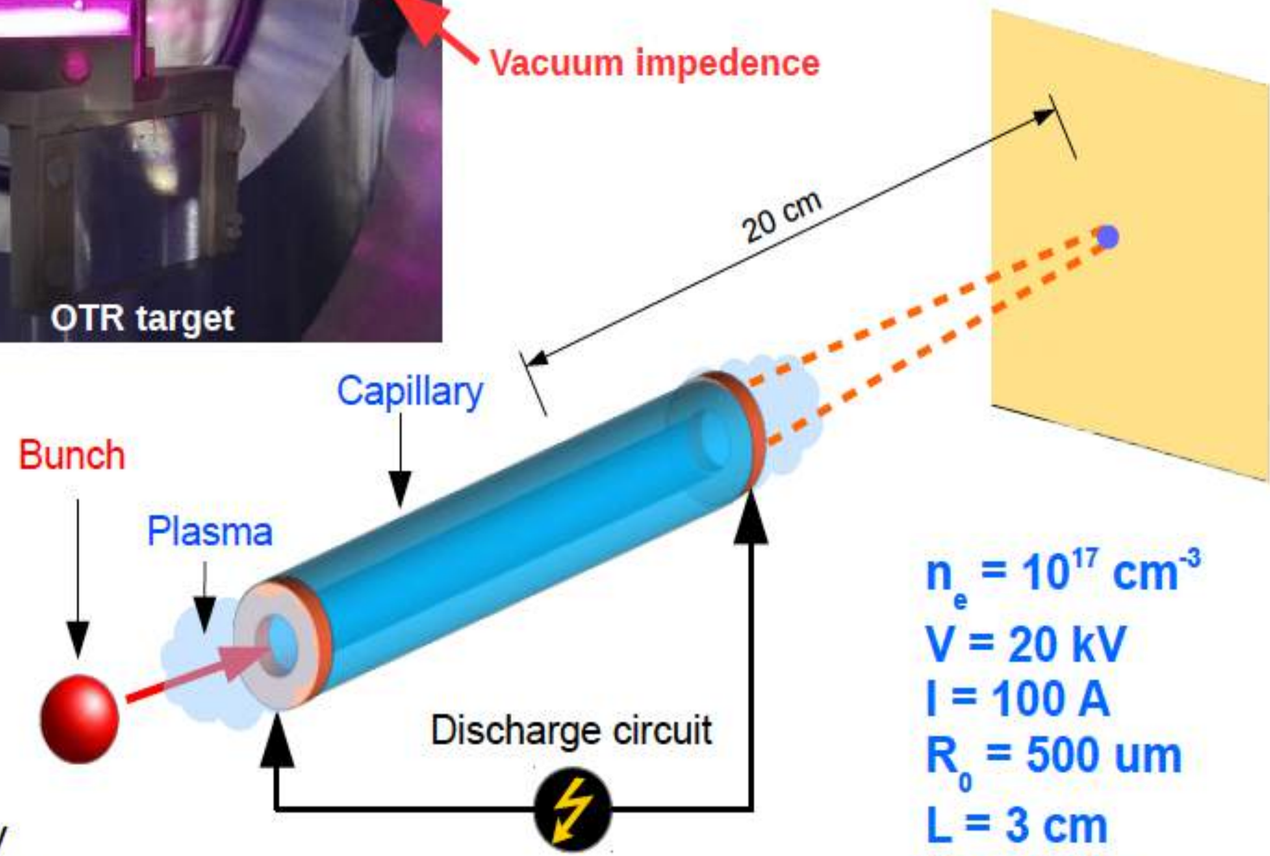
Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.

$$\frac{K_{cap}}{\gamma} = \frac{eB'_{\vartheta}}{\gamma mc} = \frac{2I_c}{\gamma I_A R_c^2}$$

Capillary Discharge

Experimental layout

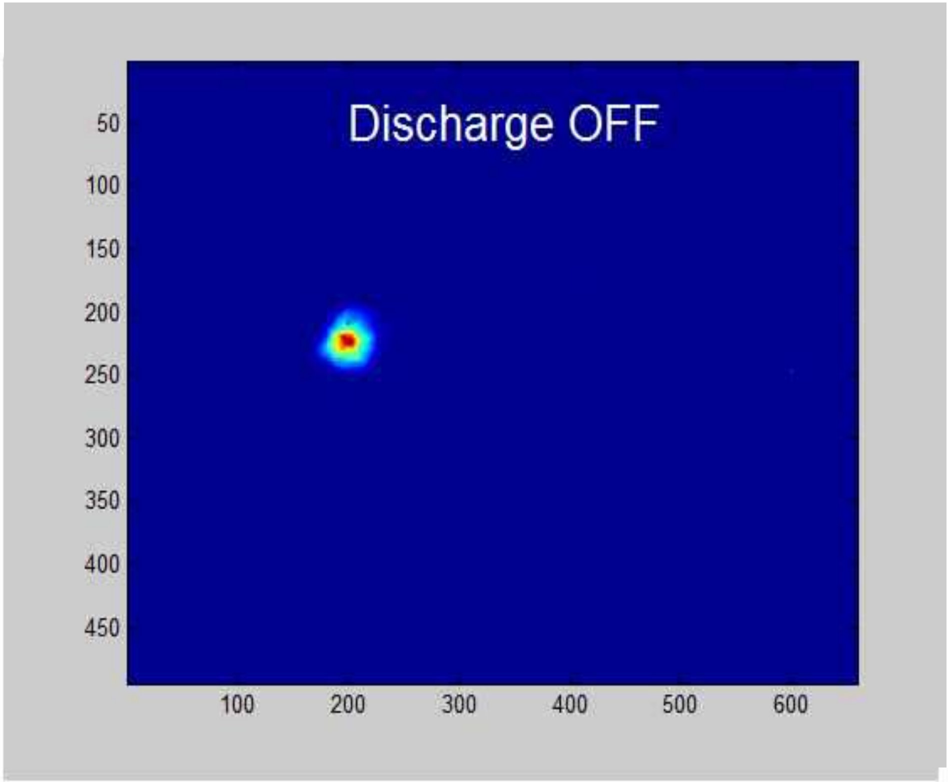


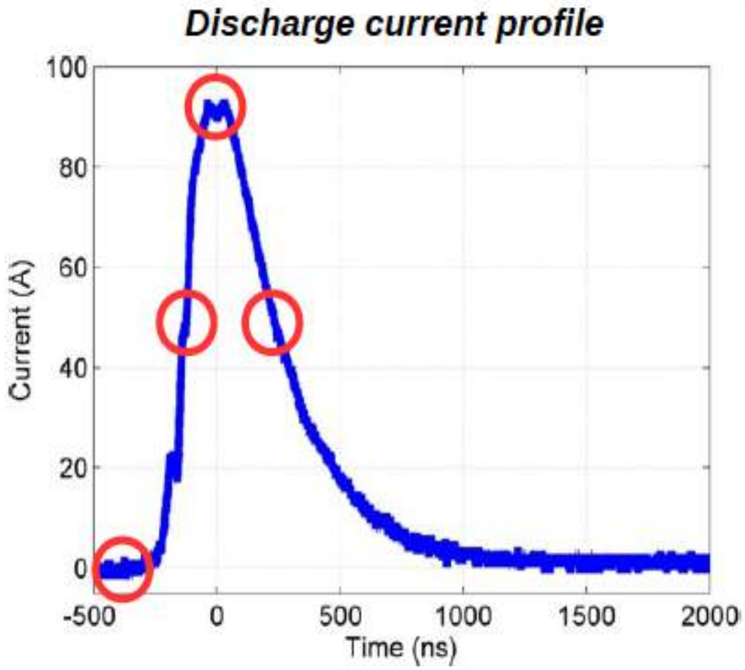


50 pC
1 ps
130 um
120 MeV
1 mm mrad

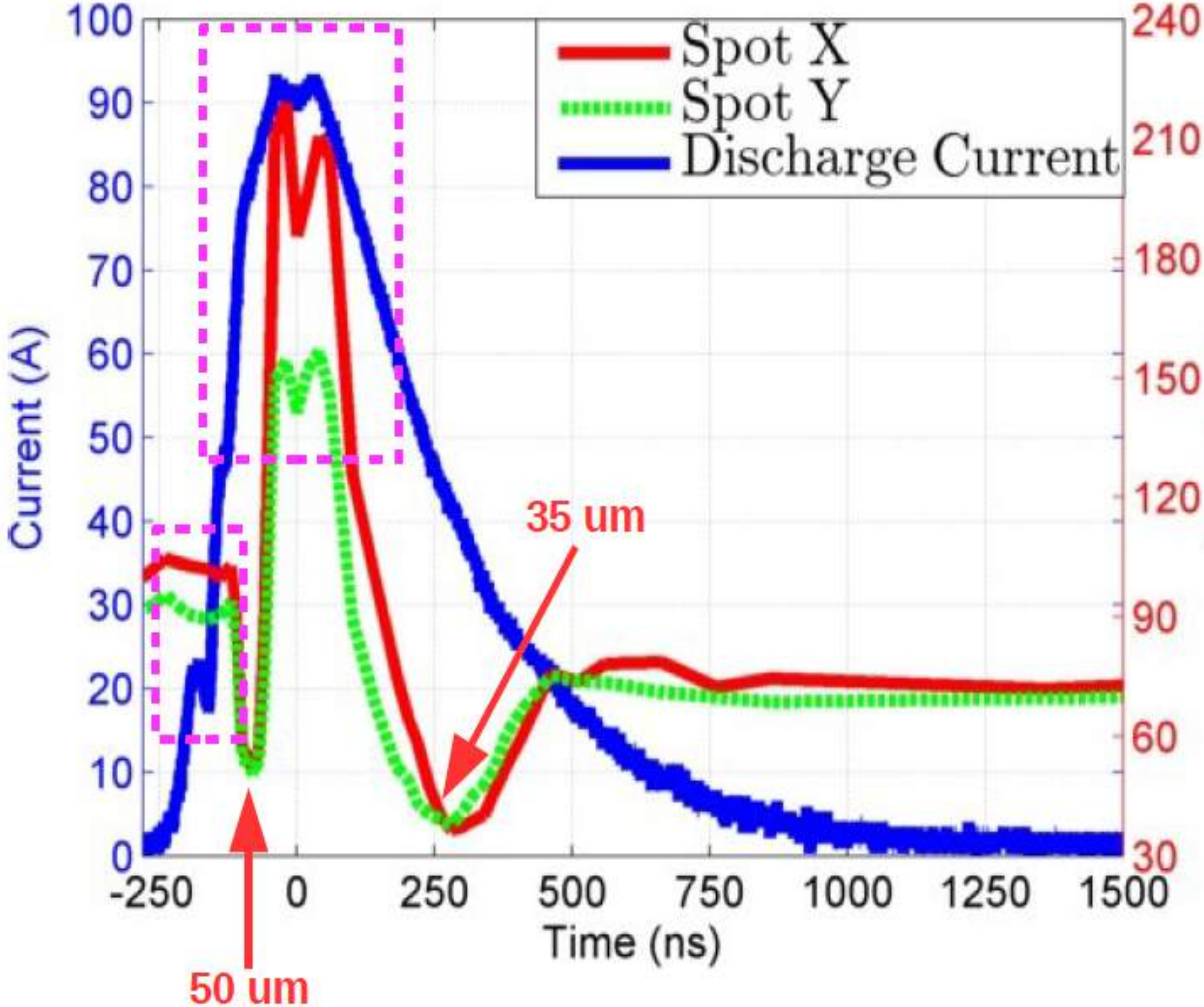
$n_e = 10^{17}$ cm^{-3}
V = 20 kV
I = 100 A
R_0 = 500 um
L = 3 cm
Sapphire

Preliminary results

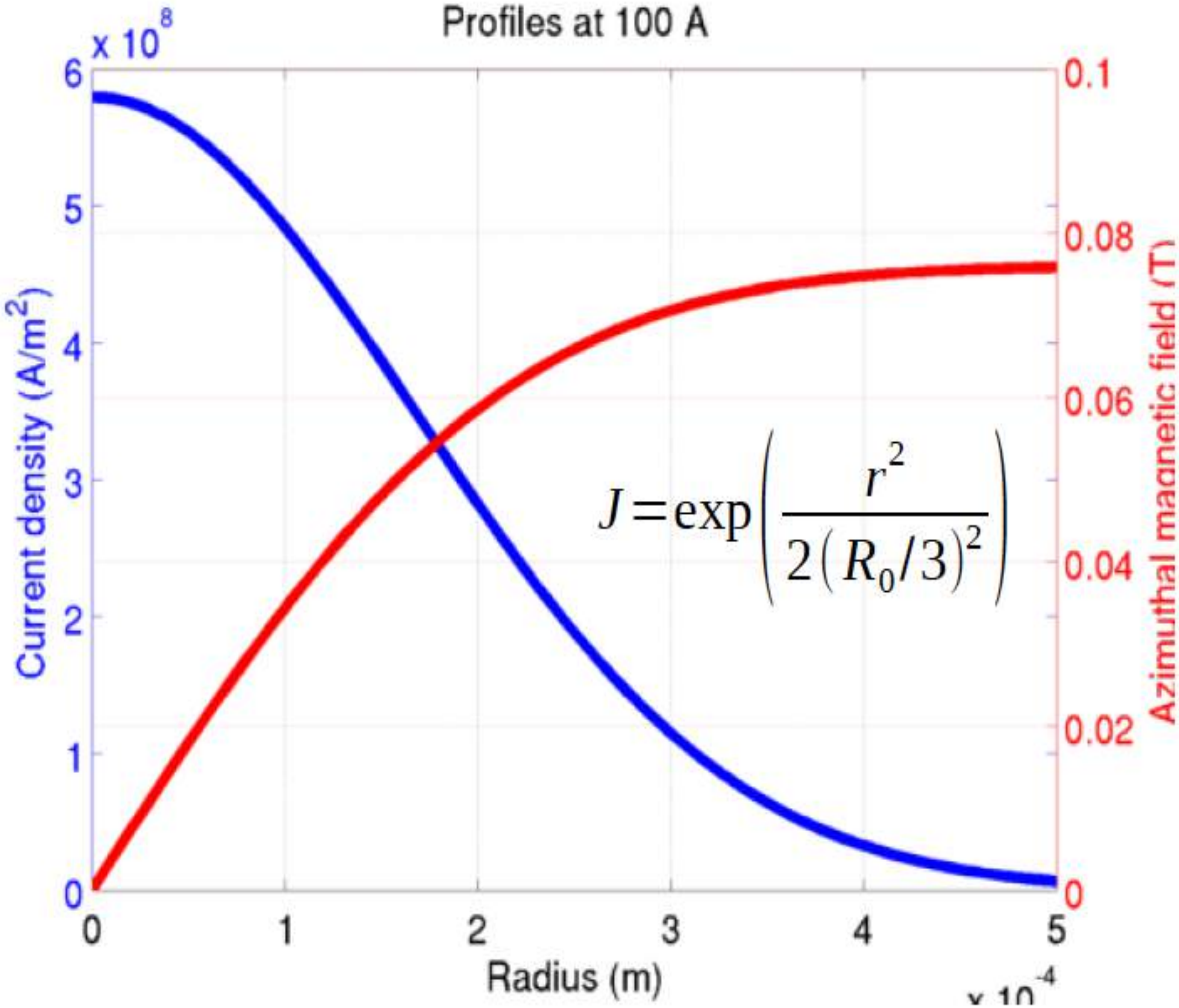




Preliminary results

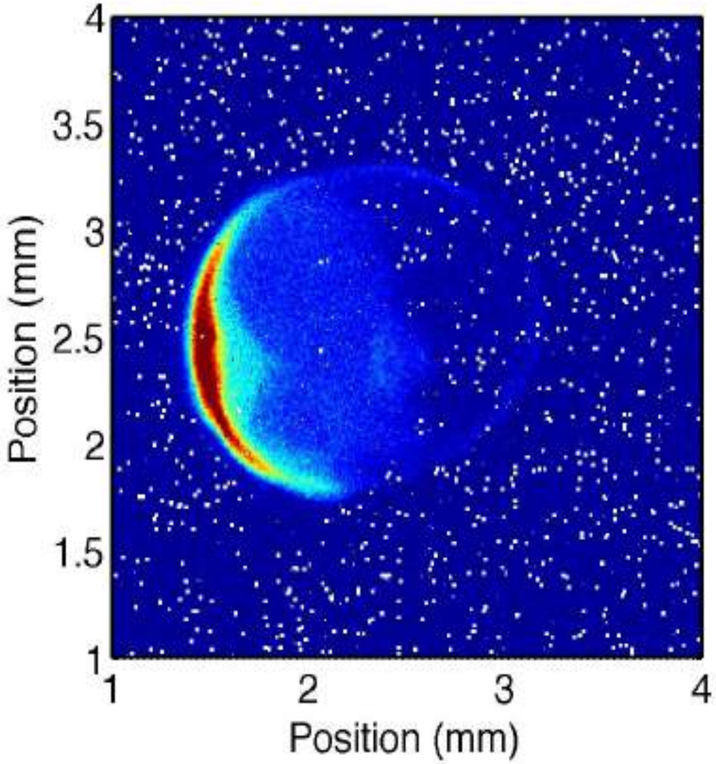


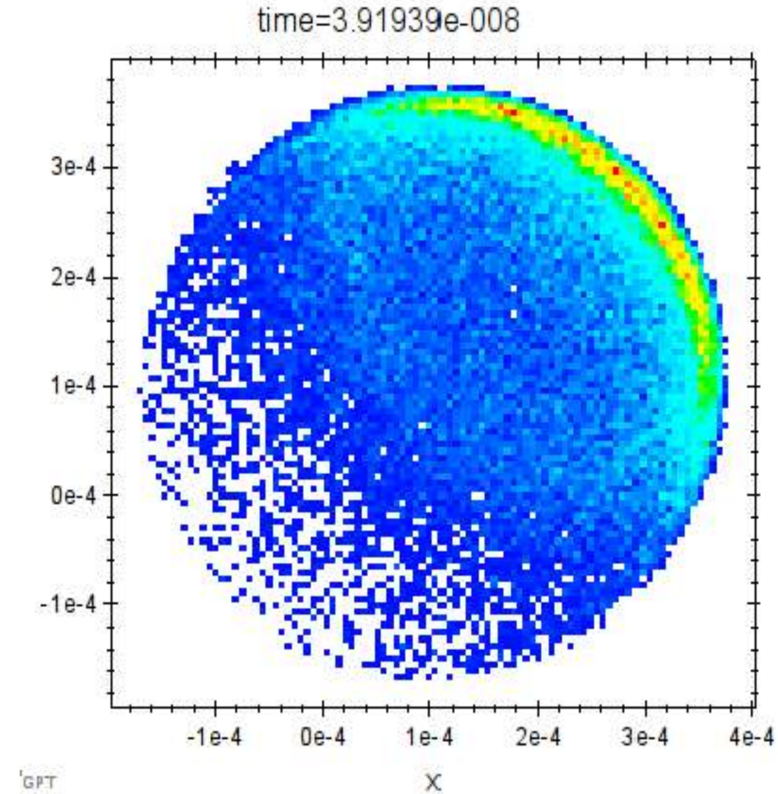
Gaussian current profiles



$$J = \exp\left(\frac{r^2}{2\left(R_0/3\right)^2}\right)$$

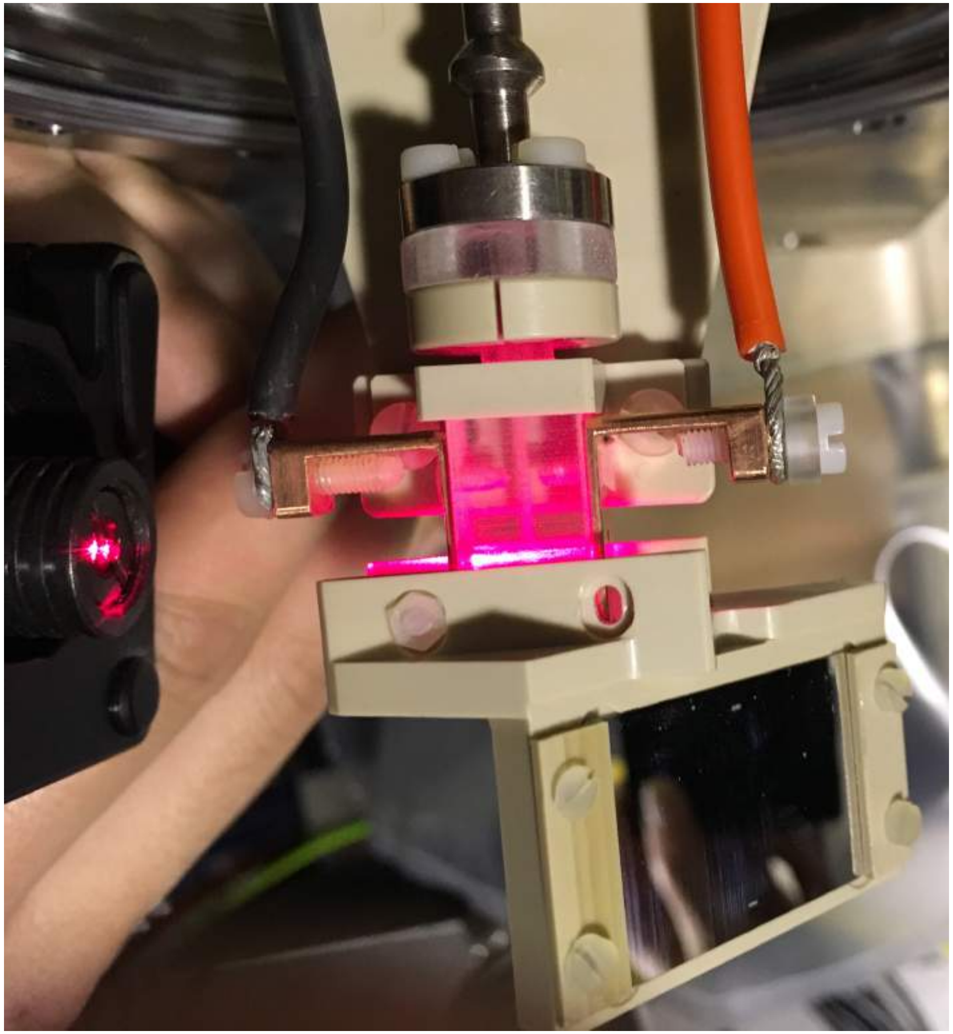
Over focusing (max current)



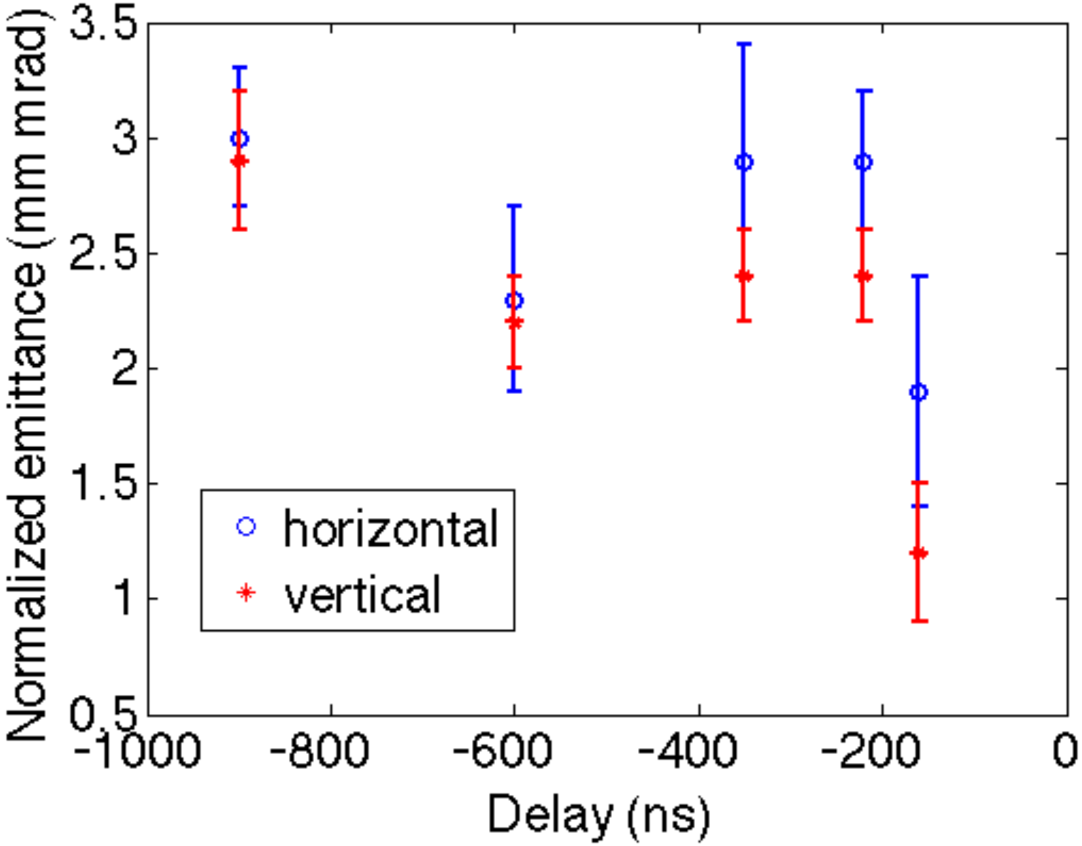


100 um offset

- **Second Run:** 1 cm long, 1 mm diameter, fully 3D printed capillary (ongoing)

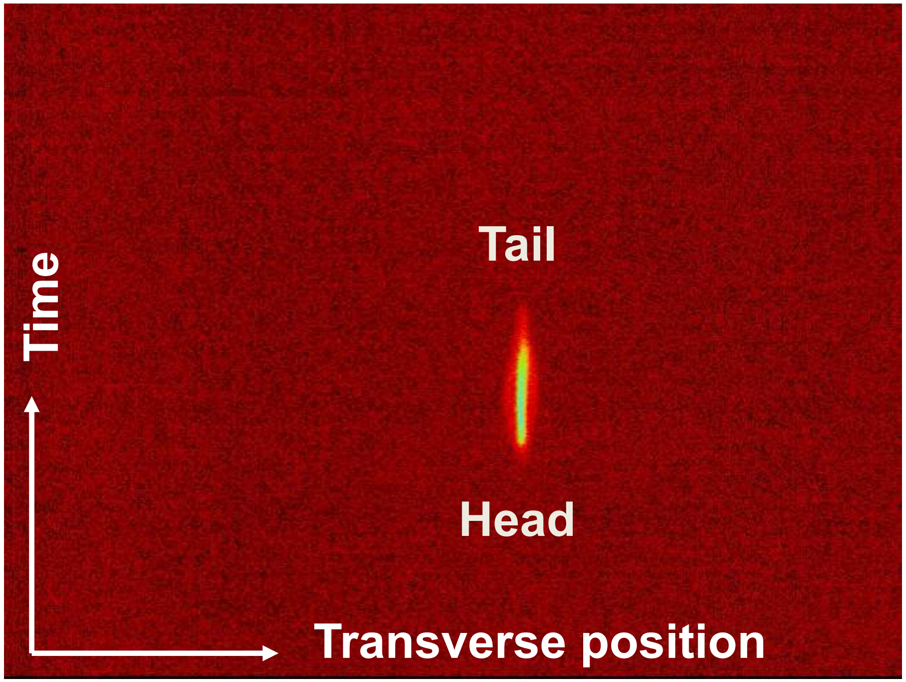


Electron beam parameters
50 pC (at the cathode)
85% transmission through the capillary
126 MeV (0.3‰ energy spread)
1 ps rms bunch length

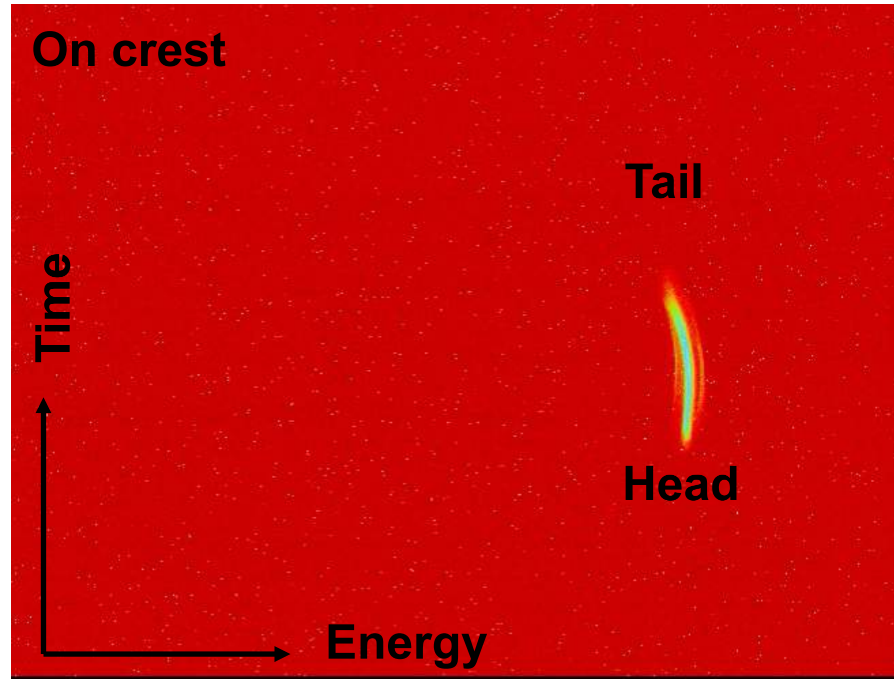


Head-tail instability induced by dielectric wakefield

RF Deflector on



Longitudinal phase space

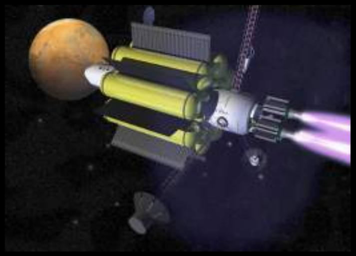


The tail is moving with respect to the head

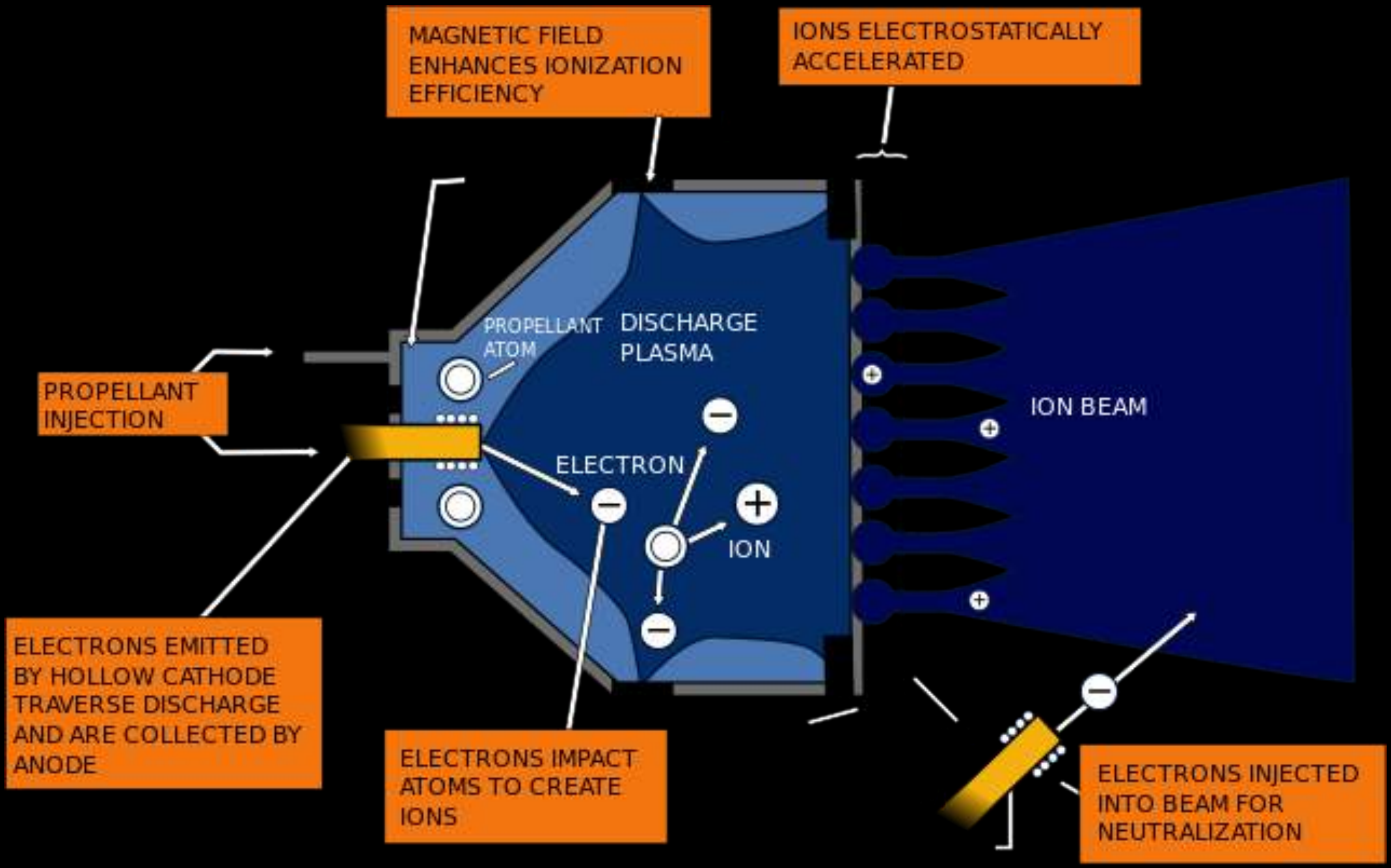
Induced energy spread

$$eE_{z,\mathrm{dec}} = eE_{r,\mathrm{surf}} \frac{\sqrt{\varepsilon_r - 1}}{\varepsilon_r} \cong -\frac{4N_b r_e m_e c^2}{a[\sqrt{(8\pi/\varepsilon_r - 1)}\varepsilon_r \sigma_z + a]},$$

Gridded electrostatic ion thrusters



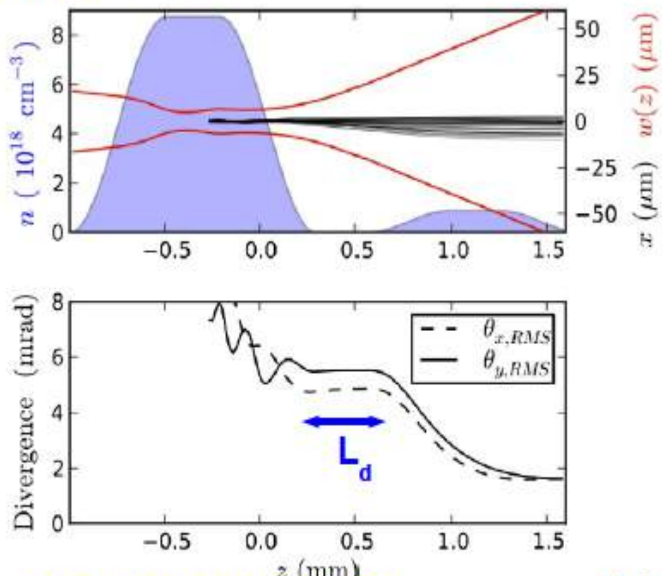
Possible discharge capillary rocket instability !?



Beam Manipulation

Stand alone, passive plasma lens: gas jet[1]

A gas jet, acting as plasma lens, is powered by the same laser extracting and accelerating the bunch



Density profile

$$n(z) = \begin{cases} n_1 & \text{for } z < 0 & \text{(First jet)} \\ 0 & \text{for } 0 < z < L_d & \text{(Drift space)} \\ n_2 & \text{for } L_d < z < L_d + L_2 & \text{(Second jet)} \end{cases}$$

Condition for optimal collimation*

$$\frac{\langle k_{\text{foc}} \rangle Z_R^2}{L_d + L_2} \tan\left(\frac{\langle k_{\text{foc}} \rangle Z_R^2}{L_d} - \frac{\langle k_{\text{foc}} \rangle Z_R^2}{L_d + L_2} \right) = 1$$

$$k_\beta = k_p / \sqrt{2\gamma}$$

Requires only one laser

Effective for energies up to

$$\gamma < \frac{3}{5} \frac{a_0^2 Z_R^4}{L_d^2 w_0^2}$$

Easily tuned for different bunches

Adequate acceptance

* this relation was derived assuming a constant emittance during drift.

Beam loading may reduce effectiveness.

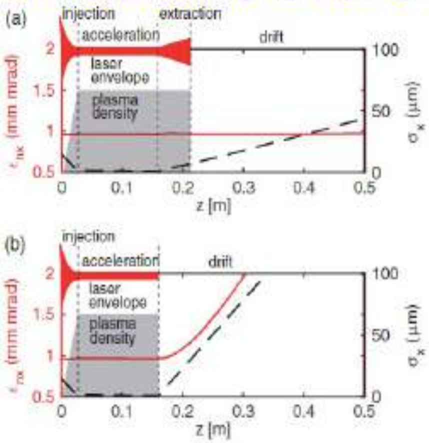
[1] R. Lehe, C. Thaury, E. Guillaume, A. Lifschitz, and V. Malka, Phys. Rev. STAB **17**, 121301 (2014)

Beam Manipulation

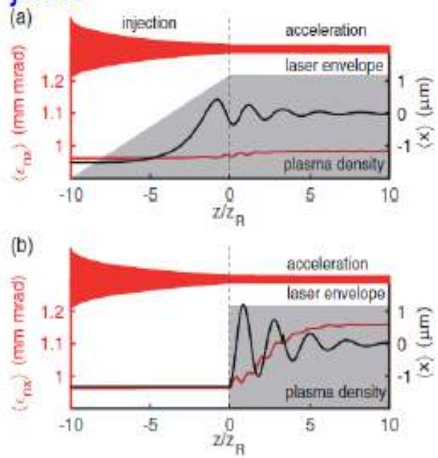
Integrated, passive plasma lens: plasma ramps & driver focusing/defocusing

A tapering at the end (beginning) of the plasma channel acts as a plasma lens and defocuses (focuses) the bunch performing matching. Moreover, the focusing (defocusing) of the driver helps in performing the process.

Emittance conservation and adiabatic focusing/defocusing

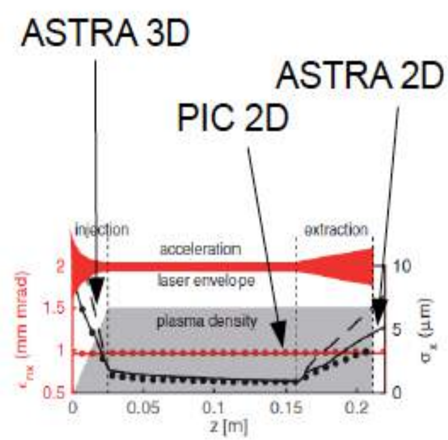


Tolerance to beam position jitters



Optimal focusing strength longitudinal profile

$$K(z) = K_0/(1 + gz)^4$$



Linear regime

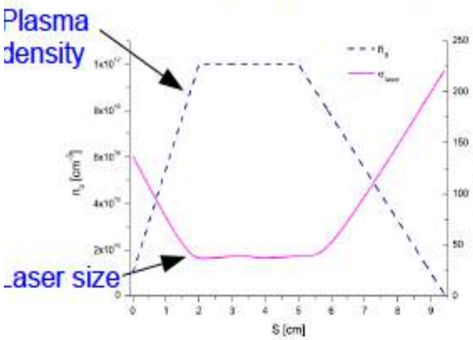
Negligible beam loading

I. Dornmair, K. Floettmann, and A. R. Maier, Phys. Rev. STAB **18**, 041302 (2015)

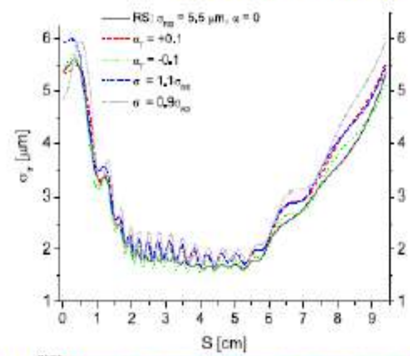
Beam Manipulation

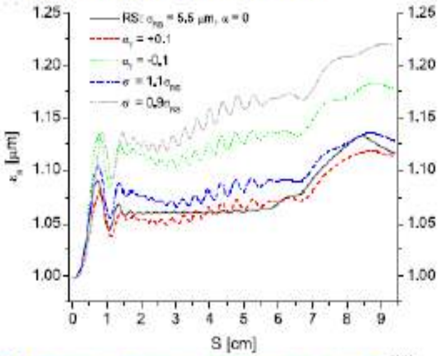
Integrated, passive plasma lens: plasma ramps & tailored driver focusing/defocusing in hollow capillary

A tapering at the end (beginning) of the plasma channel acts as a plasma lens and defocuses (focuses) the bunch performing matching. Moreover, the focusing (defocusing) of the driver is tailored to help in performing the process.

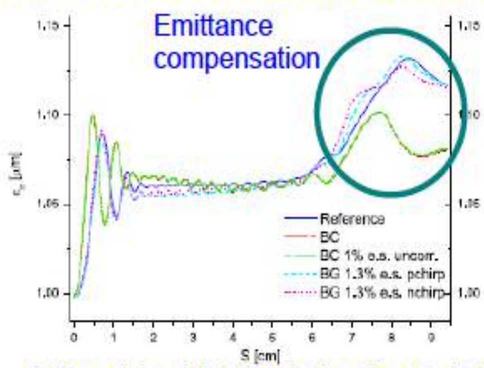


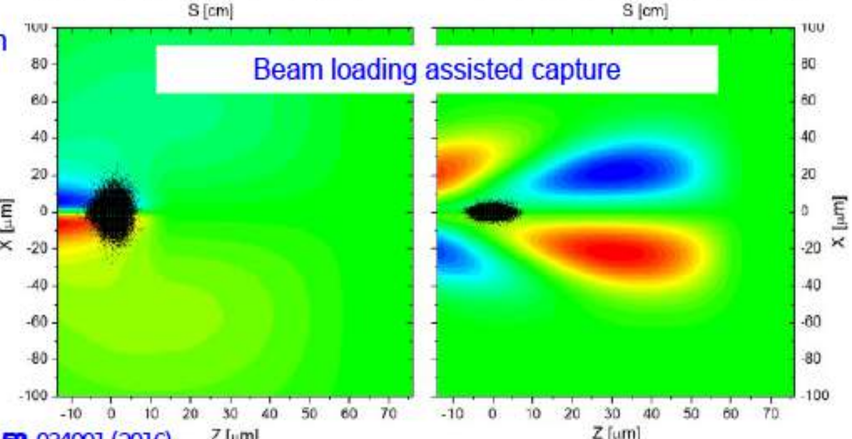
Stability vs injected beam parameters jitters





Stability vs injected beam charge distribution



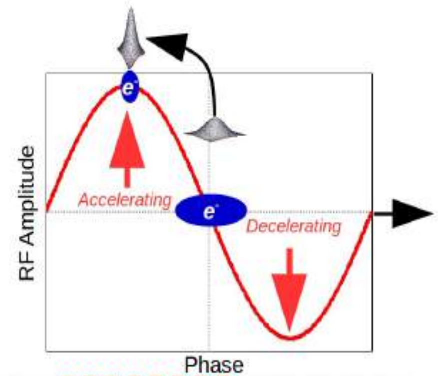


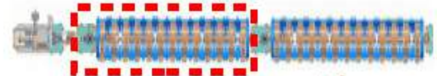
P. Tomassini and A.R. Rossi, Plas. Phys. Cont. Fus. **58**, 034001 (2016).
A.R. Rossi, et al., Nuc. Met. Phys. Res. A, http://dx.doi.org/10.1016/j.nima.2016.02.015 (in press)

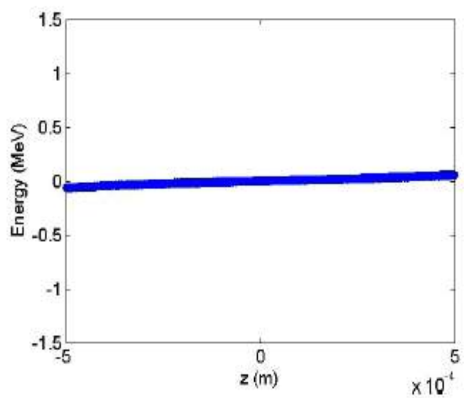
Longitudinal Beam Manipulation

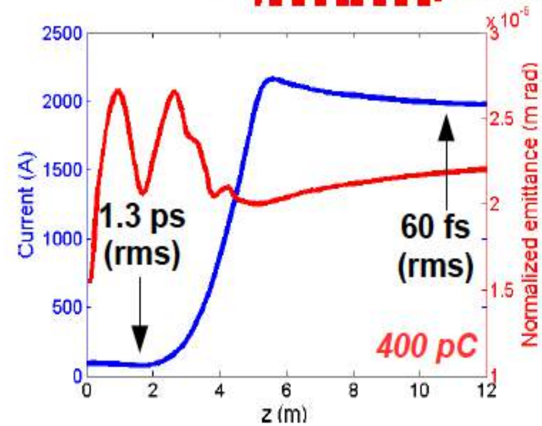
Ultra-short electron beams

- Current demands require high current beams
  - ✔ ***PWFA-LWFA***: *high wakefield amplitude (i.e. high driver density), low energy spread (i.e. short witness).*
  - ✔ ***Advanced radiation sources***: *high peak currents (FEL), short beams (broadband THz radiation).*
- Velocity bunching @ SPARC_LAB
  - ✔ *RF structure embedded in solenoid fields for* ***emittance compensation***







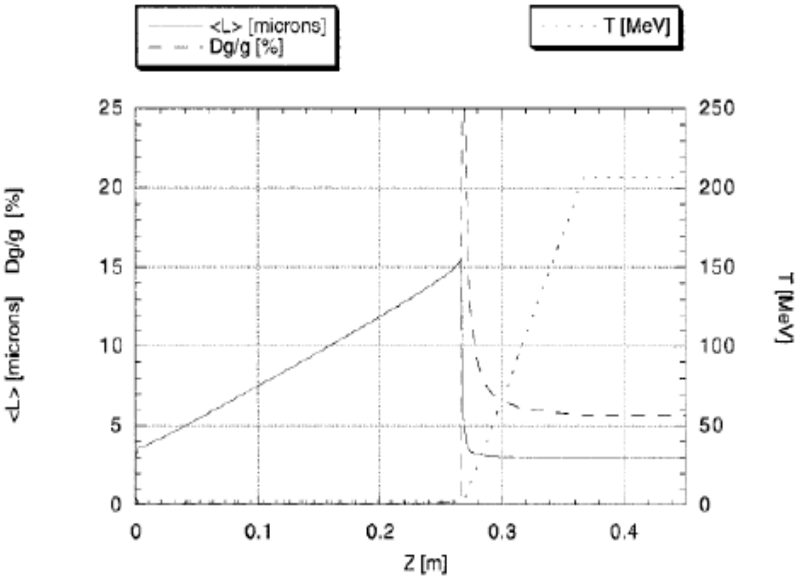


Serafini, L., M. Ferrario. "Velocity bunching in photo-injectors." AIP conference proceedings. 2001.
Ferrario, M.et al. "Experimental demonstration of emittance compensation with velocity bunching." PRL 104.5 2010.

Longitudinal Beam Manipulation

Longitudinal compression

Longitudinal compression is possible when a bunch has an energy much lower than the resonant one, i.e. when the witness is (initially) much slower than the plasma wake[1], by velocity bunching[2].



M. Ferrario, T. C. Katsouleas, L. Serafini, and Ilan Ben Zvi, IEEE Trans. Plas. Sci. 28, (2000).

- Linear regime
- No beam loading

Further readings:

- S.V. Kuznetsov and N.E. Andreev, Plas. Phys. Rep. **27**, 372 (2001).
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- S.V. Kuznetsov, Plas. Phys. Rep. **32**, 282 (2006).
- N.E. Andreev, et al., Nuc. Inst. Meth. Phys. Res. A **653**, 66 (2011).

[1] J.L. Bobin, in Proc. of the ECFA-CAS/CEFN-In-2P3-IRF/CEA-EPS Workshop, p. 58 (1987). C.S. Liu and V.K. Tripathi, *Interaction of electromagnetic waves with electron beams and plasmas*, World Scientific, Singapore, 1994.

[2] L. Serafini and M. Ferrario, LNF-00/036, 2000. L. Serafini and M. Ferrario, AIP Conf. Proc. **581**, 87 (2001).

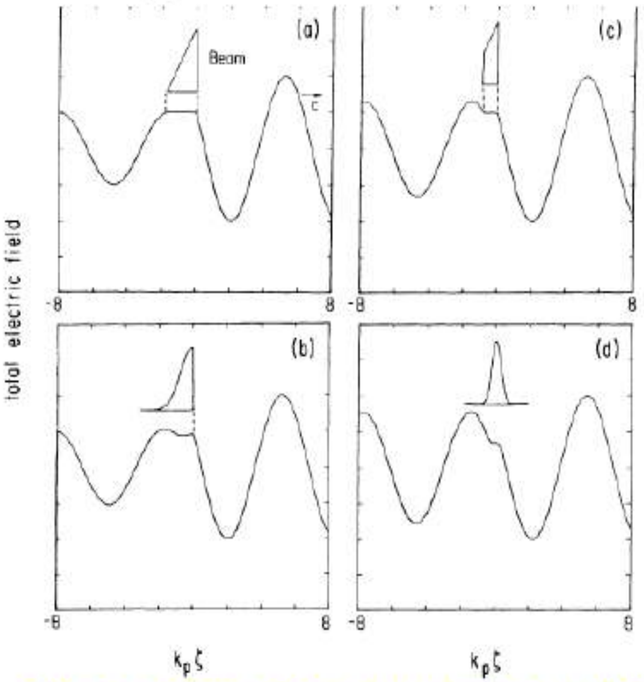
Longitudinal Beam Manipulation

Energy spread control by beam loading

One way to limit energy spread in plasma is to "flatten out" the longitudinal field along the bunch by properly tailoring the beam loading.

Optimal beam profile for linear regime

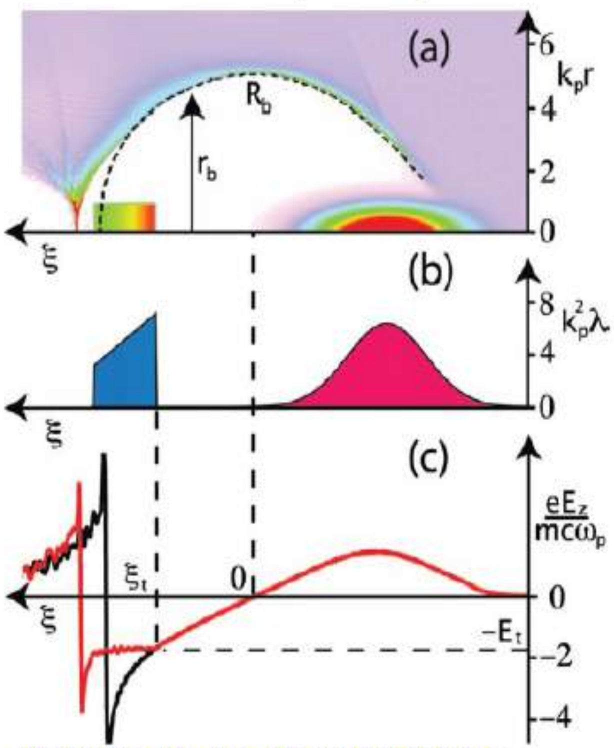
$$\rho_b(\zeta) = -\frac{k_p E_0}{4\pi}[(k_p \cos k_p\zeta_0)\zeta + (\sin k_p\zeta_0 - k_p\zeta_0 \cos k_p\zeta_0)]$$



T. Katsuleas, S. Wilks, P. Chen, J. M. Dawson and J. J. Su, Particle Accelerators **22**, 81 (1985)

Optimal beam profile for non-linear regime

$$\lambda(\xi) = E_t^2 + \frac{r_b^2}{4} = \frac{R_b^4 + r_t^4}{8r_t^2} - \sqrt{\frac{R_b^4 - r_t^4}{8r_t^2}}(\xi - \xi_t)$$



M. Tzoufras, et al., Phys. Plas. **16**, 056705 (2009)

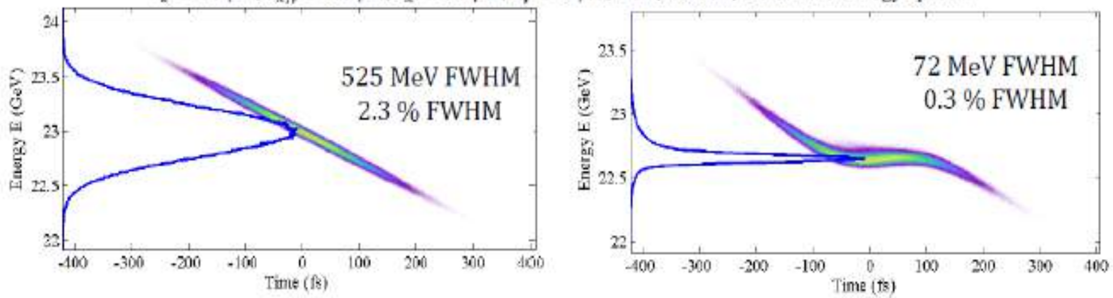
Longitudinal Beam Manipulation

Energy spread control by plasma dechirper[1]

Following the idea of corrugated pipe dechirper[2], it is possible to arrange plasma density in order to act as a plasma dechirper.

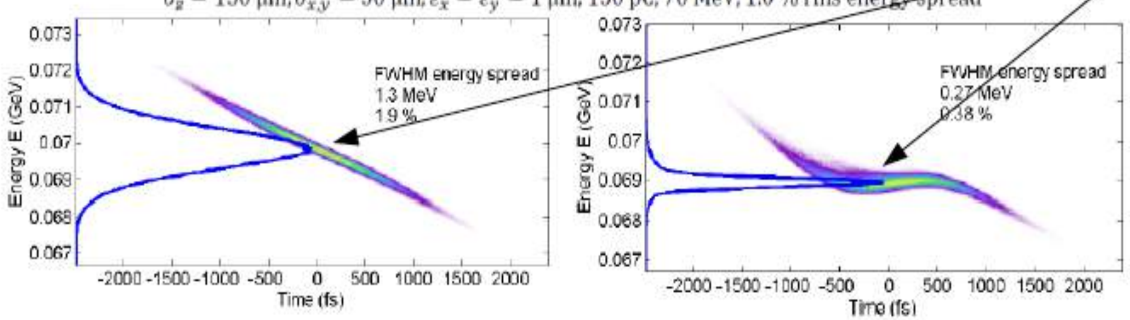
FACET beam parameters

$\sigma_z = 25\ \mu m, \sigma_{x,y} = 30\ \mu m, \varepsilon_x = 50\ \mu m, \varepsilon_y = 5\ \mu m$, 2 nC, 23 GeV, 1.0 % rms energy spread



ATF beam parameters:

$\sigma_z = 150\ \mu m, \sigma_{x,y} = 50\ \mu m, \varepsilon_x = \varepsilon_y = 1\ \mu m$, 150 pC, 70 MeV, 1.0 % rms energy spread



Works only for positive chirps

Uncorrelated energy spread is (irreversibly) increased

Tuning may still be quite critical

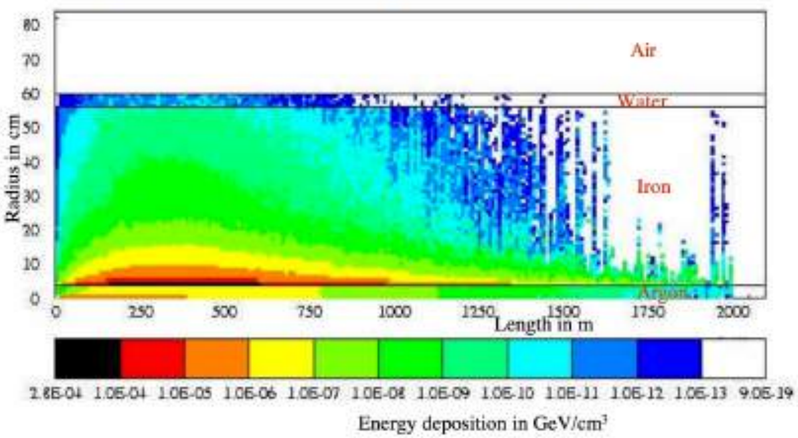
[1] V. Wacker, private communication (2015).
[2] K.L.F. Bane and G. Stupakov, Nuc. Inst. Meth. Phys. Res. **690**, 106 (2012). S. Antipov, et al., Phys. Rev. Lett. **112**, 114801 (2014).

Plasma beam dump-a comparison

Conventional beam dumps use high density materials – metal, water etc. They require high power density cooling, can produce radionuclides and (for water) explosive gasses through decomposition.
Stopping a beam with a low density material could have advantages.

Noble gas beam dump

A. Leuschner, LC-ABD dump meetings, Sept. 2005



- Very long length, but low power density.
- Reduced radionuclide production.
- No hydrogen/oxygen gas production.

Plasma beam dump

H.C. Wu, T. Tajima et al. PR-STAB 13, 101303 (2010)

- High decelerating gradients with low density dump medium.
- Effectiveness depends on bunch parameters.
- Possibility for electrical energy recovery.
- Cannot decelerate bunch head.

3 Steps towards a reliable PWA

① High Gradient – Low e- Beam Quality

② High e+e- Beam Quality – Low Gradient

③ High e+e- Beam Quality - High Gradient


The dawn of a new accelerator technology
Thank you for your attention